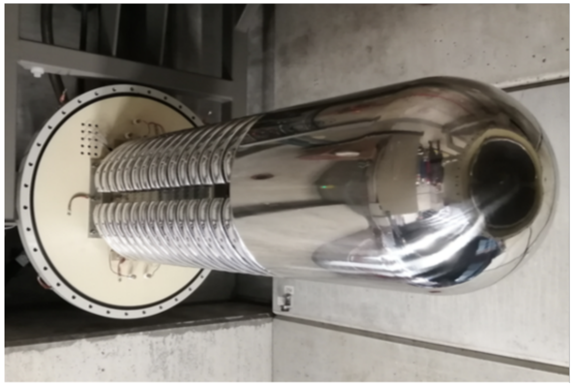
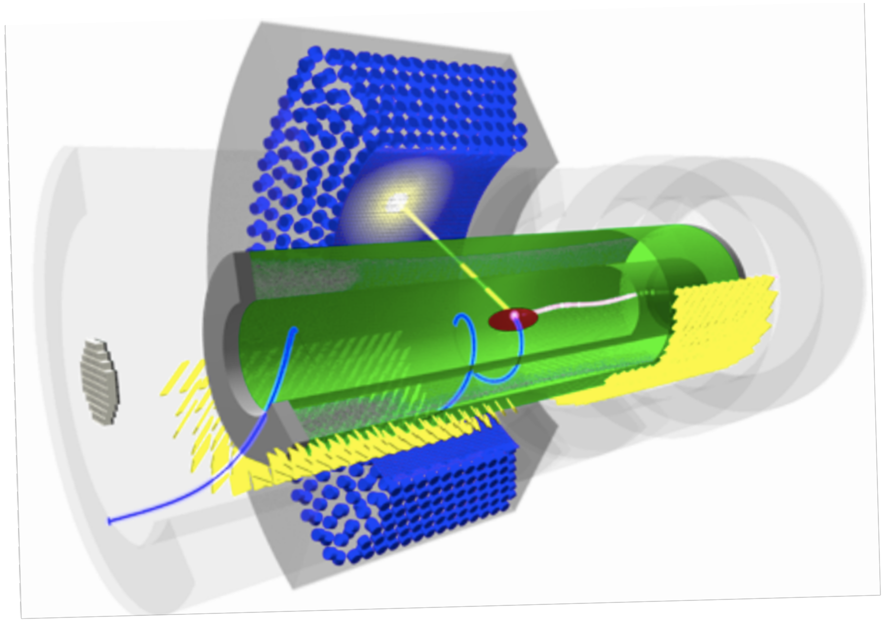




# Search for the X17 particle in the $^{7}Li\,(p, e^{+}e^{-})^{8}Be$ process with MEG II

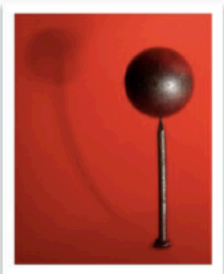
***Gianluca Cavoto*** *(Sapienza Univ Roma and INFN Roma)*
*On behalf of the MEG II collaboration*
***PSI seminar - 13th Nov 2024***

# 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

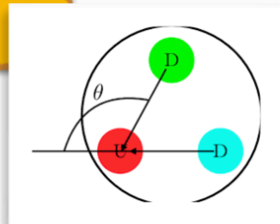


Naturalness problem

dark scalars
(twin Higgs, SUSY)

Strong CP problem

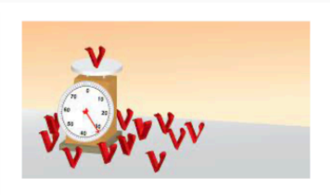
axions




S.Gori

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

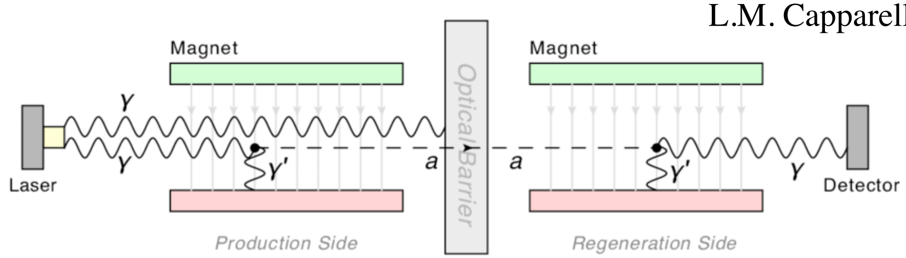
- **QCD axion**: fix the strong CP problem.
  - *why strong interactions are CP invariant while theory can develop a CP-odd term ?* (see neutron EDM)
  - In the '70s a ~10 MeV **axion *a*** was proposed to be searched in nuclear de-excitations: $^{12}C^*$ decay (rate predicted from $^{12}B$ β decay)

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: $J/\psi \to \gamma a$ ($a \to e^+e^-$)
  - beam dump experiments,
  - $(g-2)_\mu$ 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**

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

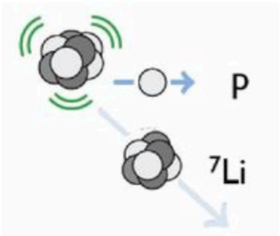
$$\frac{Q_u}{Q_d} = 2 \;\Rightarrow\; \theta_{a\pi}^{(0)} \approx \frac{4\,Q_d}{3}\frac{f_\pi}{f_a}\left(\frac{1}{2} - \frac{m_u}{m_d}\right) \approx 0.$$

being $m_u/m_d$ ~0.5

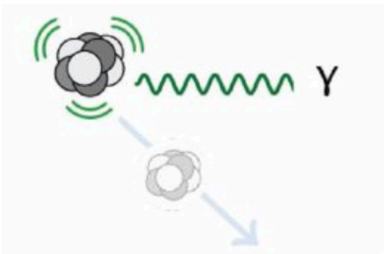
***ad hoc* model but not impossible**
**Look for e⁺e⁻ bumps!**

# Internal Pair conversion (IPC)

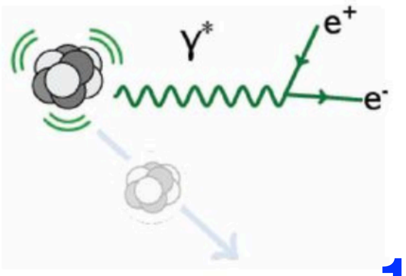
- **Nuclei can emit $e^+e^-$ instead of a photon in a nuclear de-excitation.**




**Hadronic dissociation**




**Electromagnetic Transition (γ emission)**

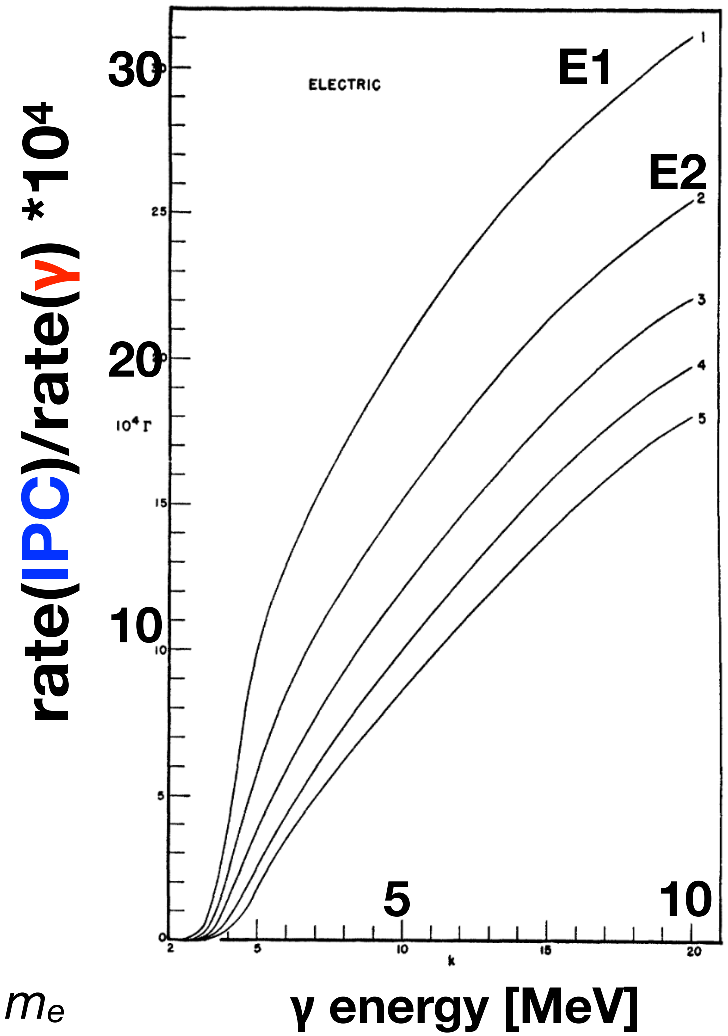



**IPC**

**1 IPC every 1000 γ**

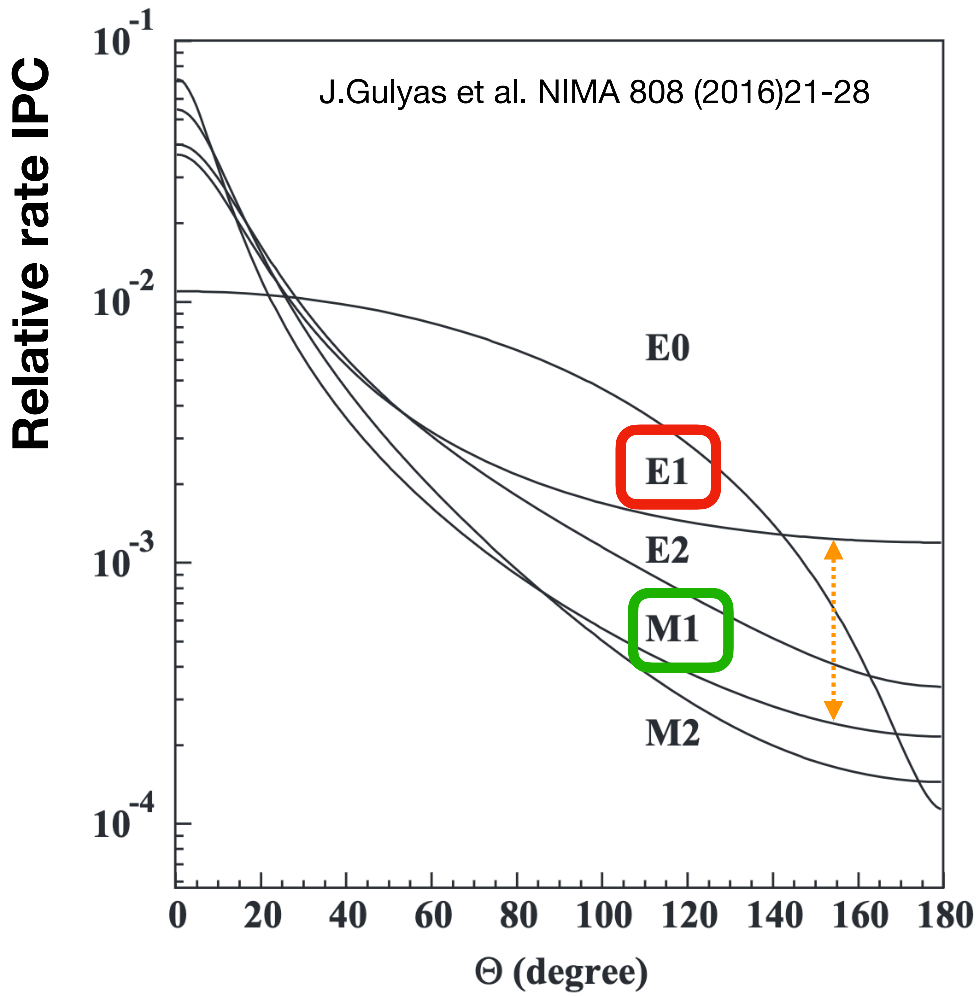
*Possible only for energy > 2 $m_e$*

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




**Multipole Order**

# Experimental signature for IPC



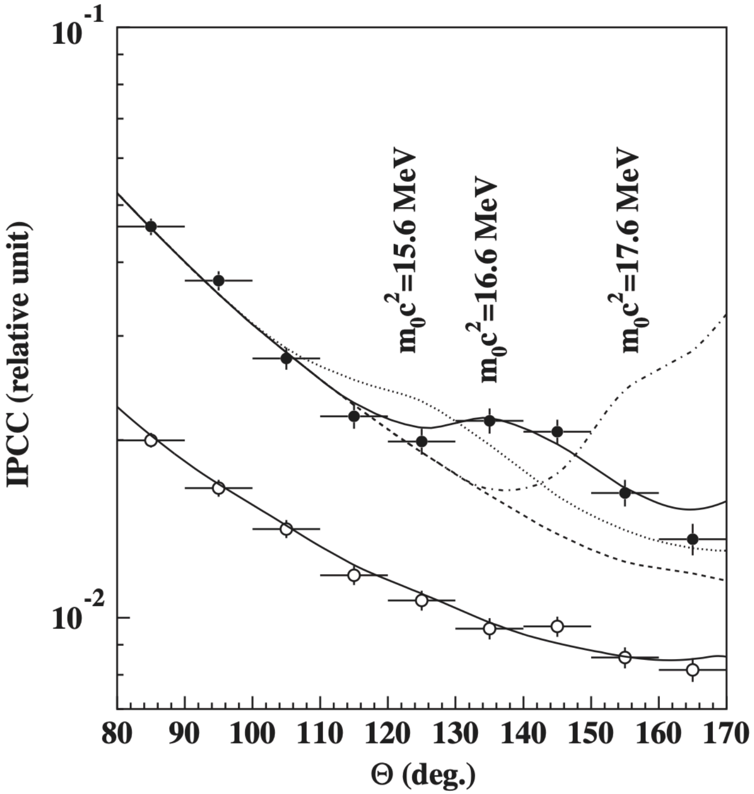

**$\Theta_{ee}$ : angular opening between $e^+e^-$**

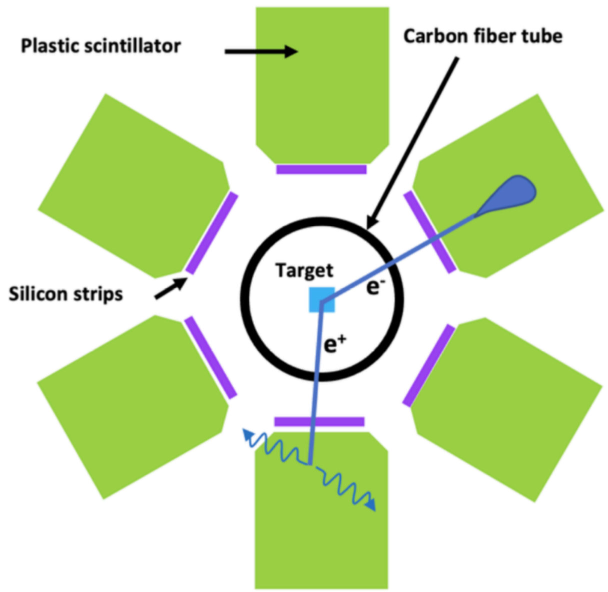
- **Smooth** decrease
- Different shape according to multipole transition type
  - M$\ell$ : **magnetic [**$(-1)^{\ell+1}$**]**
    M1 *no* parity change
  - E$\ell$ : **electric [**$(-1)^{\ell}$**]**
    E1 parity change

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 $\Theta_{ee}$ 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 ?

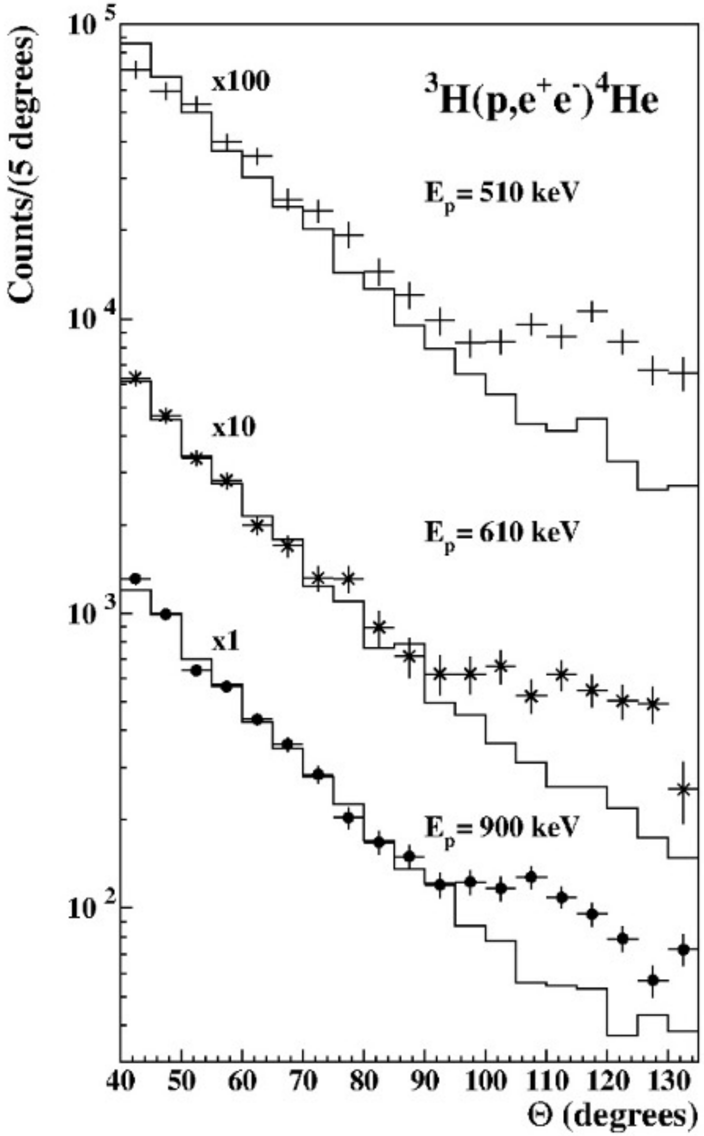
# More evidence

- 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)

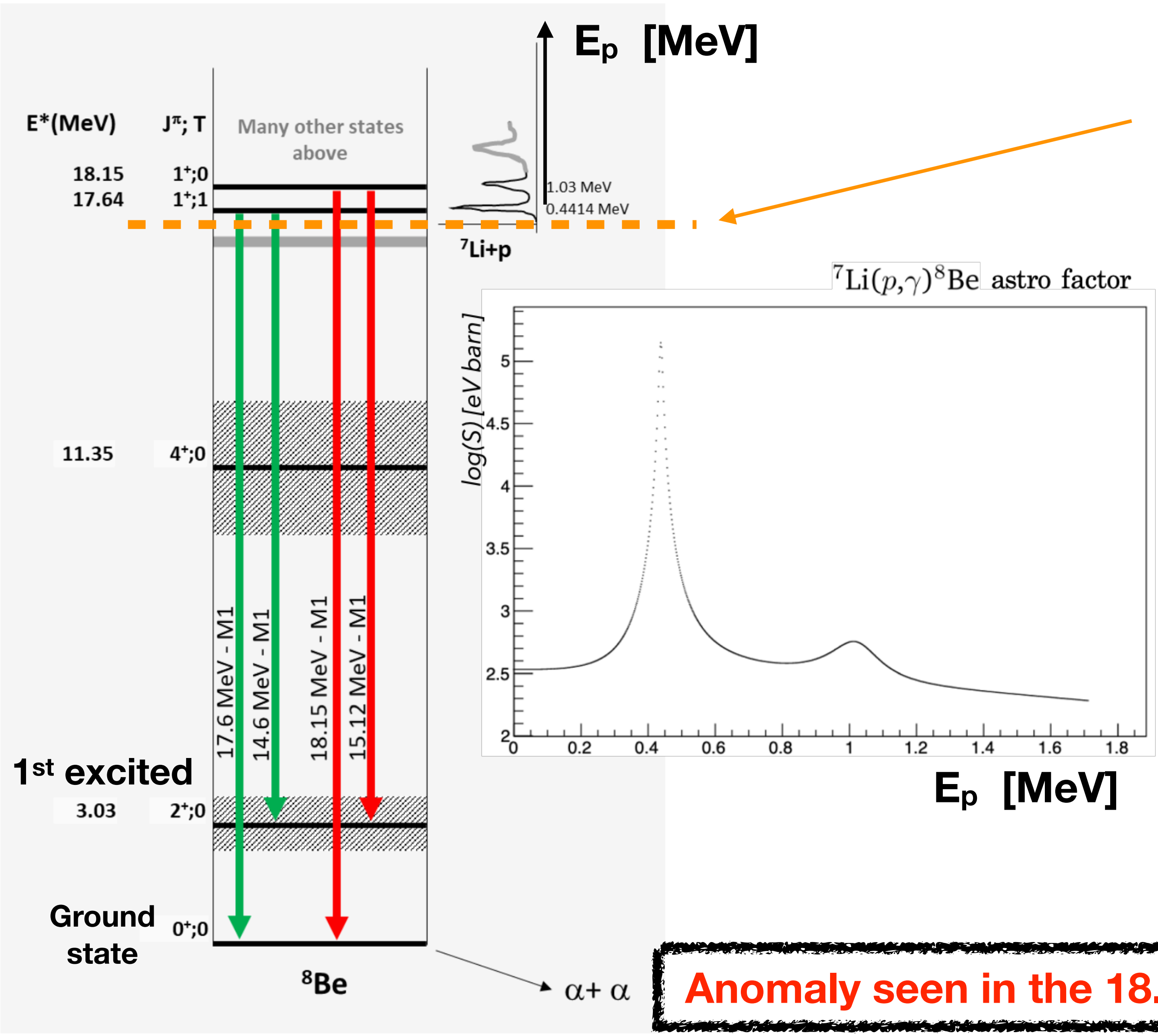
- Same anomaly in $^{11}$B(p, $e^+e^-$)$^{12}$**C** Phys. Rev. C 106, L061601
- No evidence from NA64 and NA48

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

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

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

**Anomaly seen in the 18.1 MeV transition only**

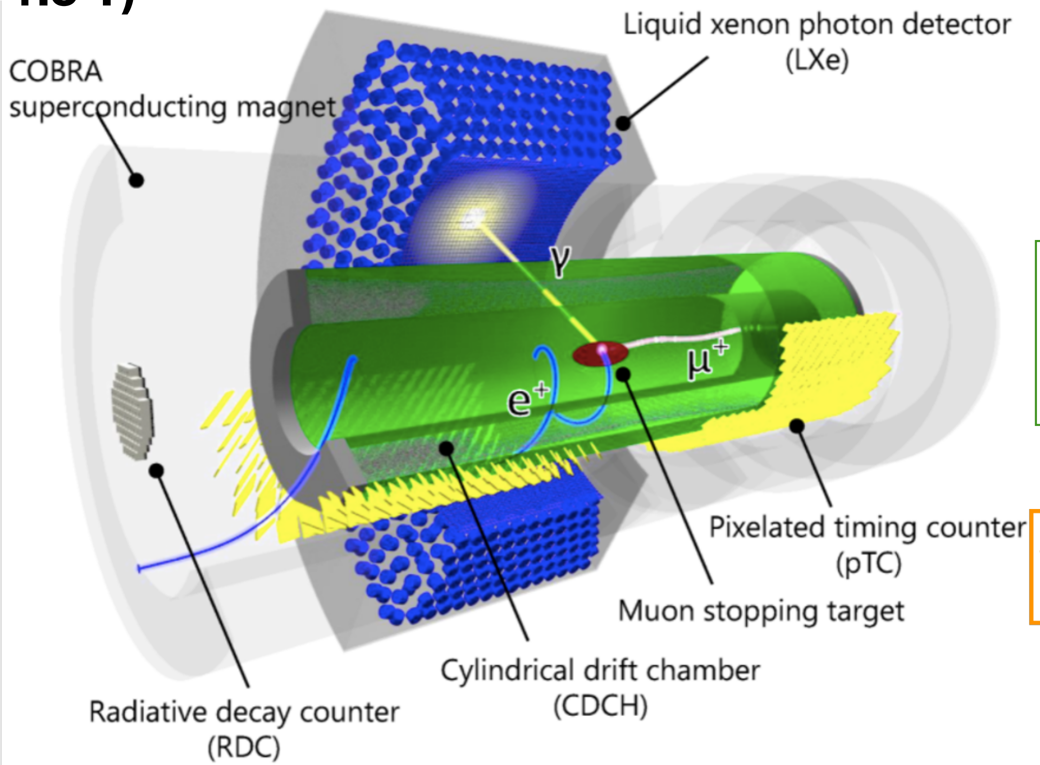
# The MEG II detector at πE5 (PSI)

- 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***

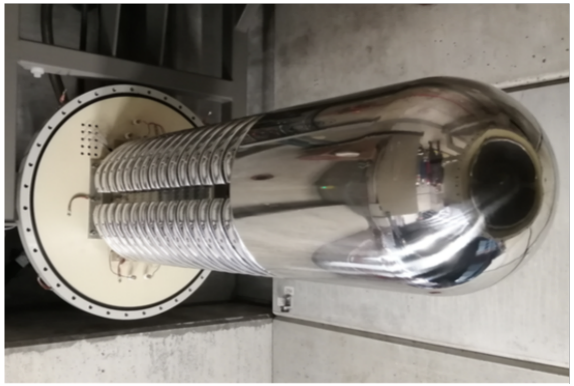
**Current best limit:**

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

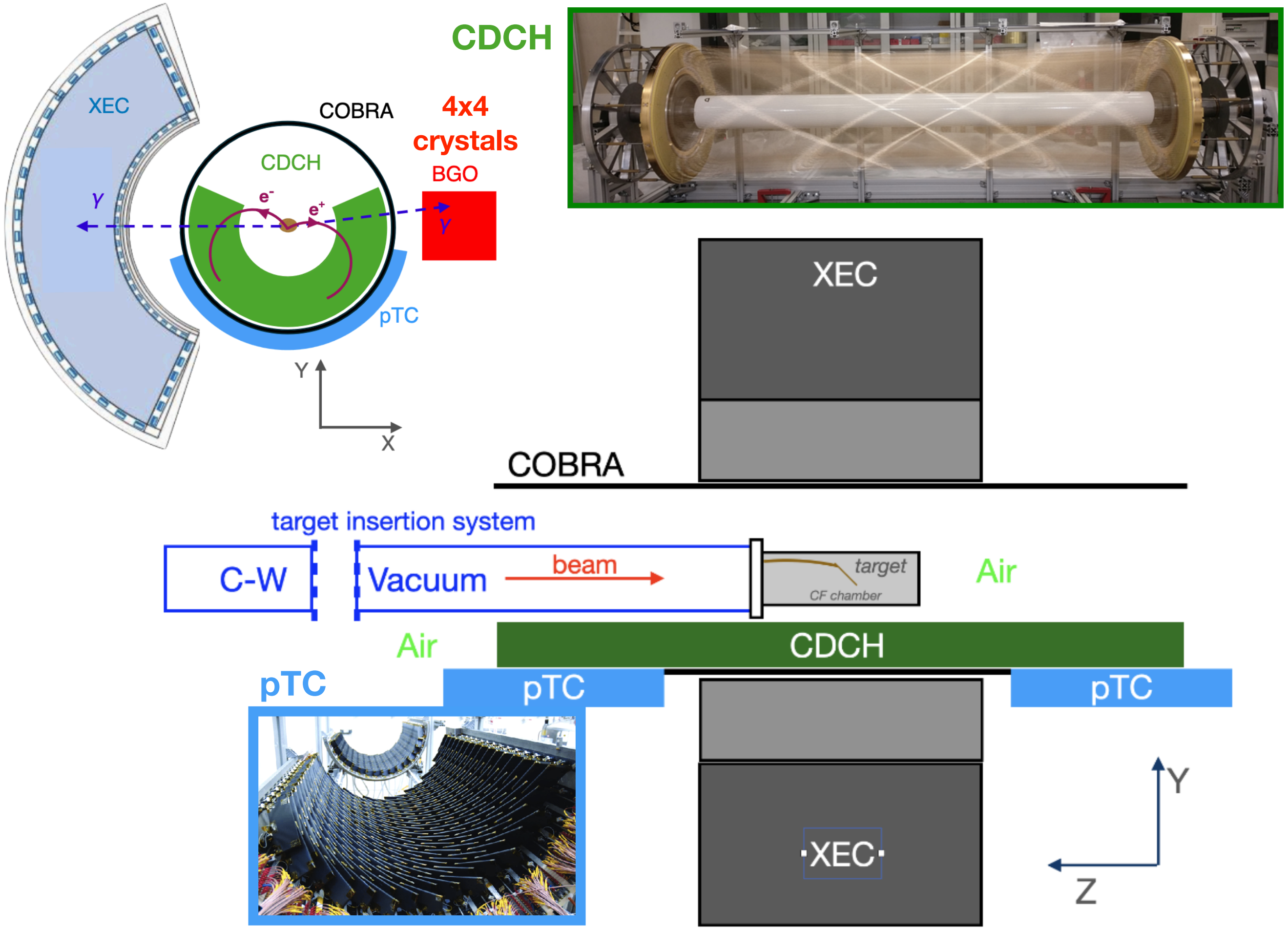
$$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 3.1 \times 10^{-13} \text{ (90\% CL)}$$

# MEG II for X17

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



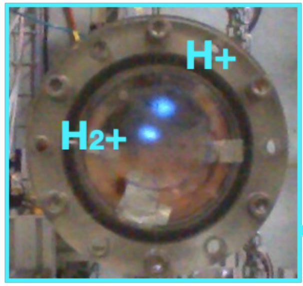
**Routinely used for XEC calibration with $^{7}$Li (p, γ )$^{8}$Be**

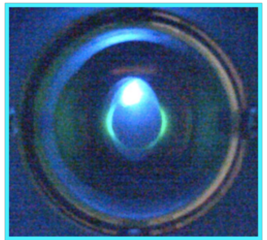



**Detecting ~10 MeV $e^+e^-$ with a magnetic spectrometer (reduced B x 0.15)**
**Different technique (but detector material budget not optimal)**

# The Cockroft Walton beam

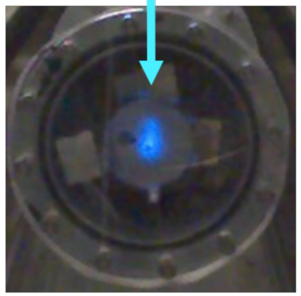
**Beam imaging with a quartz screen**



**COBRA**

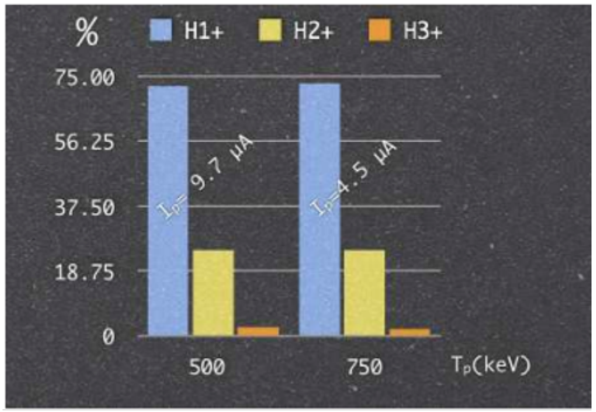
Spectrometer center



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

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

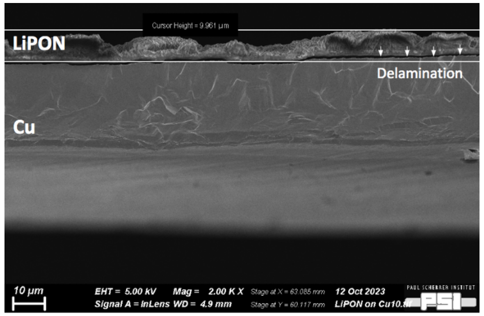
**Ion composition**

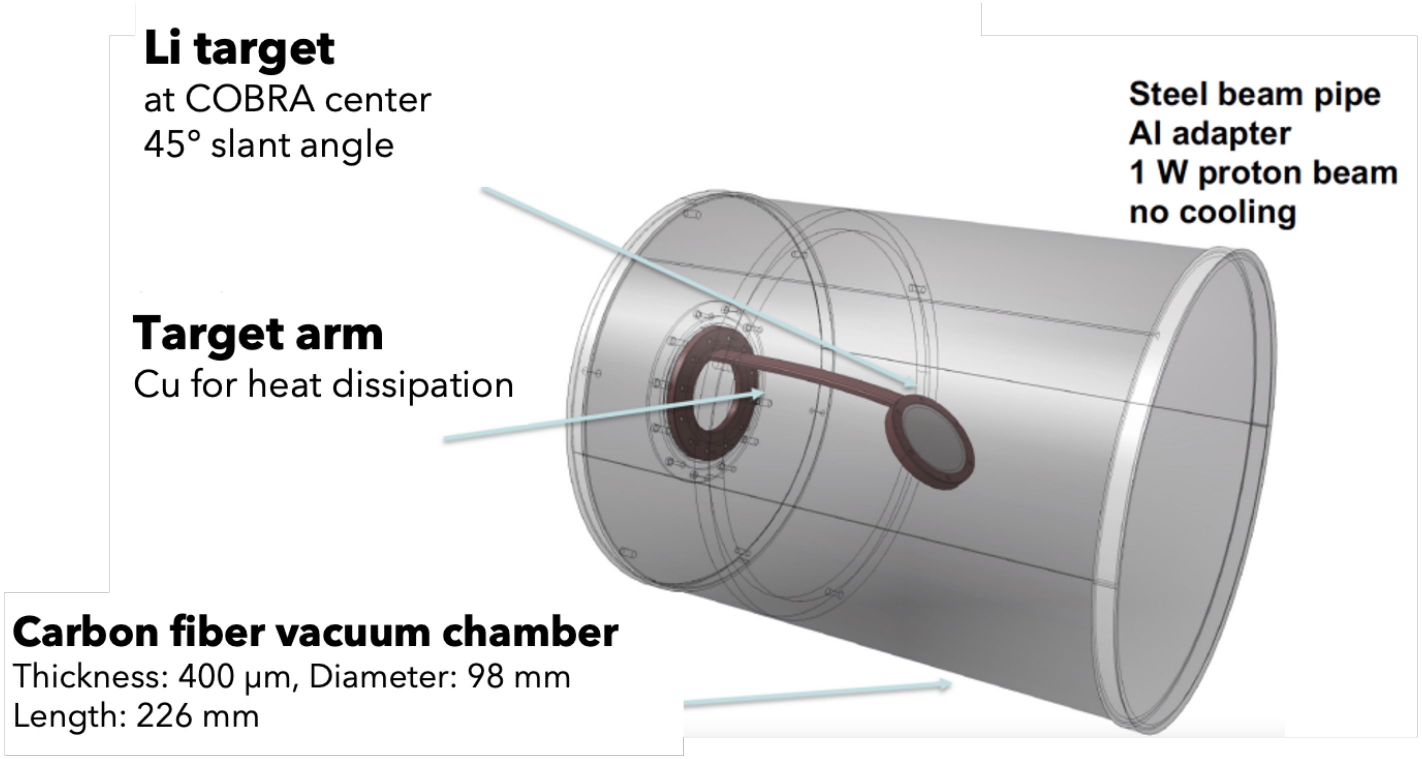


# The Li target

- 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**



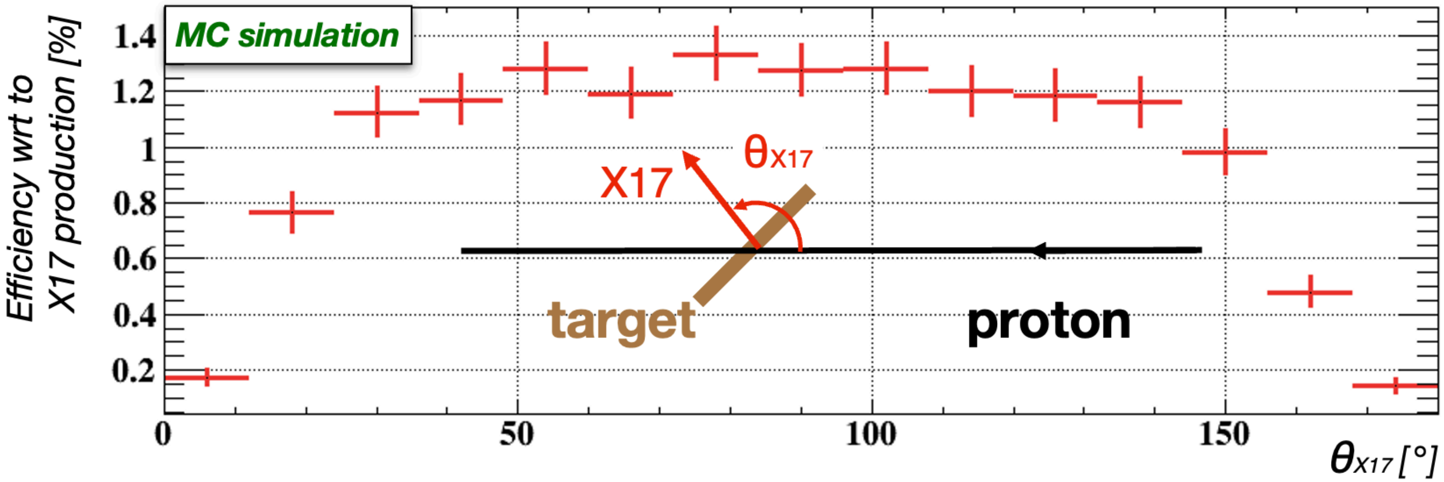

LiF target
(INFN Legnaro)
For BGO calibration

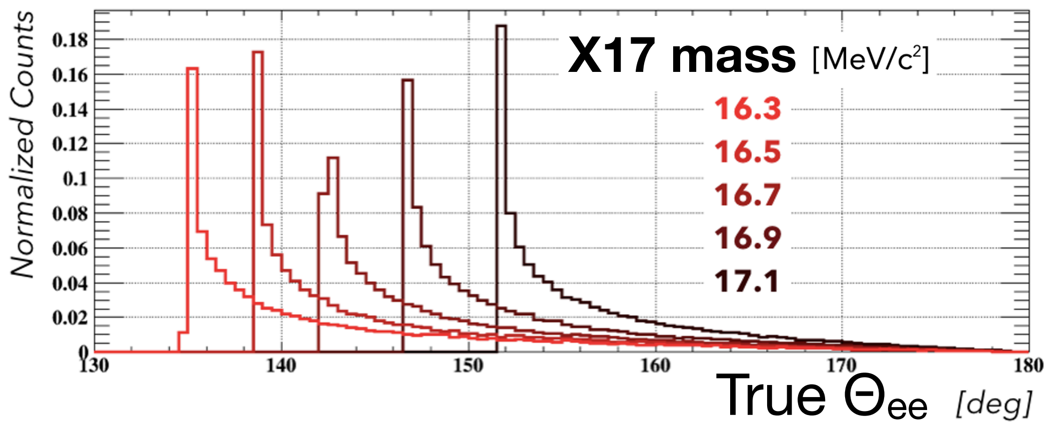
(*) Lithium phosphorus oxynitride ($Li_{3-X}PO_{4-Y}N_{X+Y}$)

# The X17 signal in MEG II

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

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




**Assuming isotropically produced**

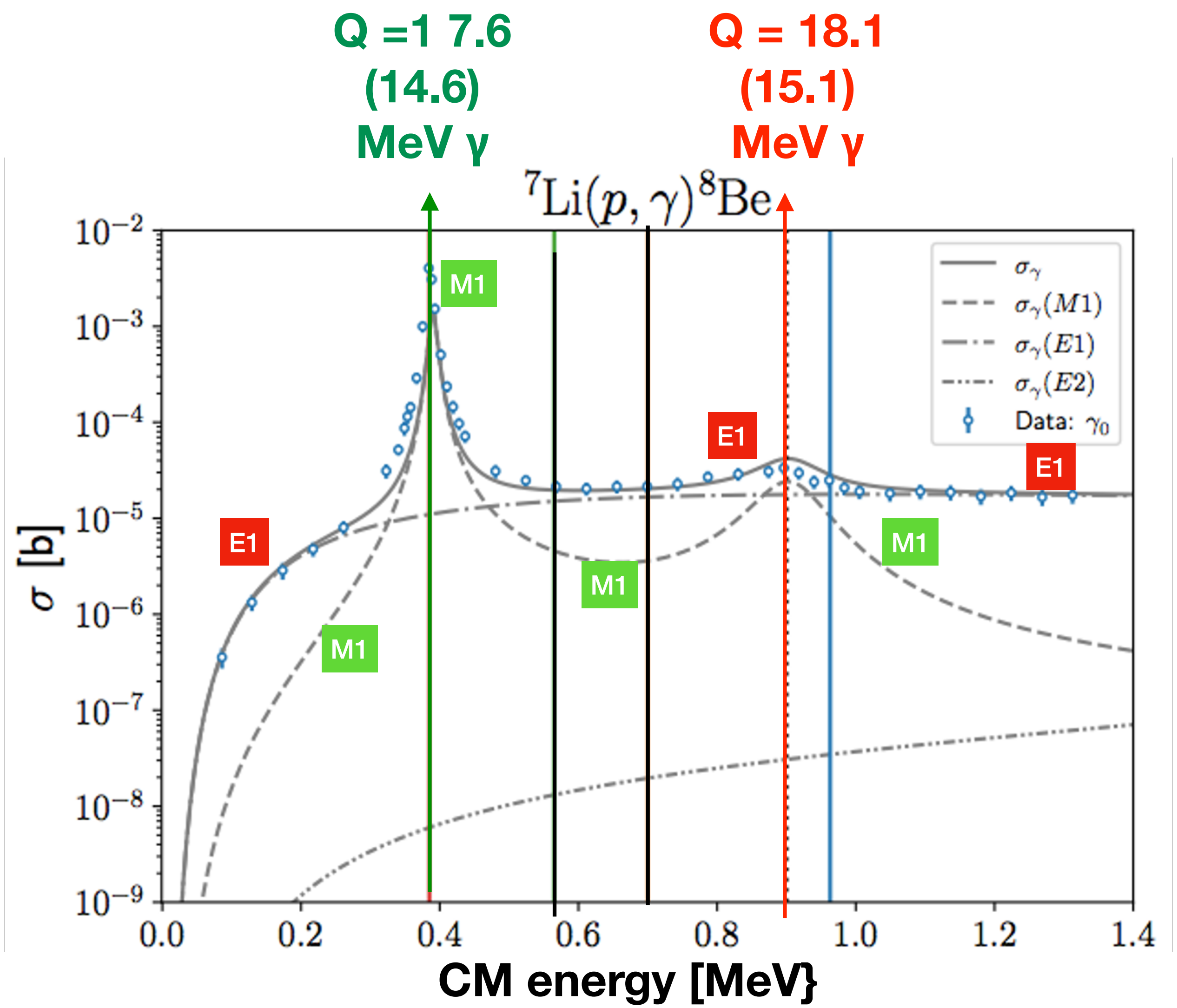
**Overall 1% detection efficiency**
**(*apparatus sub-optimal*)**

**6 deg resolution on $\Theta_{ee}$**

https://arxiv.org/abs/2308.13751

# Multipole decomposition of cross section

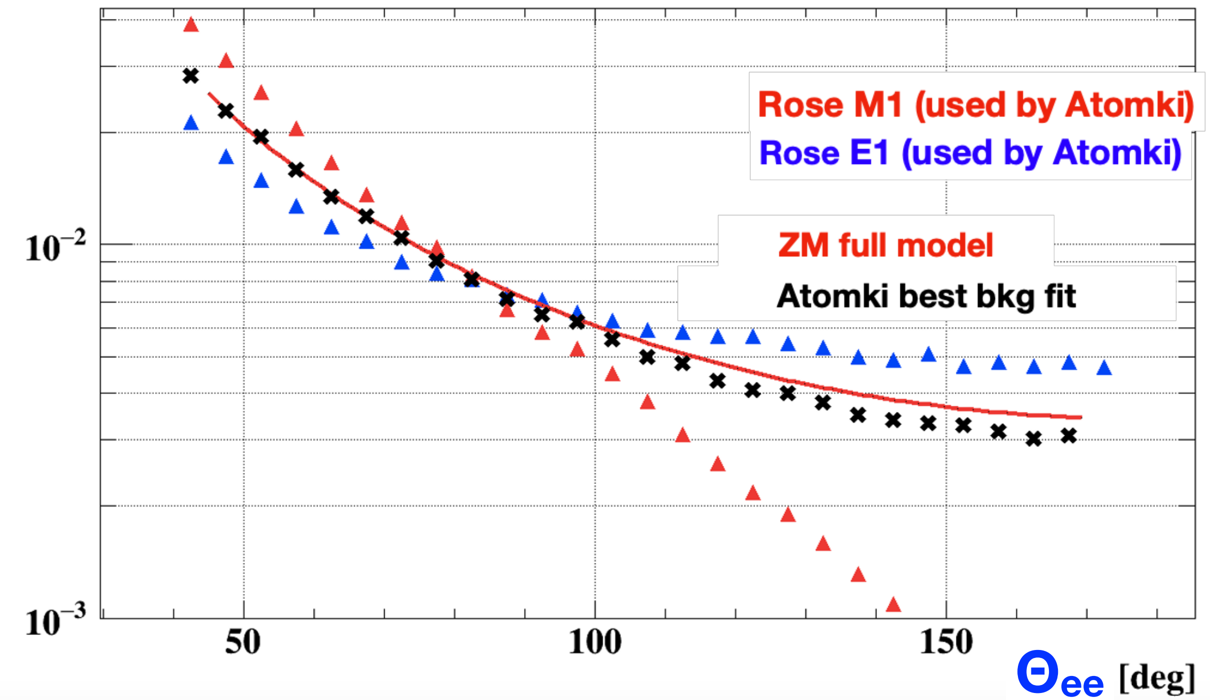
- E1 (*radiative direct capture*) might be more relevant at 1.030 MeV resonance
- Call for a detailed model
  - IPC events at large angles where signal is present



# 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)

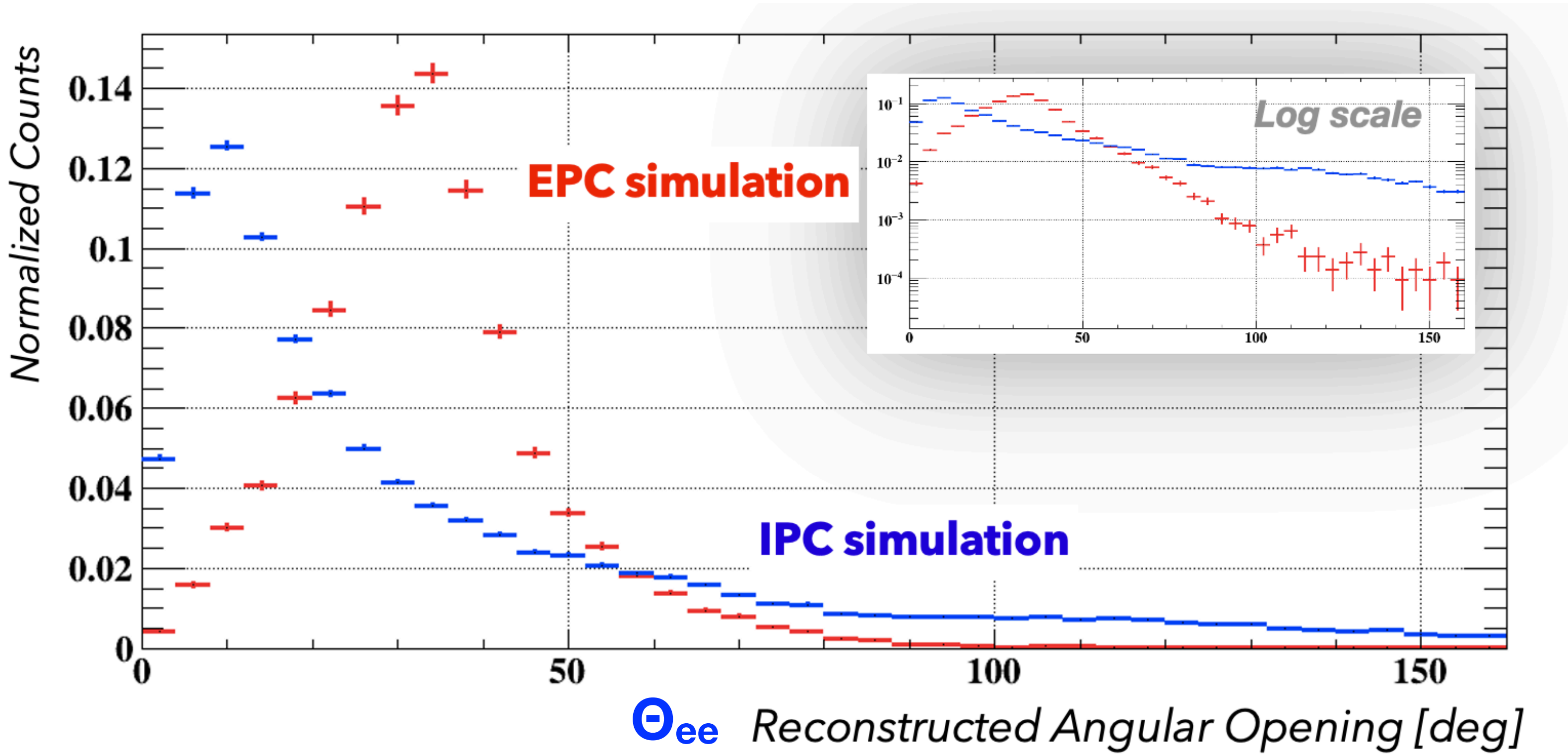



**Still not enough to explain the anomaly though…**

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

# External pair conversion (EPC)

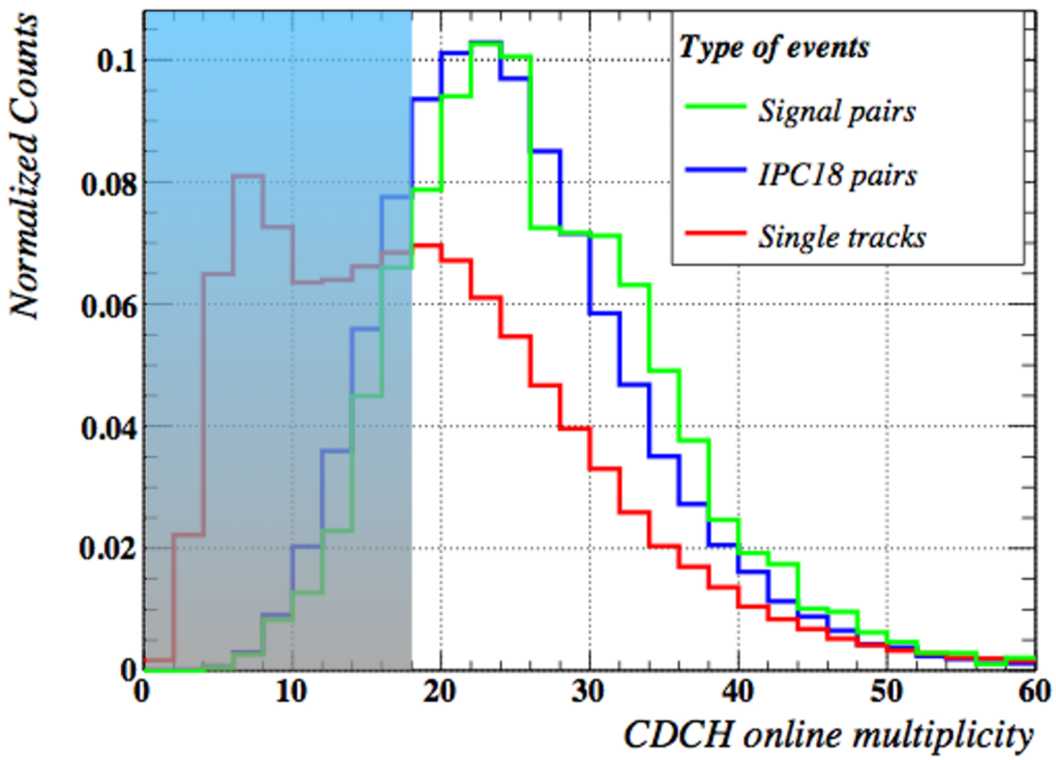
- Real photon from more copious $^{7}$Li (p, γ)$^{8}$**Be** convert in the detector material
  - Compton electrons and e+e- pairs
  - Very detector-dependent.




**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

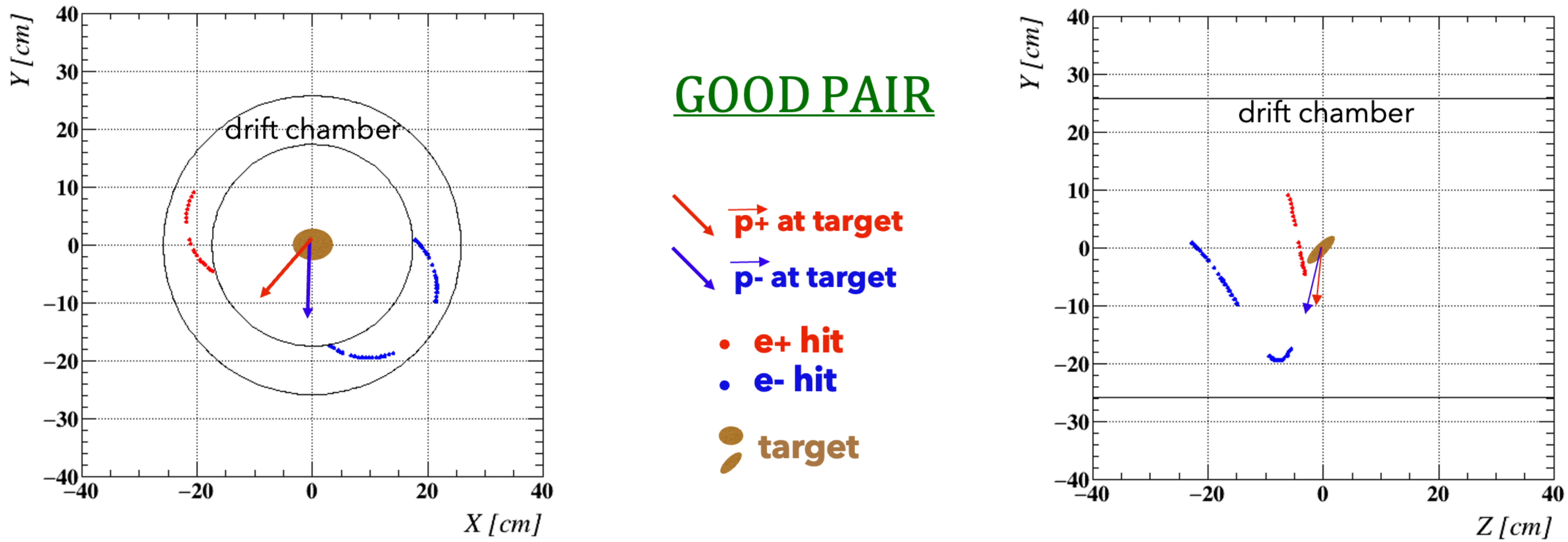
**16%** efficient on **signal** X17

Background rejection x5 larger
(than with 10 CDCH hits )

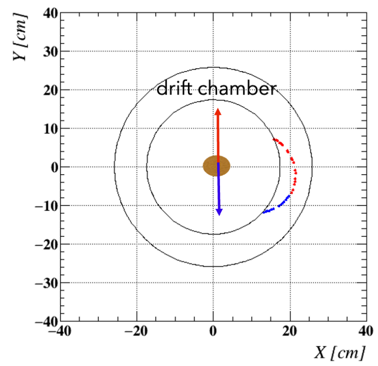
Leaves room to increase
beam current
(up to more than 10 μA)

# Track Reconstruction

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




*Fake pair:*
Single particle reconstructed as two tracks ($\Theta_{ee}$~180°)

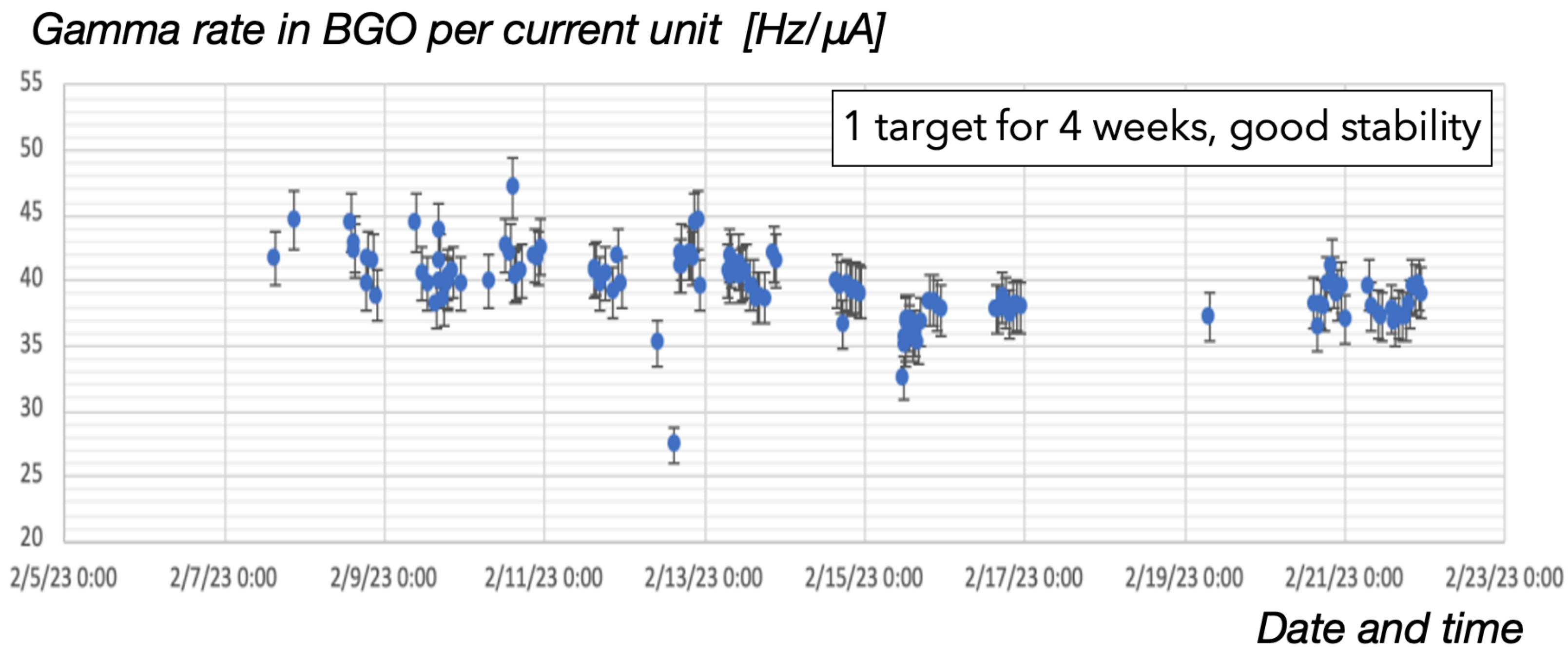



*Detailed study to suppress fakes Advanced good tracks selection implemented.*

**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

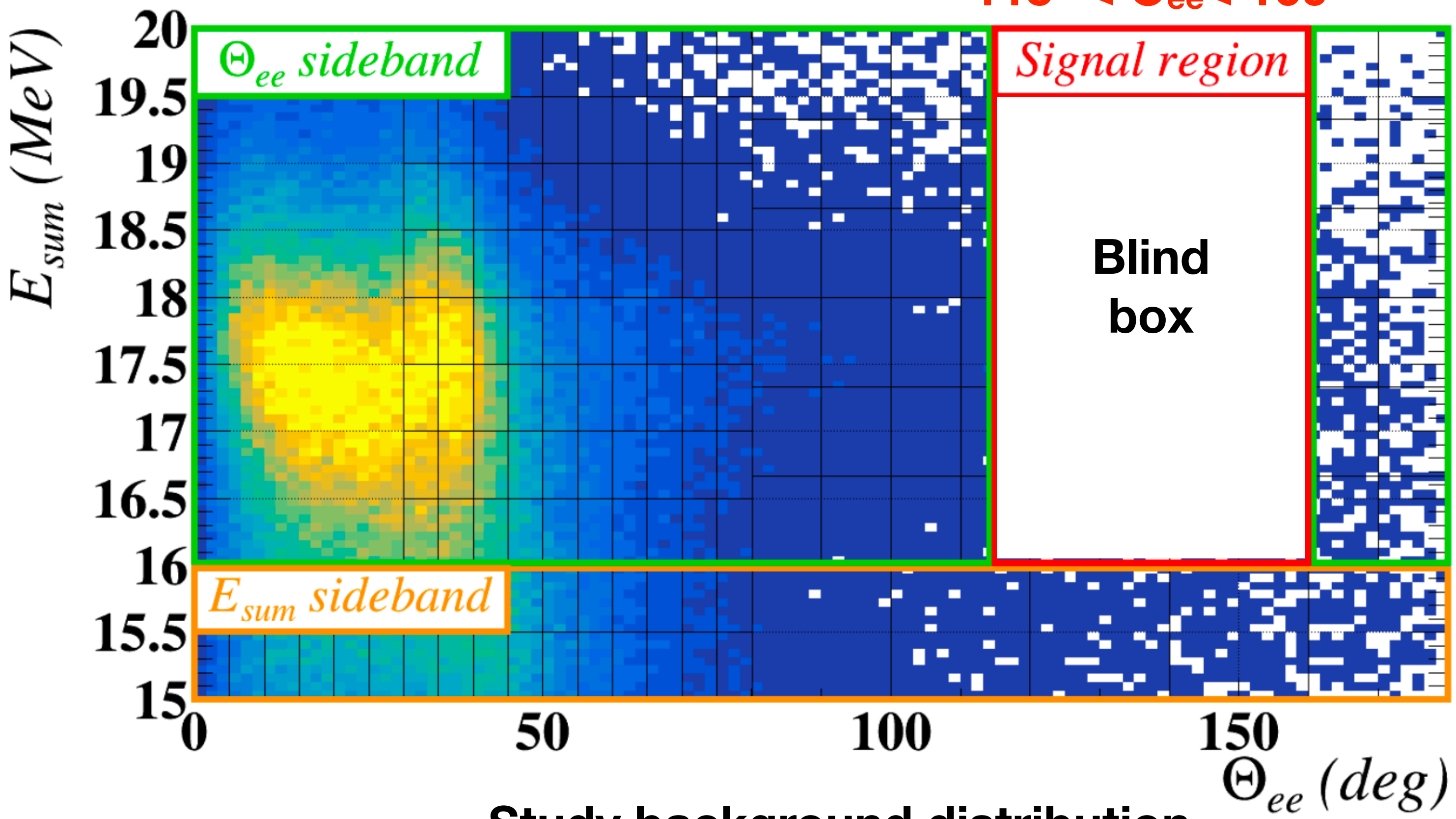



- Remarkable stability
- Beam with both $H^+$ and $H_2^+$ → events from both Q=17.6 and Q=18.1 MeV transition → **data analysis to separate them**

# Analysis strategy

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

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



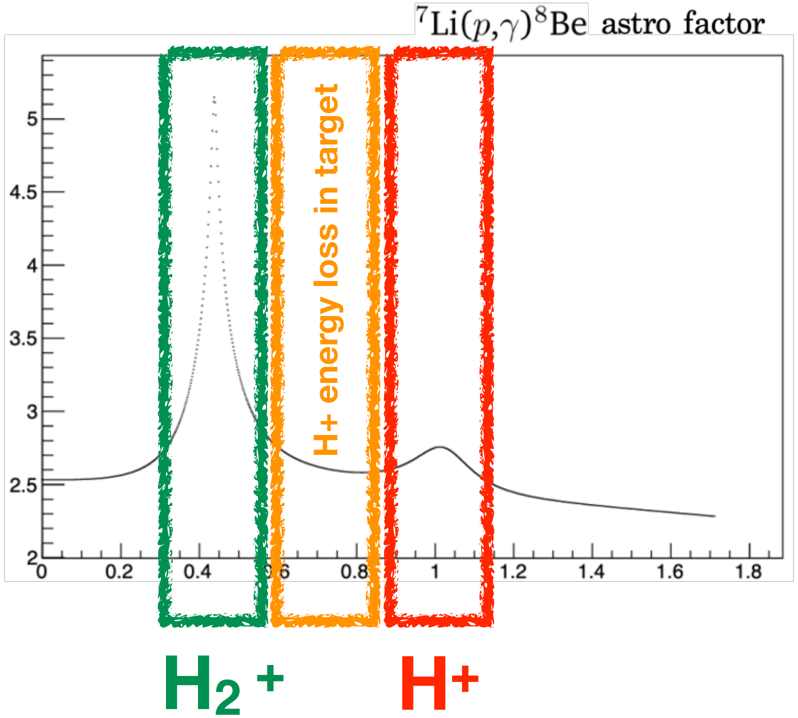

**Study background distribution**
**in sideband (data/MC comparison) before opening the box**

# 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

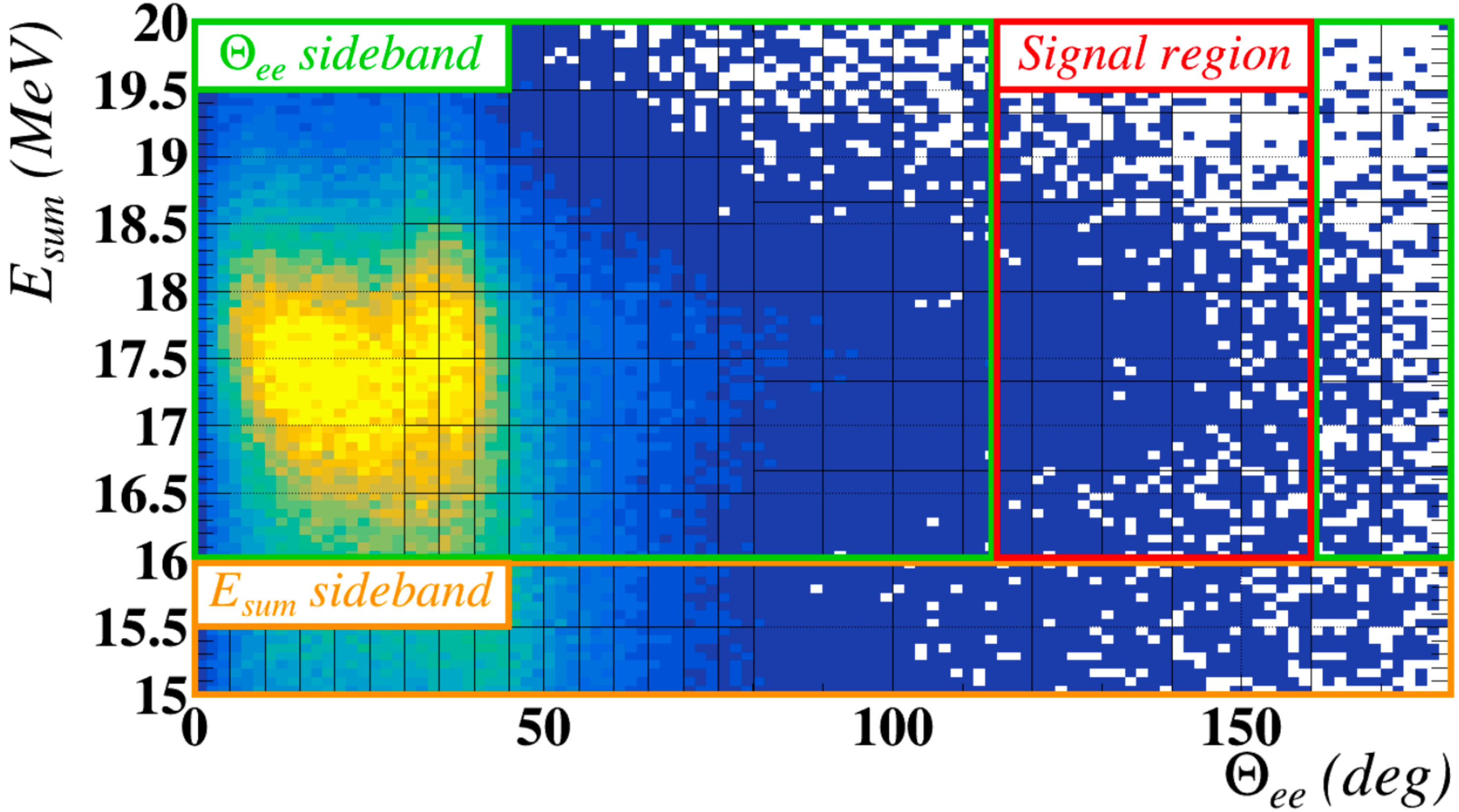
$$R_Q = \frac{\mathcal{B}(^8\mathrm{Be}^*(Q) \to {}^8\mathrm{Be} + \mathrm{X17})}{\mathcal{B}(^8\mathrm{Be}^*(Q) \to {}^8\mathrm{Be} + \gamma)}$$

- **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



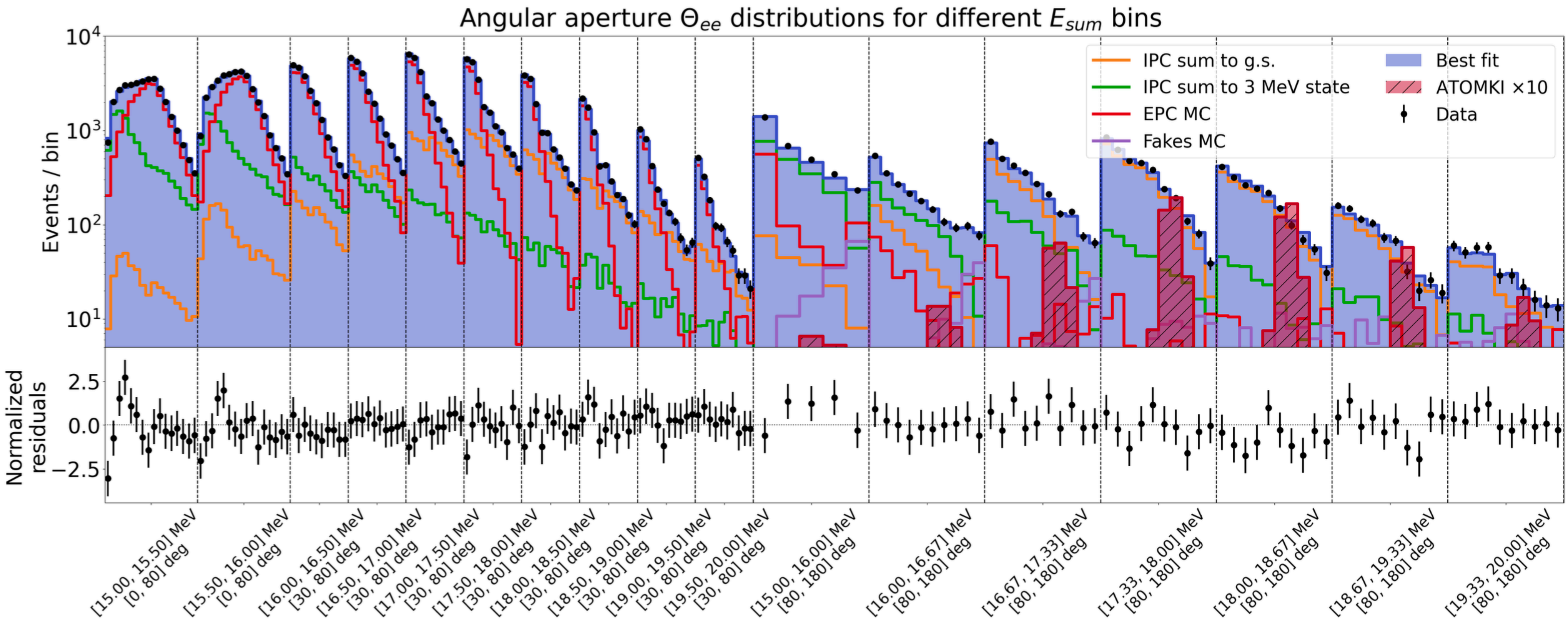

**Including Beeston-Barlow coefficients to account for MC limited statistics**

# Unblinding



$\Theta_{ee}$ 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
$\Theta_{ee}$ (deg)

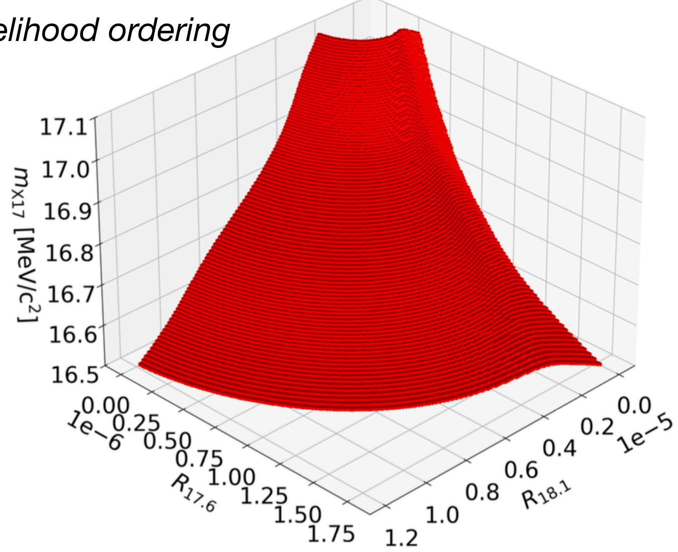
# Results from the ML fit

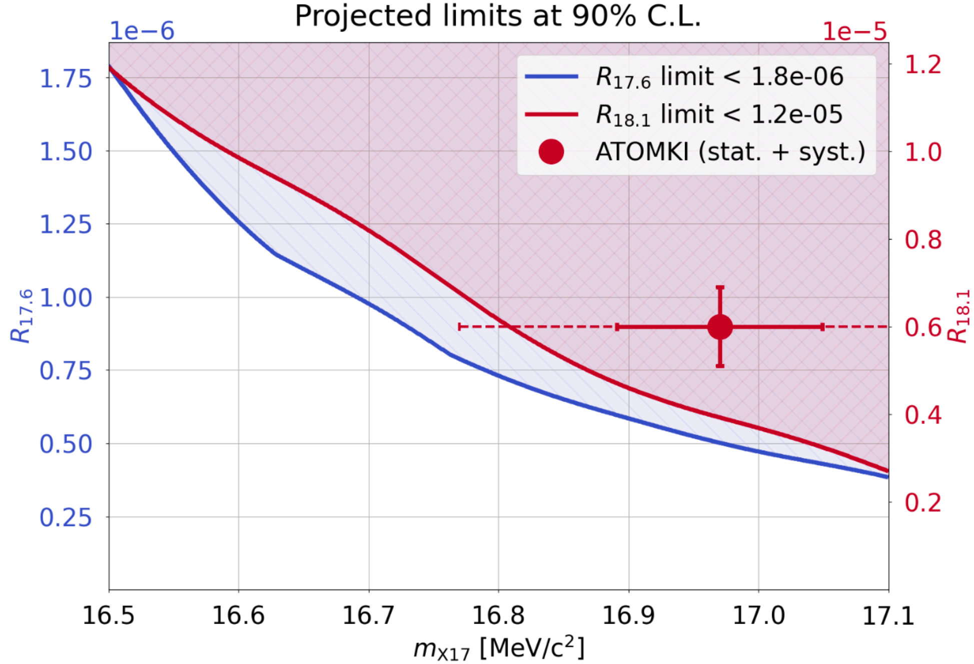



- **Best fit:**
  - 10 ± 92 signal events at Q = 18.1 MeV and none at Q = 17.6 MeV - for a $m_{X17}$ = 16.5 MeV
  - IPC: **12.6**(9)% Q = 18.1 MeV and **45.8**(13)% Q = 17.6 MeV
  - Goodness-of-fit: p-value = 10%

# 90% Confidence Limits

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




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

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

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

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

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

→ **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)**

- <u>J.L.Feng et al</u>.: X17 produced **both** at 1.030 MeV **and** at 0.440 MeV
  → *p*-value : **1.8% (2.1σ)**

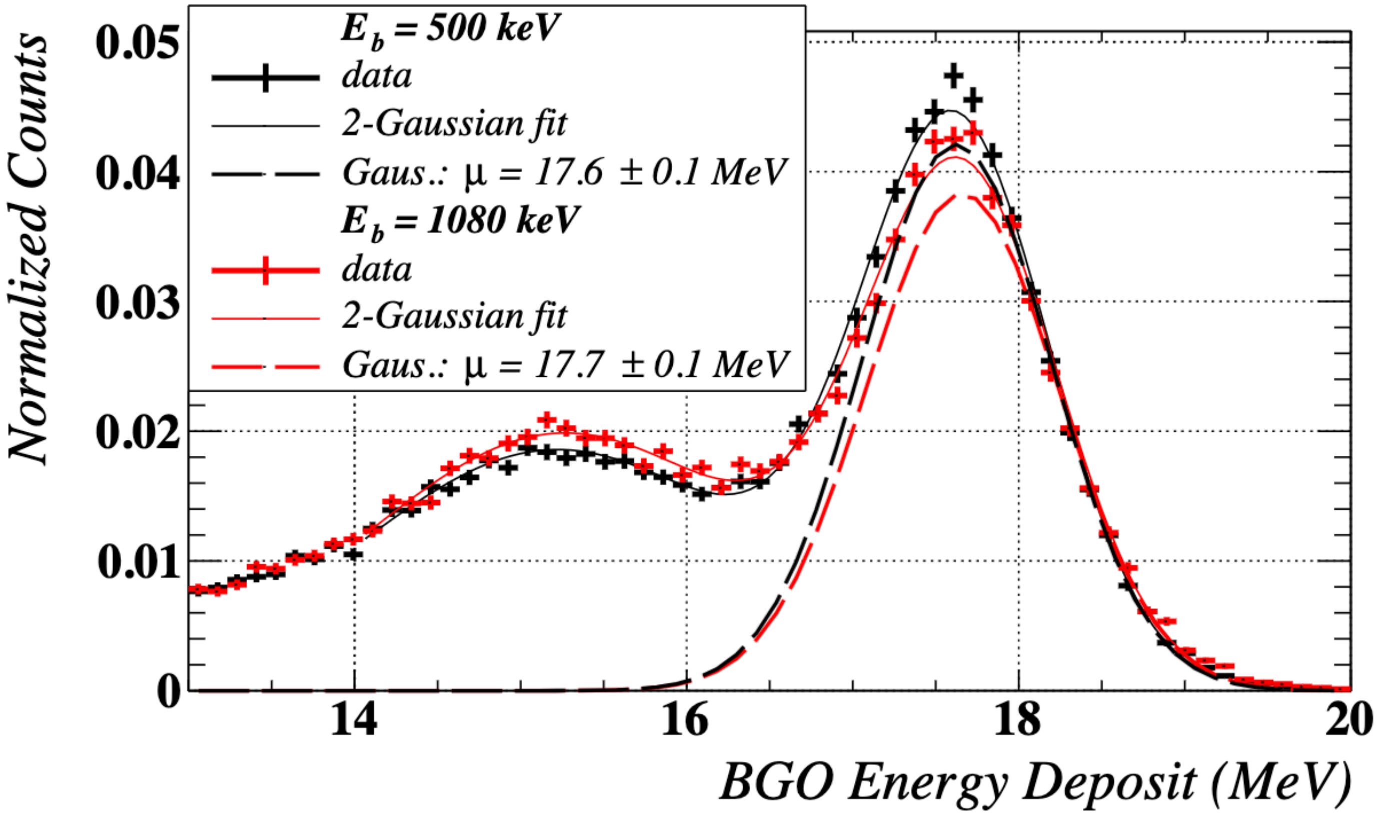
**Using $m_{X17}$=16.97(22) MeV and $R_{18.1}$ = 6 $10^{-6}$**
**Scaling $R_{17.6}$ = 0.46 $R_{18.1}$**

# Conclusion

- MEG II detector successfully studied the *$^{7}Li\ (p, e^{+}e^{-})^{8}Be$* 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 ~ 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 and removal of $H_2^+$ for a data-taking at 1.030 MeV only*

# Backup slides

# BGO spectra



Normalized Counts
0.05
0.04
0.03
0.02
0.01
0
$E_b$ = 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
14
16
18
20
BGO Energy Deposit (MeV)

# Data MC comparison for 500/1080 keV data