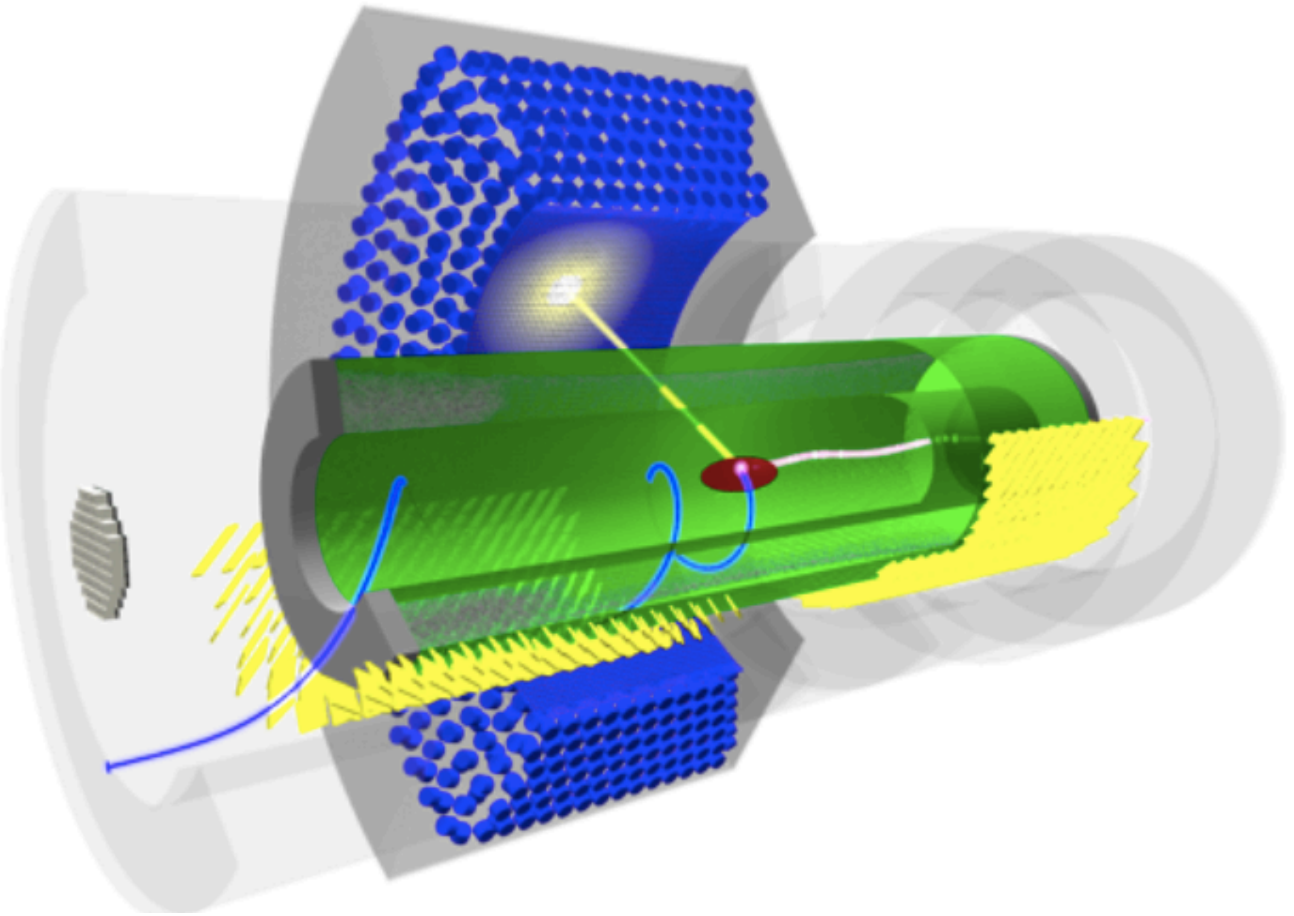
The X17 search with the MEG-II apparatus

H2020 MSCA ITN
G.A. 858199



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on behalf of the MEG-II collaboration

WPCF 2024
Toulouse, November 5th, 2024

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Outline

1) Physics motivation: the Atomki anomalies

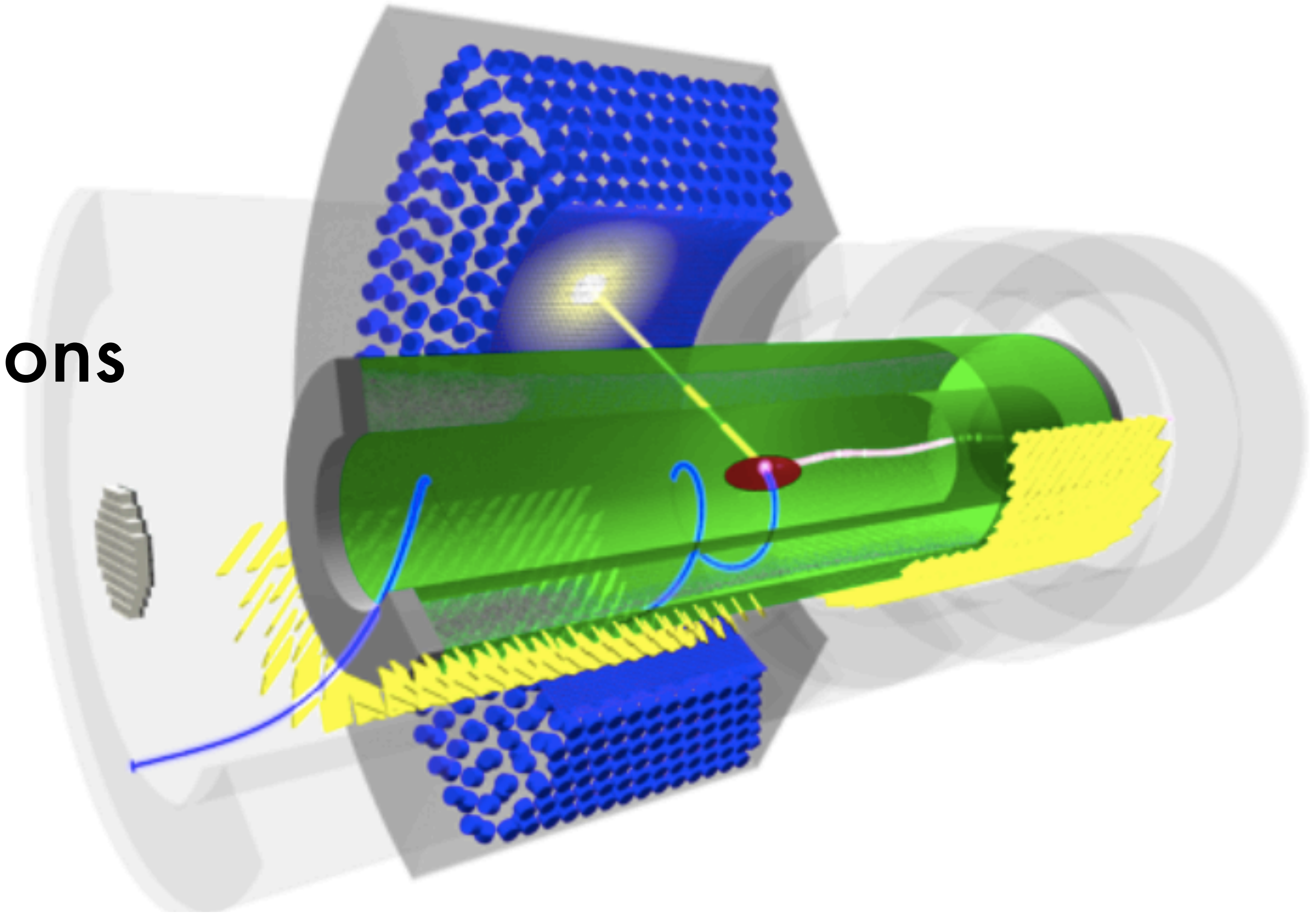
2) The MEG-II apparatus

3) Backgrounds and signal simulations

4) Pair reconstruction

5) Trigger and DAQ strategies

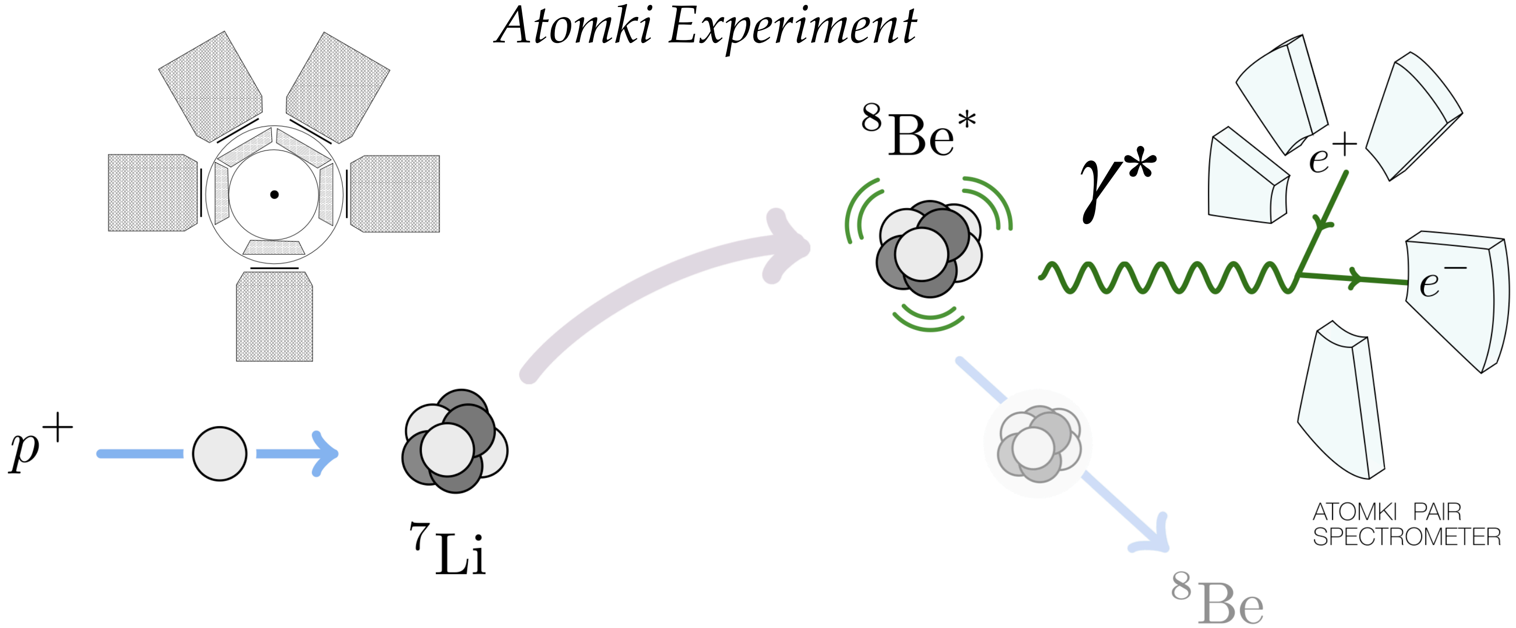
6) Collected data and analysis strategy



1) The Atomki anomalies

The Beryllium Anomaly

Atomki Experiment



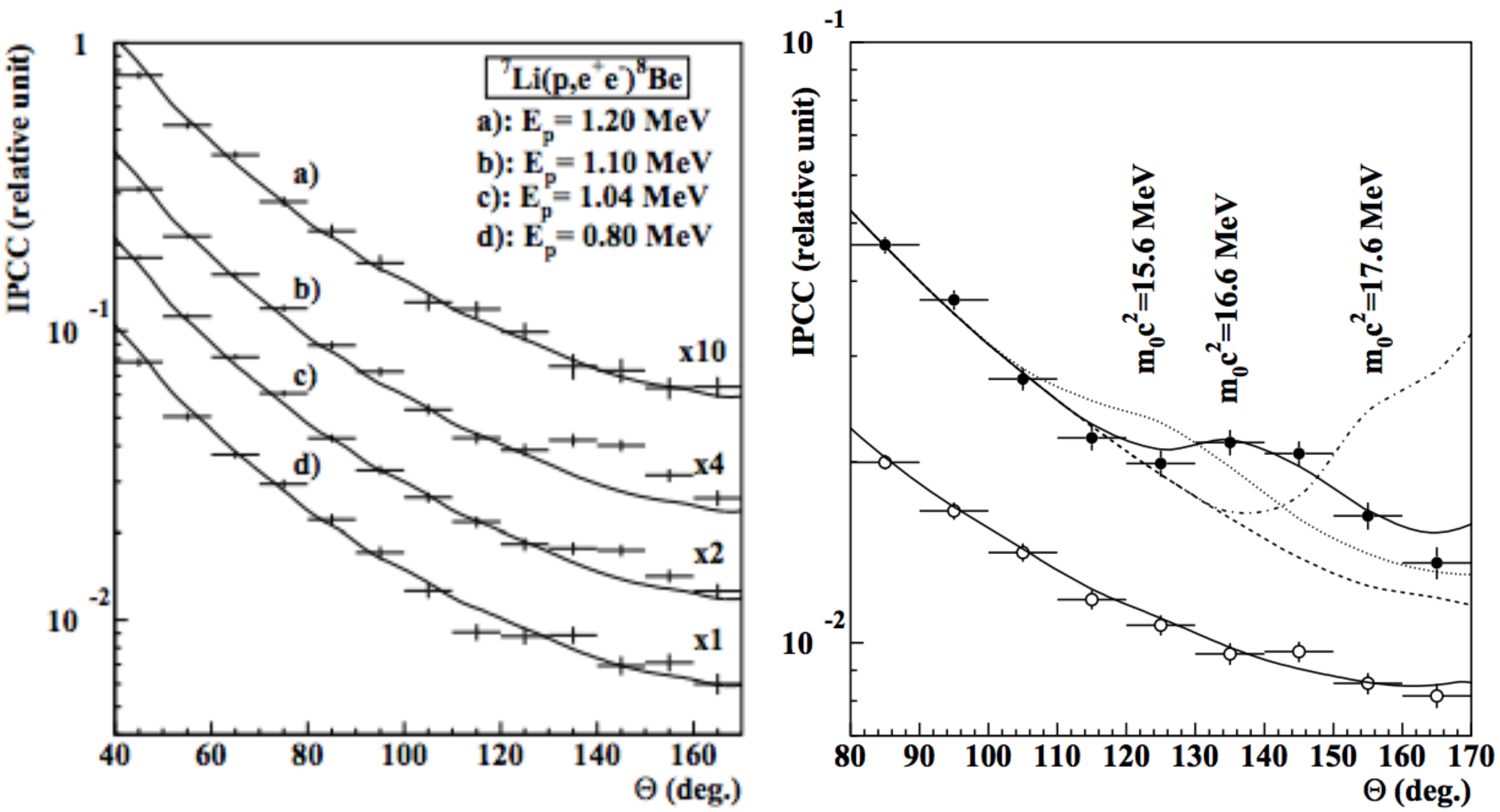
$^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}$ studied at

Ep = 800, 1040, 1100, 1200 keV

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

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

2016 Atomki results



Phys. Rev. Lett. 116, 042501

- Internal Pair Conversion (IPC) distribution shows excess at **Θ**~140° at 1100 keV

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

→ best fit $m_X = 16.70\,\mathrm{MeV/c^2}$

$BR(X) = 6 \times 10^{-6}$

wrt to γ production

→ vector boson X17? mediator of a fifth force?

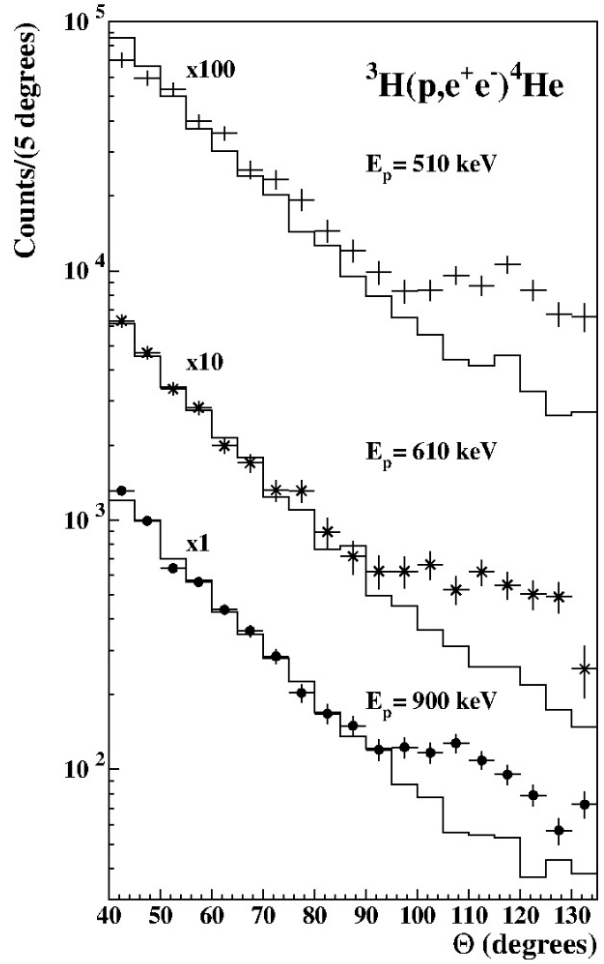
Phys. Rev. D 95, 035017

Consistent anomalies?

Phys. Rev. C 104, 044003

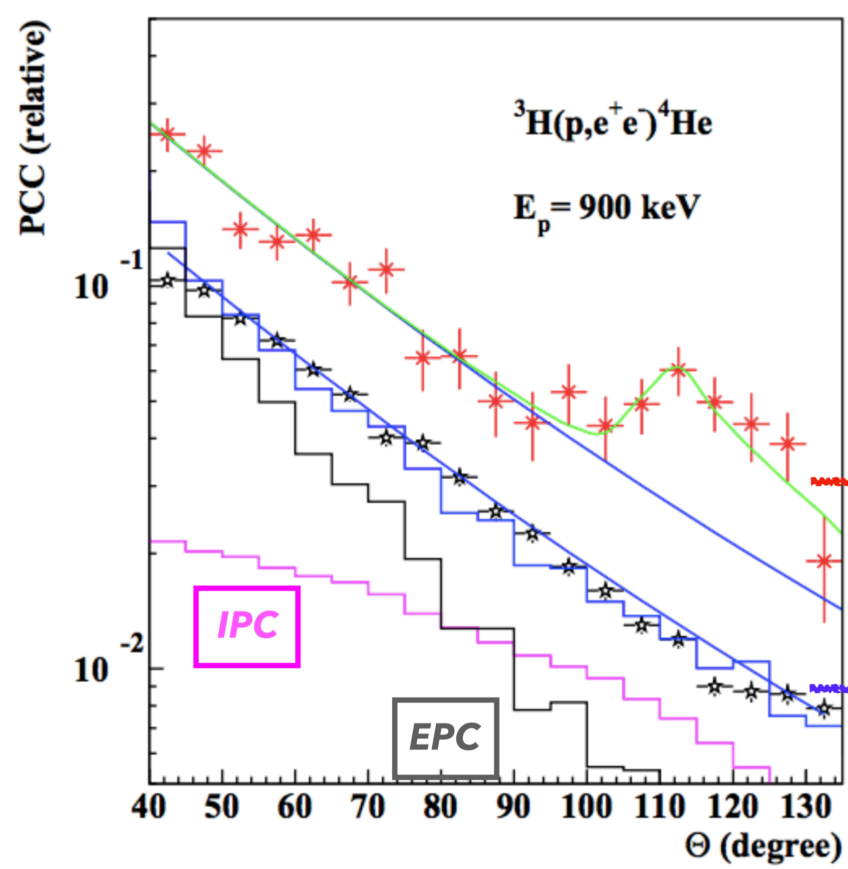
arXiv:1910.10459

Signal region



Study repeated with Tritium target

$$^3\mathrm{H}(p, e^+e^-)^4\mathrm{He}$$



$E_{sum} = E_{e+} + E_{e-}$

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

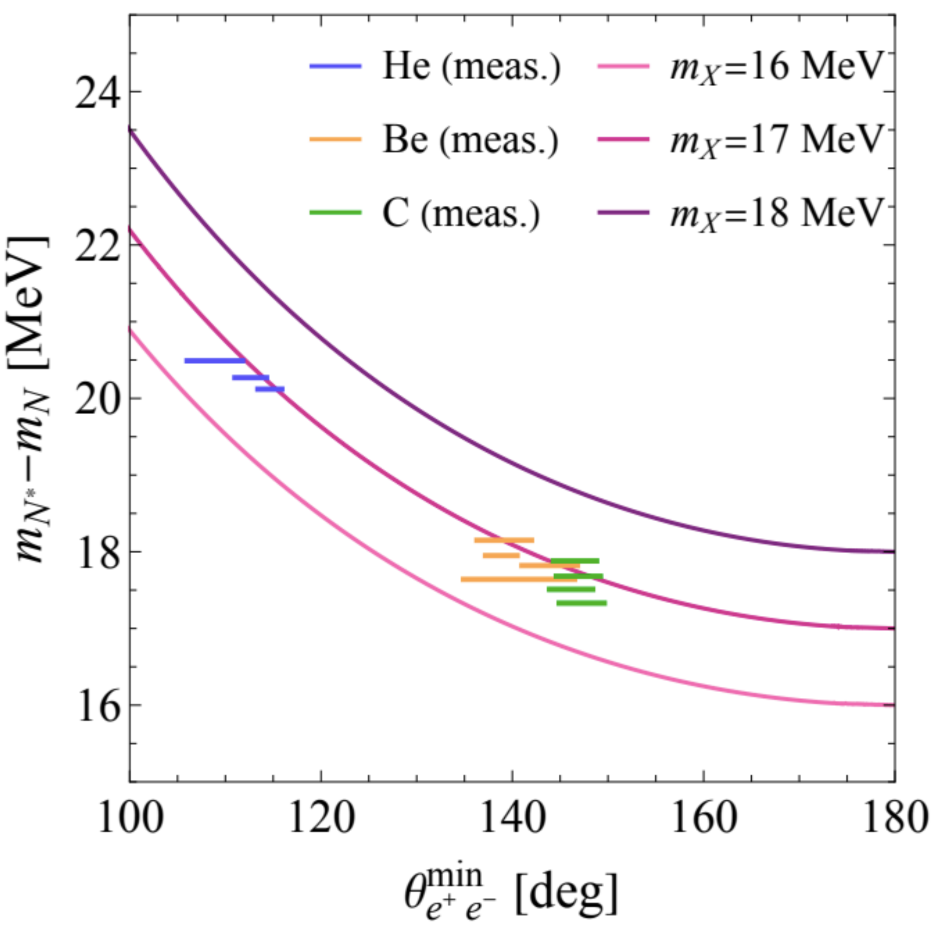
- Excess in IPC background at 115° angular opening: >6σ
- Possible explanation: a 16.84 MeV neutral boson (X17?)
- Recent excess in ^{11}B(p,γ)^{12}C as well Phys. Rev. C 106, L061601
- Other indirect searches (NA64, NA48/2): no evidence for X17 but strong constraints

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

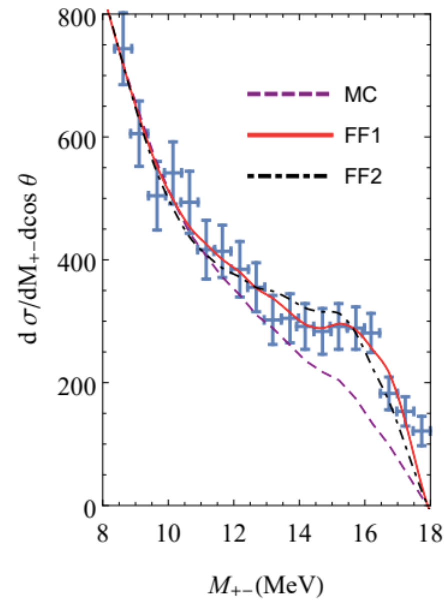
New boson or standard physics?

New boson? or Standard Model physics?

Phys. Rev. D 108, 015009



- Reported results are kinematically consistent



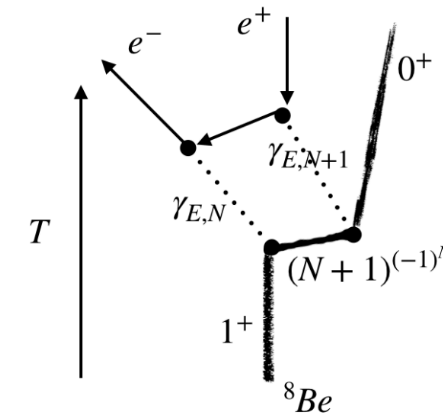
- Zhang & Miller 2017

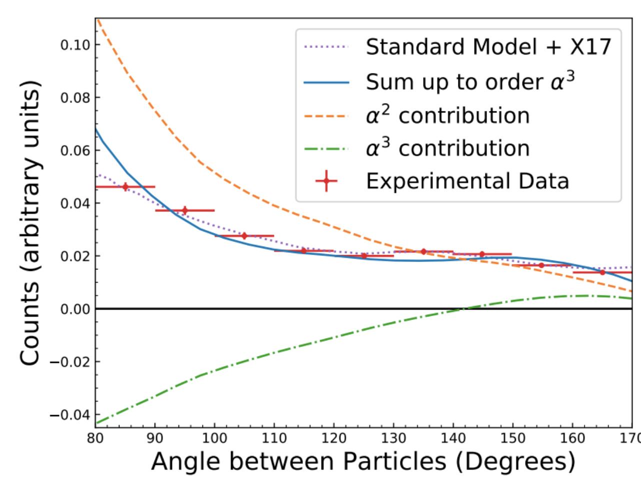
Phys. Lett. B 773, 159

Multipole interferences? Form factor?

- Koch 2021 Modified Bethe-Heitler

Nucl. Phy. A 1008, 122143





- Aleksejevs 2021 arXiv:2102.01127

IPC second-order processes included

- Hayes 2021 Phys. Rev. C 105, 055502

Underlines importance of E1/M1 multipole contribution ratio

MEG-II objectives

- 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?

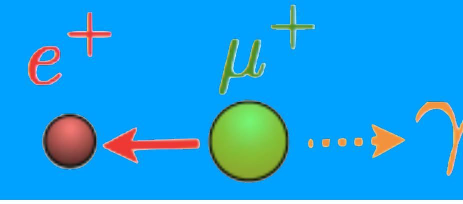
- Need for experimental confirmation: MEG-II has all elements to carry out the measurement
  - → Improved resolution
  - → Reconstruction in full solid angle
  - → Reproduction of excess?

- Engineering run in 2022
- First DAQ period in February 2023

2) The MEG-II apparatus

The MEG-II experiment

The MEG-II experiment

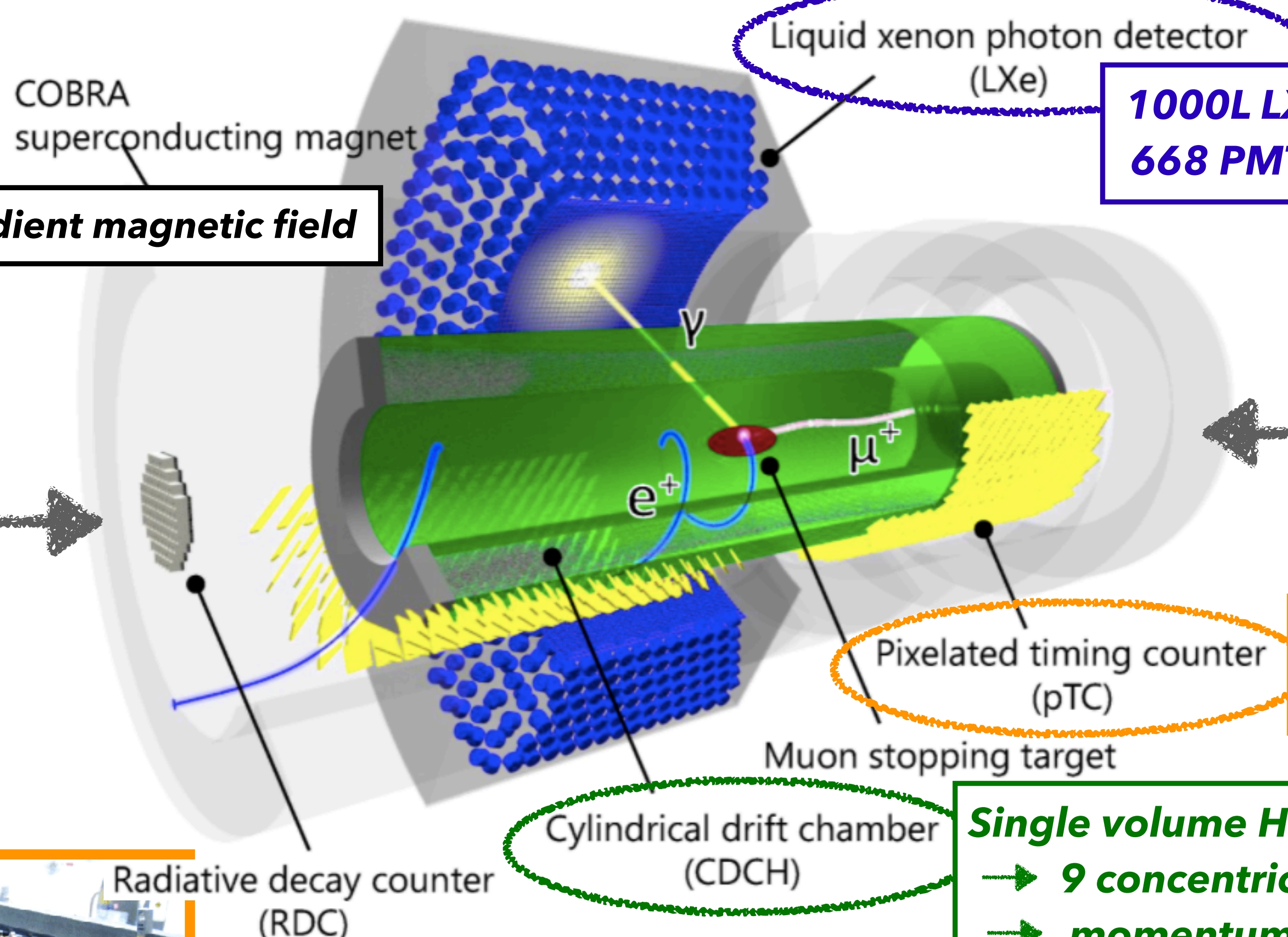


- MEG-II experiment searches for charged lepton flavour violating decay: $\mu^+ \rightarrow e^+\gamma$
- At Paul Scherrer Institute, PSI, Switzerland <u>Eur. Phys. J. C, 76(8):434</u>
- 1 order of magnitude sensitivity improvement wrt MEG: $BR(\mu \longrightarrow e\gamma) \rightarrow 6 \times 10^{-14}$

<u>Eur. Phys. J. C 78, 380</u>

MEG-II results from an intense upgrade program

Gradient magnetic field



1000L LXe tank readout by 668 PMTs and 4092 SiPMs

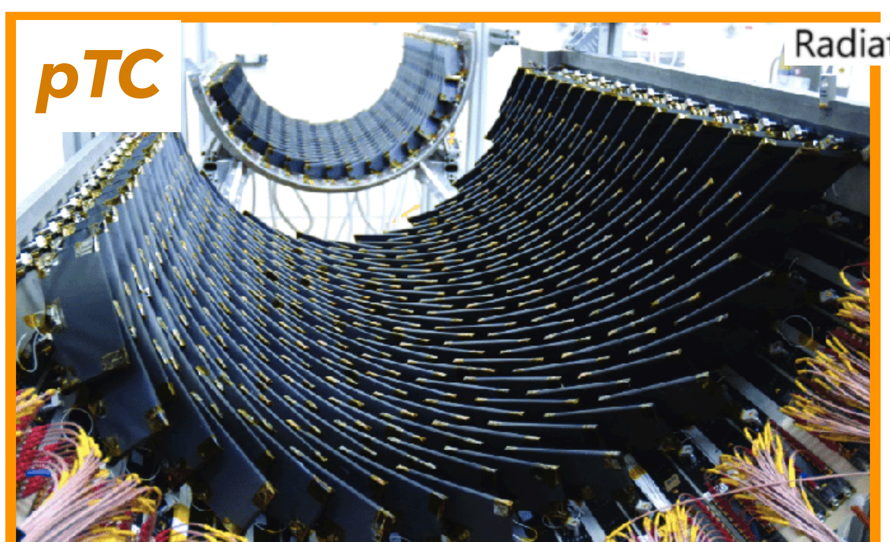
Proton beam direction for X17 search

Muon beam direction for MEG-II search

35 ps resolution
→ 512 plastic tiles

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

pTC



CDCH

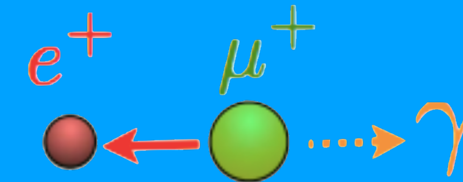
2) The MEG-II apparatus

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



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Eur. Phys. J. C 78, 380

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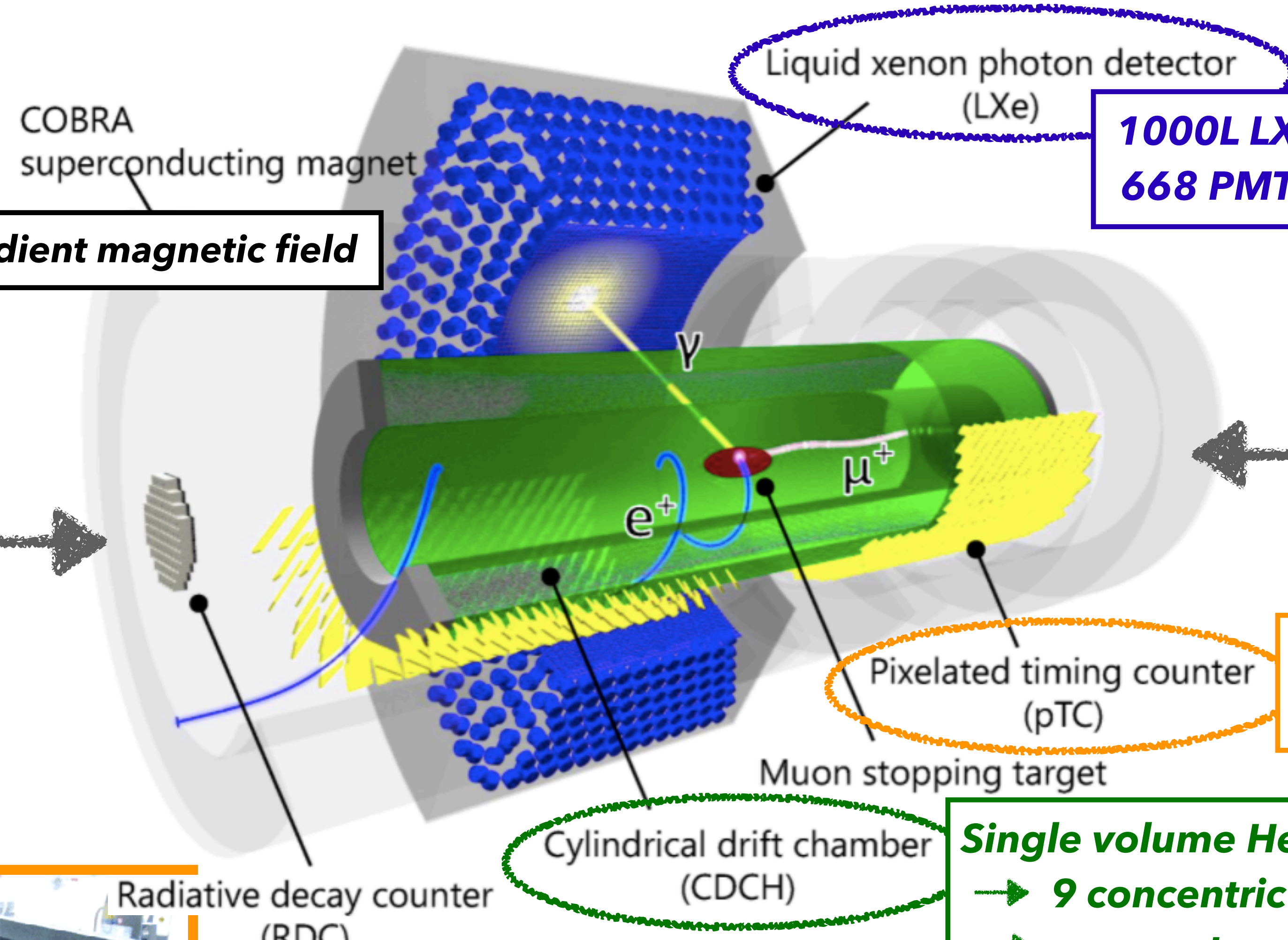

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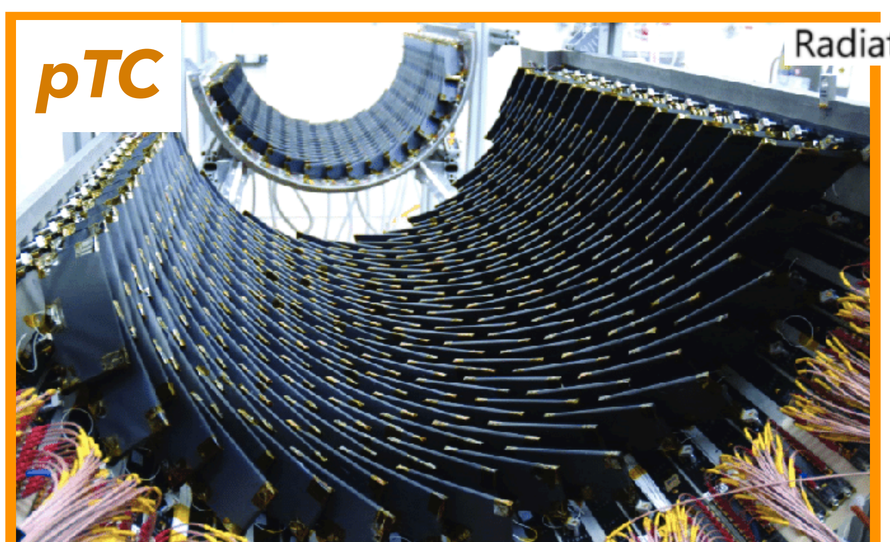


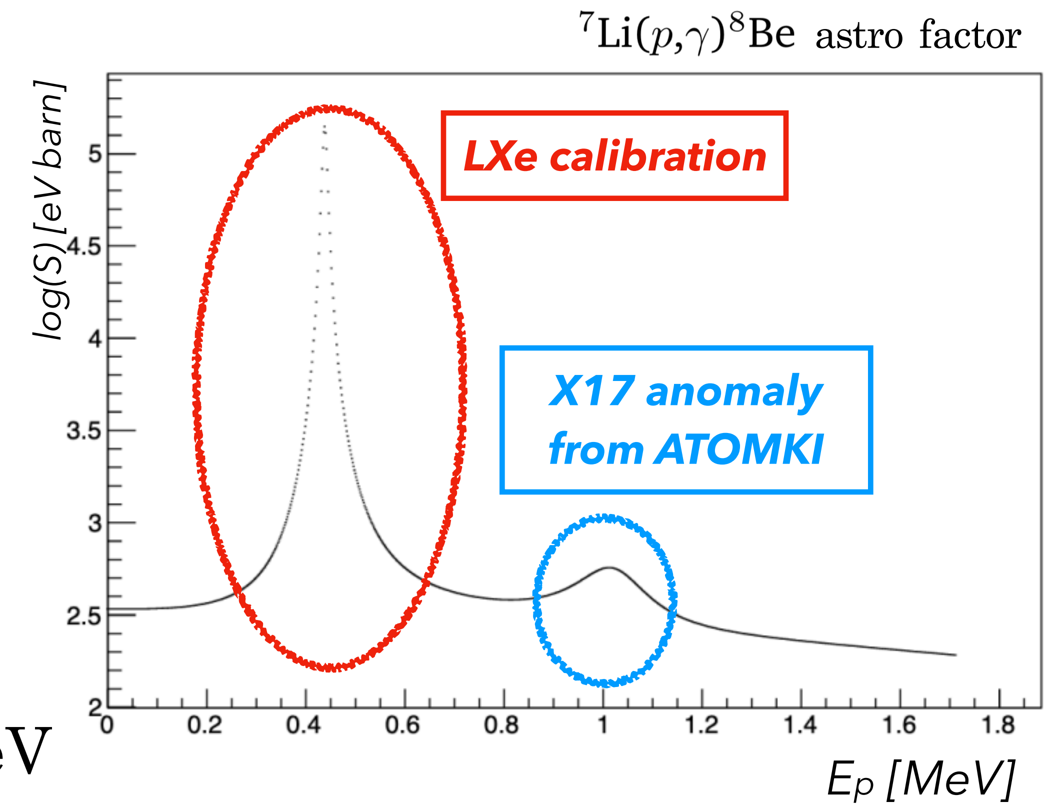
CDCH

The Cockcroft-Walton accelerator

- <u>LXe calibration</u>

  → MEG-II Cockcroft-Walton accelerator: used for calibration of LXe calorimeter

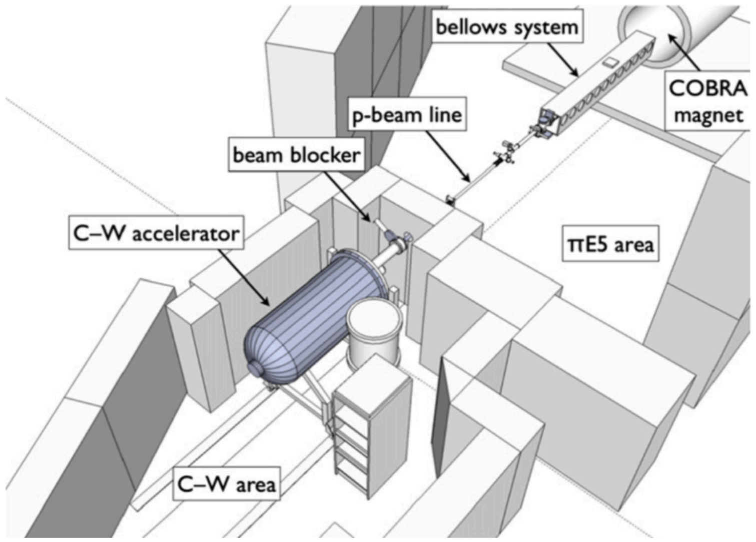
  → Proton beam impinging on Li target (0.44 MeV resonance): 17.64 MeV γ line

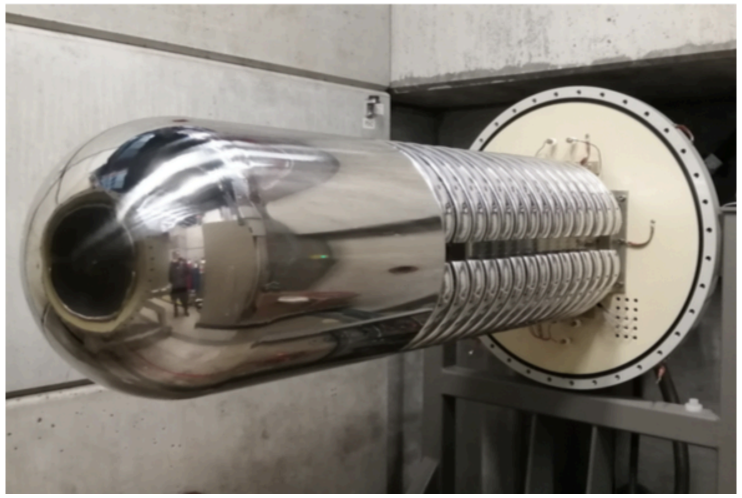


- <u>X17 search</u>

Max proton current and energy: 100 μA and 1.1 MeV

→ ideal for X17 search, 1.03 MeV resonance





Cockroft-Walton beam

- <u>Beam composition investigation and tuning</u>

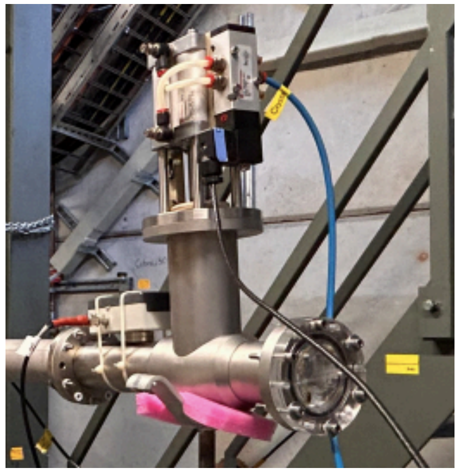
→ CW beam tuned using a quartz target: proton-induced fluorescence in the quartz, visible emission

→ Tuning made varying 4 dipolar fields along the beamline

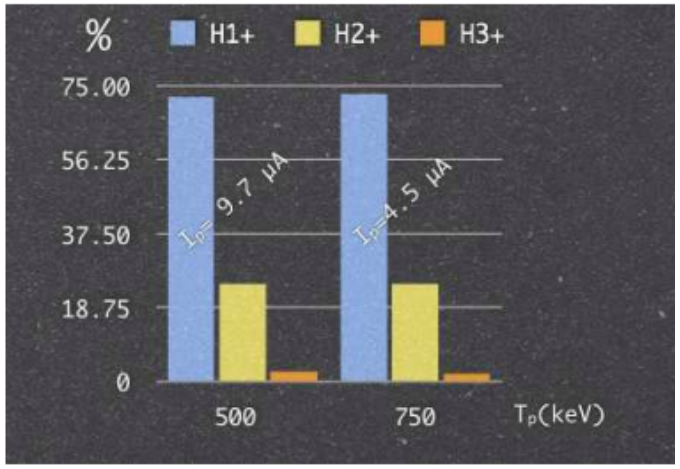
→ H_2^+ contamination in the beam

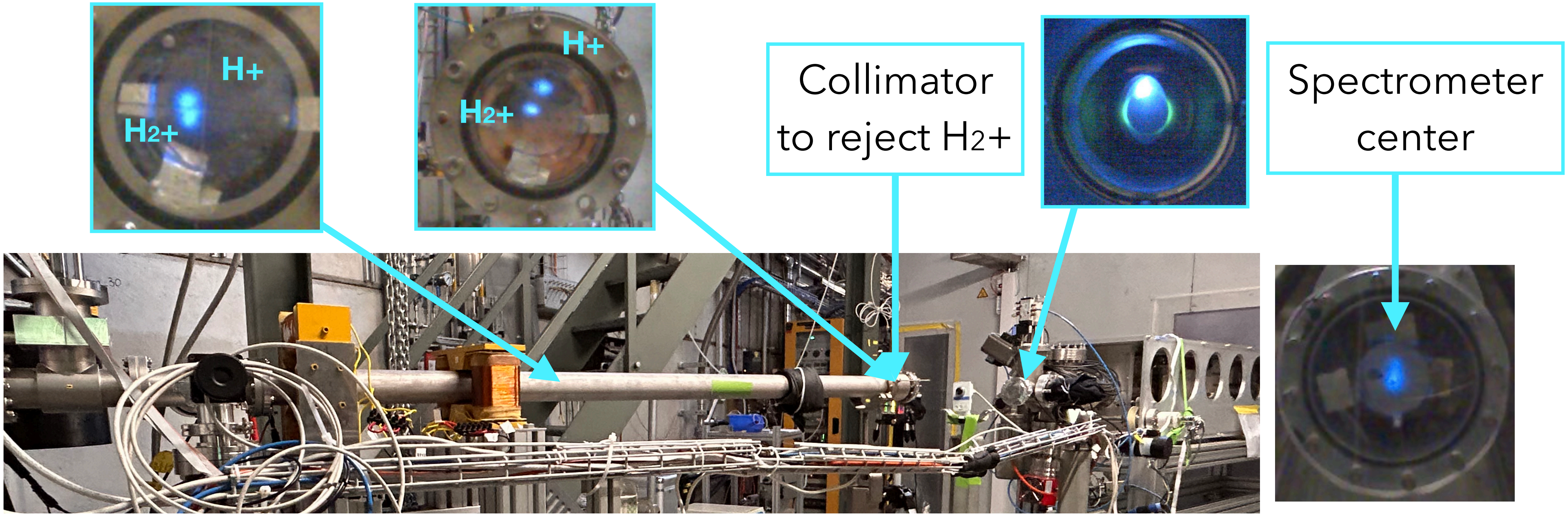
Measurement of the beam ion composition with Faraday Cup

Faraday cup



Ion composition

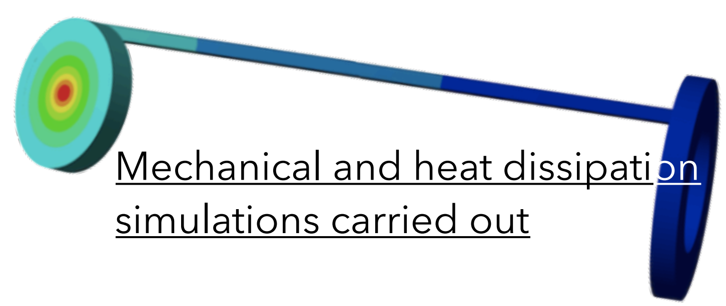




The new target region

- 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

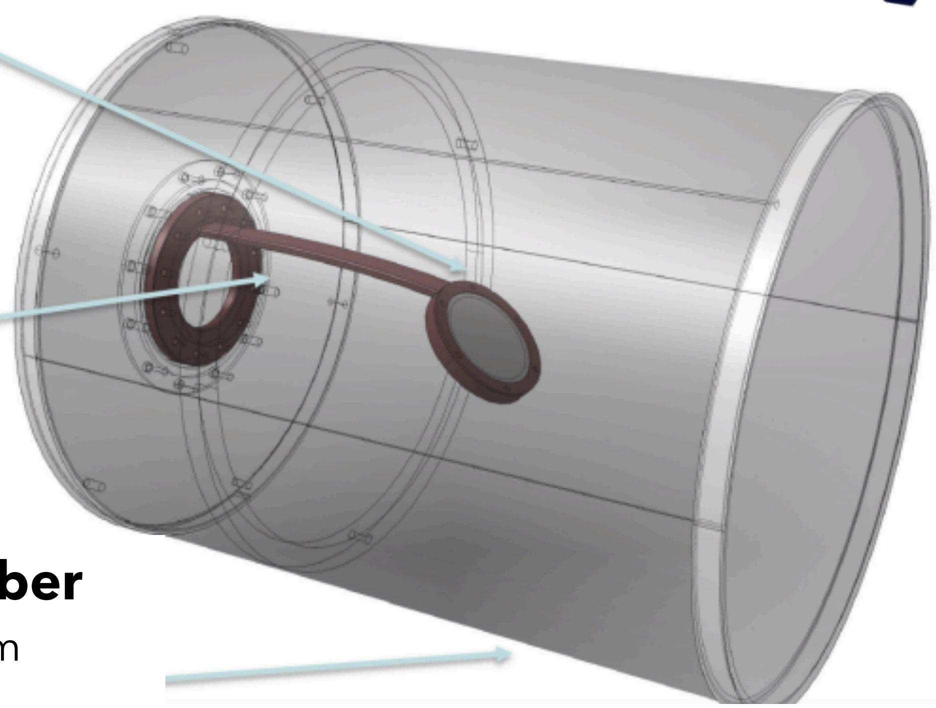
B field x0.15 wrt MEG (0.2T at center)



Mechanical and heat dissipation simulations carried out

Li target
at COBRA center
45° slant angle

Target arm
Cu for heat dissipation



Carbon fiber vacuum chamber
Thickness: 400 μm, Diameter: 98 mm
Length: 226 mm

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

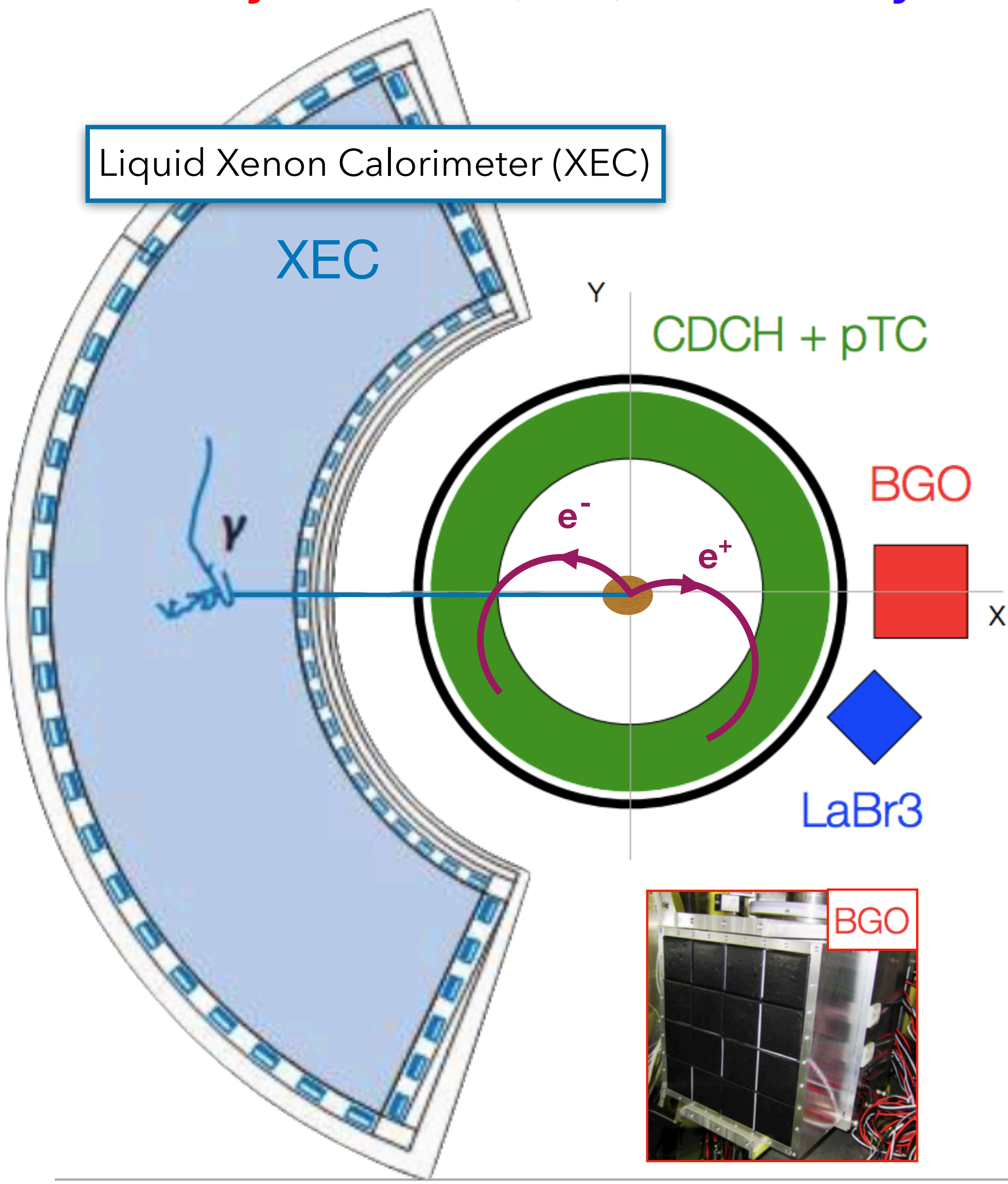
Detectors

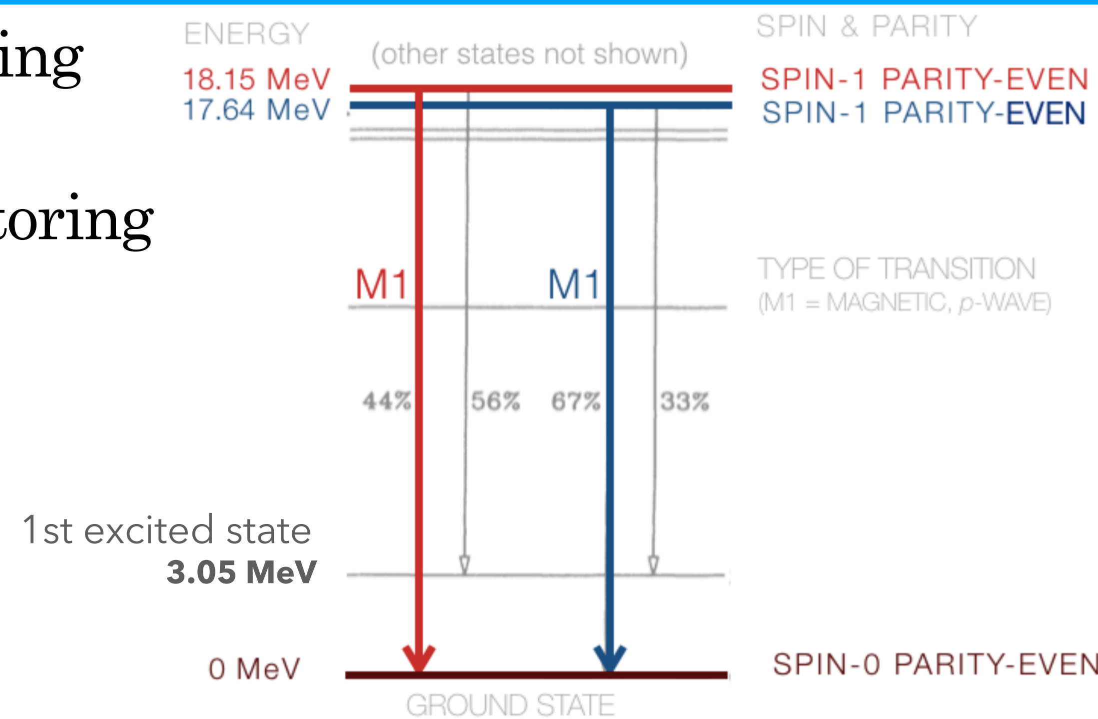
- Main gamma detector for bkg understanding

  LXe calorimeter

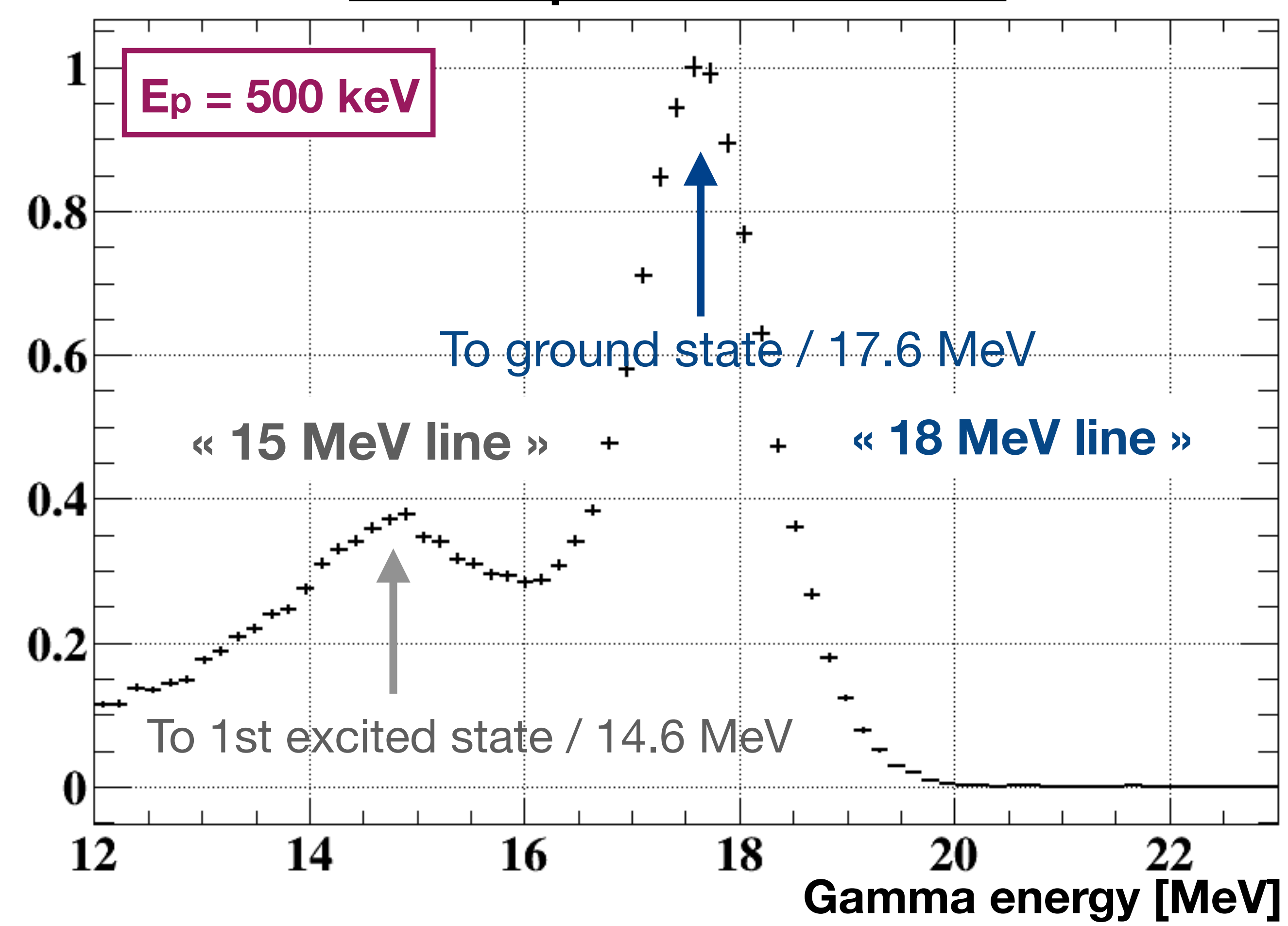
- Two additional gamma detectors for monitoring

  BGO crystal matrix (4x4) **LaBr3 crystal**





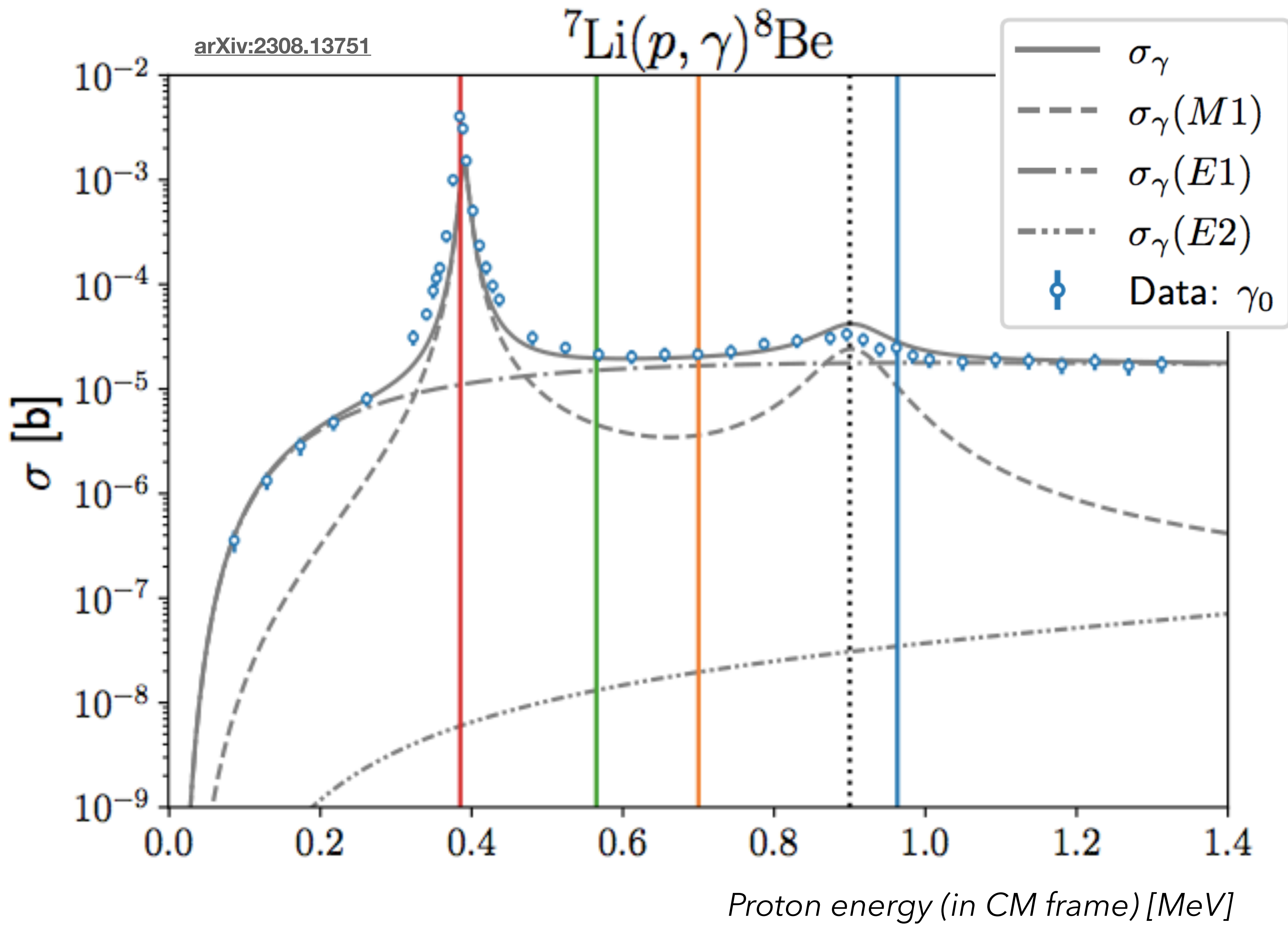
LiPON spectrum from XEC



3) Physics backgrounds and signal simulations

Multipole contributions

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



Internal Pair Conversion

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

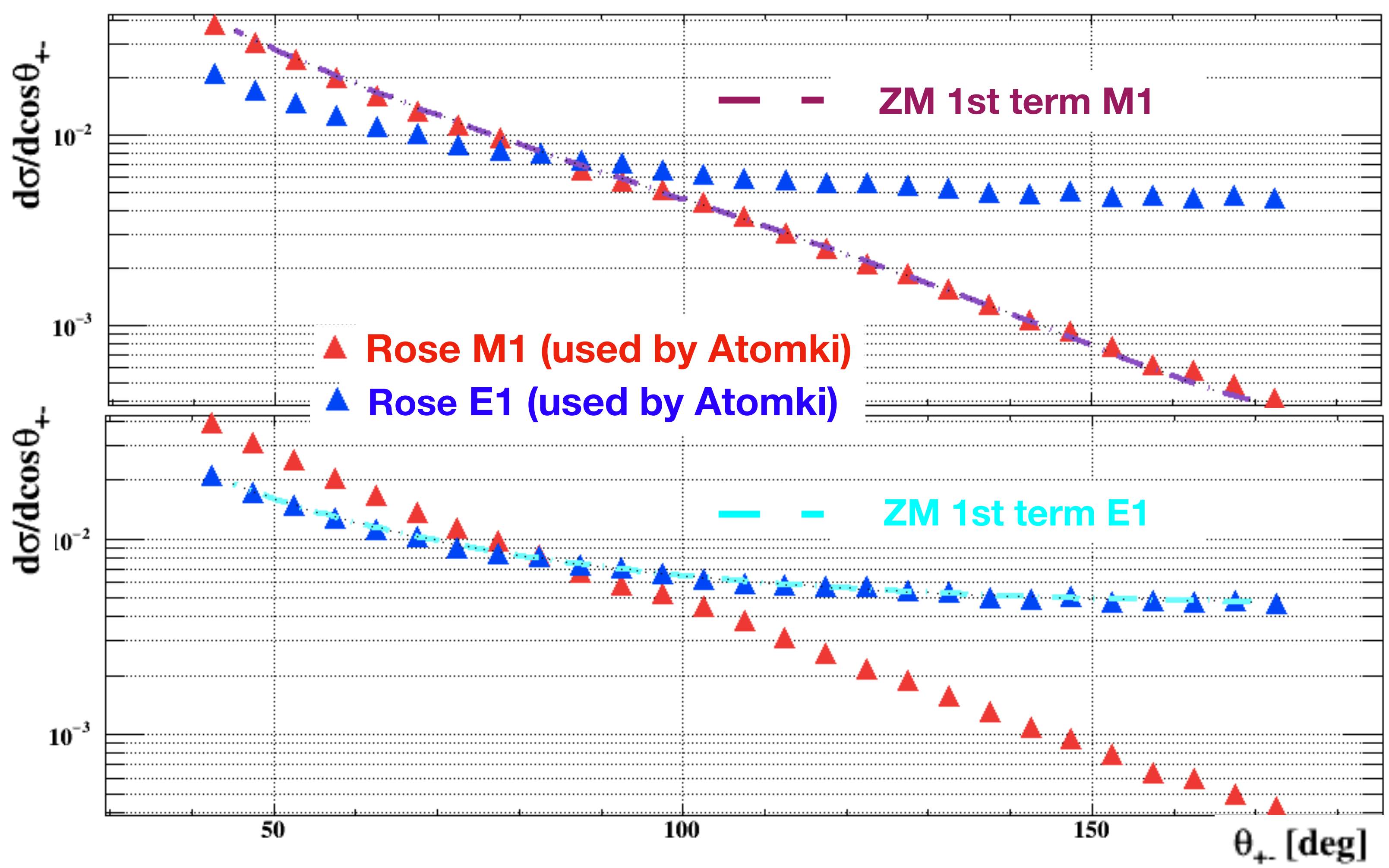
- Need for an accurate background model, IPC is dominant background in signal region
- First IPC model developed by Rose in 1949 Phys. Rev. 76, 678

→ Anisotropy and multipole interferences not included

→ Zhang and Miller in 2017 did it, ZM model
Phys. Lett. B 773, 159

$$d\sigma/d\cos\theta_{+-}dE_{+}d\cos\theta\, d\phi \propto T_{0,0} + T_{0,2}\cos 2\phi + T_{1,0}P_1 + T_{2,0}P_2 + T_{2,2}P_2\cos 2\phi + T_{3,1}\sin\theta\cos\phi + T_{4,1}\sin 2\theta\cos\phi\ , \quad (4.1)$$

Rose-equivalent ($T_{0,0}$)



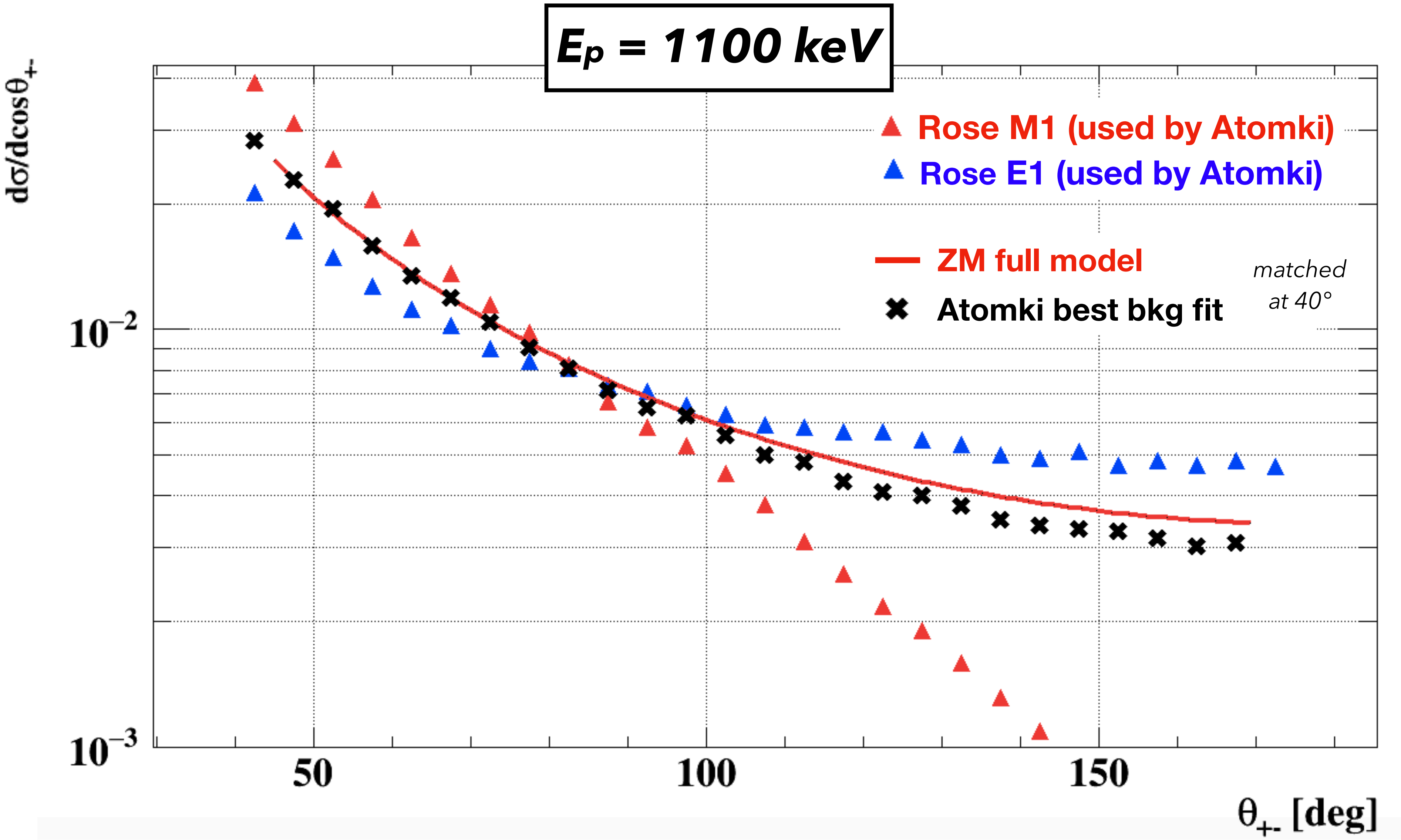
→ We implemented Zhang-Miller model

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

Internal Pair Conversion

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

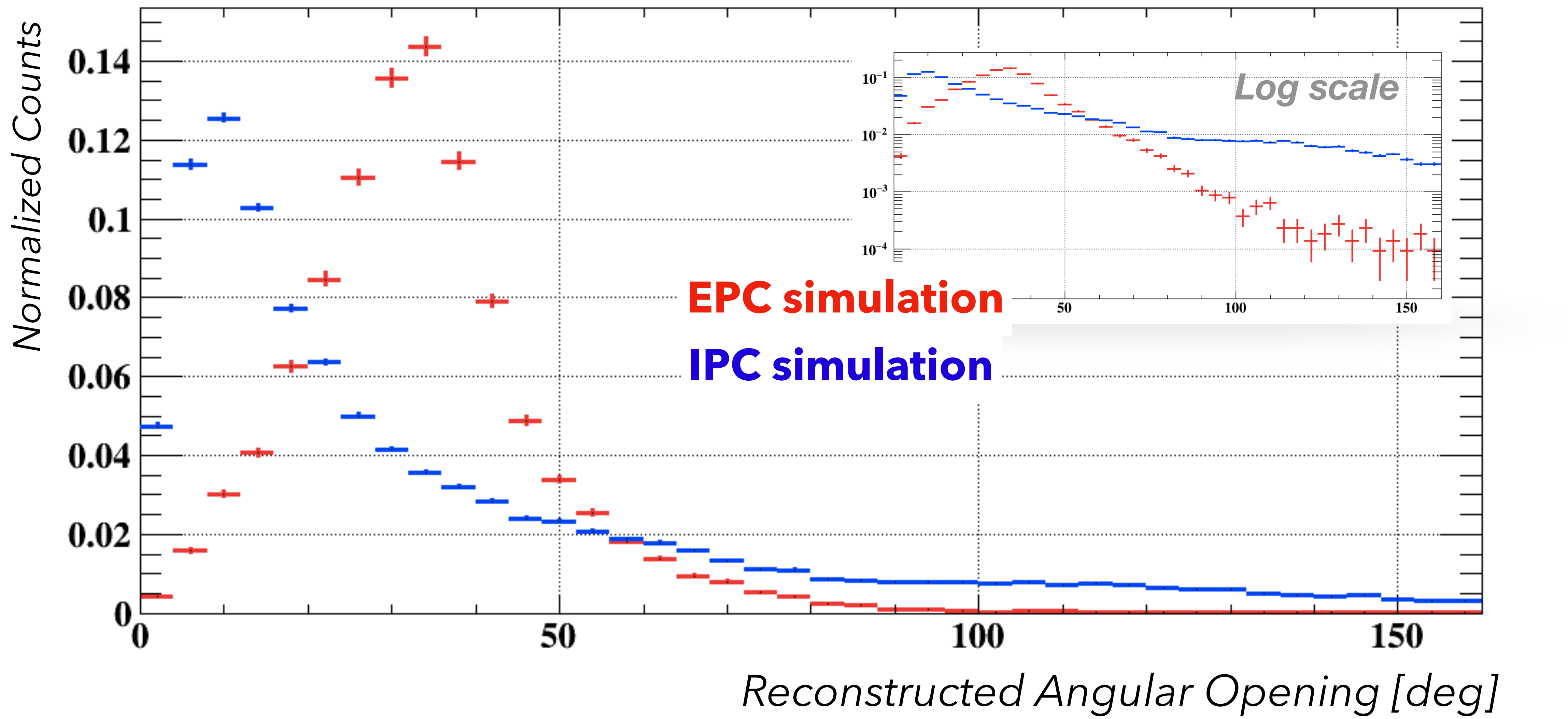
- Let's compare Atomki's background with ZM full model



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

External Pair Conversion and other bkgs

- We simulated External Pair Conversion —> gamma conversion in matter
- EPC rate was estimated to be comparable to IPC
  - → But angular opening is largely concentrated below 70°, far from the signal region

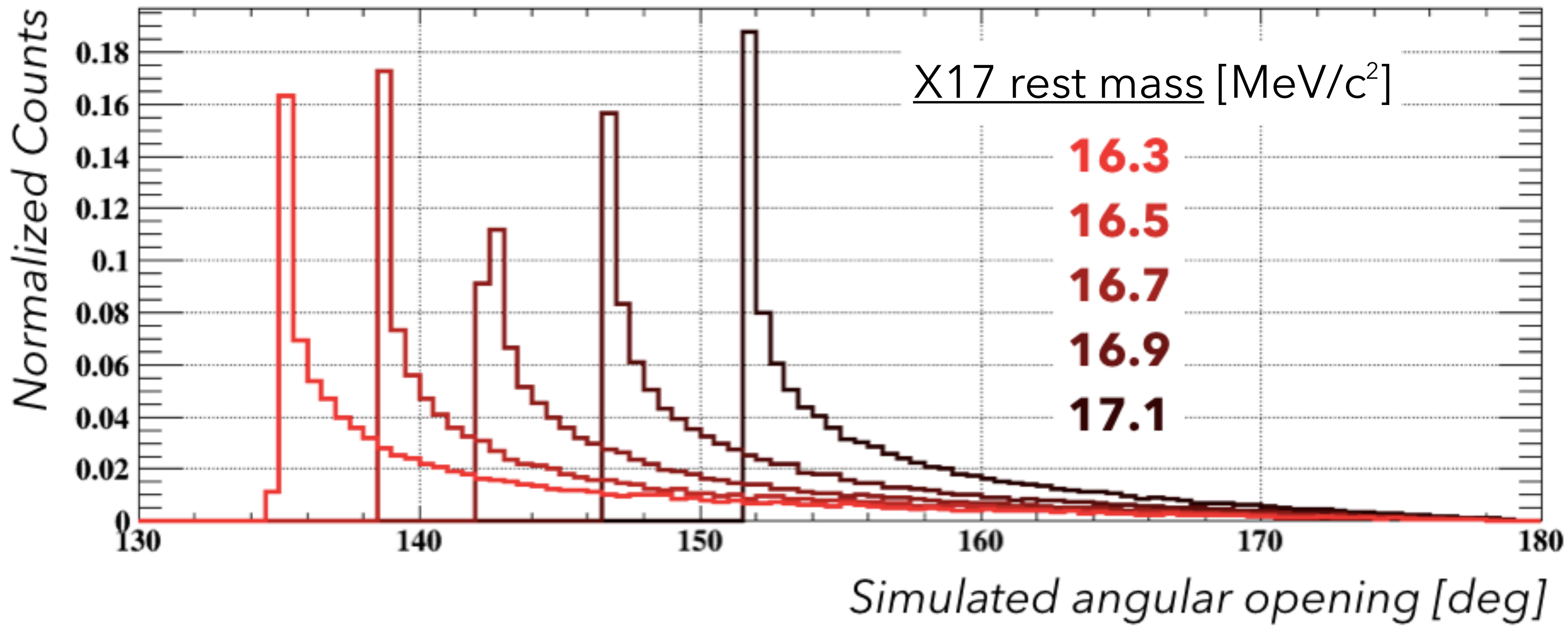


→ Almost 2 orders of magnitude below IPC in signal region

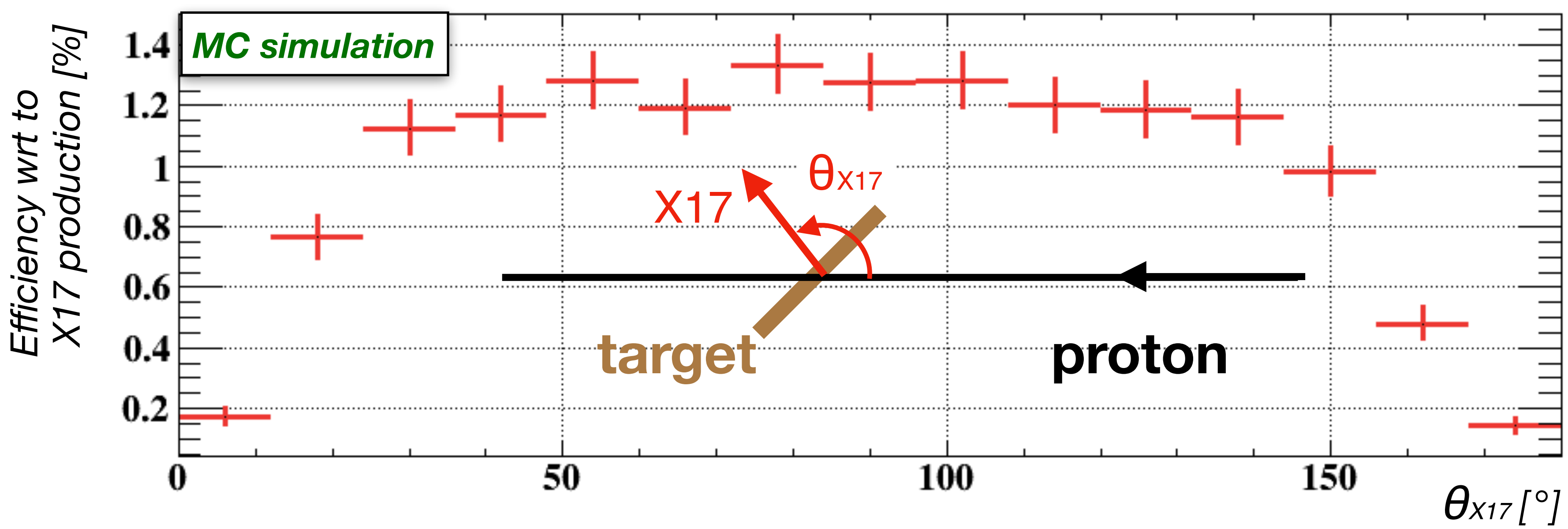
→ All photon conversion events included in full simulation

Signal 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

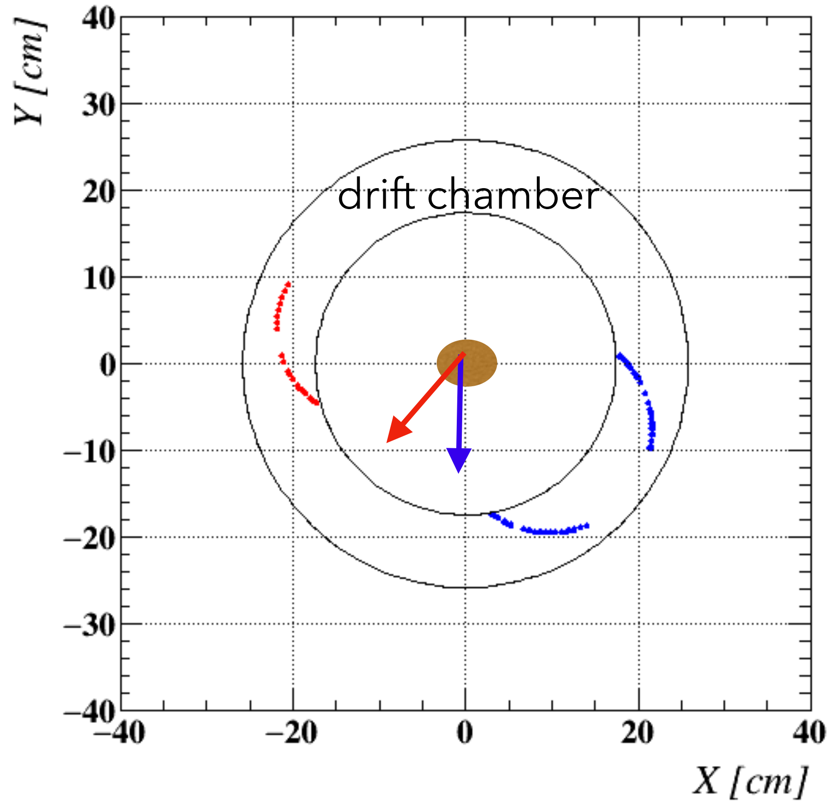


- X17 reconstructed not only in orthogonal plane
- 1% efficiency in planes between 40° and 140°

4) Pair reconstruction

Event display

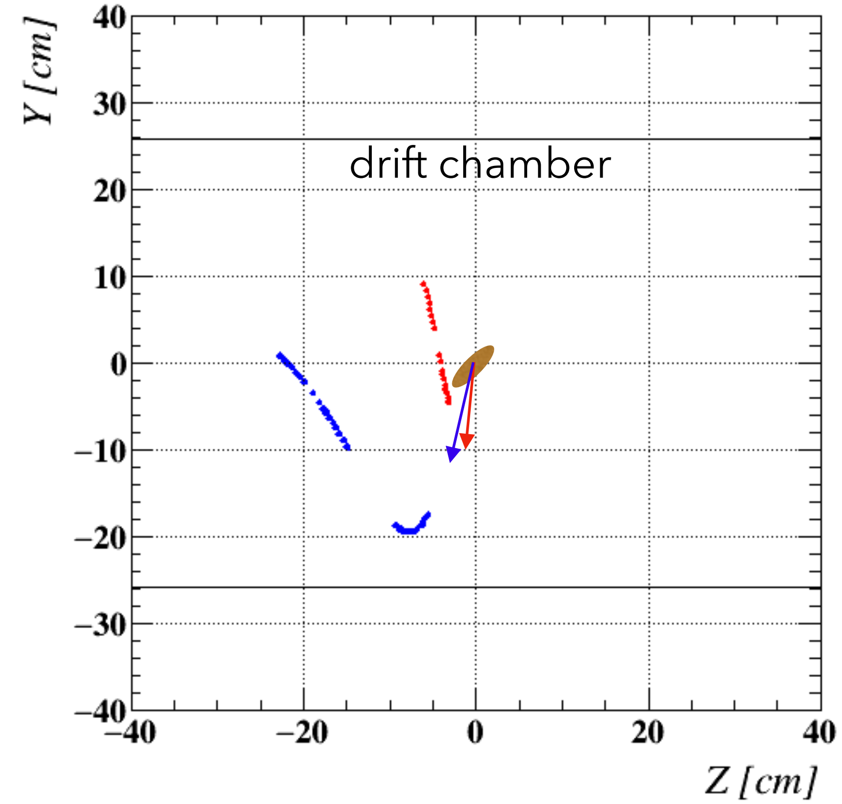
- MEG-II only reconstructs e+. Procedure was adapted for e- as well.

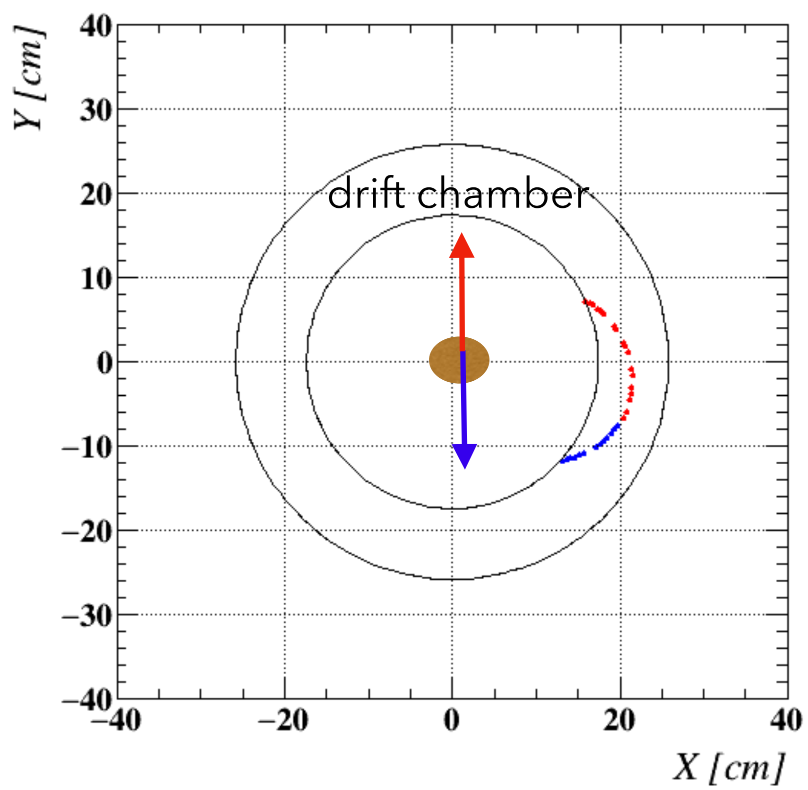


GOOD PAIR

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

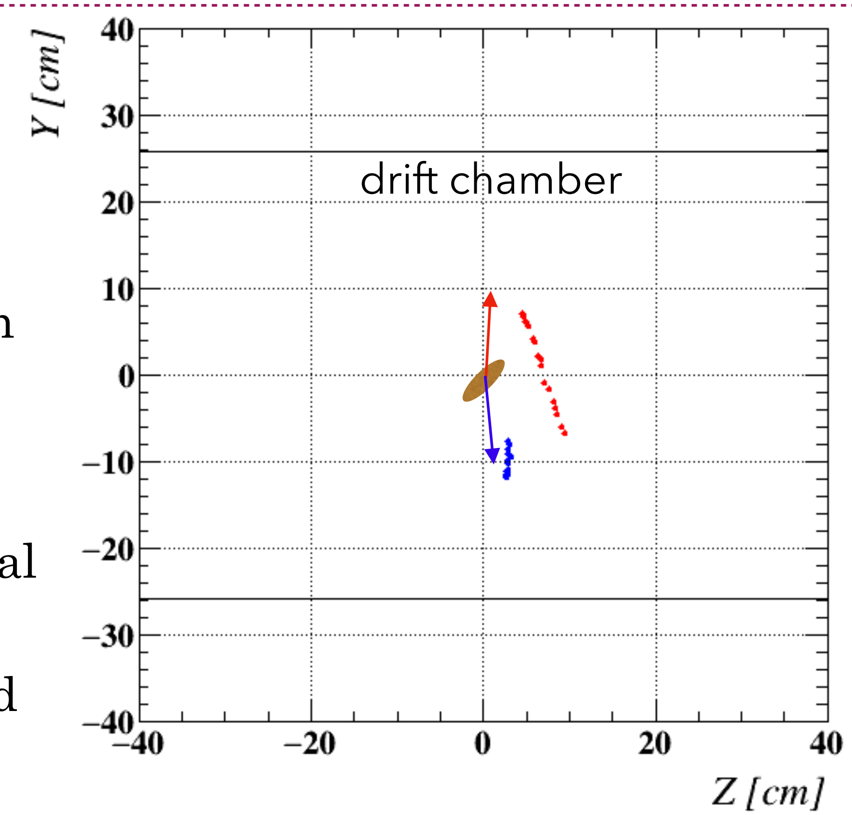
target





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

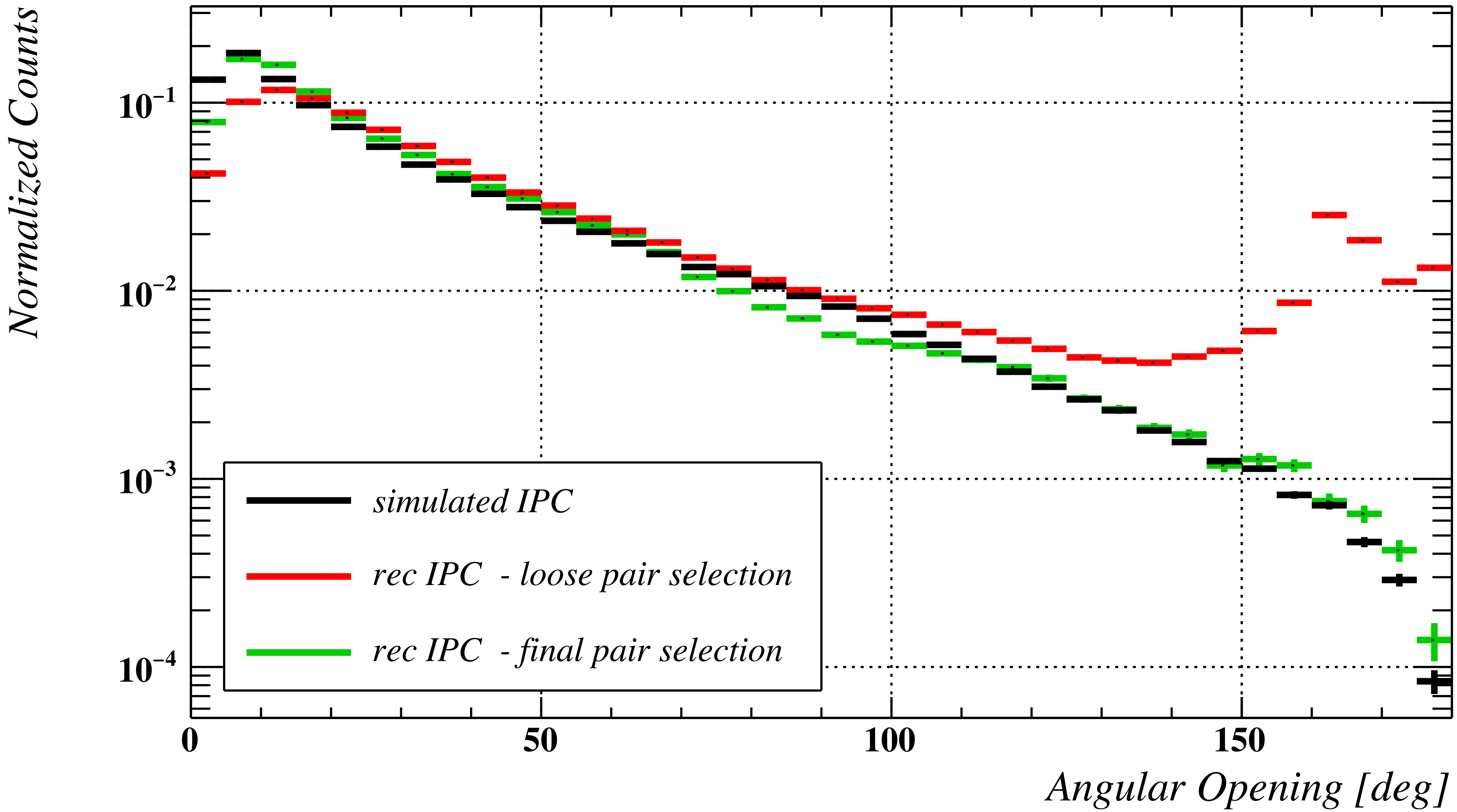


Track selection

Fake tracks
- short
- if longer, little dense
- consecutive hits distance large
- 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

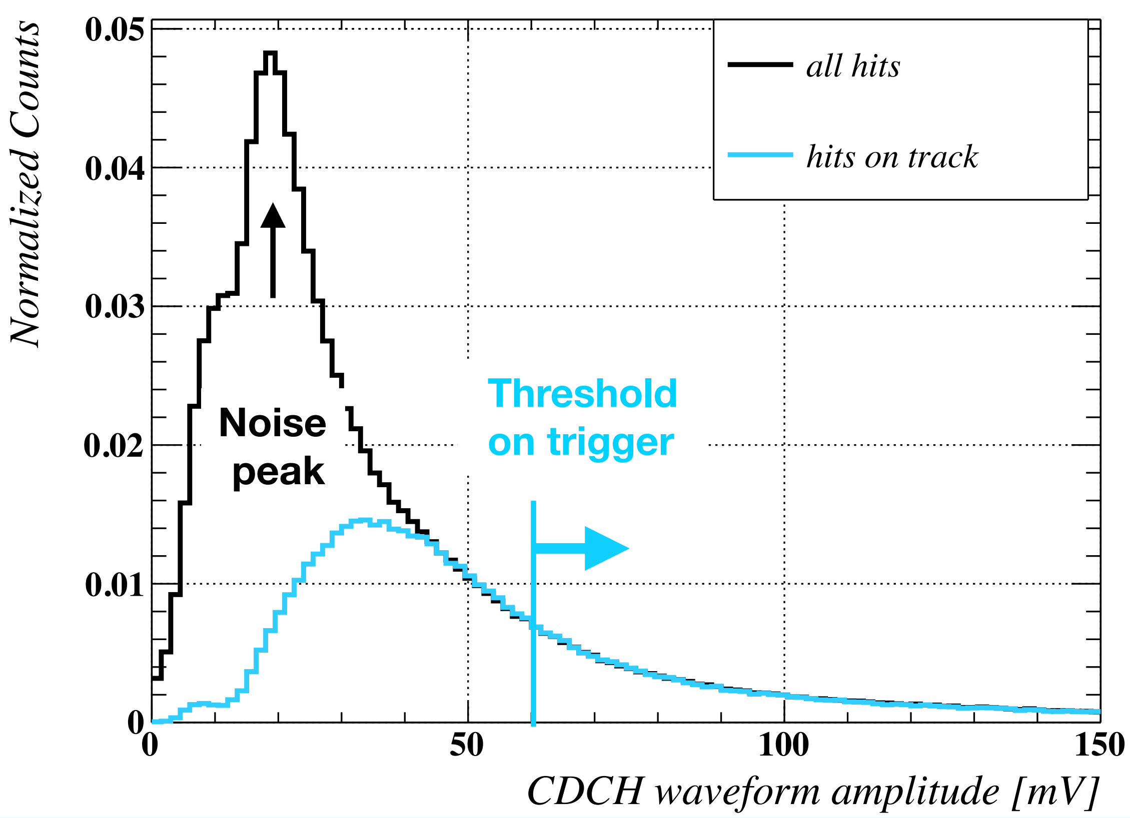
Trigger strategy

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

- To maximize significance
  - → Reduce non-signal-like contamination in trigger ↔ EPC, Single tracks, Asymmetric pairs
  - → Select signal-like pairs ↔ Pair of tracks, Opening angle > 120°, ~Symmetric momenta
  - → Increase proton current up to trigger capabilities

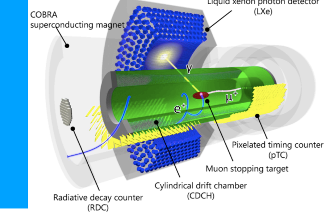
HOW TO TRIGGER ON SIGNAL-LIKE?

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



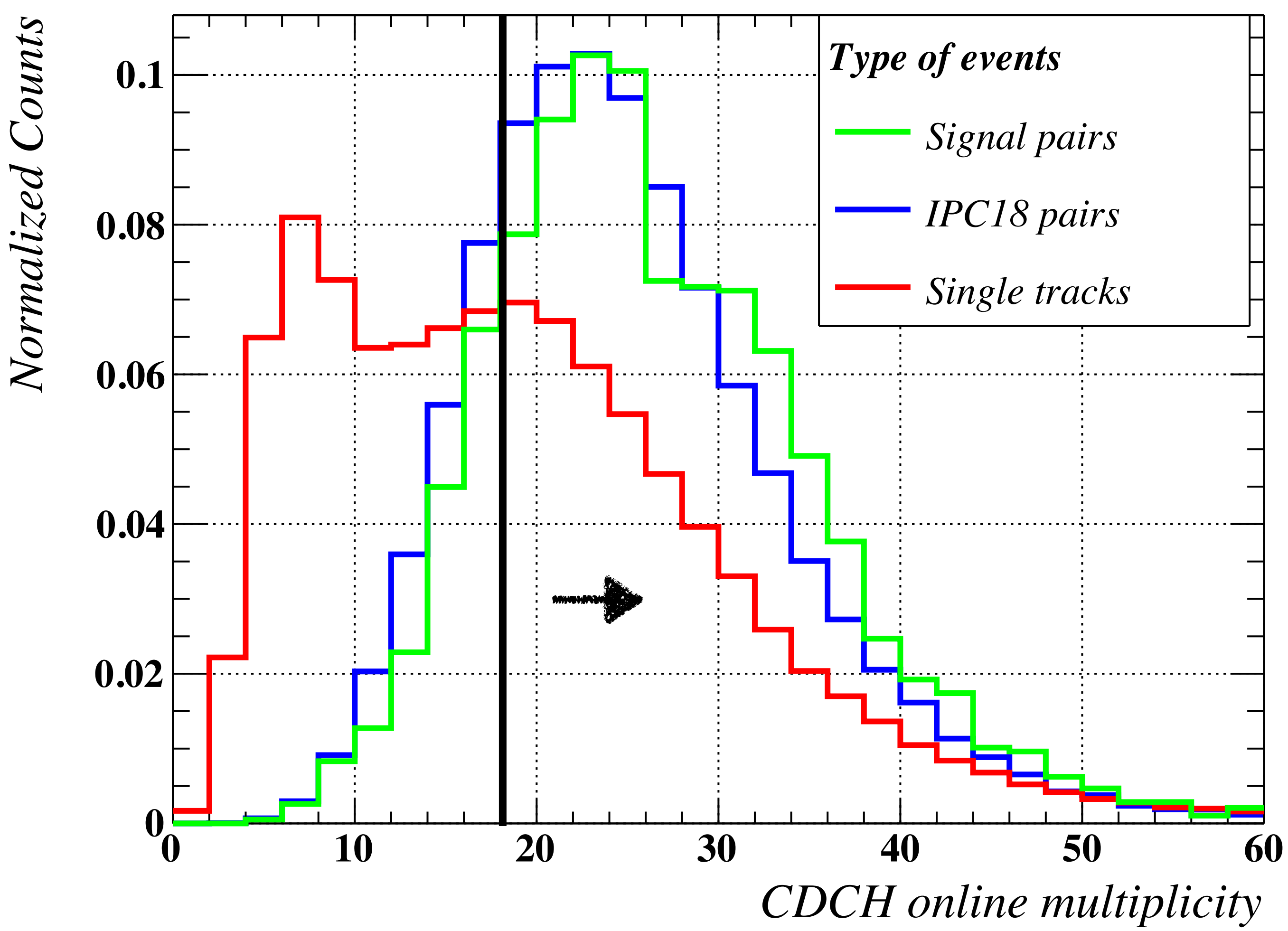
- Alternative: let's use online CDCH waveform amplitude
  - → High online threshold to trigger on good hits mostly
  - → How to exploit them?

Trigger strategy: CDCH hit multiplicity

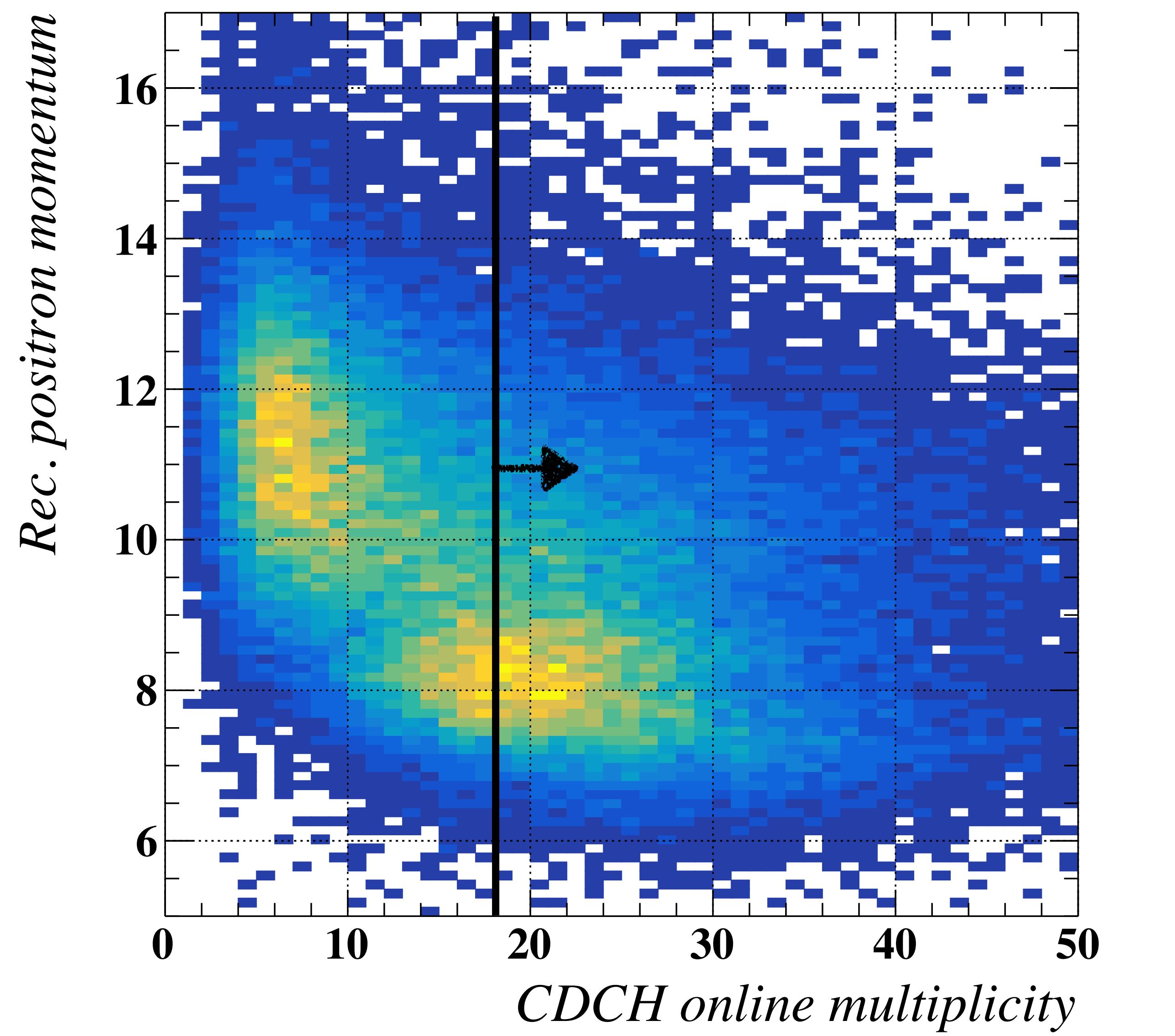


- CDCH hit multiplicity is higher for:
  - pair of tracks
  - symmetric pairs
  - tracks produced at target center

CDCH online multiplicity to reconstruct
single tracks/IPC pairs/signal pairs



Reco momentum vs CDCH online multiplicity



Trigger set as 18 hits > 60 mV

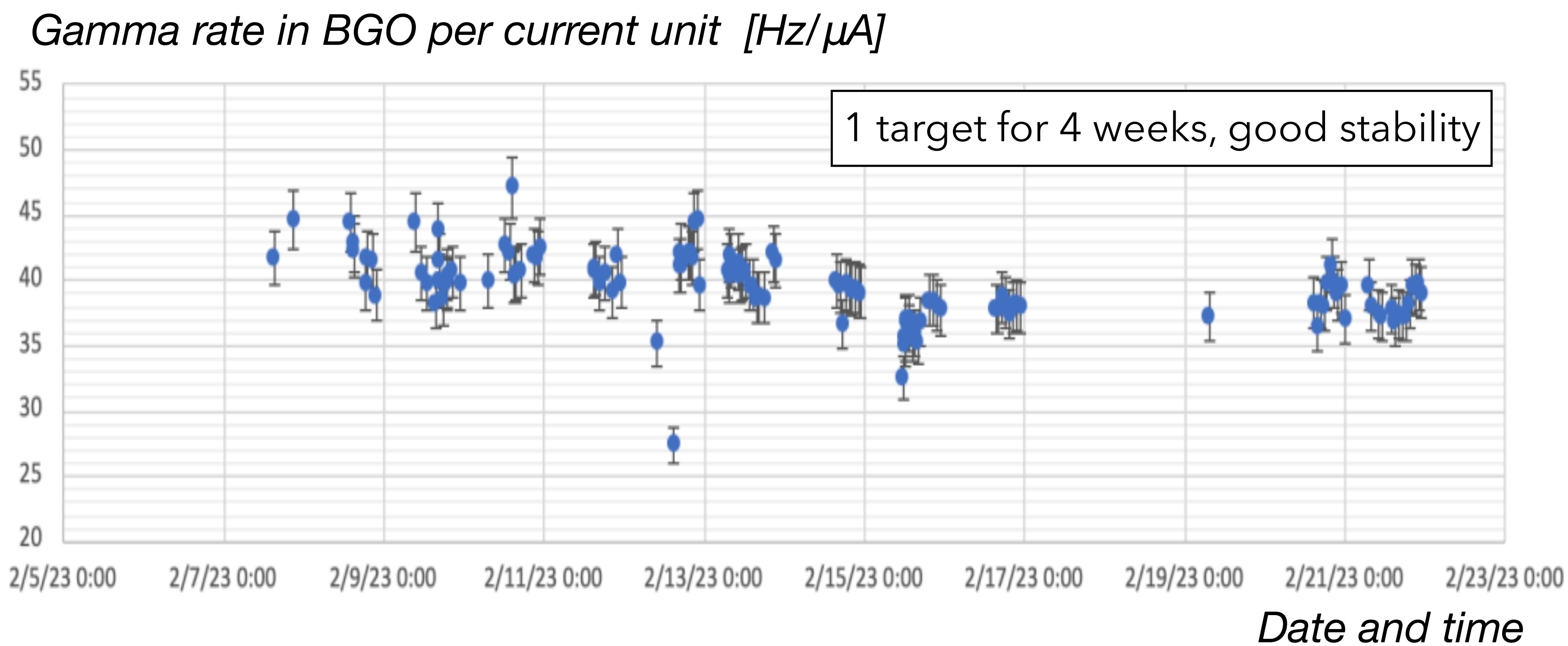
- Background rate divided by 5 (wrt. 10 hits)
- 10% signal lost
- Proton current can be largely increased

6) Collected data and analysis strategy

2023 run

- In February 2023, first run at E_{beam} = 1080 keV @I_{beam} = 10 μA
- X17 runs: sample of 25k runs of 3k events each

→ 75M triggered events → 300k pairs to be reconstructed



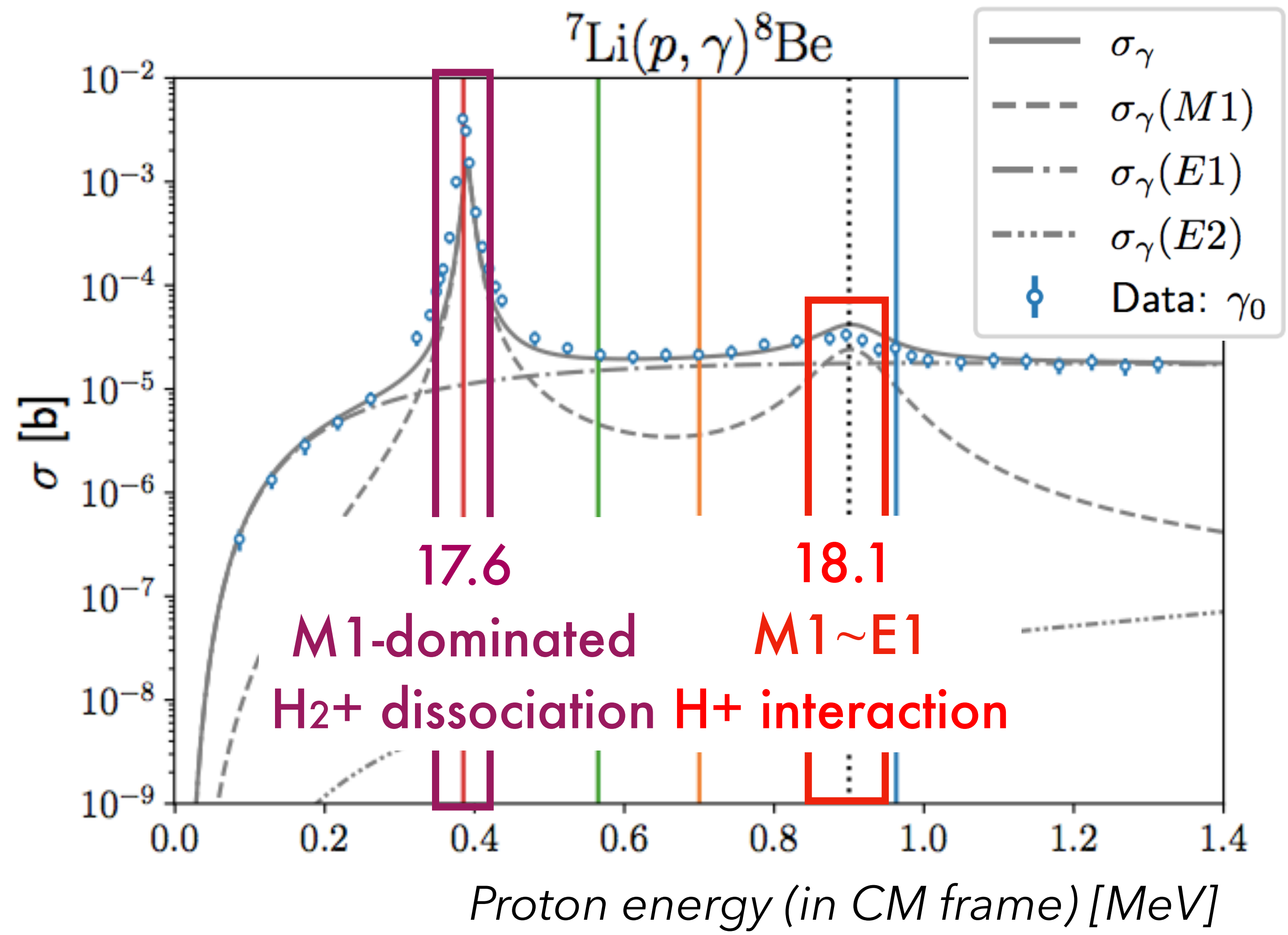
On full E_{sum} and Angular Opening range:

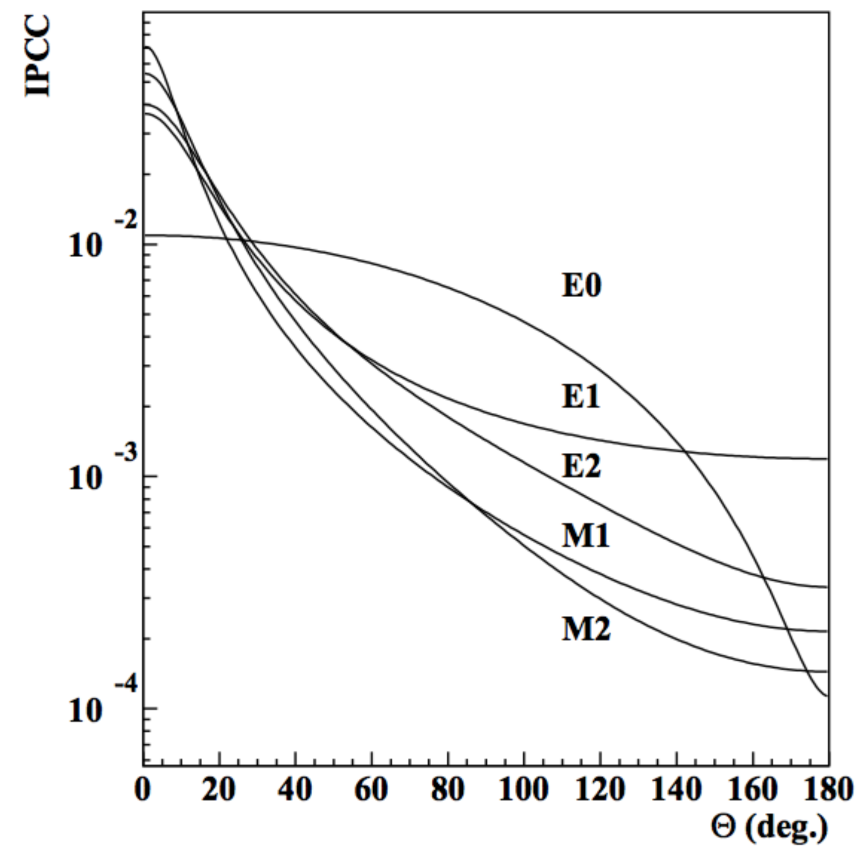
→ 60% EPC (15+18) → 40% IPC (15+18)

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

MC production

- To account for H_2+ contamination:
  Two IPC templates based on interacting proton energy





→ simultaneous search for X17 in both 440 keV and 1030 keV resonances

Analysis strategy

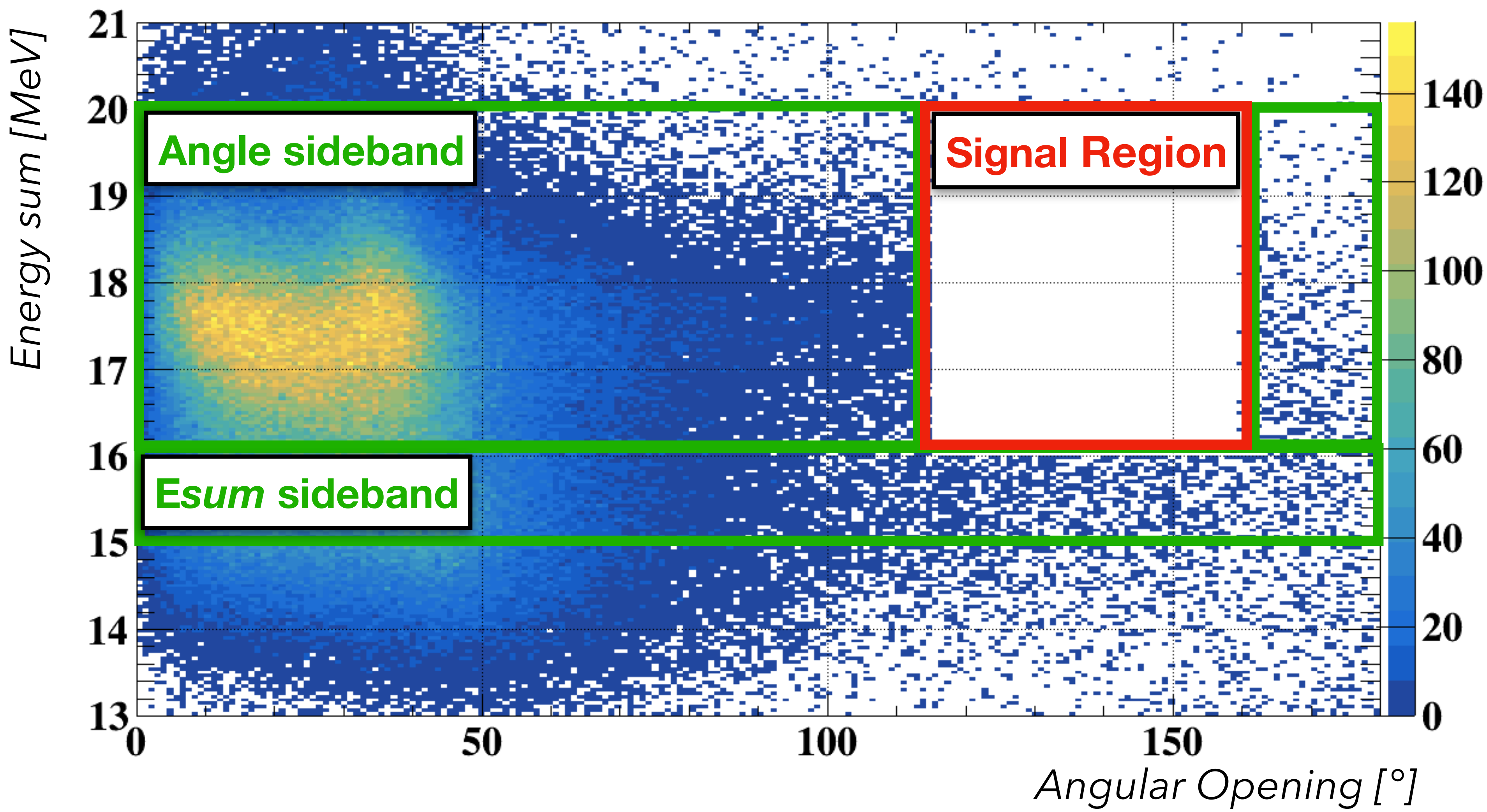
- 2D likelihood maximization: E_{sum} vs Angular Opening

- Blinded signal region defined as:

Signal Region

- **16 MeV < E_{sum} < 20 MeV**
- **115° < Angle < 160°**

- Before unblinding, understanding of background will be done in two sidebands



Angle sideband

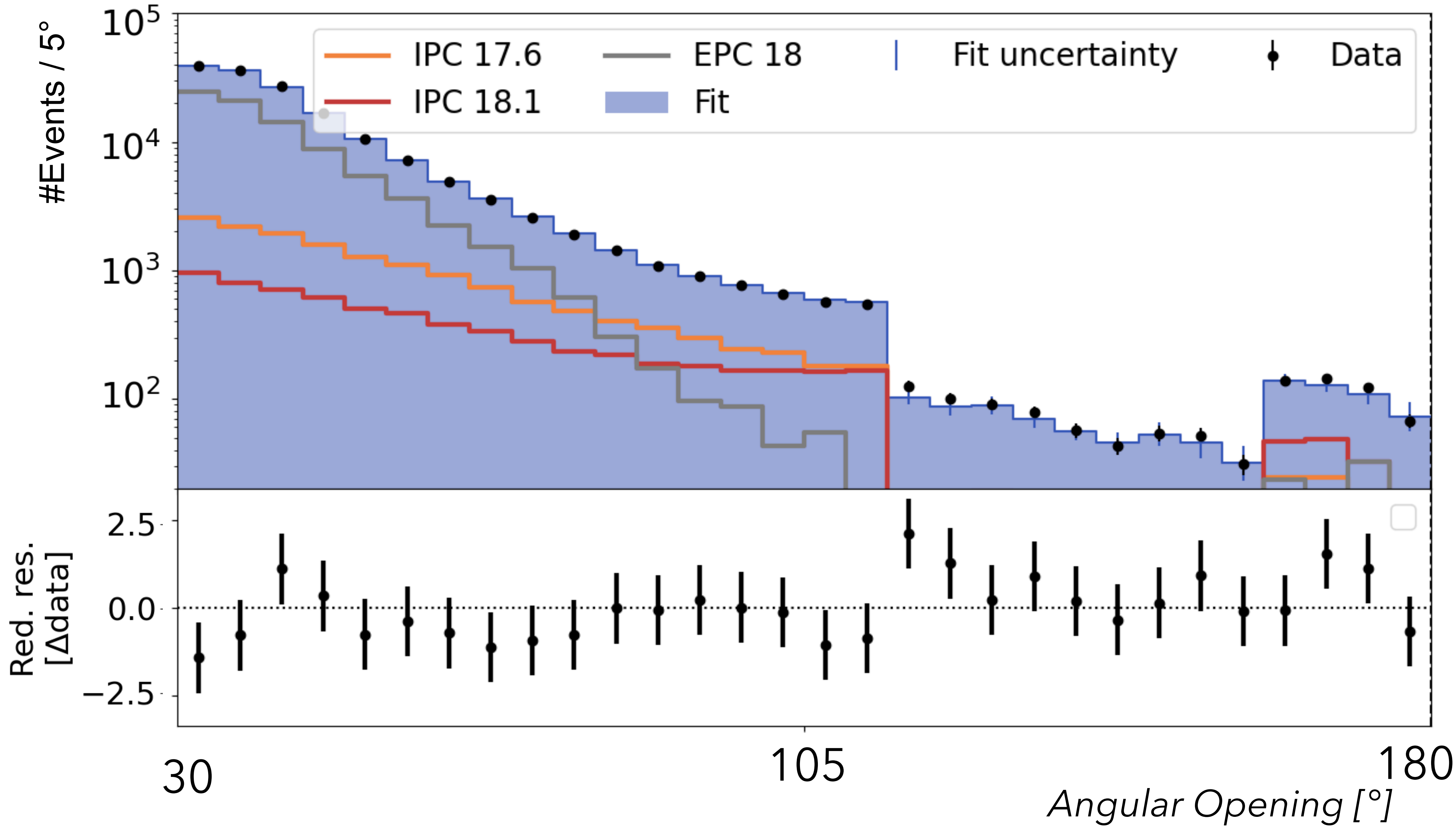
- **16 MeV < E_{sum} < 20 MeV**
- **0° < Angle < 115° OR Angle > 160°**

E_{sum} sideband

- **14 MeV < E_{sum} < 16 MeV**
- **Full angle range**

Current best fit

- 1D projection of the 2D fit



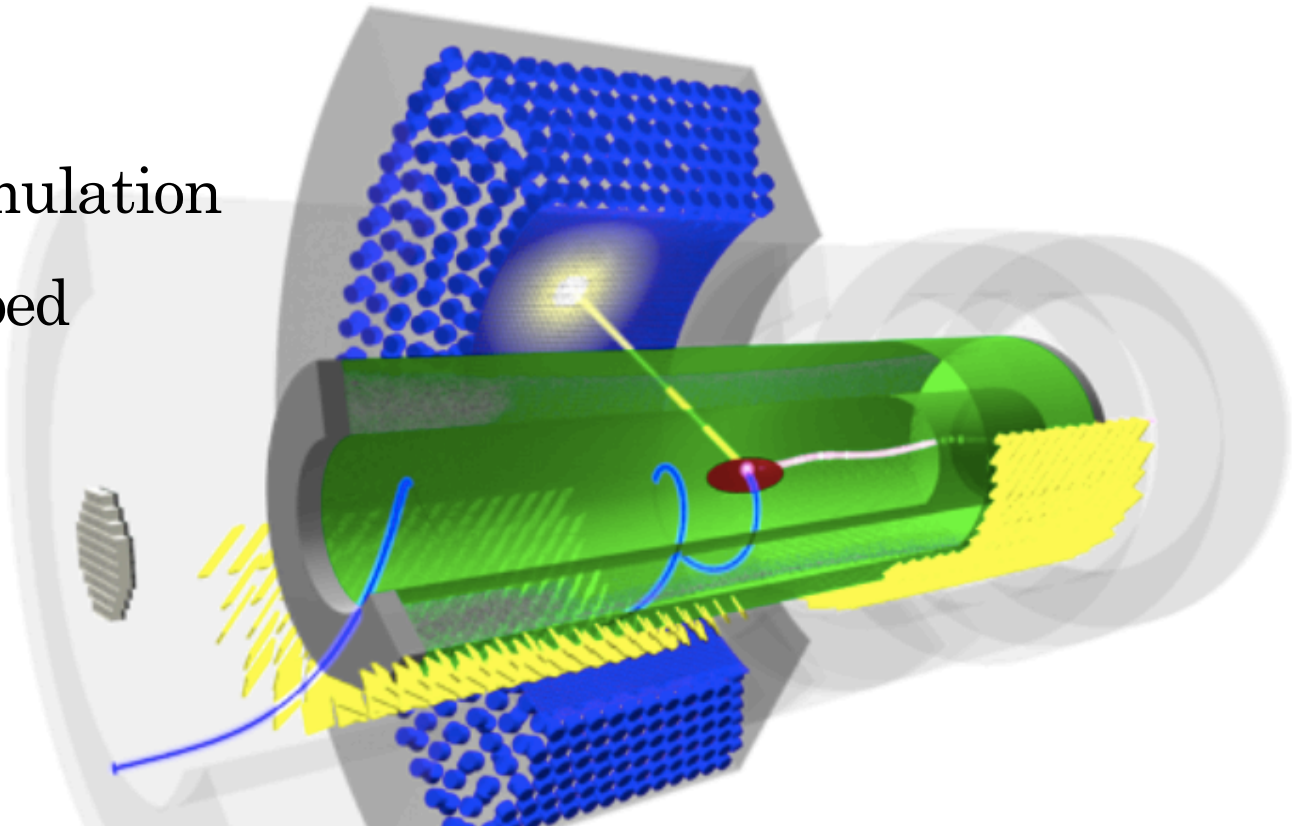
- ➔ Good understanding of the backgrounds above 30°
- ➔ Unblinded results out soon
- ➔ With this dataset, we can simultaneously search for X17 in both <u>440 keV</u> and <u>1030 keV</u> resonances

Conclusion and outlook

- Anomalous excess observed in the angular correlation of $^{7}\mathrm{Li}(p, e^{+}e^{-})^{8}\mathrm{Be}$ by the Atomki collaboration

- 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

- First run in February 2023
  → backgrounds, signal and detectors simulation
  → pair reconstruction procedure developed
  → new trigger strategy implemented
  → 2023 data was reprocessed, good background understanding
  → unblinded results out soon

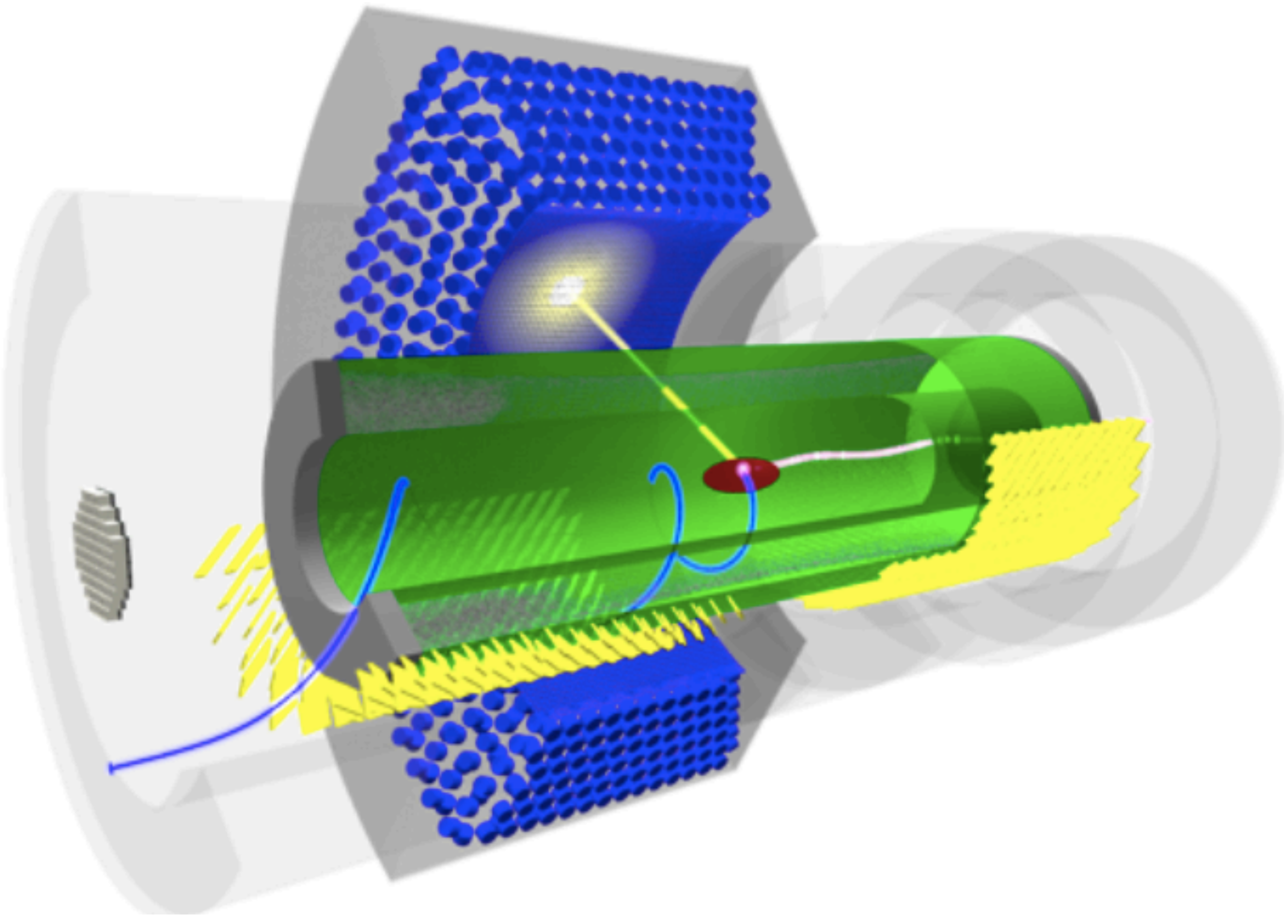


- New DAQ period @1030 keV with pure proton beam is foreseen
  → improved sensitivity

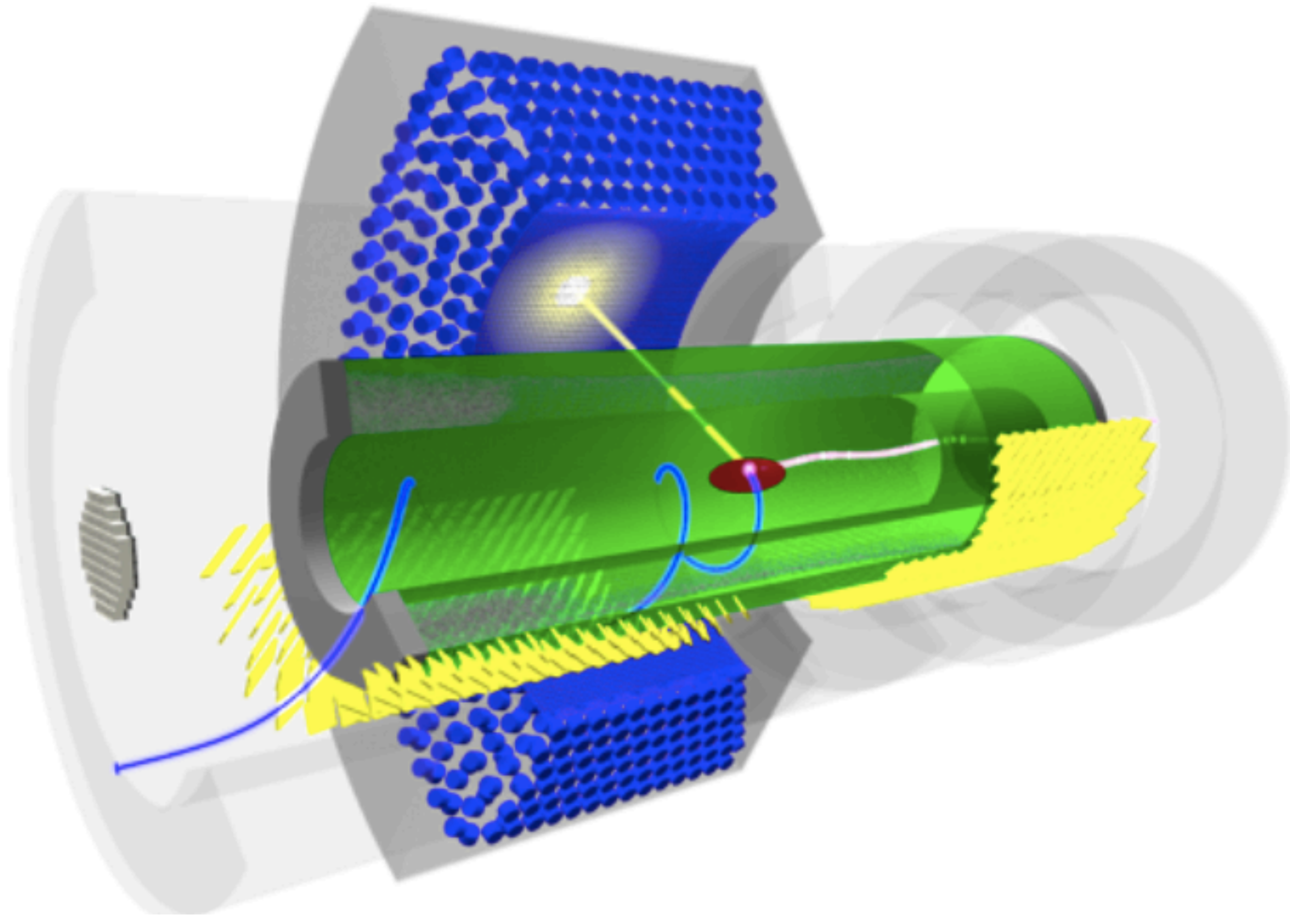
Thank you for your attention!

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

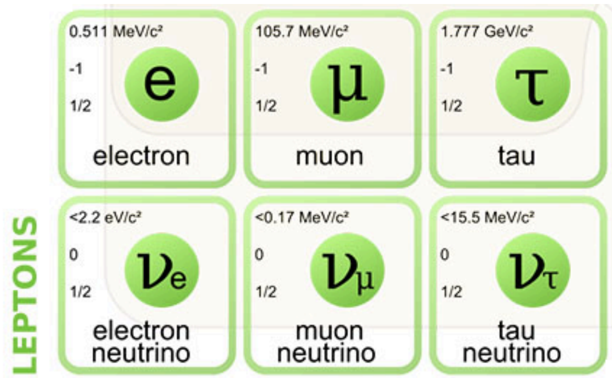
hicham.benmansour@pi.infn.it



Backup slides

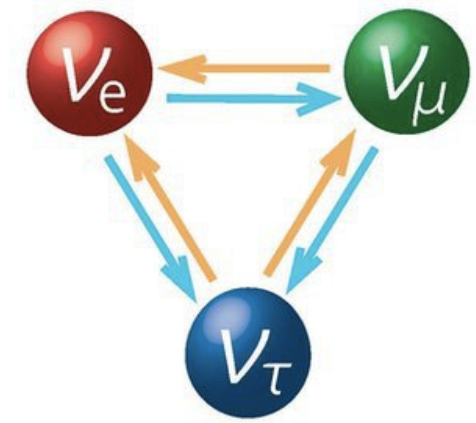


Charged Lepton Flavour Violation



- 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 → $\mu^+ \to e^+\gamma$

SM with massive neutrinos

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

BSM physics

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

accessible experimentally today

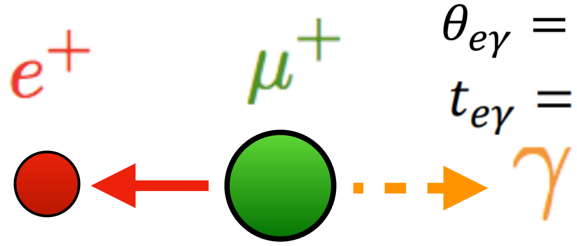
- Observation of CLFV at current sensitivities = unambiguous evidence for New Physics

Signal

Back-to-back decay at rest

$\theta_{e\gamma} = 180°$

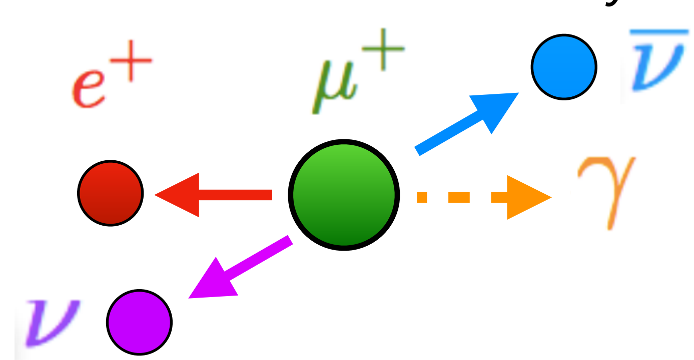
$t_{e\gamma} = 0$ s



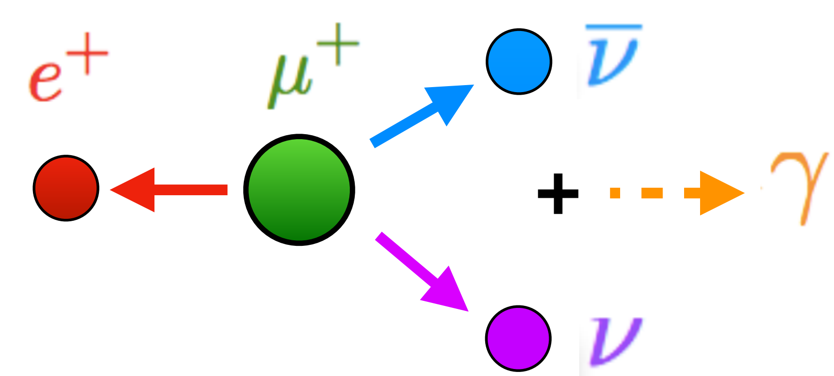
$E_\gamma = E_e = 52.8$ MeV

Backgrounds

Radiative Muon Decay



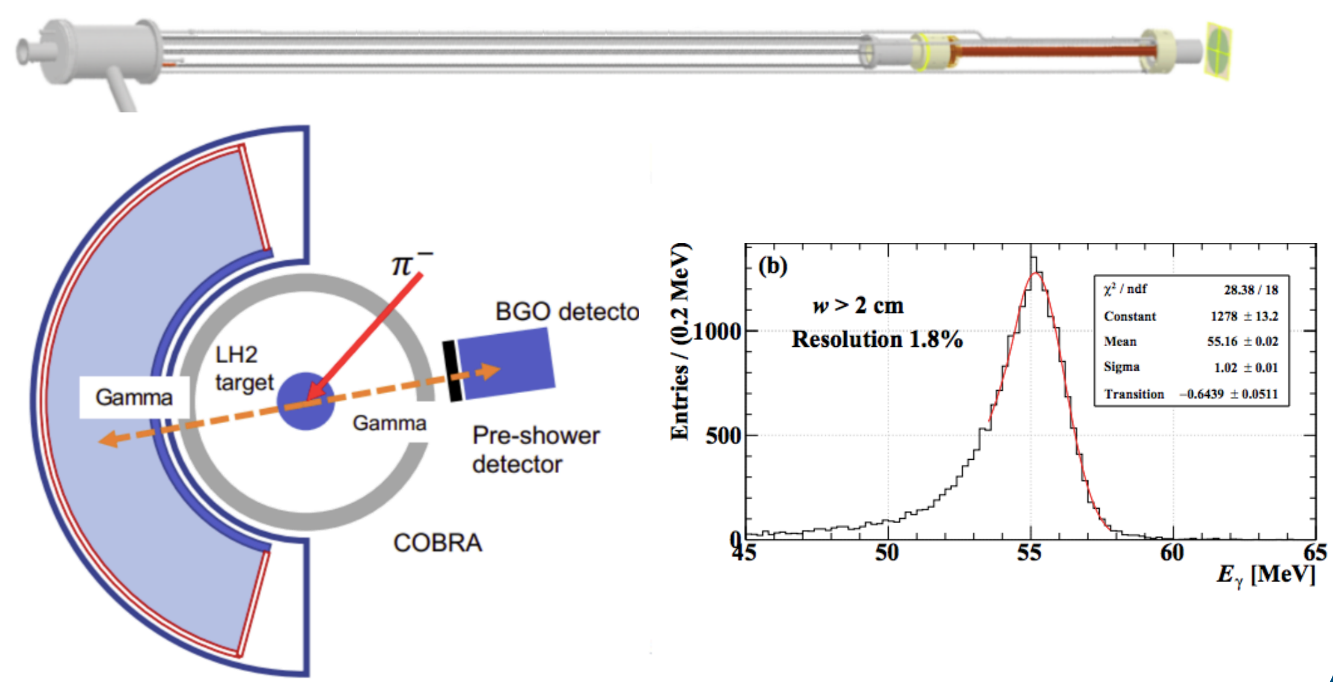
Accidental



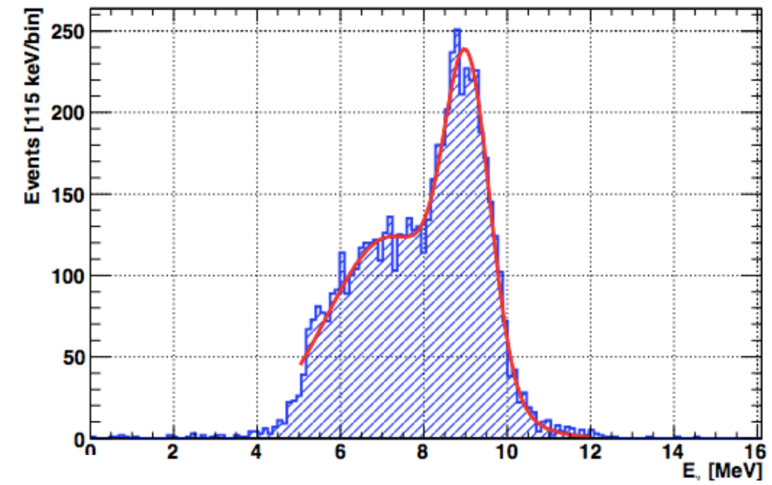
Detectors calibrations

- Search relies on an extensive and regular calibration routine

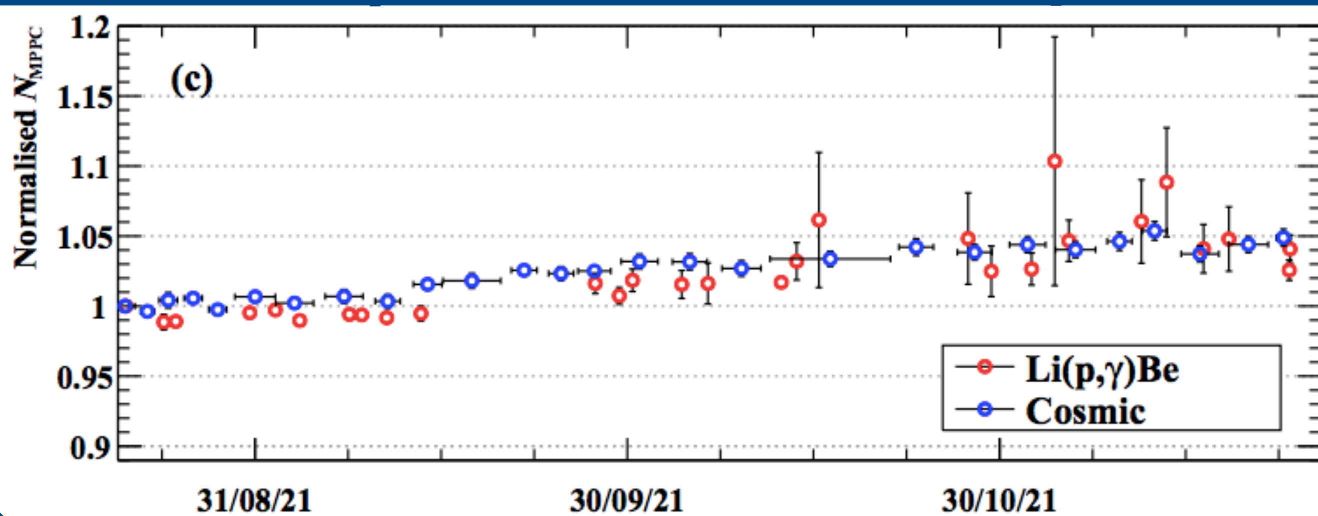
55 MeV γ	$\pi^- p \rightarrow \pi^0 n,\ \pi^0 \rightarrow \gamma\gamma$	LXe



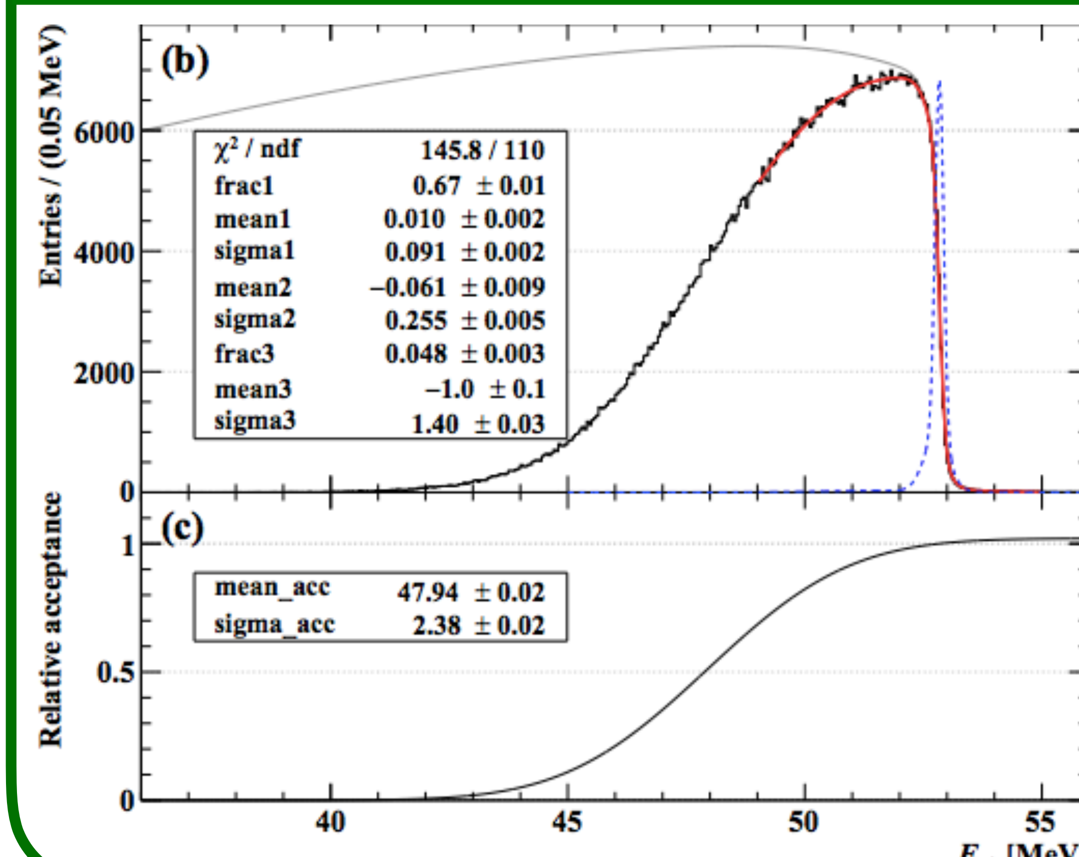
9 MeV γ	^{58}Ni$(n,\gamma)^{59}$Ni	LXe



17.6 MeV γ	^{7}Li$(p,\gamma)^{8}$Be	LXe



52.8 MeV e^+	$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$	CDCH



2022 engineering run

- 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

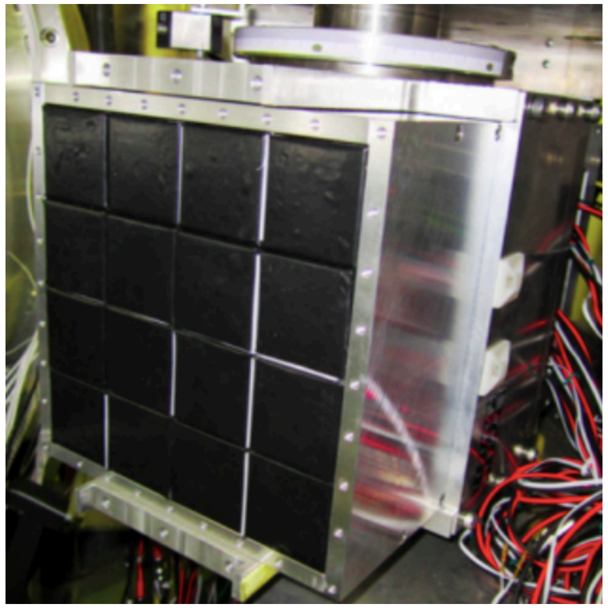
→ target region can stand high proton currents(up to 10uA) without overheating —> heat-dissipation material can be reduced (less EPC background)

Gamma detectors

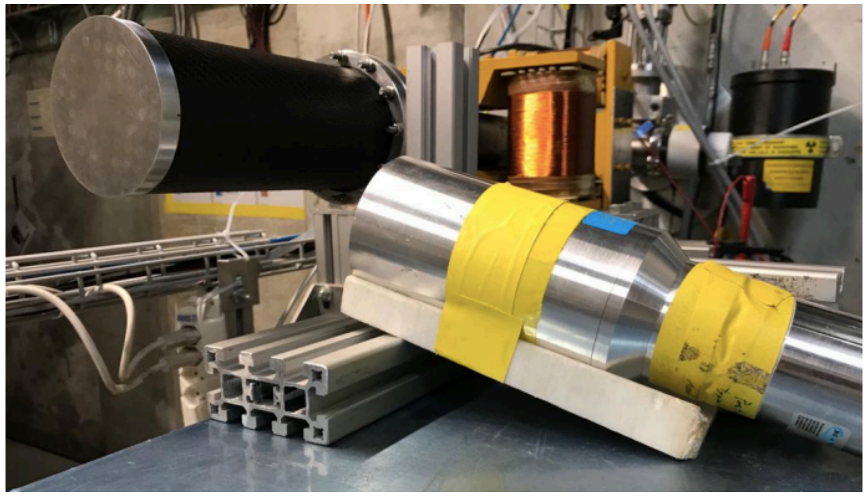
- Two additional gamma detectors

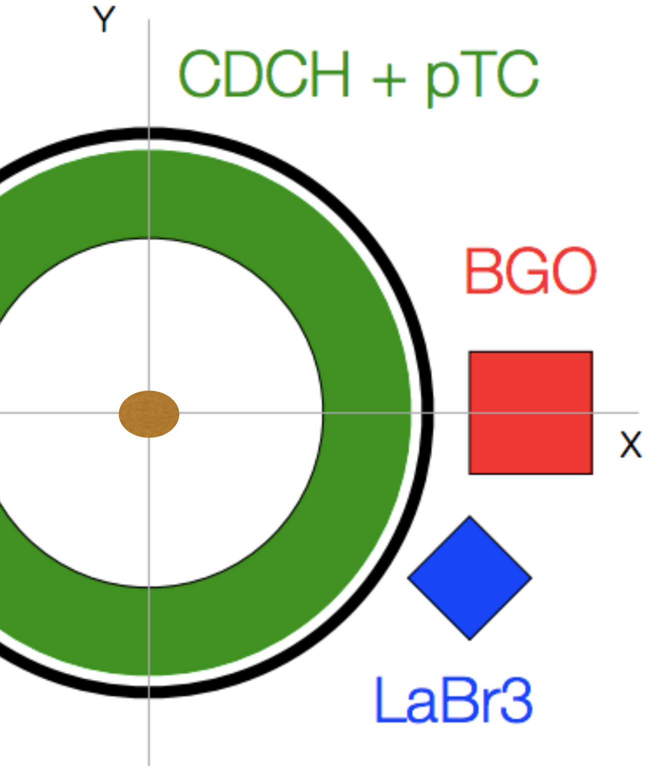
→ Stability monitoring → Signal normalisation → Daily monitoring

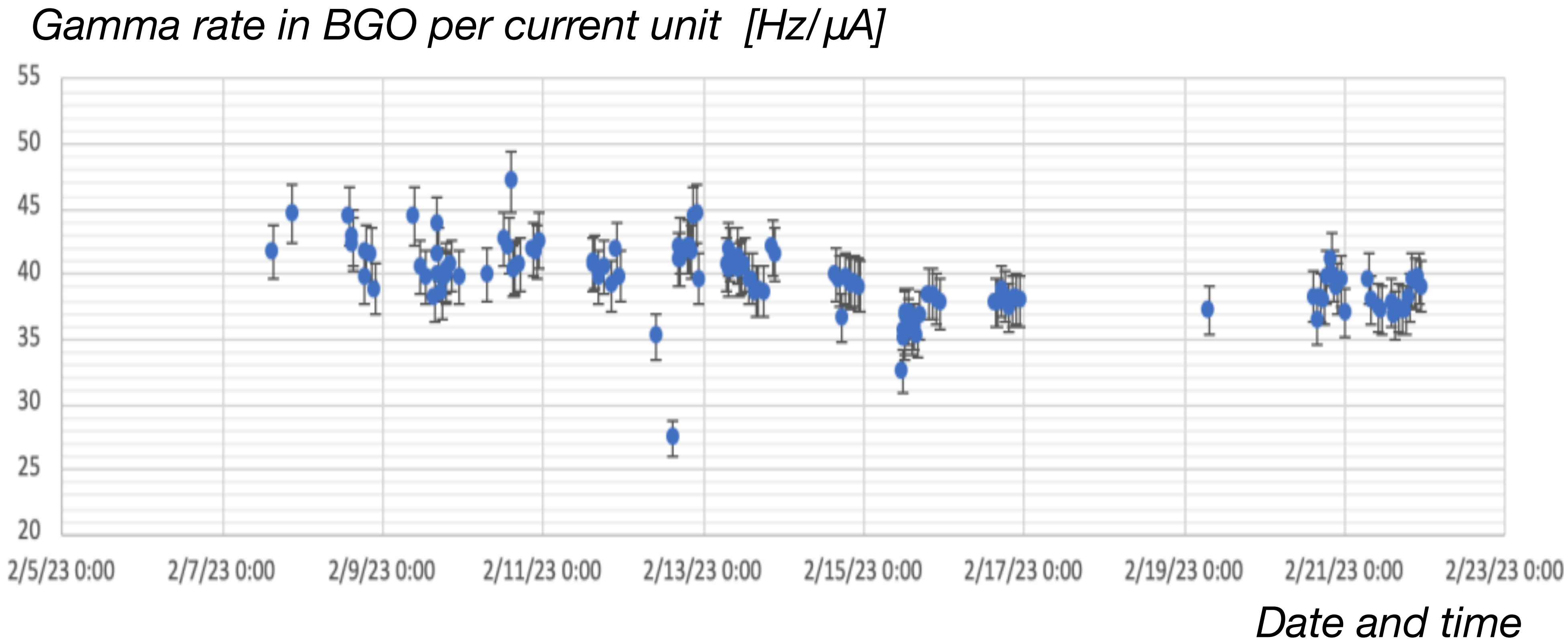
Bismuth Germanate (BGO) crystal matrix (4x4)



Lanthanum Bromide (LaBr3) crystal







Reduced magnetic field and beam tuning

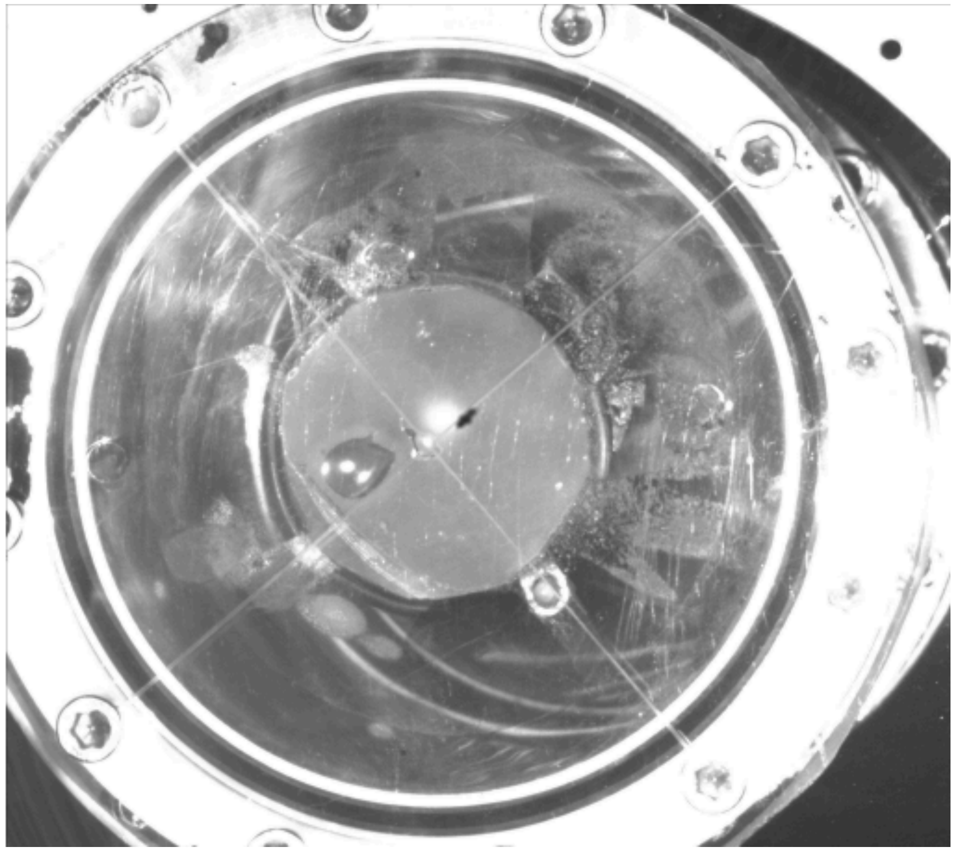
- $\mu \longrightarrow e\gamma$ search relies on 52.8 MeV positron search with default magnetic field (1.27T at COBRA center)

- for X17: energies ~6 times lower → 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
  → beam spot centered and covering the Li area

megCam - COBRA OFF



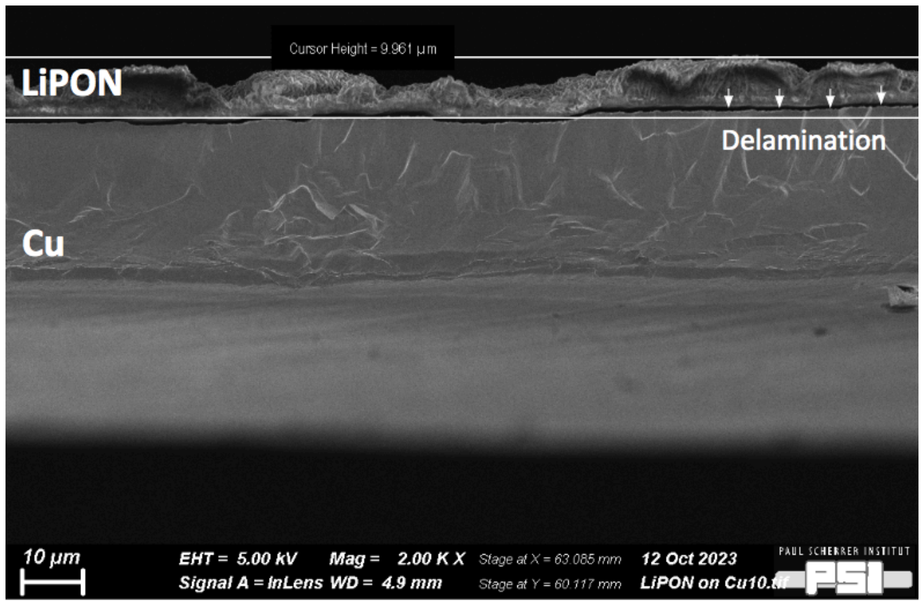
CCD camera - COBRA ON

Target studies: SEM and EDX

- Why LiPON?

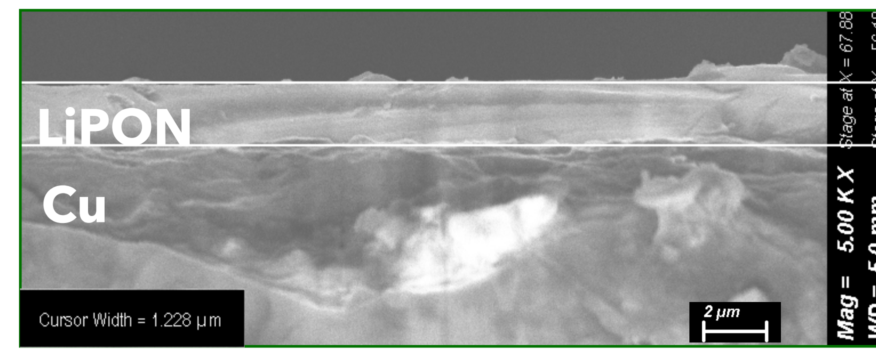
→ Stable, no F-related bkg, thin films through sputtering, developed for batteries

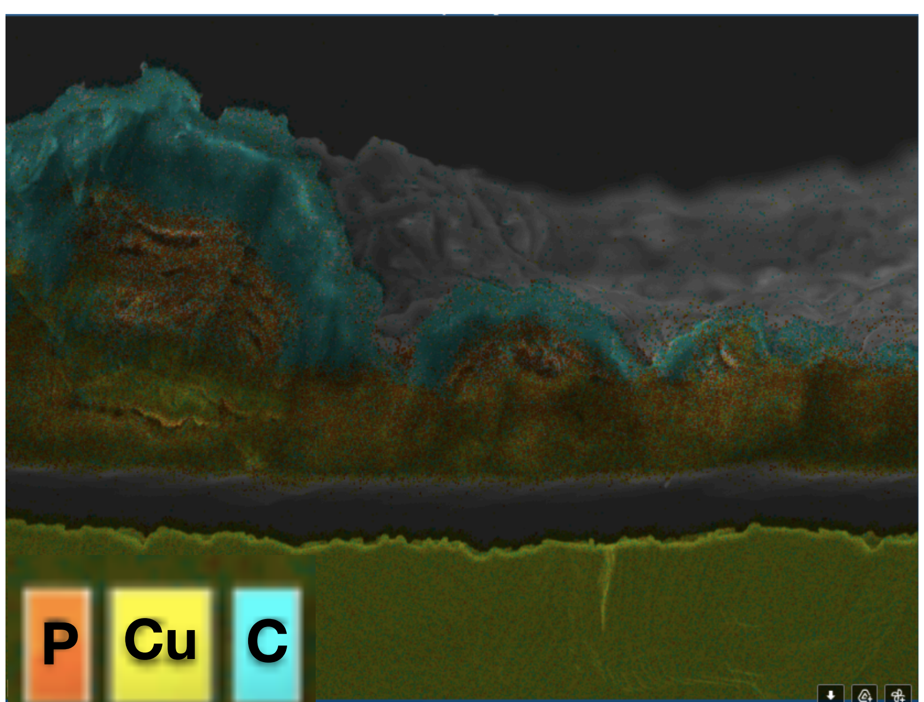
- Difficulties for production: thickness control and non-uniformity, oxidation layer



→ Delamination, pores, large thickness variations

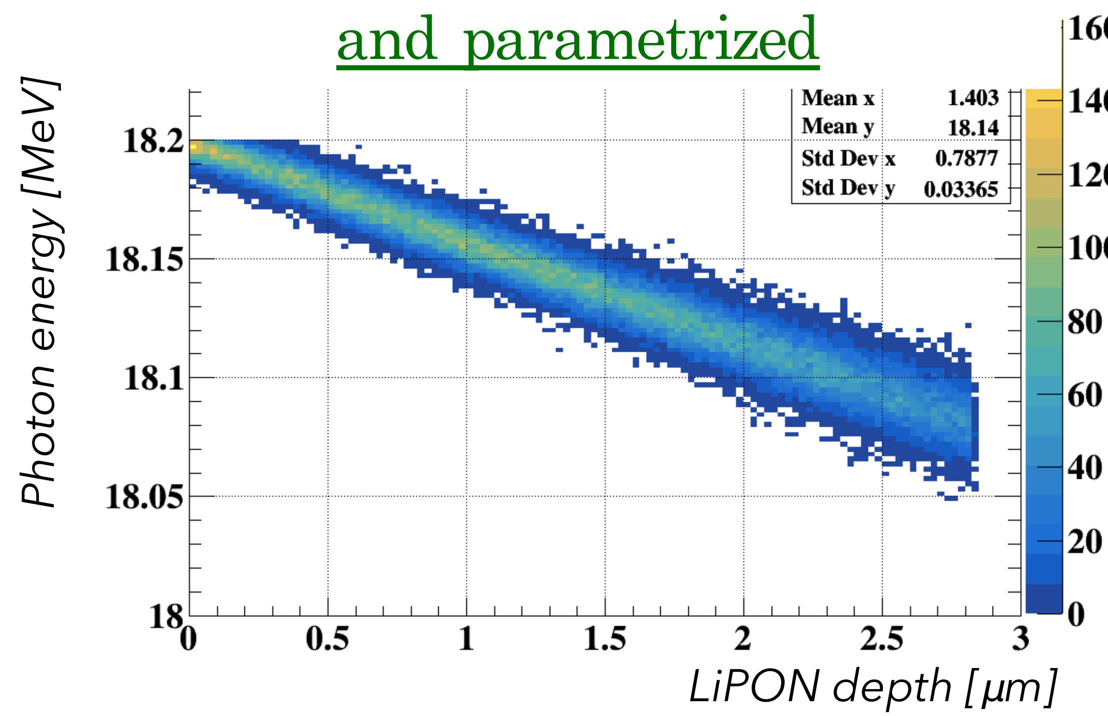
Recently, uniform thin 2-µm films were achieved at PSI





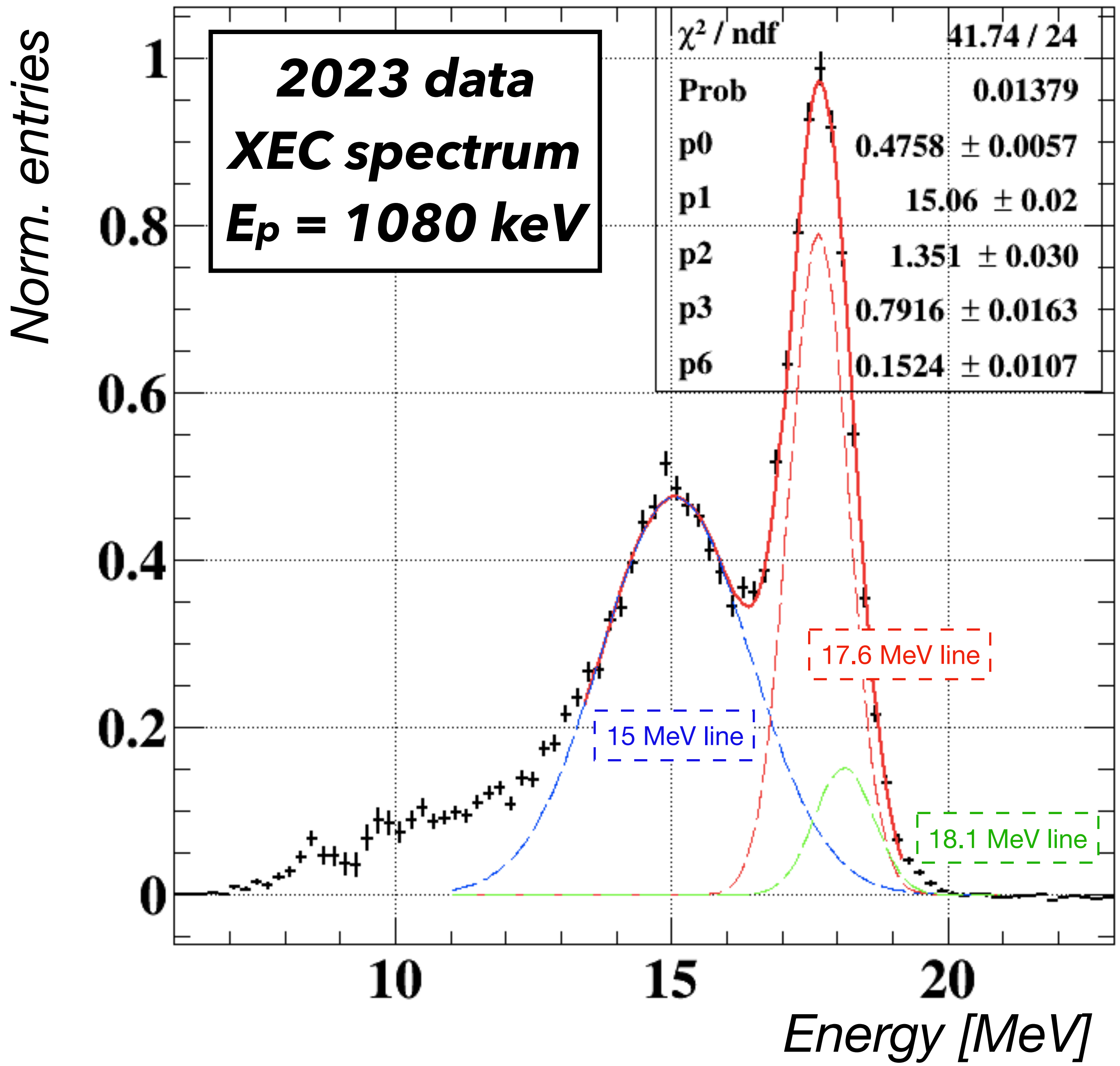
→ $LiCO_3$ on the surface

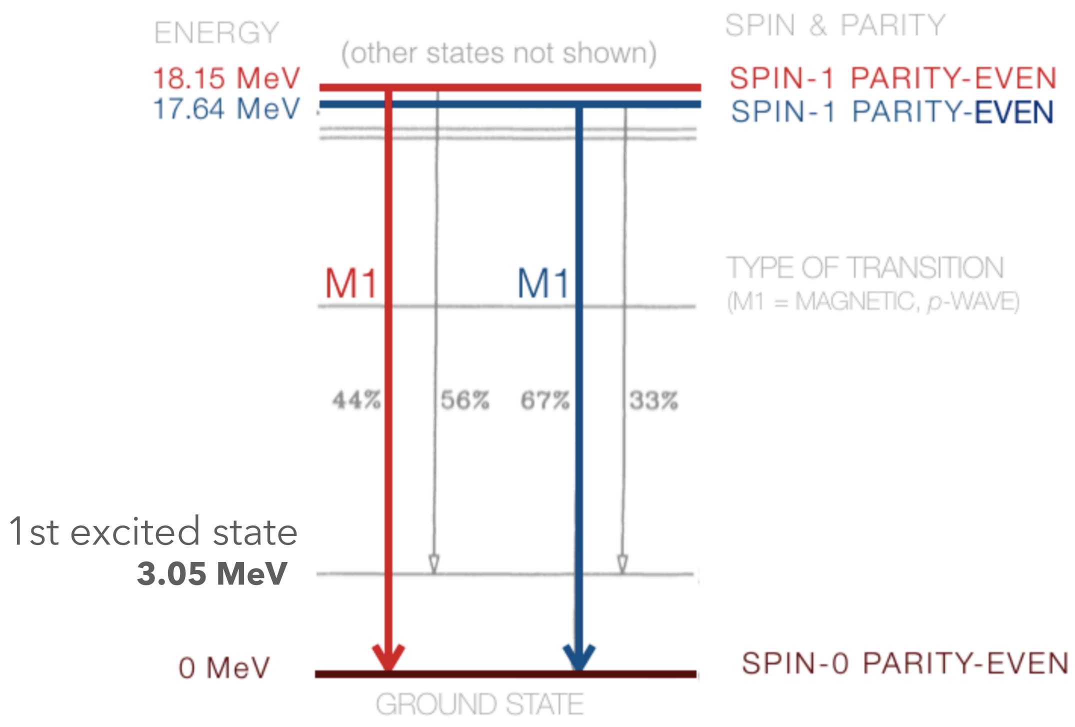
Proton energy loss simulated and parametrized



Excited transitions

- Gamma spectrum using LXe calorimeter to understand excited transitions





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

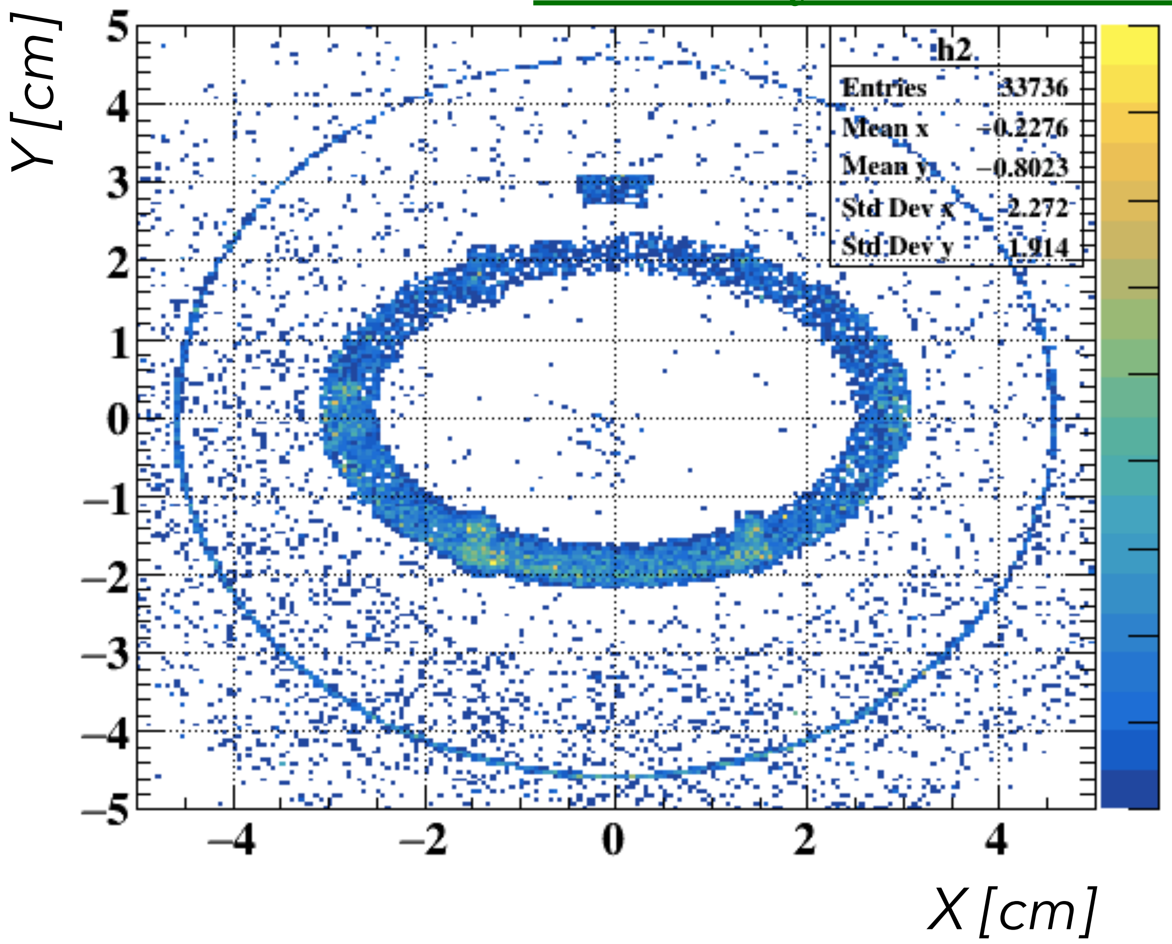
$f_{18.1}$ **~ 20 %**

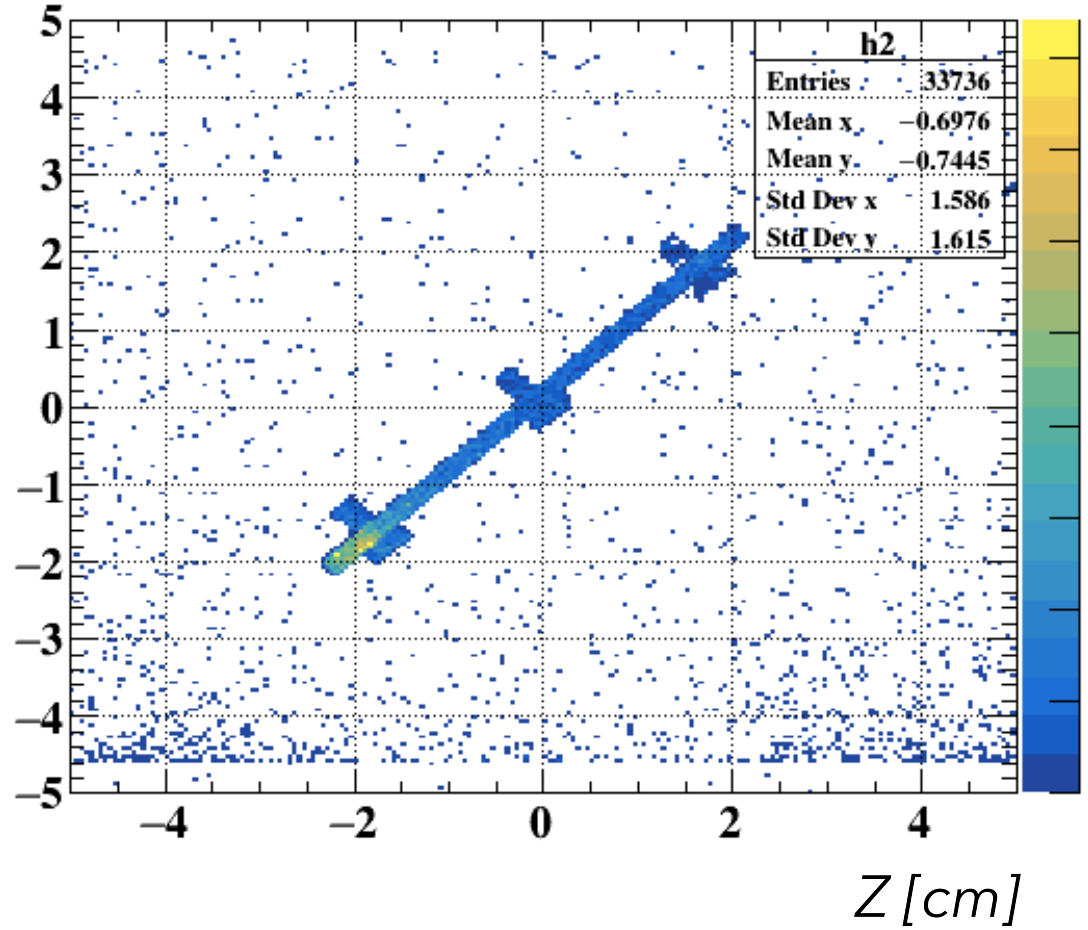
External Pair Conversion and other bkgs

- 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

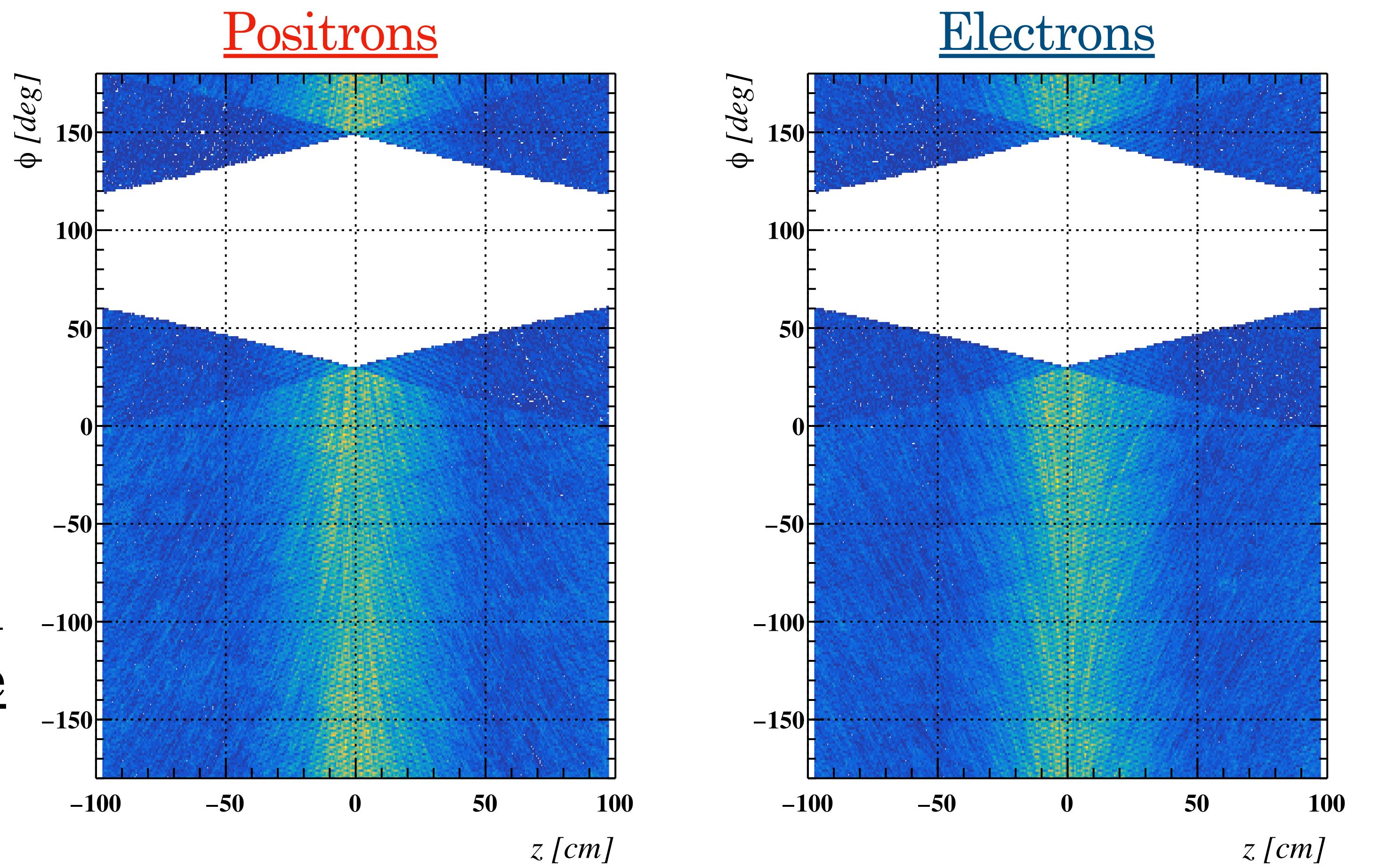
Electron reconstruction

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

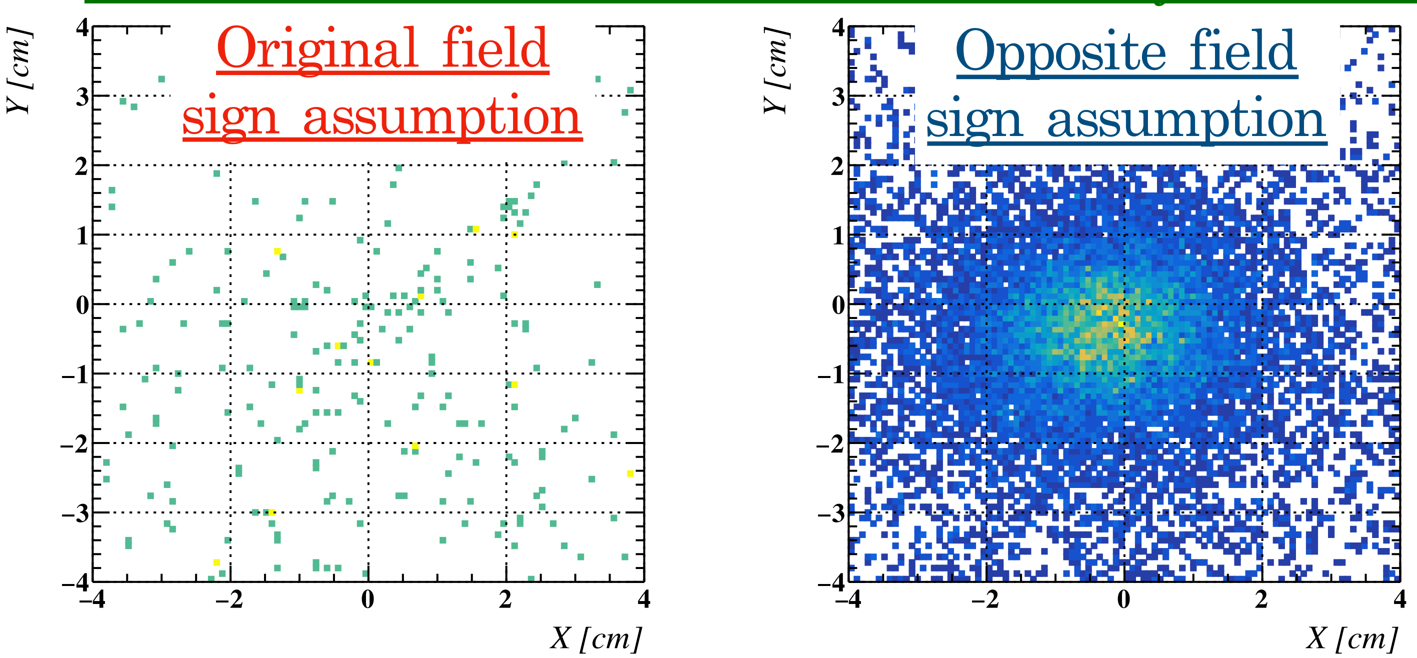
→ Simulated e+/e- tracks in CDCH

→ 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

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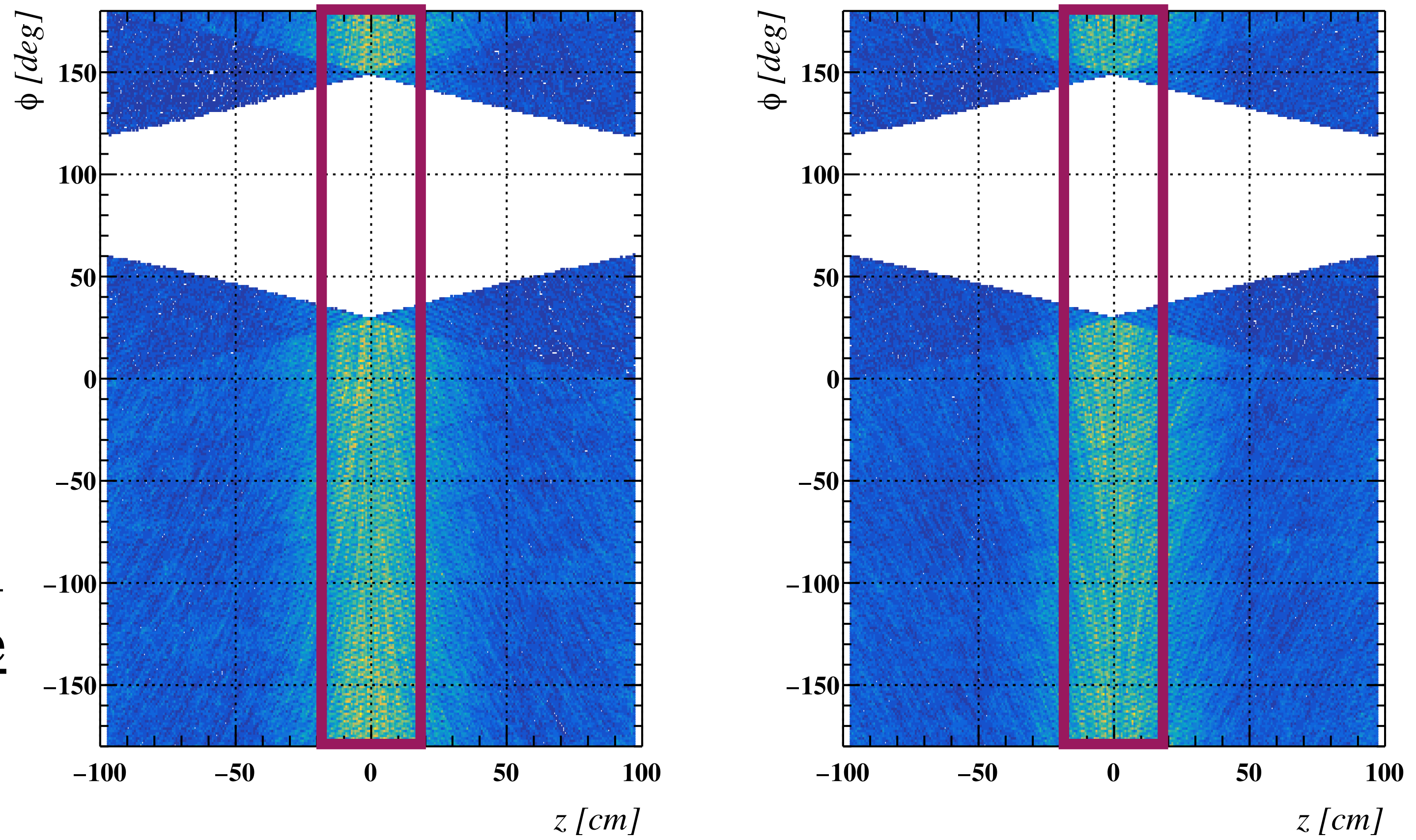

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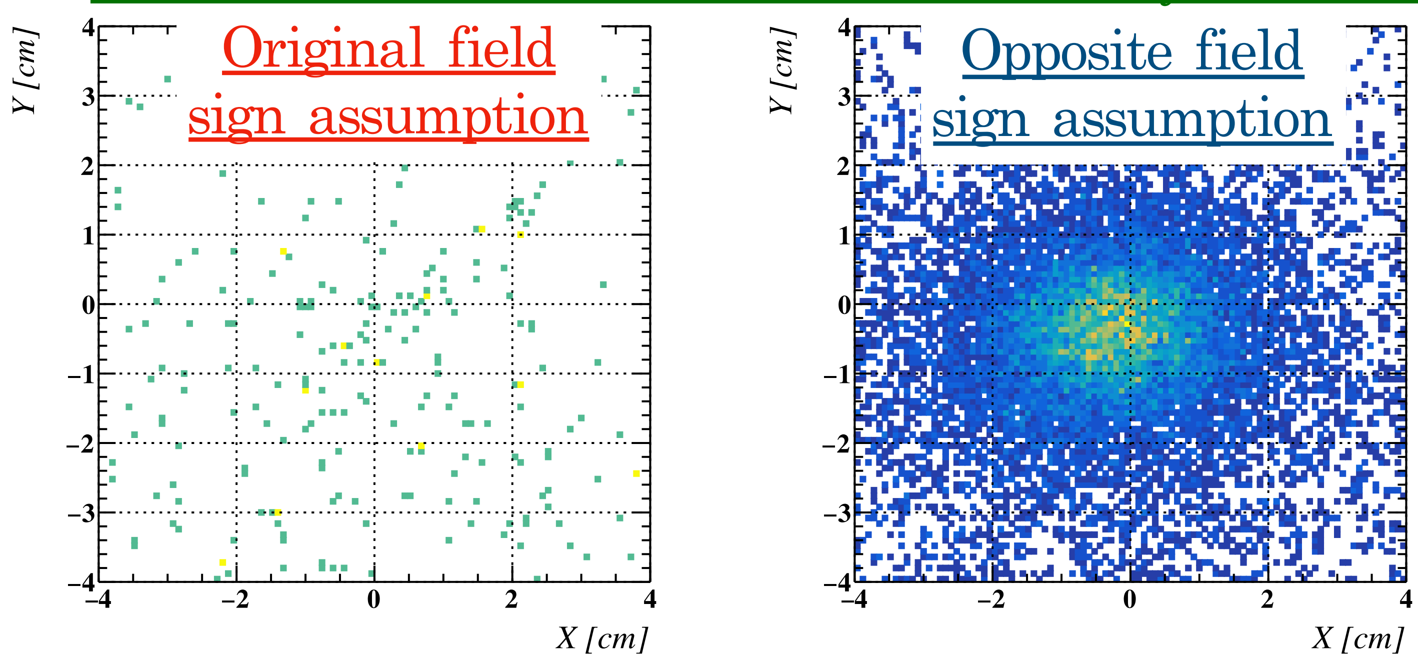
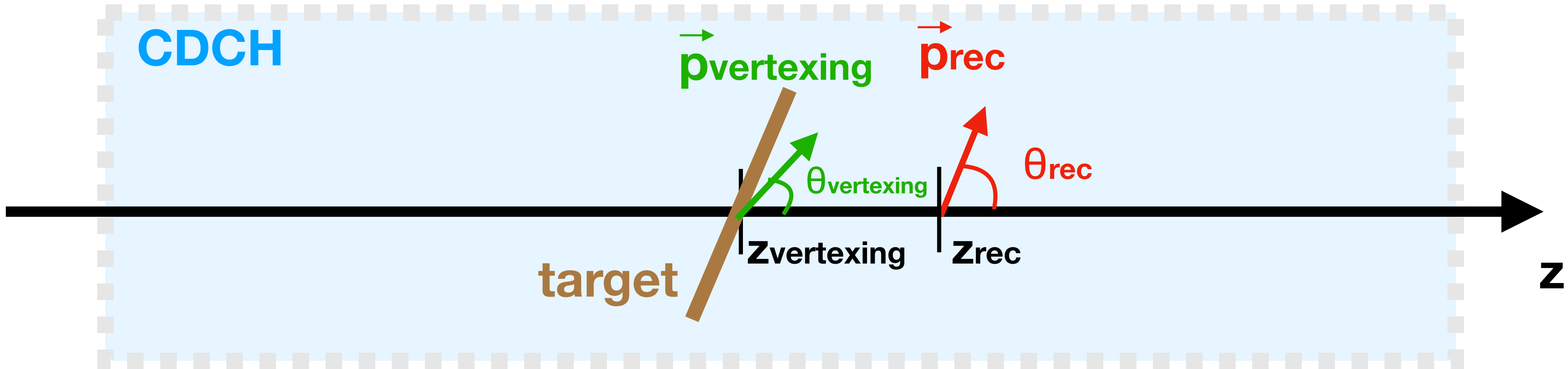


→ 99% of tracks have correct sign

→ 1% of tracks is misreconstructed

Tracks emitted orthogonal to the beam are sign-ambiguous

due to O(20cm) of air between target and CDCH and large multiple scattering
→ tracks are reconstructed O(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

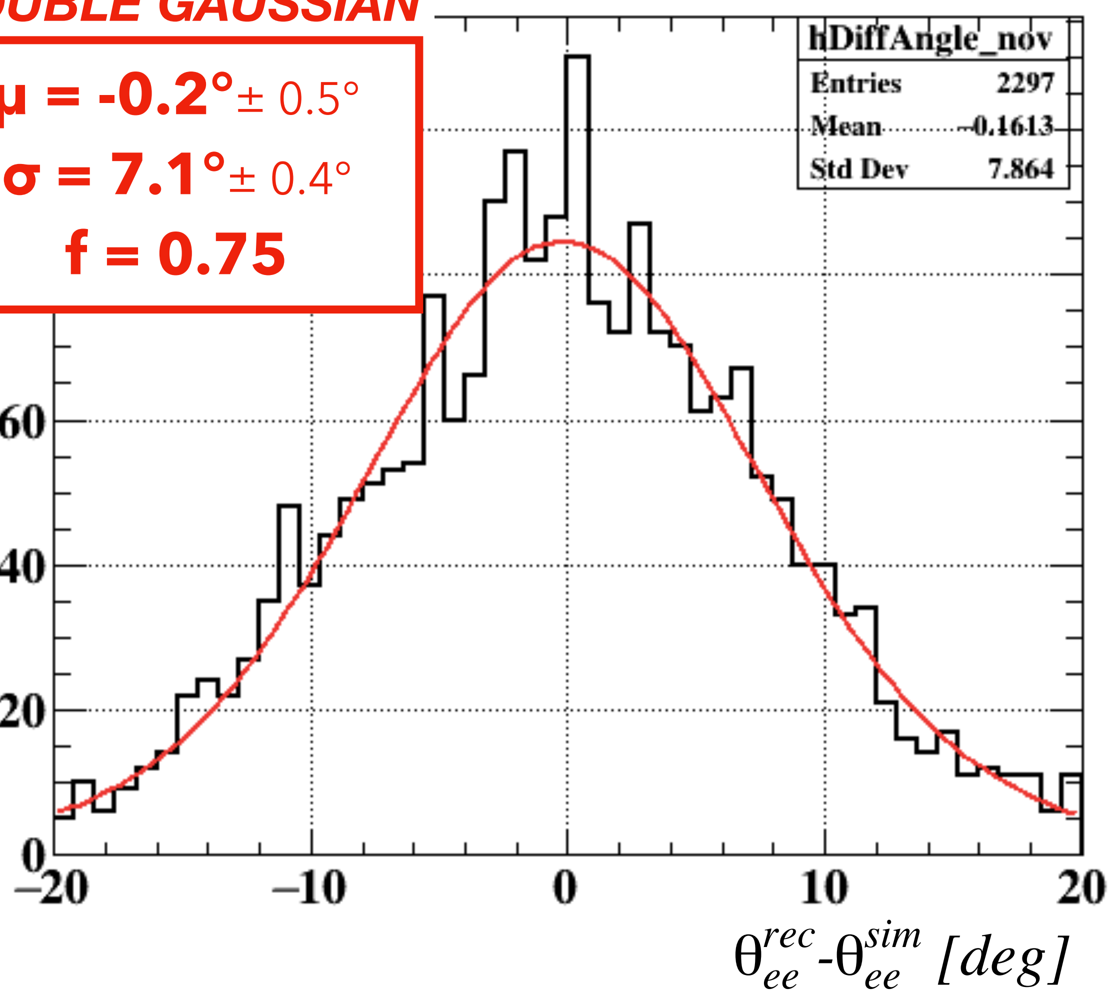
Angular Opening resolutions

X17 MC simulation

No vertexing

DOUBLE GAUSSIAN

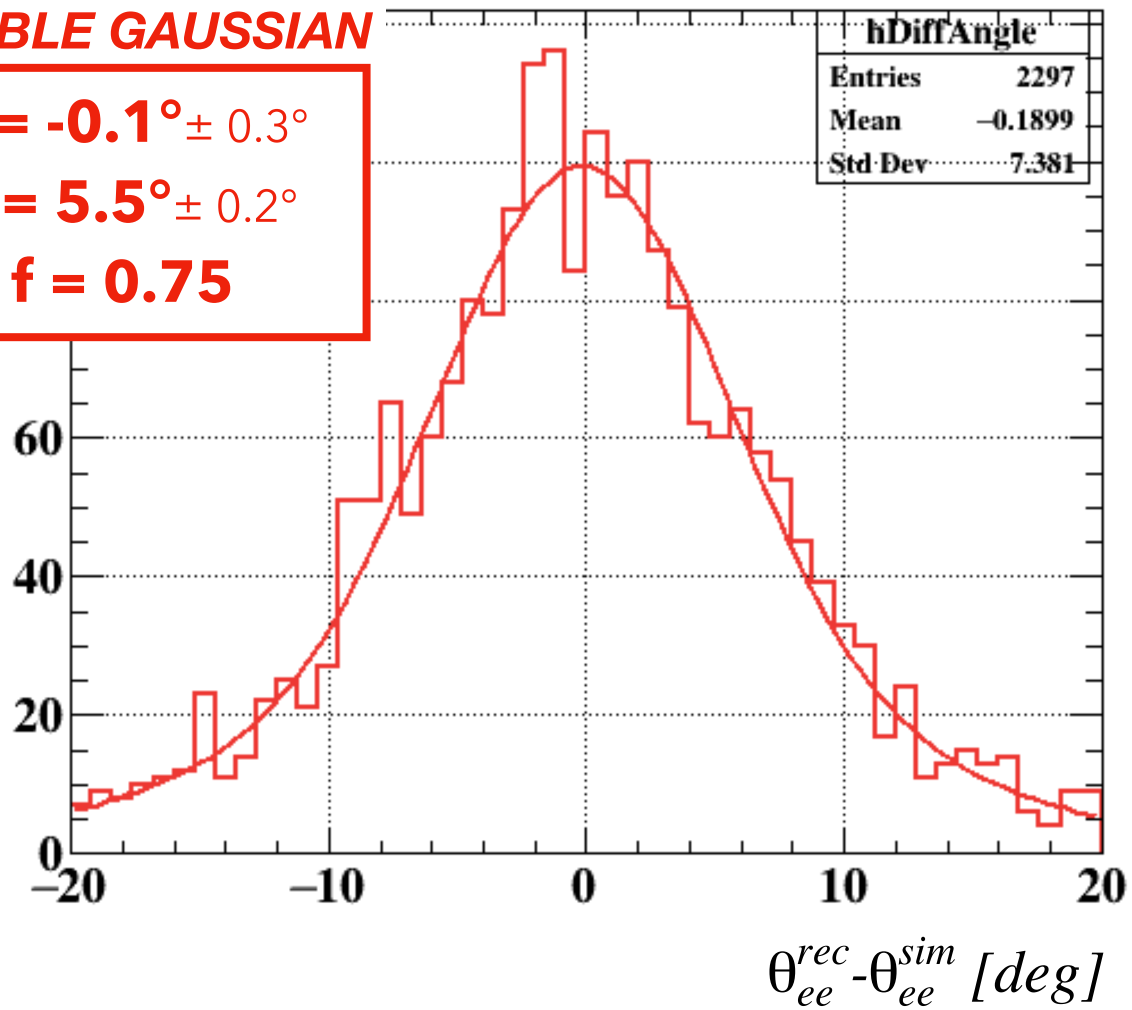
μ = -0.2°± 0.5°
σ = 7.1°± 0.4°
f = 0.75



With vertexing

DOUBLE GAUSSIAN

μ = -0.1°± 0.3°
σ = 5.5°± 0.2°
f = 0.75

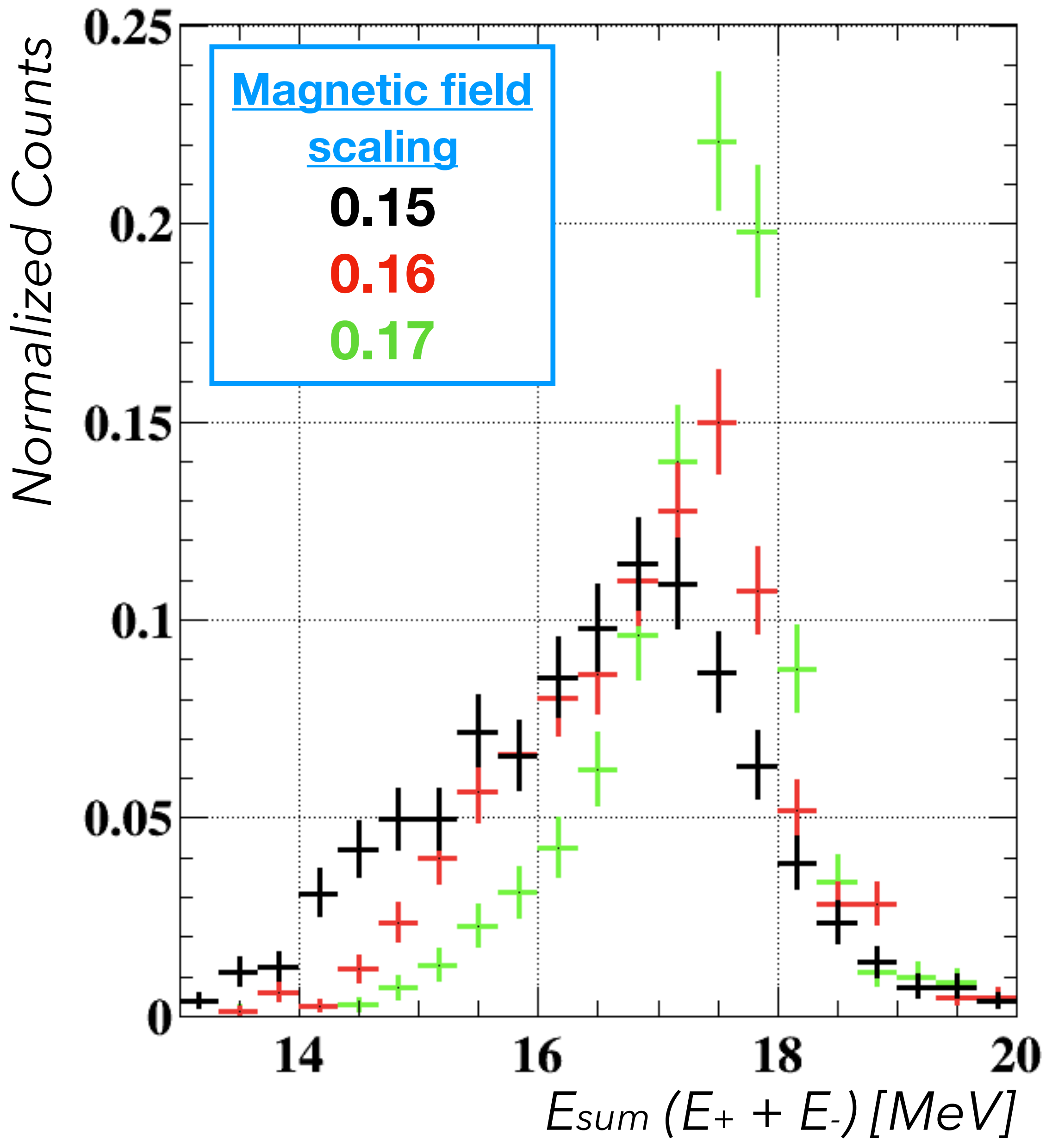


→ 25% improvement on X17 signal angular opening resolution

Reduced magnetic field

- $\mu^+ \to e^+\gamma$ search relies on 52.8 MeV positron search with default magnetic field (1.27T at COBRA center)
- for X17: energies ~6 times lower → 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	good resolution but poor efficiency (low mom outside acceptance)
0.16	good resolution + good efficiency
0.15	good resolution + good efficiency + lower E_{sum} tail for study in sidebands



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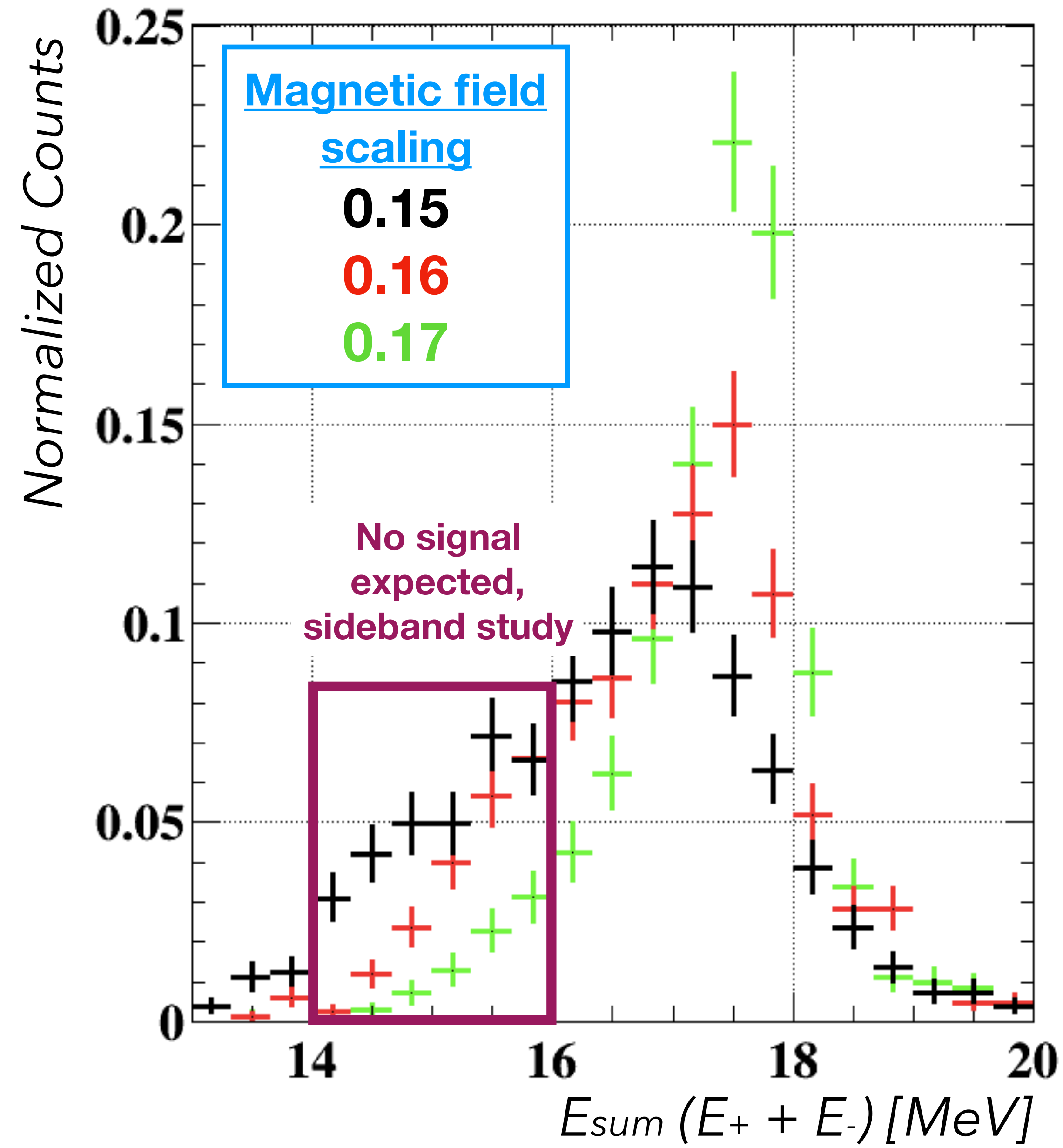
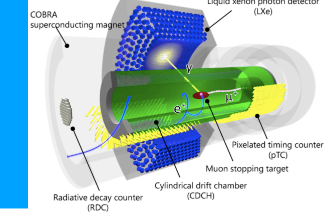
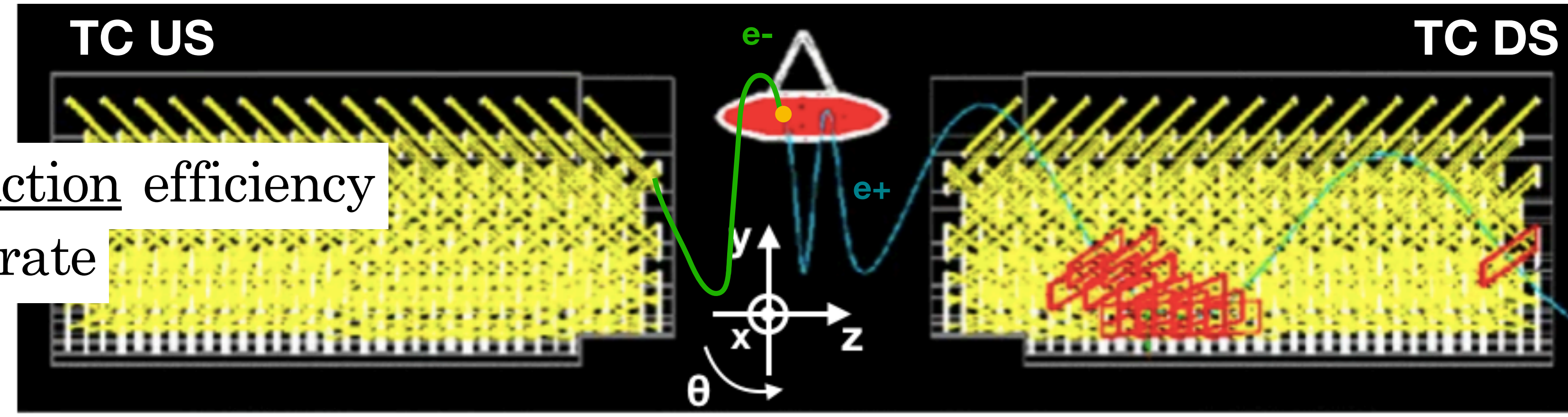


Trigger strategy: TC hit multiplicity





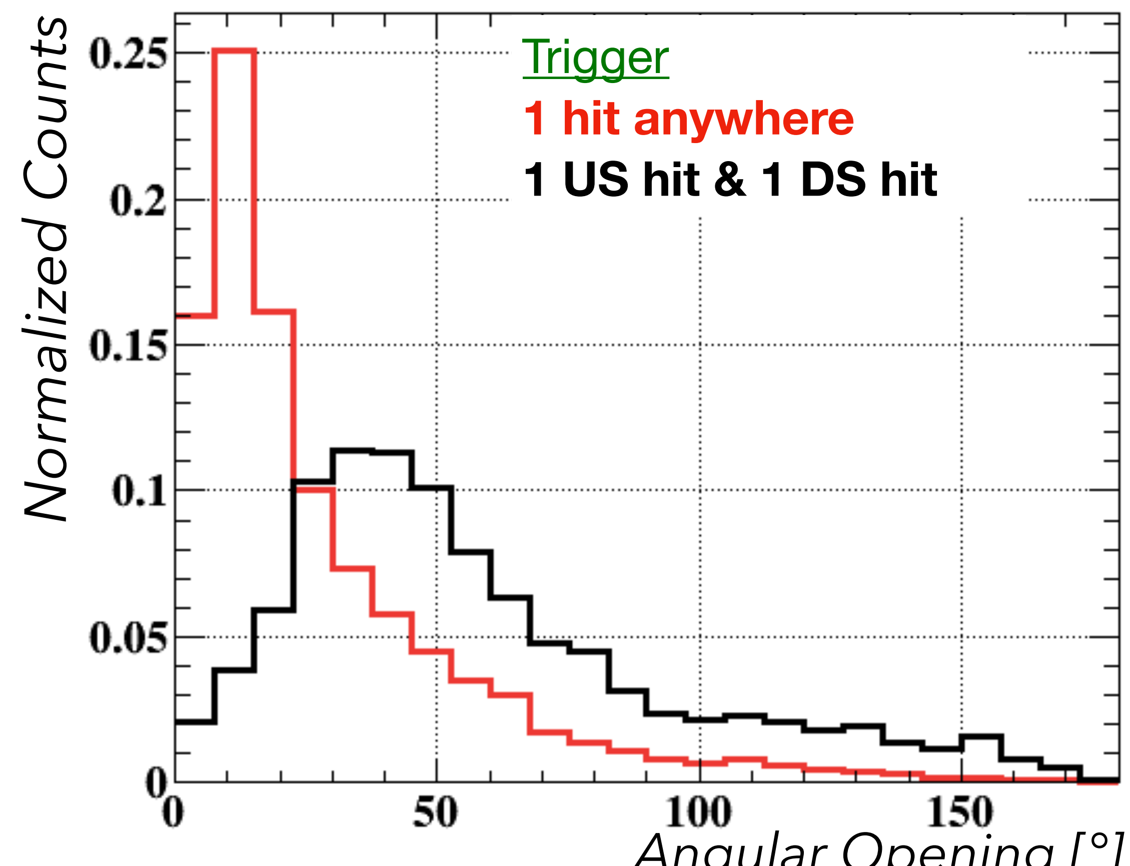
Why requesting at least 1 TC hit?

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

One trigger option:

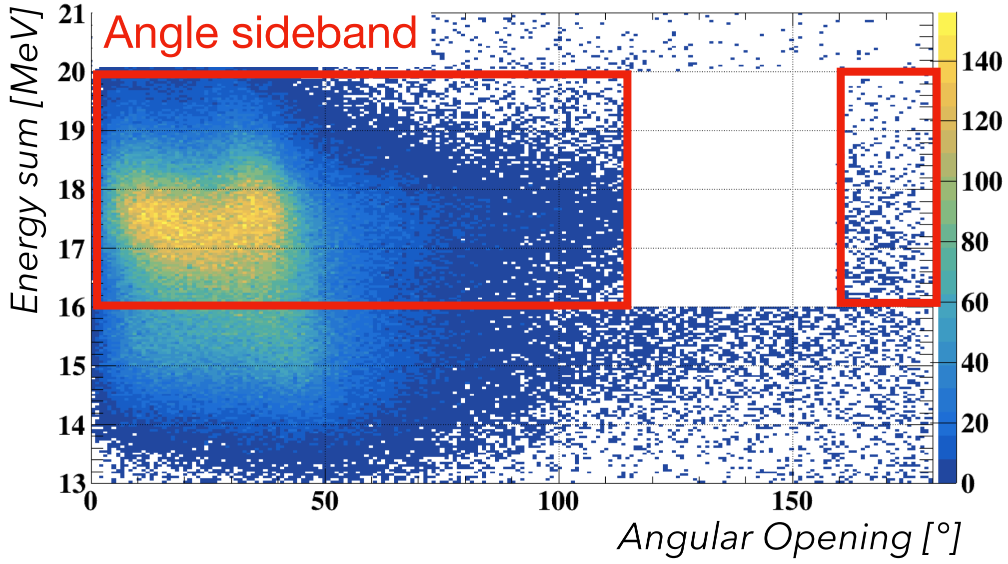
- 1 TC hit US & 1 TC hit DS
- Selects large angular opening pair
- IPC rate divided by a factor 60 (wrt to 1 TC hit)
- Total trigger rate < 1 Hz (at I_{proton} = 10μA)
- X17 rate divided by a factor 3 (wrt to 1 TC hit)
- Low angle statistics is mitigated
- Proton current limitations prevented us from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

Reconstructed IPC angular opening

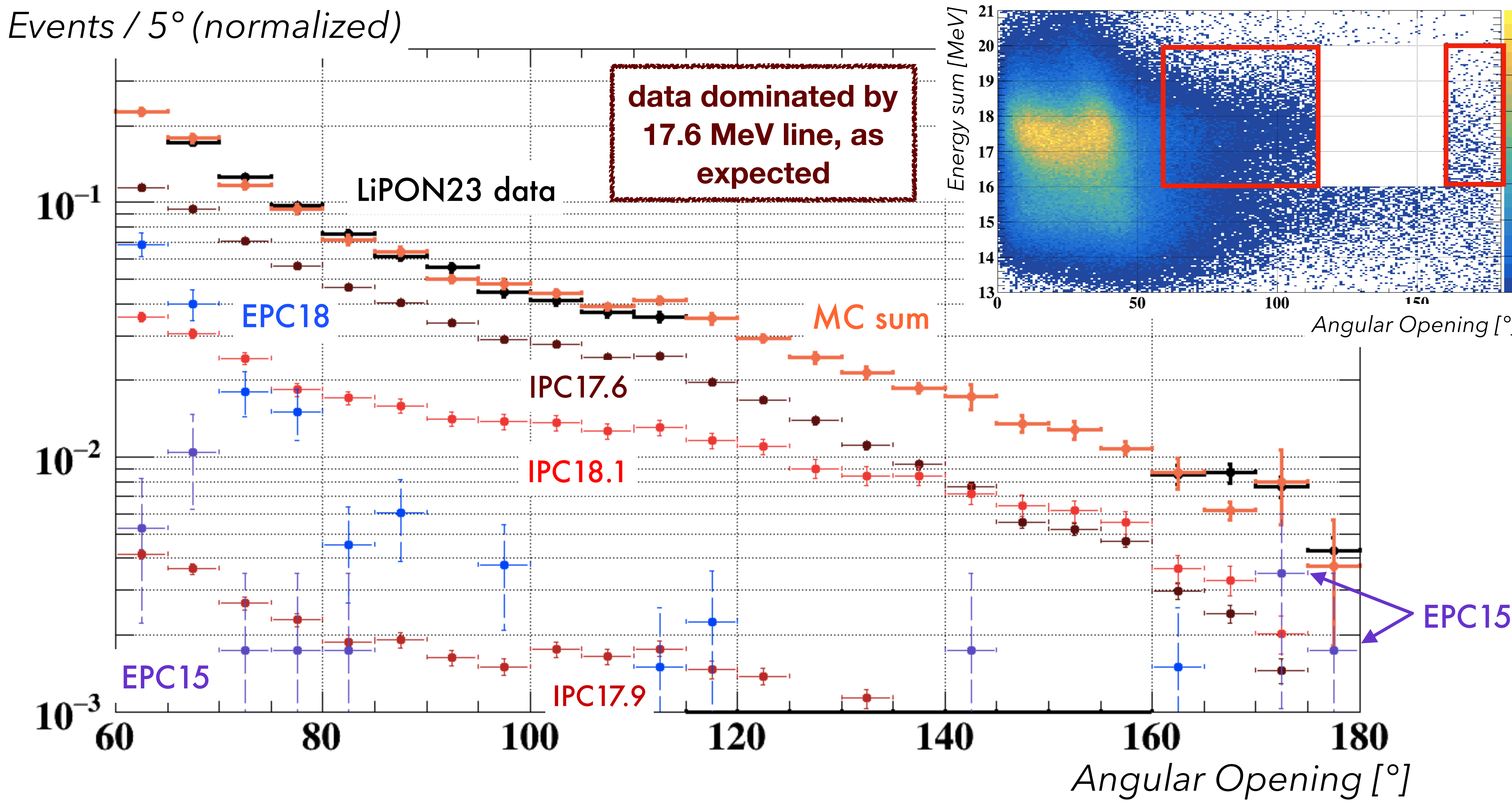


To be considered in the future but for now **1 TC hit required**

Angle sideband fit



Angle sideband fit



- large angles can be fitted with a mix of **flatter IPC** and **EPC bkg**
- further statistics will give more insight but **good understanding of various contributions**
- background is **smooth and monotonously falling in signal region**

2D template fit

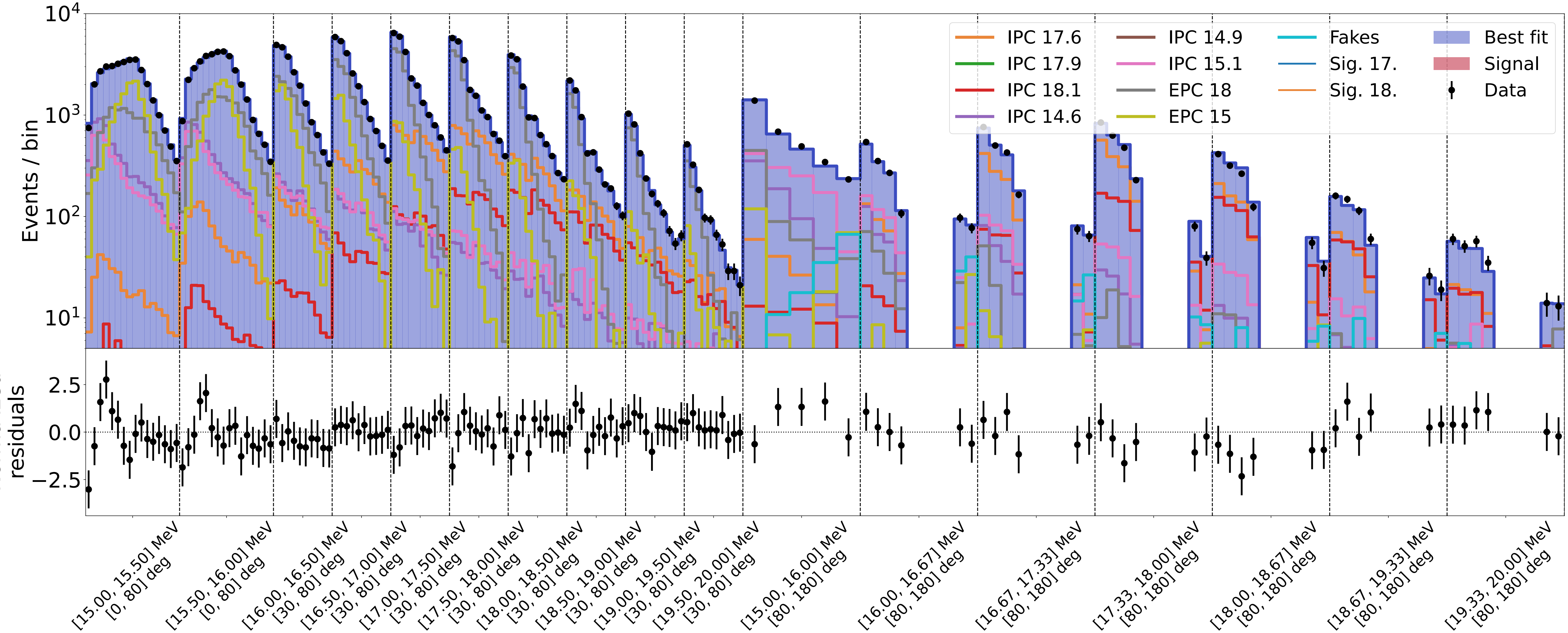
→ We can use template histograms, directly from the MC production:

- 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)
  Barlow 1993
- 2D template fit Esum vs Angle maximizing such likelihood is under investigation
- Additional constraints on ratio of proportions between **$IPC_{18,i}$** and **$IPC_{15,i}$** based on literature
- First tests on both 2023 sidebands

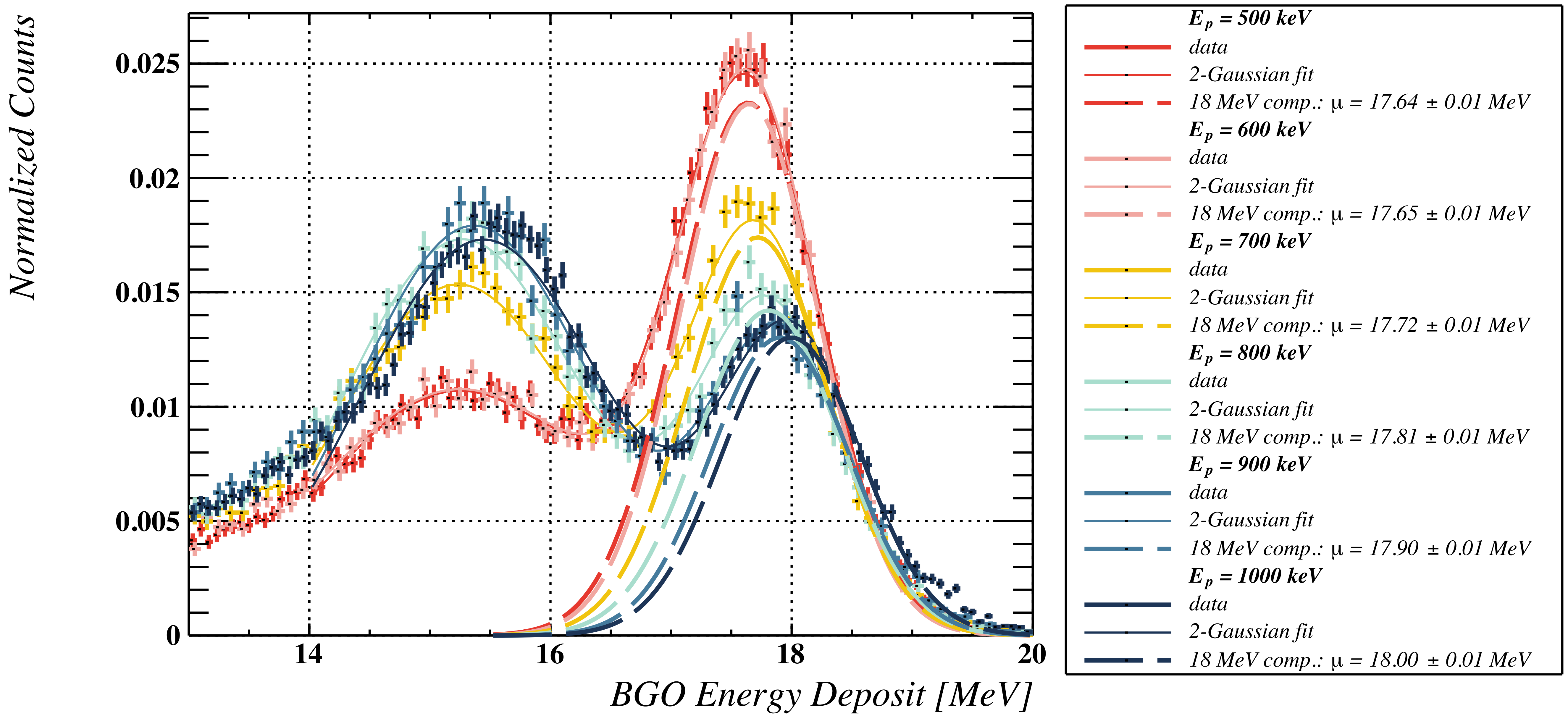
Template fit

- 2D fit in slices of Esum:



Ep scan: LiPON spectra on BGO

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



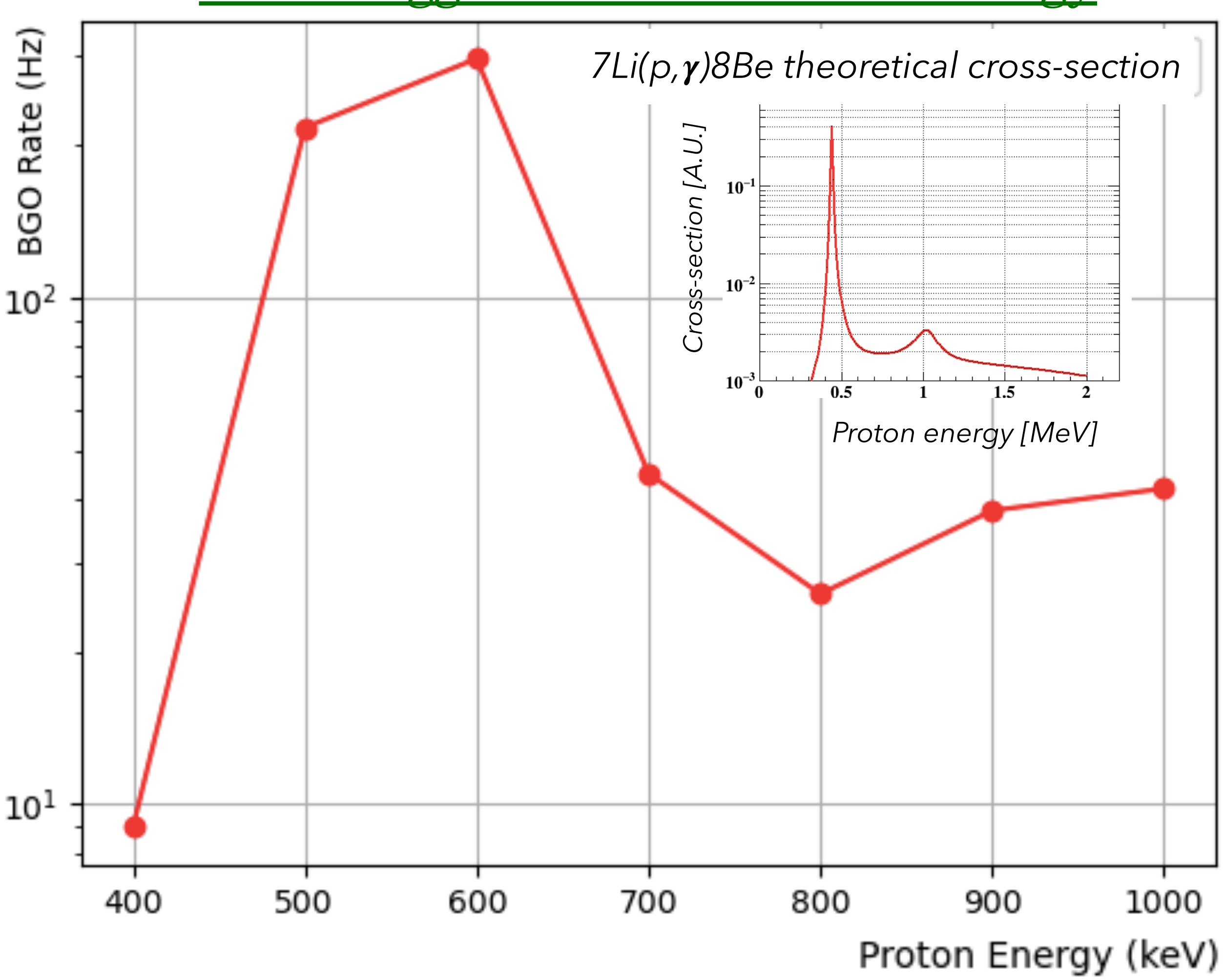
→ As expected, **clear shift of a few hundred keV. To be confirmed with final fit.** BGO PMTs gain drift considered small.

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

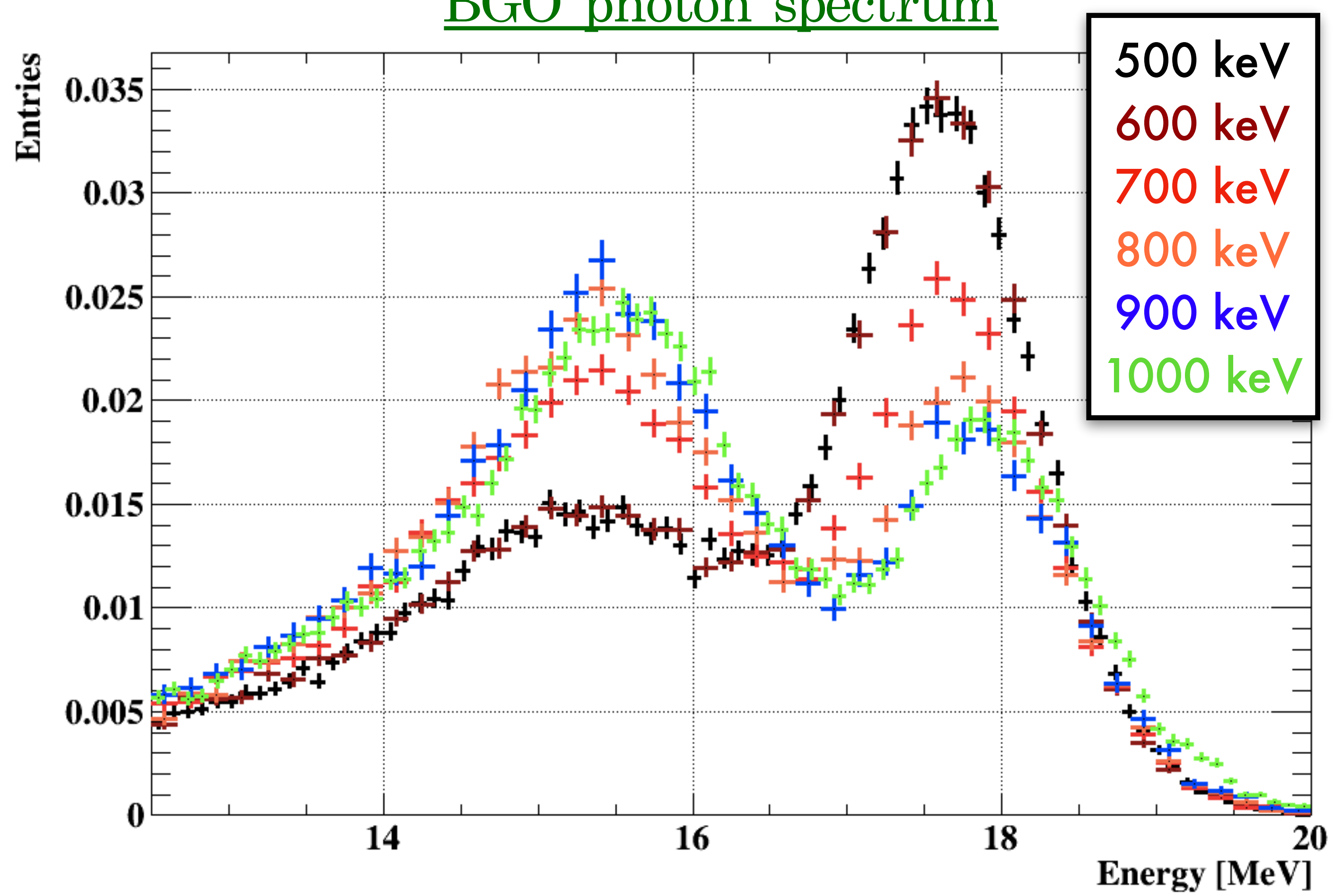
What's next?

- 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!