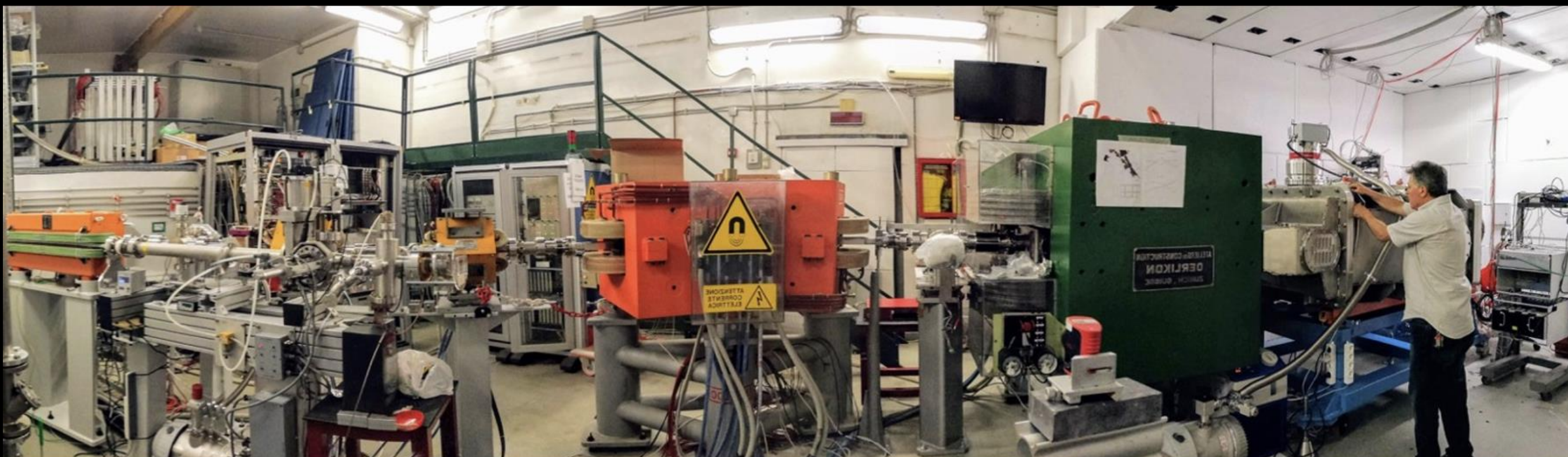
PADME report on X17 searches during Run III



Mauro Raggi, Sapienza Università di Roma & INFN Roma
on behalf of the PADME collaboration

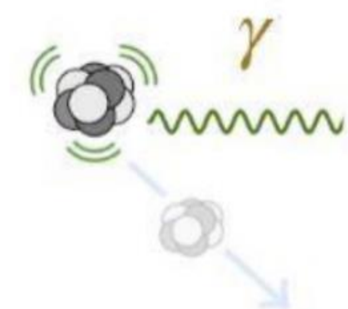
TRIUMF Dark Matter forums June 23th 2025

New physics in nuclear IPC transitions?

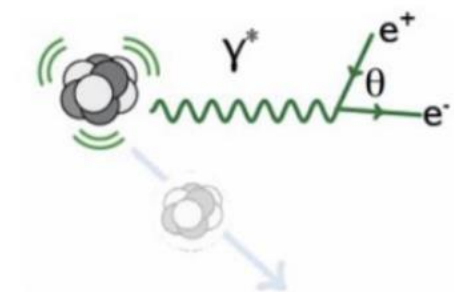
Excite the nucleus by proton capture:
choose the level by using appropriate p energy (few MeV)

Standard Model deexcitation mechanisms:
a) γ emission
b) Internal Pair Creation (IPC):
- emit an off-shell photon γ^*
- γ^* decays to e^+e^- pair

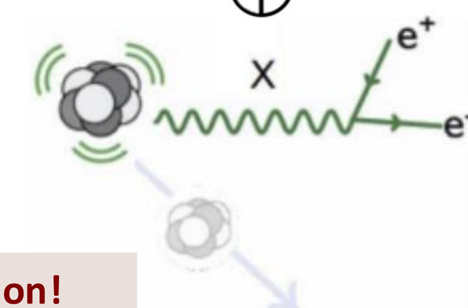
γ emission



IPC



$\oplus$



New Physics (NP) deexcitation mechanisms:
- Produce an intermediate on shell new particle X (mass M_X)
- X decays to e^+e^- pair

NP produce enhanced IPC rate and different θ_{ee} distribution!

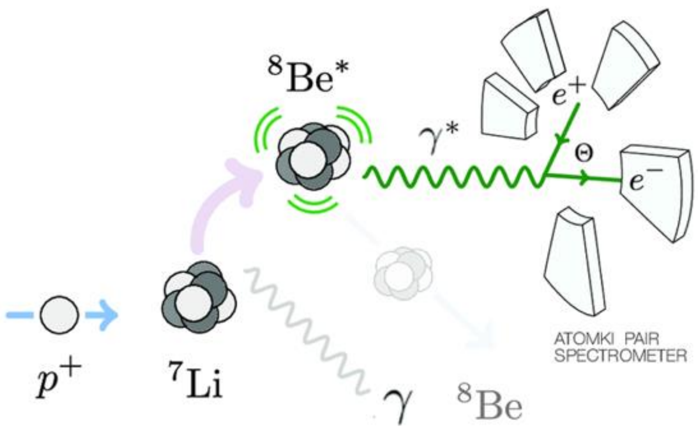
Need transitions with $\Delta E > M_X$

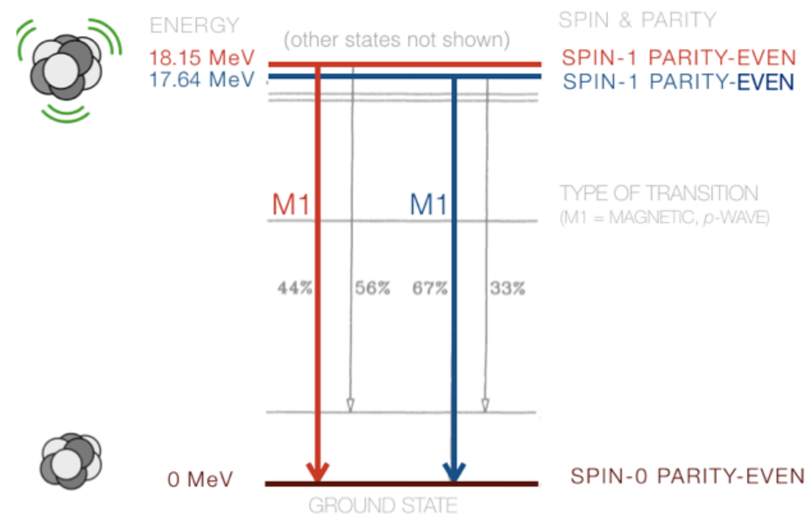
^{8}Be anomaly: first evidence 2016

PRL **116**, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. Krasznahorkay et a
PRL 116, 042501 (20



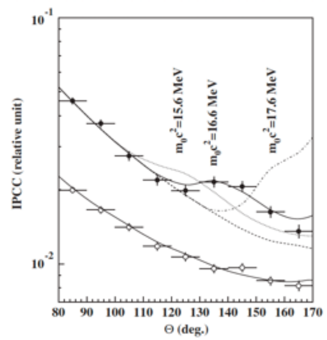


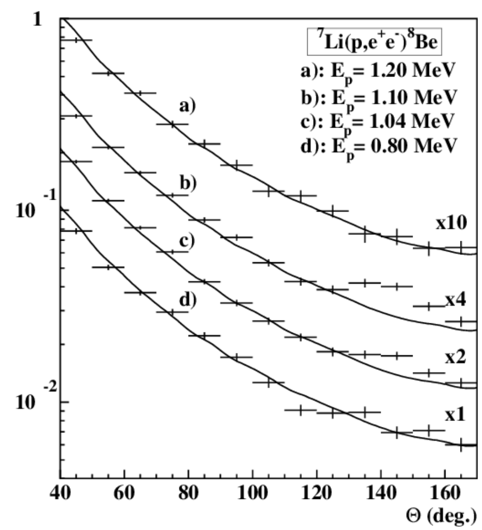
p + ^{7}Li —> ^{8}Be*(18.15 MeV) —> ^{8}Be + $e^{+}e^{-}$

Anomaly observed only in 2 over 4 proton energies

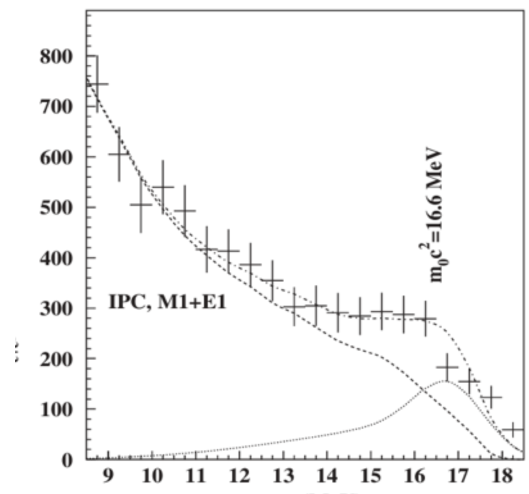
Anomaly observed only for symmetric track events

Anomaly observed only for ^{8}Be 18.15 MeV transition





6.8σ effect! not a fluctuation



$m_X c^2 = 16.70.35_{stat}0.5_{syst}$ MeV

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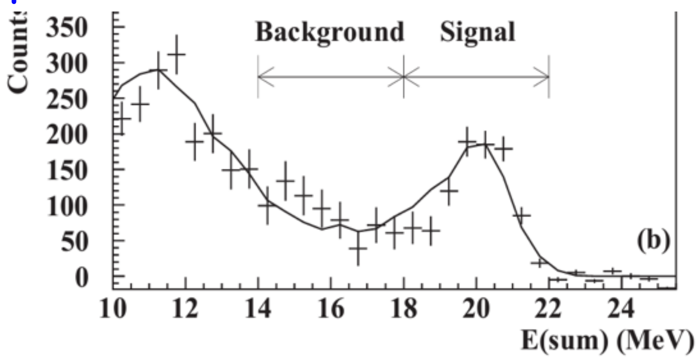
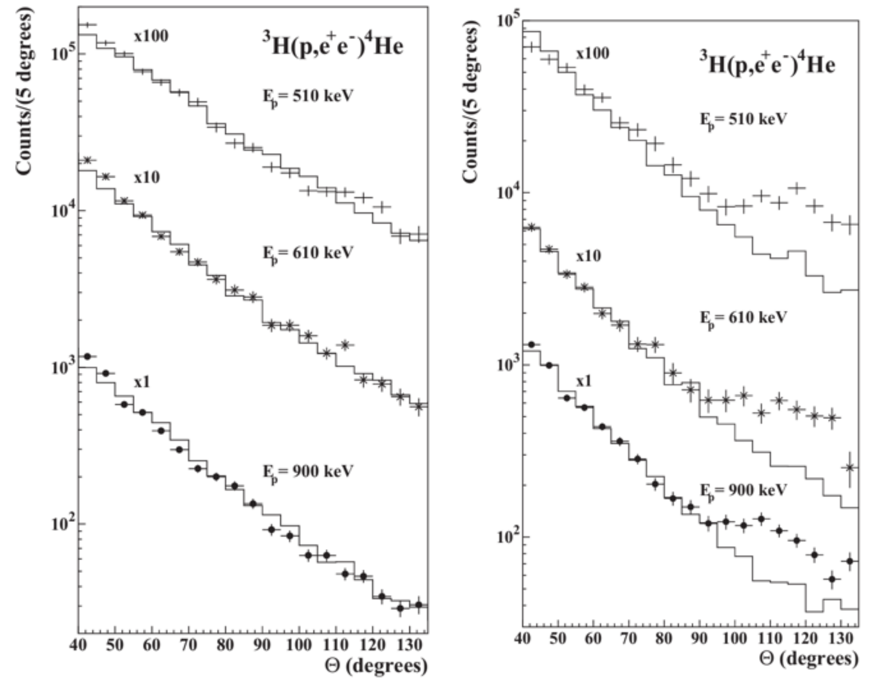
The ^{4}He Atomki anomaly: 2020

PHYSICAL REVIEW C **104**, 044003 (2021)

New anomaly observed in ^{4}He supports the existence of the hypothetical X17 particle

$p + {}^3H \longrightarrow {}^4He^* \longrightarrow {}^4He + e^+e^-$





$$m_X c^2 = 16.94 \pm 0.12_{stat} \pm 0.21_{syst}\ \text{MeV}$$

A. Krasznahorkay et al.

Phys. Rev. C 104, 044003 (2021)

E_p (keV)	IPCC $\times 10^{-4}$	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
510	2.5(3)	6.2(7)	17.01(12)	7.3σ
610	1.0(7)	4.1(6)	16.88(16)	6.6σ
900	1.1(11)	6.5(20)	16.68(30)	8.9σ
Averages		5.1(13)	16.94(12)	
^{8}Be values		6	16.70(35)	

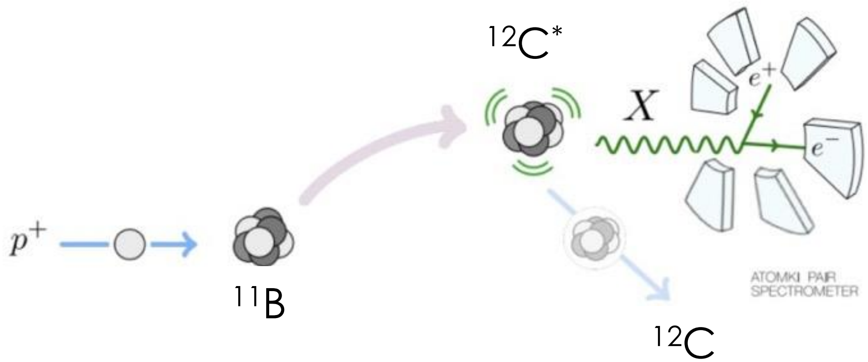
Atomki has confirmed the anomalous peak in the angular distribution of ^{8}**Be** IPC in ^{4}**He** transitions at different angle. The difference was expected **due to the higher ΔE in ^{4}He**
The ^{4}He angle indicated **same X mass value.**

The ^{12}C : September 2022

PHYSICAL REVIEW C **106**, L061601 (2022)

New anomaly observed in ^{12}C supports the existence and the vector character of the hypothetical X17 boson

A. Krasznahorkay et al.
Phys. Rev.C 106 (2022) 6



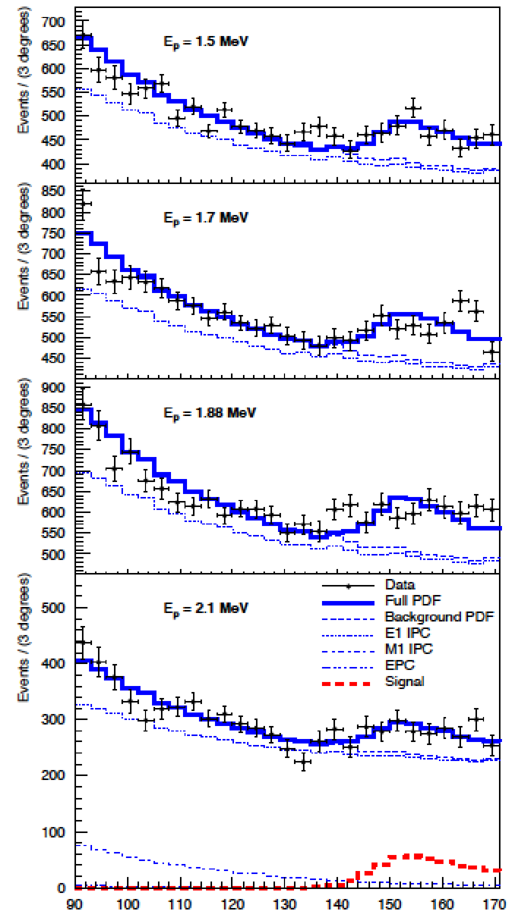
$p + {}^{11}B \rightarrow {}^{12}C^*(17.23\ \text{MeV}) \rightarrow {}^{12}C + e^+e^-$

E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	

As predicted by J. Feng et al. excess at 160°

Same X17 particle suggested by the ^{8}Be and ^{4}He anomalies

$M_X = 17.03 \pm 0.11 \pm 0.20$ MeV



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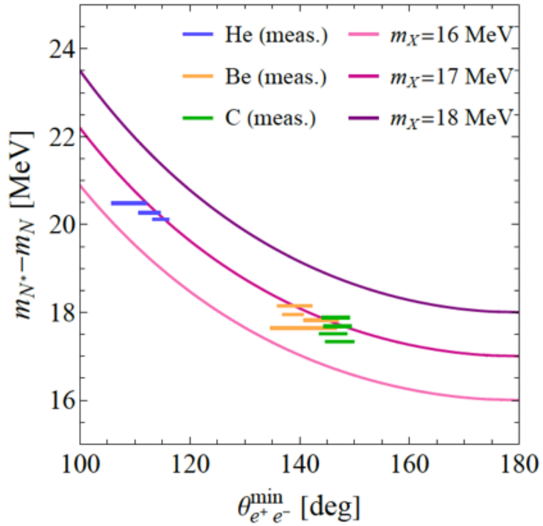
Global ΔE vs angle consistency



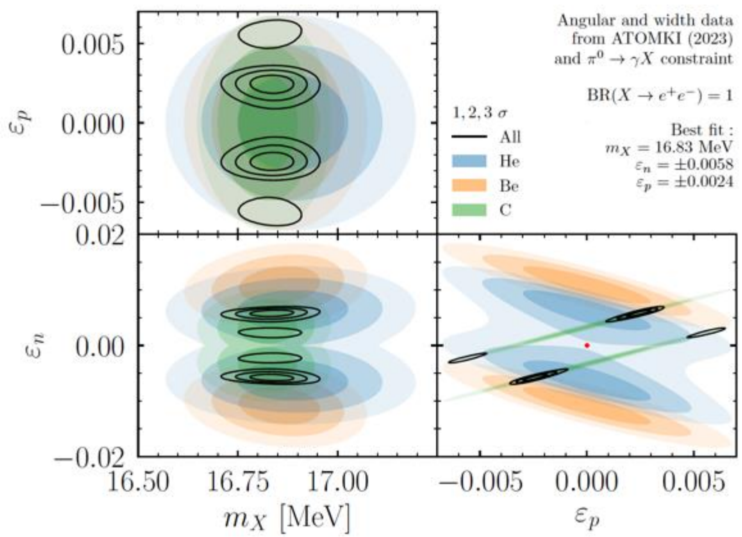
Neutrino Constraints and the ATOMKI X17 Anomaly

PHYS.REV. D 108, 015009 (2023)

Using angular data only: 11 measurements

An analysis with the angular data alone of 11 different measurements finds that the data is well described by a new particle of mass $m_X = 16.85 \pm 0.04$ MeV with an internal goodness-of-fit of 1.8σ calculated from Wilks' theorem at $\chi^2/dof = 17.3/10$. We use only the best fit

$$\theta_{ee}^{min} \approx 2\arcsin\left(\frac{m_{X17}}{m_{N*} - mN}\right)$$



Using width for each element: 3 measurements

Next, we add in to the analysis the latest width information from each element and include a prior on ε_p since X needs to couple to protons and/or neutrons on the production size. There is a stronger constraint

see the next section for more information. We find an okay fit to the data at the same mass $m_X = 16.83$ MeV, $\varepsilon_n = \pm 5.8 \times 10^{-3}$, and $\varepsilon_p = \pm 2.4 \times 10^{-3}$, see fig. 2. We note that the signs of ε_n and ε_p must be the same due to the non-trivial degeneracy structure shown clearly in the $\varepsilon_n - \varepsilon_p$ panel of fig. 2. We have confirmed that the

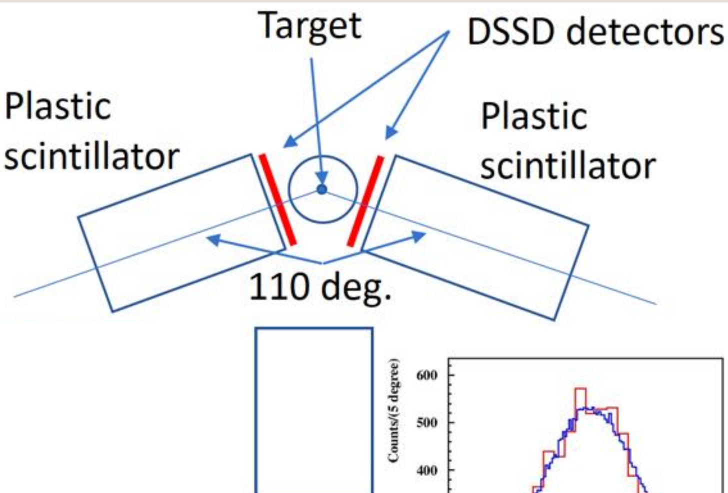
Data form ^{8}Be, ^{4}He, ^{12}C are consistent and point to: M_{X17}=16.85±0.04 MeV

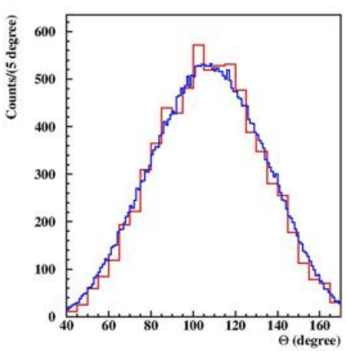
^{8}Be giant resonance anomaly: 2023

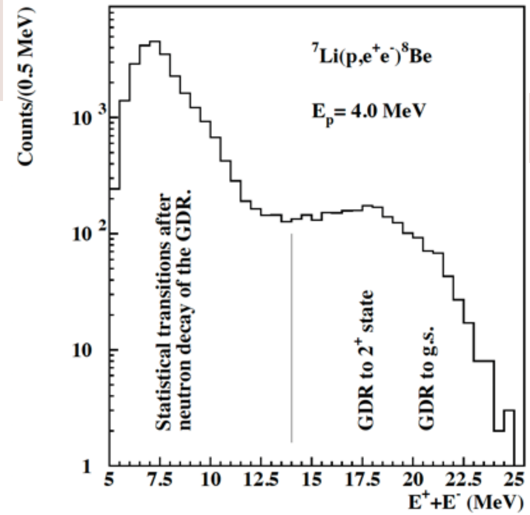
Observation of the X17 anomaly in the decay of the Giant Dipole Resonance of ^{8}Be

A. Krasznahorkay et al.
arXiv:2308.06473

Atomki group: ^{8}Be experiment in GDR region
New 2 arm spectrometer closer to the target



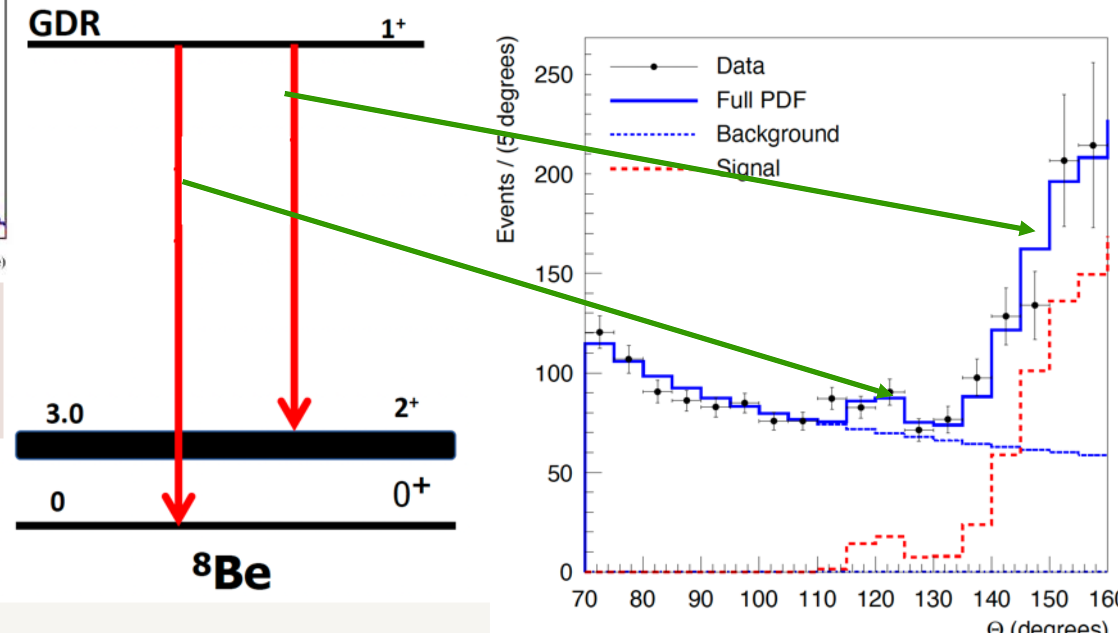




E_P up to 4 MeV

1$^+$ to 2$^+$ ~17.5 MeV

1$^+$ to 0$^+$ ~20.5 MeV



2 peak structure observed!
impressive angular agreement with particle hypothesis.

More information can be found here: ISMD 2023
https://indico.cern.ch/event/1258038/timetable/#20230822.detailed

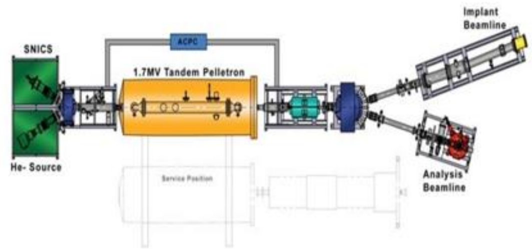
X17: the particle physics case

Theory insights based Atomki data: (assuming P conservation and resonance emission):
Scalar excluded by parity conservation in ^{8}Be
Pseudo scalar disfavoured by the ^{12}C observation

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	✘	✔	✔	✔
^{12}C(17.23)	1^-	✔	✘	✔	✔
^{4}He(21.01)	0^-	✘	✔	✘	✔
^{4}He(20.21)	0^+	✔	✘	✔	✘

What next in particle physics experiments:
Explore the all-possible solution to search for signal outside nuclear physics
Concentrate attention on Vector and Axial Vector case. Theoretically favoured solutions
Don't forget Scalars and Pseudo scalars. Nature can always be different from what we expect!
Try to be as much model independent as possible

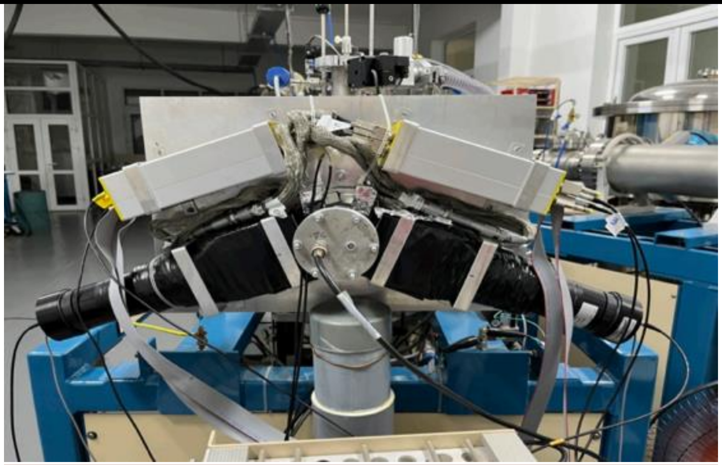
Confirmed in Vietnam 2023?



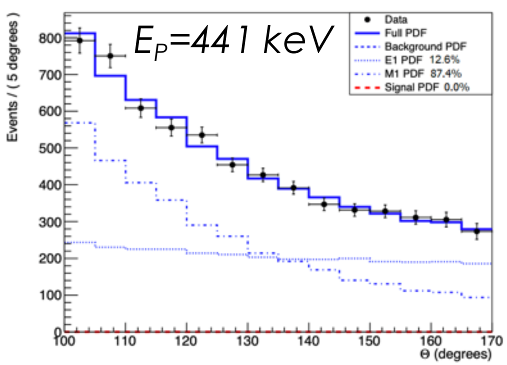
Pelletron Beamline, analysis beamline
Terminal Voltage: 1.7 MV
Ion: H^+, He^+, C^+, Si^+, Cu^+, Au^+...
Beam Current: 1nA – 2microA

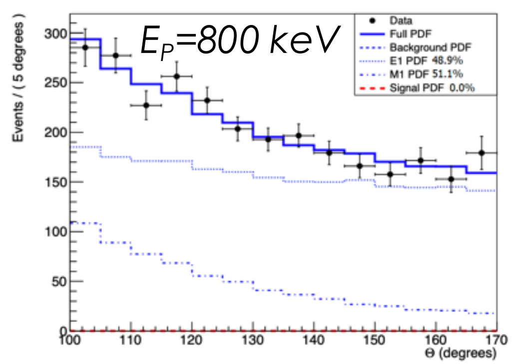
Main tasks:
RBS
PIXE
Ion implantaion
Astro nuclear reactions

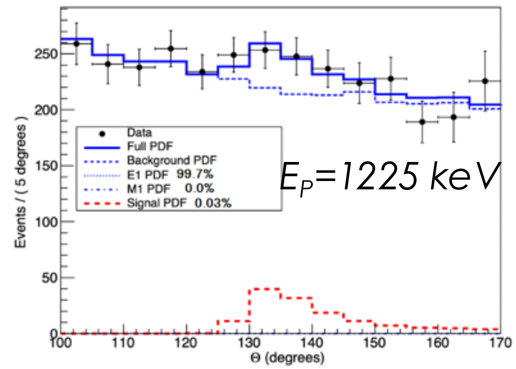
ISMD2023



2 arm spectrometer (ATOMKI like)
ATOMKI group participants
^{7}Li and ^{11}B target used.







Universe **2024**, *10*(4), 168;

Anomaly confirmed at 1225 KeV E_p. Not observed for lower bombarding energies.

Experimental directions

Atomki Nuclear
^{8}Be, ^{4}He, ^{12}C, GDR

It's the result genuine → **Nuclear physics experiments**

It's due to a new particle → **Particle physics experiments**

Nuclear physics experiments

- MEGII @ PSI
  $p^7Li \to {}^8Be^* \to {}^8Be\ e^+e^-$
  ArXiv 2411.07994
  — **Recent result**
- AN2000 @ LNL
  $p^7Li \to {}^8Be\ e^+e^-$
  LDMA (2025)
  — first data set available
- n_ToF @ CERN:
  $n^3He \to {}^4He\ e+e-$
  PRC 105, 014001
  — Proposal
- U Montreal:
  $p^7Li \to {}^8Be^* \to {}^8Be\ e^+e^-$
  arXiv:2211.11900
  — Proposal

Particle physics experiments

- NA48/2 CERN
  $\pi^0 \to \gamma\ X17 \to \gamma\ e^+e^-$
  PLB 746 (2015) 178-185
- NA64 CERN
  $eN \to eN\ X17 \to e^-e^+e^-$
  PRD 101, 071101 (2020)
- NA62 CERN
  $\pi^0 \to X17X17 \to e^+e^-\ e^+e^-$
  PRD 105, 015017 (2022)
- PADME LNF
  $e^+e^- \to X17 \to e^+e^-$
  PRD 106,115036, arXiv:2505.24797
  — **this talk**

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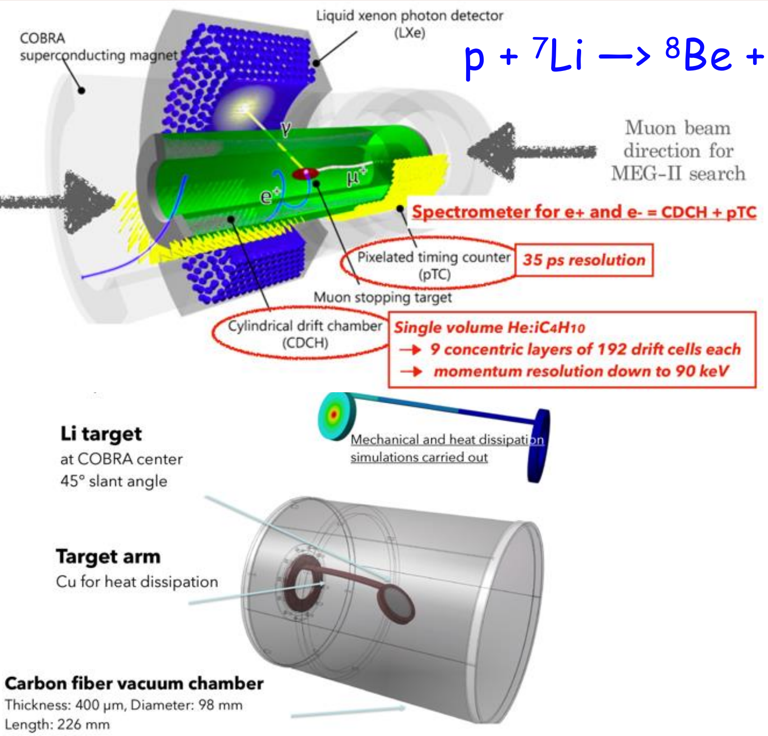
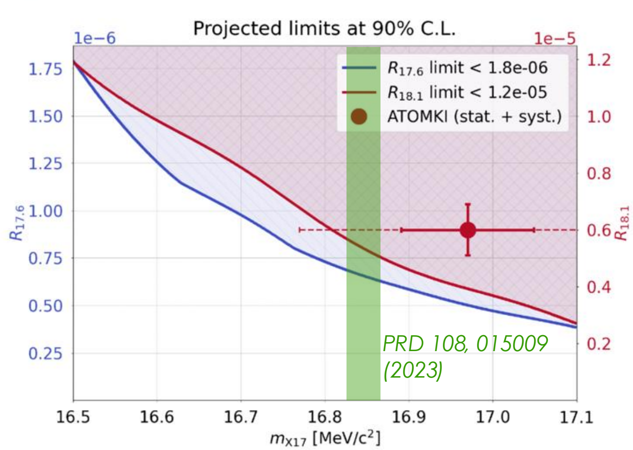
^{8}Be nuclear experiments

MEG-II @PSI X17 results arXiv:2411.07994v1



ArXiv 2411.07994

INFN RM1



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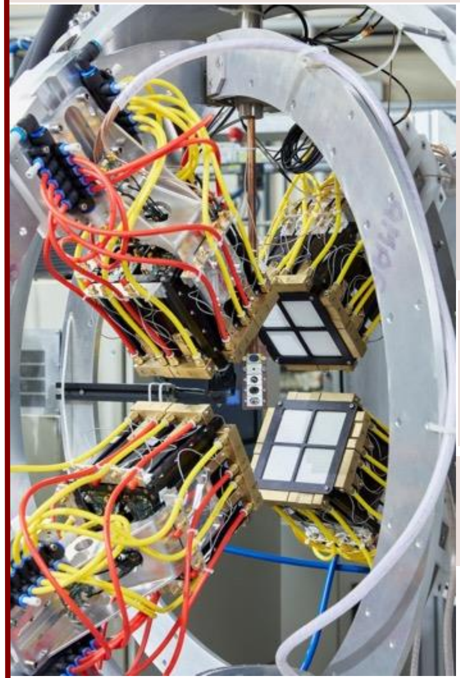
4 arm spectrometer at INFN Laboratori Nazionali di Legnaro



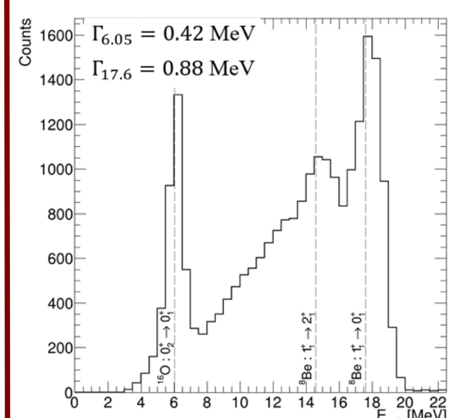
$p + {}^{7}Li \rightarrow {}^{8}Be + e^{+}e^{-}$

For the first time in vacuum spectrometer

Scintillating fibre tracking

Using AN2000 accelerator p energy up to 2 MeV Engineering run 12/2023

New physics grade run in 2024 with E_p=1MeV



BG studies with 400 KeV proton beam ongoing during this week!

EPJC **83, 230 (2023)**

LDMA (2025)

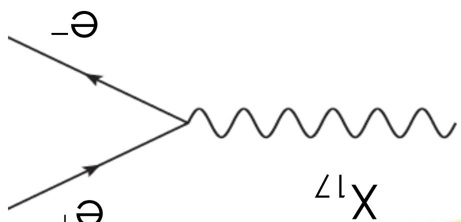
INFN RM1

As simple as possible: the resonance search

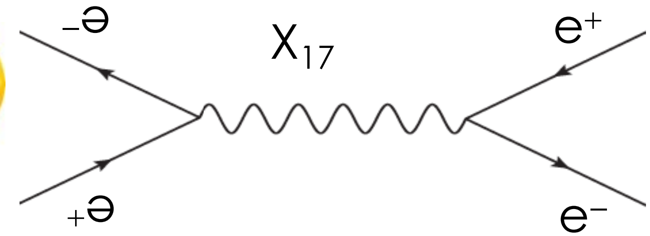
Atomki X_{17}

[M.R., E. Nardi et al. PRD 97, 095004 (2018)]

Just flip the diagram



and connect!



No model dependence just electron coupling!

Extremely high production rate Breit-Wigner enhancement

$$\sigma_{\text{res}}(E_e) = \sigma_{\text{peak}} \frac{\Gamma^2_{A'}/4}{(\sqrt{s} - m_{A'})^2 + \Gamma^2_{A'}/4} \qquad \sigma_{\text{peak}} = 12\pi/m^2_{A'}$$

Lowest possible α suppression

E. Nardi M.R. et al. *Phys.Rev.D 97 (2018) 9, 095004*

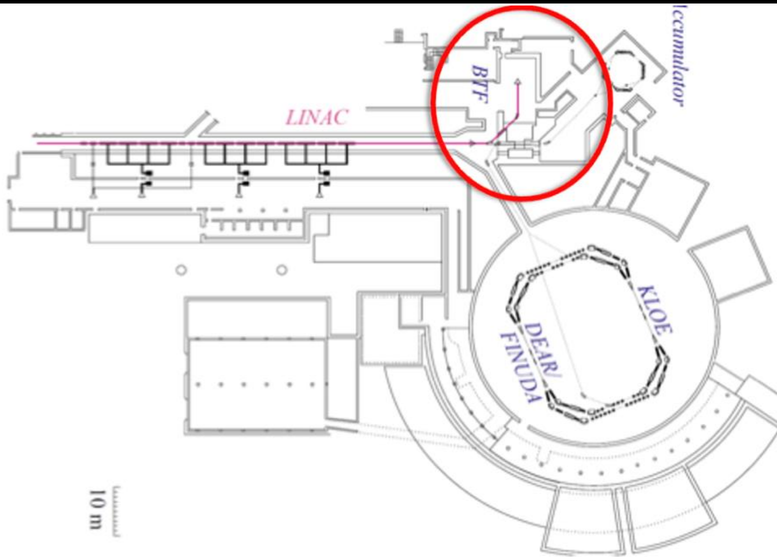
Extremely small Γ_{X17} $\Gamma_{A'} \simeq \epsilon^2 \alpha m_{A'}/3$ $<10^{-2}$ eV

We need a lot of positrons in very limited COM energy range

We can **have >1E10 e⁺ in 20KeV** CoM energy at LNF!

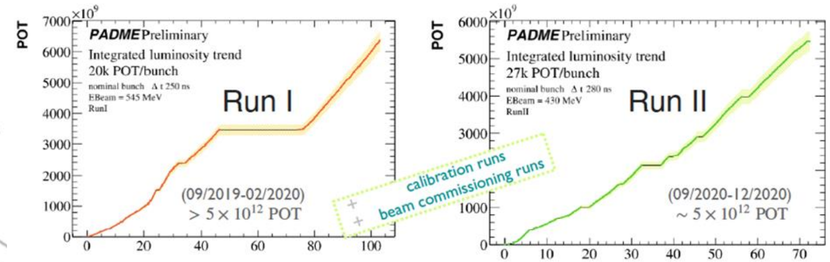
Ok **let's do that at PADME**! [L. Darmé E. Nardi, Mancini M.R. et al. PRD 106,115036]

The PADME experiment at LNF



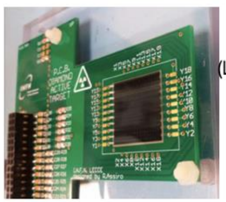
PADME is located at the Beam Test Facility of DAFNE

Data taking Invisible: Run I 2018, Run II 2020



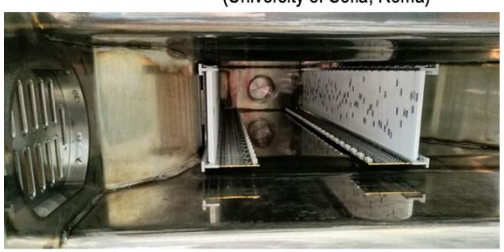
Run III 2022: dedicated search for X17

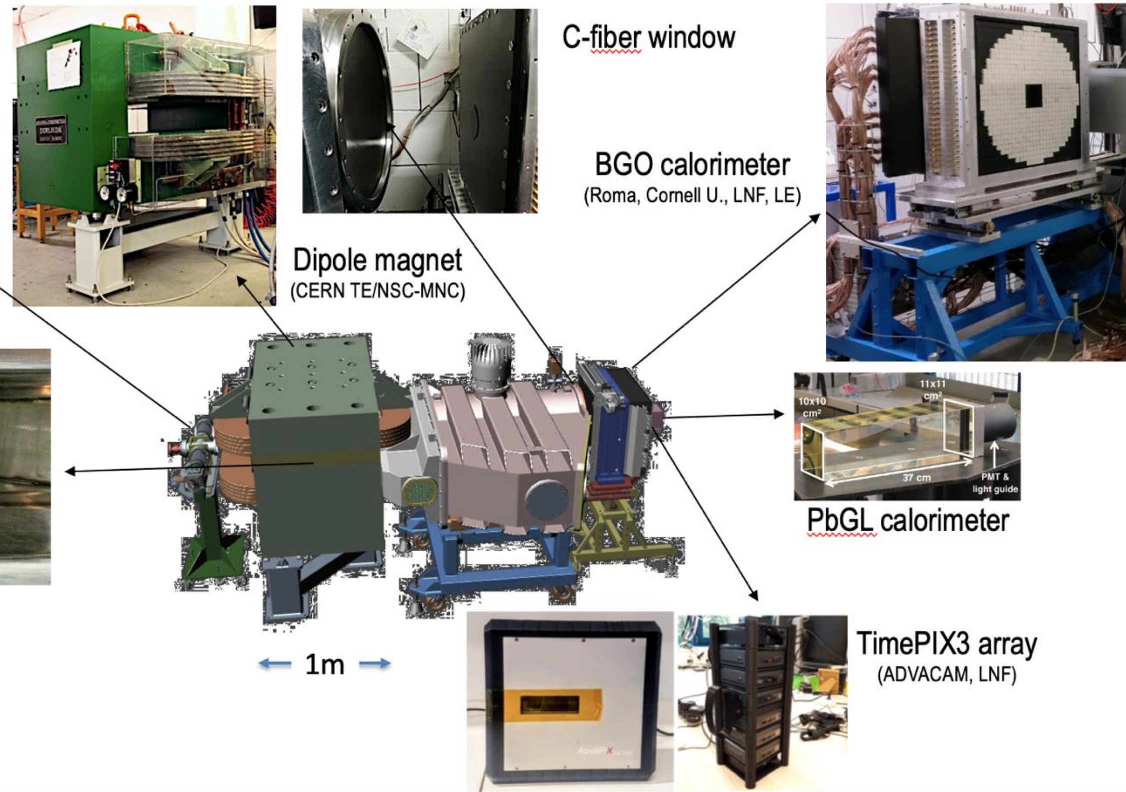
PADME detector setup



Active target
(Lecce & University Salento)

Veto scintillators
(University of Sofia, Roma)





[M.R and V. Kozhuharov
Adv. High Energy Phys. 2014 (2014) 959802]

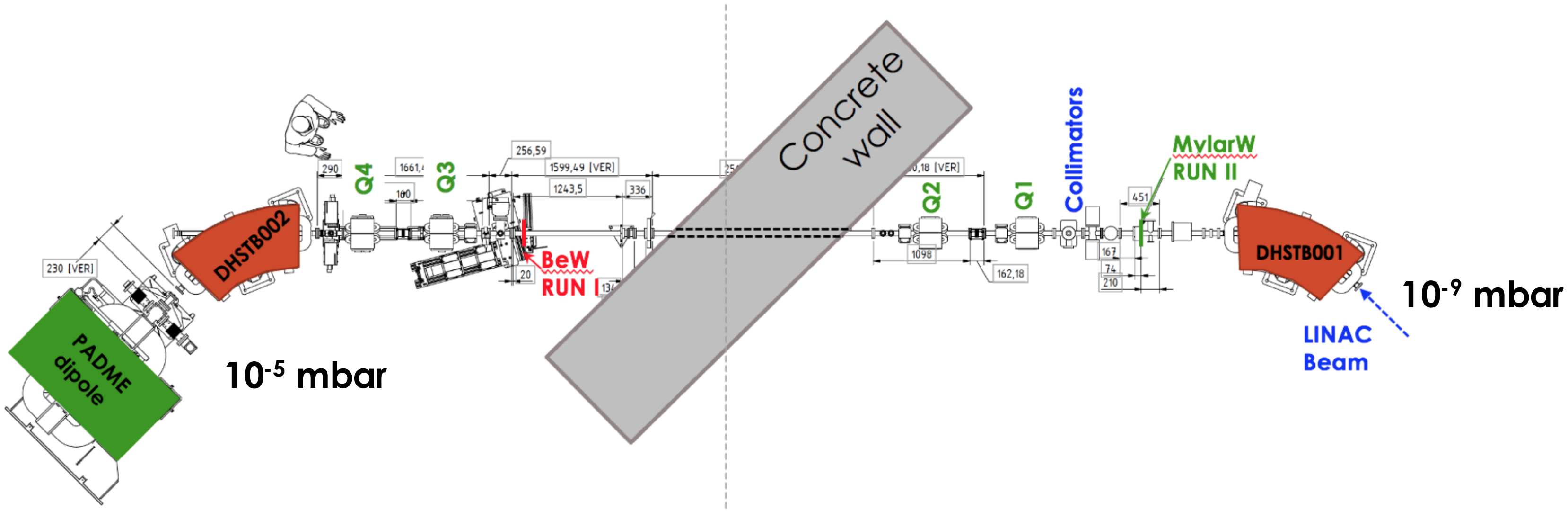
The BTF beam line and PADME

Positrons from the DAFNE LINAC 200 - 500 MeV, O(0.25%) energy spread

Repetition rate up to **49 Hz**, macro bunches of up to **250 ns** duration

Intensity must be limited below ~ 3×10^4 PoT/spill to control pile-up

Emittance ~ 1 mm x 1.5 mrad @ PADME



Past operations:

Run I e^- primary, target, e^+ selection, 250 μm Be vacuum separation [2018]

Run II e^+ primary beam, 125 μm Mylar™ vacuum separation, 28000 e^+/bunch [2019-20]

Run III dipole magnet off, ~3000 e^+/bunch, scan $s^{1/2}$ around ~ 17 MeV [End of 2022]

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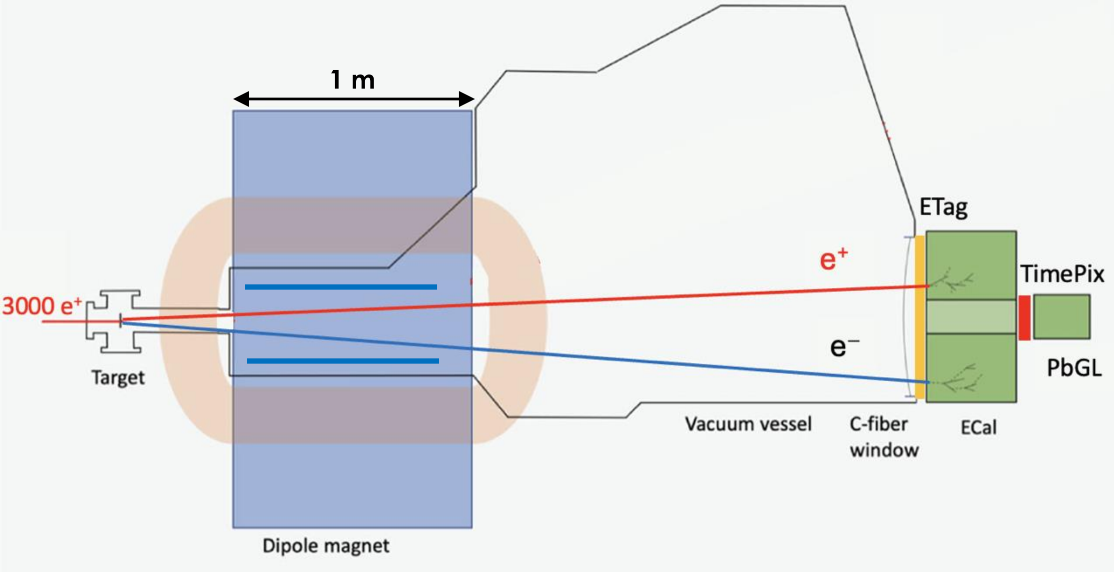
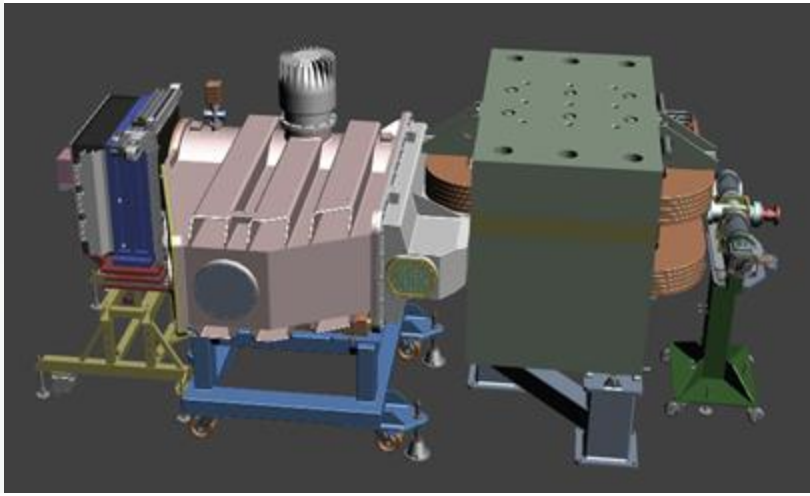
PADME detector in Run III





2022 Run-III setup adapted for the X17 search:

- **Active target, CVD polycrystalline diamond with X,Y coordinates**
- **Dipole Magnet OFF**
- **Charged-veto detectors not used**
- **ECal, 616 21x21x230 mm^3 BGO crystals**
- **Newly built ETag in front of Ecal for e/γ**
- **Timepix silicon-pixel detector for beam spot imaging**
- **Lead-glass beam catcher (NA62 LAV spare block)**

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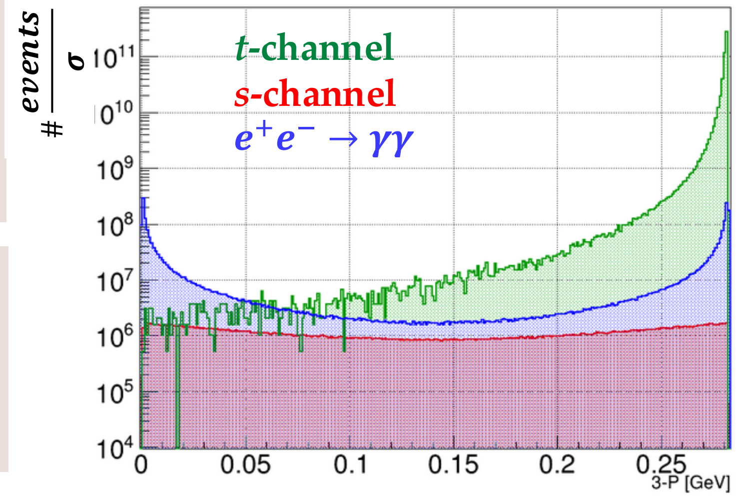
The mass scan PADME search strategy

PADME, can use resonant X17 production process

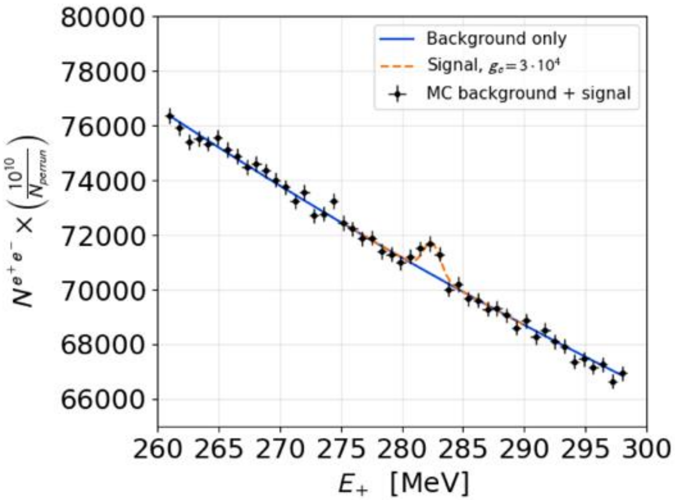
- Extremely effective in producing X17 but in a very small mass range
- Scan E_{beam}=260–300 MeV in <1 MeV steps



|p| [GeV]

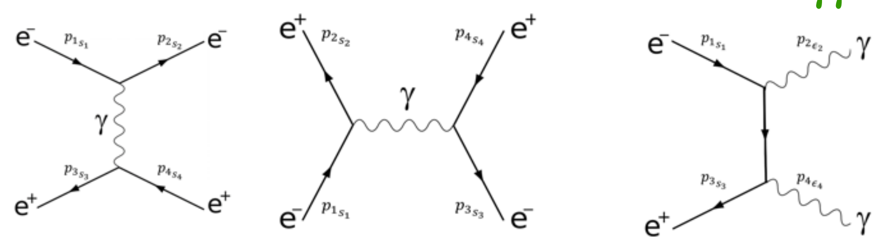
- Completely data driven no theory or MC inputs
- Signal should emerge on top of **Bhabha** BG in few points of the scan.
- Background estimated from surrounding bins.

Cartoon view of the technique



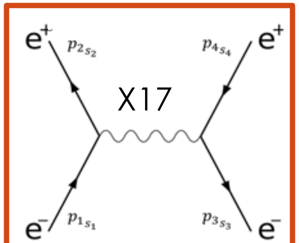
Bhabha scattering SM

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



t channel

s channel



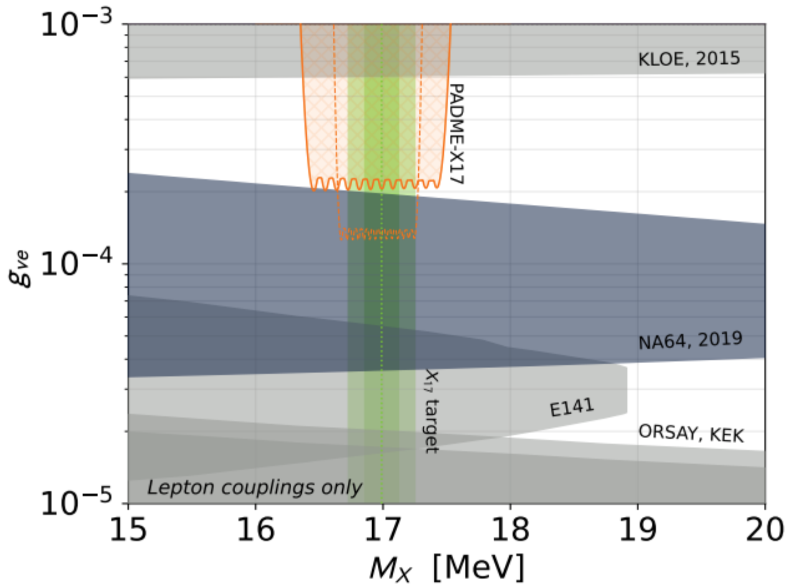
X17

BSM

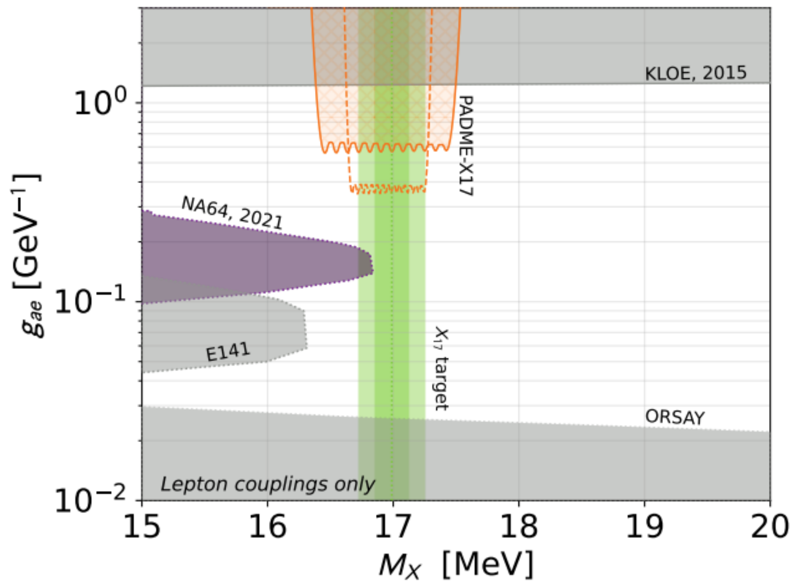
PADME expected limits

L. Darmé, M. Mancini, E. Nardi, M. Raggi
Darmé et al. Phys. Rev. D 106,115036

Vector X17



Pseudo scalar X17



BG from SM Bhabha scattering under control down to ε = few 10^{-4}
Need precise luminosity measurement and systematic errors control (<1%)
Need ~1×10^{10} POT per each energy point
PADME maximum sensitivity in the vector case

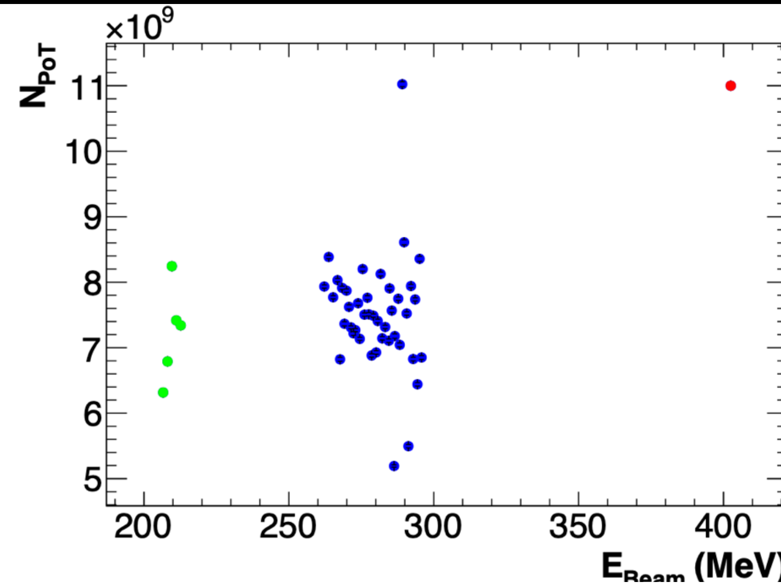
PADME Run III data set: winter 2022

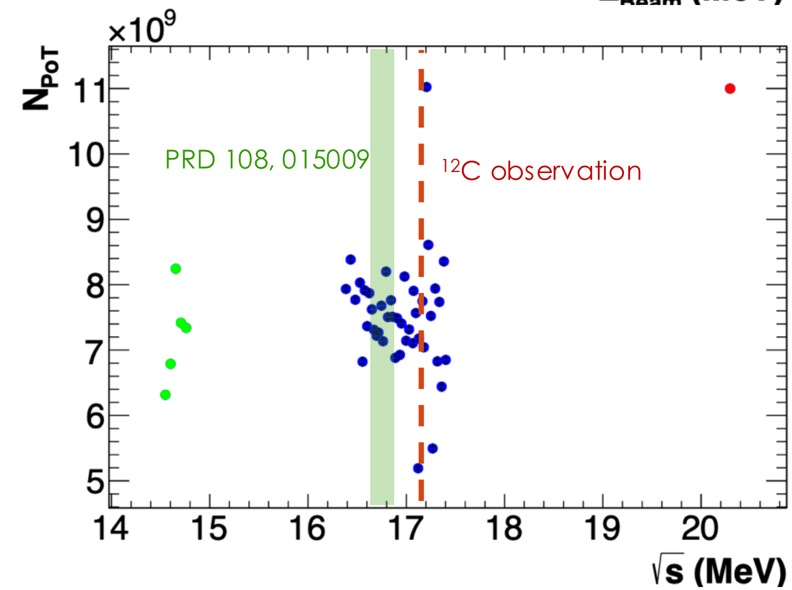
Run III PADME data set contains **3 subset**
- **On resonance: E_B range (263-299) MeV**
- **Below resonance: E_B range (205-211) MeV**
- **Over resonance: single Energy 402. MeV**

On resonance points **spaced** by **~ 0.75 MeV**
Point spacing equal to the energy resolution
Mass region 16.4 MeV <M_{X17}< 17.5 MeV
statistics ~1x10^{10} NPoT per point

Below resonance **spaced** by **~1.5 MeV**
Statistics ~ 1x10^{10} NPoT per point
Used to normalize absolute yield

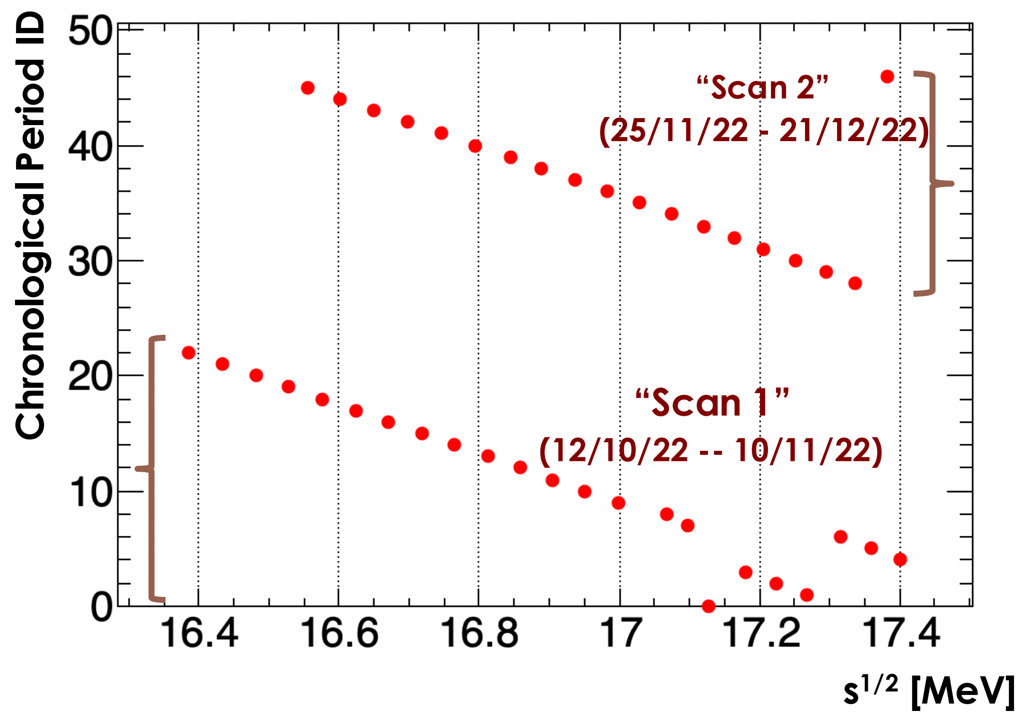
1 over resonance energy **5 different runs**
Statistics ~0.4x10^{10} PoT per run ~2E10 total
Used to validate NPoT measurement





Dots mass points explored by PADME

Run III data taking strategy: 2 scans

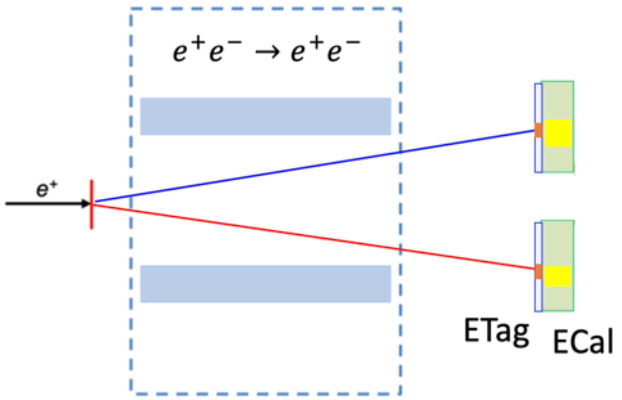


- "**Run**": DAQ **for ~8 hours**, determine beam avg position/angle, ECal energy scale
- "**Period**": a point at a **fixed beam energy**, typically lasts **24 hours**
- "**Scan**" a **chronological set of periods** typically decreasing in energy
- Scan 1 and 2 periods spaced ~ 1.5 MeV but interspersed in energy

Detailed GEANT4-based MC performed for each period

PADME Run III analysis scheme

Scatter e^+ on e^- in the diamond target to select $e^+e^- \to e^+e^-$ or $\gamma\gamma$ (2Cl)
Measure, direction and energy of each track with Ecal
Transform back to the Centre of Mass: e^+e^- are back-to-back.
Select events with **$\theta_1+\theta_2=\pi$ and $\phi_1-\phi_2=\pi$**



After selecting pure $e^+e^- \to e^+e^-$ search for unexpected excess from $e^+e^- \to X17 \to e^+e^-$ by scanning the X17 mass region.

Ultimately compare:

BG only hypothesis: $N_2(s) = N_{POT}(s) \times B(s)$

S+BG hypothesis: $N_2(s) = N_{POT}(s) \times [\, B(s) + S(s;\, M_X,\, g)\, \varepsilon_S(s)]$

Inputs:

- **$N_{POT}(s)$ number of e^+ on target from beam-catcher calorimeter**
- **$B(s)$ background yield expected per POT**
- **$S(s;\, M_X,\, g)$ signal production expected per POT for {mass, coupling} = $\{M_X, g\}$**
- **$\varepsilon_S(s)$ signal acceptance and selection efficiency**

Improving observable $\mathbf{g_R(s)}$

Try to spot deviations from SM expected 2CI yield define the analysis observable:
$g_R(s) = N_{obs}(s) / N_{exp}(s)$
If no BSM physics exist $\mathbf{g_R(s) = 1}$

Rewrite the master formula dividing $\mathbf{N_{obs}} = N_2$ by $\mathbf{N_{exp}} = \mathbf{N_{POT}(s)\ B(s)}$:

$$\underbrace{N_2(s) \,/\, (N_{POT}(s)\ B(s))}_{g_R(s)} = K(s)[\,1 + S(s; M_X, g)\ \varepsilon_S(s) \,/\, B(s)\,]$$

Different effects (see later) lead to a **linear scale deviation K(s)** from 1

The $\varepsilon_S(s) / B(s)$ cancel most of the systematic effect being the B and S acc. similar

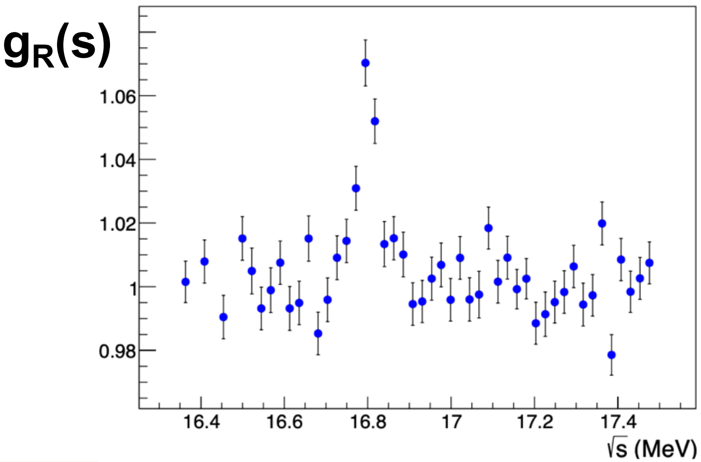
Question: is $g_R(s)$ more consistent with:

- BG only: K(s)
- S+BG = K(s) [1 + $S(s; M_X, g)\ \varepsilon_S / B$]

Nuisance parameter count:

K(s) 2, **$S(s; M_X, g)$ 3**, **$\varepsilon_S(s) / B(s)$ 2.** **Total 7**

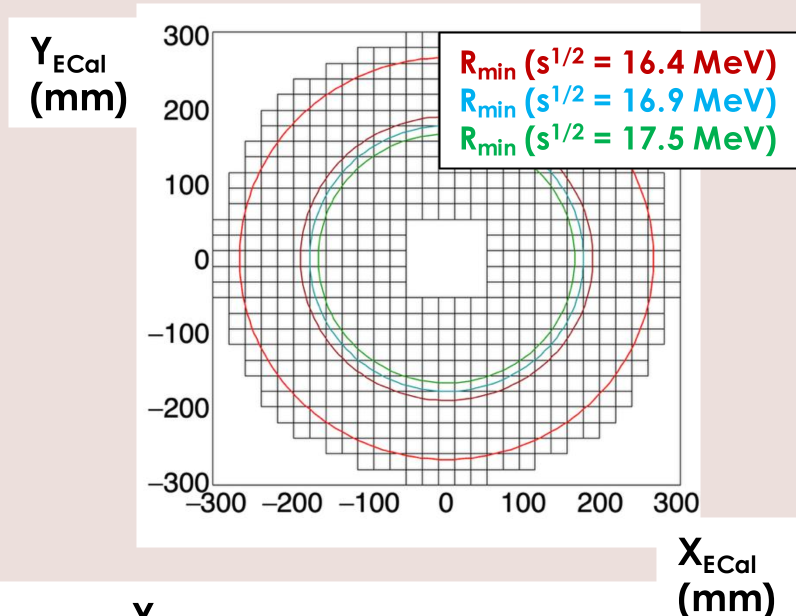
MC with M_X = 16.8 MeV, $g_V = 8\times10^{-4}$



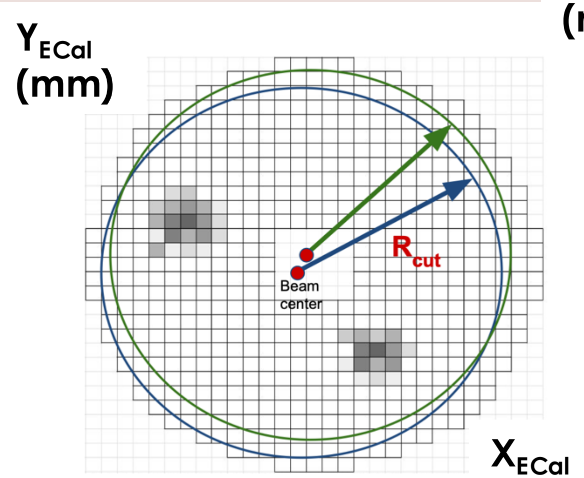
Run III concepts – N_2 selection

N_2 any two-body final state (ee + γγ) with both particles in ECal acceptance:

1. Fix R_{Max} at Ecal, away from Ecal edges
2. Given s, compute R_{Min}, E_{Min}, E_{Max}
3. Select cluster pairs:
   - With Energy > E_{min} x 0.4
   - In time within 5 ns
   - Clus1: In (R_{min}- D, R_{max}), D = 1.5 L3 crystals
   - Clus2: R > R_{min}- D
4. Select pairs back-to-back in the c.m. frame



R_{max} chosen to be away from Ecal edges by more than the size of 1 crystal cell for any period in the data set



1 □ = 1 L3 crystal = 21.5 x 21.5 mm

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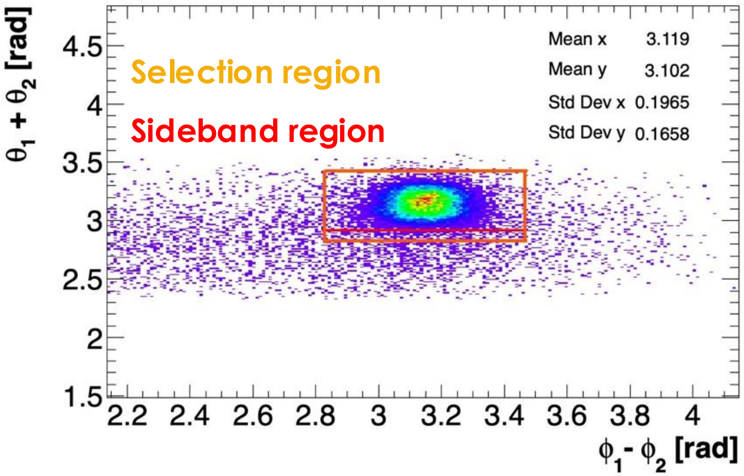
$N_2(s)$: Number of 2Cl candidates

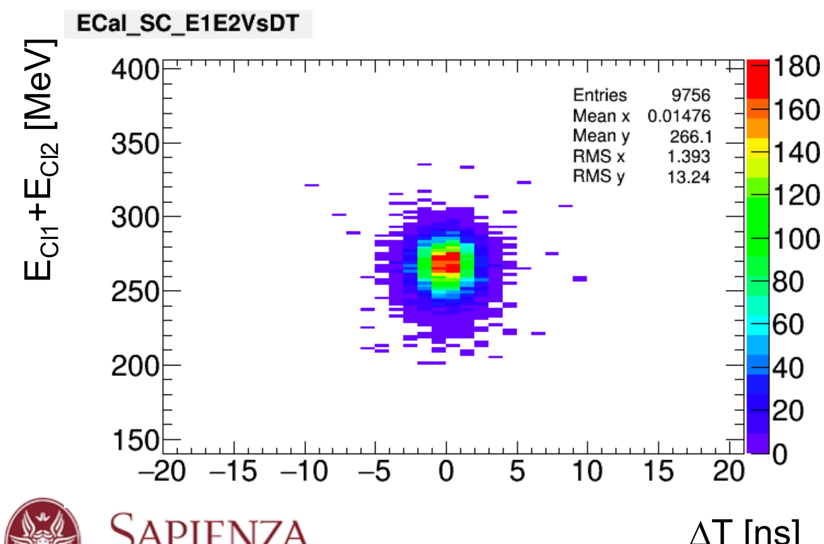
Neglecting m_e/E terms, the c.m. angles are independent on the lab energies



- Selection algorithm made as independent as possible on the beam variations:
- Retune beam center run by run with an error << mm
- Overall, make marginal use of the cluster reconstructed energy
- Main analysis cut based on CM angles only:

  $(\theta_1+\theta_2=\pi)$ and $(\phi_1+\phi_2=\pi)$

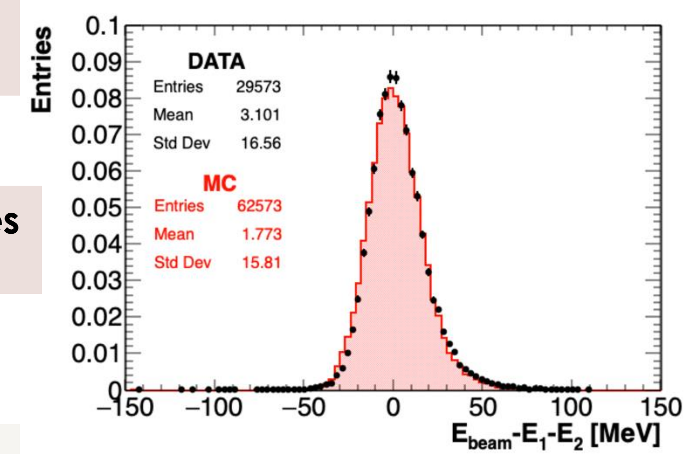
E_{tot} and ΔT used as independent cross check



Brems BG down to 4% level can be measured in data

N_2~ **30K candidates** per Energy point

Selected 2Cl events,



$N_2(s)$ candidates error budget

- Selected around 30k 2Cl candidates/period:
  Statistical error: δN_2 ~ 0.6% up to 0.7%
- SM Brems. **BG subtraction** using angular side-bands (bremsstrahlung, 4%)
  - additional statistical uncertainty **δN_2 ~ 0.3%**
- Data quality using time-averaged energy deposited on ECal:
  Overall systematic error from data quality, $\delta N_2 \ll$ %

Source	Error on N_2 per period [%]
Statistics	**~0.6**
Background subtraction	**0.3**
Total	**0.65**

B(s) expected BG/N_{PoT} error budget

B(s), the expected background/e^+, is determined with MC + data-driven checks

Source of uncorrelated error	Error on B per period [%]	Details
MC statistics	0.4	Next slide
Data/MC efficiency (Tag&Probe)	0.2	ⓘ
Cut stability	0.2	ⓘ
Beam spot position variations	0.1	ⓘ
Total	0.5	

Correlated (common) systematic errors on **B** enter in the scale K(s), e.g.:
Absolute cross section (rad. corr. at 3%), target thickness (known @ 5%)

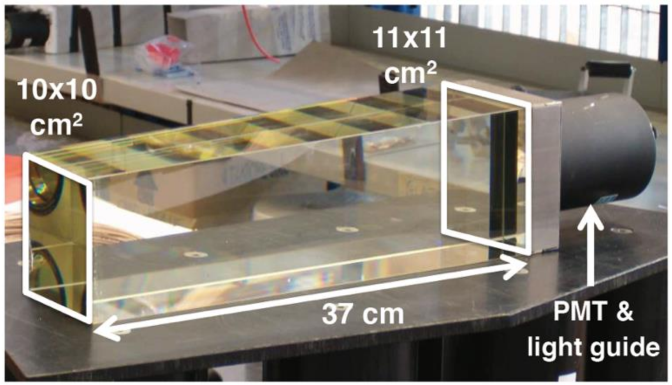
B expectation is compared to below resonance points, improving the systematic uncertainty

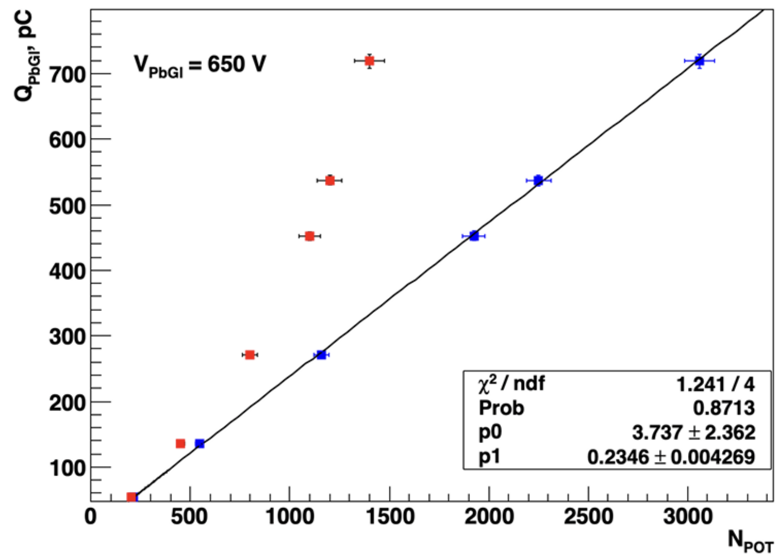
Scaling errors are accounted for

Source	Correlated B error [%]
Low-energy period statistics	0.4
Acceptance of low-energy, target thickness variations	0.5
Total	0.6

N_{PoT} calculation

Flux N_{POT} determined using Lead-glass detector charge, Q_{LG}:
$N_{POT} = Q_{LG} / Q_{1e+,\ 402\ MeV} \times 402 / E_{beam}$ [MeV]





Common systematic error dominated by Q_{1e+}
Known at 2%, see *JHEP* 08 (2024) 121

Uncorrelated systematic error due to value of E_{beam} from BES, 0.25%
Common scale error on beam energy, up to 0.5%, cancels @ 0.1%

Multiple analysis level corrections to be applied:

1. E_{Loss} @ E_{beam}/E_{Loss} @ 402 MeV: from data + MC, details
2. LG Radiation-induced response loss: from data, details

N_{PoT} error budget

Uncorrelated uncertainty on N_{POT} :

Source	Error on N_{POT} per point [%]	Source
Statistics, ped subtraction	negligible	
Energy scale from BES	0.3	BES from timepix spot s_x
Error from ageing slope	Variable, ~0.35	
Total	**0.45**	

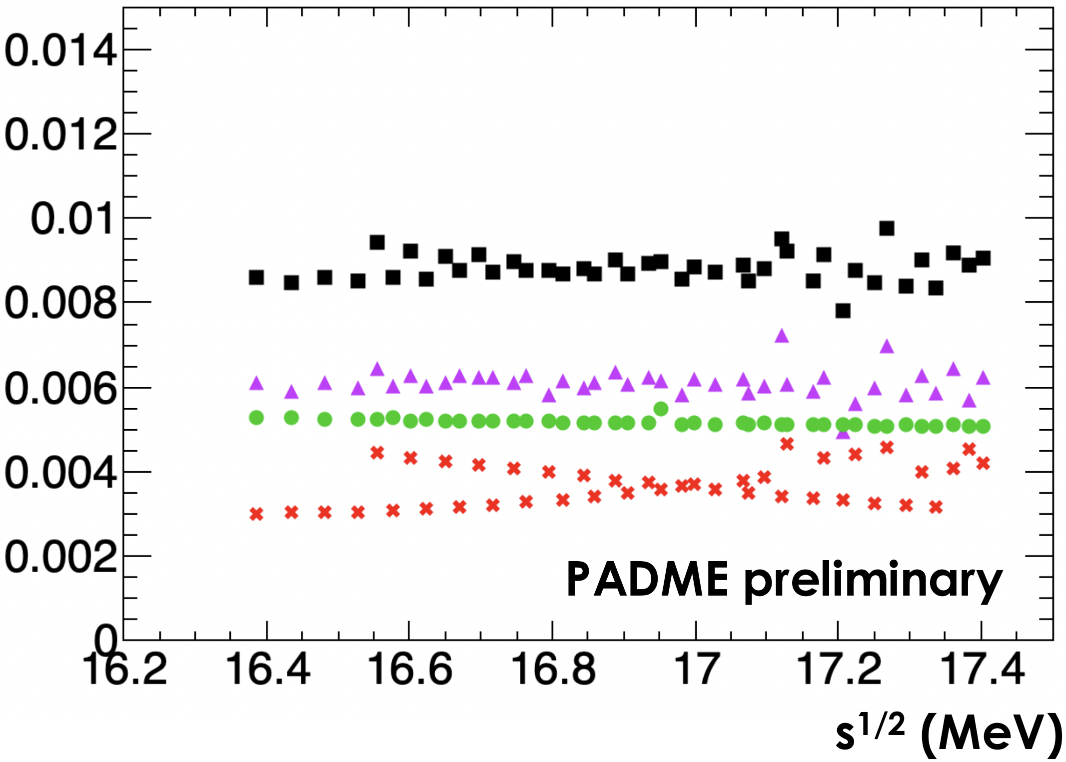
Correlated (common) systematic errors on N_{POT}:

Source	Common error on N_{POT} [%]	Source
pC/MeV	2.0	Analysis in JHEP 08 (2024) 121
E_{Loss}, data/MC	0.5	
Ageing, constant term	0.3	
Total	**2.1**	

Global $g_R(s)$ error budget

Uncorrelated uncertainty on $g_R(s) = N_2(s) / (N_{POT}(s)\ B(s))$:

Relative error per period

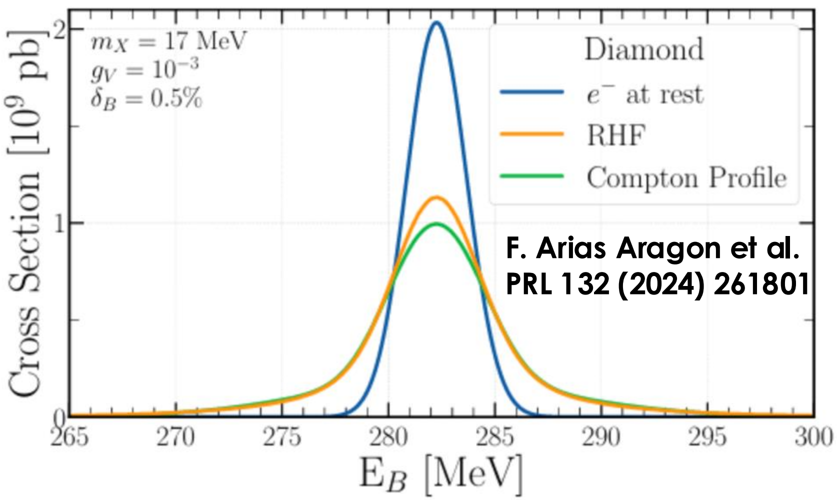


Source	Error [%]
$N^2(s)$	0.6
NPoT	0.35
B(s)	0.55
Total on $g_R(s)$	**0.89**
K(s) scale (common)	2.1

$S(s; M, g_v)$: Signal yield

Expected signal yield(s) from:
F. Arias Aragon et al. PRL 132 (2024) 261801

Includes effect of motion of the atomic electrons in the diamond target from Compton profiles

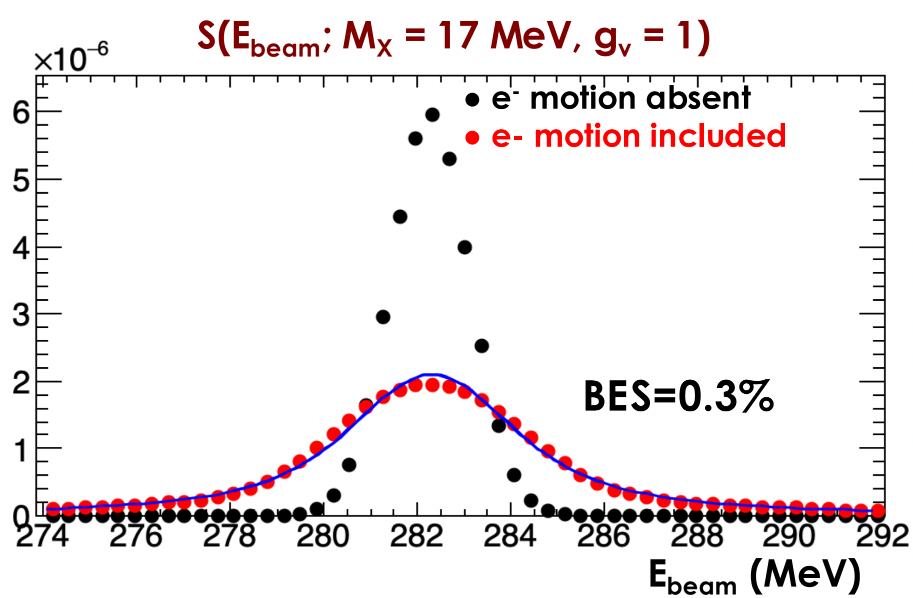


Parameterized S vs E_{beam} with a Voigt function:

- Convolution of the gaussian BES with the Lorentzian
- OK in the core within % with some dependence on BES

Uncertainty in the curve parameters as nuisances:

- Peak yield: 1.3%
- Lorentzian width around the resonance energy: 1.72(4) MeV
- Relative BES, as said: 0.025(5)%



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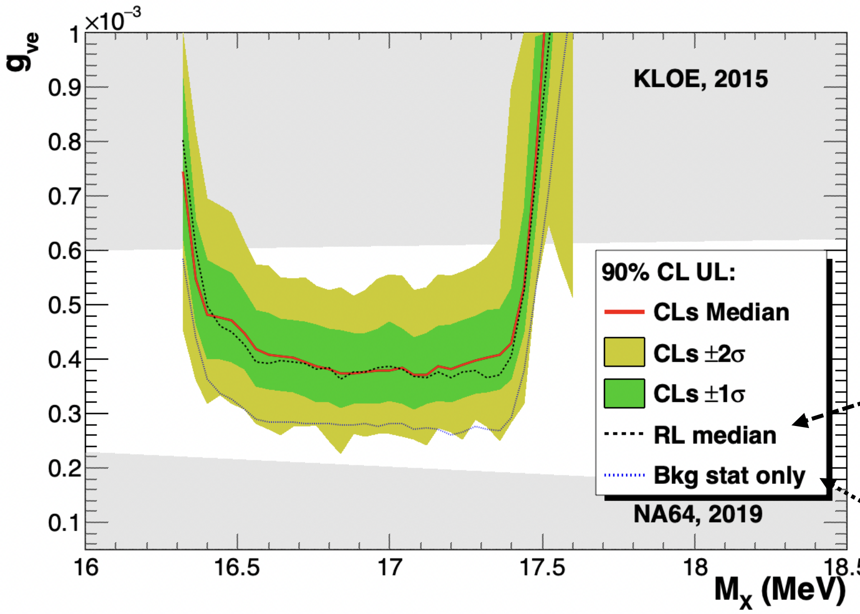
Expected sensitivity MC simulations

- Evaluate expected 90% CL UL in absence of signal
- Define Q statistic based on Likelihood ratio: $Q = L_{S+B}(g_v, M_X) \; / \; L_B$
- The likelihood includes terms for each nuisance parameter pdf
- For a given M_X, $CLs = P_S \; / \; (1 - P_B)$ is used to define the UL on g_v



The probabilities P_S and P_B are obtained using simulations, where the observables are always sampled, while the nuisance parameters stick to the B and S+B fits ("θ hat")

For comparison, we show also:

- the median of the limits obtained using the Rolke-Lopez likelihood-ranking method with the 5 periods with largest signal yield
- the purely statistical UL, $1.28 \; N_2^{1/2}$

For details, **PADME collaboration** JHEP06(2025)040

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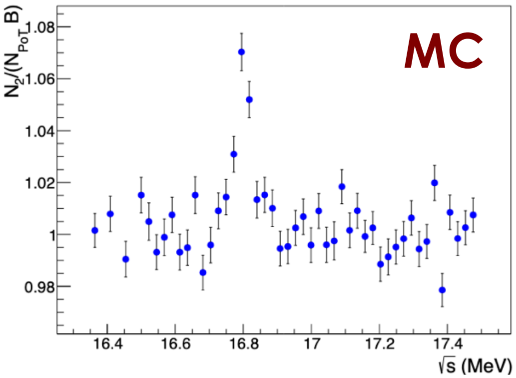
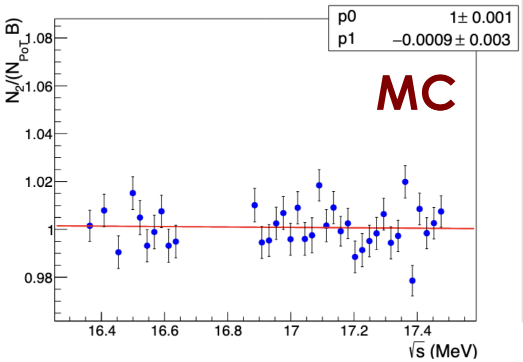
The “blind unblinding” procedure





To validate the error estimate, in presence of signal in any region of the mass scan JHEP06(2025)040

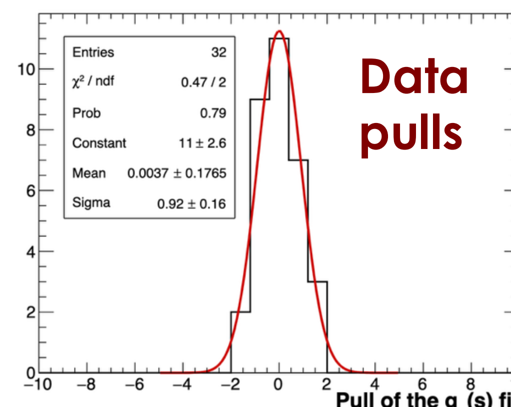
Aim to blindly define a side-band in $g_R(s)$, excluding 10 periods of the scan

Define the masked periods by minimizing χ^2 of a linear fit in $s^{1/2}$

1. Threshold on the χ^2 fit in **side-band is $P(\chi^2)$ = 20%,** corresponding to reject 10% of the times
2. If passed, check if the **fit pulls are gaussian**
3. If passed, check if a **straight-line fit of the pulls has no slope in $s^{1/2}$** (within 2 sigma)
4. If passed, check if constant term and slope of the linear fit for K(s) are within two sigma of the expectations, i.e.: ± 4% for the constant, ± 2% MeV^{-1} for the slope

Successfully applied, details in JHEP06(2025)040:

1. **$P(\chi^2)$ = 74%**
2. **Pulls gaussian fit probability 60%**
3. **Slope of pulls consistent with zero**
4. **Constant term = 1.0116(16), Slope = (-0.010 +- 0.005) MeV^{-1}**



Therefore, proceed to box opening

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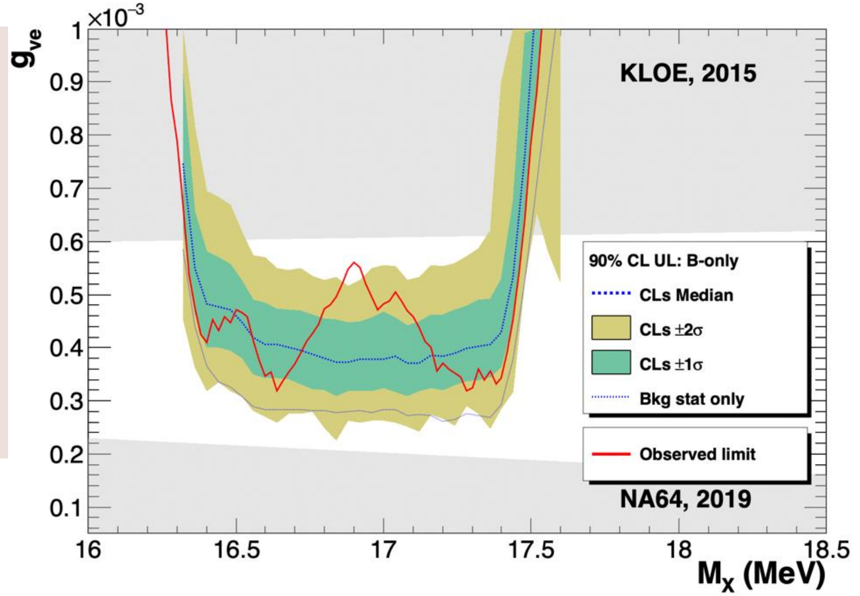
Observed limit after box opening

An **excess** is observed **beyond the 2σ local coverage** (**2.5 σ local**)

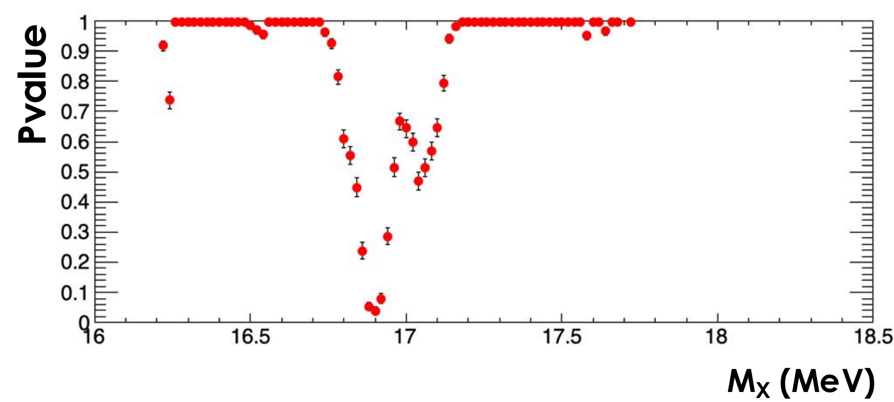
At **M_X = 16.90(2) MeV**, **g_{ve} ~ 5.6 x 10^{-4}**, the global probability dip reaches $3.9_{-1.1}^{+1.5}$ %, corresponding to (1.77±0.15) σ one-sided
(look-elsewhere calculated exactly from the toy pseudo-events)

A second excess is present at larger masses ~ 17.1 MeV, but the absolute probability there is ~ 40%



If a 3σ interval is assumed for observation following the estimate M_X = 16.85(4) of PRD 108, 015009 (2023),

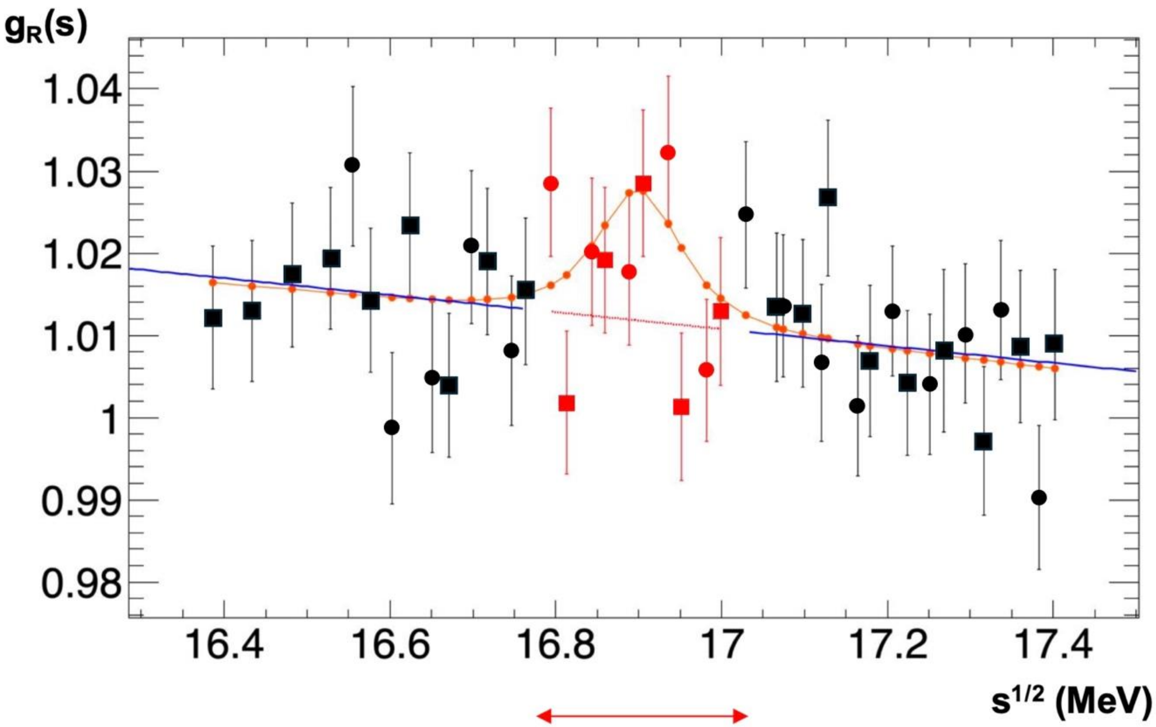
the p-value dip deepens to $2.2_{-0.8}^{+1.2}$% corresponding to (2.0±0.2) σ one-sided



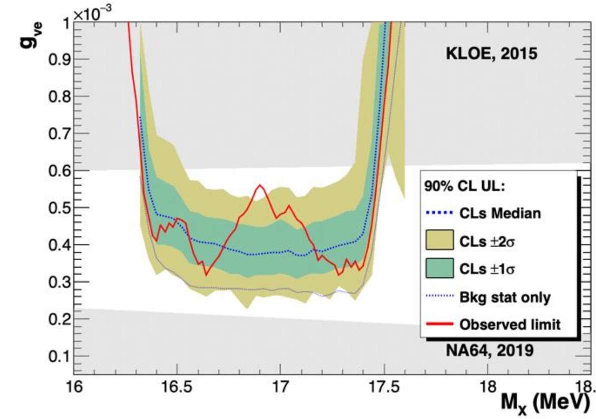
PADME collaboration: arXiv:2505.24797

Post unblinding checks: mass points

Check the data distribution vs likelihood fit done to evaluate $Q_{obs}(S+B)$
Fit probability is 60%



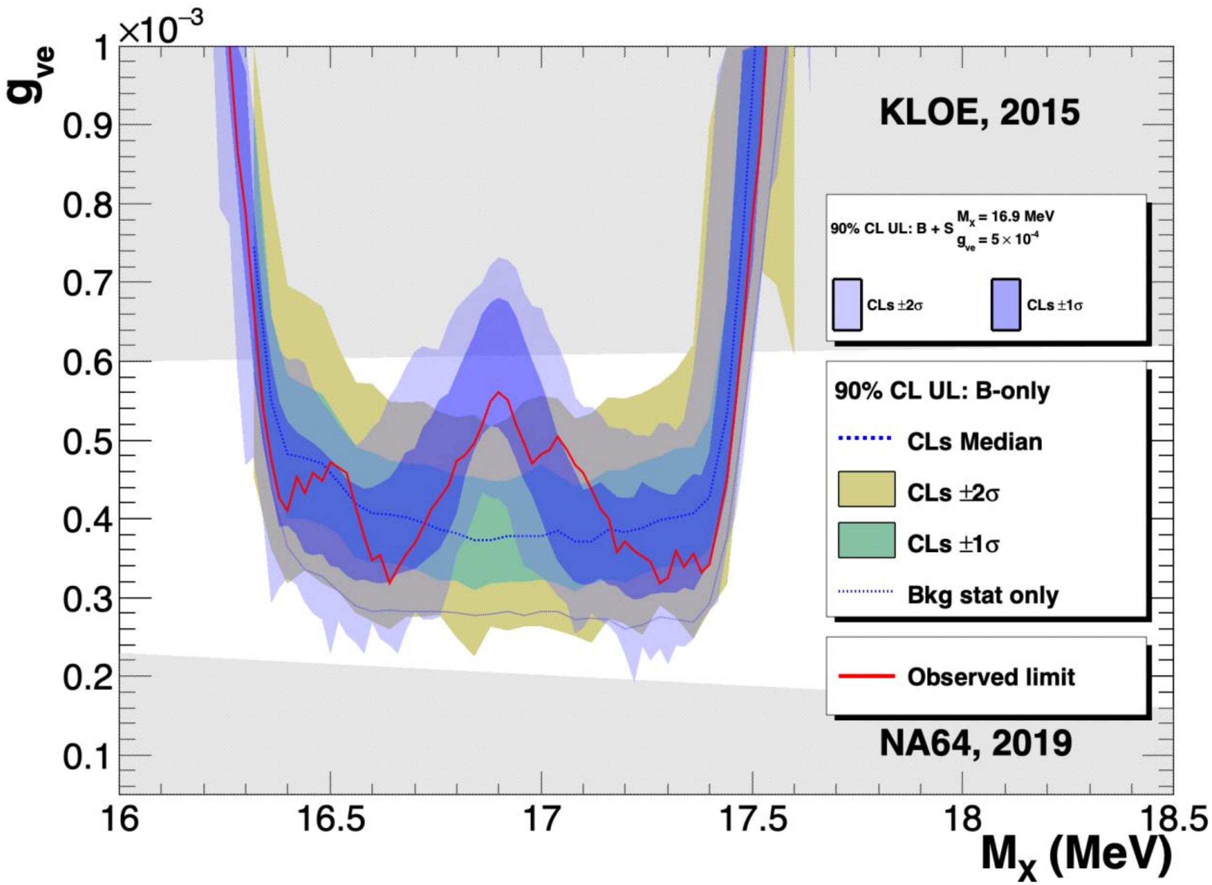
Region masked by automatic procedure



- Masked point of scan 1
- Masked point of scan 2
- Sideband point of scan 1
- Sideband point of scan 2

Post unblinding checks: excess shape

For comparison, check expected UL bands: **bkg-only** vs **B+S**(16.9 MeV, 5 × 10^{-4})



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Post unblinding checks: method

Perform the automatic procedure but fit SM BG with a constant:

Original version K(s) linear BG fit:

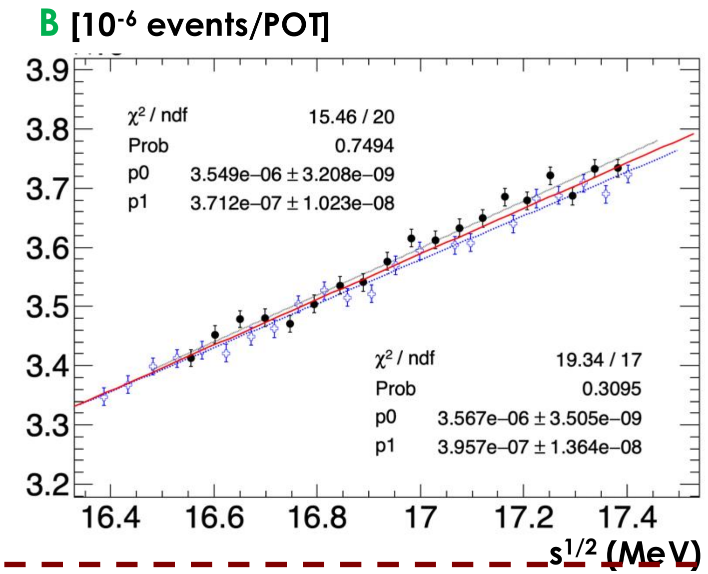
1. $P(\chi^2) = 74\%$
2. Pulls gaussian fit probability > 45%
3. Slope of pulls consistent with zero
4. Constant = 1.0116(16), Slope = (-0.010 ± 0.004) MeV^{-1}

Result using constant BG fit:

1. $P(\chi^2) = 37\%$
2. Pulls gaussian fit prob > 30%
3. Slope of pulls consistent with zero
4. Constant = 1.0112(14)

The center of the **masked region does not change**: 16.888 MeV
The **excess also remains** basically of the **same strength: 1.6σ**

Use scan1-scan2 separate parametrizations for B(s) instead of using B(s) / point:
The excess region is slightly affected but is equivalent to ~1.6 σ



Check the PCL method using CLsb, equivalent number of σ = 1.62±0.13

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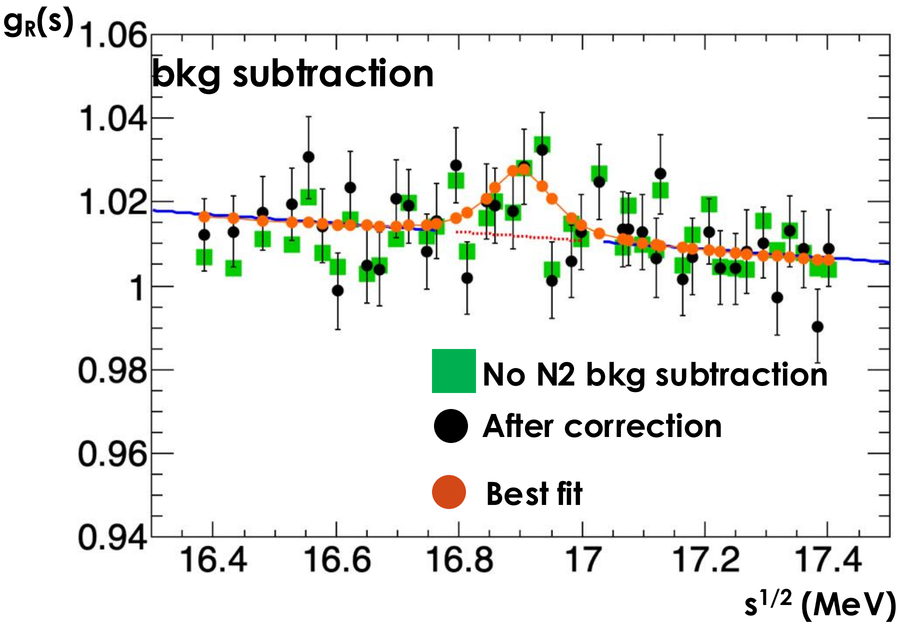
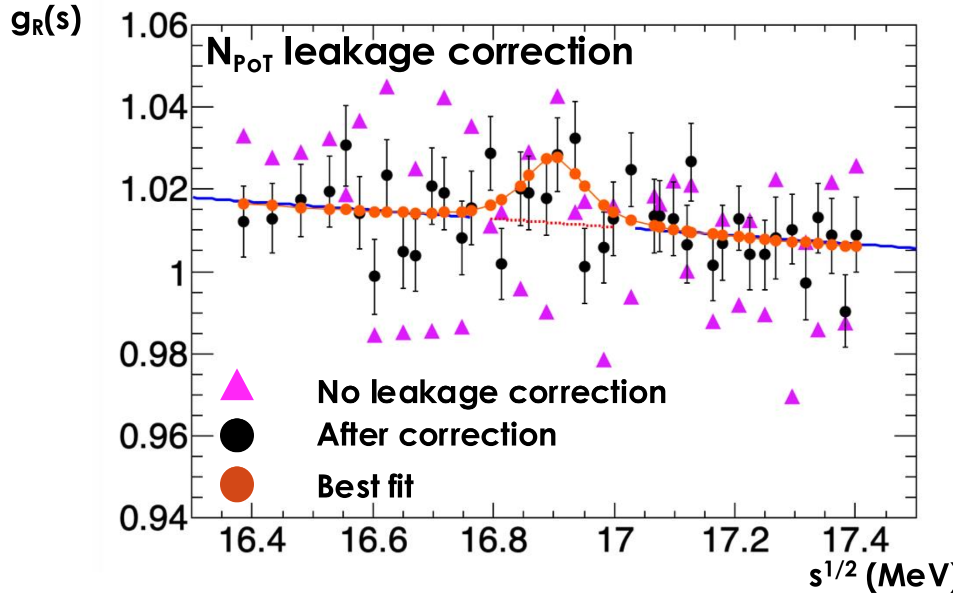
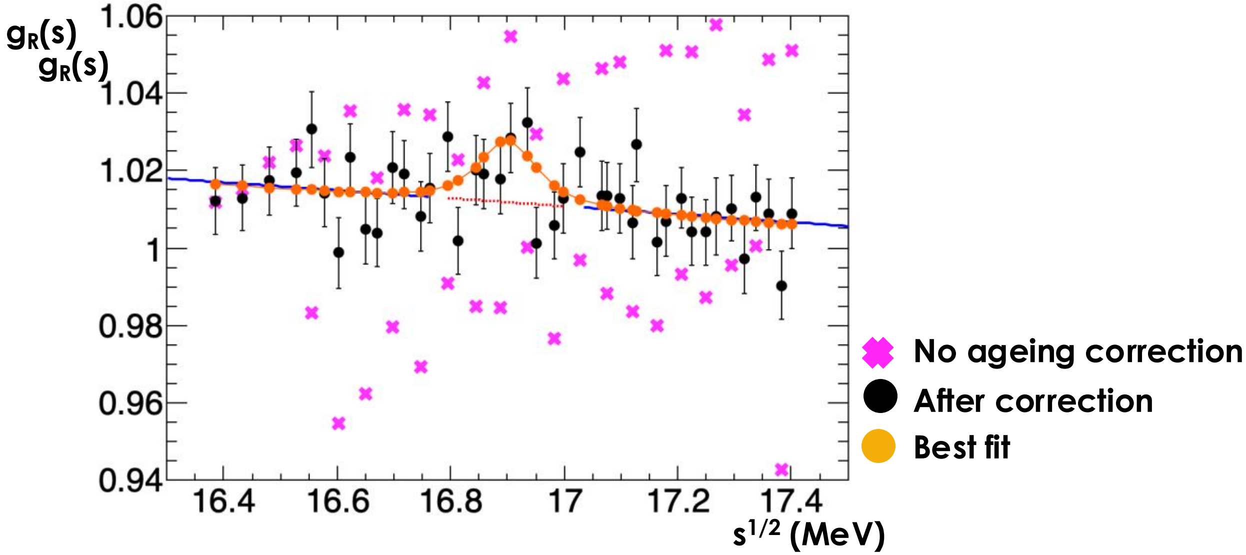
Post unblinding checks: corrections

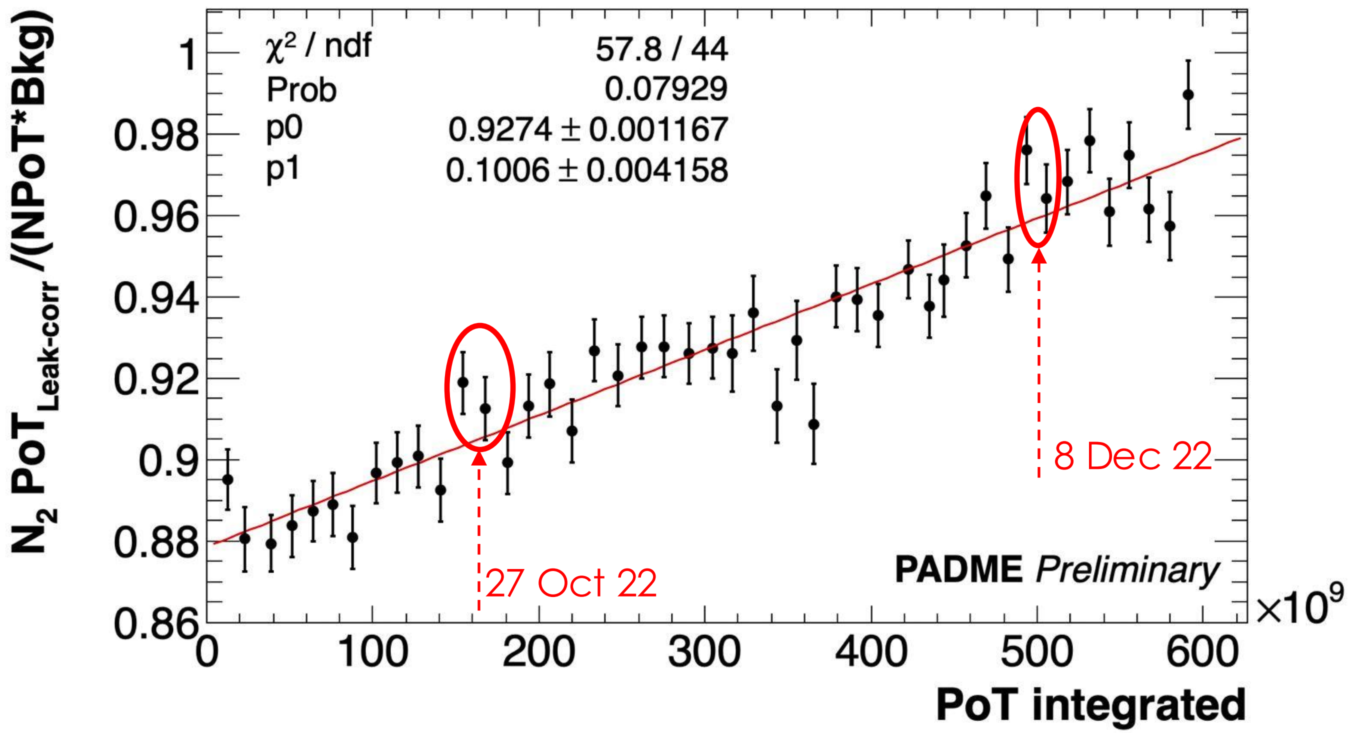






Post unblinding checks: LG ageing

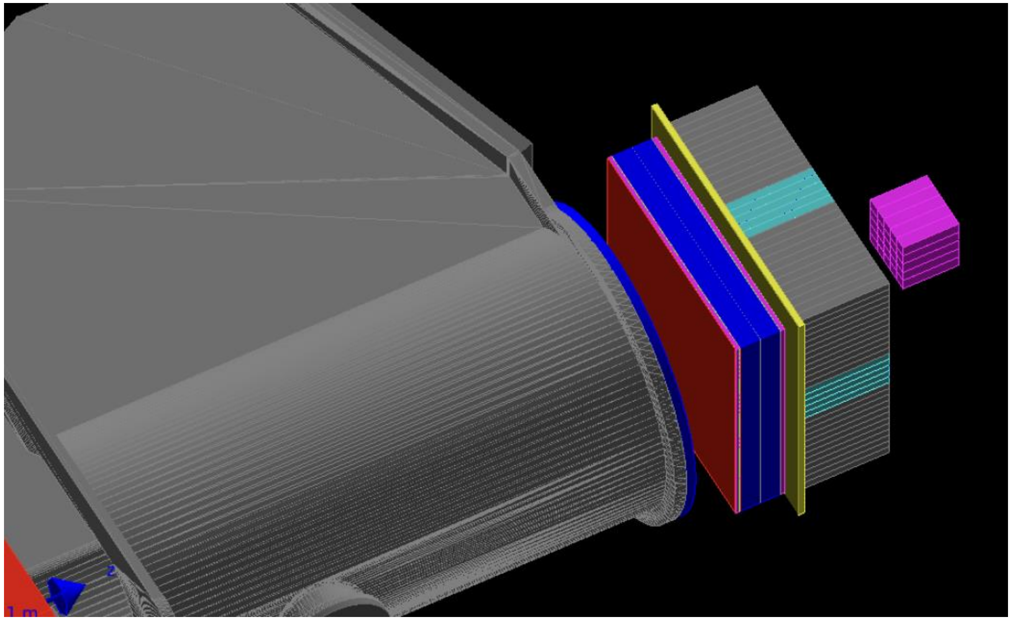
After box opening, can check ageing correction applied, slope was 0.097(7)
Fully consistent (observed excess alters only marginally)



Ongoind PADME Run IV

New data to be acquired to better clarify the excess during Run IV:

- We are commissioning a new detector for **Run IV summer + autumn 25**
- New **micromegas-based** tracker installed
  - **separate ee from γγ** thus allowing a separate analysis
  - Allows the analysis of $\mathbf{N_{ee}/N_{\gamma\gamma}}$ (remove N_{PoT} systematic)
- **New target position** closer to Ecal (**x2 acceptance**)
- Aim to **collect x4 statistics** (1.5x10^{10} PoT/energy x2 in acceptance)



PADME MicroMega chamber already installed in front of ECal and operational

Conclusions

The Run III analysis has been completed using the blind-sideband method

Overall uncertainties at 0.9% or slightly better

New exclusion limit region on X17 coupling to e^- covered in 16.5-17.5 MeV range

No indications of X17 well beyond two-sigma-equivalent global p-values

An **excess** has been observed at **16.90(2) MeV**:

Local p-value equivalent to **2.5(1)σ**

Global p-value equivalent to **1.77(15) σ**

New **data need to be acquired in 2025** to clarify the excess:

- Now commissioning PADME for Run IV (approved up to the end of 7/25)
- A **new micromegas-based tracker** to separately measure the absolute cross sections of ee/$\gamma\gamma$ thus allowing a combined analysis

Aim to acquire a N_2 x4 statistics wrt Run III data sample by the end of 2025
Discussion on detailed beam schedule during LNF SciCom 14-15 May

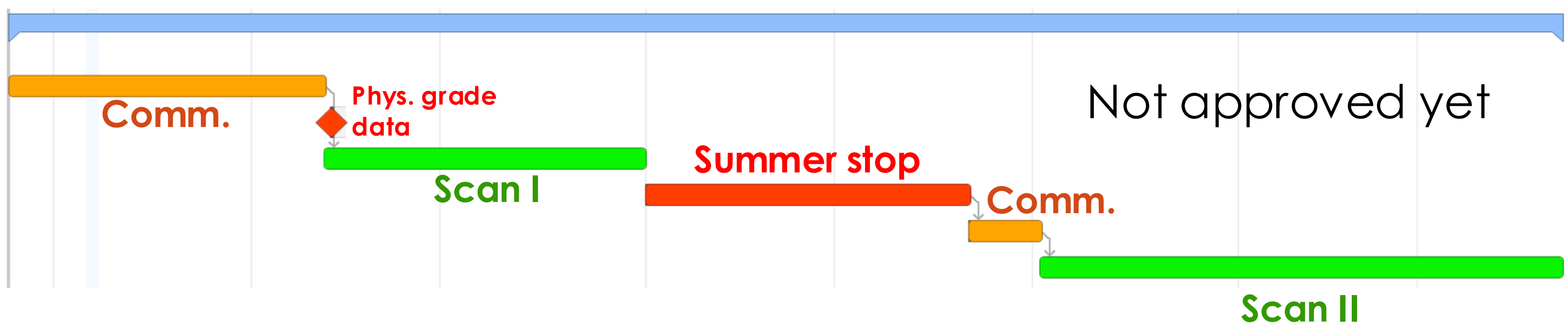
Acknowledgements…

PADME

Nothing of what I have shown would have been possible without the relentless effort of our colleagues of the LNF accelerator, theory division, technical division and the administrative service

Run IV: Tentative scheduling

- Tentative schedule to perform full Run IV in within 2025
  - Perform 2 scan with half step energy displacement as in Run III
  - 2 scans: first before summer second in autumn
  - Number of points: 30-40 total
  - Targeting a factor 4 stat per point: 2xRunning time x2 Acceptance



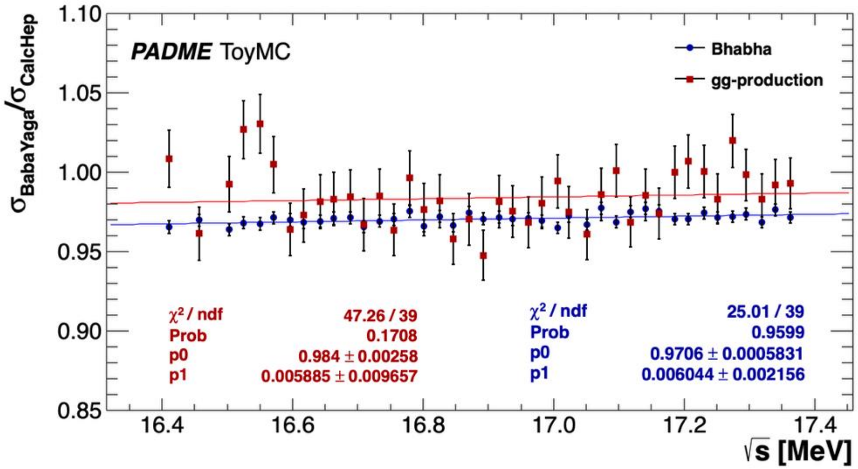
- Aim to have a set of physics grade data before the summer break
  - Each scan will have higher statistical power per point wrt Run III data sample

Final beam schedule discussion at next LNF SciCom 14-15 May

Backup slides

Possible scale effects K(s)

Radiative corrections evaluated using Babayaga, ee(γ) and $\gamma\gamma(\gamma)$



Babayaga references:

Nucl. Phys. B 758 (2006) 227

Phys. Lett B 663 (2008) 209

Possible negative offset of ~ -2.3% → comparable to the scale error of 2.1%

Possible slopes with sqrt(s):

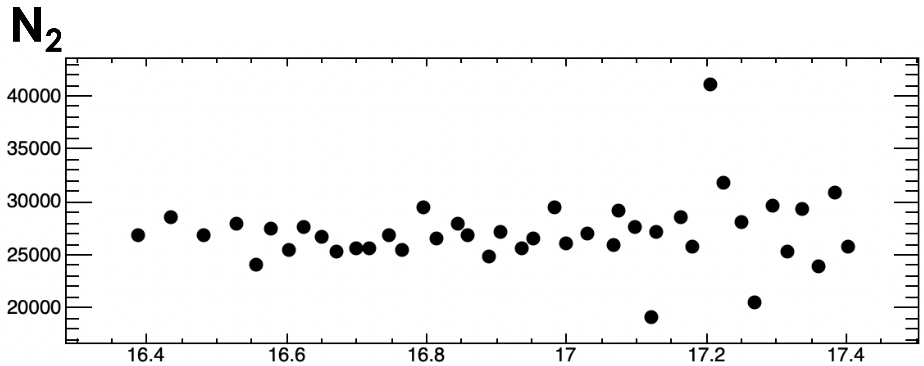
Radiative effects: slope of +0.6(2)% MeV^{-1}

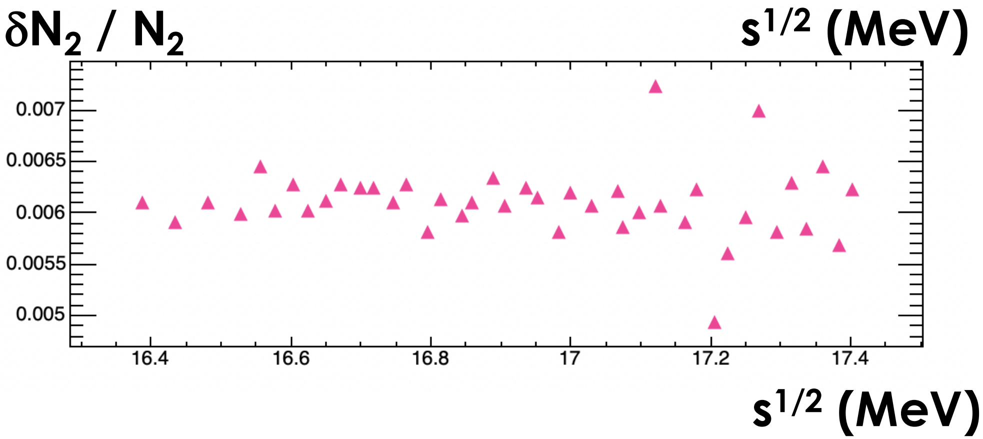
Tag & probe correction: slope of -2.2(6)% MeV^{-1}

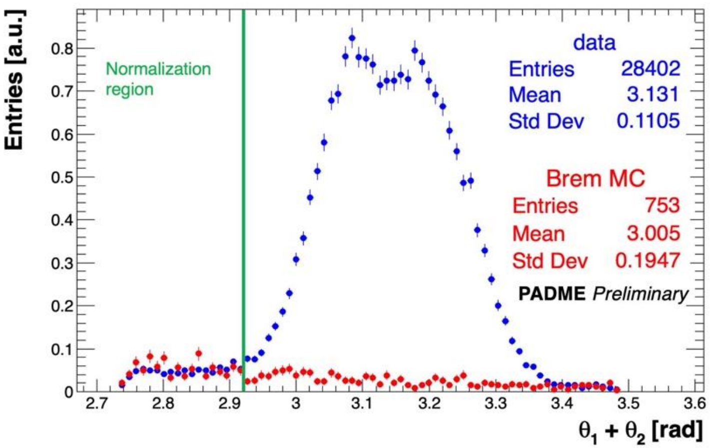
Total slope of -1.6(6)% MeV^{-1}

Details on the 2Cl count N2

Background subtraction using side-bands (bremsstrahlung, ~4%)
Correction relative variation +-1%, statistical uncertainty on δN_2 ~ 0.3%







Shape of ee signal due to residual magnetic field (MNP CERN SPS type)

44

Fully modeled using MC + detailed map

Details on background: cut stability

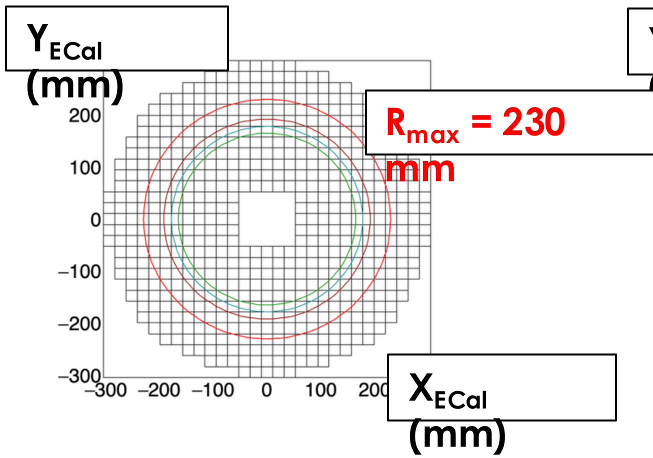
Check if MC and data yields stable vs R_{min}, R_{max} (edge effects, leakage)

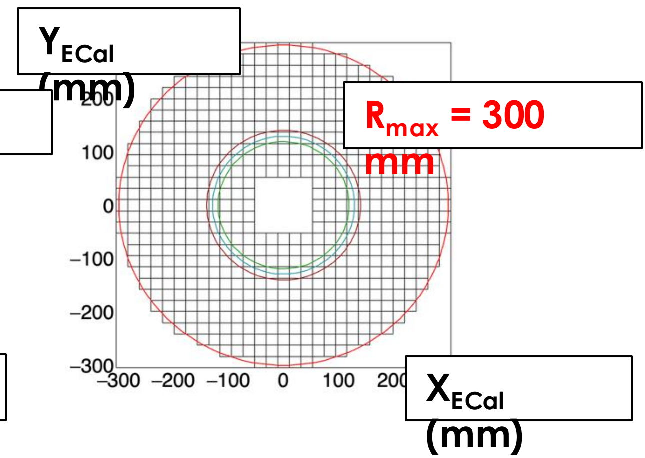
Vary R_{max} by +-2 E_{Cal} cells around nominal cut of 270 mm: 230 mm → 300 mm

Yield variation: -5%, +3%

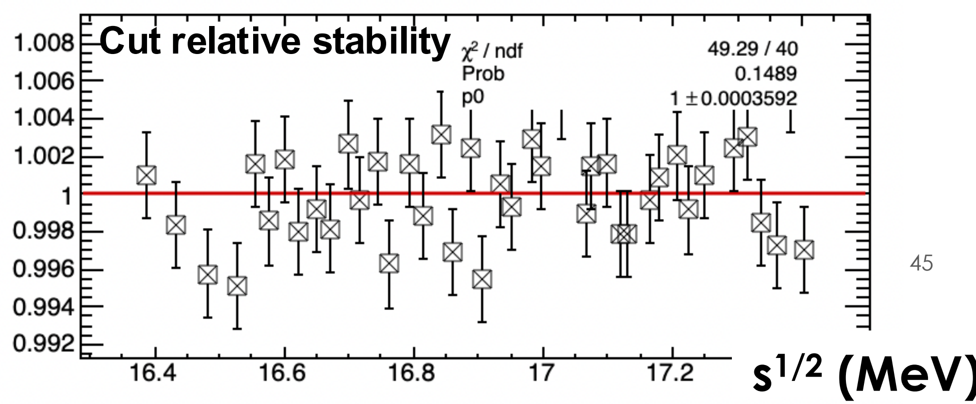
Uncorrelated error 0.3%

R_{min} -1.5 D ($s^{1/2}$ = 16.4 MeV)
R_{min} -1.5 D ($s^{1/2}$ = 16.9 MeV)
R_{min} -1.5 D ($s^{1/2}$ = 17.5 MeV)





Stability is observed within a coverage band of ±0.2%, used as additional uncorrelated systematic error on B



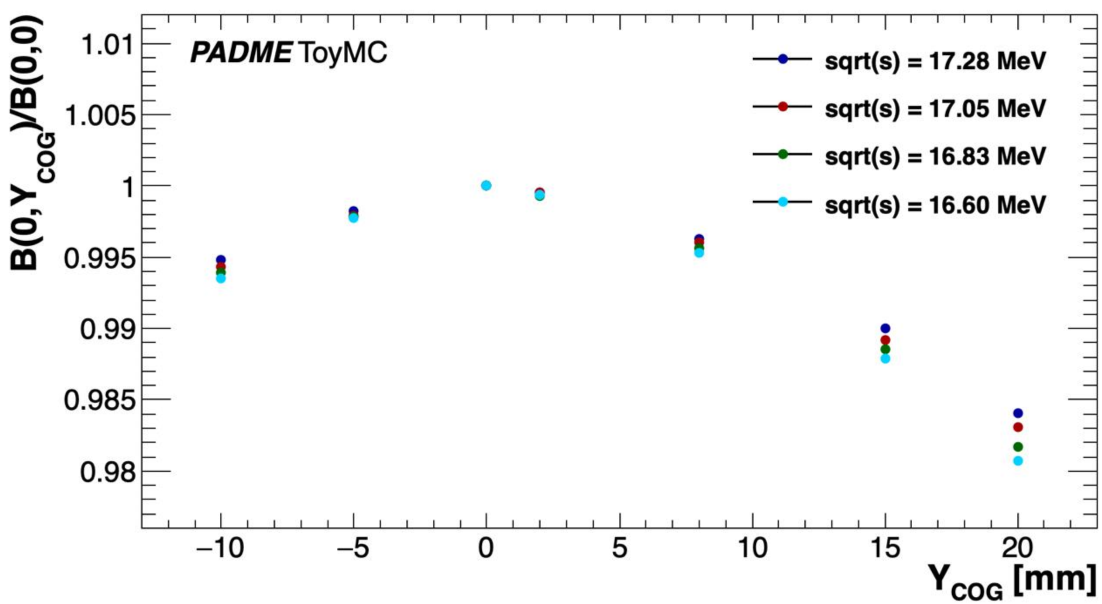
Details on BG: acceptance variations

The selection makes use of the expected beam direction, from the spot measured at the diamond target and the center of gravity (COG) of 2 body final states at ECal

Systematic shifts in the COG position translate into acceptance systematic errors

Largest effect in y due to acceptance limitations (rectangular magnet bore)
Fractional variations range from 0.08% to 0.1% mm^{-1} for $s^{1/2}$ from 16.6 to 17.3 MeV

An error of 1 mm in the COG is a conservative estimate → systematic error < 0.1%



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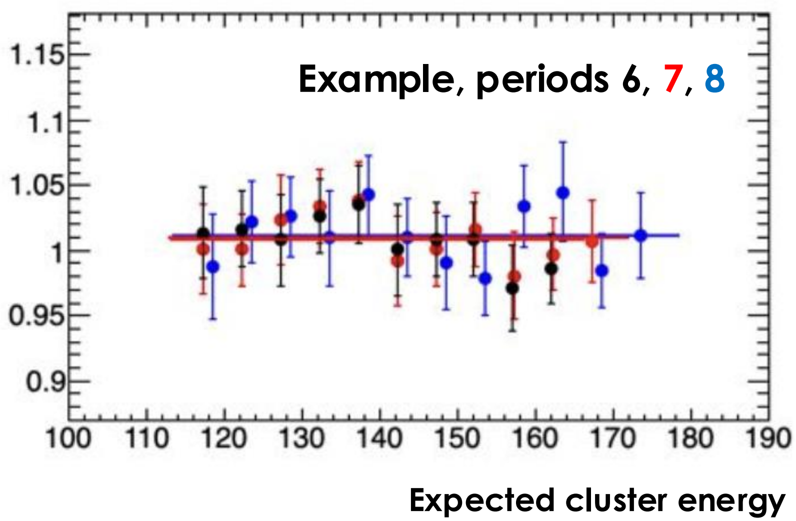
Details on BG: cluster reconstruction

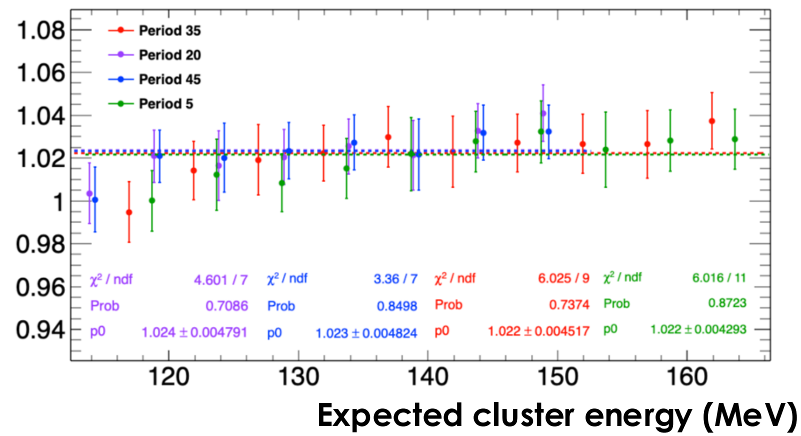
Tag and probe technique, the method-induced bias is 2.3(2)% and stable along the data set

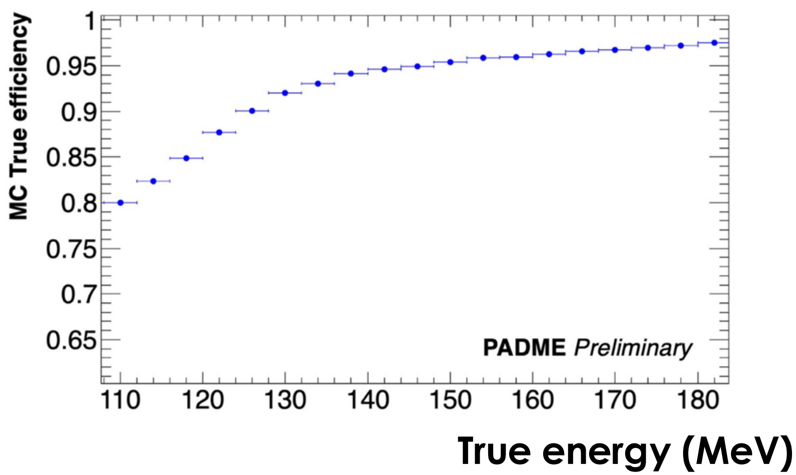
Data/MC method efficiency stable along the data set and at the few per mil

Efficiency Data/MC



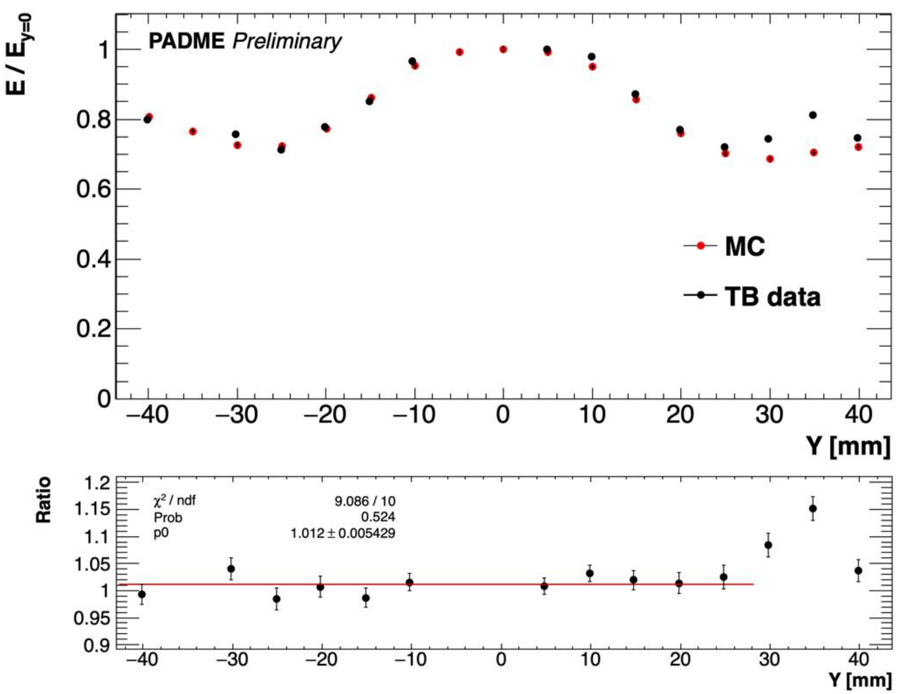
Efficiency <Method /MC true>





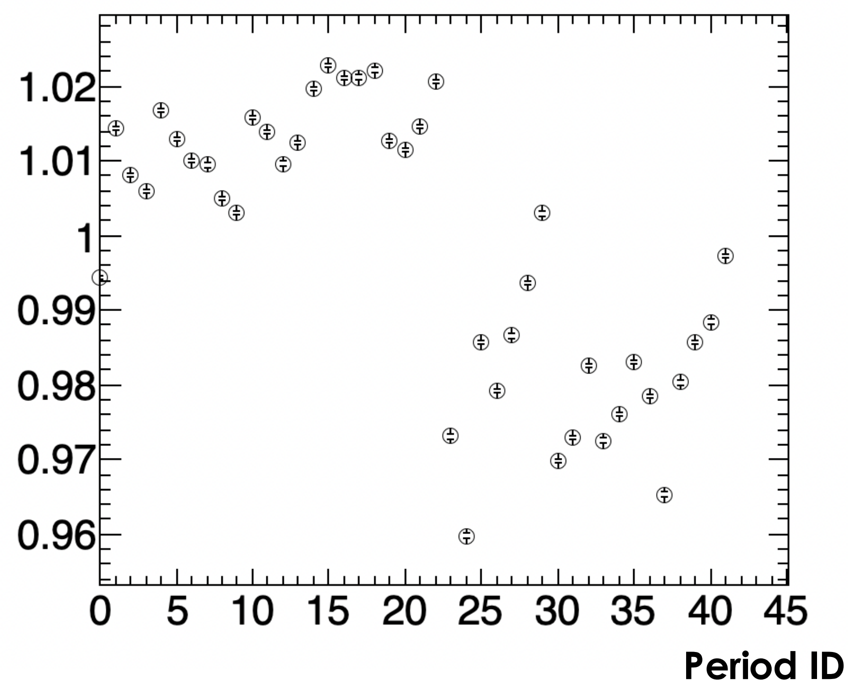
LeadGlass E_{Lost} correction

LG E_{Lost} from detailed MC vs vertical position checked against data in test beam
Very good data-MC agreement, correction 1.2%, systematic error 0.5%
Significant period-by-period variation of the correction: -4% to +2%



Region of interest

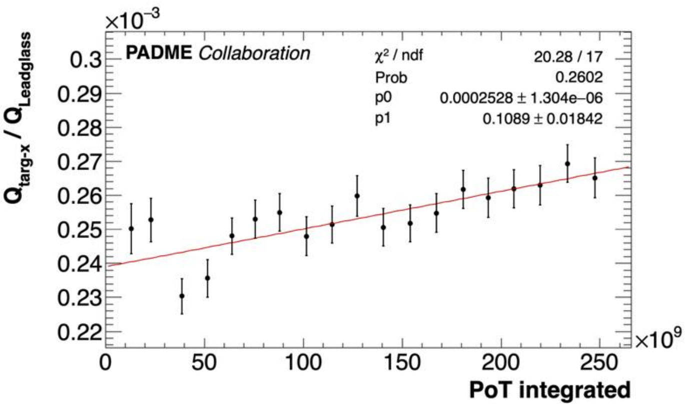
Relative LG E_{Miss} correction

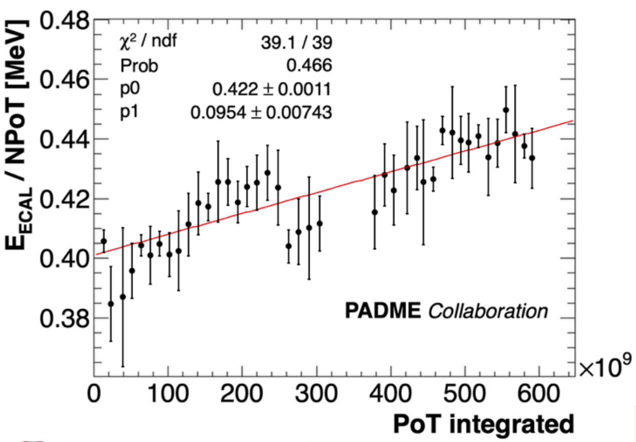


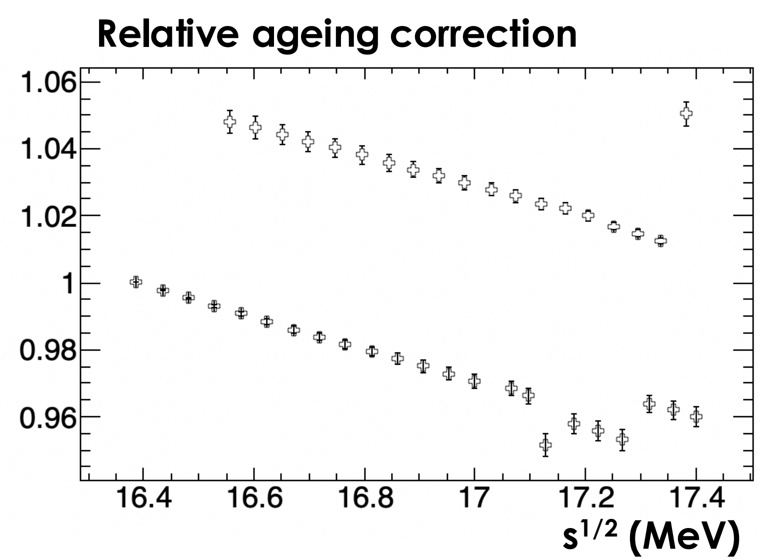
LeadGlass: ageing correction

The literature indicates possible changes in SF57 transparency for O(krad)
Estimate of Run-III dose: 2.5 krad

Estimated from 3 flux proxy observables: Q_{targ-x}/Q_{LG}, $<E_{Ecal}>/N_{PoT}$
Leadglass yield decreases with relative N_{PoT} slope of 0.097(7)
Constant term uncertainty of 0.3% added as scale error
Slope error included in N_{PoT} uncertainty

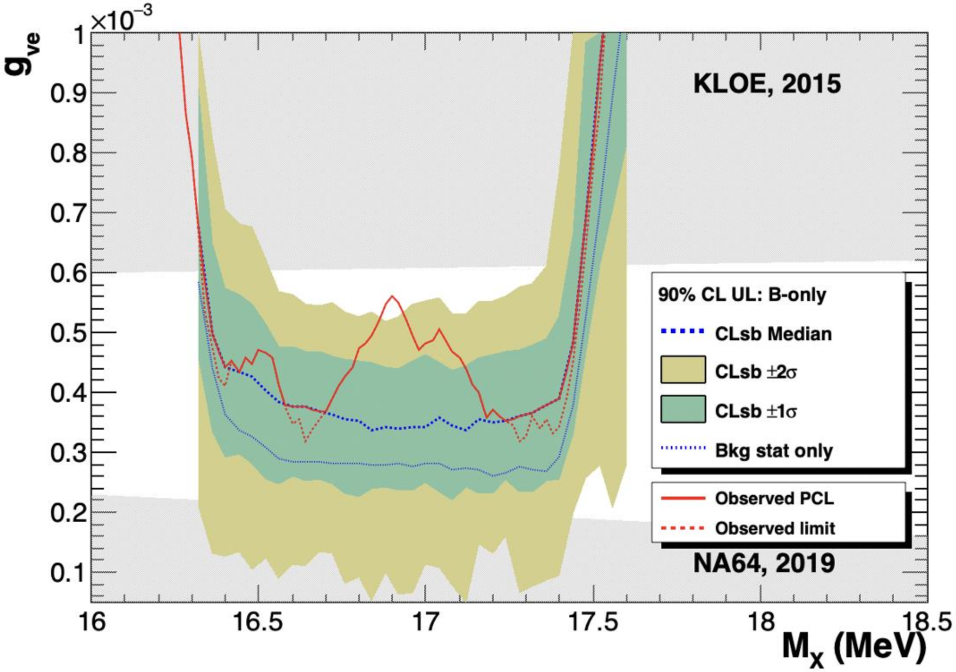


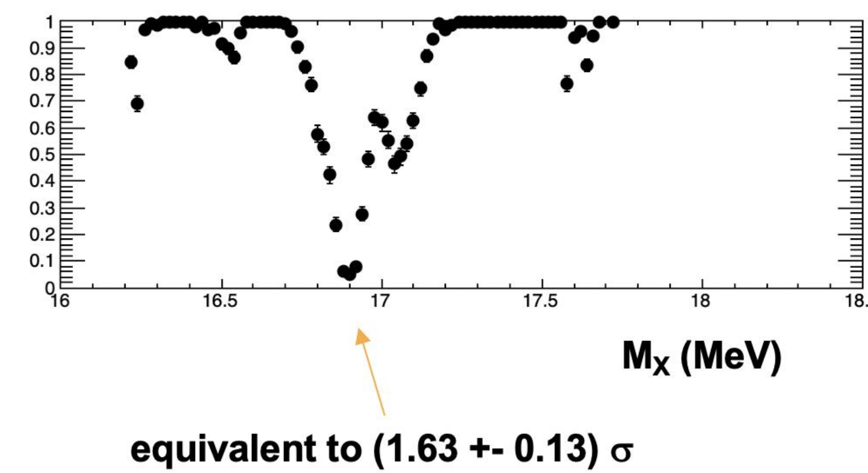




CLSb

Using CLsb but clipping to the median every downward fluctuation of the limit

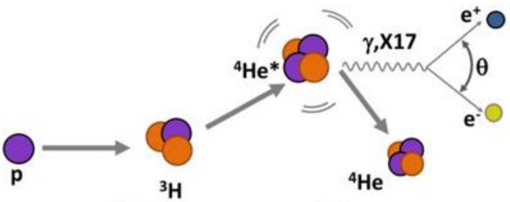




The p-value is only slightly affected, consistent with the coverage modifications of this method

Only P(signal)

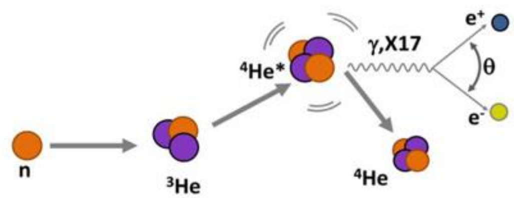
NToF: new approach to ^{4}He



$^3H(p,e^+e^-)^4He$

ATOMKI REACTION

see Carlo Gustavino



$^3He(n,e^+e^-)^4He$

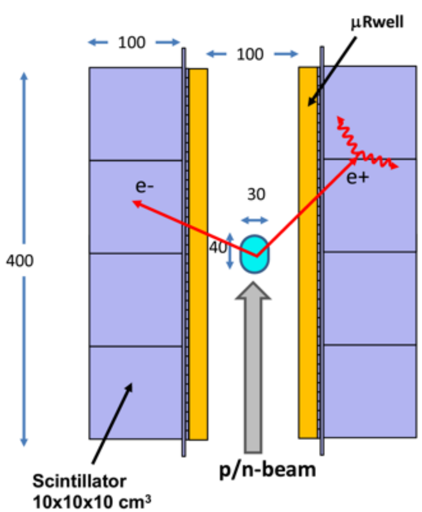
n_TOF REACTION

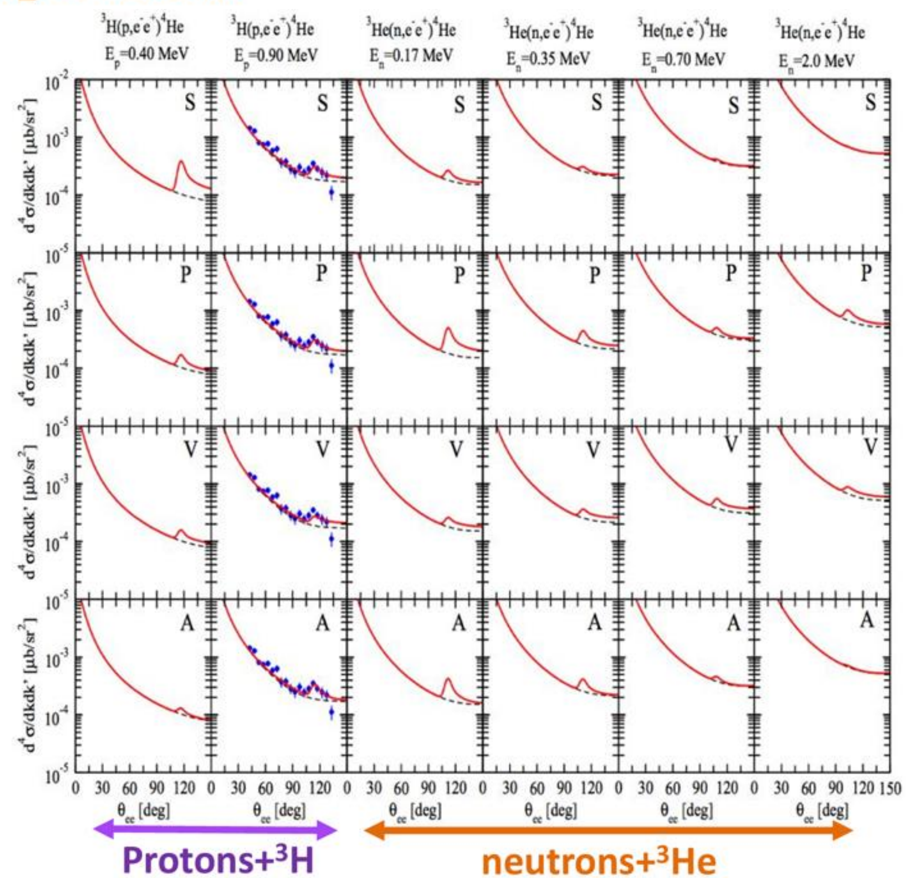
Innovative neutron beam based excitation mechanism

The only experiment proposed so far for to replicate ^{4}He anomaly

Thorough theoretical discussion to be found: Phys. Rev. C 105, 014001

Chance to have data in late 2024 early 2025





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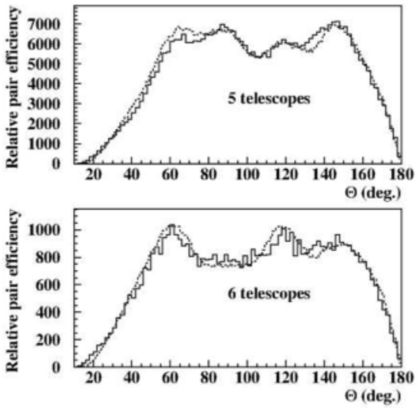
IPC experimental setup at Atomki

2 different setup used by Atomki for IPC measurements:
- **5 arms spectrometer (MWPC and 5 DE/E)**
- **6 arms spectrometer (Si strip and 6 DE/E)**

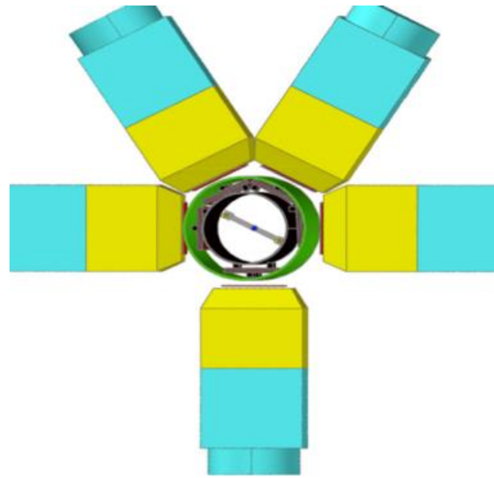
Different acceptance and detector types in ^{8}Be and ^{4}He



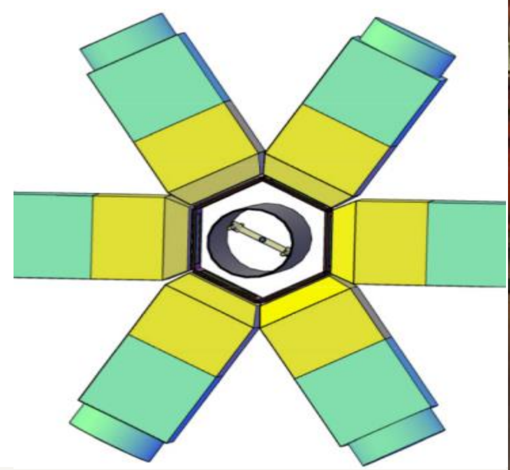
Tandetron Accelerator

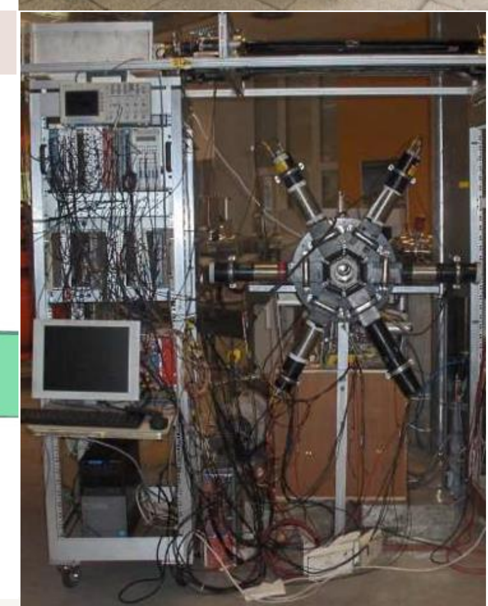
Beam current capability at 2 MV: 200 μA protons

5 arm spectrometer ^{8}Be 2016



6 arm spectrometer ^{4}He 2020



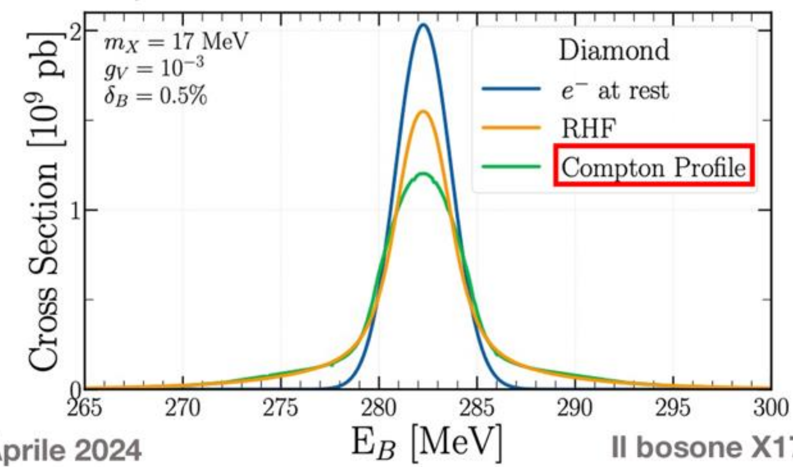


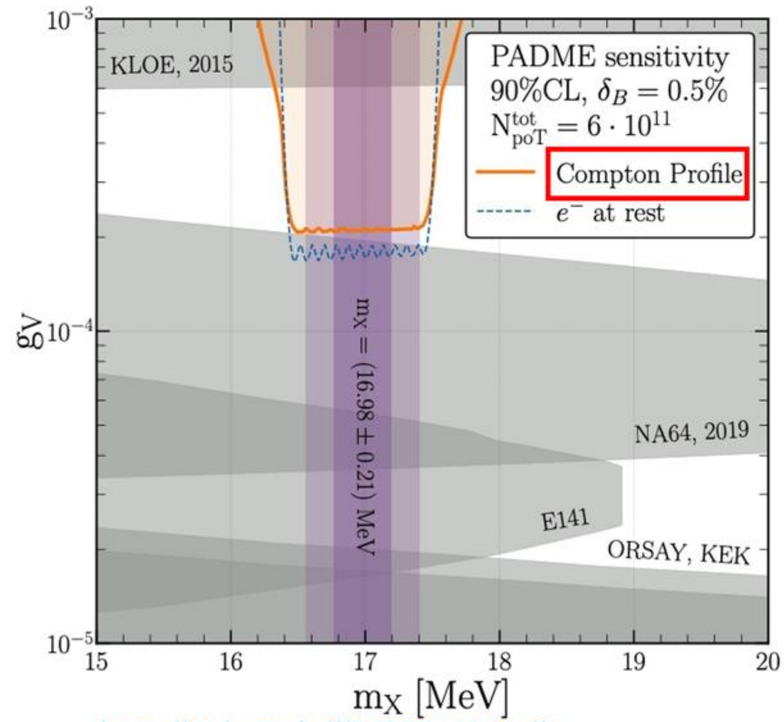
Electron motion effect in diamond

PADME Fluttuazioni dei momenti degli elettroni

INFN LNF

- Il moto degli elettroni all'interno del bersaglio di diamante provoca un allargamento dell'energia nel centro di massa.
- Questo ha diversi effetti sulla presa dati già conclusa:
  1. Abbassamento del picco di un fattore 3 e del S/B di 2
  2. La disponibilità di dati nelle bande laterali da usare per valutare il fondo si riduce di un fattore 4
  3. La sensitività dipende strettamente dall'**errore sistematico**, quest'ultimo deve essere **dell'ordine del 0.3%** per chiudere la zona dei parametri disponibile





https://arxiv.org/pdf/2403.15387.pdf

^{8}Be and ^{4}He consistency and ^{12}C

PHYSICAL REVIEW D **102,** 036016 (2020)

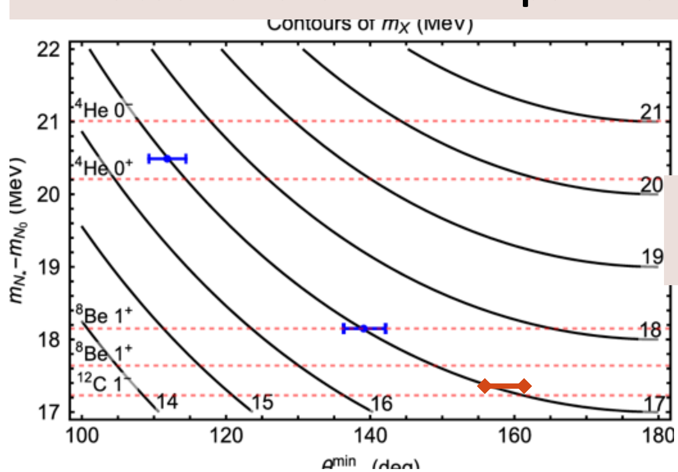
Dynamical evidence for a fifth force explanation of the ATOMKI nuclear anomalies

Feng et., Phys. Rev. D 102, 036016

Jonathan L. Feng,* Tim M. P. Tait,† and Christopher B. Verhaaren‡
Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA

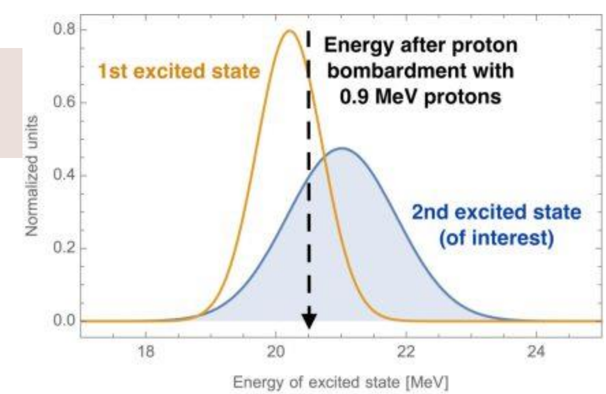
N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	✘	✔	✔	✔
^{12}C(17.23)	1^-	✔	✘	✔	✔
^{4}He(21.01)	0^-	✘	✔	✘	✔
^{4}He(20.21)	0^+	✔	✘	✔	✘

Feng et al., suggested that the X17 should be observed in ^{12}C transitions
X17 observations in ^{12}C will point to a vector or axial vector nature for X17



$$\theta_{ee}^{min} \approx 2\arcsin\left(\frac{m_{X17}}{m_{N*} - mN}\right)$$

^{12}C angle expected to be at ~160°



Can we trust the Atomki anomaly?

Evidence in favor:

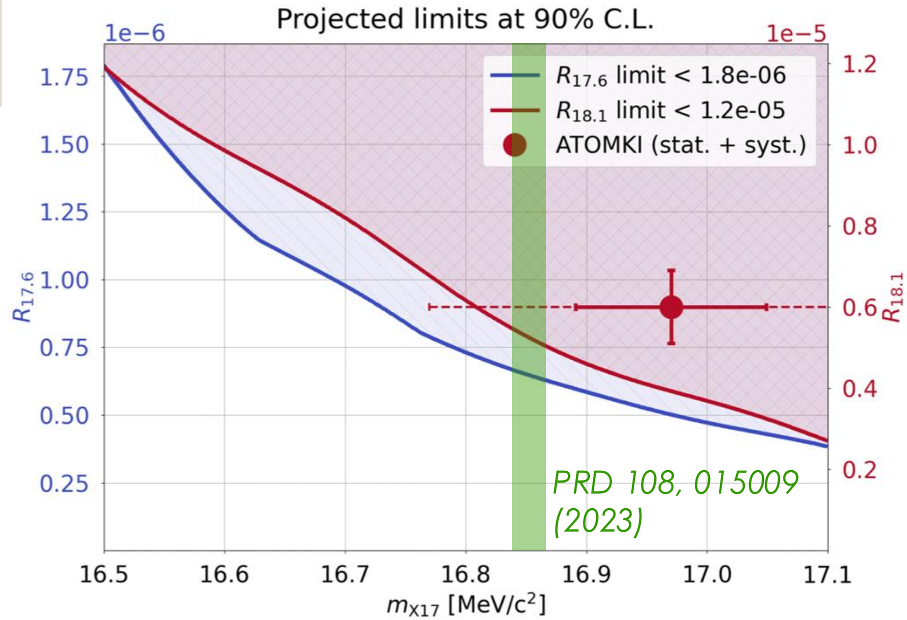
- ✓ All the three anomalies $\gtrsim 6\ \sigma$, not a statistical fluctuation
- ✓ Bumps, not general excesses. Not a single bin or a last bin effect
  - ✓ Bumps disappear $\Delta E<17$MeV and for asymmetric tracks
  - ✓ Bumps are produced by different detector configurations (2-5-6 arms)
- ✓ By introducing a single new particle, remarkable improvement of all the fits
- ✓ SM explanation theoretically strongly disfavored:
  - ✓ 8Be [Zhang+, (2017), Gysbers+, (2023)]; 4He [Viviani+, (2021)]
  - ✓ No explanation so far including all three anomalies at the same time
- ✓ ^{8}Be-^{4}He-^{12}C anomalies kinematically & dynamically consistent for V (and A): Barducci & Toni, Eur.Phys.J.C 83 (2023) 3, 230 [arXiv:2212.06453])
- ✓ For ^{12}C the effect was predicted, and confirmed by experimental data
- ✓ Additional recent evidence in GDR experiment
- ✓ Partially independent confirmation from Hanoi University

Odds against:

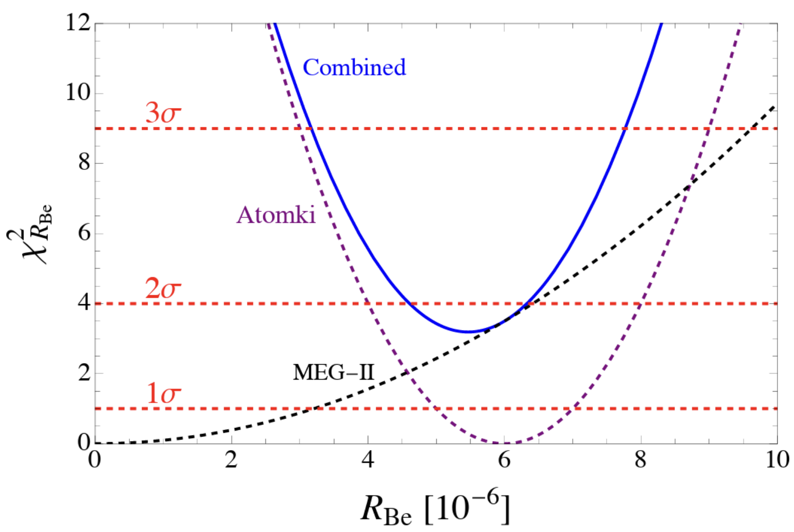
- ✓ No independent confirmation so far
- ✓ Strong constraints on the parameter space from particle physics experiments

MEG recent results

Measurement on 7Li target to reproduce 8Be ATOMKI result, no signal found



D. Barducci et al.
https://arxiv.org/pdf/2501.05507



arXiv:2411.07994

Status of theoretical understanding

Question		Answer	References
Can we explain the effect?	→	Not in within the SM	Zhang & Miller PLB 773, 2017 [nucl-th] Aleksejevs+, arXiv:2102.01127 [nucl-th] Viviani+ Phys. Rev. C 105, 014001
Is the effect due to X17?	→	Kinematic Dynamic consistent	Feng+, PRL 1604.07411 [hep-ph] Feng+, PRD 1608.03591 [hep-ph] Toni+ JHEP02(2023)154 [hep-ph]
Is X17 a vector or a scalar?	→	Vector or Axial vector	Feng+, PRD 1608.03591 [hep-ph] Toni+ JHEP02(2023)154 [hep-ph]
What is the best X17 mass value?	→	Mass fit: 16.85±0.04 Mev	B. Denton+ Phys. Rev. D 108, 015009
Is there a BSM solution?	→	Several different one	Feng+, PRL 1604.07411 [hep-ph] Phys. Rev. D 103, 055018

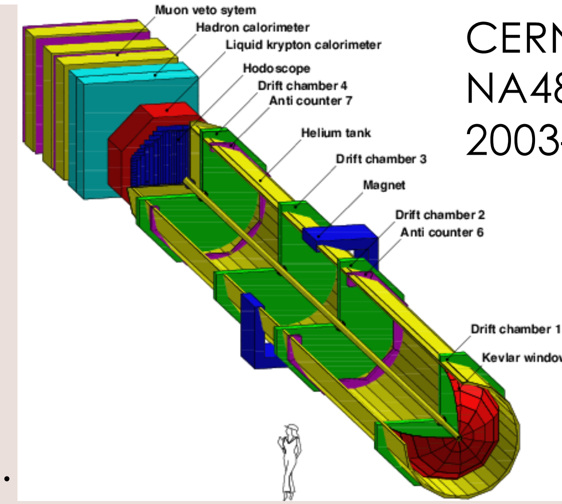
Pure dark photon: excluded NA48/2

For genuine A' $\varepsilon_f = \varepsilon q_f$ Feng et. al from the X17 rate:

$$\frac{B(^8\text{Be}^* \to {}^8\text{Be}\, X)}{B(^8\text{Be}^* \to {}^8\text{Be}\, \gamma)} = (\varepsilon_p + \varepsilon_n)^2 \frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3} \approx 5.8 \times 10^{-6}$$

[PRL 117, 071803 (2016)]

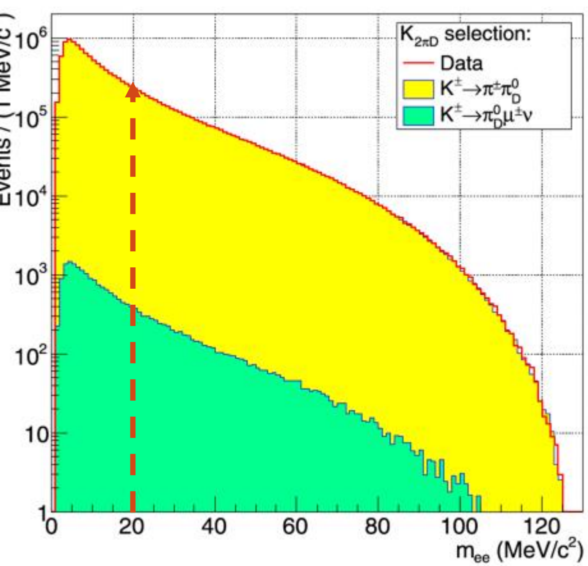
$$|\varepsilon_p + \varepsilon_n| \approx 0.011,$$

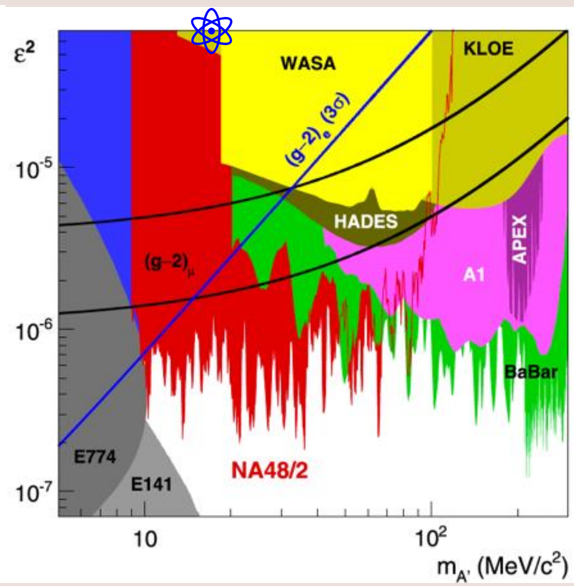


CERN NA48/2 2003-4

NA48/2 experiment limits for **A' in $K^{\pm}_{2pD}$**:
$K^{\pm} \to \pi^{\pm}\pi^0_D$ with $\pi^0_D = \gamma e^+e^-$ [PLB 746 (2015) 178-185]

In case X17 is a dark photon we should have in addition:
$\pi^0 \to \gamma X17 \to \gamma e^+e^-$
X17 should appear as a peak at 17 MeV in the m_{ee} spectrum.

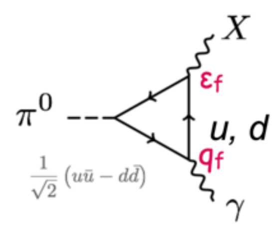




Universal coupled vector hypothesis A' firmly excluded

π-phobic/P-phobic vector particle:

[PRL 117, 071803 (2016)]



$\pi^0 \to X$ © : $|2\varepsilon_u + \varepsilon_d| < 8 \times 10^{-4}$ (NA48/2)

$B_{X17}/B_{©}$: $|\varepsilon_u + \varepsilon_d| \approx 4 \times 10^{-3}$ (Atomki)

$\varepsilon_d \approx -2\, \varepsilon_u$ (±10%) ==> $\varepsilon_p = 2\varepsilon_u + \varepsilon_d \approx 0$;

$2\varepsilon_u + \varepsilon_d \approx 0$ ==> $\pi^0 \to X$© = 0 forbidden

π-phobic vector still alive!

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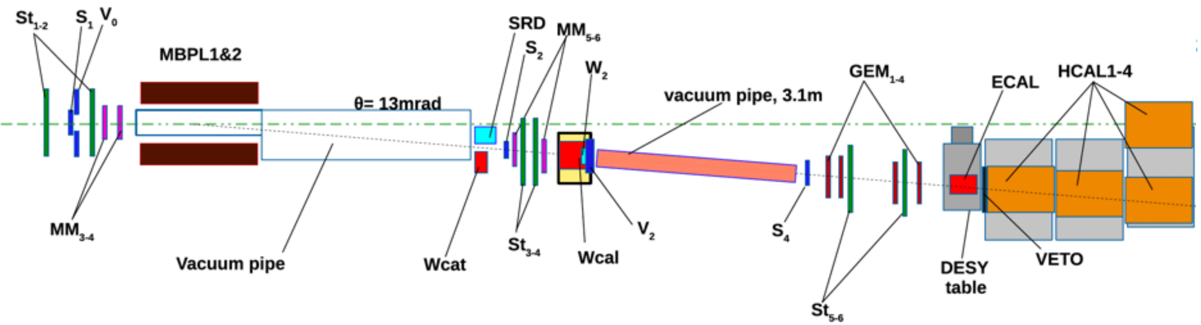
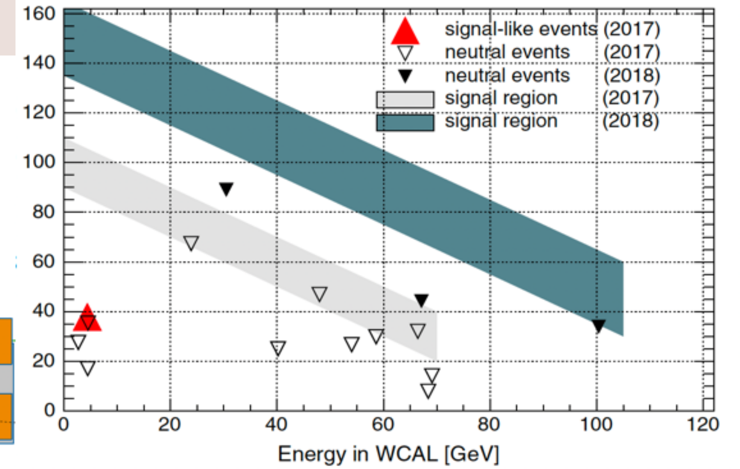
Generical vector constraints NA64

NA64 CERN NA, uses 150 GeV e^- beam on thick target.

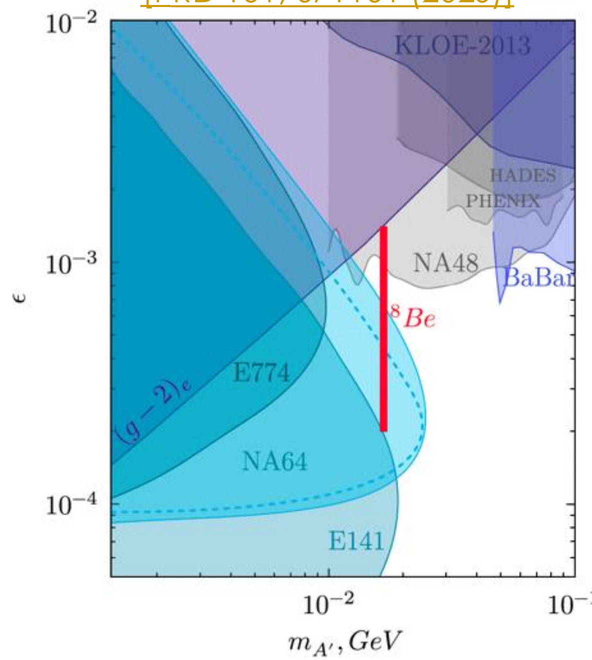
$$e^- + Z \rightarrow e^- + Z + A'(X), \qquad A'(X) \rightarrow e^+e^-$$

only e^- -> no problem with extra couplings!





[PRD 101, 071101 (2020)]



How it works:

1) Beam e^- losses part of its energy in W_{cal} before radiating.
2) After radiating A' is absrobed by W_{cal} depsiting all of its energy.
3) A' is radiated and decays after the W_{cal}
4) Energy of the ee pair from the A' decay is measured by ECal

Dump experiment:

- limited in the high ε values by X17 lifetime
- No possibility to measure mass of eventually observed events
- just counts general event excess

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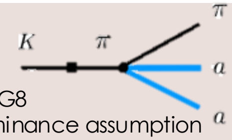
Axion like X17: excluded by NA62

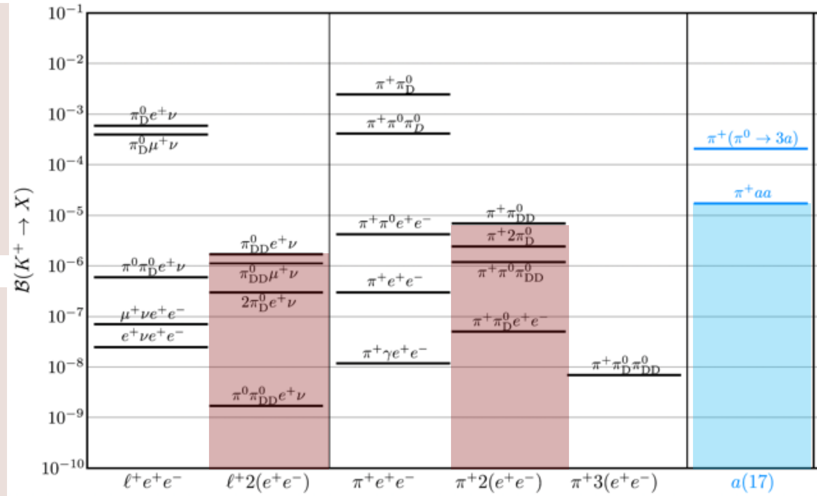
M. Pospelov noted: [PRD 105, 015017 (2022)]



χPT G8 dominance assumption

$$BR(K^+ \to \pi^+ aa) \simeq 1.7 \times 10^{-5}$$

If a=X17 X17–>e^+e^- and we have π^+4e final state
a) main SM background $K^+ \to \pi^+\pi^0_{DD}$ has lower rate
b) $m_{ee} = m_a$ is a strong kinematical constraint

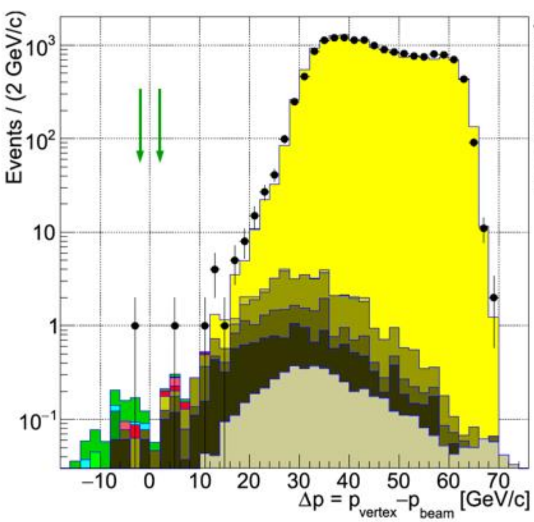


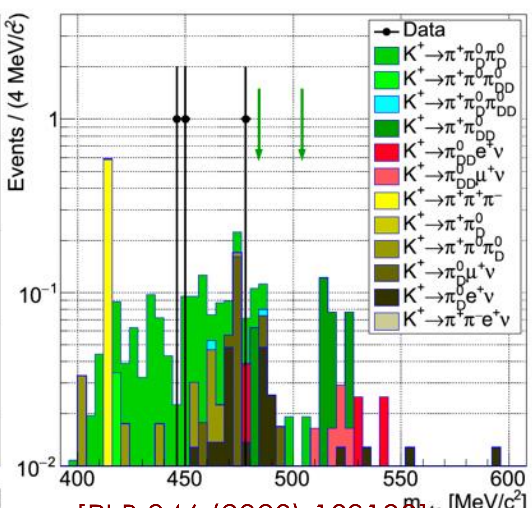
NA62 Search for $K^+ \to \pi^+ aa \to \pi^+e^+e^-e^+e^-$ [PLB 846 (2023) 138193]

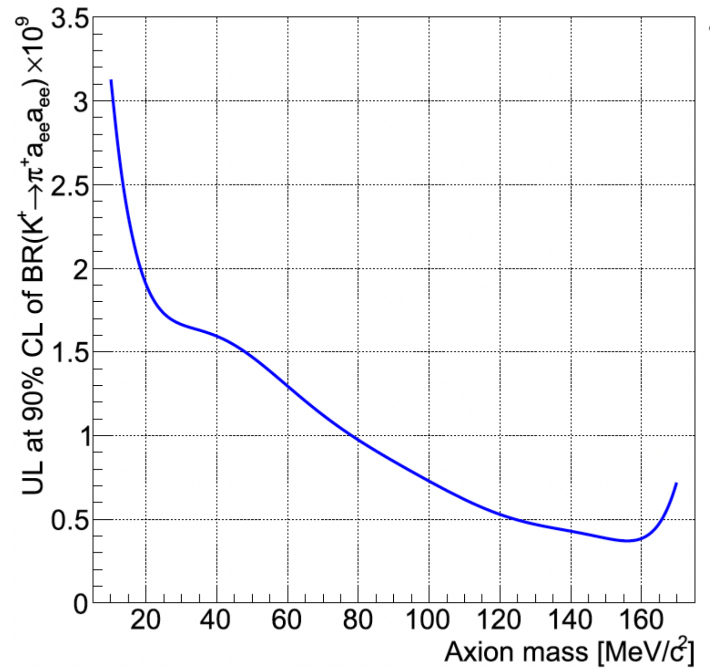
- Full NA62cdata set collected in 2017–2018
- Expected BG = 0.18±0.14 events
- No events are observed in the signal region $m_{\pi 4e} \sim m_{K+}$
- NA62 obtained:

$$BR(K^+ \to \pi^+ aa) \leq 2.1 \times 10^{-9} \ at \ 90\% \ CL$$

which rules out the QCD axion hypothesis for the X17.







[PLB 846 (2023) 138193]

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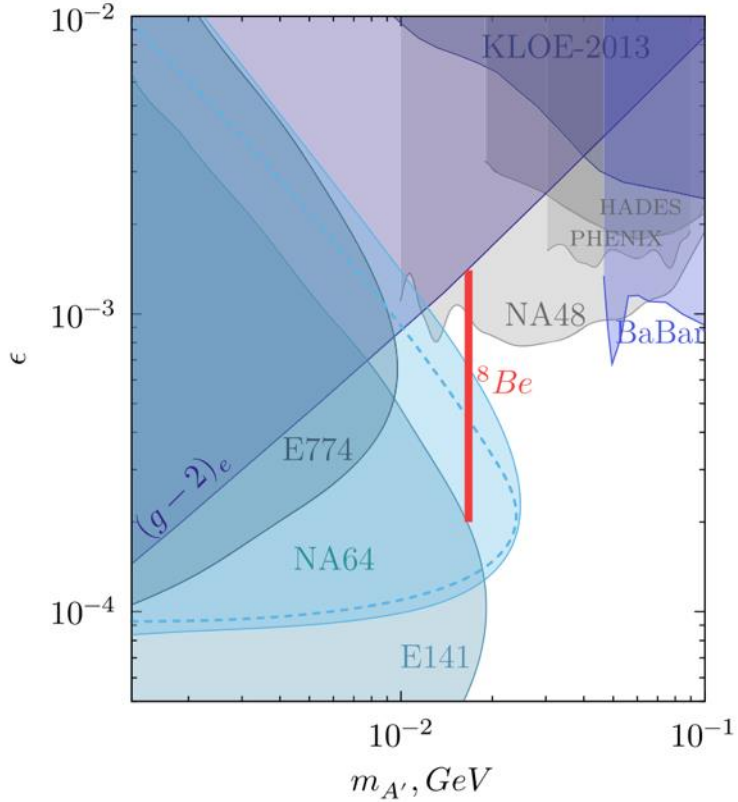
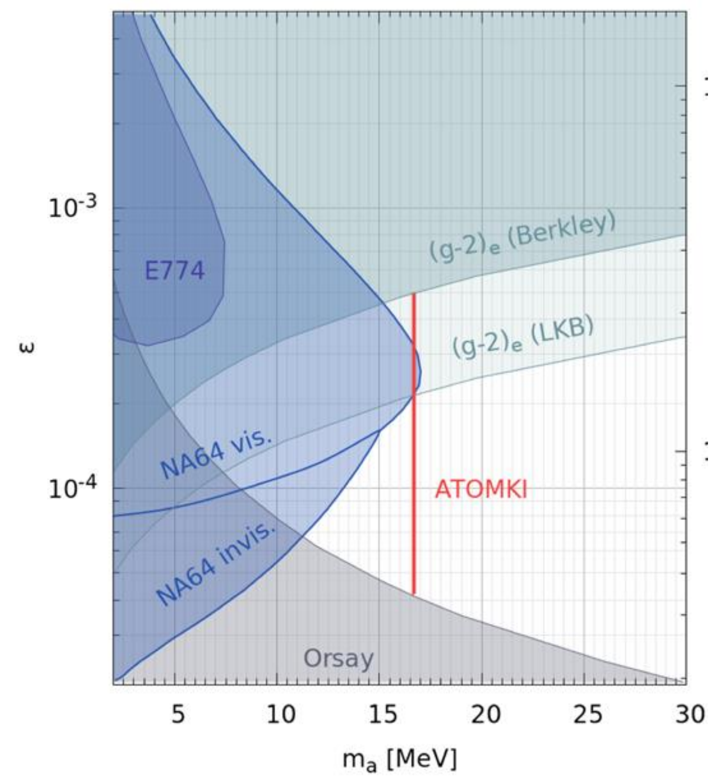
Constraints on X17: pure lepton

Phys. Rev. D 101, 071101 (R) (2020)



Phys. Rev. D 104, L111102 (2021)



X17 as a vector (V) or axial vector (A) particle:

- Theoretically favoured by ATOMKI oboservations.
- NA48/2 bound not valid for "protophobic" V and A
- $(g-2)_e$ bound weaker for vectors
- Still a lot of free parameter space for vector X17

X17 as pseudo scalar particle:

- Theoretically disfavoured by ^{12}C
- $(g-2)_e$ bound stronger for pseudo scalars
- Ruled out in pion decays ($\pi^0 \to aa$)
- Weak contraints in pure lepton-phillic models

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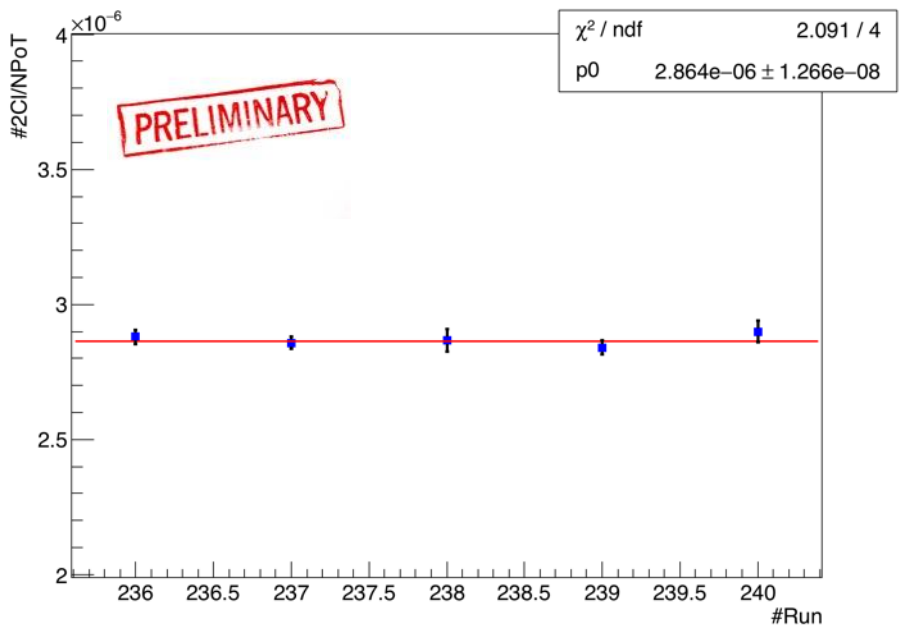
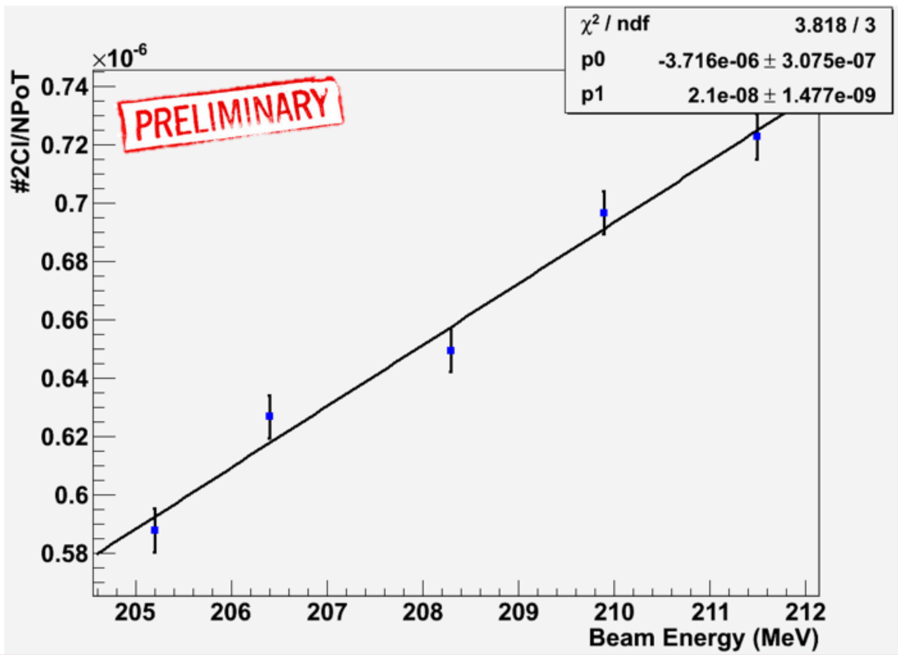
PADME out of resonance data sets

Over resonance 402 MeV



Below resonance 205-212



RMS ~0.7% over the 5 runs

Constant **fit has a good χ^2**

- No significant systematic errors

Vertical scale arbitrary

RMS <1% over the 5 energies

Good χ^2 of the linear fit

- Trend due to acceptance

- Vertical scale arbitrary:

Conclusions

8Be, 4He, 12 C GDR anomalies observed IPC at Atomki appear to be consistent with a particle physics **interpretation (X17)**
- Statistical evidence is very strong (~ 7σ for each nucleus)

SM explanations via higher order nuclear effects, interferences, higher multipoles contributions, are theoretically **(strongly) disfavoured…**

Present data from a single experiment.
- See, however, Hanoi experiment 22/08
- Additional independent validations are needed.

Intense effort for new Nucl. Phys. experiments is ongoing.
- First results expected not earlier than late 2024 early 2025.

Being based on resonant production, a particle physics experiment like **PADME will be decisive to validate/disprove the X17 hypothesis**.

Is X17 a dark matter candidate?

Is X17 is a good DM candidate? NO
- Violates the rule 1) "It should be stable" X17 decays to SM e^+e^- pairs.

Is X17 is a good WIMP candidate? NO
- X17 mass in too low for a WIMP

Is X17 a good Dark Sector candidate? maybe (too early)
- X17 mass is in the correct mass range (few MeV to < 1 GeV)
- X17 is weekly coupled to SM fermions
- X17 is similar a light mediator particle for dark sectors

Could X17 be related to the DM problem?
- If X17 it's a vector particle could act as mediator for a new $U(1)_D$ symmetry?
- In this case the DM fermions need to be at higher mass scales (M_χ >> 17MeV)

Could X17 help with other anomalies?
- If X17 it's a vector particle could help with $(g\text{-}2)_e$ and $(g\text{-}2)_\mu$ anomalies

Judging the anomaly: nature reviews

nature reviews physics

Anomalies in particle physics and their implications for physics beyond the standard model

https://doi.org/10.1038/s42254-024-00703-6

Andreas Crivellin[1,2] & Bruce Mellado[3,4]

- Experimental signature: is the experimental environment clean? Is the signal well separated from the background?
- Experimental consistency: do multiple independent measurements exist? Are they in agreement with each other?
- SM prediction: how accurate and reliable is the SM prediction? Are the results conflicting?
- Statistical significance: how sizable are the deviations from the SM predictions?
- New-physics explanation: are there models that can naturally account for the anomaly? Are they in conflict with other observables?
- Consistent connection: are there connections to other anomalies via the same new particle or model? How direct is this connection?

Table 3 | Anomalies assessed (positively, negatively or neutrally) against various criteria

Anomaly	Experimental signature	Experimental consistency	SM prediction	Statistical significance	New-physics explanation	Consistent connection
a_μ	+	0*	–	+	0	–
X17	+	0	–	+	0	0
ν_e	–	0	–	+	–	–
β	+	0	0	–	+ (–)**	+
$M \to mm'$	0	+	–	0	–	0
$b \to s\ell^+\ell^-$	+	+	0	+	0	+
$R(D^{(*)})$	–	+	+	–	–	+
m_W	0	–	+	+	+	+
$e\mu\,(+b)$	0	+	0	+	0	+
$\gamma\gamma$	+	+	+	0	+	+
$jj(jj)$	0	+	+	0	0	–
$pp \to e^+e^-$	0	+	+	–	0	–

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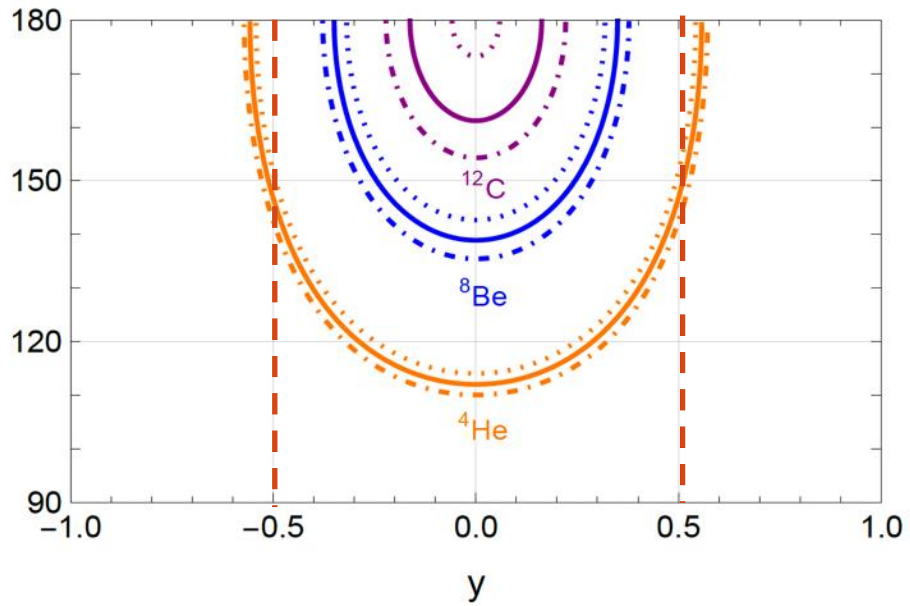
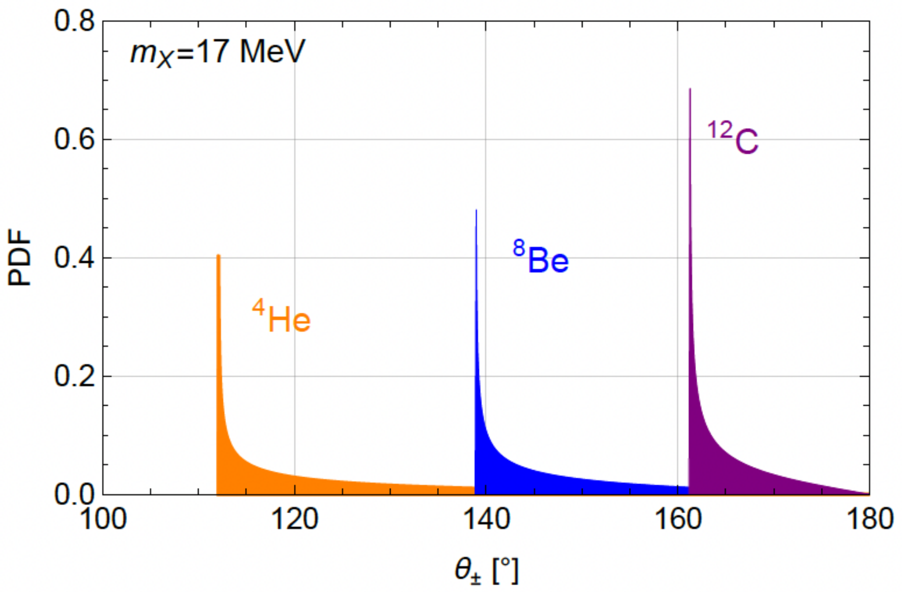
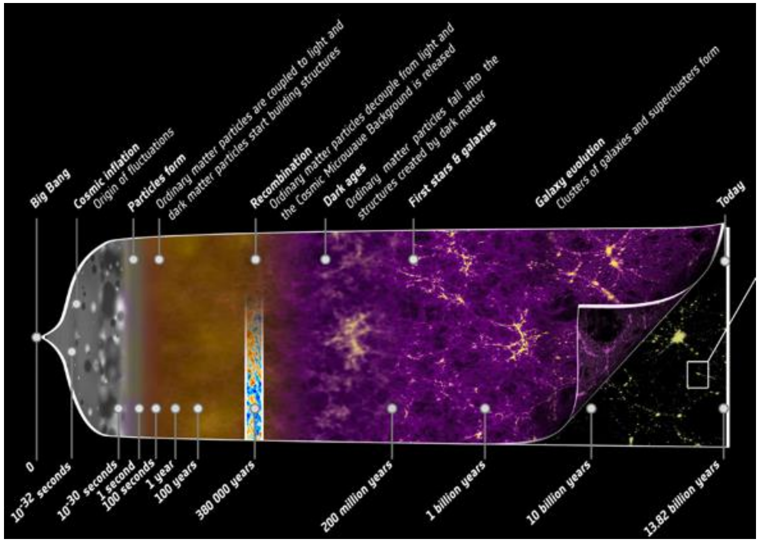
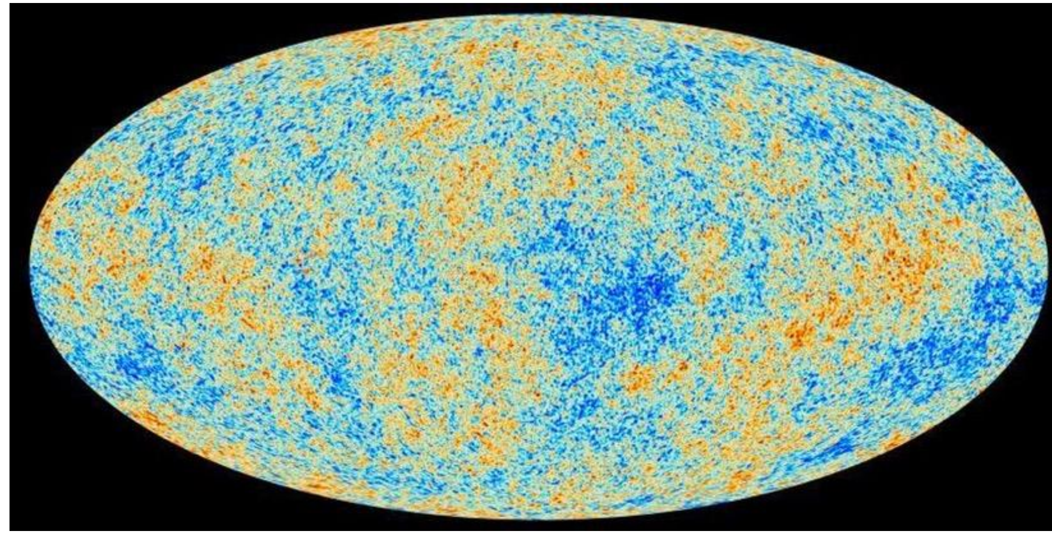
Kinematics and the y cut.





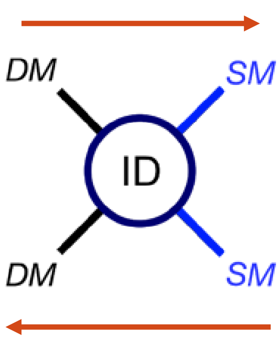
1. How Dark Matter was born





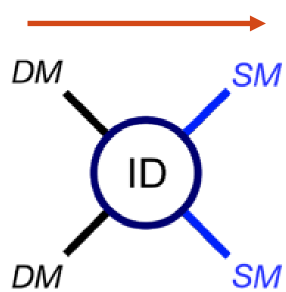
Universo caldo

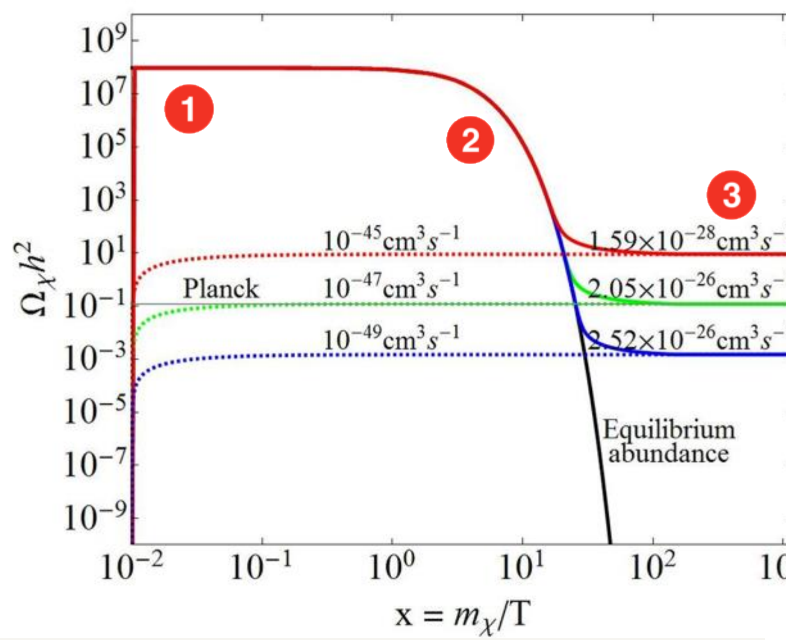
① $T>M_{DM}$ $x<1$



Cooled Universe

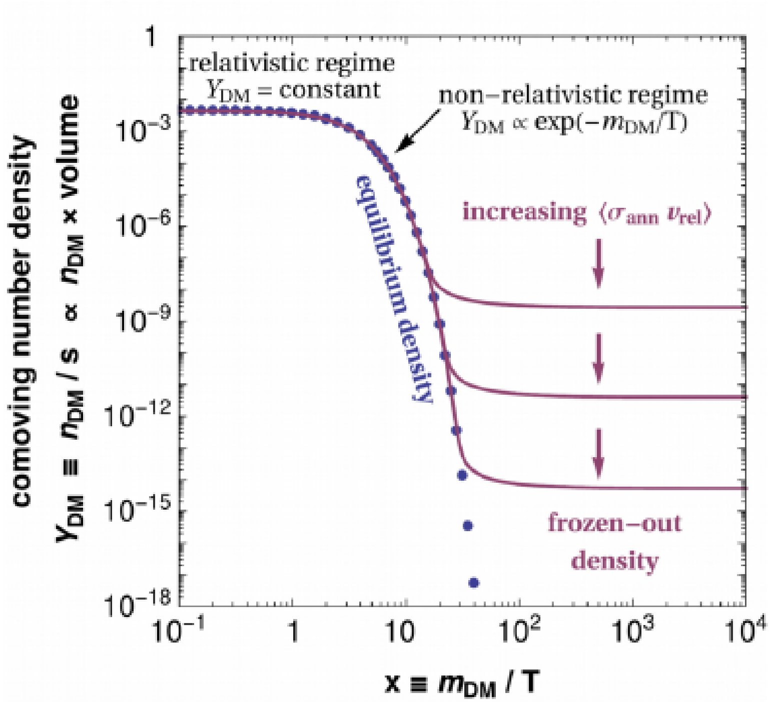
② $T<M_{DM}$ $x>1$





③ DM density too low, DM production stops
Freeze out produced a relic DM density

2. Non vogliamo nuove forze!



Dal freeze-out possiamo stabilire

$$\Omega_{DM}h^2 \sim \frac{3 \cdot 10^{-27} cm^3 s^{-1}}{\langle\sigma v\rangle}$$

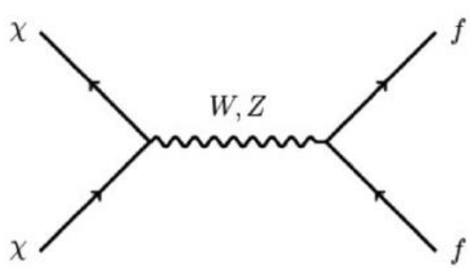
Dalle misure di CMB sappiamo che:

$\Omega_{DM}h^2 \simeq 0.1$, hence:
$\langle\sigma v\rangle \simeq 3 \cdot 10^{-26} cm^3 s^{-1}$

Senza introdurre una nuova forza ma utilizzando l'interazione debole che già abbiamo!

$$\langle\sigma v\rangle_{\rm WIMP} \sim 3 \times 10^{-26} {\rm cm^3 s^{-1}} \left(\frac{\rm TeV}{m_\chi}\right)^2$$

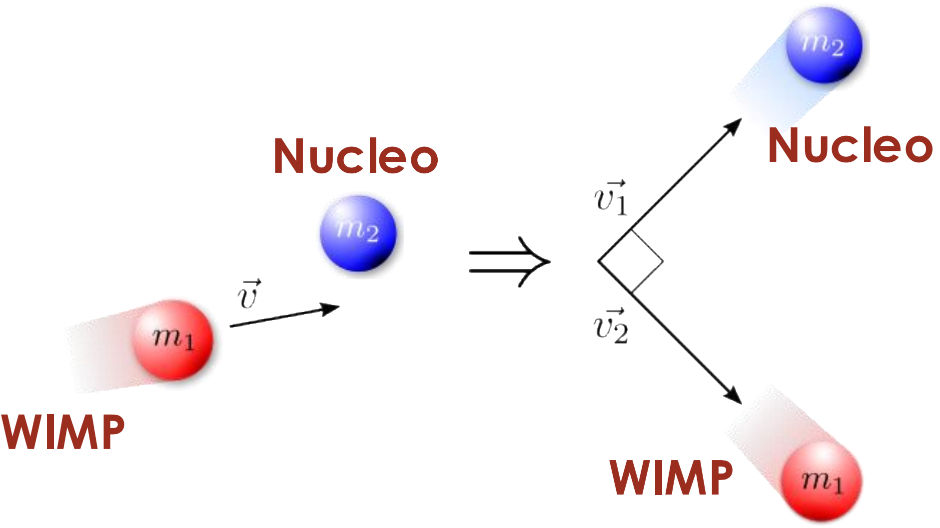
DM Wimp



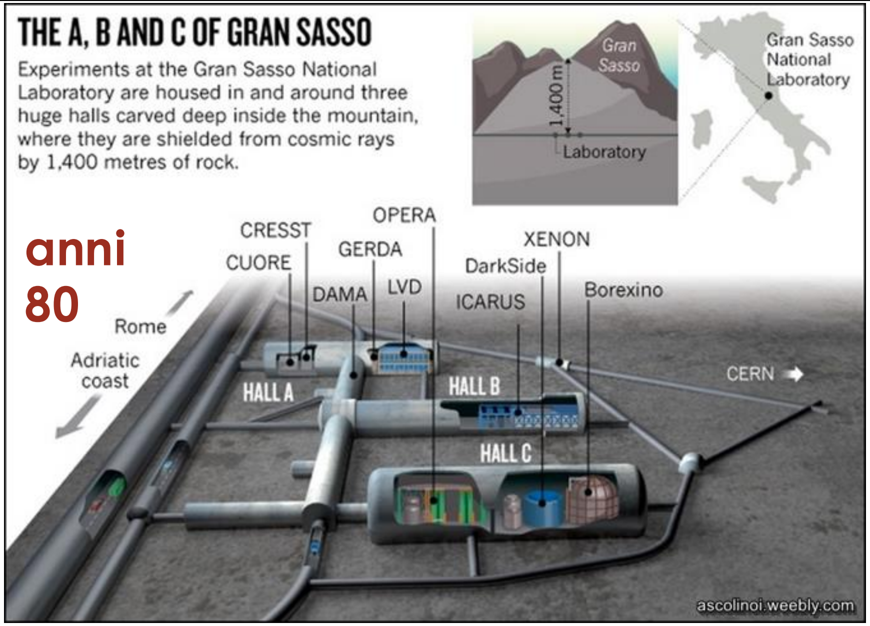
Materia ordinaria

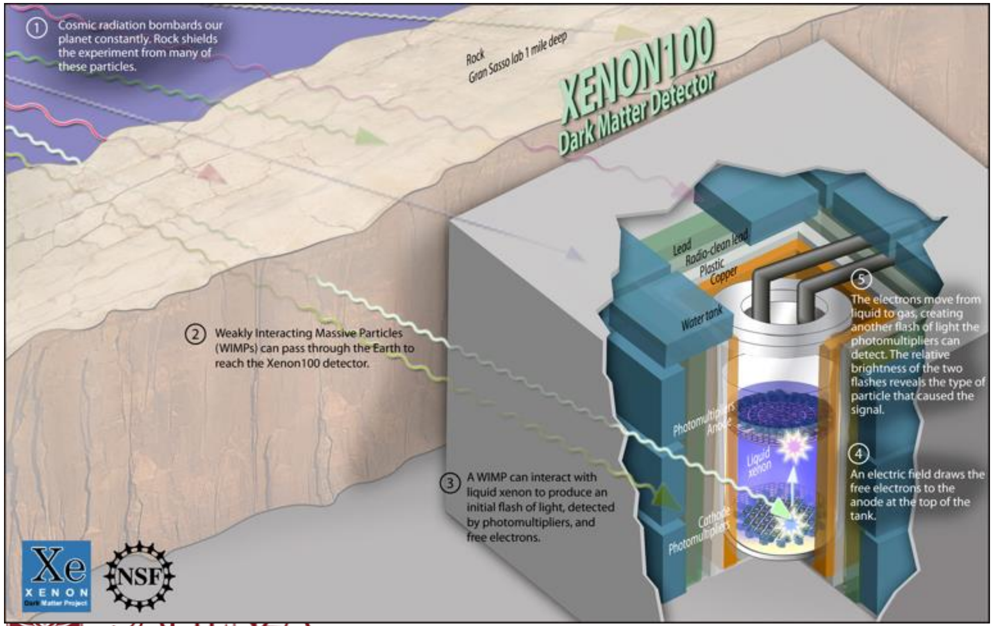
Ci serve soltanto una **particella pesante** con interazione debole ma **non nuove forze**!
Chiameremo questa **particella WIMP.**

Ricerca diretta di DM - Wimps



anni 80

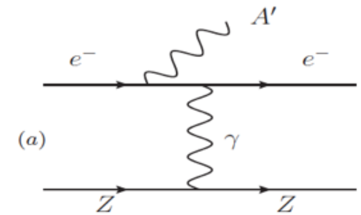




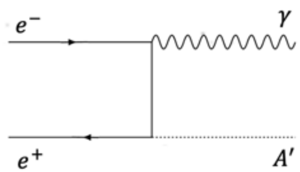
DS search: experimental approaches

- **Electron beam experiments production**
  - **Just A'-strahlung**
- **Positron based experiments**
  - **A'-strahlung**
  - **Associated production** $e^+e^- \to A'(\gamma)$
  - **Resonant production** $e^+e^- \to e^+e^-$
- **Visible decays**: $A' \to e^+e^-$ $A' \to \mu^+\mu^-$
  - **Thick target electron/protons** beam is absorbed (NA64, old dump experiments)
  - **Thin target** searching for bumps in ee invariant mass
- **Invisible searches:** $A' \to \chi\chi$
  - **Missing energy/momentum**: A' produced in the interaction of an electron beam with **thick/thin target** (NA64/LDMX)
  - **Missing mass**: $e^+e^- \to A'(\gamma)$ search for invisible particle using kinematics (Belle II, **PADME**)

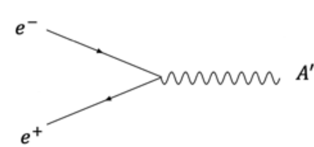
Brems.



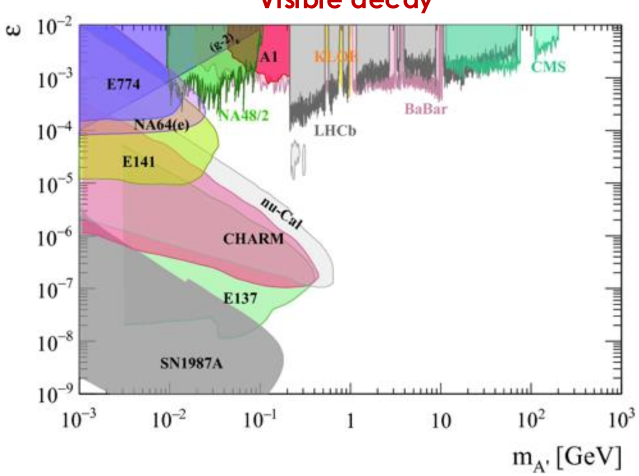
Associated production



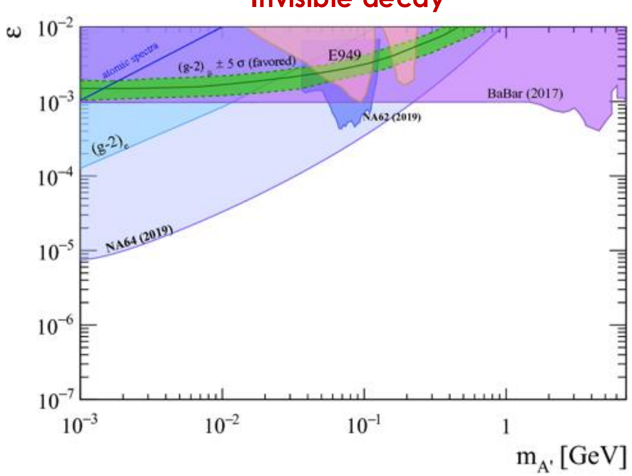
Resonant

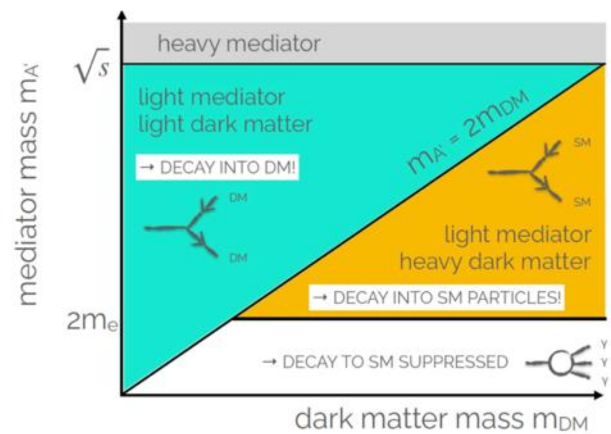


Visible decay



Invisible decay



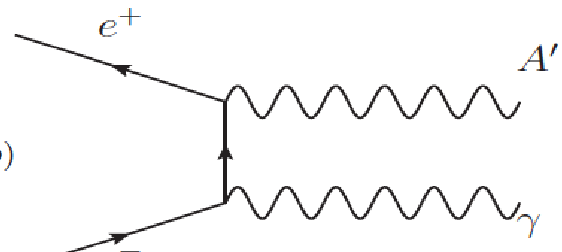


How can we make our life easier?

- We need higher production cross section!

Positron beams

(b)



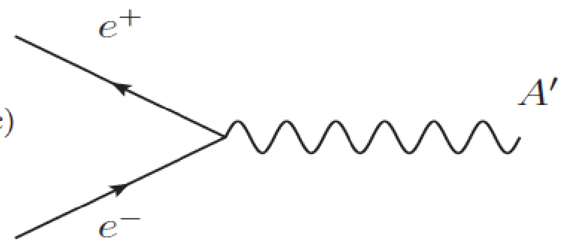
- Can move from associated to resonant production
  - b) Radiative annihilation $O(\alpha^2)$

$$\sigma_{nr} = \frac{8\pi\alpha^2}{s}\left[\left(\frac{s-m_{A'}^2}{2s}+\frac{m_{A'}^2}{s-m_{A'}^2}\right)\log\frac{s}{m_e^2}-\frac{s-m_{A'}^2}{2s}\right]$$

  - c) Resonant annihilation $O(\alpha)$

$$\sigma_{\rm res}(E_e) = \sigma_{\rm peak}\frac{\Gamma_{A'}^2/4}{(\sqrt{s}-m_{A'})^2+\Gamma_{A'}^2/4} \qquad \sigma_{\rm peak} = 12\pi/m_{A'}^2$$

(c)



- Profit for a higher production in a tiny mass region

$$\mathcal{N}_{X_{17}}^{\rm Vect.} \simeq 1.8\cdot 10^{-7} \times \left(\frac{g_{ve}}{2\cdot 10^{-4}}\right)^2 \left(\frac{1\ {\rm MeV}}{\sigma_E}\right) \qquad \mathcal{N}_{X_{17}}^{\rm ALP} \simeq 5.8\cdot 10^{-7} \times \left(\frac{g_{ae}}{{\rm GeV}^{-1}}\right)^2 \left(\frac{1\ {\rm MeV}}{\sigma_E}\right)$$

X17 observables at PADME

Several different observables can be used with different systematics

Osservabili:

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

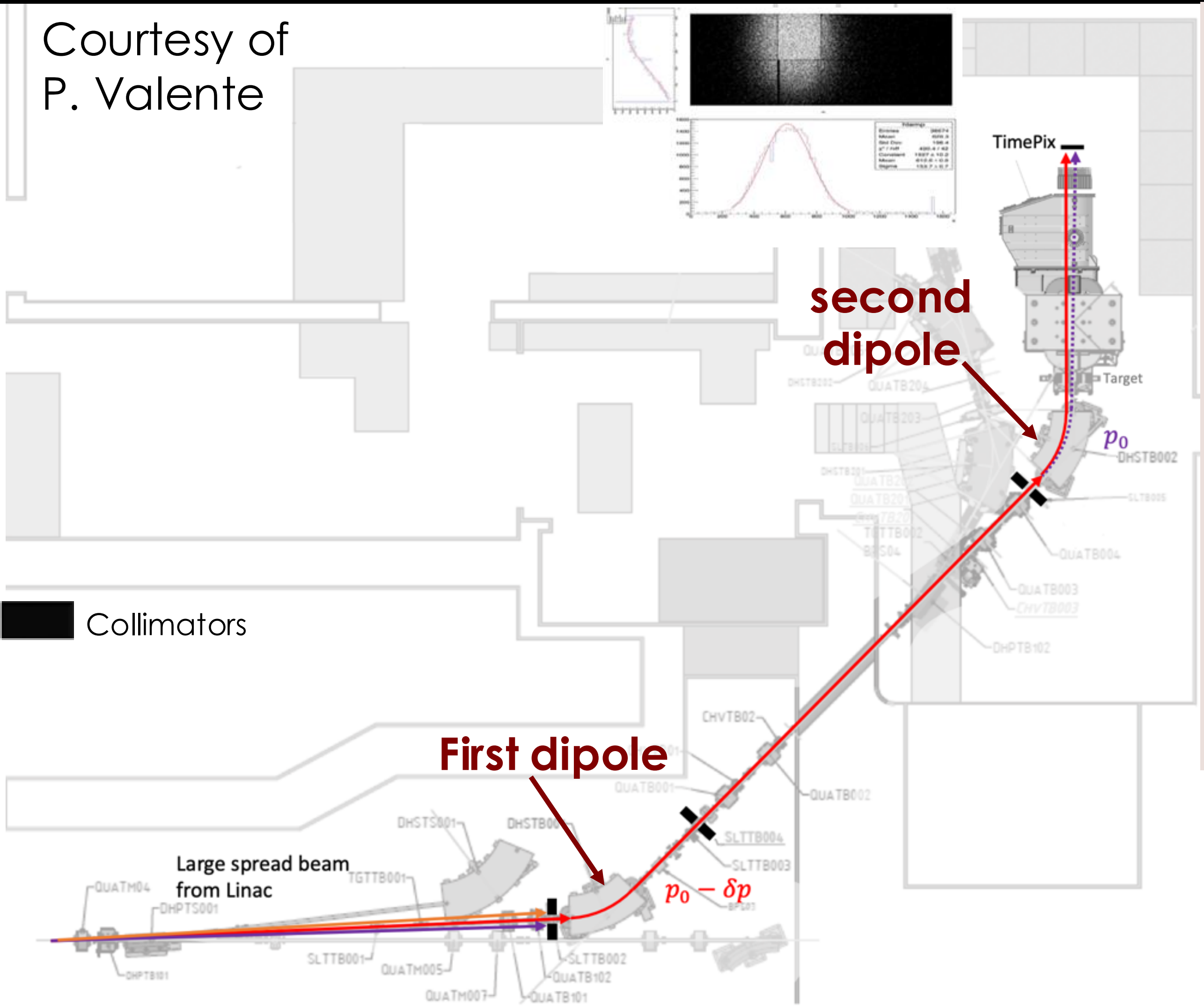
N(2cl)/NPoT ⟹ existence of X17
High statistical significance (small sensitivity loss due to small $\gamma\gamma$ BG)
No ETag related systematic errors

N(ee)/N($\gamma\gamma$) ⟹ existence of X17
Lower statistical significance due to smaller $\gamma\gamma$ 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 and N_{PoT}
$N_{\gamma\gamma}/N_{PoT}$ ⟹ pseudo-scalar nature of X_{17}
Systematic errors due to ETag tagging efficiency stability and N_{PoT}

Obtaining energy steps and resolution

Courtesy of
P. Valente



Use the first dipole magnet and collimators to select energy

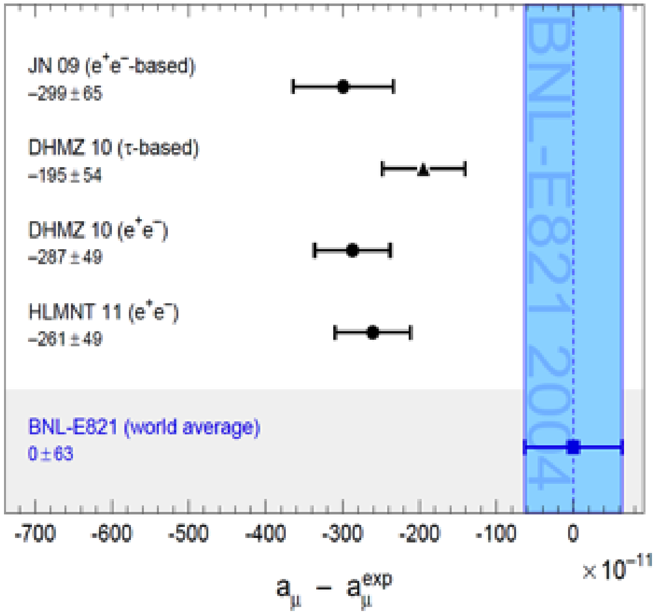
- dp ∝ collimator aperture.

Change the first dipole magnet current to change the energy

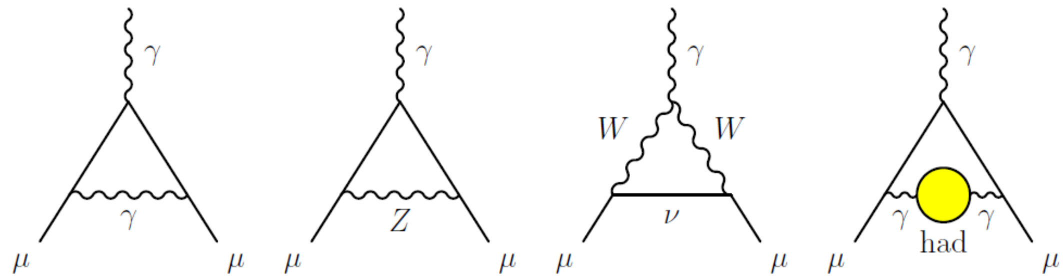
Correct the trajectory using second dipole to put the beam back on axis at PADME

Measure the displacement at the target and timePix to measure the energy step performed

Muon g-2 anomaly



g-2 in the standard model

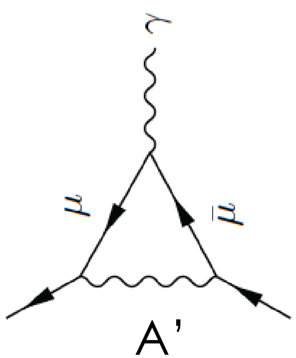


About 3σ discrepancy between theory and experiment (3.6σ, if taking into account only e+e–>hadrons)

Contribution to g-2 from dark photon

Additional diagram with dark photon exchange can fix the discrepancy (with sub GeV A' masses)

g-2 and A'

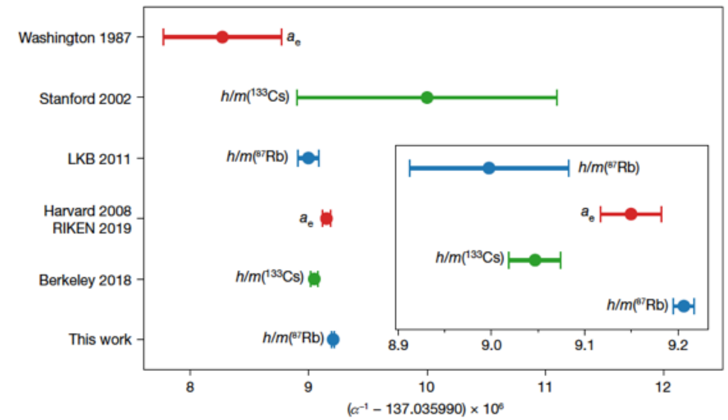


$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1\text{–}2 \cdot 10^{-3}$ and $m_V \sim 10\text{–}100\,\text{MeV}$, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark

g-2e anomaly

- Significant discrepancy in the last two results on the α determination
- Produce a modified $(g\text{-}2)_e$ exclusion which allows a region of existence of X17

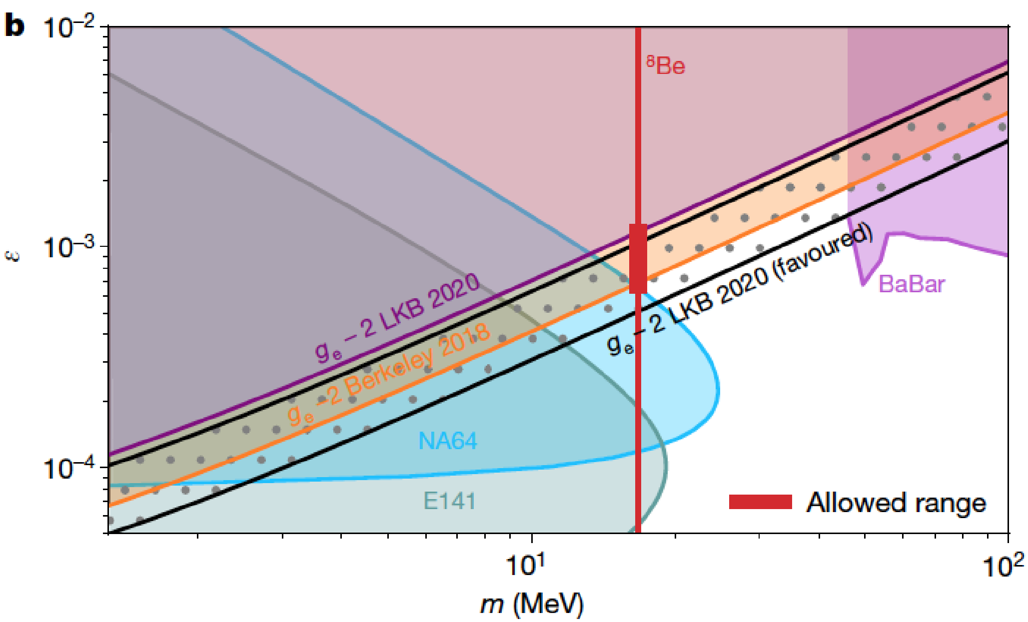


$\alpha^{-1} = 137.035999206(11)$.

The uncertainty contribution from the ratio $h/m(^{87}Rb)$ 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 $a_{e,exp}$ (ref. [9]) gives $\delta a_e = a_{e,exp} - a_e(\alpha_{LKB2020}) = (4.8 \pm 3.0) \times 10^{-13}$ $(+1.6\sigma)$, whereas comparison with caesium recoil measurements gives $\delta' a_e = a_{e,exp} - a_e(\alpha_{Berkeley}) = (-8.8 \pm 3.6) \times 10^{-13}$ (-2.4σ). The uncertainty on δa_e is dominated by $a_{e,exp}$.



Finally, the anomaly reported in the angular distribution of positron–electron pairs (e^+e^-) produced in ^{8}Be nuclear transitions[4] could be explained by the emission of a hypothetical protophobic gauge boson X with a mass of 16.7 MeV followed by the decay $X \to e^+e^-$ (ref. [30]). The X boson is parameterized by a mixing strength ε with electrons and a non-zero mass m_X. Figure 4b presents the exclusion space for those parameters. At 16.7 MeV, the upper limit of ε is set by the $g_e - 2$ value of the electron and its lower limit by electron beam dump experiments (E141[31] and NA64[32] collaborations). Recently, new results from the NA64 collaboration[33] excluded ε values lower than 6.8×10^{-4}. Because vector coupling implies $\delta a_e > 0$, the result from a caesium recoil experiment imposes strong constraints on ε; combined with the NA64 result, it rejects pure vector coupling of X(16.7 MeV) at 90% confidence level. By contrast, our measurement of α gives $\delta a_e > 0$ and favours pure vector coupling with $\varepsilon = (8 \pm 3) \times 10^{-4}$, which could explain the ^{8}Be anomaly.