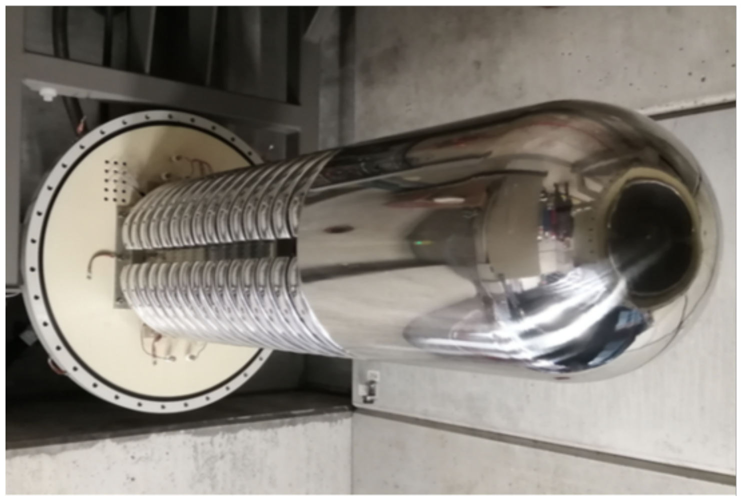
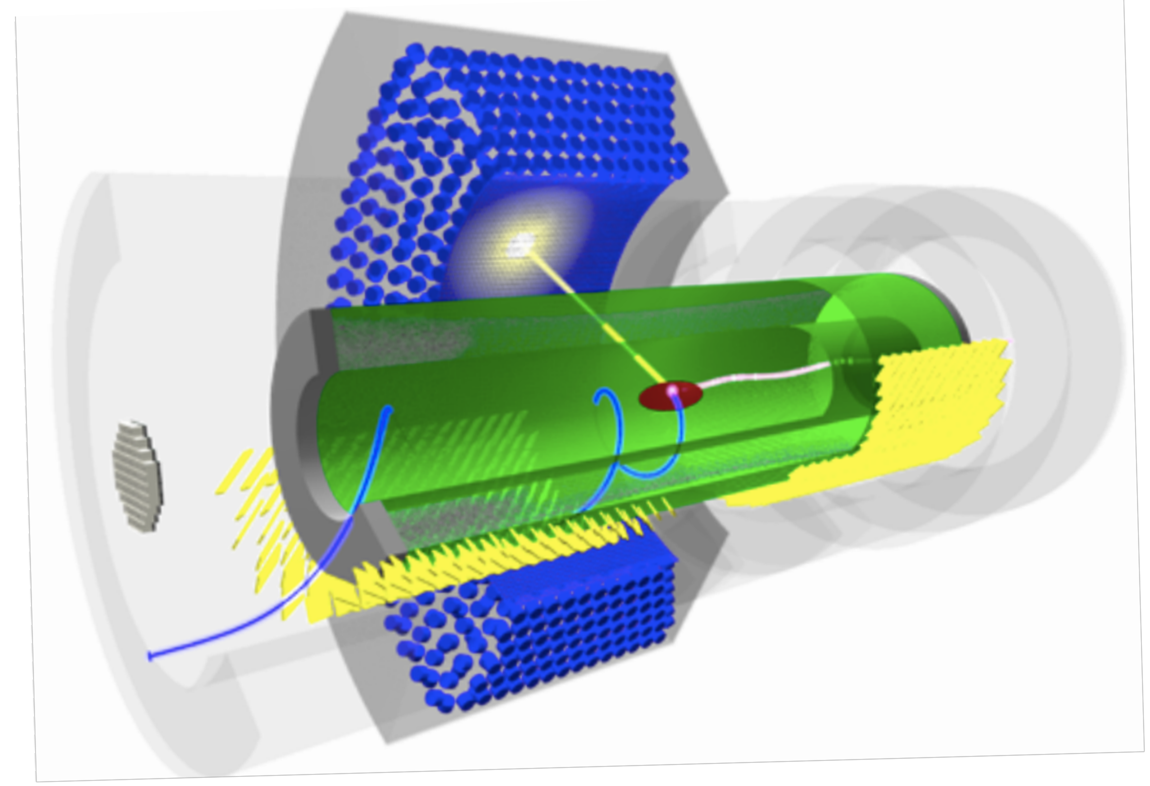




Search for the X17 particle in the $^7Li\,(p, e^+e^-)^8Be$ process with MEG II

Gianluca Cavoto *(Sapienza Univ Roma and INFN Roma)*
On behalf of the MEG II collaboration
PSI seminar - 13th Nov 2024

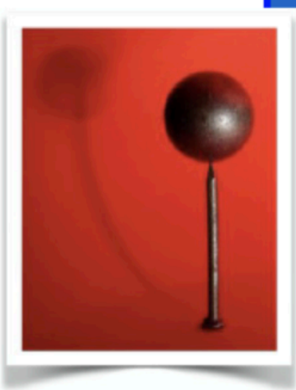
Outline

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

Reasons for more particles

- We love Standard Model but we are not totally satisfied

S.Gori

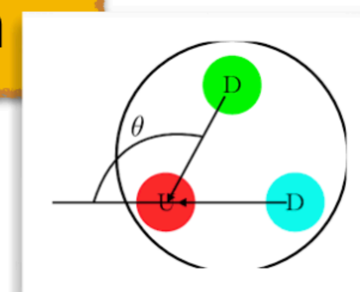


Naturalness problem

dark scalars
(twin Higgs, SUSY)

Strong CP problem

axions



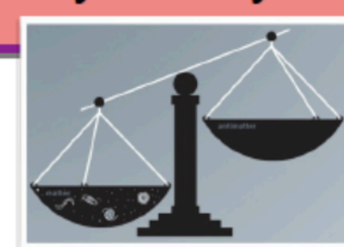
dark photons

Nature of Dark Matter

Neutrino masses

sterile neutrinos

Baryon anti-baryon asymmetry



dark scalars

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

One important example

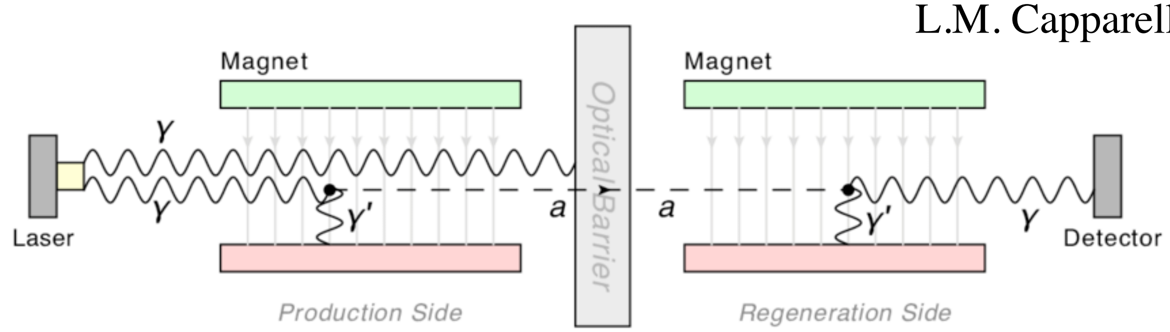
- **QCD axion**: fix the strong CP problem.
  - *why strong interactions are CP invariant while theory can develop a CP-odd term ?* (see neutron EDM)
  - In the '70s a ~10 MeV **axion *a*** was proposed to be searched in nuclear de-excitations: $^{12}C^*$ decay (rate predicted from ^{12}B β decay)

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/ψ → γa (**a → e+e-**)
  - beam dump experiments,
  - $(g\text{-}2)_\mu$ limit…
  - pion and kaon decays, …

Today,
an *invisible* ultra-light (μeV - 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)*

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

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

$$\mathcal{L}_a^{\text{eff}} = m_u\, e^{iQ_u^{\text{PQ}}\, a/f_a} uu^c + $$

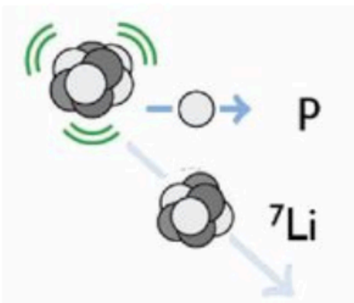
$$\frac{Q_u}{Q_d} = 2 \;\Rightarrow\; \theta_{a\pi}^{(0)} \approx \frac{4\,Q_d}{3}\frac{f_\pi}{f_a}\left(\frac{1}{2} - \frac{m_u}{m_d}\right) \approx 0.$$

being m_u/m_d ~0.5

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

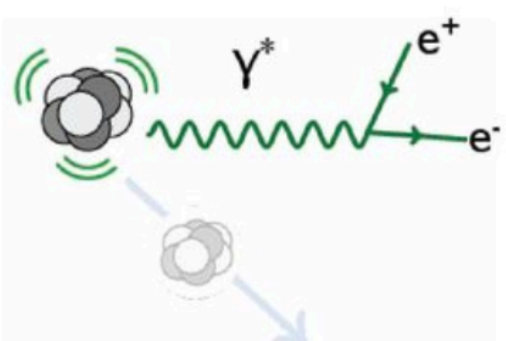
Internal Pair conversion (IPC)

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



Hadronic dissociation

Electromagnetic Transition (γ emission)

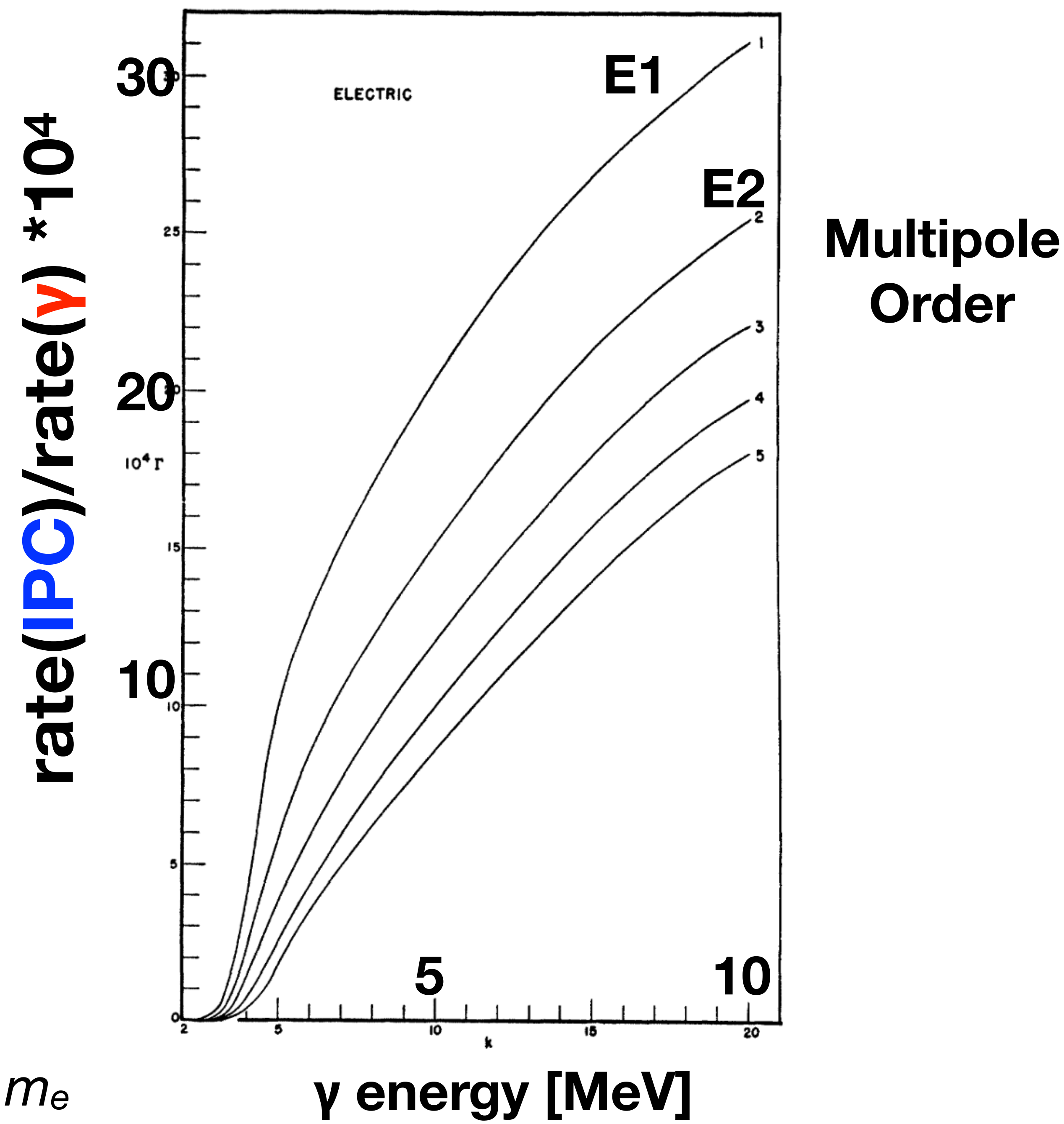


IPC

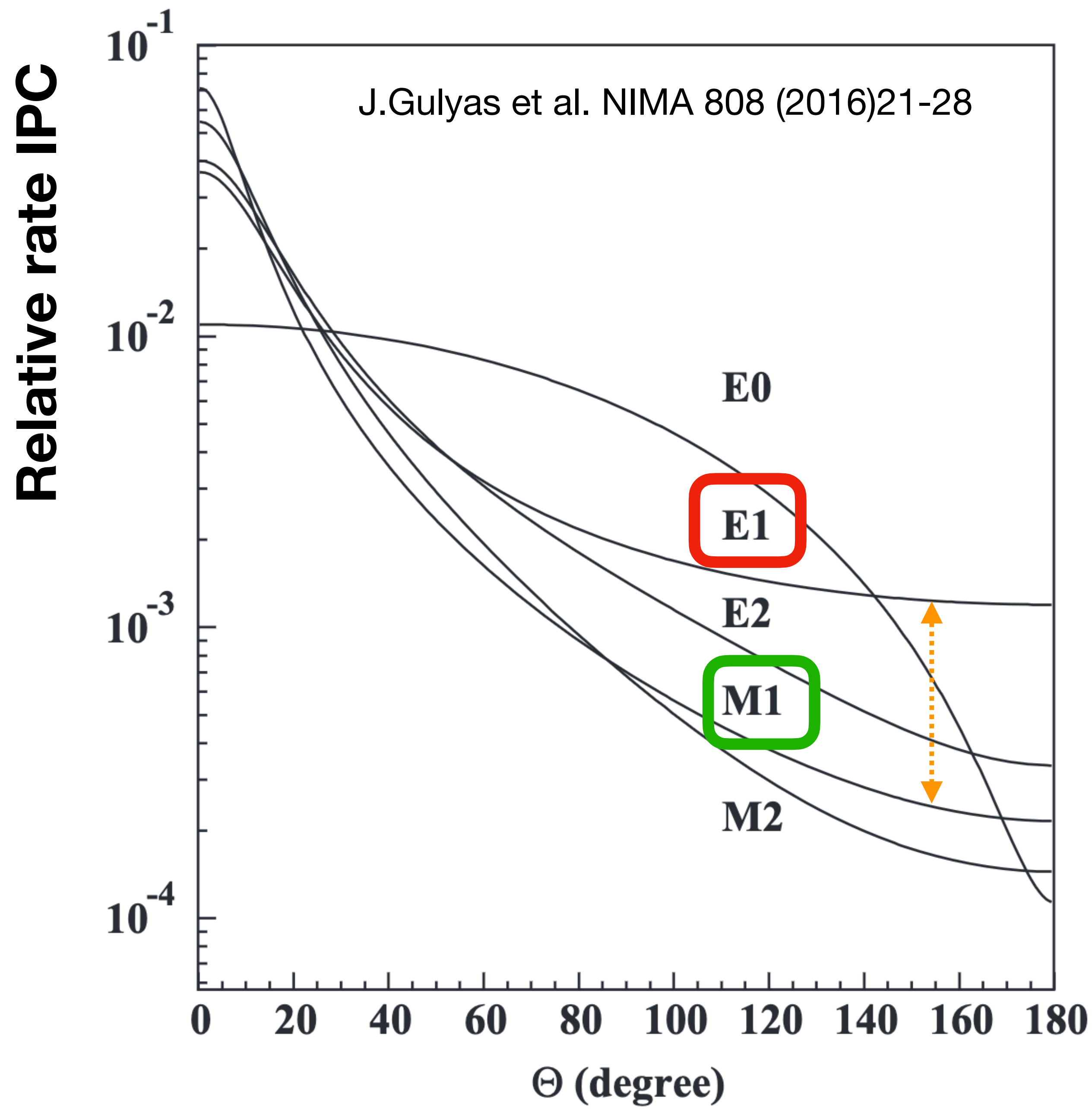
1 IPC every 1000 γ

Possible only for energy > 2 m_e

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



Experimental signature for IPC



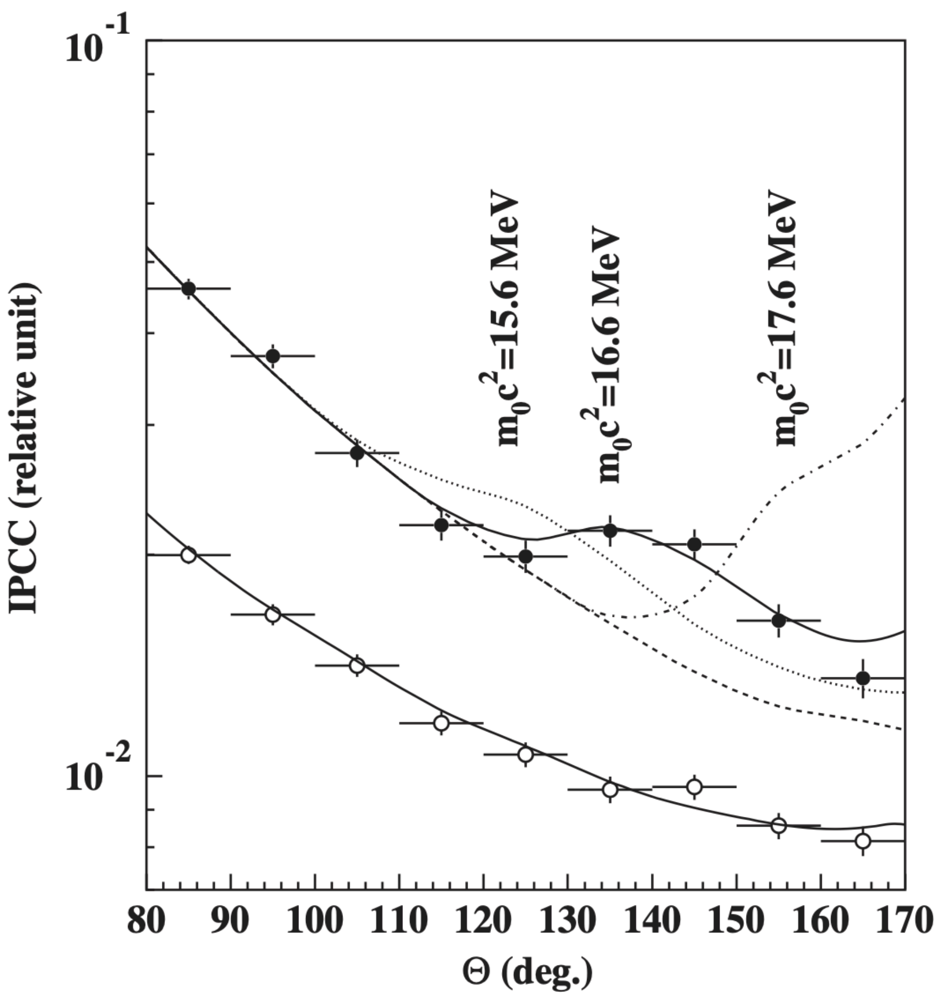
Θ_{ee} : angular opening between e^+e^-

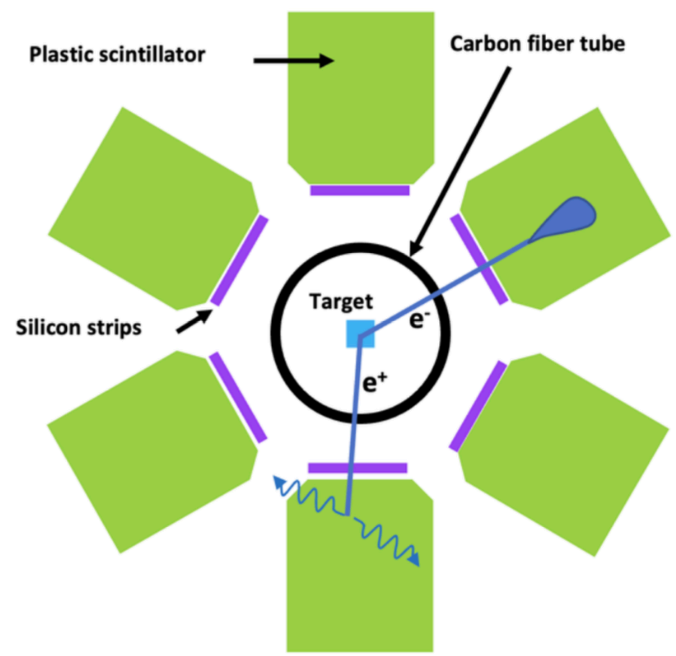
- **Smooth** decrease
- Different shape according to multipole transition type
  - Mx : **magnetic** (no parity change)
  - Ex: **electric** (parity change)

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

An unexpected(?) anomaly in **^{8}Be**

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





"Transverse-only" detector
No magnetic field

LiF and LiO targets

Proton energy
E_p = 0.5 - 1.2 MeV

- Inv. mass **m ~ 16.7 MeV**
- Rate (wrt γ) = **6 10^{-6}**

A new particle, then ?

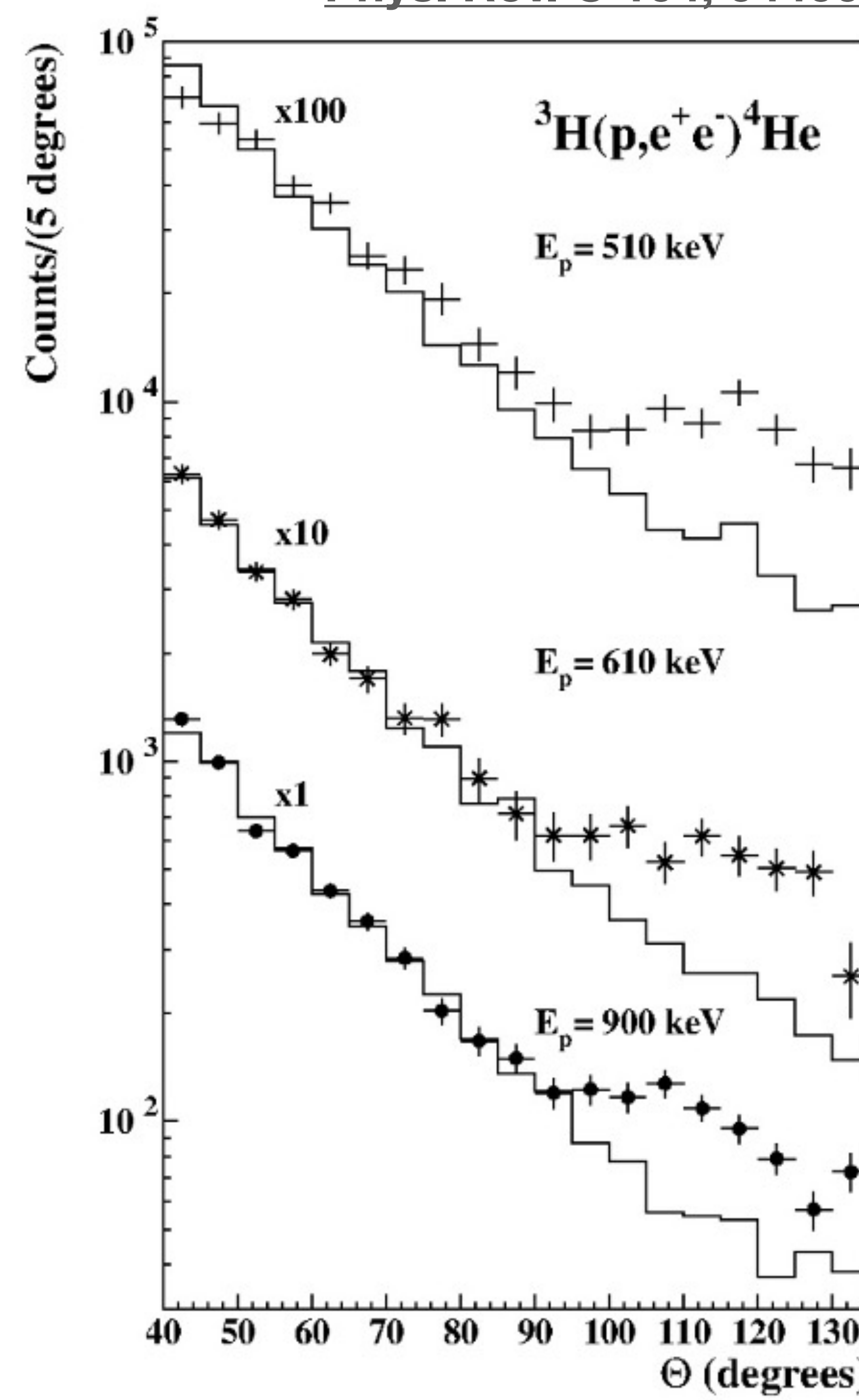
More evidence

- 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)

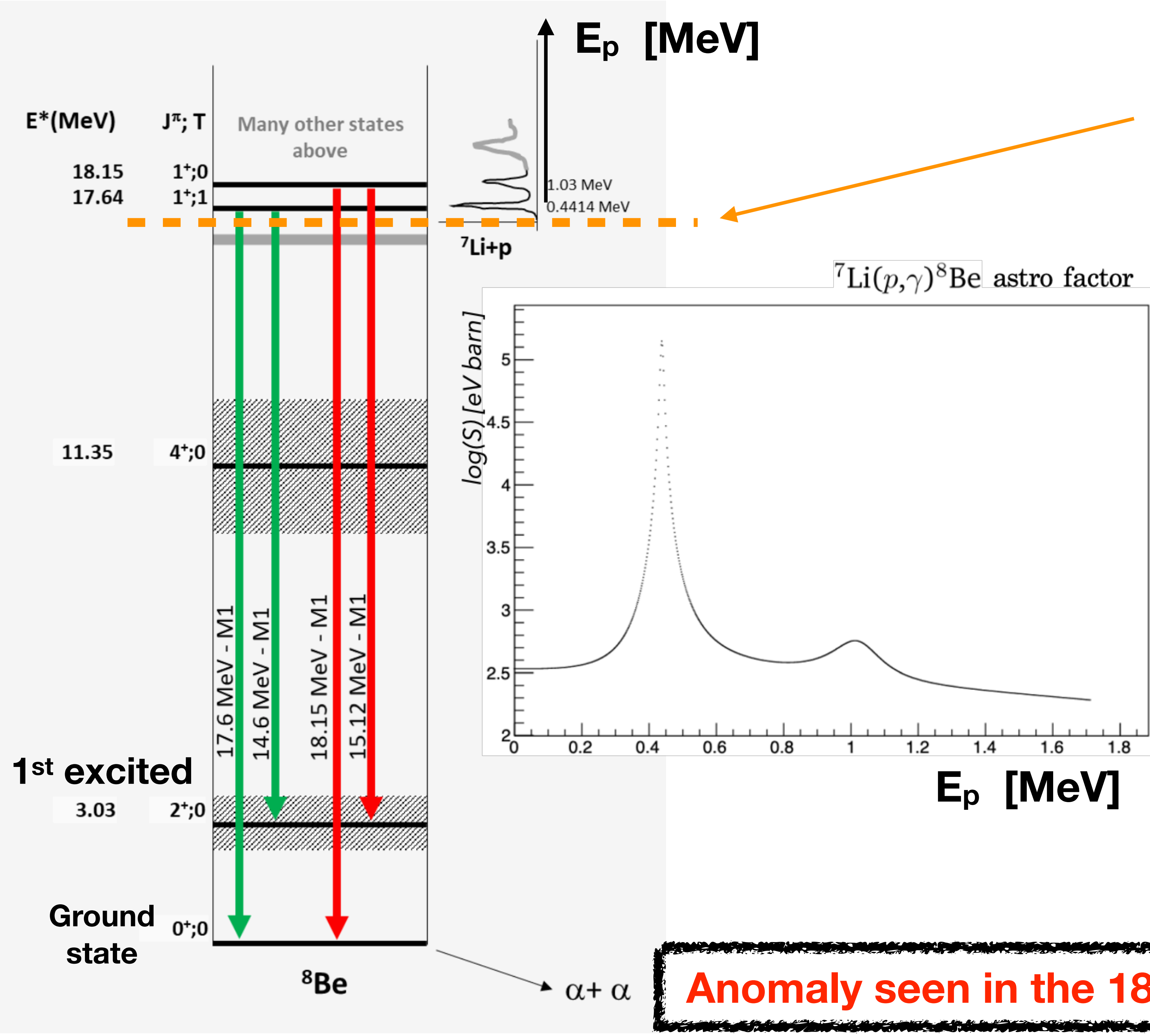
- Same anomaly in ^{11}B(p, e^+e^-)**^{12}C** Phys. Rev. C 106, L061601
- No evidence from NA64 and NA48

Phys. Rev. D. 101:071101 Phys. Lett. B 746, 178

Phys. Rev. C 104, 044003



^{8}Be levels



^{7}Li + p yields 17.255 MeV above ^{8}Be g.s. → 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_γ = Q)

$1^+ \rightarrow 2^+$ (E_γ = Q-3 MeV)

Anomaly seen in the 18.1 MeV transition only

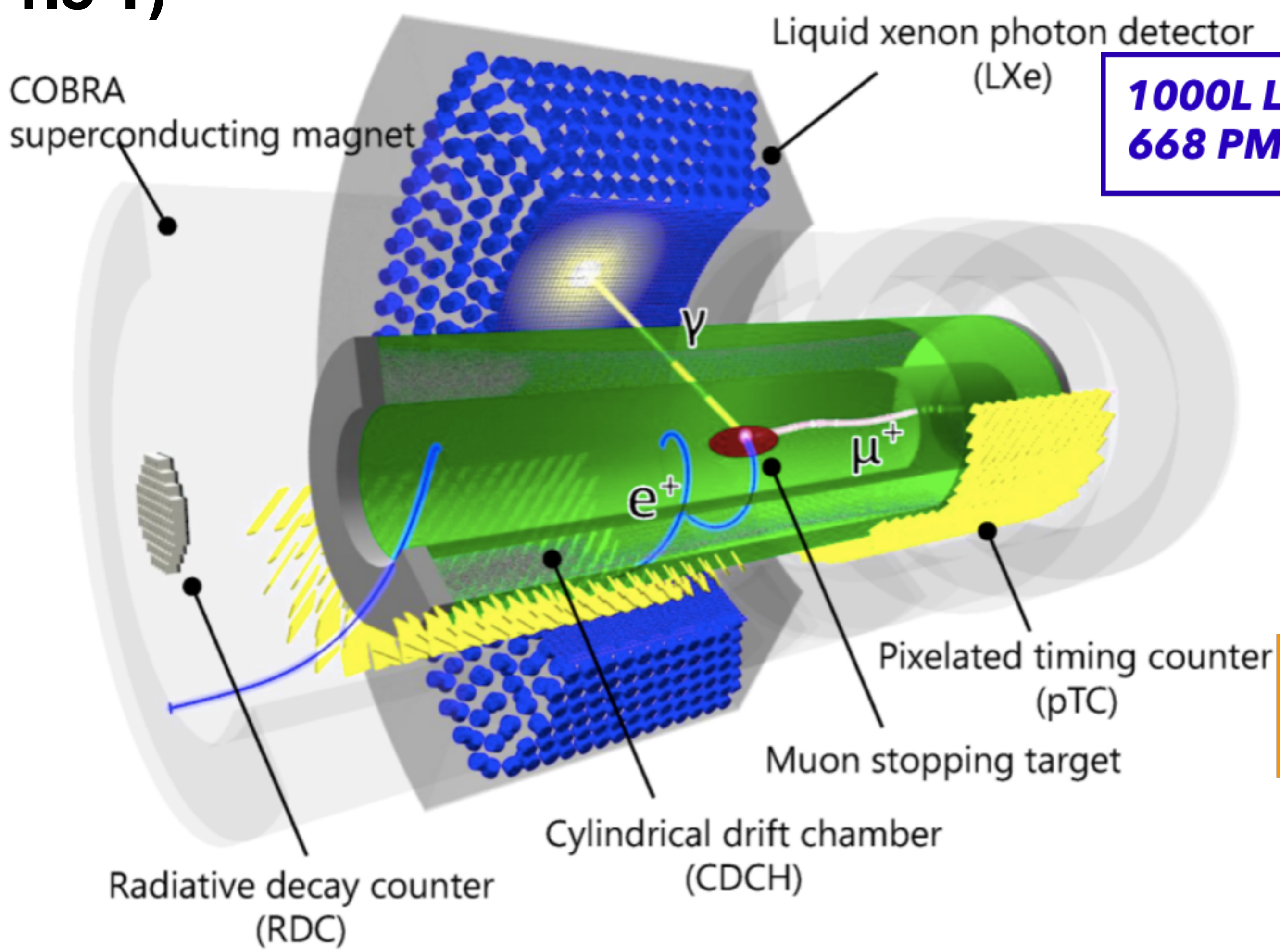
The MEG II detector at πE5 (PSI)

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

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

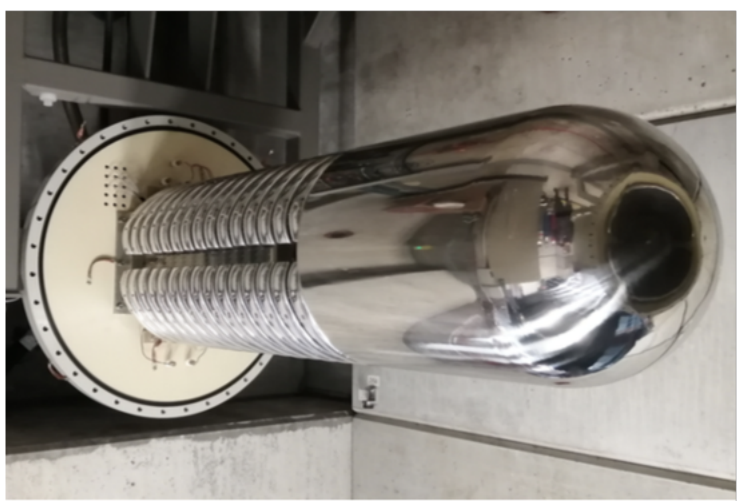
Current best limit:

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

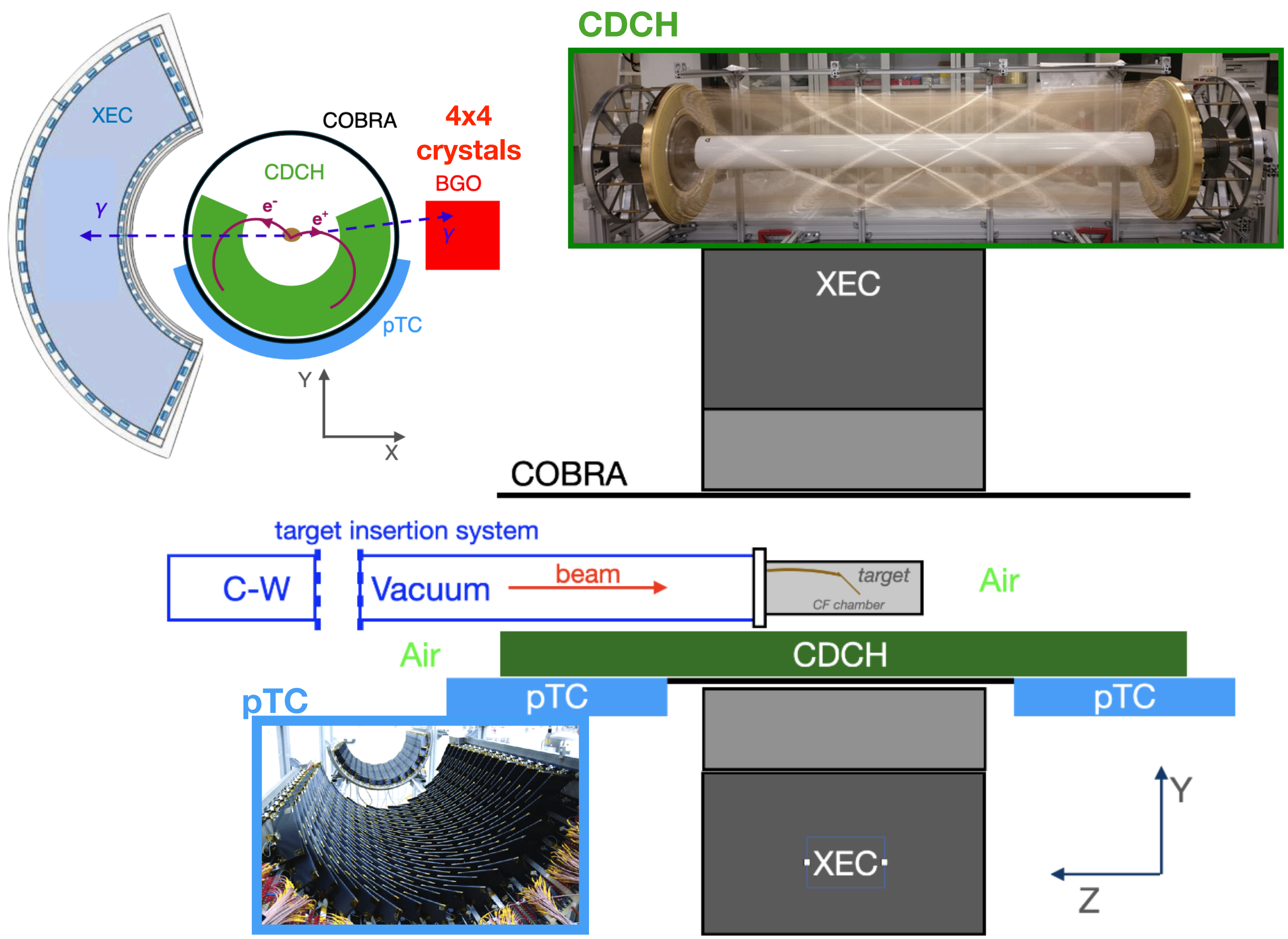
$$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 3.1 \times 10^{-13} \text{ (90\% CL)}$$

MEG II for X17

- Cockroft Walton accelerator :
- up to ~1 MeV beam
- ~ tens μA current



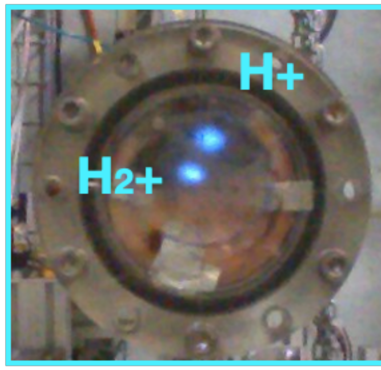
Routinely used for XEC calibration with $^{7}Li\ (p, \gamma)^{8}Be$

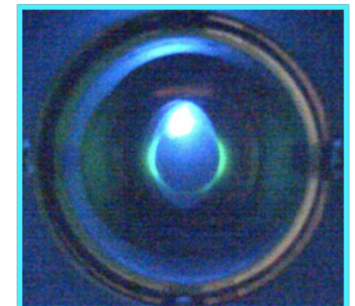


Detecting ~10 MeV $e^{+}e^{-}$ with a magnetic spectrometer (reduced B x 0.15)
Different technique (but detector material budget not optimal)

The Cockroft Walton beam

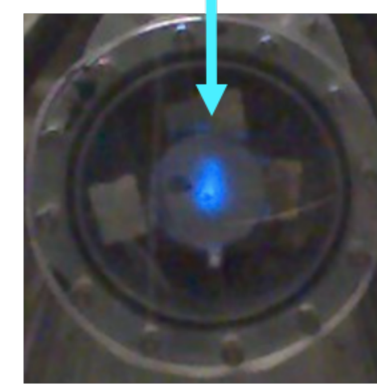
Beam imaging with a quartz screen





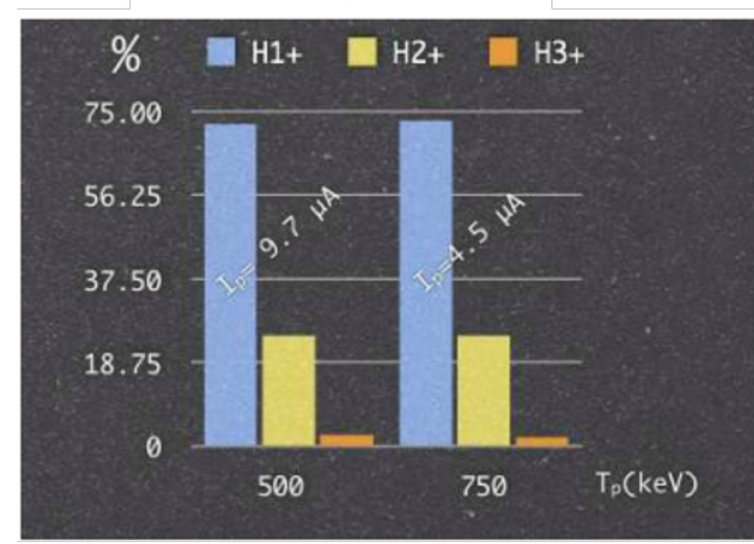
COBRA

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 $E_{beam}/2$**

Ion composition

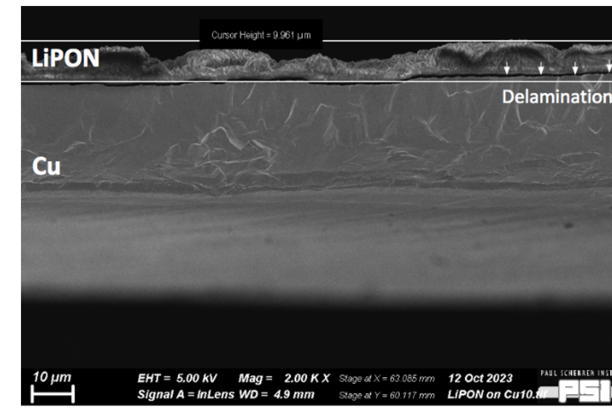


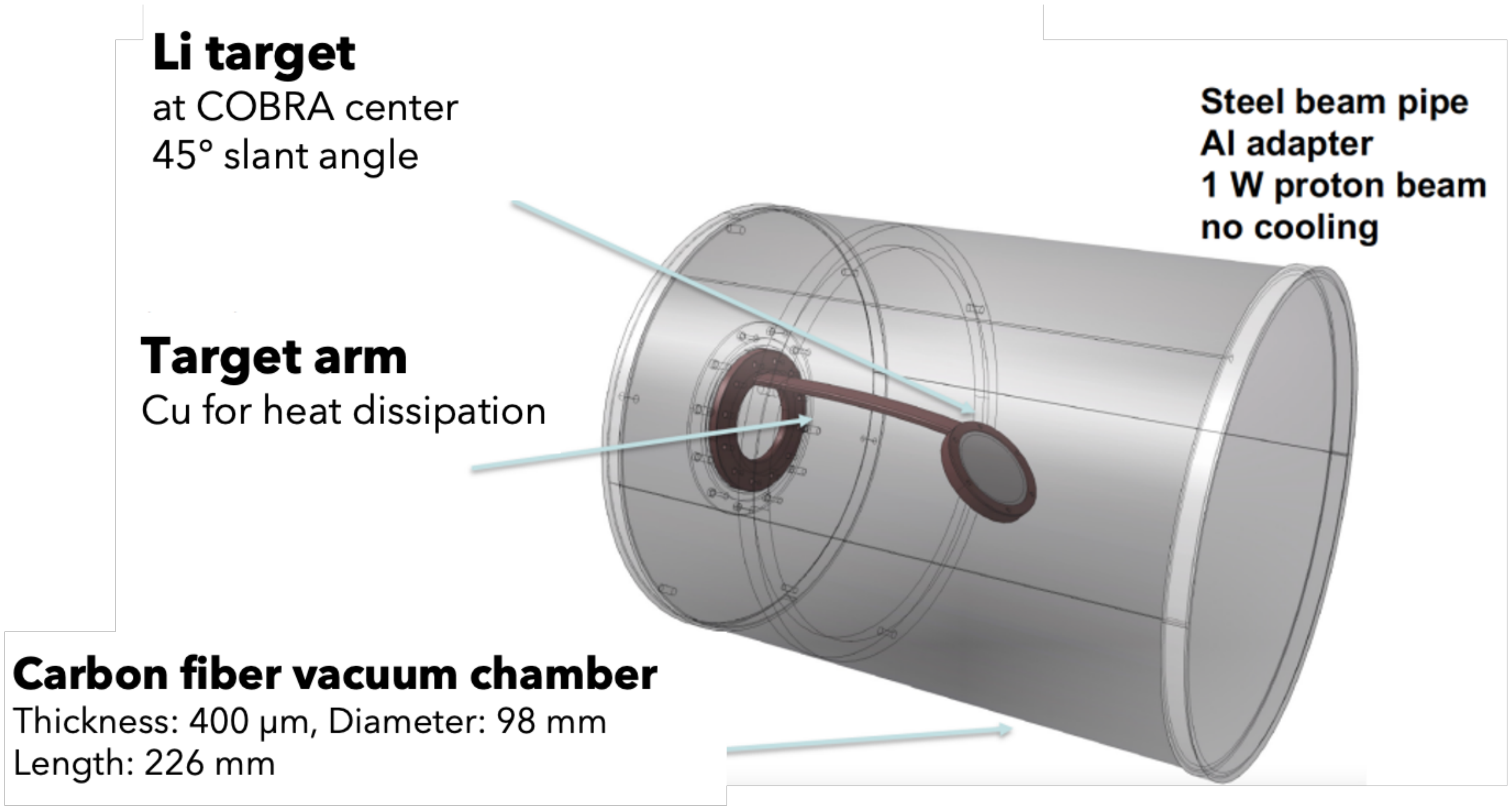
Data taking in Feb 2023 with E_{beam} = 1.080 MeV

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



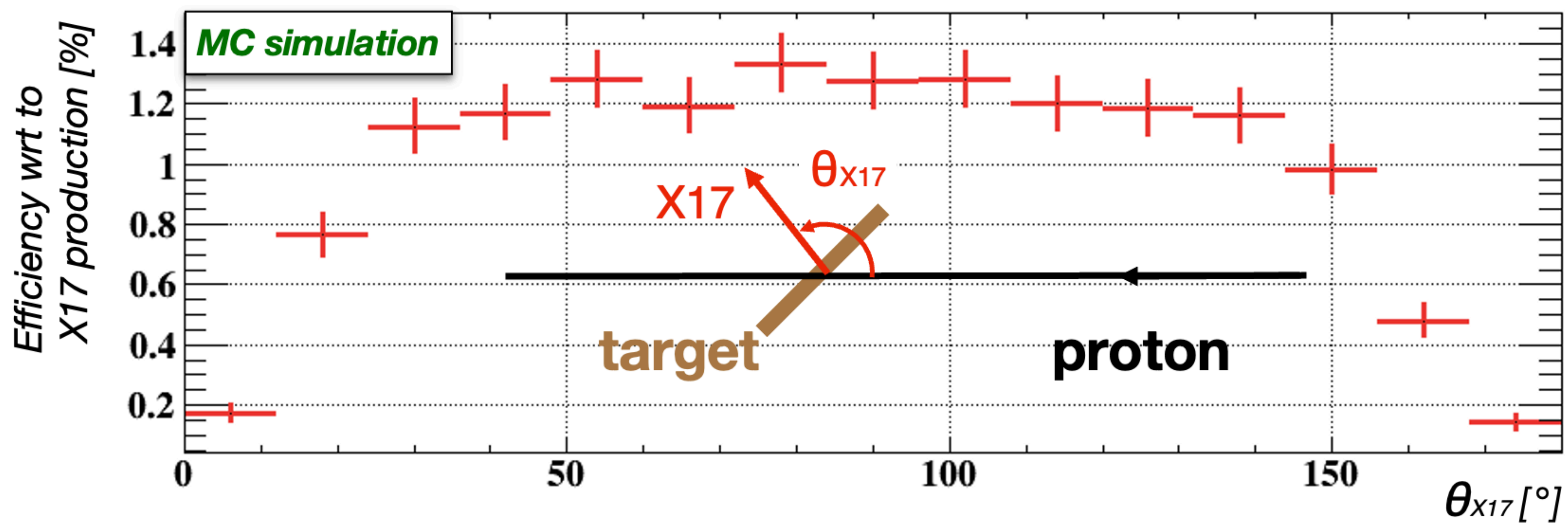


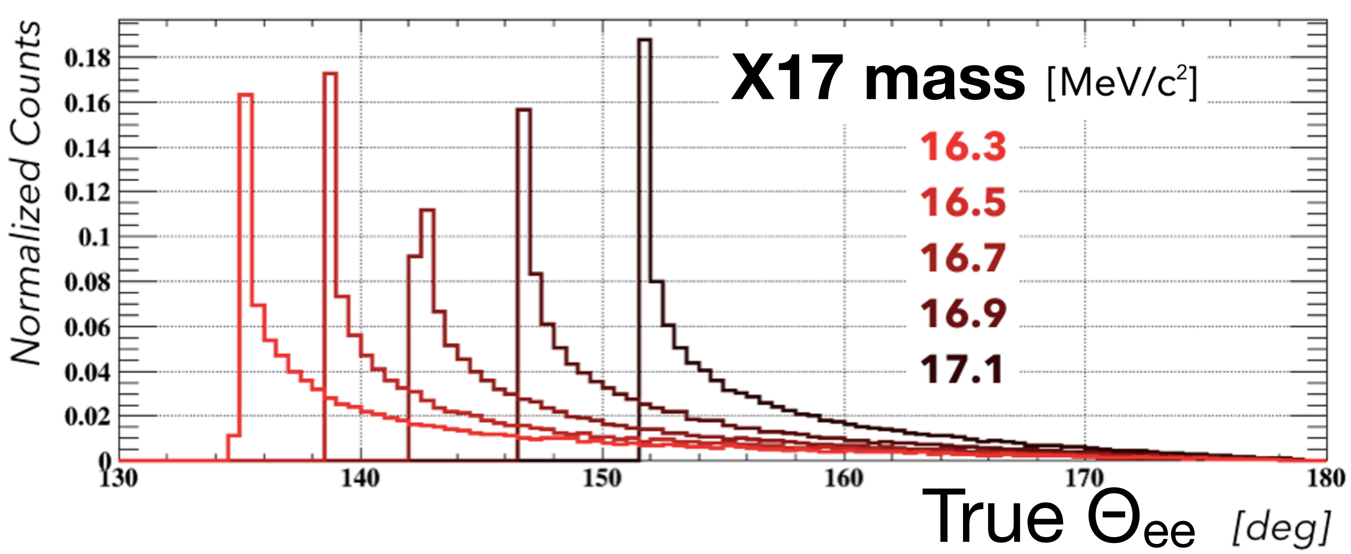
LiF target
(INFN Legnaro)
For BGO calibration

(*) Lithium phosphorus oxynitride ($Li_{3-X}PO_{4-Y}N_{X+Y}$)

The X17 signal in MEG II

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





Assumed isotropically produced

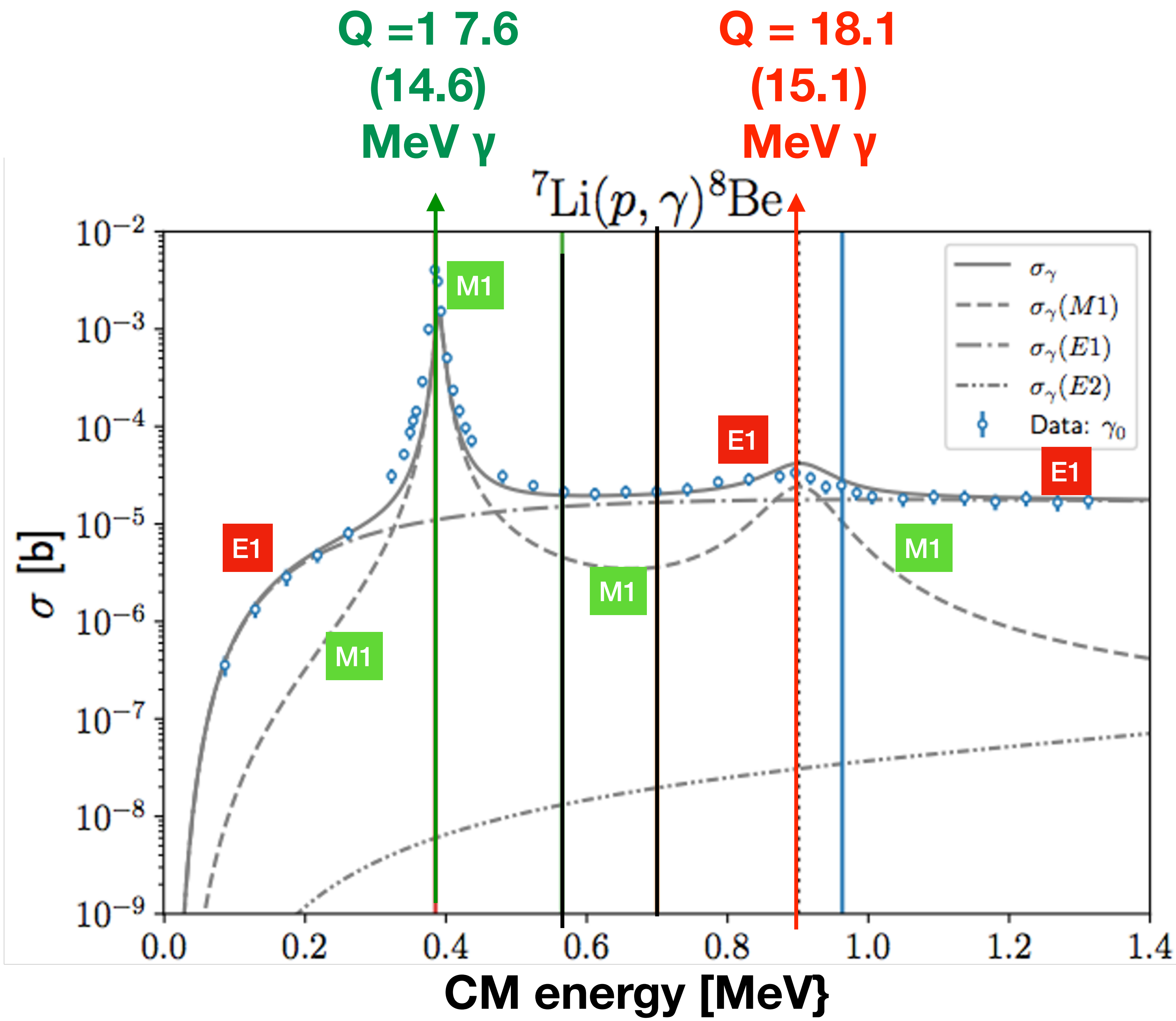
Overall 1% detection efficiency
(*apparatus sub-optimal*)

6 deg resolution on Θ_{ee}

https://arxiv.org/abs/2308.13751

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

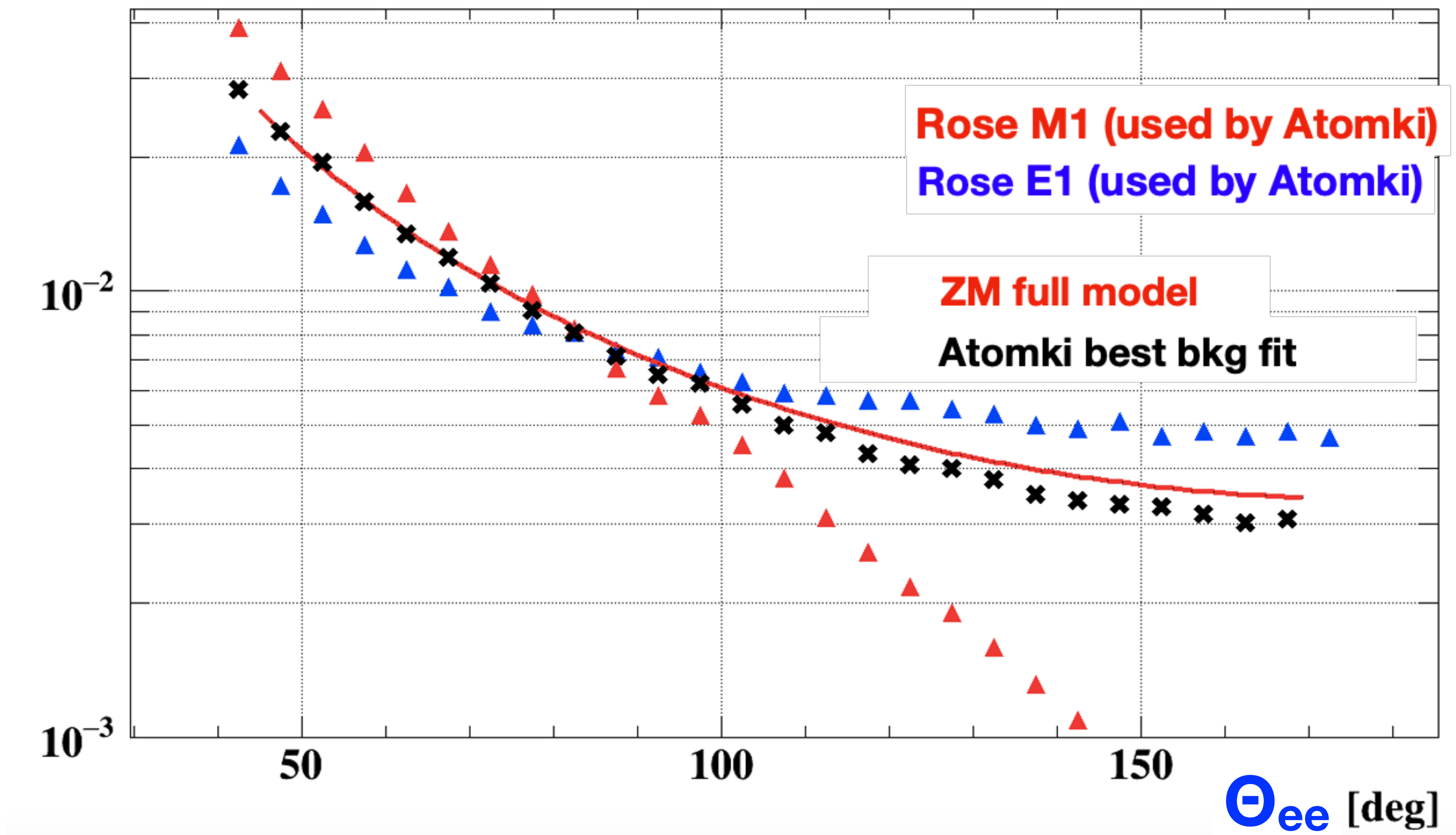


Zhang Miller PL B 773 (2017) 159-165

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)

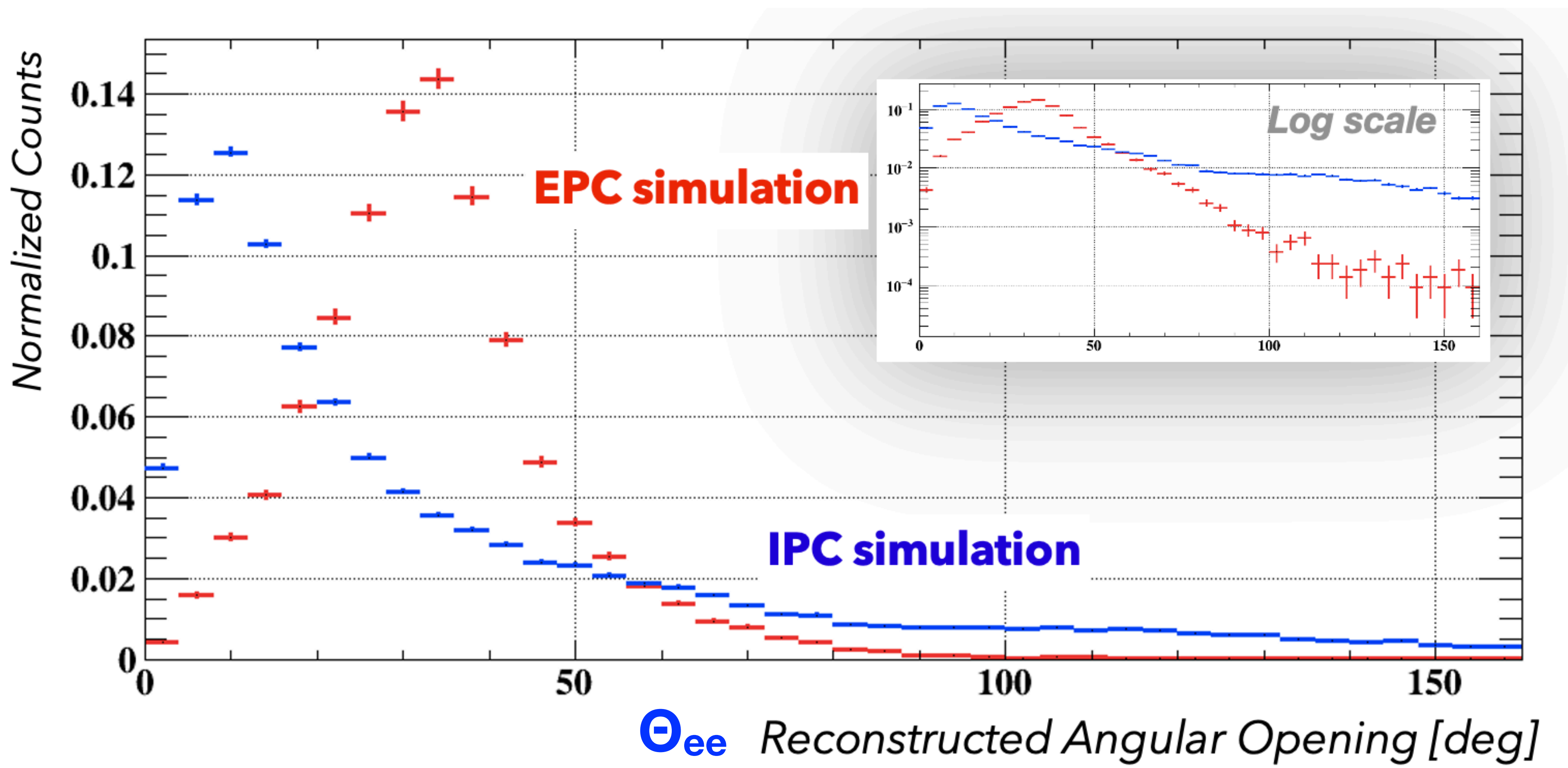


Still not enough to explain the anomaly though…

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

External pair conversion (EPC)

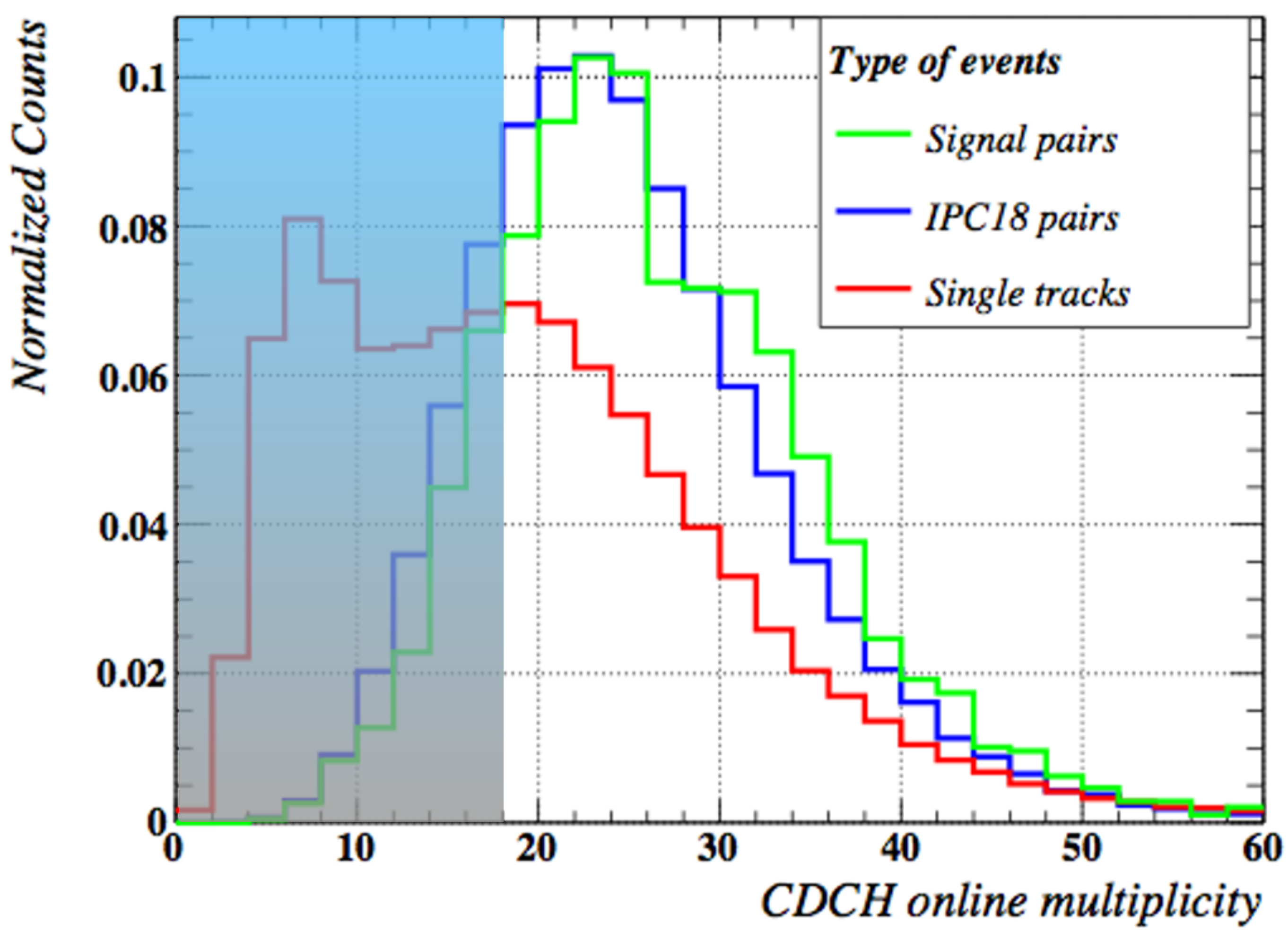
- Real photon from more copious ^{7}Li (p, γ)^{8}**Be** convert in the detector material
  - Compton electrons and e+e- pairs
  - Very detector-dependent.



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

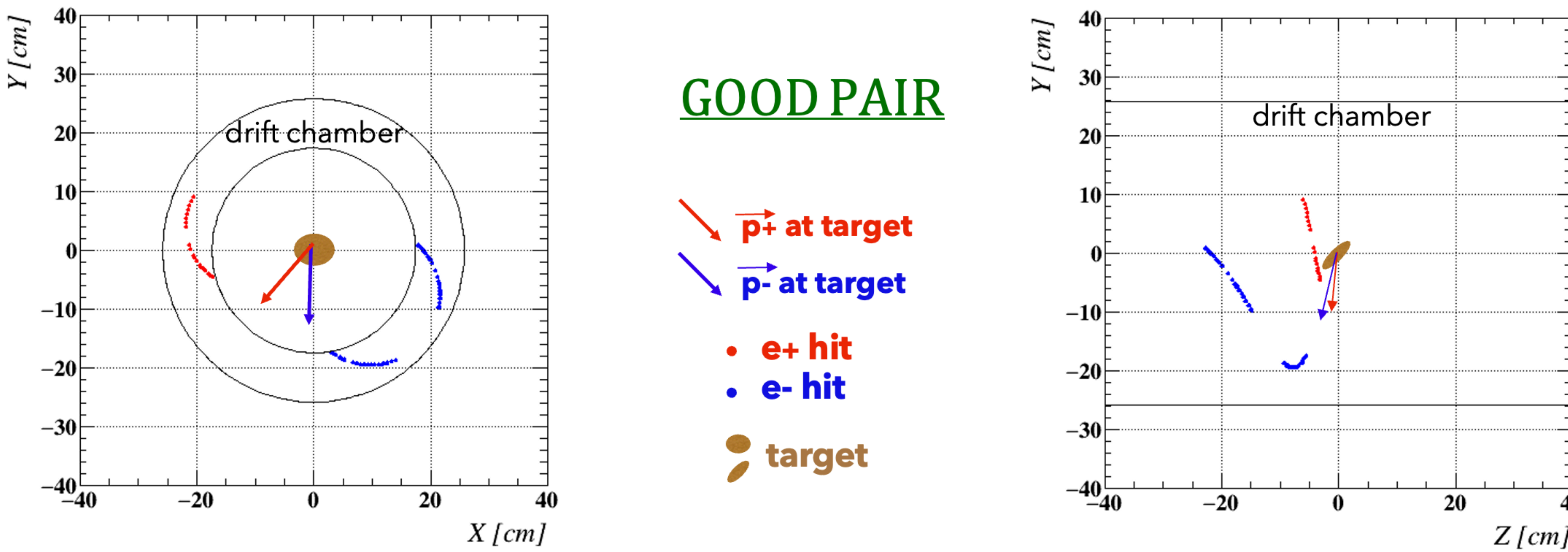
16% efficient on **signal** X17

Background rejection x5 larger
(than with 10 CDCH hits)

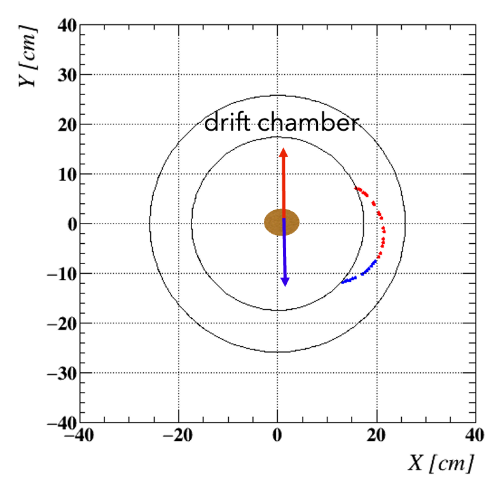
Leaves room to increase
beam current
(up to more than 10 μA)

Track Reconstruction

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



Fake pair:
Single particle reconstructed as two tracks (Θ_{ee}~180°)

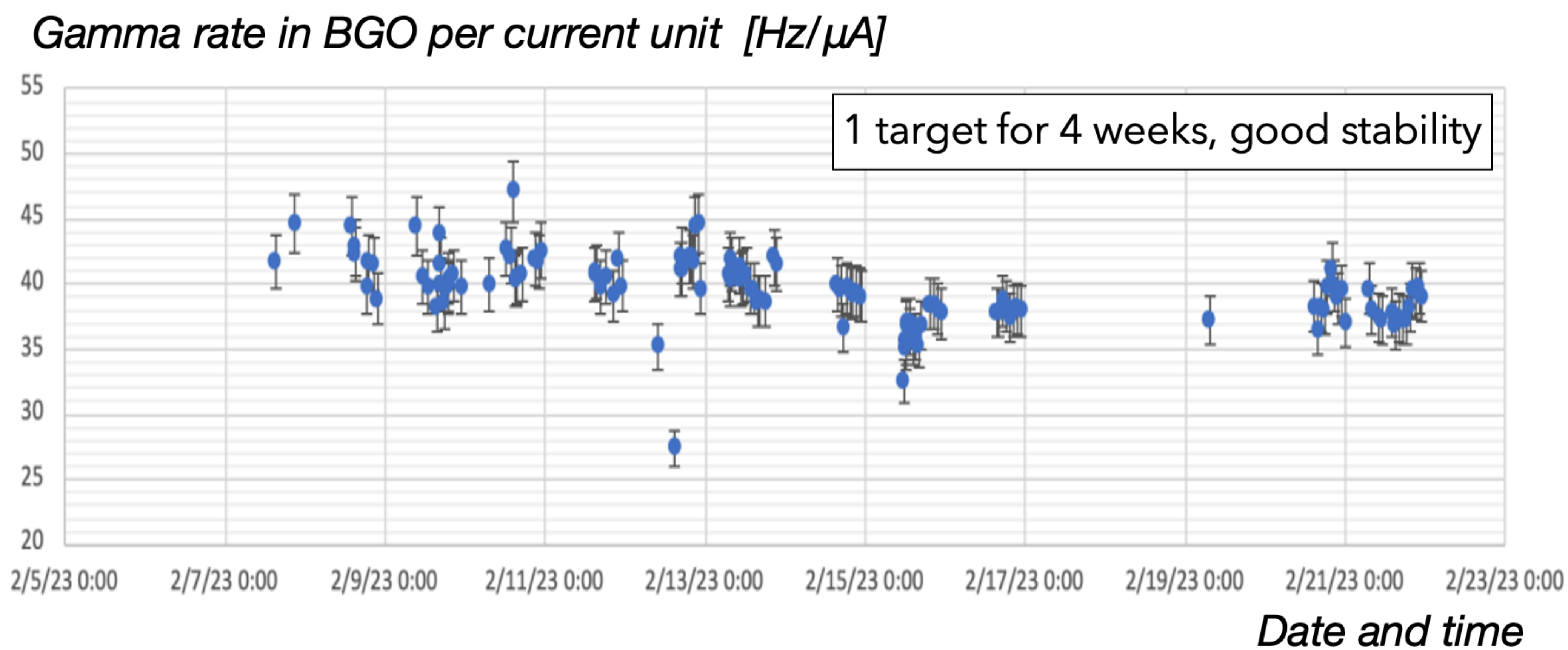


Detailed study to suppress fakes
Advanced good tracks selection implemented.

Signal efficiency (and IPC acceptance) ~2.5%

Feb 2023 data taking

- Run with Ebeam = 1.080 MeV at 10 µA
  - 75M events collected, about 300k pairs reconstructed

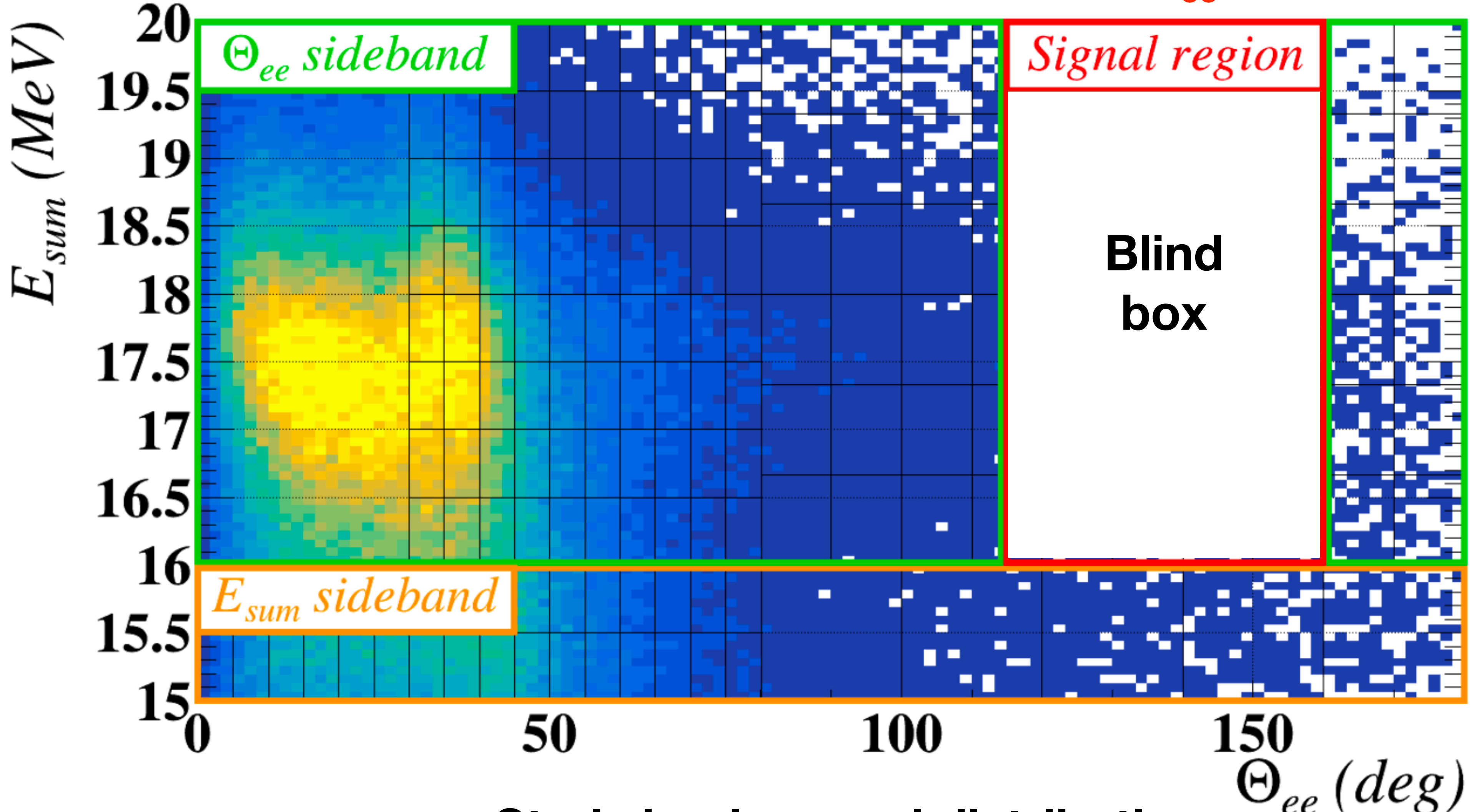


- Remarkable stability
- Beam with both H^+ and H_2^+ → events from both Q=17.6 and Q=18.1 MeV transition → **data analysis to separate them**

Analysis strategy

- Analysis variables : $\mathbf{E_{sum}} = E_{e-} + E_{e+}$ and $\mathbf{\Theta_{ee}}$

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



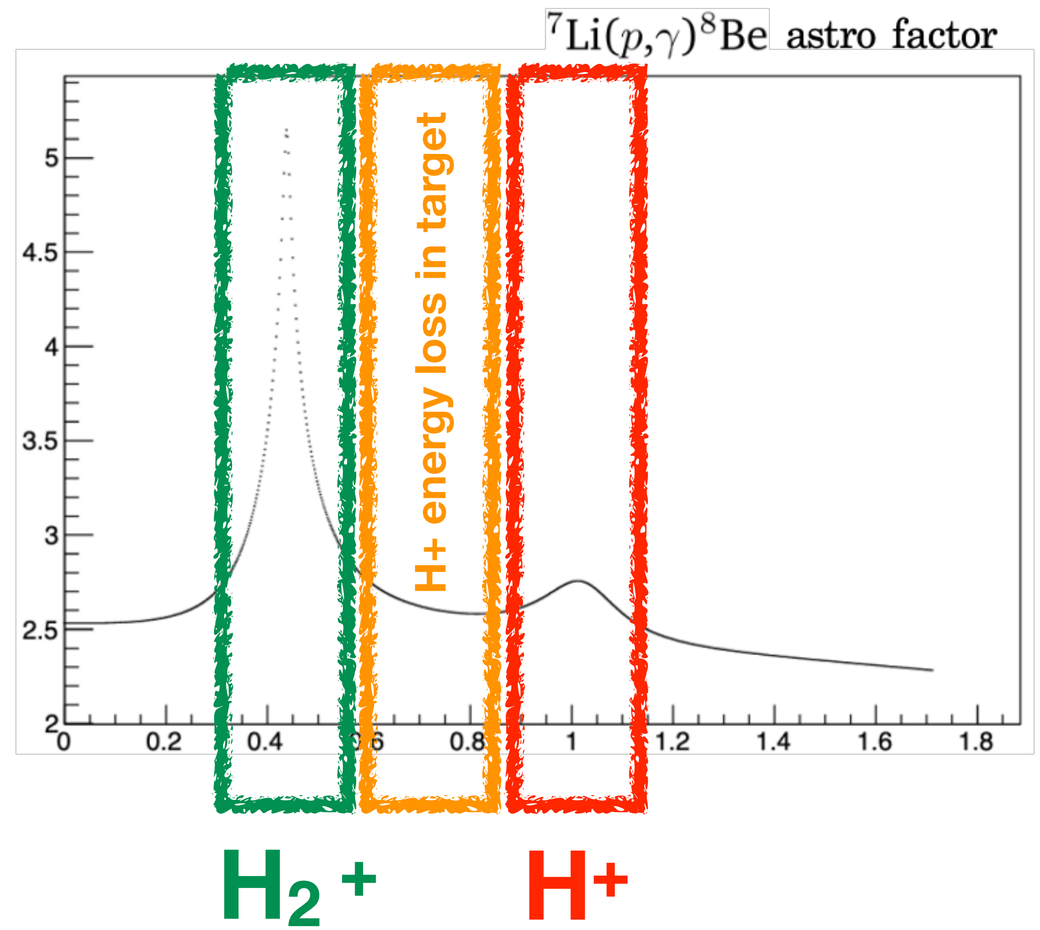
Study background distribution in sideband (data/MC comparison) before opening the box

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

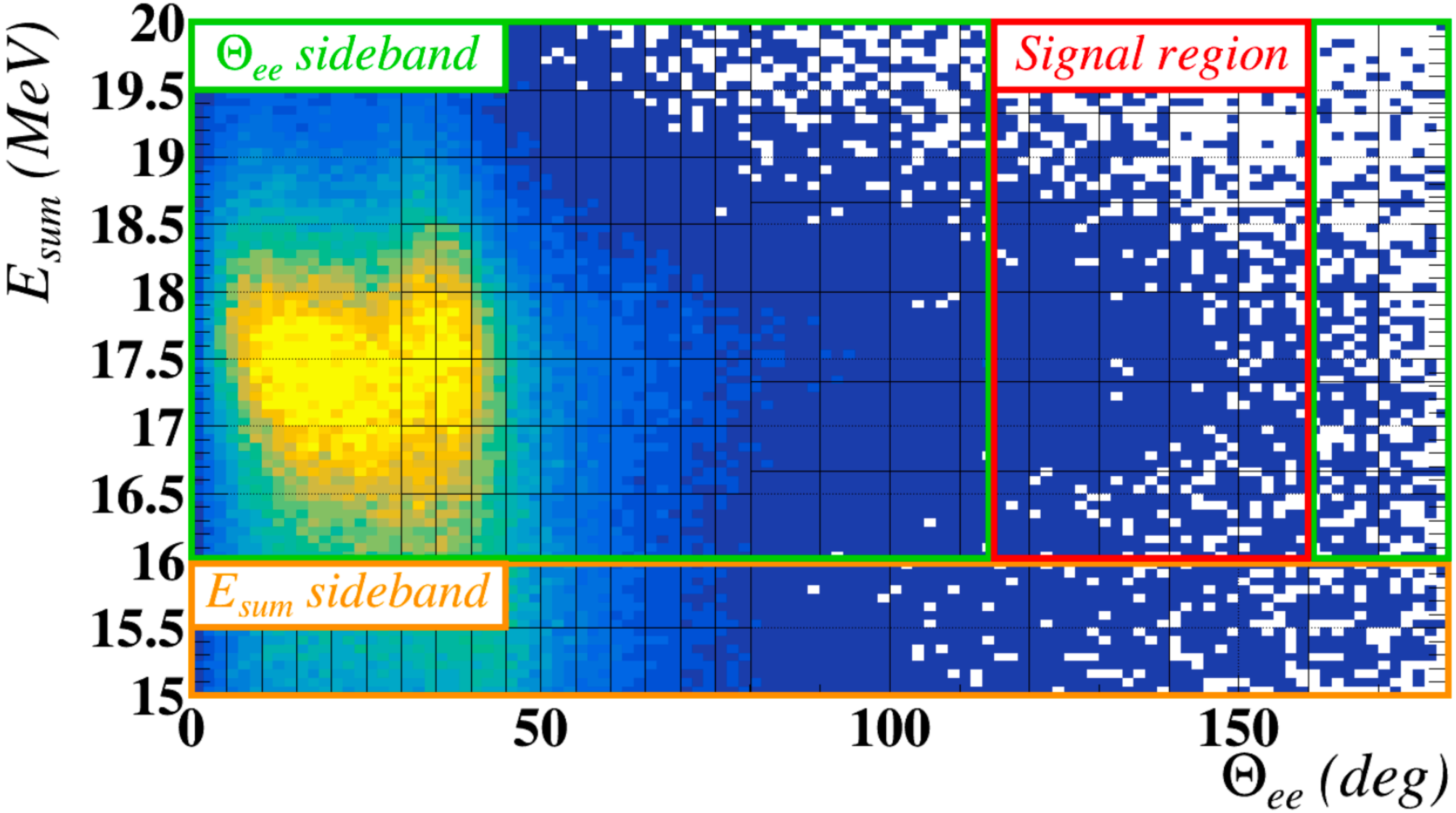
$$R_Q = \frac{\mathscr{B}(^8\mathrm{Be}^*(Q) \to {}^8\mathrm{Be} + \mathrm{X17})}{\mathscr{B}(^8\mathrm{Be}^*(Q) \to {}^8\mathrm{Be} + \gamma)}$$

- **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



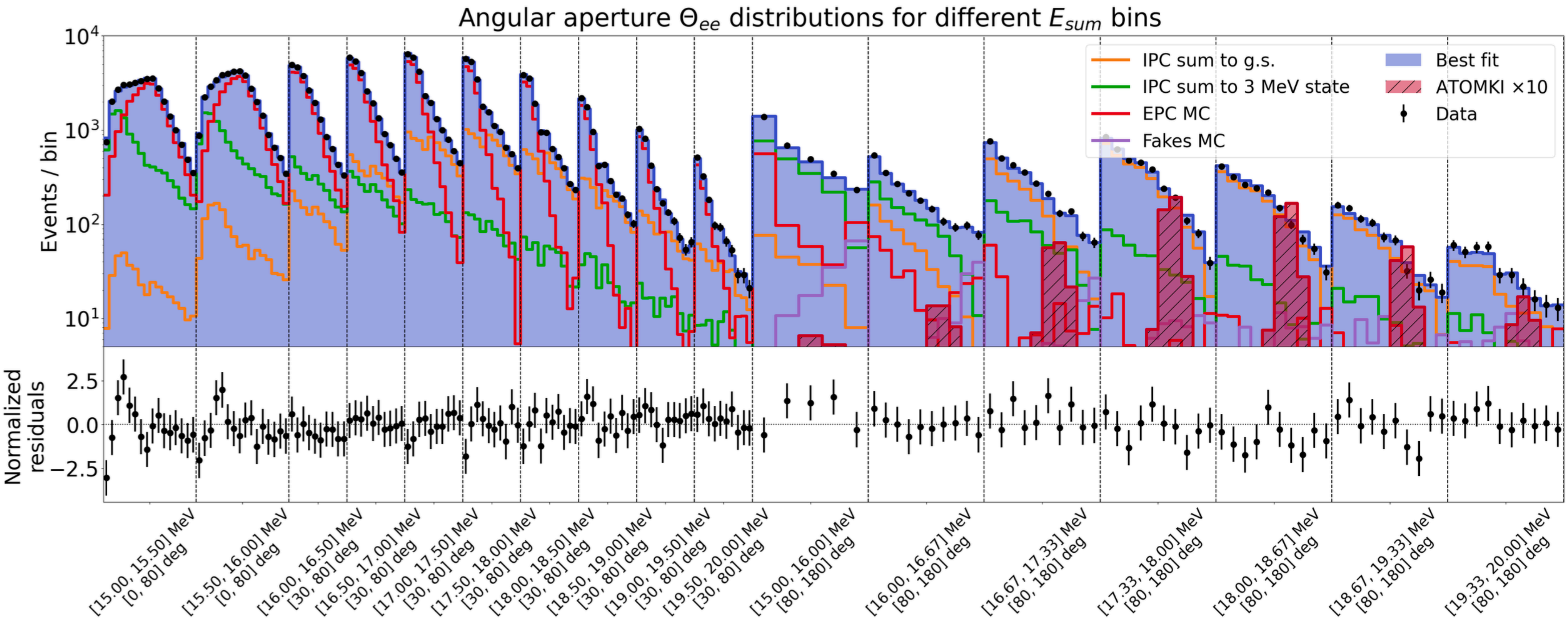
Including Beeston-Barlow coefficients to account for MC limited statistics

Unblinding



Θ_{ee} sideband
Signal region
E_{sum} sideband
E_{sum} (MeV)
20
19.5
19
18.5
18
17.5
17
16.5
16
15.5
15
0
50
100
150
Θ_{ee} (deg)

Results from the ML fit

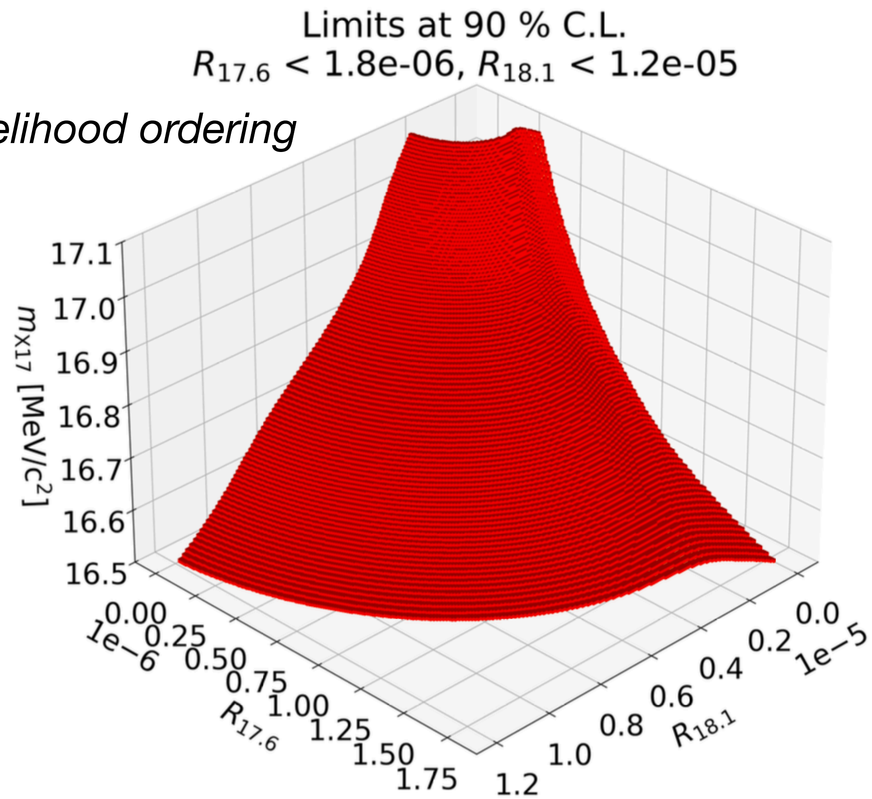


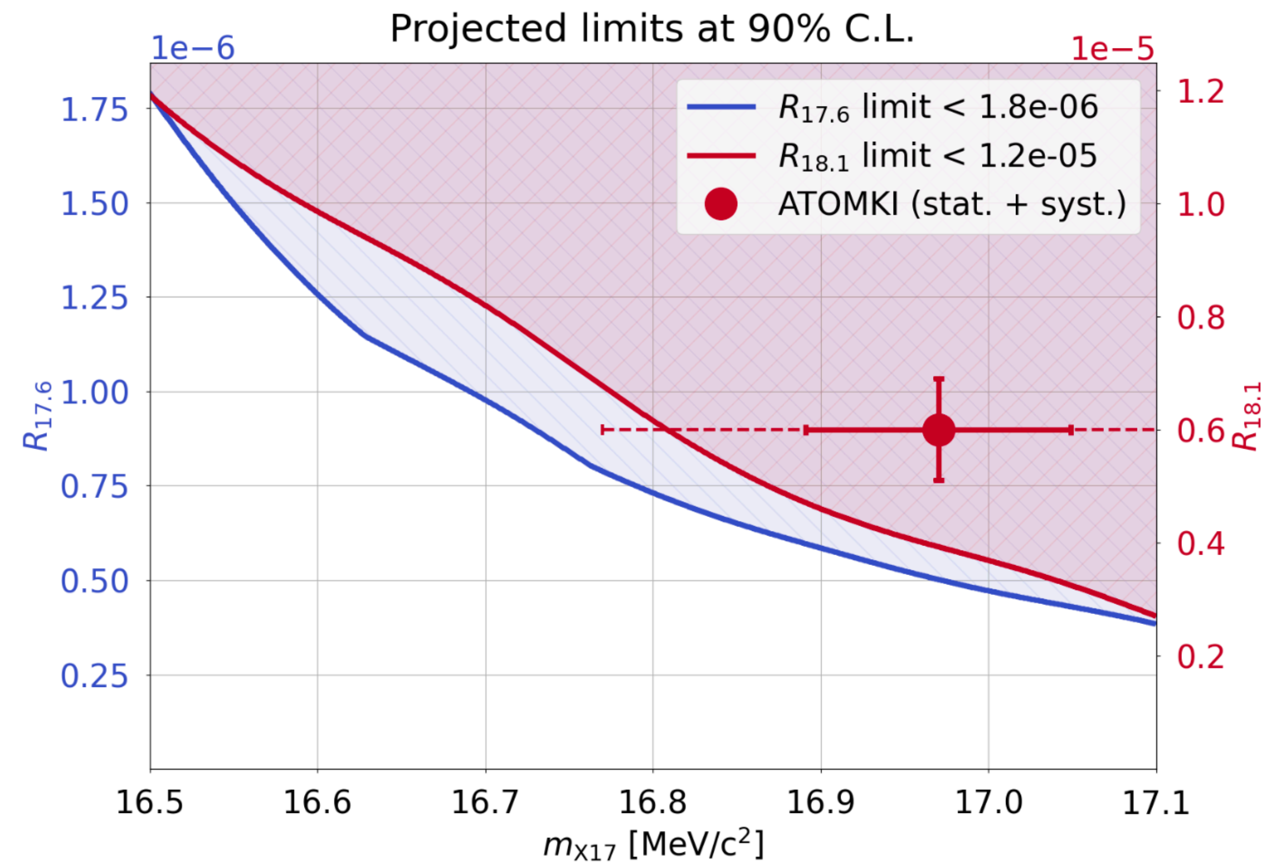
- **Best fit:**
  - 10±92 signal events at Q = 18.1 MeV and none at Q = 17.6 MeV - for a m_{X17} = 16.5 MeV
  - IPC: **12.6**(9)% Q = 18.1 MeV and **45.8**(13)% Q = 17.6 MeV
  - Goodness-of-fit: p-value = 10%

90% Confidence Limits

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

Profile likelihood ordering





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

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

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

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

$$\Gamma_Q = \frac{\mathscr{B}(^8\mathrm{Be}^*(Q) \to {}^8\mathrm{Be} + e^+e^-)}{\mathscr{B}(^8\mathrm{Be}^*(Q) \to {}^8\mathrm{Be} + \gamma)}$$

→ **3.9 10^{-3} (Q = 18.1 MeV) 3.4 10^{-3} (Q = 17.6 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 10^{-6}
Scaling $R_{17.6}$ = 0.46 $R_{18.1}$

Conclusion

- MEG II detector successfully studied the $^{7}Li\ (p,\ e^{+}e^{-})^{8}B$ 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 a m~17 MeV**

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

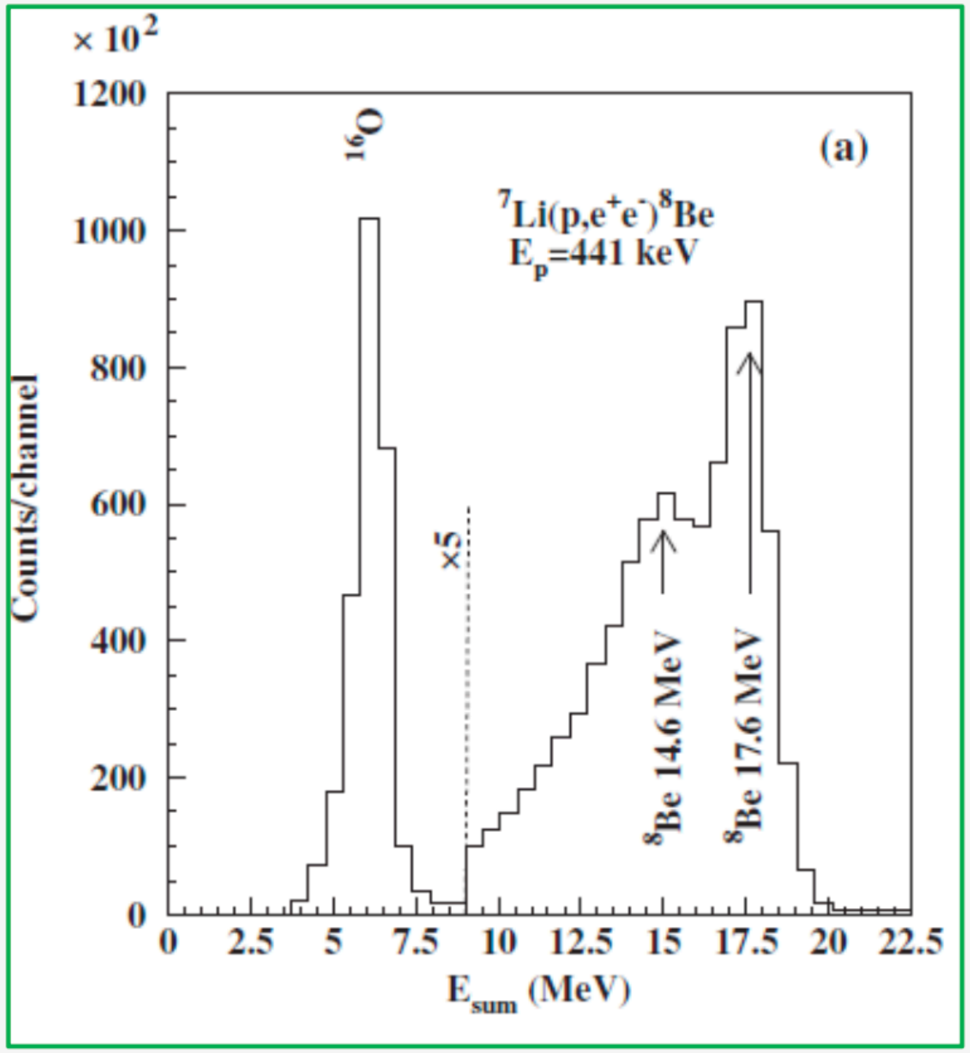
- Room to improve MEG II sensitivity if more data will be taken
  - Thinner LiPON target, removal of H_2^{+} for a run at 1.030 MeV only

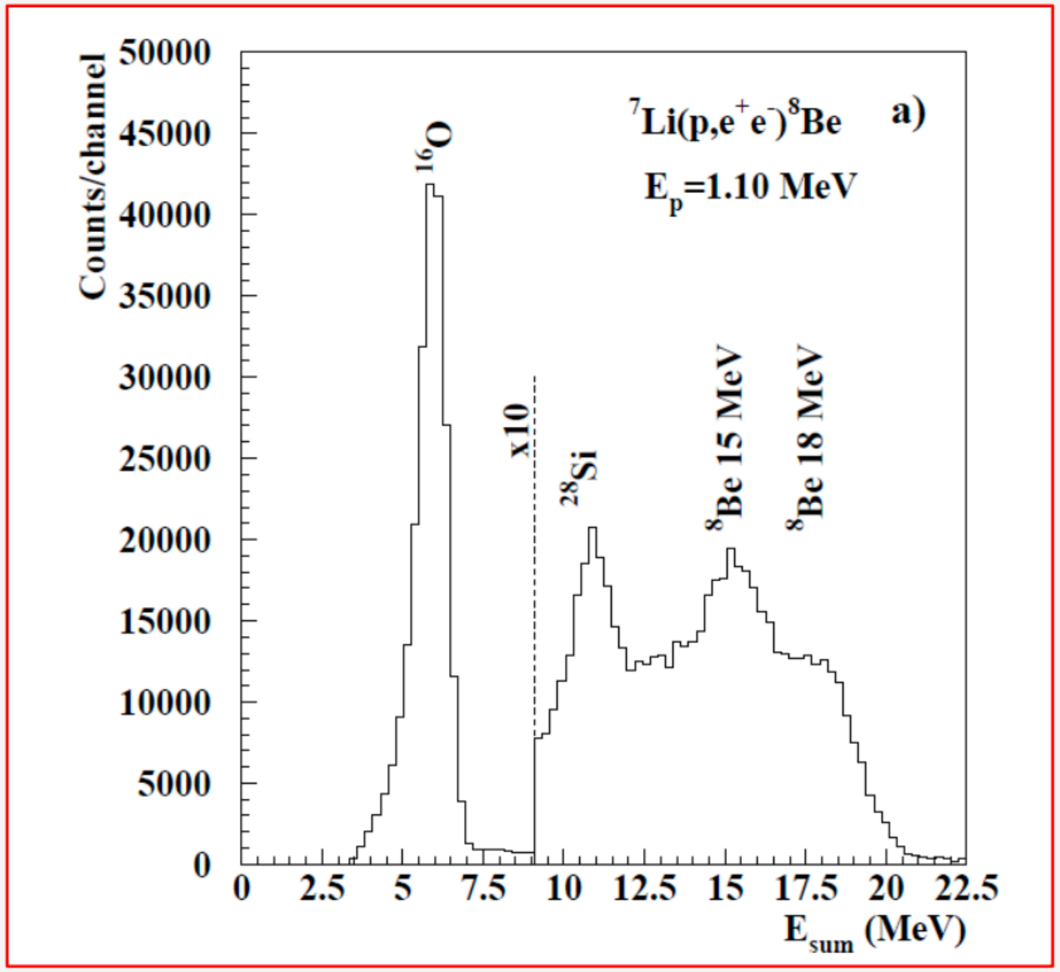
Backup slides

Quantum properties

- Viviani

Esum at ATOMKI



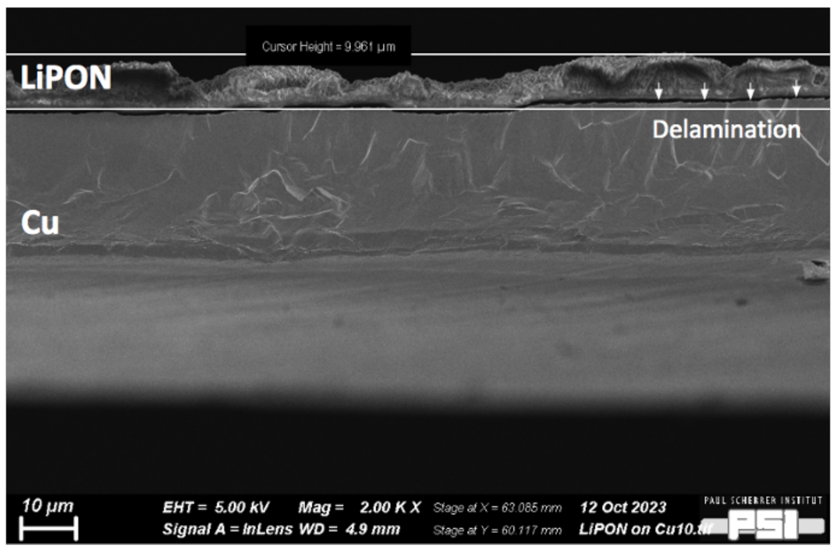


[A. J. Krasznahorkay et al, Phys Rev Lett 116, 042501 (2016)]

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

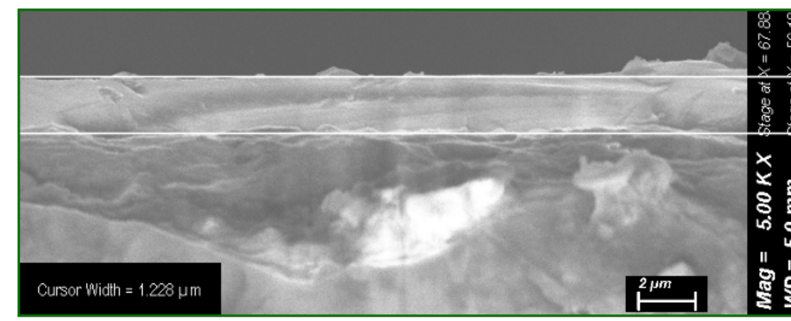
Microscopic analysis of target (SEM)

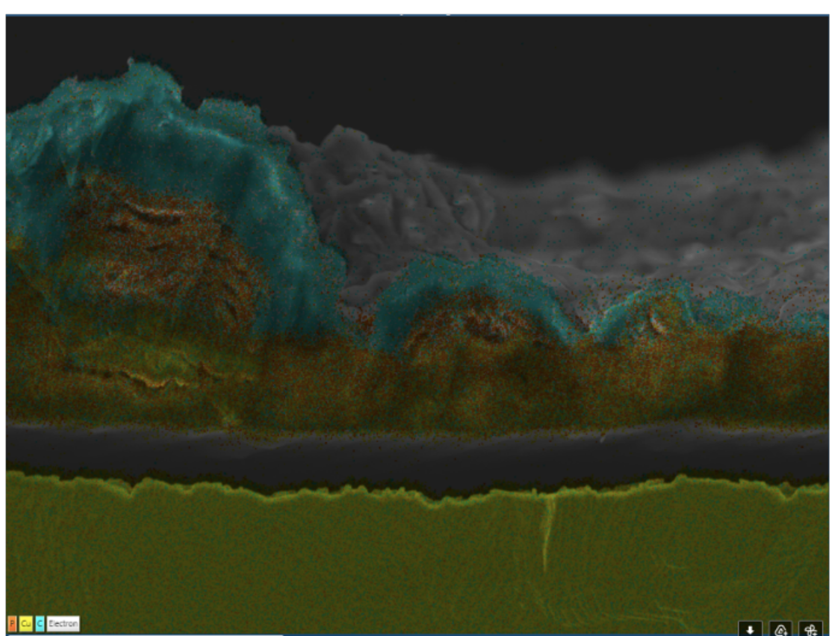
- Why LiPON?
  Stable, no F-related bkg, thin films through sputtering, developed for batteries
- Difficulties for production: thickness control and non-uniformity, oxidation layer



Delamination, pores, large thickness variations

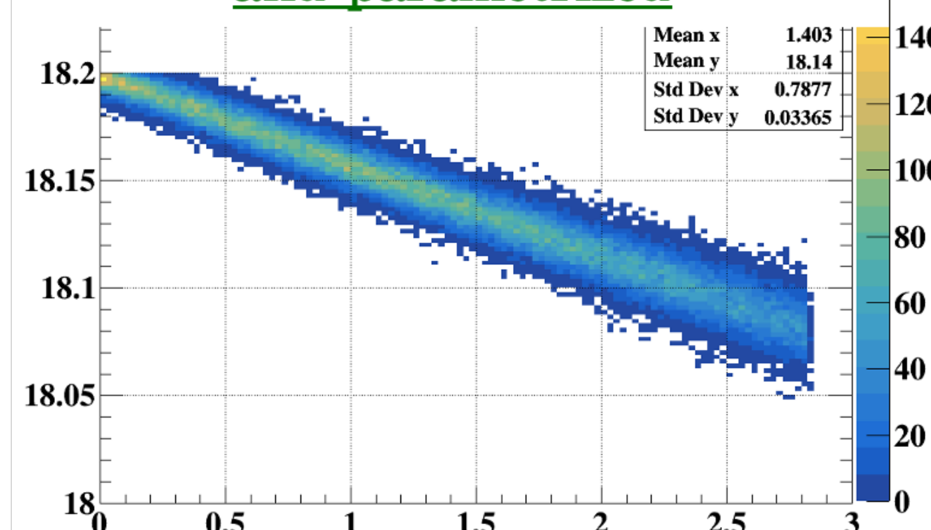
Recently, uniform thin 2-µm films were achieved at PSI



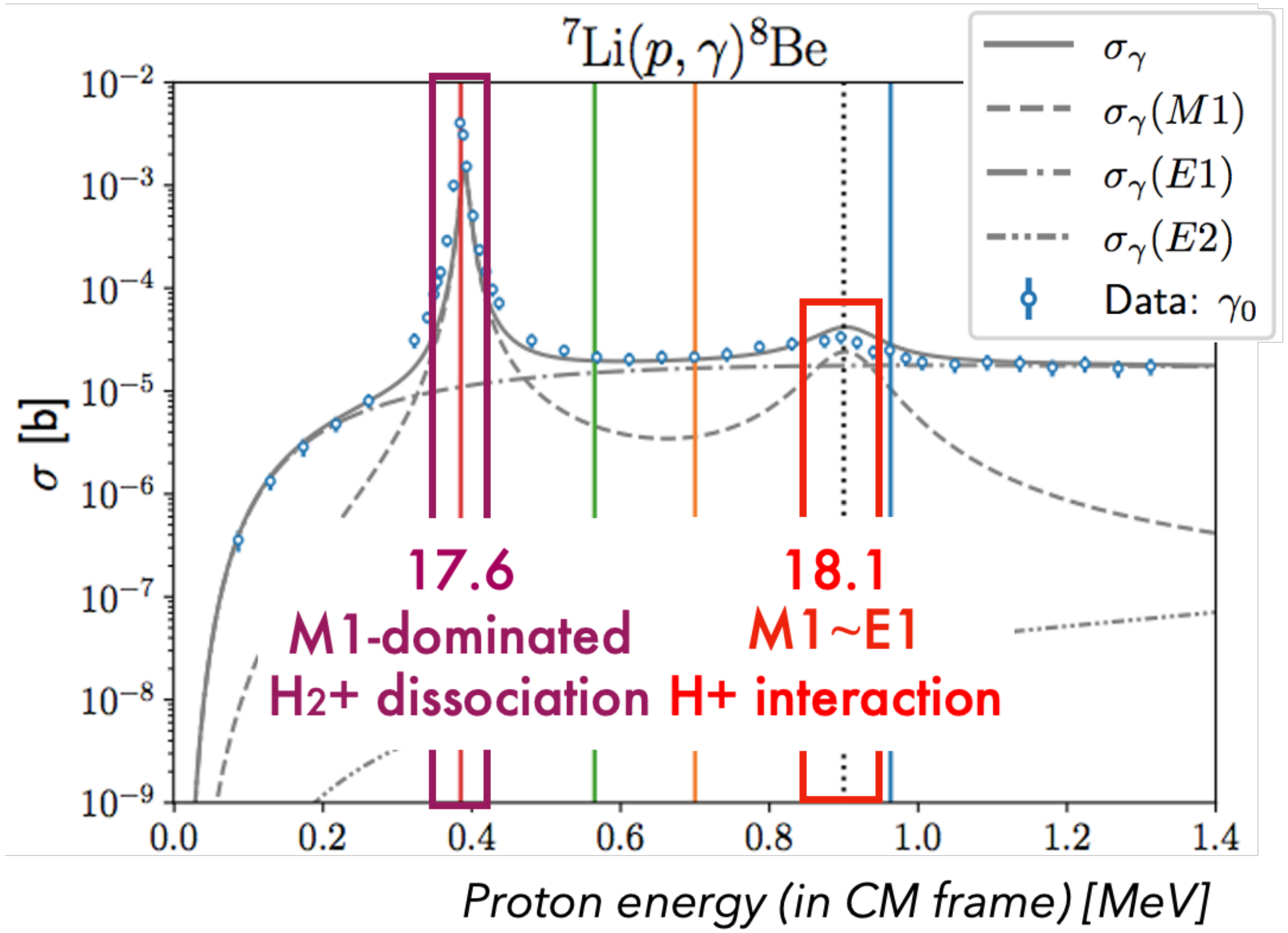


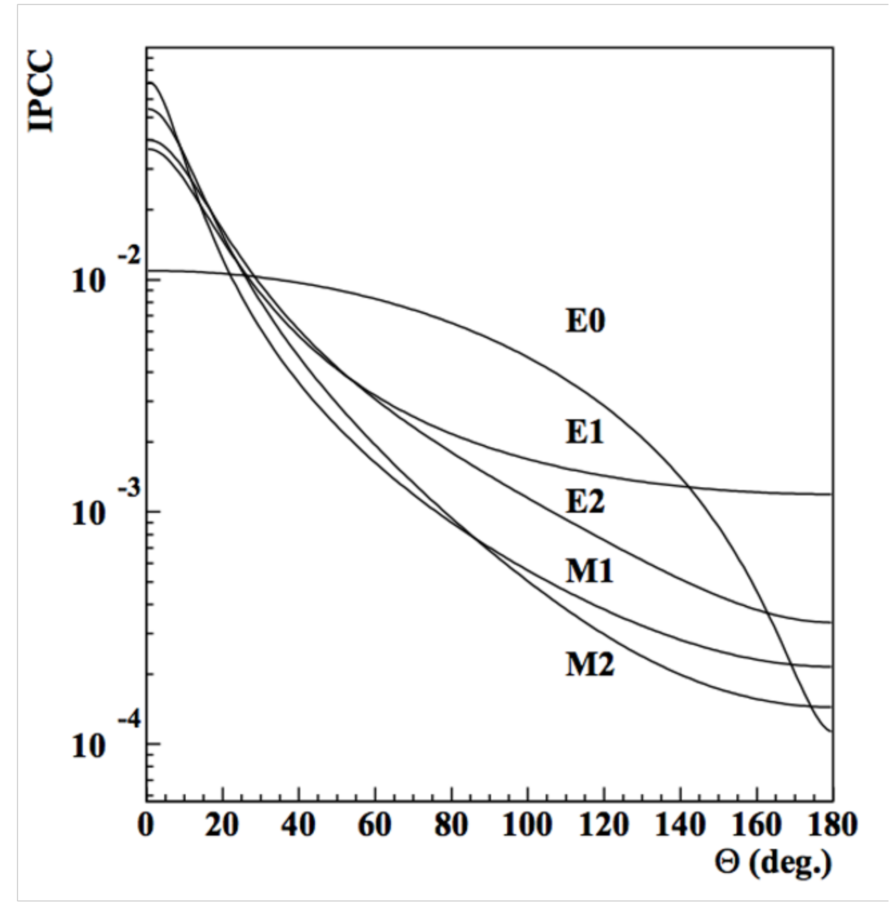
LiCO3 on the surface

Proton energy loss simulated and parametrized



Effect of mixed species beam





- Dominated by events fro 440 keV resonance (larger cross section even if H2+ are 1/3 of H+)