Search for the X17 particle with the PADME experiment

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

elisa.dimeco@lnf.infn.it

On behalf of the PADME Collaboration

Lepton-Photon 2025, August 27, 2025 - Madison (WI), USA

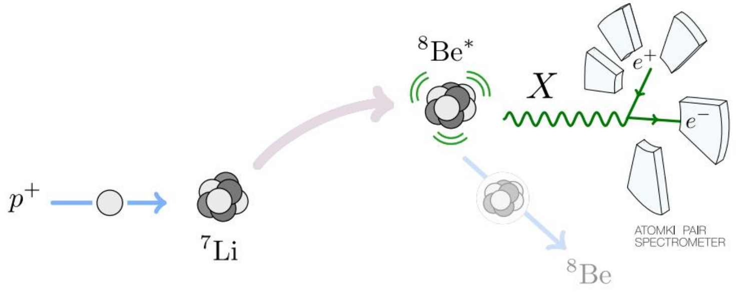
TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

INFN
Istituto Nazionale di Fisica Nucleare

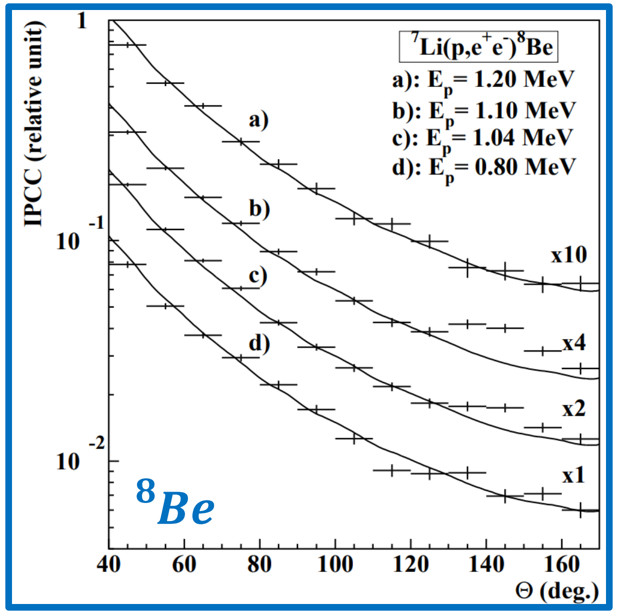
X17 anomaly @ ATOMKI

- Anomalous excesses in angular correlation of e^+e^- couples produced via IPC of ^8Be, ^4He e ^{12}C observed by the ATOMKI collaboration.

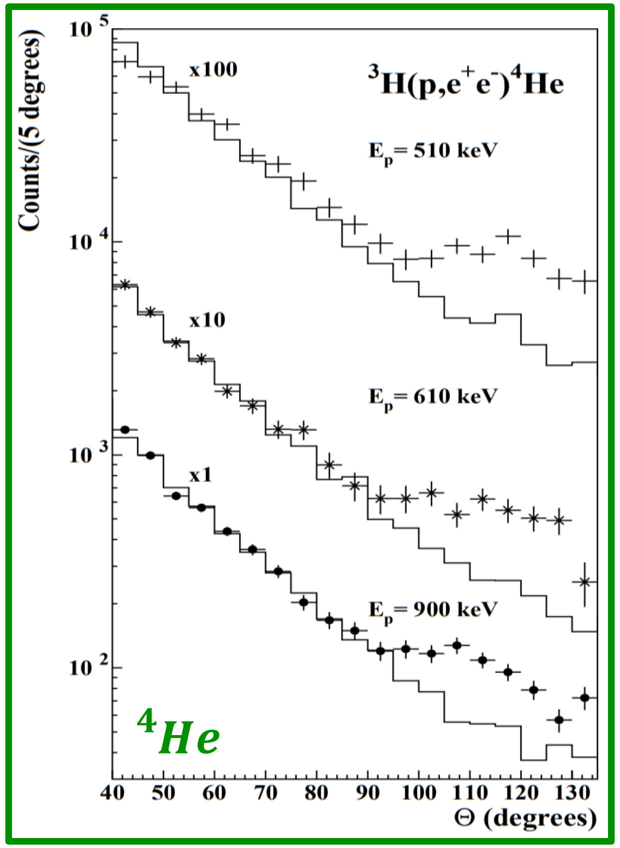
- The anomaly seems to be compatible with the production and successive decay of a **new ~17 MeV mass particle**



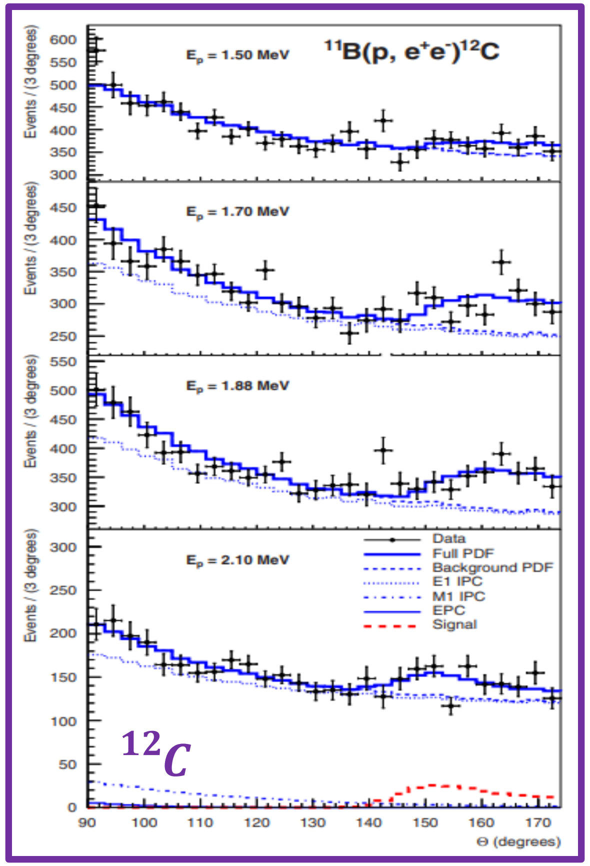
Phys.Rev.Lett. 116 (2016) 4, 042501



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



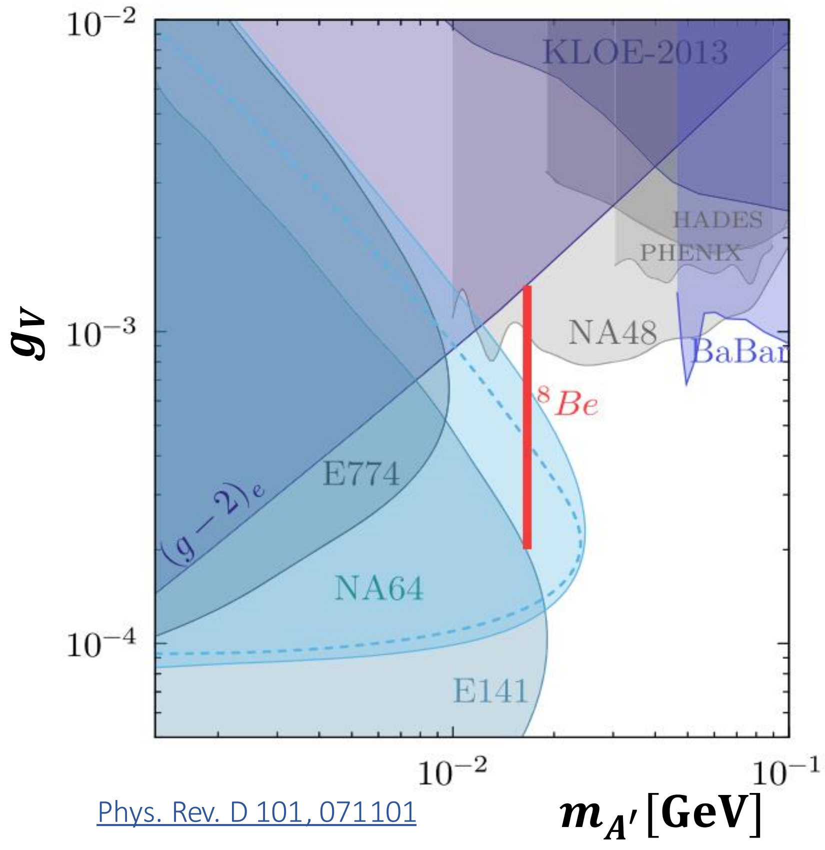
Phys. Rev. C 106, L061601



X17 as a vector or pseudo-scalar state

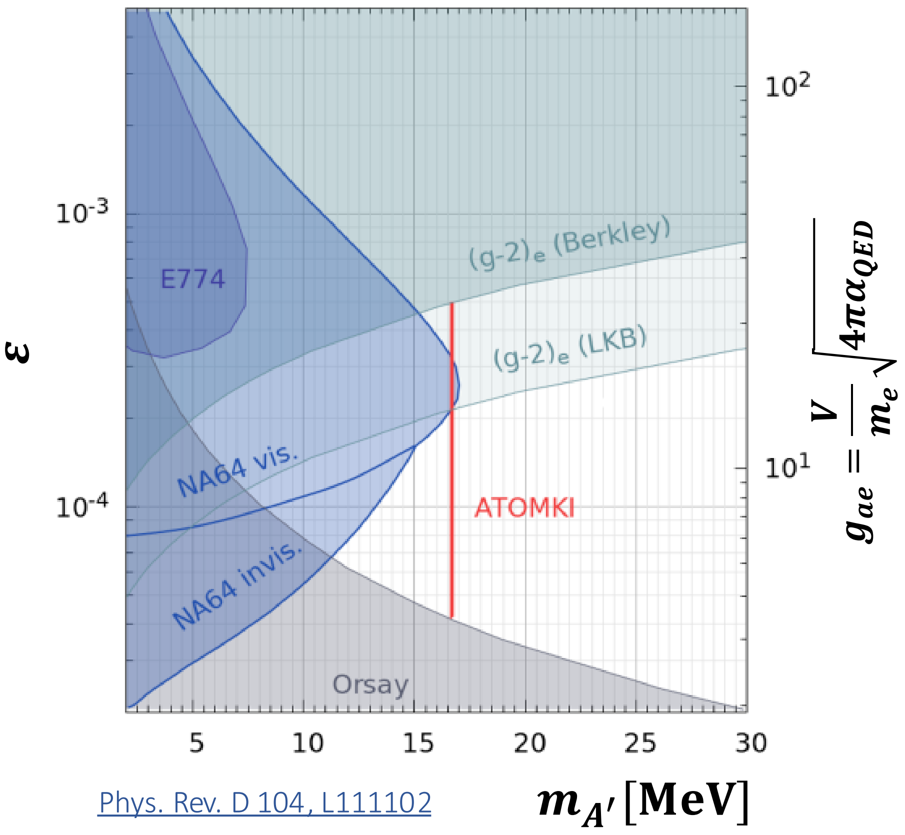
- New physics interpretations not fully excluded → still some phase-space available
- The PADME experiment is sensible to this mass range

Vector



Phys. Rev. D 101, 071101

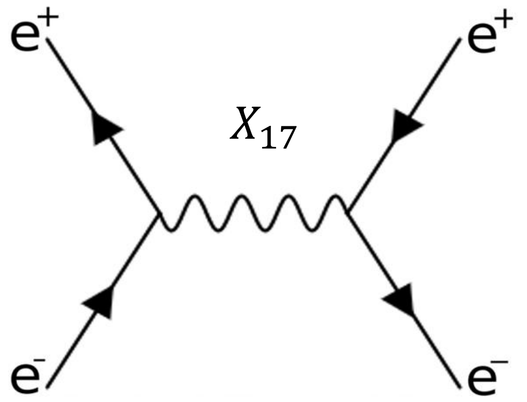
Pseudoscalar



Phys. Rev. D 104, L111102

PADME Resonant search on fixed thin target

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

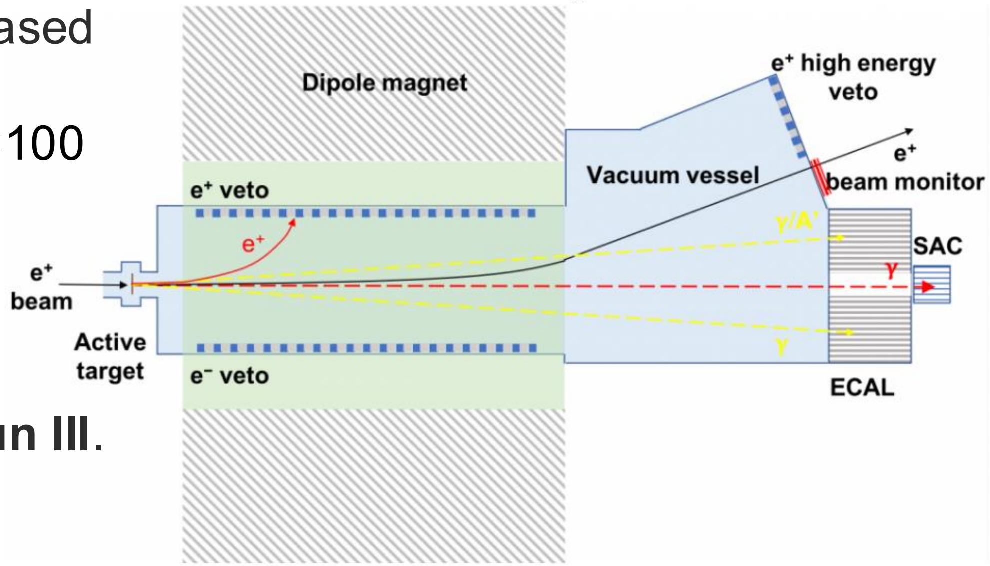


At PADME, X_{17} produced through resonant annihilation in diamond target:
Scan around $E(e^+) \sim 283$ MeV with the aim to measure two-body final state yield **N_2**

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

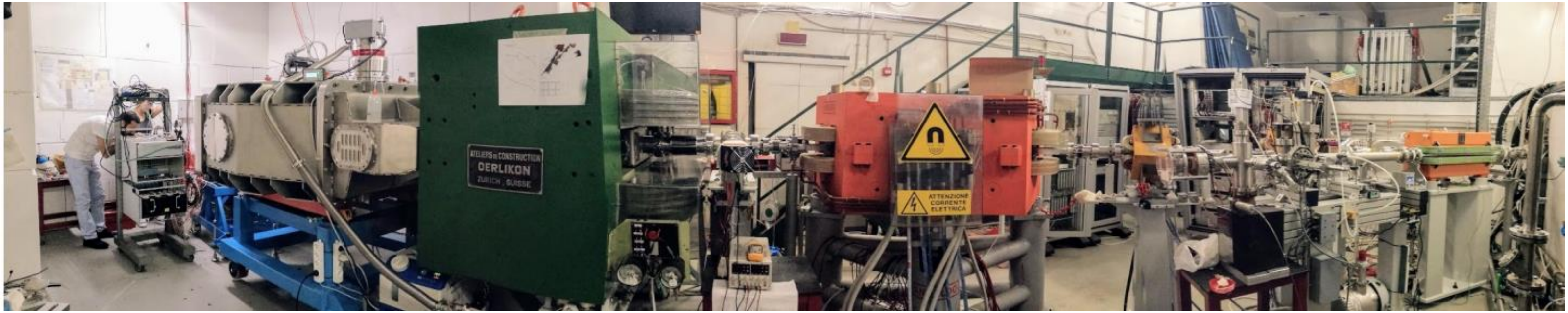
The PADME experiment

- Positron Annihilation into Dark Matter Experiment: $e^+e^- \rightarrow \gamma A'$ based @ Frascati National Laboratories (LNF-INFN).
- e^+beam (E<550 MeV) on a diamond active target 2 cm × 2 cm ×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**.

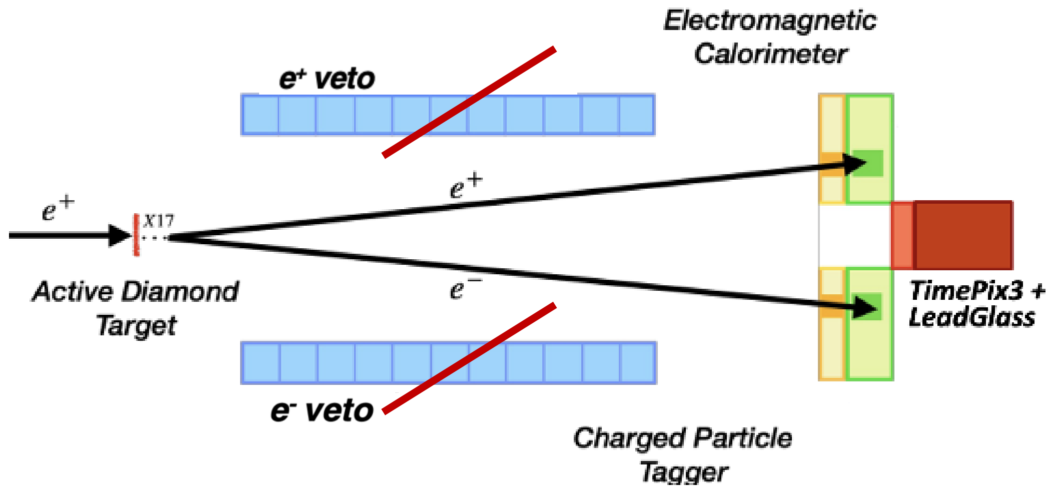
- Some modification to the setup were necessary

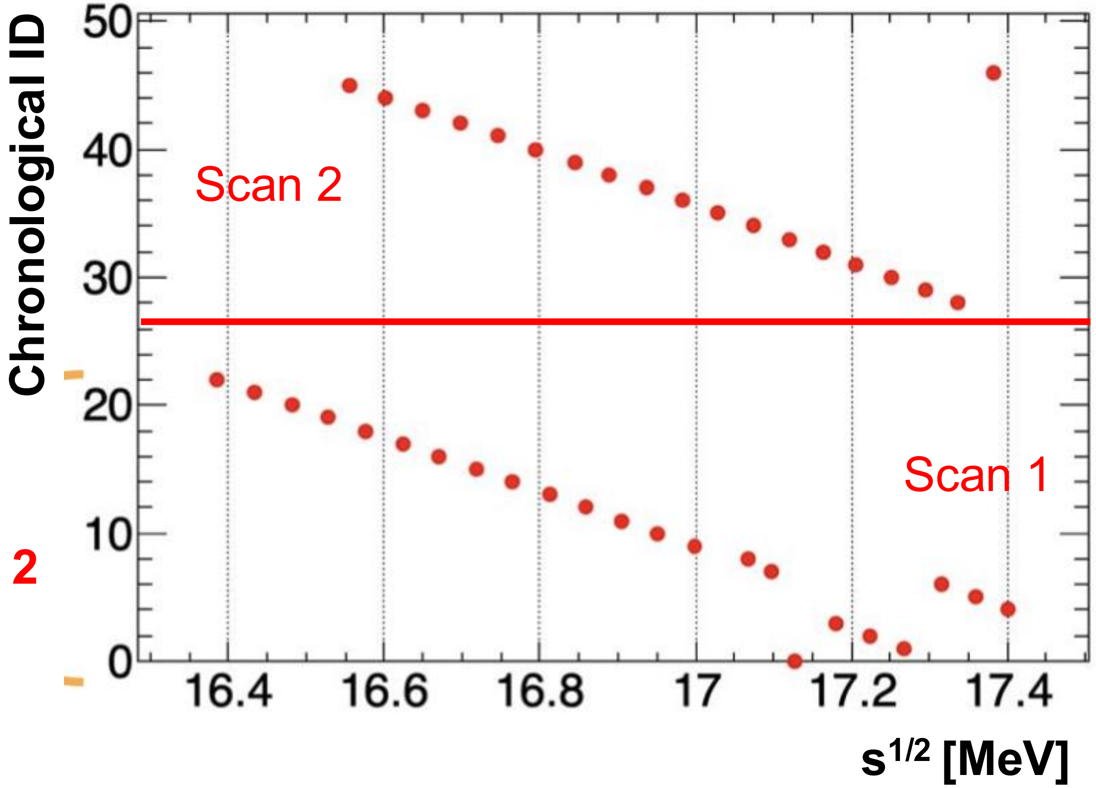


Run III

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

- PADME dipole turned off
- ETagger added to identify charged particles
- SAC replaced with a TimePix3 beam monitor and a Leadglass luminometer





Data-taking divided in 3 parts:

- **On resonance: 47 points @ (263-299) MeV → scan 1 and 2**
- **Below resonance: 5 points @ (205-211) MeV**
- **Over resonance: 5 points @ 402.5 MeV**

Analysis inputs

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

Inputs:

- $N_2(s)$ number of two-cluster events selected
- $N_{POT}(s)$ number of e^+ on target from beam-catcher calorimeter
- $B(s)$ background yield expected per POT
- $S(s; M_X, g)$ signal production expected for {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

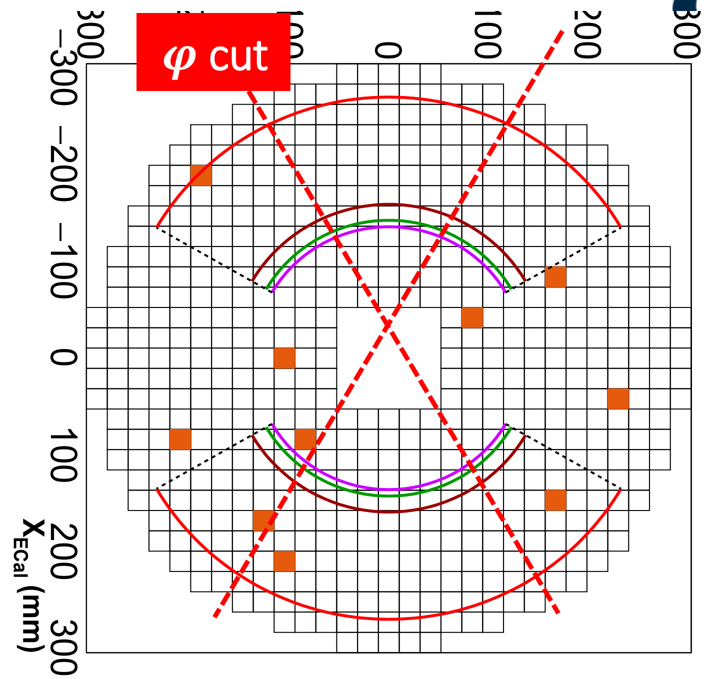
Aim: measure and evaluate systematic errors on:

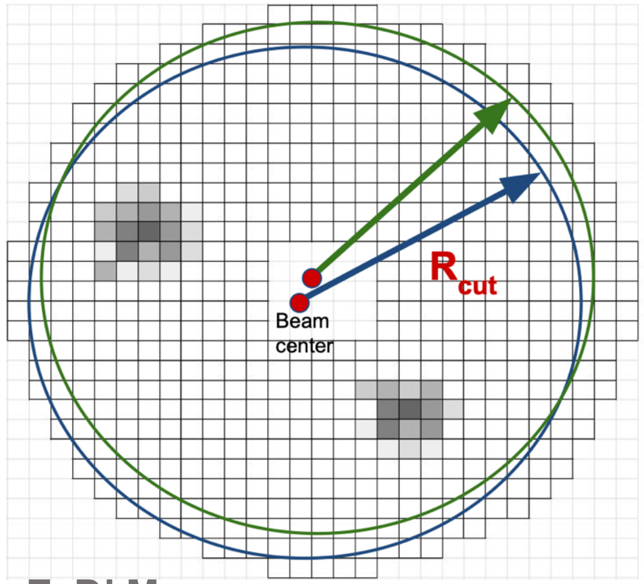
- N_{2Cl} (bkg subtracted) on data
- PoTs
- Signal Efficiency
- Signal shape
- MC Expected Yield

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
  - 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)
  - $\boldsymbol{\phi_1 - \phi_2}$ vs $\boldsymbol{\theta_1 + \theta_2}$ cut in the center of mass frame isolates the signal





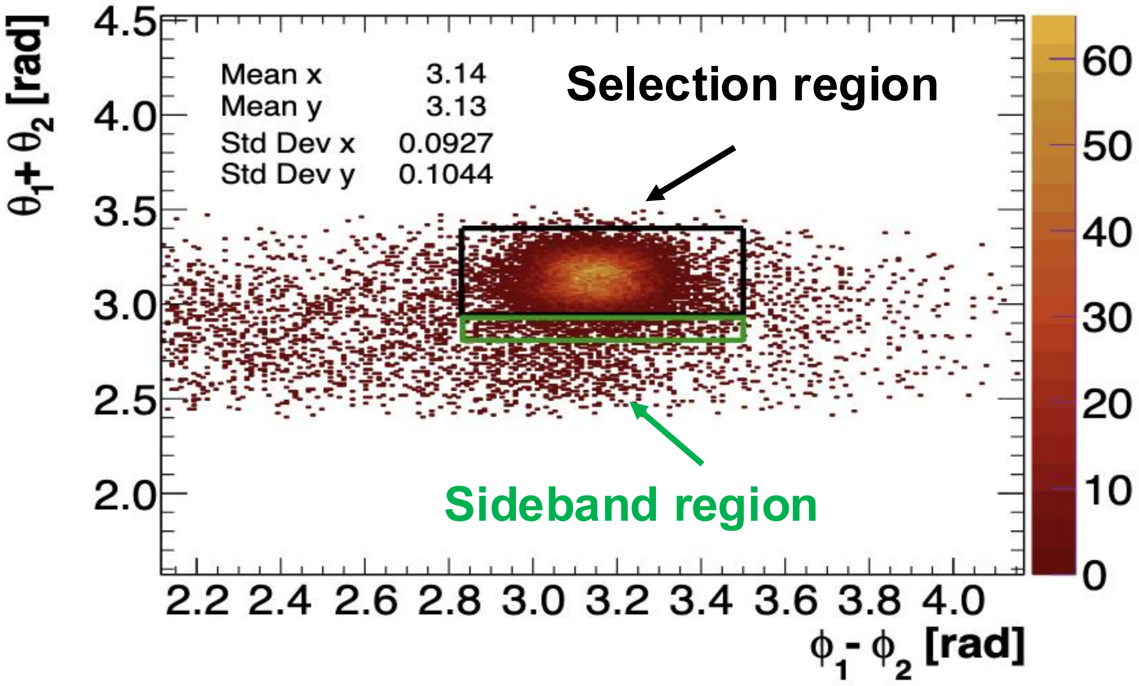
$\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ → $N_2(s)$

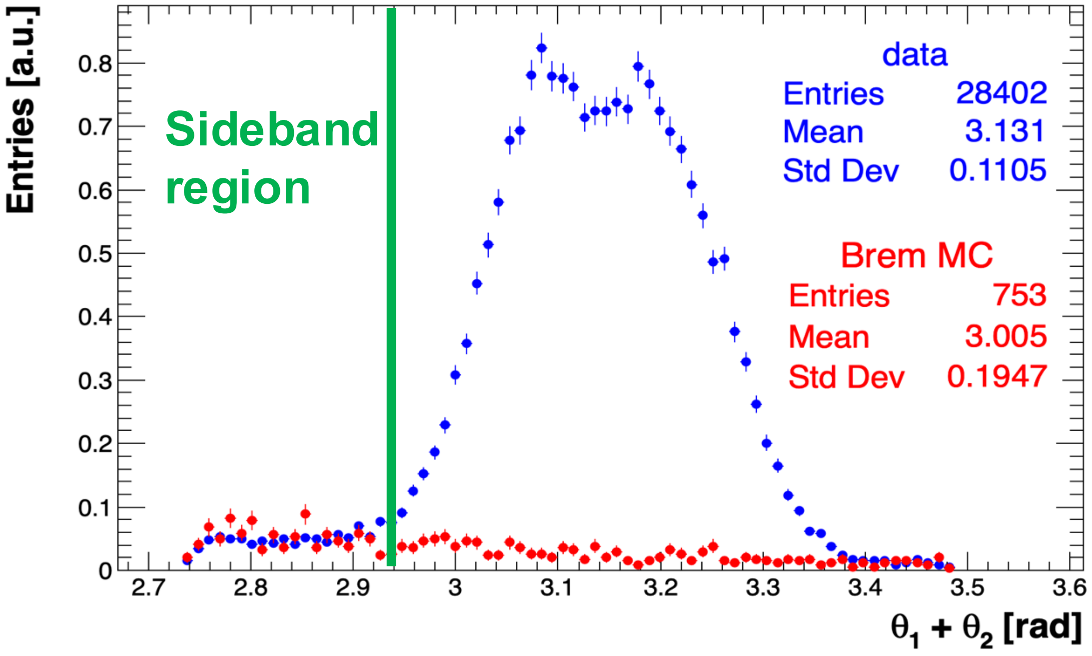
- $\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ cut isolates the signal
- **Cut range**: 3σ around the mean value
  - Flat beam bkg in $\phi_1 - \phi_2$ → bkg level < 4%
  - Bremsstrahlung tail in $\theta_1 + \theta_2$ → To be removed with MC shape using the sideband region

❖ 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**

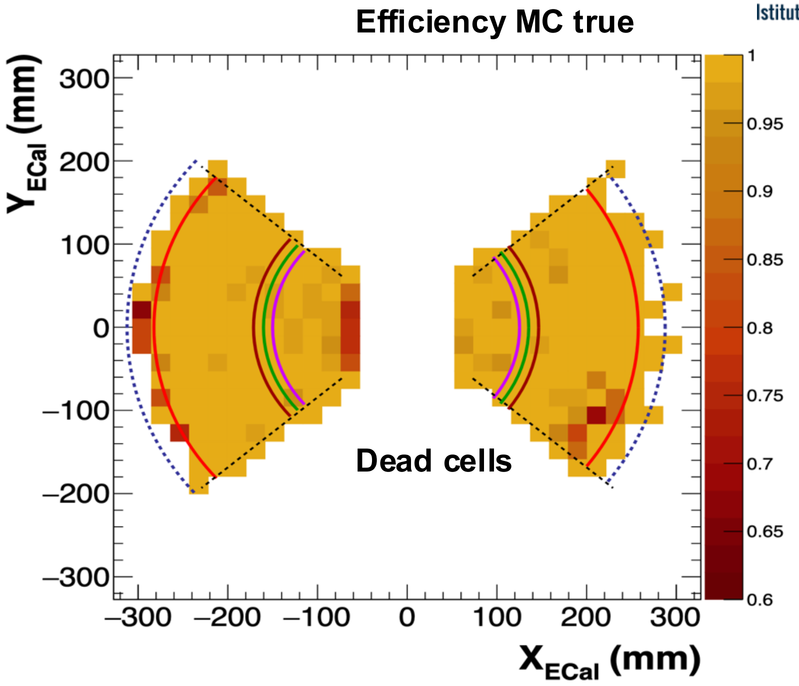


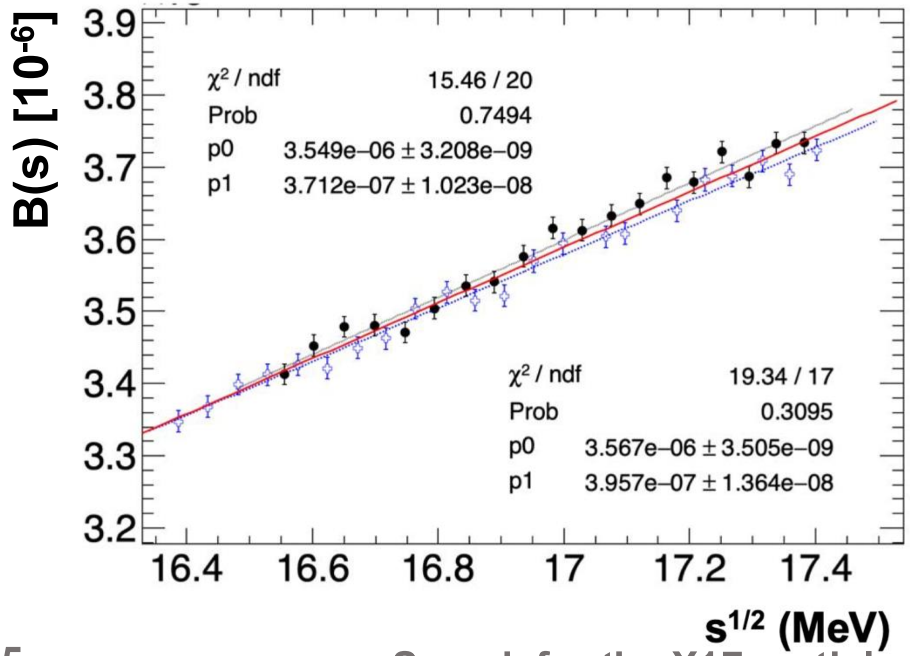


Expected Background → B(s)

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 → **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 → NPoT(s)

- 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: $Q_{target-x}$, <E_{ECal}>, period multiplets
    - LG yield decreases with relative PoT slope of 0.097(7) → Slope error included **δN_{PoT}=0.35%**
    - Constant term uncertainty of **δN_{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 **δN_{PoT}=0.5%**

Uncorrelated systematic errors

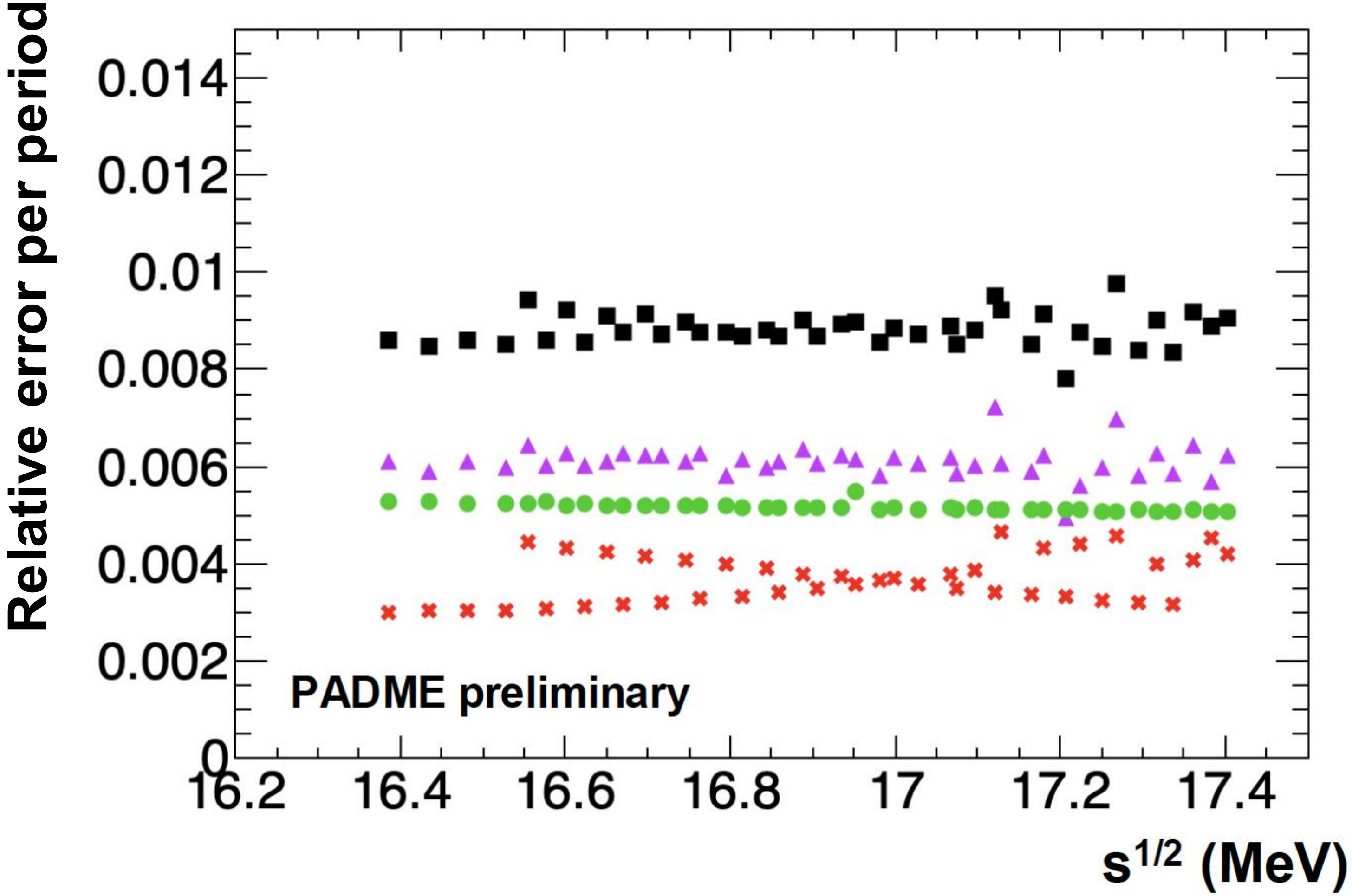
Source	Error on N_{POT} [%]
Statistics, ped subtraction	negligible
Energy scale from BES	0.3
Rad. induced loss, slope	Variable, ~0.35
Total	**0.45**

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**

Total error budget

- Uncorrelated uncertainty on $g_R(s)$ = $N_2(s)$ / (NPoT(s) B(s)):



Uncorrelated errors

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

$K(s)$, constant term

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

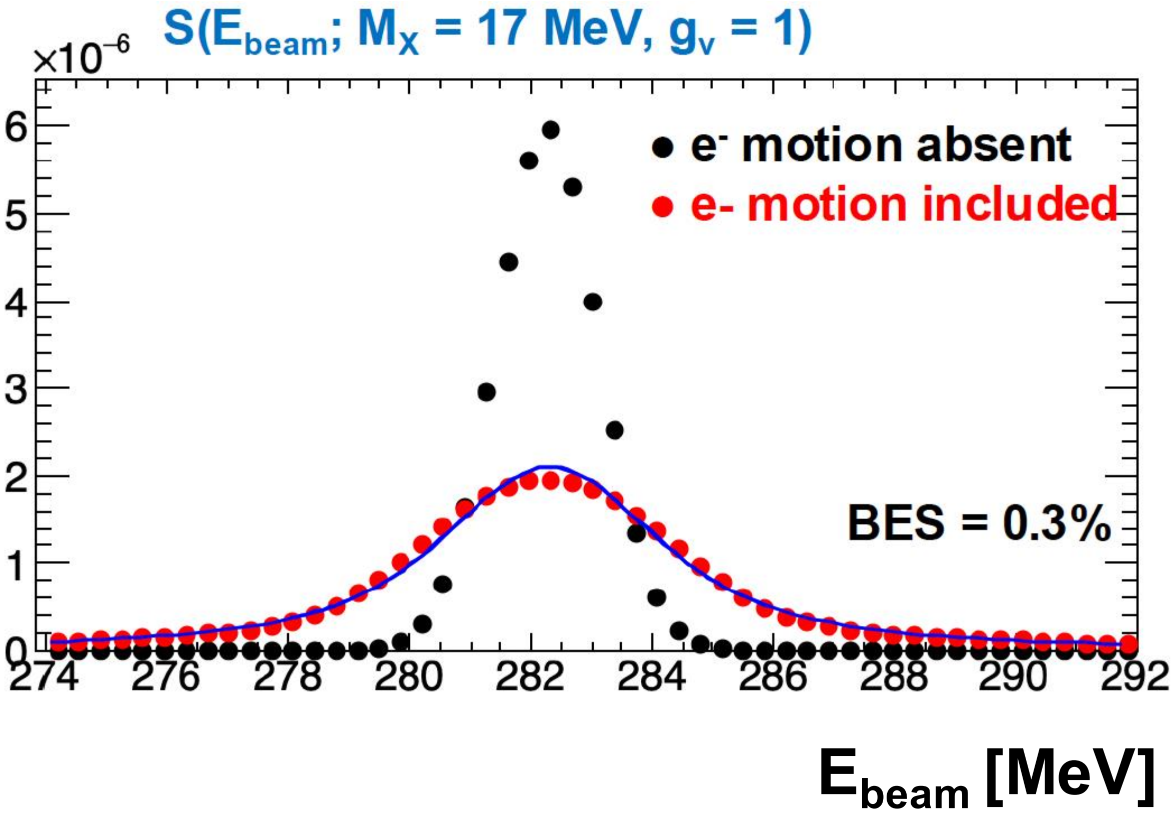
$K(s)$, $\sqrt{s}$-slope

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

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

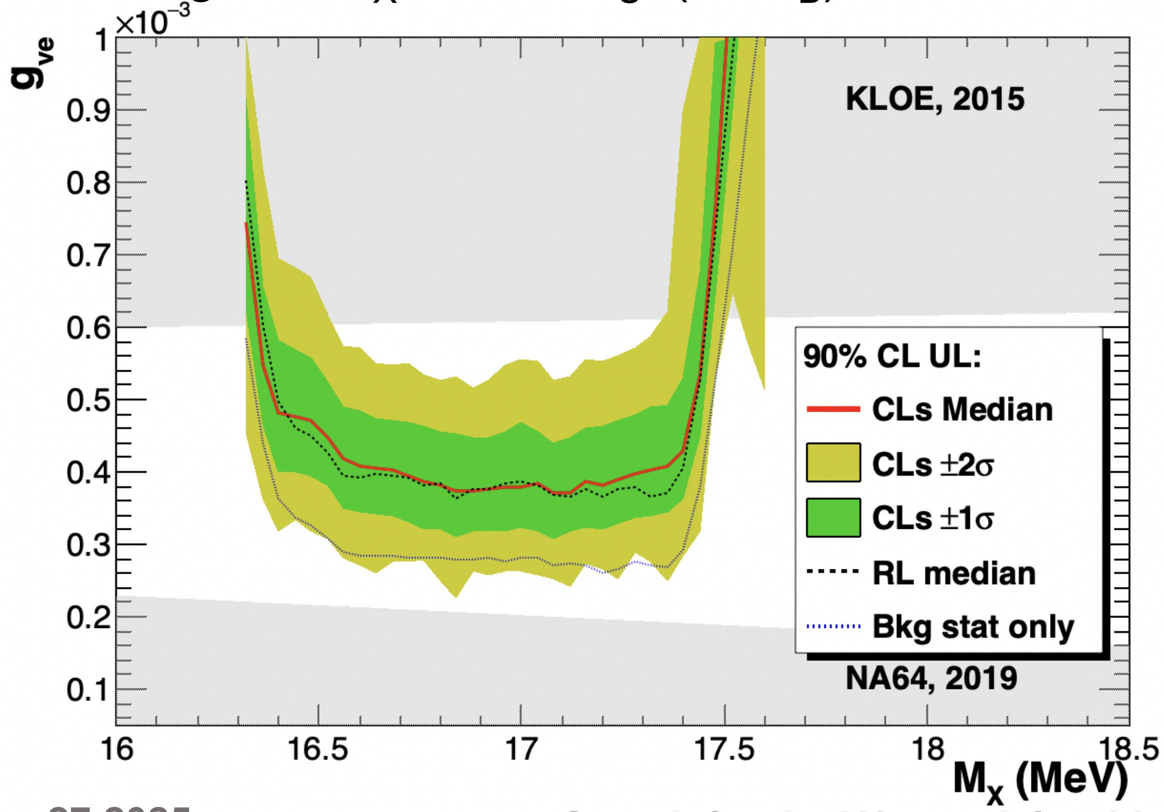
Signal shape and ε(s)/B

- 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 ε(s)/B(s) with a straight line, include fit parameters as nuisances:
  - **Errors:** δP0/P0 ~ 0.1%, δP1/P1 = 3%, correlation = -2.5%



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 = 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

PADME Unblinding procedure

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

- Aim to blindly define a side-band in $g_R(s)$, excluding 10 periods of the scan
- Define the masked periods by optimizing the probability of a linear fit in $s^{1/2}$
  1. Threshold on the χ^2 fit in side-band is $P(\chi^2) = 20\%$, corresponding to reject 10% of the times
  2. If ✅, 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.: ±4% for the constant, ±2% MeV^{-1} for the slope

Successfully applied:

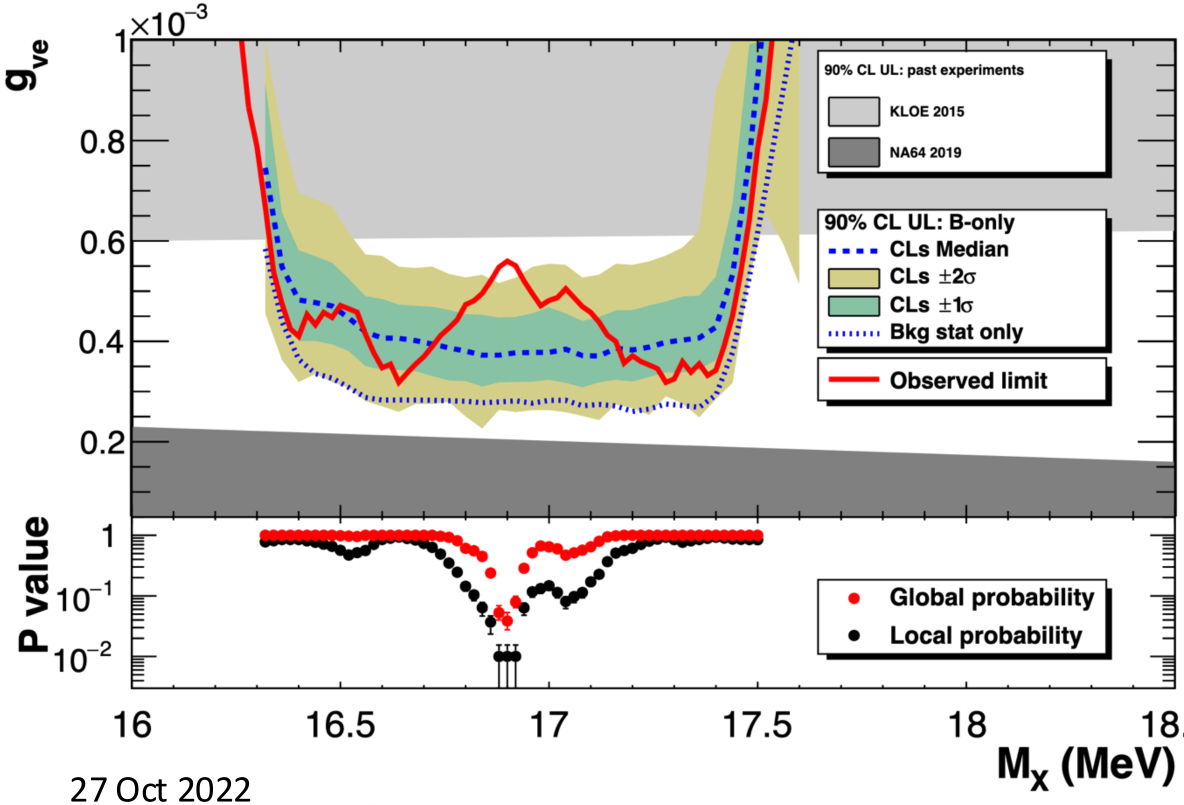
1. **$P(\chi^2) = 74\%$**
2. **Pulls gaussian fit probability 60%**
3. **Slope of pulls consistent with zero**
4. **Constant term = 1.0116(16), Slope = (-0.010 +- 0.005) MeV^{-1}**

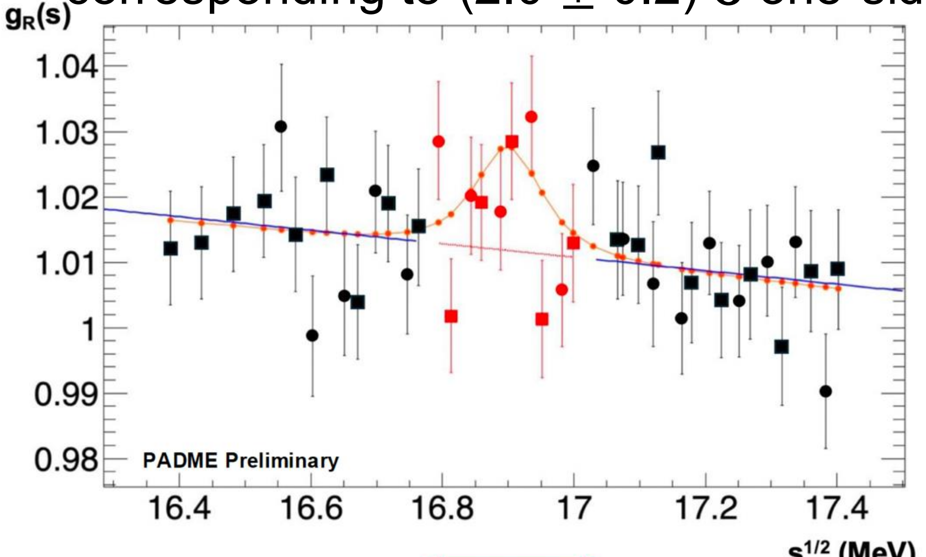
→ **Ready to unblind**

Box opening

Some excess is observed a ~2.5σ local coverage

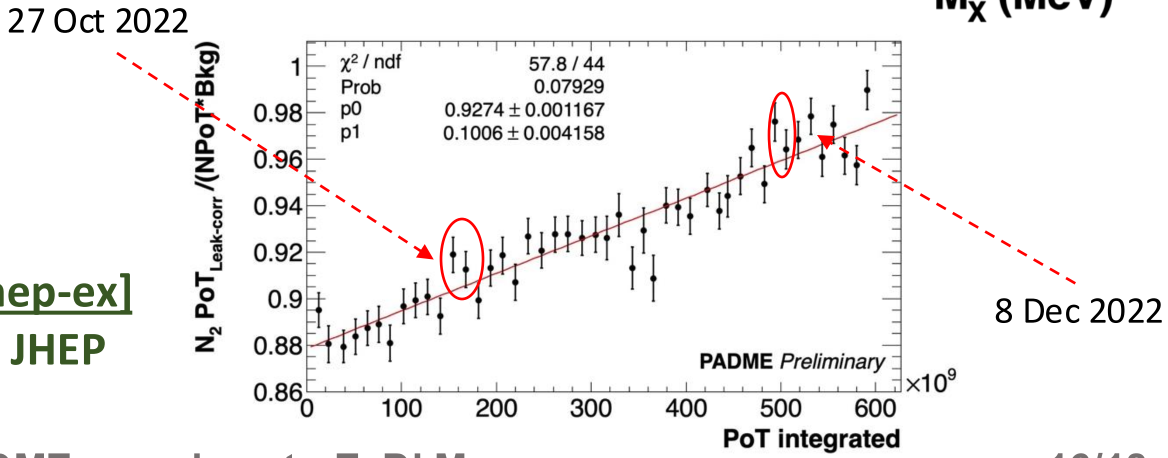
- At $\mathbf{M_X = 16.90(2)}$ **MeV**, $\mathbf{g_{ve} = 5.6 \times 10^{-4}}$, the global probability dip reaches $\mathbf{3.9_{-1.1}^{+1.5}}$ **%**, corresponding to **(1.77 ± 0.15) σ** one-sided (look-elsewhere calculated exactly from the toy pseudo-events)
  - A second excess is present at ~17.1 MeV, but the absolute probability there is ~ 40%
- If a 3σ interval is assumed for observation following the estimate M_X = 16.85(4) 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]

Minor revision from JHEP



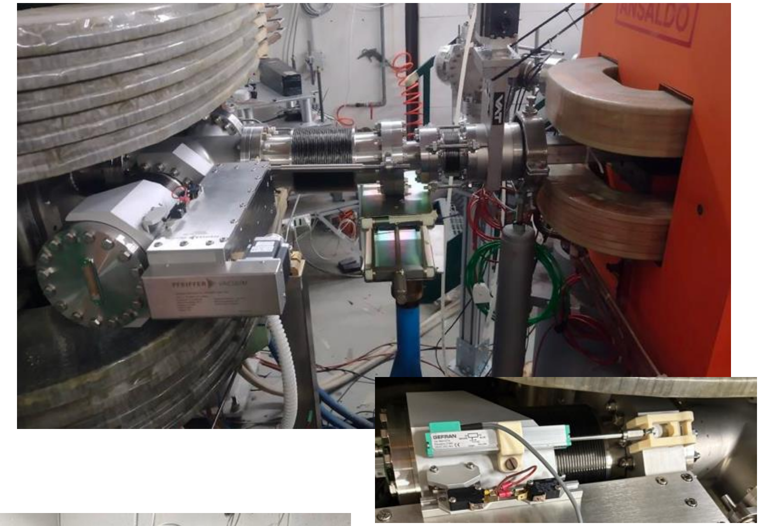
Run IV improvements overview

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

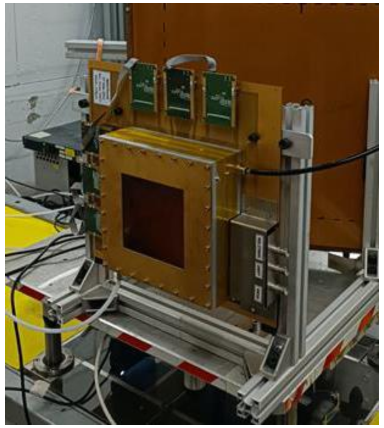
- **Diamond target** position moved downstream by ~30 cm
- Passive material removed and PADME Magnet fully degaussed → $B_{PADME} < 1$ G
- New detectors:
  - **PadMMe** MicroMegas chamber replaced the ETagger
  - **TMM** Micromegas replace the TimePix beam monitor
- Radiation loss monitor system for online LG calibration (2nd leadglass block + LED pulser)

Source	Uncertainty [%]		Improvement
	Run III	**Run IV**	
N_2	0.6	**0.3**	New target position → acceptance increased
B	0.35	**0.3**	PadMMe → 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**	

Diamond target



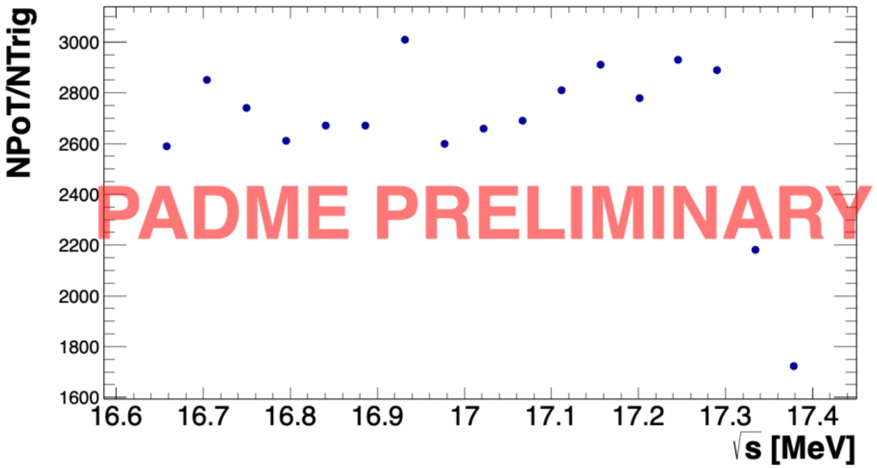
PadMMe



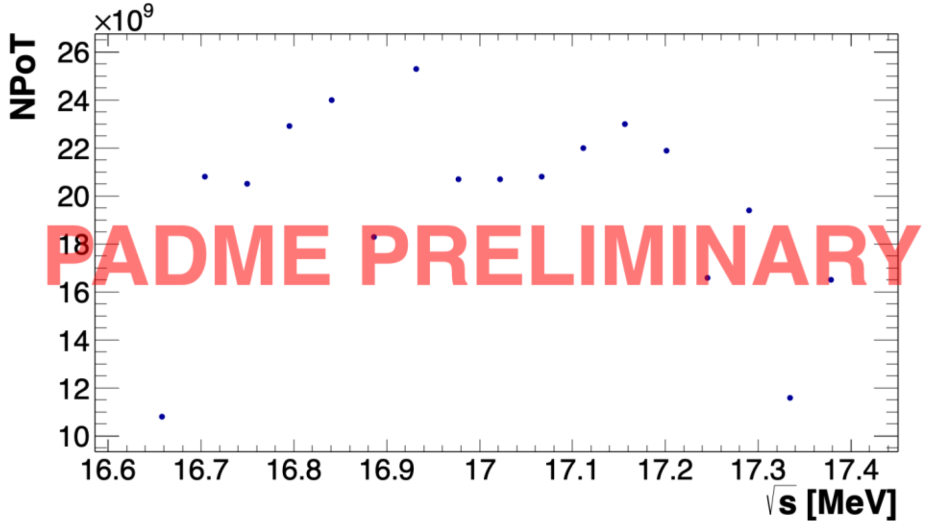
TMM

Conclusions

- The analysis has been successfully blessed using the “blind unblinding” procedure → **Overall uncertainties at 0.9% or slightly better**
- 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)σ
- New data acquired to better clarify:
  - 2 new micromegas-based tracker were installed to separately measure the absolute cross sections of ee/$\gamma\gamma$ allowing a combined analysis
  - Run IV-part 1 data already in the book: 18 energy scan points collected (~2e10 PoTs each) equally separated by 1.5 MeV in the the E_{beam} = (269.5, 295) MeV / $\sqrt{s}$ = (16.60, 17.36) 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



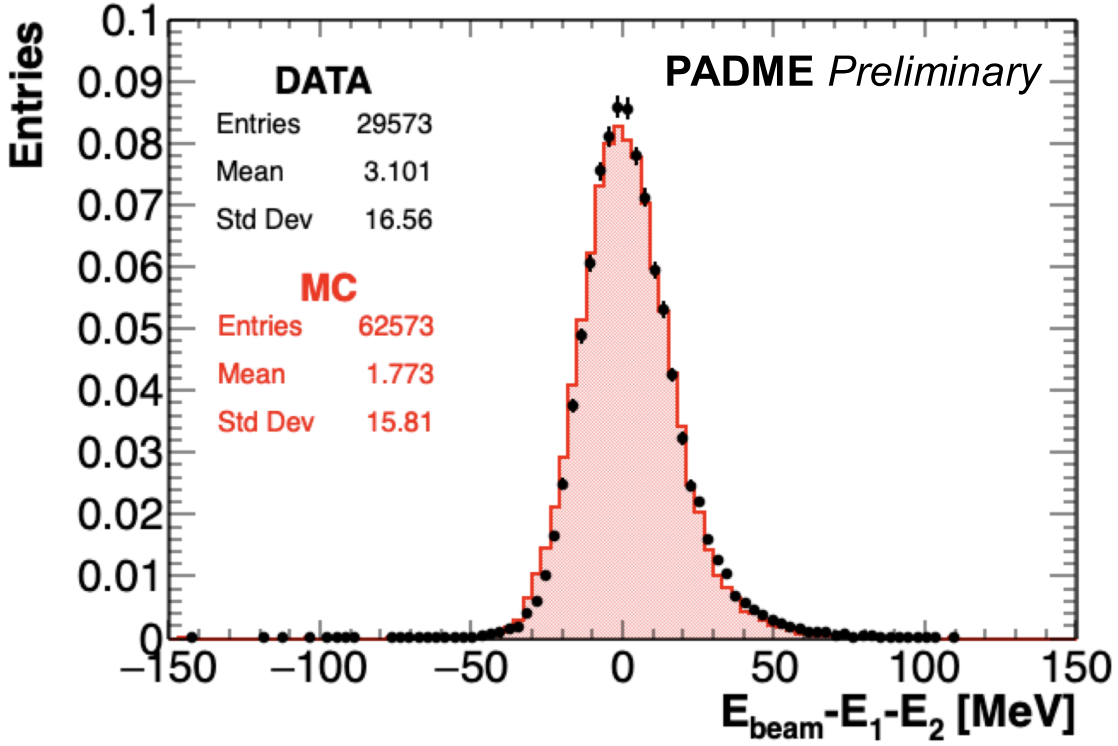
Run IV – Scan 1

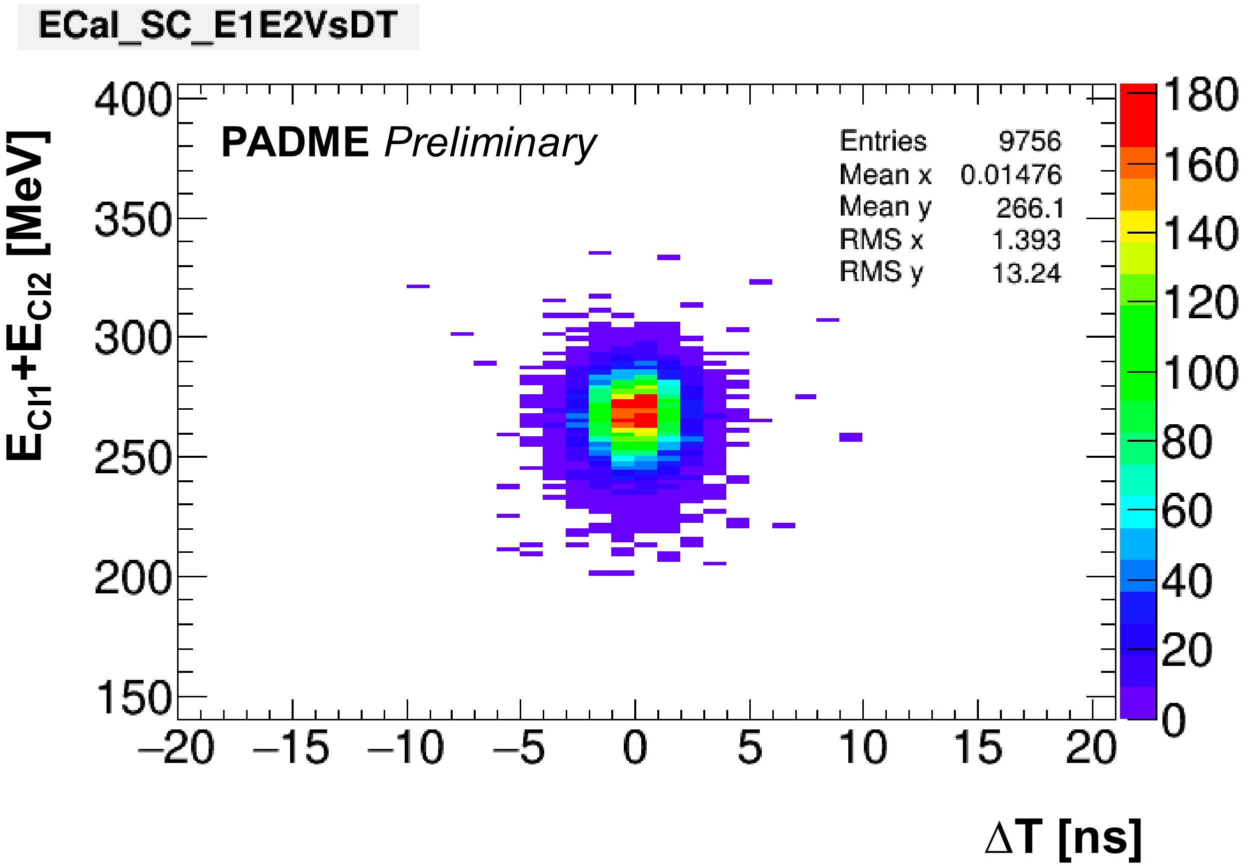


Backup slides

Events selected → $N_2(s)$

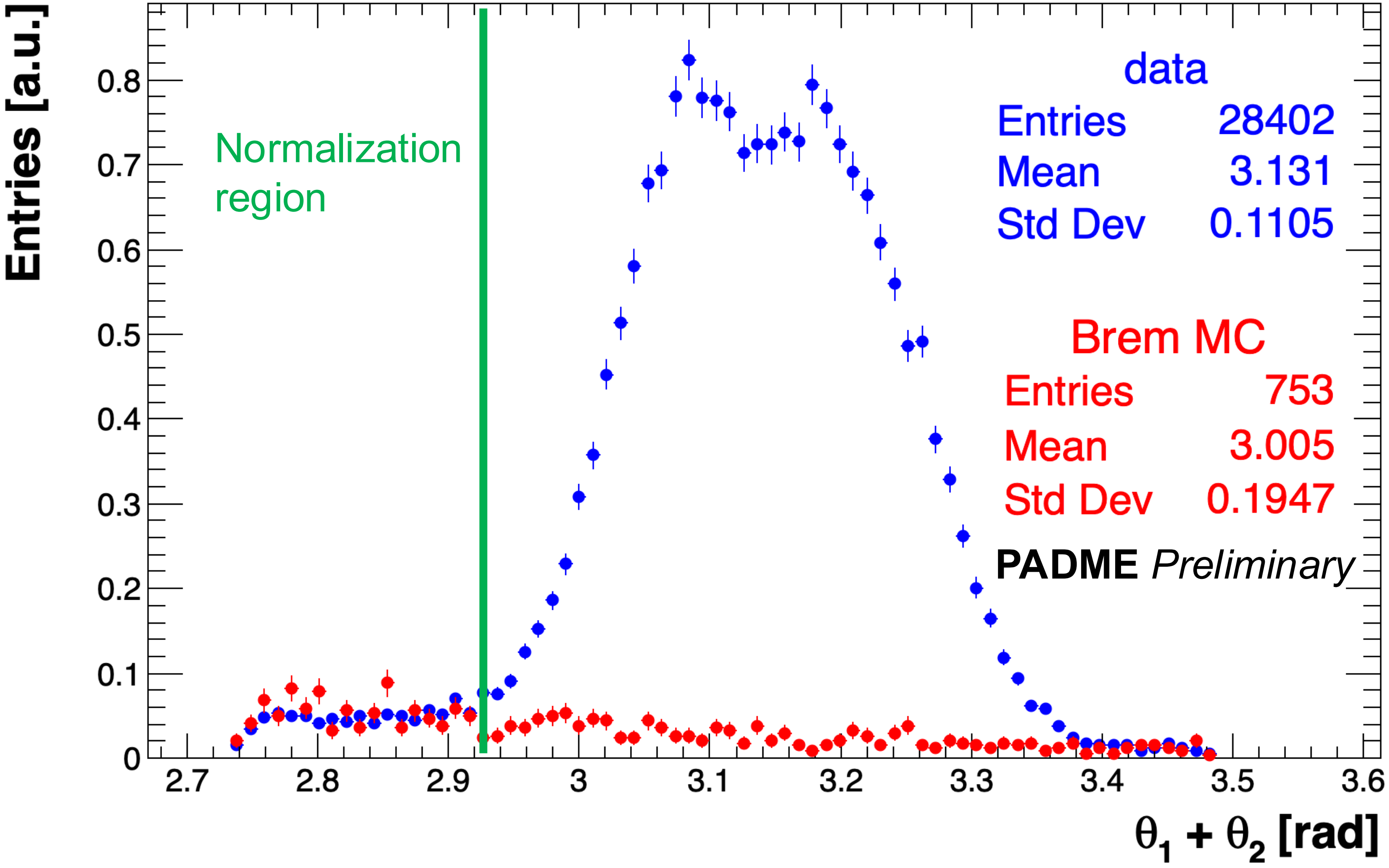
- Events surviving the whole set of cuts, also related to the time difference of the 2 Clusters
- Energy sum of the 2 clusters selected gives back the beam energy (as expected for a two-body final state)
- ECAL relative energy resolution ~ 5%





Bremsstrahlung bkg removal

- 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

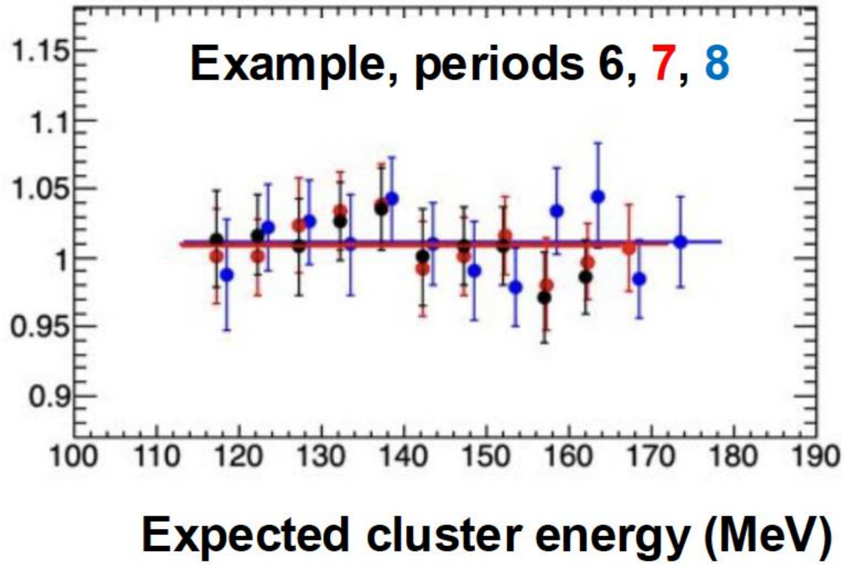


Tag and Probe → Reco efficiency

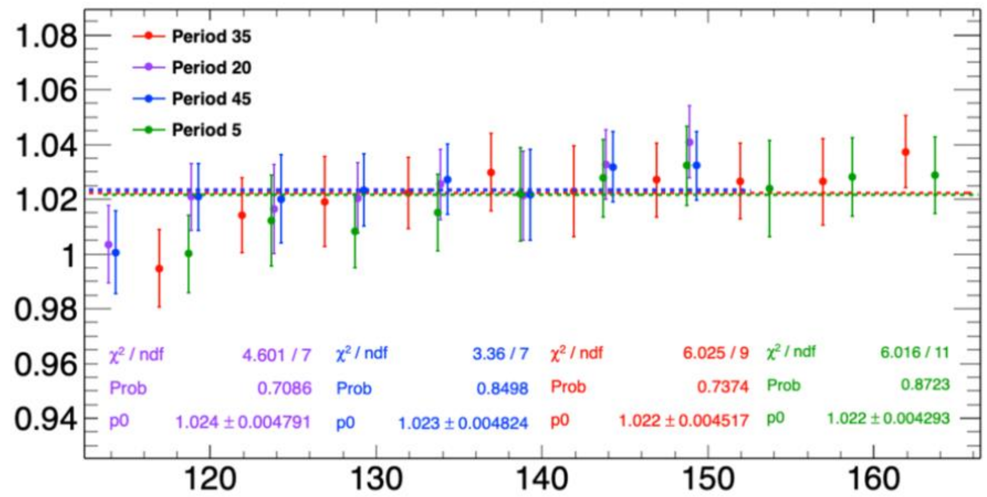
Tag and probe technique, the method-induced bias is 2.3(2)% and stable along the data set

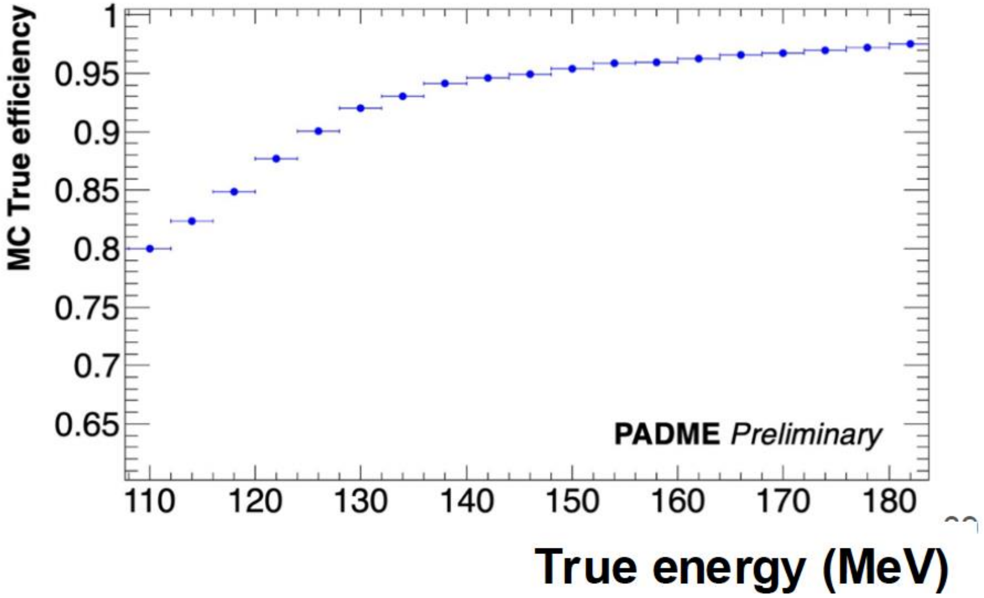
Data/MC method efficiency stable along the data set and at the few per mil

Efficiency Data/MC



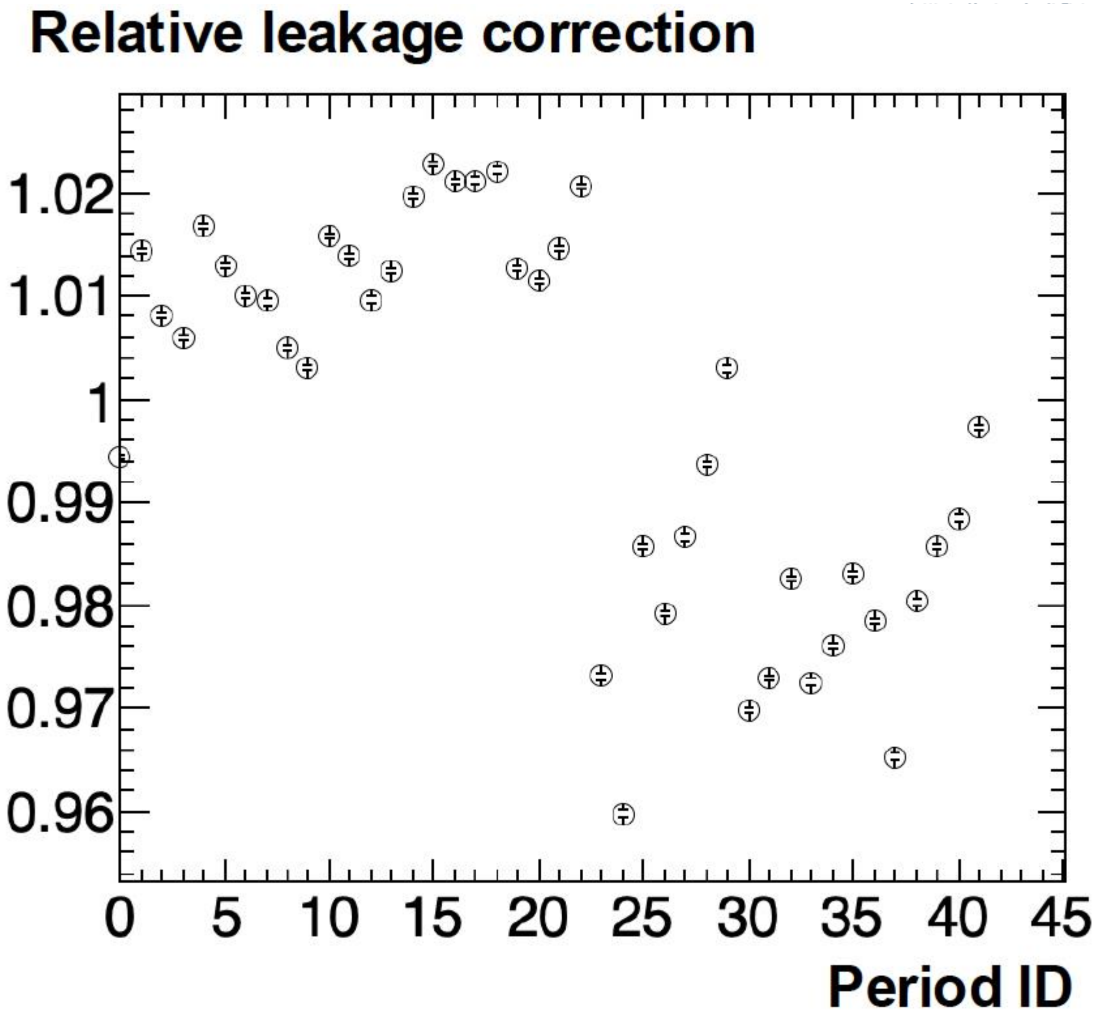
Efficiency <Method /MC true>

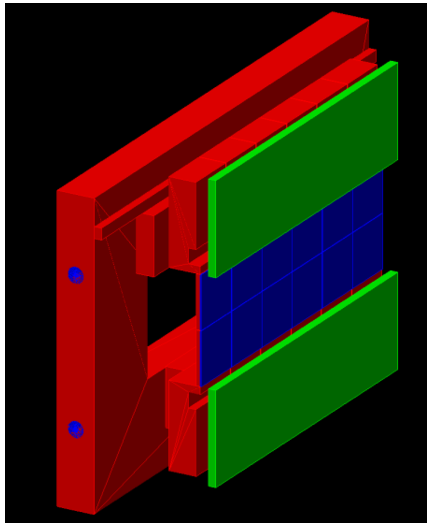




PbGl energy loss in passive material

- 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 → used the COG instead considering the Timepix-ECAL offsets and the intrinsic difference in resolution



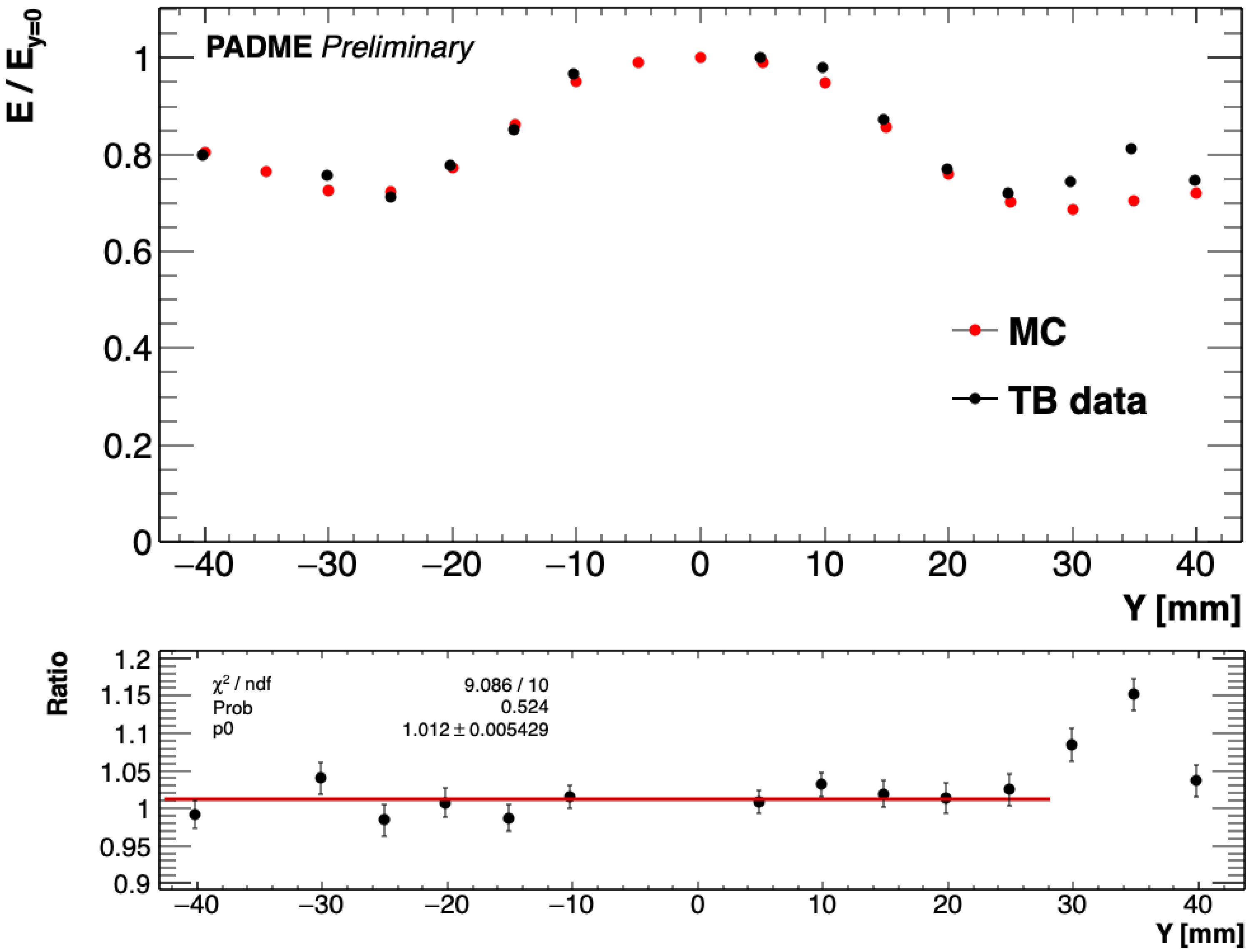


Significant period-by-period correction variation: -4% to +2%

Energy loss → Test beam

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**



Radiation damage

- 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
  - <E-ECAL>
  - Period multiplets

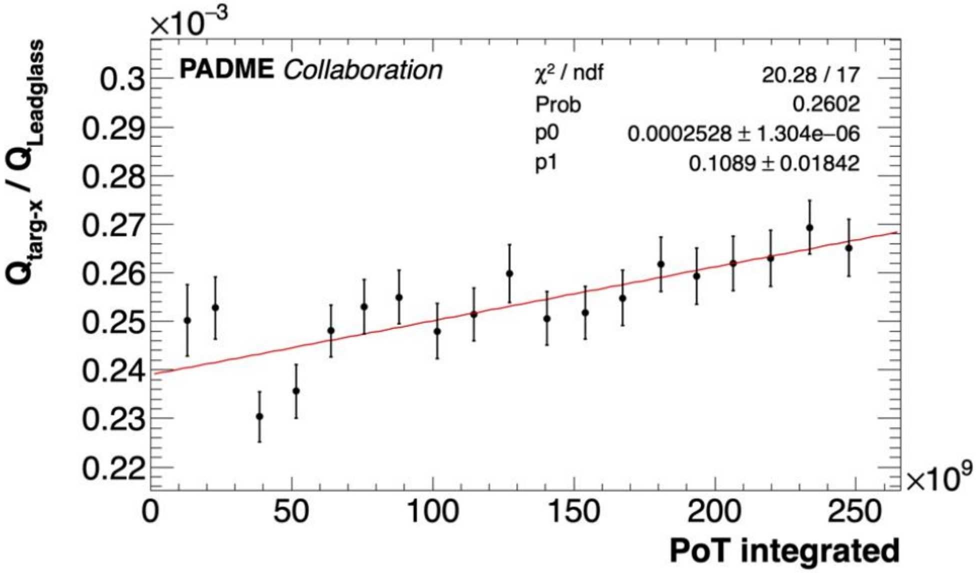
Quantity	PWO:R^{3+}	SF5 (PbO:50%) [4]	SF6 (PbO:75%) [4]
Density ($g\,cm^{-3}$)	8.28	4.07	5.19
Radiation length X_0 (cm)	0.89	2.55	1.69
Index of refraction	2.2	1.67	1.81
Cutoff in T (%) (nm)	320	340	360
Hygroscopicity	No	No	No
Melting point (°C)	1123	442	455
Radiation-hardness (rad)	$10^{7\text{-}8}$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

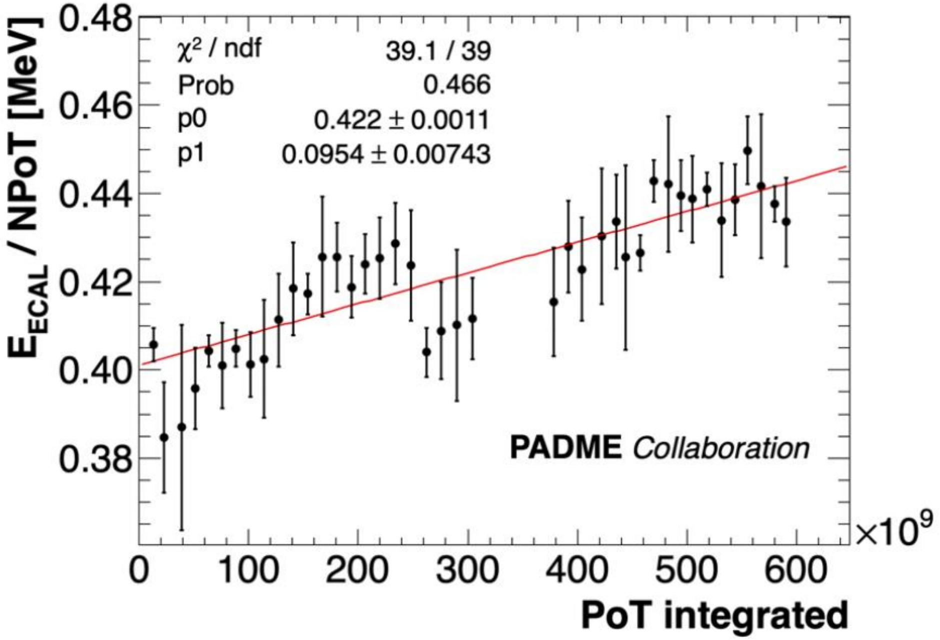
SF57 PbO concentration ~ 75%

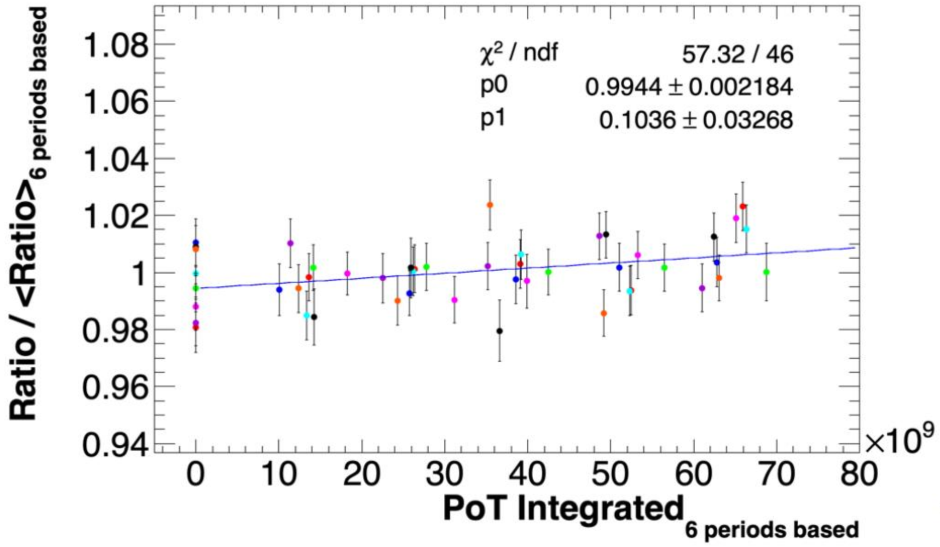
Radiation damage - 2

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 on resetting every 6 periods a compatible slope is found



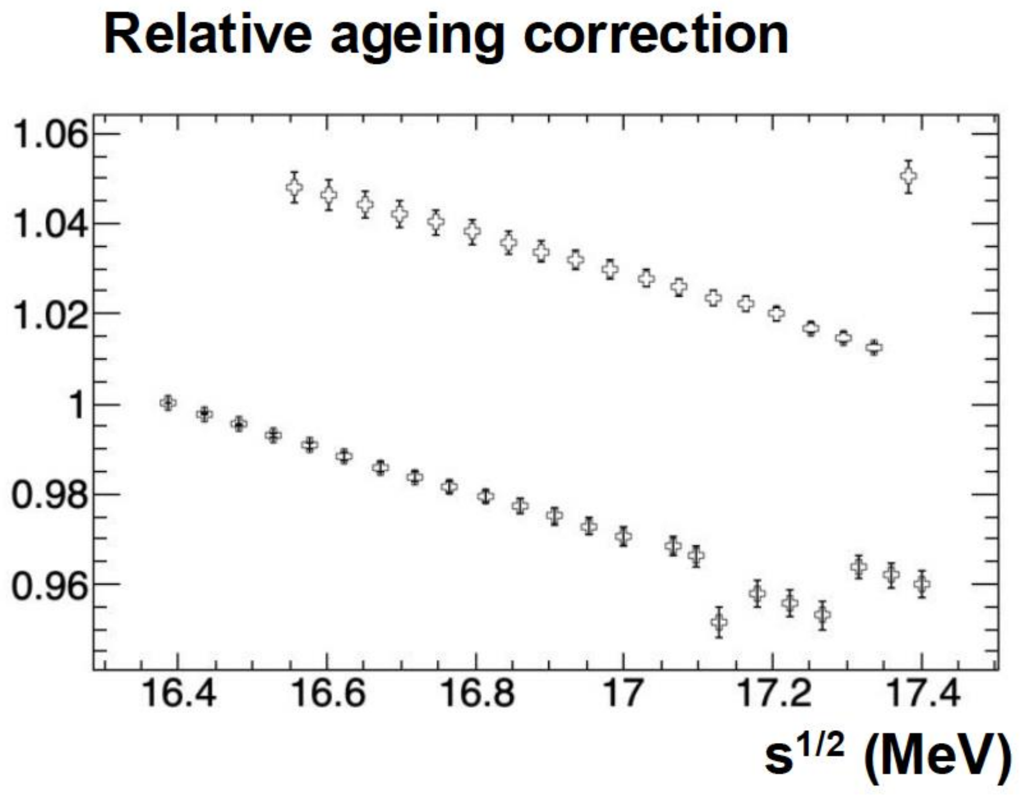




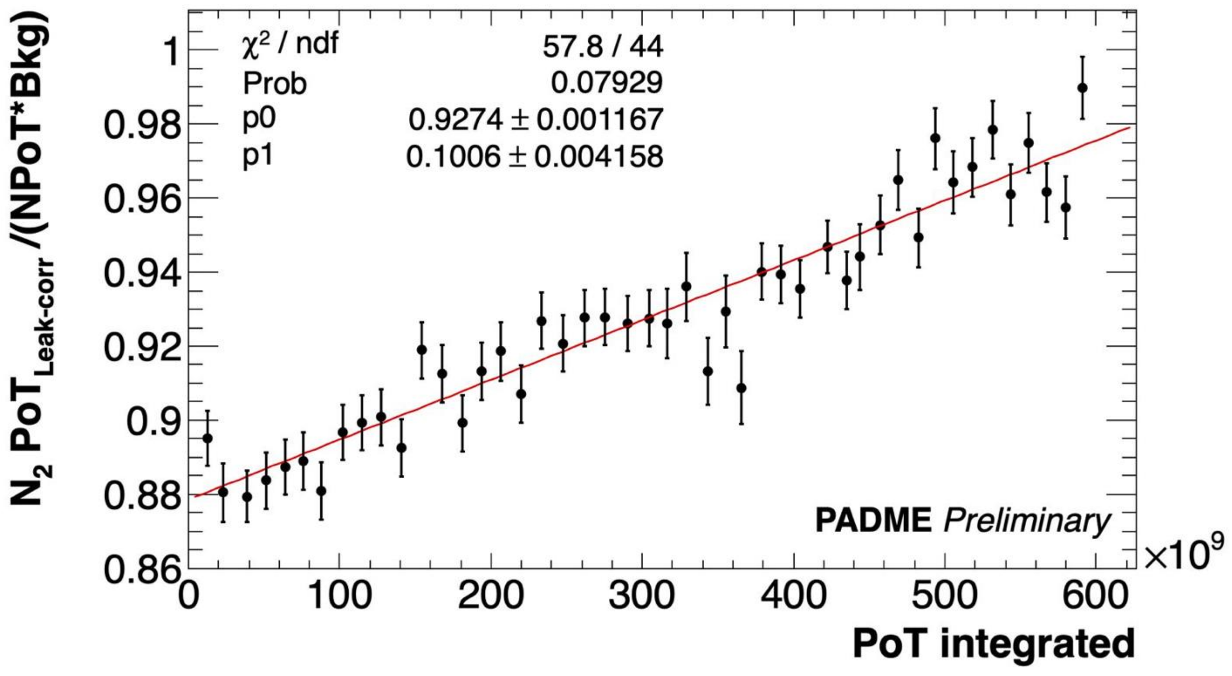
PbGl yield decreases with relative PoT slope of 0.097(7)

Radiation damage – 3

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

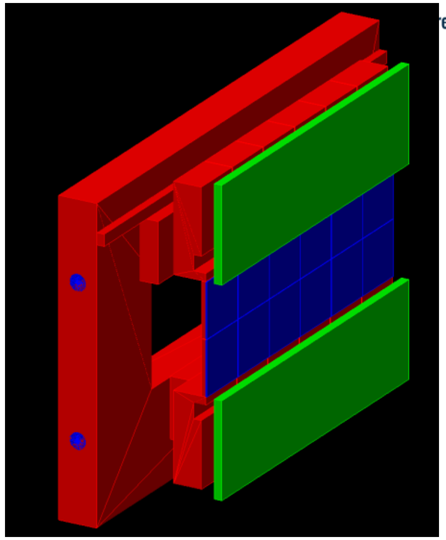


Post unblinding

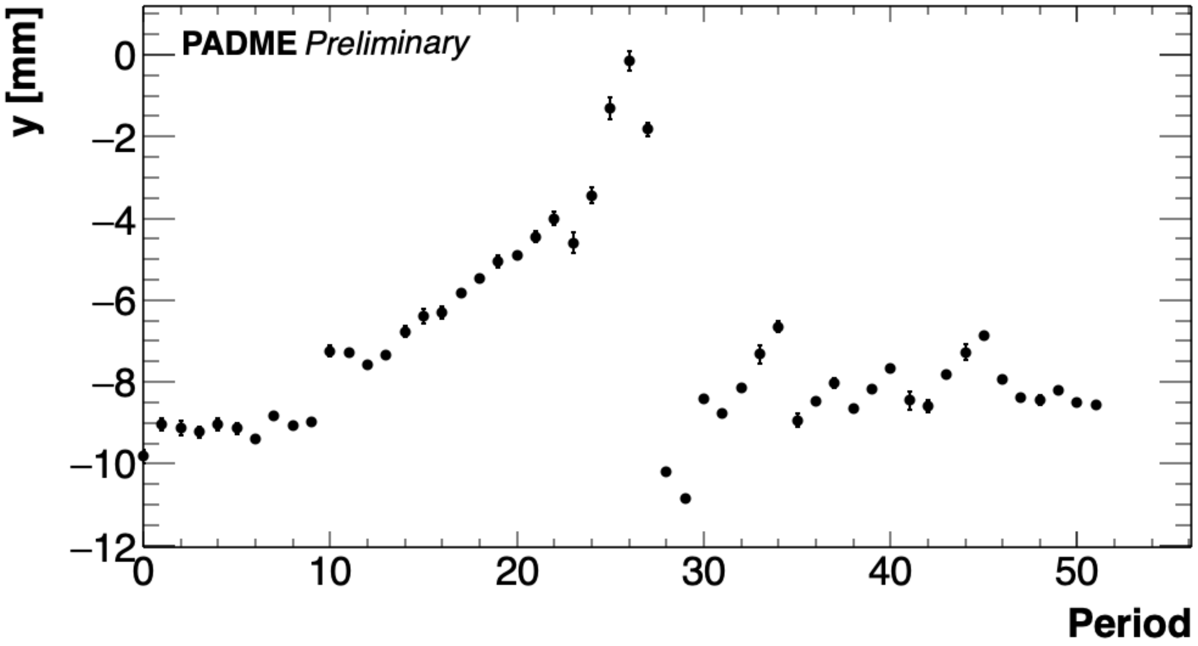


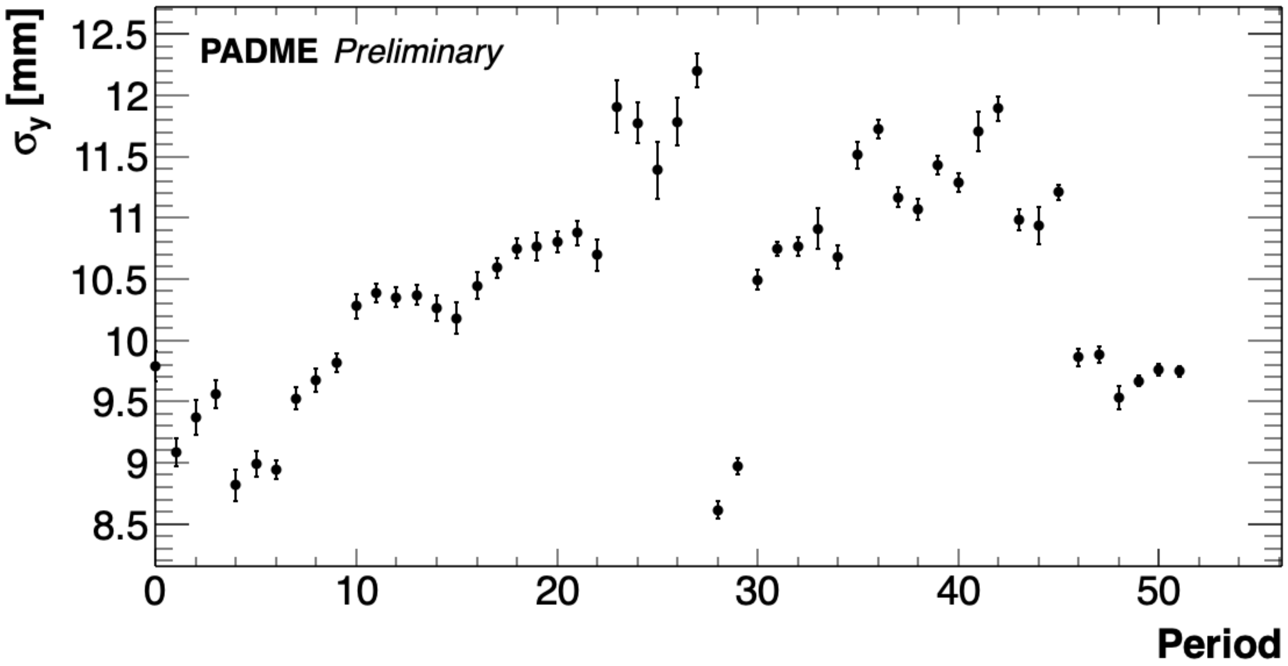
MC simulation in Run 3 (1)

- 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 → we used the COG instead considering the Timepix-ECAL offsets and the intrinsic difference in resolution



MC inputs

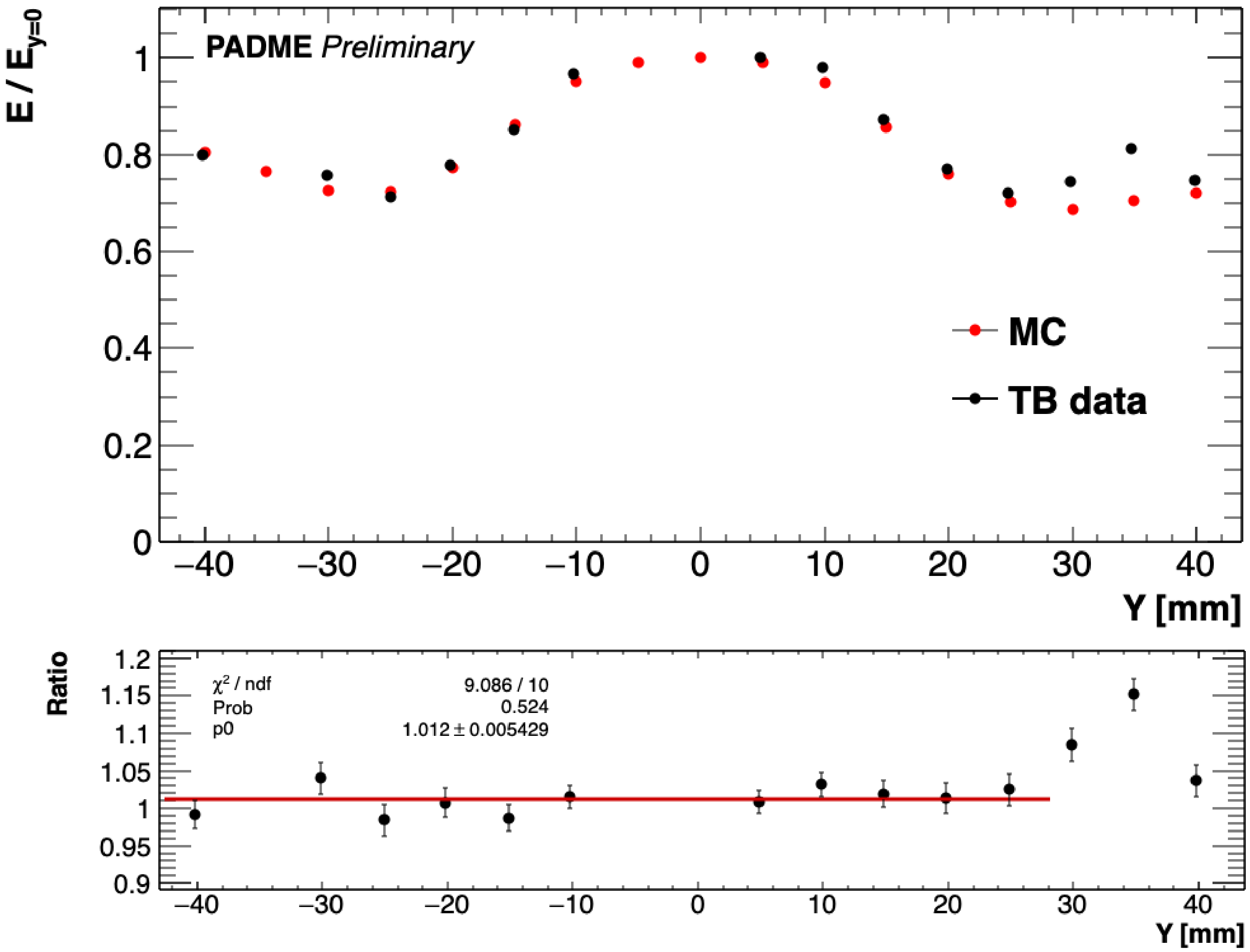




Energy leakage → Test beam

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**



Radiation damage

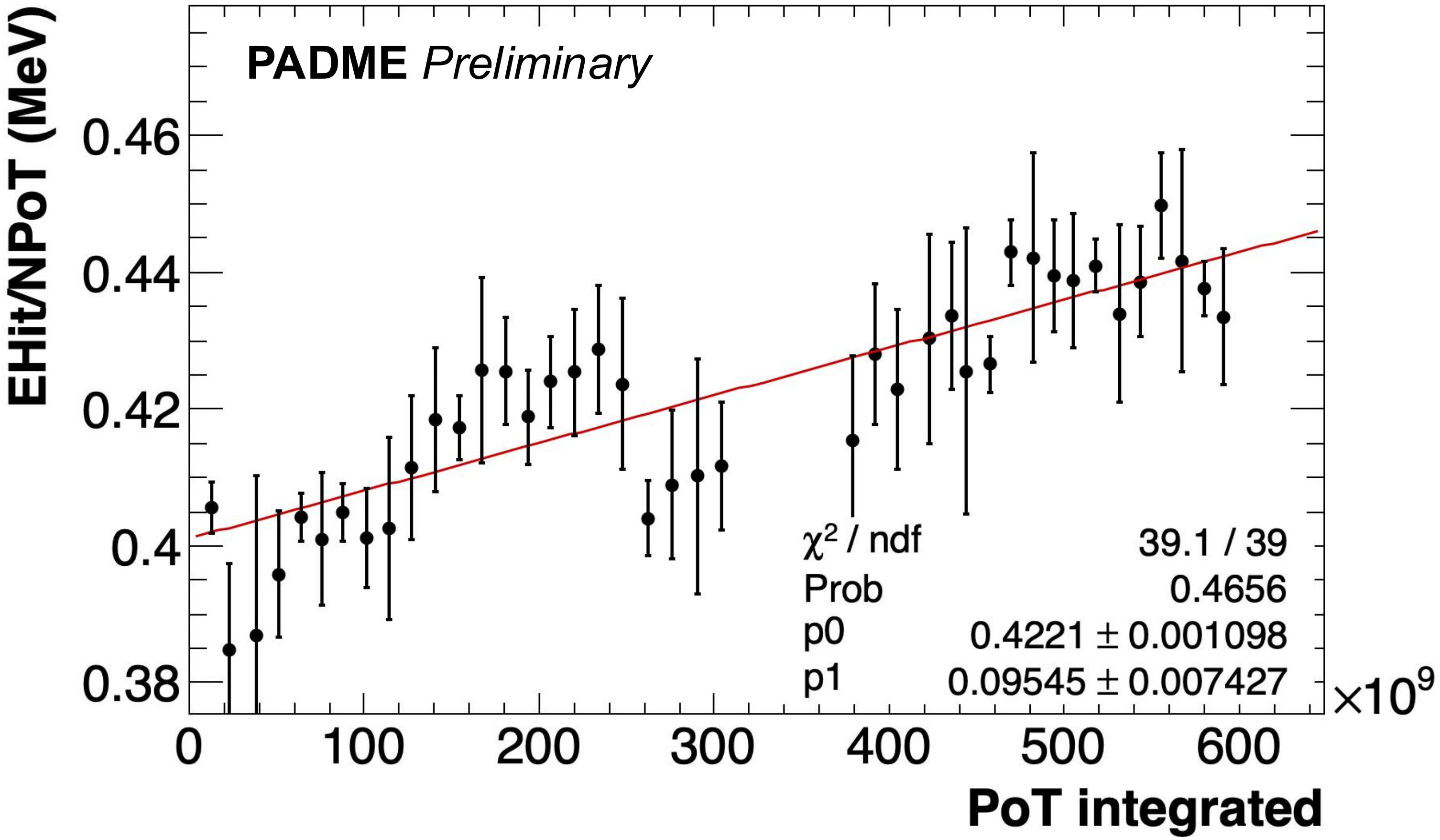
- Throughout Run 3 a total of 70e10 PoT (of ~ 300 MeV each) has passed though the Leadglass block → in terms of radiation this corresponds to a TID of 25 Gy (2.5 krad)
- The SF57 transmittance loss was never measured in literature however for similar blocks SF5-SF6 a significant loss is shown, especially near Cherenkov wavelengths. 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 ~ 75%

Radiation damage → Ehit/NPoT

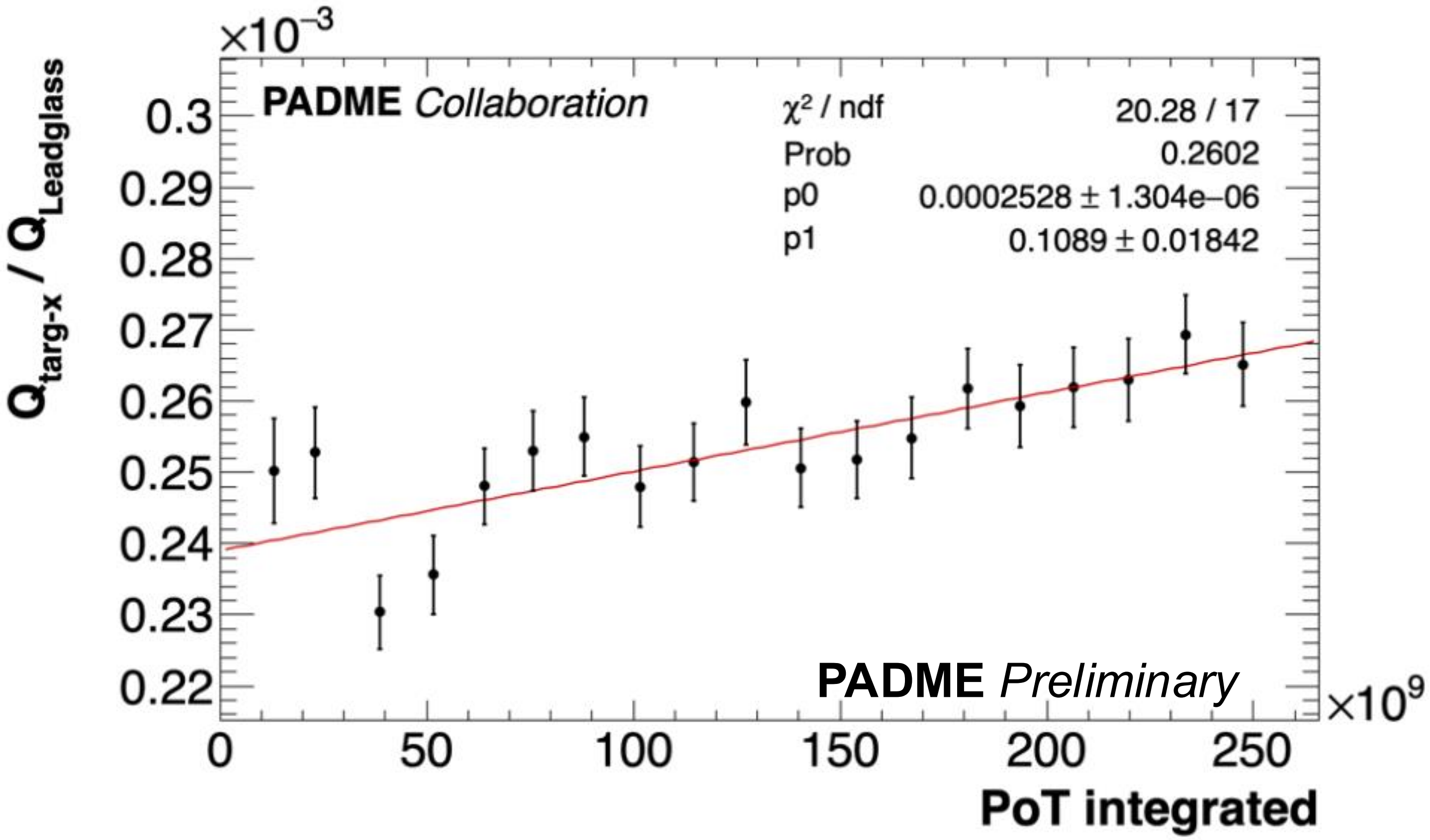
- First proof of loss of LY:
  - By looking at the ratio between the total energy per bunch in ECAL and the NPoT an increasing slope is visible → order 10%
  - Notice that EHit is particularly sensible to the beam spot variation (beam e^+ might enter) hence is prone to significant jumps between periods



Radiation damage → $Q_{targetX}/Q_{Leadglass}$

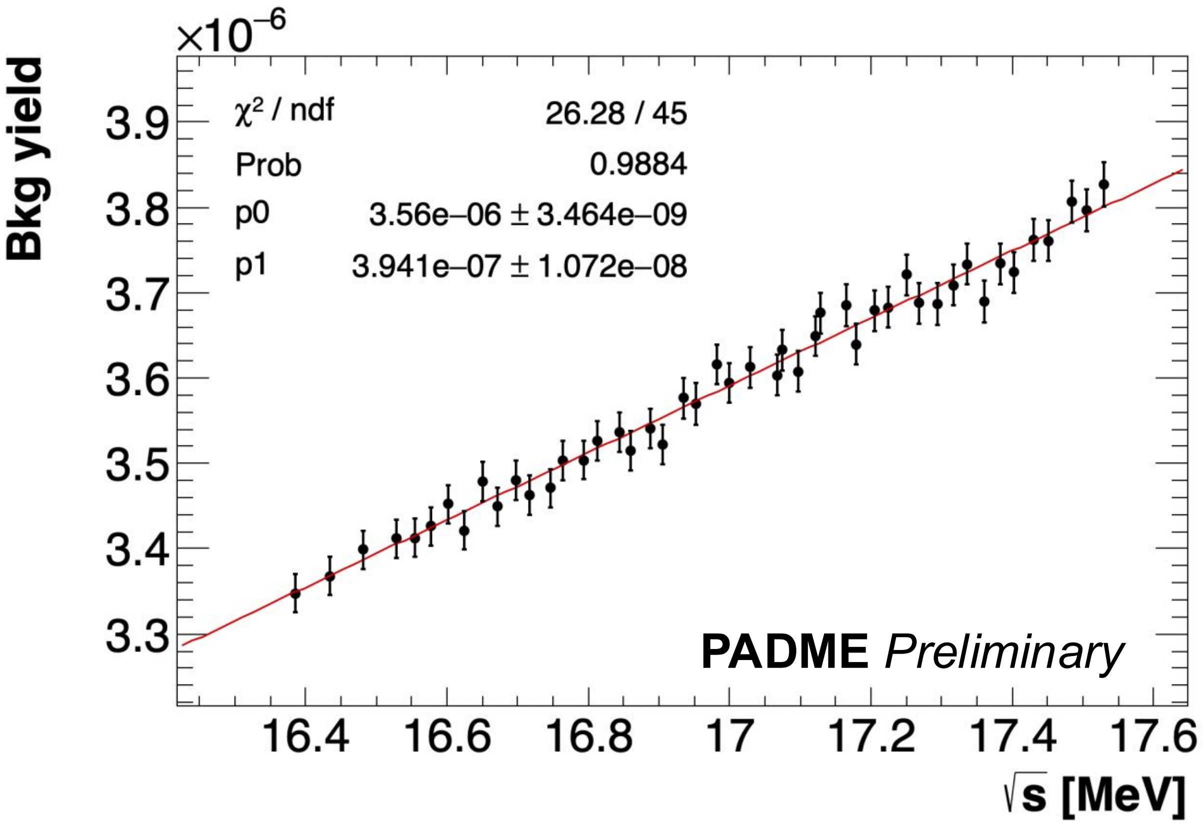
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

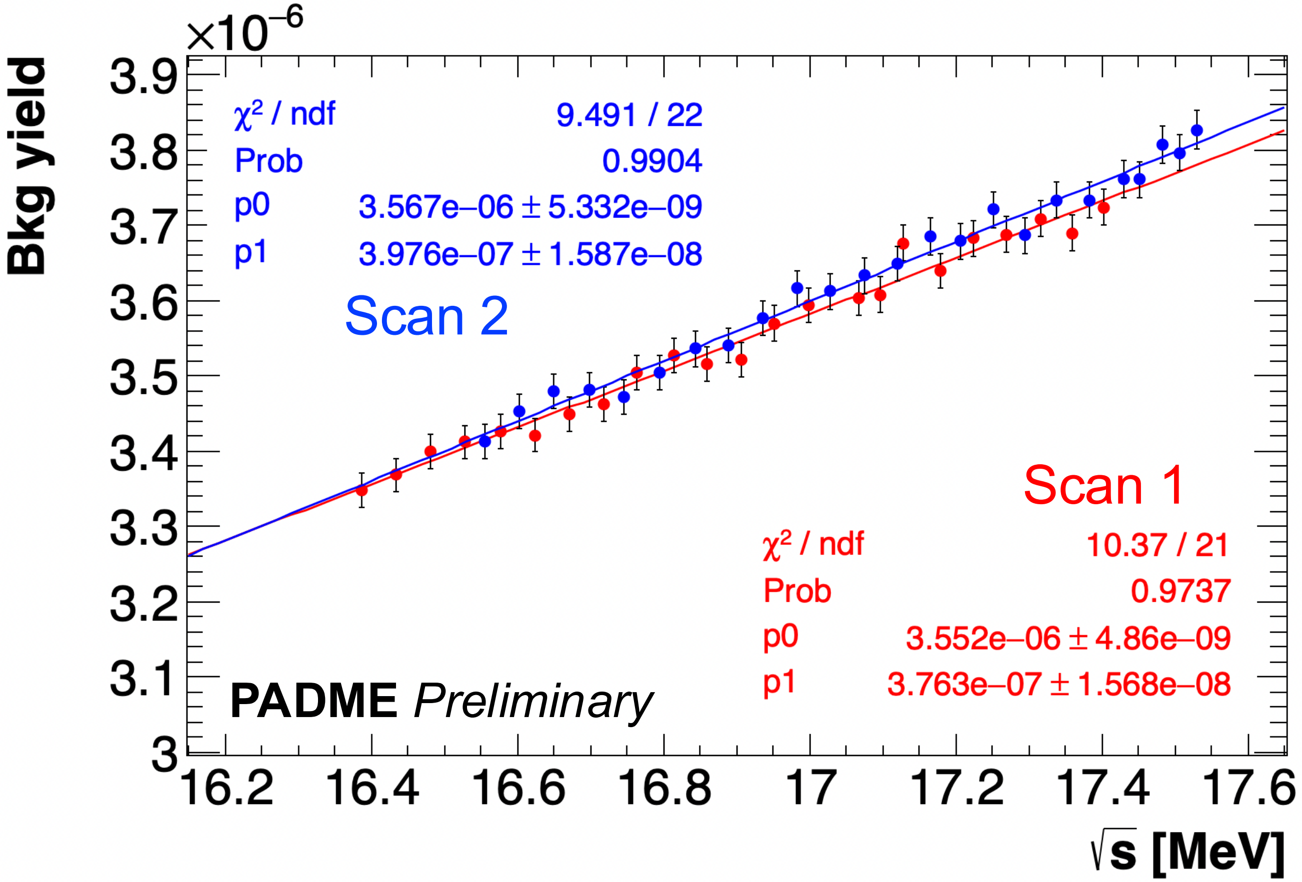
- Second proof of loss of LY:
  - Target X strips are way more sensible than Y → can be used for quantitative checks
  - Shows an increasing slope → order 10% also here
  - During scan 1 (fitted) there were no “no target runs” hence the Qx response is reliable just in that part of Run 3
- **Conclusion:**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



Bkg yield

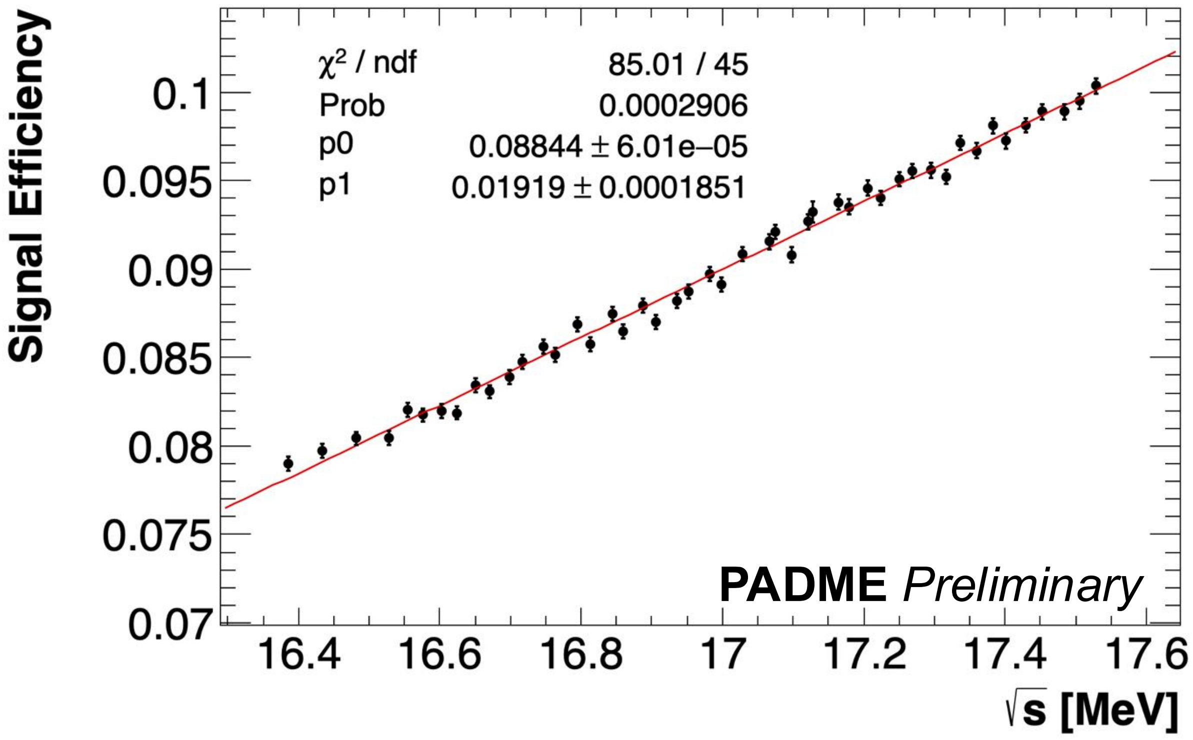
- 0.4% error → statistic, added 0.5% in quadrature to account the RMax cut systematics
- Possibility to treat separately the two scans in the sensitivity evaluation

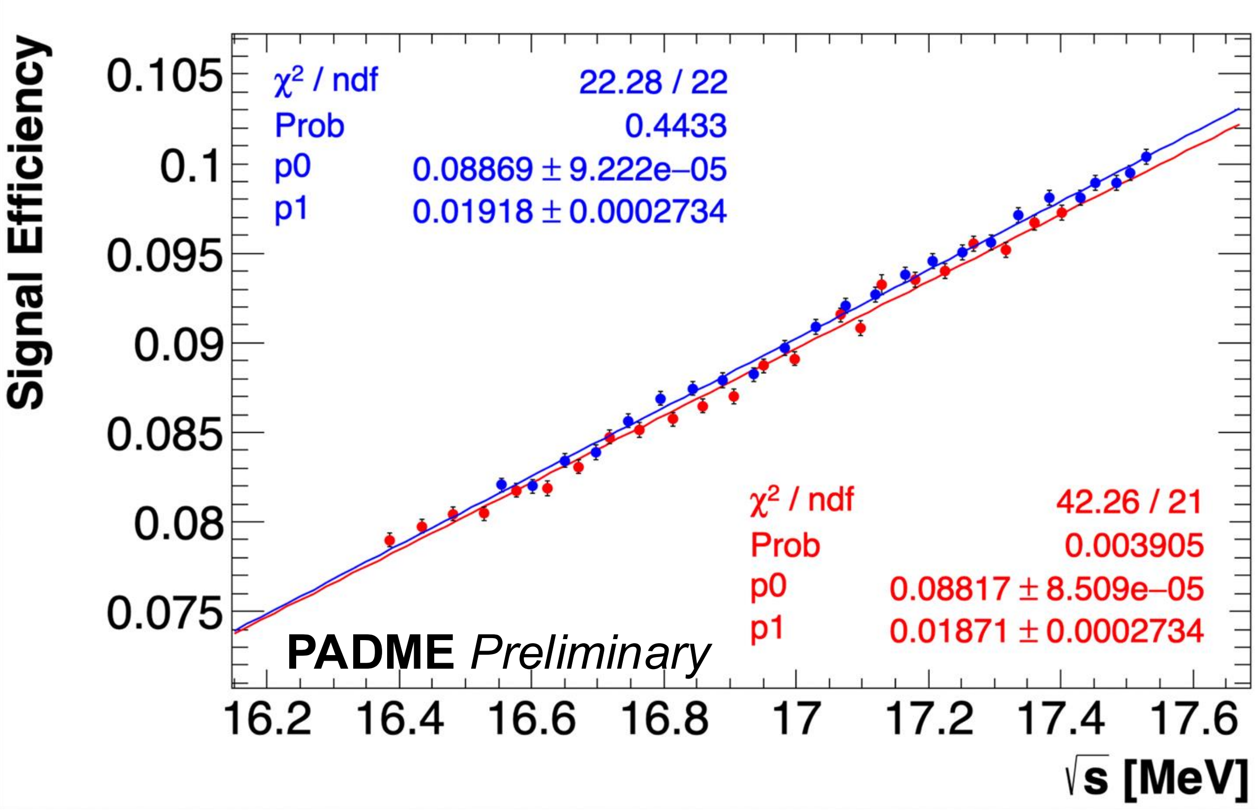




Signal efficiency

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





Rmax cut stability

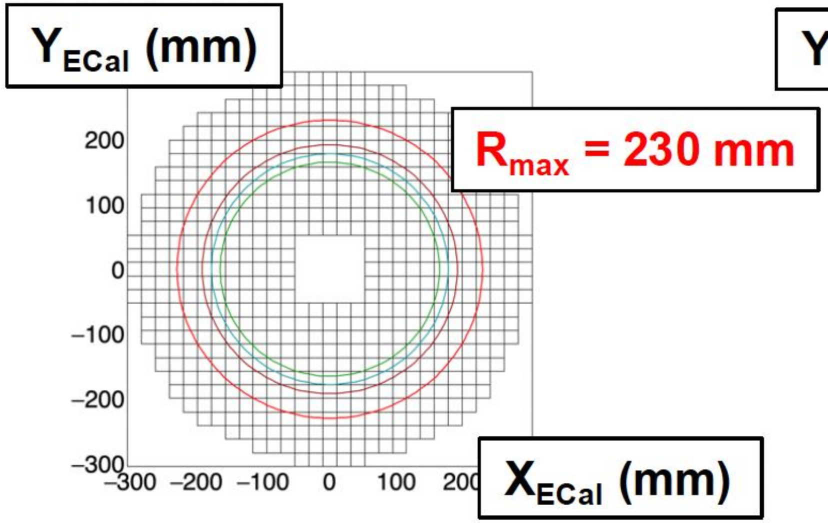
Check if MC and data yields stable vs R_{min}, R_{max} (edge effects, leakage)

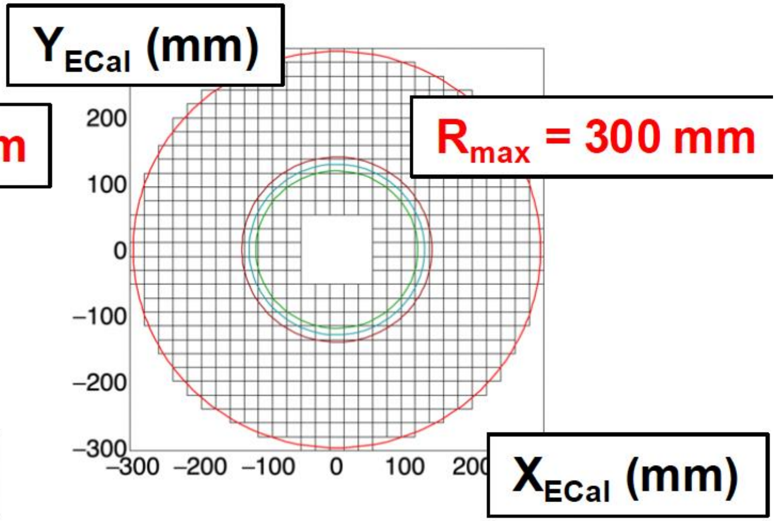
Vary R_{max} by +-2 E_{Cal} cells around nominal cut of 270 mm: 230 mm → 300 mm

Yield variation: -5%, +3%

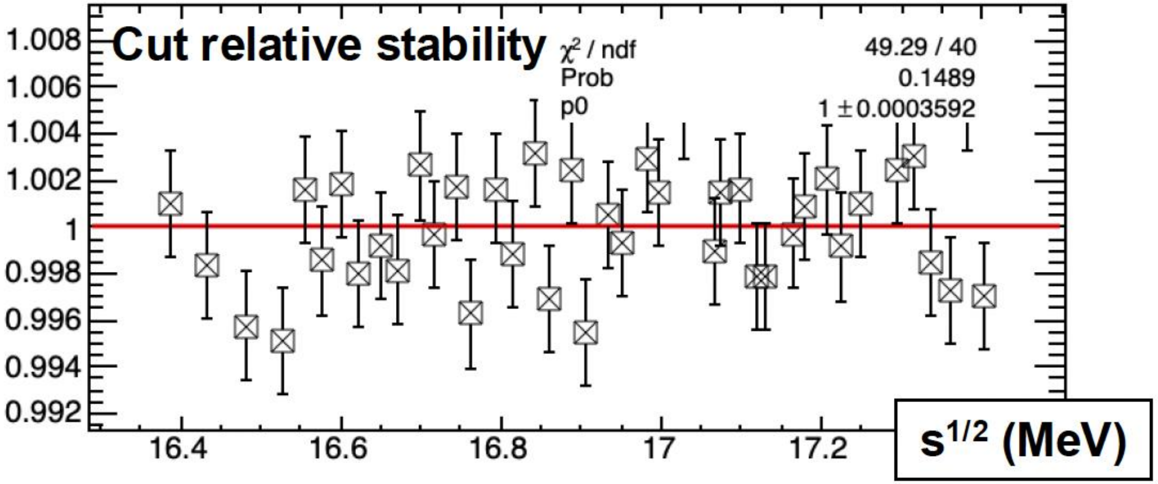
Uncorrelated error 0.3%

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



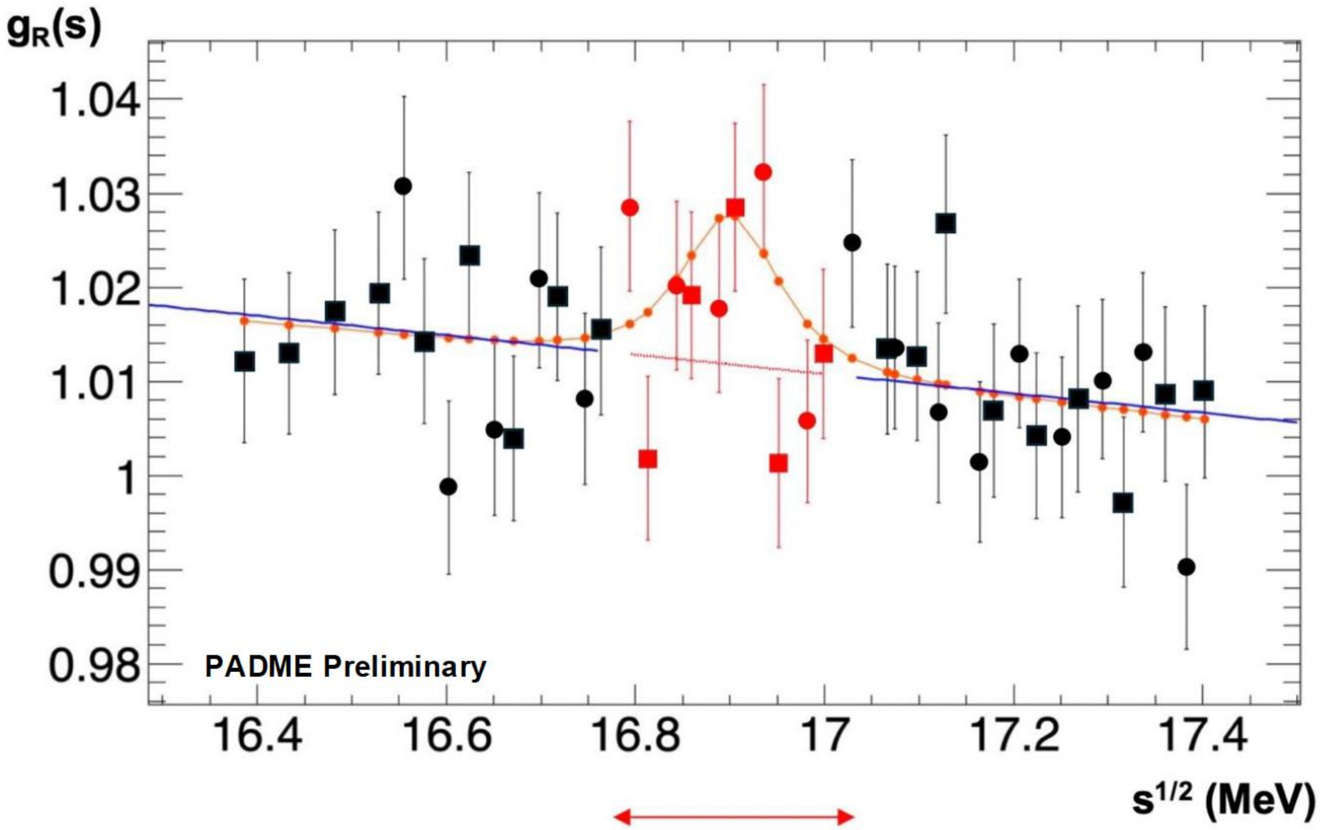


Stability is observed within a coverage band of +-0.2%, used as additional uncorrelated systematic error on B

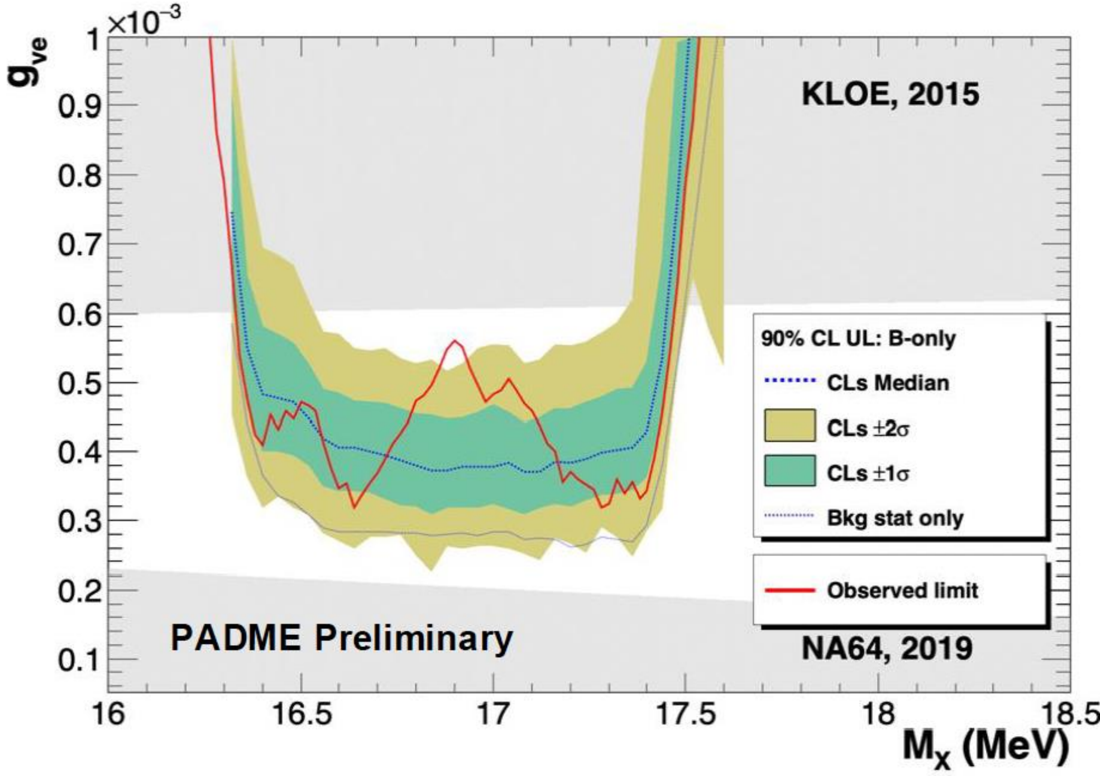


Box opening - 2

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



Region masked by automatic procedure



- Masked point of scan 1 (red square)
- Masked point of scan 2 (red circle)
- Sideband point of scan 1 (black square)
- Sideband point of scan 2 (black circle)

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)

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