

Hunting X17 at

E. Di Meco – **INFN Laboratori Nazionali di Frascati**

elisa.dimeco@lnf.infn.it

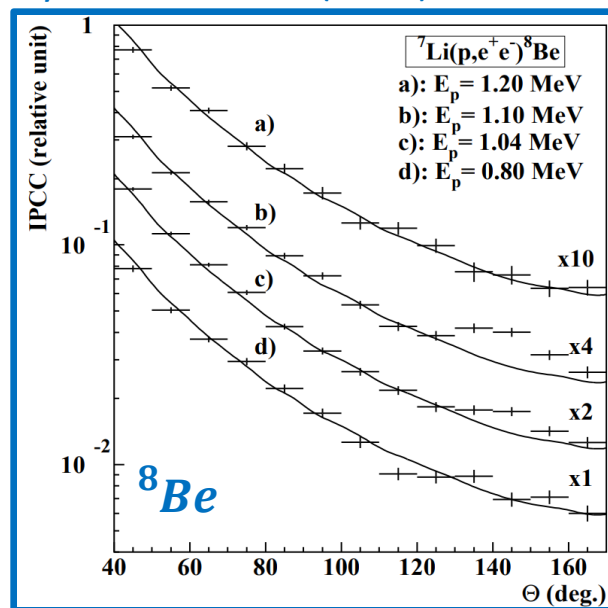
On behalf of the PADME Collaboration

Munich Dark Matter Meeting, October 14, 2025 – Max Plank Physics, Munich

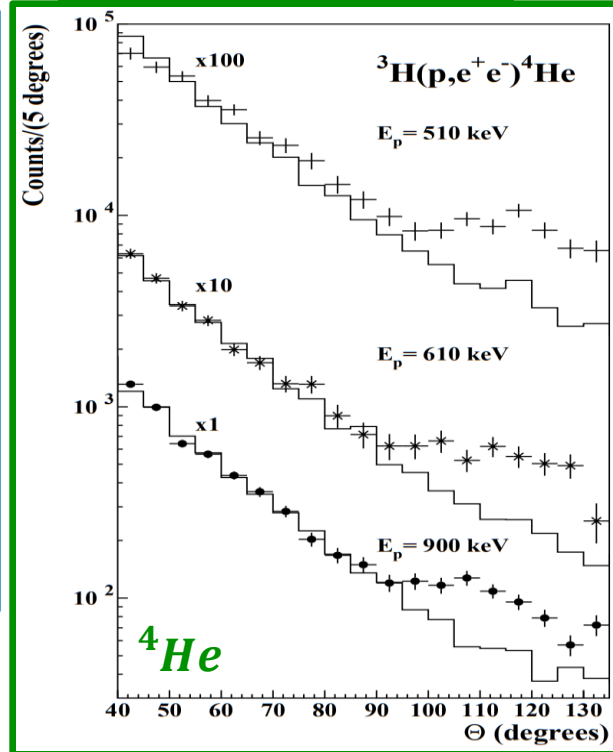
- Anomalous excesses in angular correlation of e^+e^- couples produced via Internal Pair Creation of ^8Be , ^4He and ^{12}C observed by the A. Krasznahorkay & collaborators.

- The anomaly seems to be compatible with the production and successive decay of a **new ~ 17 MeV mass particle**

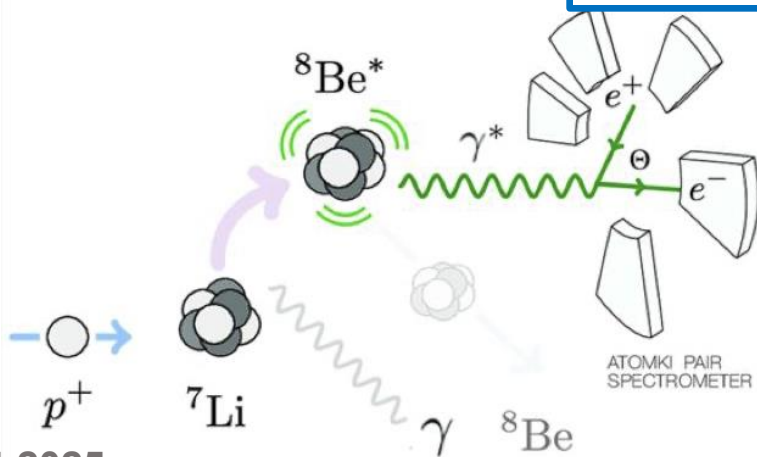
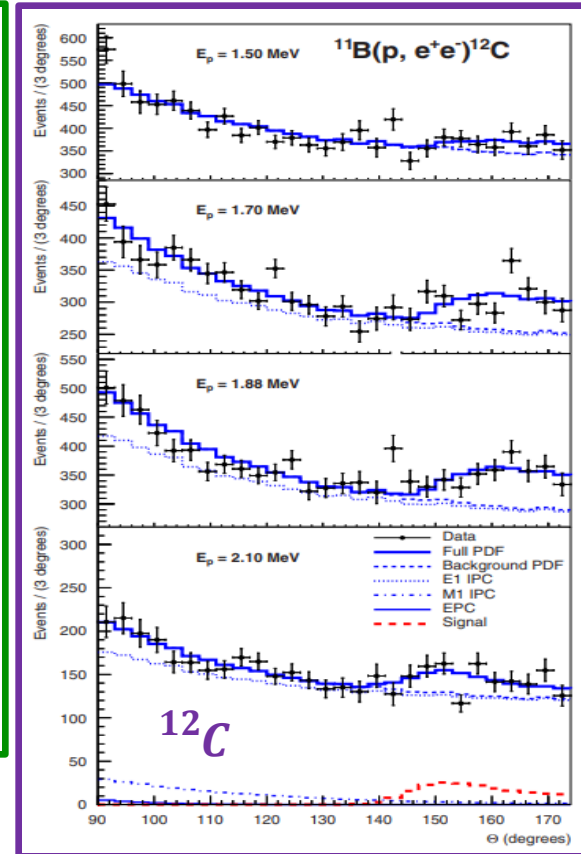
Phys.Rev.Lett. 116 (2016) 4, 042501



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



Phys. Rev. C 106, L061601

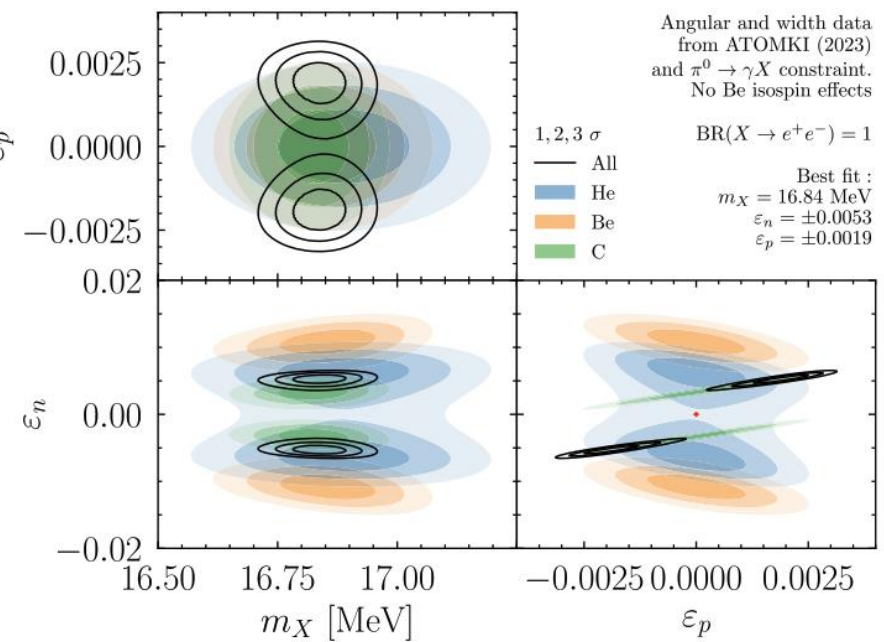


Neutrino constraints and the ATOMKI X17 anomaly PHYS.REV. D 108, 015009 (2023)

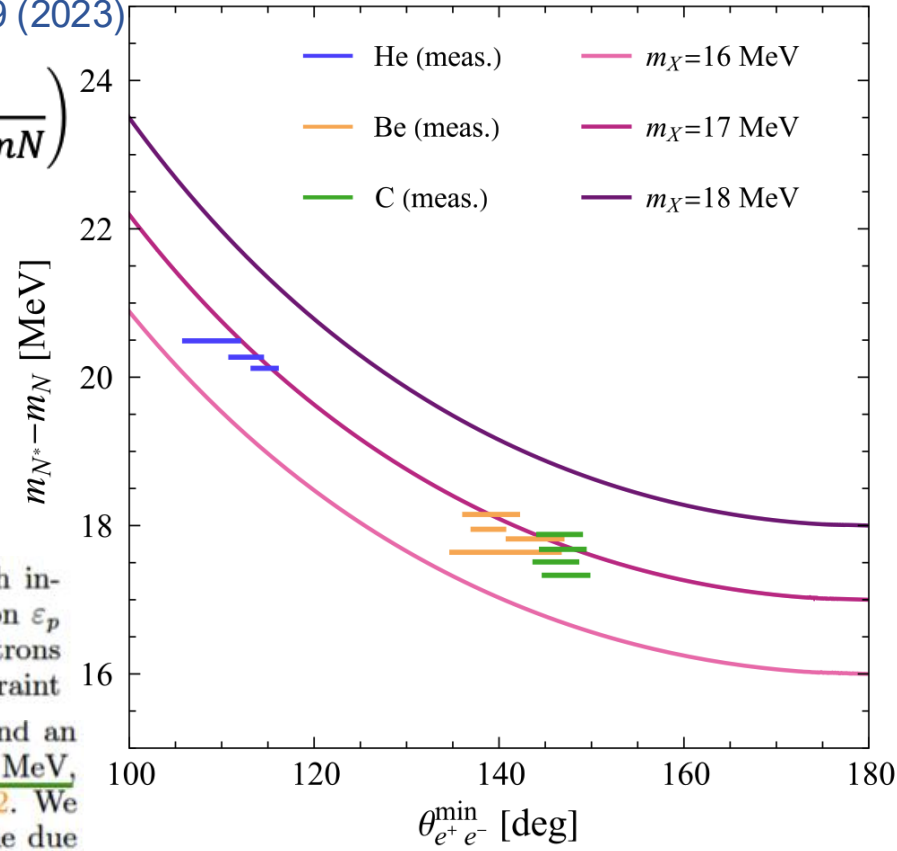
Using the angular data only (11 measurement) $\rightarrow \theta_{ee}^{min} \approx 2 \arcsin \left(\frac{m_{X17}}{m_{N^*} - m_N} \right)$

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

Using the width for (3 measurements)



Next, we add in to the analysis the latest width information from each element and include a prior on ϵ_p since X needs to couple to protons and/or neutrons on the production size. There is a stronger constraint see the next section for more information. We find an okay fit to the data at the same mass $m_X = 16.83$ MeV, $\epsilon_n = \pm 5.8 \times 10^{-3}$, and $\epsilon_p = \pm 2.4 \times 10^{-3}$, see fig. 2. We note that the signs of ϵ_n and ϵ_p must be the same due to the non-trivial degeneracy structure shown clearly in the $\epsilon_n - \epsilon_p$ panel of fig. 2. We have confirmed that the



Data from ^8Be , ^4He , ^{12}C are consistent and point to:
 $M_{X17} = 16.85 \pm 0.04$ MeV

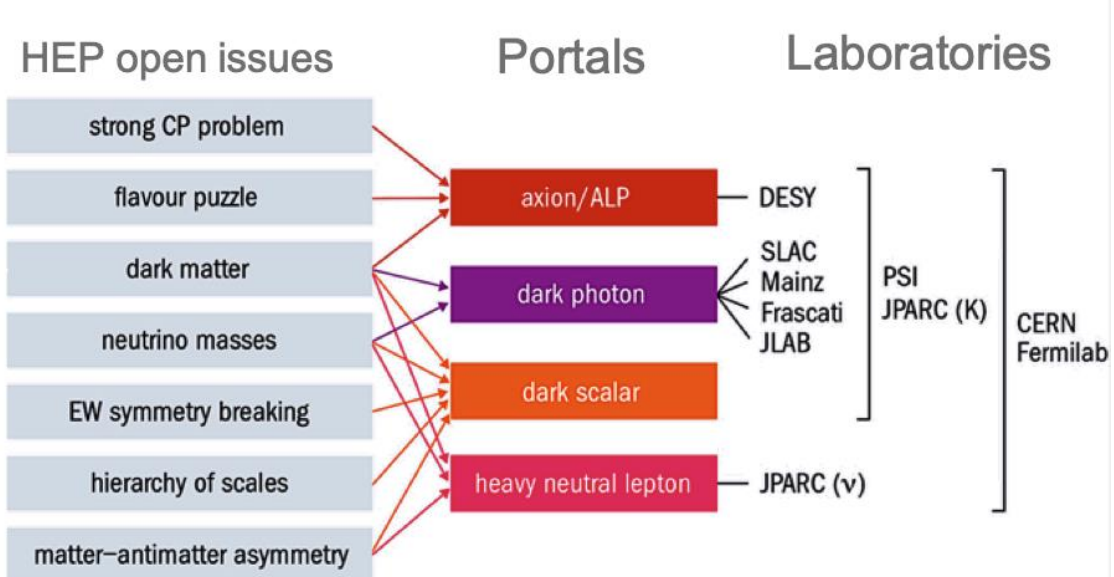
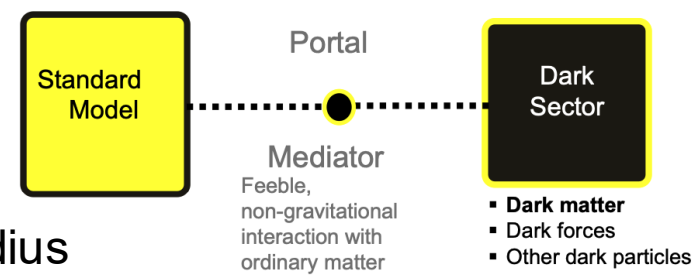
A dark matter candidate identikit:

- 1) It should be stable (or at least have an average lifespan of over 13 billion years!).
- 2) It should be electrically neutral or have strongly suppressed interaction with ordinary matter.
- 3) It should be massive to have gravitational interaction

X17



Possible portal mediator to the Dark Sector → Light DM
Dark sector candidates can explain SM anomalies: $(g-2)_m$, ^8Be , proton radius



- The mediator can have a small mass (MeV - 1 GeV)
- Dark sectors particles can have their own new forces (dark forces)
- Due to its small mass the mediator can be produced at low energy accelerators
- It can decay back to ordinary matter, “visible” decays, or not, “invisible” decays.

Theory insights based ATOMKI data: (assuming P conservation and resonance emission)

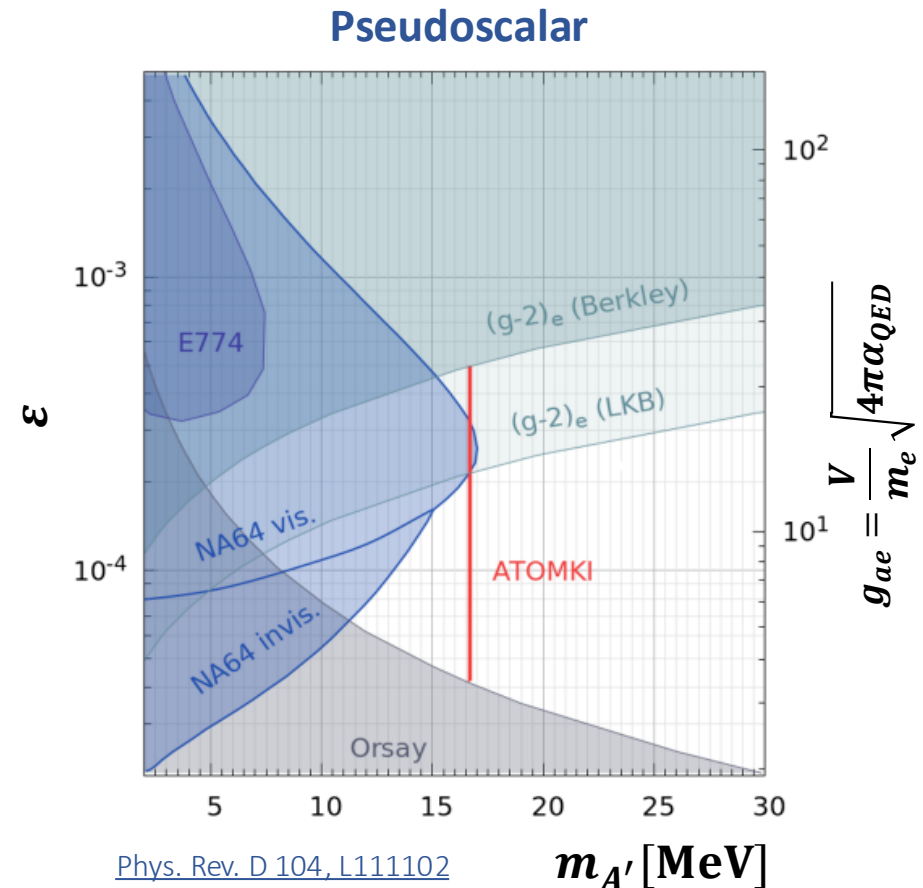
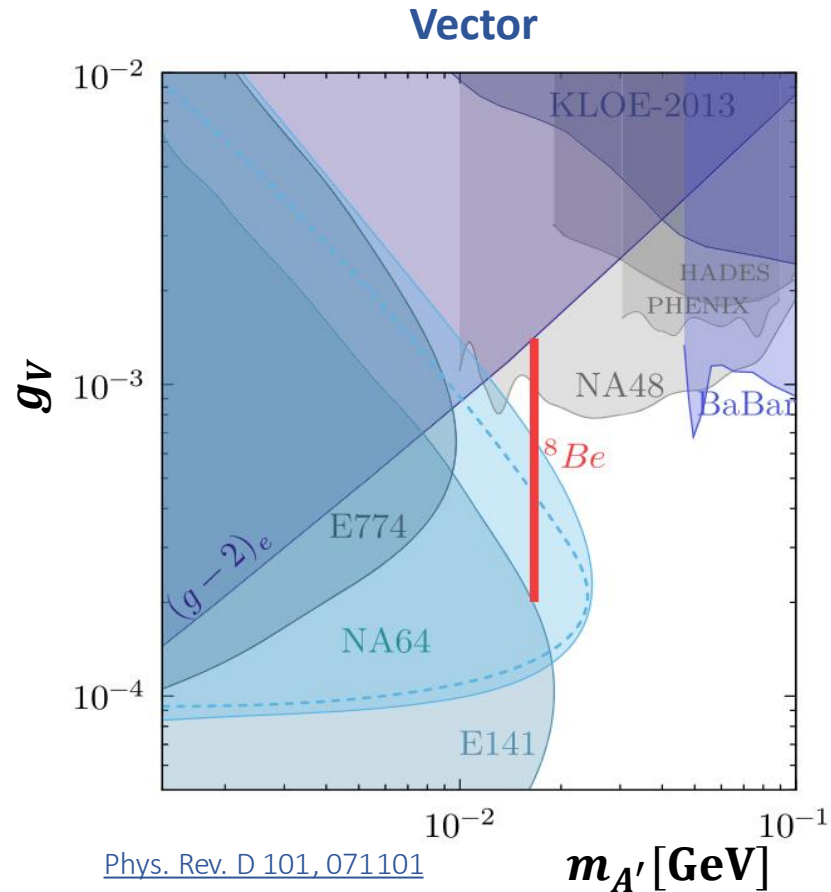
- $m_{X17} \sim 17 \text{ MeV}$, $Br(e^+e^- \rightarrow X17) \simeq 5 \times 10^{-6} Br(e^+e^- \rightarrow \gamma\gamma)$
- $\Gamma_V = 0.5 \left(\frac{g_V}{0.001}\right)^2 \text{ eV}$ for the vector case
- Scalar excluded by parity conservation in ^8Be
- Pseudo scalar disfavoured by the ^{12}C observation

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
$^8\text{Be}(18.15)$	1^+	...	$\mathcal{O}_{4P}^{(0)} (27)$	$\mathcal{O}_{5P}^{(1)} (37)$	$\mathcal{O}_{3S}^{(1)} (29), \mathcal{O}_{5D}^{(1)} (34)$
$^{12}\text{C}(17.23)$	1^-	$\mathcal{O}_{4P}^{(0)} (27)$	...	$\mathcal{O}_{3S}^{(1)} (29), \mathcal{O}_{5D}^{(1)} (34)$	$\mathcal{O}_{5P}^{(1)} (37)$
$^4\text{He}(21.01)$	0^-	...	$\mathcal{O}_{3S}^{(0)} (39)$	...	$\mathcal{O}_{4P}^{(1)} (40)$
$^4\text{He}(20.21)$	0^+	$\mathcal{O}_{3S}^{(0)} (39)$	...	$\mathcal{O}_{4P}^{(1)} (40)$	...

What next in particle physics experiments:

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

- New physics interpretations not fully excluded $\rightarrow$ still some phase-space available
- The PADME experiment is sensible to this mass range



Main techniques:

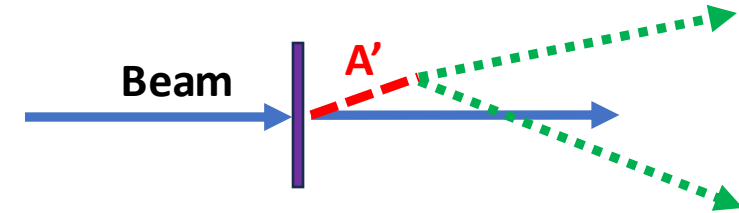
- **Fixed Target:**

1. **Thin target:**

- Direct production
- Search for decays through event reconstruction (tracking)

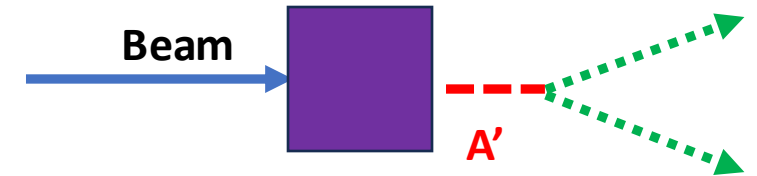
2. **Secondary beam:**

- Usually in a thick target
- Searching for new particles in meson decays $\rightarrow M_X$ usually limited by meson mass, coupling sensitivity and statistics



- **Beam Dump:**

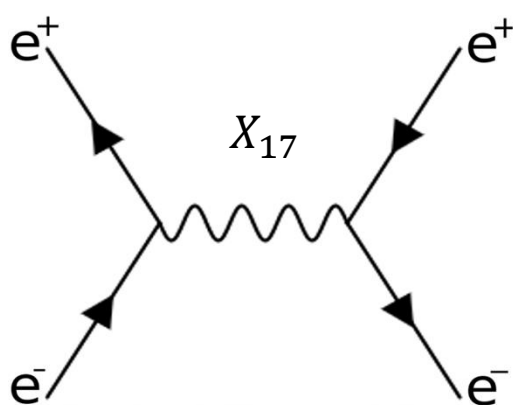
- Production: X-strahlung, shower, absorption of secondaries
- Detection: everything is signal vs kinematics of the final state
- The new particle has to survive the passage through the dump



- **e^+e^- colliders:**

- Associate production of new states
- Sensitivity depends on the resolution on invariant/missing mass of the final state
- Also searches through meson production and constrained initial state

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



Analysis strategy:

1. Change beam energy with a fine spacing in the 250-300 MeV range
2. Fit the background

3. Calibrate and measure the luminosity
4. Go bump hunting

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

$f(E_{res}, E_{beam})$ beam energy spread
 $\rightarrow$ Gaussian with spread δE

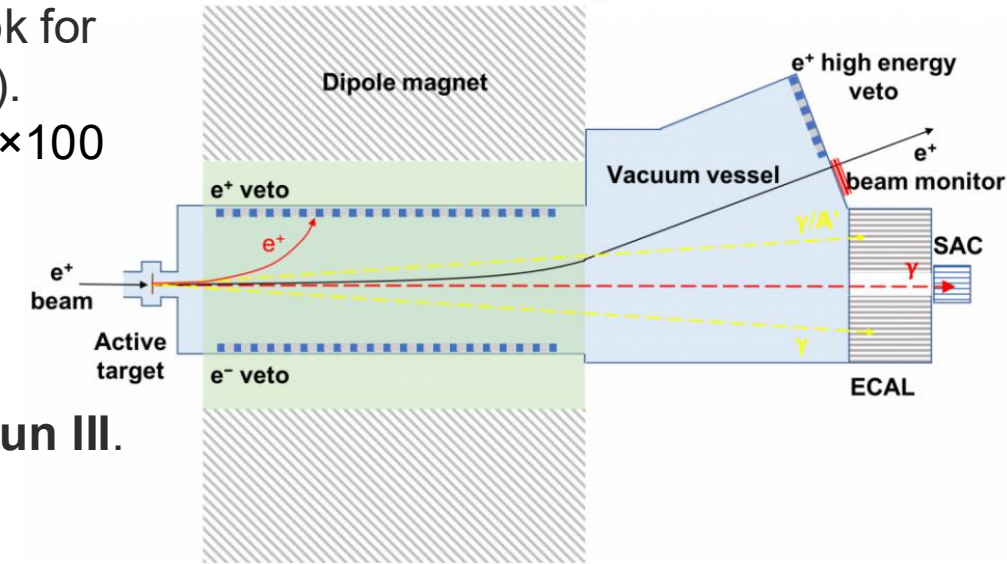
The INFN-LNF Beam Test Facility (BTF) is the perfect facility, considering its energy range, to perform this job

PADME The PADME experiment

- Positron Annihilation into Dark Matter Experiment: borned to look for $e^+e^- \rightarrow \gamma A'$ based @ Frascati National Laboratories (LNF-INFN).
- e^+ beam ($E < 550$ MeV) on a diamond active target $2\text{ cm} \times 2\text{ cm} \times 100\text{ }\mu\text{m}$
- Measure of ΔM_{miss}^2 using a BGO ECal.
- Could be sensitive to sub-GeV new physics (e.g. ALPs)

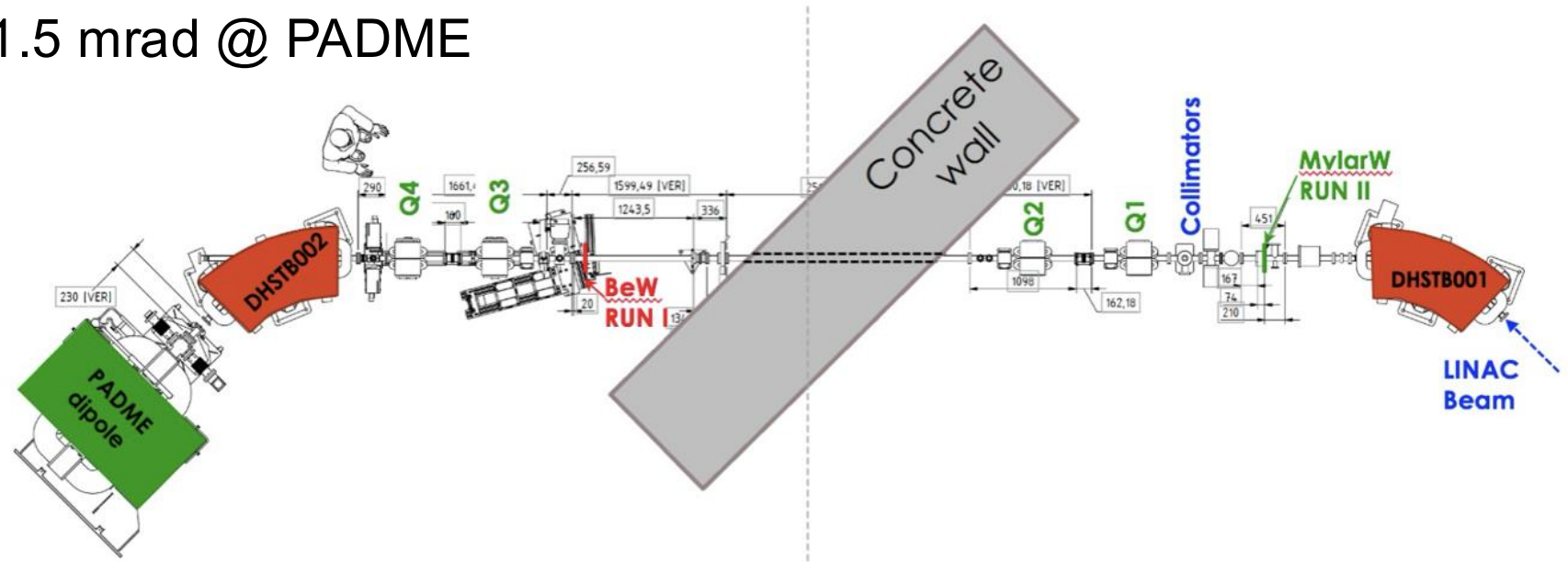
Can exploit the resonant production of X17 $\rightarrow$ fine scan: **PADME Run III.**

- Some modification to the setup were necessary



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 $\sim 3 \times 10^4$ POT / spill against pile-up
- Emittance $\sim 1 \text{ mm} \times 1.5 \text{ mrad}$ @ PADME



Past operations:

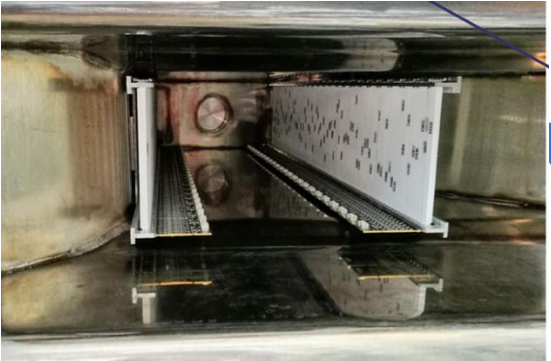
Run I e^- primary, target, e^+ selection, $250 \mu\text{m}$ Be vacuum separation (2019)

Run II e^+ primary beam, $125 \mu\text{m}$ MylarTM vacuum separation, 28000 e^+ /bunch (2019-20)

Run III dipole magnet off, ~ 3000 e^+ /bunch, scan $s^{1/2}$ around $\sim 17 \text{ MeV}$ (End of 2022)

Run IV same conditions as Run III (currently ongoing)

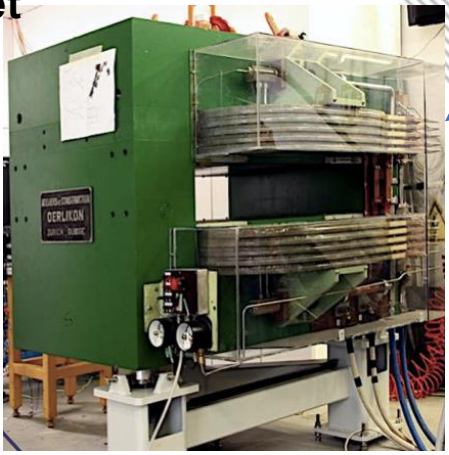
PADME – The detector



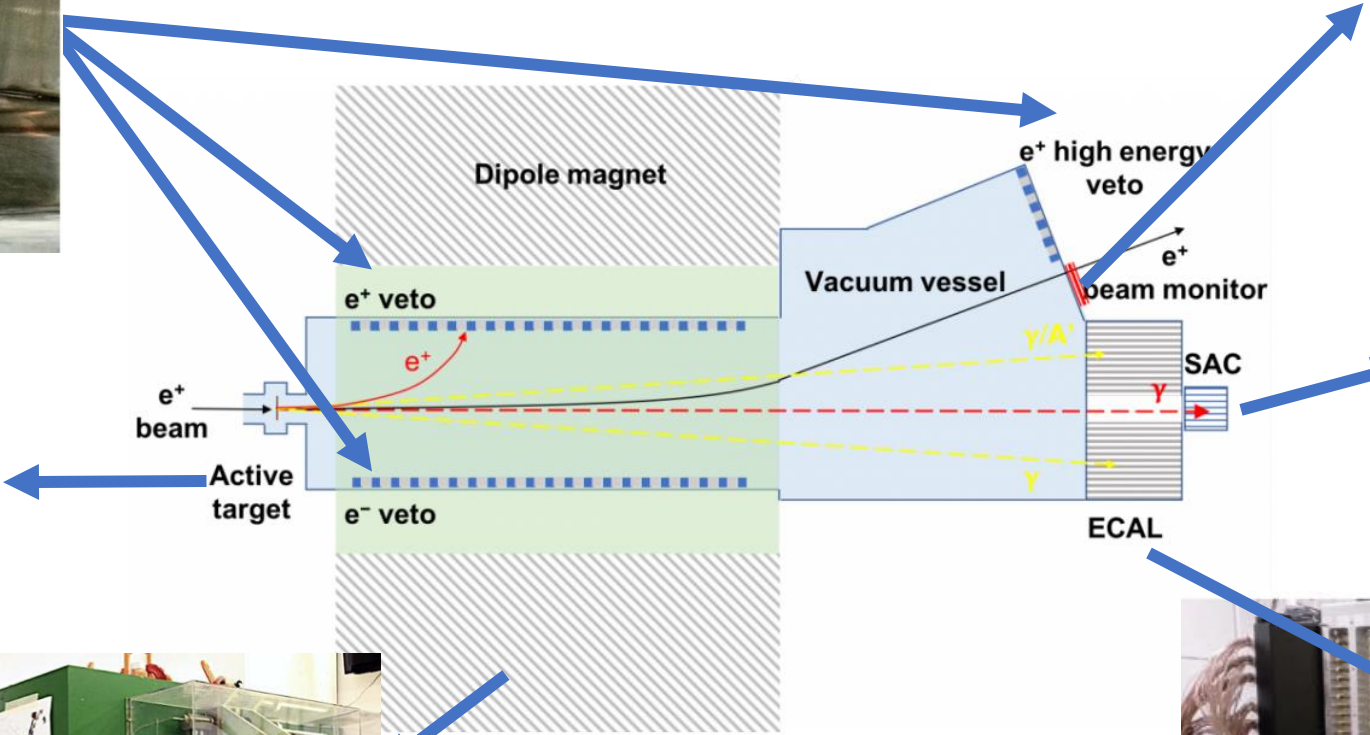
Scintillating e^+ , e^- VETO



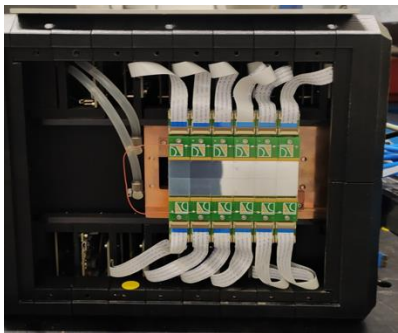
Active diamond target



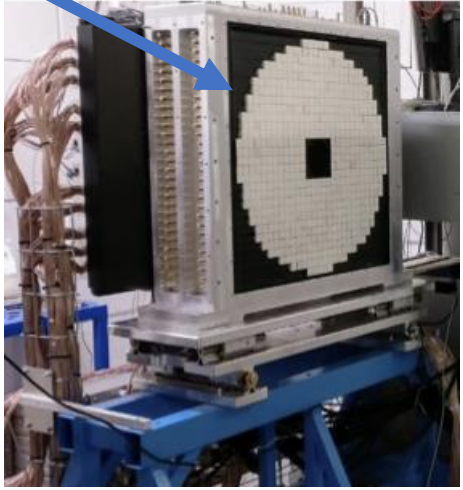
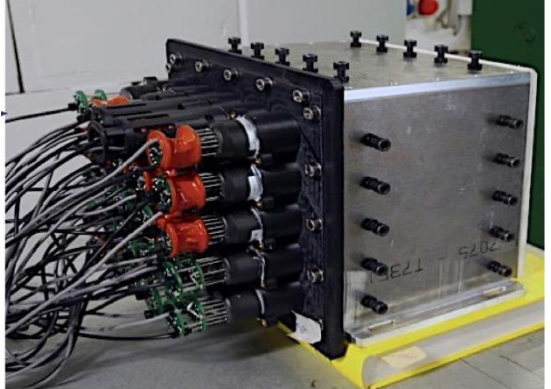
Dipole Magnet



TimePix
Beam monitor



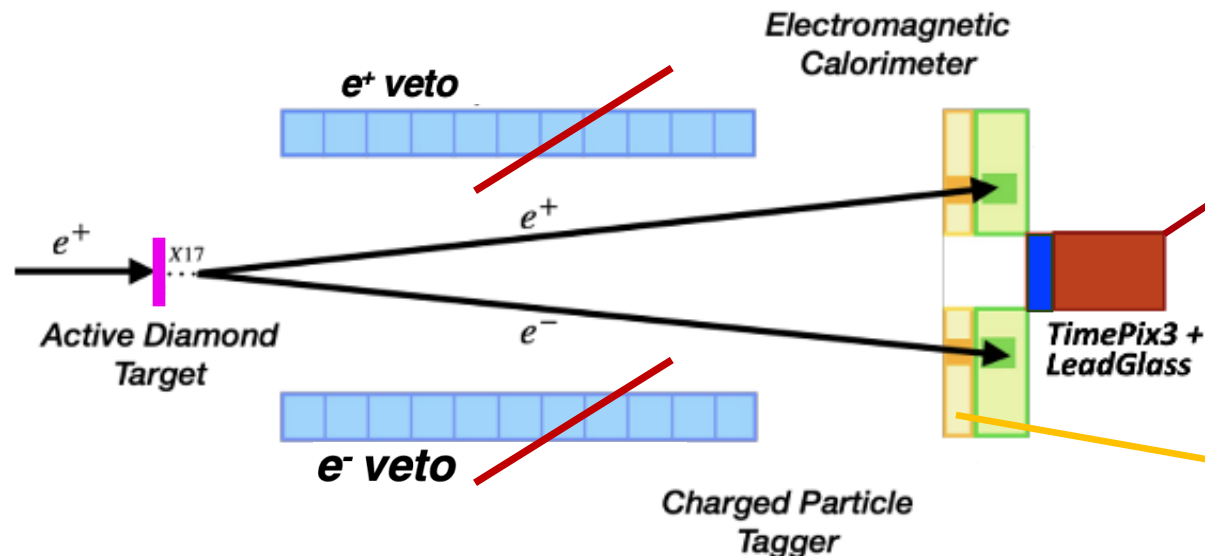
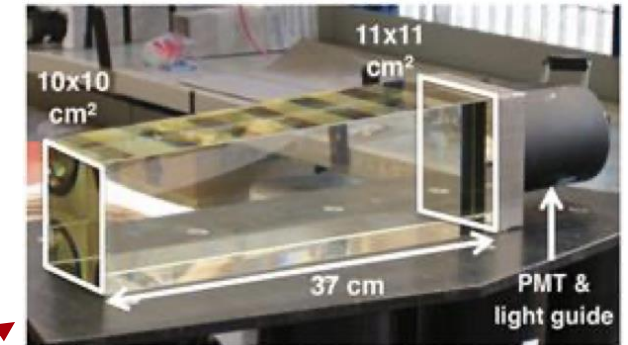
Small Angle PbF_2 calorimeter



BGO ECAL

Main SM background are Bhabha scatterings and $\gamma\gamma$ pairs productions, fitted directly from data → needed some setup optimization:

- Active diamond **target**
- **Charged particle veto** not used
- PADME dipole turned off → no magnetic field after the target interaction
- New **hodoscope** in front of ECAL added to identify charged particles
- SAC replaced with a **TimePix3** beam monitor and a **Leadglass** luminometer



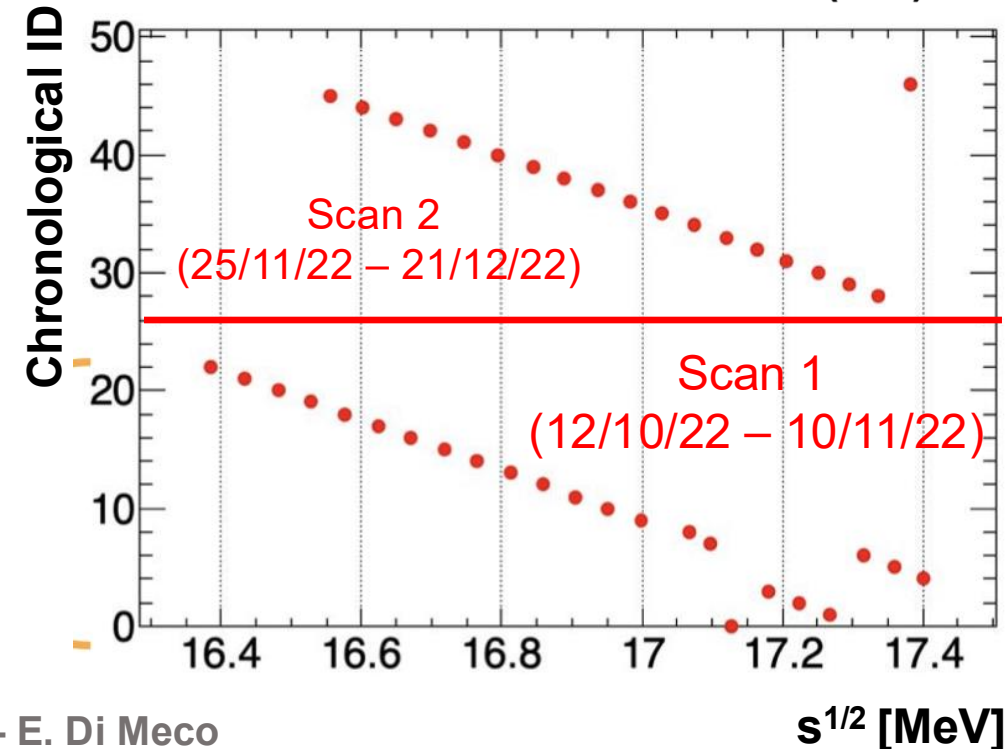
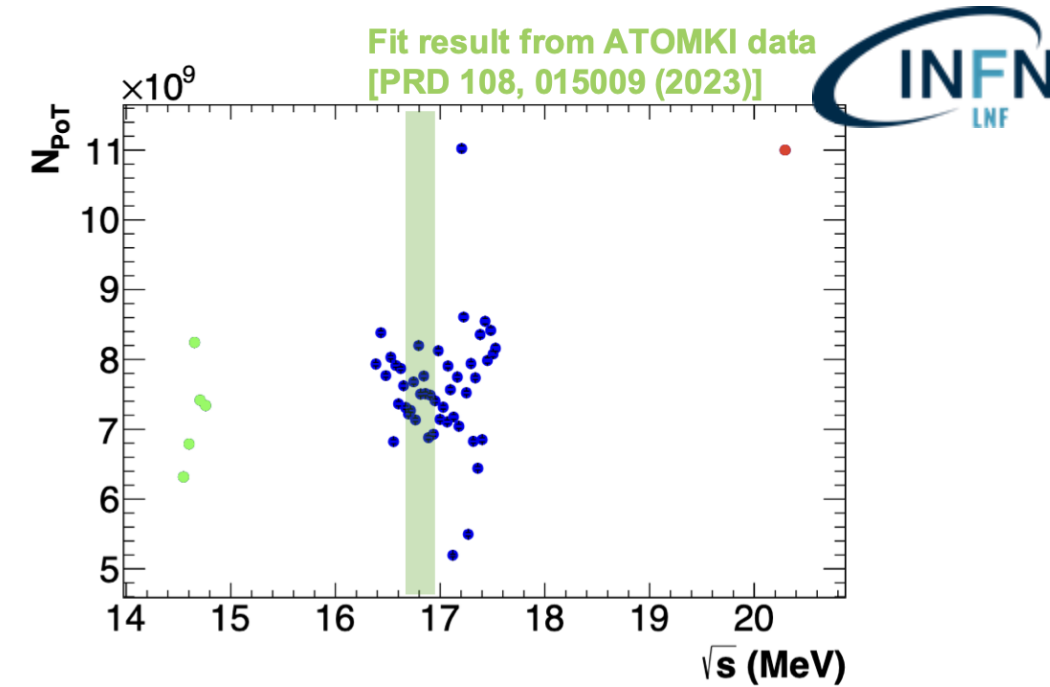
PADME Run II - dataset

Data-taking divided in 3 parts:

- **On resonance points @ (263-299) MeV → scan 1 and 2:** 0.75 MeV spacing, $16.4 \text{ MeV} < M_{X17} < 17.5 \text{ MeV}$, $\sim 1 \times 10^{10}$ NPoT per point
- **Below resonance points @ (205-211) MeV:** 1.5 MeV spacing, used to normalize the absolute yield
- **Over resonance runs @ 402.5 MeV:** 2×10^{10} stat, used to validate NPoT measurement

Some terminology:

- “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 $\sim 1.5 \text{ MeV}$ but interspersed in energy
- Detailed Geant4-based MC performed for each period



$$\frac{N_2(s)}{(N_{\text{POT}}(s) \times B(s))} = K(s) [1 + S(s; M_x, g) e_s(s)] \text{ to be compared to } \frac{N_2(s)}{(N_{\text{POT}}(s) \times B(s))} = K(s)$$

Inputs:

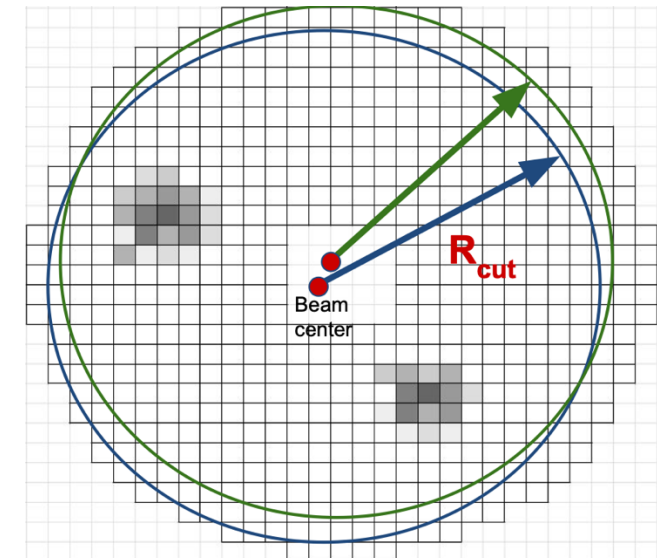
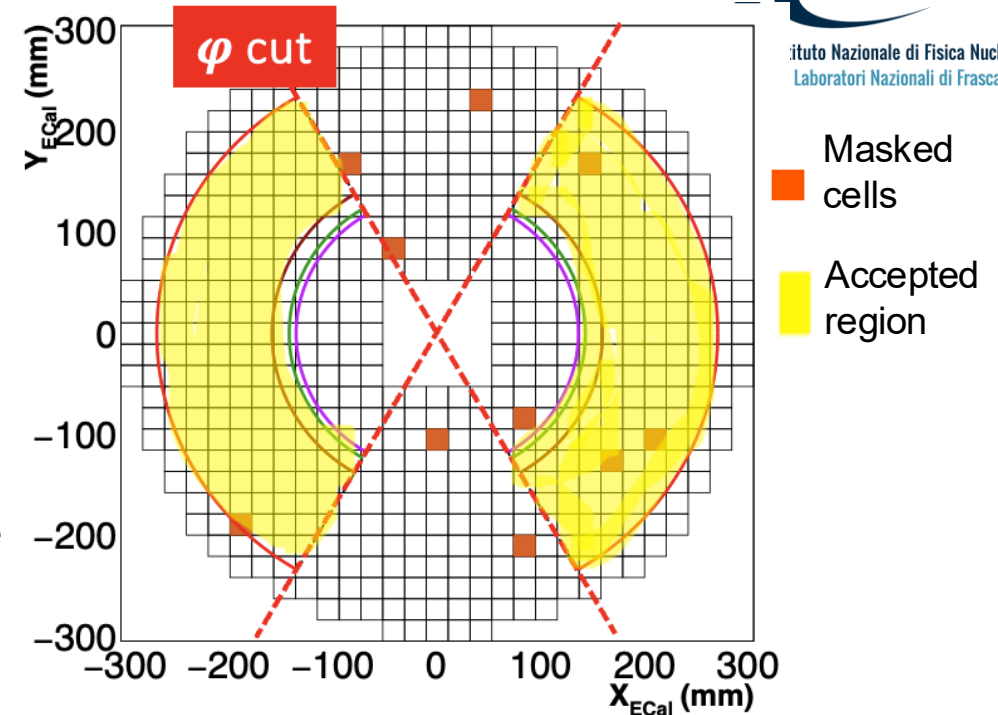
- $N_2(s)$ number of two-cluster events selected $\rightarrow$ our signal candidates
- $N_{\text{POT}}(s)$ number of e^+ on target from beam-catcher calorimeter
- $B(s)$ background yield expected per POT
- $S(s; M_x, g)$ signal production expected for $\{\text{mass, coupling}\} = \{M_x, g\}$
- $e_s(s)$ signal acceptance and selection efficiency
- $K(s)$ DATA-MC scale factor with a possible dependence from s

Aim: measure and evaluate systematic errors on:

- $N_{2\text{Cl}}$ (bkg subtracted) on data
- PoTs
- Signal Efficiency
- Signal shape
- MC Expected Yield

Selection algorithm as independent as possible on beam and detector conditions:

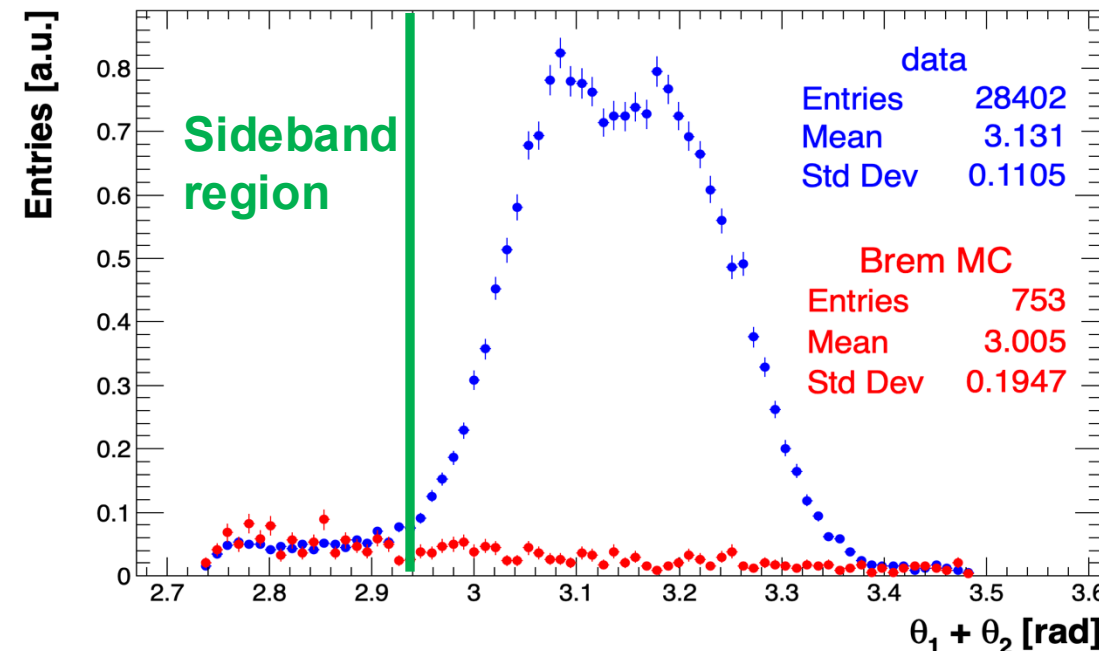
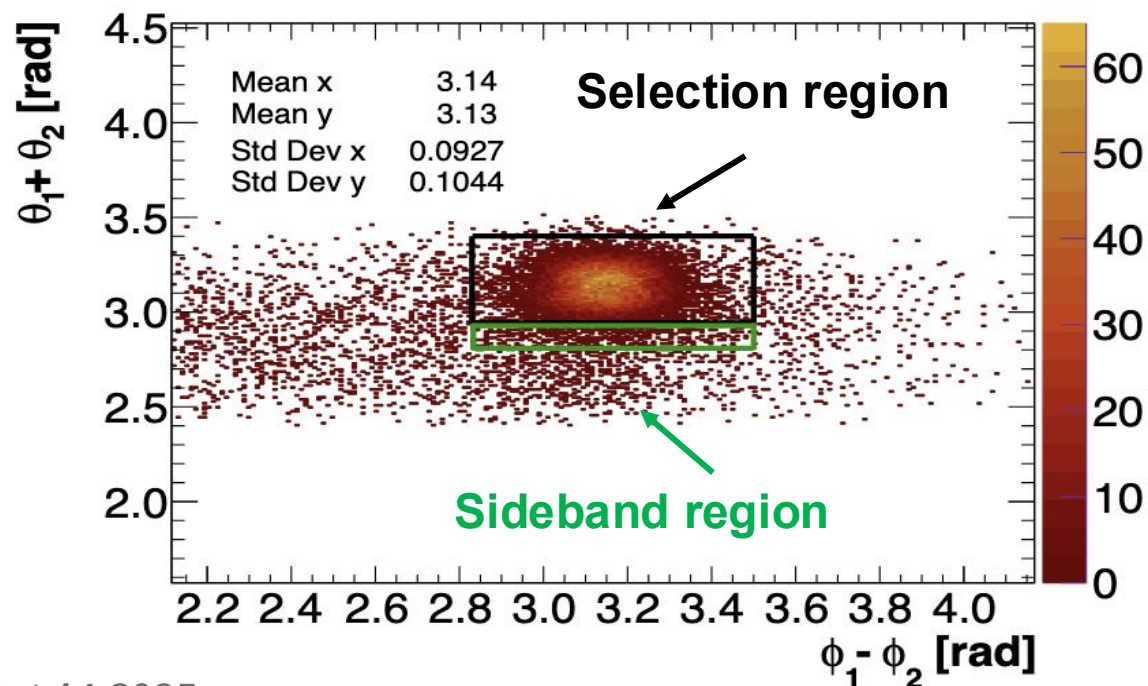
- **Selected a cluster pair with the following criteria**
 - Maximum radius defined by ECAL dimensions
 - Energy within the “two-cluster” kinematic range
 - Minimum radius within the “two-cluster” kinematic range
→ following the beam center conditions
 - ECAL Illumination affected by material along the beam line (below flange) → **Cut regions in φ**
- **Mutual cluster conditions:**
 - ΔT (clu0-clu1) < 5 ns
 - ΔR (clu0-clu1) > 60 mm (Minimum GG difference)
 - $\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ cut in the center of mass frame isolates the signal



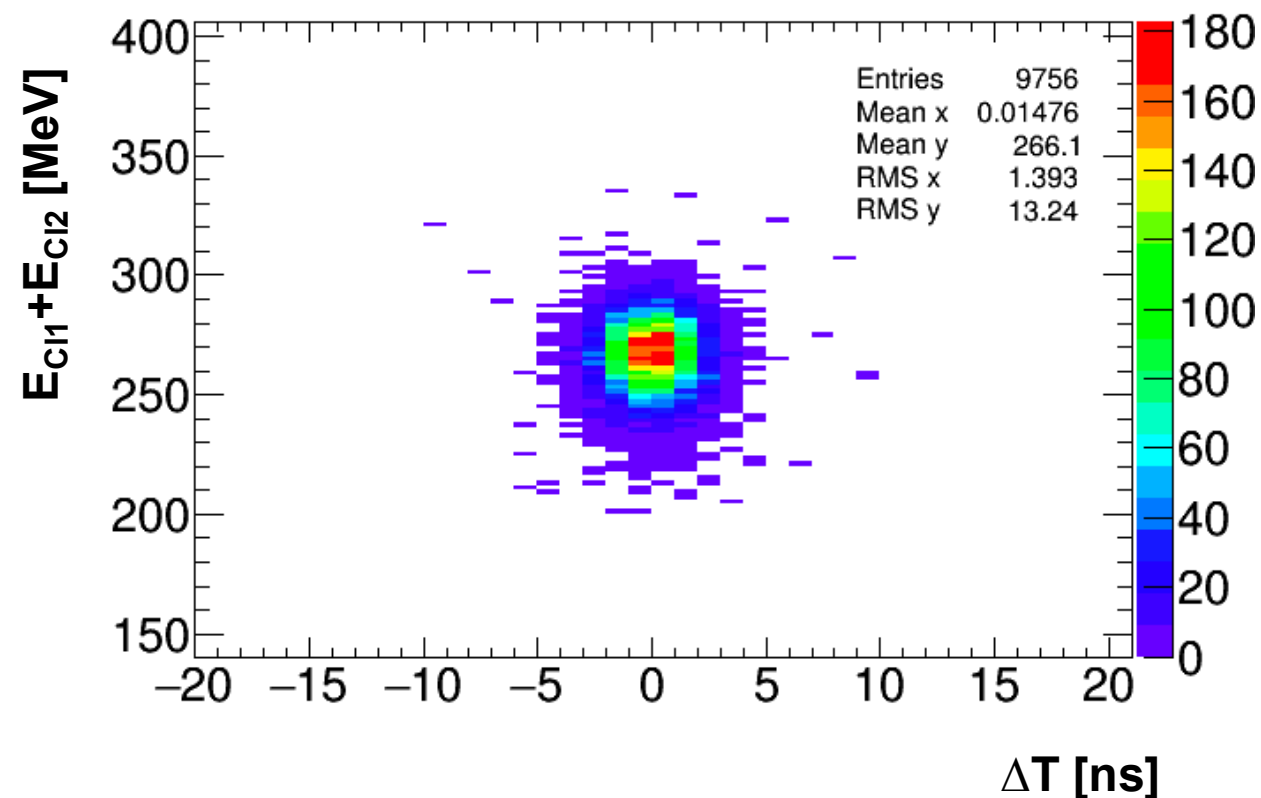
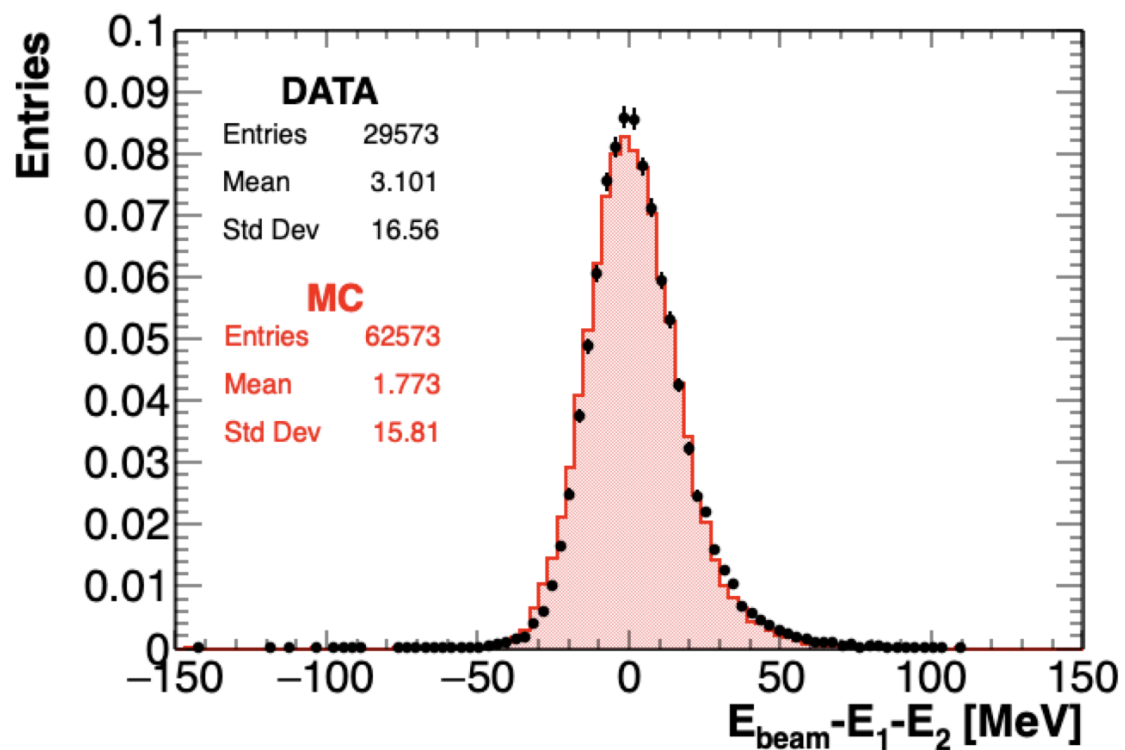
- Neglecting m_e/E terms, the c.m. angles are independent on the lab energies
- $\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ cut isolates the signal
- **Cut range:** 3σ around the mean value
 - Flat beam bkg in $\phi_1 - \phi_2 \rightarrow$ bkg level $< 4\%$
 - Bremsstrahlung tail in $\theta_1 + \theta_2 \rightarrow$ To be removed with MC shape using the sideband region

- ❖ Statistical error: $\delta N_2 \sim 0.6\%$ up to 0.7%
- ❖ Systematic uncertainty due to bkg subtraction: $\delta N_2 \sim 0.3\%$

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



- Events surviving the whole set of cuts, also related to the time difference of the 2 Clusters
- Energy sum of the 2 clusters selected gives back the beam energy (as expected for a two-body final state)
- ECAL relative energy resolution $\sim 5\%$

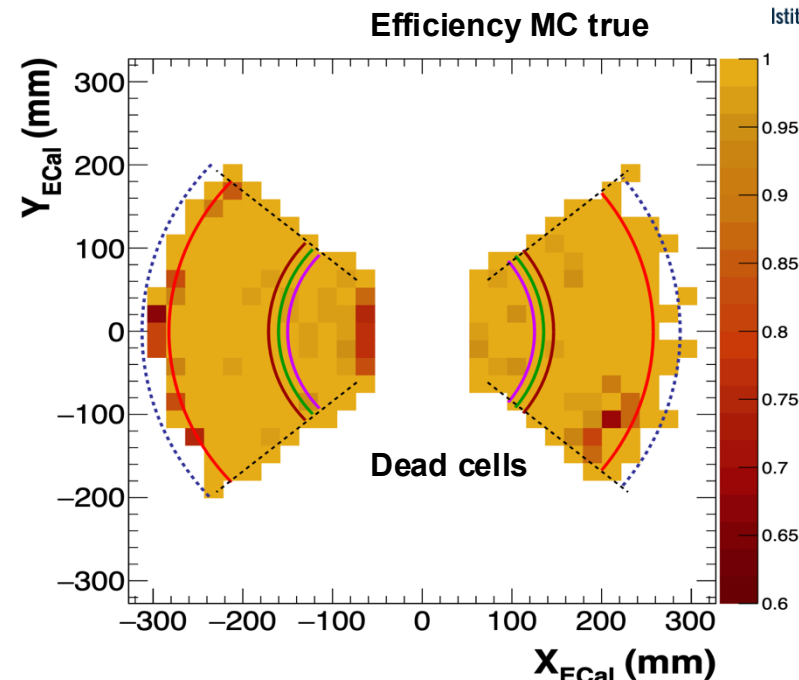
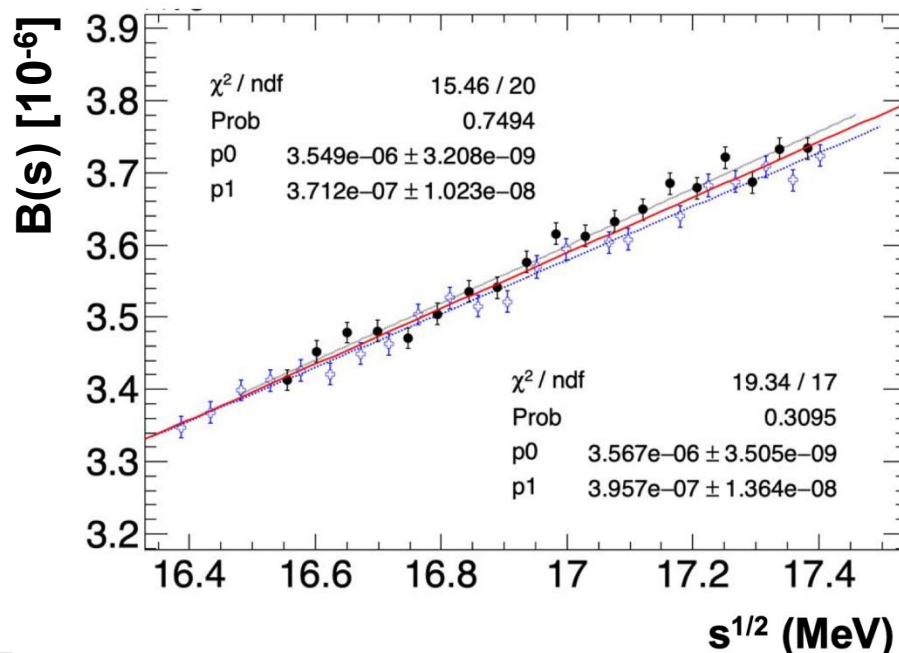


PADME Expected Background $\rightarrow B(s)$

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

Reconstruction efficiency taken into account:

- Data/MC efficiency with tag-and-probe technique
- bkg subtraction at tag level dominates the statistical-systematic error $\rightarrow \delta B = 0.35\%$
- Cut stability at MC and Data level also under control together with COG (beam) variations



Source	Error on B [%]
MC statistics	0.40
Data/MC eff. (Tag&Probe)	0.35
Cut stability	0.04
Beam spot variations	0.05
Total	0.54

- PoTs measured with the end-of-line lead glass calorimeter → 2% scale error on the calibration considered
- 2 main effects: **radiation induced loss + energy loss in passive material**
 - Run III radiation dose ~ 2.5 krad → transparency changes for O(krad)
 - ❖ Estimated from 3 flux proxy observables: $Q_{\text{target-x}}$, $\langle E_{\text{ECal}} \rangle$, period multiplets
 - ❖ LG yield decreases with relative PoT slope of 0.097(7) → Slope error included $\delta N_{\text{PoT}} = 0.35\%$
 - ❖ Constant term uncertainty of $\delta N_{\text{PoT}} = 0.3\%$ added as scale error
 - Loss due to beam movements during the whole Run III → passive material crossing
 - ❖ Checked against data of October test beam + MC simulation → systematic correlated error $\delta N_{\text{PoT}} = 0.5\%$

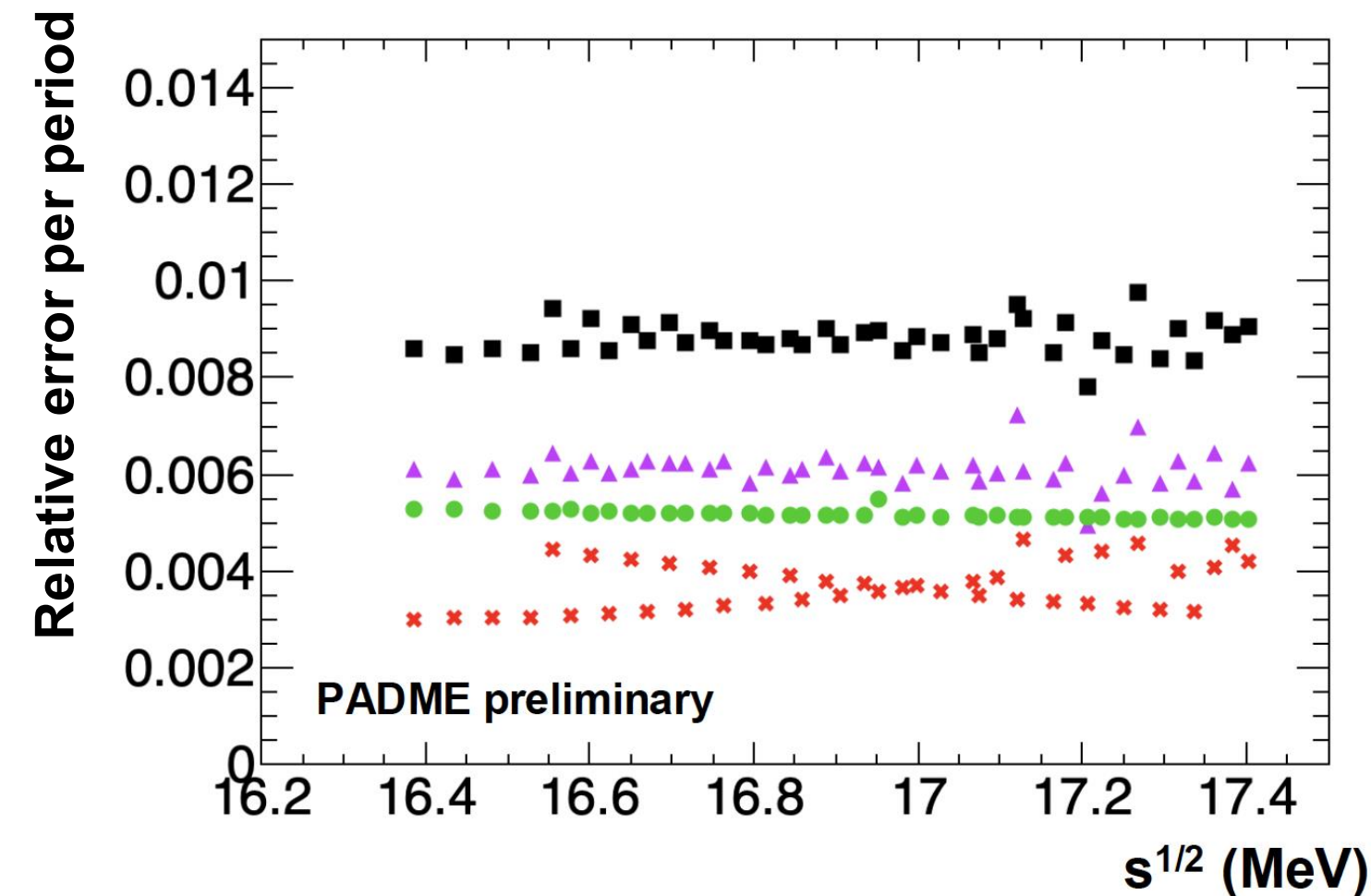
Uncorrelated systematic errors

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

Common systematic errors

Source	Common error [%]
pC / MeV (JHEP 08 (2024) 121)	2.0
Energy Loss, data/MC	0.5
Rad. induced loss	0.3
Total	2.1

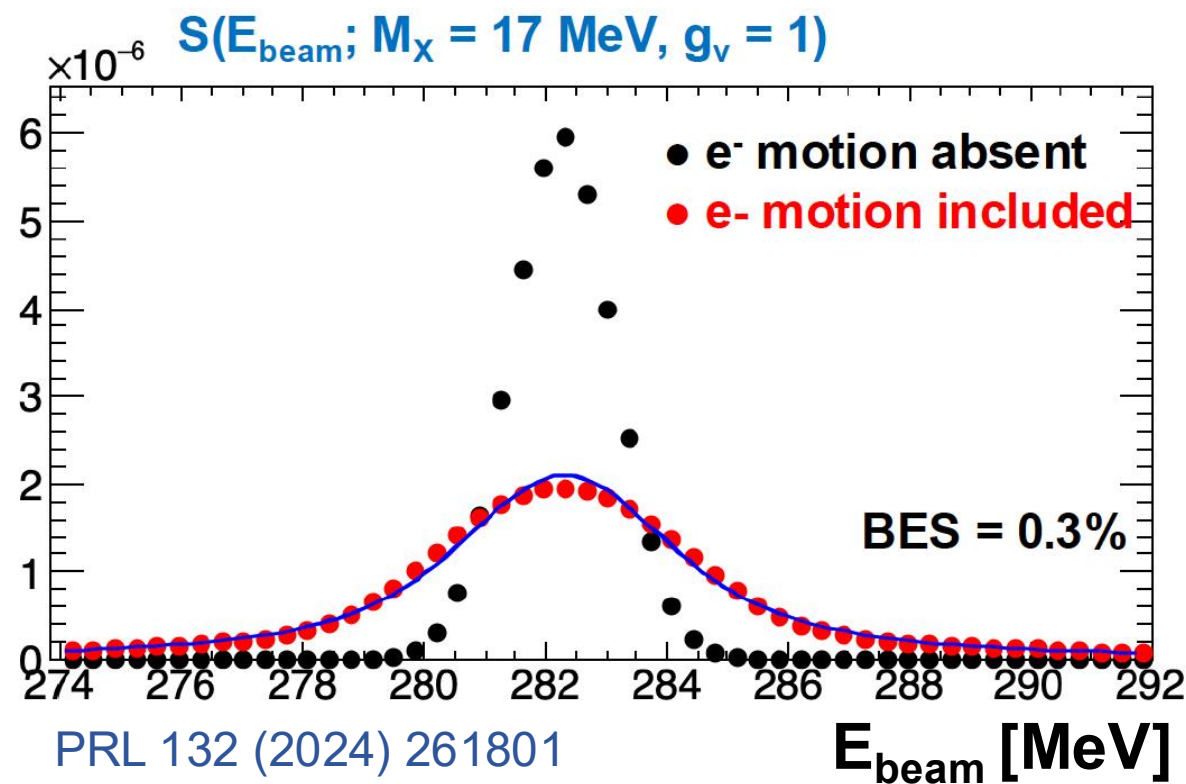
- Uncorrelated uncertainty on $g_R(s) = N_2(s) / (N_{PoT}(s) B(s))$:



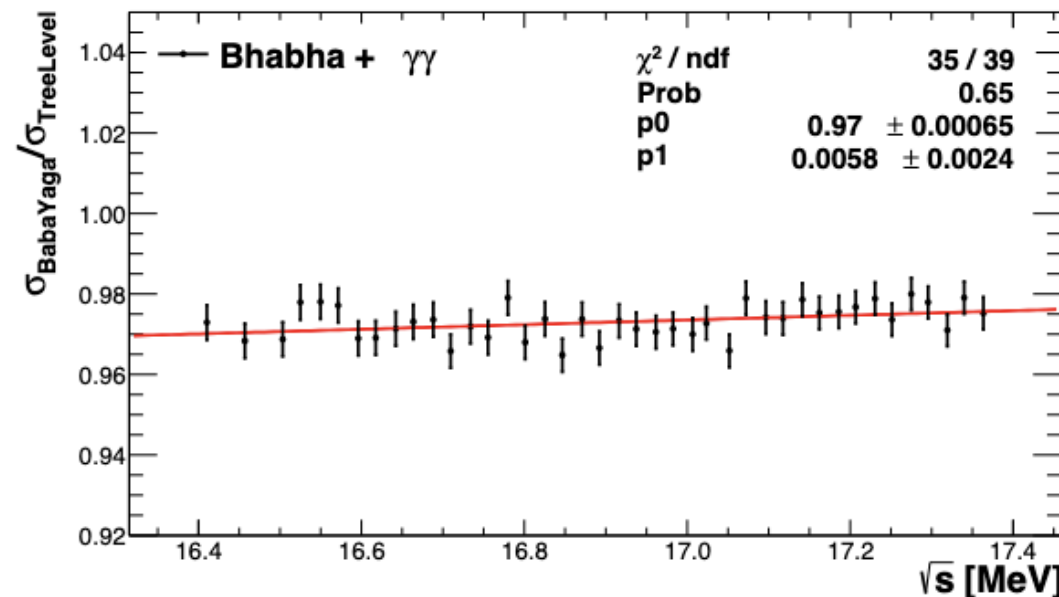
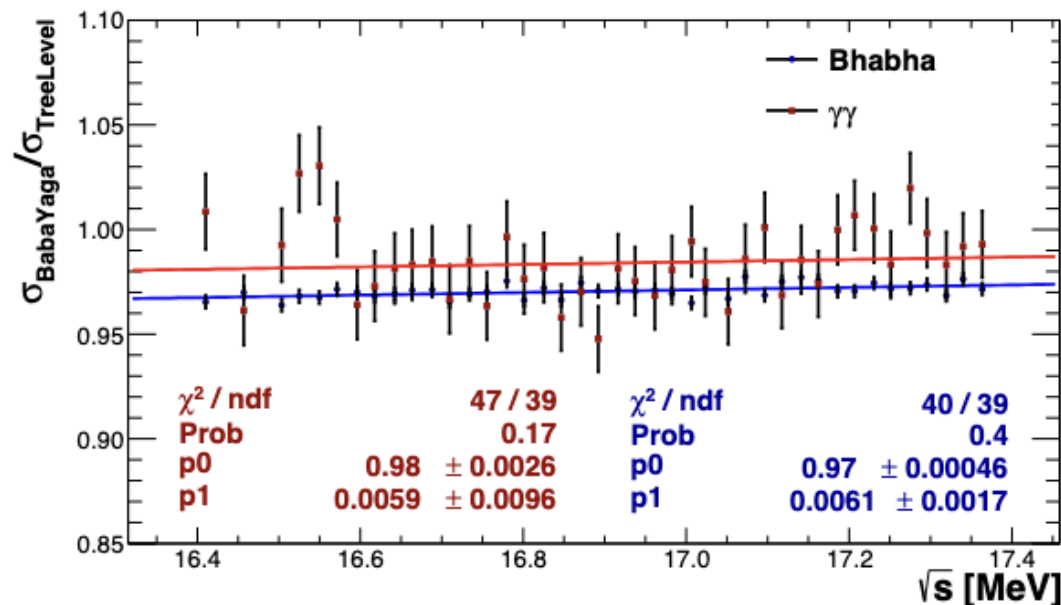
Uncorrelated errors	
Source	Uncertainty (% per energy point)
$N_2(s)$	0.60
$B(s)$	0.54
$N_{PoT}(s)$	0.35
Total on $g_R(s)$	0.88
$K(s)$, constant term	
Source	Uncertainty (%)
Lead-glass calibration	2.0
Absolute B yield	1.8
Energy-loss correction to N_{PoT}	0.5
Radiation-induced correction to N_{PoT}	0.3
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

- Next step: is $g_R(s)$ compatible with 1 or $1 + S(s) \epsilon(s)/B(s)$?

- Electron motion inside the target changes significantly the shape of the resonance → not anymore just a gaussian with σ equal to the beam energy spread
- Parameterized S vs E_{beam} with a Voigt function:
 - Convolution of the gaussian BES with the Lorentzian
- Uncertainty in the curve parameters as nuisances:
 - **Lorentzian width** around the resonance energy: 1.72(4) MeV
 - **Relative BES**: 0.025(5)%
- Expected background signal efficiency determined from MC:
 - Large cancellation of systematic errors seen using ε/B
- Fit $\varepsilon(s)/B(s)$ with a straight line, include fit parameters as nuisances:
 - **Errors**: $\delta P_0/P_0 \sim 0.1\%$, $\delta P_1/P_1 = 3\%$, correlation = -2.5%



Radiative corrections evaluated using Babayaga $\rightarrow e^+e^-(\gamma)$ and $\gamma\gamma(\gamma)$ ([Nucl. Phys. B 758 \(2006\) 227](#), [Phys. Lett B 663 \(2008\) 209](#))



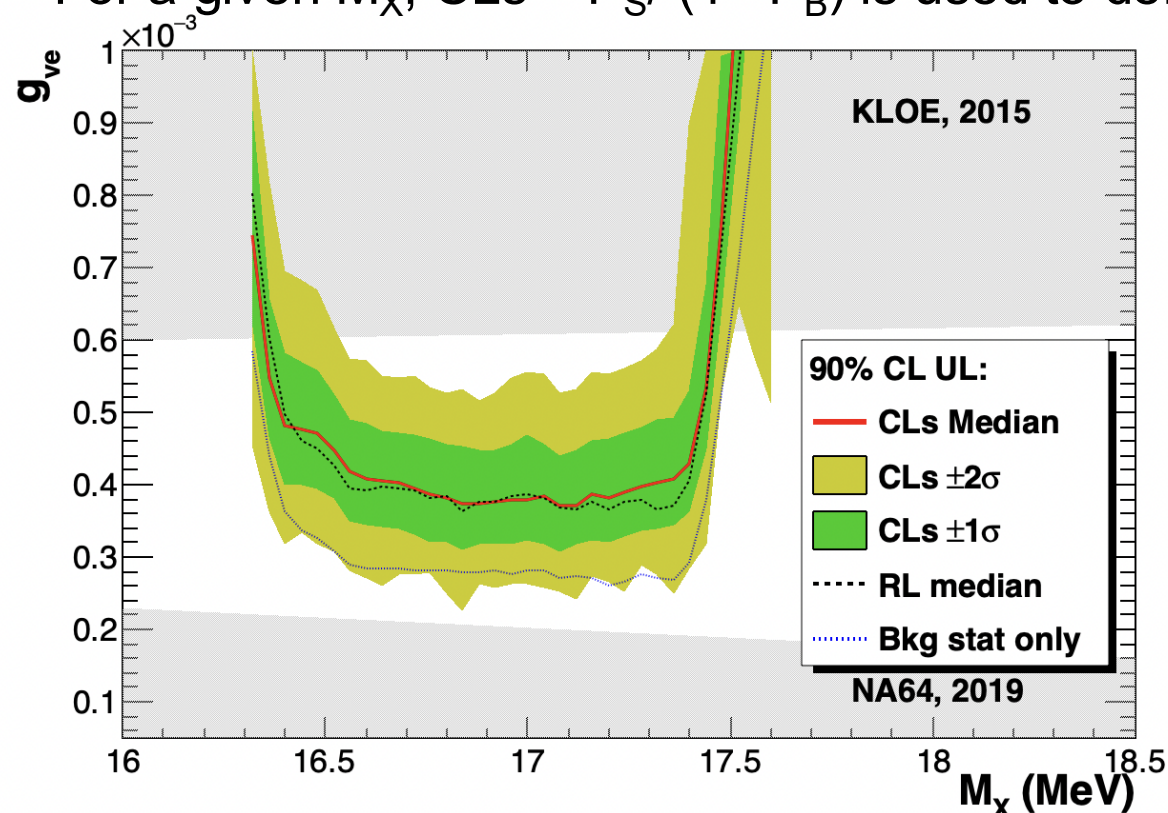
Possible offset $\rightarrow$ -2.8% @ 16.92 MeV

Possible slope with $\sqrt{s} \rightarrow$ -0.6(6)% MeV⁻¹

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) $\rightarrow$ no effect on $\epsilon(s)$

- Evaluate expected 90% CL UL in absence of signal
- Modified frequentist approach, LEP-style test statistic
- **Likelihood fits** performed for the separate assumptions of **signal + background vs background only**, define Q statistic based on Likelihood ratio: $Q = LS + B(g_{ve}, M_X) / LB$. 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_{ve}



Source	Uncertainty [%]
N_2	0.6
B	0.35
N_{PoT}	0.55
TOTAL on g_R	0.88
TOTAL on K(s)	2.1

Pseudo data (SM background) is generated accounting for the expected uncertainties of nuisance parameters + statistical fluctuations

To validate the error estimate, we applied the procedure in [JHEP 06 \(2025\) 040](#)

- 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 , check if the fit pulls are gaussian
 3. If , check if a straight-line fit of the pulls has no slope in $s^{1/2}$ (within 2 sigma)
 4. If , check if constant term and slope of the linear fit for $N_2(s)/B(s)$ are within two sigma of the expectations, i.e.: $\pm 4\%$ for the constant, $\pm 2\%$ MeV^{-1} for the slope

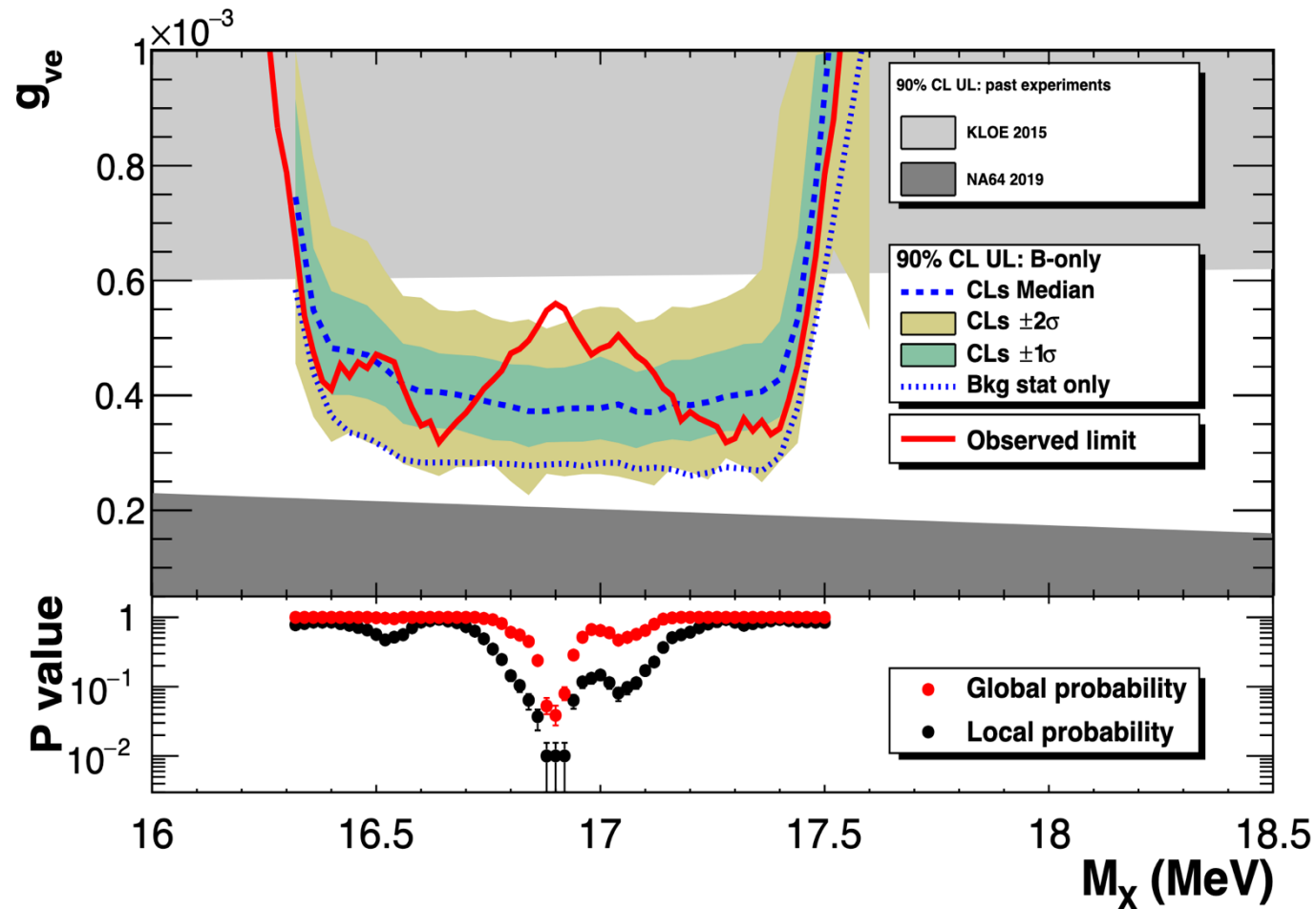
Successfully applied:

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}

 **Ready to unblind**

Some excess is observed a $\sim 2.5\sigma$ local coverage

- At $M_X = 16.90(2)$ MeV, $g_{ve} = 5.6 \times 10^{-4}$, 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 $\sim 40\%$
- If a 3σ interval is assumed for observation following the estimate $M_X = 16.85(4)$ MeV 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

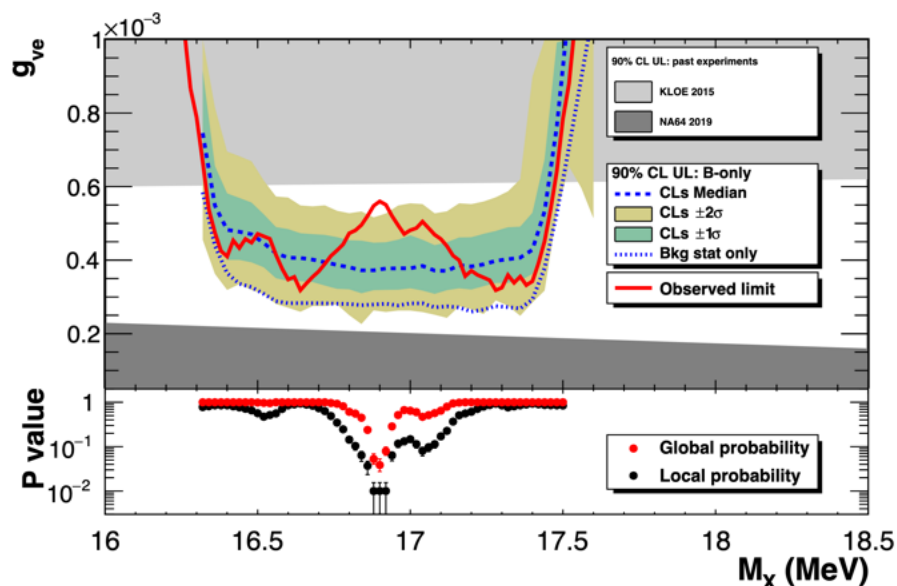


[ArXiv:2505.24797 \[hep-ex\]](#)
Accepted from JHEP

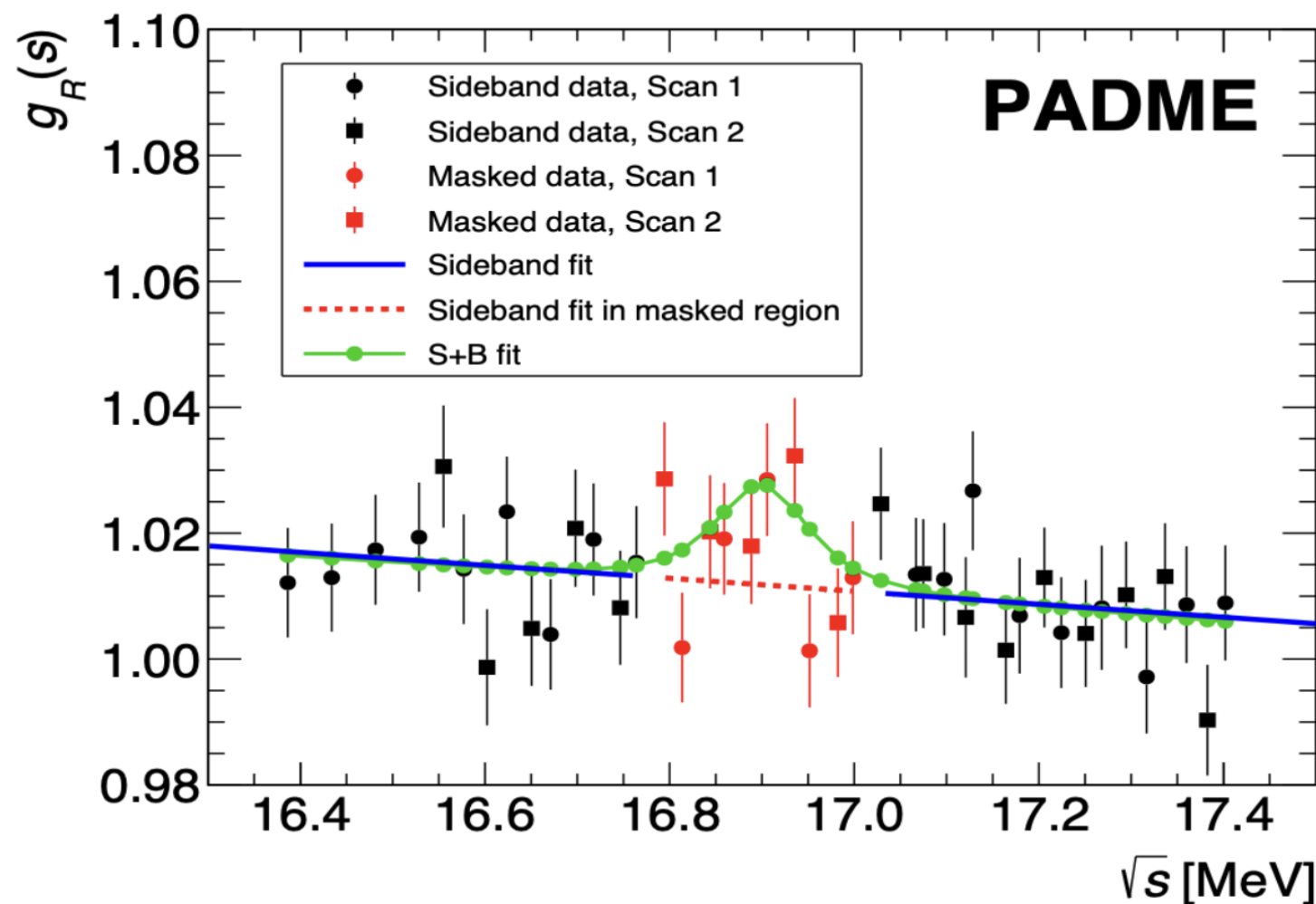
PADME Box opening - 2

Check the data distribution vs likelihood fit done to evaluate $Q_{\text{obs}}(S+B)$

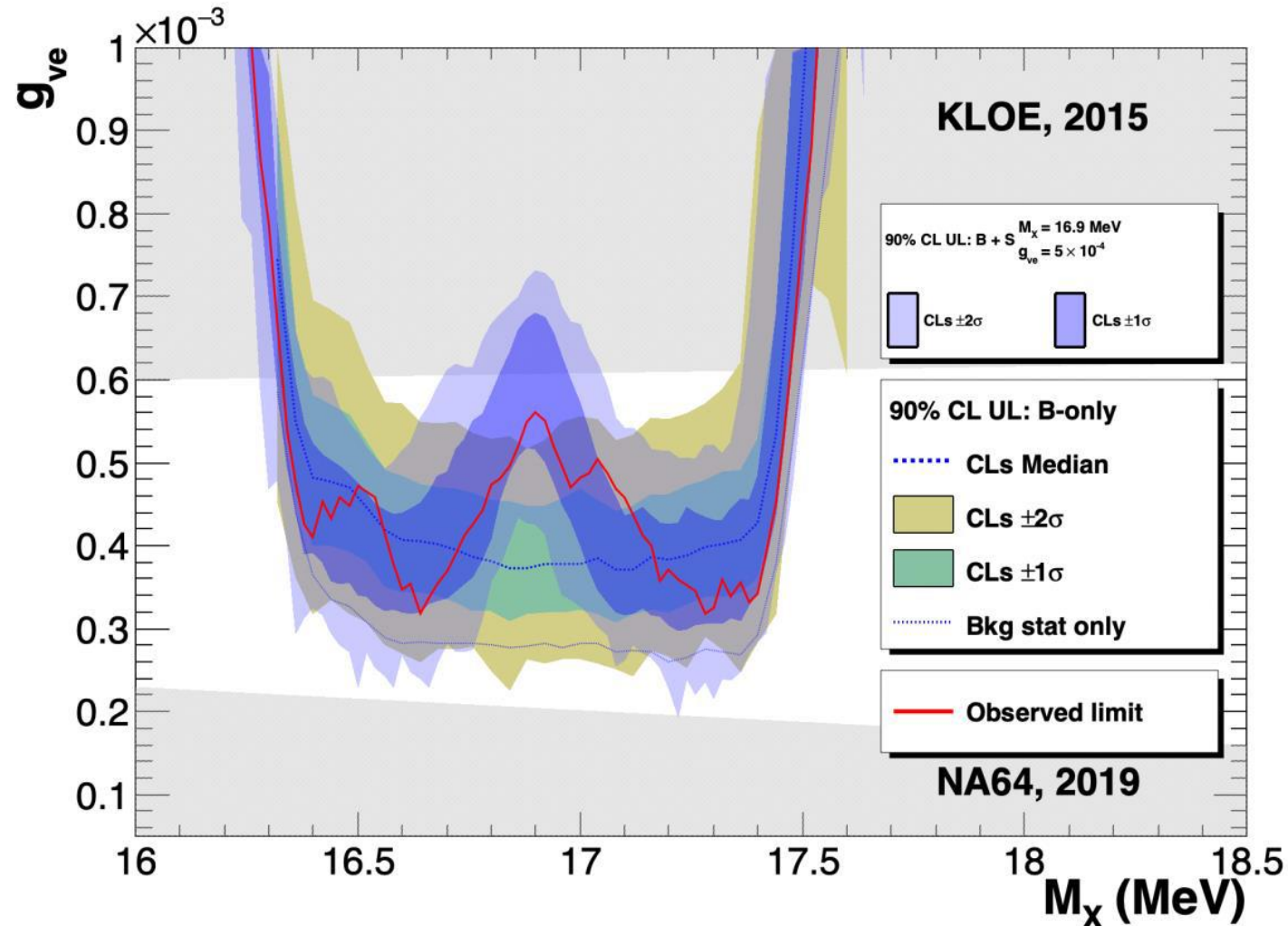
Fit probability is 60%



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

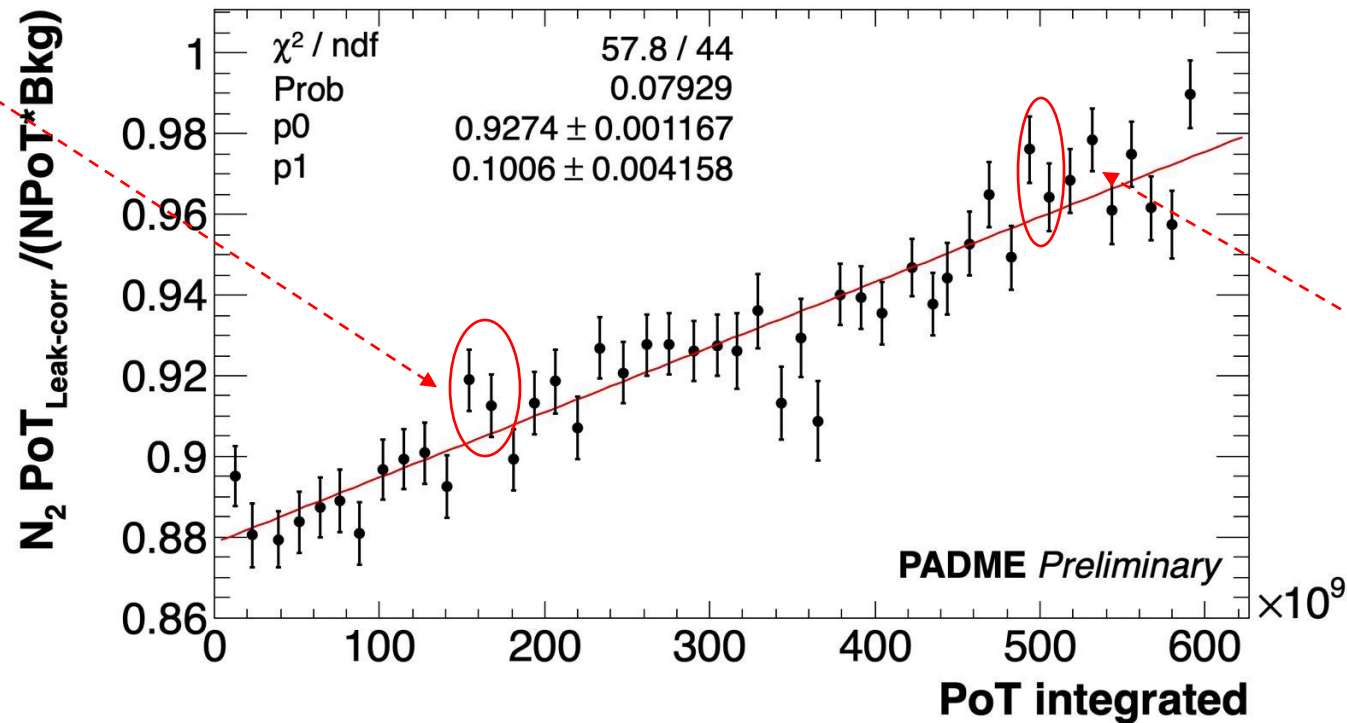


Check on the UL behaviour comparing the **bkg-only** hypothesis with the **B+S** ($m = 16.9$ MeV, $g_{\nu e} = 5 \times 10^{-4}$)



- After box opening, can check ageing correction applied, slope was 0.097(7)
- Fully consistent (observed **excess** alters only marginally)
- A very compatible slope to the one used as nuisance for the radiation induced effect is found (when not applying the correction) with no significant change in the locations of the excess (distant 1 month apart) and in the global p-value

27 Oct 2022



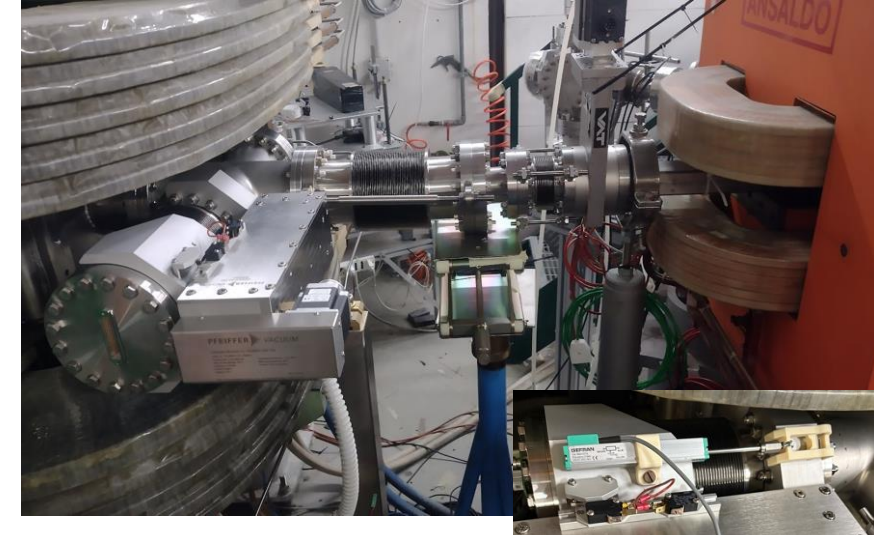
8 Dec 2022

PADME Run IV improvements overview

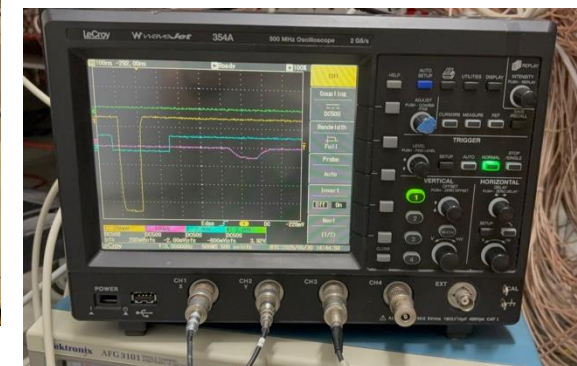
The Run IV paradigm → increase sensibility to confirm/disprove Run III result

- **Diamond target** position moved downstream by ~30 cm
- Passive material removed and PADME Magnet fully degaussed → $B_{\text{PADME}} < 1 \text{ G}$
- Beam stable in the central position along the whole data taking
→ **NO LATERAL LEAKAGE on the beam cathcer**
- **Led pulser** Tektronix AFG3101 to control the radiation induced loss
 - Independent trigger included in the DAQ
 - A second LG block installed (out of the acceptance and only acquiring the led trigger)
 - Online LG response renormalized to the not-fired-block
 - Reference for light yield response almost on the fly

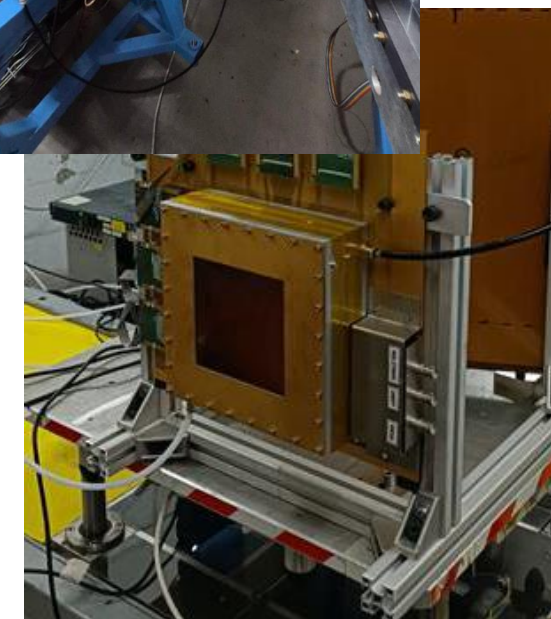
Diamond target



Led pulser



PadMMe

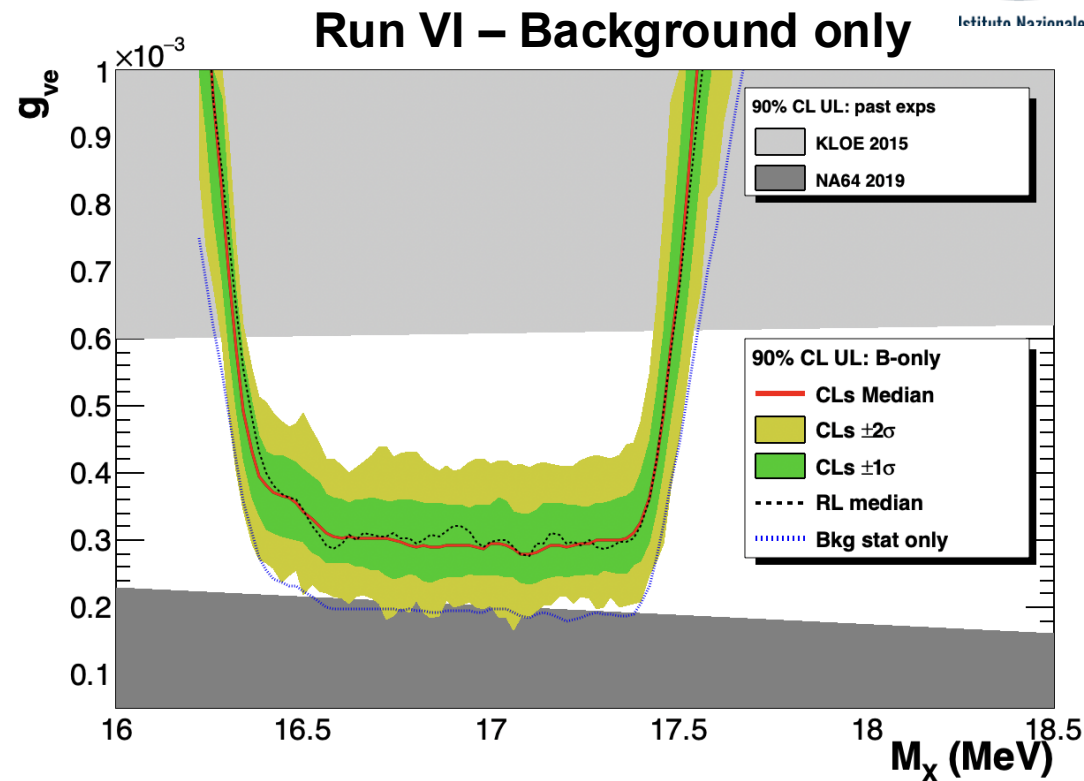
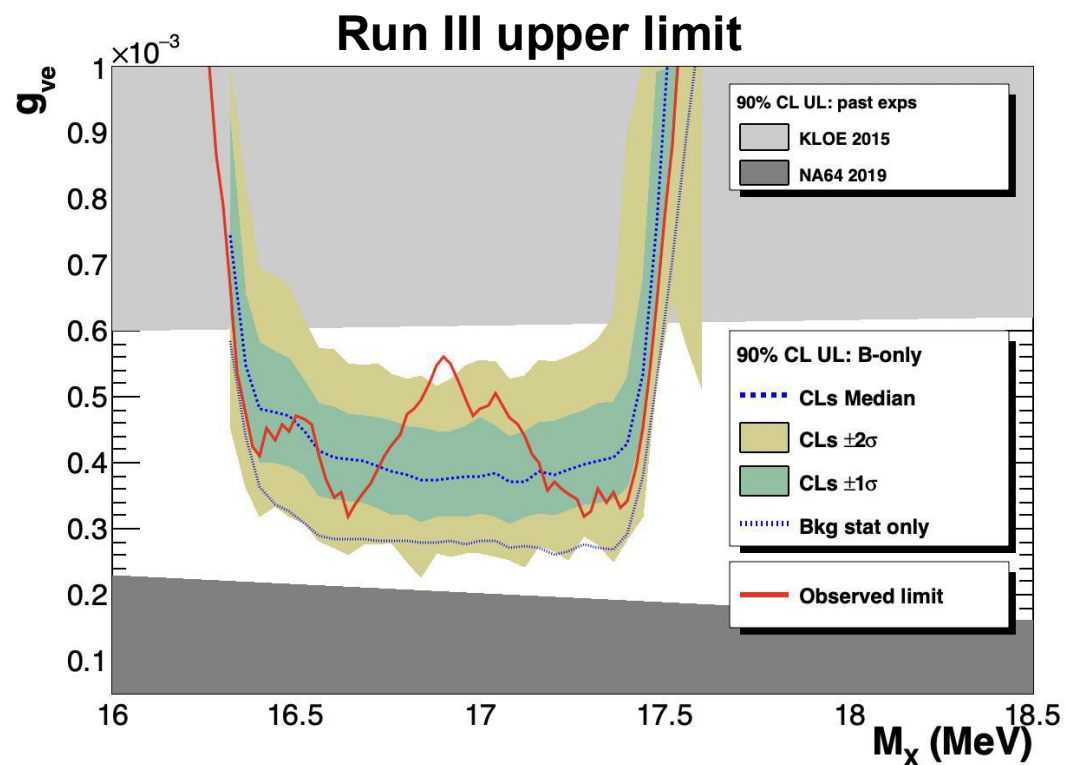


TMM

New detectors:

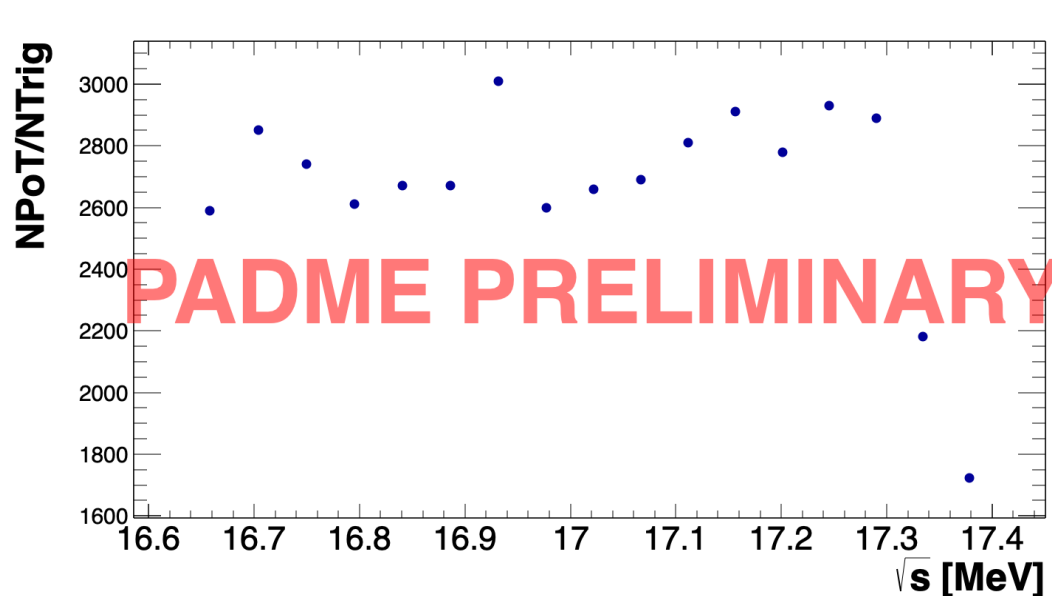
- **PadMMe** MicroMegas chamber replaced the Etagger:
 - e/γ discrimination $\rightarrow$ possible normalization to $e^+e^- \rightarrow \gamma\gamma$ process
 - Spatial resolution $\sim 350\ \mu\text{m}$ $\rightarrow$ angle disentanglement
 - Multitrack events can be collected
 - Beam spot monitor $\rightarrow$ Already implemented in the Run IV online monitor
- **TMM** Micromegas replace the TimePix beam monitor
 - Greater active area wrt TimePix and less passive material budget
 - Beam shape and spot monitor

Source	Uncertainty [%]		Improvement
	Run III	Run IV	
N_2	0.6	0.3	New target position $\rightarrow$ acceptance increased
B	0.35	0.3	PadMMe $\rightarrow$ ee/gg discrimination + better angular-momentum resolution
N_{PoT}	0.55	0.3	3 different beam spot monitor (target-PadMMe-TMM) + online LG calibration system
TOTAL	0.88	0.5	

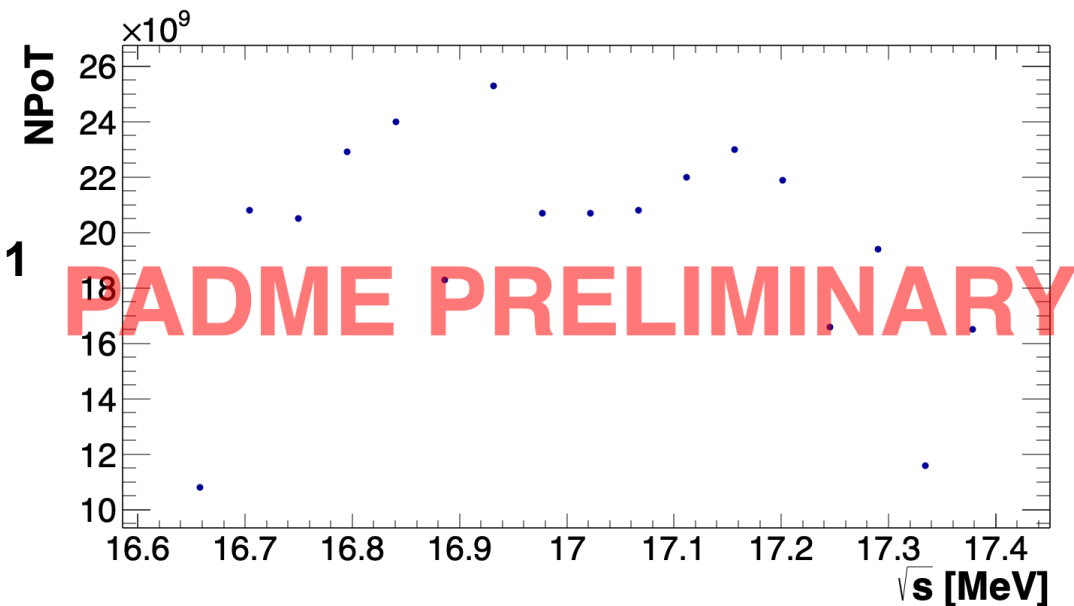


Source	Uncertainty [%]	
	Run III	Run IV
N ₂	0.6	0.3
B	0.35	0.3
N _{PoT}	0.55	0.3
TOTAL	0.88	0.5

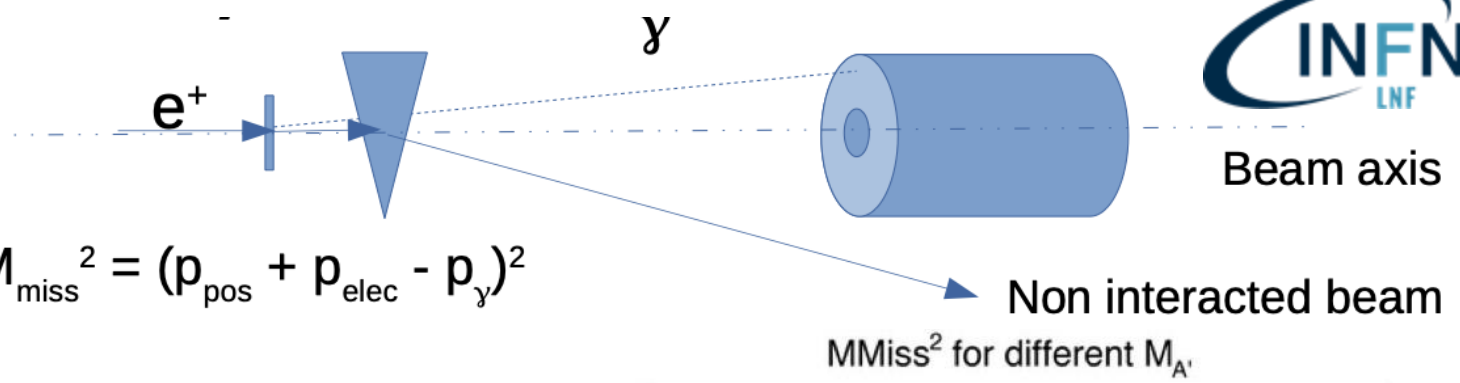
- The PADME experiment is now focused on the search of the X_{17} particle
- Run III analysis has been completed: no indications of X_{17} well beyond two-sigma-equivalent global p-values, an excess has been observed, with global p-value equivalent to $1.77(15)\sigma$
- New data acquired to better clarify:
 - Run IV-part 1 data already in the book: 18 energy scan points collected ($\sim 2e^{10}$ PoTs each) equally separated by 1.5 MeV in the the $E_{\text{beam}} = (269.5, 295) \text{ MeV} / \sqrt{s} = (16.60, 17.36) \text{ MeV}$ region
 - Run IV-part 2 already scheduled for autumn 2025
 - Scan points = 18-20 + out-of-resonance below 16 MeV and above 18 MeV



Run IV – Scan 1

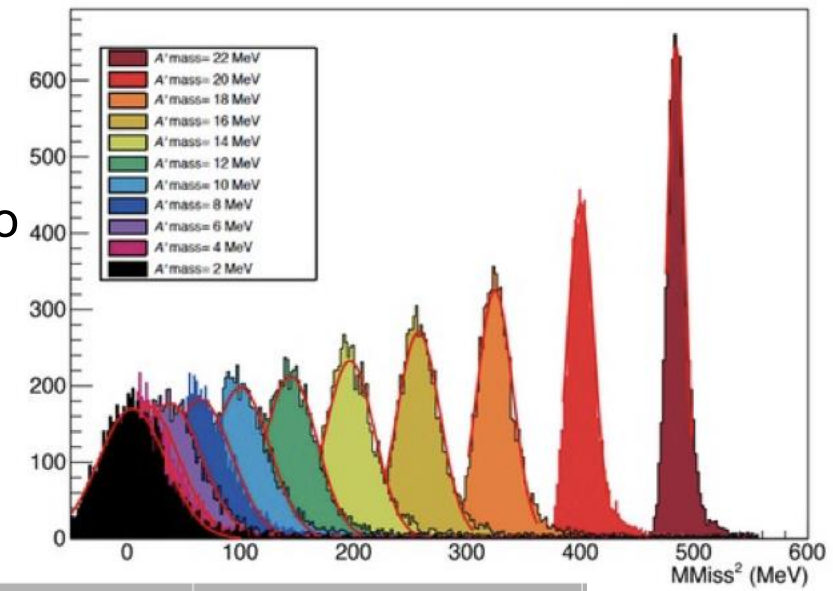


Backup slides



- $e^+e^- \rightarrow \gamma A' \rightarrow$ signal
- **Backgrounds:**

1. Bremsstrahlung in the field of the target nuclei
 - Photons mostly @ low energy, background dominates high missing masses
 - An additional lower energy positron that could be detected due to stronger deflection
2. 2 photon annihilation
 - Peaks at $M_{\text{miss}} = 0$
 - Quasi symmetric in gamma angles for $E_{\gamma} > 50$ MeV
3. 3 photon annihilation
 - Symmetry is lost $\rightarrow$ decrease in the vetoing capability
4. Radiative Bhabha scattering
 - Topology close to bremsstrahlung

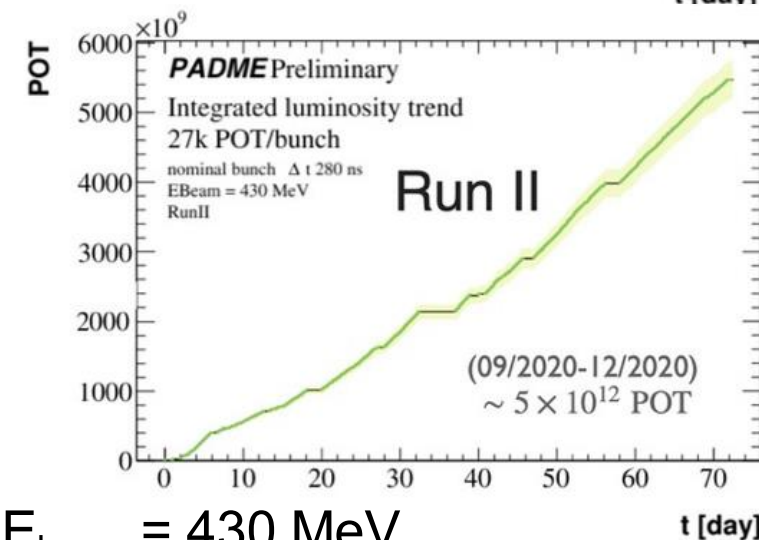
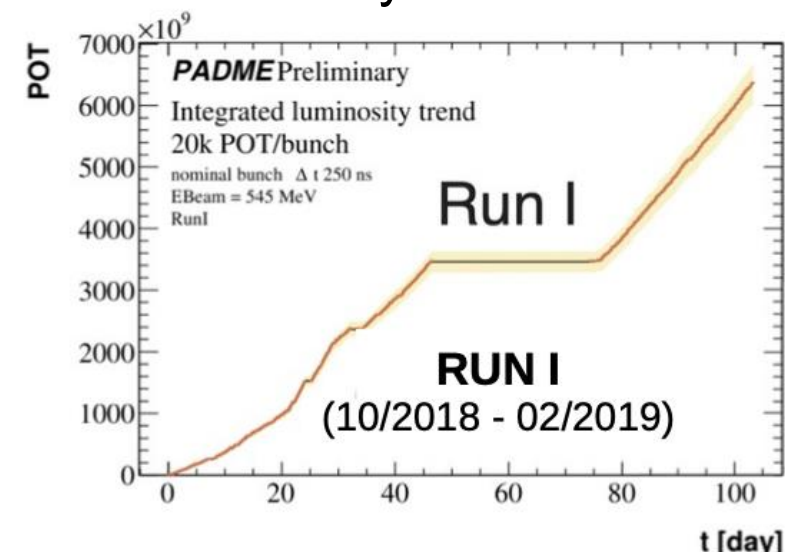


Background process	Cross section e ⁺ @550 MeV beam
$e^+e^- \rightarrow \gamma\gamma$	1.55 mb
$e^+ + N \rightarrow e^+ N \gamma$	4000 mb
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb
$e^+e^- \rightarrow e^+e^- \gamma$	180 mb

- Positron Annihilation into Dark Matter Experiment: $e^+e^- \rightarrow \gamma A'$ based @ Frascati National Laboratories (LNF-INFN).
- **e^+ beam** ($E < 550$ MeV) interacting with diamond active target $2\text{ cm} \times 2\text{ cm} \times 100\mu\text{m}$
- **Final states particles:** $e^+, e^-,$ photons
- **Aim:** Measure of ΔM_{miss}^2 using a BGO ECal.
- Sensitive to sub-GeV new physics

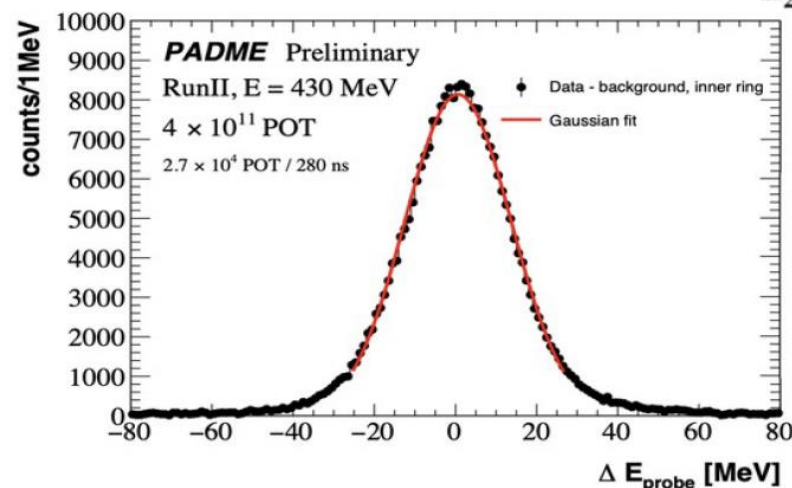
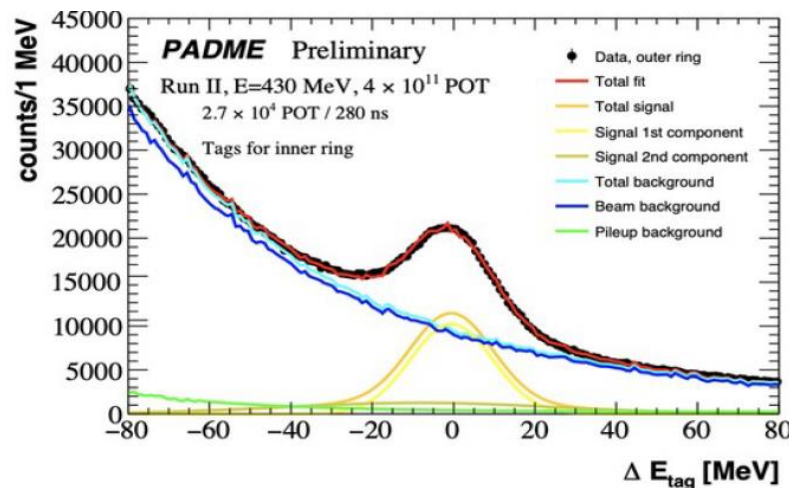
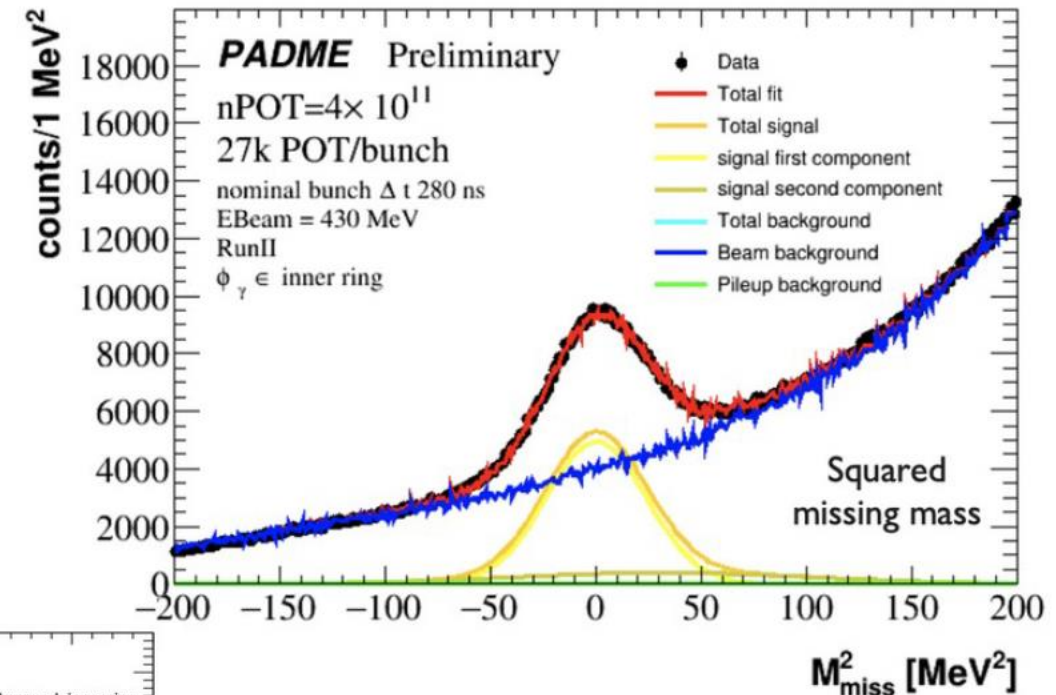


- PADME commissioning and **Run-1** started in Autumn 2018 and ended on February 25th
 - 7×10^{12} positrons on target recorded with secondary beam
 - PADME DAQ, Detector, beam, collaboration commissioning
 - Data quality and detector calibration
- PADME test beam data
 - July 2019, few days of valuable data
 - Certification of the primary beam
 - Detector performance/calibration checks
 - Primary beam with $E_{\text{beam}} = 490$ MeV
- July 2020 **Run-2**
 - New environment/detector parameter monitoring and control system
 - Remote operation confirmation
- Autumn 2020: A long data taking period with $O(5 \times 10^{12})$ e^+ on target $E_{\text{beam}} = 430$ MeV

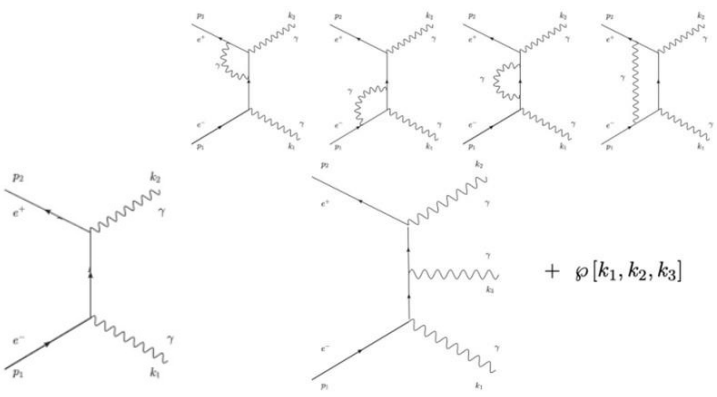


PADME SM diphotons events

- $e^+e^- \rightarrow \gamma\gamma$ cross section below 0.6 GeV known only with 20% accuracy
- Can be sensitive to sub-GeV new physics (e.g. ALP's)
- Using 10% of Run II sample
- **Tag-and-probe** method on two back-to-back clusters
 - Exploit energy-angle correlation
 - Count tag photons
 - Match using this correlation and count probes

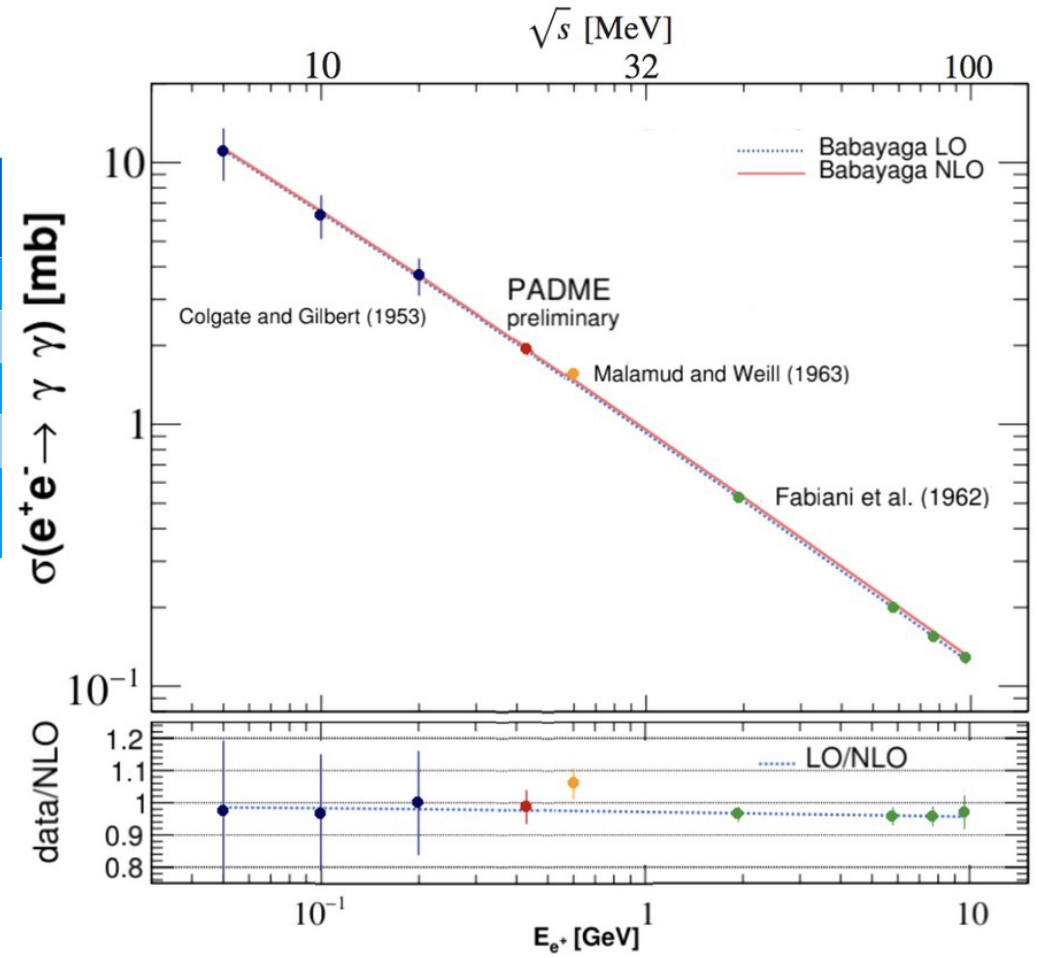
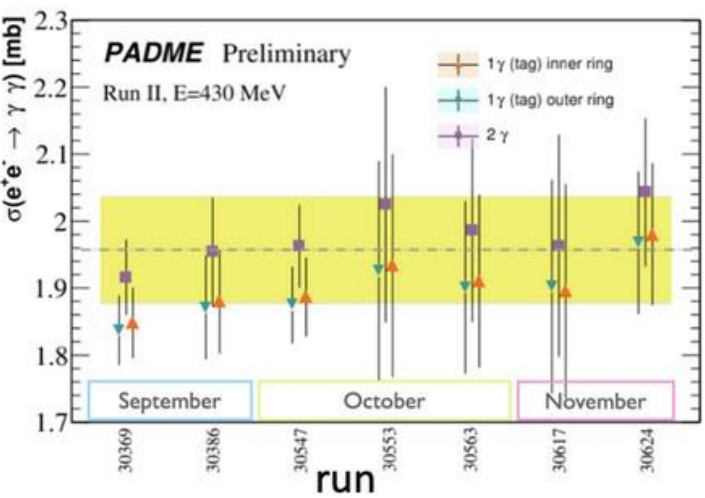
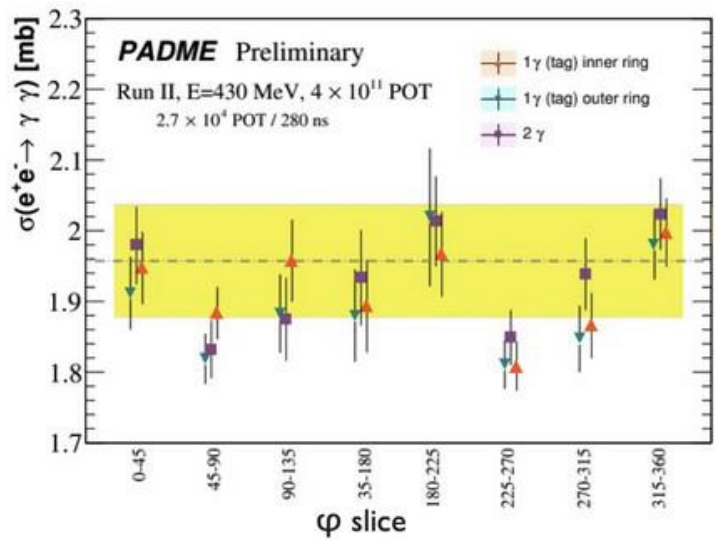


$\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.930 \pm 0.029(\text{stat}) \pm 0.099(\text{syst}) \text{ mb}$

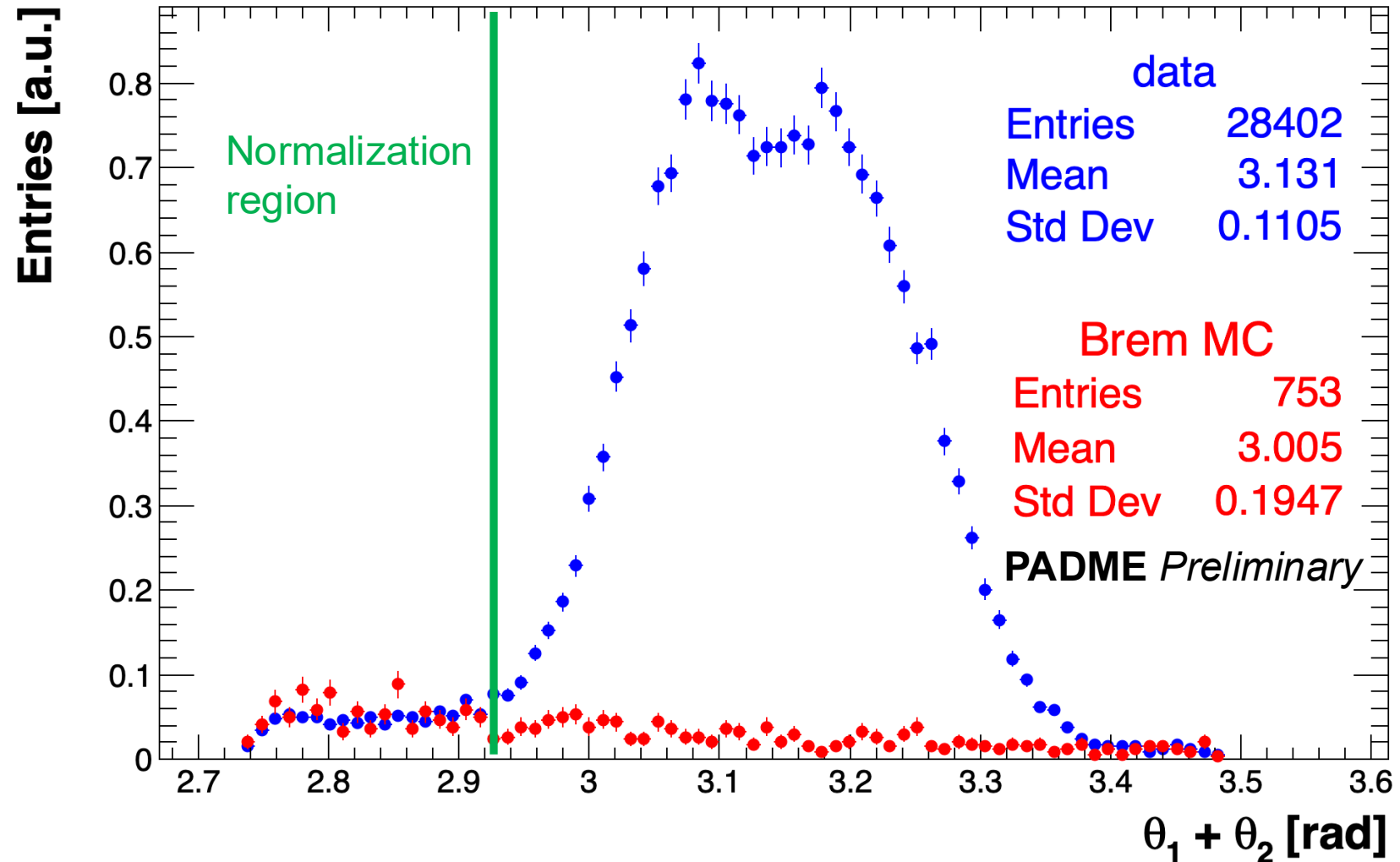


LO + NLO

Systematic effect	Contribution δ [mb]
Detector response uniformity	0.020
Background modelling	0.047
Acceptance	0.025
n POT: target calibration	0.079
Electron density (target thickness)	0.020



- In the $\theta_{cm1} + \theta_{cm2}$ distribution of the selected event in data and MC shows a Brem tail in outside the signal
- By normalizing in the (0, 2.94 rad) regions and then using the ratio between the (2.94 rad, 4 rad) integrals it is possible to get an estimate of the Brem events under the signal

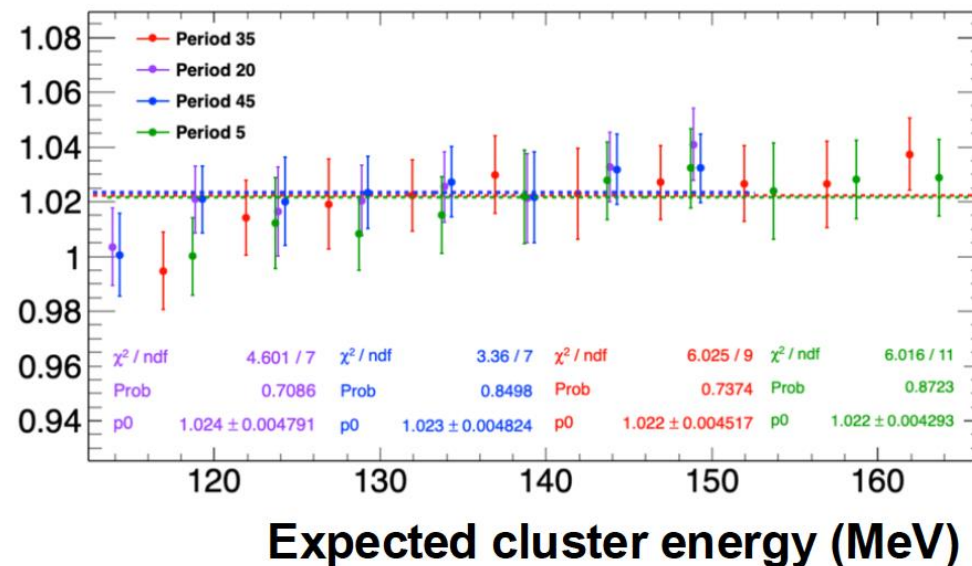


PADME Tag and Probe → Reco efficiency

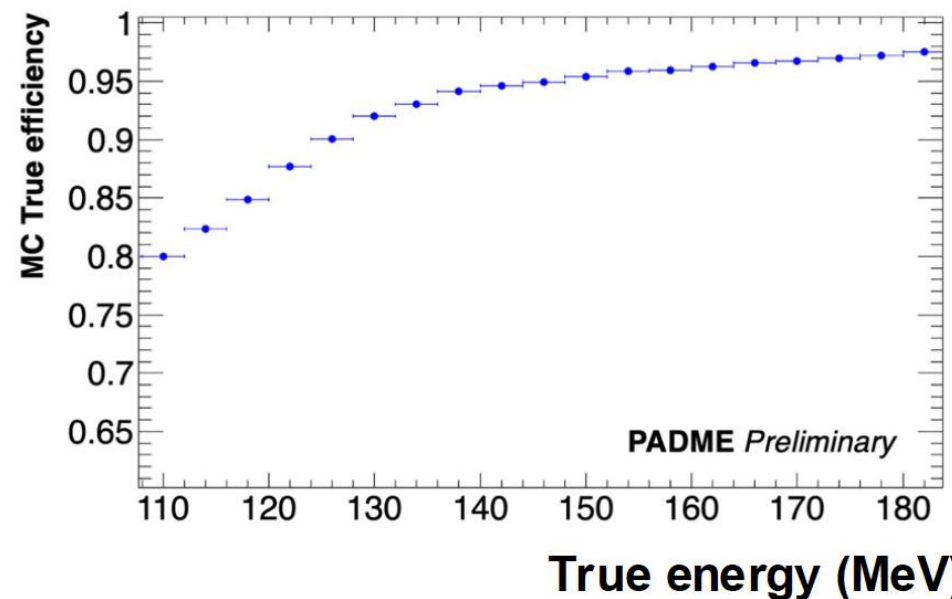
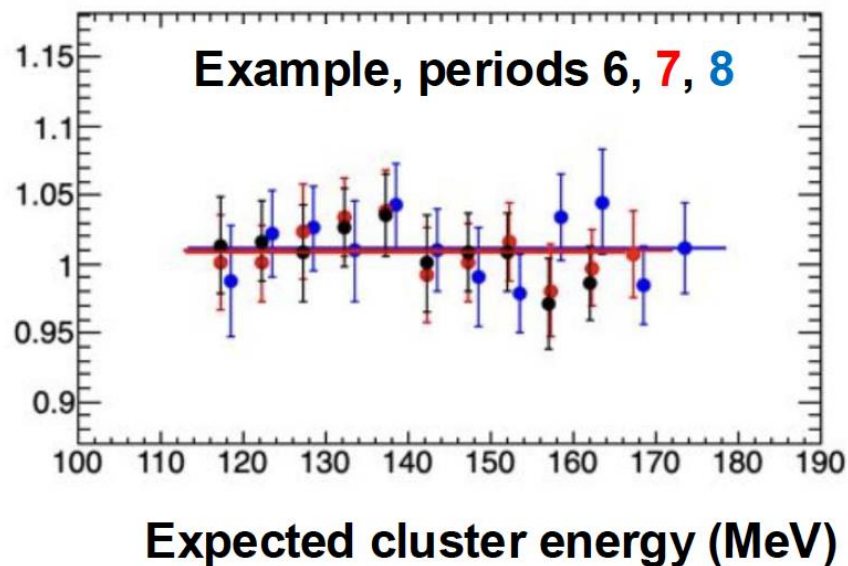
Tag and probe technique, the method-induced bias is 2.3(2)% and stable along the data set

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

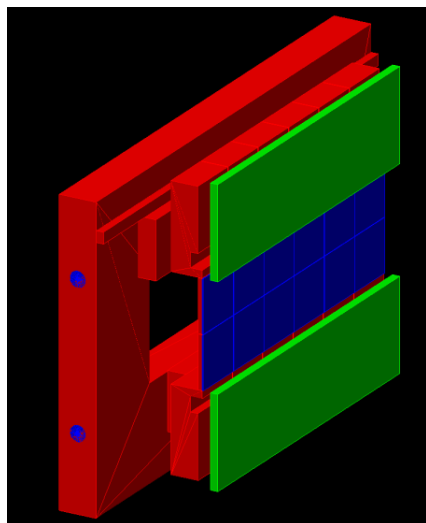
Efficiency <Method /MC true>



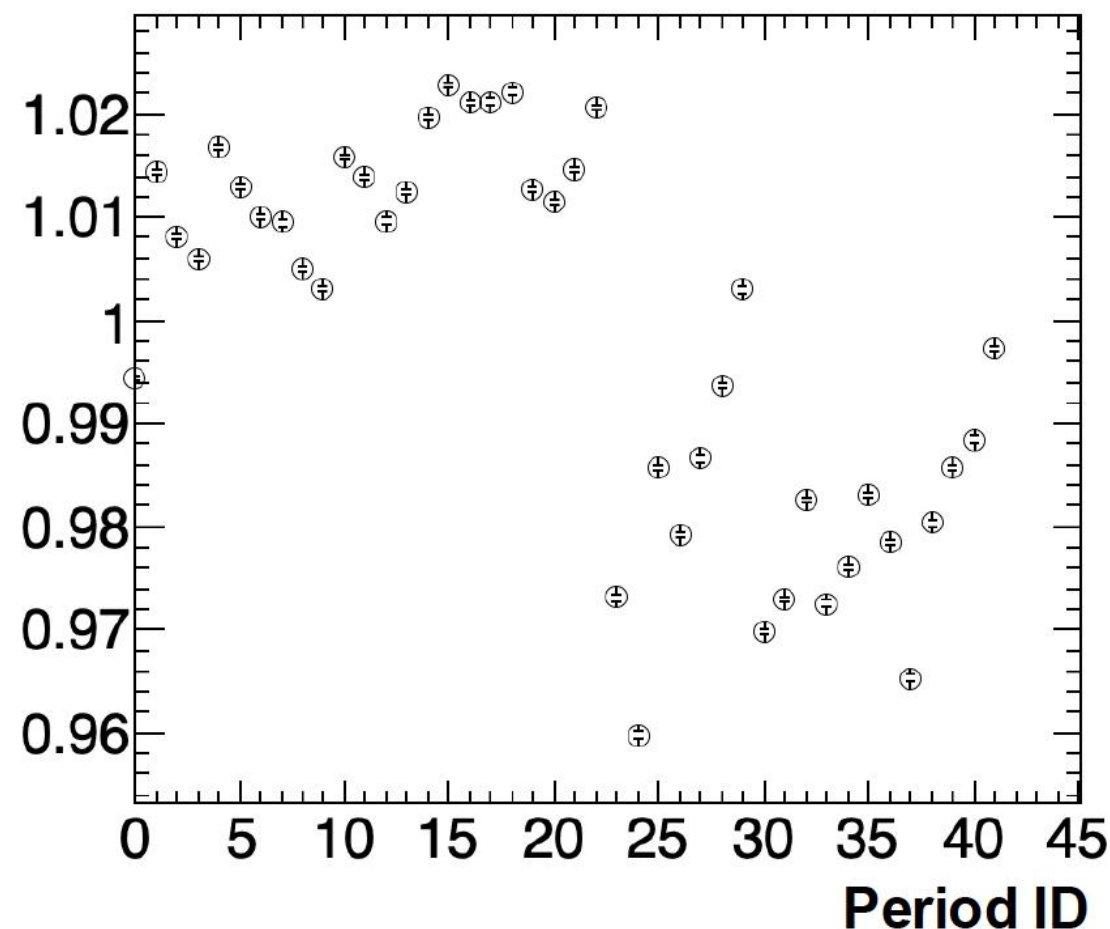
Efficiency Data/MC



- TimePix cooling geometry (mostly Cu) was described in detail in the MC simulation
- Replicate the loss due to the beam passing in the Cu in Run III is possible by using the beam spot
- Beam spot from TimePix is not available for all the periods $\rightarrow$ used the COG instead considering the Timepix-ECAL offsets and the intrinsic difference in resolution



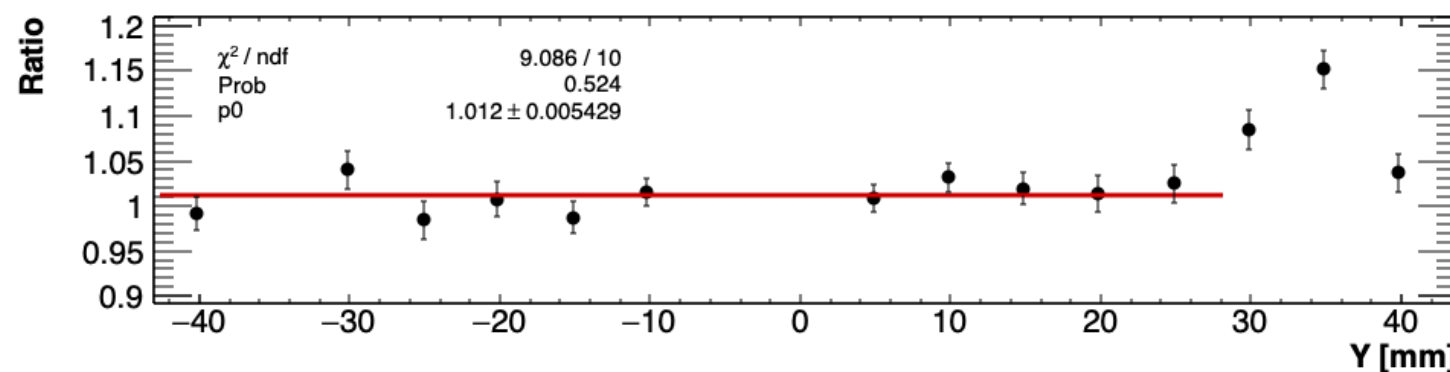
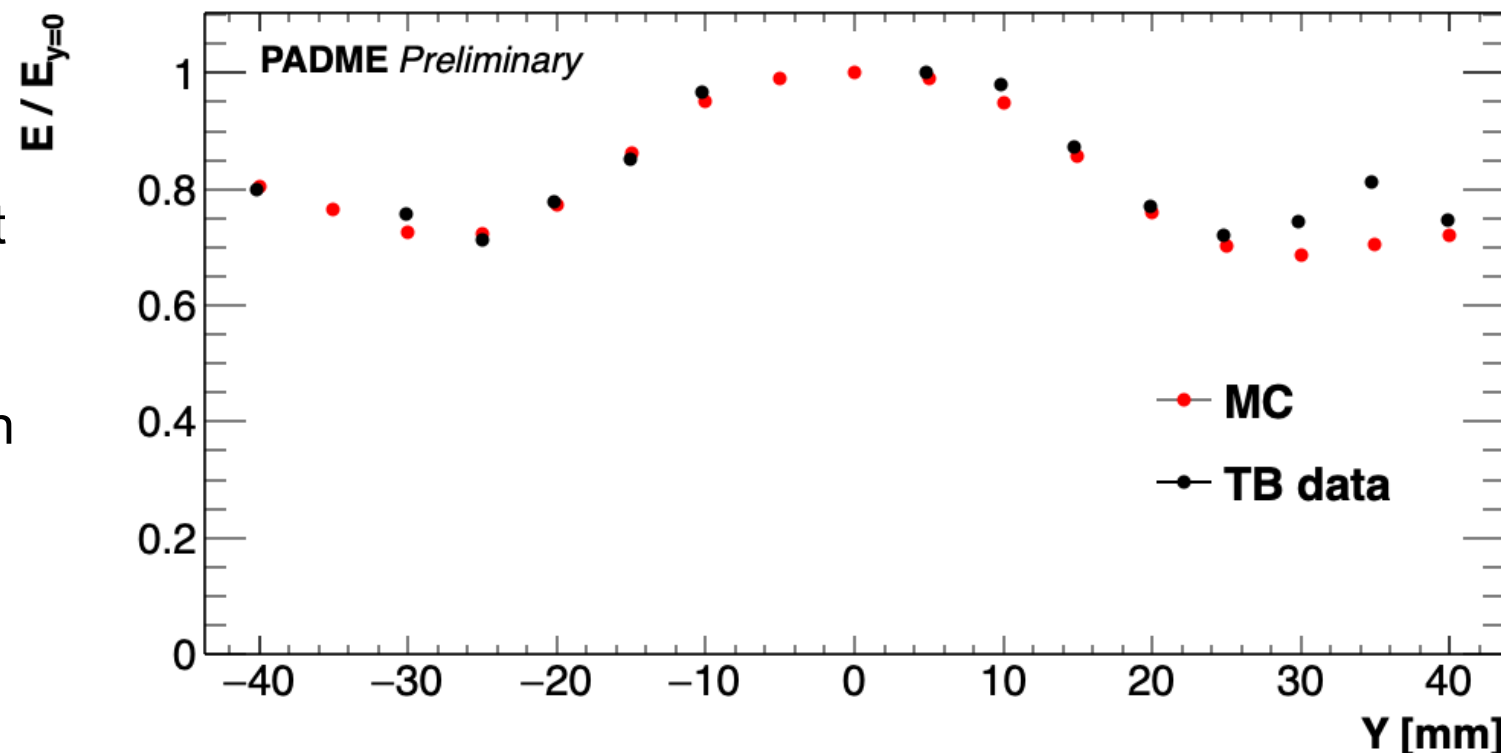
Relative leakage correction



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

How much do we trust the correction?

- Dedicated test beam taking a Y scan at PbGl level. We tried to replicate it with the MC simulation
- Good Data/MC agreement in the region where the beam was scanned during Run III
- **1.2% overall scale correction** (included in the $g_R(s)$ scale) **with a 0.5% error**



- Throughout Run III a total of $7e11$ PoT (of ~ 300 MeV each) has passed through the PbGl block corresponding to a **TID of 25 Gy** (2.5 krad)
- The SF57 transmittance loss was never measured in literature, however for similar blocks (SF5-SF6) a significant loss is shown, especially near Cherenkov wavelengths
- Used of some proxy variables to understand the level of the LY loss:
 - Q_x -target
 - $\langle E\text{-ECAL} \rangle$
 - Period multiplets

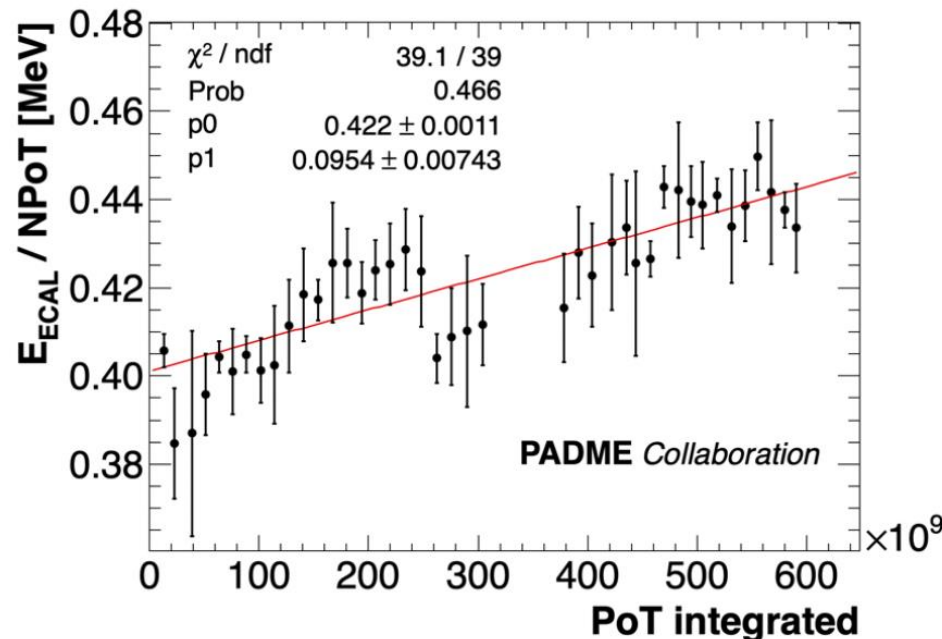
Quantity	PWO:R ³⁺	SF5 (PbO:50%) [4]	SF6 (PbO:75%) [4]
Density (g cm ⁻³)	8.28	4.07	5.19
Radiation length X_0 (cm)	0.89	2.55	1.69
Index of refraction	2.2	1.67	1.81
Cutoff in T (%) (nm)	320	340	360
Hygroscopicity	No	No	No
Melting point (°C)	1123	442	455
Radiation-hardness (rad)	10^{7-8}	10^{3-4}	10^{2-3}
Hardness (Mohs)	3		
Cleavage	(101)	None	None
Available length ^a (X_0)	30	Large	Large
Moliere radius (cm)	2.19		

SF57 PbO concentration $\sim 75\%$

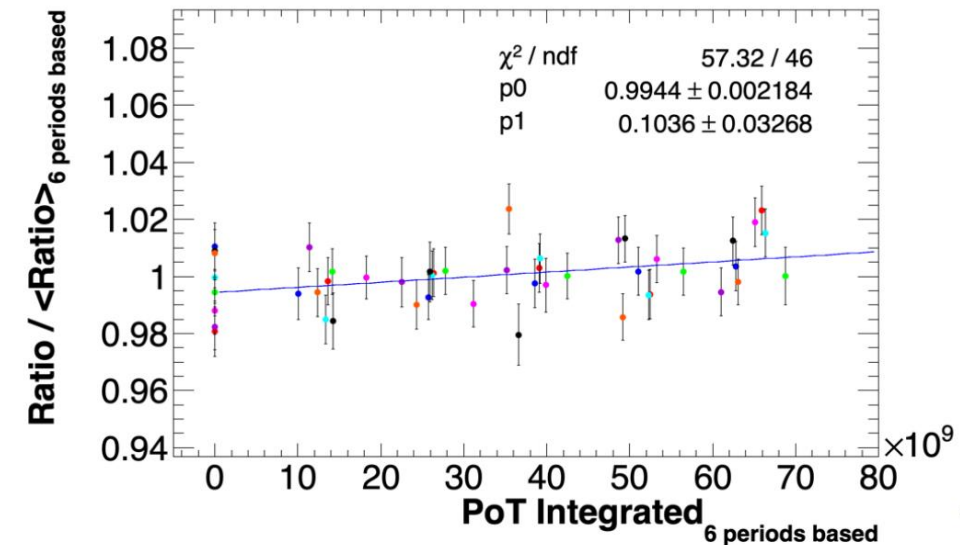
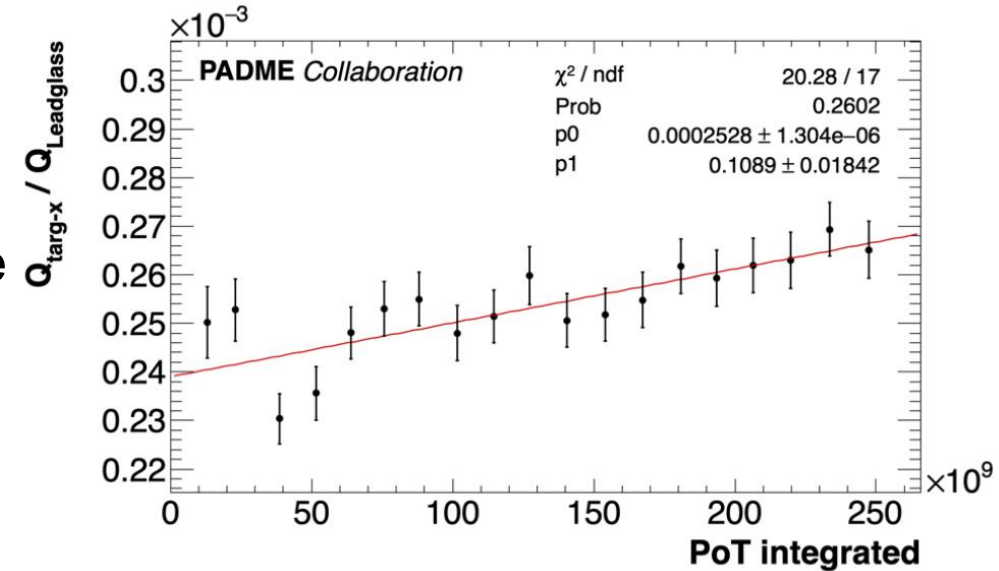
PADME Radiation damage - 2

Proof of loss of LY:

- Target X strips are way more sensible than Y $\rightarrow$ their charge can be used for quantitative checks. **10% slope found**
- The overall energy on ECAL over the N_{PoT} should be a stable quantity, also here we see a **10% slope**
- Looking at the Data/MC ratio on resetting every 6 periods a compatible slope is found

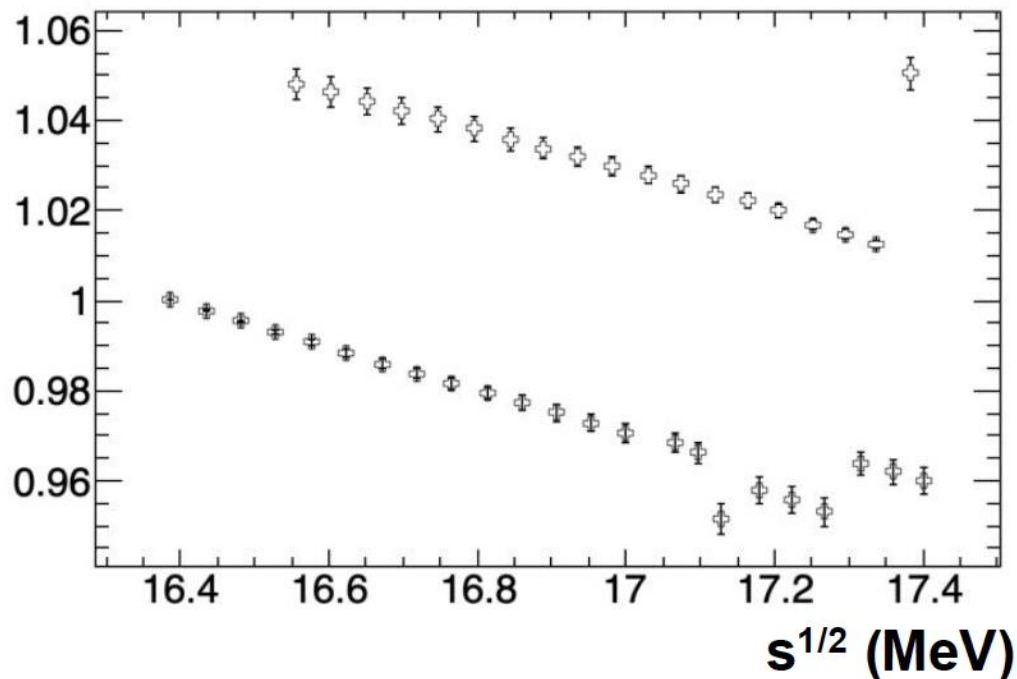


PbGI yield decreases with relative PoT slope of 0.097(7)

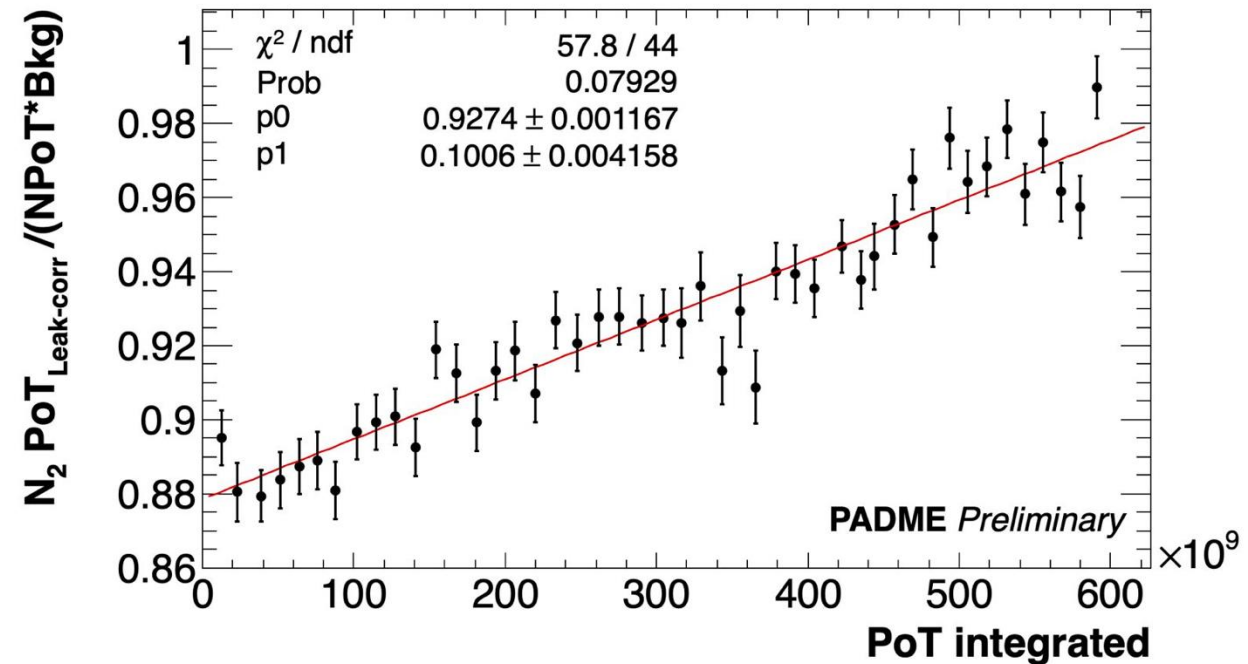


- **PbGI yield decreases with relative PoT slope of 0.097(7)**
- Constant term uncertainty of 0.3% added as scale error
- Slope error included in PoT uncertainty
- Checked the slope value on $g_R(s)$ after the unblinding $\rightarrow$ totally compatible results

Relative ageing correction



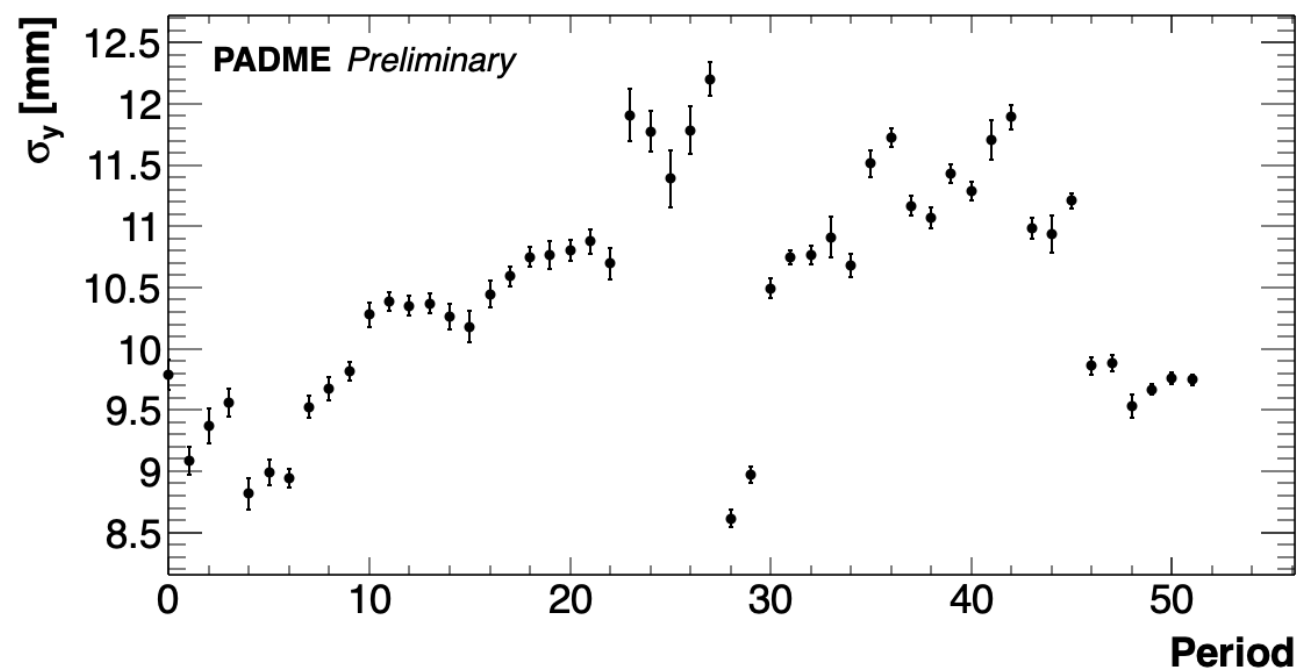
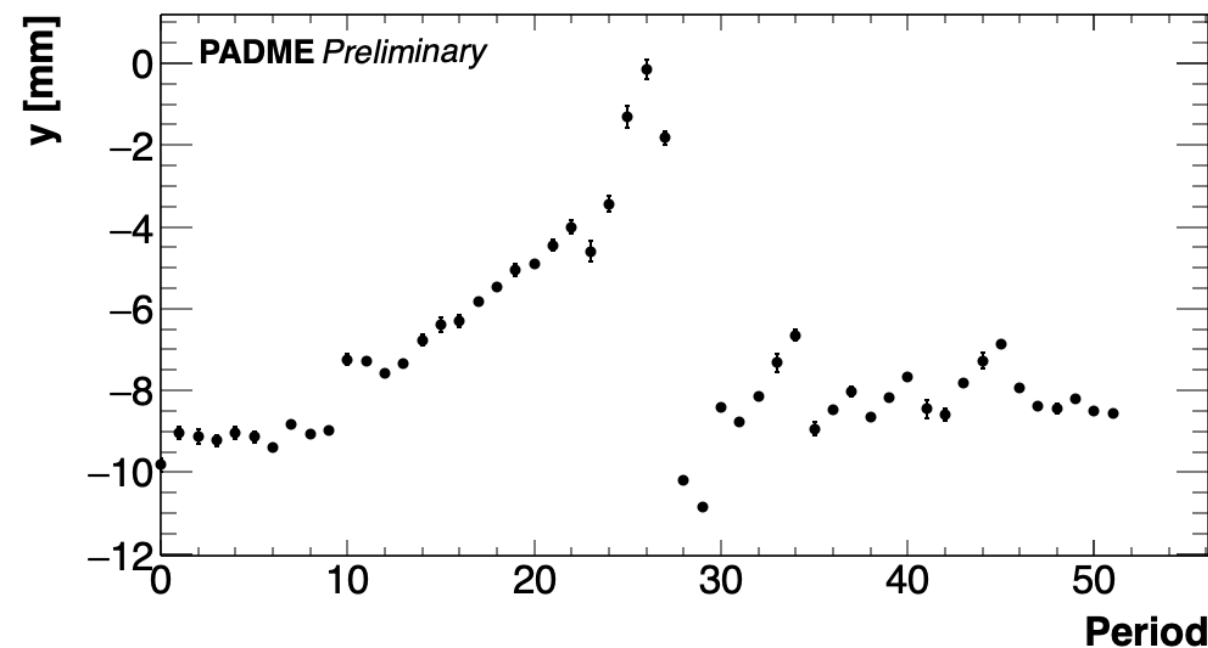
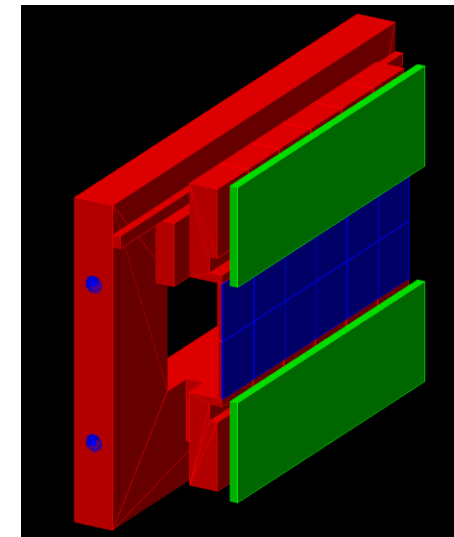
Post unblinding



PADME MC simulation in Run 3 (1)

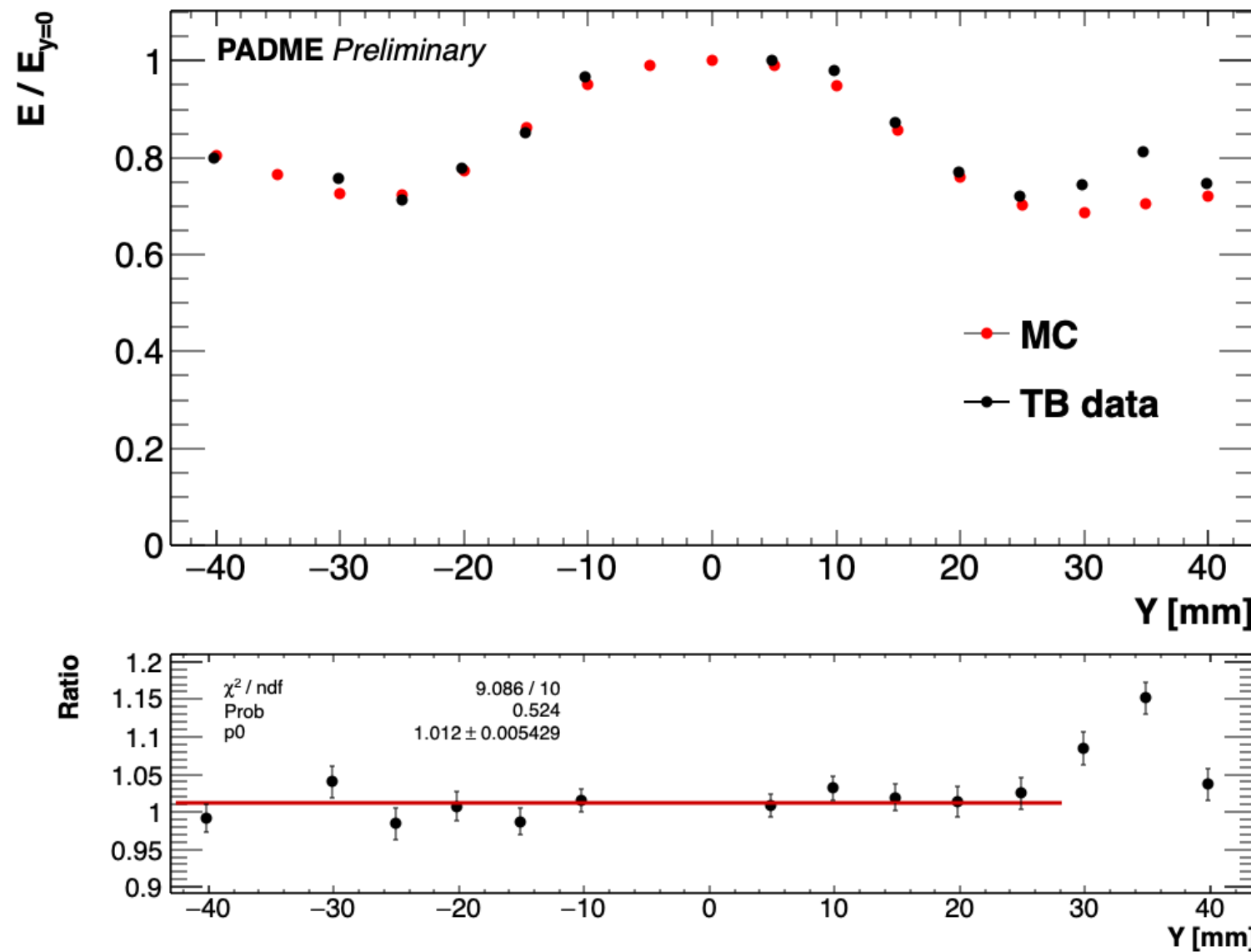
- New Timepix geometry in PadmeMC to consider passive material (Cu)
- Using the Timepix beam spot it is possible to replicate the loss due to the copper also in Run 3
- Beam spot is not available for all the periods $\rightarrow$ we used the COG instead considering the Timepix-ECAL offsets and the intrinsic difference in resolution

MC inputs



How much do we trust the correction?

- Starting from Katerina's data we tried to replicate the Y scan with PadmeMC
- Good data/MC agreement in the region where Run3 beam scanned
- **1.2% overall scale correction** (to address the Data/MC difference) **with a 0.5% error**

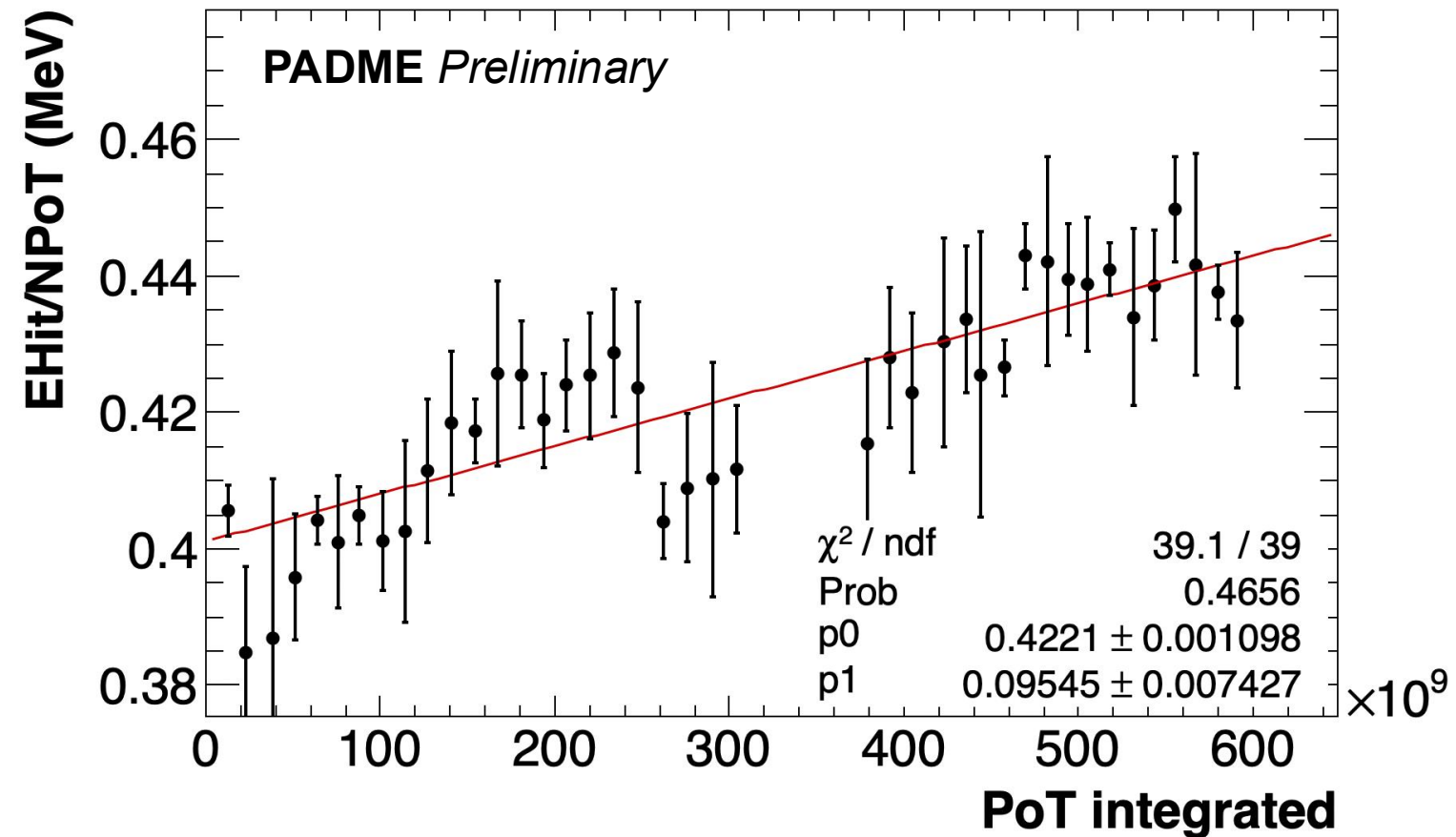


- Throughout Run 3 a total of 70×10^{10} PoT (of ~ 300 MeV each) has passed through the Leadglass block $\rightarrow$ in terms of radiation this corresponds to a TID of 25 Gy (2.5 krad)
- The SF57 transmittance loss was never measured in literature however for similar blocks SF5-SF6 a significant loss is shown, especially near Cherenkov wavelengths. Only samples doped with Ce (not our case) have shown a stronger resistance.

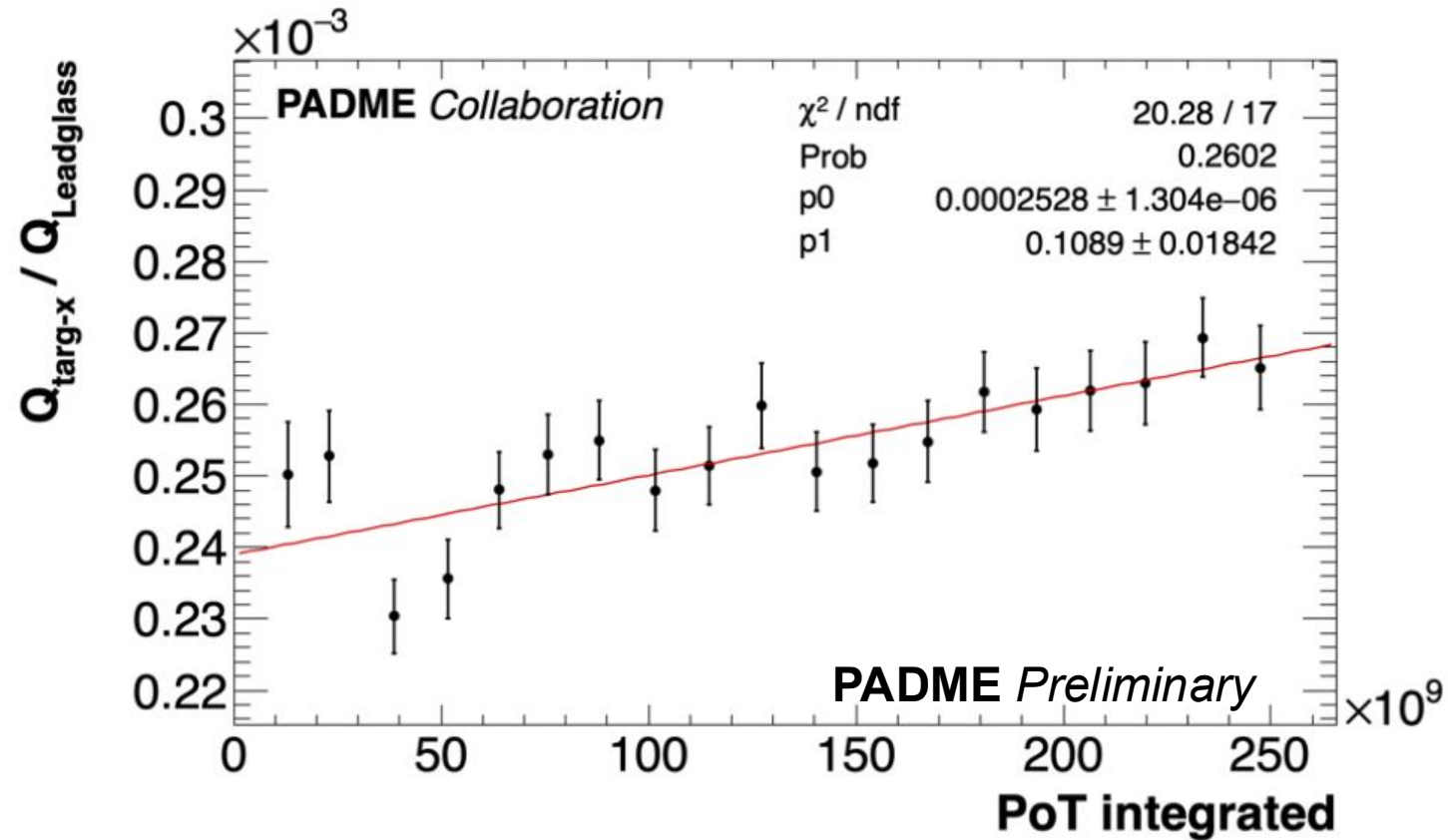
Quantity	PWO:R ³⁺	SF5 (PbO:50%) [4]	SF6 (PbO:75%) [4]
Density (g cm ⁻³)	8.28	4.07	5.19
Radiation length X_0 (cm)	0.89	2.55	1.69
Index of refraction	2.2	1.67	1.81
Cutoff in T (%) (nm)	320	340	360
Hygroscopicity	No	No	No
Melting point (°C)	1123	442	455
Radiation-hardness (rad)	10^{7-8}	10^{3-4}	10^{2-3}
Hardness (Mohs)	3		
Cleavage	(101)	None	None
Available length ^a (X_0)	30	Large	Large
Moliere radius (cm)	2.19		

SF57 PbO concentration $\sim 75\%$

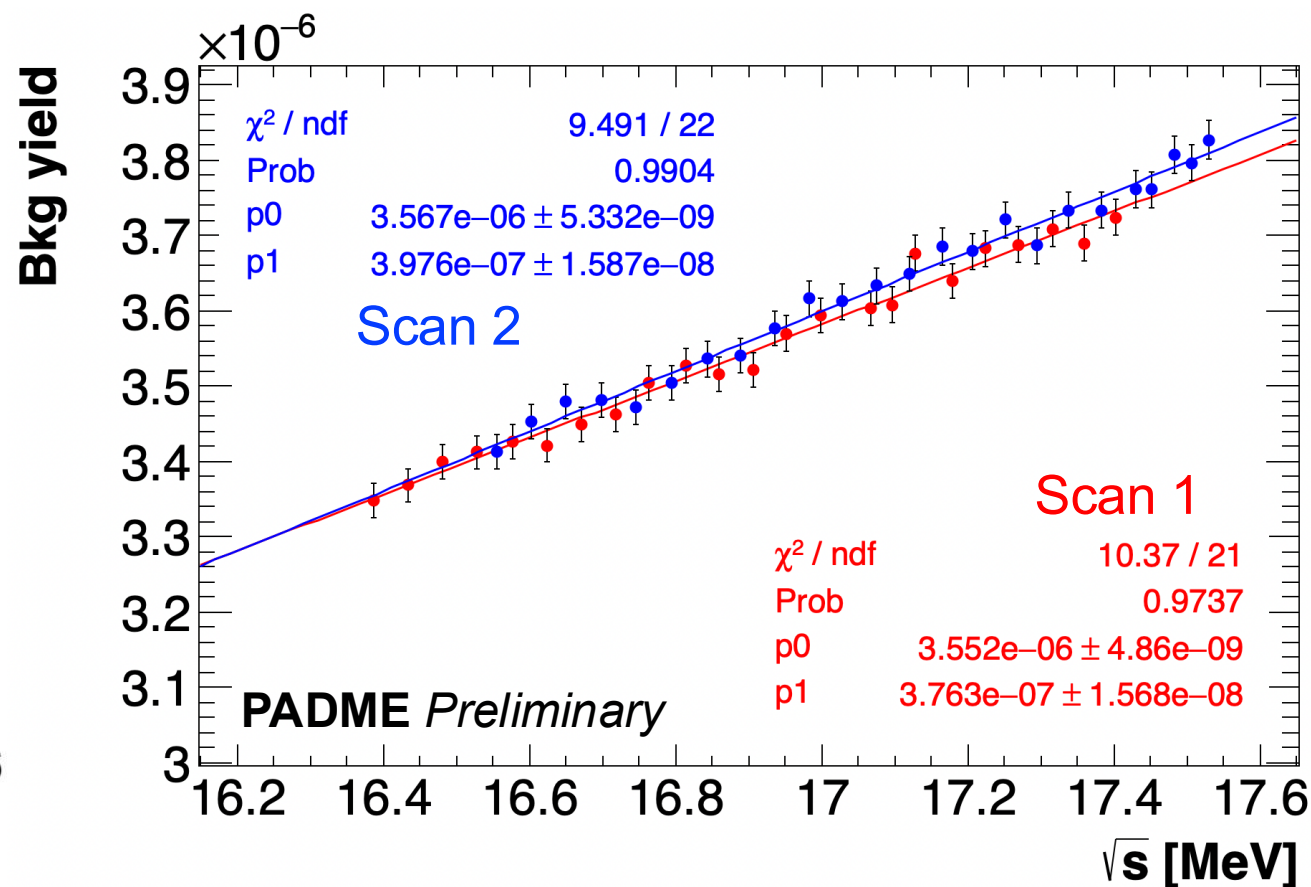
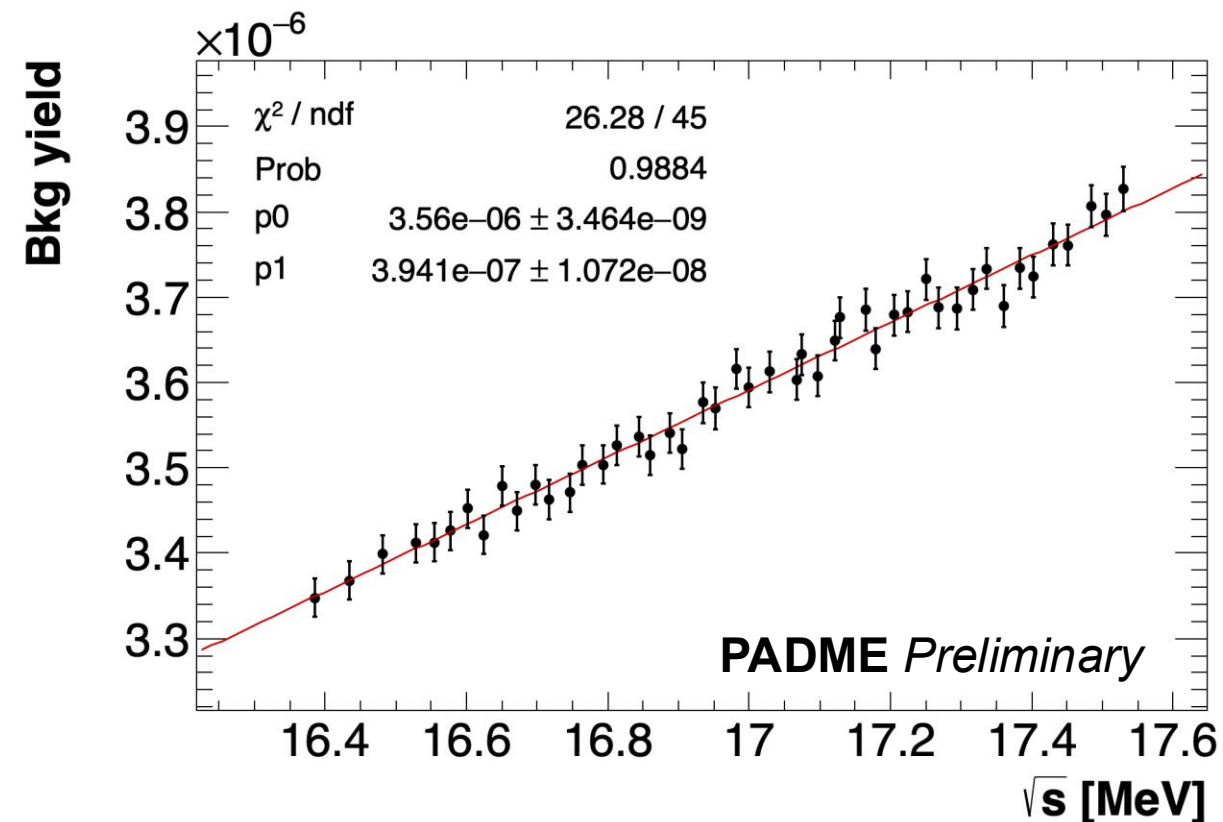
- First proof of loss of LY:
 - By looking at the ratio between the total energy per bunch in ECAL and the NPoT an increasing slope is visible → order 10%
 - Notice that EHit is particularly sensible to the beam spot variation (beam e^+ might enter) hence is prone to significant jumps between periods



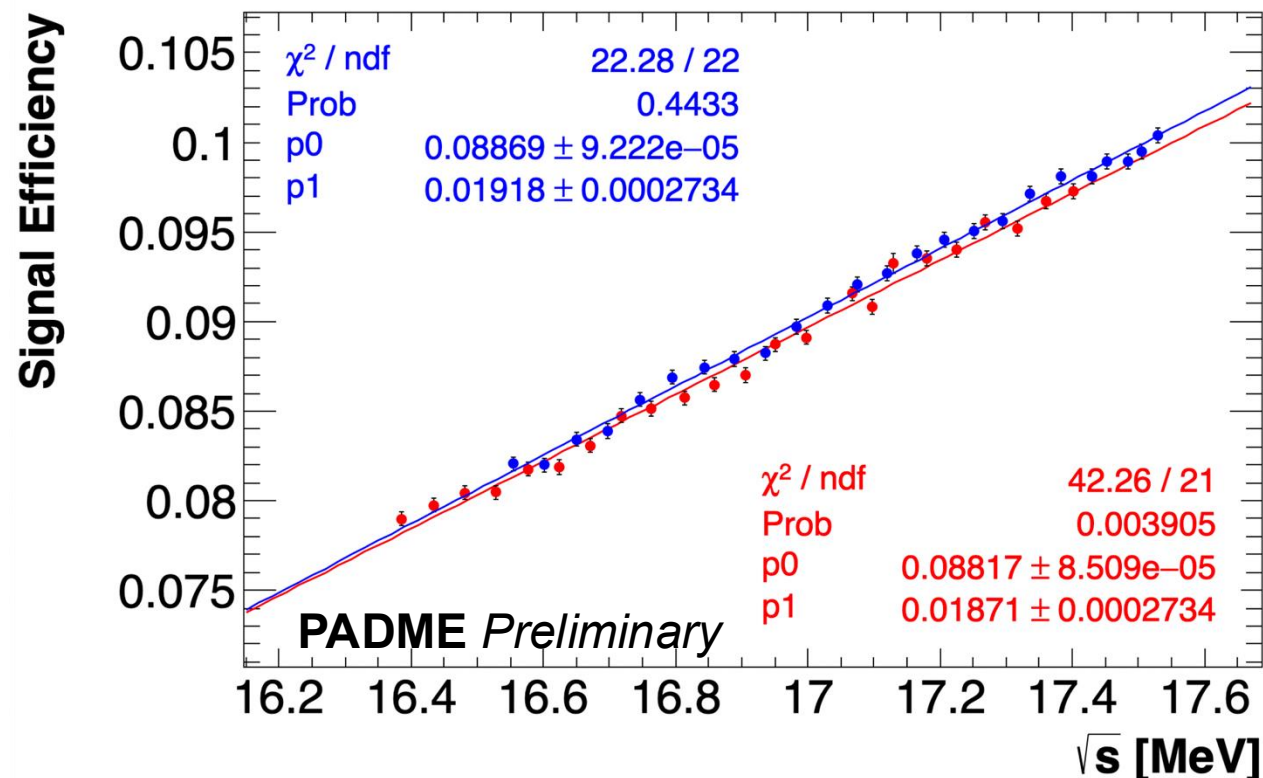
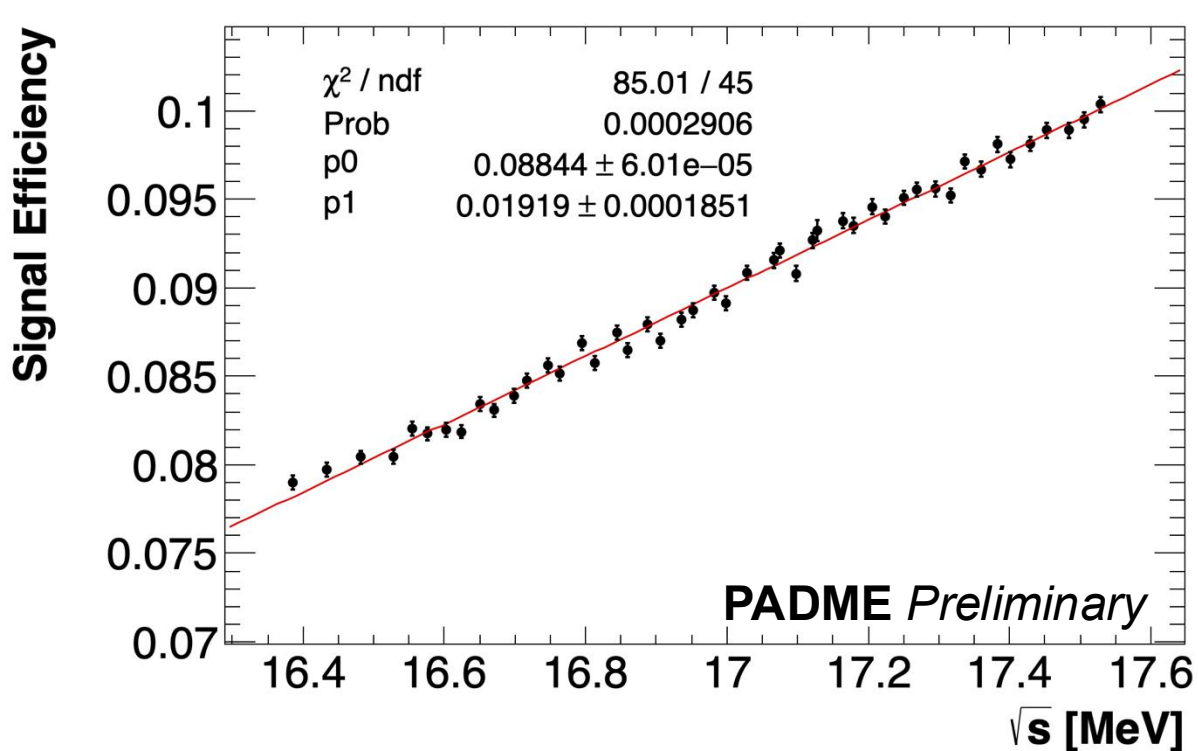
- Second proof of loss of LY:
 - Target X strips are way more sensible than Y $\rightarrow$ can be used for quantitative checks
 - Shows an increasing slope $\rightarrow$ order 10% also here
 - During scan 1 (fitted) there were no “no target runs” hence the Qx response is reliable just in that part of Run 3
- **Conclusion:** use the weighted mean of the two proofs as Integrated PoT correction $\rightarrow 0.0967 \pm 0.0068$



- 0.4% error $\rightarrow$ statistic, added 0.5% in quadrature to account the RMax cut systematics
- Possibility to treat separately the two scans in the sensitivity evaluation



- 0.4% error $\rightarrow$ only statistic
- Possibility to treat separately the two scans in the sensitivity evaluation (better χ^2)



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

Vary $R_{\max}$ by $\pm 2 E_{\text{Cal}}$ cells around nominal cut of 270 mm: 230 mm $\rightarrow$ 300 mm

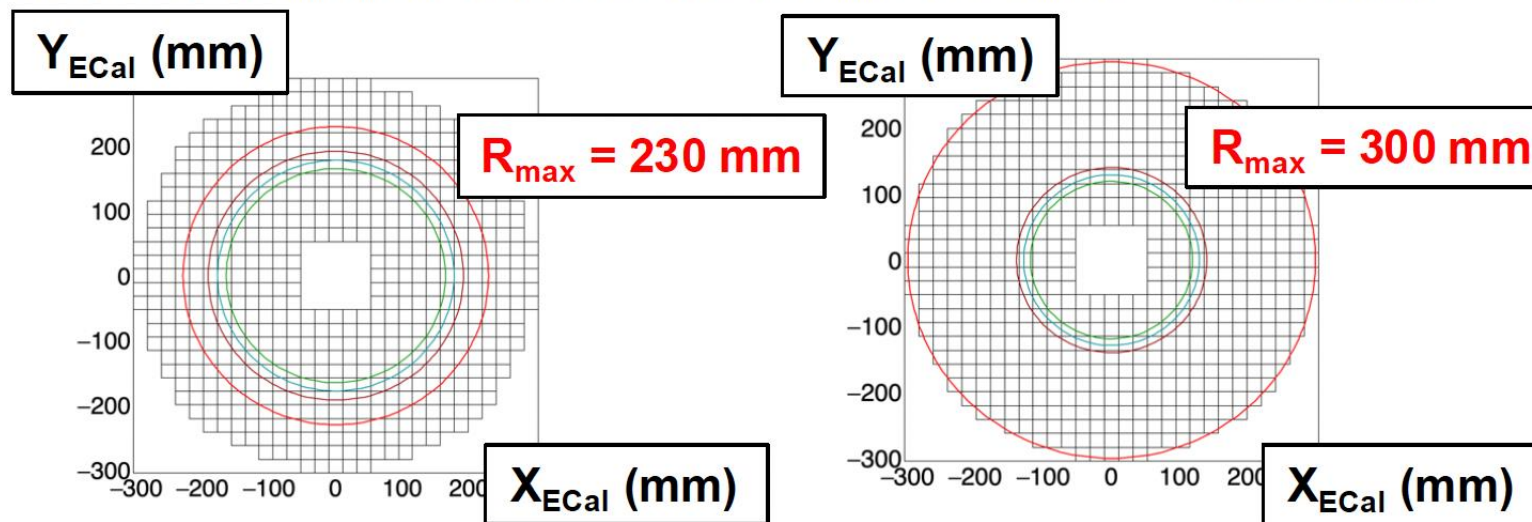
Yield variation: -5%, +3%

Uncorrelated error 0.3%

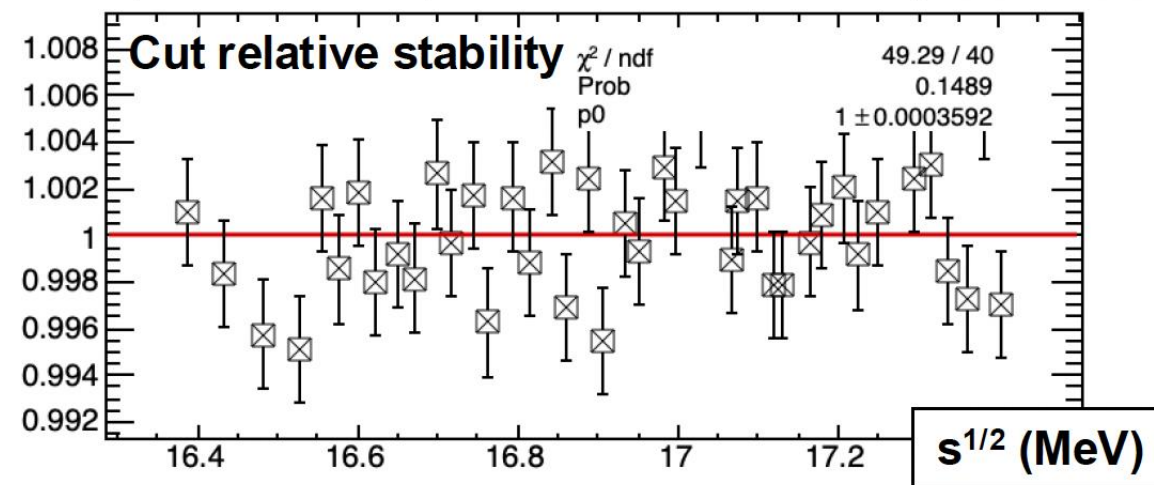
$R_{\min}$ -1.5 D ($s^{1/2} = 16.4$ MeV)

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

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

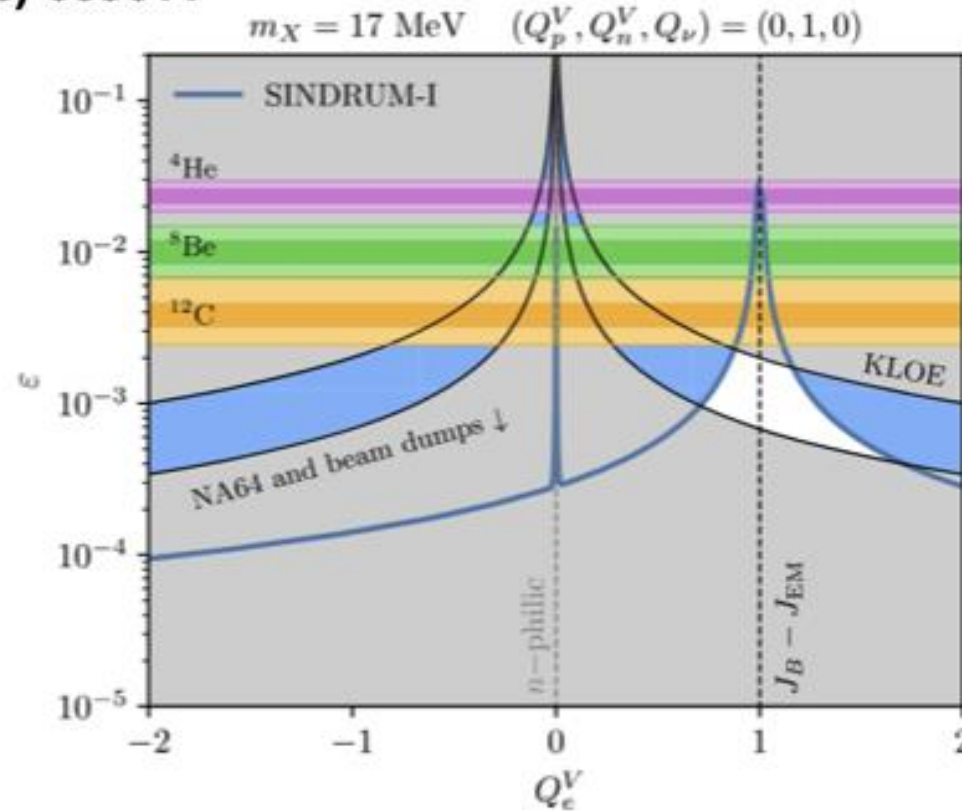


Stability is observed within a coverage band of $\pm 0.2\%$, used as additional uncorrelated systematic error on B



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

Hostert, Pospelov
PRD 108 (2023) 055011



with:

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

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?

Recent result from MEG II, [arXiv:2411.07994](https://arxiv.org/abs/2411.07994)

- Measurement on ^7Li target to reproduce ^8Be ATOMKI
→ no signal found
- ULs on $\frac{\Gamma(^8\text{Be}^* \rightarrow ^8\text{Be } X_{17}(ee))}{\Gamma(^8\text{Be}^* \rightarrow ^8\text{Be } \gamma)}$ for 17.6 and 18.1 MeV transitions

MEG II result compatible at 1.5σ with the **ATOMKI** combination $M_X = 16.85(4) \text{ MeV}$ [[Barducci, et al., JHEP 04 \(2025\) 035](#)]

Further attempts to verify:



AN2000 facility @INFN-LNL [[data taking ongoing](#)]



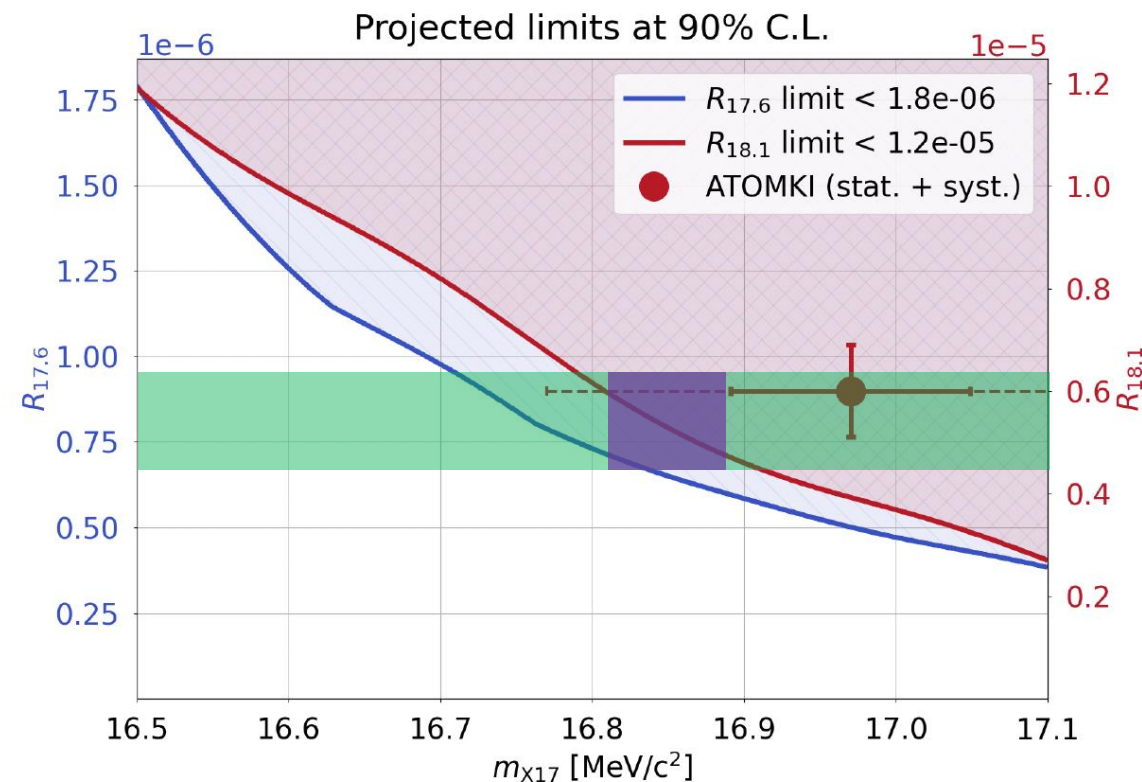
n_TOF EAR2 neutron line @CERN [[2025 proposal](#)]



Tandem accelerator @Montreal [[JPC Ser. 2391 \(2022\) 012008](#)]



Van de Graaf accelerator @IEAP Prague [[NIM. A 1047 \(2023\) 167858](#)]



B(s)

Correlated error:

- Absolute cross section (radiative. corr. at 3%),
- Target thickness known at 5% level
- B expectation is compared to below resonance points, improving the systematic uncertainty → scale error accounted for

N_{POT}(s)

Source	Common error on N _{POT} [%]
pC/MeV	2.0
Leakage, data/MC	0.5
Ageing, constant term	0.3
Total	2.1