Measurement of the X17 anomaly with the MEG II detector

Giovanni Dal Maso for the MEG II collaboration

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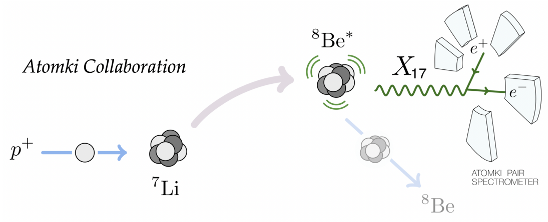
G.A. 858199

The beryllium anomaly



In 2016 the ATOMKI collaboration found an excess in the $^{7}\mathrm{Li}(\mathrm{p}, \mathrm{e}^{+}\mathrm{e}^{-})^{8}\mathrm{Be}$ reaction: an excess of event is found in the internal pair conversion (IPC).

Excess was attributed to a light boson:

- $m_{X17} = 16.98\,\mathrm{MeV}/c^2$
- BR$(X17/\gamma) = 6 \times 10^{-6}$

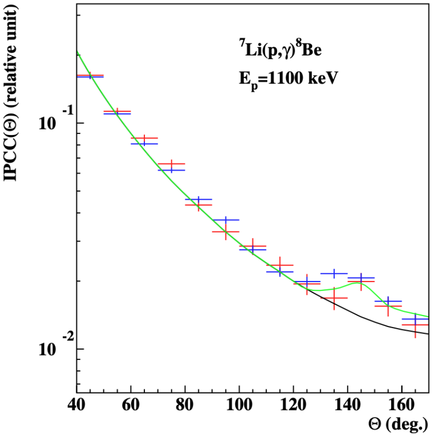


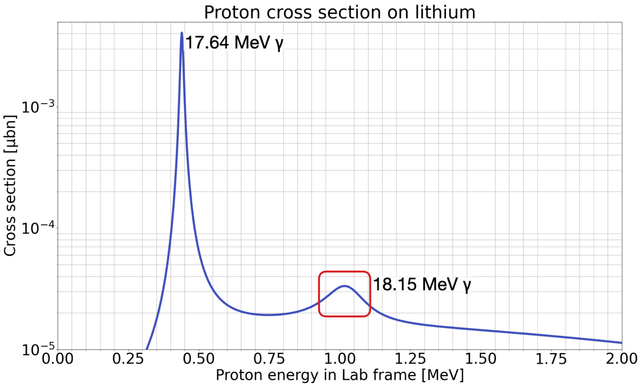
Figure: Relative angle distribution of the IPC pairs from [1].

The beryllium anomaly

The anomaly was observed in the 1.03 MeV resonance.

Additionally it was observed by ATOMKI in the $^{3}\mathrm{H}(\mathrm{p}, \mathrm{e}^{+}\mathrm{e}^{-})^{4}\mathrm{He}$ process [2] and in the $^{11}\mathrm{B}(\mathrm{p}, \mathrm{e}^{+}\mathrm{e}^{-})^{12}\mathrm{C}$ process [3].

All measurements were performed with the same detection scheme in the plane perpendicular to the proton beam.



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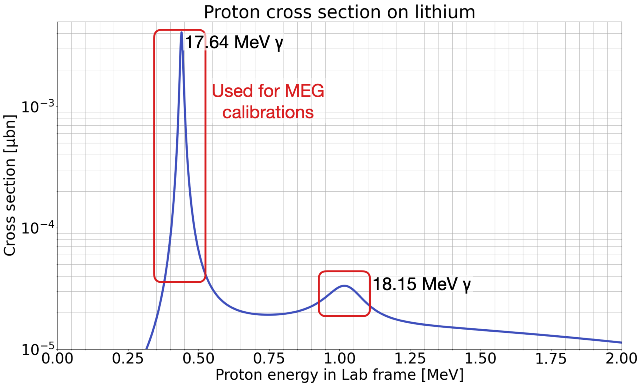

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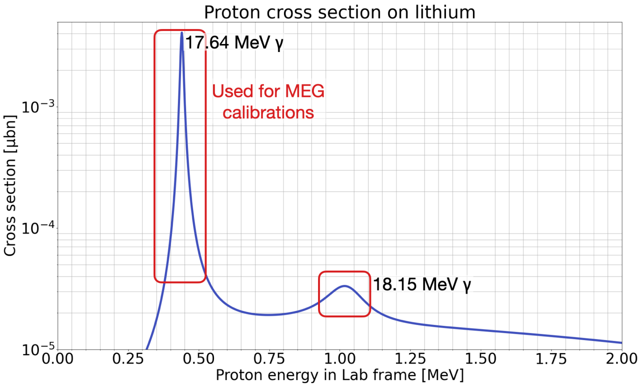
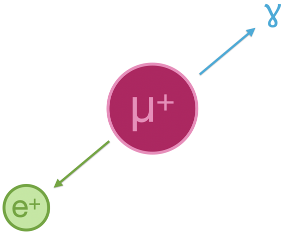
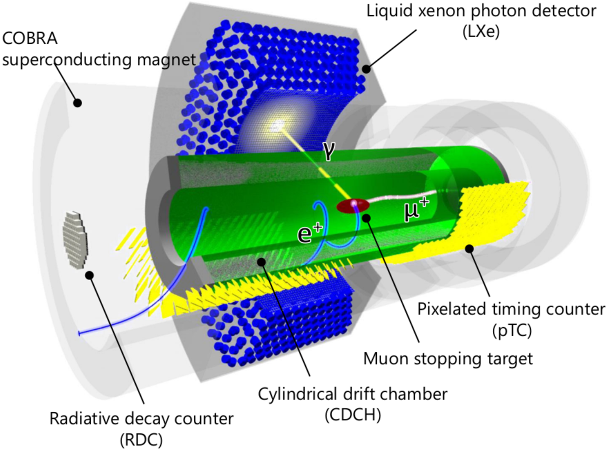
→ **Among other efforts, MEG II can provide an independent test in a wider angular acceptance.**



MEG II detector





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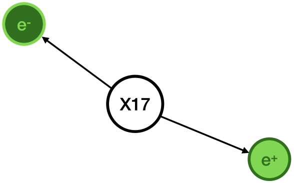
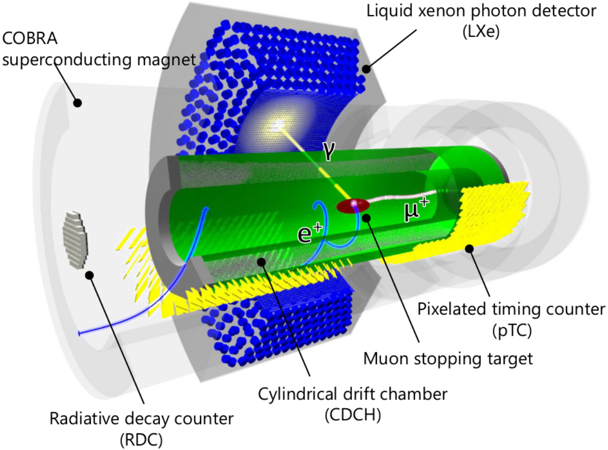


- angular aperture of the pair
- rest mass of the pair
- timing



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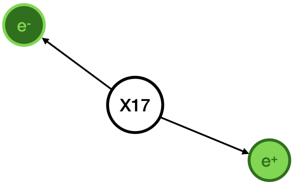

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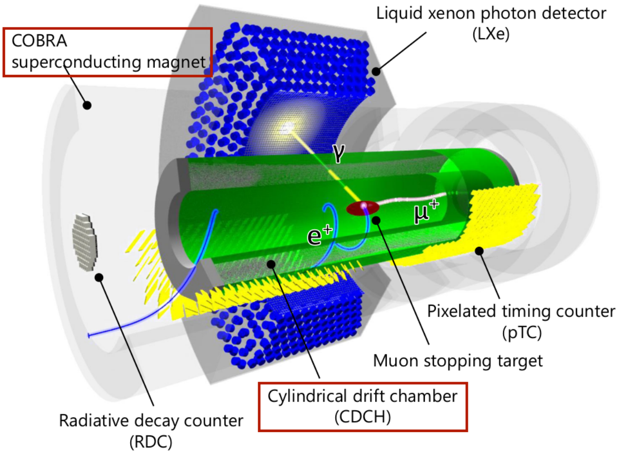

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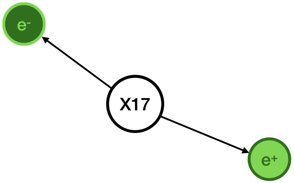

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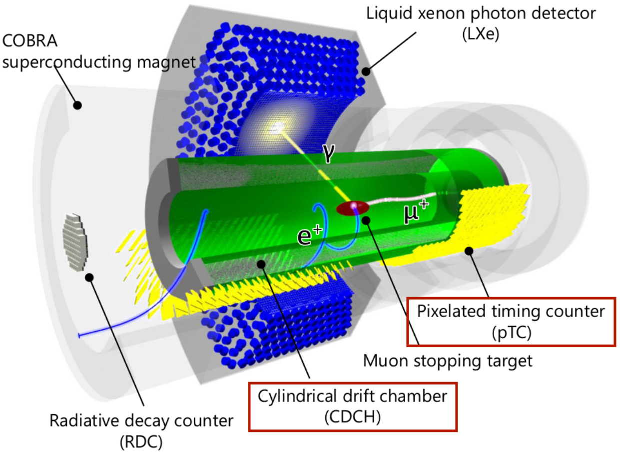

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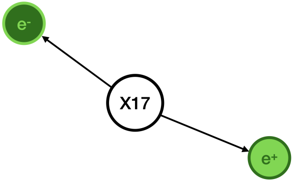
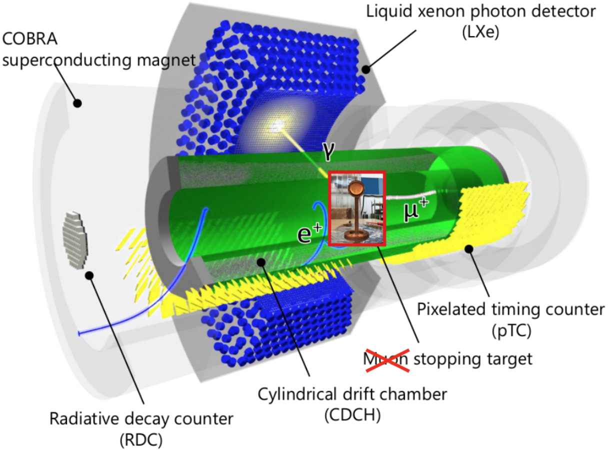


- angular aperture of the pair
- rest mass of the pair
- timing
- **lithium target**



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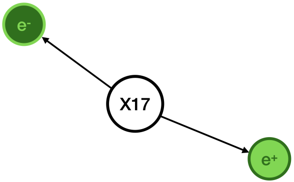
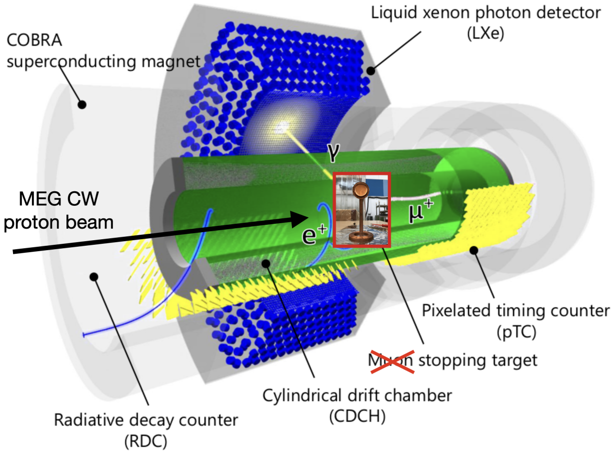


- angular aperture of the pair
- rest mass of the pair
- timing
- lithium target
- 1 MeV **proton beam**

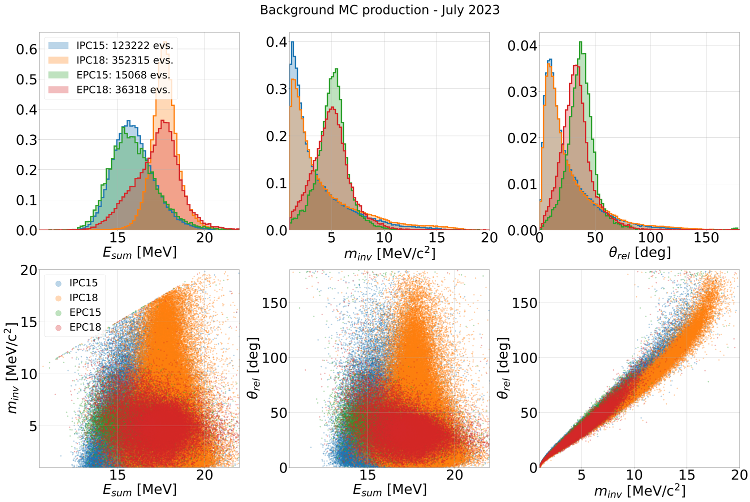


Backgrounds

The main backgrounds are:

- internal pair creation (IPC)
- external pair creation (EPC)

Both processes occur in the $15\,\text{MeV}$ and $18\,\text{MeV}$ lines.



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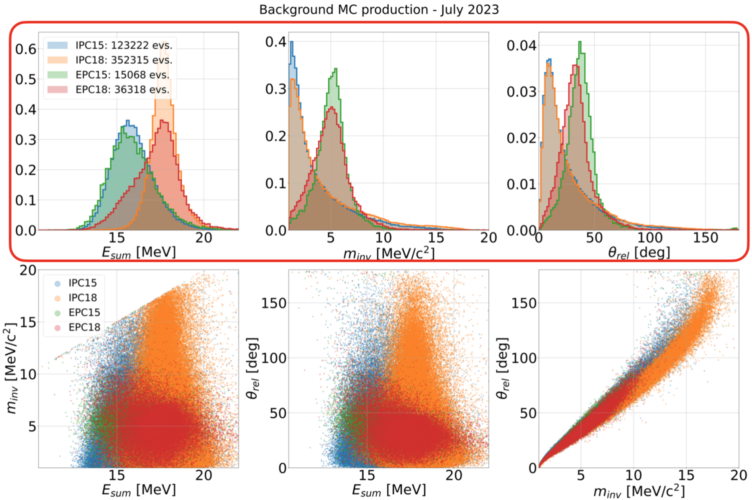

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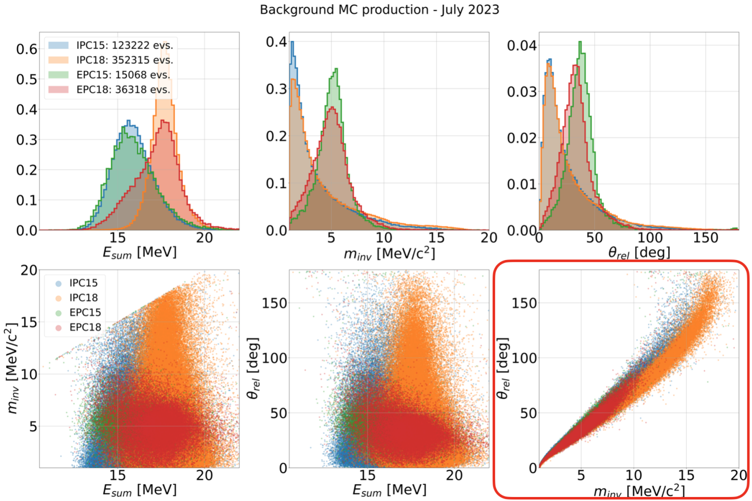

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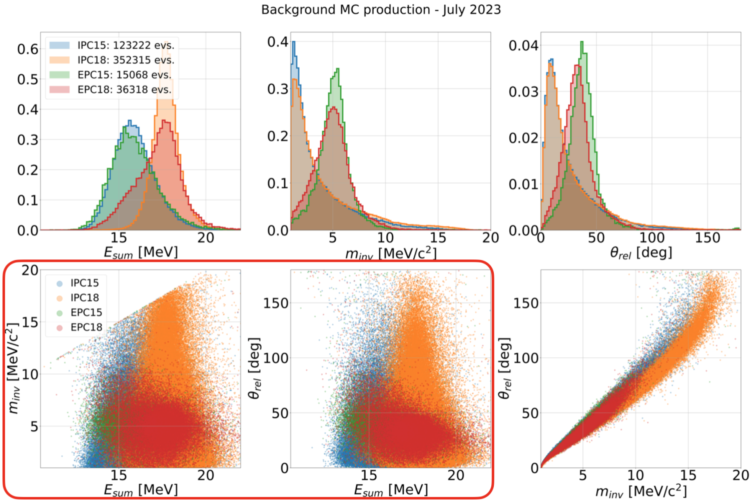
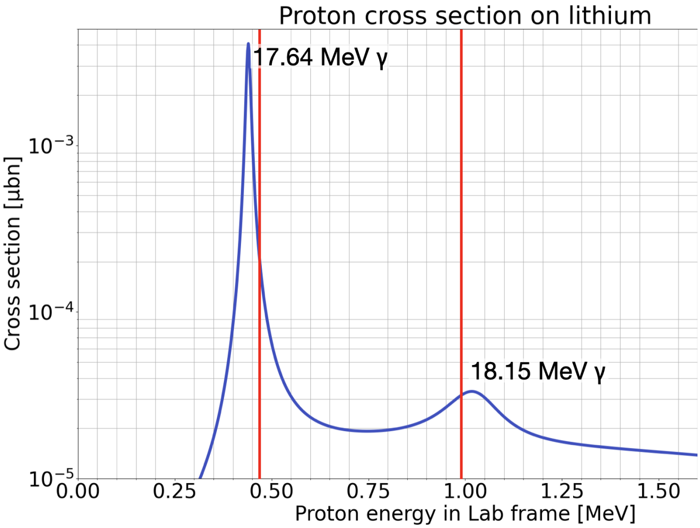


2023 physics run

During 2023 physics run:

- 4 weeks of data taking producing mostly the 17.6 MeV line
- proton beam energy at 1080 keV
- beam composition: $H^+ \sim 75\,\% - H_2^+ \sim 25\,\%$
- thick LiPON target ($\sim 7\,\mu$m)

→ The IPC backgrounds are split in three contributions from different proton interaction energies and two signal PDFs are included.



2023 data - blinding

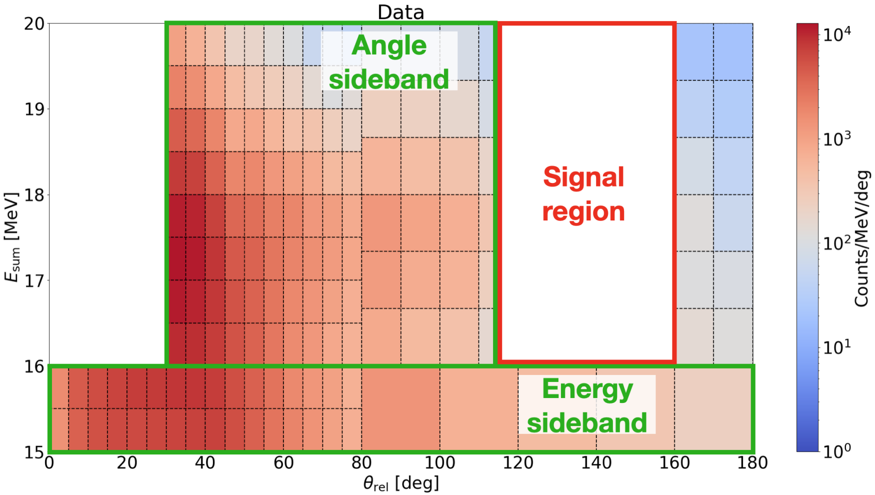
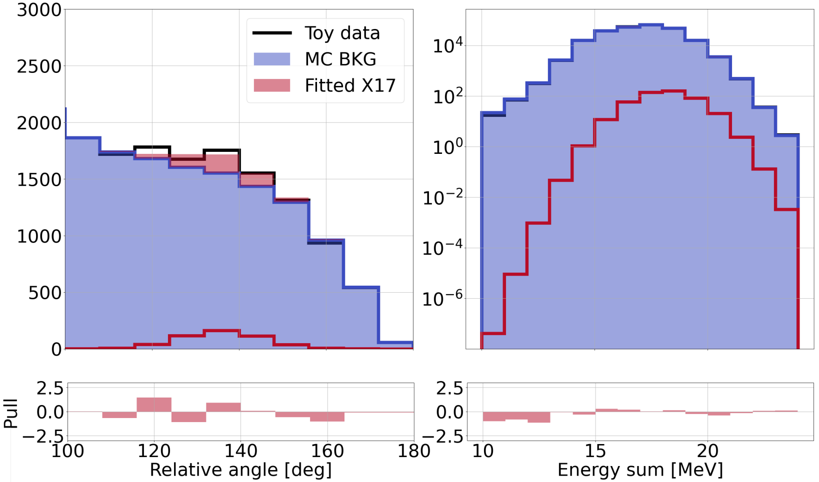


Figure: 2023 data

Likelihood analysis

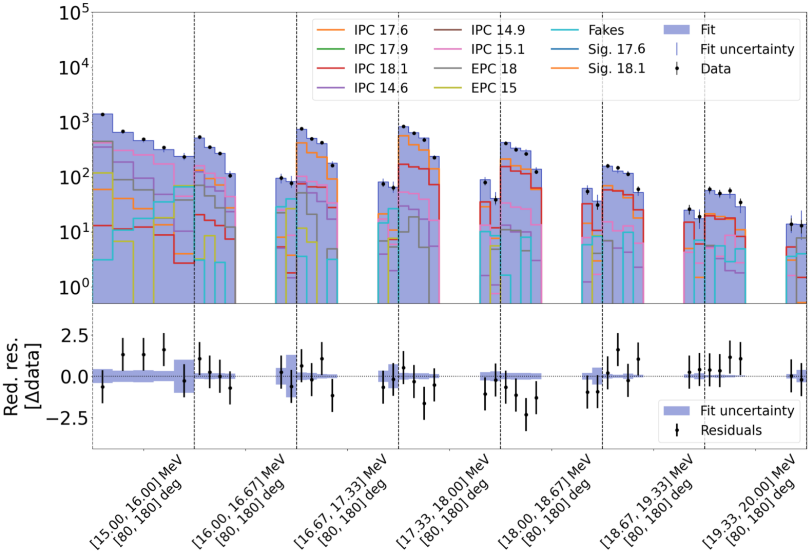
The background and the signal PDFs are modeled with histograms (templates) from the MC production.



Best fit - sidebands

From the sideband fit:

- $20\,\%$ IPC from higher energy resonance (consistent with independent measurements)
- fit p-value = $11\,\%$
- expected sensitivity (full frequentist approach): 220 events ($\sim$ ATOMKI$\times 2.3$) $\rightarrow$ **we can set a limit on both resonances**



Status

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- 2022 engineering run and 2023 physics run DONE
- Pair reconstruction and track selection DONE
- 2023 data reprocessing DONE
- Sidebands check DONE
- Mass MC production DONE
- Unblinding DONE (under collaboration review)
- An additional run aiming at exciting the 1030 keV only is planned with a higher quality target (already available) and improved beam quality (already obtained)

Thank you for your attention!

Resources

[1] A J Krasznahorkay et al. “New results on the 8Be anomaly”. In: *Journal of Physics: Conference Series* 1056.1 (July 2018), p. 012028. DOI: 10.1088/1742-6596/1056/1/012028.

[2] A. J. Krasznahorkay et al. “New anomaly observed in $^{4}\mathrm{He}$ supports the existence of the hypothetical X17 particle”. In: *Phys. Rev. C* 104 (4 Oct. 2021), p. 044003. DOI: 10.1103/PhysRevC.104.044003.

[3] A. J. Krasznahorkay et al. “New anomaly observed in $^{12}\mathrm{C}$ supports the existence and the vector character of the hypothetical X17 boson”. In: *Phys. Rev. C* 106 (6 Dec. 2022), p. L061601. DOI: 10.1103/PhysRevC.106.L061601.

[4] Daniele S. M. Alves et al. “Shedding light on X17: community report”. In: *The European Physical Journal C* 83.3 (Mar. 2023), p. 230. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-023-11271-x.

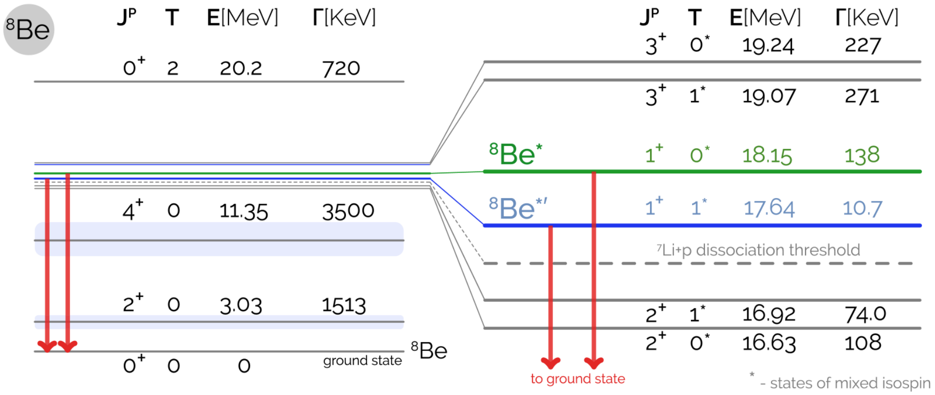
[5] M. Baak et al. “Interpolation between multi-dimensional histograms using a new non-linear moment morphing method”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 771 (2015), pp. 39–48. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2014.10.033.

[6] J.S. Conway. “Incorporating Nuisance Parameters in Likelihoods for Multisource Spectra”. In: (2011). Comments: Presented at PHYSTAT 2011, CERN, Geneva, Switzerland, January 2011, to be published in a CERN Yellow Report, pp. 115–120. DOI: 10.5170/CERN-2011-006.115. arXiv: 1103.0354.

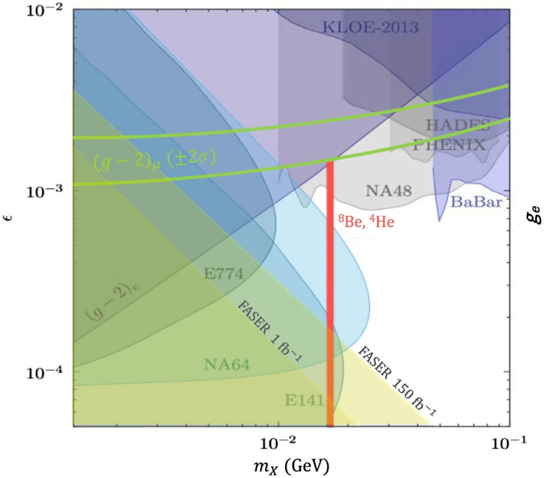
[7] Hans Dembinski and Ahmed Abdelmotteleb. “A new maximum-likelihood method for template fits”. In: *The European Physical Journal C* 82.11 (Nov. 2022), p. 1043. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-022-11019-z.

Back-up

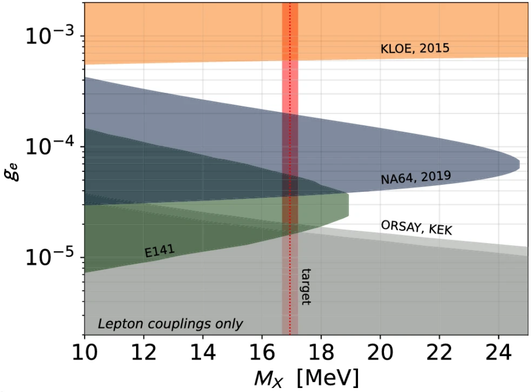
Beryllium lines



Gauge coupling limits



(a) all limits [4]



(b) lepton couplings only [4]

Shape systematics

Systematic uncertainties linked to low MC statistics can be accounted for by means of a Beeston-Barlow likelihood or by some lighter version (see later). How to account for shape systematics?

→ **Template Morphing** [5]. Just fancy name for histogram interpolation. There are different techniques to do so, but the principle is the same:

- define a systematic effect as a nuisance
- compute the MC templates as a function of different values of the nuisance (typically $\pm 1\sigma$ and nominal value)
- interpolate/extrapolate
- constrain the nuisance with an appropriate PDF, typically gaussian

Template morphing

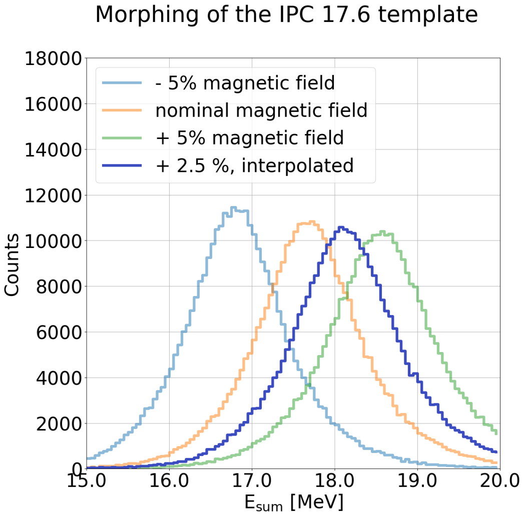
To include the treatment of systematics which cause distortions in the PDFs we can use template morphing. We can use the **vertical morphing**:

- for each population the templates are computed from MC for some value of the nuisance parameters (this is done only once)
- the estimated template is a linear combination of these histograms which depends on the value of the nuisance
- the interpolation is done on a bin wise base, so the bins are independently interpolated

Template morphing - 1 variable only

Here, the magnetic field scale is the nuisance parameter.

The reference templates are generated for scale variations of $0.5\,\%$ in the range $\pm 2.5\,\%$.



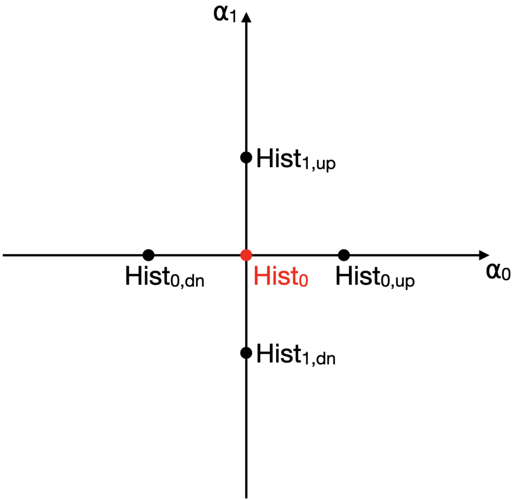
Morphing many parameters

If more nuisances are needed than just the scale of the magnetic field:

- we divide each reference template by the nominal
- we interpolate the ratios of the histograms
- for a given value of the nuisances we multiply the ratios all toghether with the nominal template

At the moment only one of such systematics is included, the magnetic field scale.

In addition to this, the signal templates are interpolated on the X17 mass (see later in the presentation).

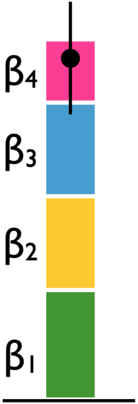


Beeston-Barlow lite

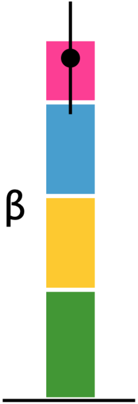
The Beeston-Barlow approach accounts for uncertainty statistics by fitting each bin of each population with a Poisson PDF.

Eventually we are interested in the effect of the total bin uncertainty. Can account it with a gaussian or **Poisson** term:

- analytic expression in both cases
- much faster
- empty template bins are ignored



(c) BB Complete



(d) BB Lite

Full likelihood

The full likelihood reads like:

$$\mathcal{L} = \mathcal{L}_{\text{data}} \times \mathcal{L}_{\text{stats}} \times \mathcal{L}_{\text{shape}} \times \mathcal{L}_{\text{constraint}} = \quad (1)$$

$$= \prod_i \Big(\frac{f_i^{D_i} e^{-f_i}}{D_i!} \times \frac{(\beta_i \mu_{eff,i})^{\mu_{eff,i}} e^{-\beta_i \mu_{eff,i}}}{\mu_{eff,i}!} \Big) \times \quad (2)$$

$$\times \prod_m \frac{1}{\sqrt{2\pi}\sigma_{\alpha_m}} e^{-\frac{(\alpha_m - \alpha_{m,0})^2}{2\sigma_{\alpha_m}^2}} \times \prod_l \frac{1}{\sqrt{2\pi}\sigma_{\alpha_l}} e^{-\frac{(\alpha_l - \alpha_{l,0})^2}{2\sigma_{\alpha_l}^2}} \quad (3)$$

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.

Likelihood parametrization

The fitted parameters are:

- The total yields of the three proton energy slices are fitted in the likelihood:
  - $\mathcal{N}_{\mathrm{IPC400}}$, number of IPC events from the 400 keV slice;
  - $\mathcal{N}_{\mathrm{IPC700}}$, number of IPC events from the 700 keV slice;
  - $\mathcal{N}_{\mathrm{IPC1000}}$, number of IPC events from the 1000 keV slice.
- The fraction of IPC 18 for each proton energy slice is fitted, with the addition of a Gaussian constraint for each of them based on the available data in the literature:
  - $p_{\mathrm{IPC17.6}} = \mathcal{N}_{\mathrm{IPC17.6}}/(\mathcal{N}_{\mathrm{IPC14.6}} + \mathcal{N}_{\mathrm{IPC17.6}})$, from BGO expected to be $66.3(17)\,\%$;
  - $p_{\mathrm{IPC17.9}} = \mathcal{N}_{\mathrm{IPC17.9}}/(\mathcal{N}_{\mathrm{IPC14.9}} + \mathcal{N}_{\mathrm{IPC17.9}})$, from literature expected to be $48.2(19)\,\%$;
  - $p_{\mathrm{IPC18.1}} = \mathcal{N}_{\mathrm{IPC18.1}}/(\mathcal{N}_{\mathrm{IPC15.1}} + \mathcal{N}_{\mathrm{IPC18.1}})$, from literature expected to be $42(2)\,\%$.
- The ratio of the acceptance of IPC 15 and IPC 18 in the MC, $\mathcal{F}_{\mathrm{IPC15}}$.
- The yields of EPC 15 and EPC 18 are fitted and unconstrained.
- The yield of the fakes is fitted and unconstrained.
- The energy scale α_{field}, included as a shape nuisance.

Beeston-Barlow lite

In this approach, a multiplicative factor is introduced to model the statistical fluctuations due to systematics.

$$f_i \to \beta_i f_i \tag{4}$$

Two possible approaches are:

- Conway's [6]: the factor is Gauss distributed. The bin likelihood is:

$$\log \mathcal{L}_i = D_i \log \beta_i f_i - \beta_i f_i - \frac{(\beta_i - 1)^2}{2\sigma_{\beta_i}^2} \tag{5}$$

$$\sigma_{\beta_i} = \frac{\sigma_{f_i}}{f_i} \tag{6}$$

- Dembinski-Abdelmotteleb's [7]: the factor is Poisson distributed. The bin likelihood is:

$$\log \mathcal{L}_i = D_i \log \beta_i f_i - \beta_i f_i + f_{i,eff} \log \beta_i f_{i,eff} - \beta_i f_{i,eff} \tag{7}$$

$$f_{i,eff} = \left(\frac{f_i}{\sigma_{f_i}}\right)^2 \to \beta_i = \frac{D_i + f_{i,eff}}{f_i + f_{i,eff}} \tag{8}$$

with $f_{i,eff}$ the number of Poisson distributed events which have a relative uncertainty equal to f_i.

Beeston-Barlow lite

In this approach, a multiplicative factor is introduced to model the statistical fluctuations due to systematics:

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$$\sigma_{\beta_i} = \frac{\sigma_{f_i}}{f_i} \tag{11}$$

- **Dembinski-Abdelmotteleb's [7]: the factor is Poisson distributed**. The bin likelihood is:

$$\log \mathcal{L}_i = D_i \log \beta_i f_i - \beta_i f_i + f_{i,eff} \log \beta_i f_{i,eff} - \beta_i f_{i,eff} \tag{12}$$

$$f_{i,eff} = \left(\frac{f_i}{\sigma_{f_i}}\right)^2 \rightarrow \beta_i = \frac{D_i + f_{i,eff}}{f_i + f_{i,eff}} \tag{13}$$

  with $f_{i,eff}$ the number of Poisson distributed events which have a relative uncertainty equal to f_i. This approach tends to Conway's at high statistics, but it's more robust in the low statistics regime.