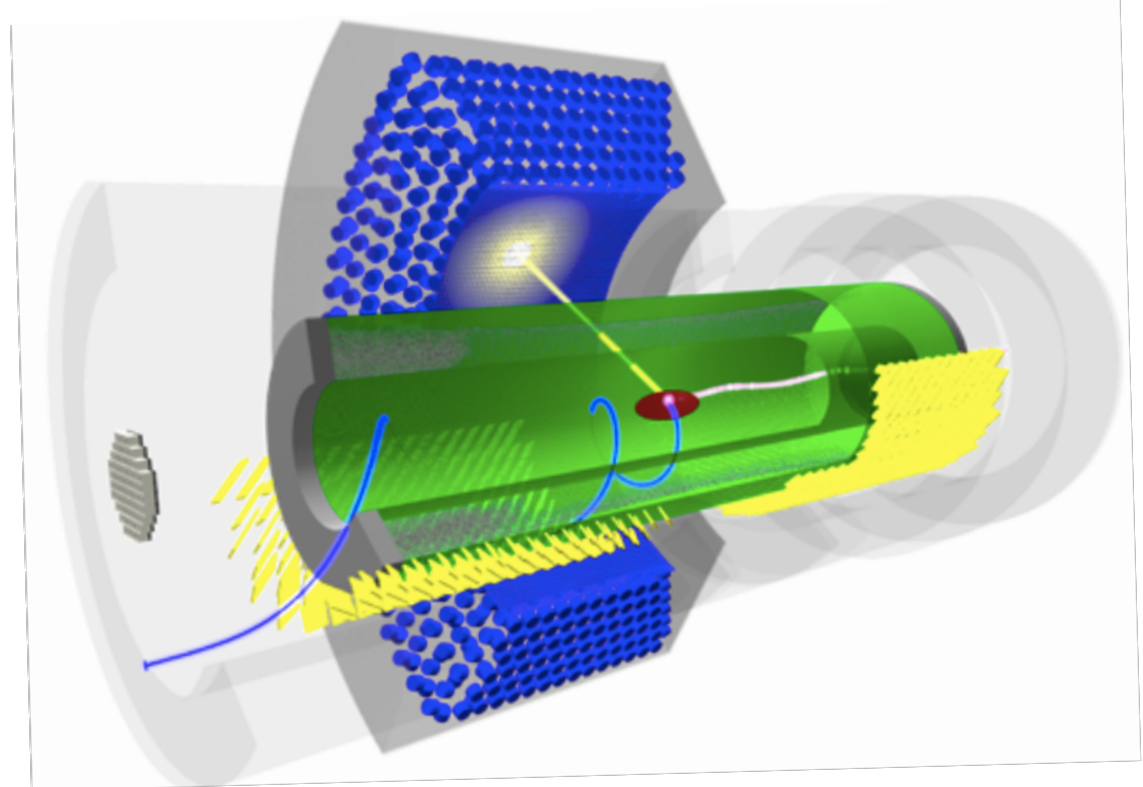
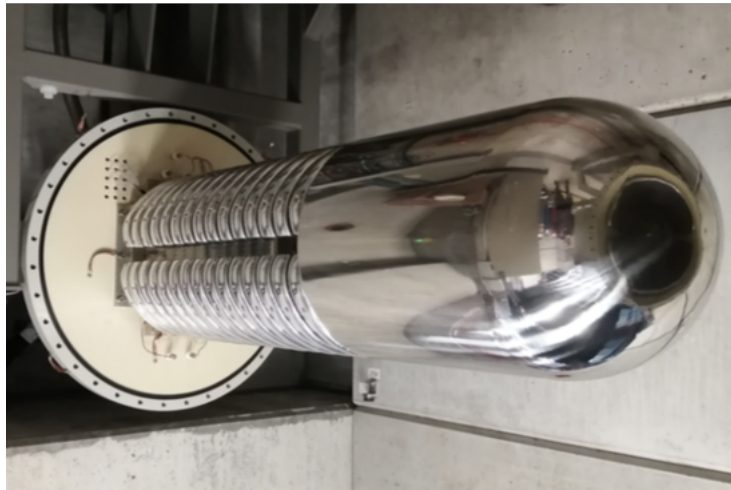




Search for the X17 particle in the ${}^7\text{Li} (p, e^+e^-){}^8\text{Be}$ process with MEG II

Gianluca Cavoto (*Sapienza Univ Roma and INFN Roma*)

On behalf of the MEG II collaboration

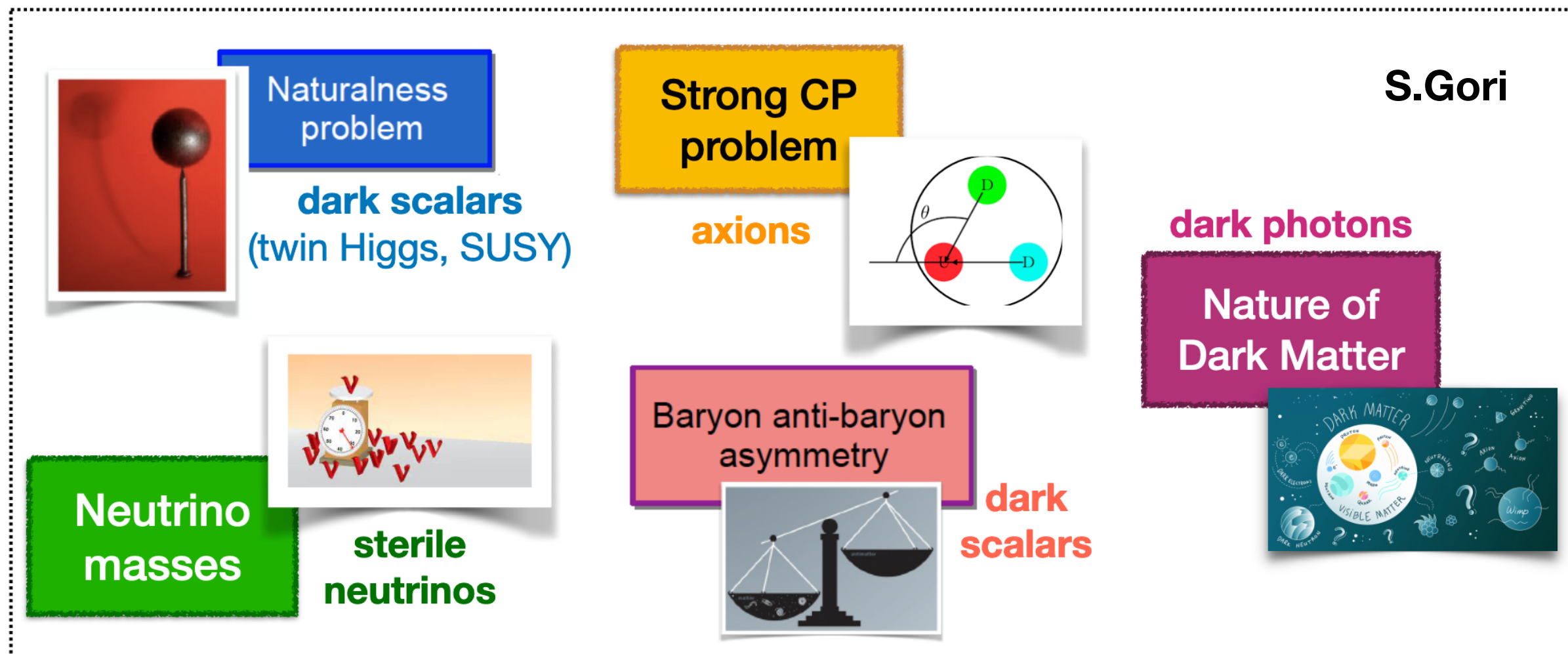
LNF seminar - 17th Sep 2025

Outline

- ▶ New particles?
- ▶ The Atomki **anomaly**
- ▶ MEG II for ${}^7\text{Li}$ (p, e^+e^-) ${}^8\text{Be}$
- ▶ **${}^8\text{Be}$ data analysis and results**

Reasons for more particles

- ▶ We love Standard Model but we are not totally satisfied



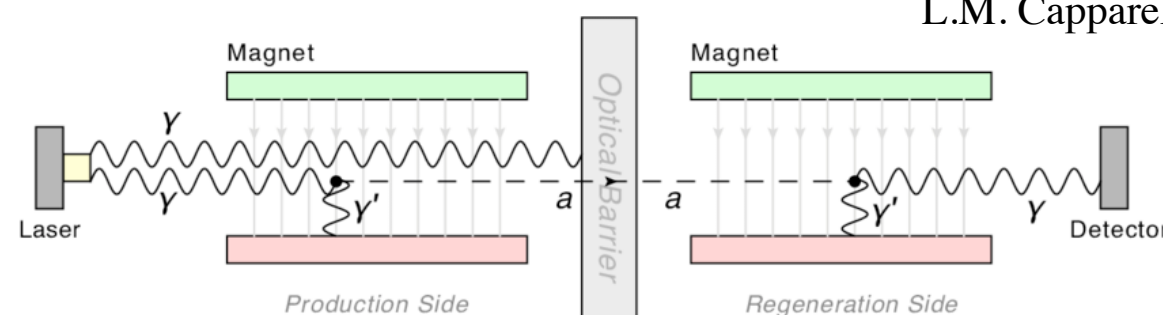
- ▶ One **Beyond SM** possibility:
an entirely new “dark” sector of new particles?

One important example

- ▶ **QCD axion**: fix the strong CP problem.
 - ▶ *why strong interactions are CP invariant while theory can develop a CP-odd term ? (see neutron EDM)*
 - ▶ In the '70s a ~ 10 MeV **axion a** was proposed to be searched in **nuclear de-excitations**: $^{12}\text{C}^*$ decay (rate predicted from ^{12}B β decay)

S. B. Treiman and F. Wilczek, Phys. Lett. 74B, 381 (1978)
- ▶ However, **visible** (*i.e. through its decay products*) **a** mostly excluded by
 - ▶ quarkonia radiative decay: $J/\psi \rightarrow \gamma a$ (**$a \rightarrow e^+e^-$**)
 - ▶ beam dump experiments,
 - ▶ $(g-2)_\mu$ limit...
 - ▶ pion and kaon decays, ...

Today,
an **invisible ultra-light ($\mu\text{eV} - \text{meV}$)**
 a is searched.



L.M. Capparelli et al, Phys. Dark Univ. 12 (2016) 37-44

Room for a “heavy” axion??

- ▶ However, an ***a*** with ***m_a ~ 10 MeV still viable IF:***
 - ▶ Coupling only to *u* and *d* quark (no heavy quark)
 - ▶ Very fast decay (no beam dump exp.)
 - ▶ No coupling to *mu* - only to electron
 - ▶ Avoiding mixing with pion! (pion-phobia)

$$\Gamma(\pi^+ \rightarrow e^+ \nu_e a) = \frac{\cos^2 \theta_c}{384\pi^3} G_F^2 m_\pi^5 \theta_{a\pi}^2 ;$$

a → e⁺e⁻

SINDRUM, PLB 175 1 (1986) 101-104

$$|\theta_{a\pi}| \lesssim (0.5 - 0.7) \times 10^{-4}.$$

- ▶ Chiral pert. theory (*u, d, e* and *a* only)

U(1) charge for *u* quark

D. S.M. Alves Phys. Rev. D 103, 055018

$$\mathcal{L}_a^{\text{eff}} = m_u e^{i Q_u^{\text{PQ}} a} f_a u u^c +$$

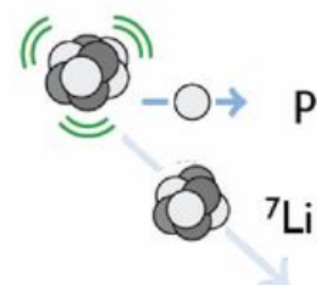
$$\frac{Q_u}{Q_d} = 2 \Rightarrow \theta_{a\pi}^{(0)} \approx \frac{4 Q_d}{3} \frac{f_\pi}{f_a} \left(\frac{1}{2} - \frac{m_u}{m_d} \right) \approx 0.$$

being $m_u/m_d \sim 0.5$

***ad hoc* model but not impossible
Look for **e⁺e⁻** bumps!**

Internal Pair conversion (IPC)

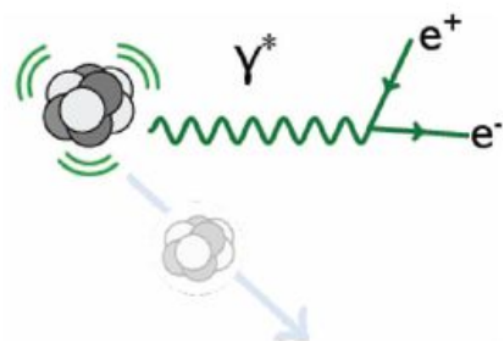
- Nuclei can emit e^+e^- instead of a photon in a nuclear de-excitation.



Hadronic
dissociation



Electromagnetic
Transition
(γ emission)

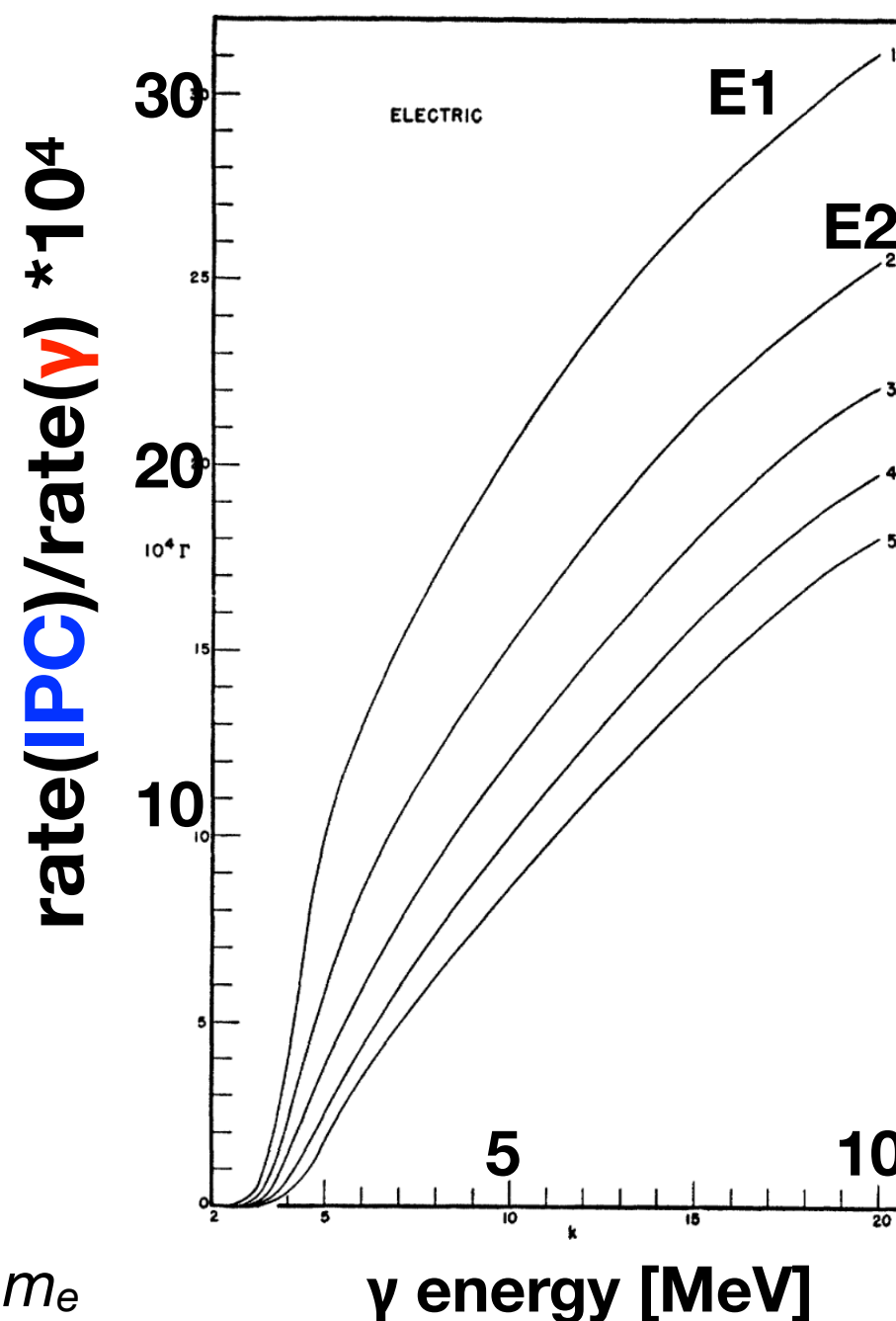


IPC

1 IPC every 1000 γ

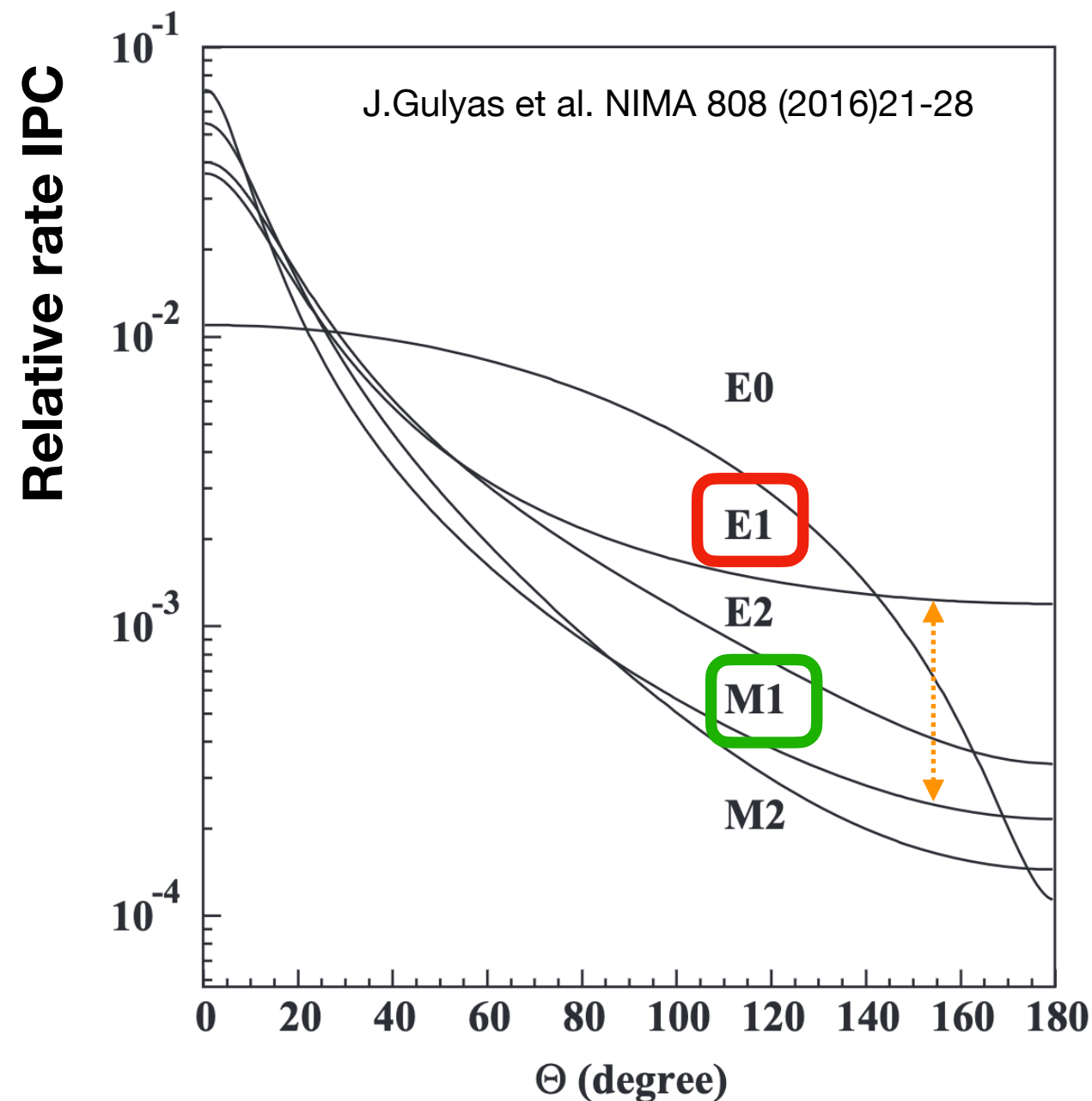
Possible only for energy $> 2 m_e$

M.E. Rose, Phys. Rev. 76, 678 (1949)



Multipole
Order

Experimental signature for IPC

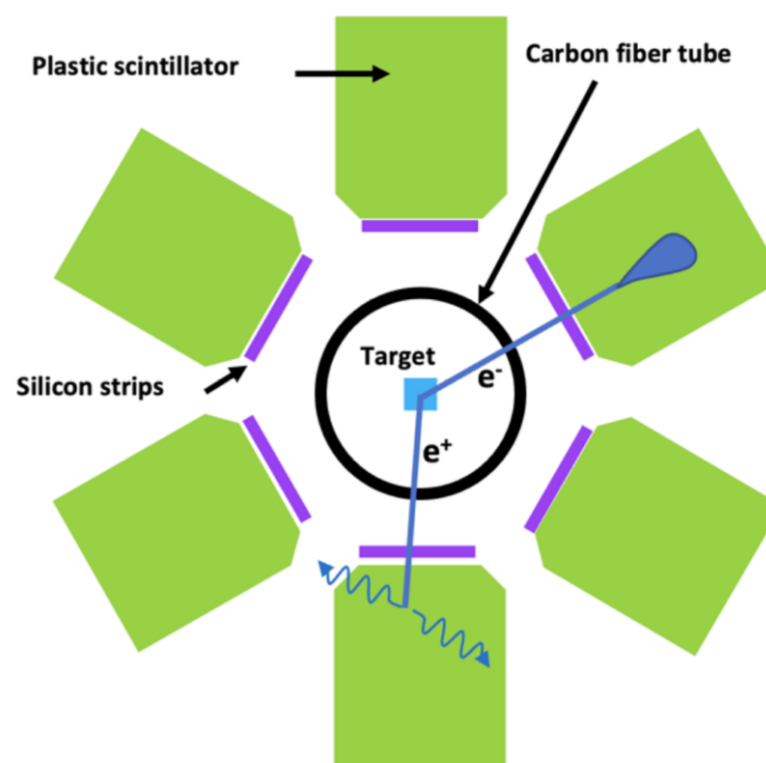
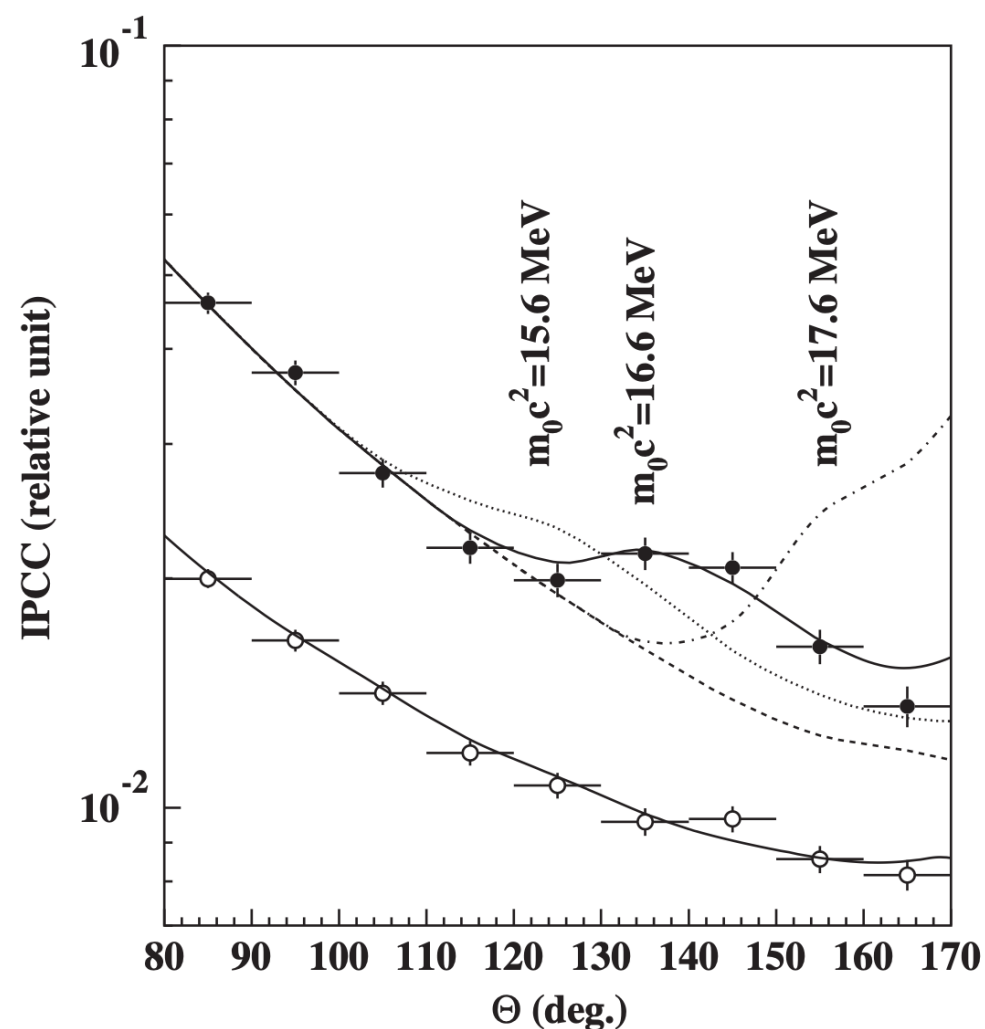


Θ_{ee} : angular opening between e^+e^-

- ▶ **Smooth** decrease
- ▶ Different shape according to multipole transition type
- ▶ $M\ell$: **magnetic** $[(-1)^{\ell+1}]$
M1 *no* parity change
- ▶ $E\ell$: **electric** $[(-1)^\ell]$
E1 parity change

An unexpected(?) anomaly in ^8Be

- ▶ In 2016 at ATOMKI (Debrecen) an anomalous distribution of Θ_{ee} was observed in $^7\text{Li} (p, e^+e^-)^8\text{Be}$



“Transverse-only” detector
No magnetic field

LiF and LiO targets

Proton energy
 $E_p = 0.5 - 1.2 \text{ MeV}$

- ▶ Inv. mass $m \sim 16.7 \text{ MeV}$
- ▶ Rate (wrt γ) = $6 \cdot 10^{-6}$

A new particle, then ?

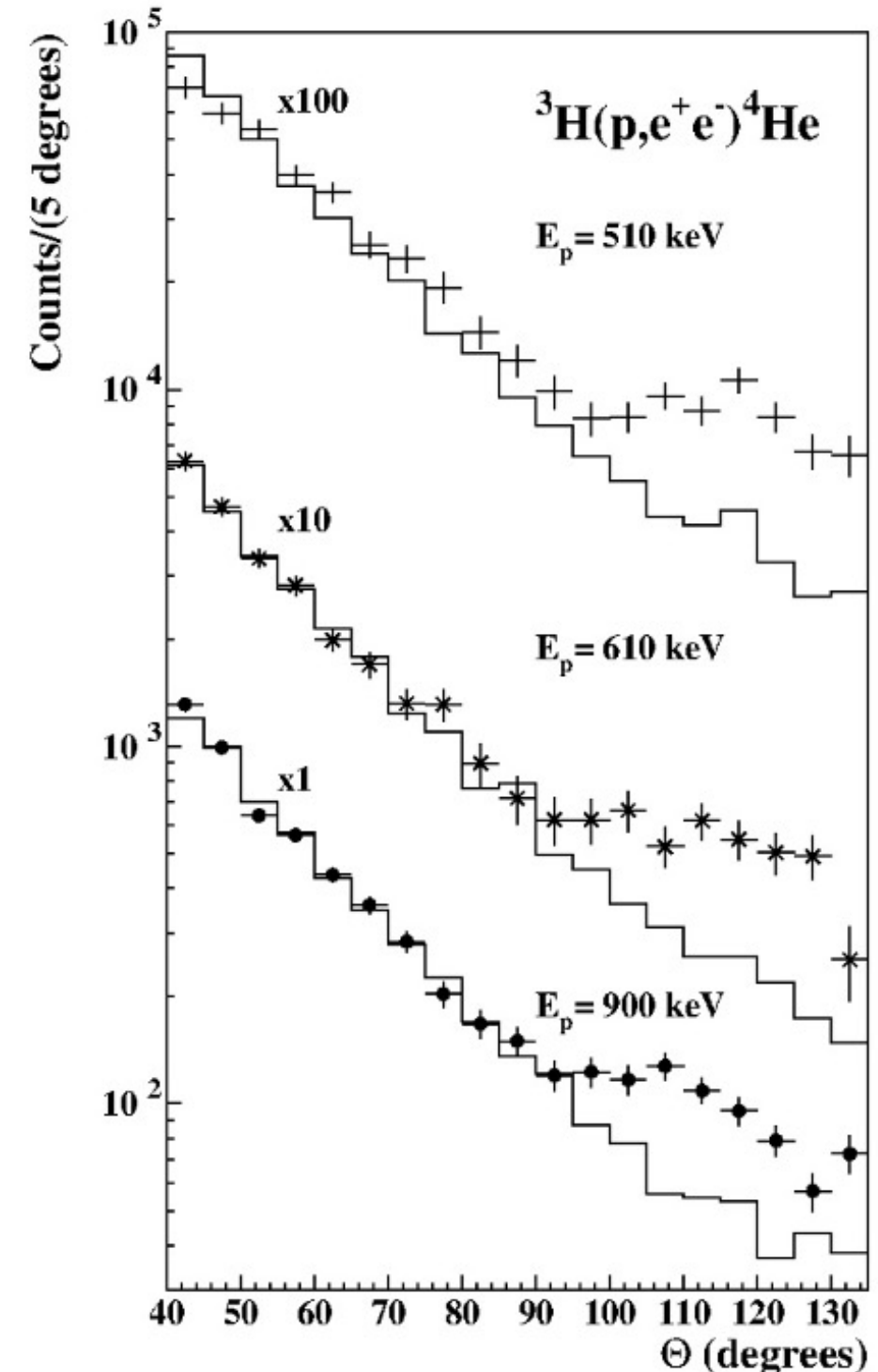
More evidence

- ▶ At ATOMKI with tritium target same anomaly in ^4He transitions at different E_p
- ▶ Kinematically consistent with ^8Be (same ~ 17 MeV inv. mass)
- ▶ Same anomaly in $^{11}\text{B}(p, e^+e^-)^{12}\text{C}$ Phys. Rev. C 106, L061601
- ▶ No evidence from NA64 and NA48

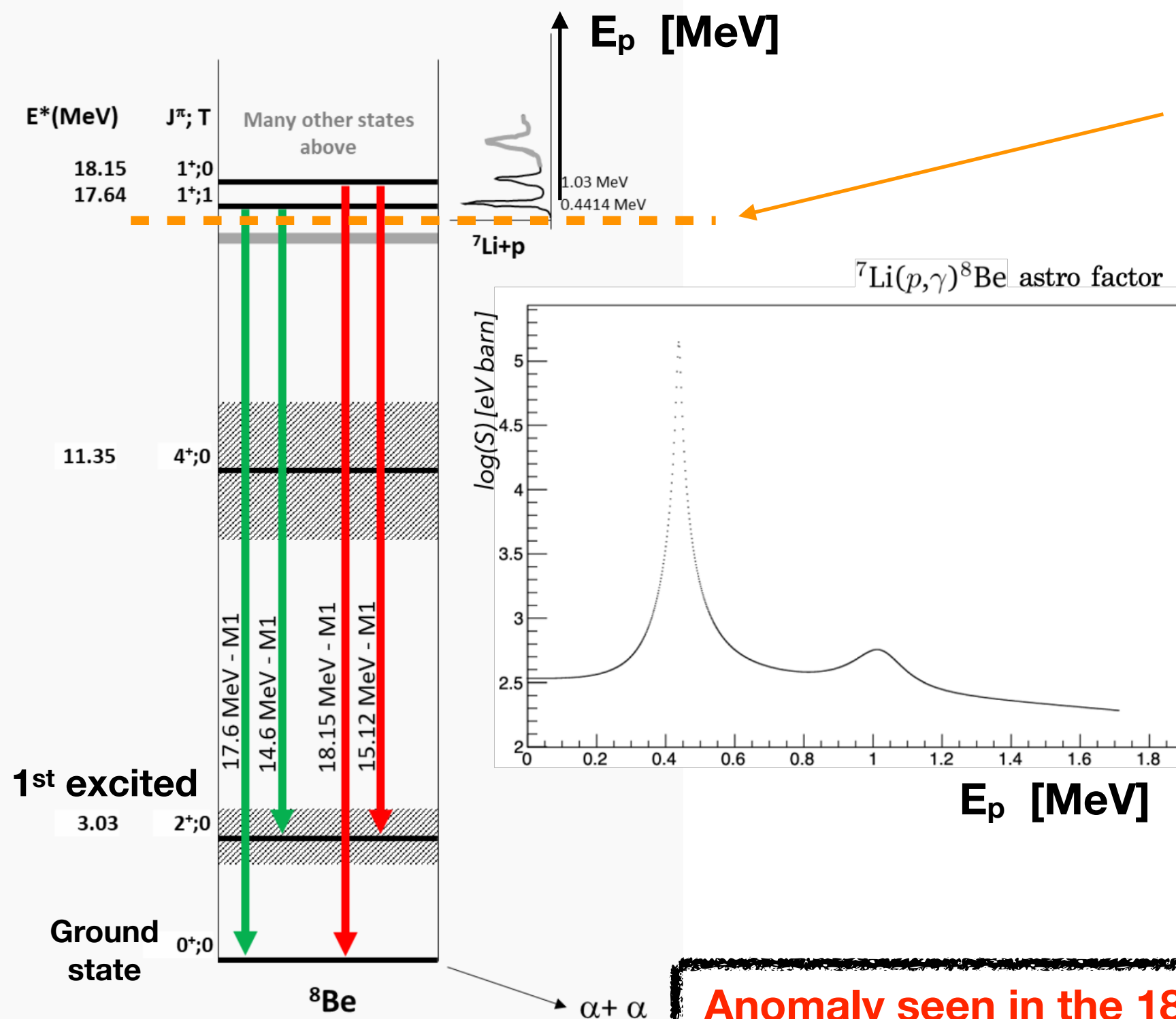
Phys. Rev. D, 101:071101

Phys. Lett. B 746, 178

Phys. Rev. C 104, 044003



^8Be levels



$^7\text{Li} + p$ yields **17.255 MeV** above ^8Be g.s. $\rightarrow$ many excited states easily accessible

Two resonances

$E_p = 0.440$ MeV $Q = 17.6$ MeV

$E_p = 1.030$ MeV $Q = 18.1$ MeV

Two (mostly M1?) transitions for each resonance

$1^+ \rightarrow 0^+$ ($E_\gamma = Q$)

$1^+ \rightarrow 2^+$ ($E_\gamma = Q - 3$ MeV)

Anomaly seen in the 18.1 MeV transition only

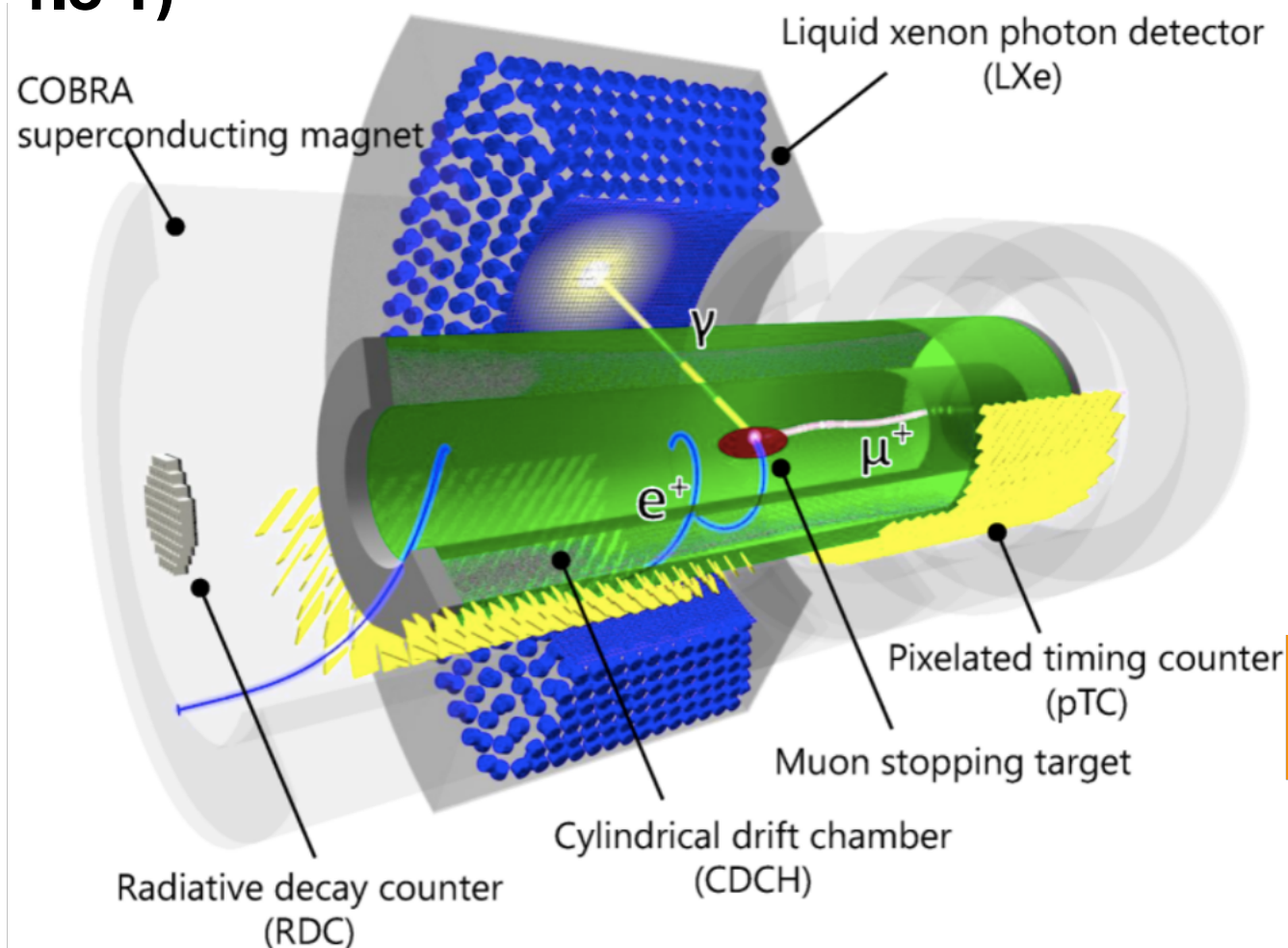
The MEG II detector at $\pi E5$ (PSI)

- Designed for cLFV search $BR(\mu \rightarrow e\gamma) \rightarrow 6 \times 10^{-14}$

Eur.Phys.J.C 84 (2024) 2, 190

Gradient Magnetic Field (Max 1.3 T)

Detect
52.8 MeV
positron
and photon



**1000L LXe tank readout by
668 PMTs and 4092 SiPMs**

CDCH
Single volume He:iC4H10
9 concentric layers of 192 drift cells each
momentum resolution up to 90 keV

**35 ps resolution
512 plastic tiles**

Current best limit:

Eur.Phys.J.C 84 (2024) 3, 216

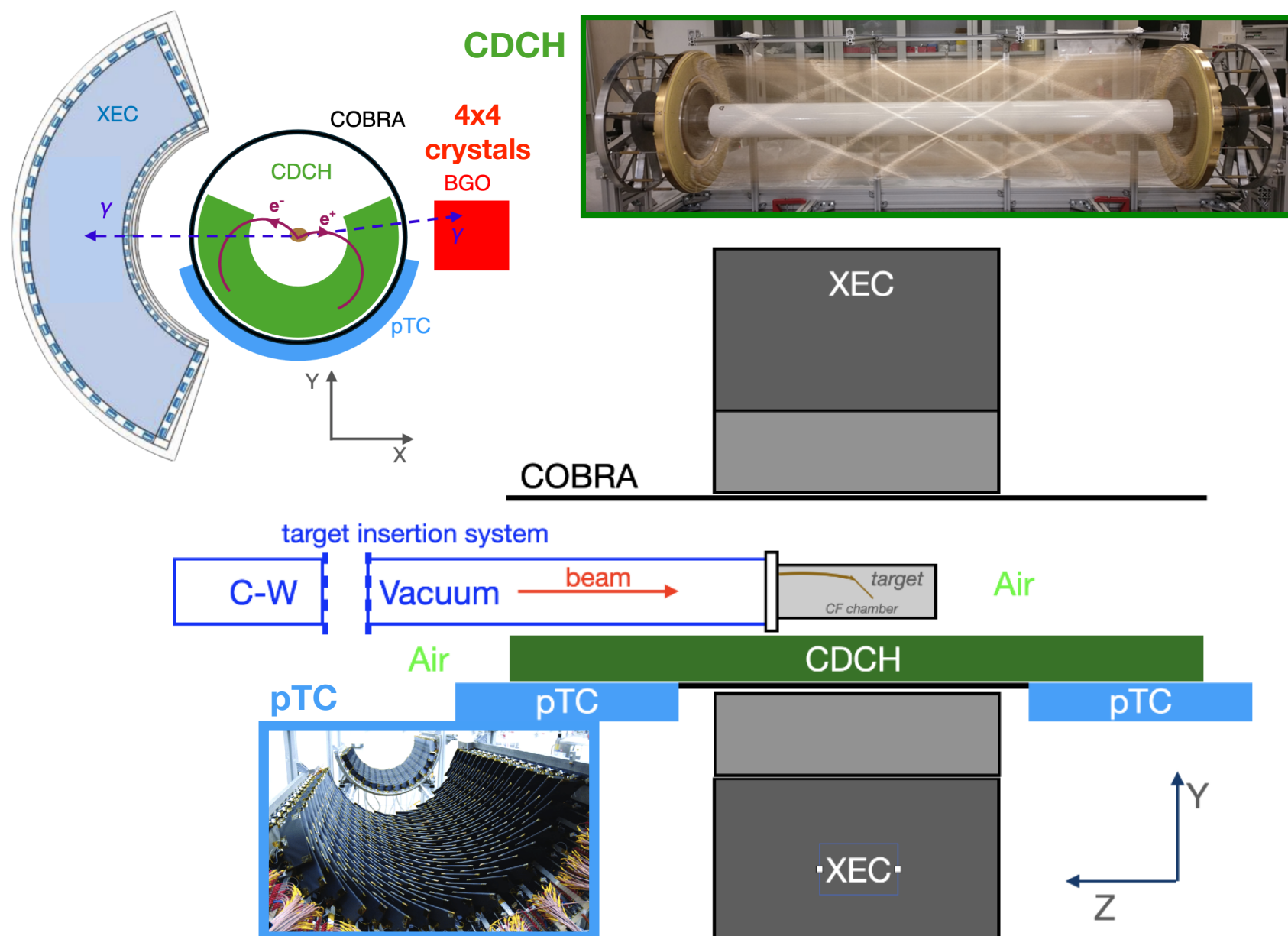
$$\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) < 3.1 \times 10^{-13} \text{ (90\% CL)}$$

MEG II for X17

- ▶ Cockroft Walton accelerator :
- ▶ up to ~ 1 MeV beam
- ▶ $\sim$ tens μA current



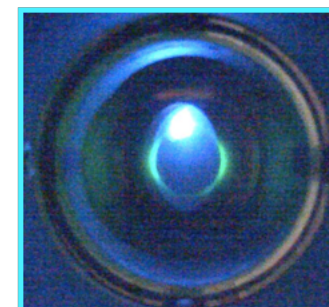
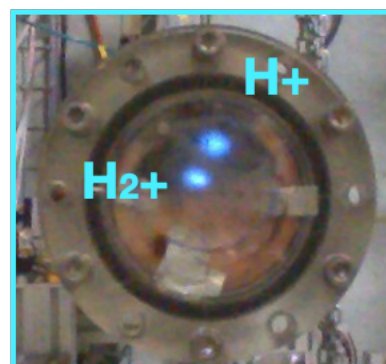
Routinely used for
XEC calibration with
 ${}^7\text{Li} (p, \gamma) {}^8\text{Be}$



Detecting ~ 10 MeV e^+e^- with a magnetic spectrometer (reduced $B \times 0.15$)
Different technique (but detector material budget not optimal)

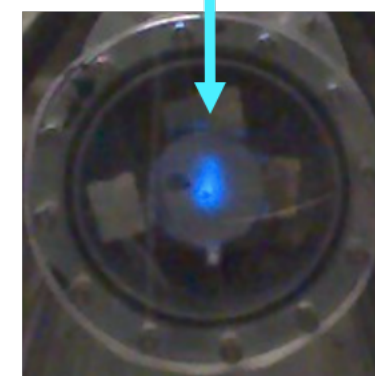
The Cockcroft Walton beam

Beam imaging with a quartz screen



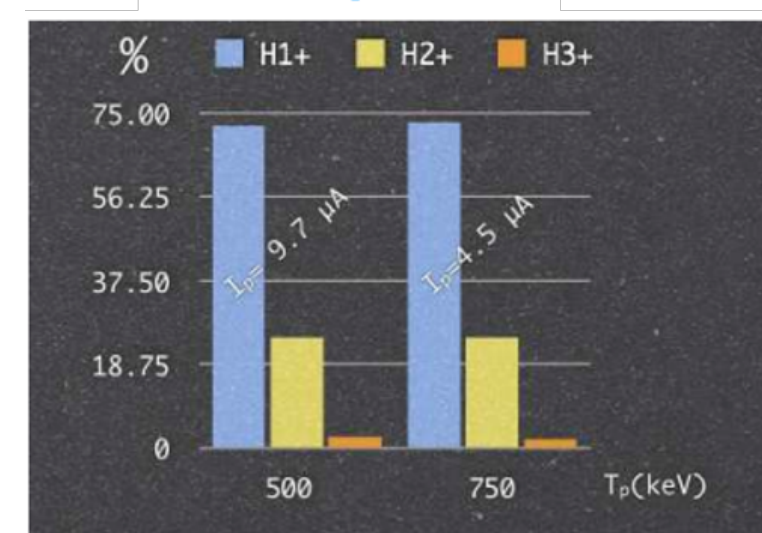
COBRA

Spectrometer center



- ▶ Steering of beam with dipoles
- ▶ Beam is a 75% / 25% H^+ / H_2^+
 - ▶ dedicated Faraday cup measurement
- ▶ Protons inside $(H_2)^+$ interact with energy $E_{\text{beam}}/2$

Ion composition

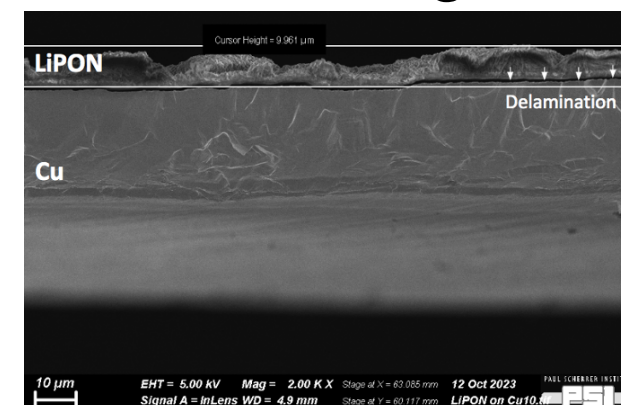


Data taking in Feb 2023 with $E_{\text{beam}} = 1.080$ MeV

The Li target

- ▶ New custom target region
 - ▶ **LiPON**(*) 2 μm on 25 μm **Cu** substrate (from PSI)
 - ▶ More stable than LiO, easier to be handled
 - ▶ However, irregular surface
 - ▶ Carbon fiber to minimize multiple Coulomb scattering

SEM image



Li target

at COBRA center
45° slant angle

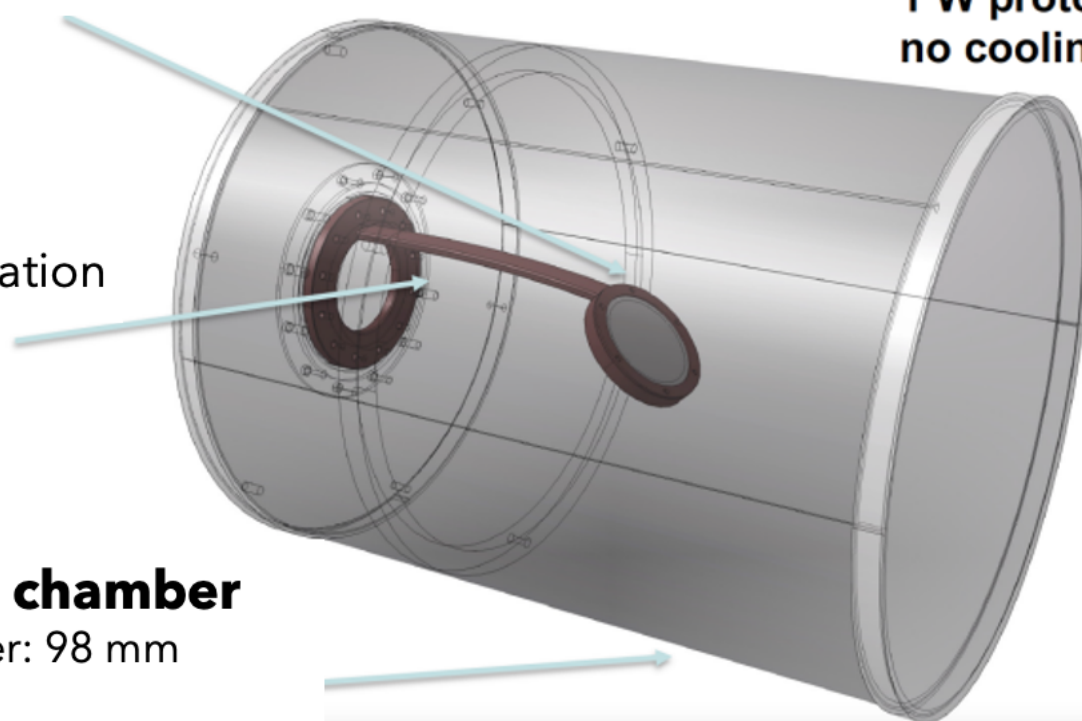
Target arm

Cu for heat dissipation

Steel beam pipe
Al adapter
1 W proton beam
no cooling

Carbon fiber vacuum chamber

Thickness: 400 μm , Diameter: 98 mm
Length: 226 mm



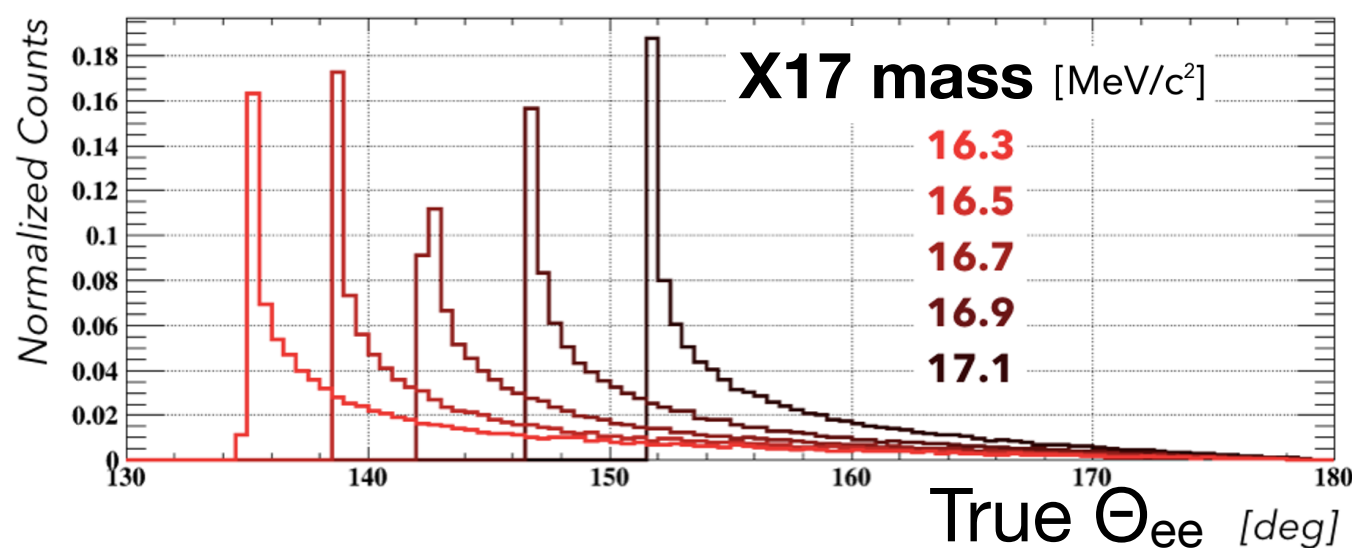
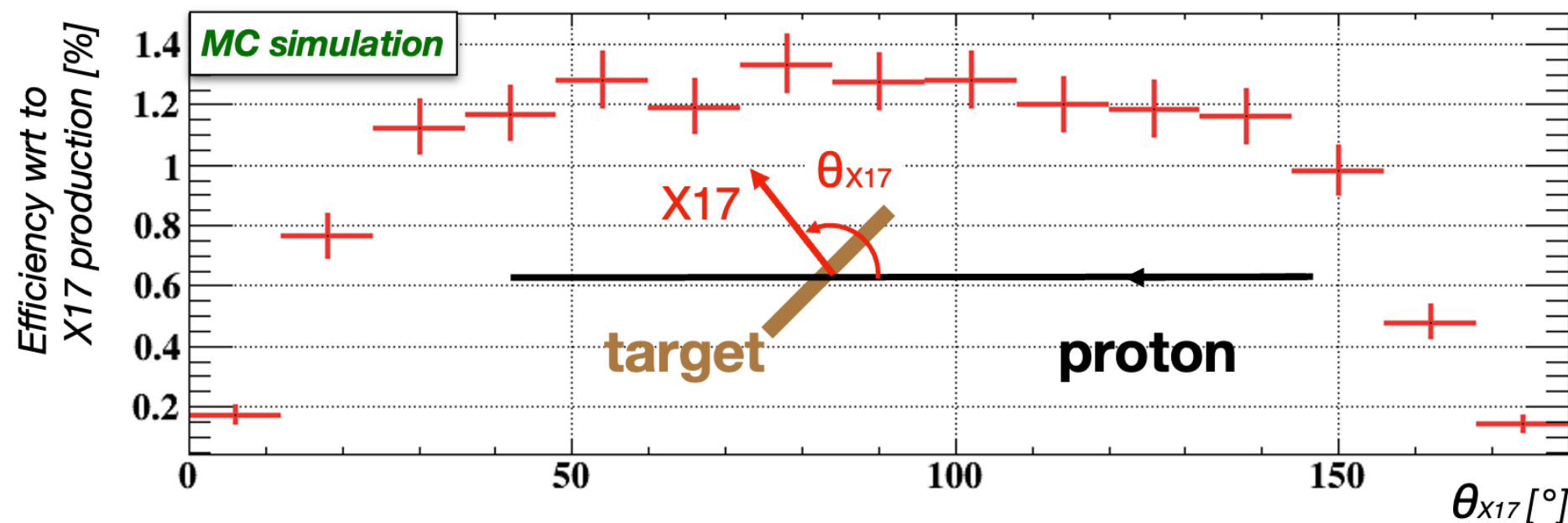
LiF target
(INFN Legnaro)
For BGO calibration

(*) Lithium phosphorus oxynitride ($\text{Li}_{3-x}\text{PO}_{4-y}\text{N}_{x+y}$)

The X17 signal in MEG II

- Different detection technique and **larger angular acceptance** than ATOMKI (only $\theta_{X17} \sim 90^\circ$)

M. Viviani, et al. Phys. Rev. C 105, 014001



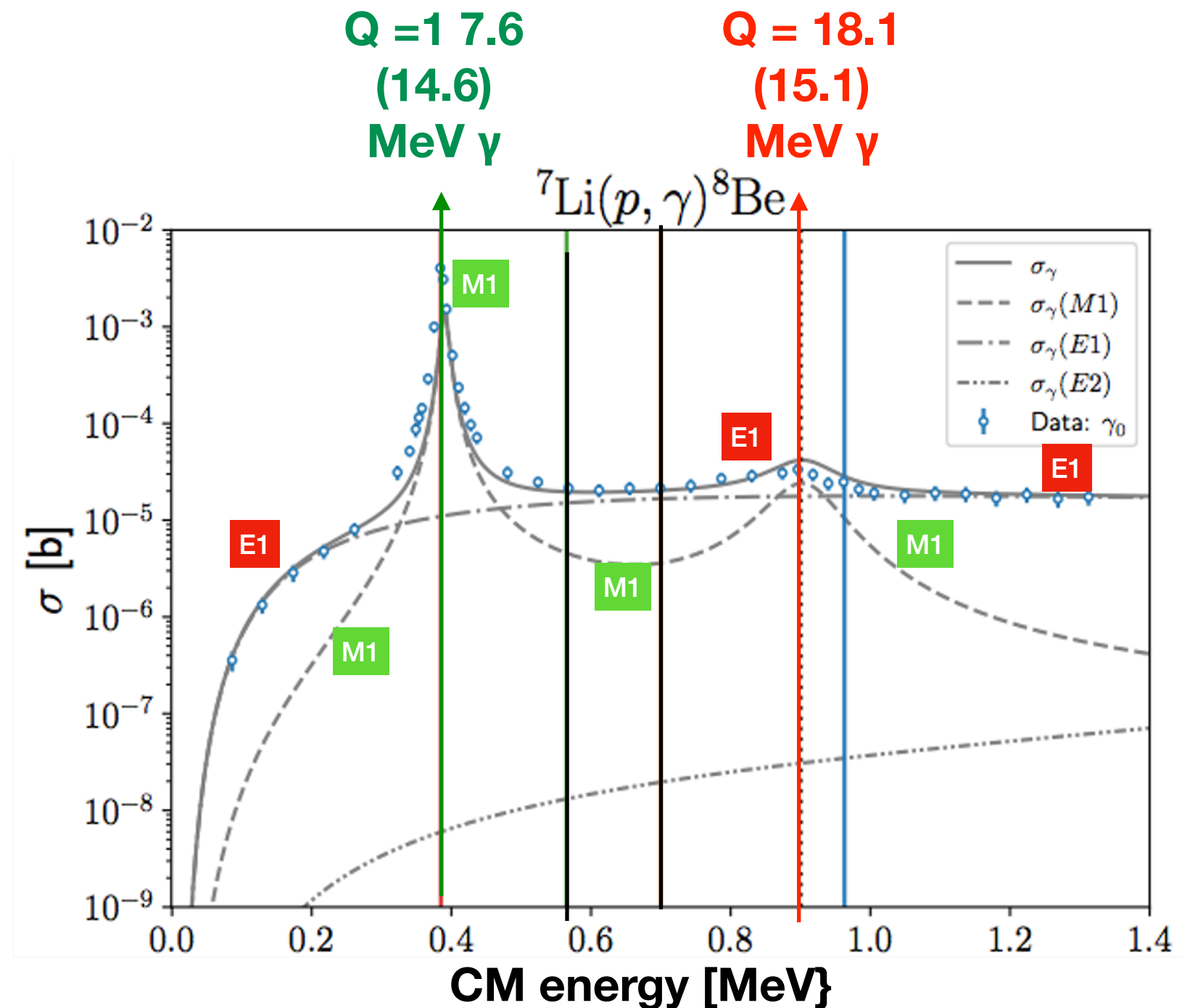
Assuming isotropically produced

Overall 1% detection efficiency
(apparatus sub-optimal)

6 deg resolution on Θ_{ee}

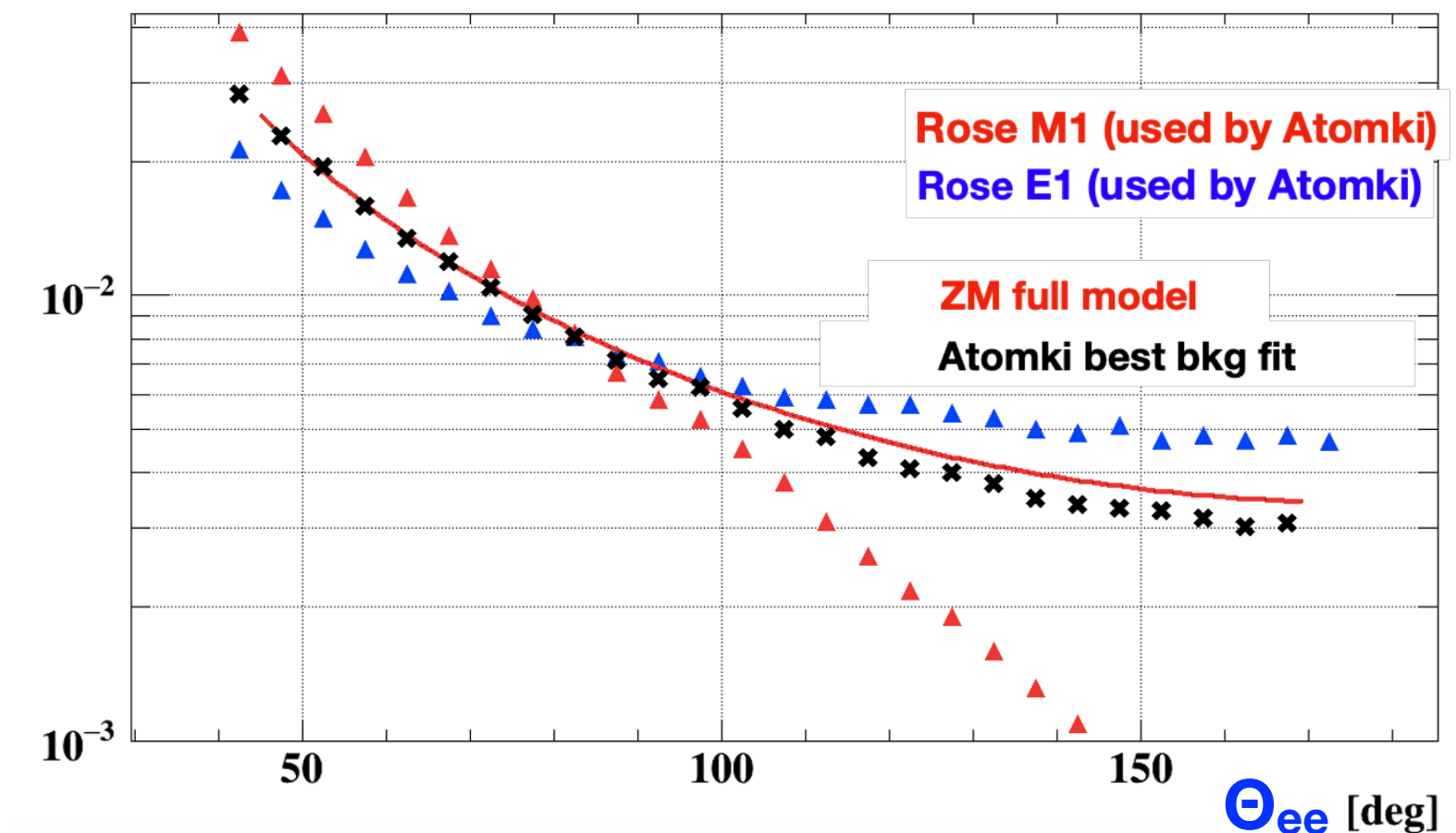
Multipole decomposition of cross section

- ▶ **E1** (*radiative direct capture*) might be more relevant at **1.030 MeV** resonance
- ▶ Call for a detailed model
- ▶ IPC events at large angles where signal is present



Advanced Model for IPC

- ▶ Rose (1949) model used at ATOMKI missing **interference** and **anisotropy** of IPC
- ▶ Implementing in our MC simulation a more complete model (Zhang-Miller)

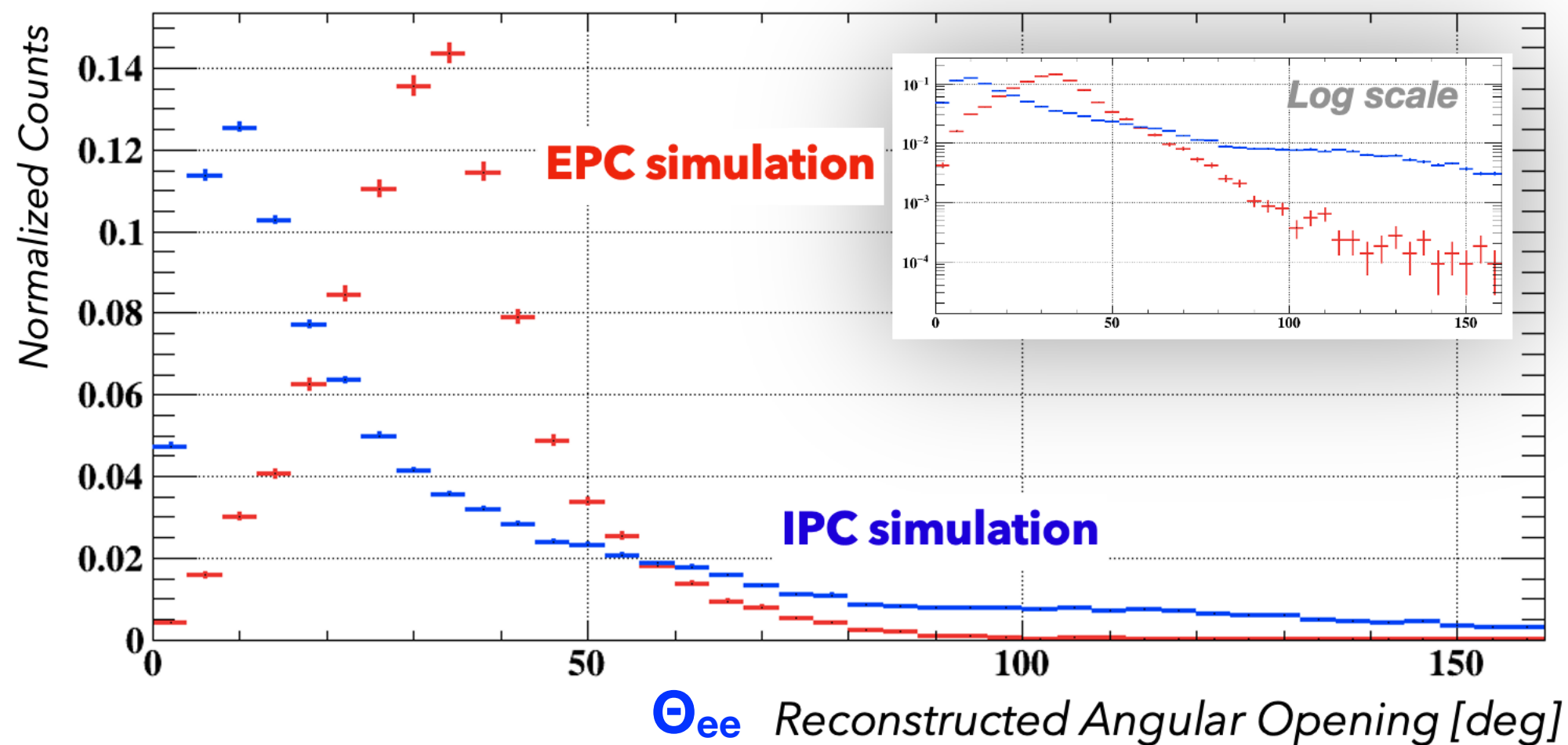


Still not enough to explain the anomaly though...

Different Θ_{ee} distribution for E1 and M1
 → separate IPC Q=**17.6 MeV** from IPC Q=**18.1 MeV**

External pair conversion (EPC)

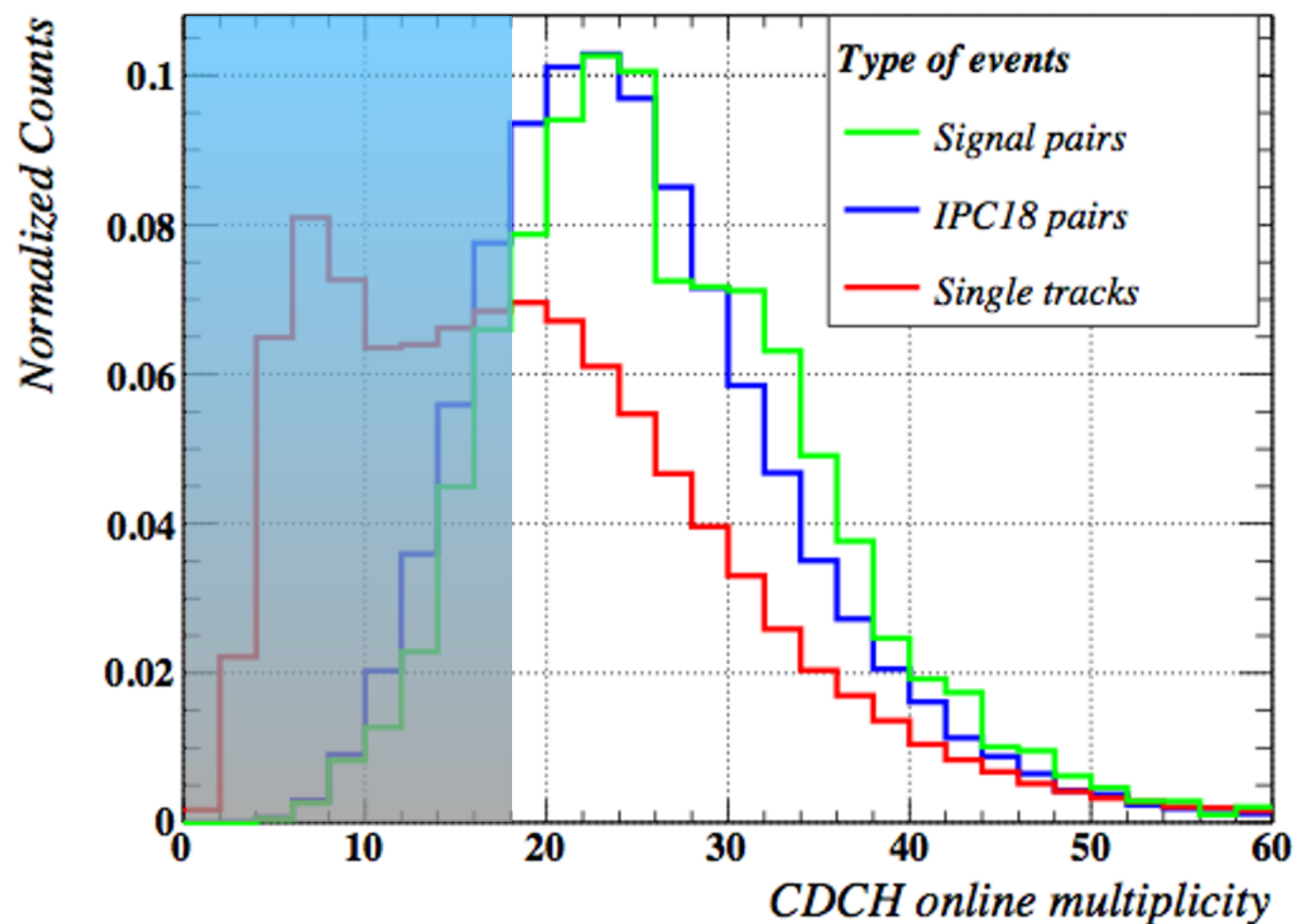
- ▶ Real photon from more copious ${}^7\text{Li} (p, \gamma){}^8\text{Be}$ convert in the detector material
- ▶ Compton electrons and e^+e^- pairs
- ▶ Very detector-dependent.



IPC x100 times larger than EPC in signal region

Trigger strategy

- ▶ Based on **pTC** and **CDCH hits to select pairs**
 - ▶ Reject single tracks, EPC, pairs asymmetric in momentum



18 CDCH hits over 60 mV threshold
+ 1 pTC hit

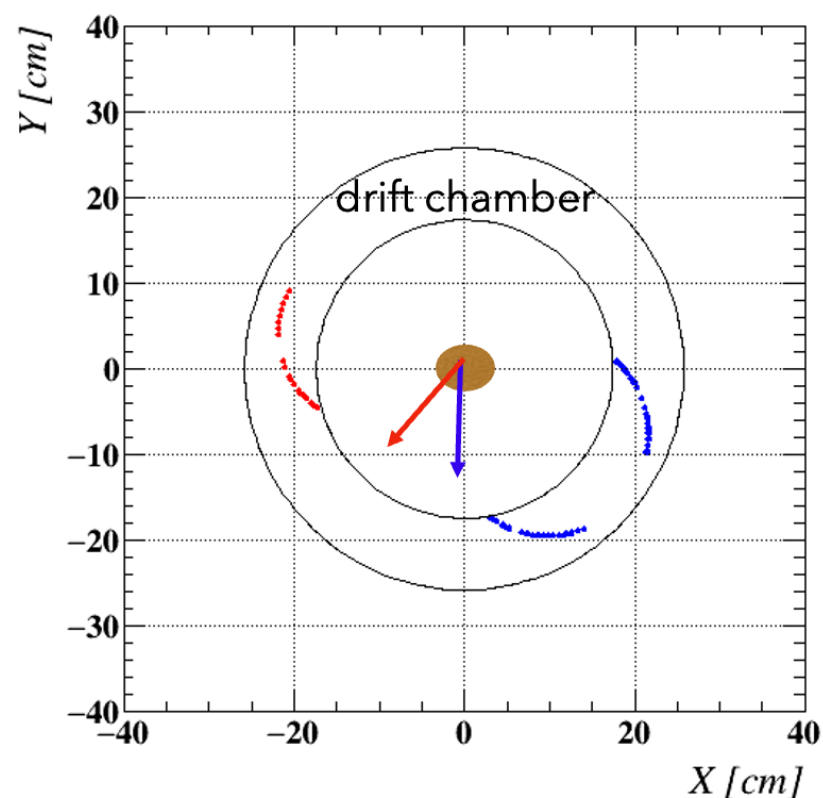
16% efficient on **signal X17**

Background rejection x5 larger
(than with 10 CDCH hits)

Leaves room to increase
beam current
(up to more than 10 μA)

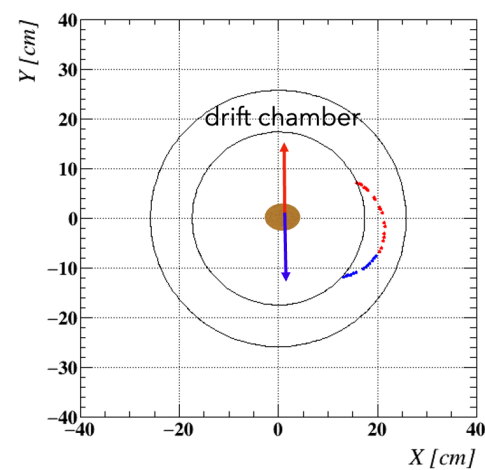
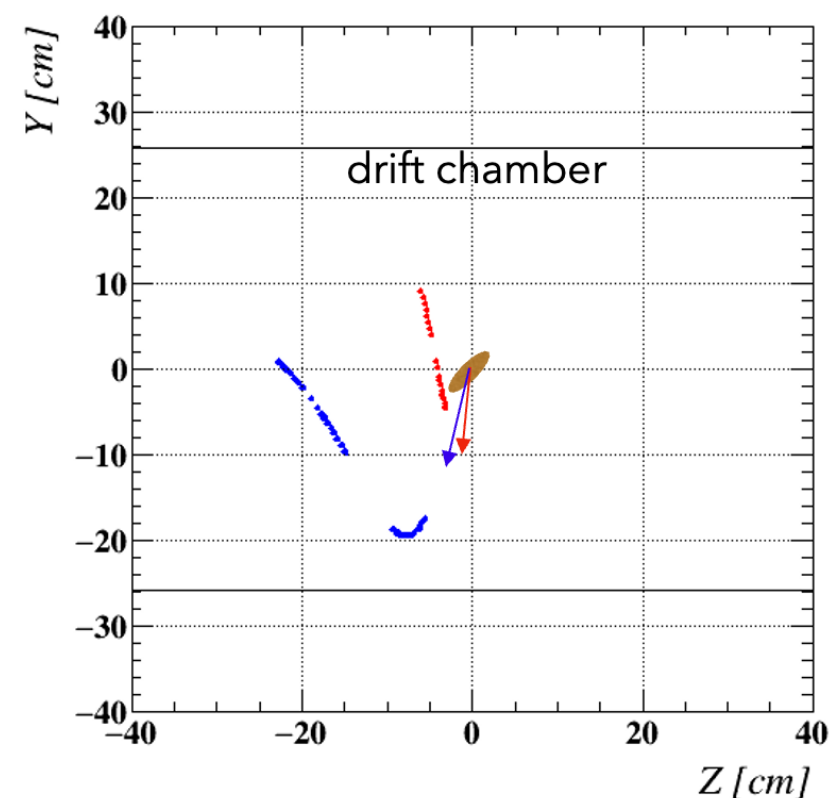
Track Reconstruction

- Based on a Kalman Filter technique (from MEG II)



GOOD PAIR

$\vec{p}^+$ at target
 $\vec{p}^-$ at target
 • e^+ hit
 • e^- hit
 target



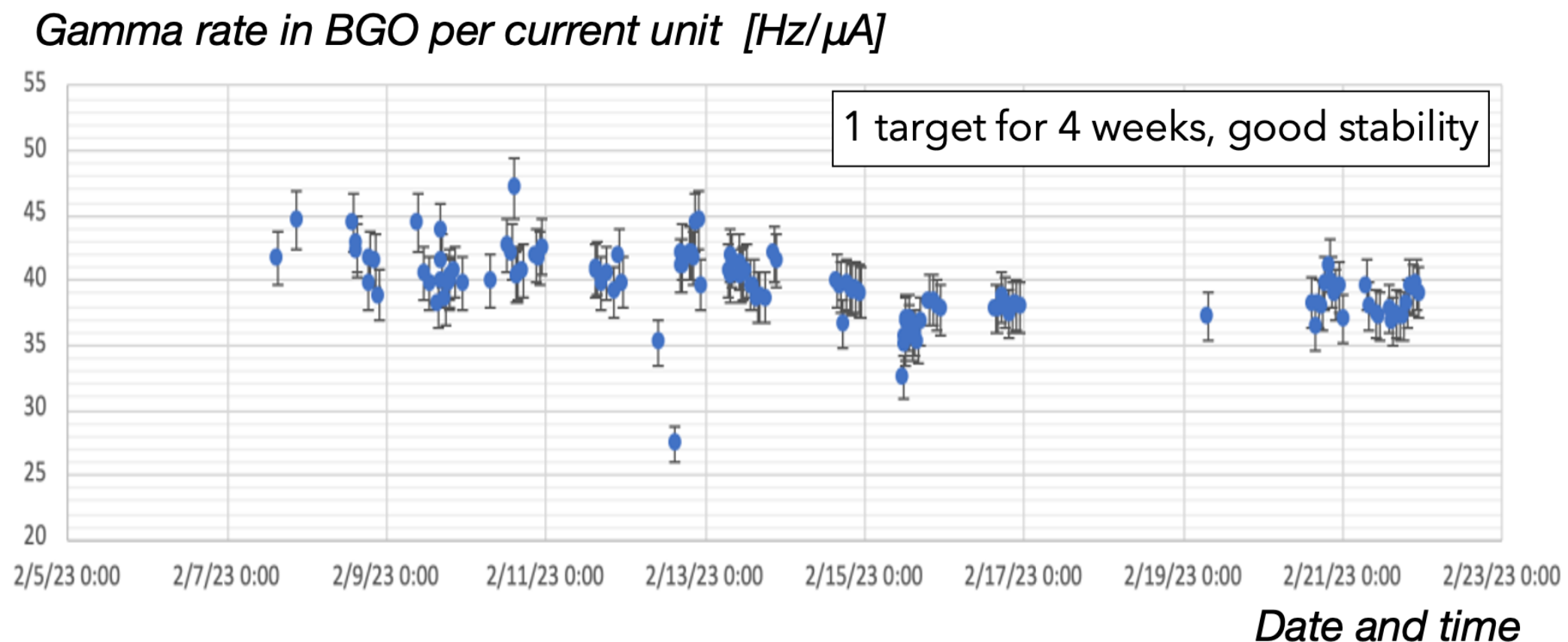
Fake pair:
 Single particle
 reconstructed as
 two tracks ($\Theta_{ee} \sim 180^\circ$)

*Detailed study to suppress fakes
 Advanced good tracks selection
 implemented.*

**Signal efficiency
 (and IPC acceptance) $\sim 2.5\%$**

Feb 2023 data taking

- ▶ Run with $E_{\text{beam}} = 1.080$ MeV at $10 \mu\text{A}$
- ▶ 75M events collected, about 300k pairs reconstructed

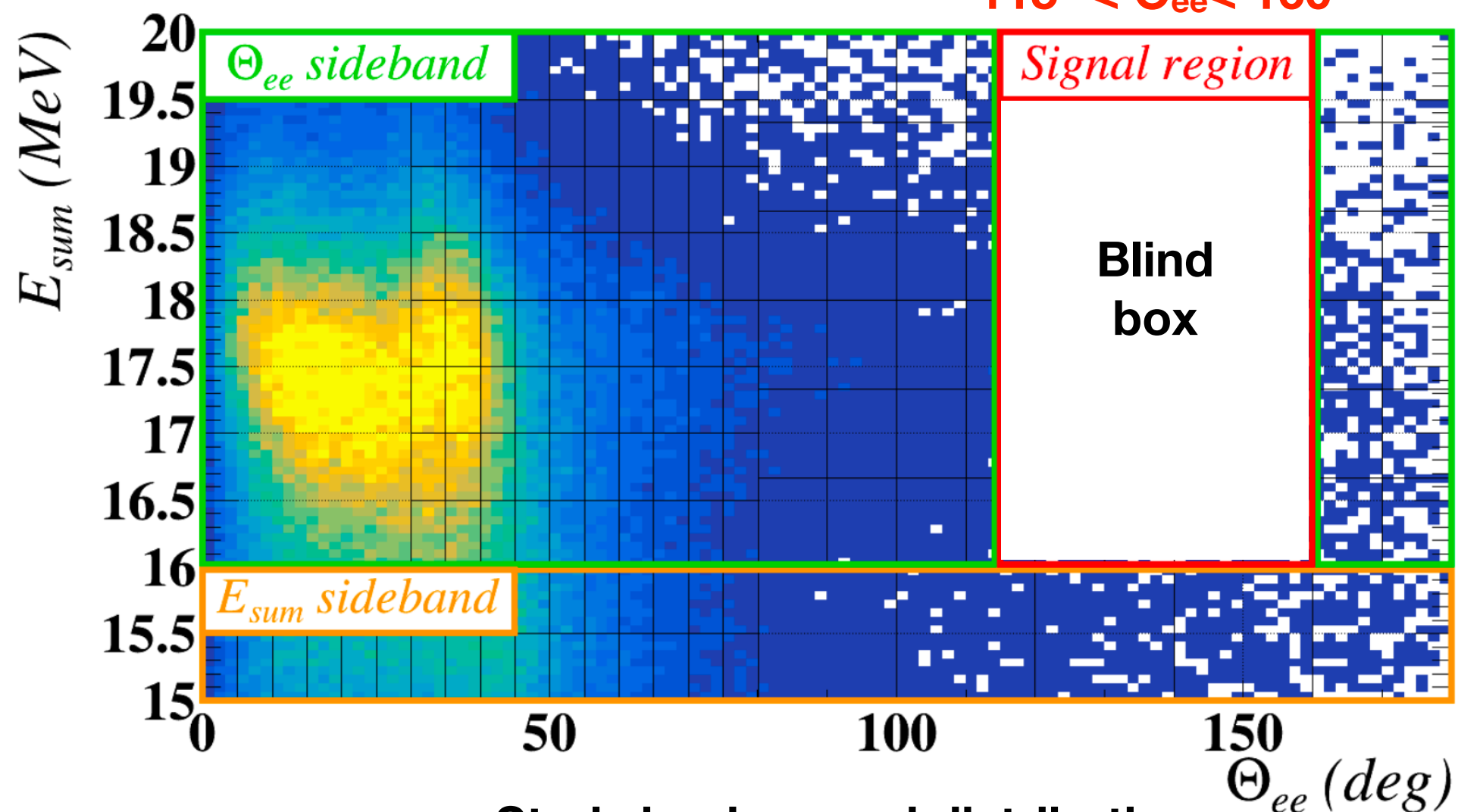


- ▶ Remarkable stability
- ▶ Beam with both H^+ and H_2^+ → events from both $Q=17.6$ and $Q=18.1$ MeV transition → **data analysis to separate them**

Analysis strategy

- Analysis variables : $E_{\text{sum}} = E_{e^-} + E_{e^+}$ and Θ_{ee}

Blinded signal region: $16 < E_{\text{sum}} < 20 \text{ MeV}$
 $115^\circ < \Theta_{ee} < 160^\circ$

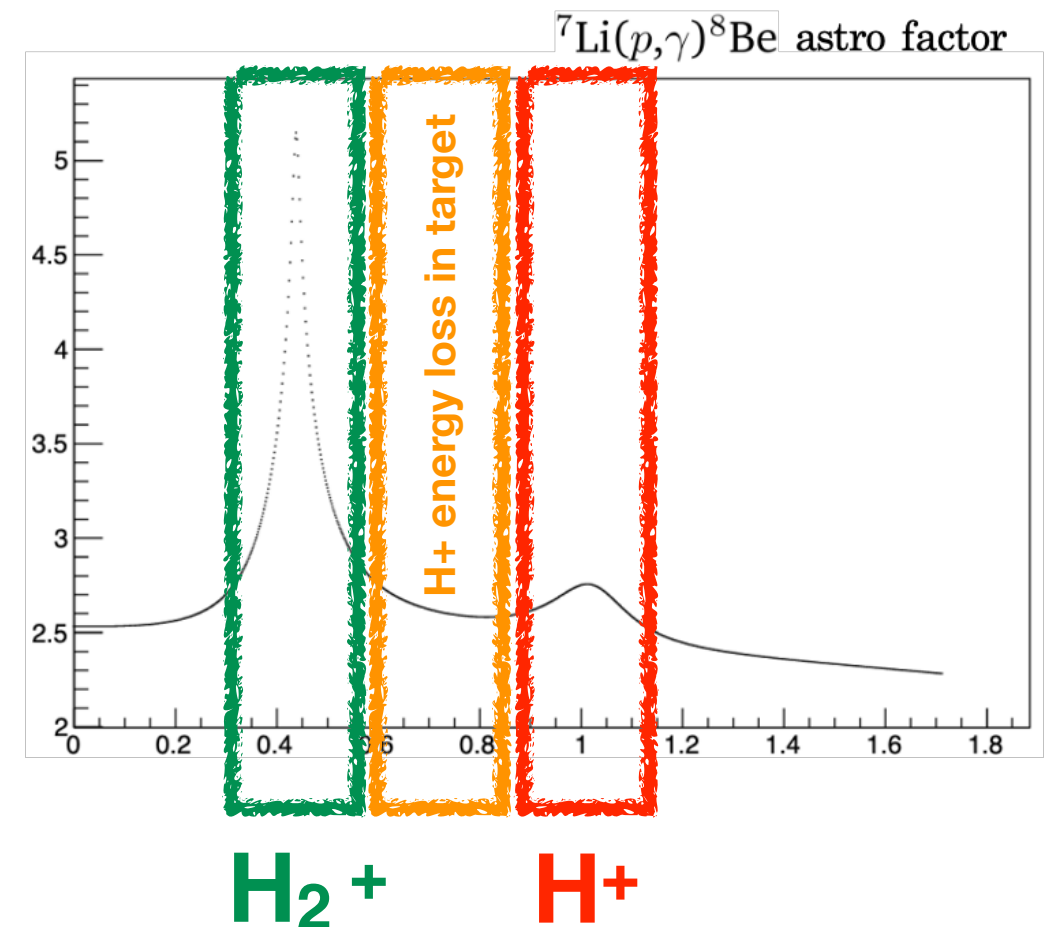


Study background distribution
in sideband (data/MC comparison) before opening the box

Maximum likelihood fit

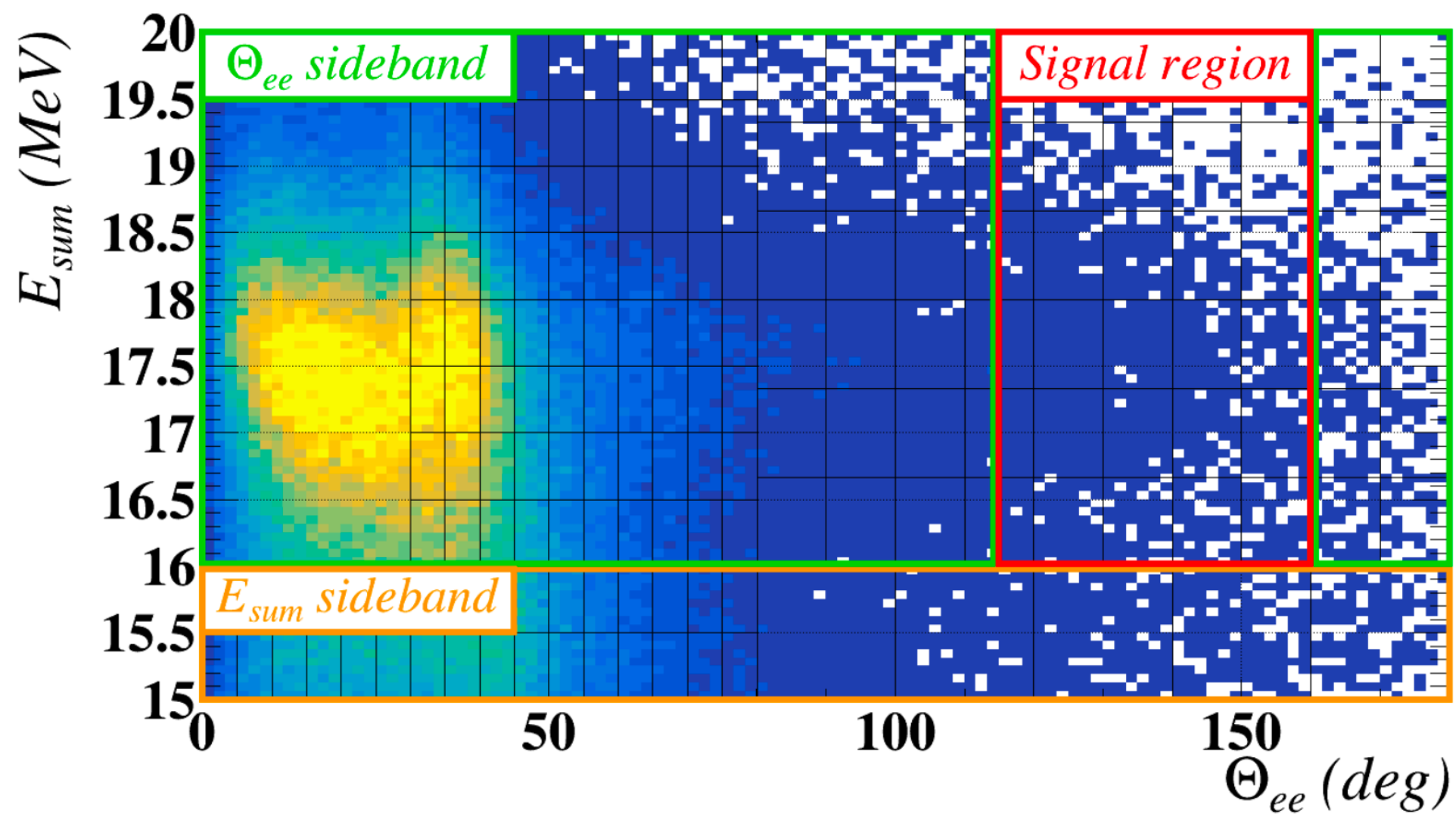
- ▶ **Binned** ML fit using **template** histograms as PDF from a detailed MC simulation
 - ▶ Extensively validated on sidebands
- ▶ Likelihood parametrised in terms of relative BF
- ▶ **Two** signal PDF's
 - ▶ one per resonance, $Q = 17.6$ and $Q = 18.1$ MeV
- ▶ **Six** IPC PDF's
 - ▶ Three E_p bins, two transition (g.s and 1st excited s.) each
- ▶ **Two** EPC PDF's
 - ▶ No E_p dependence, two transition
- ▶ **One** fake pairs PDF

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

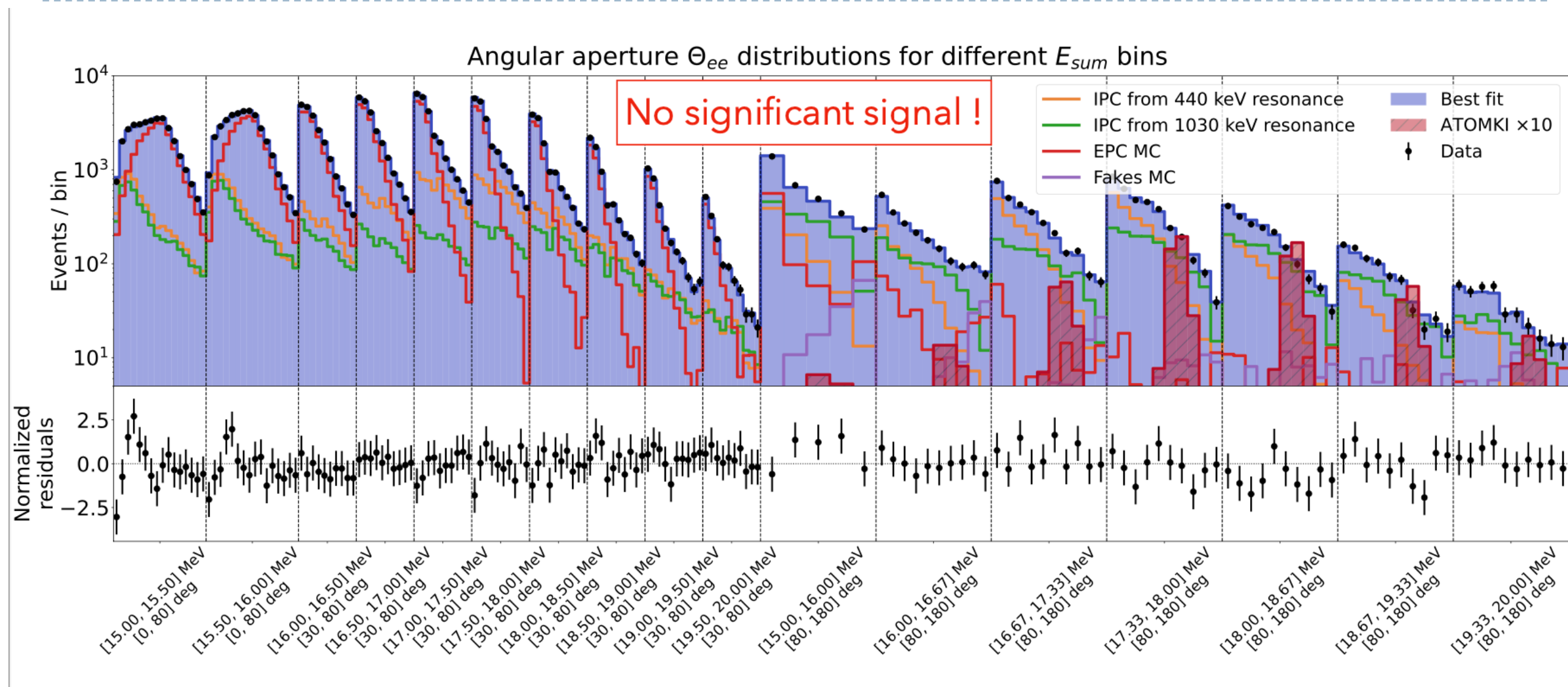


Including Beeston-Barlow coefficients to account for MC limited statistics

Unblinding



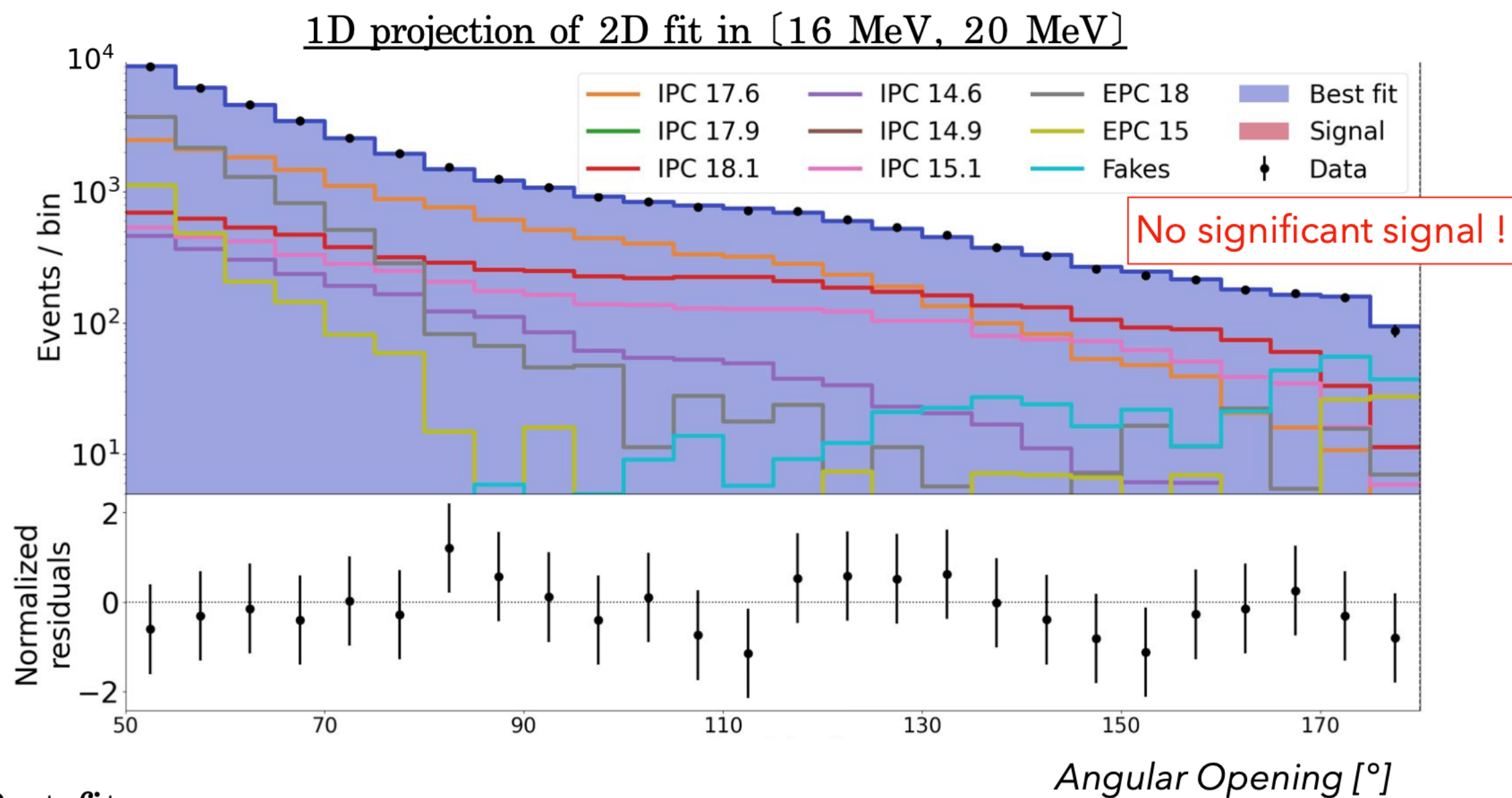
Results from the ML fit



► Best fit:

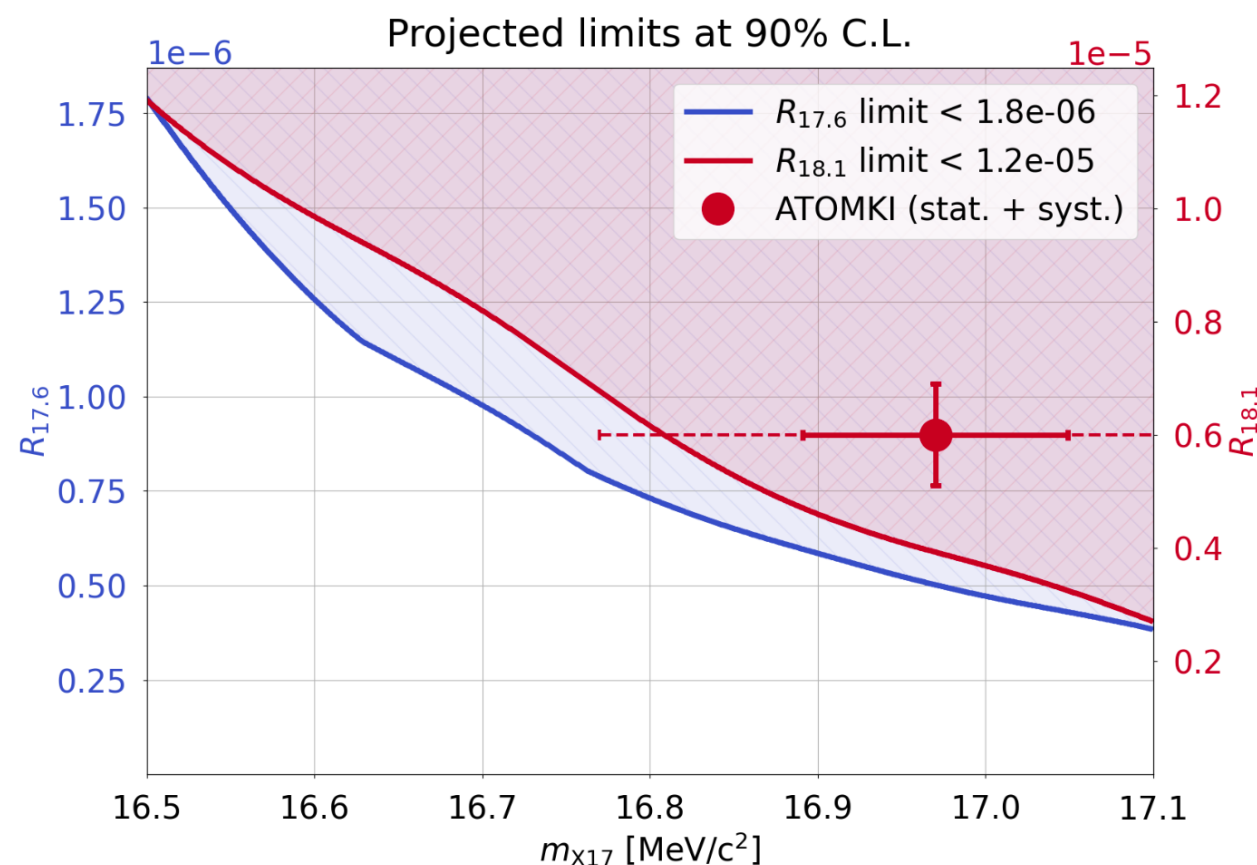
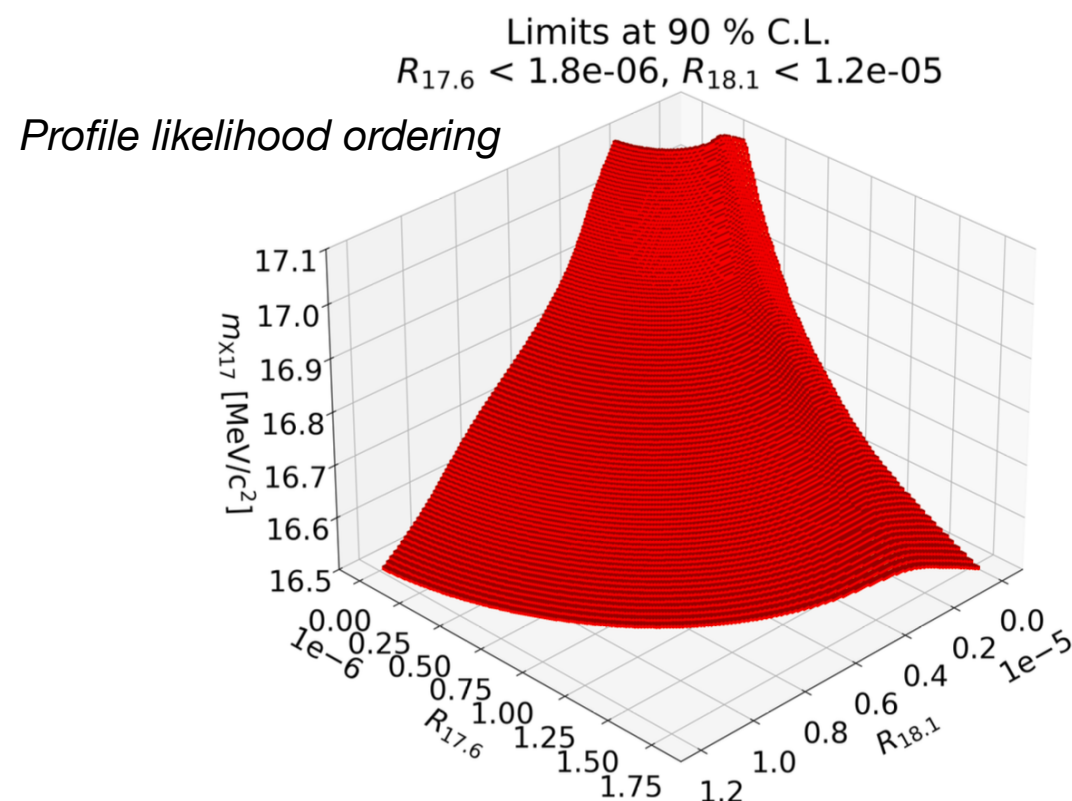
- 10 ± 92 signal events at $Q = 18.1$ MeV and none at $Q = 17.6$ MeV - for a $m_{X_{17}} = 16.5$ MeV
- IPC: **12.6(9)%** $Q = 18.1$ MeV and **45.8(13)%** $Q = 17.6$ MeV
- Goodness-of-fit: p-value = 10%

1D projection



90% Confidence Limits

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



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

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

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

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

$$\Gamma_Q = \frac{\mathcal{B}({}^8\text{Be}^*(Q) \rightarrow {}^8\text{Be} + e^+e^-)}{\mathcal{B}({}^8\text{Be}^*(Q) \rightarrow {}^8\text{Be} + \gamma)} \rightarrow 3.9 \cdot 10^{-3} (Q = 18.1 \text{ MeV}) \quad 3.4 \cdot 10^{-3} (Q = 17.6 \text{ MeV})$$

Hypothesis testing

- ▶ ATOMKI: X17 produced at 1.030 MeV **and not** at 0.440 MeV
→ p -value : **6.2% (1.5σ)**
- ▶ J.L.Feng et al.: X17 produced **both** at 1.030 MeV **and** at 0.440 MeV
→ p -value : **1.8% (2.1σ)**

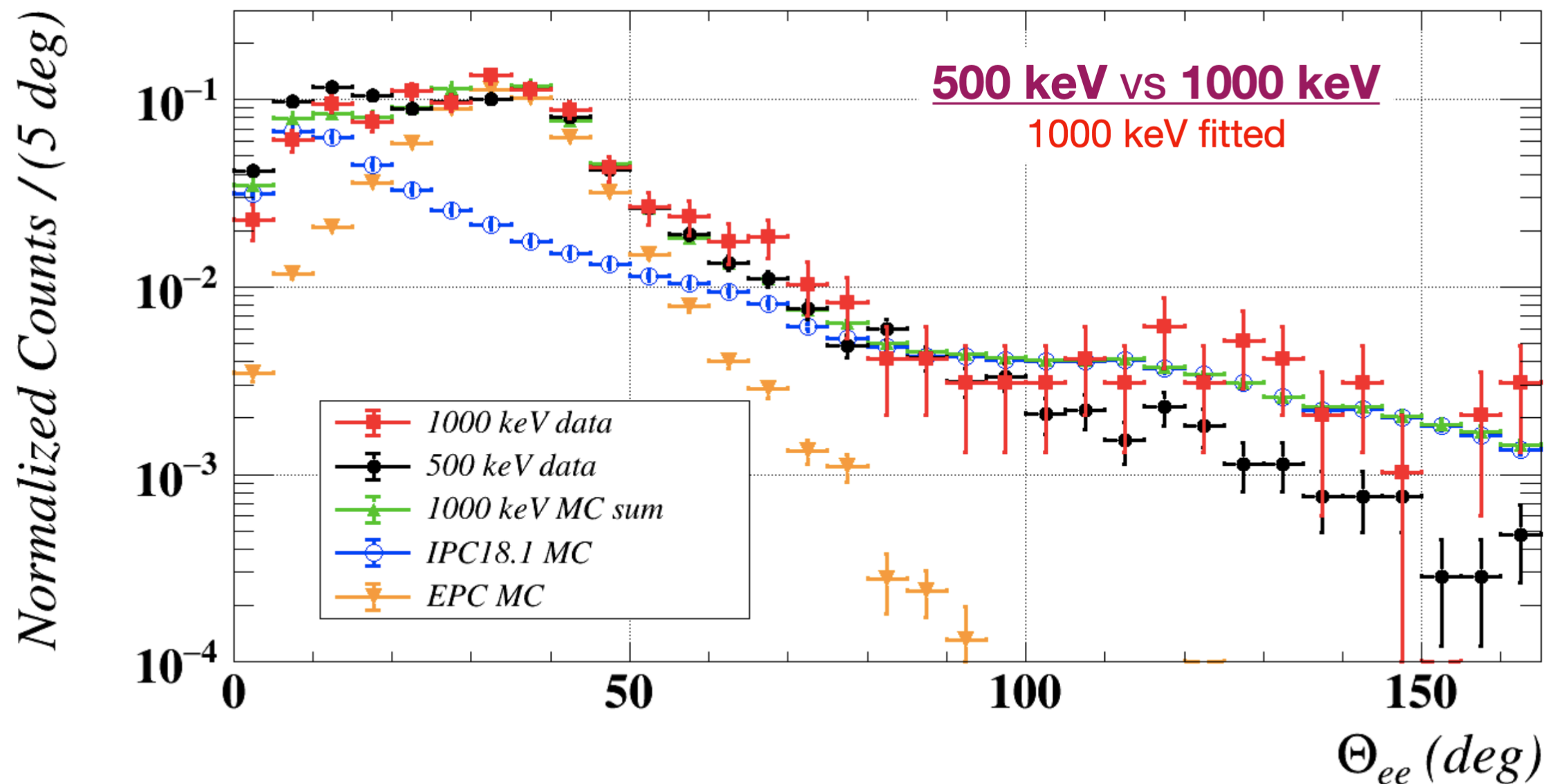
Using $m_{X17}=16.97(22)$ MeV and $R_{18.1} = 6 \cdot 10^{-6}$
Scaling $R_{17.6} = 0.46 R_{18.1}$

Conclusion

- ▶ MEG II detector successfully studied the ${}^7\text{Li} (p, e^+e^-){}^8\text{Be}$ process
- ▶ *Four weeks dedicated data taking with a special LiPON target and the MEG II C-W proton accelerator*
- ▶ Looking for a new particle as suggested by ATOMKI experiment:
 $X17 \rightarrow e^+e^-$ with a $m \sim 17 \text{ MeV}$
- ▶ **No significant signal was found in our data**
 - ▶ *ATOMKI observation was tested and excluded at 94%*

Data MC comparison for 500/1080 keV data

- Recent data at with pure $E_p = 1000$ keV - model validation!



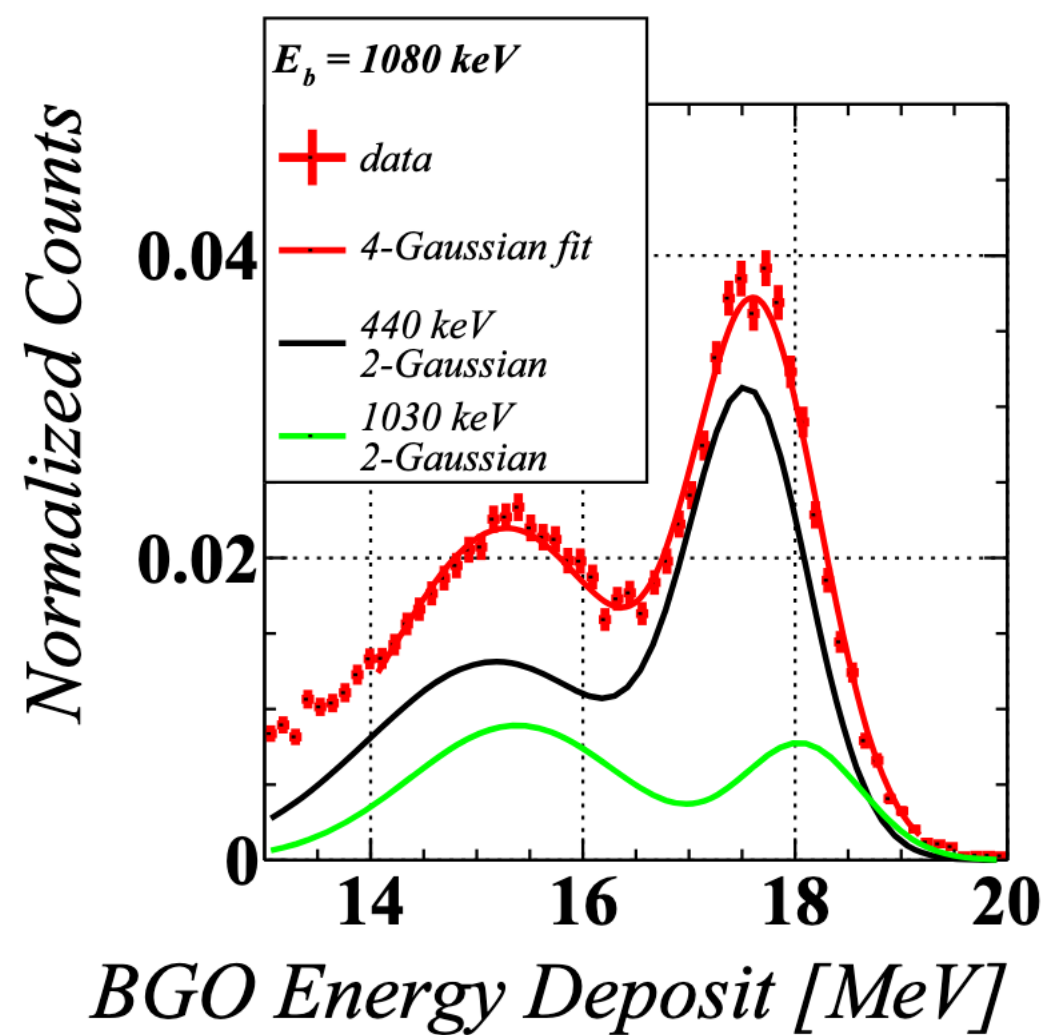
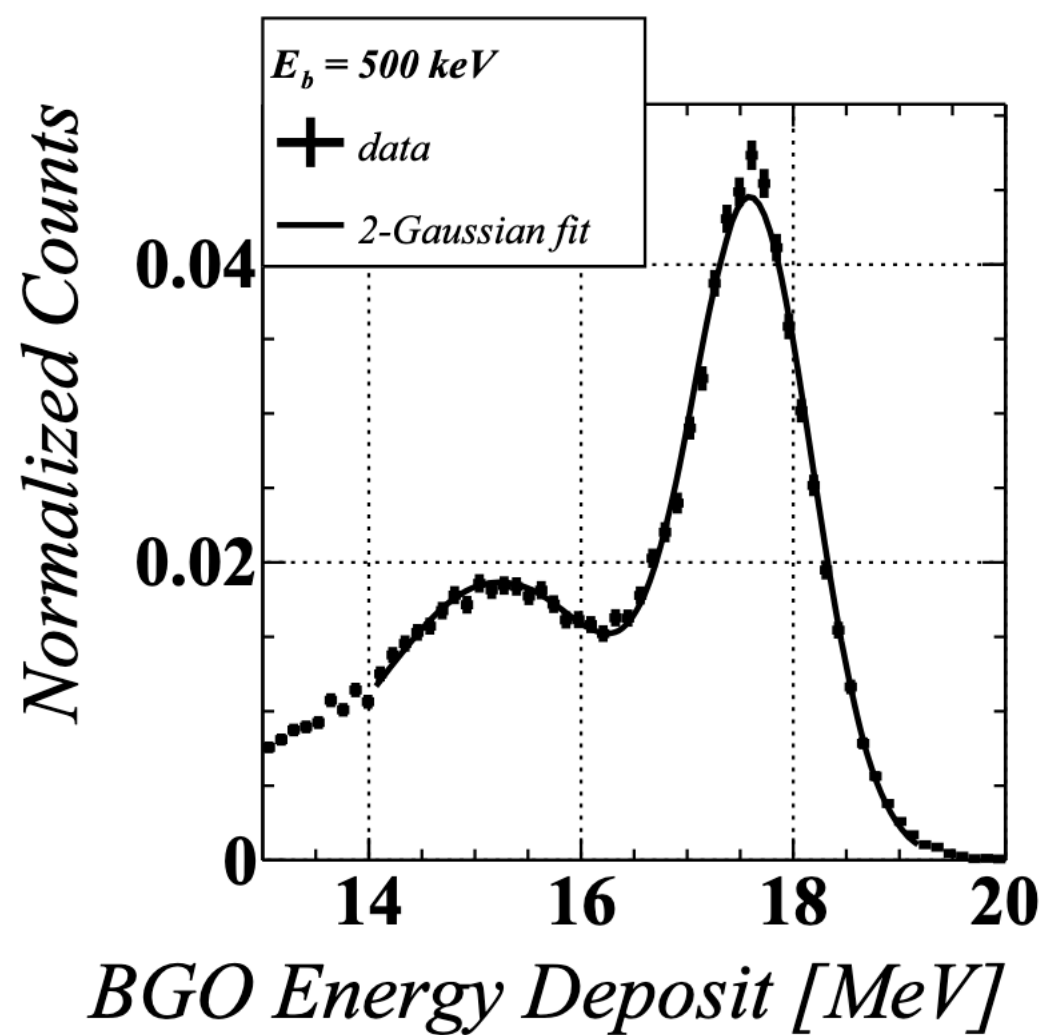
- Small dataset @1000keV (only 18.1 MeV line)
- Data well modelled by Zhang-Miller IPC model!

Outlook

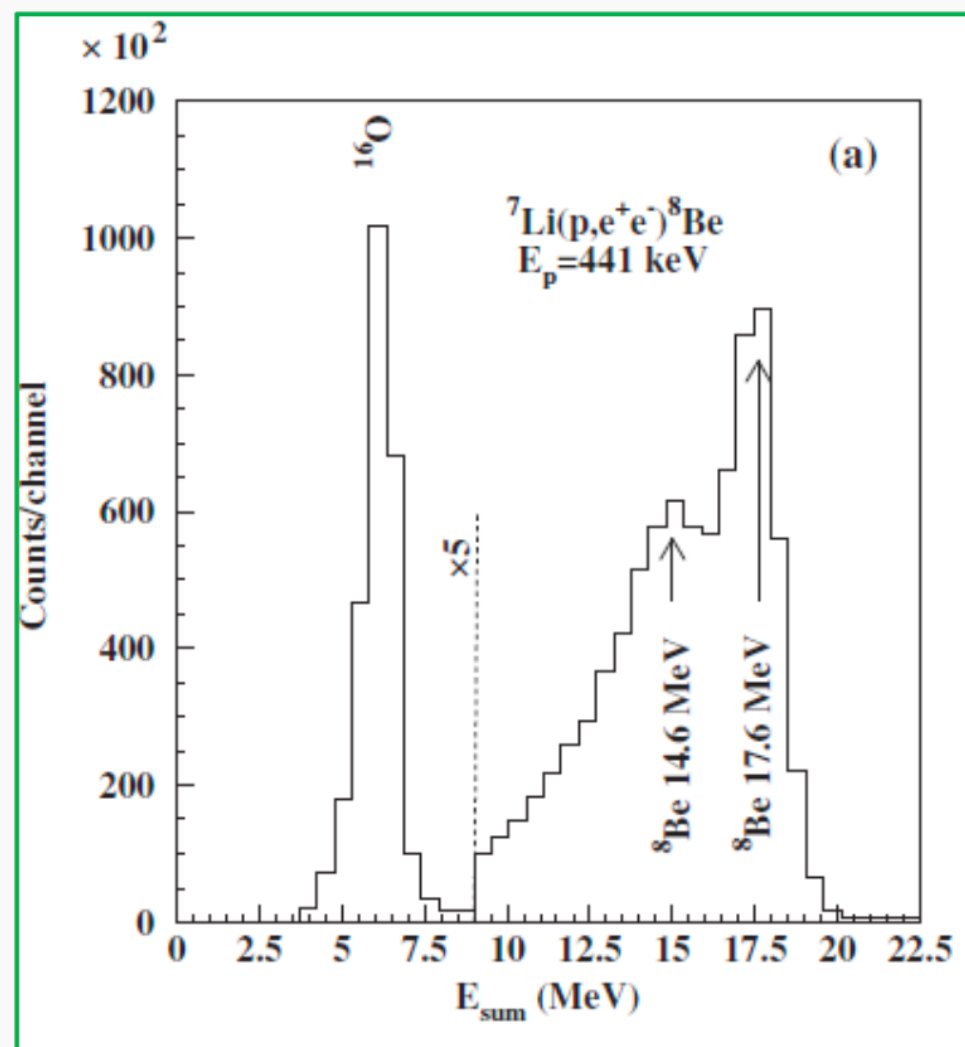
- ▶ Room to **improve MEG II sensitivity** if more data will be taken at **1030 keV** resonance
- ▶ *Thinner ($1.2\ \mu\text{m}$) LiPON target available and collimator to remove H_2^+ **both already in place.***
- ▶ Plans to collect ~ 40 days with a $30\ \mu\text{A}$ 1 MeV beam during 2026 winter shutdown (no impact on MEG regular schedule)
- ▶ A $\sim 4\sigma$ evidence for the ATOMKI hypothesis might be possible (or a 3σ exclusion)

Backup slides

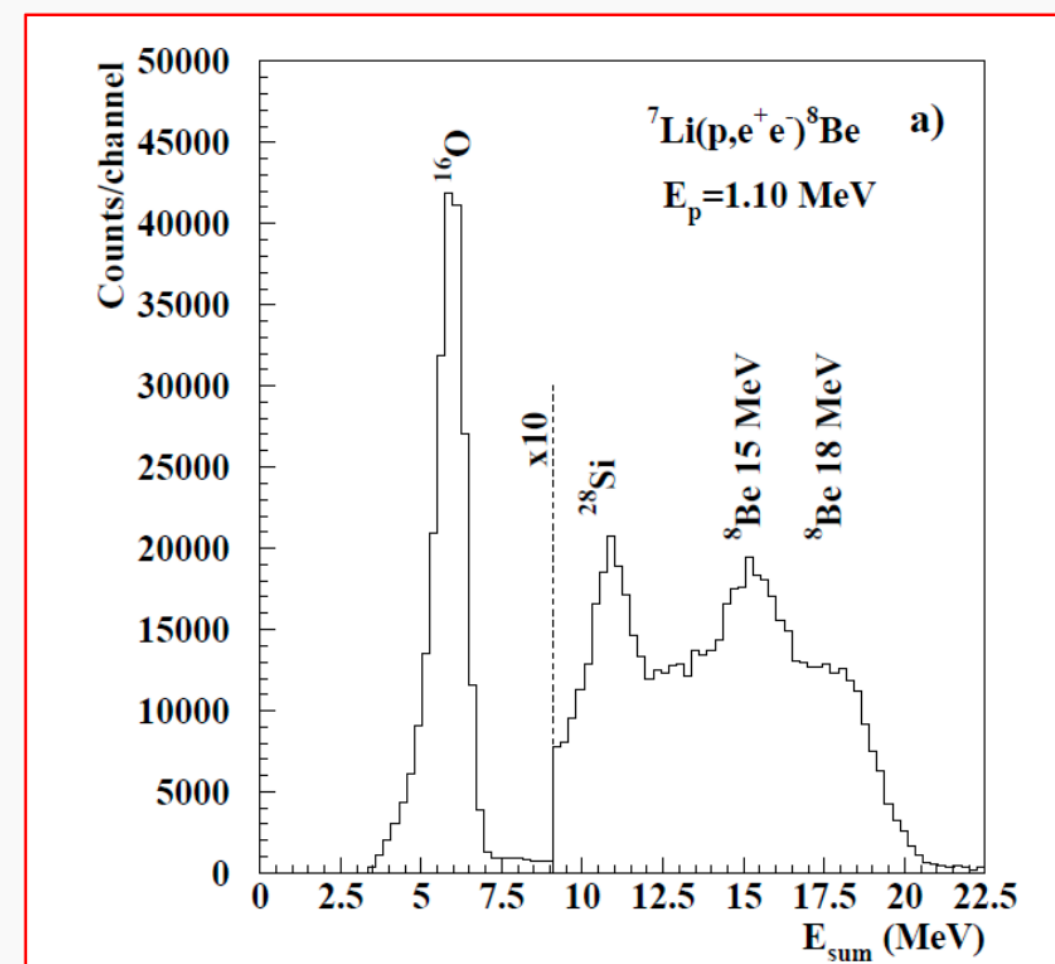
BGO spectra



Esum at ATOMKI



[A. J. Krasznahorkay et al, Phys Rev Lett 116, 042501 (2016)]



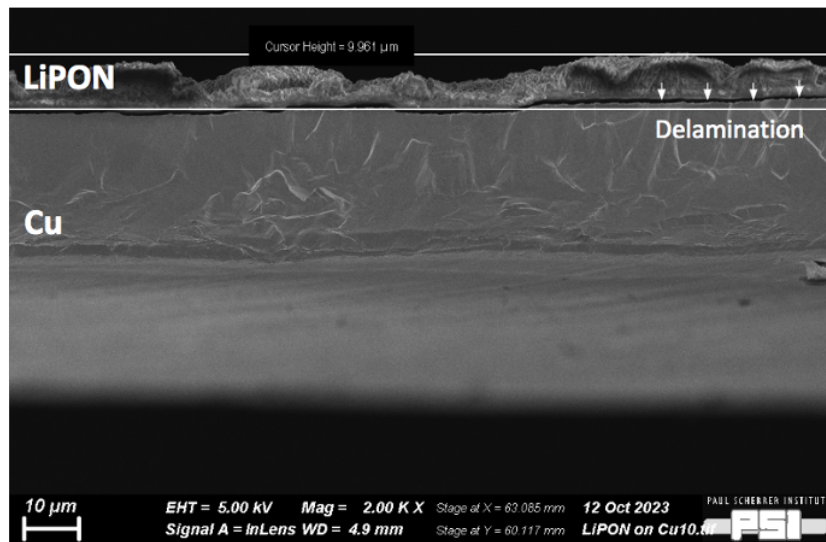
[A. J. Krasznahorkay et al, arXiv:1504.01527]

Microscopic analysis of target (SEM)

- Why LiPON?

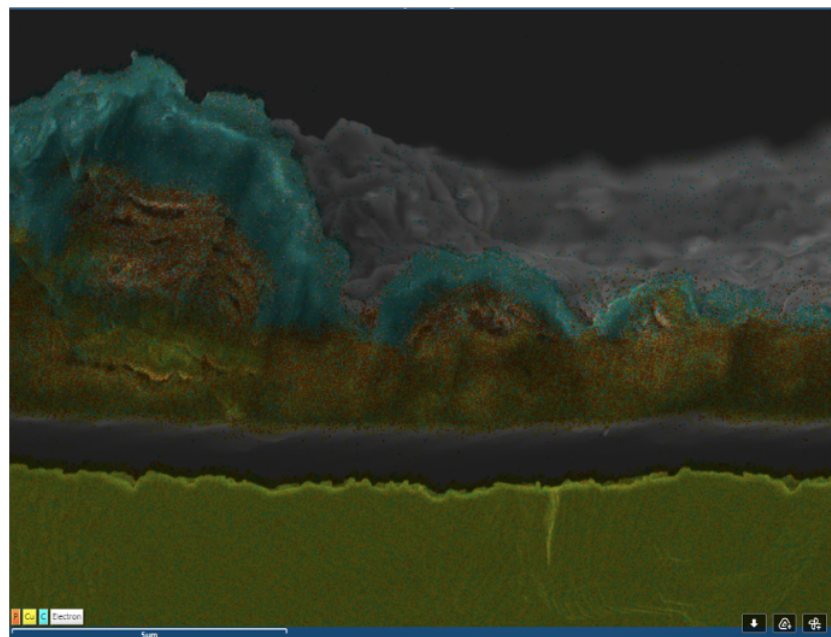
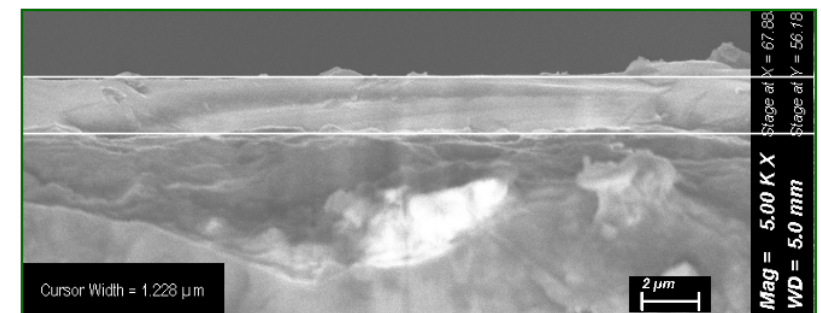
Stable, no F-related bkg, thin films through sputtering, developed for batteries

- Difficulties for production: thickness control and non-uniformity, oxidation layer



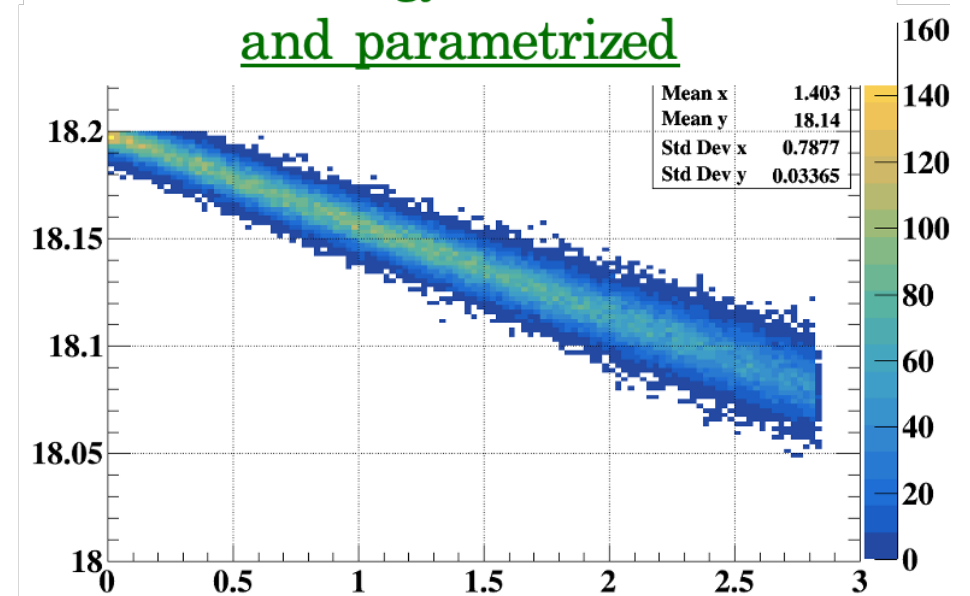
Delamination,
pores, large
thickness
variations

Recently, uniform thin 2-μm
films were achieved at PSI

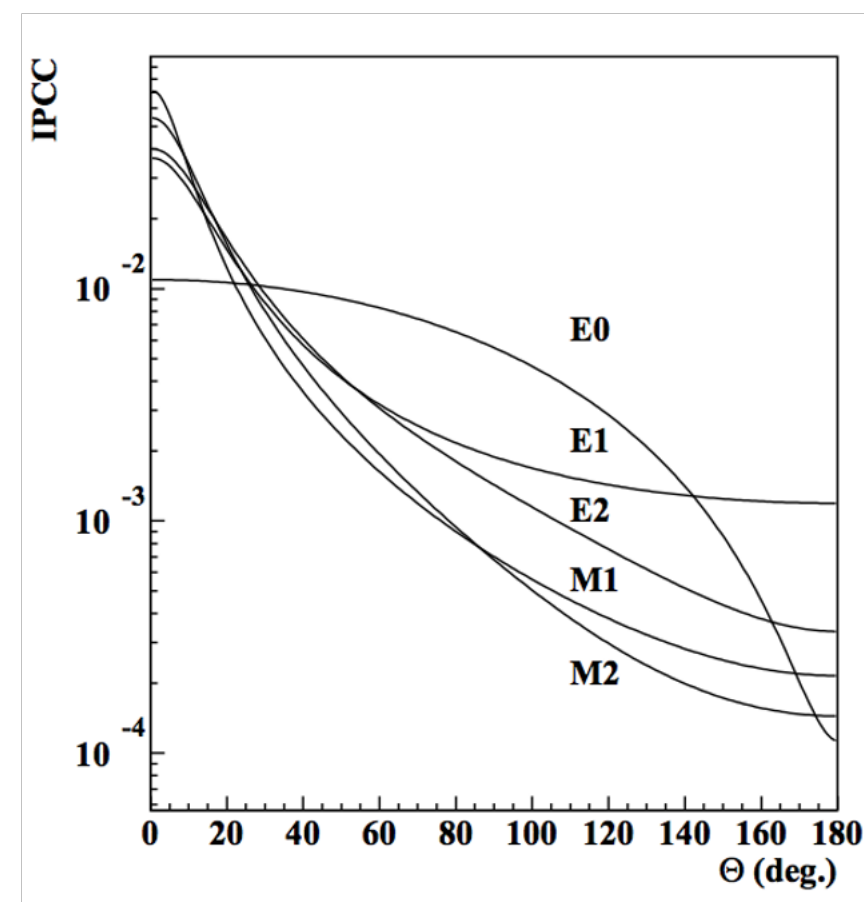
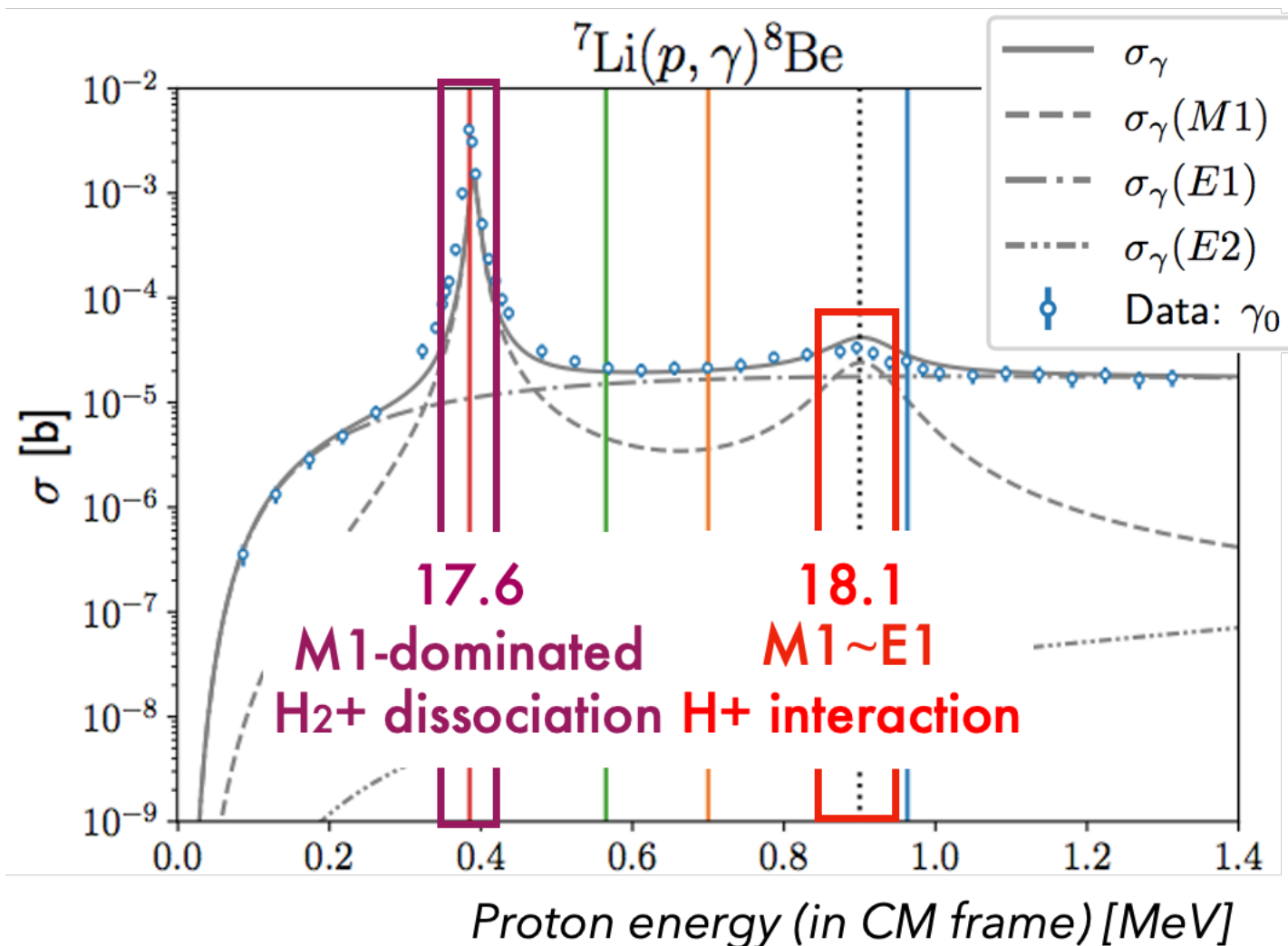


LiCO₃ on
the surface

Proton energy loss simulated
and parametrized



Effect of mixed species beam



- Dominated by events from 440 keV resonance (larger cross section even if H_2^+ are 1/3 of H^+)