UNIVERSITÀ DEL SALENTO

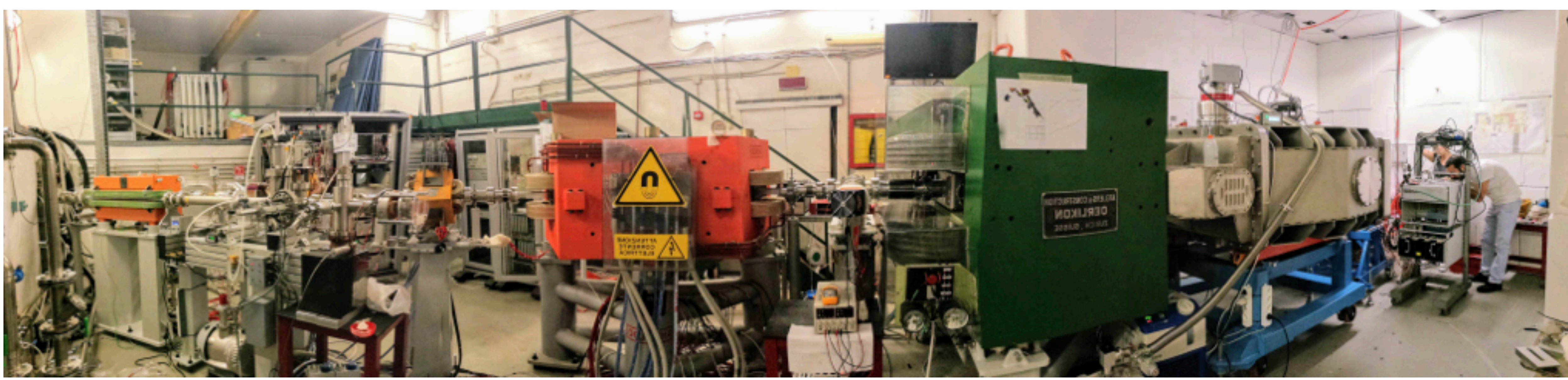
INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI LECCE

PADME

THE PADME EXPERIMENT

Isabella Oceano on behalf of PADME collaboration

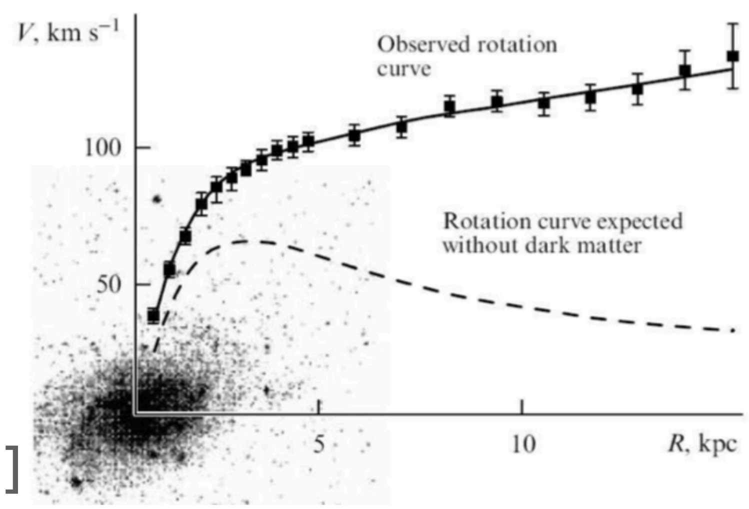
58. International Winter Meeting on Nuclear Physics



[1]arXiv:1710.10630
[2]DOI: 10.1103/PhysRevD.78.104004
[3]arXiv:1608.03591

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
  - Anomalies in nuclear transition
  - …



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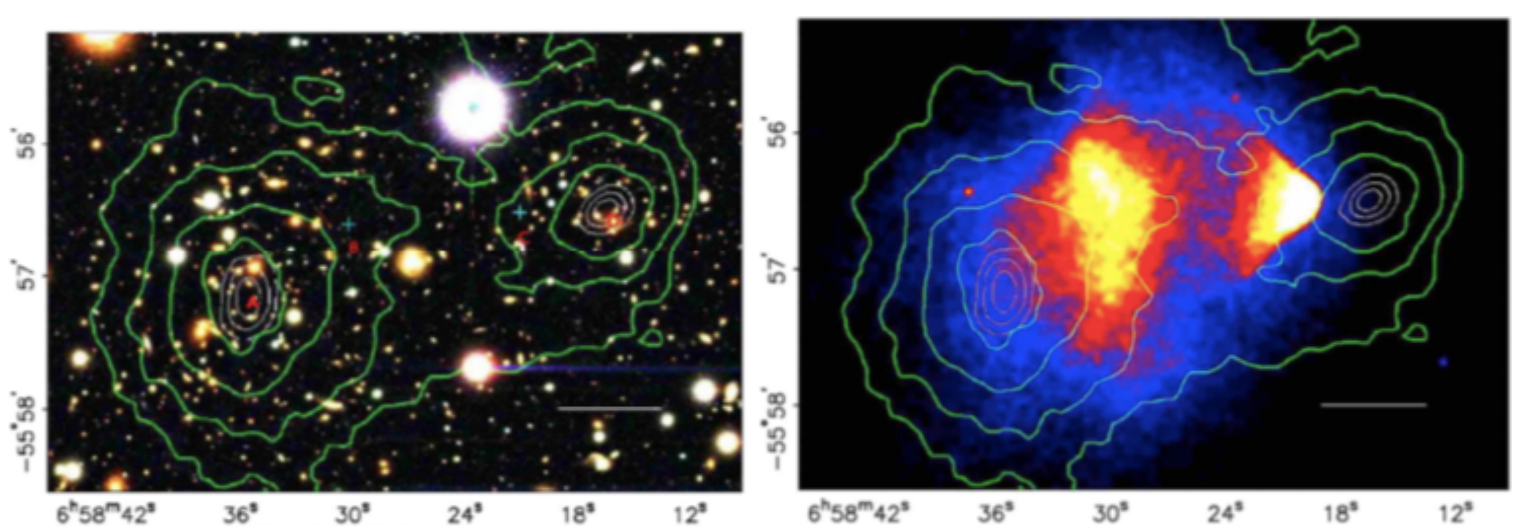
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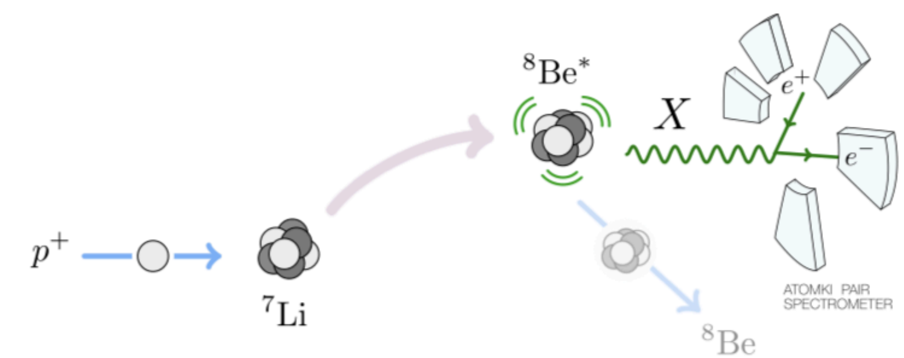


[3]

A NEW GAUGE BOSON

[1]arXiv:1608.0863

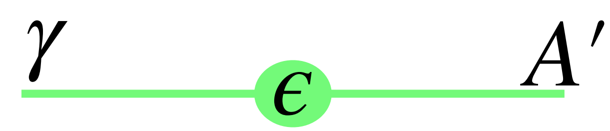
- The WIMP paradigm is challenged by LHC. A new idea introduces a hidden sector of particles interacting through a portal with the particles of the visible sector.

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

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

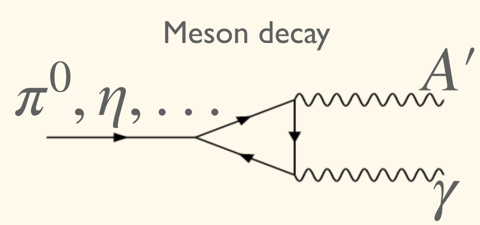
- Very weak interaction with the standard model particles via dark photon - photon mixing

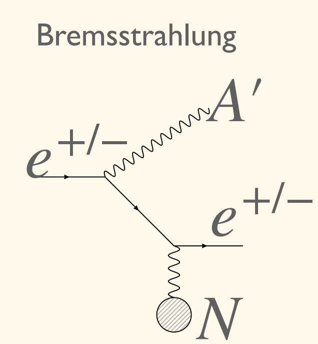
$$L_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

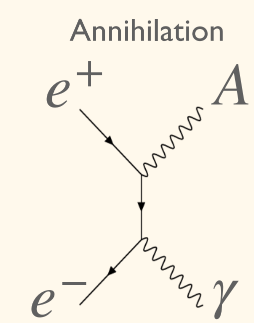


ϵ : kinetic mixing coefficient

Production mechanisms
– Meson decays
– Bremsstrahlung
– Annihilation

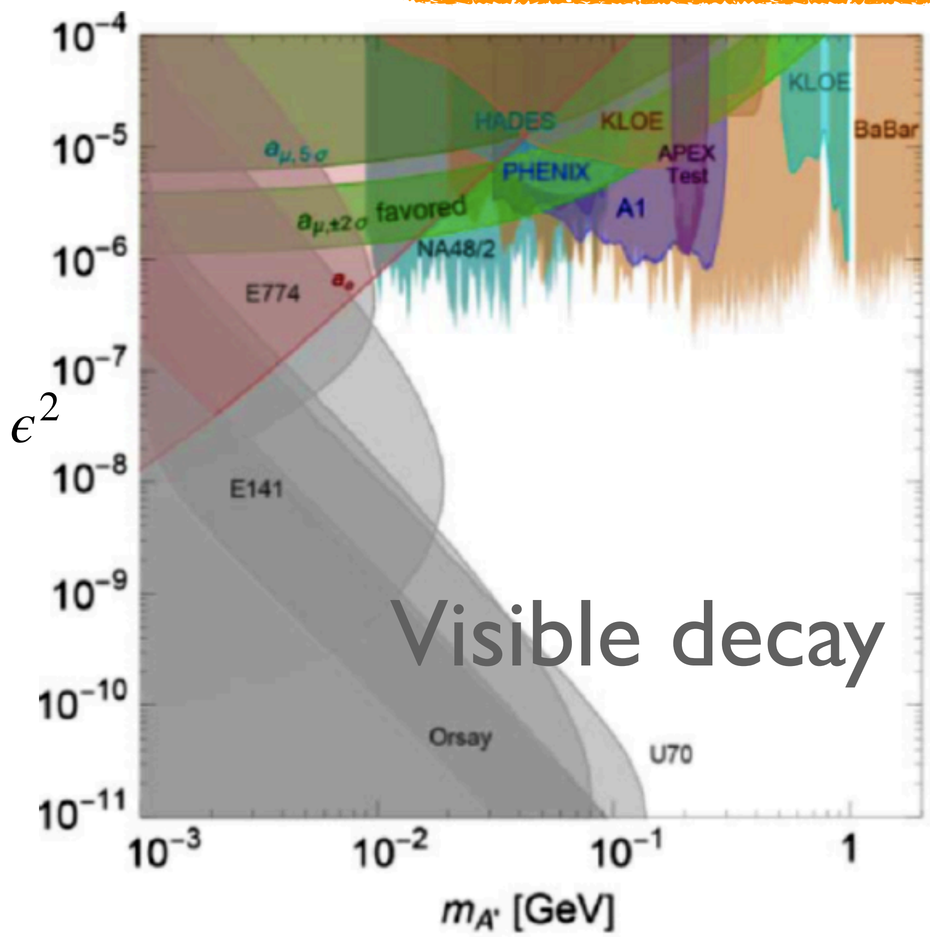


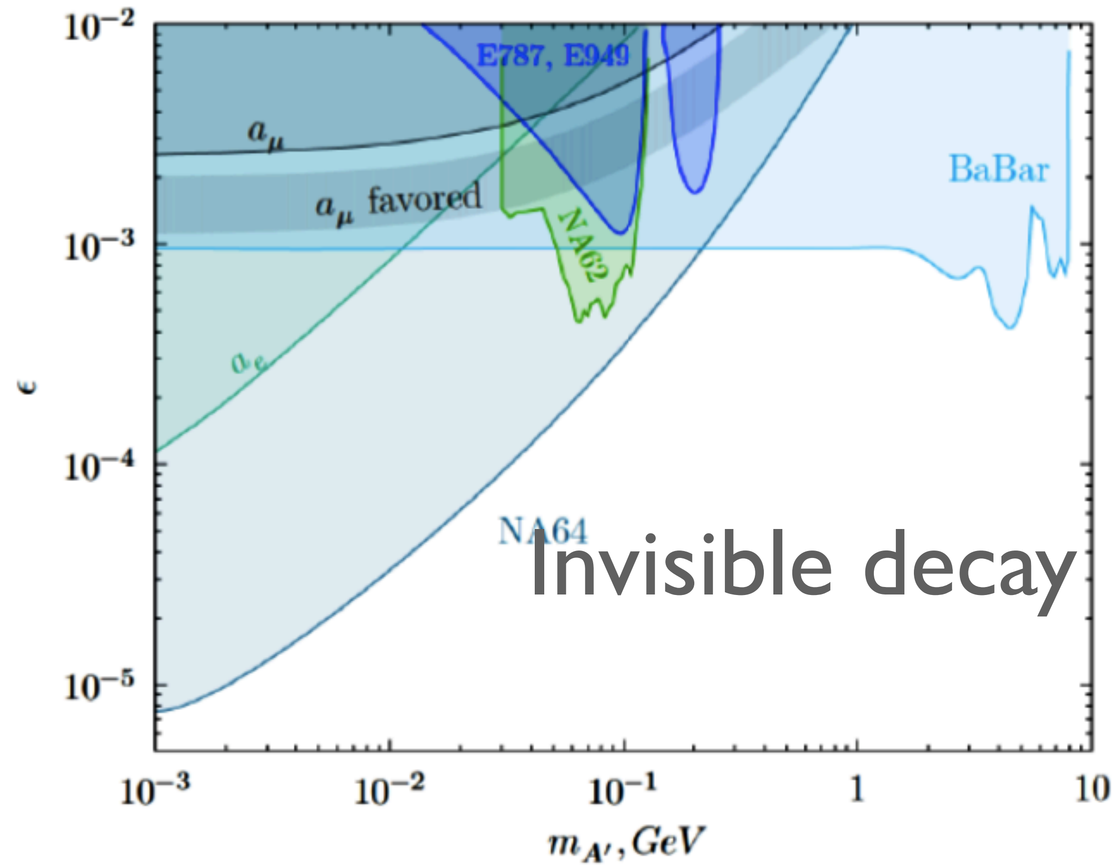




A' PARAMETER SPACE

Decays
– To SM model particles if $M_{DM} > M_{A'}$
– To DM (invisible) particles if kinematically allow



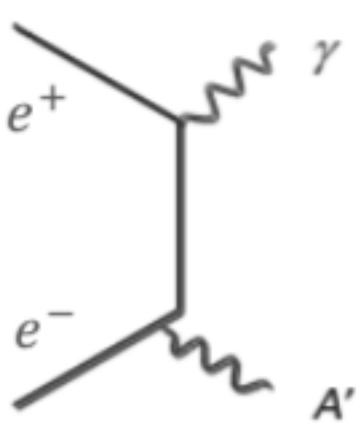


- searches into visible decay modes
  - e+e- colliders
  - e- or p beam+dump / thick target
  - e- beam + thin target
  - LHC

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

THE APPROACH OF PADME

- A' search in e+e- annihilations looking for missing mass (invisible decay) in a kinematically constrained condition
  - A positron beam on a fixed target may produce a photon and a dark photon
  - The invisible dark photon escapes detection
  - Photon momentum measured by an electromagnetic calorimeter
  - A' mass inferred from energy momentum conservation.



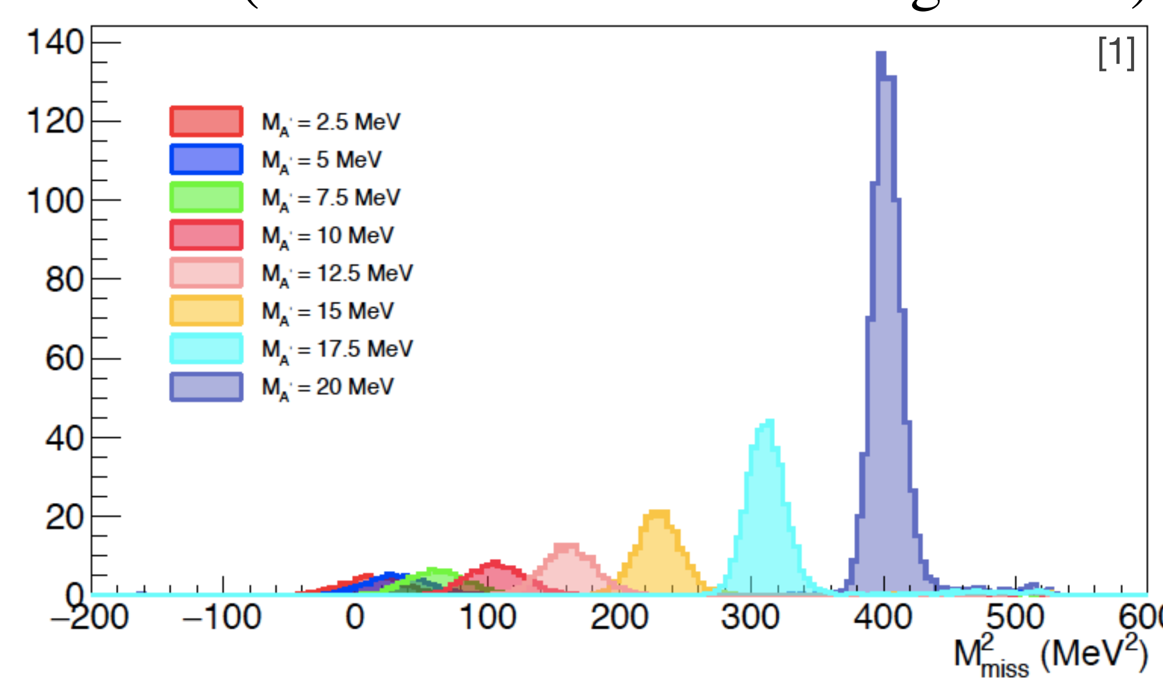
Possible A' production process

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

Detection though the missing mass method

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

$(4 \times 10^{13}$ Positron On Target POT)



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

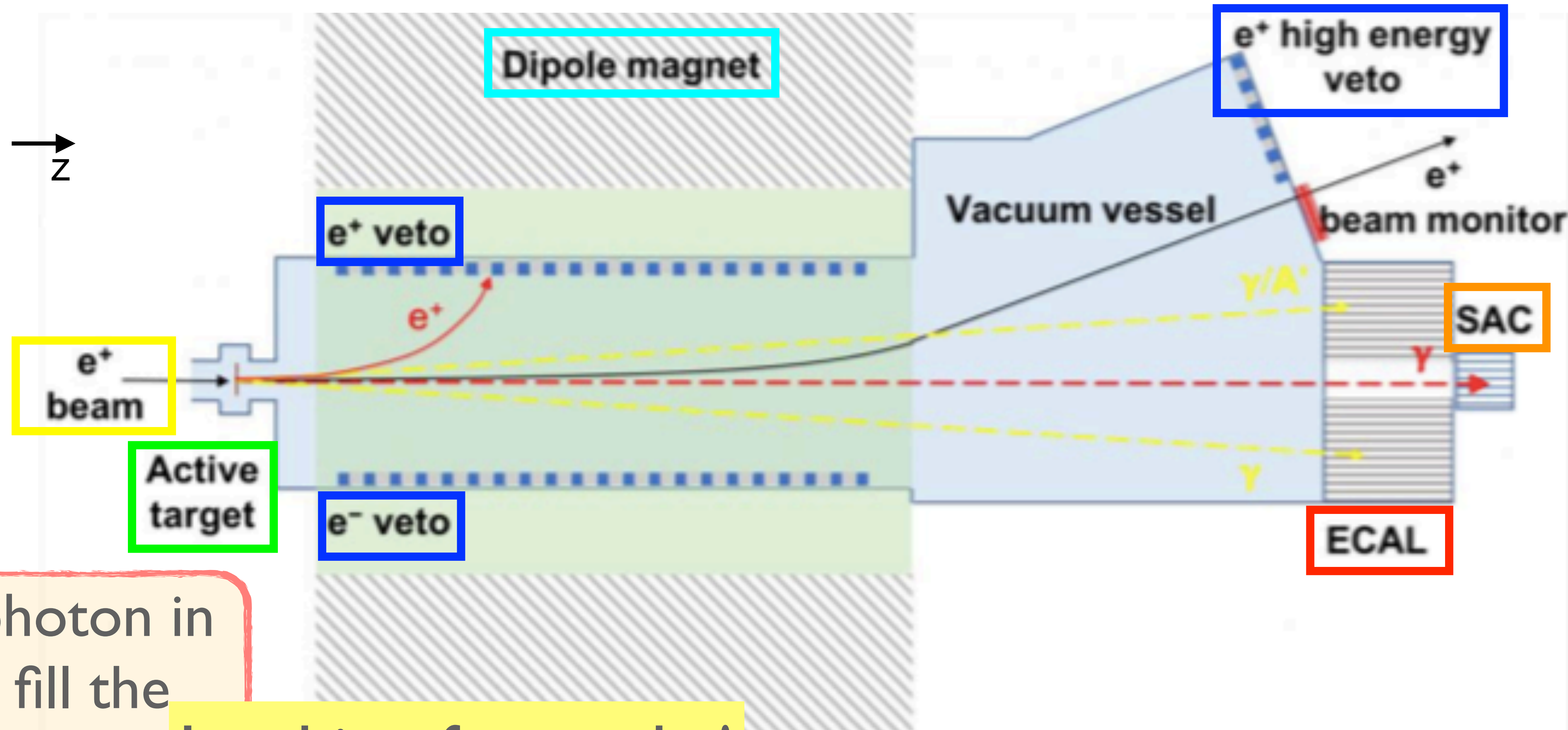
$M_{A'} = 10$ MeV

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

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 mm²) is used.
- Behind ECAL the Small Angle Calorimeter (SAC), made of a 5 x 5 PbF_2 crystals, readout based on fast photomultipliers.



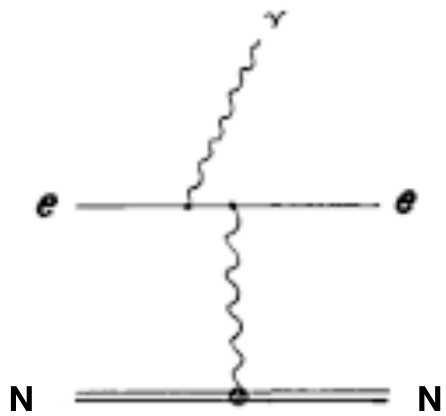
Events with only a photon in ECAL are used to fill the missing mass spectrum

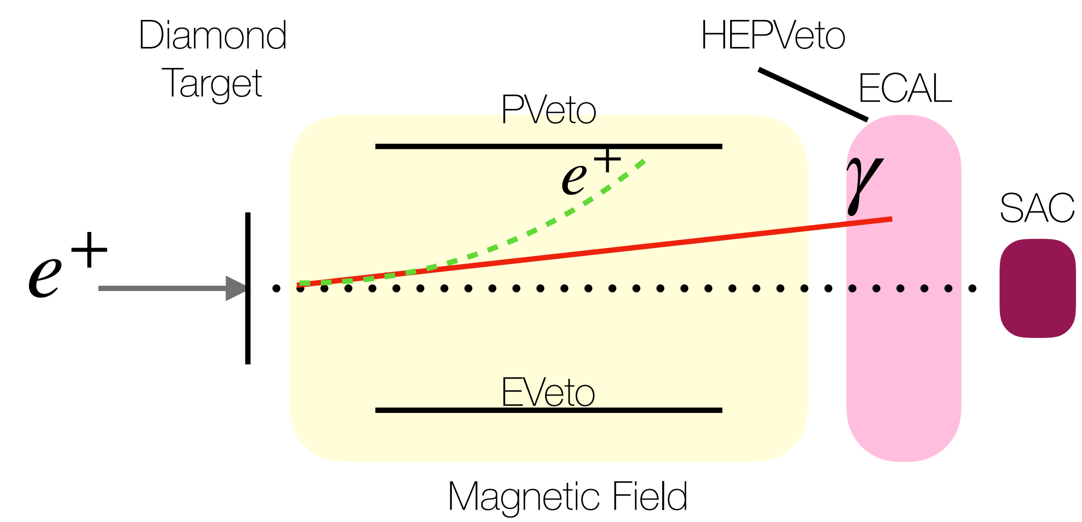
Looking for peaks!

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}

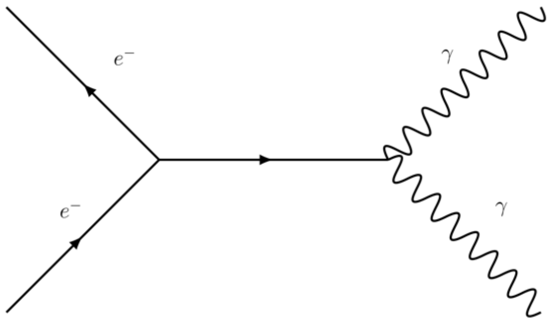
$$\sigma(e^+N \rightarrow e^+N\gamma) = 4000 \text{ mb} \qquad E_\gamma > 1 \text{ MeV}$$



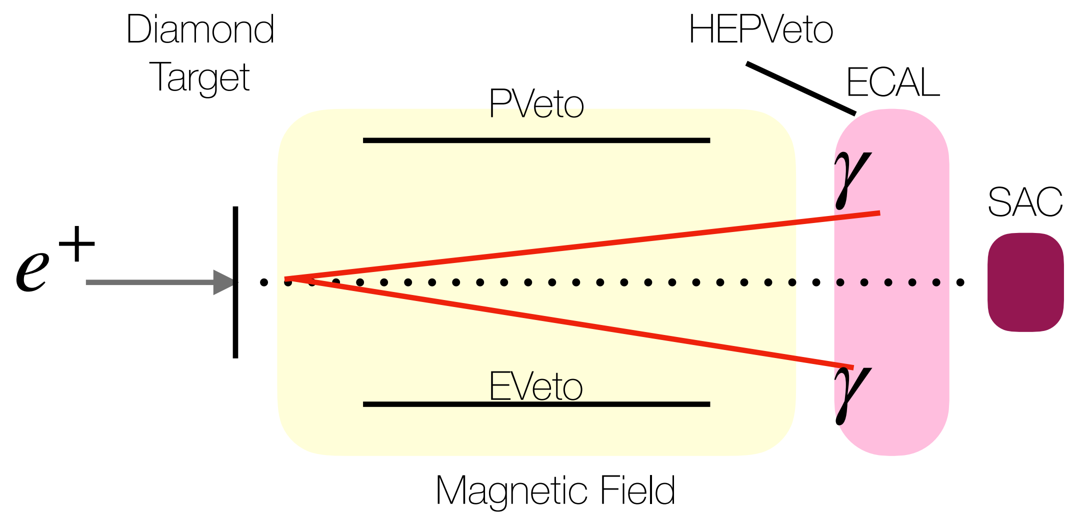


Backgrounds

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

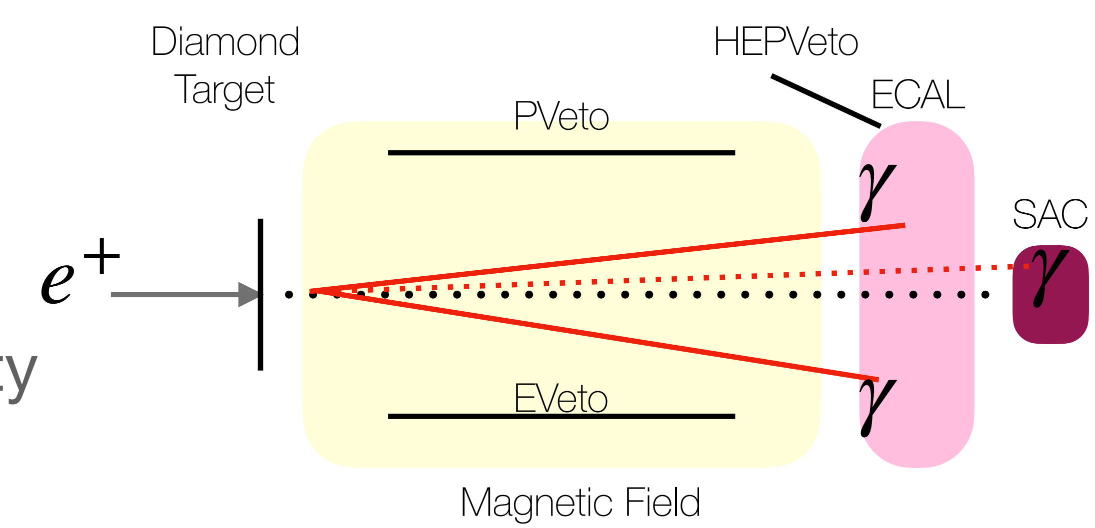


$\sigma(e^+e^- \rightarrow \gamma\gamma) = 1.55$ mb



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}
- 2 photon annihilation $e^+e^- \rightarrow \gamma\gamma$
  - symmetric in gamma azimuth; correlated energy and theta
  - Photon inefficiency gives $M_{miss} = 0$ MeV
- 3 photon annihilation $e^+e^- \rightarrow \gamma\gamma\gamma$
  - $2\ \gamma$ symmetry is lost – reduced veto capability
  - Non peaking M_{miss}



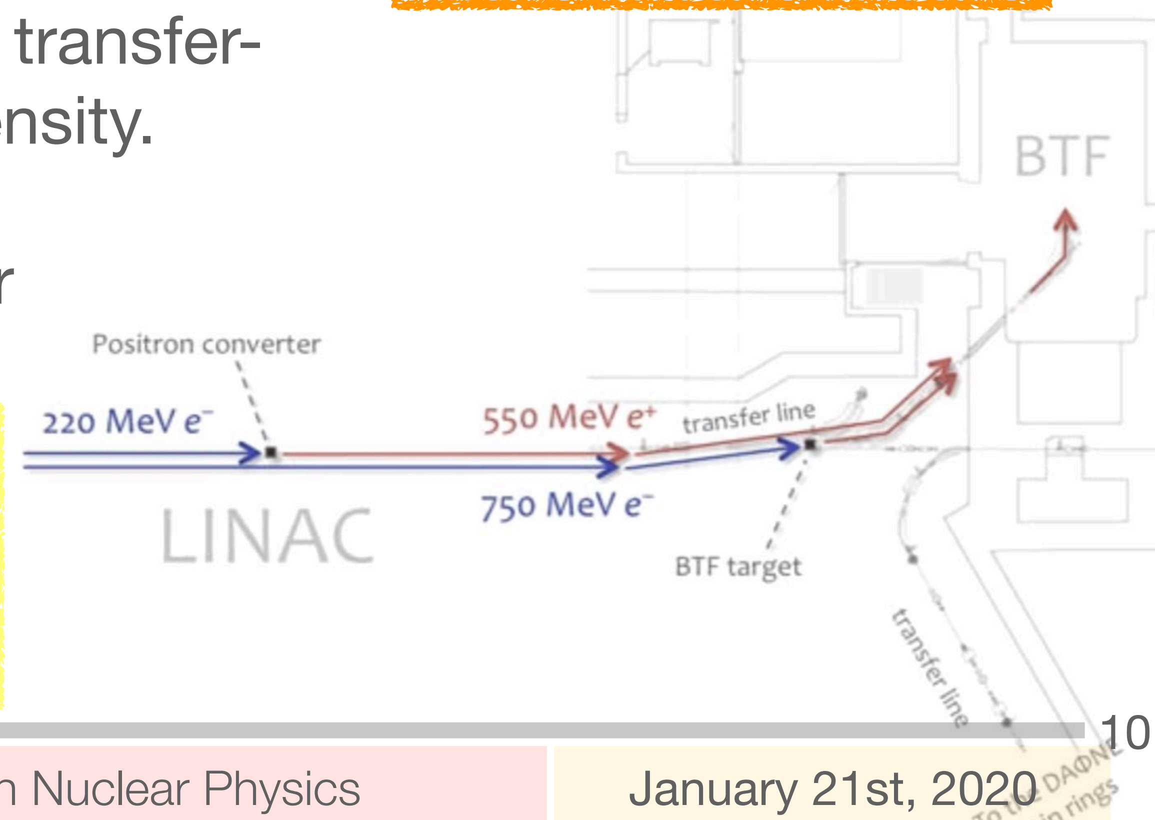
$$\sigma(e^+e^- \rightarrow \gamma\gamma\gamma) = 7.5 \times 10^{-2}\ \text{mb}$$

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
-250 ns pulse maximum duration
-~10000 e+/pulse

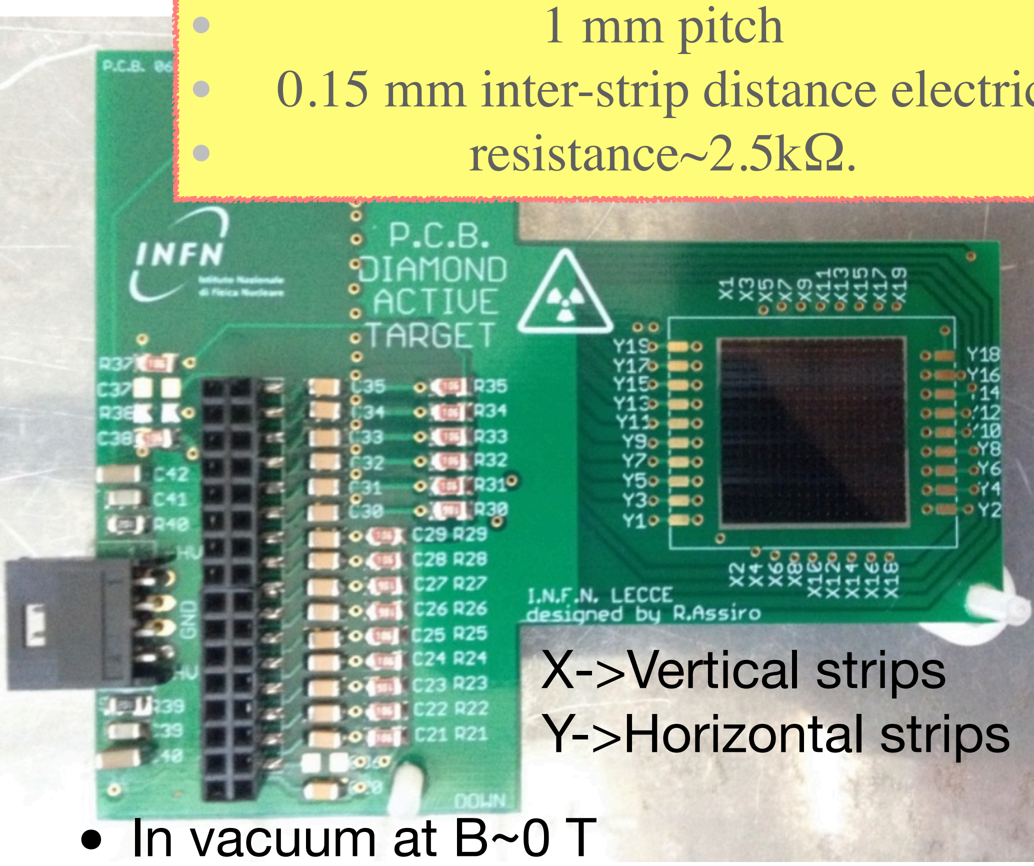


DIAMOND TARGET

- 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.

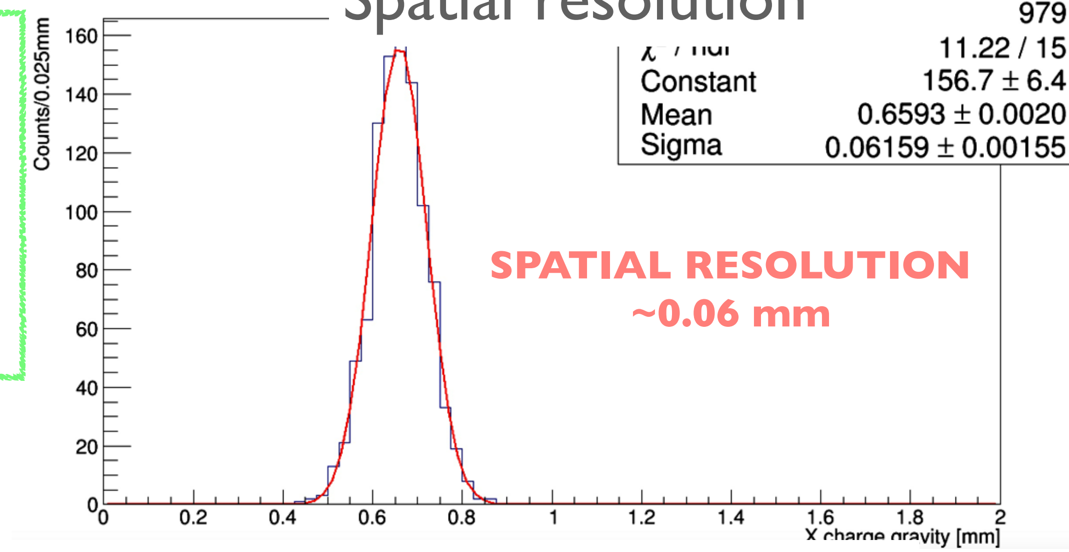
Data taken with bunch multiplicity ~ 20000 e$^+$ bunch length 250 ns and diamond



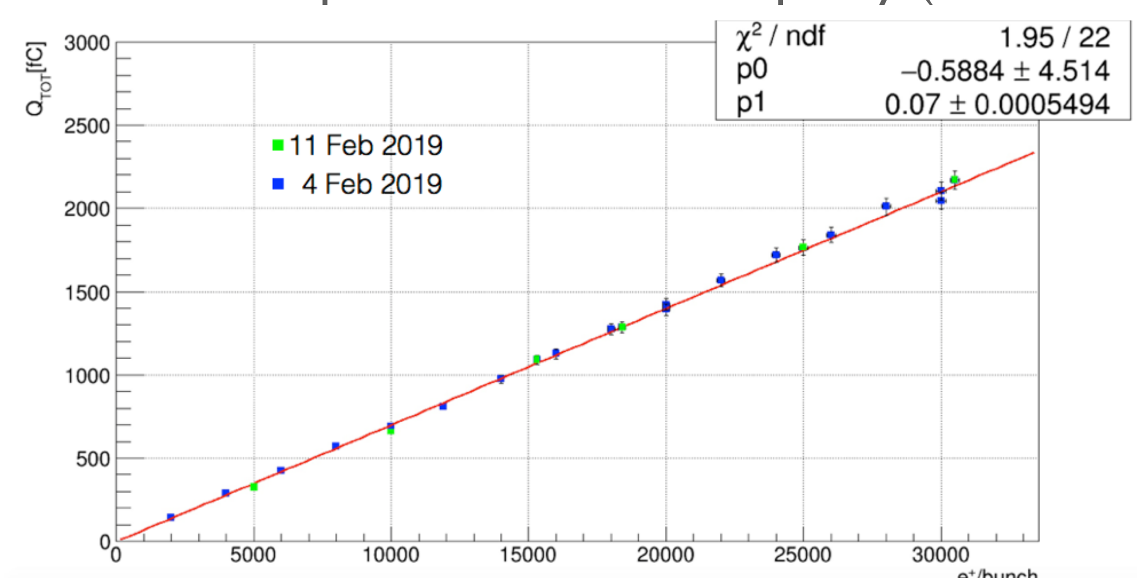
X->Vertical strips
Y->Horizontal strips

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

Spatial resolution

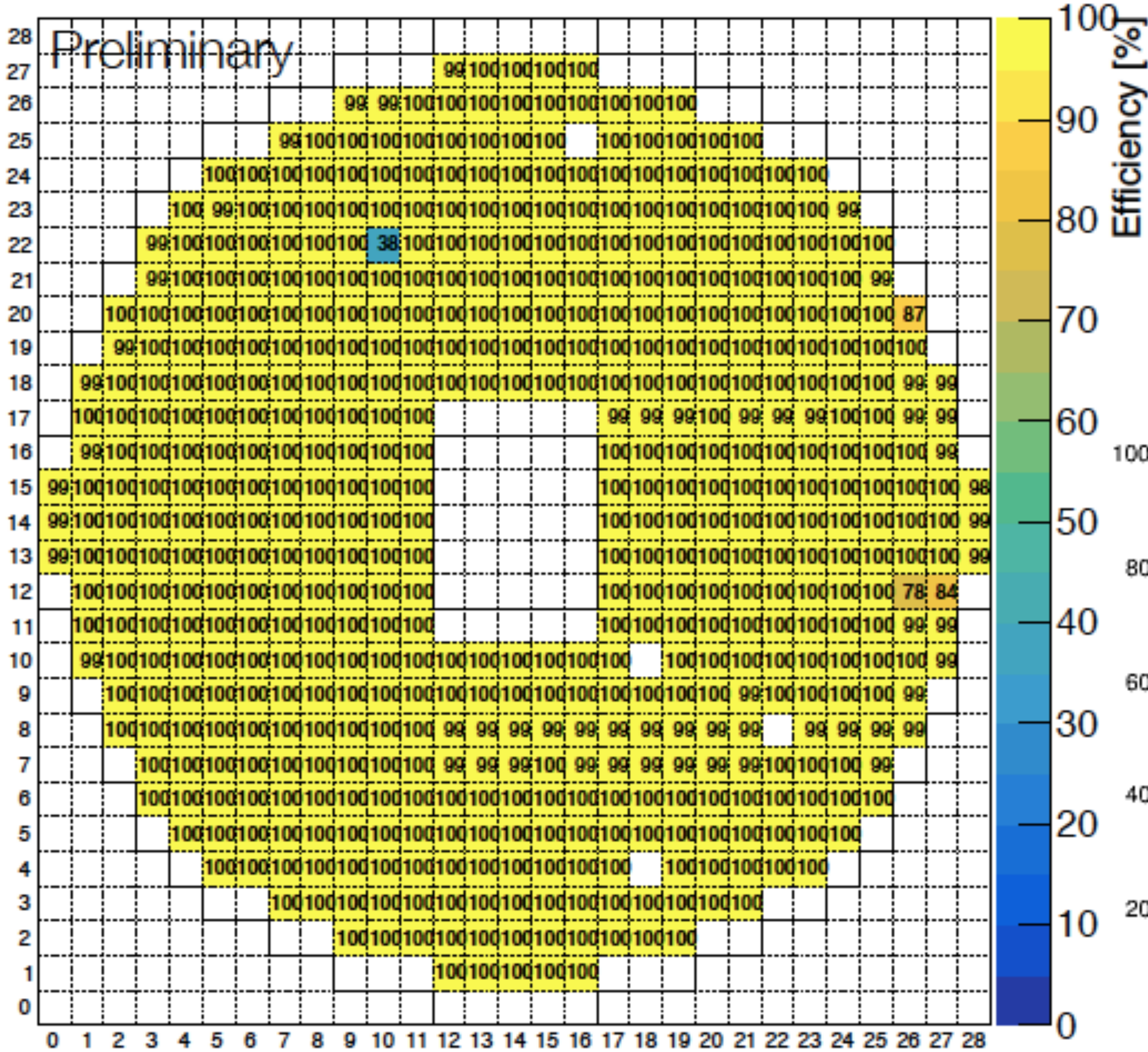


Diamond response vs bunch multiplicity (HV ~250 V)



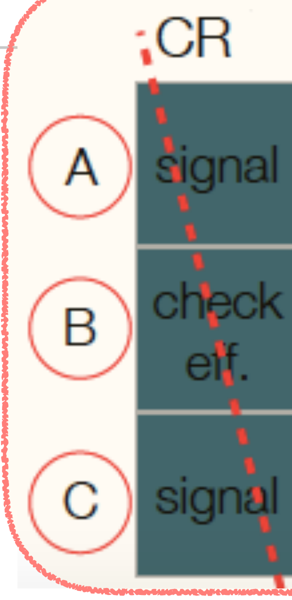
ECAL

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

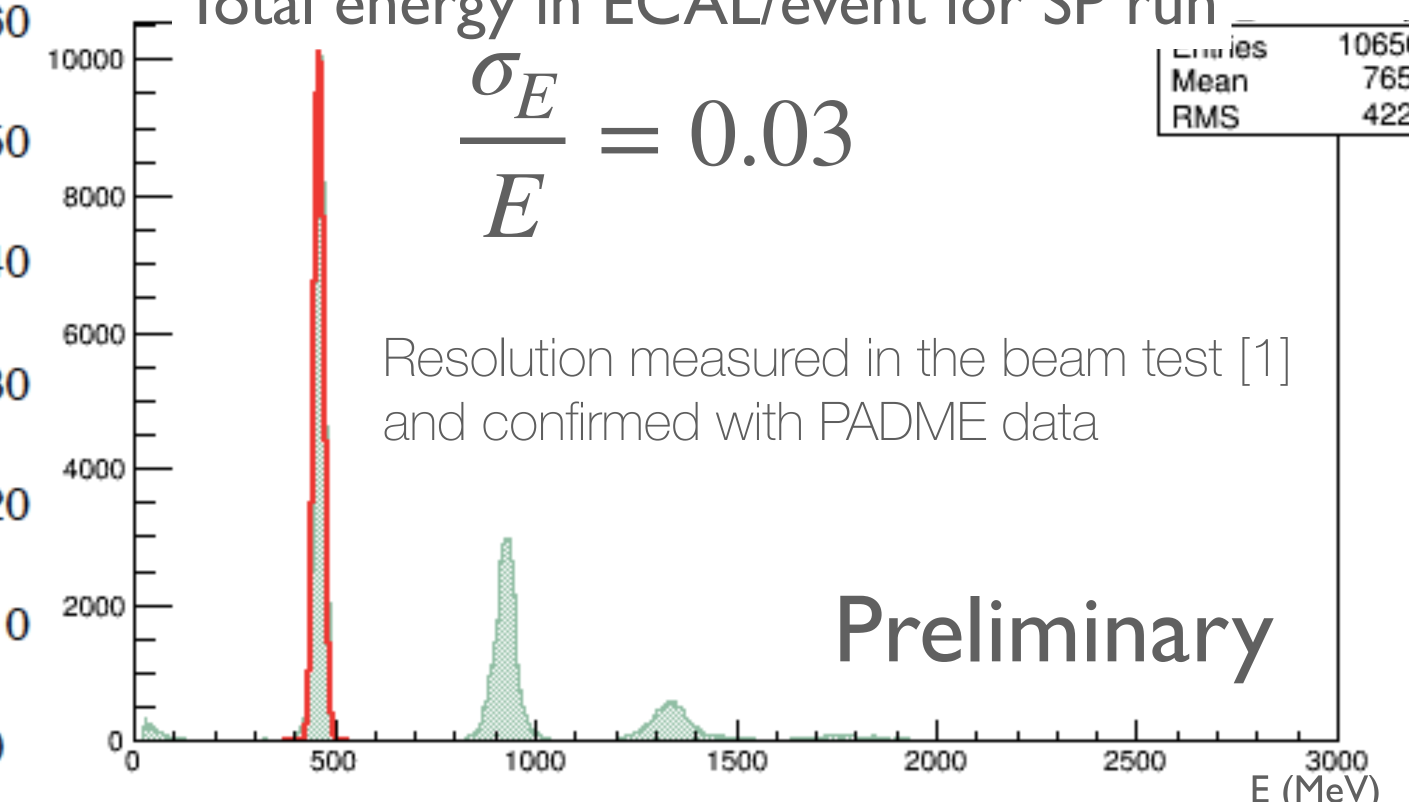


Efficiency evaluation:

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

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

Total energy in ECAL/event for SP run



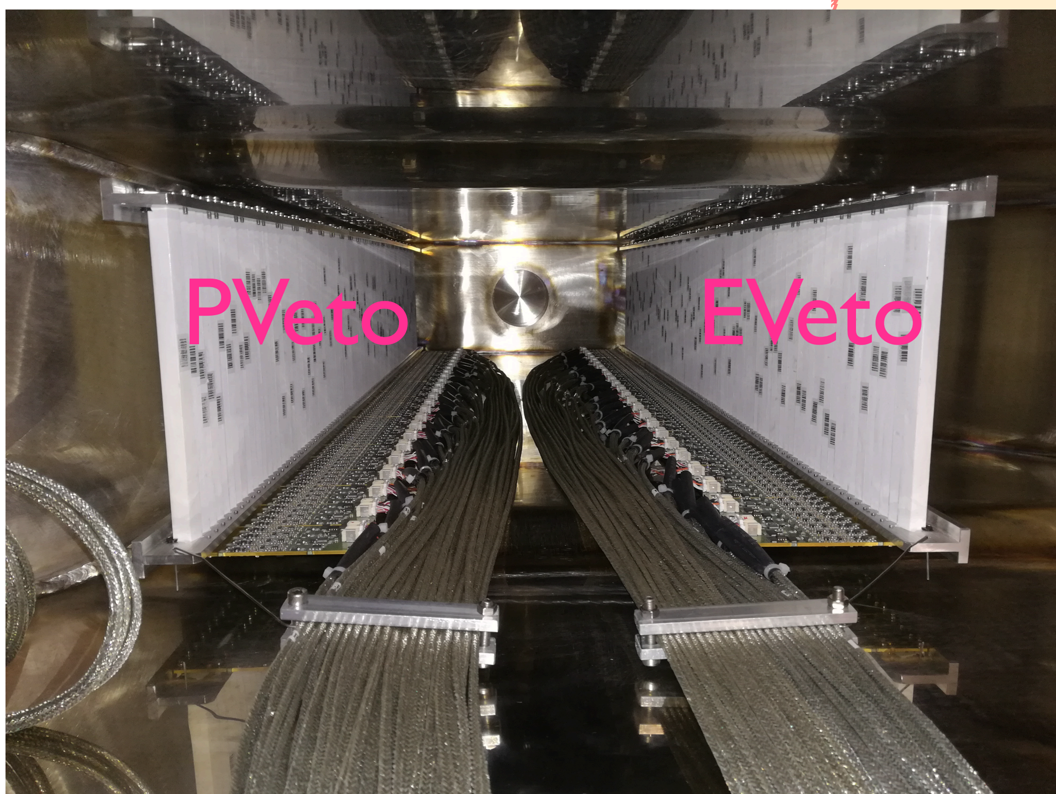
$$\frac{\sigma_E}{E} = 0.03$$

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

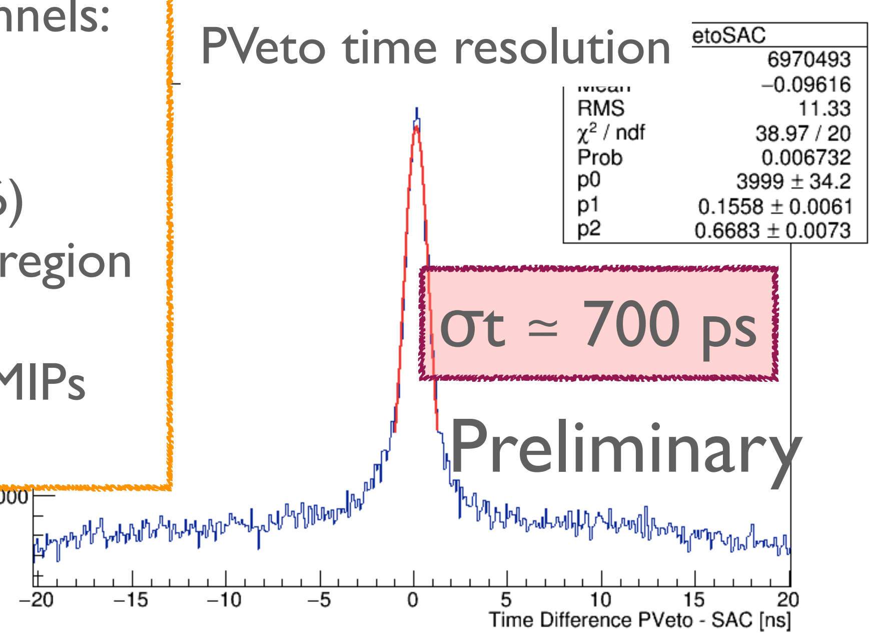
VETO & SAC

Veto System



- Plastic scintillator bars $10 \times 10 \times 200$ 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

PVeto time resolution

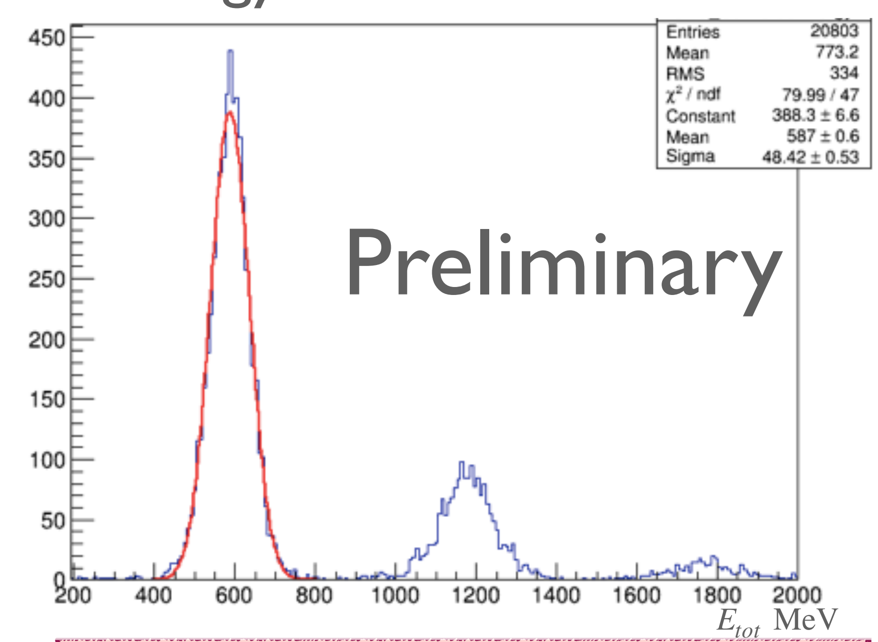


SAC

PbF_2 crystals

- 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

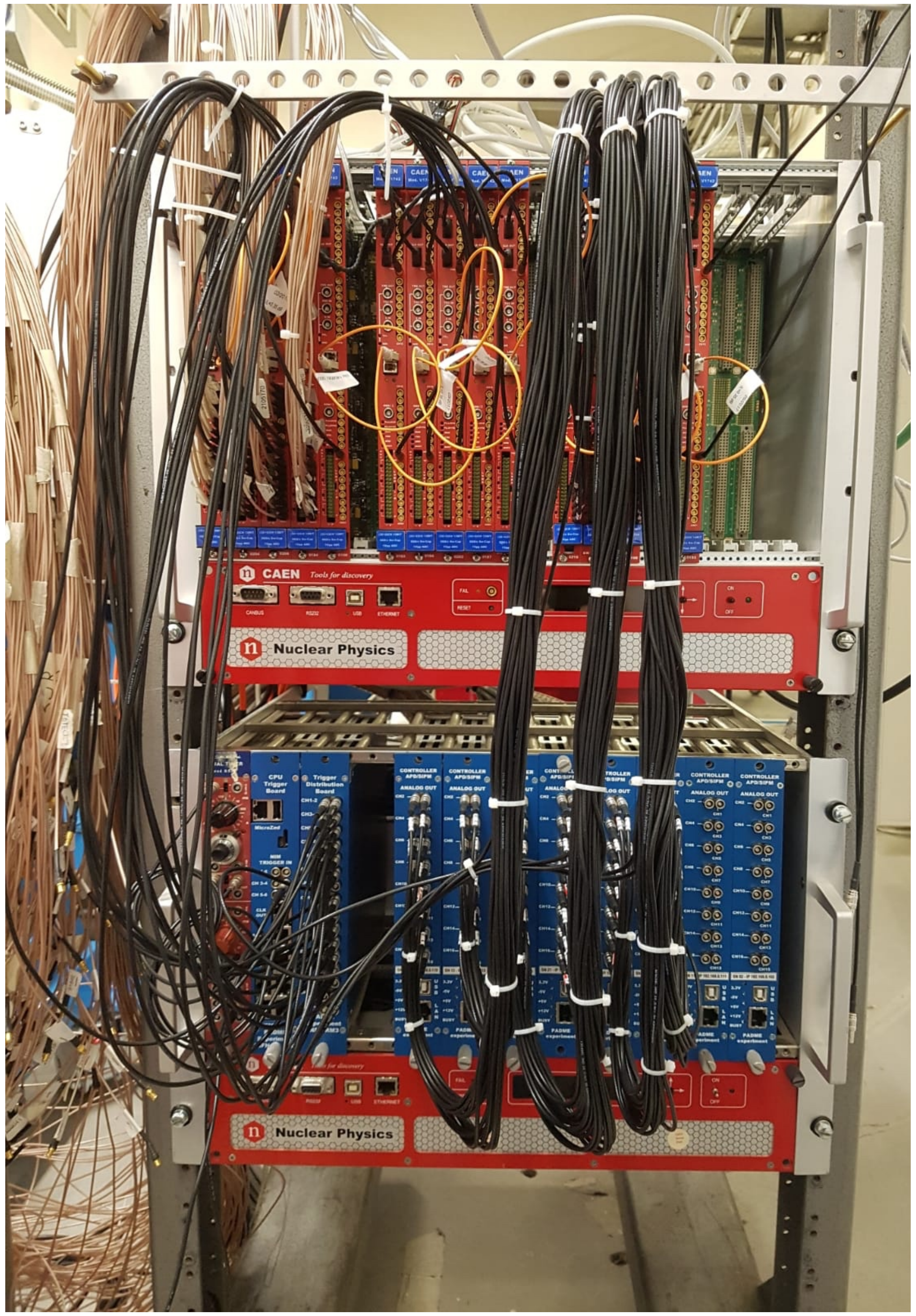
Total energy in SAC/event for SP run



$\sigma/E \simeq 10\%$ at 490 MeV
Cherenkov → 3-4 ns signals

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:

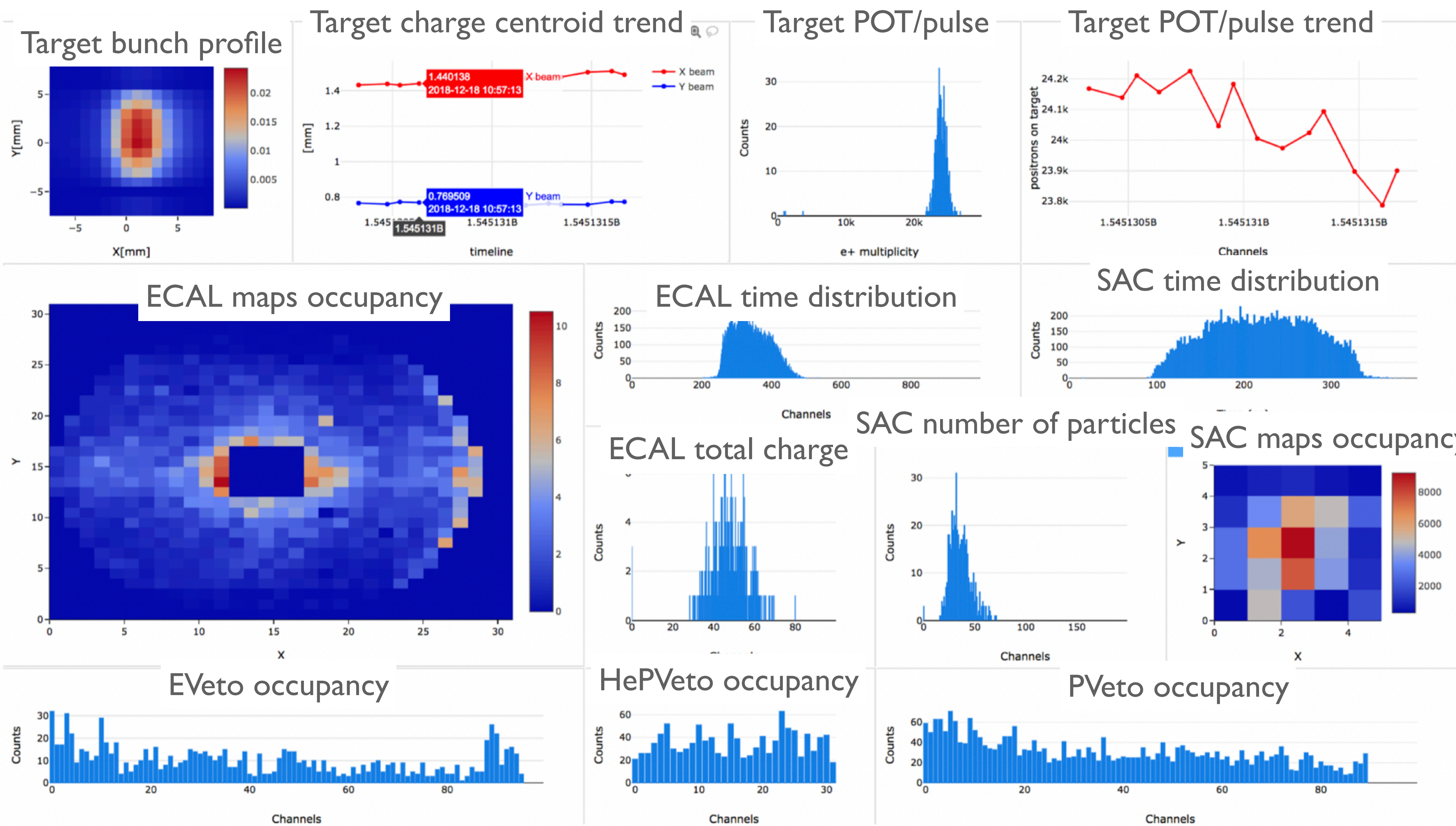
- BTF (physics run)
- Cosmic (calibration run)
- Random (pedestal studies)

DAQ

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

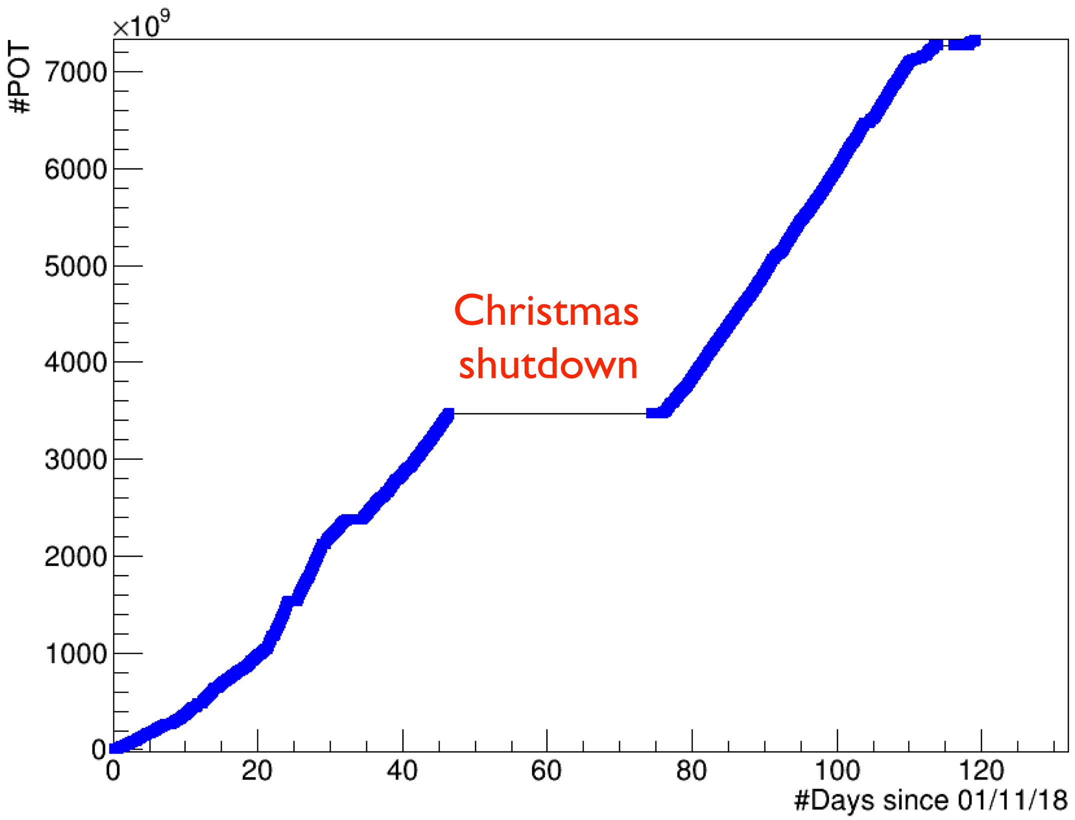
- Data size:
- ~ 900 KB/bunch
- ~ 60 MB/s sustained data throughput

PADME ONLINE MONITORING



PADME RUN I

- Successful operations and data taking from November 2018 to February 2019
- Achievements:
  - Very good and stable operation of all detectors
  - Calibration for the main detectors
  - Studies of the beam configuration using the primary and secondary positron beam
  - Collection of a sample of about 10^{12} POT (Positron On Target)
- Prospects:
  - 20000 e+/bunch → $4 \cdot 10^{13}$ in 1.2 year → $\epsilon^2 \geq 10^{-6}$ if background under control.



However:
- 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;
- Diffuse high background with secondary e+ beam.

Looking for standard model processes in PADME data

- The comparison of the data in a standard run (20000 e+/bunch) with a special run (same beam configuration) with the target off the beam line allows to establish clear signatures for the processes of two photon production and bremsstrahlung.
  - $e^+e^- \to \gamma\gamma$
  - $e^+N \to e^+N\gamma$

ANNIHILATION

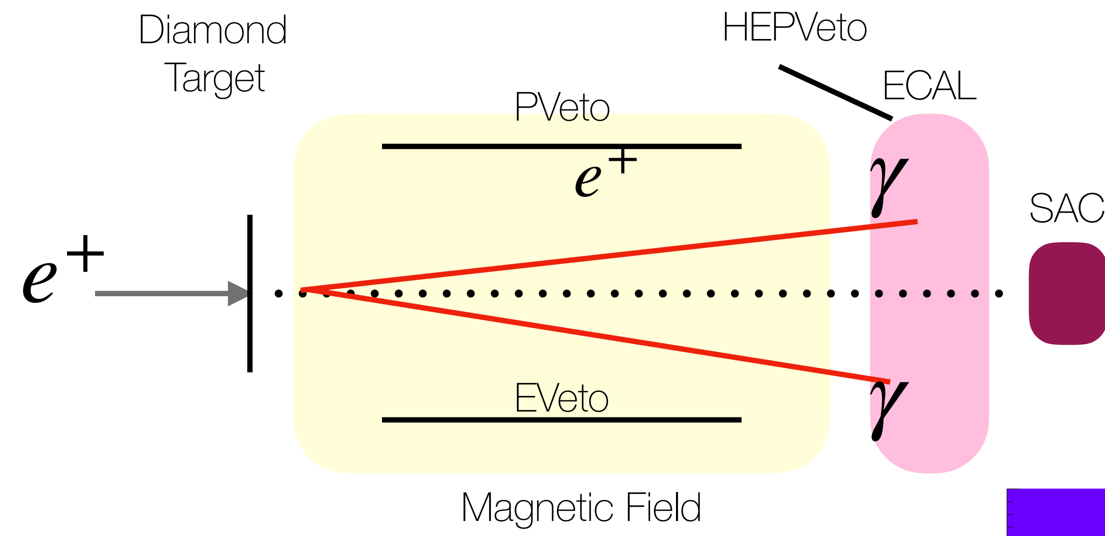
$$e^+e^- \to \gamma\gamma$$

Selection:

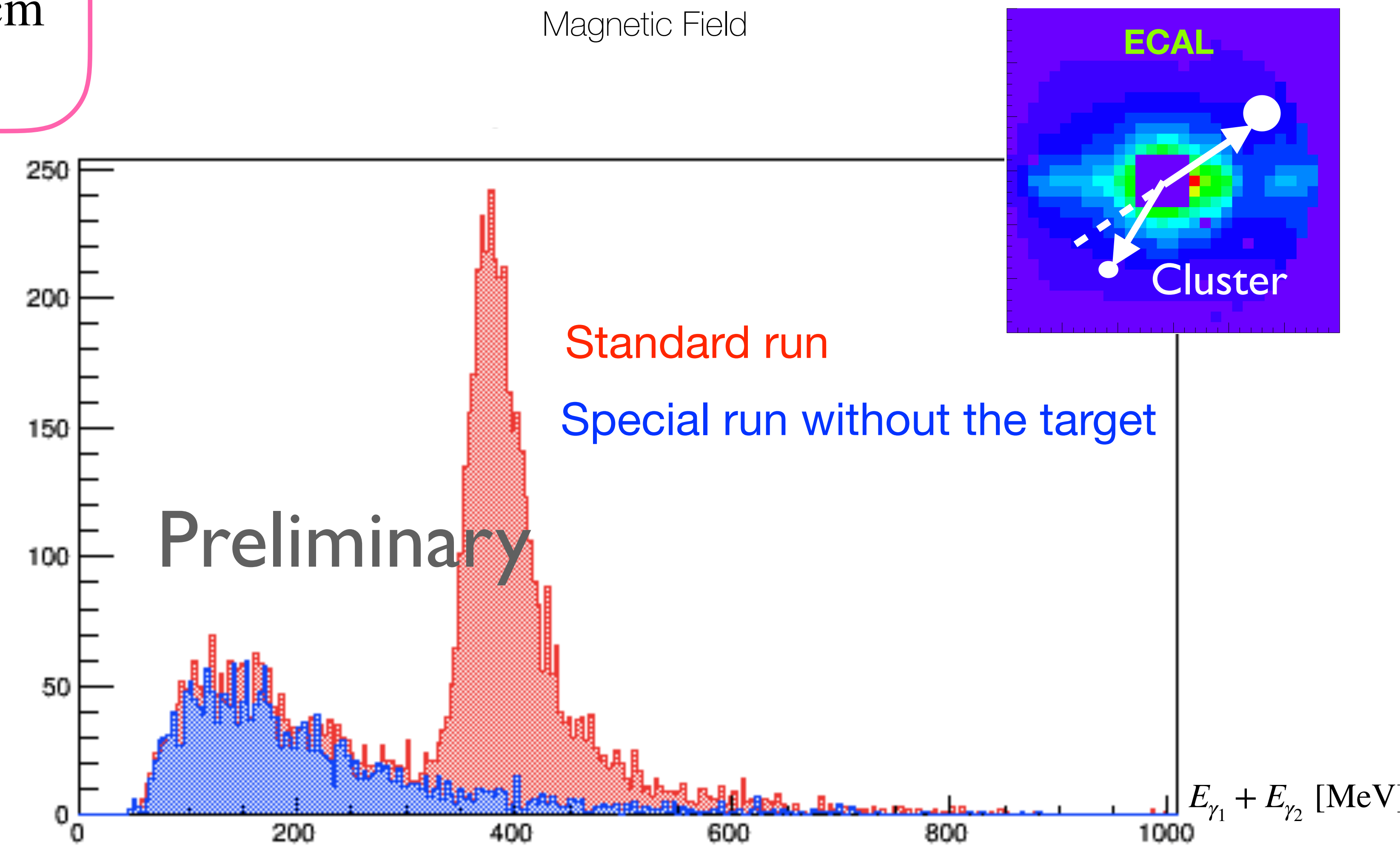
$$\Delta t < 3 \text{ ns}$$

$$x_{CoG} = \left|\frac{x_{\gamma_1} \times E_{\gamma_1} + x_{\gamma_2} \times E_{\gamma_1}}{E_{\gamma_1} + E_{\gamma_2}}\right| < 1. \text{ cm}$$

$$y_{CoG} = \left|\frac{y_{\gamma_1} \times E_{\gamma_1} + y_{\gamma_2} \times E_{\gamma_1}}{E_{\gamma_1} + E_{\gamma_2}}\right| < 1. \text{ cm}$$



Sum of the energy of two photons in e^+e^- annihilation candidate events. In red events with the target in the default position in the beam line. In blue events with the target off the beam line.

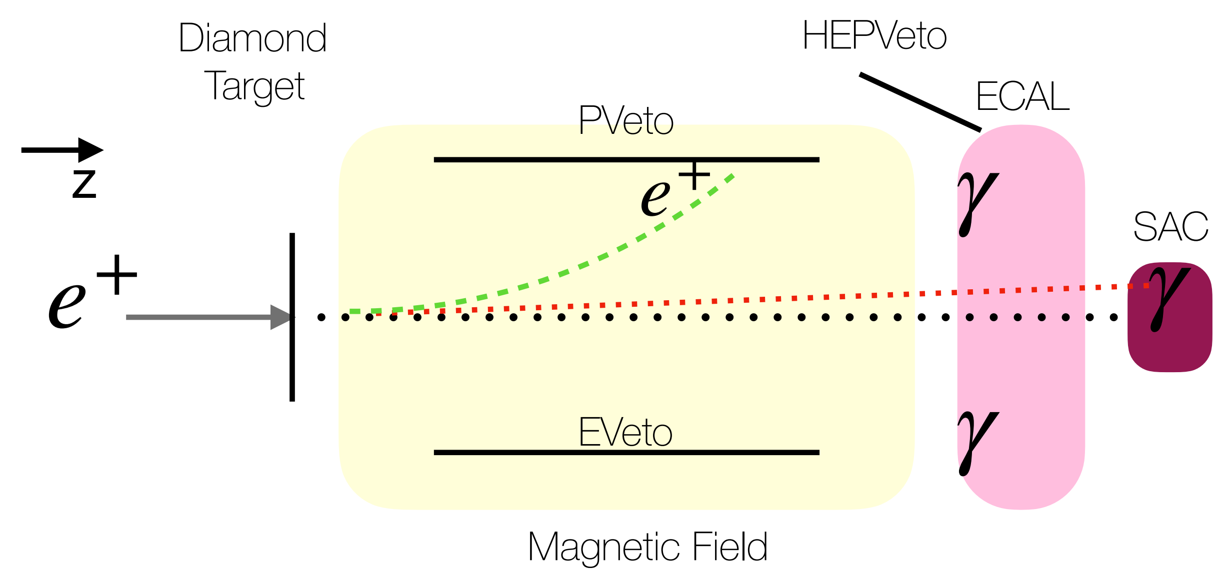


BREMSSTRAHLUNG

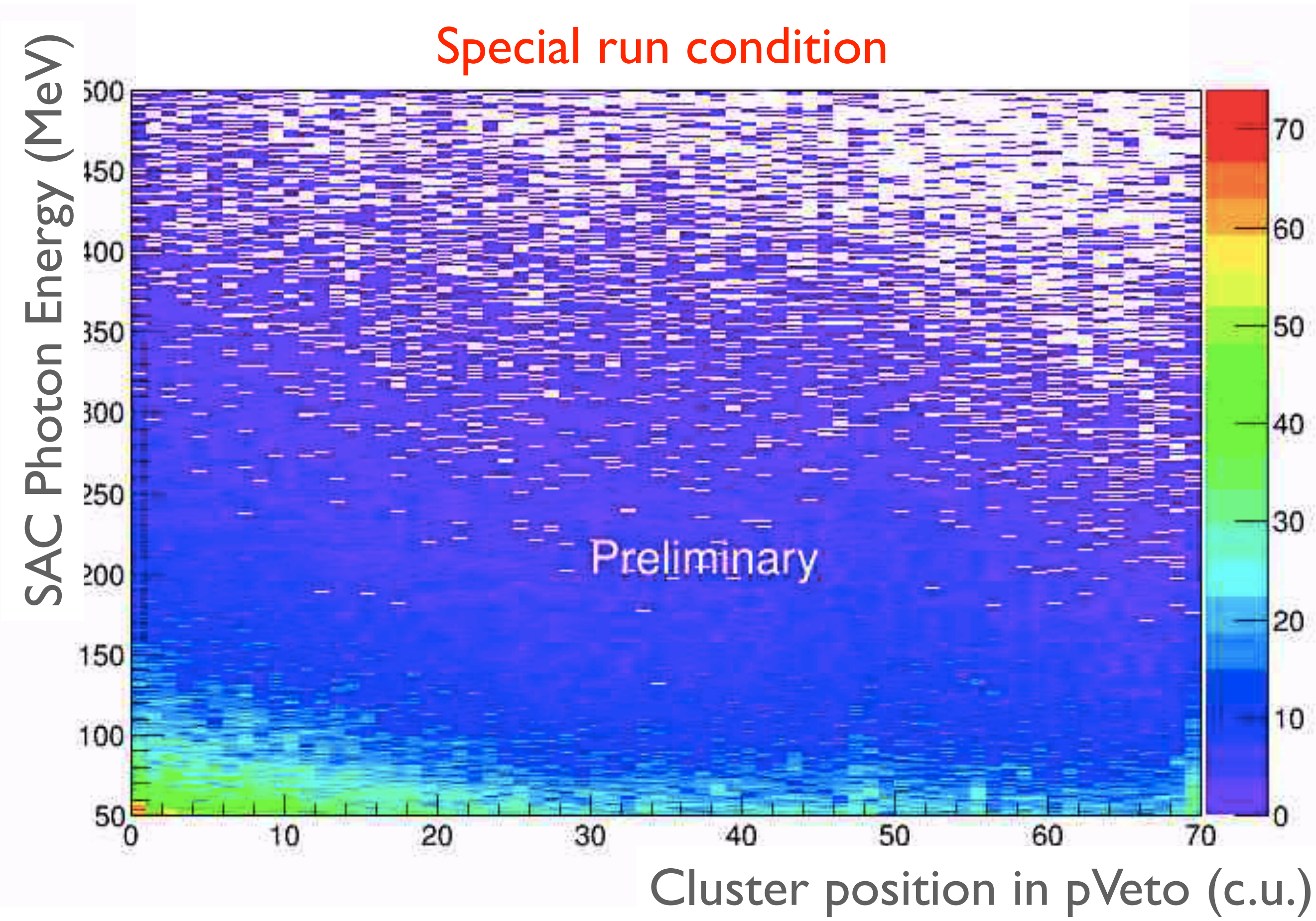
$$e^+N \rightarrow e^+N\gamma$$

Selection:

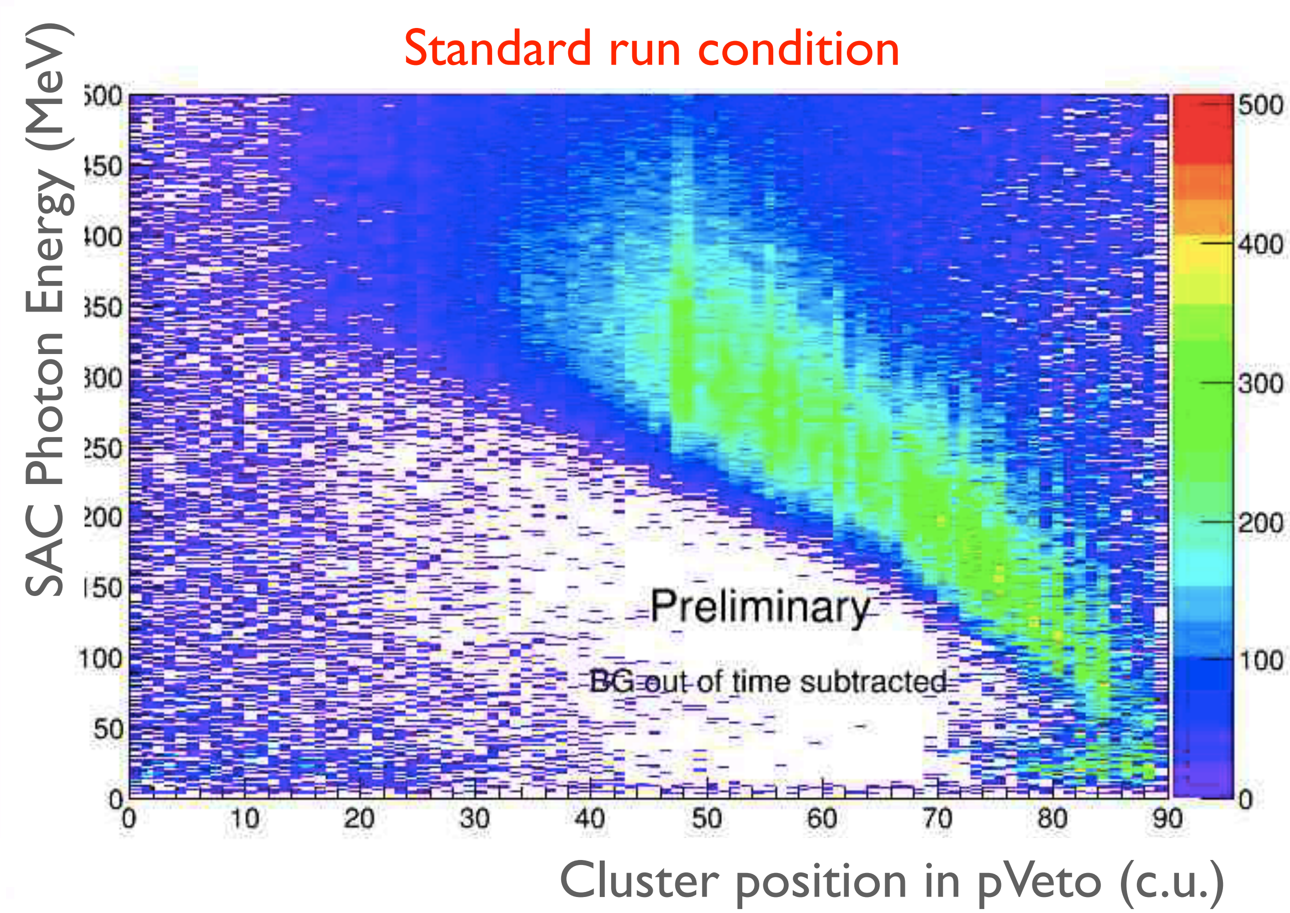
$$|t_{\gamma}^{SAC} - t_{e^+}^{PVeto}| < 1.\ \mathrm{ns}$$



Special run condition



Standard run condition

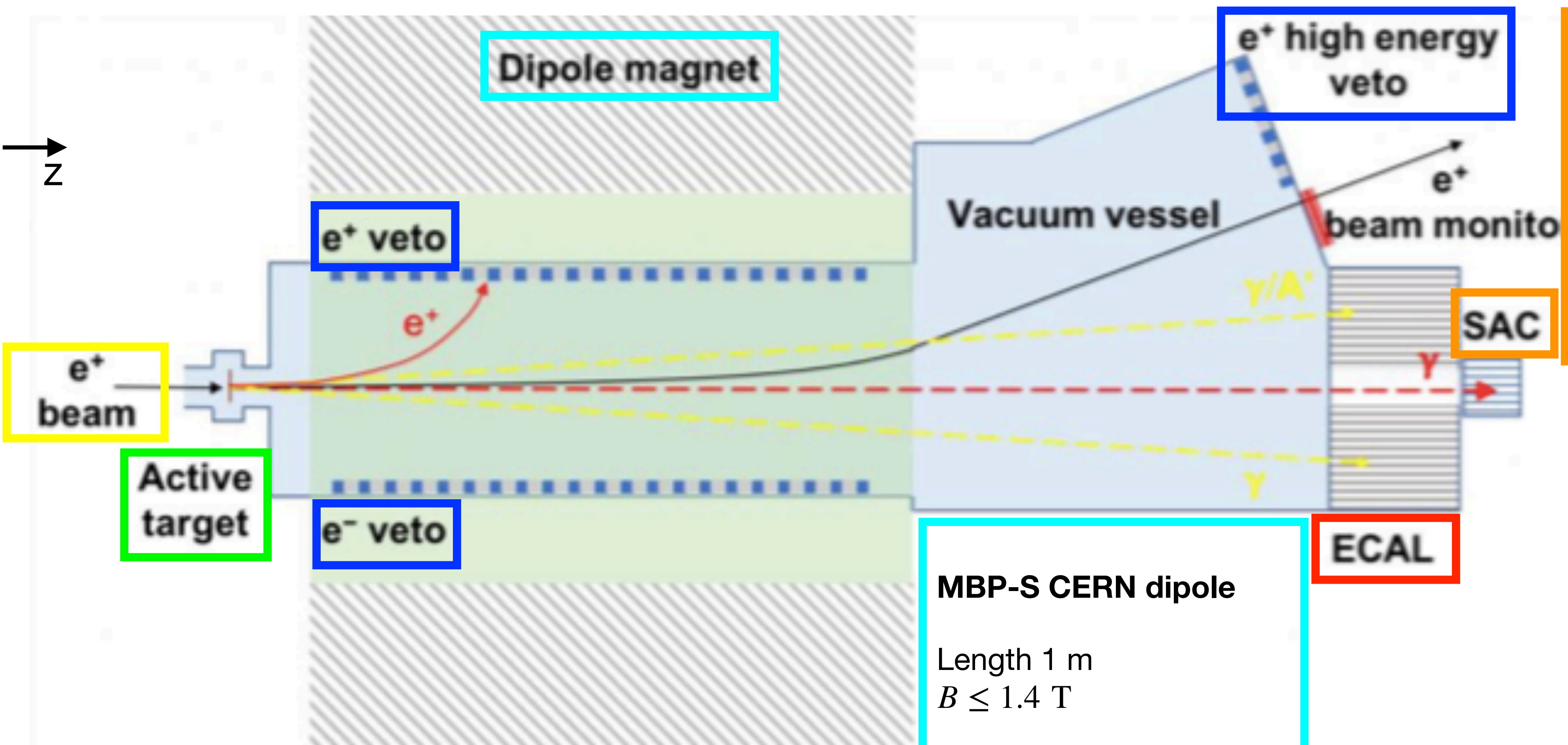


CONCLUSION

- 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. In February 2020 a second run will start.
- The understanding of the performance of the electromagnetic calorimeter and of the other detectors is well advanced. The understanding of the background induced by the beam is progressing well through MC studies and will greatly benefit of dedicated data collected in forthcoming beam tests.
- The analysis studies on the known physics (bremsstrahlung and annihilation) are successfully started and ongoing.

BACKUP

PADME EXPERIMENT



Small angle calorimeter (SAC)

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

MBP-S CERN dipole

Length 1 m
$B \leq 1.4$ T

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

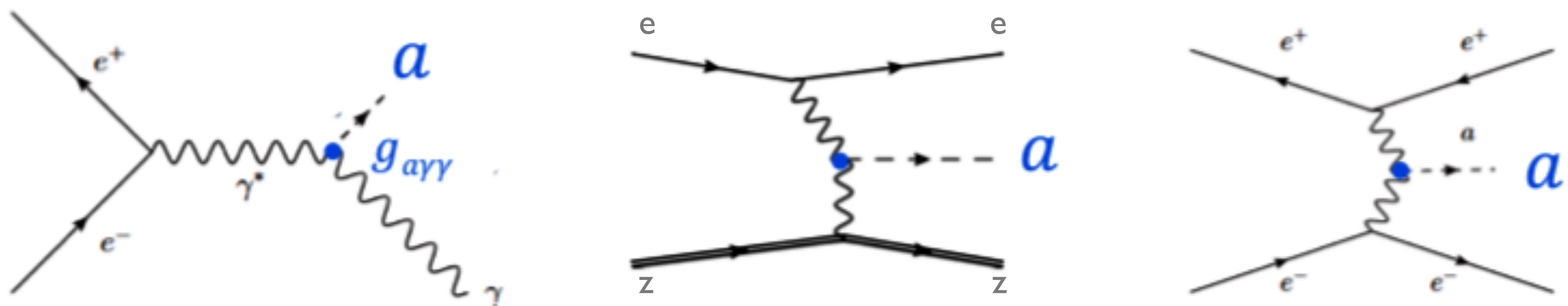
2 cm x 2 cm x 100 μm
Graphitic conductive strips with a pitch of 1 mm in orthogonal directions on the two sides for the reconstruction of the beam profile and the measurement of the beam luminosity
Number of target electrons per unit surface: N(e⁻/b) ~ 10^{-2}

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

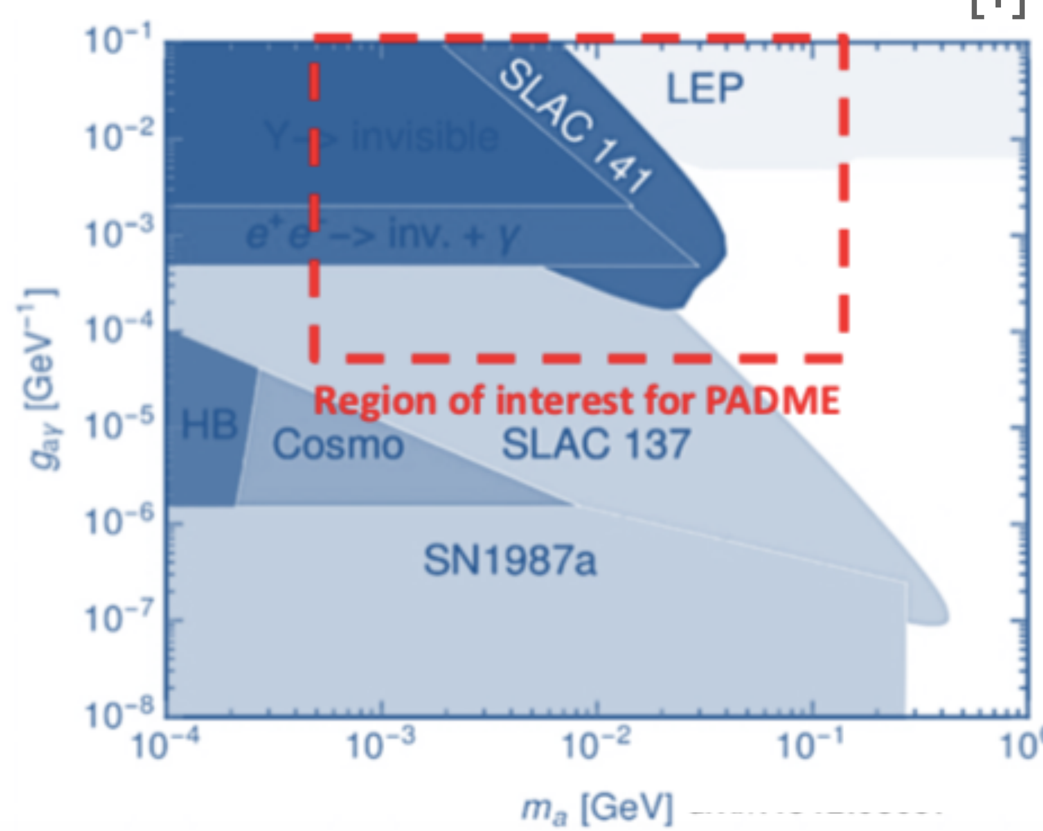
ALP AT PADME

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



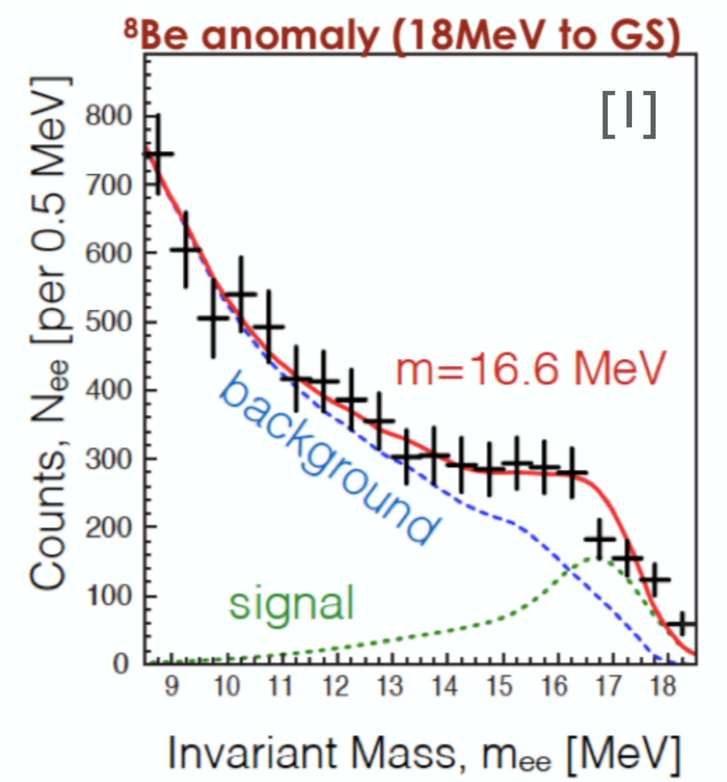
- Possible final state:
  - Visible decay $a \to \gamma\gamma\gamma, e^+e^-\gamma\gamma, Ze\gamma$
  - Invisible decay γ + missing mass;

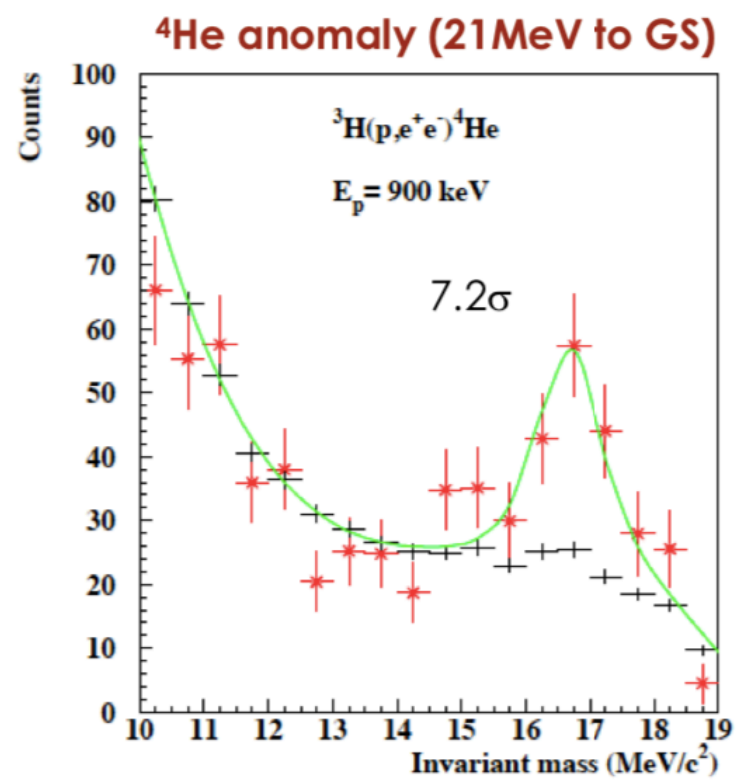
[1]

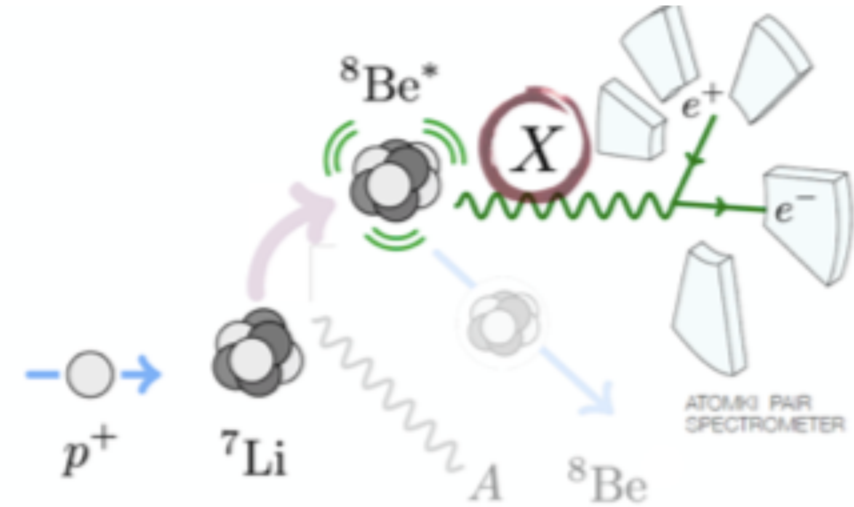


BE ANOMALY

[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
$e^+e^- \to \gamma\gamma$ 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	$\sigma(e^+e^- \rightarrow A'\gamma)$ 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