Status of the X17 search with the MEG II apparatus

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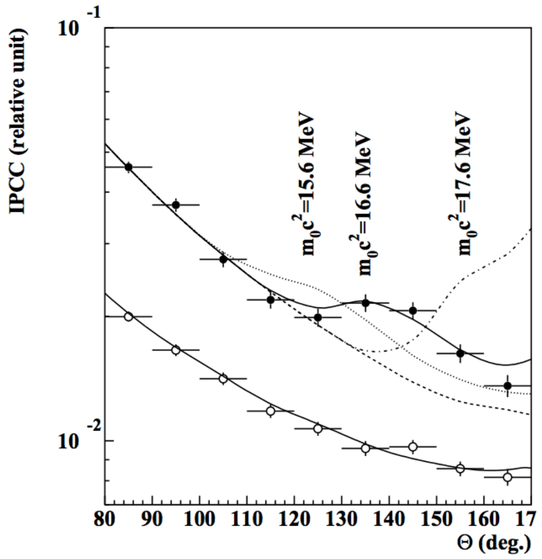
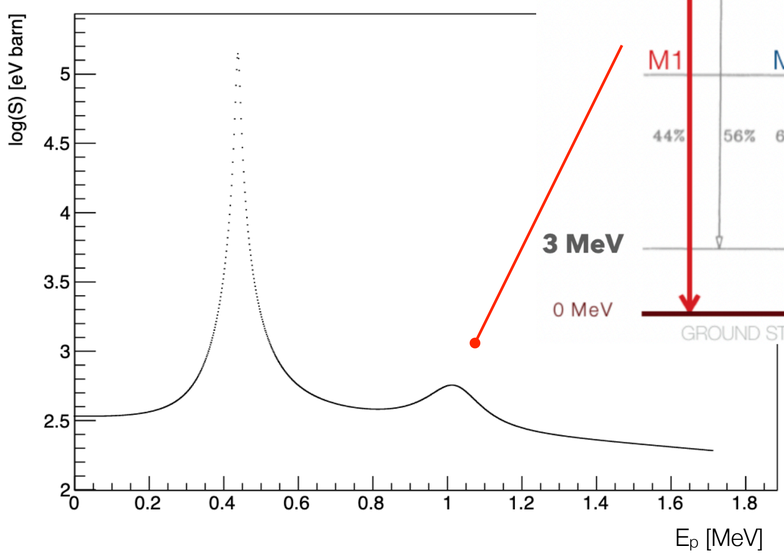
The MEGII experiment at PSI

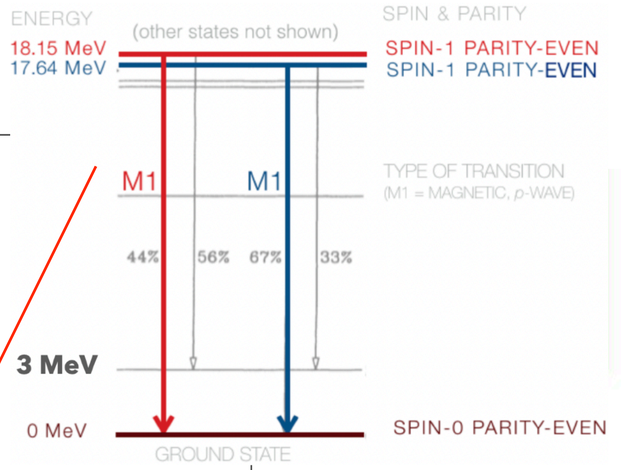
- MEGII main search: The $\mu^+ \rightarrow e^+ \gamma$ decay
- Best upper limit on the BR ($\mu^+ \rightarrow e^+ \gamma$) set by the MEG experiment (**$4.2\ 10^{-13}$** @90% C.L.) new results released with MEGII:
  - **see W. Ootani's talk at this conference**
- Searching for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~ **$6\ 10^{-14}$**
- Five observables **(E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg})** to identify $\mu^+ \rightarrow e^+ \gamma$ events

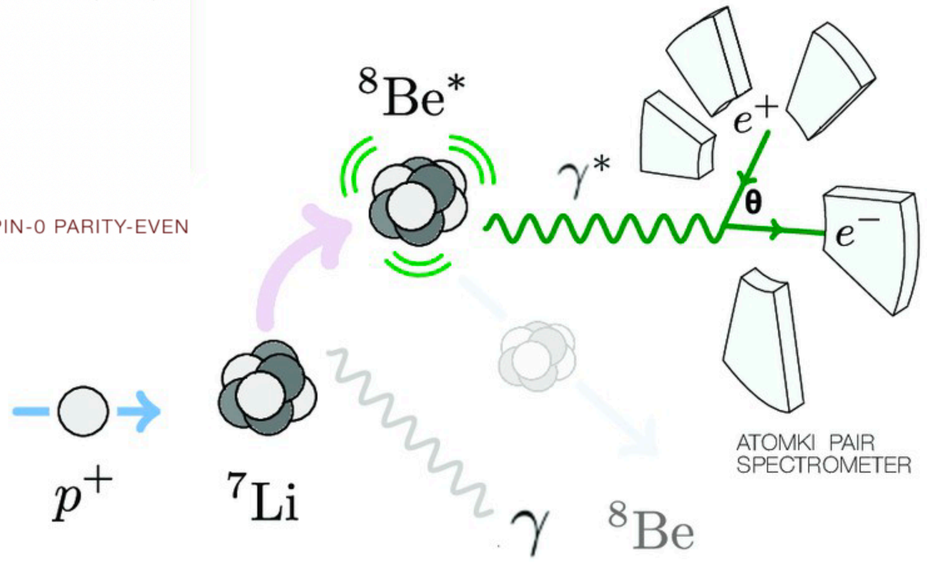
The beryllium anomaly

- Hint for the production of a neutral, 17 MeV boson, potential mediator ad a fifth force: X17 (ATOMKI collaboration)
  - Observed in the ^{7}Li(p, e+e-)^{8}Be reaction at 1100 keV
  - Observed in the ^{3}H(p,e+e-)^{4}He









Excess consistent with

- Light boson mass = 16.95 MeV/c2
- Branching ratio (X17/gamma) = 6 x 10^{-6}

Phys. Rev. Lett. 116, 042501
arXiv:2205.07744

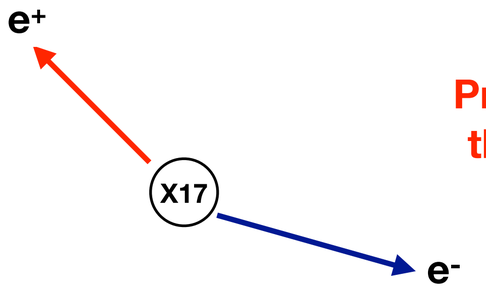
Phys. Rev. C 104, 044003

Phys. Rev. D 95, 035017

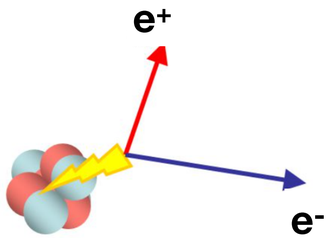
The X17 search with the MEG II apparatus

- Signal, background and experimental apparatus

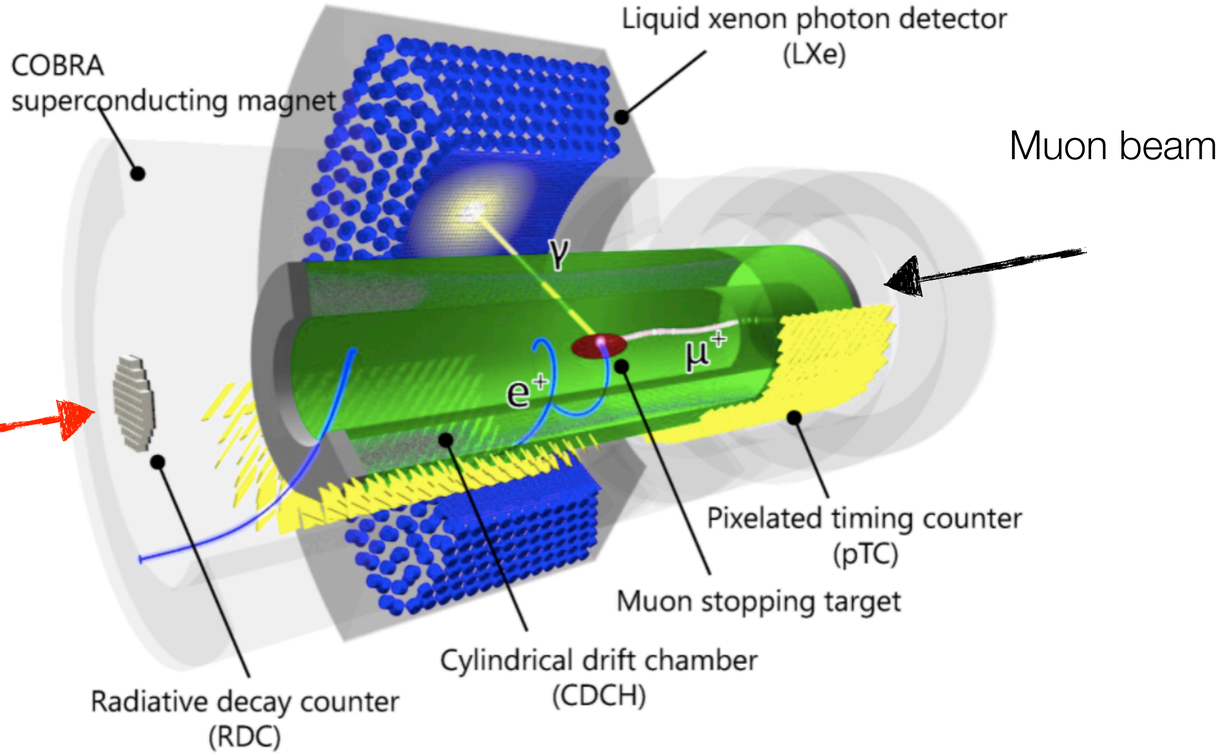
Signal



Backgrounds



Proton beam for the X17-Boson search



Gamma Internal and External Pair Conversion (IPC, EPC)

- IPC: Resonant and non-resonant
- EPC: Experimental setup material budget

with MEG II

→ **Better** invariant mass resolution

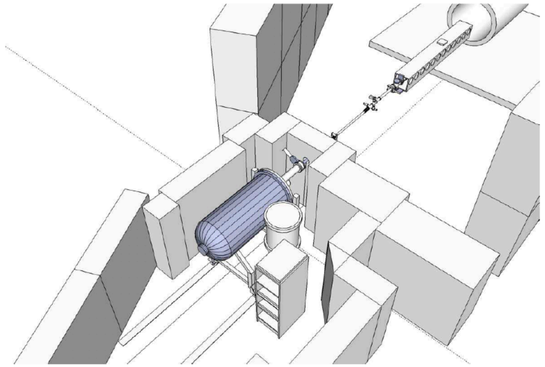
→ Detection in an **estended** angular range

The X17 search: The experimental setup

Key points:

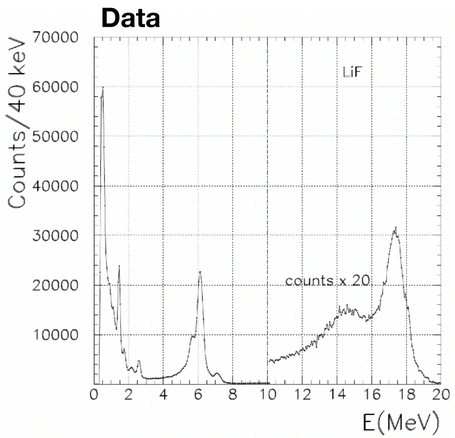
- Proton beam from the CW accelerator
- New Vacuum Chamber and tilted Li based target (LiPON, LiF)
- CDCH and pTC detectors
- Optimal magnetic field (O~0.21 T - gradient field, central value)
- XEC and auxiliary gamma detectors for
  - directly measuring the gamma backgrounds
  - stability monitoring
  - normalising the data sample
- Optimised TDAQ for
  - efficiently selecting the signal
  - rejecting the background
- Extended and optimised analysis code for
  - reconstructing both positive and negative charge particles

The MEG II CW accelerator and its beamline

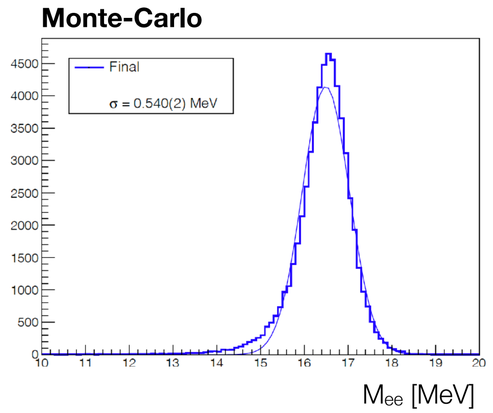


The new X17-Boson target region

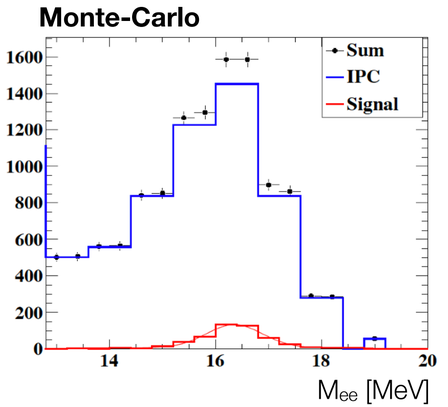
In blue the 17.6 MeV gamma line used for calibrating the XEC detector



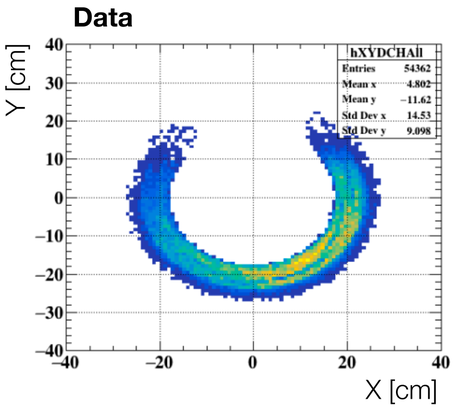
The expected reconstructed invariant mass of the e+/e- pair with the MEGII apparatus



The invariant mass distribution for the e+/e- pair produced either from the hypothetical X17 or the IPC (Internal Pair Conversion). The sum of the two is also given



An example of hit distribution (real data) in the CDCH during the pivotal data collection performed in February 2022

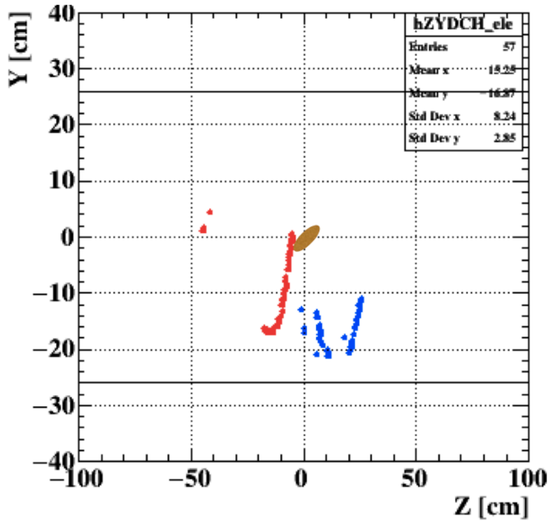


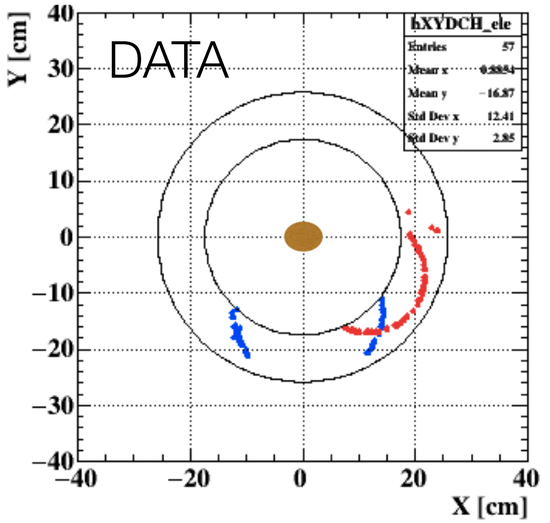
X17 analysis: a typical reconstructed e+ e- event [DATA]

- Examples of events from the **pivotal** DATA sample 2022
- Reconstruction algorithm for e^+e^- pairs
- Transversal view of the apparatus wrt to the beam direction

• Event A

p+ = 6.7 MeV
p- = 8.3 MeV
angle = 141°

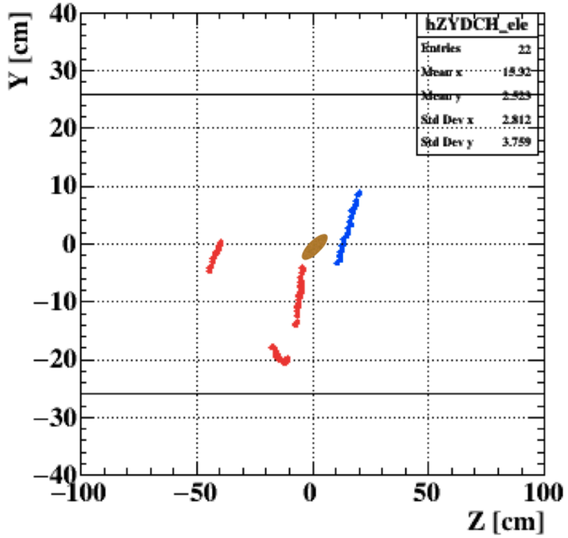


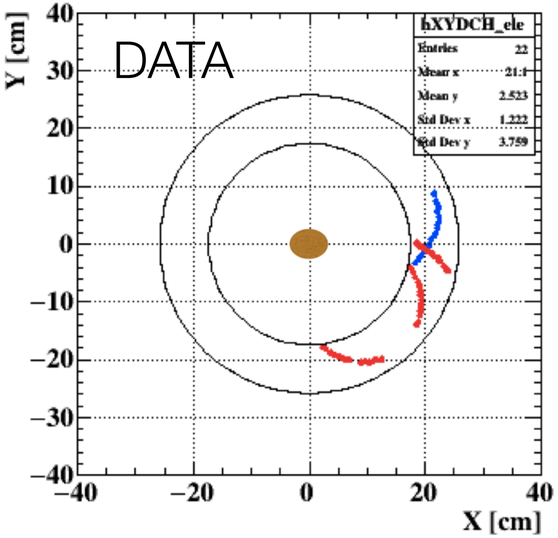


LiPON data 02/22

• Event B

p+ = 6.7 MeV
p- = 6.9 MeV
angle = 101°



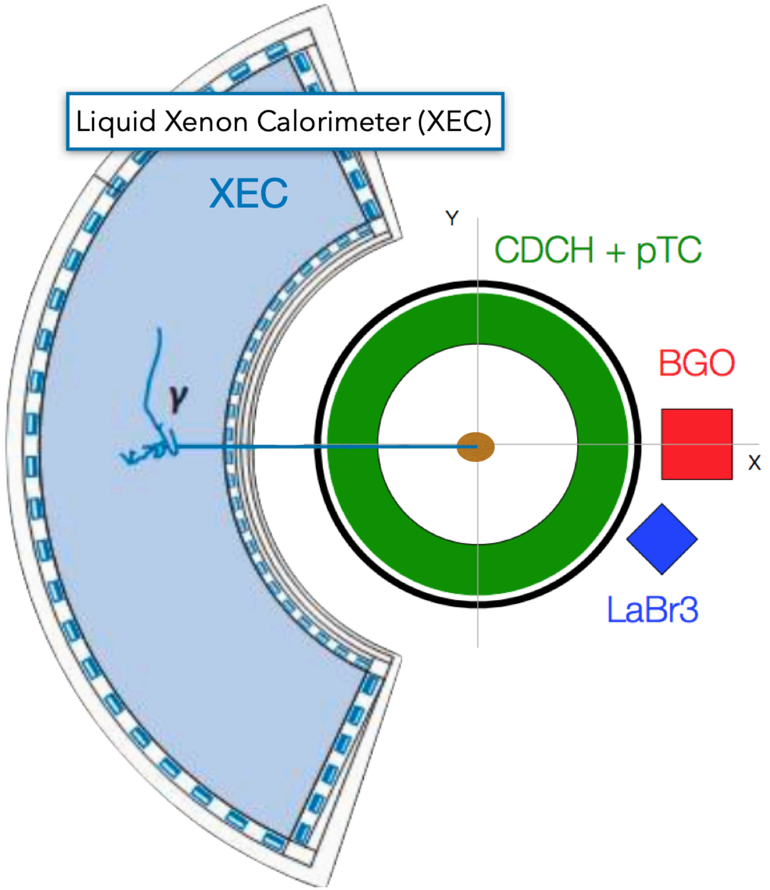


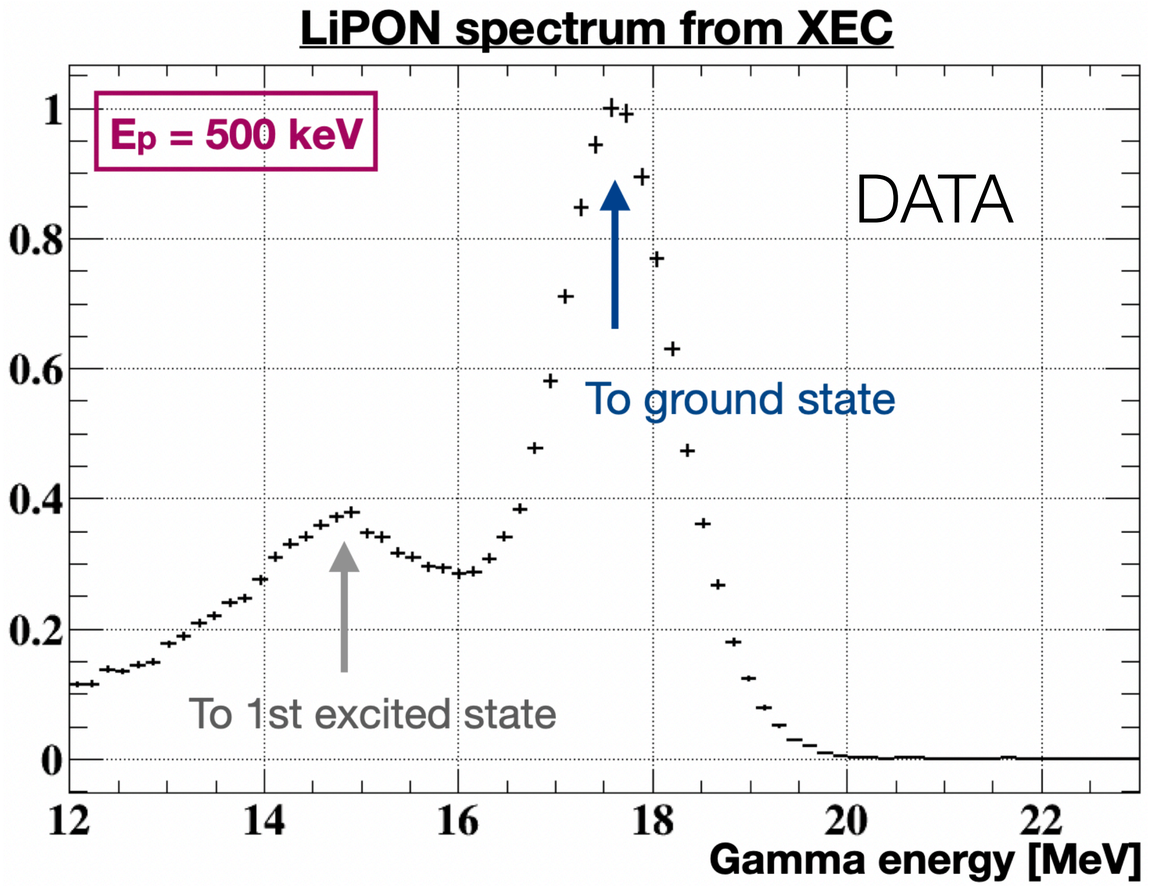
• e+ hit
• e- hit

target

X17 analysis: Gamma spectra [DATA]

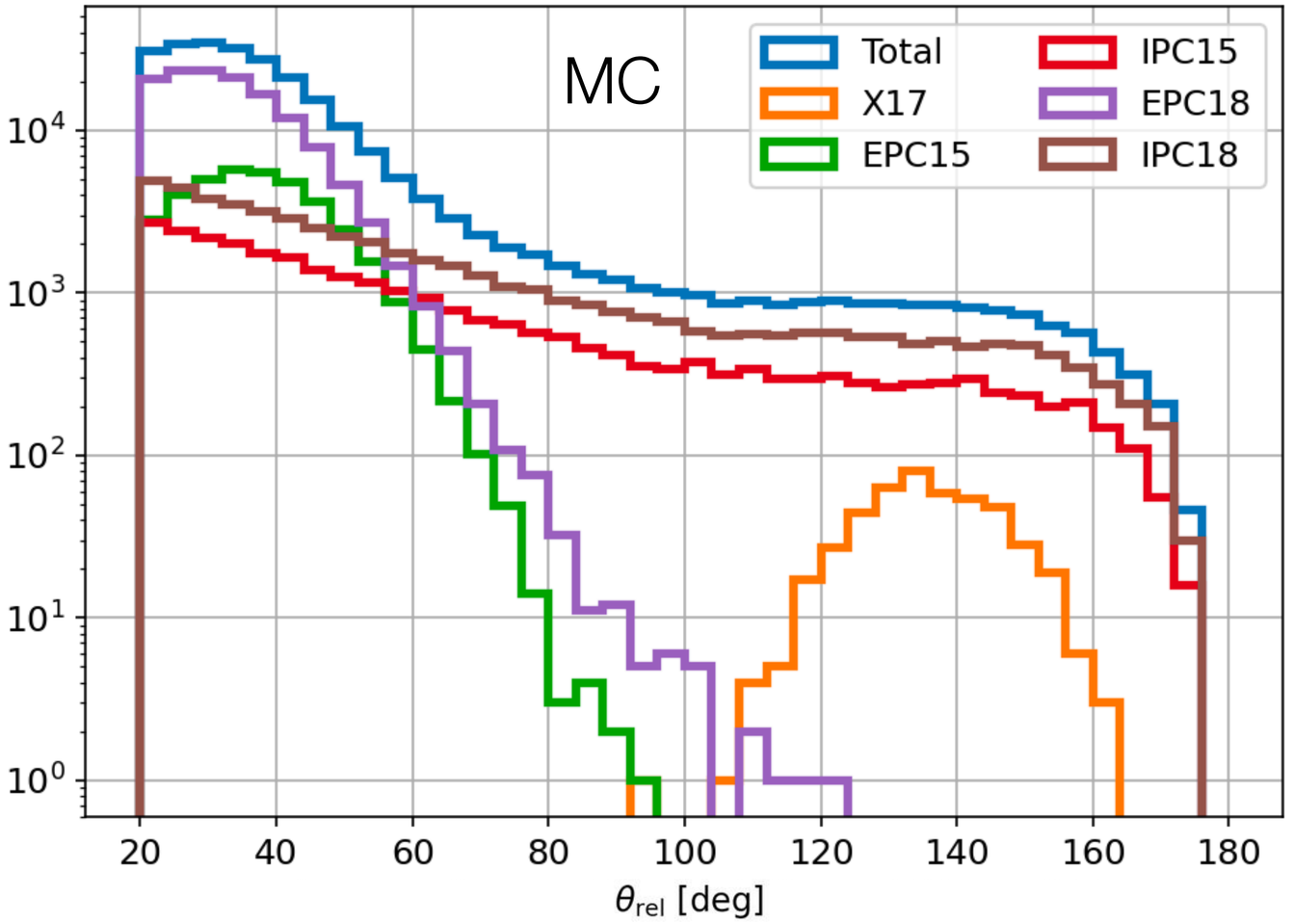
- Gamma spectra and rate crucial for the proof-of-quality of the measurement
- LXe calorimeter for background measurements
- Auxiliary gamma detectors for online monitoring (BGO and LaBr crystals)





Signal and Backgrounds [Monte Carlo]

- Example of Simulated Signal (ATOMKI BR) and Backgrounds in MEGII



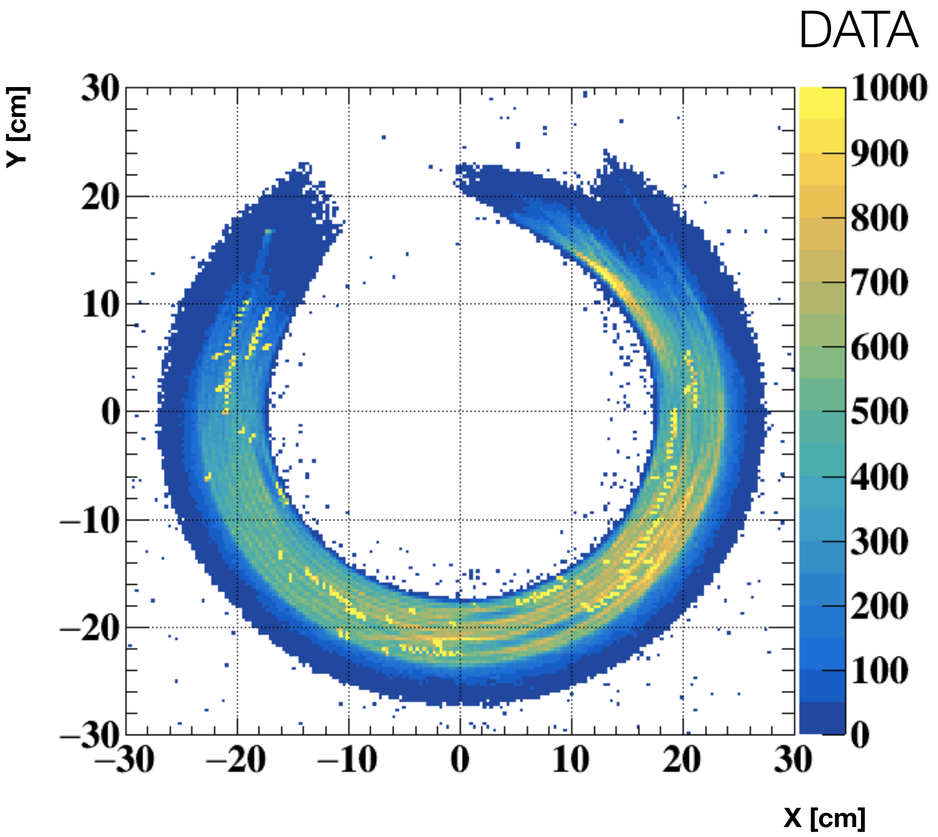
Collected data sample

- **Pivotal** run **2022**: Proton beam tuning, Mechanical/integration test of the new parts, LiF and LiPON target test, Different trigger settings, Optimised Data Taking and Reconstruction Algorithms

- **Physics** run **2023**: 4 weeks producing mainly the 17.6 MeV gamma-line
  - Proton energy at 1080 keV
  - Beam composition: H+ (~75%) and H2+(~25%)
  - Thick LiPON (~7 um)
  - Both 440 keV and 1030 keV excited simultaneously

- Statistics:
  - ~75 M Events
  - ~**300 K** Events Reconstructed pairs

- On full range of the Esum and Angular Opening angle observables:
  - ~60% EPC (14.6 + 17.6 MeV)
    - Dominant at low angle, negligible in the signal region
  - ~40% IPC (14.6 + 17.6 MeV)
    - Dominant in the signal region



Analysis strategy

- 2D Likelihood maximization: **E_{sum}** vs **Angular Opening** Observables
- Blinded **Signal Region**
- Background studies on the **Side Bands**

Likelihood definition

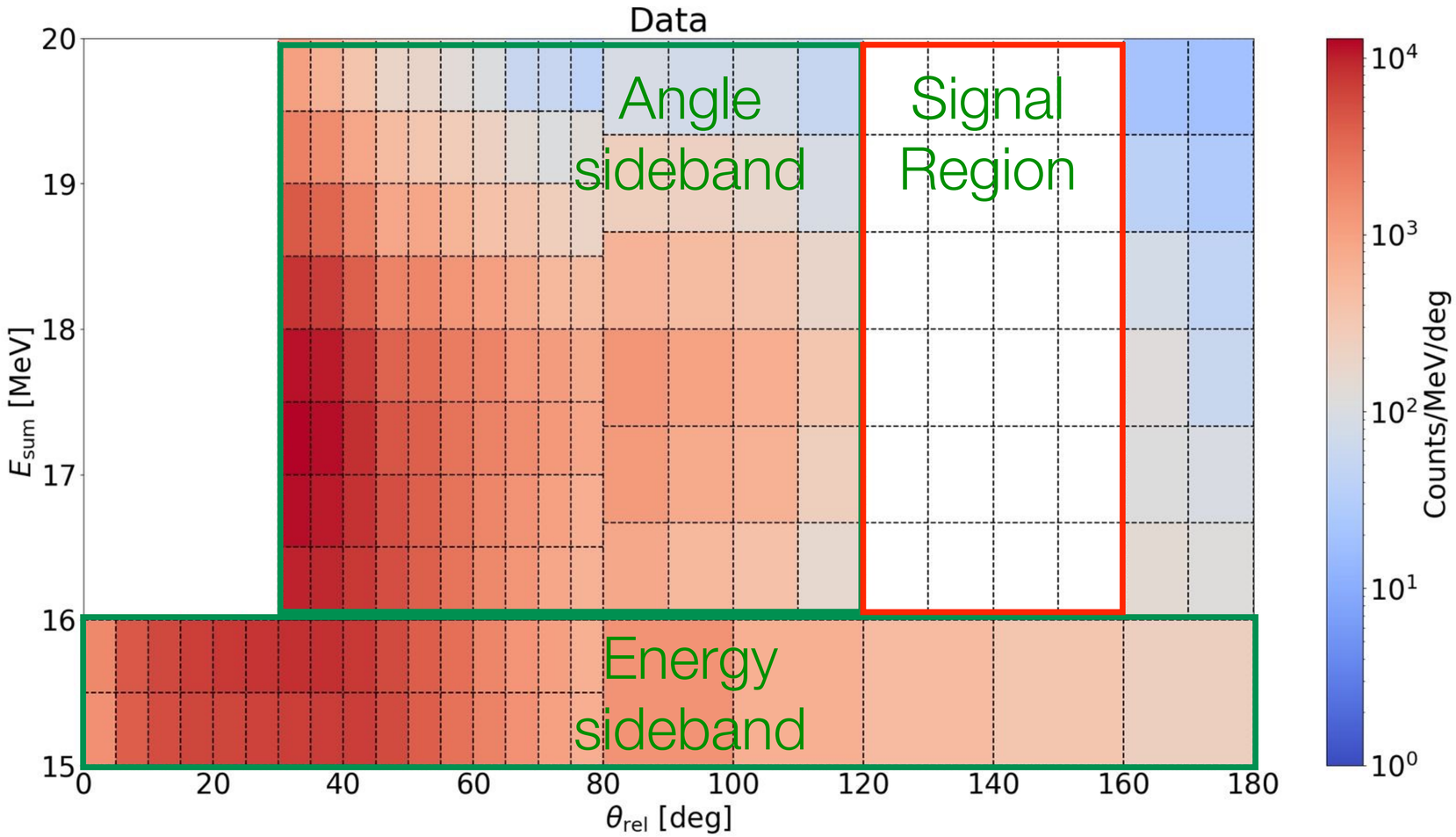
- The analysis is based on Feldman-Cousins to set C.L. on the X17 branching ratio and mass using Esum and the Angular opening as variables
- The Beeston-Barlow likelihood is defined as the following:

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\text{data}} \times \mathcal{L}_{\text{stats}} \times \mathcal{L}_{\text{shape}} \times \mathcal{L}_{\text{constraint}} = \\
&= \prod_i \left(\frac{f_i^{D_i} e^{-f_i}}{D_i!} \times \frac{(\beta_i \mu_{eff,i})^{\mu_{eff,i}} e^{-\beta_i \mu_{eff,i}}}{\mu_{eff,i}!} \right) \times \\
&\quad \times \prod_m \frac{1}{\sqrt{2\pi}\sigma_{\alpha_m}} e^{-\frac{(\alpha_m - \alpha_{m,0})^2}{2\sigma_{\alpha_m}^2}} \times \prod_l \frac{1}{\sqrt{2\pi}\sigma_{\alpha_l}} e^{-\frac{(\alpha_l - \alpha_{l,0})^2}{2\sigma_{\alpha_l}^2}}
\end{aligned}
$$

with “i” running on the bins, “m” on the shape systematics treated with morphing and “l” on additional parameters for which we have an input from theory (IPC15 percentage) or additional constraints

X17 analysis: Signal region and sidebands

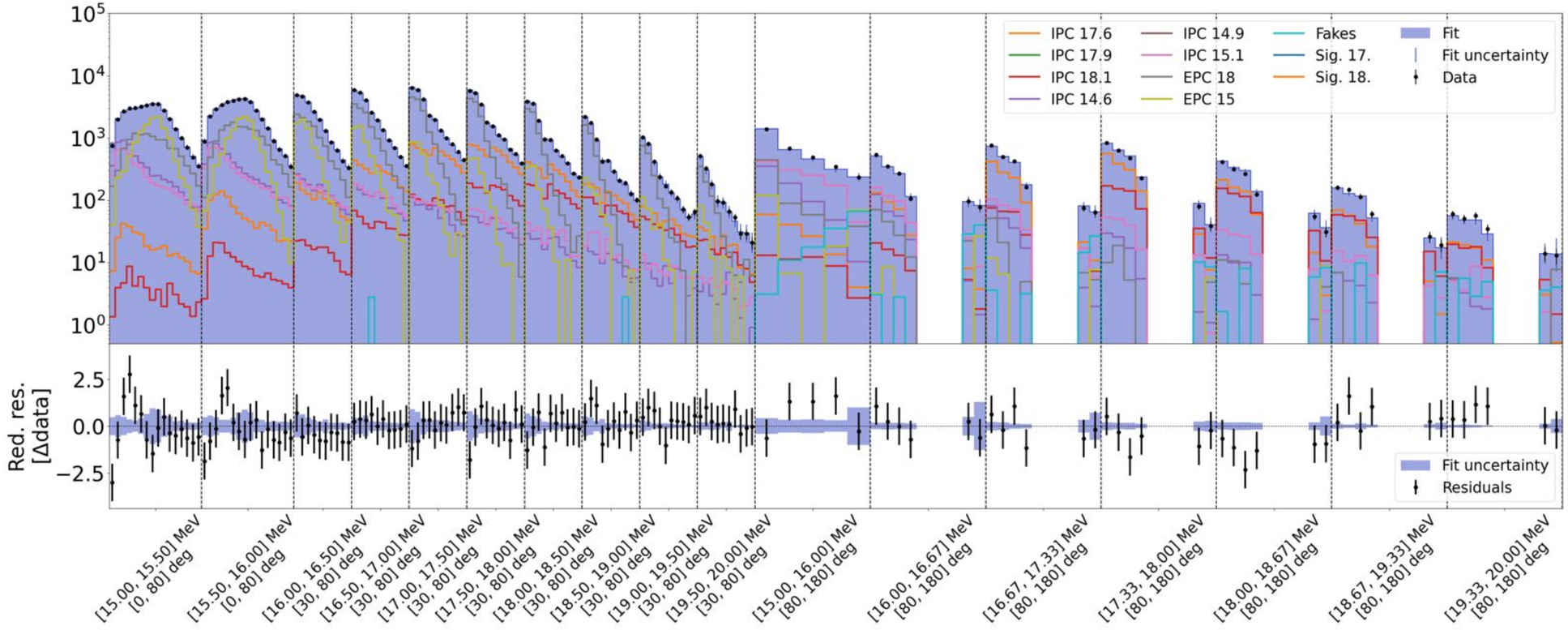
- Beeston-Barlow likelihood to account for limited MC statistic production
- Binning optimisation to account correctly for bins where some templates are empty



X17 analysis: A bit more on the sidebands

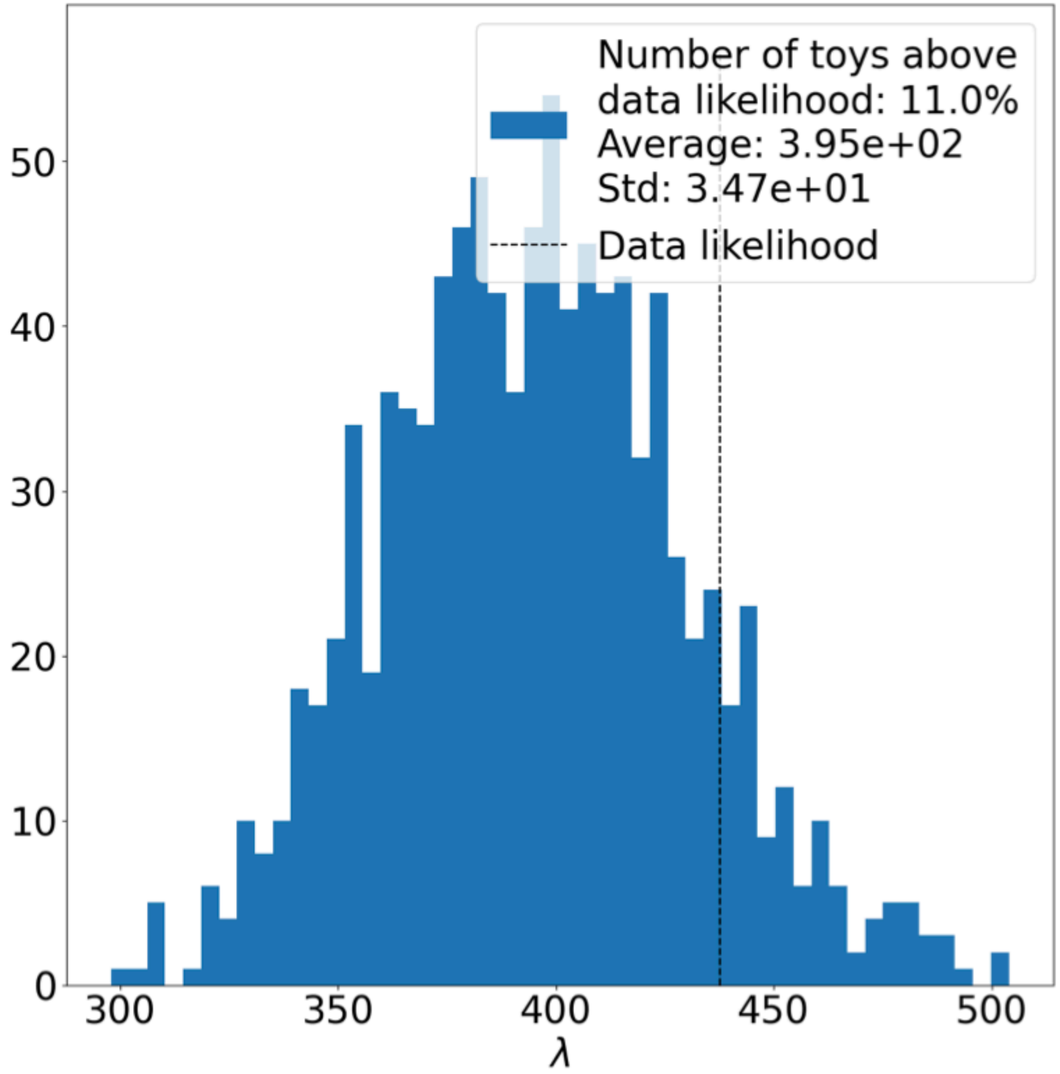
DATA

- Best US+DS fit with all MC statistics
  - Side bands reproduced
  - Sample of **17.6 MeV** [79.2%] **and 18.1 MeV** [20.8%]



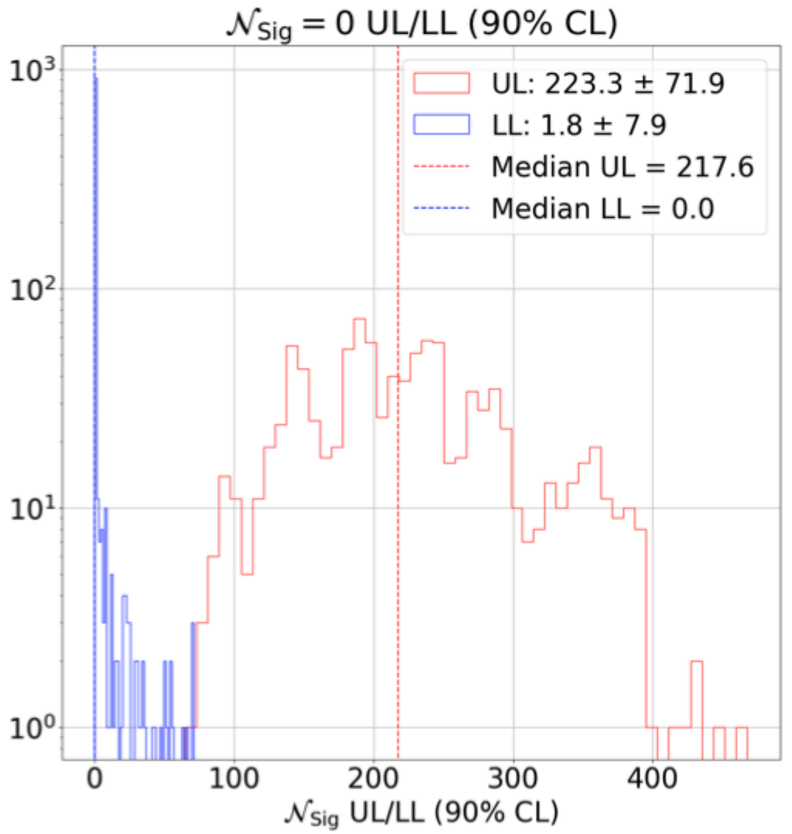
X17 analysis: Goodness of fit

- The p-value is obtained by computing the fraction of toy MCs with likelihood ratio bigger than that of data. For each toy:
  - The toy dataset is sampled around the best fit histogram assuming a Poisson distribution for each bin and including the Beeston-Barlow βs
  - The central value of the nuisance PDFs in the likelihood and the toy templates are sampled around the best fit value
  - Each toy data is then fitted

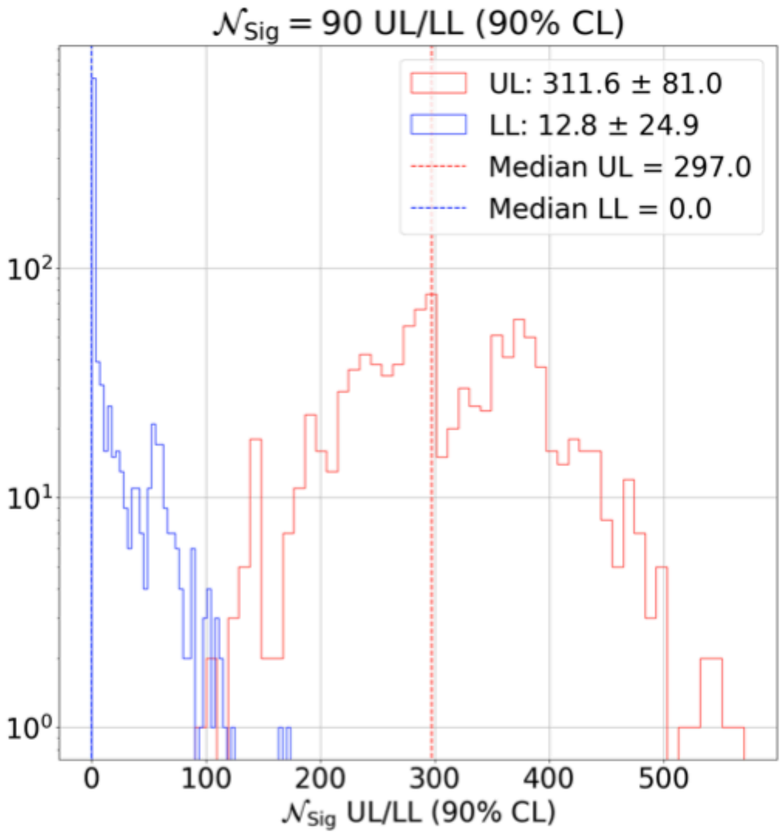


X17 analysis: FC tests

- Expected limits from sidebands under two different hypotheses



(a) Null hypothesis



(b) ATOMKI hypothesis

Current status and outlook

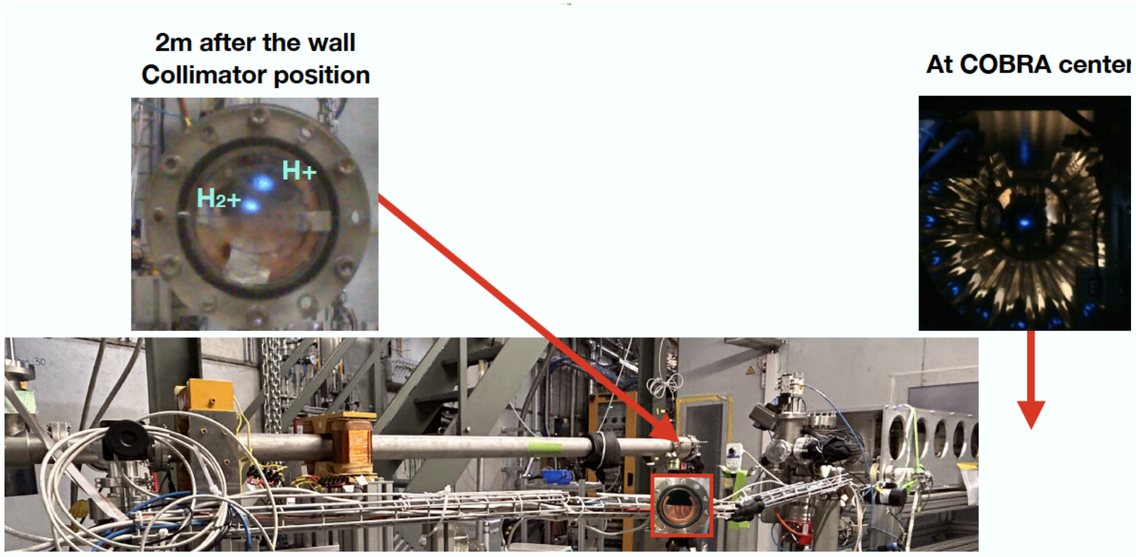
- Analysis Data 2023 well advanced
- Ready to report the results
- A X17 data collection fully exploiting the 1030 keV is foreseen during the first part of 2025 (Physics Run 2025)

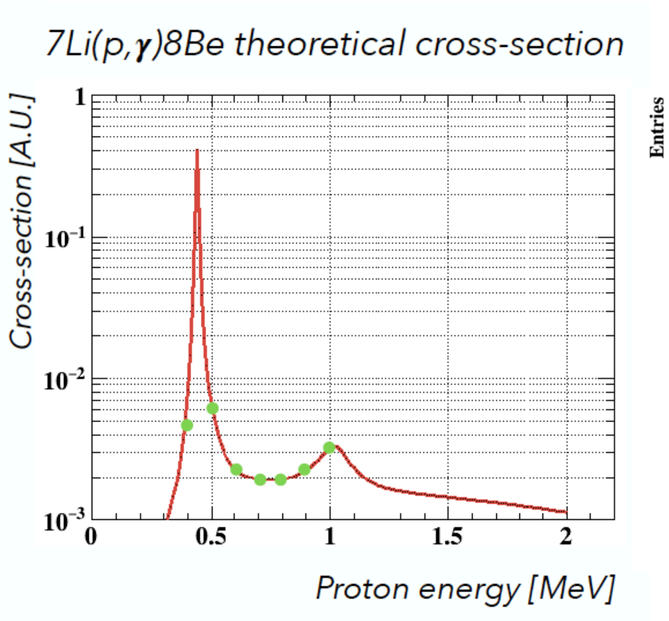
Thanks a lot for your attention and stay tuned!

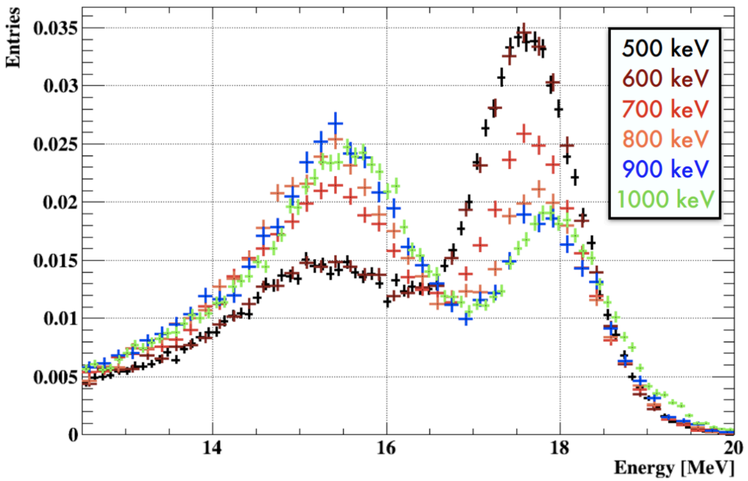
Back-up

In view of the run 2025

- Pure H+ beam: Delivered
- New thin and uniform targets: Produced. Measurement fully in line with expected H+ cross-section
- Observed pure 18.1 MeV gamma line
  - Clear shift of a few hundred keV
  - Increased proportion of « 15 MeV gamma line » wrt to « 18 MeV gamma line »







Articles:

- A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365
- A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434
- K. Afanaciev et al. (MEGII Collaboration), Eur. Phys. J C84 (2024),190
- K. Afanaciev et al. (MEGII Collaboration), Eur. Phys. J. C84 (2024), 216
- R.Barlow and C. Beeston, Com. Phys. Comm. 77.2 (1993), pp. 219–228. issn: 0010-4655. doi: https://doi.org/10.1016/0010-4655(93)90005-W. url: https://www.sciencedirect.com/science/article/pii/001046559390005W.