Status of the PADME experiment and future plans

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on behalf of the PADME collaboration

LNF Scientific Committee meeting

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The PADME approach to new-physics search

Dedicated experiment sensitive to NP coupling to e or γ @ $\sqrt{s}$ ~ 20 MeV

Production mechanisms: strahlung, radiative annihilation, resonant annihilation

Model-independent and redundant as much as possible:

use e^+ beam + fixed target, kinematics highly constrained

Exploit an existing facility: the Beam Test Facility (BTF) of the LNF complex

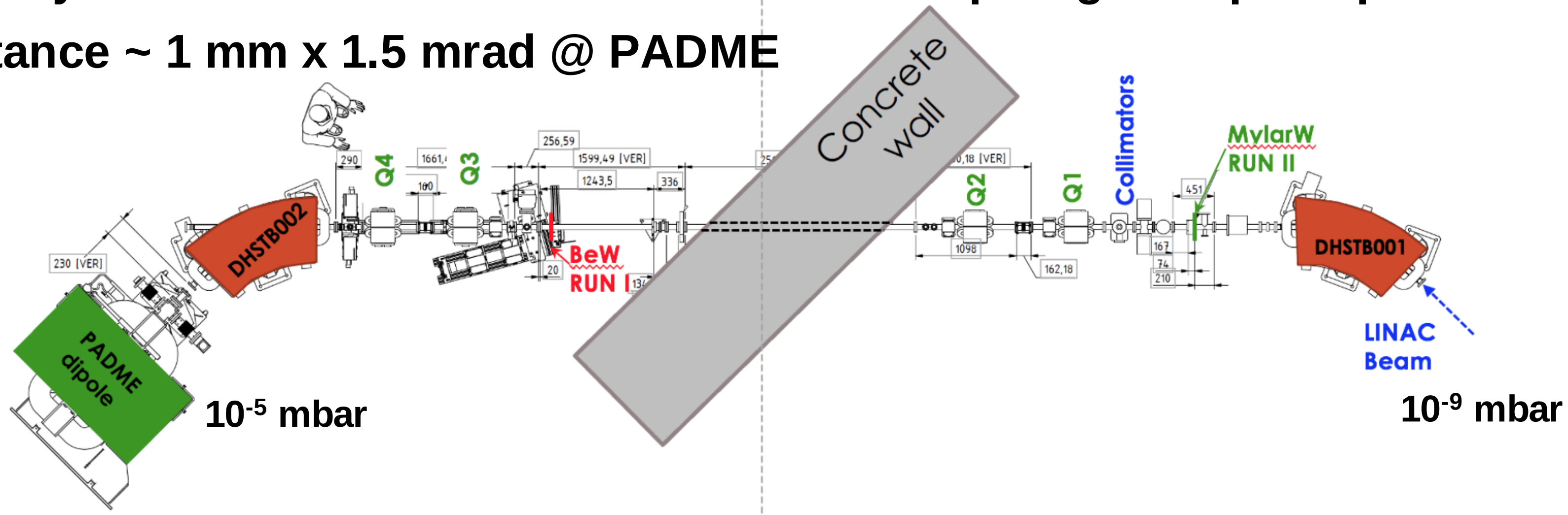
What's PADME – the facility

Positrons from the DAFNE LINAC up to 550 MeV, O(0.5%) energy spread

Repetition rate up to 49 Hz, macro bunches of up to 300 ns duration

Intensity must be limited below ~ 3 × 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]

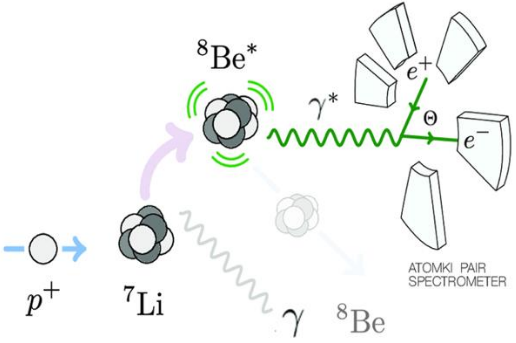
Run II e^+ primary beam, 125 μm Mylar™ vacuum separation, 28000 e^+/bunch [2019-20]

Run III dipole magnet off, ~2500 e^+/bunch, scan $s^{1/2}$ around ~ 17 MeV [End of 2022]

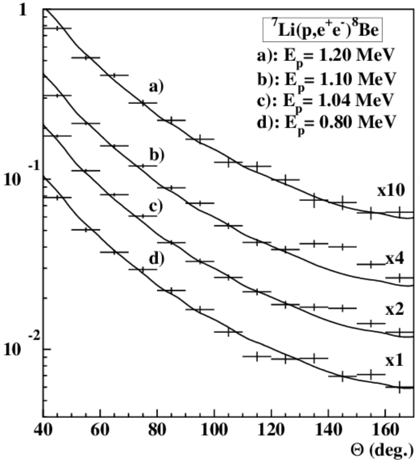
Run III

Standing anomalies in the game: "X17"

De-excitation of light nuclei via IPC, an anomaly in the decay of ^{8}Be and ^{4}He

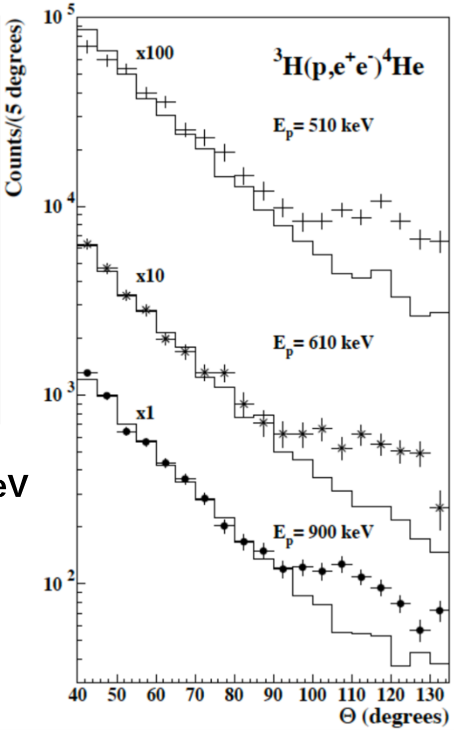


PRL 116, 042501 (2016)



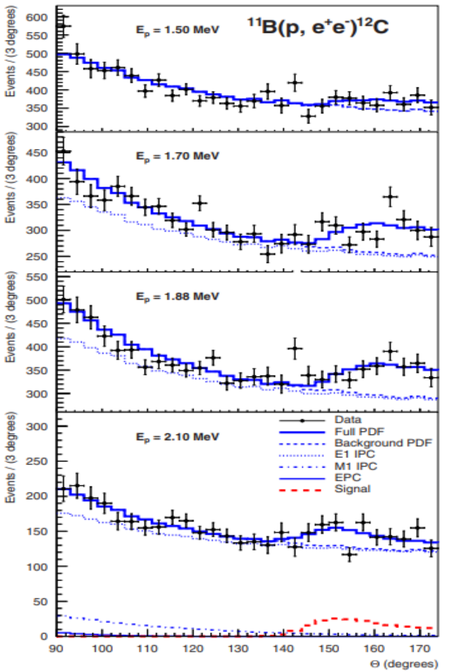
$m_\chi = (16.7 \pm 0.35 \pm 0.5)$ MeV

Phys. Rev. C 104, 044003 (2021)

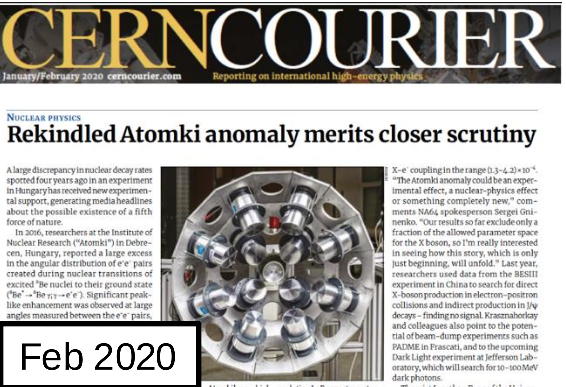


$m_\chi = (16.98 \pm 0.16 \pm 0.20)$ MeV

Phys. Rev. C 106, L061601



$m_\chi = (17.03 \pm 0.11 \pm 0.20)$ MeV



Feb 2020

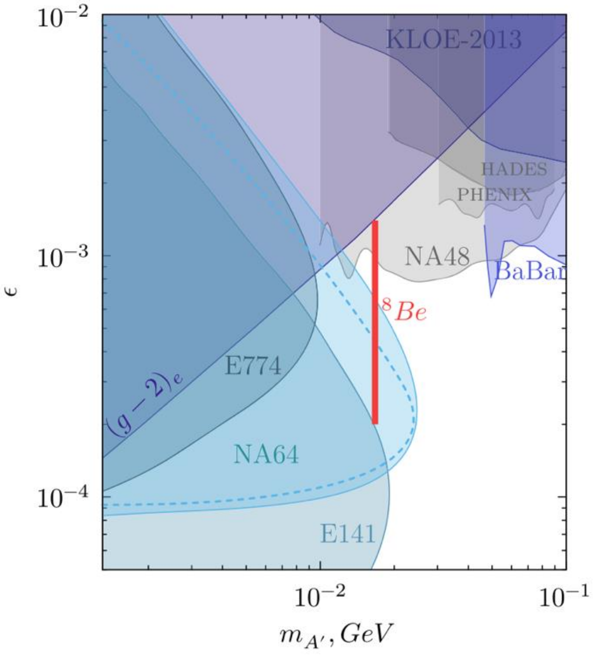
Also seen in GDR of ^{8}Be [2308.06473], in ^{8}Be/^{12}C at HUS (Vietnam)

Other efforts: e-, n beams, etc.

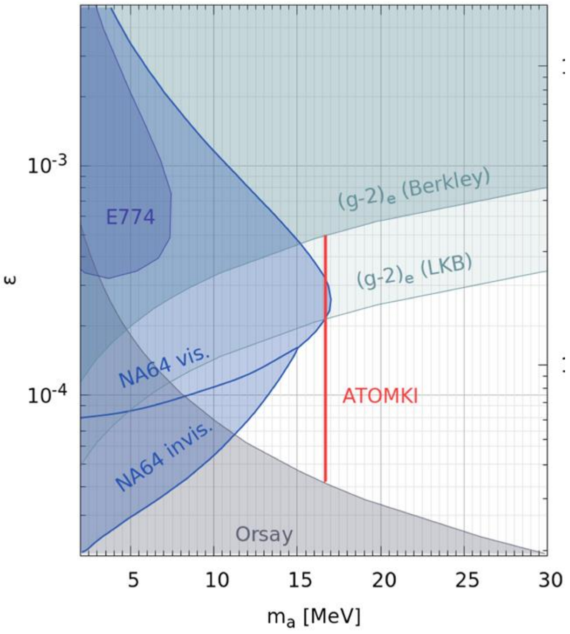
“X17” as a vector or pseudo-scalar state

New physics interpretations not fully excluded

Phys. Rev. D 101, 071101 (R) (2020)



Phys. Rev. D 104, L111102 (2021)



Novel QCD interpretations exist, too [hexadiquark states for He4, 2206.14441]

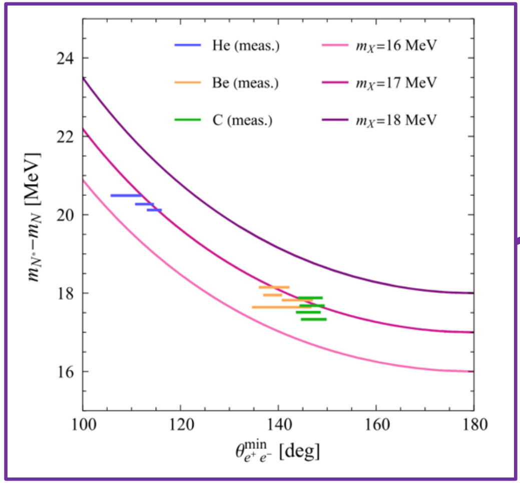
The recent MEG-II result

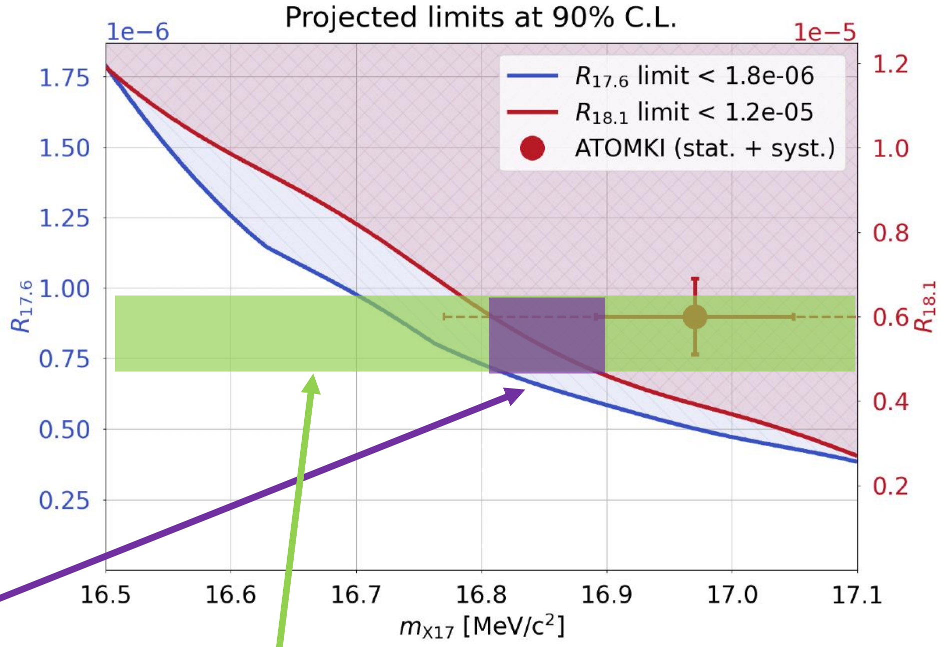
- Hypothesis of a X17 with mass > 16.97 MeV now excluded at p = 94%
- For the whole mass range available, exclusion is:

$$R_{18.1} < 1.2 \times 10^{-5} \text{ and } R_{17.6} < 1.8 \times 10^{-6}$$

- From fits in PR D 108, 015009 (2023) the best mass candidate combining ATOMKI results in:

$M_{X17} = 16.85 \pm 0.04$ MeV





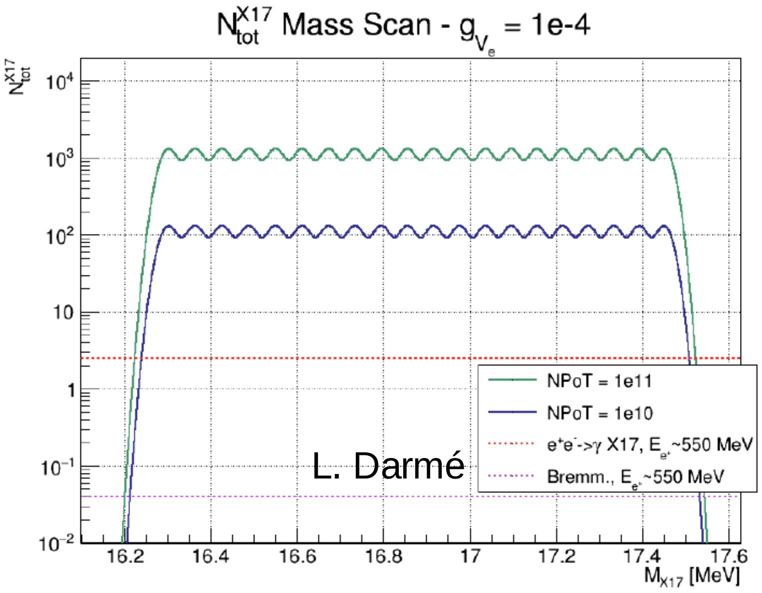
^{8}Be, PRL 116 (2016) 042501:
$16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV.

More details in the the referee session

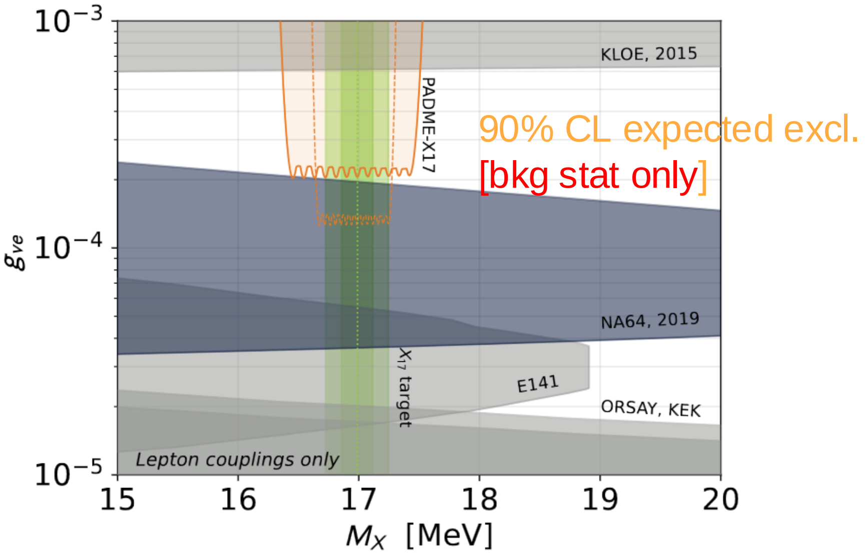
Goals before Run-III data

At PADME, an independent production mode to test existence of X17

Resonant production with $E(e^+) \sim 283$ MeV: signal should emerge on top of Bhabha s and t-channel bkg, intrinsic width ~0.01 eV [Darmé, et al., PRD 106 115036]



Run-III corresponds to the upper curve, with higher density of scan points (0.5% BES, 12 points, 2E11 POT)

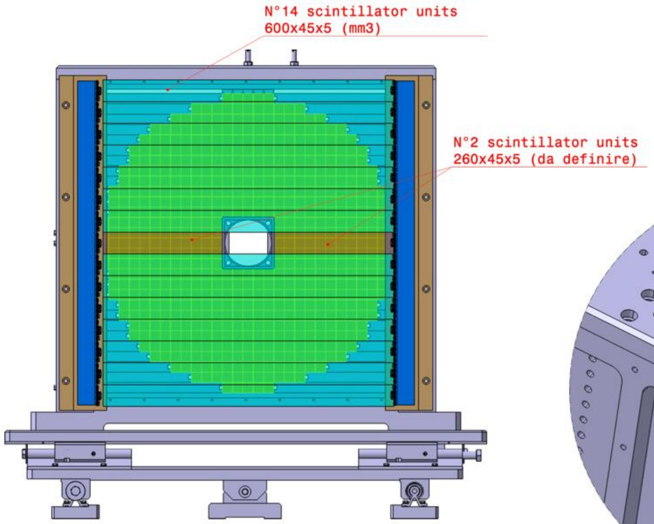


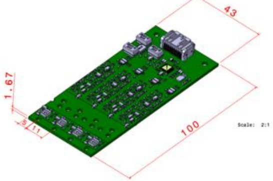
X17 via resonant-production: detector upgrade

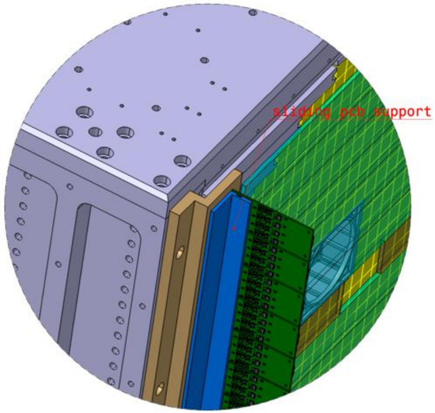
The setup for an e^+e^- resonance search is modified with resp. to Run II

Switch off the PADME dipole → increase acceptance

Distinguish e/γ in the ECAL with a new hodoscope, the E_{tag}







Built, commissioned July 2022, to be used for systematic cross checks

Overall analysis scheme

Analysis pillars:

- Independent measurement of POT
- Scan in sqrt(s) with tiny step: beam energy spread @ or < 0.5%
- Measurement of e^+ beam quadri-momentum
- Selection of $e^+e^-/\gamma\gamma$ final states

Open possibilities:

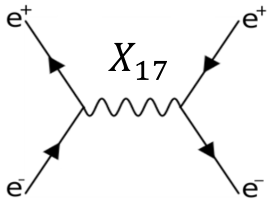
N (e^+e^-) / POT vs √s as in Darmé et al., PRD 106 (2022) 11 , 115036

N ($e^+e^- + \gamma\gamma$) / POT vs √s

N (e^+e^-) / N ($\gamma\gamma$) vs √s

Goal: (sub)% total systematic error (excl. components indep. of √s)

Overall analysis scheme



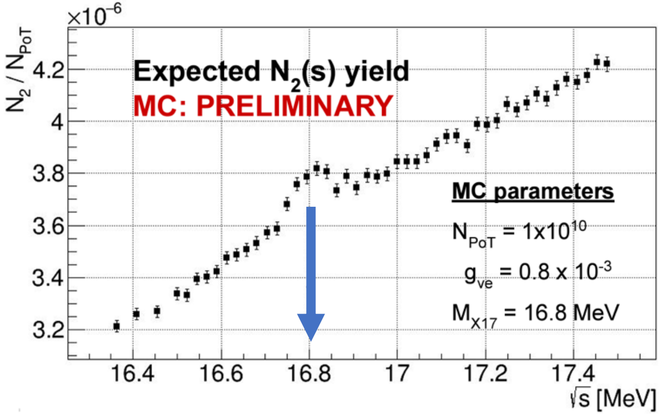
- $\sigma_{res} \propto \frac{g_{V_e}^2}{2m_e} \pi Z\, \delta(E_{res} - E_{beam})$ goes with Z → dominant process
- $\sqrt{s}$ has to be as close as possible to the expected mass → fine scan procedure with the e^+ beam → expected enhancement in $\sqrt{s}$ over the standard model background

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

$N_2(s) = N_{POT}(s) \times [\, B(s) + S(s; M_X, g)\, \varepsilon_S(s)\,]$ vs $N_2(s) = N_{POT}(s) \times B(s)$

Inputs:

- $N_{POT}(s)$ number of e+ on target from beam-catcher
- $B(s)$ background yield expected per POT
- $S(s; M_X, g)$ signal production for {mass, coupling} = {M_X, g}
- $\varepsilon_S(s)$ signal acceptance and selection efficiency



Initial projections at the start of Run III

Statistics collected (after data quality cuts): O(10^{10} POT) / point

Beam momentum spread: σ_E = 0.7 MeV/c → 0.25% relative beam spread

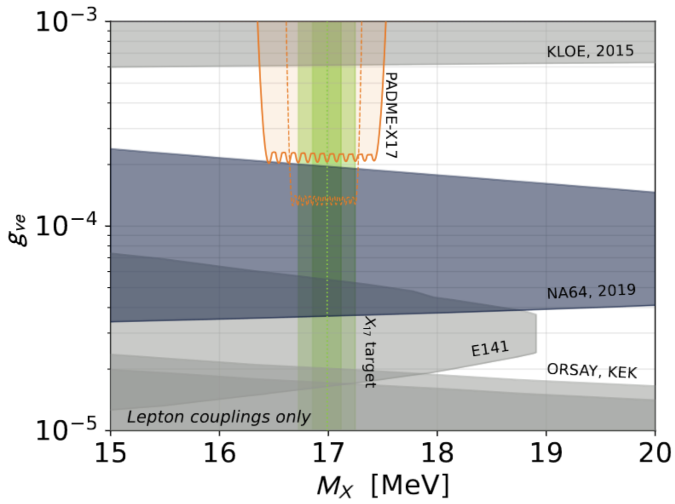
Points spaced by ΔE = 0.75 MeV/c ~ σ_E, reduce span due to binning

- **Signal counts (S) expected per point: S = 350 x (g_{ve} / 2 × 10^{-4})^2**
- **Background (B) expected per point: B ~ 45000 events**

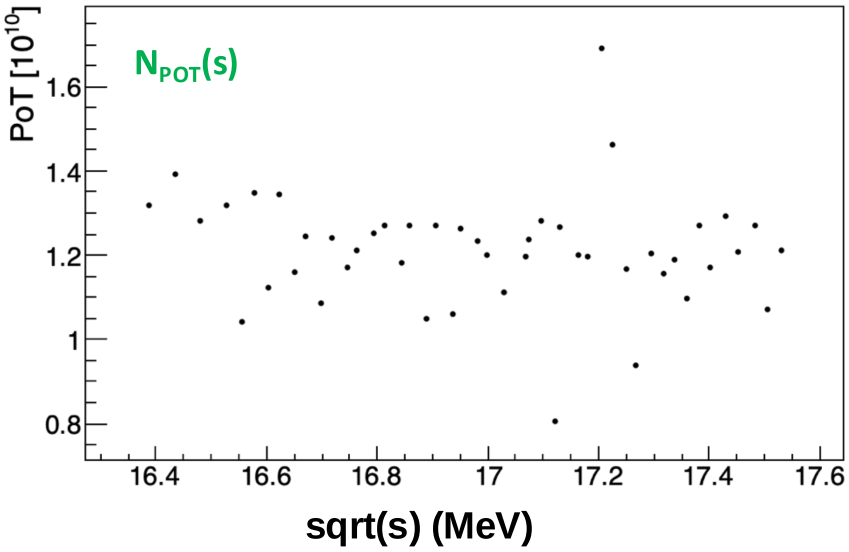
S / √B ~ 1.6 x (g_{ve} / 2 × 10^{-4})^2

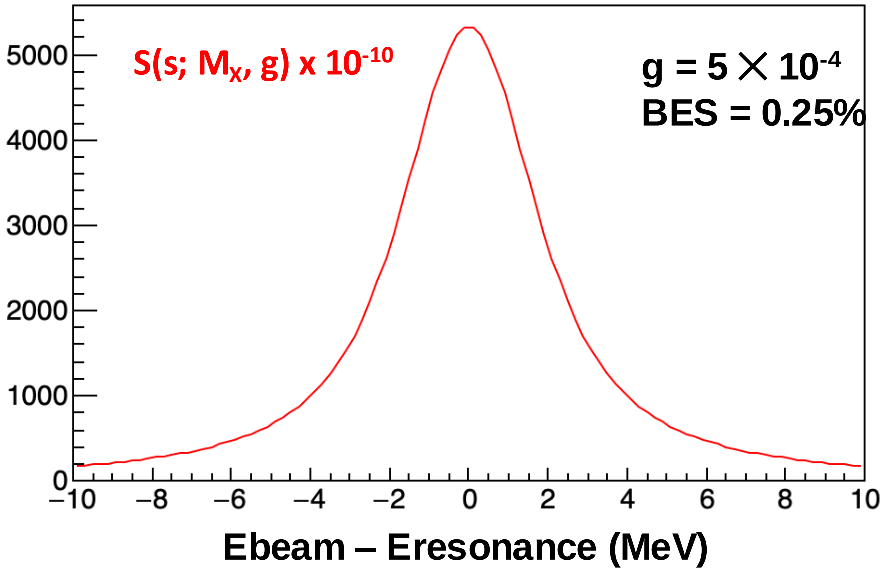
- **5σ discovery for g_{ve} > 3.5 × 10^{-4}**
- **If no signal, 90% CL excl. for g_{ve} > 0.9 × 10^{-4}**

Systematic negligible if << 1/√B = 0.5%



Teaser: summary of Run-III expectation





Statistics as planned, beam energy spread even better than expected:

PoT error kept at 0.5% (uncorrelated error only!) from beam catcher

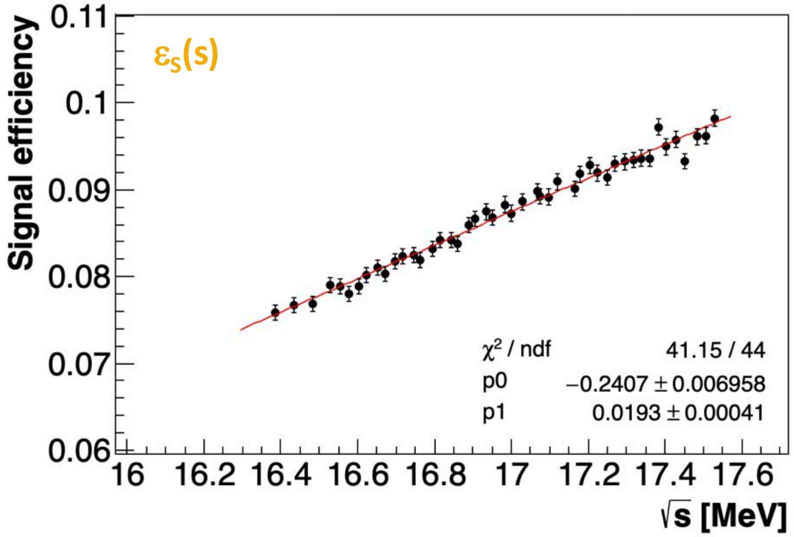
The width of the S curve is fully dominated by the electron motion:

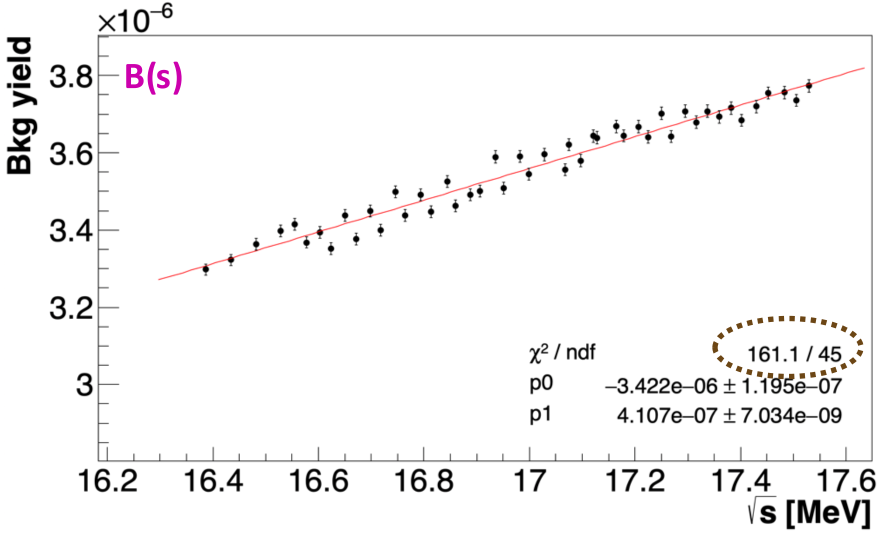
Yield at resonance lower than for e^- at rest by x 2

750 keV steps were not mandatory

Details on beam condition in Run III published in JHEP 08 (2024) 121

Teaser: summary of Run-III expectation





Efficiency lower than assumed originally by 30%:

Analysis adjustments to better cope with beam movement along the data set and reduce systematic errors for losses due to vacuum chamber material

Background varying with the data taking condition

Systematic error below 1% demanding also because of radiative corrections

Teaser: summary of Run-III expectation

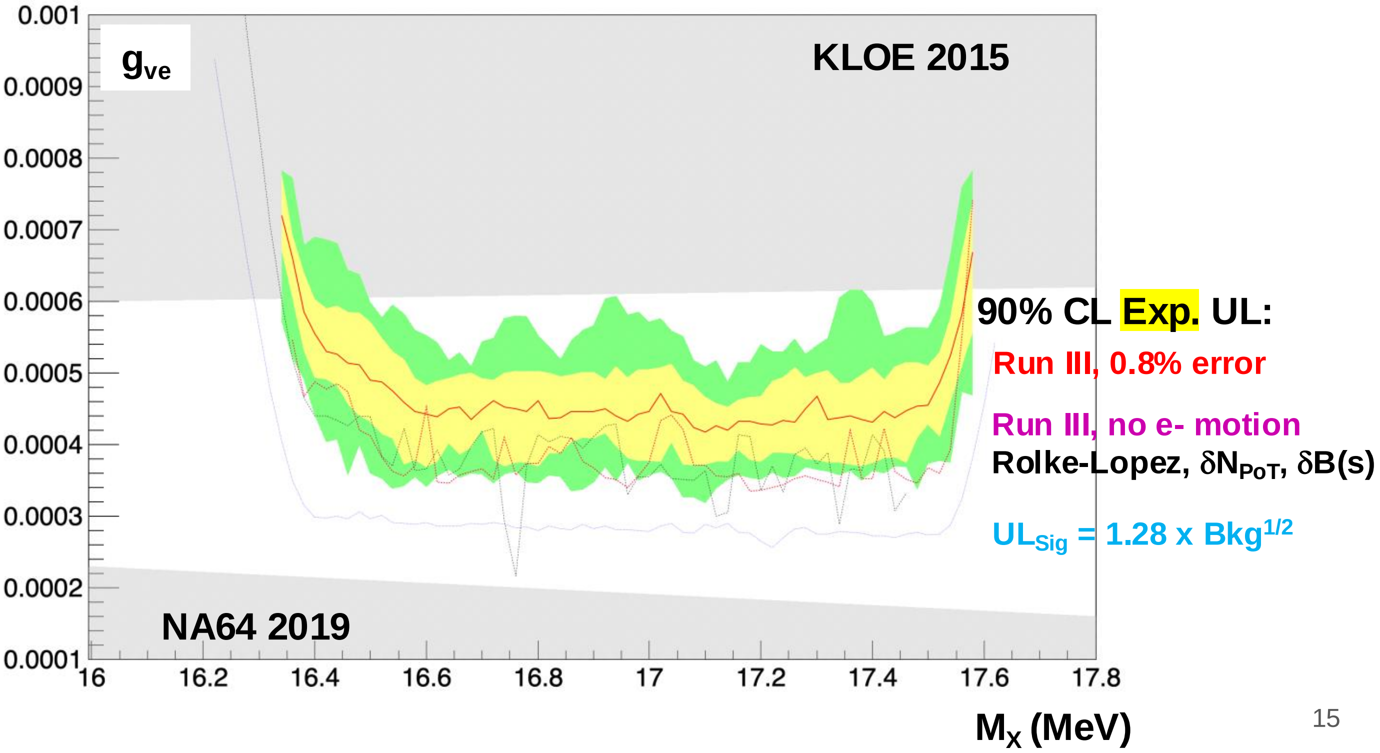
Signal box will be opened after completion of last MC production (running now)

CL_s method, $Q = -2 \ln L_{S+B} / L_B$ [compare ATL-PHYS-PUB-2011-11/CMS NOTE-2011/005, Tevatron likelihood]

Sensitivity: 90% CL UL with S=0 [200 toys for each B-only pseudo-event]

102 nuisance pars:

- B(s) true [47 pars]
- N_{PoT} true [47 pars]
- S(s; Mx,g) [3 pars]
- Absolute POT scale
- Parameters of ε/B vs s [4 pars]



Signal box opening procedure

X17 mass unknown: an automatic procedure to bless analysis maintaining the data blind

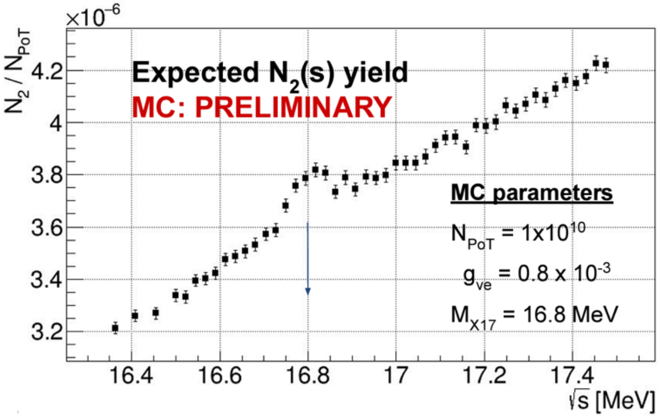
KLOE exclusion for $g_{ve} < 6\ 10^{-4}$ → assume $g_{ve} < 7 \times 10^{-3}$ → > 31 scan points "signal-free"

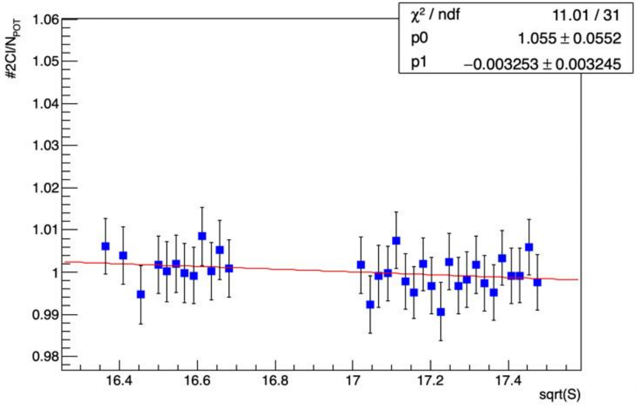
Fit $N_2(s)/\ [N_{PoT}(s)\ B(s)]$ to a linear function to account for PoT + radiative correction errors*

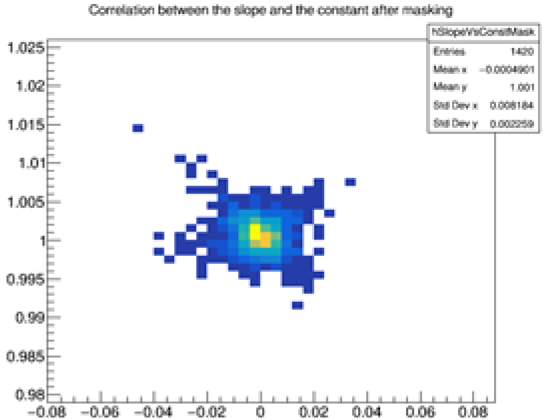
Exclude 10 points optimizing the fit likelihood while maintaining data blind

Accept and give green light if fit quality and pull stability vs s and time OK

Tests on Toy MC [mass range 16.22 – 17.72, coupling range 10^{-4} – 10^{-3}]: points excluded centered on the X17 mass, slope parameters consistent







***Paper in preparation detailing the procedure**: more details in the referee session**

Lesson learnt and improvements

Limiting effects observed after analysis of Run III:

1. **Tagger efficiency limited in separating photons from e^+/e^-**
2. **Experimental setup not enough optimized for the X17 search**
3. **Not enough emphasis put by us on monitoring to maintain stable beam conditions**
4. **Residual magnetic field in DHRTB102 not considered with due attention**

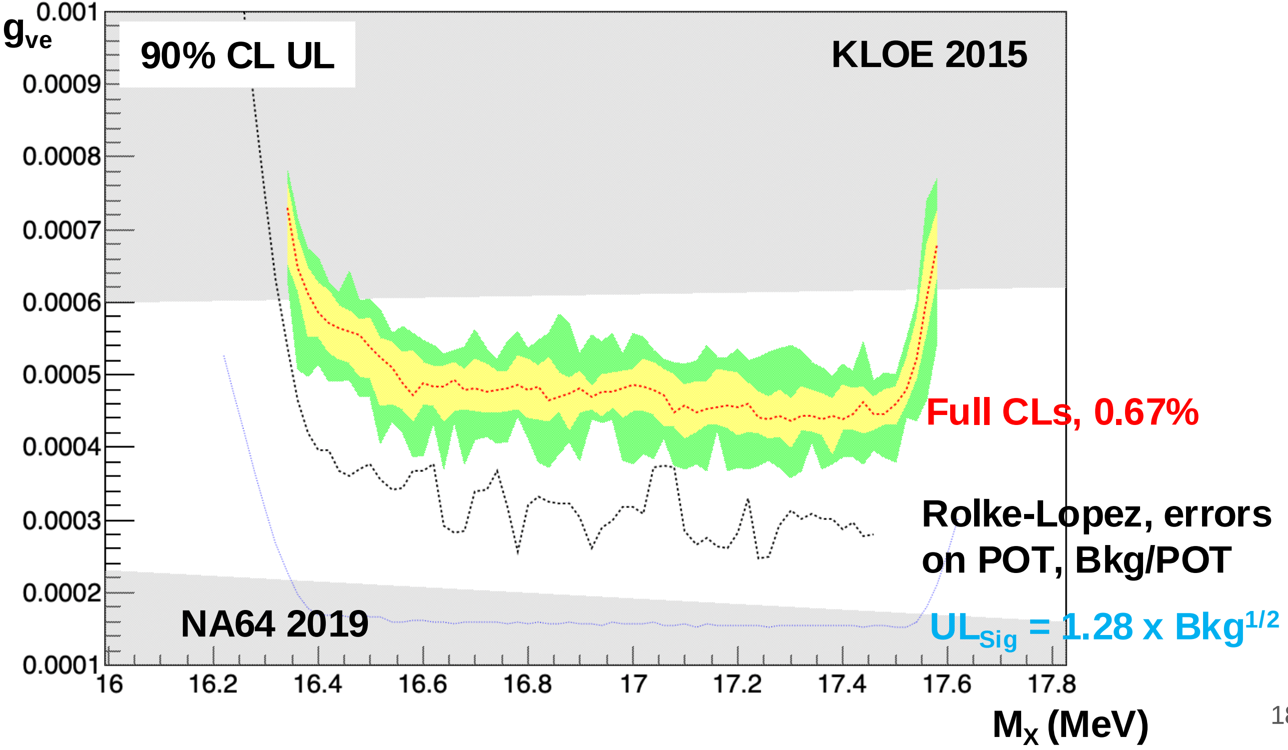
Run IV improvements proposed:

1. **Micromega chamber for angle determination + $\gamma\gamma$/ee separation**
2. **Target downstream by 30 cm + removal of material from the vetoes**
3. **Beam operation stability for each point in the data set:**
   1. **TimePix operational for entire run**
   2. **Chamber to cross check the spot determination**
   3. **Frequent no-target runs**
   4. **Lower number of points with higher intensity from 2500—3000 to 5000 e^+/bunch**
4. **Residual magnetic field down to 0.5 G**

Run IV projections

Tested 5 x 10^{10} POT / point with new geometry, normalization of e^+e^- with $\gamma\gamma$

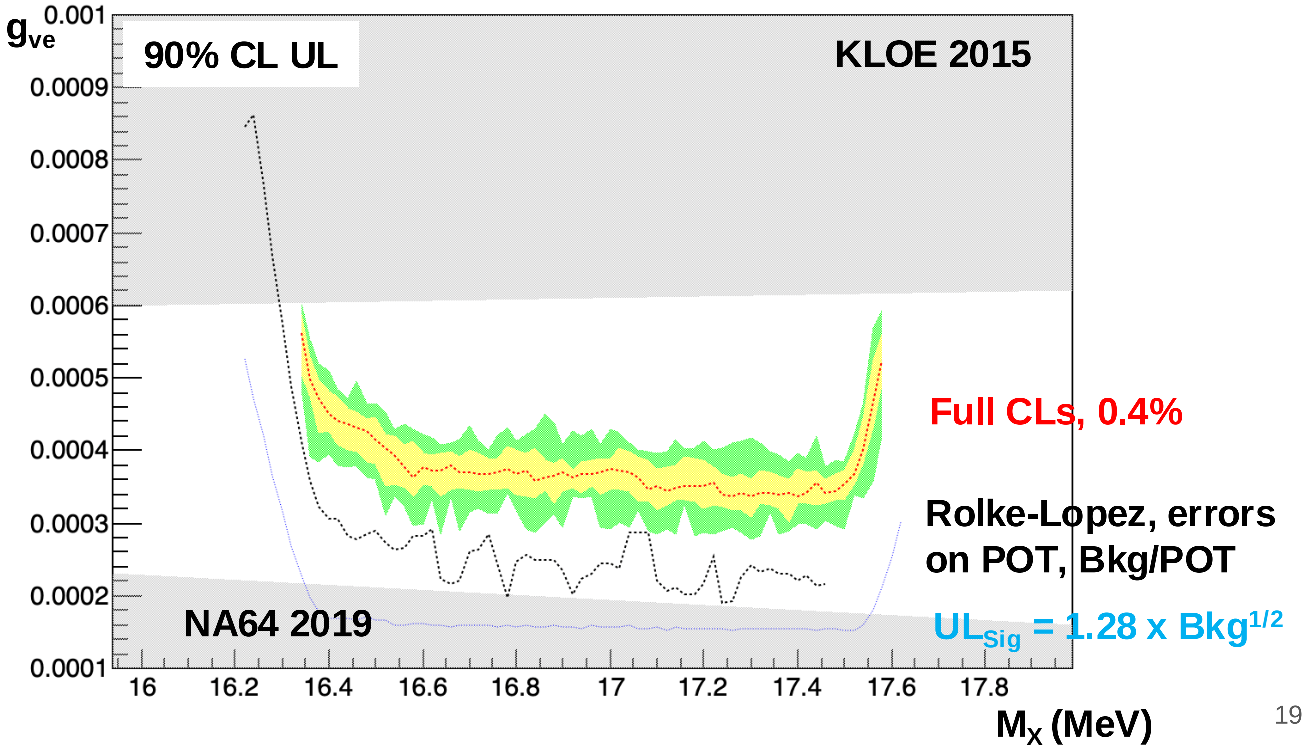
Assuming the same systematic error on B and ε_{SIG} as in Run-III, the error is dominated by the $\gamma\gamma$ statistics, still 0.6%



Run IV projections

Tested 5 x 10^{10} POT / point with new geometry, normalization of e^+e^- with $\gamma\gamma$

Assuming the same systematic error on B and ε_{SIG} as in Run-III, with the error on $\gamma\gamma$ decreased through averaging of the various scan points



Run IV proposal in a glance

Up to 10 x 10^{10} POT / point:

- **1 day for Machine Tuning to determine the beam conditions**
- **5 days of data taking**
- **1-equivalent day of no-target runs**

16 Points, 2 MeV spaced

Accounting for run efficiency of 70% + generous contingency and a possible start of data taking after chamber commissioning, a tentative planning might be:

Jan — March: chamber commissioning

April — mid July data taking

Summer break

September weeks 1-2 commissioning

Mid September — end of November data taking

Conclusions

The quality of the PADME Run III data is in line with the expectations:

<1% overall systematic error within reach

Opening the box: imminent

Unfortunately, the sensitivity is reduced by the effect of the e- motion more than anticipated, pushing the systematics down is paramount

Closing the gap with NA64 challenging:

Requires a new run with an upgraded detector + shape analysis

A tracker based on micromegas allows precision measurement of ee/$\gamma\gamma$

POT-independent and experimentally clean

Need > x4 in statistics to reduce statistical error on $\gamma\gamma$ to < 0.5%

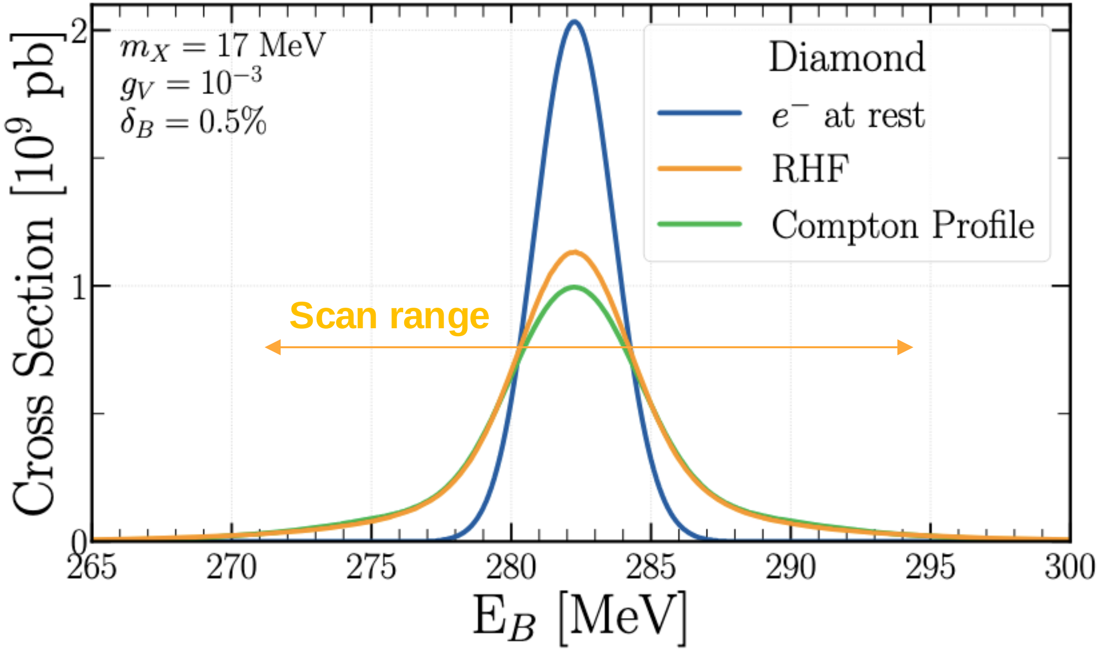
Tuning of experimental setup mandatory

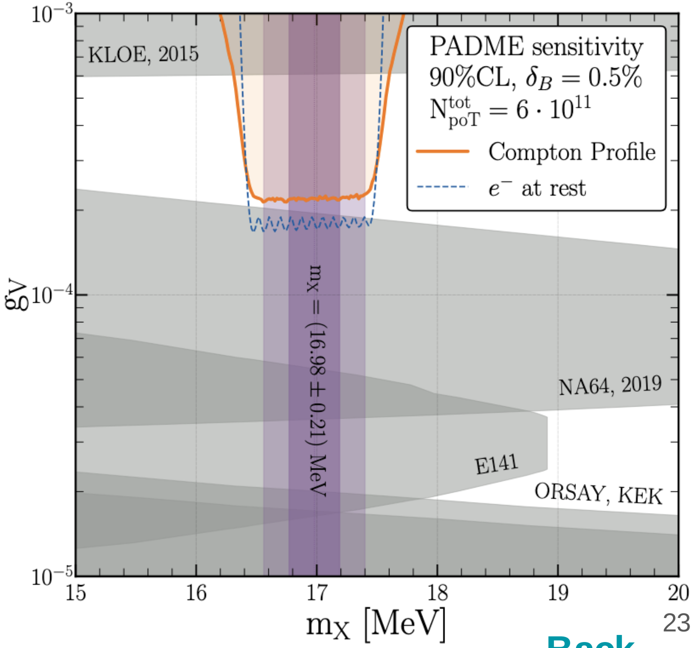
Details

X17 via resonant-production: effect of e- motion

Motion of e^- in the diamond target spreads the resonance cross section:

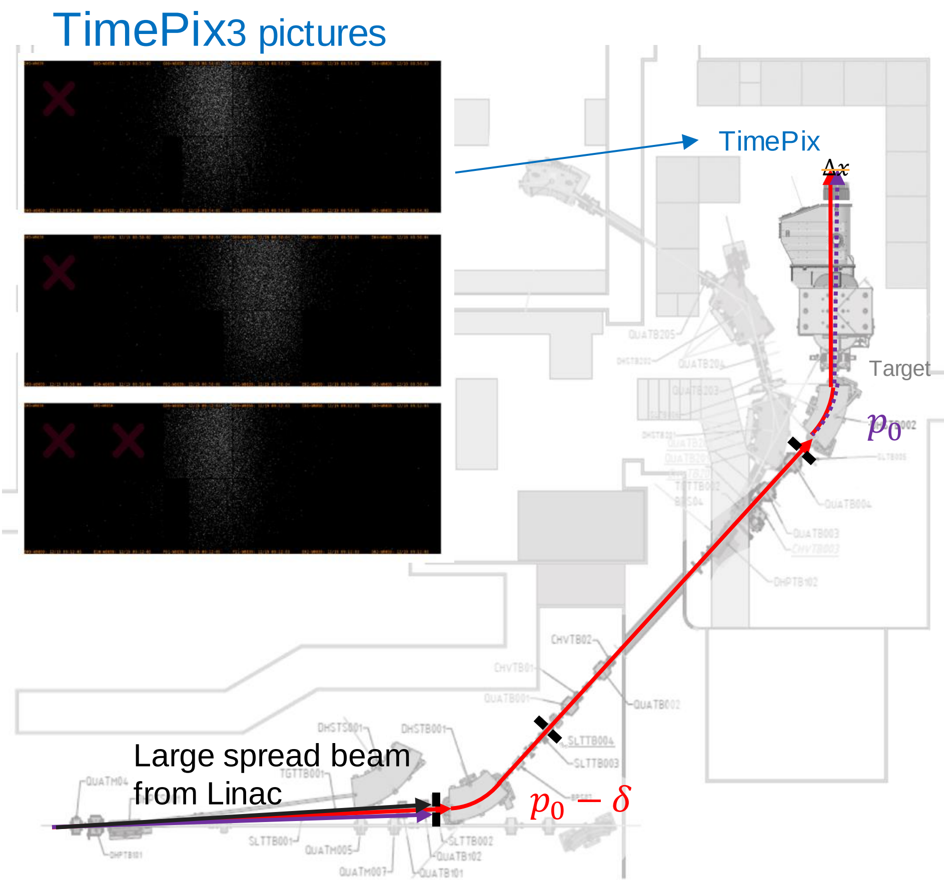
1. **Peak σ down by x2, S/B down by x2 [PRL 132 (2024) 26, 261801]**
2. **Sidebands for bkg scaling down by x4, still part of the acquired points can be used**
3. **The theory error on the expected signal yield is below 3%**





Back

Beam energy spread: better than exp.



In a spectrometer line the horizontal position of a particle with momentum $p = p_0(1+\delta)$ with $\delta = \sigma_p/p_0$, will be offset by $\Delta x = D_x\delta$, where D_x is the dispersion function; $D_x \approx L\varphi$ (L is the arm length and φ the deflection angle)

The beam spot size is given by: $\sigma_x = \sqrt{\varepsilon\beta + \left(\frac{D_x\sigma_p}{p}\right)^2}$

If the geometric beam size in absence of dispersion can be neglected, $\sqrt{\varepsilon\beta} \ll \frac{D_x\sigma_p}{p}$, we can get the spread from: $\frac{\sigma_p}{p} \approx 1/D_x \cdot \sigma_x$ NIM A515 (2003) 524

From a **run without the PADME target** (no Coulomb scattering) we estimate: $\frac{\sigma_p}{p} \approx$ **0.24%**

- Can also be computed from collimators' gaps/distances from MC, JHEP 09 (2022) 233

$$\left|\frac{\Delta E}{E}\right| = \frac{h}{2\rho} + \sqrt{2}\left(\frac{R_x}{L_1} + \frac{H}{2L_1}\right) \cong \frac{h}{2\rho} + \sqrt{2}\frac{H}{L_1}$$

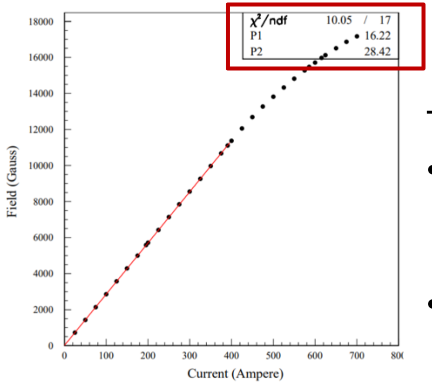
- With H=h=2 mm we get **0.22%**

MC confirms BES < ~ 0.25% N. Cim. C47 (2024) 4

Beam momentum in Run III: fully OK

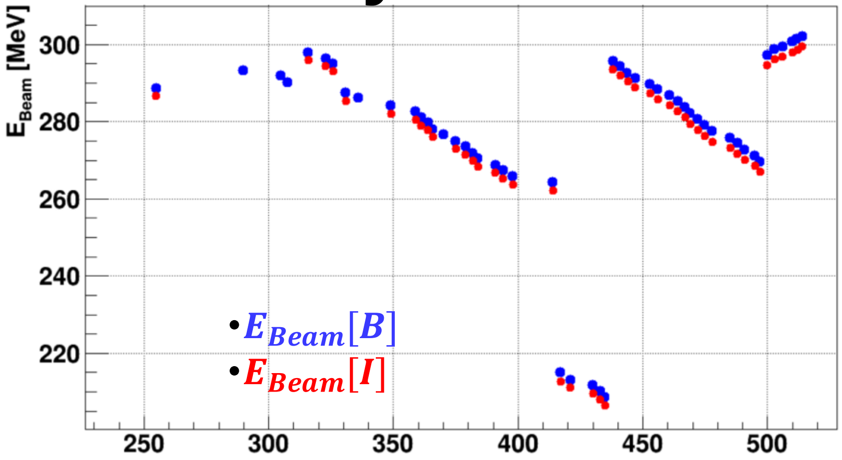
Two measurements of the energy available

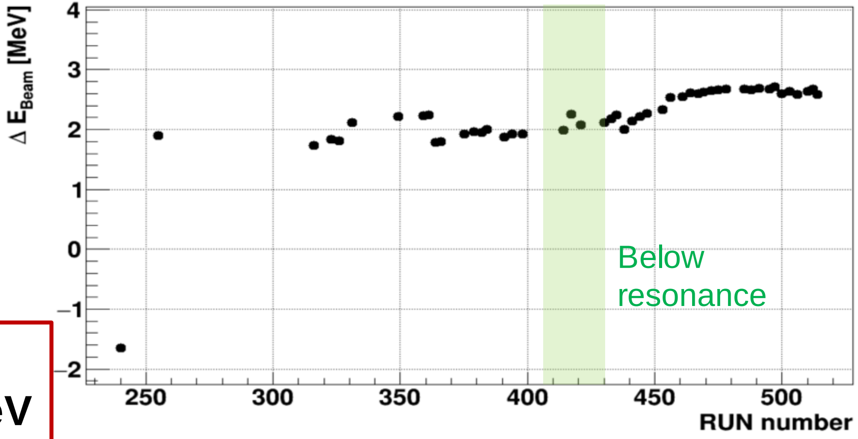
- Magnetic field (B) from Hall probe at DHSTB001: P_{Beam} [MeV] ~ 0.0551 x B[G]
- Current of DHSTB001 coils from power supply: P_{beam} [MeV] ~ 0.0551 x (K + 28.42 x I[A])



The *offset K* depends on:

- Residual magnetization – variable during the data taking
- Position of the Hall probe





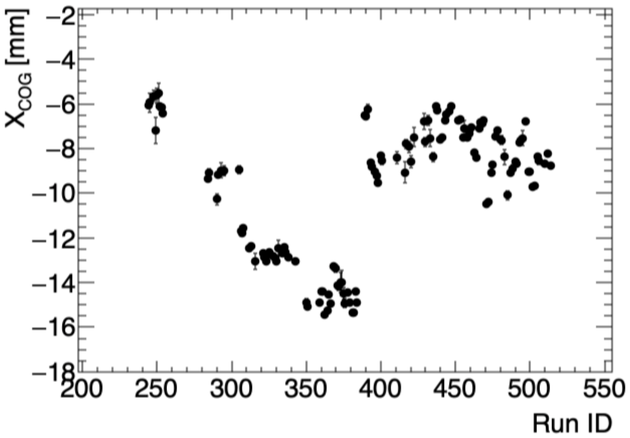
Beam energy known with ~ 2 MeV uncertainty: **OK**
conservative systematic uncertainty $\delta m_{X_{17}} \sim 30$ keV

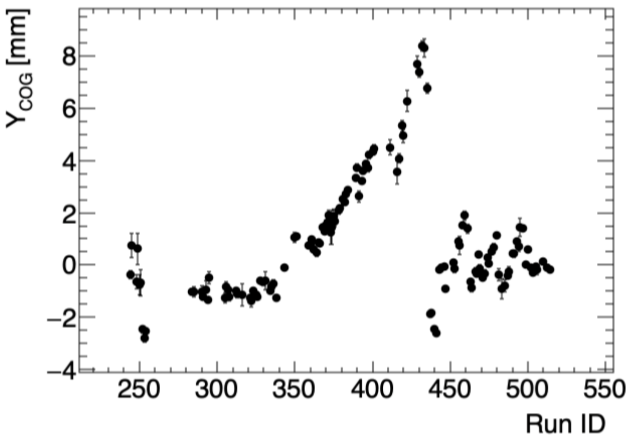
Back

Variation of beam positions in Run III

Goal of the data taking was to ensure a fine energy scanning, with the idea to correct offline for beam stability

Beam position from data: center of gravity (COG) of 2 Ecal clusters: $x_i^{COG} = \frac{x_i^1 E_1 + x_i^2 E_2}{E_1 + E_2}$



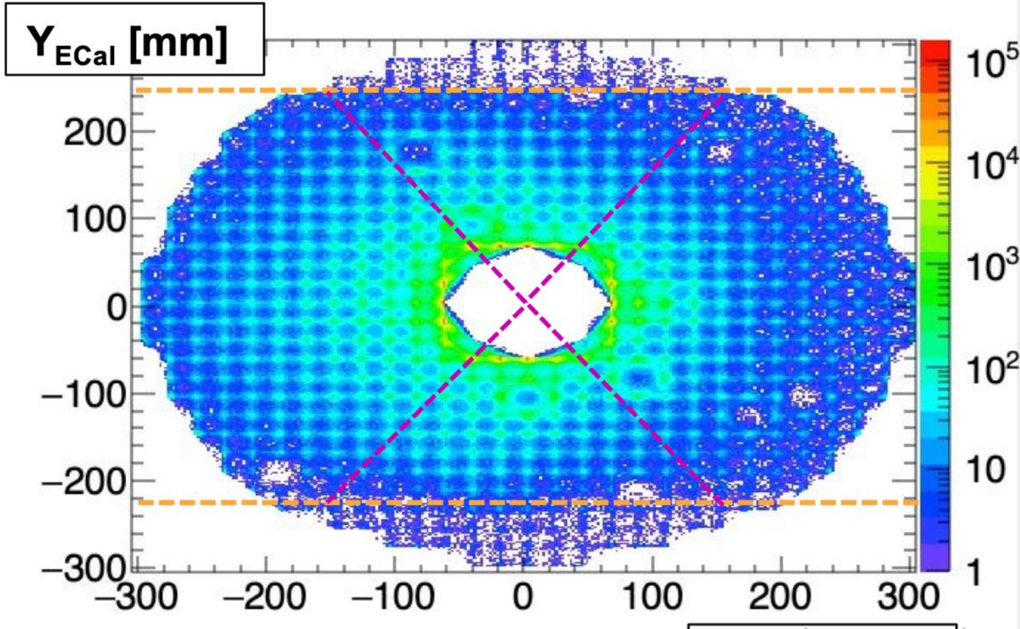


The beam position moves run by run by O(10 mm)

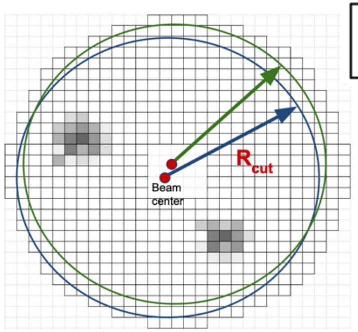
Impact of the beam position variation

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
  - Illumination affected by passive material (below flange) not controlled in MC → **Cut regions in φ**



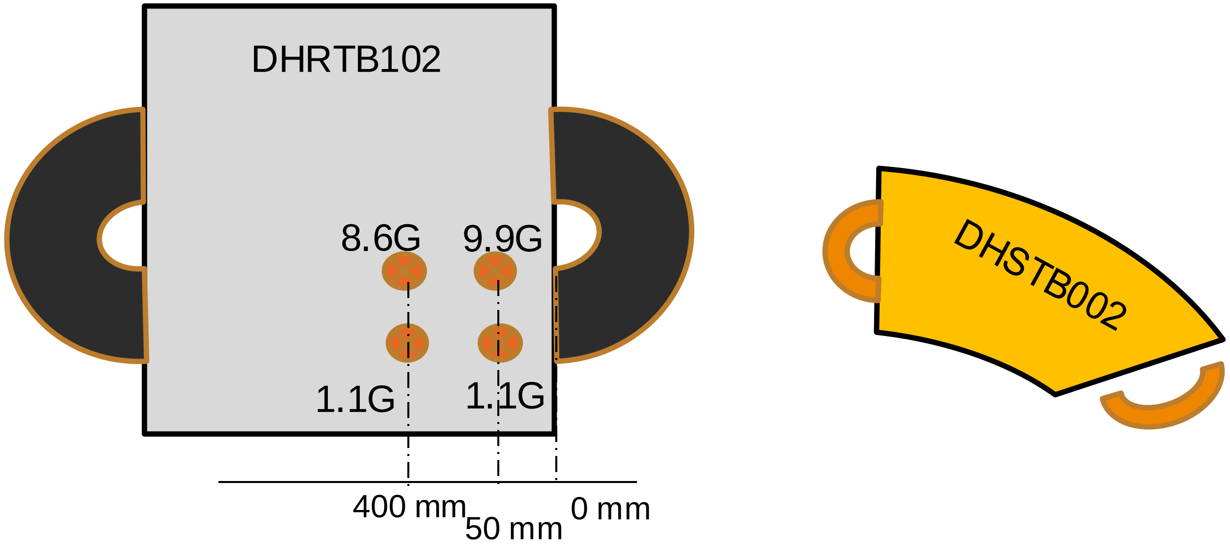
- Mutual cluster conditions:
  - ΔT (clu0-clu1) < 5 ns
  - ΔR (clu0-clu1) > 60 mm (Minimum GG difference)
  - $\boldsymbol{\phi_1 - \phi_2}$ vs $\boldsymbol{\theta_1 + \theta_2}$ cut in the center of mass frame isolates the signal



- **Residual magnetic field** imposes a systematic error

The residual magnetic field

Residual magnetic field, survey 14 November 2022: we use 12.5 G in MC



NB the values are measured on the beam line

Back

Run III statistics: fully OK

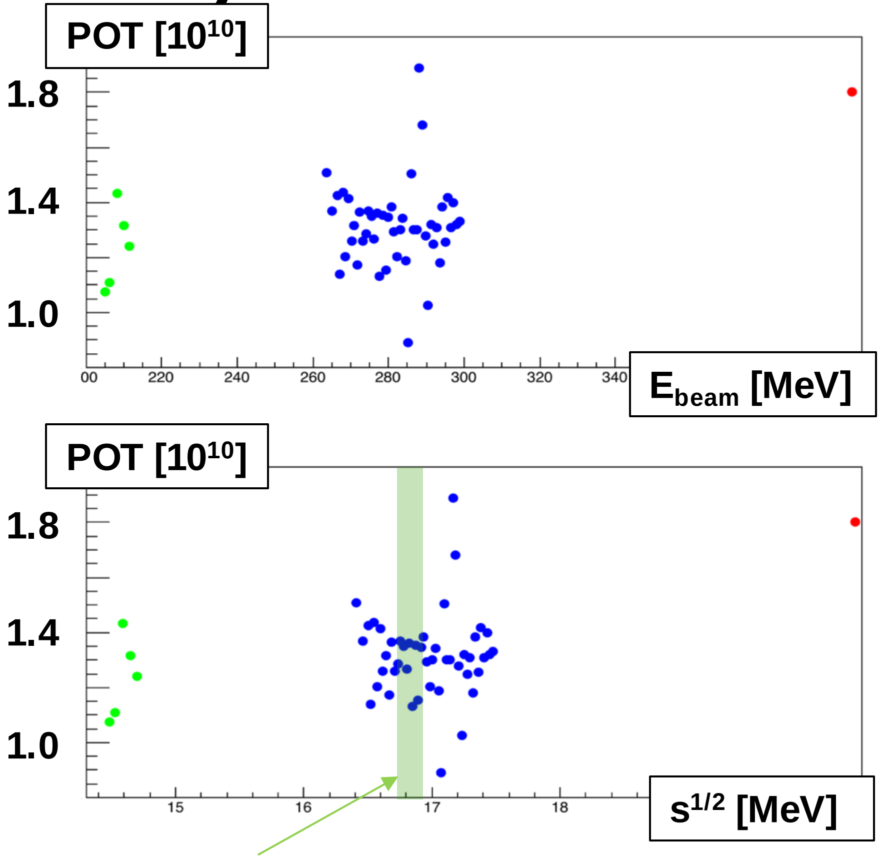
Run III PADME data set contains **3 subset**

- **On resonance: 47 points (263-299) MeV**
- **Below resonance: 5 points (205-211) MeV**
- **Over resonance: 1 energy 402. MeV**

On resonance points, mass range 16.4 — 17.5 MeV
Beam energy steps ~ 0.75 MeV ~ beam energy spread
Spread equivalent to ~ 20 KeV in mass
Statistics > 10^{10} POT per point

Below resonance points
Beam energy steps ~1.5 MeV
Statistics > 10^{10} POT per point
Used to validate analysis method

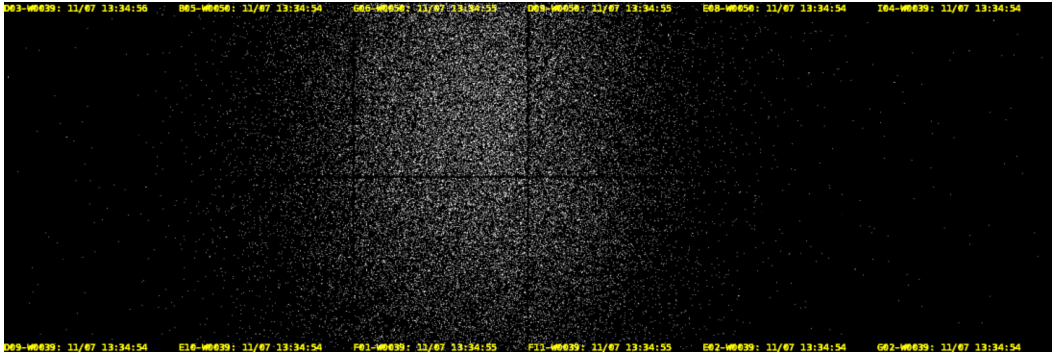
1 over resonance energy point
Statistics ~2 x 10^{10} total
Used to validate POT measurement

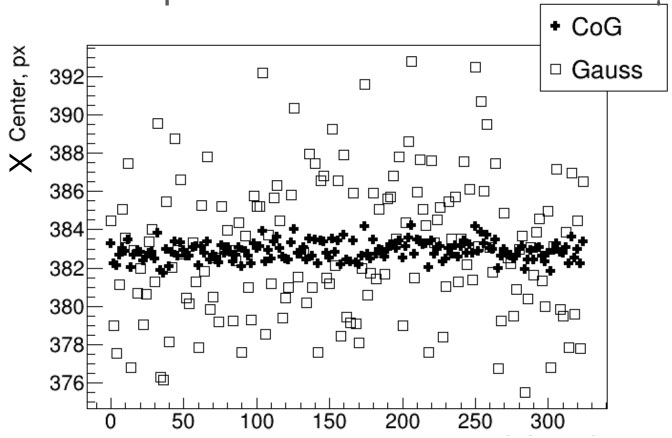


Fit result from ATOMKI data [PRD 108, 015009 (2023)]

Beam monitor with TimePix (only second part of RunIII)

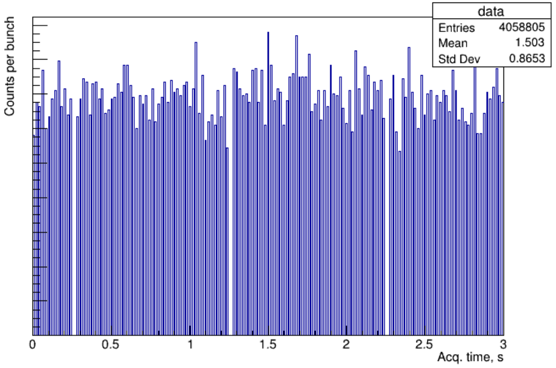
Pixel size: 55 μm,
Y beam position variation - within 100 μm



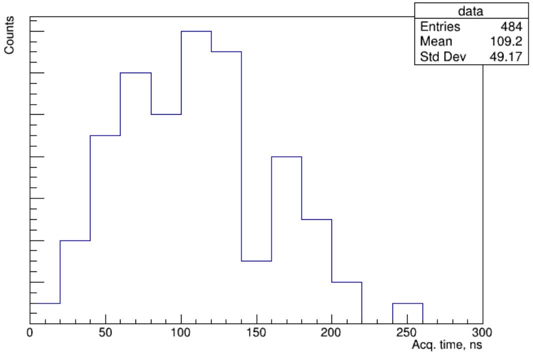


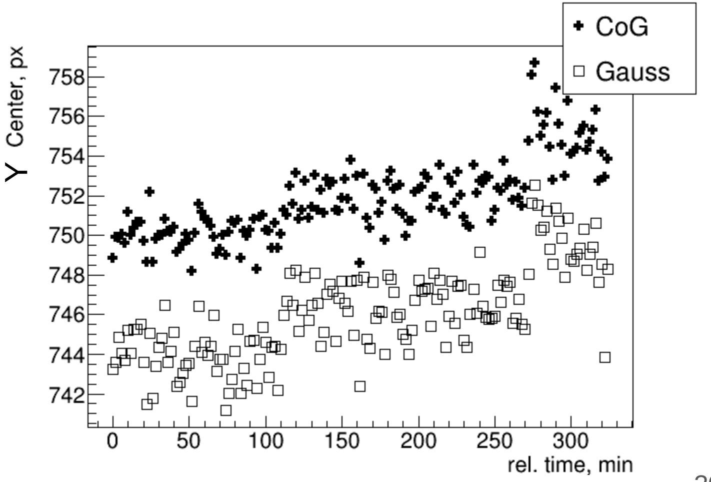
STREAMING MODE ACQUISITION

Bunch sequence

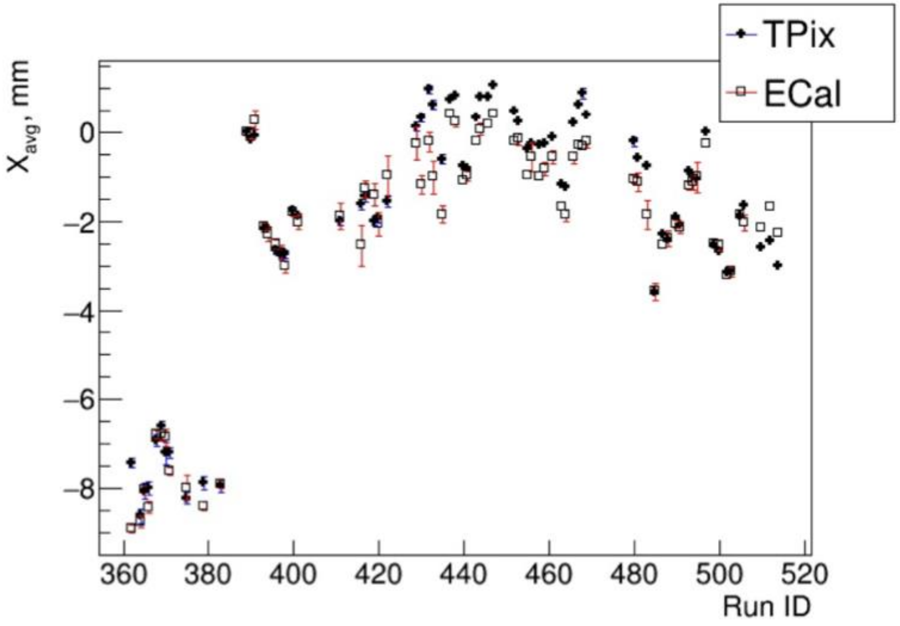


Bunch structure

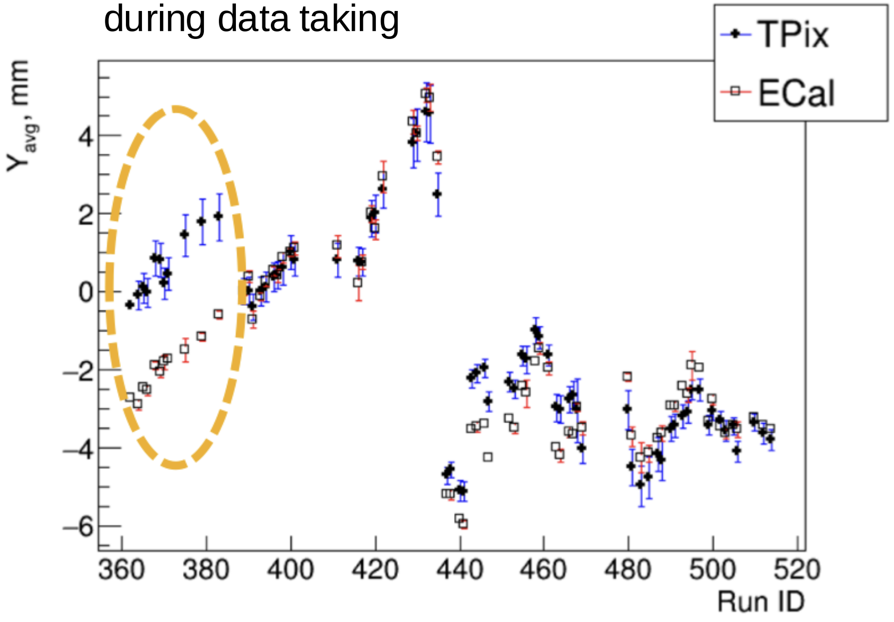




Beam monitor with TimePix



3 mm offset due to TimePix position fixed during data taking

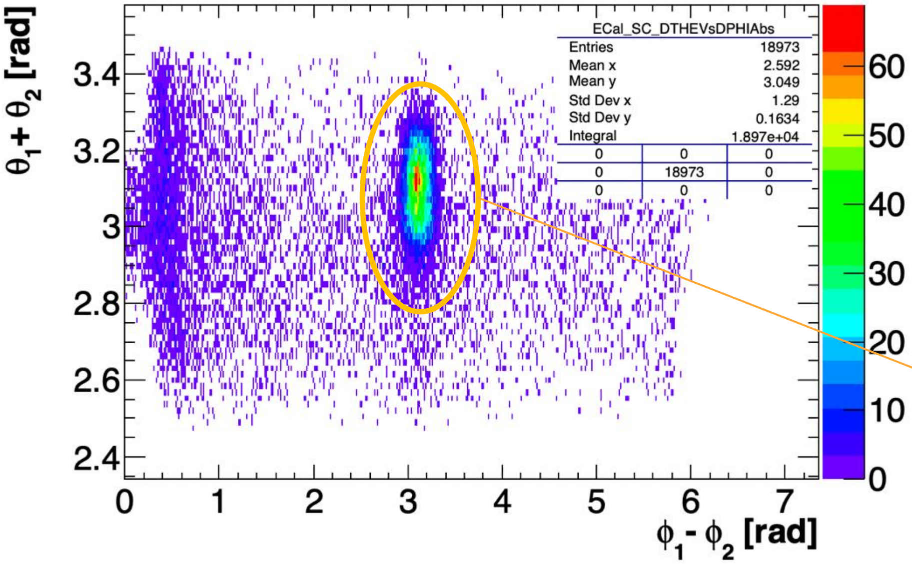


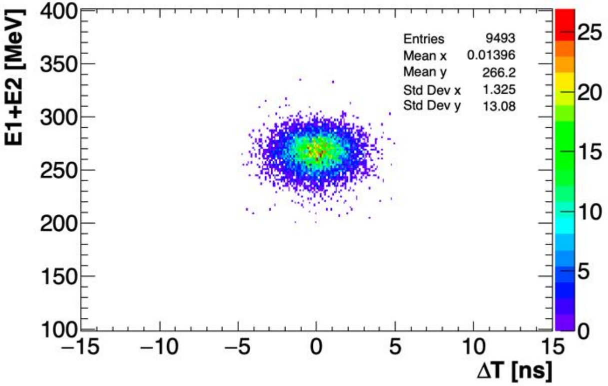
Good consistency of the position measurement using TimePix vs Ecal (for the second part of RunIII)

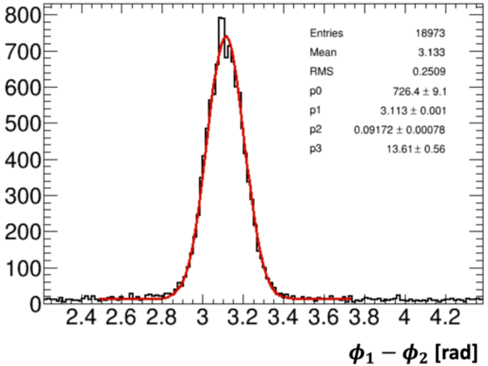
Signal selection

Selection of two clusters mutually in time [within 5 ns], in the ECAL region of interest

Enforce the kinematics expected for a two body production in the center of mass frame (no use of ECAL energy response beyond the cluster reconstruction)







Background estimation ~ 4%, taken under control from data

ECAL efficiency

ECAL efficiency from tag-and-probe technique

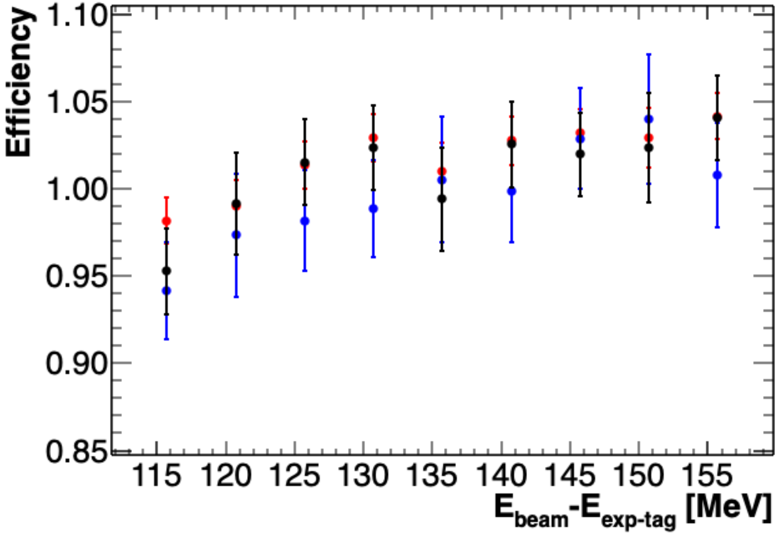
Much less background than in Run II thanks to reduced intensity

Low-energy inefficiency dominated by 15 MeV threshold on single hits

Method bias extremely limited [MC truth vs MC T&P]

Data over MC correction limited to a few % overall **given the cut on the cluster φ**

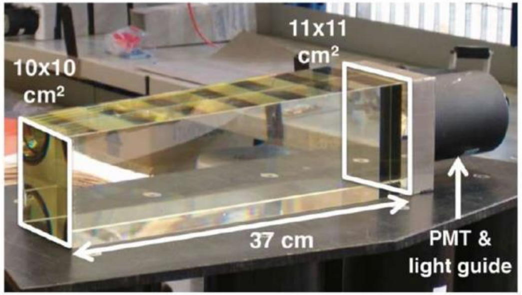
Good control of selection efficiency (at the % level)



Back

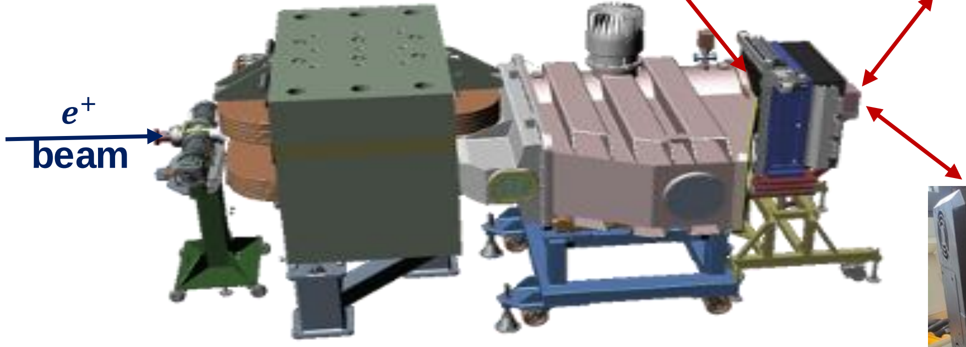
POT determination

- POT measured from a **beam catcher lead-glass block** courtesy of NA62 operated at low HV [650 V] to avoid saturation at ~3000 e+
- **Cross-calibrated** against pixel-based detector with un-deviated beam **at 2%**

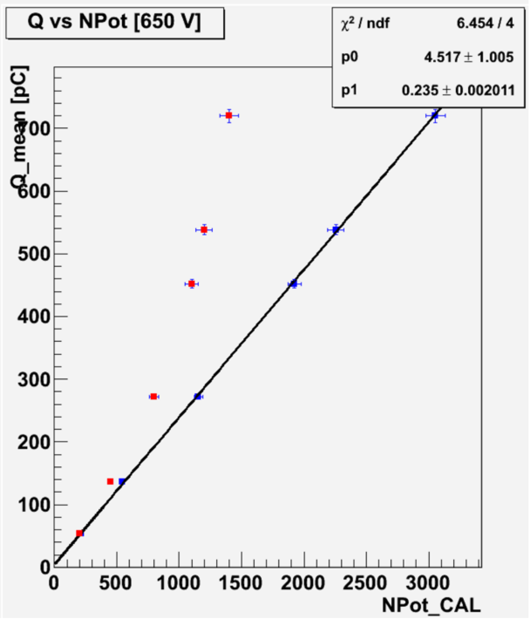


Carbon fiber window

PbGl luminometer

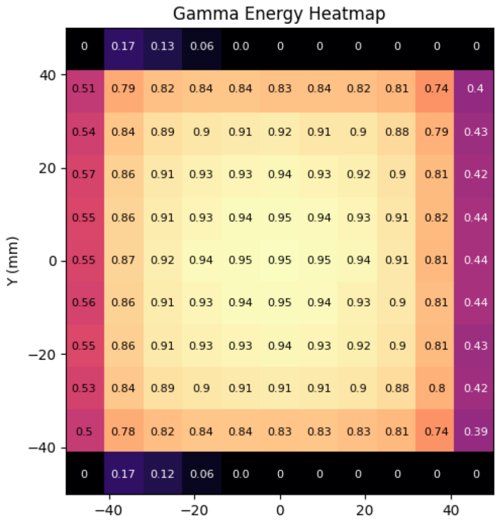


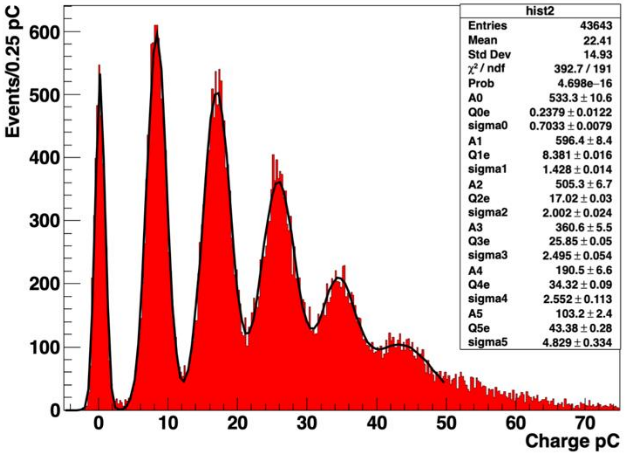
TimePix3 + support structure

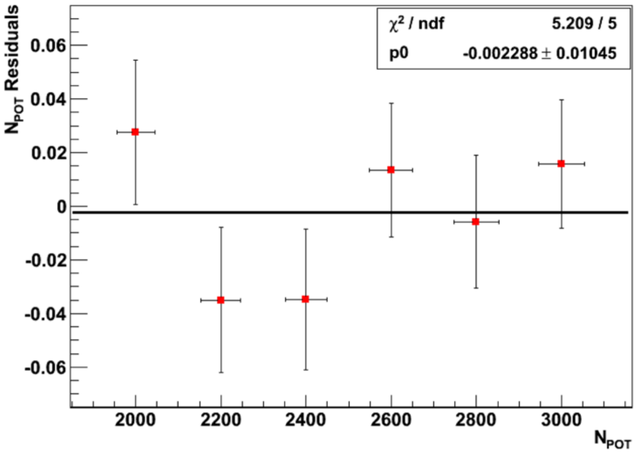


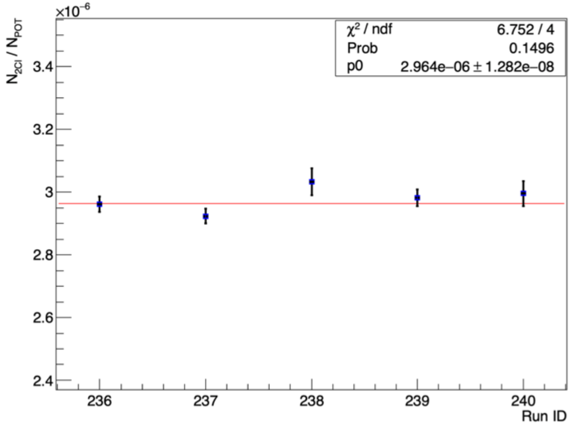
POT determination

- Independent calibration performed with single e+ at ~1000 V → gain curve is OK, but uncertainty is 8%
- When block placed at end-of-line, correct run by run for leakage: **error per point ~ 0.5%**



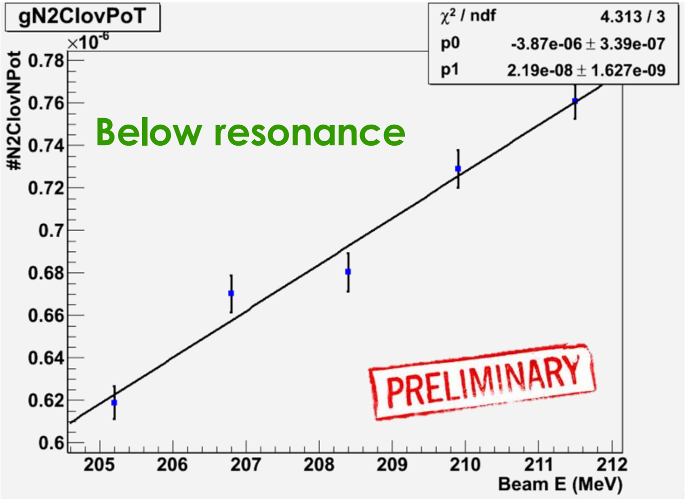


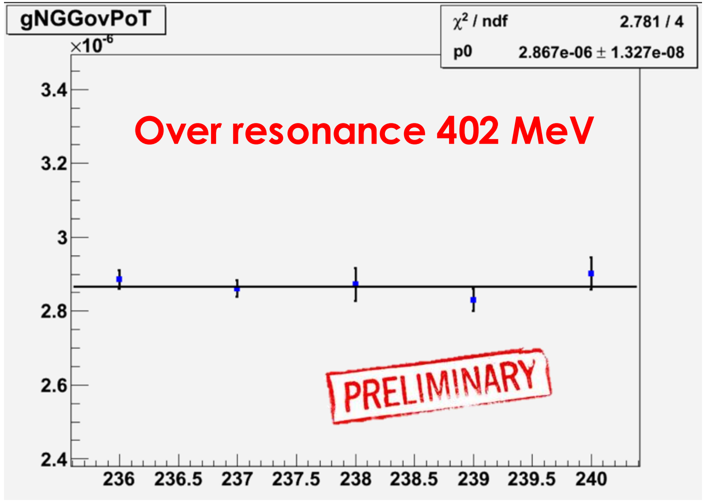




Signal selection: stability

Stability proved to be better than 1% from out of resonance points





- **RMS <1%** over the 5 energies, computed on residuals wrt the fit
- Good c^2 of the linear fit: trend due to acceptance, reproduced by MC

- **RMS ~0.7%** over the 5 runs, compatible with pure statistics
- **Fit to a constant with good c^2**, no evidence of systematic errors, even in absence of acceptance corrections

Back

X17 via resonant-production: effect of e- motion

First time we are able to reproduce the results of their statistical-only tool

Standalone tool with 146 nuisance pars:

PRELIMINARY

90% CL expected (no-signal pseudo data)

A True values of bkg/POT [47 pars]

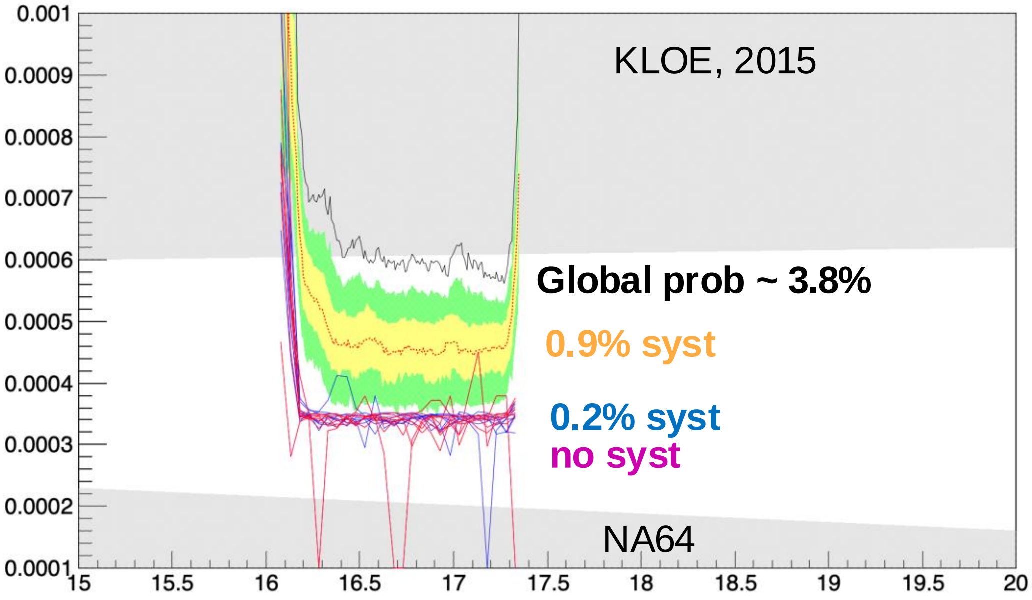
B True values of signal ε [47 pars]

C True values of POT vs sqrt(s) [47 pars]

True values of signal shape parameters [3 pars]

Absolute POT scale [1 par]

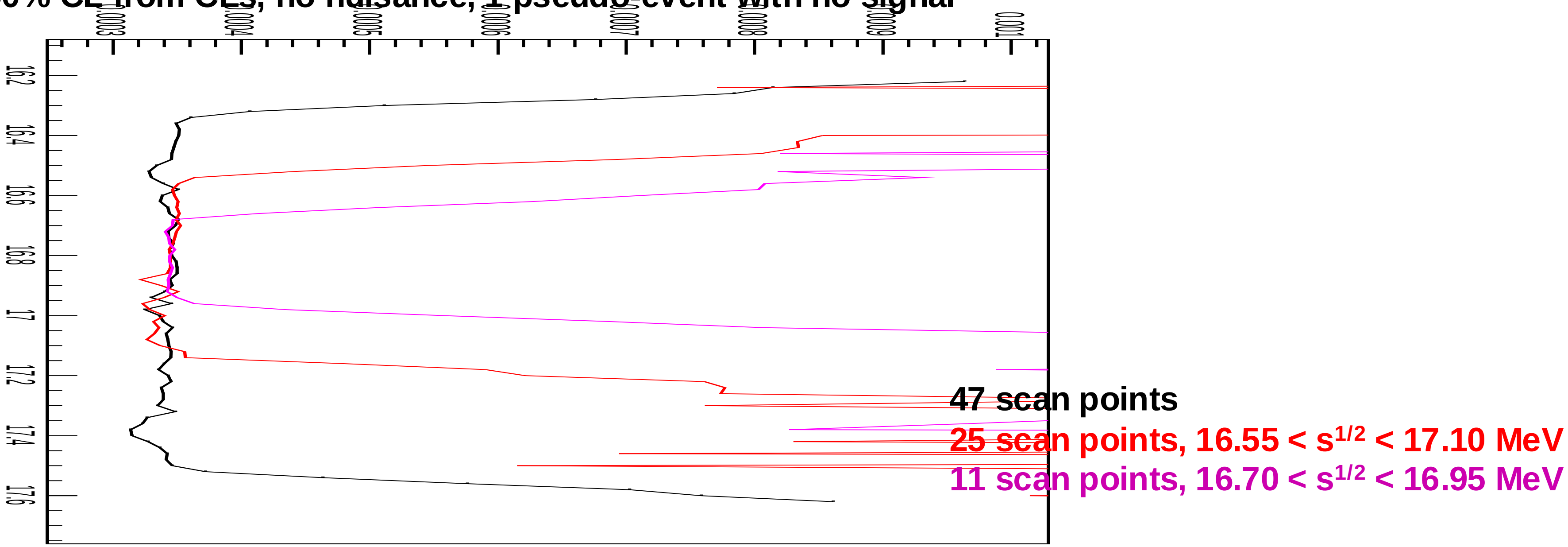
Absolute signal yield [1 par]



X17 via resonant-production: statistical tests

Check result from our CLs implementation vs number of scan points

90% CL from CLs, no nuisance, 1 pseudo-event with no signal



The idea for a new tagger

A micro pattern gas detector has a number of advantages:

- **Very high segmentation**
- **Tracking capabilities**
- **Very low X0**
- **Good resolution in xy**

Exploit the available expertise from ATLAS groups

The test beam of a micromega prototype

We already had a successful test beam in Nov23 (1week) with MM detector adapted with a 5cm drift gap, extended for TPC purposes

Experimental Setup at BTF (LNF)
2 MM chambers with 5 cm drift gap

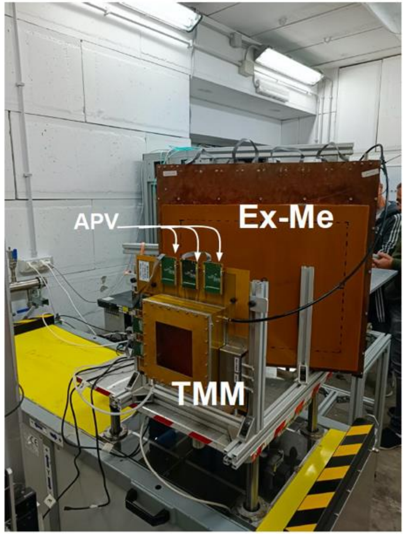
- 10x10 cm^2 TMM (x,y view)
- 40x50 cm^2 Ex-Me (1 coord.)
- Gas mixture, Ar:CF4:isobutane 88:10:2 vol%
- Electronics: APV

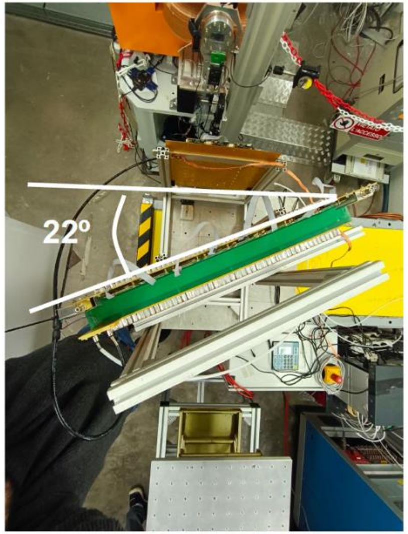
- Ex-Me chamber tilted by 22°
- O(mm) e^+ beam spot

HV (nominal):

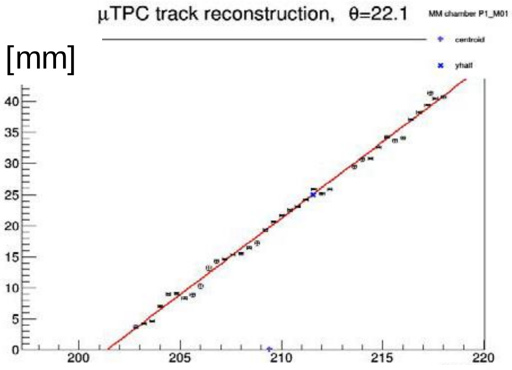
- TMM Amp: 460 V, Drift: 3 kV
- Ex-Me Amp: 490 V, Drift: 3 kV

Cost of gap extension: 5 kE



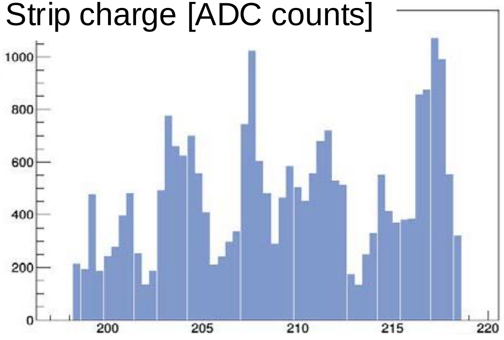


z [mm]



x [mm]

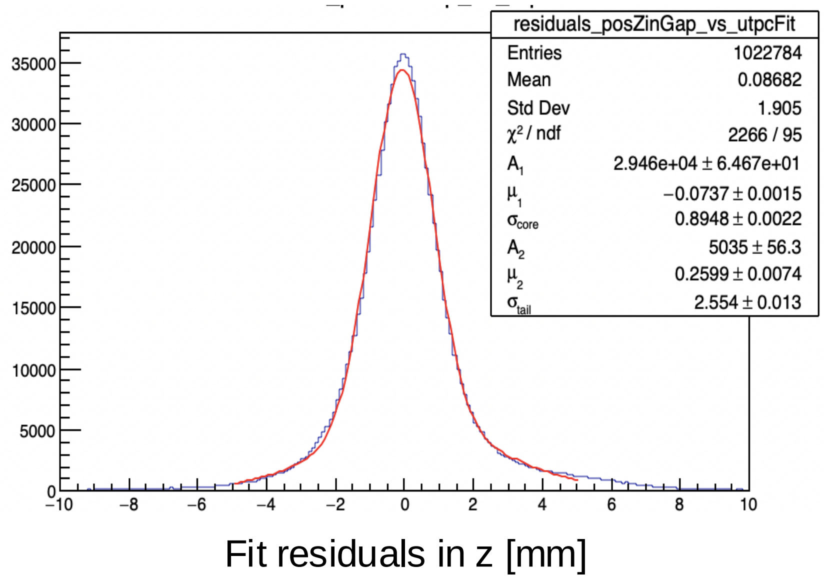
Strip charge [ADC counts]

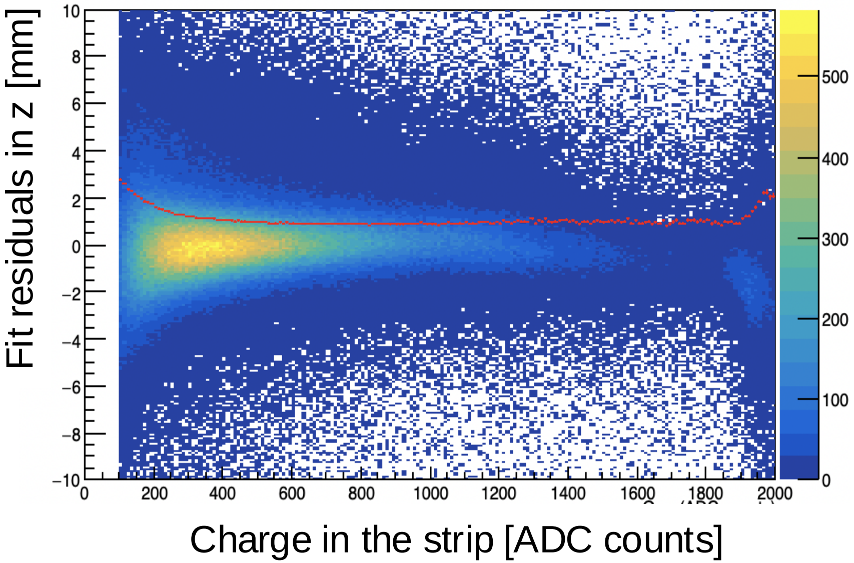


x [mm]

The test beam of a micromega prototype

The micro TPC operation is proved, the core resolution on the hit z coordinate depends on the charge and is around 1 mm

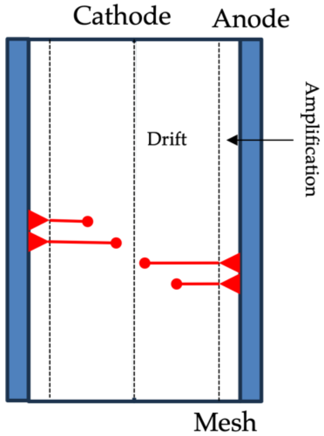




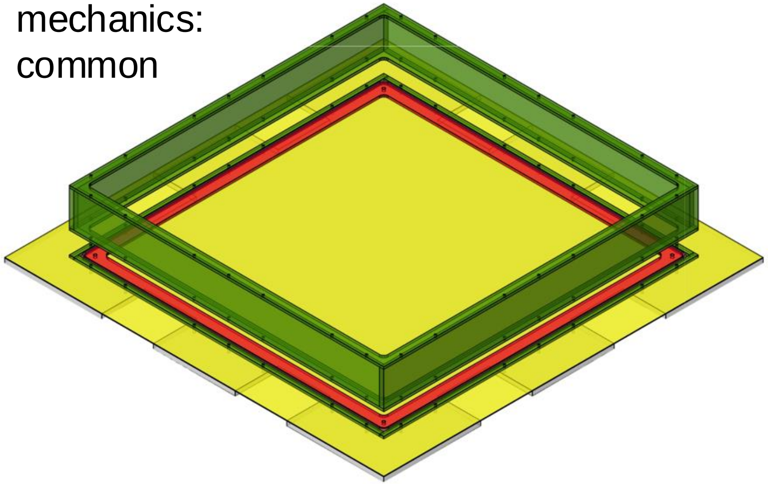
The design of a micromega tagger

Design: 2 detectors have been proposed (same mechanics to reduce costs)
- x,y strips as a baseline detectors
- diamond shaped pads read in raws: brand new design that could allow for better performances

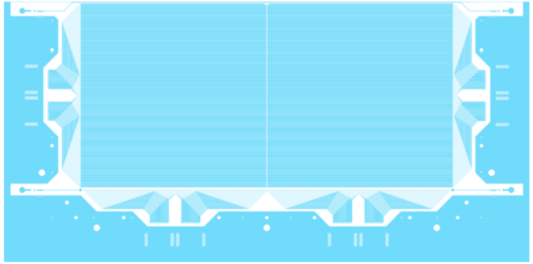
Those 2 detectors are to be tested in a 2-week test beam in May24



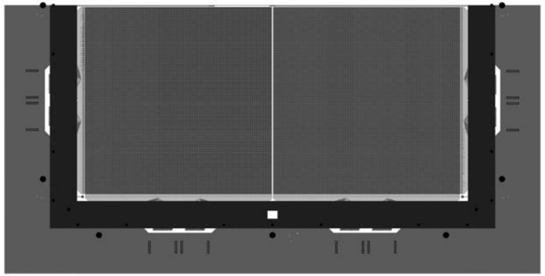
mechanics: common



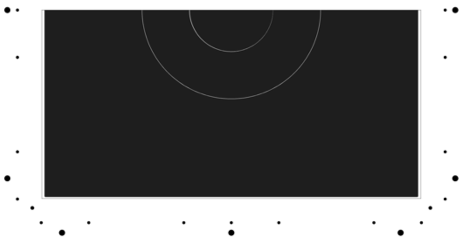
strip layout



diamond layout



resistive circuit (common, **3HV zones**)

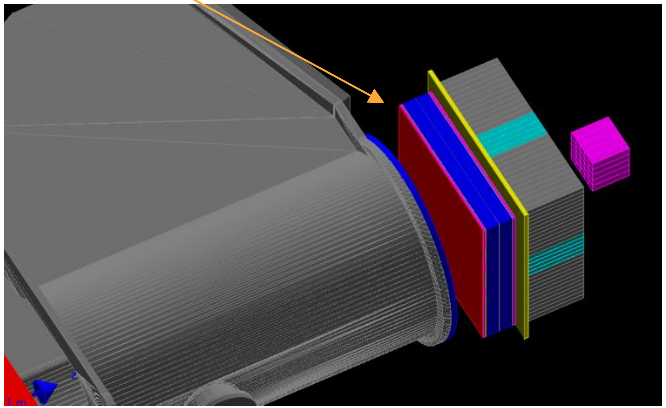


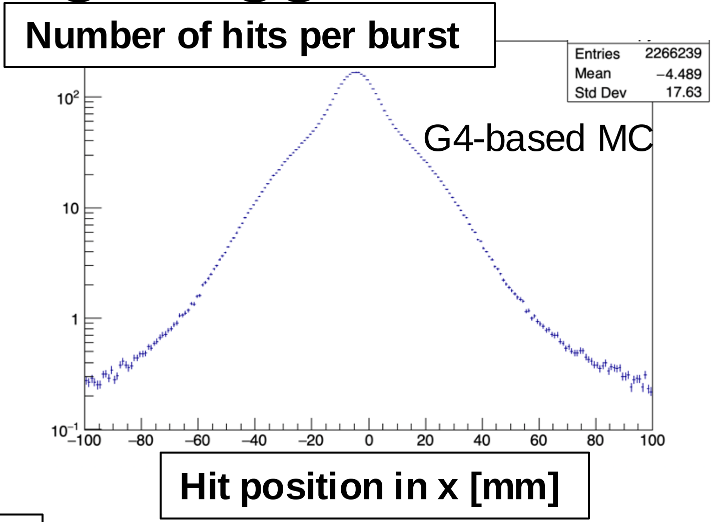
The design of a micromega tagger

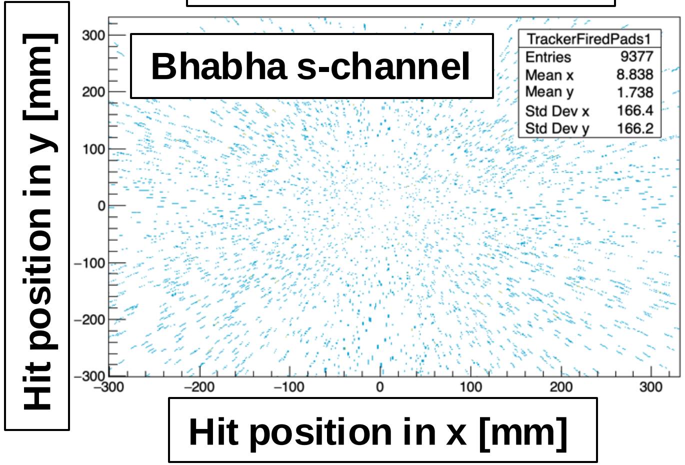
3 HV regions have been designed to cope with the higher occupancy in the central region and to operate the detector at lower amplification voltage

As determined with the test beam, this is still allowing it to act as beam monitor

The new tagger provides a reconstruction of the vertex of origin, allowing to extend the PADME program with the search for long-lived particles







The organization for a new tagger

Obviously, added a significant addition in terms of man-power and expertise:
researchers, tecnological personnel, and expert technicians

People who already joined the effort:
(LNF) M. Antonelli, G. Mancini, C. Arcangeletti, B. Ponzio, E. Capitolo, G. Pileggi, B. Buadze, L. Gongadze

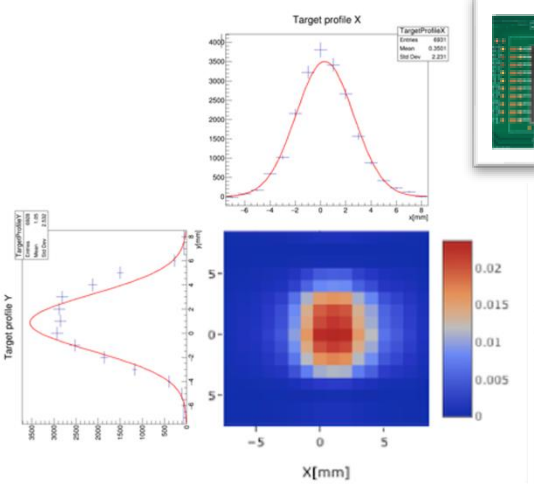
(RM1) F. Anulli
(NA) P. Massarotti, G. Sekhniaidze, P. Iengo

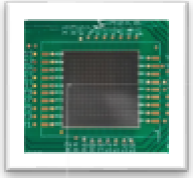
Back

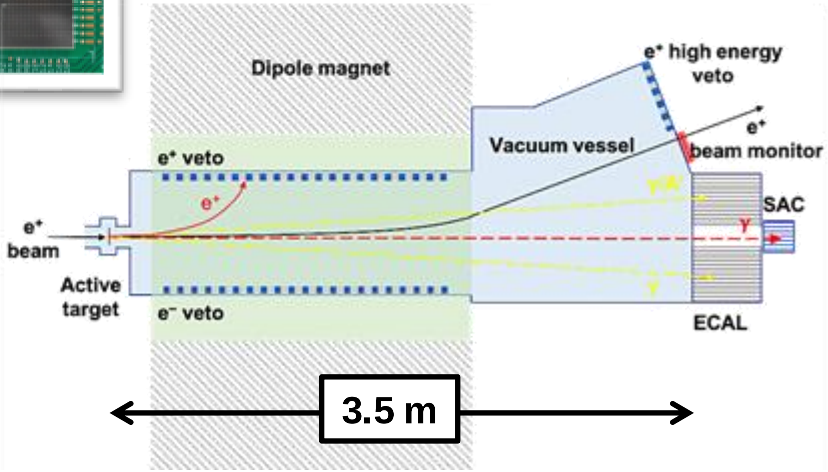
Spare slides

What’s PADME – the detector: beam monitors

1.5 × 1.5 mm^2 spot at active, 100 μm diamond target: position, multiplicity
1 × 1 mm^2 pitch X,Y graphite strips [NIM A 162354 (2019)]





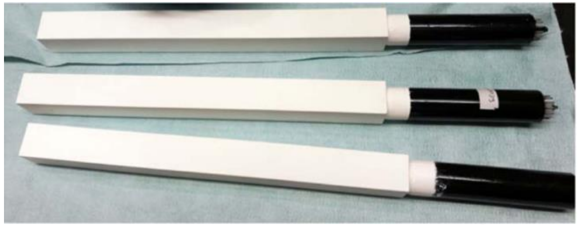


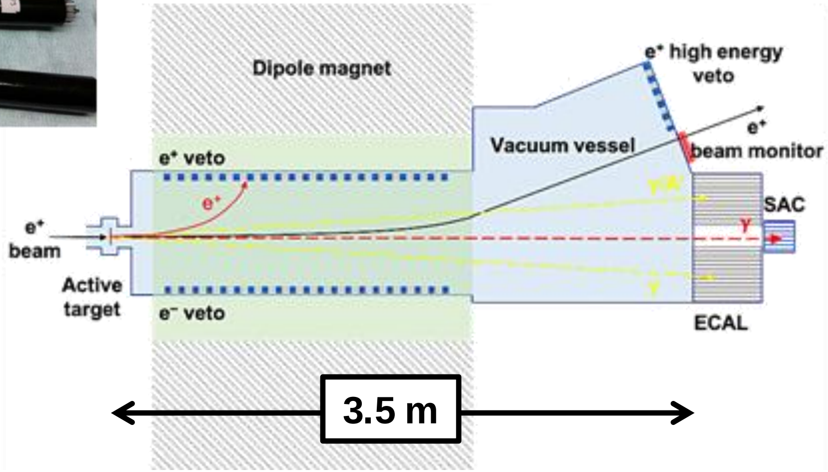
Bend by CERN MBP-S type dipole: 0.5 T field, 112×23 cm^2 gap, 70 cm long
Beam monitor (Si pixels, Timepix3) after bending: $\sigma_P/P_{beam} < 0.25\%$

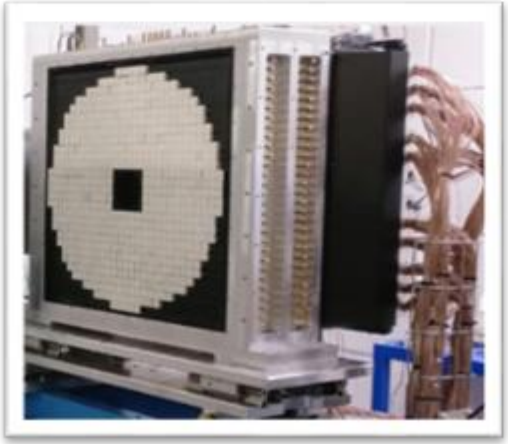
What's PADME – the detector: calorimeters

Forward calorimeter: $\sigma_E/E = 2\% / \sqrt{E[GeV]} + 0.003\% / E[GeV] + 1.1\%$

616 BGO crystals (LEP L3), 2.1 × 2.1 × 23 cm^3 [JINST 15 (2020) T10003]







Forward photons detected by fast PbF_2 small angle calorimeter (SAC)

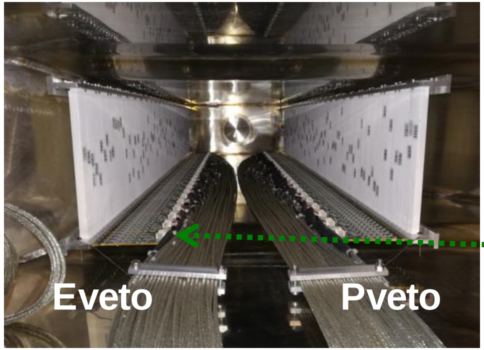
σ_T ~ 80 ps, double-pulse separation < 2 ns [NIM A 919 (2019) 89]

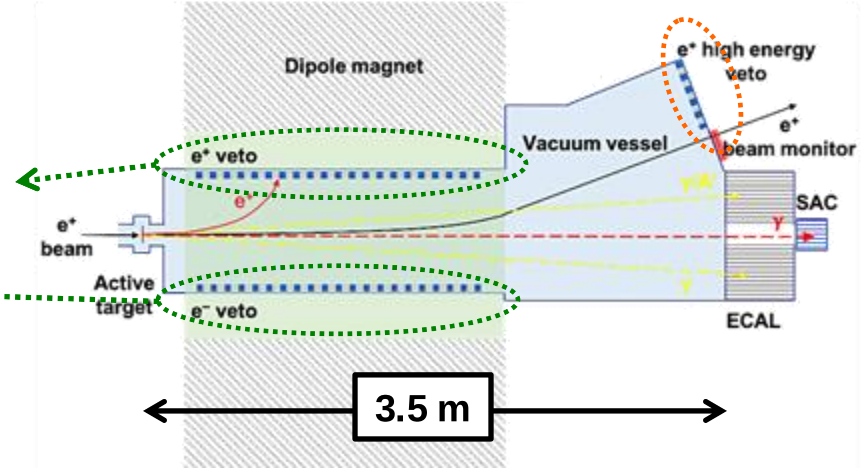
What's PADME – the detector: vetoes

Veto for e^+/e^- with scintillating bars, $1 \times 1 \times 17.8$ cm^3 [JINST 15 (2020) 06, C06017]

Inside vacuum vessel

on the sides (186 ch's) of the dipole magnet gap + forward (16 ch's)





For collinear e^+ (brems), the scintillating bar hit gives the e^+ momentum

Time resolution ~ 0.5 ns, inefficiency < 0.1% [NIM A 936 (2019) 259]

What's PADME – the TDAQ concepts

Three trigger lines: Beam based, Cosmic ray, Random

Trigger and timing based on custom board [2020 IEEE NSS/MIC, doi: 10.1109/NSS/MIC42677.2020.9507995]

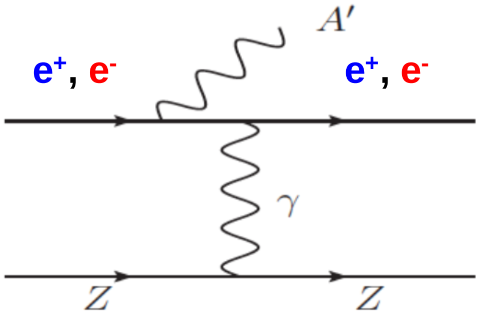
Most detectors acquired with Flash ADC's (CAEN V1742), O(10^3) ch's:

- **1 μs digitization time window**
- **1 V dynamic range, 12 bits**
- **sampling rates at 1, 2.5, 5 GS/s**

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

First experiment goal (A' invisible search) required 10^{13} POT, O(80 TB)

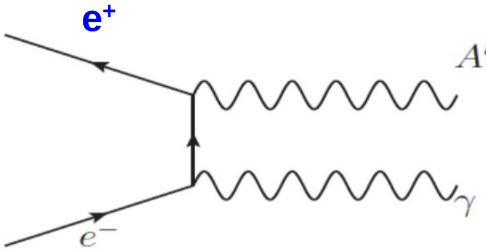
Positron vs electron beams, A' example



A' strahlung: ~ $\alpha^3 \Sigma^2 / m_A^2$, ~ $\Sigma^2 (m_A / m_e)^2 \times$ SM

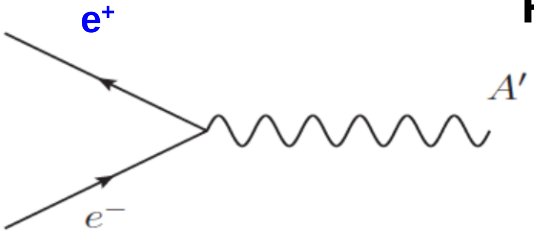
$$\frac{d\sigma}{dx\,d\cos\theta_{A'}} \approx \frac{8Z^2\alpha^3\epsilon^2E_0^2x}{U^2}\,\mathcal{L}og\left[\left(1-x+\frac{x^2}{2}\right)-\frac{x(1-x)m_{A'}^2(E_0^2x\theta_{A'}^2)}{U^2}\right]$$

with $U(x,\theta_{A'}) = E_0^2x\theta_{A'}^2 + m_{A'}^2\frac{1-x}{x} + m_e^2x$



Rad. annihilation ~ $\alpha^2 \Sigma^2 / (s - m_A^2)$, ~ $2\Sigma^2$ (m_A << s) × SM(γγ)

$$\frac{d\sigma(e^+e^-\to\gamma A')}{d\cos\theta} = \frac{\alpha\epsilon^2}{2s^2(s-m_{A'}^2)}\left(\frac{s^2+m_{A'}^4}{\sin\theta^2}-\frac{(s-m_{A'}^2)^2}{2}\right)$$



Resonant annihilation ~ α, high but extremely narrow

$$\sigma_{res}(E_e) = \sigma_{peak}\frac{\Gamma_{A'}^2/4}{(\sqrt{s}-m_{A'})^2+\Gamma_{A'}^2/4}$$

σ_{peak} ~ 0.2 b (M_A = 17 MeV) but Γ_A ~ 0.04 eV × ($\varepsilon^2 / 10^{-6}$)

Data quality and goals for Run II data

Background reduced to 0.013 MeV / e^+, finally allowing precision analyses, broadly divided in terms of final states

Two-body:

- $e^+e^- \rightarrow \gamma\gamma$, absolute cross section, luminosity [PRD 107 (2023) 1, 012008]
- $e^+e^- \rightarrow e^+e^-$, absolute cross section [concluded]
- Single photon: $e^+e^- \rightarrow \gamma X$, X as invisible A' [ongoing, new ML-based reco]

Three body:

- Three photons: $e^+e^- \rightarrow \gamma\gamma\gamma$, search for prompt a $\rightarrow \gamma\gamma$ [ongoing]
- Single photon: $e^+e^- \rightarrow \gamma e^+e^-$, search for prompt a/A' $\rightarrow e^+e^-$ [conceived]

Many body:

- Single photon: $e^+e^- \rightarrow 3(e^+e^-)$, search for prompt $e^+e^- \rightarrow$ h' A' $\rightarrow$ 3A'

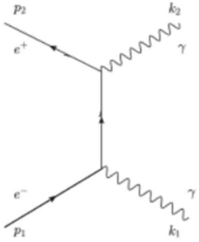
ee → γγ: result

Result compatible with SM expectation: Babayaga at NLO

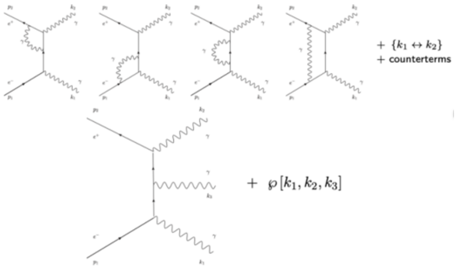
Only measurement below GeV made matching the 2 γ's: other measurements made with e^+ disappearance → implication on New Physics sensitivity

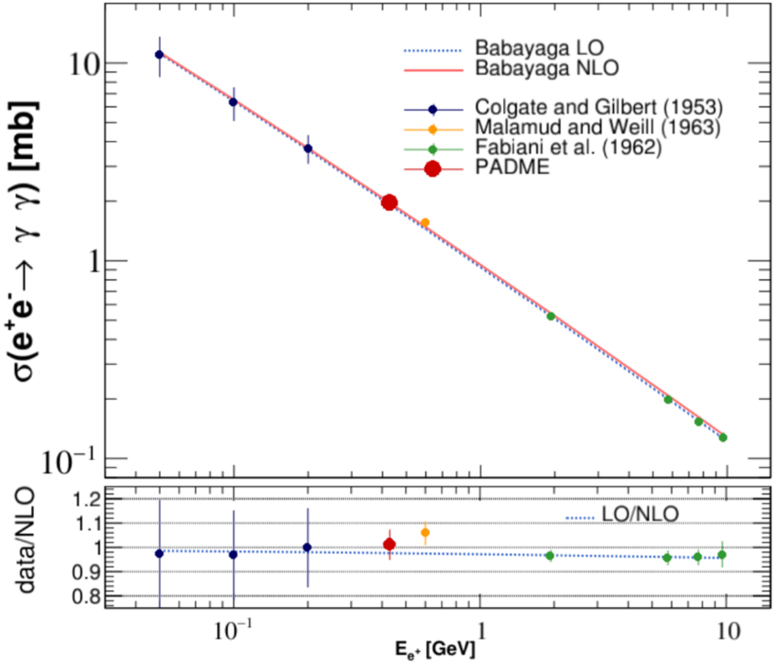
Measurement can be re-interpreted as a search for prompt decays of an ALP state, a → γγ

LO



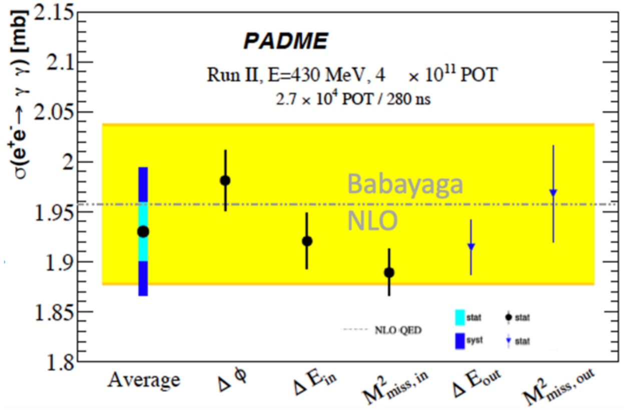
NLO

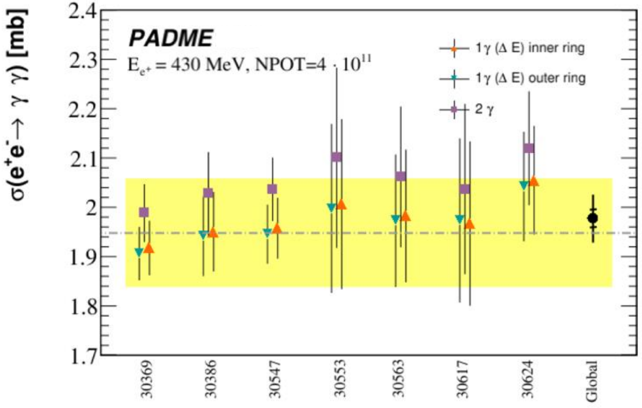


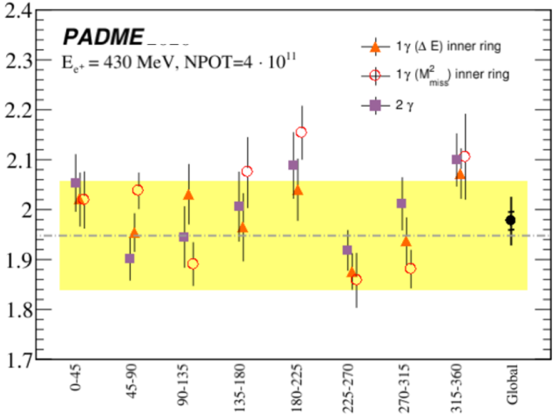


$e^+e^- \rightarrow \gamma\gamma$: results

Systematic tests: identification method, stability with data taking and R vs φ







Final result with 5.5% uncertainty:

$$\sigma(ee \rightarrow \gamma\gamma) = (1.977 \pm 0.018_{stat} \pm 0.118_{syst})\ \text{mb}$$

Uncertainty down to 3.7%* when ee → γγ is used as normalization for other searches

***Expected down to 1% if intensity down by x10**

Uncertainty summary	
Detector uniformity	0.024 mb
Background modelling	0.009 mb
Acceptance	0.037 mb
N_{POT}	0.079 mb
Electron density	0.073 mb

Measurement of $e^+e^- \rightarrow \gamma\gamma$: data set and concept

Using < 10% of Run II data, N_{POT} = (3.97 ± 0.16) ×10^{11} positrons on target

Expect $N_{ee\rightarrow\gamma\gamma}$ ~0.5 M, statistical uncertainty < 1%

Include various intensities, e^+ time profiles for systematic studies

Evaluate efficiency corrections from MC + data

Master formula:

$$\sigma_{e^+e^-\rightarrow\gamma\gamma} = \frac{N_{e^+e^-\rightarrow\gamma\gamma}}{N_{POT}\cdot n_{e/S}\cdot A_g\cdot A_{mig}\cdot \epsilon_{e^+e^-\rightarrow\gamma\gamma}}$$

N_{POT} from diamond active target

Uncertainty on e^- density $n_{e/S} = \rho N_A Z/A\ d$ depends on thickness d

Run #	NPOT [10^{10}]	e^+/bunch [10^3]	length [ns]
30369	8.2	27.0 ± 1.7	260
30386	2.8	19.0 ± 1.4	240
30547	7.1	31.5 ± 1.4	270
30553	2.8	35.8 ± 1.3	260
30563	6.0	26.8 ± 1.2	270
30617	6.1	27.3 ± 1.5	270
30624	6.6	29.5 ± 2.1	270
30654	No-target	~ 27	~ 270
30662	No-Target	~ 27	~ 270

$e^+e^- \rightarrow \gamma\gamma$: POT, target thickness

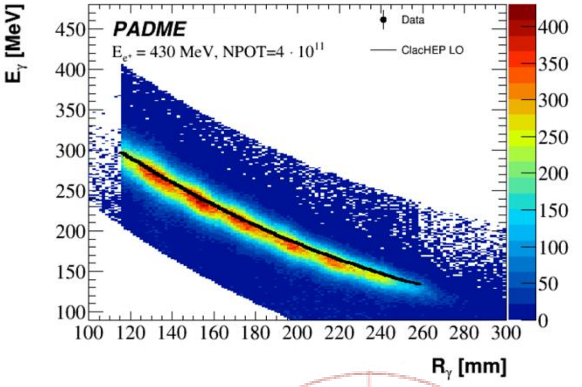
N_{POT} from active target, uncertainty is 4%:

1. **Absolute calibration by comparing with lead-glass calorimeter fully contained from 5k to 35k e+/bunch**
2. **When focusing beam into 1-2 strips, non-linear effects observed**

$n_{e/S}$ from target thickness, uncertainty is 3.7% (i.e., ~3.7 μm)

1. **Measured after assembly with profilometer with 1 μm resolution as difference with respect to the supporting surface**
2. **Correction due to roughness (quoted as 3.2 μm by producer): compare precision mass and thickness measurements on similar diamond samples**

$e^+e^- \rightarrow \gamma\gamma$: analysis strategy



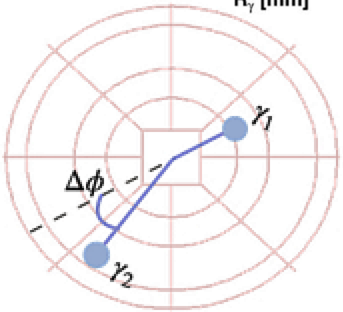
Exploit E vs θ correlation for selection, $E_{exp} = f(\theta)$

Background templates from no-target runs

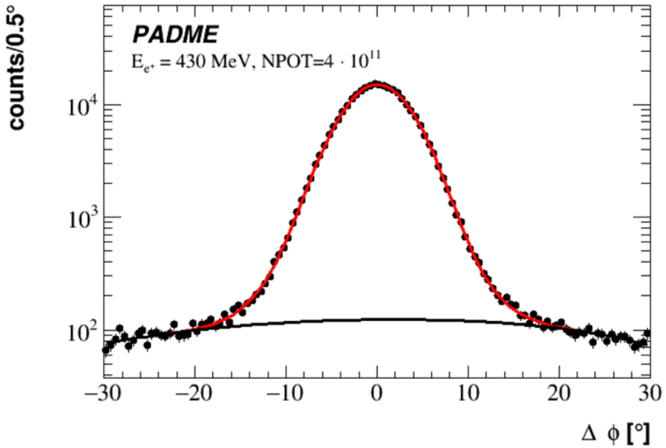
Signal samples: 2γ (bkg/sig ~ %), 1γ (bkg/sig ~1)

Data-driven Tag&Probe corrections

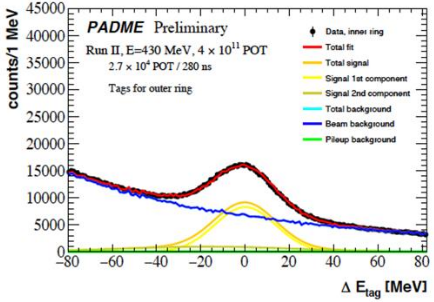
Independent measurements 2 R-bins × 8 φ-bins: bkg varies by x7

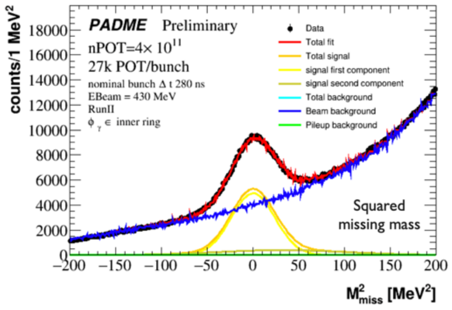


Two-photon selection

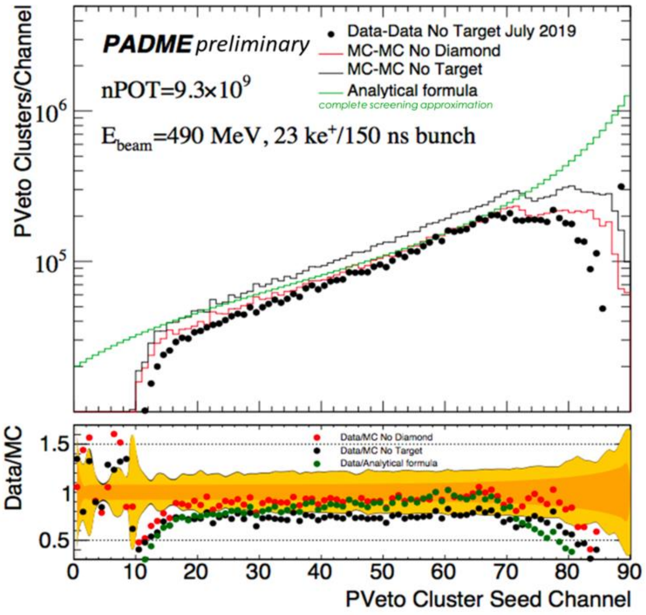


Single photon selection



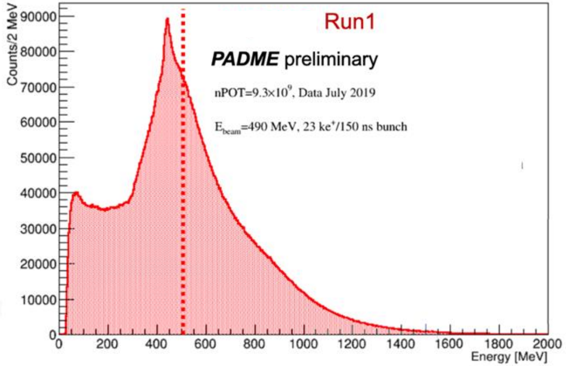


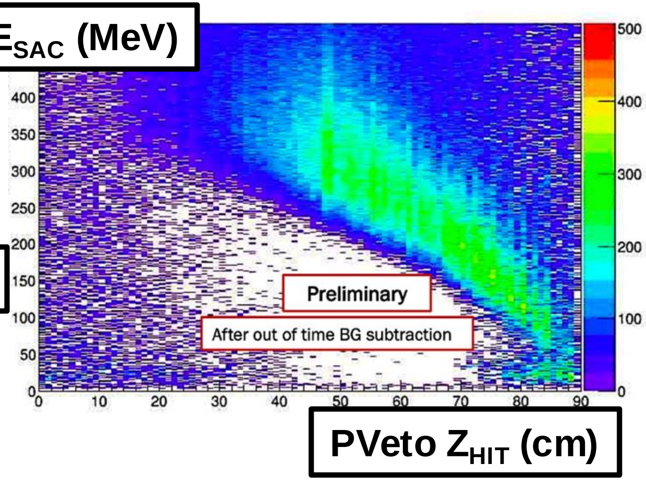
The single γ search: veto capability



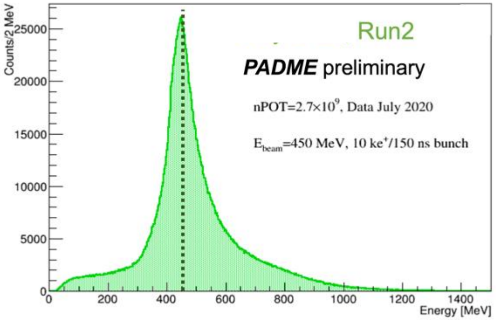
Beam background dominated by Bremsstrahlung:

- Measured with no-target runs and subtracted
- Bremsstrahlung photon distribution in agreement with **MC** and **analytical calculation**
- Main systematic uncertainties:
  - Background normalization
  - e^+ momentum scale
  - N_{POT} calibration

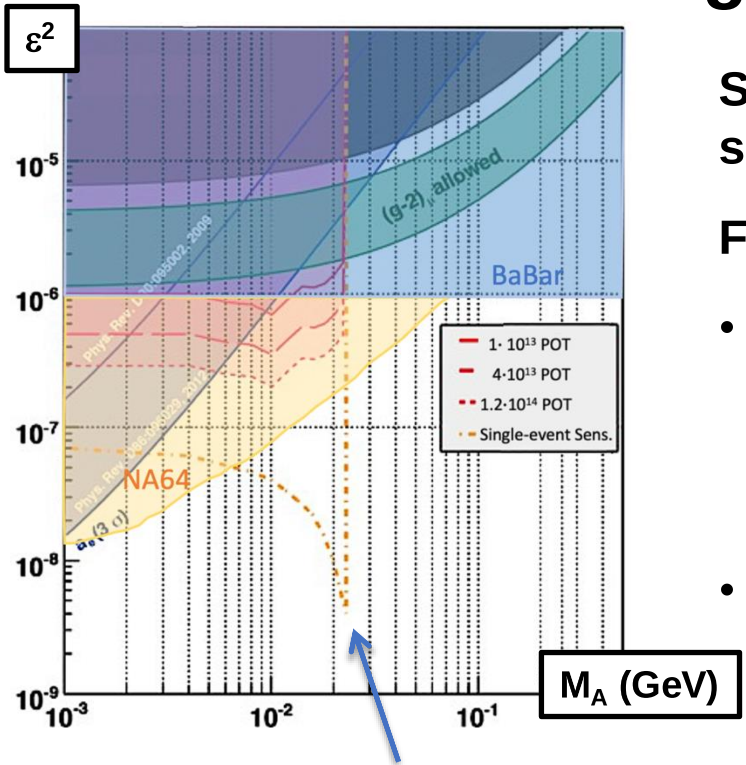




ΔT(SAC-PVETO) < 1 ns



The single γ search: status



Search presently background dominated, sensitivity scales as √bkg

For background reduction with Run II data:

- **Improved, AI-assisted ECAL reconstruction: promising double-pulse separation, time resolution, linearity [see Instruments 6 (2022) 4, 46 and talk by K. Stoimenova at CALOR 2022]**
- **Improved veto conditions using ML**

A single-particle experiment with a (quasi-) continuous beam: stretch the LINAC beam pulse using the DAFNE ring, 10^{16} POT achievable in 2 years [arXiv:1711.06877, Phys. Rev. Accel. Beams 25 (2022) 3, 033501]