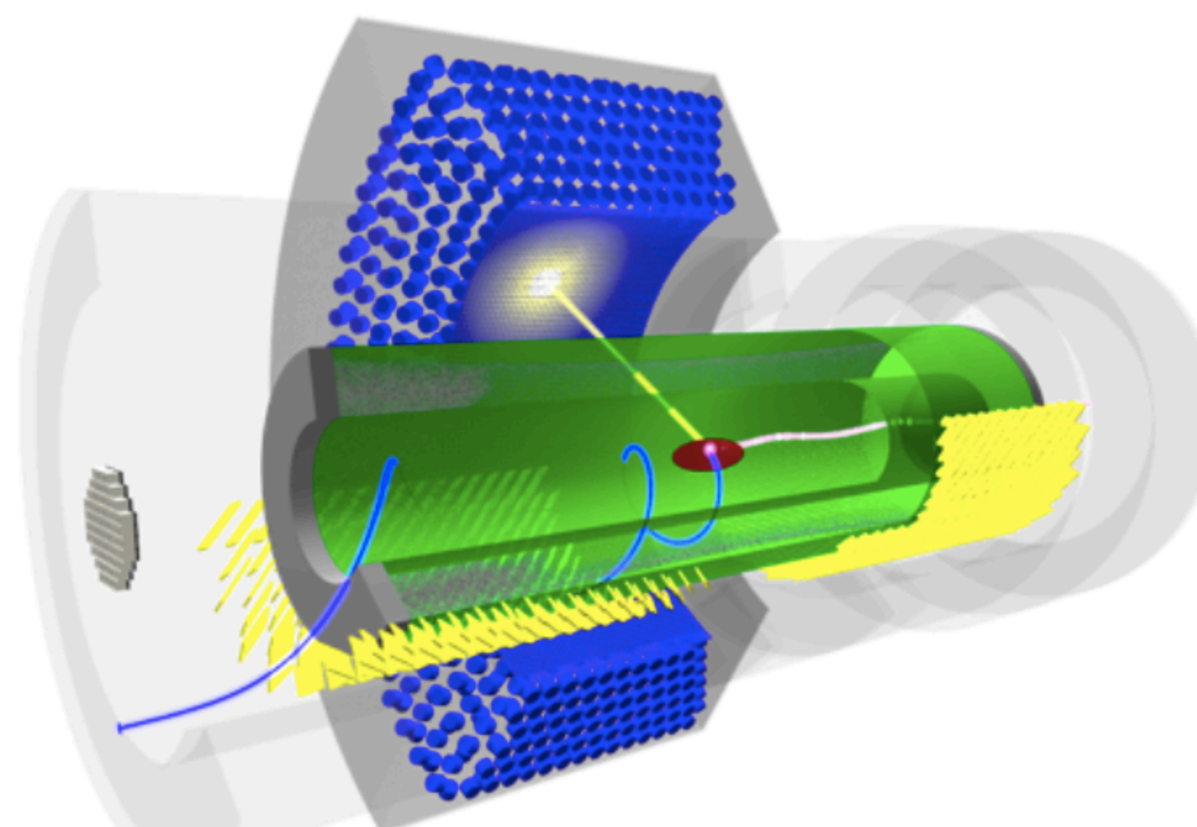
H2020 MSCA ITN
G.A. 858199

Results on the X17 search with the MEG-II apparatus

arXiv:2411.07994

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



Imperial HEP seminar
London, June 13th, 2025

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Outline

1) Physics motivation: the Atomki anomalies

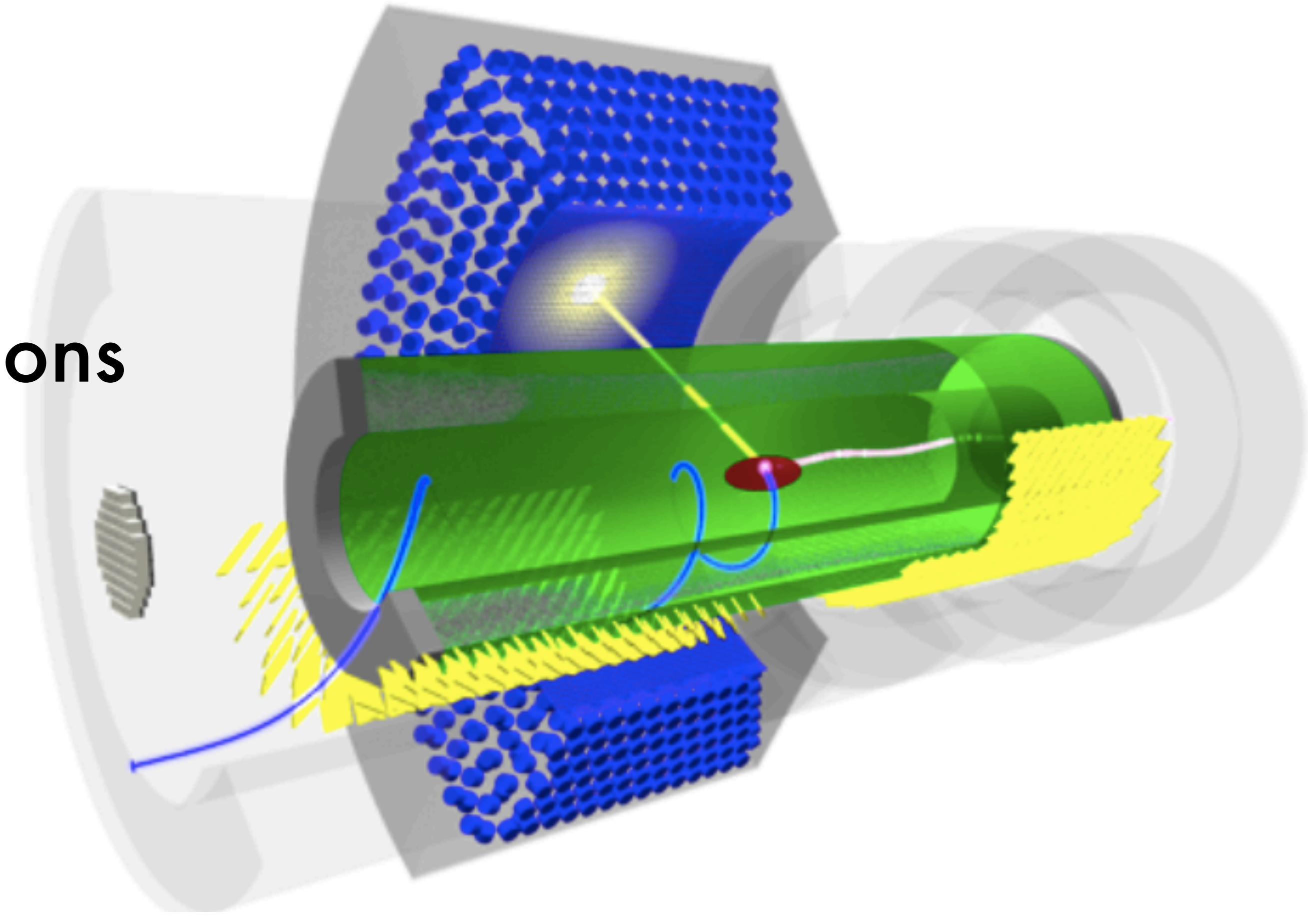
2) The MEG-II apparatus

3) Backgrounds and signal simulations

4) Pair reconstruction

5) Trigger and DAQ strategies

6) Physics dataset and X17 results



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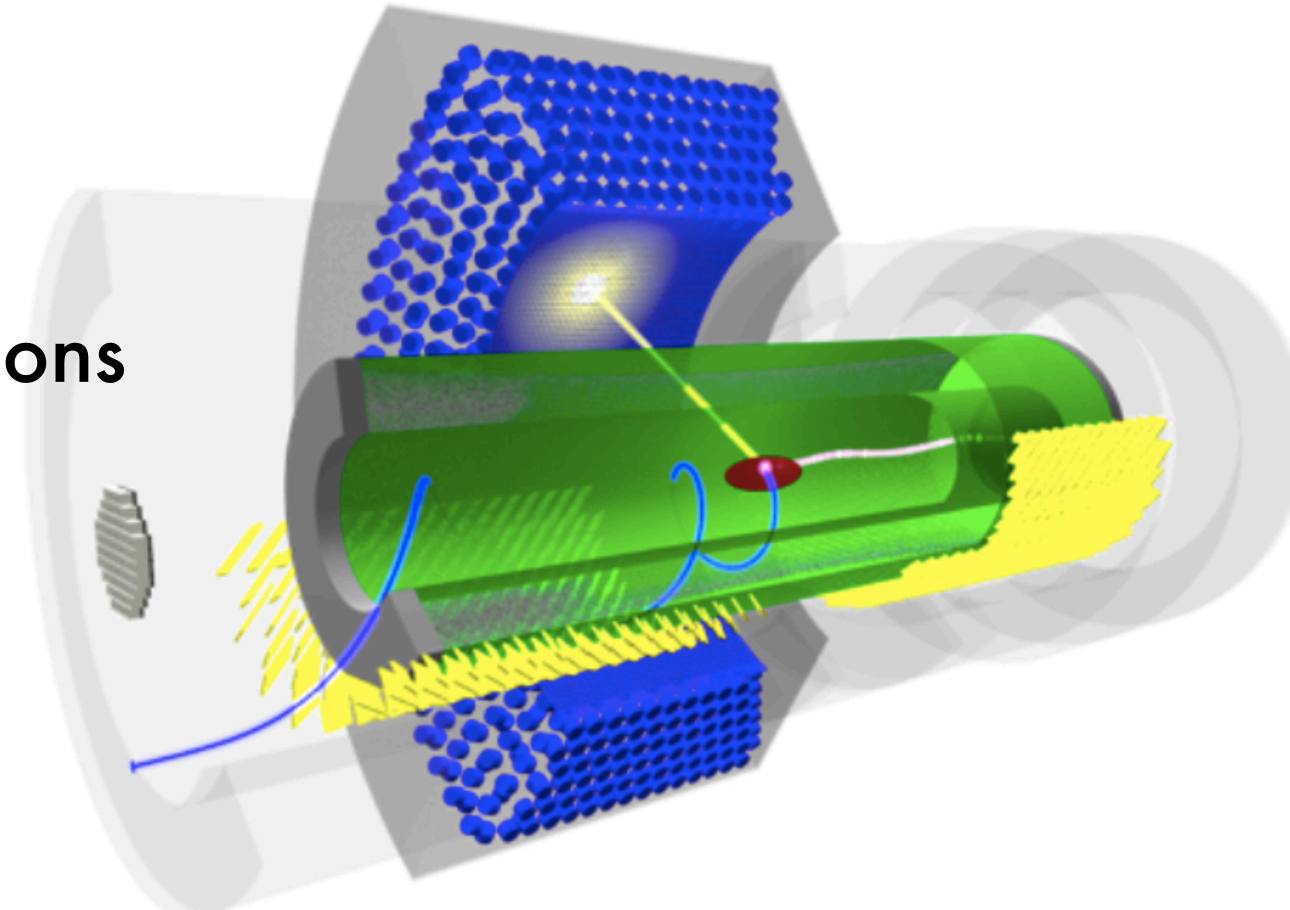
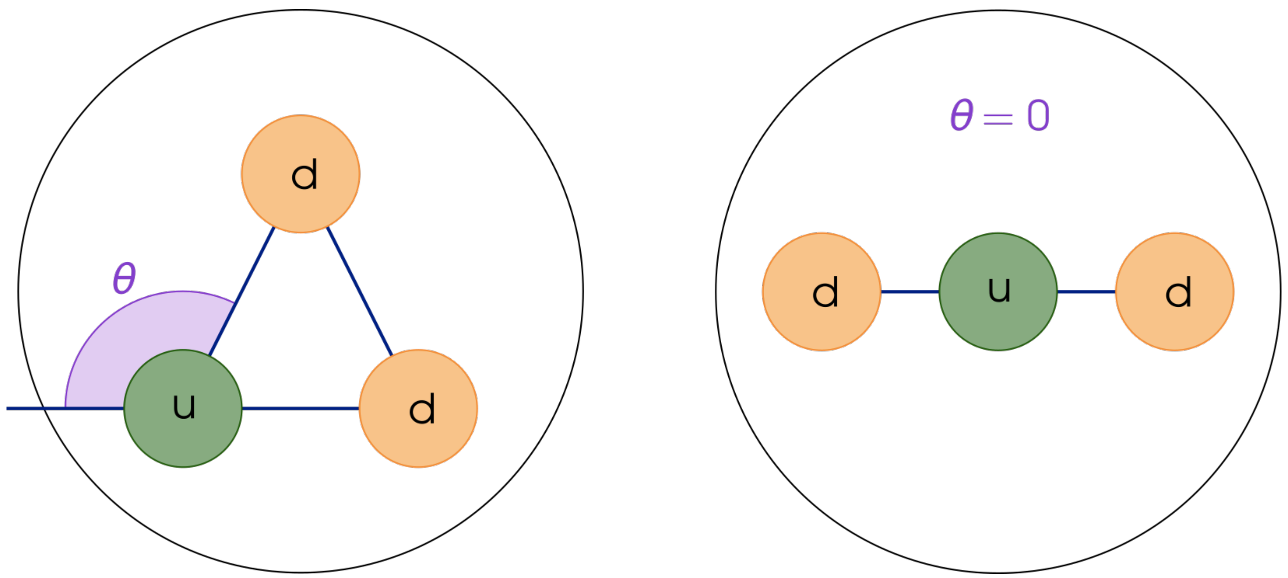


1) The Atomki anomalies

QCD axion

Strong CP problem

- QCD allows for a CP-violating term ($\propto \theta$) but experimentally appears CP-invariant (neutron EDM)



- 1970s light pseudoscalar boson was introduced to fix the strong CP problem: AXION Phys. Rev. Lett 38, 1440 (1977)

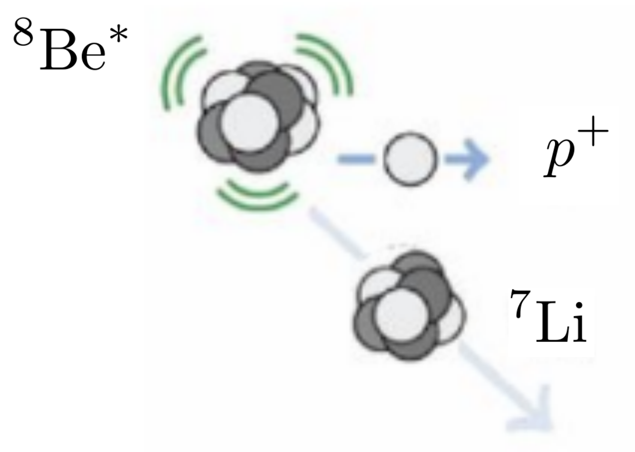
- 10 MeV axion could be found in nuclear de-excitations: ^{12}C* decay Phys. Lett. 74B, 381 (1978)

- Pion, quarkonia decays, (g-2)$_\mu$: strong limits on MeV axion $a \to e^+e^-$

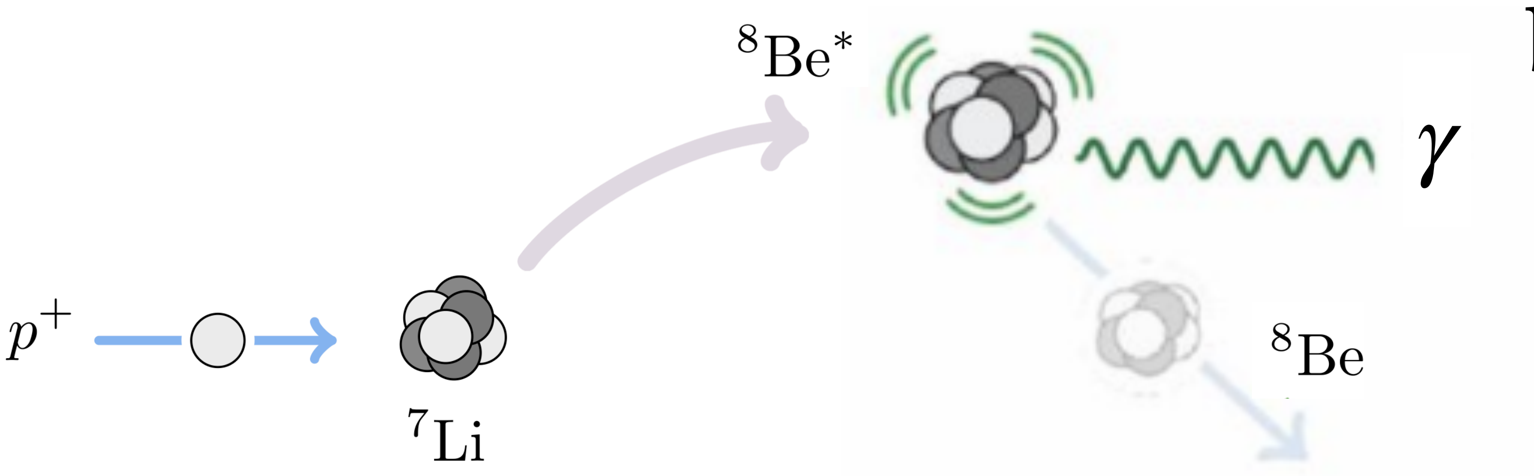
- But strong constraints on couplings gives room for MeV axion/new boson

- Let's look for a new boson (fifth force) in Beryllium (Be) decays

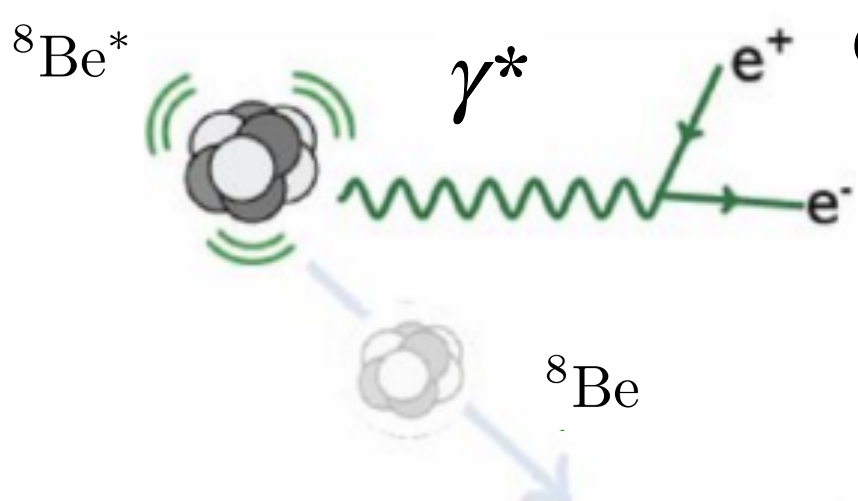
Beryllium decays



a) Hadronic dissociation
BR ~ 100%



b) Electromagnetic transition
γ-emission
BR ~ 1e-5



c) Electromagnetic transition
Direct e^+e^- emission
BR ~ 1e-8

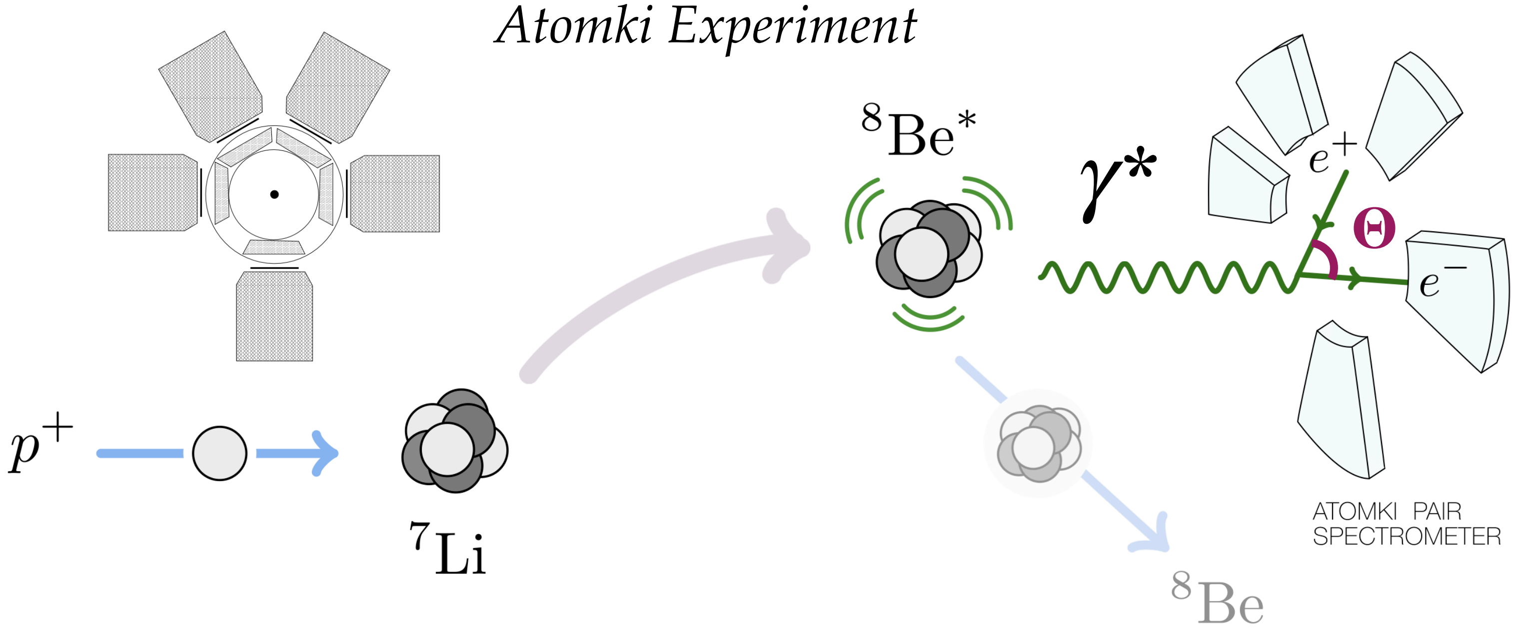
IPC = Internal Pair Conversion

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

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

①

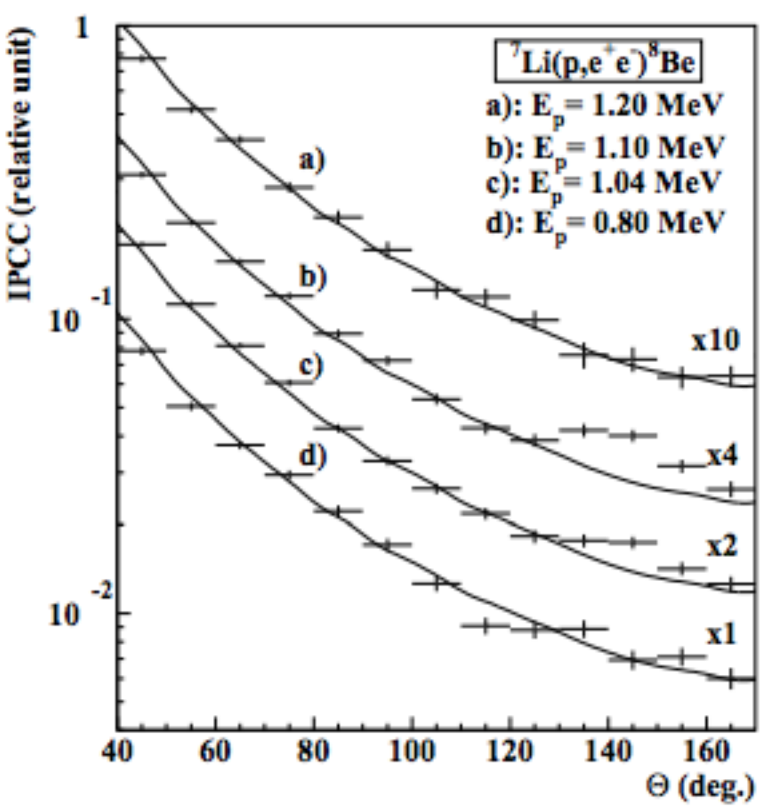
Atomki Experiment



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

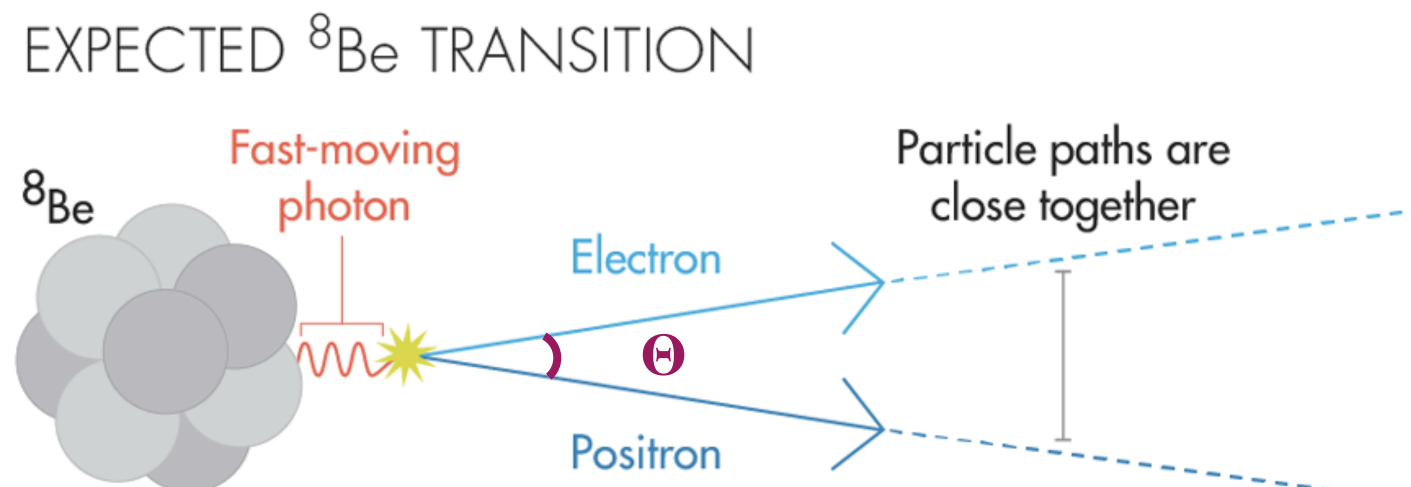
→ e+/e- energy sum and
angular opening **Θ**

2016 Atomki results



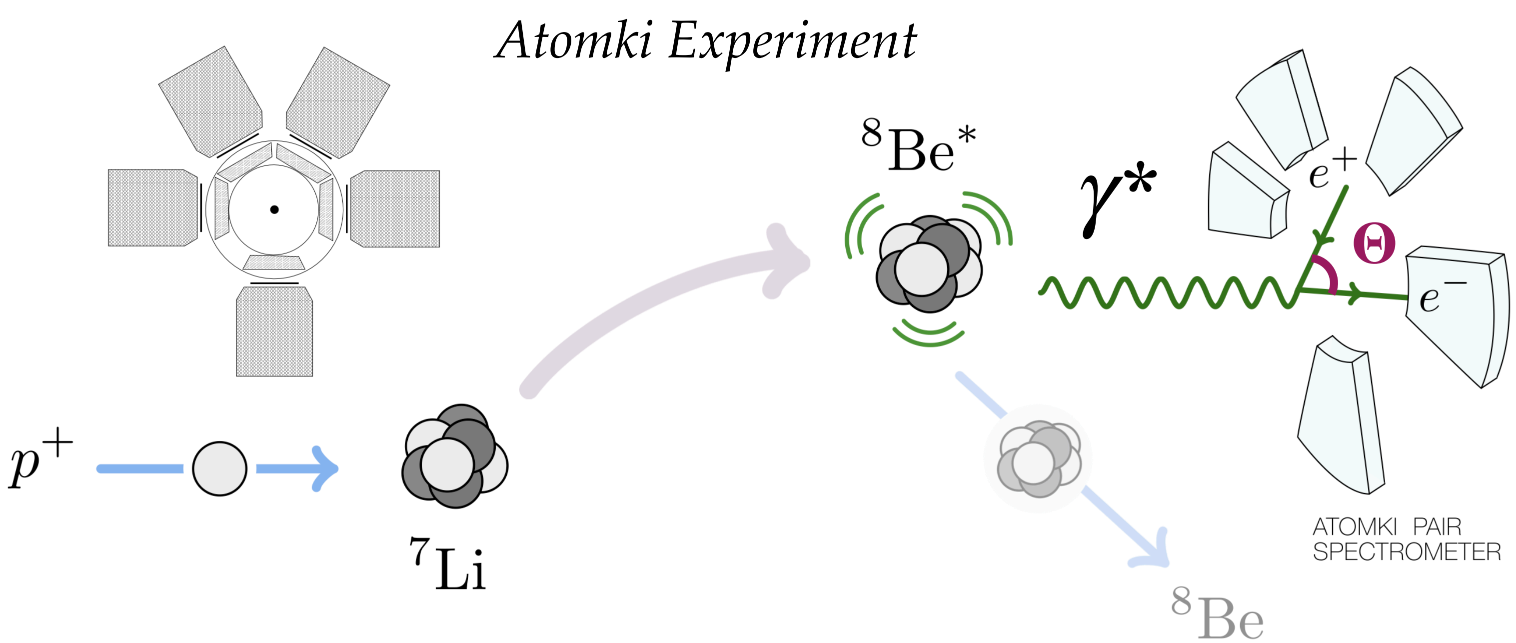
Phys. Rev. Lett. 116, 042501

IPC mostly small angles
Monotonous decrease expected



The Beryllium Anomaly

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



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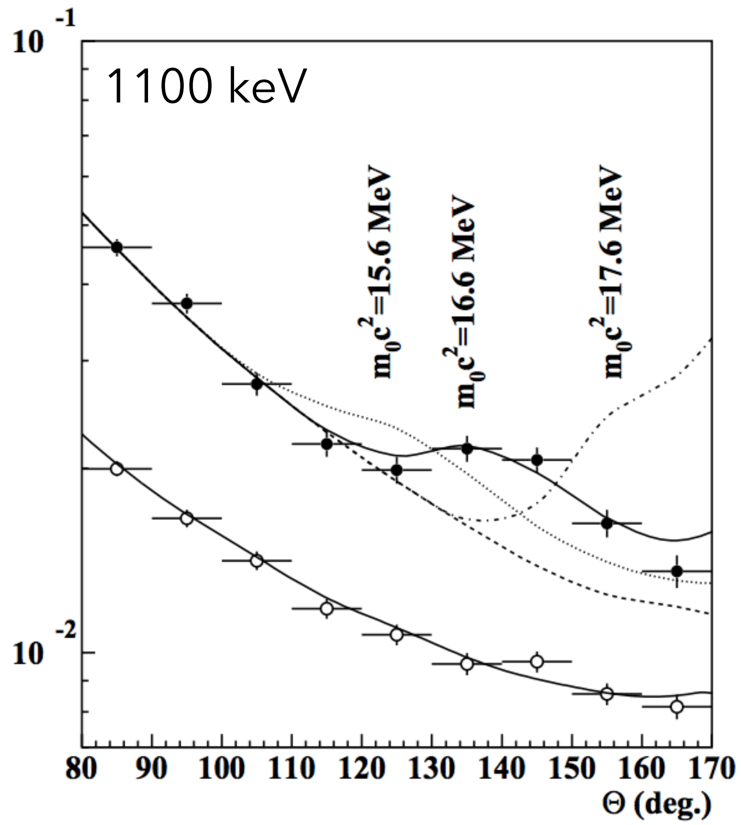
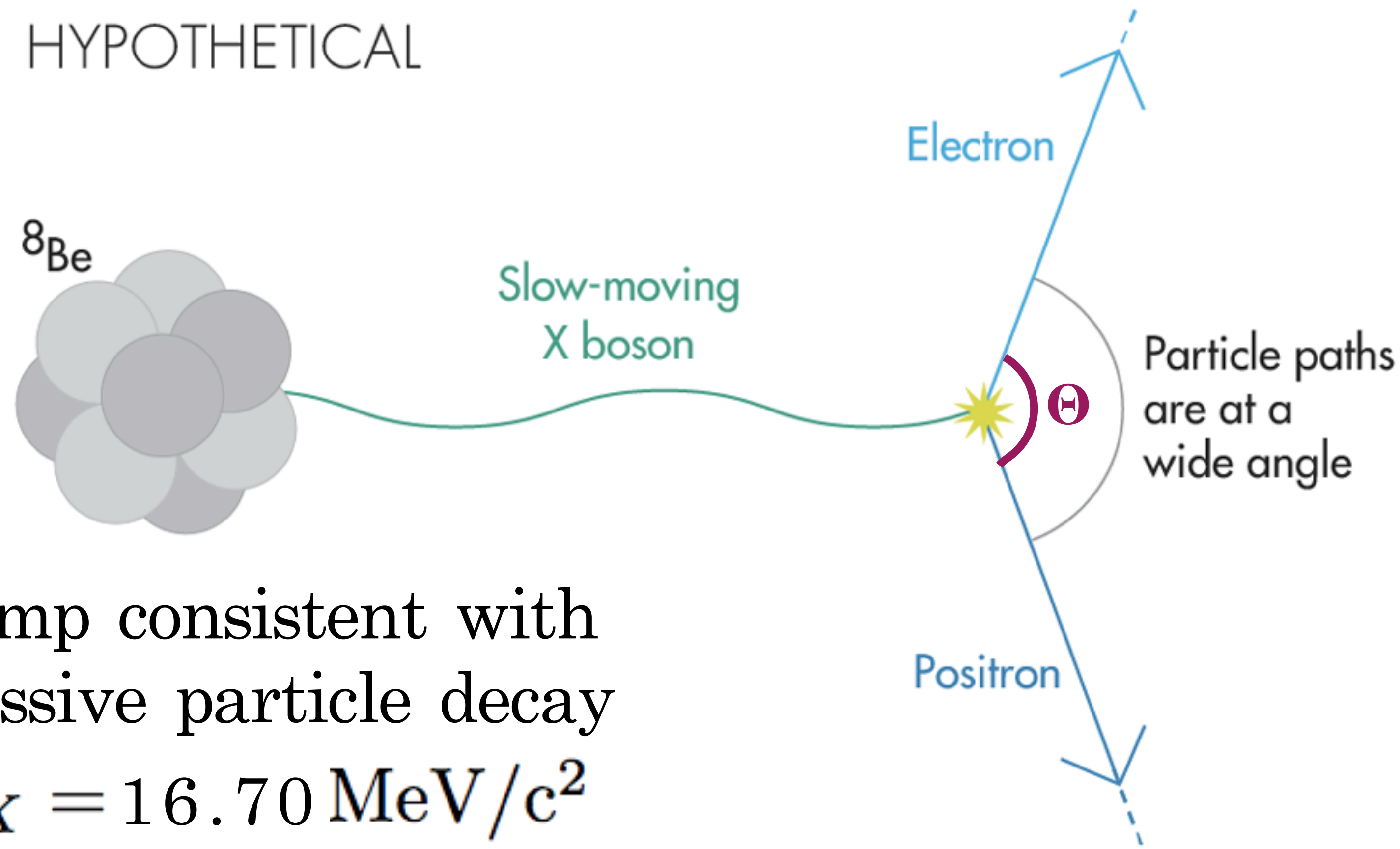


Phys. Rev. Lett. 116, 042501



→ Bump consistent with massive particle decay

→ $m_X = 16.70\ \mathrm{MeV}/c^2$

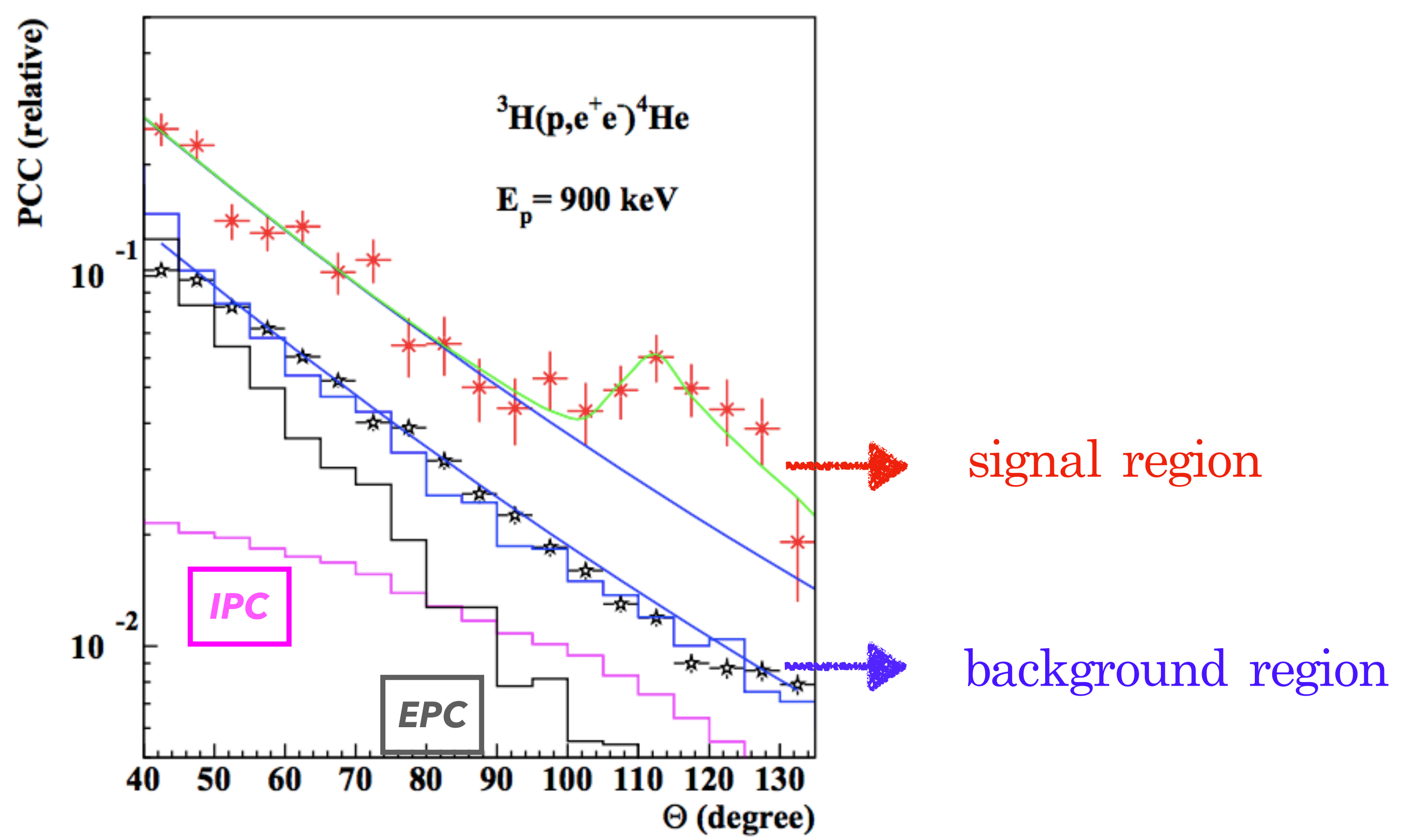
→ Fifth force? Phys. Rev. D 95, 035017

Consistent anomalies? ①

Phys. Rev. C 104, 044003 arXiv:1910.10459

Study repeated with Tritium target

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

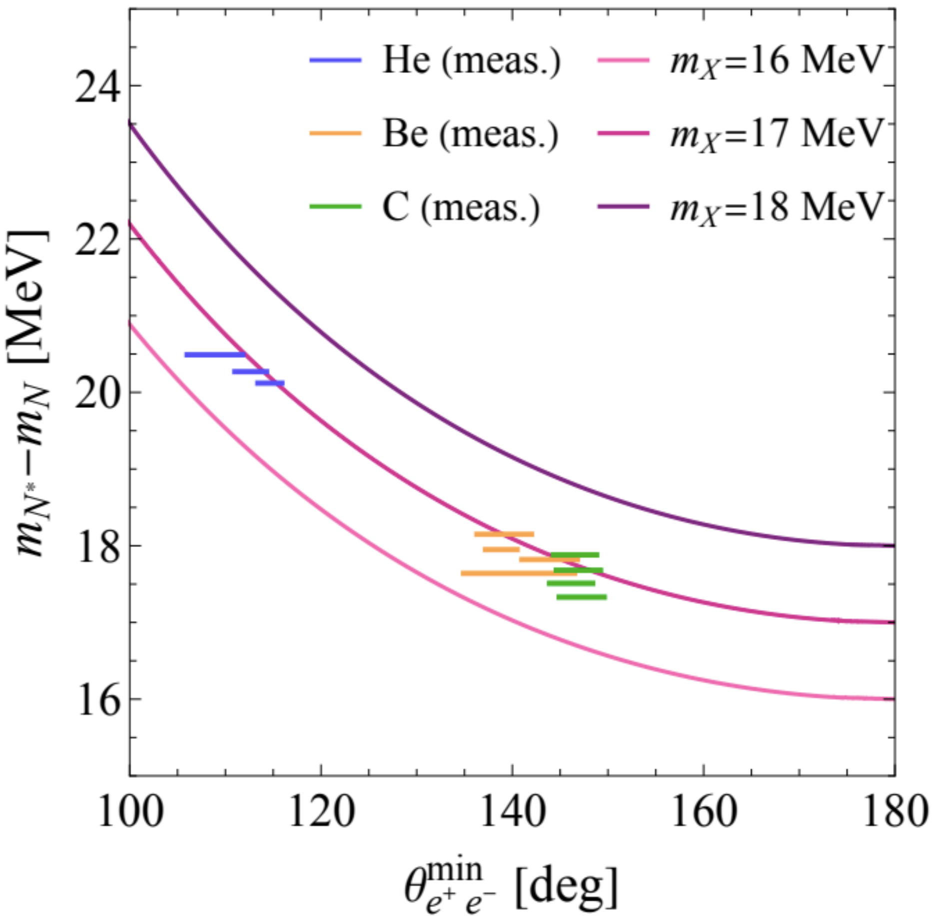


- Excess in IPC background at 115° angular opening: >6σ
- Possible explanation: a 16.84 MeV/c^2 neutral boson (X17?)
- Recent excess in $^{11}\mathrm{B}(p, e^{+}e^{-})^{12}\mathrm{C}$ as well Phys. Rev. C 106, L061601
- Other indirect searches (NA64, NA48/2): no evidence for X17 but strong constraints Phys. Rev. D, 101:071101 Phys. Lett. B 746, 178

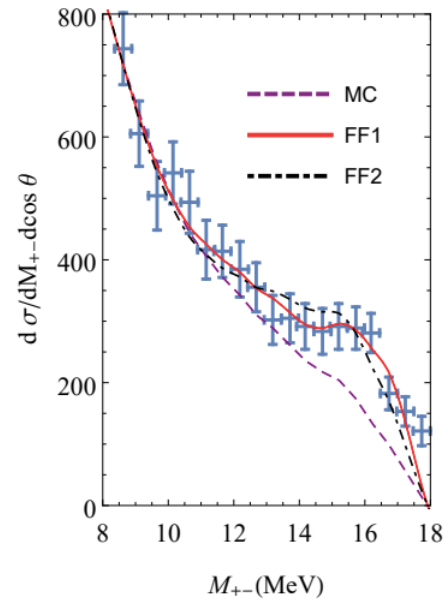
New boson or standard physics? ①

New boson? or Standard Model physics?

Phys. Rev. D 108, 015009



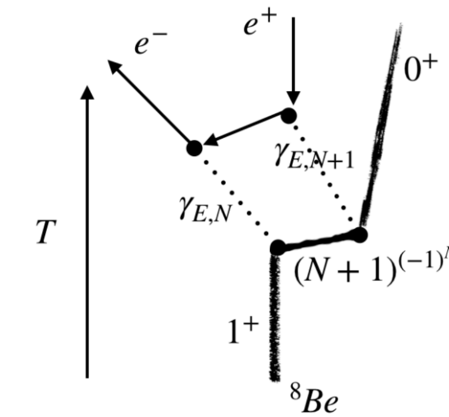
- Reported results are kinematically consistent



- Zhang & Miller 2017

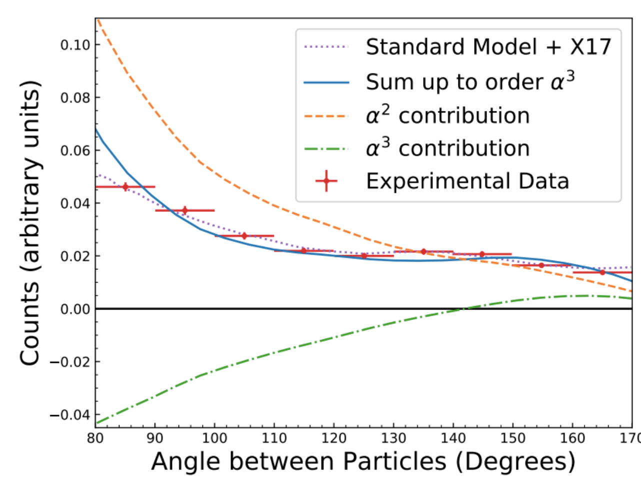
Phys. Lett. B 773, 159

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

①

- 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 <u>2022</u>
- Physics DAQ period in <u>February 2023</u>

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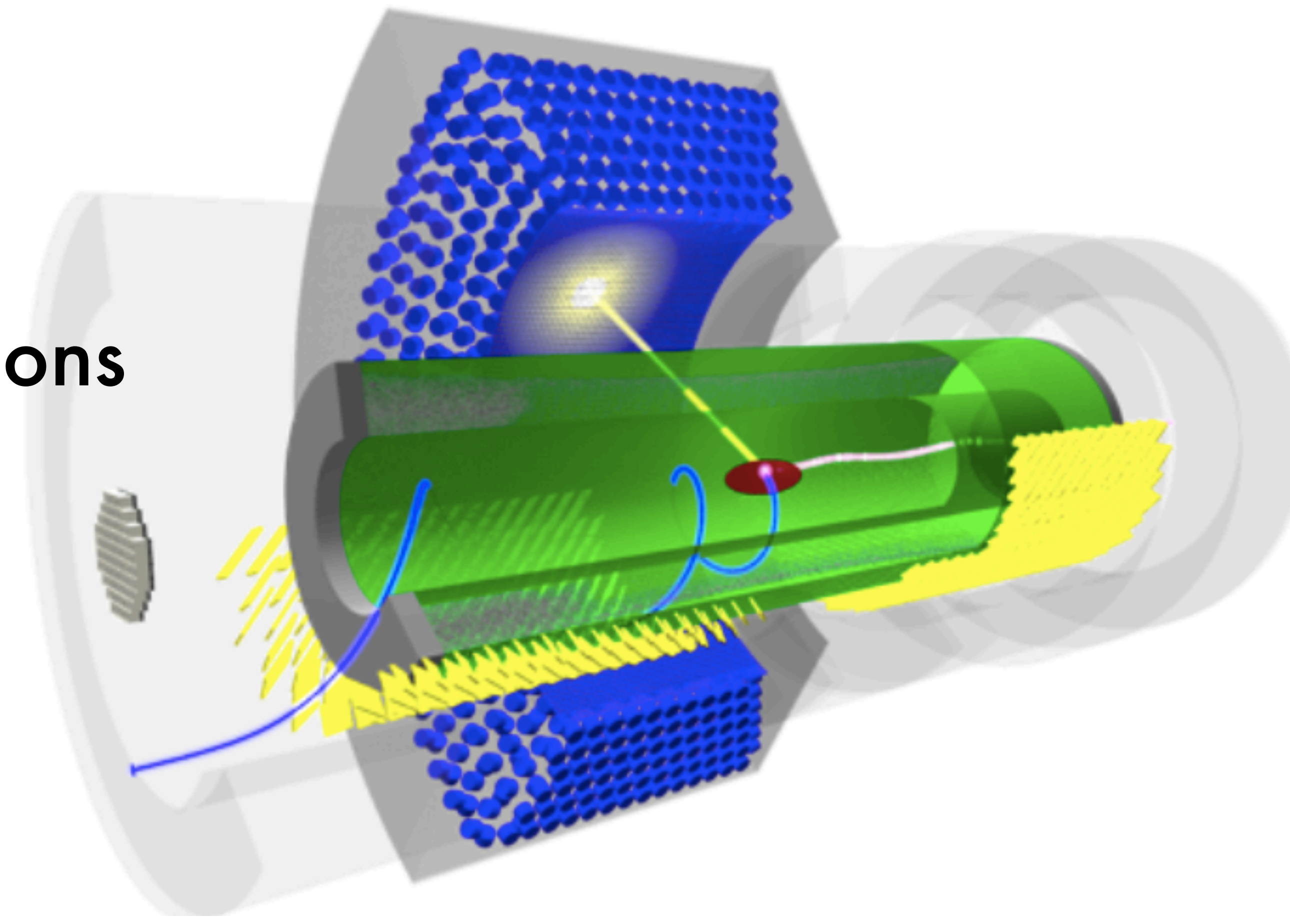
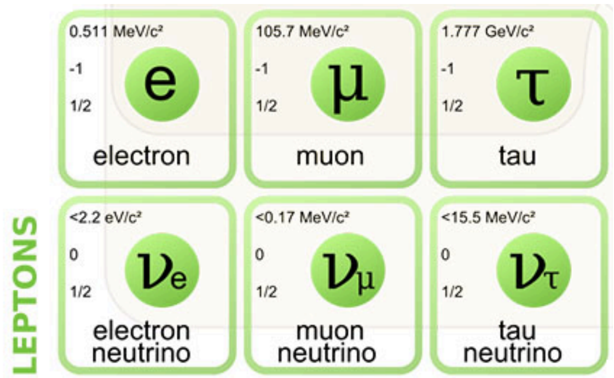


2) The MEG-II apparatus

The MEG-II experiment

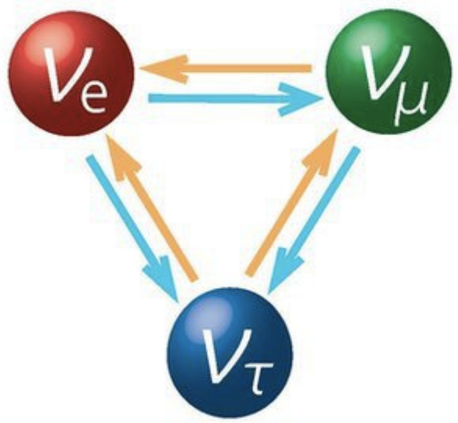
- MEG–II was originally designed to look for Charged Lepton Flavour Violation (CLFV)

Charged Lepton Flavour Violation



- Lepton flavour violation observed experimentally with neutral leptons

  → Neutrino oscillations (Super-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

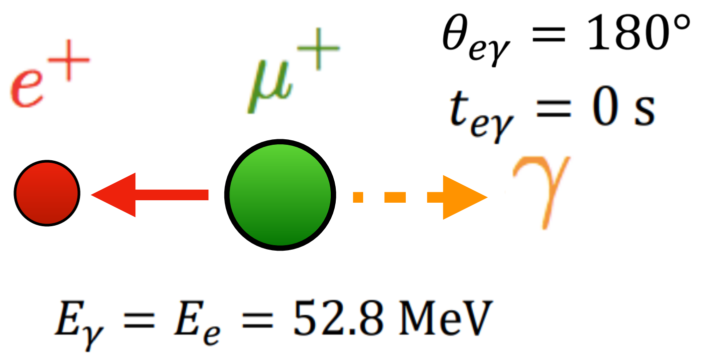
$$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$$

accessible experimentally today

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

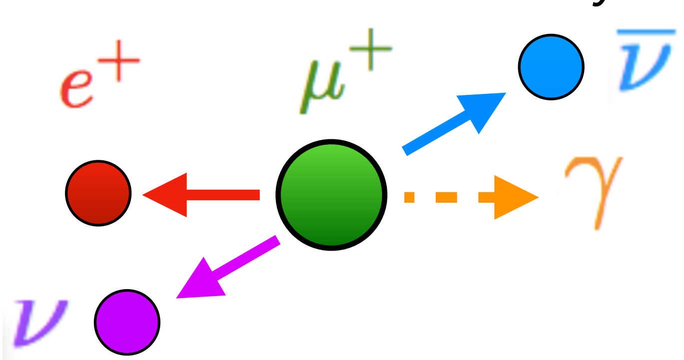
Signal

Back-to-back decay at rest

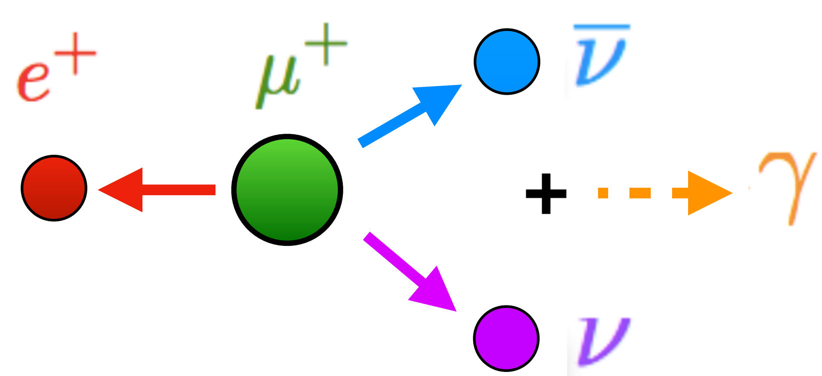


Backgrounds

Radiative Muon Decay



Accidental

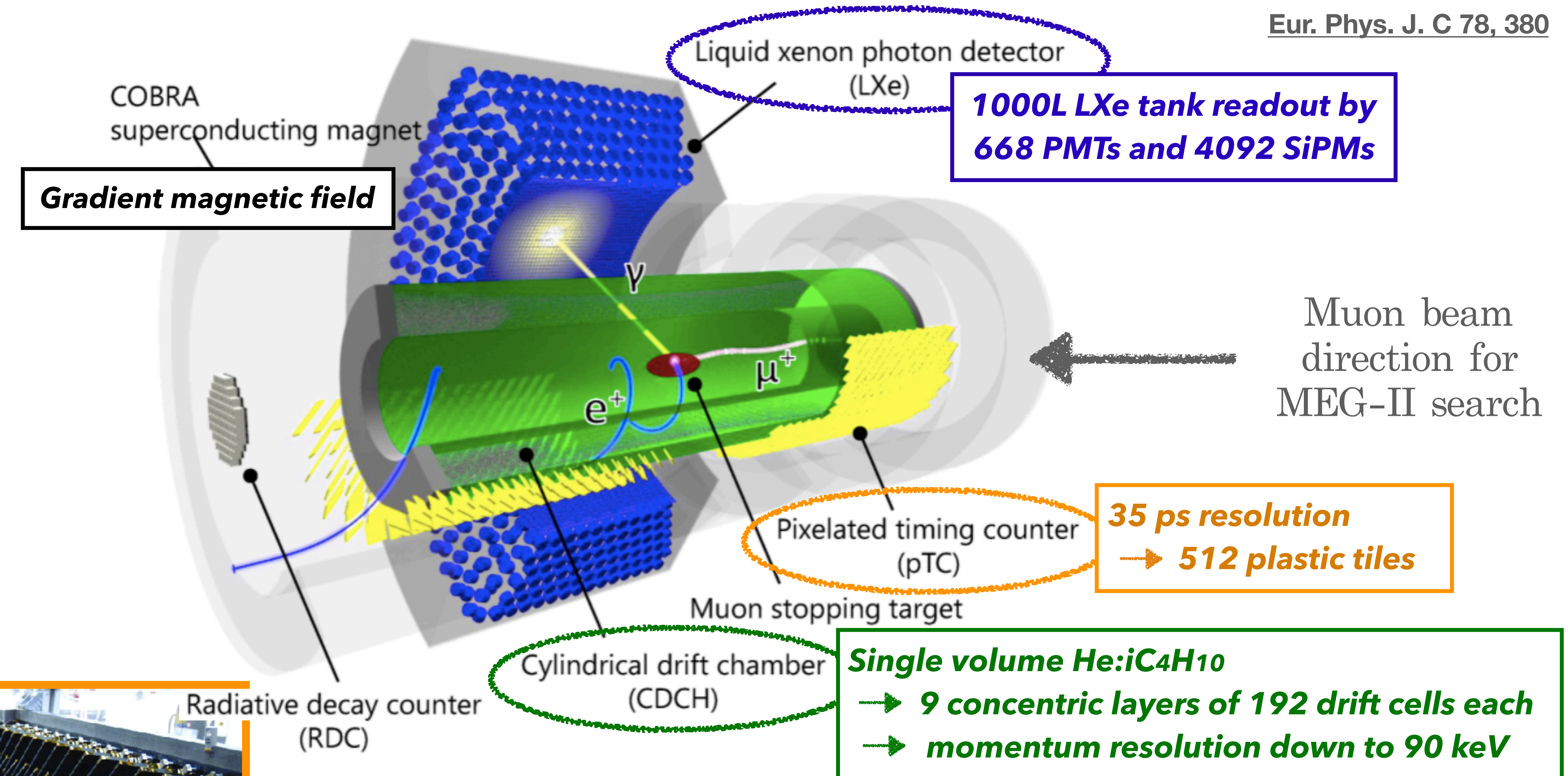


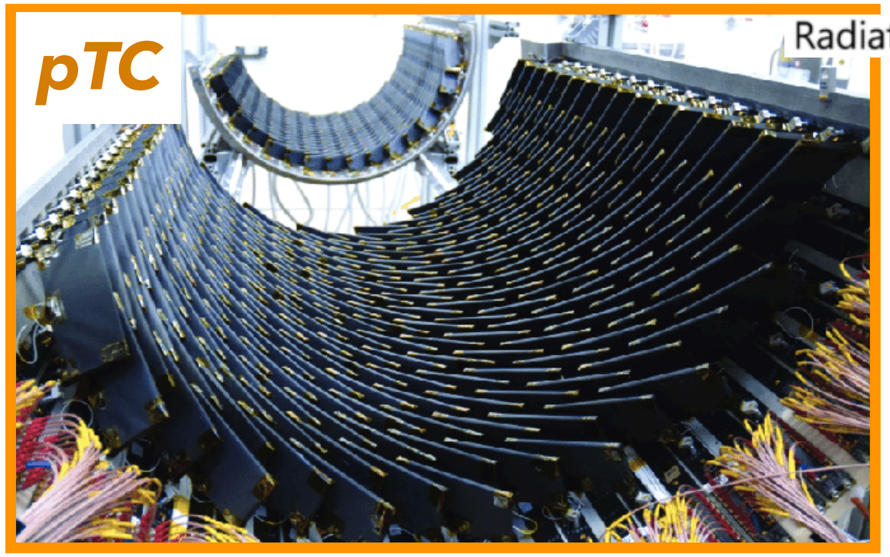
The MEG-II experiment

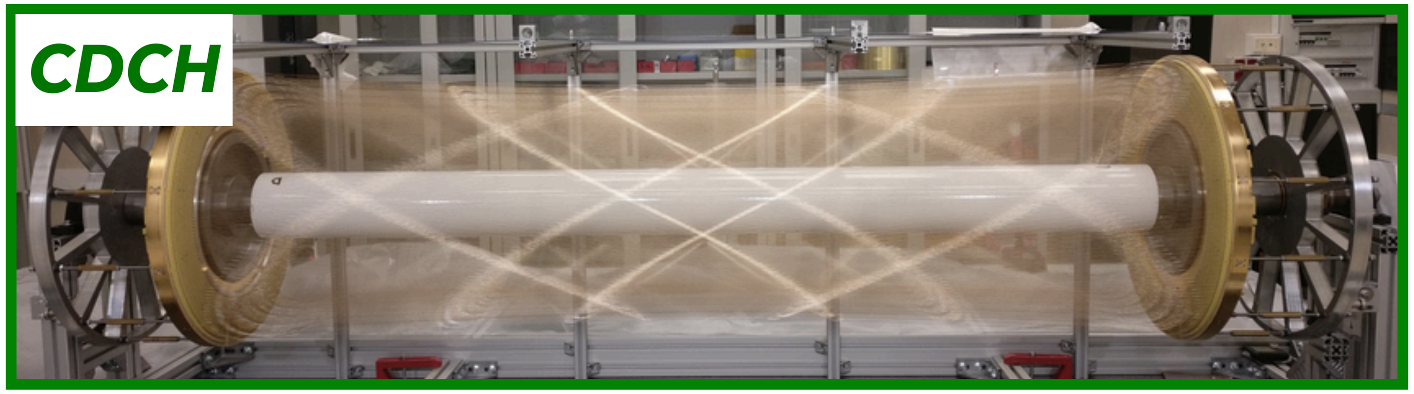
- MEG-II experiment searches for charged lepton flavour violating decay: $\mu^+ \to e^+\gamma$
- At Paul Scherrer Institute, PSI, Switzerland Eur. Phys. J. C, 76(8):434
- 1 order of magnitude sensitivity improvement wrt MEG: $BR(\mu \longrightarrow e\gamma) \to 6 \times 10^{-14}$

Eur. Phys. J. C 78, 380

MEG-II results from an intense upgrade program



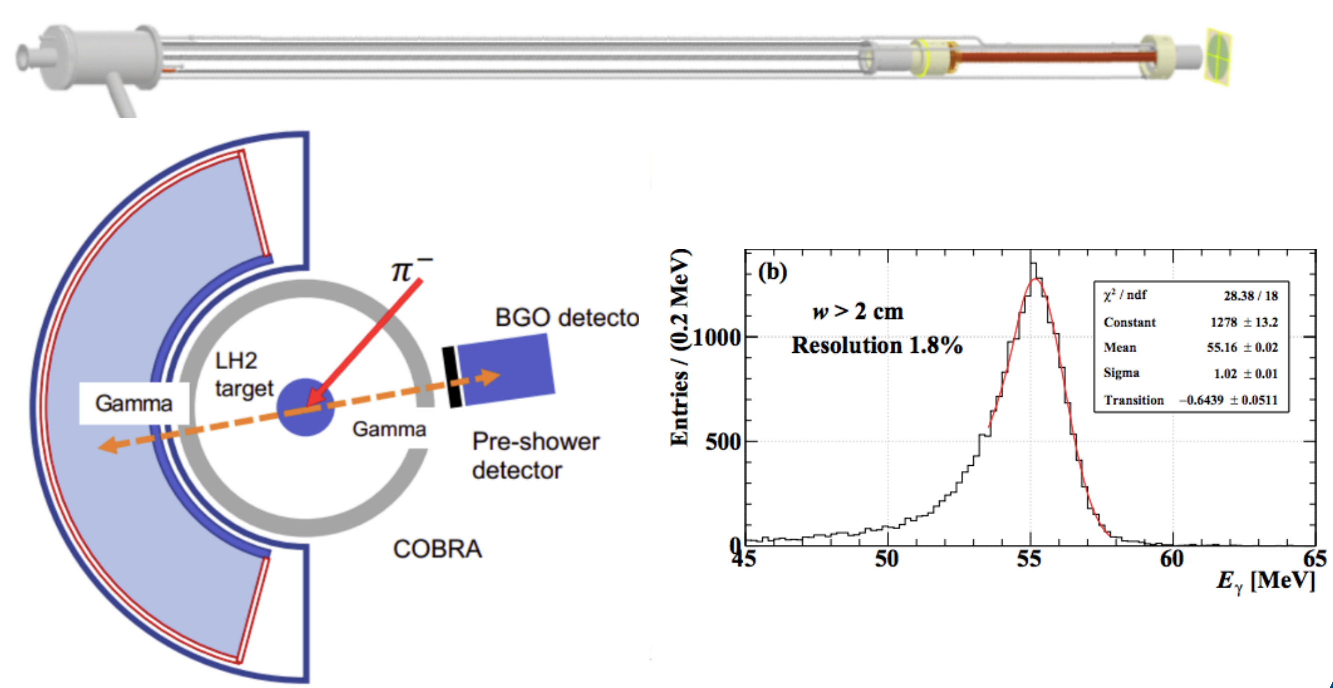




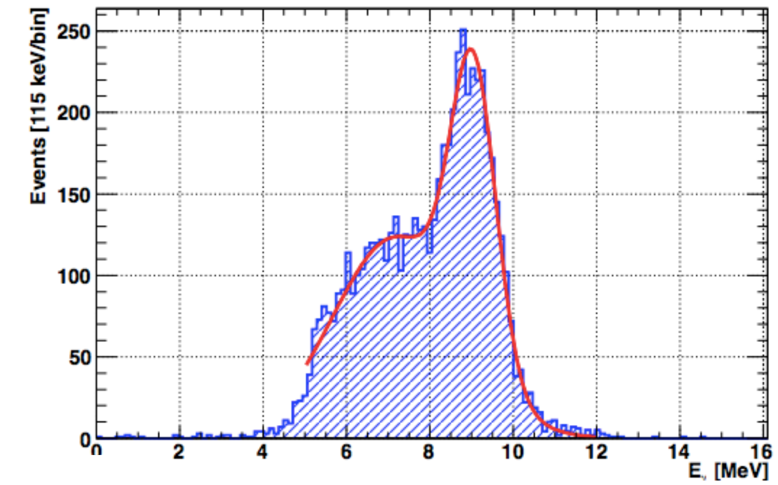
Detectors calibrations

- Search relies on an extensive and regular calibration routine

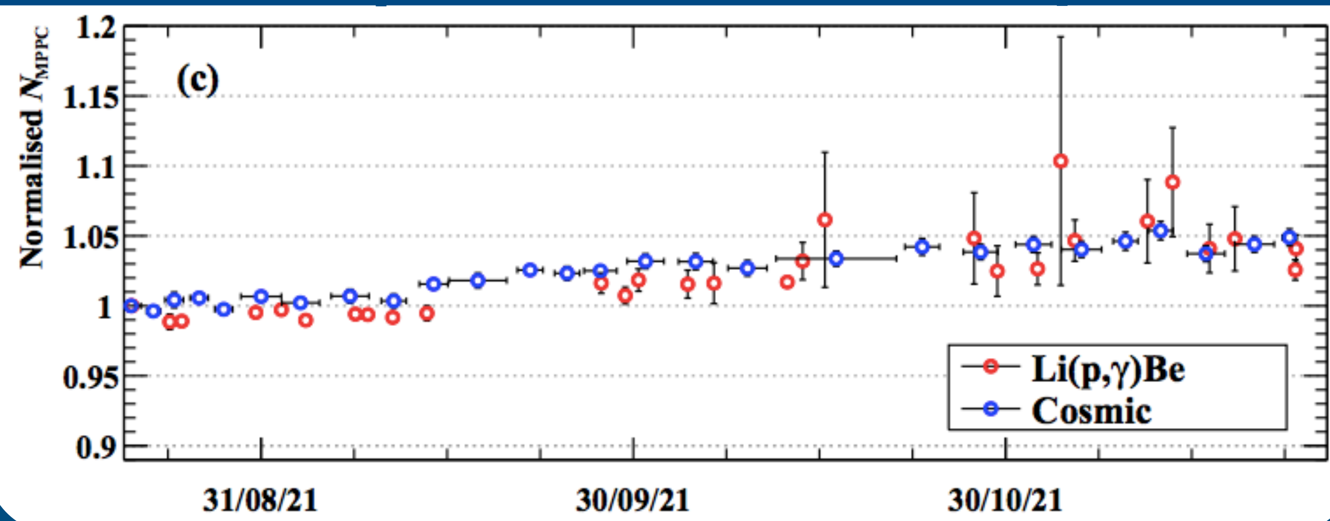
55 MeV γ	$\pi^- p \to \pi^0 n,\ \pi^0 \to \gamma\gamma$	LXe



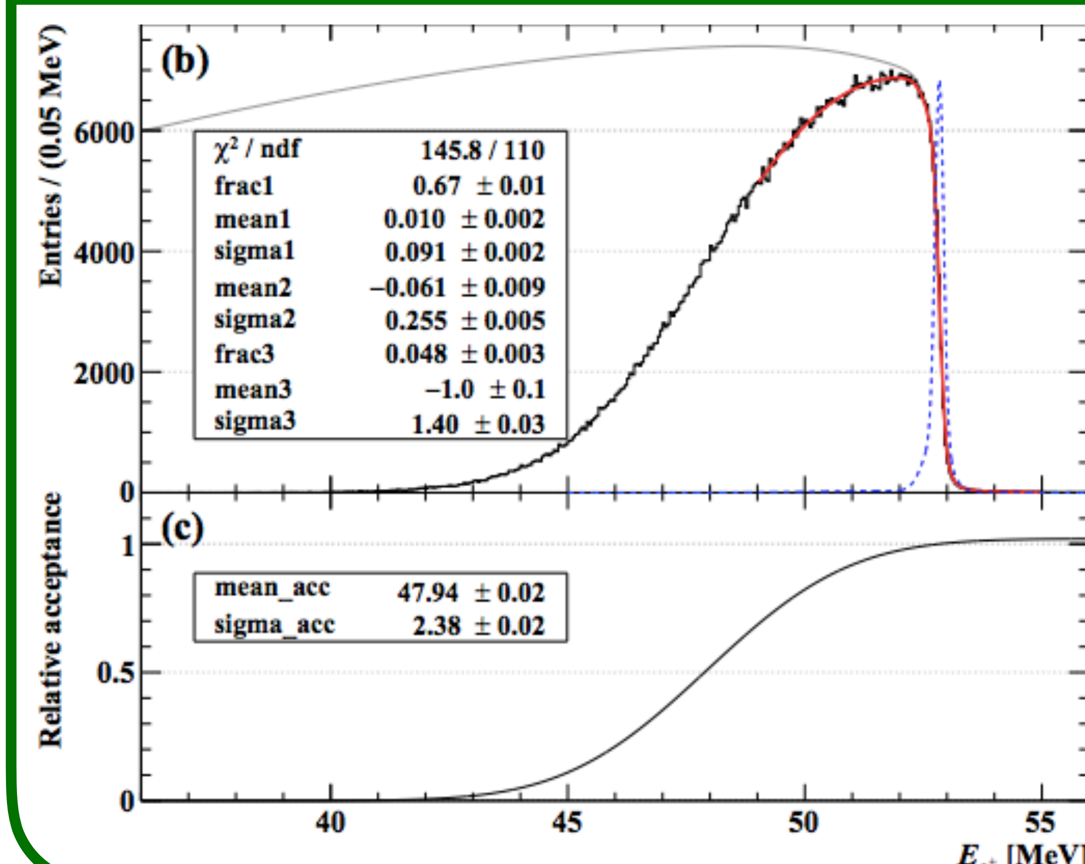
9 MeV γ	^{58}Ni$(n,\gamma)^{59}$Ni	LXe



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



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

- At Paul Scherrer Institute, PSI, Switzerland

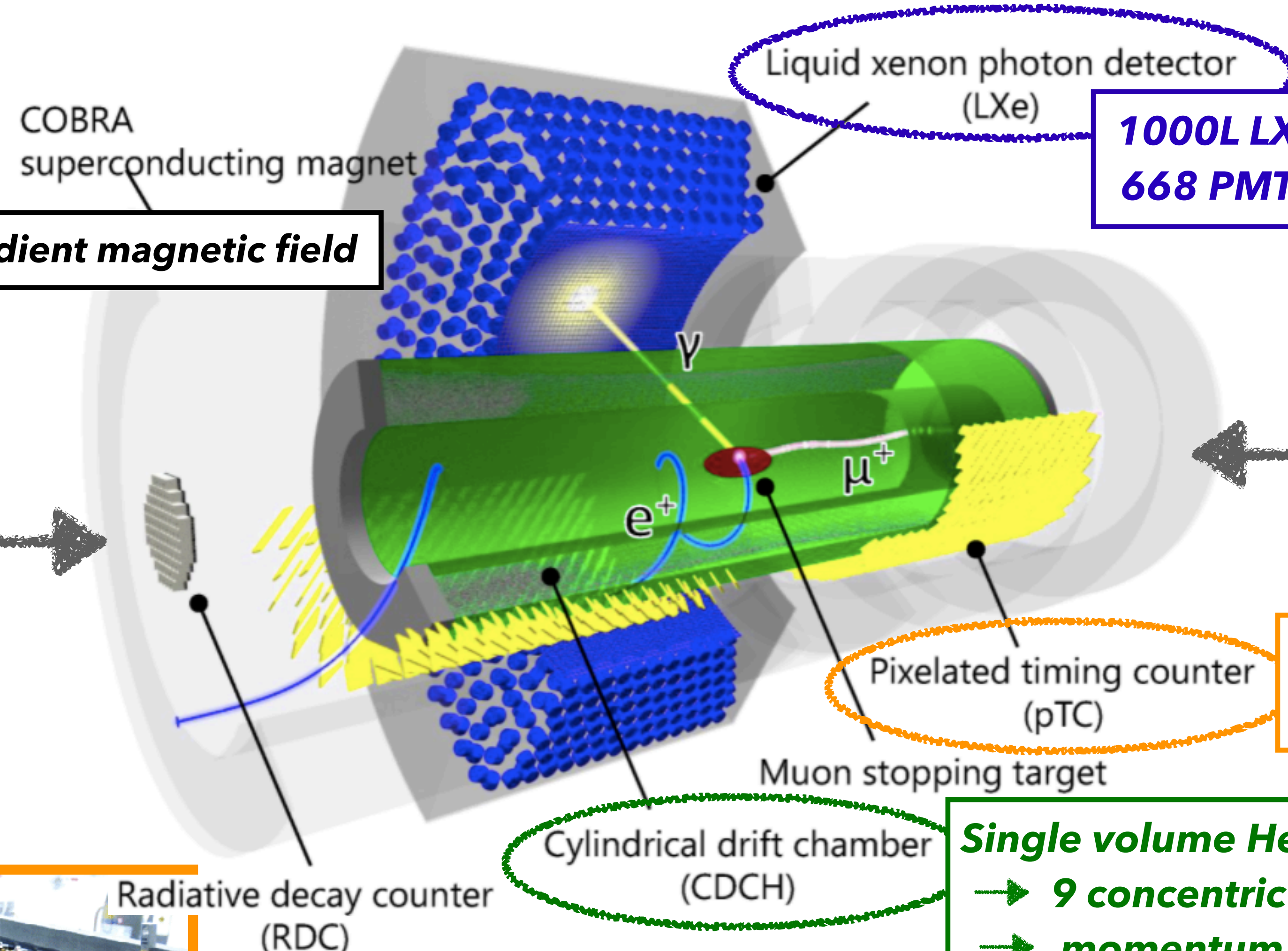
MEG-II results from an intense upgrade program

Gradient magnetic field

1000L LXe tank readout by 668 PMTs and 4092 SiPMs

Proton beam direction for X17 search

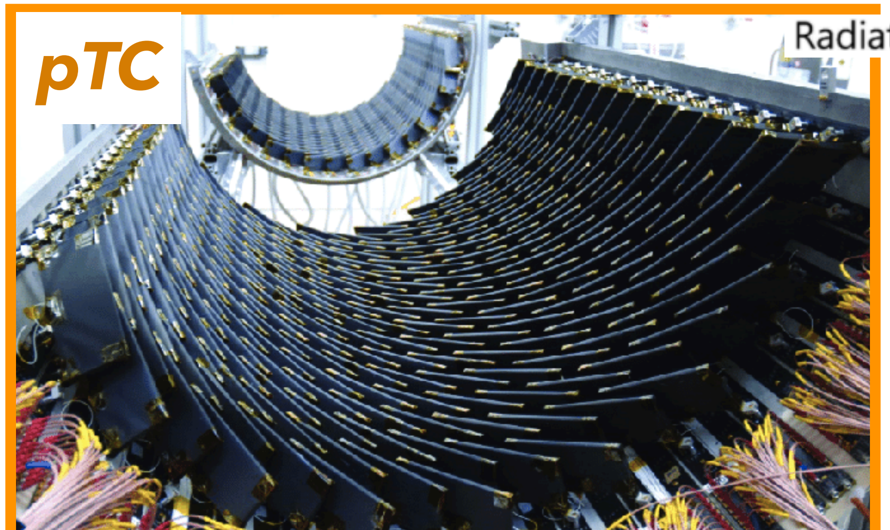
~~Muon beam direction for MEG-II search~~



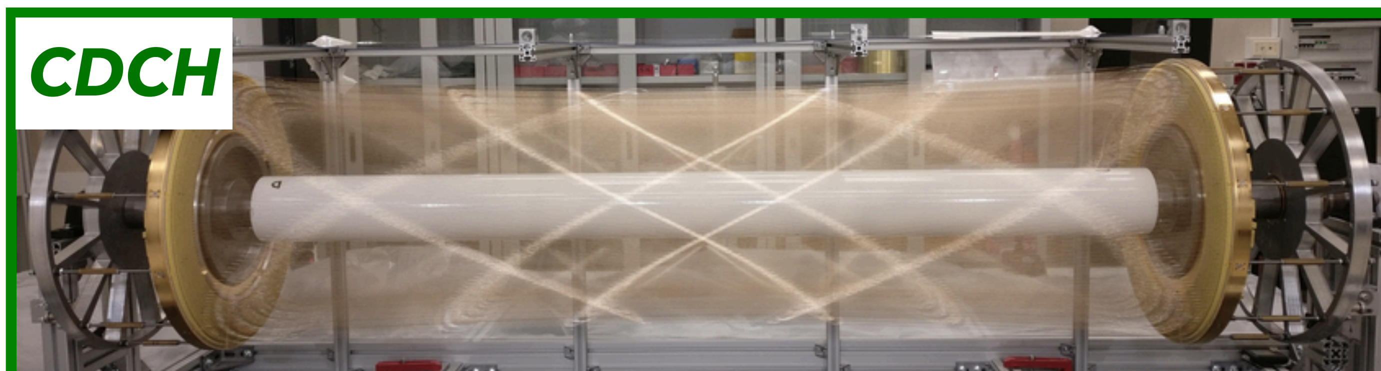
35 ps resolution
→ **512 plastic tiles**

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

pTC

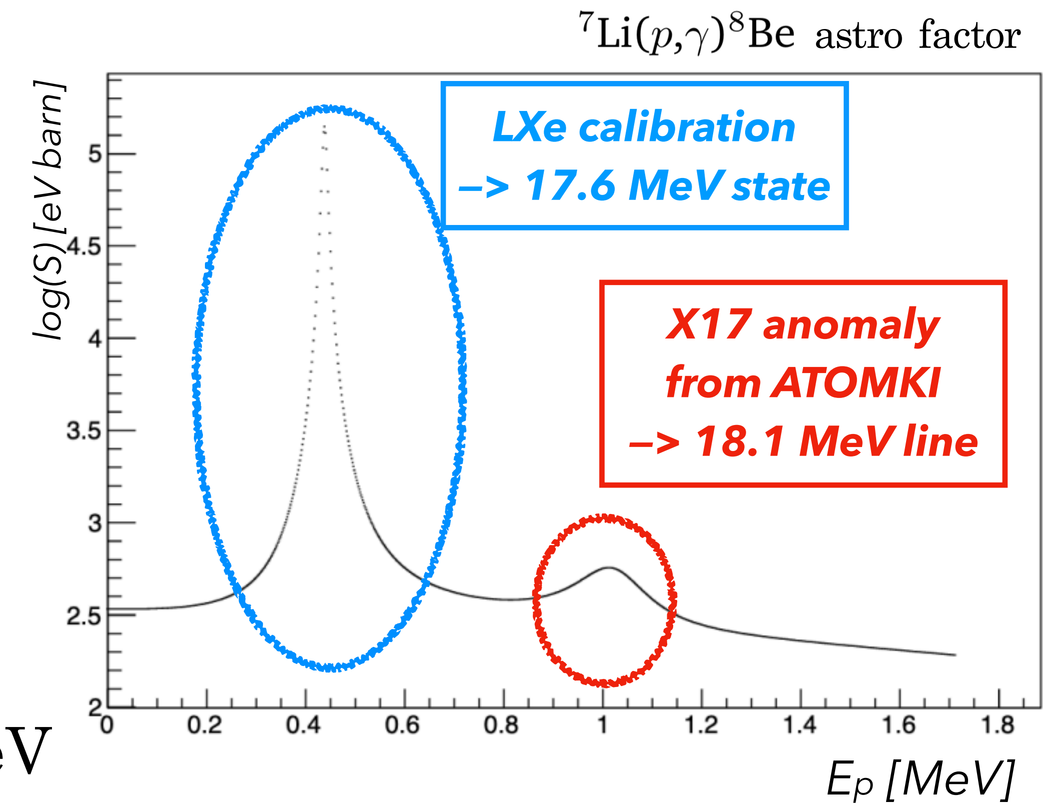


CDCH



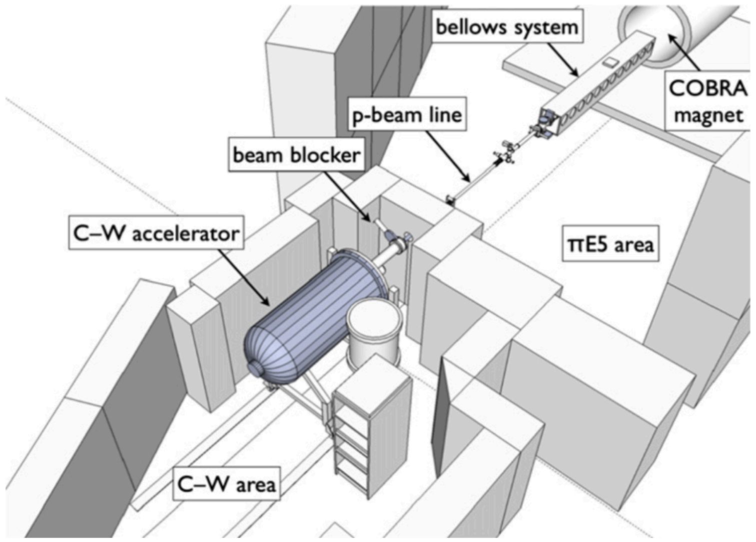
The Cockcroft-Walton accelerator ②

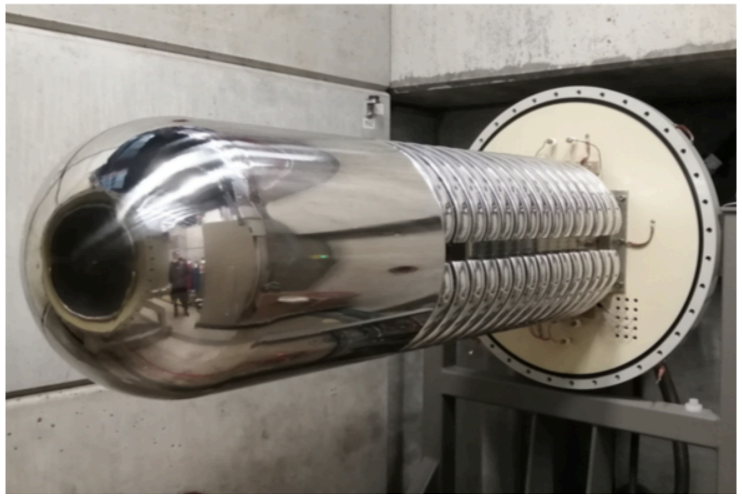
- <u>LXe calibration</u>
  - ➔ MEG-II Cockcroft-Walton accelerator: used for calibration of LXe calorimeter
  - ➔ Proton beam impinging on Li target (0.44 MeV resonance): 17.64 MeV γ line



- <u>X17 search</u>

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



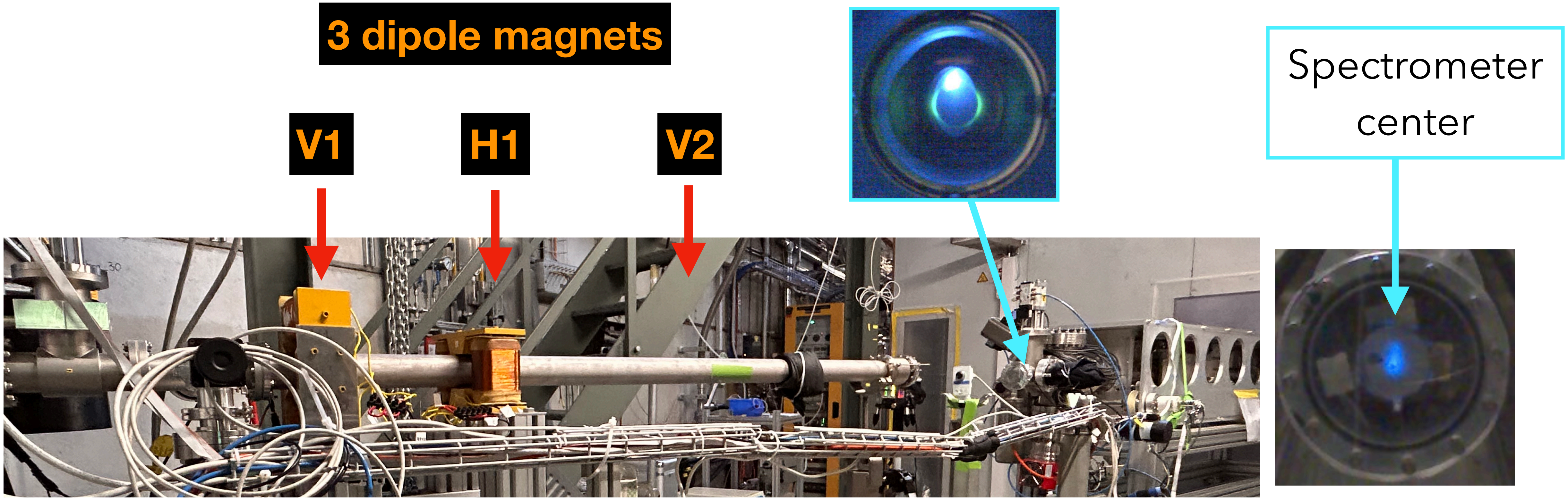


CW: beam tuning

- Beam tuning

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

→ Tuning made varying 3 dipolar fields along the beamline
  → beam spot centered and covering the target area



The new target region

- 400 μm-thick carbon fiber vacuum chamber to minimize multiple scattering

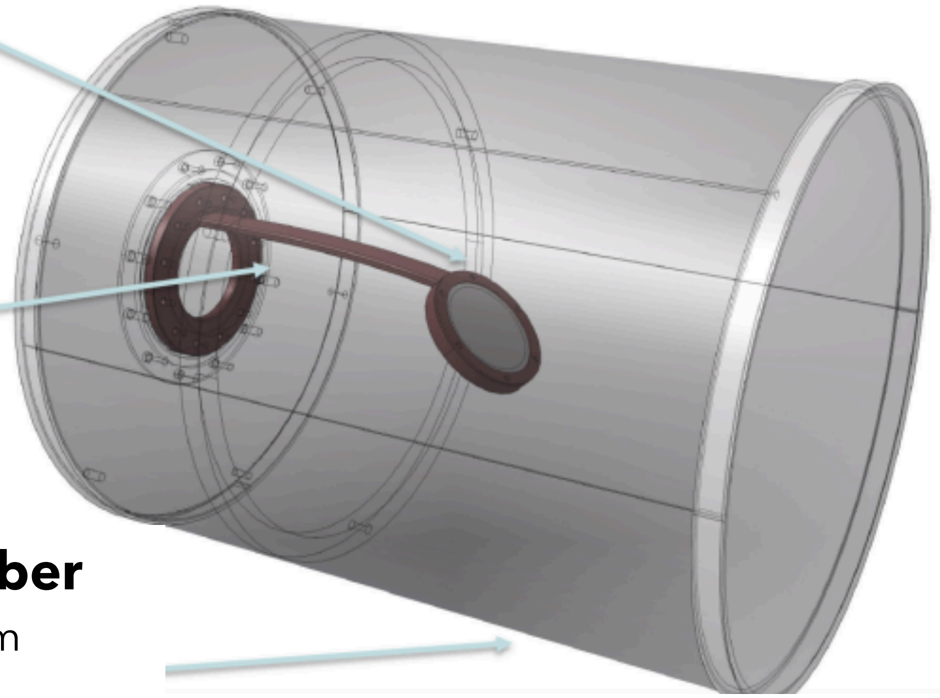
- Main target for physics run
  → 2 μm LiPON(*) on 25 μm copper substrate (by PSI)

- Target-supporting and heat-dissipating copper structure attached to CW nose

Mechanical and heat dissipation simulations carried out

Li target
at COBRA center
45° slant angle

Target arm
Cu for heat dissipation



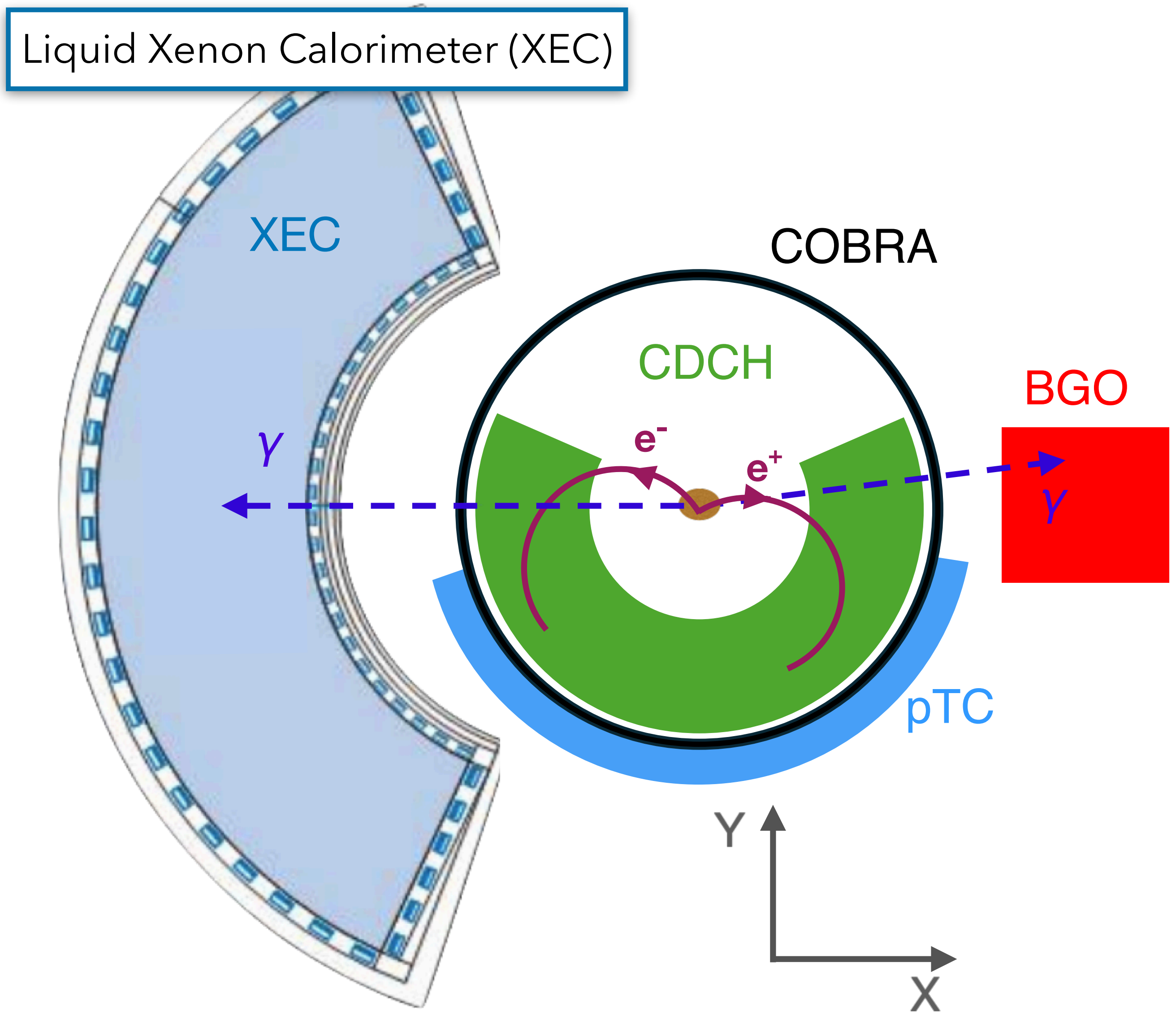
Carbon fiber vacuum chamber
Thickness: 400 μm, Diameter: 98 mm
Length: 226 mm

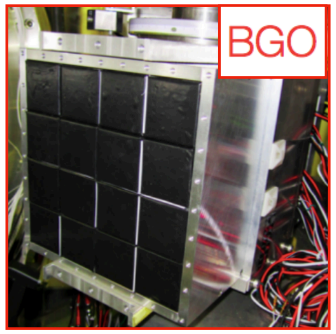
(*) Lithium phosphorus oxynitride ($Li_{3-x}PO_{4-y}N_{x+y}$)

Detectors

- Two gamma detectors for monitoring and bkg understanding

LXe calorimeter **BGO crystal matrix (4x4)**



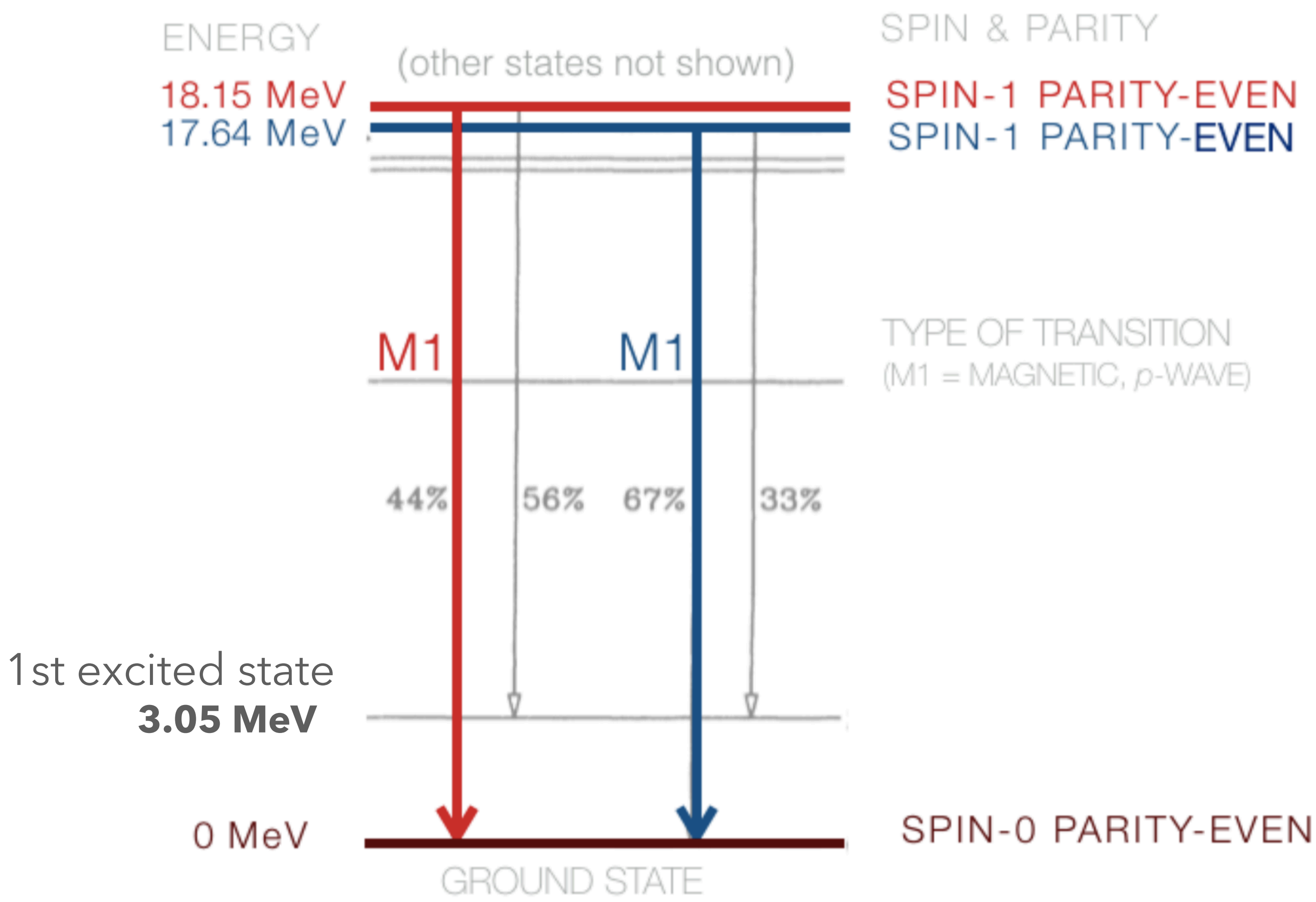


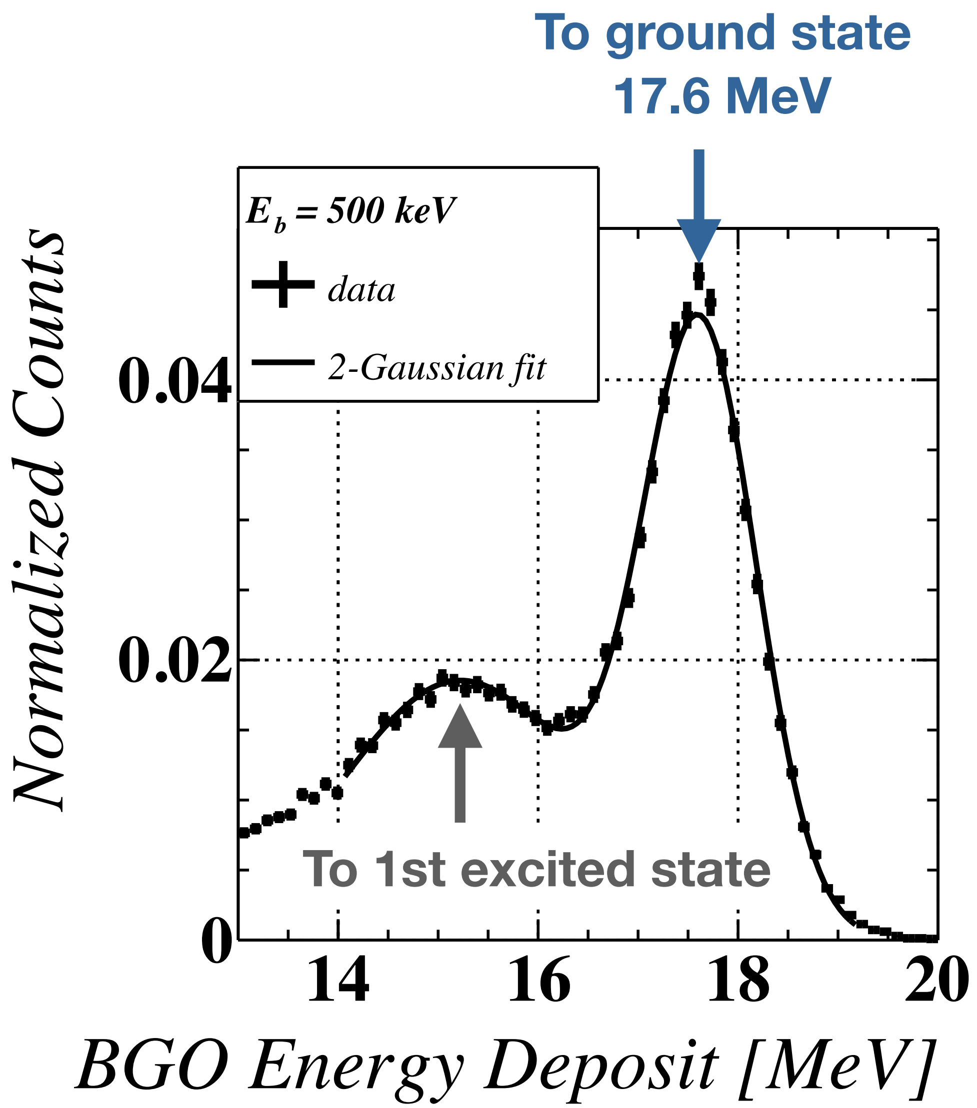
Transitions and photon spectrum

②

- Transitions both to ground state and first excited state

@500 keV, 17.6 MeV state only is excited





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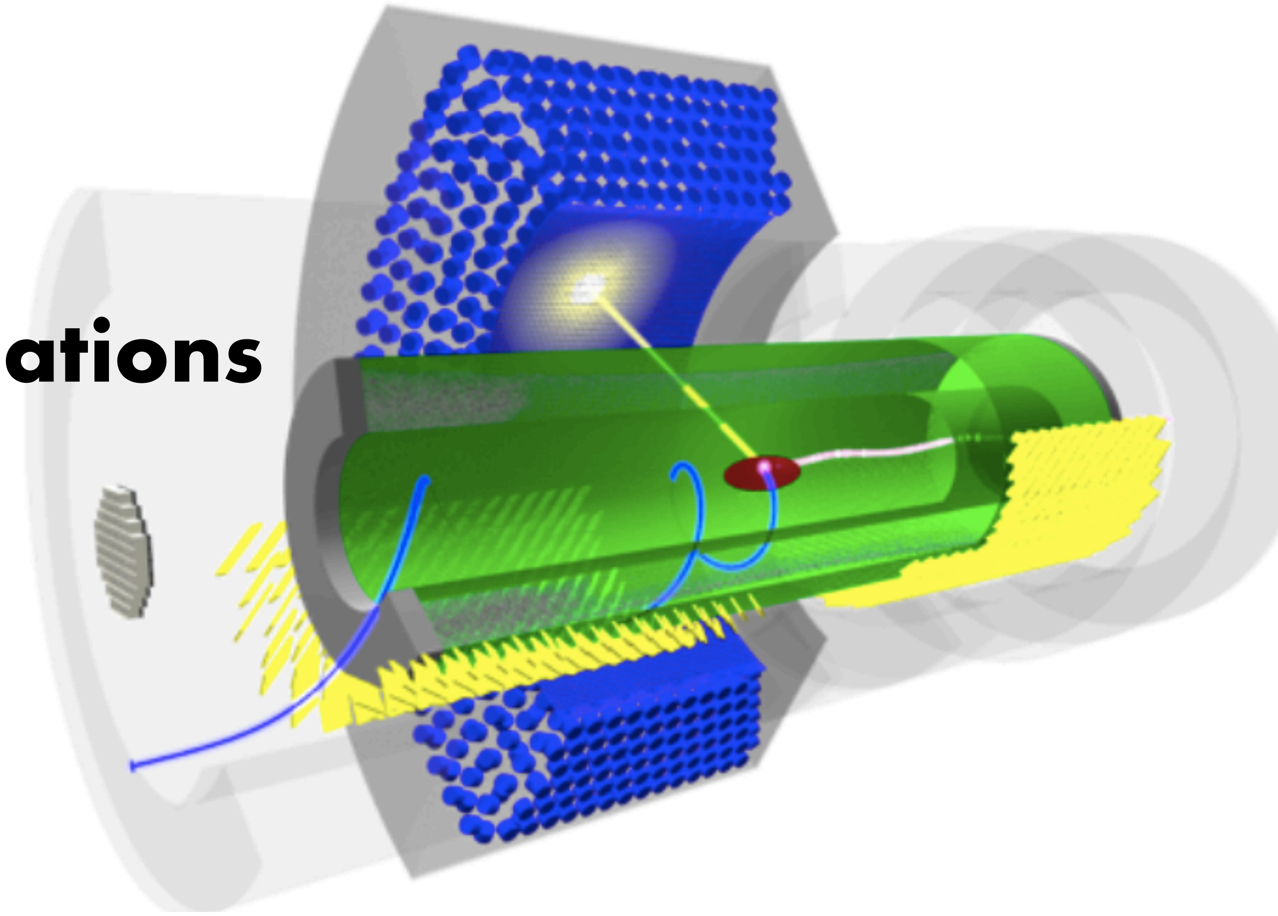
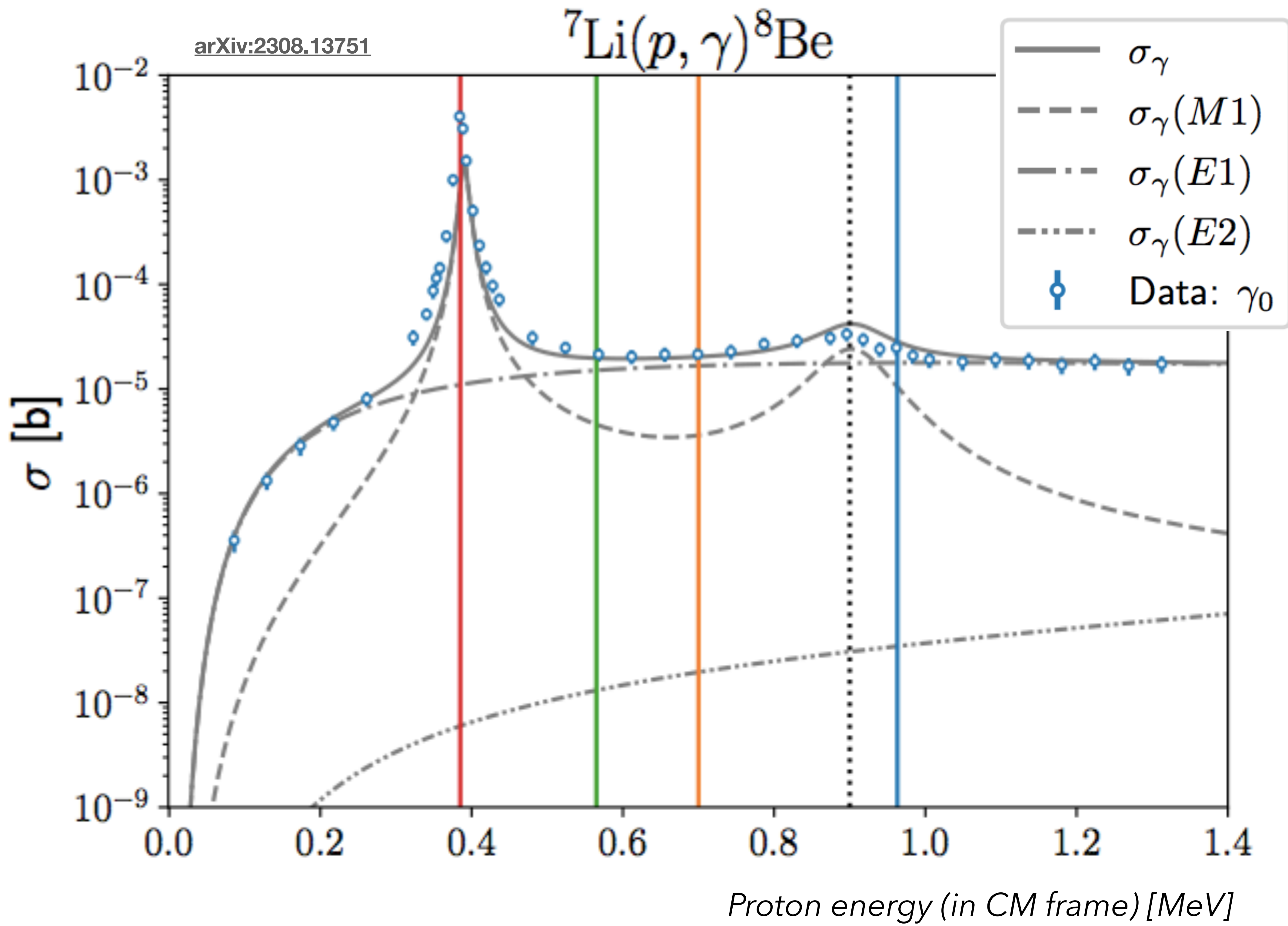


3) Physics backgrounds and signal simulations

Multipole contributions

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



Internal Pair Conversion

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

③ MEG II

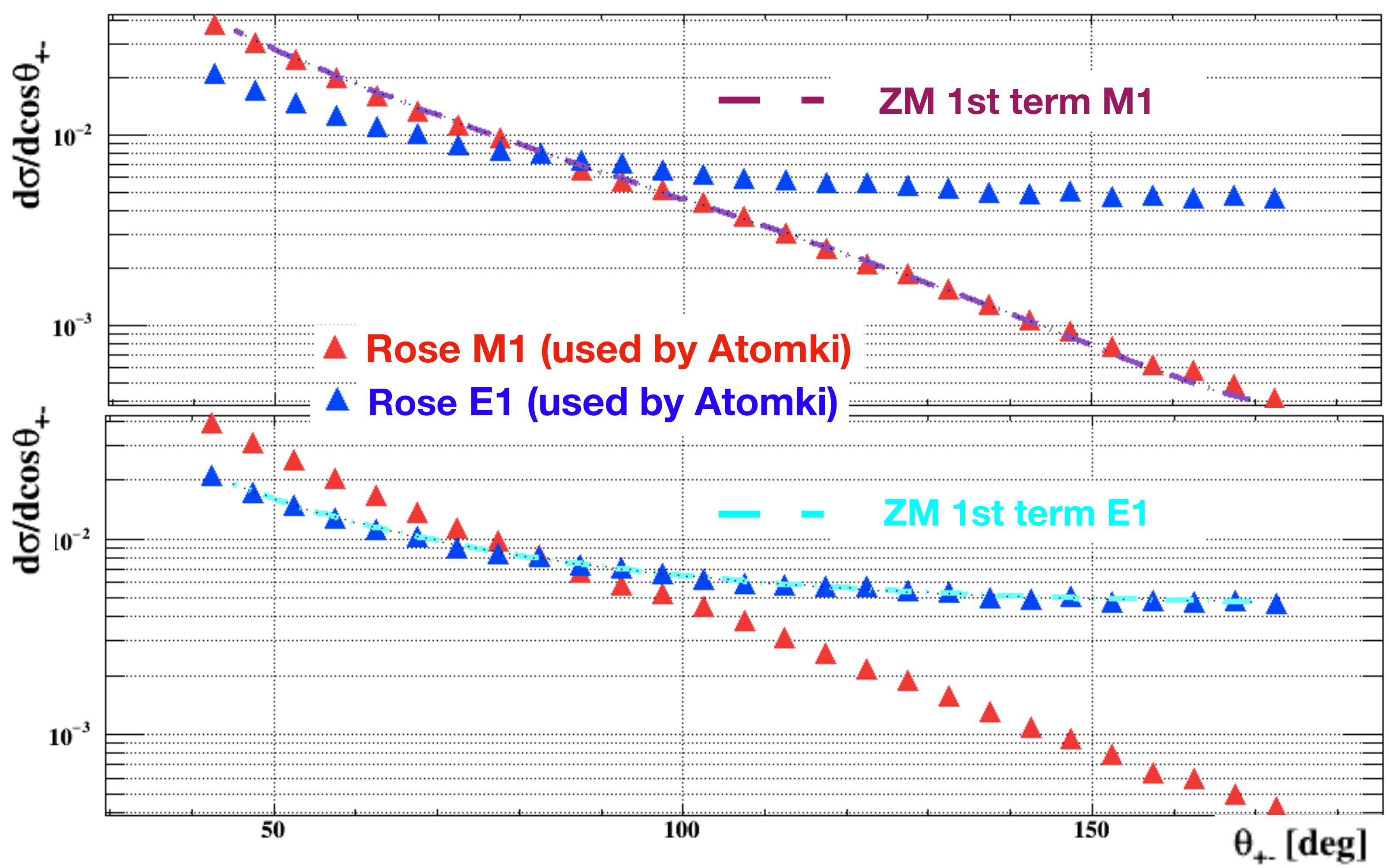
- Need for an accurate background model, IPC is dominant background in signal region
- First IPC model developed by Rose in 1949 Phys. Rev. 76, 678

→ 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



→ We implemented Zhang-Miller model

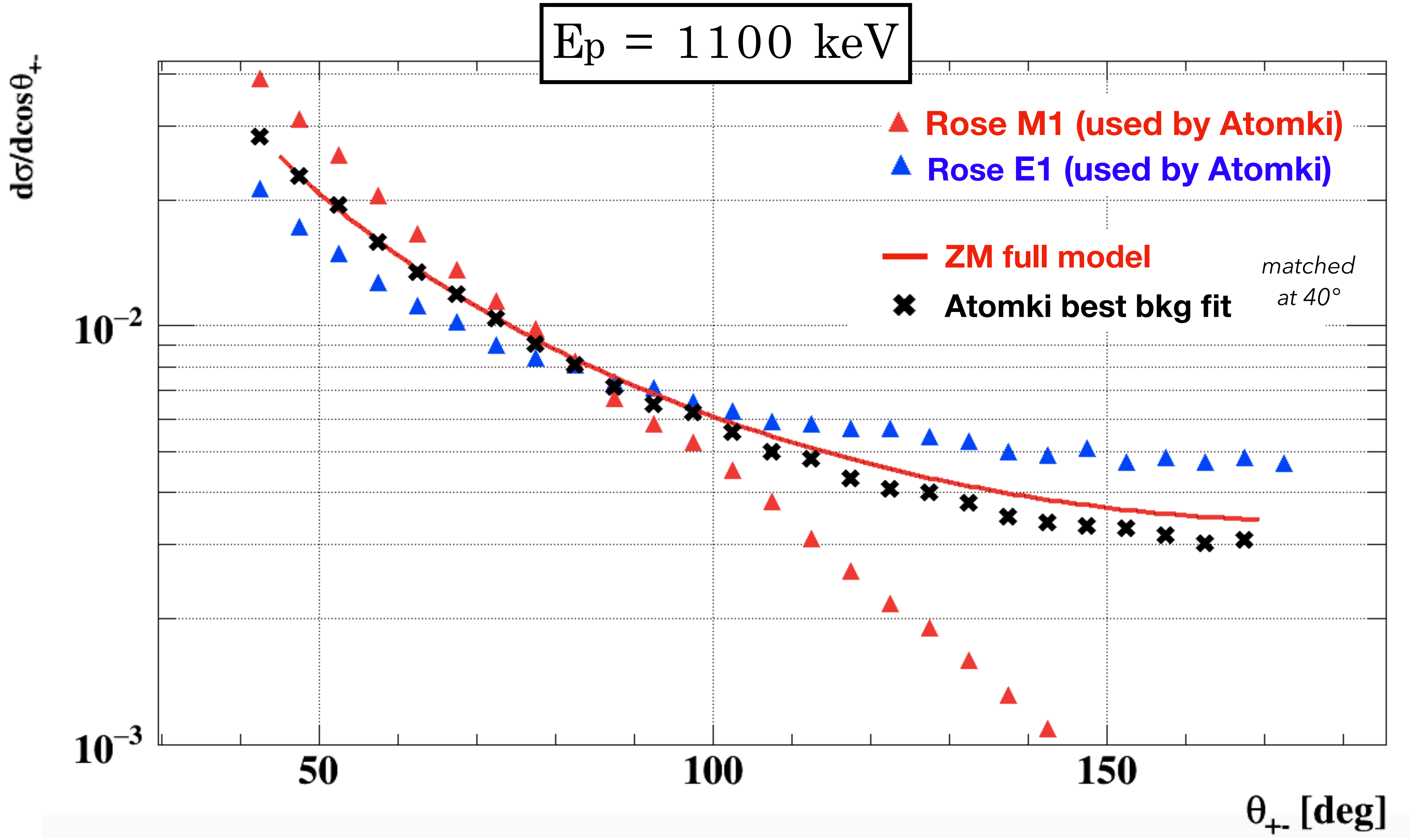
→ Rose/simplified ZM models agree for both E1 and M1 multipoles

Internal Pair Conversion

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

③

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



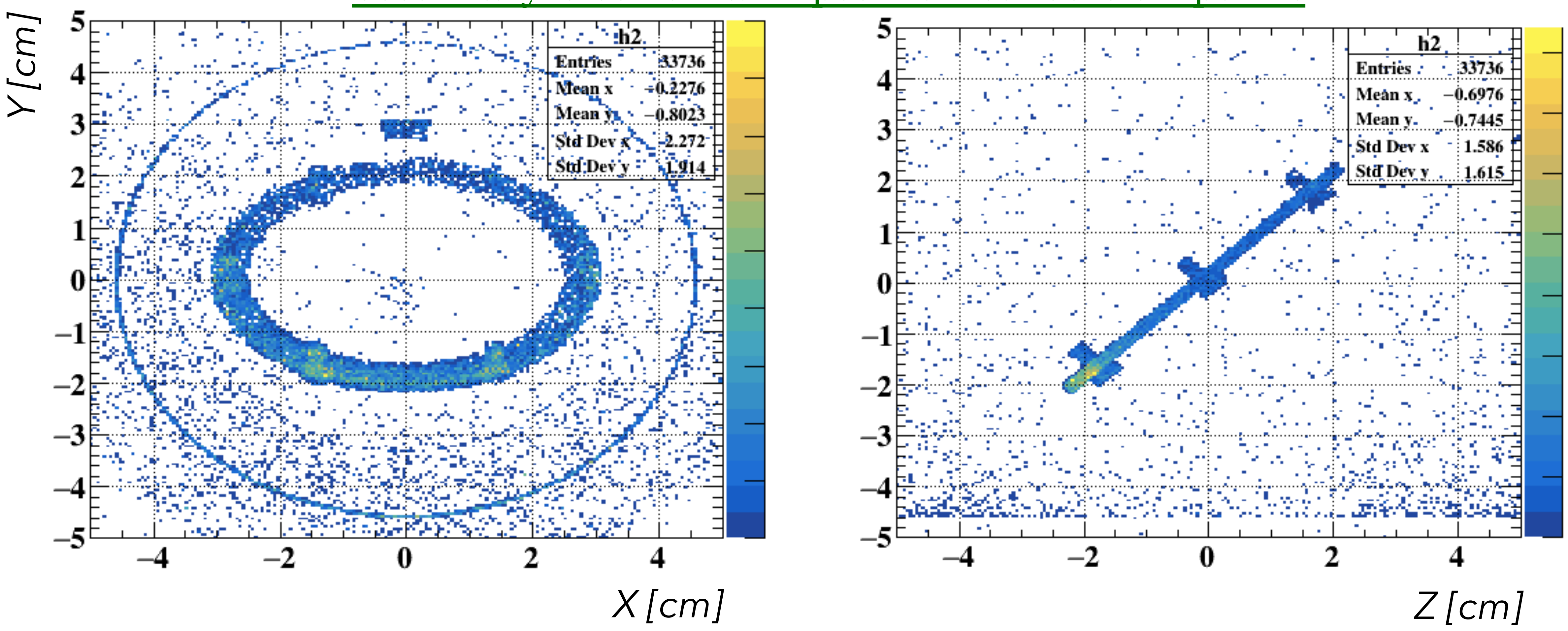
- When interferences and anisotropy terms are included
  - → IPC background shape is changed
  - → Cannot explain anomaly but can impact significance

External Pair Conversion and other bkgs ③

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

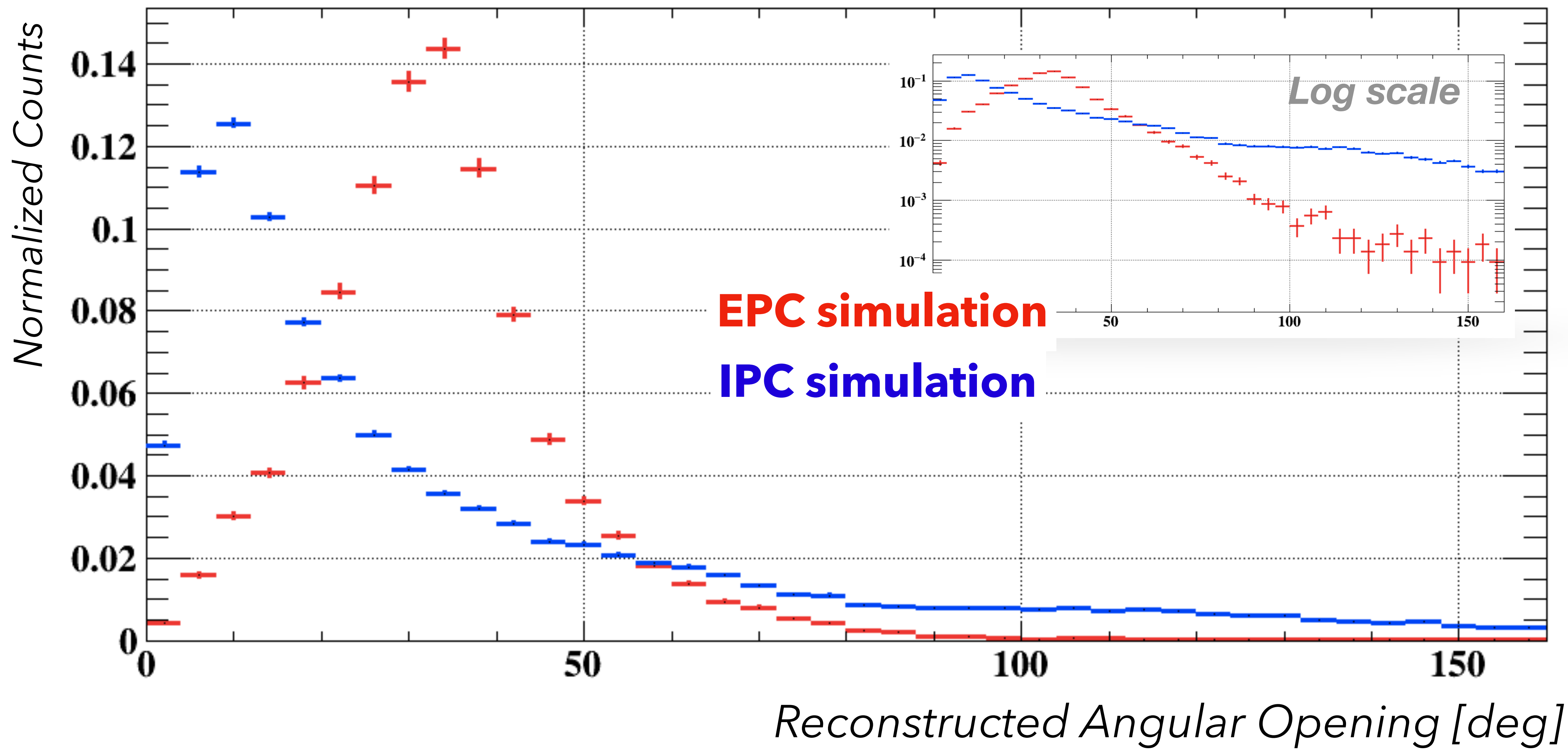
> *EPC = External Pair Conversion*
> → *γ-conversion to e+/e- pair in matter*

Secondary electron and positron conversion points



→ Dominating background is EPC and Compton in heat-dissipating Cu ring

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

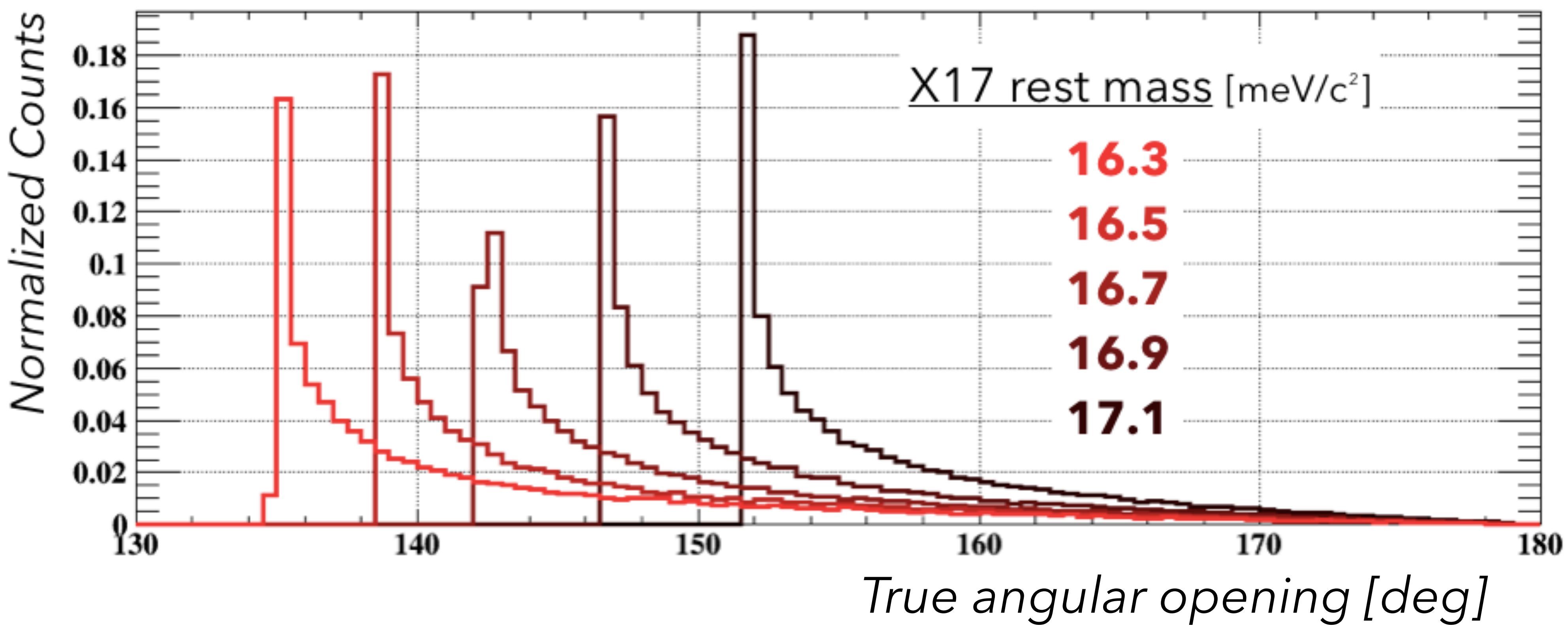


- → Almost 2 orders of magnitude below IPC in signal region
- → All photon conversion events included in full simulation

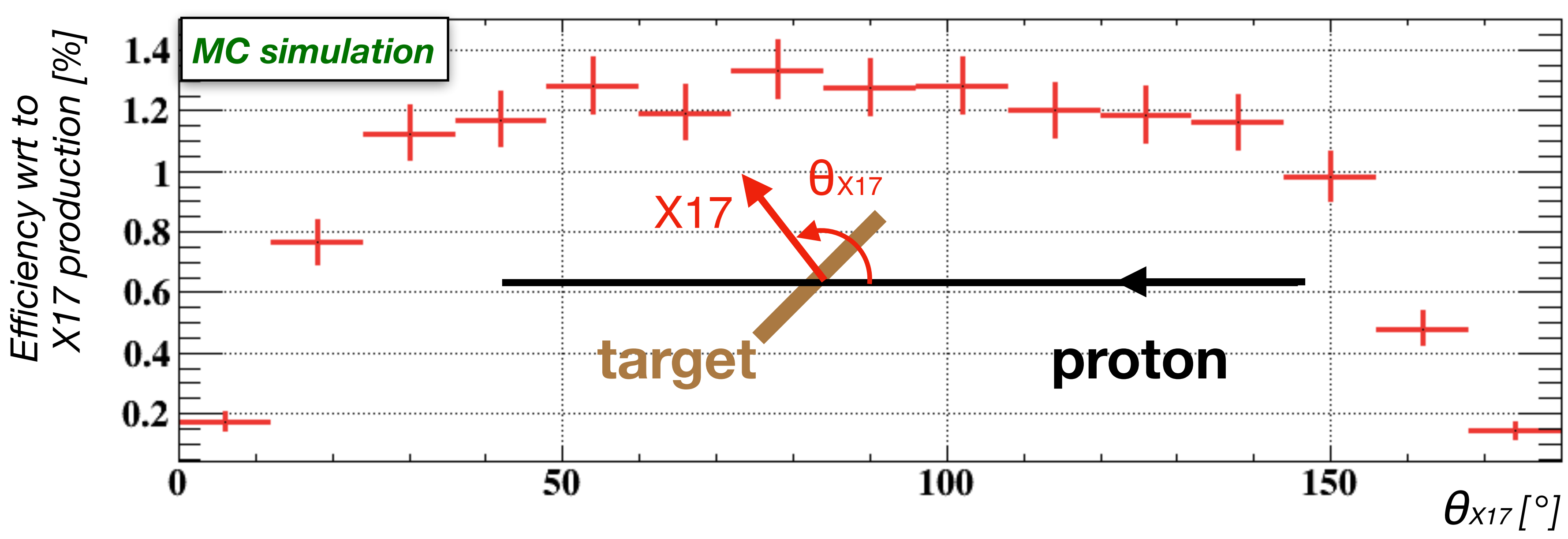
Signal simulation

③

- 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°

Outline

1) Physics motivation: the Atomki anomalies

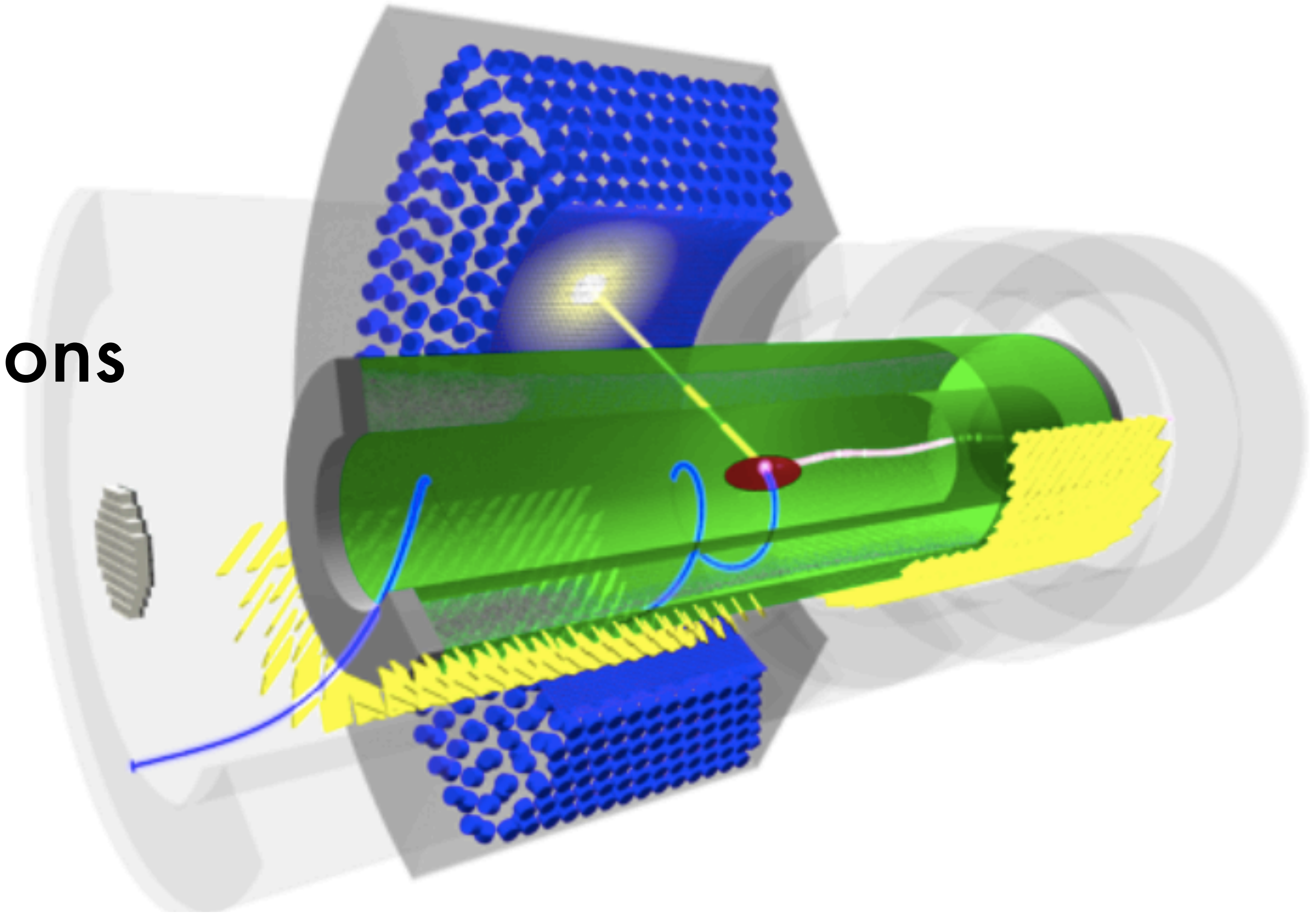
2) The MEG-II apparatus

3) Backgrounds and signal simulations

4) **Pair reconstruction**

5) Trigger and DAQ strategies

6) Physics dataset and X17 results



4) Pair reconstruction

Electron reconstruction

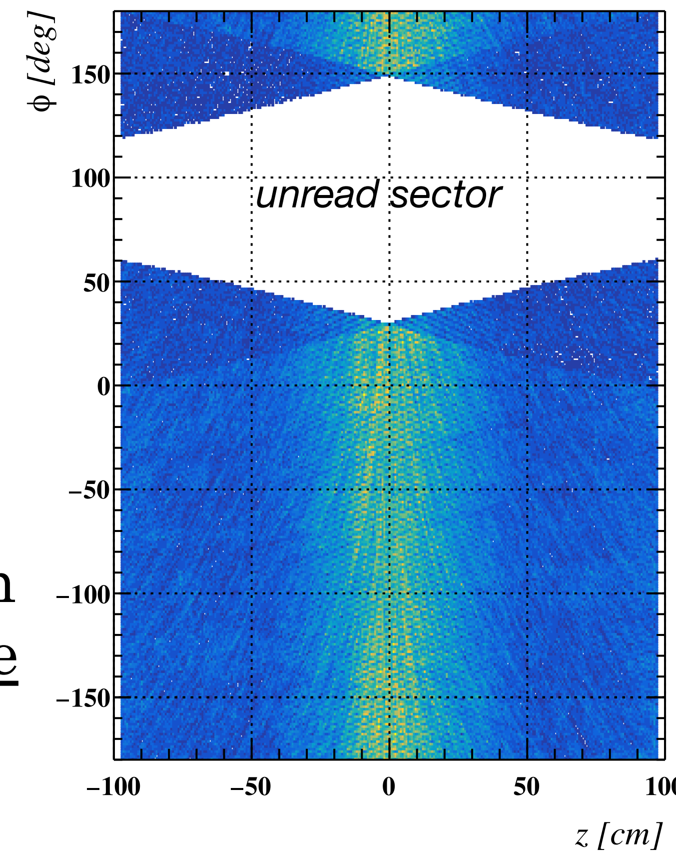
- MEG-II only reconstructs e+. Procedure was adapted for e- as well.

→ Simulated e+/e- tracks in CDCH

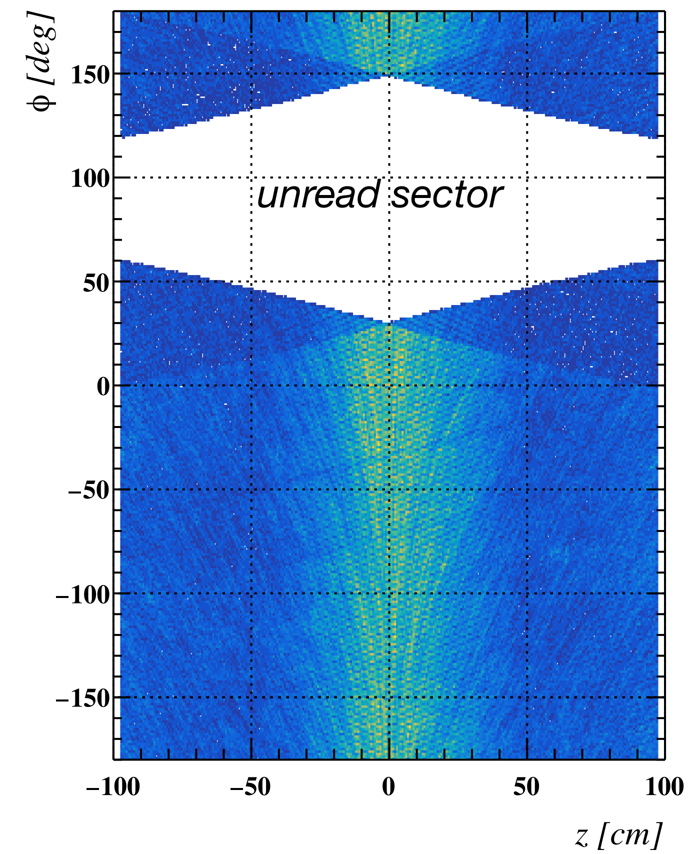
→ Both tracks can be distinguished through dp_T/dp_z sign in COBRA gradient field

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

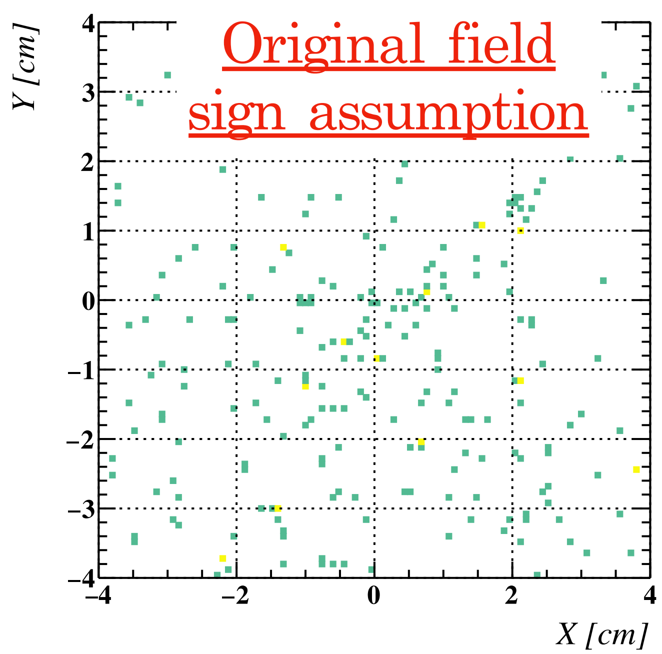
Positrons

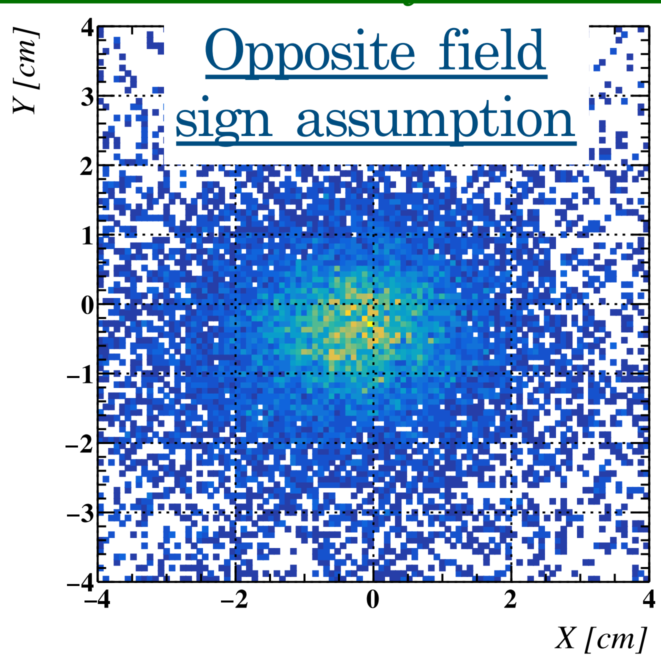


Electrons



Reconstructed vertices from electron-only simulation





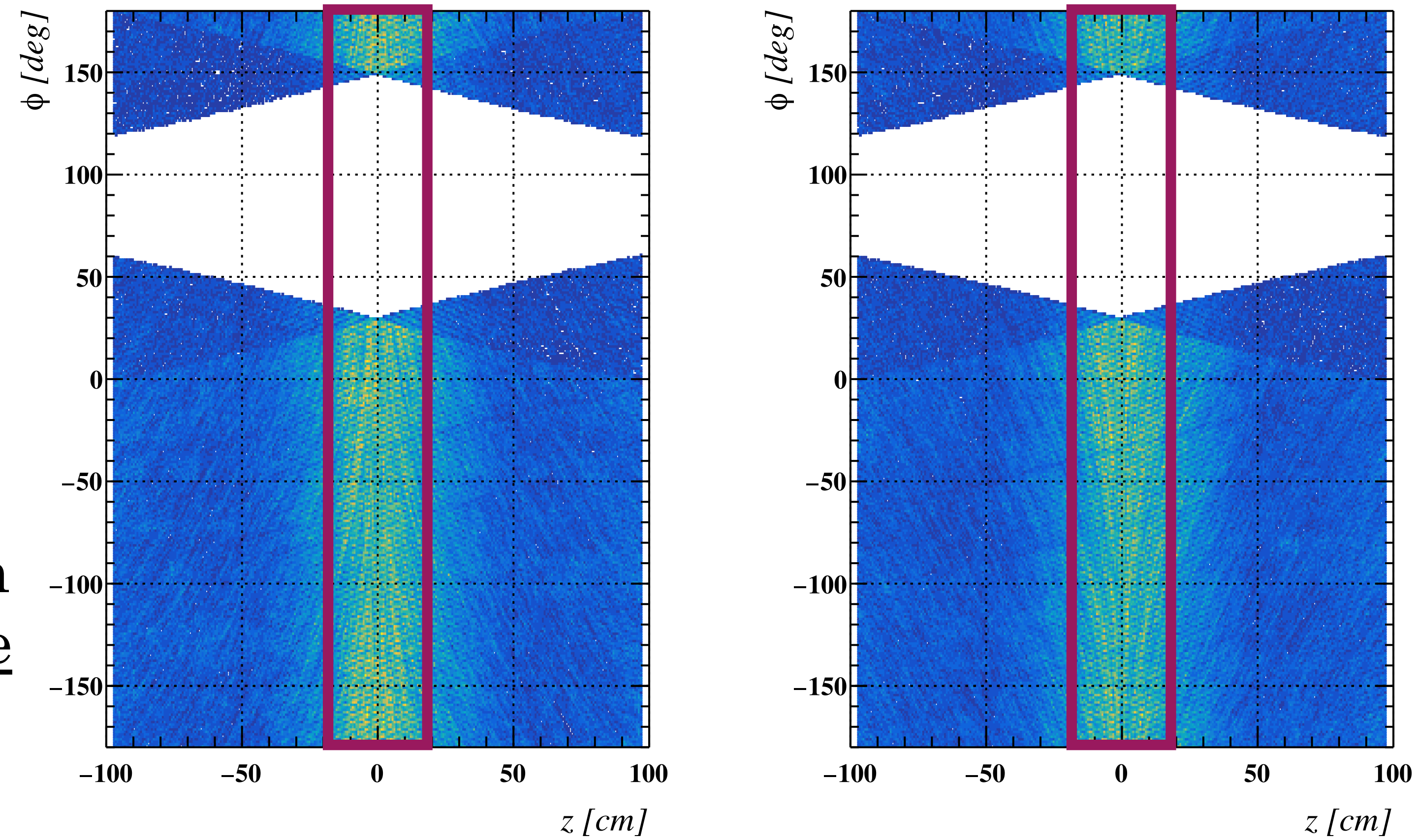
→ 99% of tracks have correct sign

→ 1% of tracks is misreconstructed

Electron reconstruction

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

Positrons | Electrons



→ Simulated e+/e- tracks in CDCH

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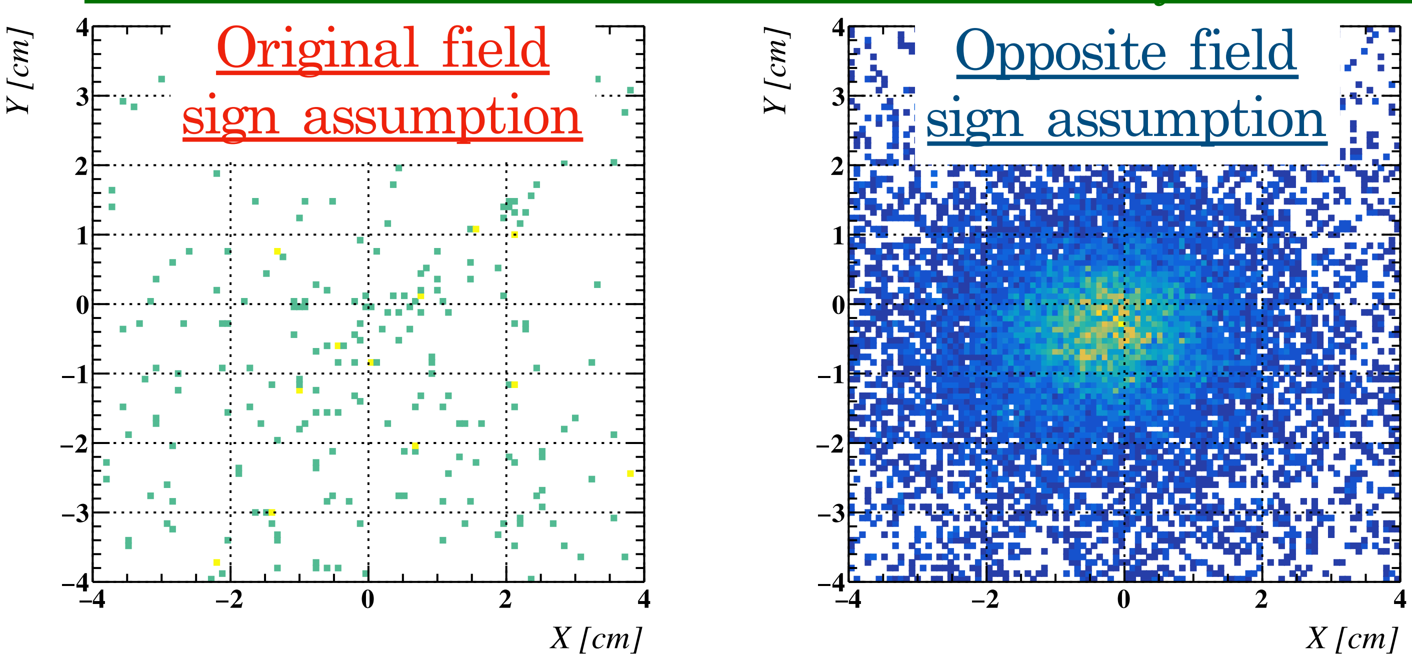
→ Electron tracks reconstructed with MEG-II's track finder inverting the COBRA field sign assumption

Reconstructed vertices from electron-only simulation



→ 99% of tracks have correct sign

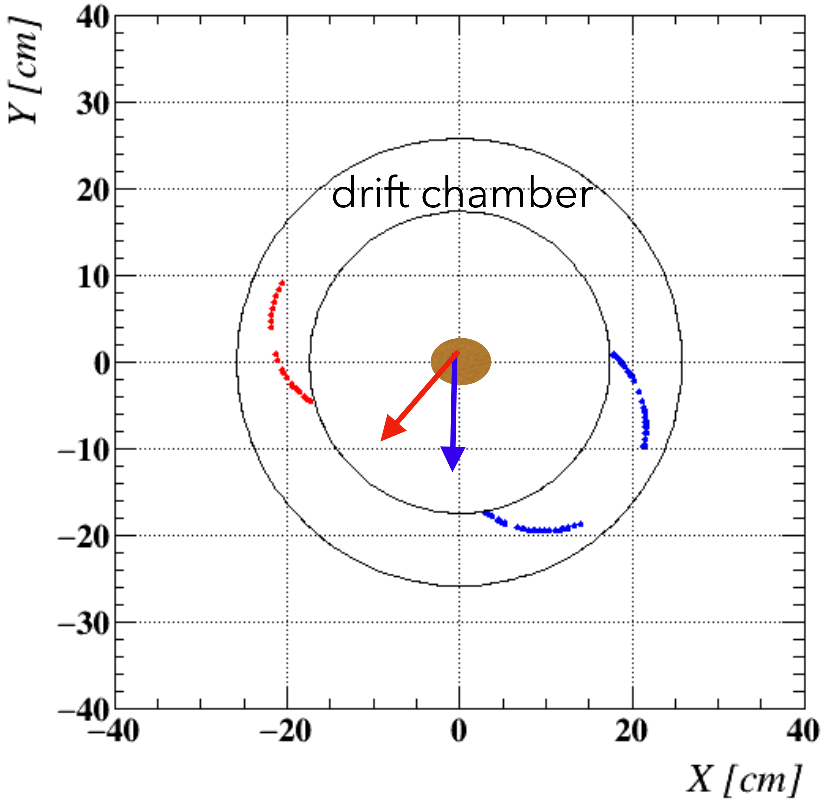
→ 1% of tracks is misreconstructed

Tracks emitted orthogonal to the beam are sign-ambiguous

Event display

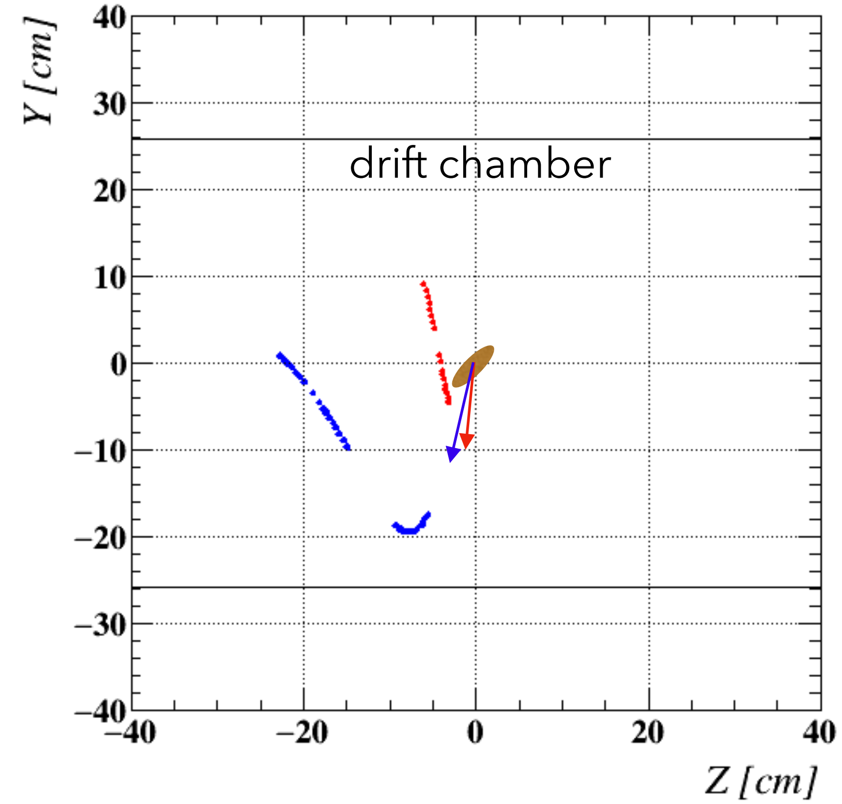
- Let's have a look at the fitted hits within the CDCH

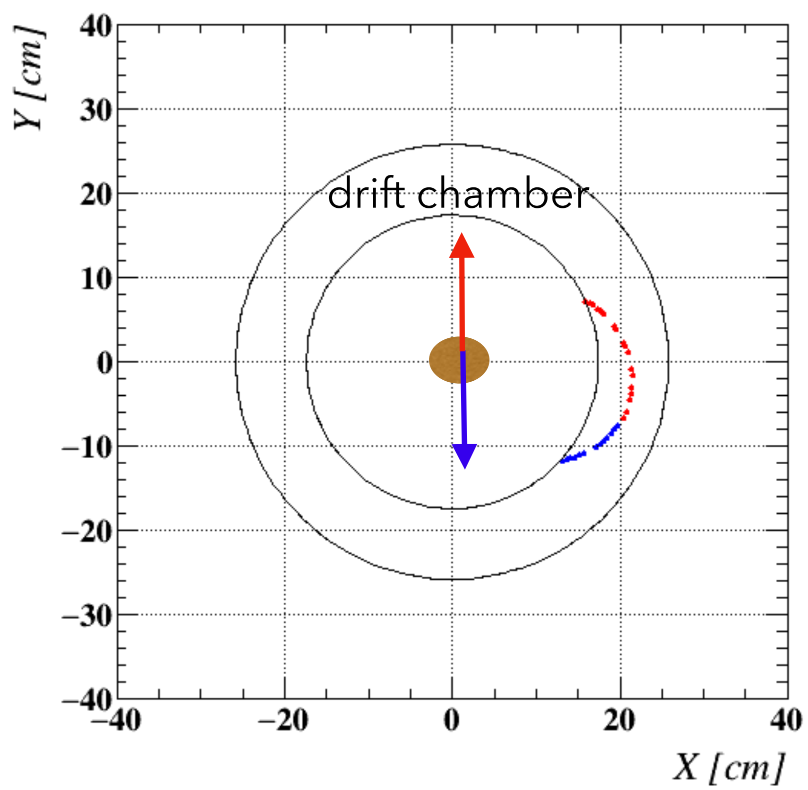
2023 data events



GOOD PAIR

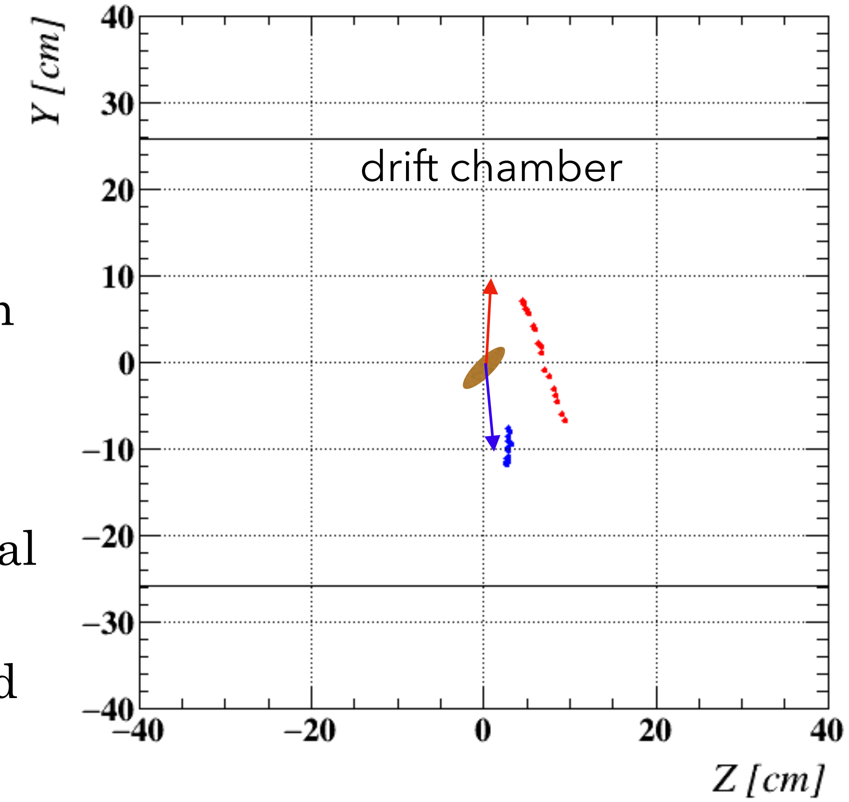
- $\vec{p}$+ at target
- $\vec{p}$- at target
- e+ hit
- e- hit
- target





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

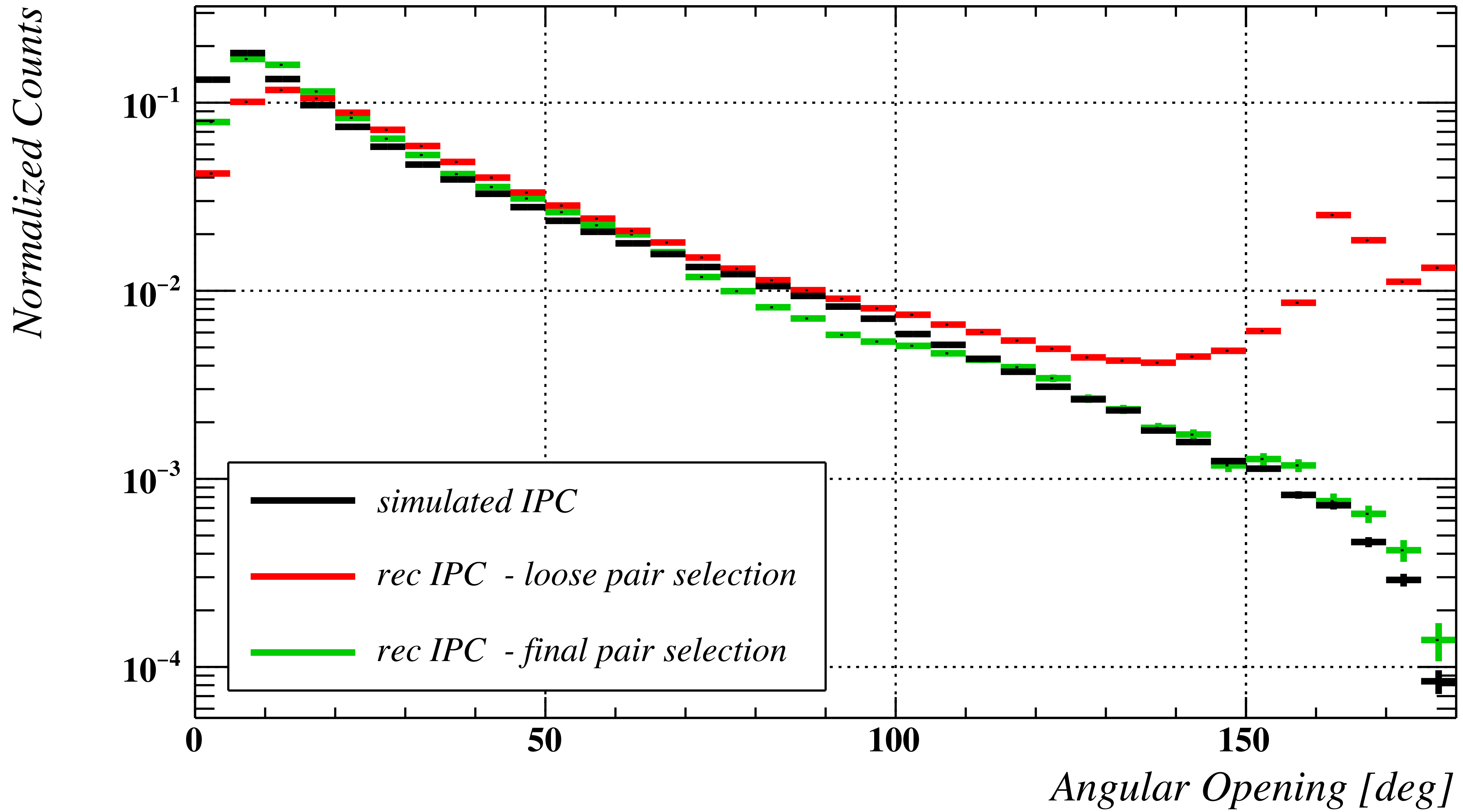


Track selection

<u>Fake tracks</u> → short → consecutive hits distance large
→ if longer, little dense → orthogonal to the beam and close to z=0

<u>Advanced track selection was developed</u>

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



Outline

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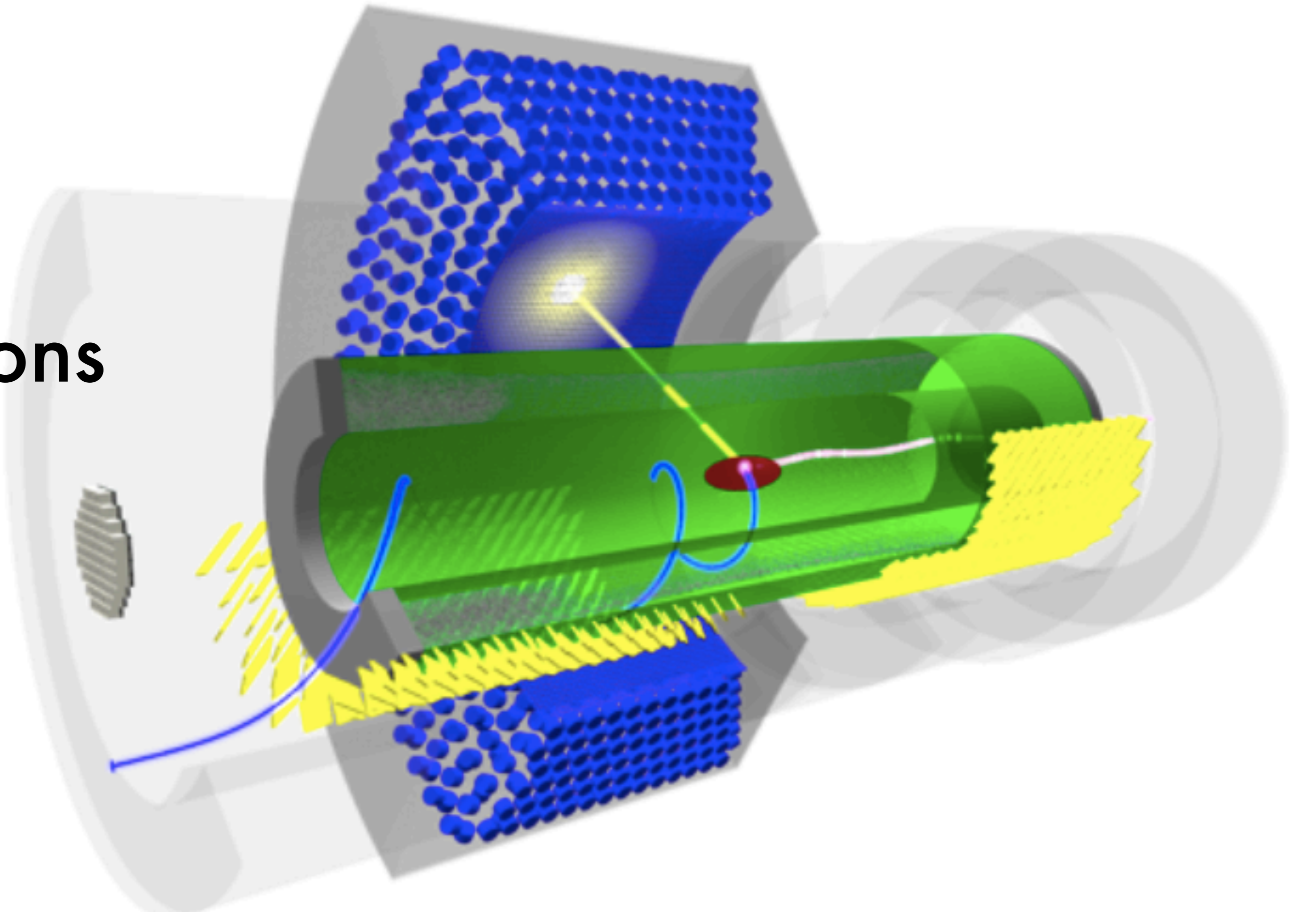
2) The MEG-II apparatus

3) Backgrounds and signal simulations

4) Pair reconstruction

5) **Trigger and DAQ strategies**

6) Physics dataset and X17 results



5) Trigger and DAQ strategies

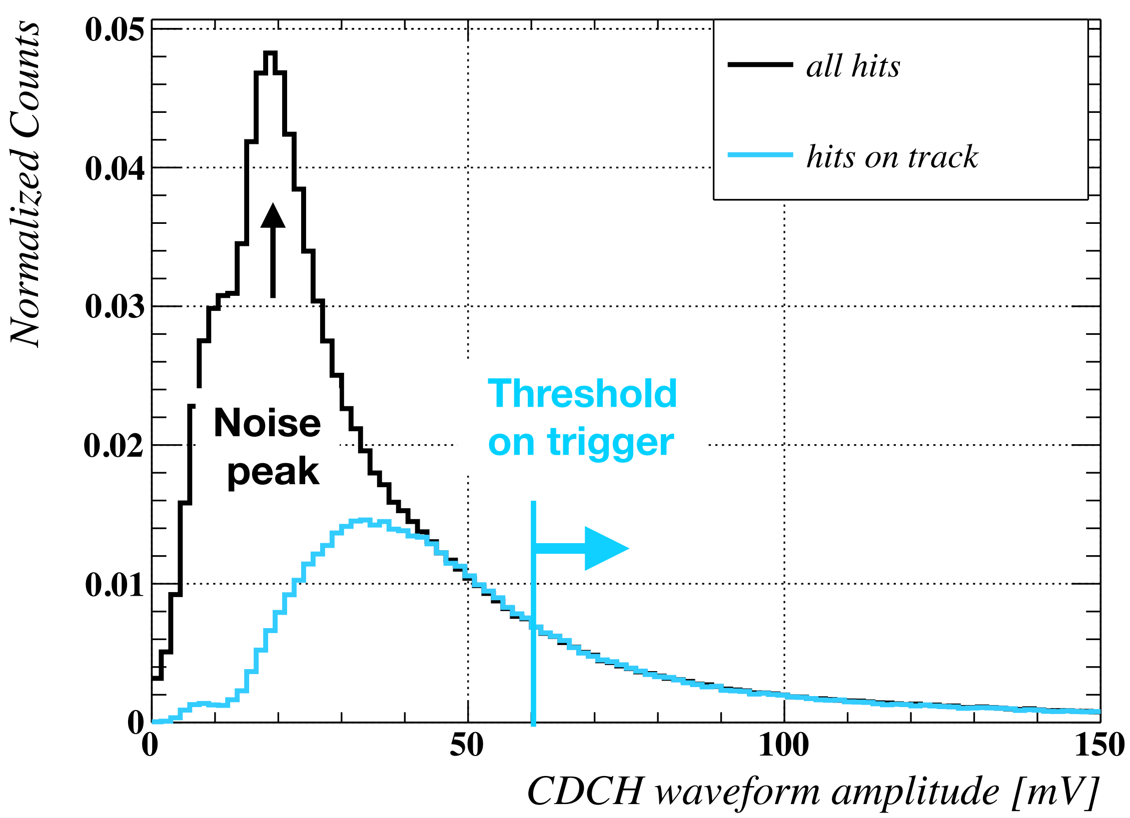
Trigger strategy

- 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

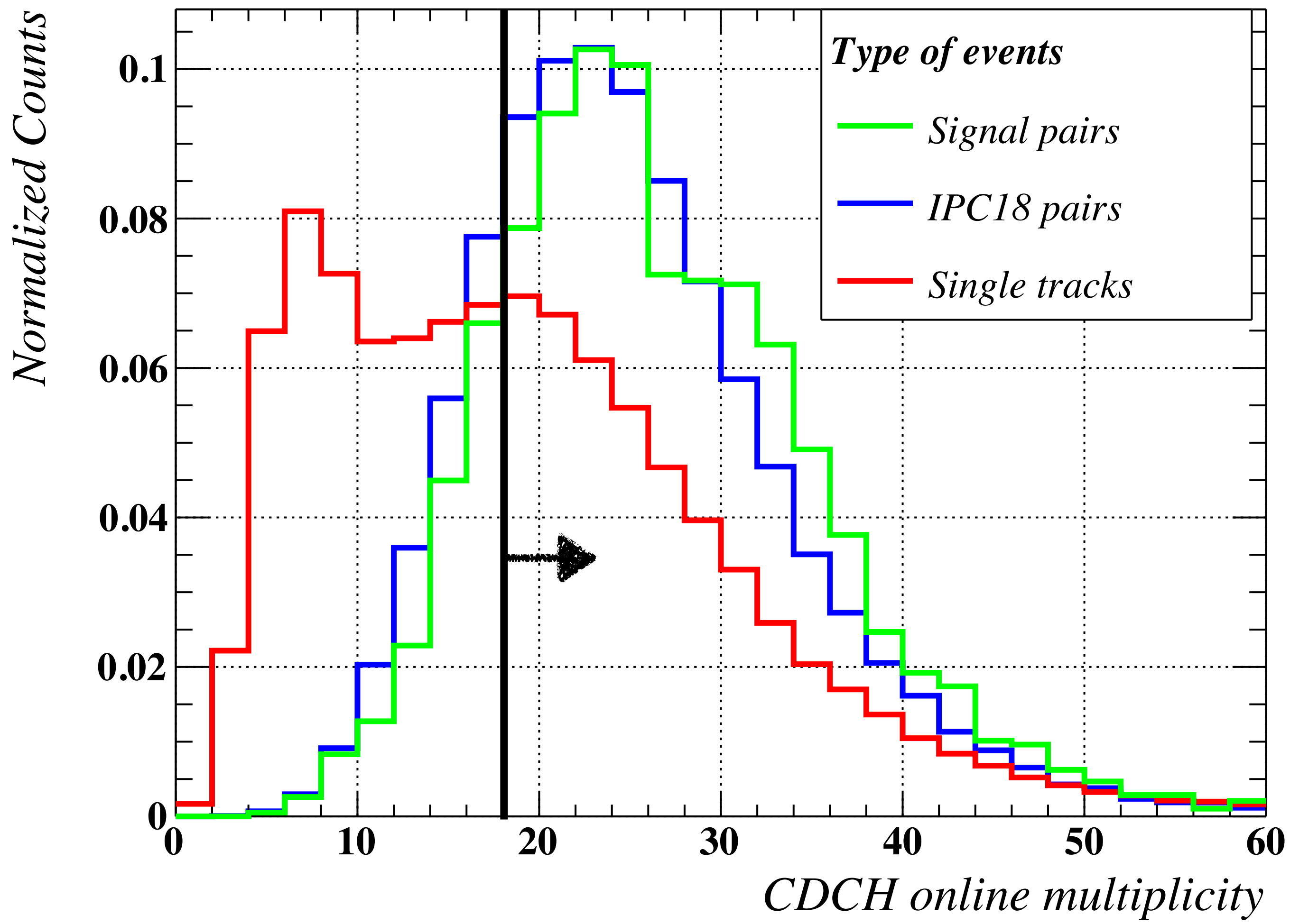


- Alternative: let's use online CDCH waveform amplitude
  - → High online threshold to trigger on good hits mostly
  - → How to exploit them?

Trigger strategy: CDCH hit multiplicity ⑤

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

<u>CDCH online multiplicity to reconstruct</u>
single tracks/IPC pairs/signal pairs



Trigger set as <u>18 hits > 60 mV</u>

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

Outline

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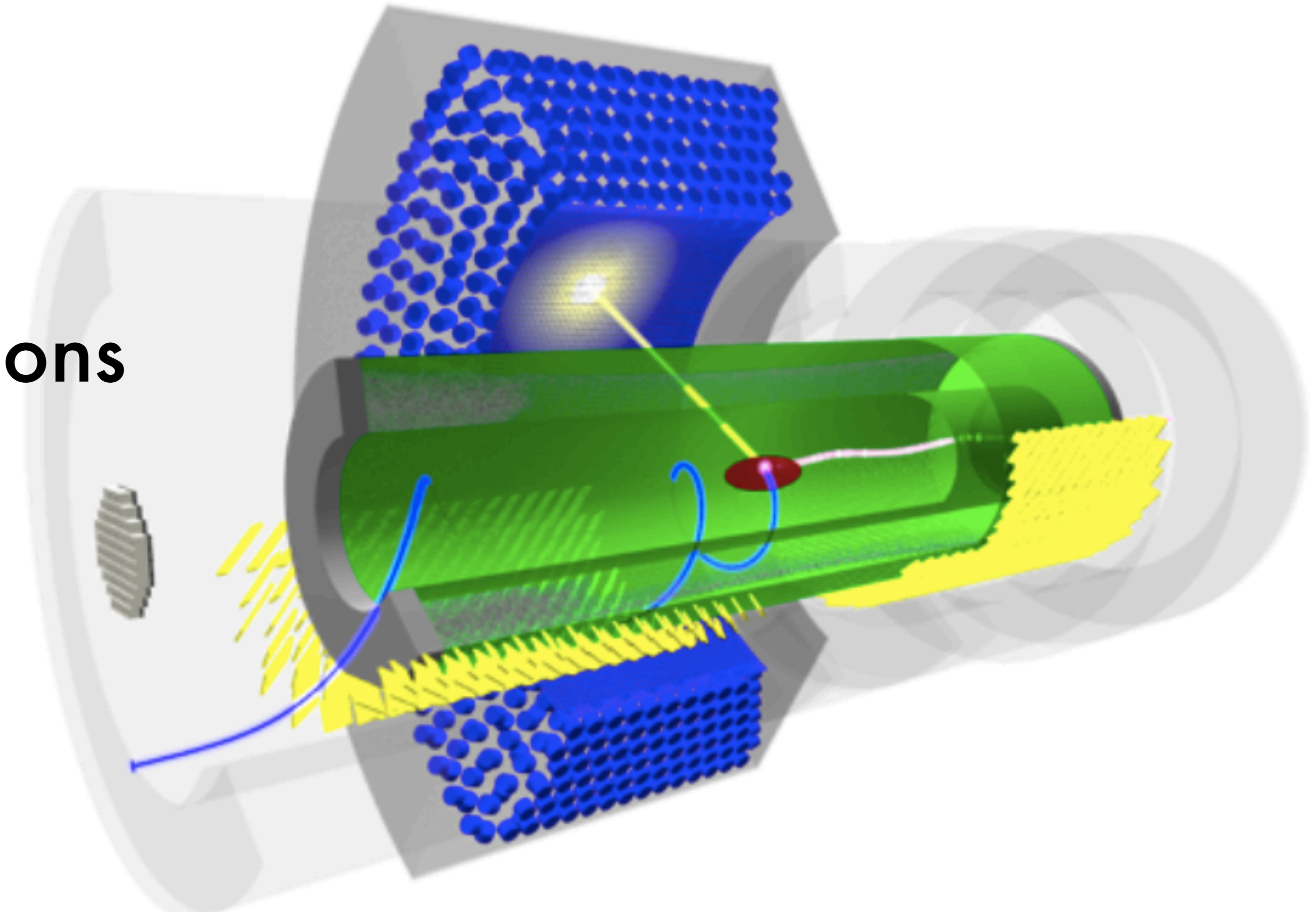
6) **Physics dataset and X17 results**



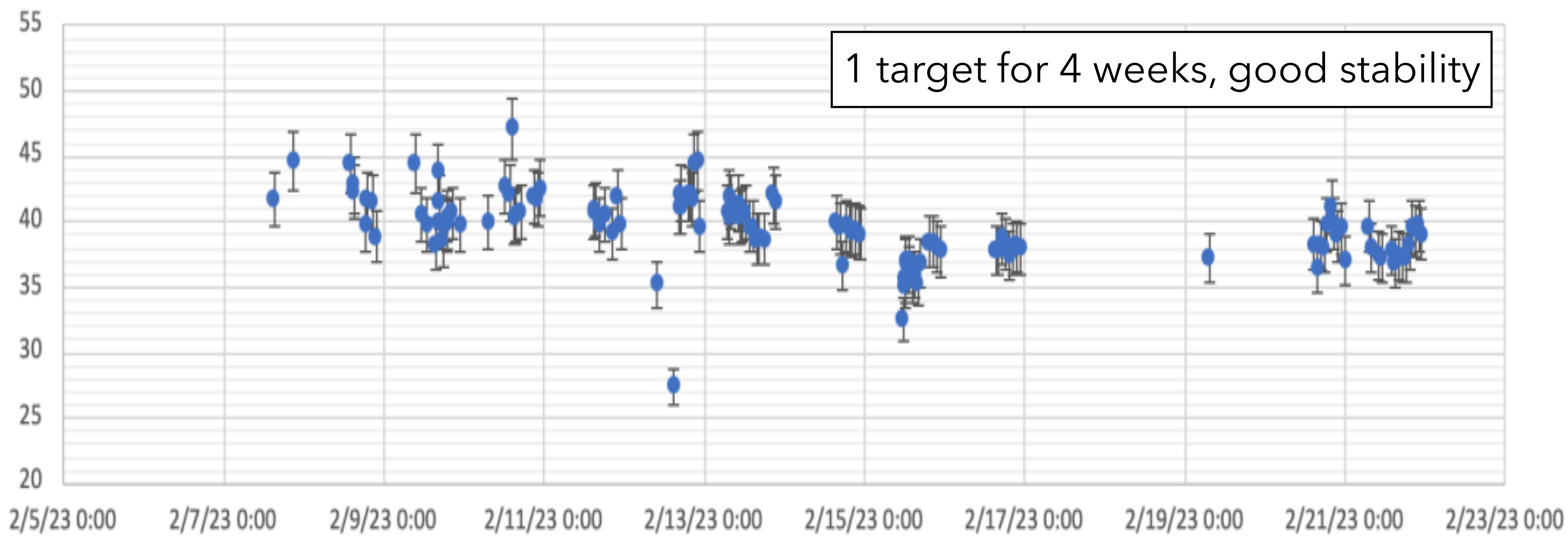
6) Physics dataset and X17 results

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 → 500k pairs to be reconstructed

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

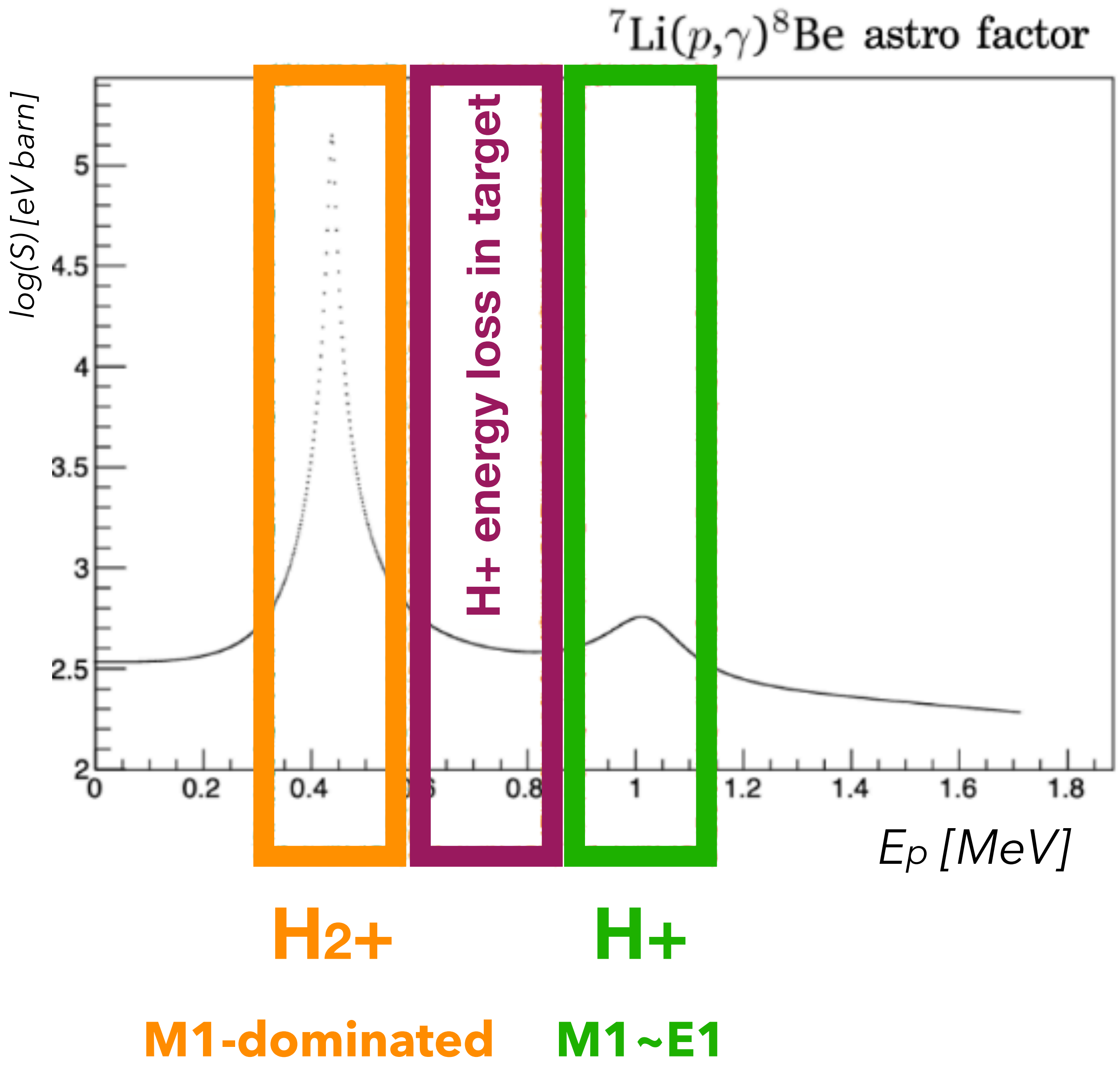


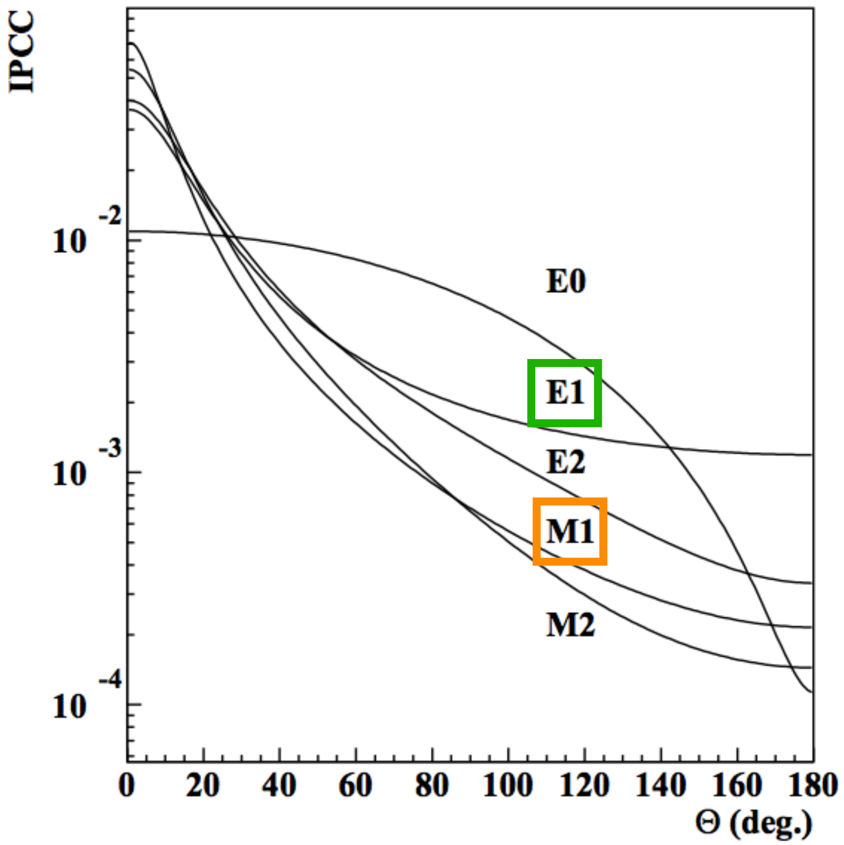
Date and time

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



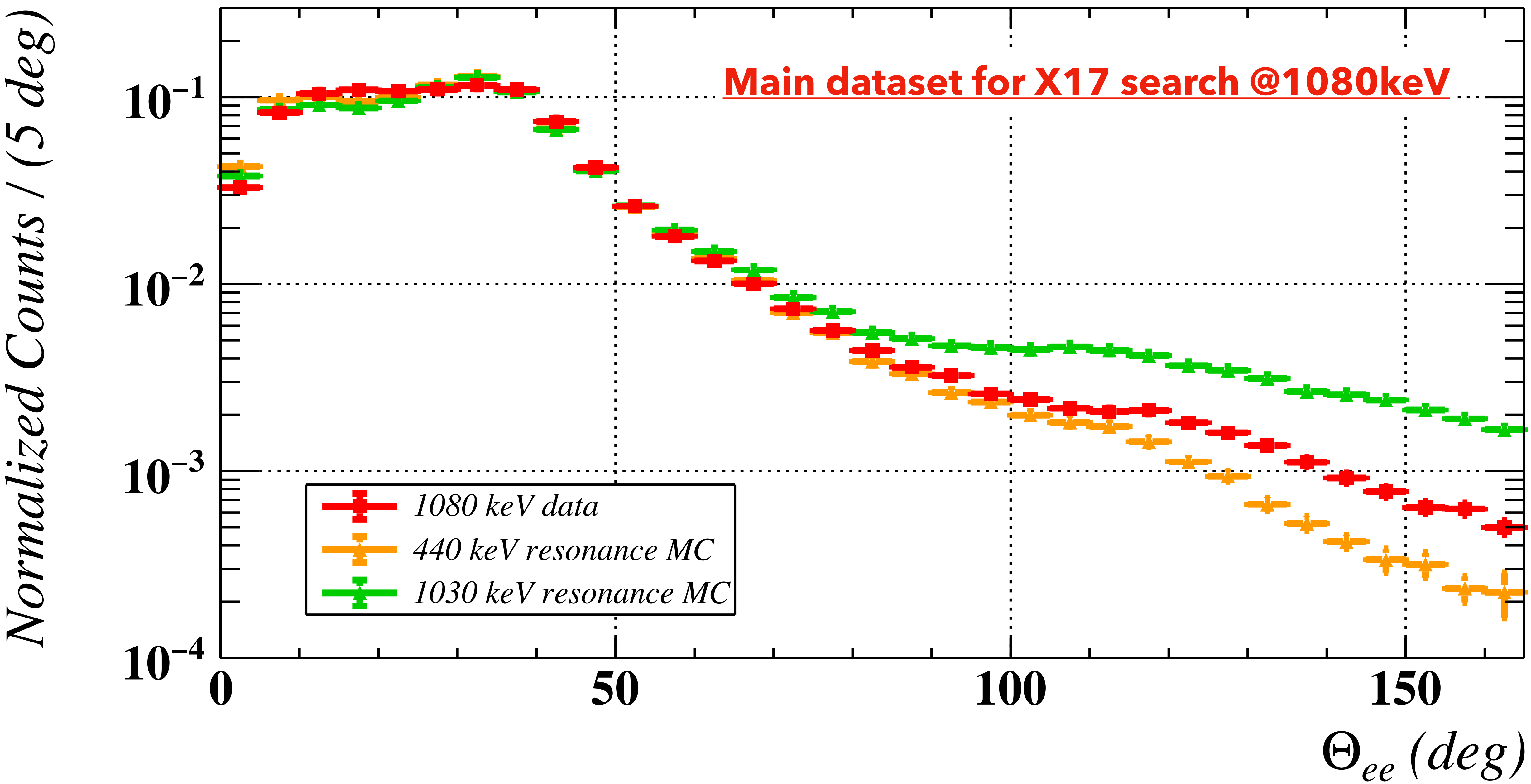


steeper IPC shape

flatter IPC shape

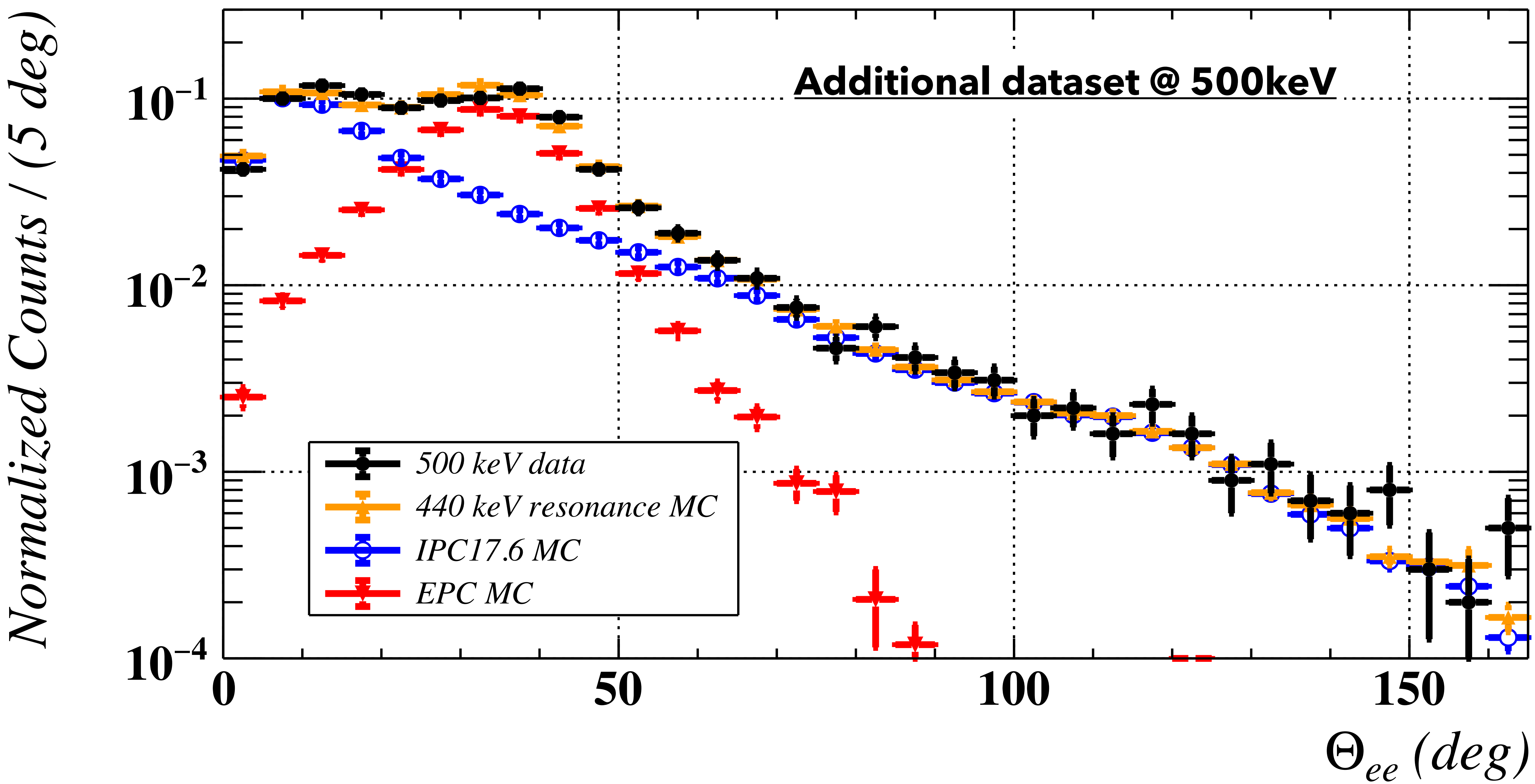
→ Resonances can be distinguished via the steepness of the IPC Angular Opening

Angular Opening spectrum @1080 keV ⑥



- 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
- We can search for anomaly in both transitions

Angular Opening spectrum @500 keV ⑥



- Small dataset @500keV (only 17.6 MeV line)
- <u>Data well modelled by Zhang-Miller IPC model</u>!

Analysis strategy

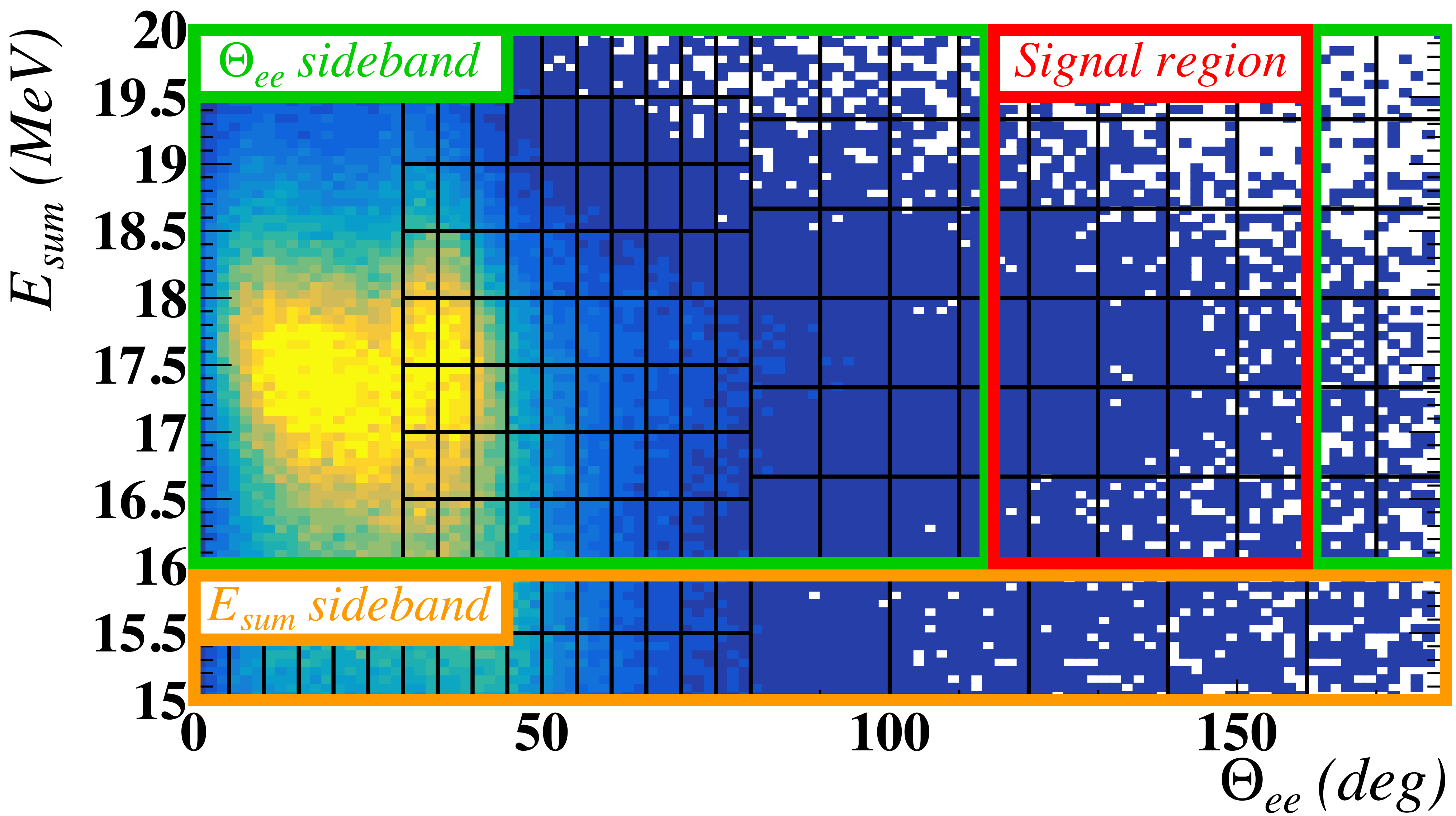
- 2D likelihood maximization: Esum vs Angular Opening

- Blinded signal region defined as:

Signal Region

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

- Before unblinding, understanding of background done in two sidebands



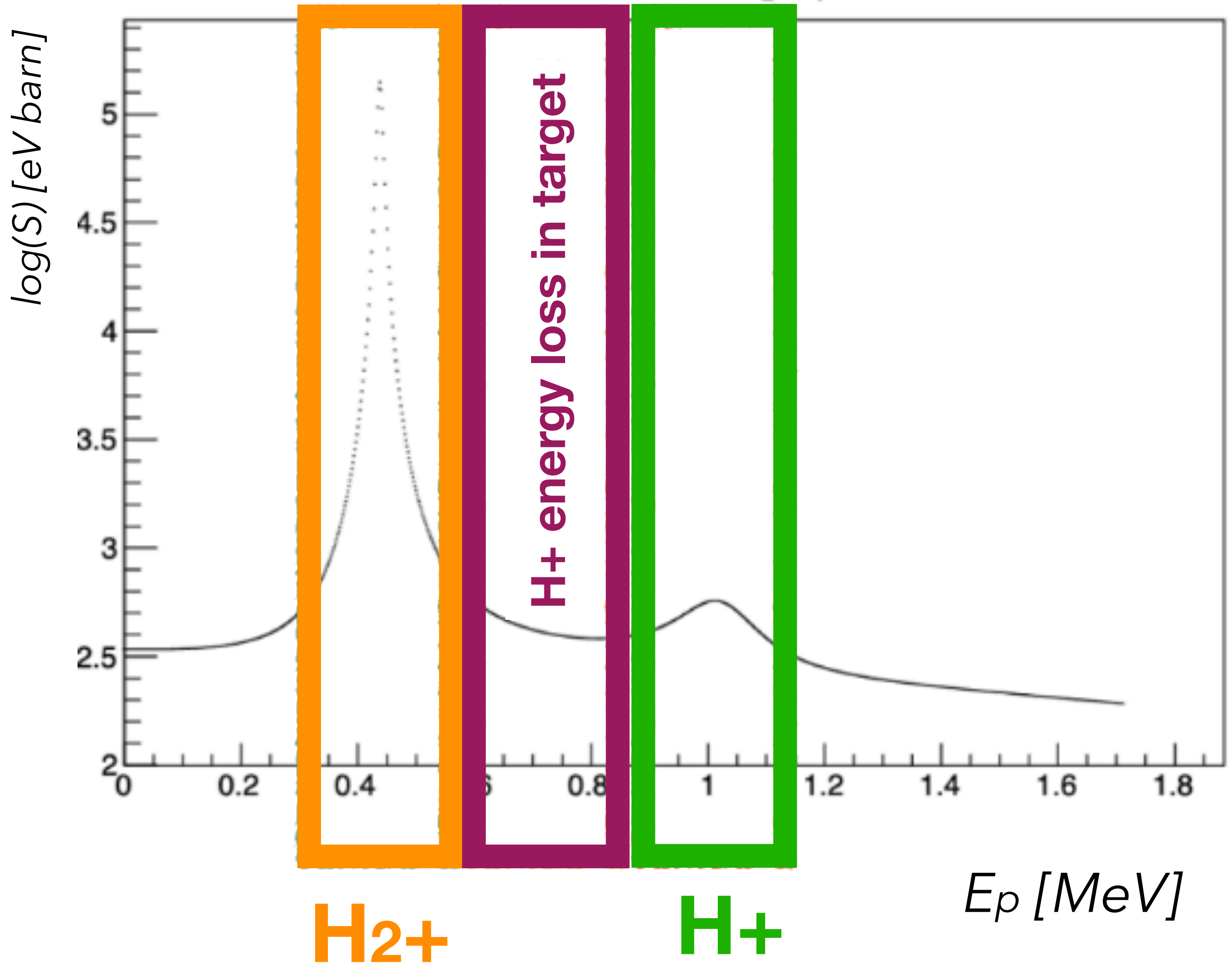
Maximum likelihood fit

- Binned max. likelihood fit using template histograms as PDF from a detailed MC simulation → validated in the sidebands
- Likelihood parametrized wrt. photon emission BR

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

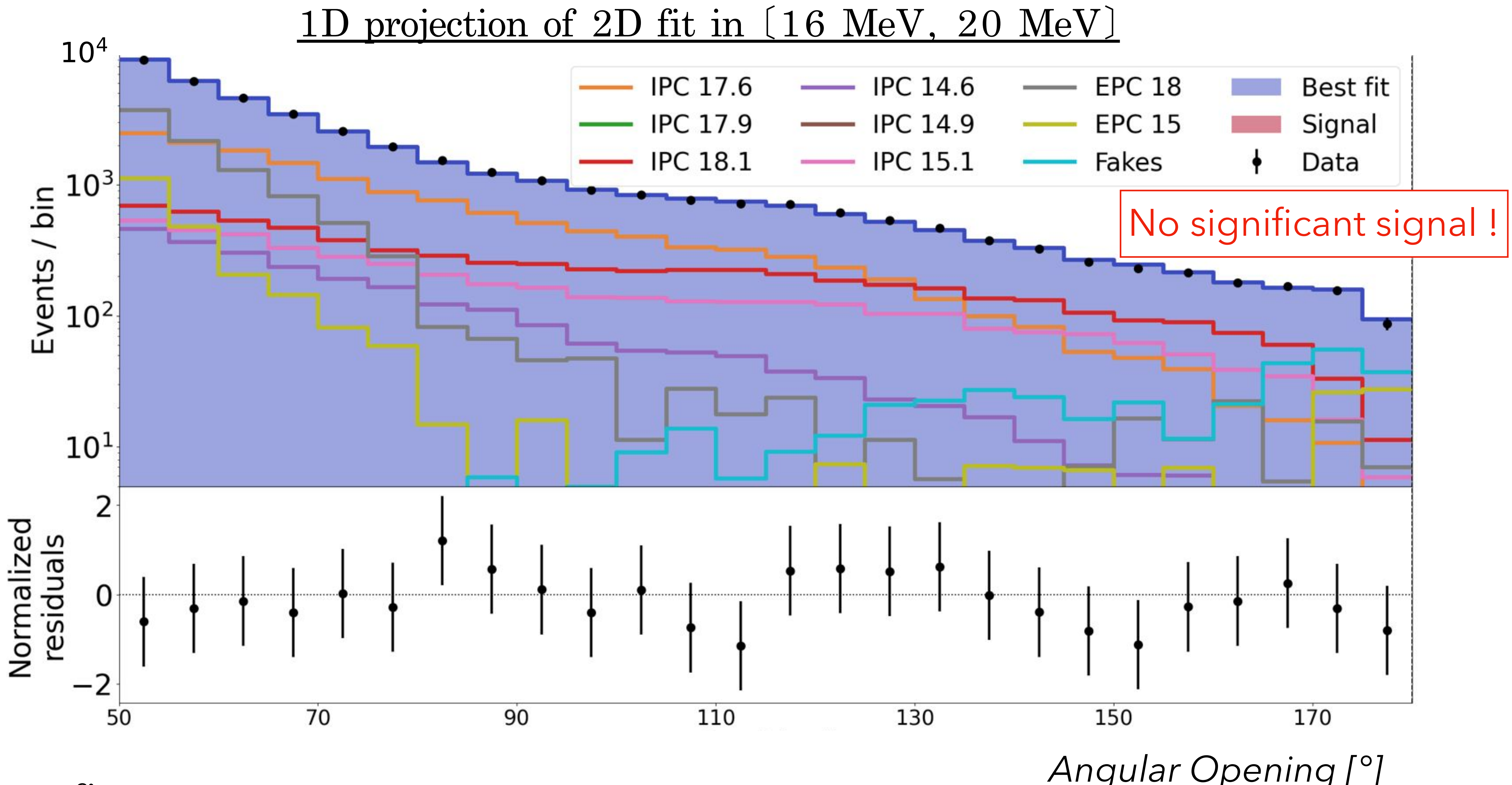
Two signal templates
→ One per resonance, Q =17.6 and Q=18.1 MeV
Six IPC templates
→ Three Ep bins,
→ Two transitions (g.s and 1st excited s.) for each bin
Two EPC templates
→ Neglected Ep dependence,
→ Transition to g.s. and 1st e.s.
One fake pairs template

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



→ Beeston-Barlow likelihood to account for MC limited statistics
Eur. Phys. J. C 82(11), 1043

Best fit

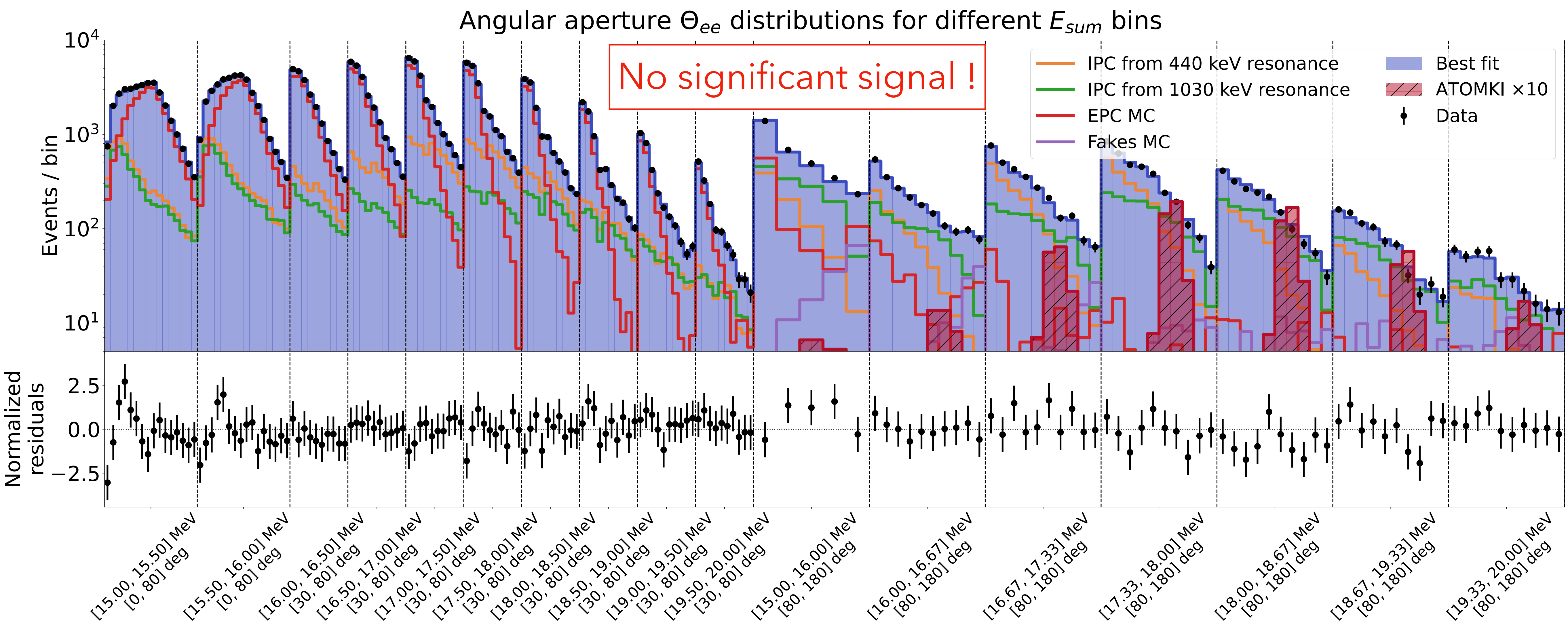


Best fit

- 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

Best fit



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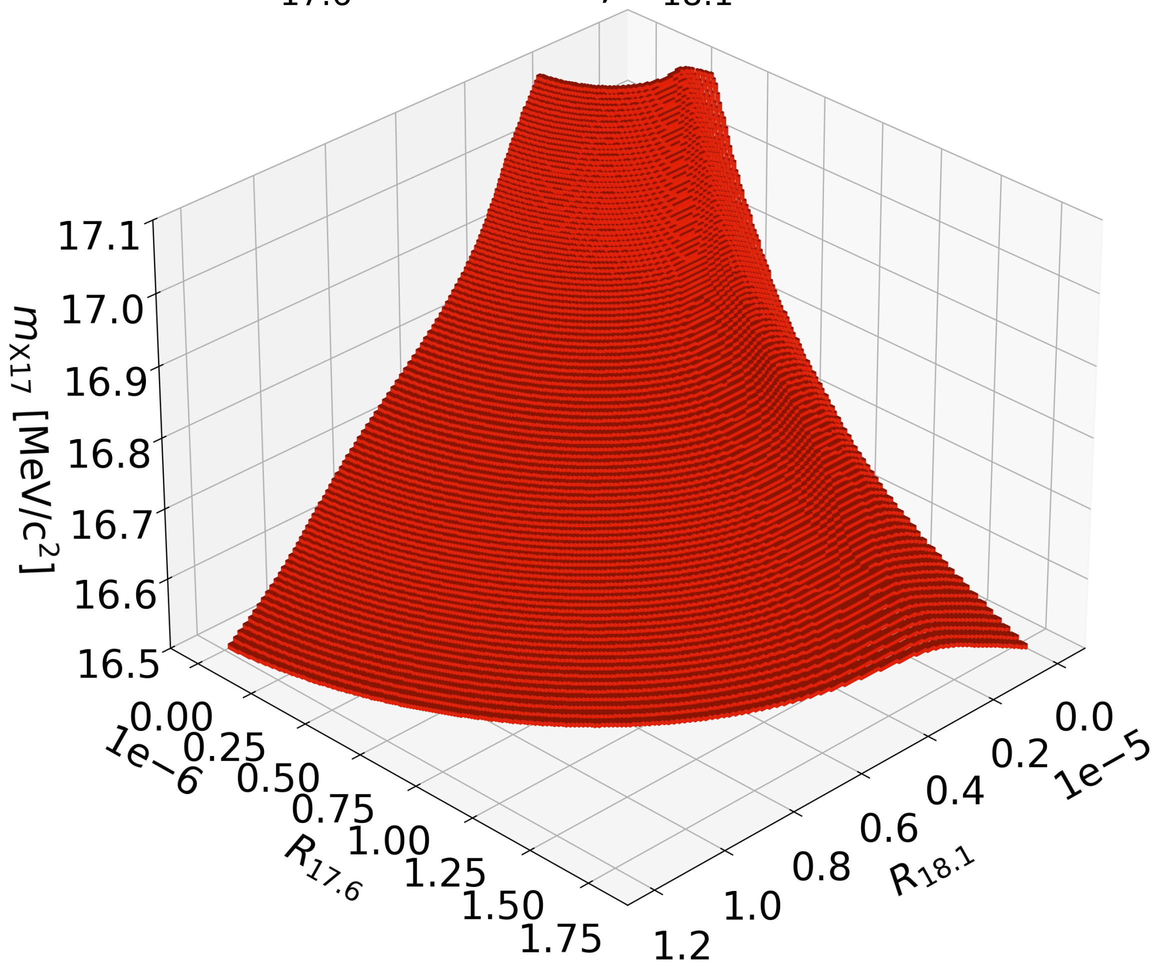
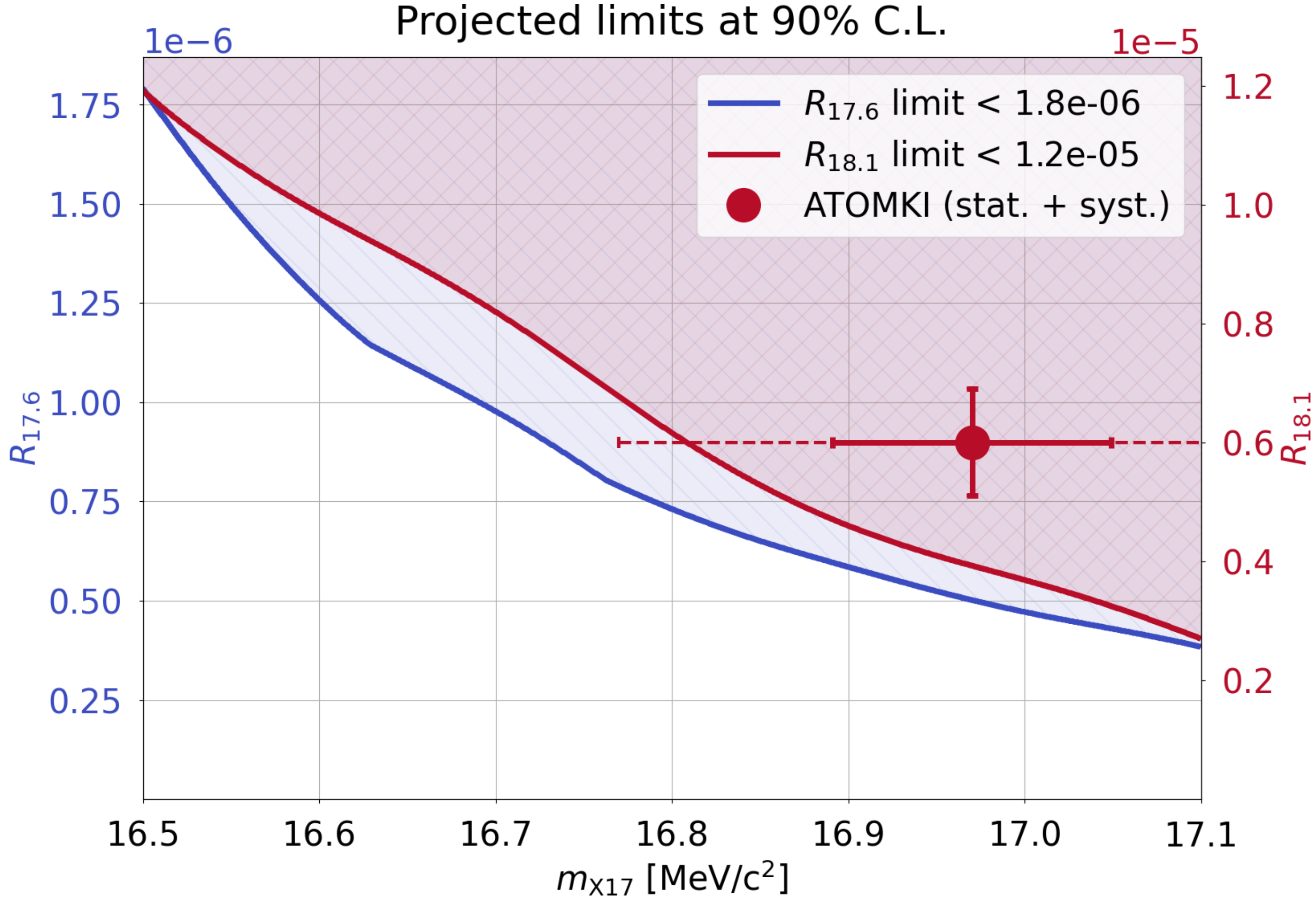
Phys. Rev. Lett. 117, 071803

90% Confidence Limits

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

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





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

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

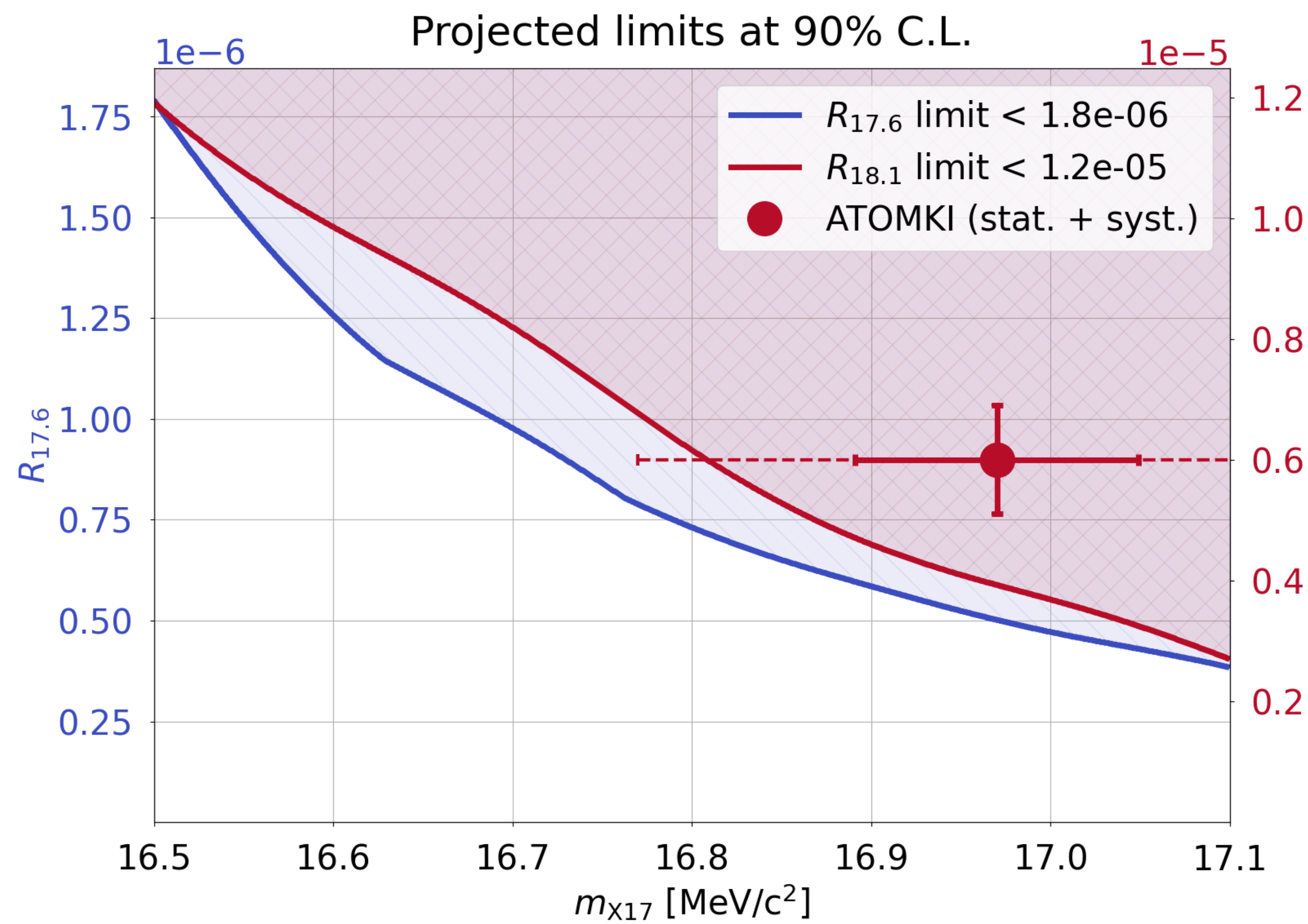
Compatibility tests

Two hypotheses were tested

Assumes:

pondered average over 3 nuclei's result

- **m =16.97(22) MeV/c²**
- **$R_{18.1}$ = 6(1)e-6**
- **$R_{17.6}$ = 0.46 $R_{18.1}$**



<u>Atomki hypothesis</u>: X17 only from <u>18.1 MeV decay</u>

incompatible at 94% (1.5σ)

<u>Feng et al. hypothesis</u>: X17 from both <u>18.1 MeV</u> and <u>17.6 MeV decay</u>

incompatible at 98% (2.1σ)

Conclusion and outlook

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

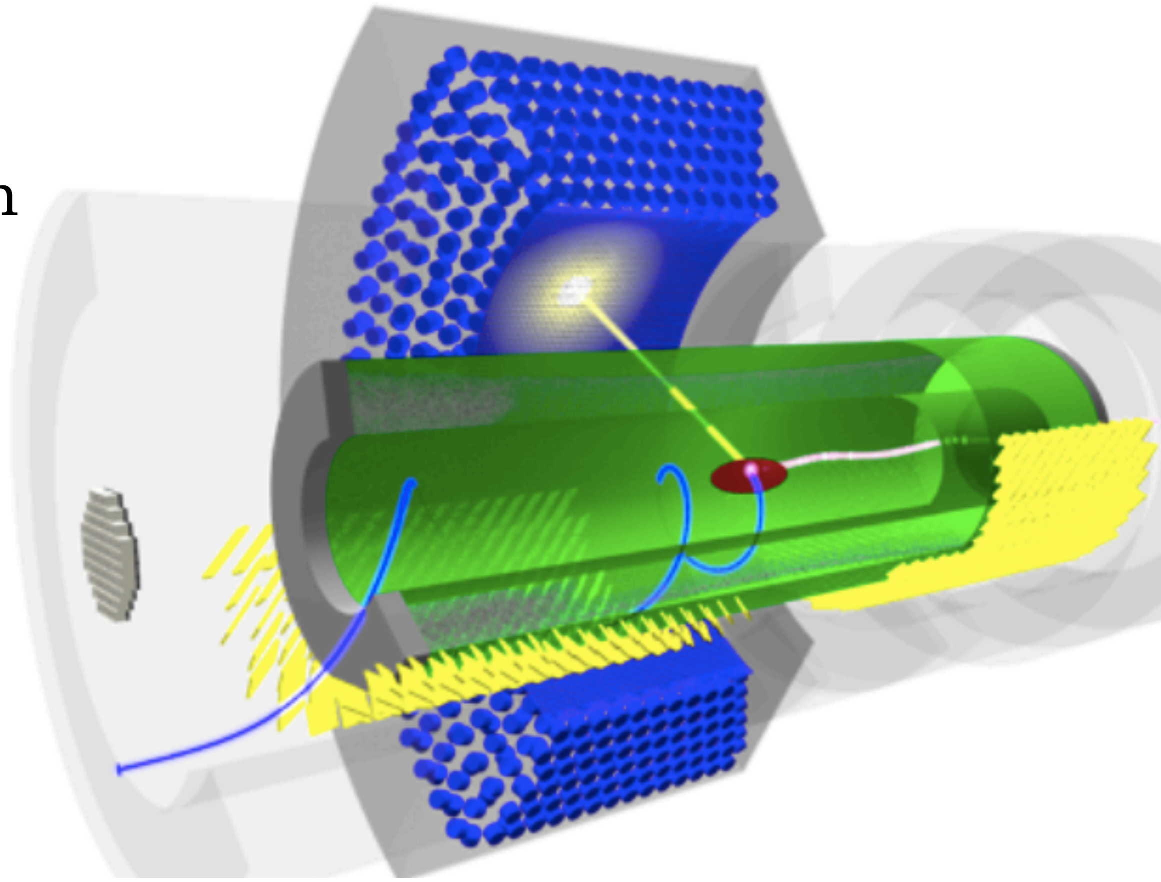
- Physics run in February 2023

→ backgrounds, signal and detectors simulation

→ 2023 data was reprocessed, good background understanding

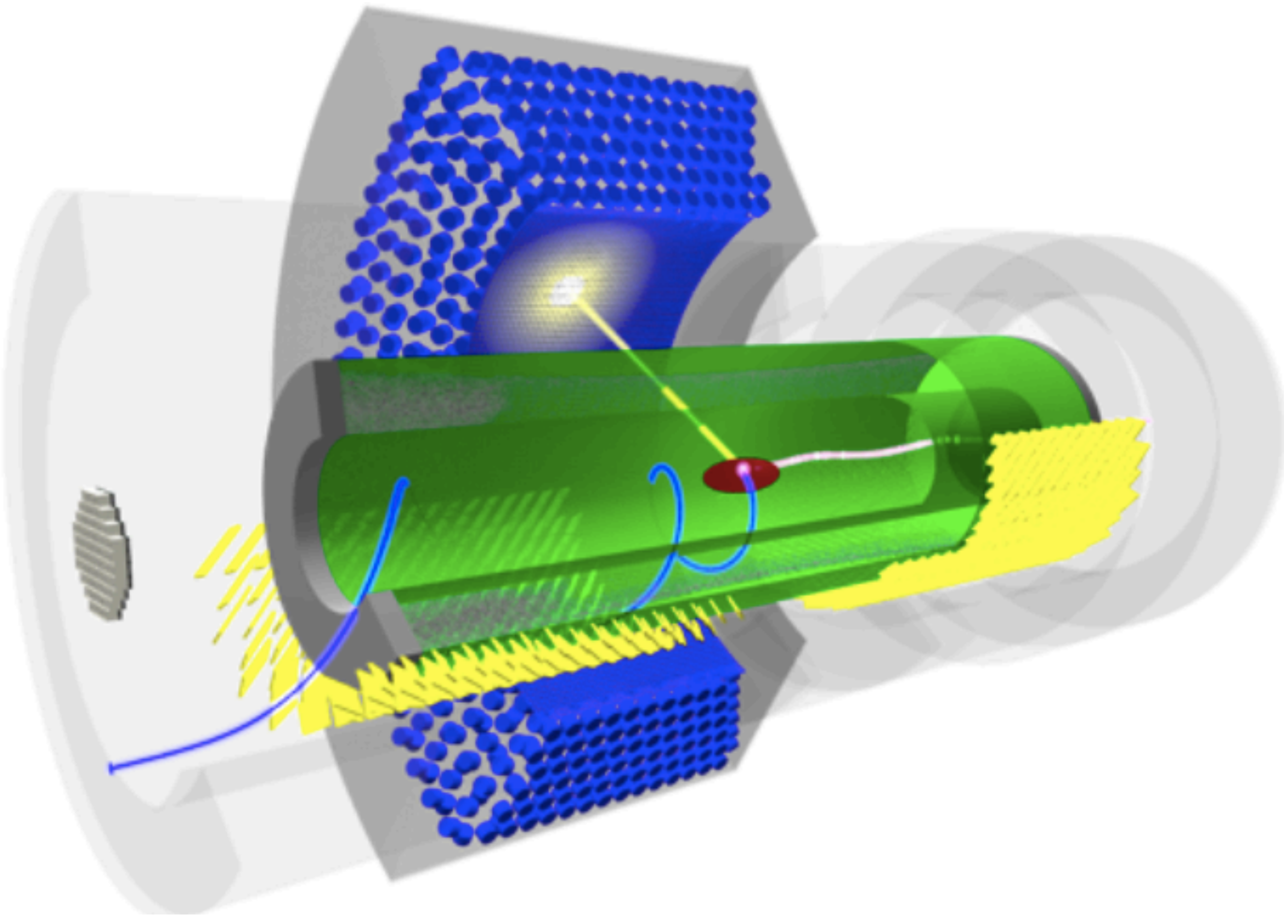
→ No significant signal was found in our data

→ 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
Università di Pisa, INFN Pisa

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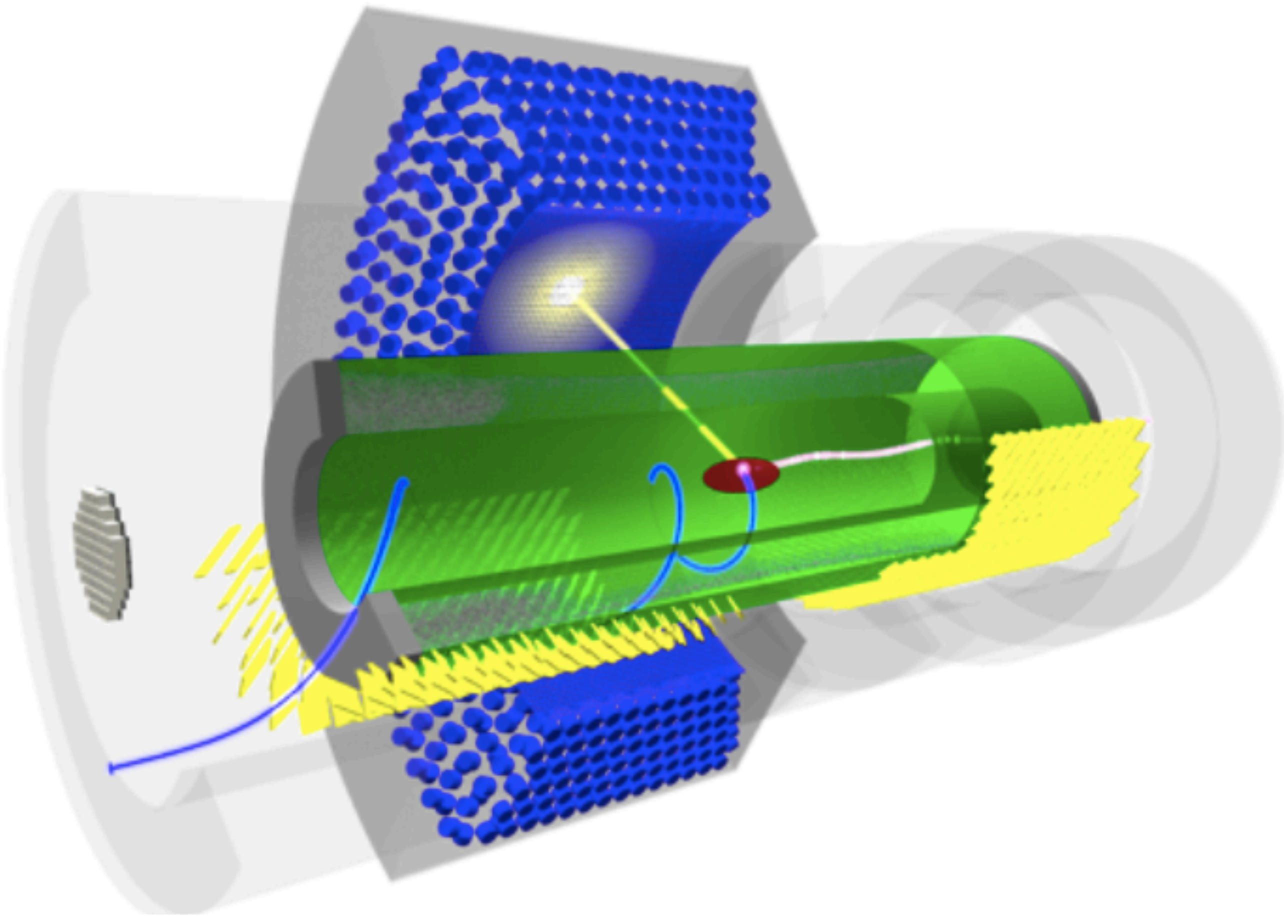
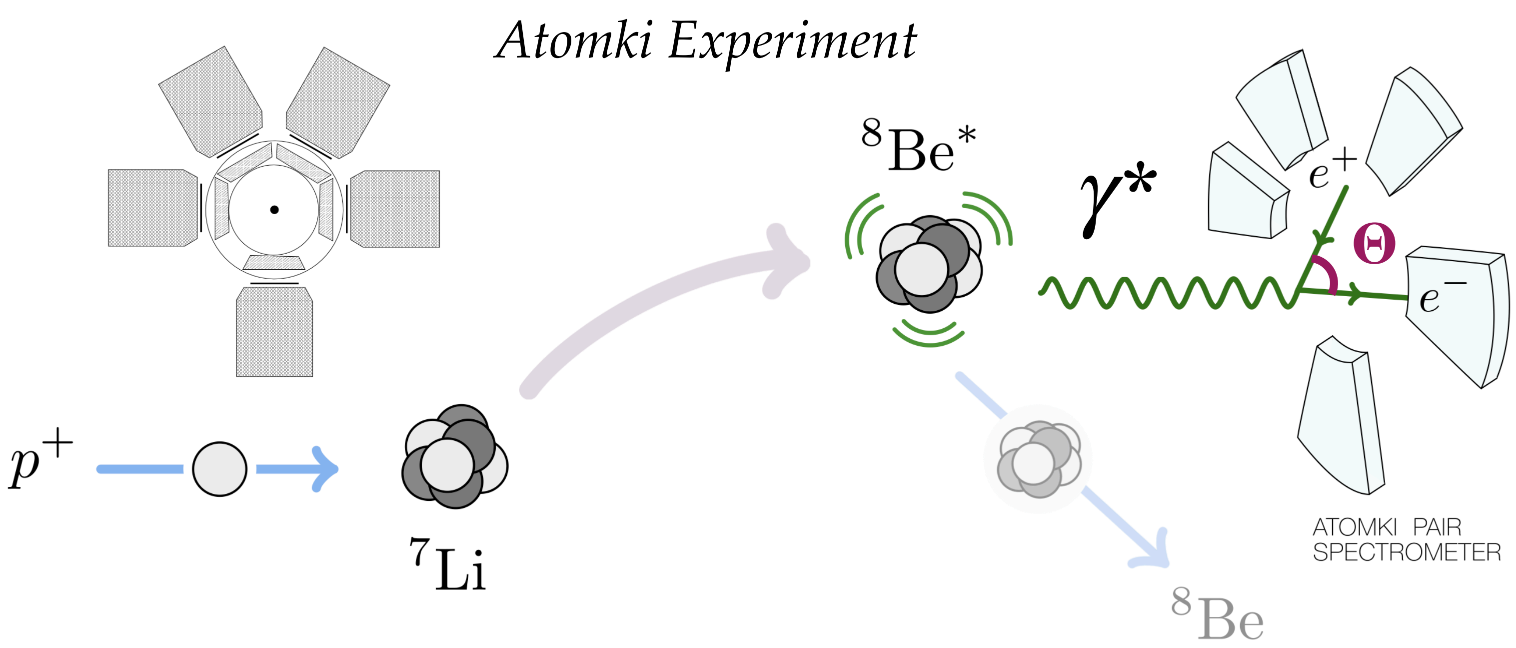
Backup slides



The Beryllium Anomaly

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

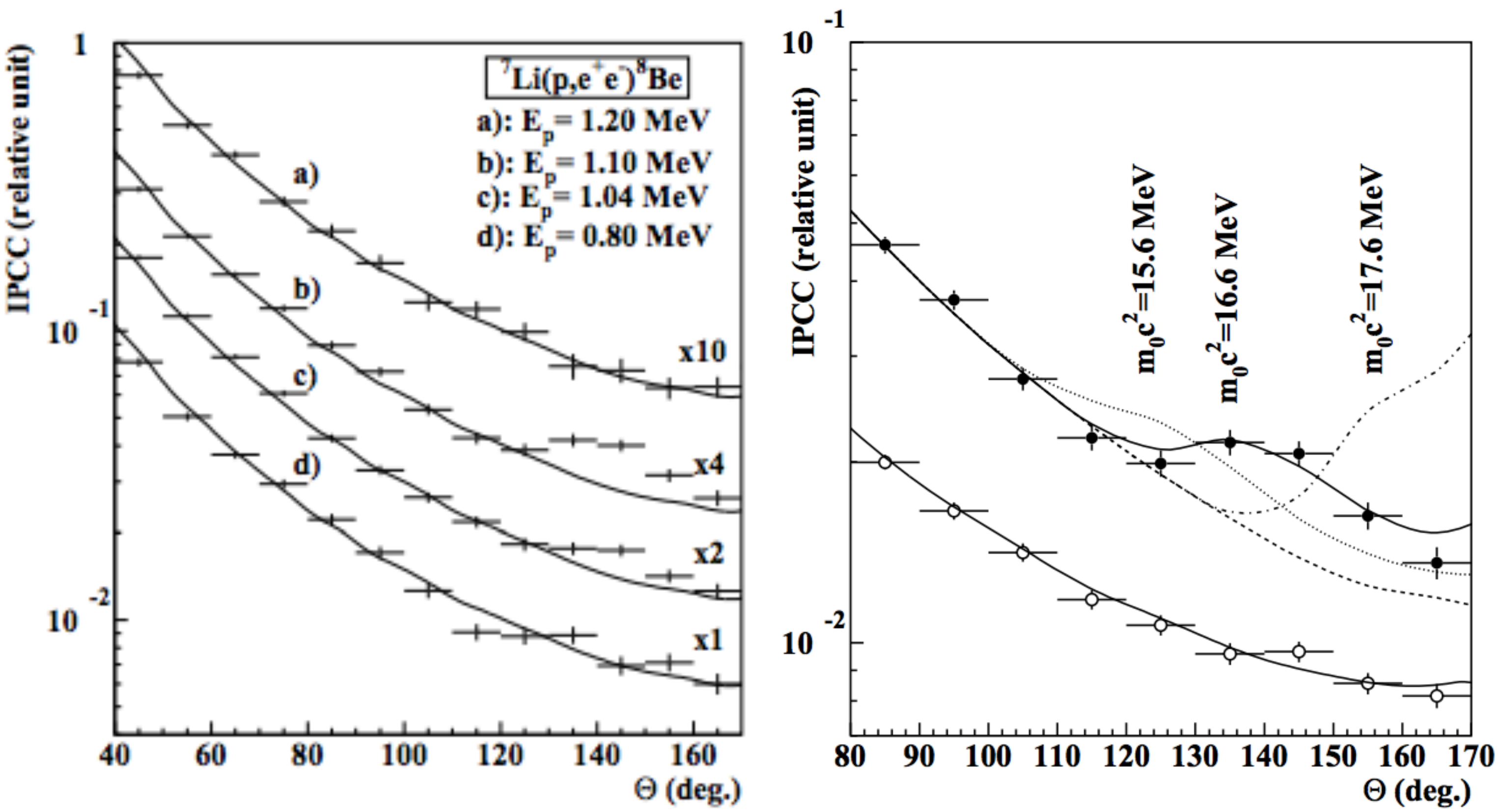
①



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

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

<u>2016 Atomki results</u>



<u>Phys. Rev. Lett. 116, 042501</u>

- 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?

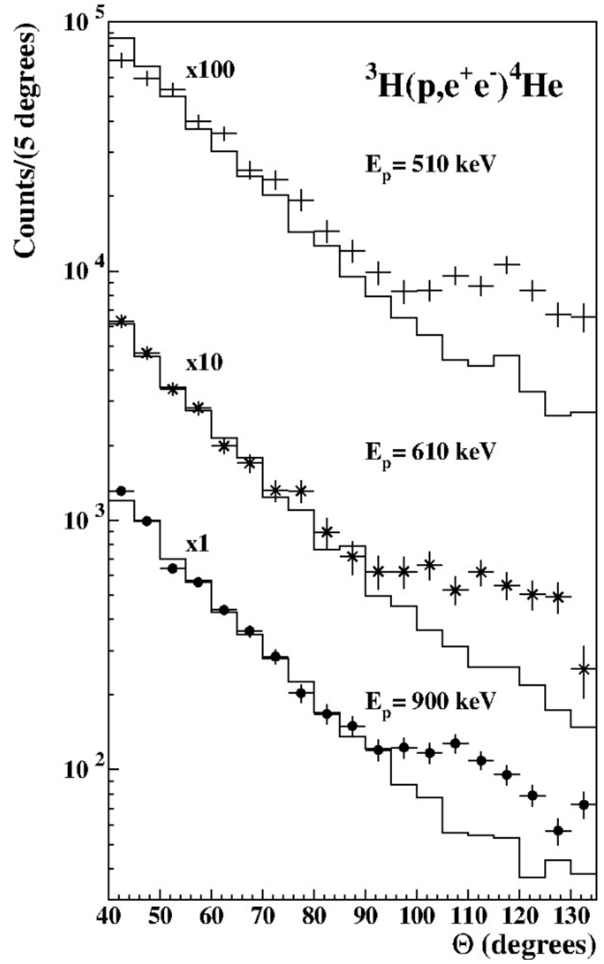
<u>Phys. Rev. D 95, 035017</u>

Consistent anomalies? ①

Phys. Rev. C 104, 044003

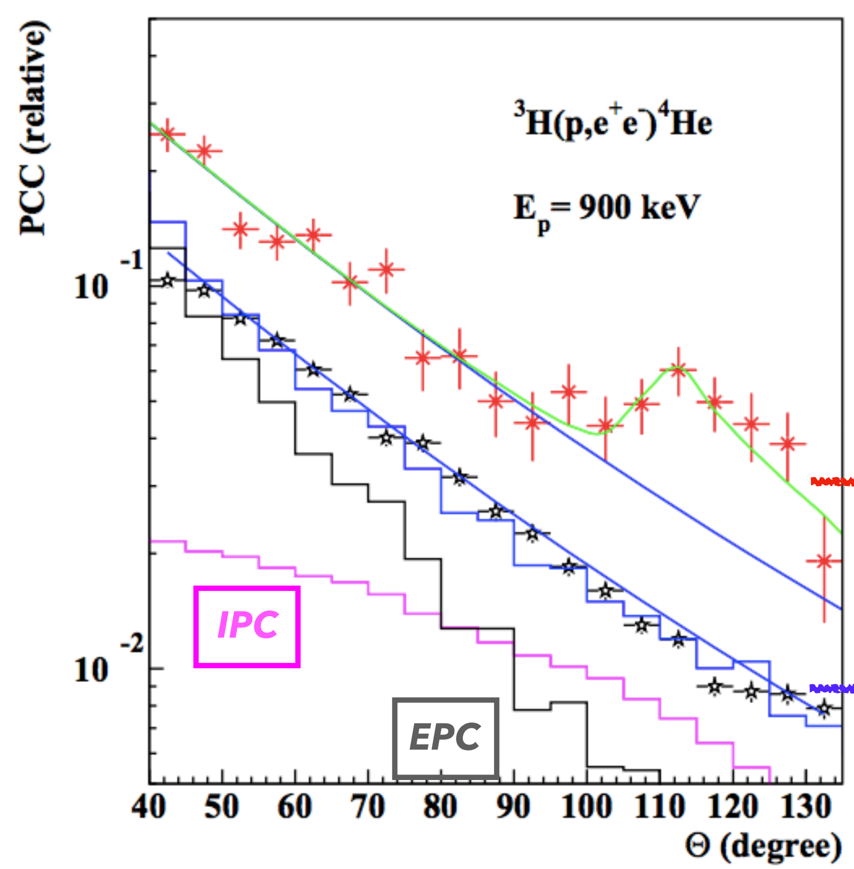
arXiv:1910.10459

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/c^2 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

Reduced magnetic field and beam tuning

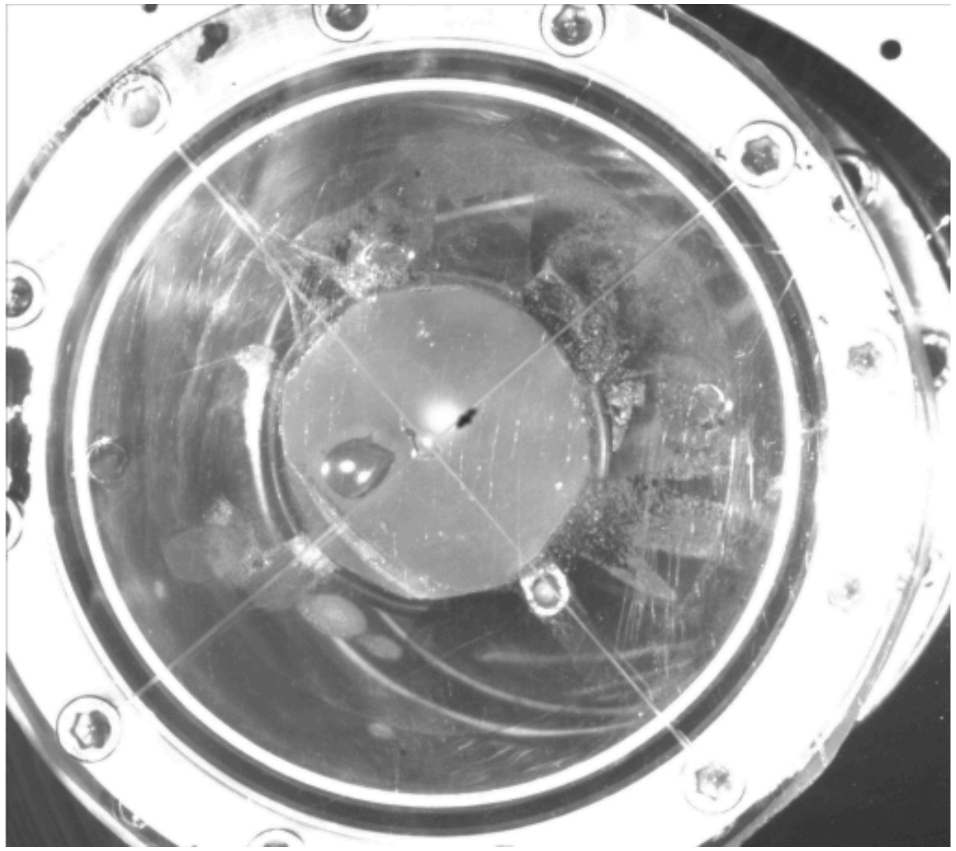
- $\mu \longrightarrow e\gamma$ search relies on 52.8 MeV positron search with default magnetic field (1.27T at COBRA center)

- 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

CW: beam tuning 2024

②

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

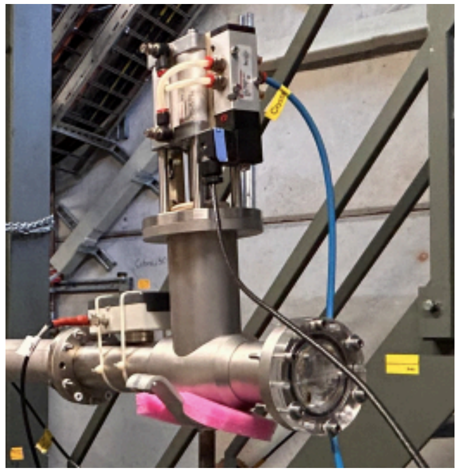
→ CW beam tuned using a quartz target: proton-induced fluorescence in the quartz, visible emission

→ Tuning made varying 4 dipolar fields along the beamline

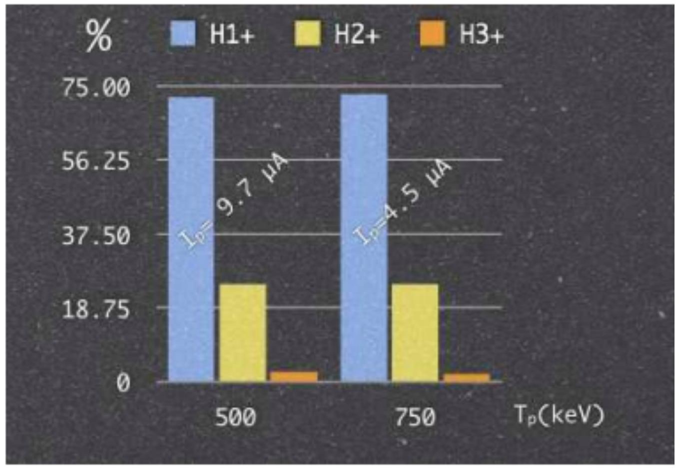
→ H_2+ contamination in the beam

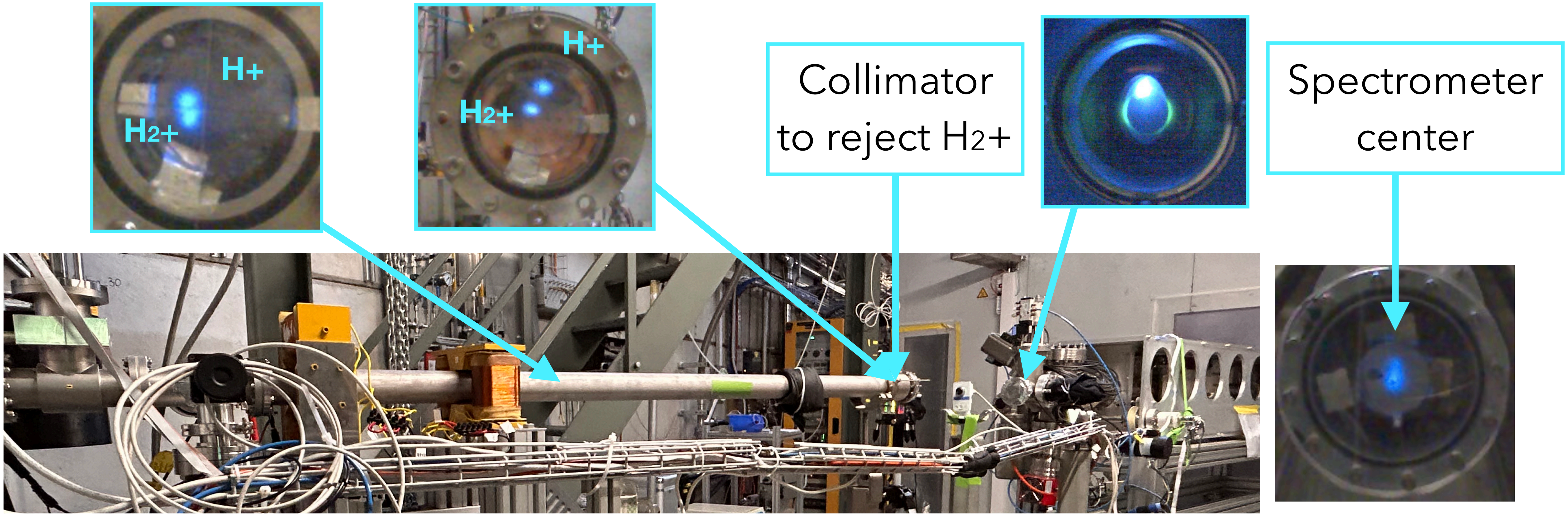
Measurement of the beam ion composition with Faraday Cup

Faraday cup



Ion composition



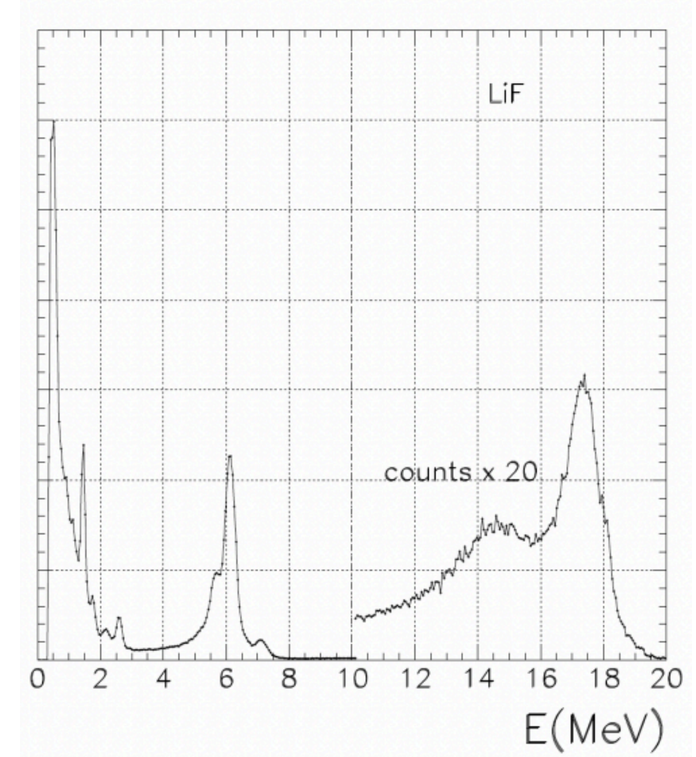


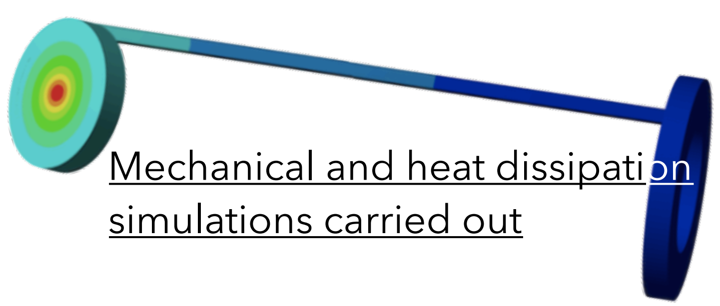
The new target region

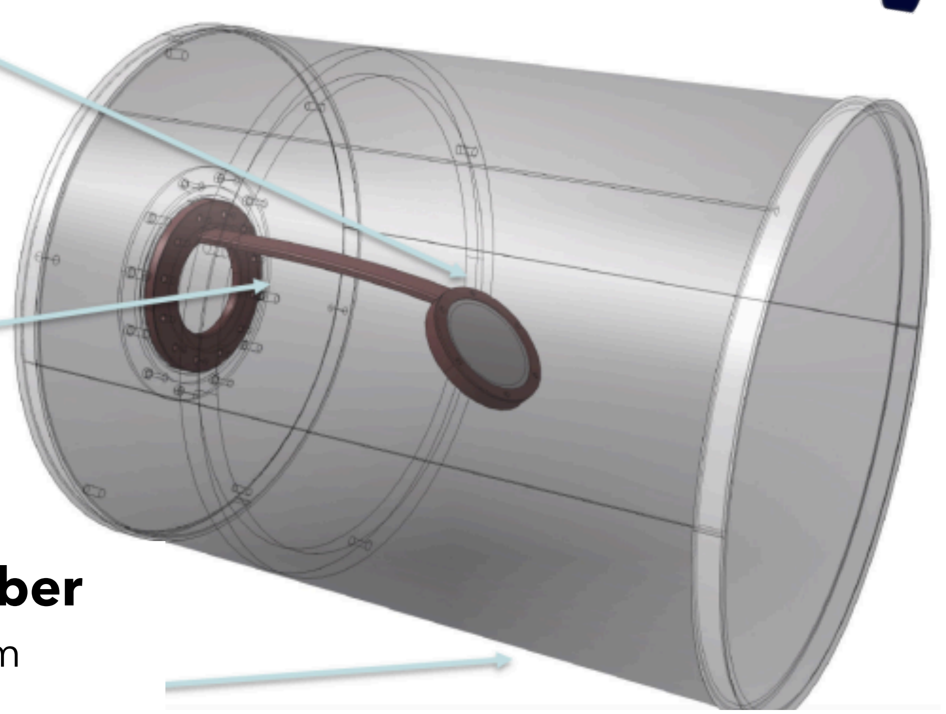
- 400 μm-thick carbon fiber vacuum chamber to minimize multiple scattering

- 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







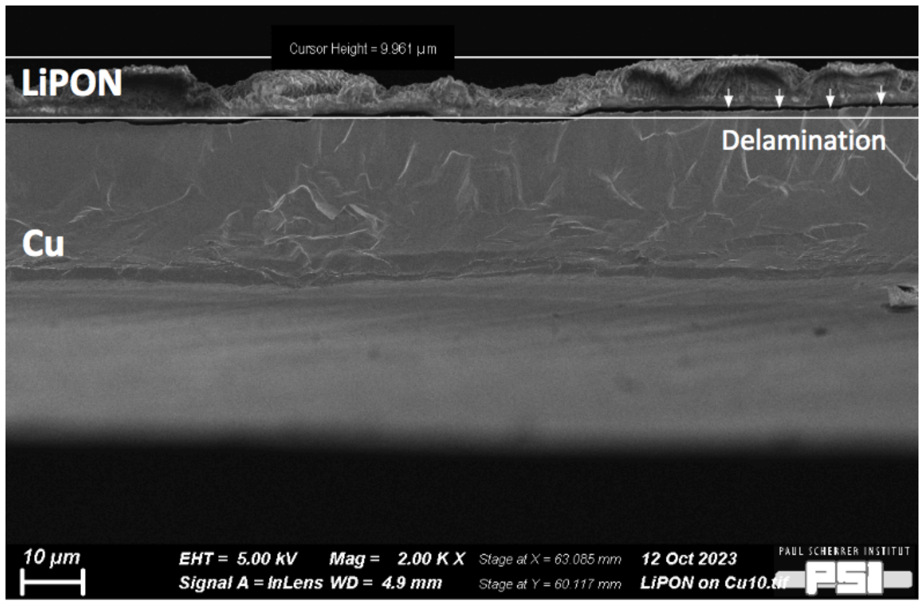
(*) Lithium phosphorus oxynitride ($Li_{3-x}PO_{4-Y}N_{x+Y}$)

Target studies: SEM and EDX

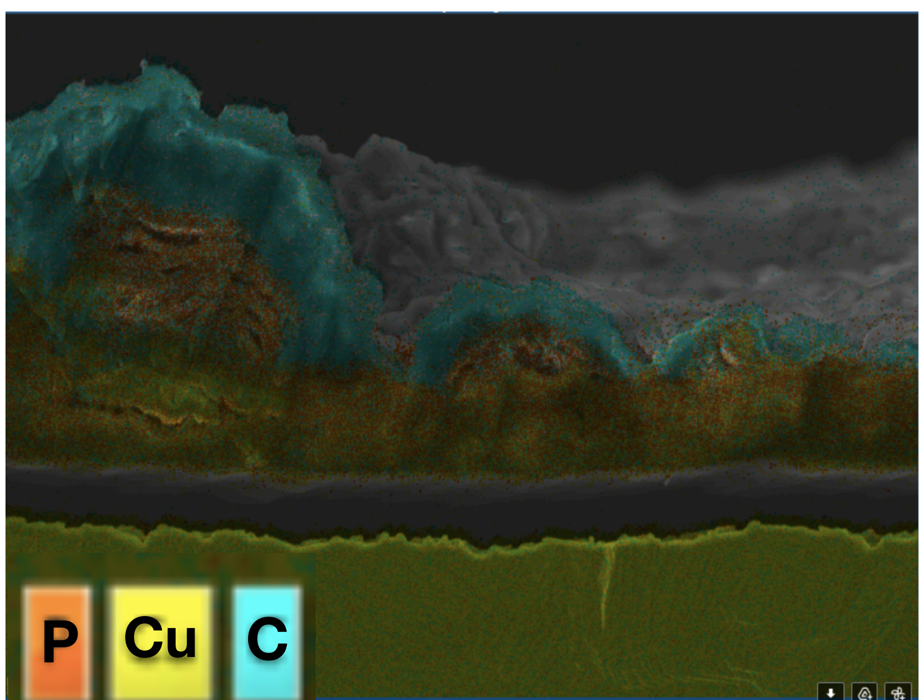
- Why LiPON?

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

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

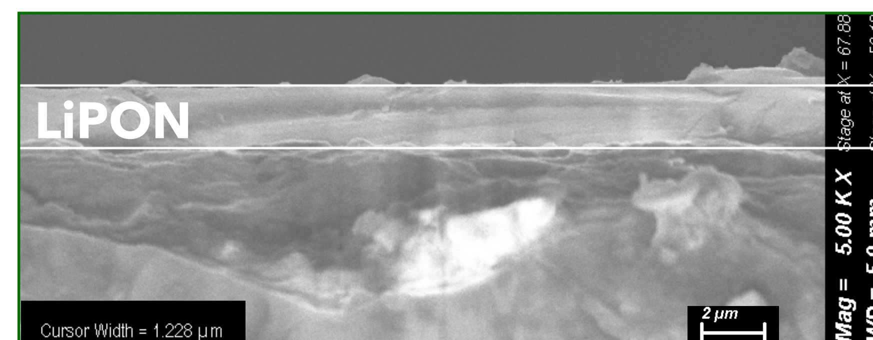


→ Delamination, pores, large thickness variations



→ $LiCO_3$ on the surface

<u>Recently, uniform thin 2-µm films were achieved at PSI</u>

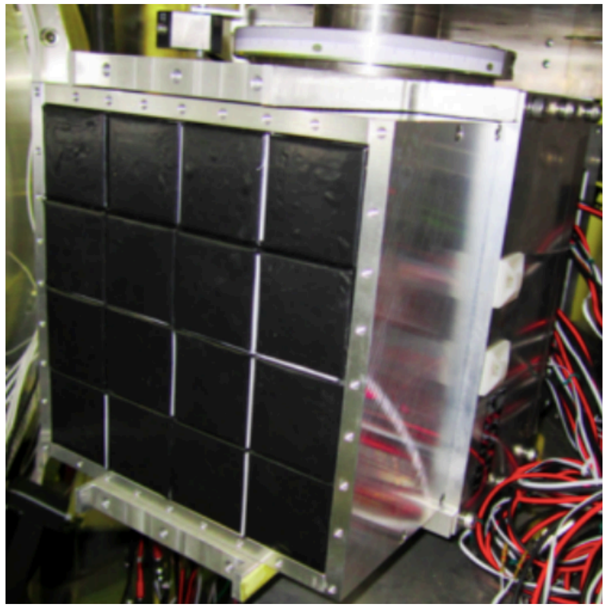


Gamma detectors

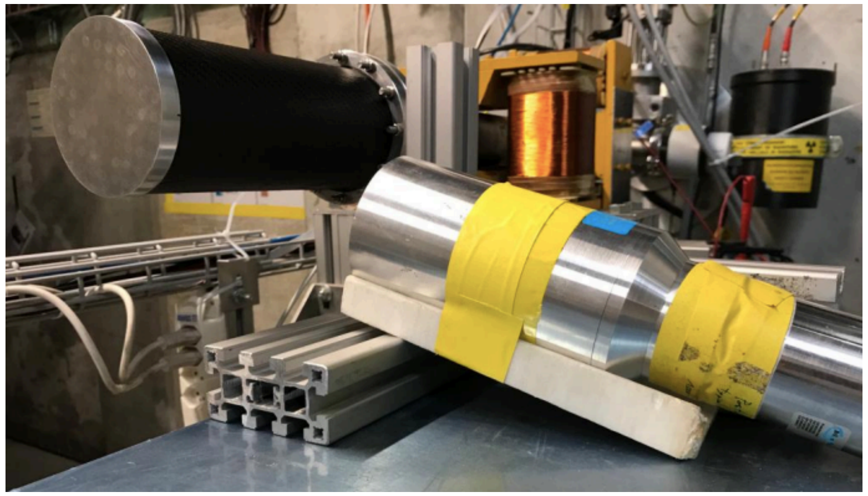
- Two additional gamma detectors

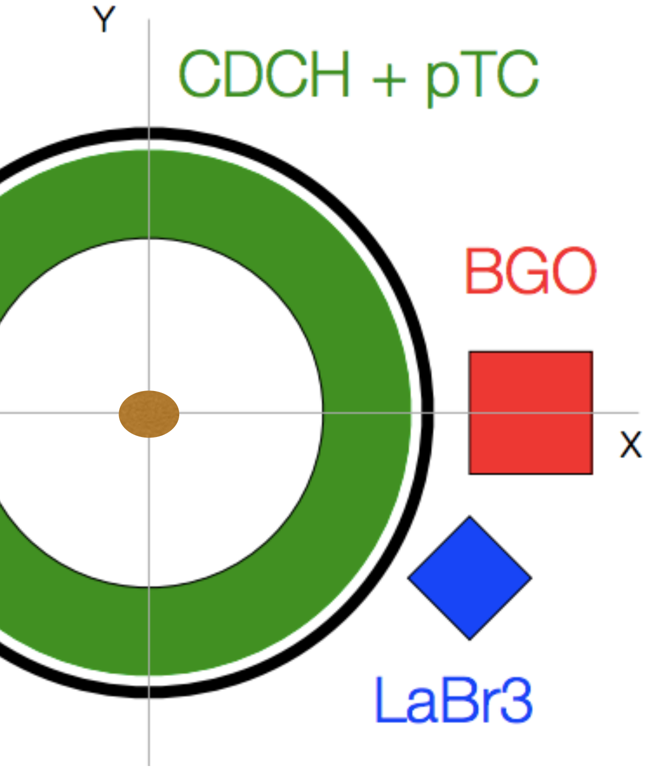
→ Stability monitoring → Signal normalisation → Daily monitoring

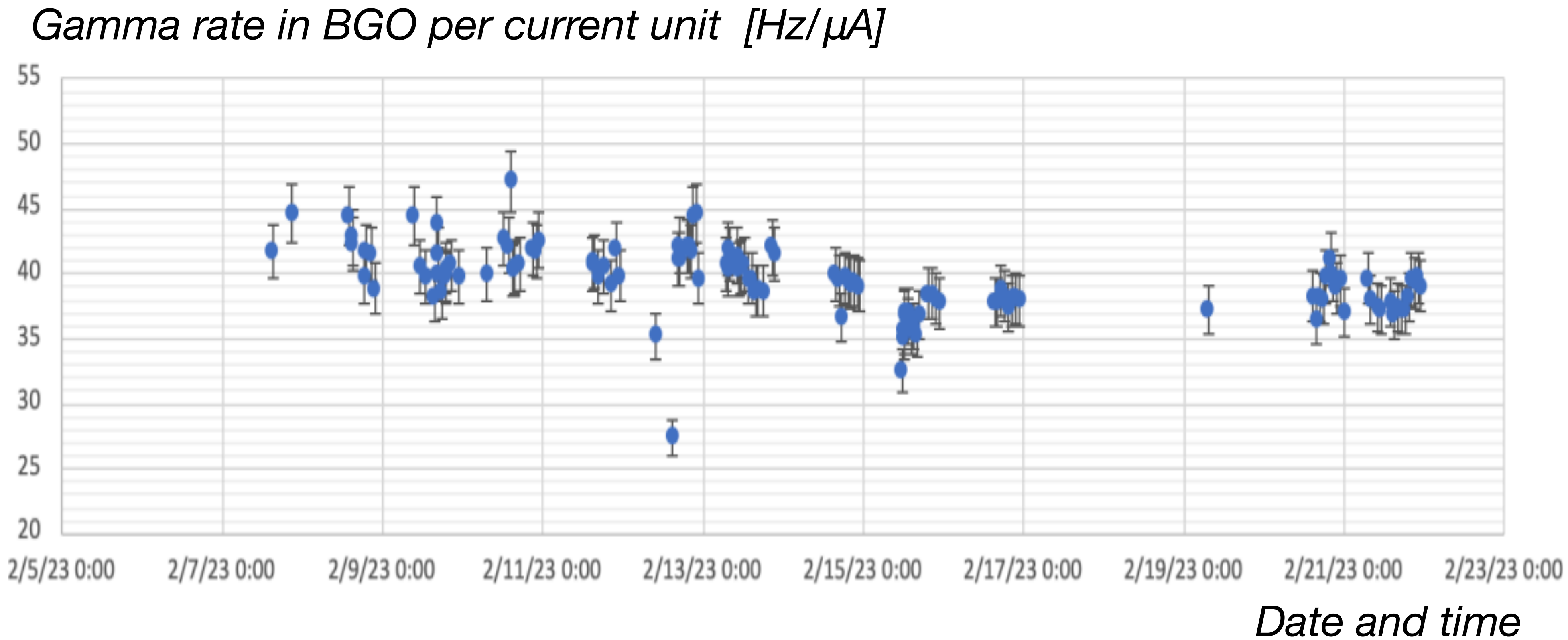
Bismuth Germanate (BGO) crystal matrix (4x4)



Lanthanum Bromide (LaBr3) crystal







Internal Pair Conversion

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

③

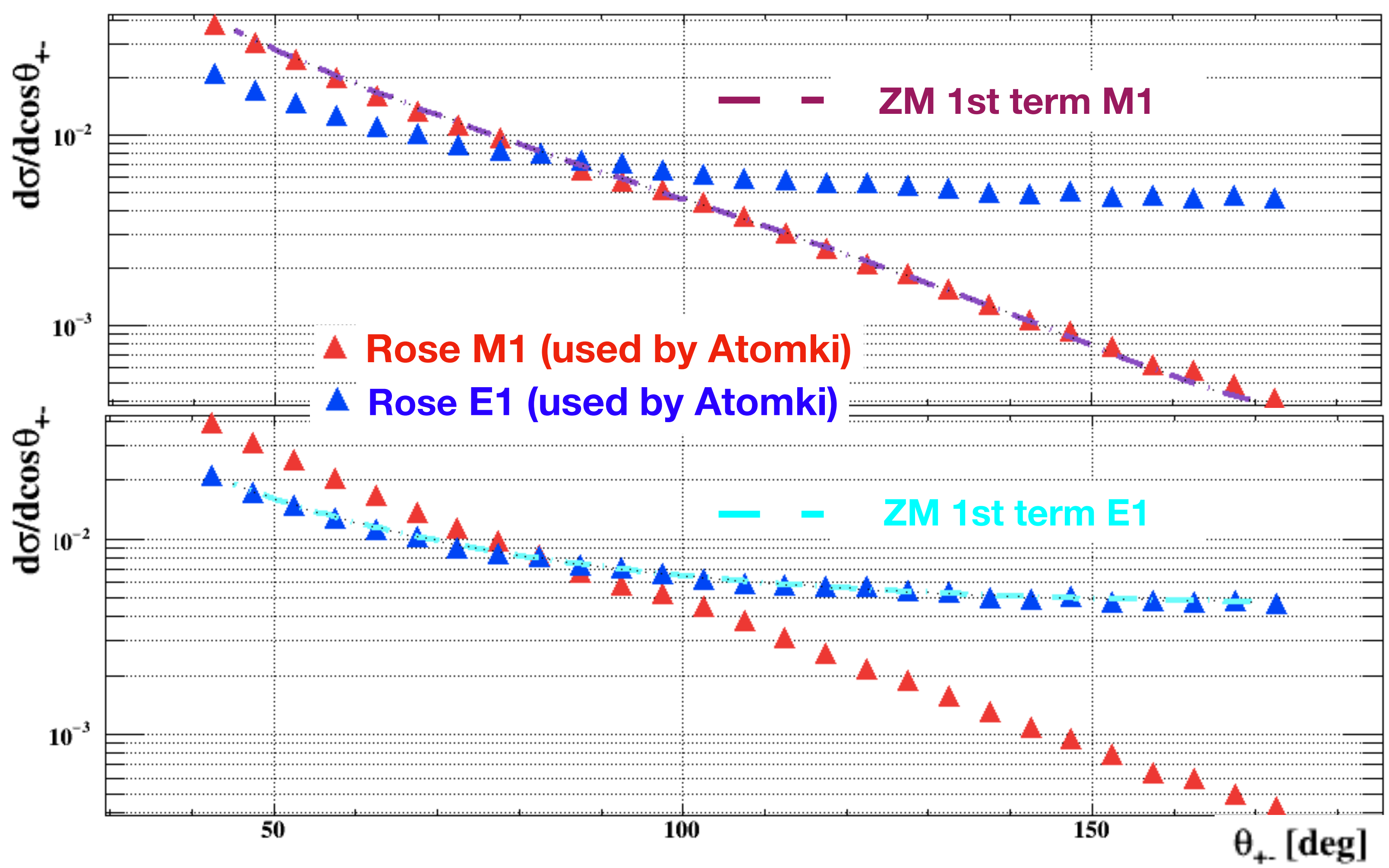
- Need for an accurate background model, IPC is dominant background in signal region
- First IPC model developed by Rose in 1949 Phys. Rev. 76, 678

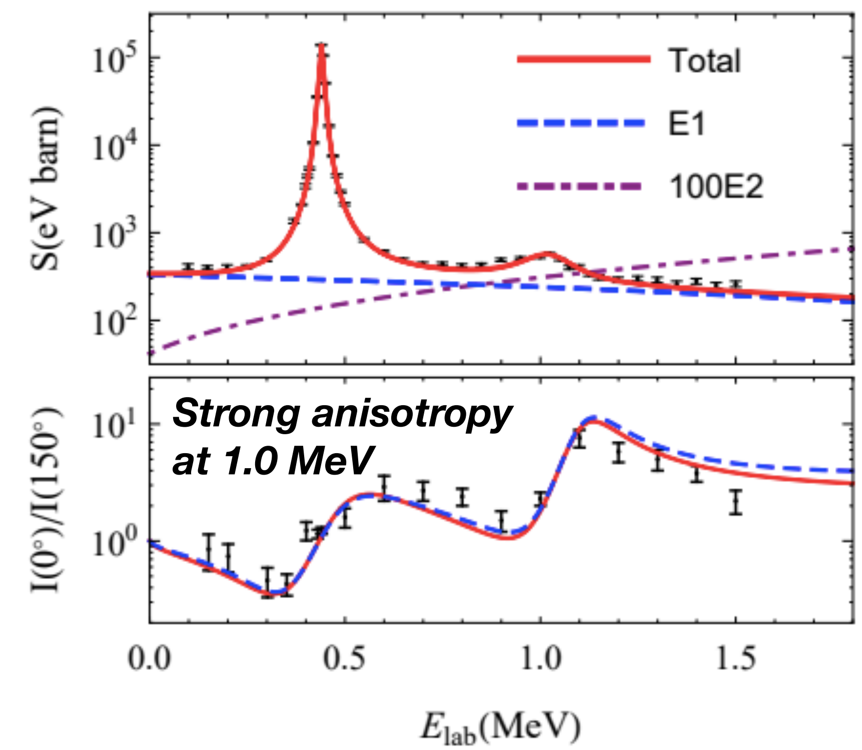
→ Anisotropy and multipole interferences not included

→ 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 ($T_{0,0}$)





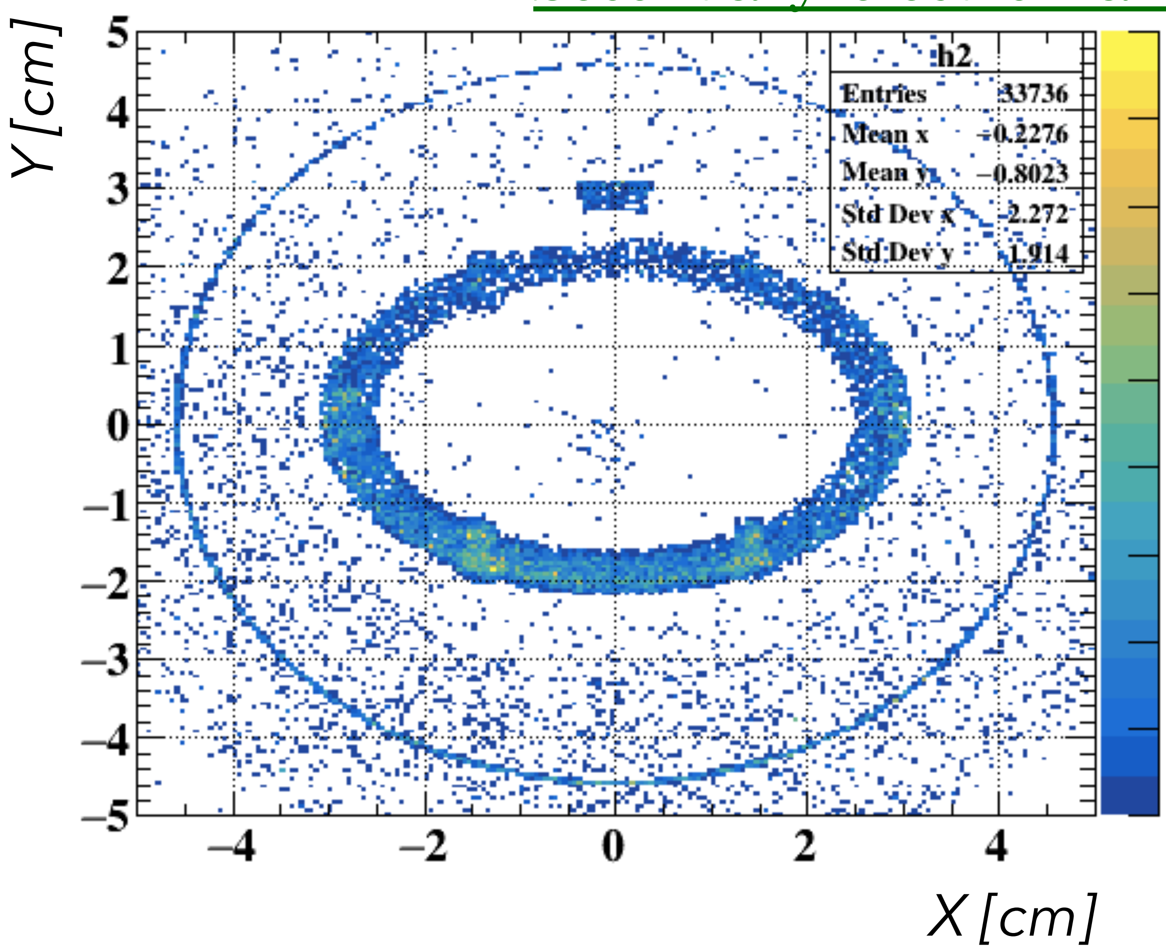
→ We implemented Zhang-Miller model

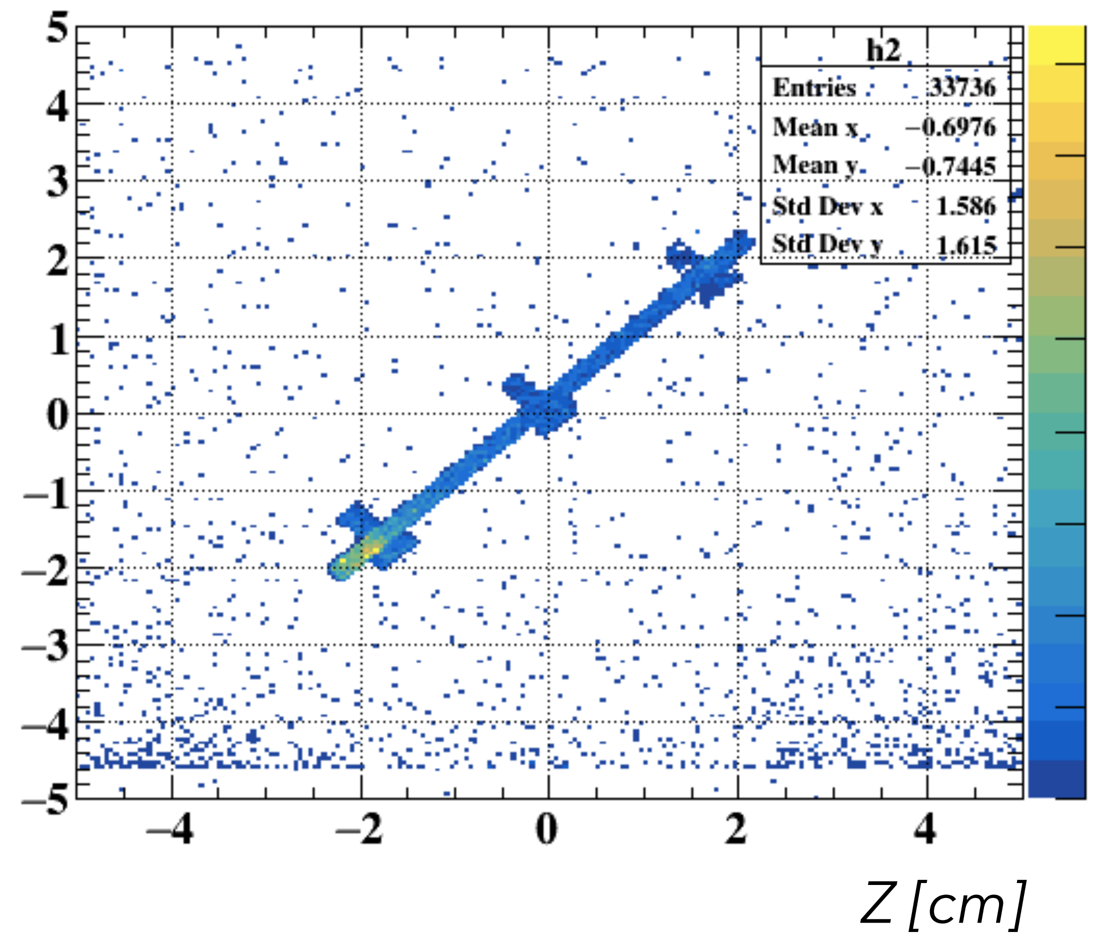
→ Rose/simplified ZM models agree for both E1 and M1 multipoles

- 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

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

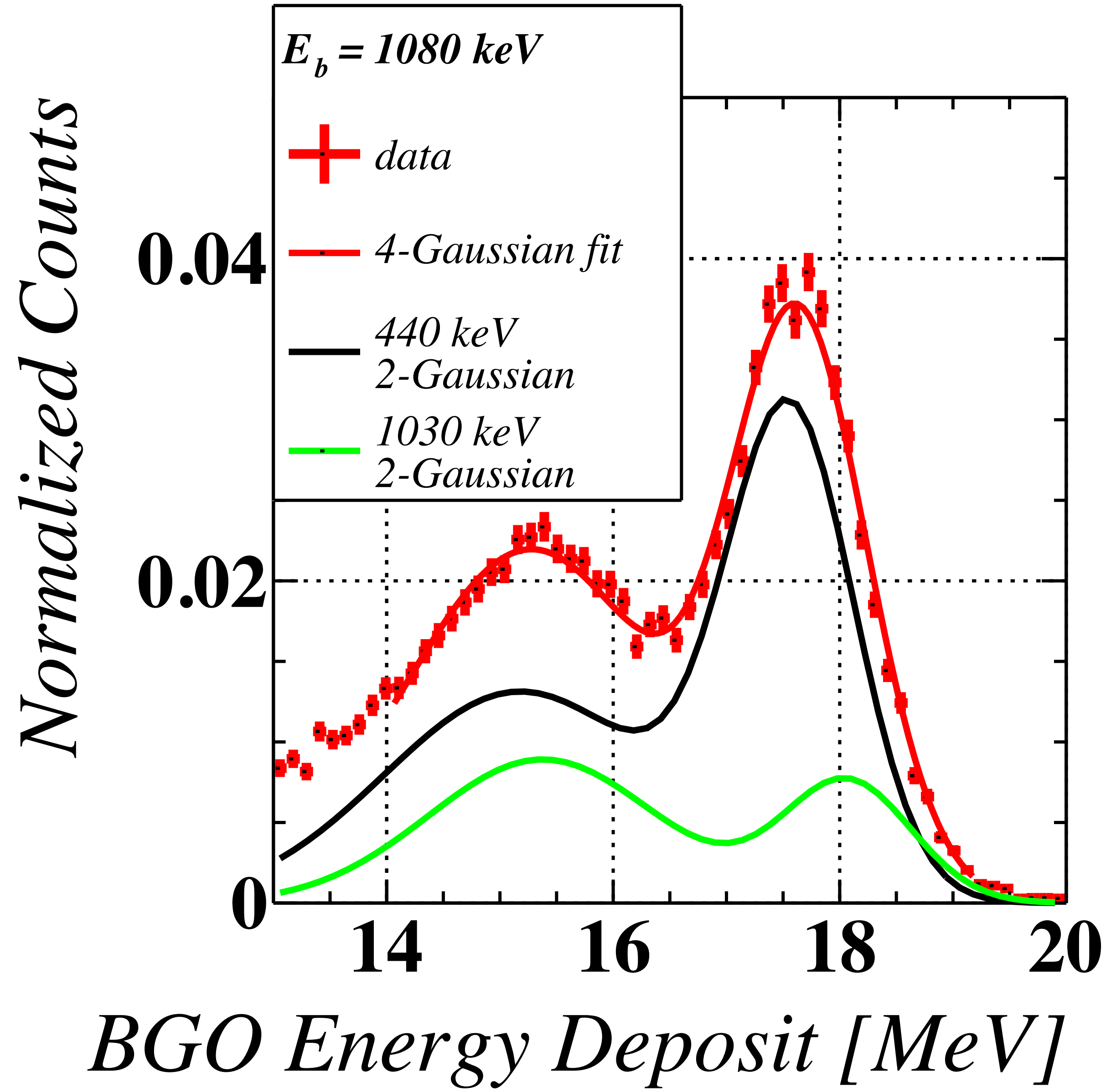
→ converting gammas from 6 MeV Fluorine line overcrowd the trigger when the LiF target is used —> only good for calibration of ancillary detectors, LiPON has to be used for X17 search

→ 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)

18.1 MeV line proportion in X17 2023 dataset

February 15th 2023

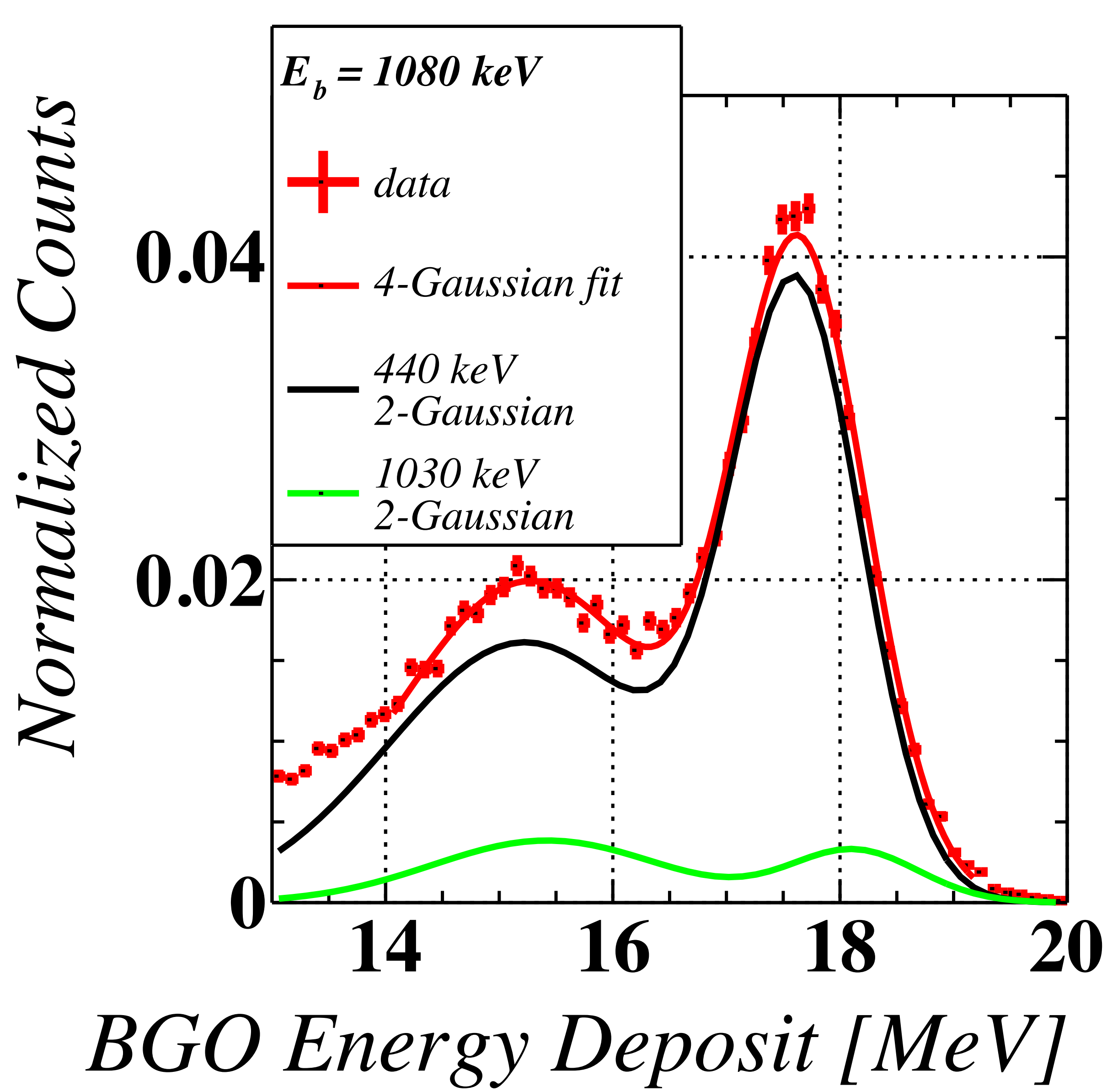


Proportion = 20%

But variations throughout the DAQ month

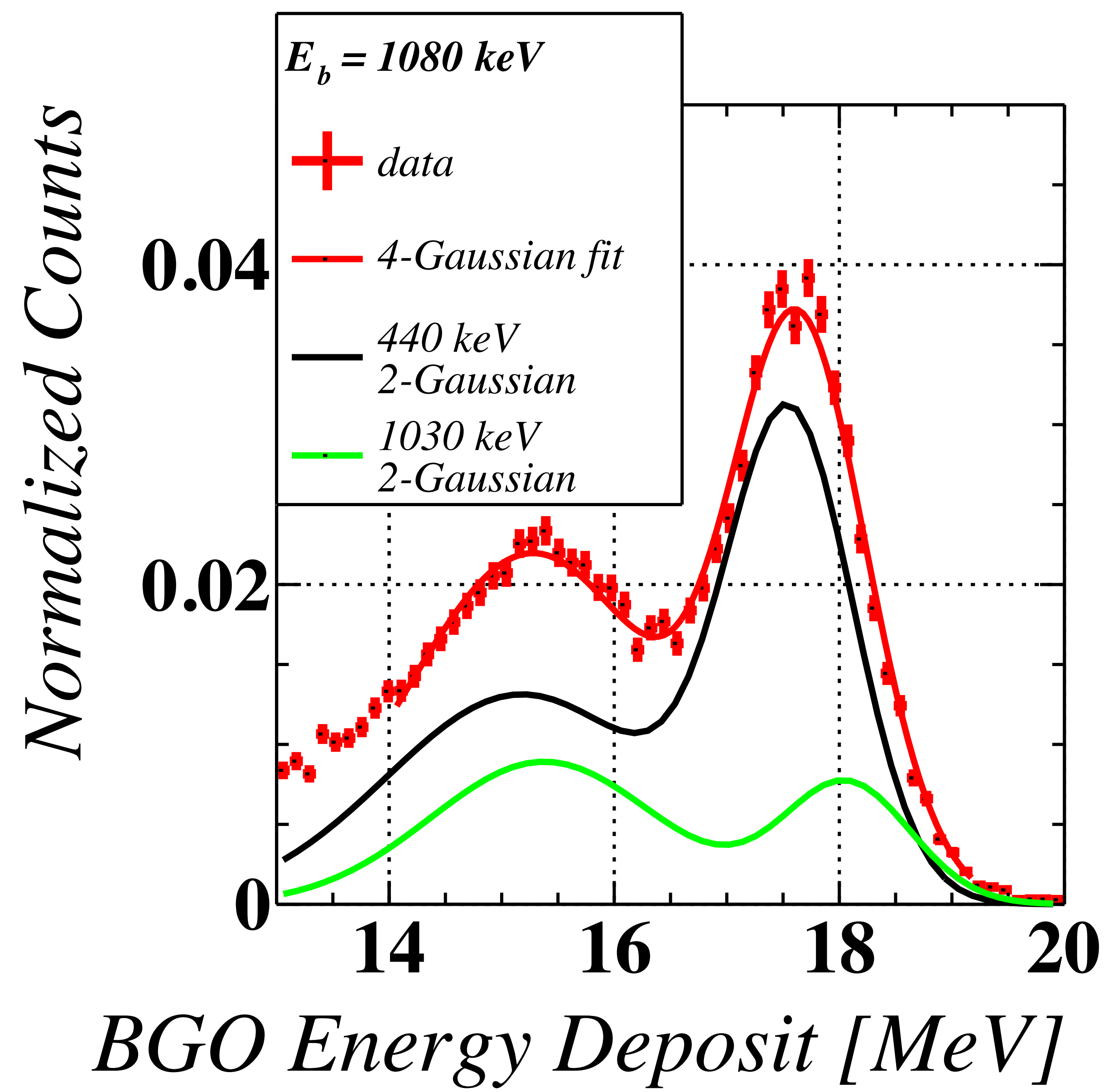
18.1 MeV line proportion in X17 2023 dataset

February 28th 2023



→ Proportion = 9%

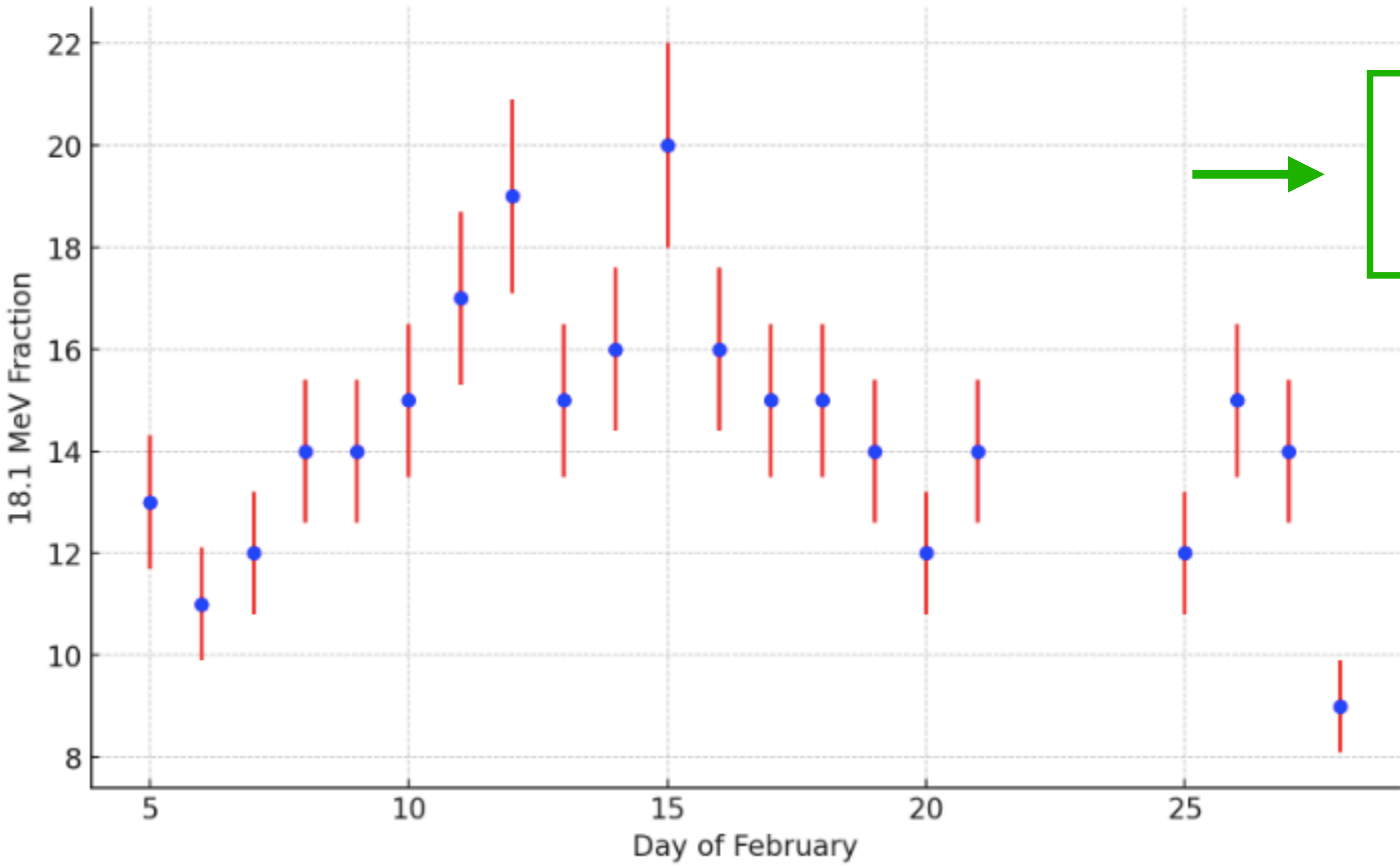
February 15th 2023



→ Proportion = 20%

Strong variations throughout the DAQ month !

Strong variations throughout the DAQ month.



15% on average but large error

Probable explanation:

1) instability of the beam dipole currents → instability of the H+ and H2+ beamspot positions on target

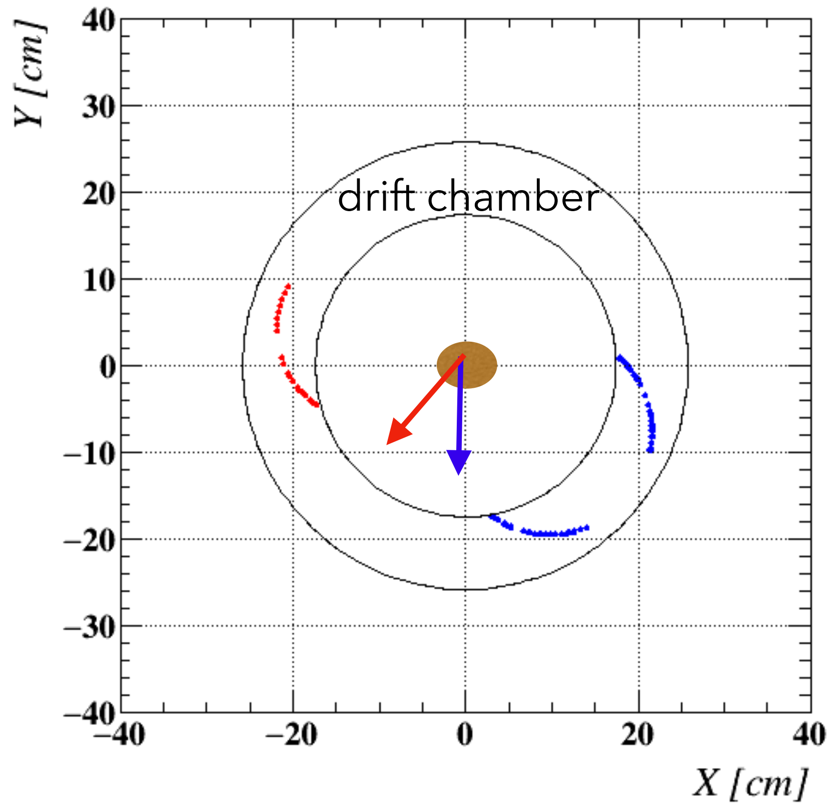
+

2) non-uniformity of LiPON deposit on target

→ **strong variations of 18.1 MeV proportion**

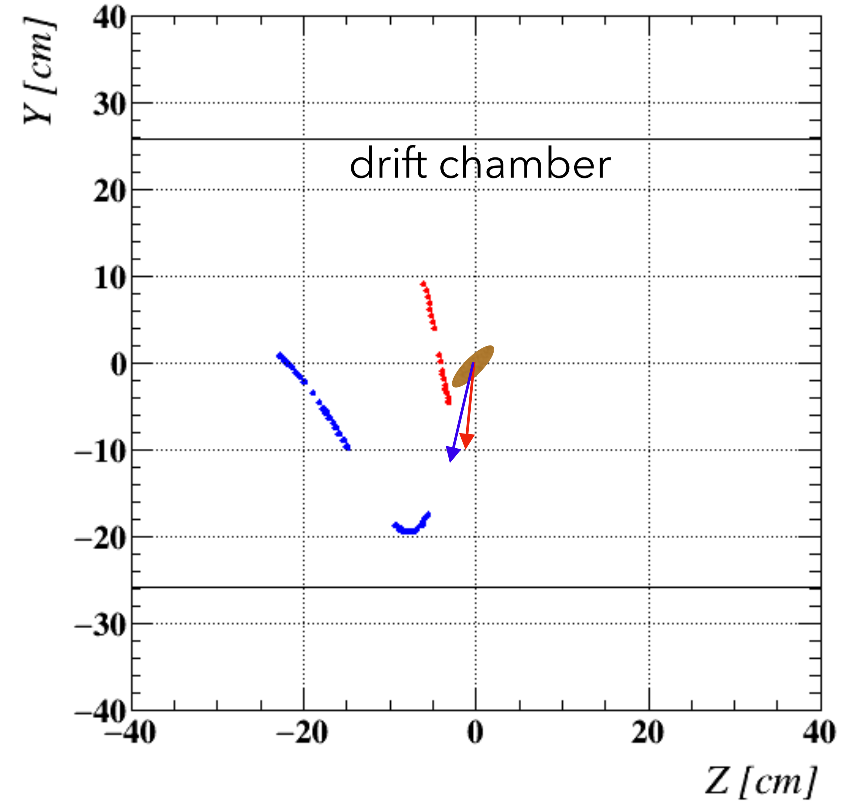
Event display

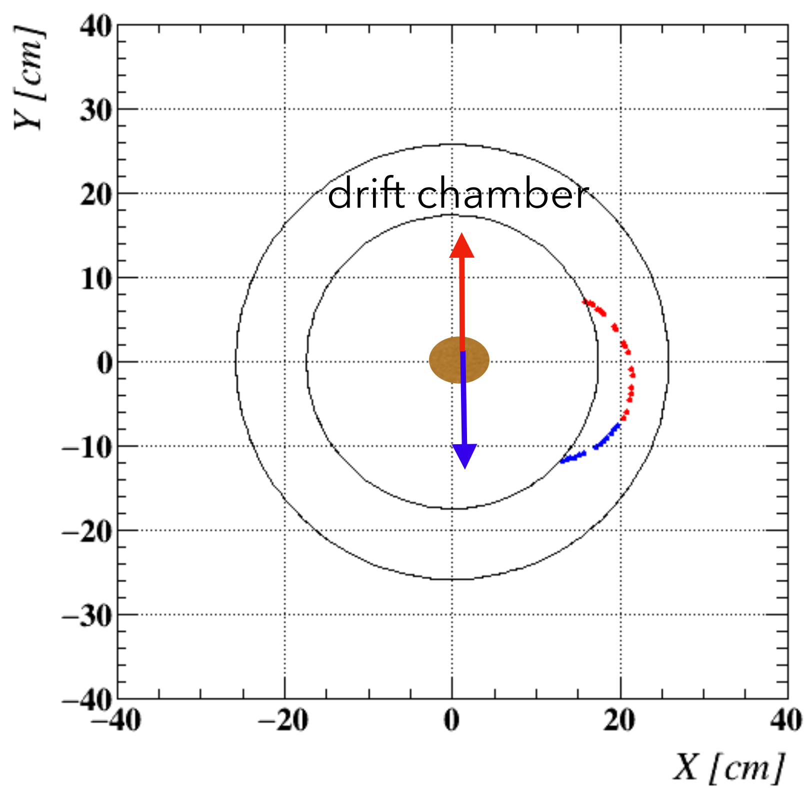
- <u>Let's have a look at the fitted hits within the CDCH</u>



GOOD PAIR

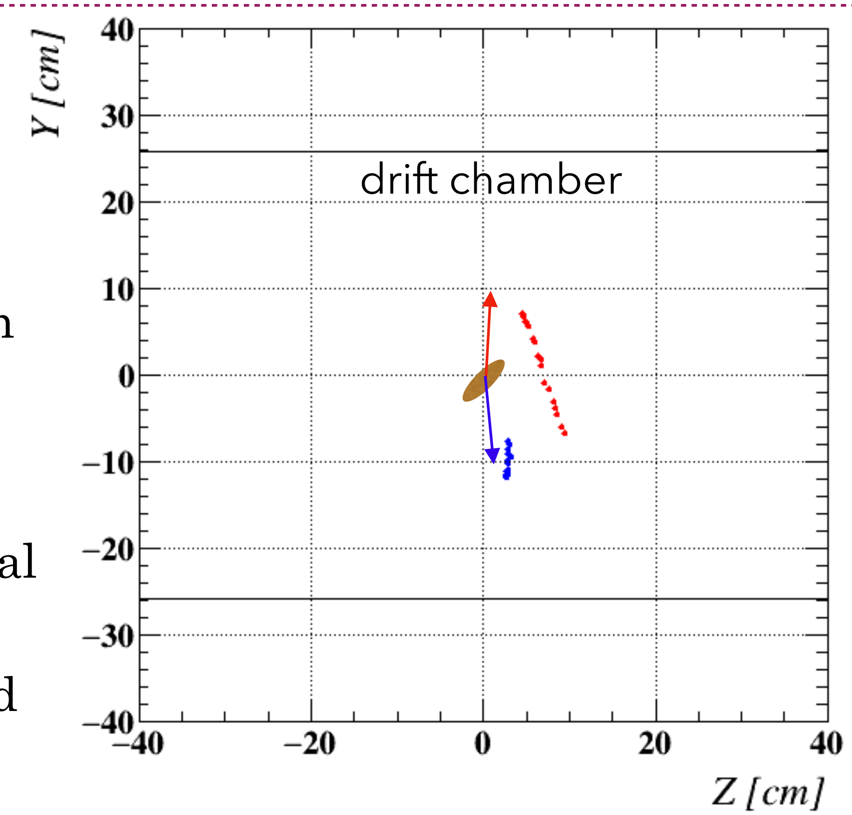
$\vec{p}$+ at target
$\vec{p}$- at target
• e+ hit
• e- hit
target





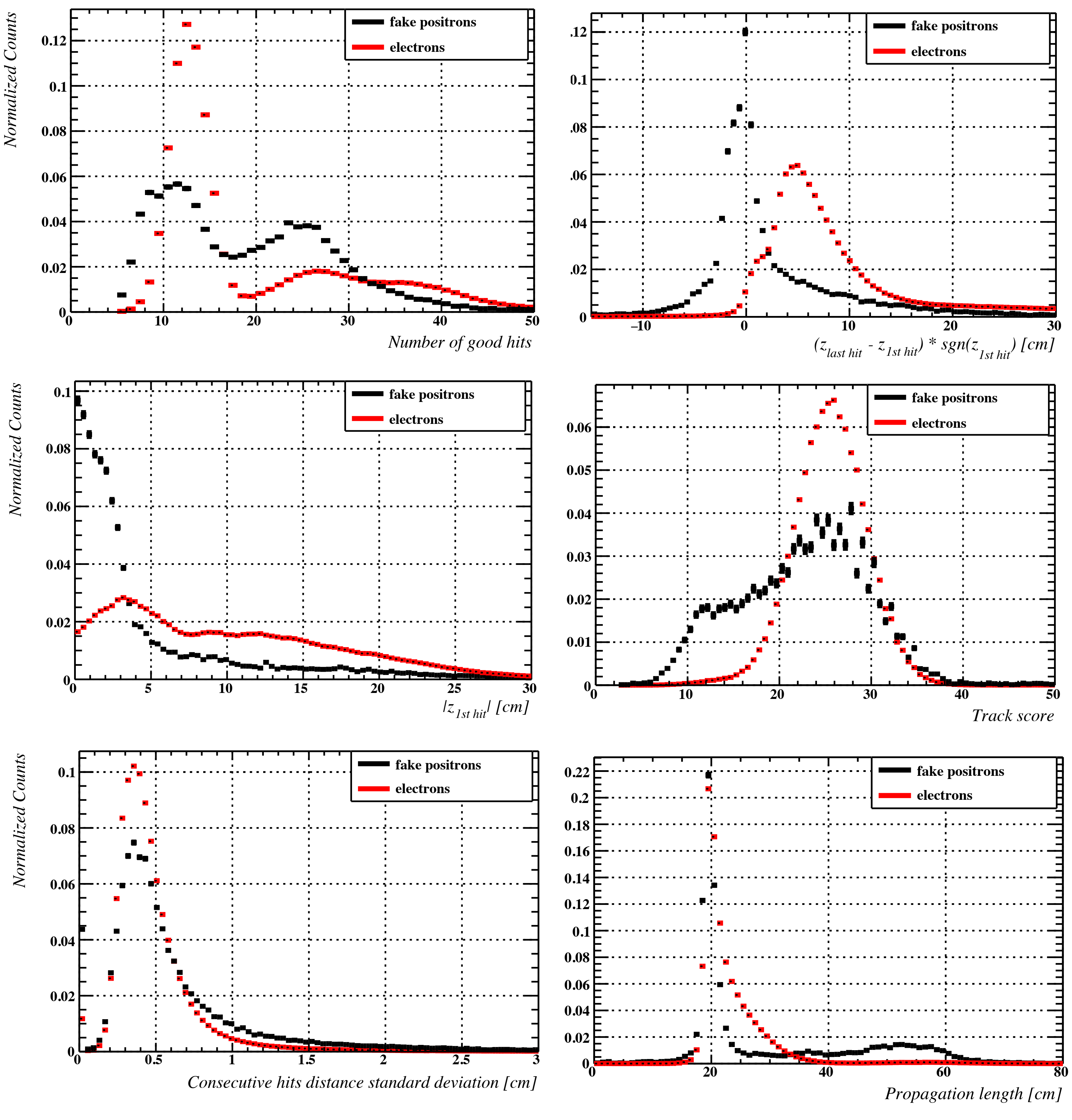
FAKE PAIR

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



Fake tracks characterization

- 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

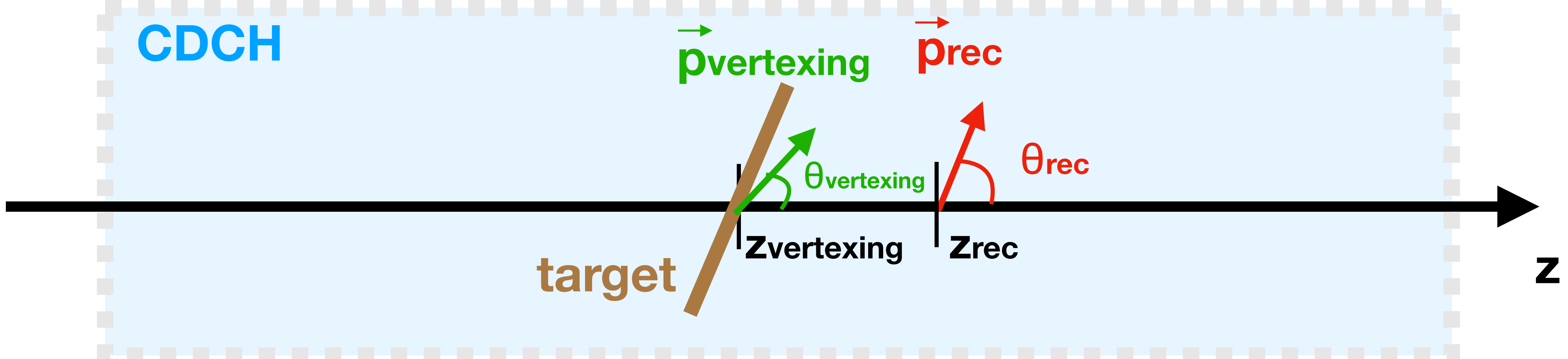
. . .

Advanced track selection was developed

- track reconstructed as a positron (including the magnetic field sign assumption)
- $T_{0,\mathrm{lasthit}} > T_{0,\mathrm{firsthit}}$;
- $(z_{\mathrm{lasthit}} - z_{\mathrm{firshit}}) \times z_{\mathrm{firshit}} > 0$ (to ensure the track goes away from the target);
- $|z_{\mathrm{firsthit}}| > 2.5$ cm;
- no hits with opposite z_{hit};
- $|z_{\mathrm{vertex}} - z_{\mathrm{beamspot}}| < 2.5$ 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 $ngoodhits + 10 \times$ hit density;

. . .

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



<u>Objective</u>: find e+ and e- common vertex
<u>How</u>: use e+ and e- state extrapolated at beam axis point of closest approach POCA + beam spot information
<u>Why</u>: improve resolutions

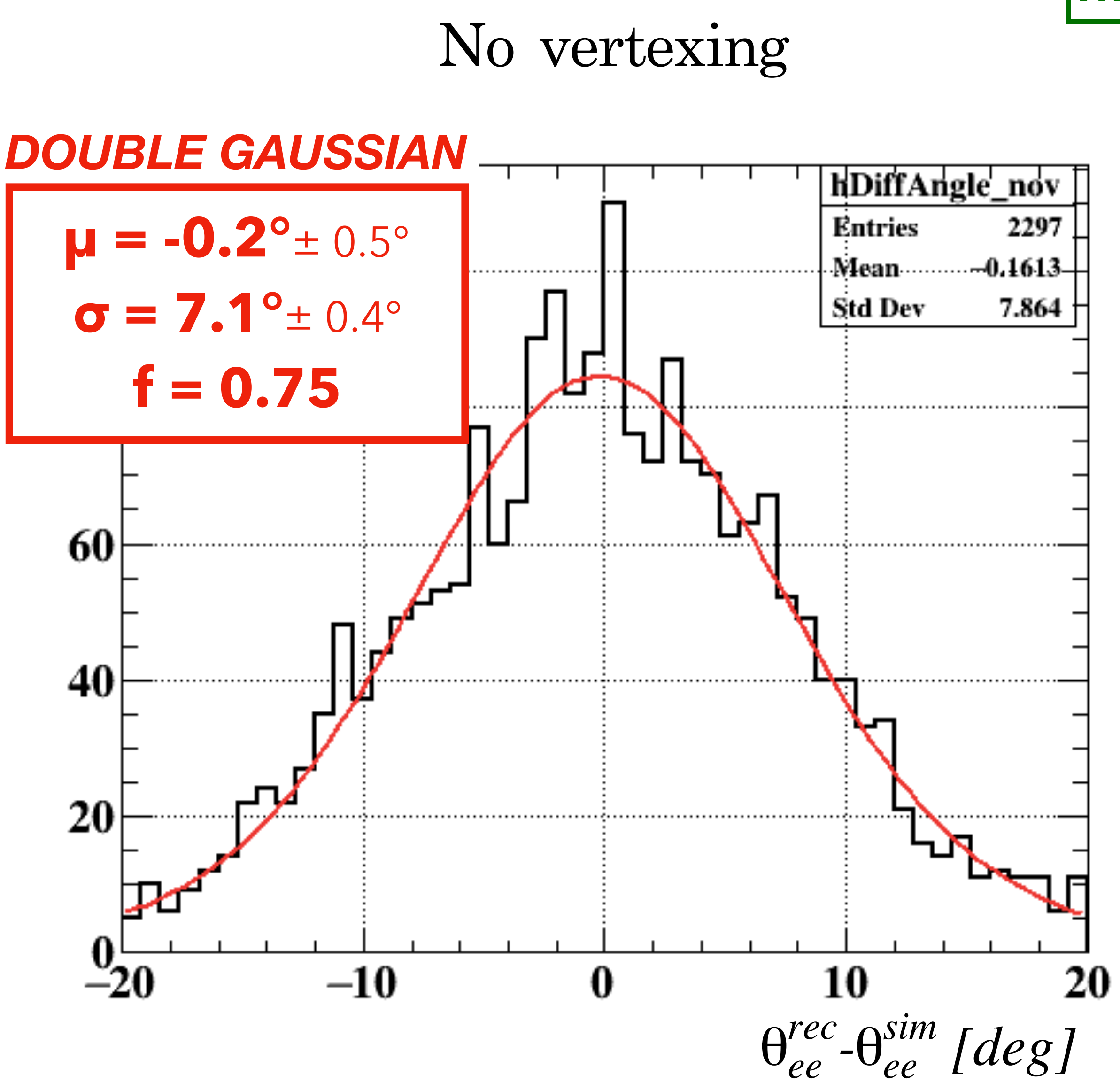
<u>Procedure</u>

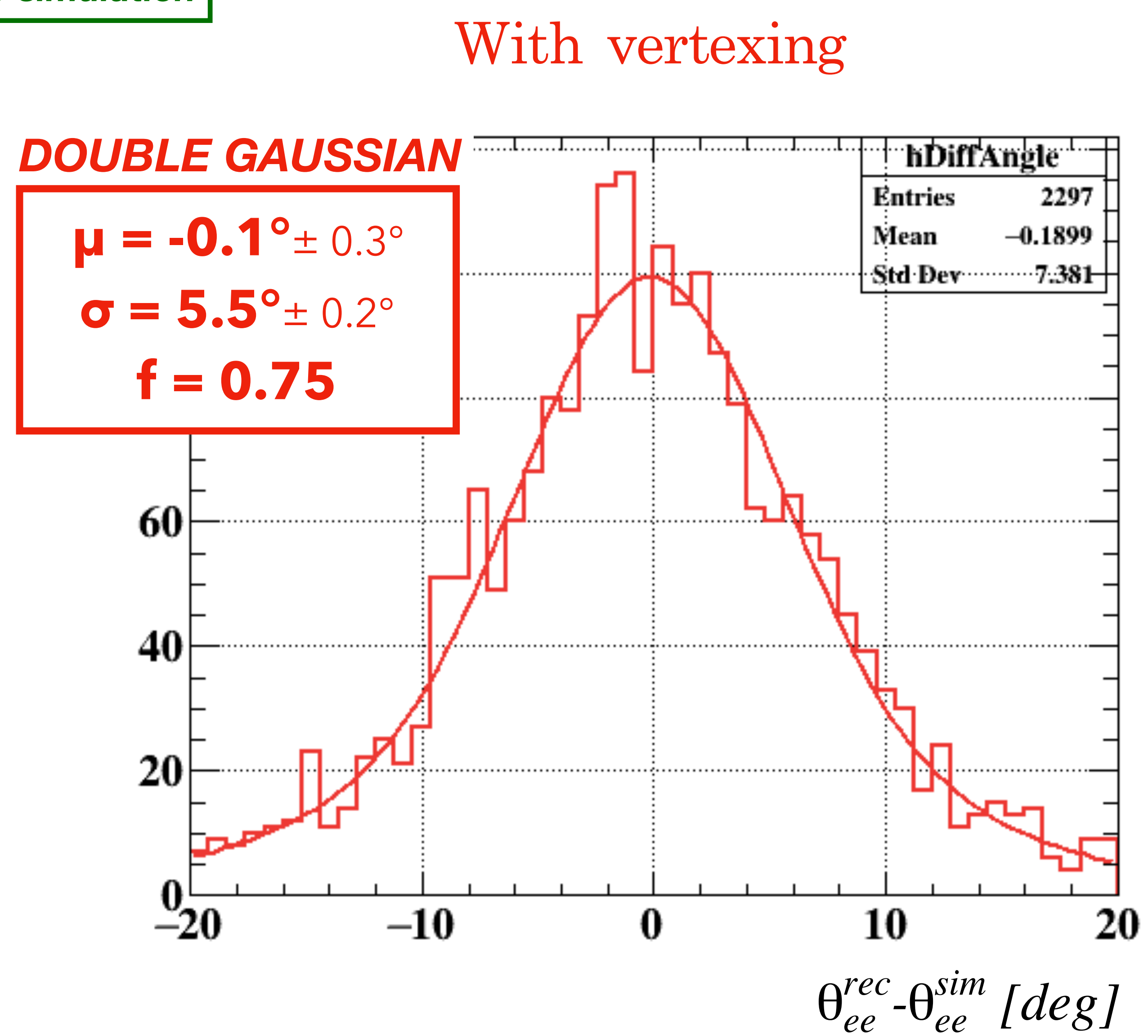
- all tracks are <u>fitted separately</u> to the z axis POCA
- selection of <u>best e+ and e- track</u>
- search for a possible <u>common vertex</u> within a beam spot constraint
- <u>vertexing tool</u>

→ RAVE (Reconstruction (of vertices) in Abstract Versatile Environments)
→ compatible with GENFIT

Angular Opening resolutions

X17 MC simulation



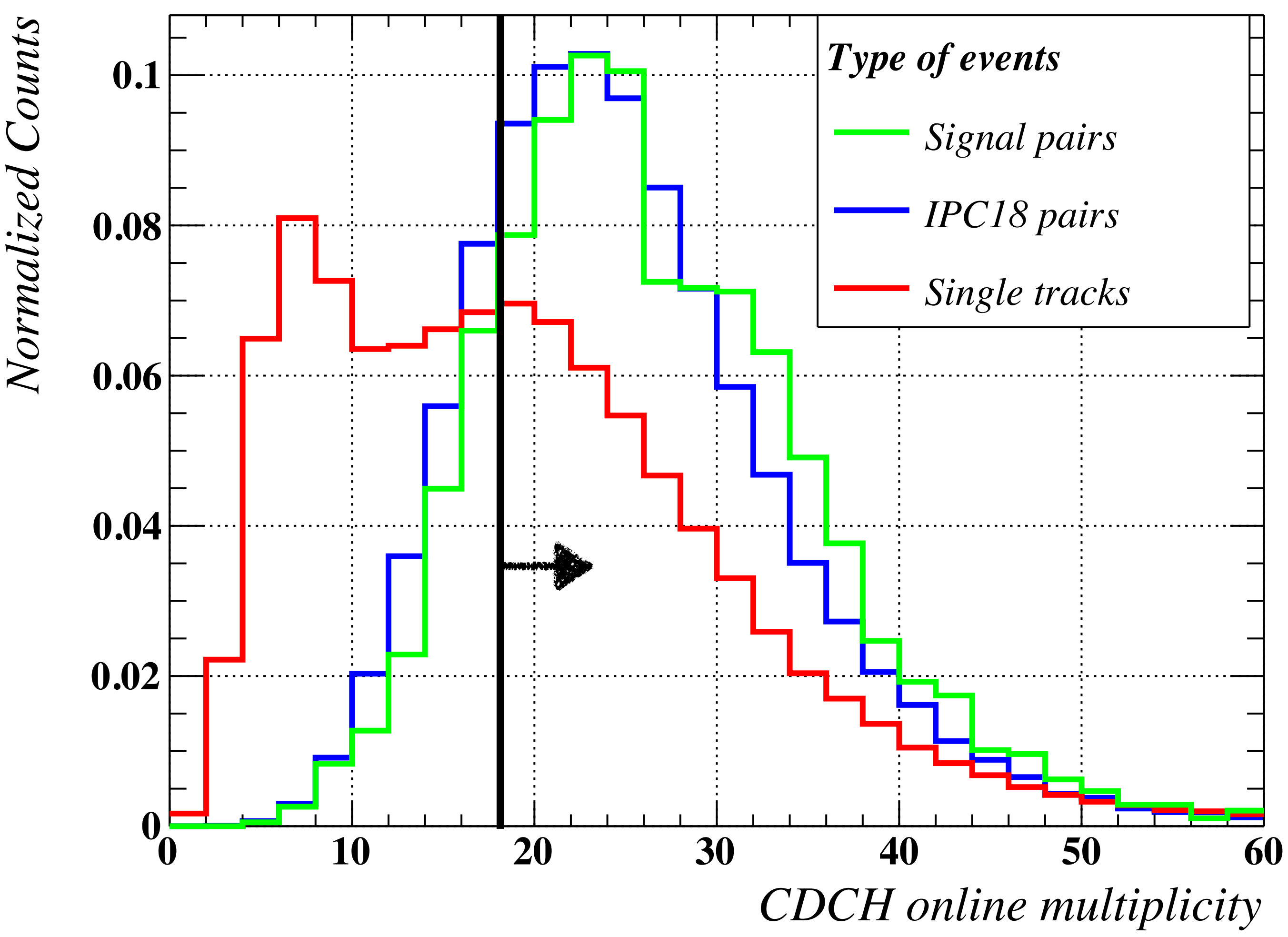


→ 25% improvement on X17 signal angular opening resolution

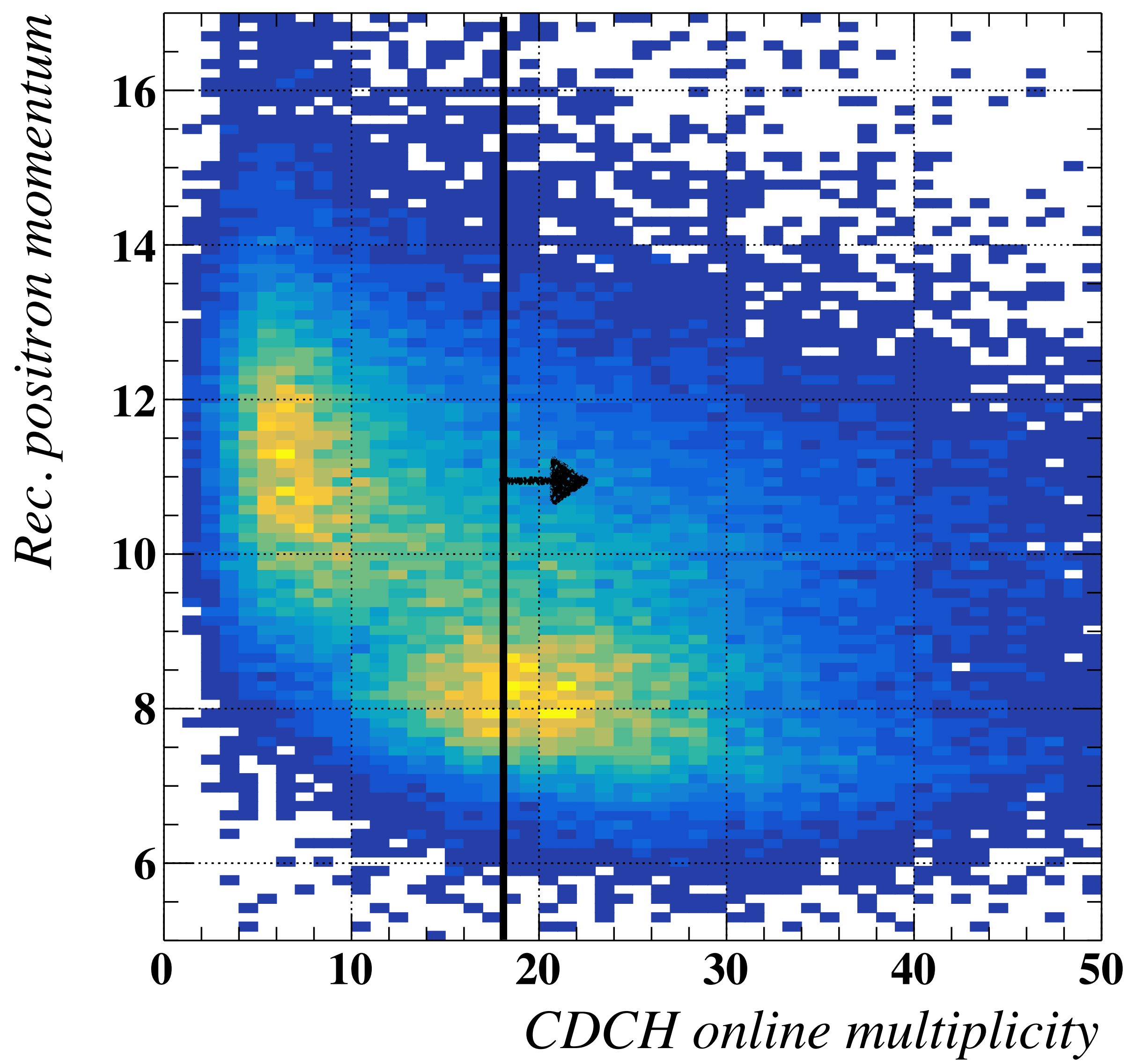
Trigger strategy: CDCH hit multiplicity ⑤

- 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



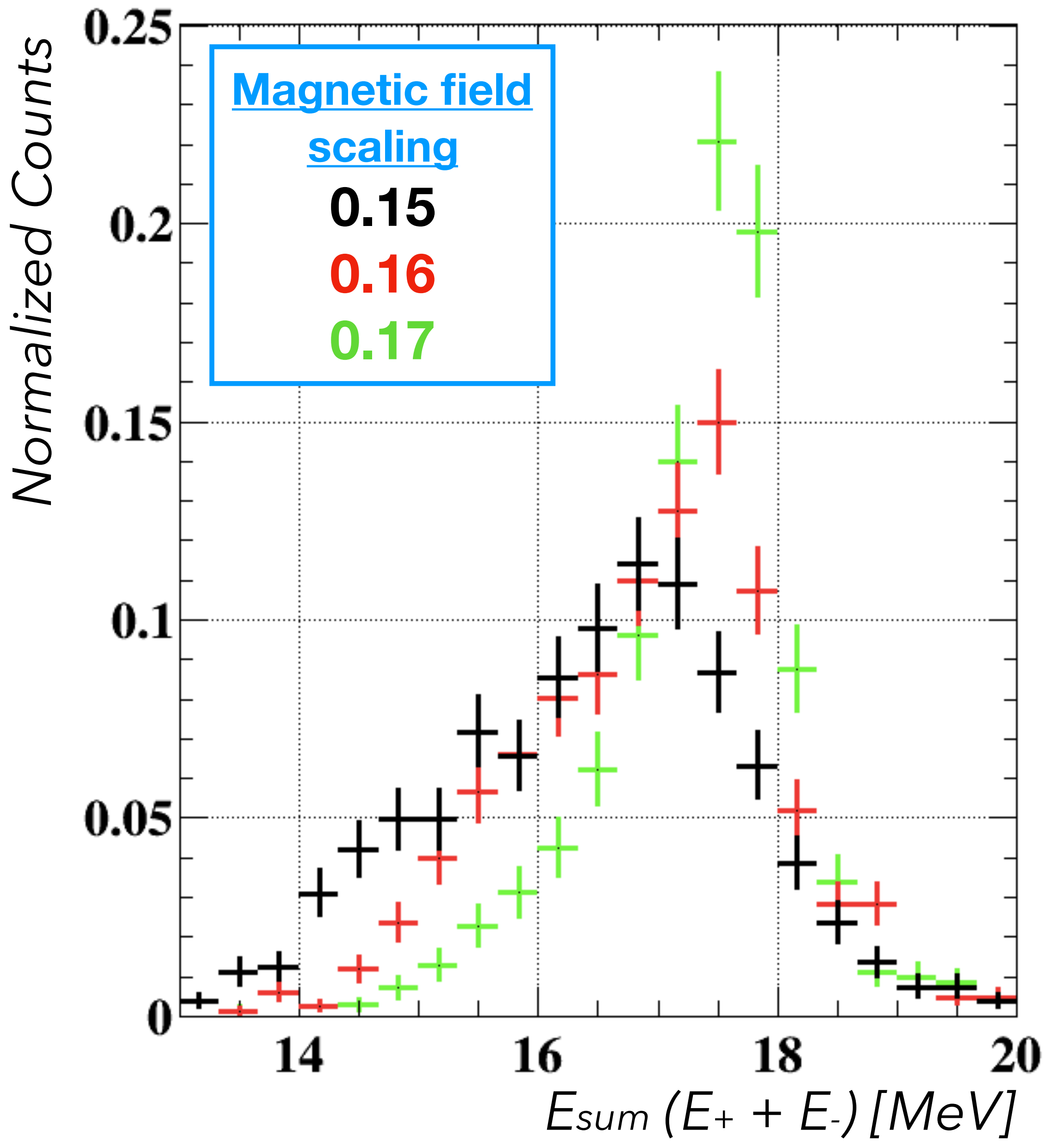
Trigger set as 18 hits > 60 mV

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

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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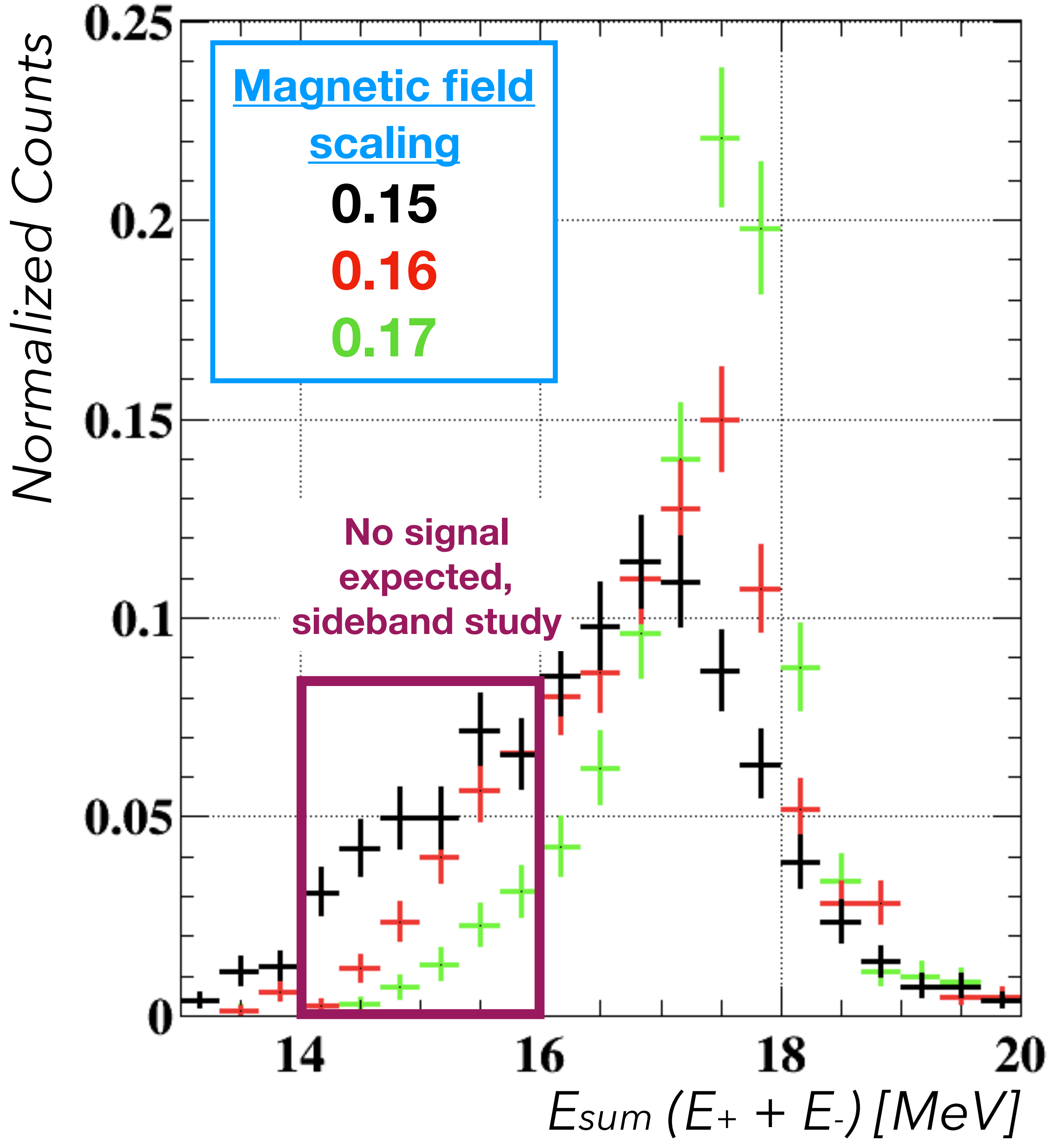
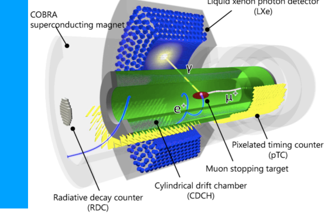
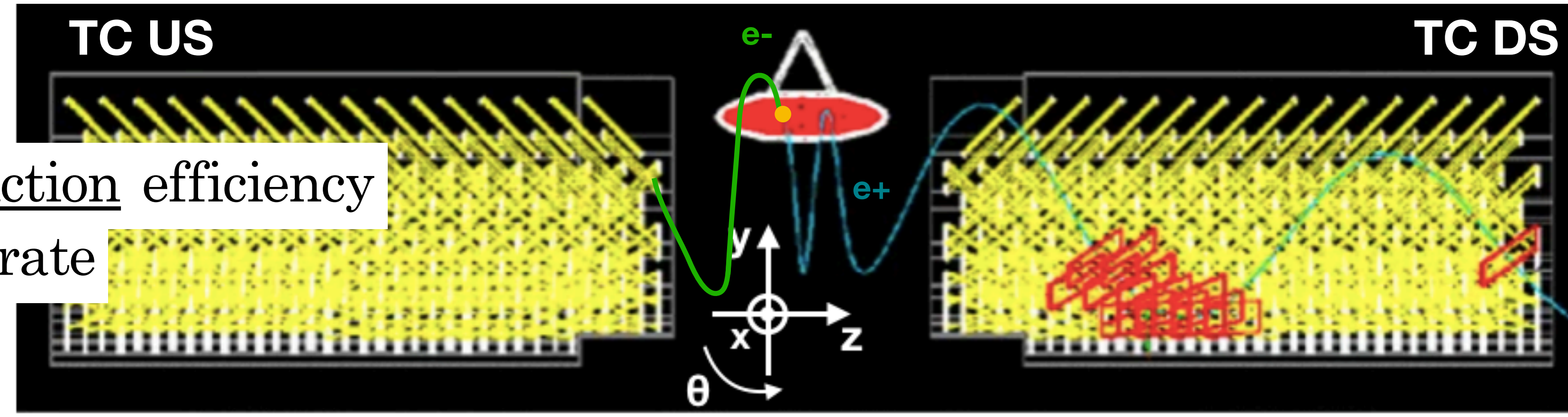


Trigger strategy: TC hit multiplicity





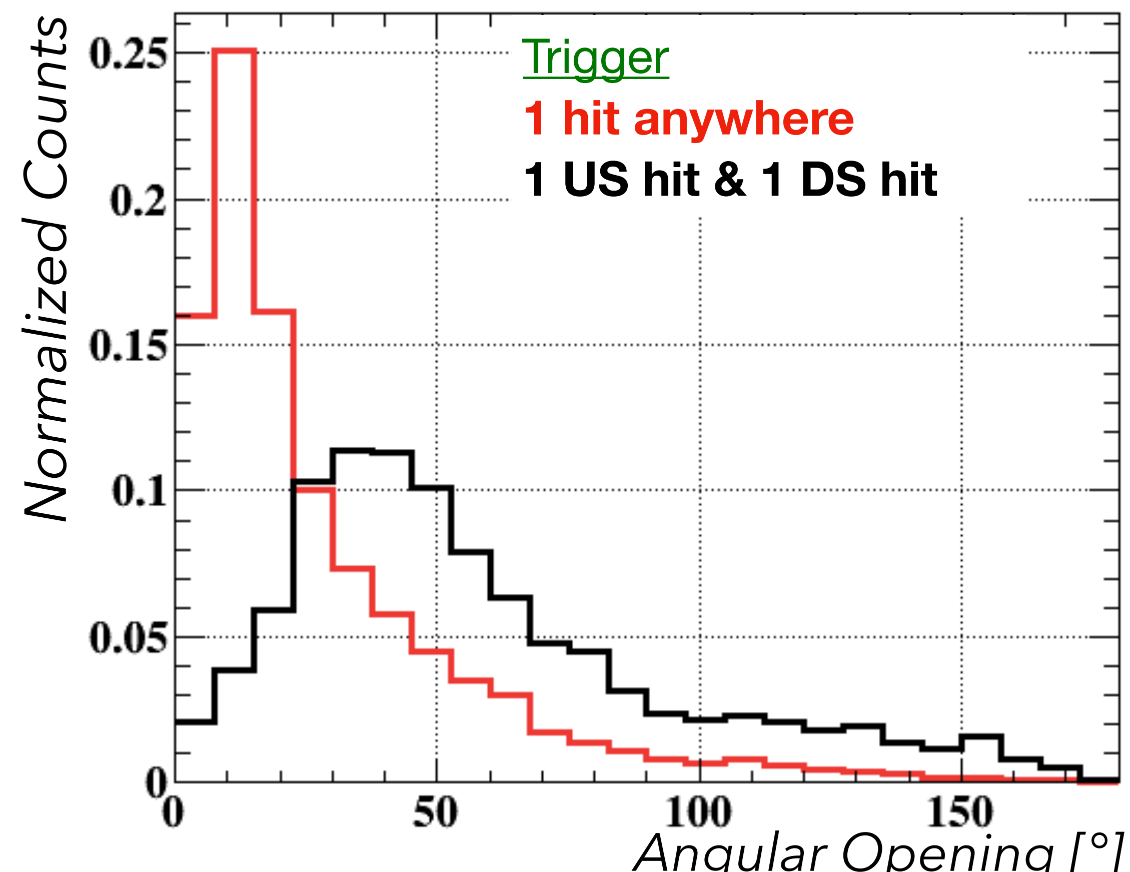
Why requesting at least 1 TC hit?

- 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**

2D template fit

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

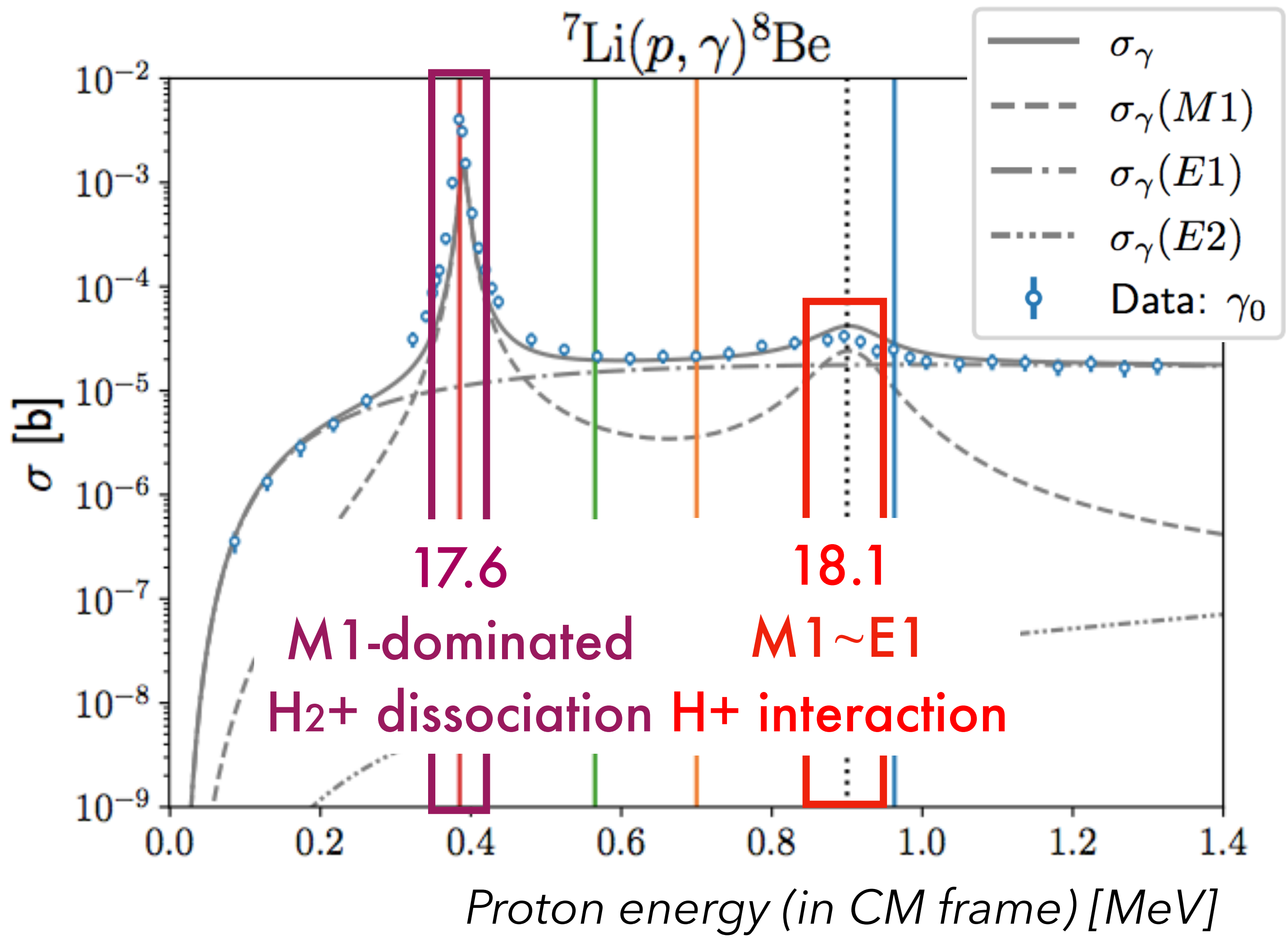
- no need for PDFs definition
- naturally accounts for linear and non-linear correlations between the fitted variables
- easy implementation of Feldman-Cousins approach to confidence belts

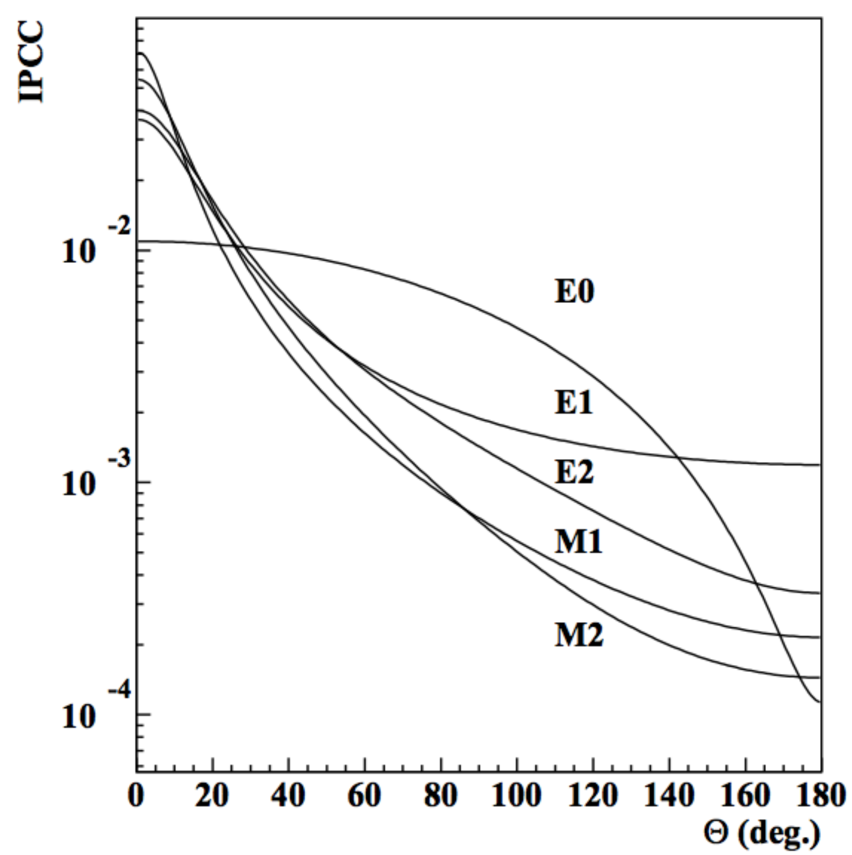
- EPC and IPC MC production are particularly time consuming.
- The effect of limited MC statistics can be accounted for in the likelihood (Beeston-Barlow likelihood)

- 2D template fit Esum vs Angle maximizing such likelihood is under investigation
- Additional constraints on ratio of proportions between $\mathbf{IPC}_{\mathbf{18,i}}$ and $\mathbf{IPC}_{\mathbf{15,i}}$ based on BGO spectra

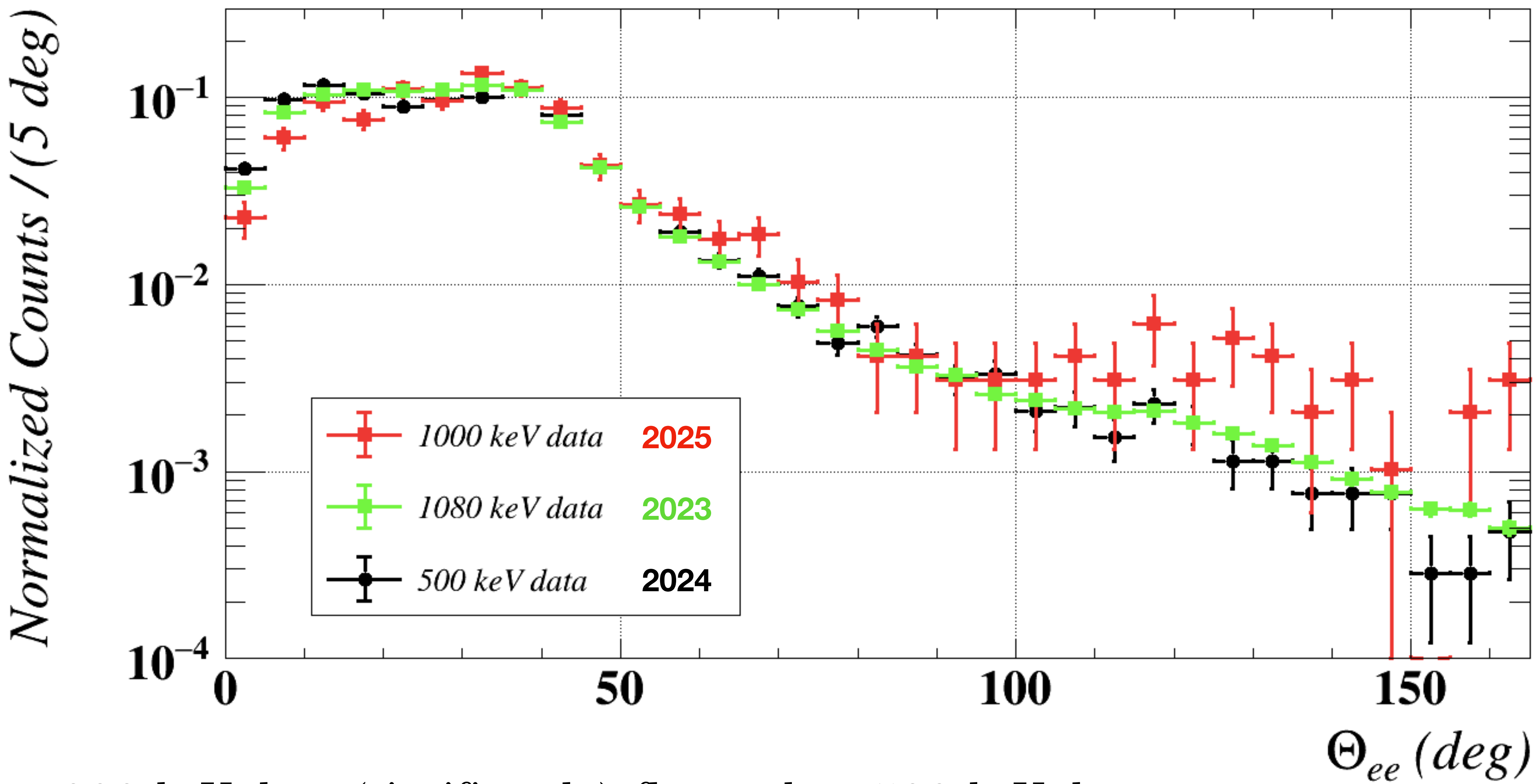
MC production

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





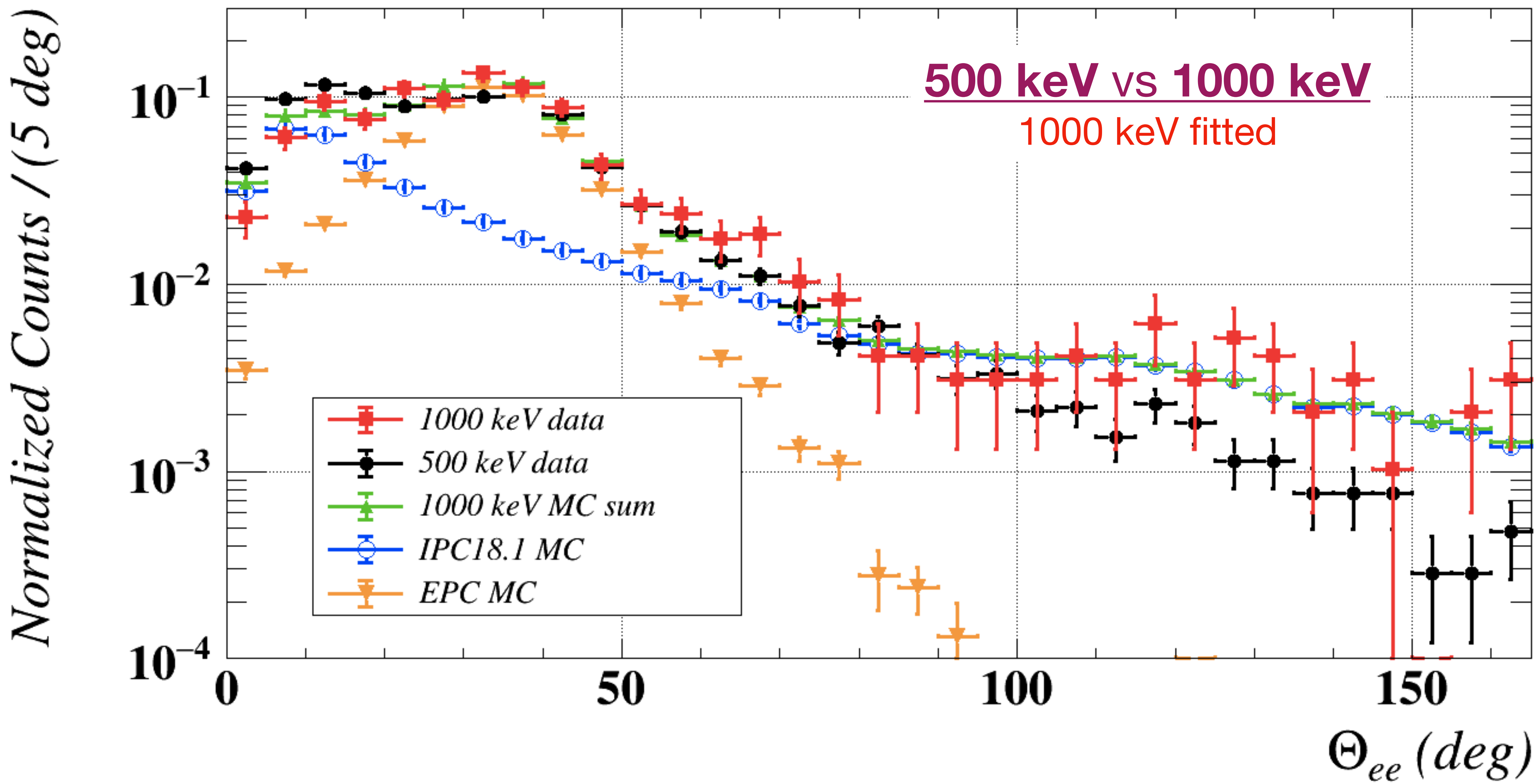
Angular Opening distribution



1000 keV data (significantly) flatter than 500 keV data: expected from higher E1 non-resonant component!

1080 keV data (preprint) shows intermediate slope:
Further confirms our analysis method!
Data is a mix of 440 keV and 1030 keV resonances

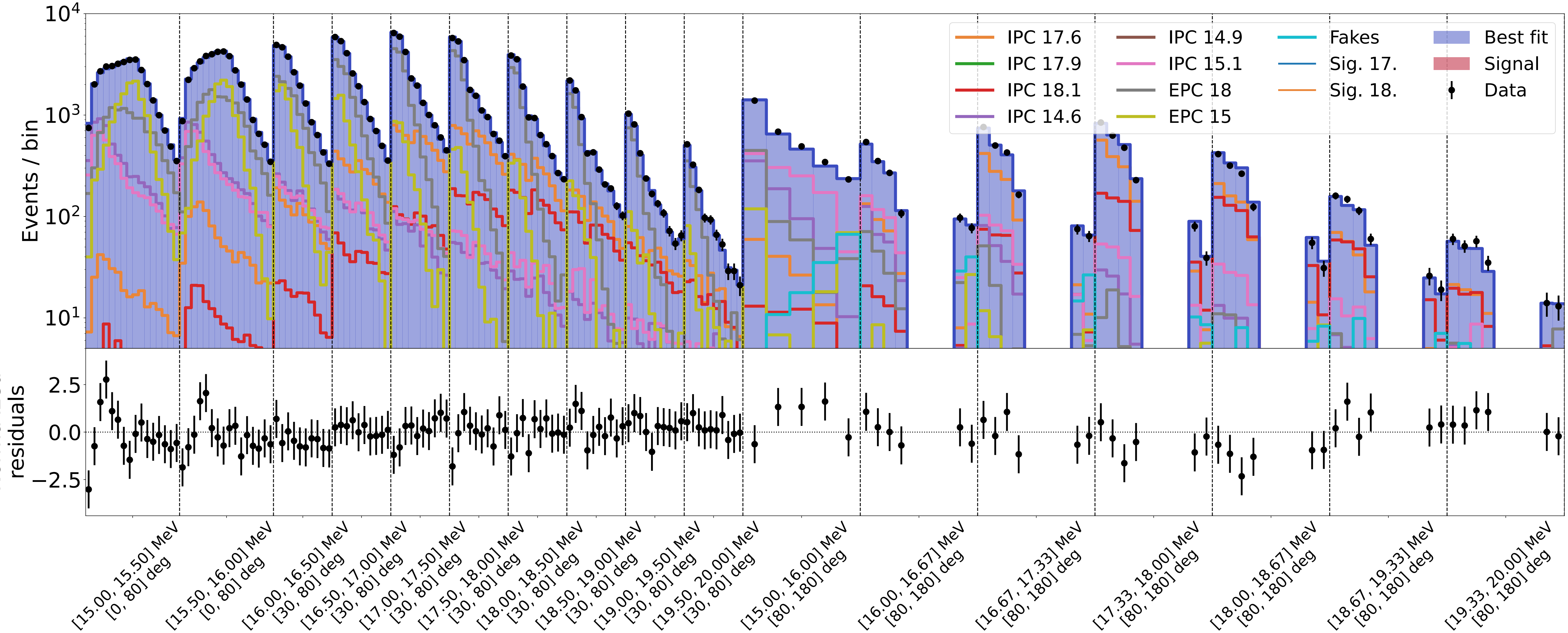
Angular Opening spectrum @500 keV ⑥



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

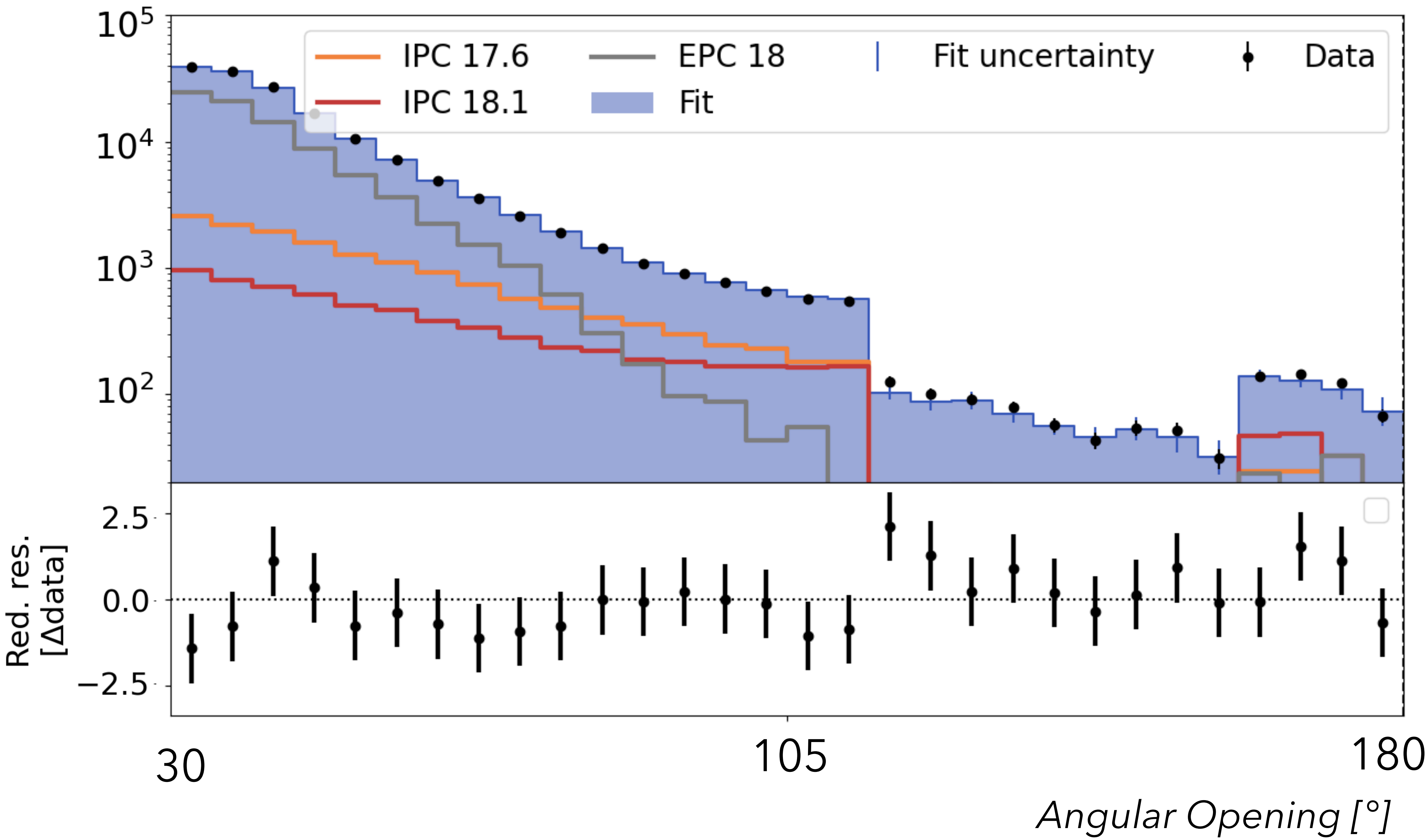
Sideband fit

- 2D fit in slices of Esum:



Current best fit

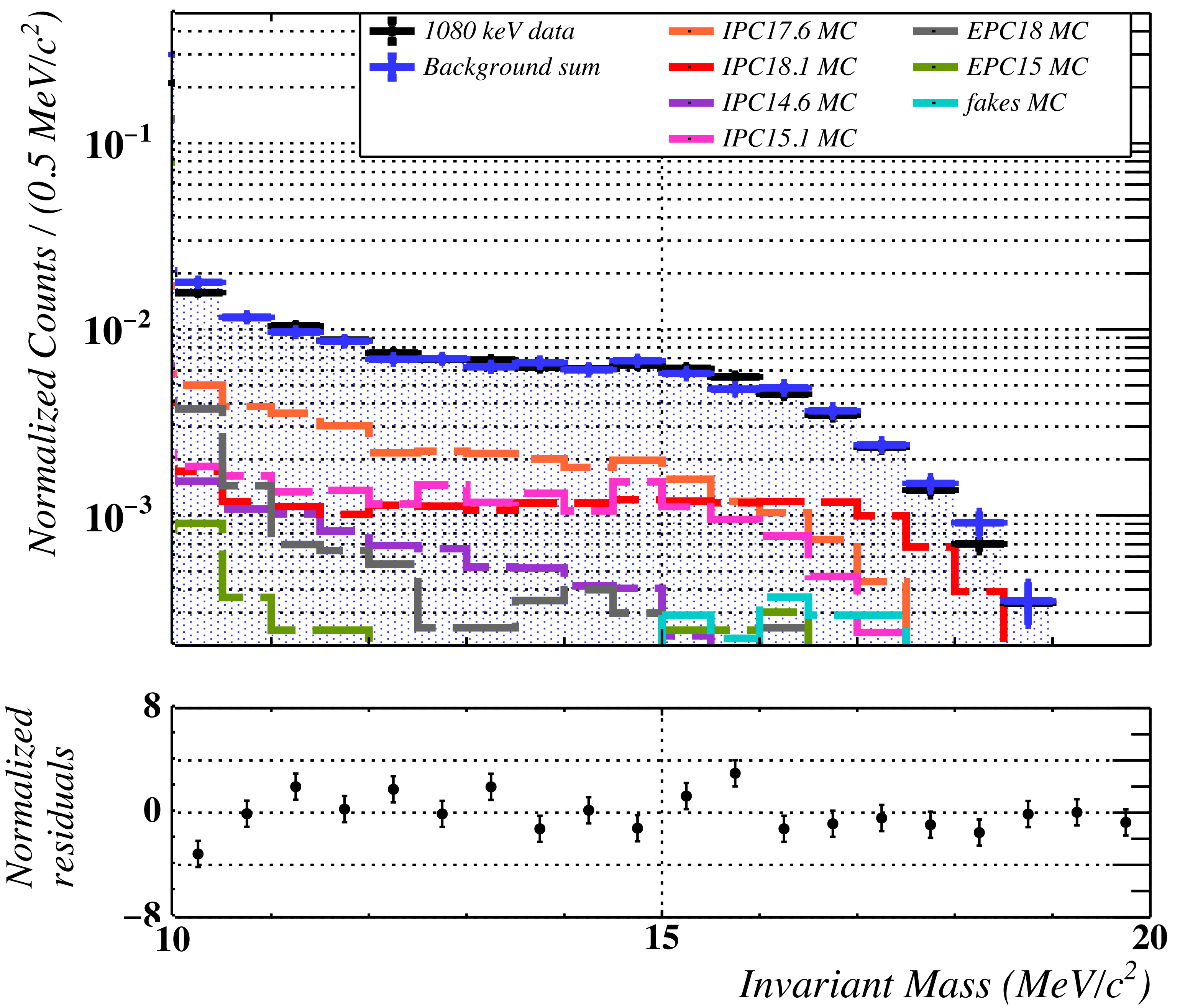
- 1D projection of the 2D fit



→ Good understanding of the backgrounds above 30°

Current best fit

- 1D Invariant Mass projection of the 2D fit



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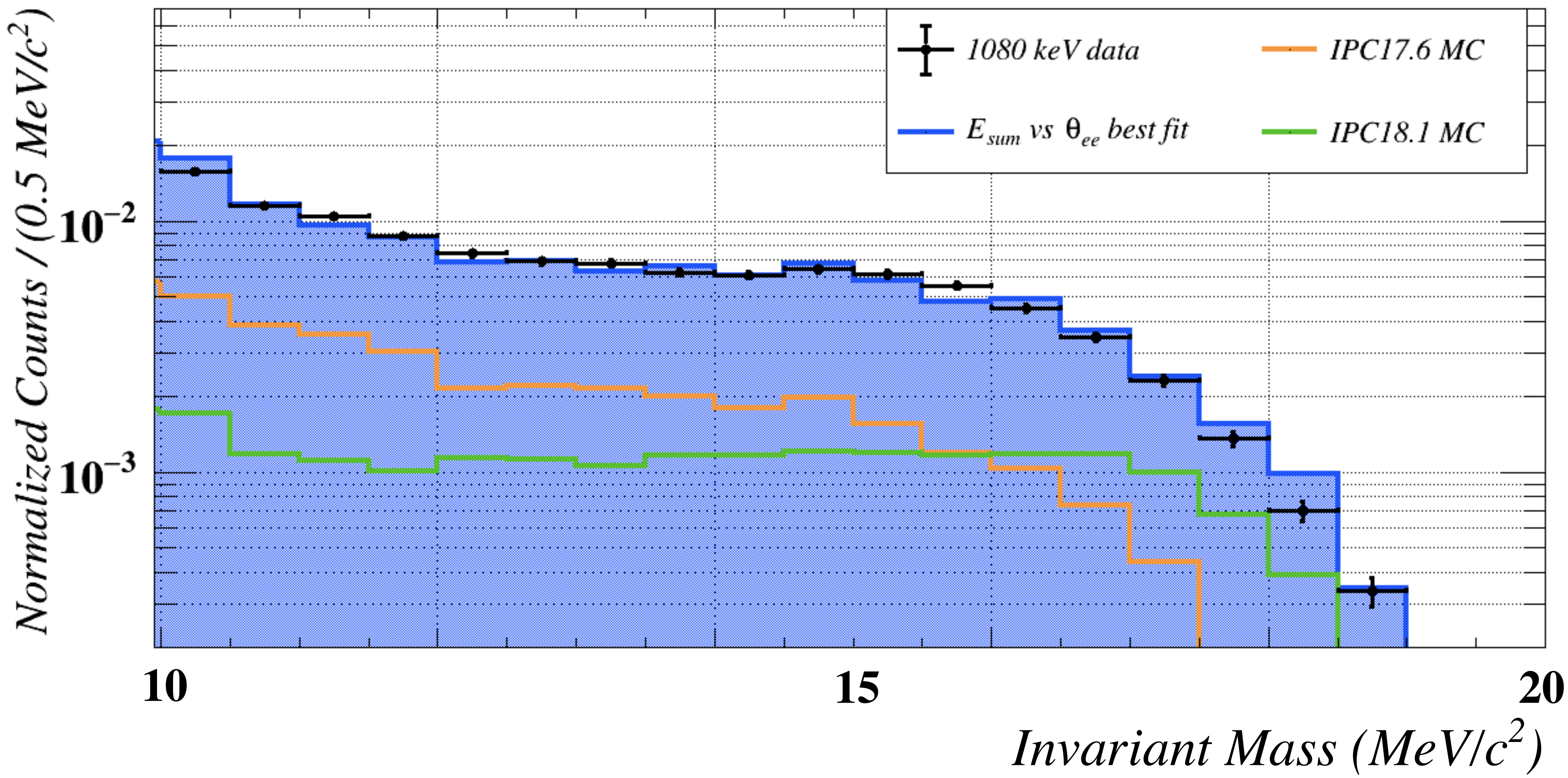
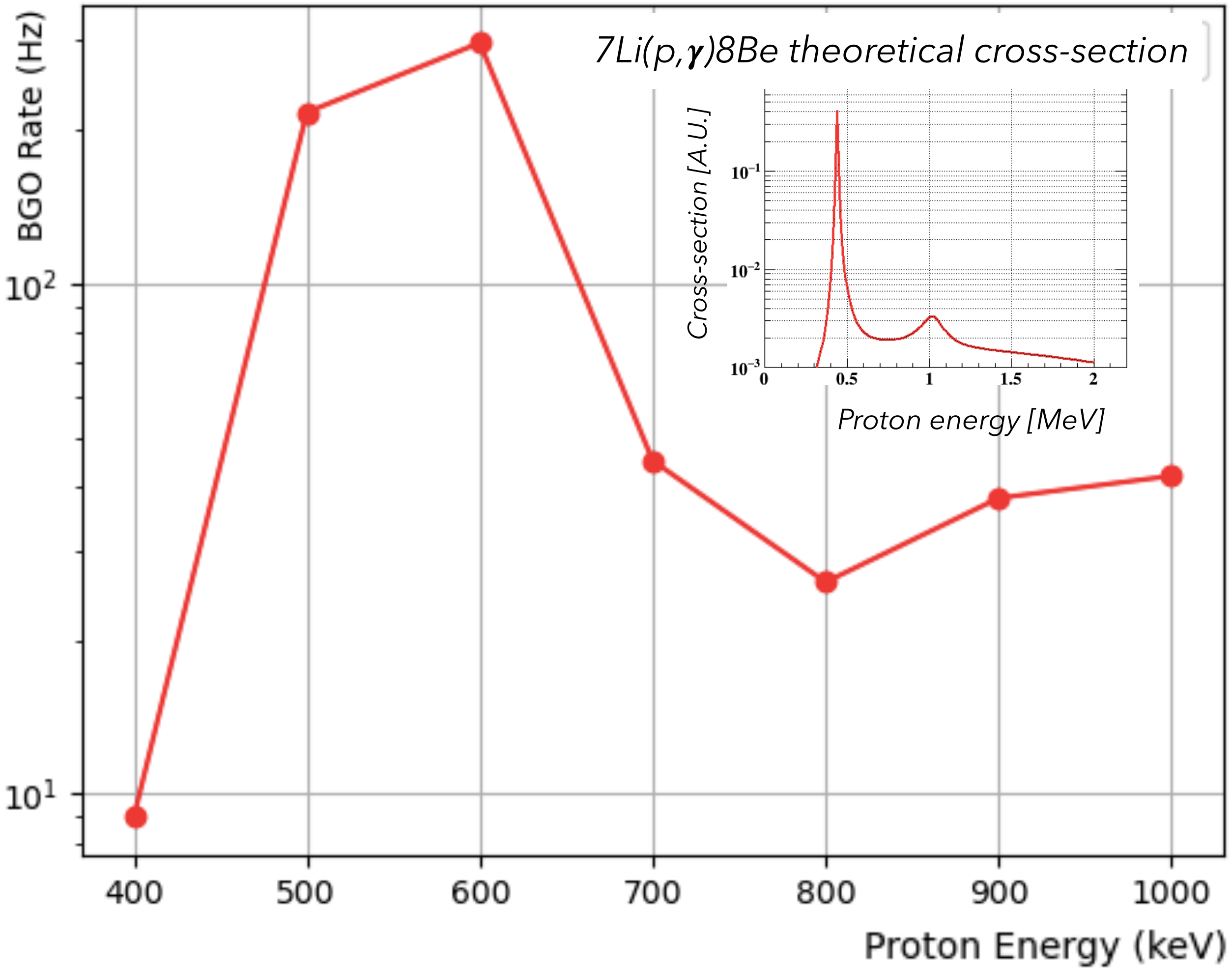


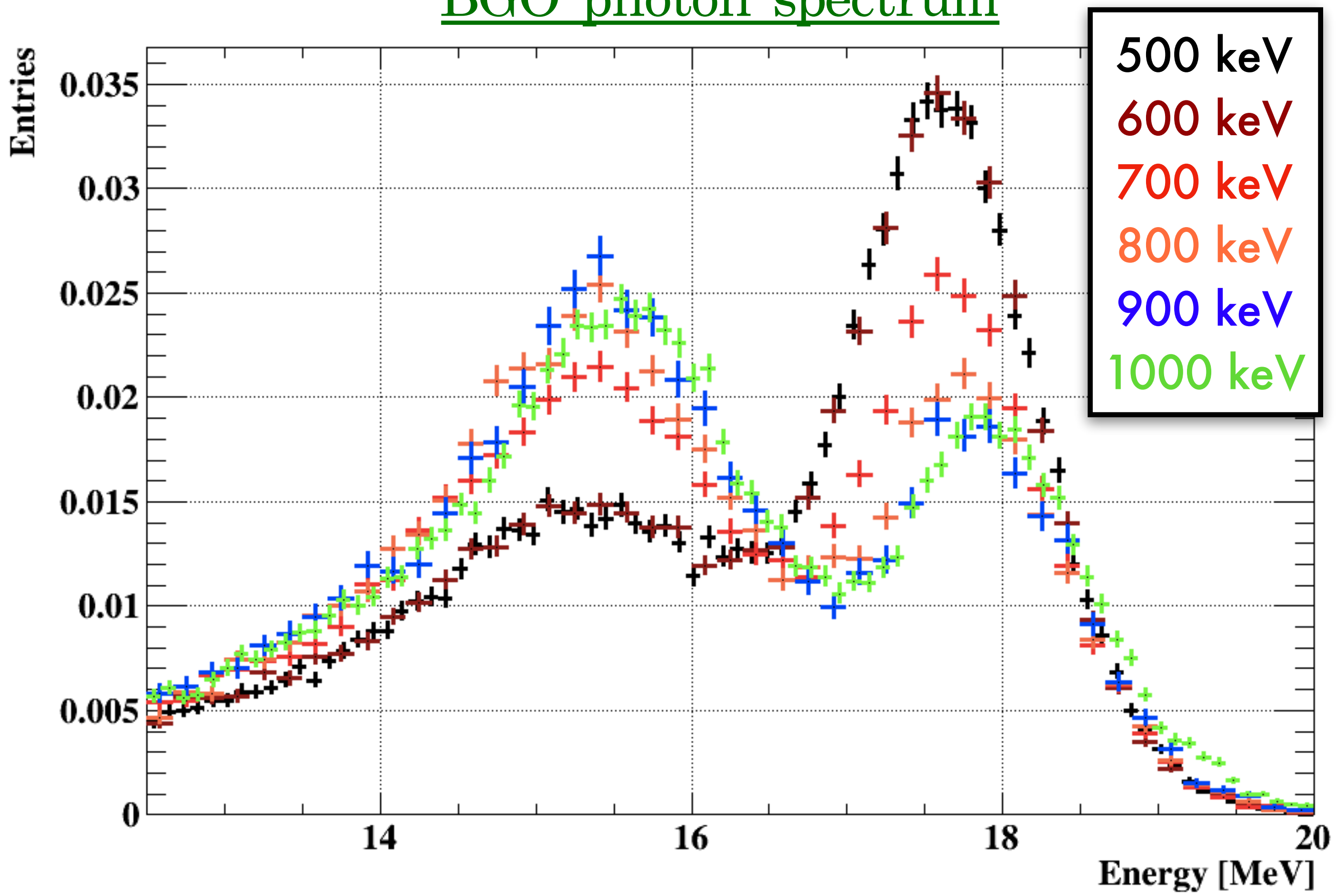
What's next?

- H_2+ 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



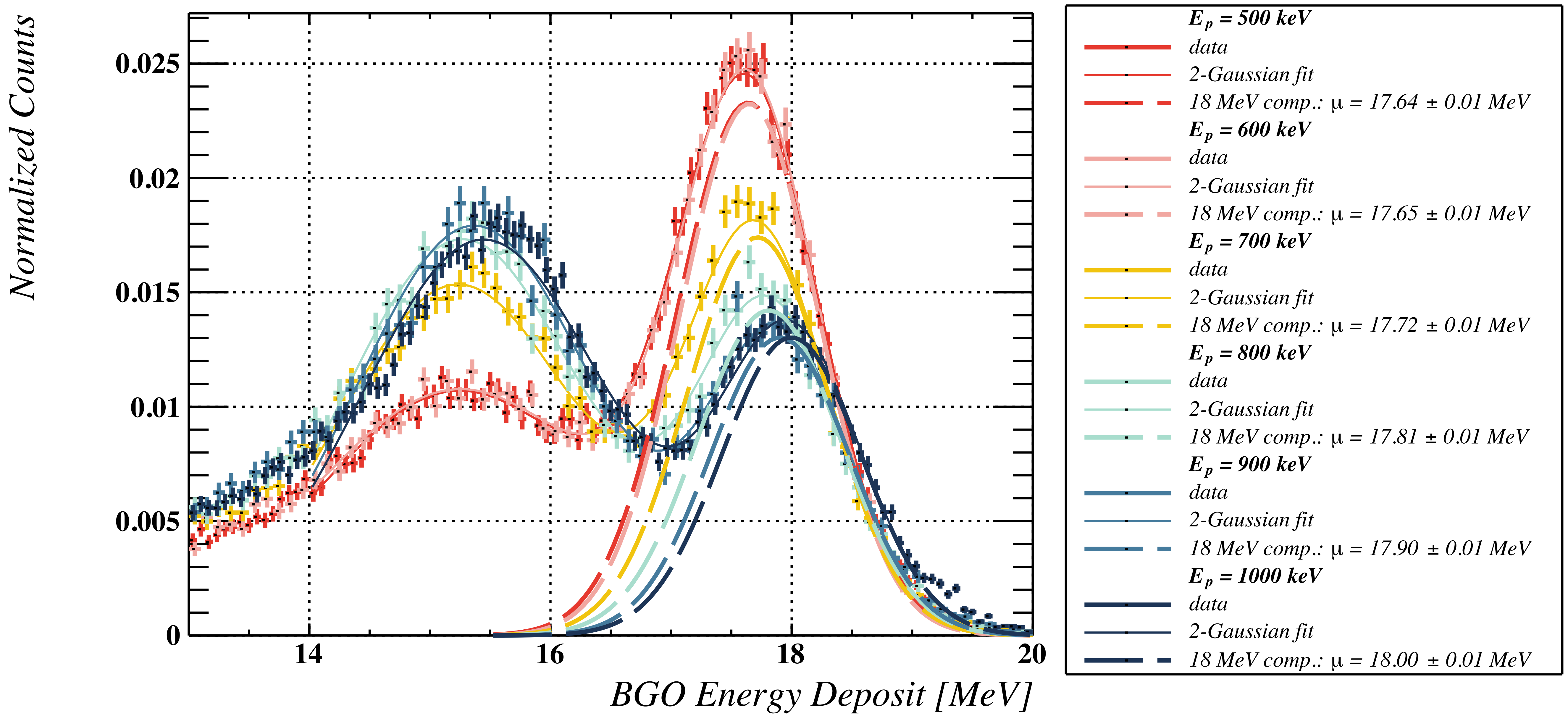
BGO photon spectrum



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

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 ≫

BGO constraint on the ML fit

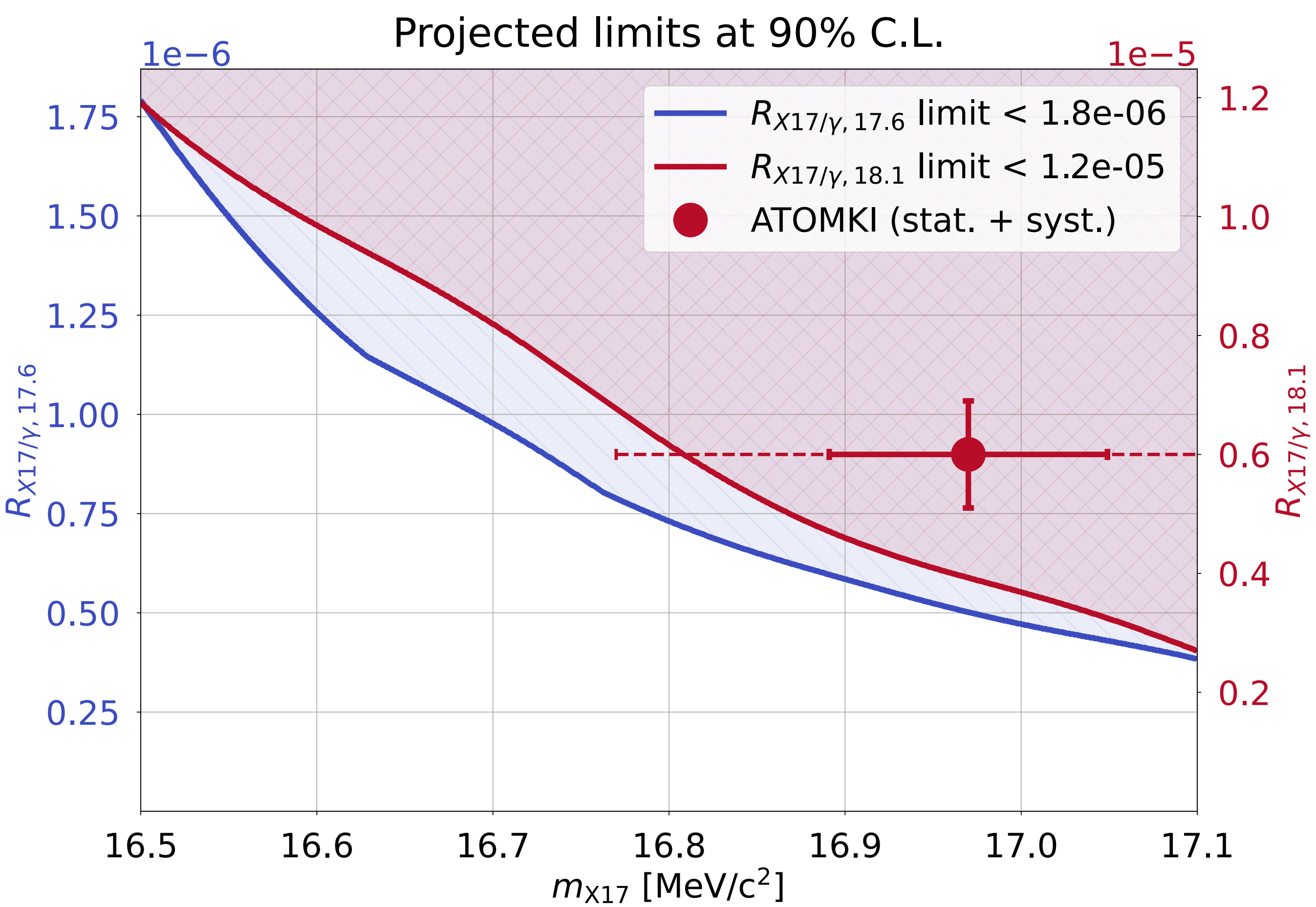
The 18 /(18+15) integral ratio are extracted from the BGO and constrain the ML fit

$\frac{18}{18+15}$	From BGO	From Zahnow 1995
E_p = 440 keV	51(2)%	69(5)%
E_p = 1030 keV	32(2)%	31(7)%

- **Reason for discrepancy at 440 keV is unclear**
- **XEC at 500 keV is consistent with BGO**
- **No good reason to favour Zahnow's results**
- **Fit re-done with Zahnow's values as a cross-check**

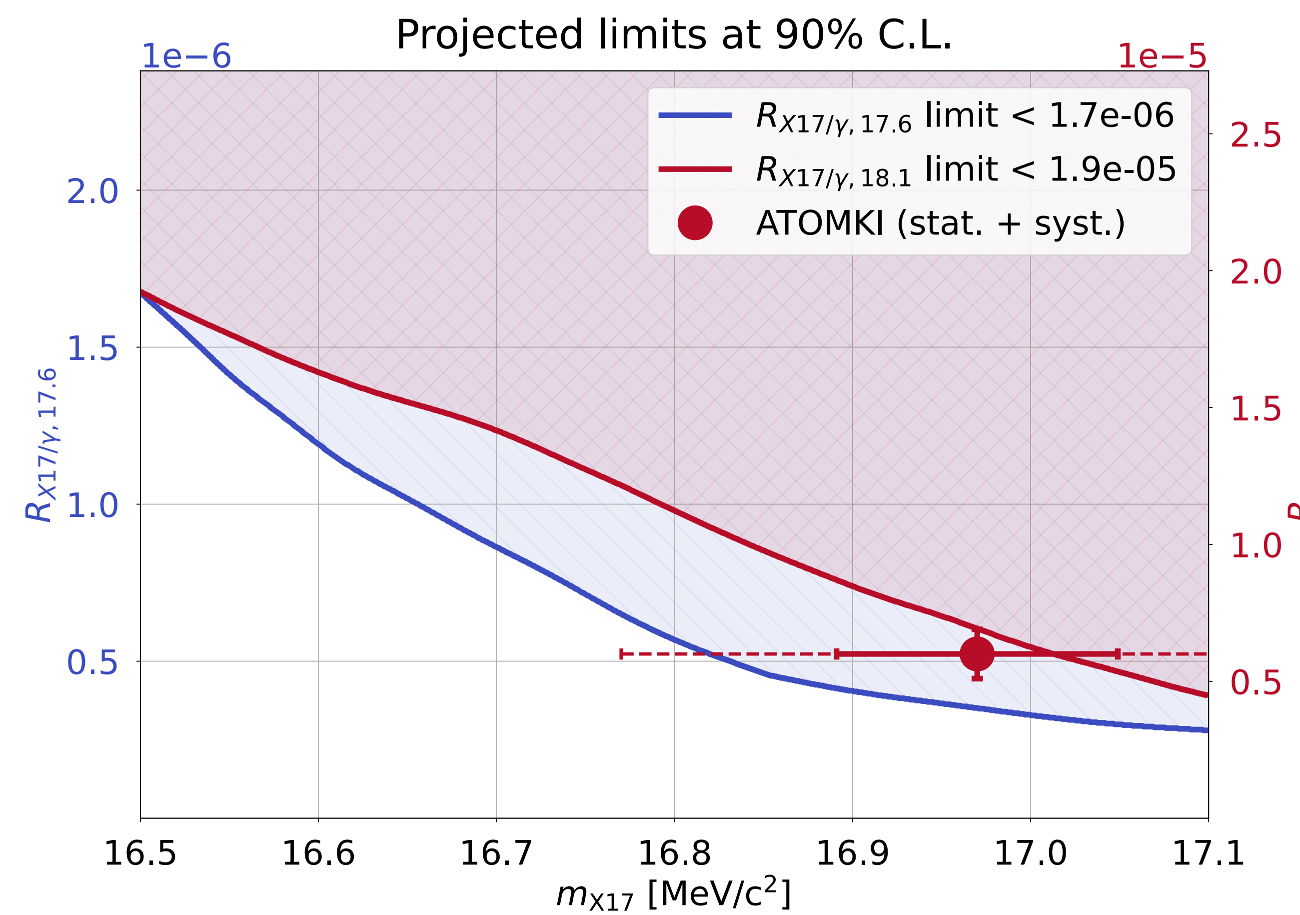
BGO constraint on the ML fit

Based on BGO constraint
Paper version



94% incompatibility with Atomki

Based on Zahnow constraint



83% incompatibility with Atomki

<u>Limits from 18.1 MeV slightly worse but results are consistent with published fit</u>