PADME Run III

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26-31 March 2023 - Obergurgl University Center
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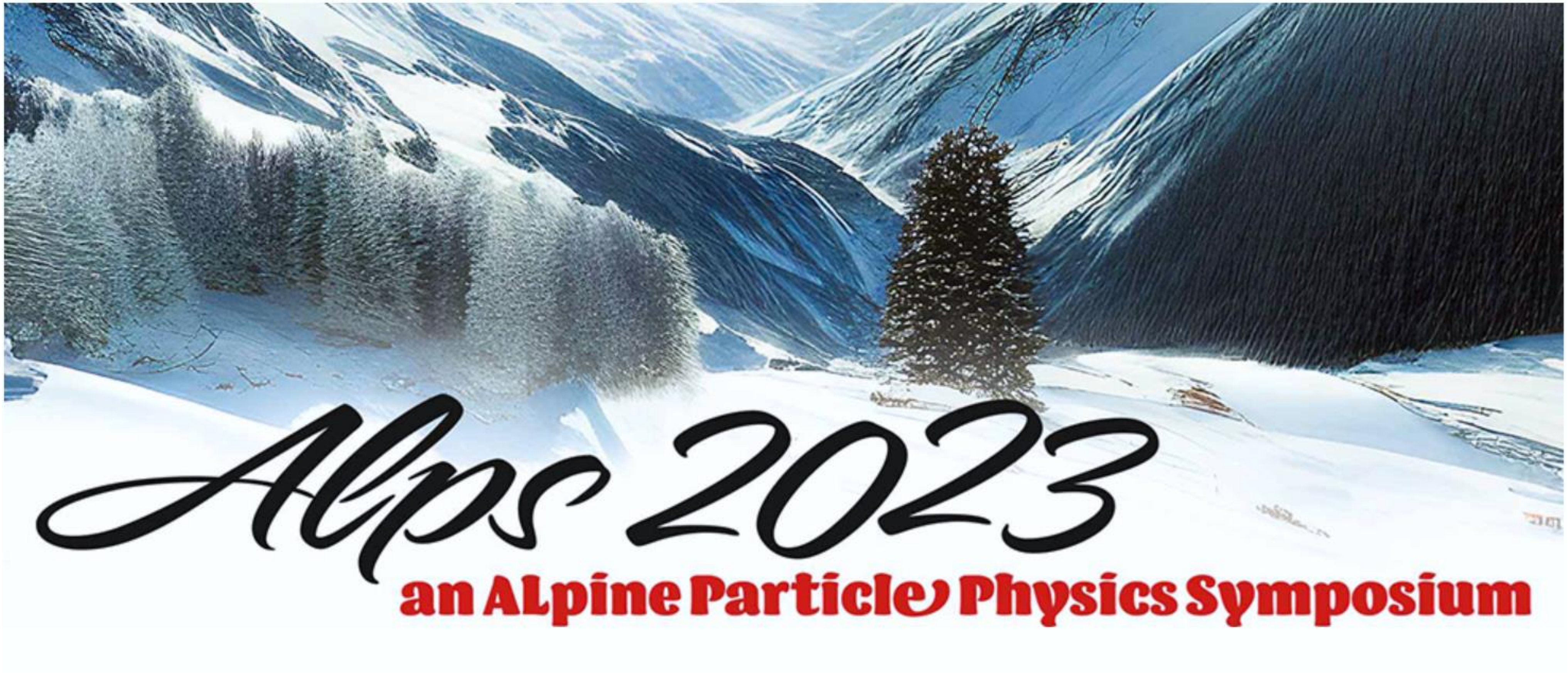


Outline

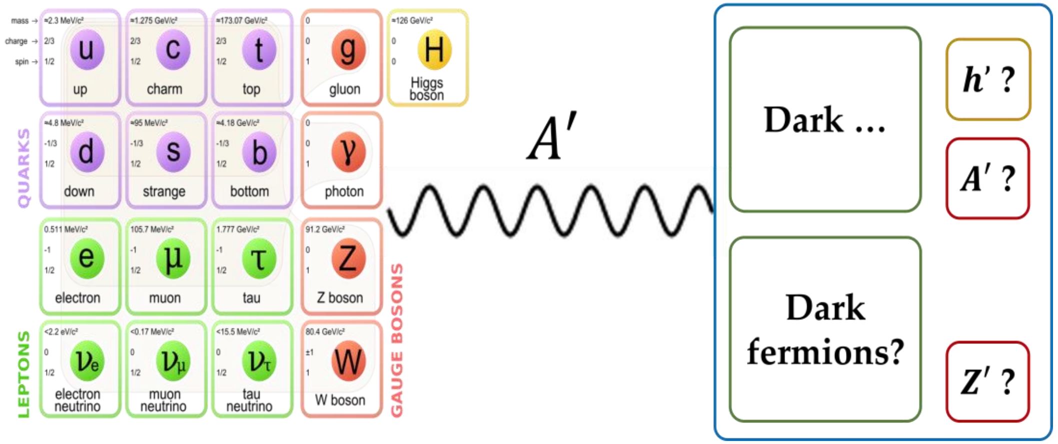
- Dark Photon models and their test @PADME
- **P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment
  - Previous Runs and first physics results
- The X_{17} anomaly @PADME and the resonant search
  - The Run III
- Conclusions and future prospects

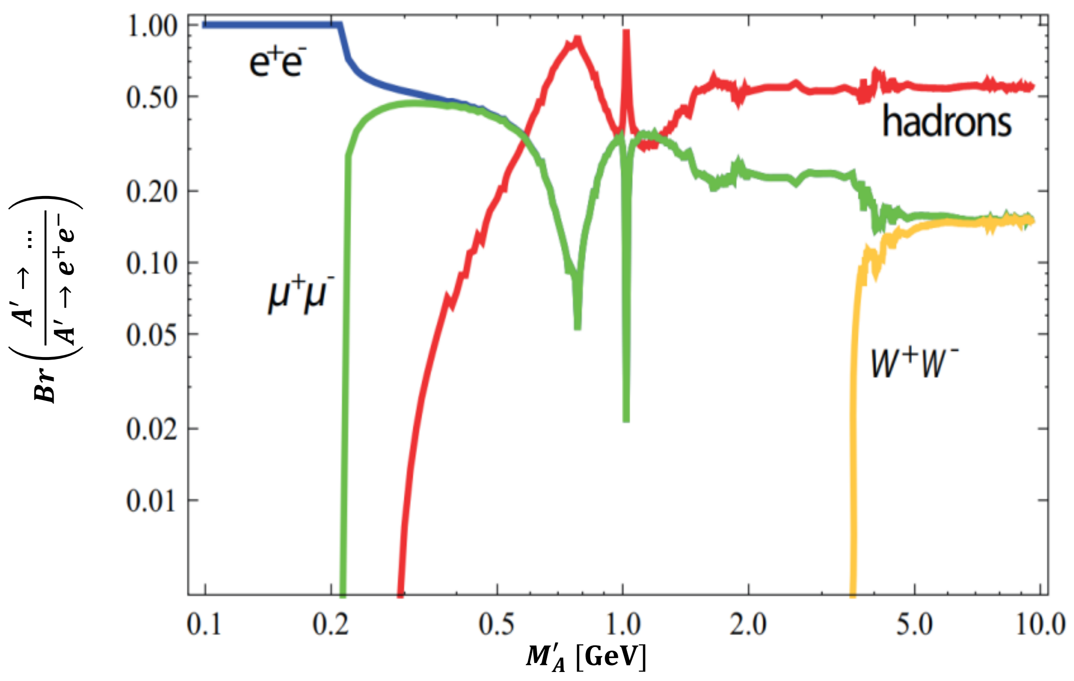
The Dark Photon portal

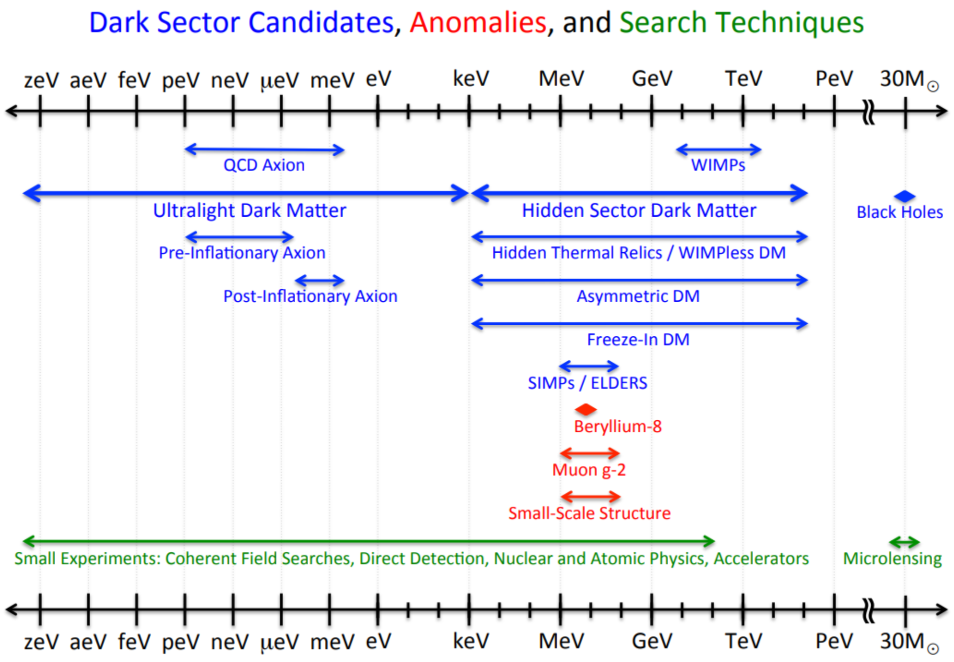
The Dark Photon A' is a massive neutral vector portal between SM and Dark Sector

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

$g_V \ll 1 \rightarrow$ hidden







arXiv:1707.04591v1

Search for A' with electron-positron reactions

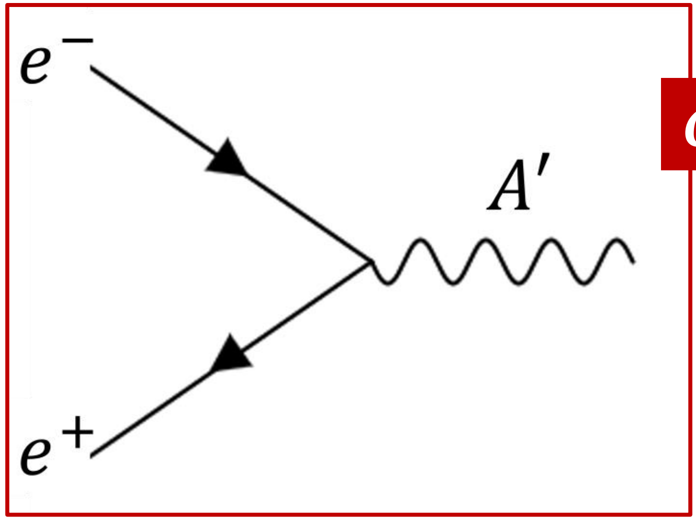
Two different production mechanisms, annihilation and emission:

- **Resonant annihilation:** $e^+e^- \rightarrow A' \rightarrow \sigma_{res}(E_{e^+}) = \frac{12\pi}{m_{A'}^2} \frac{\Gamma_{A'}^2/4}{(\sqrt{s}-m_{A'})^2+\Gamma_{A'}^2/4}$

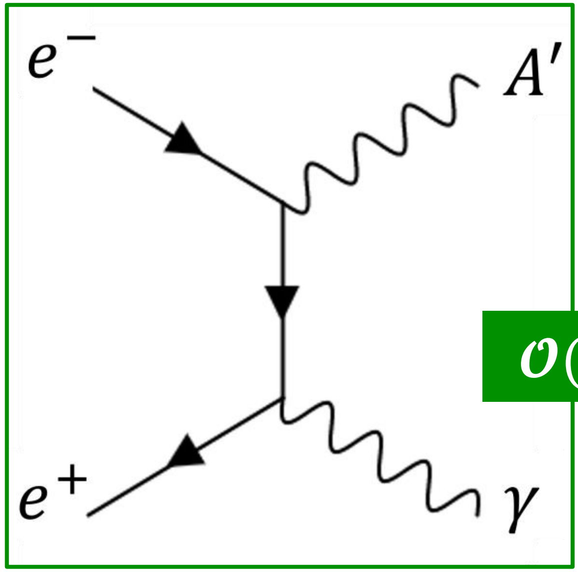
Nardi et al. Phys. Rev. D 97, 095004

- **Associated production:** $e^+e^- \rightarrow \gamma A'$
- **A'-strahlung:** $e^{\pm} Z \rightarrow e^{\pm} Z A'$

The resonant annihilation is accessible only with a positron-beam facility

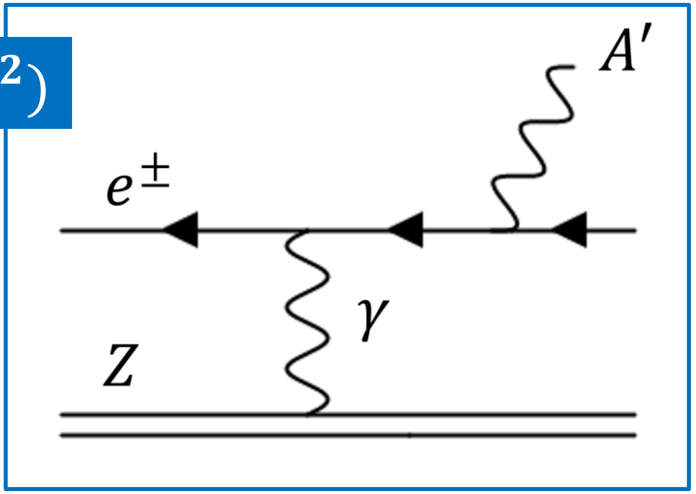


$\mathcal{O}(\alpha^0)$



$\mathcal{O}(\alpha)$

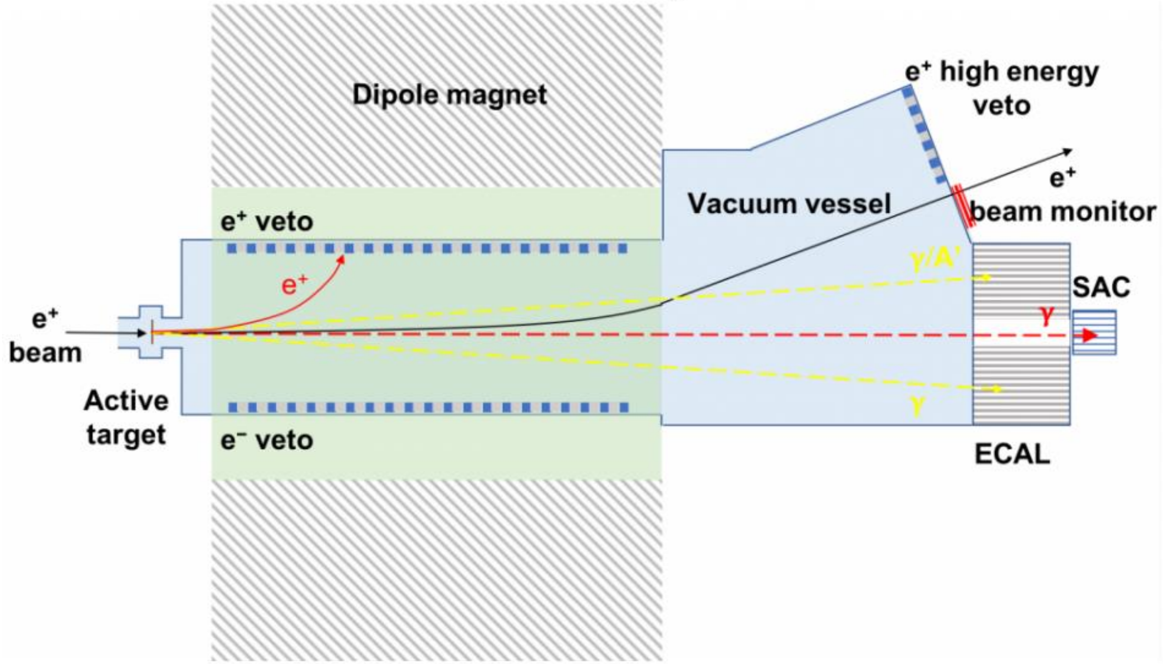
$\mathcal{O}(\alpha^2)$



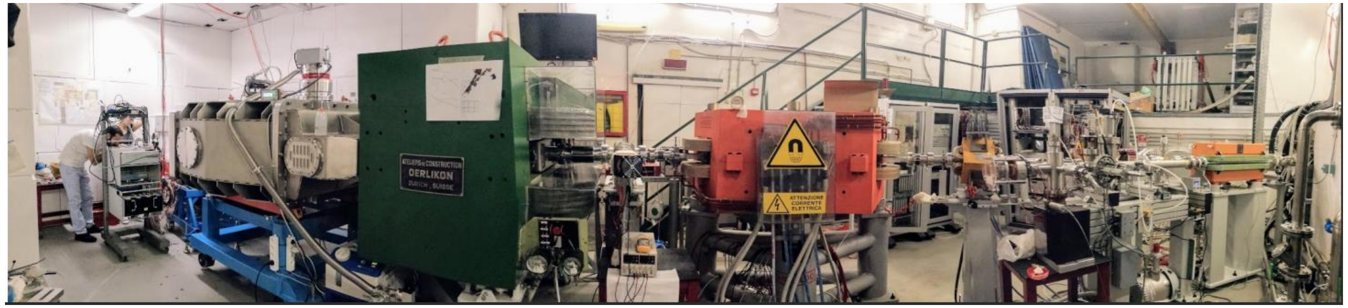
Positron Annihilation into DM Experiment

PADME is based @Laboratori Nazionali di Frascati (LNF) and it searches for A' in the associated production $e^+e^- \rightarrow \gamma A'$

- e^+-beam ($E < 550$ MeV) on 100μm active diamond target
- Dipole B-field bends out the un-interacted beam and charged particles
- Signal→ 1γ in BGO Electromagnetic Calorimeter (ECal) & nothing elsewhere, measuring ΔM^2_{miss} and giving us access to $m_{A'}$
- Bremsstrahlung rejected by ECal hole and the Small Angle Calorimeter (SAC) immediately behind
- Plastic scintillator bars as charged particle vetoes



P. Albicocco et al 2022 JINST 17 P08032



Run I and Run II data taking

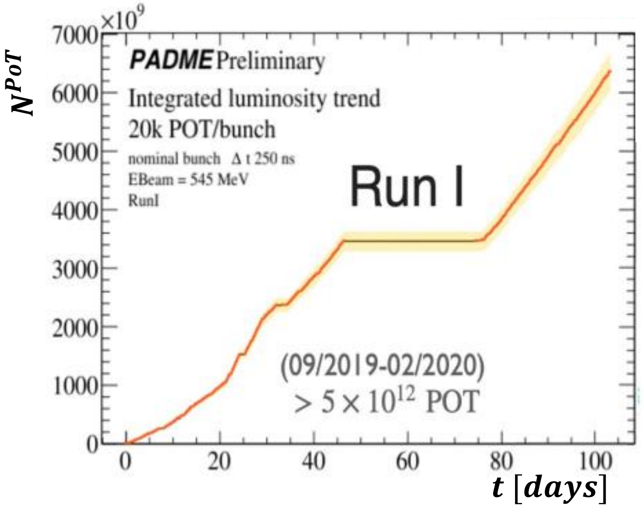
Two Runs in three configurations between September 2018 and December 2020

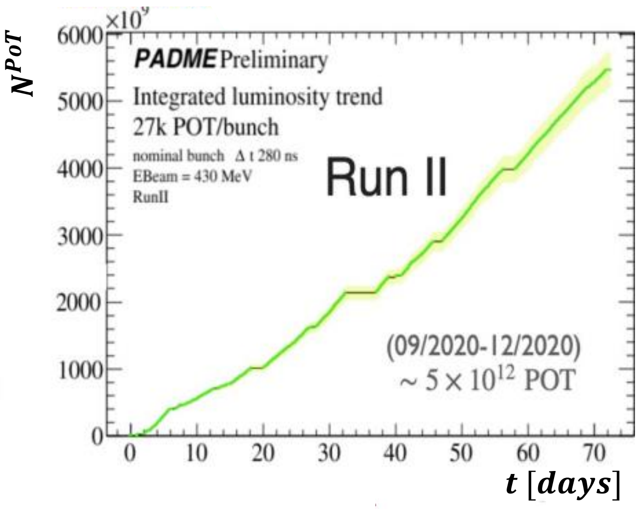
Acquired luminosities:

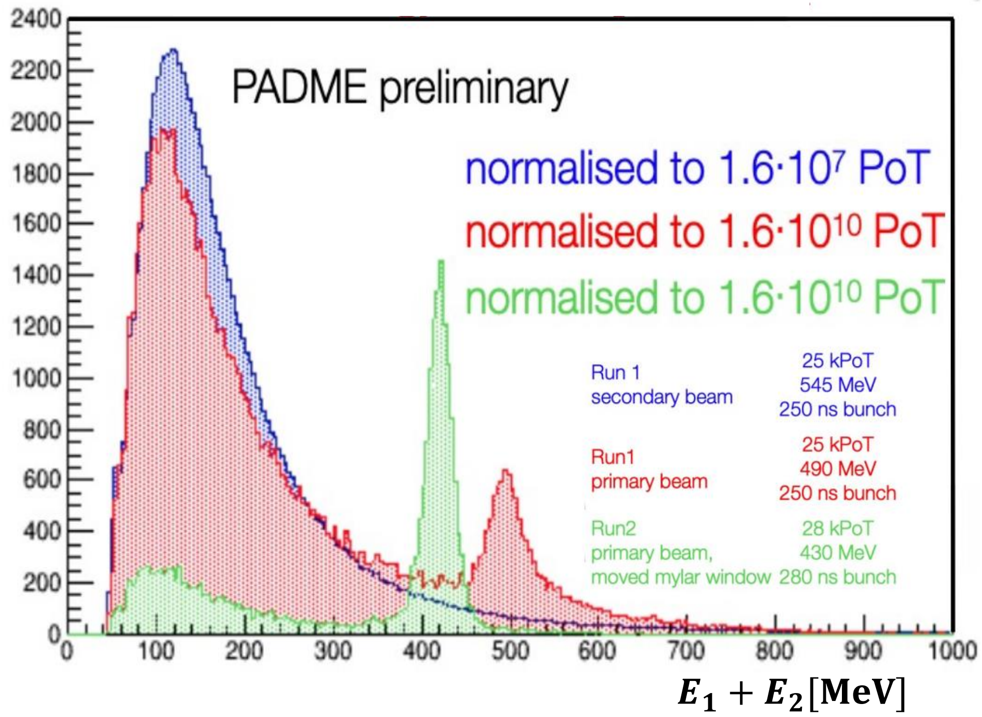
- **Run I** → $7 \times 10^{12}\ PoT$
- **Run II** → $5.5 \times 10^{12}\ PoT$
- Multiplicity $N_{bunch}^{PoT} \simeq 3 \times 10^4$

Changes between the first two runs:

- **Run Ia**: secondary beam → **Run Ib**: primary beam
  → Reduced BIB
- **Run Ib** → **Run II**: changed the vacuum separation
  → Reduced BG from vacuum window
- **Run Ib** → **Run II**: longer beam (250 → 280 ns)
  → Reduced the pile-up in detectors







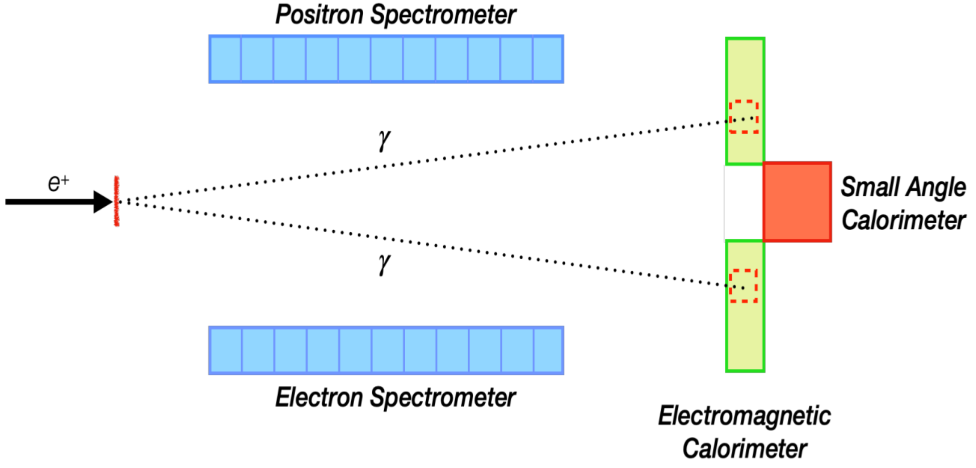
The Multi-photon annihilation measurement

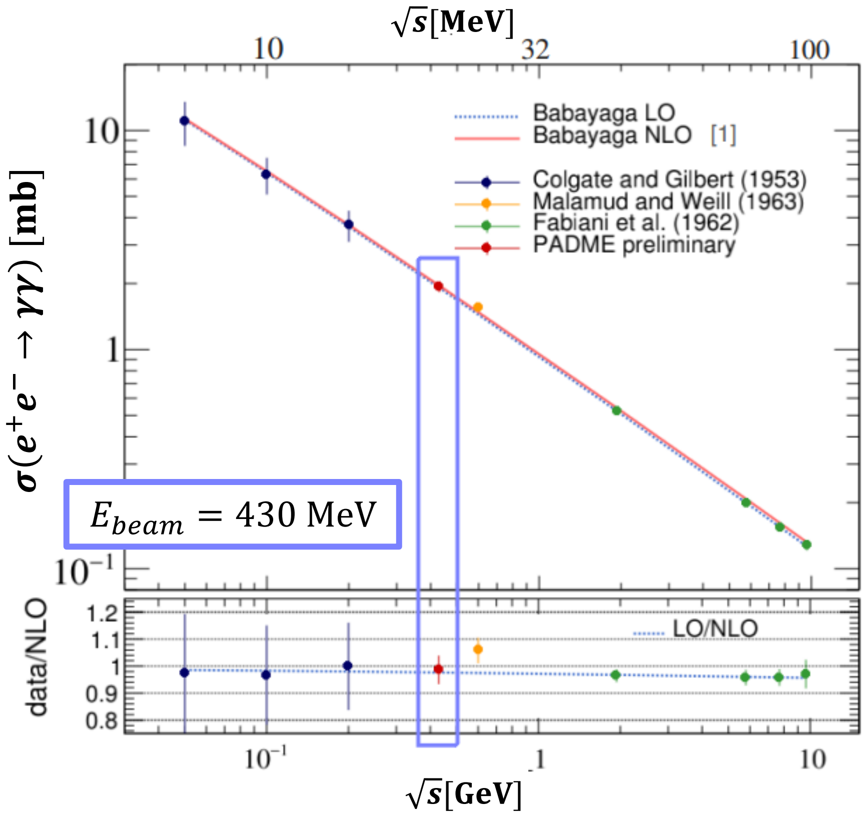
From the $\sigma\left(e^+e^- \to \gamma\gamma\ (\gamma)\right)$ measurement:

[F. Bossi *et al.* Phys. Rev. D **107**, 012008](#)

- Characterisation of ECal
- $\sigma(e^+e^- \to \gamma A') \propto g_V^2 \times \sigma(e^+e^- \to \gamma\gamma) \times \delta(M_{A'})$
- Could be sentisitive to sub-GeV new physics (e.g. ALPs)

First measurement below 500 MeV with < 20% precision with only 10% of Run II dataset





PADME → $\sigma\left(e^+e^- \to \gamma\gamma\ (\gamma)\right) = 1.930 \pm 0.029_{stat} \pm 0.057_{syst} \pm 0.020_{target} \pm 0.079_{lumi}$ mb

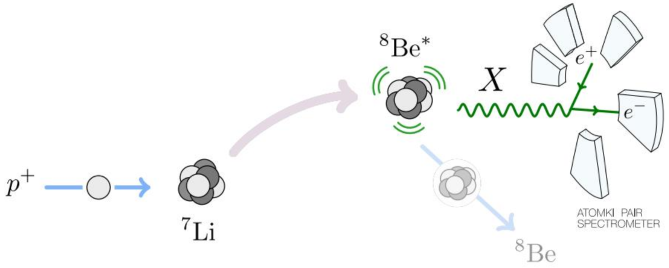
QED@NLO $\sigma\left(e^+e^- \to \gamma\gamma\ (\gamma)\right) = 1.9573 \pm 0.0005_{stat} \pm 0.0020_{syst}$ mb *Phys.Lett.B* 663 (2008) 209-213

The ATOMKI X_{17} anomaly

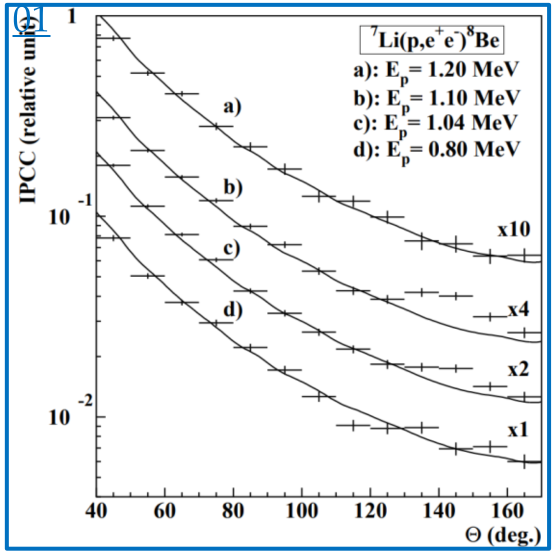
Recently, ATOMKI collaboration announced the observation of an anomaly in the angular correlation of e^+e^- pairs produced via IPC in the ^8Be, ^4He and ^{12}C .

The anomaly seems to be compatible with the production and successive decay of a new ~ 17 MeV mass mediator.

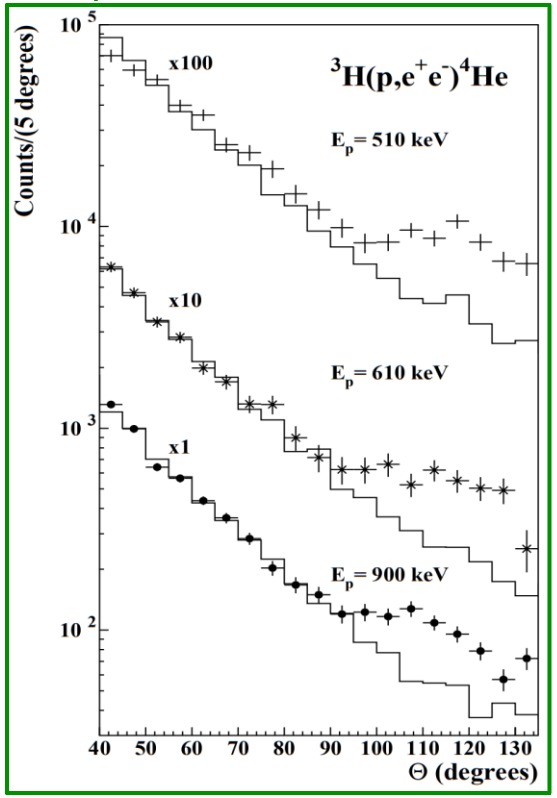
More details in E. Nardi's talk



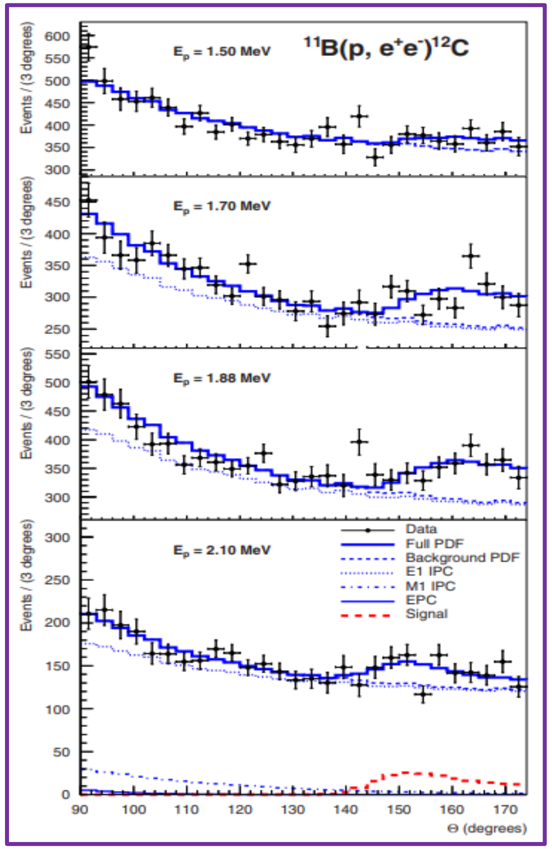
Phys.Rev.Lett. 116 (2016) 4, 0425 01



Phys.Rev.C, 104(4):044003



Phys. Rev. C 106, L061601



The X_{17} particle

According to the ATOMKI observations, the main properties of the new X_{17} particle are:

- $m_{X_{17}} \sim 17$ MeV
- $Br(e^+e^- \to X_{17}) \simeq 5 \times 10^{-6} Br(e^+e^- \to \gamma\gamma)$
- $\Gamma_V = 0.5 \left(\frac{g_V}{0.001}\right)^2$ eV for the vector case

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

As proposed by *J. Feng in 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^+	✓	✗	✓	✗

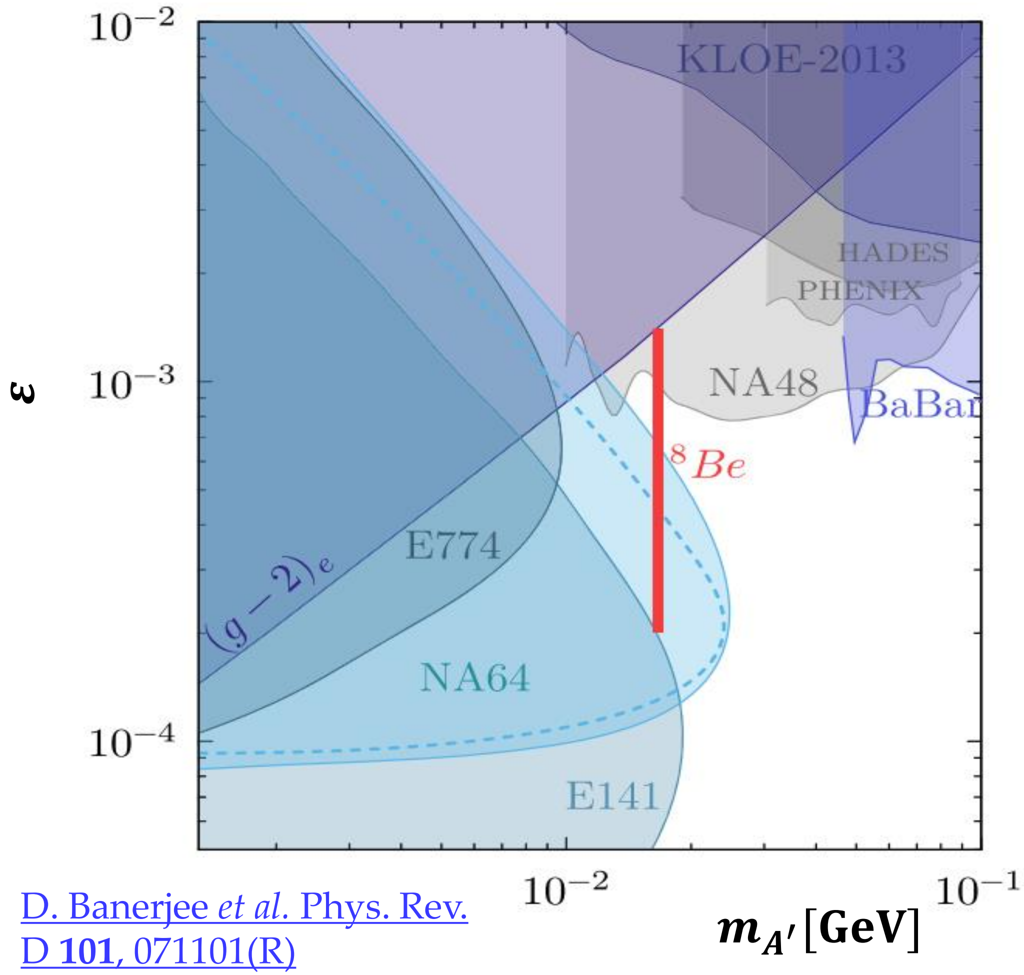
^{12}C Last results

Phys. Rev. C 106, L061601

The actual A' space of parameters

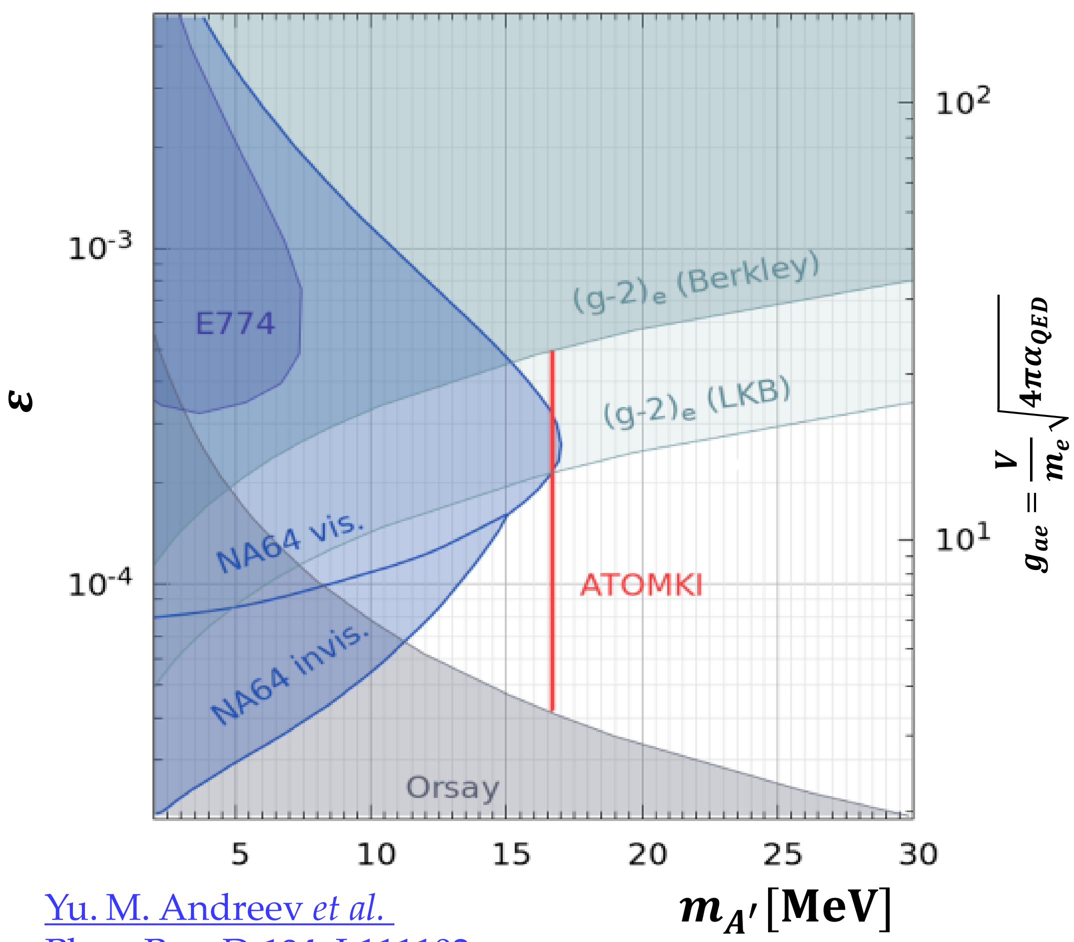
PADME expects to set limits both in the Vector and ALPs models

Vector



[D. Banerjee *et al.* Phys. Rev. D **101**, 071101(R)]

Pseudoscalar

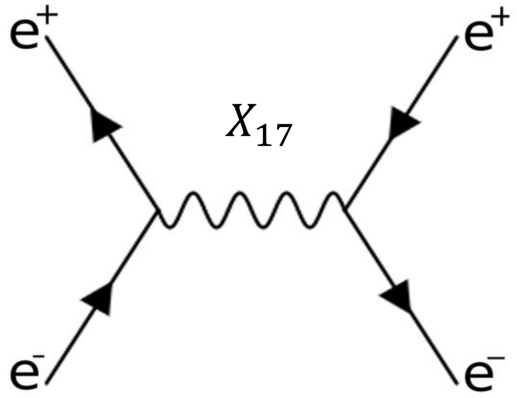


[Yu. M. Andreev *et al.* Phys. Rev. D **104**, L111102]

The X_{17} resonant search on thin target

Use resonant production and search for visible X_{17} decay in e^+e^-

LNF is actually the only laboratory providing positron beams with $E_{beam} < 500$ MeV



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

The resonant production scales only with Z and it is much larger than associated and radiative production

To exploit the resonant production, the $\sqrt{s}$ should be as close as possible to the expected mass: $\boldsymbol{E_{res} = \frac{m_{X_{17}}^2}{2m_e}}$

→ **A scanning procedure is required**

The X_{17} resonant search on thin target

Analysis strategy: vary the beam energy, fit the background, calibrate the luminosity and look for resonance

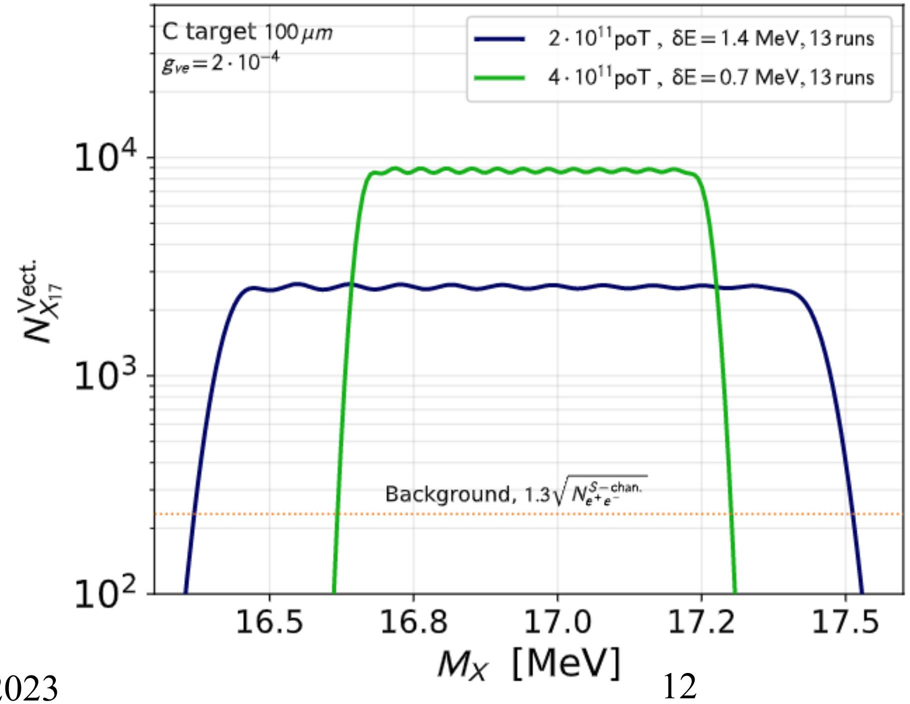
The resonance shape is exactly the one of the beam energy distribution: gaussian resonant peak

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

$f(E_{res}, E_{beam})$ is the beam spread → gaussian distribution with spread δE

Darmé et al. Phys. Rev. D 106, 115036

Main background is from Bhabha scattering and $\gamma\gamma$-production. It will be fitted directly from the data



Improvements to the set-up are required!

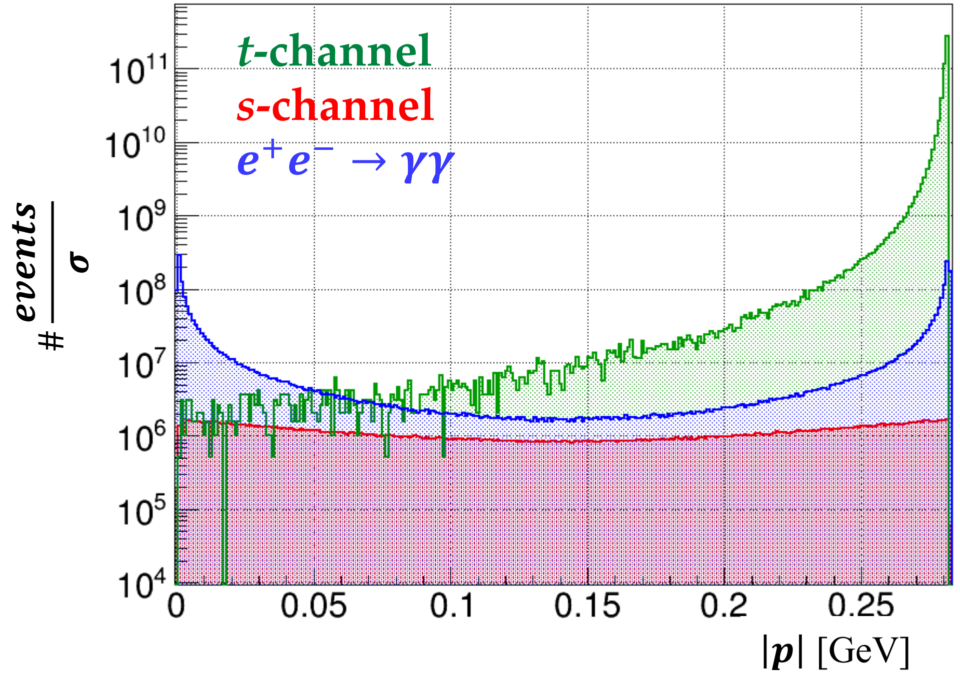
The expected Standard Model background

- $\sigma_{Bhabha} = \sigma_{s-ch} + \sigma_{t-ch}$ and processes simulated only at LO with **CalcHEP**
- Beam condition: $N^{PoT} = 2 - 4 \times 10^{11}$ and $E_{res} = 282$ MeV $\rightarrow \sqrt{s} = 17$ MeV
- X_{17} production mechanism is assumed to have the same acceptance of Bhabha s-channel
- Cuts on both final state particles on the azimuthal angle and energy

Resonant search for the X17 boson at PADME
[Phys. Rev. D 106, 115036]
Luc Darmé,[1,*] Marco Mancini,[2,†] Enrico Nardi,[3,‡] and Mauro Raggi[4,§]

$g_{V_e} = 2 \times 10^4$ and $\delta E = 1.4$ MeV

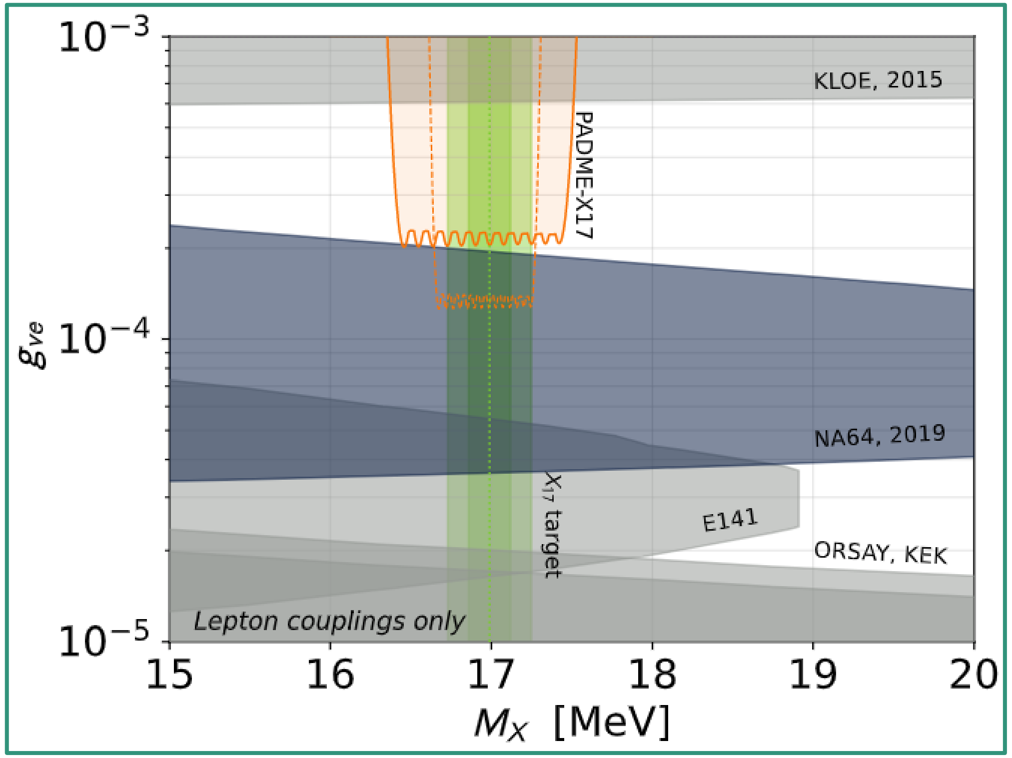
BG process	No. of Ev.	No. of Ev. in Acc.	Acc.
$e^+e^- \rightarrow e^+e^-$ (t- ch.)	5.4×10^7	6.9×10^4	0.13%
$e^+e^- \rightarrow e^+e^-$ (s- ch.)	3.2×10^4	6.4×10^3	20%
$e^+e^- \rightarrow \gamma\gamma$	2.9×10^5	1.3×10^4	4.5%
$e^+e^- \rightarrow X_{17} \rightarrow e^+e^-$	1250	250	20%

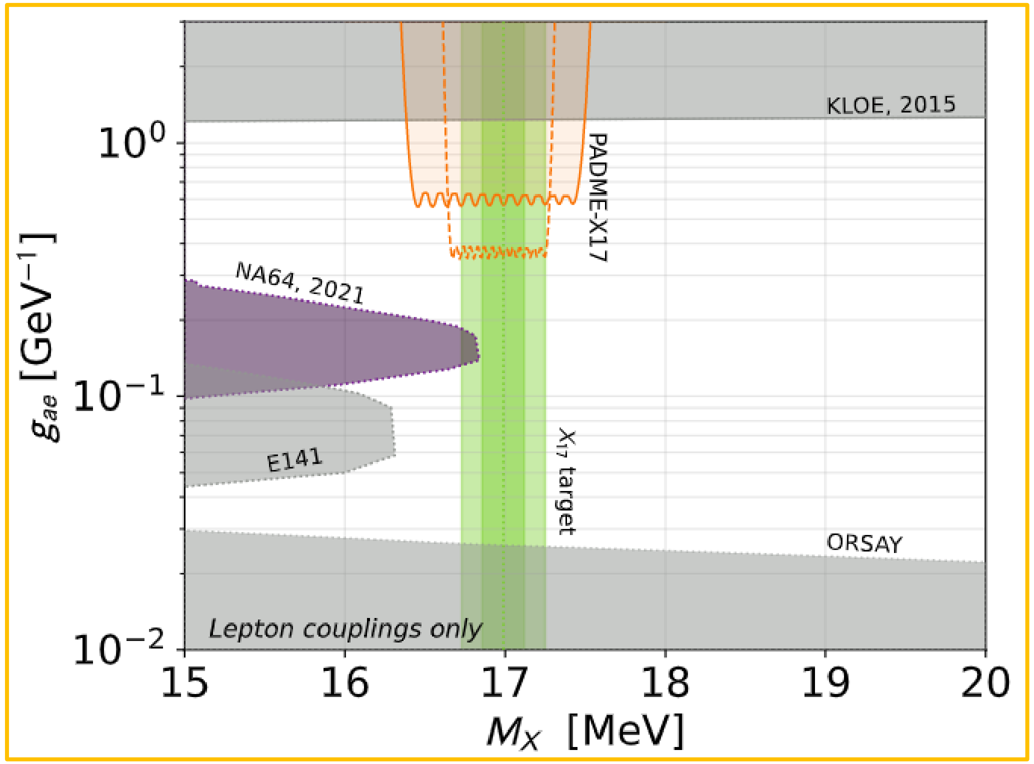


The expected phenomenological limits

Using toy MC and geometrical acceptance, we obtained expected limits both on:

- **Vector** model, covering almost the entire free parameter space
- **Pseudoscalar** model, in the case of an ALPs decaying into leptons only.

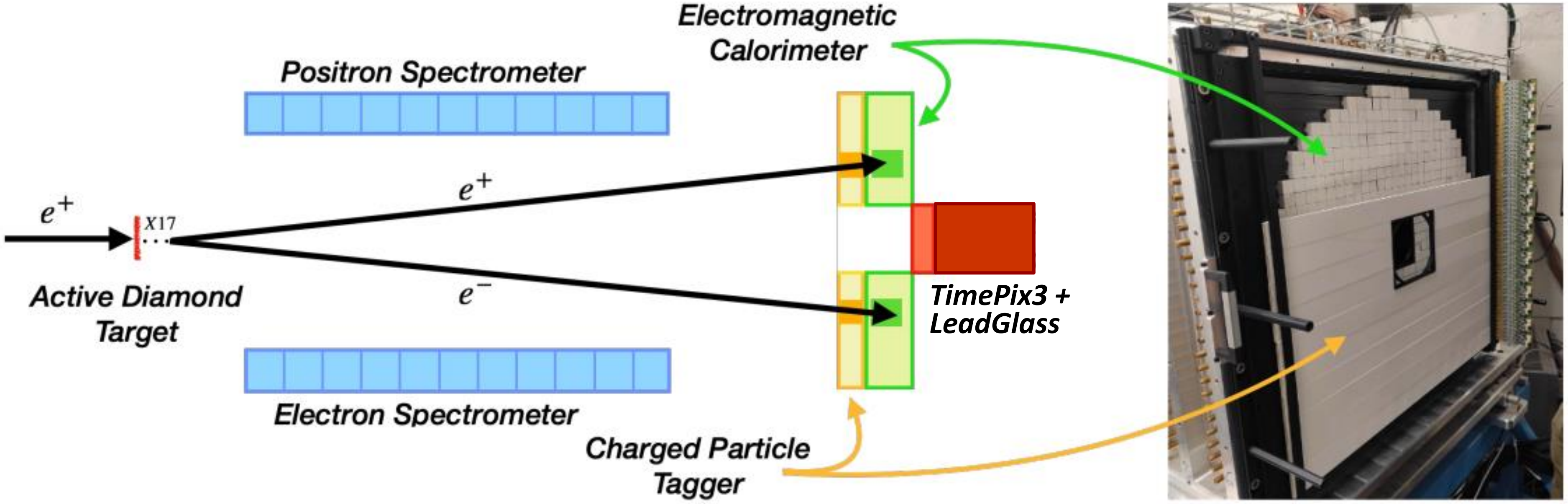




Darmé et al. Phys. Rev. D 106, 115036

The Run III experimental set-up

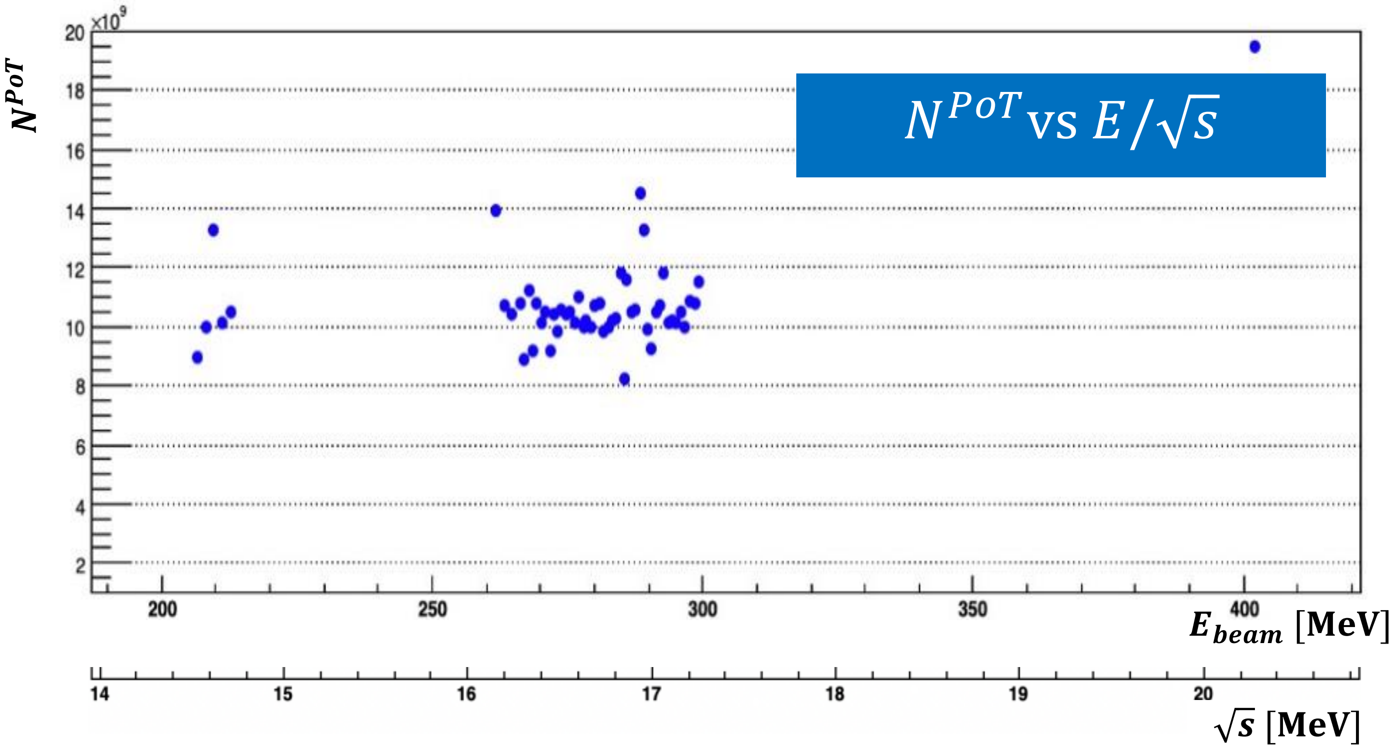
- Turned off the dipole B-Field to detect both final state particles with ECal
- Added ETagger detector of 5 mm thick plastic scintillator in front of ECal to distinguish $e^{\pm}$ from γ.
- $200\ \mathrm{MeV} \leq E_{beam} \leq 400\ \mathrm{MeV}$ positron beam
- Removed the SAC and installed a TimePix3 beam monitor and a LeadGlass detector ($10.5 \times 10.5 \times 37\ \mathrm{cm}^3$)



The data collected during Run III

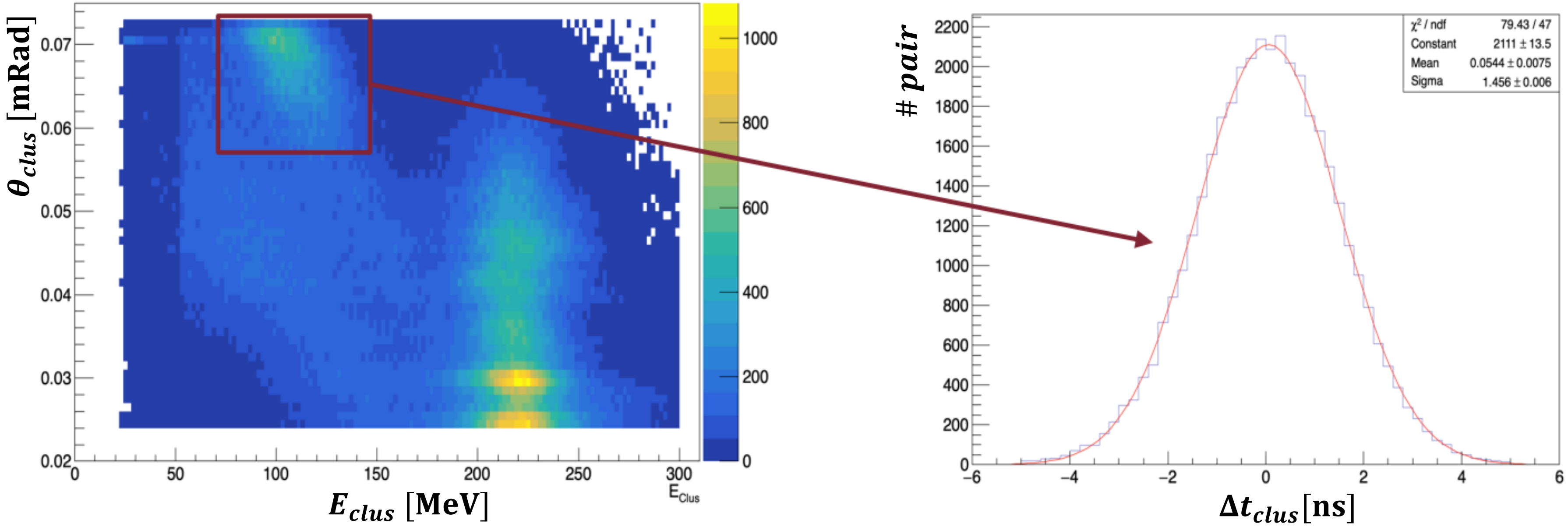
Total amount of data collected $\sim 6 \times 10^{11}\ PoT$, i.e. $\sim 10^{10}\ PoT$ per $\sqrt{s}$ point:

- 47 invariant mass points in the beam energy range 260 MeV $< E_{beam} <$ 300 MeV and $\delta E_{beam} \simeq 0.75$ MeV
- 6 points out-of-resonance: 5 points below and 1 above
- Bunch length $\Delta t_{bunch} \simeq 200$ ns and $N^{PoT}_{bunch} \simeq 2500$
- Beam intensity reduced $\times$ 10 with respect to Run II → lower pile-up BG



The data collected during Run III

Using kinematic relation between E_γ and θ_γ → very good signal-BG separation



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

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%

$g_{V_e} = 2 \times 10^4$ and $\delta E = 0.75$ MeV

The points out-of-resonance

Measure the cross section below and above the resonance:

- 5 points with $N^{PoT} \sim 10^{10}$ each and $205\ \text{MeV} \leq E_{beam} \leq 212\ \text{MeV}$
- 1 point with $N^{PoT} \sim 2 \times 10^{10}$ and $E_{beam} = 402\ \text{MeV}$
- Below the resonance the X_{17} production is kinematically not allowed and above is suppressed

Can use this dataset to:

- Compare data and MC predictions
- Study the Standard Model background
- Measure Standard Model cross-section with no eventual X_{17} enhancement
- Tune the search technique
- Establish luminosity measurement precision

Analysis strategies

Experimental quantities : $N\,(e^+e^-)$, $N\,(\gamma\gamma)$, $N\,(e^+e^- + \gamma\gamma)$, N^{PoT} → **Different observables**

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

- Accessible only if $\varepsilon_{tag}(\gamma) > 95\%$
- Need to control systematic errors from PID and N^{PoT}

Goal: keep at the % level the systematic error

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

- No error from PID, but 20% BG increment → significance worsened by 8%
- Need to control systematic errors from acceptances and N^{PoT}
- Observable less theoretically clean

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

- No error from N^{PoT} and partially cancellation of systematics from acceptances
- Need high level of control on the PID and mis-identification
- Statistical error affects the normalization → significance worsened by $\times$ 3

Conclusions and future prospects

- PADME's two runs between 2018 and 2020 allowed us to optimise running conditions and detector reconstruction
- We performed the most precise measurement of $\sigma\left(e^+e^- \rightarrow \gamma\gamma(\gamma)\right)$ below 1 GeV
- Run III completed at the of 2022 and the data analysis is in progress
  - Studying the out-of-resonance points we aim to get low energy cross section measurements of the involved SM processes
  - Relying on the toy MC simulations, we expect to set strong limits on X_{17} coupling to electrons
  - We aim to get preliminary results both on Vector and Pseudoscalar model by the end of 2023, **STAY TUNED!**

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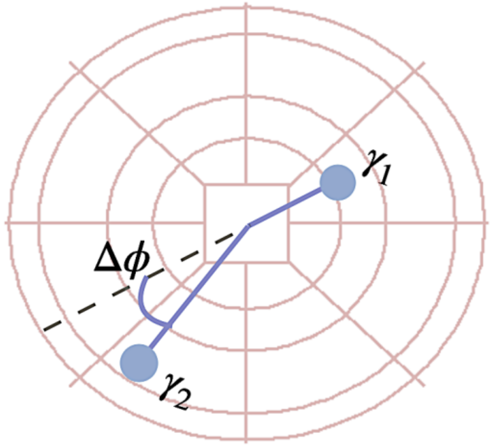
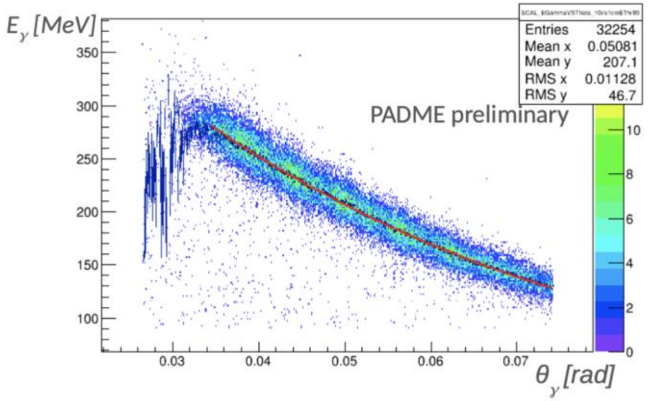
Thank you for your attention and
TURN THE DARK ON!

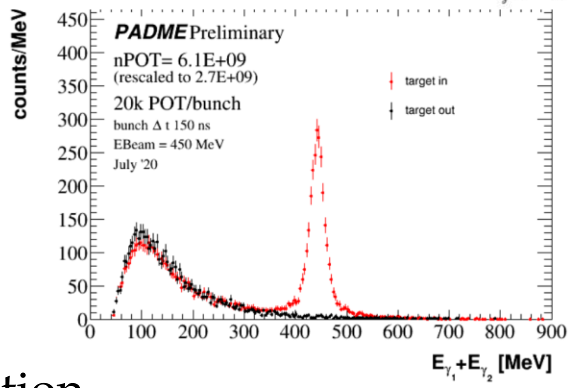
BACKUP SLIDES

$\sigma(e^+e^- \rightarrow \gamma\gamma)$ at $\sqrt{s} = 20$ MeV analysis strategy

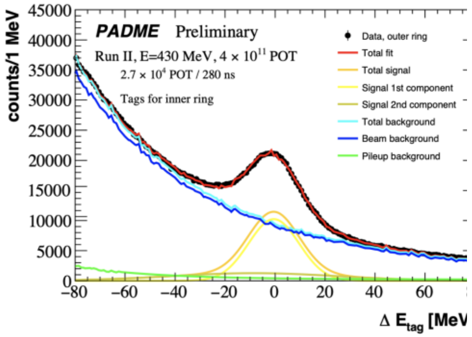
- Normalization for single photon analysis
- Independent determination of luminosity
- **SM Cross-section measurement**
- Tag-and-probe method on two back-to-back clusters
  - Exploit energy-angle correlation $E_\gamma = f(\vartheta_\gamma)$
  - Count tag photons with $E_\gamma - f(\vartheta_\gamma) \sim 0$
  - Match using $E_{\gamma 1} + E_{\gamma 2} = E_{beam}$ and count probes
- Single photons selection
  - Subtract background from **no target** runs
  - $E_\gamma - f(\vartheta_\gamma) \sim 0$ and $m^2_{miss} \sim 0$



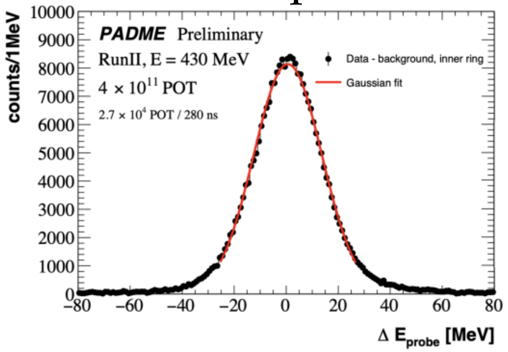




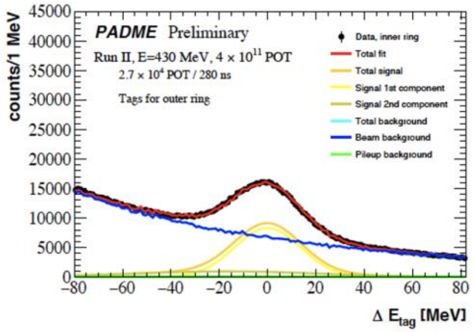
Tag photons selection

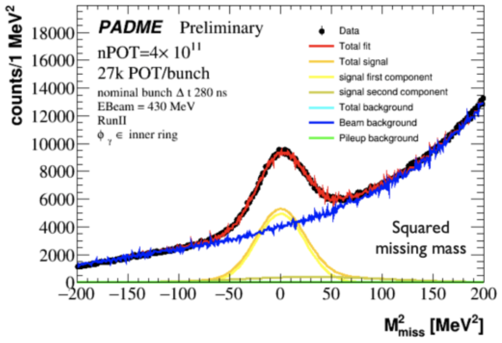


Probe photons



Single photon selection

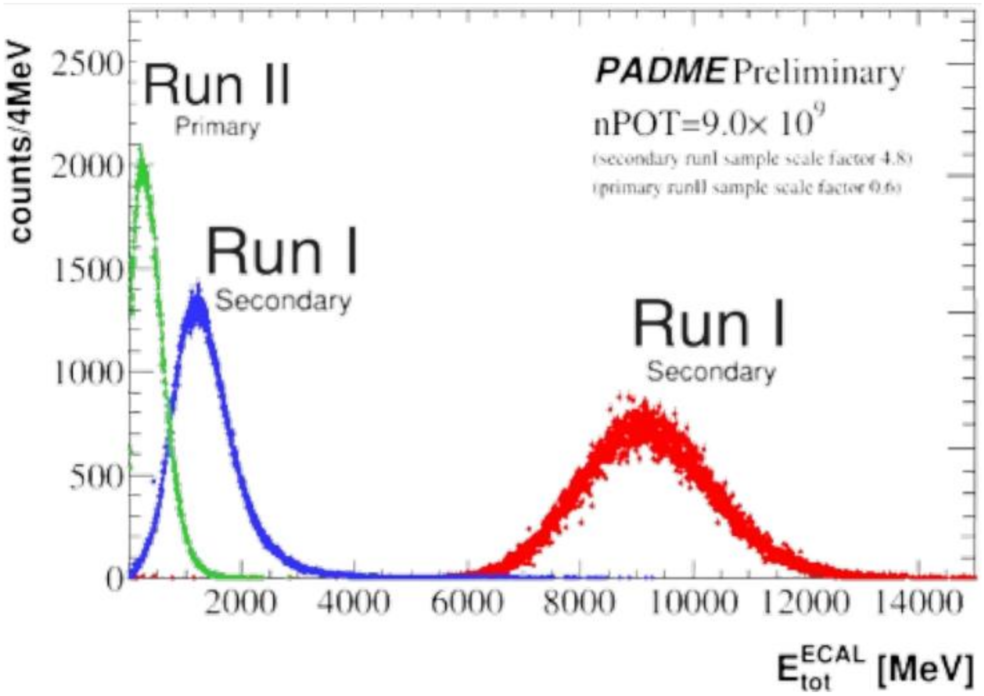




The first two runs data taking

Two runs in three configurations since installation in Sept. 2018

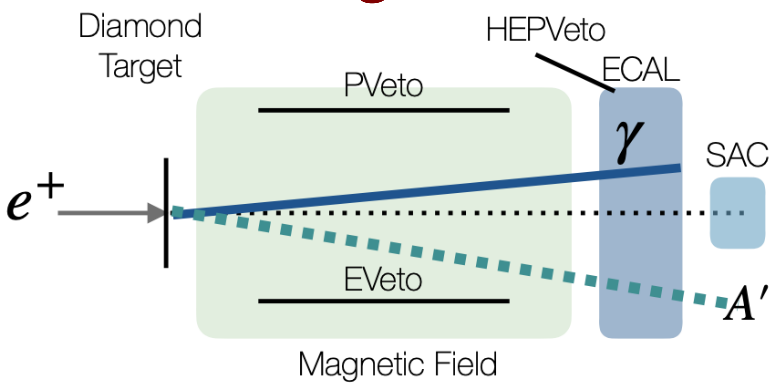
- Run Ia (Oct 2018-February 2019)
  → Secondary e^+ from e^- on Cu target before the entrance of BTF
- Run Ib (February -March 2019)
  → Primary e^+ converted immediately after the e^- production in the LINAC beam line
- Run II (Sept 2020-Dec 2020)
  → primary e^+ beam and improved beamline setup



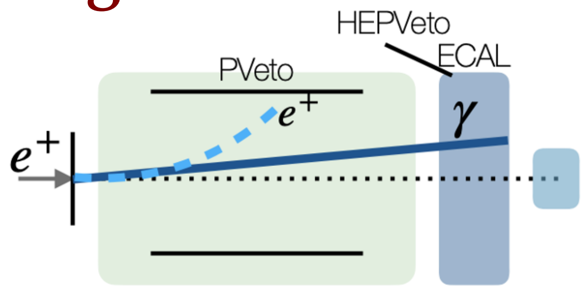
Run 1 secondary beam	25 kPoT 545 MeV 250 ns bunch
Run1 primary beam	25 kPoT 490 MeV 250 ns bunch
Run2 primary beam, moved mylar window	28 kPoT 430 MeV 280 ns bunch

A' to invisible signature Run II analysis

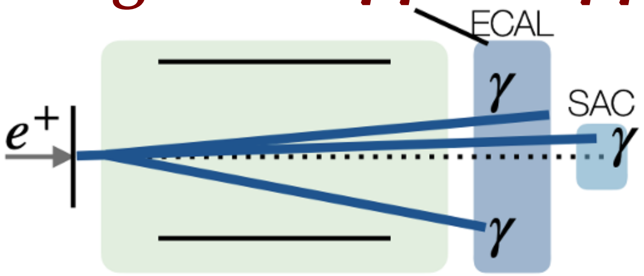
Signal:



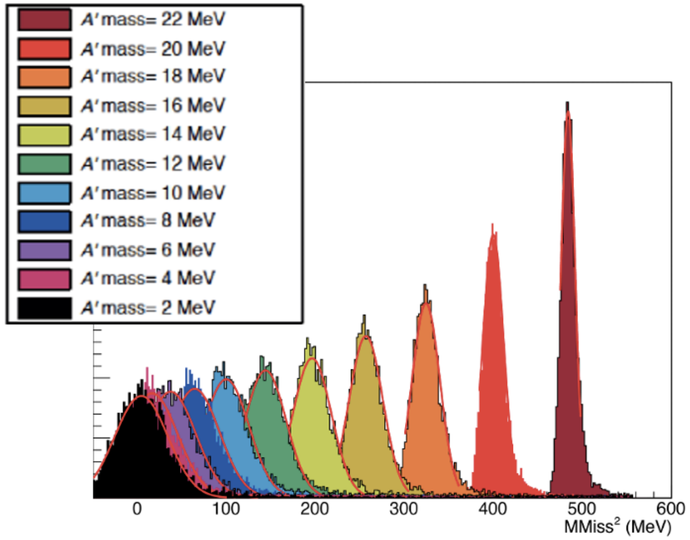
Background: Bremsstrahlung



Background: $\gamma\gamma$ and $\gamma\gamma\gamma$



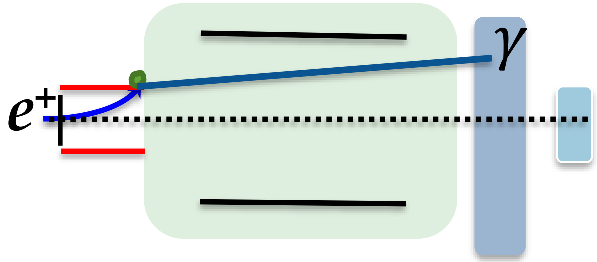
Knowing the beam momentum $\underline{p}_{e^+}$, compute: $\boldsymbol{m^2_{miss}} = (\vec{\boldsymbol{p}}_{\boldsymbol{\gamma}} - \vec{\boldsymbol{p}}_{\boldsymbol{e^+}} - \vec{\boldsymbol{p}}_{\boldsymbol{e^-}})^2$



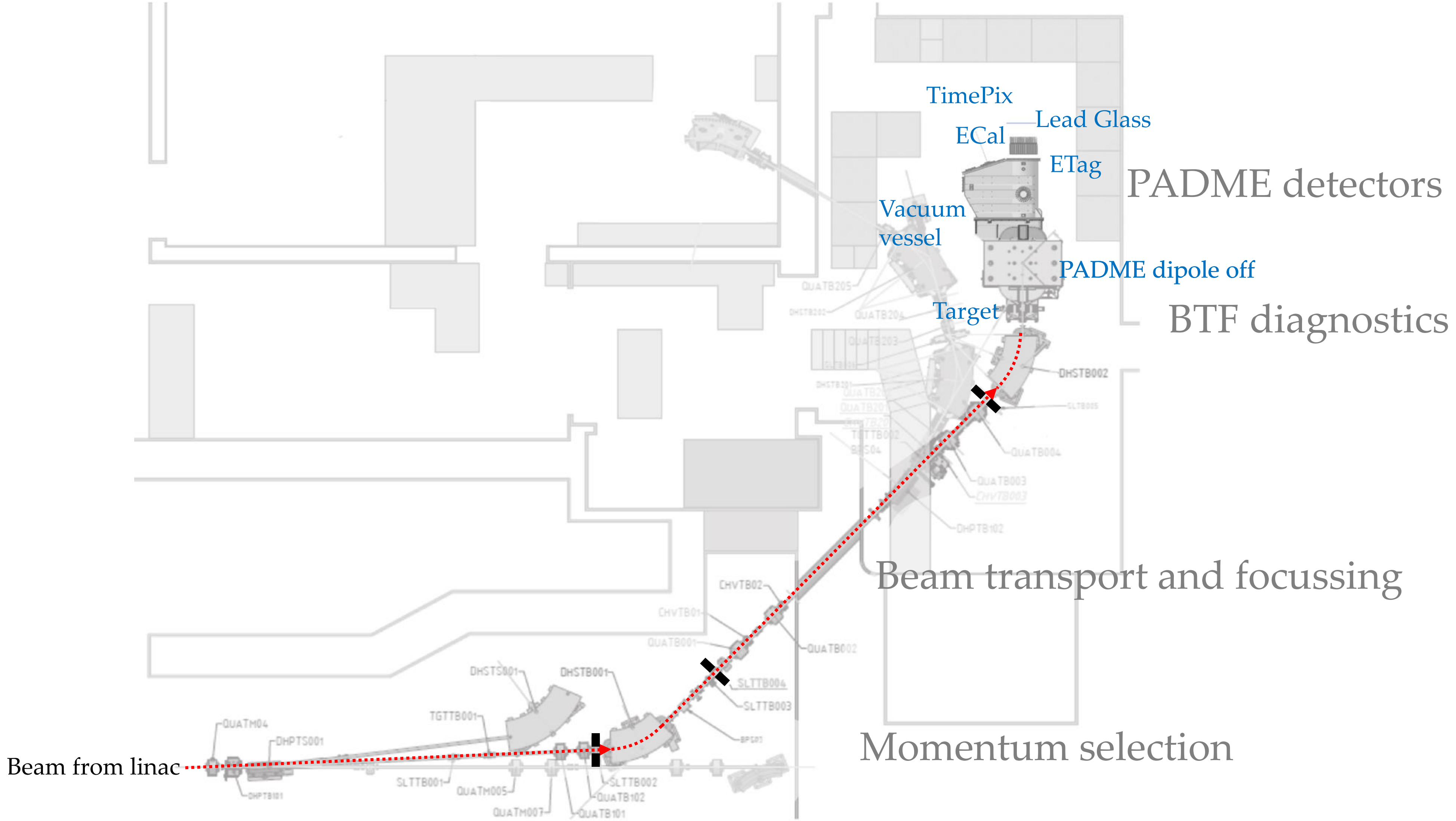
Normalize to $\gamma\gamma$ channel:

$$\frac{\Gamma(e^+e^- \to A'\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma\gamma)}\frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon\delta$$

Background: beam crash



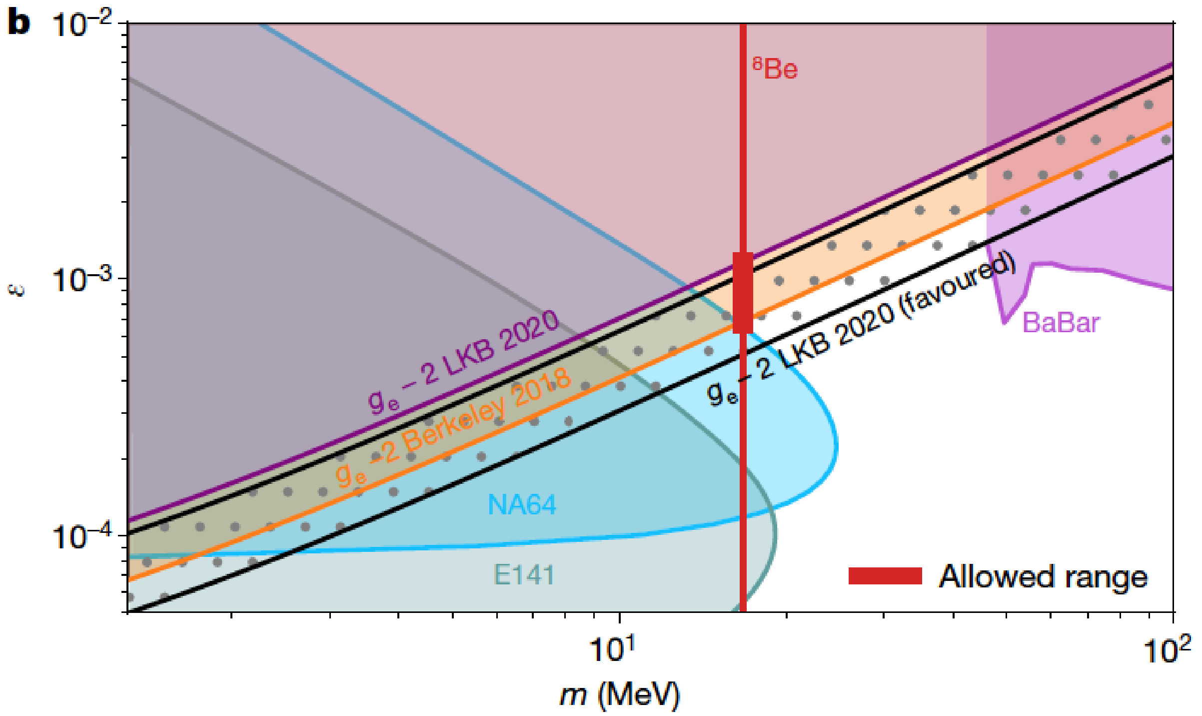
The BTF beam line and PADME

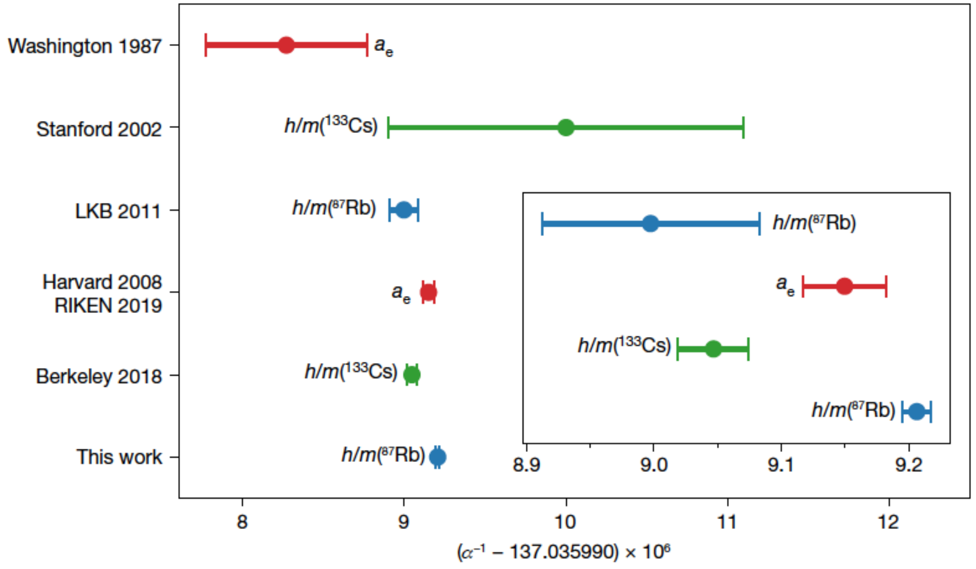


on + off, 49 pulses/s
on + on, 1 pulse/s

$(g-2)_e$ Anomaly

- Significant discrepancy in the last two results on the α determination
- Produce a modified (g-2)$_e$ exclusion which allows a region of existence of X_{17}





$\alpha^{-1} = 137.035999206(11).$

The uncertainty contribution from the ratio $h/m(^{87}\mathrm{Rb})$ is 2.4×10^{-11} (statistical) and 6.8×10^{-11} (systematic). Our result improves the

https://www.nature.com/articles/s41586-020-2964-7

experimental measurement $a_{e,\mathrm{exp}}$ (ref. [9]) gives $\delta a_e = a_{e,\mathrm{exp}} - a_e(\alpha_{\mathrm{LKB2020}}) = (4.8 \pm 3.0) \times 10^{-13}$ ($+1.6\sigma$), whereas comparison with caesium recoil measurements gives $\delta' a_e = a_{e,\mathrm{exp}} - a_e(\alpha_{\mathrm{Berkeley}}) = (-8.8 \pm 3.6) \times 10^{-13}$ (-2.4σ). The uncertainty on δa_e is dominated by $a_{e,\mathrm{exp}}$.

The protophobic vector model

Feng et al. proposed some BSM models that describe the ^{8}Be and ^{4}He anomalies basing on spin-parity and angular momentum conservation laws

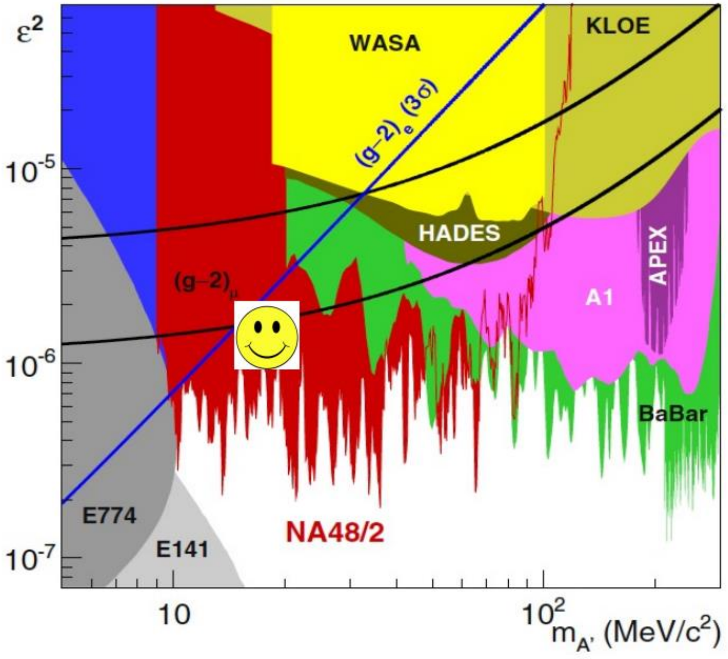
J. Feng et al, Phys.Rev.D 102 (2020) 3, 036016

FOCUS

Protophobic vector boson $J^{P}_{X17} = 1^{-}$

Protophobia is needed to consider the limitations imposed by the NA48/2 experiment determined by the $\pi^0 \to \gamma e^+ e^-$ observation

The NA48/2 collaboration, Phys. Lett. B, 746:178–185



PROTOPHOBIA: the X17 coupling with pions and protons must be suppressed to satisfy all of the experimental constrains

ETag test set-up

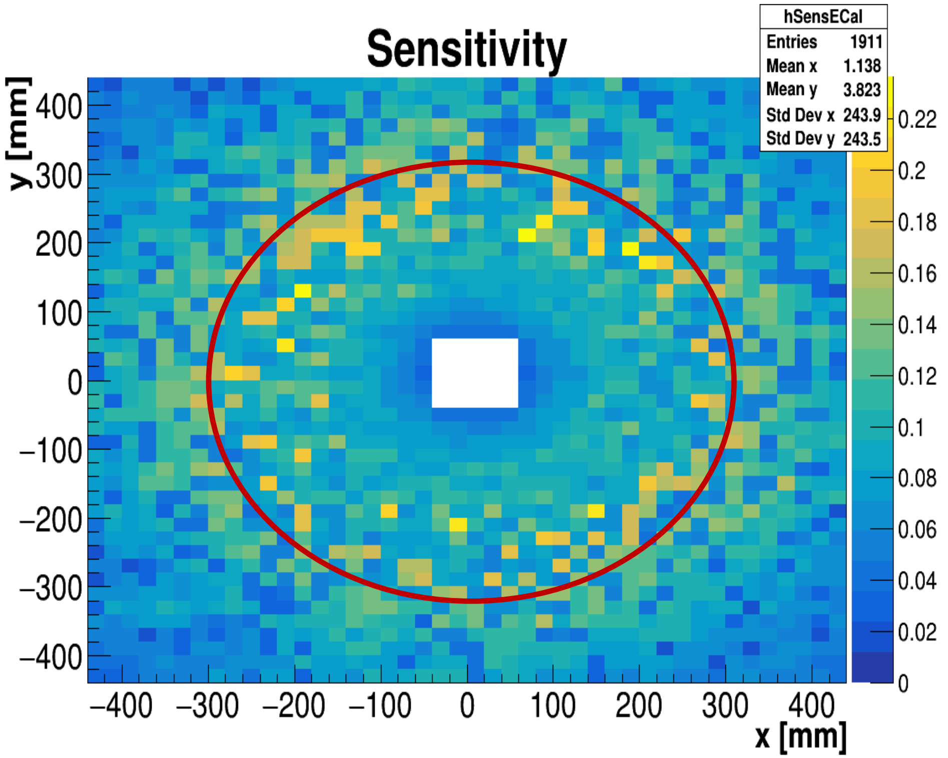
The aim ias to evaluate the efficiency and the light output on different position of an ETag slab.

- Single ETag slab (BC408 – 0.5x4x66 cm^3) readout on each side by four 50 μm SiPMs → 8 readout channels
- Source: cosmic rays
- Trigger: AND of two BGO fingers (ECal) placed over and under the DUT and crossed (discriminator thresholds 30 mV)
- Acquisition: CAEN's V1742 sampling ADCs, signals digitized at 2.5 GS/s w/out zero suppression
- 7 different position scanned → 7 different runs

Toy MC – What is currently considered

- σ_{Bhabha}^{full} considering the interference term and exchanging Z boson diagrams
- $\sqrt{s} = 17$ MeV $\rightarrow E_{beam} = 282$ MeV with spread $\sigma(E_{beam}) = 0.7$ MeV
- Target-ECal distance $\Delta Z = 3720$ mm (adding ETag)
- The energy of t-channel final state electron is required to be $E_{e_t^-} > 1$ MeV to regularize the IR divergence
- Geometry and energy Cuts on both particles (clusters):

  90 mm $< R_{max} < 270$ mm - $E > 100$ MeV
- PADME magnet shadow is included in the acceptance



Toy MC – What is still missing

- Take into account the broken ECal Scintillating Units and the inefficiency of the outermost ones
- Take into account all of the experimental effects with the full MC
- Consider $\sigma_{full} = \sigma_{full}(\sqrt{s})$ and $\alpha_{EM} = \alpha_{EM}(\sqrt{s})$ as ‘running’ parameters
- Simulate the NLOs with a more sophisticated software to improve the prediction of the theoretical cross-section
- Evaluate σ_{SM} only in the angular range of the experiment

The red lines represent the current radial cuts, so studying the events in that Scintillating Units we are not actually able to reconstruct correctly a cluster