The Golden Age of Cataclysmic Variables and Related Objects – VII
Palermo, 1 Sept. 2025

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

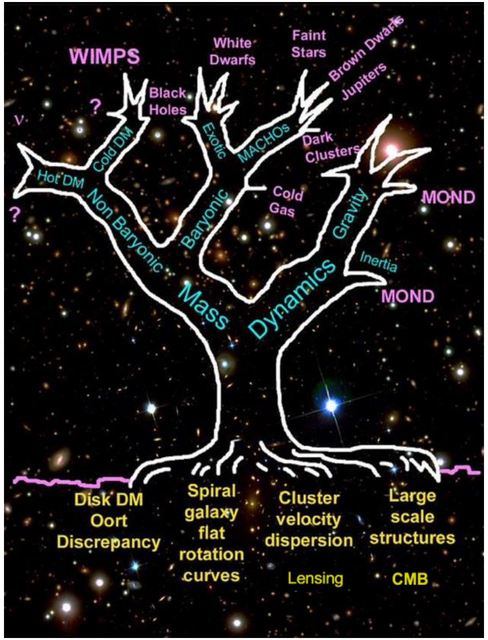
Paolo Valente

INFN ROMA

on behalf of the PADME Collaboration

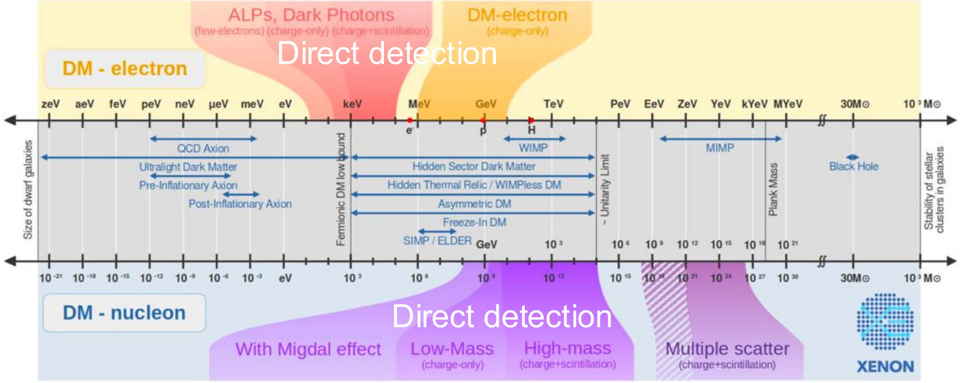
Dark matter

DM **evidence** vs. **models**



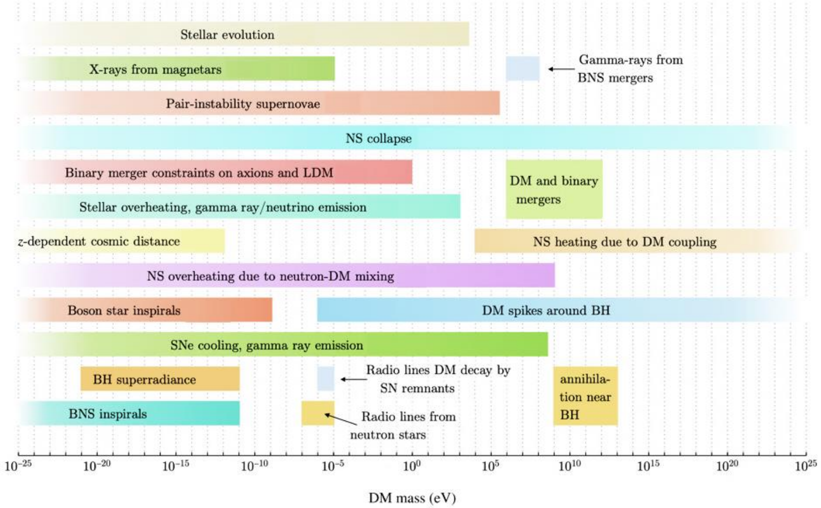
Stacy McGaugh

DM mass range: explore **50 orders of magnitude** …and more



Luca Scotto Lavina

DM mass vs. **astrophysics**



arXiv:2203.07984

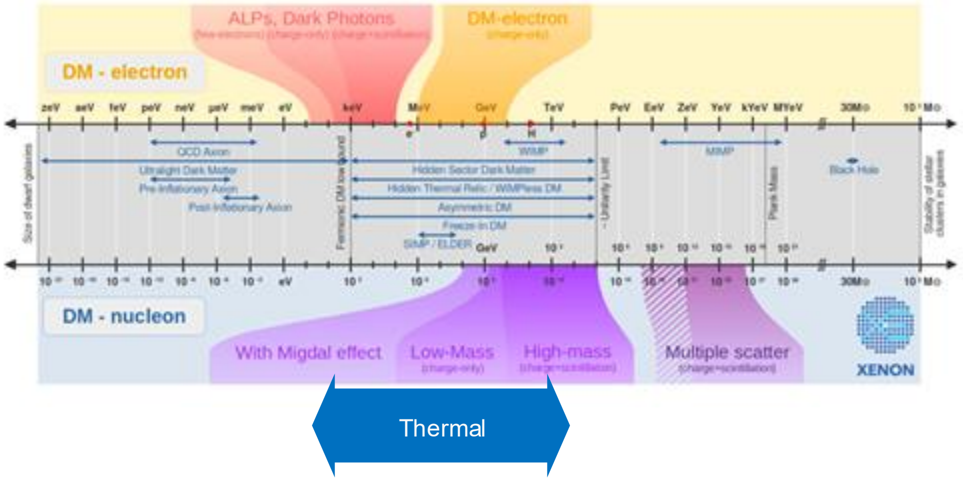
Dark sector

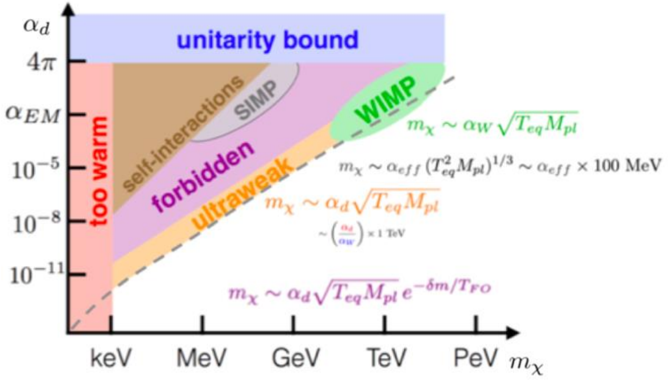
Extending the **WIMP mass range** but still in **thermal equilibrium**:

MeV-GeV "hidden-sector" states, **neutral under SM interactions**, interacting **[very feebly] with SM particles** via **new forces**

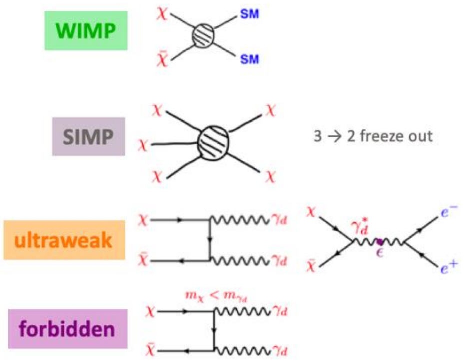
- **"Portal"** particles, not necessarily **DM candidates**
- **Multiple dark states** possible, in principle an entire **hidden sector**

This also allows to dark particles to be **produced at a [SM] particle accelerator**





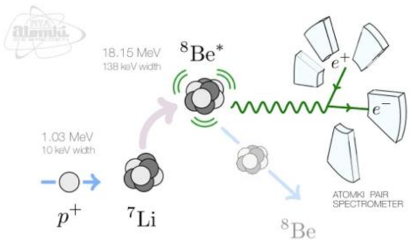
J. Ruderman

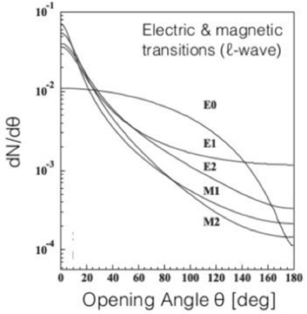


X17 “anomalies”

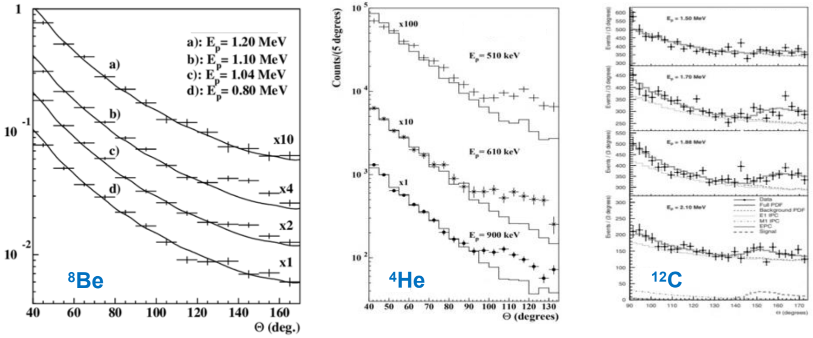
Experiments at **ATOMKI** lab [Debrecen, Hungary]:

- **Nuclear levels** are excited by a proton beam on a target nucleus [e.g. ***p* + ^{7}Li** producing **^{8}Be***]
- Then the radiative deexcitation is detected, in which the photon is **internally converted** in an electron-positron pair [^{7}Li(p, e^+e^-)^{8}Be]
- **Anomalies** observed in the **angular correlations of e^+e^- pairs**

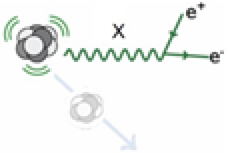




Anomaly first observed in the **decays of ^{8}Be***, then also in the deexcitation of **^{4}He*** and **^{12}C***; more recently, even in the **GDR**.



Interpreted with a **new particle** of mass approximately **17 MeV**



Observed **also at HUS (Vietnam)** in the **^{8}Be* with a different setup** [Universe 2024, 10(4)]

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X17 "anomalies"

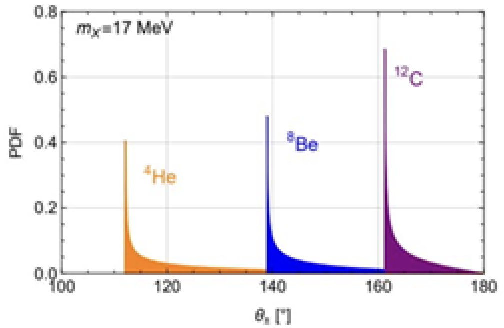
Excesses approximately consistent with the decay of a particle of mass M_X in a $N^* \rightarrow N\, X_{17}$ transition **[PRD108, 015009 (2023)] at:**

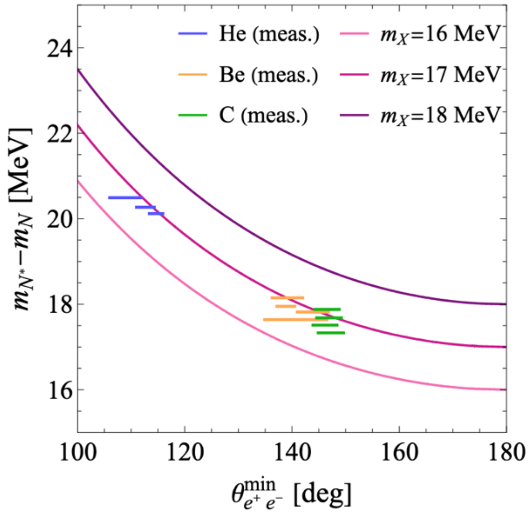
$$\theta_{min} \sim asin\left(\frac{M_X}{M_{N*} - M_N}\right);$$

^{8}Be: M_X = (16.70 ± 0.35$_{stat}$ ± 0.5$_{syst}$) MeV [PRL 116 (2016) 042501]
^{4}He: M_X = (16.94 ± 0.12$_{stat}$ ± 0.21$_{syst}$) MeV [PR C 104 (2021) 044003]
^{12}C: M_X = (17.03 ± 0.11$_{stat}$ ± 0.20$_{syst}$) MeV [PR C 106, L061601 (2022)]

Combining: **M_X=(16.85 ± 0.04) MeV**; χ^2=17.3, ndf=10, P(χ^2) = 7%

Rate measurements indicate: $\frac{\Gamma(N^* \rightarrow N\, X_{17})}{\Gamma(N^* \rightarrow N\, \gamma)} \sim$ **5x10^{-6}**

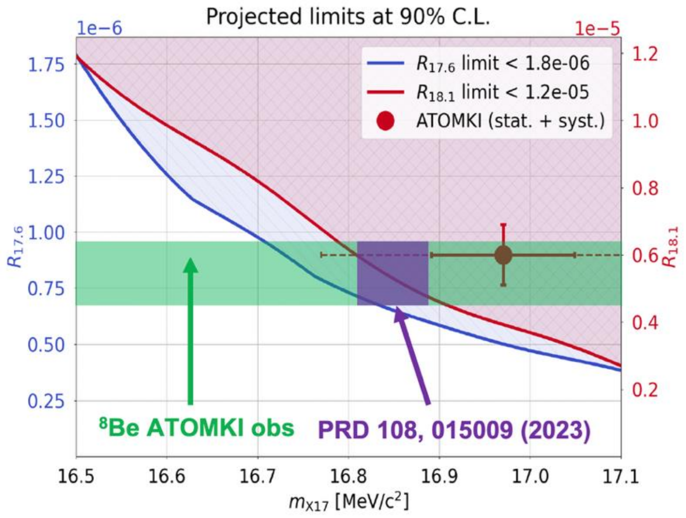




Ongoing experimental initiatives

Recent result from MEG II [arXiv:2411.07994]

- Measurement on ^{7}Li target to reproduce ^{8}Be ATOMKI result, **no excess found**
- **Upper limits** on $\Gamma(^8Be^* \rightarrow {}^8Be\ X(ee)) / \Gamma(^8Be^* \rightarrow {}^8Be\ \gamma)$ for **17.6** and **18.1 MeV** transitions



MEG-II result **still compatible at 1.5σ** with the ATOMKI combination M_X **= 16.85(4) MeV**
[JHEP 04 (2025) 035]

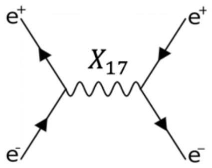
More experimental initiatives:

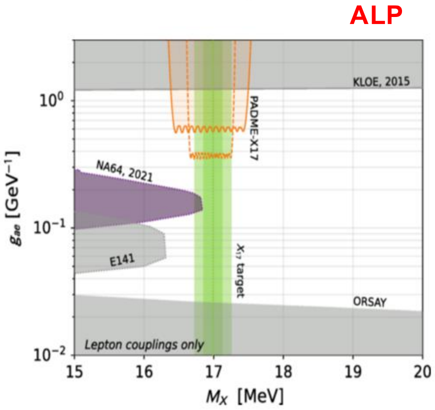
- **AN2000** electrostatic accelerator at INFN LNL [Taking data]
- At **n_TOF EAR2** neutron line at CERN [2025 proposal]
- **Tandem** accelerator in **Montreal** [JPC Ser. 2391 (2022) 012008]
- **Van de Graaf** accelerator at **IEAP Prague** [NIM A 1047 (2023) 167858]

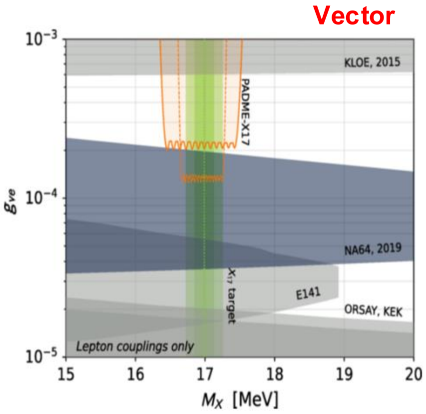
Search for a resonance on a thin target

If **X17 exists** and **decays** to e^+e^- pairs, it should also be **produced** in e^+e^- **annihilations**

Considered **pseudoscalar** (axion-like particle) and **vector** possibilities **[PRD 106 (2022) 115036]**







$\sigma \sim \alpha_{em}$ → **dominant process** wrt other pair production processes (α_{em}^2, α_{em}^3):

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

Expected **enhancement** of cross section over the SM background when $\sqrt{s}$ is close to the expected mass

Thus:

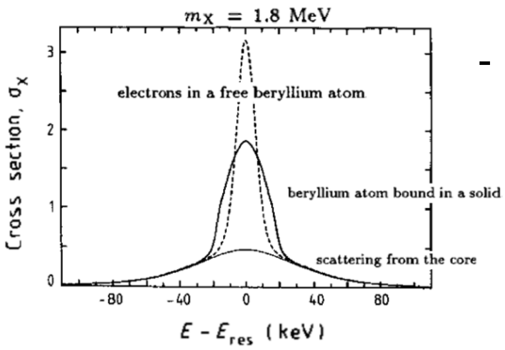
→ Fine **scan the e^+ beam energy** around the **resonance** [E_{e+}~283 MeV]

→ **Measure two-body final state yield for each energy point**

→ Cover the ATOMKI mass range [16.5 – 17.5 MeV]

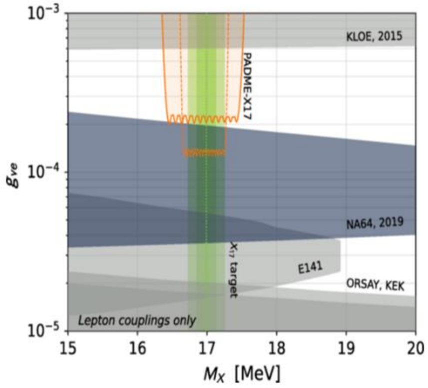
Search for a resonance on a thin target

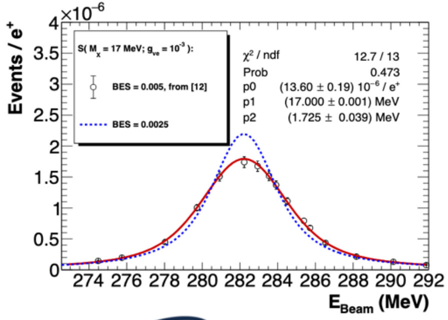
- X17 expected to be much narrower than the **spread** of the positron beam (width≈**beam energy spread**)
- **Step** of the **scan** chosen optimizing the coverage vs. width ["wavy" sensitivity]



- Not negligible broadening of the peak due to the **electron binding** energy
  [Rep. Prog. Phys. 54 (1991) 1]

Vector





- Line shape parameterized with **convolution** of **Lorentzian** and beam spread **Gaussian** [aka **Voigt** function]

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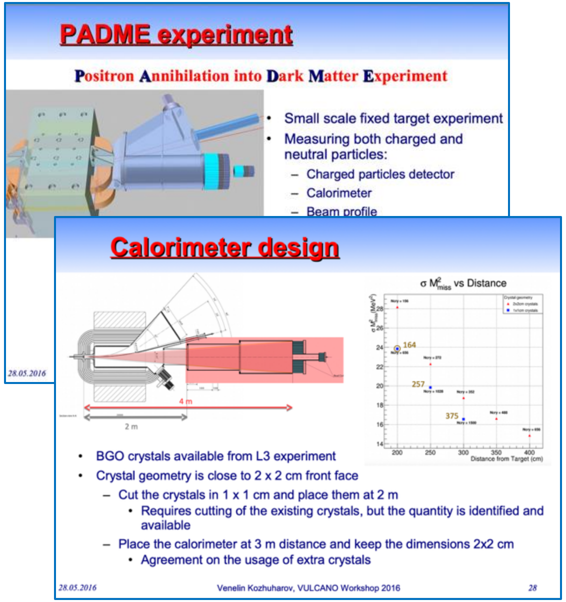
Experimental setup

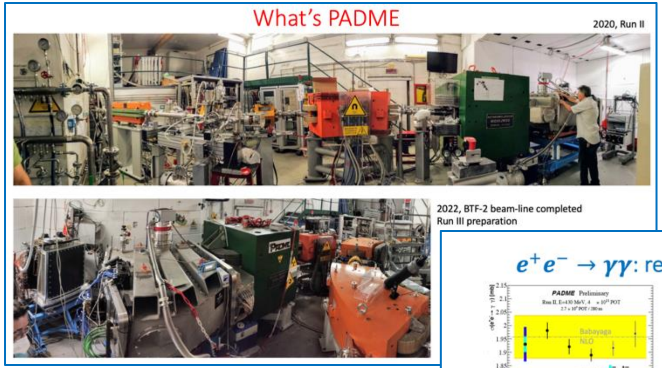
PADME initially designed for searching **invisible decays** of a **dark photon** in **associated production**: $e^+e^- \to A'\gamma$ [**Run I** and **Run II**]:

- $\sim$500 MeV e^+ beam on thin [0.1 mm] all-Carbon **active target** [PCD **diamond** with graphite strips]
- Detect **photon clusters** in a finely segmented [616, 2,1x2,1x23 cm^3] BGO calorimeter and reconstruct missing 4-momentum [$\Delta M^2_{\text{missing}}$].
- **Sweep** beam with a dipole and **veto charged particles** with plastic scintillators
- $e^+e^- \to \gamma\gamma$ cross section measurement <20 MeV **[PRD 107 (2023) 1, 012008]**



Vulcano 2016

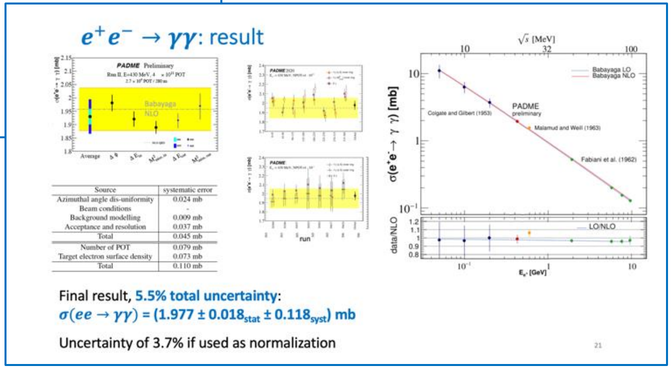
Still on paper

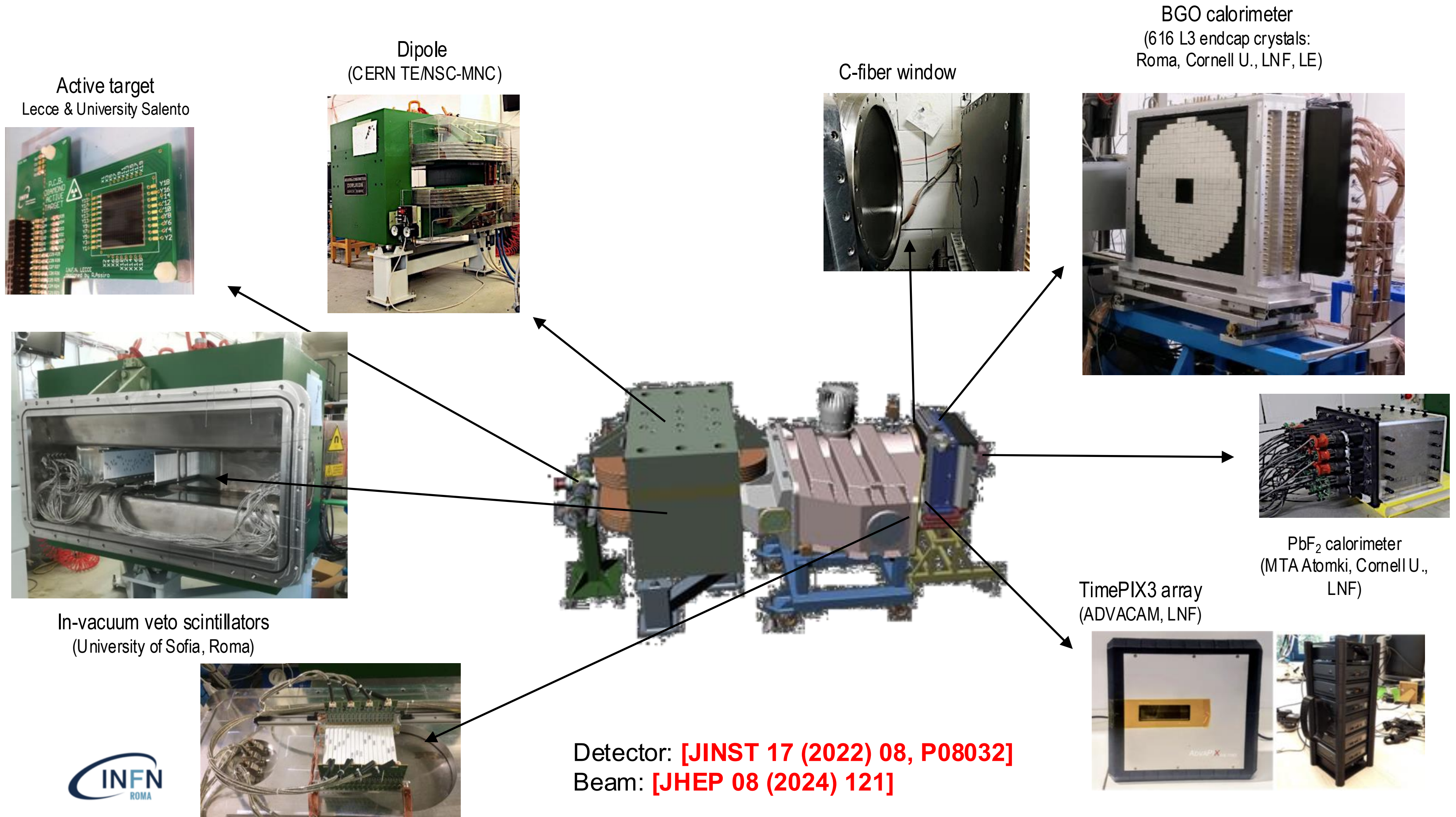


Vulcano 2022

Run I & II completed

Ready for Run III





Detector: **[JINST 17 (2022) 08, P08032]**
Beam: **[JHEP 08 (2024) 121]**

Experimental setup

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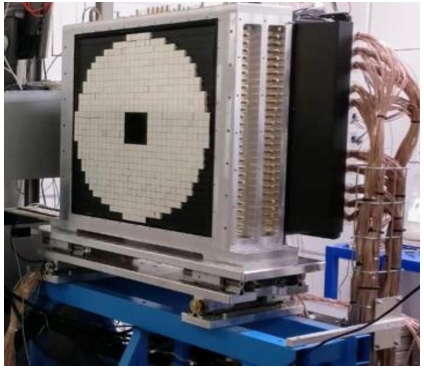
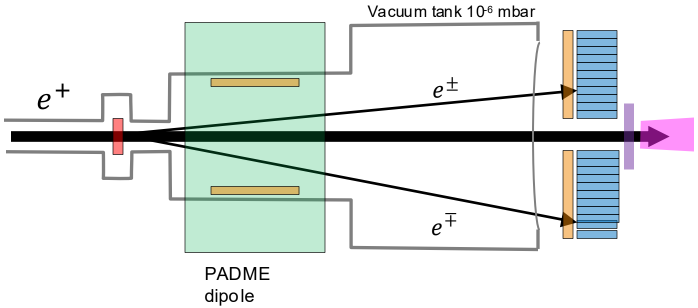
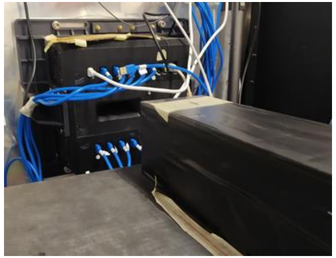


In **2022** setup **specifically adapted** for the **resonant search** $e^+e^- \to X$ [**Run-III**], in particular:

- No magnetic field [dipole off]
- New scintillating bars hodoscope in front of calorimeter for **e/γ separation**
- Timepix silicon detector array for **beam spot monitoring**
- Lead-glass **beam catcher/luminometer** (OPAL/NA62 LAV)

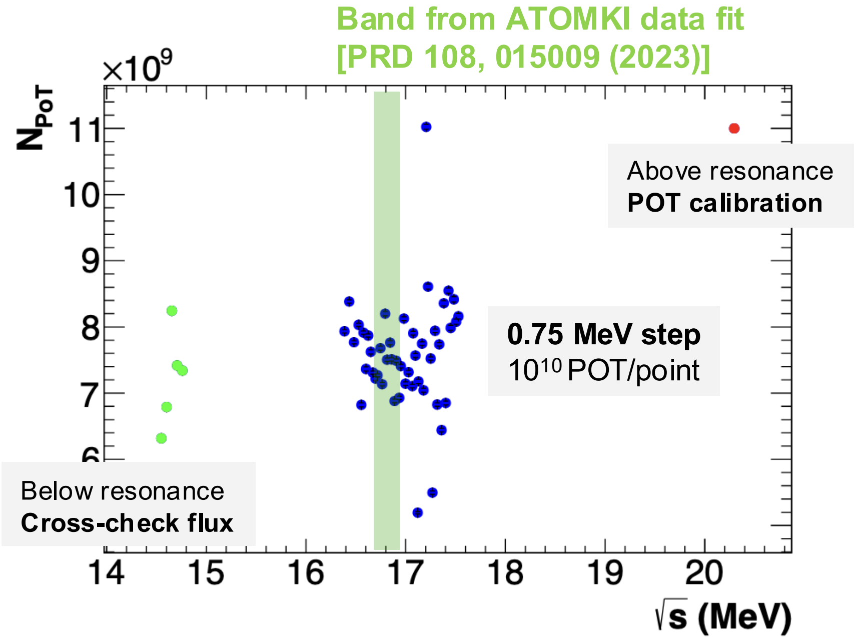


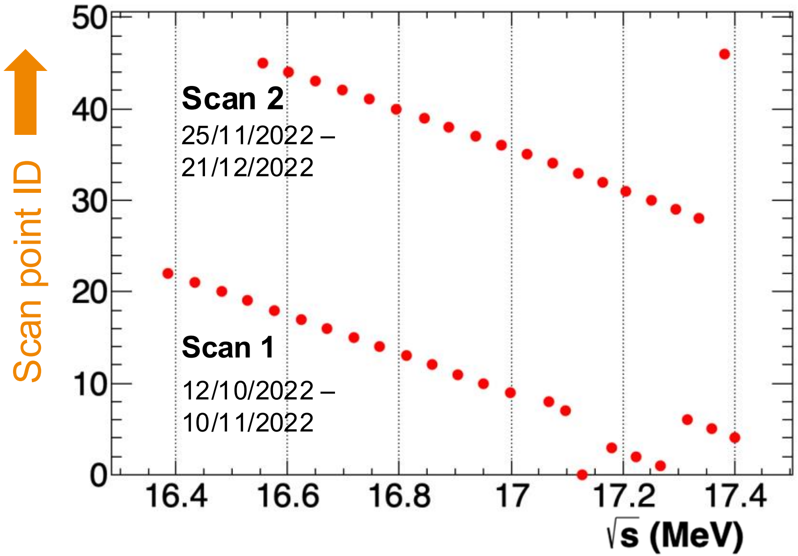


Run III data set

Actually, **two interleaved scans**, **1.5 MeV step**

Nearby energy points acquired **1.5 months** apart





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Search for a resonance on a thin target

N_2	number of **two-cluster events selected**
$N_{POT}(s)$	number of **positrons on target** from **beam catcher** calorimeter
$B(s)$	expected **background** yield **per POT**
$S(s; M_X, g)$	expected **signal per POT** for given {mass, coupling} = $\{M_X, g\}$
$\varepsilon_S(s)$	**signal acceptance** and selection **efficiency**

Evaluated by Monte Carlo

Compare: $N_2(s) = N_{POT}(s) \times \{B(s) + S(s; M_X, g) \times \varepsilon_S(s)\}$ in presence of **X17 signal**

$N_2(s) = N_{POT}(s) \times B(s)$ if **only SM**

Rewriting in terms of

$$g_R(s) = \frac{N_2(s)}{N_{POT}(s)\, B(s)}$$

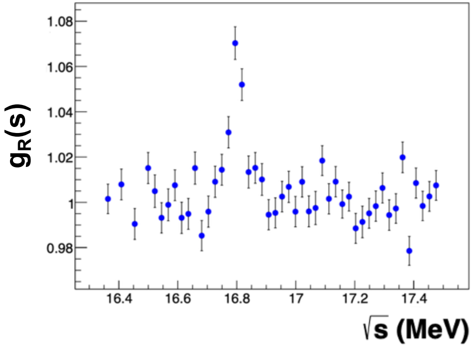
should be = 1 if only SM "**background**"

Different effects can lead to a deviation in **data** wrt **Monte Carlo**, thus introduce a **scale factor**, **K(s)**, with a possible dependance from s:

$$g_R(s) = \left\{1 + \frac{S(s; MX, g)\ \varepsilon_S(s)}{B(s)}\right\} \times K(s)$$

and **compare** with $g_R(s) = K(s)$ only, i.e. **absence of a X17 signal** on top of the SM

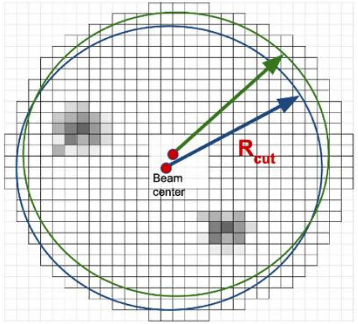
MC: M_X = 16.8 MeV, $g_V = 8\times10^{-4}$

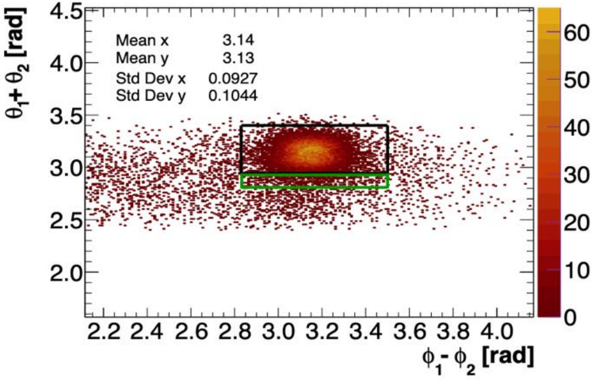


Two-cluster events selection N_2

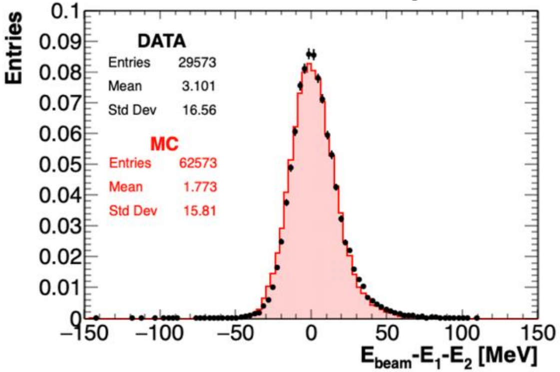
Selection algorithm as **independent** as possible **on the beam variations:**

- Retune **beam center** run by run with an error ≪ **mm**
- Overall, make **marginal use** of the cluster **reconstructed energy**
- Cut in azimuthal angle due to passive material induced background
- Neglecting **m_e/E terms**, center of mass angles **independent on the lab energies**: **select** back-to-back cluster pairs
- Background: **Bremsstrahlung** tail [on vacuum separation window] evaluated in **sideband** in $\theta_1 + \theta_2$; flat in $\phi_1 - \phi_2$
- ”Cleaning” cuts on ΔR and Δt
- **30k events** /energy point





Selected events **4% background**



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

Luminosity N_{POT}

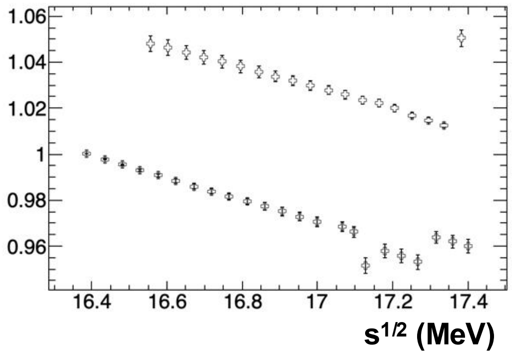
- PoTs measured with the beam catcher calorimeter [lead glass] ❼ 2% scale error [calibration]
- 2 main effects: **radiation induced loss + energy loss in passive material** [variations of crossed passive material due to beam movements]

Source	Uncorrelated error on N_{POT} [%]
Statistics, ped subtraction	negligible
Energy scale from BES	0.3
Error from rad. induced loss, **slope**	Variable, ~0.35
Total	**0.45**

BES from Timepix **beam spot** σ_x

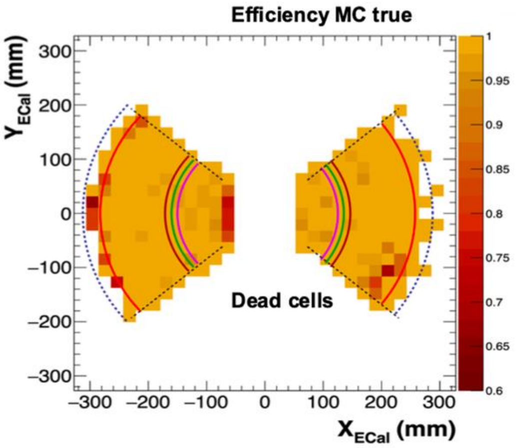
Source	Common error on N_{POT} [%]
pC / MeV	2.0 [JHEP 08 (2024) 121]
Energy loss, data/MC	0.5
Rad. induced loss, **constant term**	0.3
Total	**2.1**

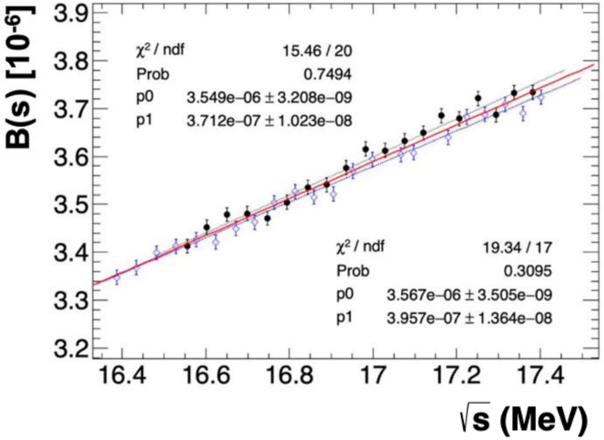
Relative rad-induced correction



Expected background B

- **Expected background B(s)** determined by MC + data-driven checks: **tag and probe**
- **Linear** dependence from s
  - Fit used only as a **check**
  - B(s) expectation is compared to **below resonance** points
- Common systematic errors enter in the **scale K(s)**: radiative corrections [~3%], target thickness [~4%]



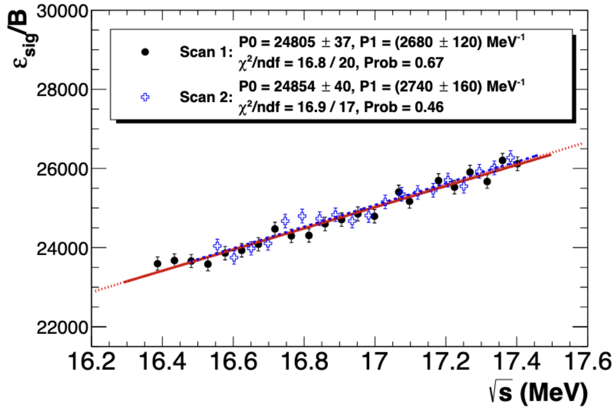


Source	Error on B [%]
MC statistics	0.4
Data/MC (tag&probe)	0.2
Cut stability	0.2
Beam spot	0.1
Total	**0.5**

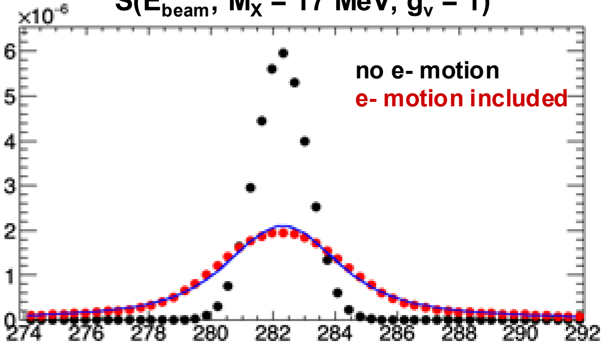
Signal acceptance and efficiency ε

- Compare $g_R(s)$ to K(s) × [1 + S(s; M,g_v) ε/B]: large **cancellation** of **systematic errors**
- Efficiency ε **determined from MC**
- Fit ε/B($s^{1/2}$) with a **straight line**, include **fit parameters as nuisances** [2 parameters]
  - **Separate fits** for **scan 1** and **scan 2**, mutually **compatible**
  - Reproduced with Monte Carlo
- Uncertainty on **signal shape**: 3 **nuisance parameters** [fit of Voigt function]

δP0/P0 ~ 0.1%,
δP1/P1 = 3%, correlation = -2.5%



S(E_{beam}; M_X = 17 MeV, g_v = 1)



Peak **yield**: uncertainty 1.3%
Lorentzian width: 1.72(4) MeV
Relative **BES**: 0.025(5)%

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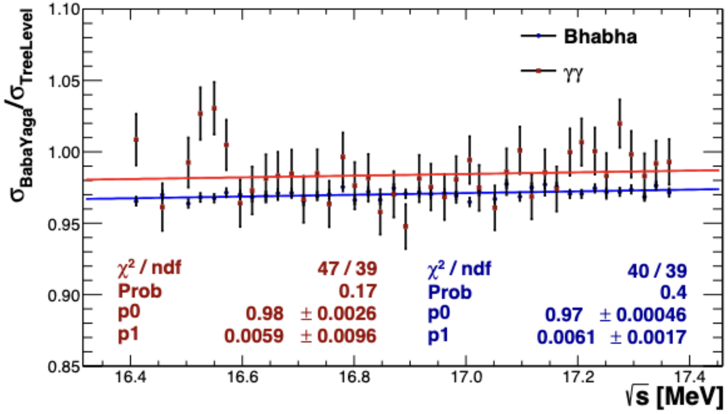
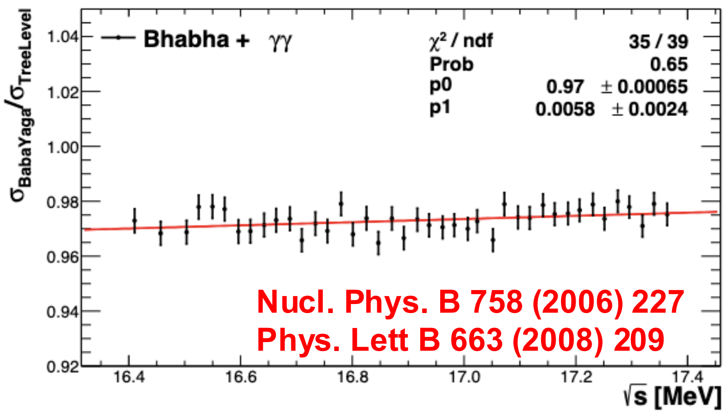
Scale effects, K(s)

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





Fit to linear function: **2 nuisance parameters** in the analysis

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

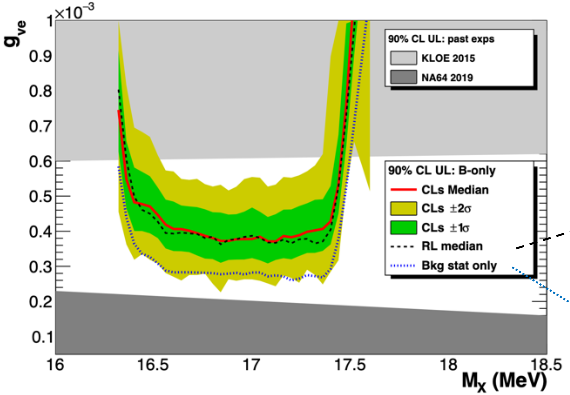
Insertion of **Babayaga-generated events in the MC** (up to 10 γ's) → **no effect on ε**

Sensitivity

- Evaluate expected **90% CL upper limit** in absence of signal
- Likelihood fits on separate assumption of Background only and Signal+Background
- Define **Q statistic** based on **likelihood ratio**: $Q = \frac{L_{S+B}(g_v, MX)}{L_B}$
- The **likelihood** includes terms for each nuisance parameter pdf
- For a **given** M_X compute $CLs = \frac{P_S}{1 - PB}$ used to define the **UL on** g_v

Probabilities P_S and P_B obtained using **simulations**, where the observables are always **sampled**, and with the nuisance parameters fixed to the B and S+B fits

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

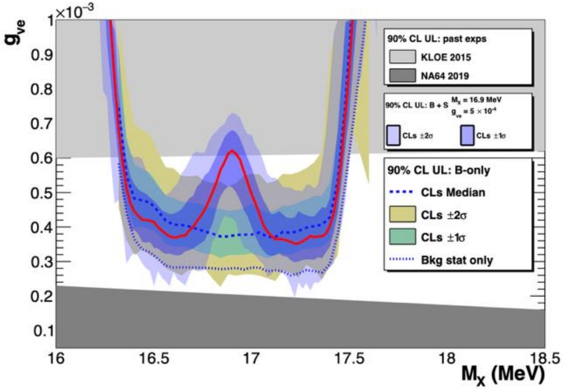


Expected limit [MC]
Background-only

Median of the limits using the Rolke-Lopez likelihood-ranking method with the 5 energy points with largest signal yield

$1.28\sqrt{N_2}$

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



Expected limit [MC]
Signal+Background
(16.9 MeV, 5 × 10^{-4})

INFN ROMA

For details: [arXiv:2505.24797]

The "blind unblinding" procedure

To validate the error estimate applied procedure described in **[JHEP 06 (2025) 040]**

Define a **side-band** in $g_R(s)$, **excluding 10 energy points** of the scan in a **blind way**

Masked periods **defined** by **optimizing** the probability of a **linear fit** in $\sqrt{\mathbf{s}}$

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}

At **90%CL** additional errors **<1%**

Proceed to box opening

INFN ROMA

Run III result

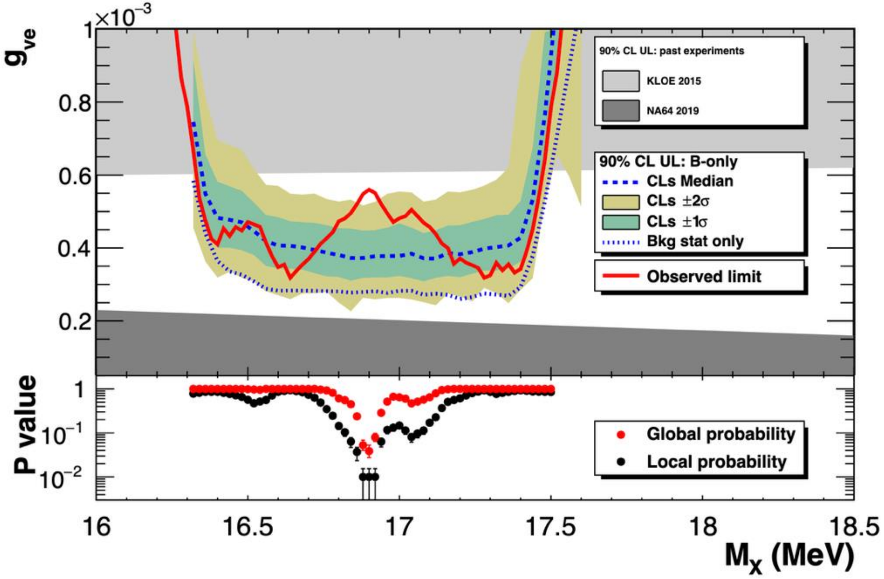
Excess is observed **beyond** the **2σ** coverage **(2.5 σ local)**

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%

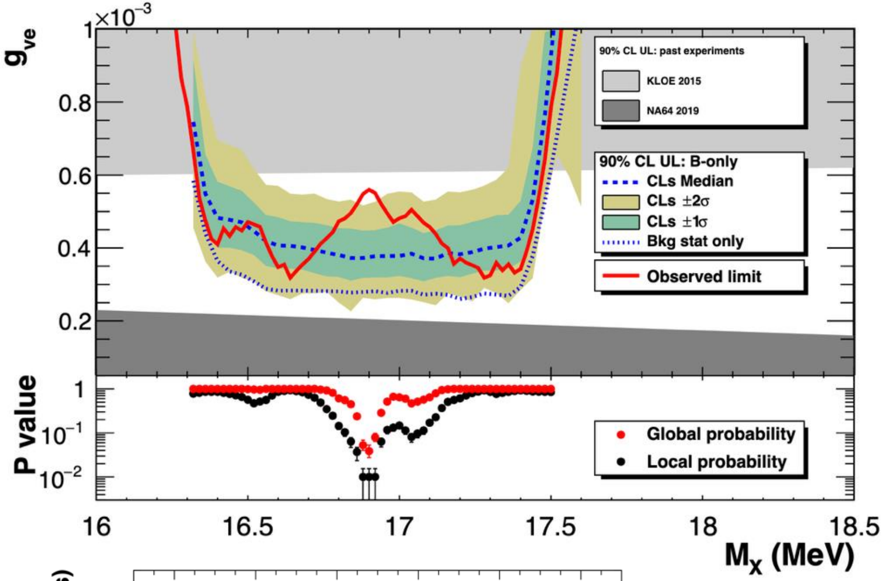
If a **3σ interval** is assumed for observation following the estimate **M_X = 16.85(4)** of **PRD 108, 015009 (2023)**, the p-value dip deepens to **$2.2_{-0.8}^{+1.2}$%** corresponding to **(2.0±0.2) σ one-sided**

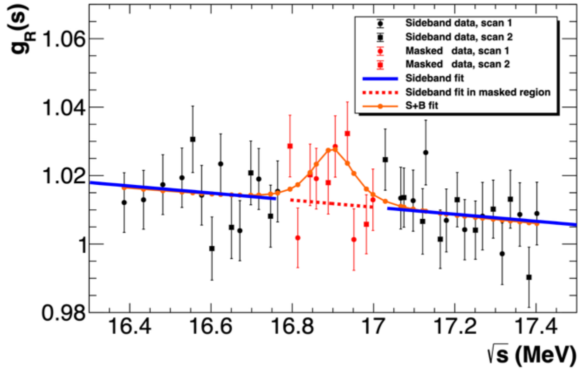


Run III result

Check the **data distribution** vs. **likelihood fit** to evaluate $Q_{obs}(S+B)$

Fit probability is 60%

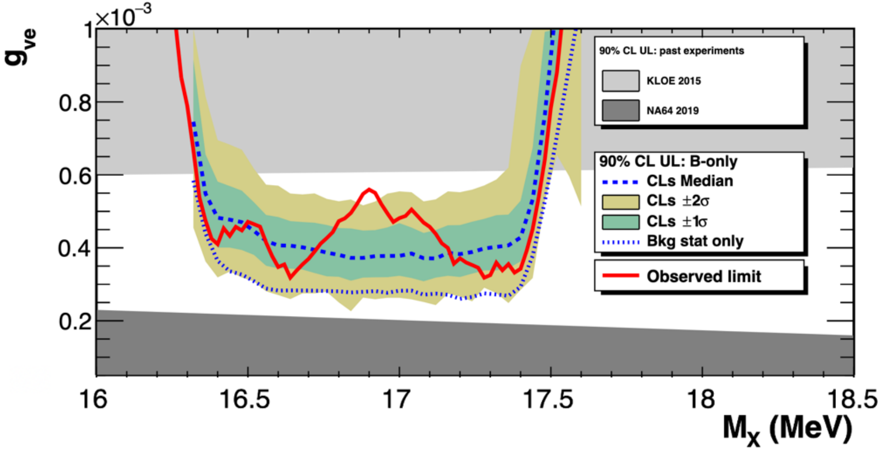


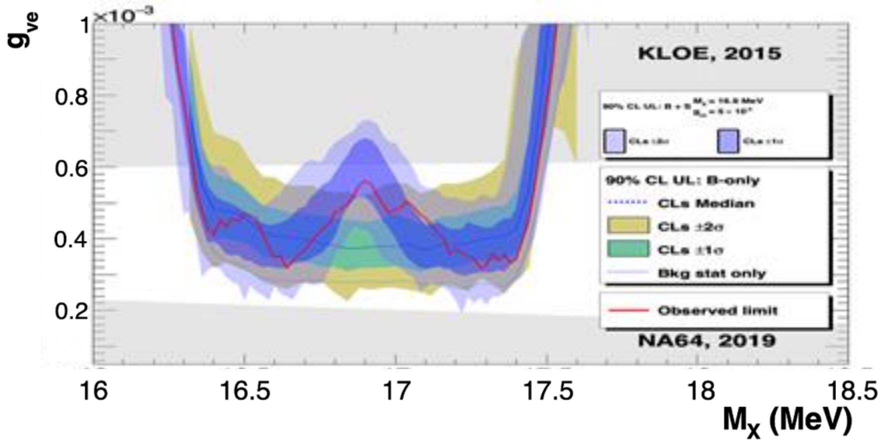


In red: region masked by the automatic blinding procedure

Run III result

For comparison:
Check the **expected UL bands** in the **Background-only** hypothesis
vs.
Signal+Background(16.9 MeV, 5 × 10^-4^)





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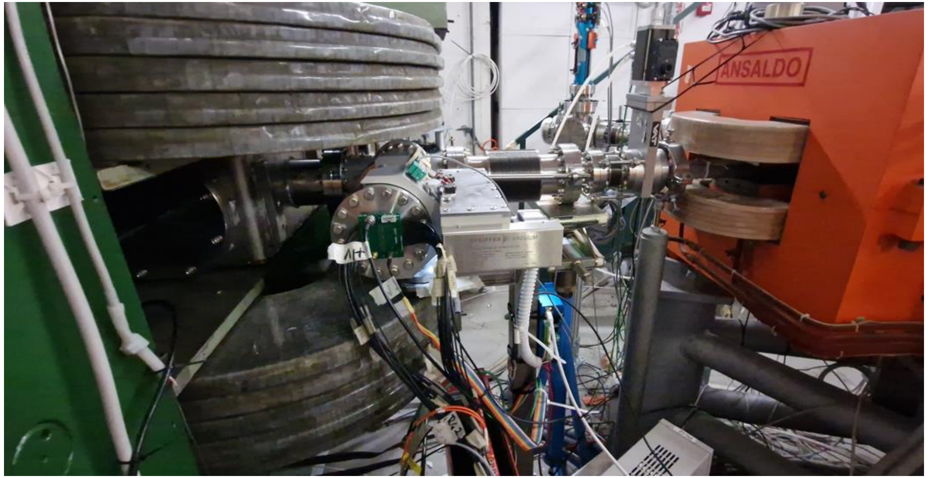
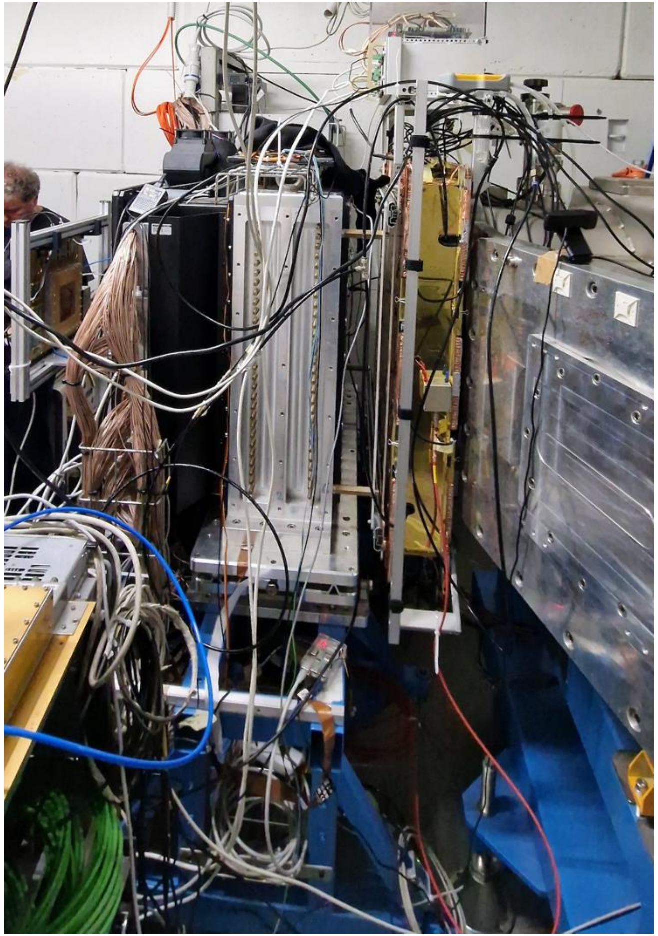
Optimized setup for Run IV

New data set being acquired [Run IV]
- Set the target closer to the calorimeter, **increase acceptance**
- Residual dipole magnetic field reduced [<1G]
- Improved readout of target position
- **New detectors**





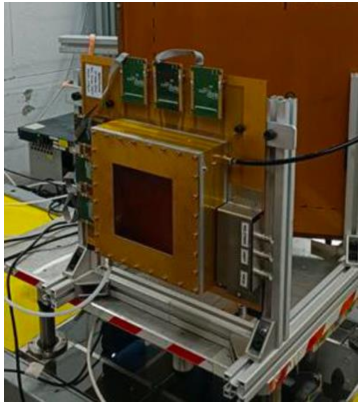
Optimized setup for Run IV

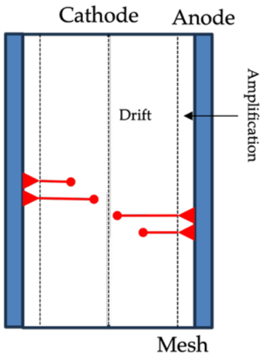
New detectors for Run IV

- ATLAS micromegas-based **tracker** to separately measure the absolute cross sections of **ee/γγ**, replacing the scintillating bar hodoscope
- **Improvement in angle resolution, also provides beam spot**
- **Smaller micromegas chamber** for monitoring the **beam spot** behind the calorimeter, replacing the Timepix array
- **Additional leadglass + LED pulser** for monitoring **radiation induced losses** in beam catcher

Tracker

Monitor chamber





Two 5 cm gaps, can operate in TPC mode

Resistive circuit (common, 3 HV zones)

Run IV data set

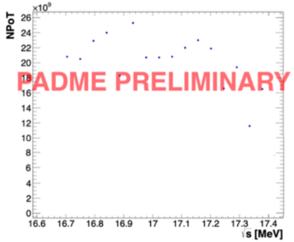
Improvements Run IV wrt Run III:

- **Increase acceptance**: allow even safer treatment for edge effects
- **Increase monitoring** power and **redundancy**: better stability
- **Alternative flux determinations**: $\gamma\gamma$, new end of line monitor, target, chamber
- **Increase statistics**: 1.5×10^{10} POT per energy point

Expectations for Run IV:

- $\times$**2 acceptance** increase
- $\times$**2 statistics** increase
- 2.5 days for data collection, 3000 e^+/spill as in Run III
- Points divided into 2 scans as in Run III

Run IV-part 1 data already on tape: **18 energy scan points collected** ($\sim2\times10^{10}$ PoTs each) equally **separated by 1.5 MeV** in the range E_{beam} = (269.5, 295) MeV; $\sqrt{s}$ = (16.60, 17.36) MeV



Run IV-part 2 already scheduled for autumn 2025: add 18-20 scan points, **offset by 0.75 MeV**

+ out-of-resonance below 16 MeV and above 18 MeV

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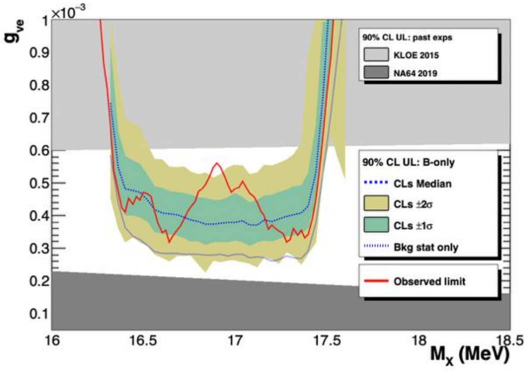
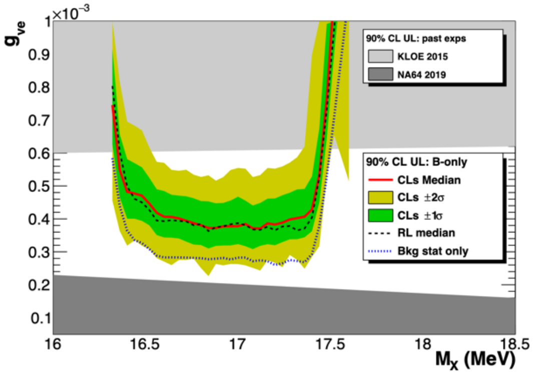
Run IV projections

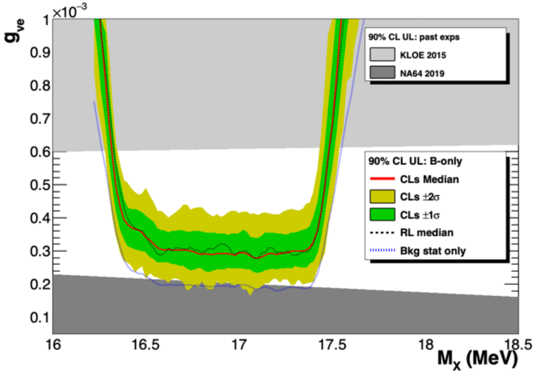
Run III observed



Run III – expected background only



Run IV – expected background only



Source	Uncertainty [%]		Note
	Run III	Run IV	
N_2	0.6	0.3	Increased acceptance
N_{PoT}	0.35	0.3	Redundant measurement + online calibration
B	0.55	0.3	Better $ee/\gamma\gamma$ separation, improved angular resolution
Total on g_R	0.89	0.5	

Conclusions

- The “X_{17}” excess remains **not confirmed** but **not disproved**

  No SM explanation viable

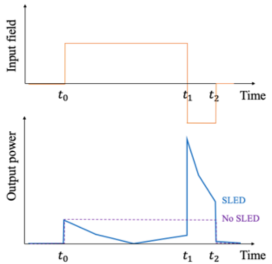
- **PADME** is in a **favorable condition to clarify**
  - Data from **4×10^{11} e^+ on target** used for **resonance search** in the mass region **16.4 –17.4 MeV** with a **blind analysis**
  - **Overall uncertainties of 0.9%** on **40+ points** have been obtained
  - **No indication of X_{17}** with global p-values well beyond **2σ**
  - An **excess at 16.90 MeV** with a local **p-value 2.5 σ**, **global 1.77(15) σ**
- A **new data taking** with an **upgraded detector** is **ongoing:** Jun-Nov 2025, possible extension beginning of 2026

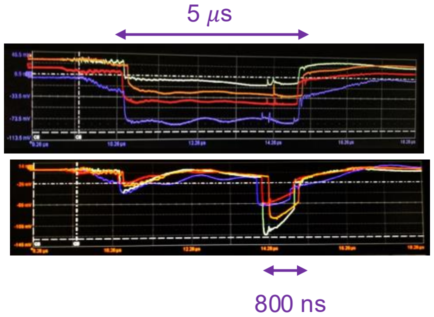
Future perspectives

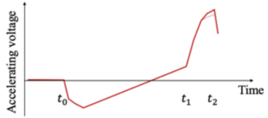
What if the Run IV result **will confirm the excess**, but **not conclusively**, e.g. getting a significance still be below 5σ?

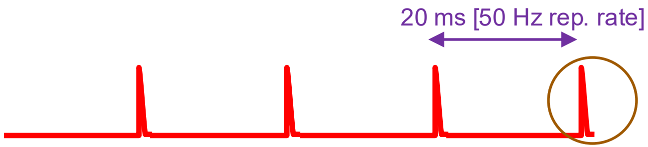
How to improve?

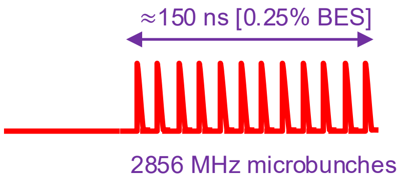
- The **dominant uncertainty** in the Run IV result will be most likely the **systematics**, even though the improved geometry and the **new detectors** should improve wrt Run III, in particular if ee, $\gamma\gamma$ final states can be used **separately**
- From the **statistics** point of view the main limitation is the maximum **length** of the Frascati BTF **positron beam**
  - $\approx$**400 ns** is the maximum obtained beam pulse length, with an acceptable momentum spread, due to the not-flat shape of the **accelerating voltage of the LINAC** [given by the SLED compression of the RF power for doubling the energy gain of the S-band cavities].
  - On the other side, the **density of positrons** in the beam $\times$ **density of the electrons** in the target = the maximum **number of annihilations** that can be handled by the PADME detectors with acceptable levels of **pile-up** is $\approx$**10^2 ns^{-1}** for a **0.1 mm thick C target**











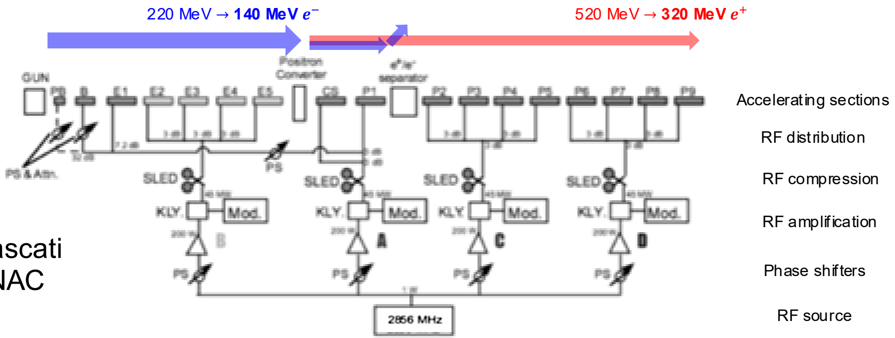
Future perspectives

- However, **10^2 ns^{-1}** for a **0.1 mm thick C target**, is a **compromise** between the requirement of controlling the **pile-up** and the need for a **significant statistics** in a reasonable time
- A significant **improvement of the background rejection** can be obtained **further diluting the positron beam**, down to the "**single annihilation**" regime
- Such a configuration requires **much longer beam pulses or a much higher repetition rate** to get a competitive statistics [a **continuous positron beam** would be ideal]
- For the **X17 search**, the other main requirement for the positron beam is to exceed 17.5 MeV in mass, i.e. reaching at least **$E_{beam} \approx 300$ MeV**
- A number of possible solutions, using the Frascati infrastructure, has been proposed in **arXiv:2001.10258**
  - Assuming to **by-pass of the SLED** RF compression and given the filling time of the cavities, **$\approx 2\ \mu s$** pulses should be obtained
  - Assuming a reduction of the maximum energy of a **factor 1.6**, a **320 MeV** positron maximum energy is achievable
  - Slight reduction of the positron current due to lower energy of electrons in the first sections not an issue

SLED-out

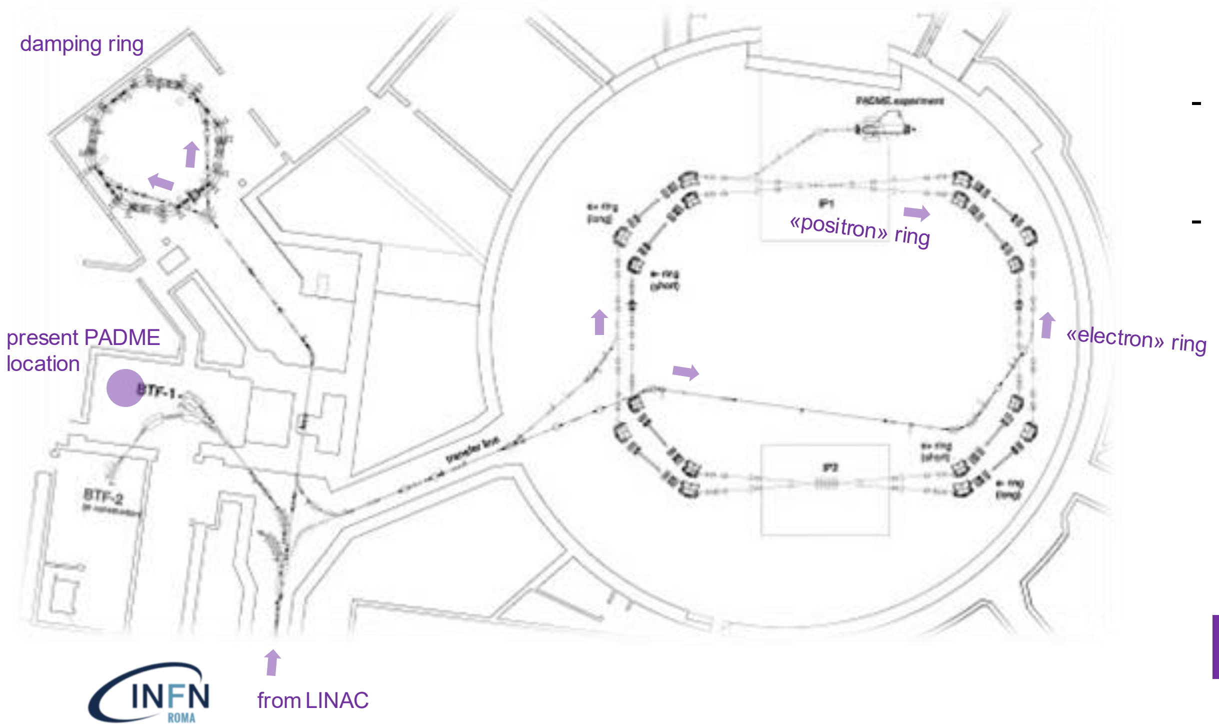
SLED-in

Frascati LINAC



Future perspectives

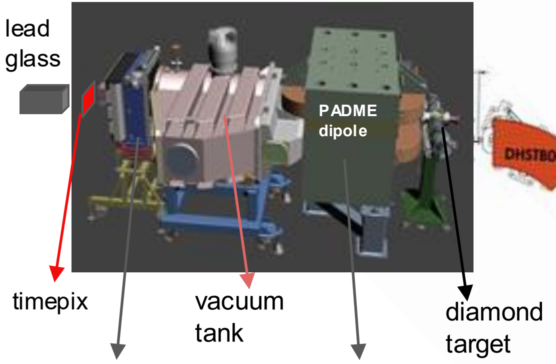
- A more **ambitious** idea, but still **feasible in the context of Frascati infrastructure**, would be to use **one ring** of the DAFNE collider complex [1 damping ring + 2 main rings] as **pulse stretcher** of the LINAC positron beam, as proposed here: **[arXiv:1711.06877]** and here: **[J. Phys. Conf. Ser. 1067 (2018) 6, 062006]**

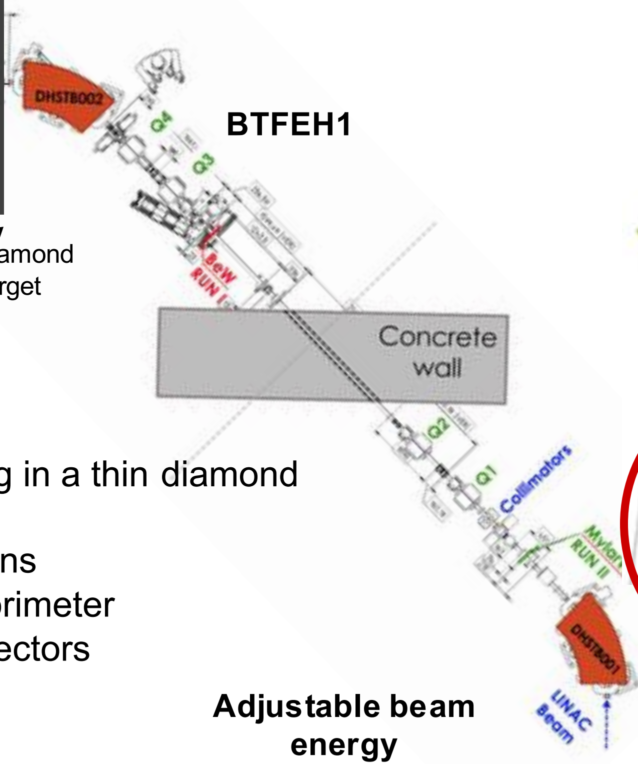


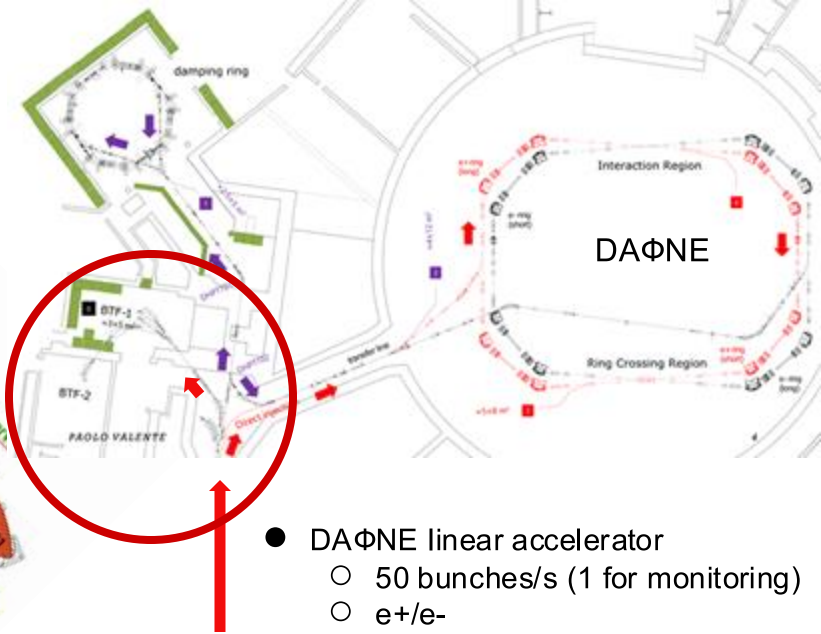
- **O(0.1 ms)** long positron pulses can be obtained, depending on the configuration
- Original proposal using the conventional $n+\frac{1}{3}$ **resonant extraction**
- Possible use of coherent effects in **bent crystals [channeling]** for assisting the extraction in place of an electrostatic septum

See Marco Garattini's talk

Additional material



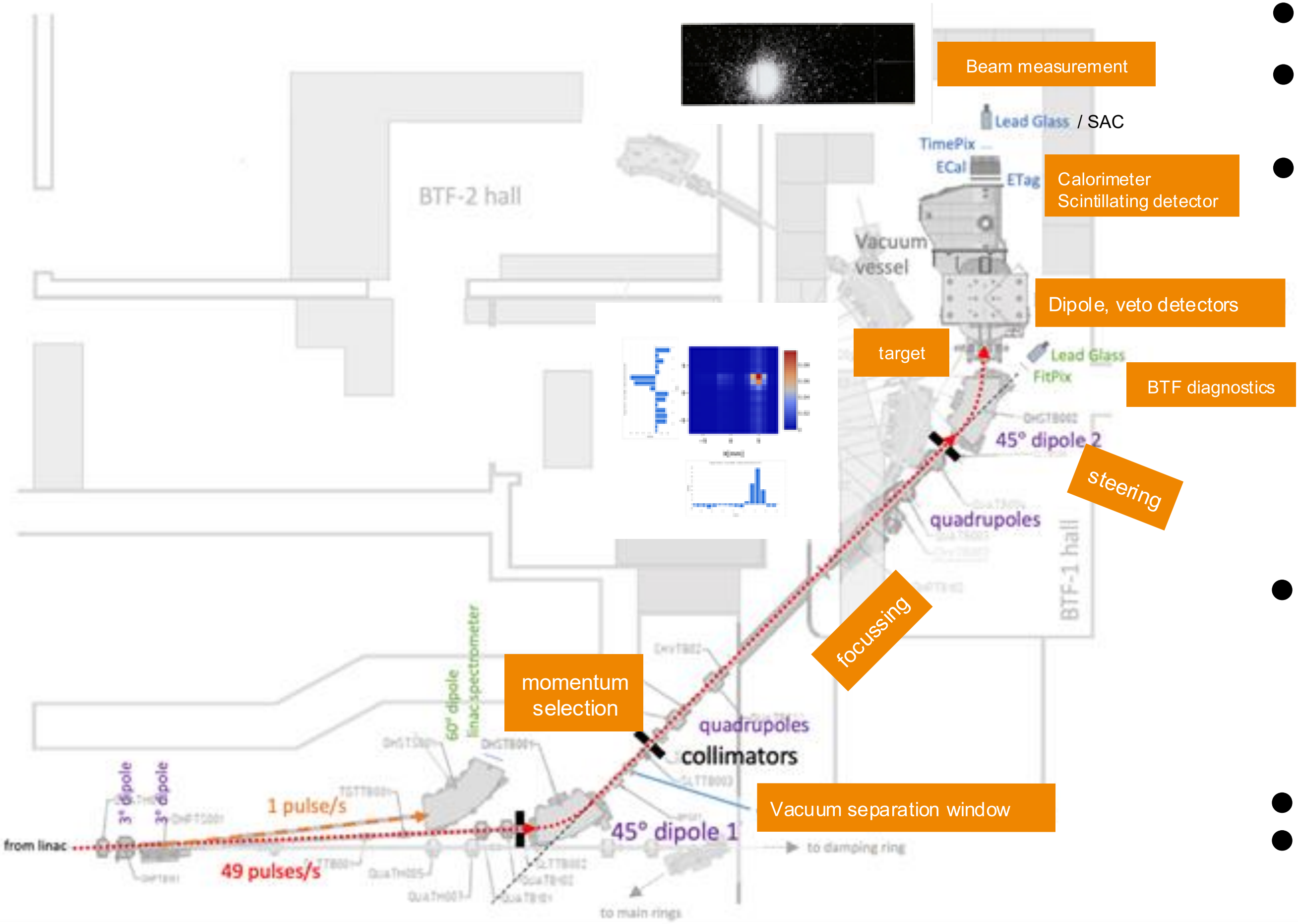


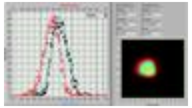


- Accelerated e⁺ interacting in a thin diamond active target
- Final states: e⁺, e⁻, photons
  - Electromagnetic calorimeter
  - Charged particle detectors
- Beam measurement
  - Timepix
  - Lead Glass

Adjustable beam energy
100 MeV - 500 MeV

- DAΦNE linear accelerator
  - 50 bunches/s (1 for monitoring)
  - e+/e-
  - Up to O(300ns) macro-bunches
- BTF beam spot: 1 mm
- Beam divergence: 1-1.5 mrad





- Accelerated e^+ interacting in a thin diamond active target
- Final states: e^+, e^-, photons
  - Electromagnetic calorimeter
  - Charged particle detectors
- **Beam measurement**
  - Timepix
  - Lead Glass

- DAΦNE linear accelerator
  - 50 bunches/s (1 for monitoring)
  - Electrons and positrons
  - Up to O(300ns) macro-bunches
  - **Adjustable** momentum: 100-530 MeV
  - **Adjustable** intensity
- BTF beam spot: 1 mm
- Beam divergence: 1-1.5 mrad

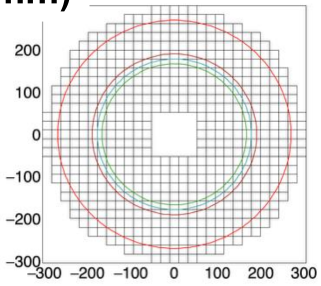
Run III concepts – Signal selection

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 BGO crystal cell for any period in the data set

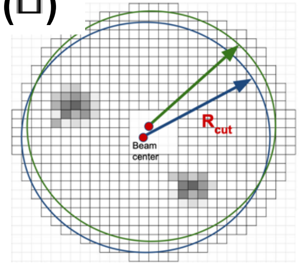
Y_{ECal} (mm)



X_{ECal} (mm)

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

Y_{ECal} (□)



X_{ECal} (□)

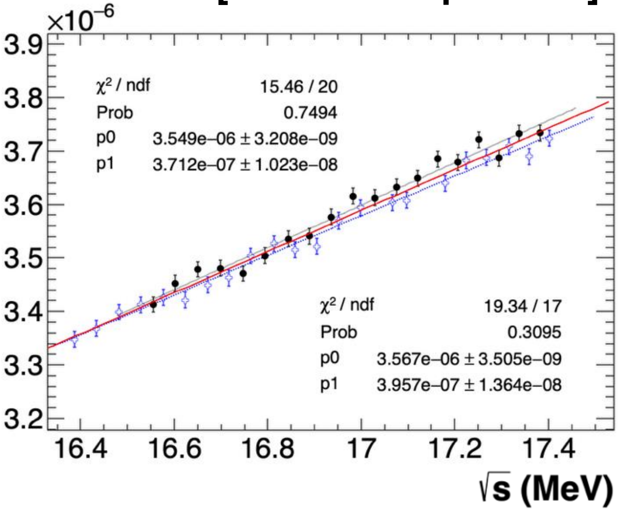
1 □ = 1 BGO crystal
= 21.5 x 21.5 mm

Details on expected background: s dependence

Expected background B determined from MC, stat error per period: $\delta B \sim 4 \times 10^{-3}$

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)

Box opening – Other checks

Checked other sensitivity methods

Perform the automatic procedure but fit with a constant:

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

Original version:
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}

The center of the masked region does not change: 16.888 MeV

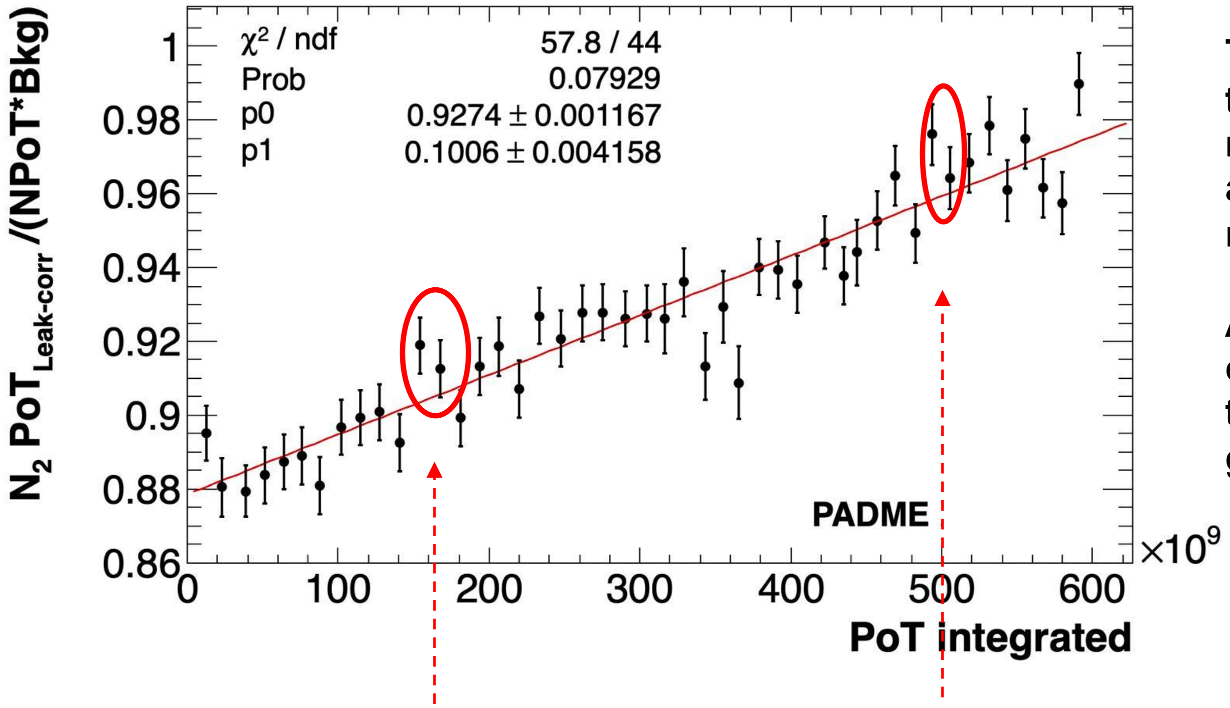
The excess also remains basically of the same strength: 1.6σ

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

Box opening – IV Check of correction

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

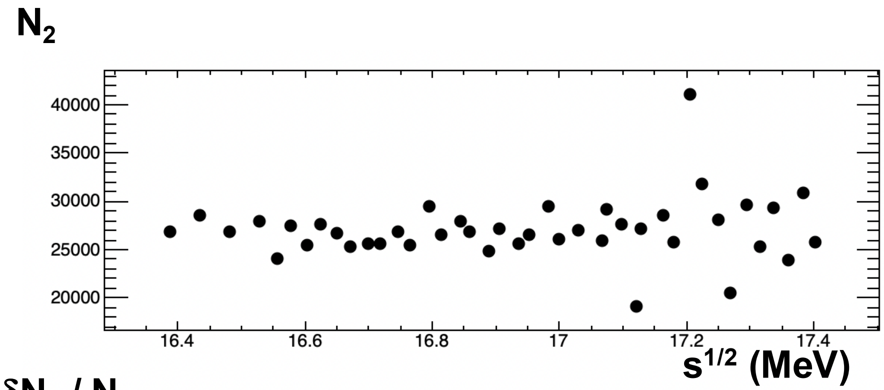


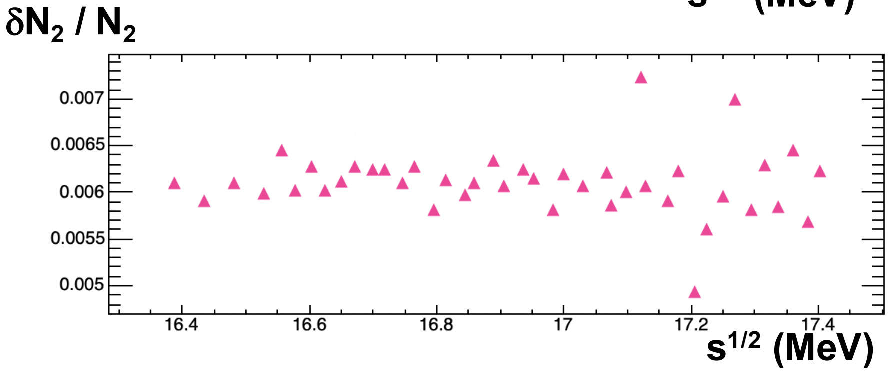
The slope has been used to correct for the radiation-induced effect, acting as a separate nuisance

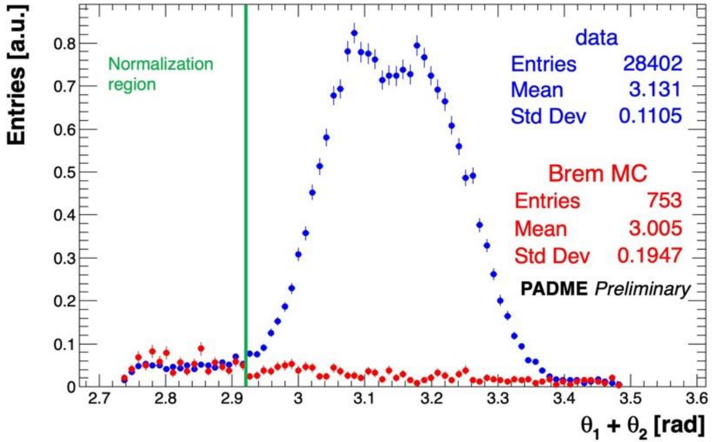
Again no significant change in the location of the excess and in the global p-value

Details on the event count N_2

Background subtraction using side-bands (Bremsstrahlung, ~4%)
Correction relative variation +-1%, statistical uncertainty on $\delta N_2 \sim 0.3\%$







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

Fully modeled using MC + detailed map

Details on background: cut stability

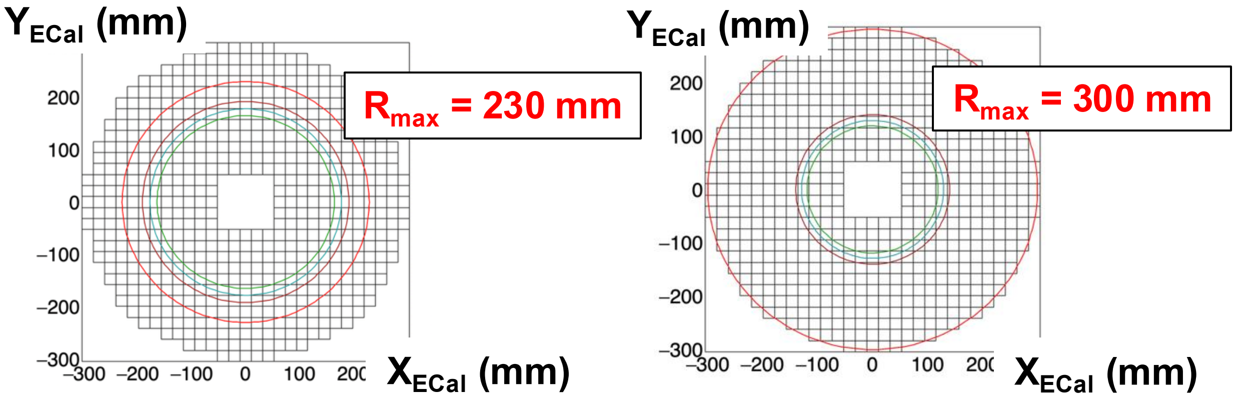
Check if MC and data yields stable vs R_{min}, R_{max} (edge effects, leakage)

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

Yield variation: ~10%

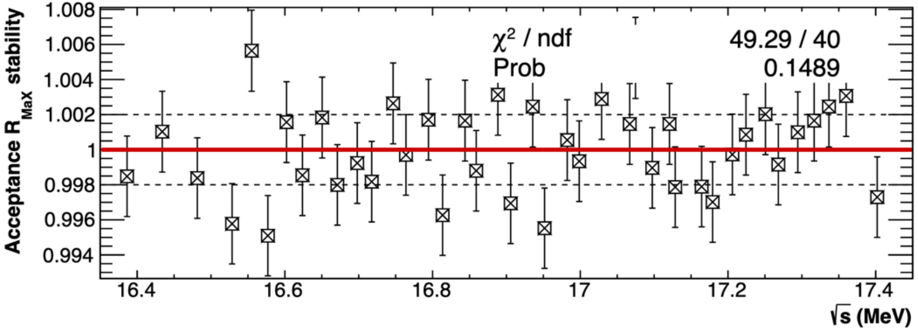
Uncorrelated error 0.3%

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



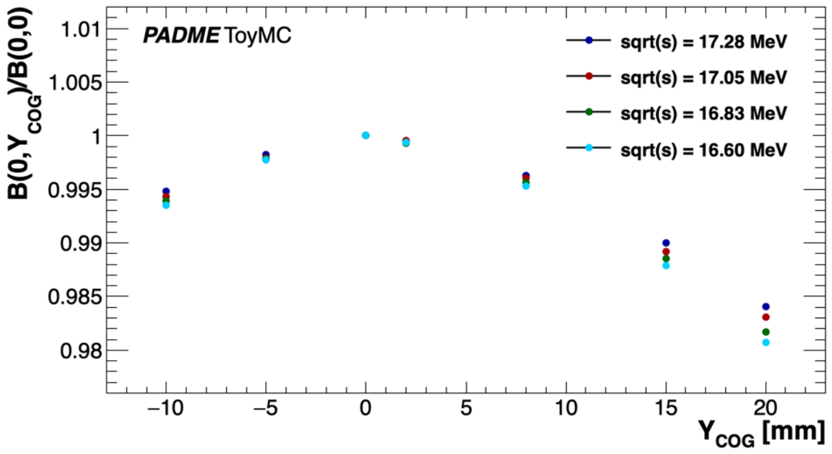
Details on background: acceptance variations

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%



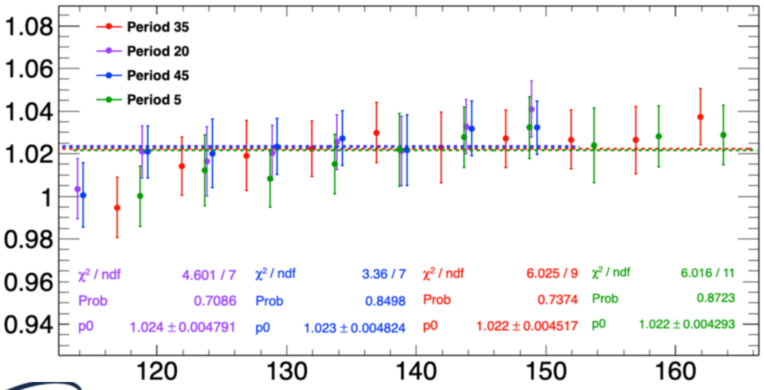
Details on background: cluster reconstruction

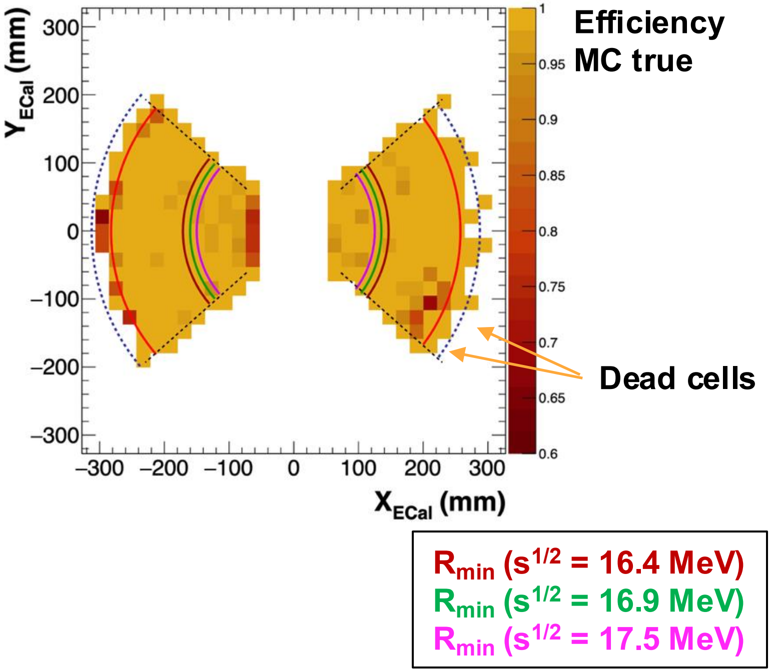
Efficiency around 1 within few % except in specific regions (Ecal edges, dead cells)

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

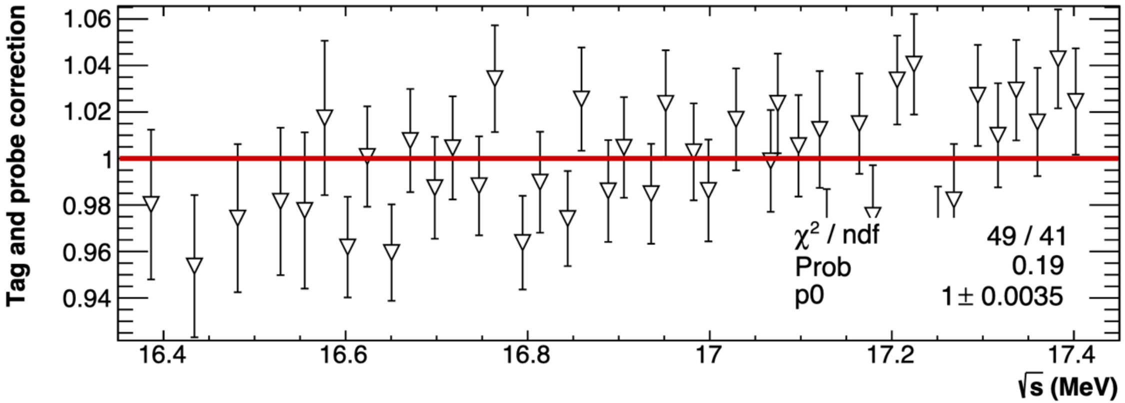
Check of reconstruction efficiency:

- 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%

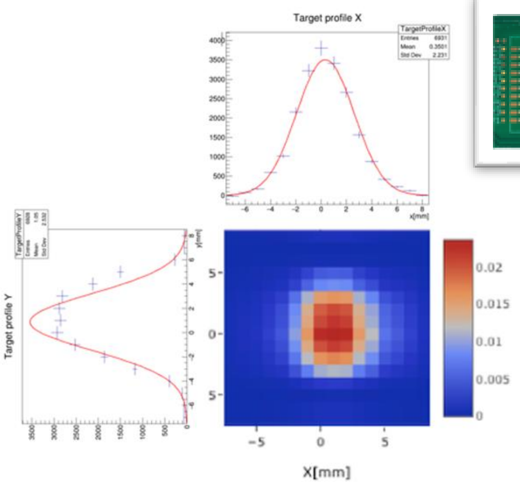
No correction applied per period, statistical-systematic error of 0.35%

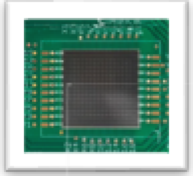


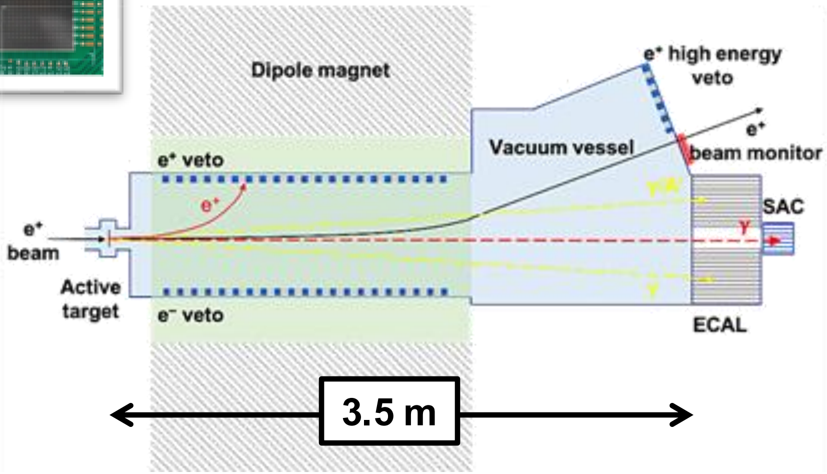
PADME: beam monitors

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: $\sigma_P/P_{beam} < 0.25\%$

PADME: TDAQ concept

Three trigger lines: Beam based, Cosmic ray, Random

Trigger and timing based on custom board
[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

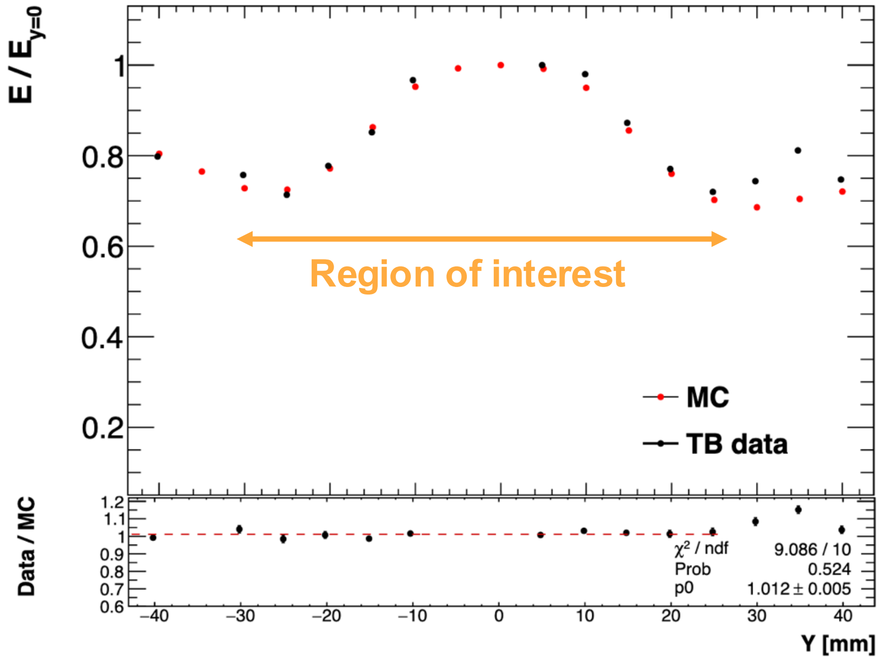
Level 0 acquisition with zero suppression, ×10 reduction → 200 KB / ev.
Level 1 for event merging and processing, output format ROOT based

Details on the flux N_{POT}: leakage correction

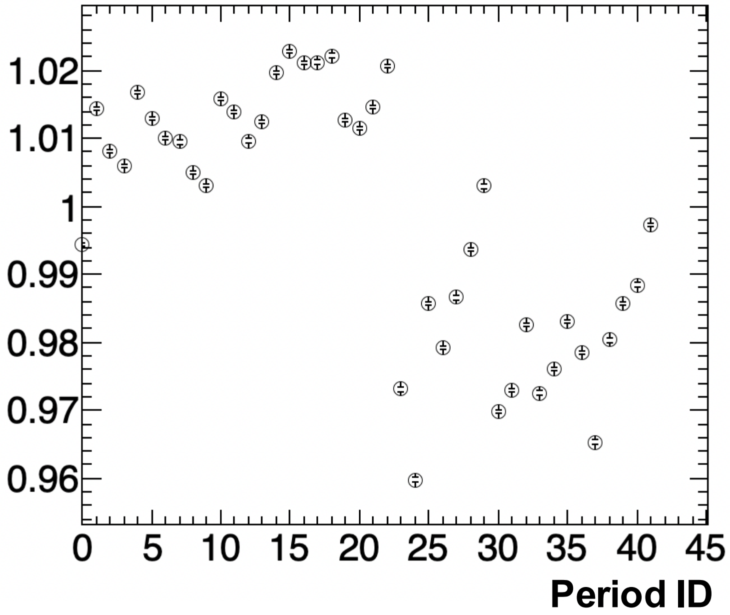
Loss from detailed MC vs vertical position checked against data in test beam

Very good data-MC agreement, correction 1.2%, systematic error 0.5%

Significant period-by-period variation of the correction: -4% to +2%



Relative leakage correction



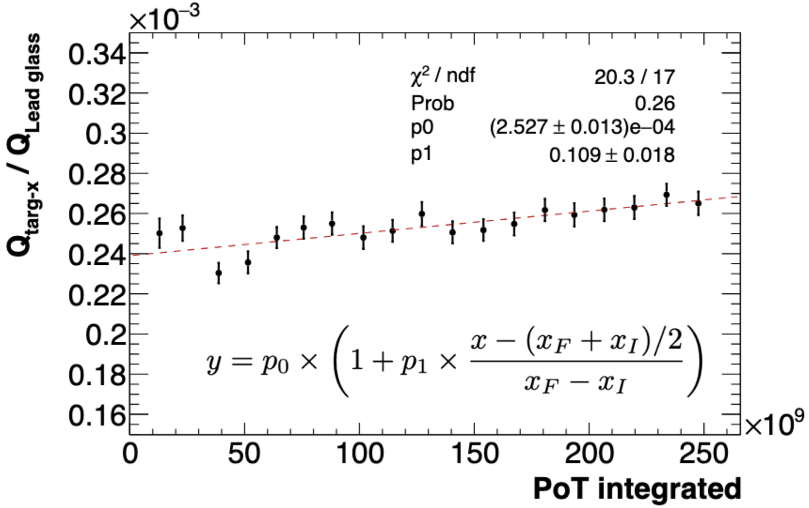
Details on the flux N_{POT}: rad-induced correction

Literature indicates possible changes in SF57 transparency for O(krad)

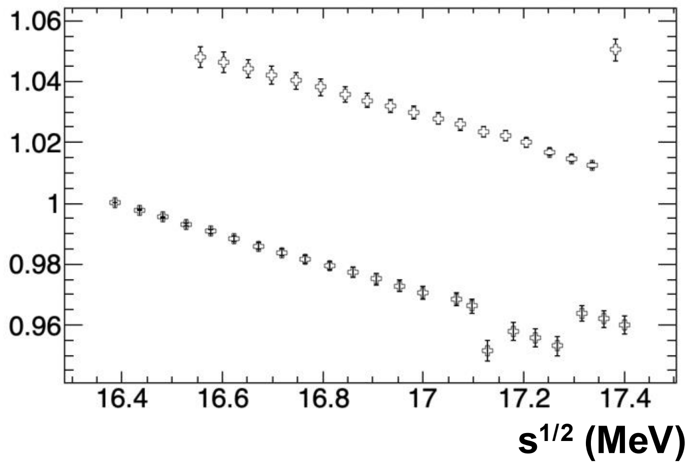
- Estimate of Run-III dose: 2.5 krad

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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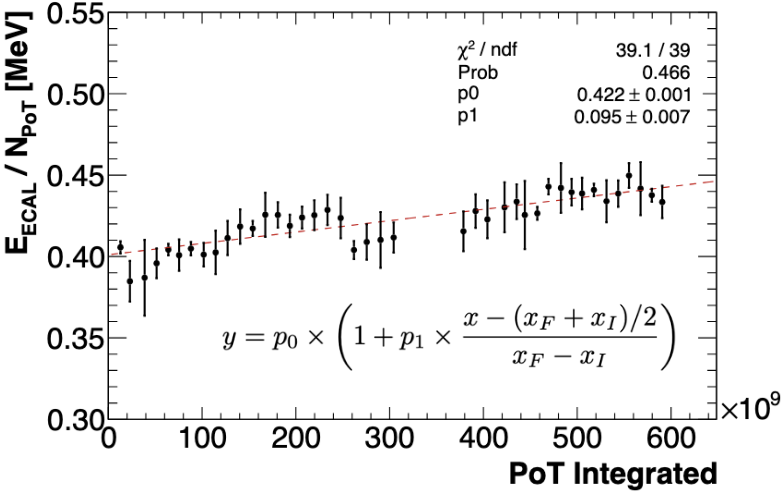
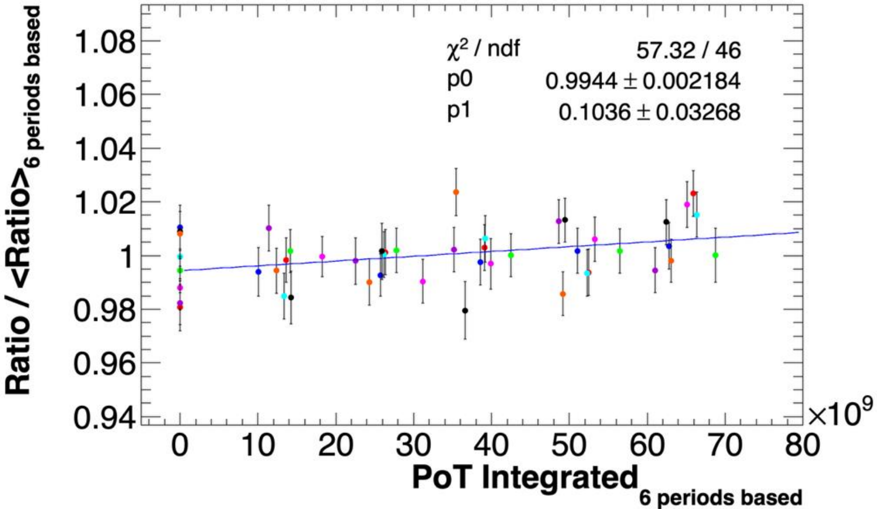
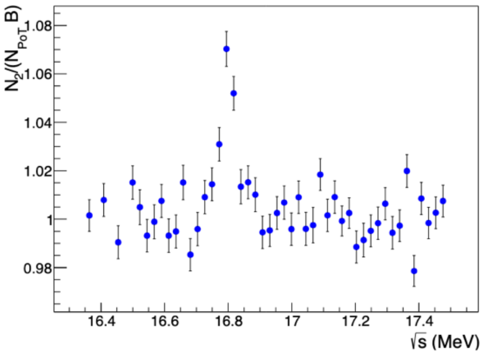
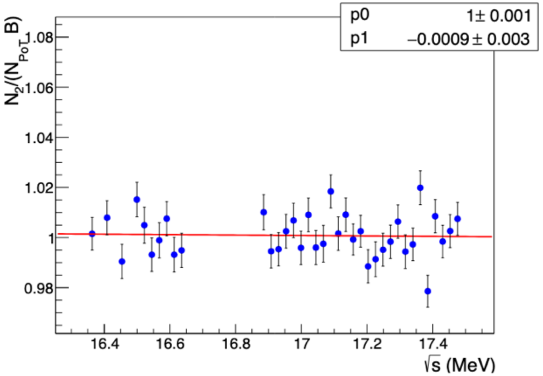


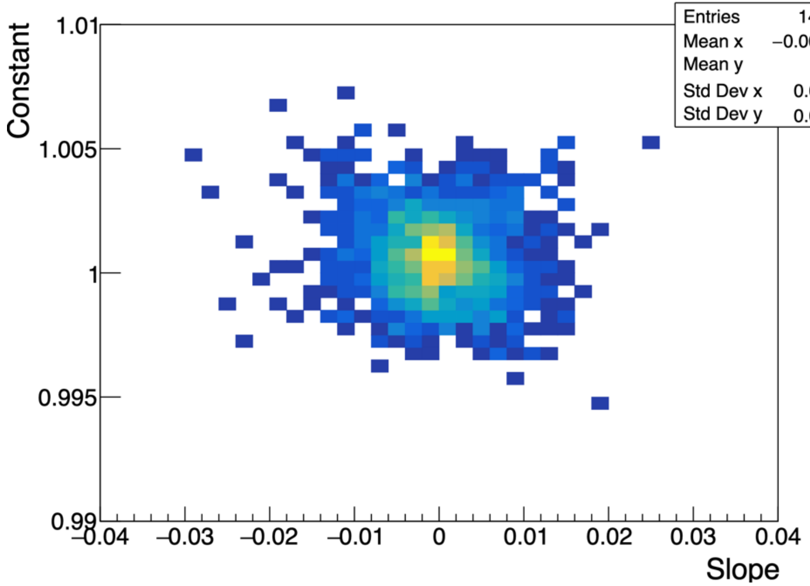


The blind unblinding procedure: details





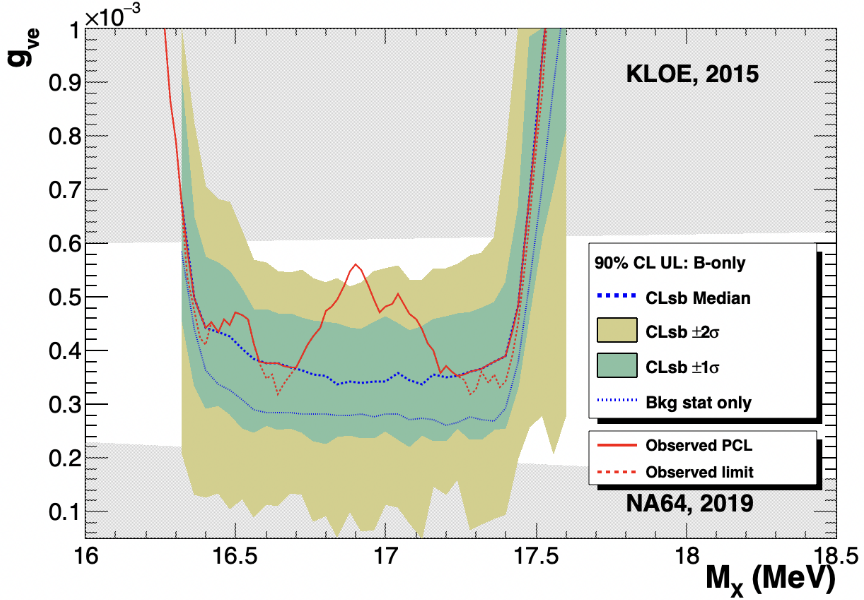
Constant term and slope of the optimized fit estimate the true values for K(s)
Results of the procedure ran on toy experiments with constant = 1, slope = 0



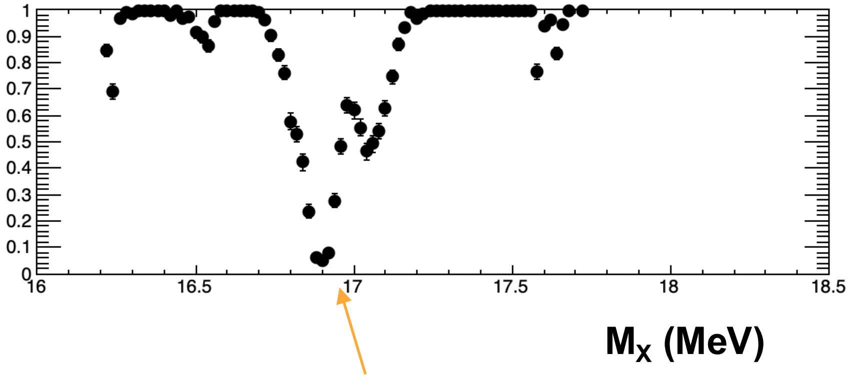
Moreover the procedure correctly finds the central location of signals when present

The PCL method

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



Global p-value



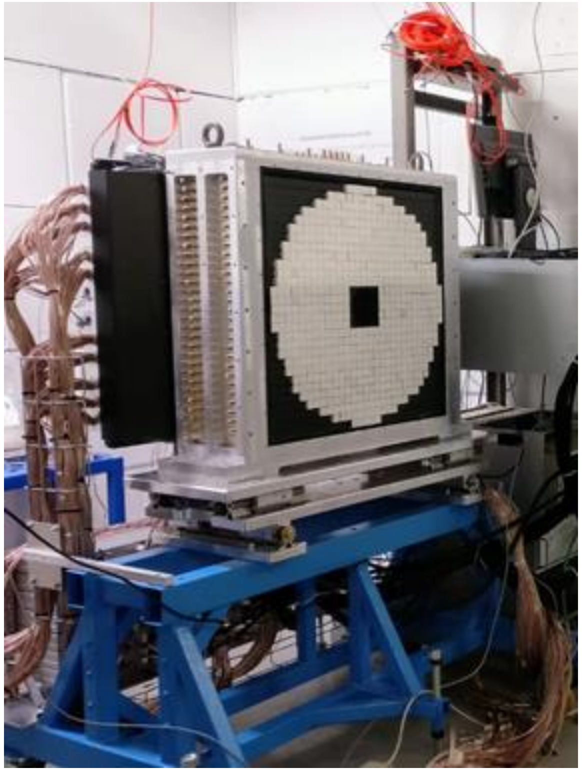
equivalent to (1.63 +- 0.13) σ

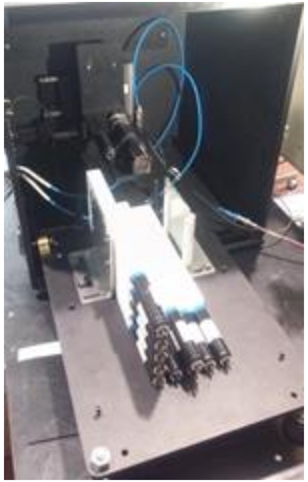
The global p-value is only slightly affected, consistent with the coverage modifications of this method

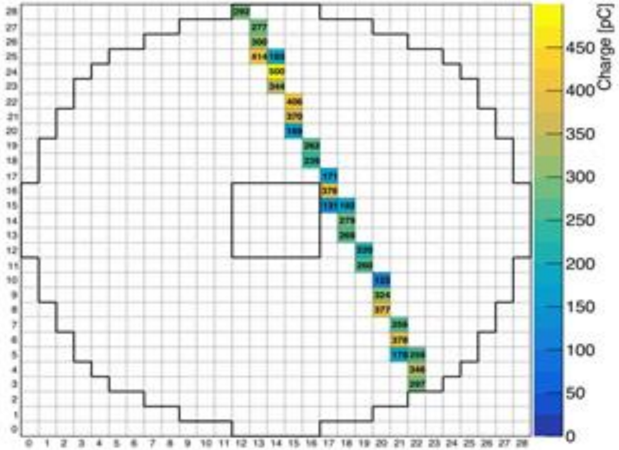
PADME: calorimeter

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)







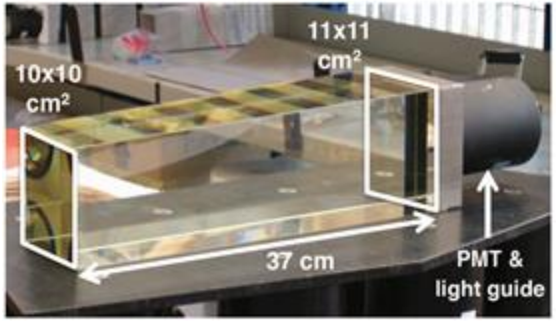
Calibration at several stages:

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

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



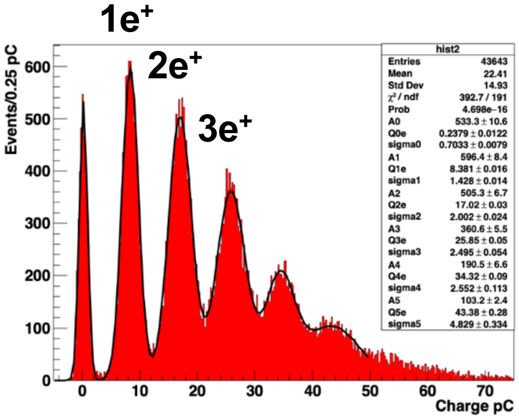


Figure 16. Single particle charge spectrum.

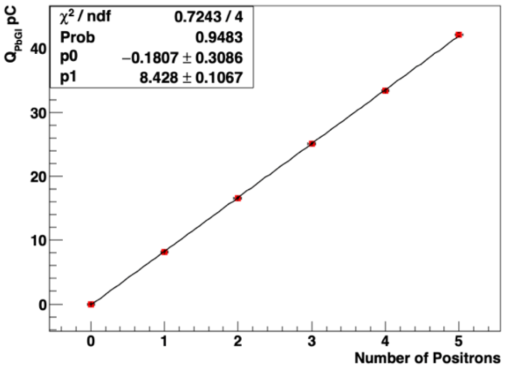
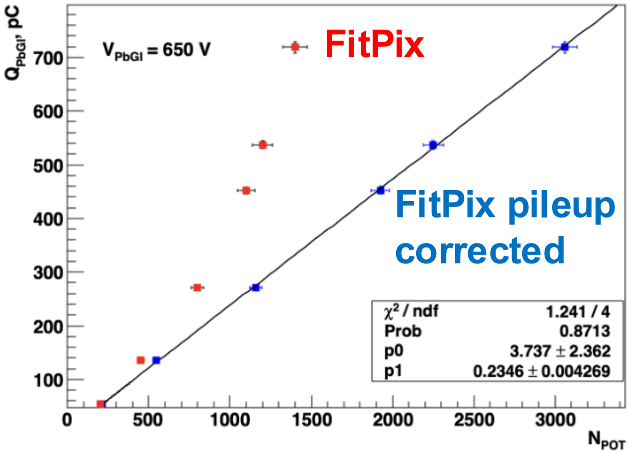


Figure 17. Fit to the single particle response.



The 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