La ricerca di X17 a PADME: dai risultati di Run III agli upgrade di Run IV

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Per la collaborazione PADME

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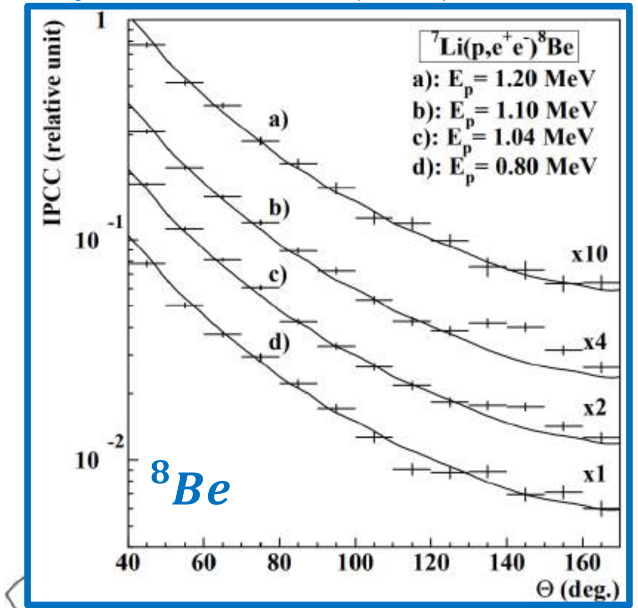
INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

X17 anomaly @ ATOMKI

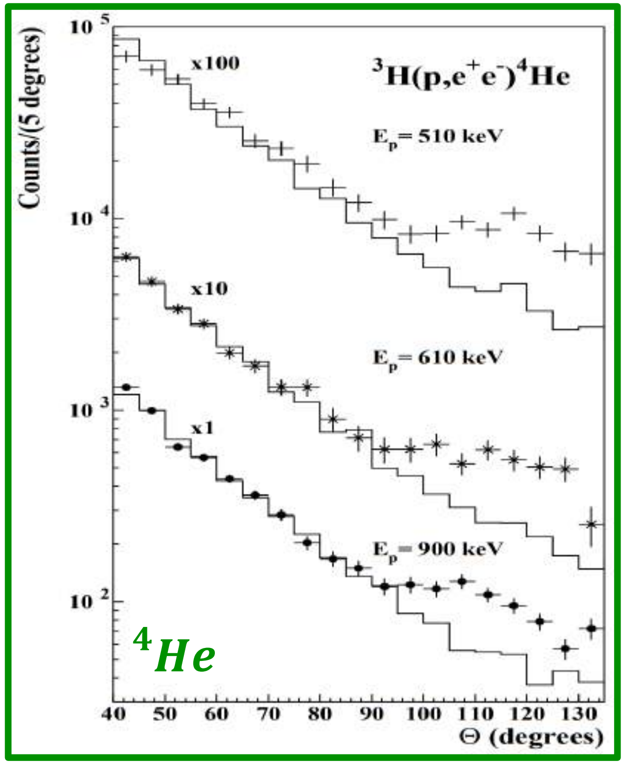
- Anomalous excesses in angular correlation of e^+e^- couples produced via Internal Pair Creation of ^8Be, ^4He and ^{12}C observed by A. Krasznahorkay & collaborators

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

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



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



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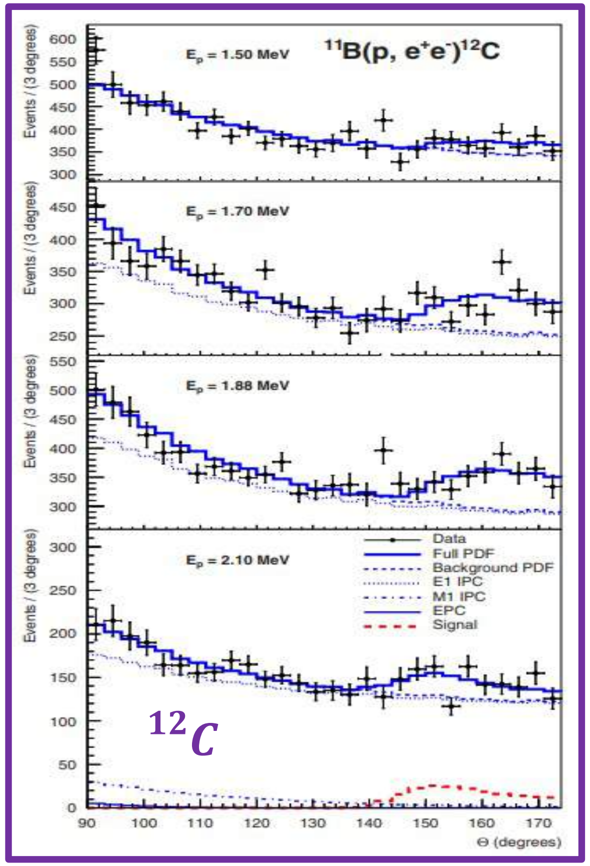
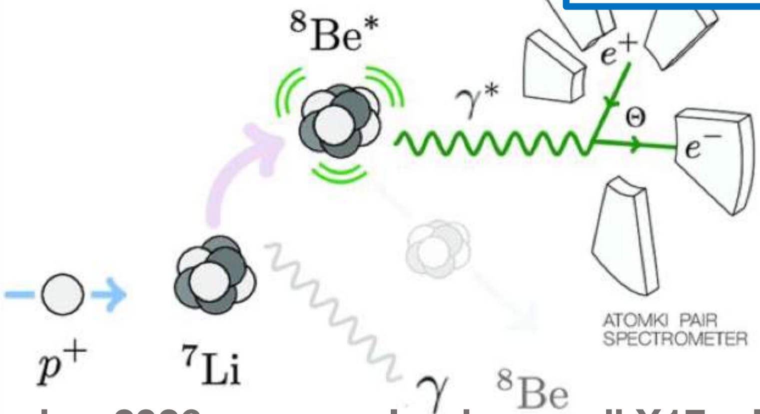
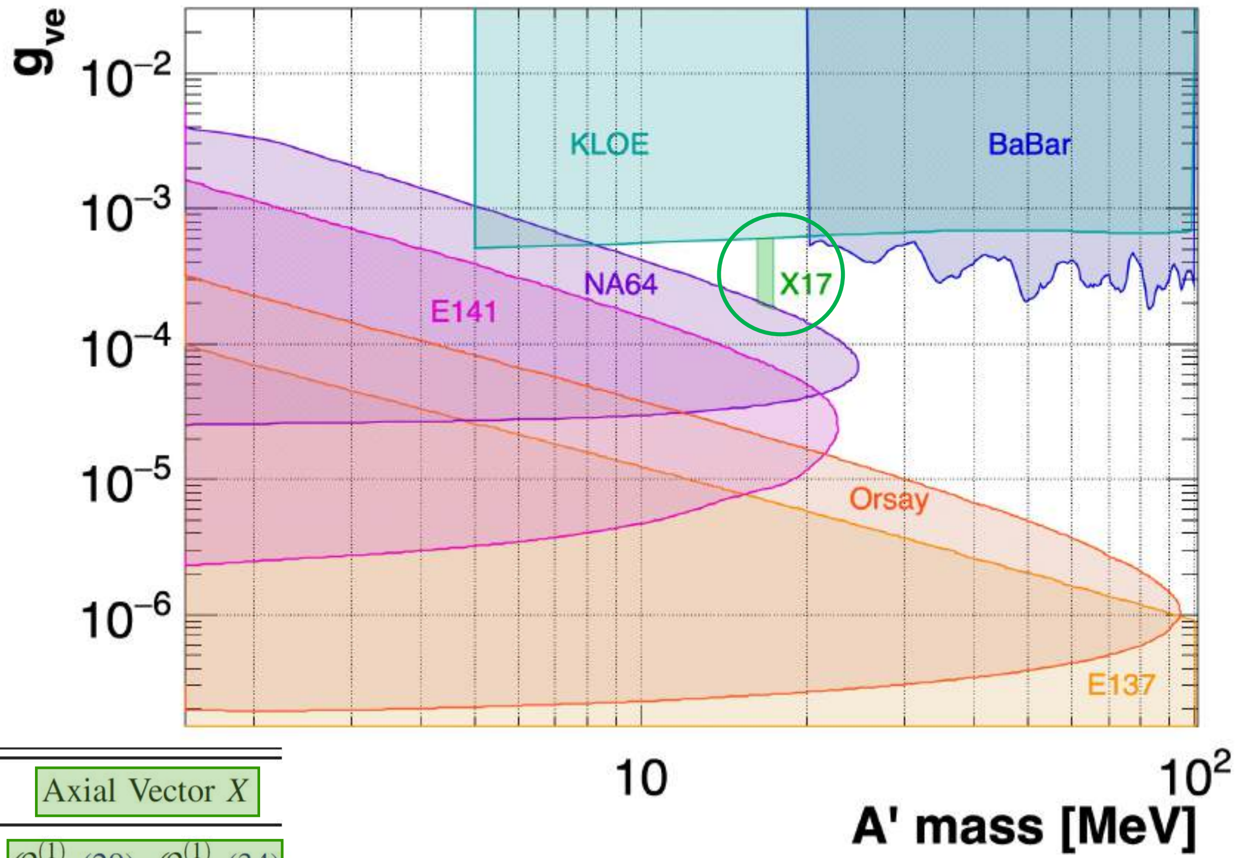




X17 phase space

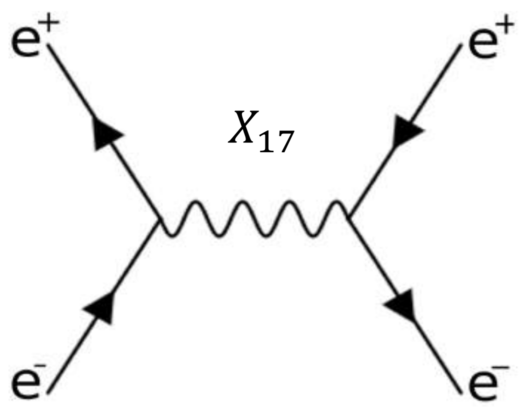
- **New physics interpretations** not fully excluded → still some phase-space available
- Vector and Axial-Vector models are theoretically favoured (imposing parity conservation on ATOMKI observations)
- The PADME experiment is sensitive to this mass range



N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}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}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}He(21.01)	0^-	...	$\mathcal{O}_{3S}^{(0)}$ (39)	...	$\mathcal{O}_{4P}^{(1)}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}_{3S}^{(0)}$ (39)	...	$\mathcal{O}_{4P}^{(1)}$ (40)	...

Resonant search on fixed thin target

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



Analysis strategy:

1. Change beam energy with a fine spacing in the 250-300 MeV range
2. Determine the expected background
3. Calibrate and measure the luminosity
4. Bump hunt while keeping a blind analysis

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

$f(E_{res}, E_{beam})$ beam energy spread

→ Gaussian with spread $\boldsymbol{\delta E}$

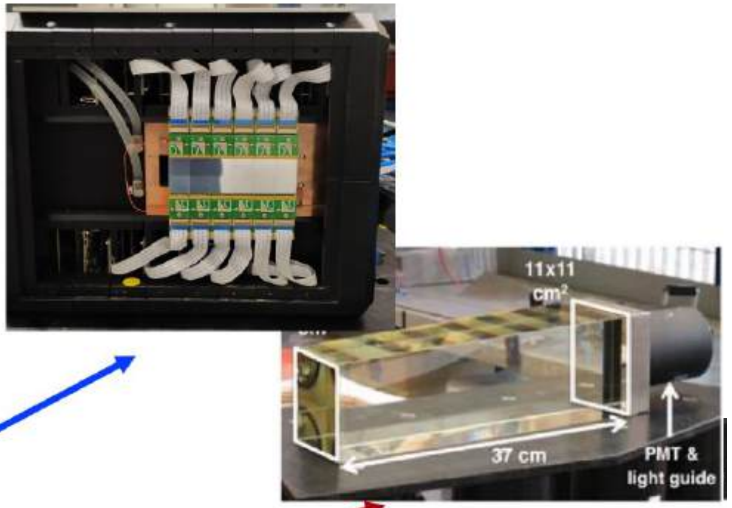
The INFN-LNF Beam Test Facility (BTF) and the PADME experiment is well suited to perform this job

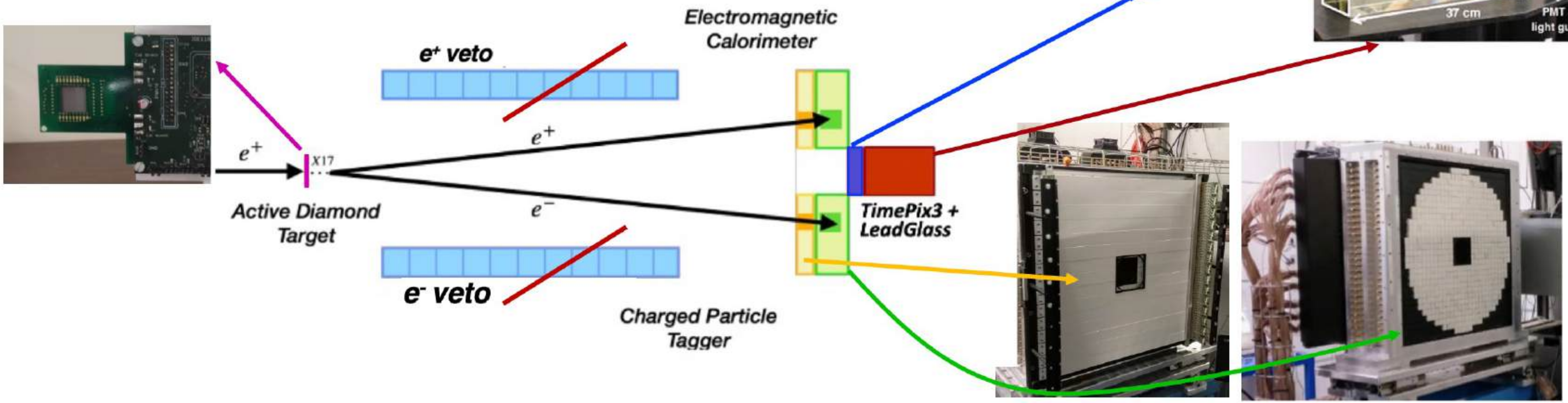
Run III - setup

Main SM background processes are Bhabha scattering and $\gamma\gamma$ pair production, evaluated directly from data

Setup optimized:

- Active diamond **target**
- **Charged particle veto** not used
- **ECal**: 616 BGO crystals, each 21×21×230 mm^3
- PADME dipole turned off → no magnetic field after the target interaction
- New **hodoscope** (ETag) in front of ECAL added to identify charged particles
- End of line **TimePix3** beam monitor and a **Leadglass** luminometer





Analysis strategy

Strategy: compare the yield of 2 EM cluster events collected by ECal with the SM expected one

→created a custom $\mathbf{g_R(s)}$ observable sensible to BSM physics

$g_R(s) = N_2(s) / (N_{PoT}(s) \times B(s)) = K(s)\,[1 + S(s; M_X, g)\,\varepsilon_S(s)/B(s)\,]$ to be compared to

$g_R(s) = N_2(s) / (N_{PoT}(s) \times B(s)) = K(s)$

Inputs:

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

Aim: measure and evaluate systematic errors on:

- N_2 (bkg subtracted) on data
- PoTs
- MC expected yield
- Signal shape
- Signal efficiency

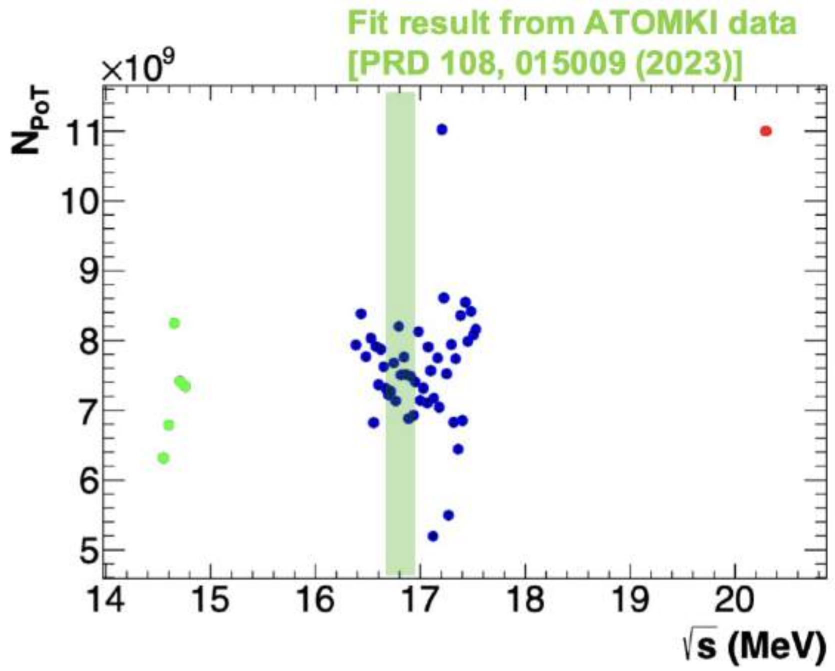
Run III - dataset

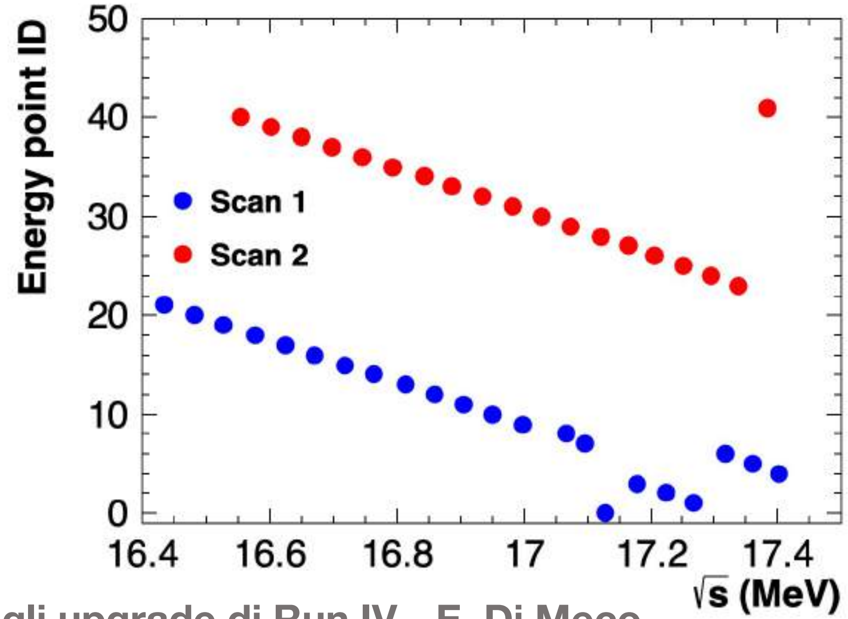
Data-taking divided in 3 parts:

- **On resonance points @ (263-292) MeV → scan 1 and 2:** 0.75 MeV spacing, 16.4 MeV < M_{X17} < 17.4 MeV, ~ 0.8x10^{10} N_{PoT} per point
- **Below resonance points @ (205-211) MeV:** 1.5 MeV spacing, used to normalize the absolute yield
- **Over resonance runs @ 402.5 MeV:** 1.2x10^{10} stat, used to validate N_{PoT} measurement

We defined:

- "Period": a point at a fixed beam energy, typically lasting 24 hours
- "Scan" a chronological set of periods typically decreasing in energy
- **Scan 1 and 2 periods spaced ~ 1.5 MeV but interspersed in energy**
- **Detailed Geant4-based MC performed for each period**

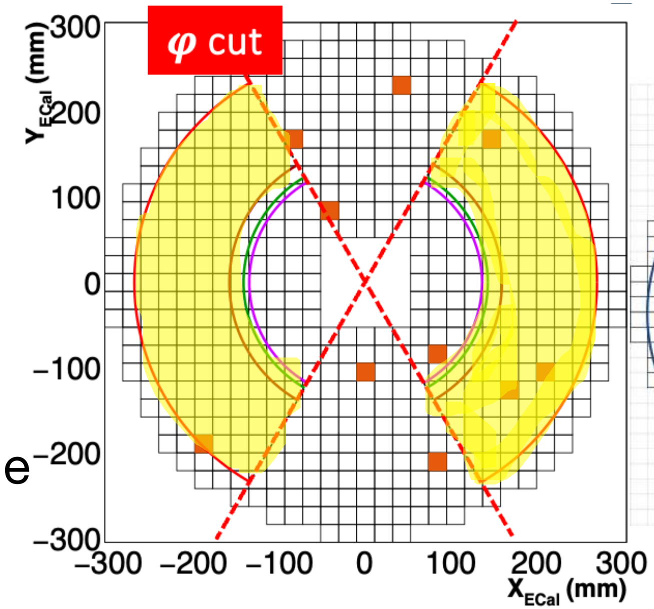


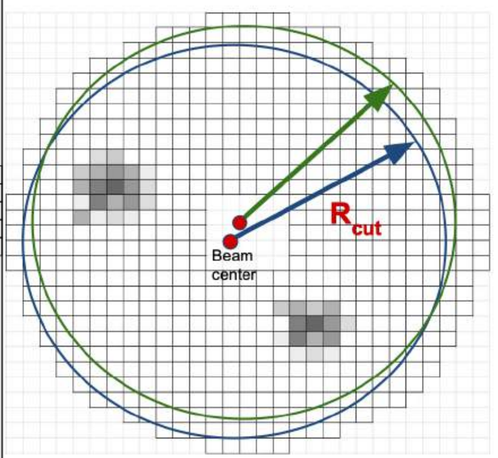


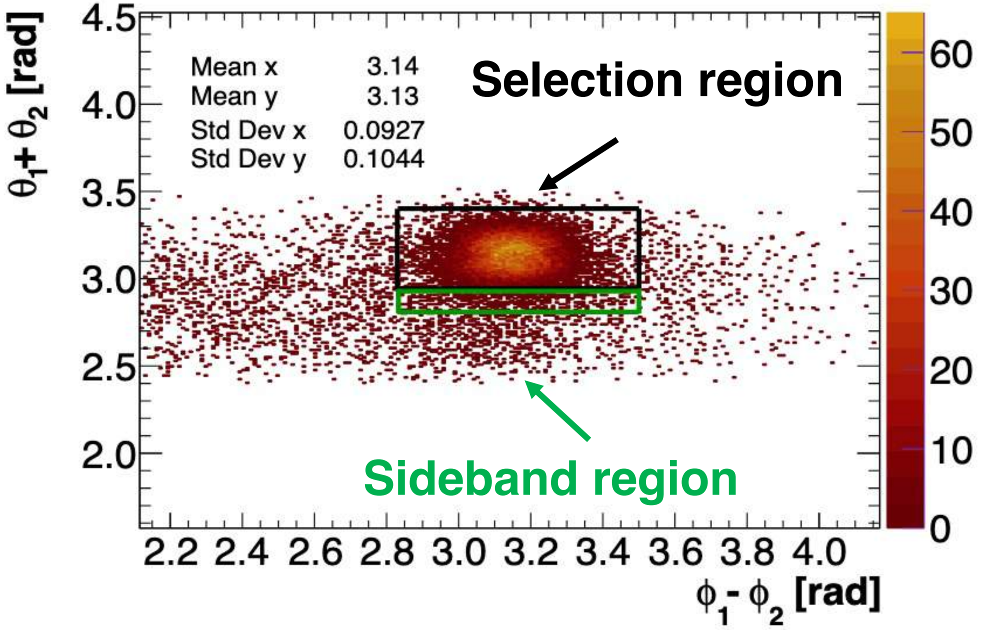
Selection cuts

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 with the center following the beam Center of Gravity (CoG)
  - Minimum radius within the “two-cluster” kinematic range → following the beam center conditions
  - Energy dictated by the radius
  - ECAL illumination affected by material along the beam line not well reproduced in MC → **Cut regions in φ**
- **Mutual cluster conditions:**
  - ΔT (clu0-clu1) < 5 ns
  - ΔR (clu0-clu1) > 60 mm (Minimum $\gamma\gamma$ difference)
  - $\boldsymbol{\phi_1 - \phi_2}$ vs $\boldsymbol{\theta_1 + \theta_2}$ cut in the Center of Mass (CoM) frame isolates the signal

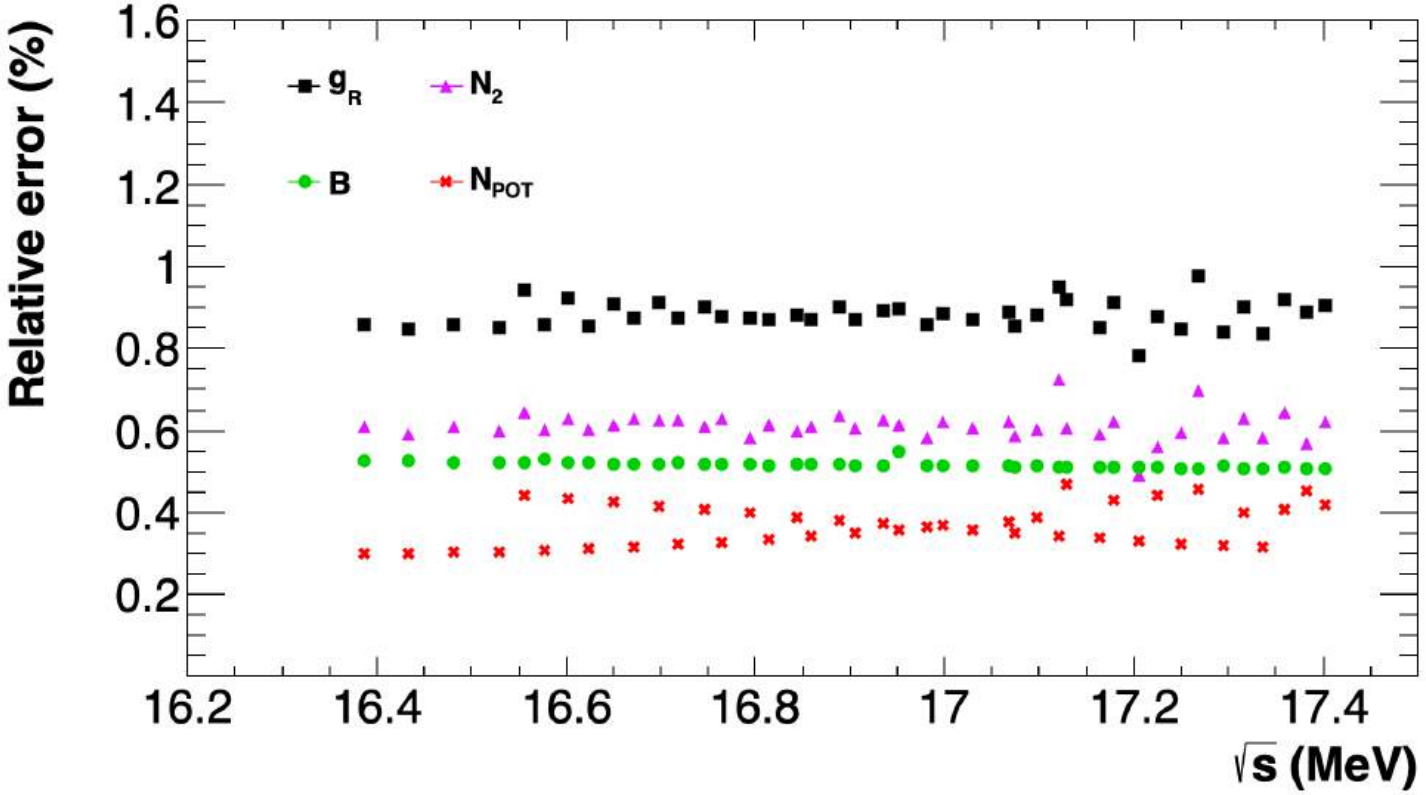






Total error budget

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
$N_{\text{PoT}}(s)$	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

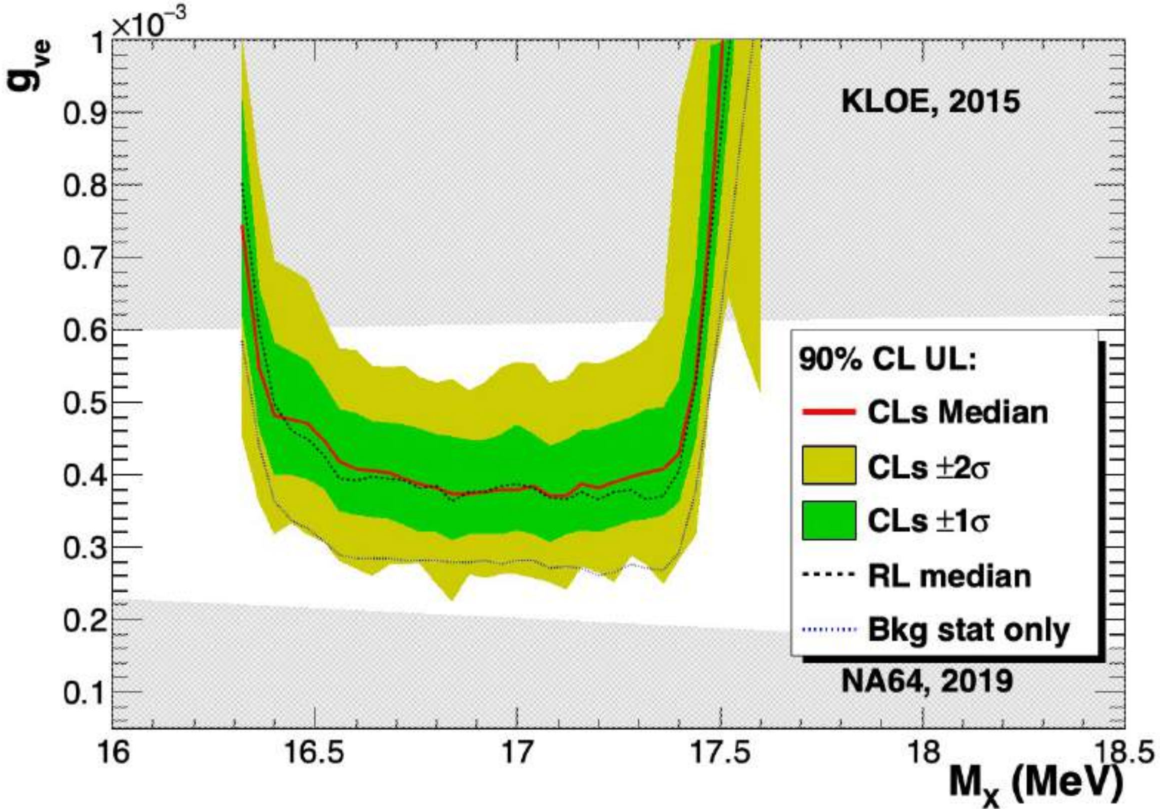
$K(s)$, $\sqrt{s}$-slope

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

is $g_R(s)$ compatible with $K(s)$ or $K(s)(1+ S(s)\ \varepsilon(s)/B(s))$?

Expected sensitivity

- 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: $Q = L(S + B(g_{ve}, M_X))/ L(B)$. The likelihood includes terms for each nuisance parameter pdf
- For a given M_X, $CLs = P_S/ (1 - P_B)$ is used to define the UL on g_{ve}



Source	Uncertainty [%]
N_2	0.6
B	0.54
N_{PoT}	0.35
TOTAL on g_R	**0.88**
TOTAL on K(s)	**2.8**

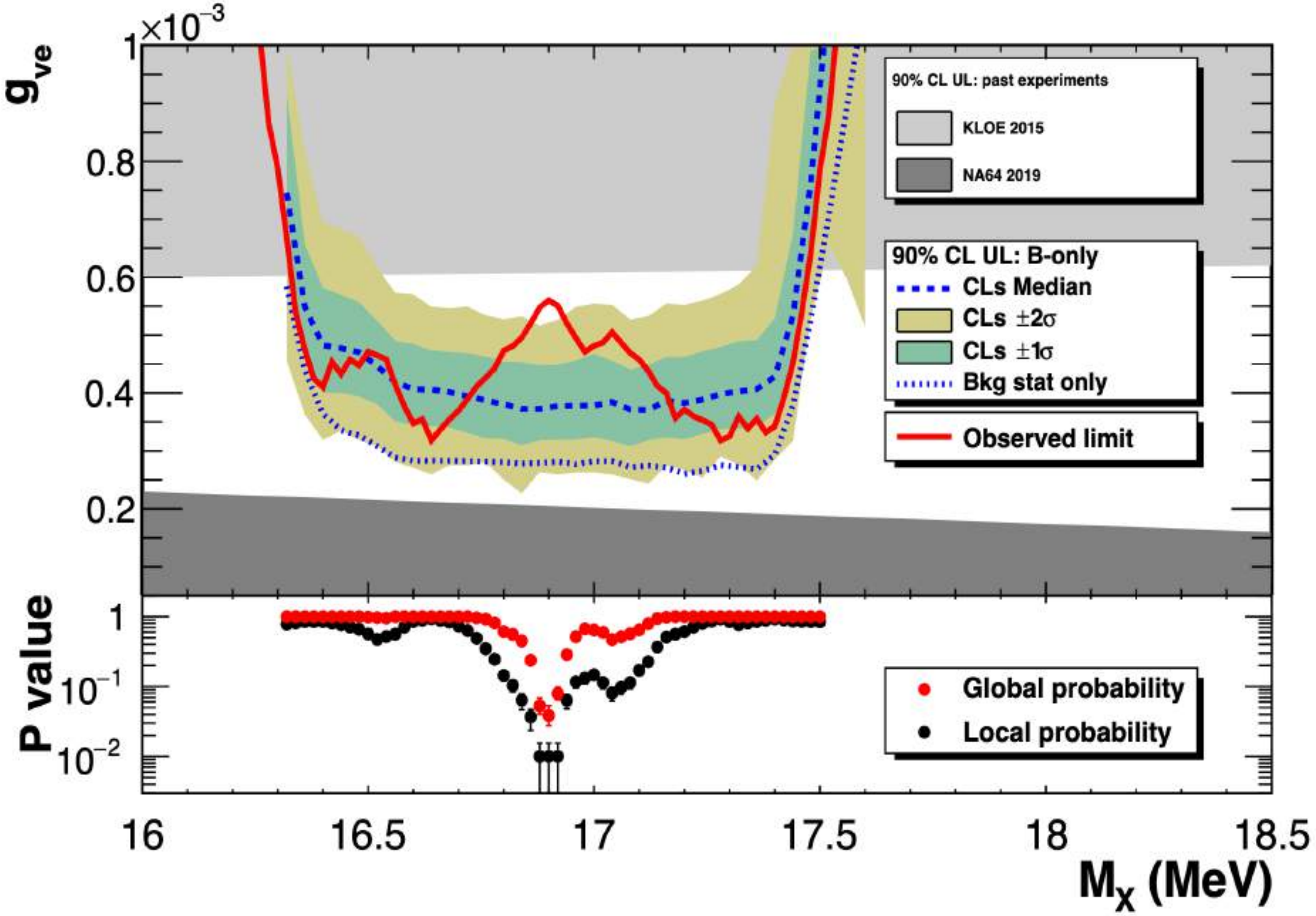
Pseudo data (SM background) is generated accounting for the expected uncertainties of nuisance parameters + statistical fluctuations

To validate the error estimate, we applied a blind-unblinding procedure described in JHEP 06 (2025) 040

Box opening

Some excess is observed a ~2.5σ local coverage

- 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)
- 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



Box opening - 2

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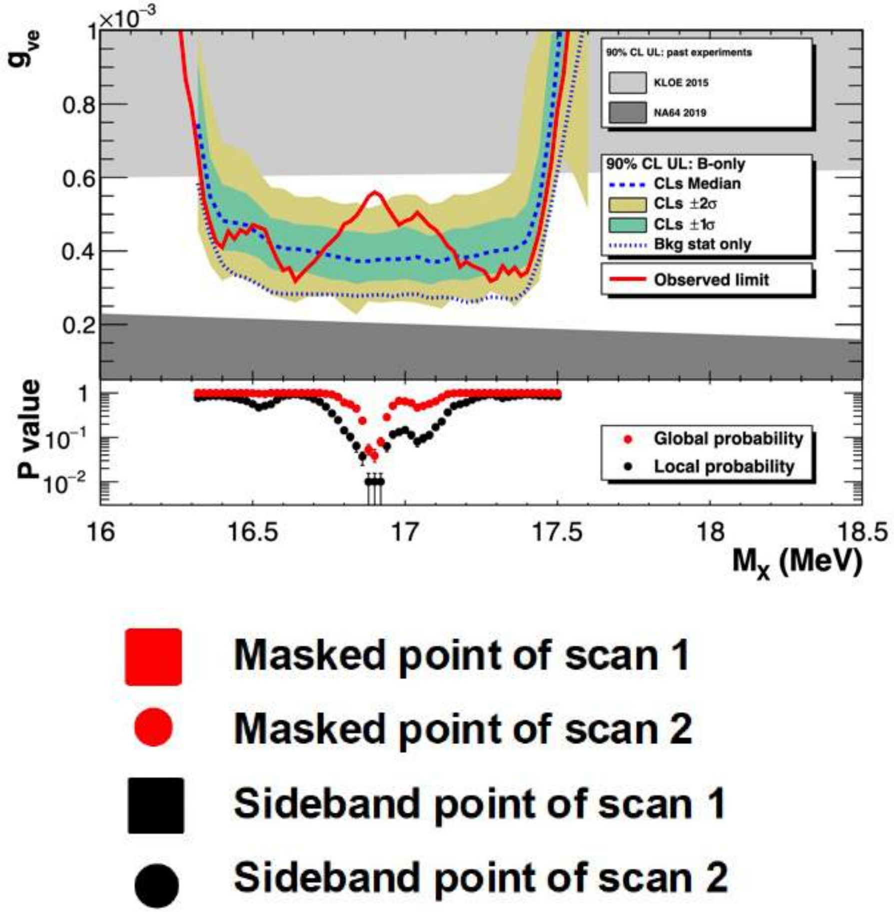
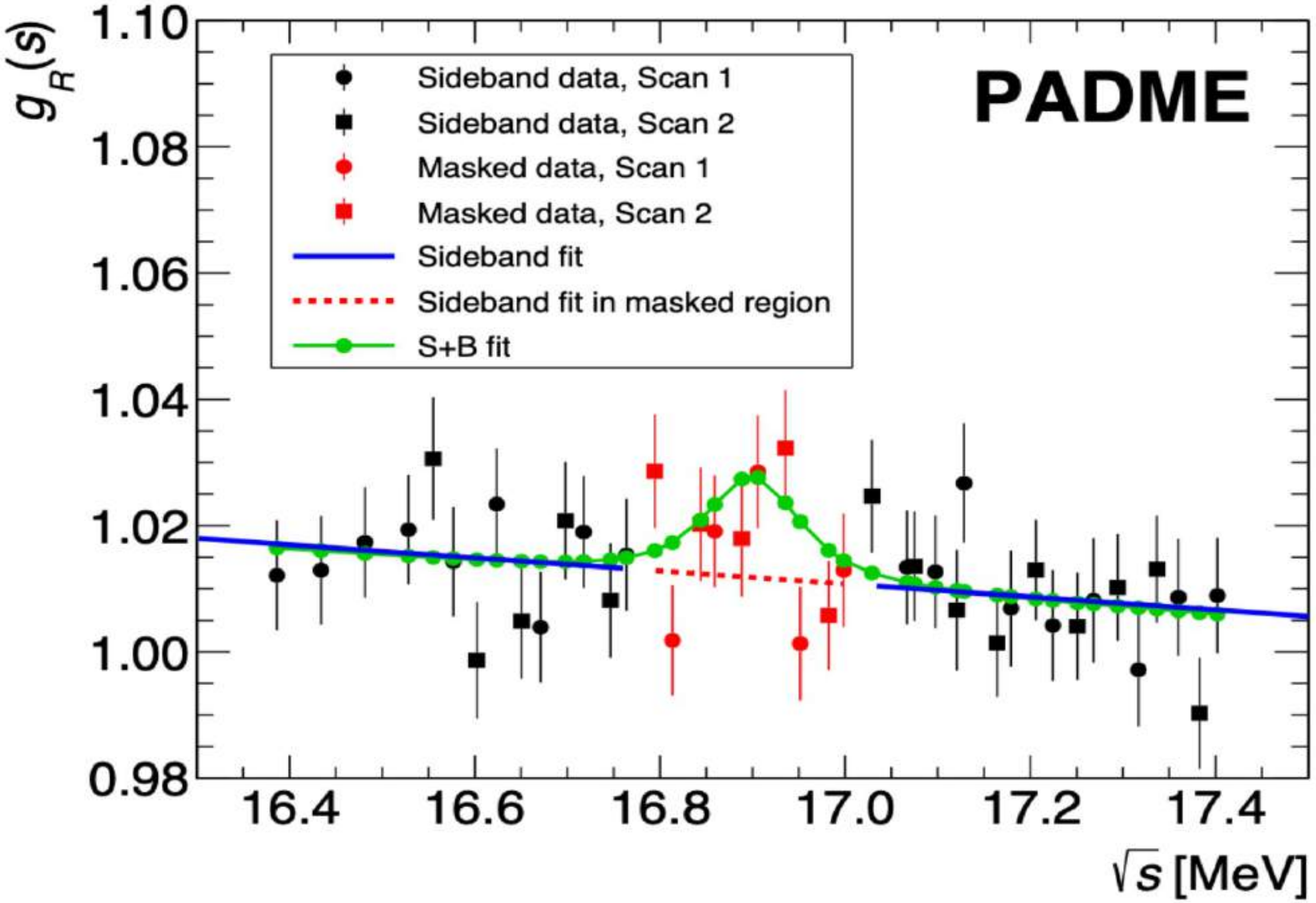
Check the data distribution vs likelihood fit done to evaluate $Q_{obs}(S+B)$

Fit probability is 60%





Run IV improvements overview

Run III result is not conclusive → need to collect more data

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

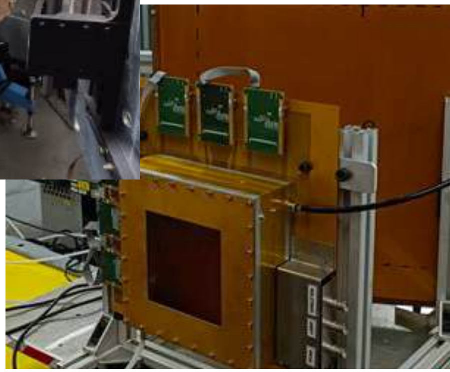
- **Diamond target** position moved downstream by ~30 cm → acceptance increased
- Beam stable in the central position along the whole data taking→ **To minimize lateral leakage on the beam catcher**

New detectors:

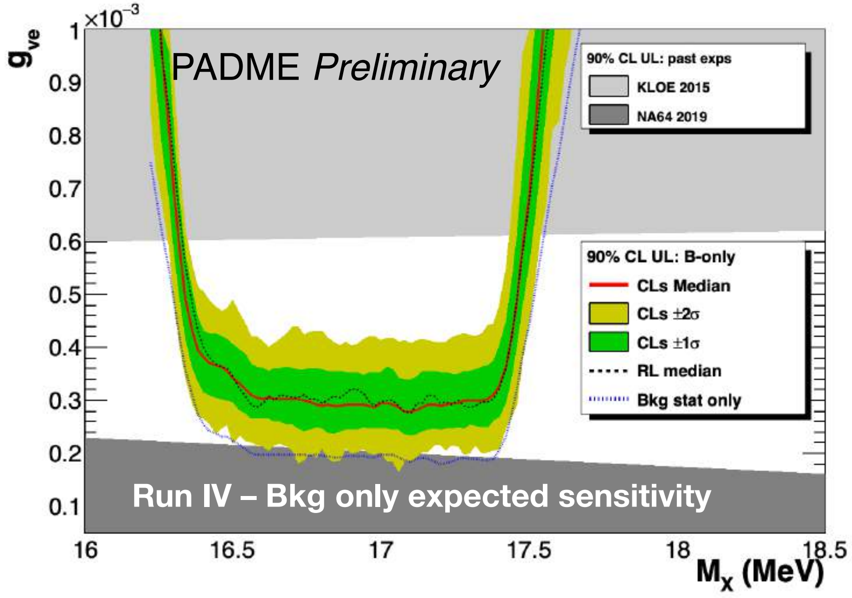
- **PadMMe** Micromegas chamber replaced the ETag:
  - e/γ discrimination, tracking capabilities, available as beam spot monitor
- **TMM** Micromegas replace the TimePix3 beam monitor:
  - Greater active area wrt TimePix3 and less passive material budget
  - Beam shape and spot monitor

PadMMe

TMM

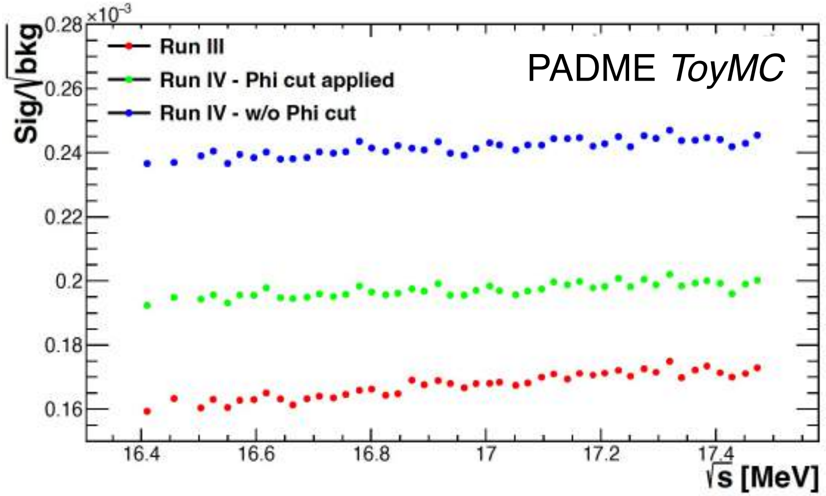


Source	Uncertainty [%]		Improvement
	Run III	**Run IV**	
N_2	0.6	**0.3**	New target position → acceptance increased
B	0.54	**0.3**	PadMMe → ee/γγ discrimination + better angular-momentum resolution
N_{PoT}	0.35	**0.3**	3 different beam spot monitor (target-PadMMe-TMM) + online LG calibration system
TOTAL	**0.88**	**0.5**	

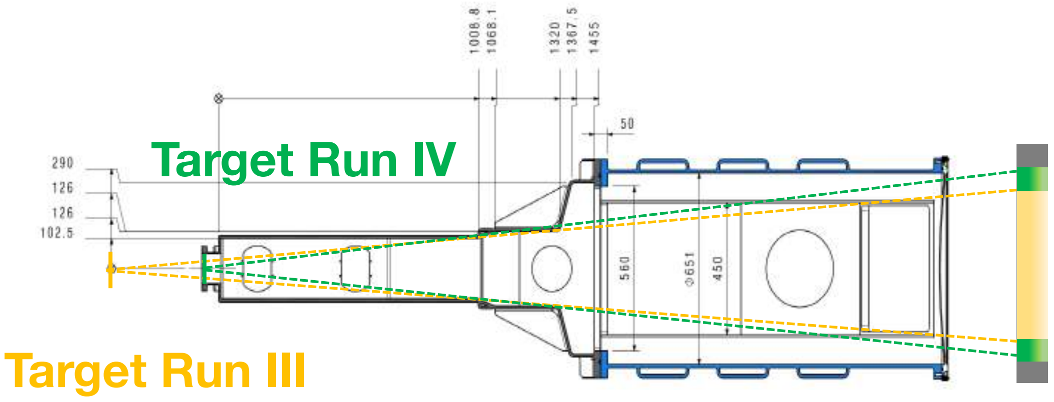


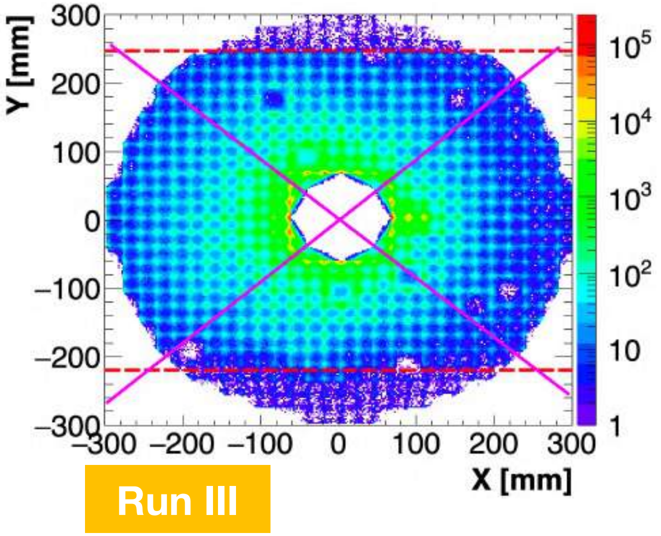
PADME Diamond target → acceptance

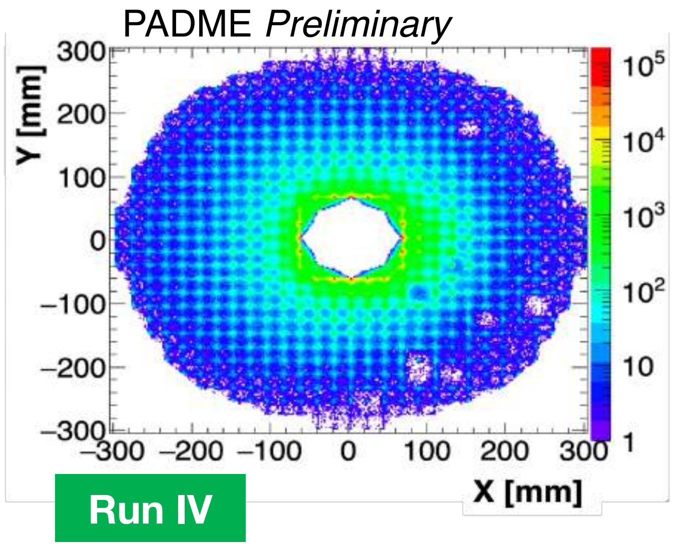
Run period	Target-ECal	θ_{lab} @ 17 MeV	R range @ 17 MeV	Magnet shadow
Run III	3700 mm	48 – 73 mrad	177 – 270 mm	249 mm
Run IV	3360 mm	43 – 80 mrad	146 – 270 mm	268 mm



- ϕ_{lab} -cut can be totally removed or adapted
- Acceptance region enlarged → $\frac{Sig}{\sqrt{Bkg}}$ increases, as well as the yield
- Residual magnetic field in PADME dipole completely degaussed
- Run-by-run Run IV luminosity increases by a factor of 2 wrt Run III

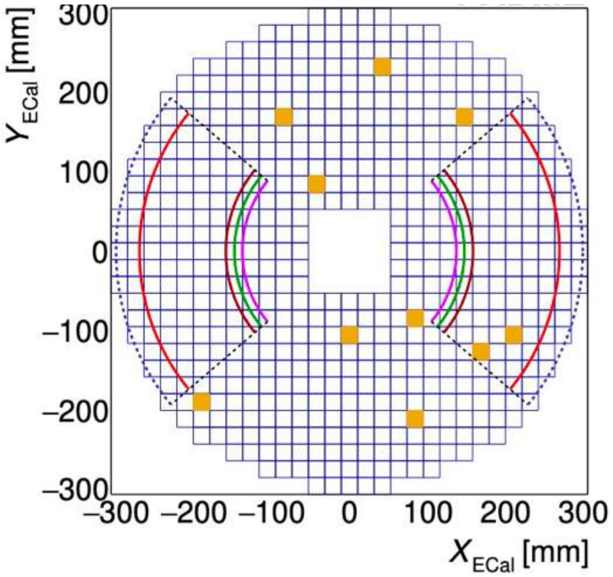


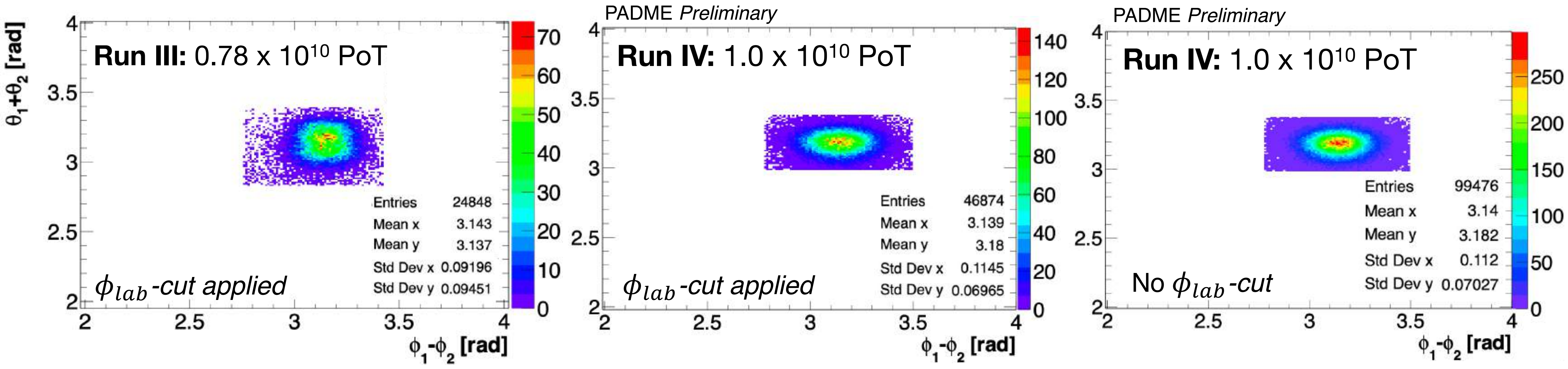




Preliminary look at the selection

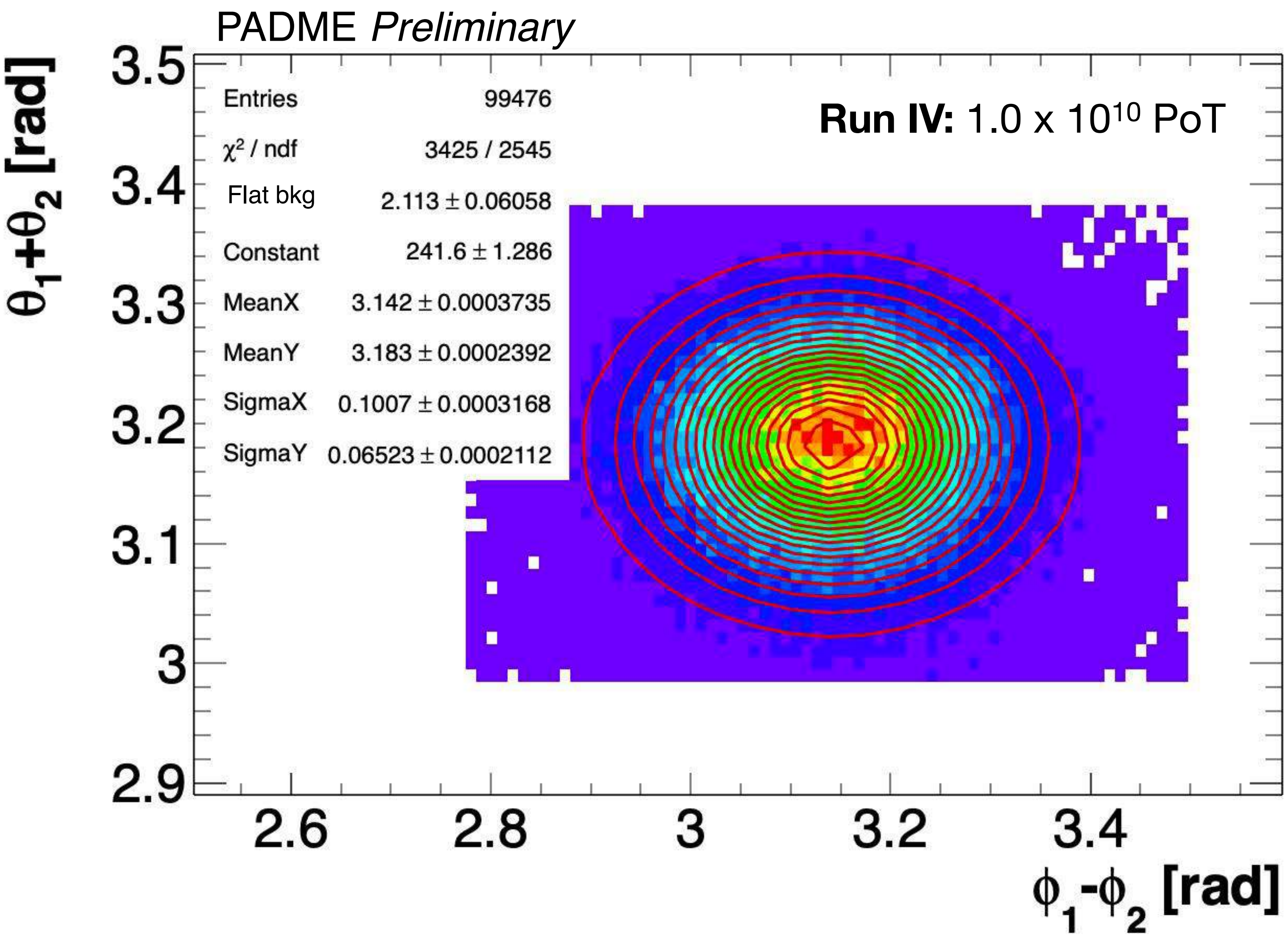
- Two body final states selected using ECal clusters position information
- Acceptance checked in a possible "*worst case scenario*" → Low-energy cluster R_{Max} below 270 mm, ϕ_{lab} cut applied
  - **Yield increases x1.5** (as expected, MC) ✅
- **Yield increases more 2.5** when NOT appling the ϕ_{lab} cut and enlarging the low-energy cluster acceptance
  - expected 2.3 from ToyMC, however Bremsstrahlung background must be subtracted, and lead-glass calibration not finalized yet





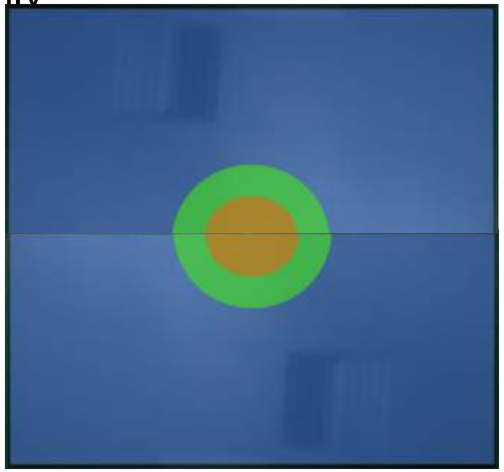
Preliminary look at the selection -2

- Selected events signal can be fitted with a 2D Gaussian + constant
- **Preliminary flat bkg evaluation:** from 4% at Run III to 7% at Run IV, still manageable
- Stat error on the yield <~0.5%
- Aimed ~ 0.35% for $2x10^{10}$ POT →basically OK

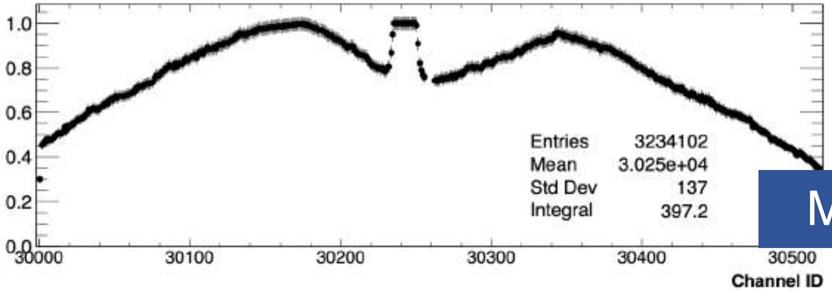


PADMME – MicroMegas tracker

- e/γ discrimination → would reduce bkg by 20% - charged final states only
- Access to different observables N_2/N_{PoT}, ee/N_{PoT}, $ee/\gamma\gamma$
- Tag and probe improves
- Main features:
    - $65x65x10\ cm^3$ - gas mixture ($Ar:CF_4:Iso=88:10:2$)
    - Hit efficiency > 90%
    - Spatial resolution ~ 350 μm → angle disentanglement
    - Multitrack events can be collected
- **Beam monitor capability** → central region at low gain (orange+green)
- **Need to face very high occupancy → well reproduced by MC**

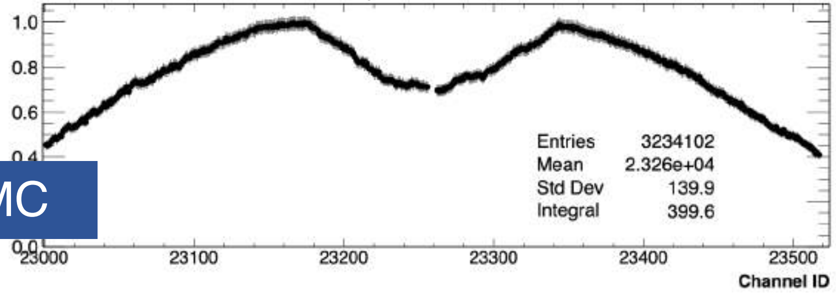


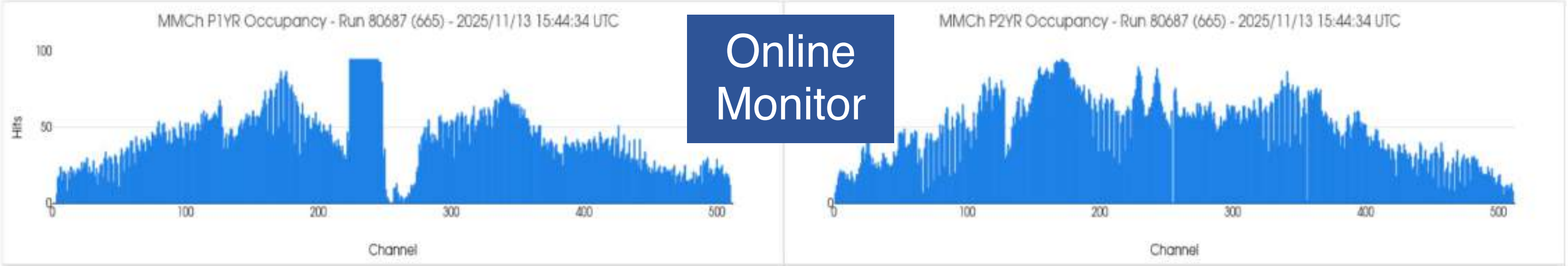
PADME MC *Preliminary*



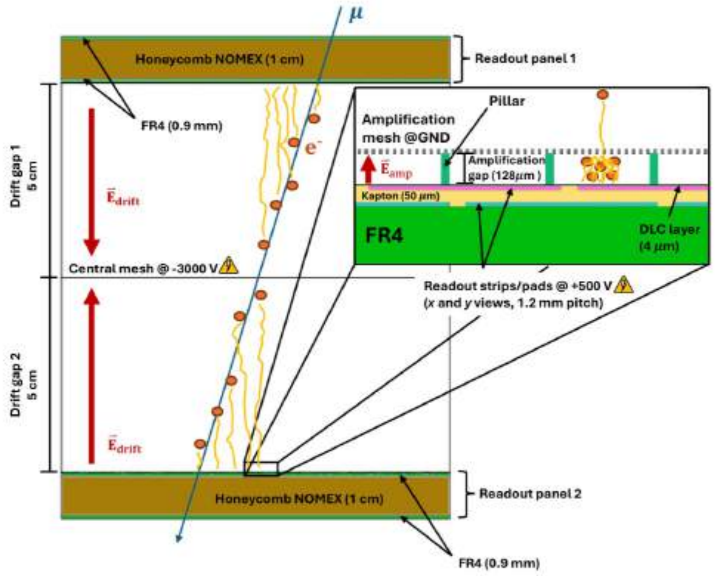
MC

PADME MC *Preliminary*





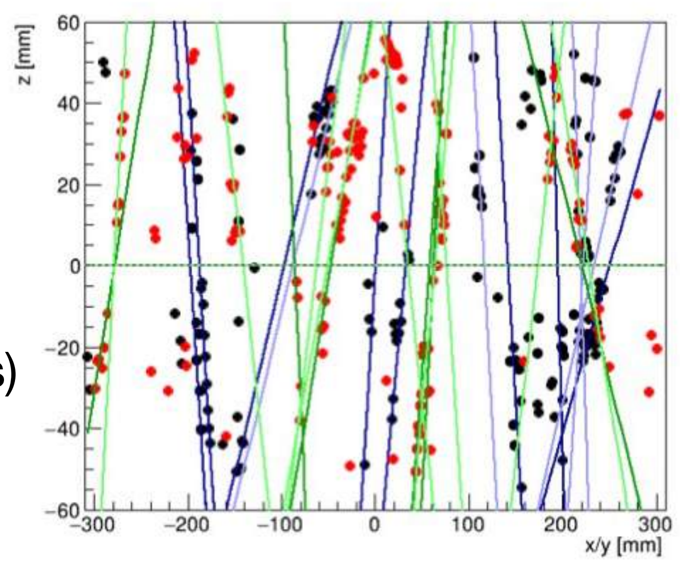
Online Monitor



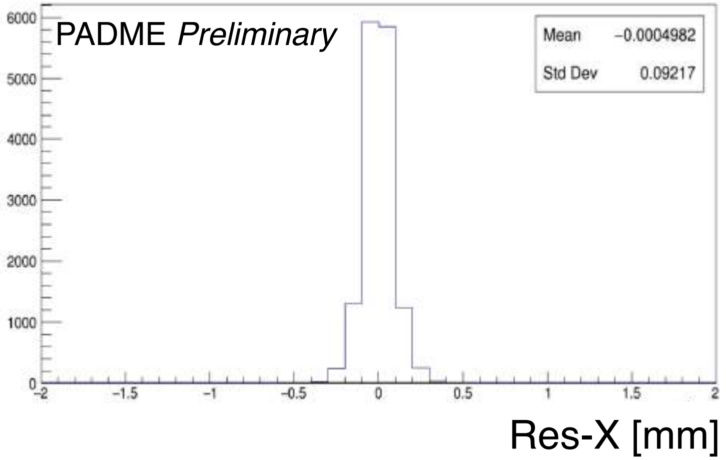
PADMME – MicroMegas tracker -2

- Large **combinatory** in pattern recognition
  - ~3500/4096 hits
  - ~200 track candidates found w/o Interaction Point (IP) constraint
  - IP-oriented pattern recognition algorithm
- Each charged particle measured in 2 planes – both X and Y coordinates
  - 4 tracks (2D) expected for charged particle, so-called Level-0 tracks
  - High efficiency but a Level-0 track requirement has high bkg component (fakes)
  - Need at least 2/3 out of 4 coincidence
  - Level-1 track: 2 planes coincidence

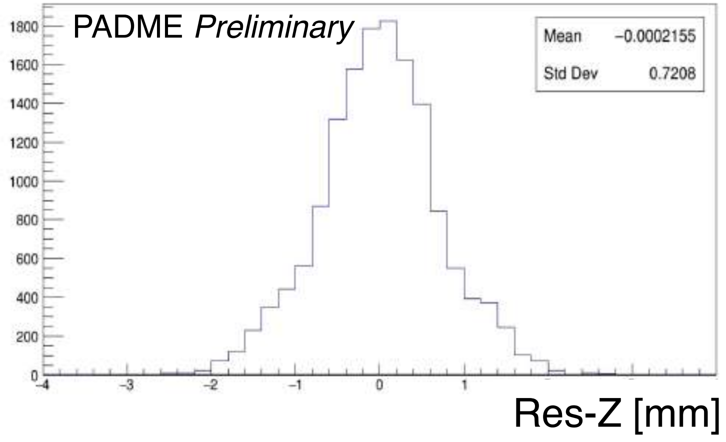
Lateral view



X direction track residual

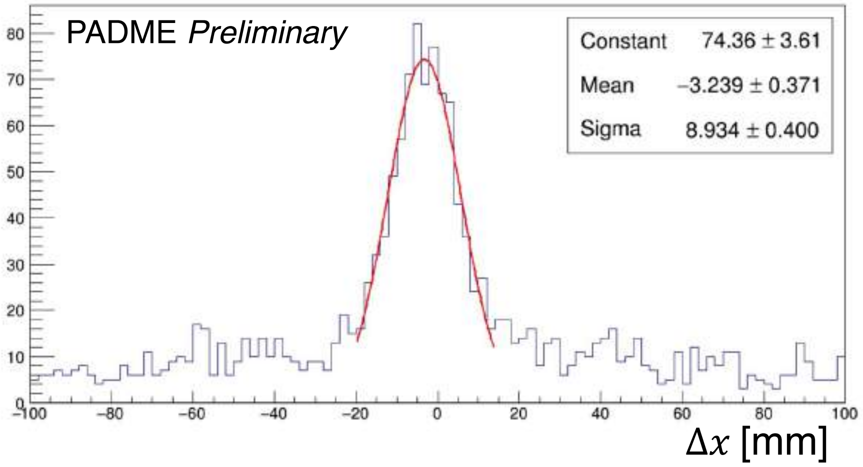


Z direction track residual



$\sigma_z \simeq 700\ \mu\mathrm{m}$

Track to cluster association

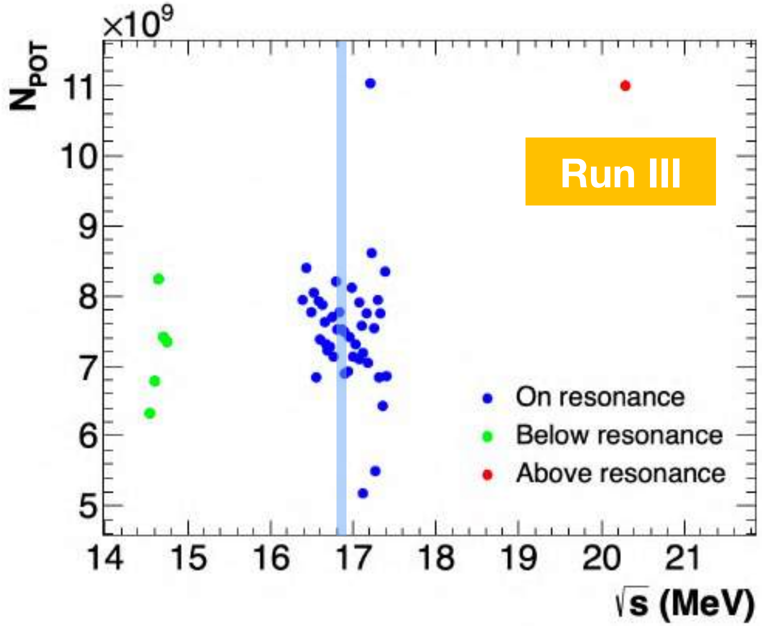


$\sigma_x \simeq 9\ \mathrm{mm}$, ECAL dominated

Run IV data taking

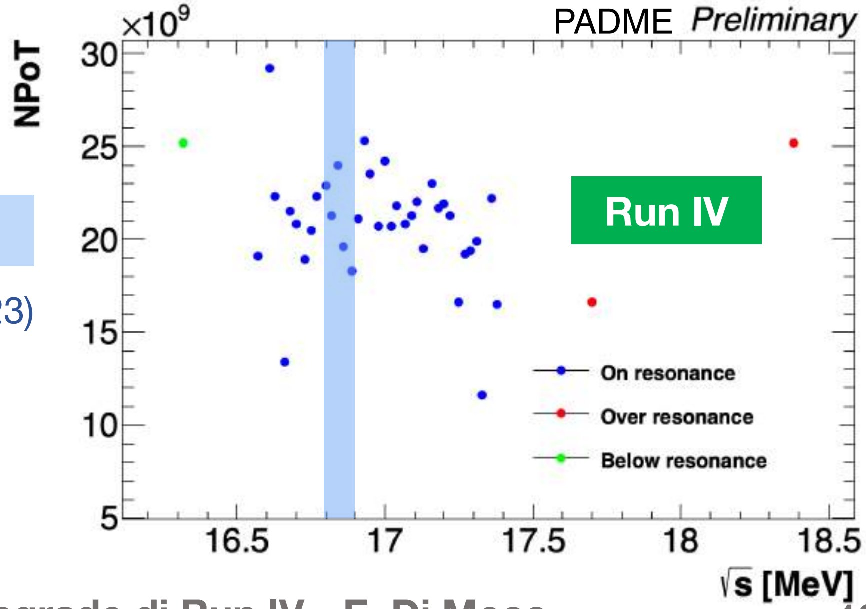
Data-taking divided again 3 parts: **below**, **on**, **over resonance**, collected 39 points + 15 no target datasets

	Run III	Run IV
On resonance	42 points: **Scan 1** -22 pts / **Scan 2** – 20 pts	36 points: **Scan 1** and **2** – 18 points each
N_{PoT}	~0.8×10^{10} PoT per point	~2.2×10^{10} PoT per point
E_{beam}	263-292 MeV range, with 0.75 MeV spacing	268-295 MeV range, with 0.75 MeV spacing
Below resonance	5 points between 205-212 MeV	1 point @ 260 MeV
Over resonance	1 point @ 402 MeV	2 points @ 300 and 330 MeV



$m_{X17} = (16.85 \pm 0.04)$ MeV

PHYS.REV. D 108, 015009 (2023)



Conclusions

Run III:
- Overall systematic uncertainty below 0.9% achieved for the entire Run III dataset
- No statistically significant signal observed largest fluctuation at M_X = 16.90 MeV (2.5σ local – 1.5σ global)
- Results interpreted with a frequentist CLs procedure to set upper limits (vector-boson hypothesis).

Run IV:
- 36 energy scan points ($\geq 2\times10^{10}$ PoT each) equally separated by 0.75 MeV in the region close to the resonance
- **Signal yield increased by a factor of ~ 2.5 wrt Run III** (luminosity+acceptance)
- Ongoing developments:
  - Use of tracks information
  - MC productions
  - Redundant beam parameter measurements
  - Finalization of event reconstruction algorithm

Aim: Improve sensitivity (higher statistics and better control of systematics) aiming at a factor of 2 error reduction

Backup slides

Dark sector candidate hypothesis

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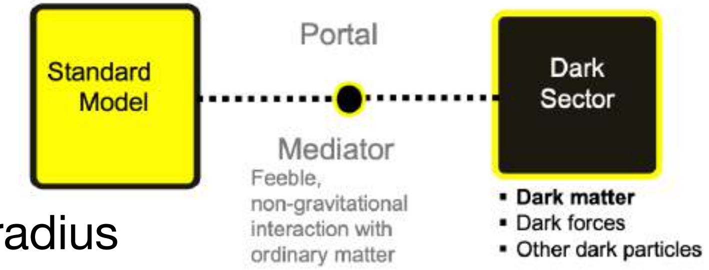
A dark matter candidate identikit: **X17**

1) It should be stable (or at least have an average lifespan of over 13 billion years!). ❌

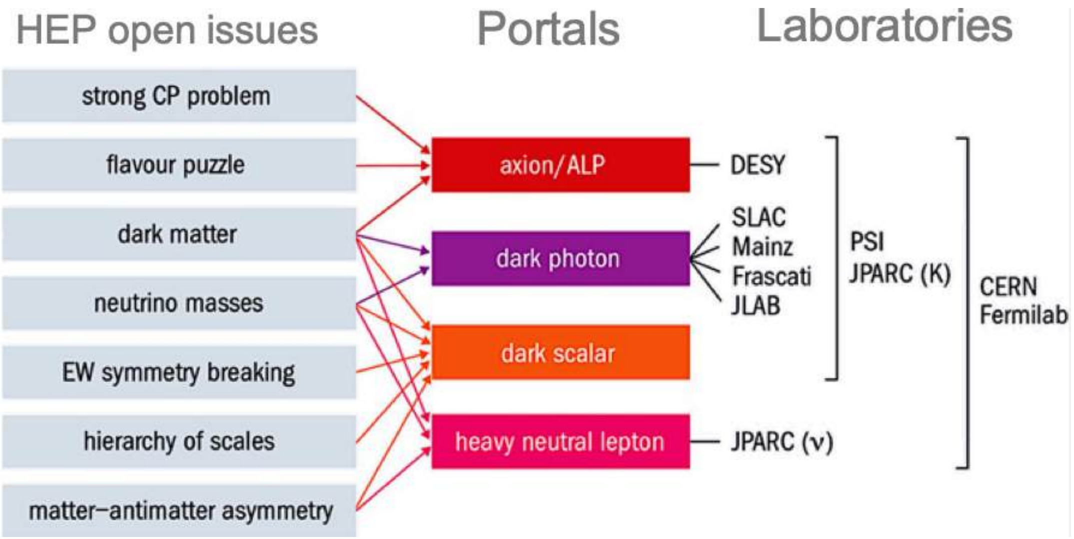
2) It should be electrically neutral or have strongly suppressed interaction with ordinary matter. ✅

3) It should be massive to have gravitational interaction ✅



Possible portal mediator to the Dark Sector → Light DM

Dark sector candidates can explain SM anomalies: $(g-2)_{m}$, ^{8}Be, 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.

X17 particle hypotheses

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

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

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

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

Experiments interested in X17

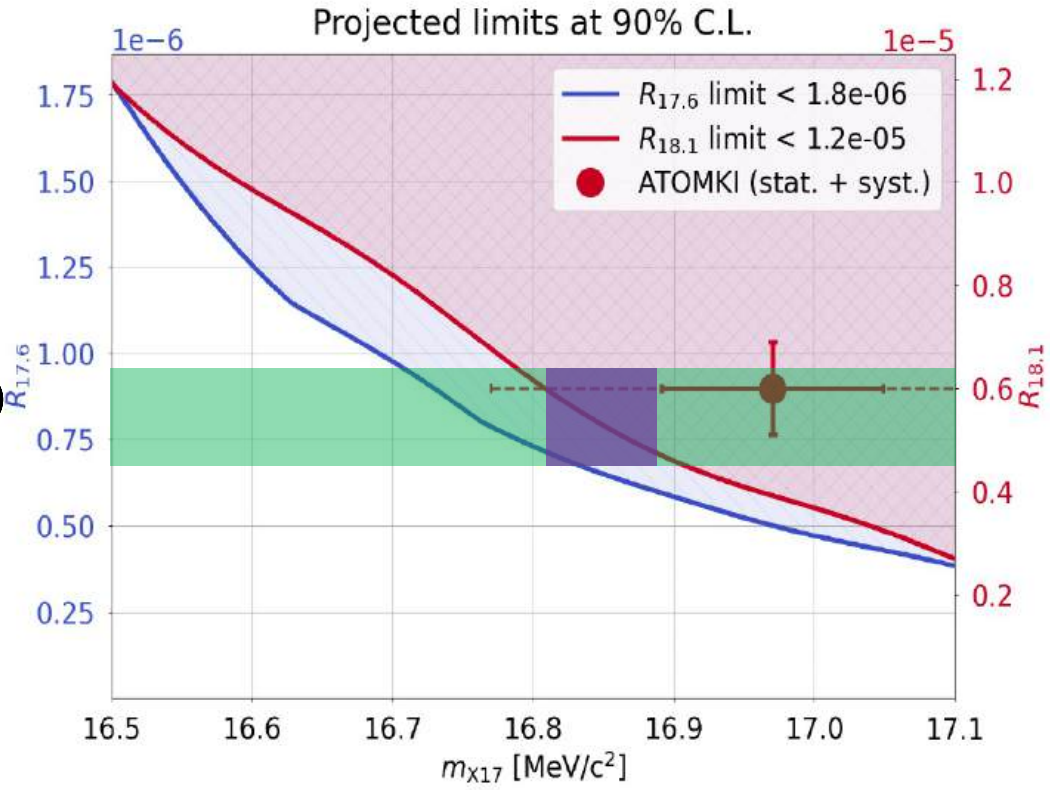
Recent result from MEG II, Eur.Phys.J.C 85 (2025) 7, 763

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

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

Further attempts to verify:

- **AN2000** facility @INFN-LNL [analysis ongoing]
- **nTOF EAR2** neutron line @CERN [2025 proposal]
- **MAGIX** high resolution spectrometer experiments @MESA (Mainz)
- **DarkMesa** beam dump experiment @MESA (Mainz)
- **DarkLight** at TRIUMF facility @Vancouver
- Jefferson Lab LDM search @JLab - **PRad-II, HPS, BDX**, ...

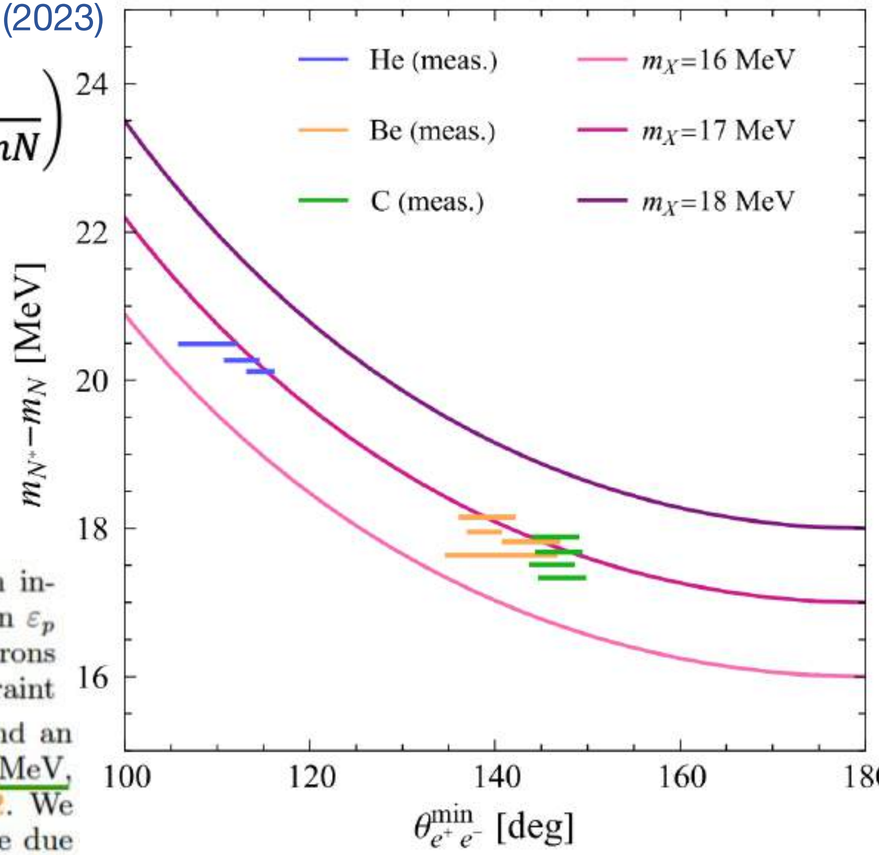


Global ΔE vs angle consistency

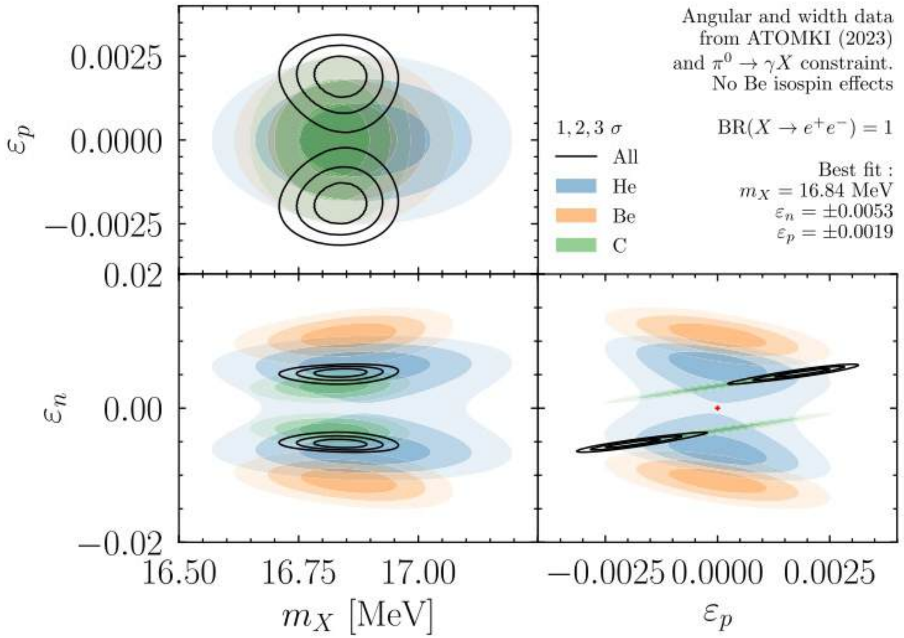
Neutrino constraints and the ATOMKI X17 anomaly PHYS.REV. D 108, 015009 (2023)

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

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)

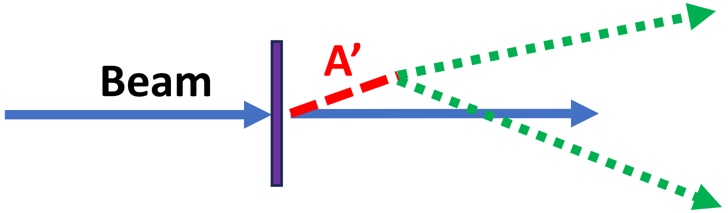


Next, we add in to the analysis the latest width information from each element and include a prior on ε_p since X needs to couple to protons and/or neutrons on the production size. There is a stronger constraint see the next section for more information. We find an okay fit to the data at the same mass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

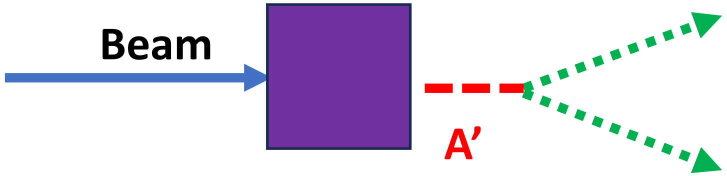
Data form ^{8}Be, ^{4}He, ^{12}C are consistent and point to:
M_{X17}=16.85 ± 0.04 MeV

Light DM search techniques @ accelerators

Main techniques:

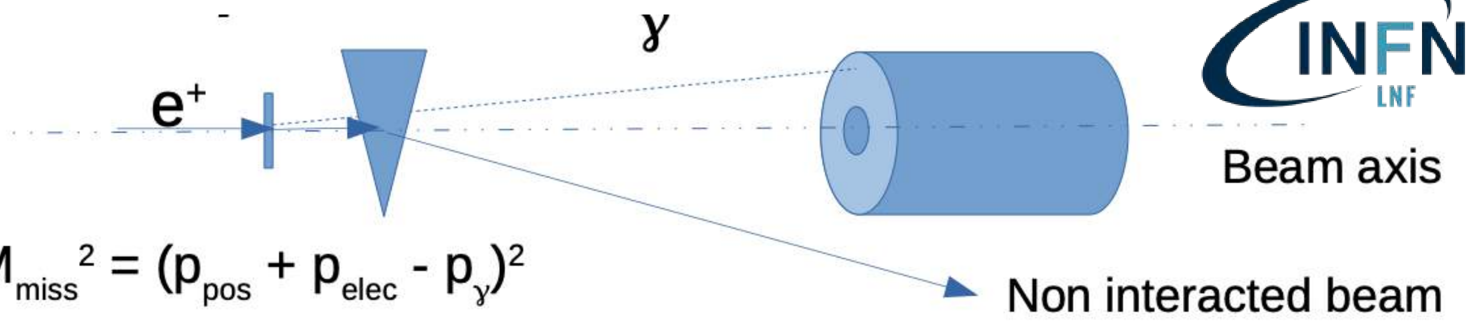


- **Fixed Target:**
  1. Thin target:
     - Direct production
     - Search for decays through event reconstruction (tracking)
  2. Secondary beam:
     - Usually in a thick target
     - Searching for new particles in meson decays → M_X usually limited by meson mass, coupling sensitivity and statistics



- **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

PADME Physics case

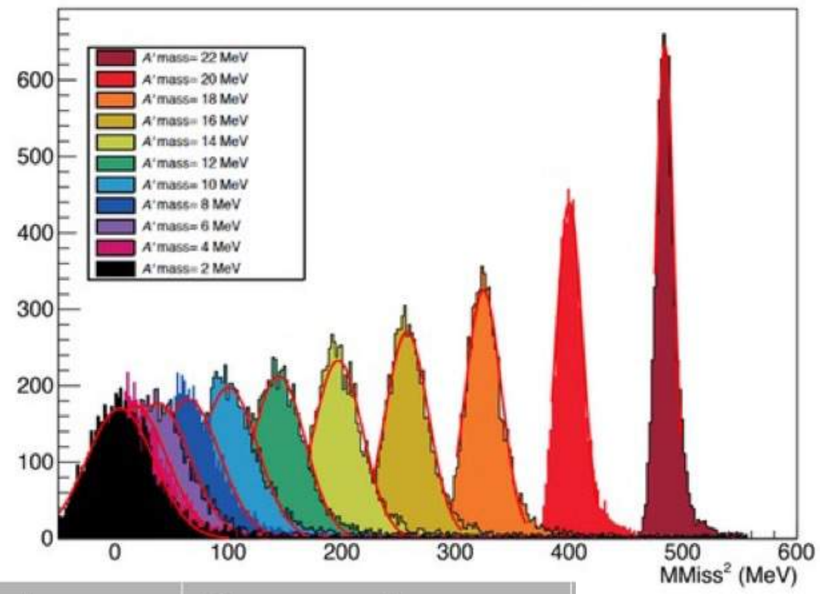


$$M_{miss}^2 = (p_{pos} + p_{elec} - p_{\gamma})^2$$

- $e^+e^- \to \gamma A'$ → 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 $M_{miss} = 0$
   - Quasi symmetric in gamma angles for $E\gamma > 50$ MeV
3. 3 photon annihilation
   - Symmetry is lost → decrease in the vetoing capability
4. Radiative Bhabha scattering
   - Topology close to bremsstrahlung

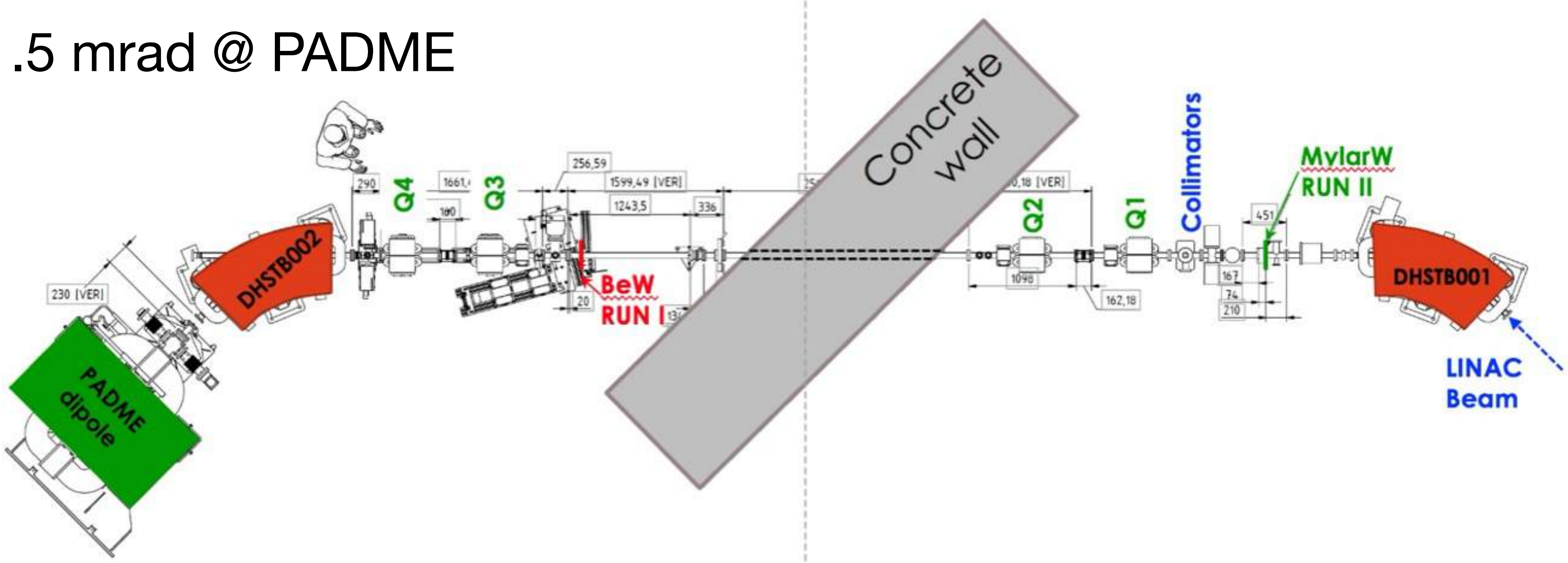
MMiss² for different $M_{A'}$



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

PADME – The facility

- Positrons from the DAΦNE LINAC up to 550 MeV, O(0.25%) energy spread
- Repetition rate up to 49 Hz, macro bunches of up to 300 ns duration
- Intensity must be limited below ~ 3 $\times 10^4$ PoT / spill against pile-up
- Emittance ~1 mm x 1.5 mrad @ PADME

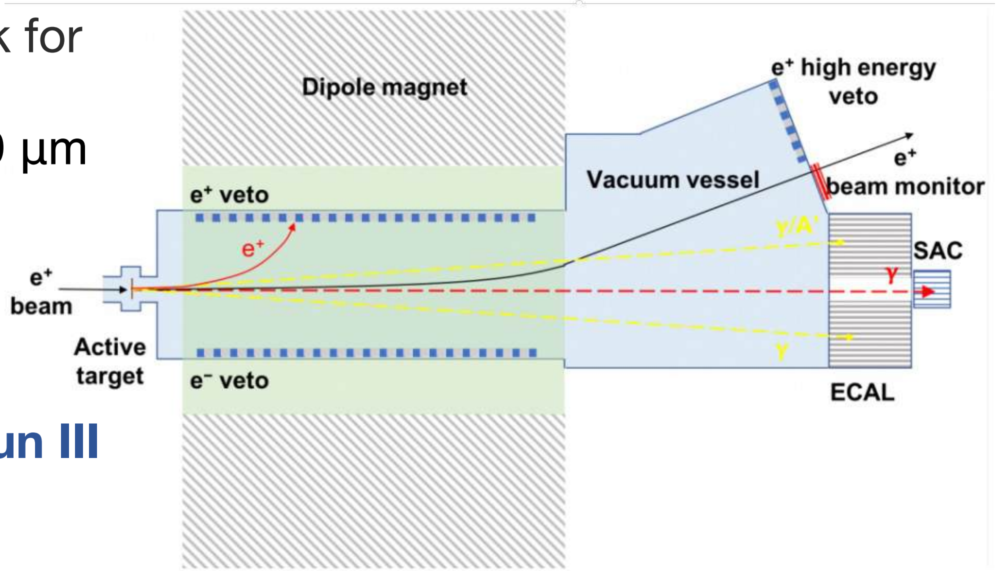


Past operations:

- **Run I** — e^- primary, target, e^+ selection, 250 μm Be vacuum separation (2019)
- **Run II** — e^+ primary beam, 125 μm Mylar™ vacuum separation, 28000 e+/bunch (2019-20)
- **Run III** — dipole magnet off, ~3000 e^+/bunch, scan $\sqrt{s}$ around ~ 17 MeV (End of 2022)
- **Run IV** — same conditions as Run III (completed November 2025)

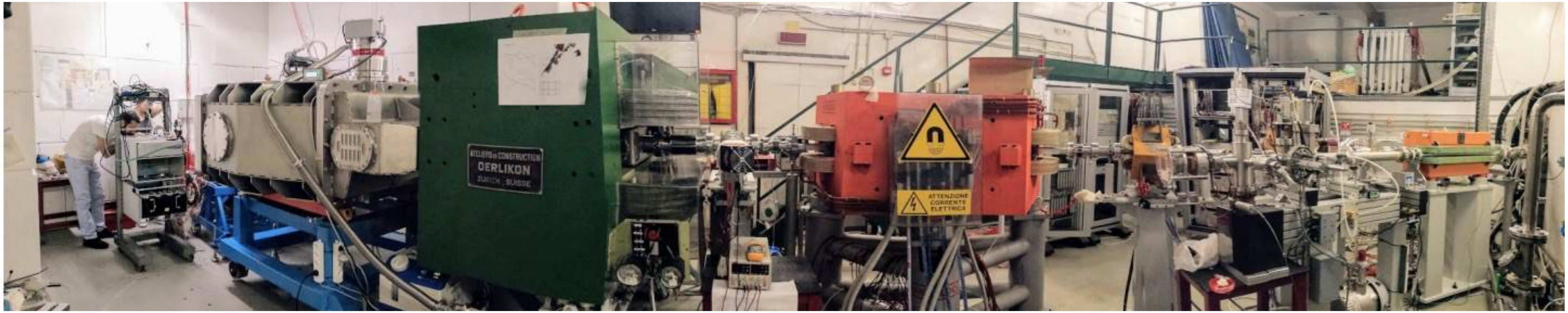
The PADME experiment

- 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 2×2 cm^2 ×100 µm
- Measure of ΔM^2_{miss} using a BGO ECal
- Could be sensitive to sub-GeV new physics (e.g. ALPs)

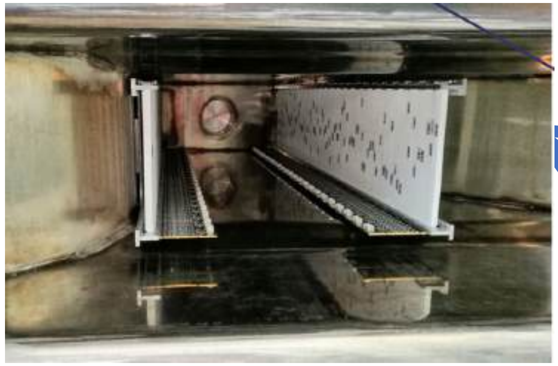


Can exploit the resonant production of X17 → fine scan: **PADME Run III**

- Some modification to the setup were necessary

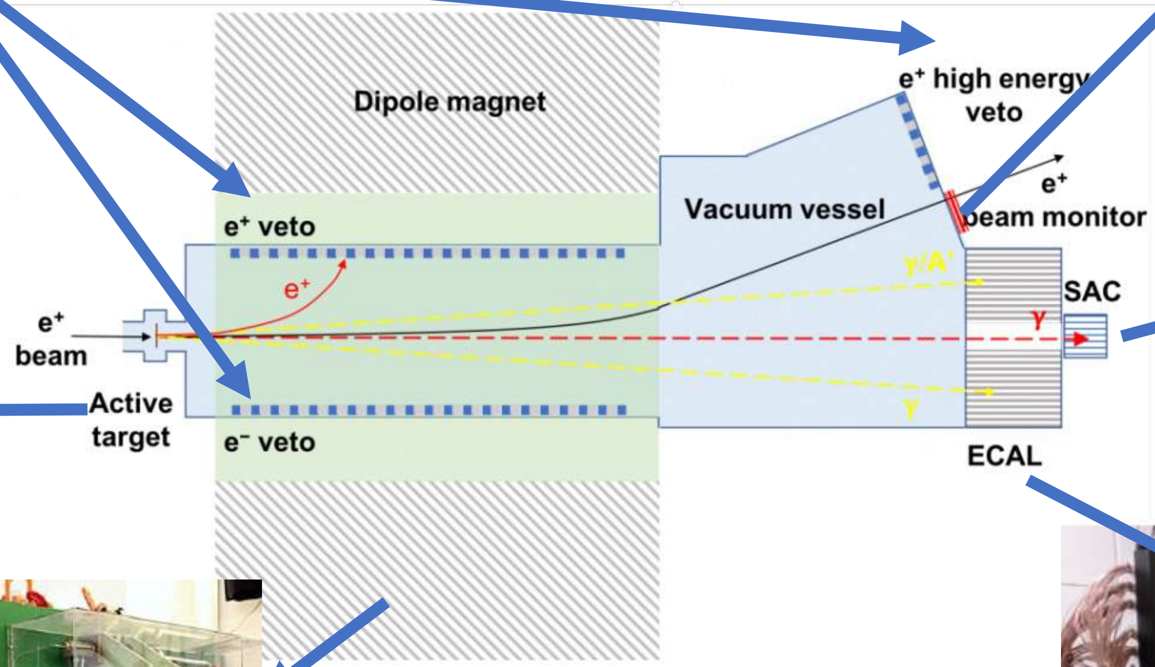


PADME – The detector

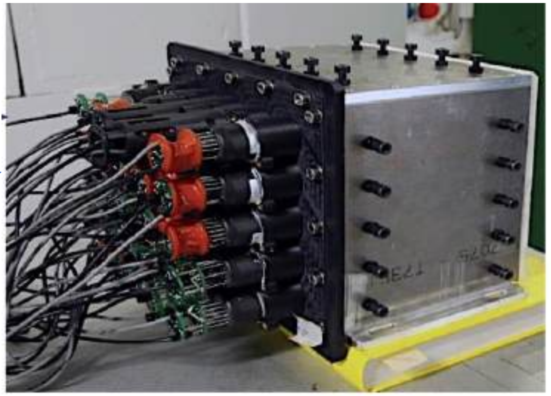


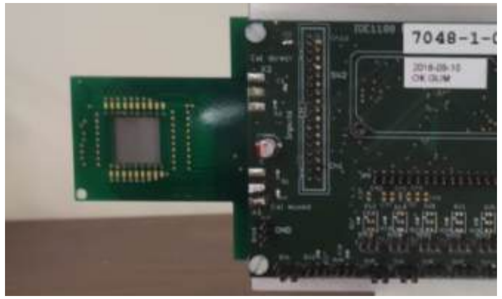
Scintillating e^+, e^- VETO

TimePix3
Beam monitor

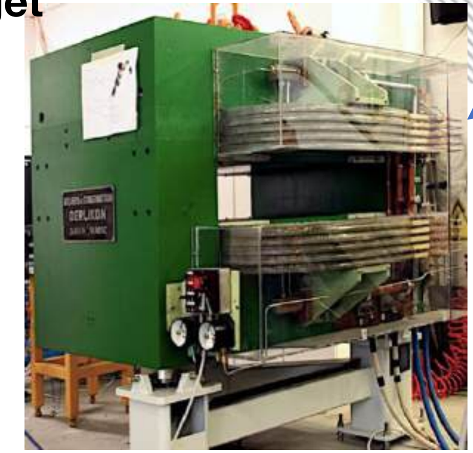


Small Angle PbF_2 Calorimeter

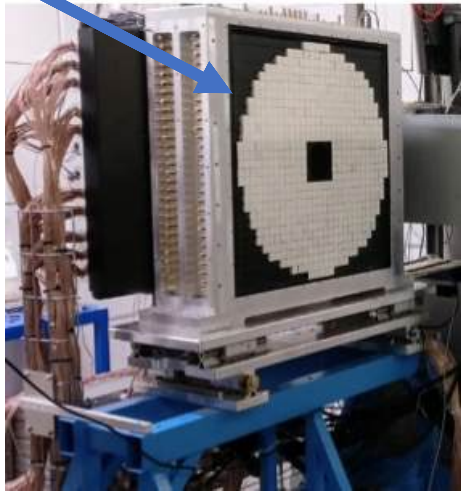




Active diamond target



Dipole magnet

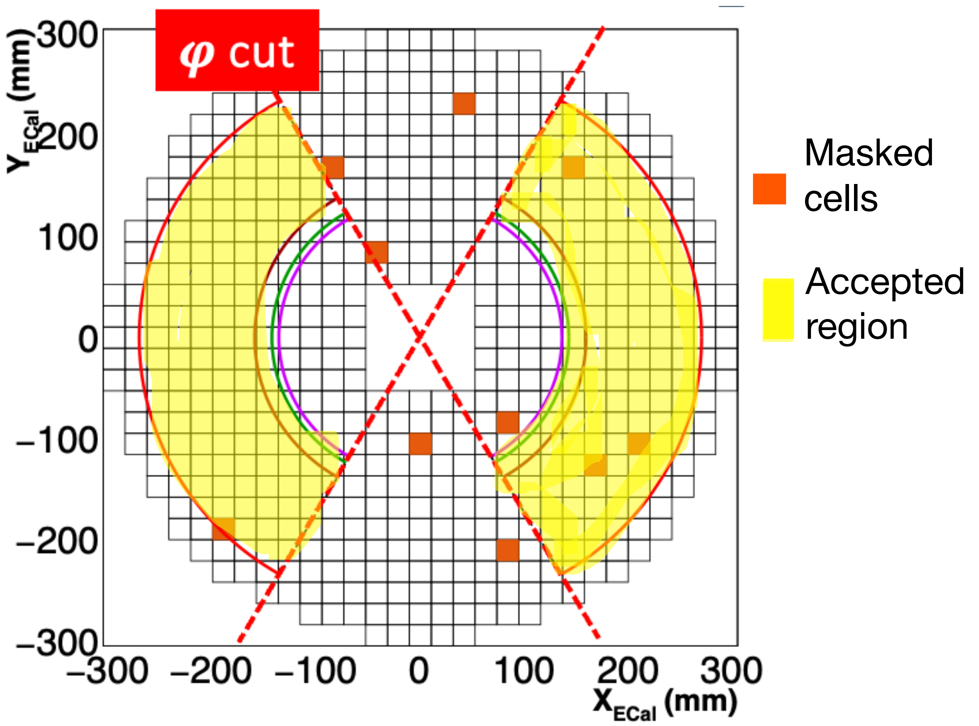


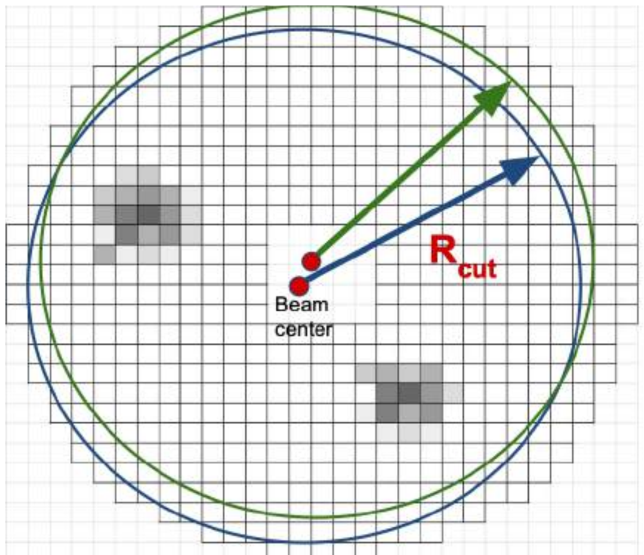
BGO ECAL

N_2 selection cuts

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 with the center following the beam Center of Gravity (CoG)
  - Minimum radius within the “two-cluster” kinematic range → following the beam center conditions
  - Energy dictated by the radius
  - ECAL illumination affected by material along the beam line not well reproduced in MC → **Cut regions in φ**
- **Mutual cluster conditions:**
  - ΔT (clu0-clu1) < 5 ns
  - ΔR (clu0-clu1) > 60 mm (Minimum $\gamma\gamma$ difference)
  - $\boldsymbol{\phi_1 - \phi_2}$ vs $\boldsymbol{\theta_1 + \theta_2}$ cut in the Center of Mass (CoM) frame isolates the signal





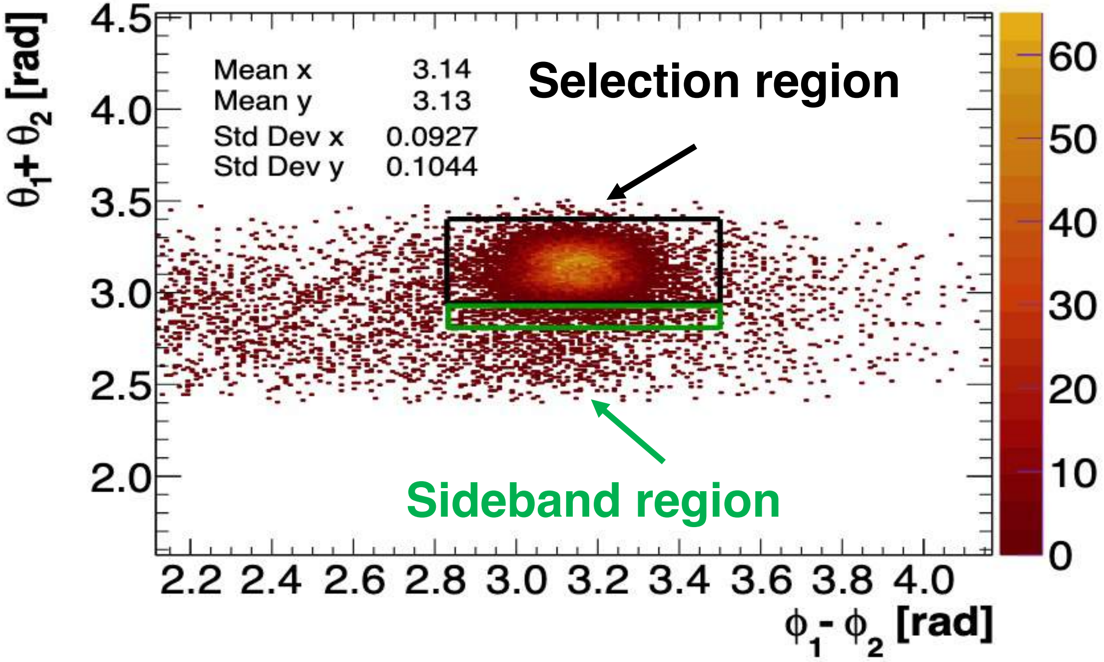
$\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ → $N_2(s)$

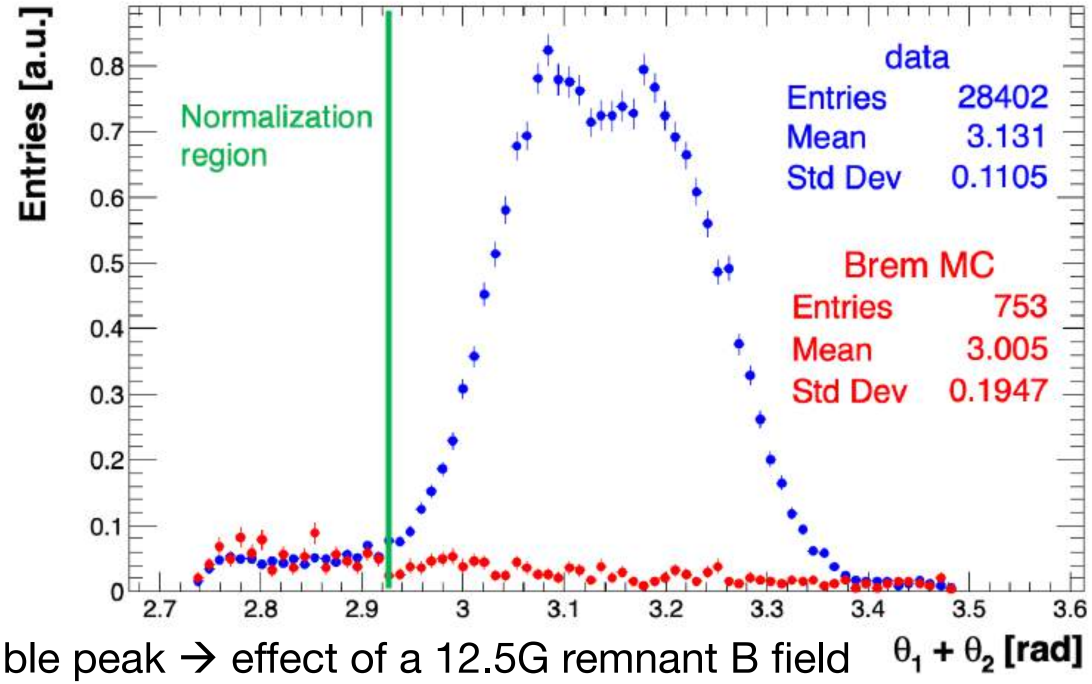
- Neglecting m_e/E terms, the c.m. angles are independent on the lab energies
- $\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ cut isolates the signal
- **Cut range**: 3σ around the mean value
  - Flat beam bkg in $\phi_1 - \phi_2$ → bkg level < 4%
  - Bremsstrahlung tail in $\theta_1 + \theta_2$ → Removed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

❖ Statistical error: **δN_2 ~0.6% up to 0.7%**

❖ Systematic uncertainty due to bkg subtraction: **δN_2 ~ 0.3%**

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



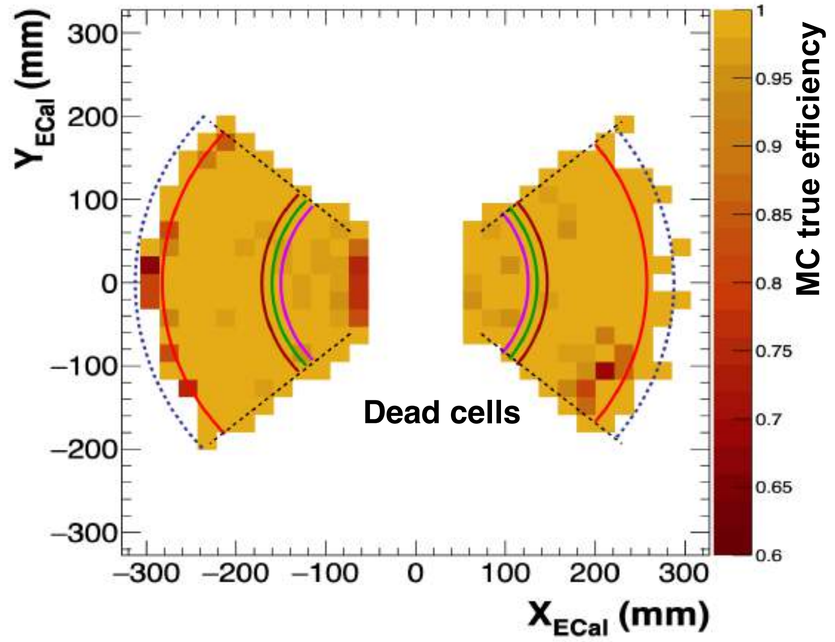


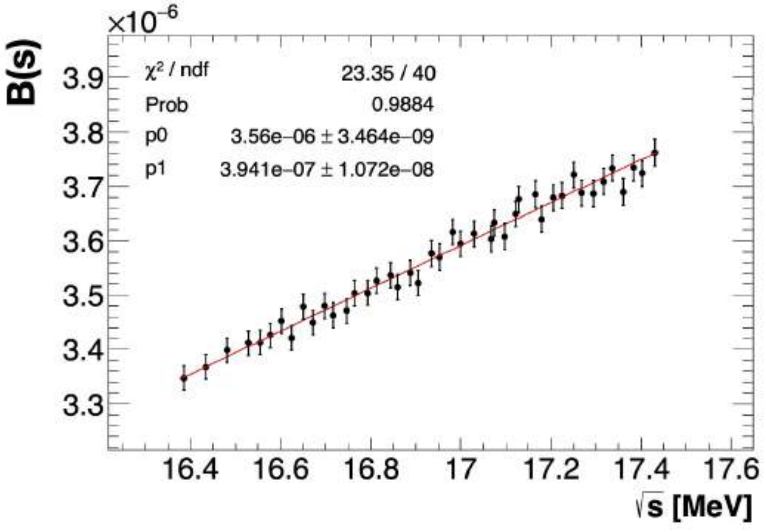
Double peak → effect of a 12.5G remnant B field

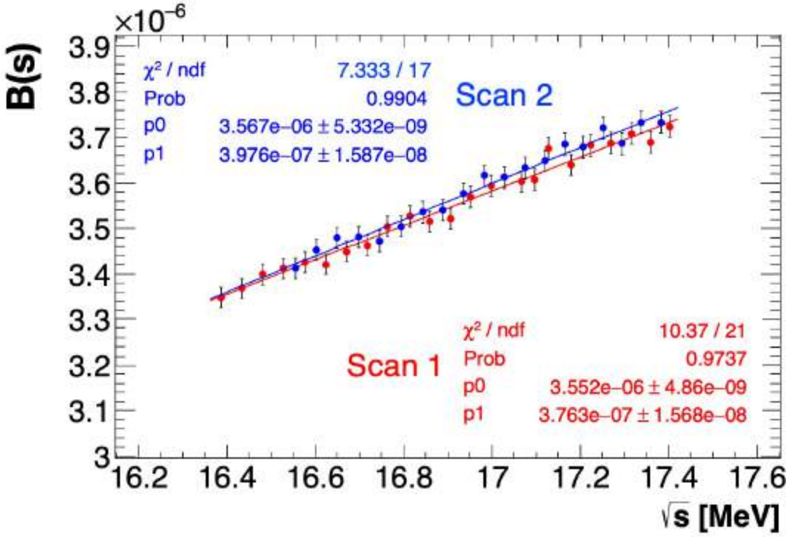
Expected Background → B(s)

The expected background / e+, **B(s)**, is determined with MC + data-driven checks
Reconstruction efficiency considered:

- Data/MC efficiency with tag-and-probe technique, exploiting two-body decay kin→ together with statistics, represents the major source of error on this observable **δB = 0.35%**
- Cut stability at MC and Data level also under control together with CoG (beam) variations



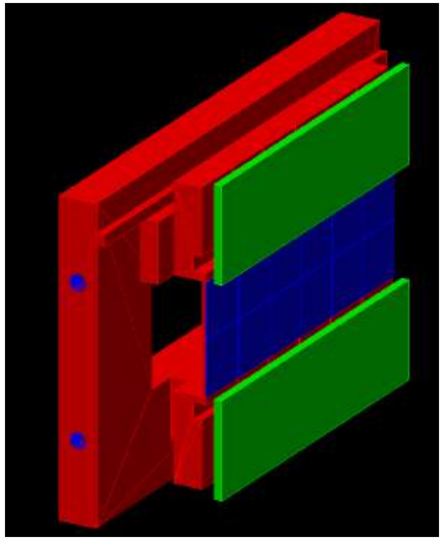




Source	Error on B [%]
MC statistics	0.40
Data/MC eff. (Tag&Probe)	0.35
Cut stability	0.04
Beam spot variations	0.05
Total	**0.54**

Positron on Target → $N_{PoT}(s)$

- PoTs measured with the end-of-line Leadglass calorimeter → **2%** scale error on the calibration considered, measurement validated on over-resonance dataset
- Two main effects to be accounted for in the flux measurement:
  - **Energy loss in TimePix3 cooling system** → strictly related to beam spot variations
    - Beam crossed different amount of passive material along the scan
    - Effect estimated from MC simulation and validated on Test Beam data → systematic correlated error δN_{PoT}**=0.5%**
  - **Radiation induced loss** → TID of 2.5 krad
    - Transparency changes for O(krad) for similar blocks
    - Estimated from flux proxy observables: $Q_{target\text{-}x}$, $\langle E_{ECal} \rangle$
    - LG yield decreases with relative PoT slope of 0.097(7) → Slope error included δN_{PoT}**=0.35%** uncorrelated
    - Constant term uncertainty of δN_{PoT}**=0.3%** added as scale error



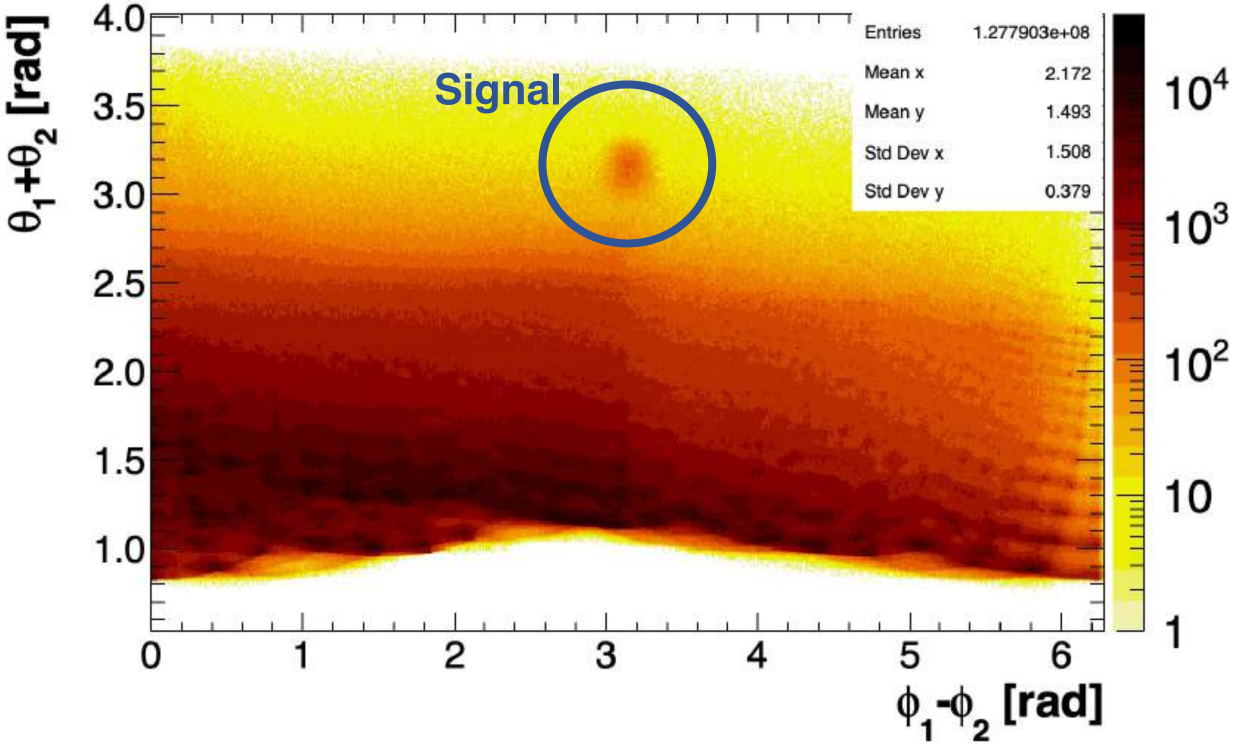
Uncorrelated systematic errors

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

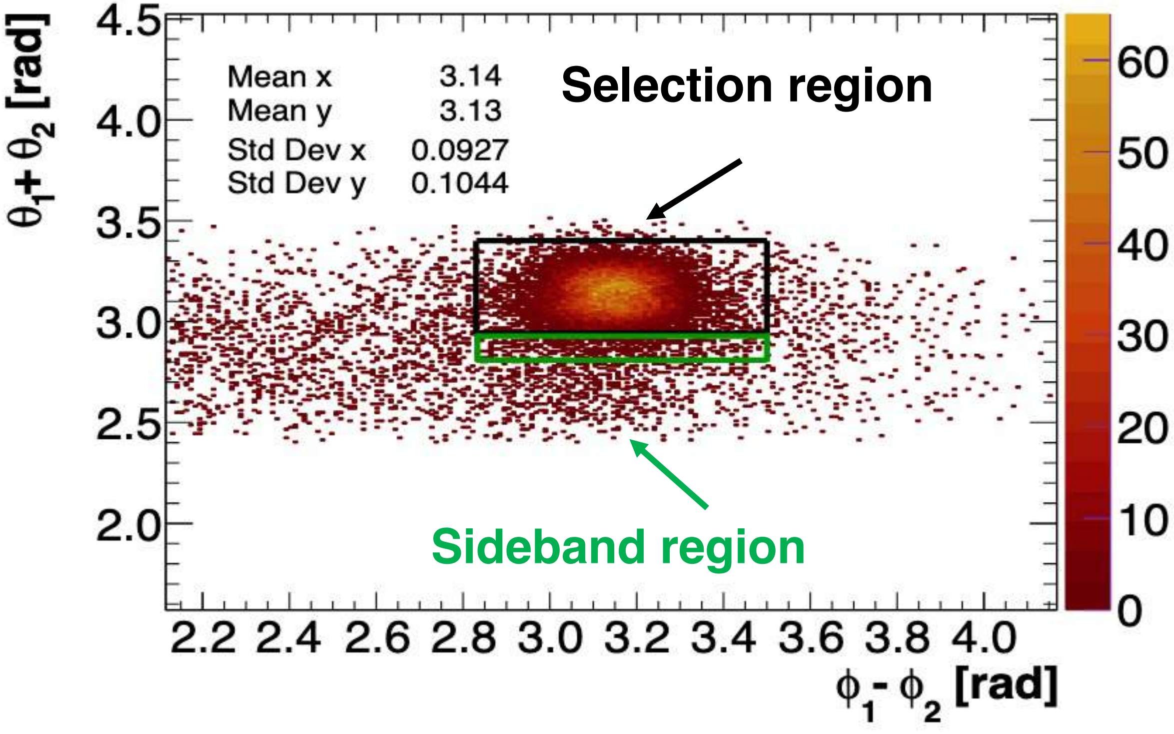
$\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ → $N_2(s)$

- Neglecting m_e/E terms, the CoM 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 $\phi_1 - \phi_2$ → bkg level < 4%
  - Bremsstrahlung tail in $\theta_1 + \theta_2$ → ~ 7% for each scan point

No cuts



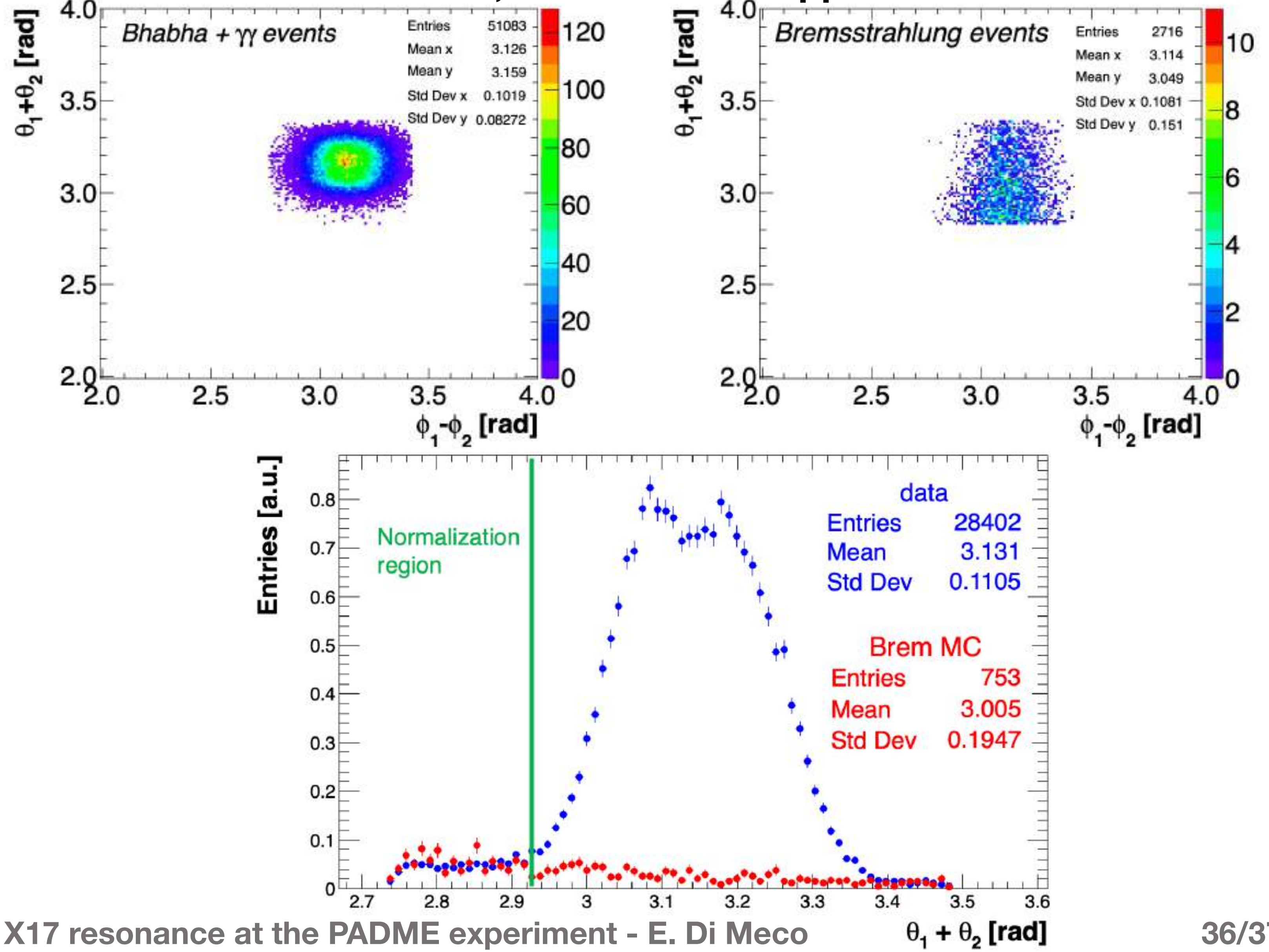
After clusters selection cuts



Residual Bremsstrahlung bkg removal

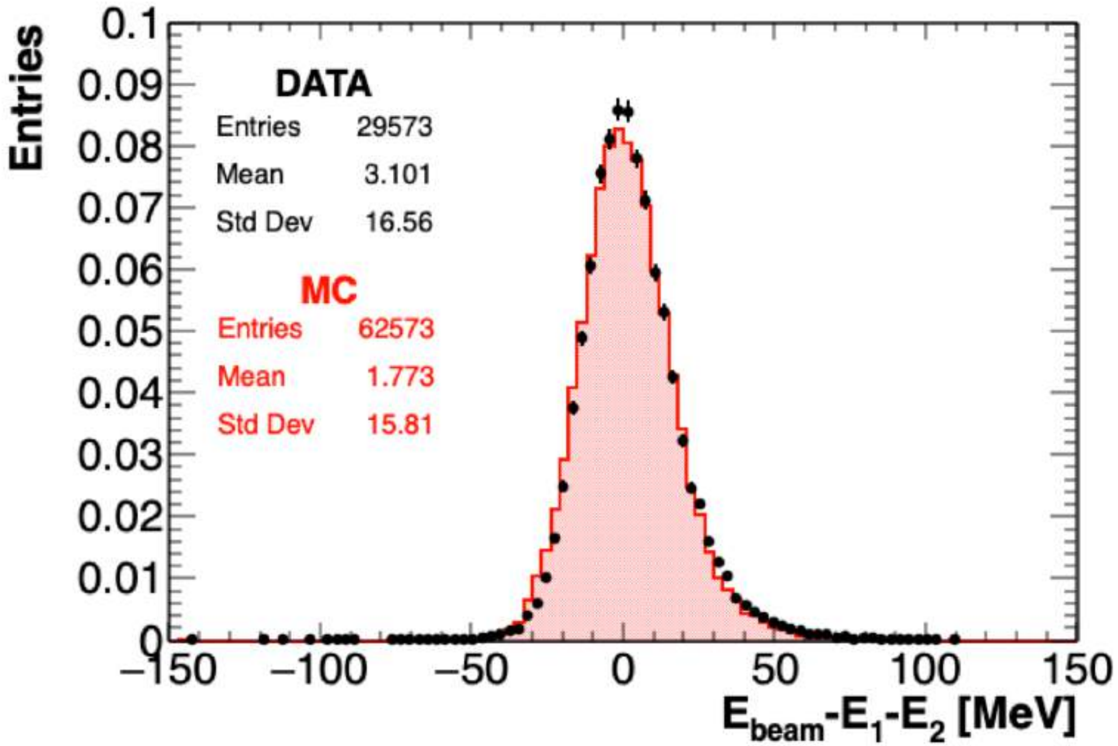
- The $\theta_{CoM1} + \theta_{CoM2}$ distribution shows a Bremsstrahlung tail outside the signal region, both in data and MC
- By normalizing in the (0, 2.94) rad region and then using the ratio between the (2.94, 4) rad integrals, it is possible to get an estimate of the Bremsstrahlung events under the signal

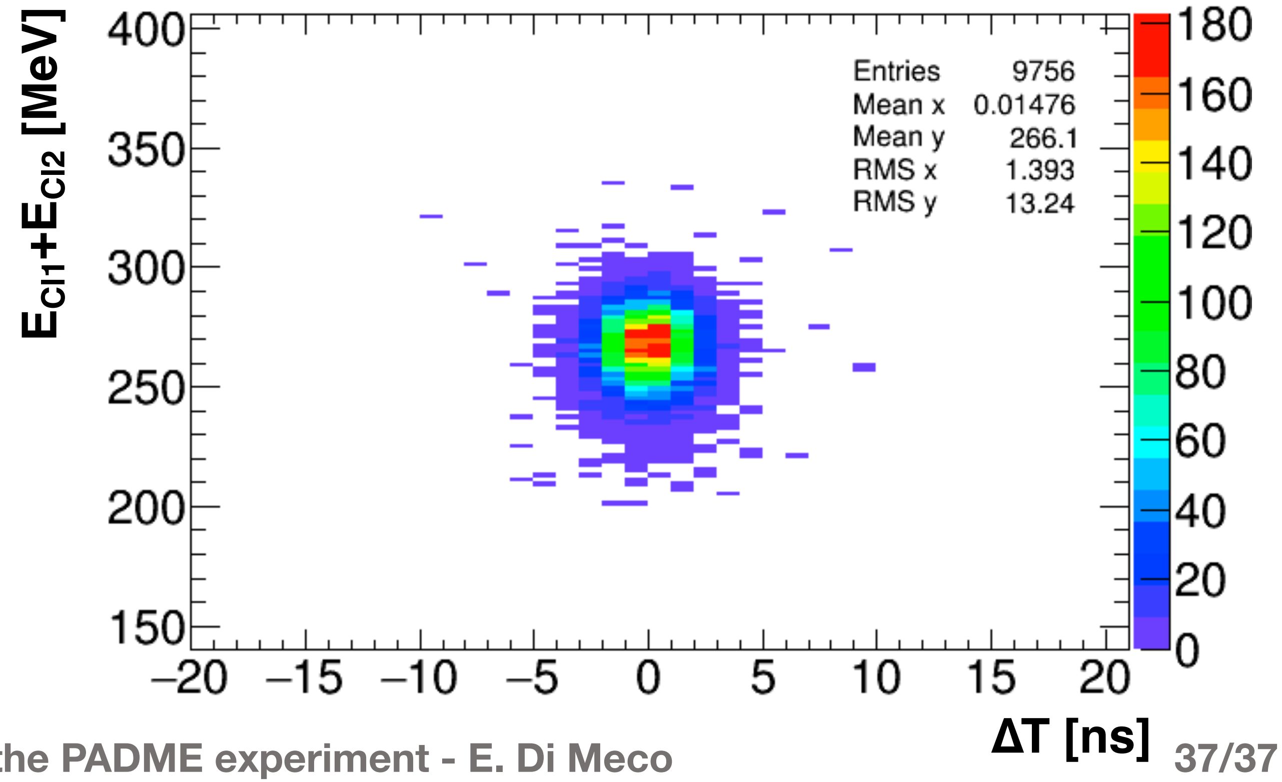
True MC, selection cuts applied



$N_2(s)$ events selected quality

- **Validation of the selection sample**:
  - Energy sum of the 2 selected clusters gives back the beam energy (as expected for a 2-body final state)
  - Correlates in the two-clusters time difference as expected
  - Good data/MC agreement in all the variables used for selection cuts
- ECAL relative energy resolution ~ 5%



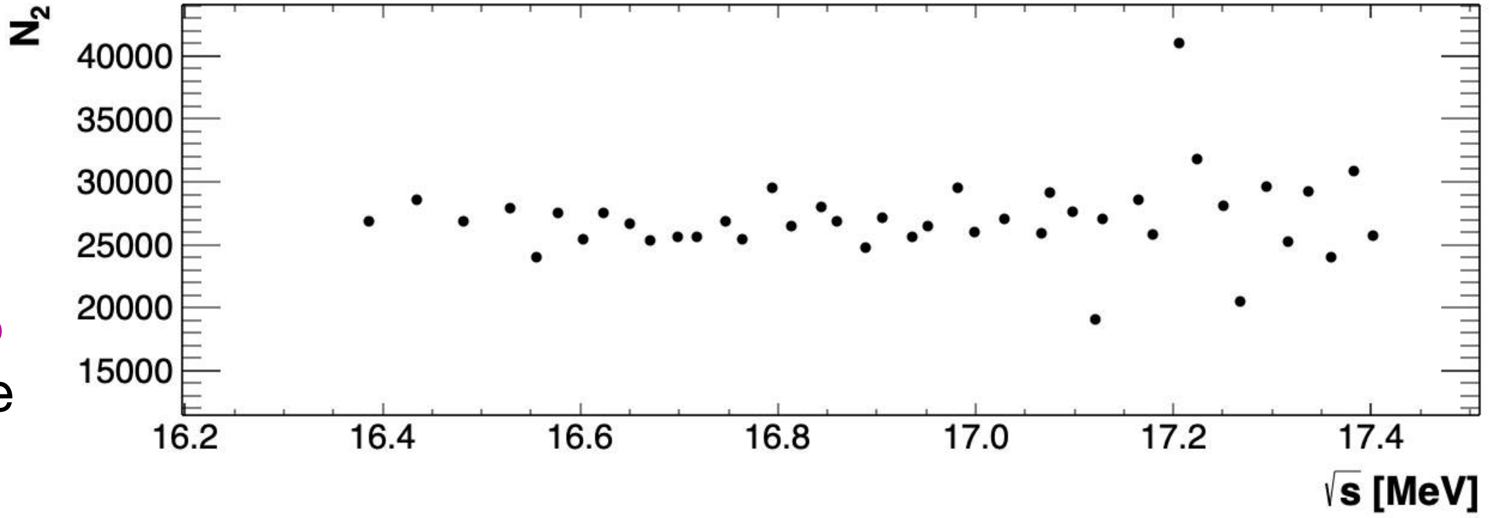


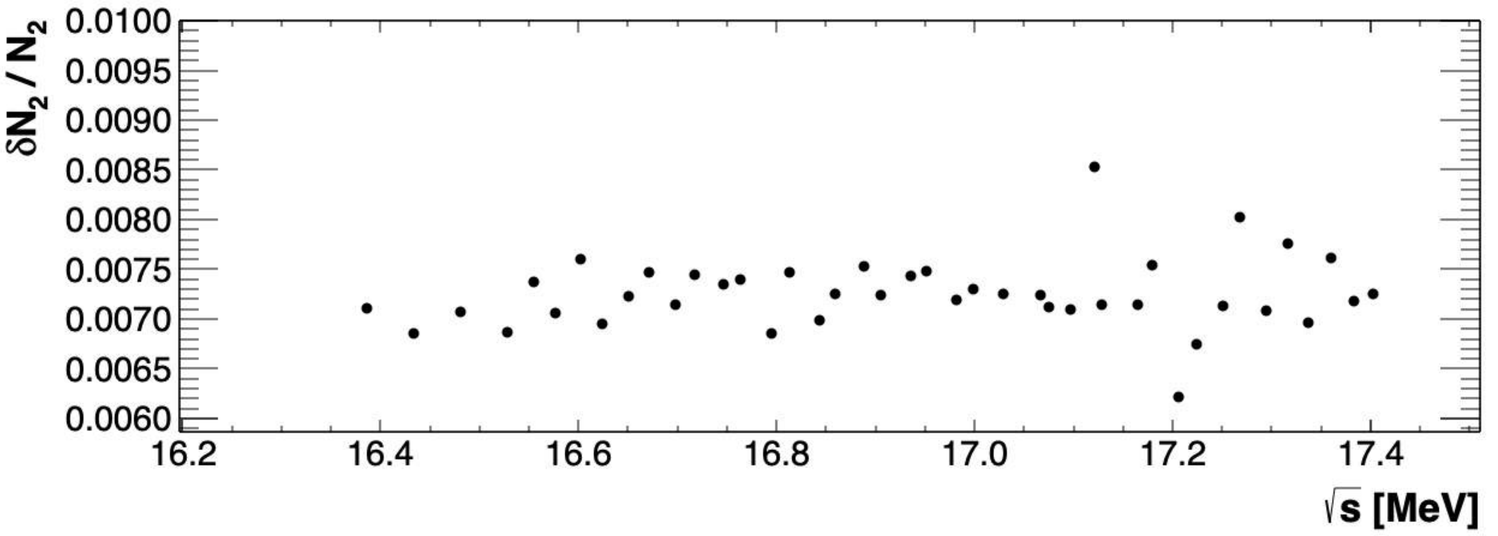
$N_2(s)$ over Run III

~30k two Cluster events collected for each point

- Statistical error → dominant contribution to the uncorrelated systematics: **δN_2 ~0.6% up to 0.7%**
- Additional systematic uncertainty due to bkg subtraction: **δN_2 ~ 0.3%**

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

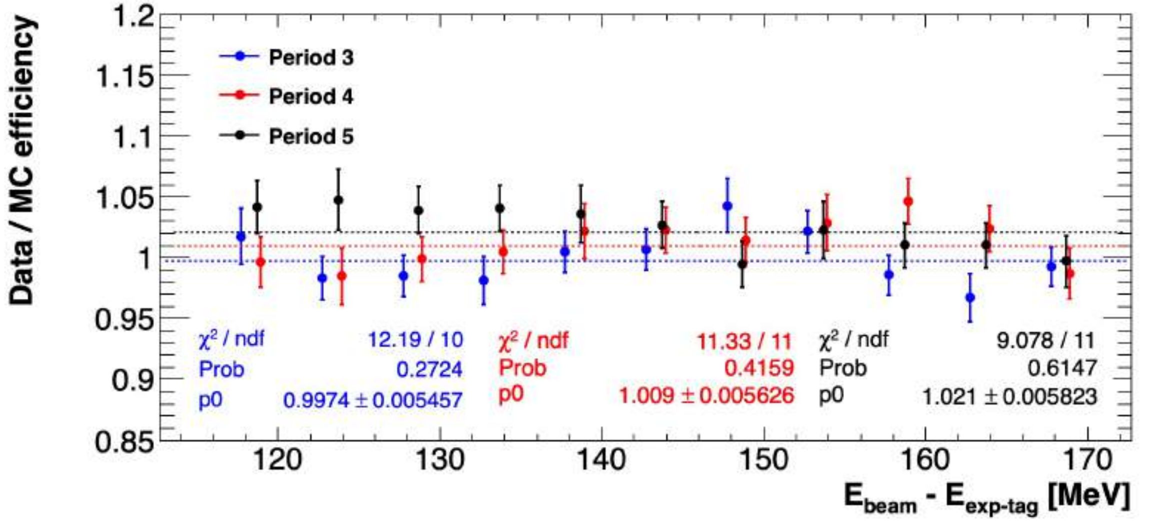


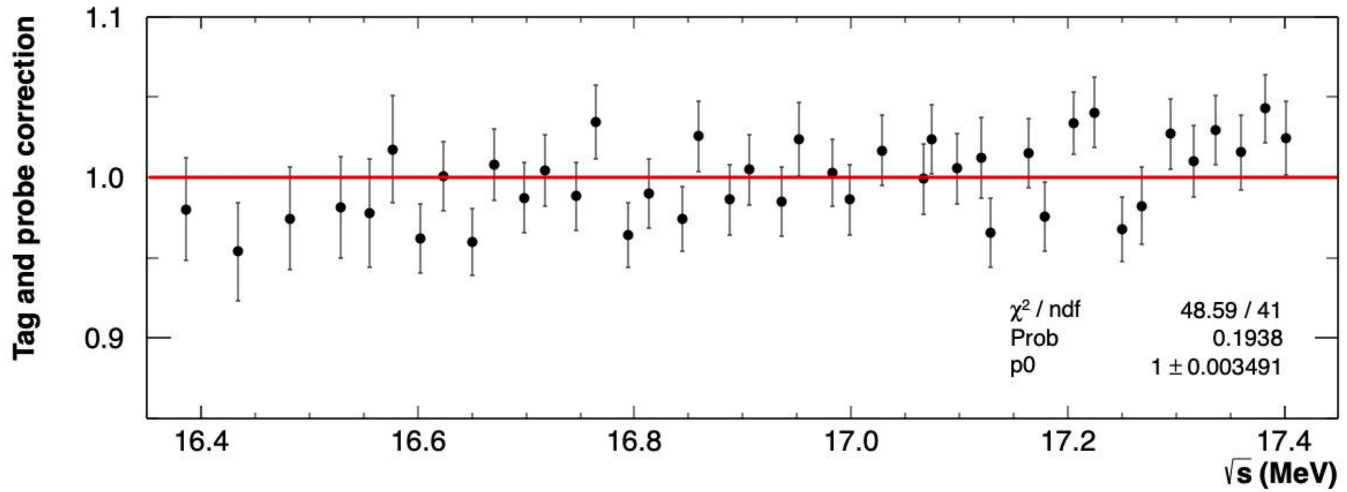


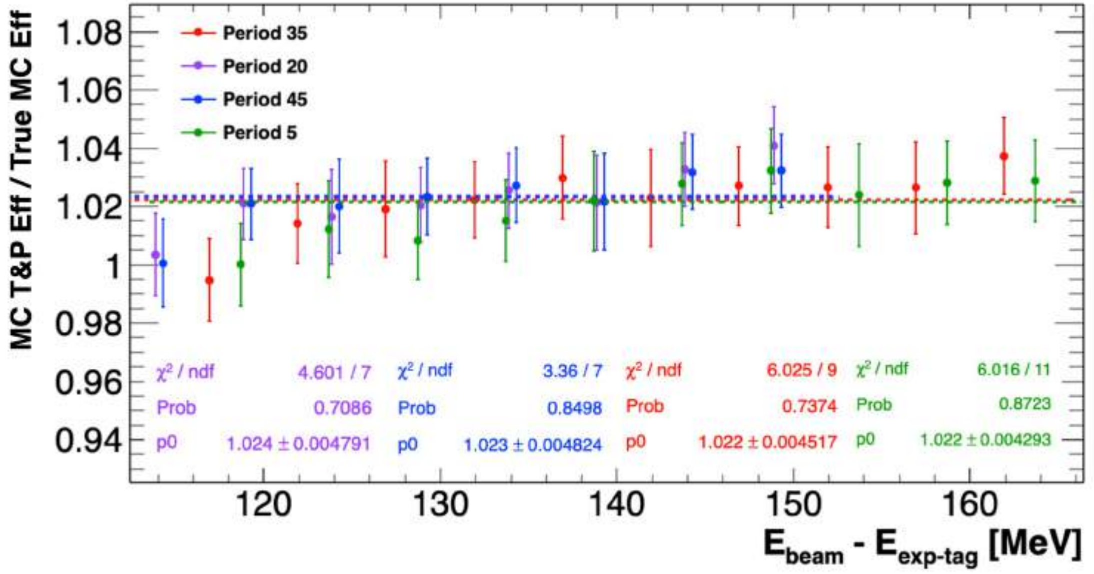
Tag and Probe - Results

ECAL reco efficiency evaluated using the **Tag and Probe** method

- Checked the stability of the Data/MC ratio as a function of the probe energy and azimuthal angle
- Checked the stability of the True MC/T&P MC efficiency ratio as a function of the probe energy
- **Evaluated the T&P correction** (meaned over the cluster energies) **along the whole data-taking**
- Bkg subtraction at tag level dominates the statistical-systematic error → **δB = 0.35%**

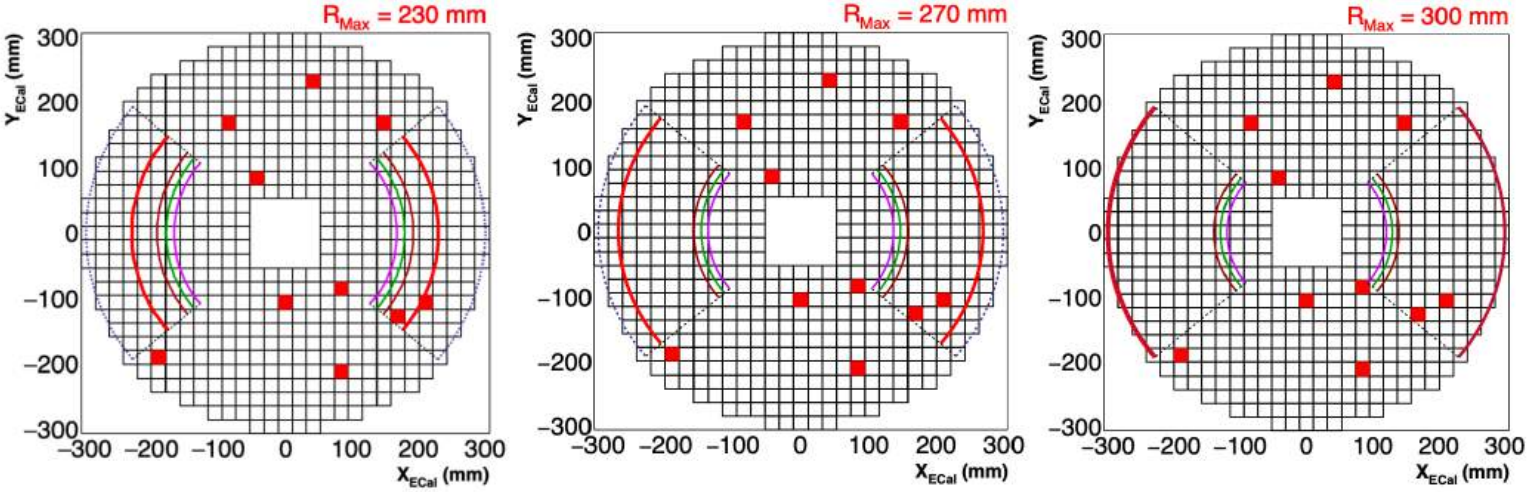


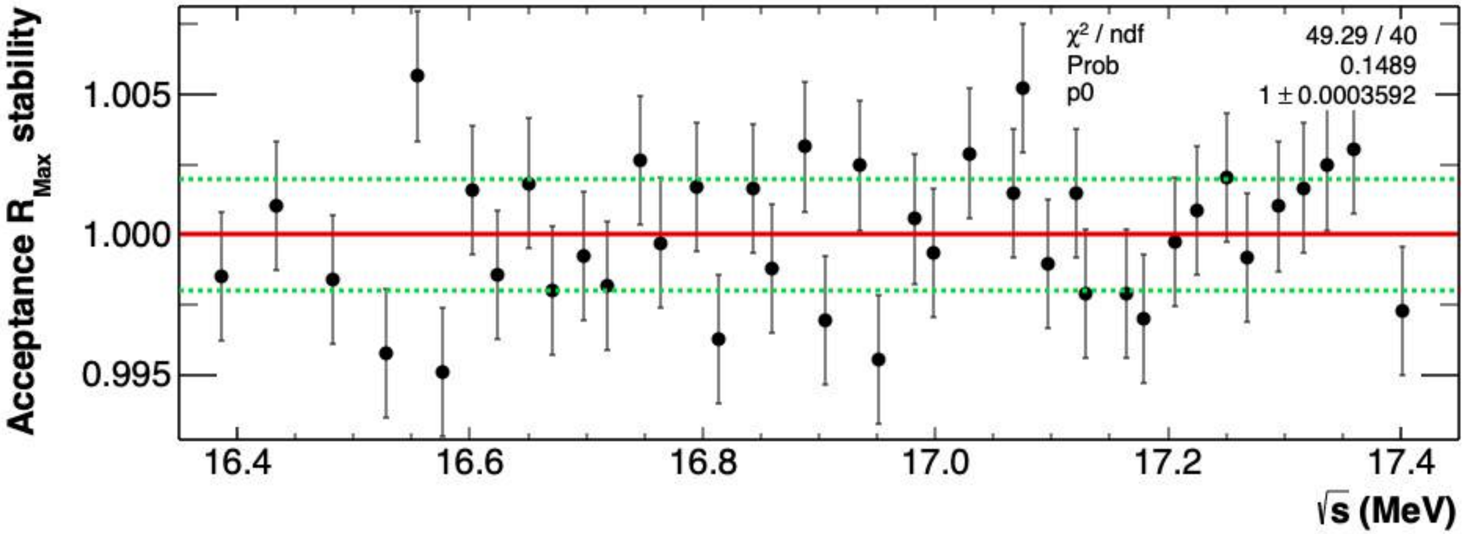




Radial cut stability

- Check if the MC and data yields are stable wrt Radial cuts ($R_{Max} \rightarrow R_{Min}$) to estimate edge effects and leakage
- We varied R_{Max} by $\pm$ 2 ECal cells around nominal cut of 270 mm → reached 230 and 300 mm
- **Yield variation:** -5% , 3% → fitted with a constant and extracted a **0.04% uncorrelated error**
- Stability is observed within a coverage band of $\pm$ 0.2%, used as additional correlated systematic error on **B(s)**

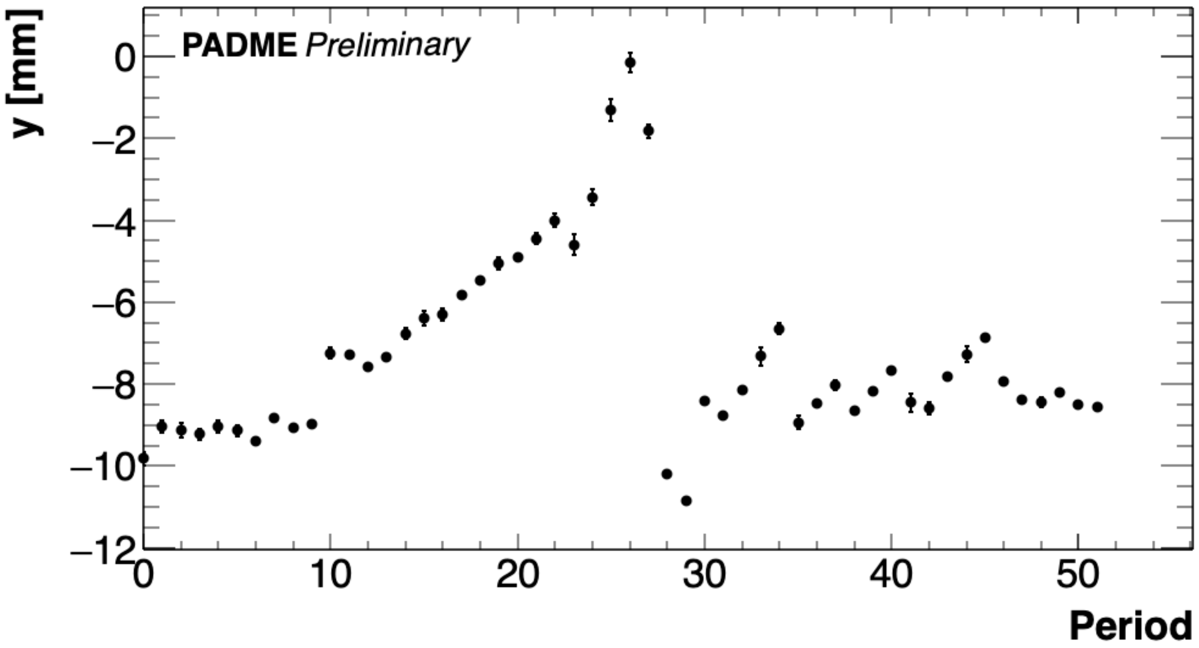


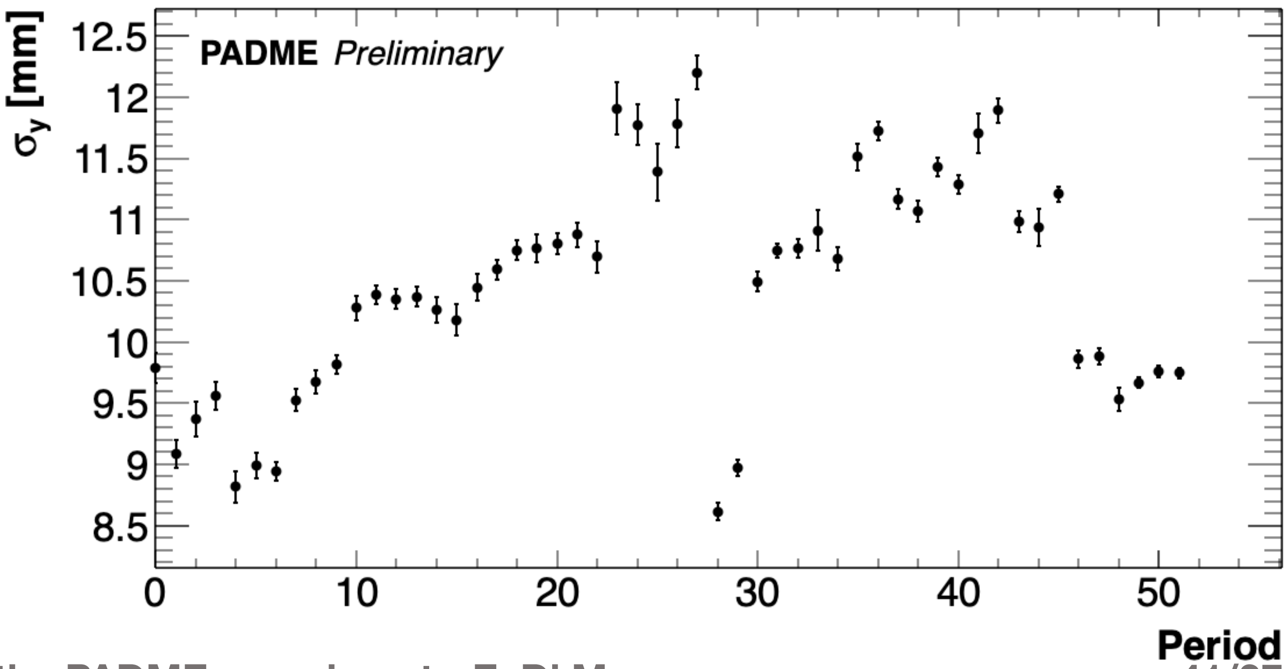


Flux MC simulation in Run 3

- TimePix3 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 → effect sensible to beam-Y variations
- Beam spot from TimePix3 is not available for all the periods → used the COG instead considering the TimePix3-ECAL offsets and the intrinsic difference in resolution

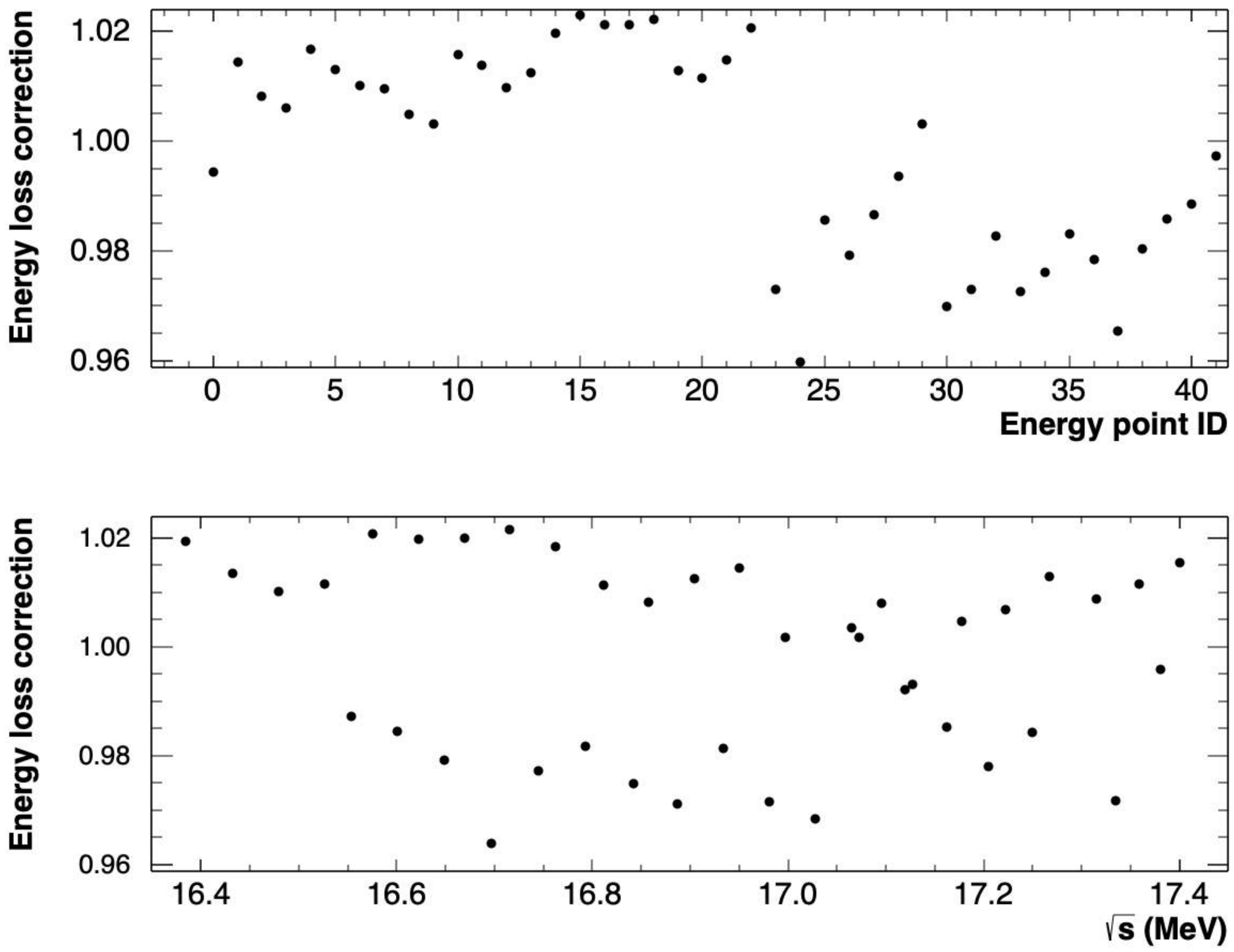
MC inputs





PbGl energy loss during Run 3

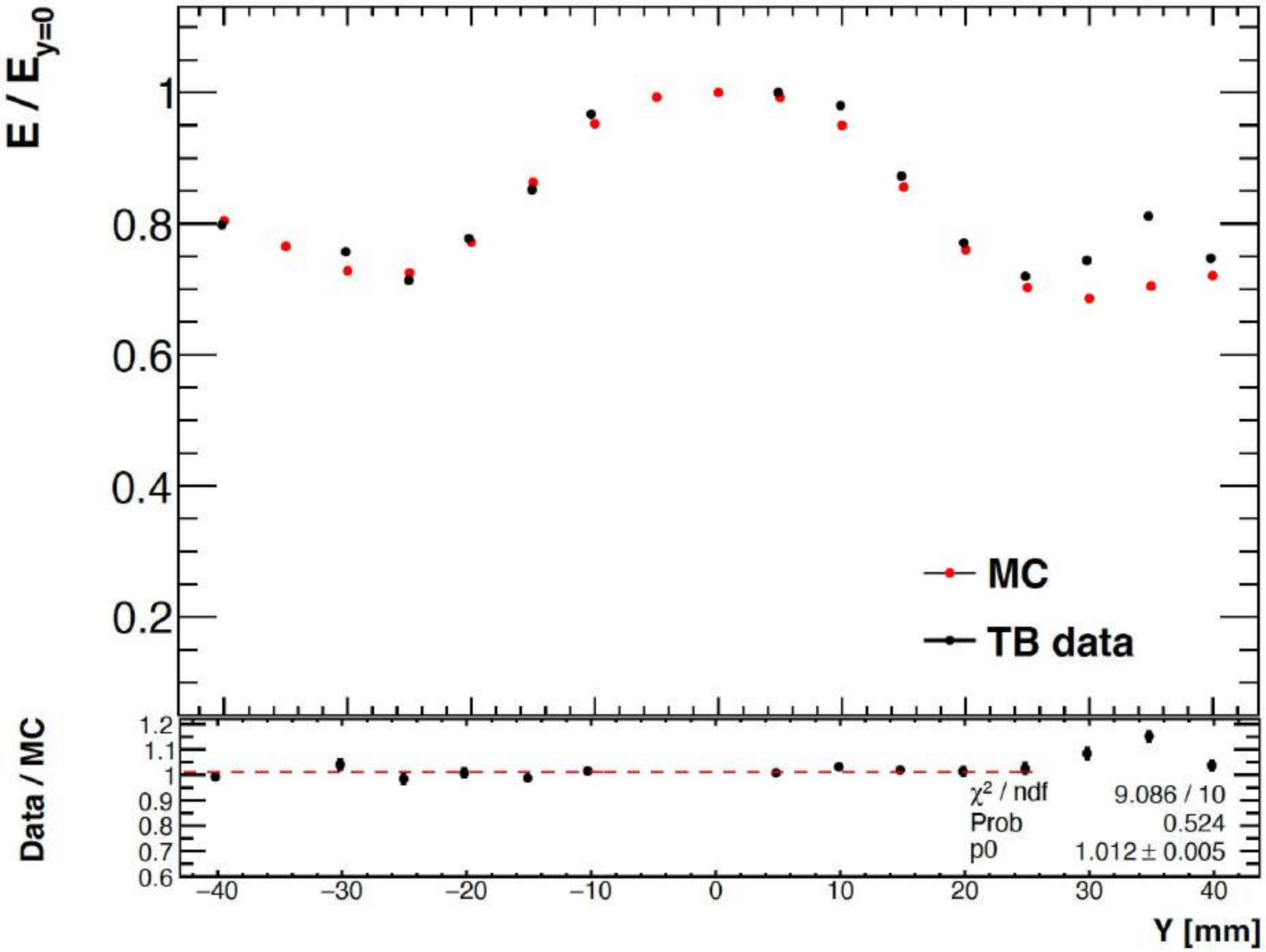
- **Significant period-by-period correction variation: -4% to +2%**
- MC derivation → data needed to compare and validate



Test beam validation

How much do we trust the correction?

- We had a dedicated test beam and took a Y scan at Leadglass level. Then we tried to replicate the Y scan with the MC simulation
- Good data/MC agreement in the region where Run III beam scanned
- **1.2% overall scale correction** (included in the $g_R(s)$ scale) with a 0.5% correlated error



Radiation damage

- Throughout Run 3 a total of 70x10^{10} PoT (of ~ 300 MeV each) has passed though the PbGl block → 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
- Used of some proxy variables to understand the level of the LY loss: Q x-target, <E-ECal>, period multiplets

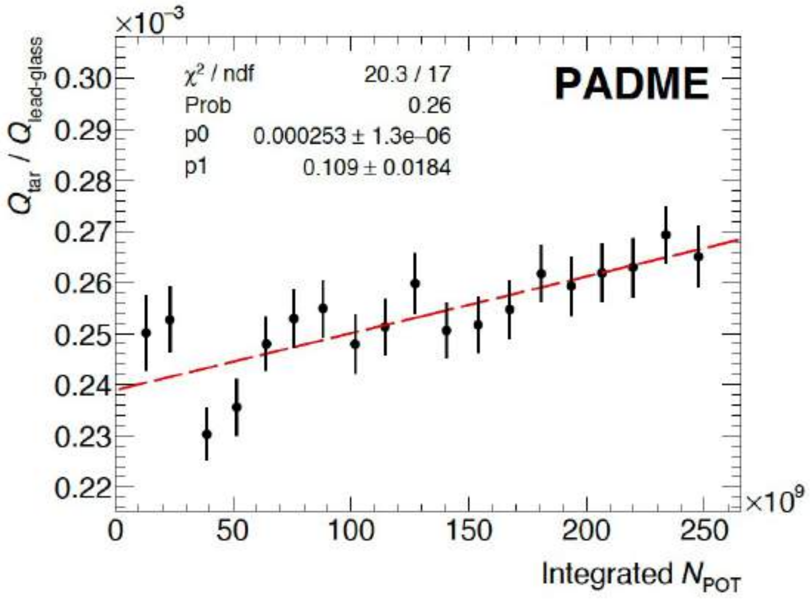
Quantity	$PWO:R^{3+}$	SF5 (PbO:50%)	SF6 (PbO:75%)
Density [g cm^{-3}]	8.28	4.07	5.19
Radiation length X_0 [cm]	0.89	2.55	1.69
Index of refraction	2.2	1.67	1.81
Cutoff in T [nm]	320	340	360
Hygroscopicity	No	No	No
Melting point [°C]	1123	442	455
Radiation-hardness [rad]	10^{7-8}	10^{3-4}	10^{2-3}

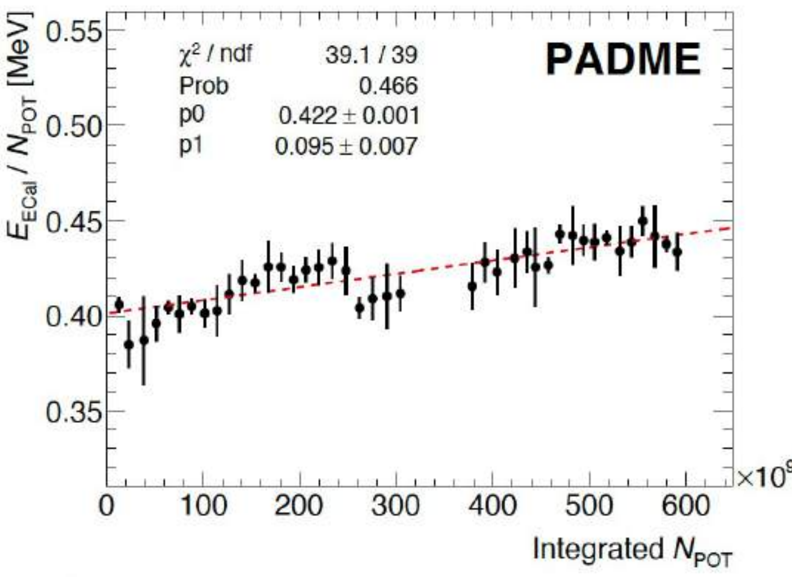
SF57 PbO concentration ~ 75%

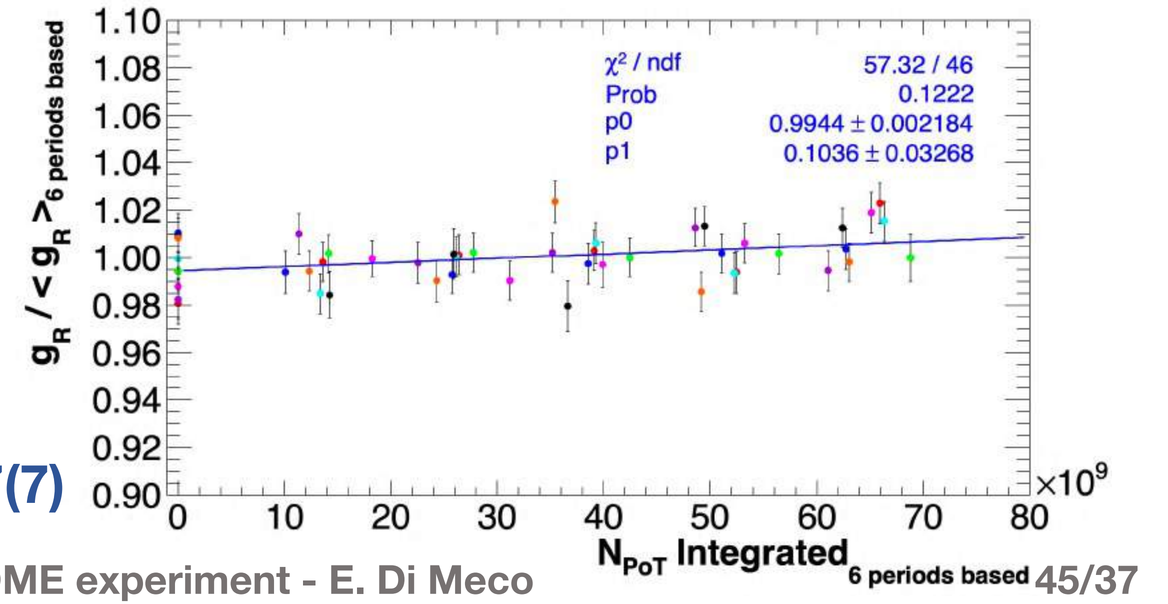
Radiation damage - 2

Proof of loss of LY:

- Target X strips are way more sensible than Y → 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 separated every 6 periods and scaled to their average a compatible slope is found from simultaneous fits



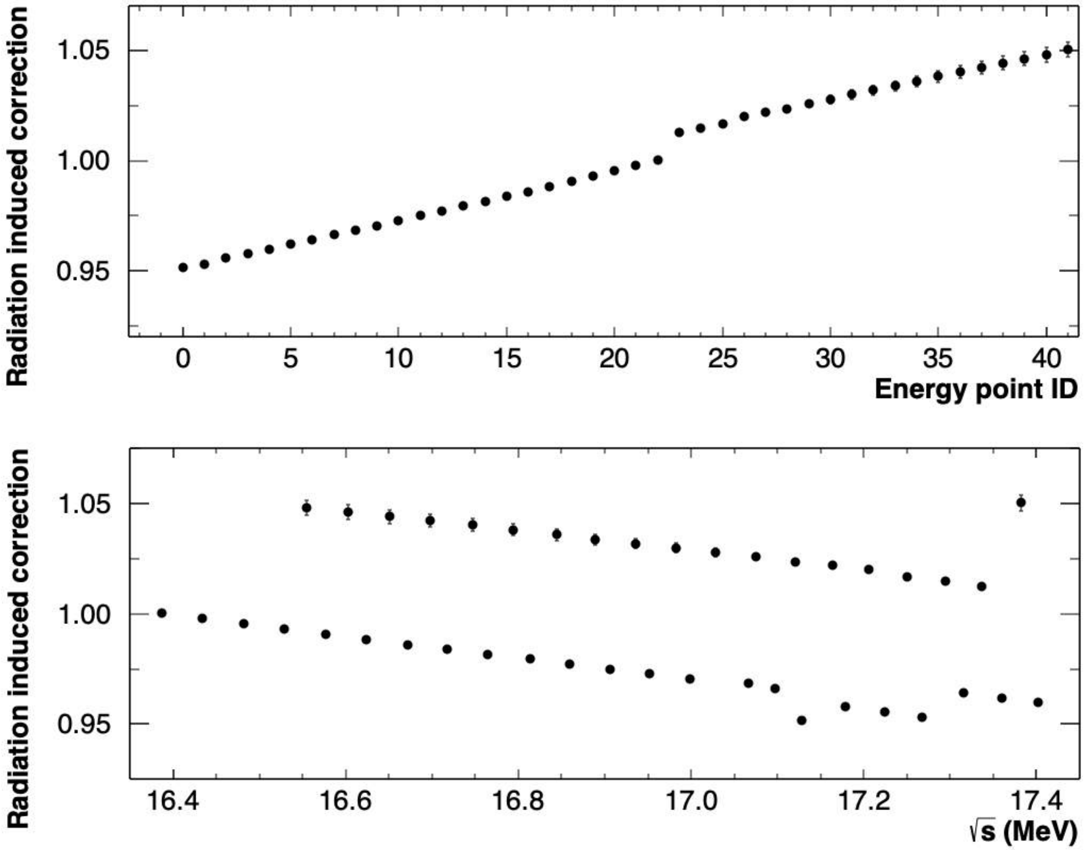




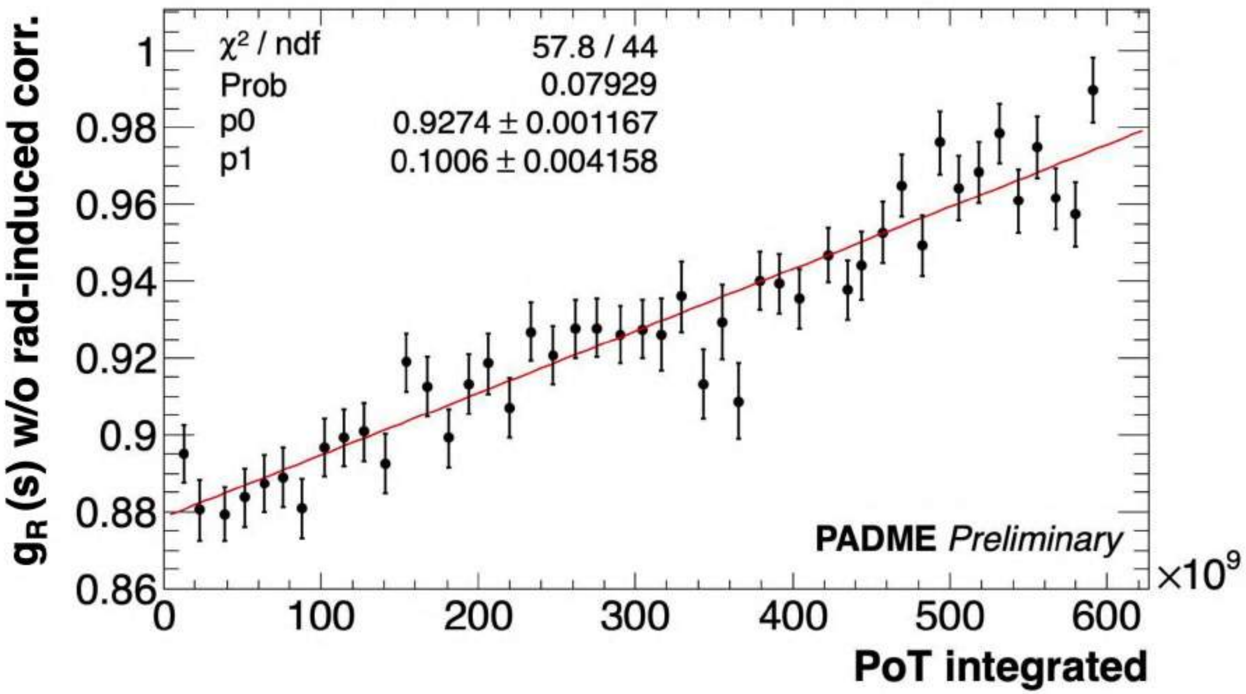
PbGl yield decreases with relative PoT slope of 0.097(7)

Radiation damage – 3

- **PbGl yield decreases with relative PoT slope of 0.097(7)**
- Constant term uncertainty of 0.3% added as correlated error
- Slope error included in PoT uncorrelated uncertainty → 0.35%
- Checked the slope value on $g_R(s)$ after the unblinding → totally compatible results

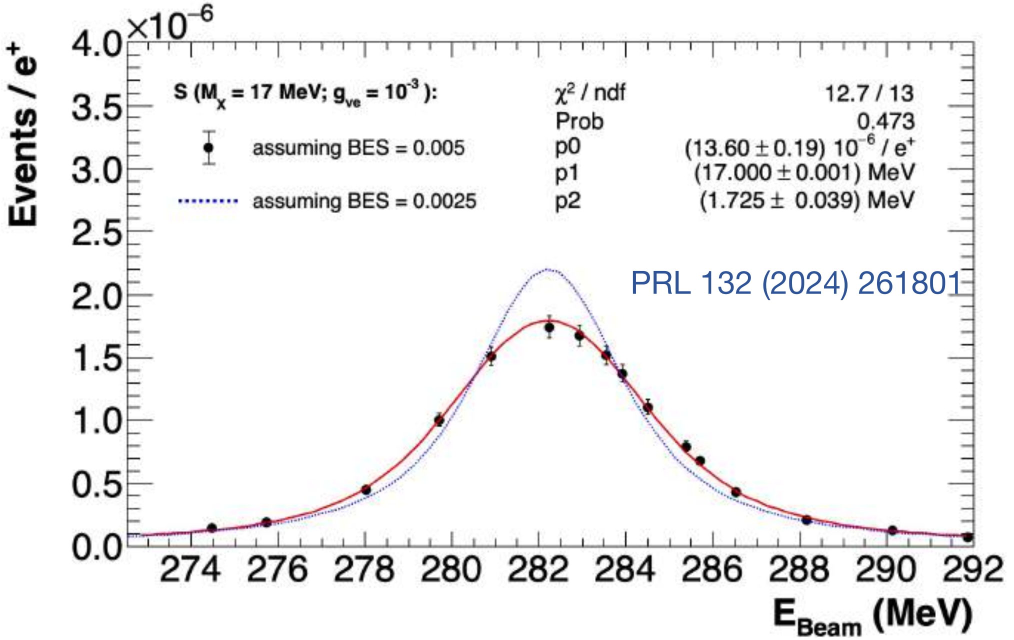


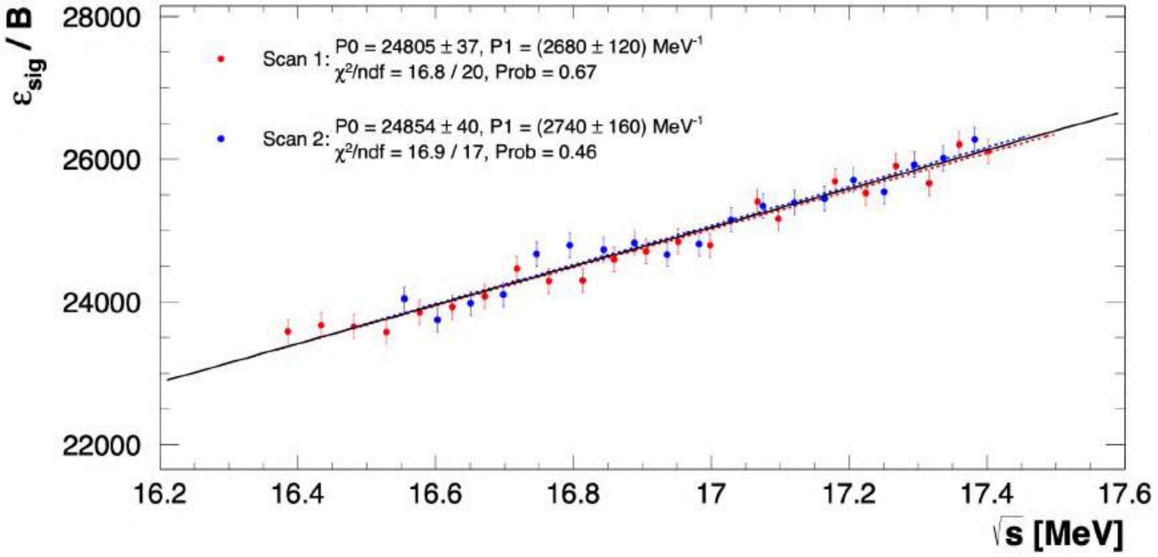
Post unblinding



Signal shape and ε(s)/B

- Atomic electron motion changes significantly the resonance shape → not anymore just a gaussian with σ equal to the BES
- 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 signal efficiency determined from MC:
  - Large cancellation of systematics seen using **ε/B**
- Fit ε(s)/B(s) with a straight line, include fit parameters as nuisances:
  - **Errors:** δP0/P0 ~ 0.1%, δP1/P1 = 3%, correlation = -2.5%



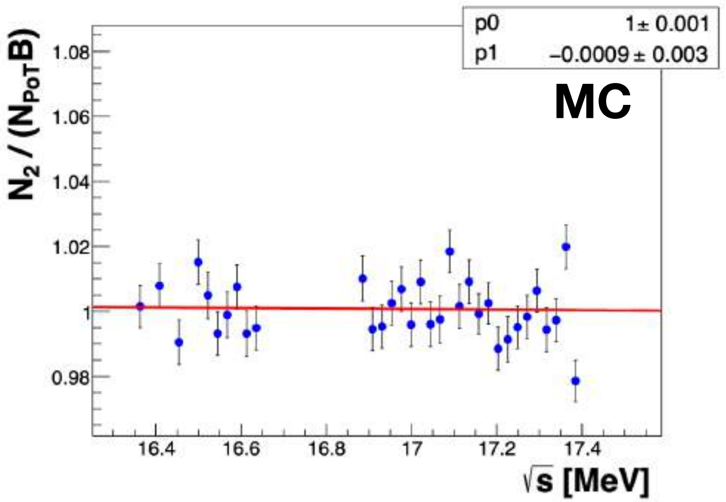


Blind-unblinding procedure

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 scar**
- Define the masked periods by **optimizing the probability of a linear fit in $s^{1/2}$**

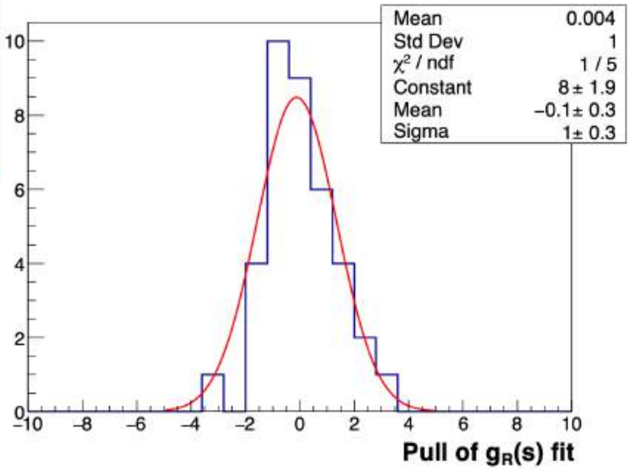
1. Threshold on the χ^2 fit in side-band is $P(\chi^2) = 20\%$, corresponding to reject 10% of the times
2. If ✅, check if the fit pulls are gaussian
3. If ✅, check if a straight-line fit of the pulls has no slope in $s^{1/2}$
4. If ✅, check if constant term and slope of $g_R(s)$ are within two sigma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

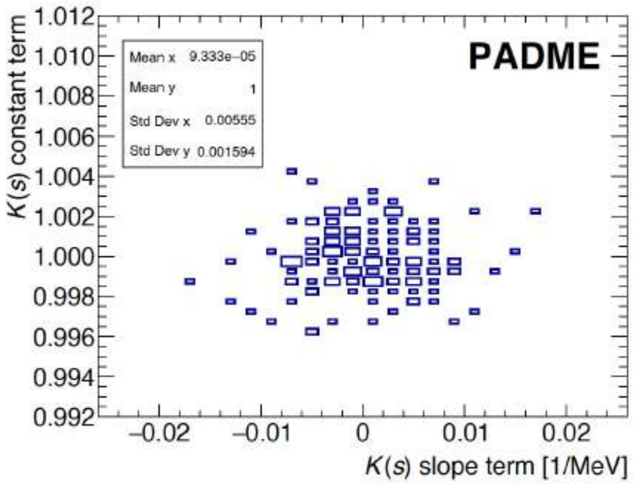


Successfully applied:

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}

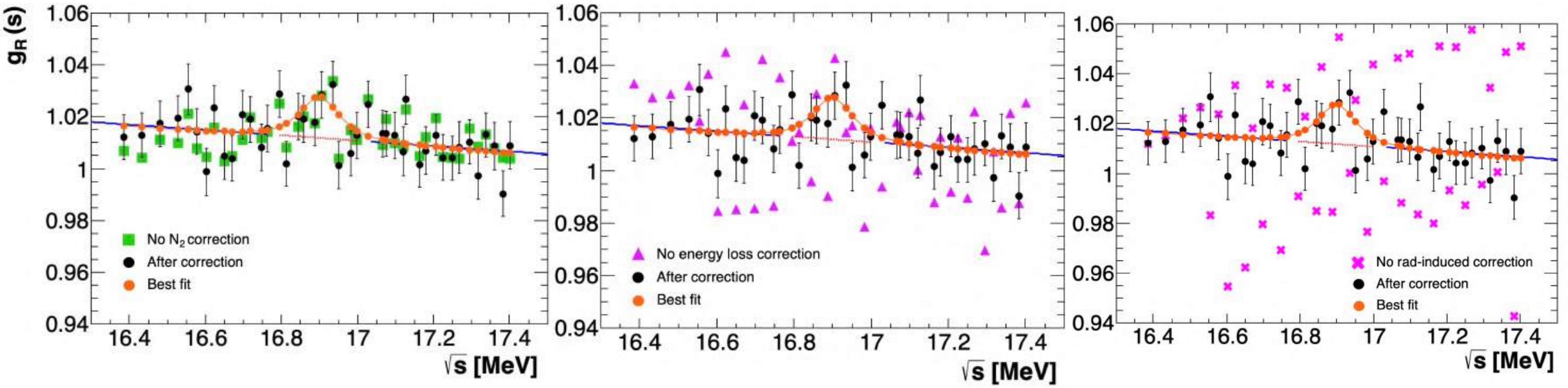
Ready to unblind





Box opening – Check of corrections

After box opening, check on the impact of each correction to the result → each rescaled to their mean value to match the fully-corrected $g_R(s)$



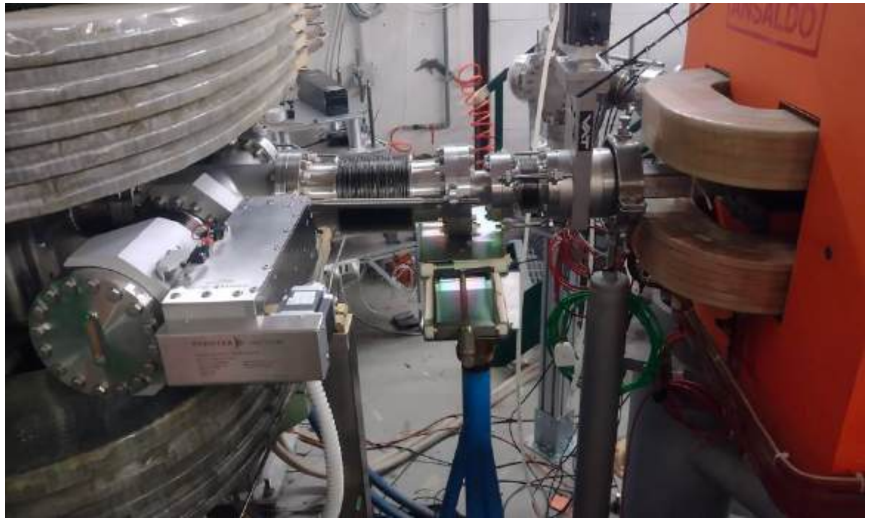
Run IV improvements overview

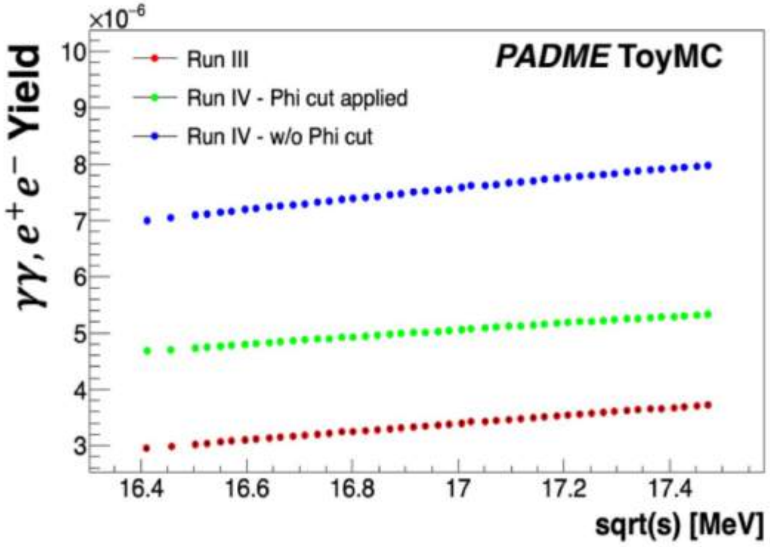
Run III result is not conclusive → need to collect more data

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

- **Diamond target** position moved downstream by ~30 cm
- Passive material removed and PADME Magnet fully degaussed → $B_{PADME} < 1$ G
- Beam stable in the central position along the whole data taking
  → To minimize lateral leakage on the beam catcher
- **Led pulser** Tektronix AFG3101 to control the radiation induced loss
  - Independent trigger included in the DAQ
  - A second PbGl block installed (out of the acceptance and only acquiring the led trigger)
  - Online PbGl response renormalized to the not-fired-block
  - Reference for light yield response almost online

Diamond target



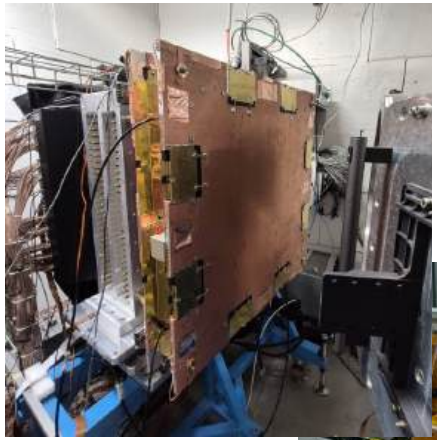


Run IV improvements overview

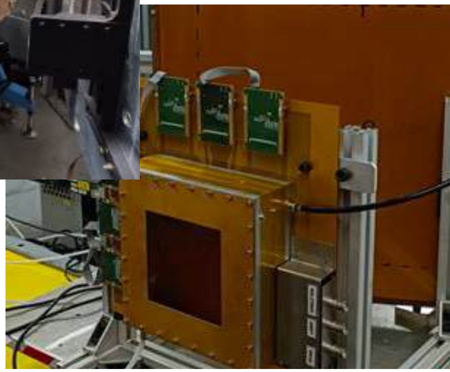
New detectors:

- PadMMe Micromegas chamber replaced the ETag:
  - e/γ discrimination → possible normalization to $e^+e^- \rightarrow \gamma\gamma$ process
  - Spatial resolution ~ 350 μm → angle disentanglement
  - Multitrack events can be collected
  - Beam spot monitor → Already implemented in the Run IV online monitor
- TMM Micromegas replace the TimePix3 beam monitor:
  - Greater active area wrt TimePix3 and less passive material budget
  - Beam shape and spot monitor

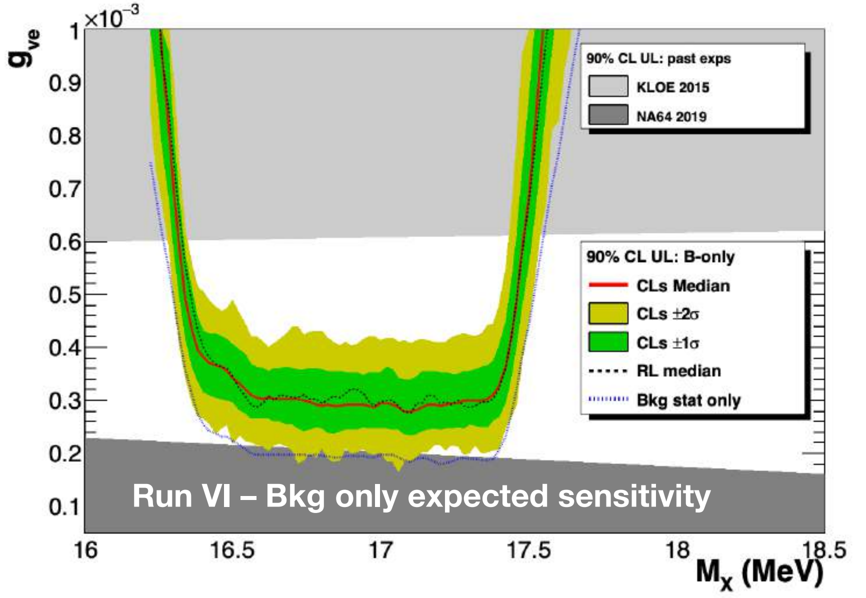
PadMMe



TMM



Source	Uncertainty [%]		Improvement
	Run III	Run IV	
N_2	0.6	0.3	New target position → acceptance increased
B	0.54	0.3	PadMMe → ee/$\gamma\gamma$ discrimination + better angular-momentum resolution
N_{PoT}	0.35	0.3	3 different beam spot monitor (target-PadMMe-TMM) + online LG calibration system
TOTAL	**0.88**	**0.5**	

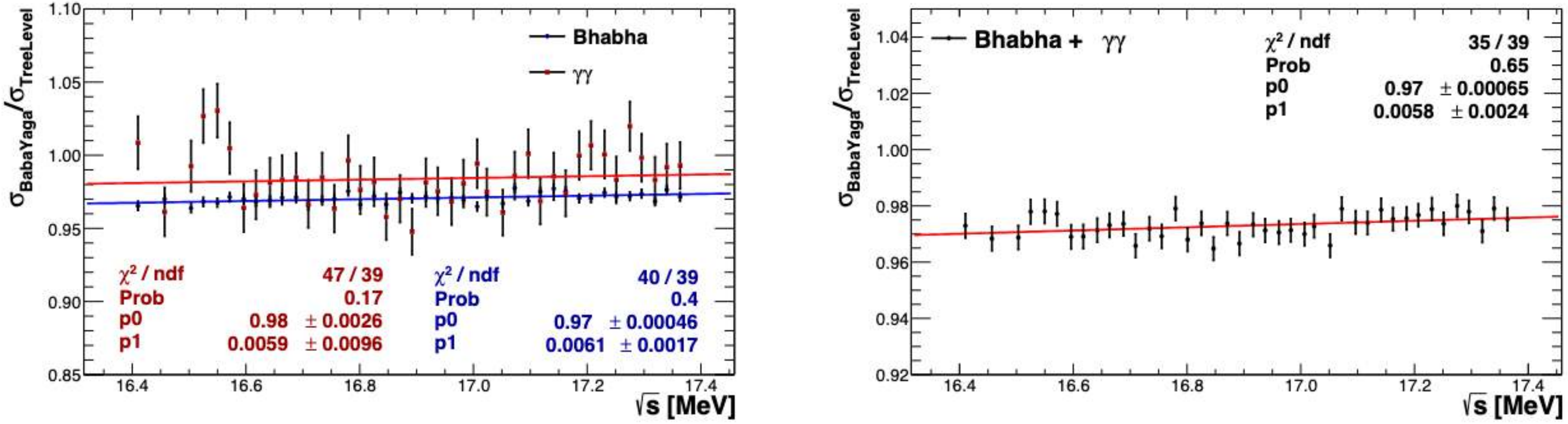


My direct contributions:

- **Run III**
  - **Detectors:**
    - ECal cells intercalibration and absolute calibrations
    - ETag performance evaluations
    - TimePix3 run-by-run beam spot evaluations
  - **Analysis:**
    - **N_2, B, N_{PoT}** observable measurements and systematics evaluations
    - Developed True MC information at ECal level and T&P procedure
    - Implemented flux corrections and background removals
- **Run IV**
  - ECAL system coordinator for Run IV data-taking
  - 3 weeks period as Run Coordinator
  - Managing ECAL only analysis
  - In charge of Run IV MC software and productions

Possible K(s) scale effects

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



Possible offset → -2.8% @ 16.92 MeV
Possible slope with $\sqrt{s}$ → -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) → no effect on ε(s)

CLs Method

The S+B likelihood depends on the X17 MX and gve as well as on a set of nuisance parameters θ.

$$L(\text{data}|M_X, g_{ve}, \theta) = \left(\prod_{s_i} \frac{1}{\sqrt{2\pi\sigma^2_{g_R(s_i)}}} e^{-\frac{(g_R(s_i) - g_{R,\exp}(s_i))^2}{2\sigma^2_{g_R(s_i)}}} \right) \times P(\theta),$$

P(θ): probability density associated with a particular configuration of nuisance parameters. s_i runs over the energy points

For fixed values of MX and gve, the test statistic employed is the "Tevatron-like" version

$$Q(M_X, g_{ve}) = -2 \ln \frac{L_{\max}(s+b)}{L_{\max}(b)} = -2 \ln \frac{L(\text{data} \mid M_X, g_{ve}, \hat{\theta}_{(M_X, g_{ve})})}{L(\text{data} \mid \hat{\theta})},$$

For each pair (MX, gve), sets of toy MC pseudo-experiments are used to compute the median observed test statistic Q_{obs}(MX, gve) together with the p-values p_s(MX, gve) and p_b:

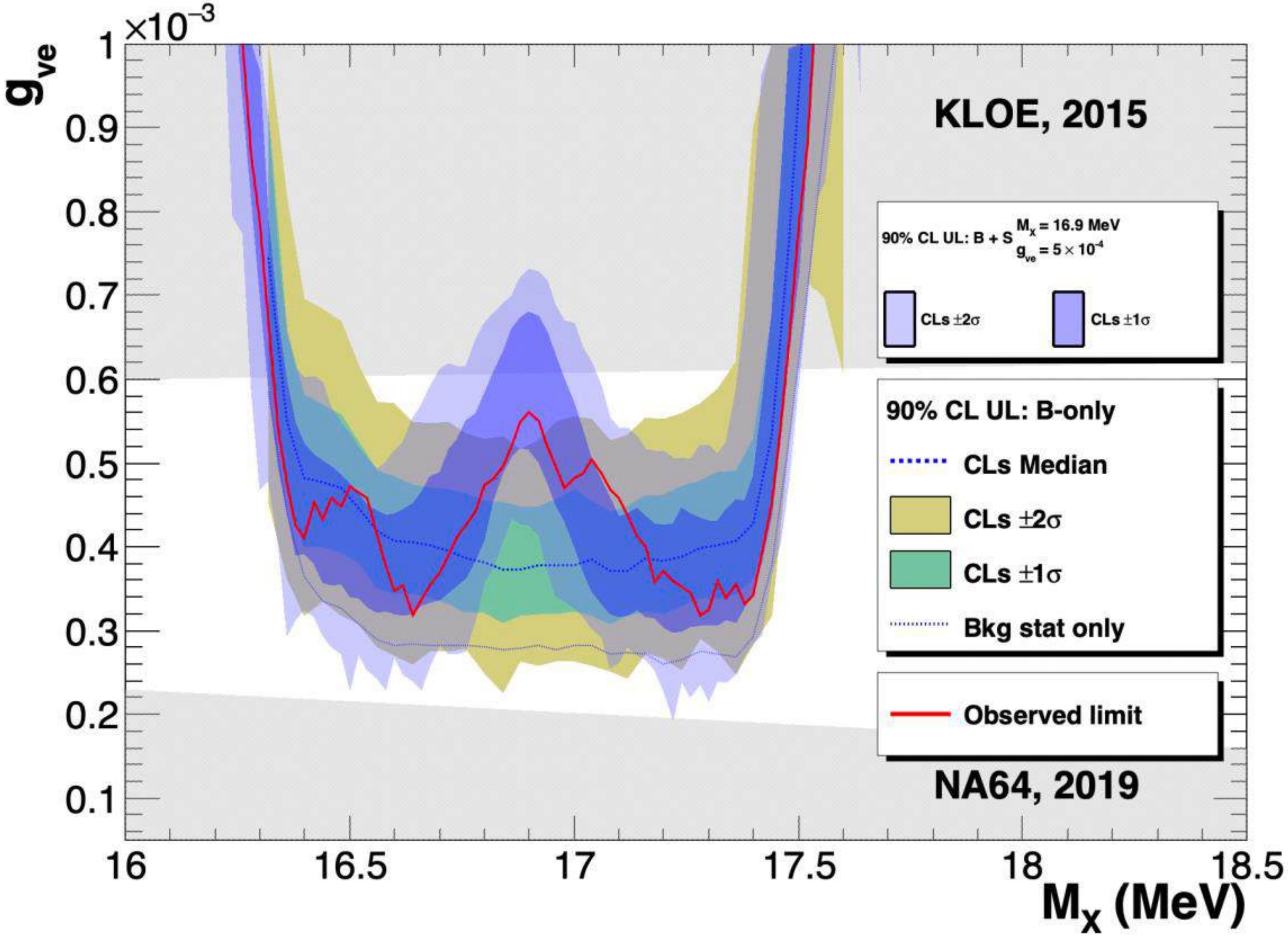
$$p_s(M_X, g_{ve}) = P\Big(Q(M_X, g_{ve}) \geq Q^{\text{obs}}(M_X, g_{ve})\Big) \qquad 1 - p_b = P\Big(Q(M_X, g_{ve}) \geq Q^{\text{obs}}(M_X, g_{ve})\Big),$$

The confidence level is then defined as $CL_s(M_X, g_{ve}) = \frac{p_s(M_X, g_{ve})}{1 - p_b}.$ For a given mass MX, values of gve are excluded at confidence level (1 – α) whenever $CL_s(M_X, g_{ve}) < \alpha.$

Nuisance are quantities that are usually not of primary physical interest, but whose uncertainties influence the prediction of the measured observables they encode systematic effects that must be propagated through the likelihood evaluation

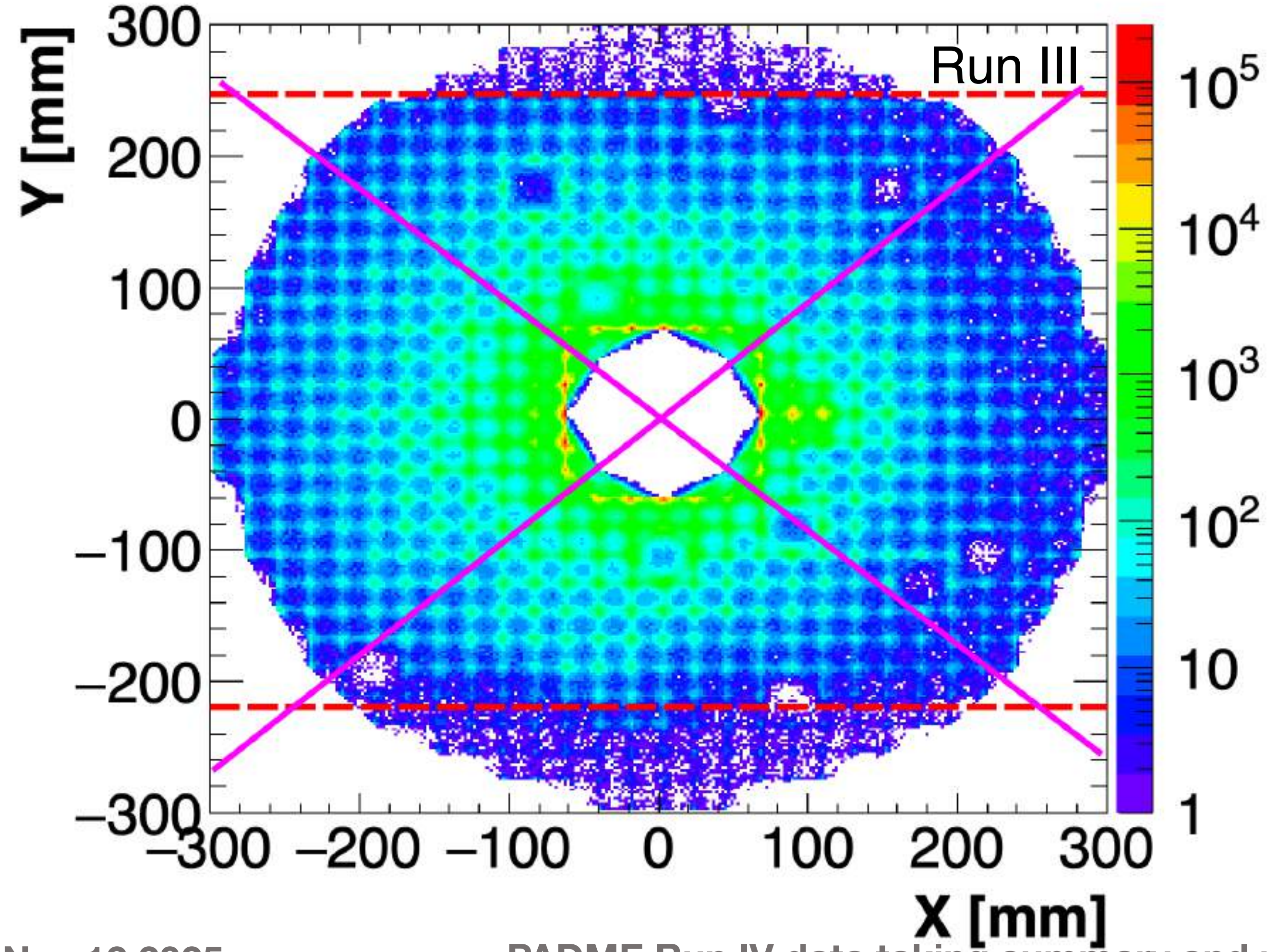
Box opening - Upper limits check

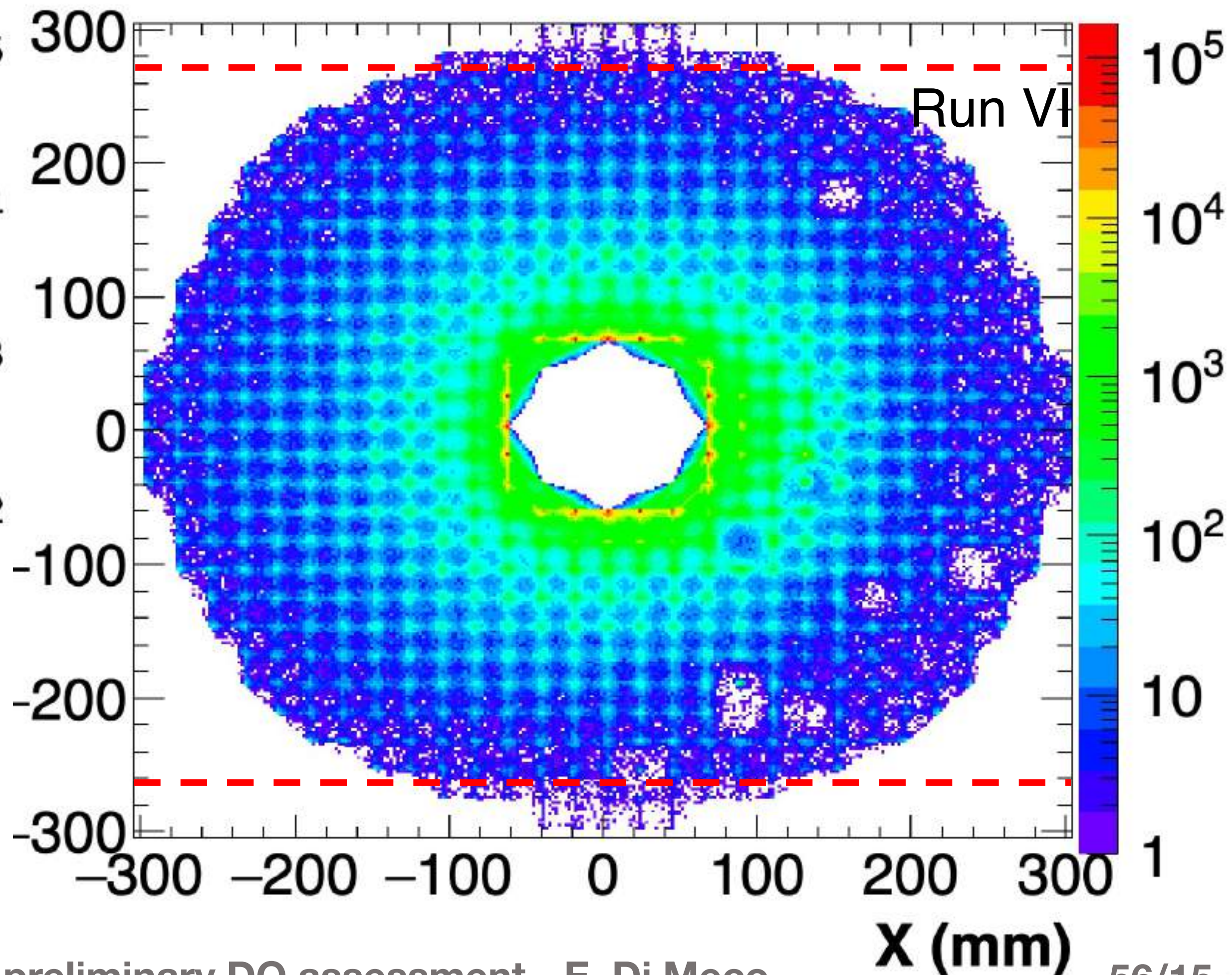
Check on the UL behaviour comparing the **bkg-only** hypothesis with the **B+S**(m= 16.9 MeV, g_{ve} = 5x10^{-4})



Magnet shadow in Run IV

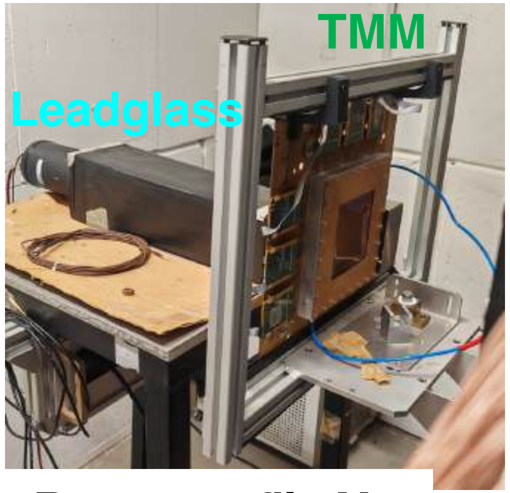
- Notably less pronounced magnet bore shadow effect → only the upper and last line of crystals and symmetric ✅
- Need to verify the effect on Tag and Probe (T&P) efficiency

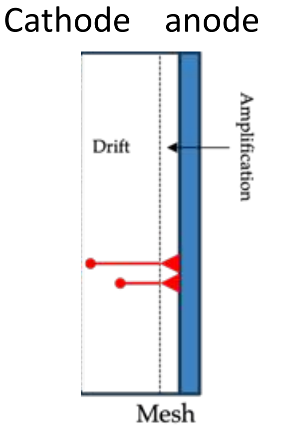




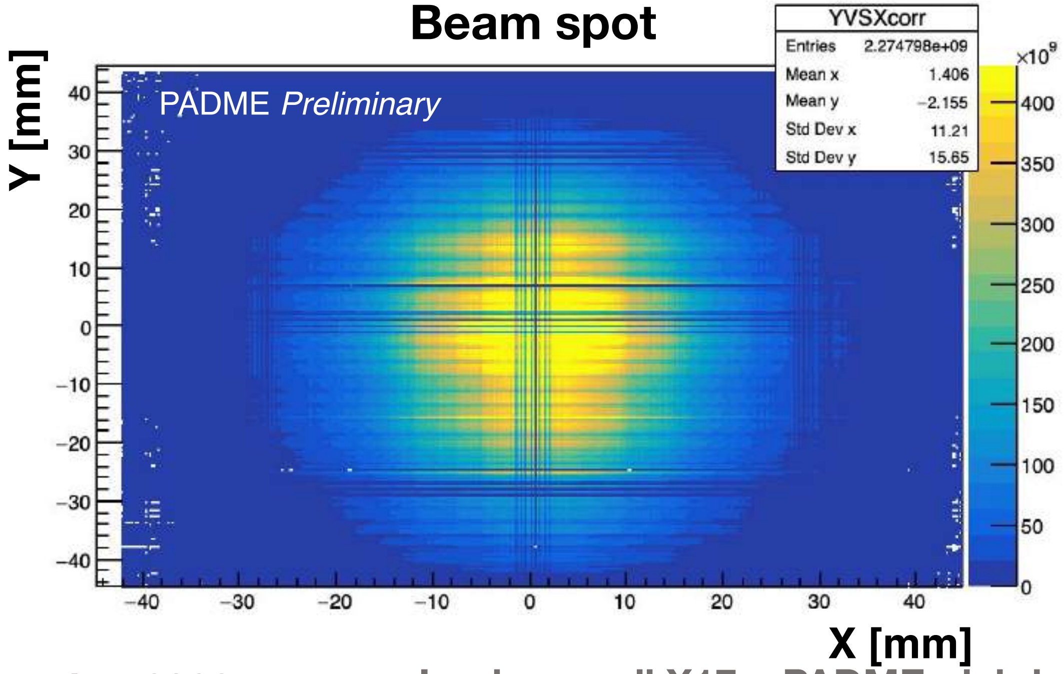
TMM – beam monitor detector

- A **10x10x5 cm^3 MicroMegas detector**:
  - Connected in series to the PadMMe - same gas mixture (Ar:CF4:Iso=88:10:2)
  - Readout: 6APVs
  - HV 350 V, Drift 300 V
  - Chamber placed in front of the LeadGlass
- Larger active area wrt TimePix and less passive material budget
- Beam spot and flux monitor
- Proper metrology alignment **not yet implemented**

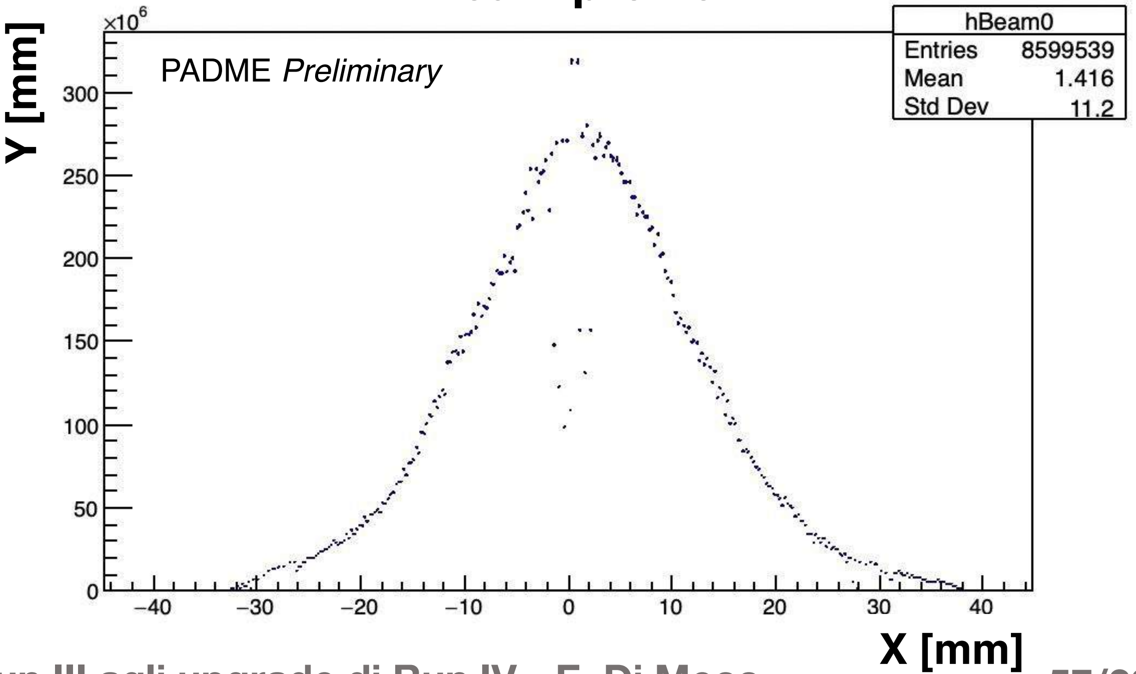




Beam spot

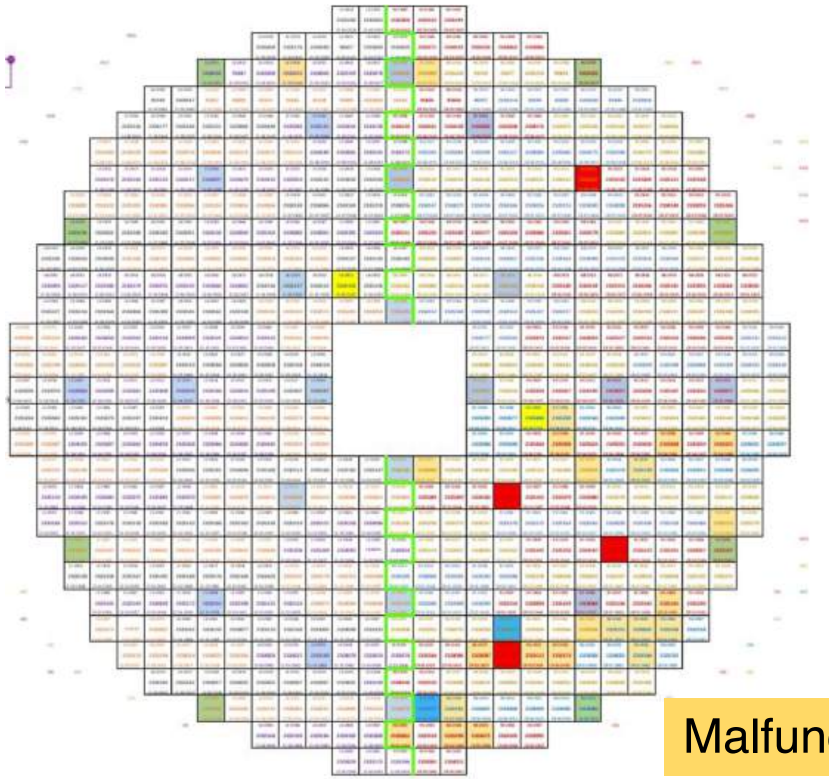


Beam profile X

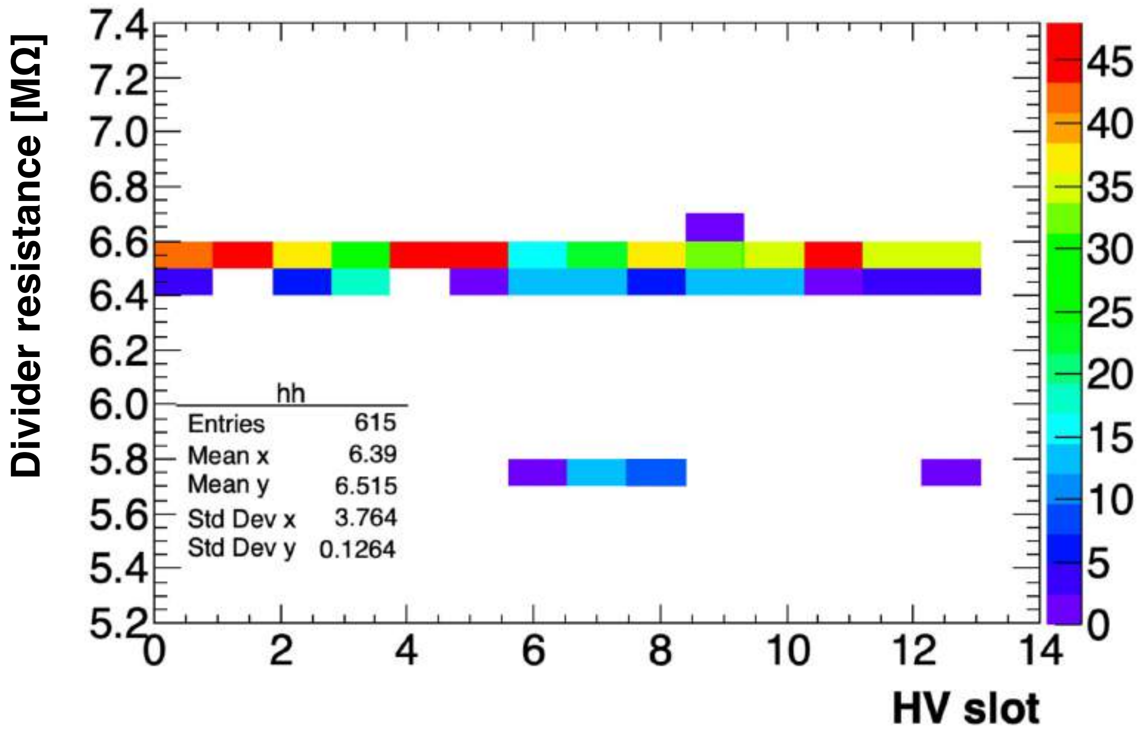


To keep in mind …

- ECal has several malfunctioning units probably due to HV failures → all in the bottom-right region
- Lower gain due to a short-circuit of one of the last dynodes capacitor → now at higher HV (1500 V vs typical ~1200 V)
- Not yet implemented an energy-point dependent recalibration of these units → we'll need a full cosmic ray analysis on all the dataset
- T&P does not show major problems for now, but we'll need to see how the MC behaves



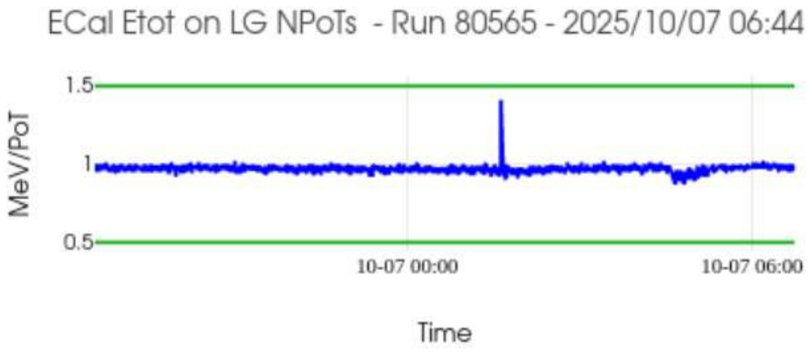
Malfunctioning units



Lead-glass LY monitoring

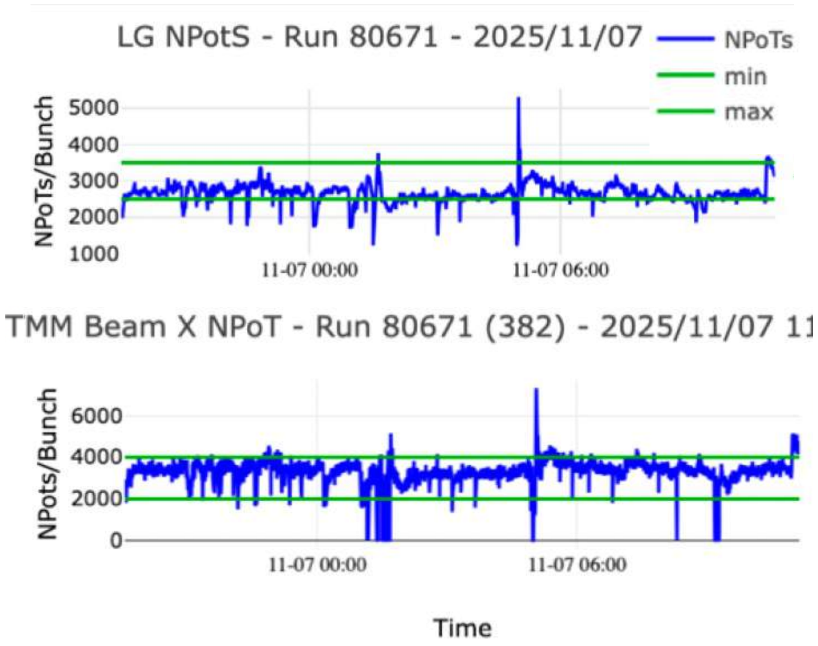
- During Run III a 10% LY loss was observed because of the integrated dose
- We expect some losses also in this case → this time we can monitor it closely with different observables reducing the error on the correction to be applied
- A dedicated setup was implemented with a second out-of-beam lead-glass and a special “LED” trigger coming from a pulsed off-beam LED-blue light split on both LG blocks

E_{ECAL}/ NPoT per bunch

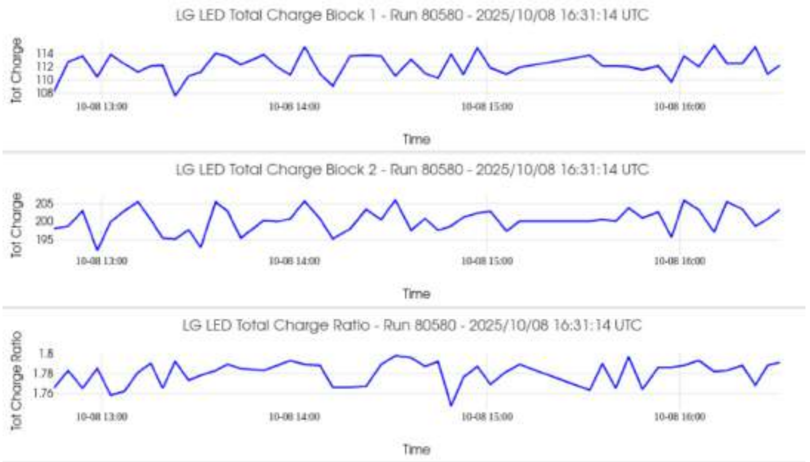


- Monitored to be as close to 1 as possible → indicator of the background in the ECal low radius regions

TMM charge



LED triggers ratio



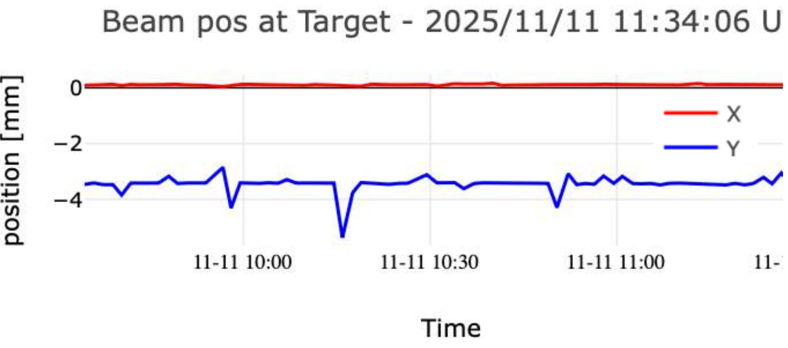
- Stable LED response in time
- Ratio to be compared throughout the whole Run IV

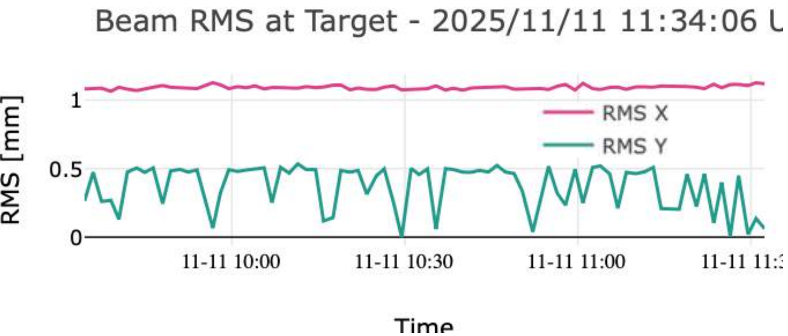
Position Monitoring

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

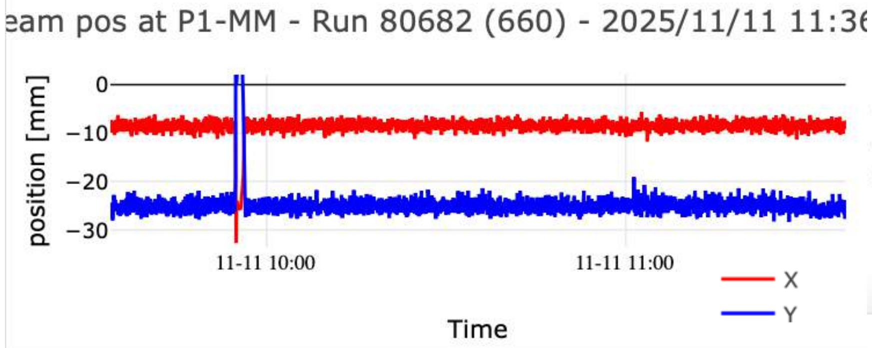
- Position variations might lead to systematic errors in the MC Bkg evaluation due to not well reproduced acceptances → kept under control in Run III but now also strictly monitored during the data-taking

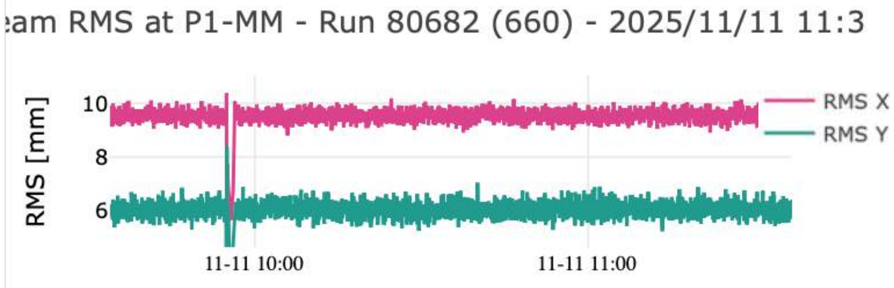
Target position



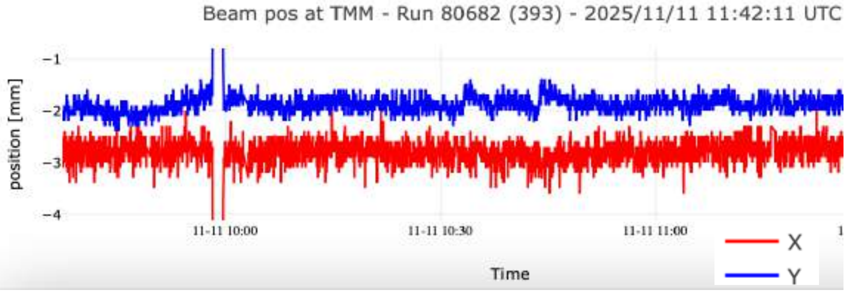


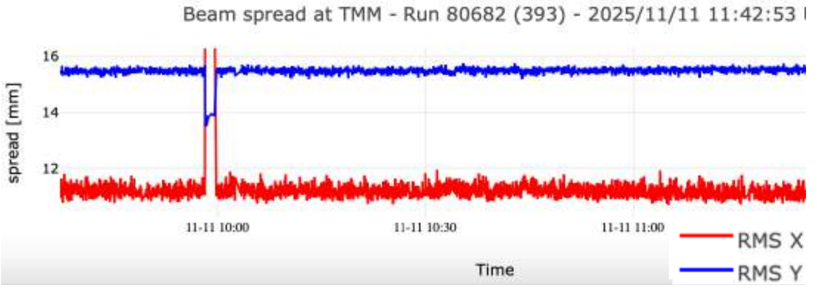
MM position





TMM position



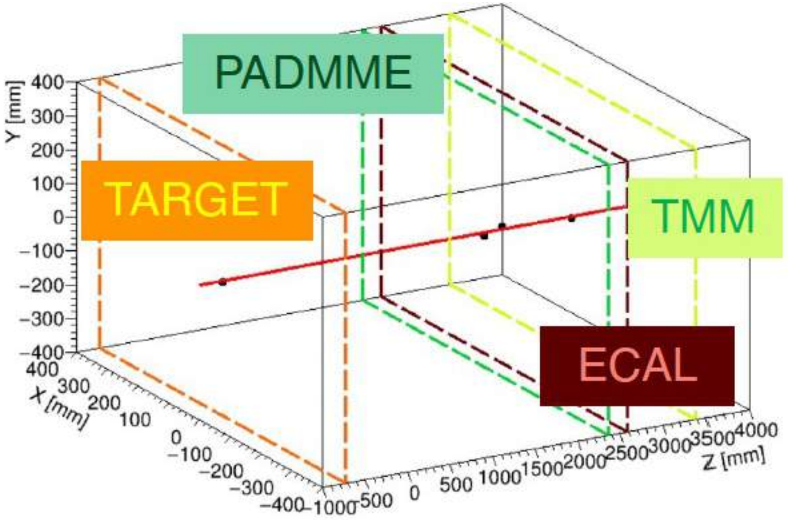


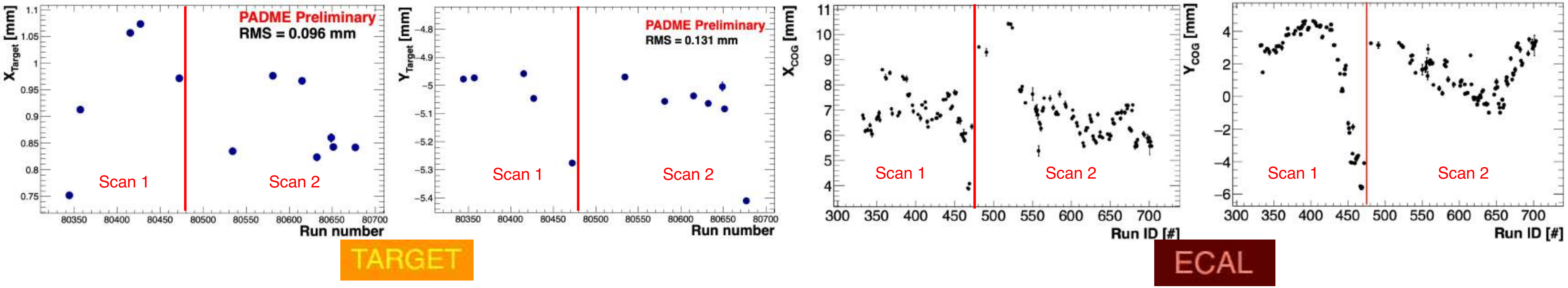
Beam conditions

Beam monitor at 4 different levels using different methods

- Aiming at measuring: position, angle, beam spread and beam divergence

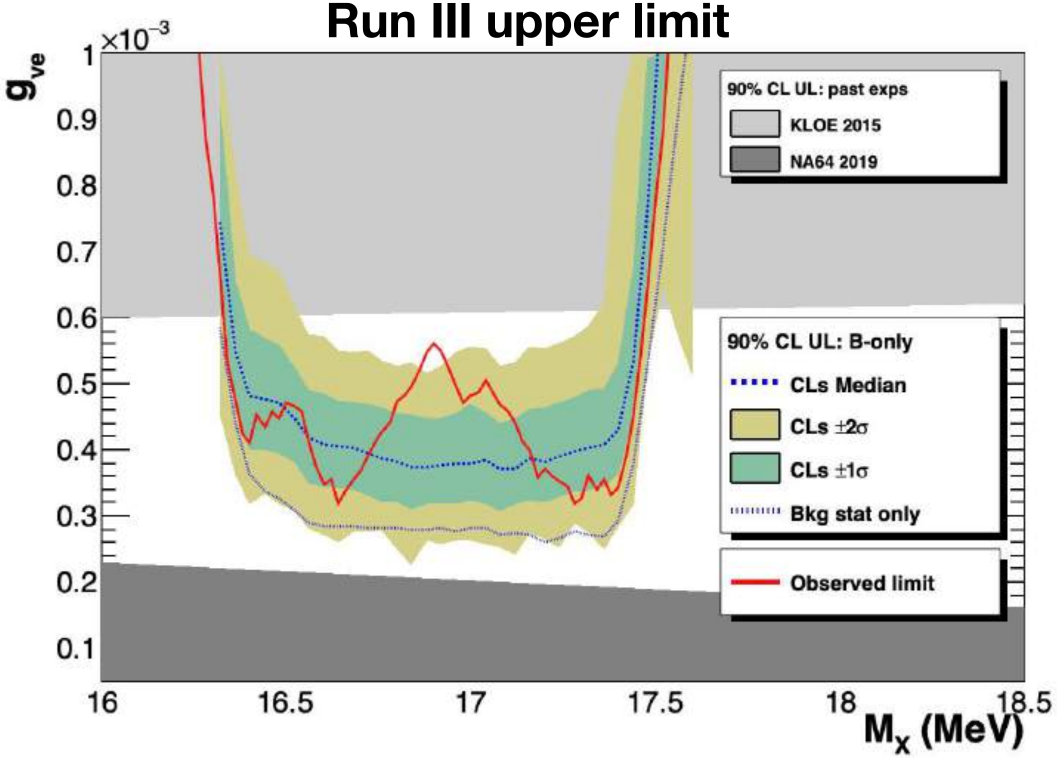
- **Target**: charged-weighted mean over the 3 fired strips
  - Beam position stable within 100-150 μm + consistently hitting the same strip pair ($X = 1$, $Y = -5$) throughout the data taking
  - Spread and full scan evaluation still ongoing
- **PadMMe** and **TMM** analysis ongoing
- **ECAL:** beam parameters estimated using the two-clusters center of gravity (CoG)
  - Significant variation on the Y coordinate → motivated by the fixed quadrupole optics adopted in Scan 1



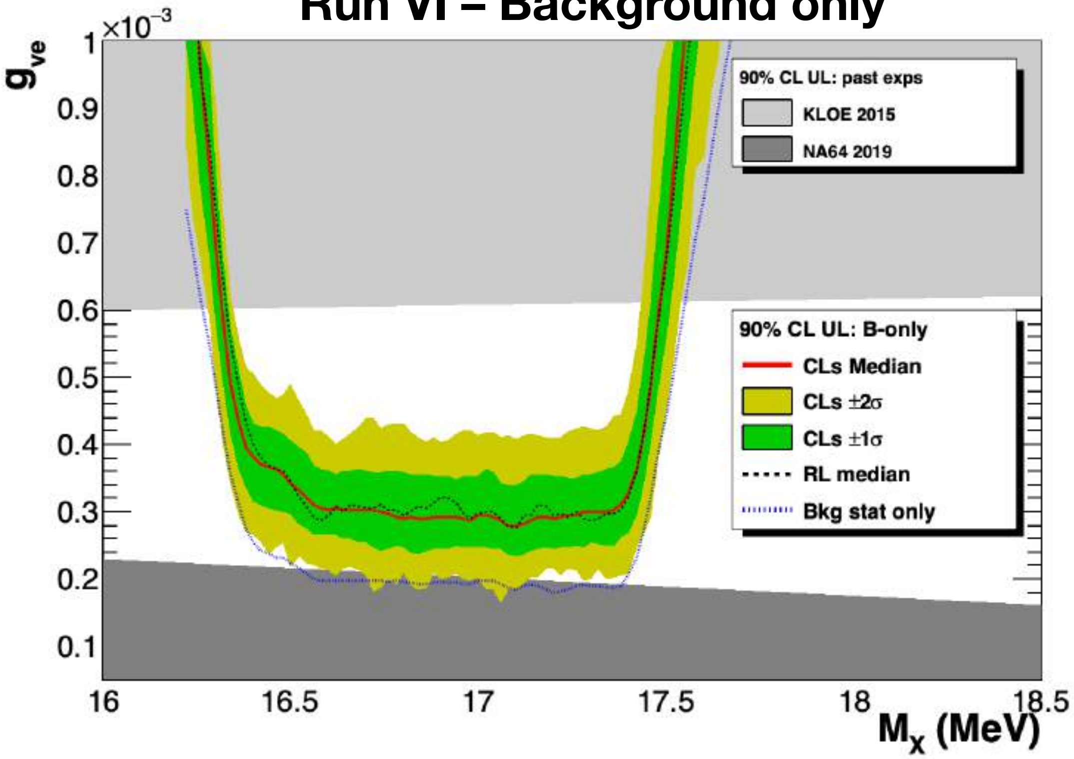


Run IV projections

Run III upper limit



Run VI – Background only



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**

Sources of correlated error

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

NPoT(s)

Common systematic errors

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