Searching for the X17 with the PADME experiment

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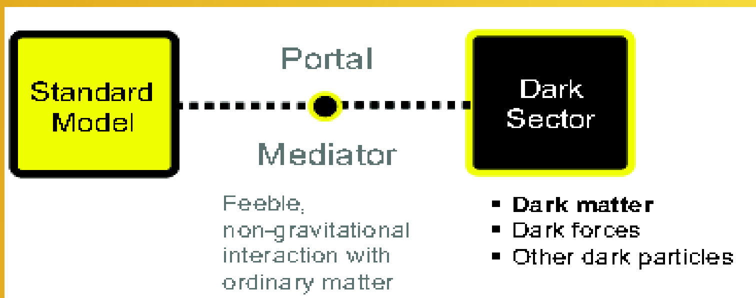
Outline

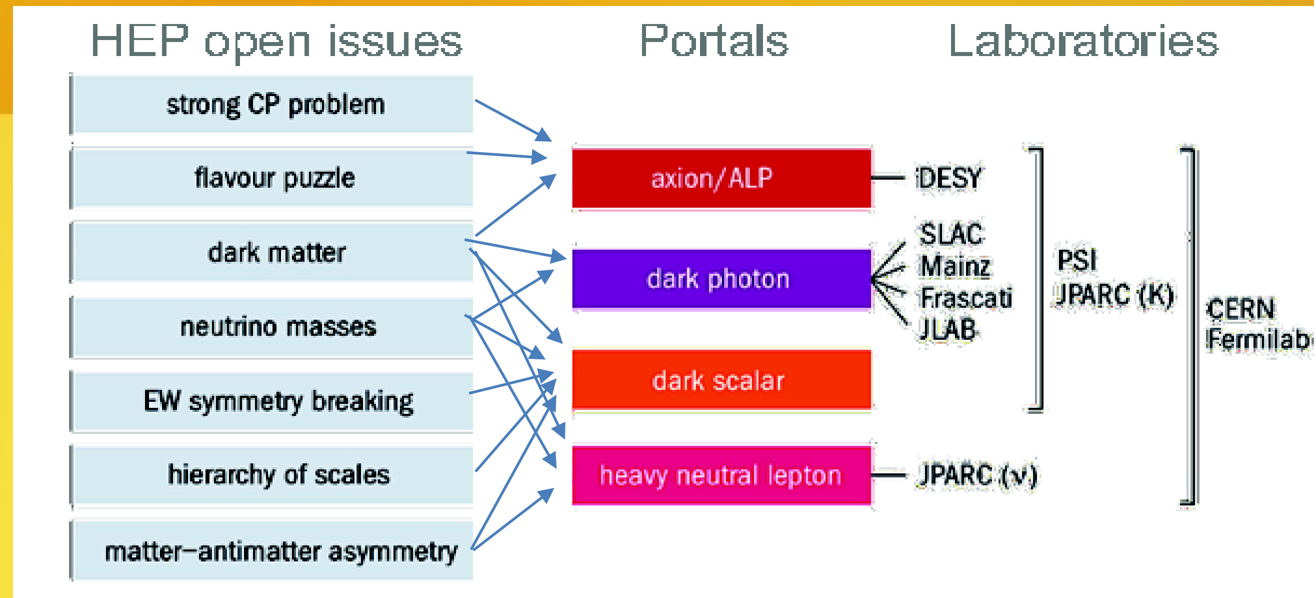
- The dark sector paradigm
- **P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment
  - First physics results from Run II
- The "^{8}Be anomaly" @ ATOMKI
- The X17 particle resonant search @PADME
  - The Run III
  - First look at off-resonance data
- Conclusions

The dark sector paradigm

Dark matter existence from cosmological observations

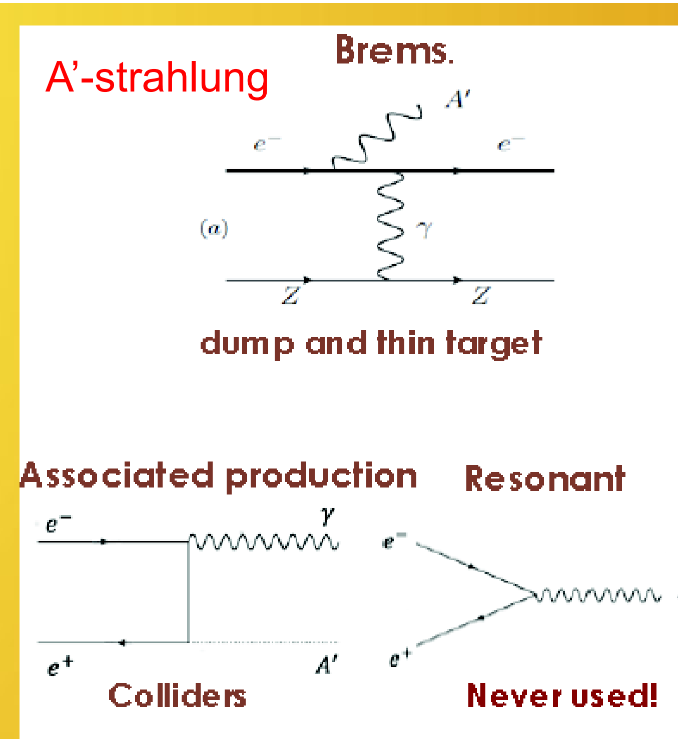
Do we have a "portal" between Dark Sector and SM ?





Dark sector candidates can explain some SM anomalies:
(g-2)$_\mu$, ^{8}Be, proton radius, ...

- mediator can have a **small mass** $\mathcal{O}$(MeV -100 MeV)
  and can be **produced at low energy accelerators**
- It can **decay back to ordinary matter "visible"** or **"invisible"**



If Dark sector *U'(1)*

$$\mathcal{L} \sim g_V q_f \overline{\psi}_f \gamma^\mu \psi_f A'_\mu$$

$$g_V \ll 1$$

Dark Photon A'
(with mass)

Electron beam production :

- Only A'-strahlung

Positron beam production :

- A'-strahlung
- Associated production $e^+e^- \rightarrow A'(\gamma)$
- Resonant production $e^+e^- \rightarrow e^+e^-$

The PADME Experiment

Visible decays: $A' \rightarrow e^+e^-$ $A' \rightarrow \mu^+\mu^-$

- **Thick target** : electrons/protons beam is absorbed (NA64, old dump exp.)
- **Thin target** : searching for bumps in e^+e^- invariant mass

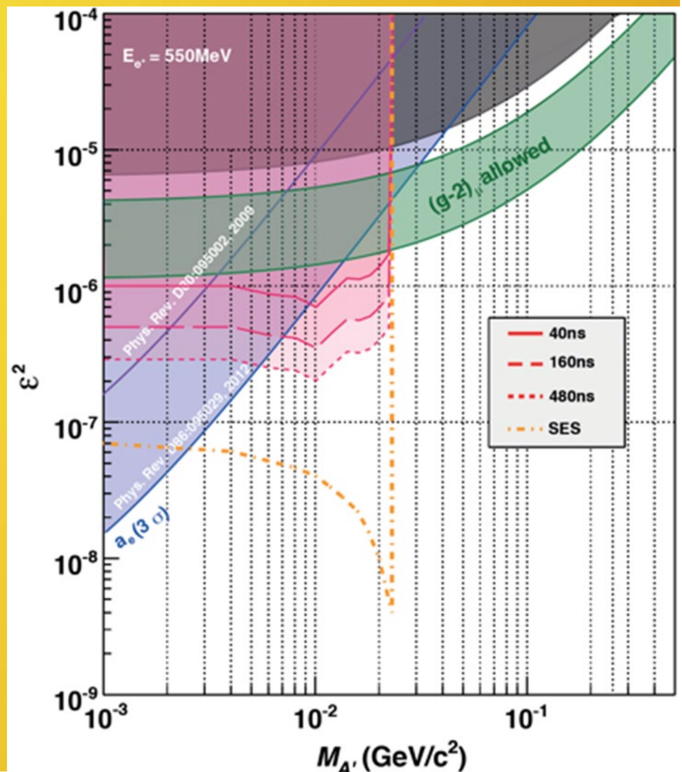
Invisible searches: $A' \rightarrow \chi\chi$

- **Missing energy/momentum**: A' produced in the interaction of an electron beam with thick/thin target (NA64/LDMX)
- **Missing mass**: $e^+e^- \rightarrow A'(\gamma)$ search for invisible particle using kinematics (Belle II, **PADME**)

The search for the dark sector mediator "dark photon" *A'* in invisible decay is the main goal of PADME

Positron **A**nnihilation into **D**ark **M**atter **E**xperiment at INFN LNF BTF-Linac beam line

INFN Roma, INFN Frascati, INFN Lecce, La Sapienza University, Politecnico di Torino e INFN Sezione di Torino, MTA Atomki Debrecen, University of Sofia, Cornell University, US William and Mary College



Invariant Missing Mass peak search over continuous background

PADME can explore in model independent way region to $\varepsilon \approx 10^{-3}$

$m_{A'} < 23.7$ MeV (E_{beam} = 550 MeV - LNF Linac)

coupling of any new light particle produced in e^+e^- annihilation can be limited: Dark Photon, Axion Like Particles, Dark Higgs, new proto-phobic vector boson, ...

PADME setup (Run I and Run II)

Positron beam of ≤ 500 MeV/c@50 Hz
Macro-bunches max length **Δt < 300 ns**
Number of annihilations proportional to
$N^{e+}_{beam} \times N^{e-}_{target}$
Limited intensity (pile-up) **< 3×10^4 PoT/pulse**

Active polycrystalline diamond target
2×2 cm^2 – **100 μ thick**
x,y graphitized strips r/out
Beam size, position, time ,Ne$^+$

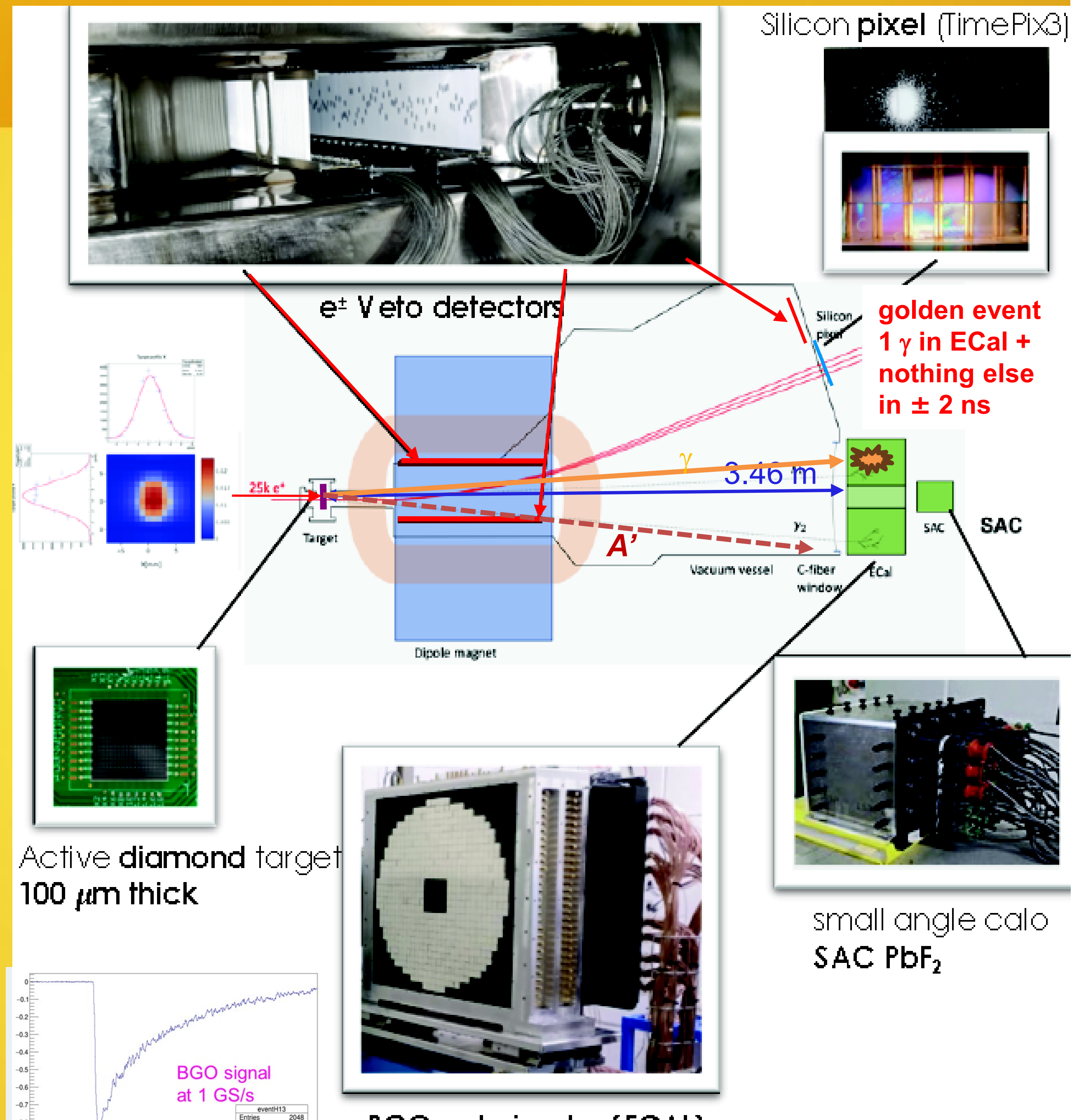
1 m **dipole magnet** **(0.5-0.6 T)** to :
Sweep away non-interacting positrons
Tag positrons loosing energy by Bremmstr

Scintillating bar veto detectors inside vacuum vessel – r/out SiPM
Positron and electron detection inside magnetic gap
Additional **veto** for e^+ irradiating soft γ near beam exit

BGO EM Calorimeter (ECAL)
616 $21\times21\times230$ mm^3 **BGO** - r/out PMT
≈ 20.5 X_0 depth
Cylindrical shape with **central hole** (Bremmstr)
E, Θ, time measurement

Small angle EM Calorimeter (SAC)
25 $30\times30\times140$ mm^3 **PbF_2** - r/out **fast** PMT
Covering central hole
E, Θ, time measurement

Silicon pixel Beam Monitor **(TimePix3)**
used to tag exiting positrons
(E), x, y, time measurement



RunI and RunII data taking

2 runs in **3** configurations between September 2019 and December 2020 (during the pandemics)

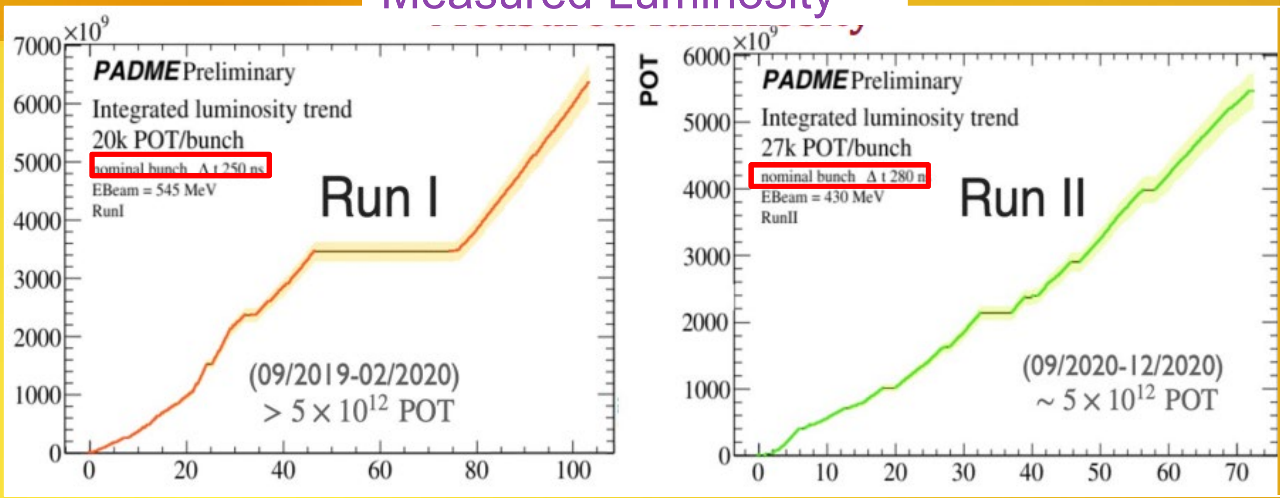
Acquired luminosity measurements :

Run I → 6 x 10^{12} PoTs

Run II → 5.5 x 10^{12} PoTs

Luminosity precision : 5%

Measured Luminosity



Changes between the runs :

Run Ia : secondary beam → Run Ib : primary beam

Reduced Background

Beam energy reduced 545 → 490 MeV

Detailed MC simulation of beamline (JHEP 09 (2022), 233)

Run Ib → Run II : changed vacuum sep. window

250 μm Be window → 125 μm Mylar

Reduced background from vacuum window

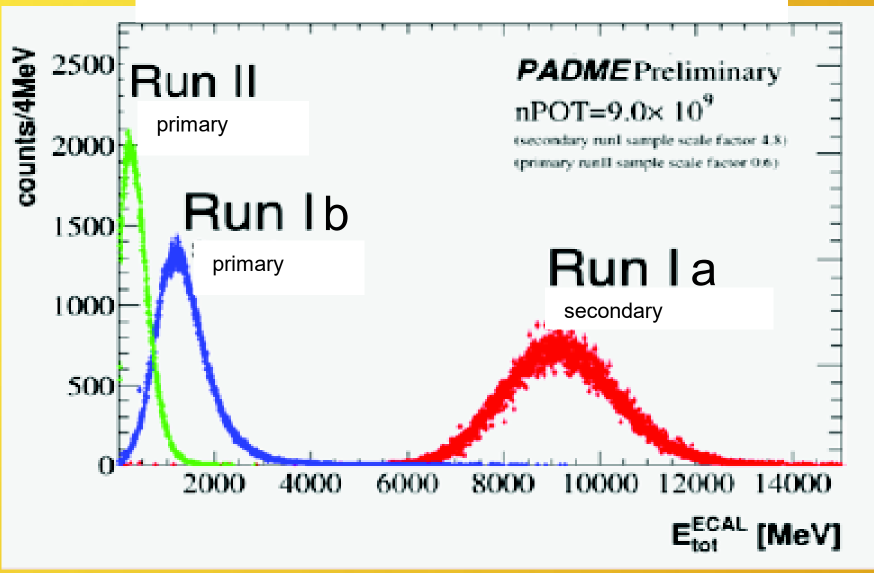
Beam energy reduced 490 → 430 MeV

More PoTs/bunch (20 K→ 27 K)

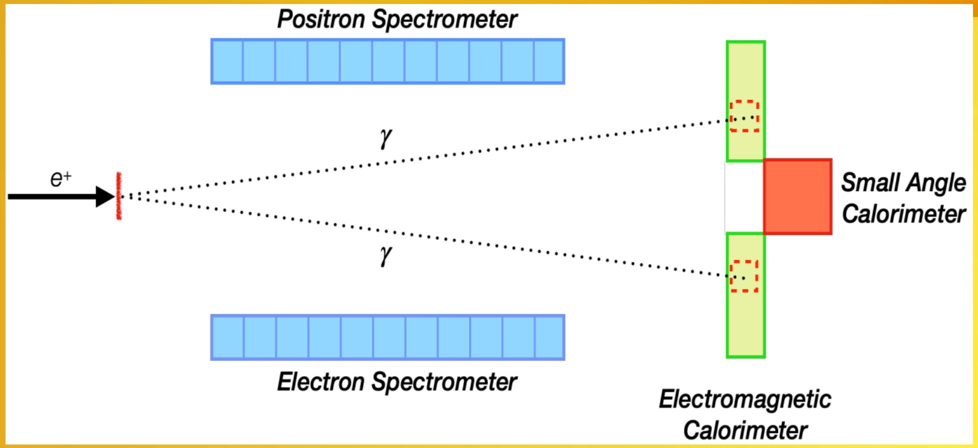
Longer bunches (250 → 280 ns) and more stable bunch structure

→ reduced the pileup in the detector

Total ECAL energy per event



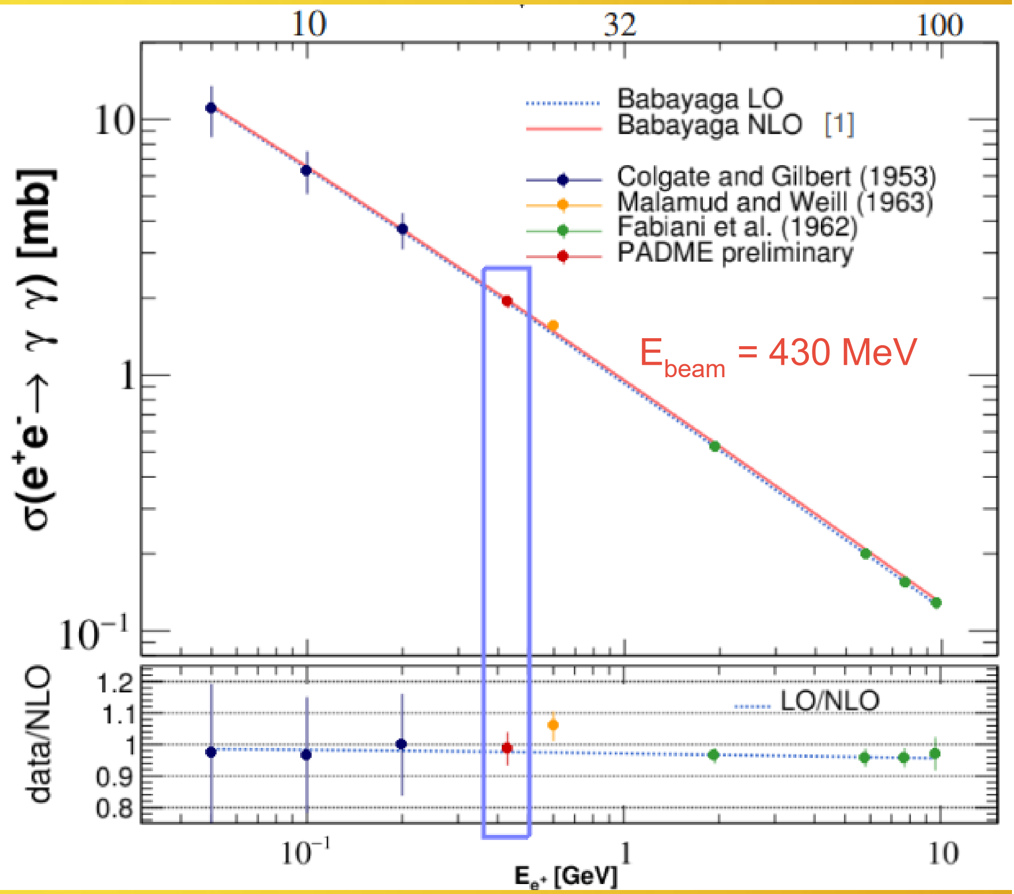
First physics measurement: multi photon annihilation



From PADME Run II (part of 2020 data set) :

- Characterisation of ECAL
- Could be sensitive to sub-GeV new physics (e.g. ALPs, ...)

PhysRevD.107.012008 (2023)



First direct measurement below 500 MeV with **~ 5 % precision** (both Gilbert '53 and Malamud '63 measured e^+ disappearance rates)

PADME : $\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.977 \pm 0.018_{stat} \pm 0.045_{syst} \pm 0.110_{(n.collisions)}$ mb

QED@NLO : $\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.9478 \pm 0.0005_{stat} \pm 0.0020_{syst}$ mb

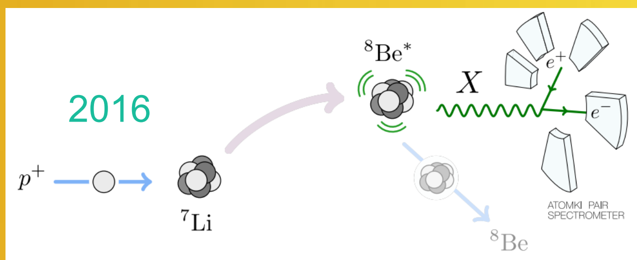
Phys. Lett. B 663 (2008) 209-213

A fundamental step towards the invisible dark photon analysis (ongoing..)

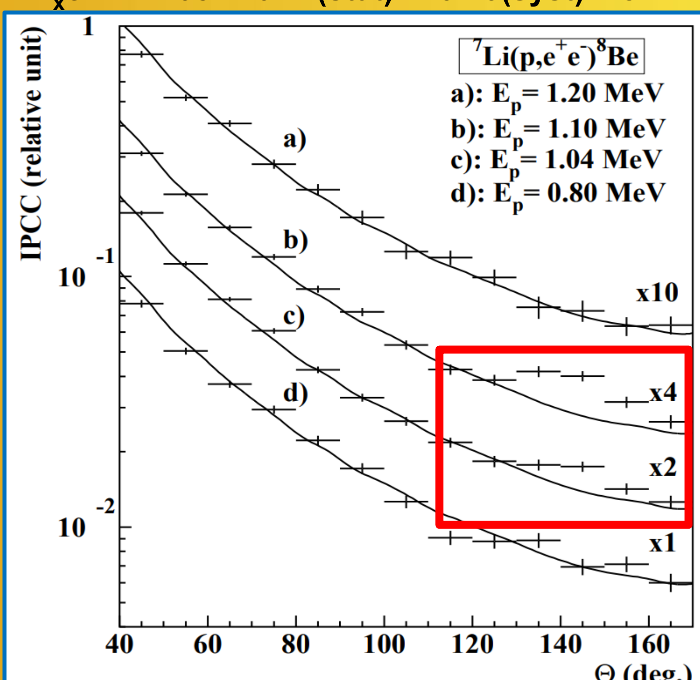
The "^{8}Be anomaly"

Collaboration at ATOMKI institute in Hungary studying IPC decays of excited nuclei in 3 different experiments : ^{8}Be (2016) / ^{4}He (2020) / ^{12}C (2022)

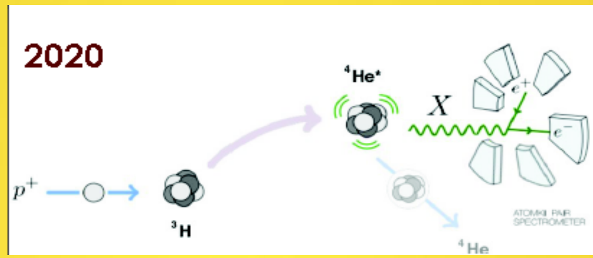
- In **all 3** experiments finds **anomaly** in decay of **large angle** e^+e^- pairs compatible with production of a new particle of **~ 17 MeV** mass
- Statistical significance very strong : ~ 7 σ **for each experiment**



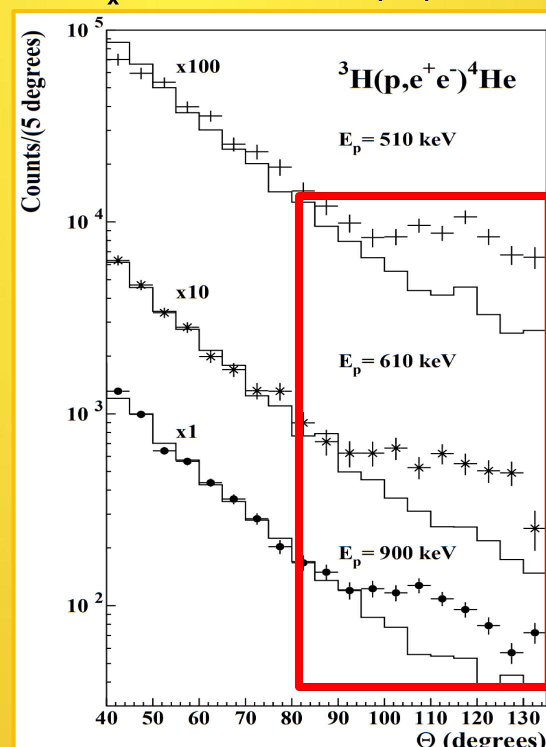
M_xc^2 = 17.03 ± 0.11(stat) ± 0.20(syst) MeV



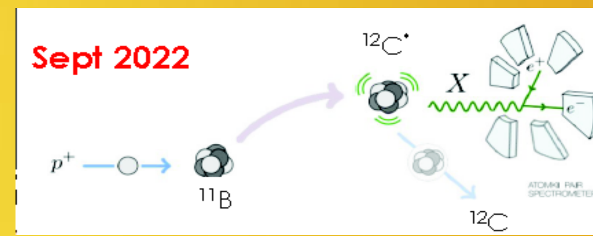
Phys Rev Lett.116.042501



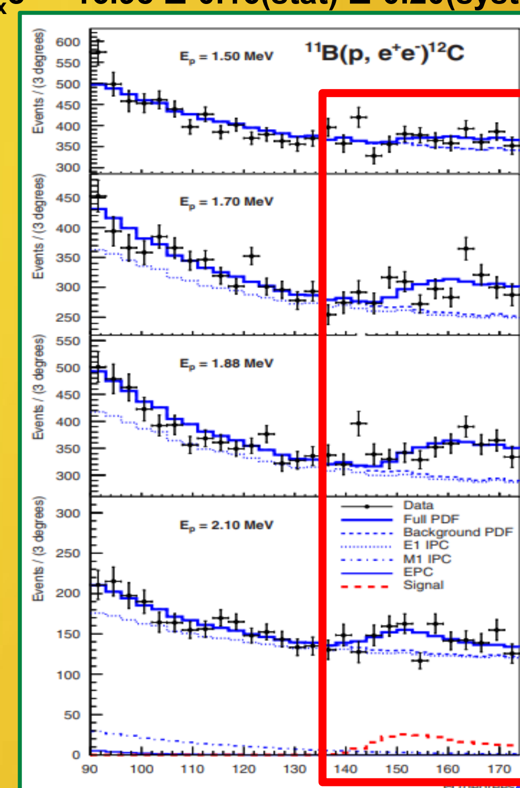
M_xc^2 = 17.01 ± 0.16(tot) MeV



Phys. Rev. C 104(4):044003



M_xc^2 = 16.98 ± 0.16(stat) ± 0.20(syst) MeV



Phys. Rev. C 106, L061601

The X17 particle

From the ATOMKI observations, the main properties of the **new X_{17} particle** are :

- $M_{X17} \simeq 17$ MeV **Proto-phobic** Feng et al. , PRL 117(7) 071803, 2016
- $Br\ (e^+e^- \to X_{17}) \simeq 5 \times 10^{-6}\ \ Br(e^+e^- \to \gamma\gamma)$
- $\Gamma_V \simeq 0.5\ (g_V/0.001)^2$ eV $< 10^{-2}$ eV for the vector case

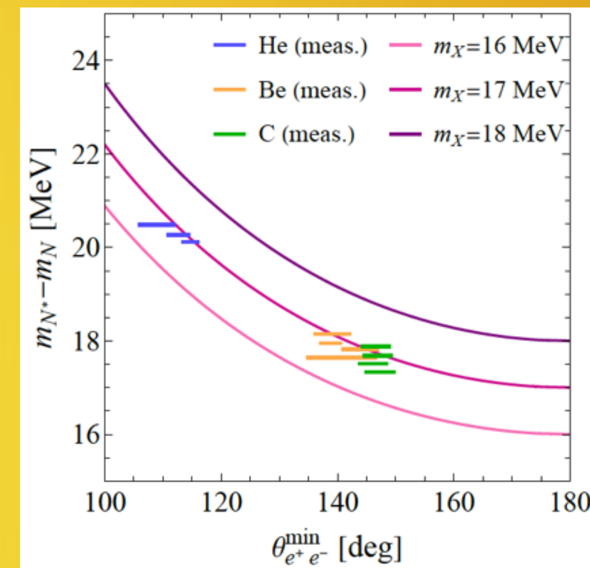
The **X_{17} hypothesis** is **kinematically** consistent for **all** the 3 experiments

Phys. Rev. D **108**, 015009

Using angular data only : 11 measurements

$\theta^{min}_{ee} \approx 2 \arcsin\ (m_{x17}/m_{N*} - m_N)$

$$m_X = 16.85 \pm 0.04 \text{ MeV}$$



The spin-parity selection rules $J_* = L \oplus J_0 \oplus J_X$ and $P_* = (-1)^L P_0 P_X$ are required to identify the nature of the new mediator

From the ^{12}**C** results **preferred** assignments are a vector or an axial-vector particle and seem to exclude a scalar or pseudoscalar one.

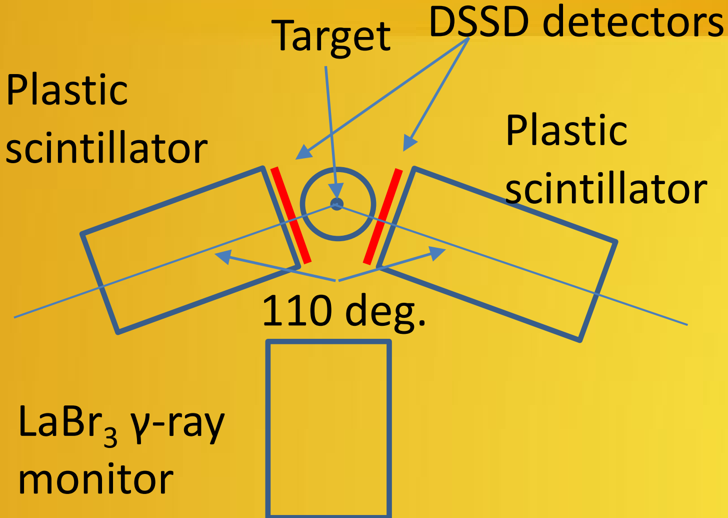
Phys.Rev.D 102 (2020) 3, 036016

N_*	J_*^P	Scalar X17	Pseudoscalar X17	Vector X17	Axial Vector X17
^{8}Be(18.15)	1^+	✗	✓	✓	✓
^{12}C(17.23)	1^-	✓	✗	✓	✓
^{4}He(21.01)	0^-	✗	✓	✗	✓
^{4}He(20.21)	0^+	✓	✗	✓	✗

^{12}C Last results

Observation of X17 anomaly in decay of the Giant Dipole Resonance

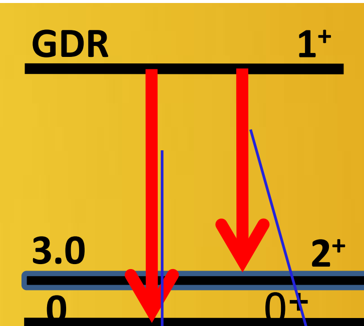
NEW



PHYSICAL REVIEW C VOLUME 14, NUMBER 1 JULY 1976

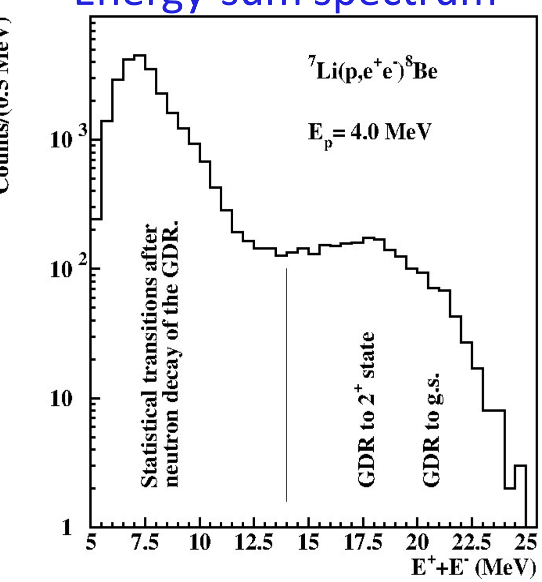
Giant $E1$ resonances in ^{8}Be from the reaction ^{7}Li$(p,\gamma)^8$Be†

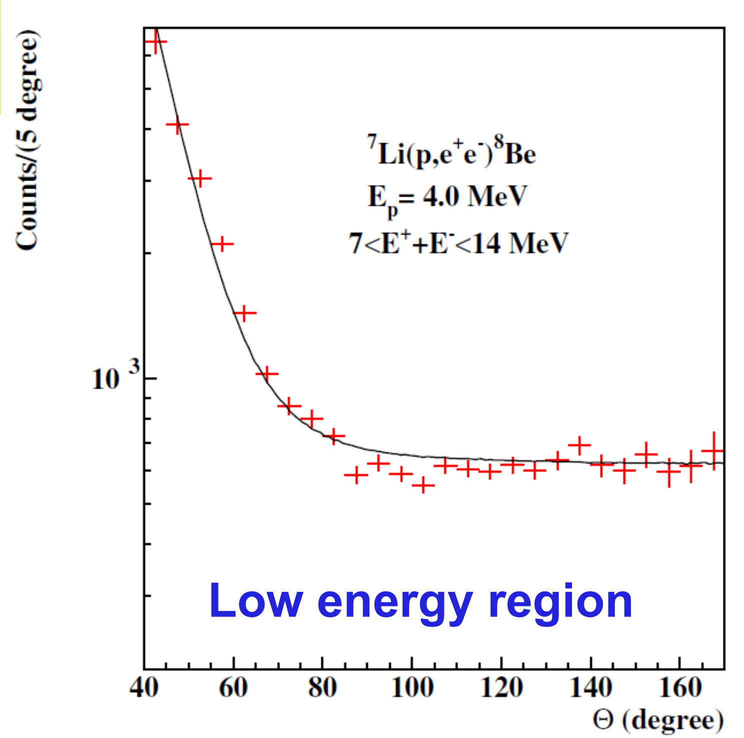
G. A. Fisher,* P. Paul,‡ F. Riess,§ and S. S. Hanna
Department of Physics, Stanford University, Stanford, California 94305
(Received 21 January 1976)

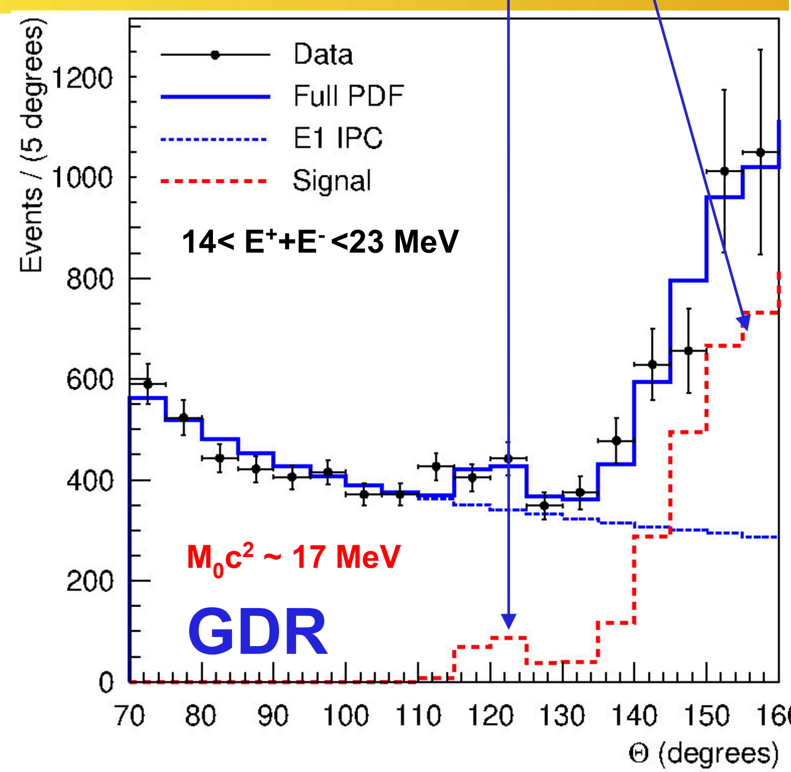


A.J. Krasznahorkay Talk ISMD 2023
arXiv:2308.06473 [nucl-ex]

Energy-sum spectrum





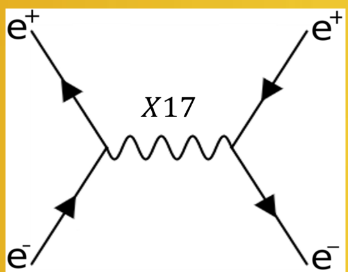


Search for X17 using resonant production on thin target

Planned for 2022 a **dedicated Run** of **PADME** to study the X17 particle

Idea : use **resonant** production and search for **visible** X_{17} decay into e^+e^-

PADME@LNF is actually the **only** facility in the world capable to do this measurement



$$\sigma_{res} \propto \frac{g_{V_e}^2}{2m_e}\pi Z\,\delta(E_{res}-E_{beam})$$

The **resonant** production scales only with Z and it's **much larger** than the associated and radiative production (BW enhancement)

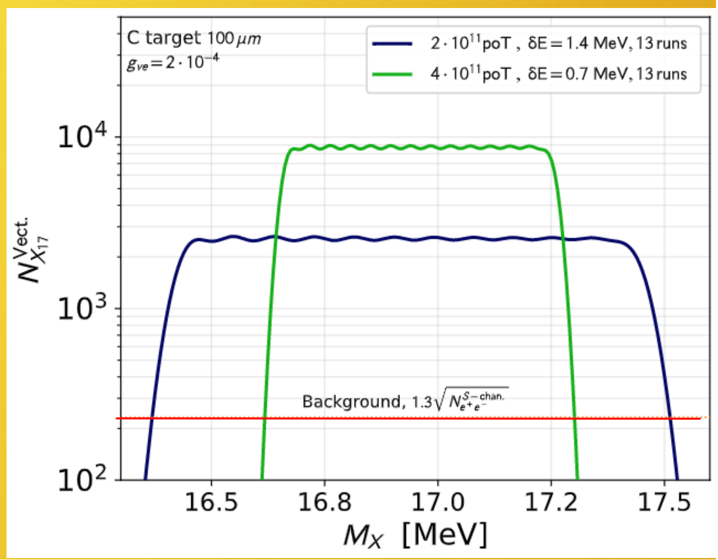
To exploit **resonant** production the center of mass energy should be **as close as possible** to the expected mass : $E_{res} = M^2_{x17}/m_e$ → A **scanning** procedure is needed

Darmé et al. Phys. Rev. D 106,115036 : analysis strategy - vary the beam energy, fit the background, calibrate the luminosity and look for resonance.

$$N_{X_{17}}^{perPoT} \simeq \frac{g_{V_e}^2}{2m_e}\ell_{tar}\frac{N_A\rho Z}{A}f(E_{res},E_{beam})$$

The resonance shape is exactly the one of the beam energy distribution : $f(E_{res},E_{beam})$ is a **gaussian** distribution with **spread** δ_E

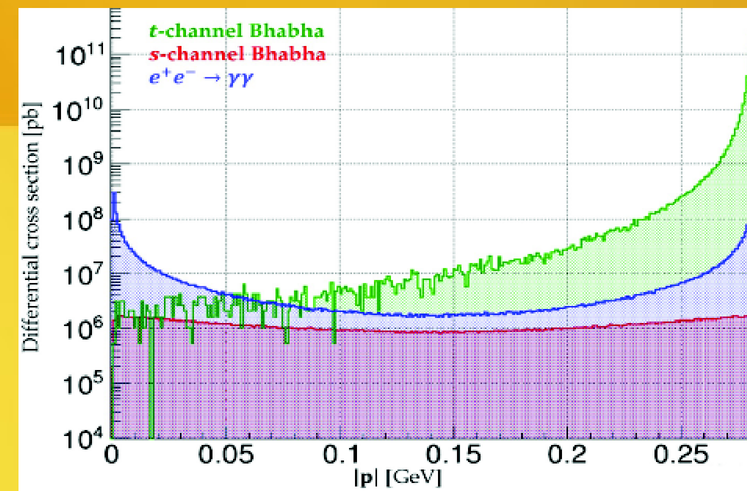
Thousands of events with just **1E11 PoT**



The expected SM background

The main backgrounds are from **Bhabha scattering** and **$\gamma\gamma$ production**.
They can be fitted **directly from data.**
$\sigma_{Bhabha} = \sigma_{s\text{-}ch} + \sigma_{t\text{-}ch}$ processes are simulated only at LO

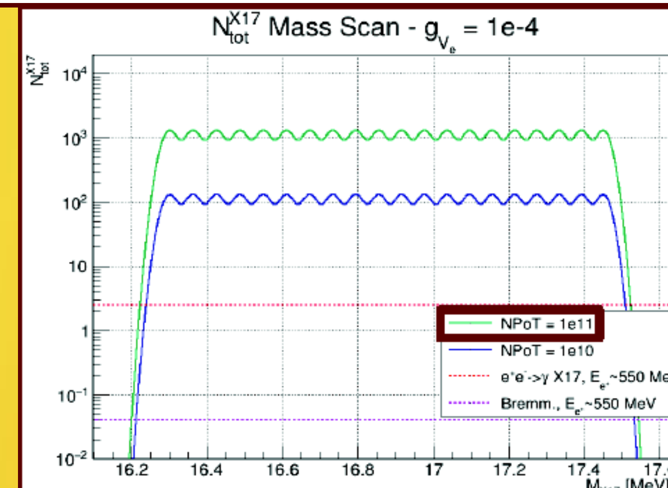
X17 production mechanism is assumed to have the same acceptance of Bhabha s-channel



Resonant search for the X17 boson at PADME

Luc Darmé,[1,*] Marco Mancini,[2,†] Enrico Nardi,[3,‡] and Mauro Raggi[4,§]

Phys. Rev. D 106, 115036

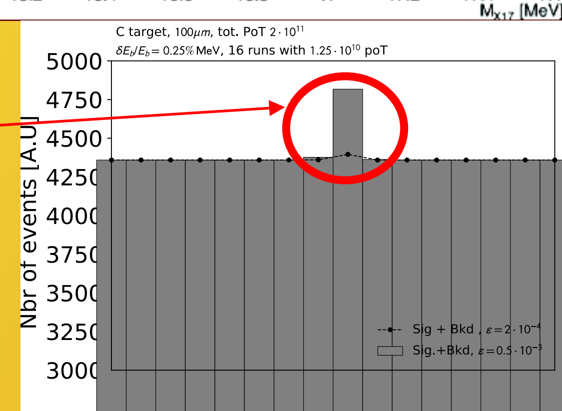


For : $N^{PoT} = 1 \times 10^{11}$, E_{beam}= 282 MeV → $\sqrt{s}$ ~ 17 MeV
Cuts on both final state particles :
- Azimuthal angle : 25.5 mrad < $\Theta_{1,2}$ < 77 mrad
- Final energy $E_{1,2}$ > 100 MeV
- Assumed detector efficiency ~ 100 %

$g_{ve} = 2 \times 10^{-4}$ and δE = 1.4 MeV

BG process	No. of Ev.	No. of Ev. in Acc.	Acc.
$e^+e^- \to e^+e^-$ (t-ch.)	5.4×10^7	6.9×10^4	0.13%
$e^+e^- \to e^+e^-$ (s-ch.)	3.2×10^4	6.4×10^3	20%
$e^+e^- \to \gamma\gamma$	2.9×10^5	1.3×10^4	4.5%
$e^+e^- \to X_{17} \to e^+e^-$	1250	250	20%

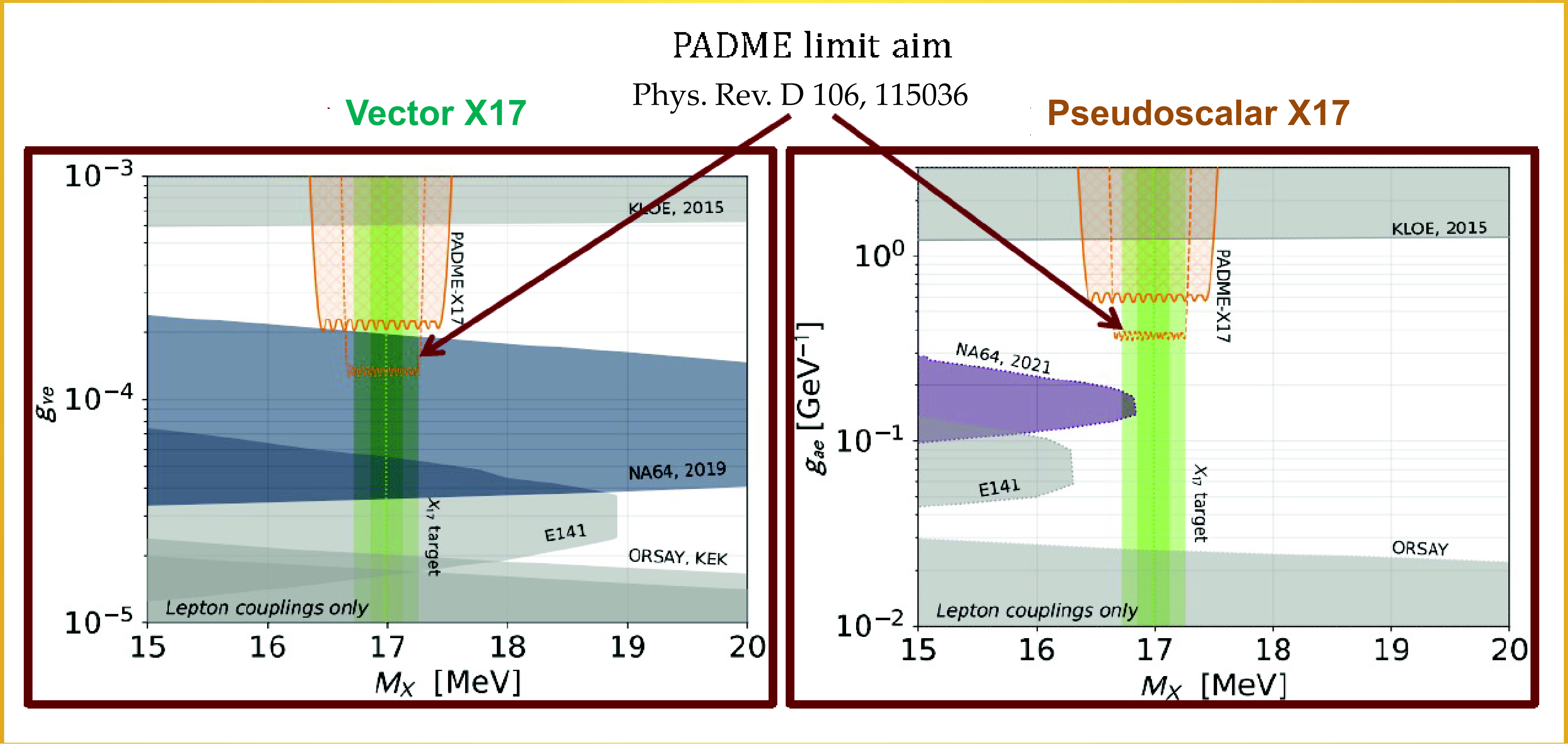
Resonant Signal should emerge on top of ***Bhabha BG*** in one or more points of the scan.



Expected limits

BG from SM Bhabha scattering under control down to ε = few 10^{-4}
Challenge : achieve an extremely precise **luminosity** measurement and **systematic** errors control (<1%)
Order 10^{10} PoT per each scan point

Under these assumptions, we aim to set limits both on:
Vector model, covering almost the entire free parameter space
Pseudoscalar model, in the case of an ALPs decaying into leptons only.
PADME maximum sensitivity is in the **vector** case



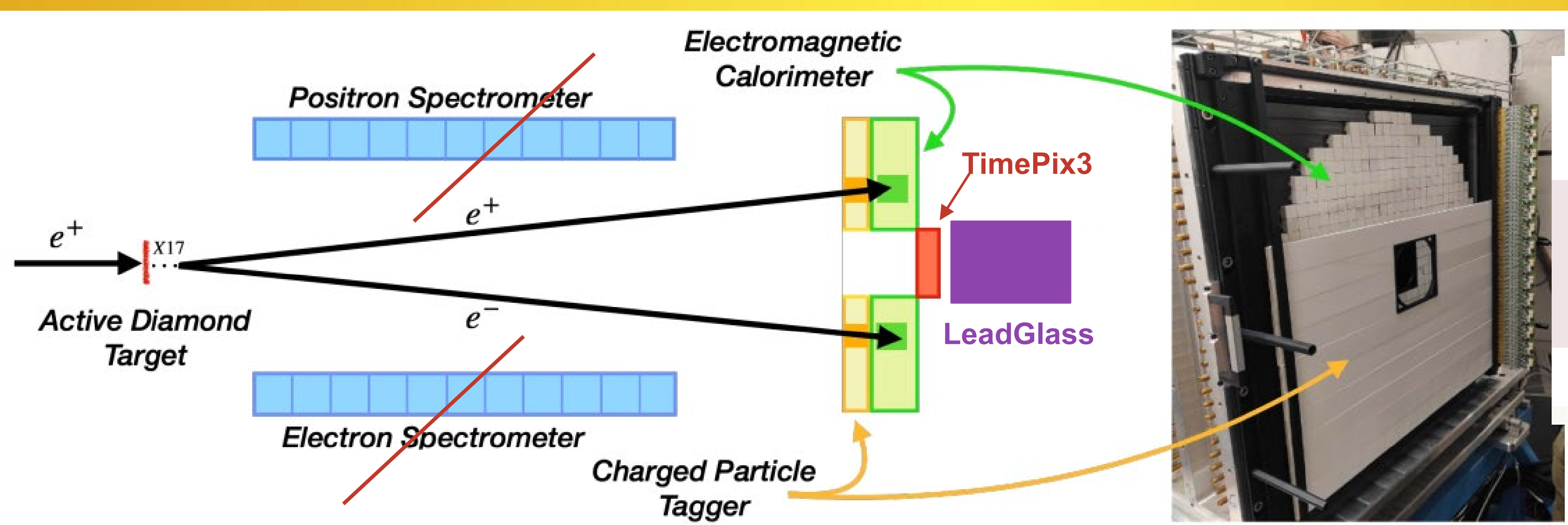
The Run III experimental setup

Improvements to the PADME set-up are required for the X17 resonant search !

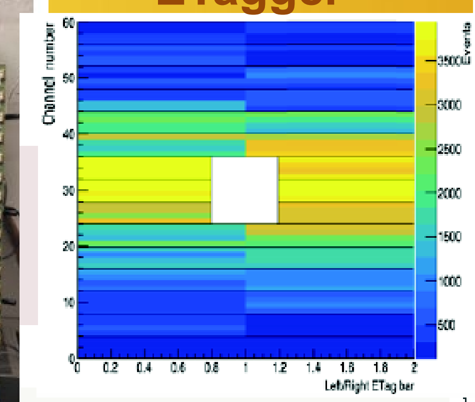
- Using PADME veto it is impossible to reconstruct e^+e^- mass having no vertex info
- Idea: identify $e+e- \rightarrow e+e-$ using the **ECAL calorimeter** only, as $\gamma\gamma$ events in Run II

  $\rightarrow$ **NO magnetic field** to get both final state particles in **ECAL**
- To distinguish e^+e^- from $\gamma\gamma$: **charged** particle detector **(Etagger)** - 5 mm plastic **scintillators** double sided SiPM r/out

  Increased **target-ECAL** distance (+17 cm) $\rightarrow$ changes acceptances
- Removed the **SAC** and installed back of hole the **TimePix3 Beam monitor** and a LeadGlass Detector with PMT readout **(Luminosity monitors)**

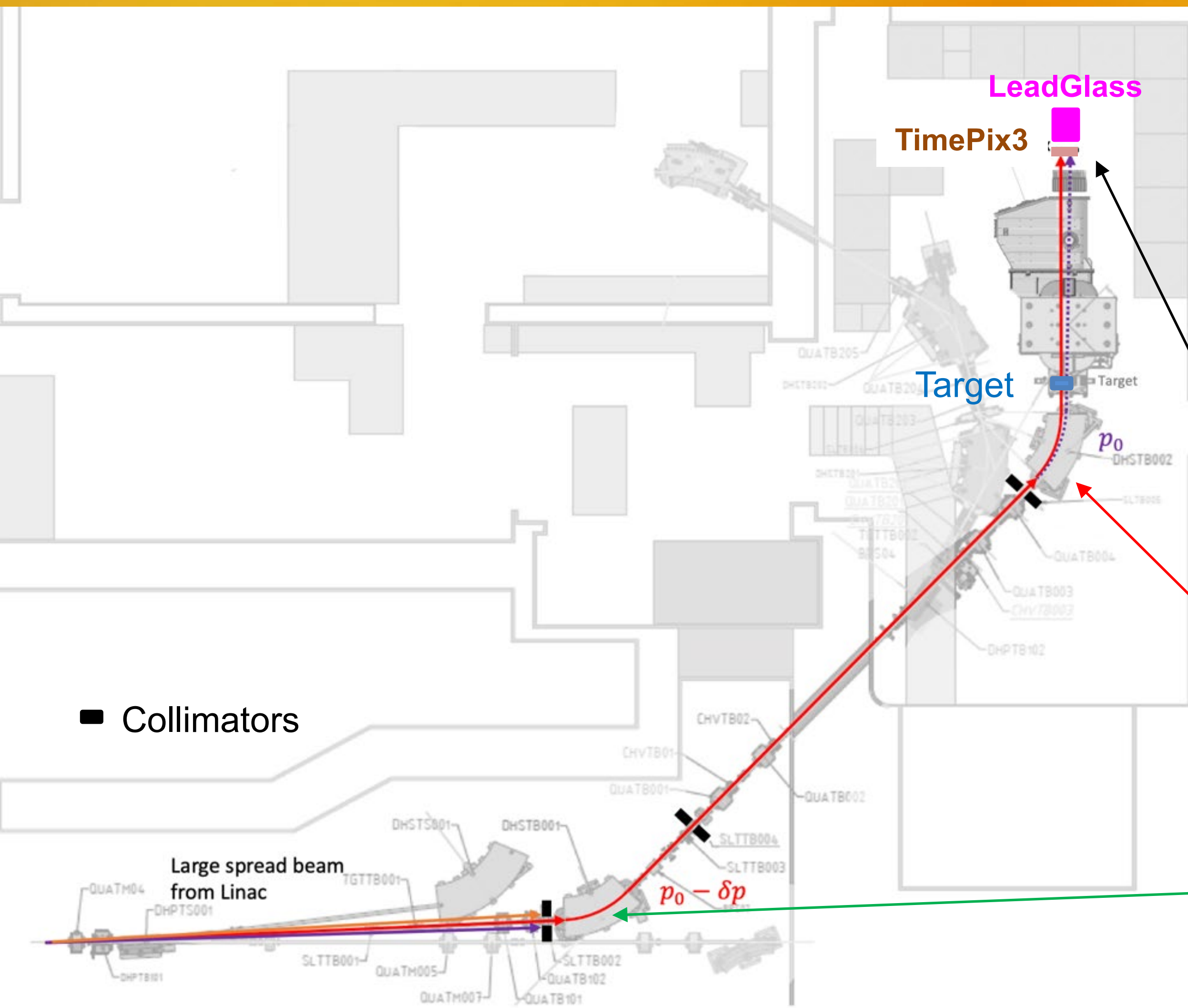


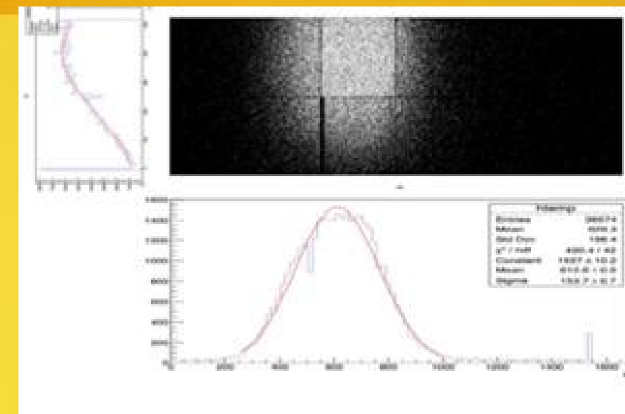
ETagger



Thanks to the enhanced production cross section can reduce N^{PoT}/bunch by factor 10.
$\rightarrow$ Much lower pile-up and better energy resolution

Energy beam selection and Resolution





Measure displacement with TimePix3 to compute energy step

Second dipole used to correct trajectory and center beam on PADME axis

First dipole used to select energy

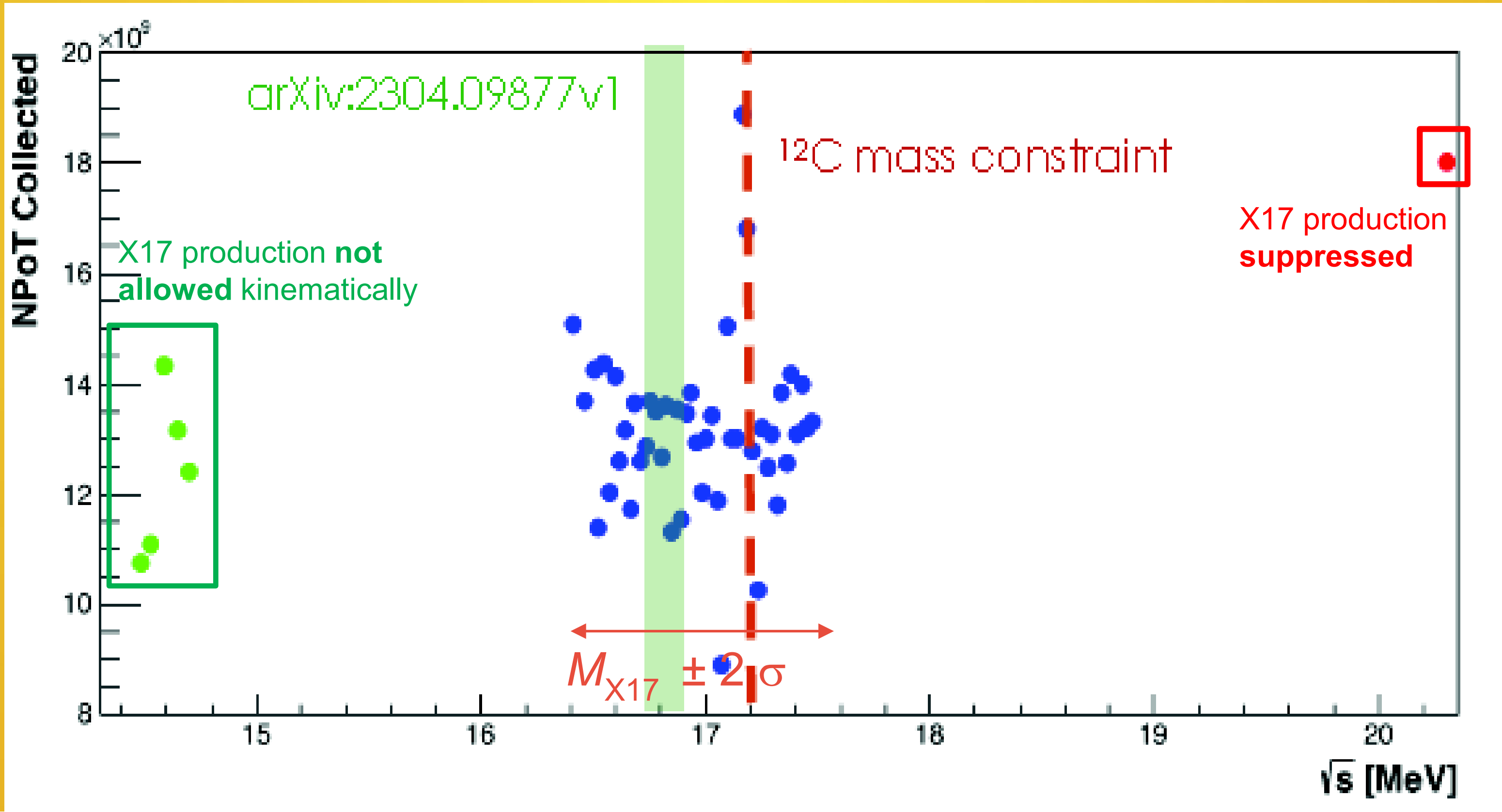
The **luminosity** and **beam energy** are measured by a combination of LeadGlass, target and TimePix3 beam monitors.

Data collected during RunIII

Total amount of data collected ~ 6x10^{11} PoTs (~ 10^{10} PoTs per point) :
47 invariant mass points in beam energy range **260 MeV < E_{beam} < 300 MeV**
(± 2σ mass around predicted region by Atomki) with δE_{beam} **~ 0.75 MeV**
precision on the mass measurement will be : (17.47-16.36)/47 ~ 24 KeV

and 6 points out-of-resonance : 5 points below + 1 above (5 runs) **(SM & syst estimates)**
and 4 points without target **(beam background studies)**

Bunch length ~ *200-250 ns* , N^{PoT}_{Bunch} ~ *2500* at *f* ~ 50 Hz



Observables and possible measurements

Observables :

$$\frac{N(e^+e^-)}{N^{PoT}} \text{ vs } \sqrt{s} \qquad \frac{N(\gamma\gamma)}{N^{PoT}} \text{ vs } \sqrt{s}$$

$$\frac{N(e^+e^-+\gamma\gamma)}{N^{PoT}} \text{ vs } \sqrt{s}$$

$$\frac{N(e^+e^-)}{N(\gamma\gamma)} \text{ vs } \sqrt{s}$$

Goal: keep at the % level the systematic errors, in particular the luminosity

Several different observables can be used with different outcomes:

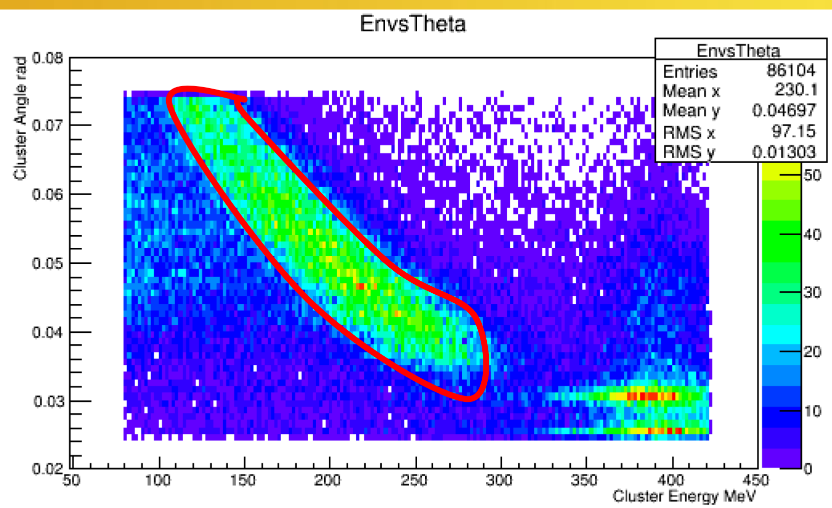
- $N(2cl)/N_{PoT}$ = existence of X_{17}
  - High statistical significance
  - No ETag related systematic errors
- $N(2e)/N(2\gamma)$ = existence of X_{17}
  - ETag efficiency and systematics
  - lower statistical significance due to 2γ cross section
  - Do not depend on N_{PoT} (no N_{PoT} systematic) error dominated by tagging efficiency
- N_{e+e-}/N_{PoT} = vector nature of X_{17}
  - Systematic errors due to ETag tagging efficiency stability
- $N_{\gamma\gamma}/N_{PoT}$ = pseudo-scalar nature of X_{17}
  - Systematic errors due to ETag tagging efficiency stability

First look at off-resonance data

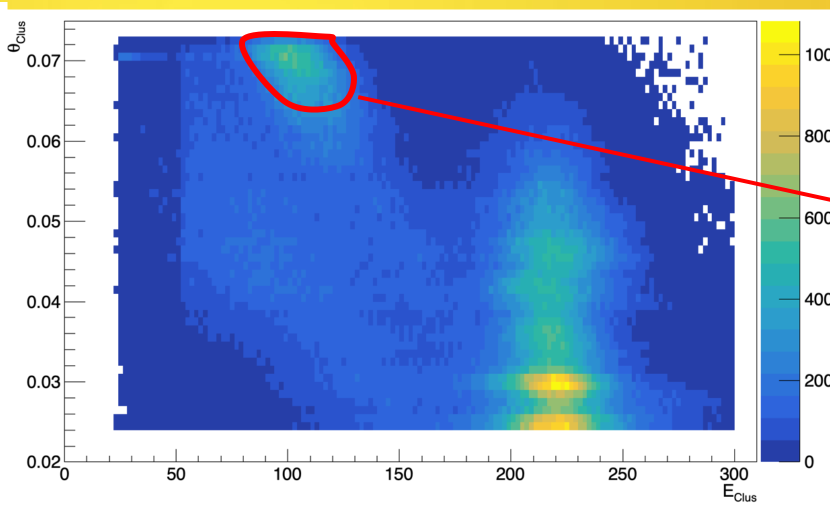
First selection aimed at N(2cl)/N_{PoT} studies :
2 clusters in time in ECal (Δt < 5 ns) + energy, radius cuts **and** reasonable Centre of Gravity

Using kinematic relation between E_γ and Θ_γ → good signal-background separation
compatible with a 2-body final state : beam background and Bhabha t-channel seem under control

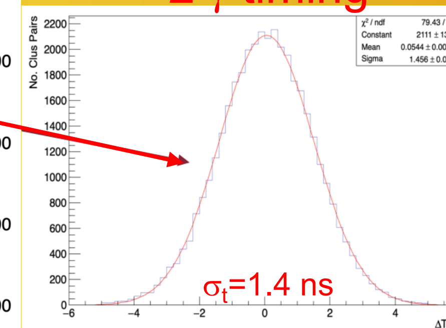
Above : 402 MeV



Below : 205 MeV



2 γ timing



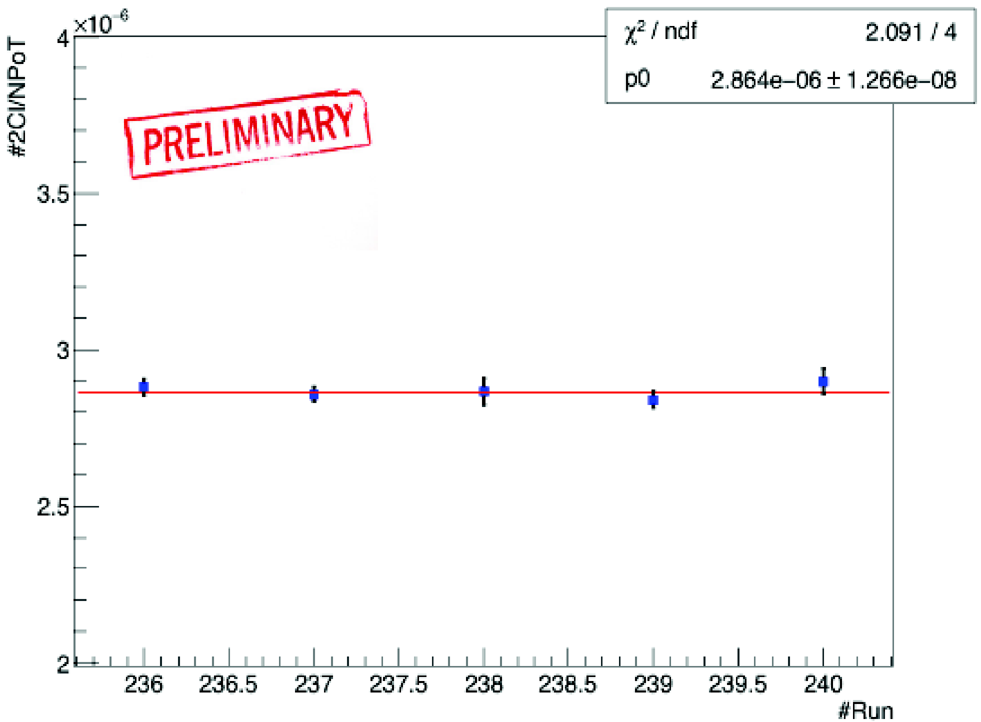
Recently, we **updated** the Toy MC introducing the correct experimental parameters.
With respect to preliminary predictions, the BG decreases, while the signal increases

g_{ve} = 2 x 10^{-4} and δE = 0.75 MeV

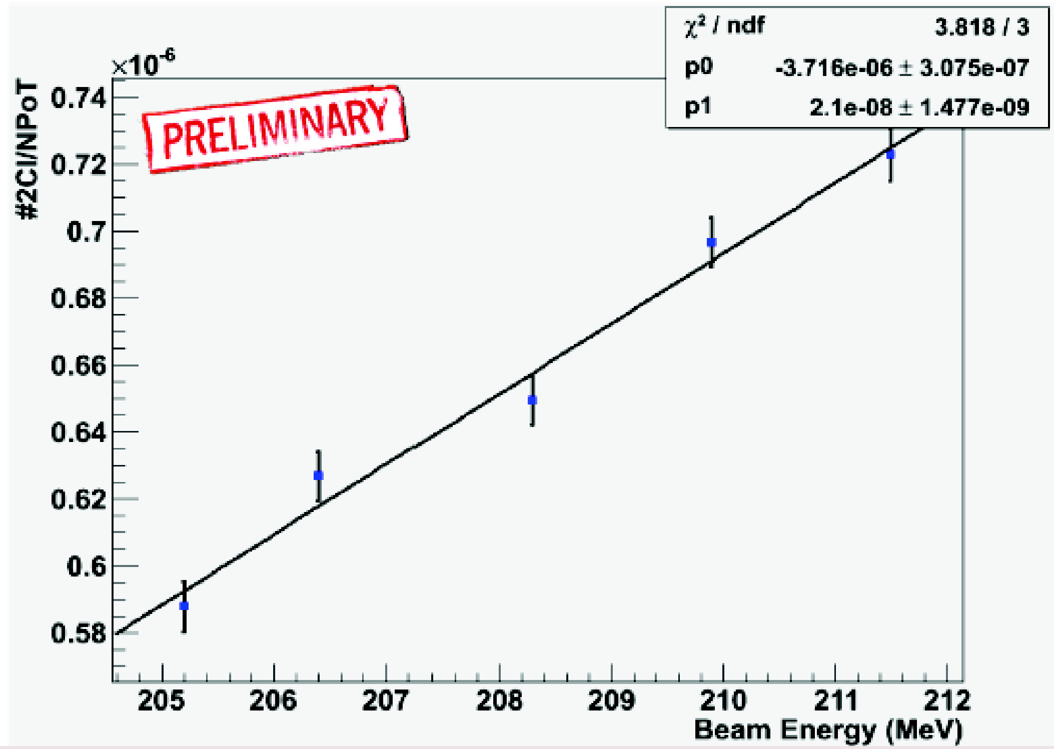
Process	# of Ev.	# of Ev. in Acc.	Acc.
$e^+e^- \to e^+e^-$ (t-ch.)	$5.4 \cdot 10^7$	$4.3 \cdot 10^4$	0.08%
$e^+e^- \to e^+e^-$ (s-ch.)	$3.2 \cdot 10^4$	$4.3 \cdot 10^3$	13.6%
$e^+e^- \to e^+e^-$ (full)	$5.4 \cdot 10^7$	$3.9 \cdot 10^4$	0.07%
$e^+e^- \to \gamma\gamma$	$2.9 \cdot 10^5$	$8.7 \cdot 10^3$	3%
$e^+e^- \to X_{17} \to e^+e^-$	2600	350	13.6%

First look at off-resonance data set

Over resonance 402 MeV



Below resonance

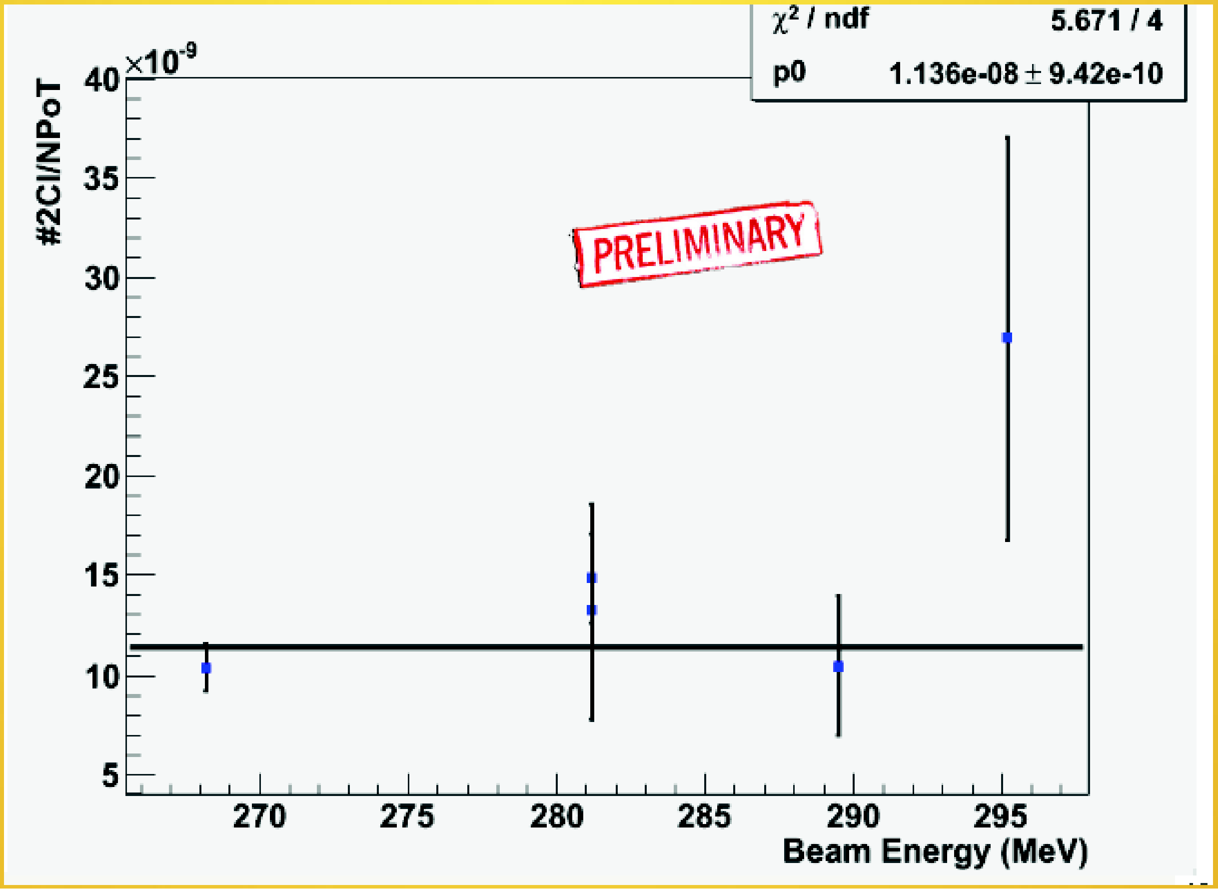


- **RMS ≈ 0.7%** over the 5 runs
  Compatible with pure statistics
- Constant fit has a **good** χ^2
  No significant systematics
- Vertical scale : arbitrary
  No acceptance corrections applied

- **RMS < 1%** over the 5 energies
  Computed on residuals wrt the fit
- Linear fit has a **good** χ^2
  Trend due to acceptance
  Trend reproduced by MC
- Vertical scale : arbitrary
  No acceptance corrections applied

Beam background estimates

- **No-target** data sets used to measure the **beam background** contamination in data sample
  The set contains data collected **at different beam energies**
- Running **the same selection code** on no-target data we can get the contamination from **beam halo background** in the signal selection
- **#2Cl(notTarget)/#2Cl(DATA) ≈ 1E-8/2E-6 : few permille**
- **Background seems stable**



Conclusions

In 2019/2020 **PADME** performed 2 physics runs, collecting > 5×10^{12} PoT each

$\sigma(e+e- \rightarrow \gamma\gamma) = (1.977 \pm 0.018\ stat \pm 0.0119\ syst)$ mb **PhysRevD.107.012008 (2023)**

very good agreement with QED NLO

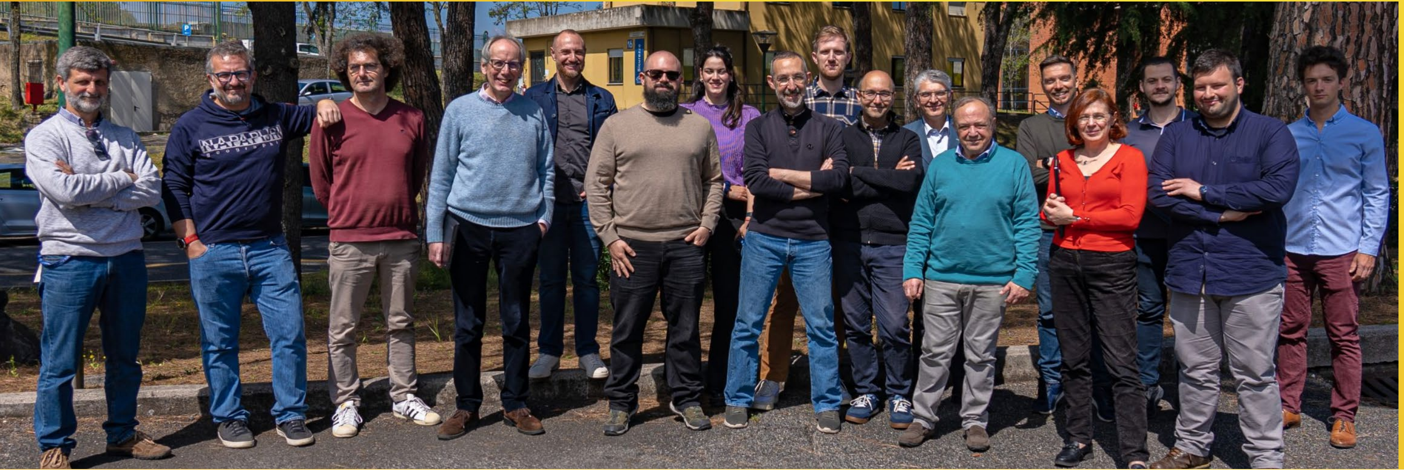
PADME Run III scan for **the X_{17} particle** successfully made in 2022

- High quality data (47 points) collected for **16.35 MeV < M_{X17} < 17.5 MeV**
- Beam Background and BhaBha are under control
- Data quality variables identified allowing to reject beam instabilities
- Strategy established to approach the resonance region

Next steps:

- Move into the closer sidebands first and then "unblind" resonance region
- Improve data/MC agreement

Many thanks to the **LNF LINAC team** and all the **accelerator division**
for the excellent efficiency and quality of the machine operation during PADME Run III.



STAY TUNED …
More results coming soon !

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