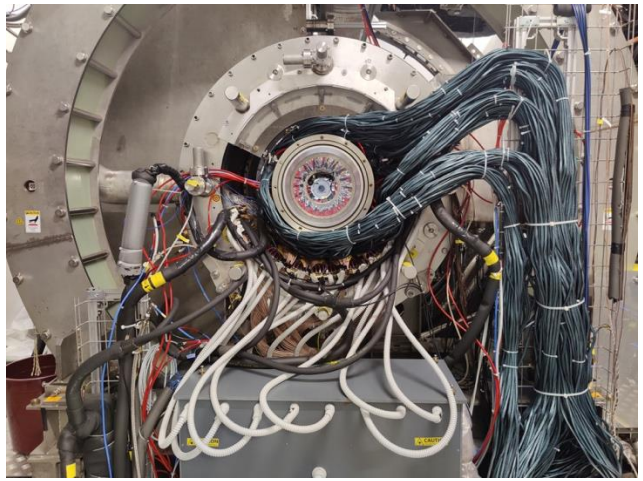
The X17 Search at the MEG II Experiment



Cecilia Voena

Sapienza University, Physics Department

& INFN Roma

on behalf of the MEG II collaboration

EPS-HEP 2025, 7-11 July
Marseille France

The MEG II Experiment

- Search for the charged lepton flavor violating decay $\mu \to e\gamma$ **(New Physics!)**

- Most recent result:

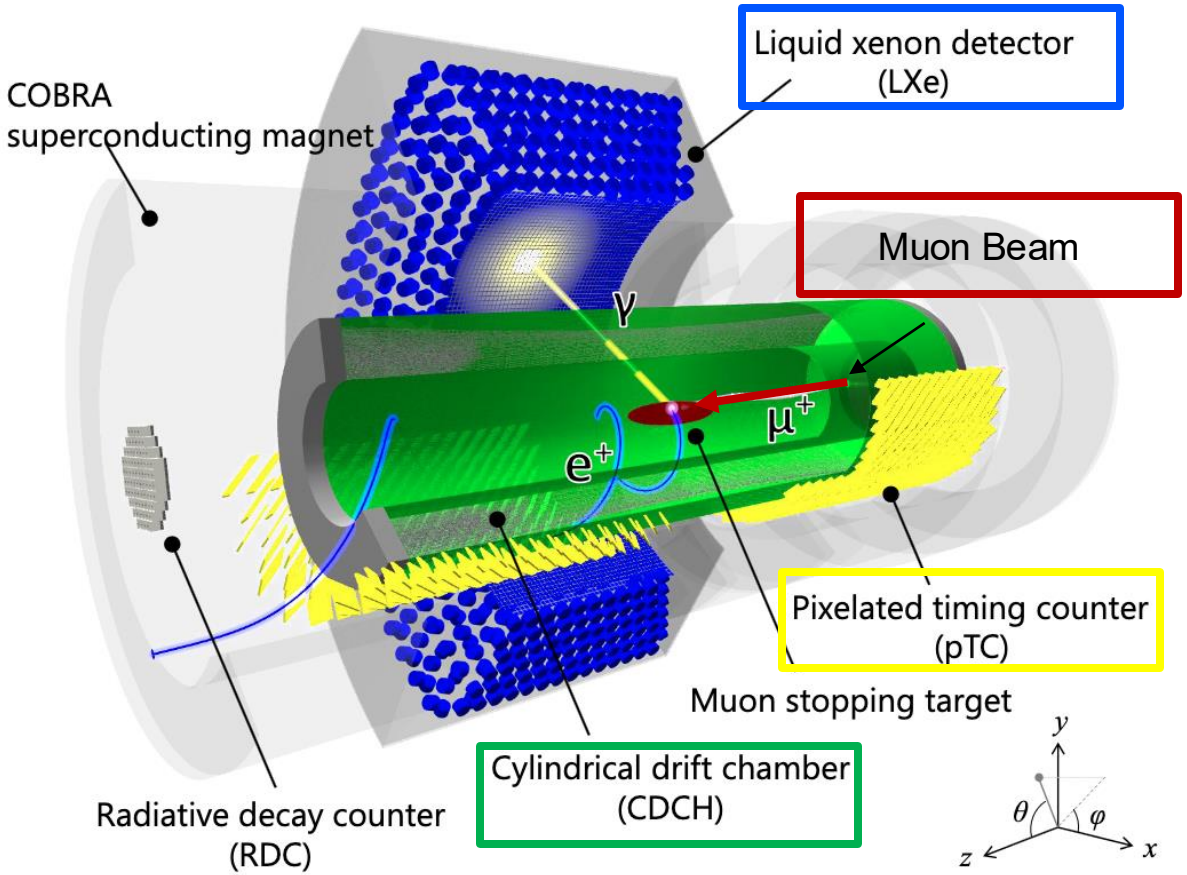
  BR($\mu \to e\gamma$) < 1.5 x 10^{-13} @90% C.L.

  arXiv 2504.15711 (accepted by EPJC)

  → talk from A. Oya yesterday (T07)

- Although designed for $\mu \to e\gamma$, MEG II can also perform other searches, like X17 (but non only)

now taking data
@Paul Scherrer Institute (Switzerland)

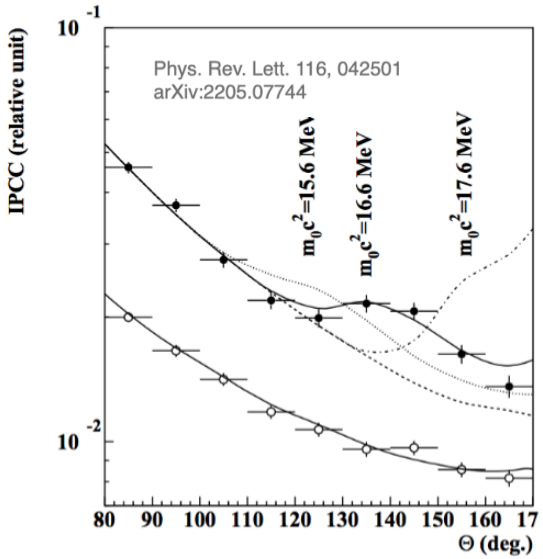


The X17 History

- In 2016 at ATOMKI (Debrecen)
- While studying **IPC** (Internal Pair Conversion) in the nuclear reaction:

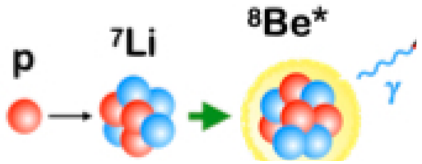
  ^{7}Li (p, e^+e^-)^{8}Be
  at the Be*(18.1 MeV) resonance @ E_p ~ 1 MeV

- Anomaly observed in the e^+e^- opening angle distribution
  → **Berillium anomaly**

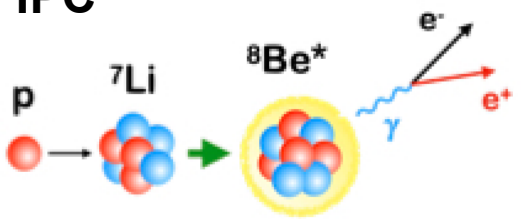


- Invariant mass **m ~ 17 MeV**
- Rate (vs γ) ~ 6 x 10^{-6}
- Confirmed in subsequent measurements with other nuclei

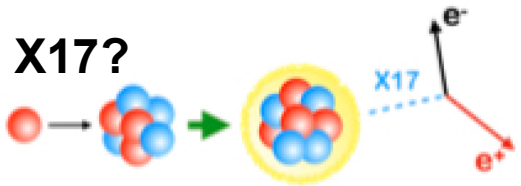
Radiative



IPC



X17?

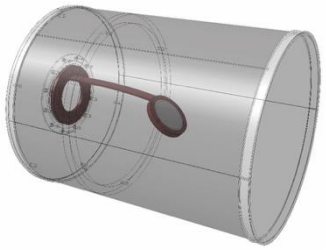


A new particle?
X17?

The X17 Search @ MEG II

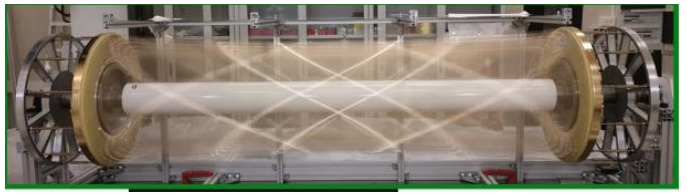
- **Proton source**: **CW accelerator** that we use for Liquid Xenon Calorimeter calibration with ^{7}Li (p,γ)^{8}Be
  - We use normally E_p~441 keV
  - Can arrive up to E_p~1.1 MeV

- **Dedicated target**: LiPON(*) target
  - 7μm average thickness



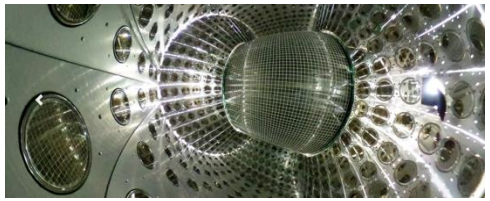
(*) Lithium phosphorus oxynitride (Li3-XPO4-YNX+Y)

- e^+e^- spectrometer: **drift chamber** in the (reduced) COBRA magnetic field

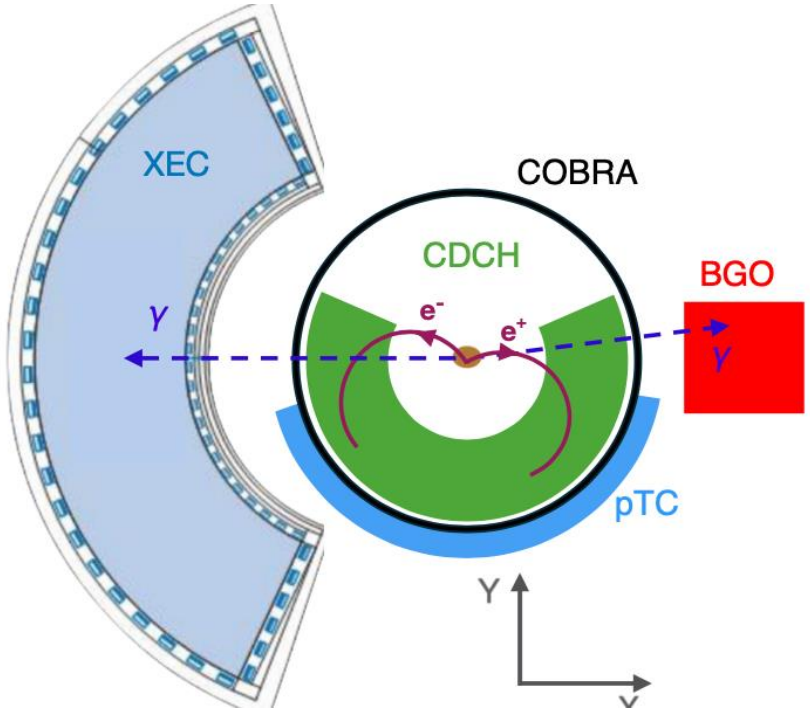


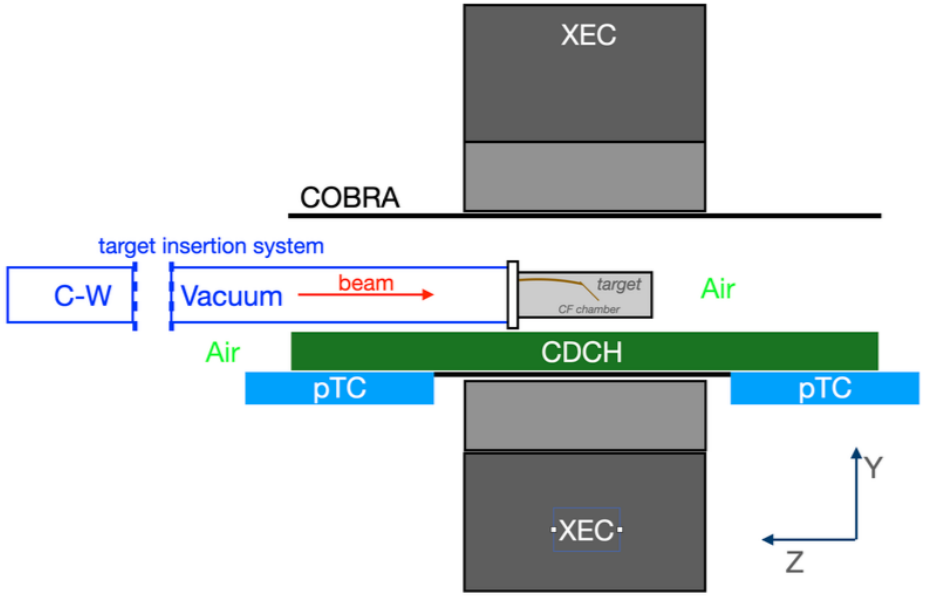
- **Timing detector** used for trigger and analysis

- **Liquid Xenon calorimeter + BGO detector**: auxiliary detectors for photon spectrum studies



Experimental Setup

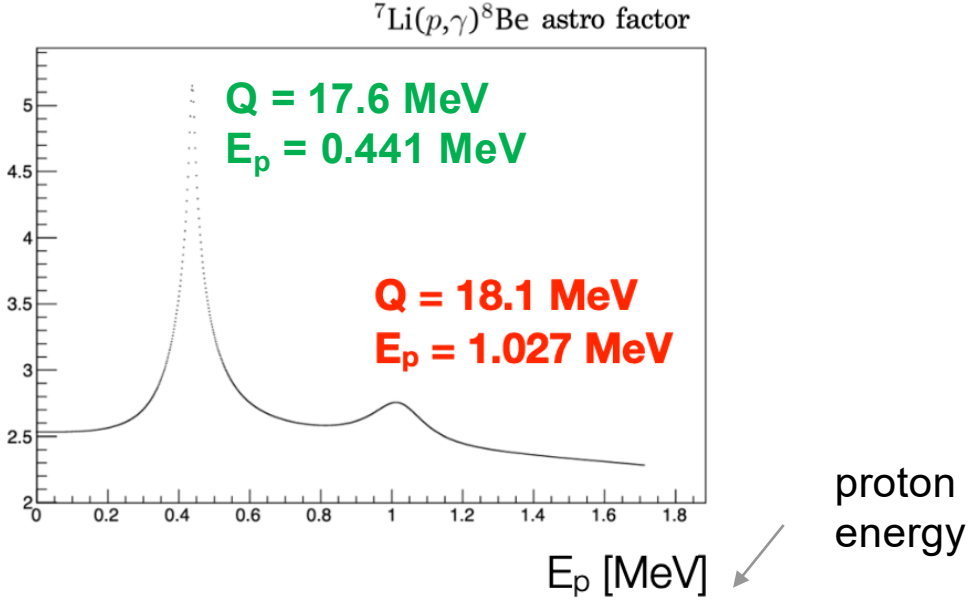


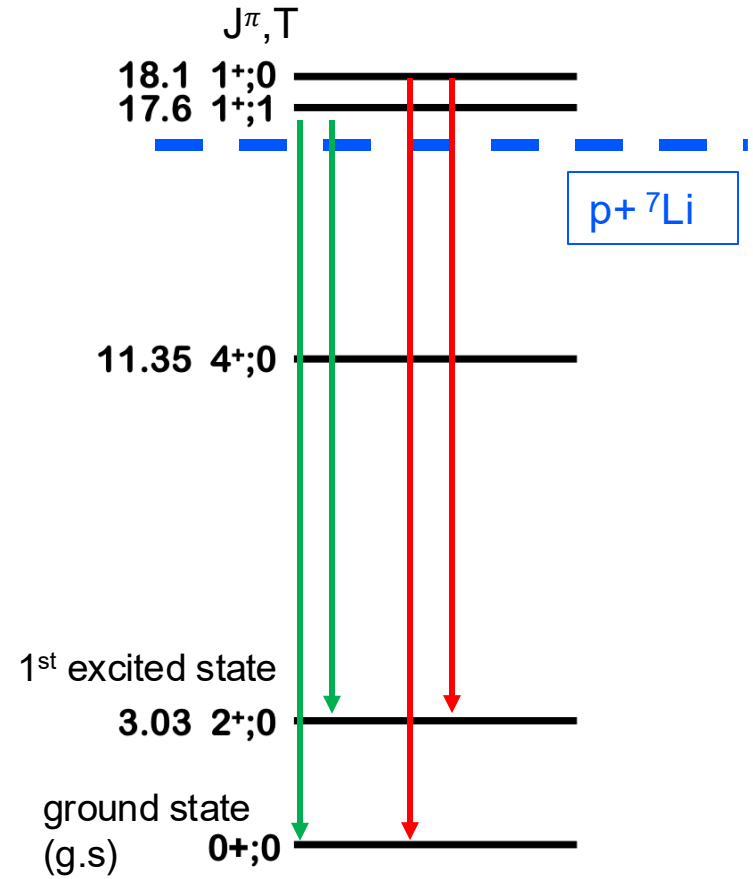


^{8}Be Levels

- **Two resonances** can be easily excited in the p+^{7}Li reaction:

E_p = 0.441 MeV, Q = 17.6 MeV
E_p = 1.027 MeV, Q = 18.1 MeV



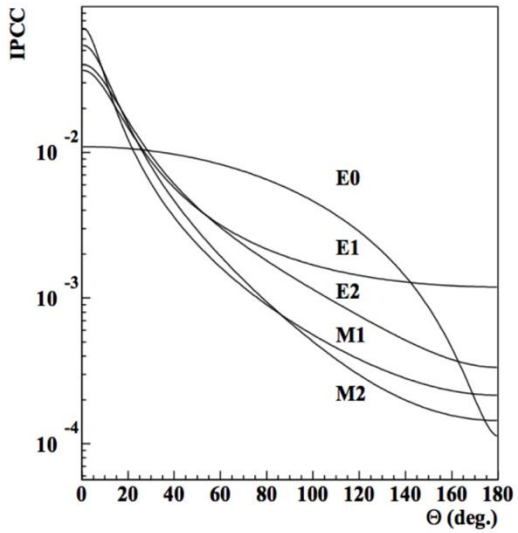


- **Two (M1) transitions for each resonance**
  1+ → 0+ (E_γ = Q)
  1+ → 2+ (E_γ = Q-3 MeV)

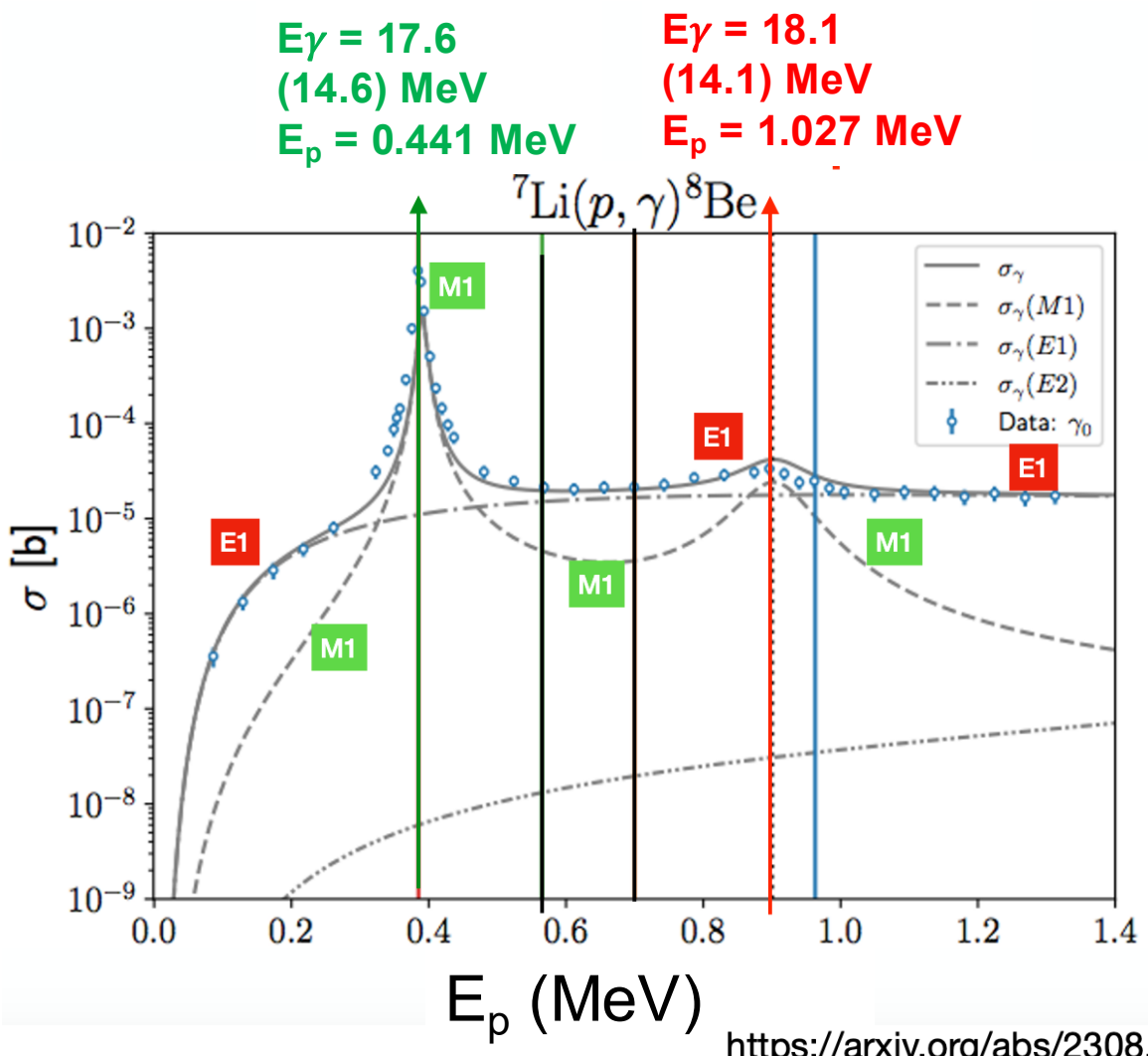
Multipole Decomposition

- Besides resonant transitions (**M1**), **radiative direct capture** (mostly **E1**) is present and interfering

→ **Different Θ_{e+e-} distribution**
→ **possible to separate IPC from different transitions**



J.Gulyas et al. NIMA 808 (2016)21-28

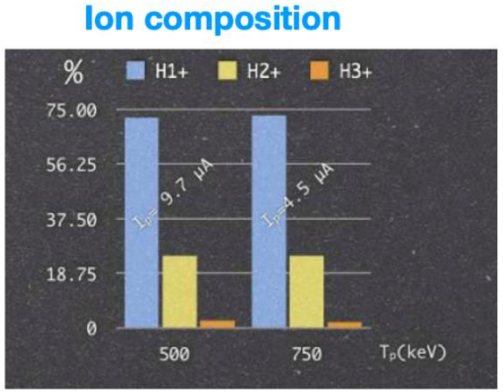


https://arxiv.org/abs/2308.13751

February 2023 MEG II X17 Run

- CW setup: E_{beam} = 1.080 MeV at 10 μA
- The CW beam is a 75%/25% H^+/H_2^+
  - Protons inside H_2^+ interact with energy ~$E_{beam}/2$

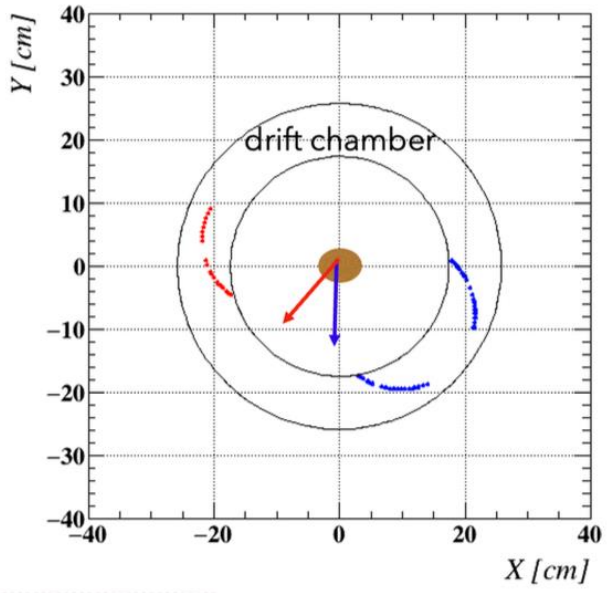
We excite both 18.1 MeV and 17.6 MeV Be resonances



- Anomaly seen only in the 18.1 MeV transition to the g.s.
  - But kinematically possible also in the 17.6 MeV transition to the g.s.

- We have the opportunity to **search for X17 in both transitions**

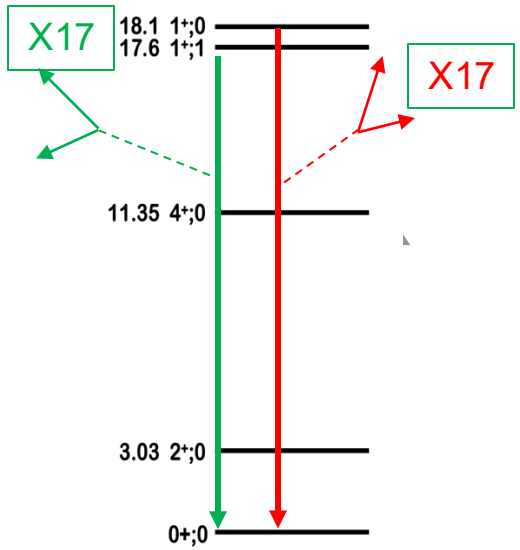
- 75M events collected (4 weeks), about **300k pairs reconstructed**



Signal and Backgrounds

- **Signal**: **e^+e^- coming from $Be^* \rightarrow$ X17 $\rightarrow e^+e^-$**
  possibly from both 18.1 and 17.6 MeV transitions to g.s

Signal

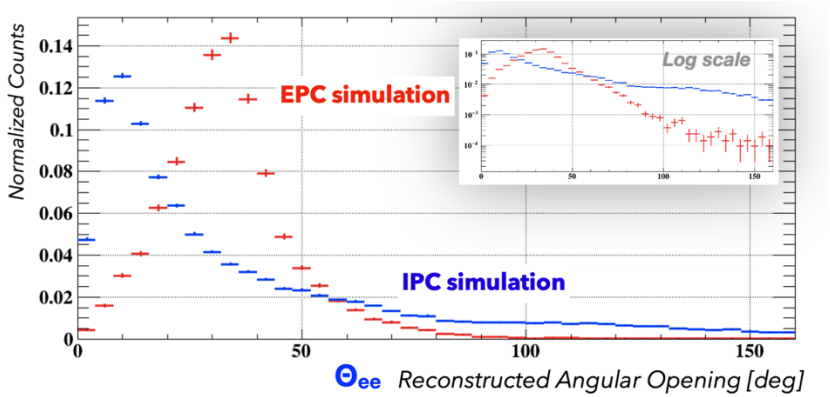


- **Backgrounds**:

  - **IPC** of gammas from:
    transitions to g.s. or 1st excited state of
    18.1 MeV, 17.6 MeV excited states
    or of intermediate energies

Background accurately modeled in Monte Carlo with the Zhang-Miller model
[Phys. Lett. B 773, 159648 2017]

  - **EPC** (External Pair Creation)
    of gamma conversion in materials from
    either transitions



Analysis Strategy

- We use two observables:

  - $\mathbf{E_{sum}}$ = total e^+e^- energy
  - $\mathbf{\Theta_{e+e-}}$ = opening e^+e^- angle

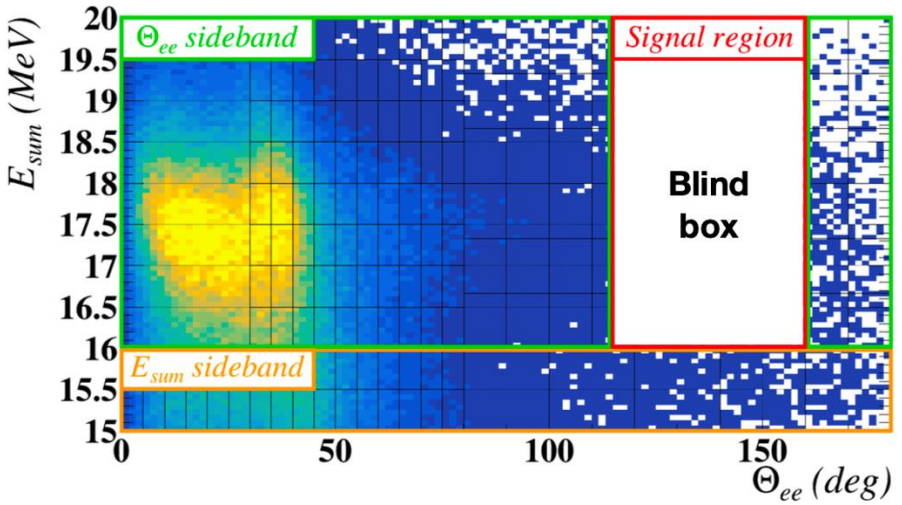
- The two variables are used in a 2-dimensional **Maximum Likelihood fit** including all possible signal and background components

- **Blind analysis**:

  - We looked into the signal region only once we could demonstrate that:

our method correctly described the data in the sidebands

our method was capable of discriminating the different background components



Maximum Likelihood (ML) Fit

- **Binned** ML fit using **template** histograms as PDF from MC simulation

- **Two signal PDFs**
  - One per resonance, Q = 17.6 MeV and Q = 18.1 MeV

- **Two** signal PDF's
  - One per resonance
    (Q = 17.6 and Q = 18.1 MeV)

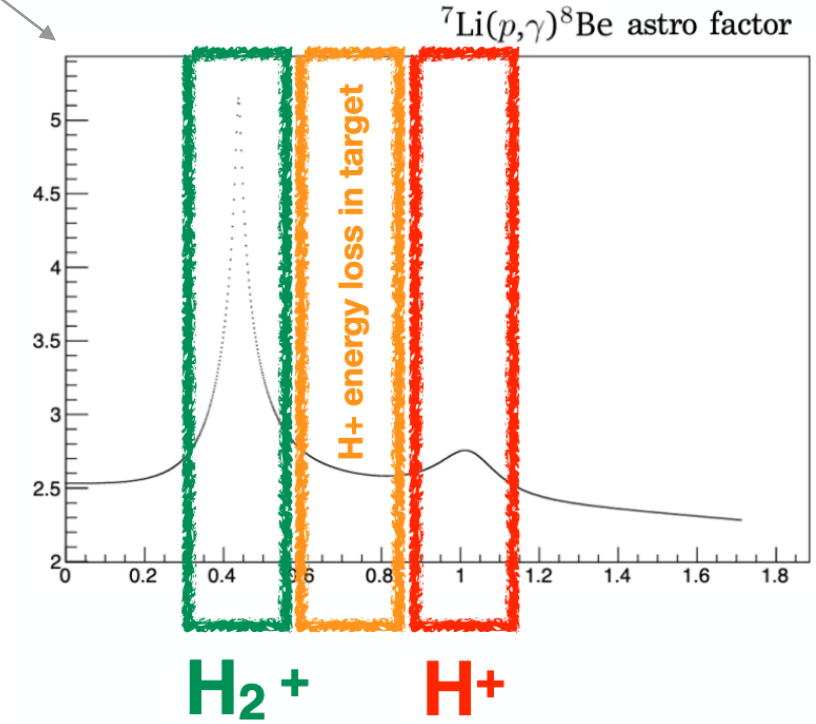
- **Six** IPC PDF's
  - Three Ep bins
  - Two transitions
    (g.s and 1st excited s.) each

- **Two** EPC PDF's
  - No Ep dependence
  - Two transitions

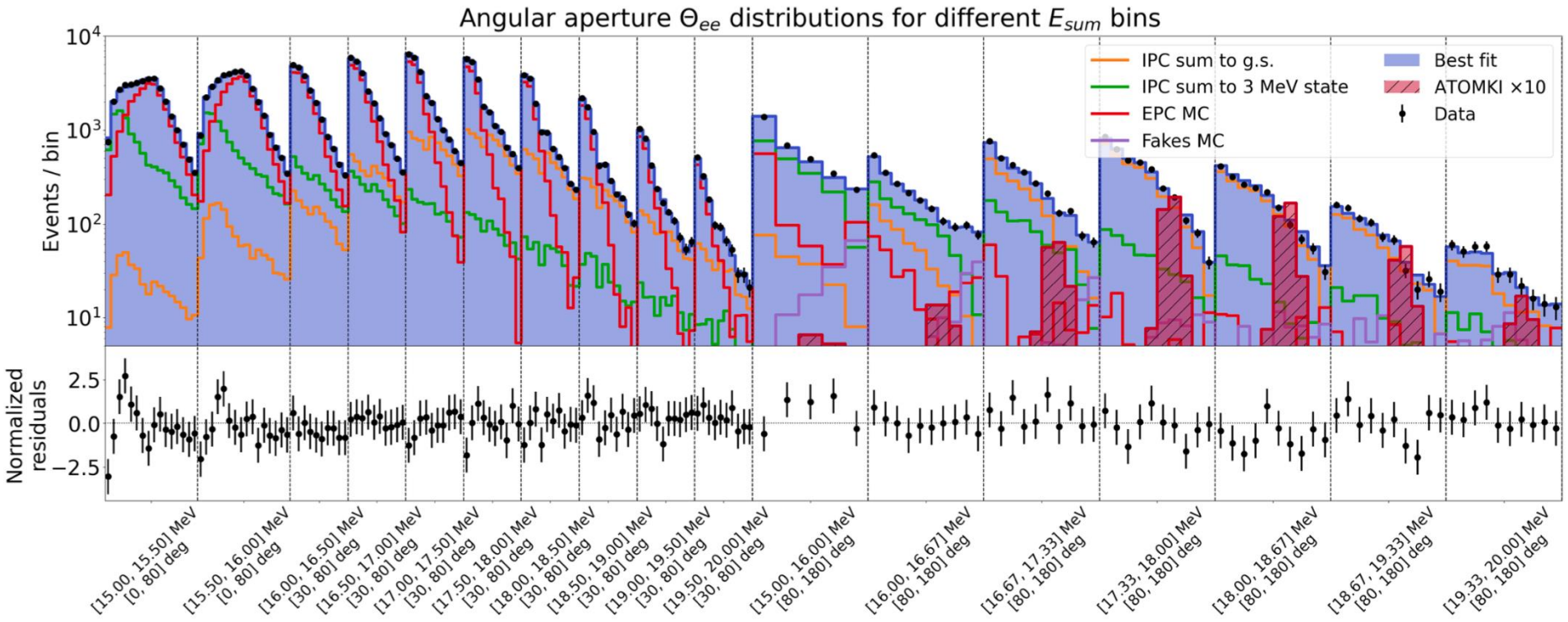
- **One** fake pairs PDF

to take into account the presence of H_2^+ ions in our beam and energy loss of H^+

Systematic effects (energy scale, mass dependence, relative acceptance) are all included as nuisance parameters



Unblinding: Results from ML Fit



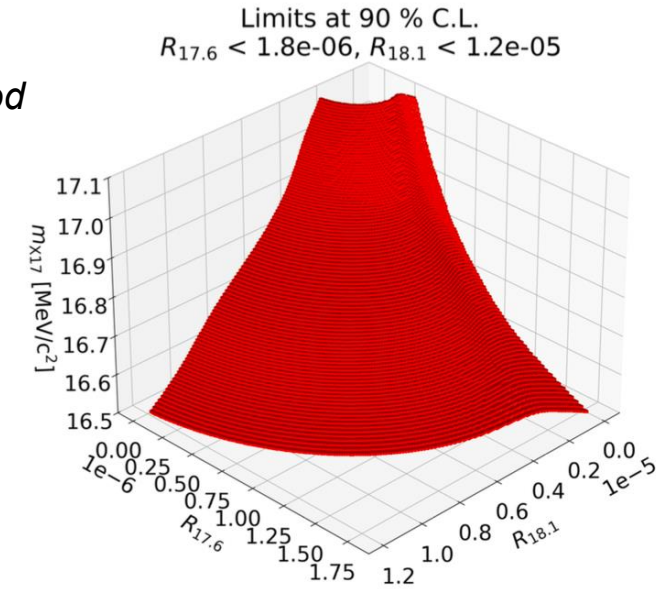
Best fit (goodness-of-fit: p-value = 10.5 %):

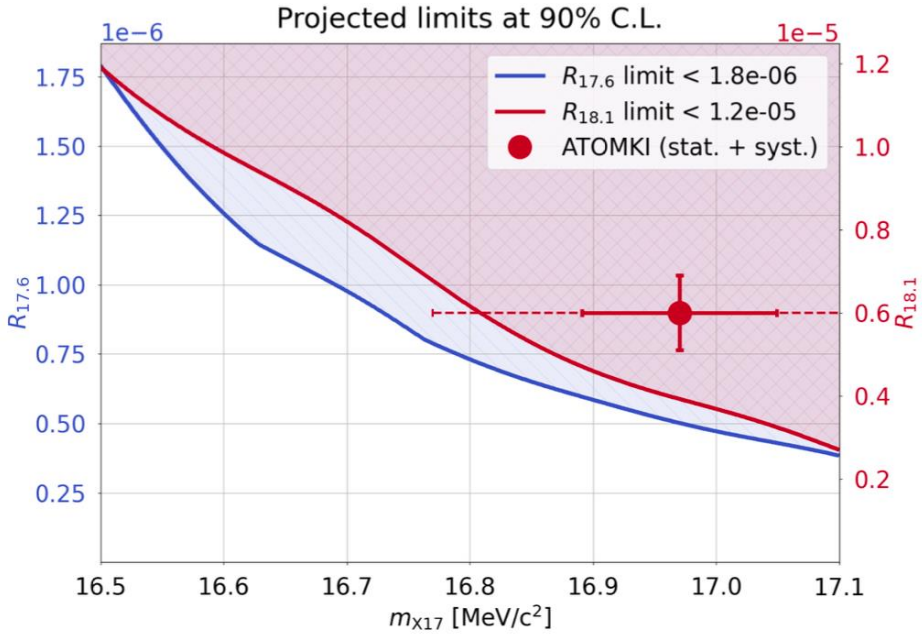
no significant signal

	18.1 MeV —> g.s.	17.6 MeV —> g.s.	intermediate	any —> 1st exc.
SIGNAL EVENTS	10 ± 92 @ m_X = 1.65 MeV	0	n.a.	n.a.
IPC COMPOSITION	(12.6 ± 0.9) %	(45.8 ± 1.3) %	0	rest

Upper Limits at 90% C.L.

Feldman Cousins with profile likelilhood ordering





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

arXiv 2411.07994
accepted by EPJC

$R_{17.6} < 1.8 \times 10^{-6}$ **$N^{sig}_{17.6}$ < 200**

$R_{18.1} < 1.2 \times 10^{-5}$ **$N^{sig}_{18.1}$ < 230**

p-value for ATOMKI result: 6.2% (1.5σ)

Conclusions and Perspectives

- MEG II detector successfully studied the $^{7}Li\ (p, e^{+}e^{-})^{8}Be$ process
  - Four weeks dedicated data taking with a special LiPON target and the C-W proton accelerator

- Looking for a new particle as suggested by ATOMKI experiment: X17 → $e^{+}e^{-}$ with mass~17 MeV

- Measurement affected by presence of H_2^+ ions
  - more background, but possibility to study 17.6 resonance

- No significant signal was found in our data
  - ATOMKI observation was tested and excluded at ~94%

- A **new data-taking** period is being considered with:

  - removal of H_2^+ for a run at 1.030 MeV only (already tested)
  - thinner LiPON target

Backup

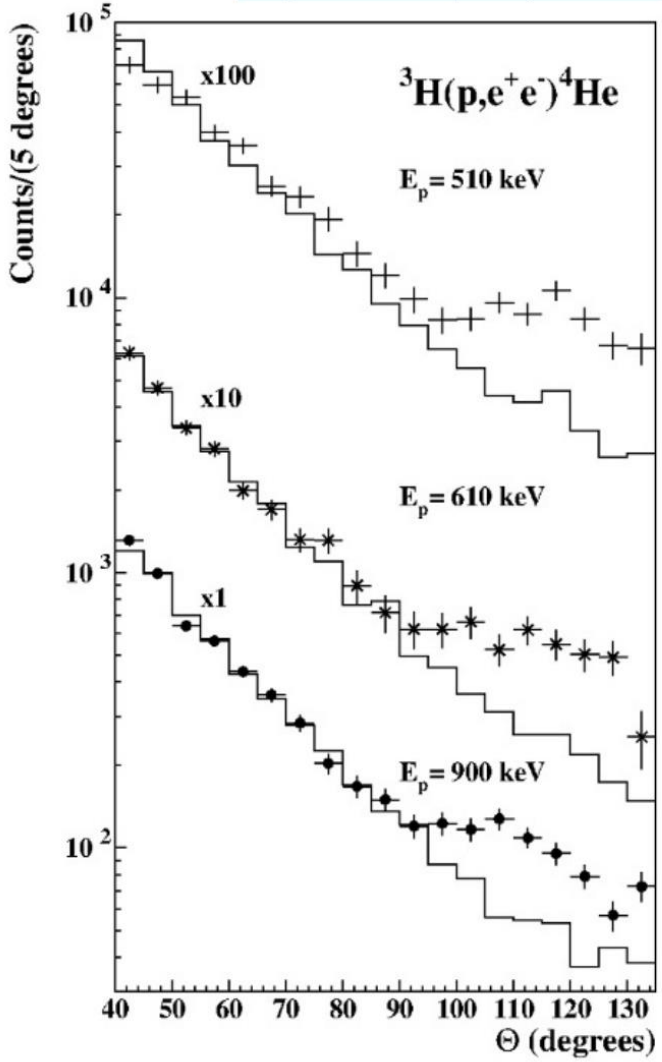
Other Evidences

- At ATOMKI with tritium target
  same anomaly in ^{4}He transitions at different E_p
  - Kinematically consistent with ^{8}Be (same ~17 MeV inv. mass)

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

Phys. Rev. C 106, L061601

Phys. Rev. C 104, 044003



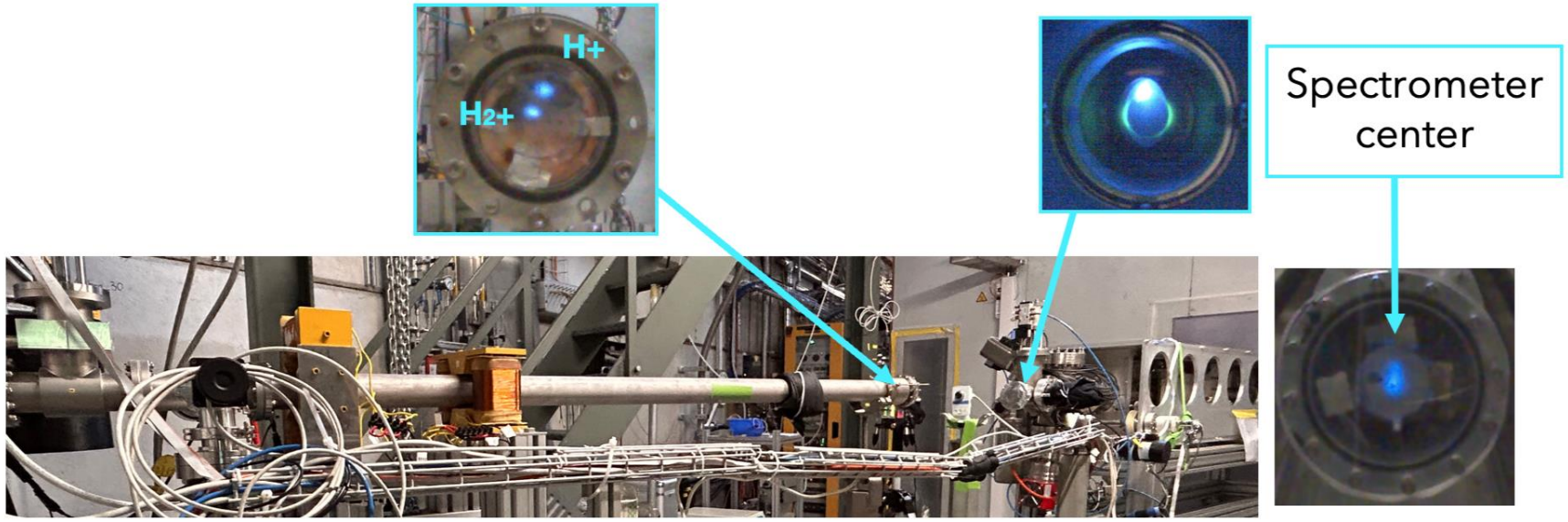
The CW Proton Beam

- **Data taking in Feb 2023 with E_{beam} = 1.080 MeV**

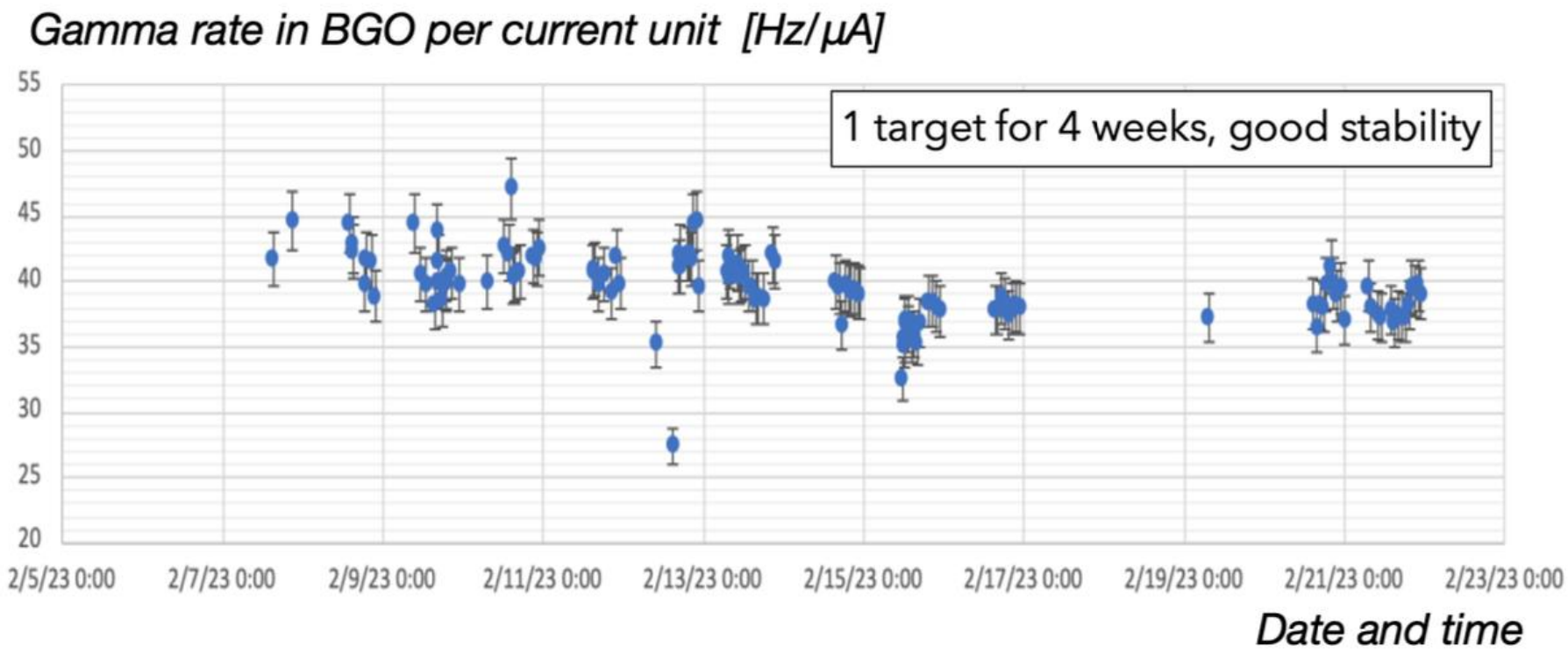
- The beam is a 75% / 25% H^+/H_2^+
  - Protons inside H_2^+ interact with energy ~$E_{beam}/2$

=> **We excite both 18.1 MeV and 17.6 MeV resonances**

- H_2^+ removal can be implemented with dipoles + collimators
  - not available during February run



Stability During Run



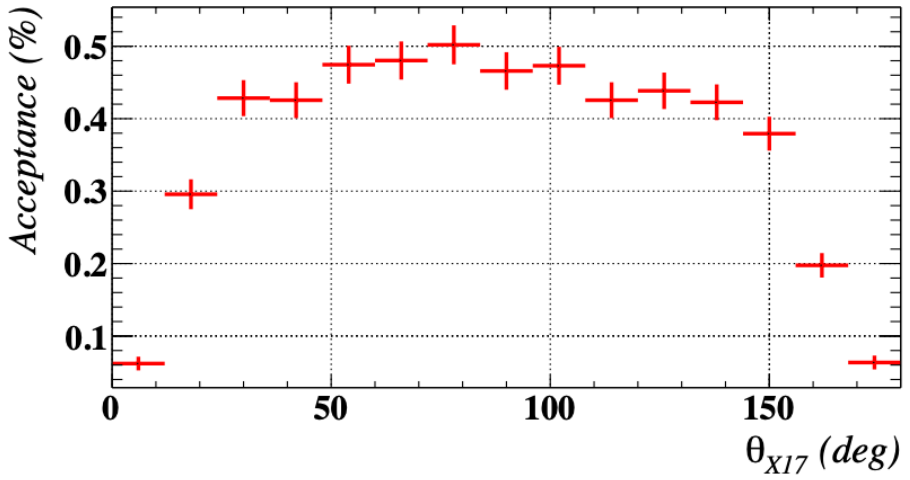
Trigger and Pair Reconstrution

- **Trigger logic**
  - pTC trigger fired when at least one tile is hit
  - CDCH trigger fired when a number of hits are simultaneously reconstructed on both wires' readout sides.

- **Event reconstruction**
  - the MEG II track reconstruction algorithms were modified to reconstruct both e^+ and e^- and optimized for the kinematics

Selection
$n_{hits} \geq 10$
$\lvert z_{vtx} - z_b \rvert \leq 2.5$ cm
$T_{0l} - T_{0f} \geq 0$
$(z_l - z_f) \times sgn(z_f) \geq 0$
propagation length ≥ 35 cm
if $10 \leq n_{hits} \leq 16$, $\mu_{hit} \geq 1.1$ hits/cm
if $\mu_{hit} > n_{hits}/12 - 2/3$: $\mu_{hit} \geq 0.8$ hits/cm track score ≥ 20
Consecutive hits distance std < 0.9 cm
$\lvert z_f \rvert \geq 2.5$ cm
$z_{mean} \times (\theta - 90°) < 0$
No hits in common between e^+ and e^- tracks
e^+e^- vertices distance < 3 cm

Performances



	X17 16.9 MeV/c^2	IPC 18 MeV	EPC 18 MeV
trigger selection eff.	16%	4.7%	0.026%
e^+ selection eff. (wrt trg)	24%	26%	13%
e^+e^- selection eff. (wrt trg)	2.5%	2.3%	0.6%
Θ_{ee} resolution [deg]	5.6 ± 0.2	5.5 ± 0.1	//
E_{sum} resolution [MeV]	0.58 ± 0.02	0.69 ± 0.01	//

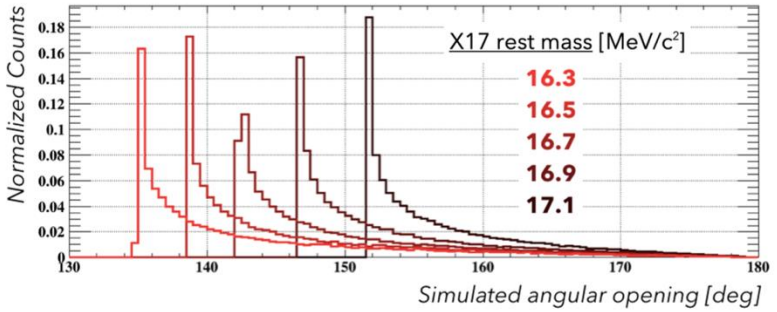
Technical Details of ML Fit

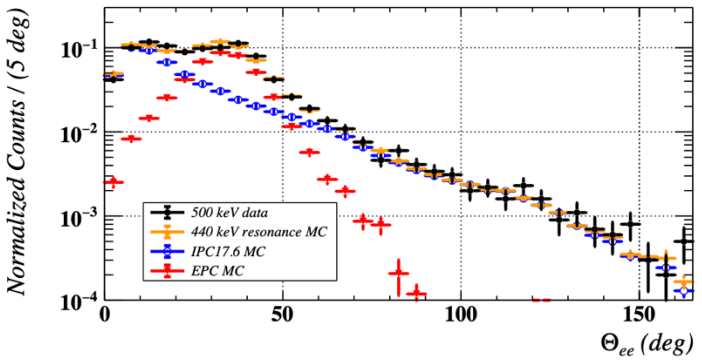
- X17 mass in the range allowed by kinematics and ATOMKI results

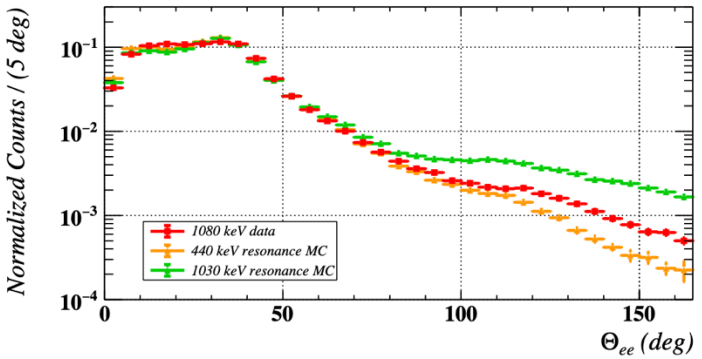
- Mass dependence of signal PDFs from histogram morphing [Nucl. Instr. Meth. A 771, 39659 (2015)]

- Systematics from limited MC statistics treated with the lite Beston-Barlow approach [EPJ C 82(11), 1043 (2022)]

- Systematic effects (energy scale, mass dependence, relative acceptance) are all included as nuisance parameters







Likelihood Function

$$\mathscr{L} = \mathscr{L}_{\mathrm{D}} \times \mathscr{L}_{\mathrm{S}} \times \mathscr{L}_{\mathrm{C}}$$

$$\mathscr{L}_{\mathrm{D}}(\Omega, \alpha_m, \beta_i) = \prod_i \frac{f_i(\Omega, \alpha_m, \beta_i)^{D_i} e^{-f_i(\Omega, \alpha_m, \beta_i)}}{D_i!}$$

$$\mathscr{L}_{\mathrm{S}}(\Omega, \alpha_m, \beta_i) = \prod_i \frac{(\beta_i \mu_{eff,i}(\Omega, \alpha_m))^{\mu_{eff,i}} e^{-\beta_i \mu_{eff,i}(\Omega, \alpha_m)}}{\mu_{eff,i}(\Omega, \alpha_m)!}$$

$$\mathscr{L}_{\mathrm{C}}(\alpha_m) = \prod_m \frac{1}{\sqrt{2\pi}\sigma_{\alpha_m}} e^{-\frac{(\alpha_m - \alpha_{m,0})^2}{2\sigma_{\alpha_m}^2}}$$

$$f_i = \beta_i \sum_j \mathscr{N}_j a_{ij}$$

$$\sigma_{\beta_i} = \sqrt{\sum_j \mathscr{N}_j^2 \sigma_{a_{ij}}^2}$$

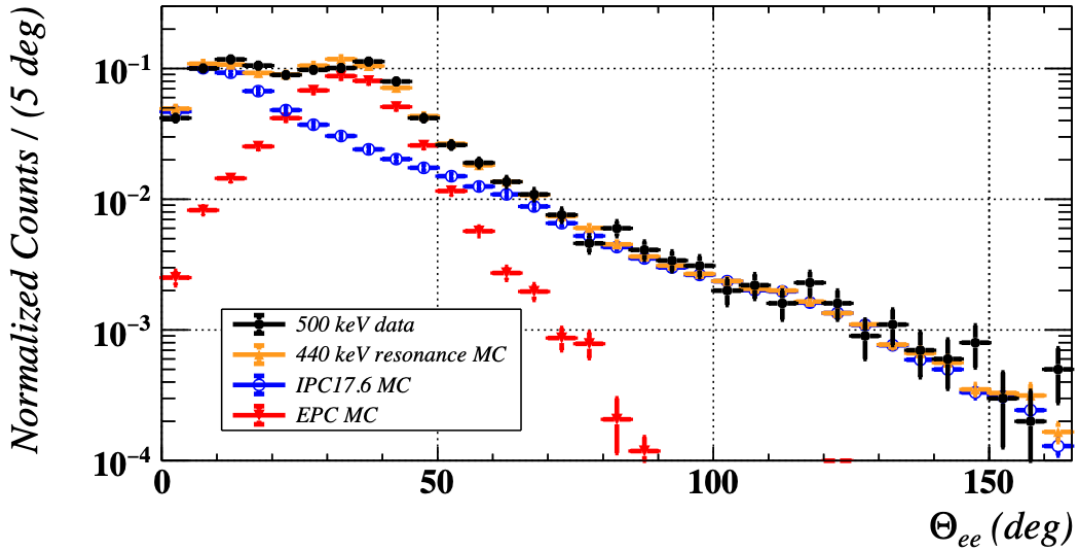
$$\Omega = (R_{17.6}, R_{18.1}, m_{\mathrm{X17}}, \mathscr{N}_{\mathrm{IPC}}\ \mathscr{N}_{\mathrm{EPC}}, \mathscr{N}_{\mathrm{Fake}})$$

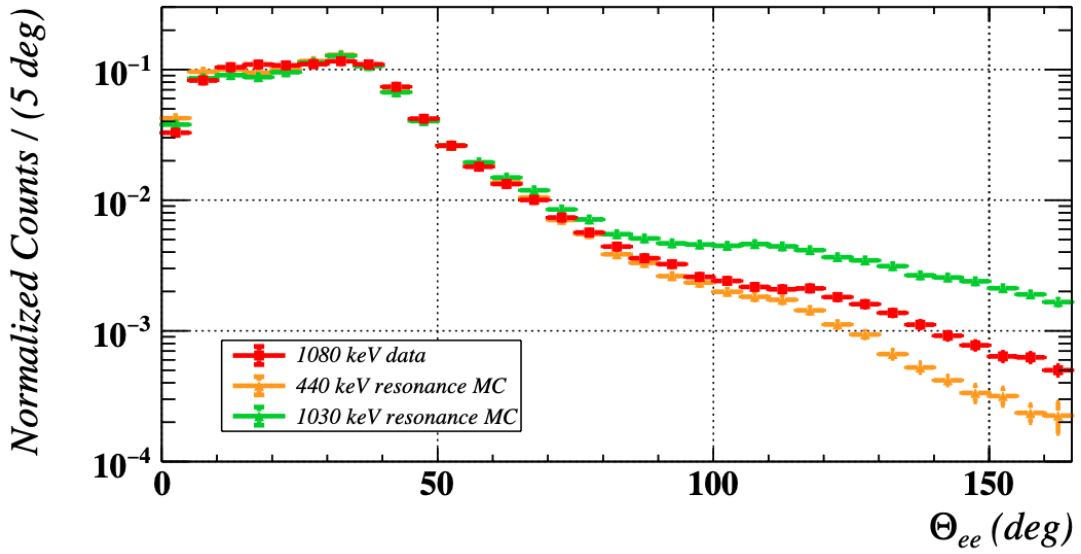
$$\alpha_m = (p_{\mathrm{IPC17.6}}, p_{\mathrm{IPC17.9}}, p_{\mathrm{IPC18.1}}, \alpha_{field}, k(m_{\mathrm{X17}}))$$

$$\beta_i$$

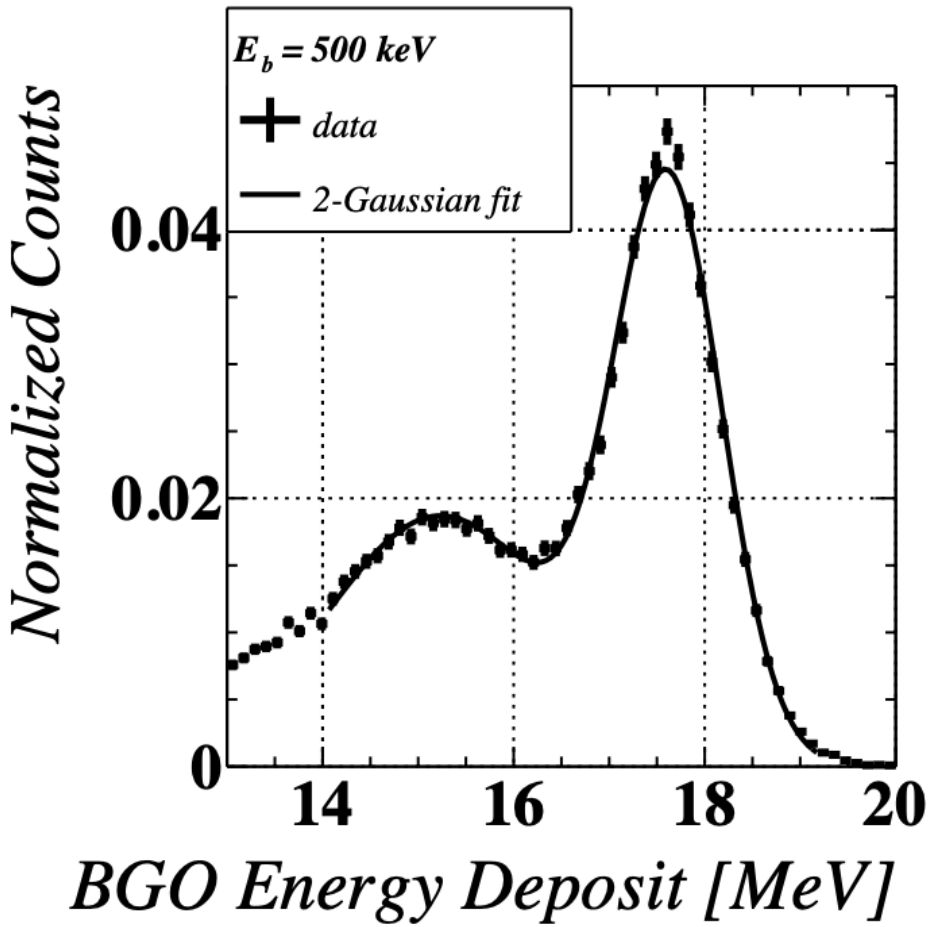
nuisance parameters

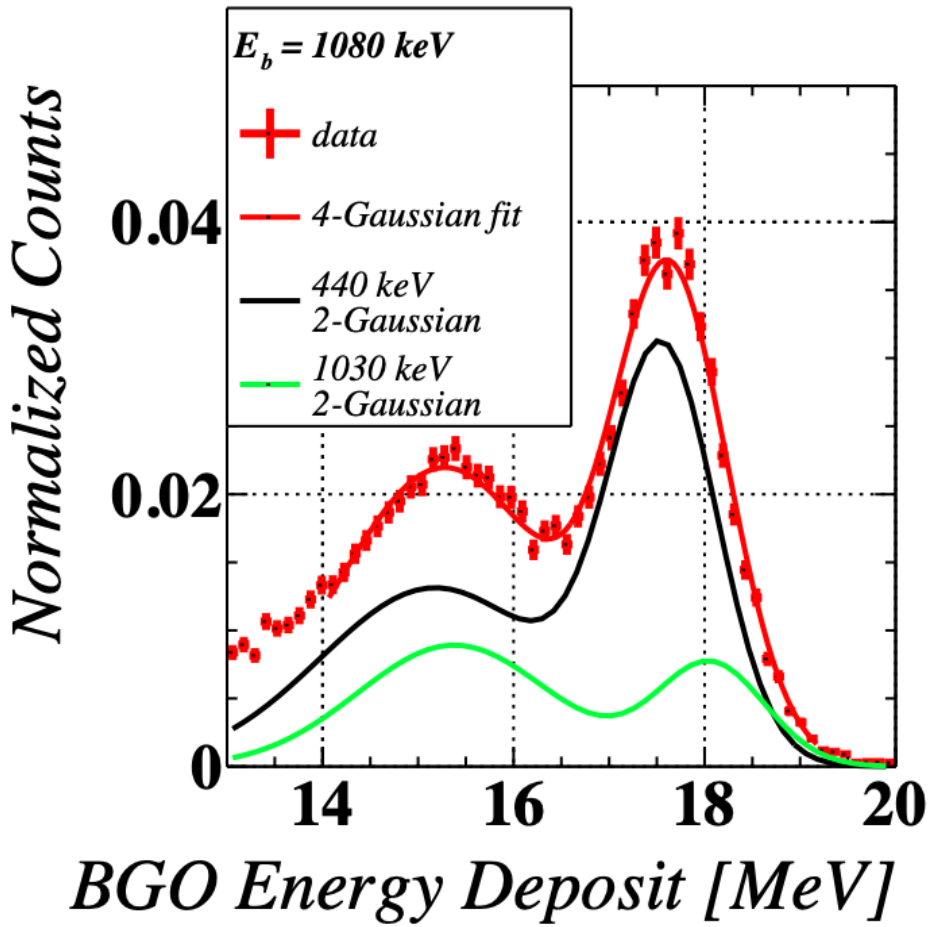
Data/MC Validation





BGO Fits


E_b = 500 keV
data
2-Gaussian fit
Normalized Counts
0.04
0.02
0
14
16
18
20
BGO Energy Deposit [MeV]


E_b = 1080 keV
data
4-Gaussian fit
440 keV
2-Gaussian
1030 keV
2-Gaussian
Normalized Counts
0.04
0.02
0
14
16
18
20
BGO Energy Deposit [MeV]