Recent results from the MEG-II experiment

Probing Physics Beyond the Standard Model

61st International winter meeting on Nuclear Physics

Bormio, 27 – 31 January 2025

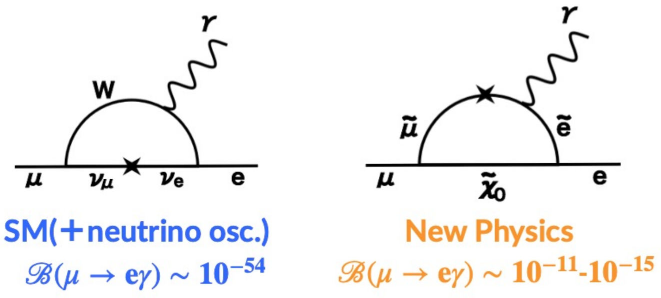
INFN Marco Grassi

Outline

- Muons as probes for New Physics
- Results on $\mu^+ \to e^+\gamma$ search (2021 data sample)
- Search for the X17 boson
- Perspectives in search for Axion Like Particles
- Final remarks

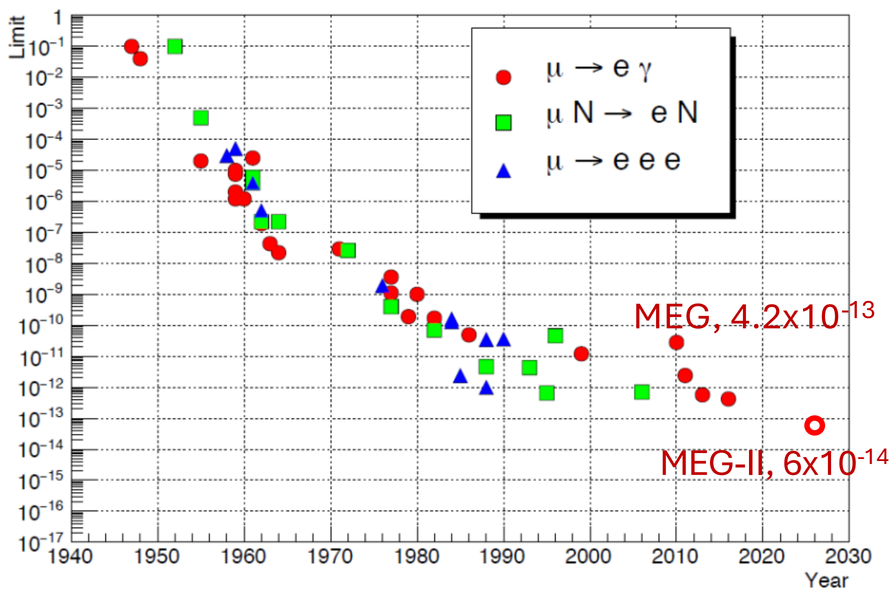
Why to Search for $\mu^+ \rightarrow e^+\gamma$

- In SM flavour conservation is not protected by a gauge symmetry
- $\mu^+ \rightarrow e^+\gamma$ in SM is highly suppressed because of the tiny neutrino mass
- Several BSM models predict a sizeable rate for $\mu^+ \rightarrow e^+\gamma$



- The branching ratio is a sensitive probe of the scale of new physics $\mathfrak{B} \propto \frac{1}{\Lambda^4}$. Values up to 10^3 TeV are accessible.

History plot



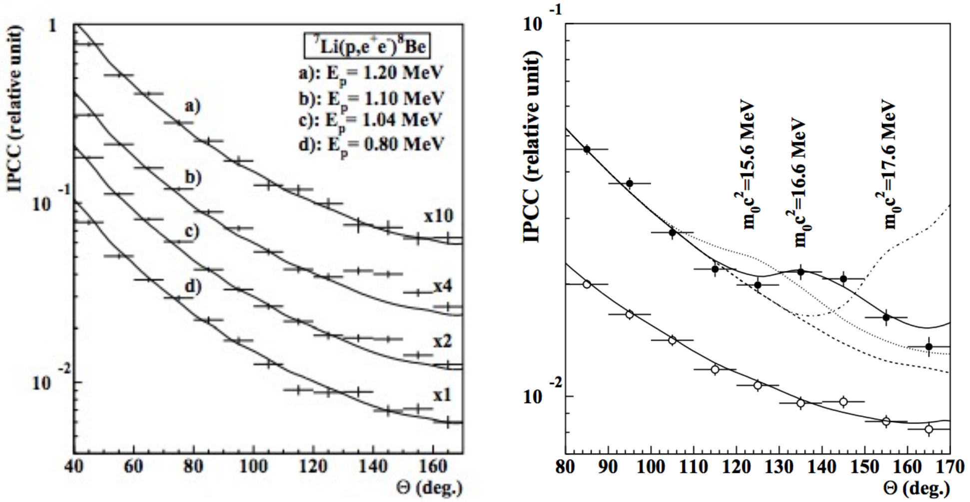
(Riv. Nuovo Cimento 41 (2018) 71)

The observation of the $\mu^+ \rightarrow e^+\gamma$ decay would constitute unambiguous experimental evidence of BSM physics

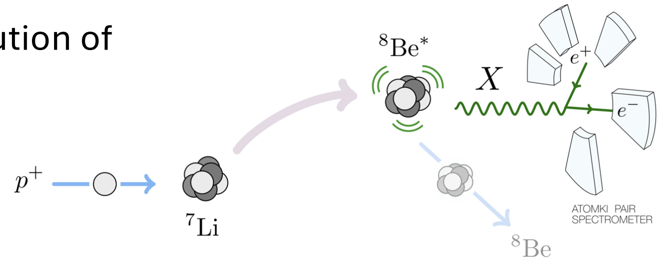
The X17 boson

- An experiment at Atomki reported an anomaly in the angular distribution of the Internal e^+e^- Pairs Conversion of the $^7Li(p,e^+e^-)^8Be$ process

Krasznahorkay et al. , 2016



Phys.Rev.Lett.116, 042501



- The excess has been observed at $\Theta \sim 140°$ for Ep = 1100 KeV
- It could be the decay of a light boson named X17 with
  - $\mathfrak{B}(X) = 6 \times 10^{-6}$ wrt γ production
  - m_X = 16.70 MeV / c^2

(Phys. Rev. D 95, 035017)

If confirmed this observation would constitute direct evidence of a particle not foreseen in the SM

Axion like particles

- Models with ALPs that could generate charged Lepton Flavor Violations have been proposed
- These models could solve the strong CP problem and provide a source for DM
- The ALP mass can be very light and the decay constant very large, however, the LFV coupling could enable experimental observation in muon decays

Y.Ema et Al. JHEP 01(2017)096
L.Calibbi et Al. Phys.Rev.D 95(2017) 095009
M.Linster et Al. JHEP 08(2018)058
L.Calibbi et Al. JHEP 09(2021)173

ALPs and MEG

- The Collaboration already published results for the process $\mu \rightarrow e^{+}a \rightarrow \gamma\gamma$ with the ALP decaying in the MEG apparatus

Euro.Phys.J. C80(2020)858

- Our theorist friends have recently evaluated the MEG-II detector sensitivity in specific low intensity muon beams and relaxed threshold conditions for the channel $\mu \rightarrow ea\gamma$ in the case of long-lived axions

Y.Jho et Al. JHEP 10(2022)29

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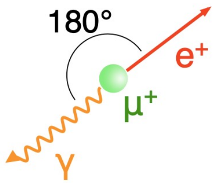
- Final remarks

The search for $\mu^+ \to e^+\gamma$

Signal



- Two bodies decay at rest
  - Simultaneous ($t_{e\gamma} = 0$)
  - Monochromatic energies ($E_e = E_\gamma \approx 52.8$ MeV)
  - Back-to-back ($\Theta_{e\gamma} = 180°$)

Beam intensity, Acceptance, Branching ratio, Efficiencies

Signal $N_{sig} = R_\mu \times T \times \Omega \times \mathfrak{B} \times \epsilon_\gamma \times \epsilon_e \times \epsilon_{sel}$

Bkg $N_{acc} \propto R_\mu^2 \times T \times (\, \Delta E_\gamma^2 \times \Delta E_e \times \Delta t_{e\gamma} \times \Delta\Theta_{e\gamma}^2)$

Acq. time, Detector resolutions

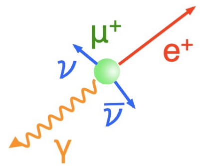
Key elements:

- intense continuous beamline
- high-resolution detectors

Background

Dominant (98%)

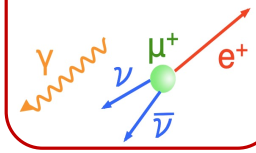
Prompt-physics



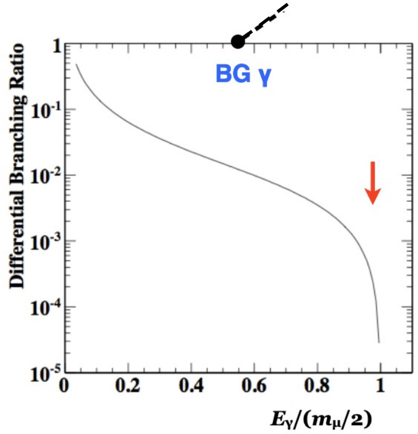
$\mu \to e\nu\bar{\nu}\gamma$

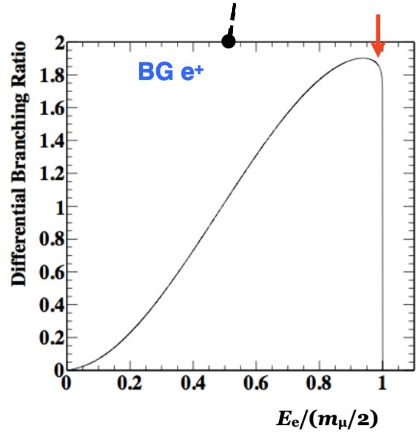
$\mu \to e\nu\bar{\nu}\gamma$
$ee \to \gamma\gamma$
$eZ \to eZ\gamma$

Accidental



$\mu \to e\nu\bar{\nu}$

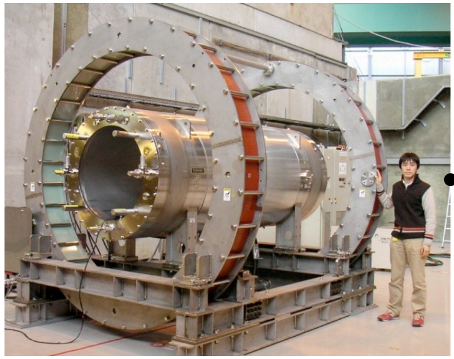


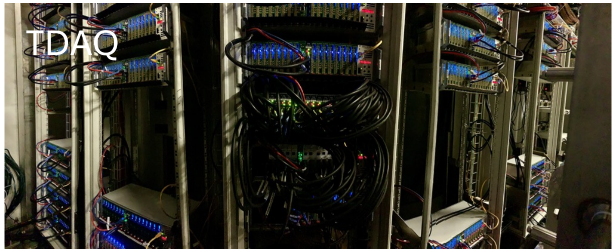


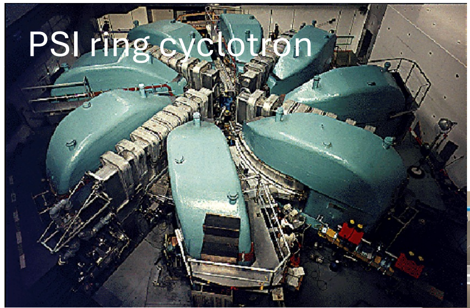
The MEG-II experiment at PSI

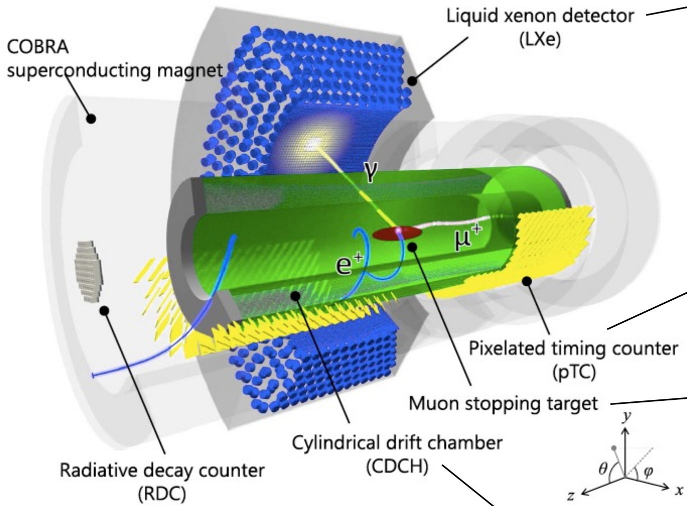
Target BR sensitivity 6 x 10 $^{-14}$

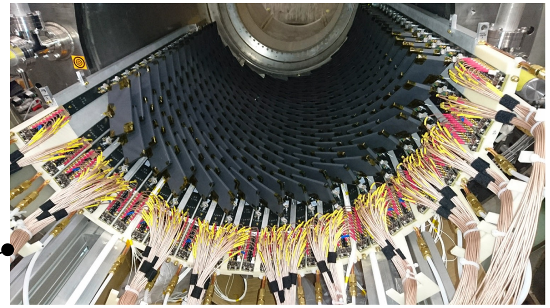
(x10 better than MEG)

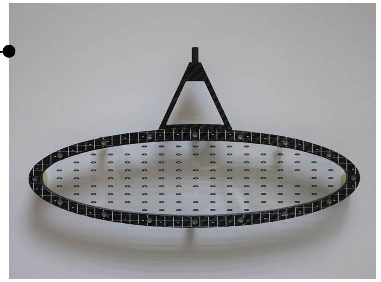


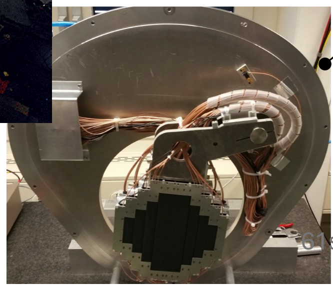






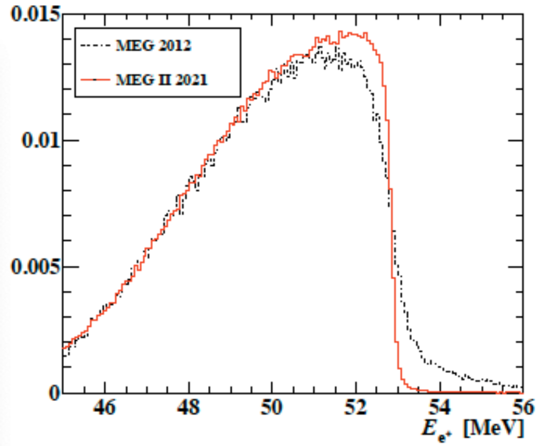






MEG-II Detector's Performance Highlights

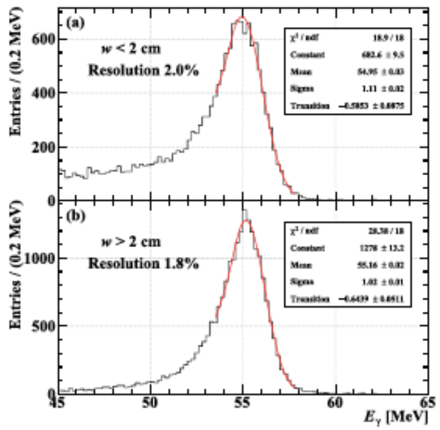
Positron tracking



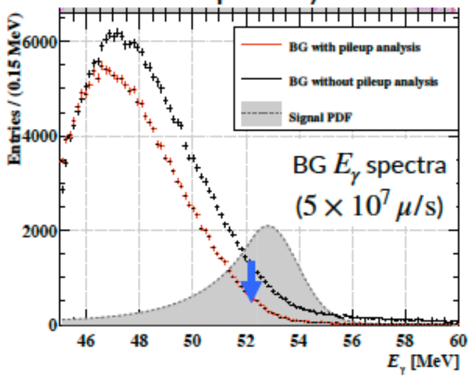
- Energy resolution: **90 keV**
  (↔ 320 keV@MEG)
- Efficiency: **67 % @$3 \times 10^7 \mu/s$**
  (↔ 30 % @MEG)

Photon energy

Energy resolution

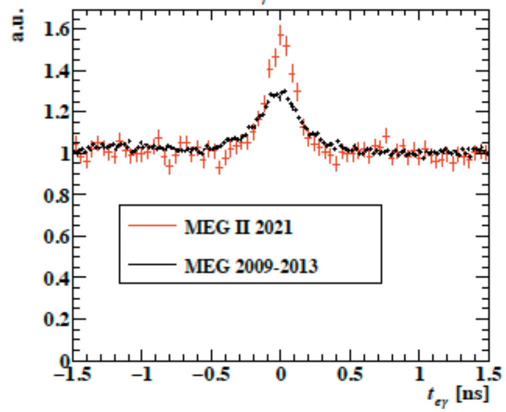


Pileup analysis



- High-granularity and uniform readout by MPPCs
- Energy resolution: **2.0%/1.8% for (conv. depth: <2cm/>2cm)**
- **Pielup BG reduction by 35%** at 48-58MeV ($5 \times 10^7 \mu/s$)

Relative timing



- Overall resolution **79** ps
  (↔122 ps@MEG)

MEG II Collaboration, Euro.Phys.J. C84(2024)190

Detector's performances for 2021 dataset analysis

Resolutions	MEG	MEG-II Proposal	MEG-II Achieved
E_e (keV)	320	100	89
θ_e (mrad)	9.4	3.7	7.2
ϕ_e (mrad)	8.7	6.7	4.1
z_e/y_e (mm) core	2.4/1.2	1.6/0.7	2.0/0.74
E_γ (%)[w<2cm)/(w>2cm)	2.4/1.7	1.7/1.7	2.0/1.8
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.4/2.4/5.0	2.5/2.5/5.0
$t_{e\gamma}$ (ps)	122	70	78
Efficiencies			
ε_γ (%)	63	69	62
ε_e (%)	30	65	67
ε_{TRG} (%)	~99		80

>90 % since 2022
close to 98% this year

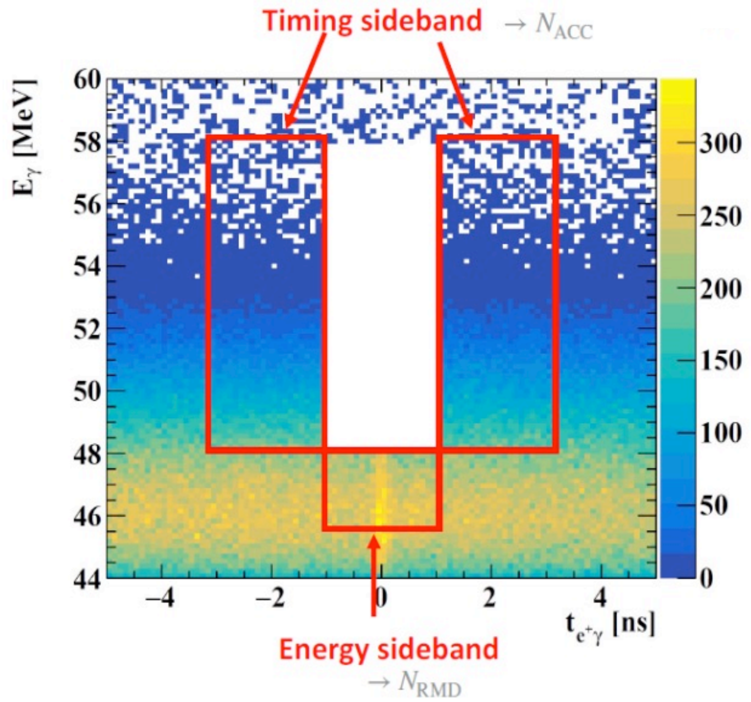
- Significant improvements over MEG
- Close, or even better, the MEG-II design values
- Further calibrations and analysis refinements will improve these figures

$\mu^+ \to e^+\gamma$ Analysis Strategy

- Kinematics observables of the $\mu^+ \to e^+\gamma$ decay

$$\vec{x_i} = (t_{e\gamma}, E_\gamma, E_e, \theta_{e\gamma}, \phi_{e\gamma})$$

- Strategy: blind likelihood analysis
  - Blinding box: $45 < E_\gamma < 58$ MeV , $|t_{e\gamma}| < 1$ ns
  - Background events constrained from sidebands N_{RMD}, N_{ACC}
  - PDFs from sidebands and measured detector resolutions
  - Maximum Likelihood to estimate N_{sig} in the analysis region
    - $45 < E_\gamma < 58$ MeV
    - $52.2 < E_e < 53.5$ MeV
    - $|t_{e\gamma}| < 0.5$ ns
    - $|\theta_{e\gamma}| < 40$ mrad
    - $|\phi_{e\gamma}| < 40$ mrad



- Two independent analyses
  - Per-event PDFs with two angular observables $\theta_{e\gamma}, \phi_{e\gamma}$ reference
  - Constant PDFs with single relative angle $\Theta_{e\gamma}$ crosschecking

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$$\mathcal{L}(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{ACC}}, x_{\mathrm{T}}) = \frac{e^{-(N_{\mathrm{sig}}+N_{\mathrm{RMD}}+N_{\mathrm{ACC}})}}{N_{\mathrm{obs}}!} C(N_{\mathrm{RMD}}, N_{\mathrm{ACC}}, x_{\mathrm{T}}) \times \prod_{i=1}^{N_{\mathrm{obs}}} \left(N_{\mathrm{sig}} S(\mathbf{x_i}) + N_{\mathrm{RMD}} R(\mathbf{x_i}) + N_{\mathrm{ACC}} A(\mathbf{x_i})\right),$$

where

- S, R and A are the PDFs
- N_{RMD}, N_{ACC} , x_T are constrained nuisance parameters
- N_{sig} is the signal
- x_T target misalignment parameter
- 3 more variables are included $t_{RDC} - t_{LXe}, E_{RDC}, n_{pTC}$

Systematics

- Major sources of systematics uncertainties
  - detector misalignment
  - E_γ scale
  - normalisation
- Technical treatment in PDFs
  - nuisance parameter in pdf
  - random fluctuating
- Effect on sensitivity
  - ~5% (was 13% in MEG)

Parameter	Impact on sensitivity
$\phi_{e\gamma}$ uncertainty	1.1 %
E_γ uncertainty	0.9 %
$\theta_{e\gamma}$ uncertainty	0.7 %
Normalization uncertainty	0.6 %
$t_{e\gamma}$ uncertainty	0.1 %
E_e uncertainty	0.1 %
RDC uncertainty	< 0.1 %

Normalisation

$$\mathfrak{B}(\mu^+ \to e^+\gamma) = \frac{N_{sig}}{N_\mu}$$

- Normalisation factor

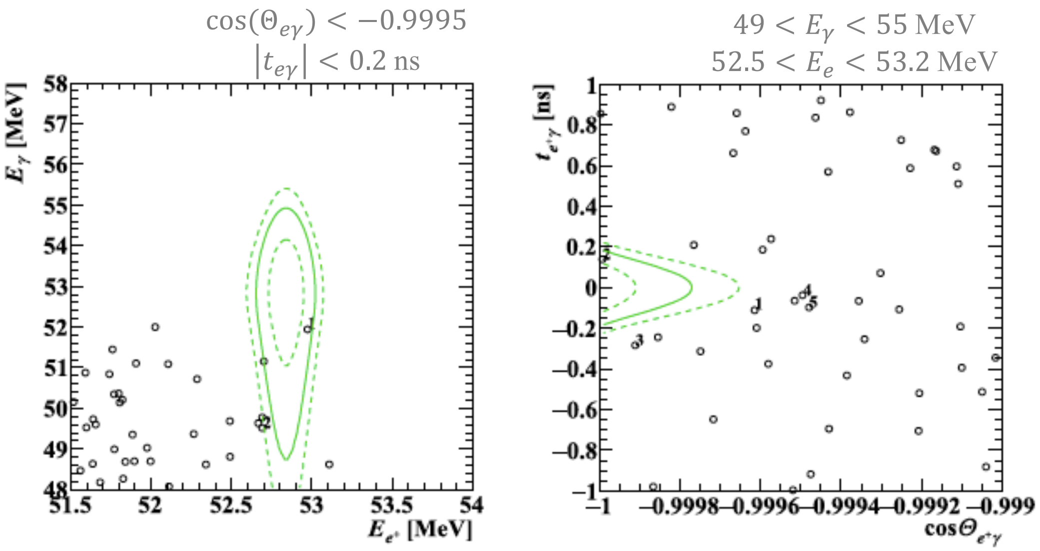
  N_μ = number of measured muons
- Two independent methods
  - Counting Michel positrons
  - Counting RMD
- Both acquired in parallel to $\mu^+ \to e^+\gamma$
  - variation of the detector conditions
  - muon beam intensity

Data set 2021

- Normalisation of the 2021 data set

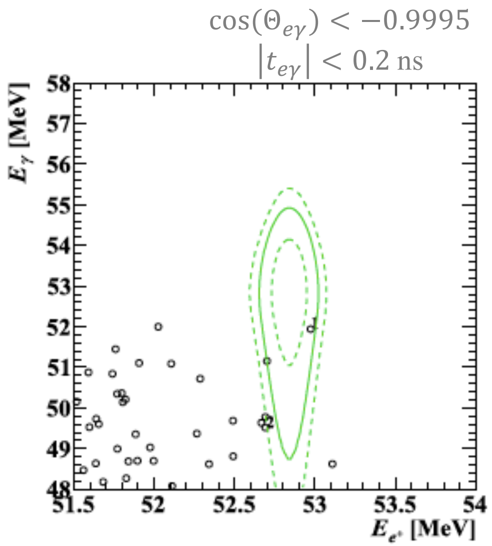
$$N_\mu = (2.64 \pm 0.12)\times 10^{12}$$

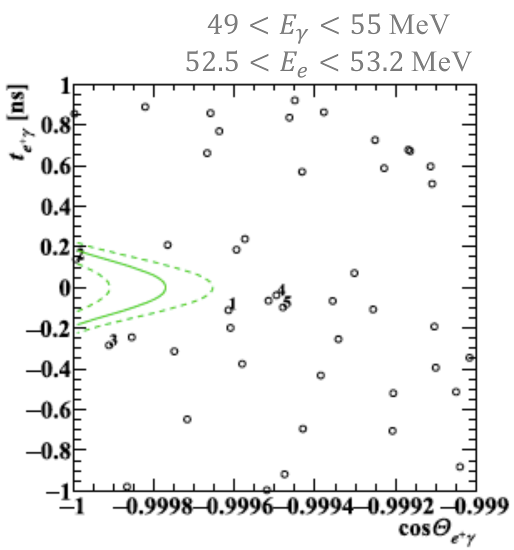
Event Distribution after 2021 data unblinding

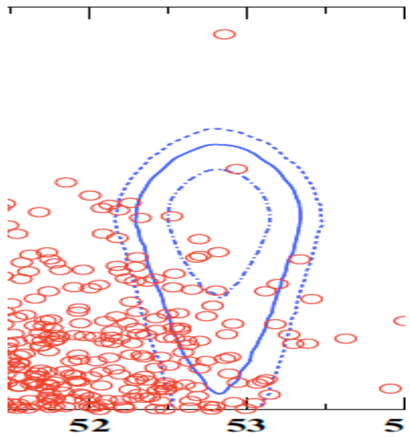


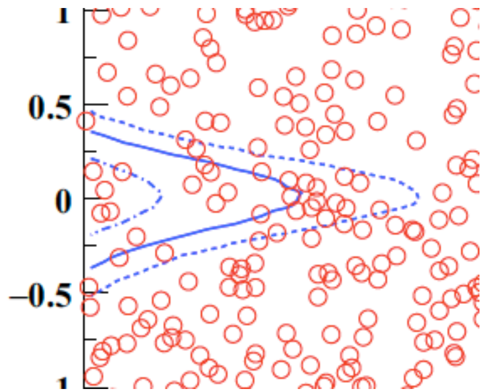
- Observed events in the analysis region = 66
- N_{sig} at 0
- N_{RMD}, N_{ACC} , even when not constrained, are compatible with sidebands values

Event Distribution after Unblinding





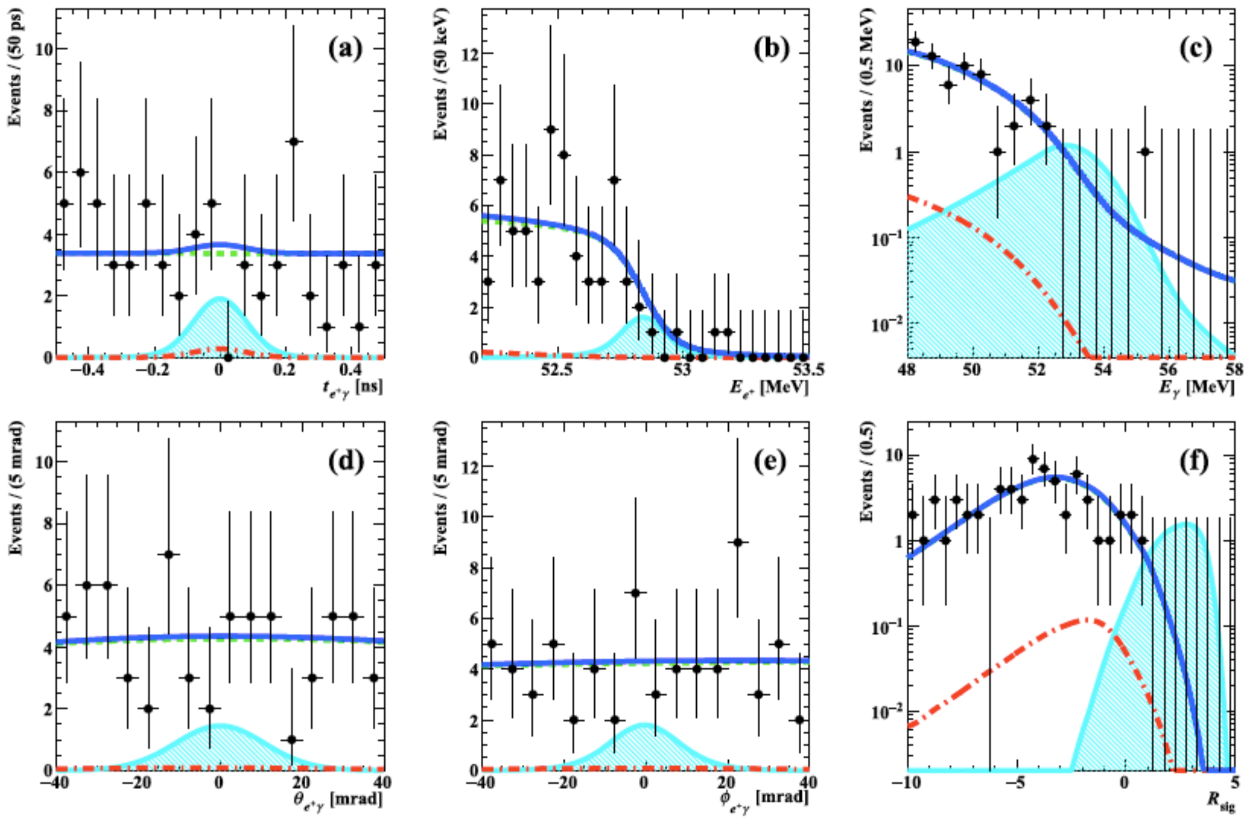




- visual comparison with the full MEG data set

(not fully fair because of the different sizes of the projections)

Projections of Likelihood Fit



Caption

- experimental data
- ACC background
- RMD background
- signal (x4)
- best-fit PDFs

(f) relative signal likelihood

$$f_{RMD} = 0.02\,, f_{ACC} = 0.98$$

$$R_{\rm sig} = \log_{10}\left(\frac{S(\boldsymbol{x}_i)}{f_{\rm RMD}R(\boldsymbol{x}_i) + f_{\rm ACC}A(\boldsymbol{x}_i)}\right)$$

The result of the 2021 MEG II data set

- Feldman-Cousins prescription with profile likelihood ratio ordering

- 90% C.L. upper limit on branching ratio

MEG II (2021) $\mathfrak{B}_{90} = 7.5\times10^{-13}$

MEG II - MEG combined $\mathfrak{B}_{90} = 3.1\times10^{-13}$

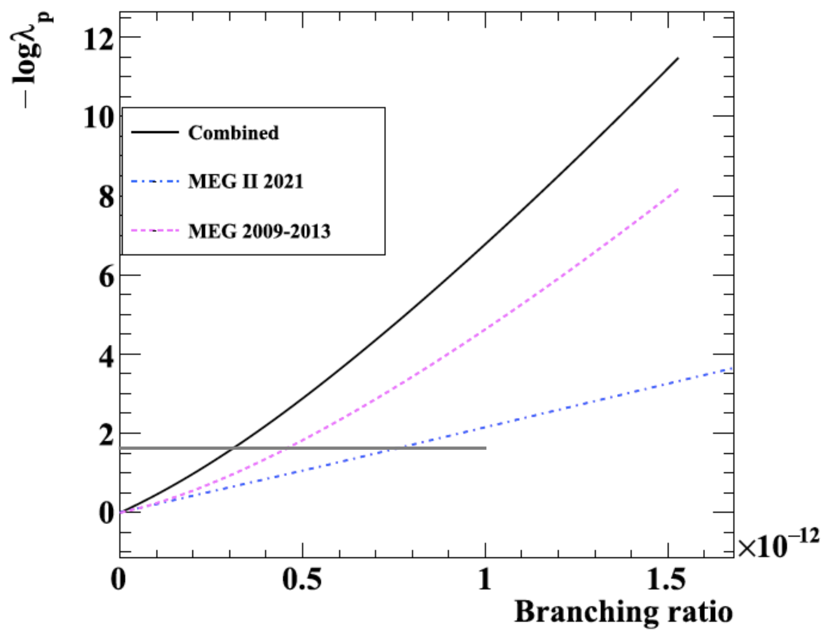
- Sensitivity

MEG II (2021) $\mathcal{S}_{90} = 8.8\times10^{-13}$

MEG II - MEG combined $\mathcal{S}_{90} = 4.3\times10^{-13}$

MEG II Collaboration, Euro.Phys.J. C84(2024)216

MEG: $\mathfrak{B}_{90} = 4.2\times10^{-13}$ $\mathcal{S}_{90} = 5.3\times10^{-13}$



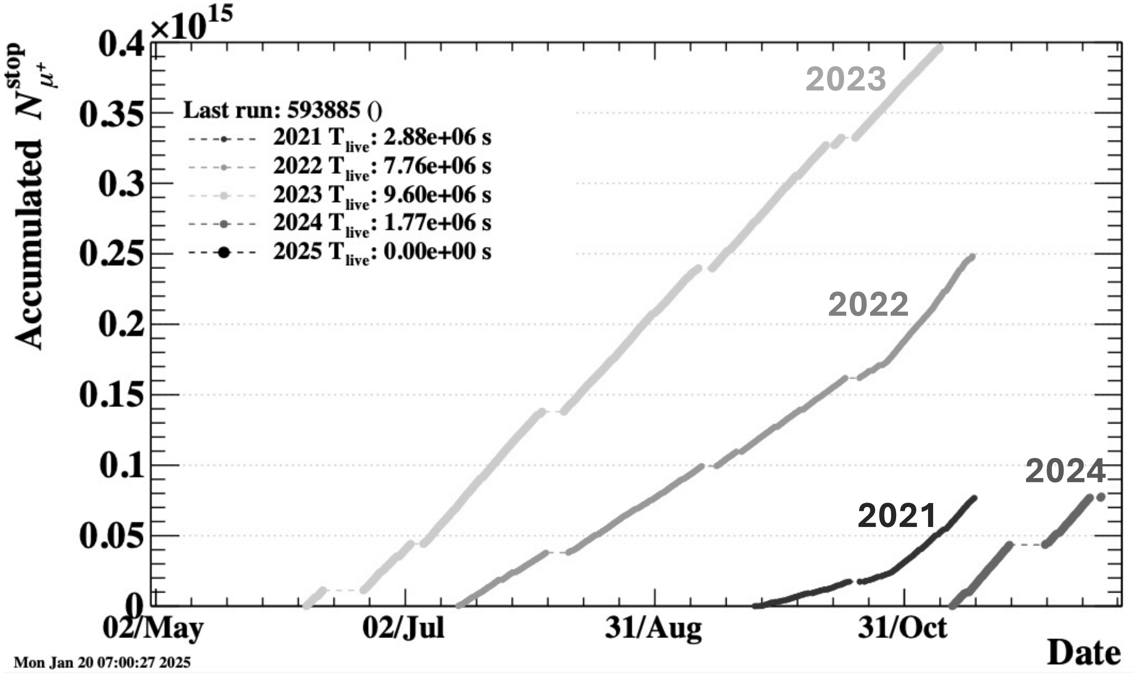
The two results are combined in a simplified manner, setting a threshold on the negative log likelihood-ratio curve instead of following the Feldman–Cousins approach.

Physics data acquired so far

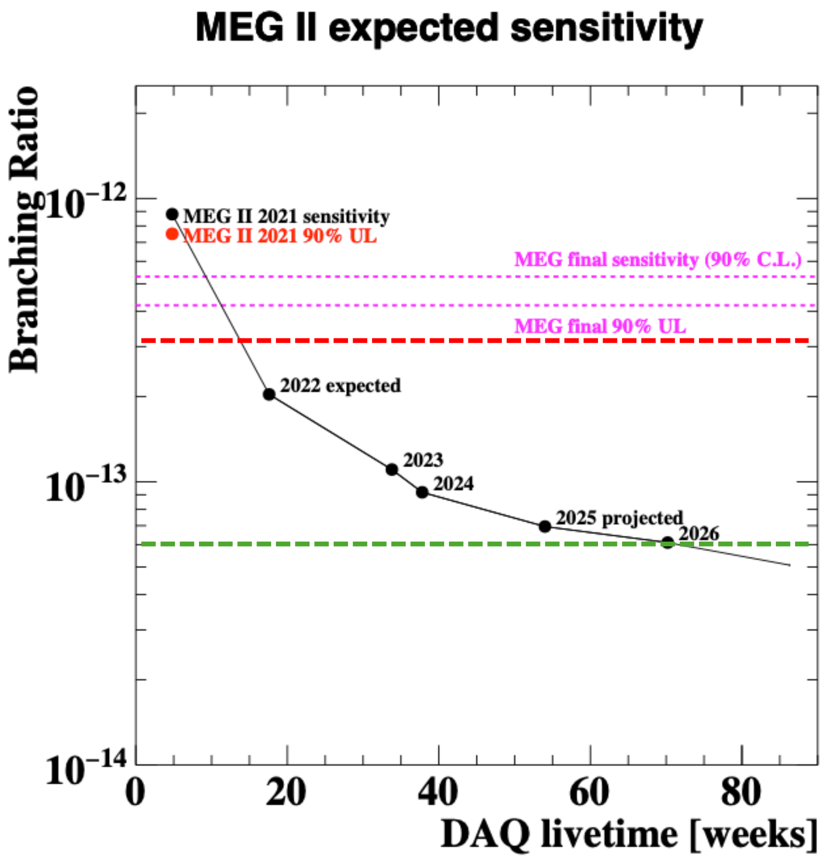
- 2021: first physics run with the full detector first result of MEGII recently published
  (Euro. Phys. J. C84(2024)216)
- 2022: Long and stable run in optimal conditions ready for unblinding
- 2023: Largest statistics ever acquired data processing in progress
- 2024: 4 months in standby for repair works at PSI He cryoplant

MEG II total statistics
8.1×10^{14} mu stop

10 times the 2021 published statistics



Perspectives in $\mu^+ \to e^+\gamma$ search



New best UL (MEG+MEG II):
$\mathcal{B}_{90}$=3.1x10^{-13}

MEG II proposal goal:
$\mathcal{S}_{90} = 6\times10^{-14}$

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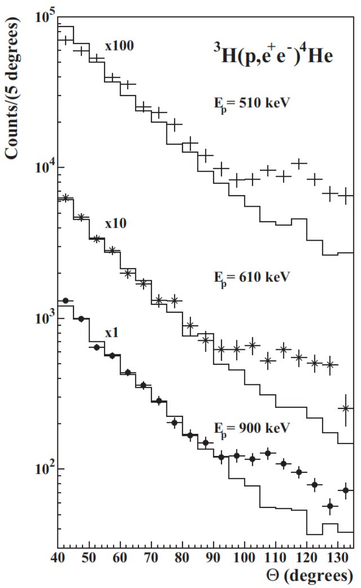
The X17 boson

- The *Krasznahorkay et al*. at Atomki confirmed the e^+e^- pairs excess in the ^8Be

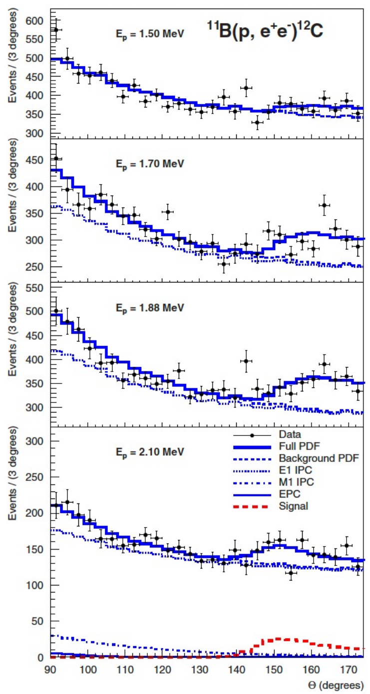
$^3H(p,e^+e^-)^4He$

Phys.Rev.C 104(2021)044003



$^{11}B(p,e^+e^-)^{12}C$

Phys.Rev.C 106(2022)L061601



1. The interpretation of the 2016 result is a new boson
   - m_X = 16.70 MeV / c^2 only from 18.1 MeV resonance

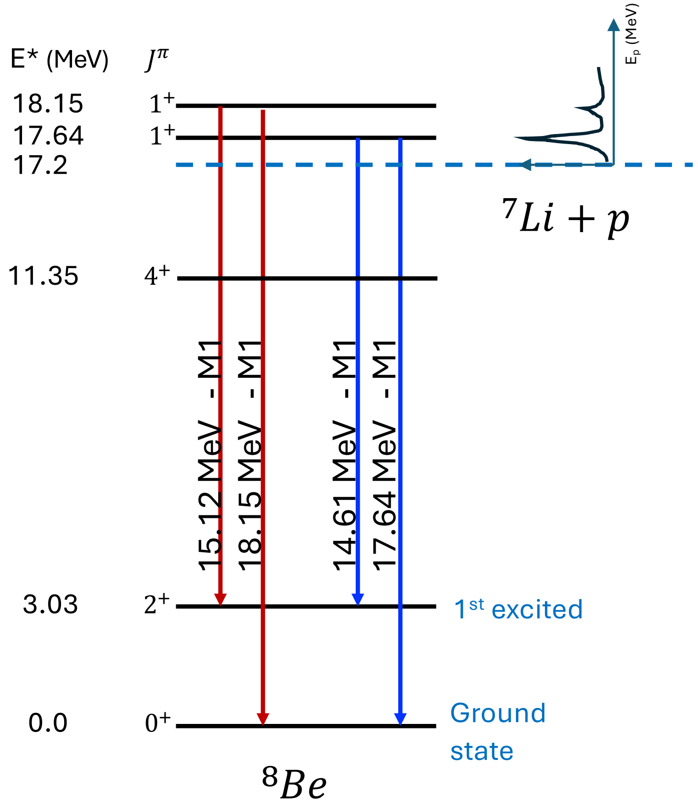
2. With different production channels and detector techniques,
   - NA48/2 Phys.Lett.B 746(2015)178
   - NA64 Phys.Rev.D 101(2020)071101

   put upper limits on the X17

3. Expectation revision including Standard Physics effect
   - Zhang and Miller include amplitude interference and form factors Phys.Lett.B 773(2017)159
   - Koch modifies the Bethe – Block Nucl.Phys.A 1008(2021)122143
   - Aleksejevs computes internal pair conversion with second order loops arXIV:2102.01127

The X17 production

Simplified Be levels



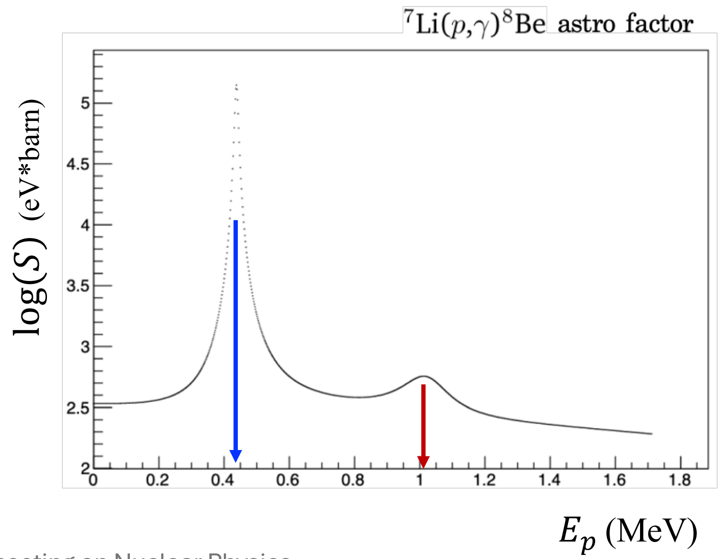
- The state $^7Li + p$ yields 17.2 MeV above the ^8Be ground state
  → many ^8Be excited states are easily accessible
- Cross section to the resonant excited states are very different

$$E_p = 0.440\ \text{MeV} \quad Q = 17.6\ \text{MeV}$$

$$E_p = 1.030\ \text{MeV} \quad Q = 18.1\ \text{MeV}$$

A further non-resonant state is present at 17.9 MeV

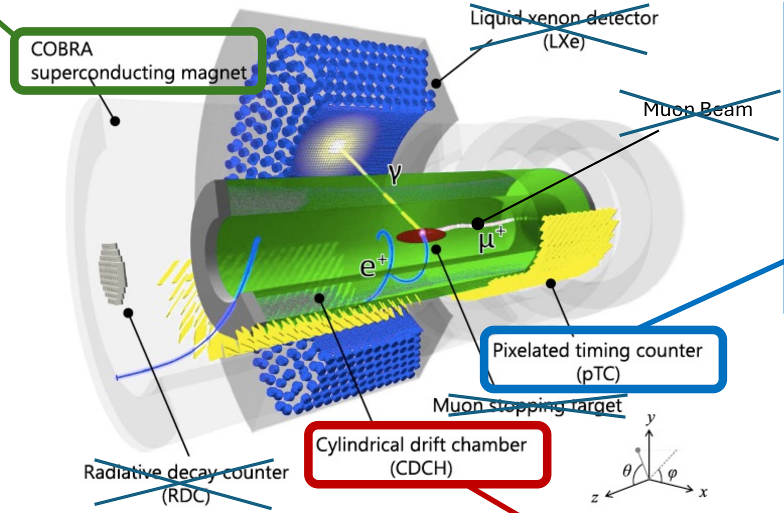
- Two γ transitions for each excited state

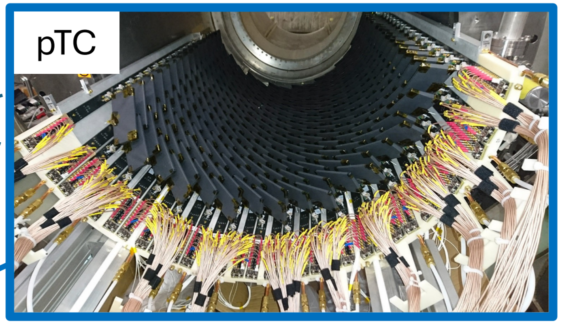


X17 search with the MEG-II experiment

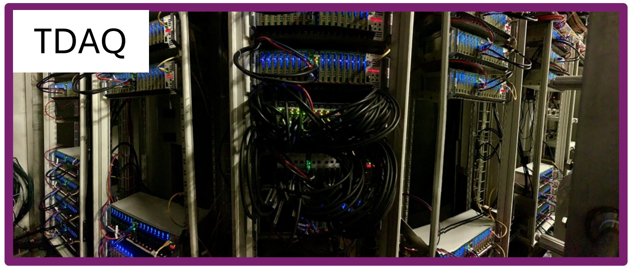
- event signature $^{7}Li(p,e^{+}e^{-})^{8}Be$
- exploit the high-performance MEG II detectors

Thin-wall SC solenoid with a gradient magnetic field:
- 1.27T center
- 0.49T both ends
- **Field reduced at 15%**

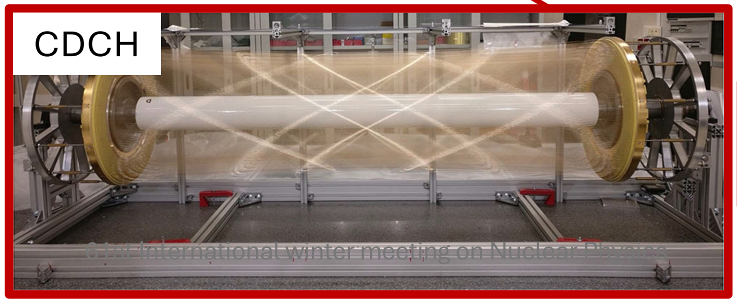




Two sectors made of 256 scintillating BC422 tiles read by Advansid SiPMs
- Time obtained by averaging the tile times on average : **8 tiles hit**
- **timing resolution 43 ps**



Integrated Trigger and DAQ system with full custom boards and crates
- 9000 channels
- Waveform digitizer at 1.6 GSPS with DRS chip
- Flexible FPGA based trigger with latency <450ps



Single volume drift chamber filled He:C_4H_{10}
- 9 layers of 192 cells at full stereo readout
- **momentum resolution ~90 KeV/c**

MEG II Calibration Methods

- Among the many calibration tools to calibrate the Lxe calorimeter we have a dedicated Cockcroft Walton proton accelerator
- $E_P = 440\ \mathrm{KeV}$ to excite the 17.6 MeV line
- Very low current given the large cross section

C-W proton accelerator

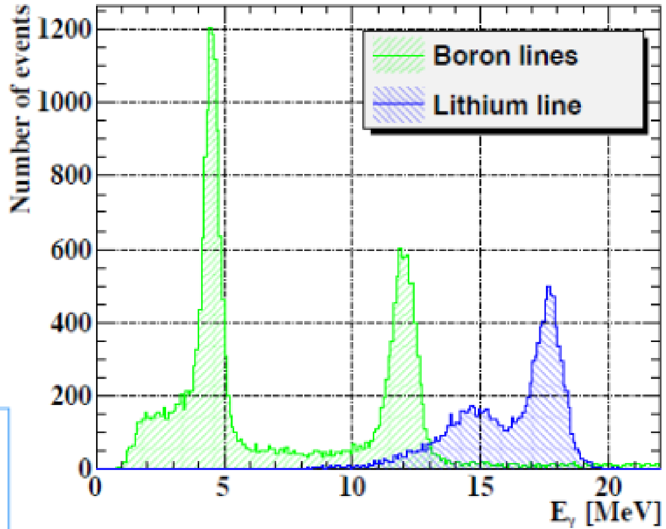
Up to 1 MeV proton on $LiBO_4$ target

Energy calibration line :

$$p\ {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be}\ \gamma(17.6\ \mathrm{MeV})$$

XEC-pTC time alignment with line :

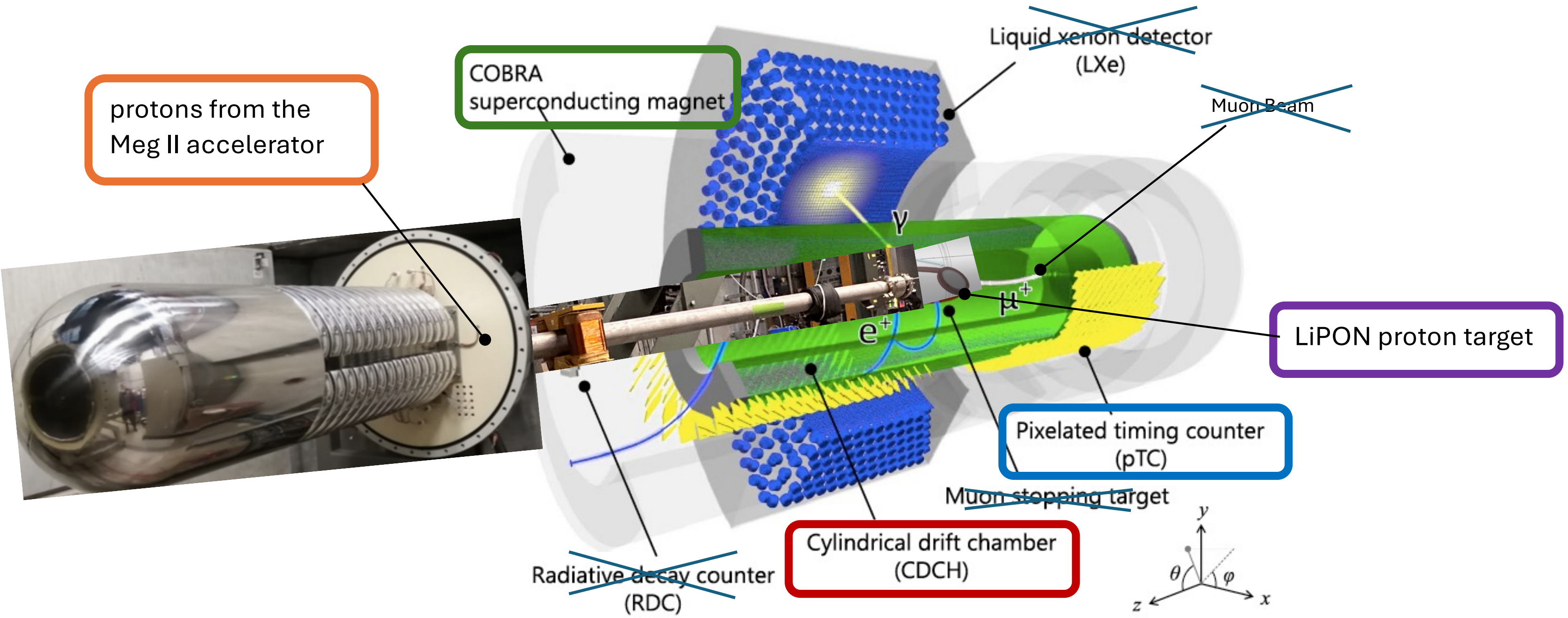
$$p\ {}^{11}\mathrm{B} \rightarrow {}^{12}\mathrm{C}\ \gamma(11.6\ \mathrm{MeV})\ \gamma(4.4\ \mathrm{MeV})$$



X17 search with the MEG-II experiment

- Changes for the X17 search
  - replace the muon target with a LiPON (*) target for proton
  - remove the RDC and install a proton beamline for the CW accelerator

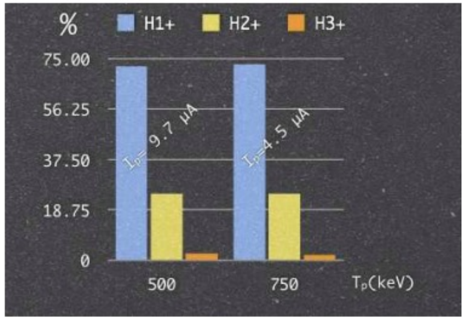
(*) Lithium phosphorus oxynitride ($Li_{3-X}PO_{4-Y}N_{X+Y}$)

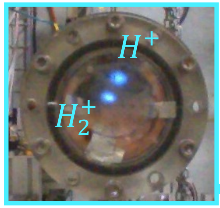


The proton beam

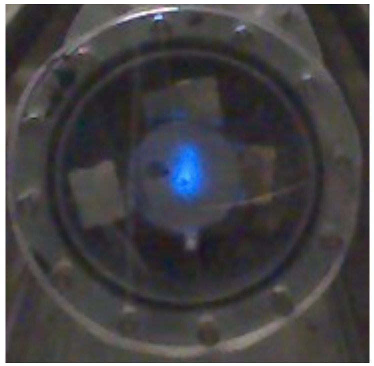
- Beam imaging with proton induced fluorescence on quartz crystal
- Beam centring at the spectrometer centre with dipoles
- Proton beam composed of 75% H^+ and 25% H_2^+
  - *irrelevant for the MEG II standard calibration*
  - *increased complexity for the X17 search due to the the excitation of both resonances (17.6 and 18.1 MeV) and reduced statistics on 18.1 MeV*

Ion composition



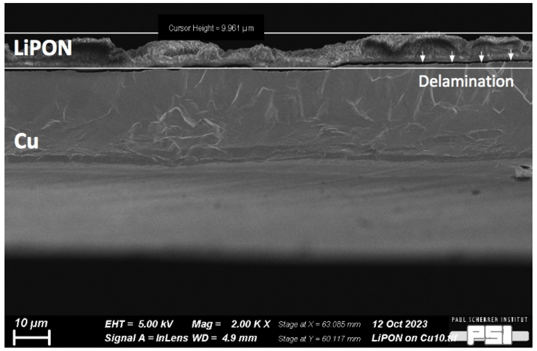


Spectrometer center

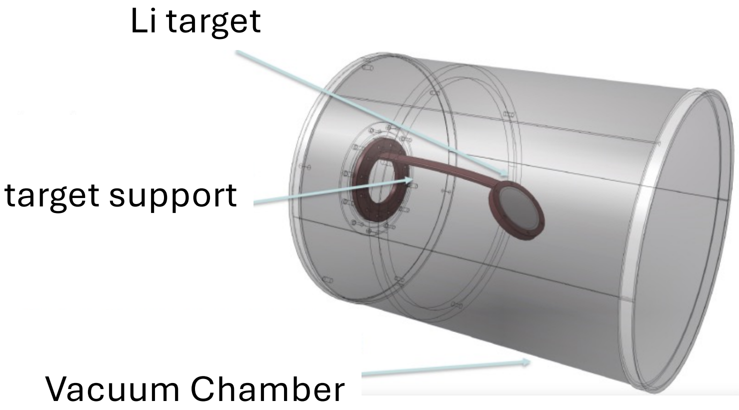


The Li target

- Standard MEG II targets (LiF and $LiBO_4$) not adequate for background and production issues
- Calibration target: $5 \mu m$ thick LiF target on 25 μm copper substrate (by INFN - LNL)



- Main target:
  - 7 μm thick LiPON (*) on a 25 μm Cu substrate (implanted at PSI)
  - Copper target support for heat dissipation at 45° slant angle
  - Light carbon fiber vacuum chamber to minimize multiple scattering



- *Target too thick: high energy H^+ populate the 17.6 MeV resonance*
- *Irregular surface, delamination from copper substrate*

(*) Lithium phosphorus oxynitride ($Li_{3-X}PO_{4-Y}N_{X+Y}$)

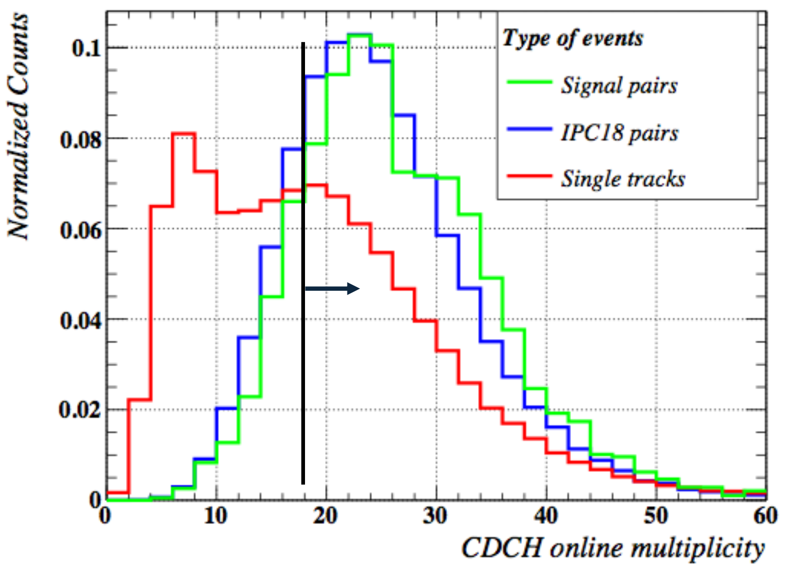
Event Type and Trigger

Event Types

- Signal: e^+e^- from X17 decay
- IPC: Internal Pair Conversion *(direct e^+e^- creation in Be)*
- EPC: γ conversion to e^+e^- in matter
- Single: single tracks from γ interactions *(relevant for trigger and event reconstruction)*

Trigger

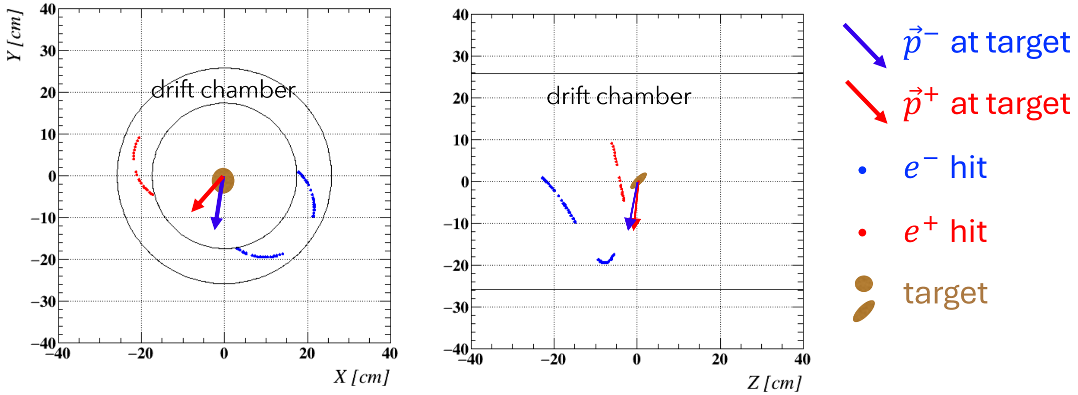
- New algorithm on FPGA: defined CDCH hit multiplicity at TDAQ level (*not used in $\mu^+ \to e^+\gamma$ search)*
- Trigger: coincidence of at least 18 hits on the CDCH and 1 hit in the pTC

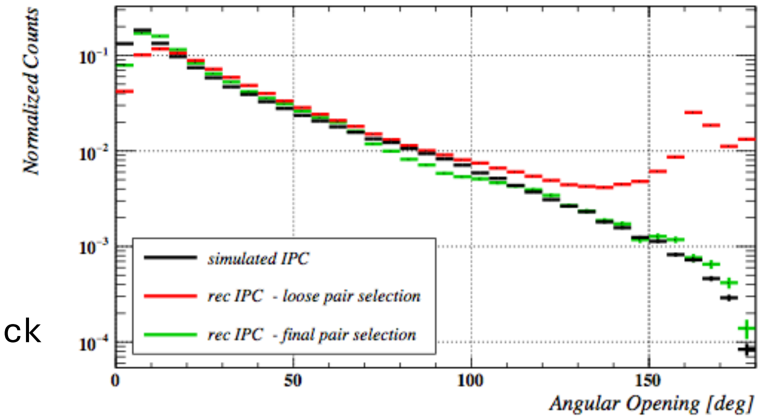


- Optimization between rejection of single tracks, EPC and asymmetric pairs
- *16% efficiency on signal*

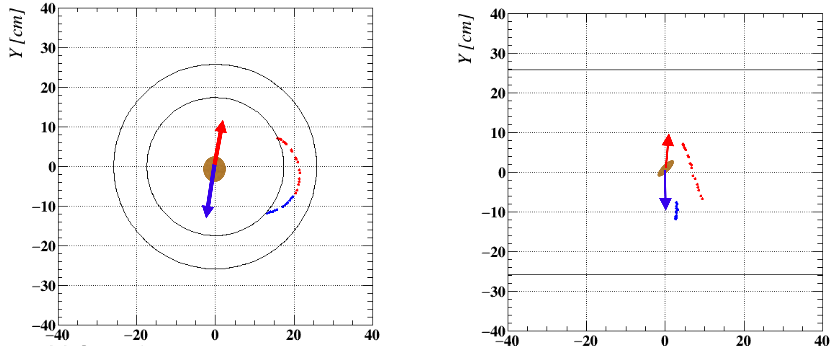
Reconstruction Algorithms

- MEG II algorithms optimized for e^+ reconstruction. Included the e^- tracking





- Fake events, reconstructed close to $\Theta_{ee} \approx 180°$, are removed with track quality requirements. Main source 2 segments of the same track.

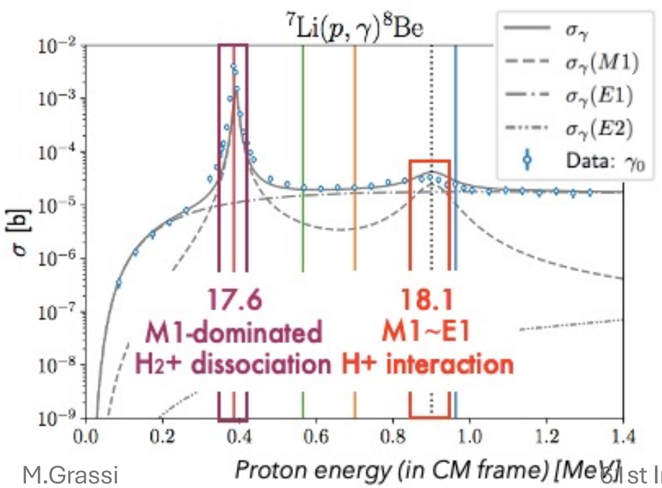


- Checks of the reconstruction algorithms and the track quality requirements on simulated IPC events
- non-physical reconstruction effects are removed

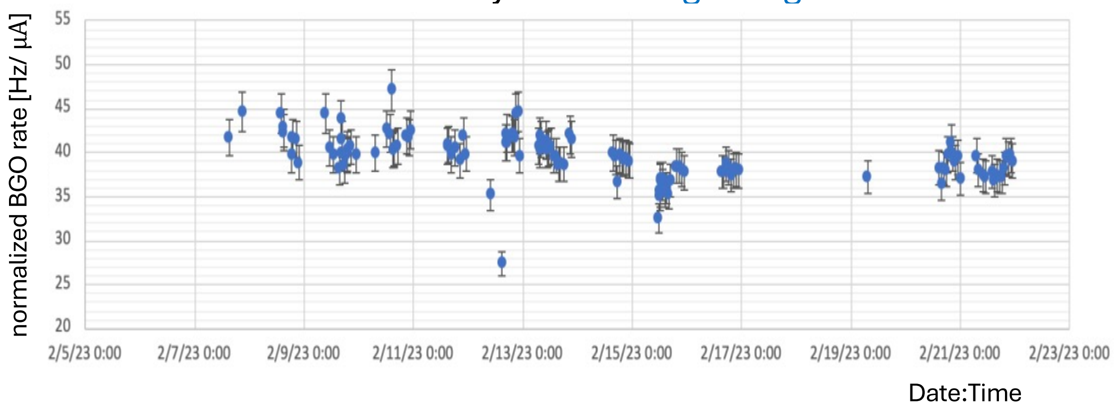
Data Sample

- Data collected in Feb.2023 with $E_{beam} = 1080$ KeV , $I_{beam} = 10$ μA (+ a small sample at 440 KeV)
- 75M events collected and 300k pairs reconstructed
- event categories from 17.6 and 18.1 MeV
  - 60% EPC
  - 40% IPC

➢ Huge simulation effort



- γ –rate monitor with BGO crystal shows sufficient stability and no target degradation

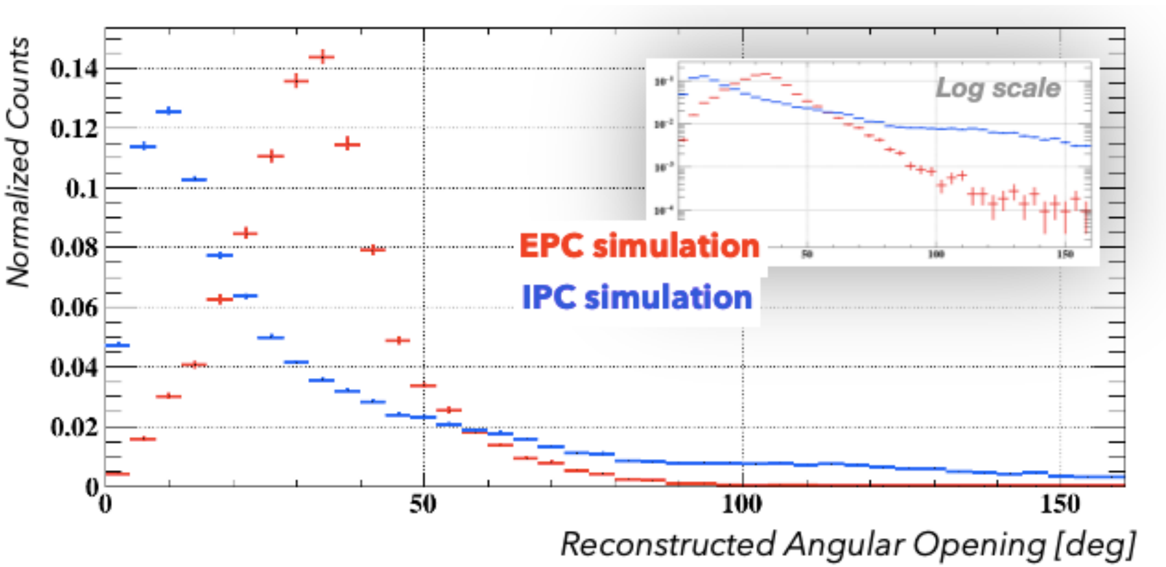


➢ Simultaneous search for X17 in both 440 KeV and 1030 KeV resonances

- relative population determined directly with the CDCH e+e- tracks

Background and Simulation

- *Krasznahorkay et al.* used a model for IPC developed by Rose. Phys.Rev. 76(1949)678
- We adopted the Zhang and Miller model, which includes E1-M1 interference and anisotropies. Phys.Lett.B 773(2017)159
  - Good agreement with original Rose model, it differs on tails

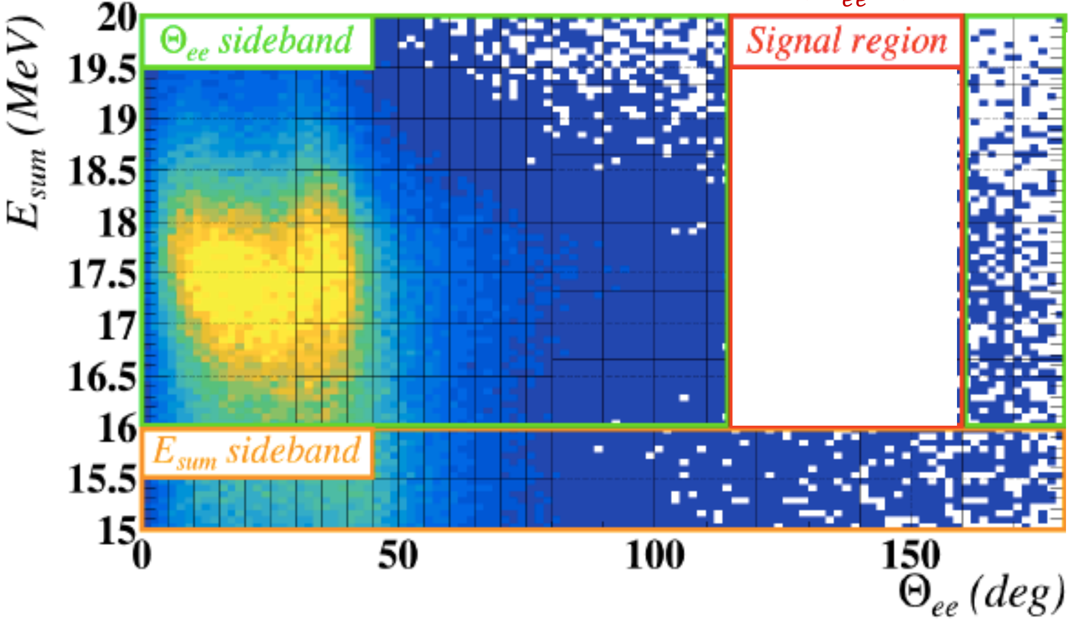


- EPC: real photon from the dominant $^7Li(p,\gamma)^8Be$ reaction interact in the detector material
  - detailed detector modelling
  - large statistics
- IPC is dominant in the signal region (x100 the EPC)

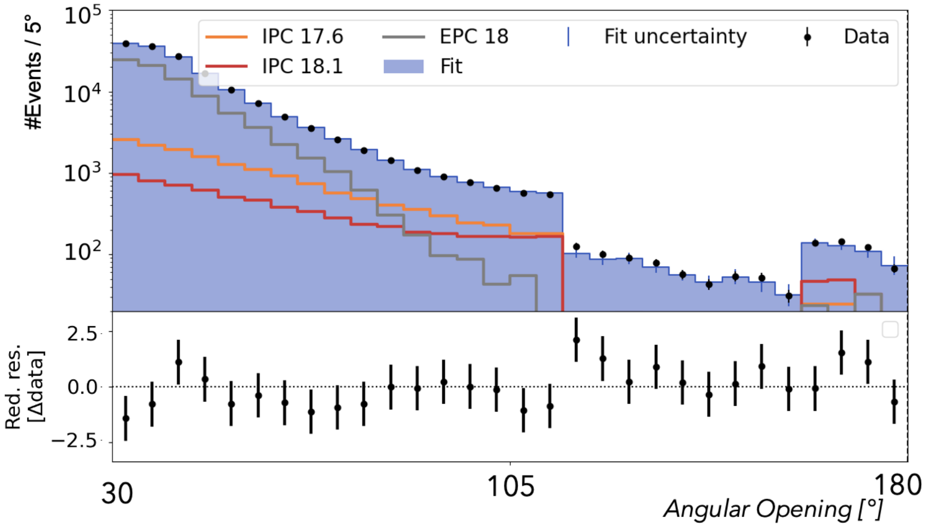
Analysis Strategy

- "Blind likelihood analysis" with the blinding variables
  - angular opening of the pair $\Theta_{ee} = \cos^{-1}\left(\frac{\mathbf{p}_+ \cdot \mathbf{p}_-}{|\mathbf{p}_+||\mathbf{p}_-|}\right)$
  - sum of the energies $E_{sum} = E_+ + E_-$

$16\ \text{MeV} < E_{sum} < 20\ \text{MeV}$
$115° < \Theta_{ee} < 160°$



- tuning of the simulation and model validation on the sidebands
- good simulation of the background above 30°

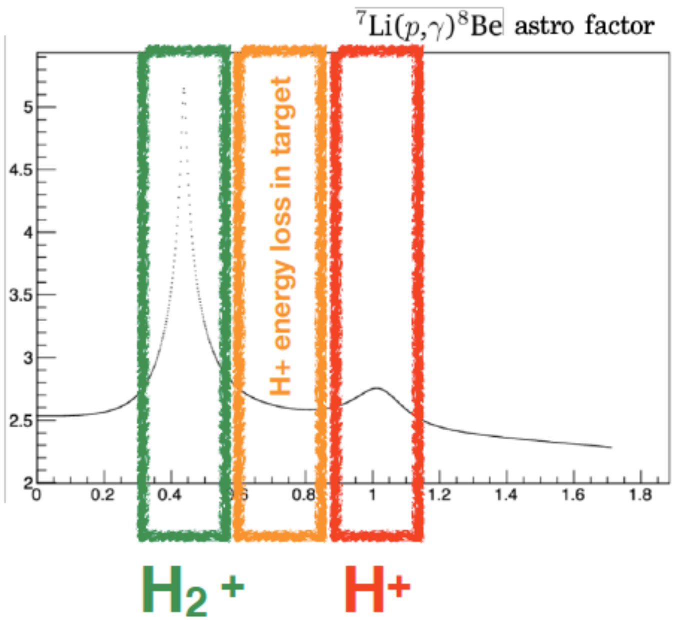


X17 Analysis

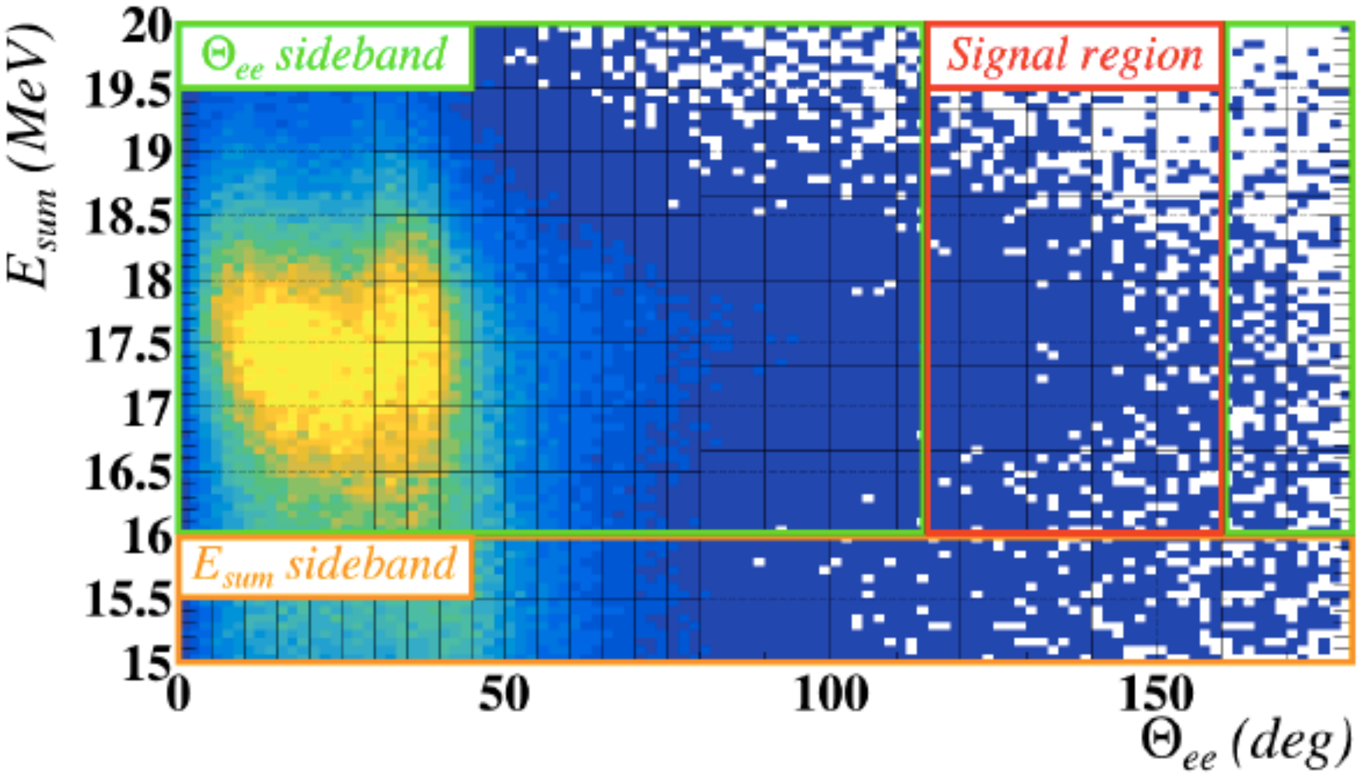
- Binned Maximum Likelihood fit
  - using template PDF histograms from detailed MC simulation
  - extensively validated on sidebands
- Likelihood parametrised in terms of relative Branching Fraction

$$R_Q = \frac{\mathscr{B}(^8\mathrm{Be}^*(Q) \to {}^8\mathrm{Be} + \mathrm{X17})}{\mathscr{B}(^8\mathrm{Be}^*(Q) \to {}^8\mathrm{Be} + \gamma)}$$

  - **Two** signal PDFs for Q = 17.6 and 18.1 MeV
  - **Six** IPC PDFs for the two main resonances and the non-resonant 17.9 MeV, each one times the two transitions to GS and 1st excited
  - **Two** EPC PDFs for the two main resonances
  - **One** fake pairs PDF

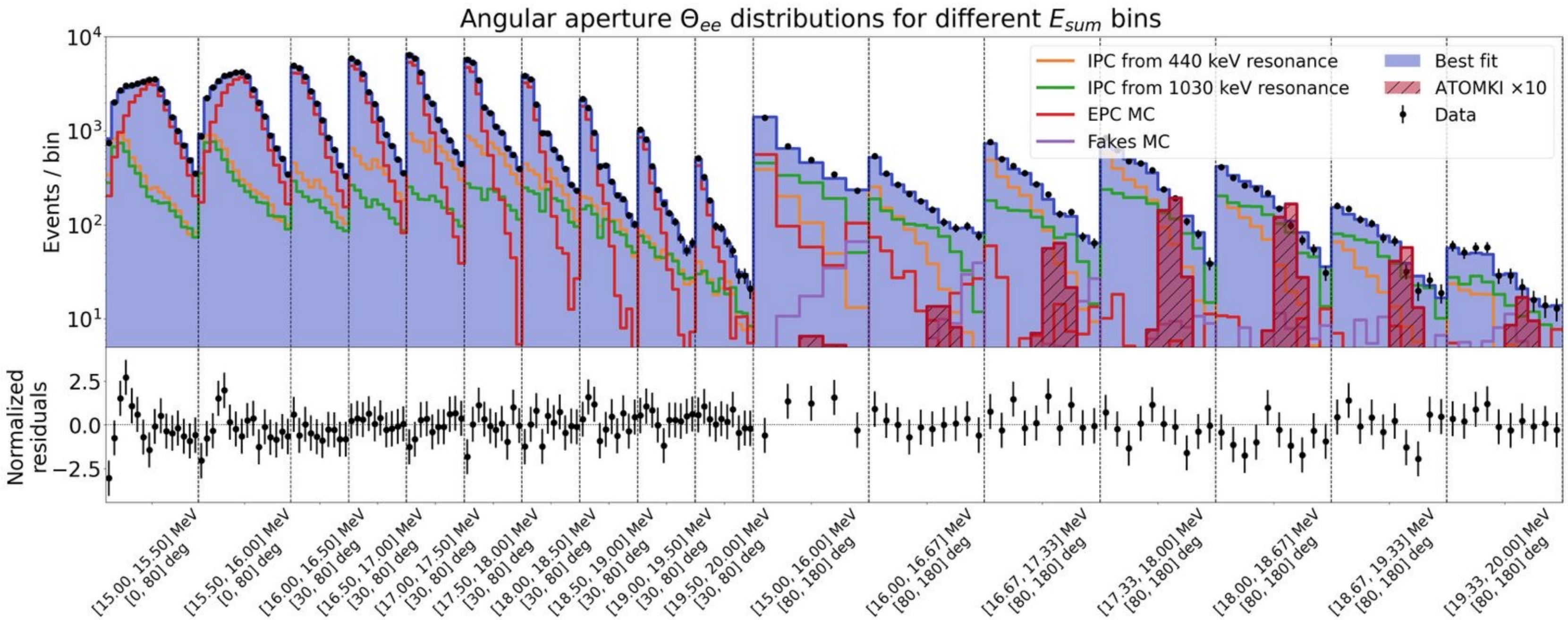


Unblinding



Θ_{ee} sideband
Signal region
E_{sum} sideband
E_{sum} (MeV)
Θ_{ee} (deg)
20
19.5
19
18.5
18
17.5
17
16.5
16
15.5
15
0
50
100
150

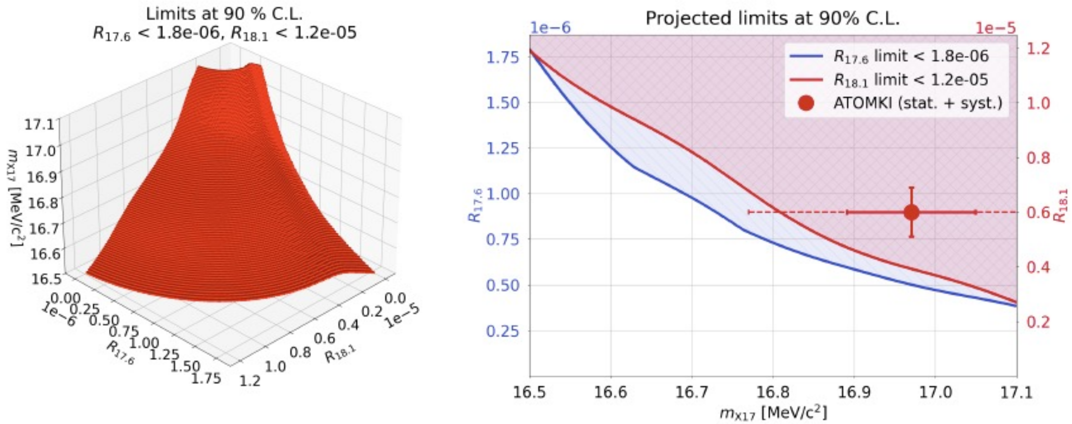
Likelihood Projections



- Best fit
  - N_{X17} : 10 ± 92 for 18.1 MeV , 0 for 17.6 MeV
  - IPC : 12.6 ± 0.9 % for 18.1 MeV, 45.8 ± 1.3 % for 17.6 MeV, 0 for 17.9 MeV
  - M_{X17} : 16.5 MeV/c^2
  - goodness of fit : p-value 10.5%

90% Confidence Regions

- Systematic effects (energy scale, resolutions, mass dependence, relative acceptance) are included as nuisance parameters
- three-dimensional confidence regions with profile likelihood ordering



- The 90% C.L. region includes the null hypothesis, indicating no significant excess

$$\boldsymbol{R_{17.6} < 1.8\times10^{-6}} \quad \text{corresponding to } N_{sig}(17.6) < 200$$

$$\boldsymbol{R_{18.1} < 1.2\times10^{-5}} \quad \text{corresponding to } N_{sig}(18.1) < 230$$

- Compatibility test with the average mass of the three *Krasznahorkay et al.* observations on Be, He and C : p-value 6.2%

X17 Search Conclusion

- The $^{7}Li(p, e^{+}e^{-})^{8}Be$ process has been successfully studied with the MEG II detector
- No significant signal of a new particle decaying to e+e- was found in our data
- The reported observation by *Krasznahorkay et al.* was tested and excluded at 94% p-value

Perspectives

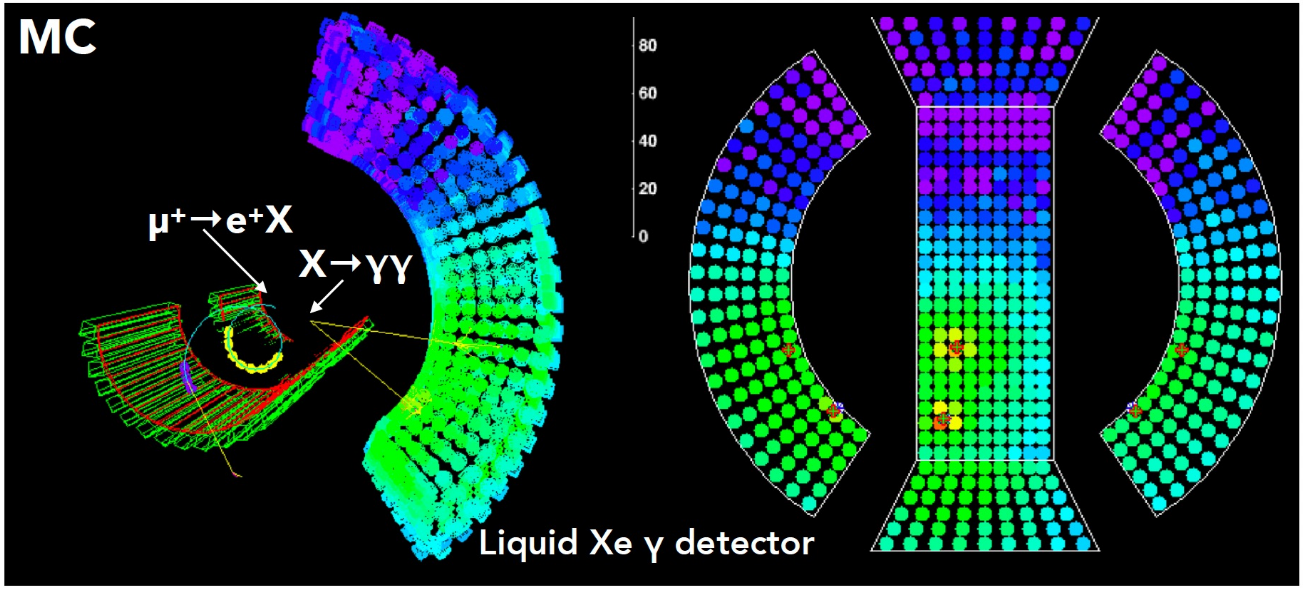
- Two major improvements will enable distinct studies of the 2 resonances
  - A new LiPON target 2 μm thick has been produced at PSI
  - Separation and collimation of H_2^+ have already been achieved

Outline

- Muons as probes for New Physics
- Results on $\mu^+ \rightarrow e^+\gamma$ search (2021 data sample)
- Search for the X17 boson
- Perspectives in search for Axion Like Particles
- Final remarks

$\mu \to e^+ a \to \gamma\gamma$ search

- Published with MEG
- Exploit the LXe imaging capability
- The ALP decay vertex is not reconstructed.
- explored region:
  - $m_a = 20 \div 45 \,{}^{\mathrm{MeV}}/_{c^2}$
  - decay length < 1 cm
- Reduced beam intensity
- 5 events were found with no statistical significance including look-elsewhere effect



$\mu \to e^{+}a \to \gamma\gamma$ Search

- Publis
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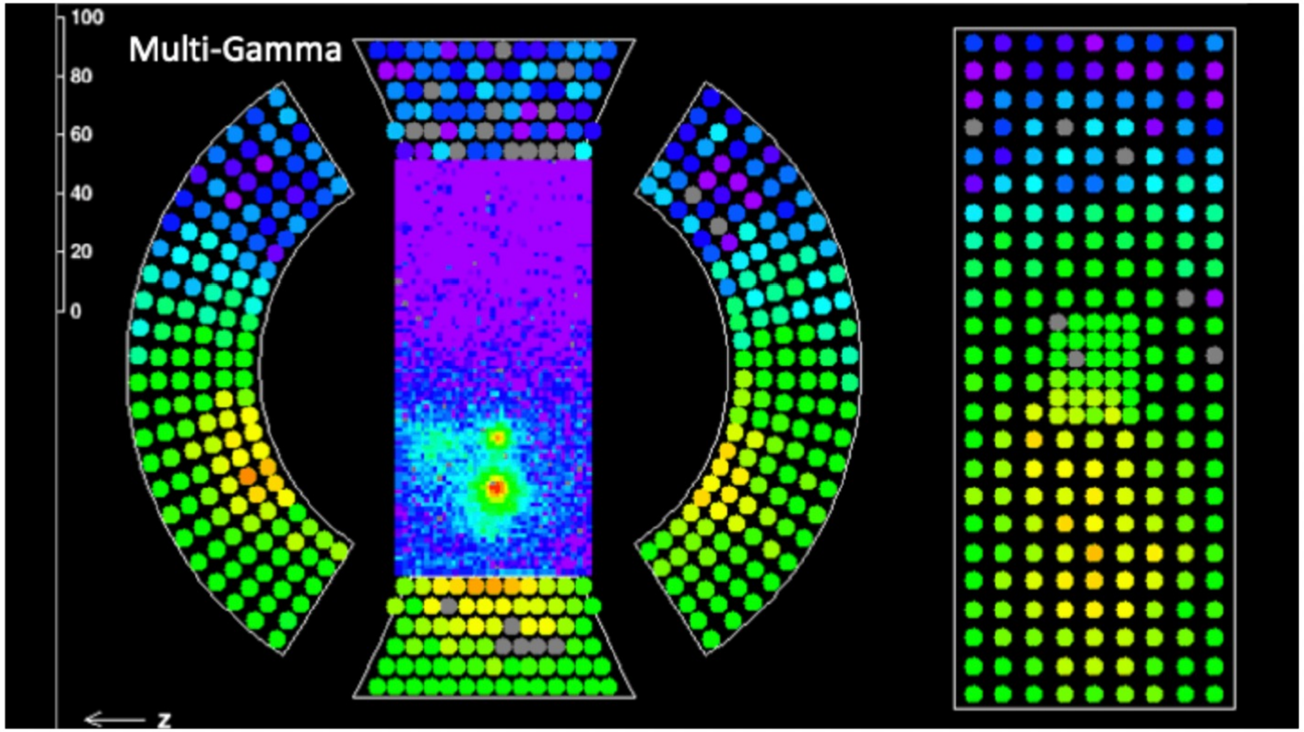
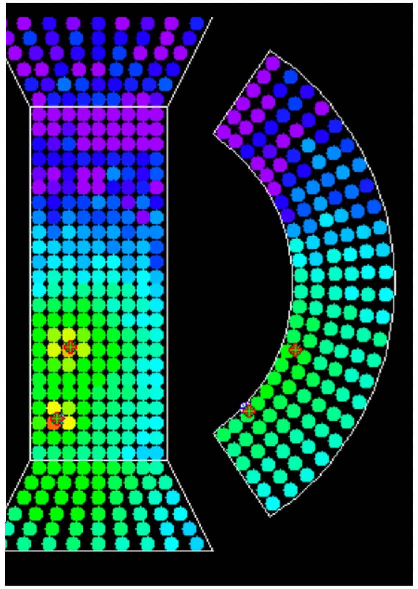
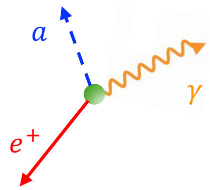


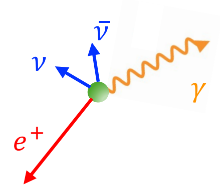


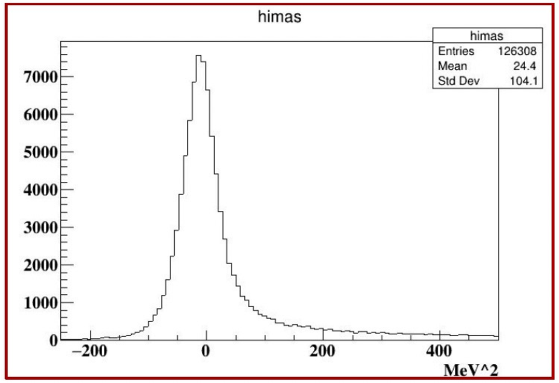
With MEG II we have 10x more statistics and better Lxe front face imaging

$\mu \to e^+ a\gamma$ **Search**

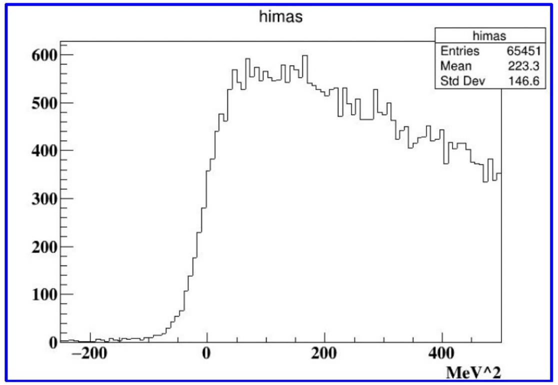
- The event topology is similar to the Radiative Muon Decay
- Search in the invariant mass square of the couple $e^+\gamma$ at $m^2 \approx 0$ for time coincident emission



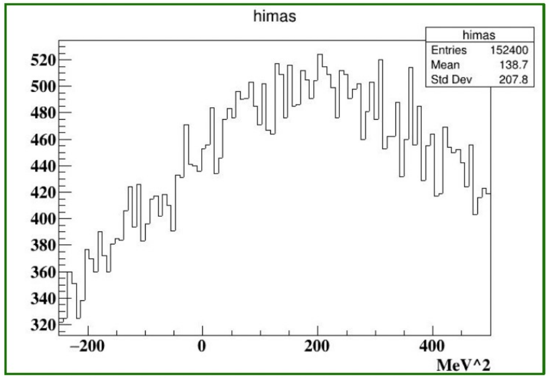




signal



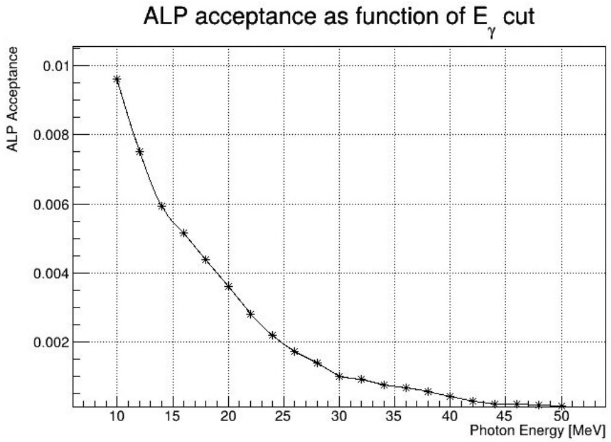
RMD



accidental

$\mu \to e^+ a\gamma$ Search

- Acceptance increases lowering the E_γ threshold
- Constraint by DAQ rate < 40 Hz
- Accidental background (dominant with the MEG beam) becomes negligible at reduced beam intensity



- reduced beam intensity data were taken for calibration purposes
- a further optimized sample has been collected in 2024 with $E_\gamma > 14$ MeV

Year	R_μ [μ/s]	Time (sec.)	E_γ [MeV]	k_{ALP}
2021	1.0×10^6	322080 (~ 3.7 *d.*)	20.0	4.9×10^7
2022	8.7×10^5	193421 (~ 2.2 *d.*)	20.0	2.5×10^7
2023	2.0×10^6	234790 (~ 2.7 *d.*)	18.0	8.5×10^7

MEG II estimated sensitivity

Total normalization factor

$$k_{ALP}^{tot} = 1.59 \times 10^8$$

Single event sensitivity

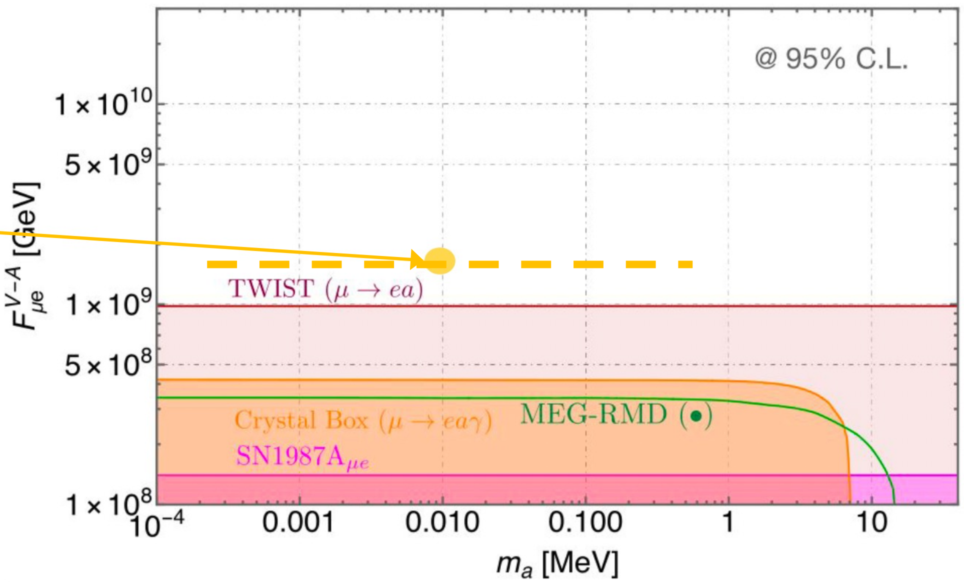
$$\mathcal{S}_{ALP}^{tot} = \frac{1}{k_{ALP}^{tot}} = 6.29 \times 10^{-9}$$

Lower Limit Estimates

- Preliminary estimates of the lower limit on the ALP decay constant can be inferred

$$F_{\mu e}^{V-A} > 1.52\times10^{9} \text{ GeV}$$

  with 8.7 days of data already collected
- This could exceed the best limit set by the TWIST collaboration
- The analysis is in progress



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- Final remarks

Final Remarks

- The MEG II detector, with resolutions and efficiencies close or better than the design values, is operated at PSI

- The $\mu^+ \rightarrow e^+\gamma$ search with the 2021 data sample has been published with no evidence of signal

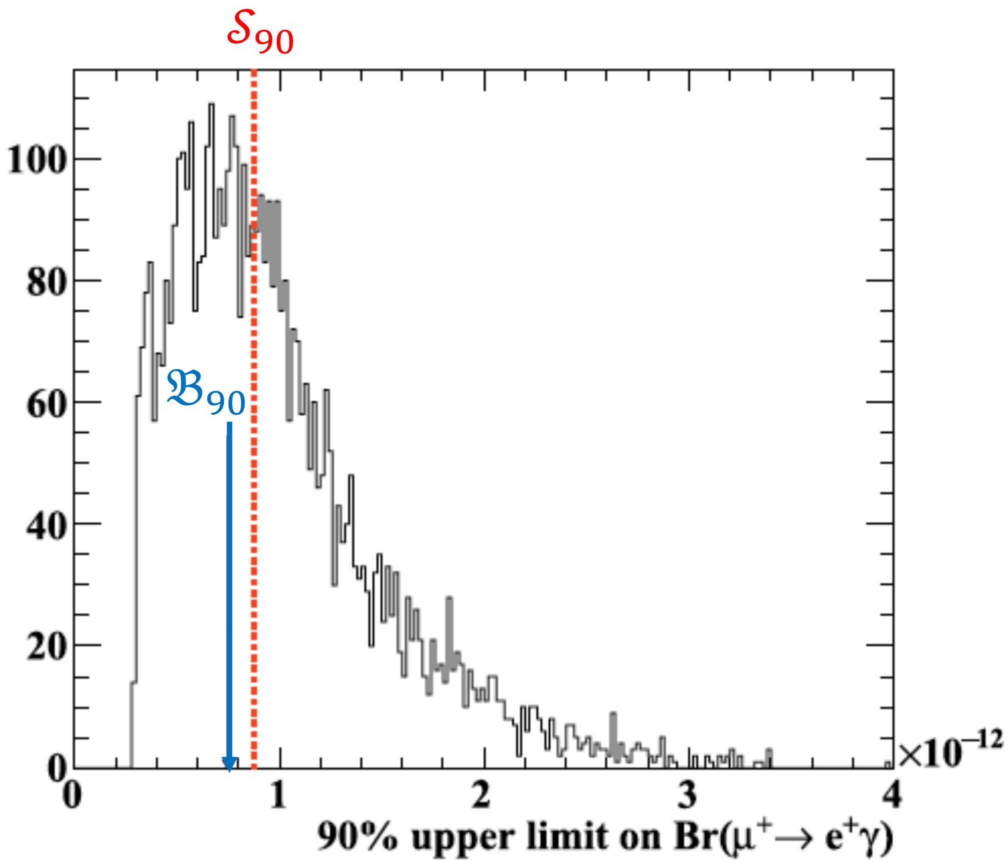
- A data sample 10 times larger has been already acquired

- X17 and Axion Like Particle searches demonstrated the MEG II detector's sensitivity to other phenomena beyond the SM

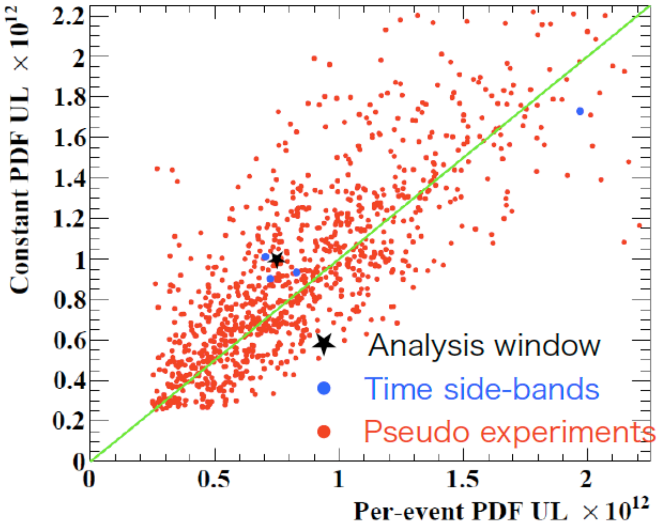
Additional material

$\mu^+ \rightarrow e^+\gamma$ 2021 Sensitivity

- The sensitivity $\mathcal{S}_{90}$ for the 2021 data sample, defined as the median of the distribution of the 90% CL upper limits computed for an ensemble of pseudo-experiments with a null-signal hypothesis, is 8.8×10^{-13}
- Comparable to the whole data set of MEG 5.3×10^{-13}



$\mu^+ \rightarrow e^+\gamma$ Consistency Checks



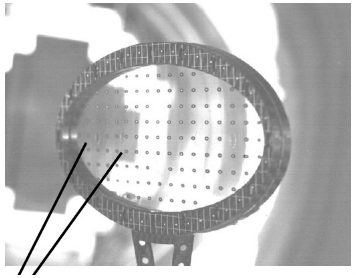
- comparison of the two analyses

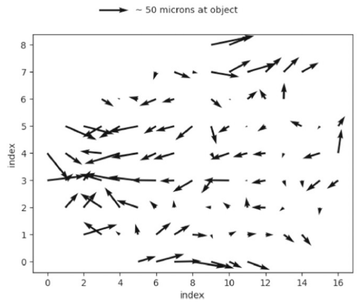
  Constant PDF vs Per-event PDF

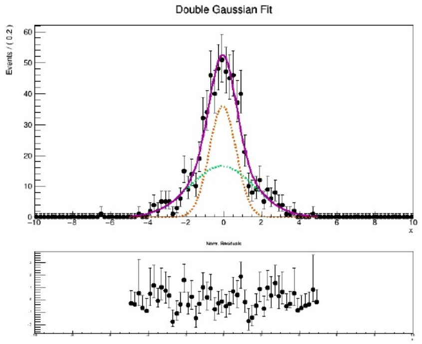
- N_{RMD}, N_{ACC} , when not constrained from sidebands, are compatible with constrained values

Systematics Reduction $\theta_{e\gamma}$ and $\phi_{e\gamma}$

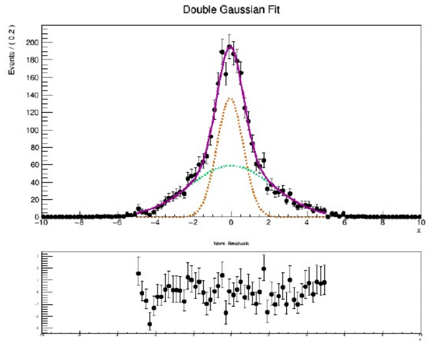
- better control of the BC400 target position
  - deformation controlled with photogrammetric measurements





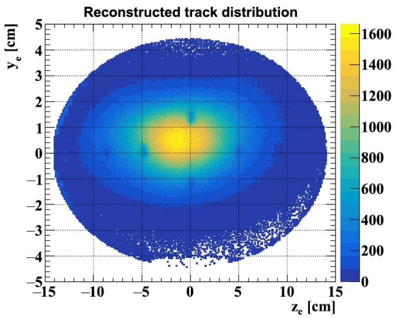


(a) Year 2021.



(b) Year 2022.

  - target holes imaging with positrons



- Absolute position uncertainty from $100\ \mu m$ to $35\ \mu m$

- the relative positioning of LXe and CDCH with cosmic ray tracks become

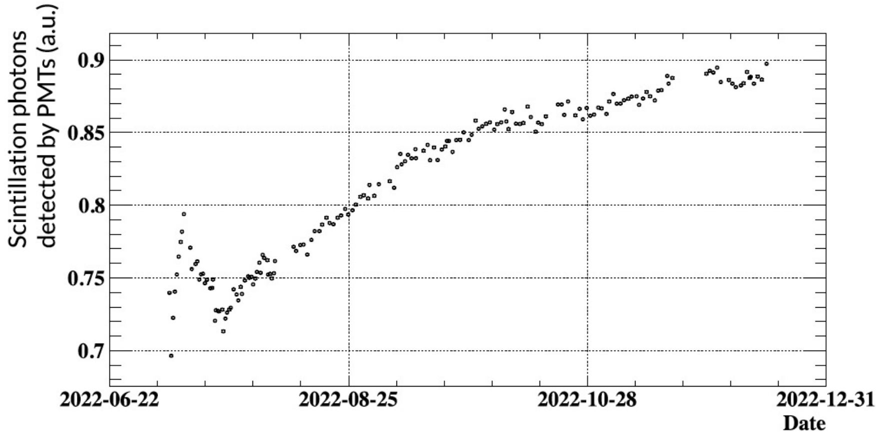
$$\sigma_Z(2021) = 410\ \mu m$$

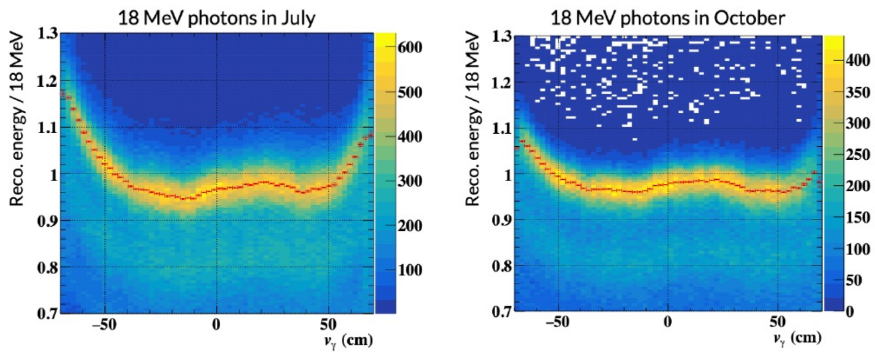
$$\sigma_Z(2022) = 290\ \mu m$$

(it was $730\ \mu m$)

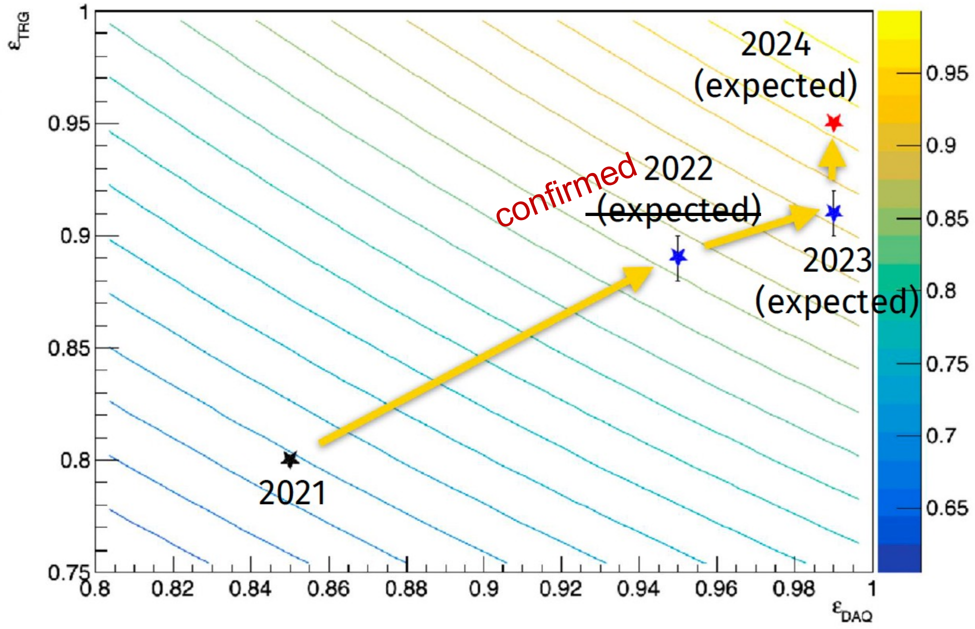
Systematics Reduction: E_γ

- Xe purity and MPPC PDE vary during data taking
- time-dependent non-uniformity correction have been improved



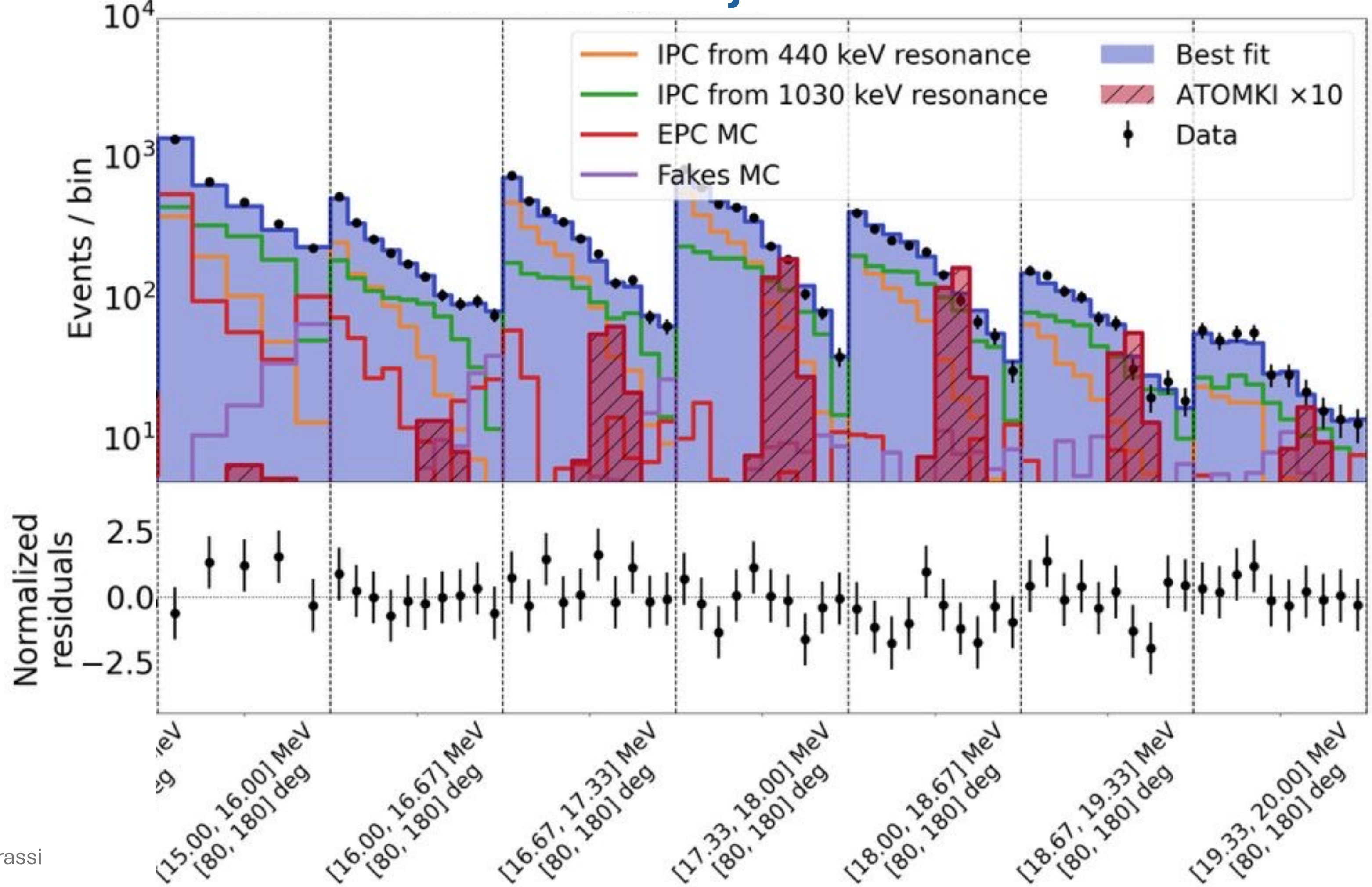


Statistics: ε_{TRG} and ε_{DAQ}



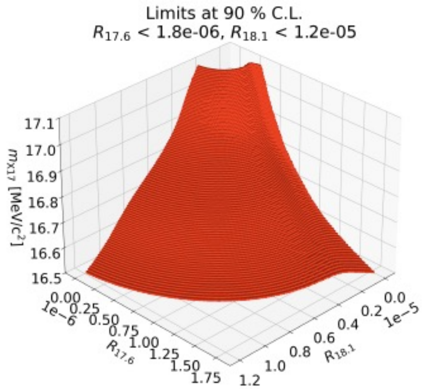
- improvements of trigger firmware, direction-matching implementation and DAQ software
  - sharper photon threshold with online trigger primitives
  - more efficient direction matching tables correlating LXe entrance face to the pTC tiles

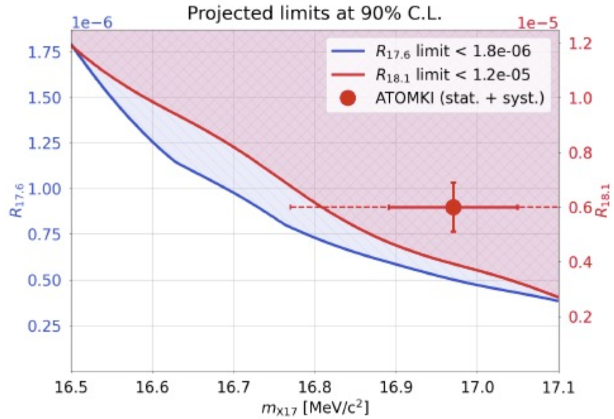
Likelihood Projections



X17 90% Confidence Regions

- three-dimensional confidence regions with profile likelihood ordering





- The 90% C.L. region includes the null hypothesis, indicating no significant excess, upper limits on the relative BR $R_{17.6} < 1.8\times10^{-6}$ $R_{18.1} < 1.2\times10^{-5}$
- Compatibility test with the *Krasznahorkay et al.* observations: p-value 6.2%
- Compatibility test with the *Feng et Al* hypothesis: p-value 1.8 %

Phys.Rev.Lett. 117(7) 071803 (2016)

Krasznahorkay et al. observations

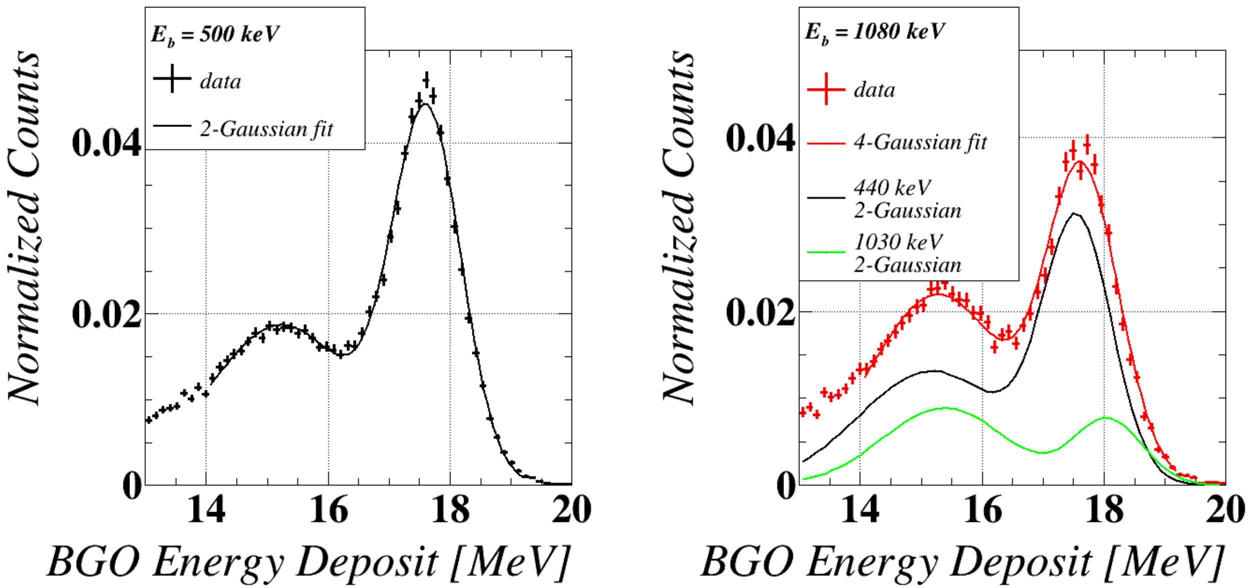
- 2016: Be(18.1) $m(X17) = 16.7 \pm 0.35 \pm 0.5$ MeV/c^2

  Be(17.6) no statistical evident signal
- 2017: Be(17.6) $m(X17) = 17.0 \pm 0.5 \pm 0.5$ MeV/c^2
- 2021: He(20.2) $m(X17) = 16.94 \pm 0.12 \pm 0.21$ MeV/c^2
- 2022: C(17.2) $m(X17) = 17.03 \pm 0.11 \pm 0.2$ MeV/c^2

- We assume the reported observations are coming from the same particle. We performed an average of the *Krasznahorkay et al.* measurements, with simple statistical combinations of the errors, resulting in $m(X17) = 16.97 \pm 0.22$ MeV/c^2

X17 BGO data

- An auxiliary BGO calorimeter is used to independently check:
  - the beam stability
  - target deterioration
  - relative decay rate of the excited states to the ground and first excited states



- The relative proportion of 17.6 and 18.1 lines agrees with the CDCH e+e- analysis