Search for a new 17 MeV resonance via e^+e^- annihilation with the PADME experiment

Tommaso Spadaro* on behalf of the PADME collaboration

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Light bosons - Historical perspective

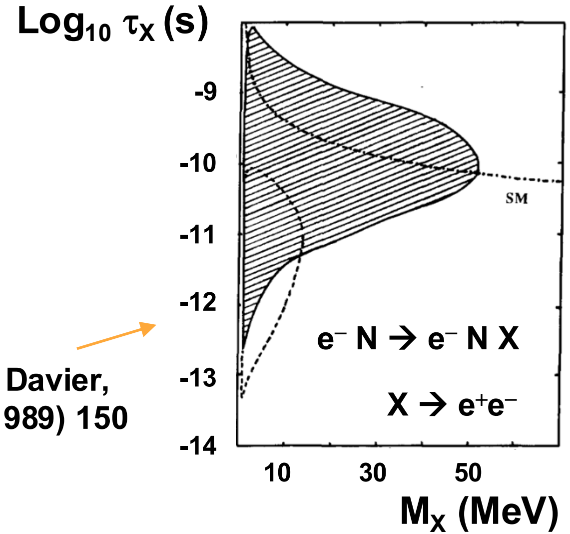
In the 80's, an ultra-light (1--100 MeV) boson was a new-physics possibility

Masses above 200 MeV excluded by J/Ψ, ϒ → γa and K decays

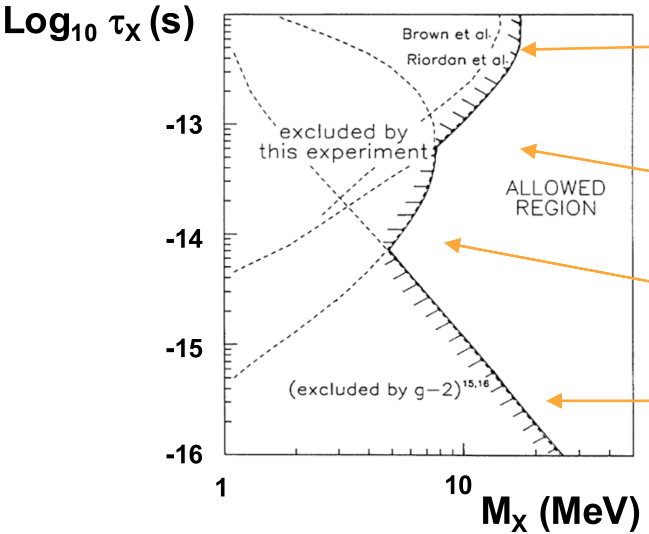
Excess of e^+e^- events observed at M ~ 1.8 MeV with U Curium collisions at GSI

PRL 51 (1983) 2261, PLB 137 (1984) 41, PRL 54 (1985) 1761

Beam-dump experiments kicked in, excluding masses M_X < 10 MeV for $\tau_X > 10^{-15}$ s



Saclay: M. Davier, PLB 229 (1989) 150



FNAL E605: Brown et al. PRL 57, 2101 (1986)

SLAC: Riordan, et al. PRL 59 (1987) 755

FNAL E774: Bross, et al. PRL 67 (1991) 2942

$(g\text{-}2)_e$ at 10^{-7} Van Dyck, et al. PRL 38 (1977) 310

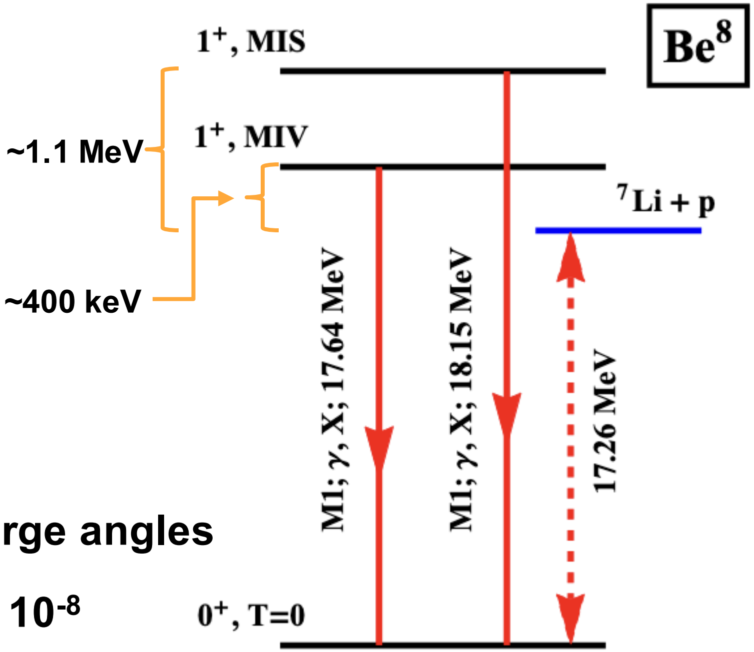
Historical perspective – nuclear techniques

Excess disproved but triggered part of the nuclear physics community

To explore up to 20 MeV, $\tau < 10^{-15}$ s, focused on internal-pair conversion (IPC) decays of strongly bound excited nuclei, e.g.: p $^{7}Li \rightarrow {}^{8}Be^* \rightarrow \gamma^* \rightarrow e^+e^-$

IPC spectroscopy has a long tradition
[M.E. Rose, PR 76 (1949) 678]

- **IPC ~ 10^{-3}—10^{-4} of γ decay and exp.ly clean**
- **Angular correlation sensitive to M/E poles**
- **Especially good at high energy, low poles**



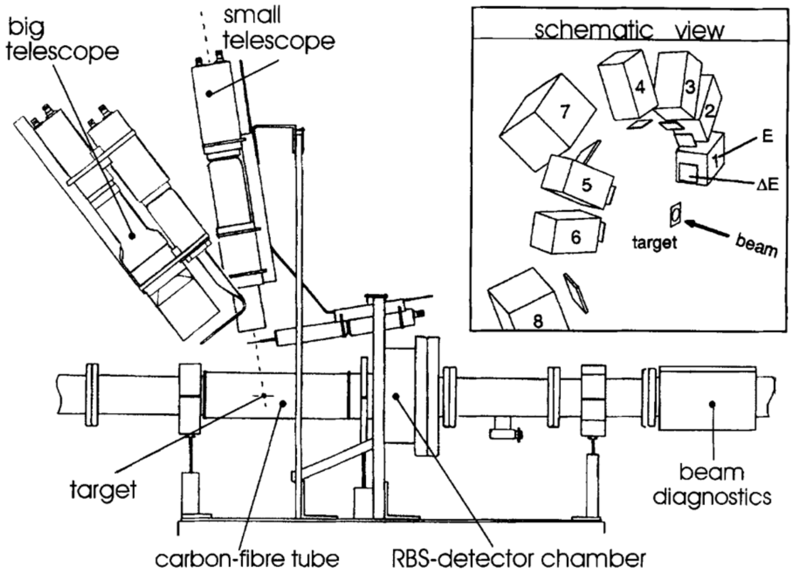
Advantages of ^{8}Be excited states:

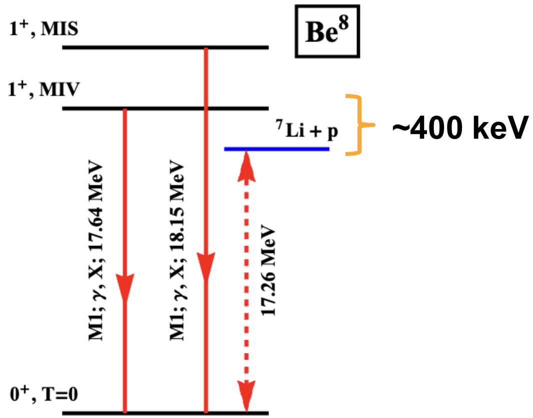
1. **Among the highest γ-transition energies**
2. **Excited states widths small (10, 140 keV)**
3. **Opening angles for M1 transitions fall steep at large angles**

B($^{8}Be^* \rightarrow {}^{8}Be\ \gamma$) ~ 1.4 x 10^{-5}, B($^{8}Be^* \rightarrow {}^{8}Be\ e^+e^-$) ~ 5.5 x 10^{-8}

Historical perspective – first observations

Using 441 keV protons to excite the 17.64 MeV transition an excess in the e^+e^- opening angle distribution was found [F.W.N. de Boer PLB 388 (1996) 235]





Excess later disproved
[Tilley, et al., NPA 745 (2004) 155]

For reaction (a) electron/positron pair decay from ^{8}Be*(17.6, 18.15) $J^\pi = 1^+$ levels was measured in a search for M1 de-excitation via pair production that would indicate the involvement of a short-lived isoscalar axion 4–15 MeV/c^2 in mass. While an anomaly is seen in the pair production, the overall results are not consistent with the involvement of a neutral boson [1996DE51,1997DE46,2001DE11]. Limits of $< 10^{-3}$ [1990DE02] and 4.1×10^{-4} [2001DE11] were obtained for the axion to γ-ray ratio.

Historical perspective – recent developments

The field developed in experimental accuracy [Gulias et al., NIM A 808 (2016) 21, refs therein]

The ATOMKI five-harm spectrometer is a step forward

- Improved angular acceptance: range and efficiency uniformity
- Improved calibration against known signals
- Better energy resolution
- Improvement in target preparation (thickness, substrate, holder)

Calorimeter: ~ 82 x 86 x 80 mm^3 plastic scintillator, δ_E/E ~ 4% @ 17.6 MeV

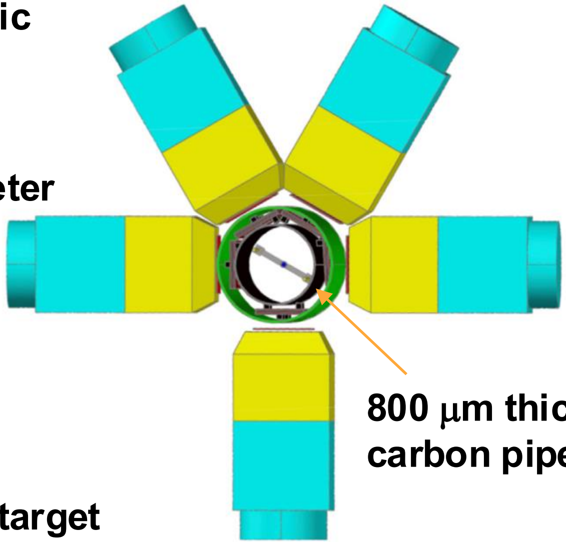
PID: 52 x 52 x 1 mm^3 plastic scintillator in front of calorimeter

Tracker: MWPC Ar:CO2 80:20, ~1% X_0, Provide $\delta\theta \sim 2^o$

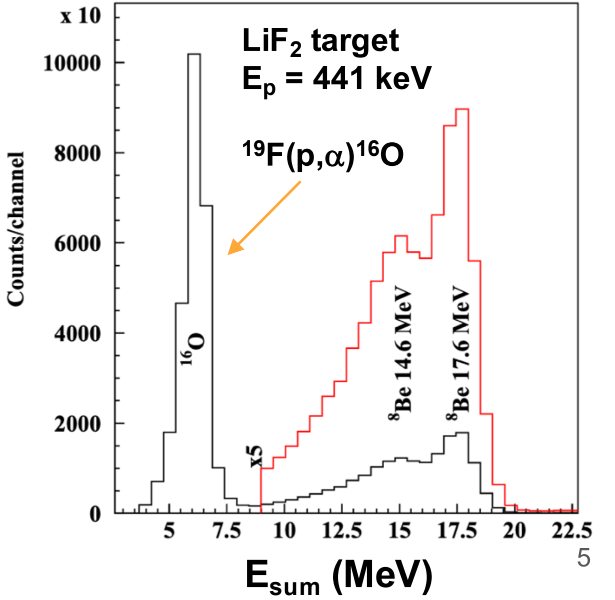
Target: 1 mm^2 LiF_2, evaporated on 10 μm Al

Faraday cup 150 mm downstream of target

γ ray counter, clover Ge with BGO veto, 250 mm downstream of target



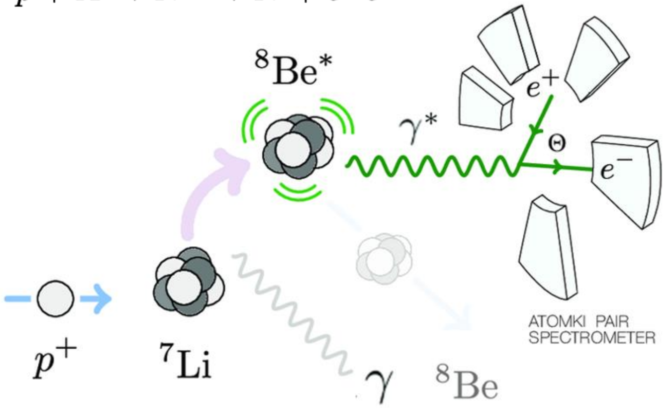
800 μm thick carbon pipe



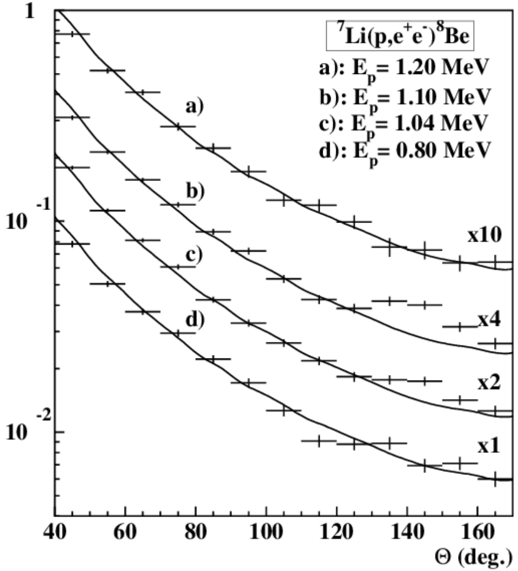
IPC Results – ^{8}Be*…

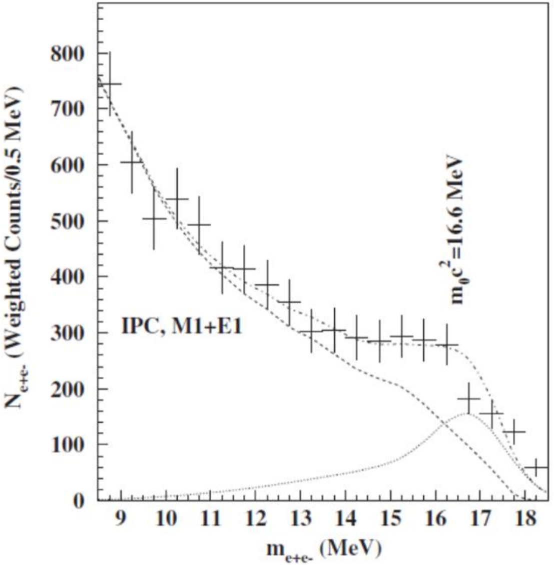
Anomalies in IPC angular correlations revealed, attributed to decays of ^{8}Be*

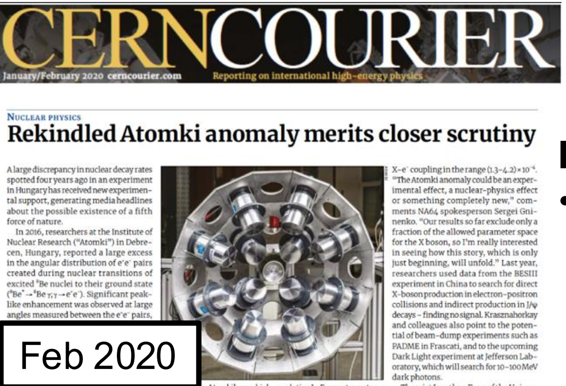
$$p + A \rightarrow N^{\star} \rightarrow N + e^{+}e^{-}$$



PRL 116 (2016) 042501







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Nuclear physics

Rekindled Atomki anomaly merits closer scrutiny

A large discrepancy in nuclear decay rates spotted four years ago in an experiment in Hungary has received new experimental support, generating media headlines about the possible existence of a fifth force of nature.

In 2016, researchers at the Institute of Nuclear Research ("Atomki") in Debrecen, Hungary, reported a large excess in the angular distribution of e⁺e⁻ pairs created during nuclear transitions of excited ^{8}Be nuclei to their ground state (^{8}Be* → ^{8}Be γ; γ → e⁺e⁻). Significant peak-like enhancement was observed at large angles measured between the e⁺e⁻ pairs,

X–e⁻ coupling in the range (1.3–4.2) × 10^{-4}. "The Atomki anomaly could be an experimental effect, a nuclear-physics effect or something completely new," comments NA64 spokesperson Sergei Gninenko. "Our results so far exclude only a fraction of the allowed parameter space for the X boson, so I'm really interested in seeing how this story, which is only just beginning, will unfold." Last year, researchers used data from the BESIII experiment in China to search for direct X-boson production in electron–positron collisions and indirect production in J/ψ decays – finding no signal. Krasznahorkay and colleagues also point to the potential of beam-dump experiments such as PADME in Frascati, and to the upcoming Dark Light experiment at Jefferson Laboratory, which will search for 10–100 MeV dark photons.

Feb 2020

Interpreted with a new particle of mass:

- ^{8}Be: $M_X = (16.70 \pm 0.35_{stat} \pm 0.5_{syst})$ MeV

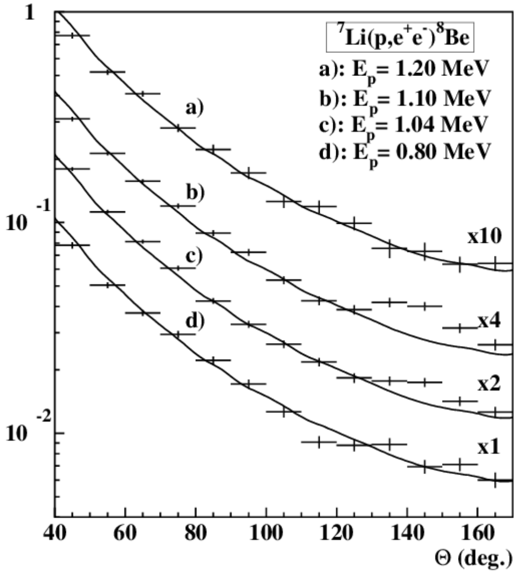
^{8}Be result confirmed w upgraded 6-arm spectrometer, J Phys Conf Ser 1056 (2018) 012028

IPC Results – …and ^{4}He*

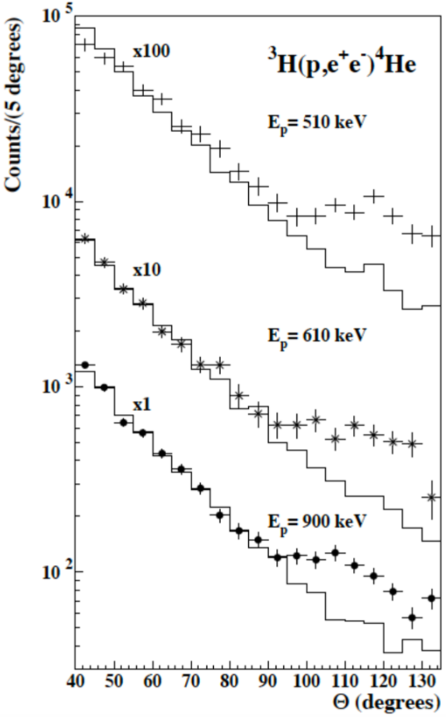
Anomalies in IPC angular correlations revealed, attributed to decays of ^{8}Be*, ^{4}He*

$$p + A \to N^\star \to N + e^+e^-$$

PRL 116 (2016) 042501



PR C 104 (2021) 044003



Interpreted with a new particle of mass:

- ^{8}Be: $M_X = (16.70 \pm 0.35_{stat} \pm 0.5_{syst})$ MeV
- ^{4}He: $M_X = (16.94 \pm 0.12_{stat} \pm 0.21_{syst})$ MeV

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NUCLEAR PHYSICS

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X–e^- coupling in the range $(1.3–4.2)\times10^{-4}$. "The Atomki anomaly could be an experimental effect, a nuclear-physics effect or something completely new," comments NA64 spokesperson Sergei Gninenko. "Our results so far exclude only a fraction of the allowed parameter space for the X boson, so I'm really interested in seeing how this story, which is only just beginning, will unfold." Last year, researchers used data from the BESIII experiment in China to search for direct X-boson production in electron–positron collisions and indirect production in J/ψ decays – finding no signal. Krasznahorkay and colleagues also point to the potential of beam-dump experiments such as PADME in Frascati, and to the upcoming Dark Light experiment at Jefferson Laboratory, which will search for 10–100 MeV dark photons.

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IPC – Other recent results

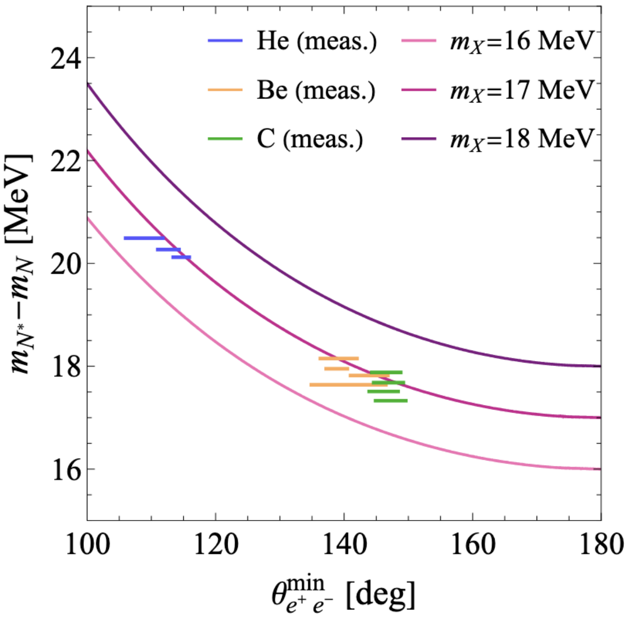
Anomalies observed at ATOMKI in the $^{12}C^*$ 17.2 MeV state [PRC 106 (2022) L061601] and at HUS (Vietnam) in the $^{8}Be^*$ with a different apparatus

Angular excesses ~ consistent with being due to a particle of mass M_X in a $N^* \rightarrow N\ X_{17}$ transition [Denton, Gehrlein PRD108, 015009 (2023)]:

$$\theta_{min} \sim \mathrm{asin}\,[\,M_X / (M_{N^*} - M_N)\,]$$

$$M_X = (16.85 \pm 0.04)\ \mathrm{MeV},$$

$$\chi^2 = 17.3,\ \mathrm{ndf} = 10,\ P(\chi^2) = 7\%$$



The rate measurements indicate

$$\Gamma(N^* \rightarrow N\ X_{17}) / \Gamma(N^* \rightarrow N\ \gamma) \sim 5 \times 10^{-6}$$

but <u>have some internal tension</u>, esp. ^{12}C vs $^{8}Be/^{4}He$

Isospin effects or direct p capture might change the picture

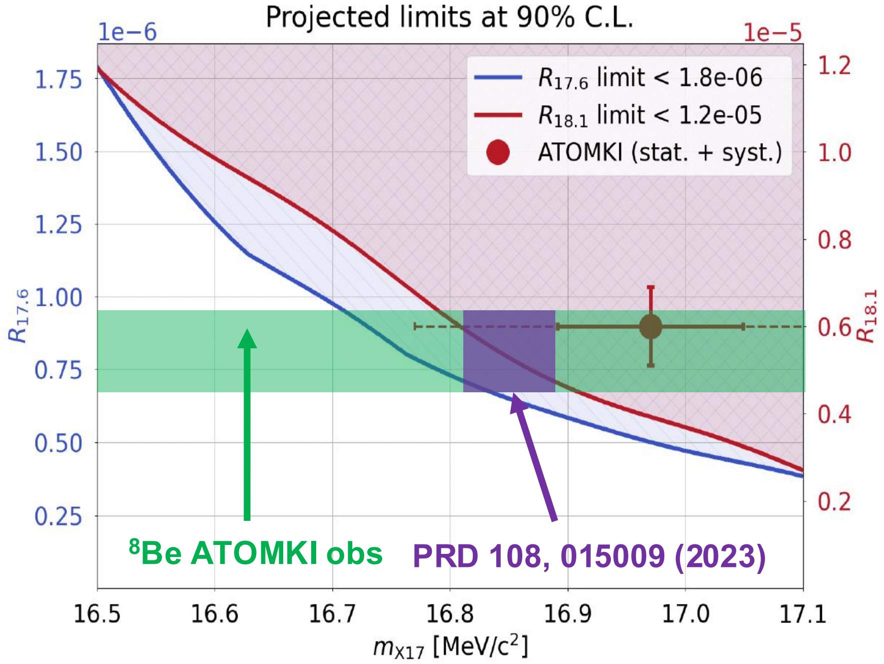
Other efforts ongoing to verify

Recent result from MEG II, arXiv:2411.07994 still to be published

Measurement on ^{7}Li target to reproduce ^{8}Be ATOMKI result, <u>no signal found</u>

ULs on $\Gamma(^{8}Be^{*} \rightarrow {}^{8}Be\ X(ee)) / \Gamma(^{8}Be^{*} \rightarrow {}^{8}Be\ \gamma)$ for 17.6, 18.1 MeV transitions

MEG-II result compatible at 1.5 σ with the ATOMKI combination M_X = 16.85(4) MeV
[Barducci, et al. ,JHEP 04 (2025) 035]



Further attempts to verify:

- At the AN2000 facility of the INFN National Laboratories of Legnaro [In data taking]
- At n_TOF EAR2 neutron line CERN [2025 proposal]
- Tandem accelerator in Montreal [G. Azuelos et al., JPC Ser. 2391 (2022) 012008]
- Van de Graaf accelerator at IEAP Prague [Cortez et al, NIM A 1047 (2023) 167858]

The interpretation is not straightforward

Is this a SM phenomenon? No firm explanation [JHEP 02 (2023) 154 and refs therein]

It might be a "protophobic" vector: coupling to n's much stronger than to p's, and to e's much stronger than to ν's [Feng et al, PRL 117 (2016) 071803]

- This way, it evades the constraint from $\pi^0 \to \gamma X$, $X \to e^+e^-$ @ NA48/2 [PLB 746 (2015) 178]
- ...but if so, it would be produced from the continuum more than from resonance states [Zhang, Miller PLB 813 (2021) 136061]
- …which might be the case in ATOMKI [N. J. Sas et al., arXiv:2205.07744]

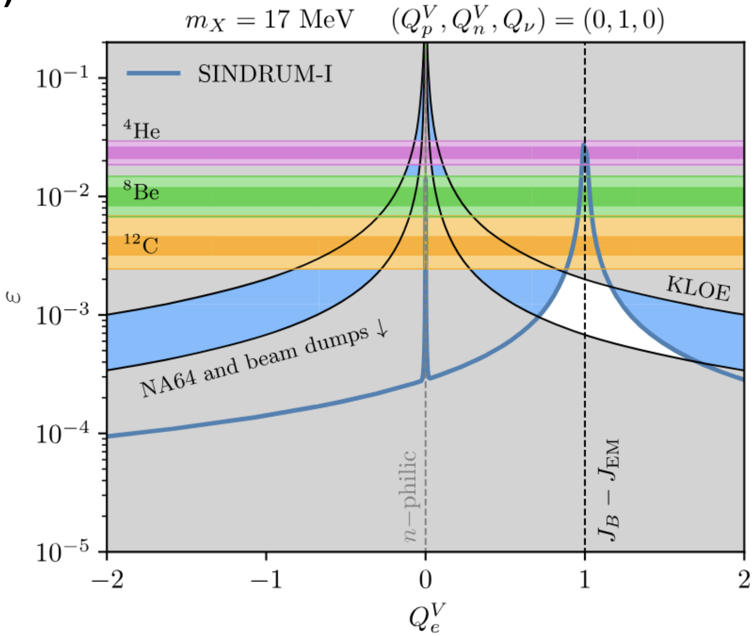
Analyses of J^P assignments [JHEP 02 (2023) 154, JHEP04 (2024) 035]

- not a scalar if parity is conserved in the transition $^8Be^*(1^+) \to {}^8Be(0^+)$ X
- not a pseudoscalar, as above, due to observation of $^{12}C^*(1^-) \to {}^{12}C(0^+)$ X
- a protophobic vector, constrained by SINDRUM $\pi^+ \to e^+\nu\, e^+e^-$ [PRD 108 (2023) 055011]
- an axial vector, also severely constrained
- a spin-2 state, severely disfavored by SINDRUM limit

The protophobic vector interpretation

ATOMKI rates excluded by Sindrum $\pi^+ \to e^+\nu\, e^+e^-$ or KLOE-2 $e^+e^- \to \gamma X \to \gamma\, e^+e^-$

Hostert, Pospelov
PRD 108 (2023) 055011



with:

$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{m_X^2}{2} X_\mu X^\mu + e\varepsilon X_\mu \mathcal{J}_X^\mu,$$

with:

$$\mathcal{J}_X^\mu = \sum_{f=\{e,u,d,\nu\}} \bar{f}\gamma^\mu (Q_f^V + Q_f^A \gamma^5) f$$

The rates of the ATOMKI results seem not even mutually compatible

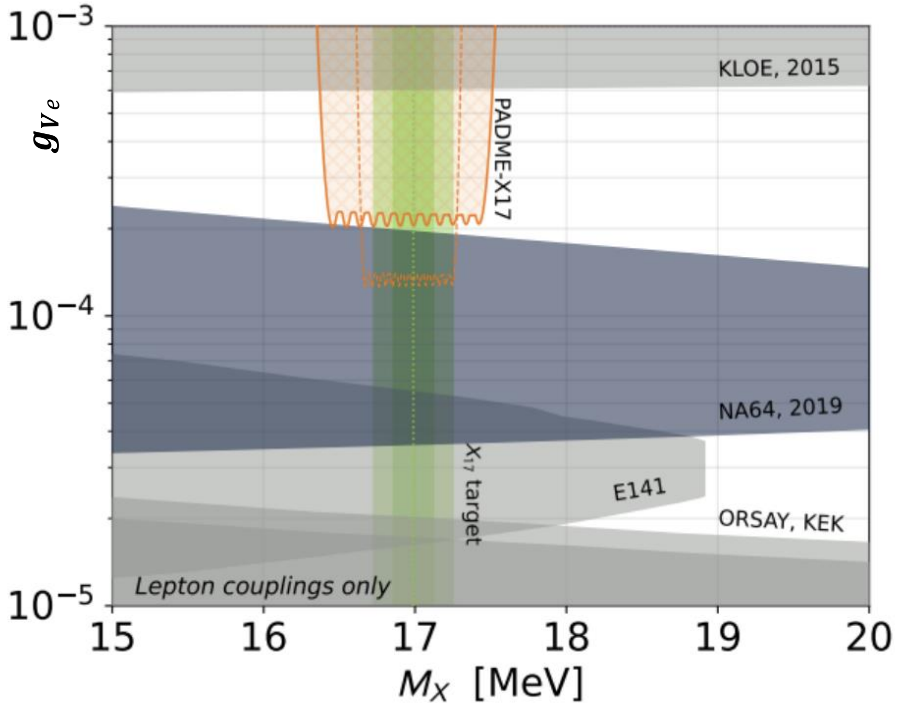
The contribution of direct proton capture may change this picture?

Can a particle-physics search help in clarifying?

Search for a resonance on a thin target

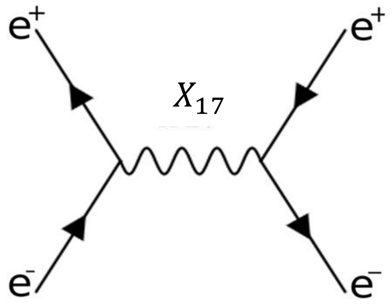
- The basics of a resonance search are discussed in Darmé et al., PRD 106 (2022) 115036
- In the present talk, for brevity, I will focus on a Vector state interpretation with:

$$\mathcal{L}^{\mathrm{Vect.}} \supset \sum_{f=e,u,d} X_{17}^{\mu} \bar{f} \gamma_{\mu} (g_{vf} + \gamma^5 \tilde{g}_{vf}) f$$



Search for a resonance on a thin target

- $\sigma_{res} \propto \frac{g_{Ve}^2}{2m_e} \pi Z\, \delta(E_{res} - E_{beam})$ goes with α_{em} → dominant process with respect to alternative signal production processes (α_{em}^2, α_{em}^3)
- $\sqrt{s}$ has to be as close as possible to the expected mass → fine scan procedure with the e^+ beam → expected enhancement in $\sqrt{s}$ over the standard model background



With a positron beam, X_{17} can be produced through resonant annihilation in thin target: Scan around $E(e^+) \sim 283$ MeV and measure two-body final state yield N_2

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

to be compared to $N_2(s) = N_{POT}(s) \times B(s)$

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

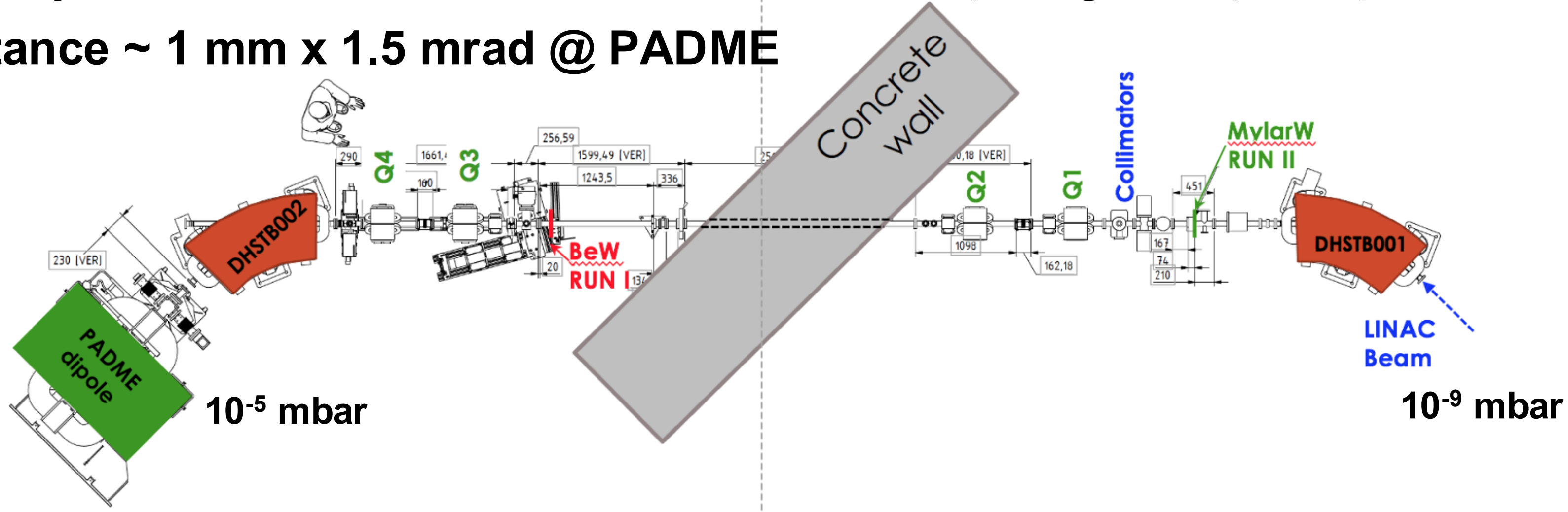
What's PADME – the facility

Positrons from the DAΦNE LINAC up to 550 MeV, O(0.25%) energy spread

Repetition rate up to 49 Hz, macro bunches of up to 300 ns duration

Intensity must be limited below ~ 3 × 10^4 POT / spill against pile-up

Emittance ~ 1 mm x 1.5 mrad @ PADME



Past operations:

Run I e^- primary, target, e^+ selection, 250 μm Be vacuum separation [2019]

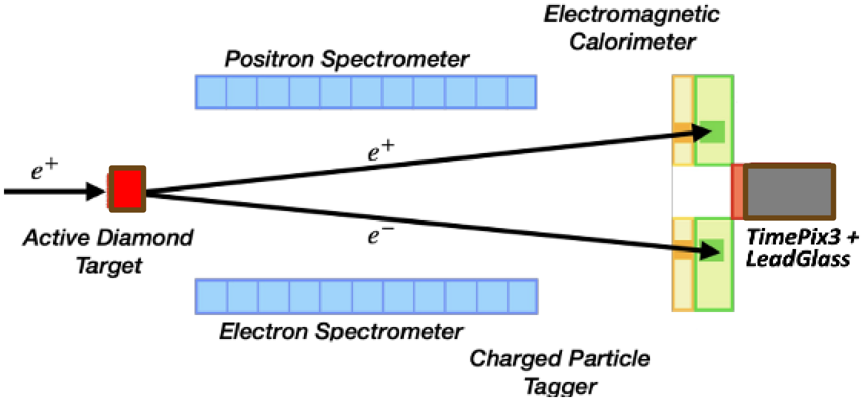
Run II e^+ primary beam, 125 μm Mylar™ vacuum separation, 28000 e^+/bunch [2019-20]

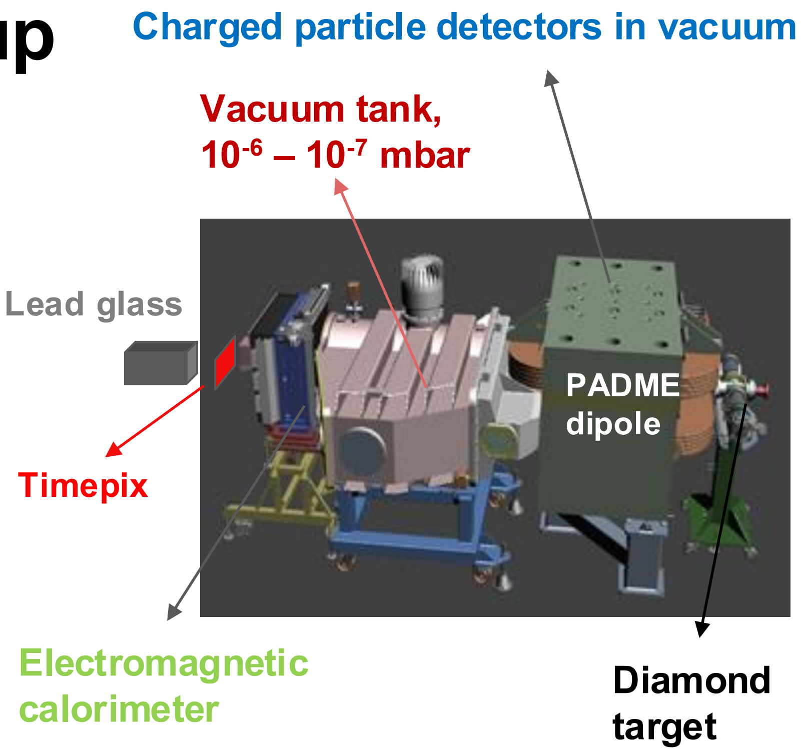
Run III dipole magnet off, ~3000 e^+/bunch, scan $s^{1/2}$ around ~ 17 MeV [End of 2022]

Run-III setup

2022 Run-III setup adapted for the X17 search:

- **Active target**, polycrystalline diamond
- **No magnetic field**
- **Charged-veto detectors not used**
- **ECal: 616 BGO crystals, each 21x21x230 mm^3**
- **Newly built hodoscope in front of Ecal for e/γ**
- **Timepix silicon-based detector for beam spot**
- **Lead-glass beam catcher (NA62 LAV spare block)**





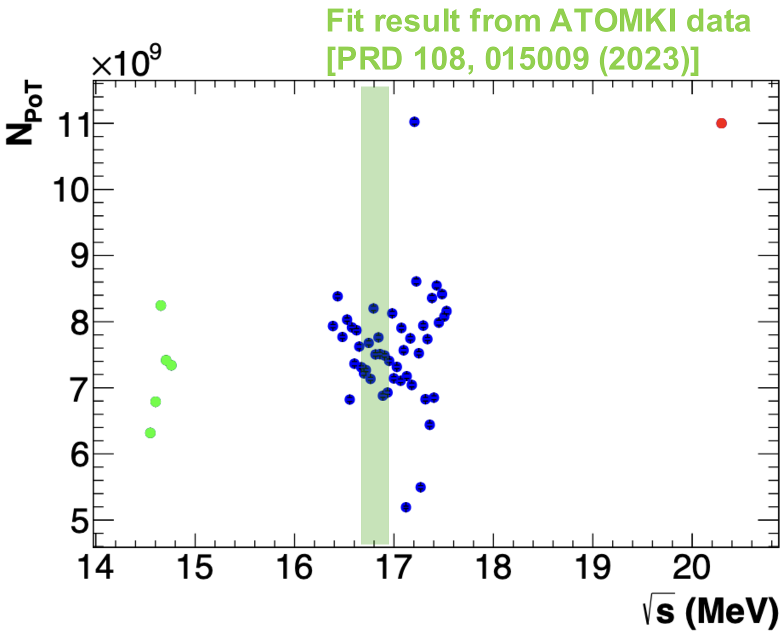
X17 via resonant-production: Run III

Run III PADME data set contains **3 subset**
- **On resonance points (263-299) MeV**
- **Below resonance points (205-211) MeV**
- **Over resonance, energy 402 MeV**

1 over resonance energy point
Statistics ~2 x 10^{10} total
Used to calibrate POT absolute measurement

On resonance points, mass range 16.4 — 17.5 MeV
Beam energy steps ~ 0.75 MeV ~ beam energy spread
Spread equivalent to ~ 20 KeV in mass
Statistics ~ 10^{10} POT per point

Below resonance points
Beam energy steps ~1.5 MeV
Statistics ~ 0.8 x 10^{10} POT per point
Used to cross-check the flux scale



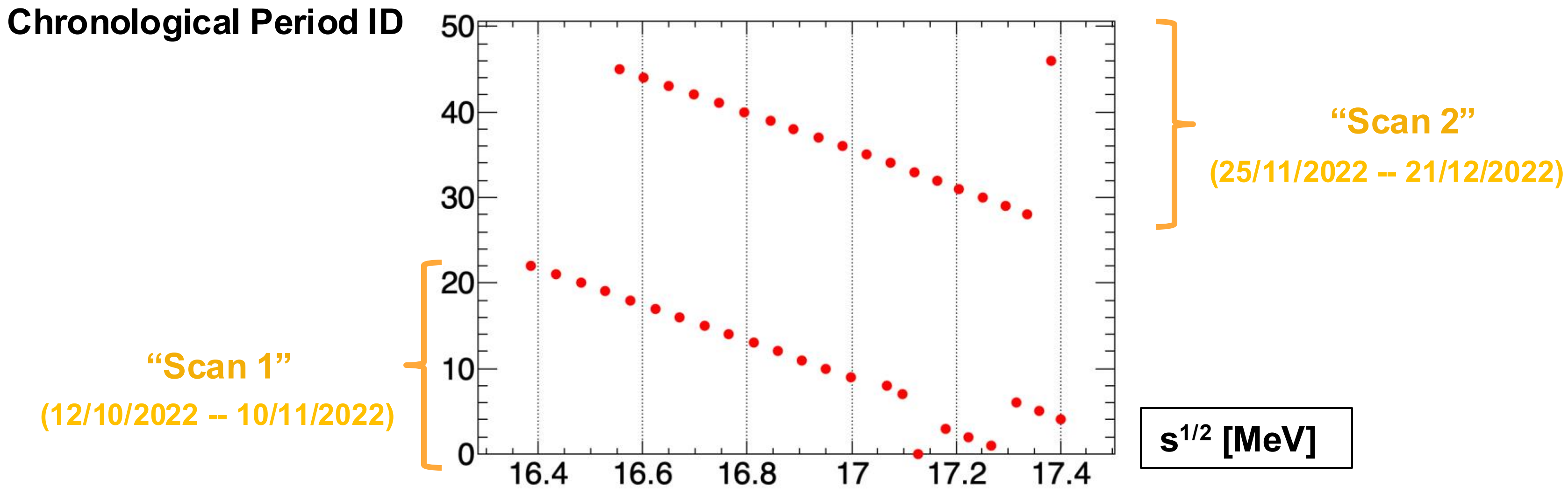
Run-III concepts

“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 <u>interspersed in energy</u>

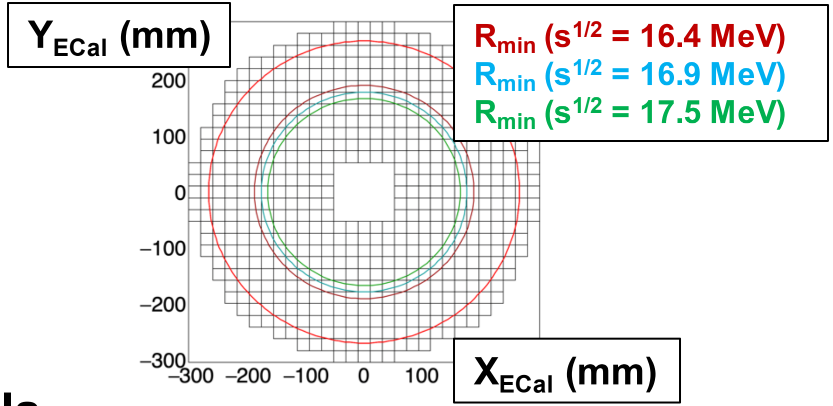


Detailed GEANT4-based MC performed for each period

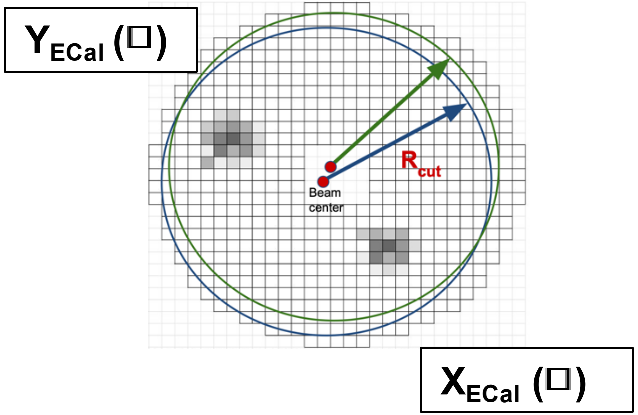
Run-III concepts – the signal selection

Select any two-body final state (ee, $\gamma\gamma$) with both daughters in ECal acceptance:

1. Fix R_{Max} at Ecal, away from Ecal edges
2. Given s, derive 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



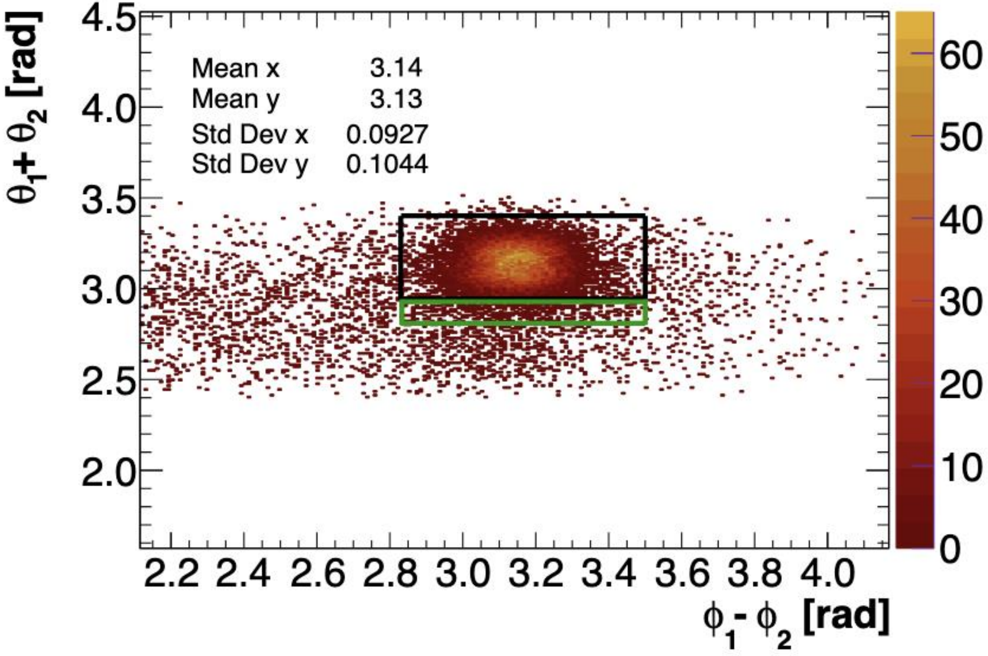
Rmax chosen to be away from Ecal edges by more than the size of 1 L3 crystal cell for any period in the data set



1 □ = 1 L3 crystal = 21.5 x 21.5 mm

Run-III concepts – the signal selection

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



Selection region

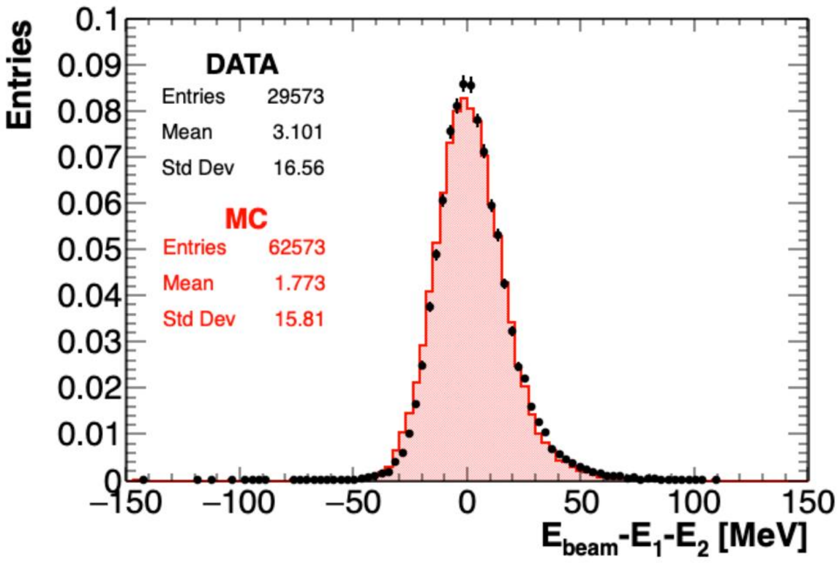
Sideband region

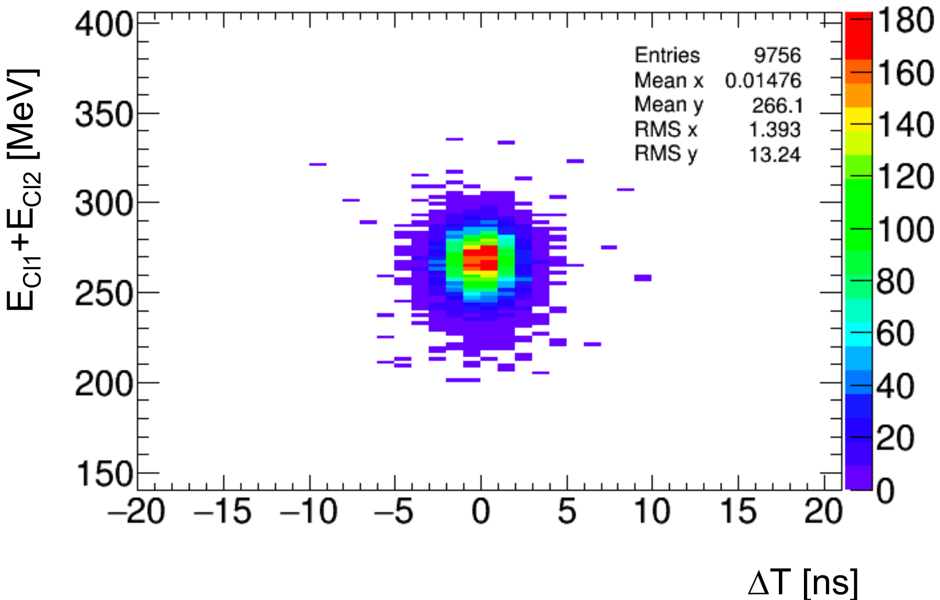
Run-III concepts – the signal selection

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**

Selected events, 4 % background





Grand scheme of the analysis

Rewrite the master formula as:

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

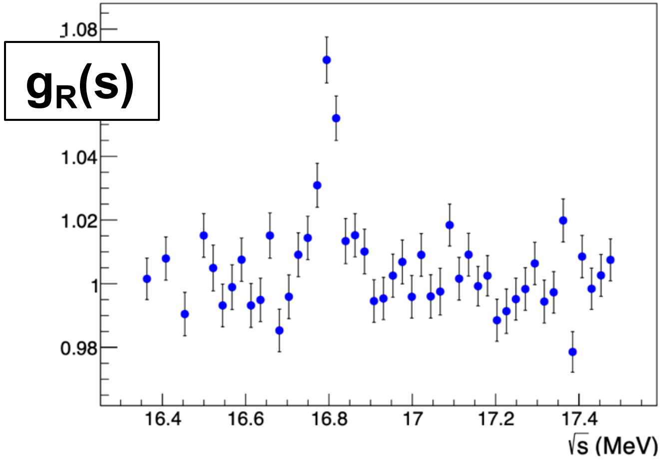
The analysis observable is $g_R(s)$

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

Question: is $g_R(s)$ more consistent with
- **K(s) or with**
- **K(s) [1 + $S(s;\, M_X,\, g)\; \varepsilon_S \,/\, B$]?**

7 nuisance parameters for the S+B scenario:
2 for K and ε_S/B, 3 for S

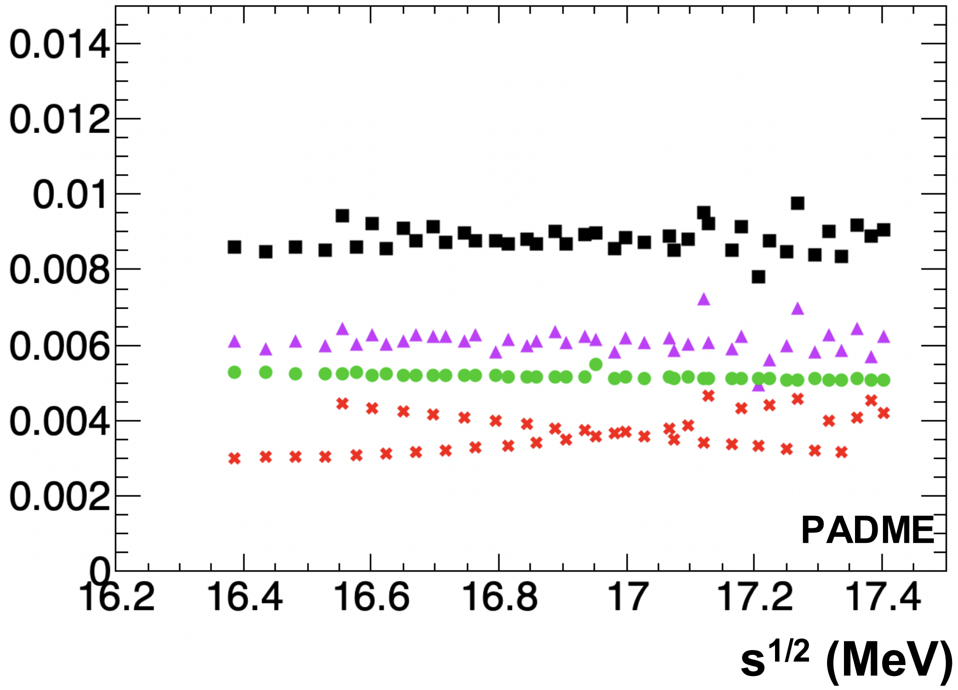
MC with M_X = 16.8 MeV, g_V = 8x10^{-4}



Grand analysis scheme: g_R error budget

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

Relative uncorrelated error per period



Uncorrelated errors

Source	Uncertainty (% per energy point)
$N_2(s)$	0.60
$B(s)$	0.54
$N_{\mathrm{PoT}}(s)$	0.35
Total on $g_R(s)$	0.88

$K(s)$, constant term

Source	Uncertainty (%)
Lead-glass calibration	2.0
Absolute B yield	1.8
Energy-loss correction to N_{PoT}	0.5
Radiation-induced correction to N_{PoT}	0.3
Total	2.8

$K(s)$, $\sqrt{s}$-slope

Source	Expected value (%/MeV)
Radiative corrections	$-0.6 \pm 0.2 \pm 0.6$
Total	-0.6 ± 0.6

The N_2 event yield error budget

Selection counts around 30k / period:

Statistical error: δN_2 ~ 0.6% up to 0.7%

Background subtraction using angular side-bands (bremsstrahlung, 4%)

Carries additional statistical uncertainty δN_2 ~ 0.3%

Data quality using time-averaged energy deposited on ECal:

Dominated by primary beam (brems. on upstream vacuum separation window)
Contribution of two-body events negligible
A few % of the spills are outliers and removed
Overall systematic error from data quality, $\delta N_2 << \%$

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

Grand analysis scheme: B

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

Source	Error on B per period [%]	Details
MC statistics	0.40	Next slide
Data/MC efficiency (Tag&Probe)	0.35	here
Cut stability	0.04	here
Beam spot variations	0.05	here
Total	0.54	

Correlated (common) systematic errors on B enter in the scale K(s), e.g.:

Absolute cross section (rad. corr. at 3%), target thickness (known @ 4%)

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

Scaling errors are accounted for

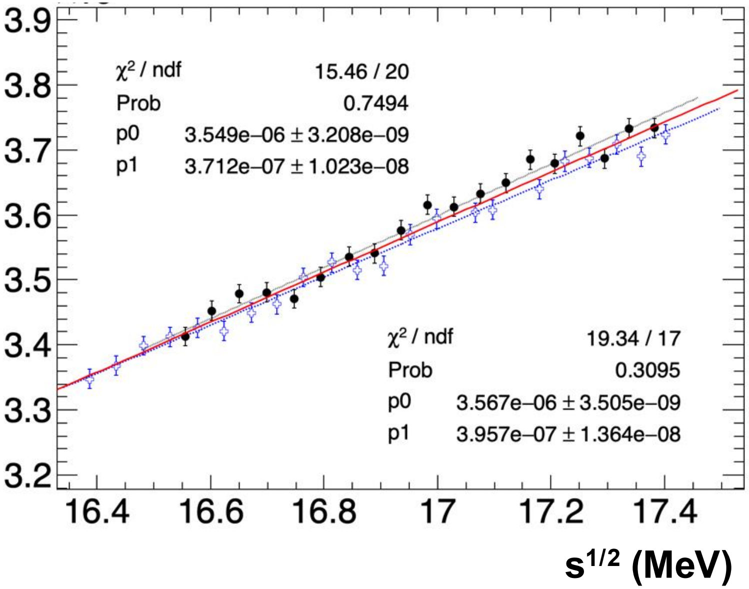
Source	Correlated B error [%]	Details
Low-energy period statistics	0.40	
Acceptance of low-energy, s slope	1.80	here
Total	1.85	

Details on expected background: s dependence

Expected background B determined from MC, stat error per period: $\delta B \sim 4\times10^{-3}$

Fit of $B(s^{1/2})$ with a straight line (only including statistical errors here)

B [10^{-6} events per POT]



Fit mode	P0 [10^{-6}]	P1 [10^{-7} / MeV]	Corr	Fit prob
Only scan1	3.549(3)	3.71(10)	0.12	75%
Only scan2	3.567(4)	3.96(13)	-0.19	31%
All periods	3.558(2)	3.85(8)	-0.008	9%

Background curve slightly depend on the scan

Considered in alternative analysis (see later)

Grand analysis scheme: N_{POT}

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 corrections to be applied:

1. **Energy-loss: from data + MC, details here**
2. **Radiation-induced response loss: from data, details here**

Grand analysis scheme: N_{POT} error budget

Uncorrelated uncertainty on background N_{POT} :

Source	Error on N_{POT} per point [%]	Source
Statistics, ped subtraction	negligible	
Energy scale from BES	0.3	BES from timepix spot σ_x
Error from rad. induce slope	Variable, ~0.35	here
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
Energy loss, data/MC	0.5	here
Rad. induced loss, constant term	0.3	here
Total	2.1	

Grand analysis scheme: signal yield / POT, S

Analysis compares $g_R(s)$ to $K(s)$ x $[1 + S(s; M, g_v)\ \varepsilon/B]$

Expected signal yield from PRL 132 (2024) 261801, includes effect of motion of the atomic electrons in the diamond target from Compton profiles

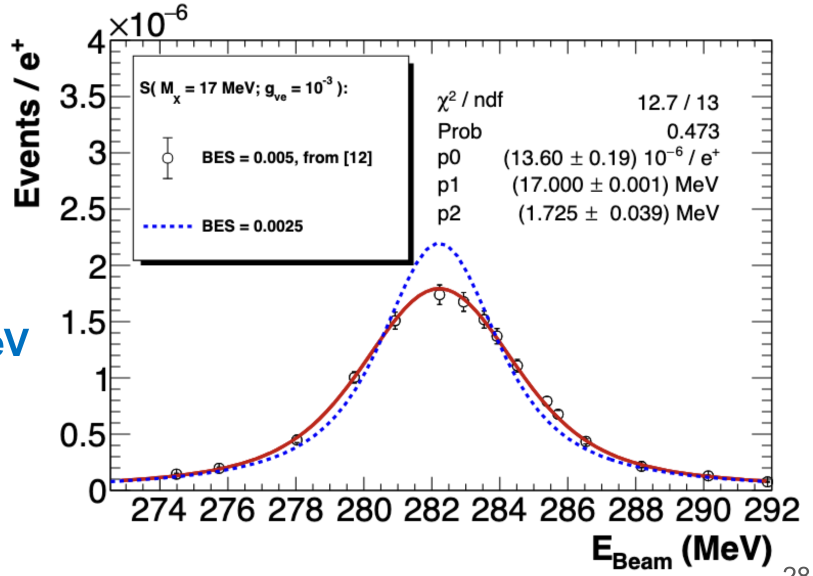
Parameterized S vs E_{beam} with a Voigt function:

- 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 resonance energy: 1.72(4) MeV
- Relative BES, as said: 0.025(5)%

$S(E_{beam}; M_X = 17\text{ MeV}, g_v = 10^{-3})$



Points from PRL 132 (2024) 261801

Grand analysis scheme: ε/B

Analysis compares $g_R(s) = N_2 / (B \times N_{POT}) $ to $K(s)\,[1 + S(M,g_v)\ \varepsilon/B]$

Expected background signal efficiency ε determined from MC:

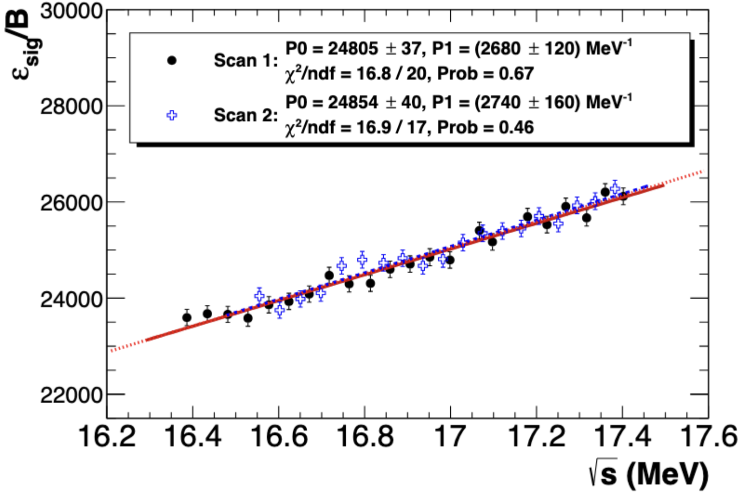
Beam spot vs run from COG, negligible uncertainty from COG error

Large cancellation of systematic errors seen using ε/B

Fit $\varepsilon/B(s^{1/2})$ with a straight line, include fit parameters as nuisances:

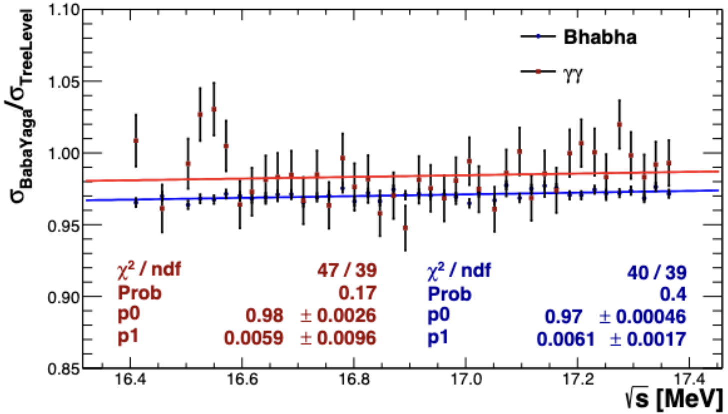
Separate fits for scan1 and 2, mutually compatible (only stat errors for B, ε)

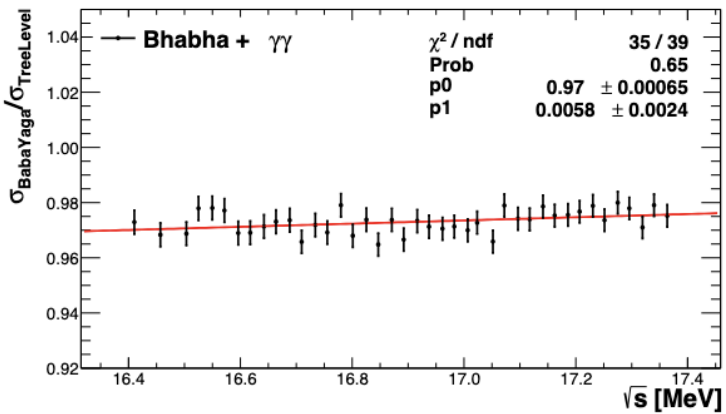
Behavior reproduced with MC



Possible scale effects, K(s)

Radiative corrections evaluated using Babayaga, ee(γ) and γγ(γ)





Possible offset ~ -2.9% @ 16.92 MeV
Possible slope with $s^{1/2}$: -0.6(6)% MeV^{-1}

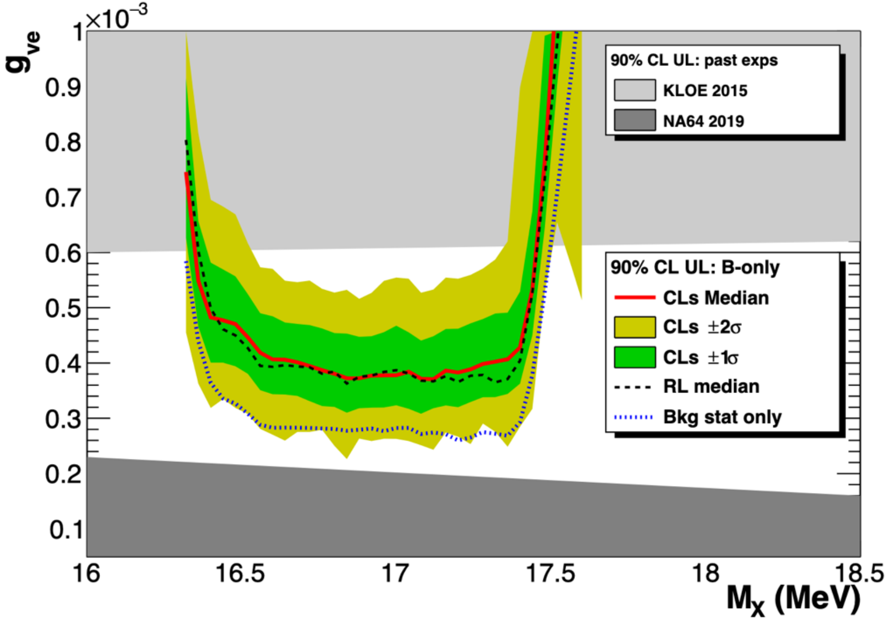
Babayaga references:
- Nucl. Phys. B 758 (2006) 227
- Phys. Lett B 663 (2008) 209

The scaling with the below resonance is affected by a -1.5(1.5)% shift because of radiative correction, but the expected total error covers for it: 1.8%(B) + 2.1%(N_{PoT}) = 2.8%

Insertion of Babayaga-generated events in the MC (up to 10 γ's) → no effect on ε

Grand analysis scheme: expected sensitivity

- **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:

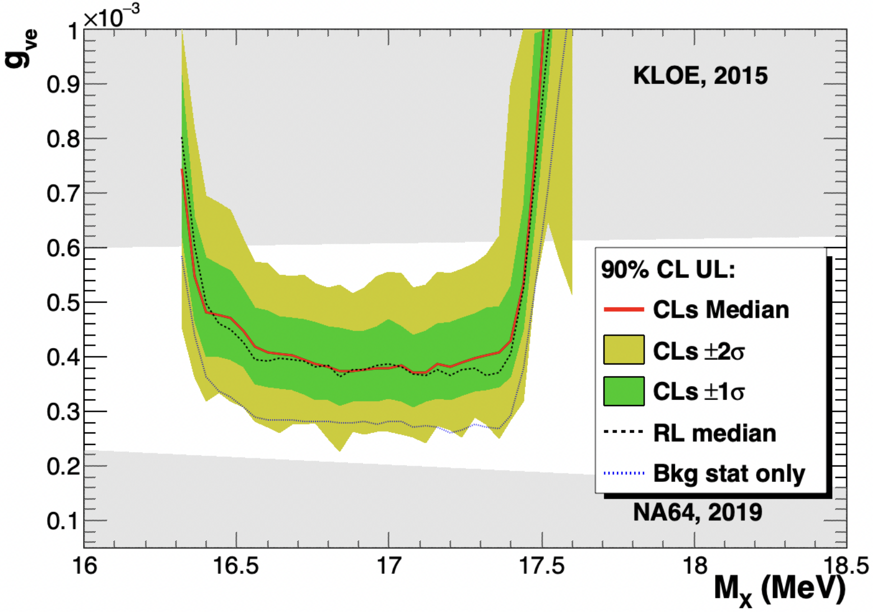
- the median of the limits obtained using the Rolke-Lopez likelihood-ranking method with the 5 periods with largest signal yield
- the purely statistical UL, $1.28\ N_2^{1/2}$

For details, arXiv:2503.05650 [accepted by JHEP]

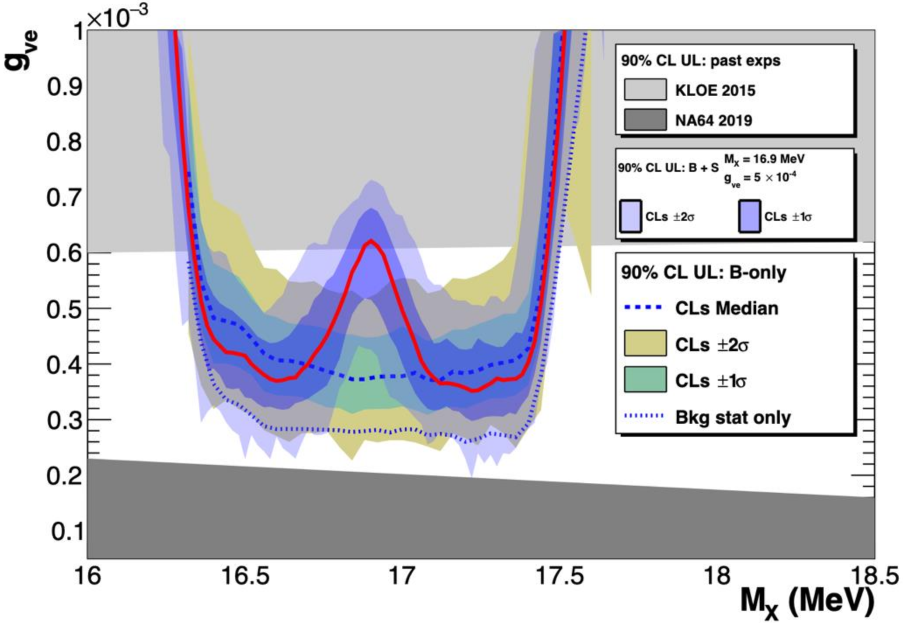
Grand analysis scheme: expected sensitivity

- **In presence of a signal, the expected limit is weaker**

Background only



Signal + background, M_X = 16.9 MeV, g_{ve} = 5 x10^{-4}



The "blind unblinding" procedure

To validate the error estimate, we applied the procedure in 2503.05650 [hep-ex]

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

Define the masked periods by optimizing the probability 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.: +/- 4.8% for the constant, (-0.6 +/- 1.2) % MeV^{-1} for the slope

Successfully applied:
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}

Error estimate validated: @ 90%CL no additional errors can be present > 1%
Therefore, proceed to box opening

Box opening

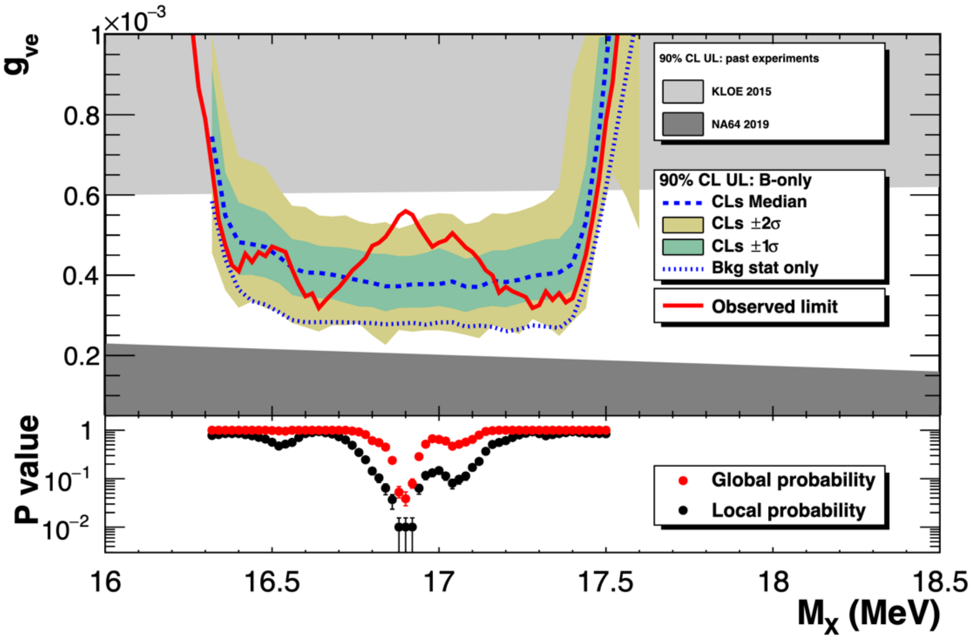
Some excess is observed beyond the 2σ local coverage (2.5 σ local)

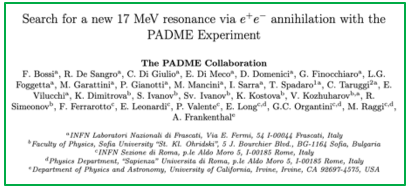
At M_X = 16.90(2) MeV, g_{ve} = 5.6 x 10^{-4}, the global probability dip reaches $3.9_{-1.1}^{+1.5}$ %, corresponding to (1.77 +- 0.15) σ one-sided (look-elsewhere calculated exactly from the toy pseudo-events)

A second excess is present at ~ 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

For details, see ArXiv:2505.24797 [hep-ex]





Search for a new 17 MeV resonance via e^+e^- annihilation with the PADME Experiment

The PADME Collaboration

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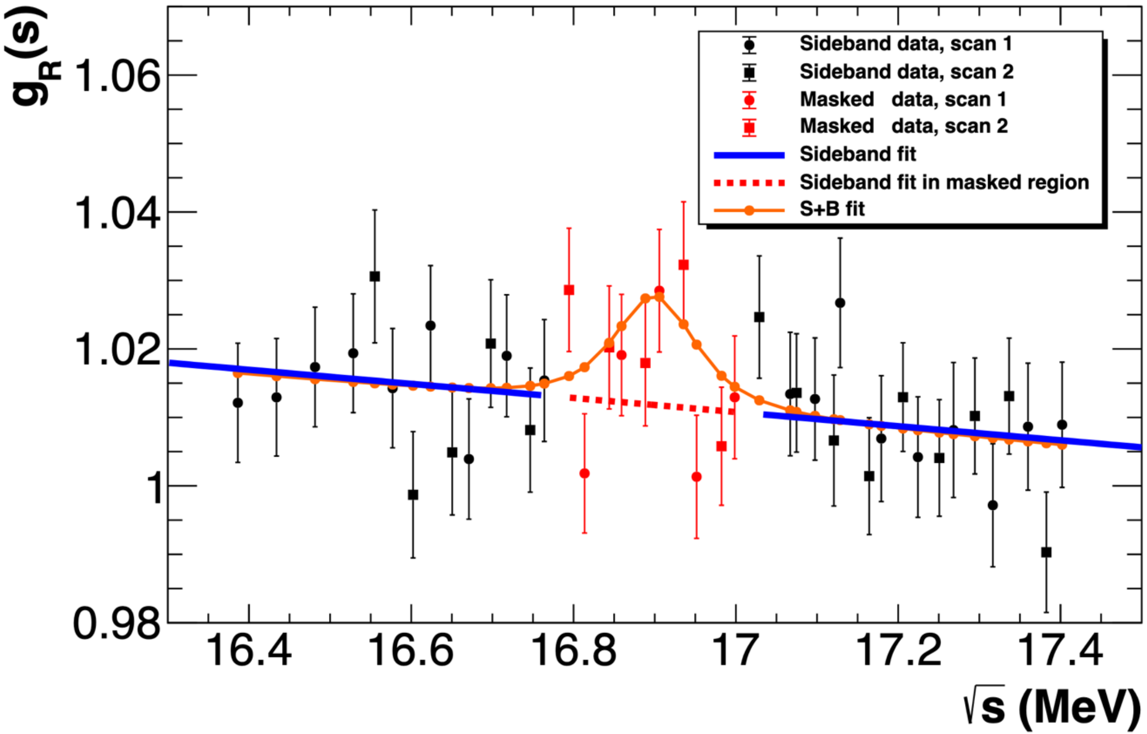
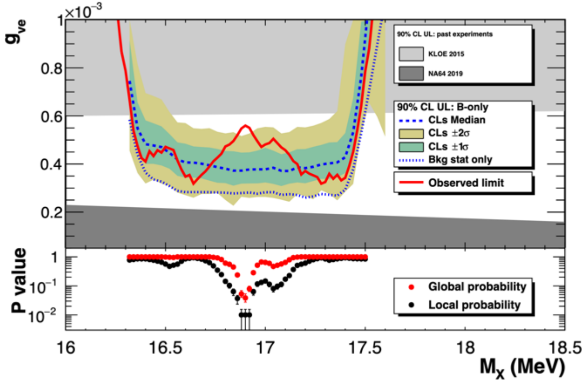
Box opening - II

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



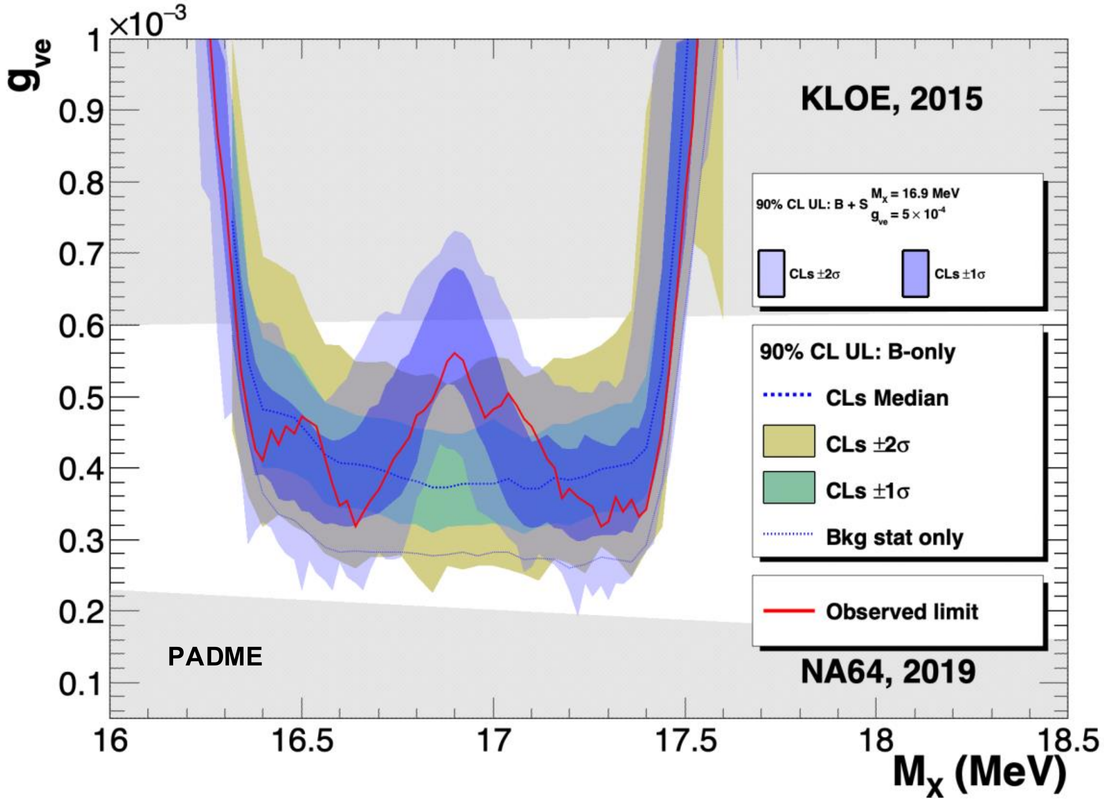
Region masked by automatic procedure



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

Box opening – II – UL comparison

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



Box opening – III Other checks

Checked other sensitivity methods

Perform the automatic procedure but fit with a constant:

Result:	Original version:
1. $P(\chi^2) = 37\%$	1. $P(\chi^2) = 74\%$
2. Pulls gaussian fit prob > 30%	2. Pulls gaussian fit probability > 45%
3. Slope of pulls consistent with zero	3. Slope of pulls consistent with zero
4. Constant = 1.0112(14)	4. Constant = 1.0116(16), Slope = (-0.010 +- 0.004) MeV^{-1}

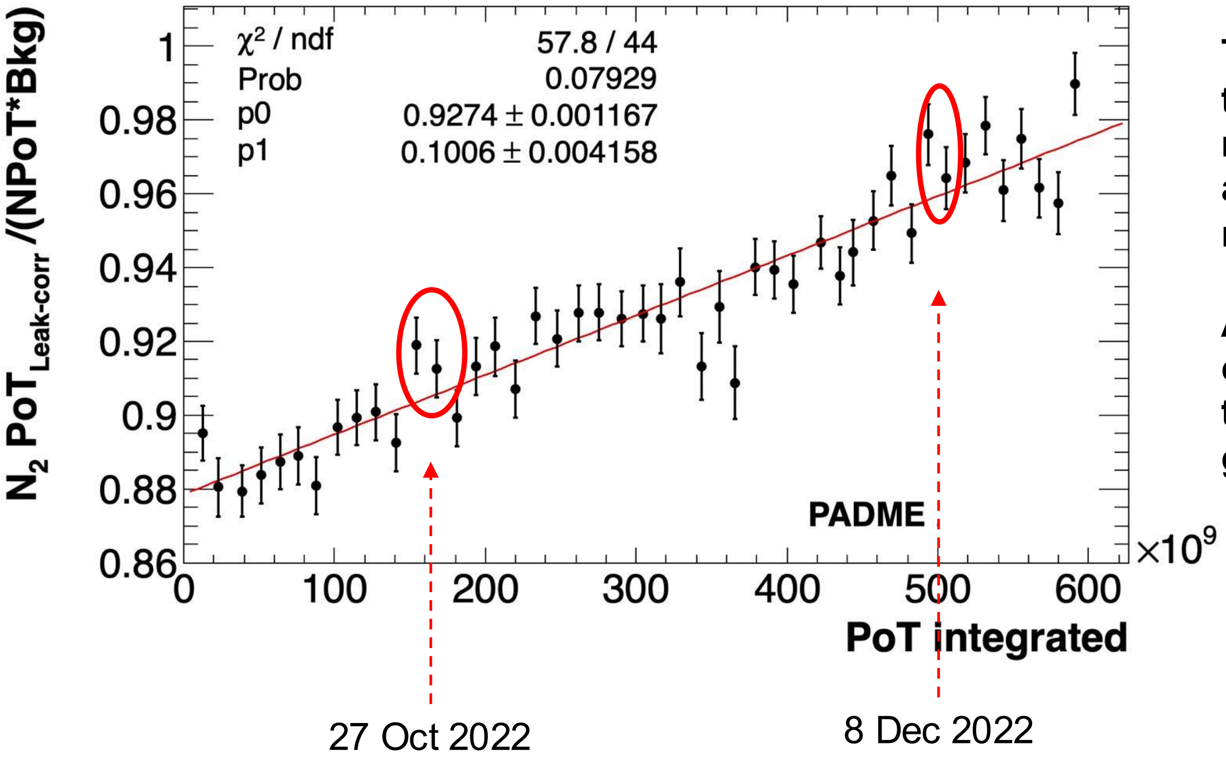
The center of the masked region does not change: 16.888 MeV
The excess also remains basically of the same strength: 1.6σ

Use scan1-scan2 separate parametrizations for B(s) instead of using B(s) / point:
Excess region only slightly affected and equivalent to ~1.6 σ

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

Box opening – IV Check of correction

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



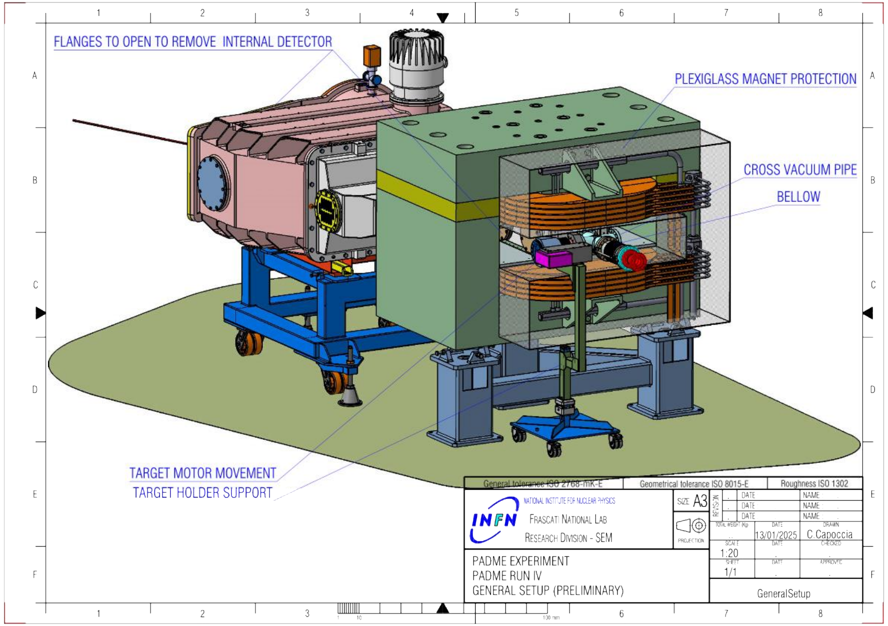
The slope has been used to correct for the radiation-induced effect, acting as a separate nuisance

Again no significant change in the location of the excess and in the global p-value

The case for a PADME Run IV – an optimized setup

New data set to be acquired to better clarify:

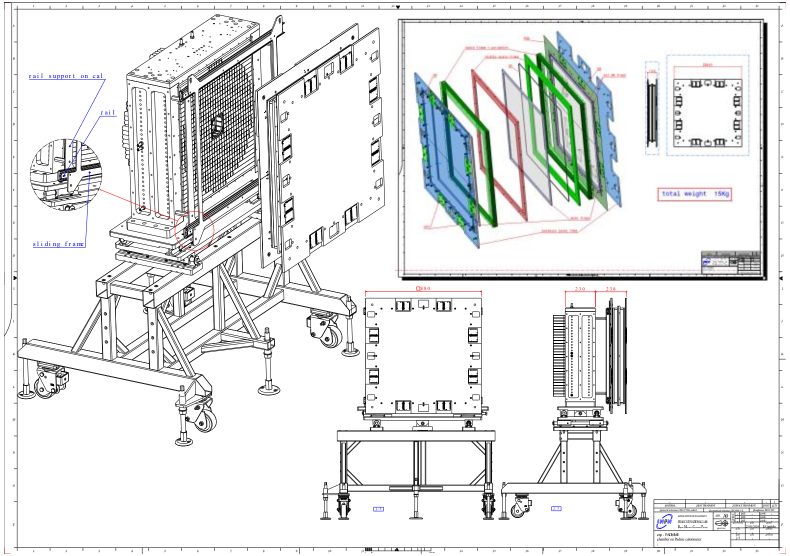
- **set the target closer to the ECal, increase acceptance by x2**
- **possible with a new support for motor actuator**



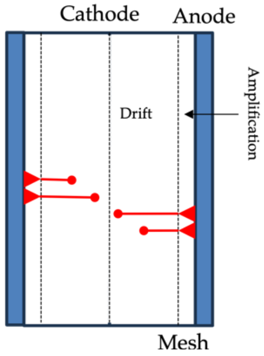
Run IV – new tracking detector

A new detector for Run IV:

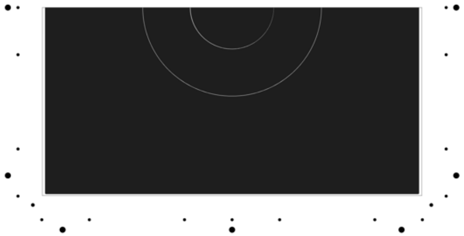
- **micromegas-based tracker to separately measure the absolute cross sections of ee/γγ thus allowing a combined analysis**
- **Improvement in angle resolution, also provides beam spot, see here**



Two 5 cm gaps, can operate in TPC mode



Resistive circuit (common, 3HV zones)



New experts joined from LNF, Roma1, Neaples INFN sections with expertise in ATLAS micromegas

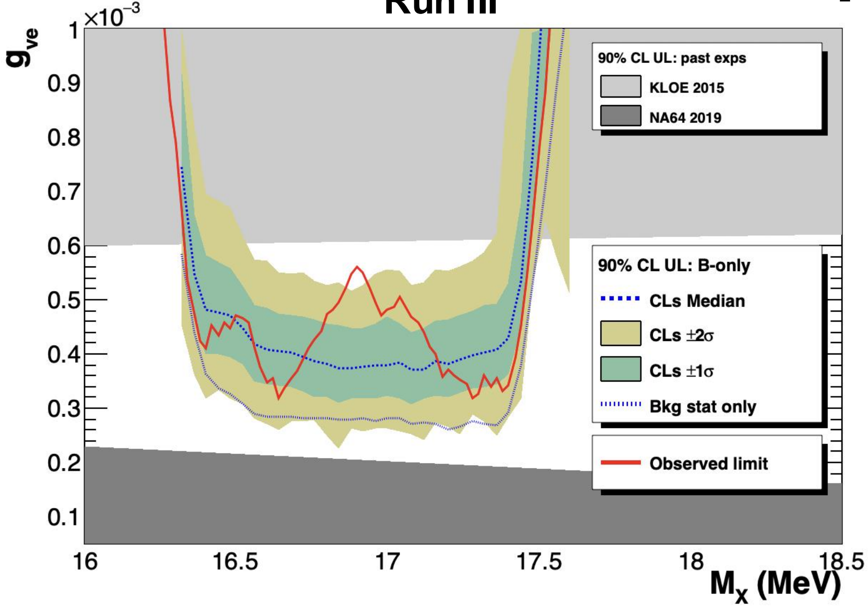
Run IV assumptions

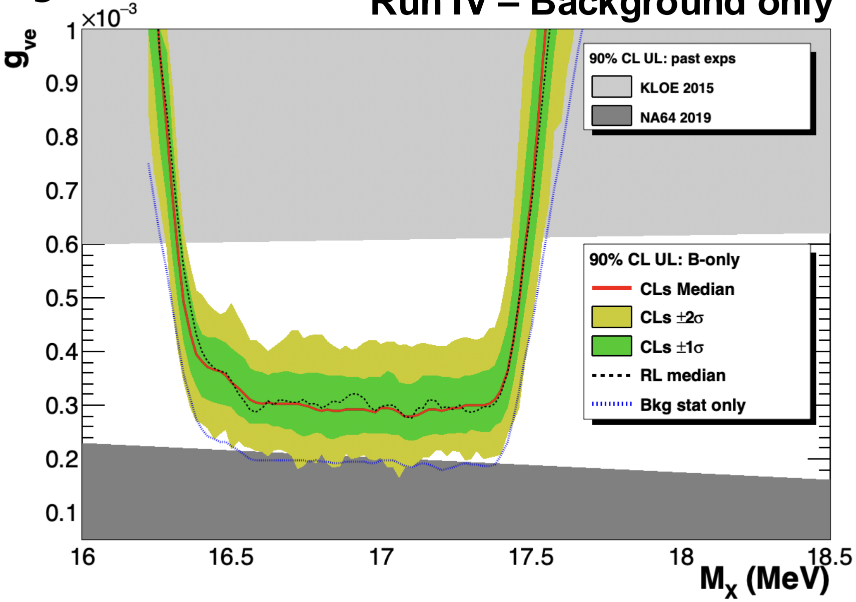
Lessons for Run IV to improve:

- **Increase monitoring power and redundancy: guarantee better stability**
- **Alternative flux determinations: $\gamma\gamma$, new end of line monitor, target, chamber**
- **Increase acceptance: allow even safer treatment for edge effects**
- **Increase statistics per energy point**

Assumptions for Run IV:
- **x2 acceptance increase (target closer to ECal)**
- **x2 statistics increase, 1.5×10^{10} POT per energy point**
- **2.5 days for data collection, 3000 e^+ / spill as in Run III**
- **Points divided into 2 scans: 16—20 points per scan**

Run IV projections





Source	Uncertainty [%]		Note
	Run III	Run IV	
N_2	0.6	0.3	Uncorrelated
N_{PoT}	0.35	0.3	Uncorrelated
B	0.55	0.3	Uncorrelated
Total on g_R	0.89	0.5	Uncorrelated

Conclusions

The possible observation of a new light neutral particle from internal pair conversion stimulated a number of experimental and theoretical activities

The “X_{17}” excess remains not confirmed but not disproved in nuclear physics

No SM explanation viable

The PADME experiment is in a favorable position to clarify

Data from 4 x 10^{11} e^+ on target used for resonance search in the mass region 16.4—17.4 MeV with a blind analysis

Overall uncertainties of 0.9% on 40+ points have been obtained

No indications of X_{17} with global p-values well beyond 2σ

An excess at 16.90 MeV: local p-value 2.5 σ, global 1.77(15) σ

A new data taking with an upgraded detector is ongoing

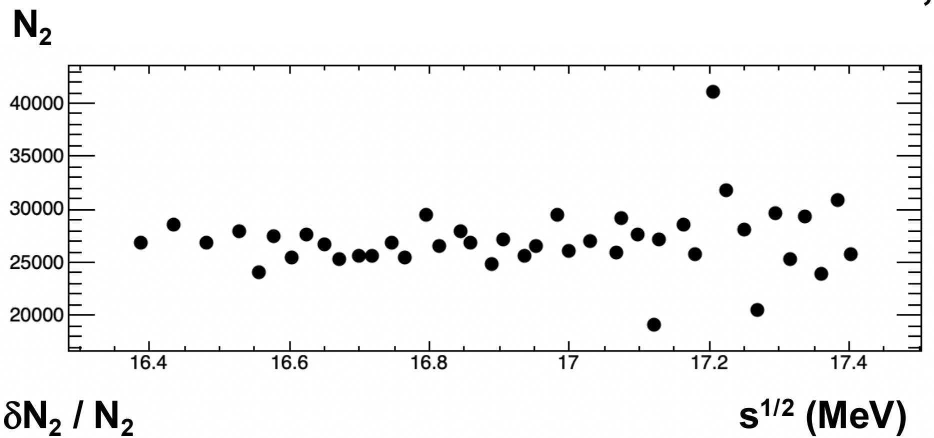
Other particle-physics techniques to join the effort to confirm/disprove X17

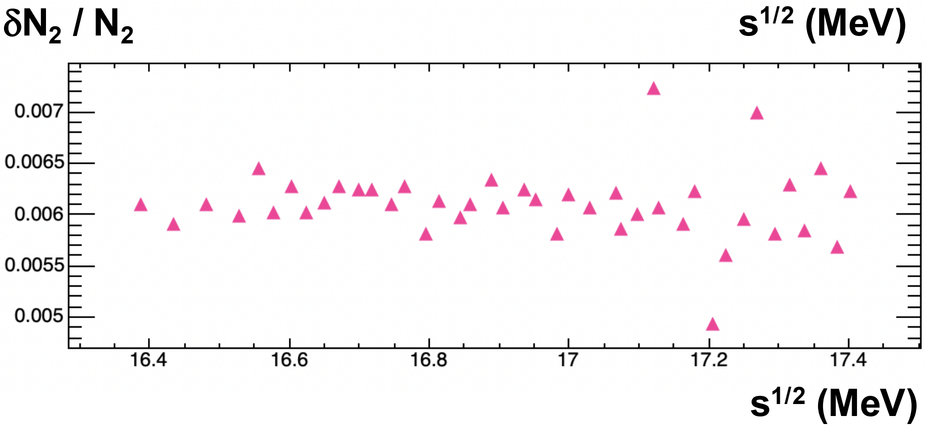
Additional material

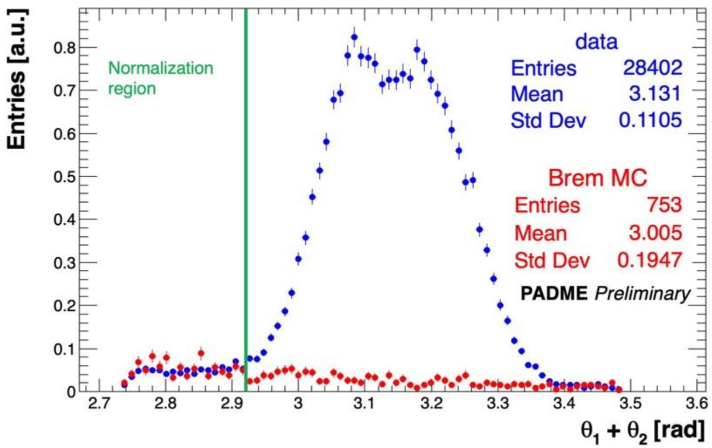
Details on the event count N_2

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)

Fully modeled using MC + detailed map

Details on background: cut stability

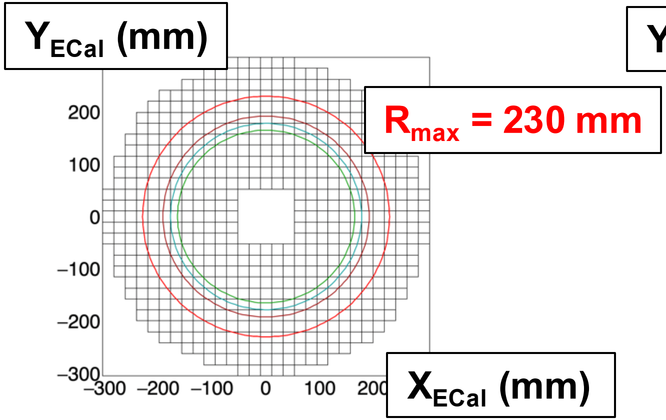
Check if MC and data yields stable vs R_{min}, R_{max} (edge effects, leakage)

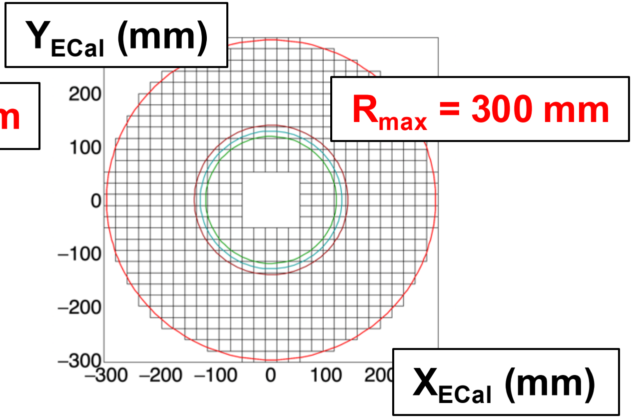
Vary R_{max} by +-2 E_{Cal} cells around nominal cut of 270 mm: 230 mm → 300 mm

Yield variation: ~10%

Uncorrelated error 0.3%

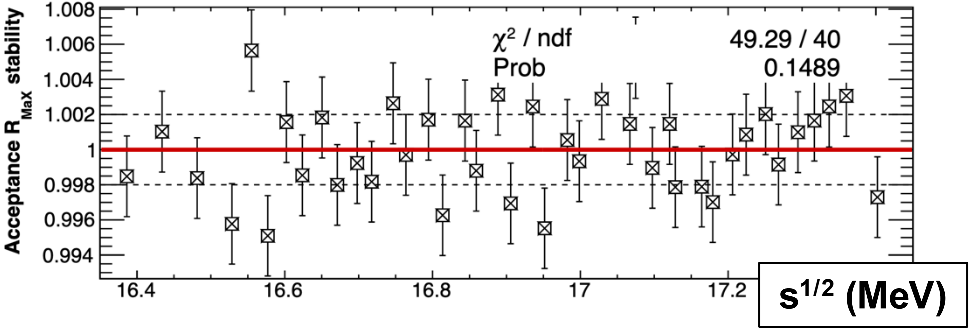
R_{min} -1.5 D ($s^{1/2}$ = 16.4 MeV)
R_{min} -1.5 D ($s^{1/2}$ = 16.9 MeV)
R_{min} -1.5 D ($s^{1/2}$ = 17.5 MeV)





Stability is observed within a coverage band of +-0.2%, add 0.035% uncorrelated systematic error on B

Cut relative stability



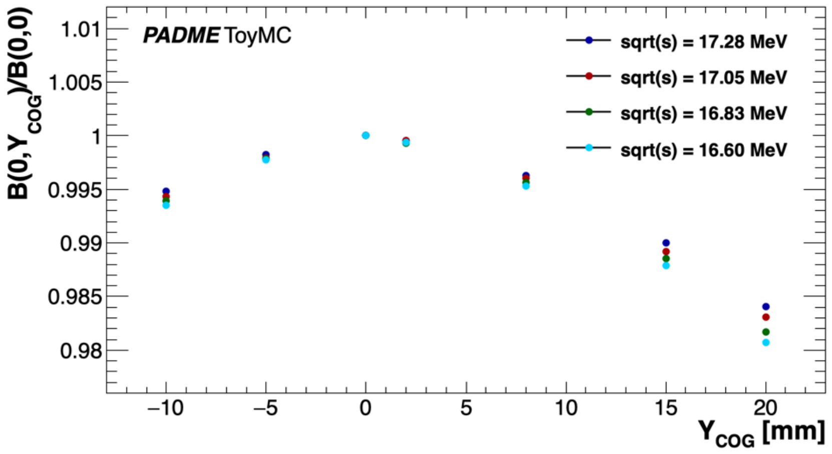
Details on background: acceptance variations

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 16.4 to 17.4 MeV

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

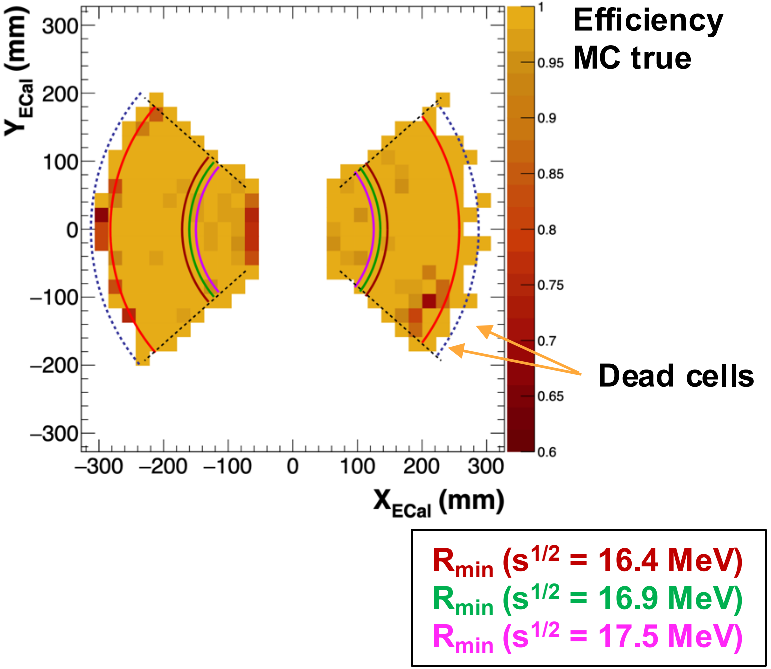


Details on background: cluster reconstruction

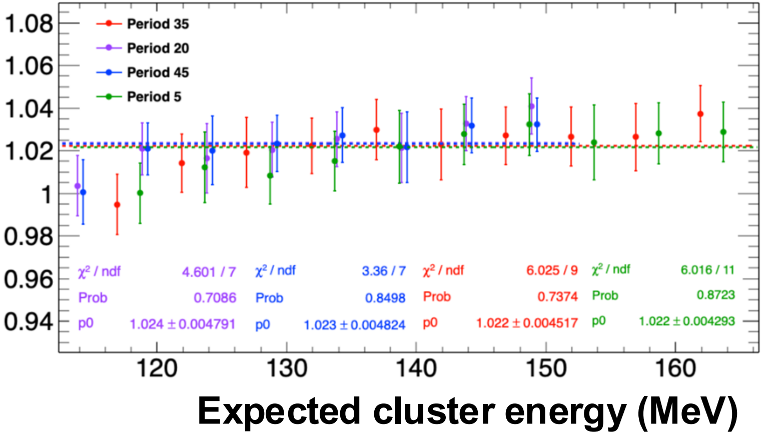
Efficiency around 1 within few % except in specific regions (Ecal edges, dead cells)

Tag & probe: method-induced bias 2.3(2)%, stable along the data set

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



Efficiency <Method /MC true>



Details on background: cluster reconstruction

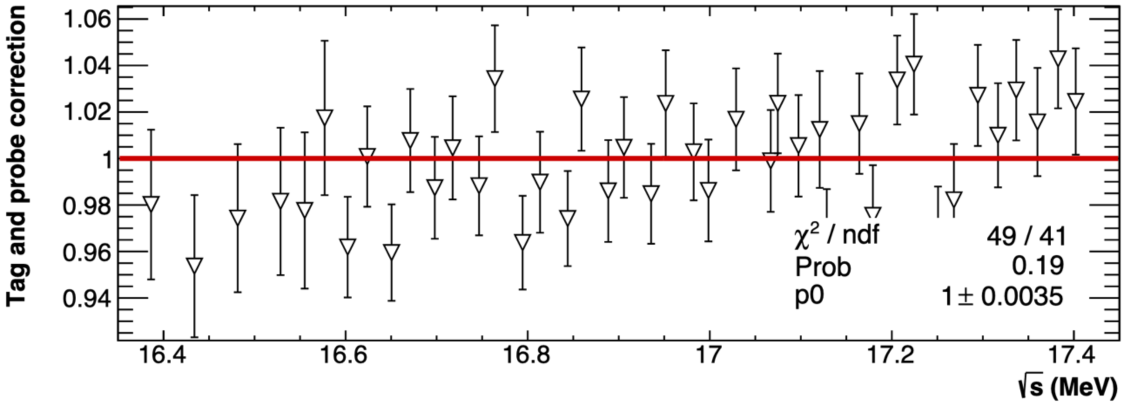
Check of reconstruction efficiency:

Efficiency for data and MC evaluated using tag-and-probe technique
Statistical error dominated by background subtraction at tag level

Data/MC energy-flat, compatible with 1, error O(1%) per period

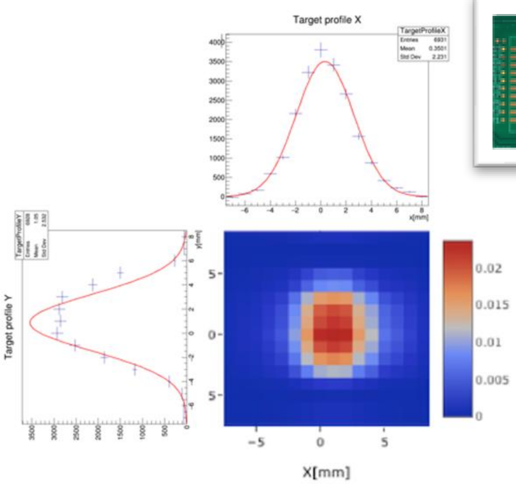
<Data/MC> vs period, P_{Fit}(const) ~ 20%

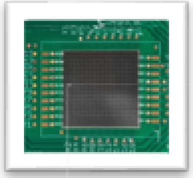
No correction applied per period, statistical-systematic error of 0.35%

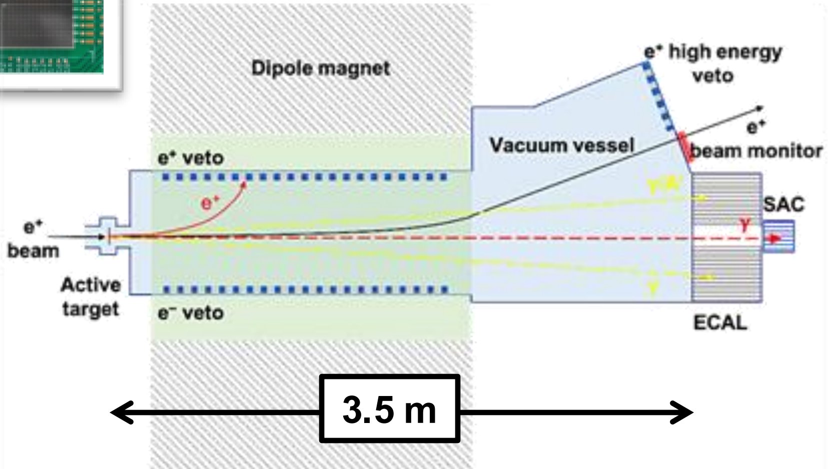


What's PADME – the detector: beam monitors

1.5 × 1.5 mm^2 spot at active, 100 μm diamond target: position, multiplicity
1 × 1 mm^2 pitch X,Y graphite strips [NIM A 162354 (2019)]







CERN MBP-S type dipole: 112×23 mm^2 gap, 70 cm long
Beam monitor (Si pixels, Timepix3) after bending: $\sigma_P/P_{beam} < 0.25\%$

What's PADME – the TDAQ concepts

Three trigger lines: Beam based, Cosmic ray, Random

Trigger and timing based on custom board [2020 IEEE NSS/MIC, doi: 10.1109/NSS/MIC42677.2020.9507995]

Most detectors acquired with Flash ADC's (CAEN V1742), O(10^3) ch's:

- **1 μs digitization time window**
- **1 V dynamic range, 12 bits**
- **sampling rates at 1, 2.5, 5 GS/s**

Level 0 acquisition with zero suppression, ×10 reduction → 200 KB / ev.
Level 1 for event merging and processing, output format ROOT based

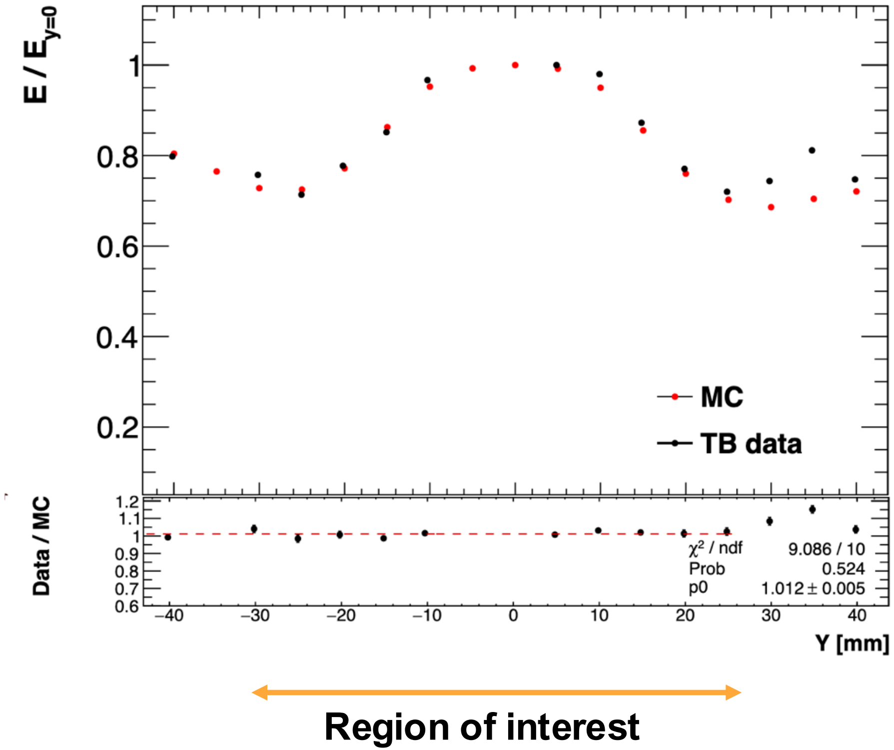
First experiment goal (A' invisible search) required 10^{13} POT, O(80 TB)

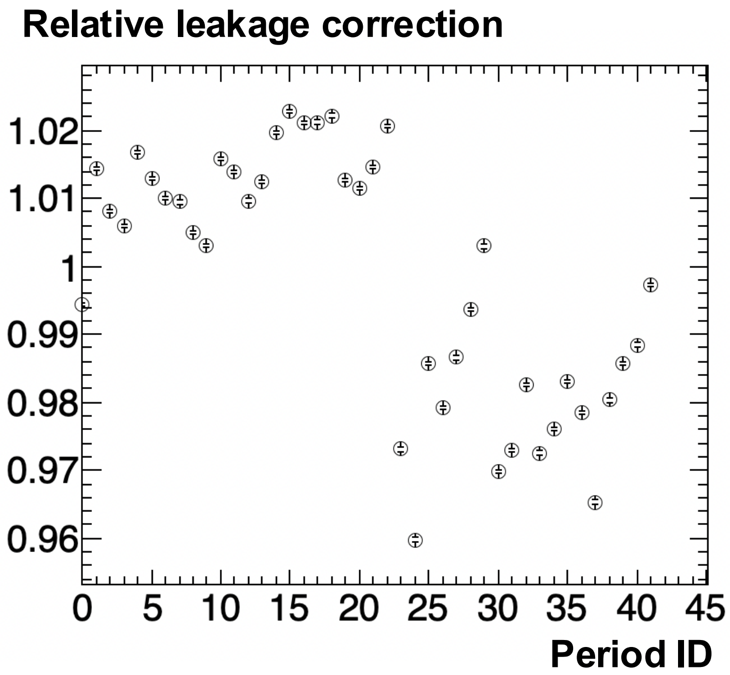
Details on the flux N_{POT}: leakage correction

Loss 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%





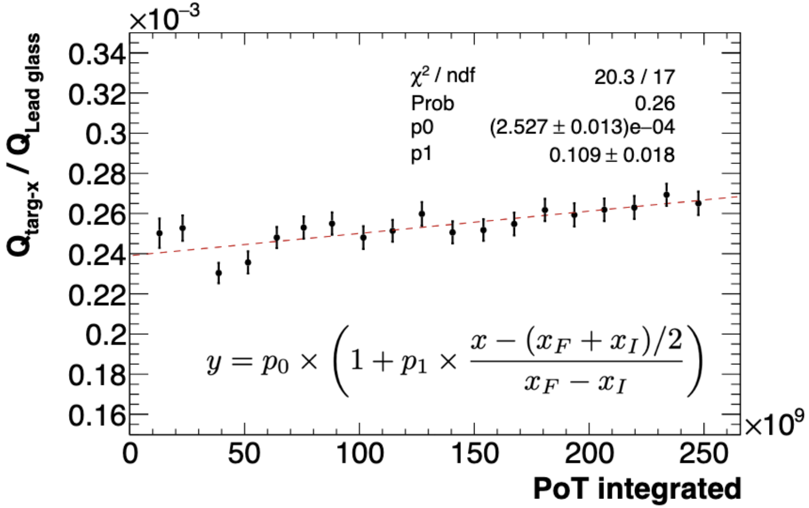
Details on the flux N_{POT}: rad-induced correction

The literature indicates possible changes in SF57 transparency for O(krad)

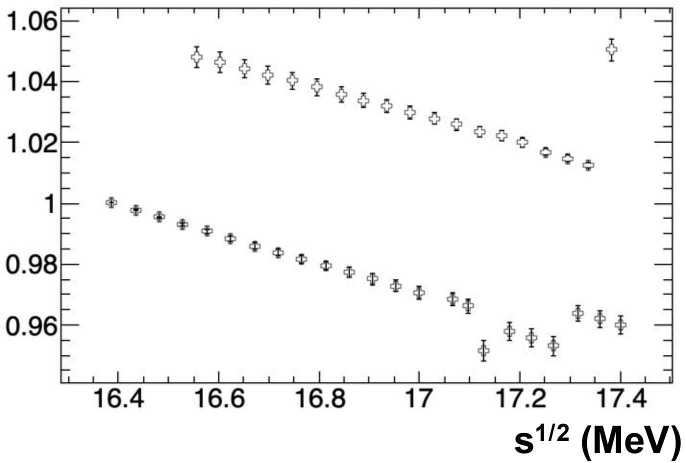
Estimate of Run-III dose: 2.5 krad

Estimated from 3 flux proxy observables: Qx target, <E_{Ecal}>, period multiplets

- Leadglass yield decreases with relative POT slope of 0.097(7)
- Constant term uncertainty of 0.3% added as scale error
- Slope error included in POT uncertainty



Relative rad-induced correction



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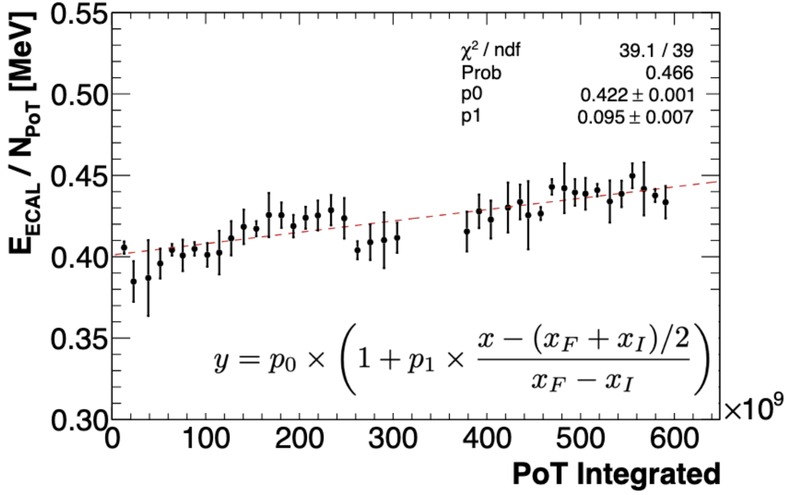
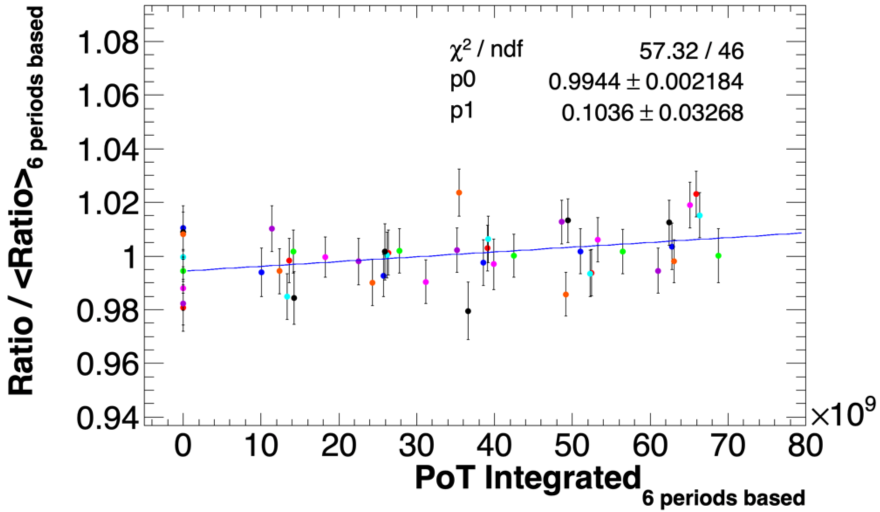




Measurement of $e^+e^- \rightarrow \gamma\gamma$: data set and concept

Using < 10% of Run II data, $N_{POT} = (3.97 \pm 0.16) \times 10^{11}$ positrons on target

- **Expect $N_{ee\rightarrow\gamma\gamma}$ ~0.5 M, statistical uncertainty < 1%**
- **Include various intensities, e^+ time profiles for systematic studies**
- **Evaluate efficiency corrections from MC + data**

Master formula:

$$\sigma_{e^+e^-\rightarrow\gamma\gamma} = \frac{N_{e^+e^-\rightarrow\gamma\gamma}}{N_{POT} \cdot n_{e/S} \cdot A_g \cdot A_{mig} \cdot \epsilon_{e^+e^-\rightarrow\gamma\gamma}}$$

N_{POT} from diamond active target

Uncertainty on e^- density $n_{e/S} = \rho N_A Z/A\, d$ depends on thickness d

Run #	NPOT $[10^{10}]$	e^+/bunch $[10^3]$	length [ns]
30369	8.2	27.0 ± 1.7	260
30386	2.8	19.0 ± 1.4	240
30547	7.1	31.5 ± 1.4	270
30553	2.8	35.8 ± 1.3	260
30563	6.0	26.8 ± 1.2	270
30617	6.1	27.3 ± 1.5	270
30624	6.6	29.5 ± 2.1	270
30654	No-target	~ 27	~ 270
30662	No-Target	~ 27	~ 270

$e^+e^- \rightarrow \gamma\gamma$: POT, target thickness

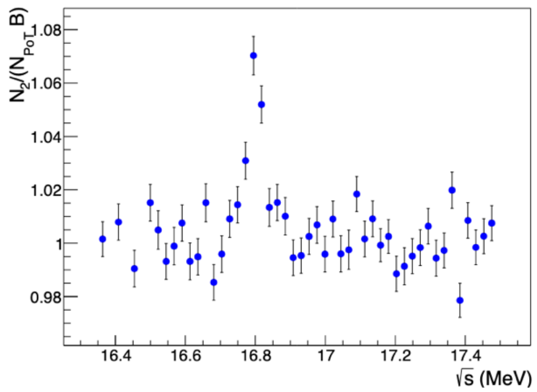
N_{POT} **from active target, uncertainty is 4%:**

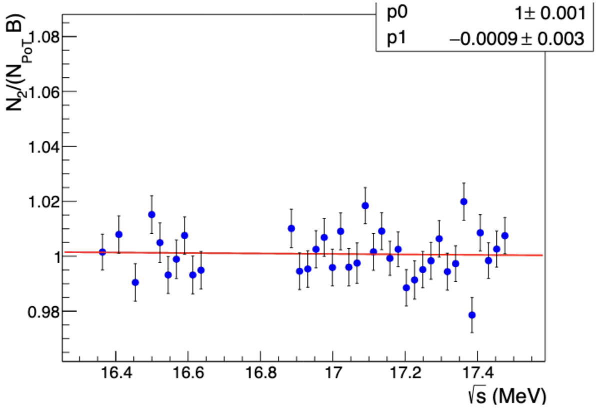
1. **Absolute calibration by comparing with lead-glass calorimeter fully contained from 5k to 35k e+/bunch**
2. **When focusing beam into 1-2 strips, non-linear effects observed**

$n_{e/S}$ **from target thickness, uncertainty is 3.7% (i.e., ~3.7 μm)**

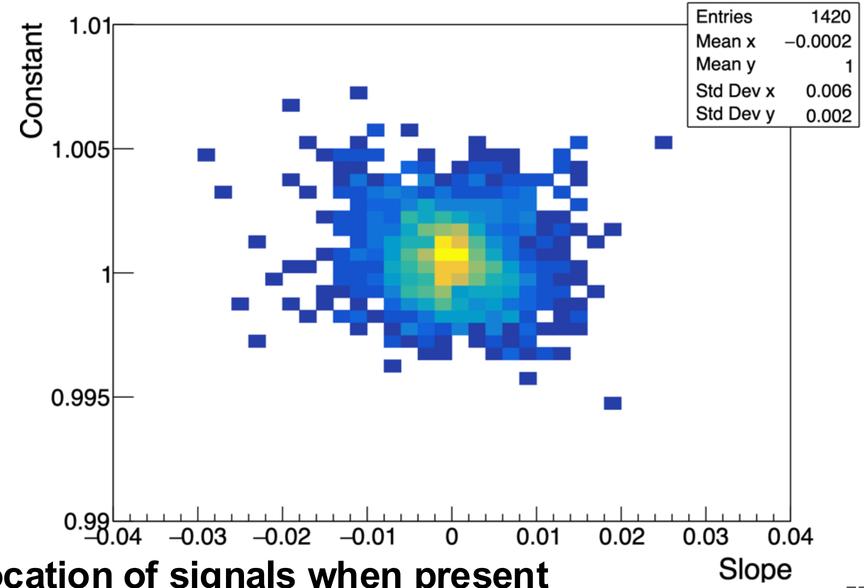
1. **Measured after assembly with profilometer with 1 μm resolution as difference with respect to the supporting surface**
2. **Correction due to roughness (quoted as 3.2 μm by producer): compare precision mass and thickness measurements on similar diamond samples**

The blind unblinding procedure: details





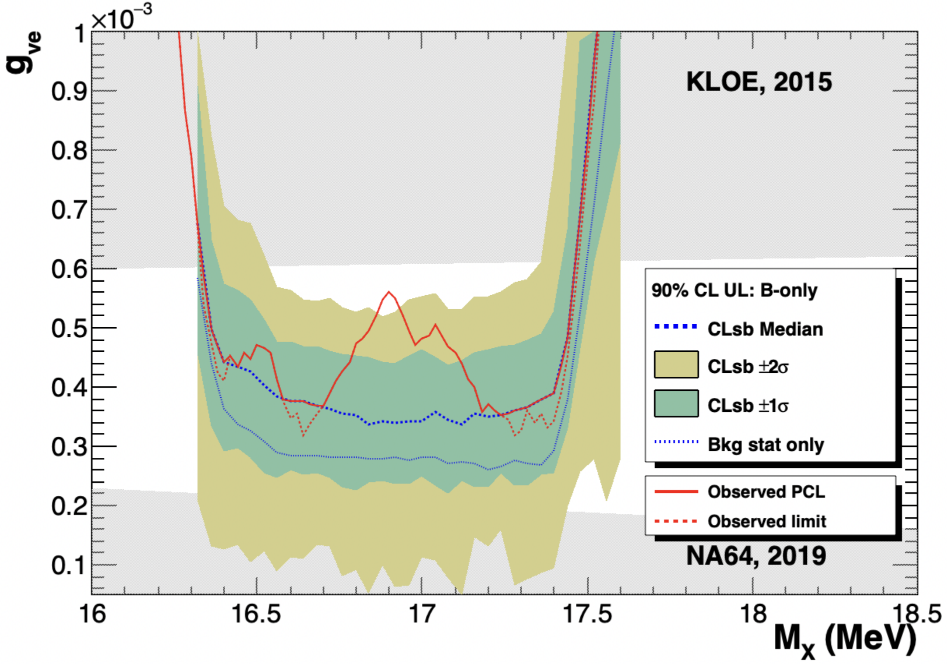
Constant term and slope of the optimized fit estimate the true values for K(s)
Results of the procedure ran on toy experiments with constant = 1, slope = 0



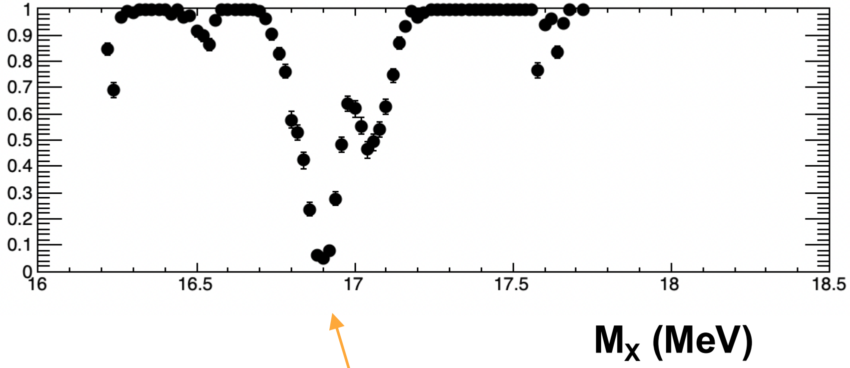
Moreover the procedure correctly finds the central location of signals when present

The PCL method

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



Global p-value



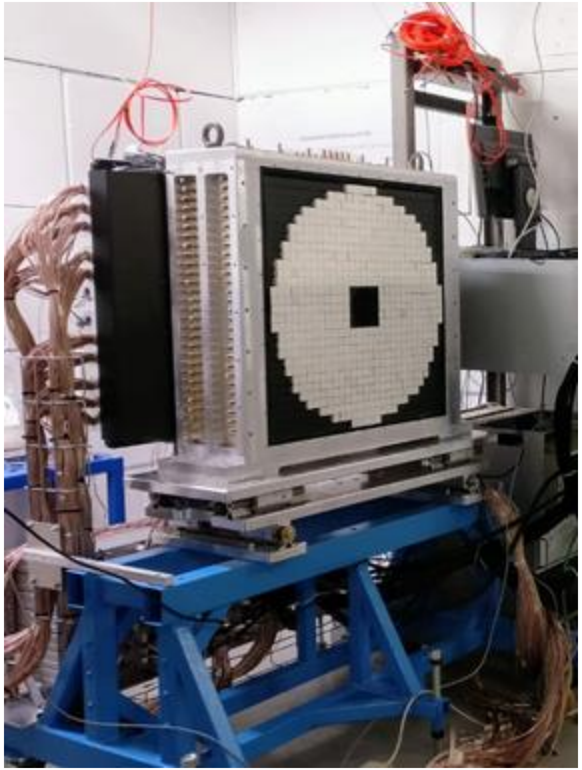
equivalent to (1.63 +- 0.13) σ

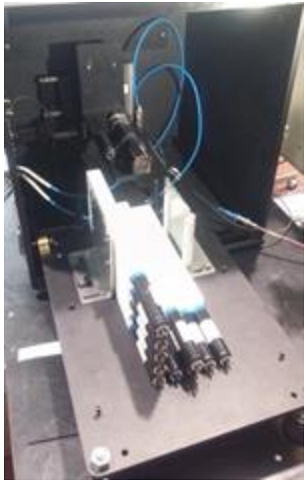
The global p-value is only slightly affected, consistent with the coverage modifications of this method

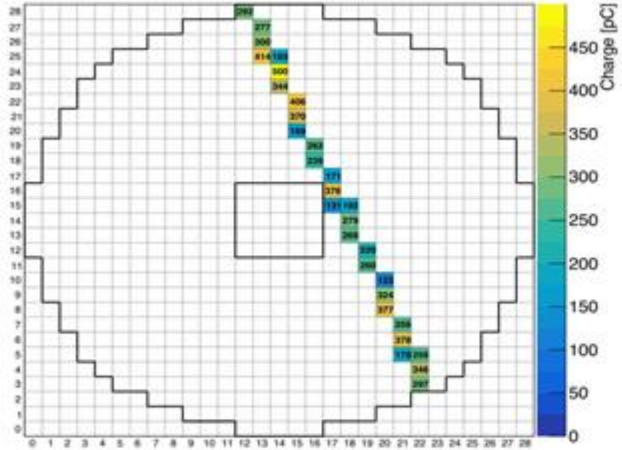
The PADME ECal

The main detector for the signal selection [JINST 15 (2020) T10003]:

- 616 BGO crystals, 2.1 x 2.1 x 23 cm^3
- BGO covered with diffuse reflective TiO_2 paint + 50–100 μm black tedlar foils (optical isolation)







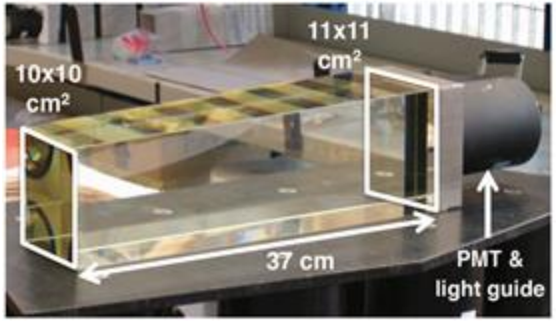
Calibration at several stages:

- BGO + PMT equalization with ^{22}Na source before construction
- Cosmic-ray calibration using the MPV of the spectrum
- Temperature monitoring + scale correction data driven

The PADME beam catcher calorimeter

The main detector for the flux determination [JHEP 08 (2024) 121]:

- SF57 block, reused from OPAL, tested for the NA62 LAV detector [JINST 12 (2017) 05, P05025]
- Several testing campaigns
  - A few positrons
  - O(2000) PoT - cross-calibration with the BTF FitPix



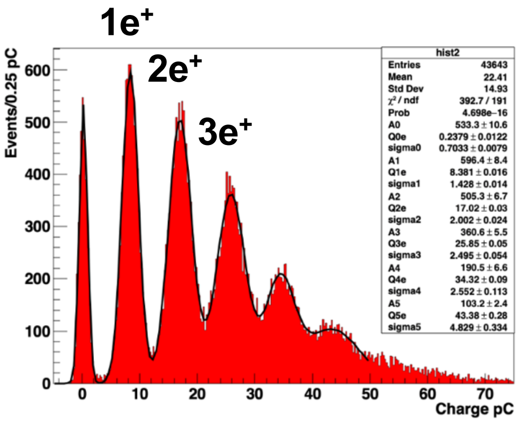


Figure 16. Single particle charge spectrum.

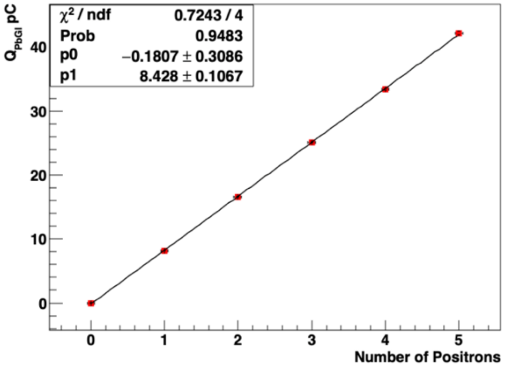
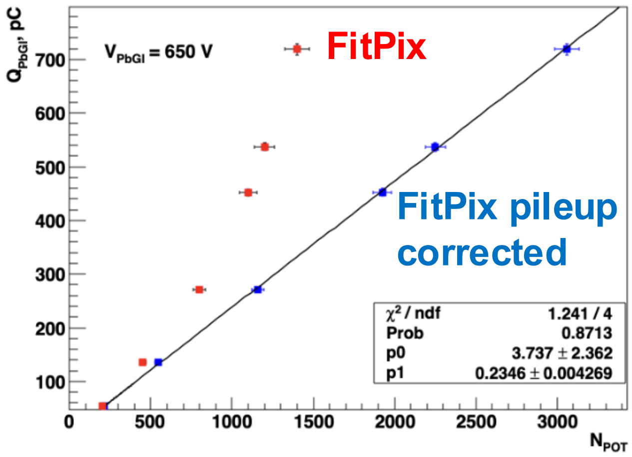


Figure 17. Fit to the single particle response.

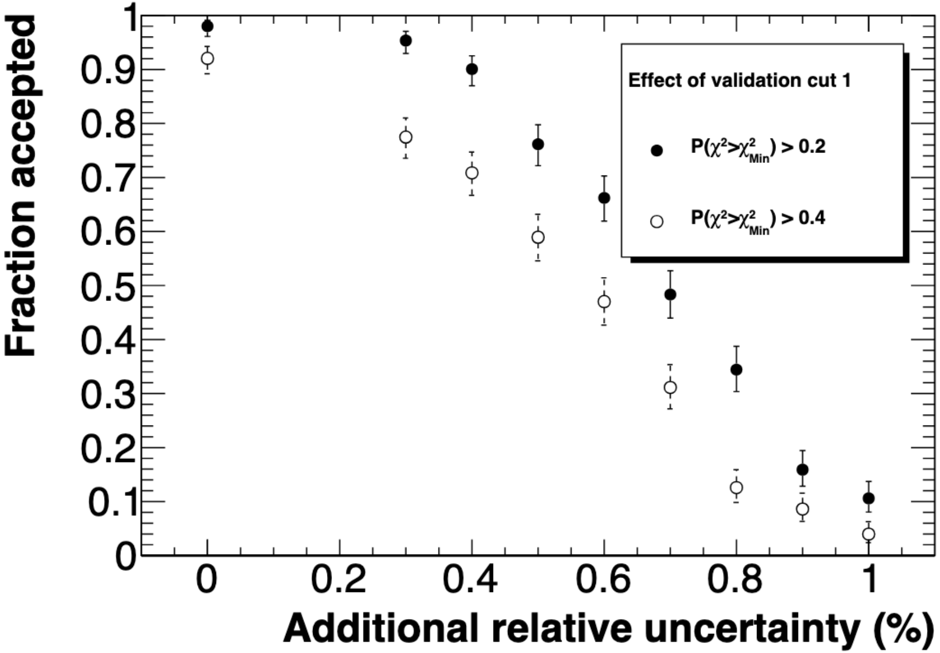


The blind unblinding constraining power

Determine the number of times an experiment outcome would be rejected in presence of additional uncorrelated errorsx

- With the cut applied, errors > 1% are excluded at 90% CL

- Had we put a tighter condition, we would have excluded additional errors at 0.8% but at the cost of risking to reject by statistical fluctuations ~8% of the outcomes



The new micromega-based tracker

Detector installed with the novel diamon-shaped readout

- Outer dimensions 88 x 88 cm^2
- Readout by APV25
- Time window up to 675 ns (drift time ~500 ns)
- Gas mixture: Ar:CF_4:Isobutane = 88:10:2
- Provides beam spot with uncertainty $\sigma_{x,y}$ ~ 30 μm
- Track points with $\sigma_{x,y}$ ~ 350 μm and σ_z ~ 2 mm per point