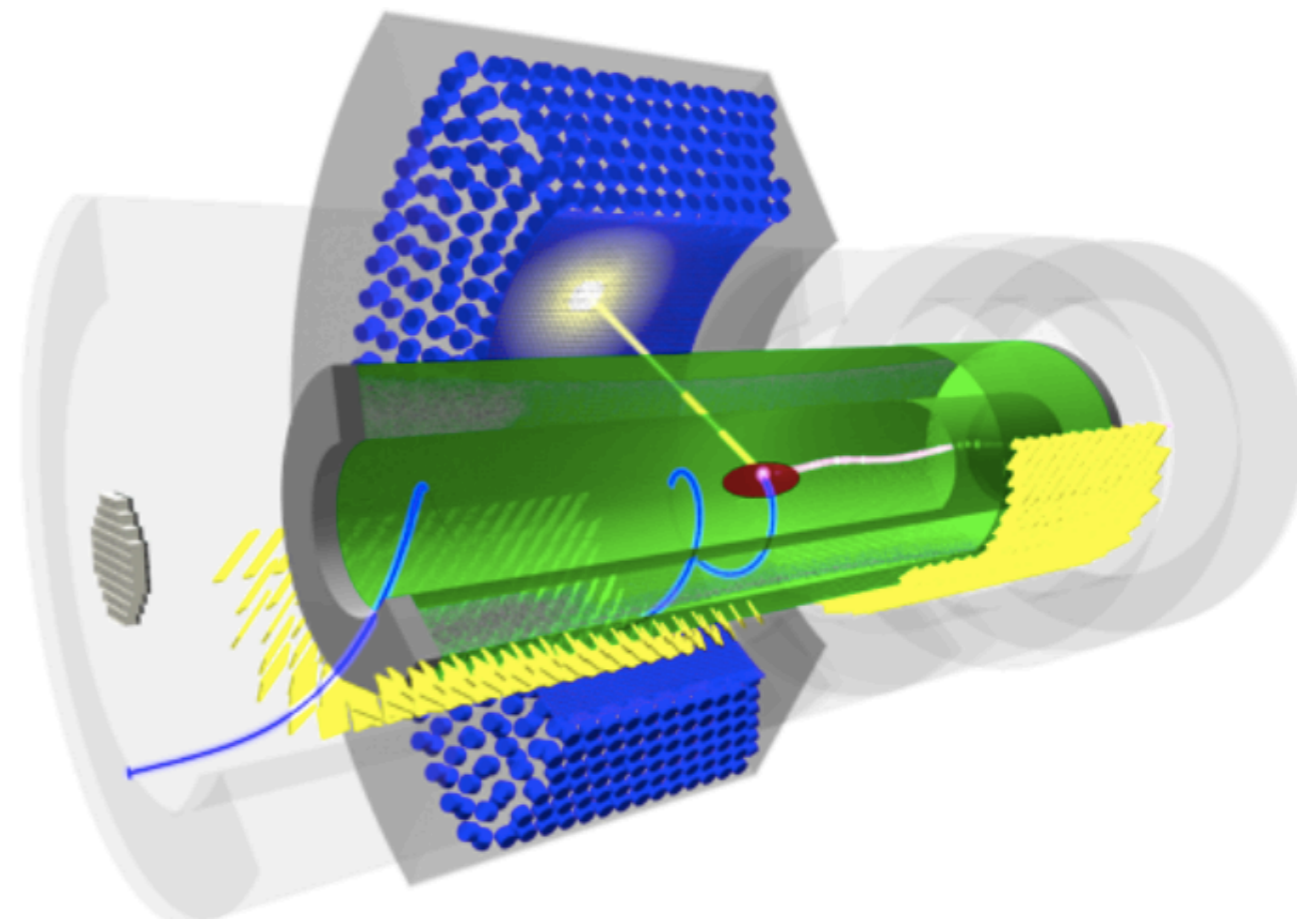


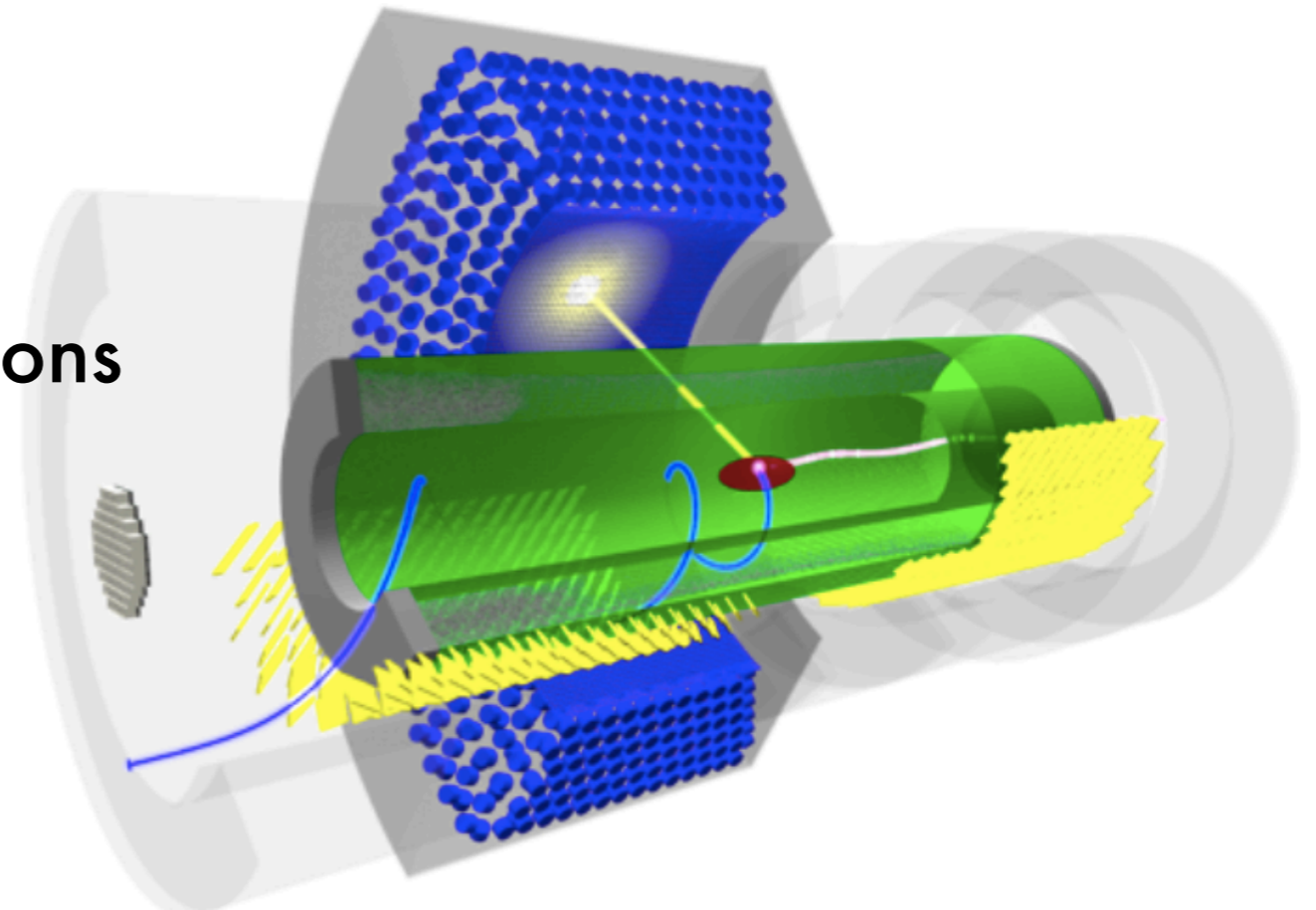
Results on the X17 search with the MEG-II apparatus

Hicham Benmansour, INFN Pisa
on behalf of the MEG-II collaboration

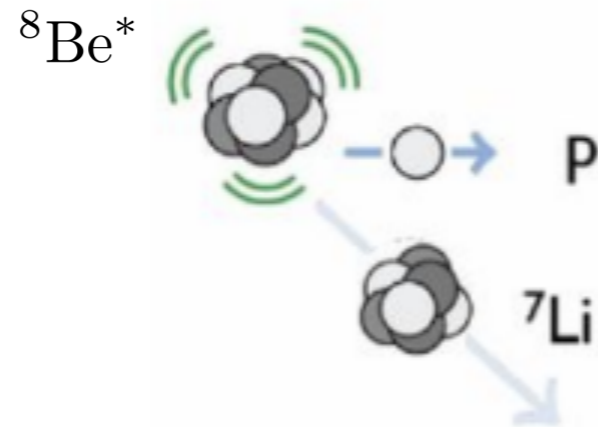
INFN Pisa seminar
Pisa, November 18th, 2024



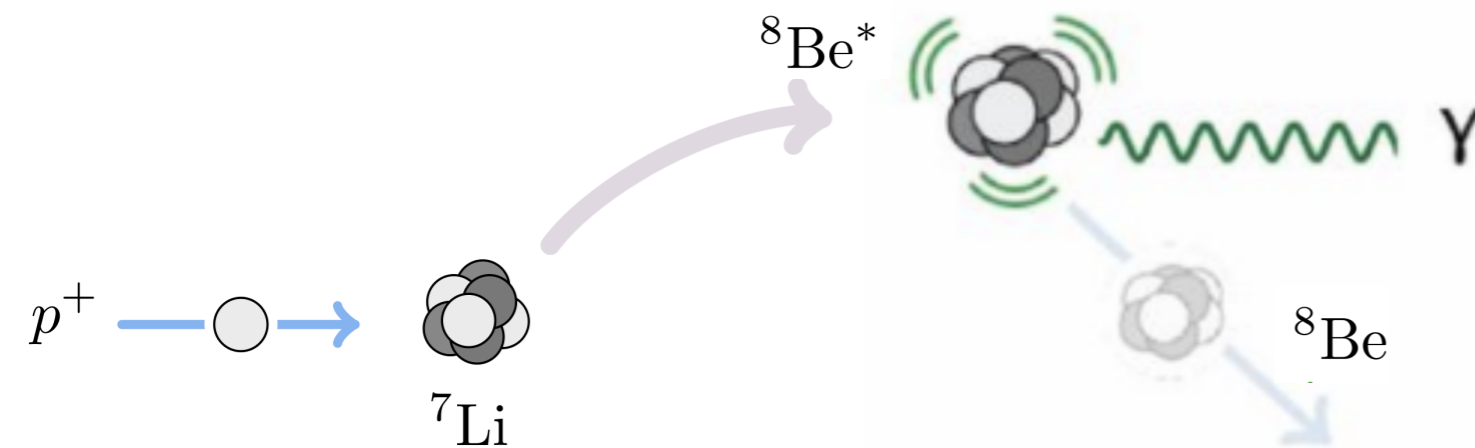
- 1) Physics motivation: the Atomki anomalies
- 2) The MEG-II apparatus
- 3) Backgrounds and signal simulations
- 4) Pair reconstruction
- 5) Trigger and DAQ strategies
- 6) Physics dataset and X17 results



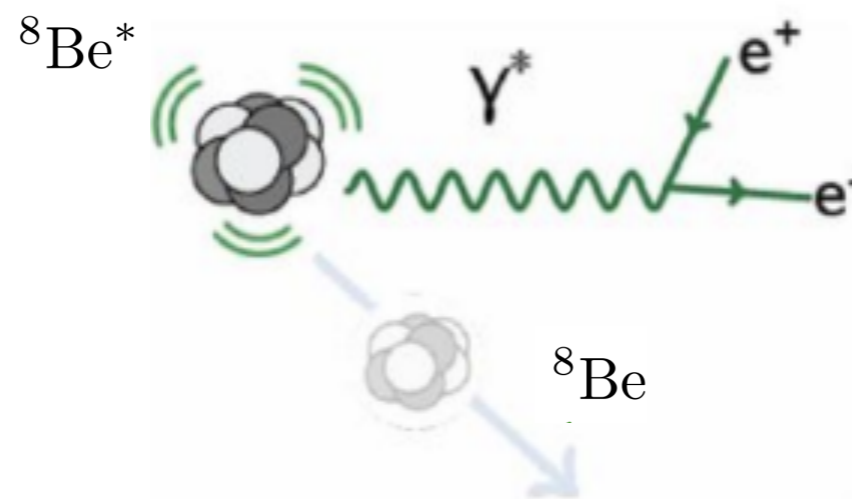
1) The Atomki anomalies



a) Hadronic dissociation
BR $\sim 100\%$

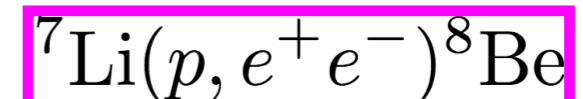


b) Electromagnetic transition
 γ -emission
BR $\sim 1e-5$



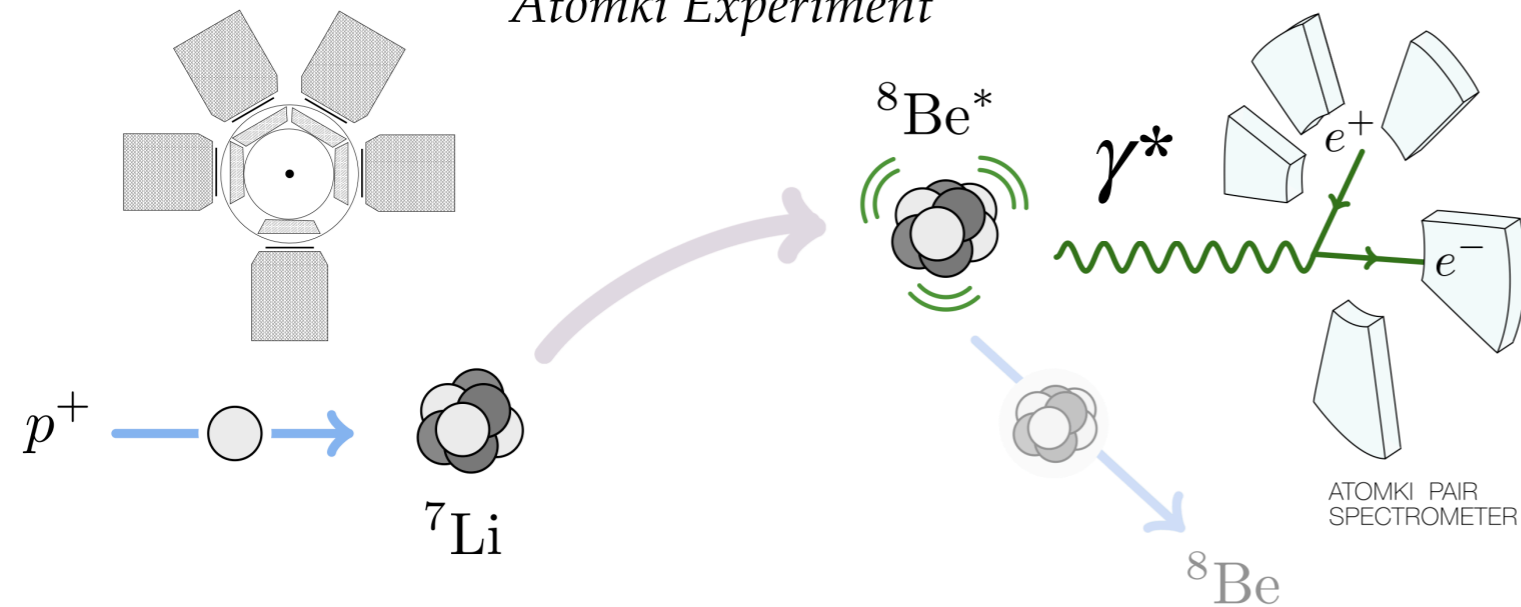
c) Electromagnetic transition
Direct e^+e^- emission
BR $\sim 1e-8$

\rightarrow IPC = Internal Pair Conversion



The Beryllium Anomaly

Atomki Experiment

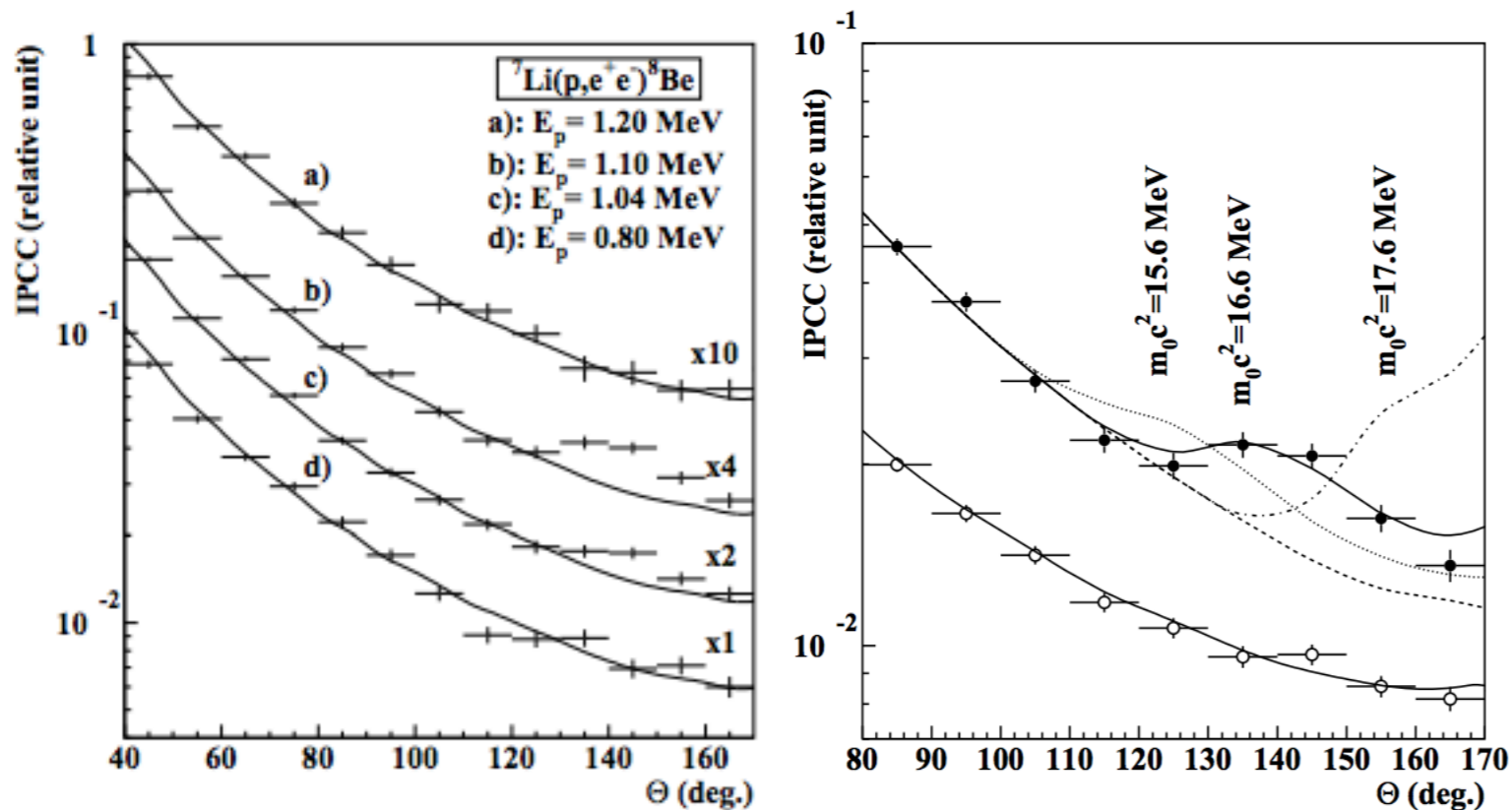


${}^7\text{Li}(p, e^+e^-){}^8\text{Be}$ studied at $E_p = 800, 1040, 1100, 1200$ keV

→ e^+/e^- energy sum and angular opening Θ

IPC = Internal Pair Conversion
 → direct e^+/e^- pair creation
 → rare process: 1 every 1000 γ

2016 Atomki results



Phys. Rev. Lett. 116, 042501

- Internal Pair Conversion (IPC) distribution shows excess at $\Theta \sim 140^\circ$ at 1100 keV

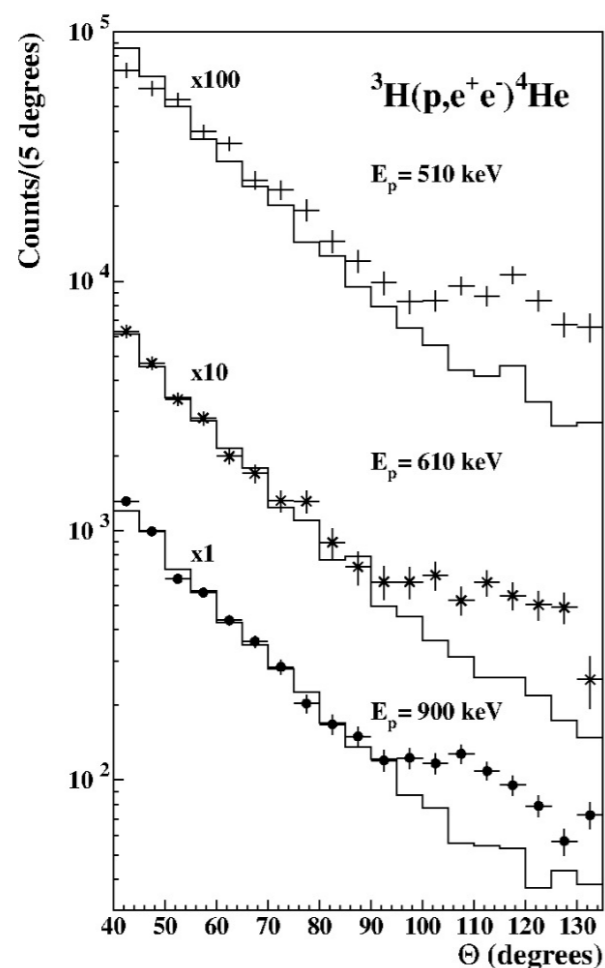
→ 1 possible explanation: decay of a light particle emitted during proton capture

→ best fit $m_X = 16.70 \text{ MeV}/c^2$
 $BR(X) = 6 \times 10^{-6}$ wrt to γ production

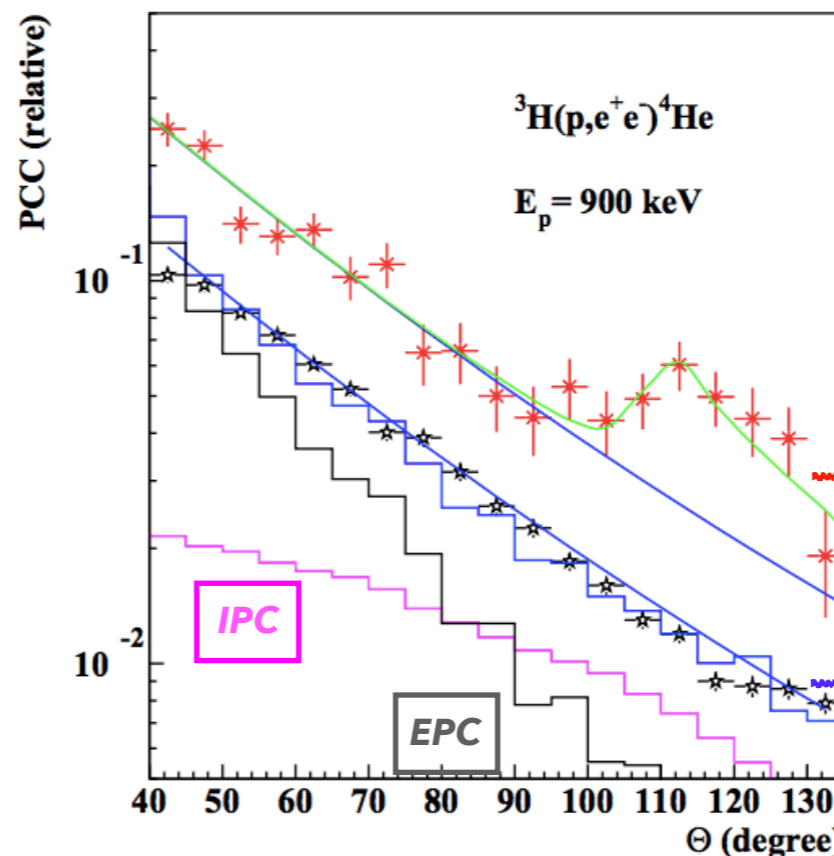
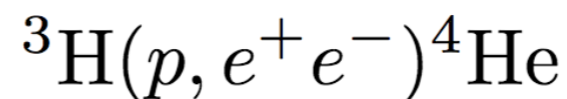
→ vector boson X17?
 mediator of a fifth force?

Phys. Rev. D 95, 035017

Signal region



Study repeated with Tritium target



$$E_{\text{sum}} = E_{e^+} + E_{e^-}$$

IPC = Internal Pair Conversion
 → direct e⁺/e⁻ pair creation

EPC = External Pair Conversion
 → γ-conversion in matter

E_{sum} signal region

E_{sum} background region

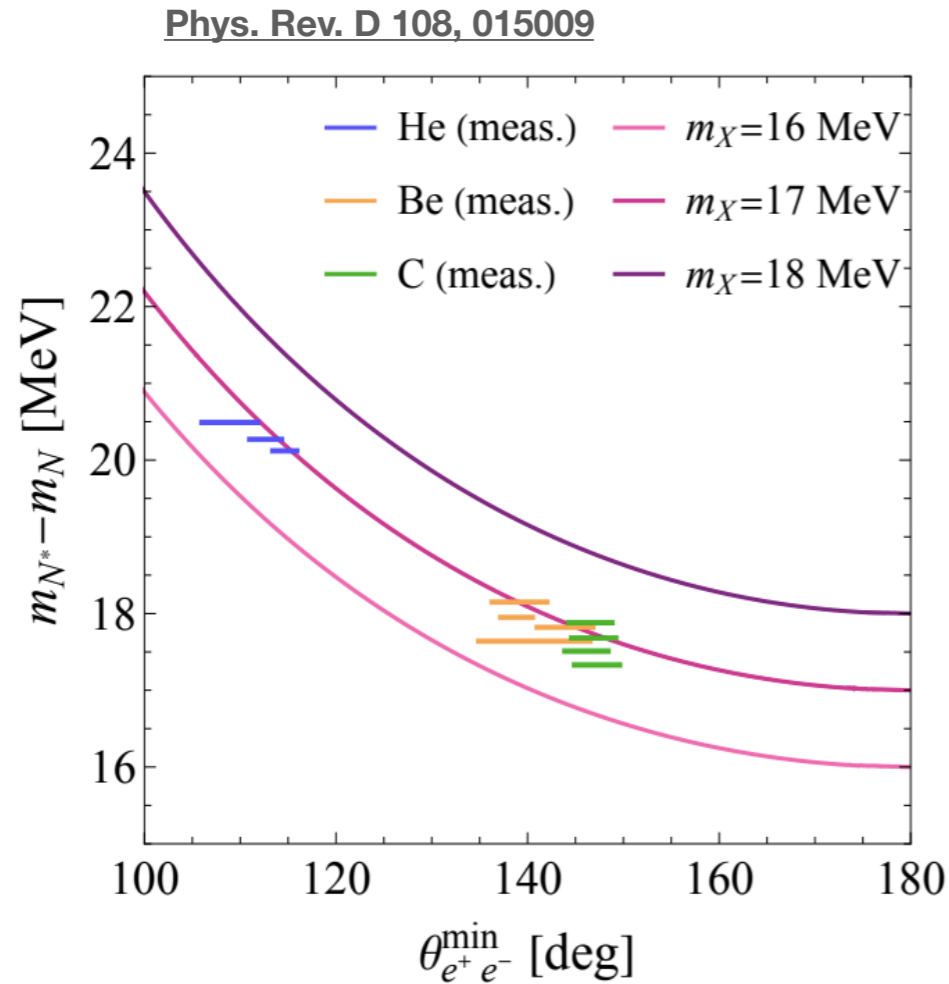
- Excess in IPC background at 115° angular opening: $>6\sigma$
- Possible explanation: a 16.84 MeV/c² neutral boson (X17?)
- Recent excess in ${}^{11}\text{B}(p, \gamma) {}^{12}\text{C}$ as well [Phys. Rev. C 106, L061601](#)
- Other indirect searches (NA64, NA48/2): no evidence for X17 but strong constraints

[Phys. Rev. D, 101:071101](#) [Phys. Lett. B 746, 178](#)

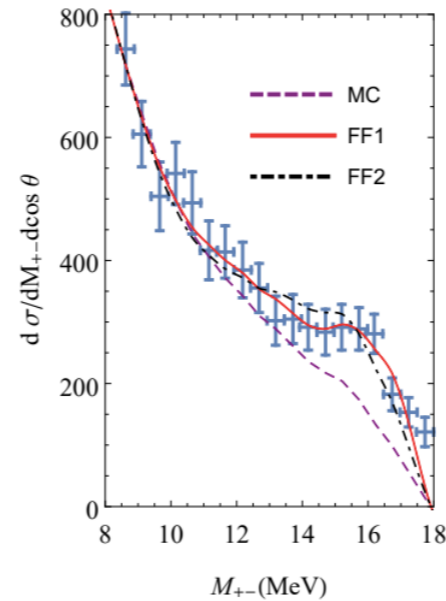
New boson?

or

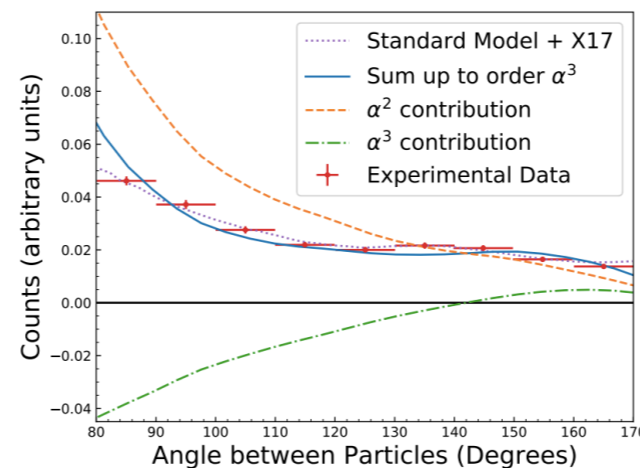
Standard Model physics?



- Reported results are kinematically consistent



- Koch 2021 Modified Bethe-Heitler
Nucl. Phys. A 1008, 122143

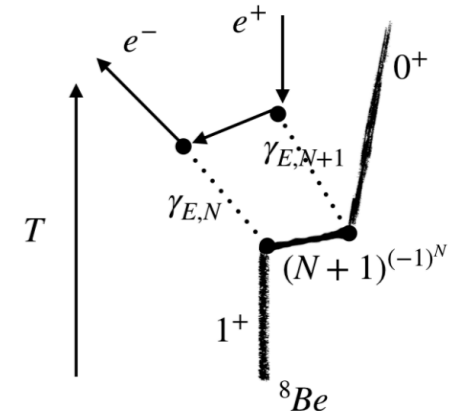


- Hayes 2021 Phys. Rev. C 105, 055502
Underlines importance of E1/M1 multipole contribution ratio

- Zhang & Miller 2017

Phys. Lett. B 773, 159

Multipole interferences?
Form factor?



- Aleksejevs 2021 arXiv:2102.01127
IPC second-order processes included

- Hint for the production of a neutral, 17 MeV boson, potential mediator of a fifth force: X17
- Can the measurement be reproduced with an independent setup?
- Need for experimental confirmation: MEG-II has all elements to carry out the measurement
 - Improved resolution
 - Reconstruction in full solid angle
 - Reproduction of excess?
- Engineering run in 2022
- First DAQ period in February 2023

2) The MEG-II apparatus

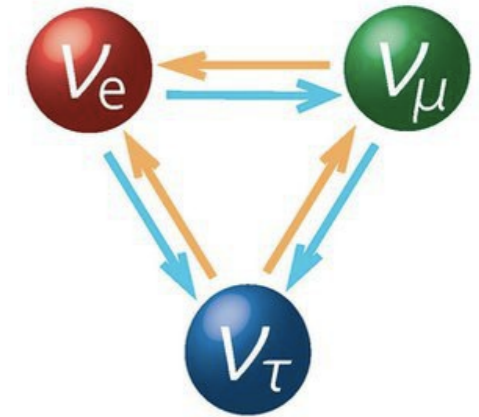
The MEG-II experiment

Charged Lepton Flavour Violation

| | | | |
|---------|--|--|---|
| LEPTONS | $0.511 \text{ MeV}/c^2$ -1 $1/2$ electron | $105.7 \text{ MeV}/c^2$ -1 $1/2$ muon | $1.777 \text{ GeV}/c^2$ -1 $1/2$ tau |
| | $<2.2 \text{ eV}/c^2$ 0 $1/2$ electron neutrino | $<0.17 \text{ MeV}/c^2$ 0 $1/2$ muon neutrino | $<15.5 \text{ MeV}/c^2$ 0 $1/2$ tau neutrino |

- Lepton flavour violation observed experimentally with neutral leptons

→ Neutrino oscillations (Kamiokande, SNOLAB)



- No Charged Lepton Flavour Violation (CLFV) observed so far
- Neutrinoless muon decay is a CLFV golden channel → $\mu^+ \rightarrow e^+ \gamma$

SM with massive neutrinos

$$\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) \approx 10^{-54}$$

BSM physics

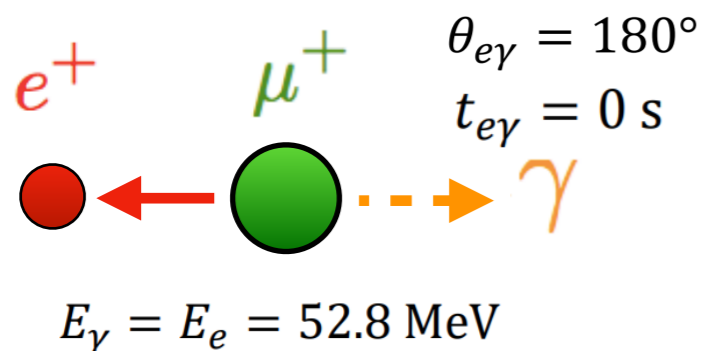
$$\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) \gg 10^{-54}$$

accessible experimentally today

- Observation of CLFV at current sensitivities = unambiguous evidence for New Physics

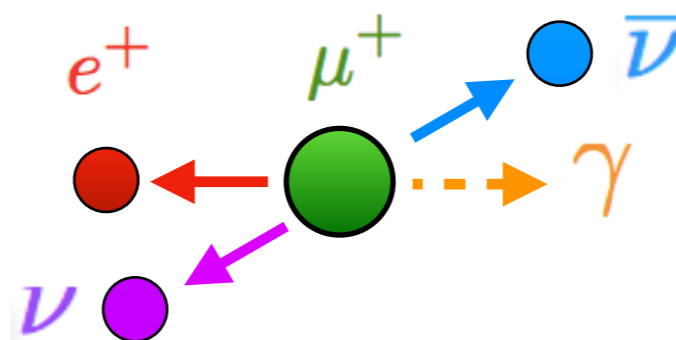
Signal

Back-to-back decay at rest

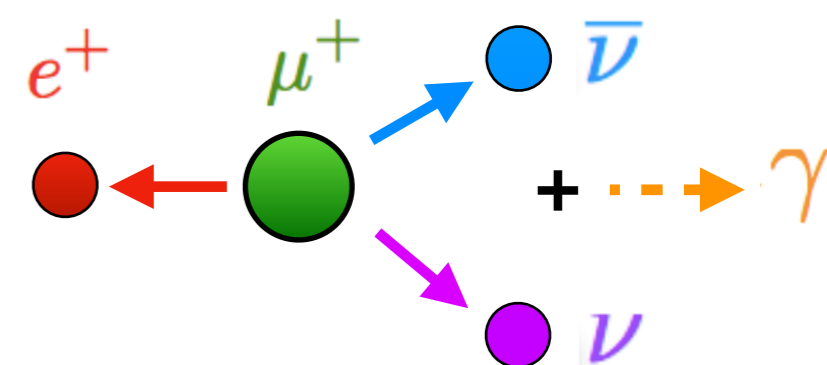


Backgrounds

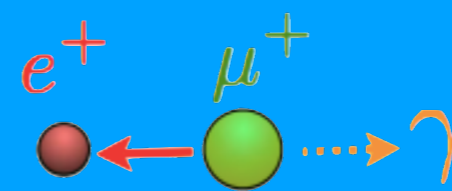
Radiative Muon Decay



Accidental

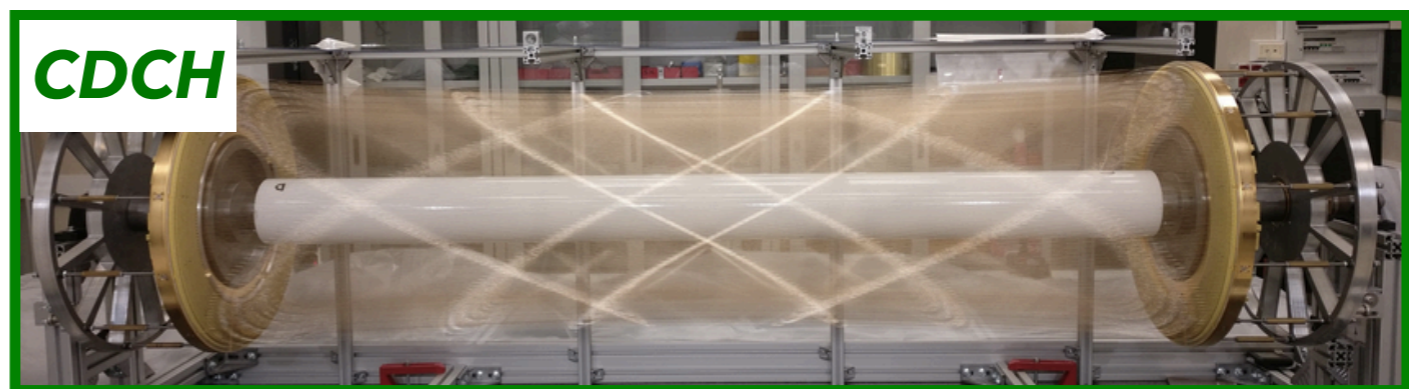
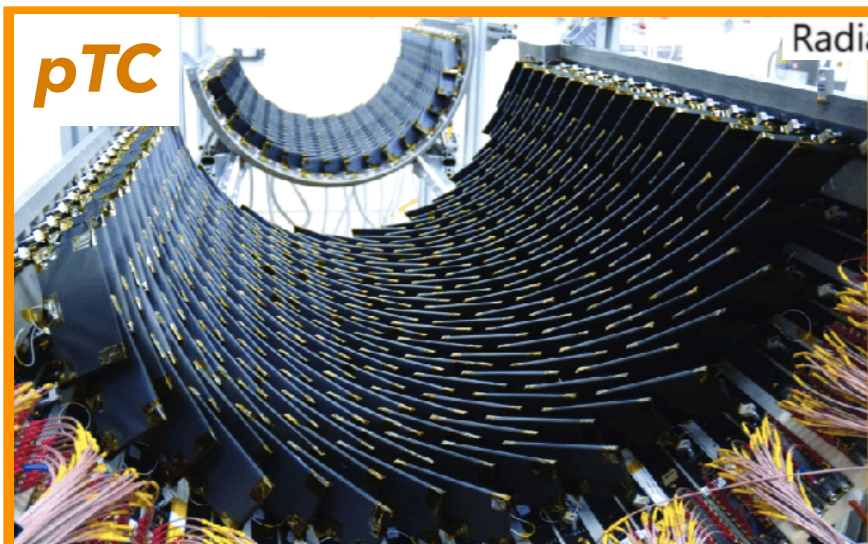
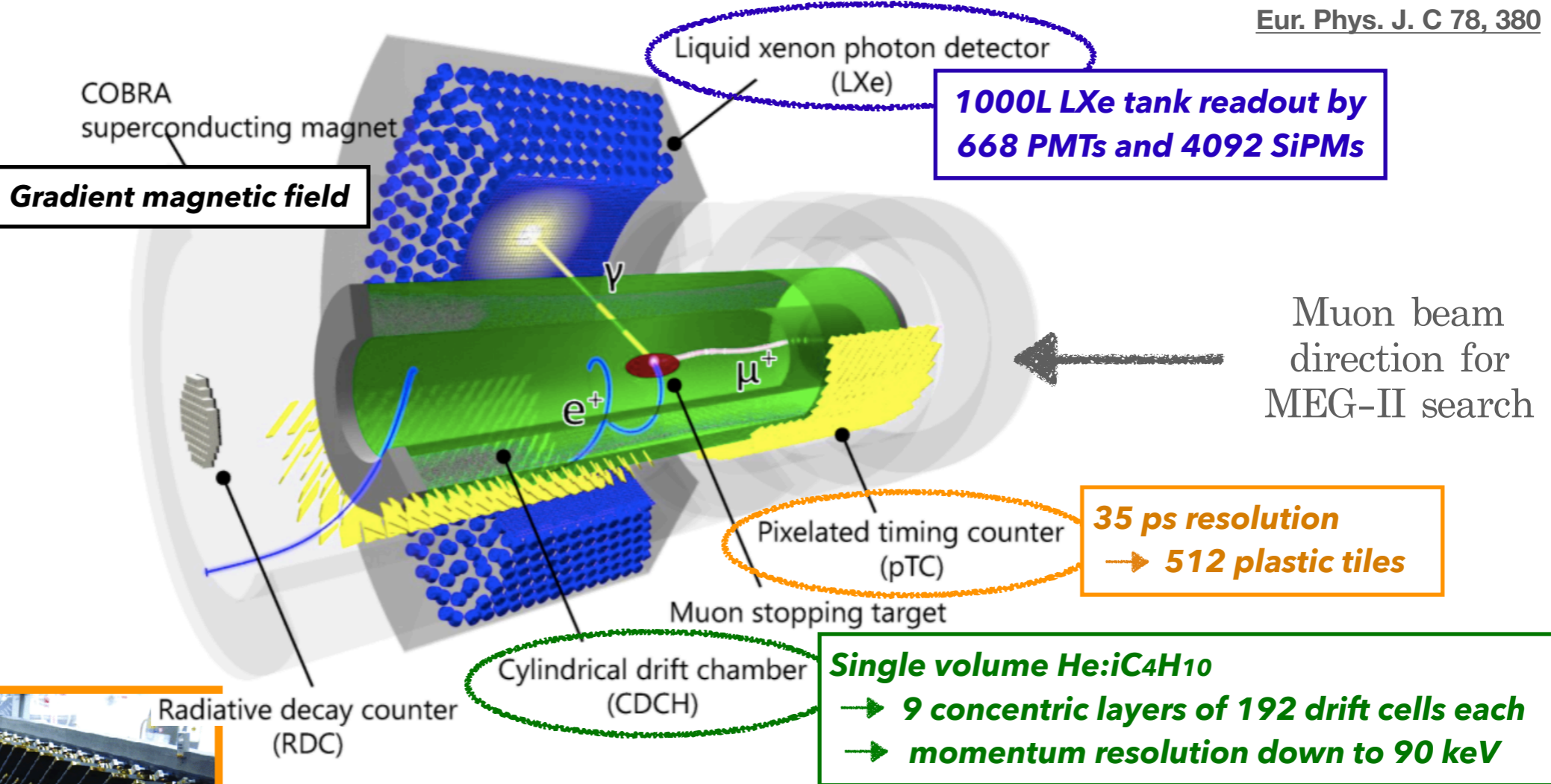


The MEG-II experiment



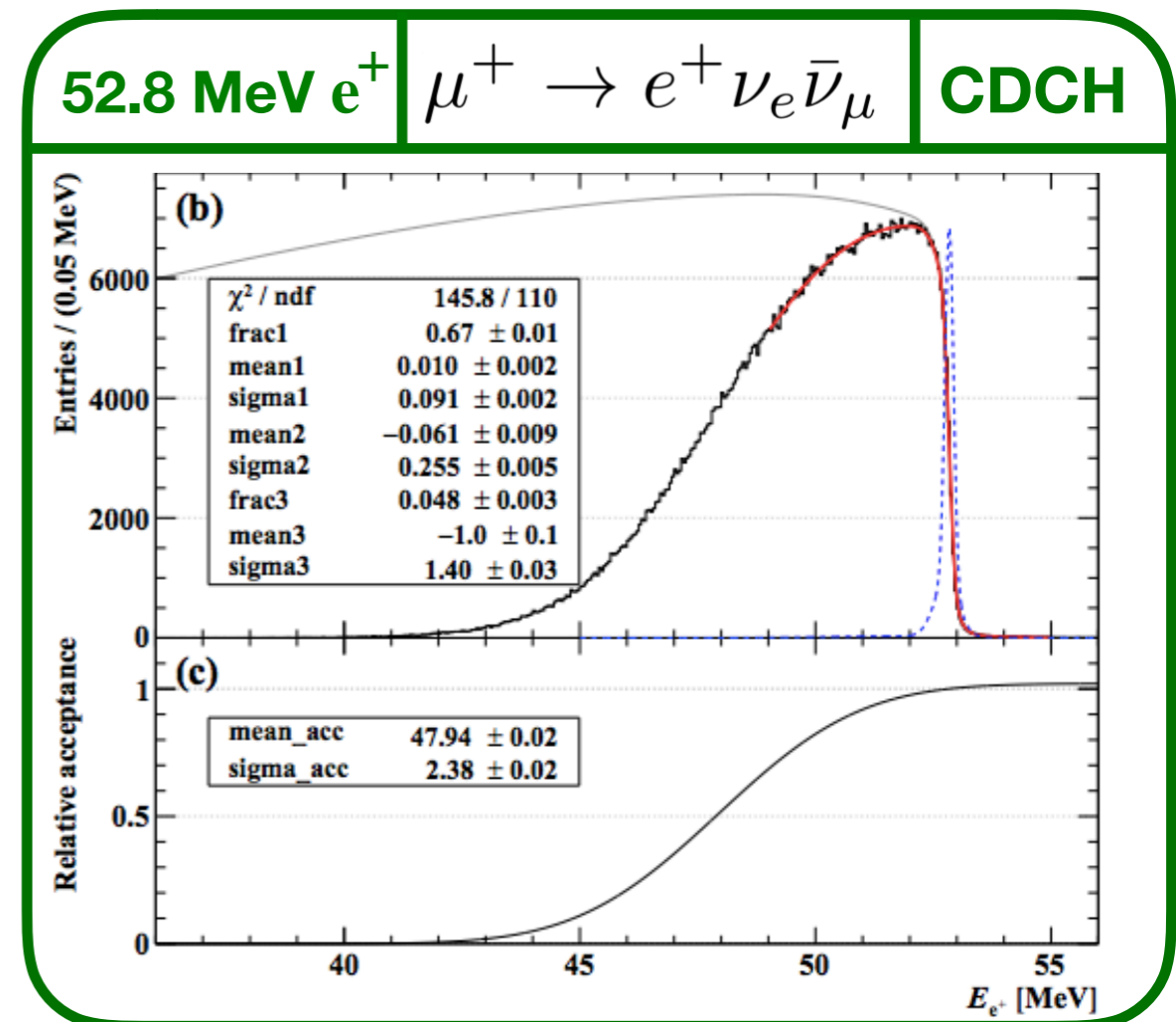
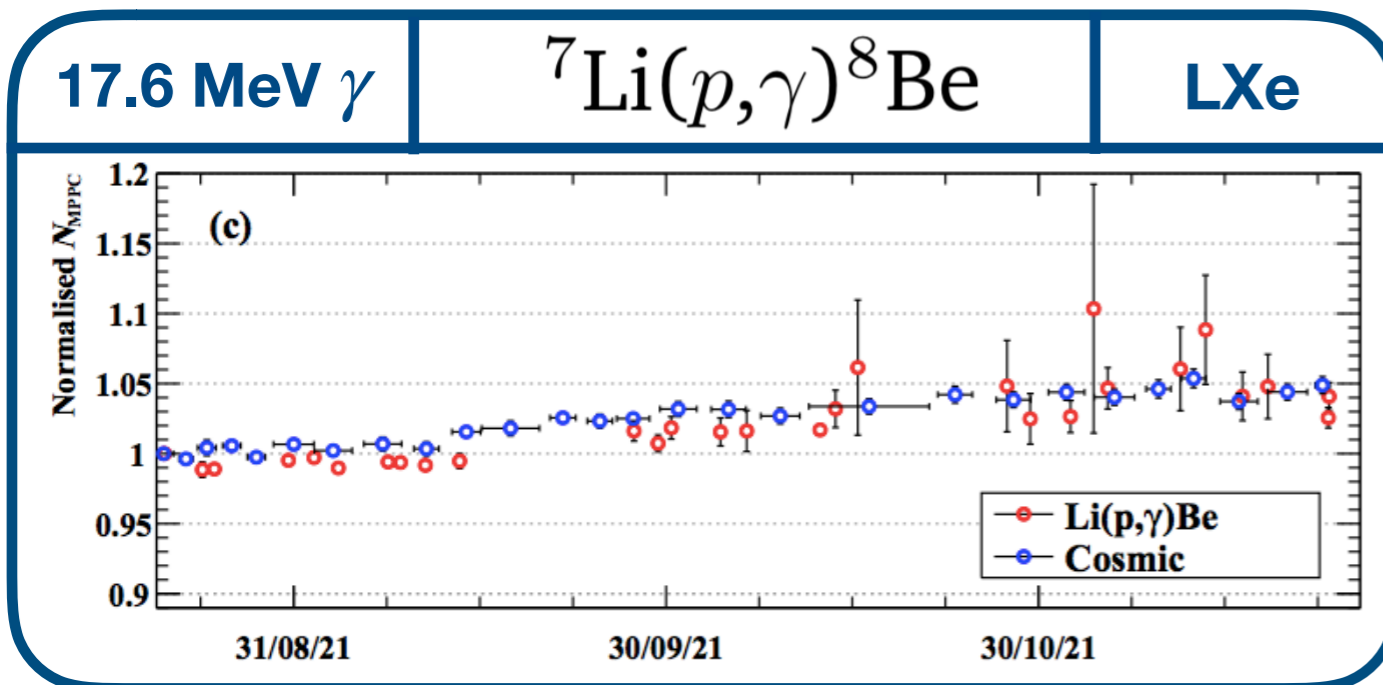
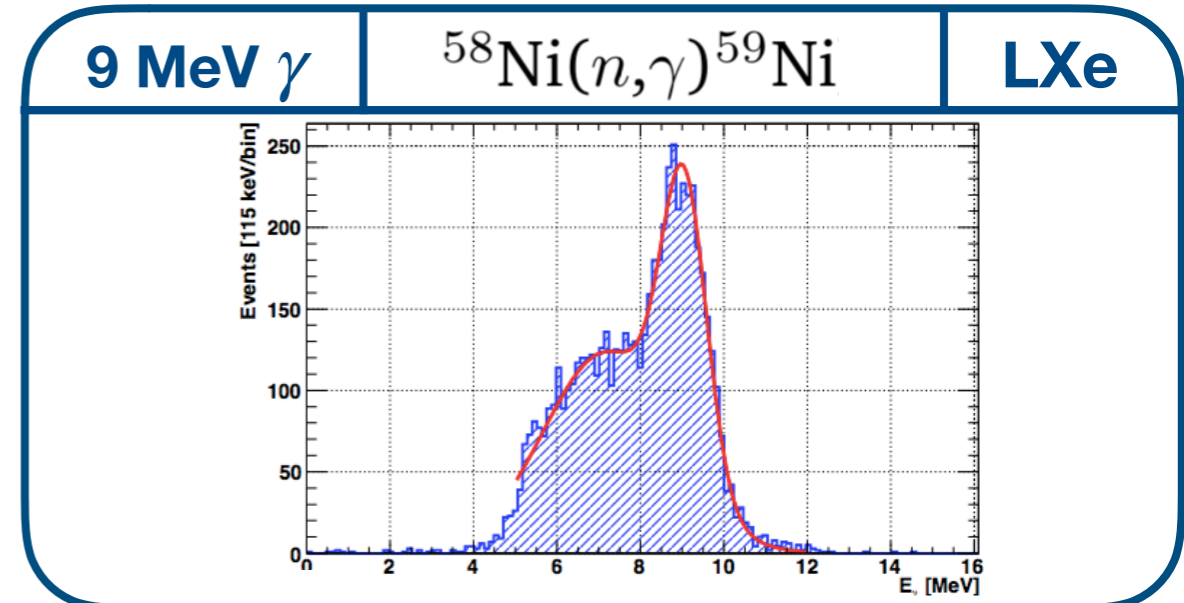
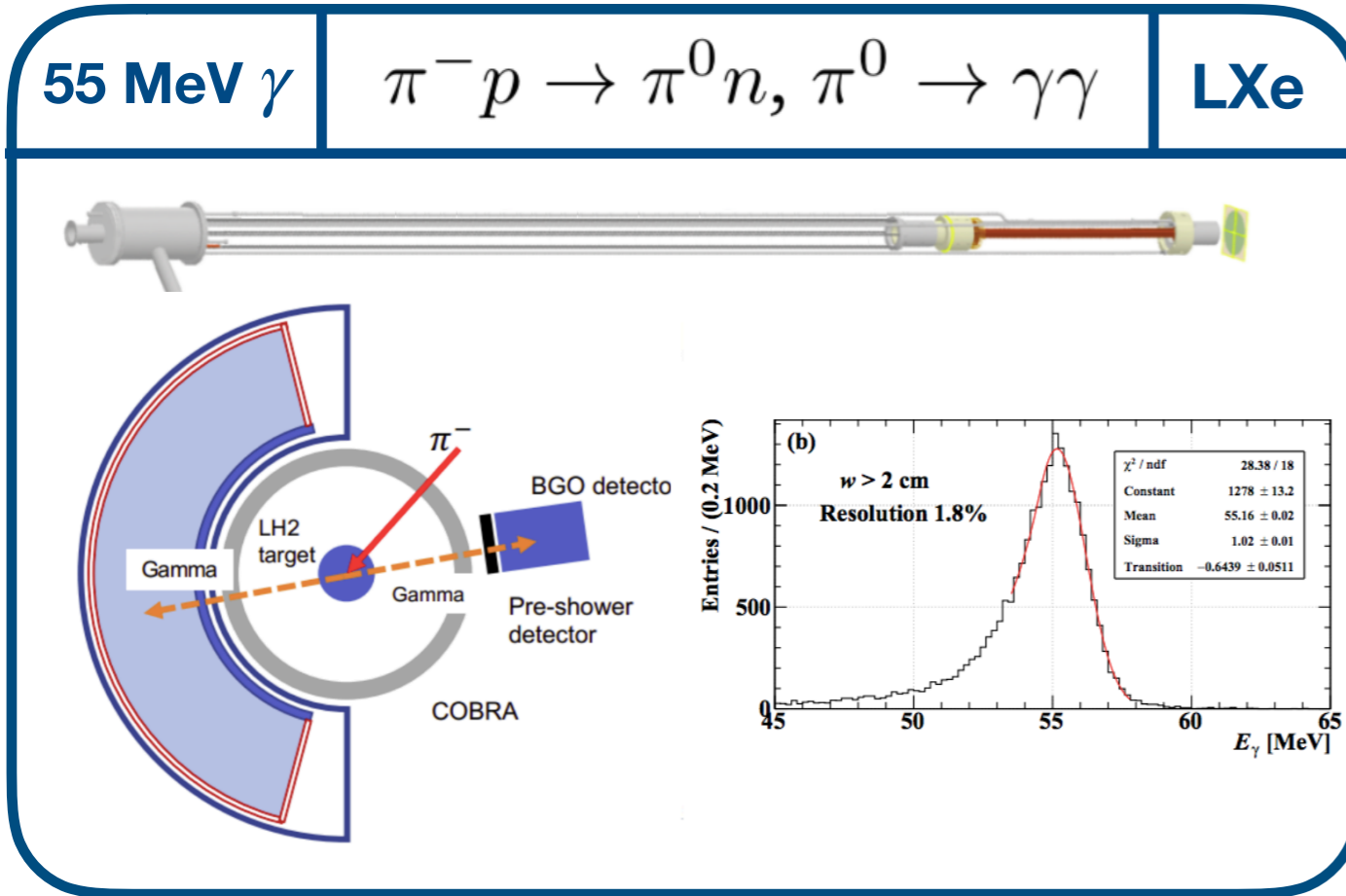
- MEG-II experiment searches for charged lepton flavour violating decay: $\mu^+ \rightarrow e^+ \gamma$
- At Paul Scherrer Institute, PSI, Switzerland Eur. Phys. J. C, 76(8):434
- 1 order of magnitude sensitivity improvement wrt MEG: $BR(\mu \rightarrow e\gamma) \rightarrow 6 \times 10^{-14}$ Eur. Phys. J. C 78, 380

MEG-II results from an intense upgrade program



Detectors calibrations

- Search relies on an extensive and regular calibration routine

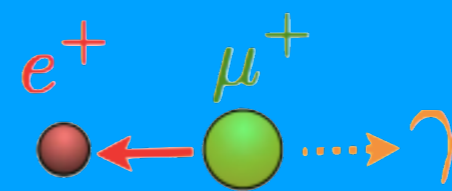


2) The MEG-II apparatus

Adapting for the X17 search

- We need to measure the direction and momentum of both electron and positron
- MEG-II highly performing spectrometer can be used for the X17 search:
 - MEG-II CW accelerator as proton beam
 - X17-dedicated target in place of the muon target
 - gamma auxiliary detectors
 - reduced magnetic field
 - optimized TDAQ

The MEG-II experiment



- MEG-II experiment searches for charged lepton flavour violating decay: $\mu^+ \rightarrow e^+ \gamma$
- At Paul Scherrer Institute, PSI, Switzerland Eur. Phys. J. C, 76(8):434
- 1 order of magnitude sensitivity improvement wrt MEG: $BR(\mu \rightarrow e\gamma) \rightarrow 6 \times 10^{-14}$ Eur. Phys. J. C 78, 380

MEG-II results from an intense upgrade program

Gradient magnetic field

Liquid xenon photon detector (LXe)

1000L LXe tank readout by 668 PMTs and 4092 SiPMs

Proton beam direction for X17 search

~~Muon beam direction for MEG-II search~~

Pixelated timing counter (pTC)

35 ps resolution → 512 plastic tiles

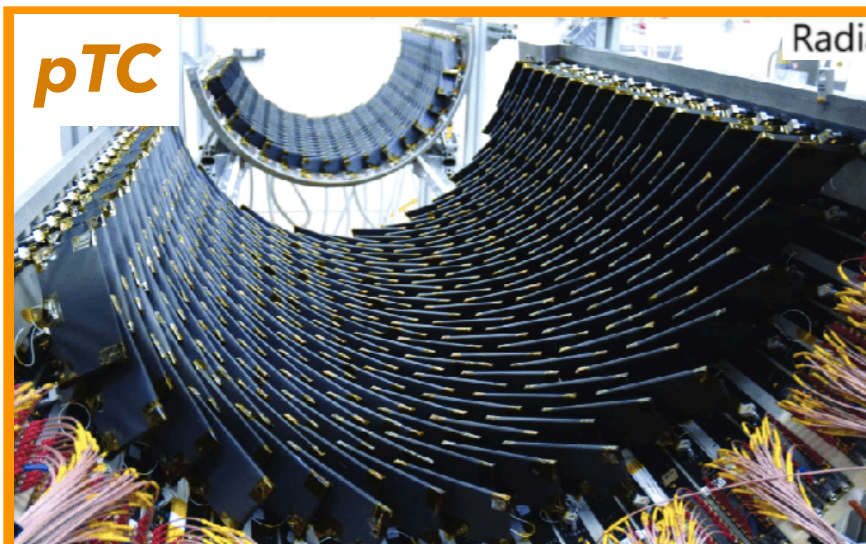
Muon stopping target

Cylindrical drift chamber (CDCH)

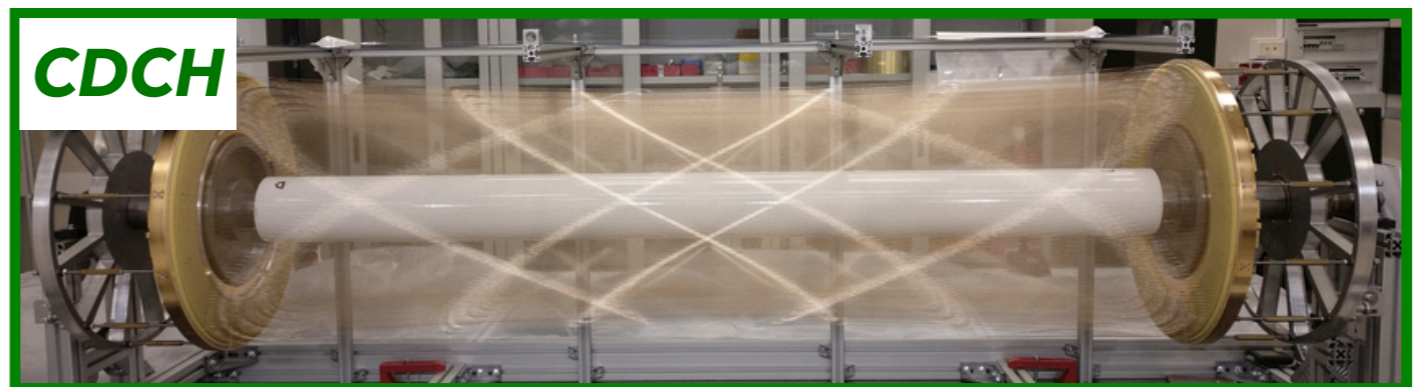
Single volume He:iC4H10

- 9 concentric layers of 192 drift cells each
- momentum resolution down to 90 keV

Radiative decay counter (RDC)



CDCH



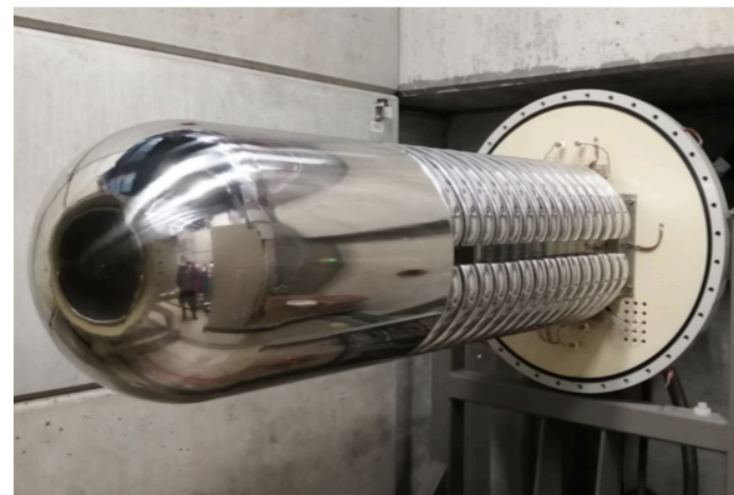
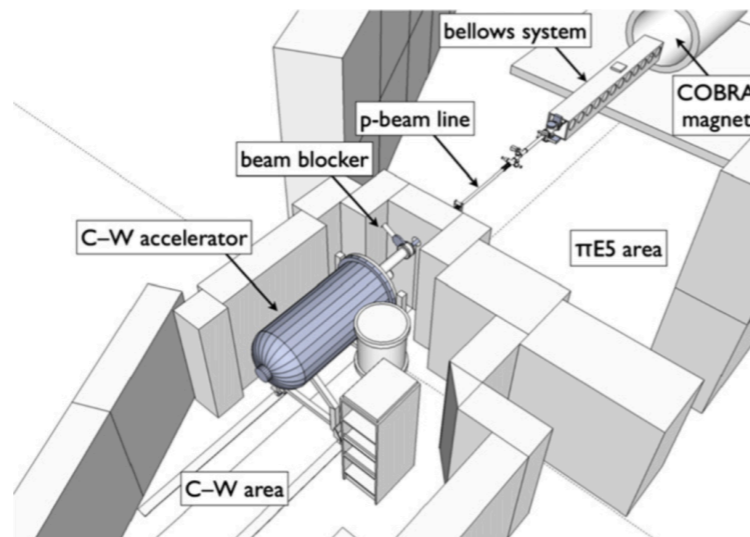
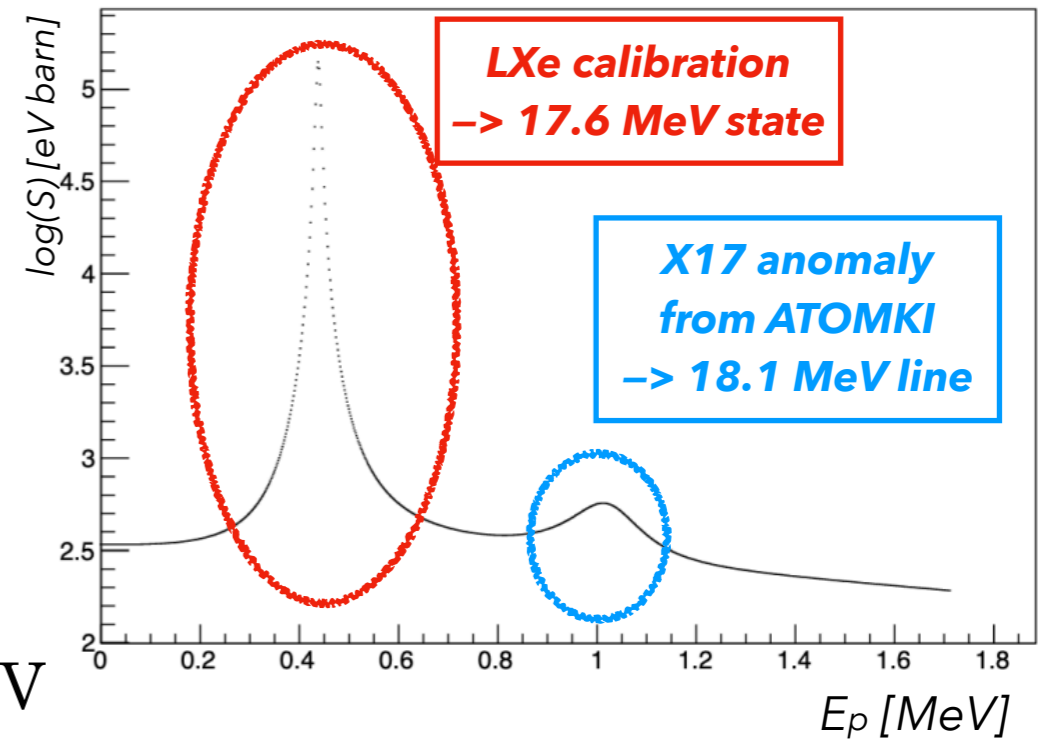
- LXe calibration

- MEG-II Cockcroft-Walton accelerator: used for calibration of LXe calorimeter
- Proton beam impinging on Li target (0.44 MeV resonance): 17.64 MeV γ line

- X17 search

- Max proton current and energy: 100 μ A and 1.1 MeV
- ideal for X17 search, 1.03 MeV resonance

${}^7\text{Li}(p,\gamma){}^8\text{Be}$ astro factor

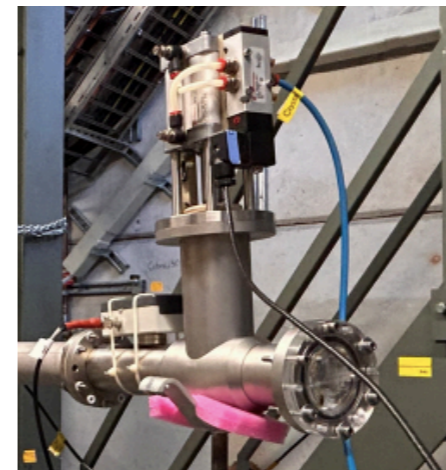


- Beam composition investigation and tuning

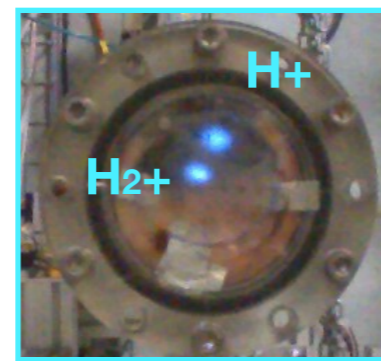
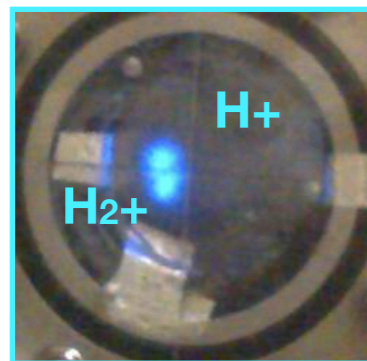
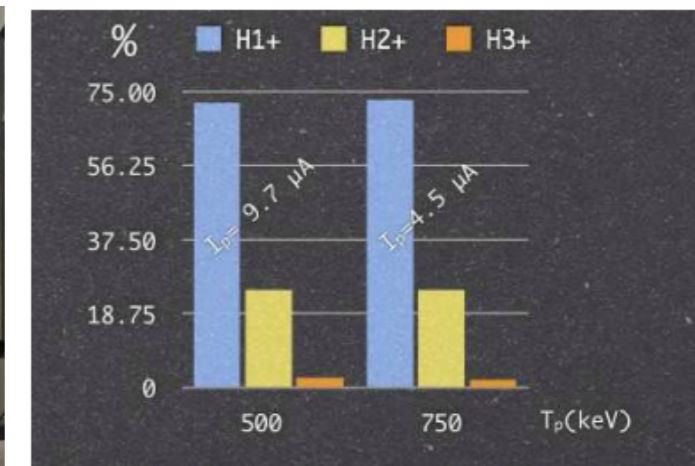
- CW beam tuned using a quartz target: proton-induced fluorescence in the quartz, visible emission
- Tuning made varying 4 dipolar fields along the beamline
- H₂⁺ contamination in the beam

Measurement of the beam ion composition with Faraday Cup

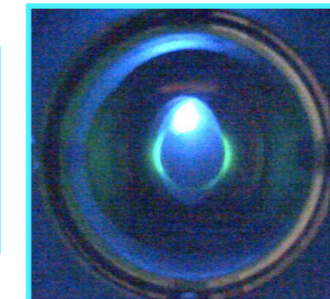
Faraday cup



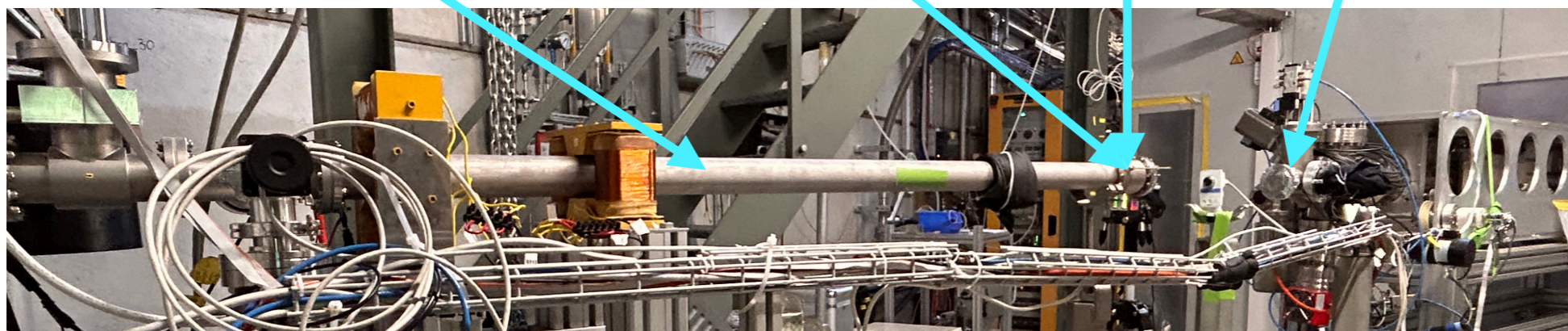
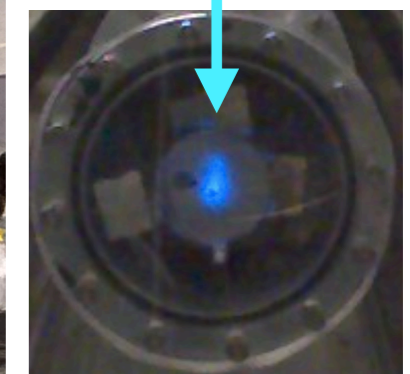
Ion composition



Collimator to reject H₂⁺

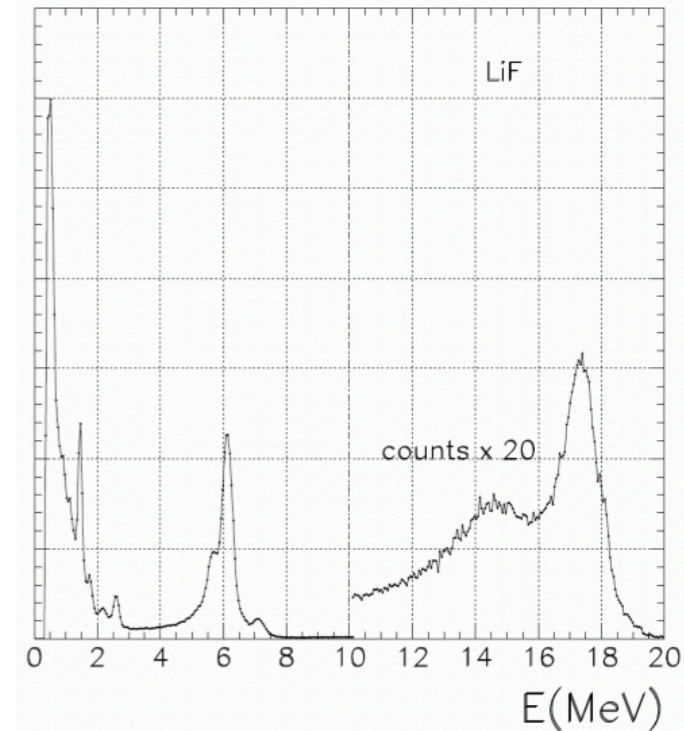


Spectrometer center



The new target region

- 400 μm -thick carbon fiber vacuum chamber to minimize multiple scattering
- Main target for physics run
 - 2 μm LiPON^(*) on 25 μm copper substrate (by PSI)
- For gamma detectors calibration
 - 5 μm LiF on 10 μm copper substrate (by INFN Legnaro)
- Target-supporting and heat-dissipating copper structure attached to CW nose



Li target

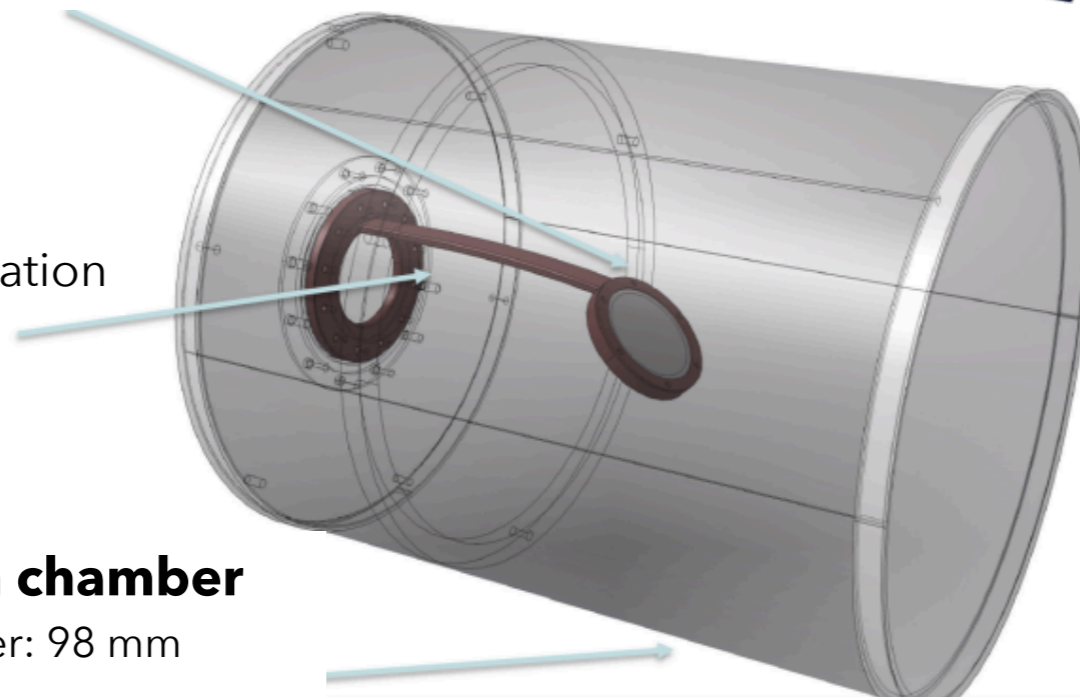
at COBRA center
45° slant angle



Mechanical and heat dissipation simulations carried out

Target arm

Cu for heat dissipation



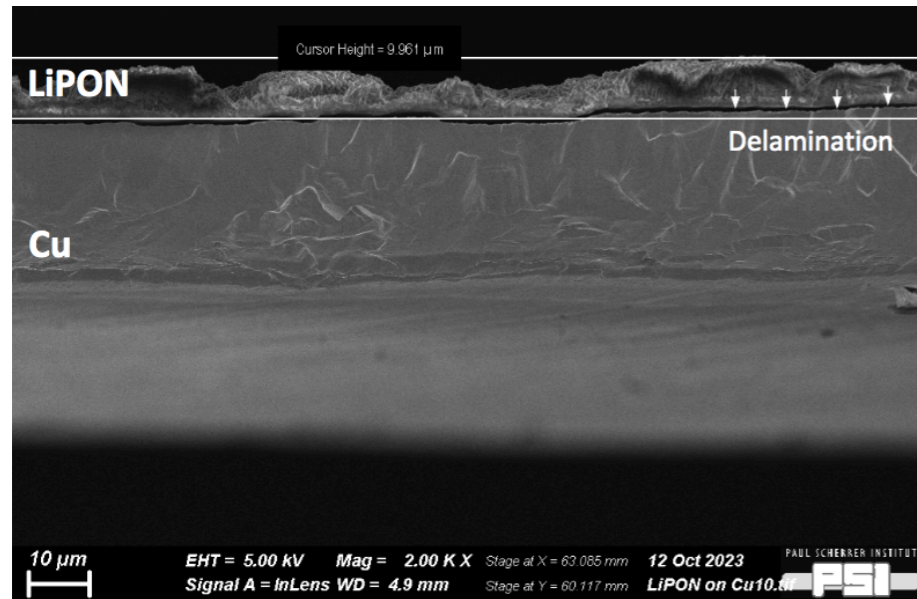
Carbon fiber vacuum chamber

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



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

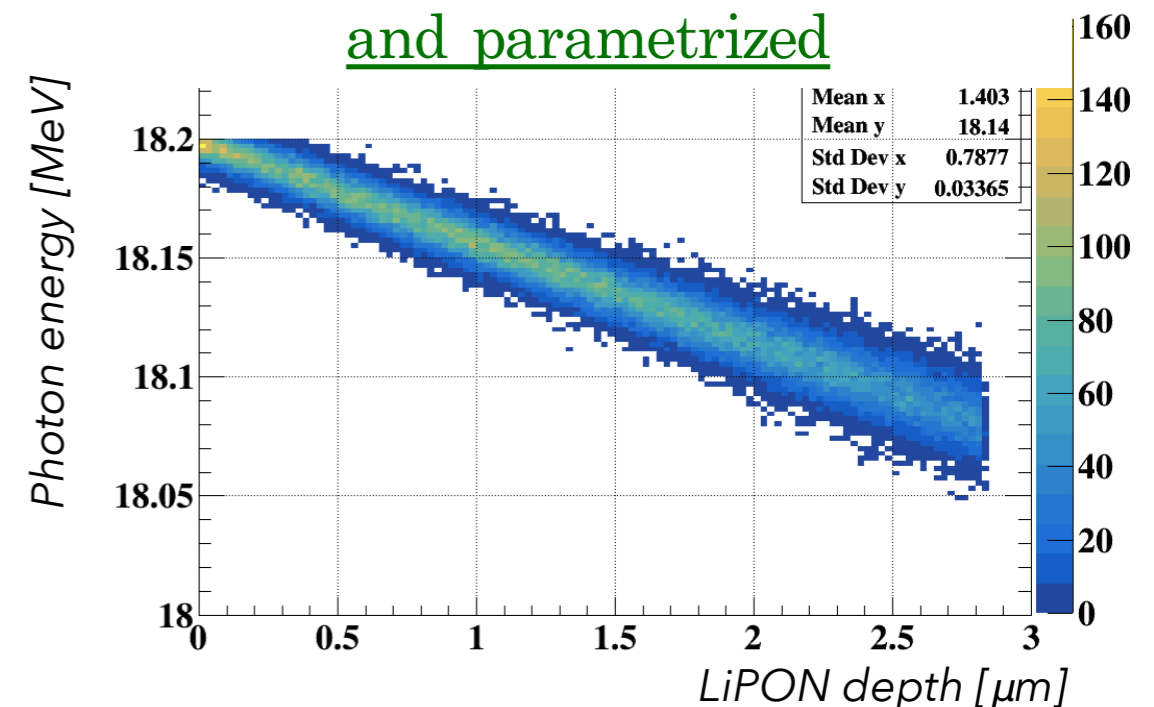
- Why LiPON?
 - Stable, no F-related bkg, thin films through sputtering, developed for batteries
- Difficulties for production: thickness control and non-uniformity, oxidation layer



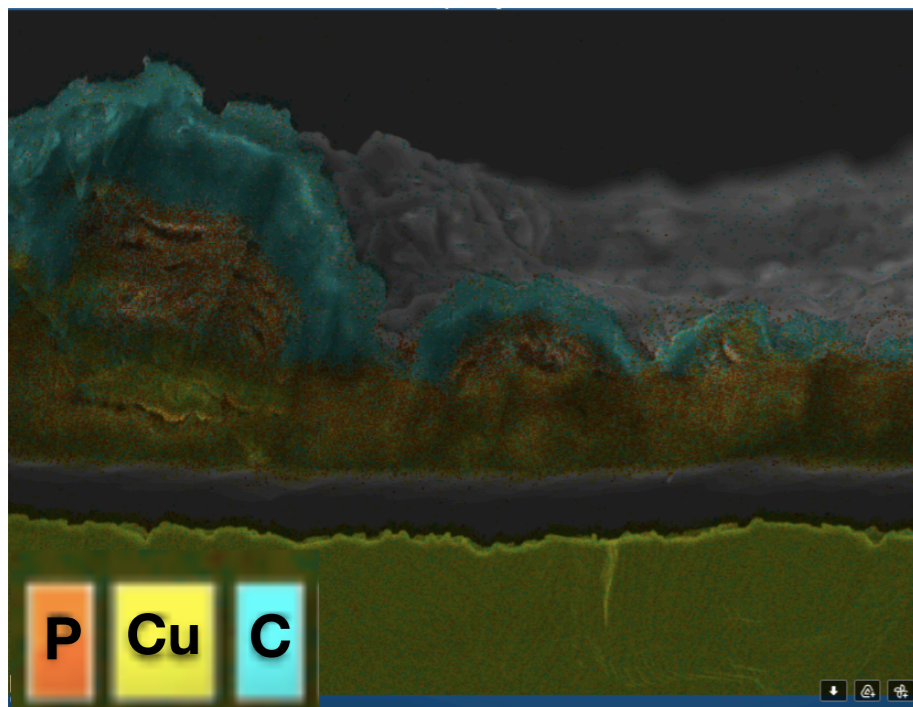
→ Delamination, pores, large thickness variations



Proton energy loss simulated and parametrized

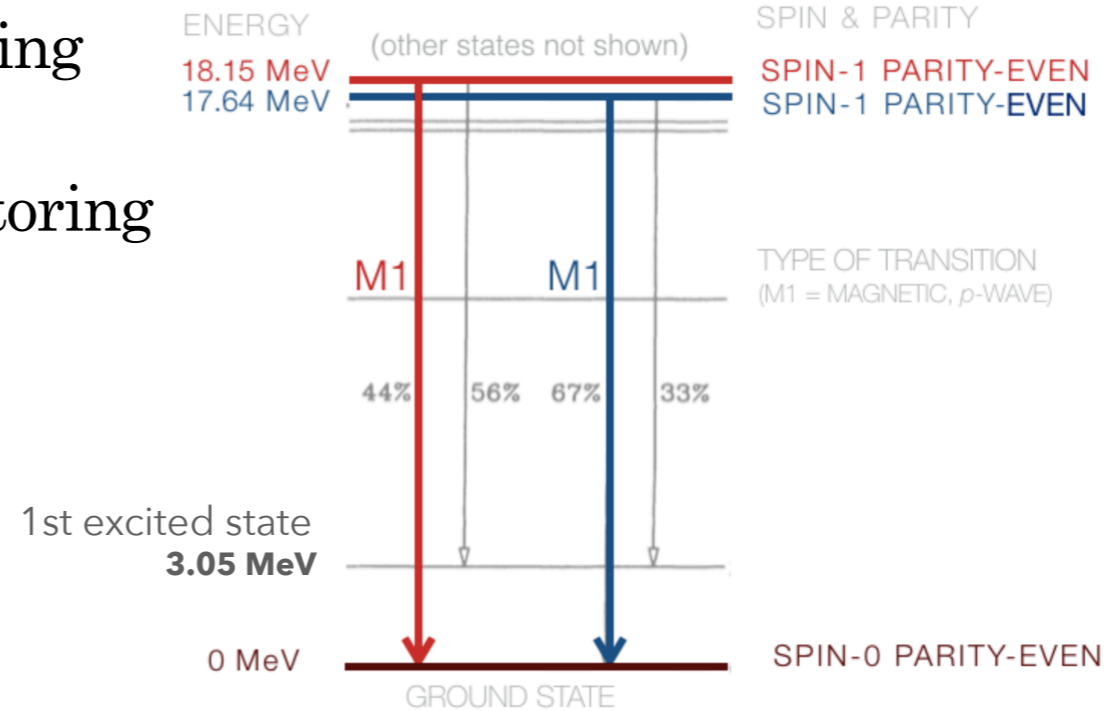
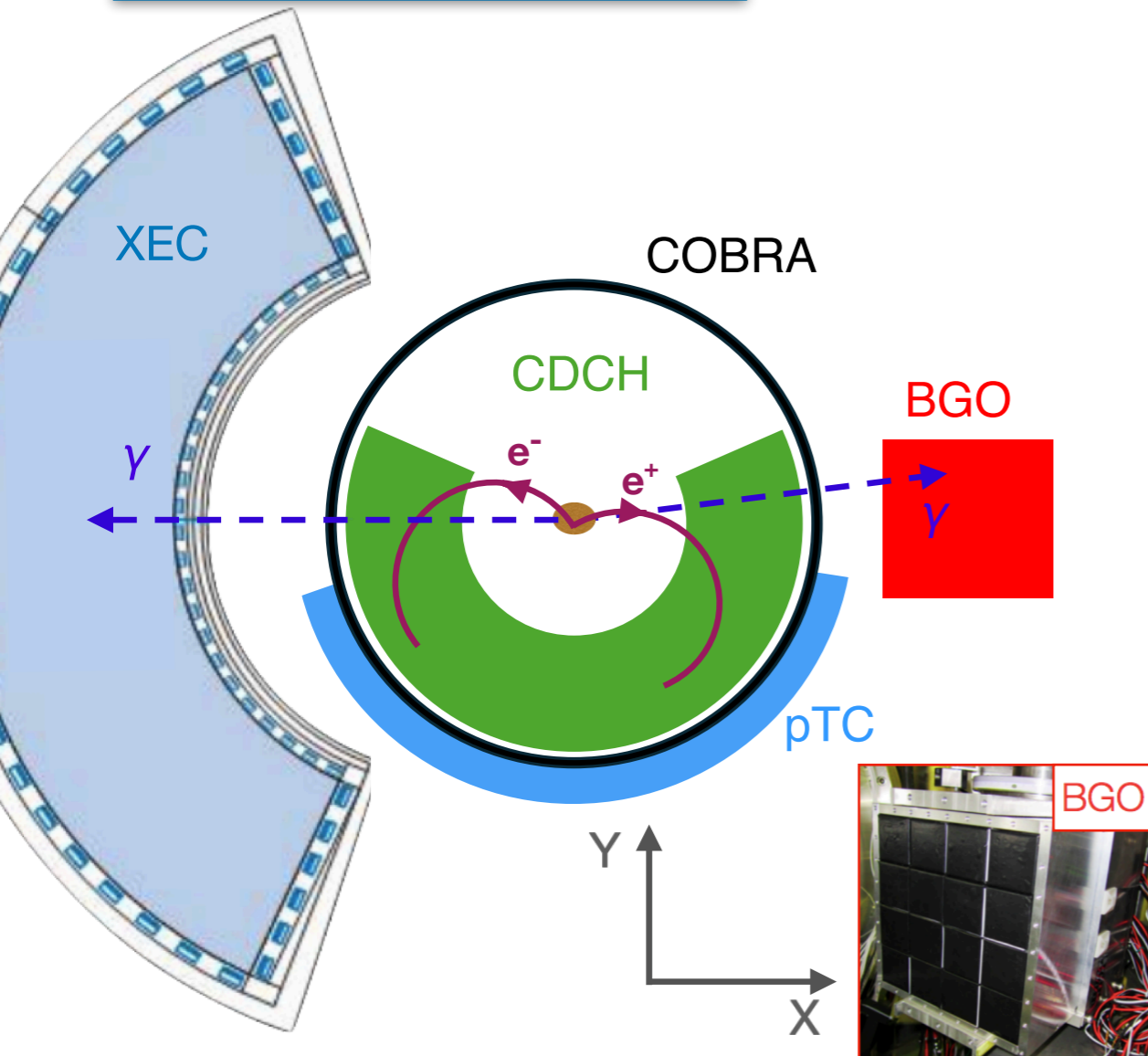


→ LiCO_3 on the surface

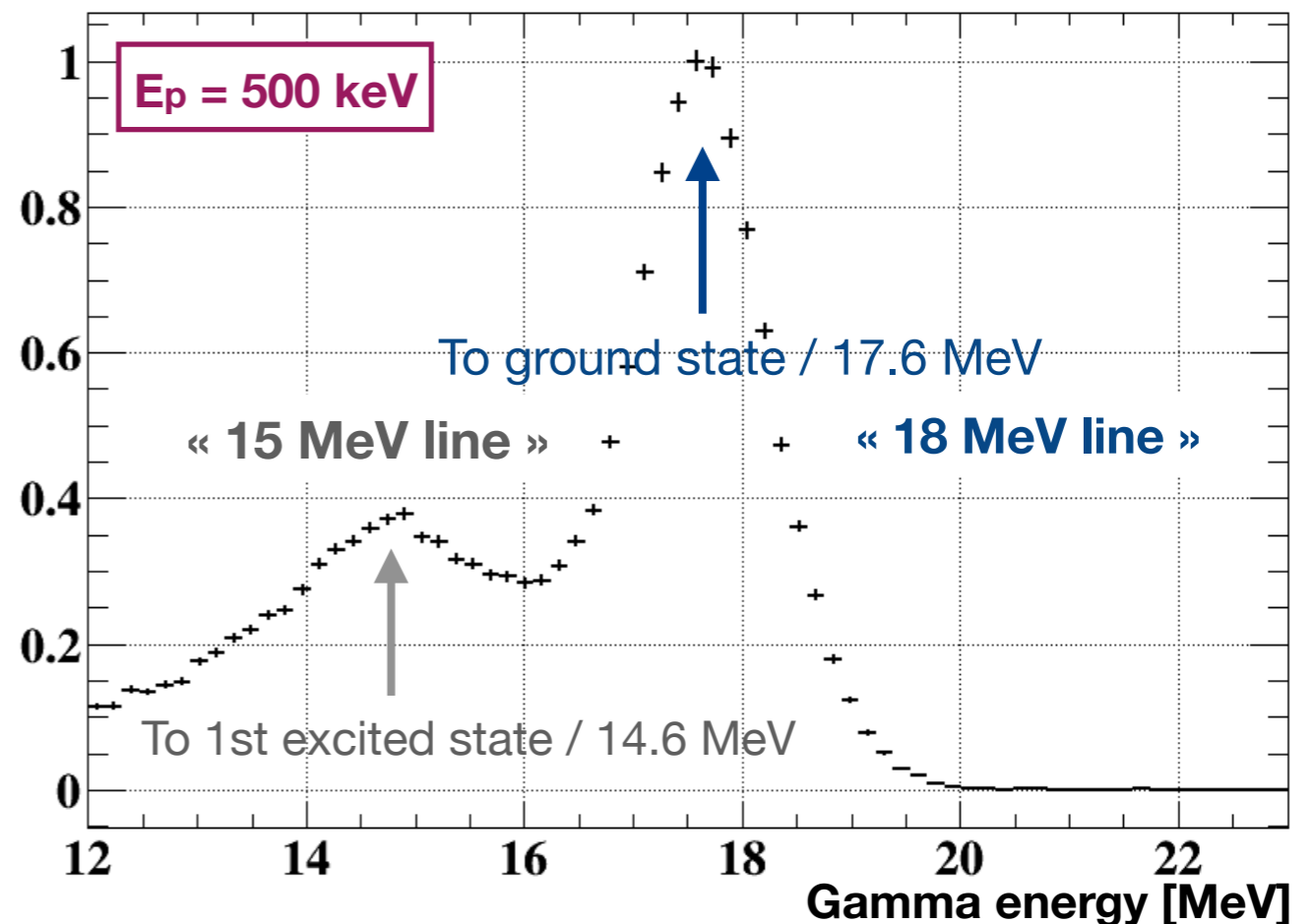


- Main gamma detector for bkg understanding
LXe calorimeter
- Two additional gamma detectors for monitoring
BGO crystal matrix (4x4) **LaBr3 crystal**

Liquid Xenon Calorimeter (XEC)

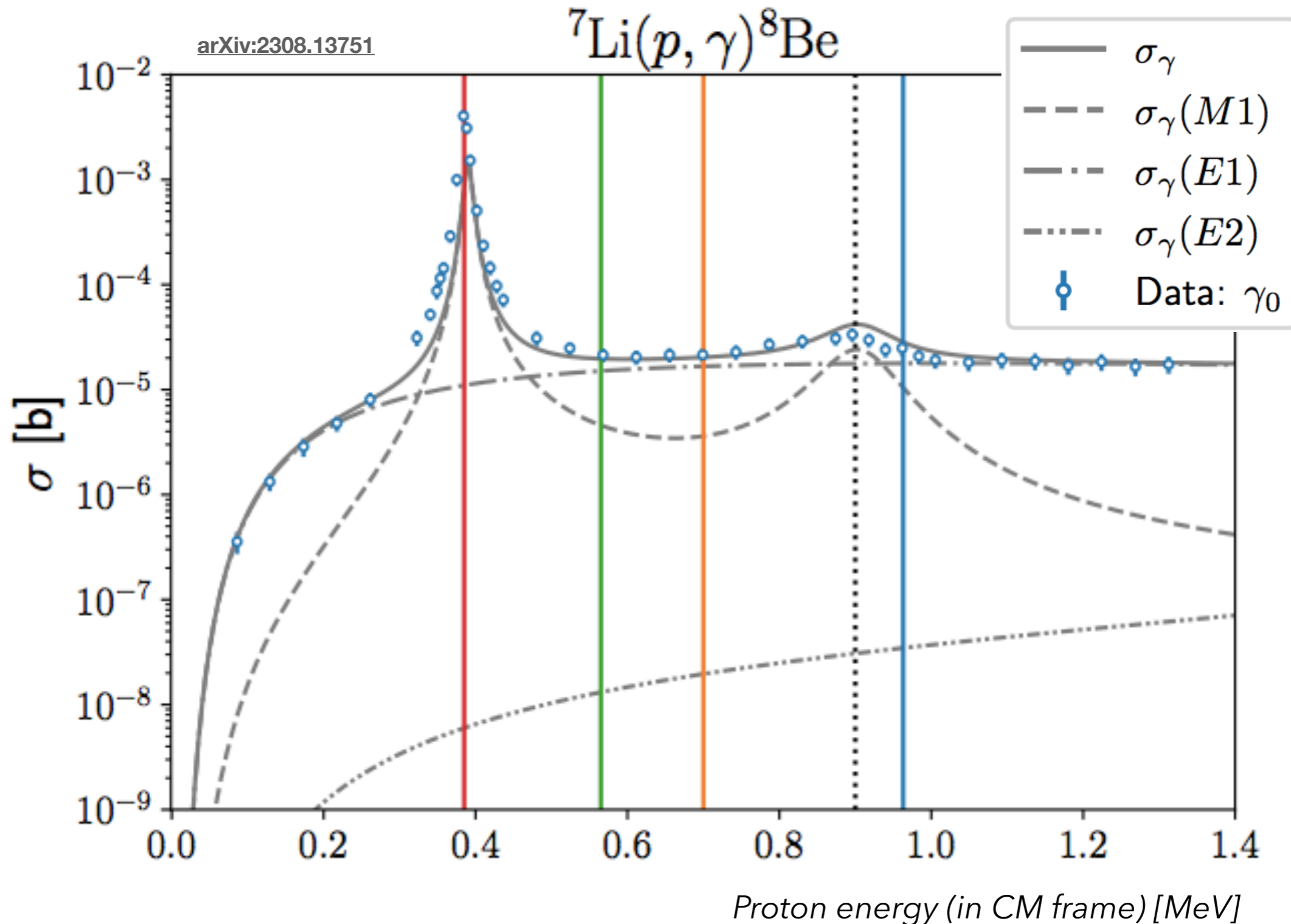


LiPON spectrum from XEC



3) Physics backgrounds and signal simulations

- Cross-section multipole contributions is largely dependent on proton energy



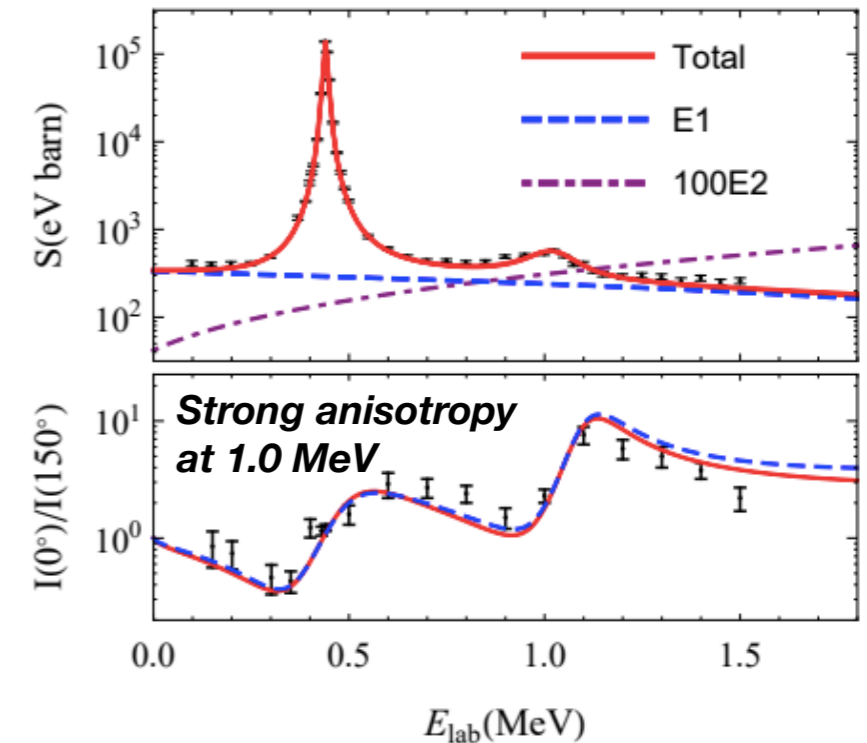
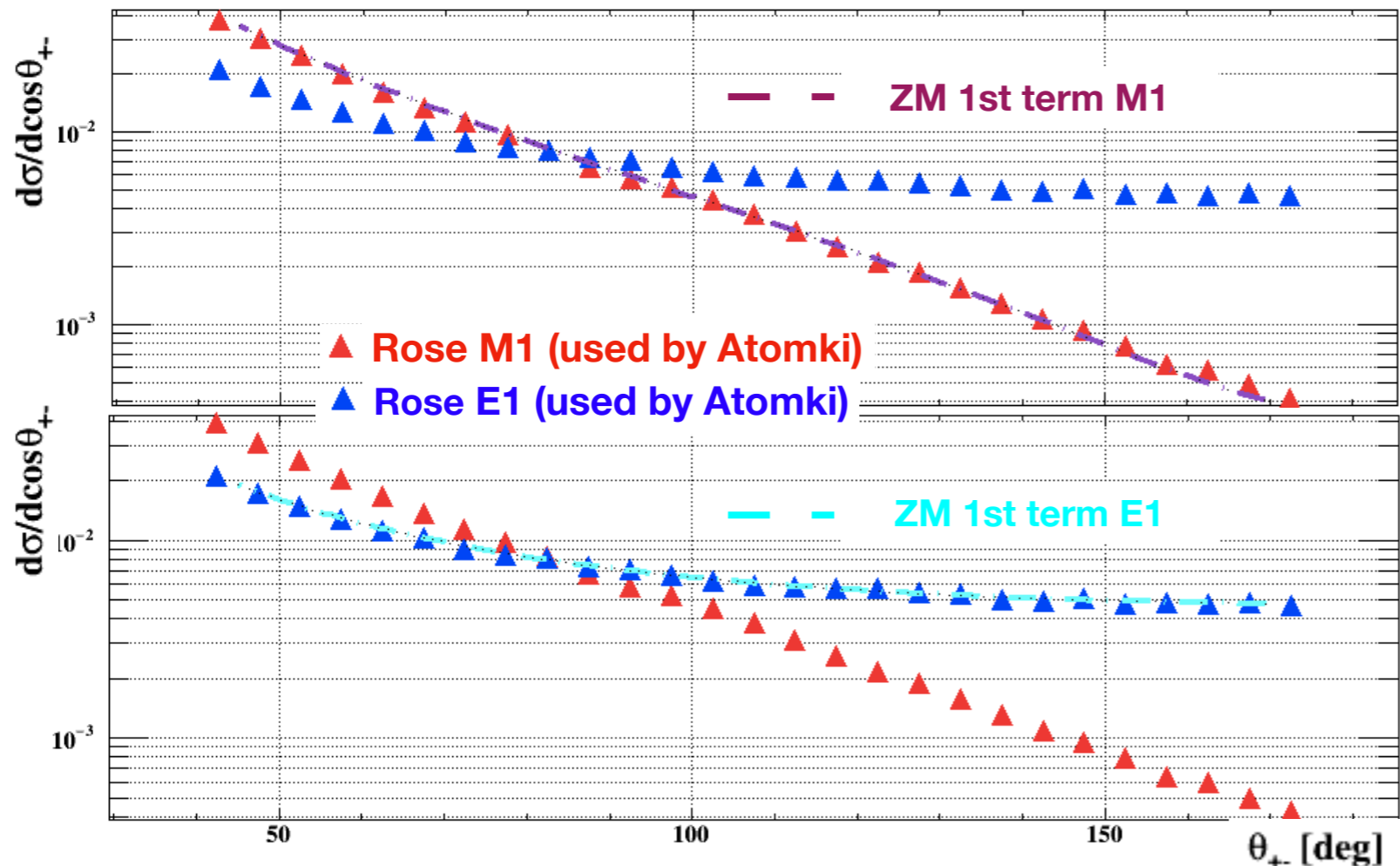
- Need for an accurate background model, IPC is dominant background in signal region
- First IPC model developed by Rose in 1949 [Phys. Rev. 76, 678](#)

→ Anisotropy and multipole interferences not included

→ Zhang and Miller in 2017 did it, ZM model

[Phys. Lett. B 773, 159](#)

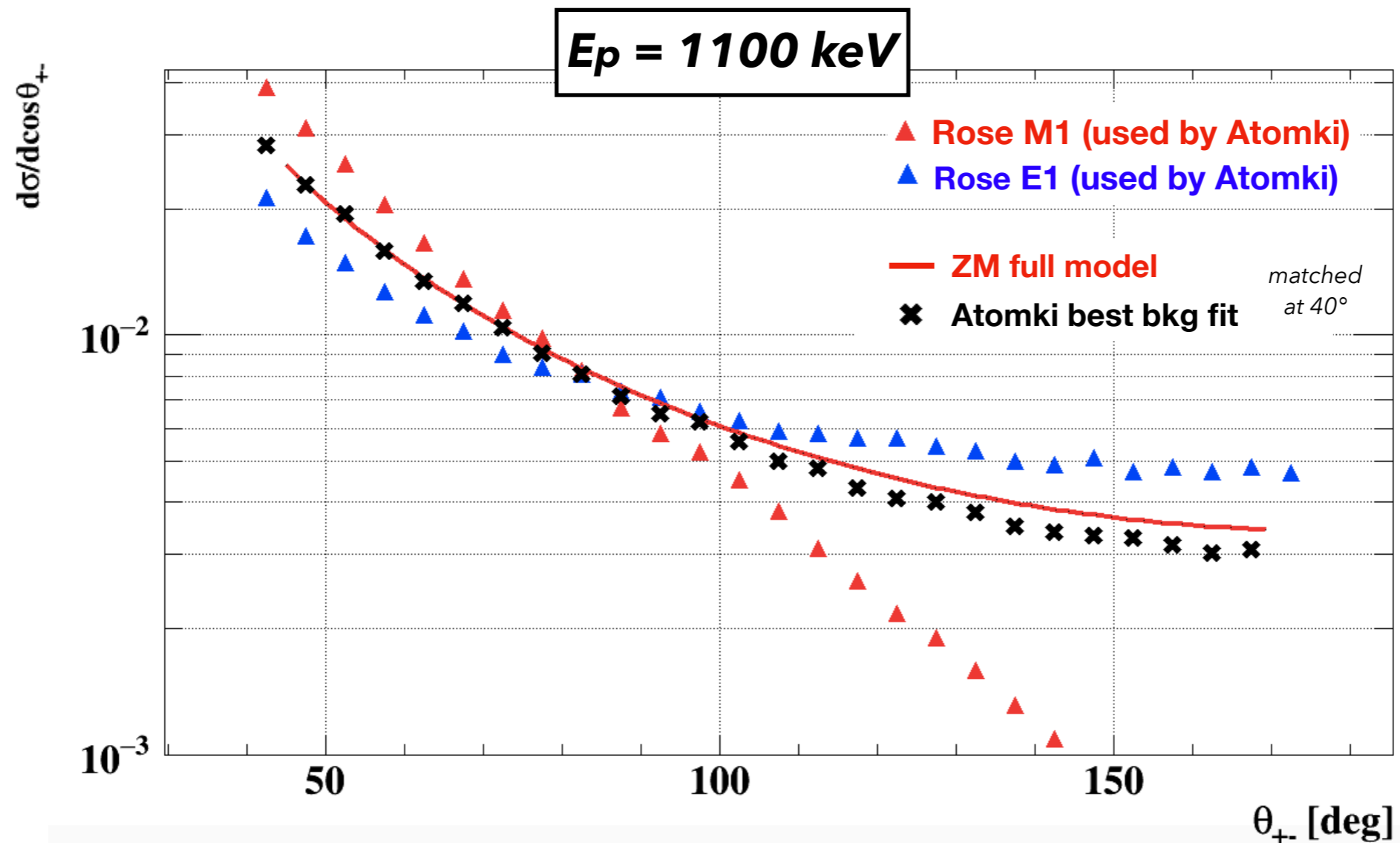
$$\begin{aligned}
 & d\sigma/d\cos\theta_{+-}dE_+d\cos\theta d\phi \\
 & \propto \underbrace{T_{0,0}}_{\text{Rose-equivalent}} + T_{0,2} \cos 2\phi + T_{1,0} P_1 + T_{2,0} P_2 + T_{2,2} P_2 \cos 2\phi \\
 & + T_{3,1} \sin\theta \cos\phi + T_{4,1} \sin 2\theta \cos\phi, \quad (4.1)
 \end{aligned}$$



→ We implemented Zhang-Miller model

→ Rose/simplified ZM models agree for both E1 and M1 multipoles

- Let's compare Atomki's background with ZM full model

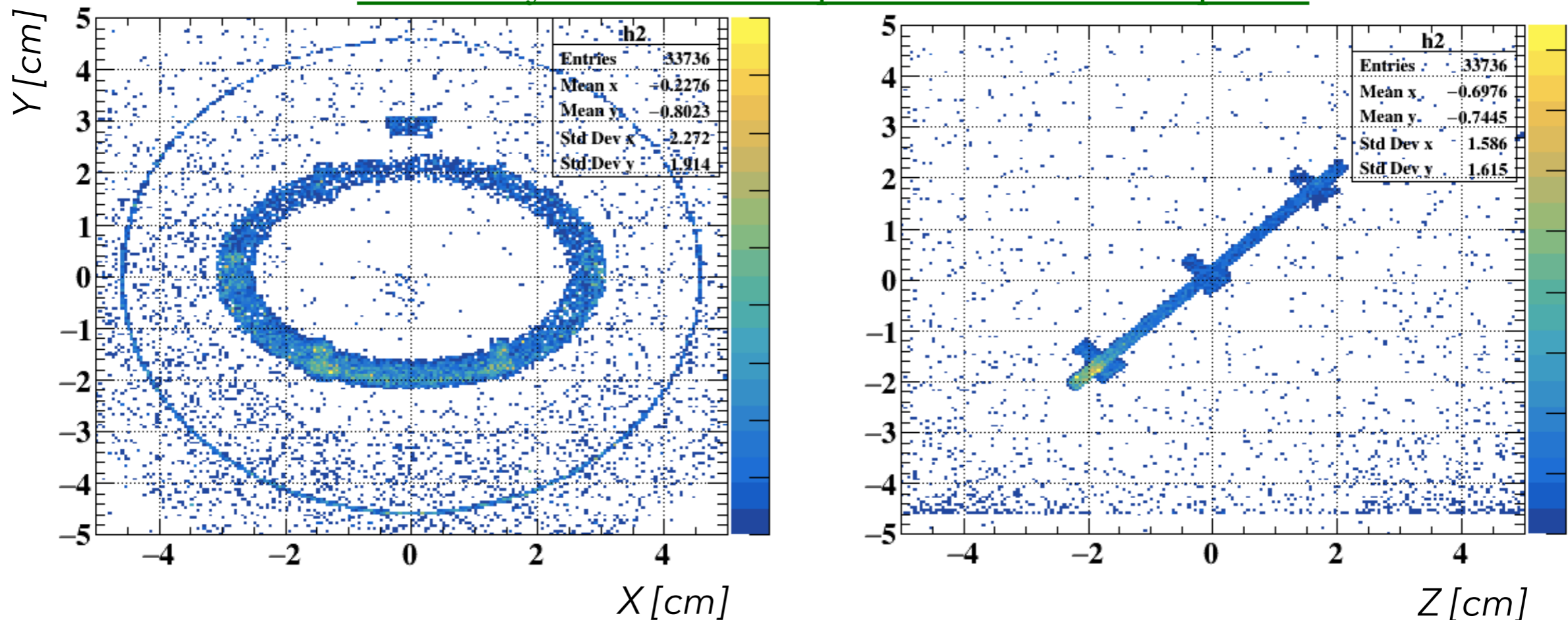


- When interferences and anisotropy terms are included
 - IPC background shape is changed
 - Cannot explain anomaly but can impact significance

- Other backgrounds can impact the search
 - Need to be carefully studied and estimate probabilities
 - Complete setup with target, surrounding region, all detectors and all material was simulated
 - Large photon (18 and 15 MeV lines) simulation at beamspot position

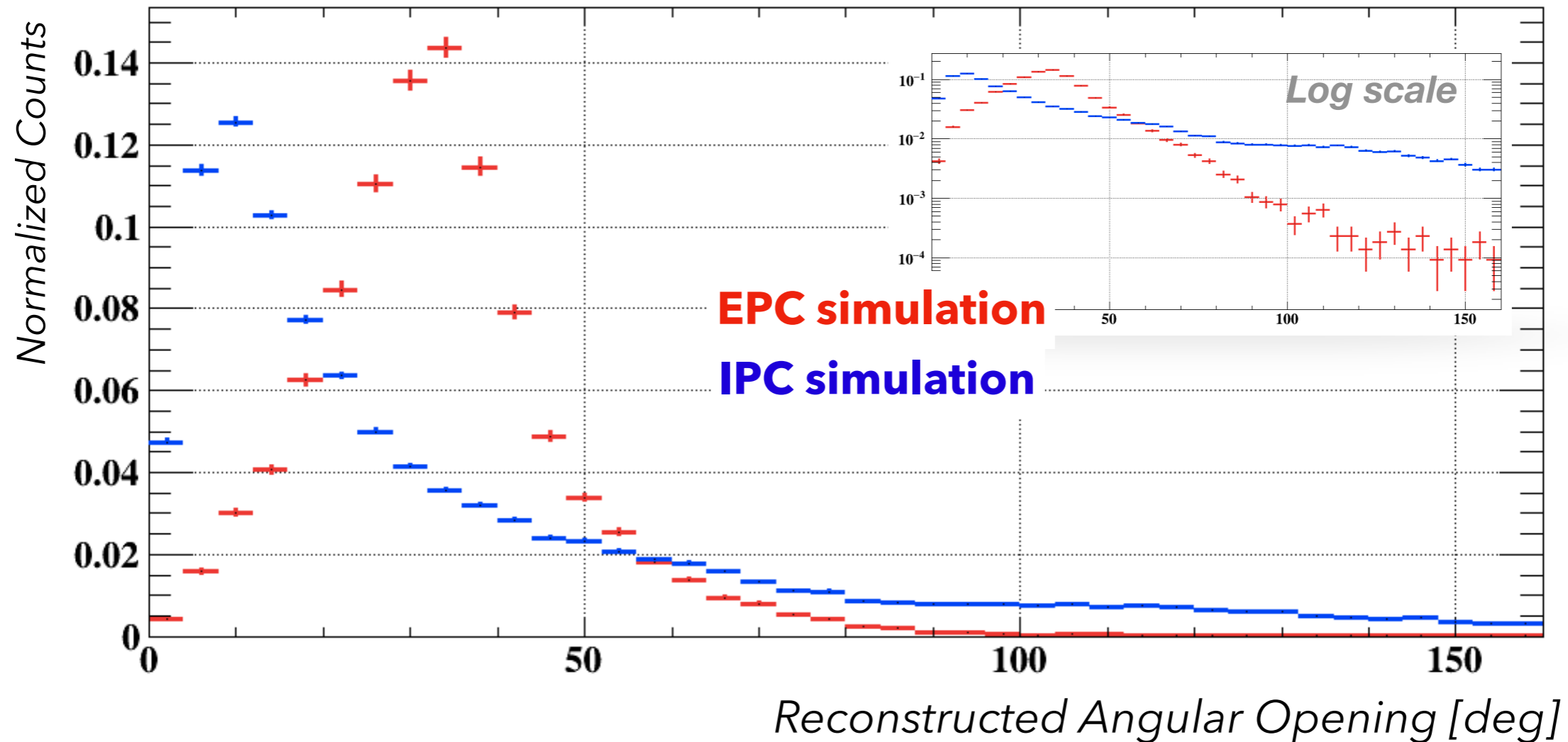
EPC = External Pair Conversion
 → γ -conversion to e^+/e^- pair in matter

Secondary electron and positron conversion points



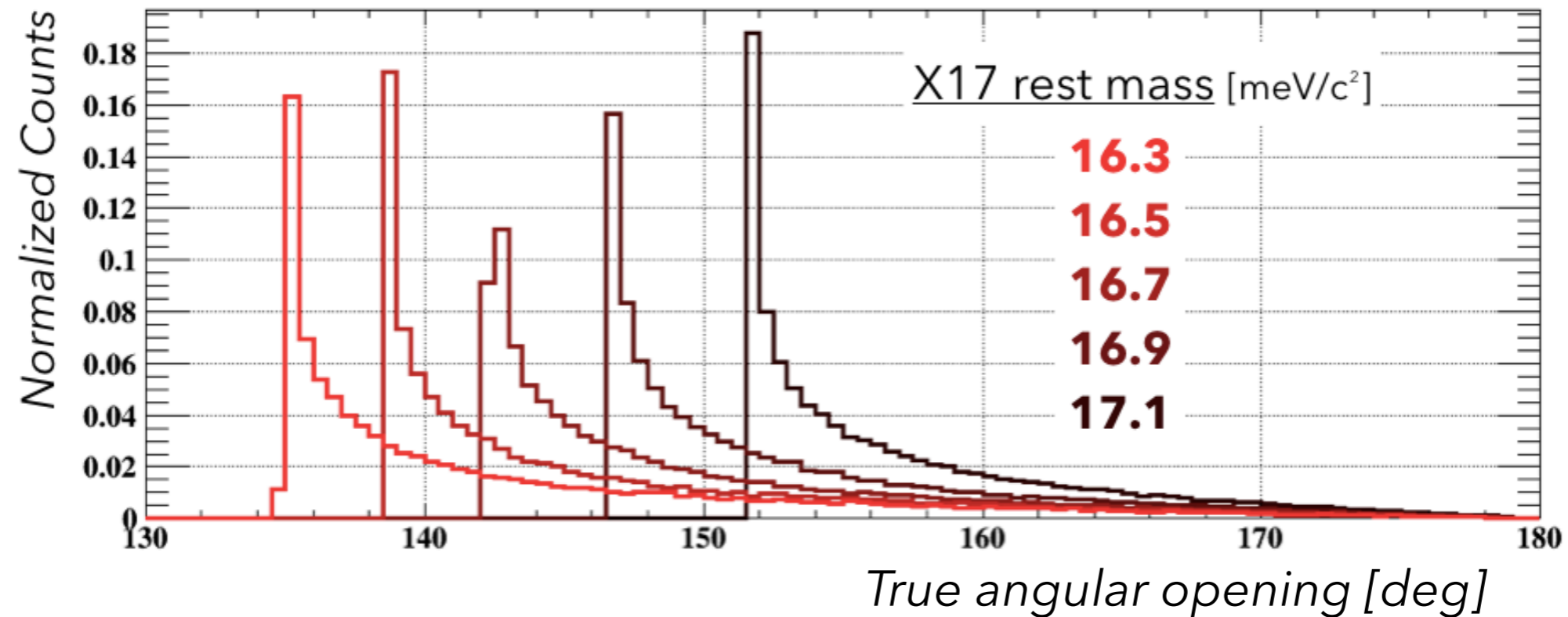
- Dominating background is EPC and Compton in heat-dissipating Cu ring
- With magnetic field and cylindrical design, reduced low-energy background

- EPC rate was estimated to be comparable to IPC
 - ➔ But angular opening is largely concentrated below 70° , far from the signal region

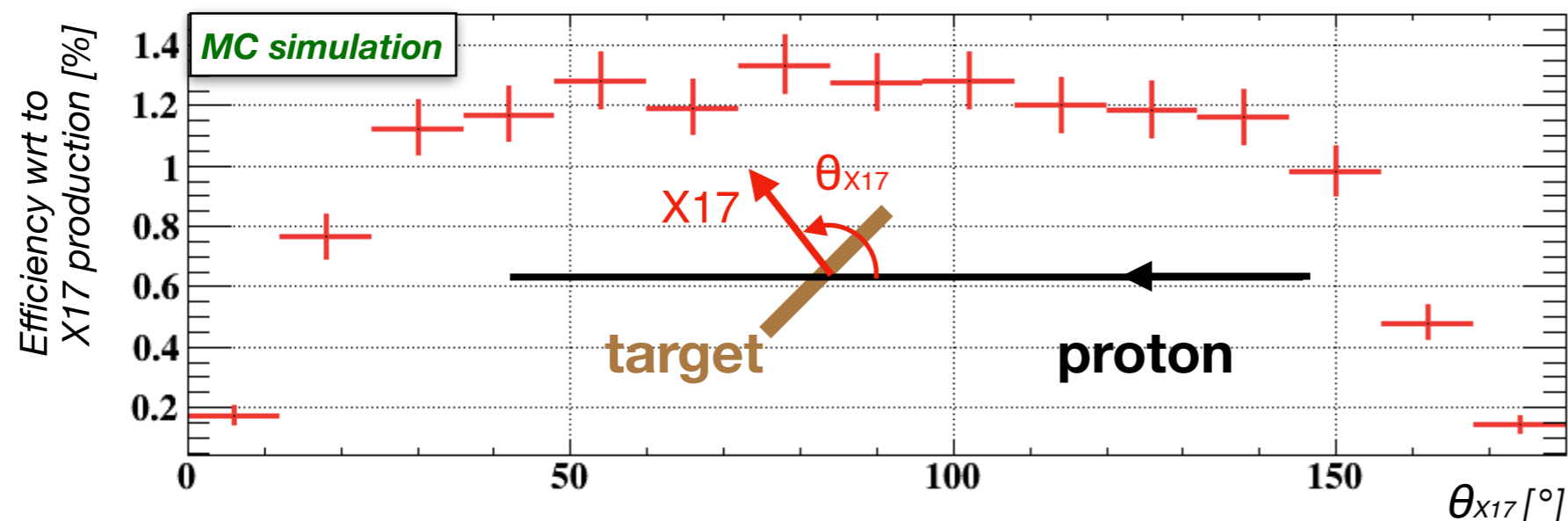


- ➔ Almost 2 orders of magnitude below IPC in signal region
- ➔ All photon conversion events included in full simulation

- We want to carry X17 search in both 0.44 and 1.02 MeV resonances
- X17 is assumed isotropically produced



- Atomki has carried out the search only in plane orthogonal to beam



- X17 reconstructed not only in orthogonal plane
- 1% efficiency in planes between 40° and 140°

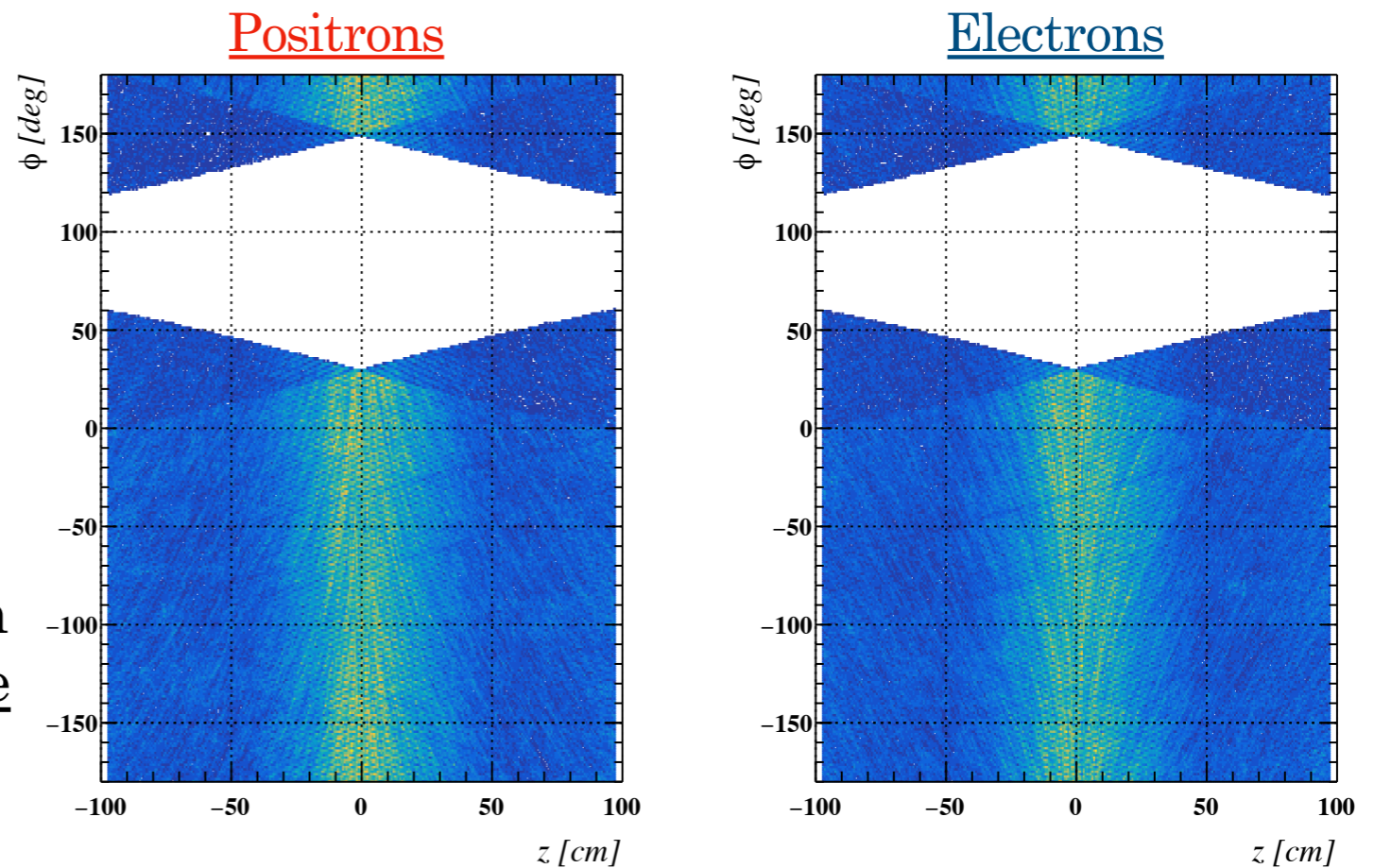
4) Pair reconstruction

- MEG-II only reconstructs e+. Procedure was adapted for e- as well.

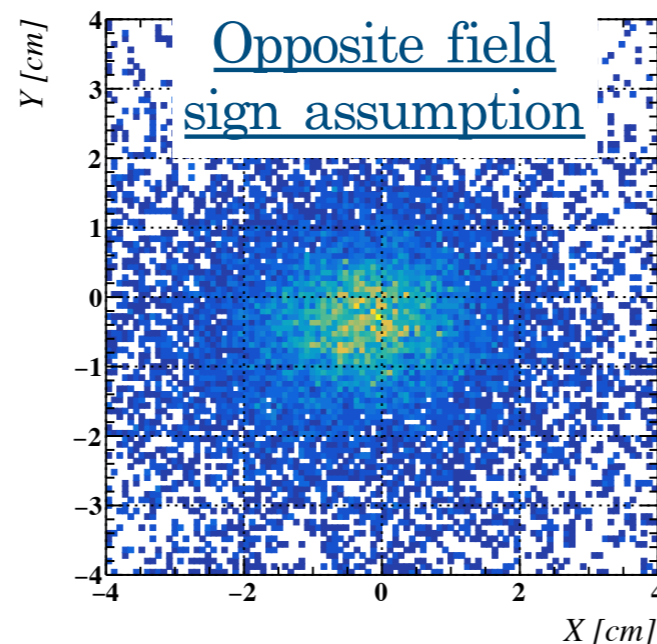
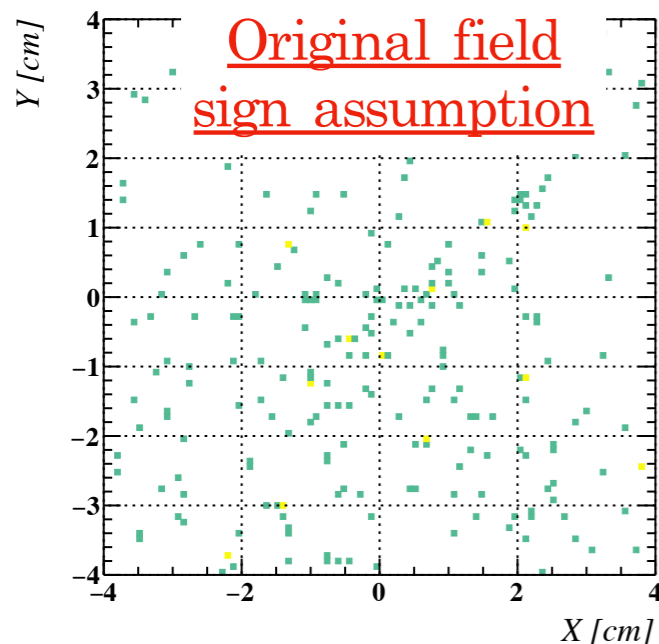
→ Simulated e+/e- tracks in CDCH

→ Both tracks can be distinguished through dp_T/dp_z sign in COBRA gradient field

→ Electron tracks reconstructed with MEG-II's track finder inverting the COBRA field sign assumption



Reconstructed vertices from electron-only simulation



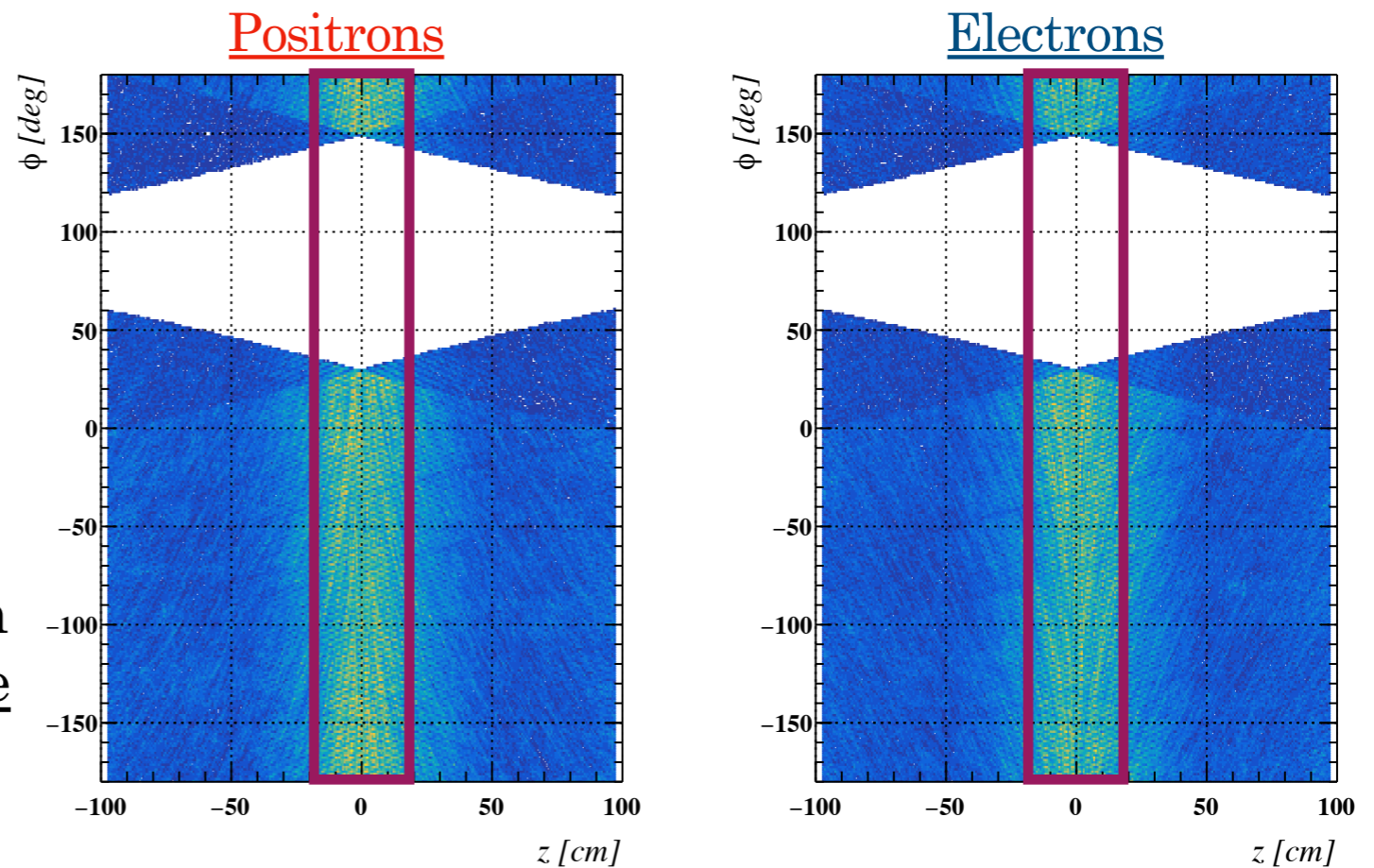
- 99% of tracks have correct sign
- 1% of tracks is misreconstructed

- MEG-II only reconstructs e+. Procedure was adapted for e- as well.

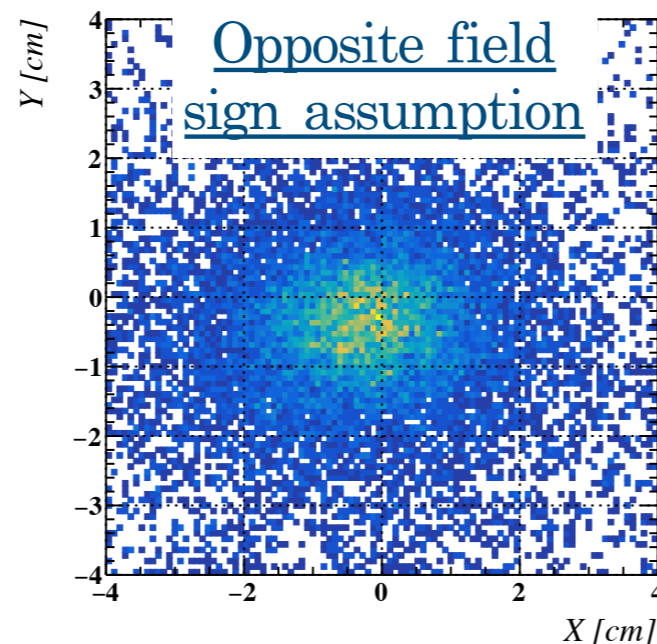
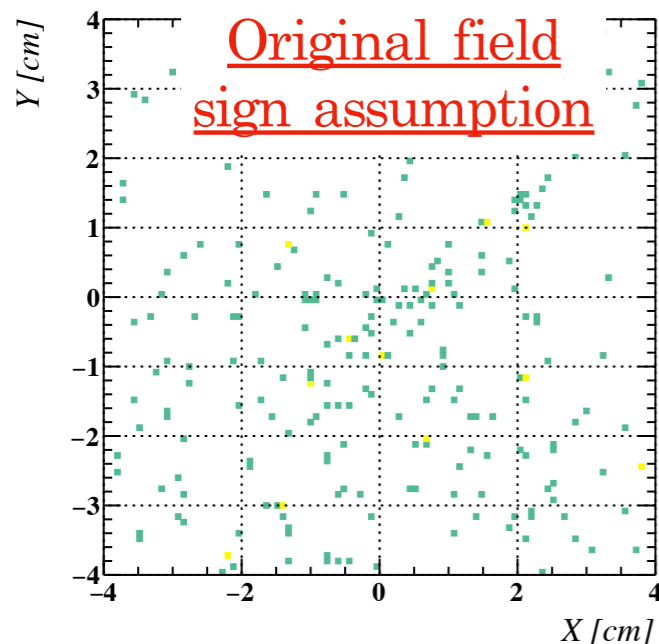
→ Simulated e+/e- tracks in CDCH

→ Both tracks can be distinguished through dp_T/dp_z sign in COBRA gradient field

→ Electron tracks reconstructed with MEG-II's track finder inverting the COBRA field sign assumption



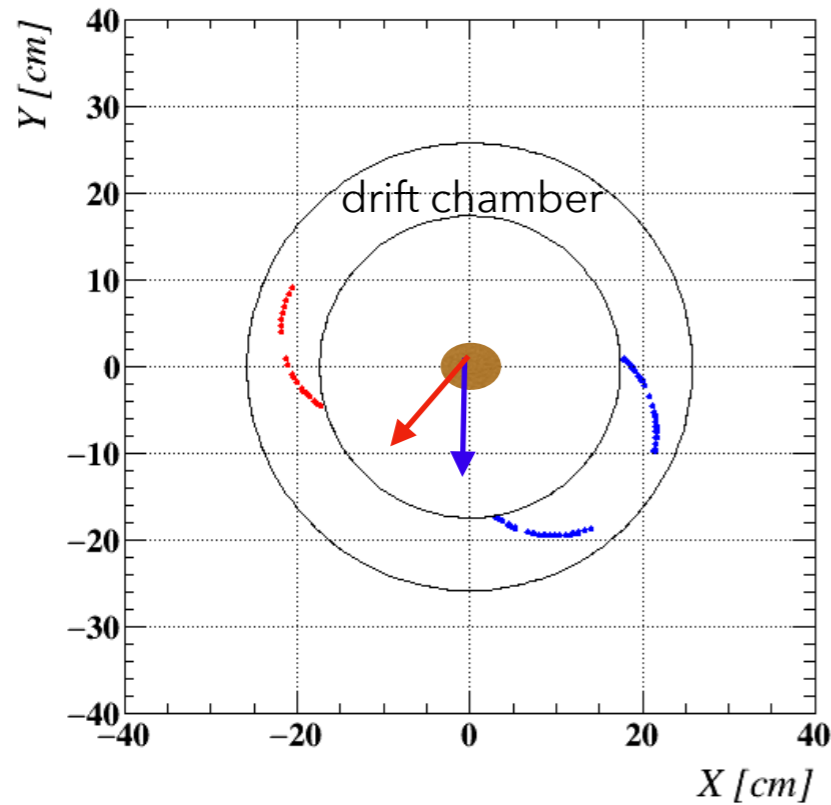
Reconstructed vertices from electron-only simulation



- 99% of tracks have correct sign
- 1% of tracks is misreconstructed

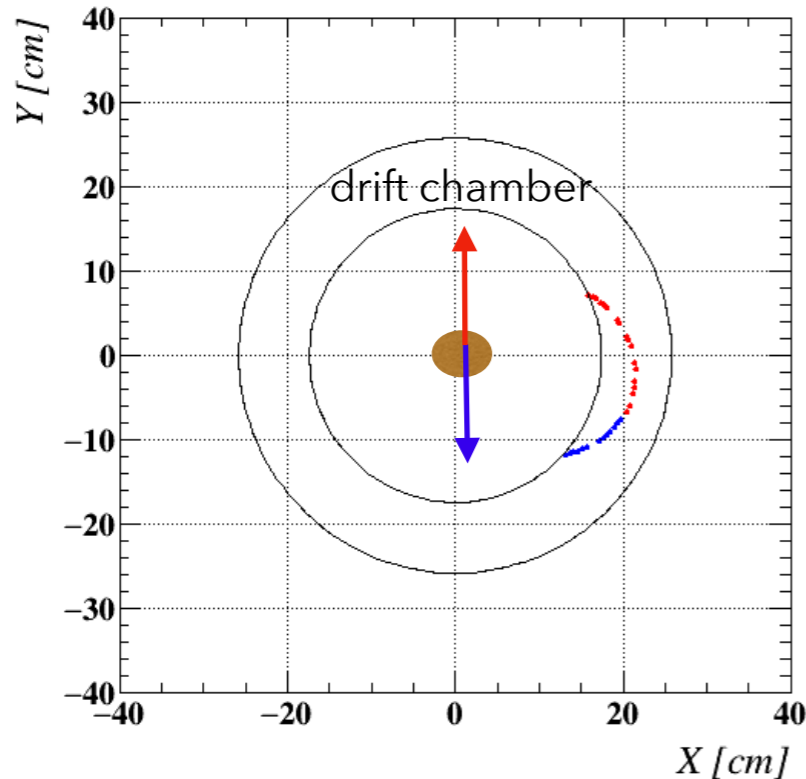
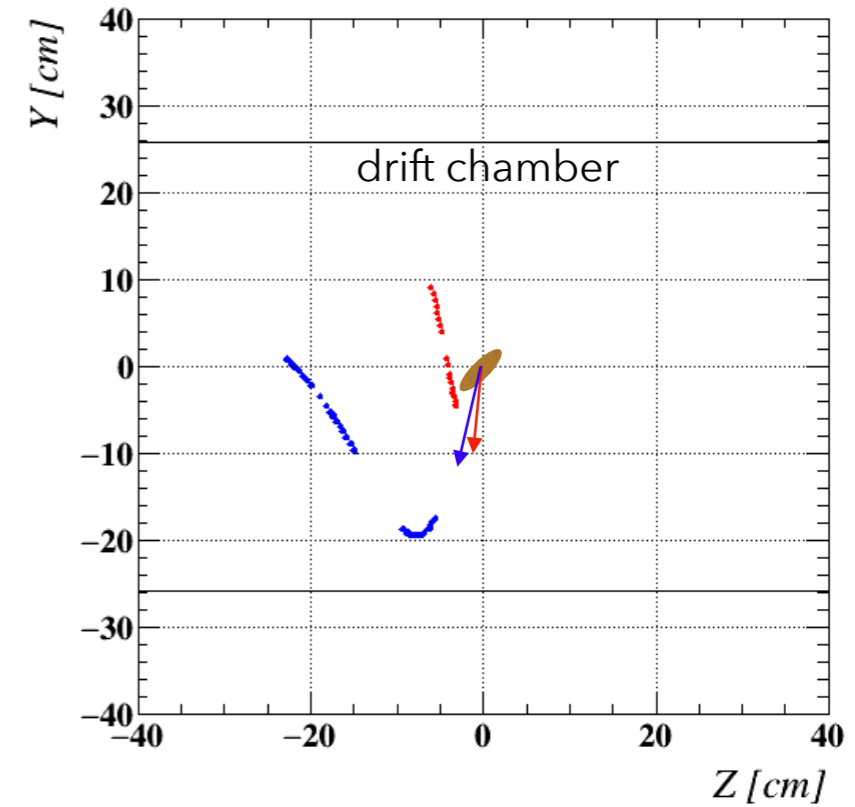
Tracks emitted orthogonal to the beam are sign-ambiguous

- Let's have a look at the fitted hits within the CDCH



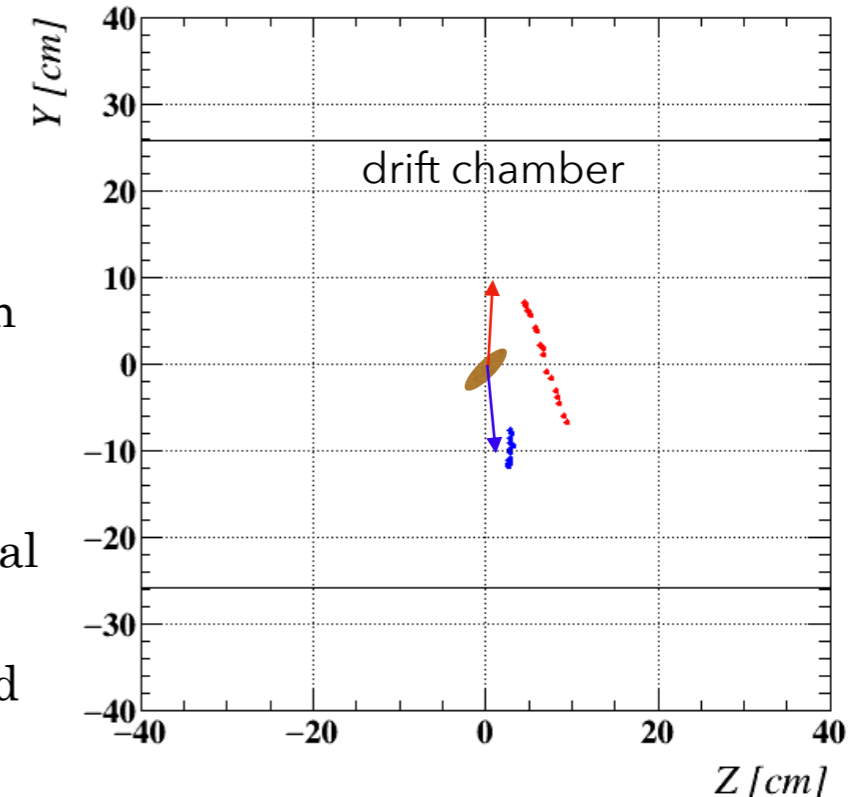
GOOD PAIR

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



FAKE PAIR

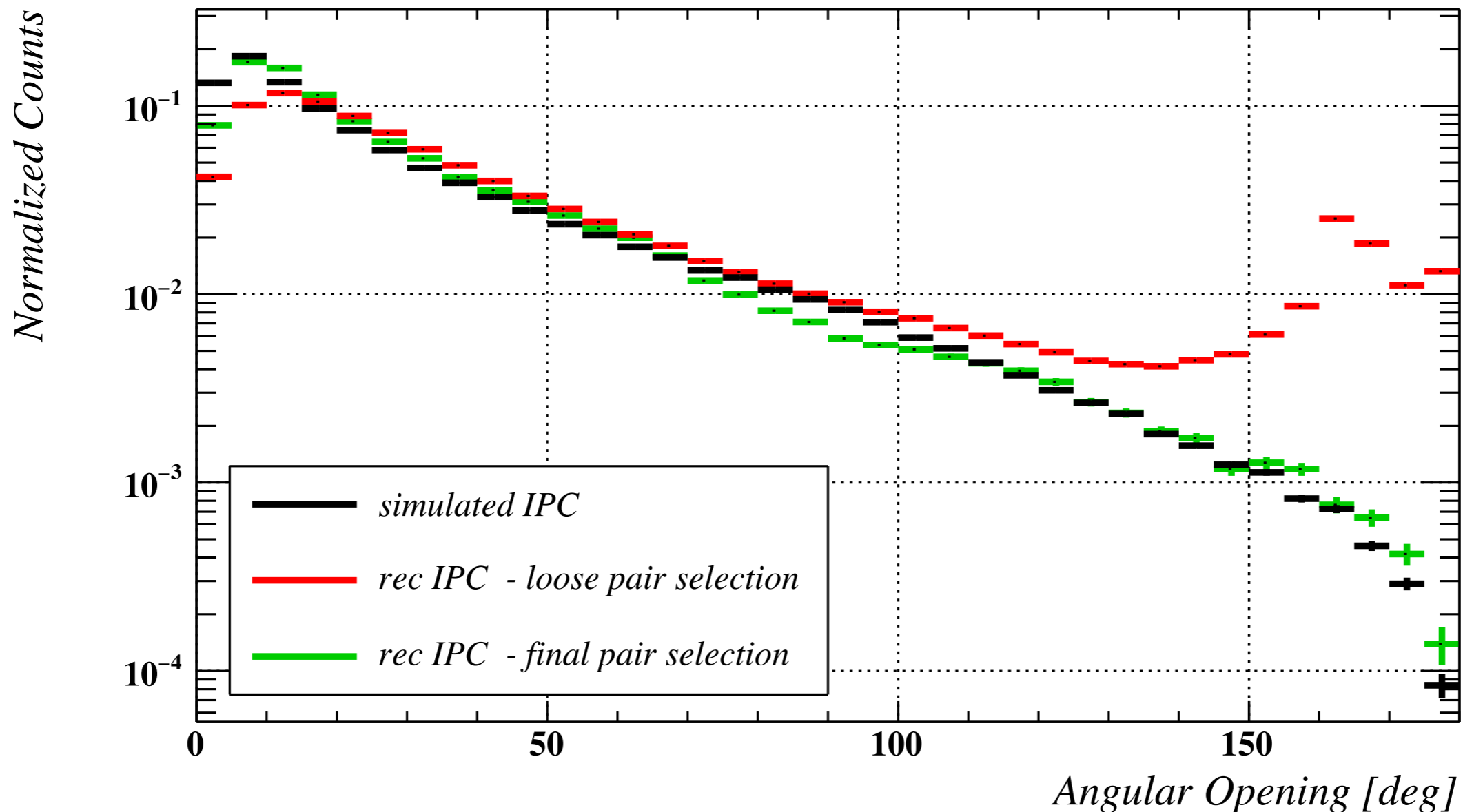
- Two pieces of the same track reconstructed with opposite sign
- Back-to-back reconstructed
- Dangerous, close to signal region
- Need to characterize and reject these



- Fake tracks
- short
 - consecutive hits distance large
 - if longer, little dense
 - orthogonal to the beam and close to $z=0$

Advanced track selection was developed

- With full selection, IPC simulated monotonous shape is recovered
- Remaining fakes in signal region estimated to be negligible



5) Trigger and DAQ strategies

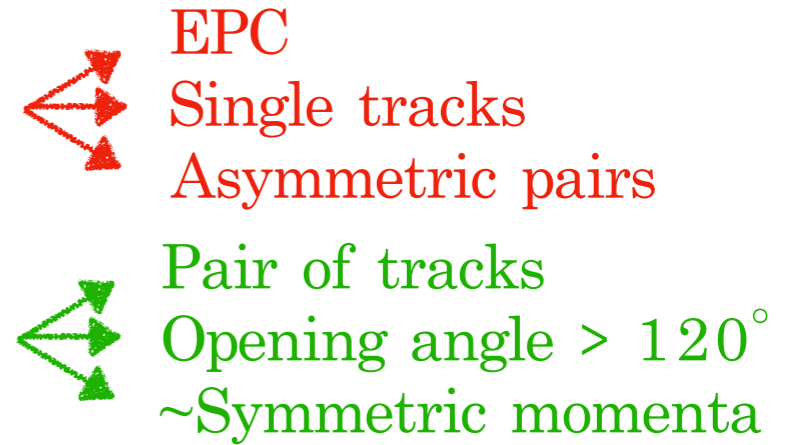
- S/B (X17 to IPC ratio) in signal region is fixed by physics

- To maximize significance

→ Reduce non-signal-like contamination in trigger

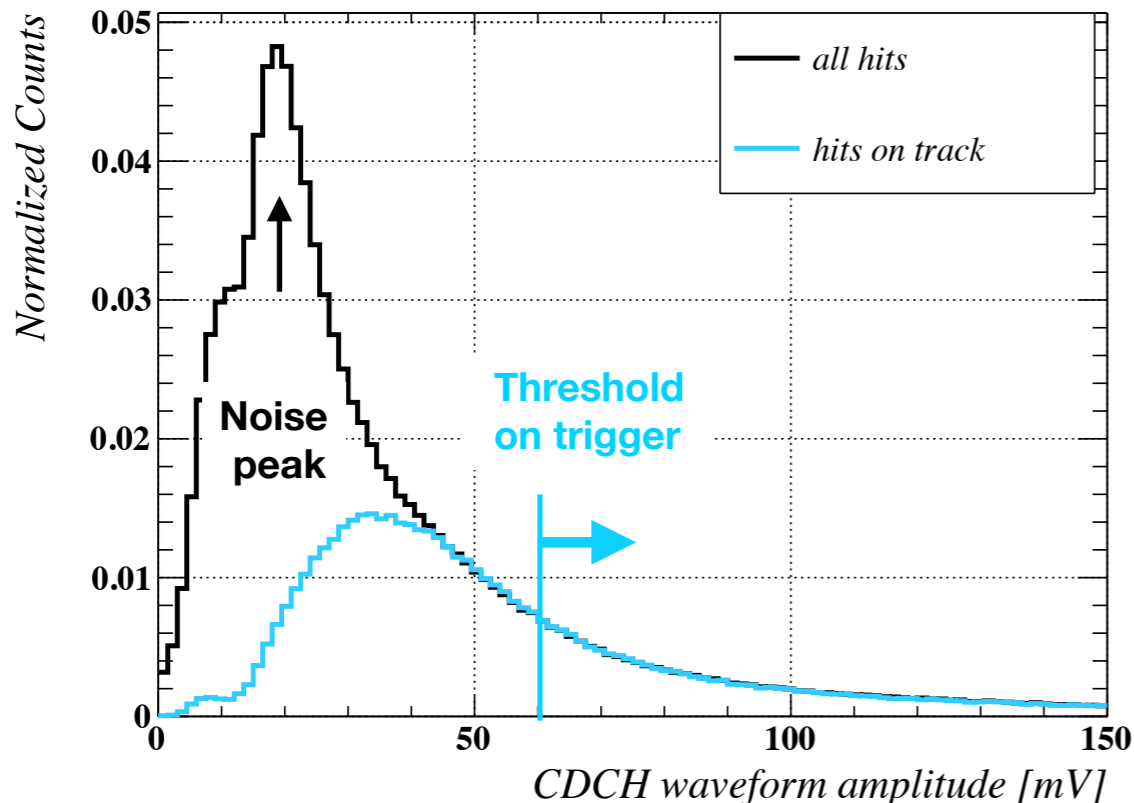
→ Select signal-like pairs

→ Increase proton current up to trigger capabilities



HOW TO TRIGGER ON SIGNAL-LIKE?

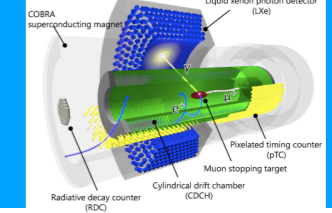
- In practice, difficult because of no online access to CDCH hit coordinates
- No CDCH trigger for MEG: one to be developed for X17 search



- Alternative: let's use online CDCH waveform amplitude

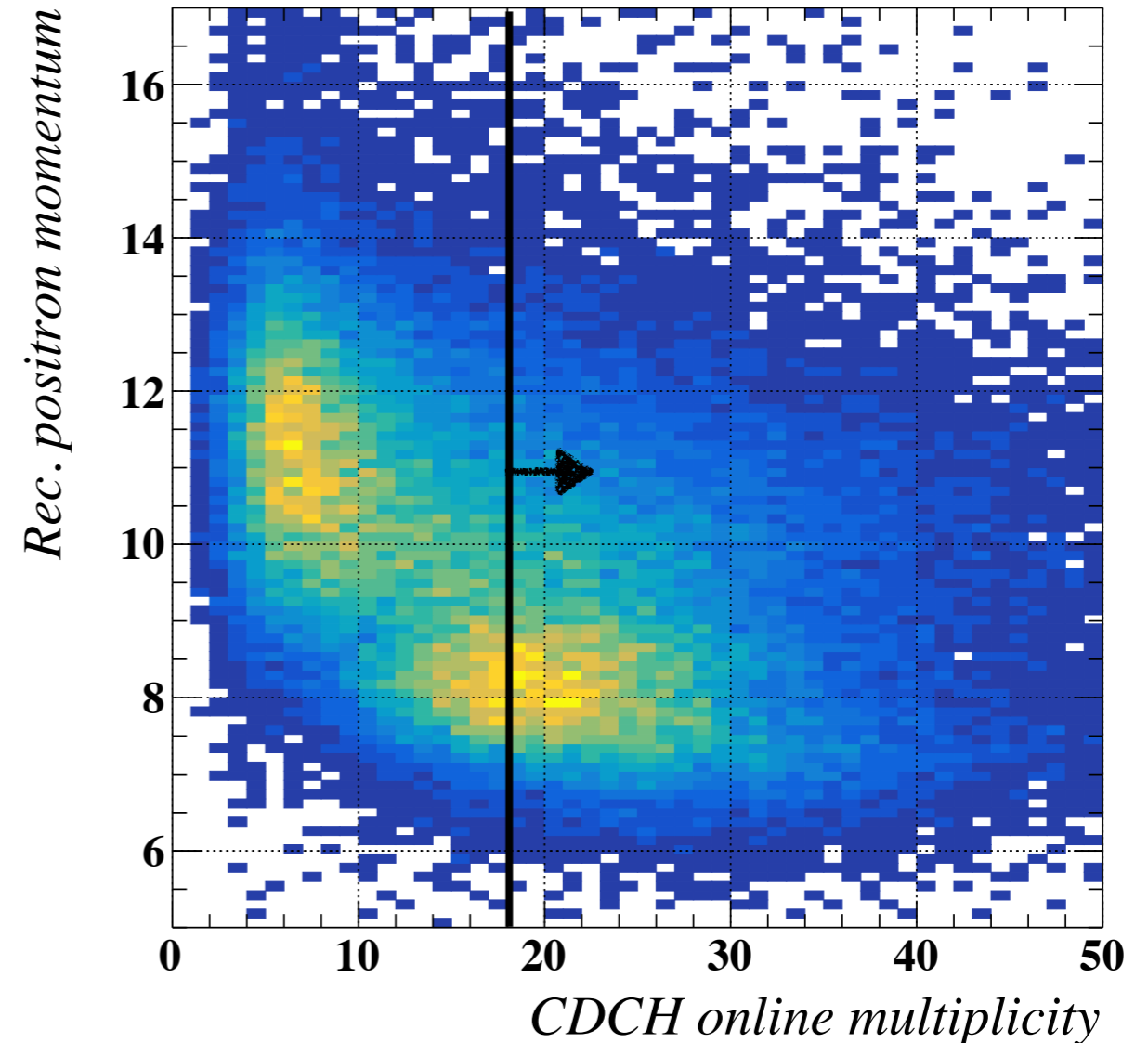
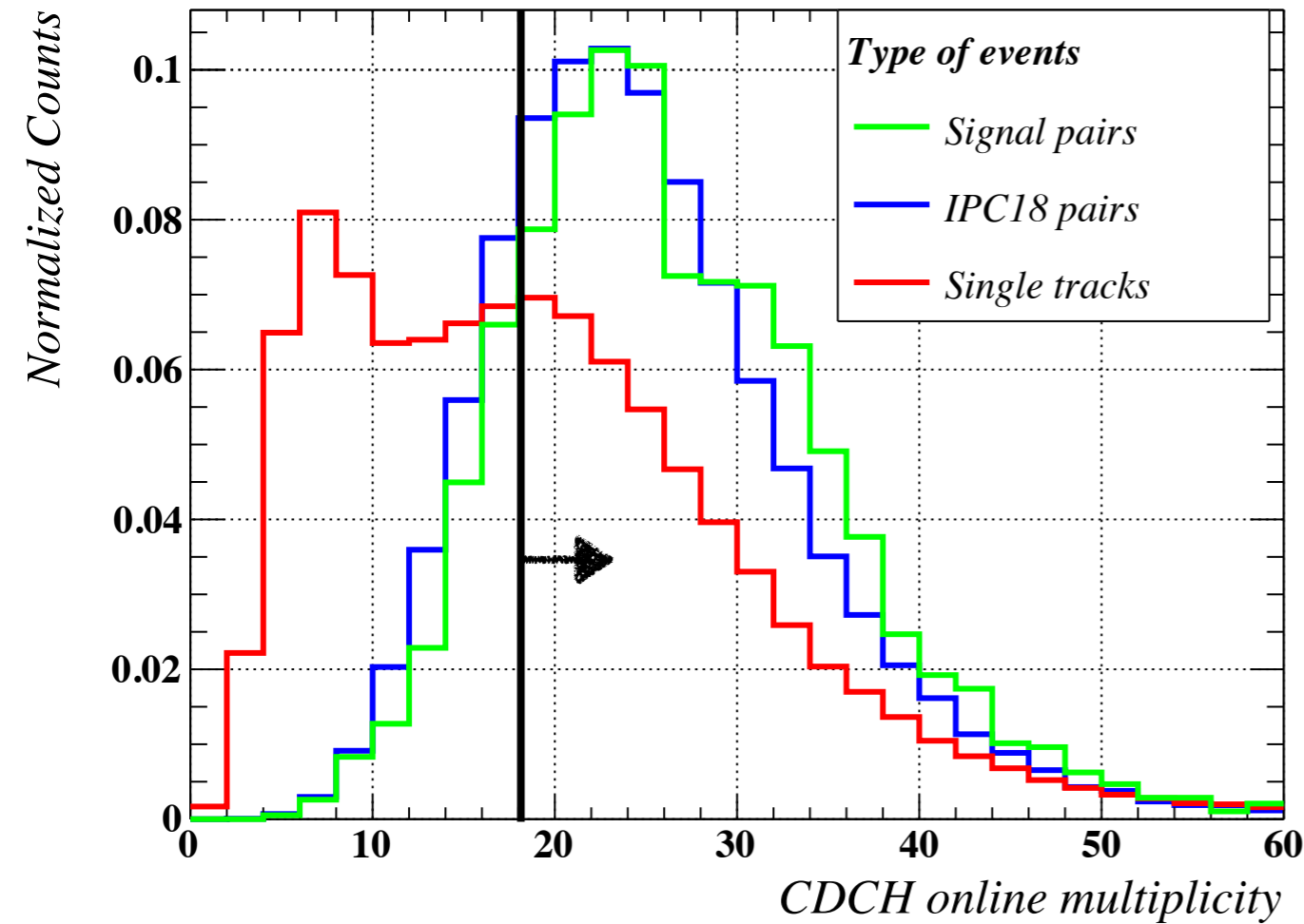
- High online threshold to trigger on **good hits** mostly
- How to exploit them?

Trigger strategy: CDCH hit multiplicity



- CDCH hit multiplicity is higher for:
 - pair of tracks
 - symmetric pairs
 - tracks produced at target center
- CDCH online multiplicity to reconstruct
 single tracks / IPC pairs / signal pairs

Reco momentum vs CDCH online multiplicity



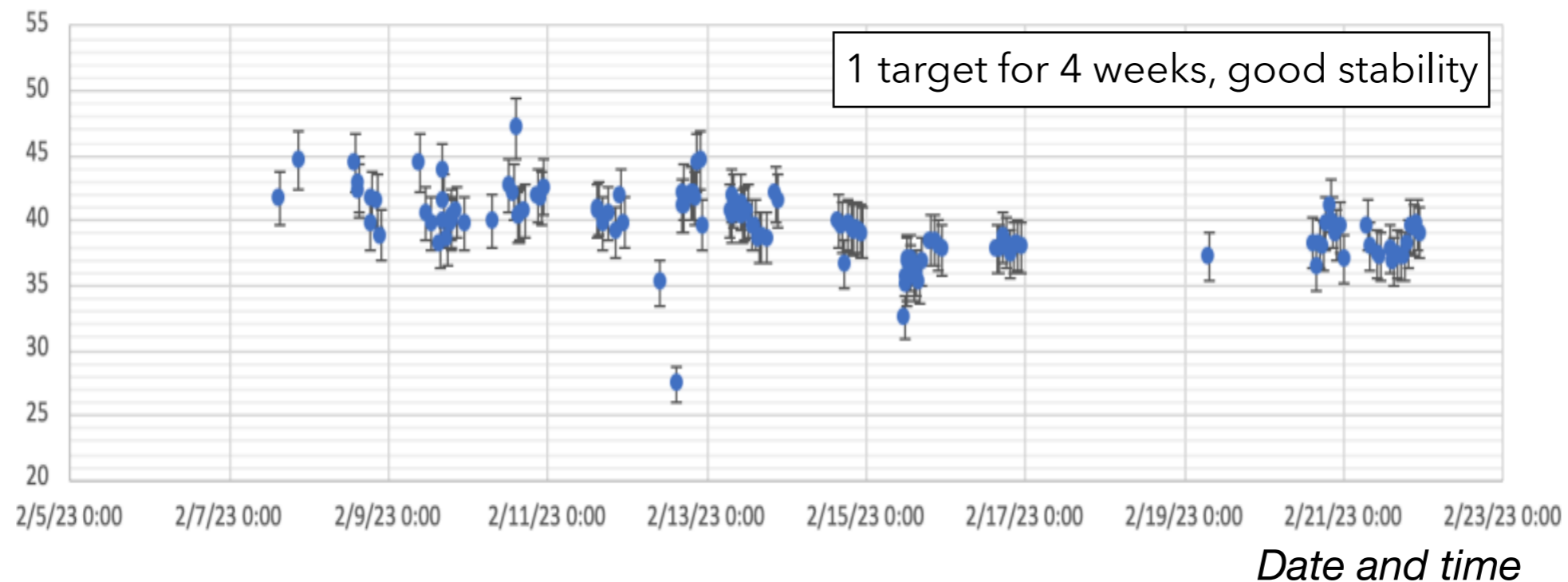
Trigger set as 18 hits > 60 mV

- Background rate divided by 5 (wrt. 10 hits)
- 10% signal lost
- Proton current can be largely increased

6) Physics dataset and X17 results

- In February 2023, first run at $E_{\text{beam}} = 1080 \text{ keV}$ @ $I_{\text{beam}} = 10 \mu\text{A}$
- X17 runs: sample of **25k** runs of **3k** events each
 - **75M** triggered events
 - **300k** pairs to be reconstructed

Gamma rate in BGO per current unit [Hz/ μA]



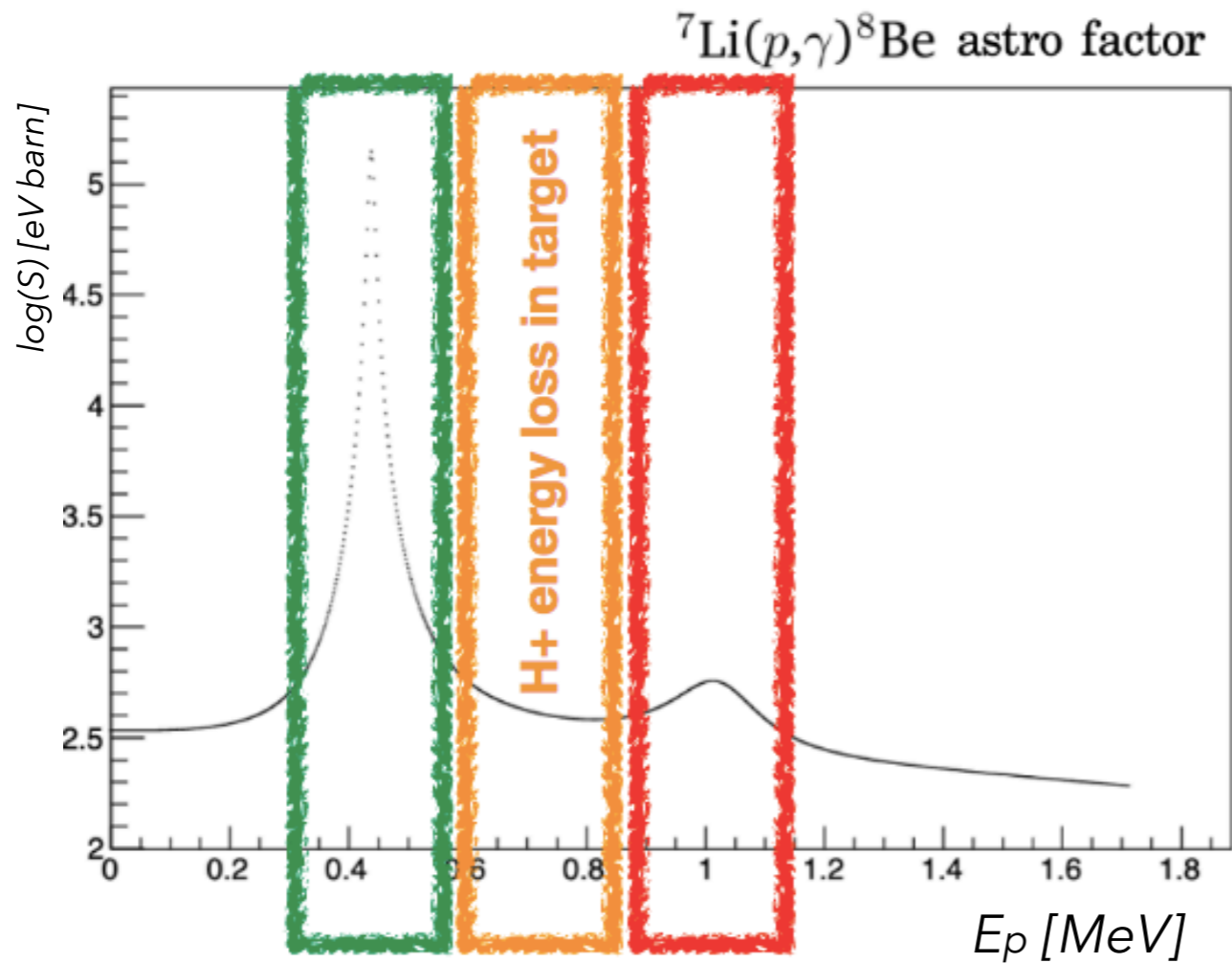
On full E_{sum} and Angular Opening range:

→ **60%** EPC (15+18)

→ **40%** IPC (15+18)

Unfortunately, we have had contamination from H_2^+ within proton beam

3 proton energy regions

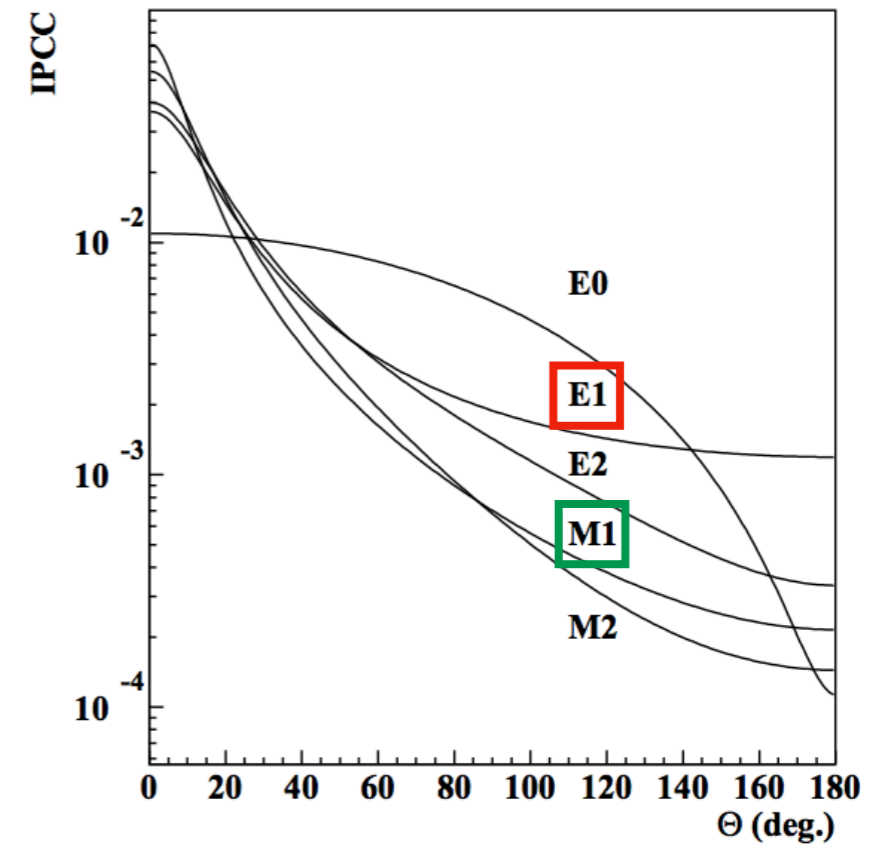


H₂⁺

M1-dominated

H⁺

M1~E1

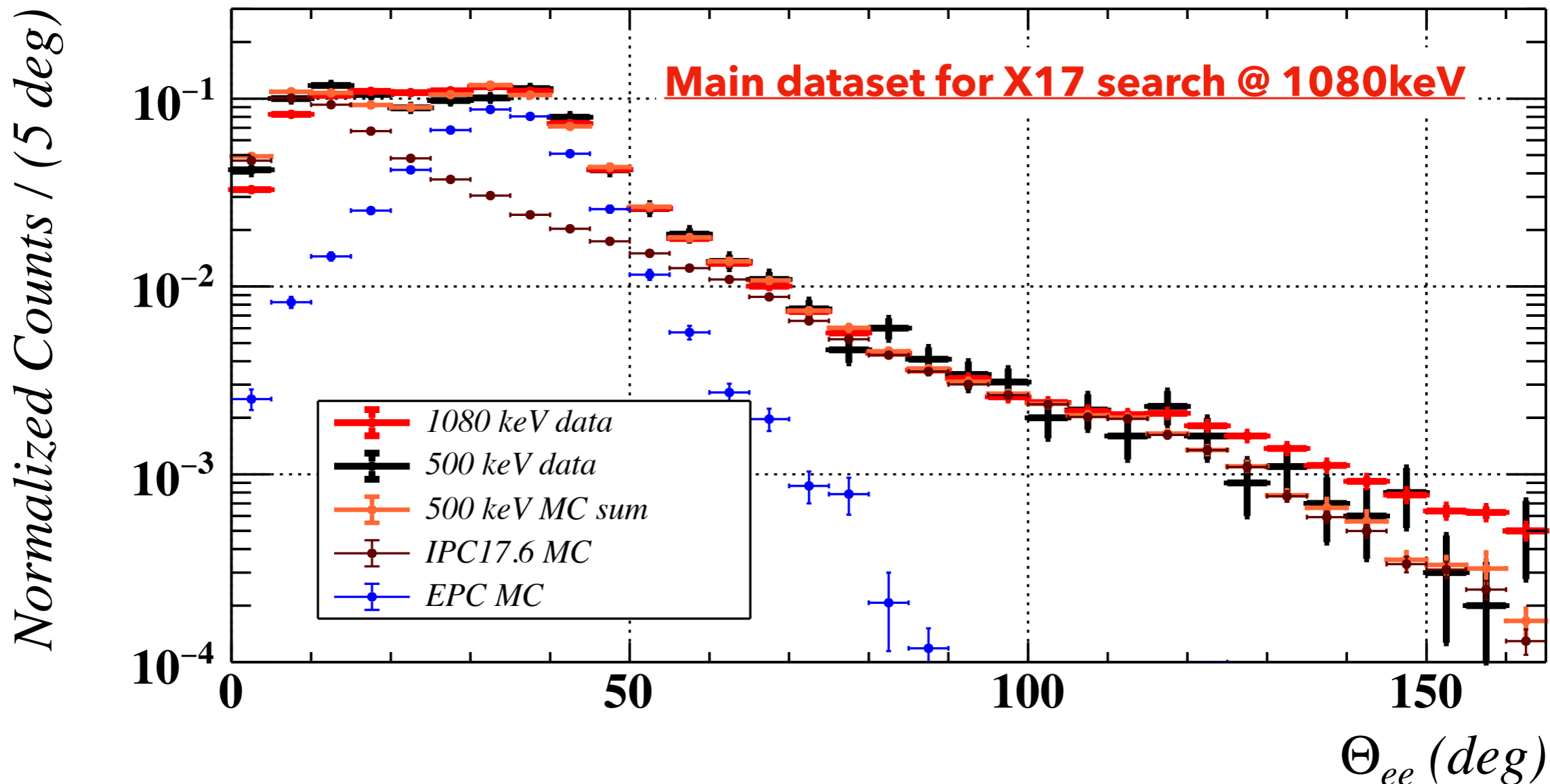


steeper IPC shape

flatter IPC shape



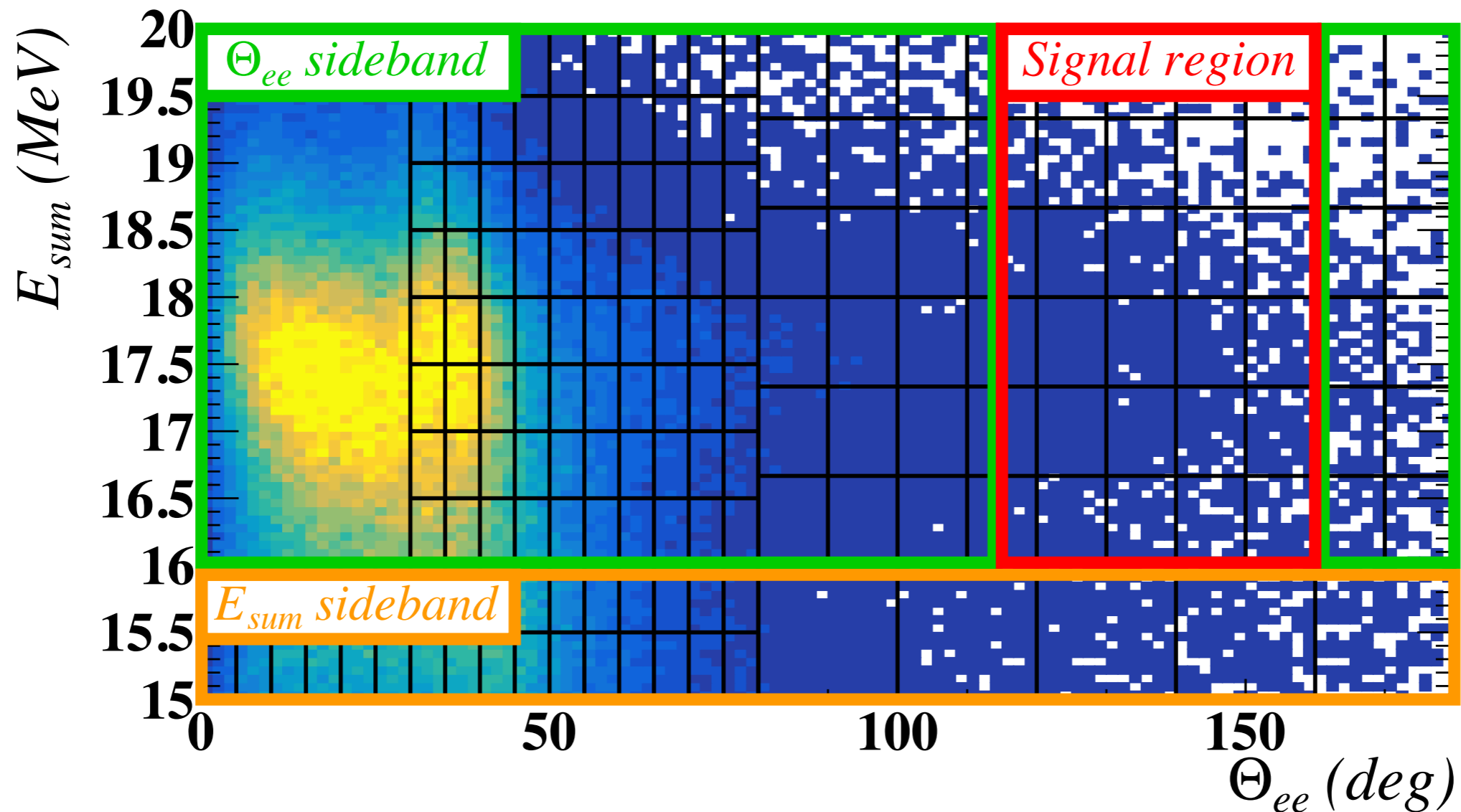
Resonances can be distinguished via the steepness of the IPC Angular Opening



- ➔ Small dataset @500keV (only 17.6 MeV line) compared to main dataset @1080keV
- ➔ Data well modelled by Zhang-Miller IPC model!
- ➔ 18.1 MeV presence at 1080 keV leads to E1-enriched flatter shape at large angles
- ➔ 17.6 MeV line / 18.1 MeV line → 80% / 20% of our main dataset

- 2D likelihood maximization: E_{sum} vs Angular Opening

- Blinded signal region defined as:
 - **Signal Region**
 - $16 \text{ MeV} < E_{sum} < 20 \text{ MeV}$
 - $115^\circ < \text{Angle} < 160^\circ$
- Before unblinding, understanding of background done in two sidebands



- Binned max. likelihood fit using template histograms as PDF from a detailed MC simulation → validated in the sidebands

- Likelihood parametrized wrt. photon emission BR

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

Two signal templates

- One per resonance, $Q = 17.6$ and $Q = 18.1$ MeV

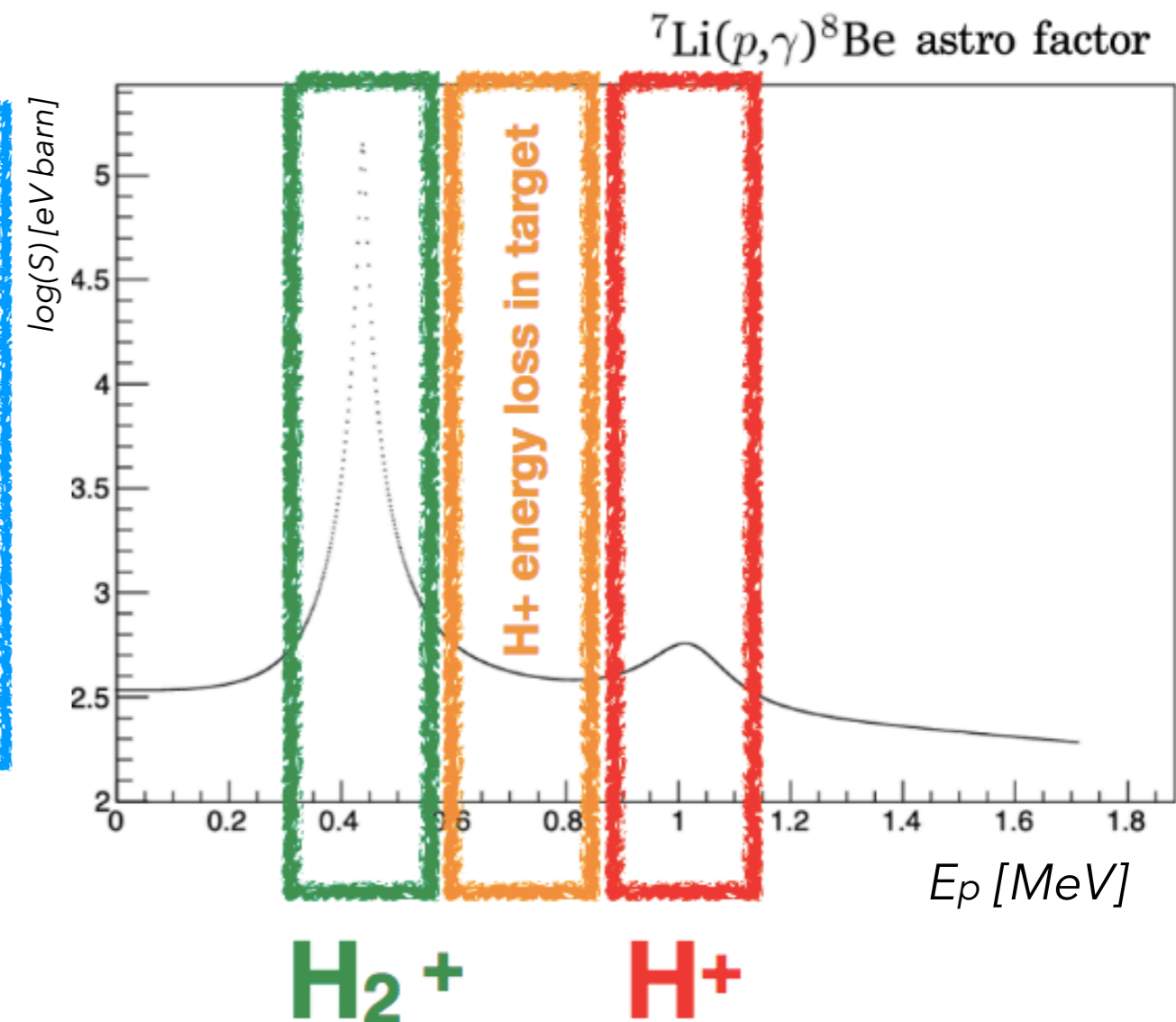
Six IPC templates

- Three E_p bins,
- Two transitions (g.s and 1st excited s.) for each bin

Two EPC templates

- Neglected E_p dependence,
- Transition to g.s. and 1st e.s.

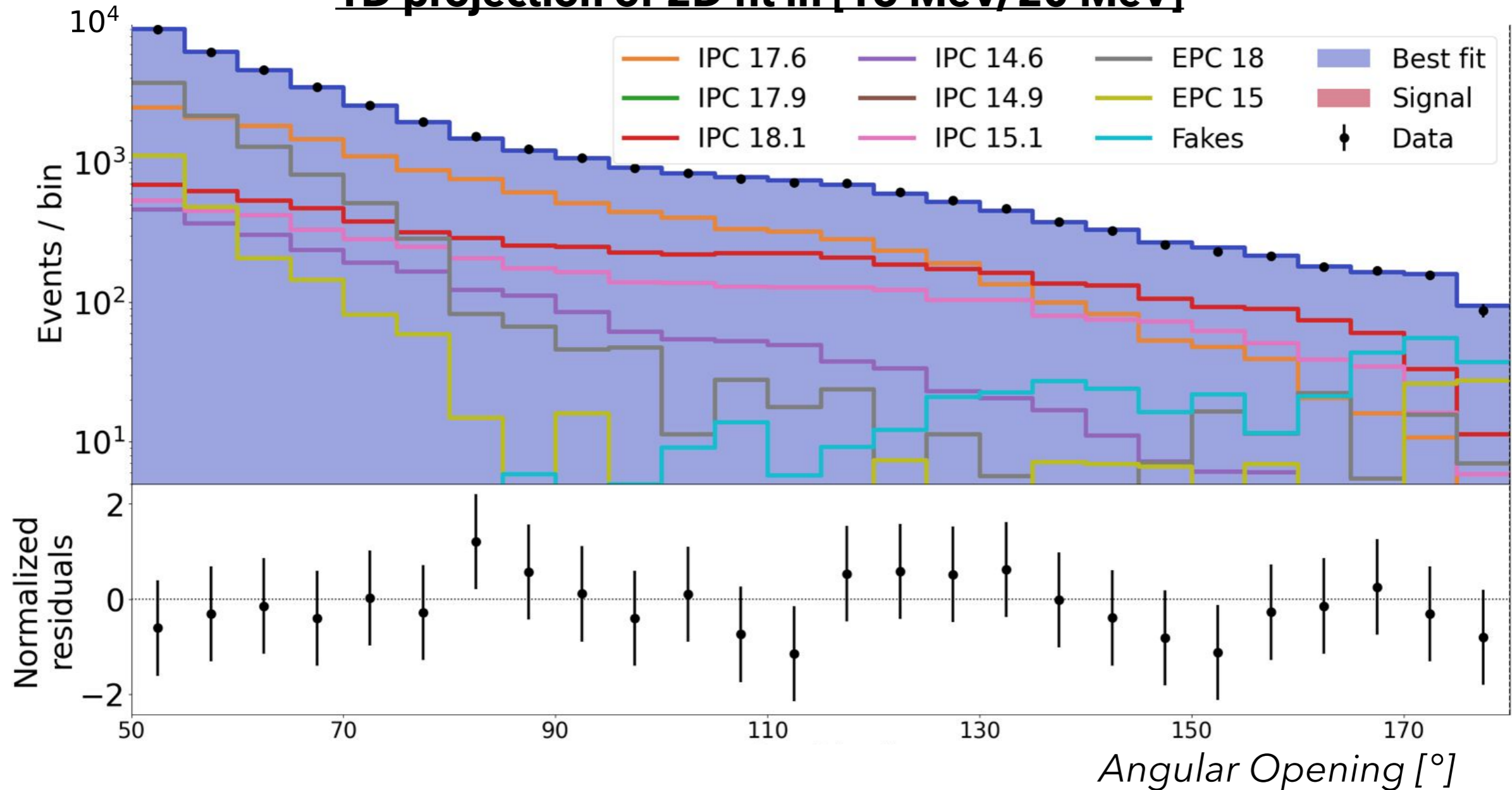
One fake pairs template



- Beeston-Barlow likelihood to account for MC limited statistics

[Eur. Phys. J. C 82\(11\), 1043](#)

1D projection of 2D fit in [16 MeV, 20 MeV]

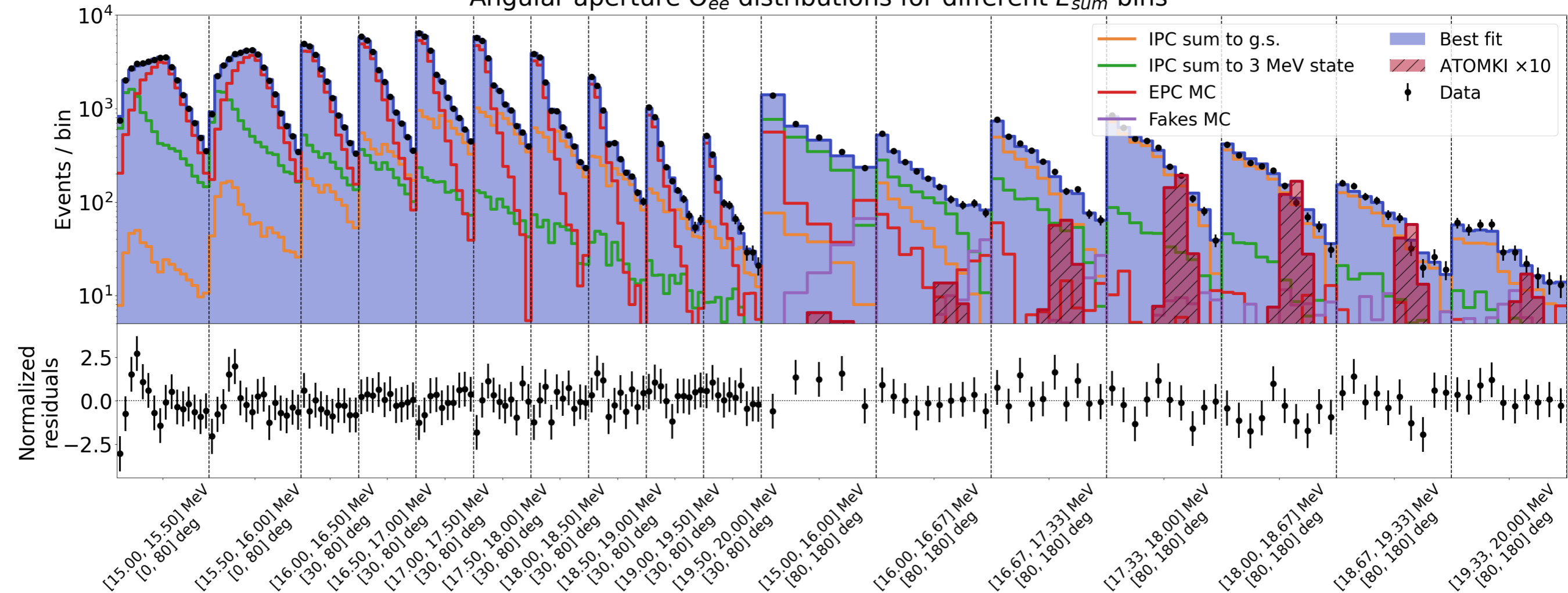


Best fit

- ➔ Goodness-of-fit: p-value = 10%
- ➔ 10 signal events at $Q = 18.1$ MeV, O(100) were expected based on Atomki
- ➔ 0 signal event at $Q = 17.6$ MeV, O(300) were expected based on Atomki/Feng et al
- ➔ Compatibility test carried out, results in next slides

Phys. Rev. Lett. 117, 071803

Angular aperture Θ_{ee} distributions for different E_{sum} bins



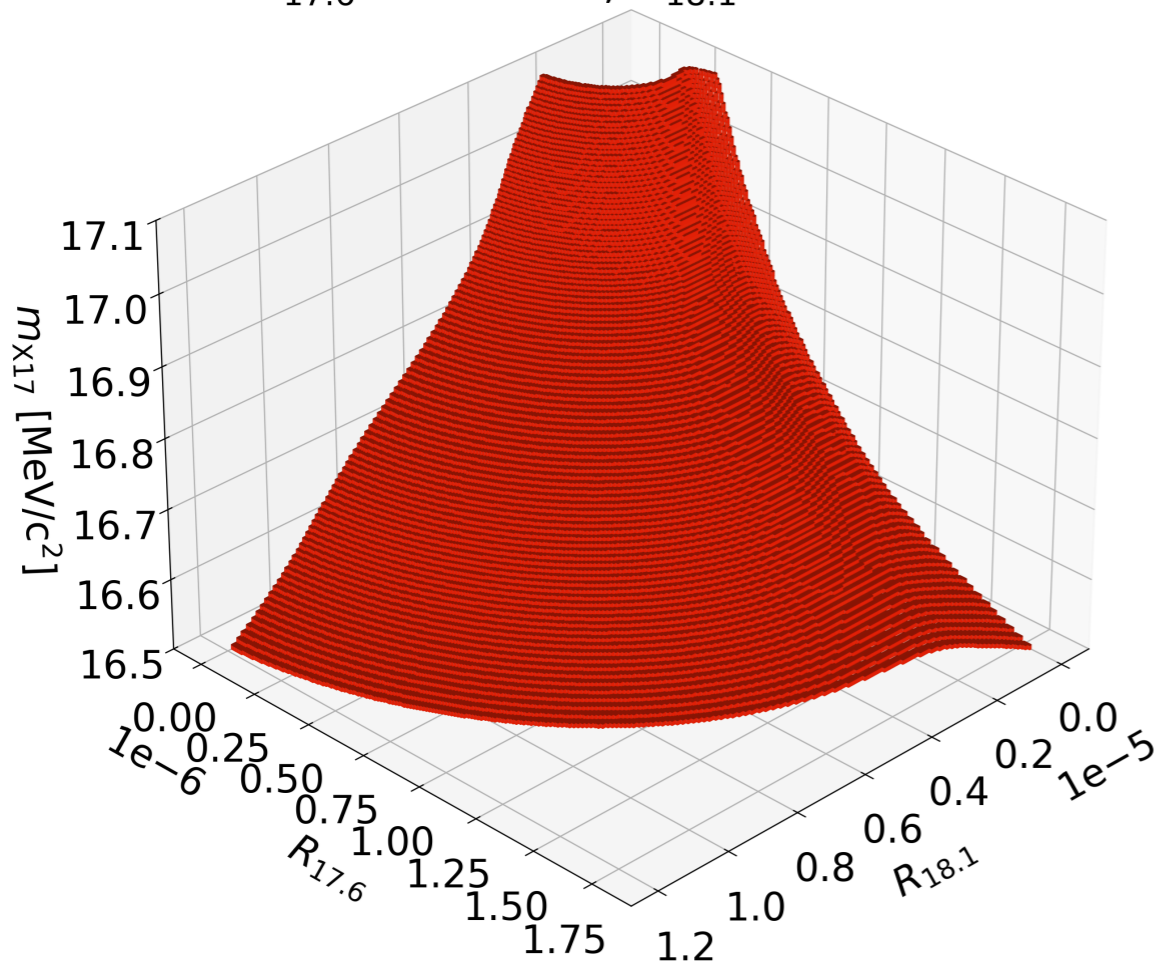
Best fit

- ➔ Goodness-of-fit: p-value = 10%
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- ➔ Compatibility test carried out, results in next slides

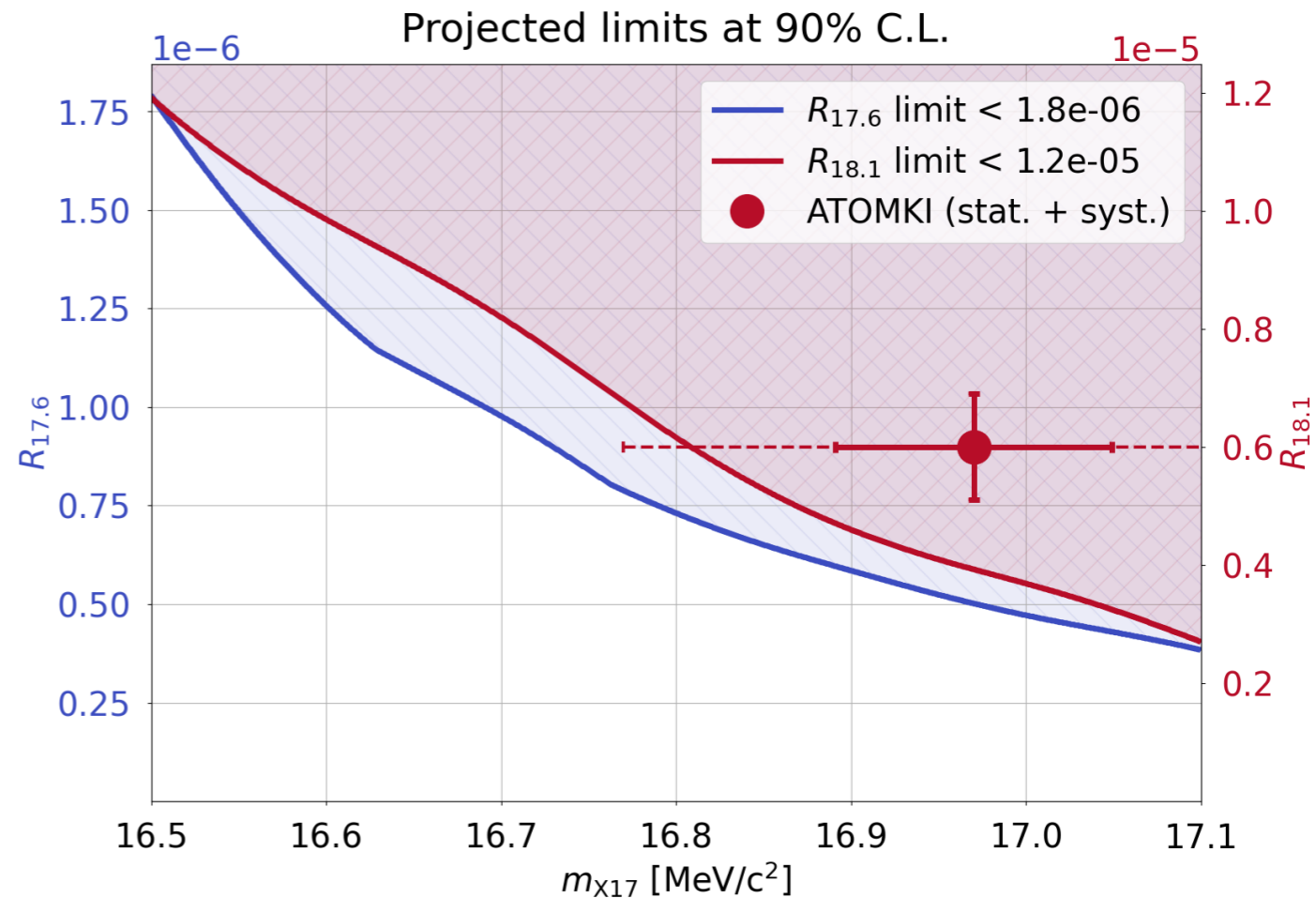
[Phys. Rev. Lett. 117, 071803](#)

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

Limits at 90 % C.L.
 $R_{17.6} < 1.8 \times 10^{-6}$, $R_{18.1} < 1.2 \times 10^{-5}$



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



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

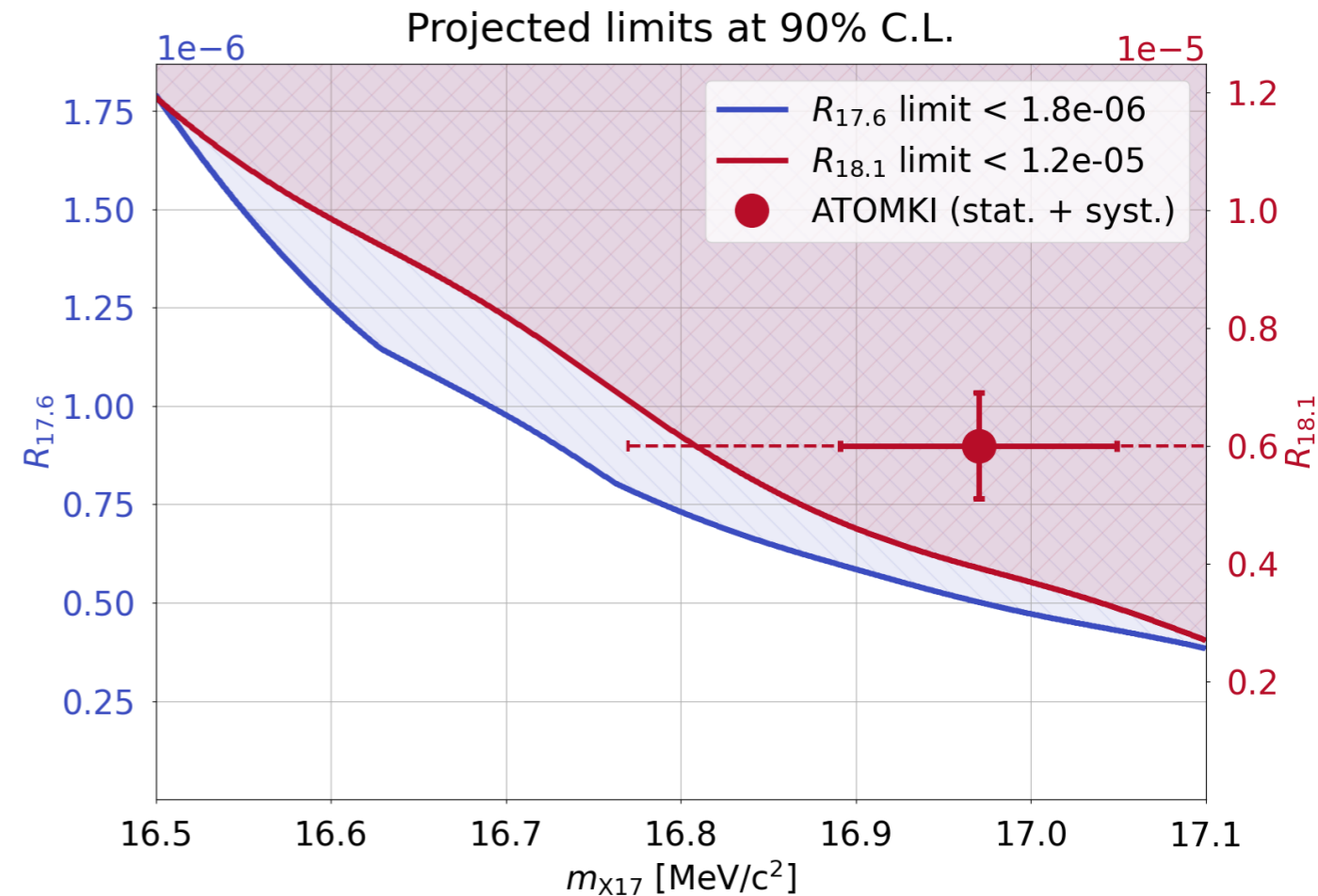
$$R_{18.1} < 1.2 \times 10^{-5}$$

Two hypotheses were tested

Assumes:

- $m = 16.97(22) \text{ MeV}/c^2$
- $R_{18.1} = 6(1)e-6$
- $R_{17.6} = 0.46 R_{18.1}$

*pondered average over
3 nuclei's result*



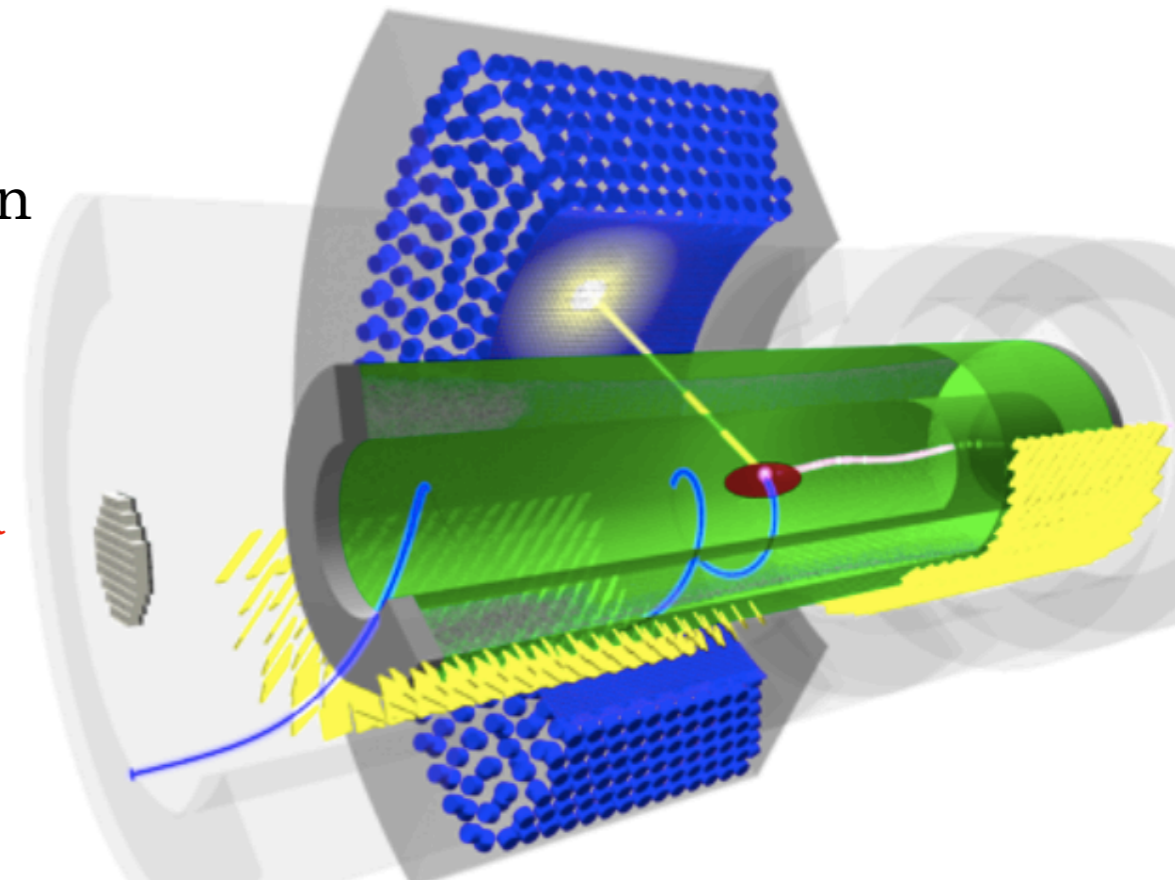
Atomki hypothesis: X17 only from 18.1 MeV decay

incompatible at 94% (1.5σ)

Feng et al. hypothesis: X17 from both 18.1 MeV and 17.6 MeV decay

incompatible at 98% (2.1σ)

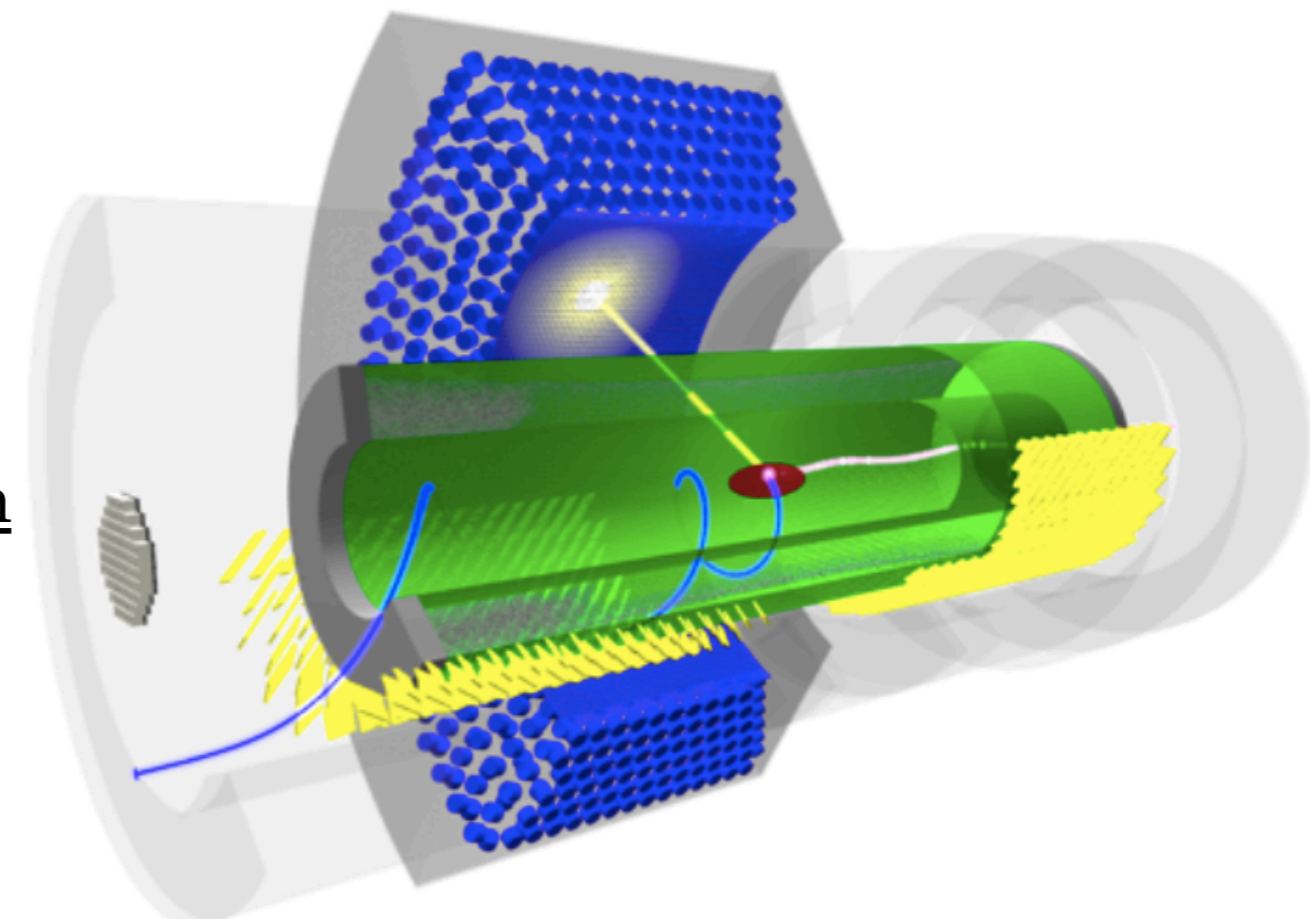
- Anomalous excess observed in the angular correlation of ${}^7\text{Li}(p, e^+e^-){}^8\text{Be}$ by the Atomki group
- The MEG-II collaboration has designed, tested and built all the elements to perform the X17 search in an independent manner
 - better understanding of the X17 anomaly
- Physics run in February 2023
 - backgrounds, signal and detectors simulation
 - 2023 data was reprocessed, good background understanding
 - No significant signal was found in our data
 - ATOMKI observation was tested and excluded at 94%
- New DAQ period @1030 keV with pure proton beam is foreseen
 - improved sensitivity



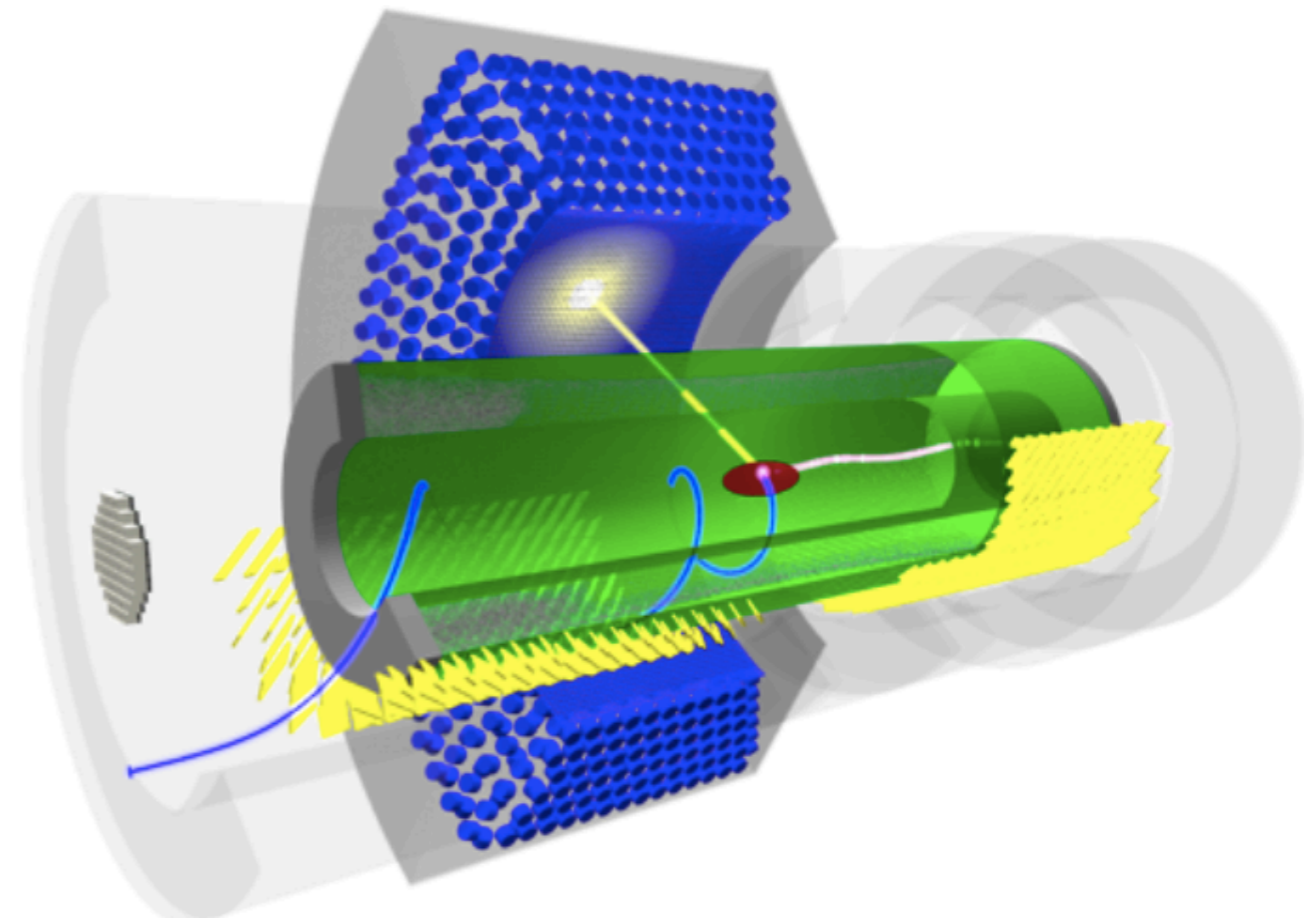
Thank you for your attention!

Hicham Benmansour, INFN Pisa
on behalf of the MEG-II collaboration

hicham.benmansour@pi.infn.it



Backup slides

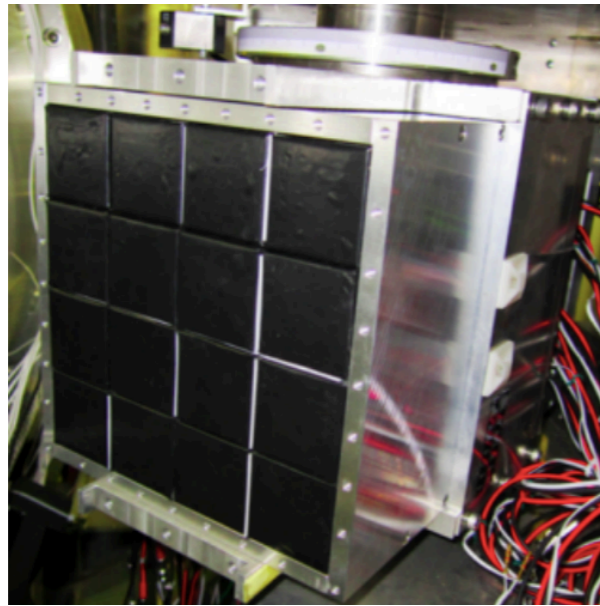


- With all elements mentioned above, engineering run in February 2022
- Objectives:
 - define optimal experimental setup and final TDAQ configuration
 - understand backgrounds
 - optimize target region
 - develop reconstruction algorithm
- Take-aways from 2022 run
 - converting gammas from 6 MeV Fluorine line overcrowd the trigger when the LiF target is used → only good for calibration of ancillary detectors, LiPON has to be used for X17 search
 - CDCH multiplicity condition (18 hits on each detector end) strongly suppresses trigger contamination and improves reconstruction
 - target region can stand high proton currents (up to 10uA) without overheating → heat-dissipation material can be reduced (less EPC background)

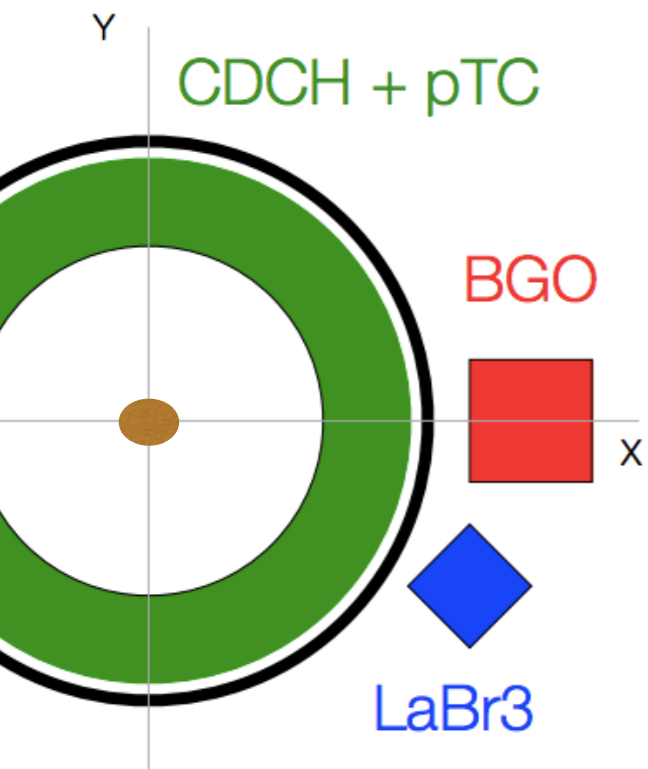
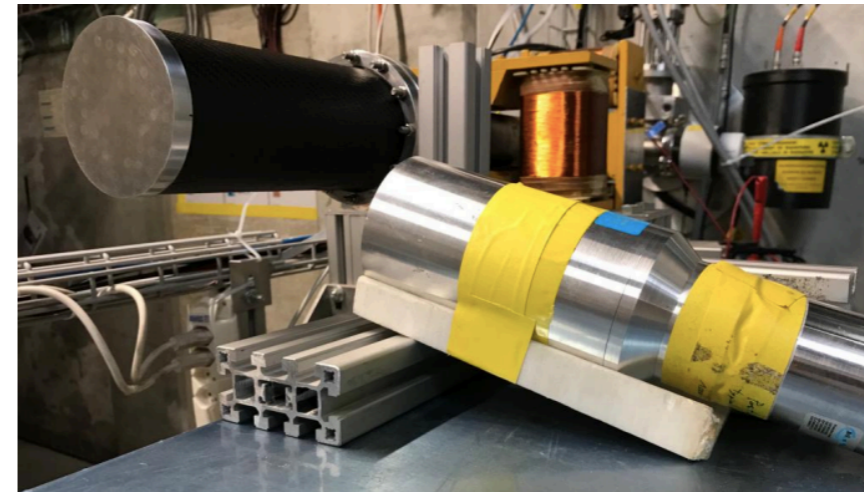
- Two additional gamma detectors

→ Stability monitoring → Signal normalisation → Daily monitoring

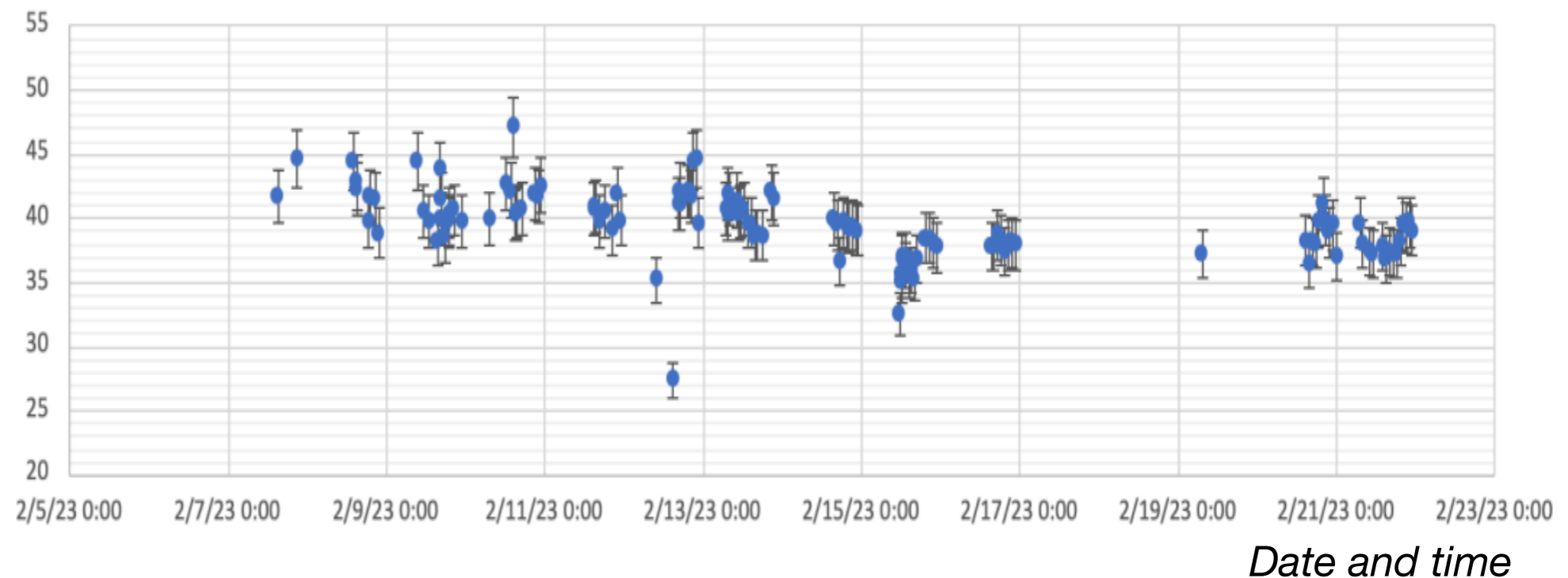
Bismuth Germanate (BGO) crystal matrix (4x4)



Lanthanum Bromide (LaBr₃) crystal



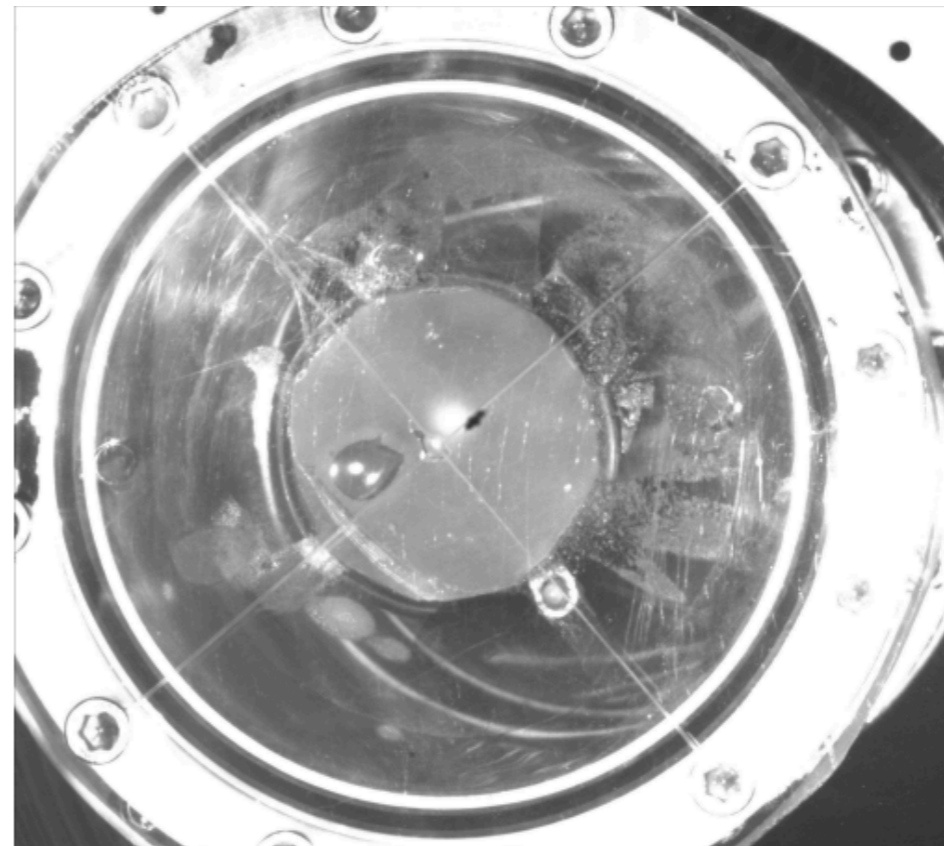
Gamma rate in BGO per current unit [Hz/ μ A]



- $\mu \rightarrow e\gamma$ search relies on 52.8 MeV positron search with default magnetic field (1.27T at COBRA center)
- for X17: energies ~ 6 times lower \rightarrow scaling of the field by a factor 0.15
- CW tuned using a quartz target: proton-induced fluorescence in the quartz, visible emission
- Tuning made varying 3 dipolar fields along the beamline to center the beam \rightarrow beam spot centered and covering the Li area

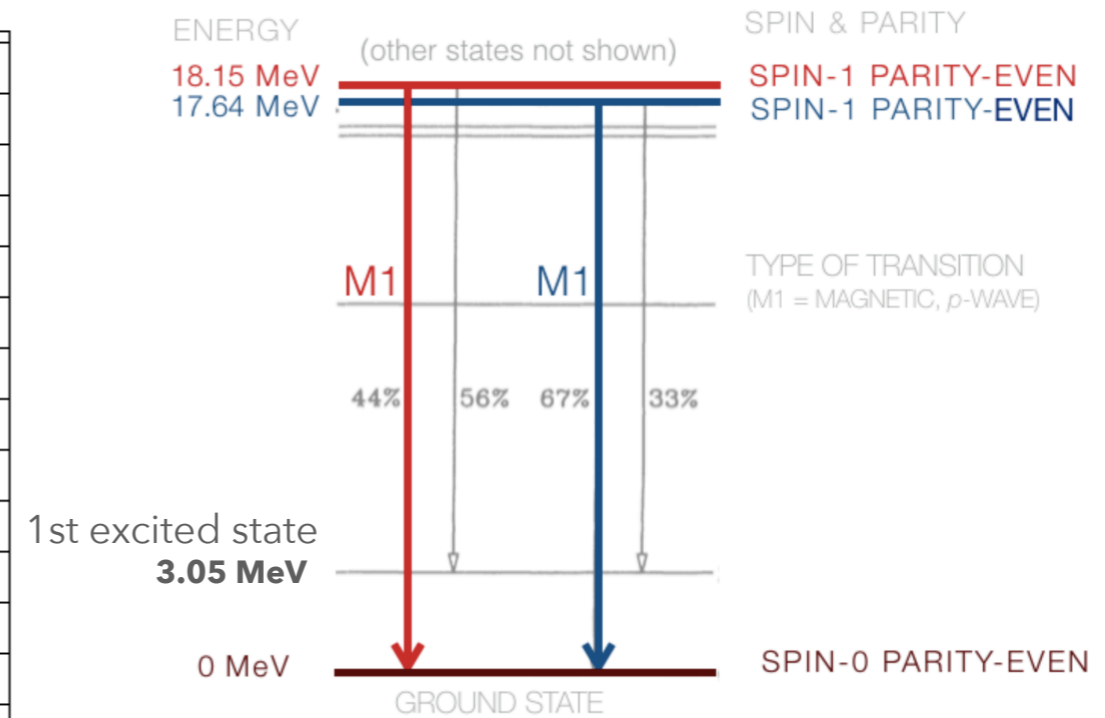
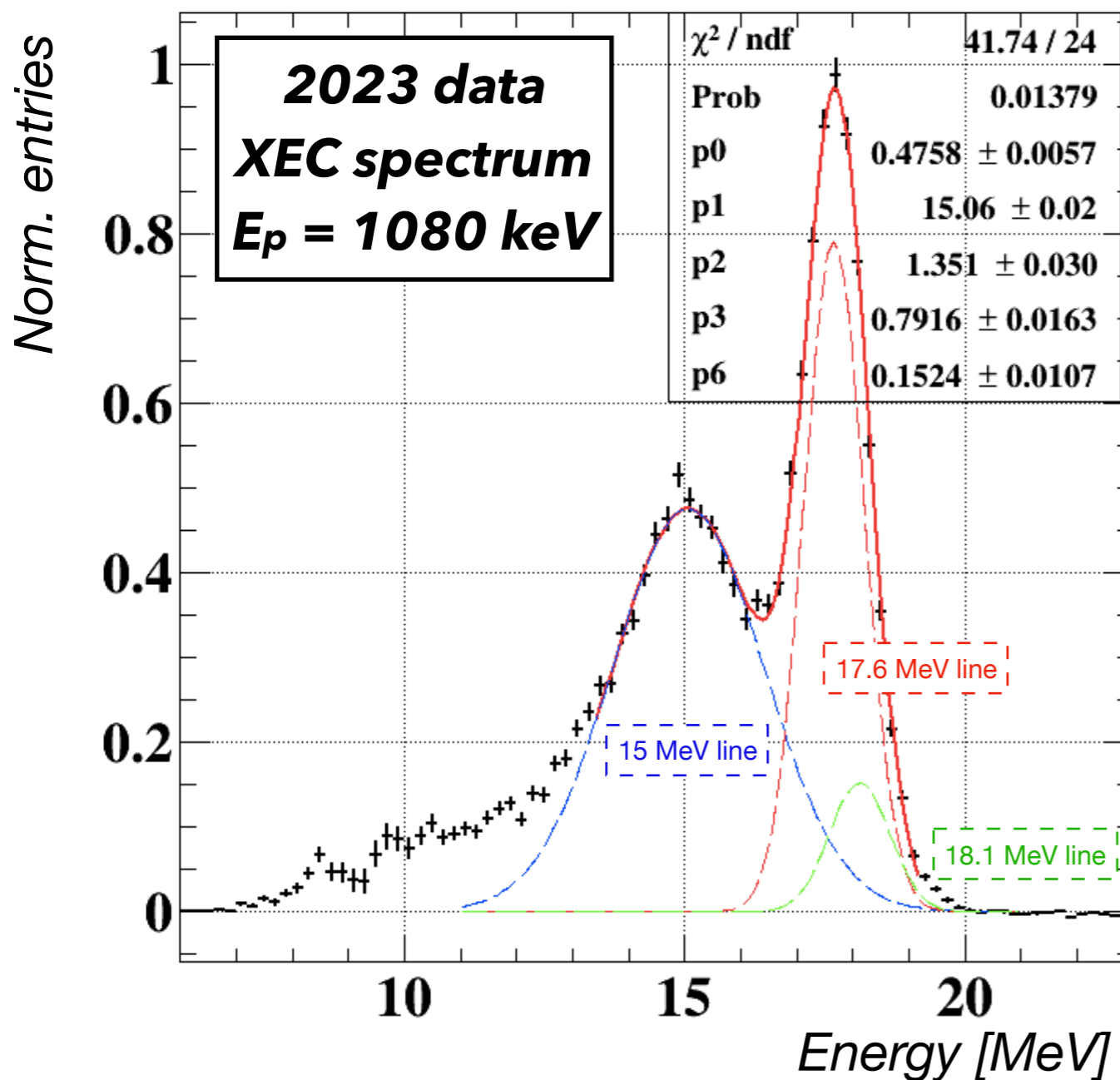


megCam - COBRA OFF



CCD camera - COBRA ON

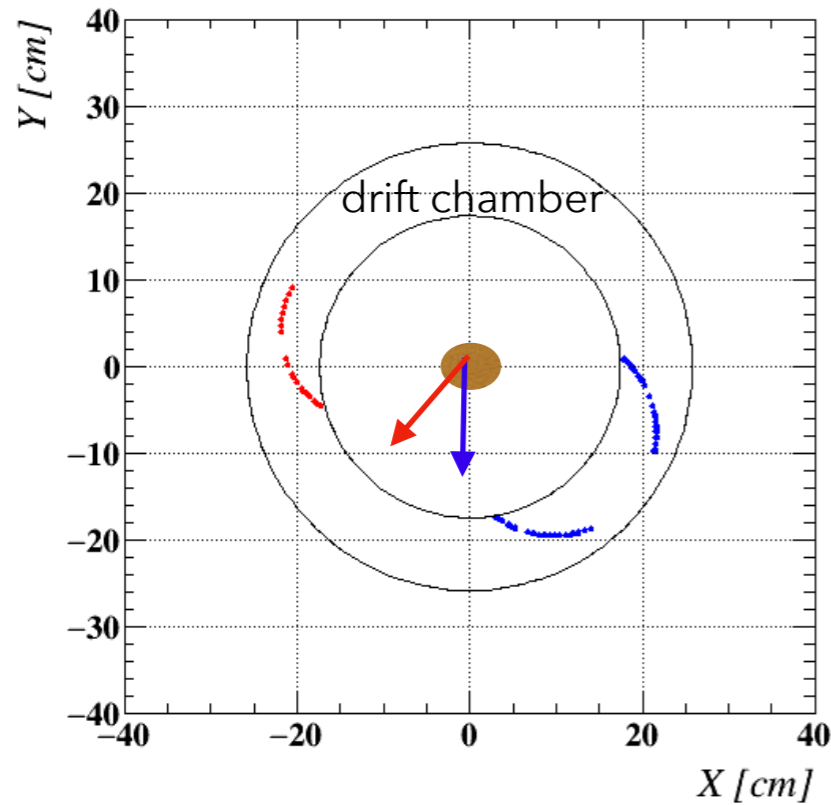
- Gamma spectrum using LXe calorimeter to understand excited transitions



**Fraction of 18.1 MeV line
(wrt 17.6+18.1) can be extracted:**

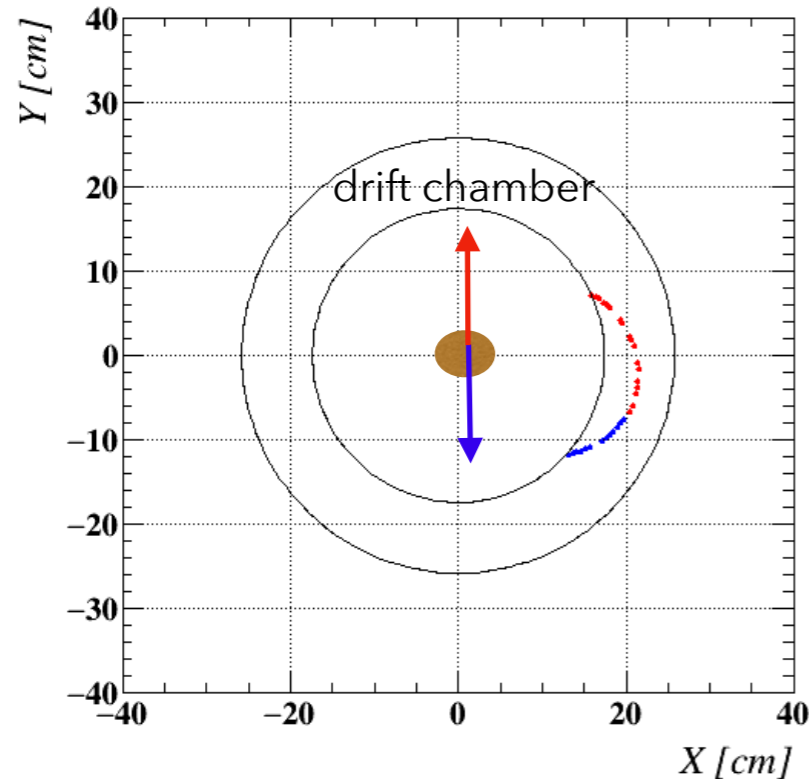
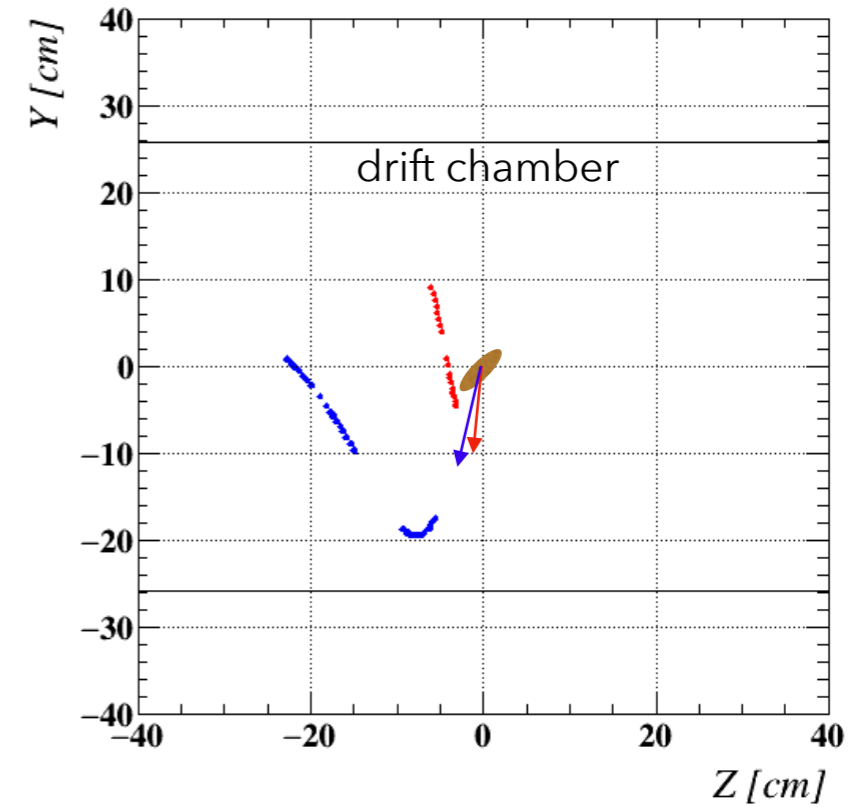
$$f_{18.1} \sim 20\%$$

- Let's have a look at the fitted hits within the CDCH



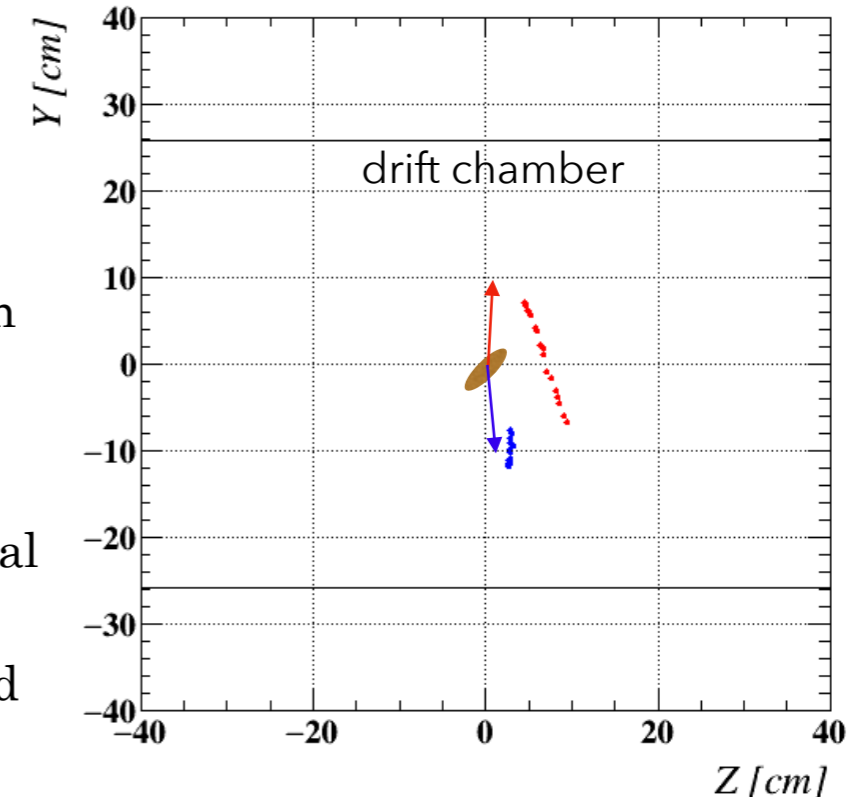
GOOD PAIR

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

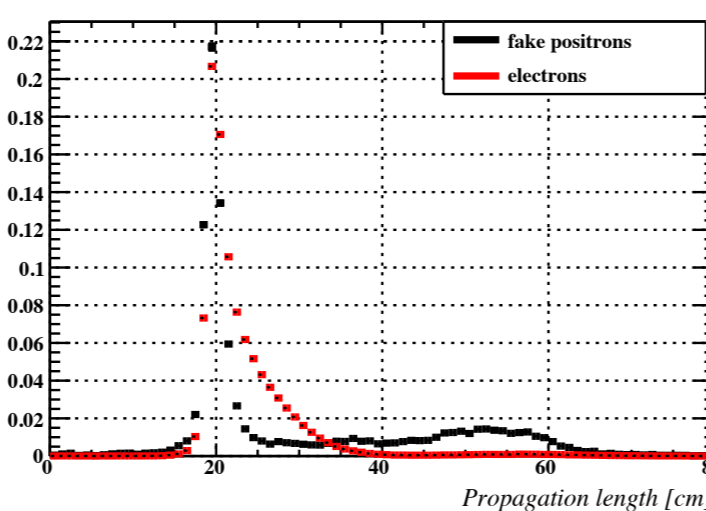
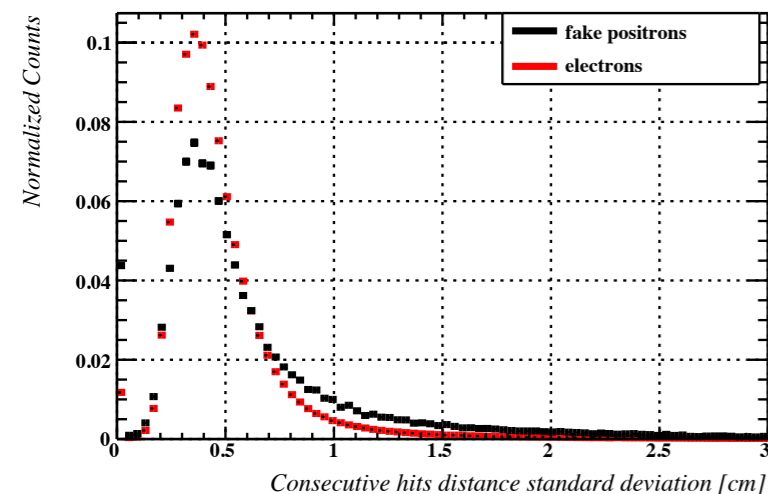
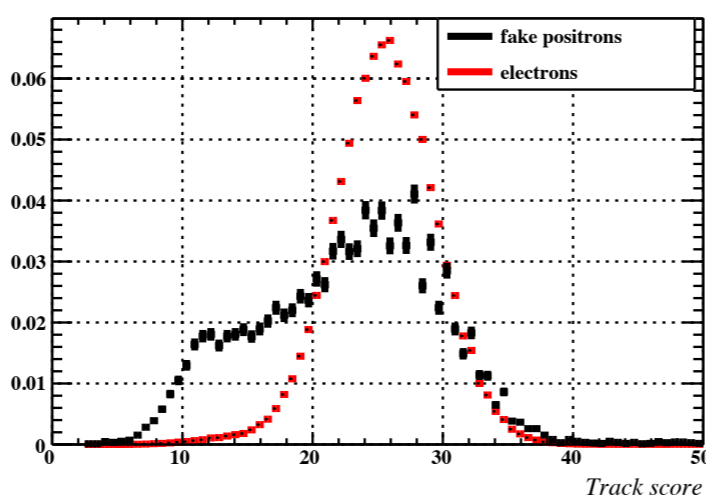
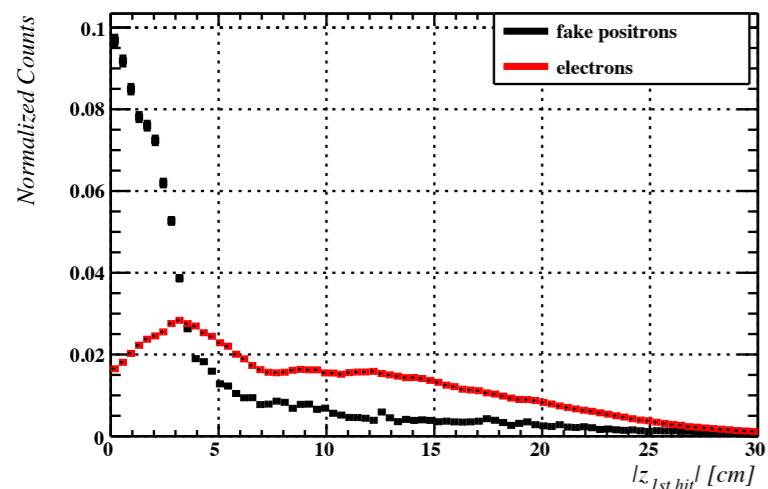
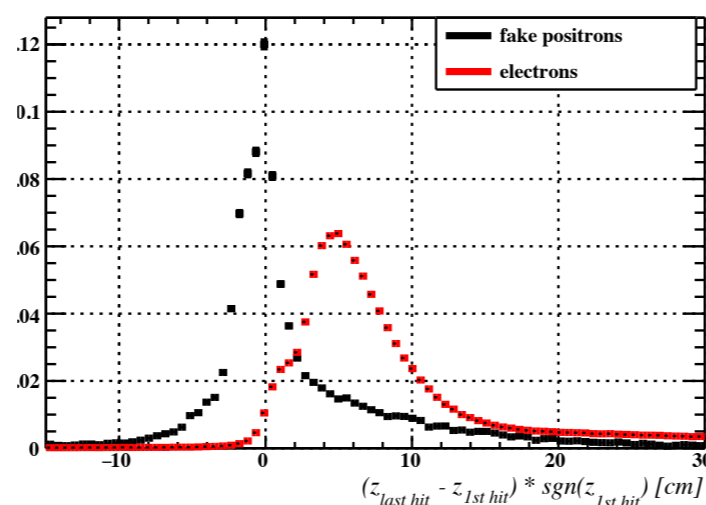
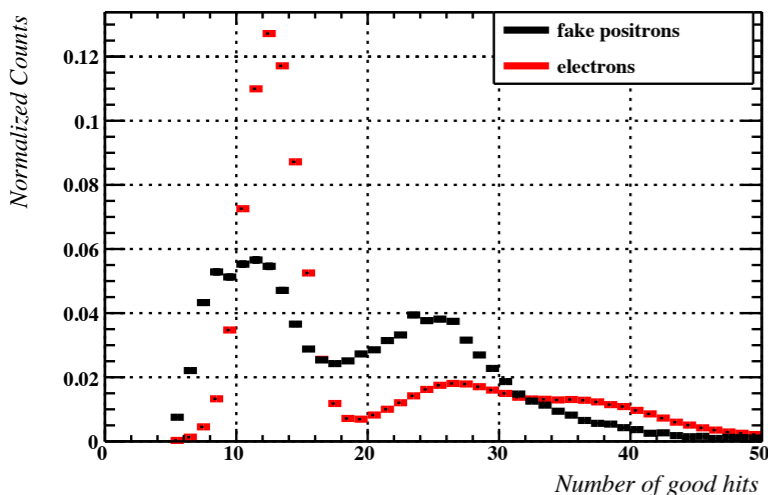


FAKE PAIR

- Two pieces of the same track reconstructed with opposite sign
- Back-to-back reconstructed
- Dangerous, close to signal region
- Need to characterize and reject these



- Deep characterization of fake tracks: 50 observables investigated



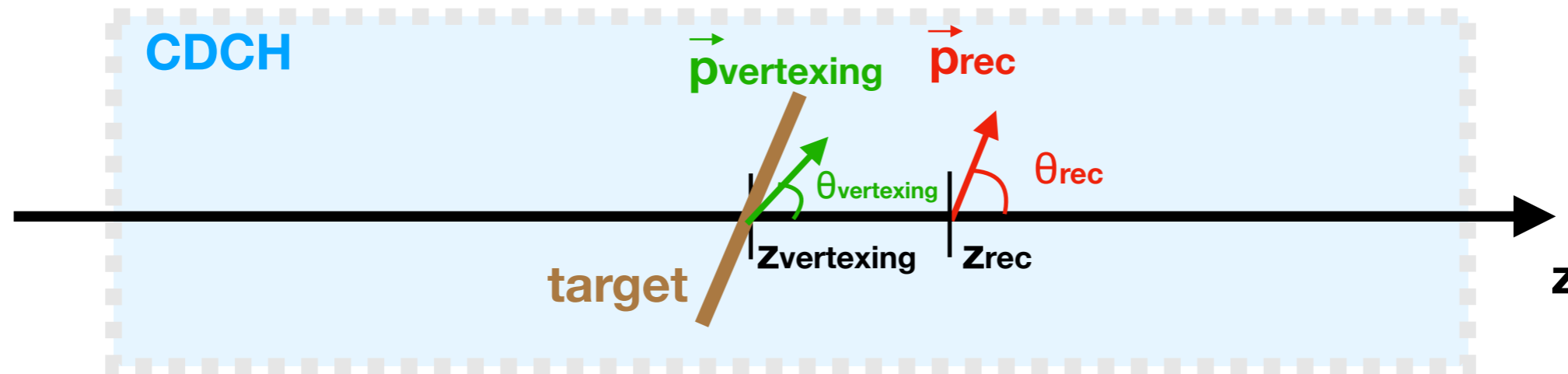
Fake tracks

- short
- if longer, little dense
- consecutive hits distance large
- close to $z=0$
- large propagation length

Advanced track selection was developed

- track reconstructed as a positron (including the magnetic field sign assumption)
- $T_{0,lasthit} > T_{0,firsthit}$;
- $(z_{lasthit} - z_{firshit}) \times z_{firshit} > 0$ (to ensure the track goes away from the target);
- $|z_{firshit}| > 2.5$ cm;
- no hits with opposite z_{hit} ;
- $|z_{vertex} - z_{beamspot}| < 2.5$ cm, z_{vertex} being the z coordinate of the track z-axis POCA and $z_{beamspot}$ the best estimate of the z coordinate of the beamspot center on target;
- propagation length from the first hit to the z-axis POCA smaller than 35 cm (to ensure the fitted track includes the first turn)
- number of fitted hits ($ngoodhits$) equal or larger than 10;
- if $10 \leq ngoodhits \leq 16$, track hit density should be > 1.1 hits/cm;
- half-turn tracks (tracks which never exit the chamber) should have an average hit density > 0.8 hits/cm and a track score > 20 , track score being defined as $ngoodhits + 10 \times \text{hit density}$;

due to $O(20\text{cm})$ of air between target and CDCH and large multiple scattering
→ tracks are reconstructed $O(\text{cm})$ away from the true vertex



Objective: find e^+ and e^- common vertex

How: use e^+ and e^- state extrapolated at beam axis point of closest approach POCA + beam spot information

Why: improve resolutions

Procedure

- all tracks are fitted separately to the z axis POCA
 - selection of best e^+ and e^- track
 - search for a possible common vertex within a beam spot constraint
 - vertexing tool
- RAVE (Reconstruction (of vertices) in Abstract Versatile Environments)
- compatible with GENFIT

Angular Opening resolutions

X17 MC simulation

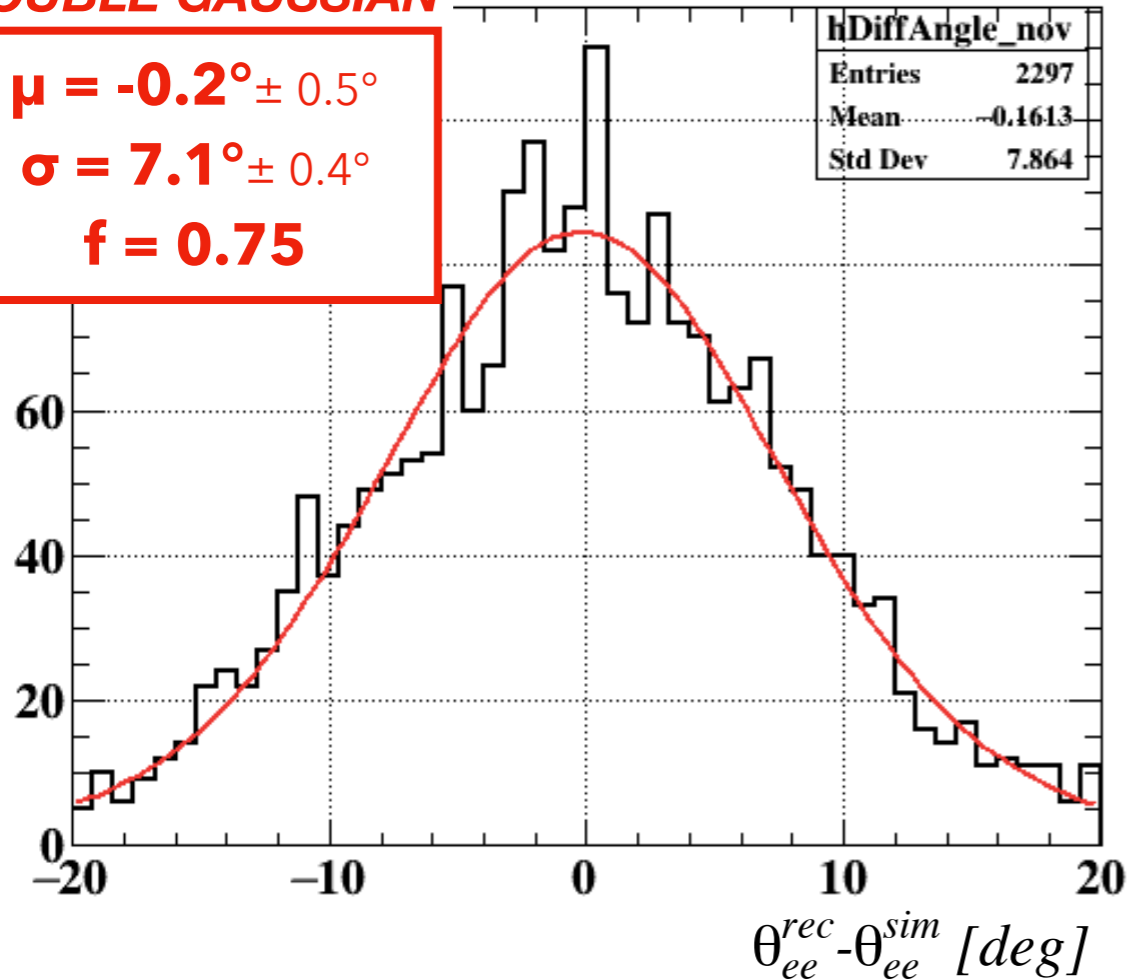
No vertexing

With vertexing

DOUBLE GAUSSIAN

$$\begin{aligned}\mu &= -0.2^\circ \pm 0.5^\circ \\ \sigma &= 7.1^\circ \pm 0.4^\circ \\ f &= 0.75\end{aligned}$$

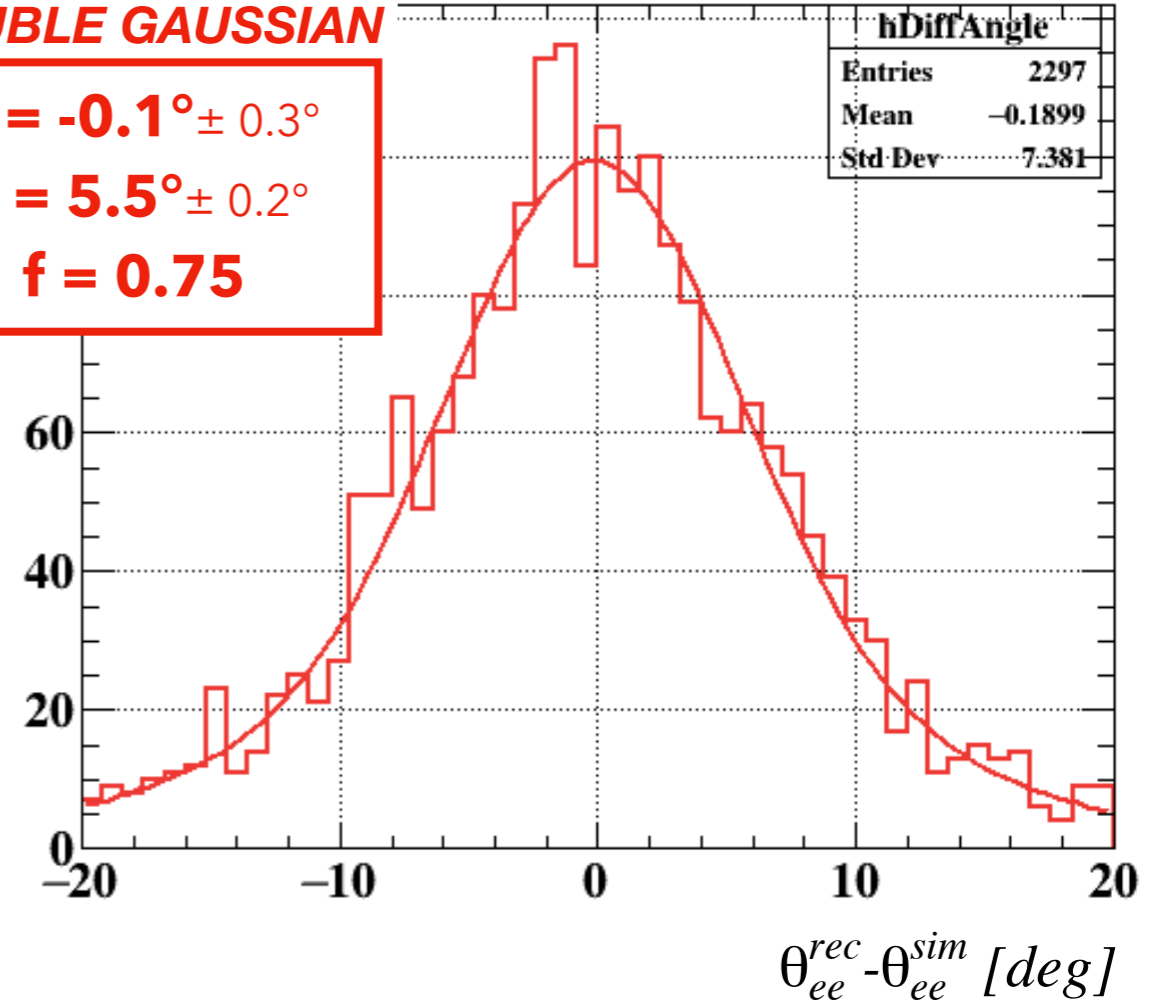
| hDiffAngle_nov | |
|----------------|---------|
| Entries | 2297 |
| Mean | -0.1613 |
| Std Dev | 7.864 |



DOUBLE GAUSSIAN

$$\begin{aligned}\mu &= -0.1^\circ \pm 0.3^\circ \\ \sigma &= 5.5^\circ \pm 0.2^\circ \\ f &= 0.75\end{aligned}$$

| hDiffAngle | |
|------------|---------|
| Entries | 2297 |
| Mean | -0.1899 |
| Std Dev | 7.381 |

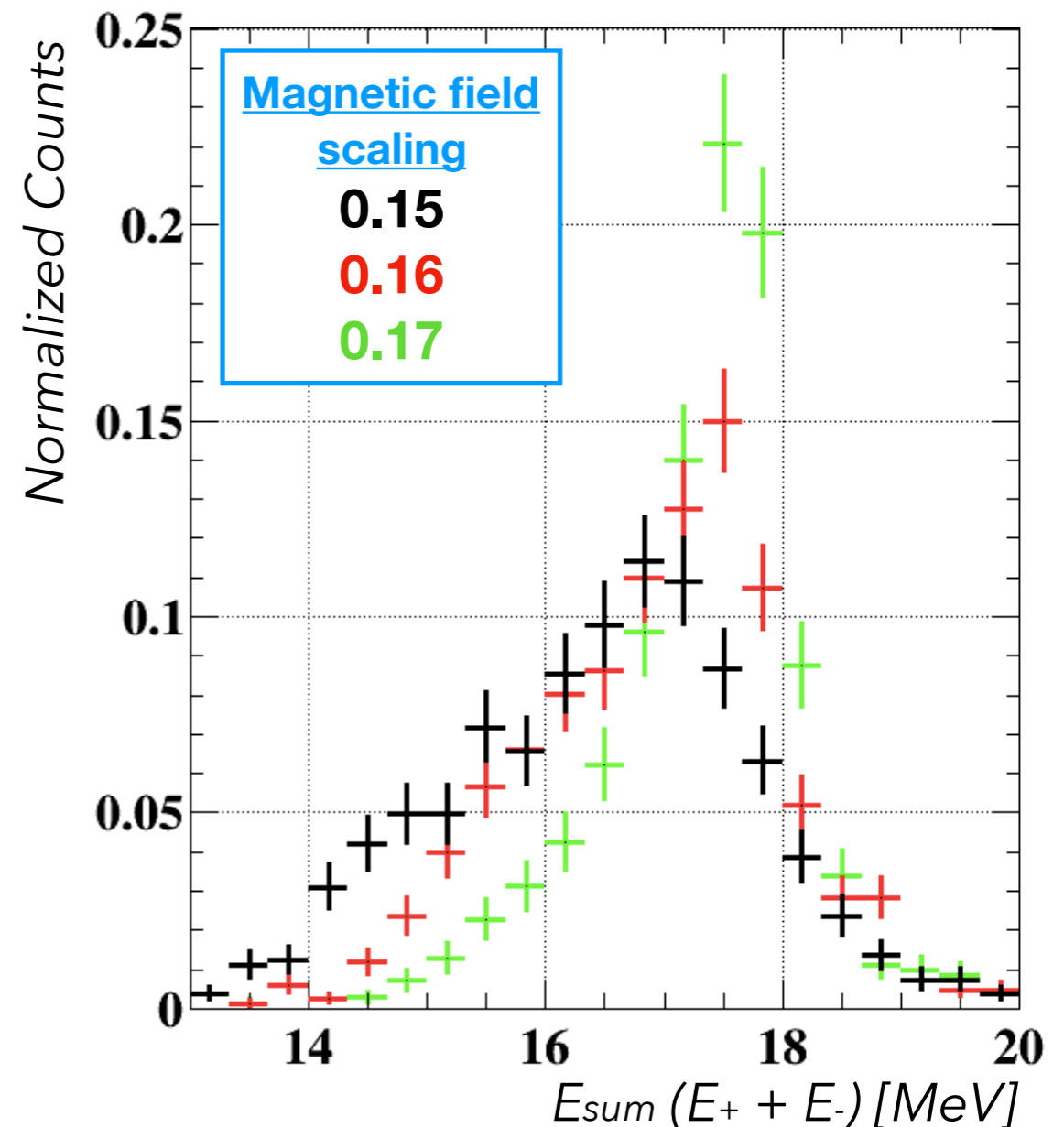


→ 25% improvement on X17 signal angular opening resolution

Reduced magnetic field

- $\mu^+ \rightarrow e^+ \gamma$ search relies on 52.8 MeV positron search with default magnetic field (1.27T at COBRA center)
- for X17: energies ~ 6 times lower \rightarrow scaling of the field by a factor 0.15 wrt. default
- Signal and backgrounds simulation with different field strengths to estimate the best signal efficiency and resolution

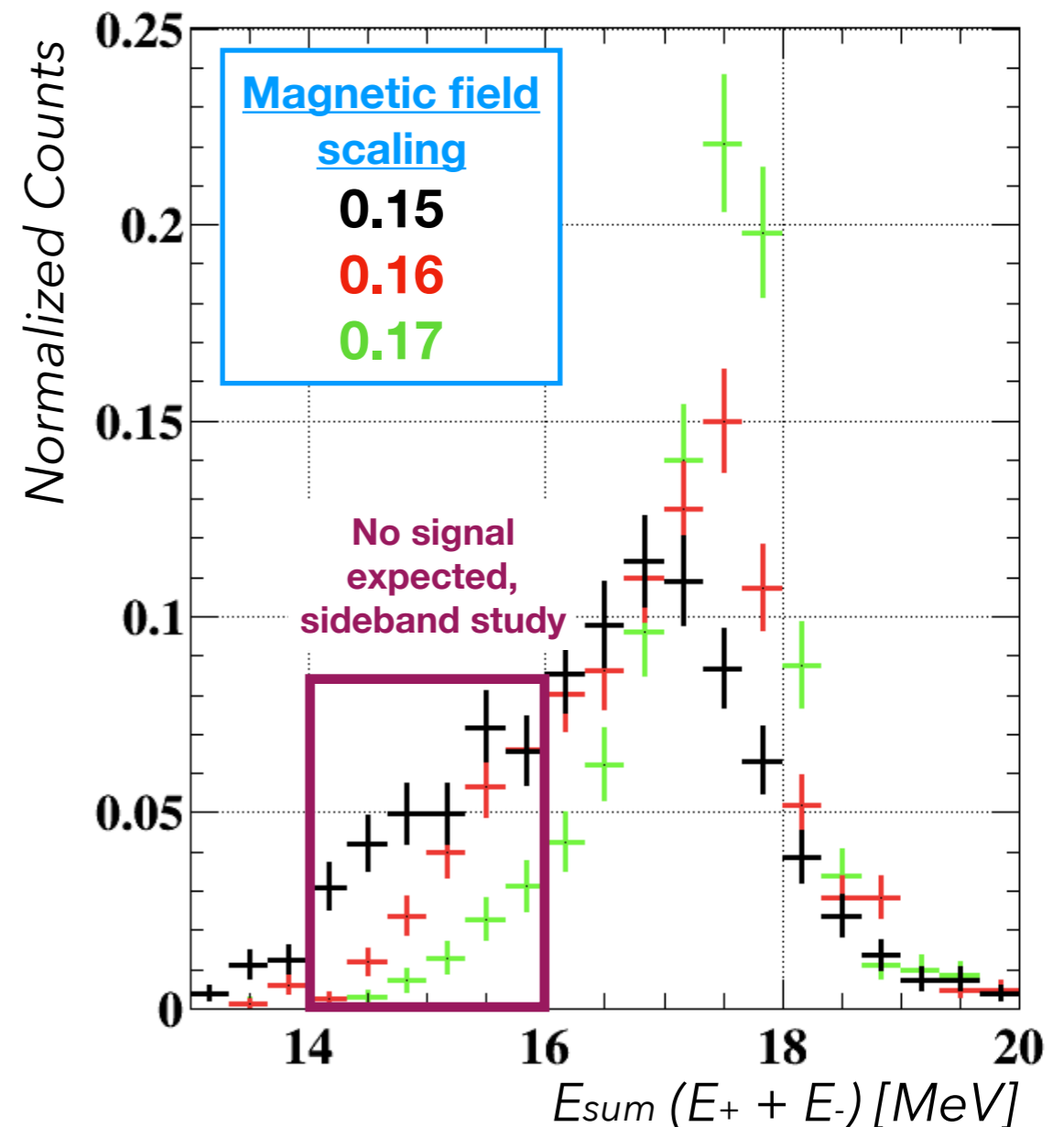
| Field scaling | Comments |
|---------------|---|
| 0.17 | <u>good</u> resolution but poor efficiency (low mom outside acceptance) |
| 0.16 | <u>good</u> resolution + <u>good</u> efficiency |
| 0.15 | <u>good</u> resolution + <u>good</u> efficiency + <u>lower</u> E_{sum} tail for study in sidebands |



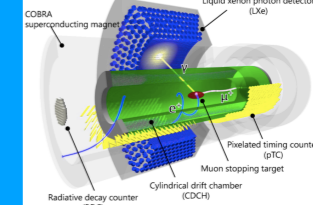
Reduced magnetic field

- $\mu^+ \rightarrow e^+ \gamma$ search relies on 52.8 MeV positron search with default magnetic field (1.27T at COBRA center)
- for X17: energies ~ 6 times lower \rightarrow scaling of the field by a factor 0.15 wrt. default
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| Field scaling | Comments |
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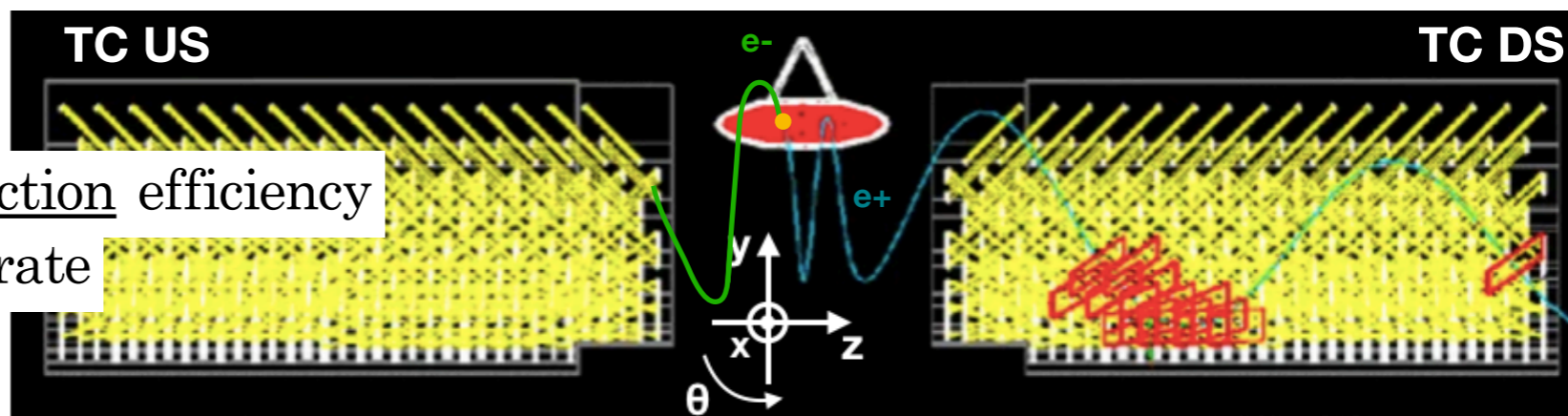


Trigger strategy: TC hit multiplicity



Why requesting at least 1 TC hit?

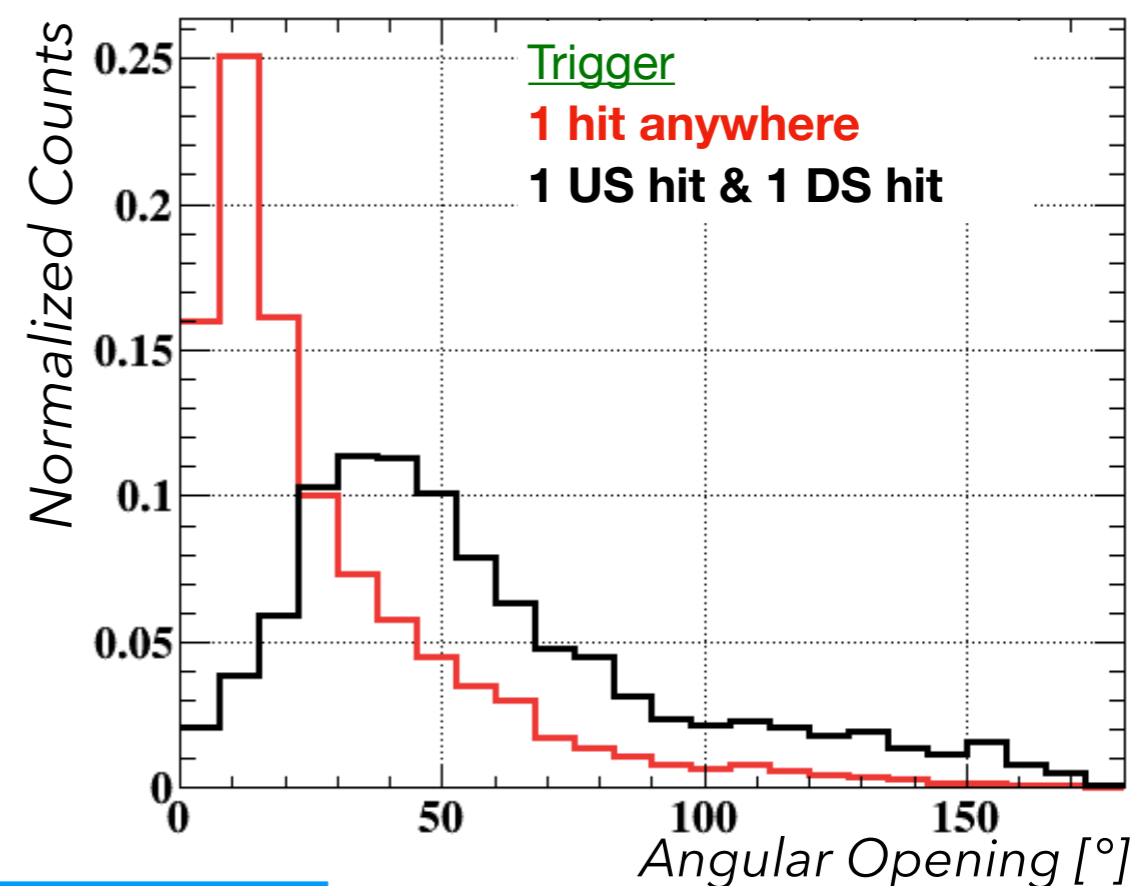
- largely improves track reconstruction efficiency
- less pileup, allows higher beam rate



One trigger option:

- 1 TC hit US & 1 TC hit DS
- Selects large angular opening pair
- IPC rate divided by a factor 60 (wrt to 1 TC hit)
- Total trigger rate < 1 Hz (at $I_{\text{proton}} = 10\mu\text{A}$)
- X17 rate divided by a factor 3 (wrt to 1 TC hit)
- Low angle statistics is mitigated
- Proton current limitations prevented us from making it advantageous

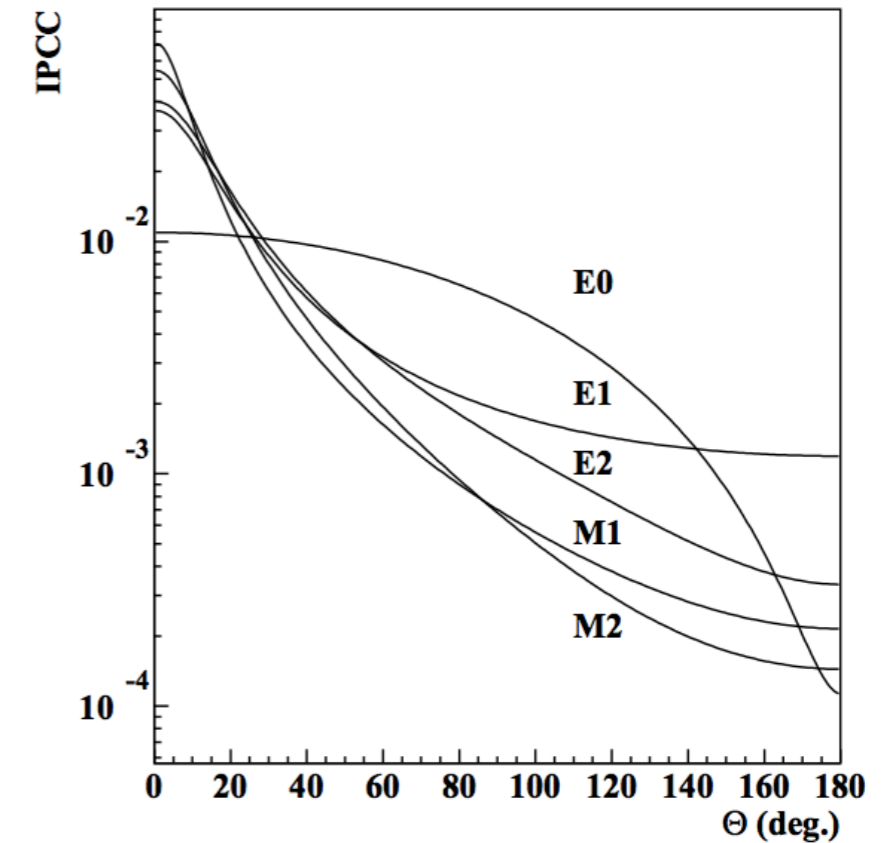
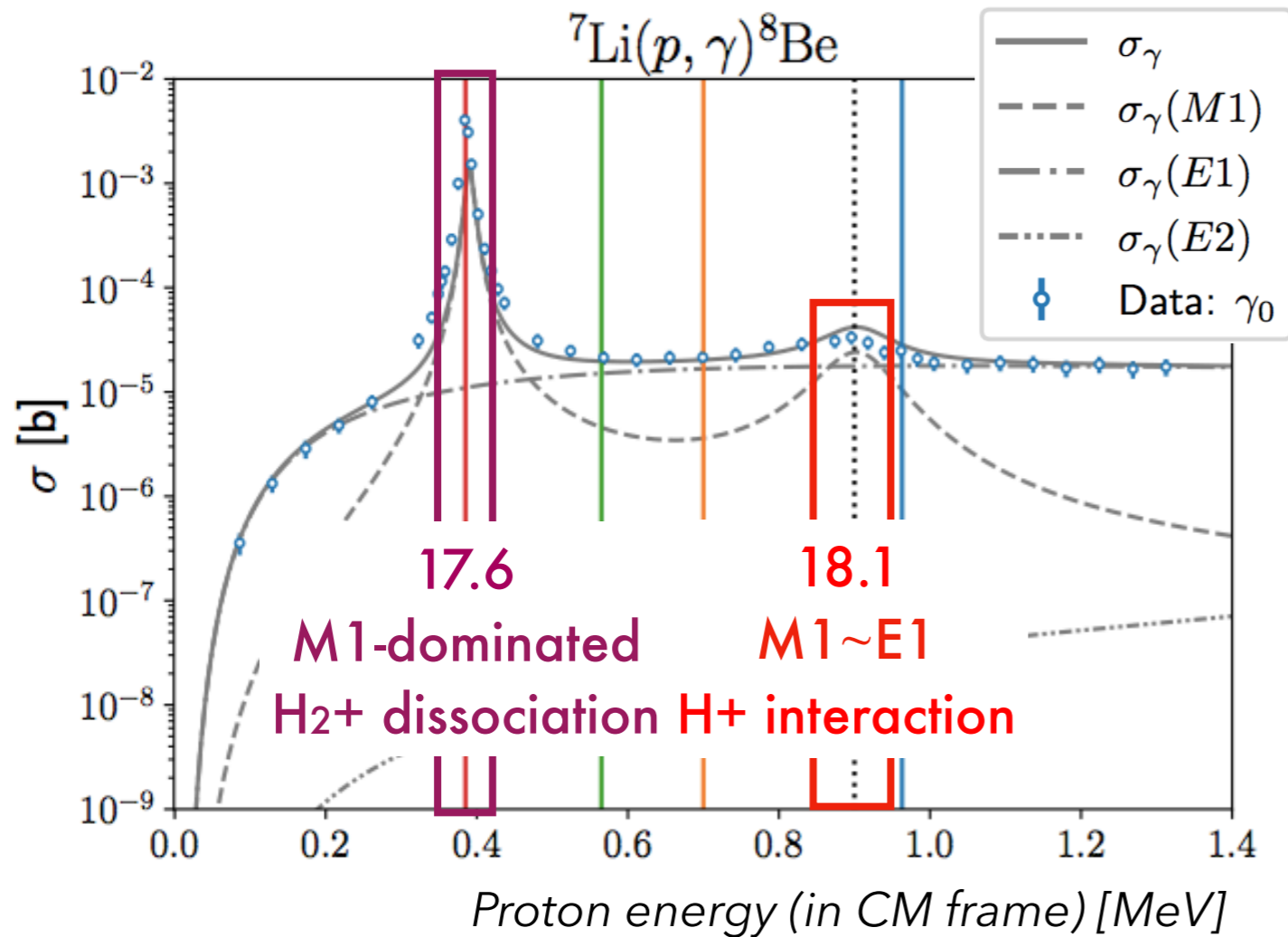
Reconstructed IPC angular opening



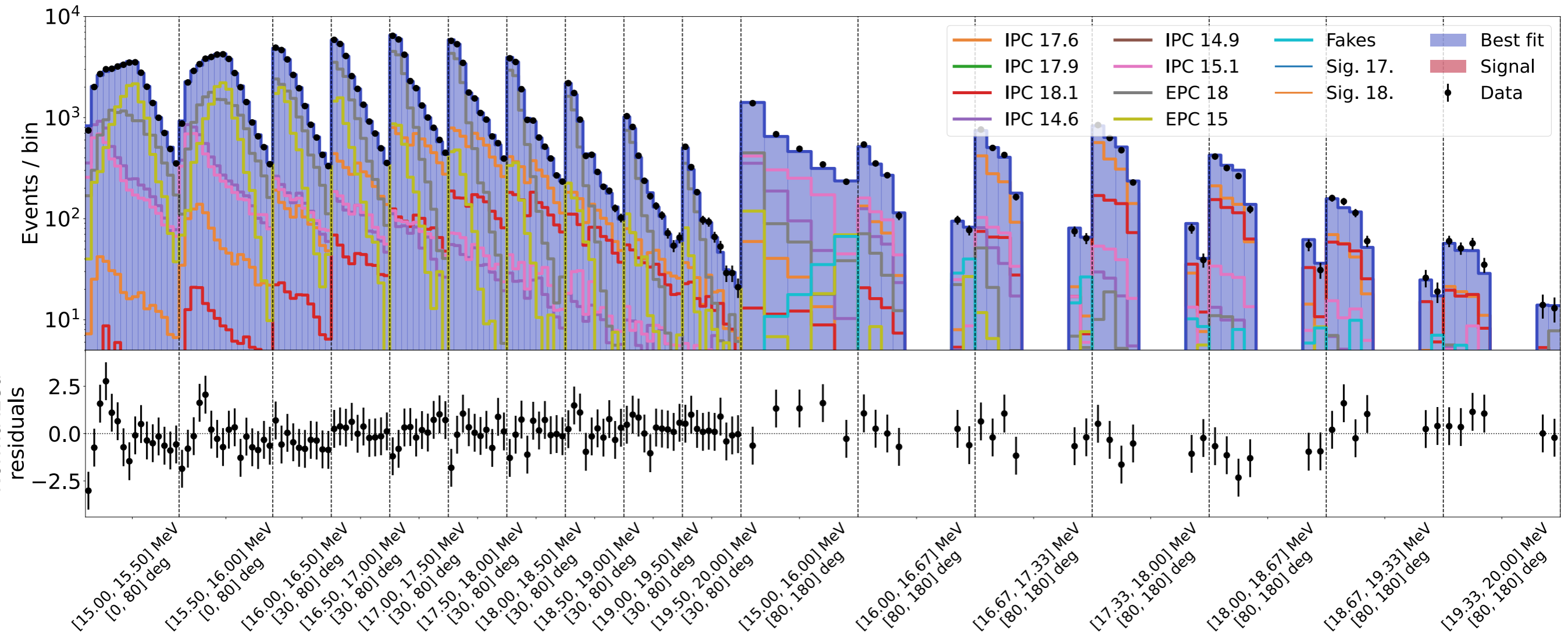
To be considered in the future but for now 1 TC hit required

- We can use template histograms, directly from the MC production:
- no need for PDFs definition
 - naturally accounts for linear and non-linear correlations between the fitted variables
 - easy implementation of Feldman-Cousins approach to confidence belts
-
- EPC and IPC MC production are particularly time consuming.
 - The effect of limited MC statistics can be accounted for in the likelihood (Beeston-Barlow likelihood)
 - 2D template fit Esum vs Angle maximizing such likelihood is under investigation
 - Additional constraints on ratio of proportions between **IPC18,i** and **IPC15,i** based on BGO spectra

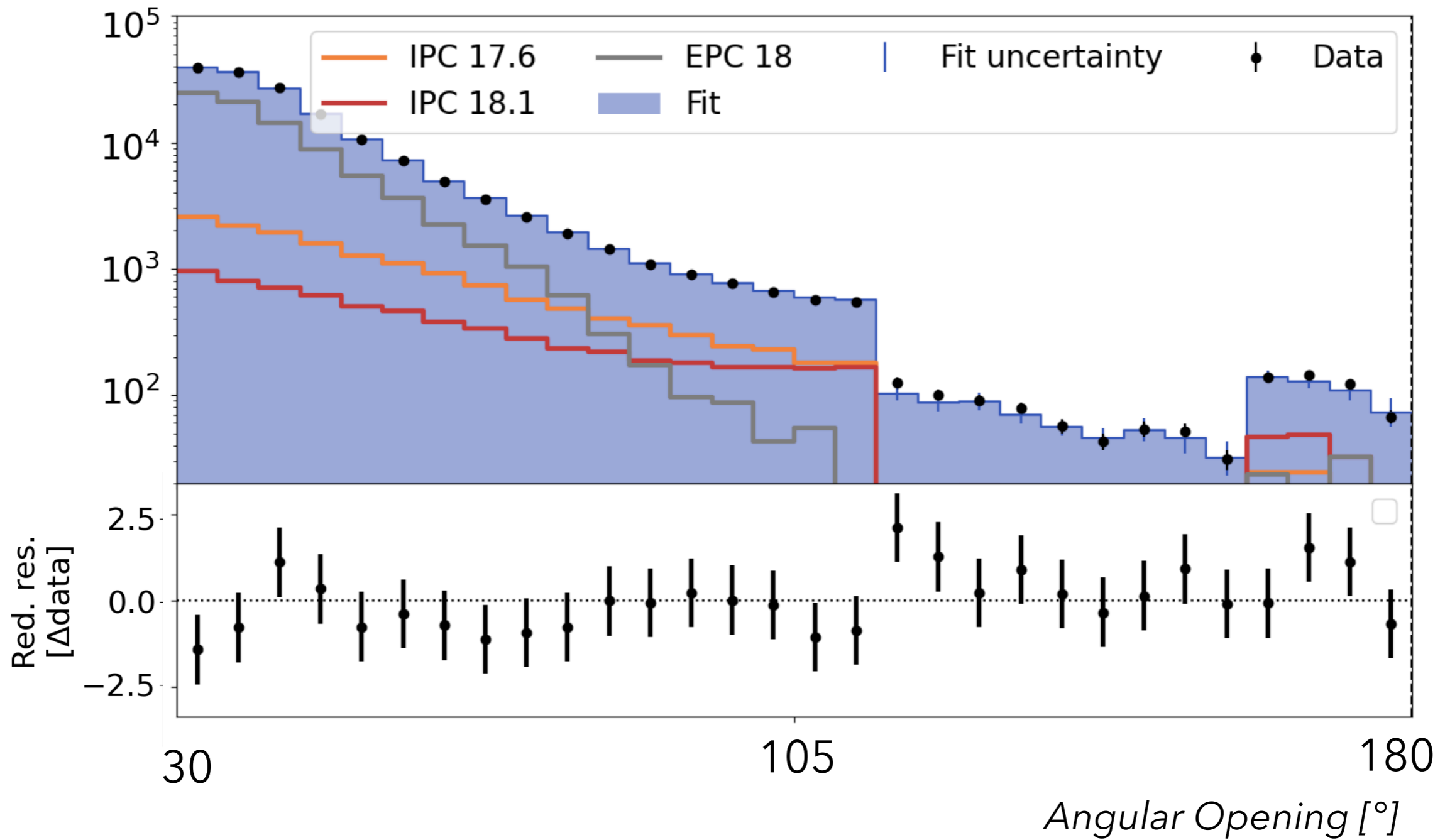
- To account for H₂⁺ contamination:
Two IPC templates based on interacting proton energy



- 2D fit in slices of E_{sum} :

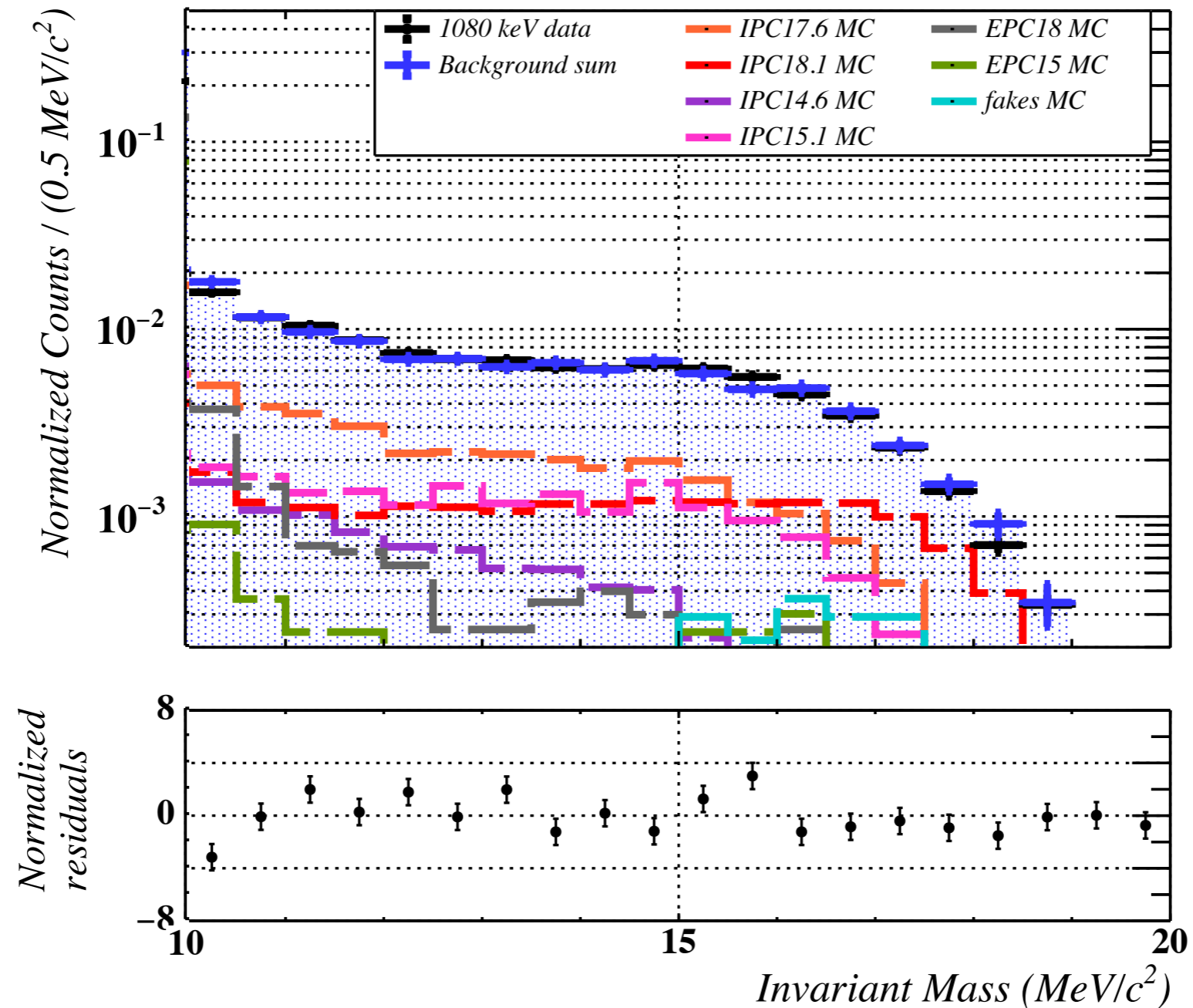


- 1D projection of the 2D fit



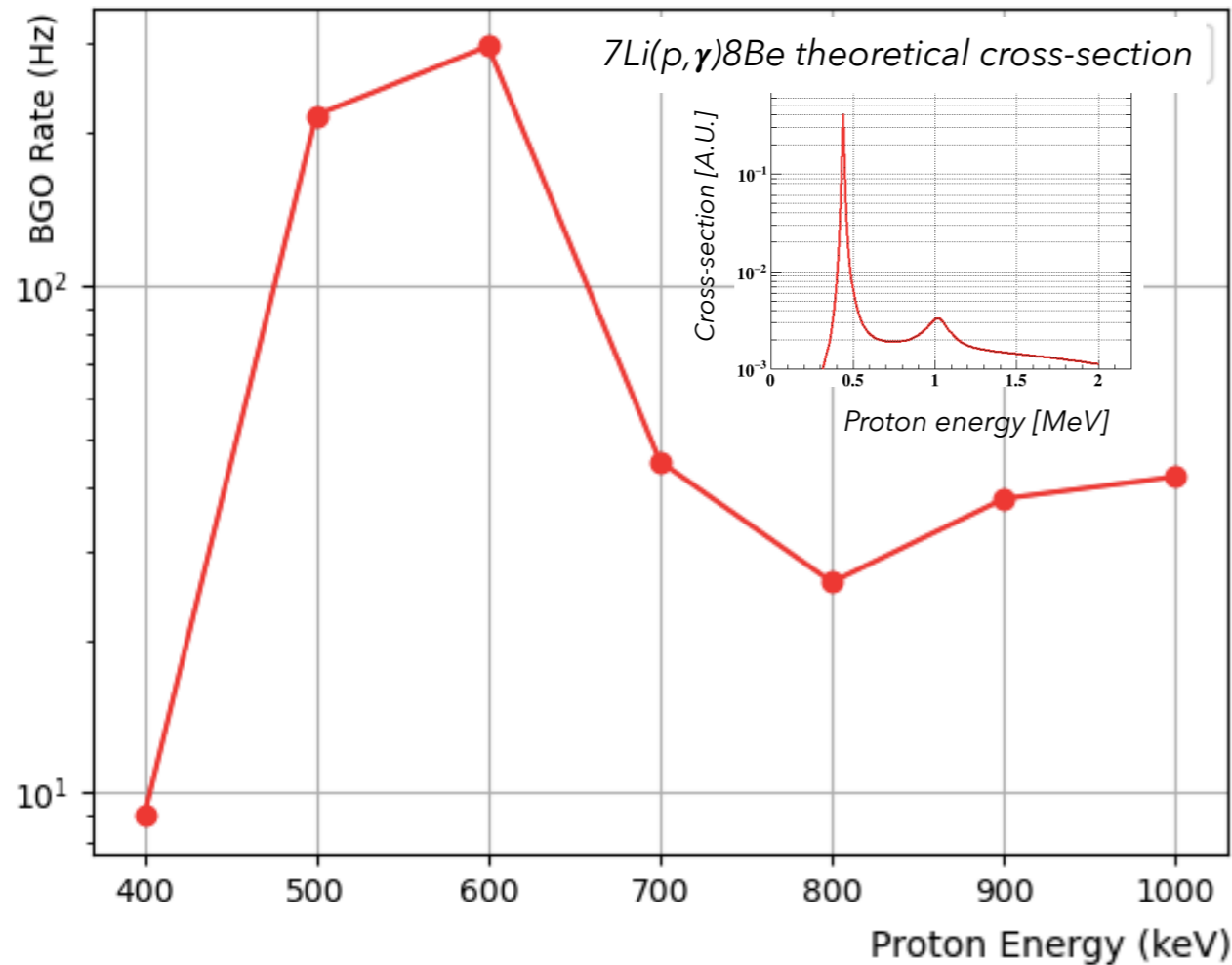
→ Good understanding of the backgrounds above 30°

- 1D Invariant Mass projection of the 2D fit

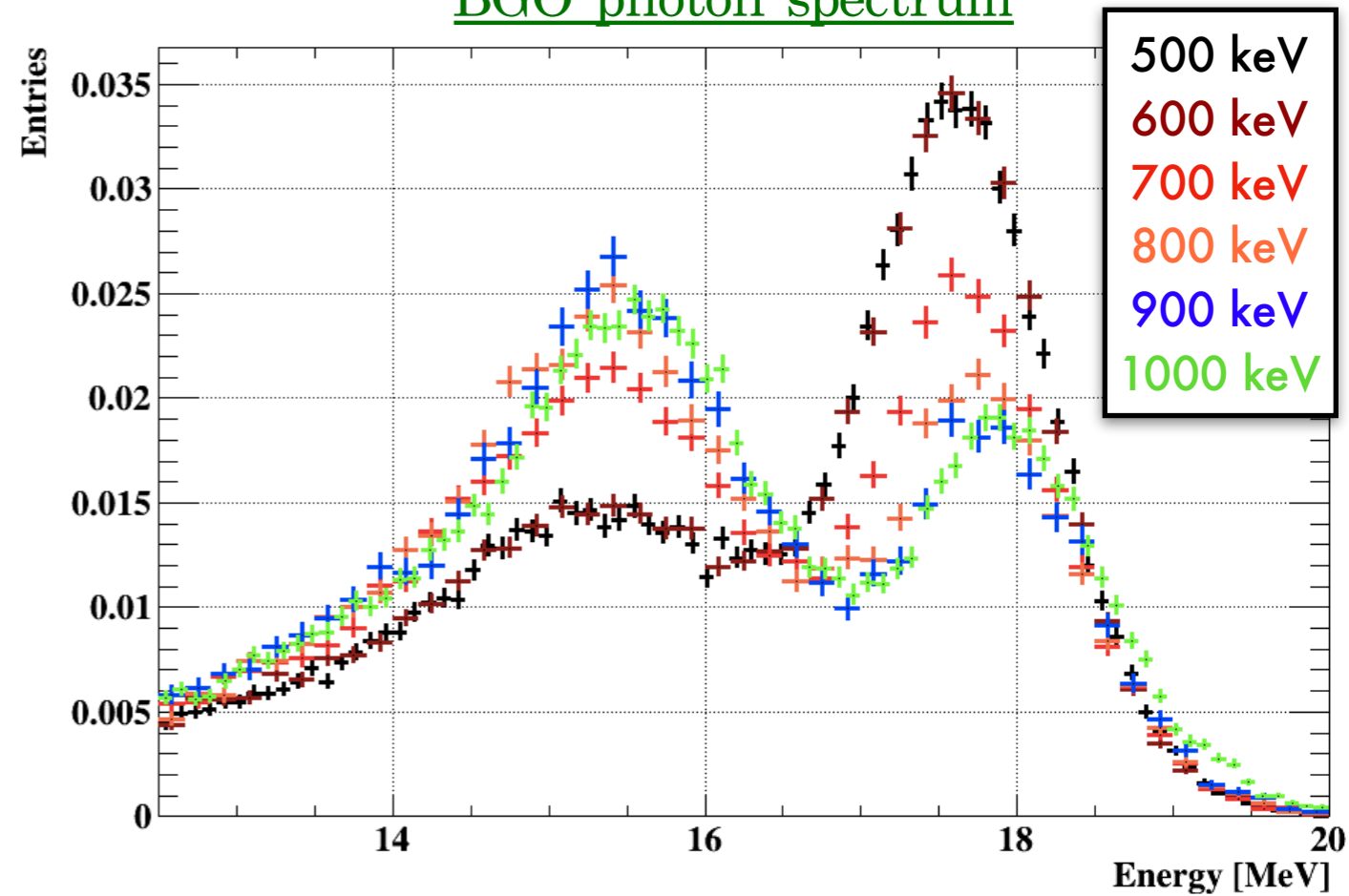


- H₂⁺ contamination was mitigated
- New thin 1.9 μm LiPON target installed
- Anisotropy measurements changing BGO position
- Ep scan with BGO @7 different proton energies

BGO trigger rate vs Proton energy

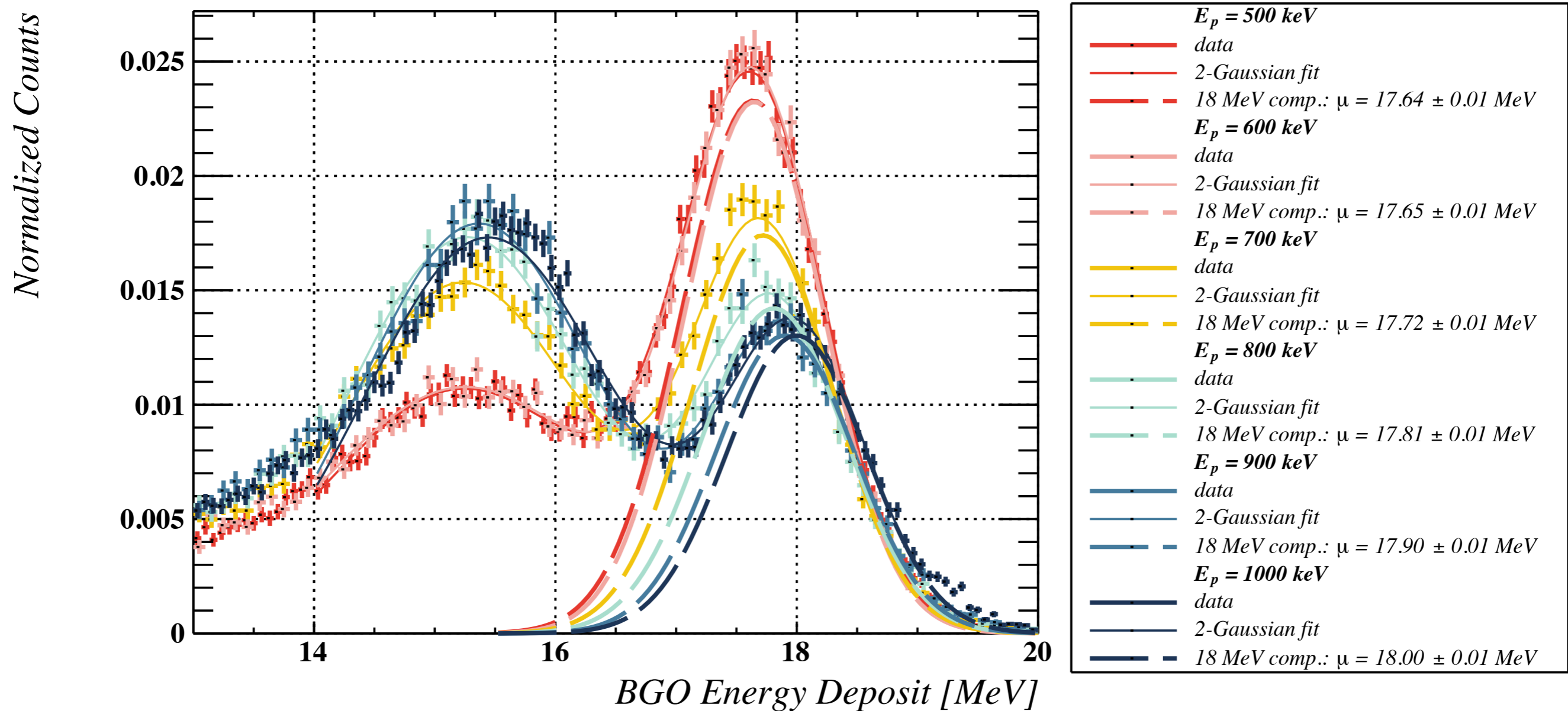


BGO photon spectrum



- Measurement fully in line with expected H⁺ cross-section
- 18.1 MeV line was observed: ready for next DAQ!

➔ **A few hours of data were taken as well:** spectra are shown here



➔ As expected, **clear shift of a few hundred keV. To be confirmed with final fit.**

BGO PMTs gain drift considered small.

➔ As expected, **increased proportion of « 15 MeV line »**