

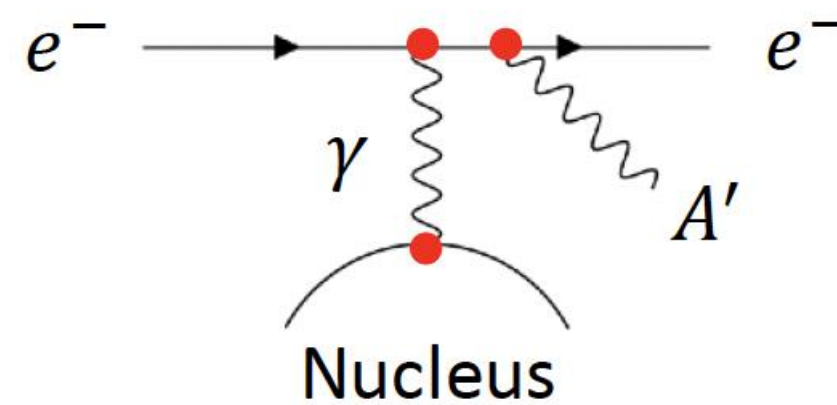


**Paolo Massarotti (University of Naples Federico II and INFN Naples) on behalf of the PADME Collaboration**

**10<sup>th</sup> Workshop on Theory, Phenomenology and Experiments in Flavour Physics, 29<sup>th</sup> September 2026**

## Dark bremsstrahlung

$$m_{A'} < E_{beam}$$

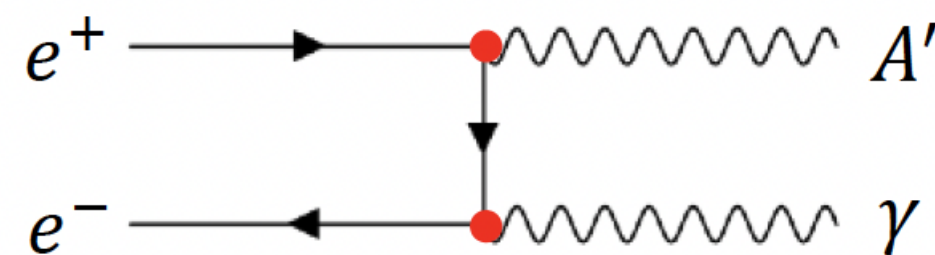


$$\sigma \propto \frac{\epsilon^2 \alpha^3}{m_{A'}^2}$$

Missing momentum

## Associated production

$$m_{A'} < \sqrt{2m_e E_{beam}}$$

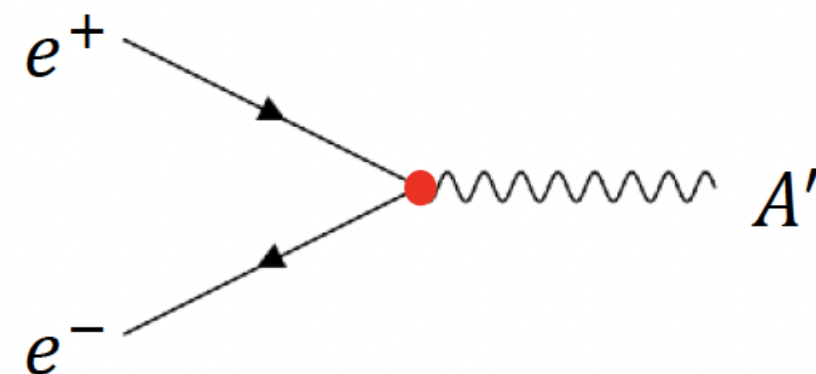


$$\sigma \propto \epsilon^2 \alpha^2$$

Missing mass

## Resonant annihilation

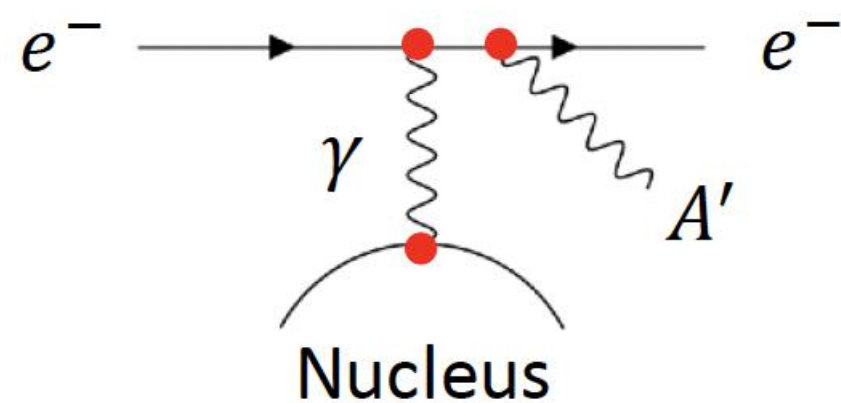
$$m_{A'} \approx \sqrt{2m_e E_{beam}}$$



$$\sigma \propto \epsilon^2 \alpha$$

## Dark bremsstrahlung

$$m_{A'} < E_{beam}$$

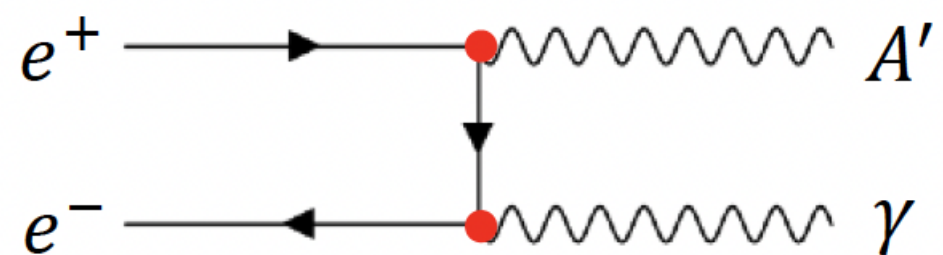


$$\sigma \propto \frac{\epsilon^2 \alpha^3}{m_{A'}^2}$$

Missing momentum

## Associated production

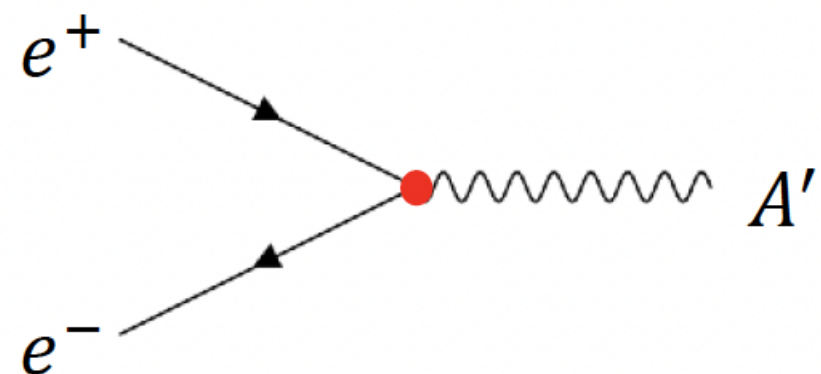
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## Resonant annihilation

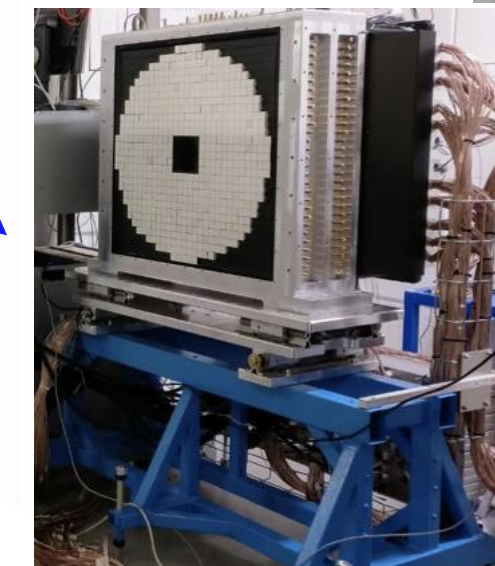
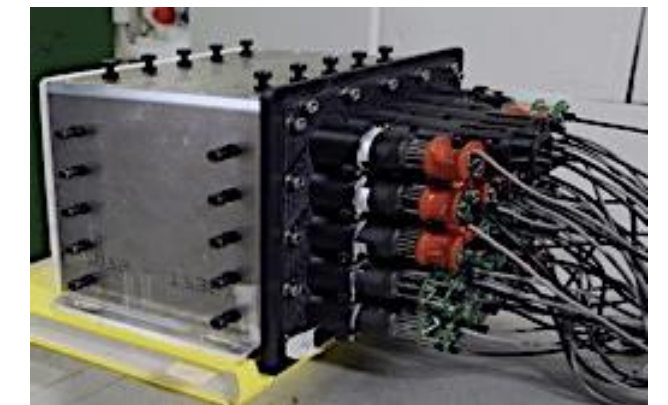
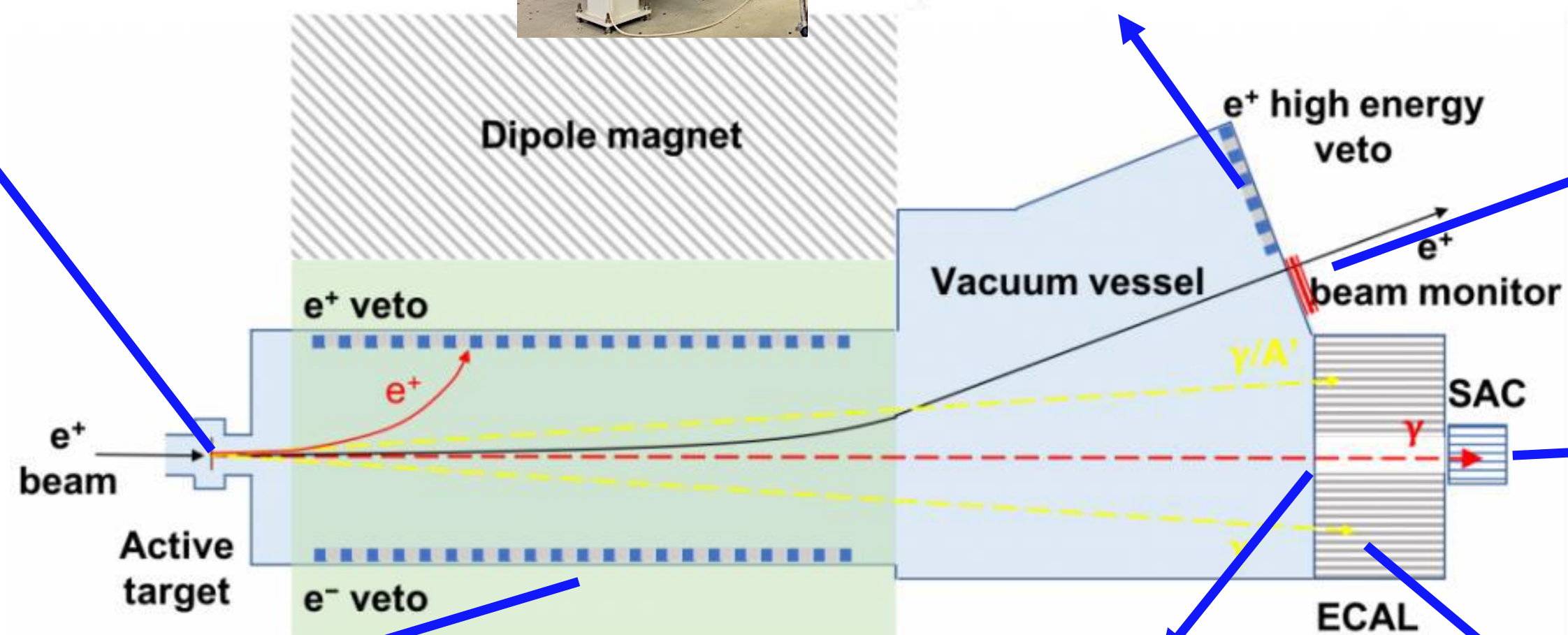
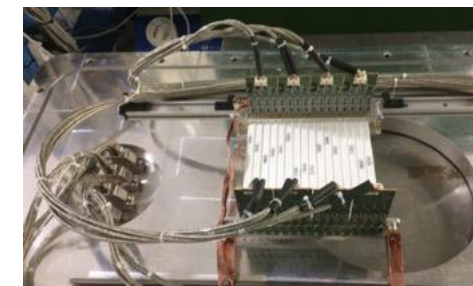
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$$\sigma \propto \epsilon^2 \alpha$$

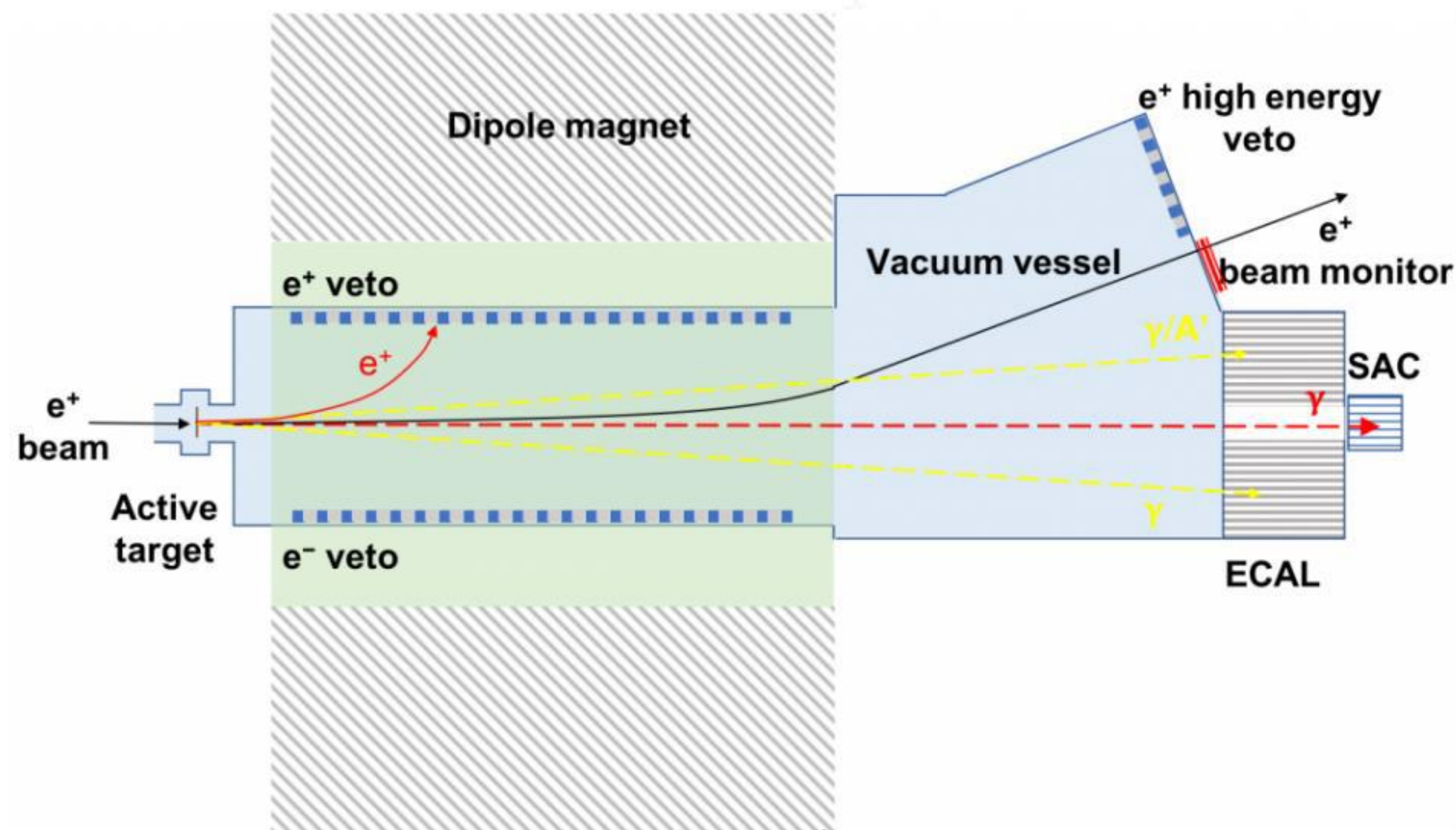
PADME Run I & II (A')

PADME Run III & IV (X17)



**PADME** (**P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment) was designed to search for  $A'$  (dark photon) at BTF (LNF) through resonant annihilation ( $e^+e^- \rightarrow \gamma A'$ ) of  $e^+$  beam ( $E < 550 \text{ MeV}$ ) on 100  $\mu\text{m}$  thick diamond target.

- magnetic dipole to curve charged particles
- Signal:  $1\gamma$  in the BGO crystals of the Electromagnetic Calorimeter (ECal) + nothing else  $\rightarrow$  access to  $\Delta M_{\text{miss}}^2$  and infer on  $m_{A'}$
- Bremsstrahlung suppressed thanks to the central hole of ECal and the Small Angle Calorimeter (SAC)
- Plastic scintillator used as charged particle veto

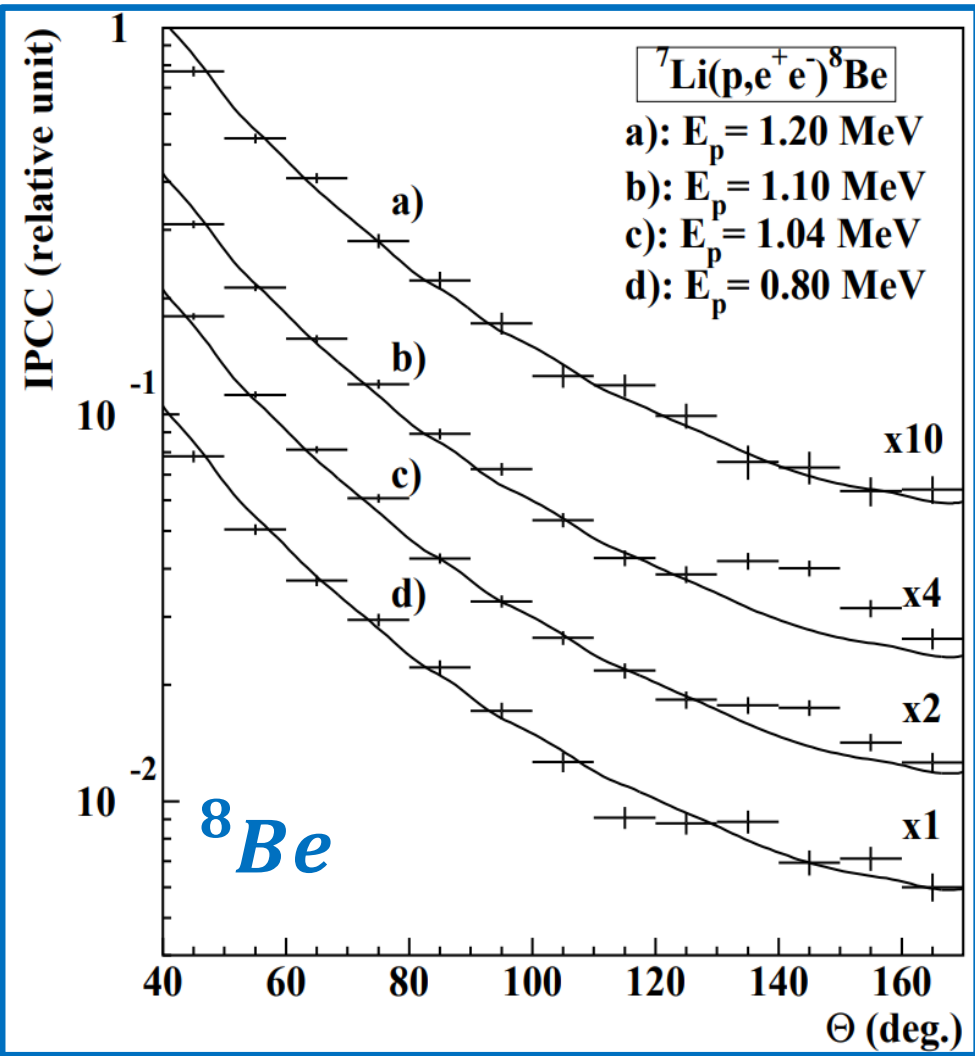
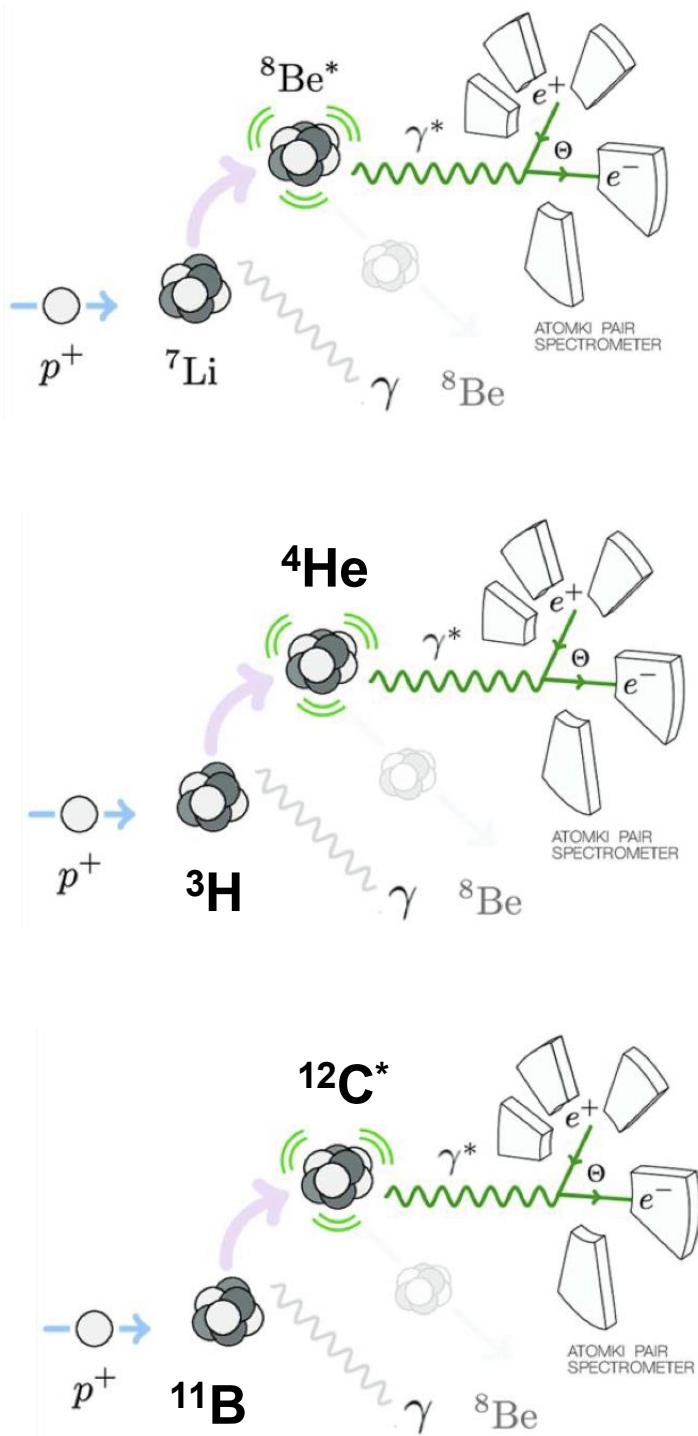


ATOMKI Collaboration:

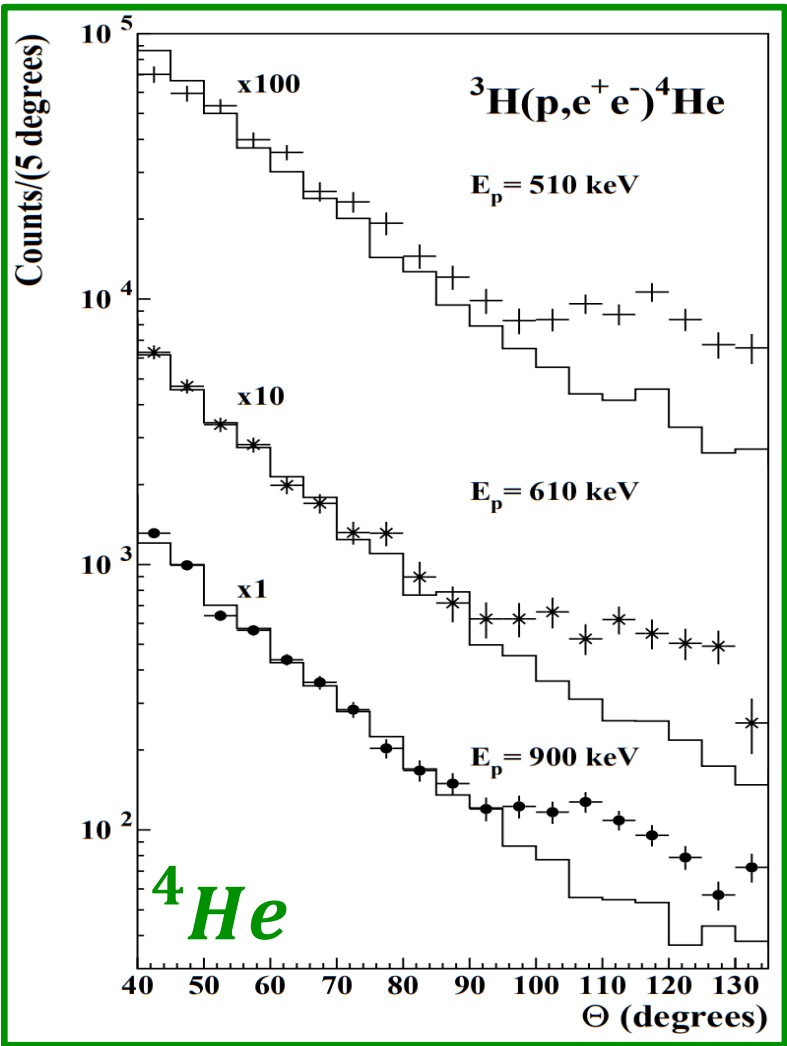
Anomalous excesses in angular correlation of  $e^+e^-$  couples produced via Internal Pair Creation of  $^8\text{Be}$ ,  $^4\text{He}$  and  $^{12}\text{C}$  observed by A.

Krasznahorkay & collaborators

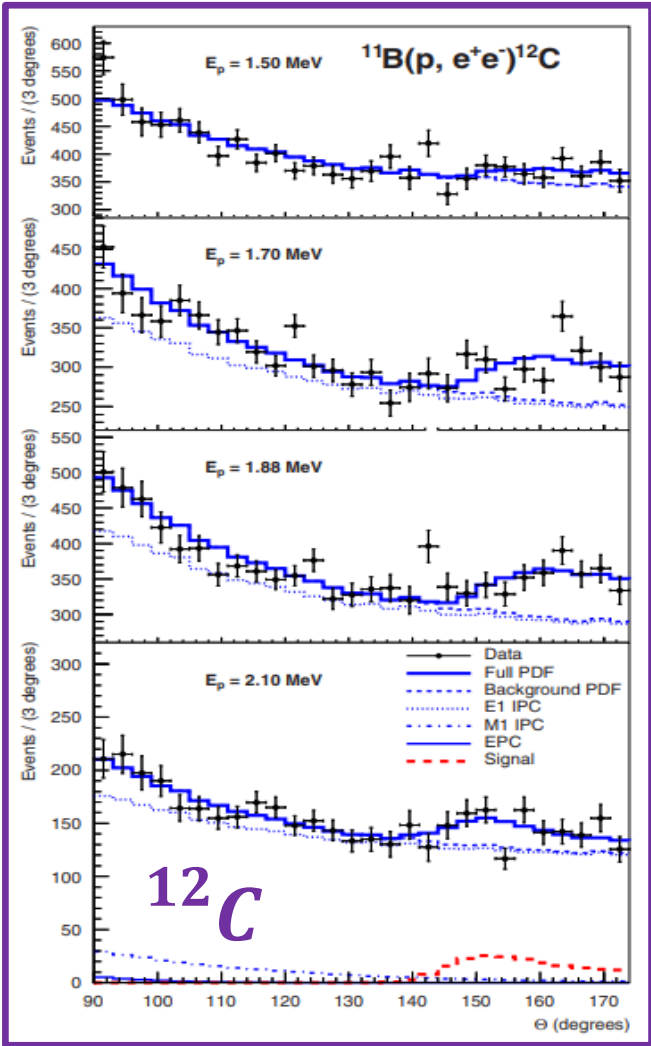
Phys.Rev.Lett. 116 (2016) 4, 042501



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



Phys. Rev. C 106, L061601

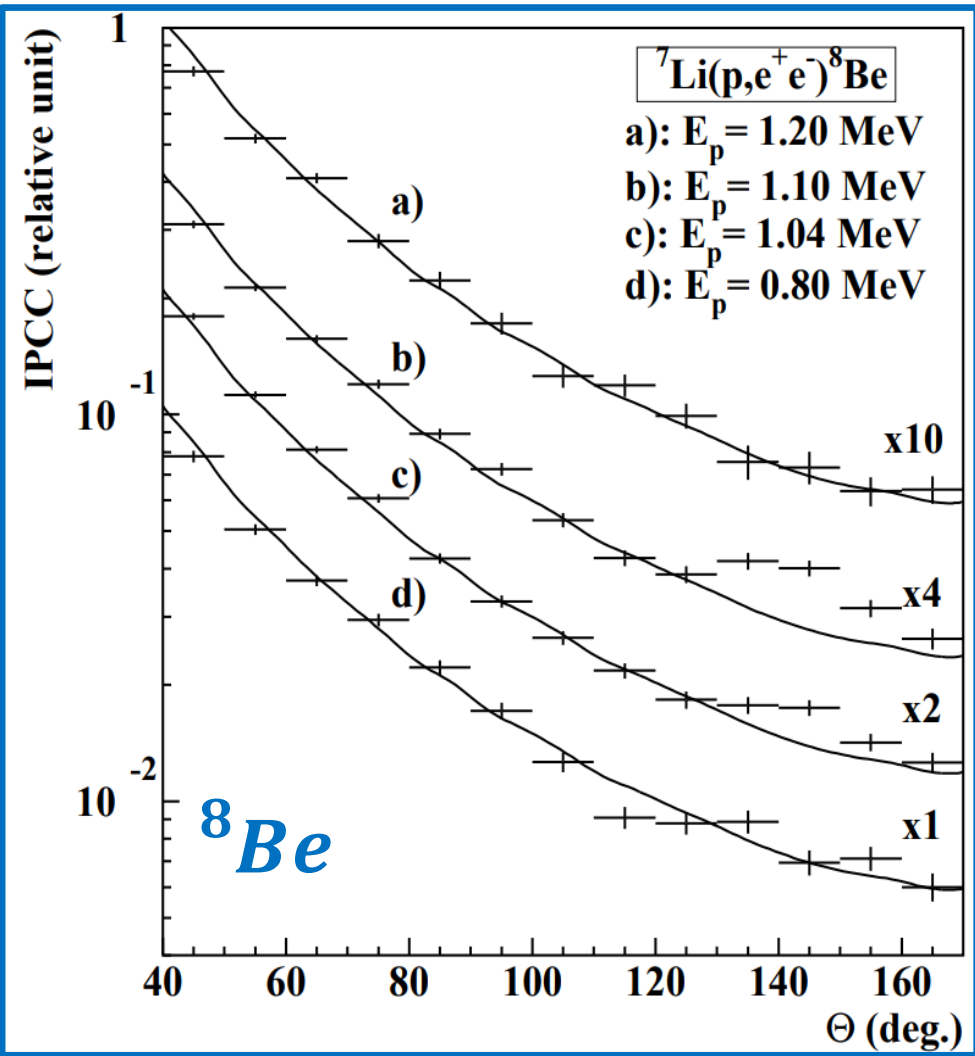


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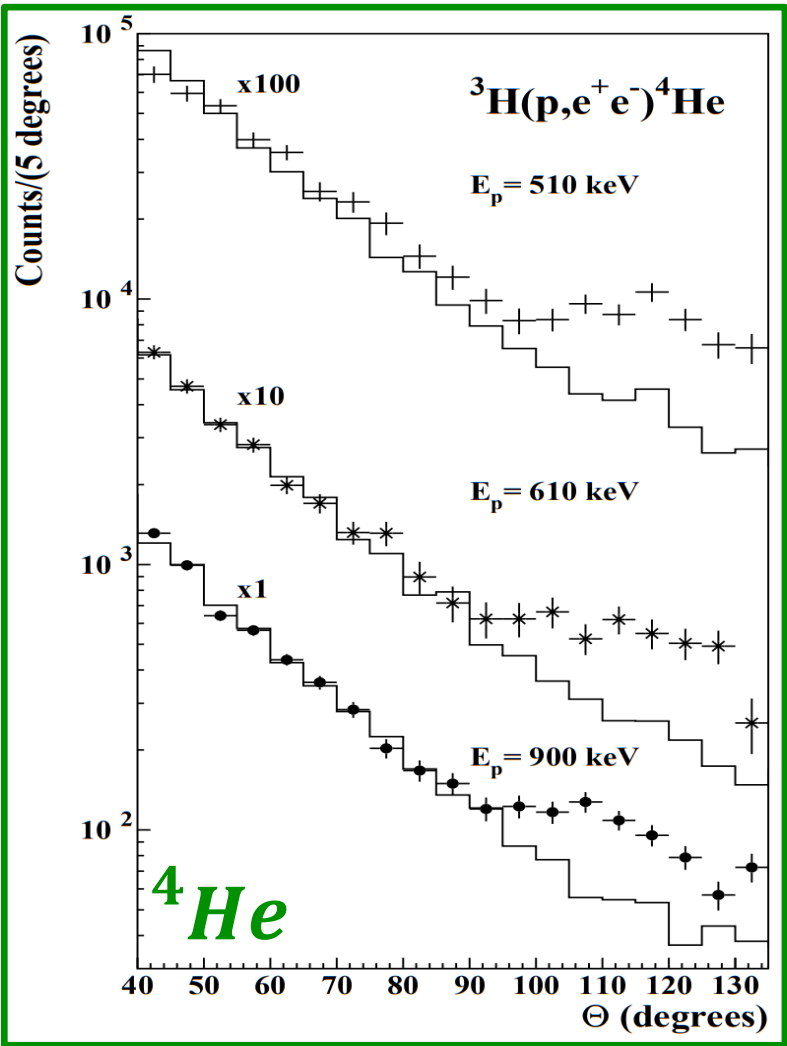
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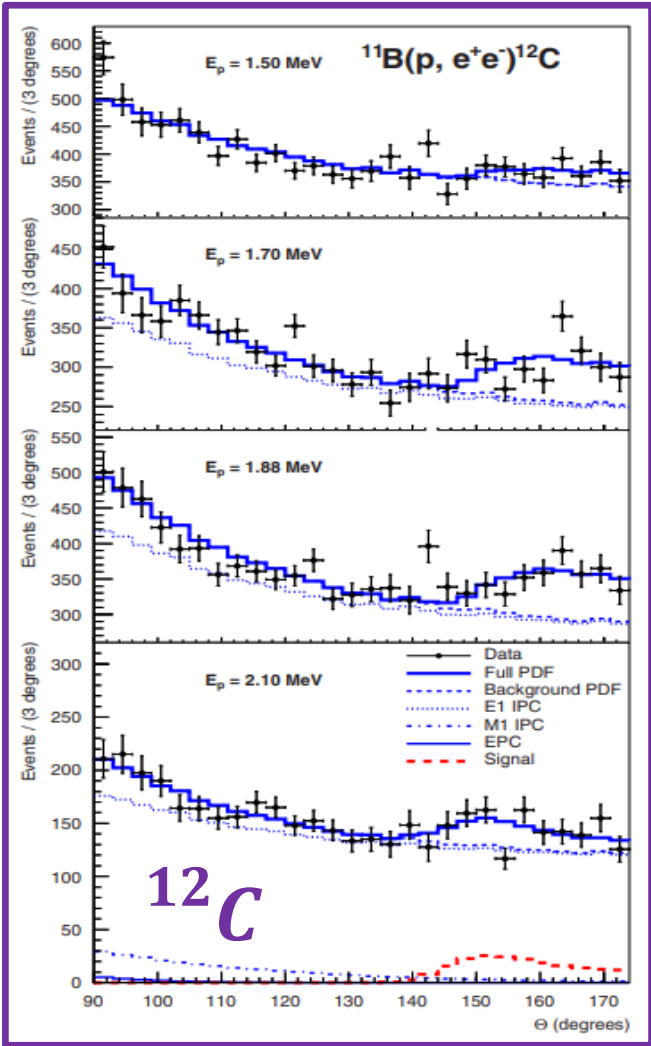
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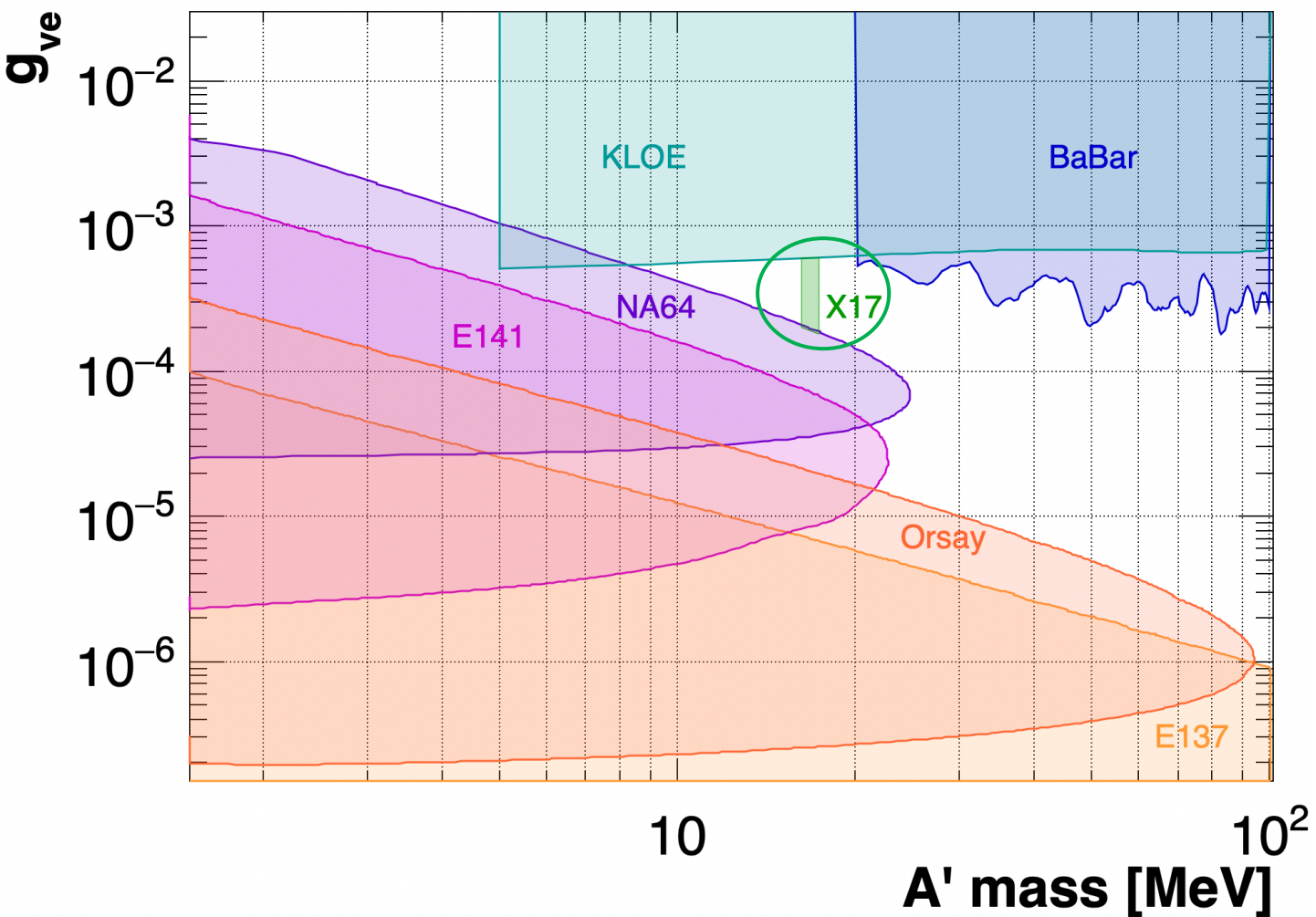
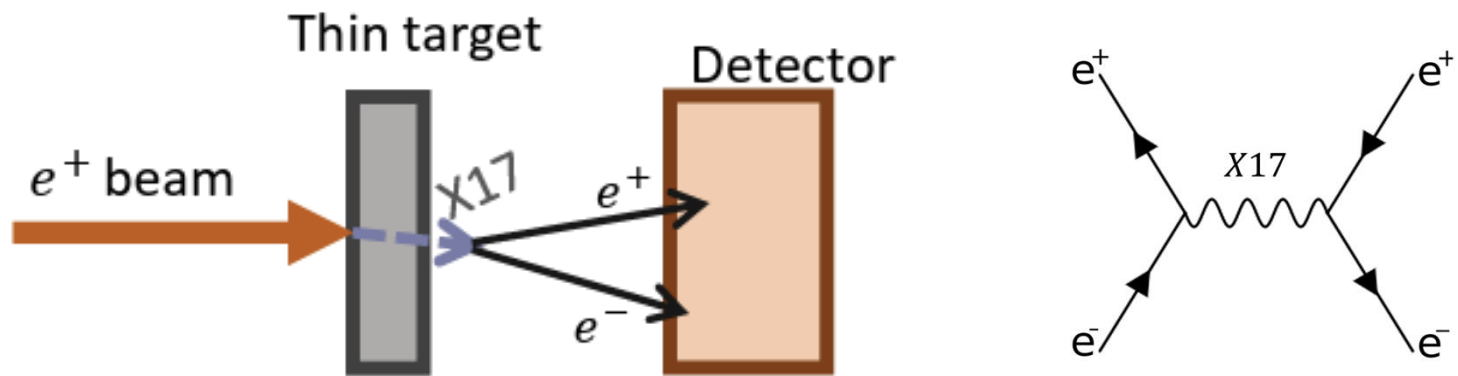
$$\theta_{ee}^{min} \approx 2\arcsin\left(\frac{m_{X17}}{m_{N^*} - m_N}\right)$$

The anomaly seems to be compatible with the production and decay of a new  $\sim 17$  MeV mass particle

PADME is searching for such an excess in collider collisions of  $e^+$  on fixed target at the Beam Test Facility (BTF) of the LNF

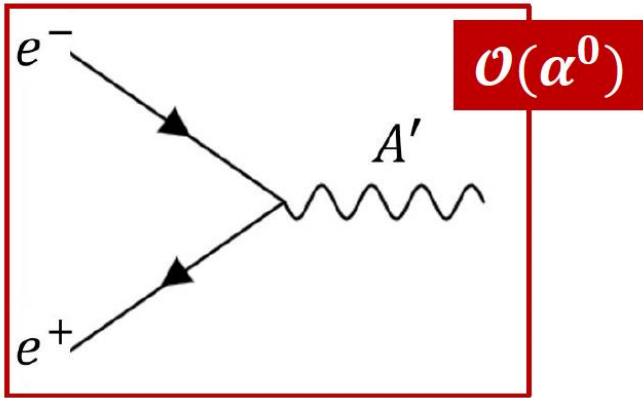
Vector and Axial-Vector models are theoretically favoured (imposing parity conservation on ATOMKI observations)

still some phase-space available for X17



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

$\sigma_{res} \propto \frac{g_{ve}^2}{2m_e} \pi Z \delta(E_{res} - E_{beam})$  Resonant annihilation is the dominant process with respect to alternative signal production processes  $e^+ e^- \rightarrow A'$



# Strategy for X17

$\sigma_{res} \propto \frac{g_{Ve}^2}{2m_e} \pi Z \delta(E_{res} - E_{beam}) \rightarrow$  Search performed through resonant annihilation

$\sqrt{s}$  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

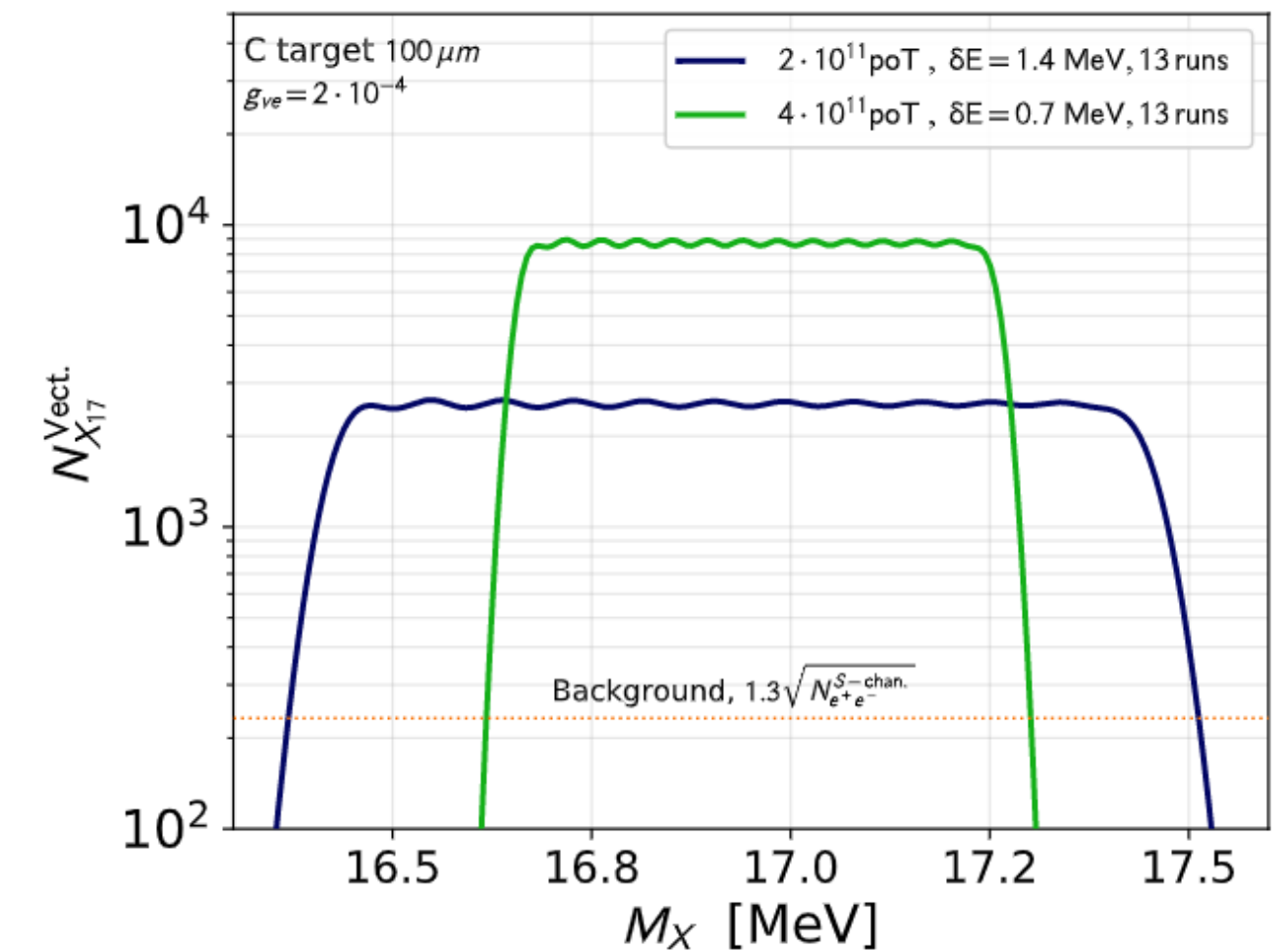
A beam energy of 282 MeV leads to an available c.m. energy of  $\sqrt{s} \approx 17$  MeV

- energy scan with step of 0.7 MeV performed between 260 MeV and 300 MeV ( $10^{10}$  positrons on target per point) aiming to measure 2 body final state yield  $N_2(s)$
- In the approximation with  $e^-$  at rest, expected number of  $X_{17}$  events is:

$$N_{vector}^{perPoT} \simeq \frac{g_{Ve}^2}{2m_e} \ell_{tar} \frac{N_A \rho Z}{A} f(E_{res}, E_{beam}) \sim 1.8 \times 10^{-7} \times \left( \frac{g_{Ve}}{2 \cdot 10^{-4}} \right)^2 \left( \frac{1 \text{ MeV}}{\sigma_E} \right)$$

where the beam energy spread  $\sigma_E$  has to be kept below 0.5%

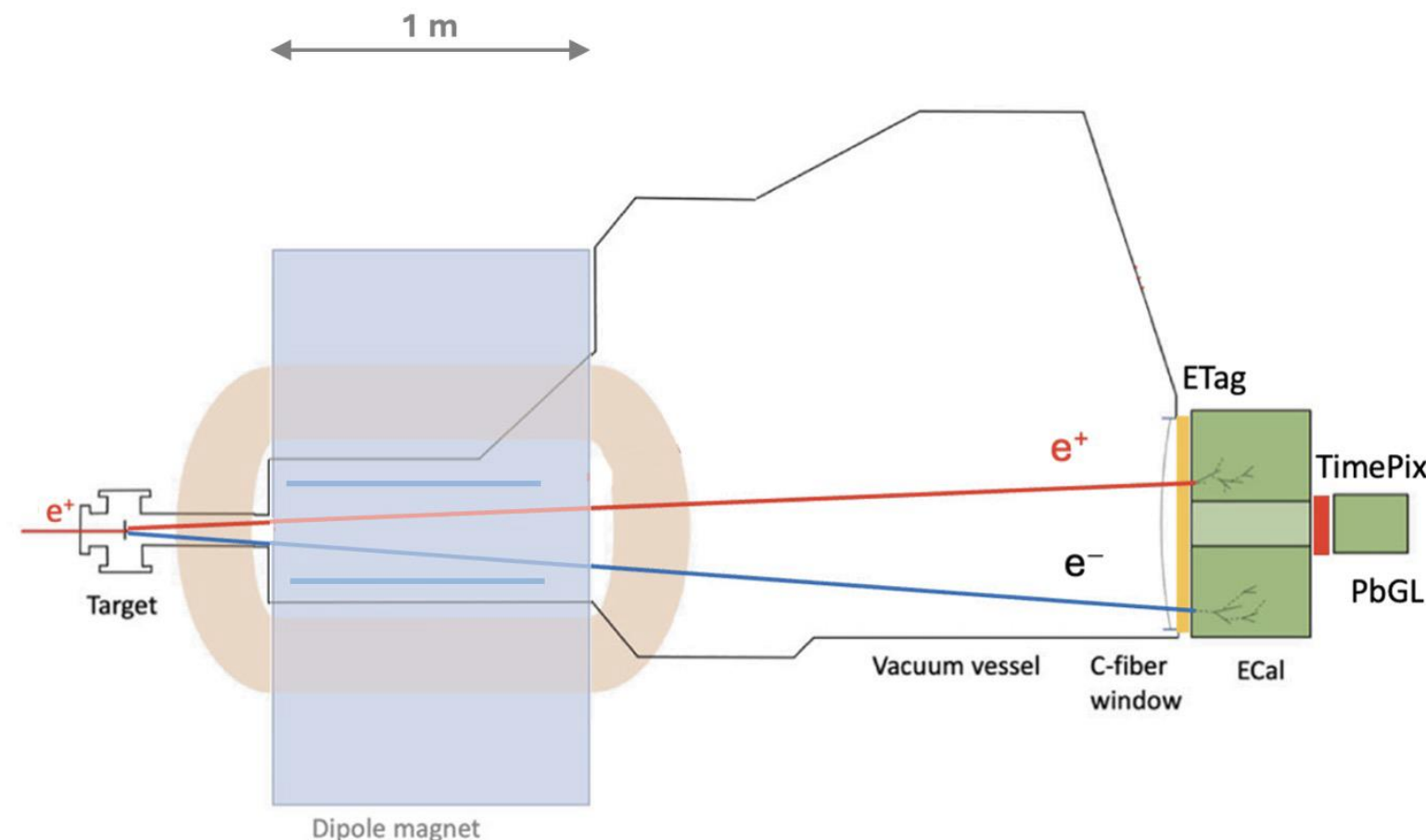
PhysRevD.106.115036



**Analysis strategy: fine scan of the beam energy, bkg fitting, luminosity calibration and ... search for the resonance!**

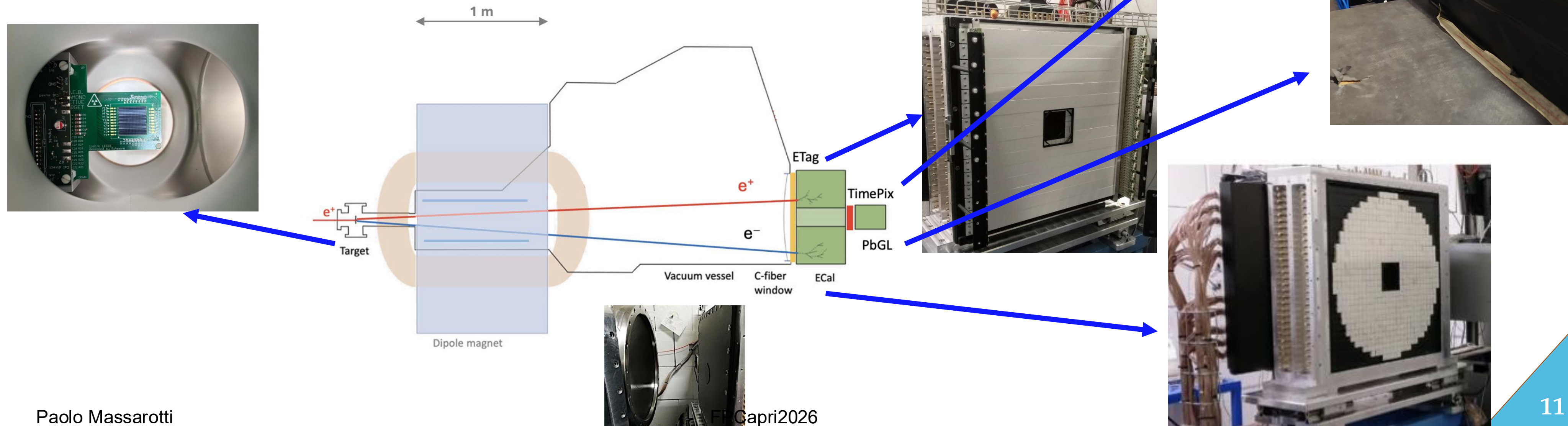
Main SM background processes are Bhabha scattering and  $\gamma\gamma$  pairs production, evaluated directly from data therefore some setup optimization is necessary:

- Active diamond **target**
- **Charged particle veto** not used
- **ECal**: 616 BGO crystals, each  $21 \times 21 \times 230$  mm<sup>3</sup>
- PADME dipole turned off  $\rightarrow$  no magnetic field after the target interaction
- New **hodoscope (ETag)** in front of ECAL added to identify charged particles (PID)
- End of line **TimePix3** beam monitor and a **Leadglass** luminometer (better POT measurement)



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## Data-taking divided in 3 parts:

**On resonance points @ (263-292) MeV → scan 1 and 2:** 0.75 MeV spacing, 16.4

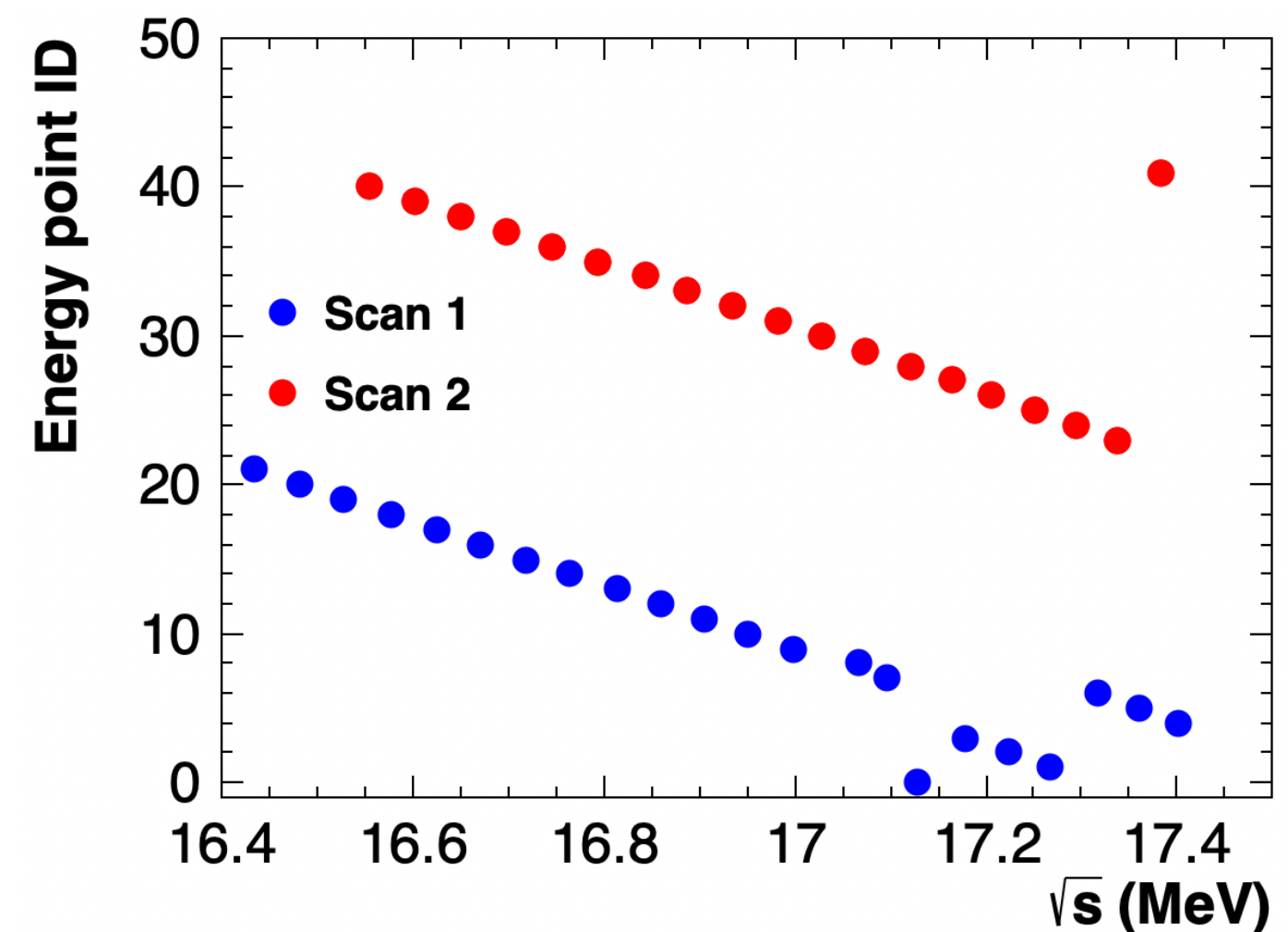
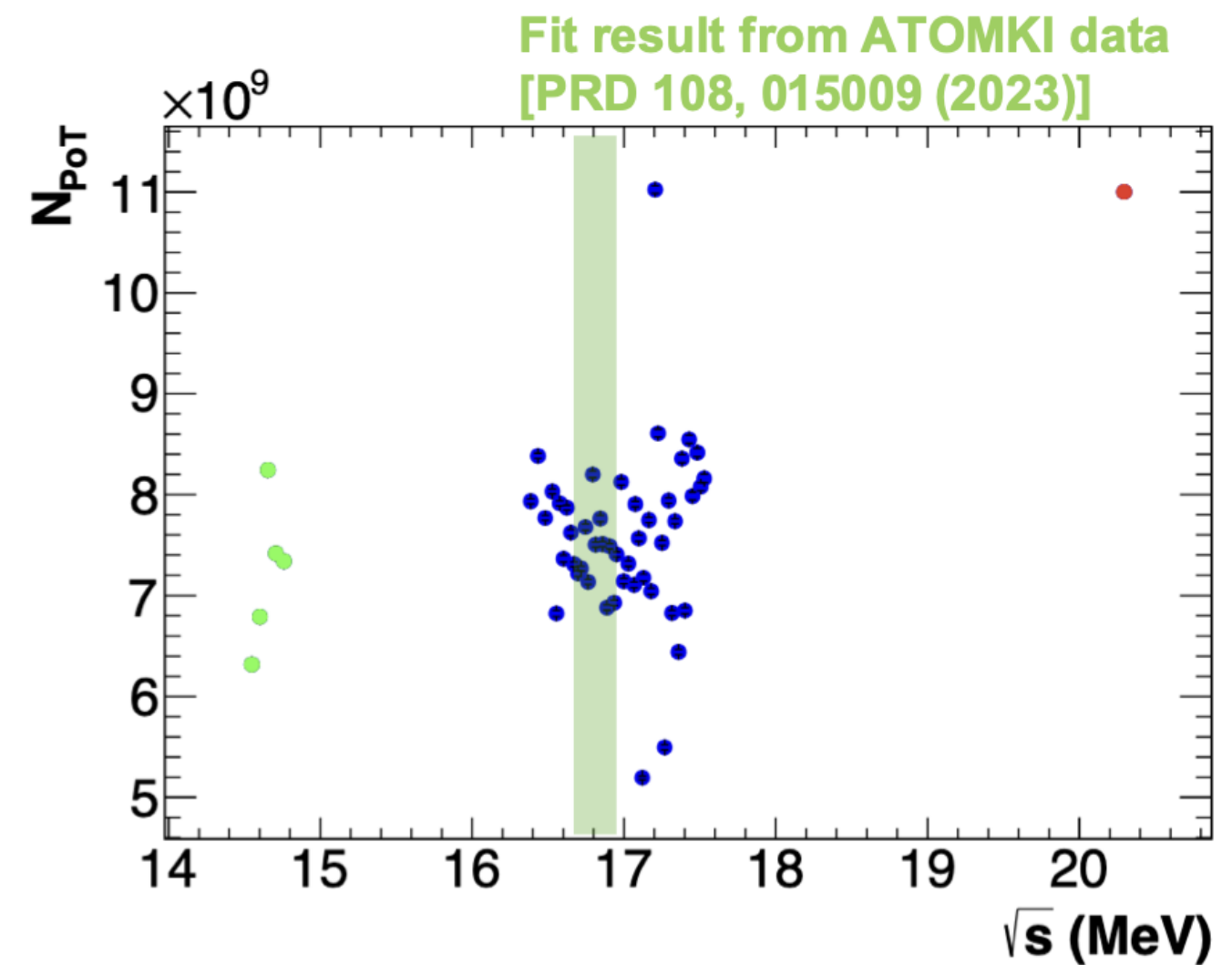
MeV <  $M_{X17}$  < 17.4 MeV,  $\sim 0.8 \times 10^{10}$   $N_{PoT}$  per point

**Below resonance points @ (205-211) MeV:** 1.5 MeV spacing, used to normalize the absolute yield

**Over resonance runs @ 402.5 MeV:**  $1.2 \times 10^{10}$  stat, used to validate  $N_{PoT}$  measurement

We define:

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

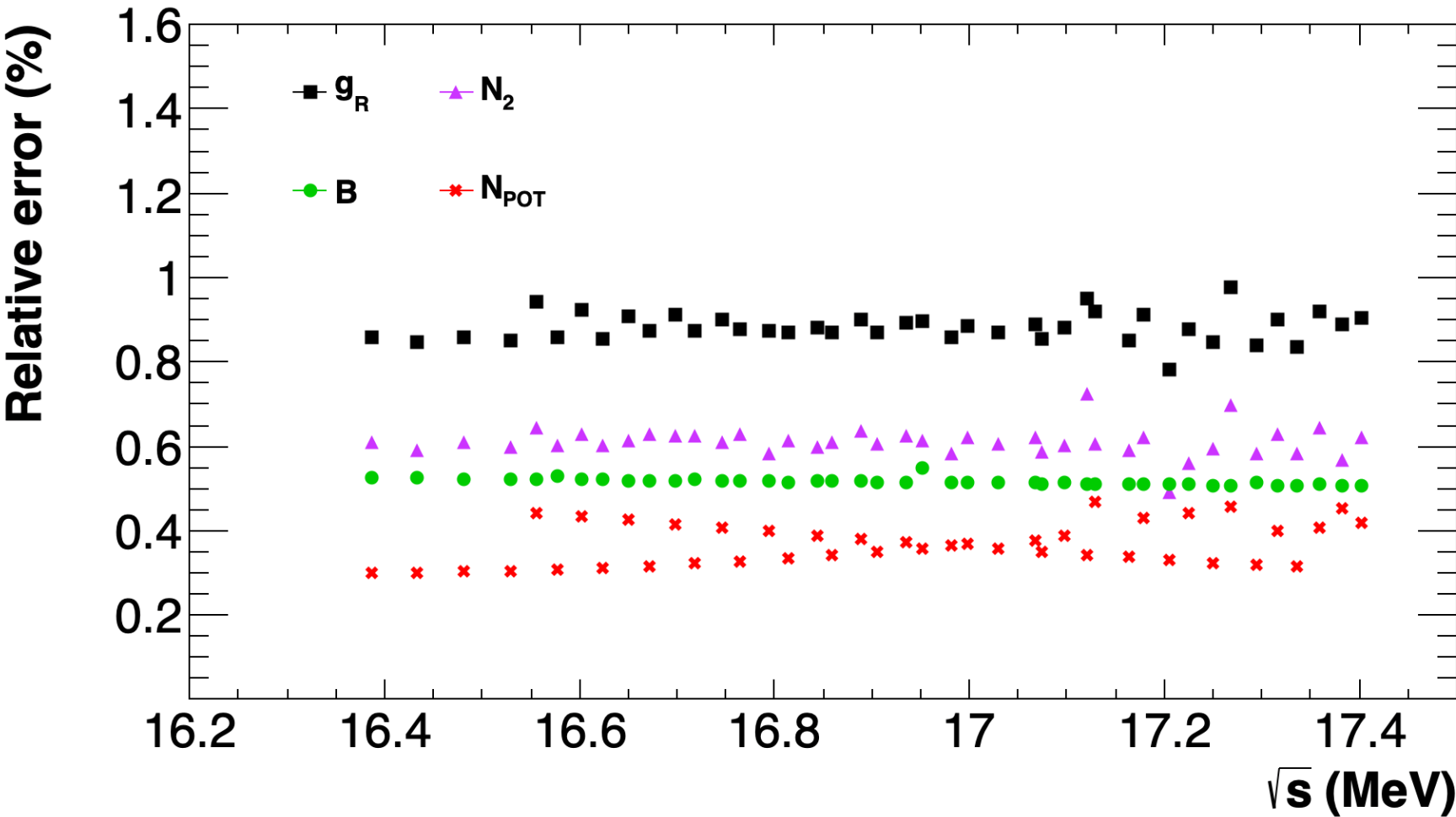


**Strategy:** compare the yield of 2 EM cluster events collected by ECal with the SM expected one, creating a custom  $g_R(s)$  observable sensible to BSM physics

$$g_R(s) = N_2(s) / (N_{PoT}(s) \times B(s)) = K(s) [1 + S(s; M_X, g) \epsilon_S(s)/B(s) ]$$
  
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  $\{mass, coupling\} = \{M_X, g\}$
- $\epsilon_S(s)$  signal acceptance and selection efficiency
- $K(s)$  DATA-MC scale factor with a possible dependence from  $s$   
(radiative effects)



| 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                                     | $-0.6 \pm 0.6$                   |

**Strategy:** compare the yield of 2 EM cluster events collected by ECal with the SM expected one, creating a custom  $g_R(s)$  observable sensible to BSM physics

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

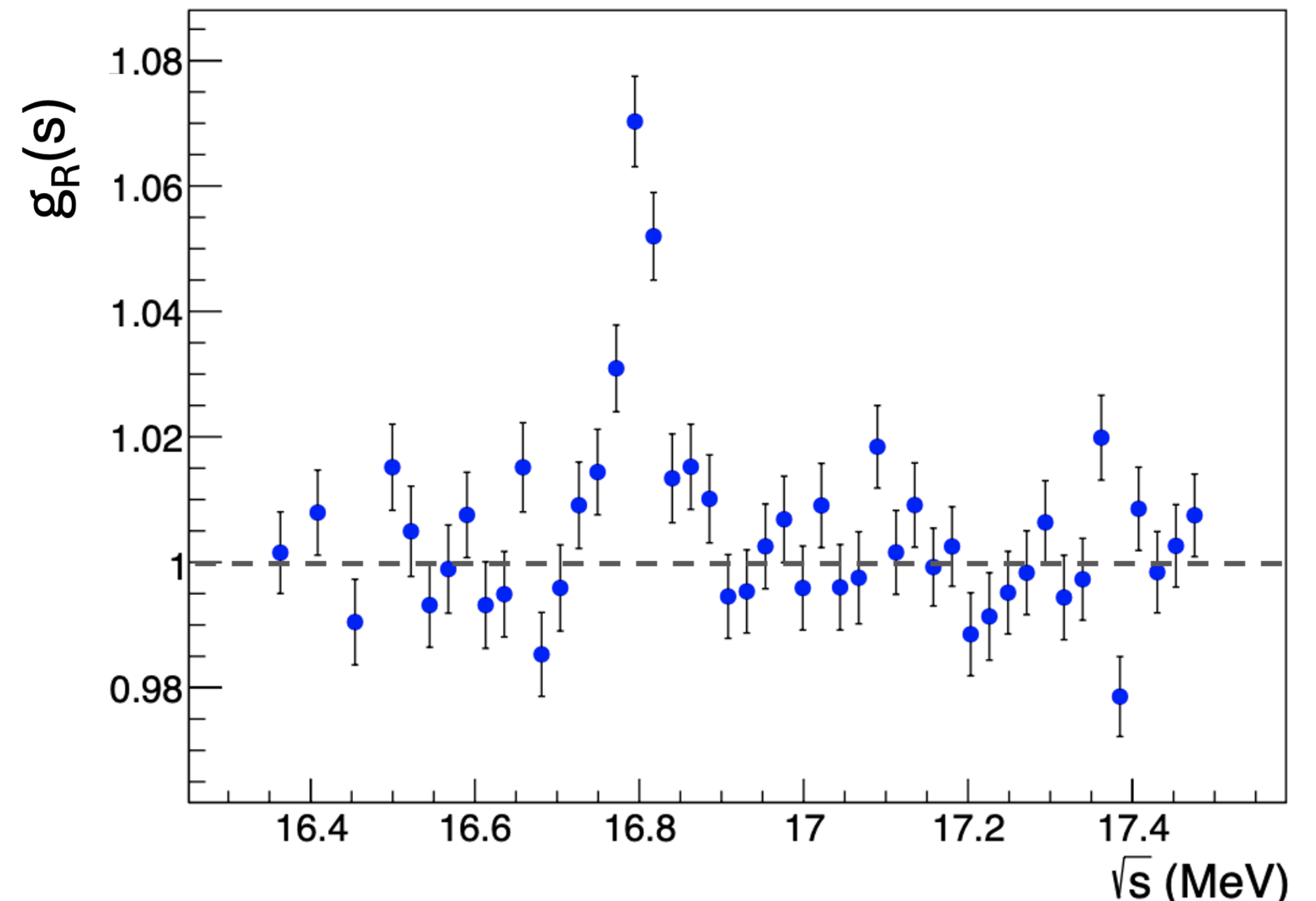
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MC Simulation with  $M_X=16.8$  MeV,  $g_V = 8 \times 10^{-4}$



# RunIII: expected sensitivity

**Likelihood fits** performed for separate assumptions of **S+B vs B**,

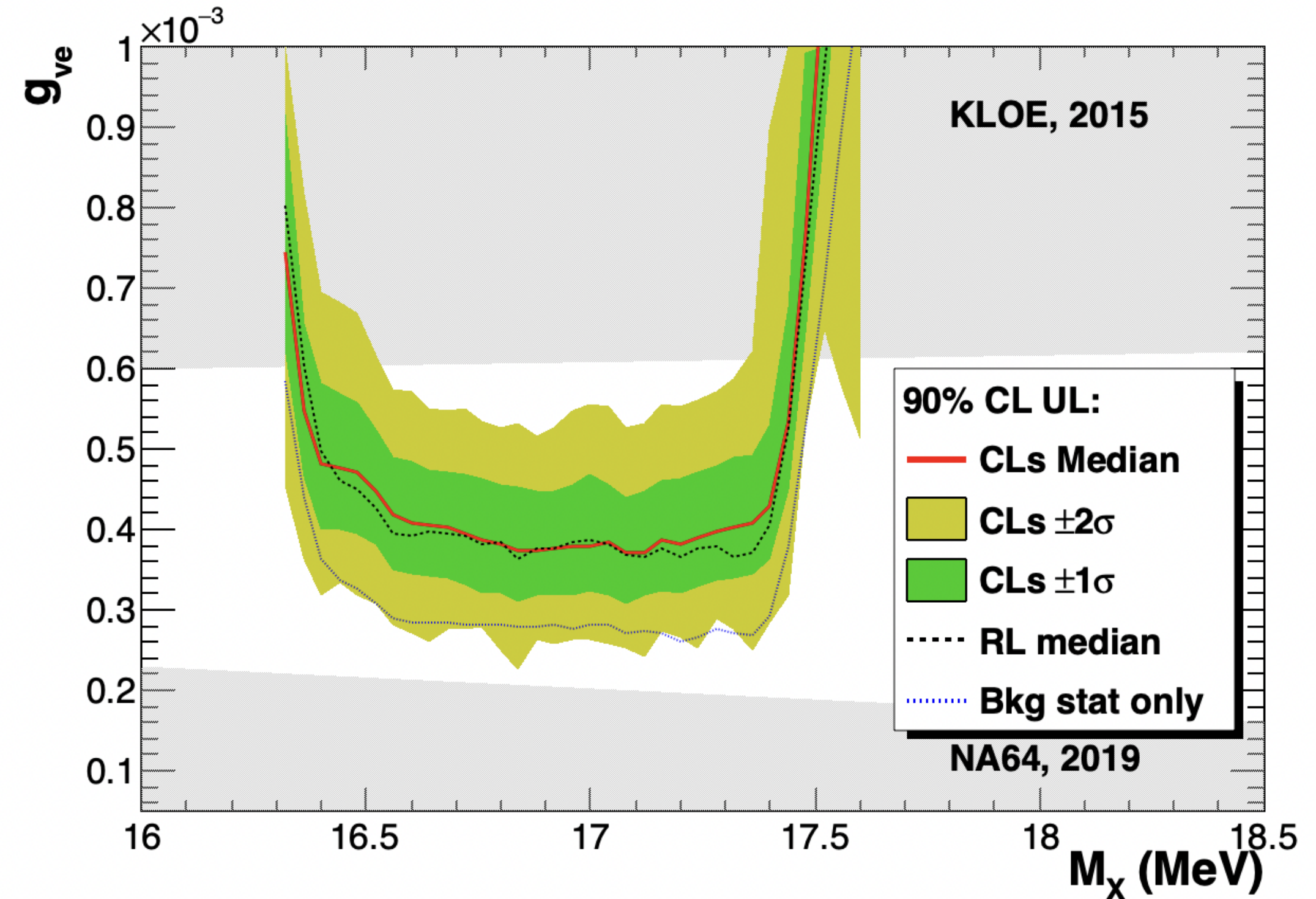
Q statistic based on Likelihood ratio:  $Q = L(B + S(g_{ve}, M_X)) / L(B)$

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  $g_{ve}$

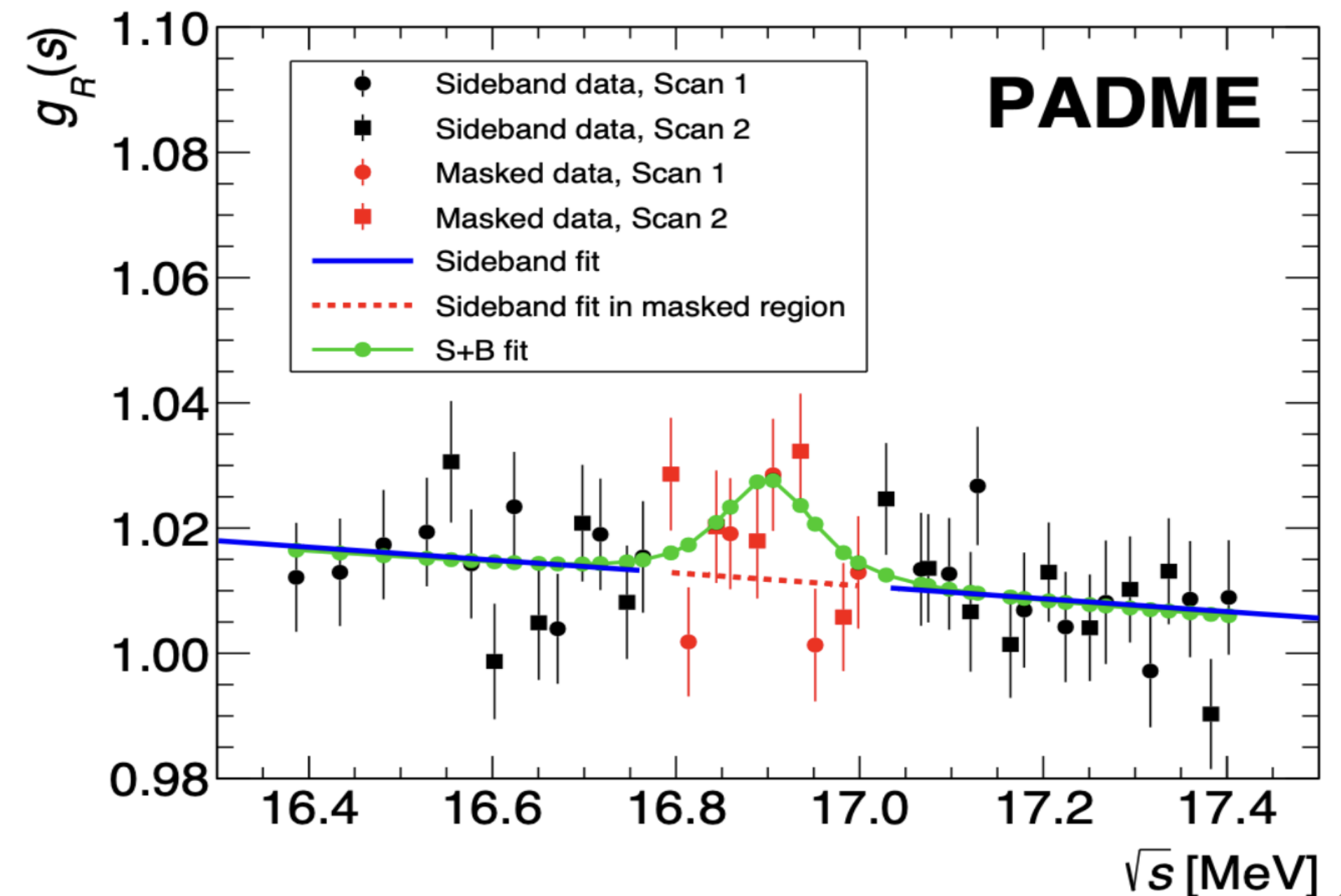
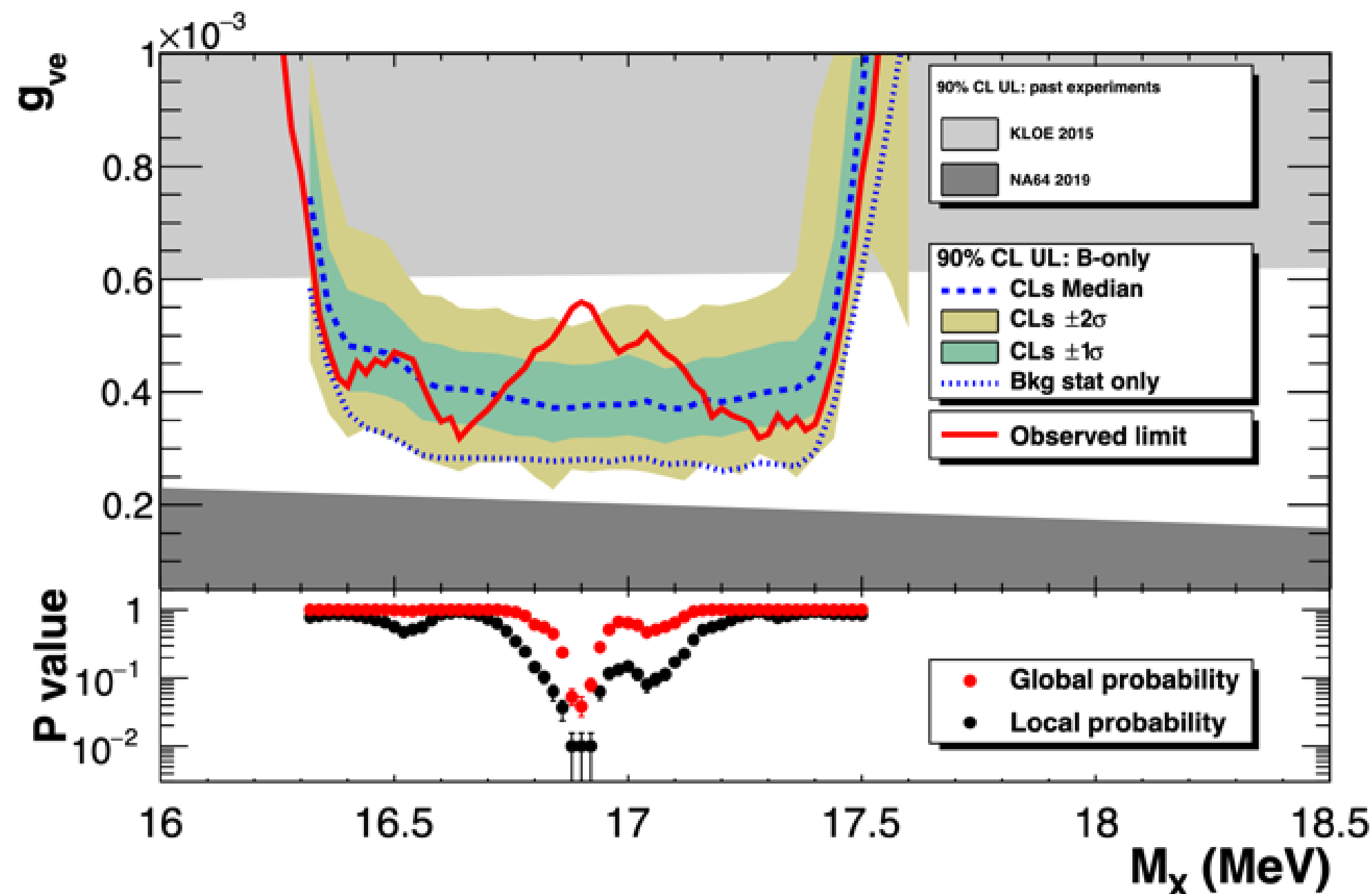
**Blind-unblinding procedure:** [JHEP06\(2025\)040](#)

- 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  $s^{1/2}$**



## Opening the box 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  $(1.77 \pm 0.15)\sigma$  one-sided (look-elsewhere calculated exactly from the toy pseudo-events)
- If a  $3\sigma$  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  $(2.0 \pm 0.2) \sigma$  one-sided



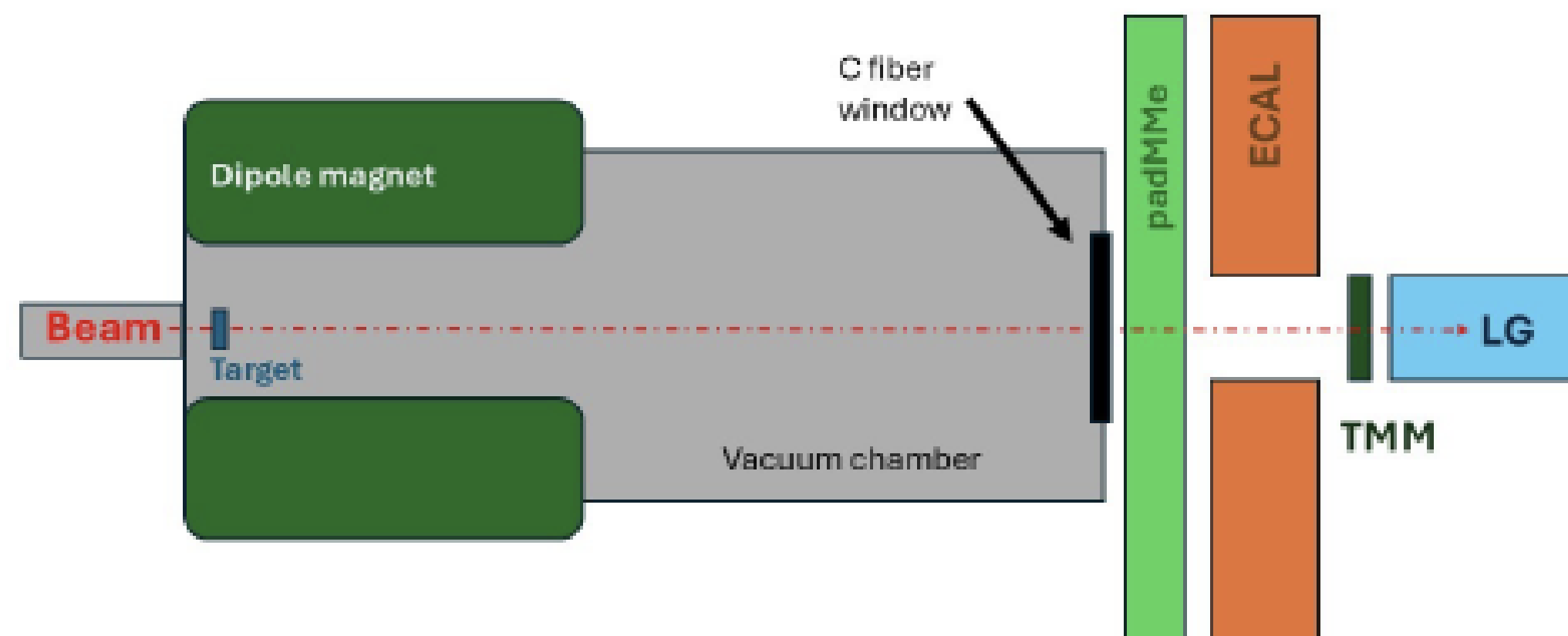
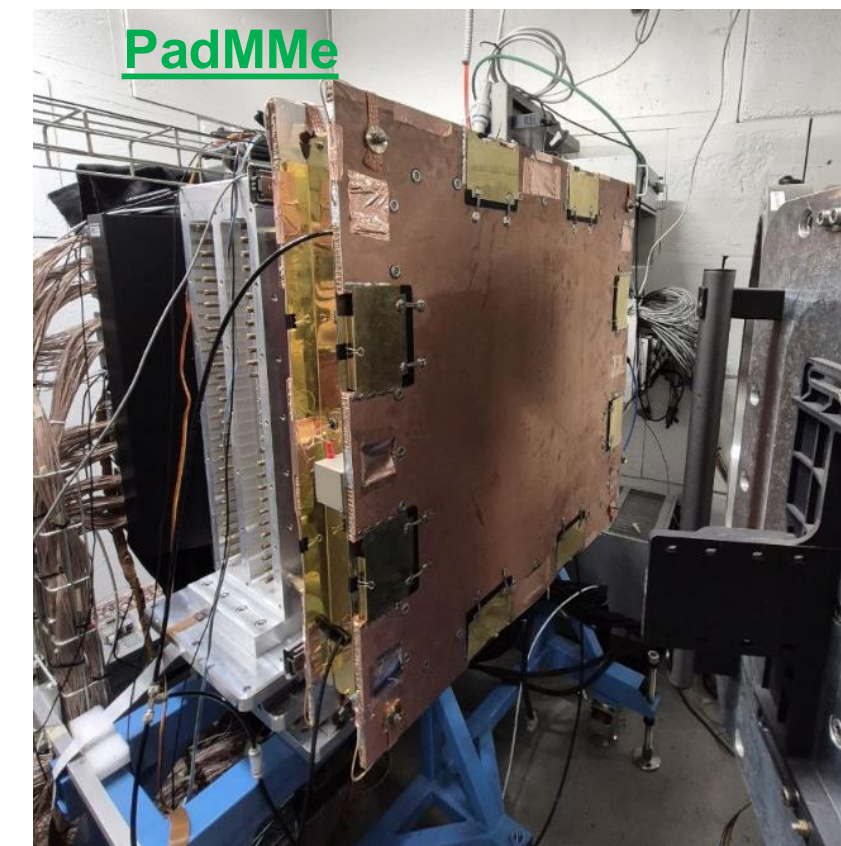
**Run III result is not conclusive: need to collect more data**

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

- **Diamond target** moved downstream by  $\sim 30$  cm to improve acceptance
- Beam stable in the central position along the whole data taking for minimizing lateral leakage on the beam catcher

**New detectors:**

- **PadMMe** Micromegas chamber replaced the ETag:  
e/ $\gamma$  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



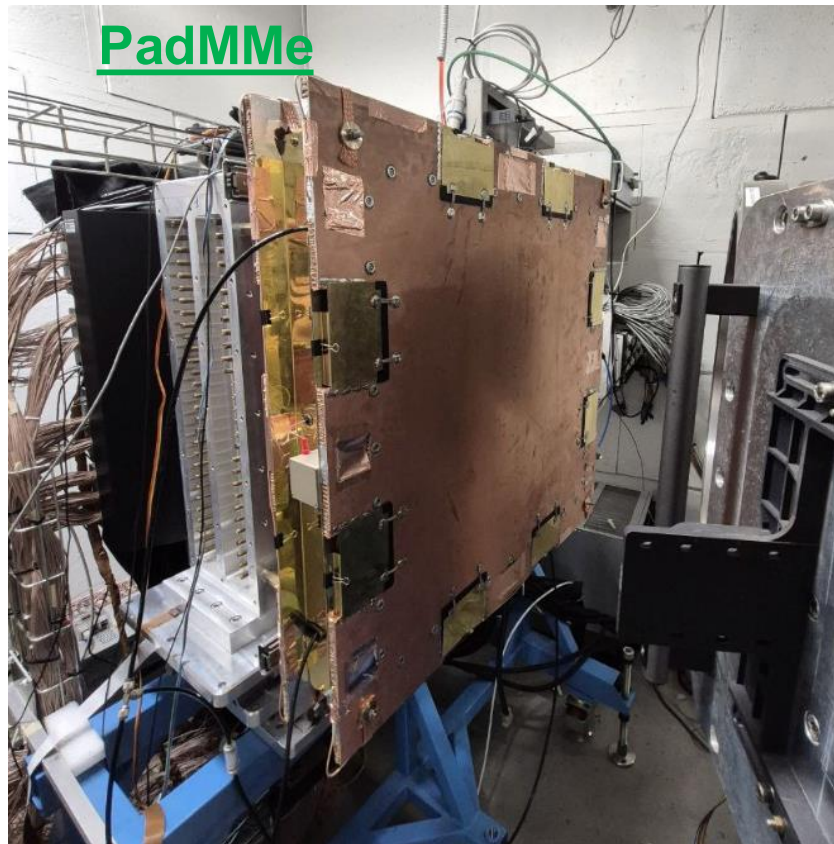
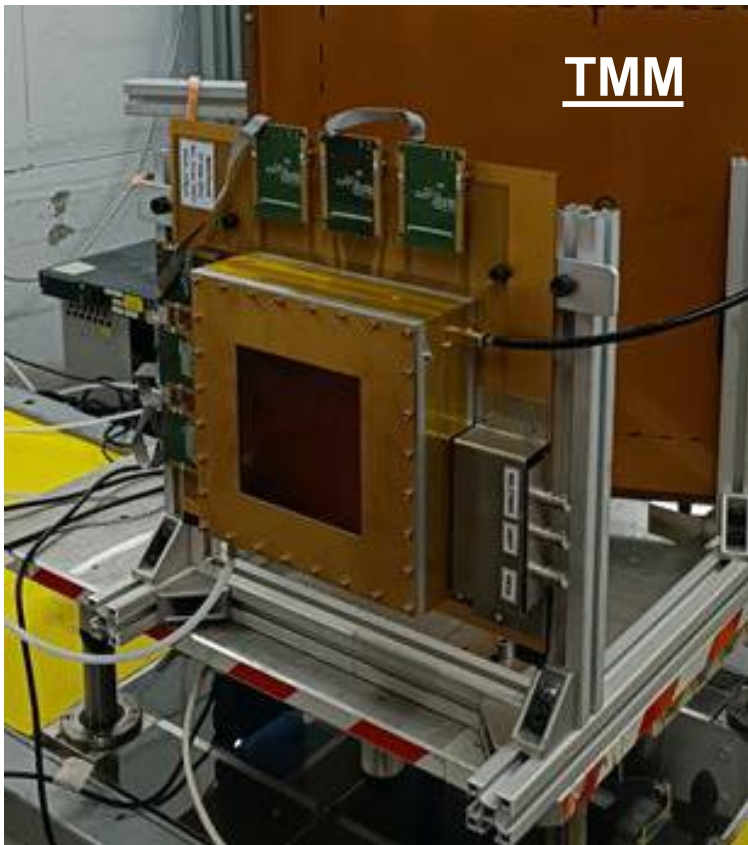
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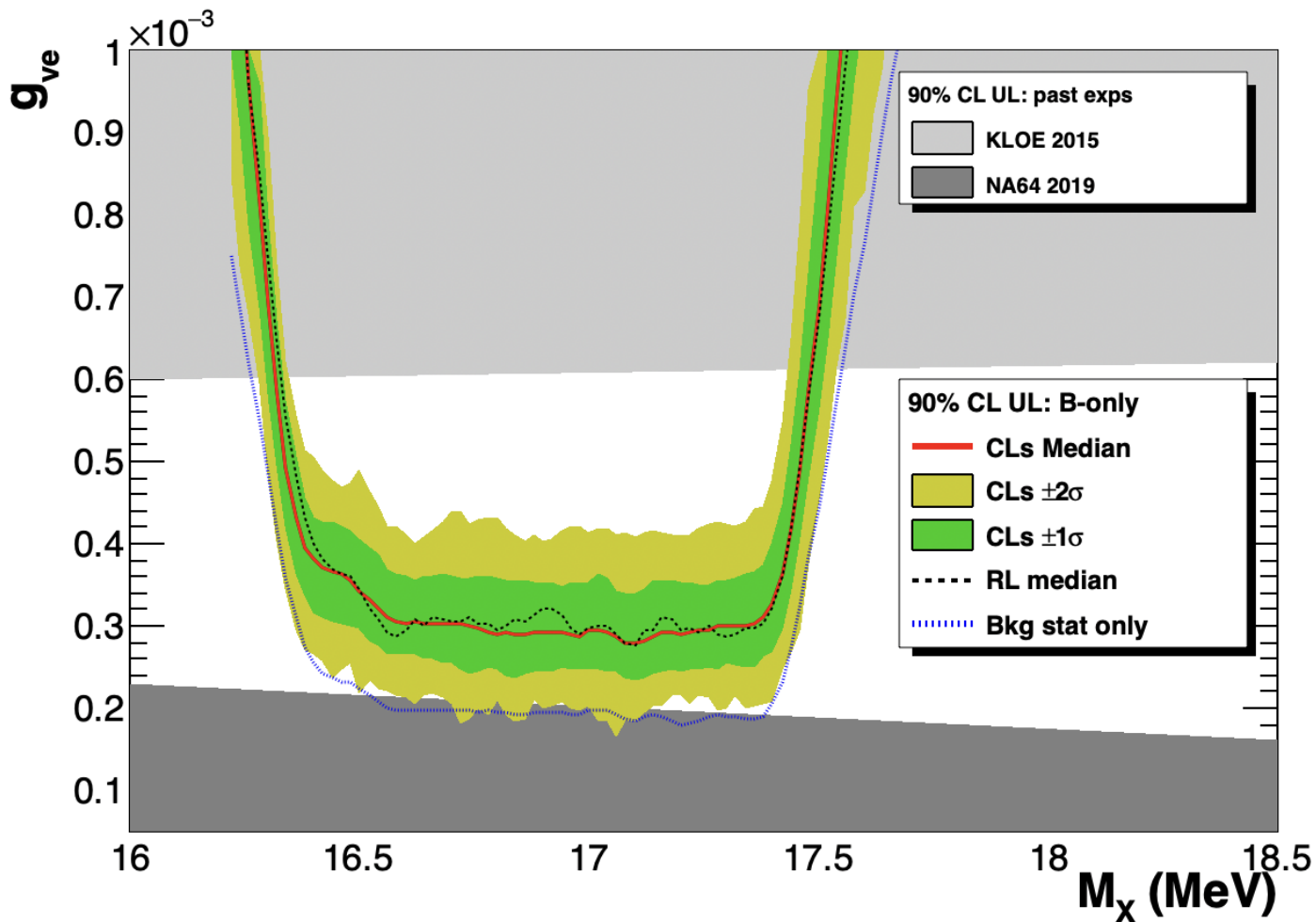
- **Diamond target** moved downstream by ~30 cm for acceptance increasing
- Beam stable in the central position along the whole data taking for minimizing lateral leakage on the beam catcher

New detectors:

- **PadMMe** Micromegas chamber replaced the ETag:  
e/γ discrimination, tracking capabilities, available as beam spot monitor
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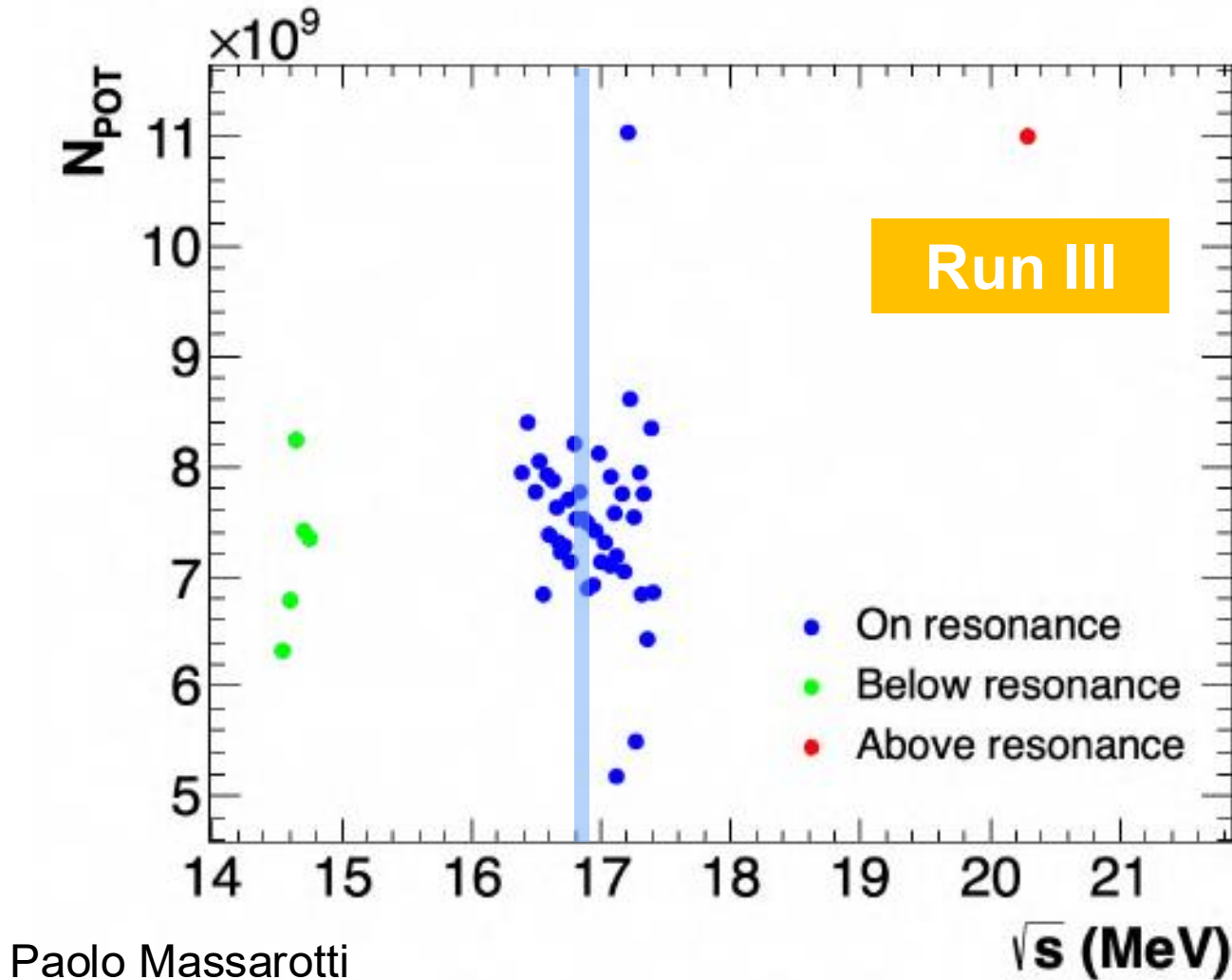


| Source           | Uncertainty [%] |        | Improvement                                                                      |
|------------------|-----------------|--------|----------------------------------------------------------------------------------|
|                  | Run III         | Run IV |                                                                                  |
| N <sub>2</sub>   | 0.6             | 0.3    | New target position → acceptance increased                                       |
| B                | 0.54            | 0.3    | PadMMe → ee/γγ discrimination + better angular-momentum resolution               |
| N <sub>PoT</sub> | 0.35            | 0.3    | 3 different beam spot monitor (target-PadMMe-TMM) + online LG calibration system |
| TOTAL            | 0.9             | 0.5    |                                                                                  |

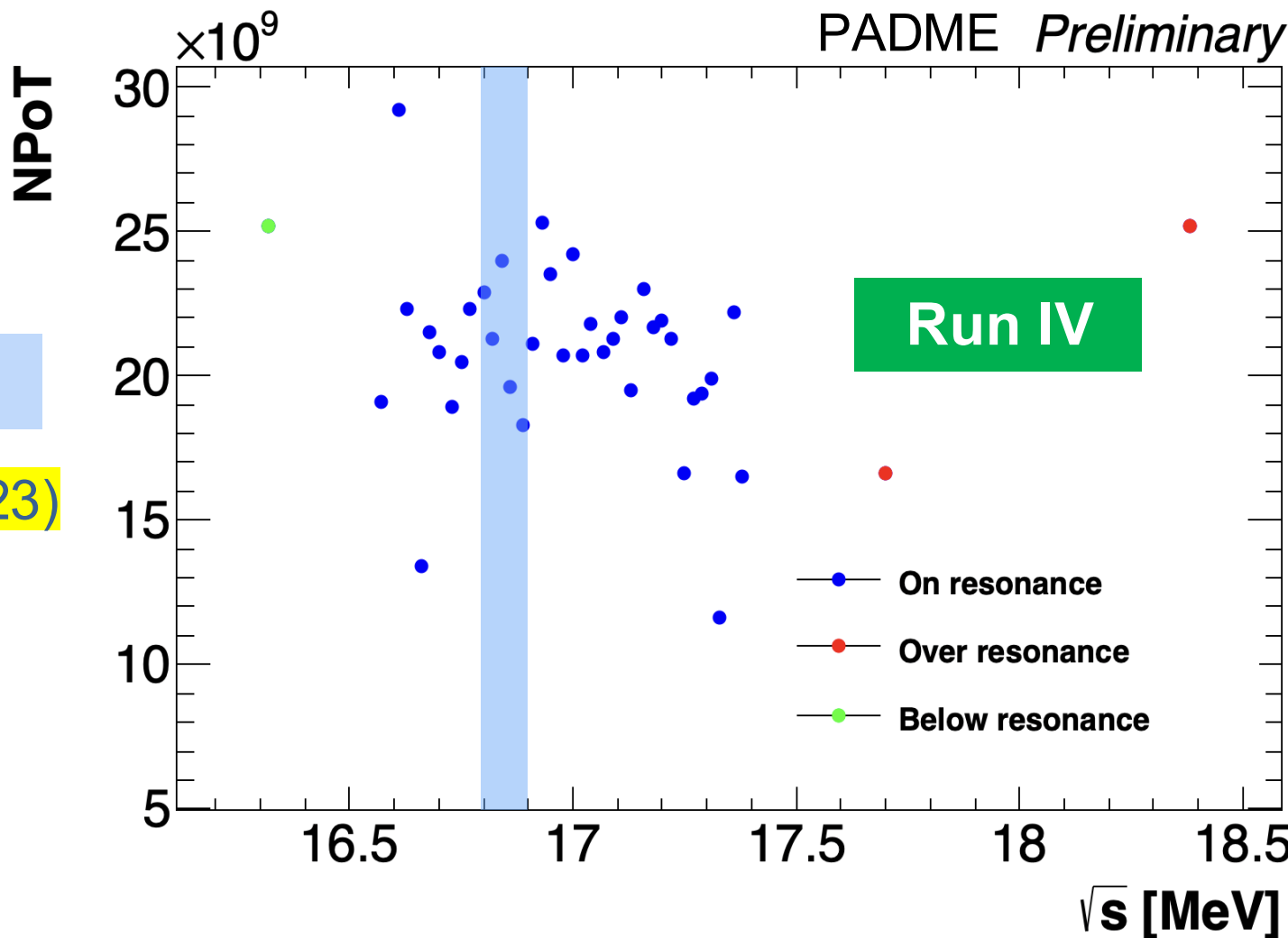


Data-taking divided again 3 parts: **below**, **on**, **over** resonance, collected 39 points + 15 no target datasets spread among the others for better control of the beam-induced background

|                   | Run III                                                   | Run IV                                                 |
|-------------------|-----------------------------------------------------------|--------------------------------------------------------|
| On resonance      | 42 points: <b>Scan 1</b> -22 pts / <b>Scan 2</b> – 20 pts | 36 points: <b>Scan 1</b> and <b>2</b> – 18 points each |
| N <sub>PoT</sub>  | ~0.8x10 <sup>10</sup> PoT per point                       | ~2.2x10 <sup>10</sup> PoT per point (x3 wrt RUN III)   |
| E <sub>beam</sub> | 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                             |

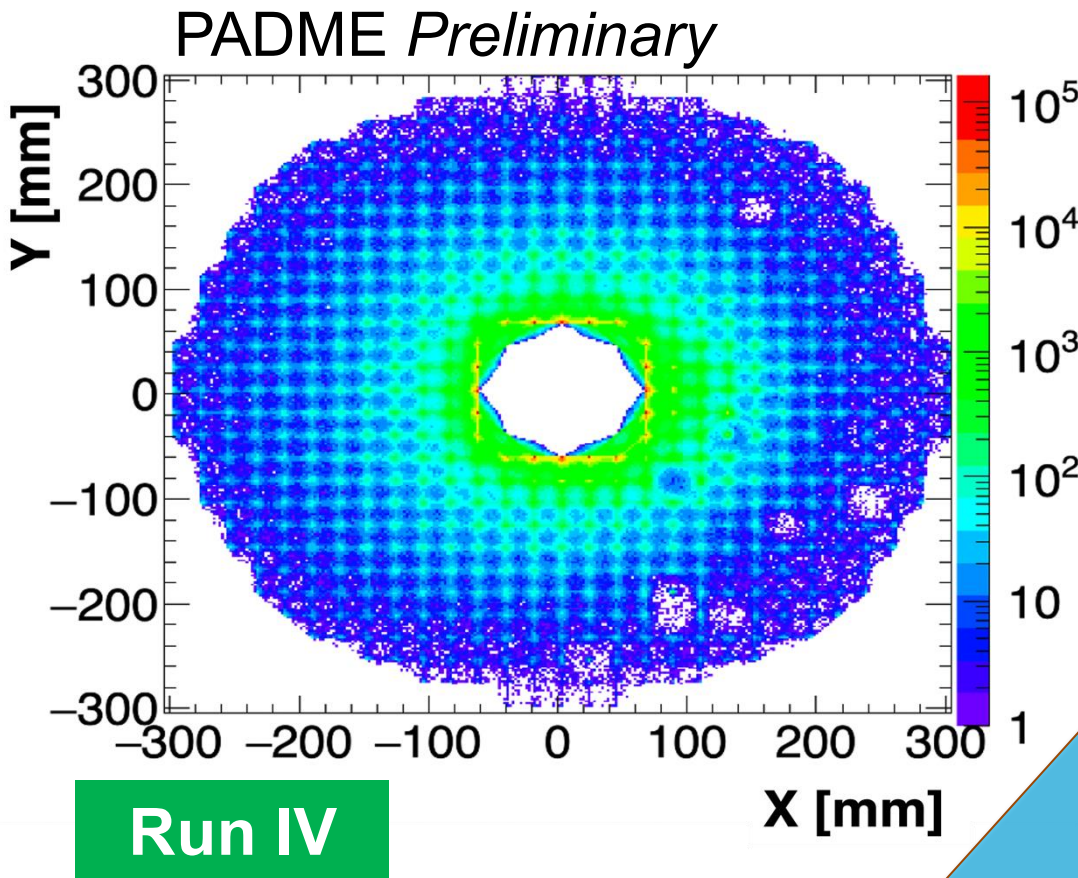
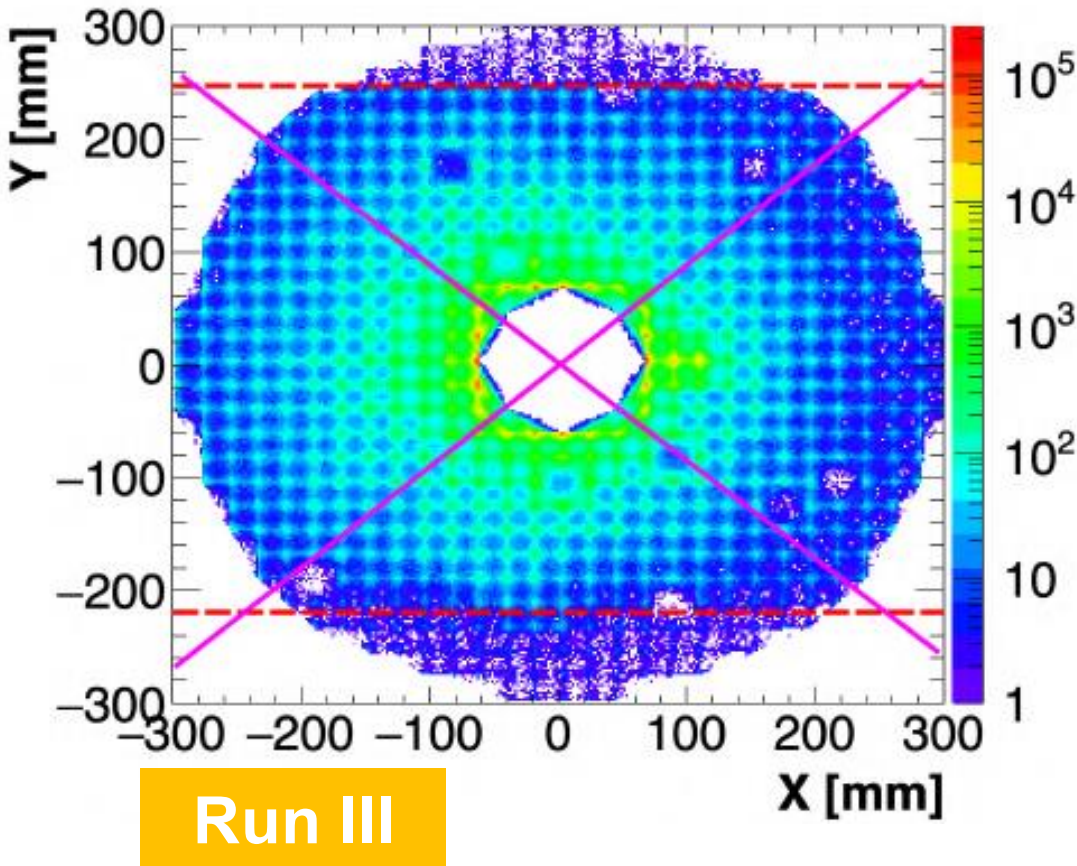
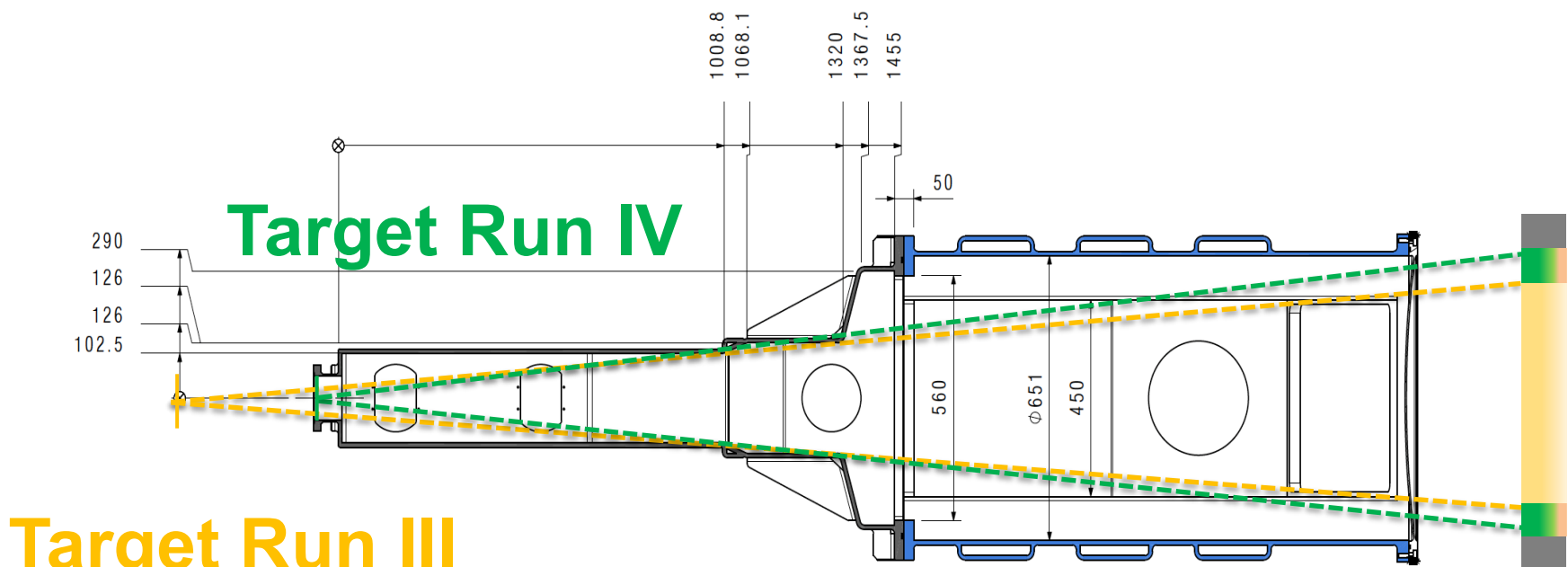
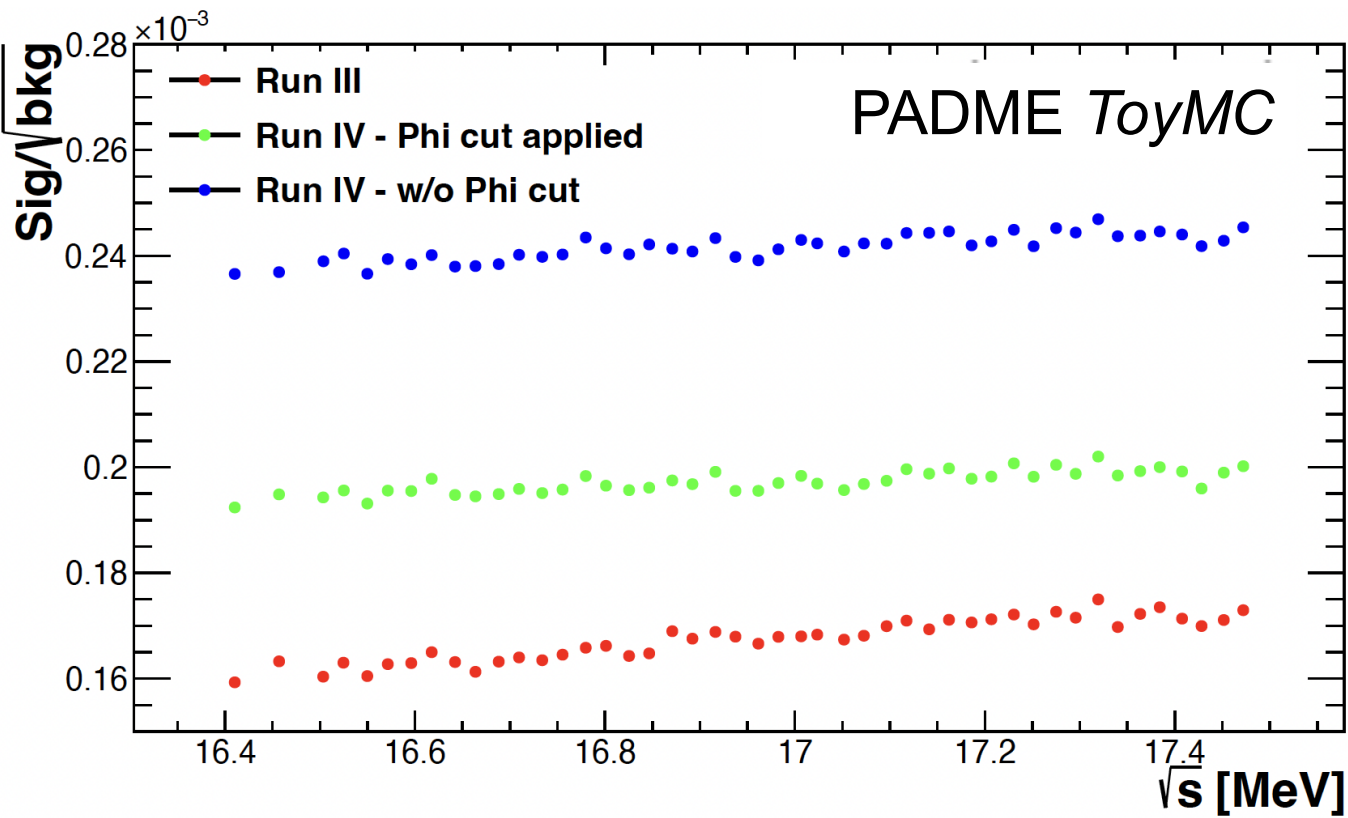


$m_{X17} = (16.85 \pm 0.04) \text{ MeV}$   
PHYS.REV. D 108, 015009 (2023)



| Run period | Target-ECal | $\theta_{lab}$ @ 17 MeV | R range @ 17MeV | 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        |

- $\phi_{lab}$  -cut can be totally removed or adapted
- Acceptance region enlarged:  $\frac{Sig}{\sqrt{Bkg}}$  increases by 50%
- Residual magnetic field in PADME dipole completely degaussed
- Run-by-run Run IV luminosity increases by a factor of 2.5 wrt Run III



The TMM is a 10x10x0.5 cm<sup>3</sup> MicroMegas detector:

Connected in series to the PadMMe - same gas mixture (Ar:CF4:Iso=88:10:2)

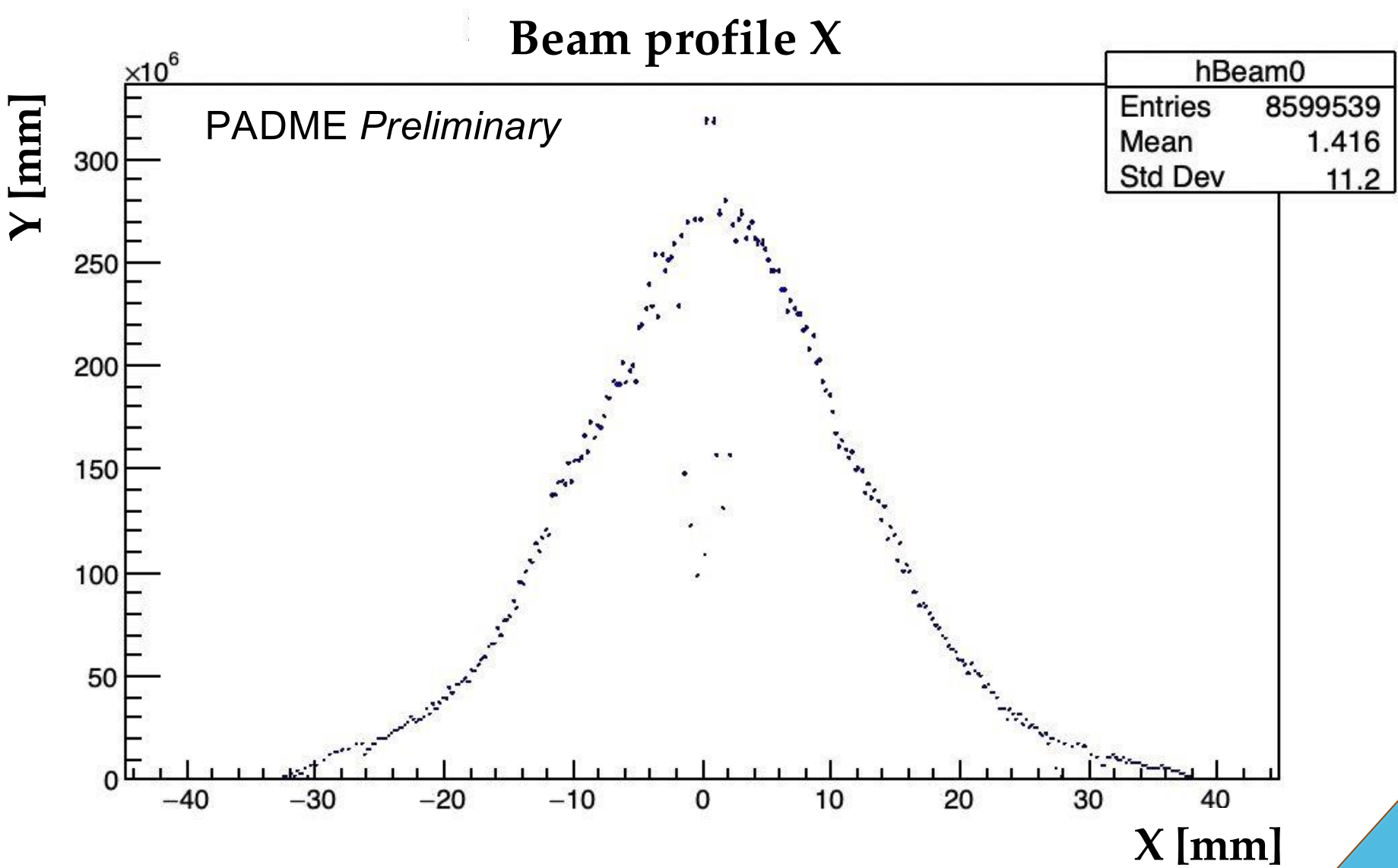
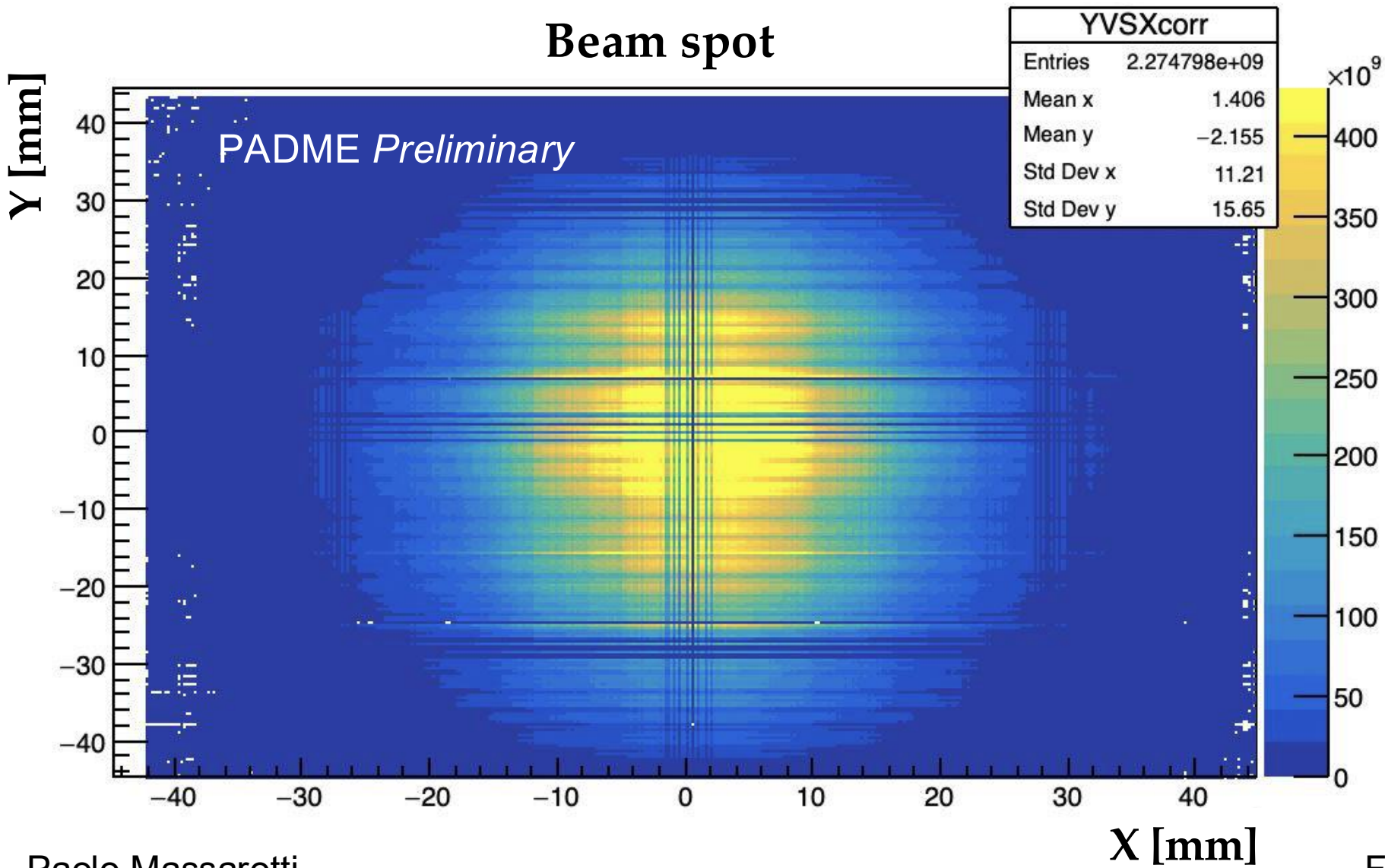
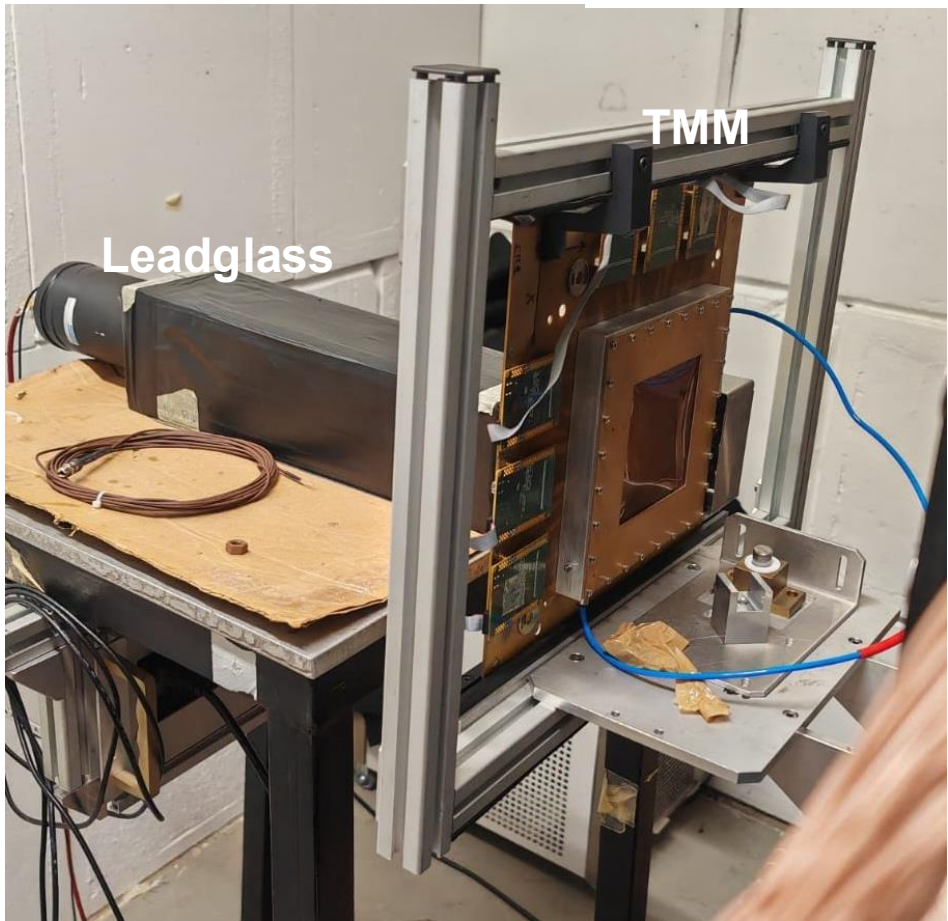
Readout: 6APVs

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



$e/\gamma$  discrimination should reduce bkg by 20% selecting charged final states only

Access to different observables on top of  $N_2/N_{PoT}$  :  $ee/N_{PoT}$ ,  $ee/\gamma\gamma$

Improvement in the the Tag and probe efficiency

Main features:

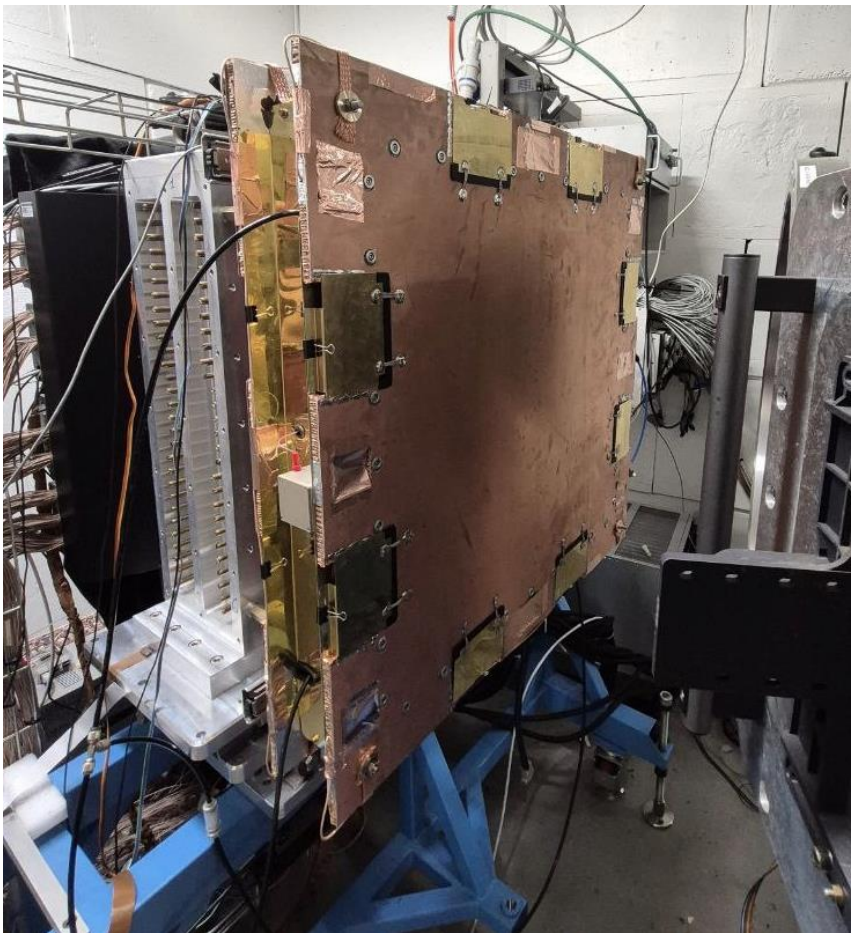
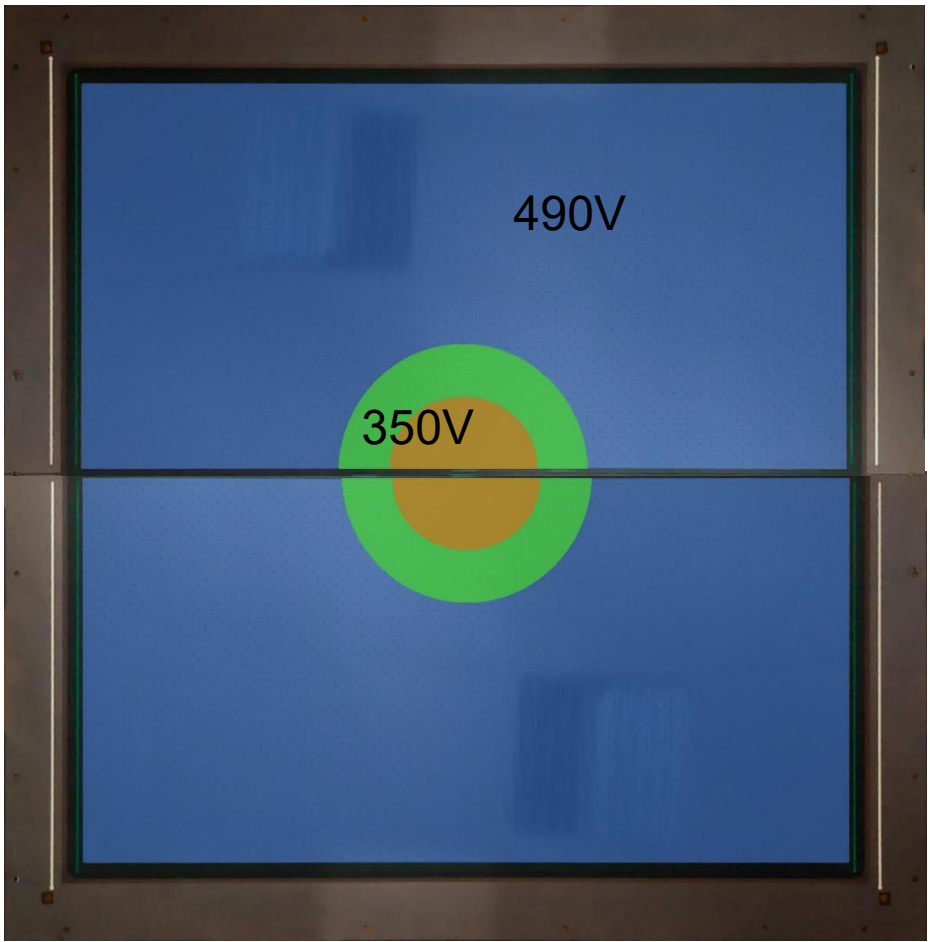
65x65x10 cm<sup>3</sup> - gas mixture (Ar:CF4:Iso=88:10:2)

Hit efficiency > 90%

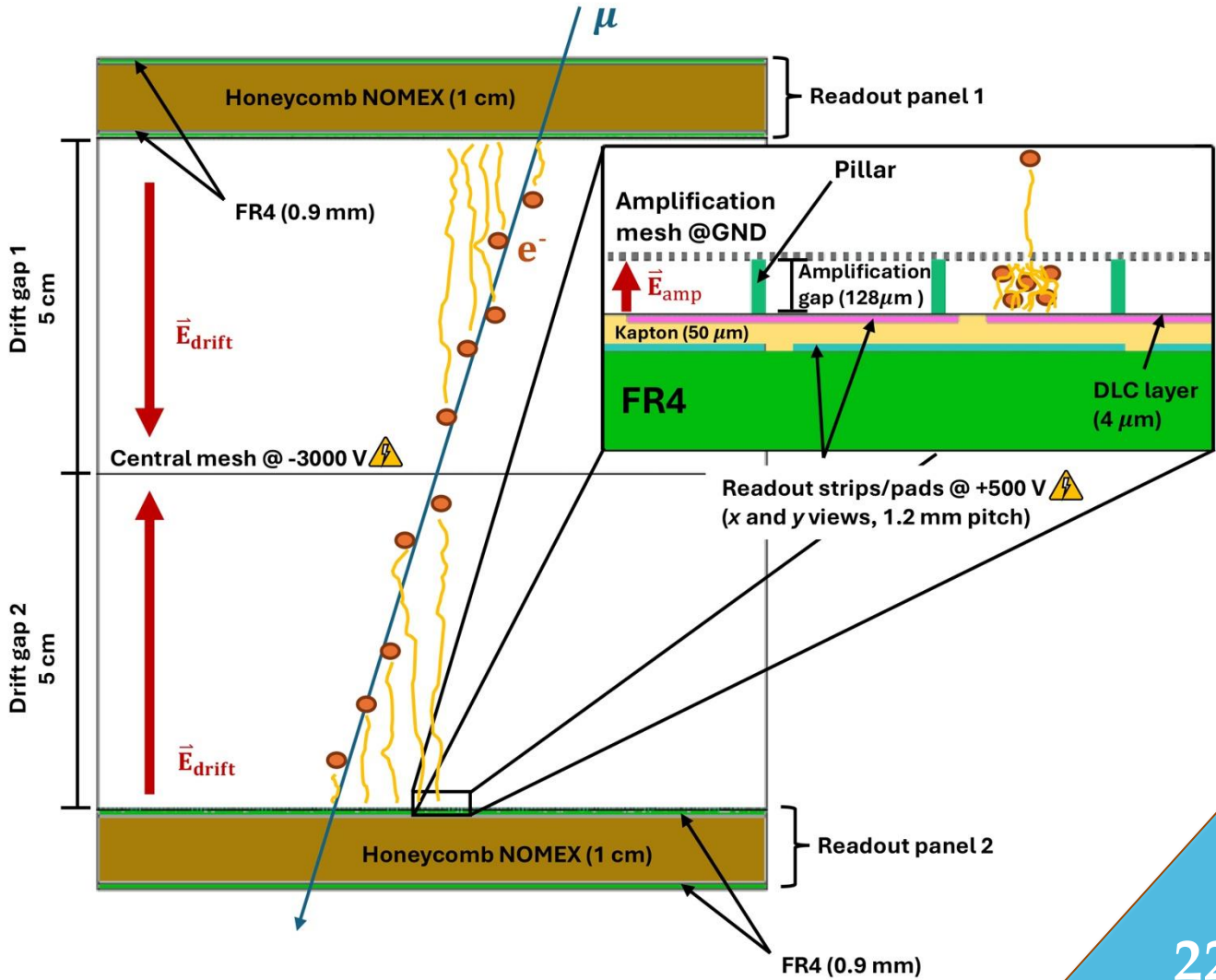
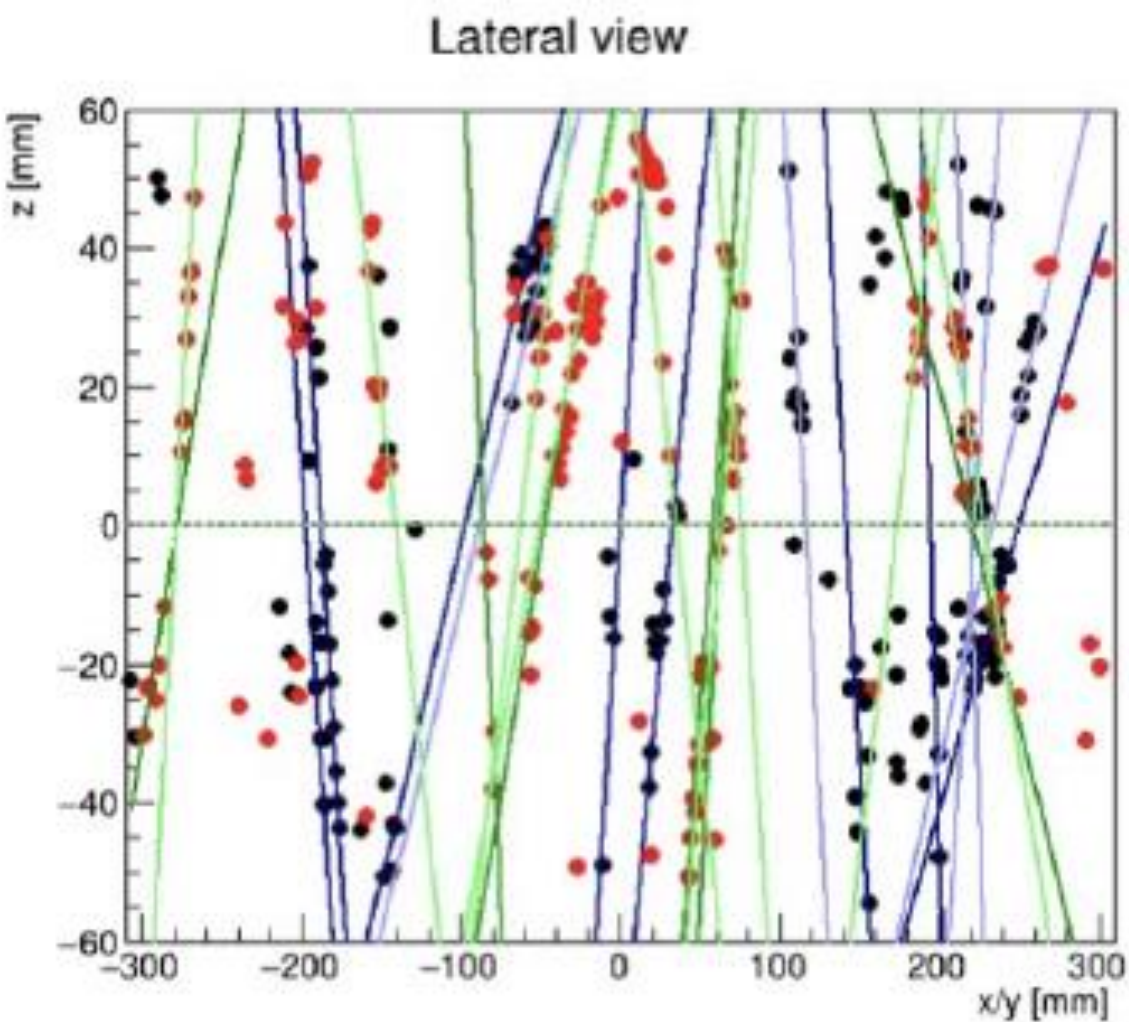
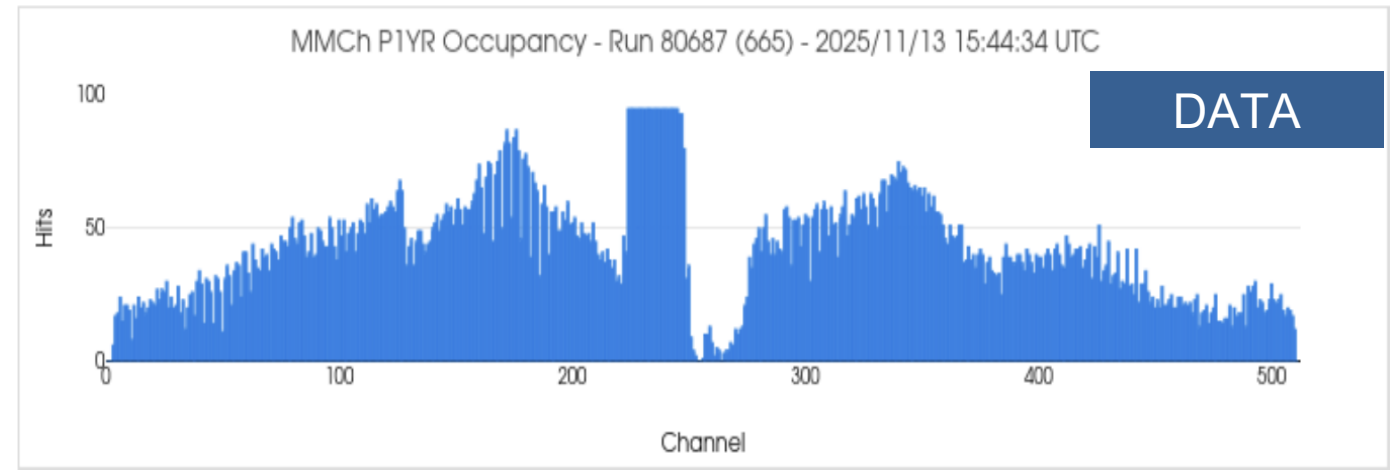
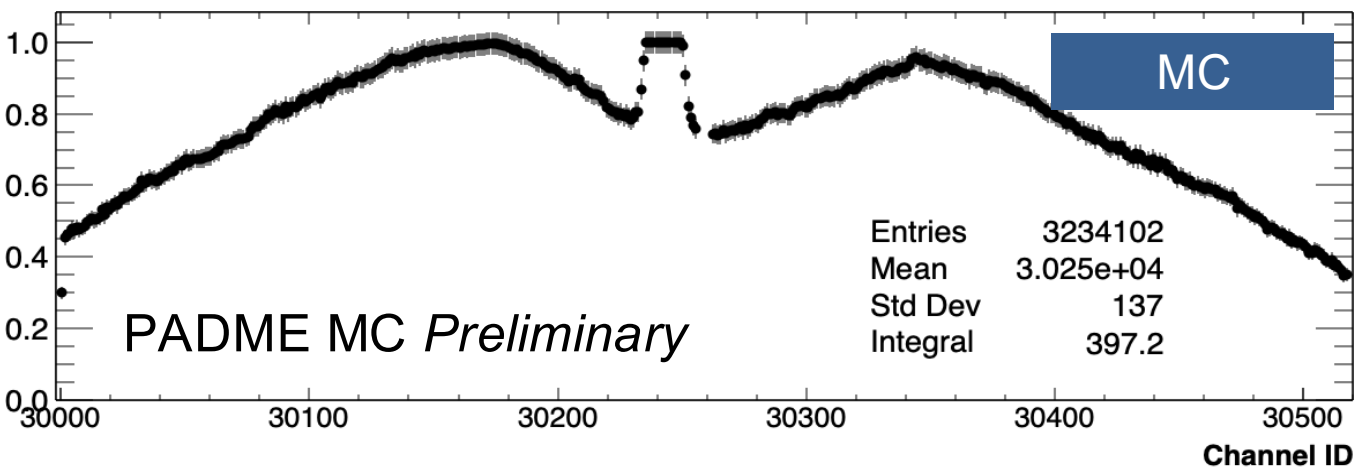
Spatial resolution ~ 350  $\mu$ m  $\rightarrow$  angle disentanglement

Multitrack events can be collected

**Beam monitor capability**  $\rightarrow$  central region at low gain (orange+green)



High occupancy well modelled in MC



## Huge **combinatory** in pattern recognition with 3000 e<sup>+</sup>/spill

~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

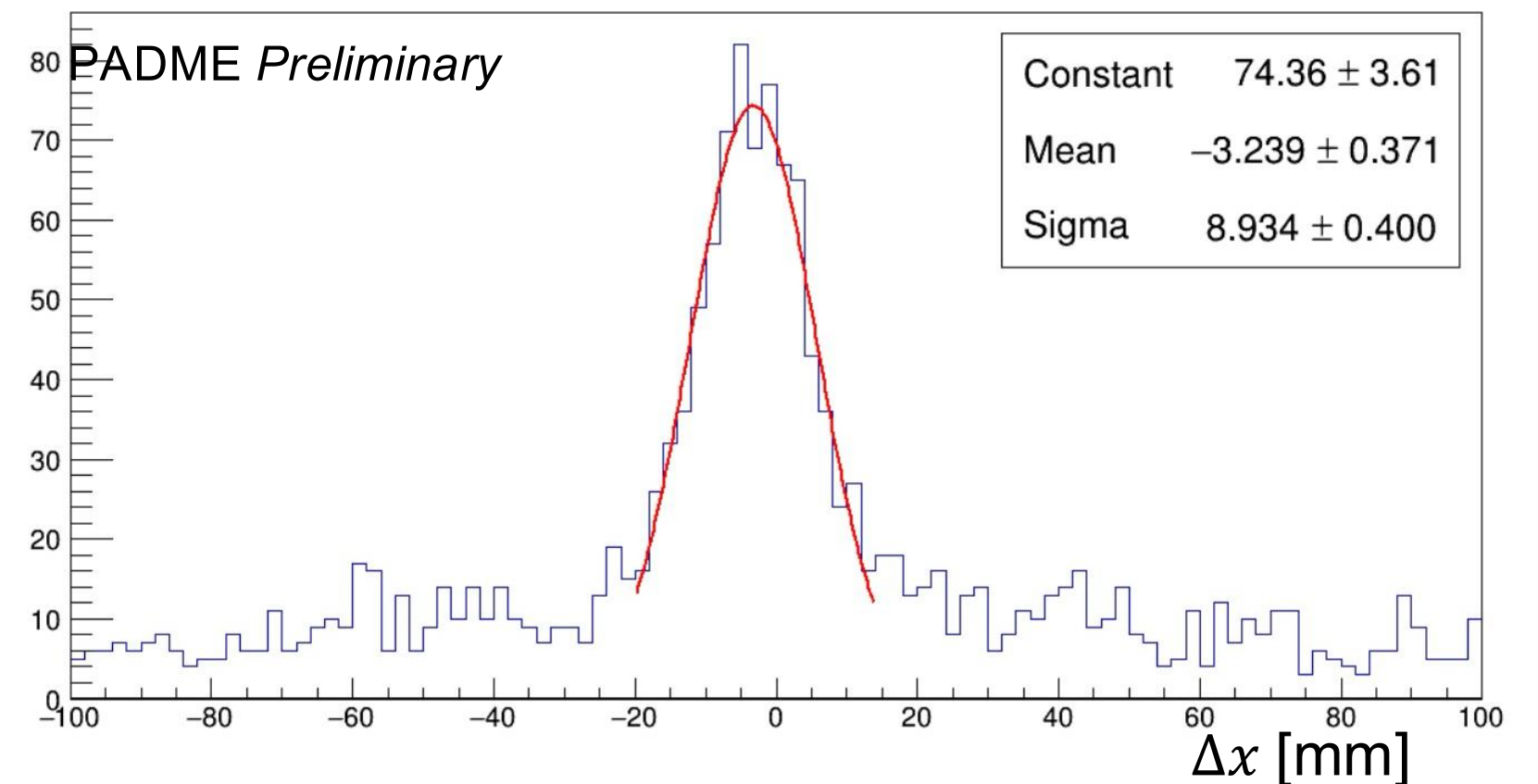
**Level-0 tracks** correspond to track segments in each plane and coordinate

- High efficiency but also high fakes level: need at least 2/3 out of 4 coincidence

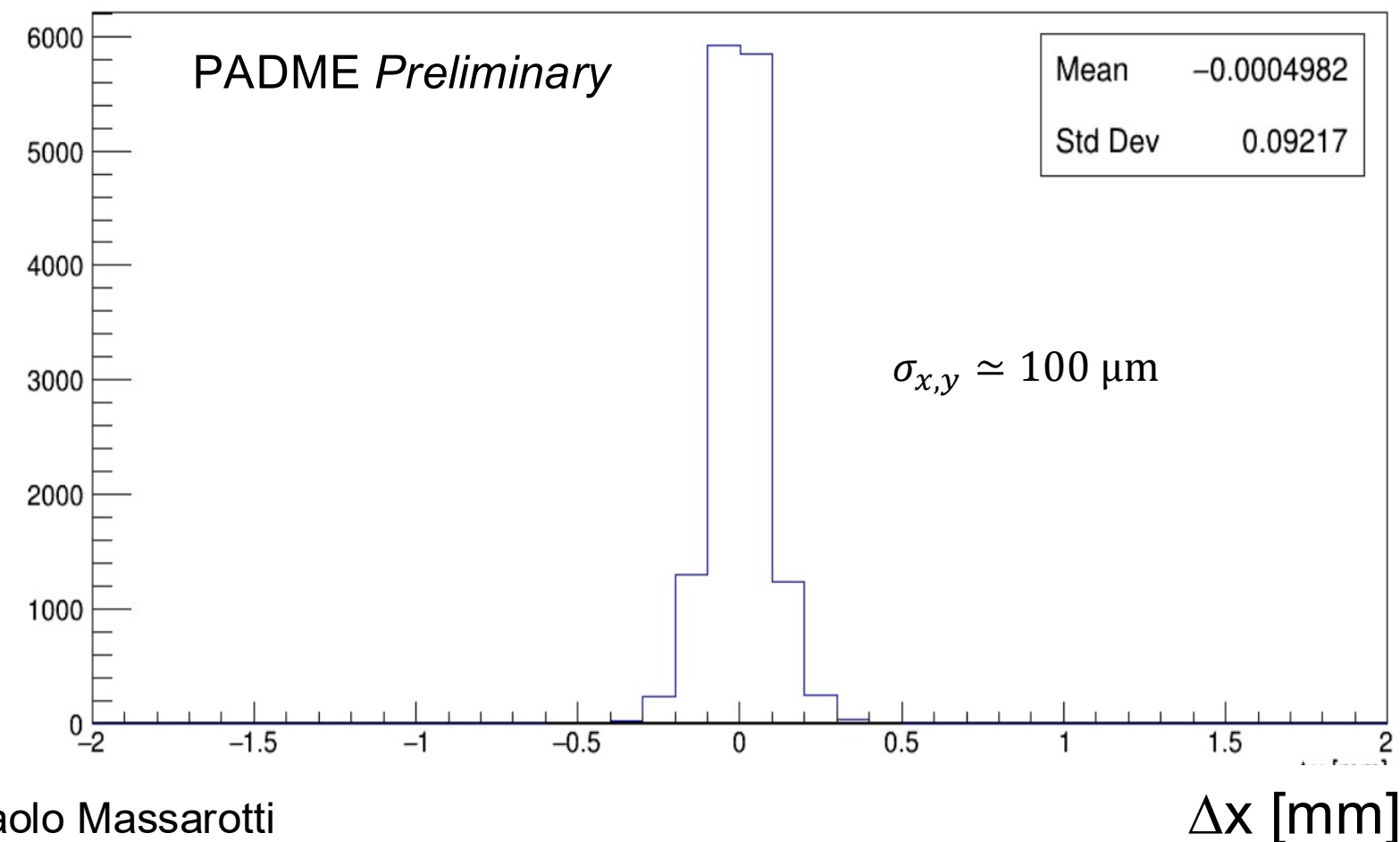
**Level-1 track:** 2 planes coincidence

- Requiring the matching with ECal clusters fakes are further reduced

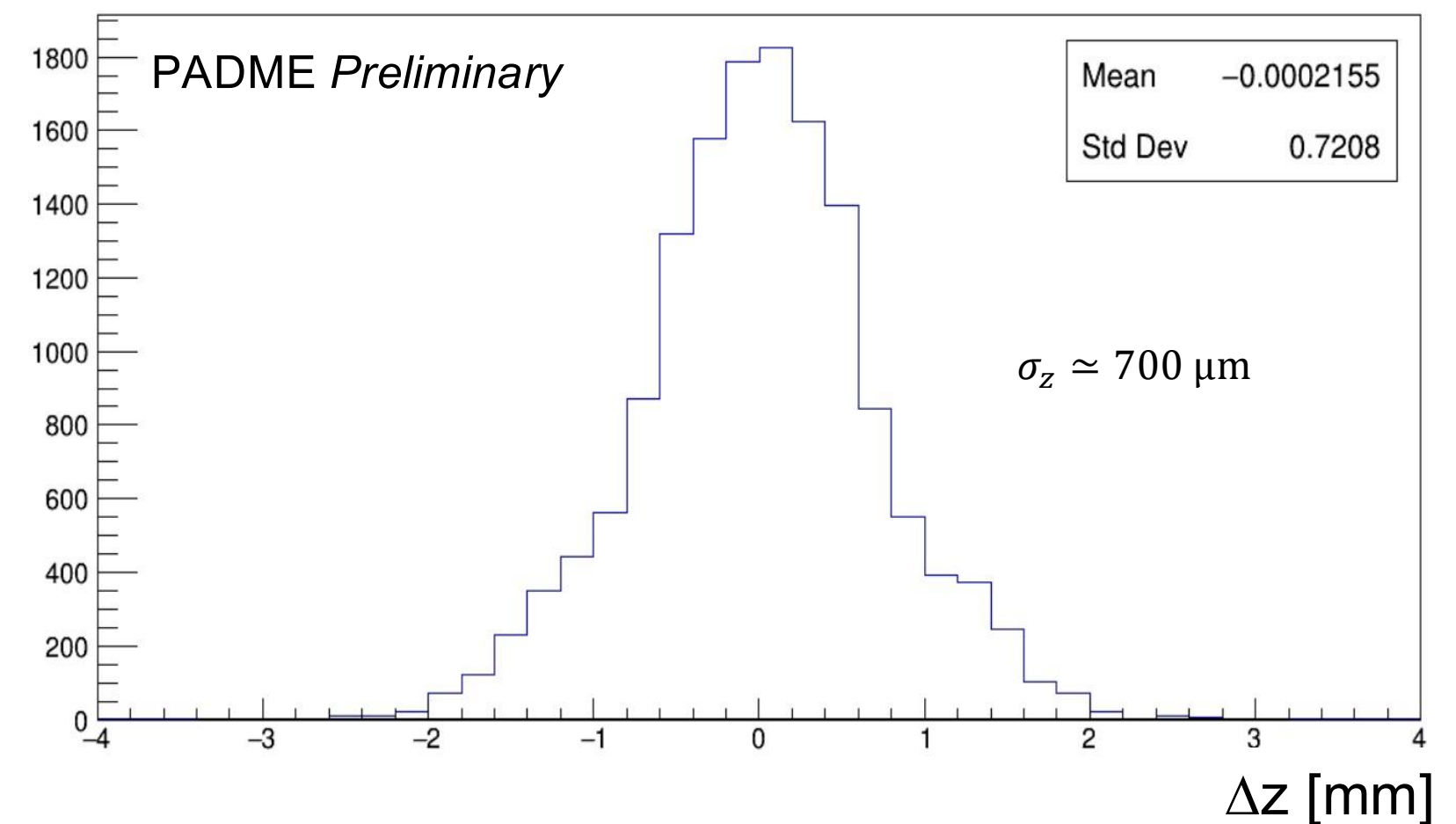
## Track to cluster association



## X direction track residual



## Z direction track residual



## 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 ( $2.5\sigma$  local –  $1.5\sigma$  global)
- Results interpreted with a frequentist CLs procedure to set upper limits (vector-boson hypothesis)

## Run IV:

- Aim to Improve sensitivity (higher statistics and better control of systematics) aiming at a factor of 2 error reduction
- 36 energy scan points ( $\geq 2 \times 10^{10}$  PoT each) equally separated by 0.75 MeV in the around resonance region
- Signal yield increased by a factor of  $\sim 2.5$  wrt Run III (luminosity+acceptance)
- Ongoing developments:
  - Use of tracks information
  - MC productions
  - Redundant beam parameter measurements
  - Finalization of event reconstruction algorithm

# Backup Slides

Active target plays a role in beam conditions and multiplicity monitoring

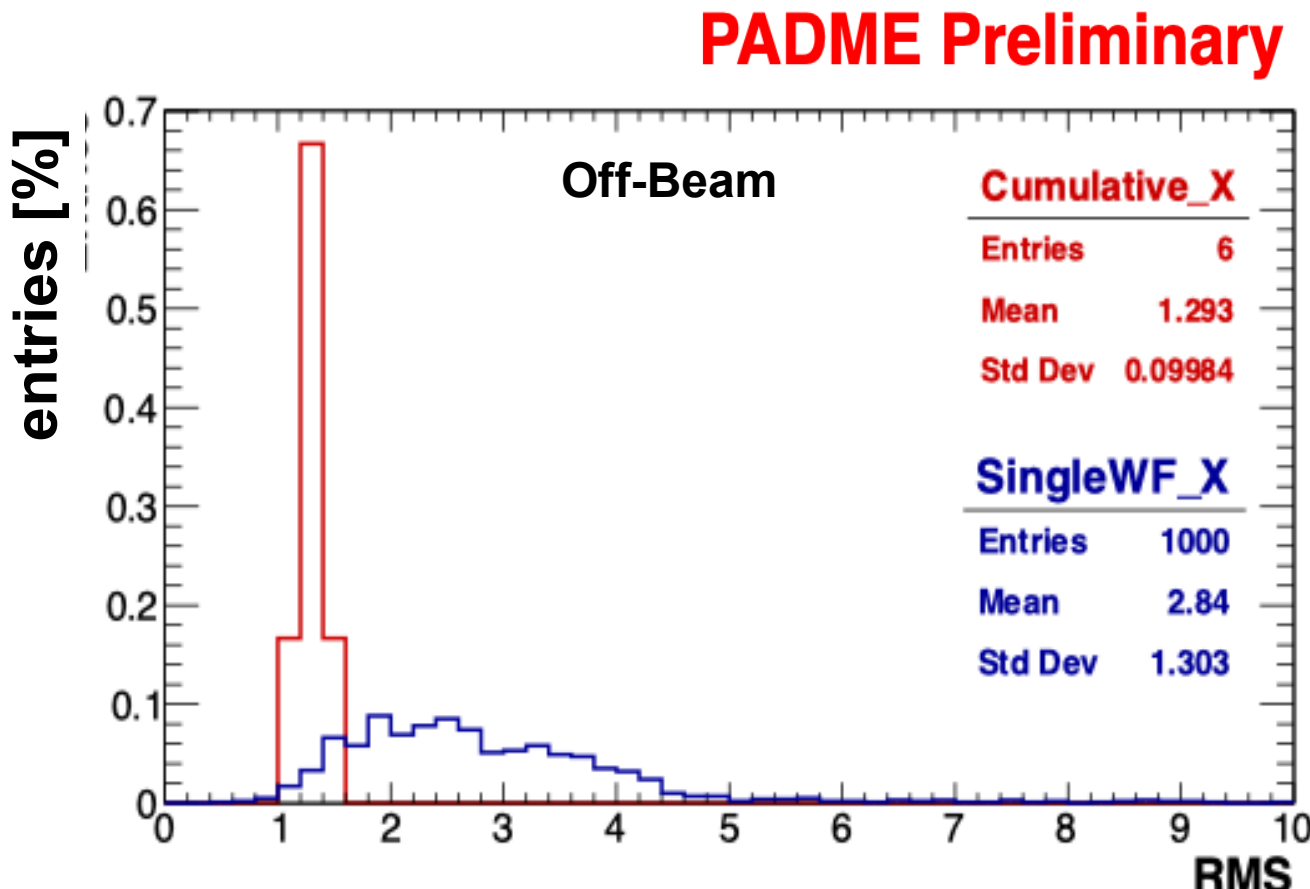
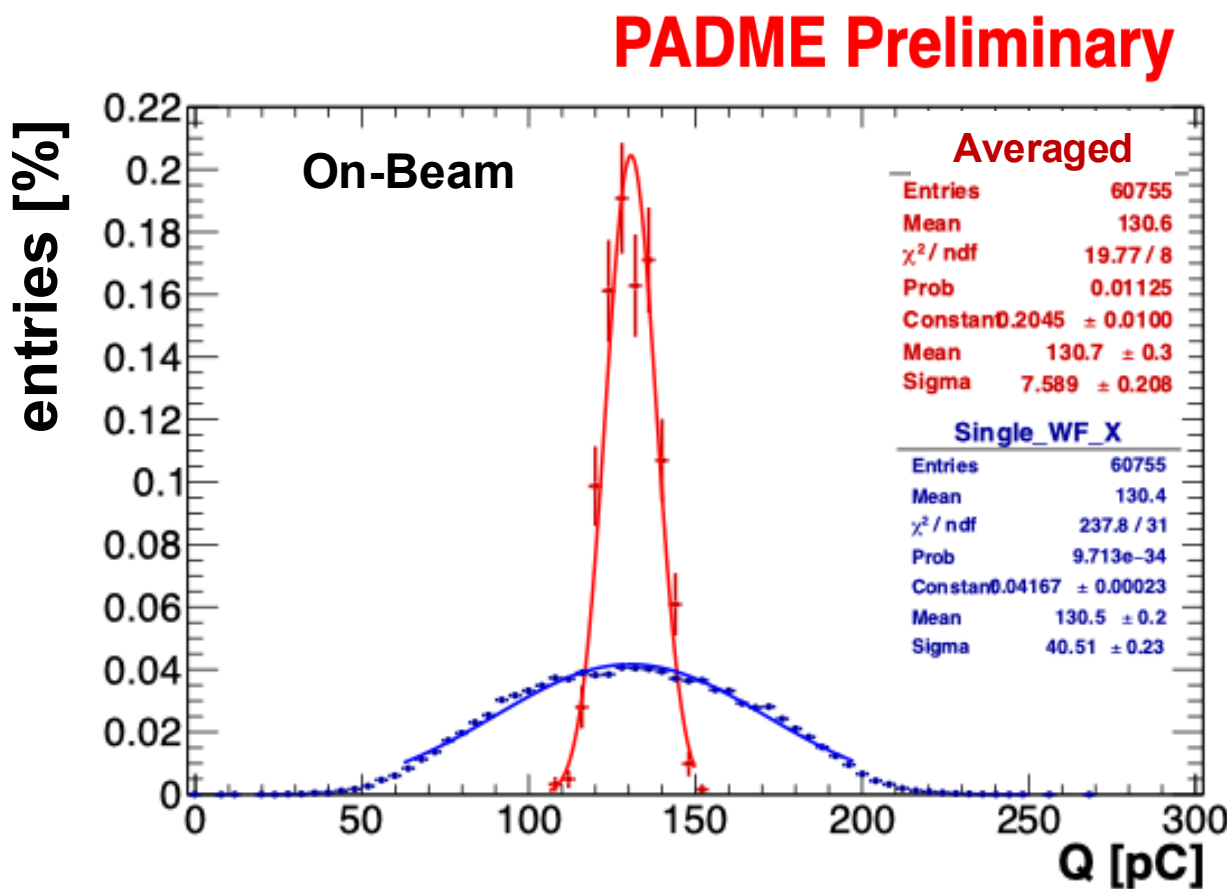
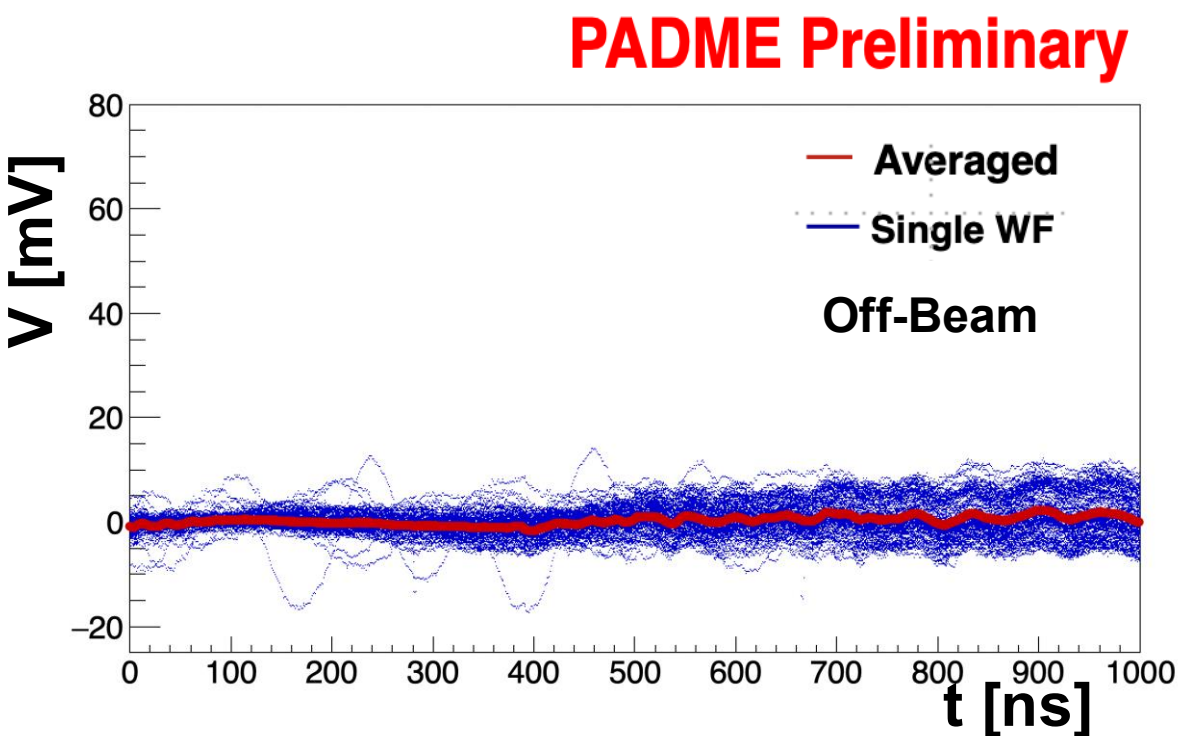
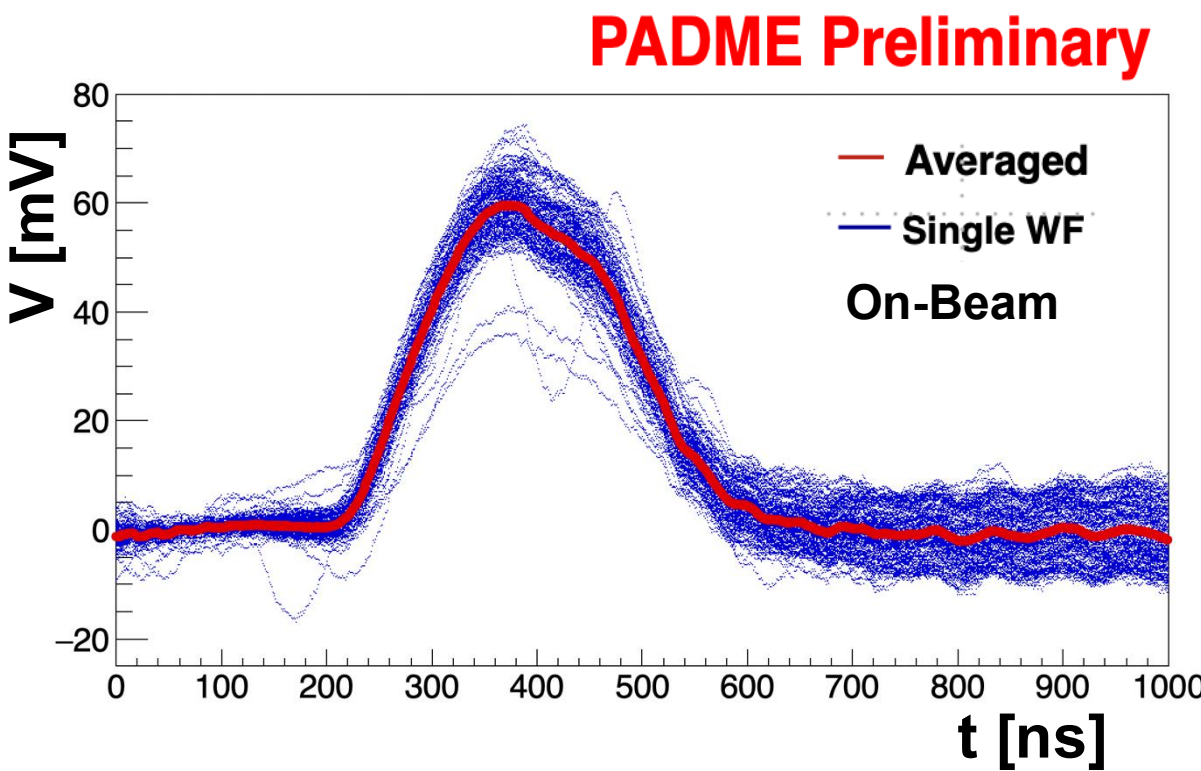
Target waveforms are affected by common-mode noise (e.g. induced capacitance effects on strips nearby the beam-fired)

- Channel-by-channel **different noise pattern**
- Beam/Off-Beam different structure

Averaged waveform over  $\mathcal{O}(100)$  wf mitigating the random noise structures

$$V_{cum}(t) = \frac{1}{N_{cum}} \times \left[ \sum_{i=0}^{N_{cum}} V_i(t) - \sum_{i=0}^{N_{cum}} \left( \frac{1}{N_{ped}} \sum_{t=0}^{t_{ped}} V(t) \right)_i \right]$$

Charge integration:  $Q = \sum_{t_{start}}^{t_{stop}} \frac{V(t)}{Z}$  (if  $V(t) \leq 0 \Rightarrow V(t) = 0$ )



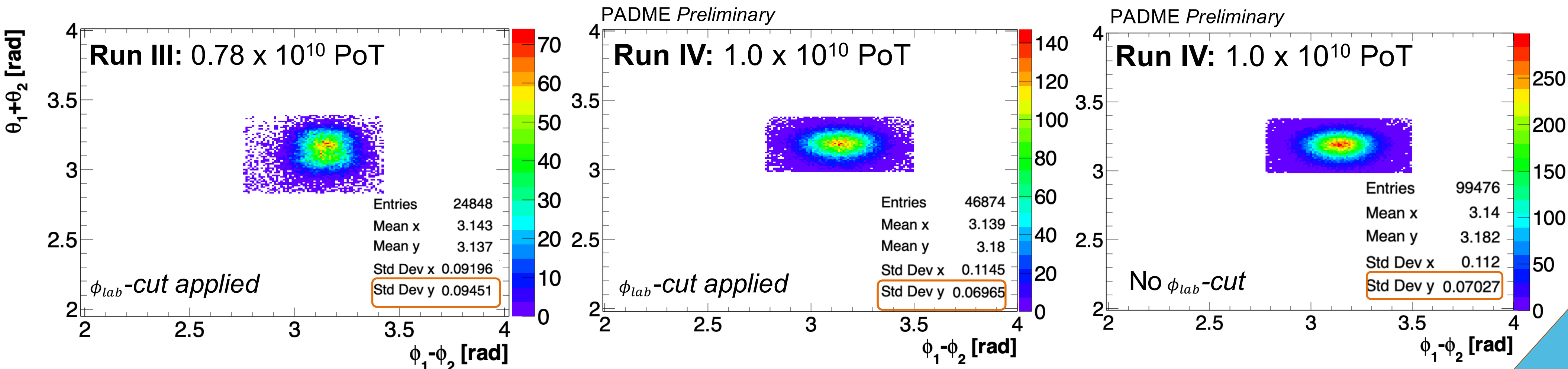
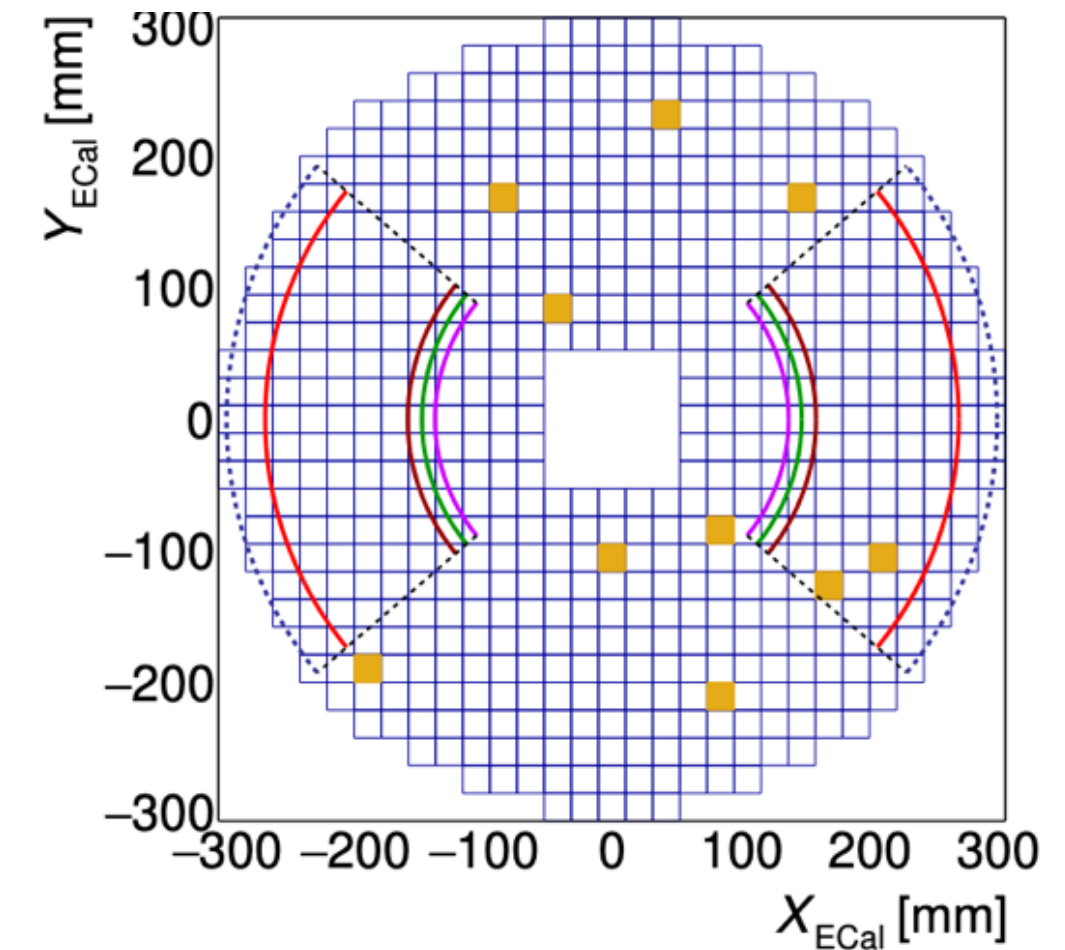
Two body final states selected using ECal clusters position information

Acceptance checked in a possible “worst case scenario”

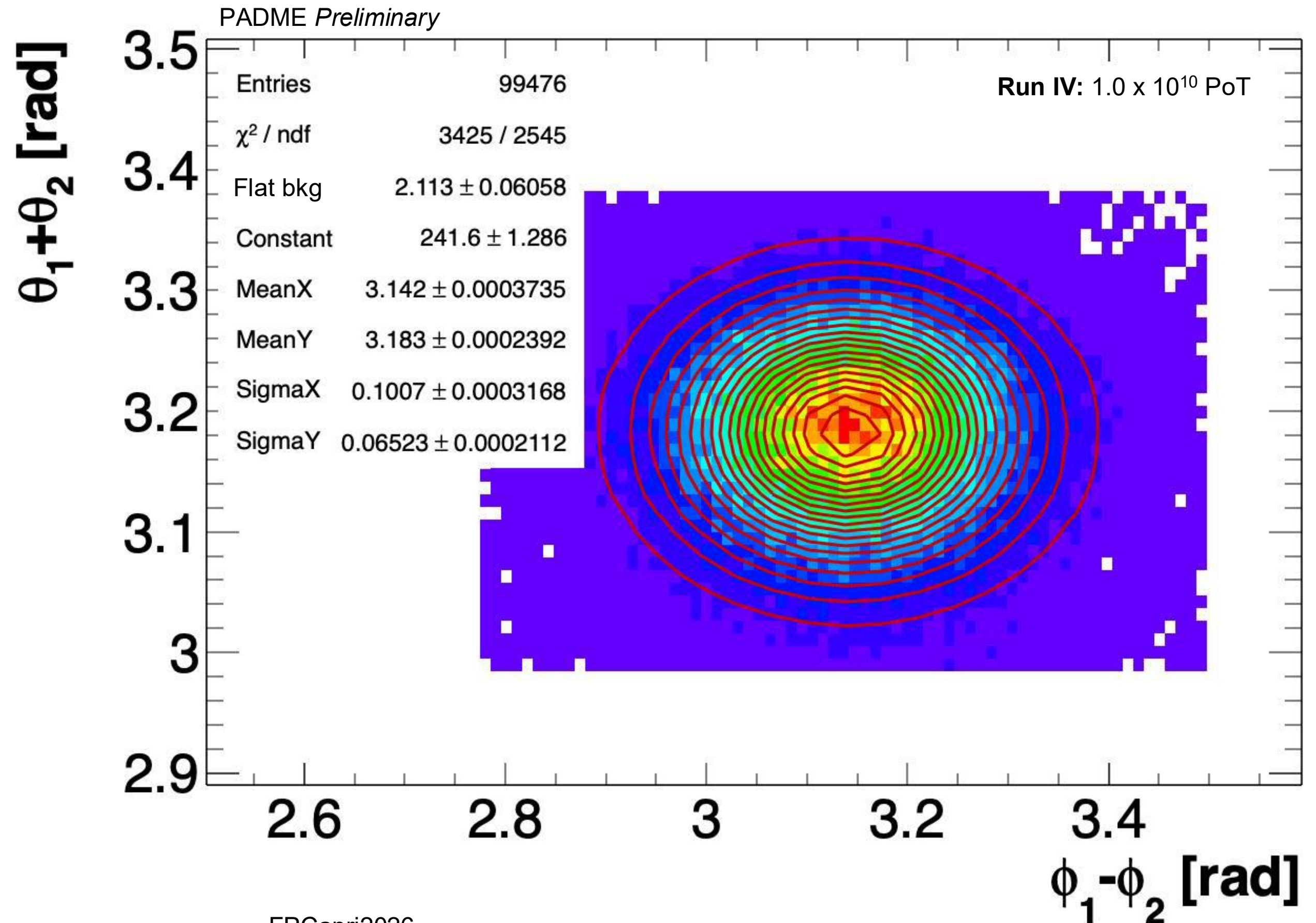
→ Low-energy cluster  $R_{\text{Max}}$  below 270 mm,  $\phi_{\text{lab}}$  cut applied

Yield increases x1.5 (as expected from MC studies)

Yield increases more 2.5 when NOT applying the  $\phi_{\text{lab}}$  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



- 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
- Improvement in  $S/\sqrt{S+B}$  by a factor 1.5 wrt to RunIII
- Stat error on the yield aimed at  $\sim 0.35\%$  for  $1 \times 10^{10}$  POT



## RunIV: 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

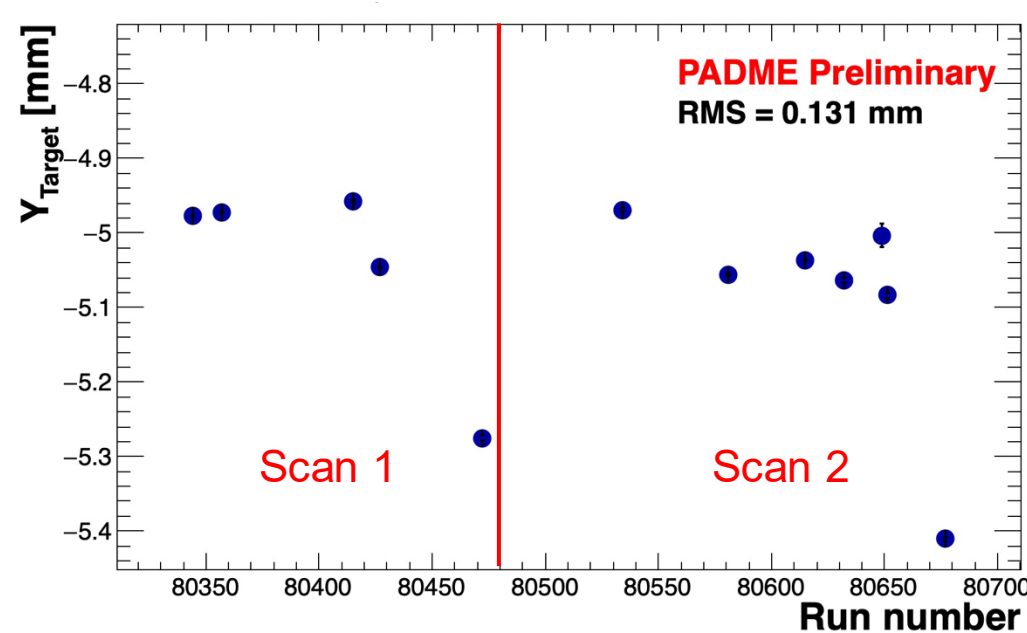
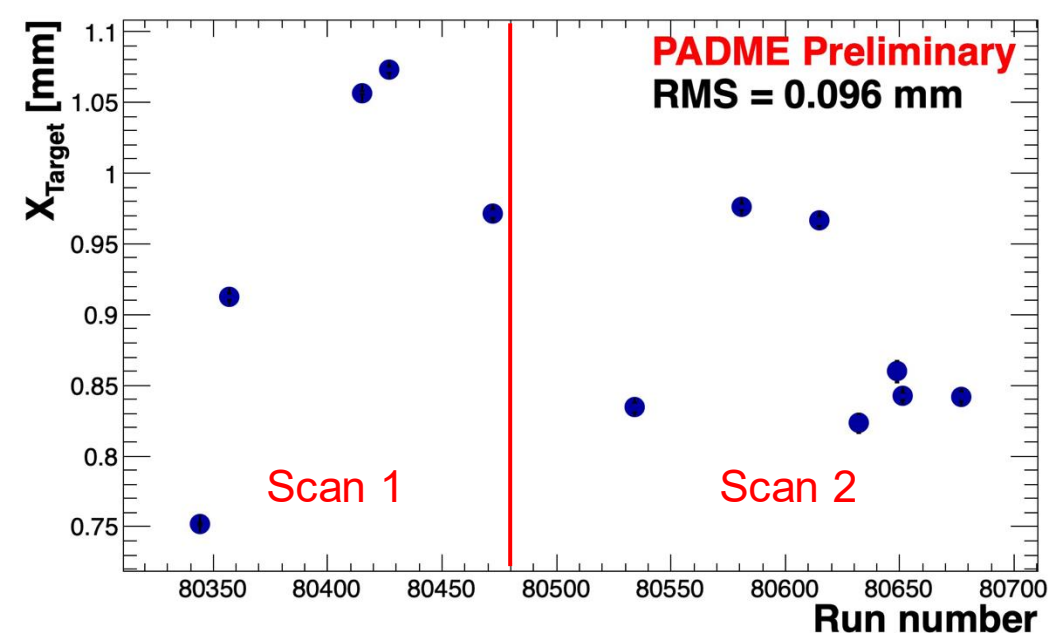
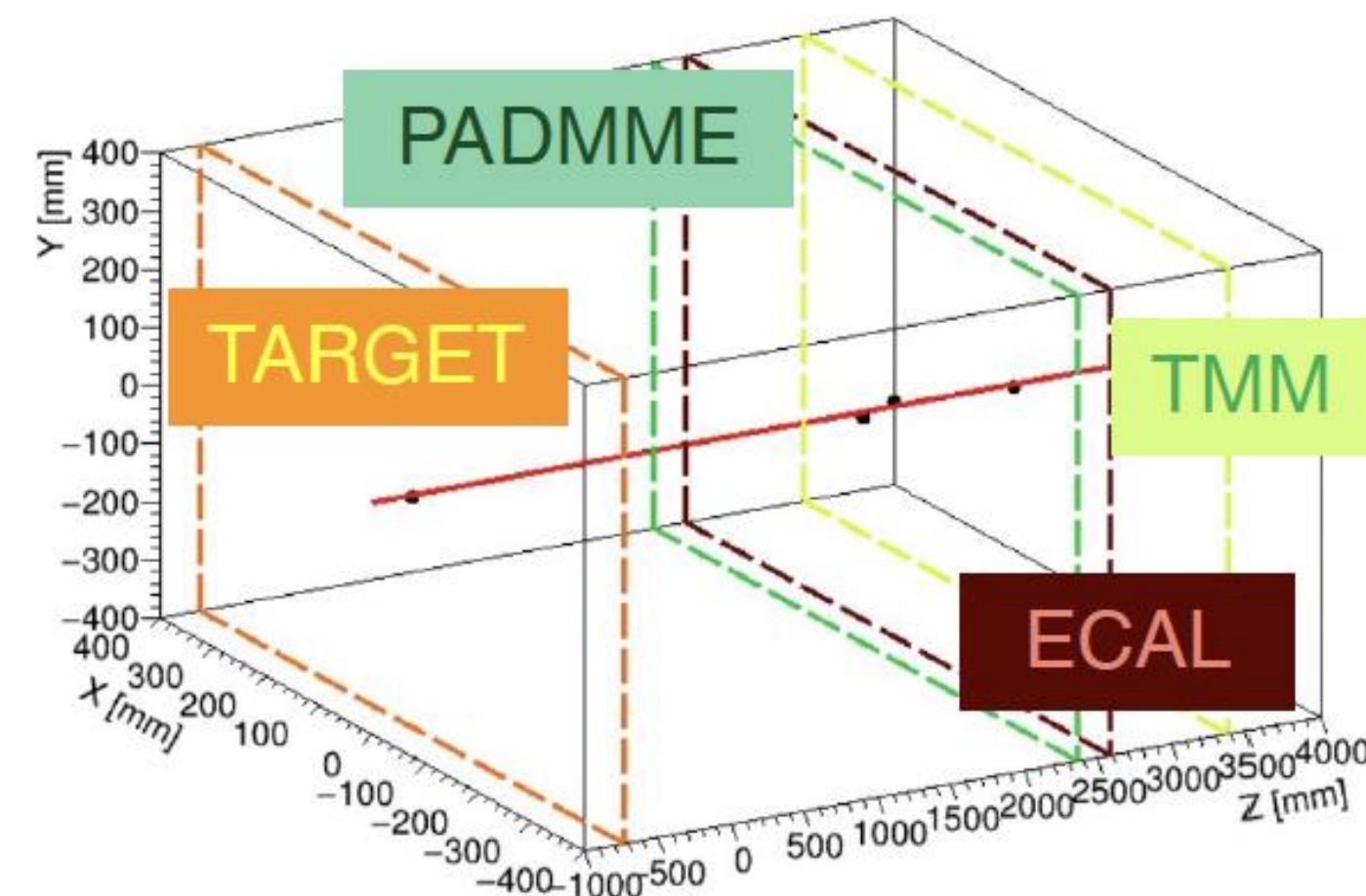
**Beam position stable within 100-150  $\mu\text{m}$**  + consistently hitting the same strip pair  
( $X = 1$ ,  $Y = -5$ ) throughout the data taking

Spread and full scan evaluation still ongoing

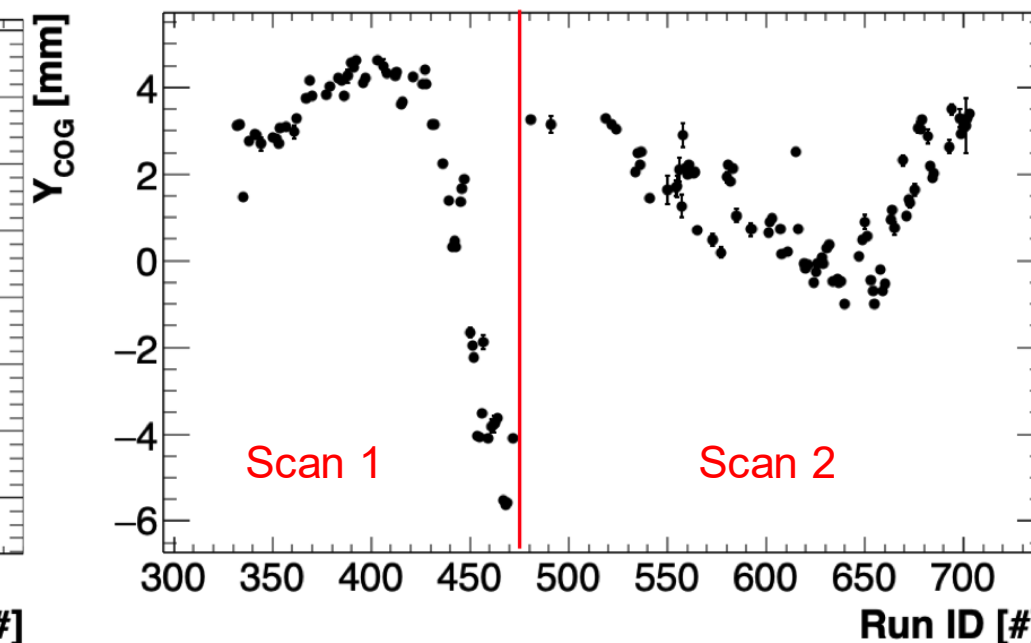
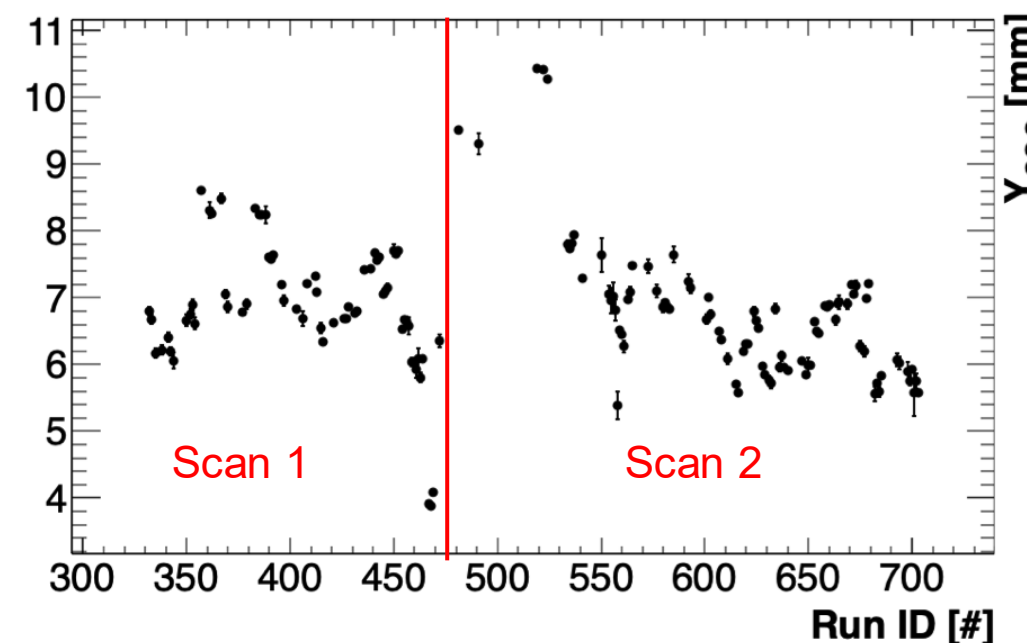
**PadMMe** and **TMM** analysis ongoing

**ECAL**: beam parameters estimated using the two-clusters center of gravity (CoG)

**Beam position stable at few mm level in X** (at cm level in RunIII),  
at cm level in Y (vertical correctors as in RunIII)



**TARGET**



**ECAL**

On the basis of the ongoing analysis of the acquired data during RUN IV and during the test runs, we are currently evaluating the possibilities to significantly increase the sensitivity of the experiment in future running campaign

## Near future prospects (timescale autumn 2027) in terms of upgrades to the present PADME setup:

- target change with Be or other (lighter material)
- decreasing the multiple scattering
  - running without the carbon fiber window using a He volume
  - refurbish the tracker to remove most of passive material along the beam (1 single gap + mylar window)

## Looking forward : target material

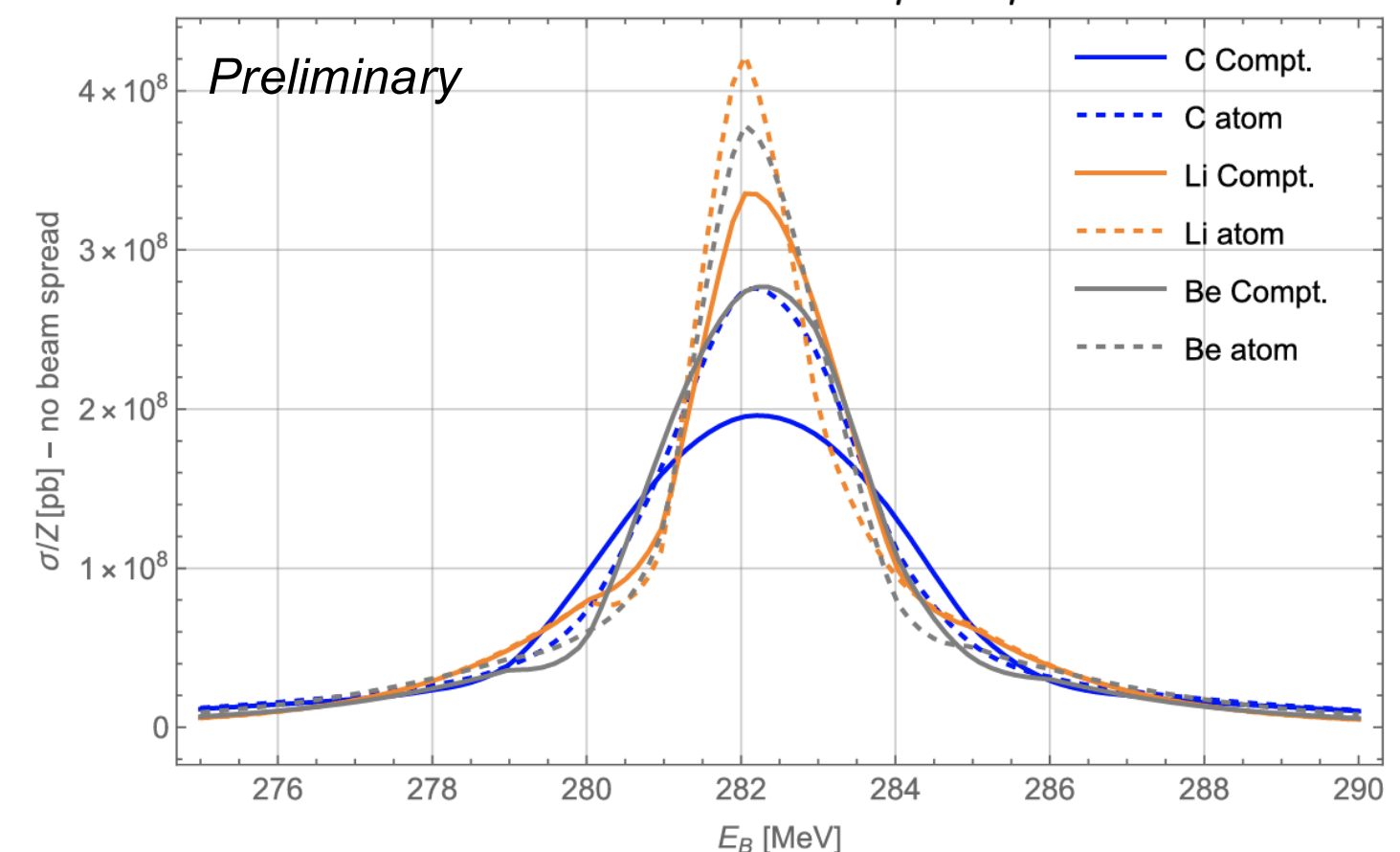
- The target material is a critically important tool in mitigating electron motion effects

Fitting to a Lorentzian (first step in PADME analysis, further convolved with a Gaussian)

- $\Gamma_C \sim 1.9$  MeV
- $\Gamma_{be} \sim 1.3$  MeV
- $\Gamma_{li} \sim 1.1$  MeV

- Needs to be included in a systematic experimental study
  - More systematic target material exploration needed

*NB - LiH also a possibility - Compton profile closer to Be*



Luc Darné