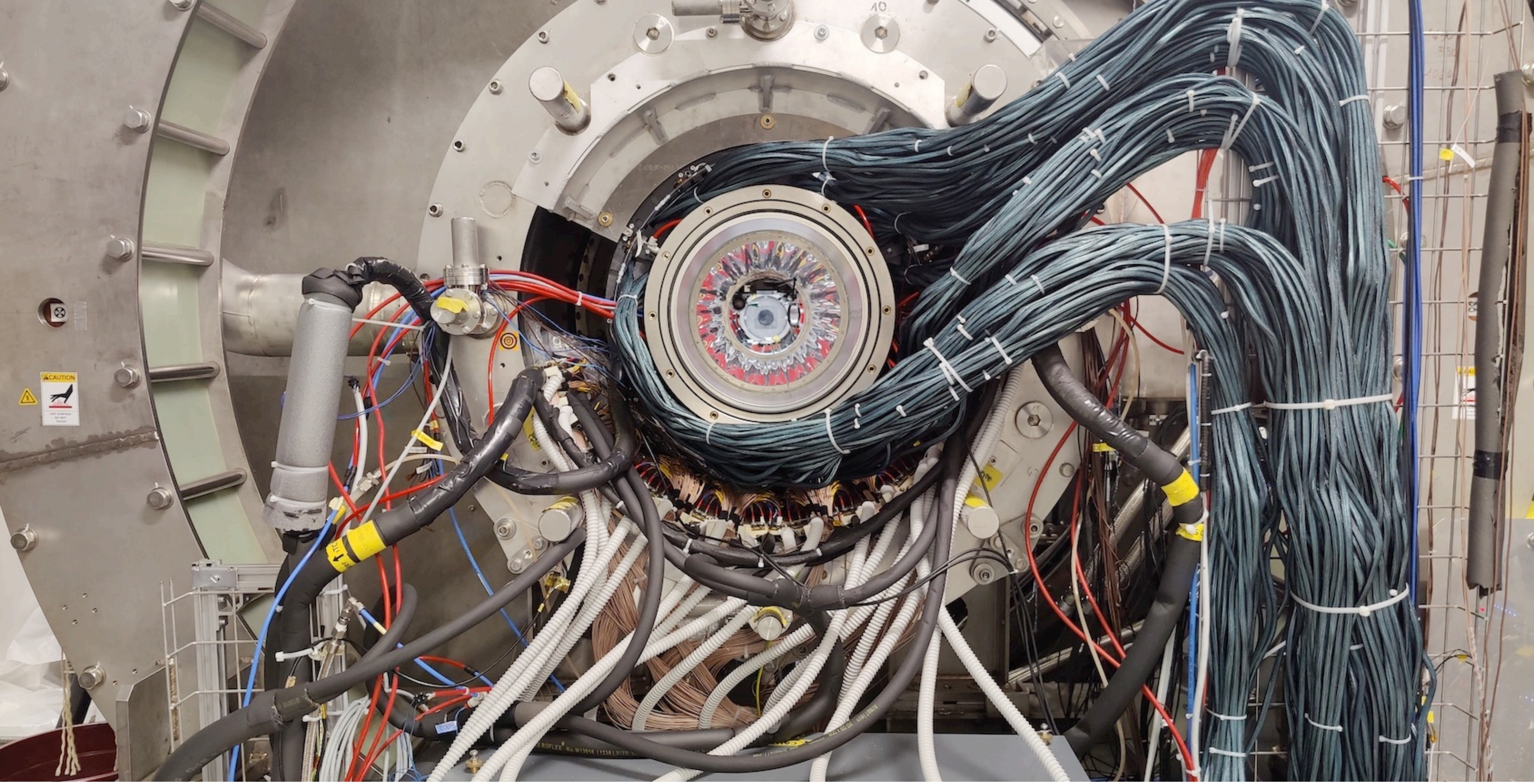
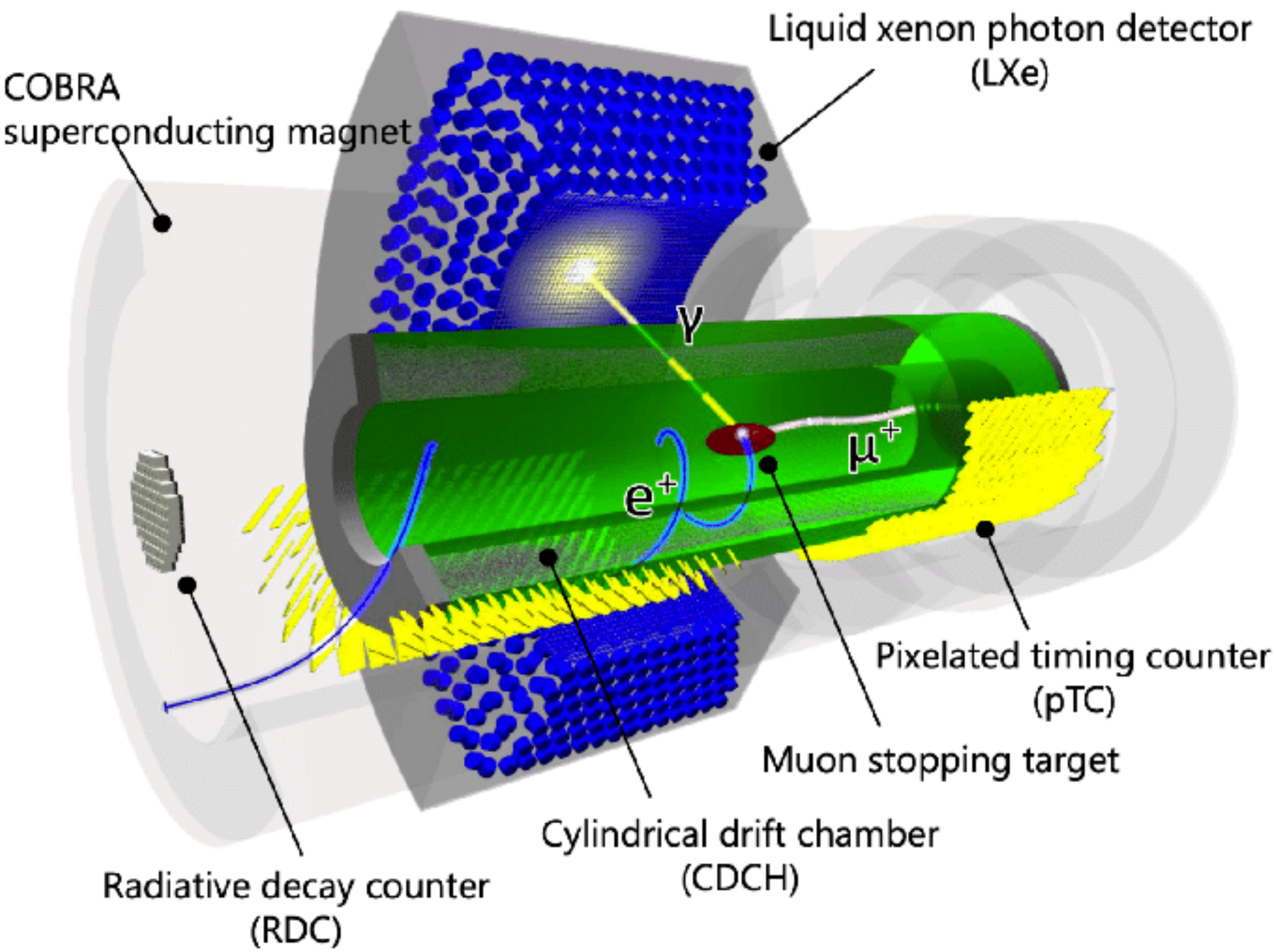


Recent X17 results from the MEG II experiment

Istituto Nazionale di Fisica Nucleare

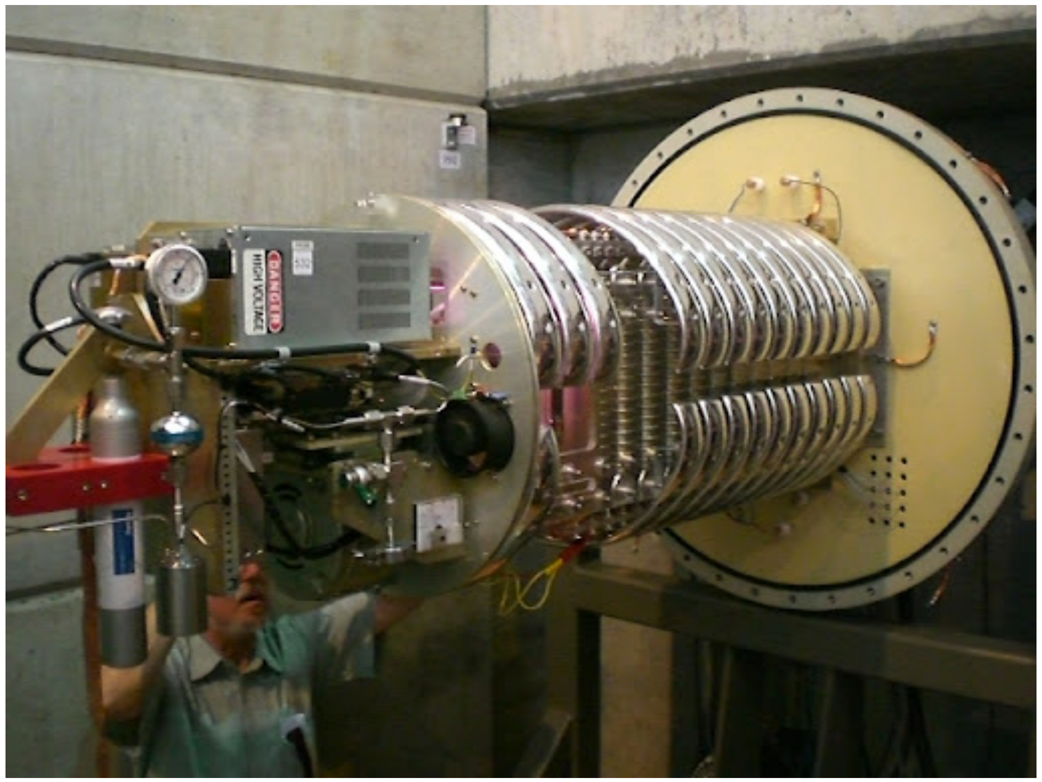
Francesco Renga, INFN Roma
for the MEG II Collaboration

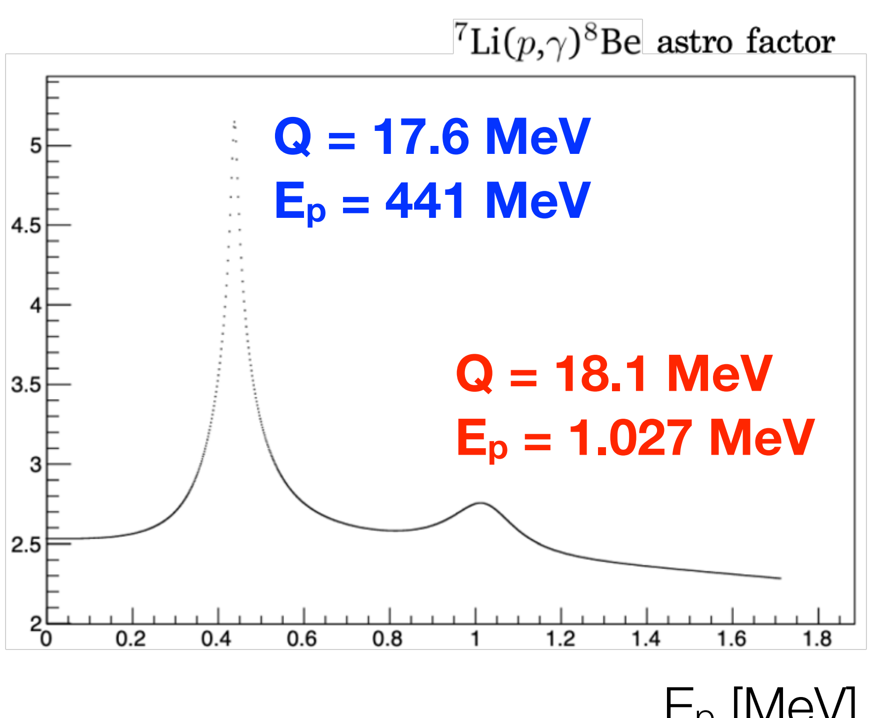
The MEG II experiment



- Designed to search for the LFV decay $\mu \to e\gamma$
- LXe photon detector
- Positron spectrometer:
  - Drift chamber (CDCH)
  - Timing scintillators
  - Magnetic field up to 1.6 T
- Ancillary detectors for background rejection and calibrations

X17 in the MEG II setup

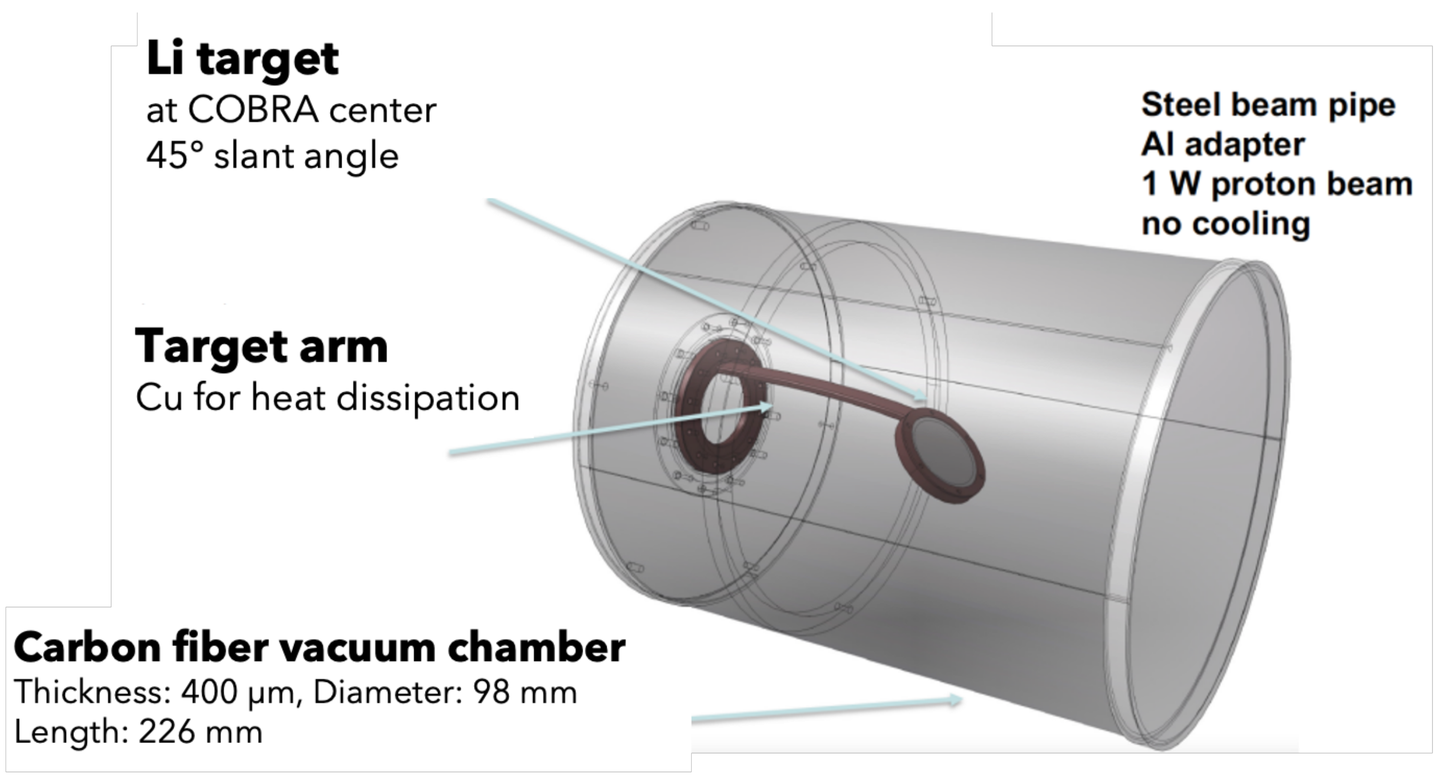




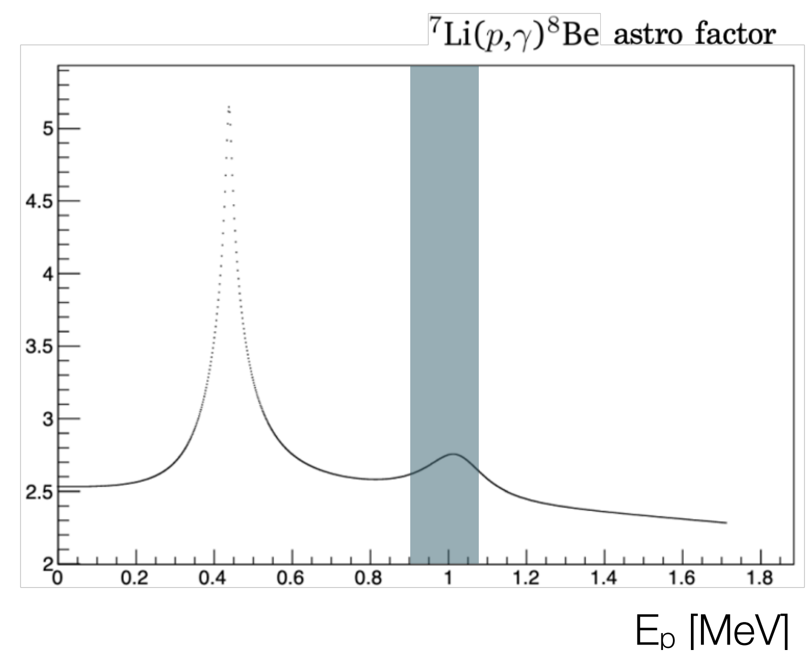
- Cockroft-Walton (CW) accelerator to calibrate the LXe detector with gamma lines from $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$
  - normally used at E_p ~ 500 keV to excite the Q = 17.6 MeV resonance of $^8\mathrm{Be}$
  - can go up to ~ 1 MeV to excite the Q = 18.1 MeV resonance (where X17 anomaly was observed at ATOMKI in $^7\mathrm{Li}(p,e^+e^-)^8\mathrm{Be}$)
- e^+e^- pairs from gamma conversion or X17 decay can be reconstructed in the magnetic spectrometer (with an optimized reduction of the magnetic field)
  - larger polar angle acceptance compared to the ATOMKI experiments

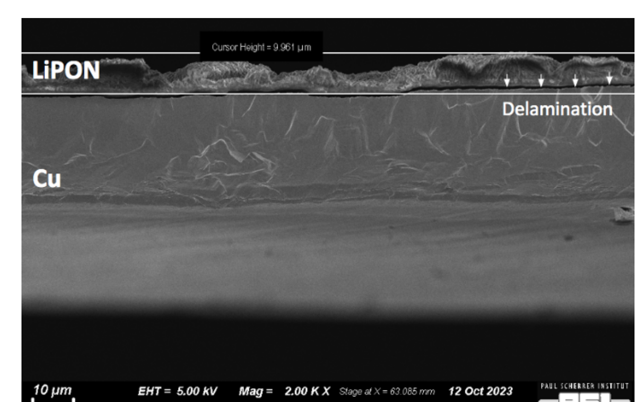
Target and target region

- Relatively thick target and beam pipe are used in normal CW operations for LXe calibrations
- Dedicated target and vacuum chamber to minimize the material budget for $X17 \rightarrow e^+e^-$ search



- 18.1 MeV resonance is wide and continuum contamination is relevant
  - best $S/\sqrt{B}$ ratio by scanning the resonance via energy loss —> relatively thick target (2 μm LiPON)

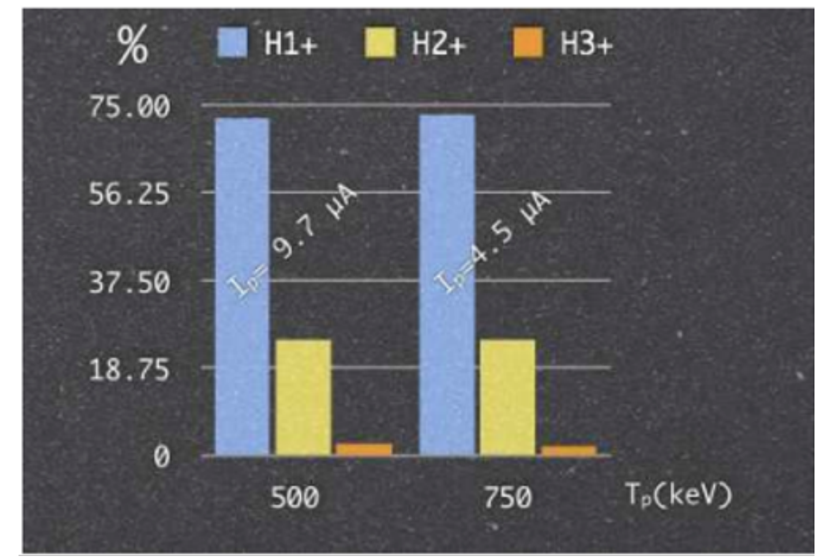


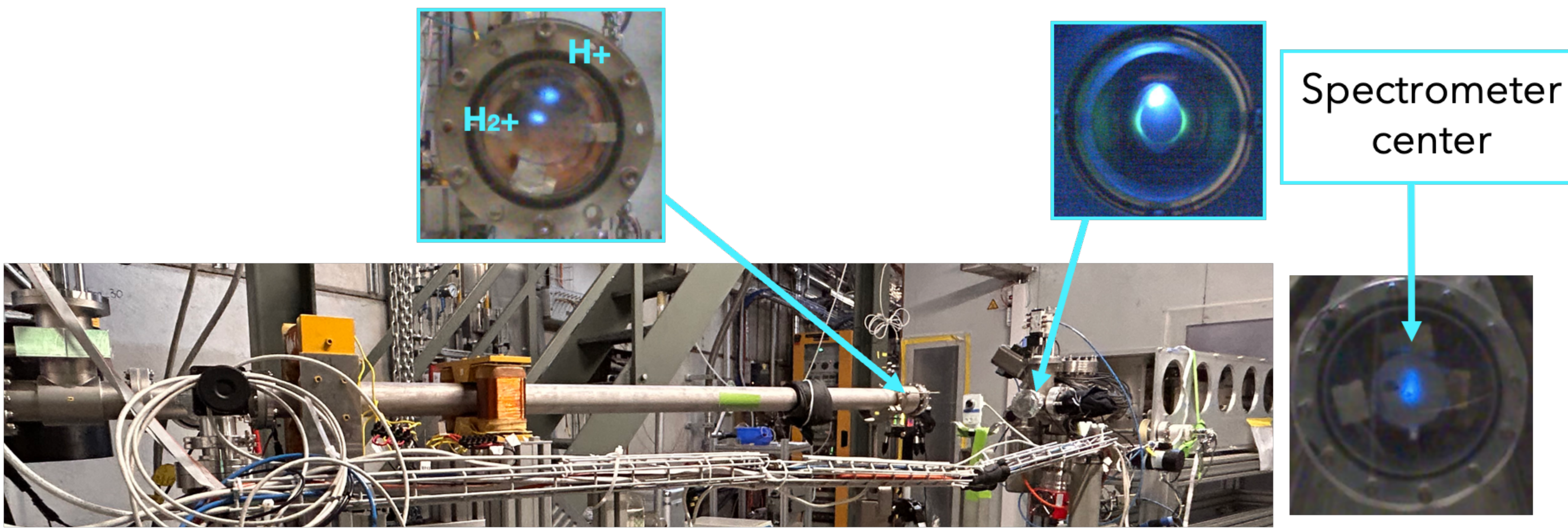


Proton beam

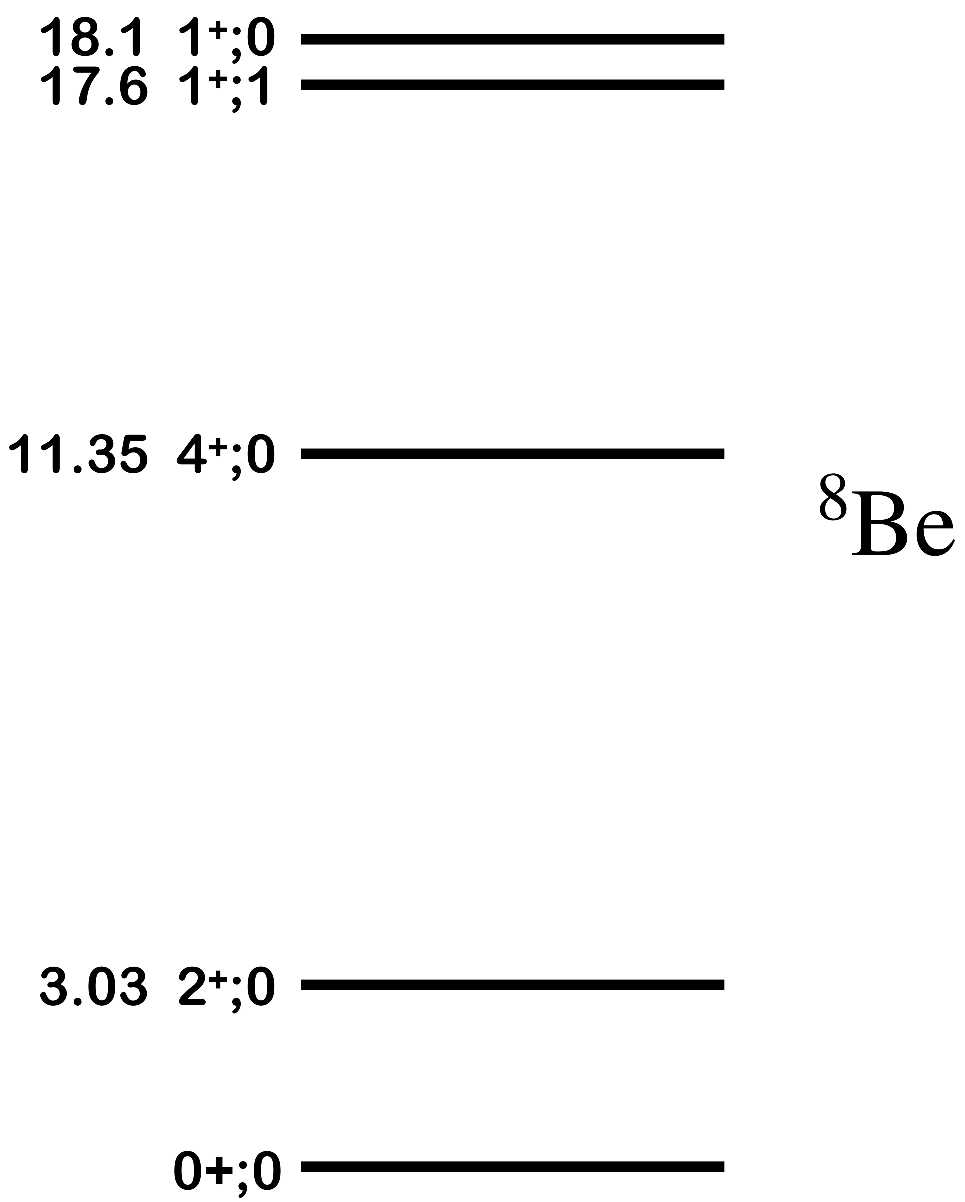
- **E_p = 1.080 MeV**
- The beam is not a pure H^+ one:
  - relevant H_2^+ component —> at E ~ 1 MeV we excite both 18.1 MeV (from H^+) and 17.6 MeV (Ep ~ 500 MeV from each proton in H_2^+) resonances
- H_2^+ removal can be implemented with dipoles + collimators
  - not available during our 2023 data-taking run

Ion composition



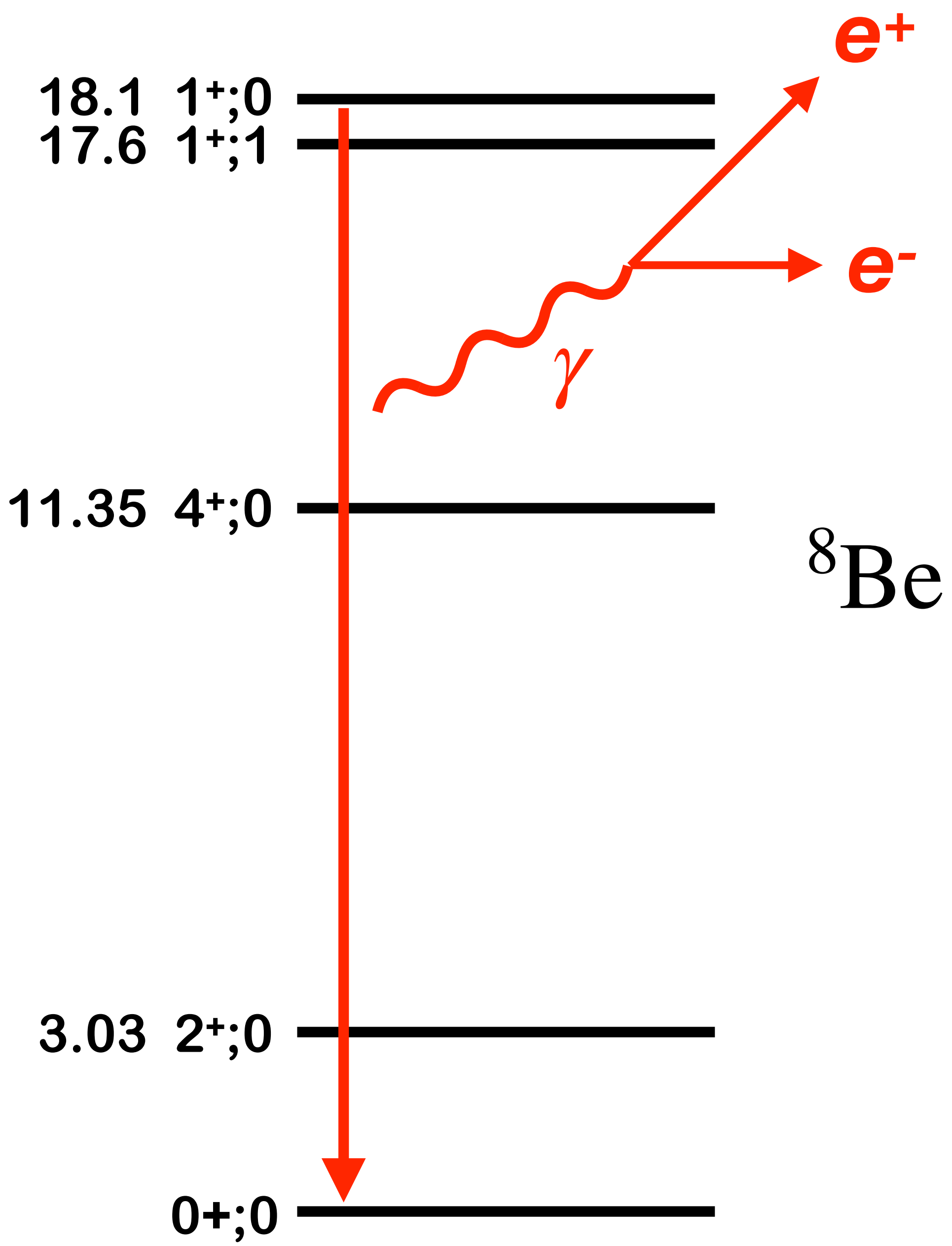


Signal and Backgrounds



Signal and Backgrounds

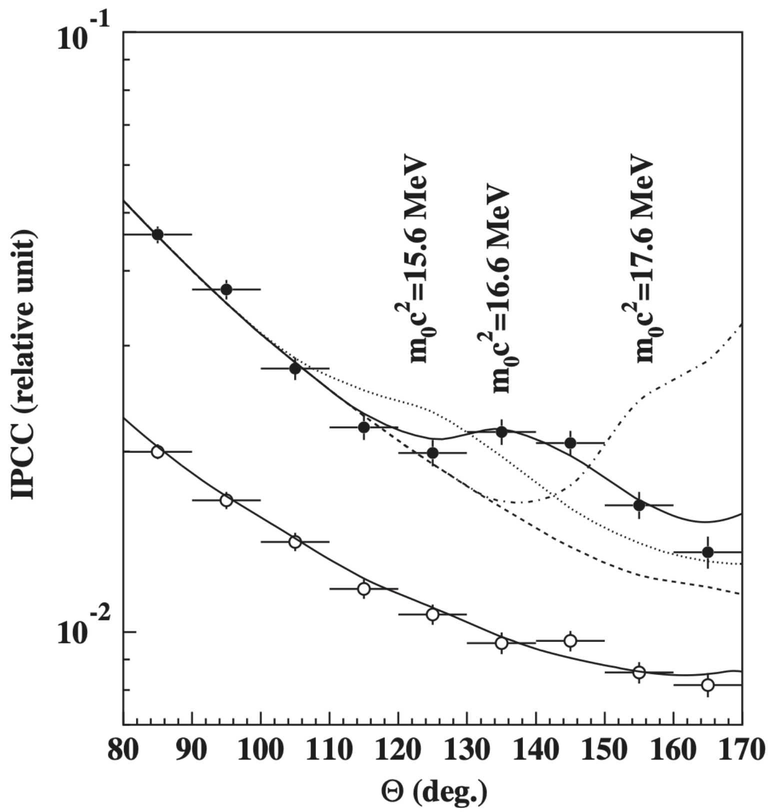
- At E_p ~ 1 MeV, the 18.1 MeV —> ground state (g.s.) M1 transition is expected

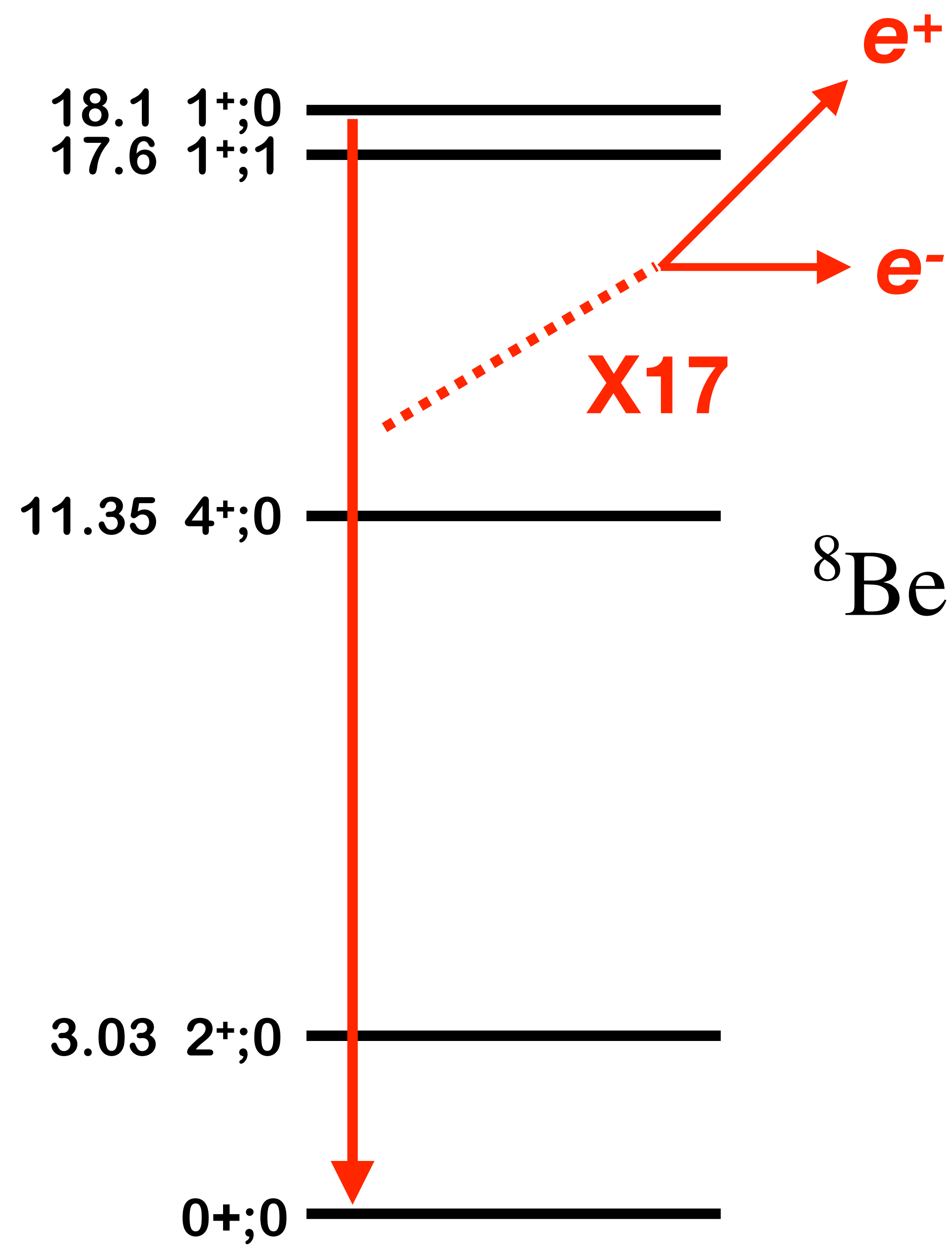


Signal and Backgrounds

- At Ep ~ 1 MeV, the 18.1 MeV —> ground state (g.s.) M1 transition is expected

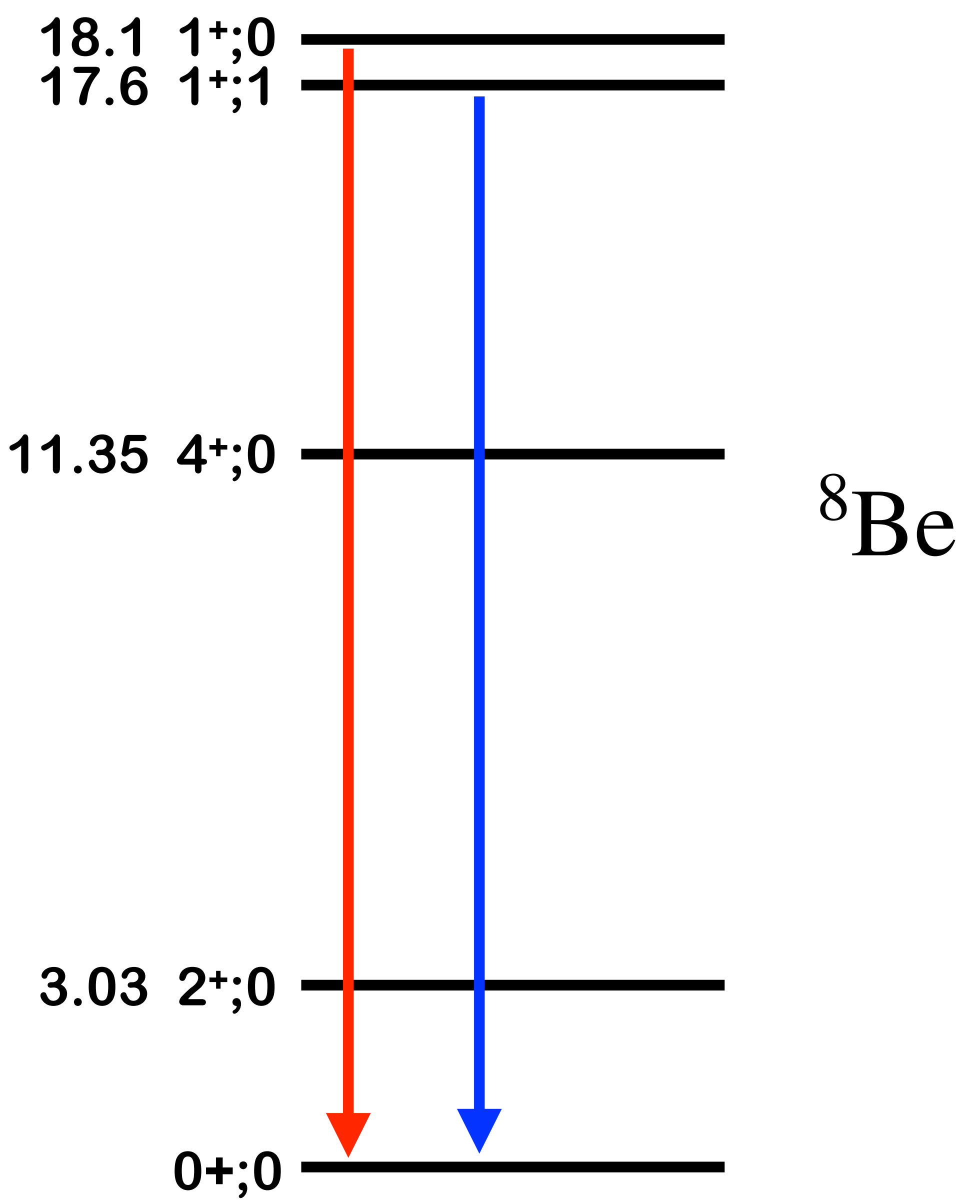
This is the transition where the X17 signal is also expected to be observed as an ***anomaly in the spectrum of the relative e^+e^- angle***





Signal and Backgrounds

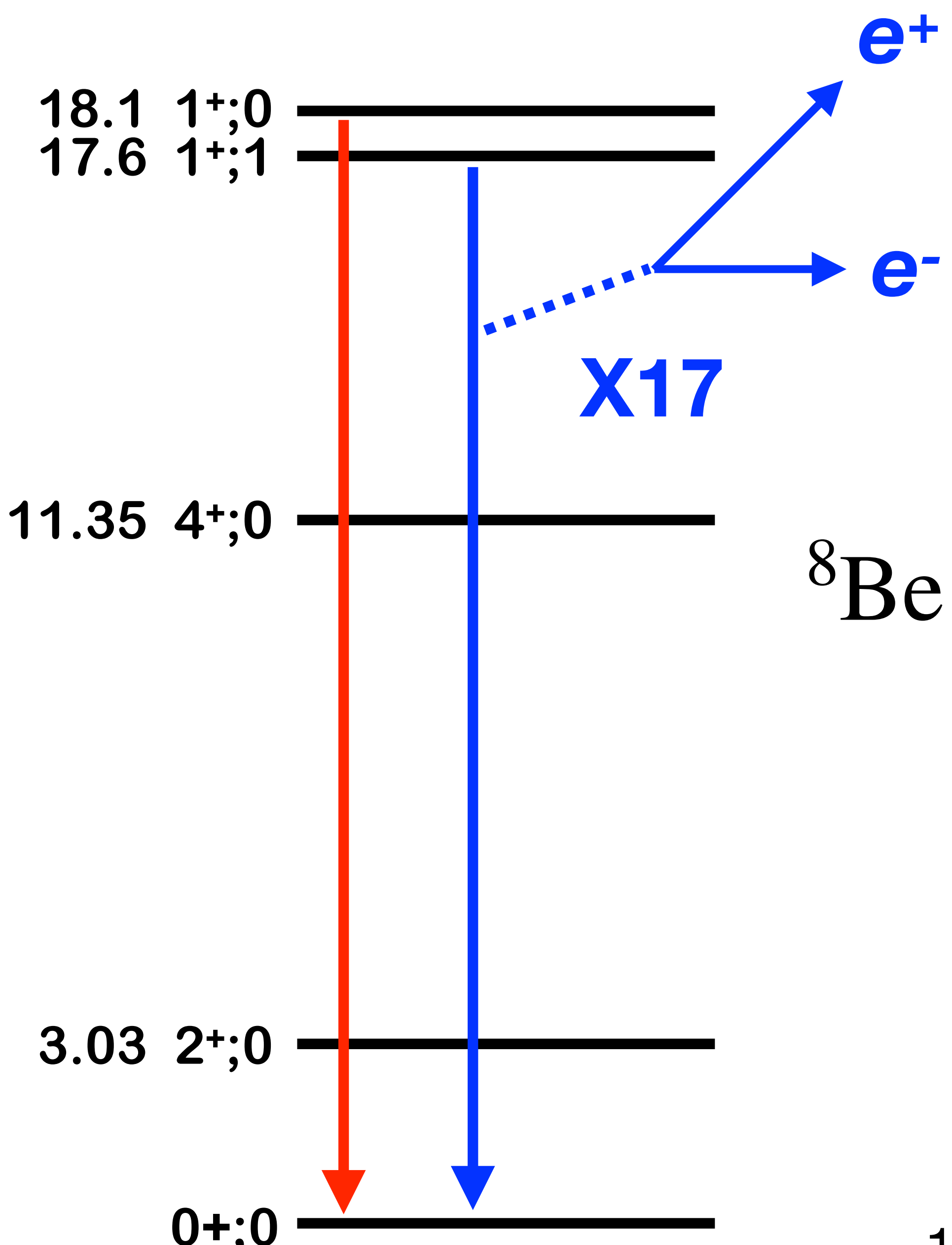
- At Ep ~ 1 MeV, the 18.1 MeV —> ground state (g.s.) M1 transition is expected
- Our beam also excites 17.6 MeV transitions



Signal and Backgrounds

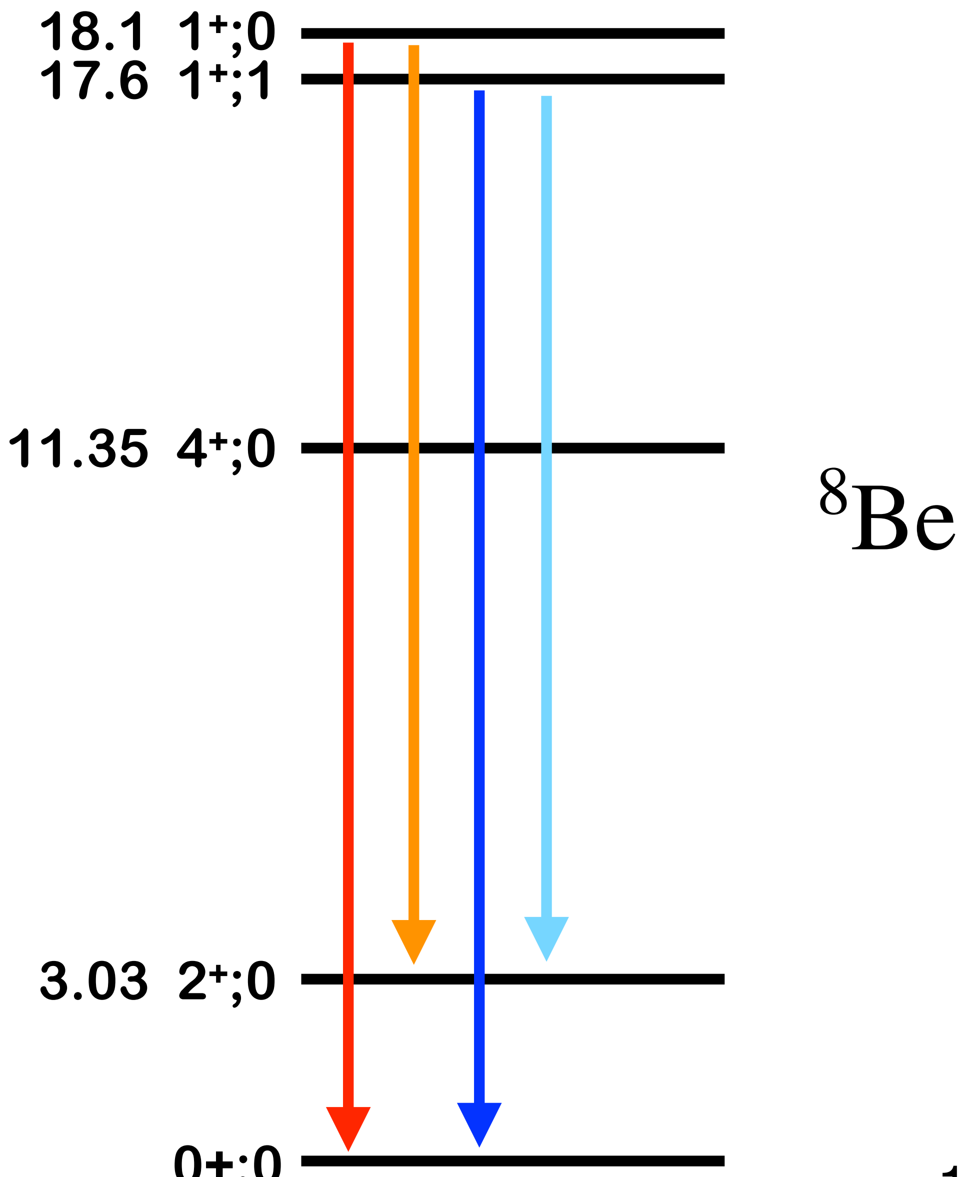
- At Ep ~ 1 MeV, the 18.1 MeV —> ground state (g.s.) M1 transition is expected
- Our beam also excites 17.6 MeV transitions

X17 production is kinematically allowed also in this transition



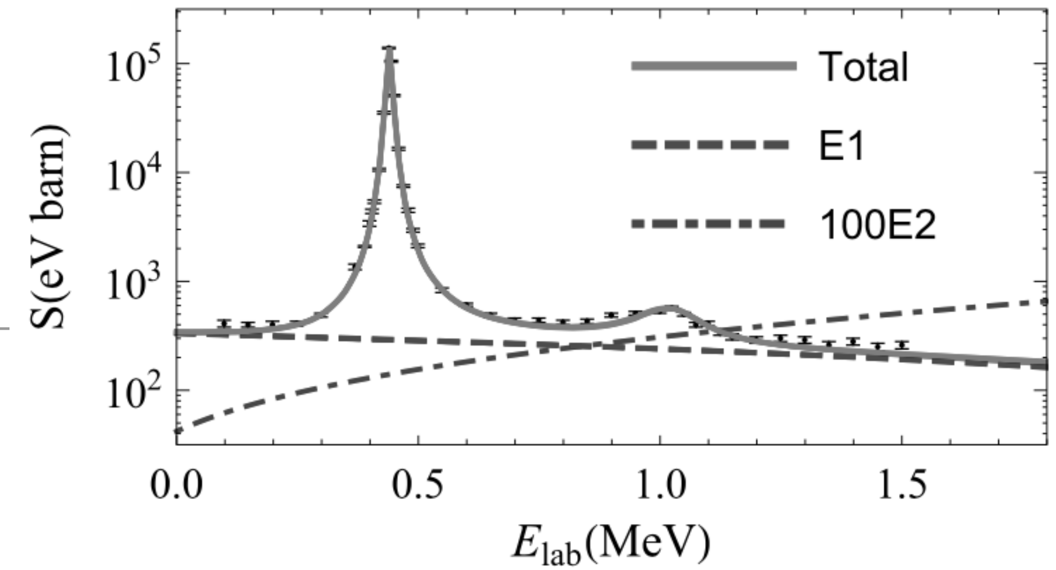
Signal and Backgrounds

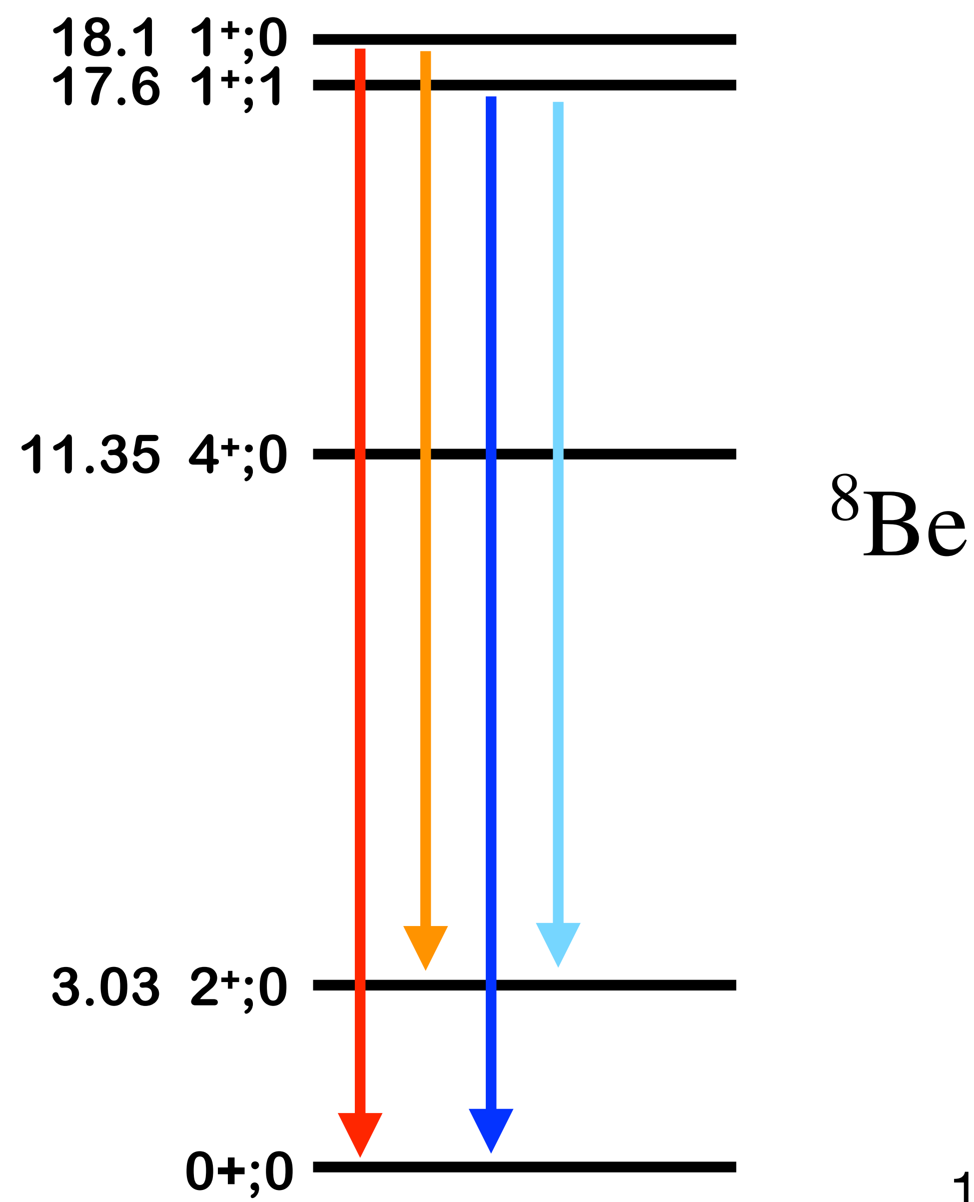
- At Ep ~ 1 MeV, the 18.1 MeV —> ground state (g.s.) M1 transition is expected
- Our beam also excites 17.6 MeV transitions
- Resonances can also deexcite into 1st excited state (3.03 MeV)



Signal and Backgrounds

- At Ep ~ 1 MeV, the 18.1 MeV —> ground state (g.s.) M1 transition is expected
- Our beam also excites 17.6 MeV transitions
- Resonances can also deexcite into 1st excited state (3.03 MeV)
- E1 continuum is also present and **interfering**





Signal and Backgrounds

- At Ep ~ 1 MeV, the 18.1 MeV —> ground state (g.s.) M1 transition is expected
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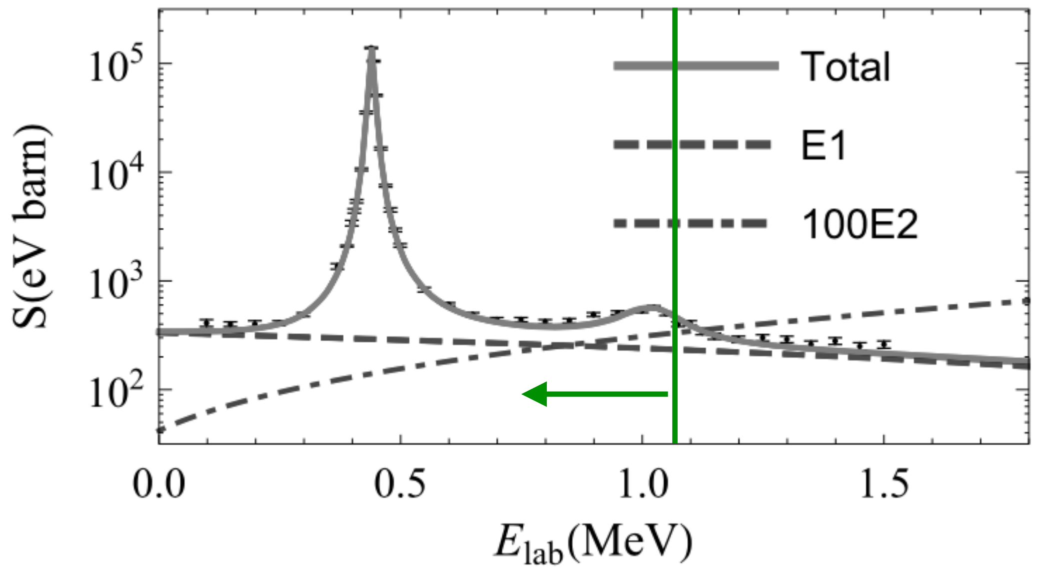
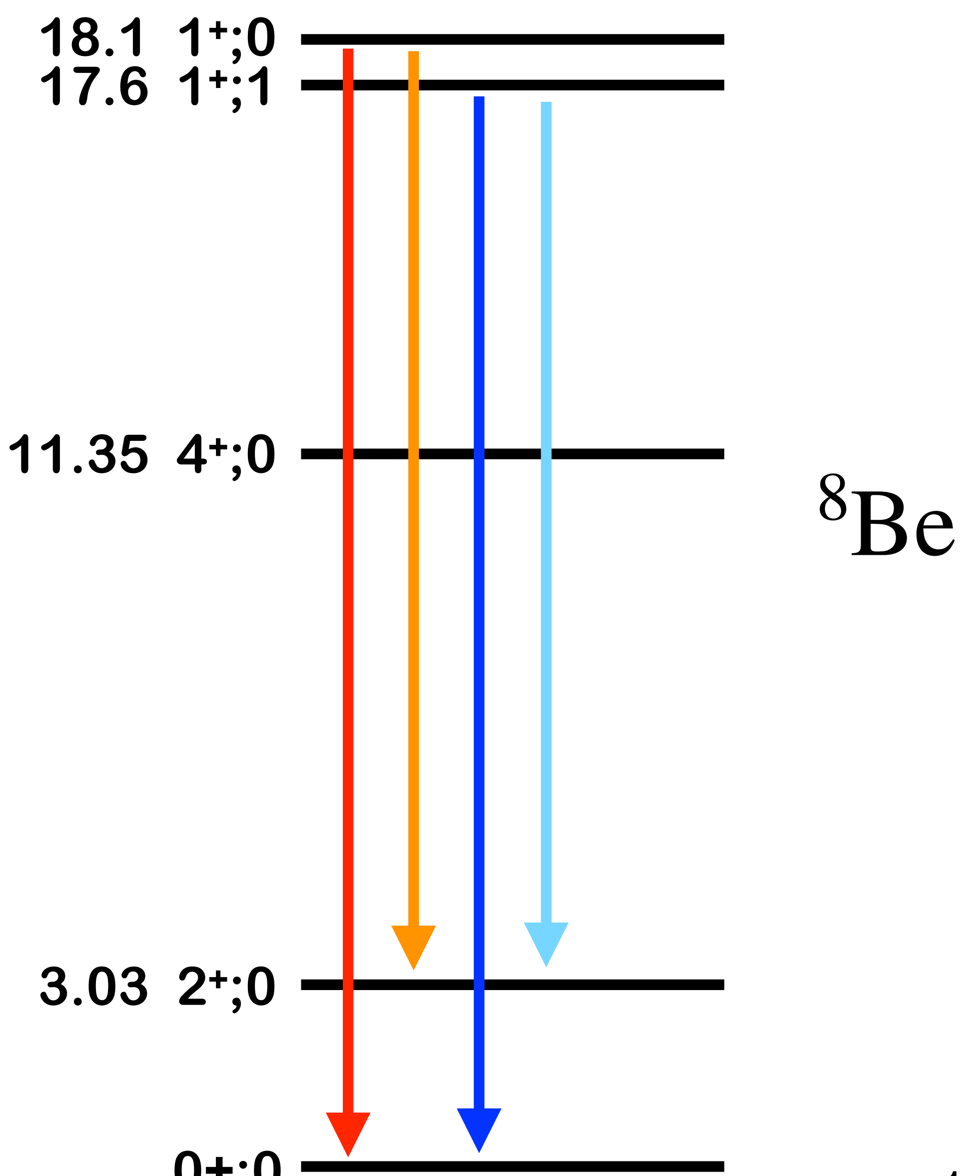
- E1 continuum is also present and **interfering**
- **Energy loss** in the target can also enhance the continuum contribution at intermediate energies





Signal and Backgrounds

- At Ep ~ 1 MeV, the 18.1 MeV —> ground state (g.s.) M1 transition is expected
- Our beam also excites 17.6 MeV transitions
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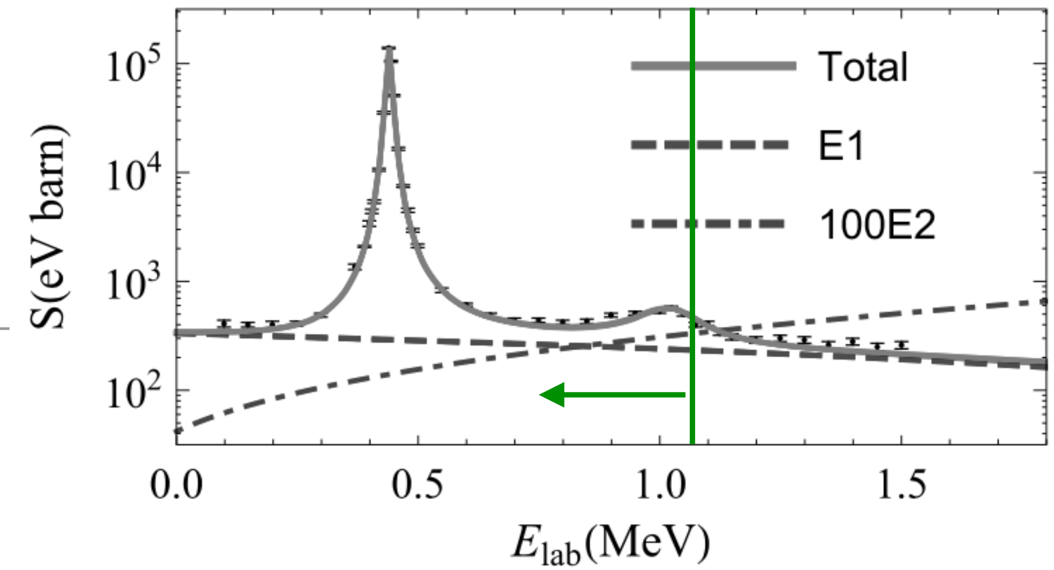
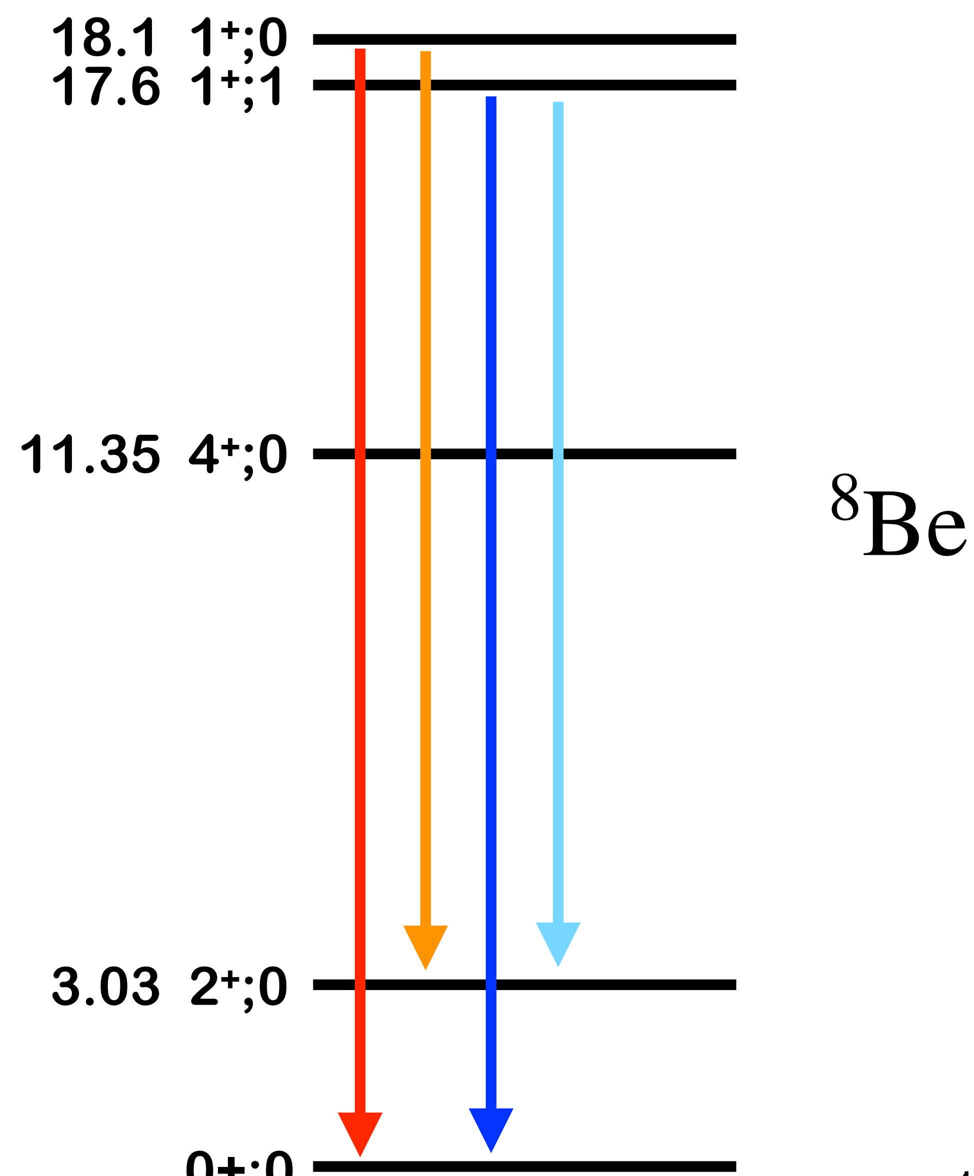


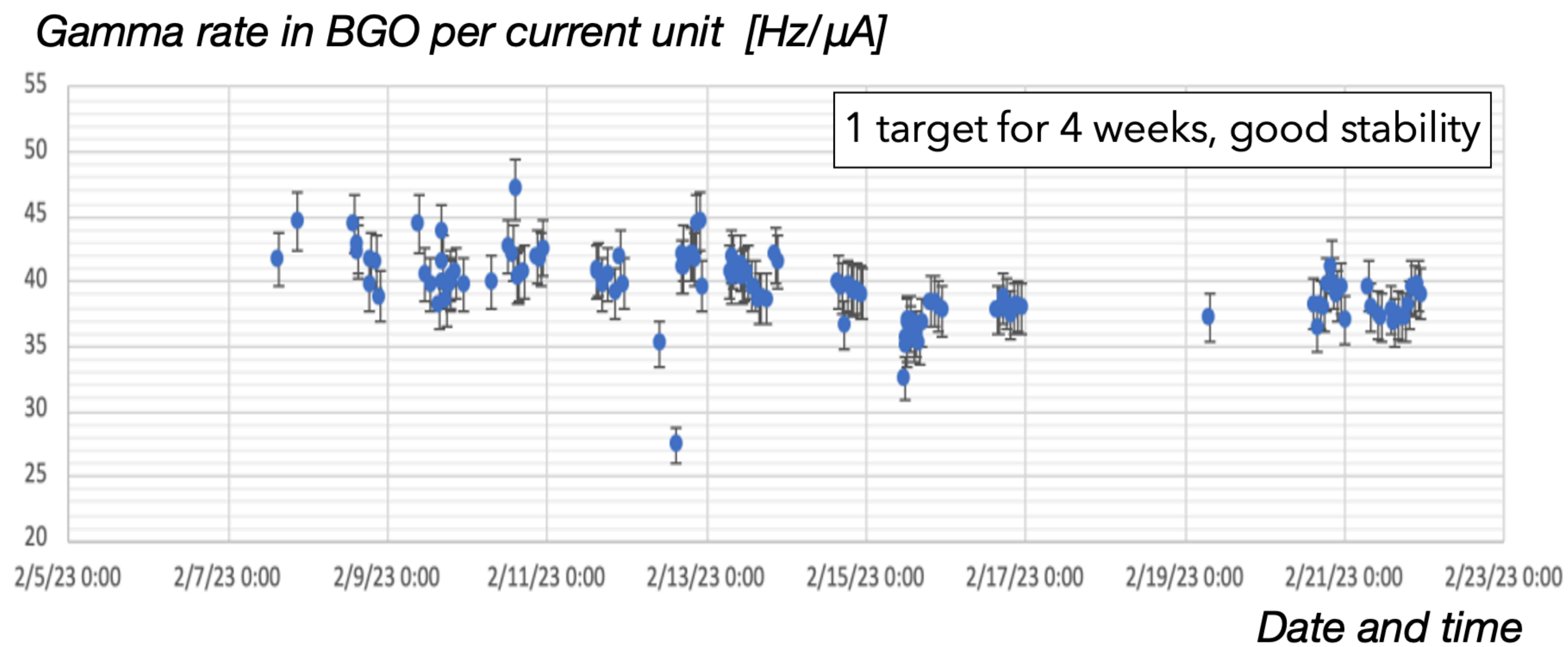
BACKGROUNDS

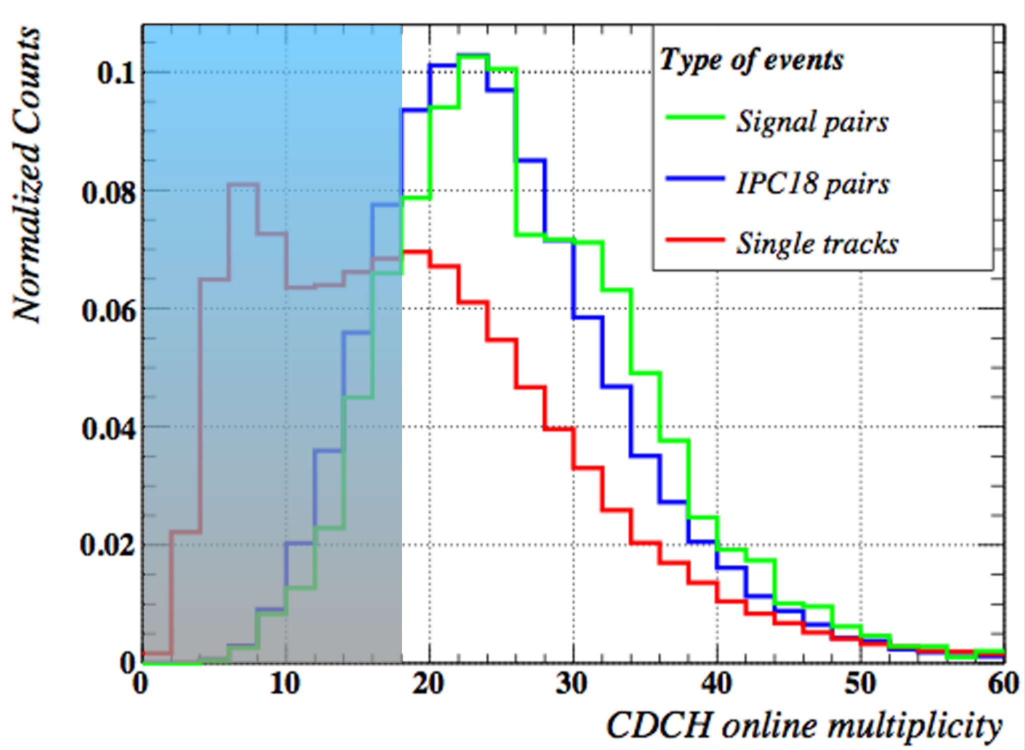
- **internal pair conversion (IPC) of gamma's from either:**
  - **g.s. or 1st excited state transitions**
  - **18.1 MeV, 17.6 MeV, or intermediate energies**
  - **resonant or continuum**
- **external pair conversion (EPC) of gamma's in materials**
  - **from either transition**



Data acquisition

- We collected data for ~ 4 weeks in Feb. 2023
- Beam stability monitored looking at gamma's with an auxiliary BGO detector





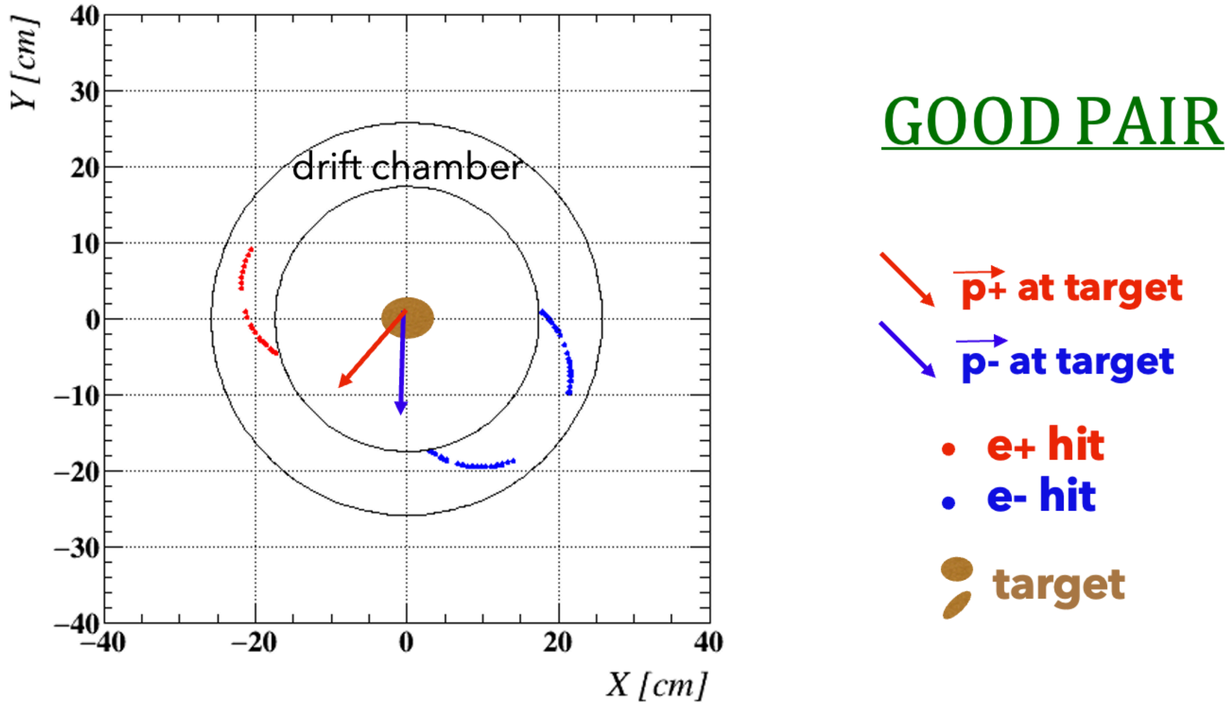
- Trigger logic based on timing detectors and CDCH multiplicity, optimized to enhance the signal contribution

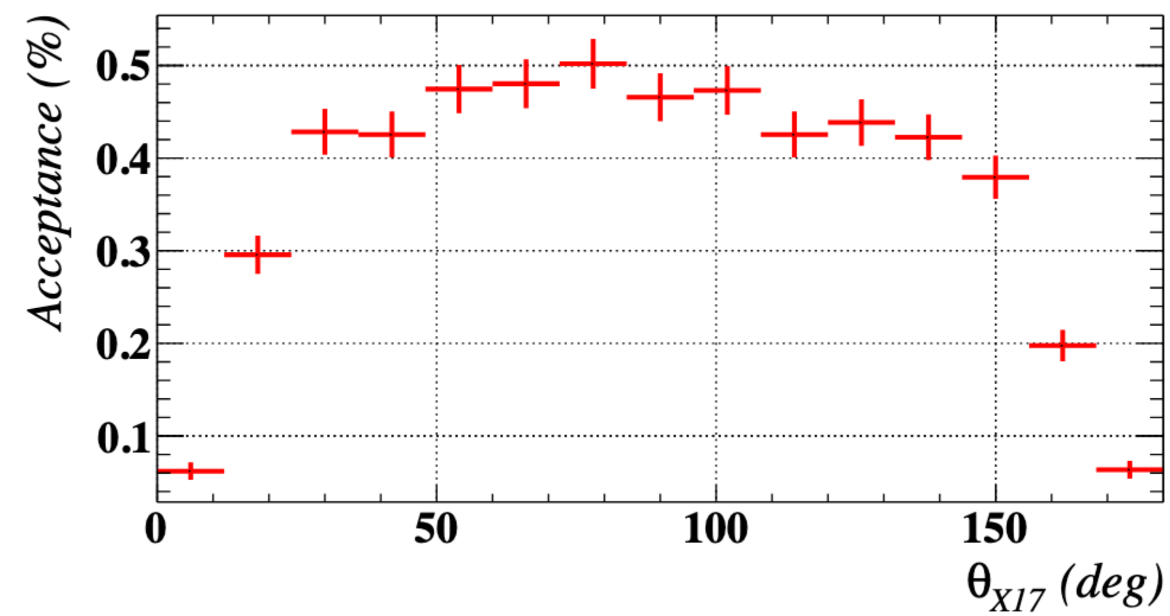
> 18 CDCH hits over 60 mV threshold
+ 1 timing counter hit

16% efficient on signal X17

Rejects single tracks, EPC, pairs asymmetric in energy

Event reconstruction





- The MEG II track reconstruction algorithms were modified to reconstruct both e+ and e- and optimized for the $\mathrm{X17} \rightarrow e^{+}e^{-}$ kinematics
  - Kalman-filter-based pattern recognition + deterministic annealing track fit
- The geometrical configuration of the CDCH limits the achievable efficiency to pairs with **small energy asymmetry** (-0.3 < y < 0.3) in a restricted range of azimuthal angle
  - **trigger x acceptance x efficiency ~ 0.45%**

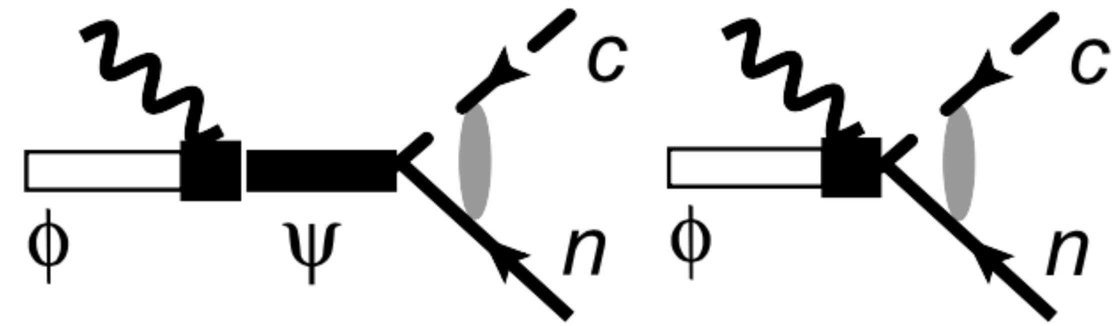
$$y = \frac{E_{+} - E_{-}}{E_{+} + E_{-}}$$

Analysis strategy

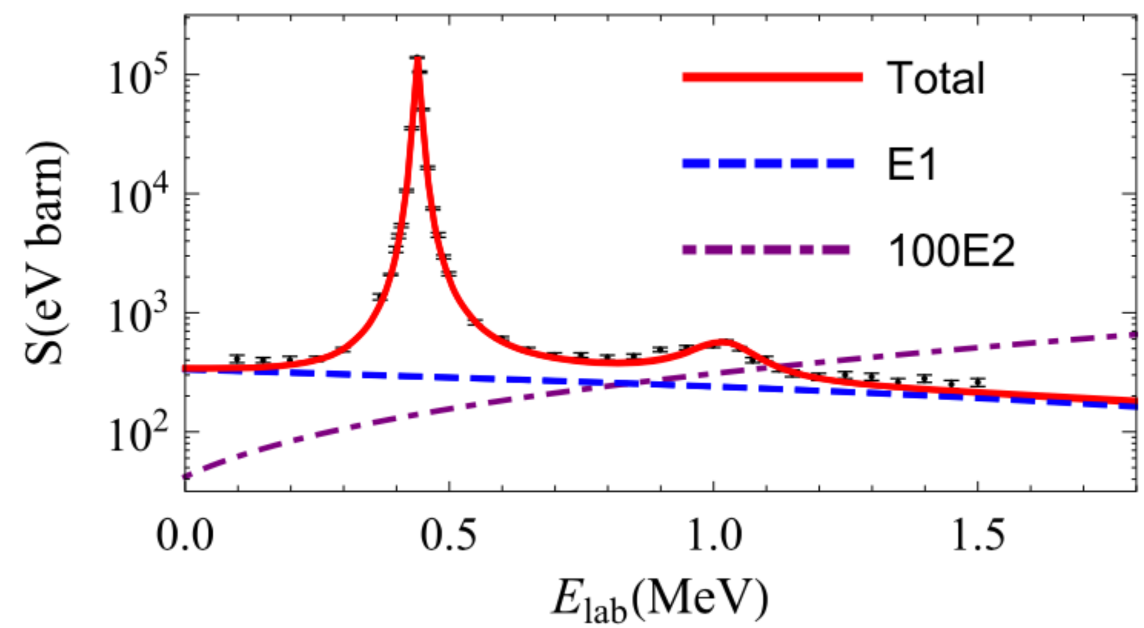
- We need to separate the signal from different background components — we can exploit:
  - E_{sum} = total e^+e^- energy (= Q for transitions to the g.s.; = Q - 3.03 MeV for transitions to the 1st exc. state)
  - θ_{e+e-} = relative e^+e^- angle
- The two variables are used in a 2-dimensional **Maximum Likelihood fit** including all possible signal and background components:
  - PDFs from MC simulations —> good detector model + good theoretical model

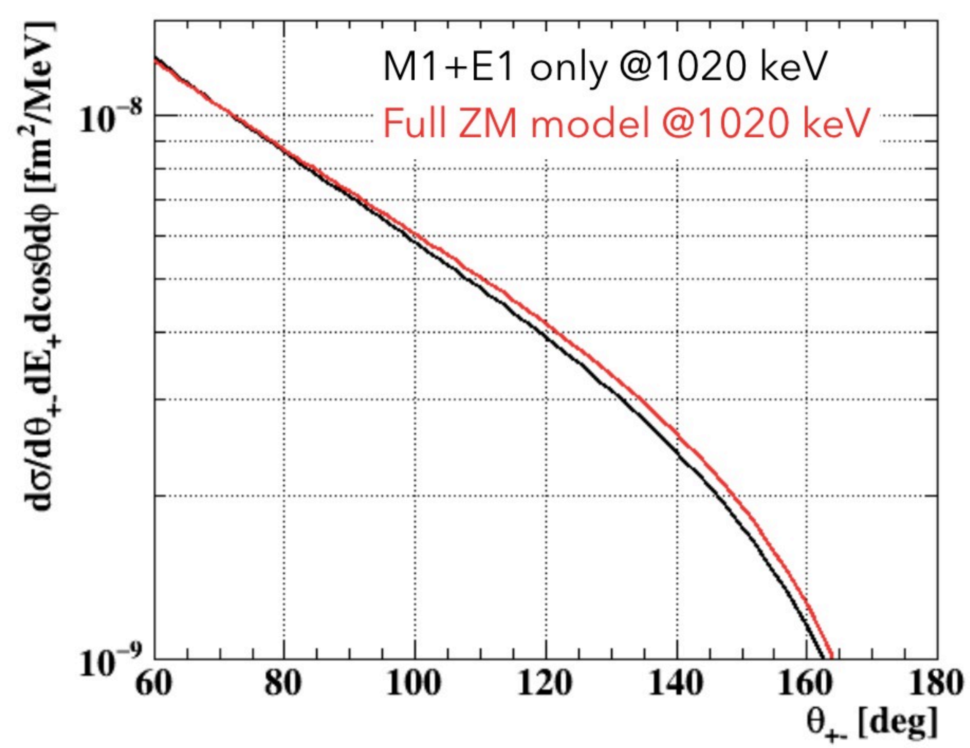
Theoretical model

- Incoherent multipolar decomposition is insufficient to correctly describe e^+e^- spectra with large statistics
- We adopted the model by X. Zhang and G. A. Miller **[Phys. Lett. B 773, 159648 (2017)]**
  - Effective Lagrangian, including M1 resonances + Eℓ continuum contributions
- The model was included in our Monte Carlo simulation and validated in collaboration with the authors
- Ab-initio calculations by Gysbers et al. to be considered in the future **[Phys. Rev. C 110 (2024) 1, 015503]**

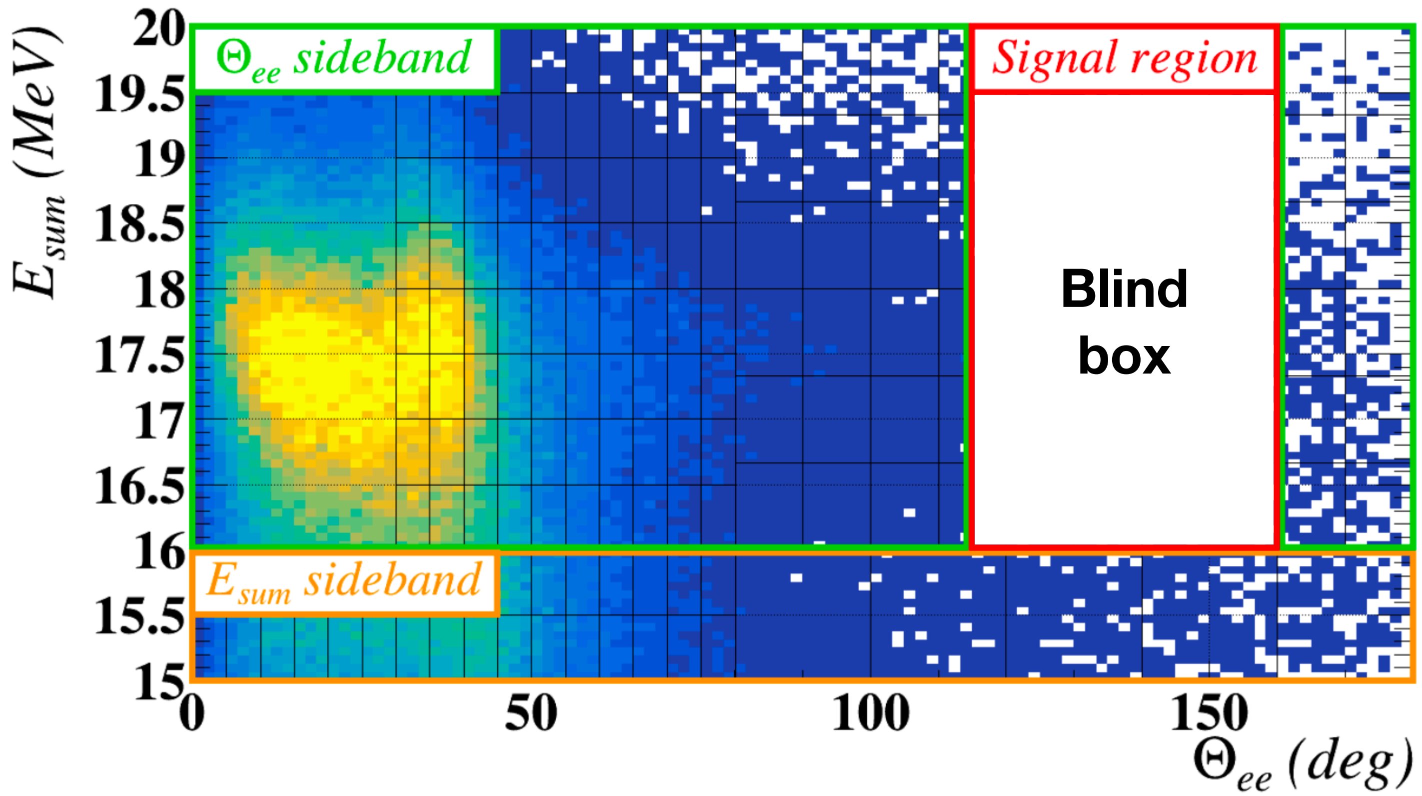


M1 resonances **Eℓ continuum**



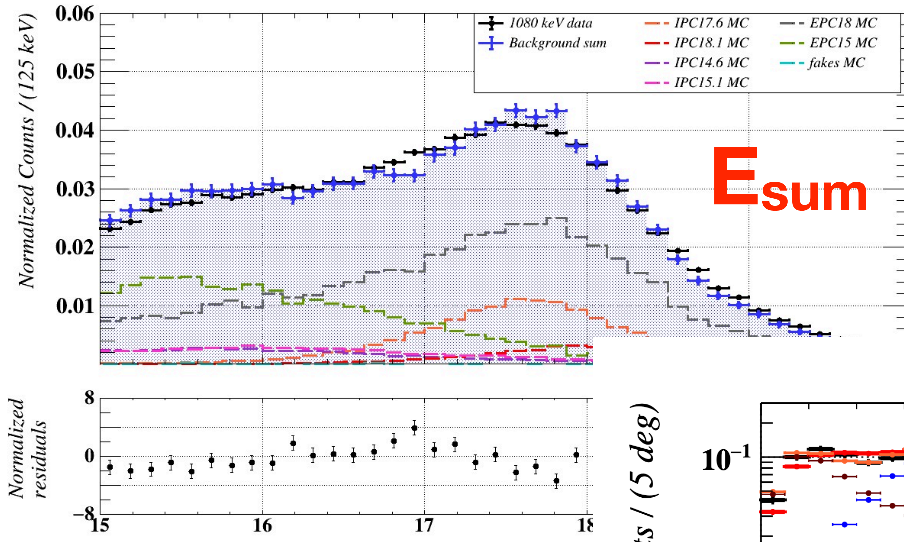


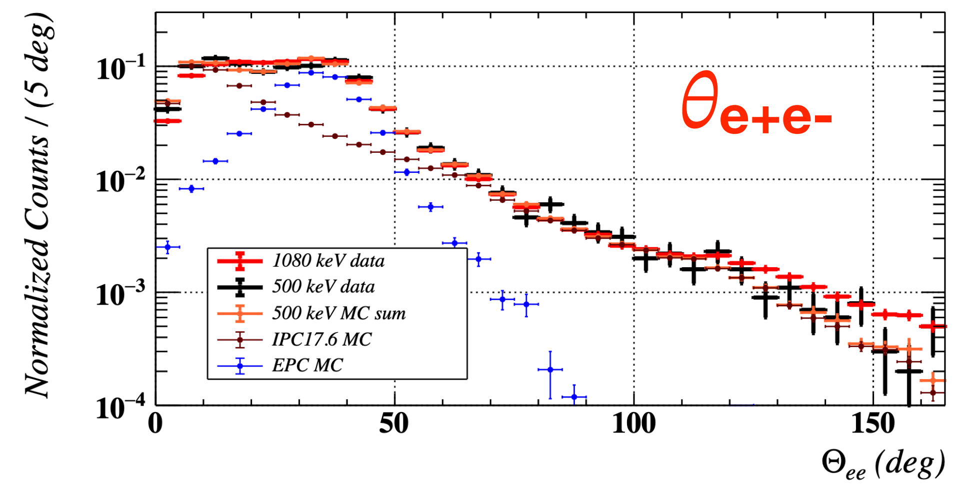
Blind analysis and sidebands



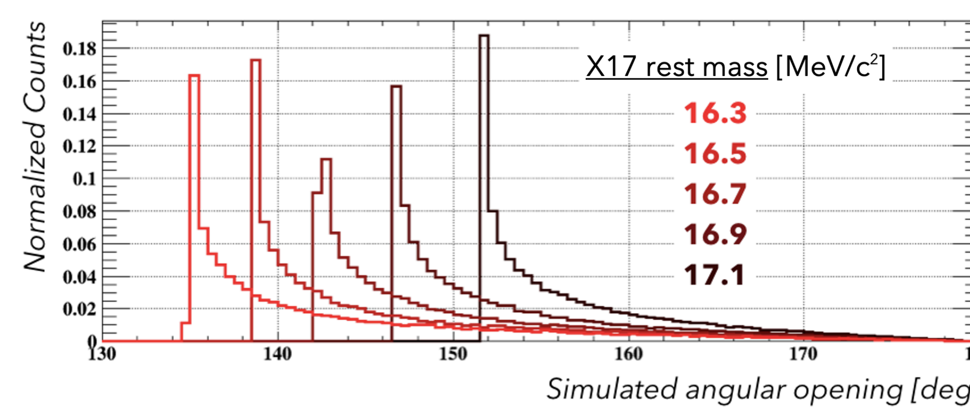
- The analysis procedure was developed and validated without looking into the region of the E_{sum} v.s. θ_{e+e-} plane where the signal is expected
- We looked into the signal region only once we could demonstrate that:
  - our method correctly described the data in the sidebands
  - our method was capable of discriminating the different background components

Binned Likelihood





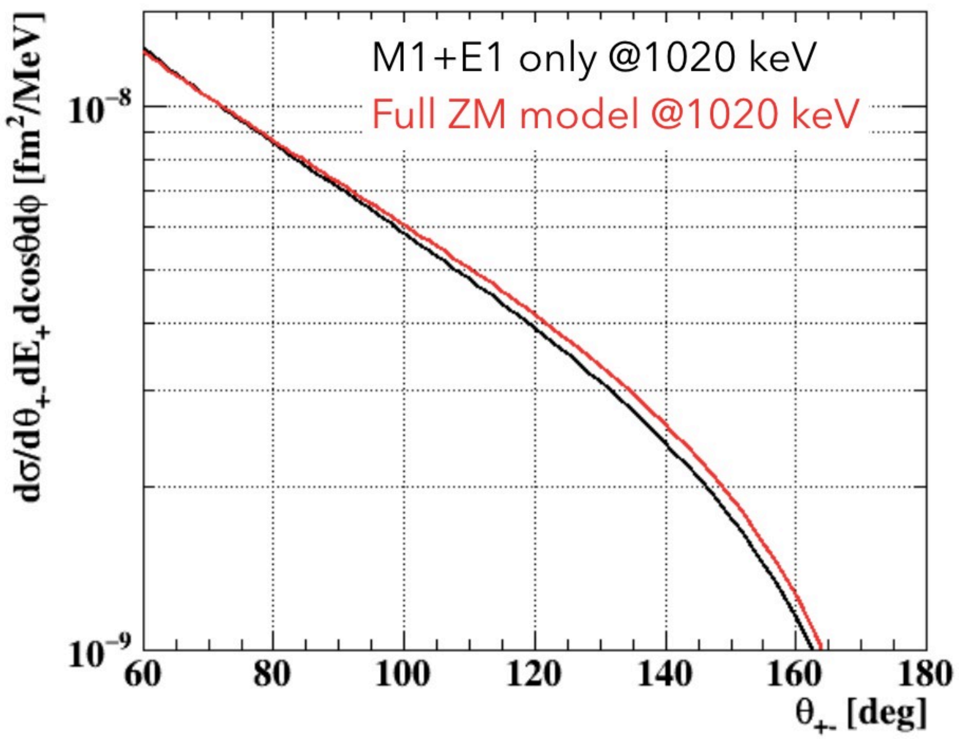
- 2 observables: E_{sum} and θ_{e+e-}
- 11 event species:
  - 2 signals: X17 from 17.6 MeV and 18.1 MeV transitions to g.s.)
  - 6 IPC: (17.6 + 18.1 + intermediate energies) x (g.s. + 1st excited)
  - 2 EPC: g.s. + 1st exc. (no relevant E_p dependence was observed)
  - 1 fake pairs (single track segments reconstructed as two tracks)
- 12 parameters: 2 signal rates + X17 mass + 9 background yields
  - X17 mass in the range allowed by kinematics and ATMOKI results (within 2.5σ)
- Technical aspects:
  - 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)]**



Discrimination of fit components

- Is our fit capable of separating the different background components? **Yes!**

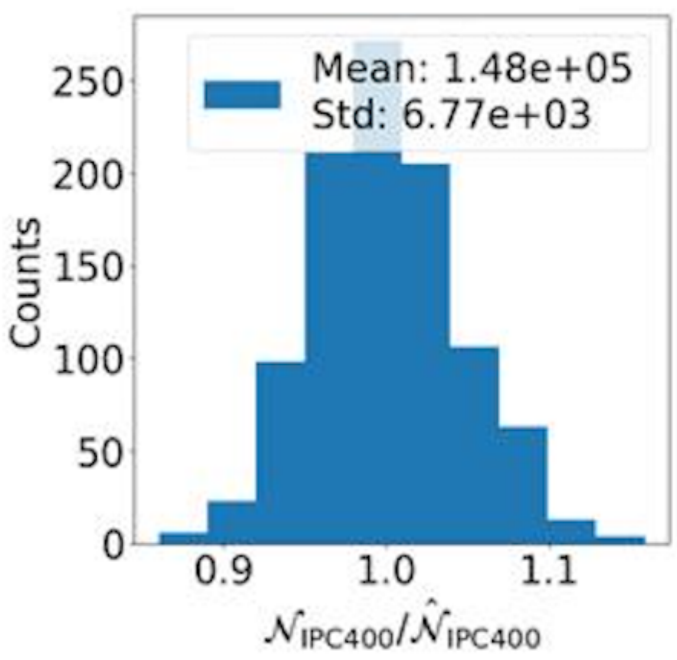
Enabled by Physics



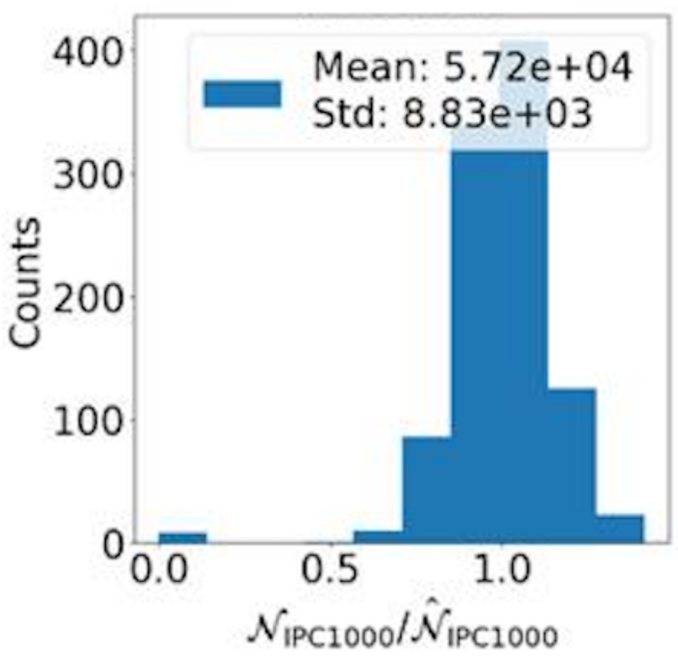
*Due to **interference** between M1 and E1, and **acceptance** effects, IPC components are linearly independent (each one cannot be described as a linear combination of the others)*

Proved by Statistics

17.6 MeV IPC

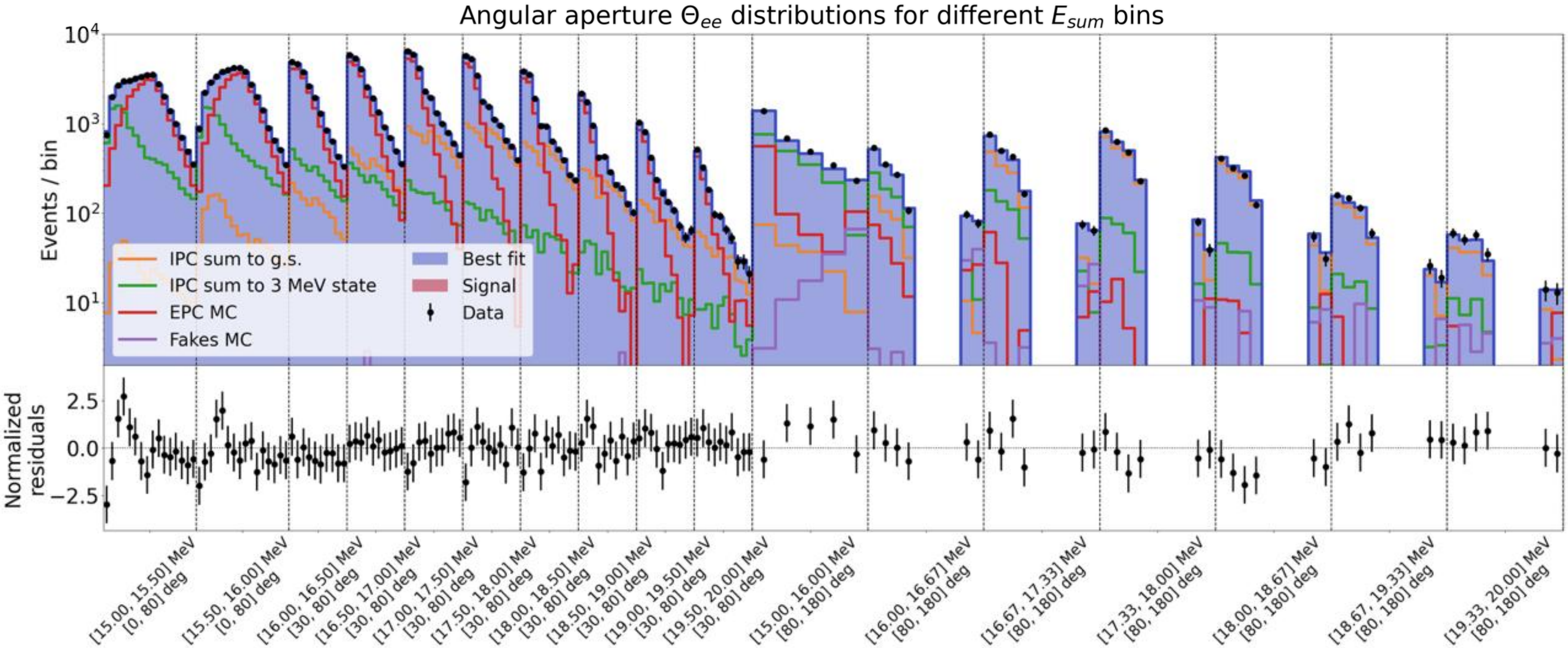


18.1 MeV IPC



*Before unblinding, a variety of tests on **toy MC experiments** proved that the fit separates correctly the different signal and background species (good distributions of fitted yields)*

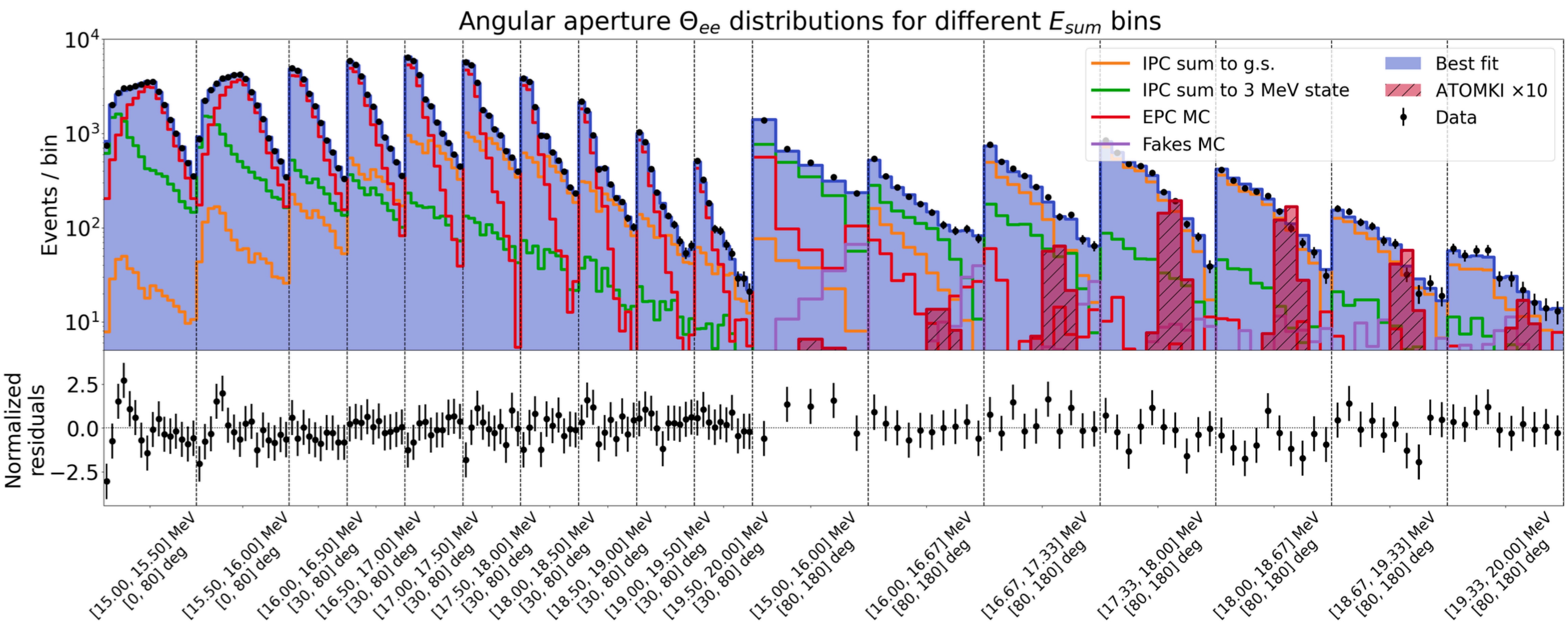
Validation of the ML fit in the sidebands



- Uncertainties from MC statistics inflated by a factor of $\sqrt{3}$ before unblinding to include additional systematic uncertainties for data/MC disagreements

Fit results

Goodness-of-fit: p-value = 10%

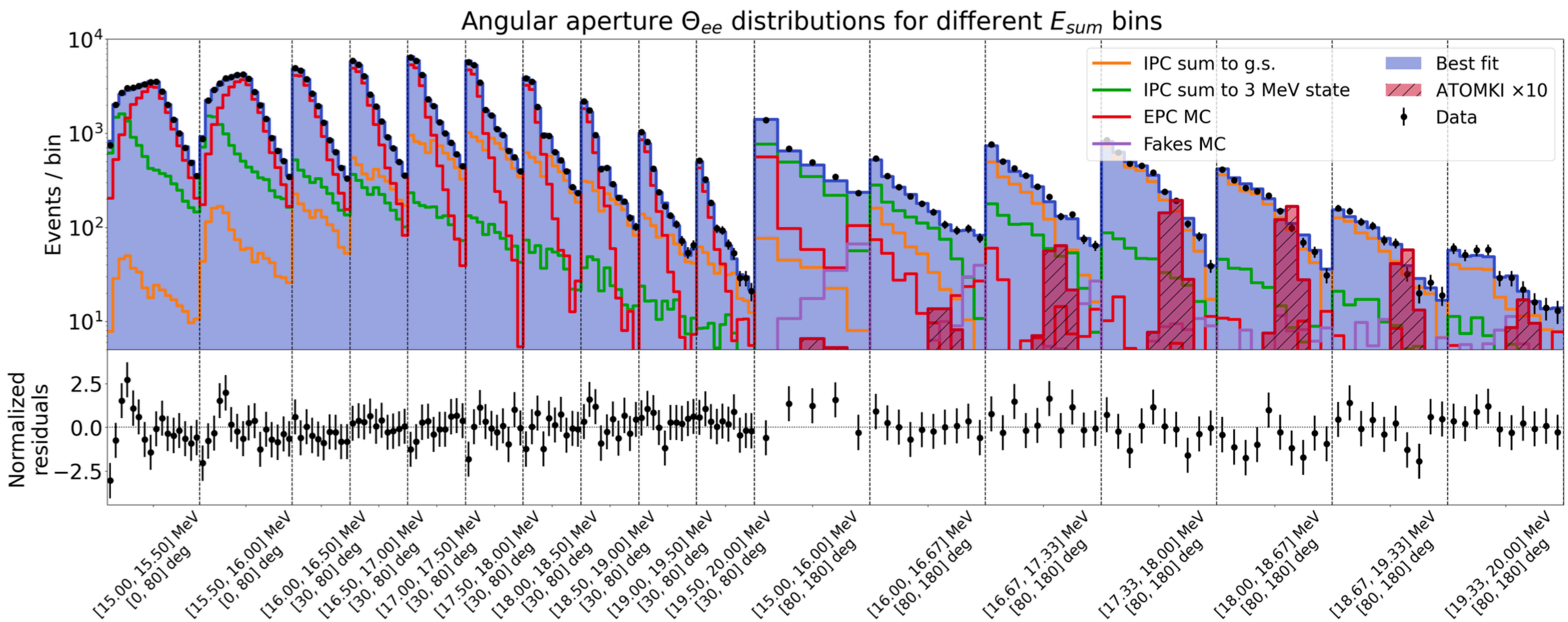


BEST FIT

	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**

Fit results

Goodness-of-fit: p-value = 10%



BEST FIT

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

Fit results

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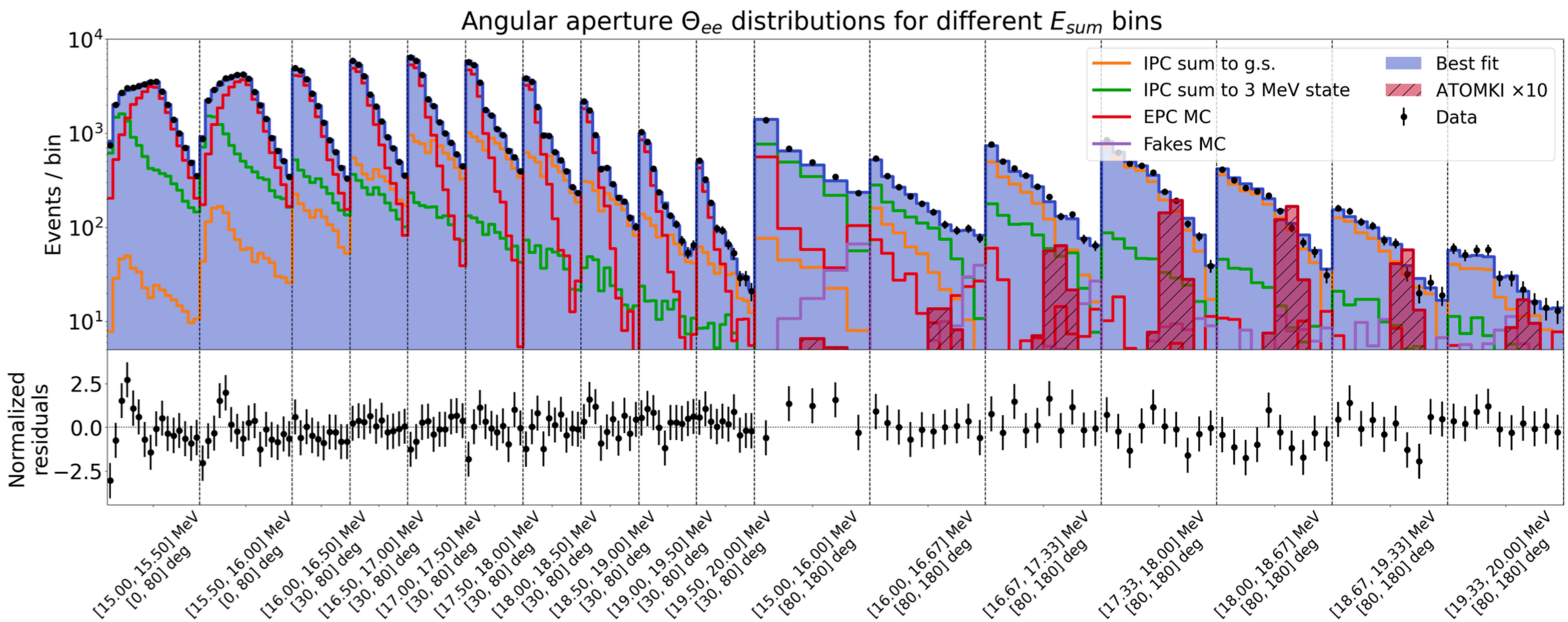


BEST FIT

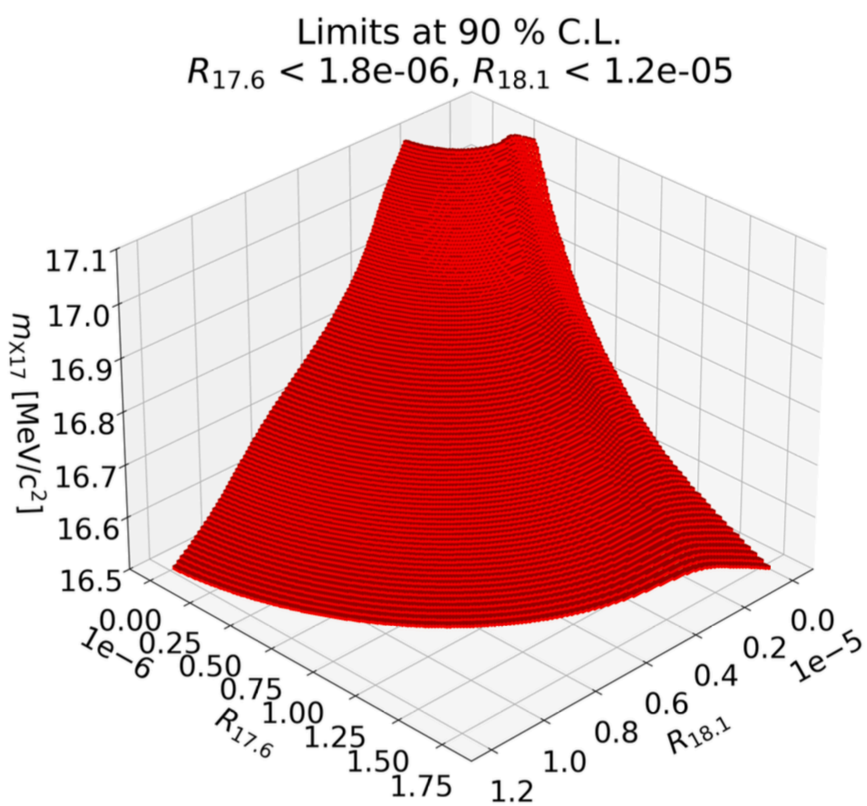
No significant signal

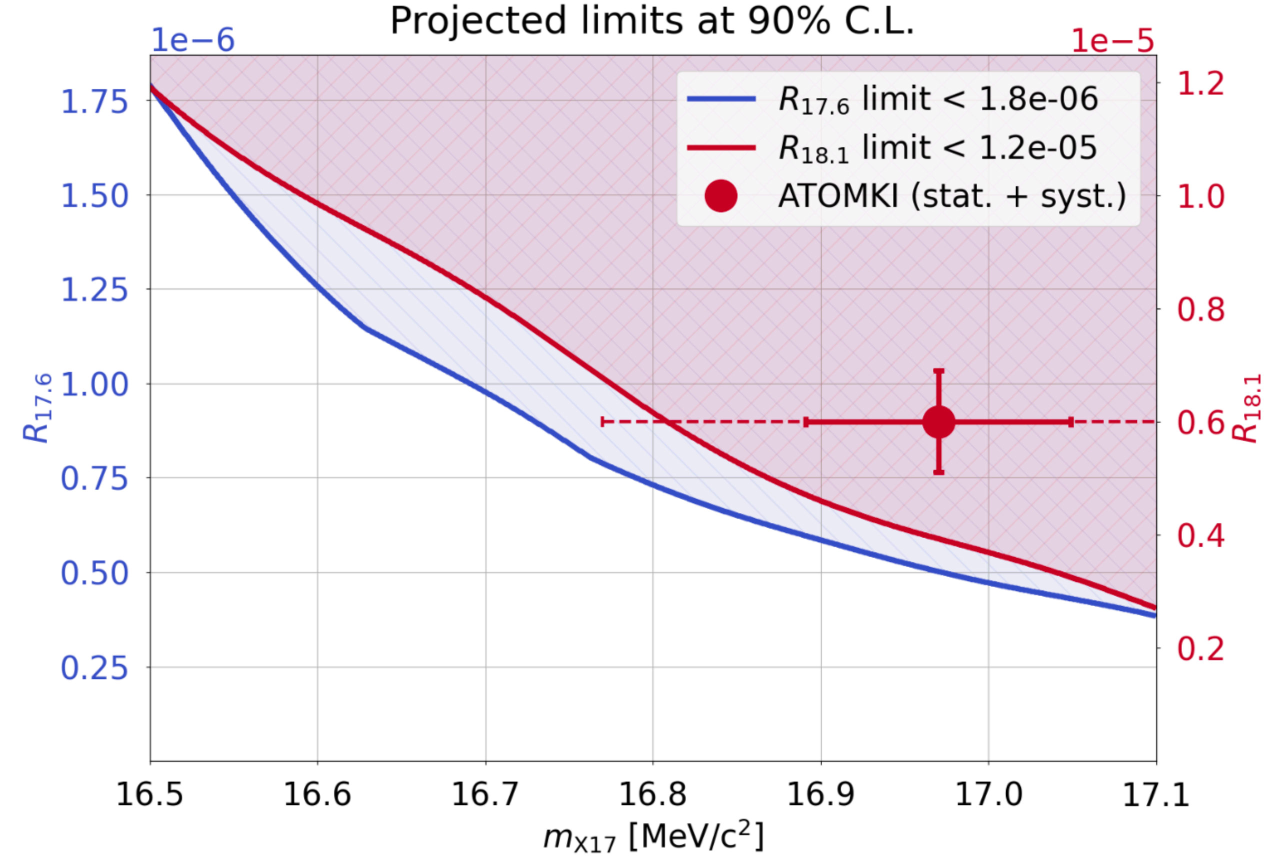
Energy loss doesn't push protons significantly out of the 18.1 MeV resonance

	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

Confidence regions

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





- Our result is a **3D confidence interval** at 90% C.L. on signal BR relative to gamma emission (R_Q) and X17 mass, following the Feldman-Cousins prescription
- The interval is conservatively projected in 1D or 2D, by taking the maximum extension of the interval in the projection parameter or plane

$$R_{17.6} < 1.8 \times 10^{-6}$$

$N^{sig}_{17.6} < 200$

$$R_{18.1} < 1.2 \times 10^{-5}$$

$N^{sig}_{18.1} < 230$

Hypothesis tests

- We also performed two exemplificatory hypothesis tests (others could be considered):

  - No X17 production at 17.6 MeV, production at 18.6 MeV with X17 mass and rate according to the combination of ATOMKI results **[*]** **—> p-value 6.2% (1.5σ)**

  - X17 production at both 17.6 MeV and 18.1 MeV, with rates scaled according to J. Feng et al. **[Phys. Rev. Lett. 117(7), 071803 (2016)]** **—> p-value 1.8% (2.1σ)**

[*] Journal of Physics: Conference Series 1056, 012028 (2018).
arXiv:1910.10459
Phys. Rev. C 106, L061601599 (2022)

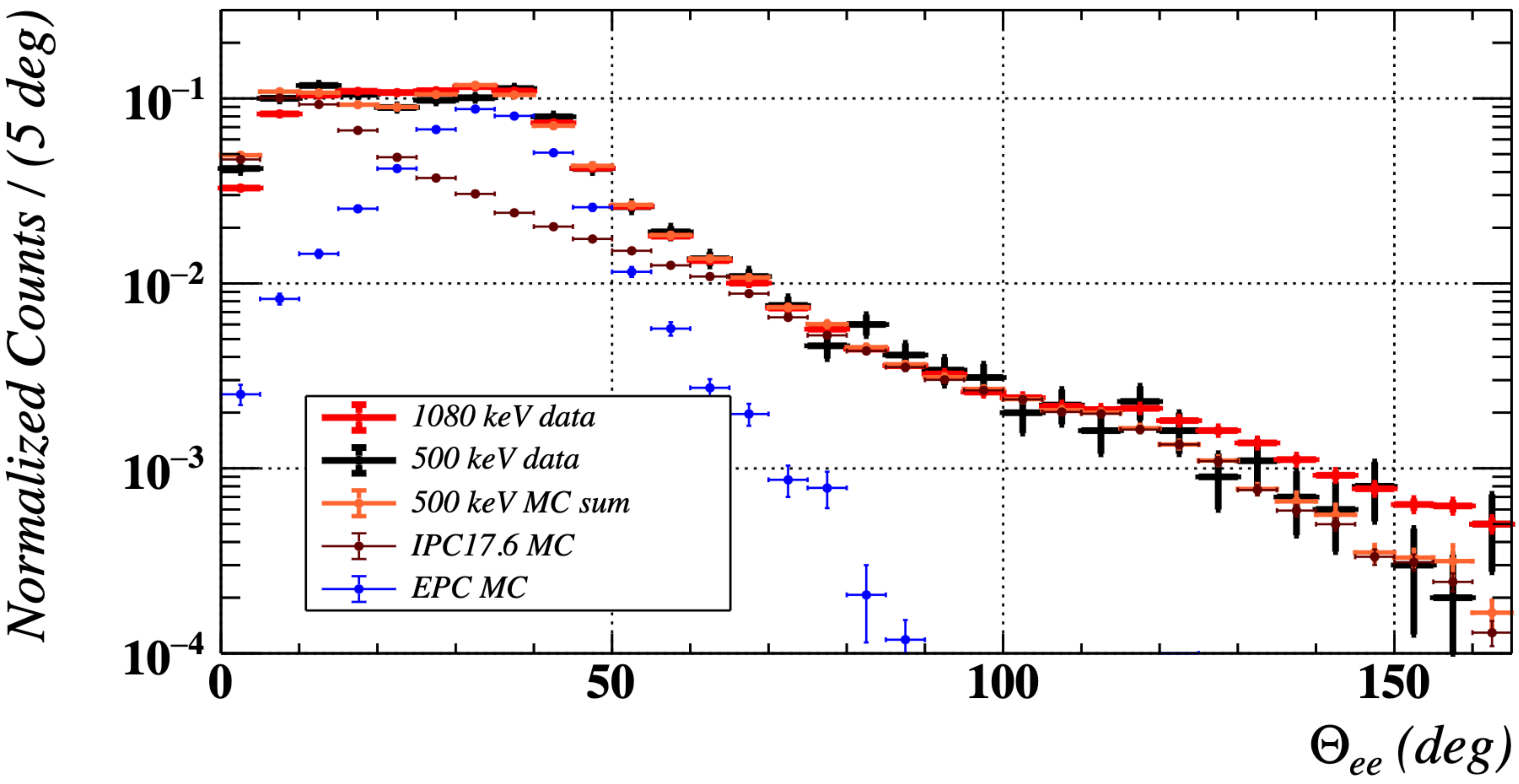
Future perspectives

- A new data-taking run to be performed in the upcoming weeks is under consideration:
    - $\mathbf{H}^+$ beam selection (already tested and proved)
    - thinner and more uniform LiPON target
- We are considering the implementation of ab-initio calculations in our MC, for independent control of the background PDFs

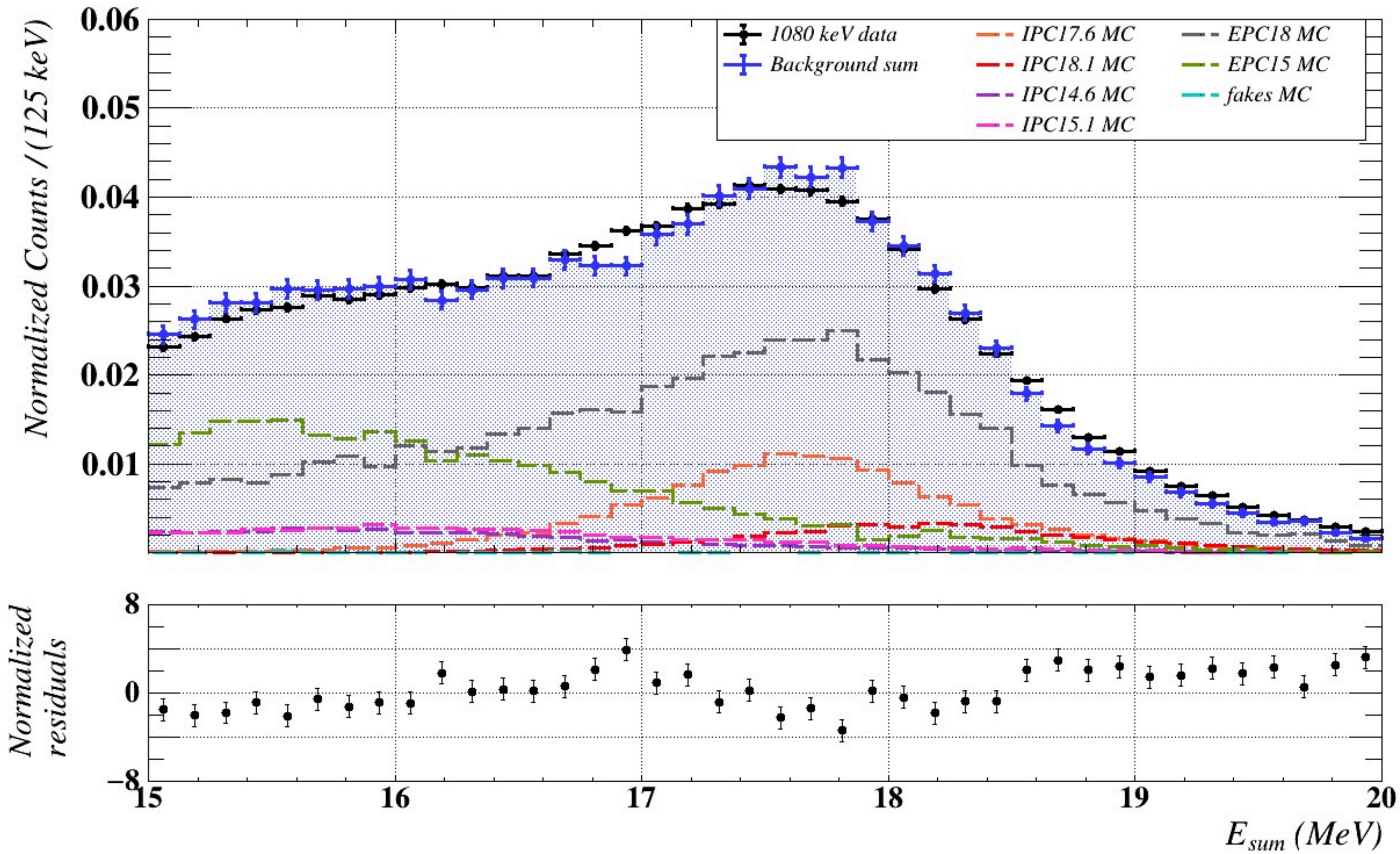
Conclusions

- X17 can be searched at MEG II in $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$ reactions, with protons from a dedicated CW accelerator and e^+e^- tracking in a magnetic spectrometer with large polar acceptance
- First data-taking run in 2023, affected by H_2^+ component in the beam
  - additional backgrounds, but possibility to study X17 production at 17.6 MeV
  - a carefully implemented analysis strategy was proved to be able to separate the different components
- We could not observe the X17, and we set limits and tested hypotheses derived from the ATOMKI results:
  - X17 production at the rate observed at ATOMKI is disfavoured but not fully rejected (p-value = 6.3%)

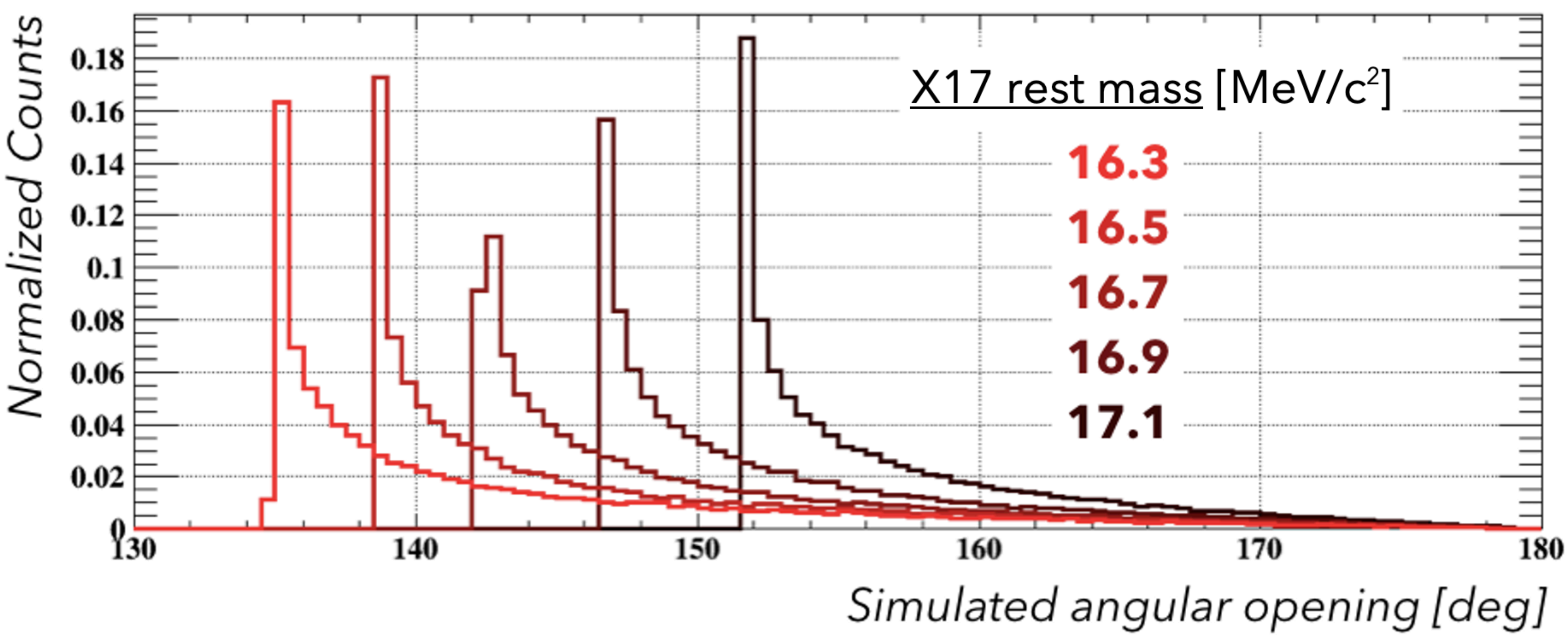
Backup



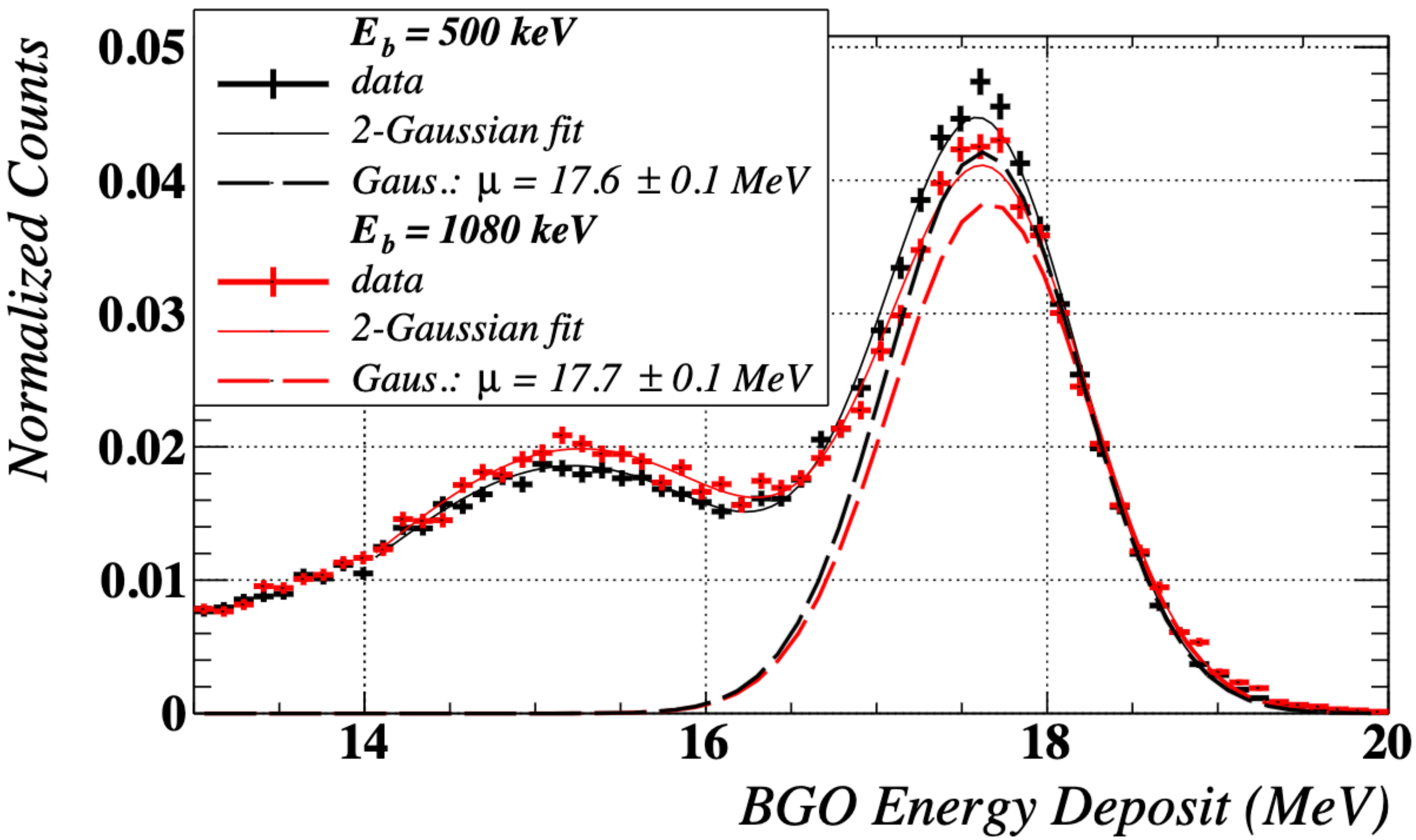
Normalized Counts / (5 deg)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
50
100
150
Θ_{ee} (deg)
1080 keV data
500 keV data
500 keV MC sum
IPC17.6 MC
EPC MC



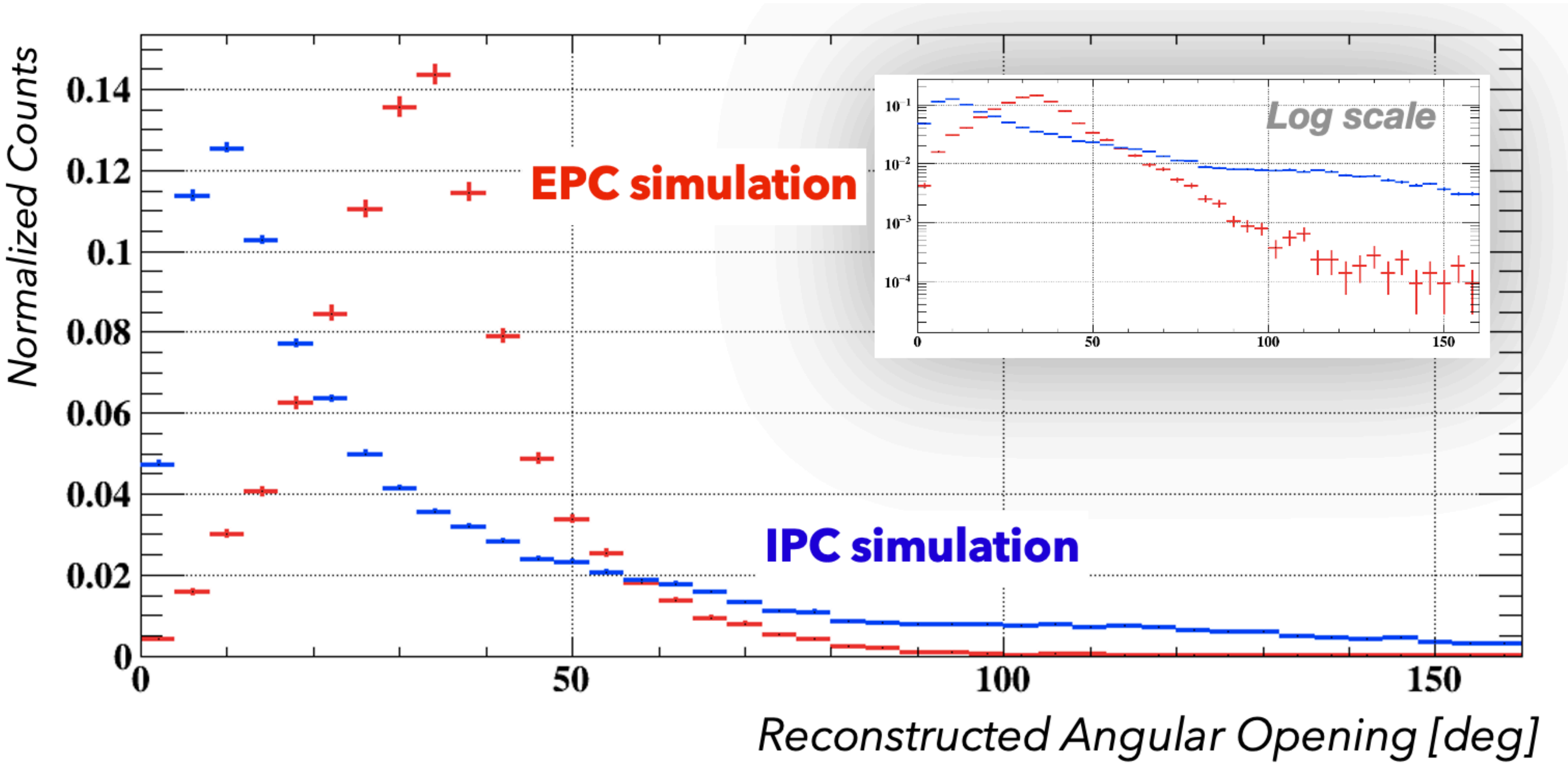
1080 keV data
Background sum
IPC17.6 MC
IPC18.1 MC
IPC14.6 MC
IPC15.1 MC
EPC18 MC
EPC15 MC
fakes MC
Normalized Counts / (125 keV)
0.06
0.05
0.04
0.03
0.02
0.01
Normalized residuals
8
0
−8
15
16
17
18
19
20
E_sum (MeV)



Normalized Counts
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
130
140
150
160
170
180
Simulated angular opening [deg]
X17 rest mass [MeV/c²]
16.3
16.5
16.7
16.9
17.1



$E_b = 500$ keV
data
2-Gaussian fit
Gaus.: μ = 17.6 ± 0.1 MeV
$E_b = 1080$ keV
data
2-Gaussian fit
Gaus.: μ = 17.7 ± 0.1 MeV
Normalized Counts
0.05
0.04
0.03
0.02
0.01
0
14
16
18
20
BGO Energy Deposit (MeV)



Normalized Counts
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
50
100
150
Reconstructed Angular Opening [deg]
EPC simulation
IPC simulation
Log scale