Status of the MEGII experiment

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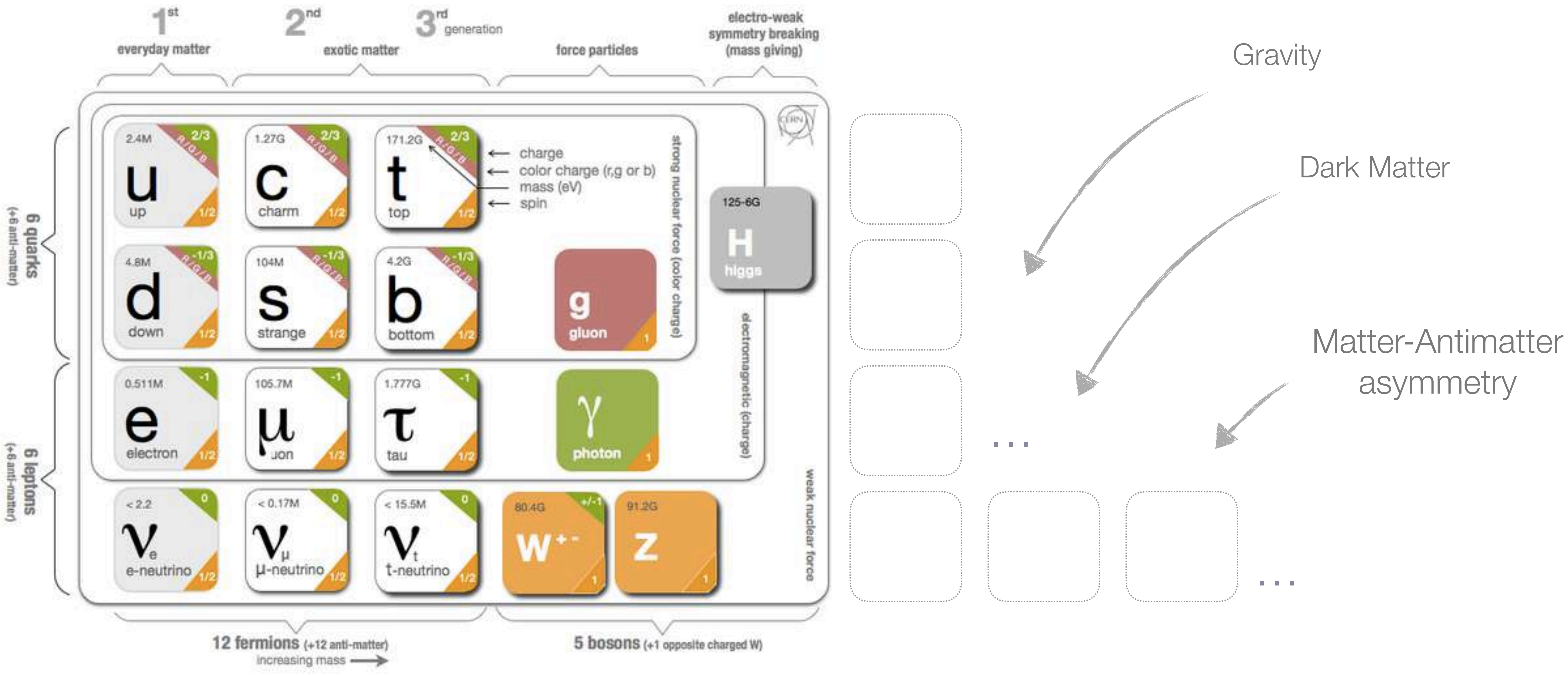
On behalf of the MEGII collaboration
September 26th 2025
SSP 2025

Content

- Physics cases
- Muon beams
- The MEGII experiment at PSI
- The most recent MEGII Result based on data sample 2021-2022
- Other more exotic searches: X17 and ALPs
- Outlook

The role of the low energy precision physics

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory



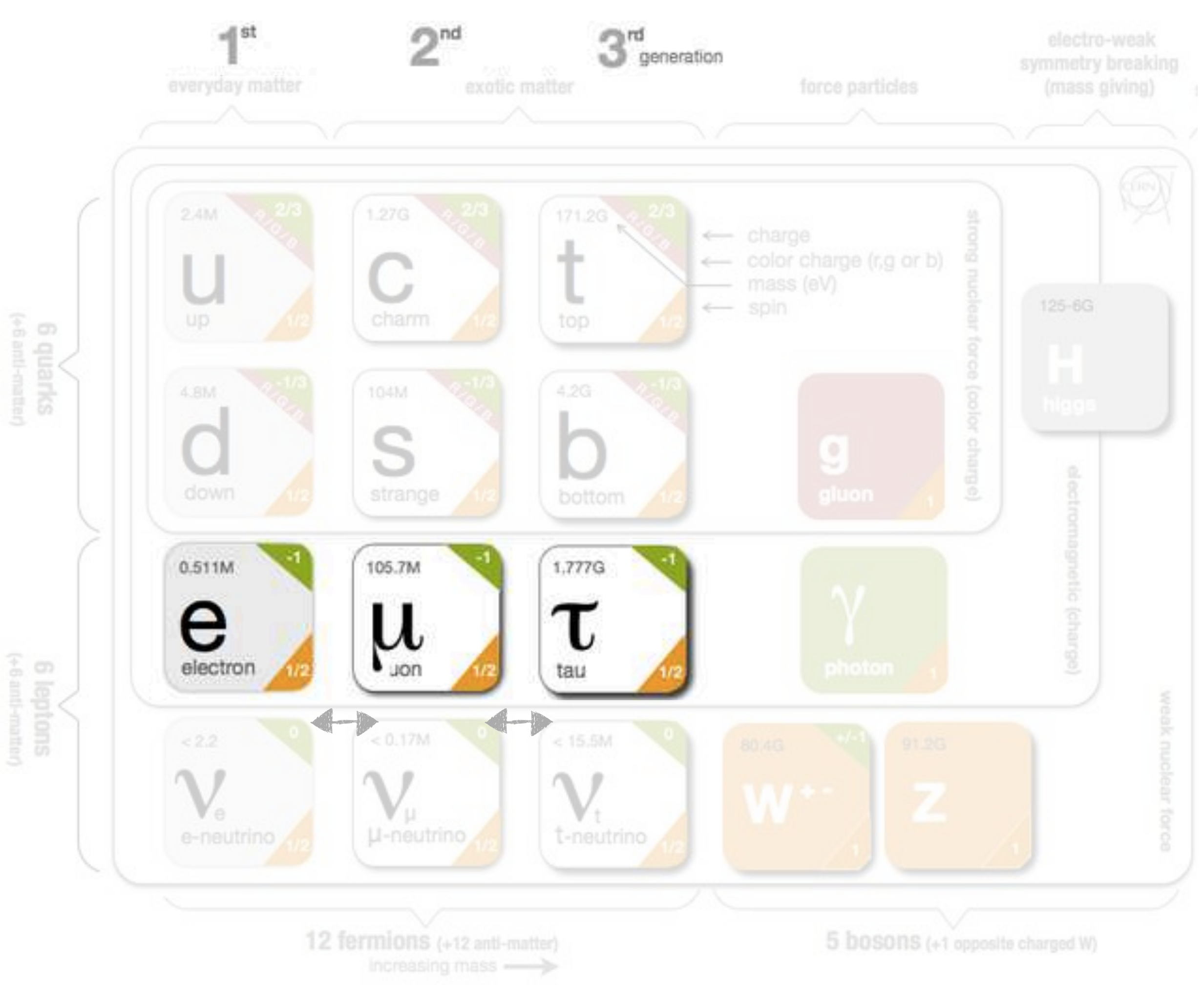
Focus here on:

- muon cLFV

- Low energy precision physics: **Rare/forbidden decay searches**, **symmetry tests**, **precision measurements** very sensitive tool for unveiling **new physics** and probing very **high energy scale**

Charged lepton flavour violation search: Motivation

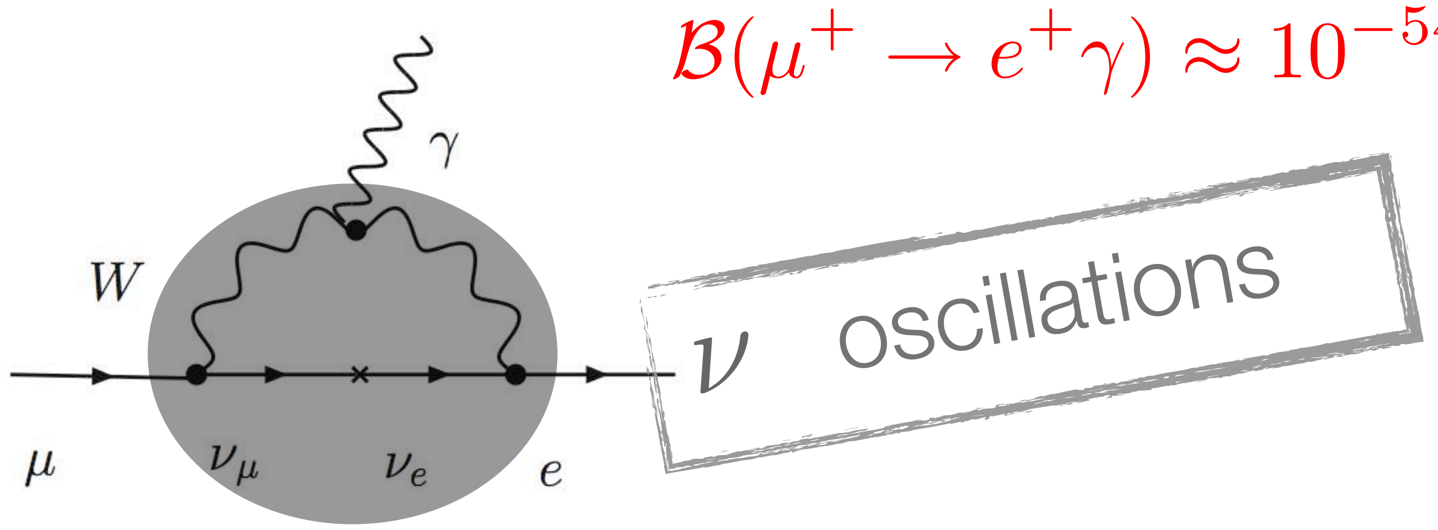
- **Neutrino oscillations**: Evidence of physics Behind Standard Model (BSM). **Neutral lepton flavour violation**
- **Charged lepton flavour violation: NOT** yet observed
- An experimental **evidence** of cLFV at the current sensitivities will be a **clear signature of New Physics**



$\Delta N_i \neq 0$ with i = 1,2,3

SM with massive neutrinos (Dirac)

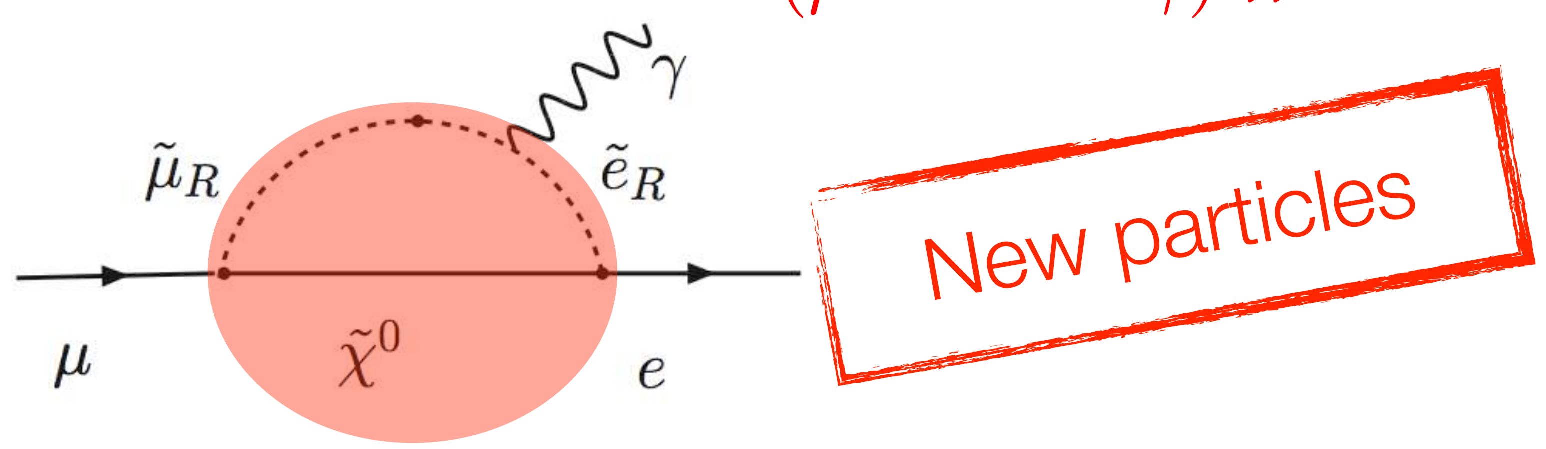
$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) \approx 10^{-54}$



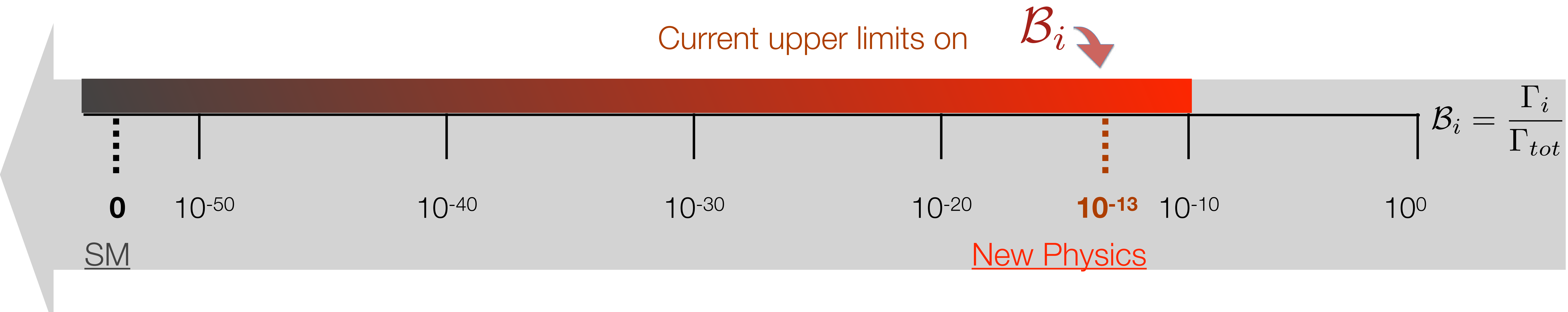
too small to access experimentally

BSM

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

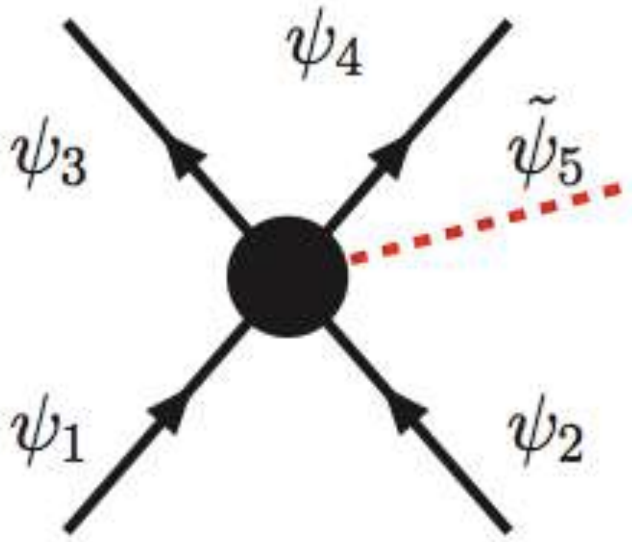


an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)



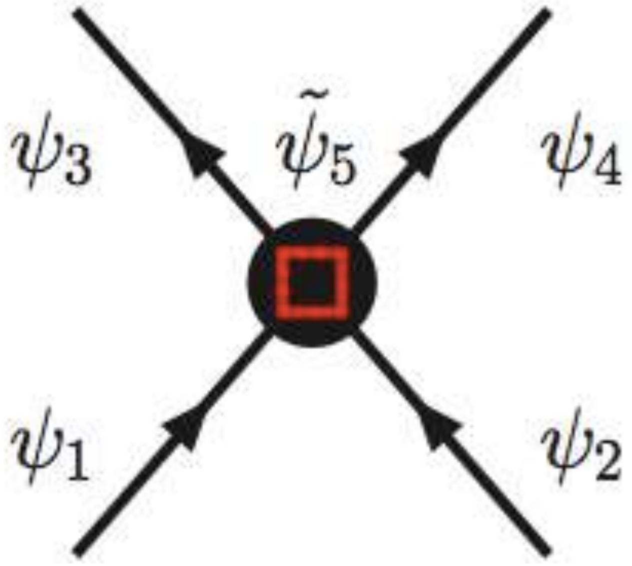
Complementary to “Energy Frontier”

Energy frontier



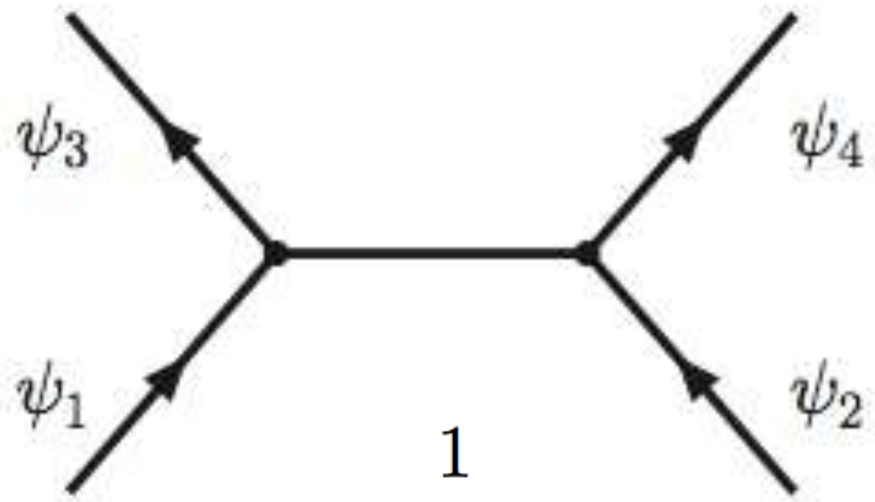
Real BSM particles

Precision and intensity frontier

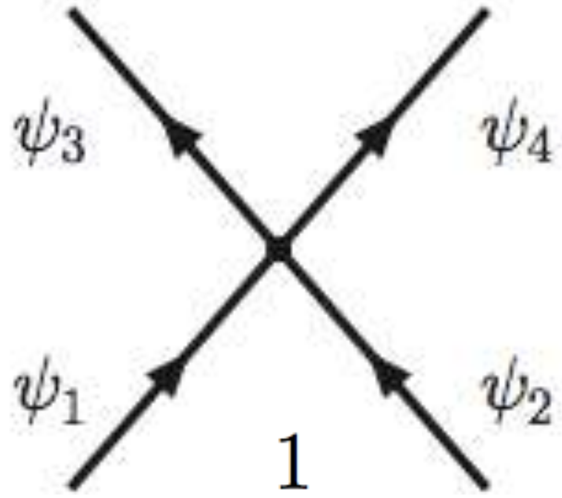


Virtual BSM particles

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$



$$\frac{1}{p^2 - M^2}$$



$$\frac{1}{\Lambda^2}$$

Unveil new physics

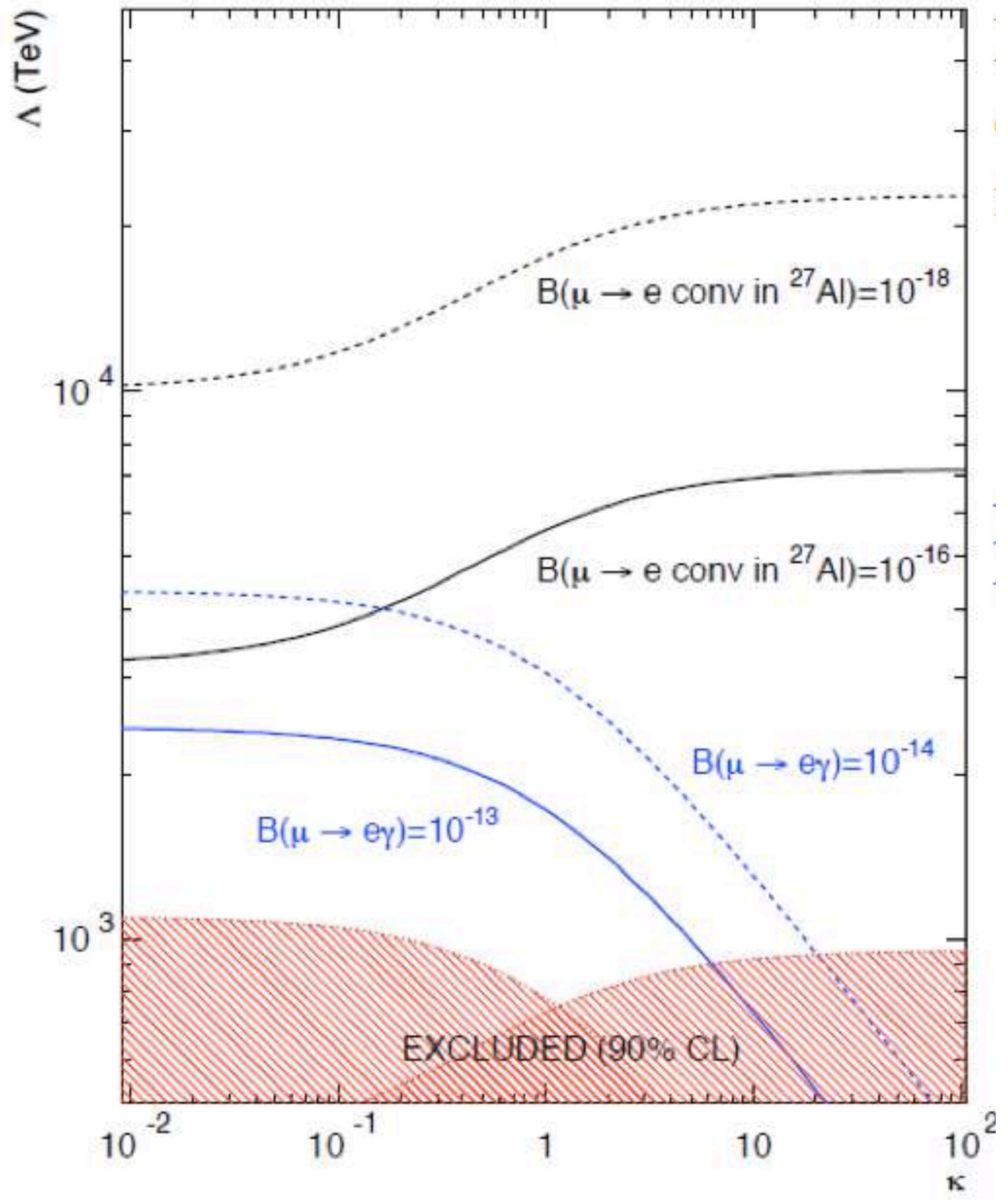
Probe energy scale otherwise unreachable

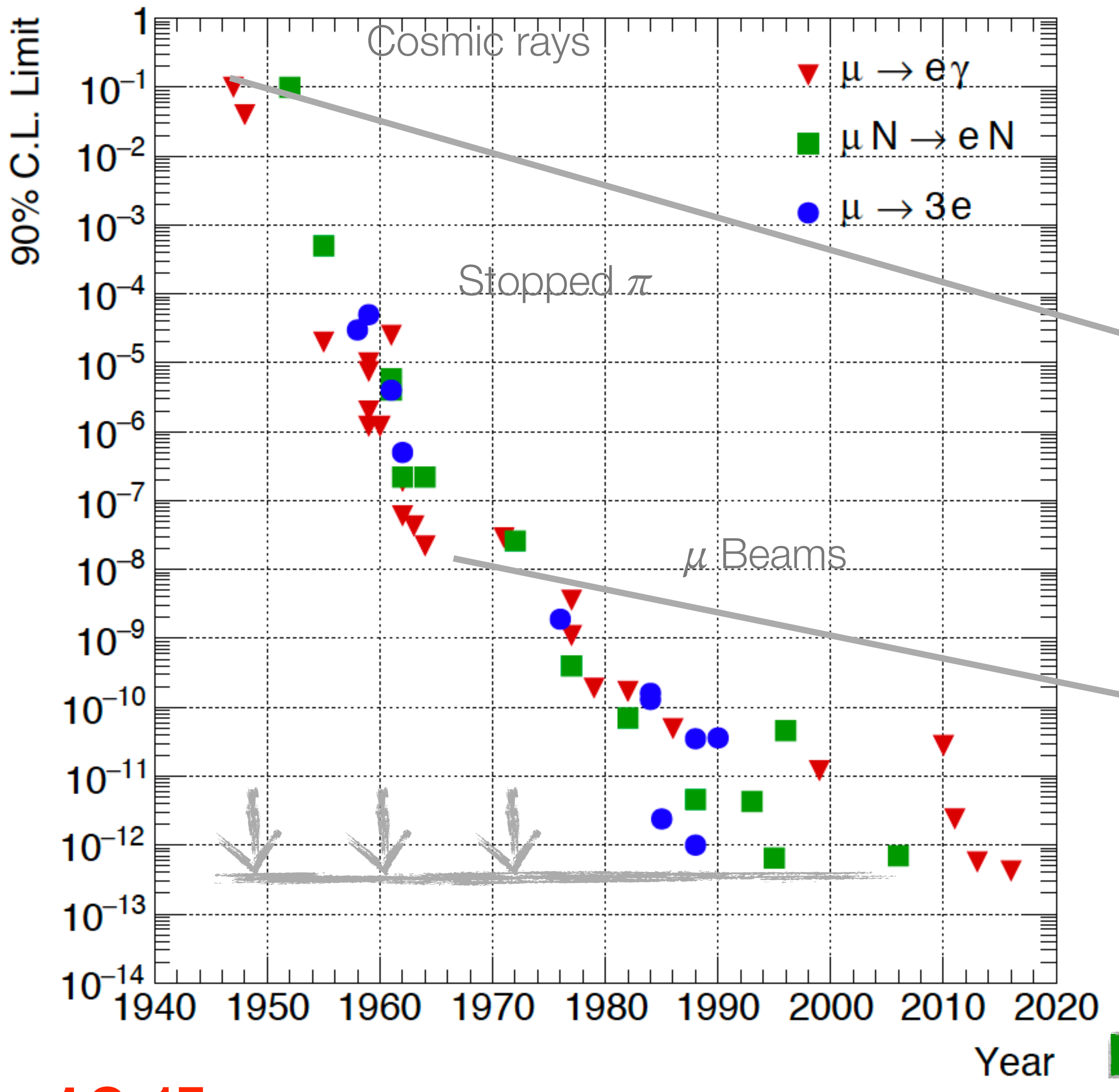
E > 1000 TeV

CLFV searches with muons: Status and prospects

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2 x 10^{-13}	~ 6 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	few x 10^{-17}

- In the near future impressive sensitivities via the so called “golden” muon channels
- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV
- Probing energy scale otherwise unreachable at the energy frontiers
- **Note**: τ ideal probe for NP w. r. t. μ (Smaller GIM suppression, stronger coupling, many decays). μ most sensitive probe due to huge statistics (= muon campus)





10^{-17}

$\mu \neq e^*$

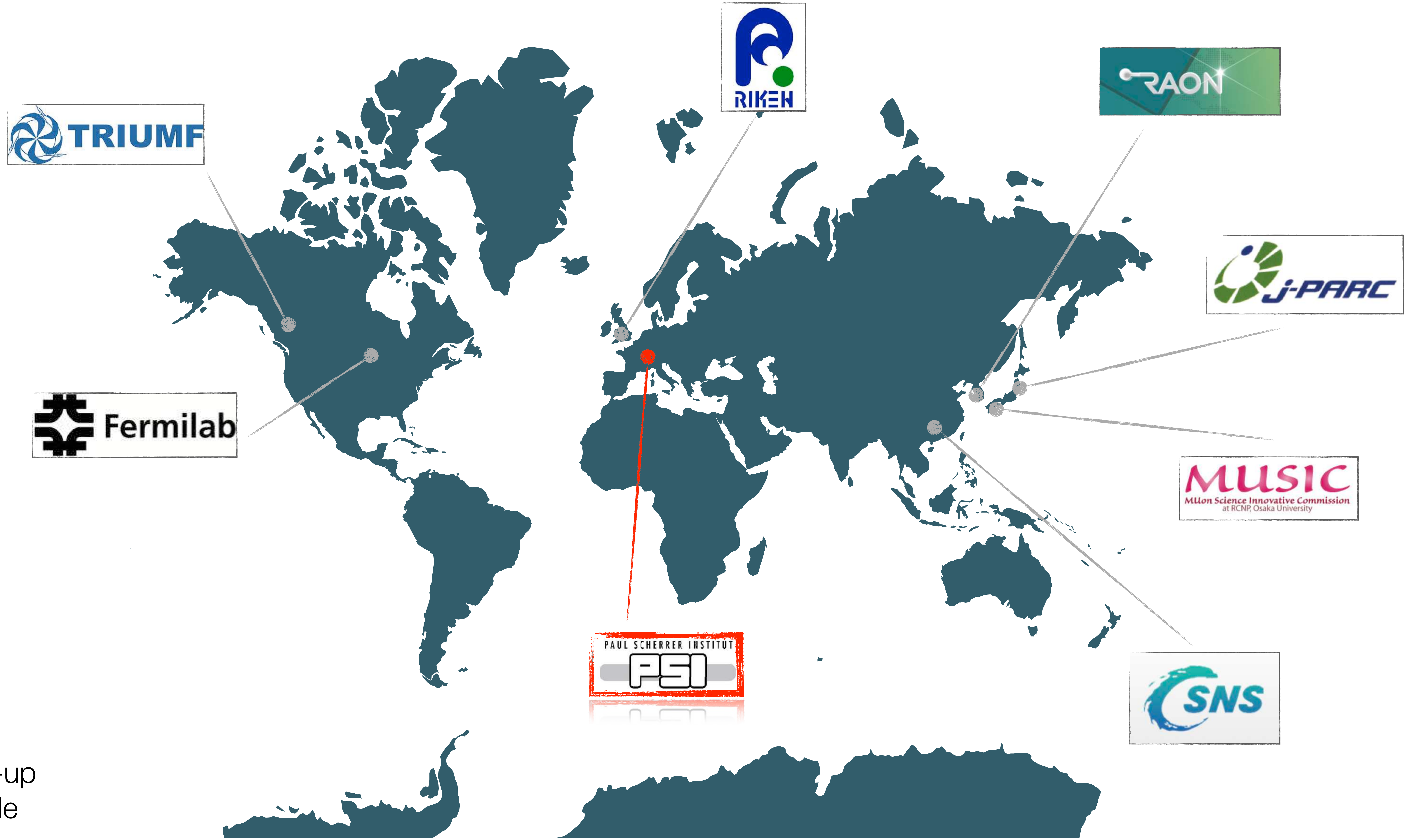
1947:
Pontecorvo and
Hincks

$\nu_\mu \neq \nu_e$

1962:
Lederman, Schwartz, and Steinberger
1988 Nobel

In the near future O(5-10) years: Impressive sensitivity

Muon beams worldwide

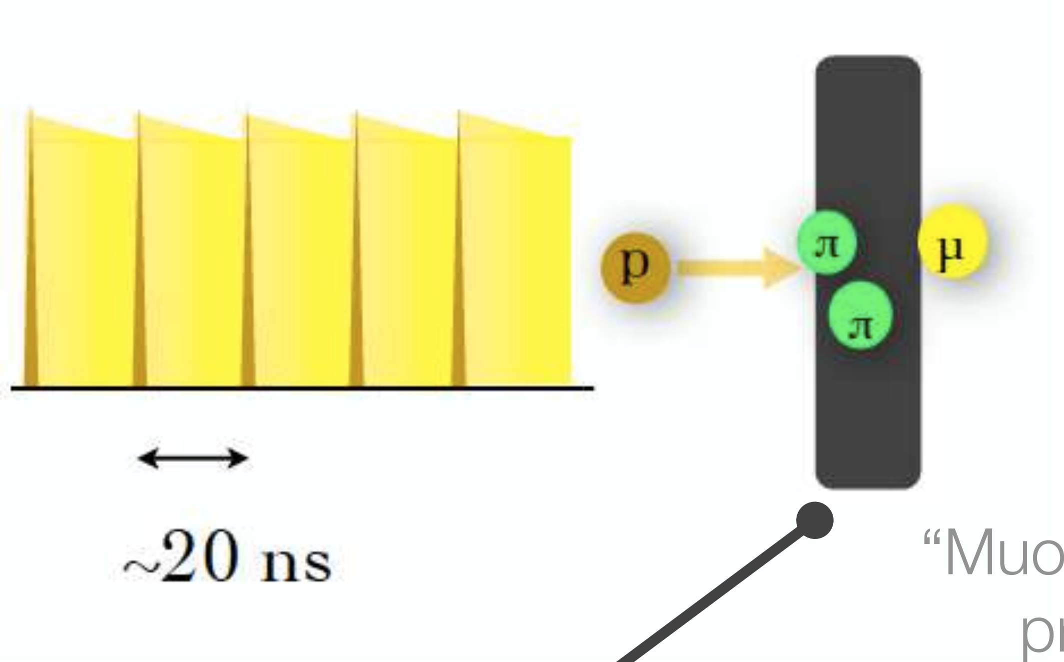


Note: See the back-up for a summary table

PSI's muon beams

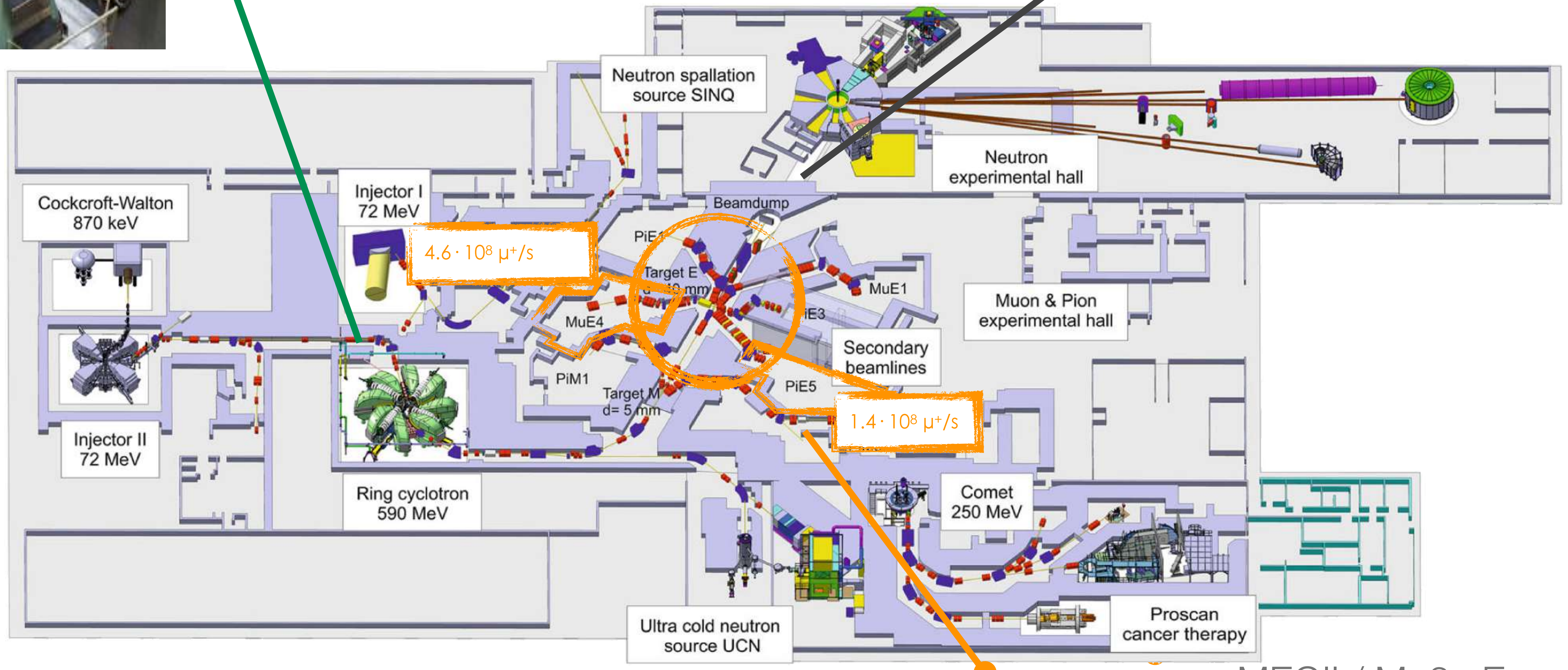
- PSI delivers the most intense continuous (DC) low momentum (surface) muon beam in the world up to few x 10^8 mu/s (28 MeV/c, polarised beam (**Intensity Frontiers**)

590 MeV proton ring cyclotron
1.4 MW



Proton RF ~ 50 MHz
"DC" muon beam

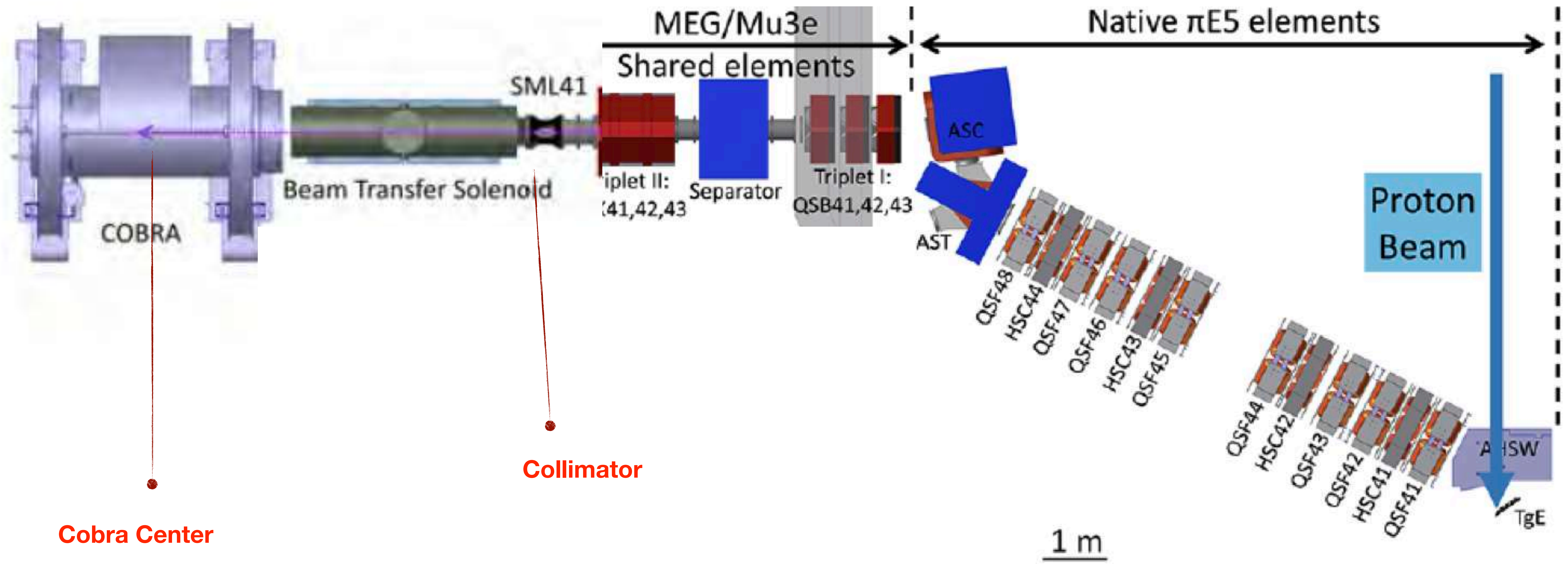
"Muon" Target "E" production



MEGII / Mu3e Experimental area

The MEGII beam line

- MEGII beam requirements:
  - **Intensity O(10^8 muon/s), low momentum p = 28 MeV/c**
  - **Small straggling and good identification of the decay region**
- MEG II beam settings released since 2019. More then 10^8 mu/s can be transport into Cobra (**up to 2.32e8@2.2 mA during the 2023 beam time at the collimator**)



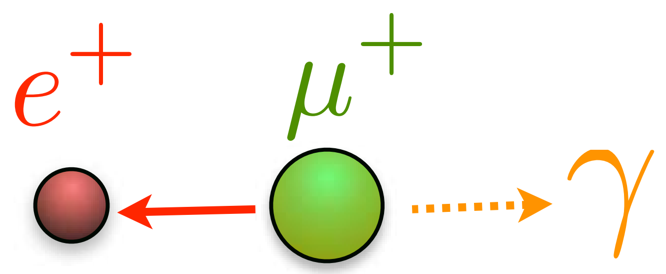
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365

A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434

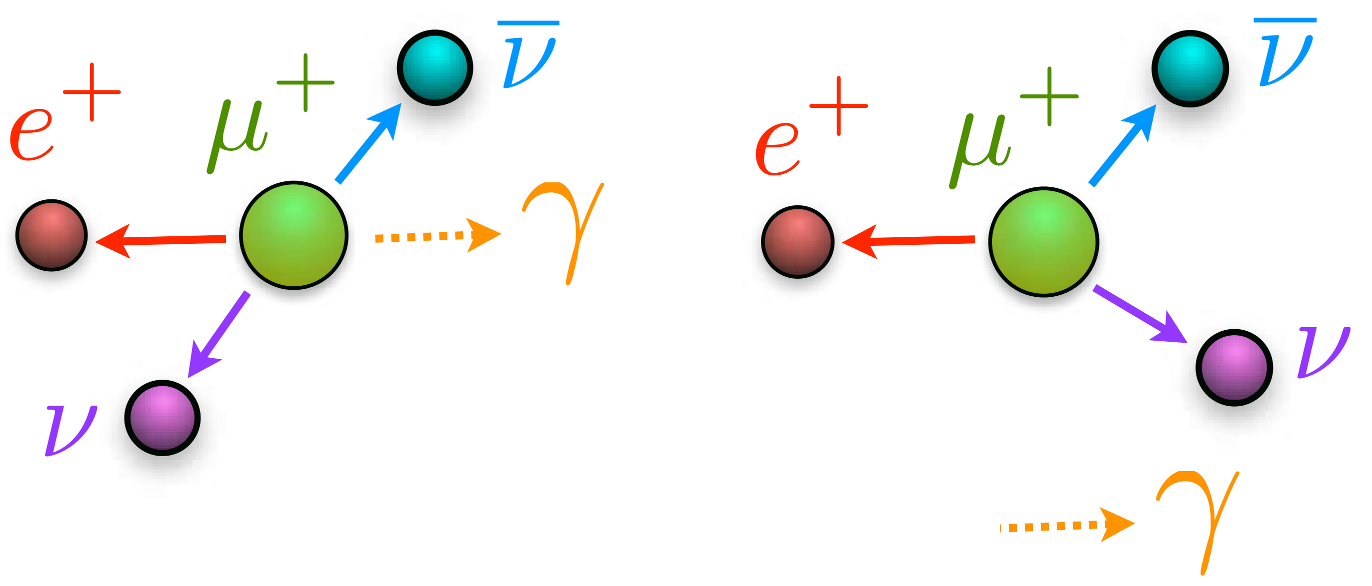
The MEGII experiment at PSI

- Best upper limit on the BR ($\mu^+ \rightarrow e^+ \gamma$) set by the MEG experiment (**$4.2\ 10^{-13}$** @90% C.L.)
- Searching for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~ **$6\ 10^{-14}$**
- Five observables **(E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg})** to identify $\mu^+ \rightarrow e^+ \gamma$ events

Signature



Backgrounds



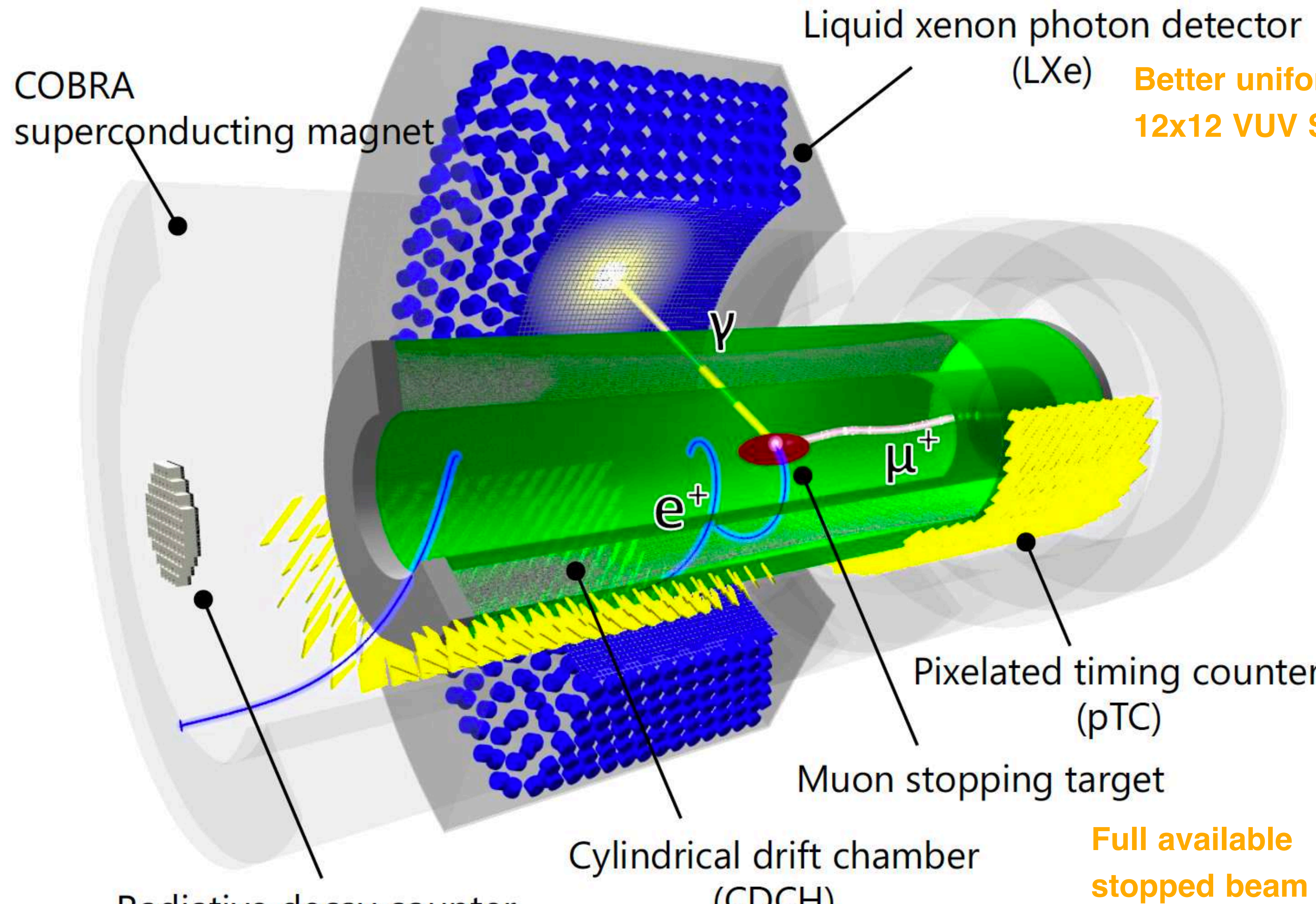
New electronics: WaveDAQ

~9000 channels at 5GSPS

2x Resolution everywhere

Updated and new Calibration methods

Quasi mono-chromatic positron beam



Better uniformity w/ 12x12 VUV SiPM

2x Beam Intensity

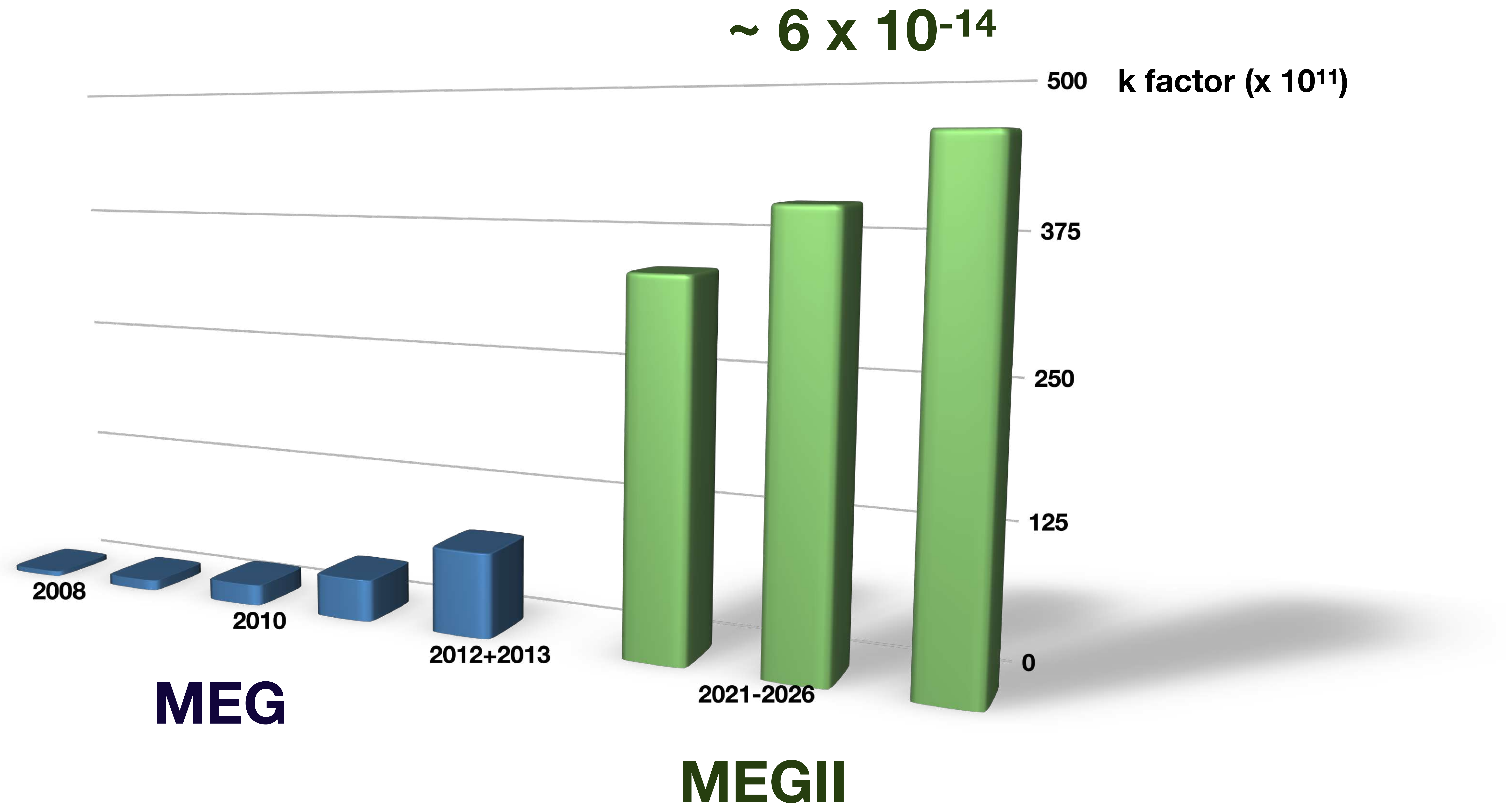
35 ps resolution w/ multiple hits

Full available stopped beam intensity 7×10^7

Single volume $He:iC_4H_{10}$

Background rejection

Where we will be



How the sensitivity can be pushed down?

- More sensitive to the signal...

high statistics

$$SES = \frac{1}{R \times T \times A_g \times \varepsilon(e^+) \times \varepsilon\,(gamma) \times \varepsilon(TRG) \times \varepsilon(sel)}$$

Beam rate
Acquisition time
Geometrical acceptance
Detector efficiency
Selection efficiency

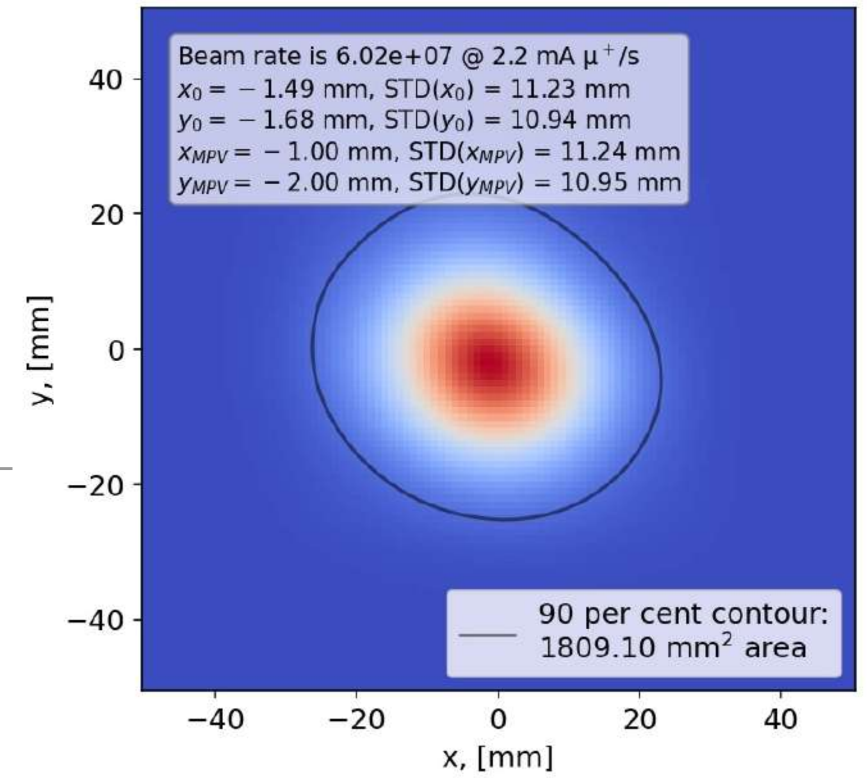
- More effective on rejecting the background...

high resolutions

$$B_{acc} \sim R \times \Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2$$

Positron Energy resolution
Gamma Energy resolution
Relative timing resolution
Relative angular resolution

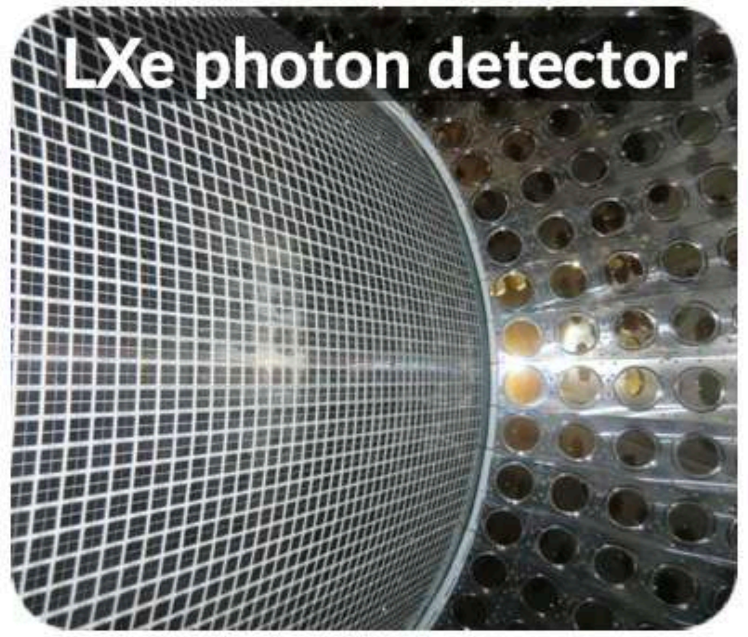
The MEGII experiment at work



- Up to 5 x 10^7 stopped μ^+

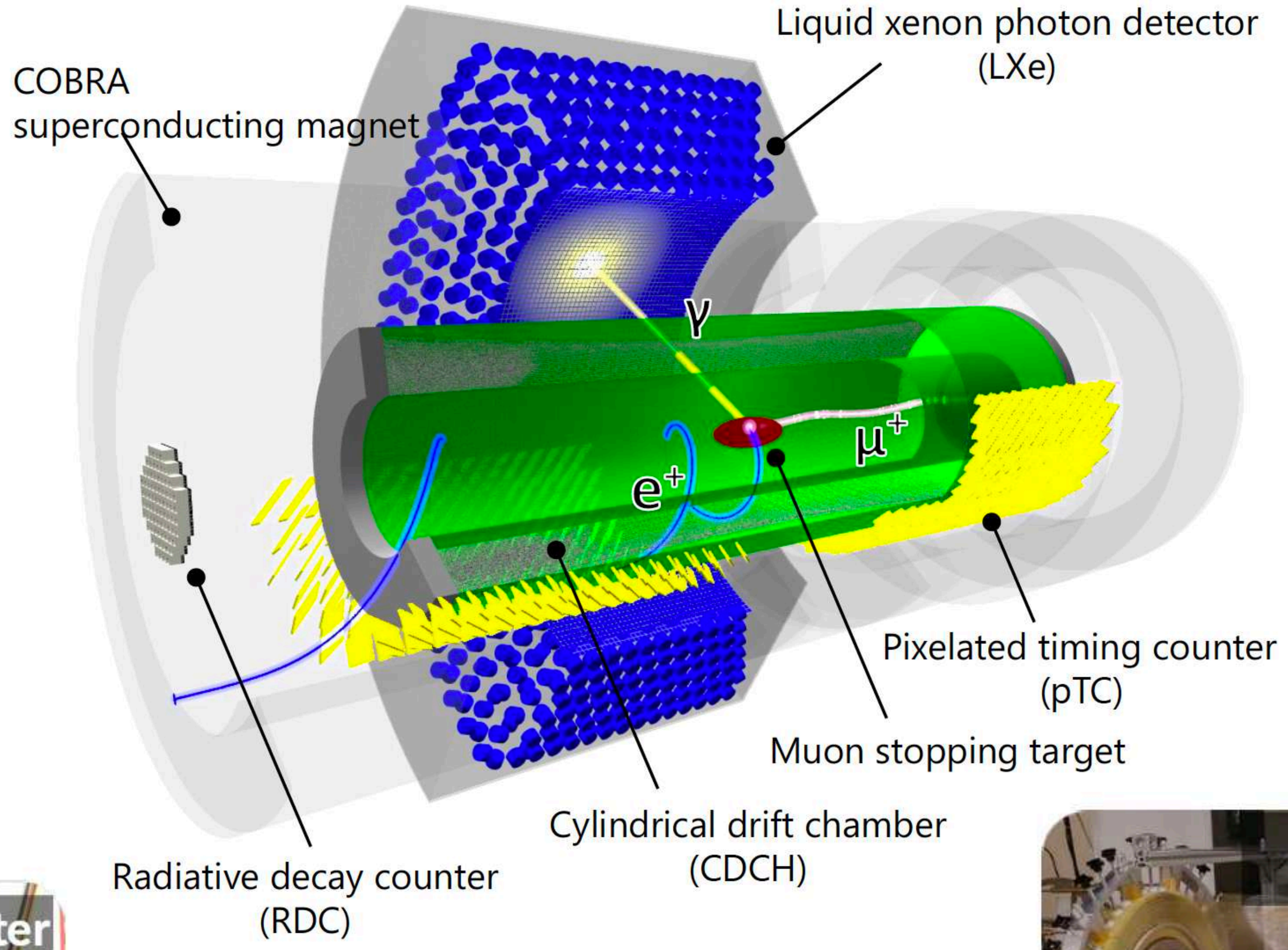
- After a major upgrade, the MEGII detector started data taking in 2021

Eur. Phys. J. C84 (2024) 190

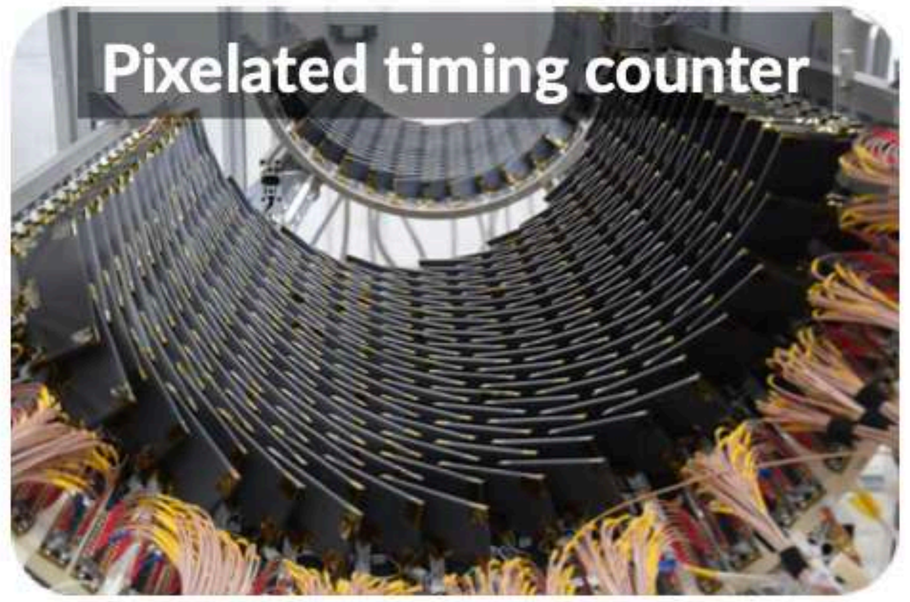


- LXe 900L (~2.7ton)
- Highly granular scintillation readout with SiPM(×4092) + PMT(×668)

- ~9000ch waveform readout



- New in MEG II
- BG-γ suppression by identifying associated low mom. positron

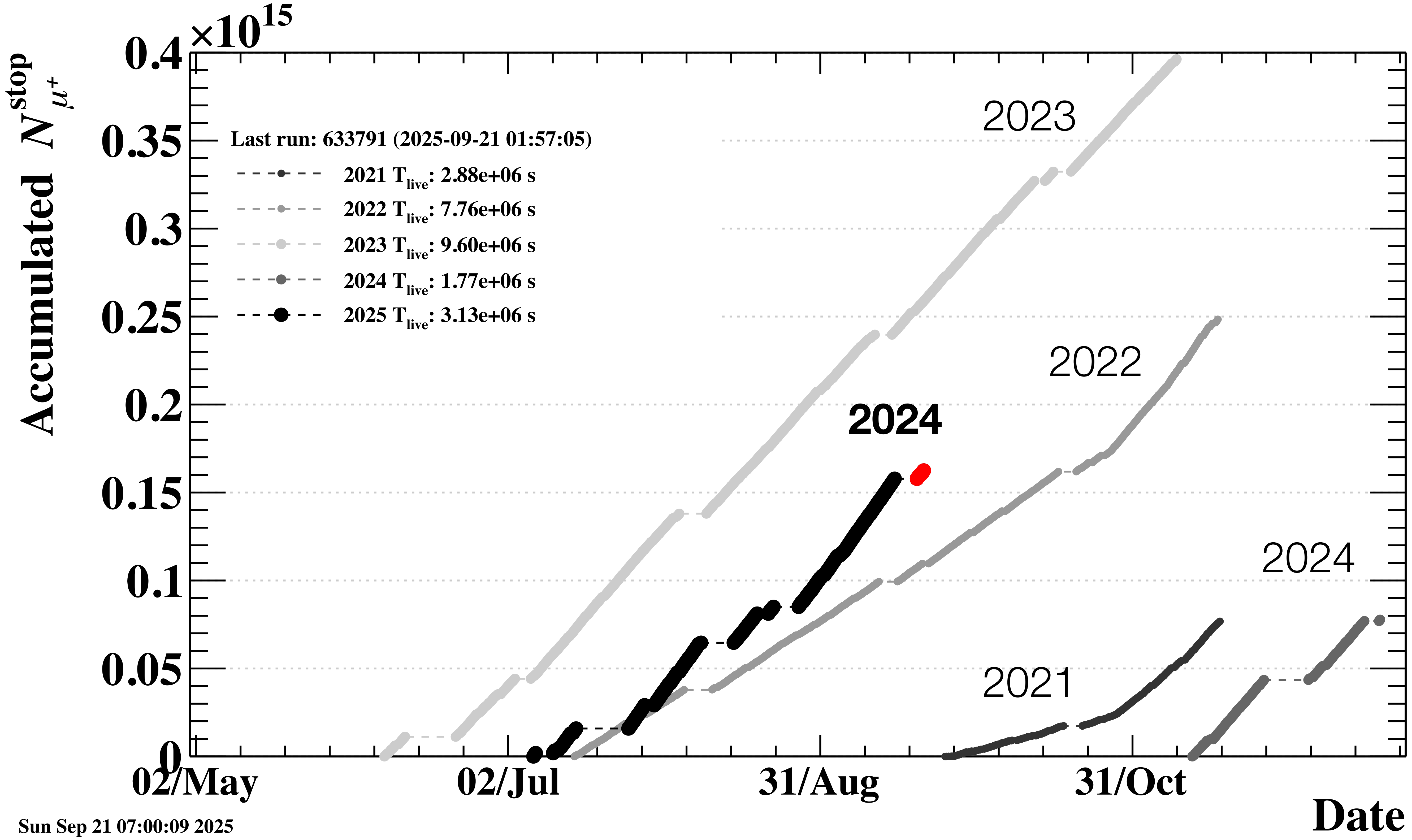


- ×512 fast plastic scintillator plates
- 40ps time resolution averaged over multiple hits

- Ultra-low-mass with single gas-volume
- Drift cells with stereo wires

Physics Run: Data collection

- **2021**: **first** physics run with the full detector first result of MEGII **published** (**Eur. Phys. J. C84 (2024) 216**)
- **2022**: long and stable run in optimal conditions: **discussed in this talk and will be published soon**
- **2023**: **largest statistics ever** acquired data analysis ongoing
- **2024**: **~5 months in standby** due to technical problem at PSI
- **2025: Ongoing since beginning of July**



μ⁺ → e⁺ γ Analysis Strategy

- **Observables to characterise $\mu^+ \to e^+\gamma$ signal**

  $t_{e\gamma}, E_\gamma, E_e, \theta_{e\gamma}, \phi_{e\gamma}$

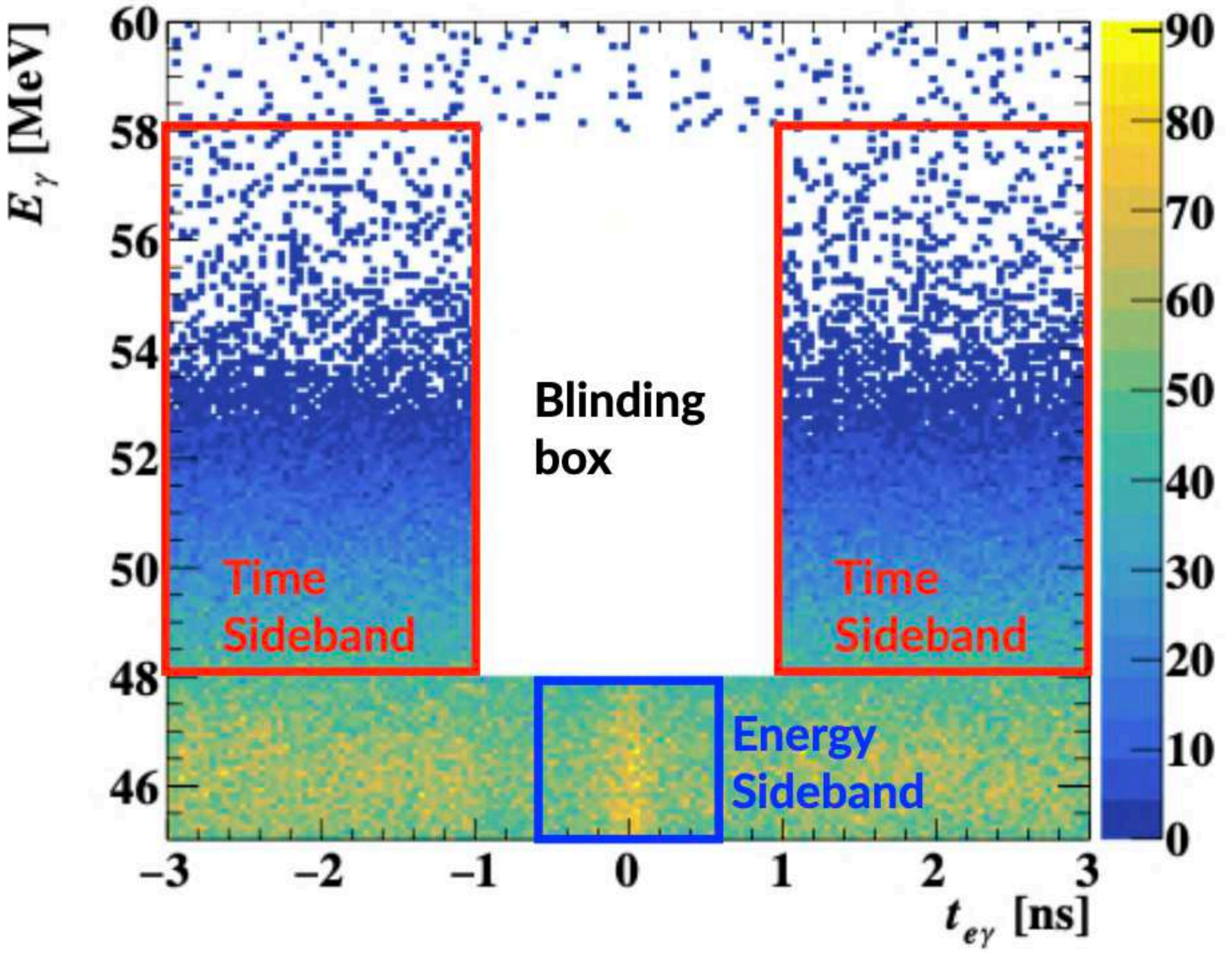
- **Blinding signal region**
  - Blind box: $48 < E_\gamma < 58\,\mathrm{MeV},\ |t_{e\gamma}| < 1\,\mathrm{ns}$
  - BG study at sidebands
    - Accidental BG at time sidebands
    - RMD at energy sidebands

- **Maximum likelihood analysis to estimate N_{sig}**
  - Likelihood fit to analysis window:

    $48 < E_\gamma < 58\,\mathrm{MeV}, 52.2 < E_e < 53.5\,\mathrm{MeV}$

    $|t_{e\gamma}| < 0.5\,\mathrm{ns}, |\phi_{e\gamma}| < 40\,\mathrm{mrad}, |\theta_{e\gamma}| < 40\,\mathrm{mrad}$

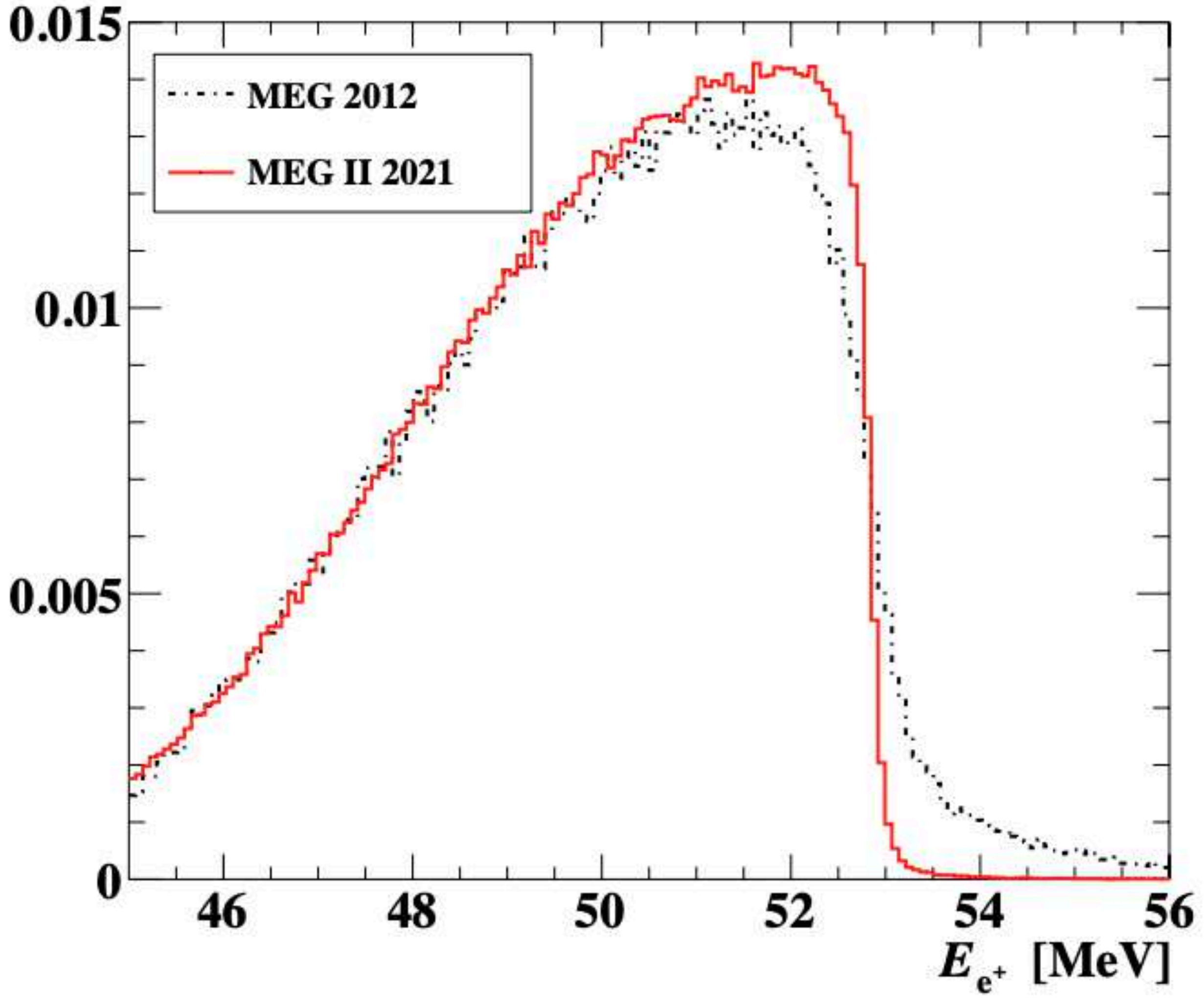
- **Two independent analyses**
  - **Per-event PDFs with two angular observables $\theta_{e\gamma}$, $\phi_{e\gamma}$** (← reference)
  - **Constant PDFs with single angular observable $\Theta_{e\gamma}$** (← crosschecking)



$$\mathcal{L}(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{ACC}}, x_{\mathrm{T}}) = \frac{e^{-(N_{\mathrm{sig}}+N_{\mathrm{RMD}}+N_{\mathrm{ACC}})}}{N_{\mathrm{obs}}!} C(N_{\mathrm{RMD}}, N_{\mathrm{ACC}}, x_{\mathrm{T}}) \times \prod_{i=1}^{N_{\mathrm{obs}}} (N_{\mathrm{sig}} S(\vec{x}_i) + N_{\mathrm{RMD}} R(\vec{x}_i) + N_{\mathrm{ACC}} A(\vec{x}_i)) ,$$

Detector performance highlights

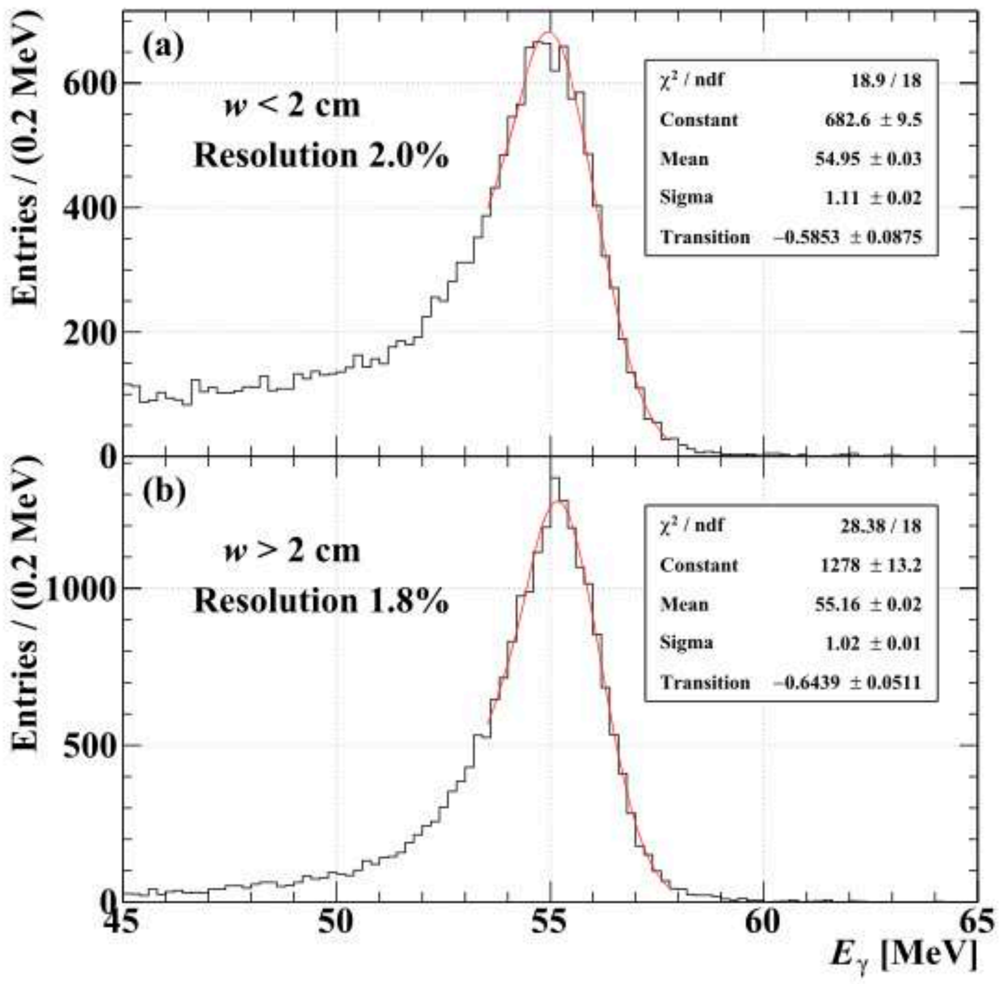
Positron tracking



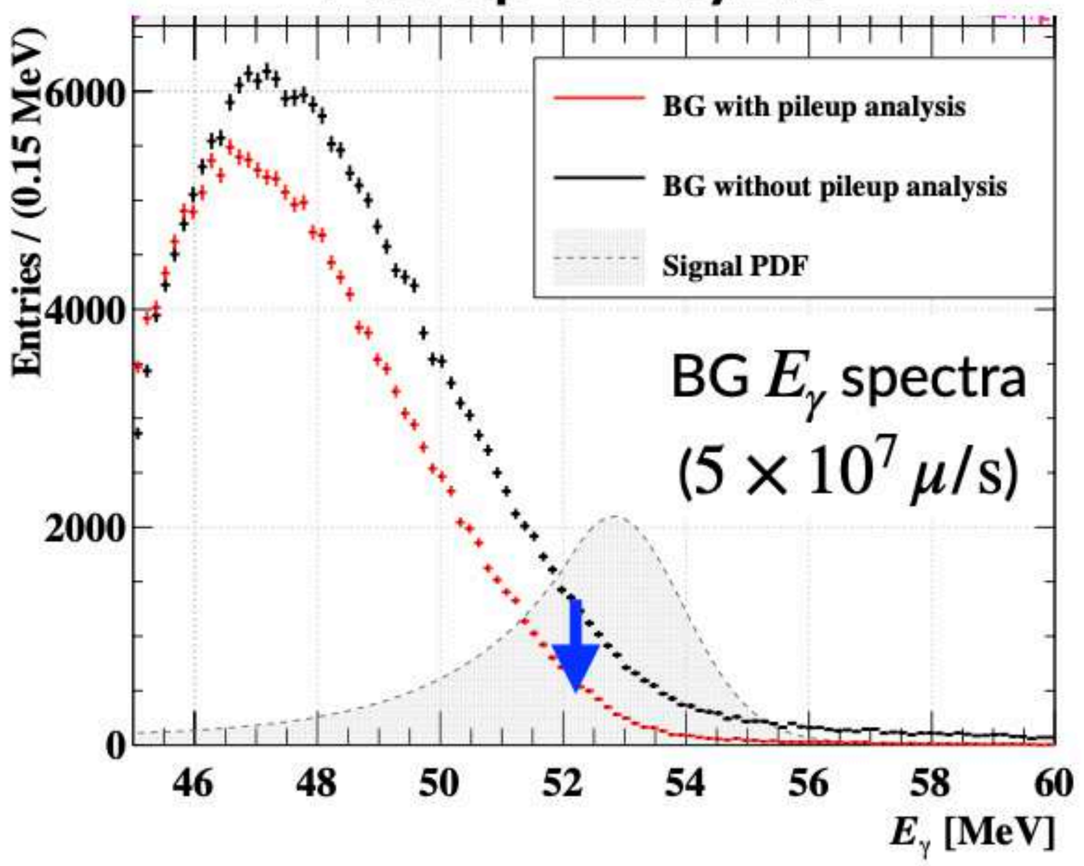
- Energy resolution: **90 keV**
  (↔ 320 keV@MEG)
- Efficiency: **67 % @ $3 \times 10^7 \mu/s$**
  (↔ 30 % @MEG)

Photon energy

Energy resolution

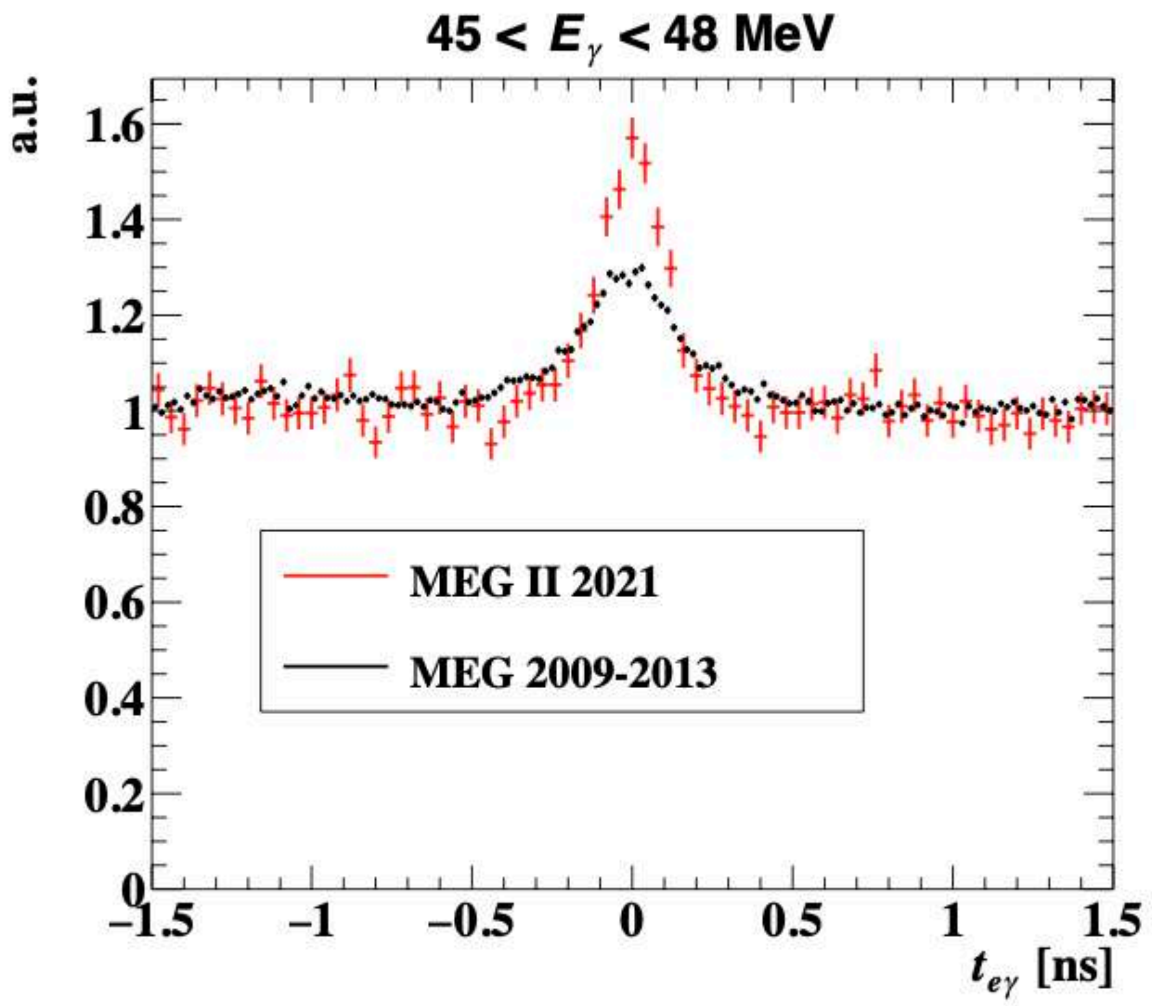


Pileup analysis



- High-granularity and uniform readout by MPPCs
- Energy resolution: **2.0%/1.8% for (conv. depth: <2cm/>2cm)**
- **Pielup BG reduction by 35%** at 48-58MeV ($5 \times 10^7 \mu/s$)

Relative timing



- Overall resolution: **84 ps**
  (↔122 ps@MEG)

Significant improvement over MEG

Detector performance summary

Resolution	MEG	MEG II data 2022 (2021)
E_e (keV)	320	89
θ_e (mrad)	9.4	3.8
ϕ_e (mrad)	8.7	6.2
z_e/y_e (mm) core	2.4/1.2	1.76/0.61
E_γ(%) (w<2 cm)/(w>2 cm)	2.4/1.7	2.4(2.0)/1.9(1.8)
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.5/2.5/5.0
$t_{e\gamma}$ (ps)	122	78
Efficiency (%)		
Trigger	≈ 99	91 (88)
Gamma-ray	63	63
Positron	30	67

Significant improvement over MEG

Normalization and systematics

Normalisation

$$\mathcal{B}(\mu^+ \to e^+\gamma) = \frac{N_{\rm sig}}{k}$$

- **Normalisation factor k**
  = # effectively measured muons (=1/SES)
- **Two independent methods**
  - Counting Michel positrons
    - Pre-scaled Michel positron trigger
    - Include positron efficiency and beam rate instability
  - Counting RMD events
    - RMD events in energy sideband
- **Combined normalisation factor**

(1.35 +- 0.07) x 10^{13}

Systematics

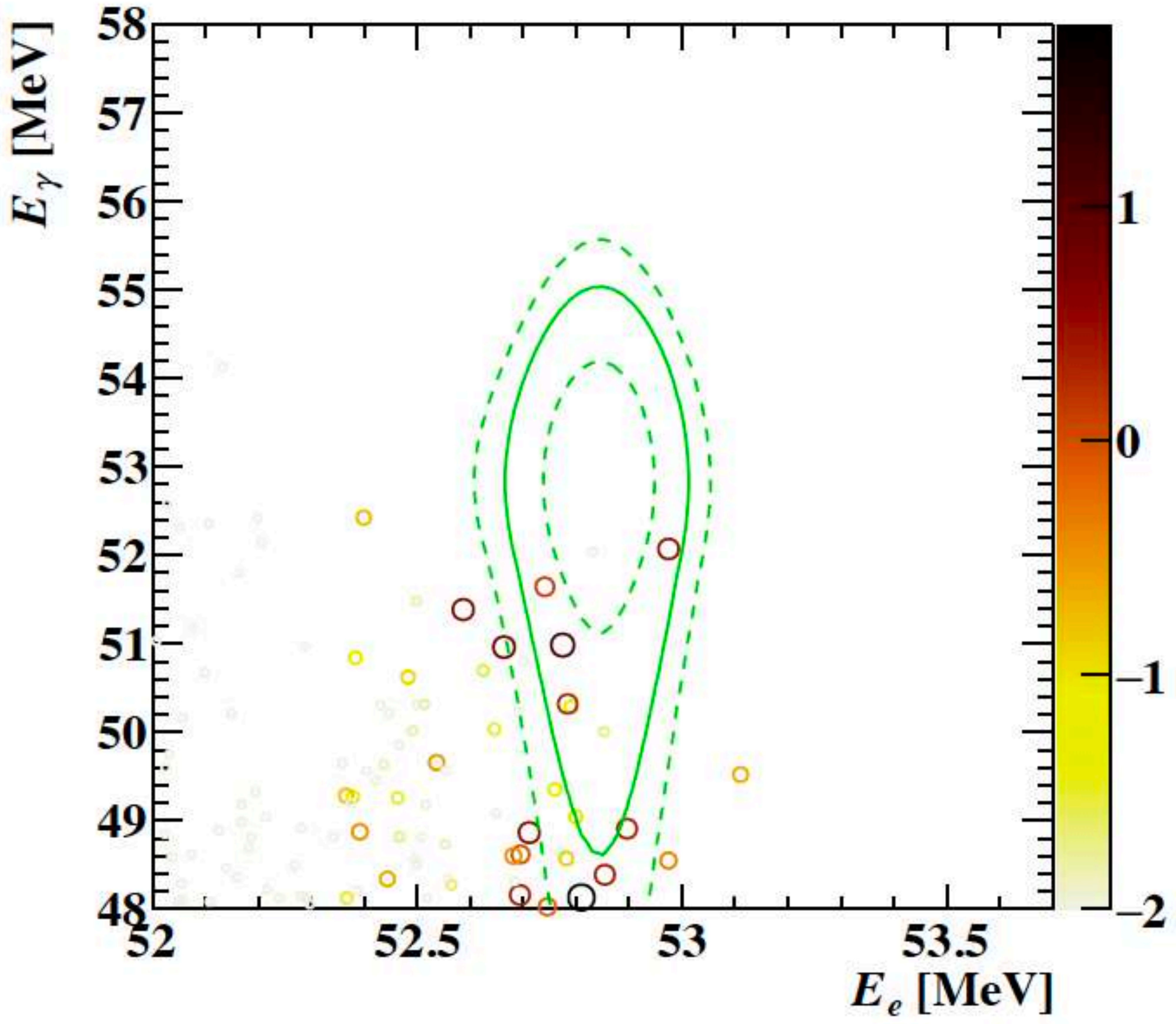
- **Major sources for systematics**
  - Detector alignment
  - E_γ scale
  - Normalisation
- **Effect on sensitivity ~3%**
  - Better controlled than MEG (~13%)

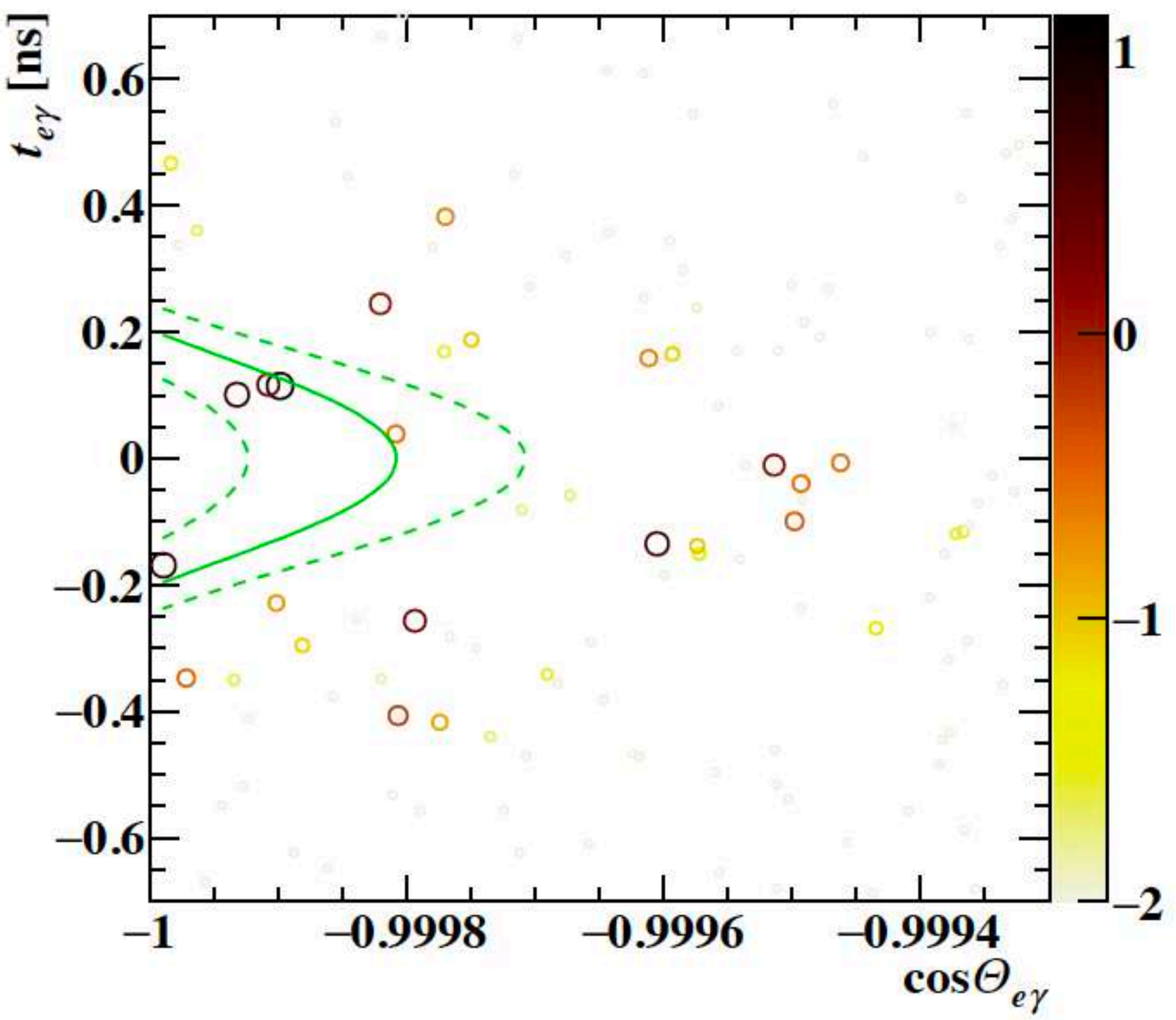
Parameter	Impact on sensitivity
$\phi_{e\gamma}$ uncertainty	1.1 %
E_γ uncertainty	0.9 %
$\theta_{e\gamma}$ uncertainty	0.7 %
Normalization uncertainty	0.6 %
$t_{e\gamma}$ uncertainty	0.1 %
E_e uncertainty	0.1 %
RDC uncertainty	< 0.1 %

Event distribution after unblinding

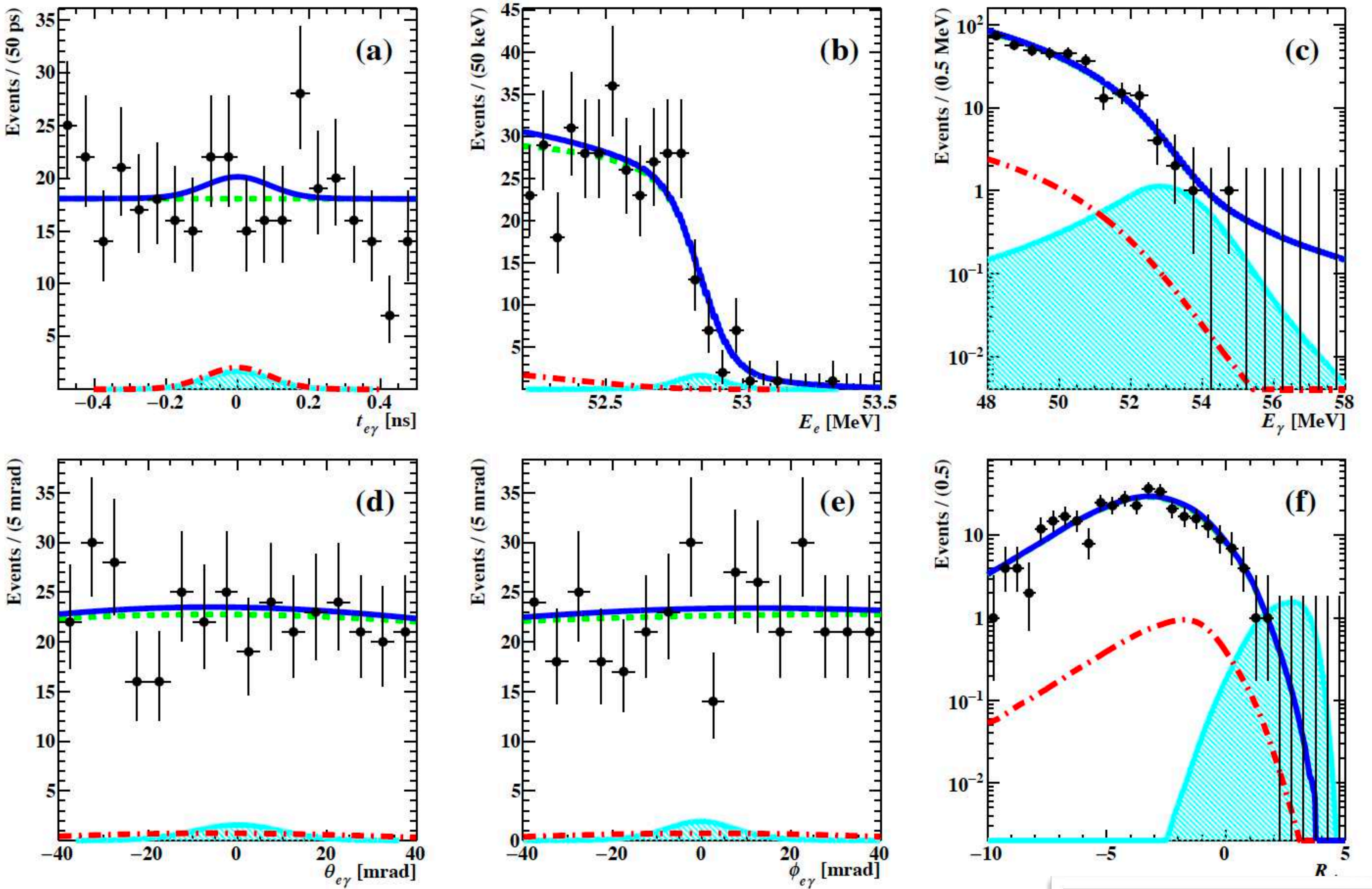
- No excess of events over expected BG around the signal region

PDF contours (1, 1.64, 2σ)





Likelihood fit and result



N_{sig} UL × 4

Accidental

RMD

$$R_{sig} = \log_{10}\left(\frac{S(\boldsymbol{x}_i)}{f_{RMD}R(\boldsymbol{x}_i) + f_{ACC}A(\boldsymbol{x}_i)}\right)$$

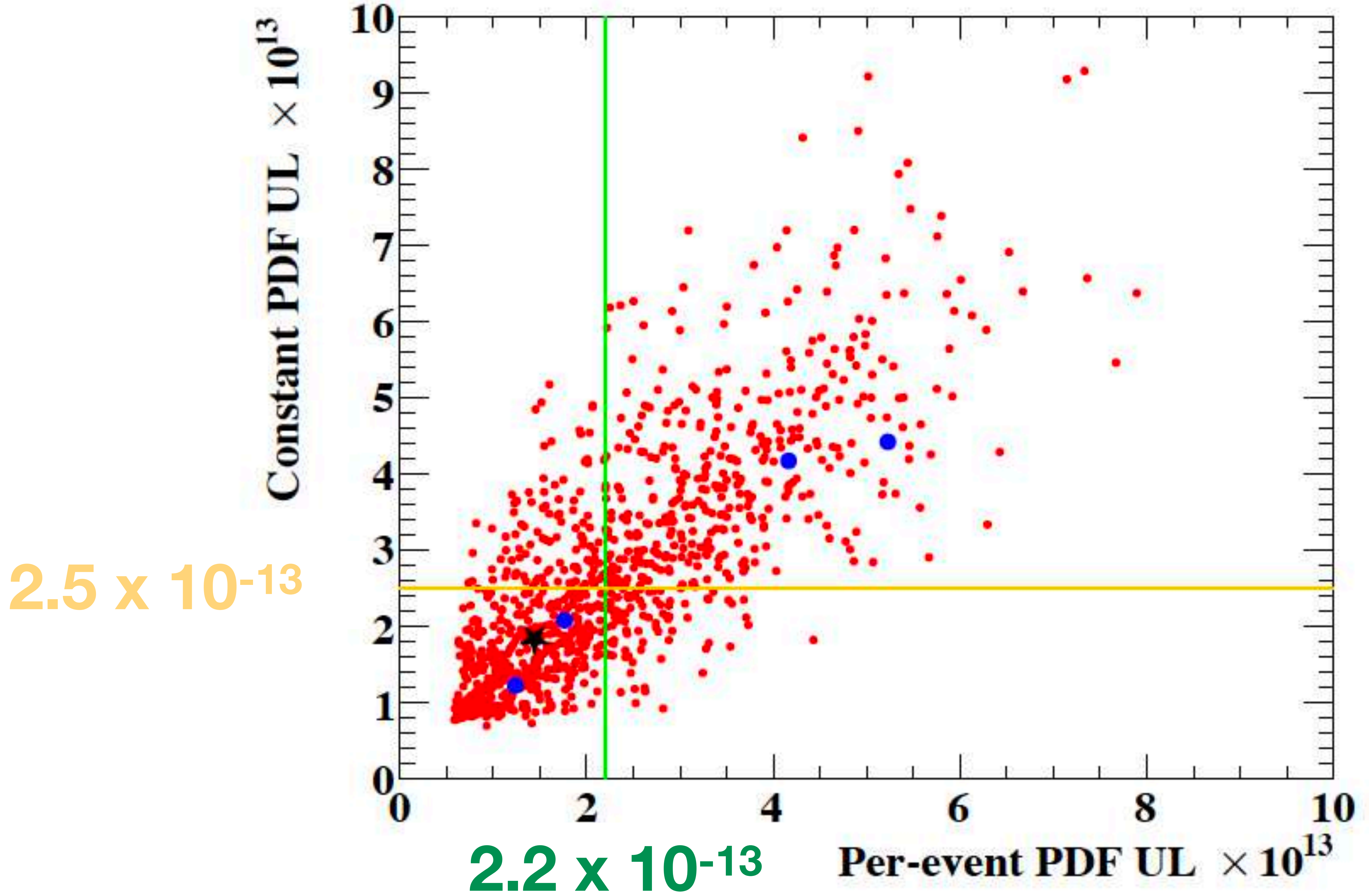
The 90% C.L. upper limit on the branching ratio on $\mu^+ \to e^+ \gamma$ based on 2021+2022 data is

$$\mathcal{B}_{90} = 1.5\times10^{-13}$$

Sensitivity and Confidence interval

- Two independent analysis: Per-event PDF and constant PDF
- Sensitivity: pseudo-experiments with a null signal hypothesis - generated according to the PDFs and number of background events from the sidebands
- Confidence interval based on the Feldman-Cousins prescription with profile likelihood ordering

Scatter plot of the 90 % C.L. upper limits



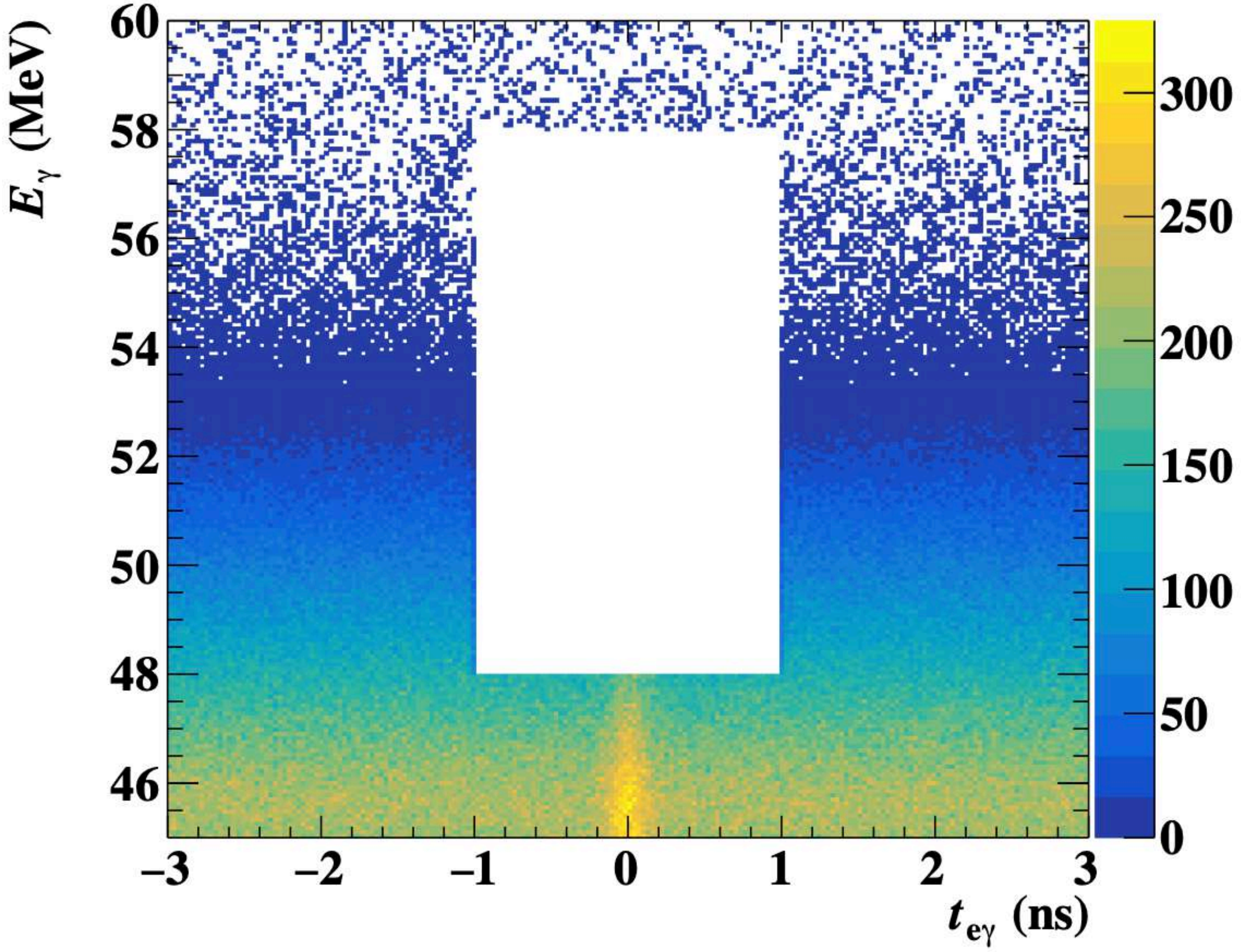
*An **ensemble** of pseudo-experiments with a null-signal hypothesis for the two analyses*

*The **blue dots** and the **black star** are the upper limits measured in the **time side-bands and** in the **signal** region*

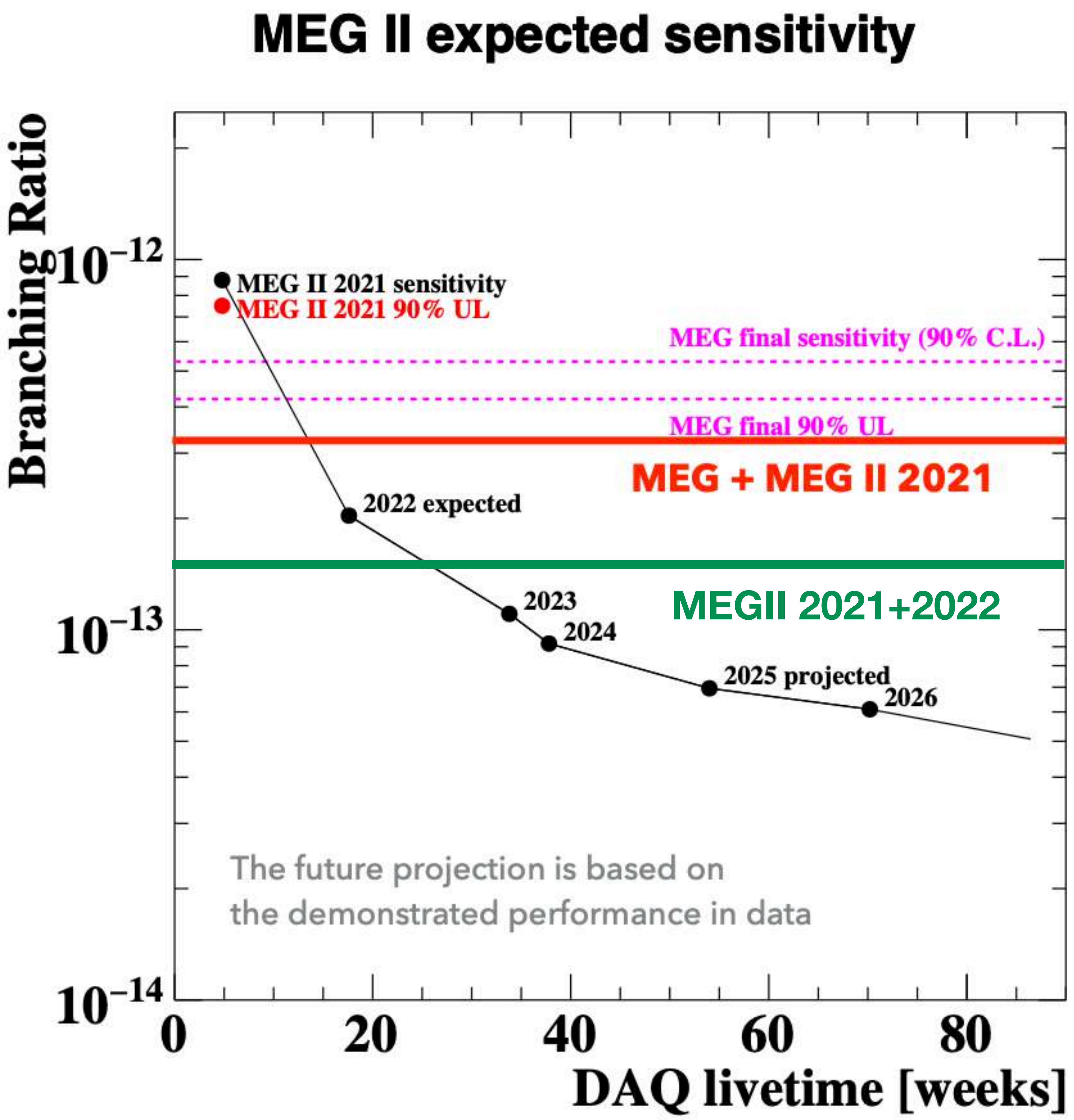
$$\mathcal{B}_{90} = 1.5\times10^{-13}$$

Where we are…

- The analysis of the 2023 data is progressing in parallel



Where we are aiming at…



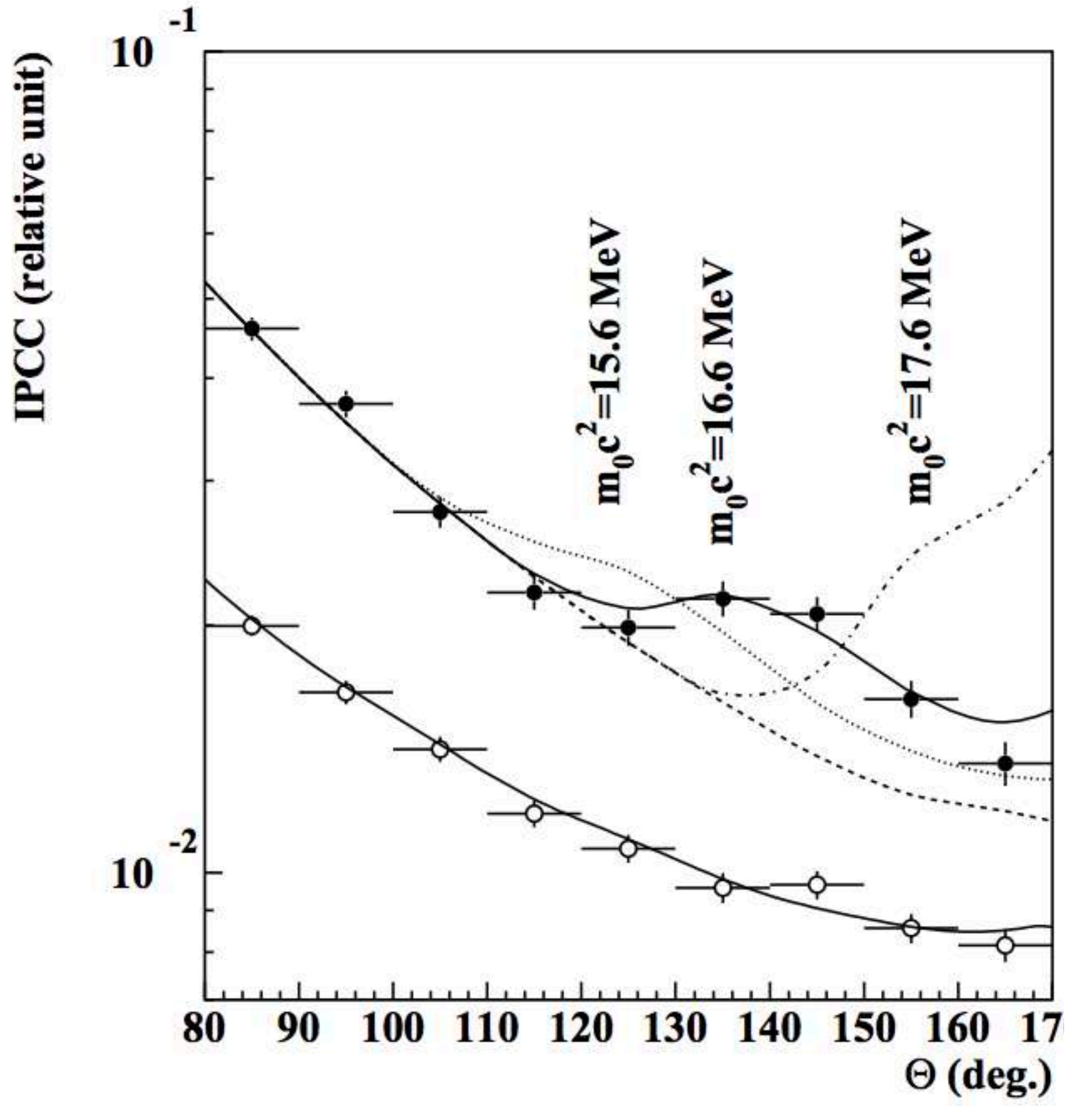
The beryllium anomaly

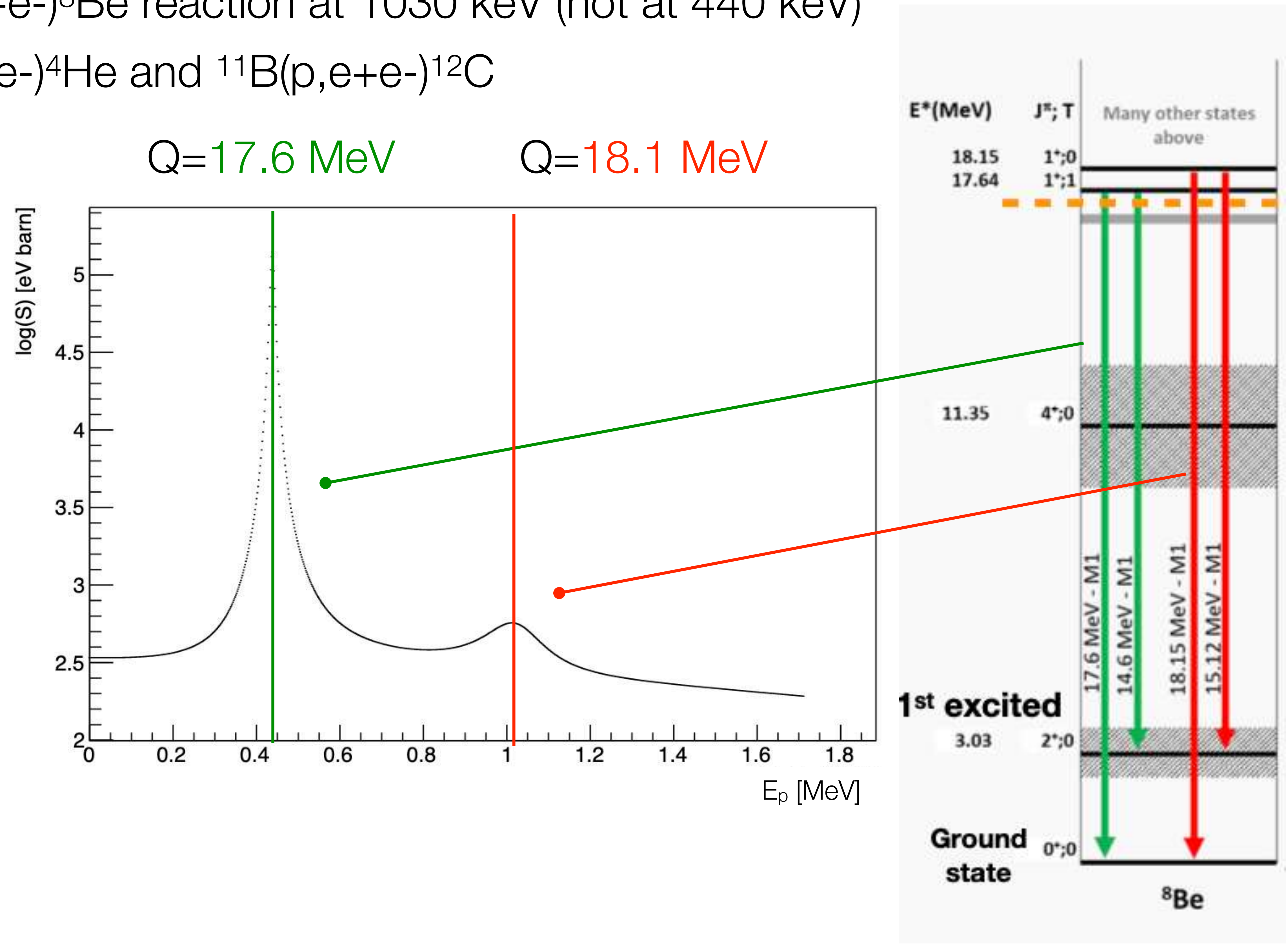
- Hint for the production of a neutral, 17 MeV boson, potential mediator of a fifth force: X17 (ATOMKI collaboration)
  - Observed in the $^{7}Li(p, e+e-)^{8}Be$ reaction at 1030 keV (not at 440 keV)
  - Observed in the $^{3}H(p,e+e-)^{4}He$ and $^{11}B(p,e+e-)^{12}C$

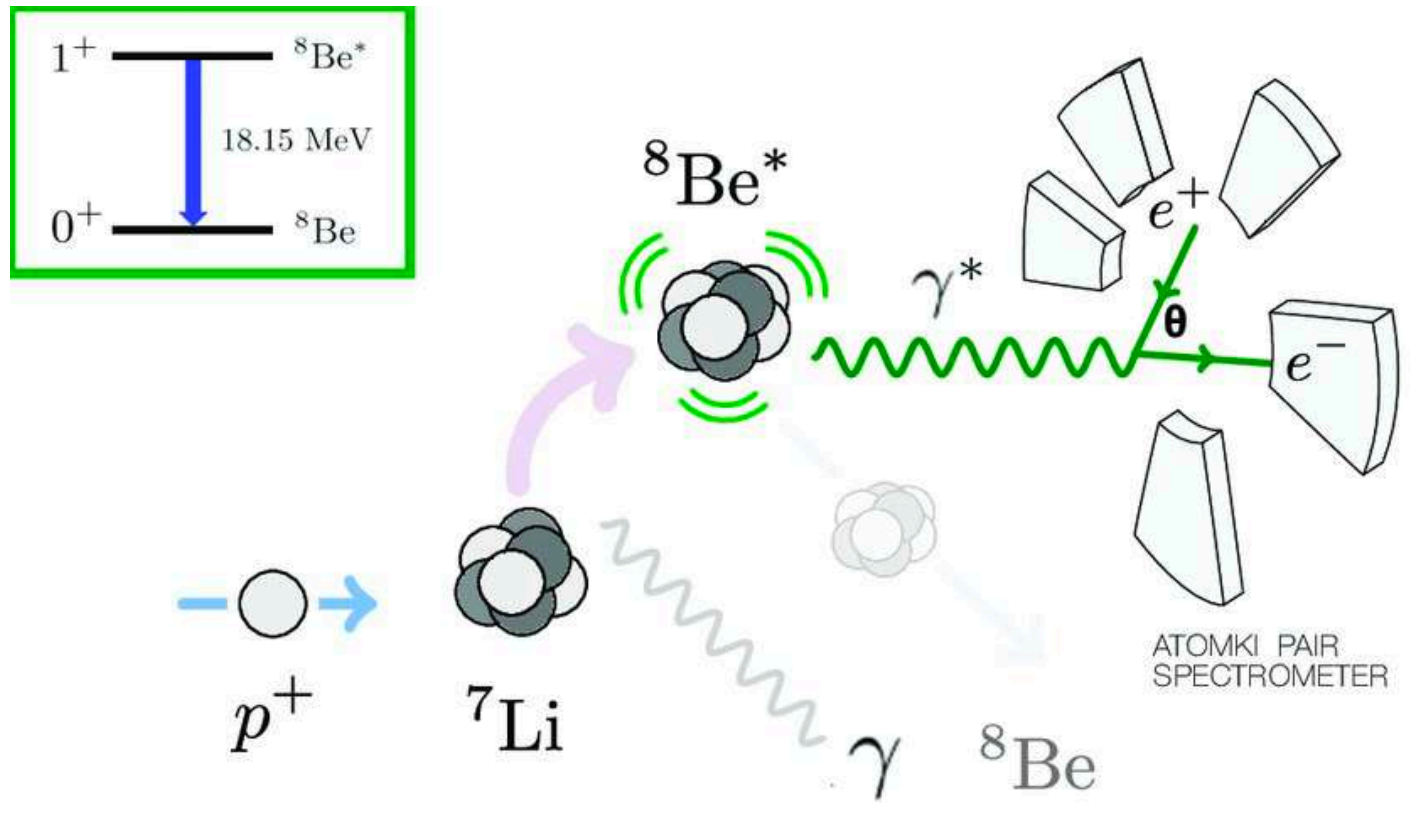
Phys. Rev. Lett. 116, 042501
arXiv:2205.07744

Phys. Rev. C 104, 044003

Phys. Rev. D 95, 035017







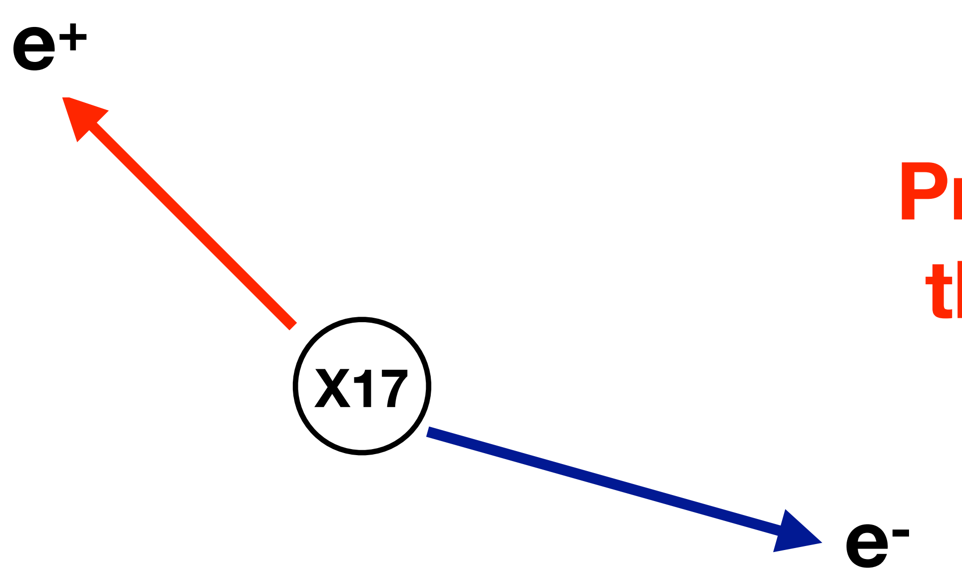
Excess consistent with

- Light boson mass = 16.95 MeV/c^2
- Branching ratio (X17/gamma) = 6×10^{-6}

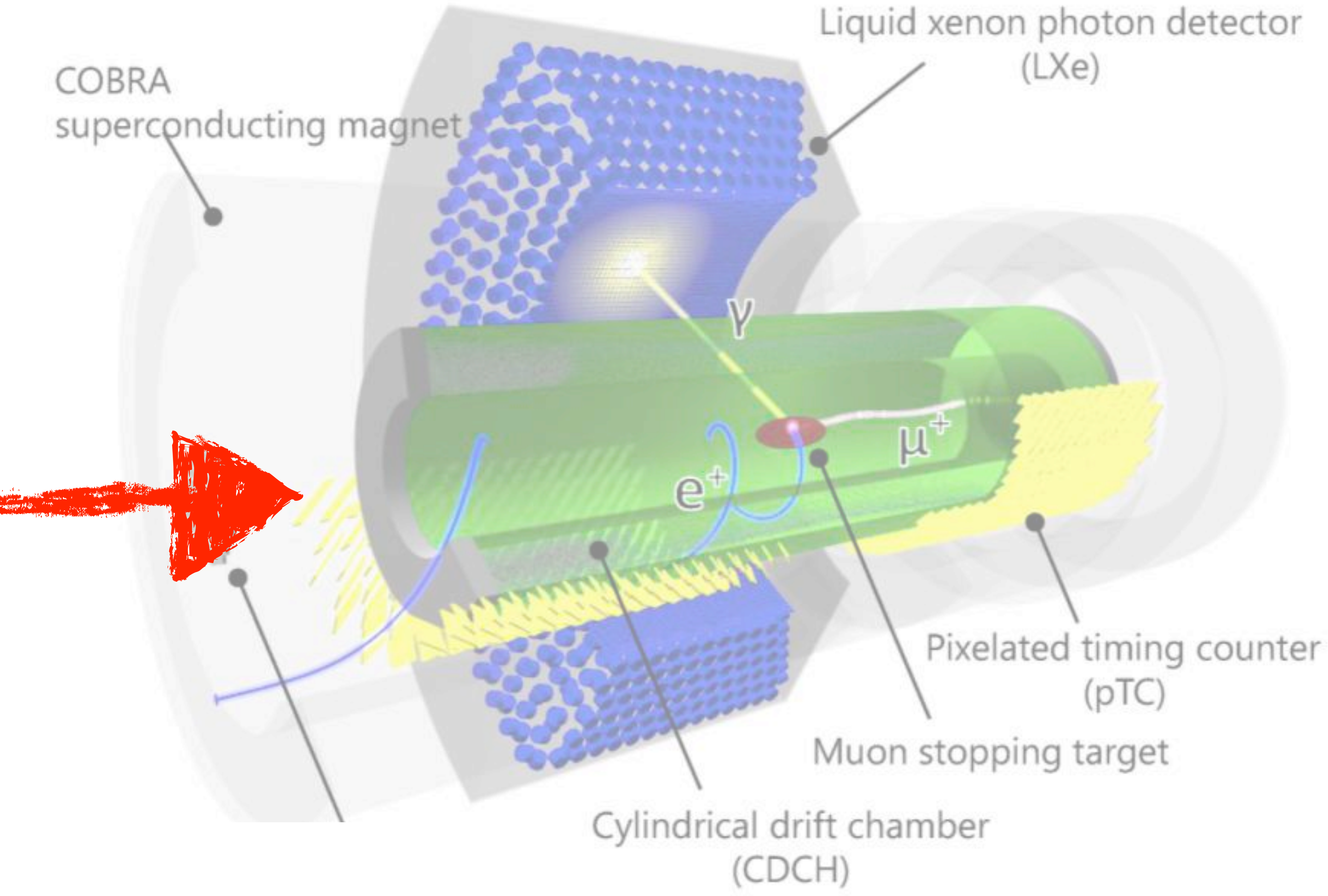
The X17 search with the MEG II apparatus: Signal and backgrounds

- Signal, background and experimental apparatus

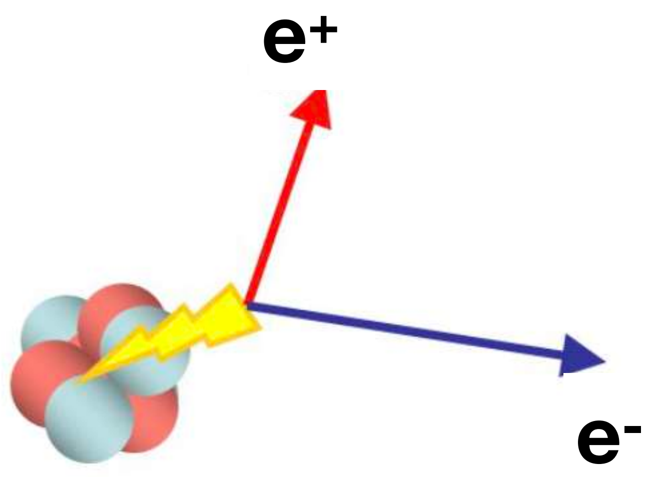
Signal



Proton beam for the X17-Boson search



Backgrounds



Gamma Internal and External Pair Conversion (IPC, EPC)
- IPC: Resonant and non-resonant
- EPC: Experimental setup material budget

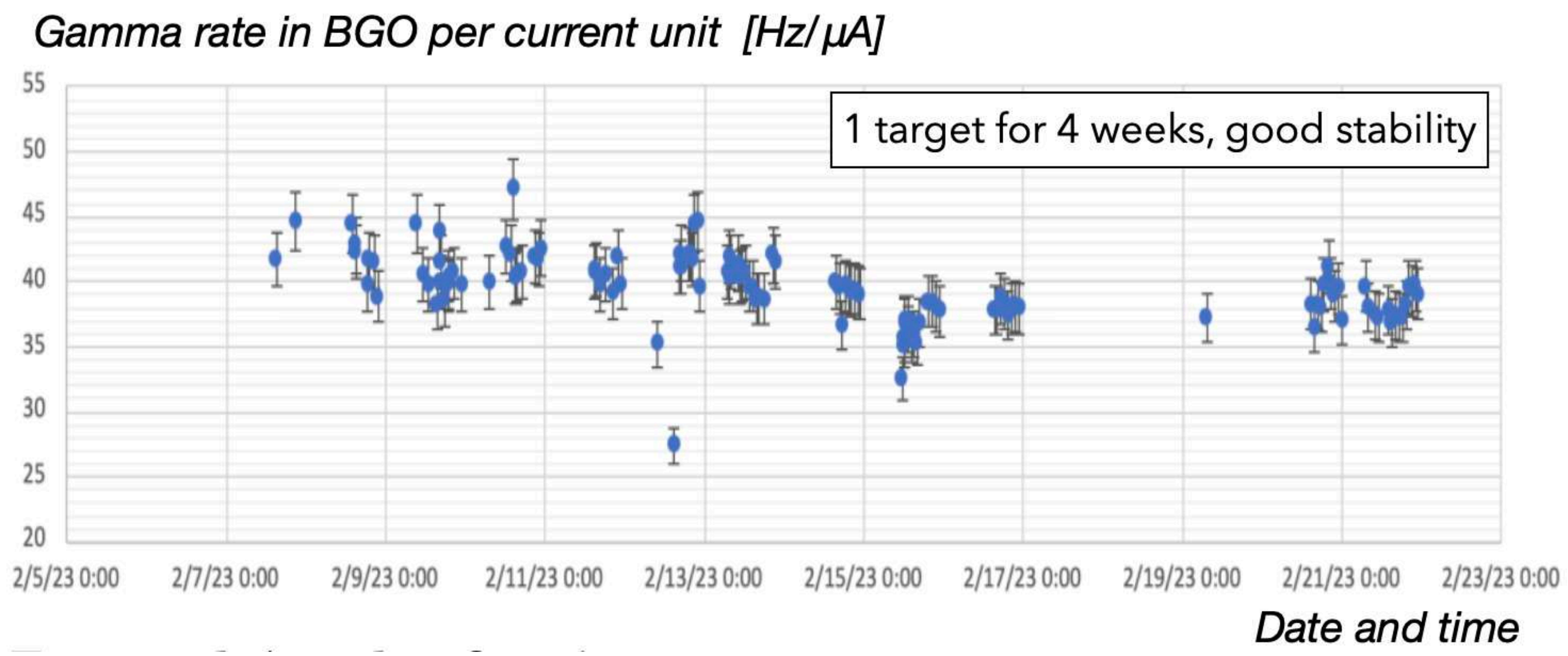
with MEG II

→ Detection in an **extended** angular range

Collected data sample

- **Pivotal** run **2022**: Proton beam tuning, Mechanical/integration test of the new parts, LiF and LiPON target test, Different trigger settings, Optimised Data Taking and Reconstruction Algorithms

- **Physics** run **2023**: 4 weeks producing mainly the 17.6 MeV gamma-line
  - Proton energy at 1080 keV
  - Beam composition: H+ (~75%) and H2+(~25%)
  - Thick LiPON (~7 um)
  - Both 440 keV and 1030 keV excited simultaneously



- Statistics:
  - ~75 M Events
  - ~**500 K** Events Reconstructed pairs

- On full range of the Esum and Angular Opening angle observables:
  - ~60% EPC (Dominant at low angle), ~40% IPC (Dominant in the signal region)

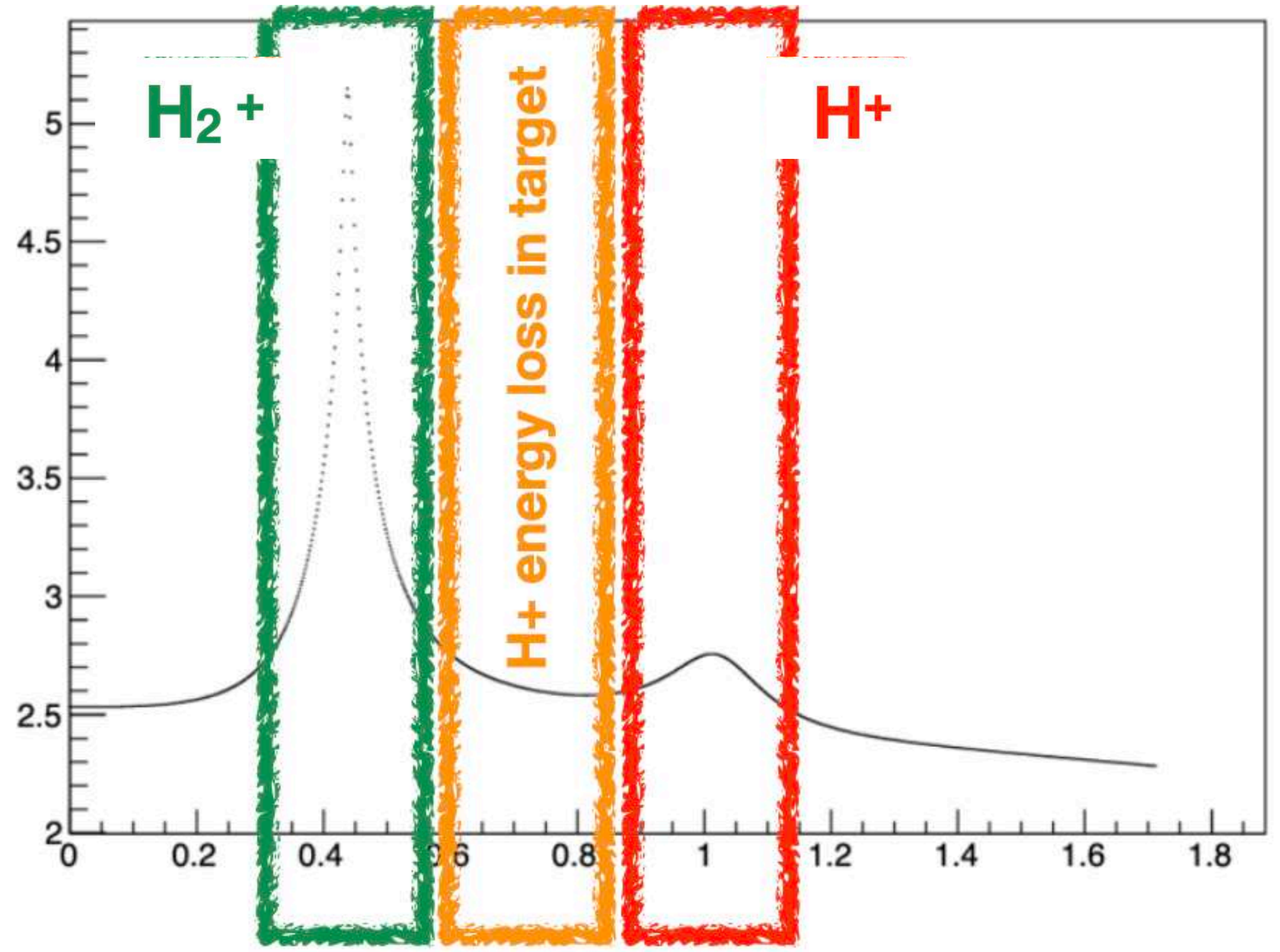
Analysis strategy

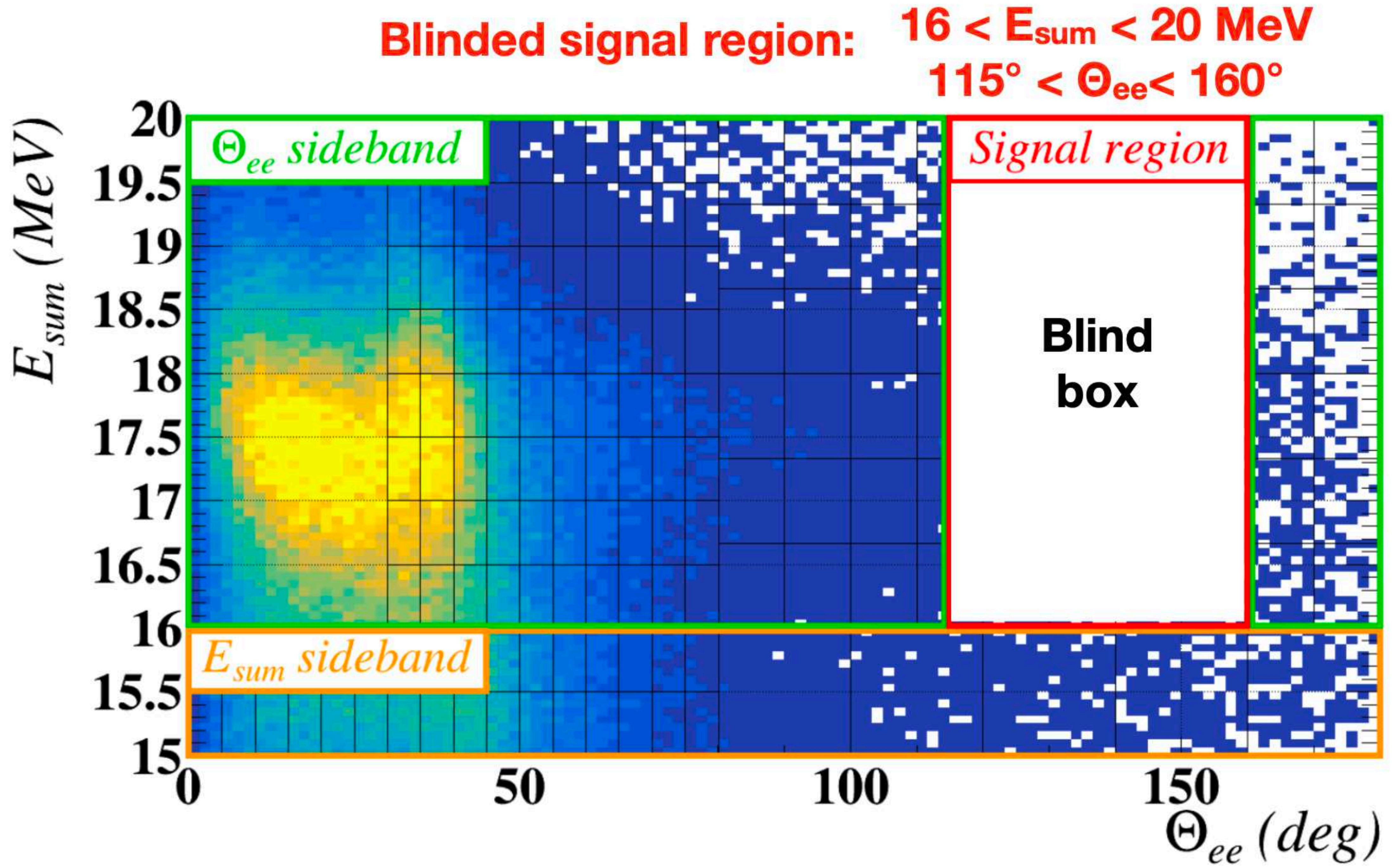
- 2D Likelihood maximization: $\mathbf{E_{sum} = E_{e+} + E_{e-}}$ vs **Angular Opening** Observables
  - Likelihood parametrised in terms of relative BF

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

- Blinded **Signal Region**
- Background studies on the **Side Bands**

- **Two** signal PDF's
  - One per resonance
  - Q =17.6 and Q=18.1 MeV
- **Six** IPC PDF's
  - Three Ep bins
  - Two transition (g.s and 1st excited s.) each
- **Two** EPC PDF's
  - No Ep dependence
  - Two transition
- **One** fake pairs PDF

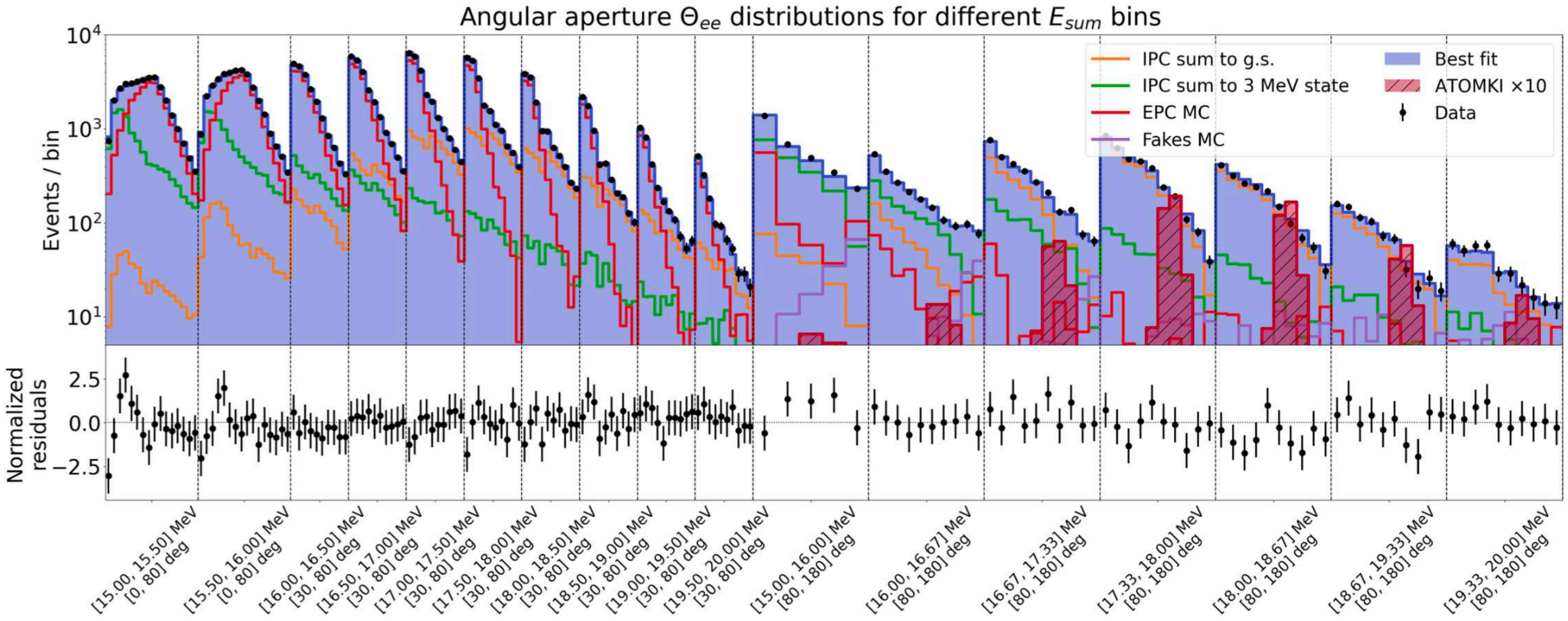




Results from the ML fit

Best fit

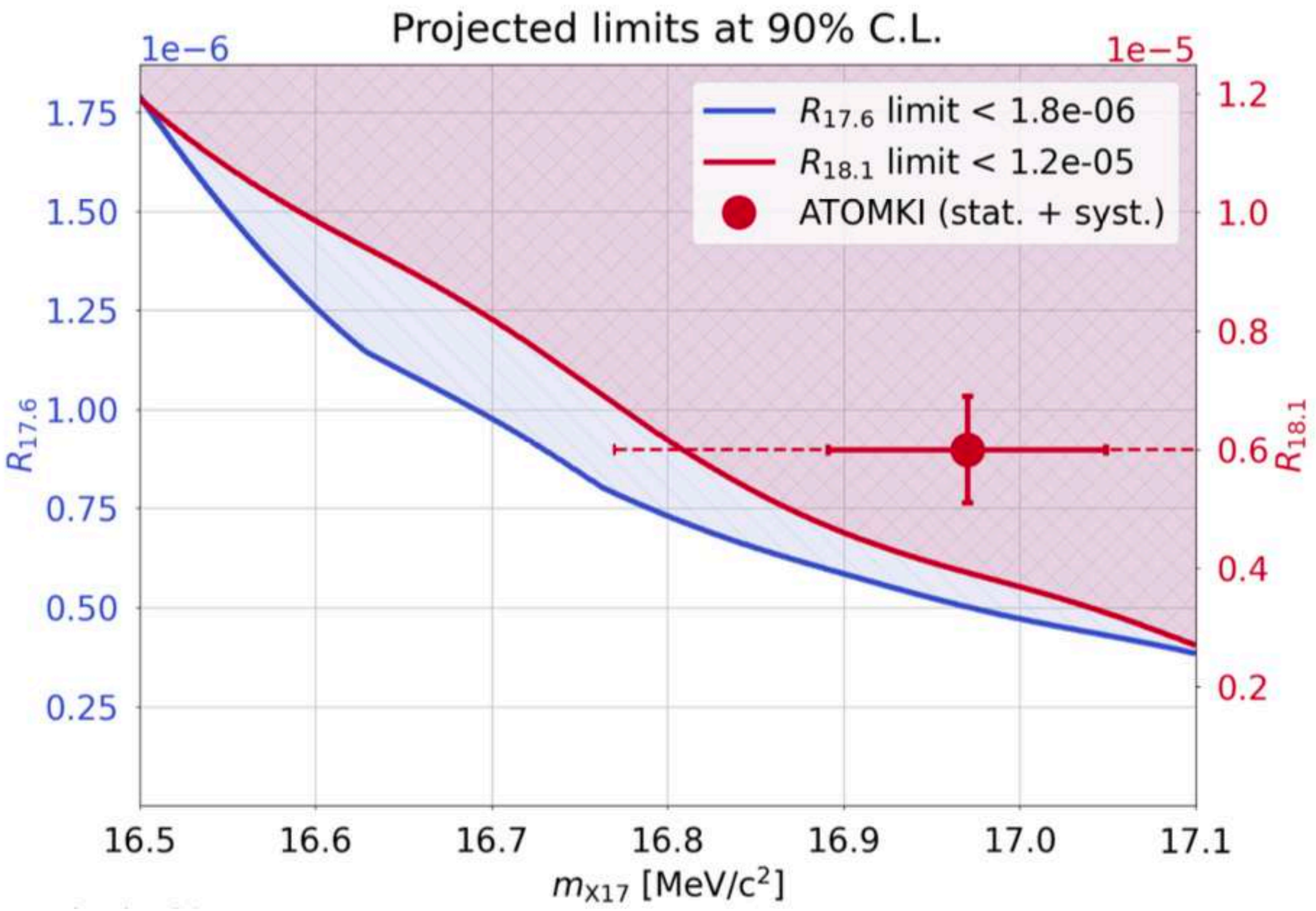
- Sample of **17.6 MeV** [78.4%] **and 18.1 MeV** [21.6%]
- **10+-92 signal events at Q = 18.1** MeV for a mX17 = 16.5 MeV, O(100) expected based on ATOMKI
- **0+-68 signal event at Q = 17.6** MeV - for a mX17 = 16.5 MeV, O(300) expected based on ATOMKI/Feng et al.
- IPC: **12.6**(9)% Q = 18.1 MeV and **45.8**(13)% Q = 17.6 MeV
- Goodness-of-fit: p-value = **10%**



Afanaciev K., et al (MEG II collaboration)
Eur. Phys. J. C 85 (2025) 7, 763

90% Confidence Limits

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



$R_{17.6.}$ < 1.8 x 10^{-6}

corresponding to Nsig (17.6) < 200

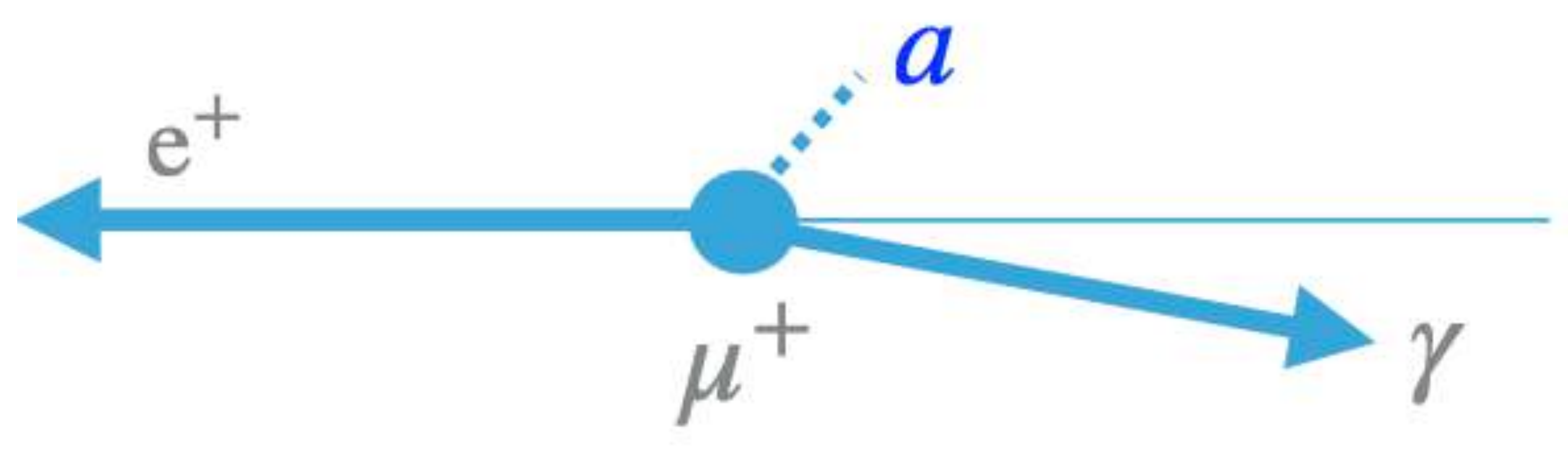
$R_{18.1.}$ < 1.2 x 10^{-5}

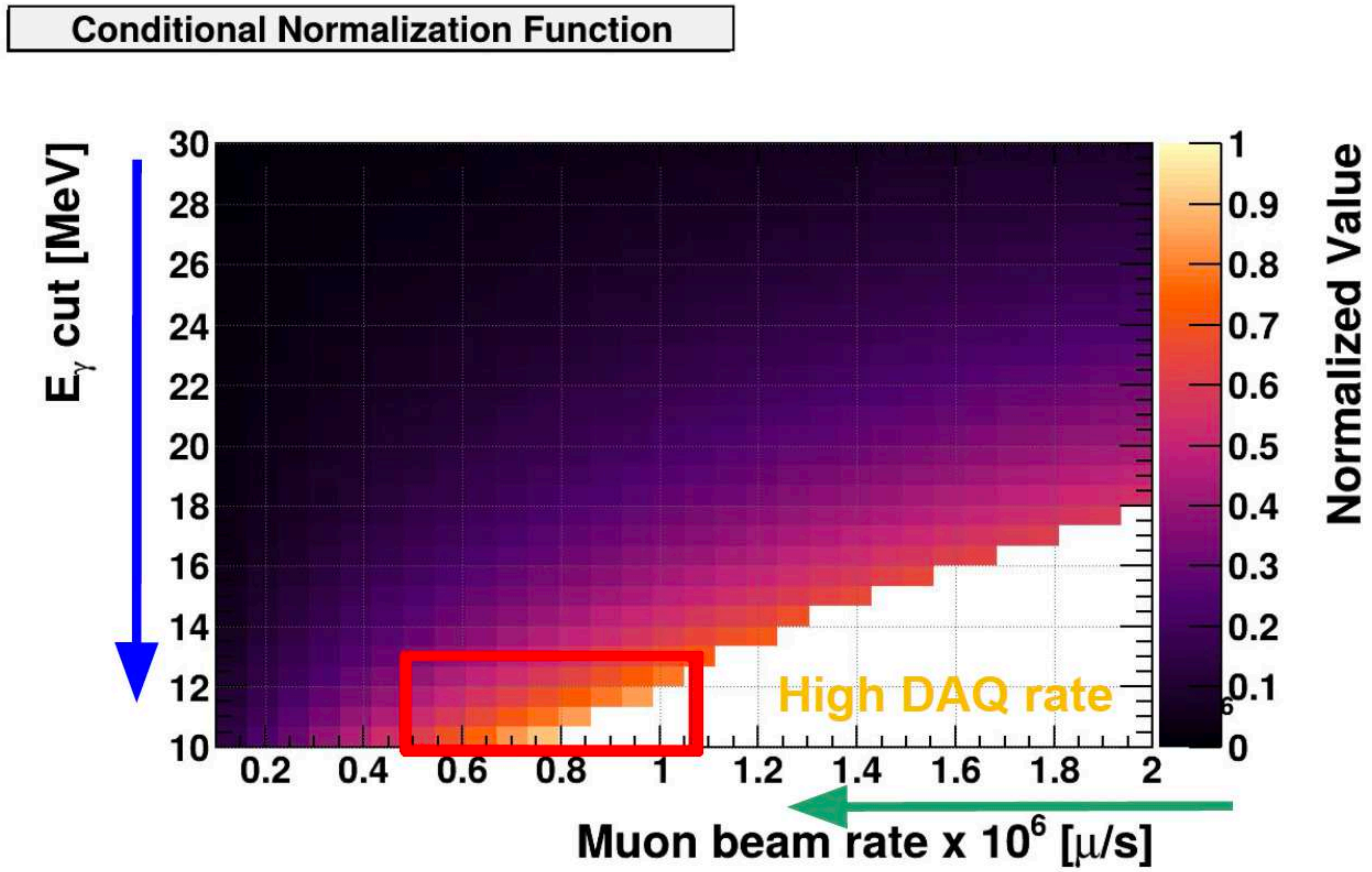
corresponding to Nsig (18.1) < 230

- MEGII plans to continue X17 data taking during the next HIPA shutdown 2026, Exploiting further the only 1030 keV resonance (assuming NO conflicts with the main MEG data taking)

Axion-like particle (ALP) searches with MEGII

- The muon decay to ALP should just look like a radiative muon decay (RMD)
- It features different topology from MEG decay → 3 body instead of 2 in the final state
    - different trigger selections to maximize signal acceptance
        - low photon energy cut → Eg > 10 MeV
        - no back to back topology
        - need for lower beam rate to keep the trigger under 50 Hz
- Use calibration data taken for a few days with low photon energy (>18MeV) at low beam rate (~10^6/sec)





Axion-like particle (ALP) searches with MEGII

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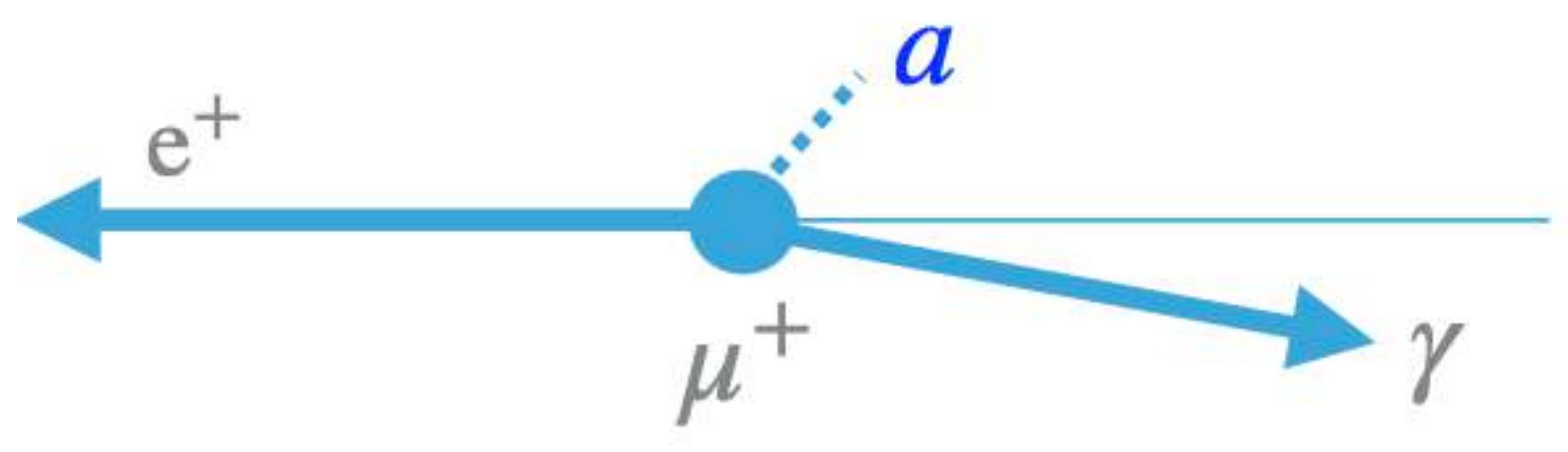
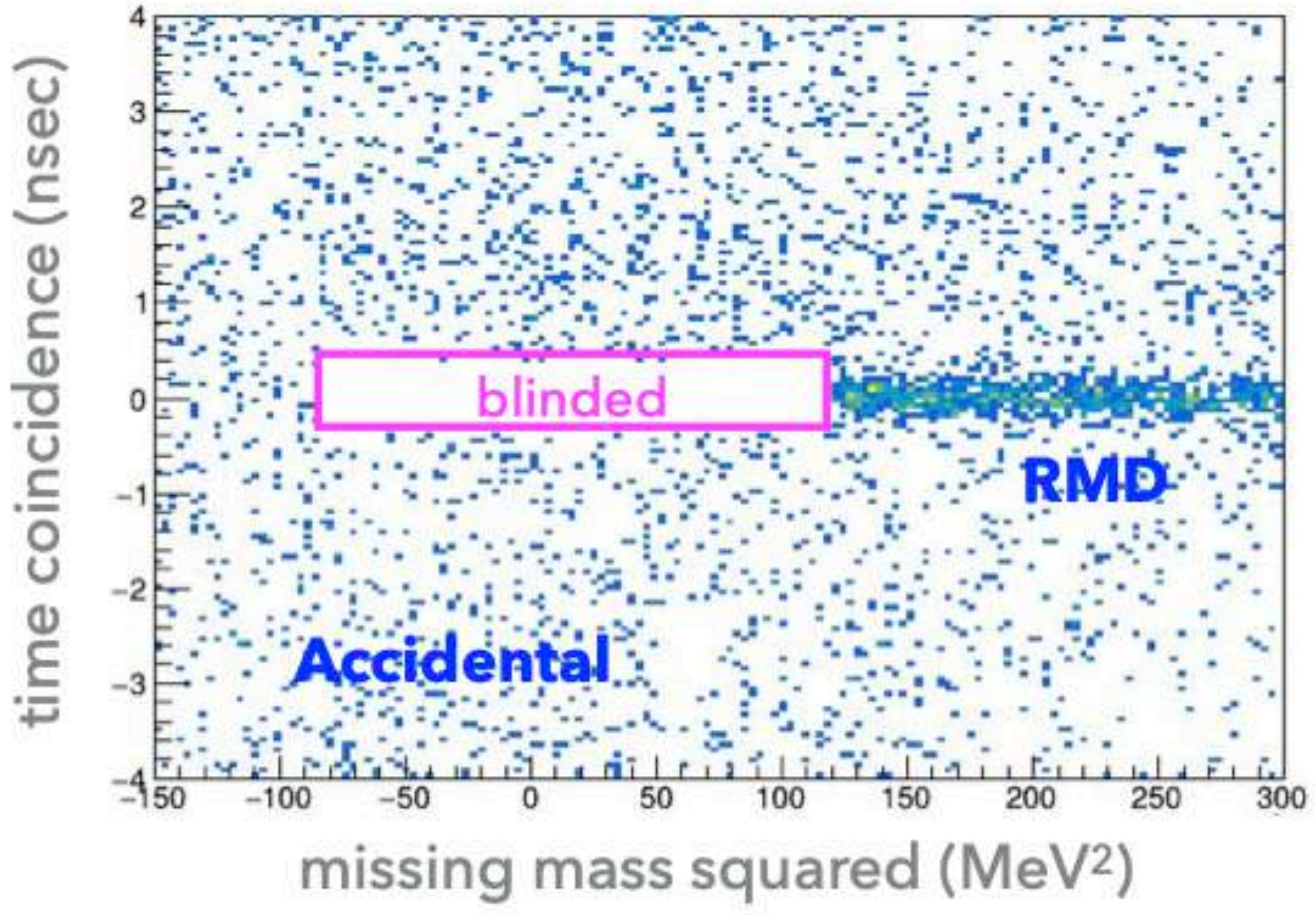
    - need for lower beam rate to keep the trigger under 50 Hz
- Use calibration data taken for a few days with low photon energy (>18MeV) at low beam rate (~10^6/sec)
- **The ongoing analysis indicates that we can exceed the TWIST limit**





Summary

- Astonishing sensitivities in muon precision physics at intensity frontiers are ongoing and foreseen for the incoming future
- **Rare/forbidden decay searches, precision measurements and symmetry tests remain among the most exciting places where to search for new physics with strong synergy and connection with the energy and cosmology frontiers**
- MEGII started data taking since 2021 and is expected to accomplish his scientific aim collecting all needed data by 2026
  - **A new upper limit on the $\mu^+ \to e^+ \gamma$** decay has been set based on the 2021+2022 data: **B (90% CL) < 1.5 10^{-13}**
- More exotic searches are also ongoing with the MEGII apparatus
  - The X17 search: Based on the 2023 data set, the ATOMKI observation - **hypothesis of X17** production via the decay of only the 18.1 MeV excited ^{8}Be state - **is excluded at 94% C.L.**
    - MEGII plans to continue X17 data taking during the next HIPA shutdown 2026, exploiting further the only 1030 keV resonance (assuming NO conflicts with the main MEG data taking)
  - The **cLFV ALPs** search: MC sensitivity using only the **2021+2022** datasets statistics shows that we can exceed the TWIST limit
  - **Analysis** expected to be **completed** by end of 2025

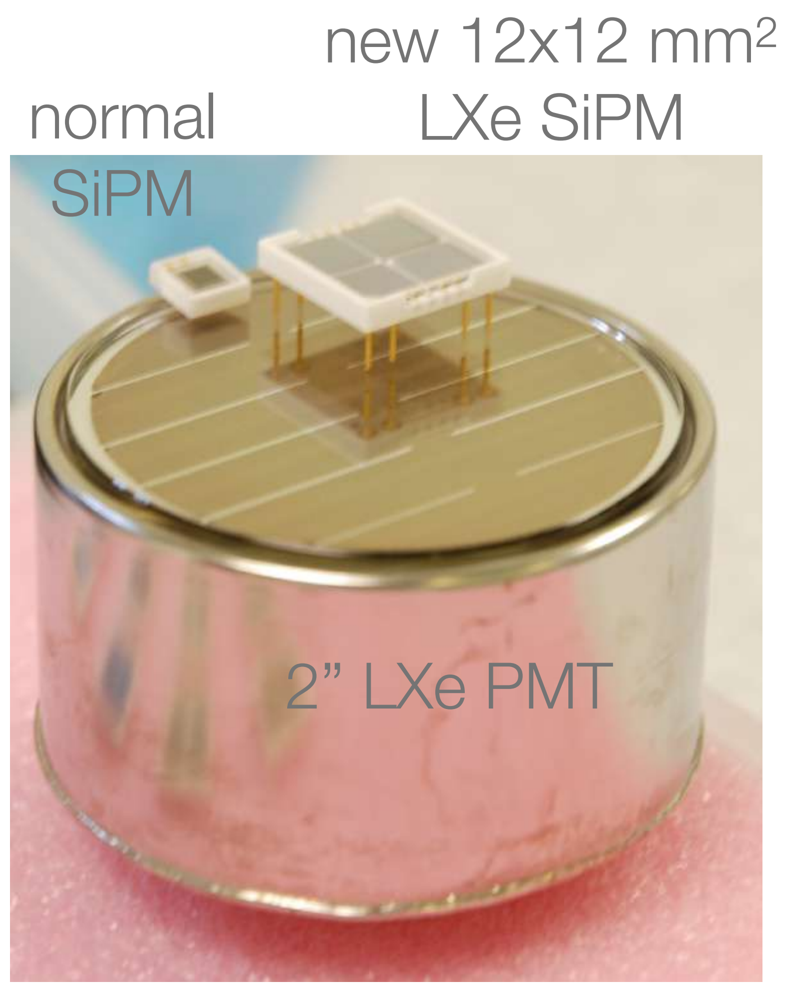
The MEGII collaboration

Thanks a lot for your attention !!!

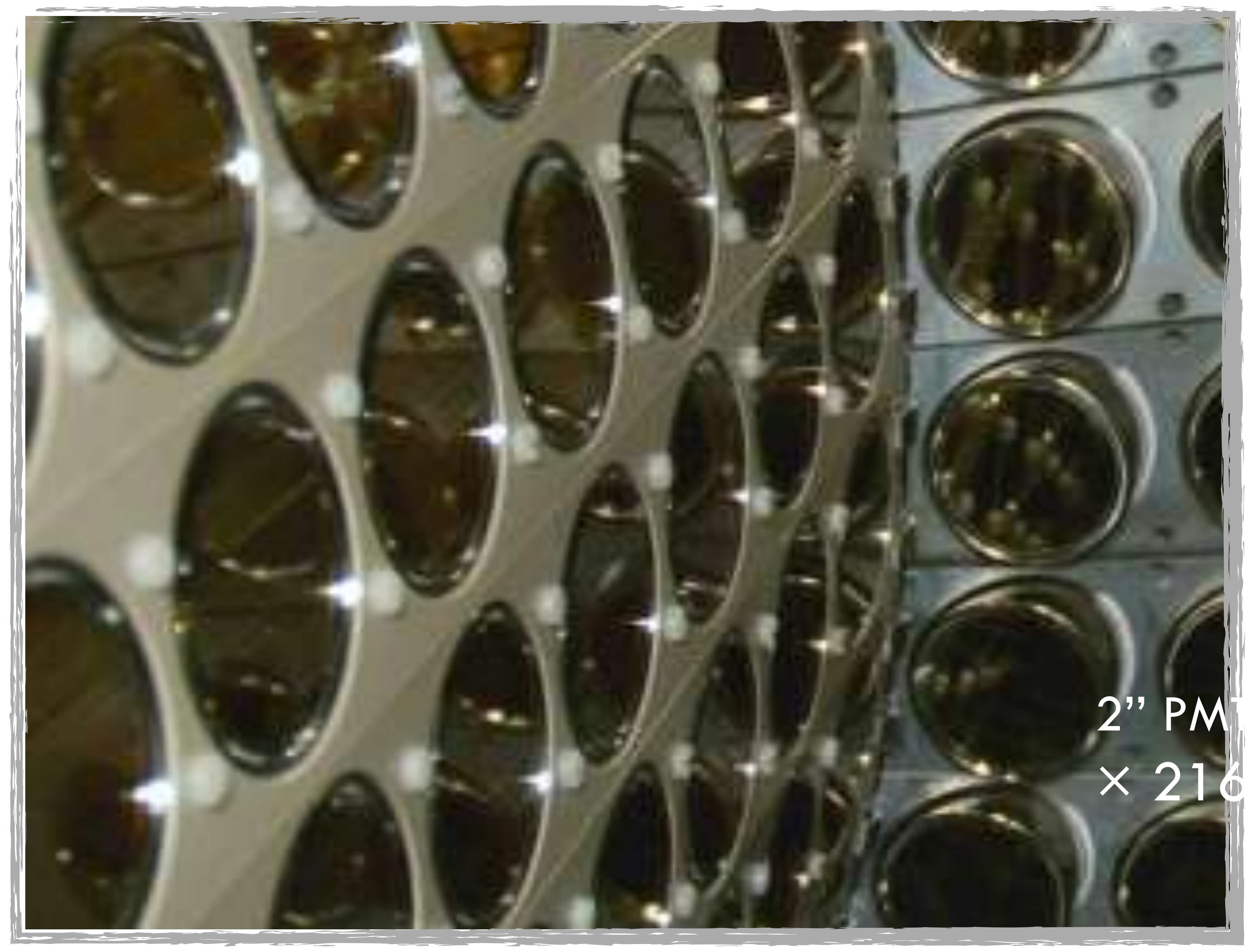
Back-up

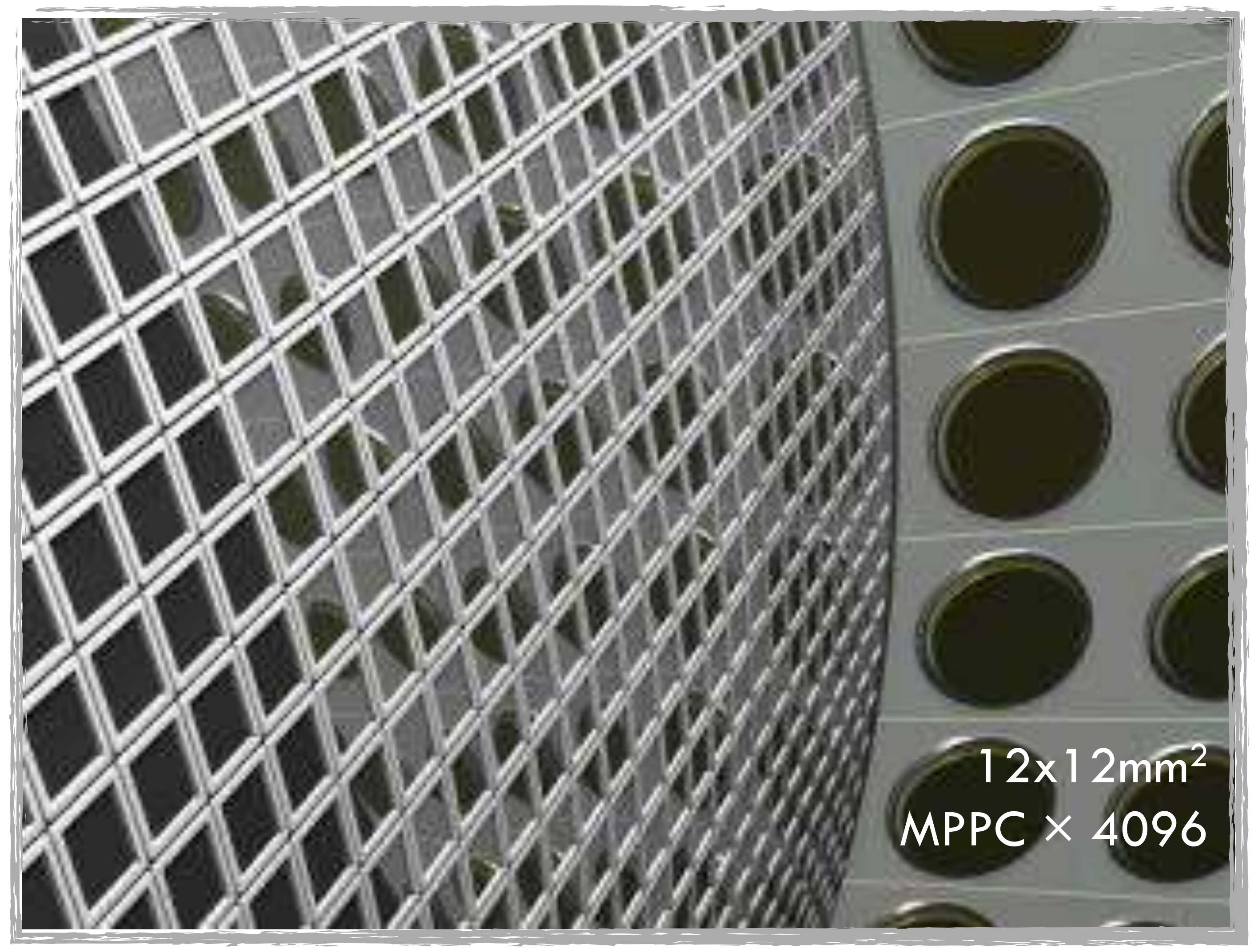
MEGII: The upgraded LXe calorimeter

- Increased uniformity/resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency

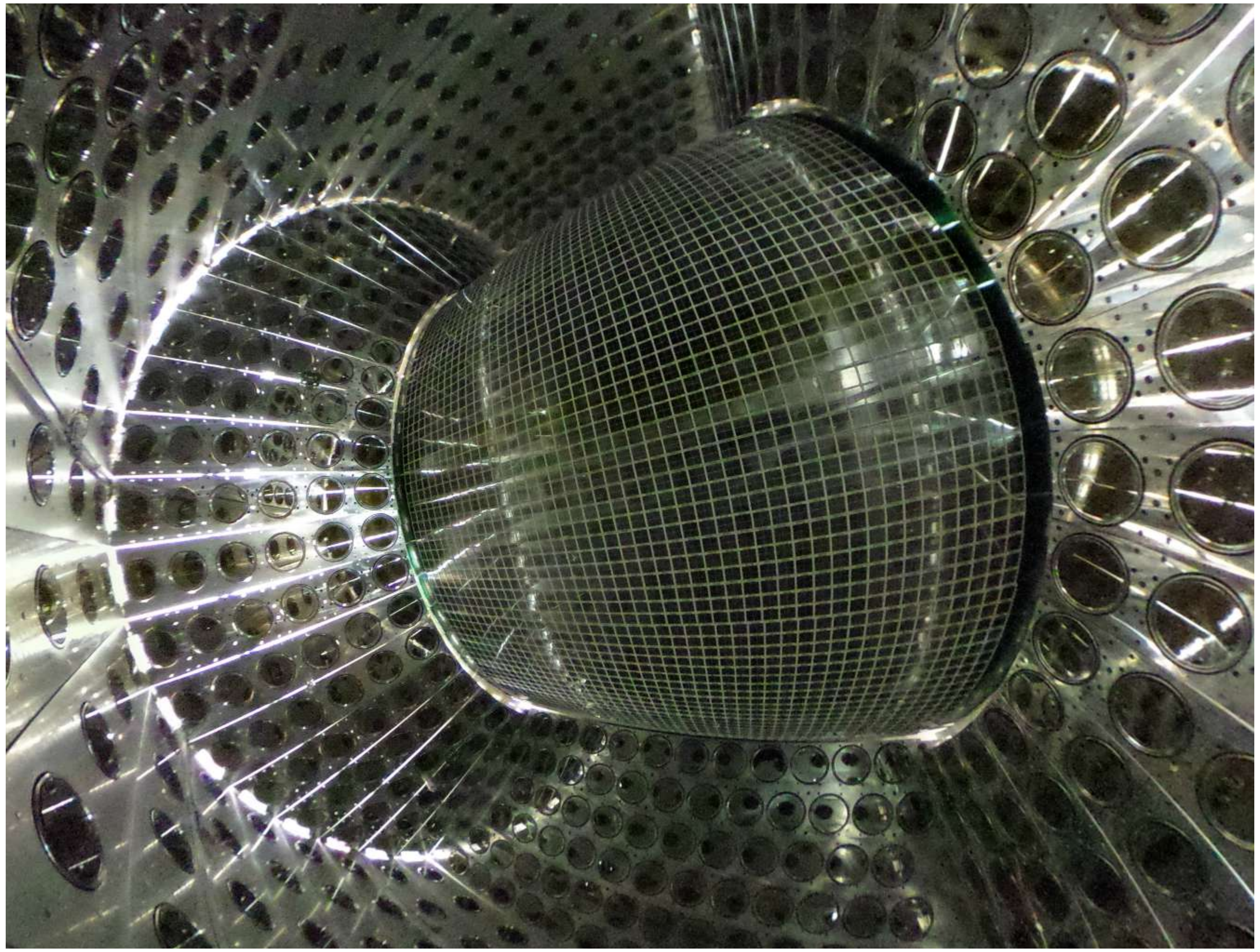


	MEG	MEGII
u [mm]	5	2,4
v [mm]	5	2,2
w [mm]	6	3,1
E [w<2cm]	2,4%	1,1%
E [w>2cm] (w<2cm)m)	1,7%	1,0%
t [ps]	67	60

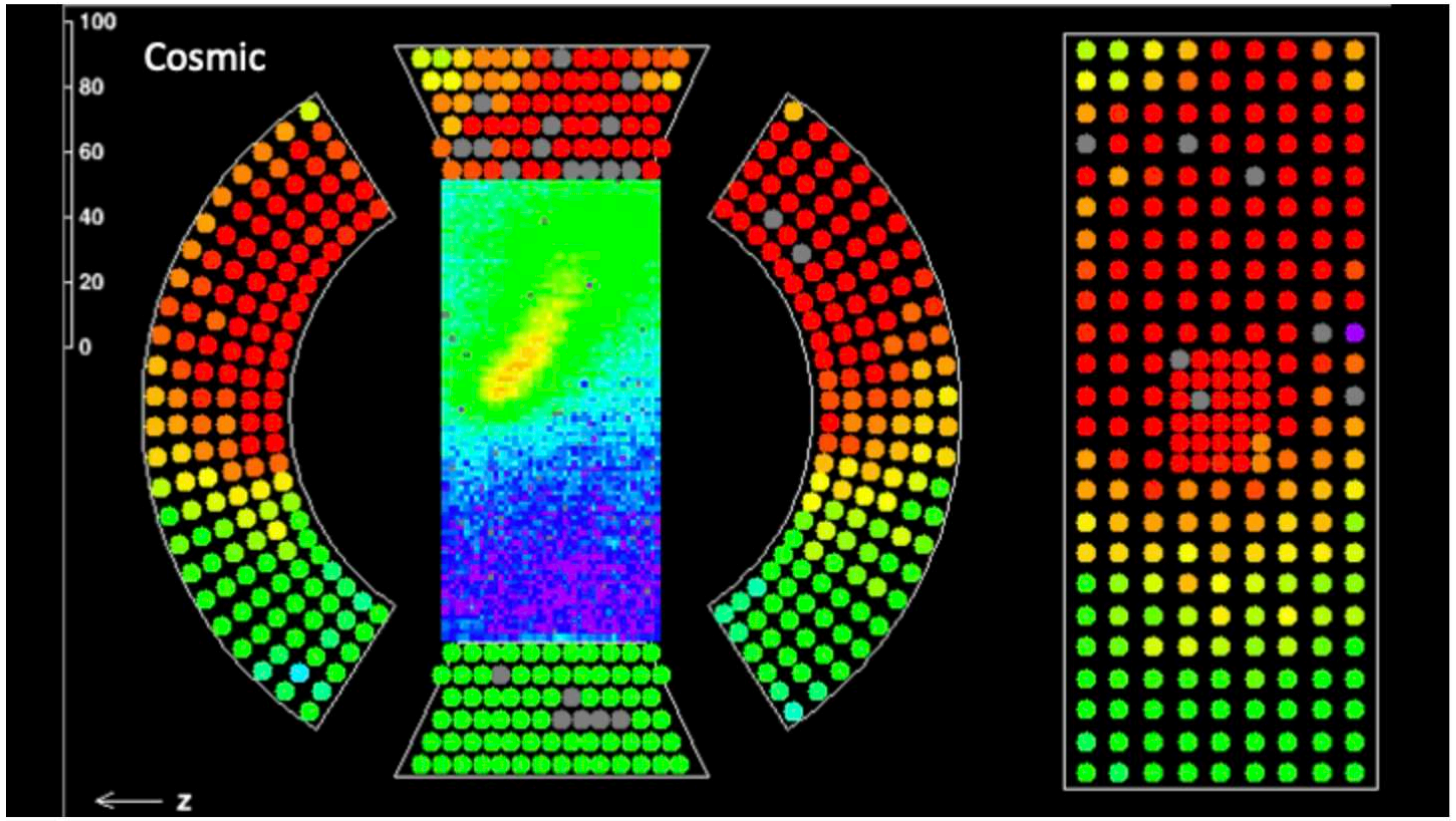


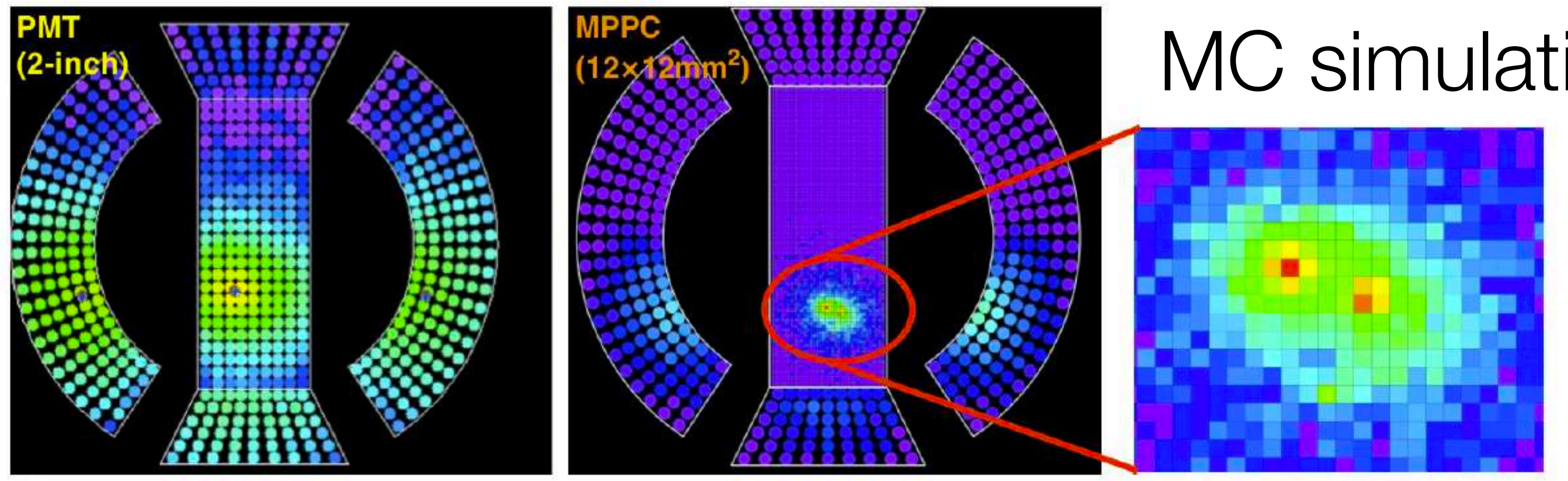


MEGII: The upgraded LXe calorimeter



Data





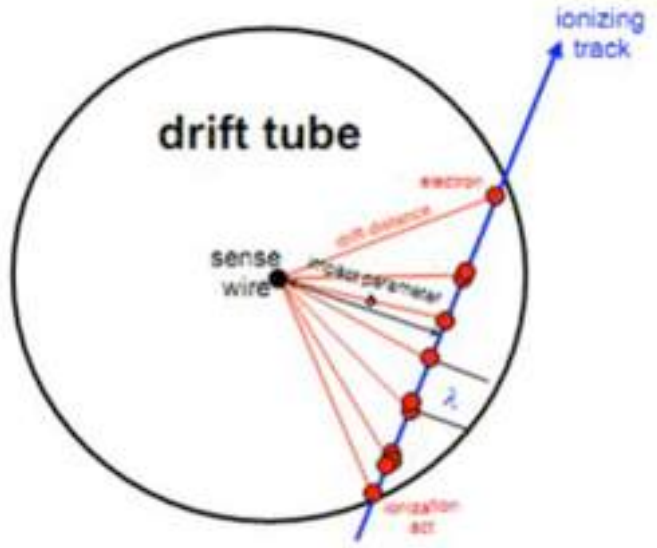
MC simulation

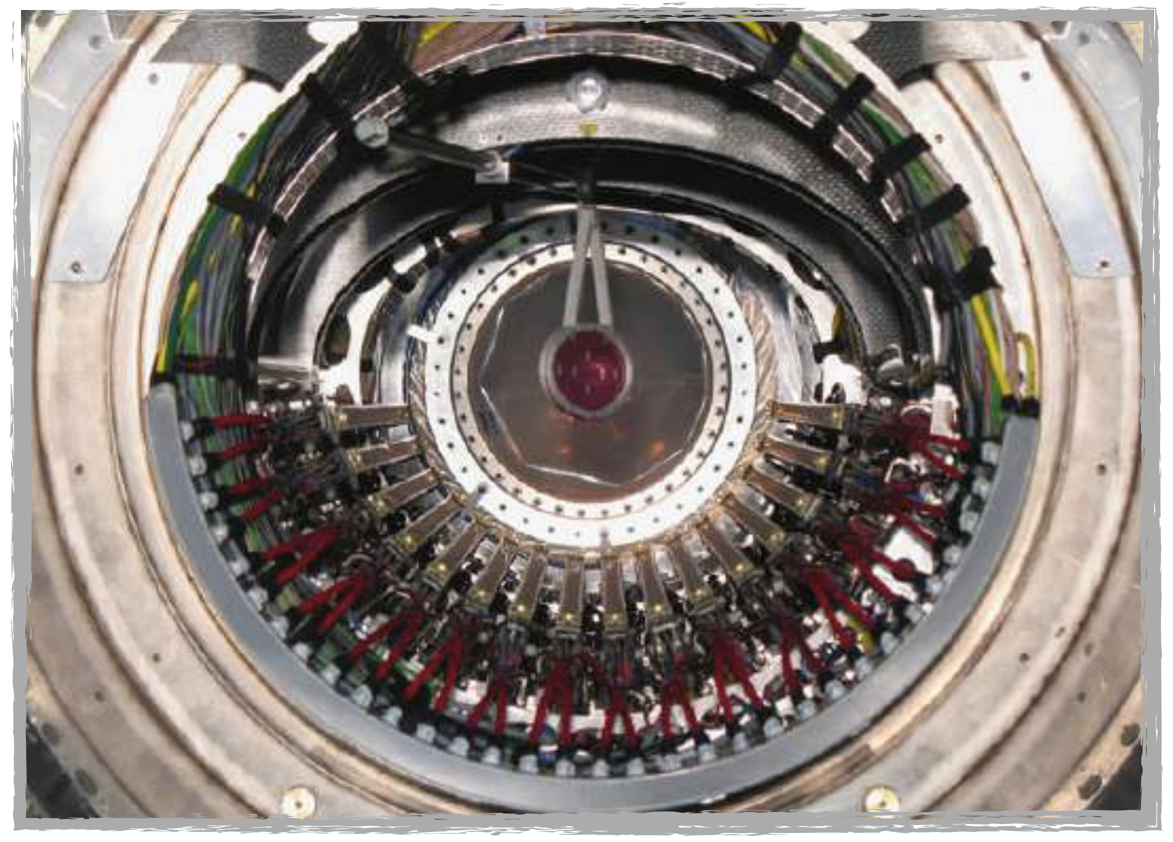
MEGII: The new single volume chamber

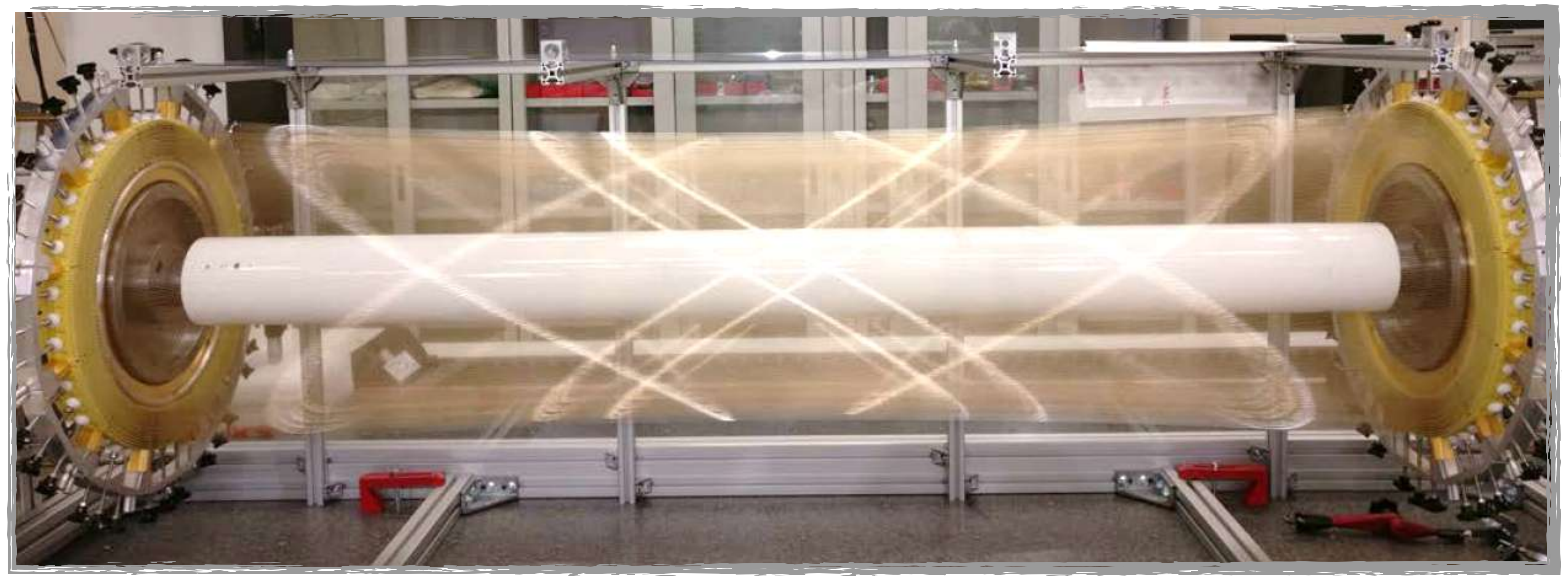
- Improved hit resolution: σ_r ~< 120 um (210 um)
- High granularity/Increased number of hits per track/ cluster timing technique
- Less material (helium: isobutane = 90:10, $1.6 \times 10^{-3}\ X_0$)
- High transparency towards the TC
- Detector performance in final conditions: analysis ongoing

	MEG	MEGII
p [keV]	306	90
θ [mrad]	9,4	6,3
ϕ [mrad]	8,7	5,0
ϵ [%]*	40	70

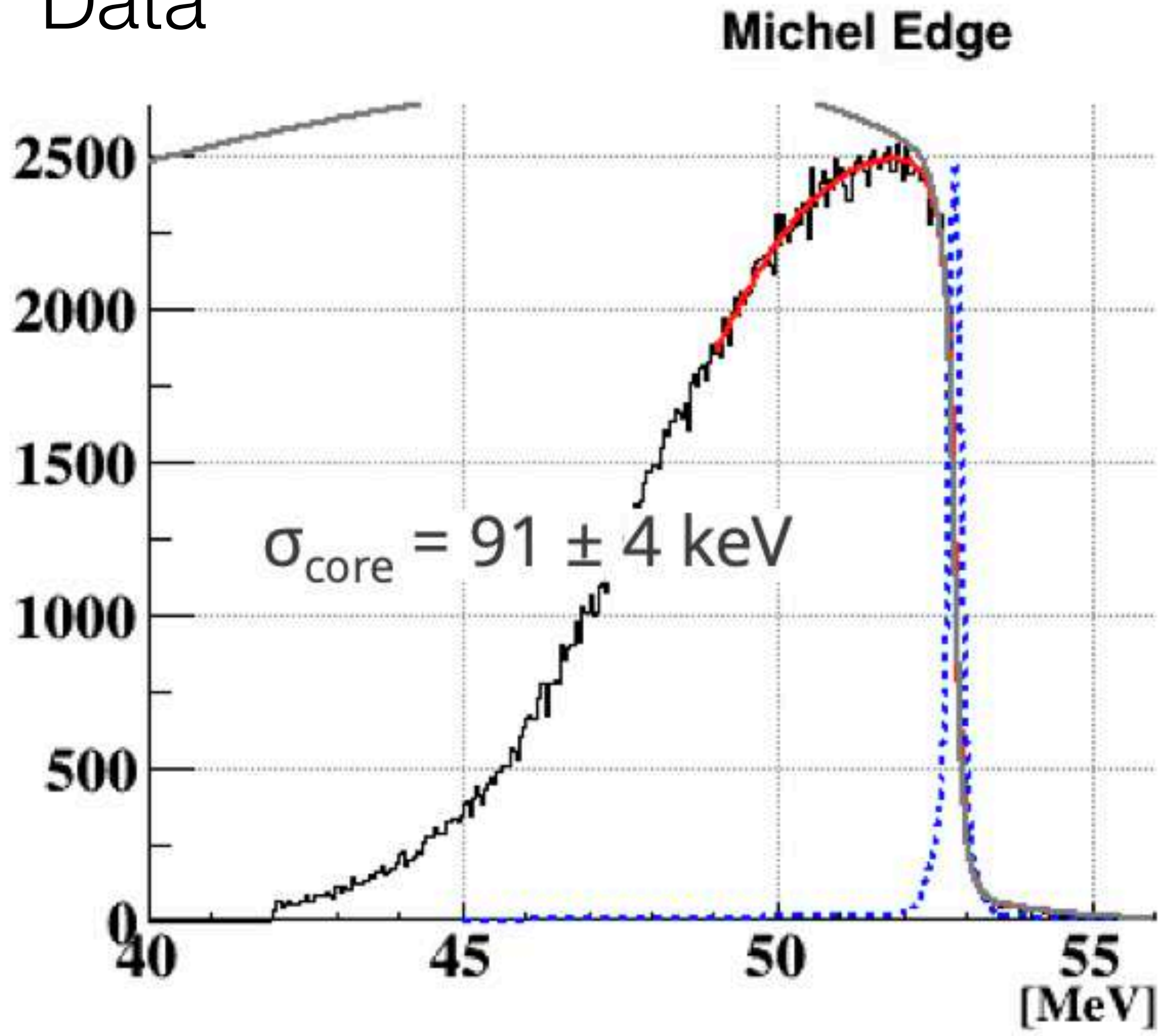
(*) It includes also the matching with the Timing Counter





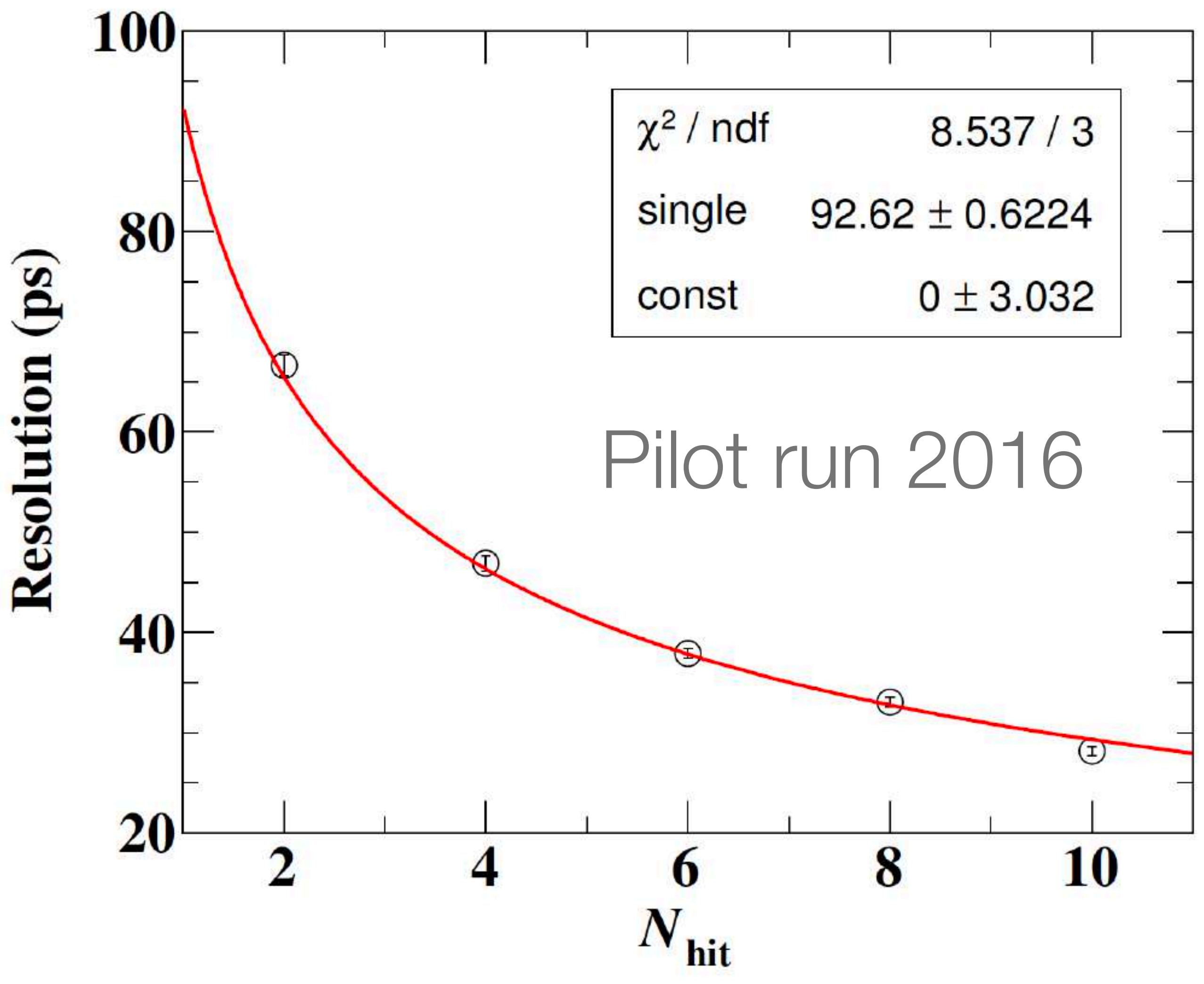


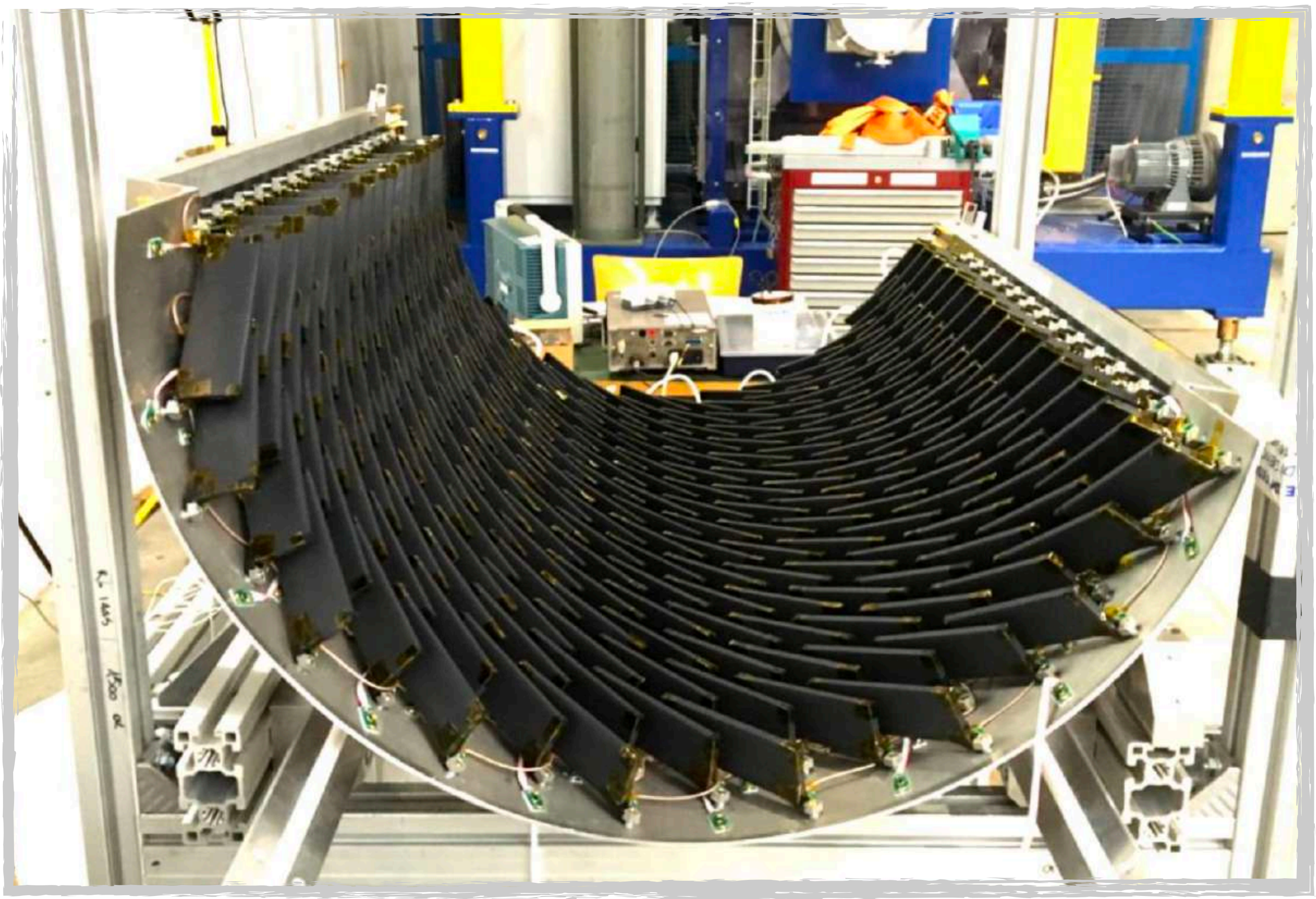
Data



MEGII: the pixelized Timing Counter

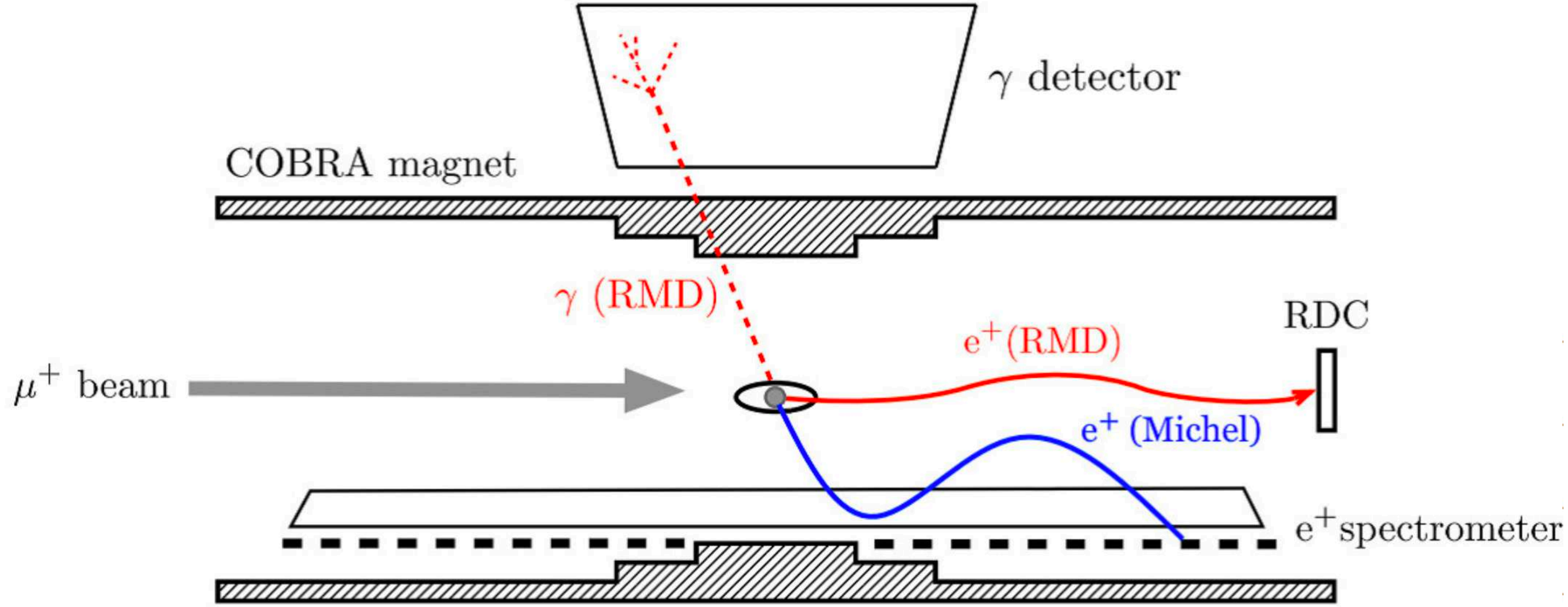
- Higher granularity: 2 x 256 of BC422 scintillator plates (120 x 40 (or 50) x 5 mm³) readout by AdvanSiD SiPM ASD-NUM3S-P-50-High-Gain
- Improved timing resolution: from 70 ps to 35 ps (multi-hits)
- Less multiple scattering and pile-up
- Assembly: Completed
- Expected detector performances confirmed with data during pre-eng. 2016 and 2017

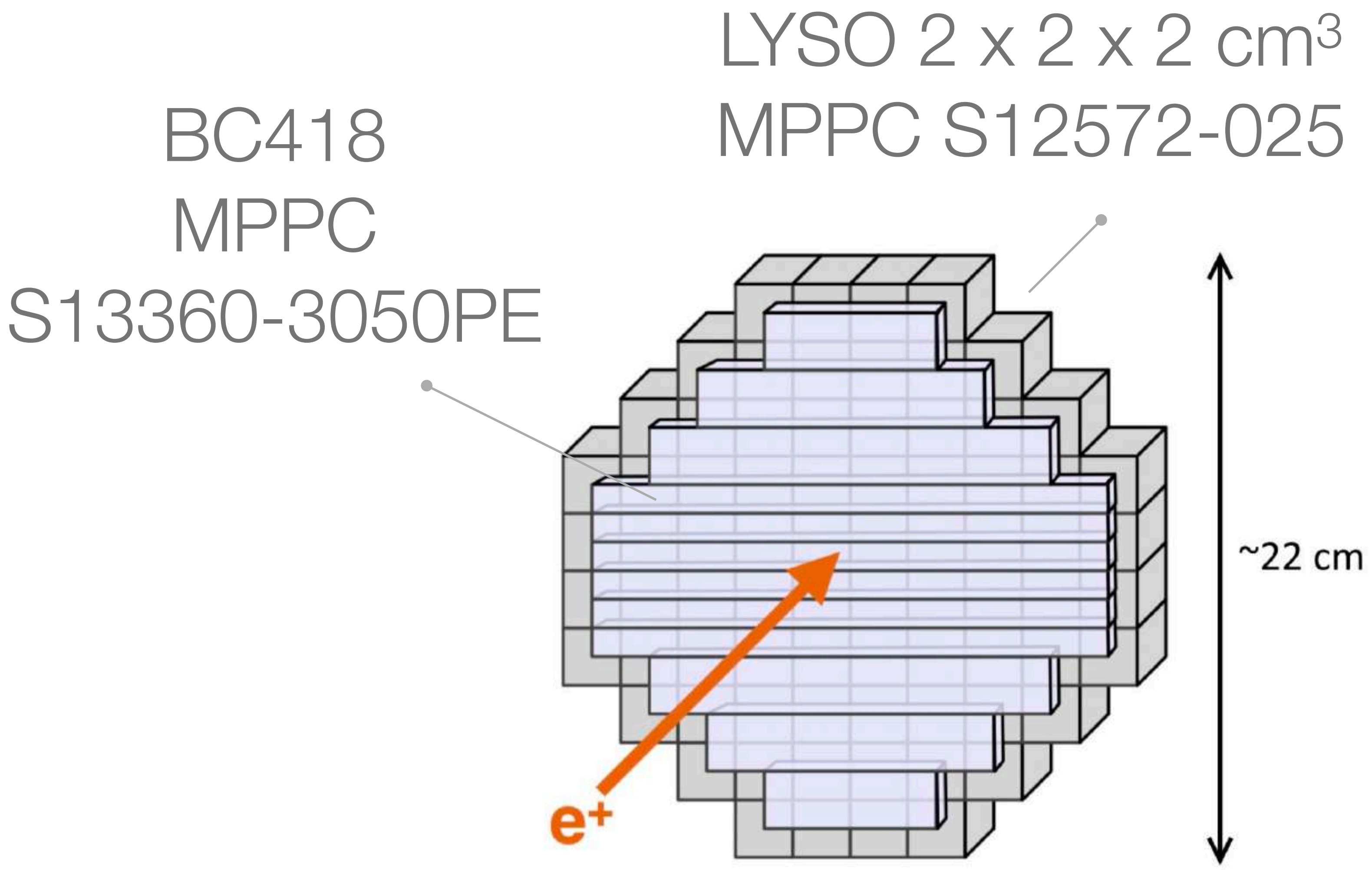




MEGII: The Radiative Decay Counter

- Added a new auxiliary detector for background rejection purpose. Impact into the experiment: Improved sensitivity by 20%
- Commissioning during the 2016 pre-engineering run
- Status: Implemented since the beginning of MEGII

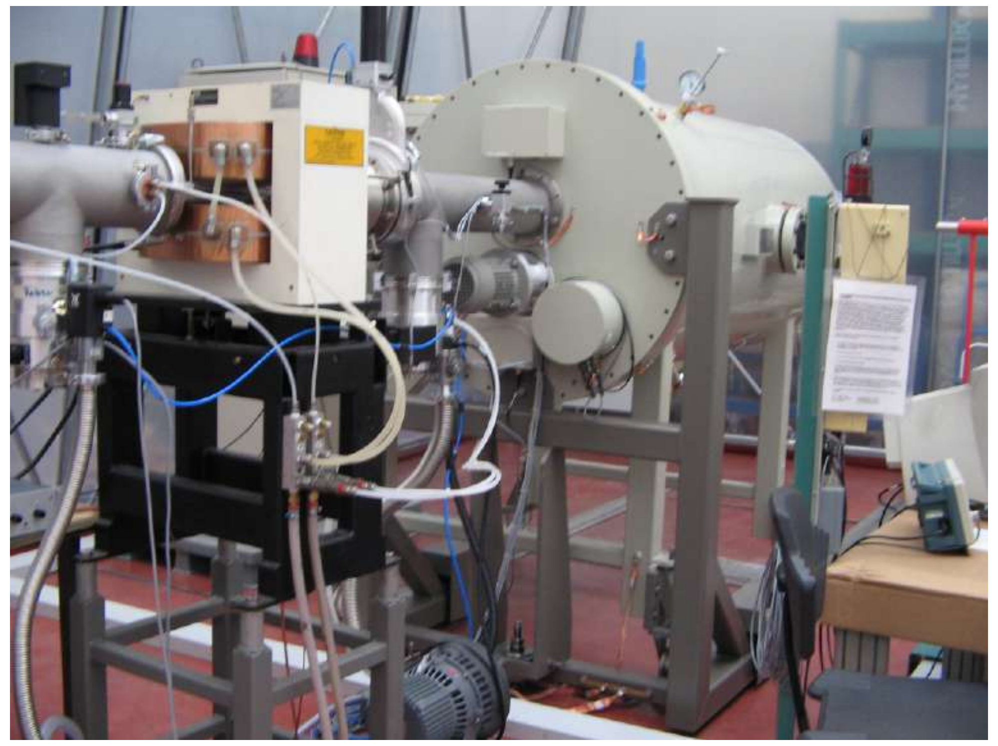


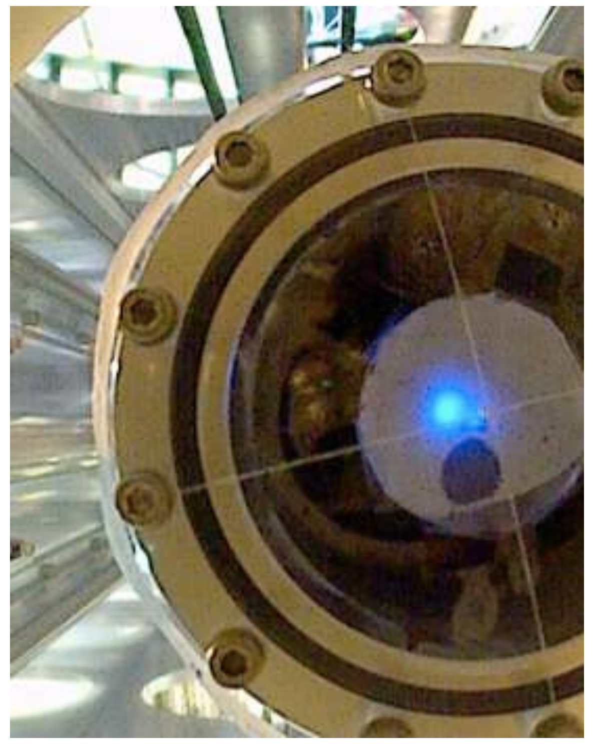


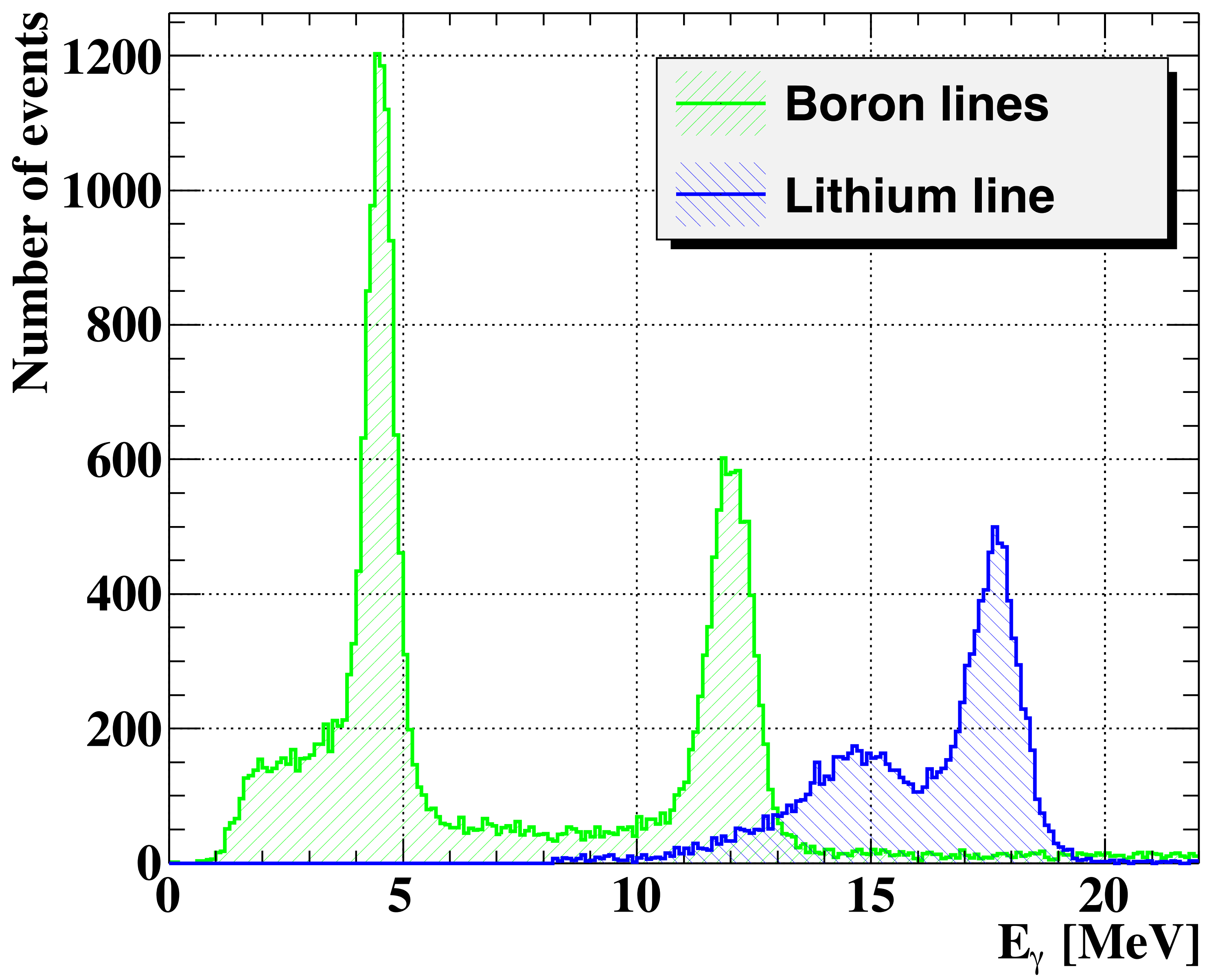
MEG: The calibration methods

- Multiple calibration and monitoring methods: detector resolution and stability are the key points in the search for rare events over the background

Process		Energy (MeV)	Frequency
CEX reaction	$\mathrm{p}(\pi^-, \pi^0)\mathrm{n}, \pi^0 \rightarrow \gamma\gamma$	55, 83	annually
C-W accelerator	$^{7}\mathrm{Li}(p, \gamma_{17.6})^{8}\mathrm{Be}$	17,6	weekly
	$^{11}\mathrm{B}(\mathrm{p}, \gamma_{11.6})^{12}\mathrm{C}$	4.4&11.6	weekly
Neutron Generator	$^{58}\mathrm{Ni}(n, \gamma_9)^{59}\mathrm{Ni}$	9	daily
Mott Positrons	$\mathrm{p}(\mathrm{e}^+, \mathrm{e}^+)\mathrm{p}$	53	annually



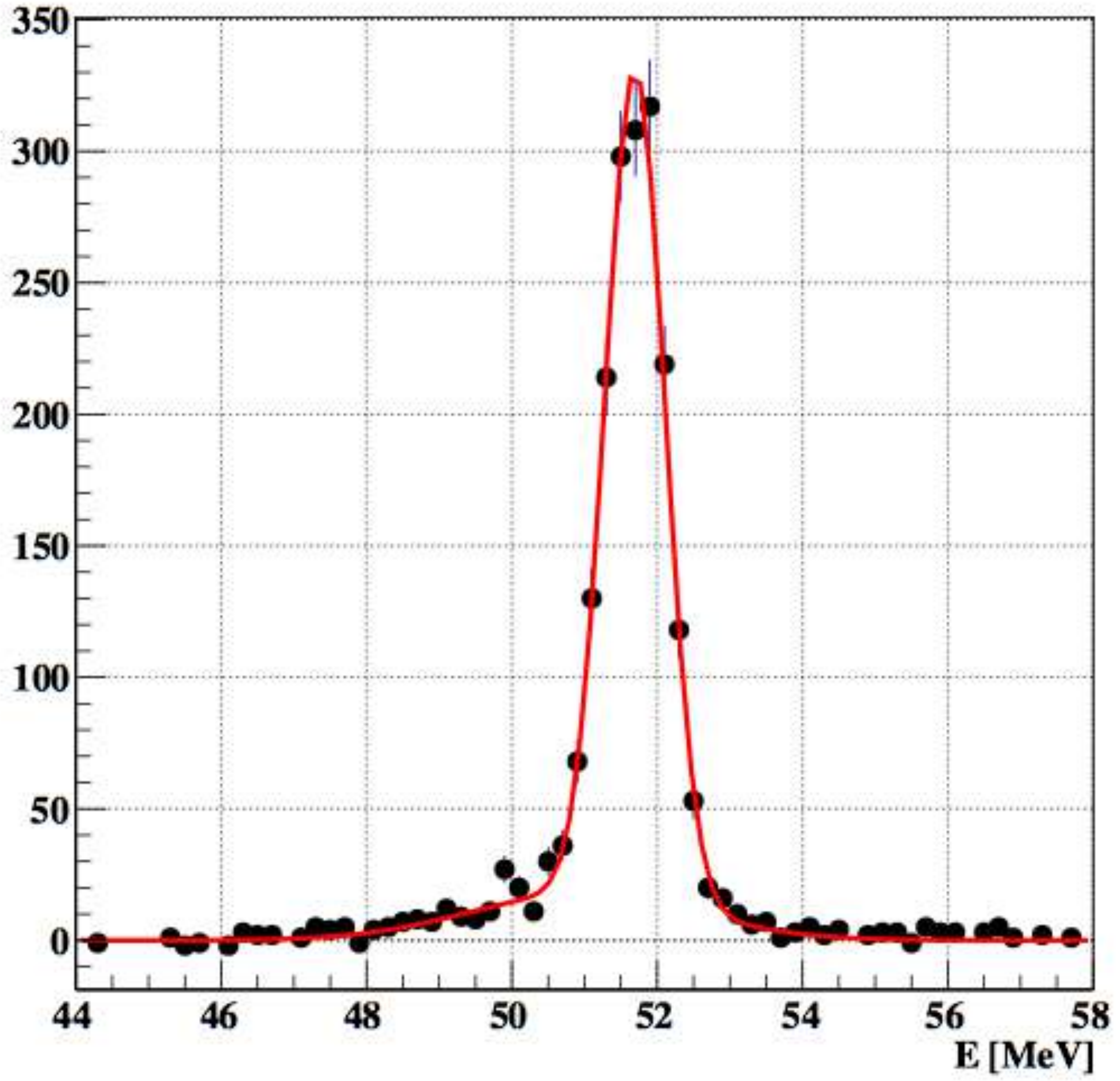




MEGII: new calibration methods and upgrades

- CEX reaction: $p(\pi^-,\pi^0)n$, $\pi^0 \to \gamma\gamma$
- 1MV Cockcroft-Walton accelerator
- Pulsed D-D Neutron generator
- NEW: Mott scattered positron beam to fully exploit the new spectrometer
- NEW: SciFi beam monitoring. Not invasive, ID particle identification, vacuum compatible, working in magnetic field, online beam monitor (beam rate and profile)
- NEW: Luminophore (CsI(Tl) on Lavsan/Mylar equivalent) to measure the beam properties at the Cobra center
- NEW: LXe X-ray survey
- NEW: Laser system for the pTC

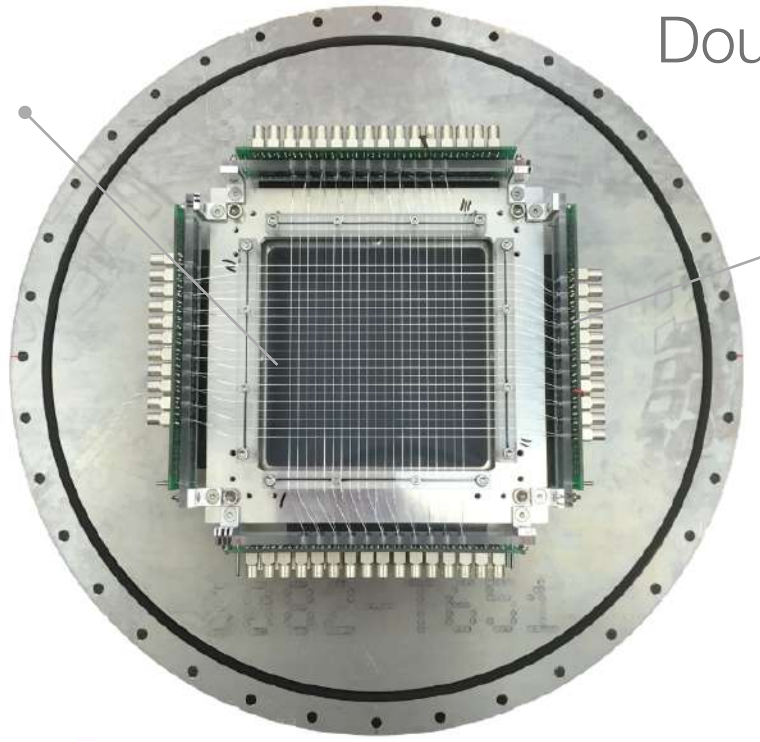
Monochromatic e-line



pTC's laser

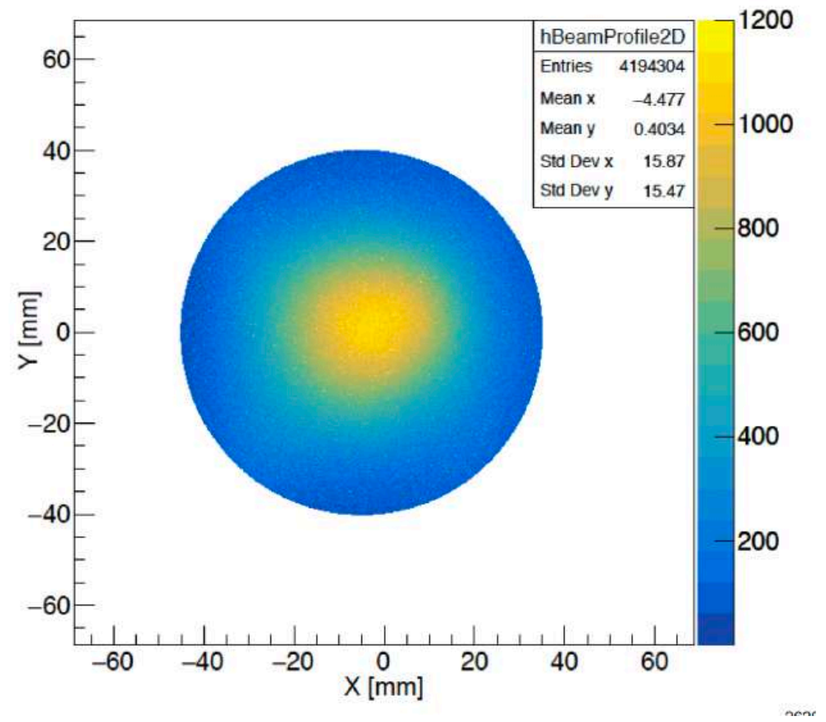
MC BCF12 250 x 250 um^2 scintillating fibers

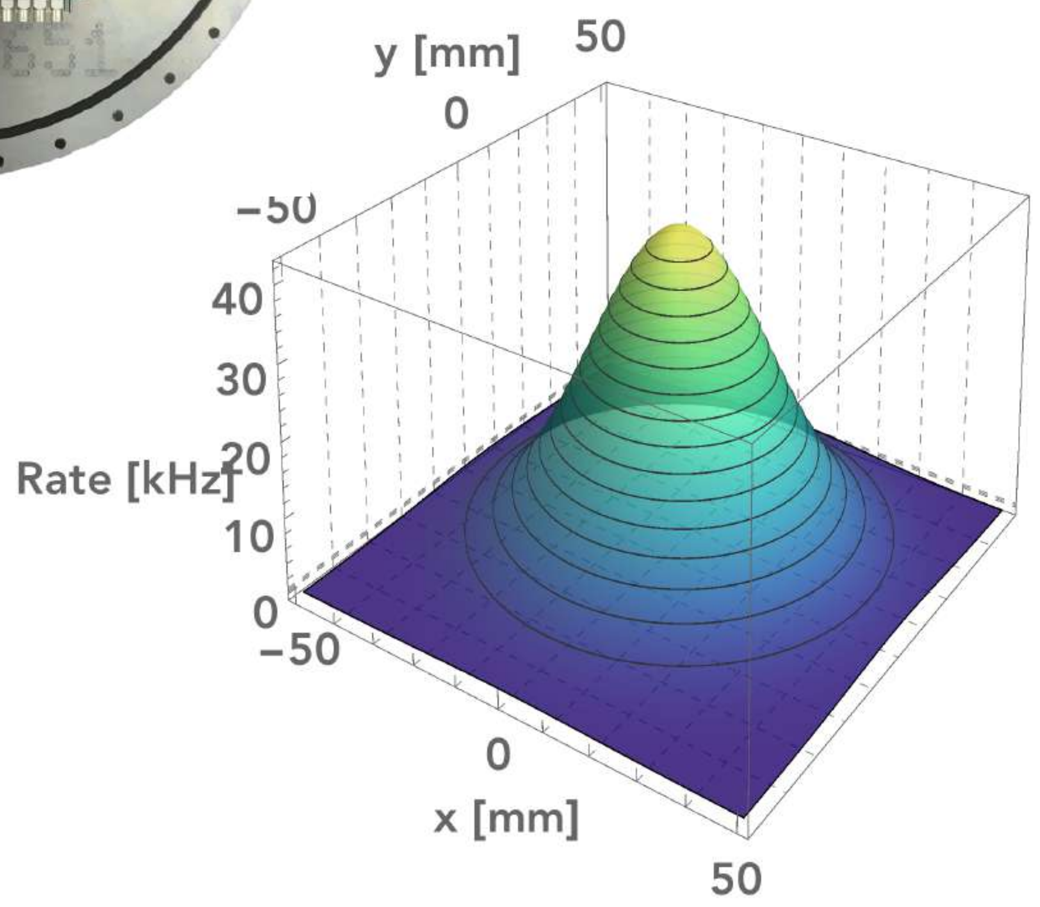
Double readout: MPPC S13360-3050C



SciFi

Luminophore





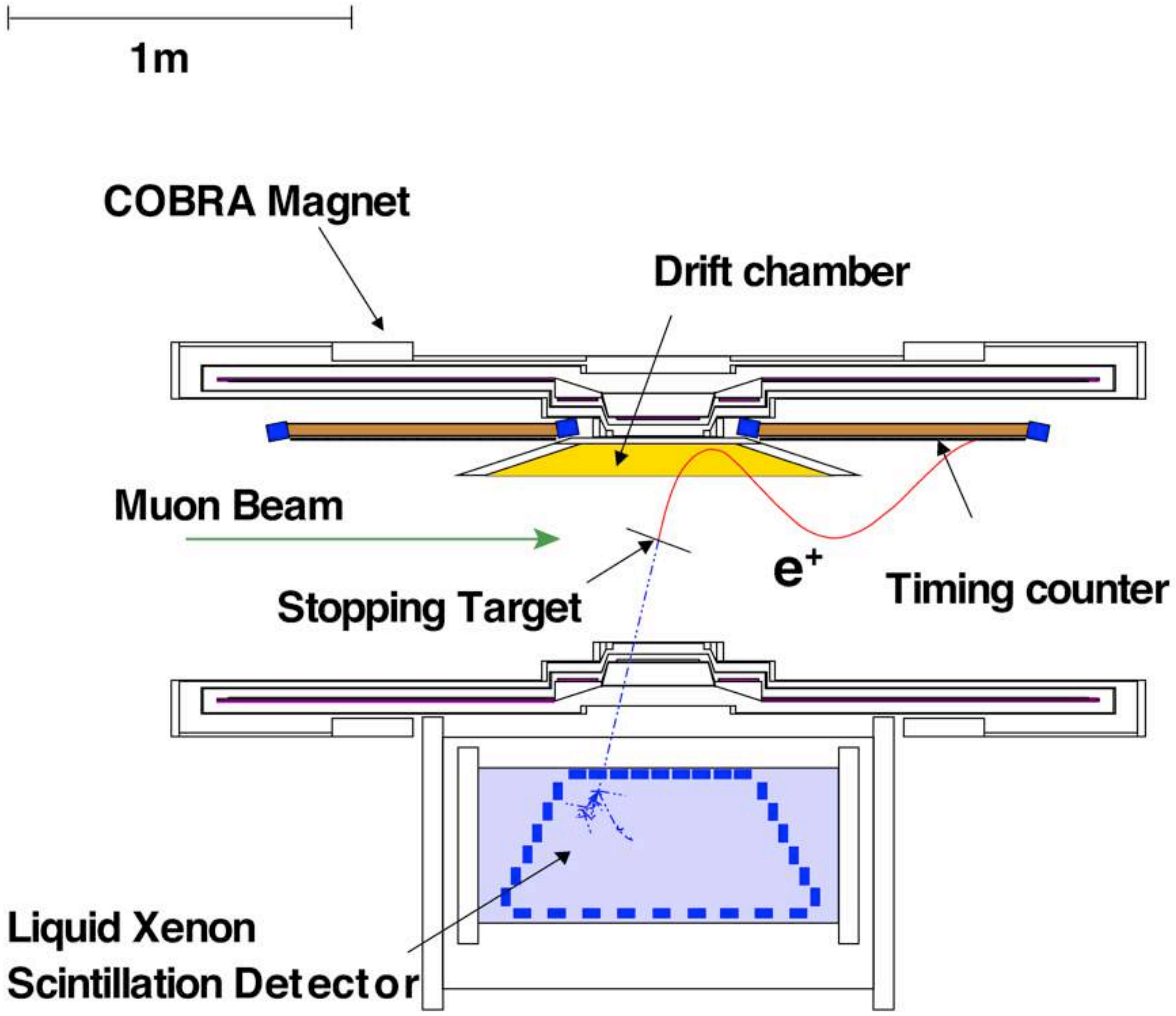
MEGII: The new electronic - DAQ and Trigger

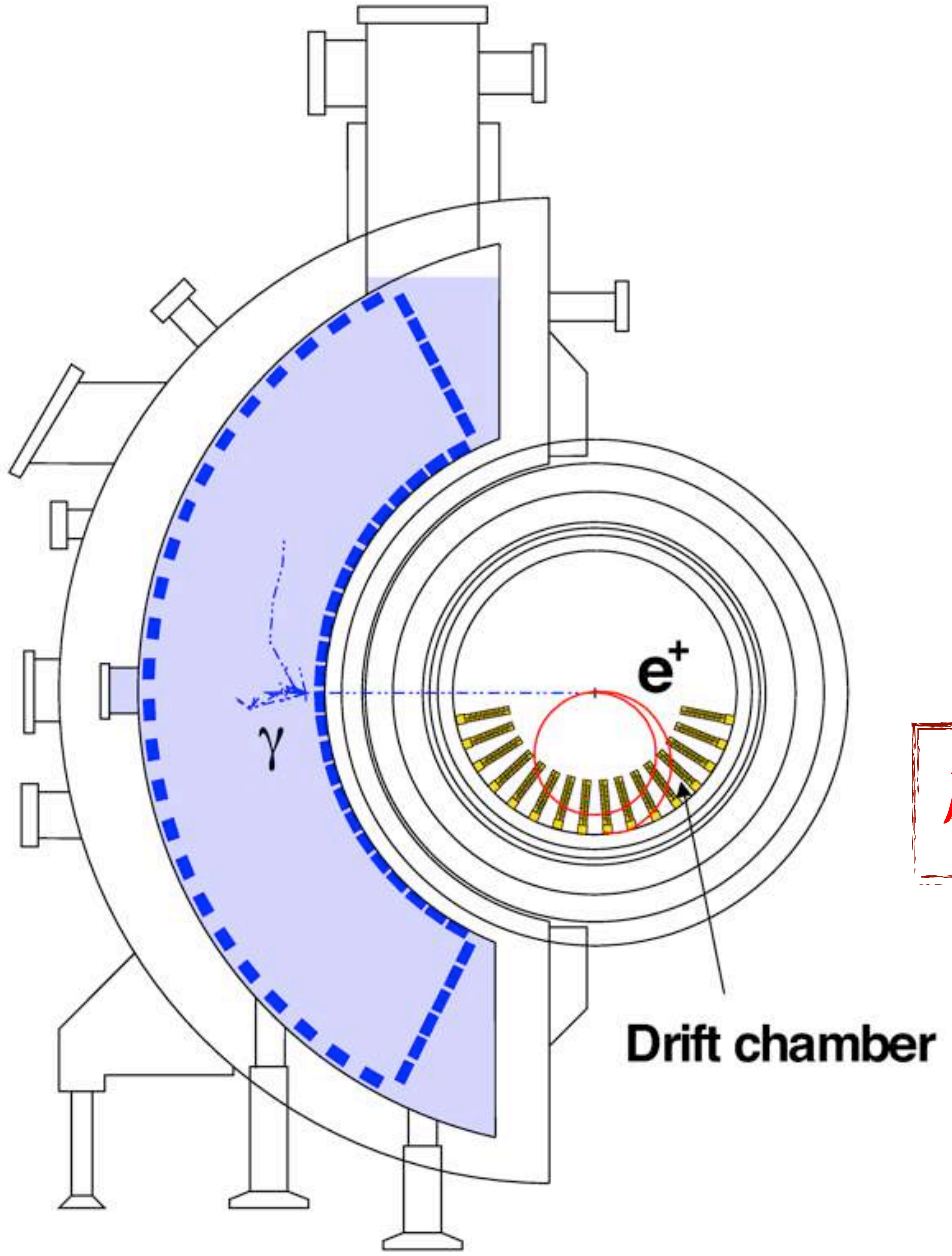
- DAQ and Trigger
  - ~9000 channels (5 GSPS)
  - Bias voltage, preamplifiers and shaping included for SiPMs
- Run 2021: Electronics fully installed and tested with all sub-detectors and calibration tools
- Run 2021: All calibration and physics trigger configurations released. Since 2021 running (MEGII data taking started)

A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434

A step back: The MEG experiment

- The MEG experiment aimed to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~10^{-13} (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events



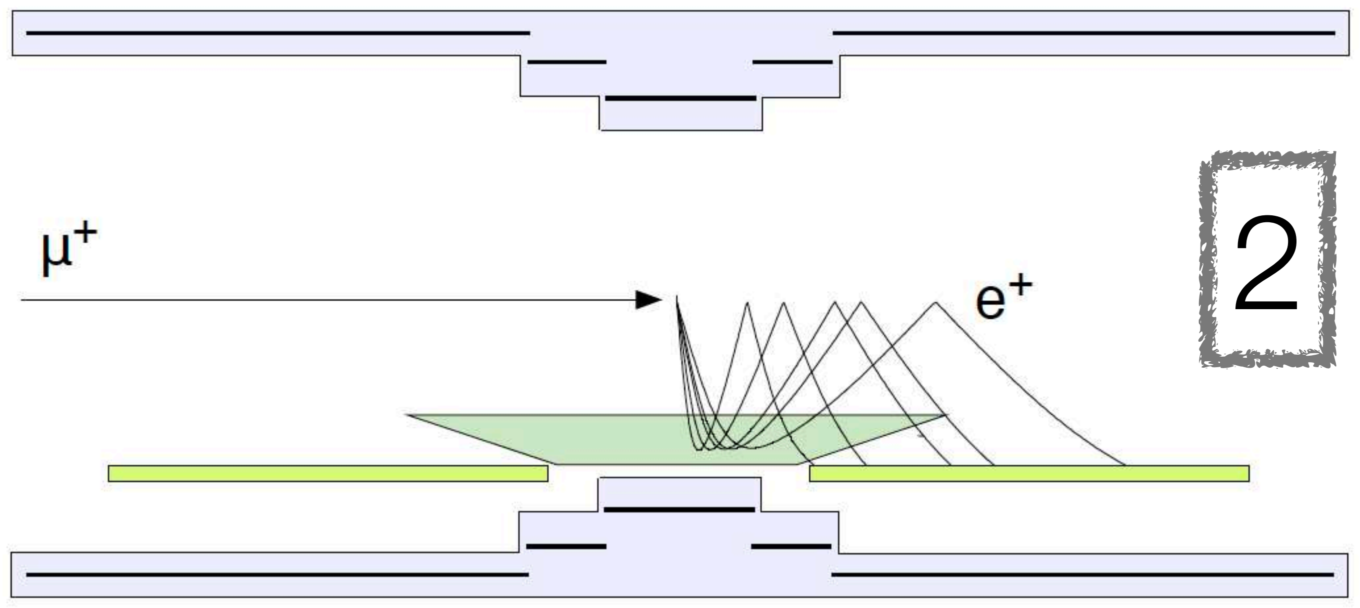


Full data sample:
2009-2013
Best fitted branching ratio
at 90% C.L.:

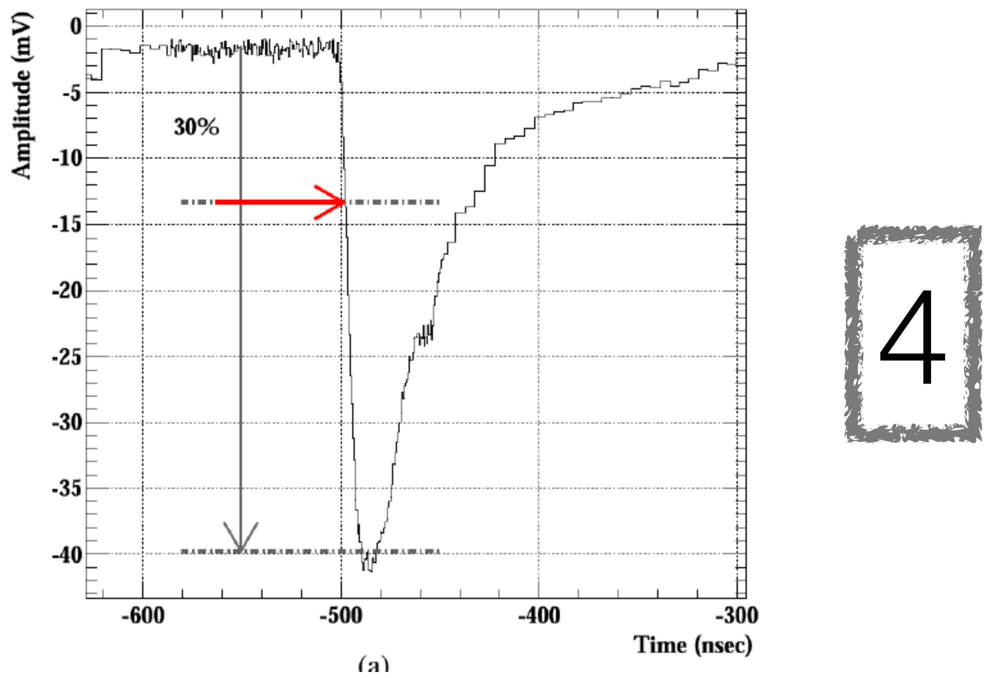
$$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$$

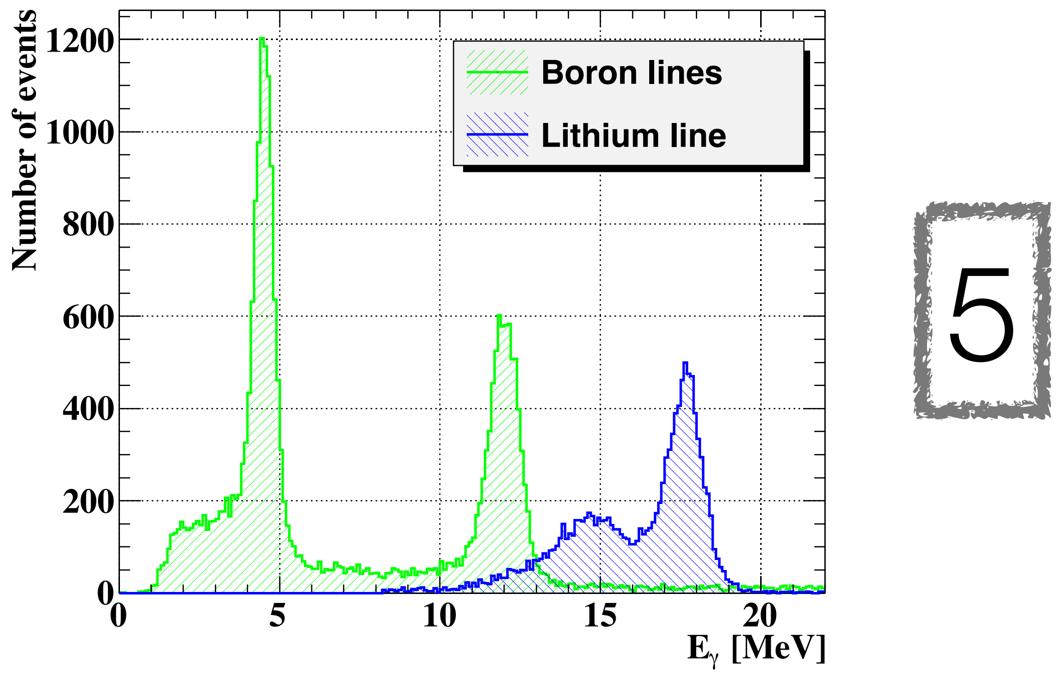
MEG: The key elements

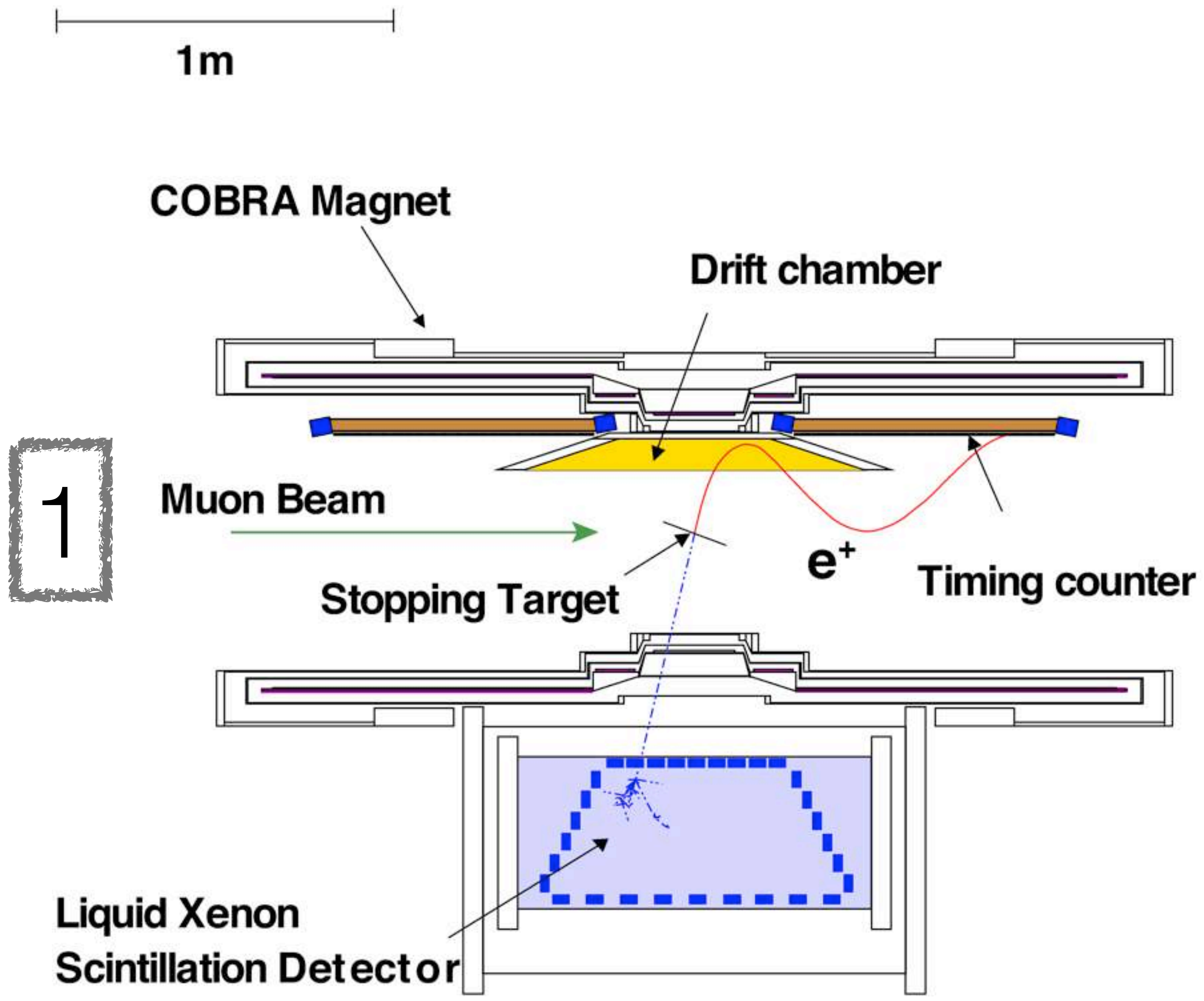
1. The world's intense low momentum muon beam stopped in a thin and slanted target
2. The gradient field e+-spectrometer
3. The innovative Liquid Xenon calorimeter
4. The full waveform based DAQ (digitization up to 1.6 GSample/s)
5. Complementary calibration and monitoring methods

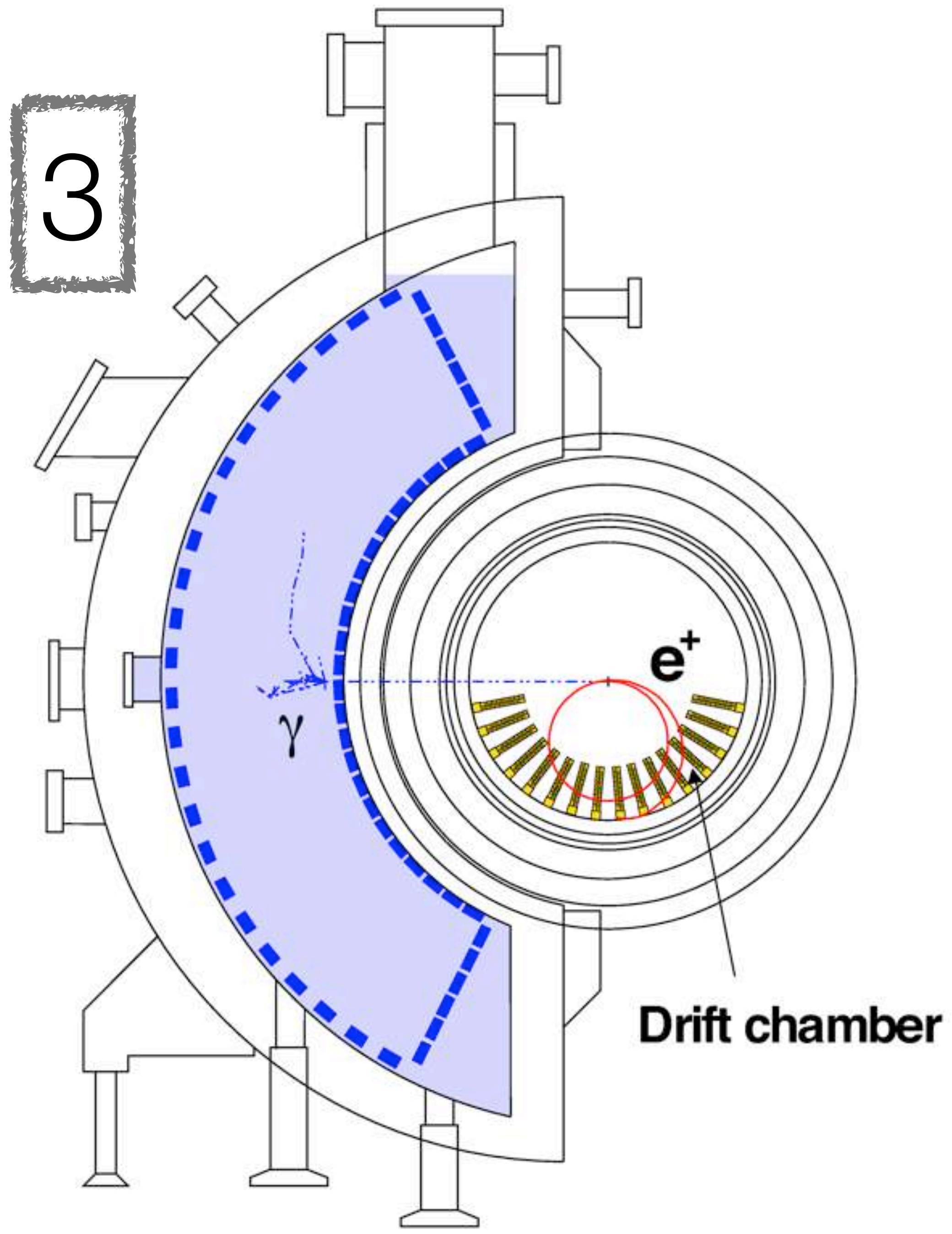


a) Constant projected bending radius for positrons with equal momentum.

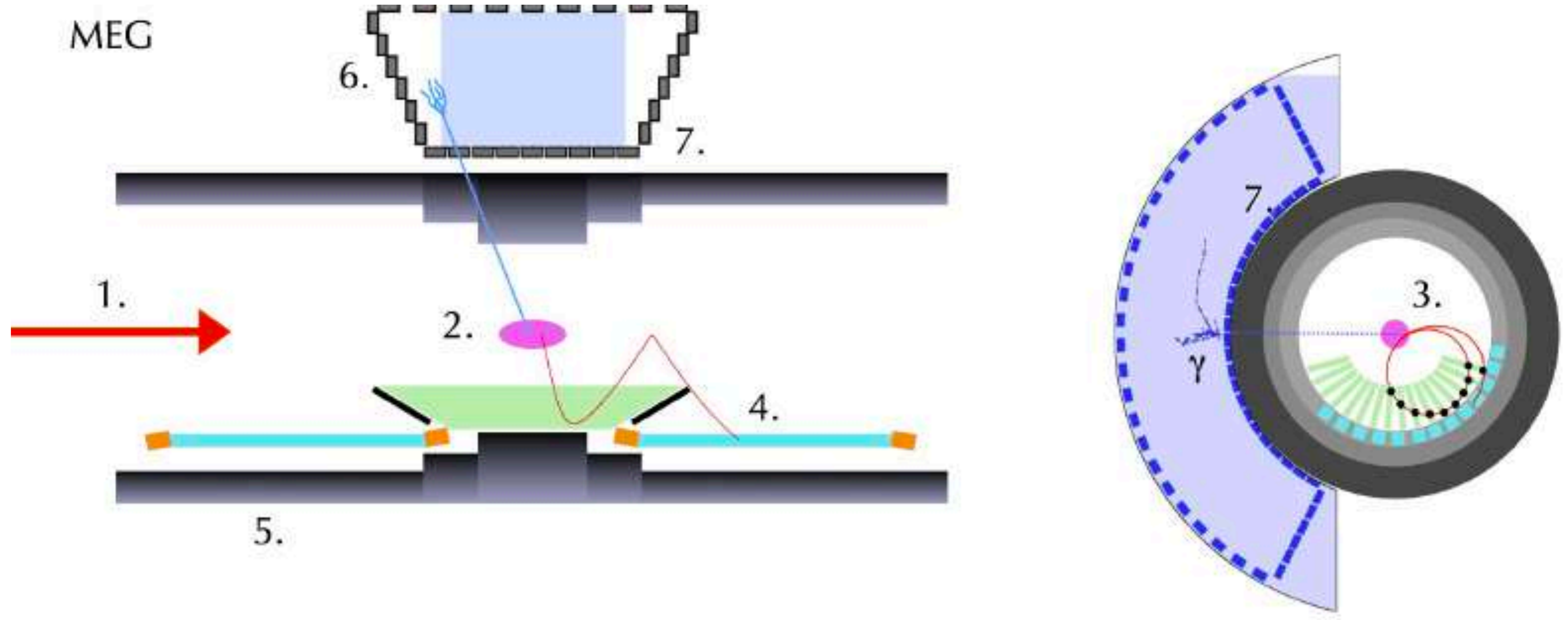




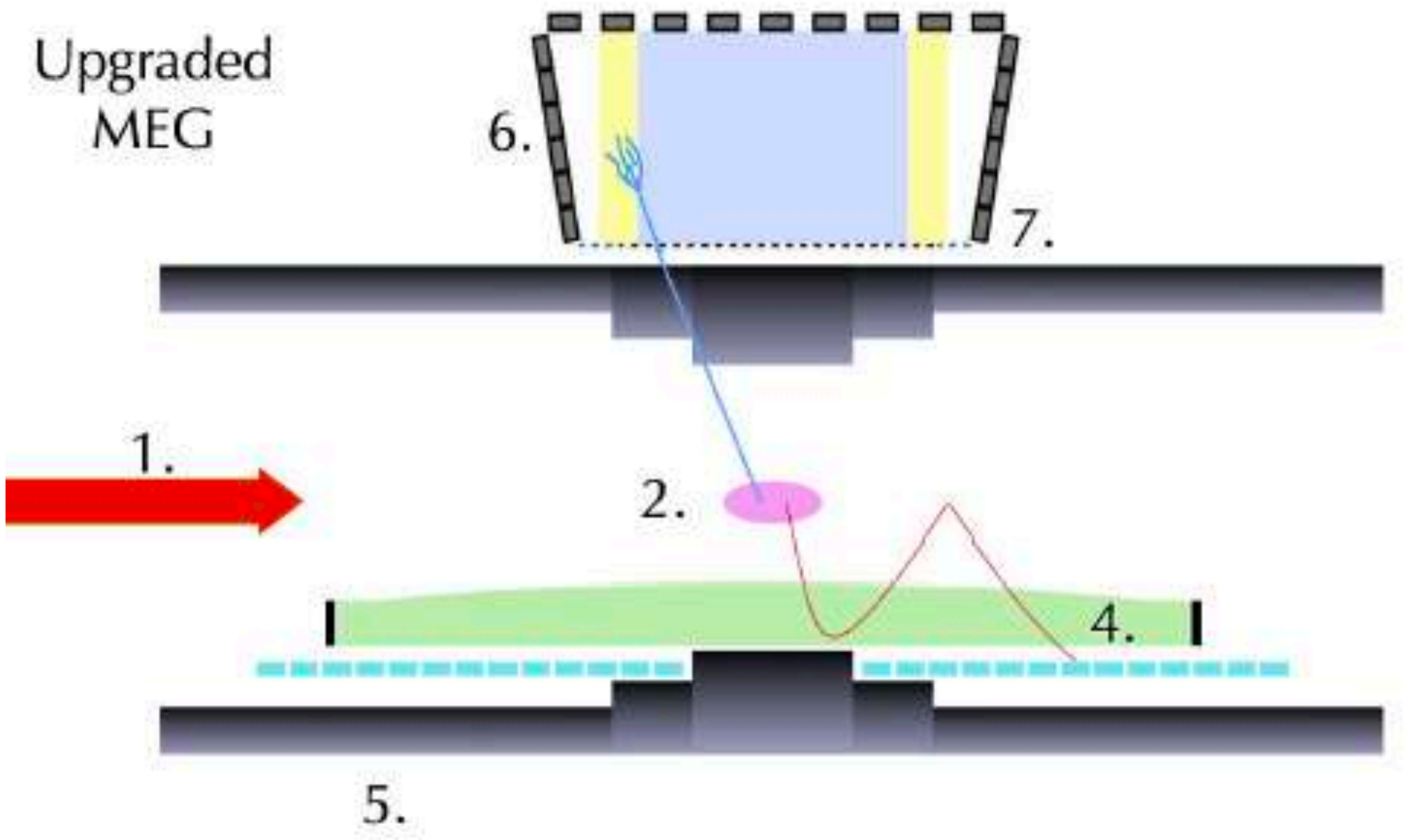


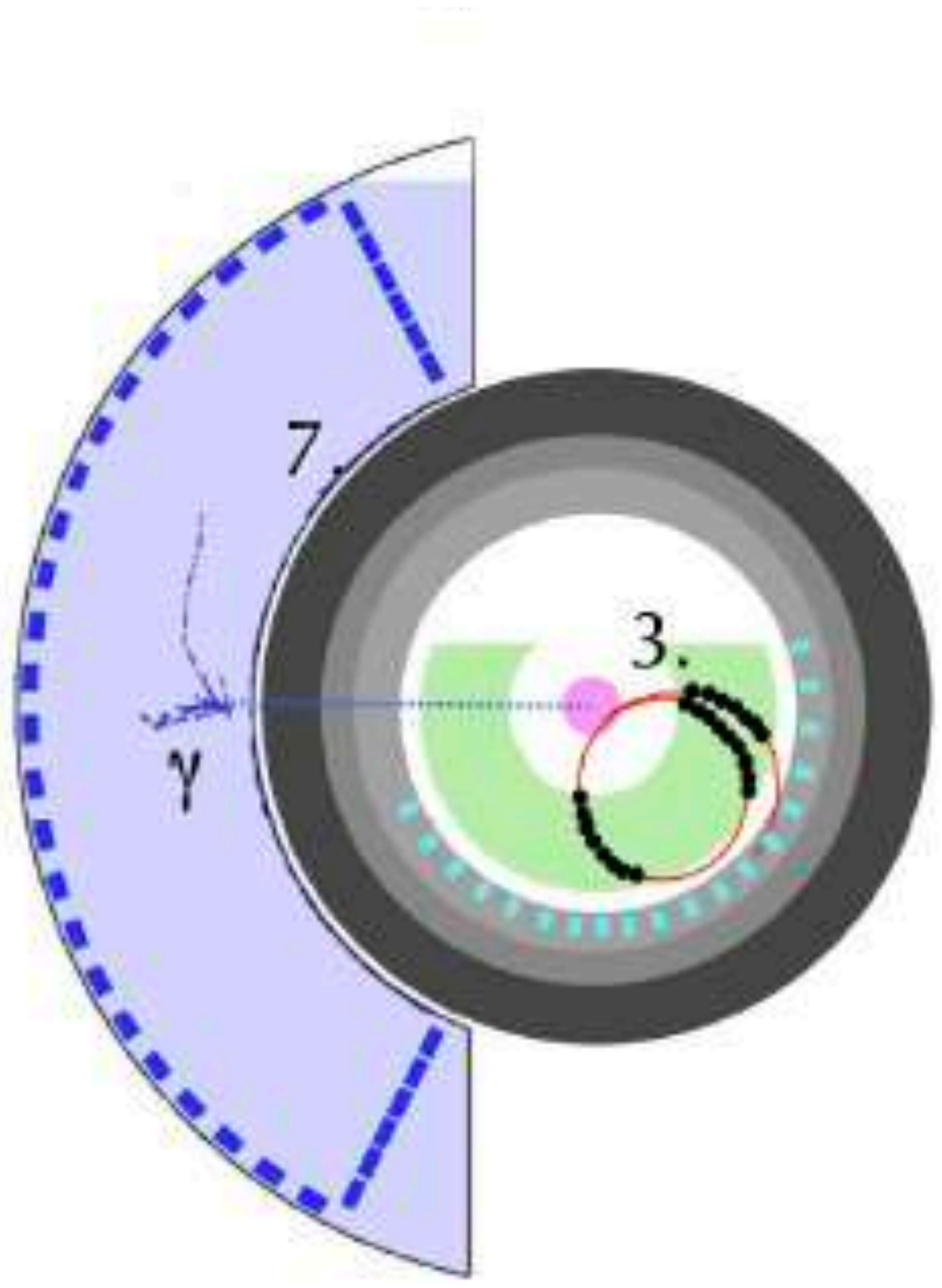


The MEG experiment vs the MEGII experiment



The MEG experiment vs the MEGII experiment

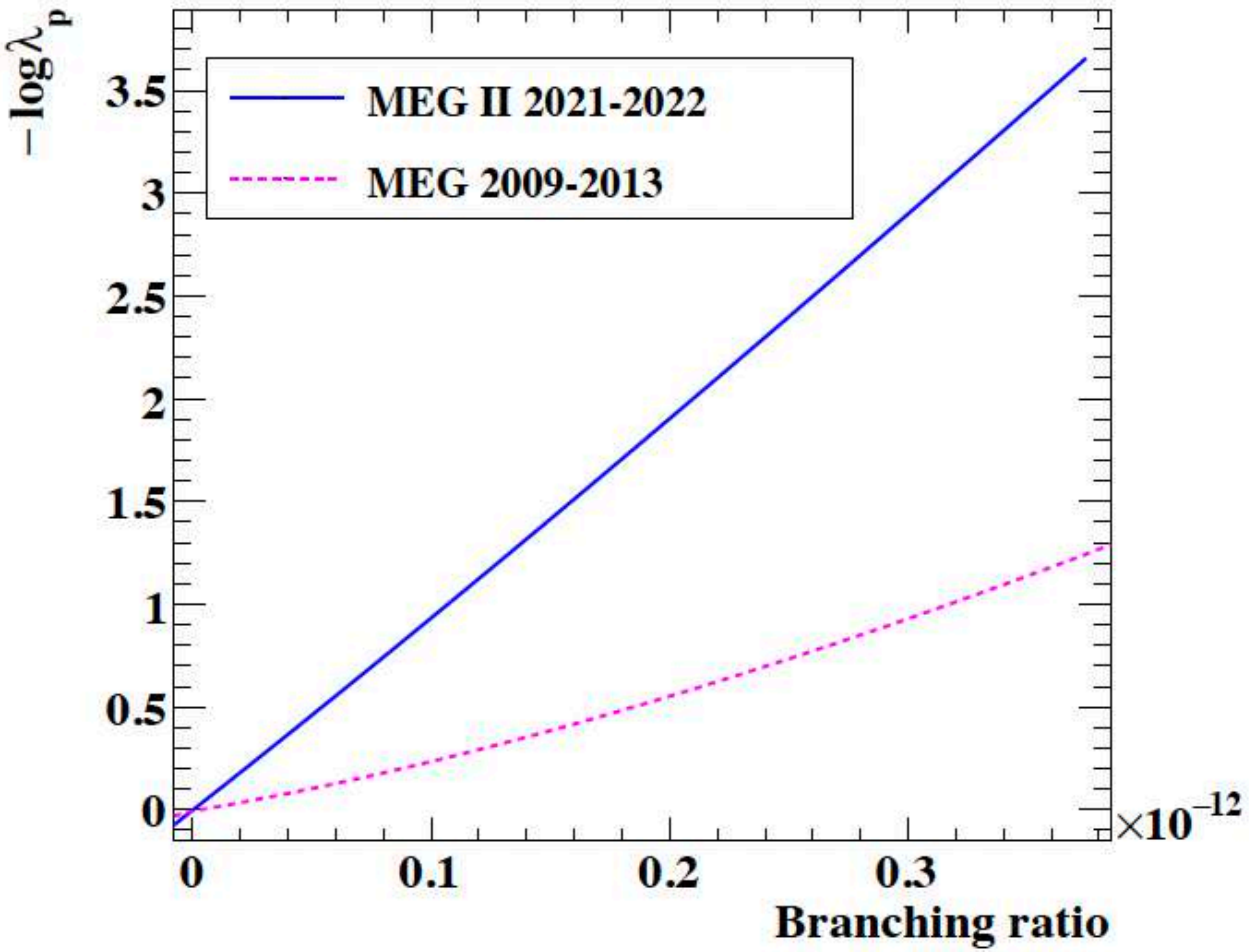




DC and Pulsed muon beams - present and future

Laboratory	Beam Line	DC rate (μ/sec)	Pulsed rate (μ/sec)
PSI (CH) (590 MeV, 1.3 MW)	$\mu E4, \pi E5$ HiMB at EH	$2 \div 4 \times 10^8$ (μ^+) $\mathcal{O}(10^{10})$ (μ^+) (>2018)	
J-PARC (Japan) (3 GeV, 210 kW) (8 GeV, 56 kW)	MUSE D-Line MUSE U-Line COMET		$3 \times 10^7 (\mu^+)$ $6.4 \times 10^7 (\mu^+)$ $1 \times 10^{11} (\mu^-)$(2020)
FNAL (USA) (8 GeV, 25 kW)	Mu2e		$5 \times 10^{10} (\mu^-)$(2020)
TRIUMF (Canada) (500 MeV, 75 kW)	M13, M15, M20	$1.8 \div 2 \times 10^6 (\mu^+)$	
RAL-ISIS (UK) (800 MeV, 160 kW)	EC/RIKEN-RAL		$7 \times 10^4 (\mu^-)$ $6 \times 10^5 (\mu^+)$
KEK (Tsukuba, Japan) (500 MeV, 25 kW)	Dai Omega		$4 \times 10^5 (\mu^+)$(2020)
RCNP (Osaka, Japan) (400 MeV, 400 W)	MuSIC	$10^4 (\mu^-) \div 10^5 (\mu^+)$ $10^7 (\mu^-) \div 10^8 (\mu^+)$(>2018)	
JINR (Dubna, Russia) (660 MeV, 1.6 kW)	Phasotron	$10^5 (\mu^+)$	
RISP (Korea) (600 MeV, 0.6 MW)	RAON	$2 \times 10^8 (\mu^+)$(>2020)	
CSNS (China) (1.6 6eV, 4 kW)	HEPEA	$1 \times 10^8 (\mu^+)$(>2020)	

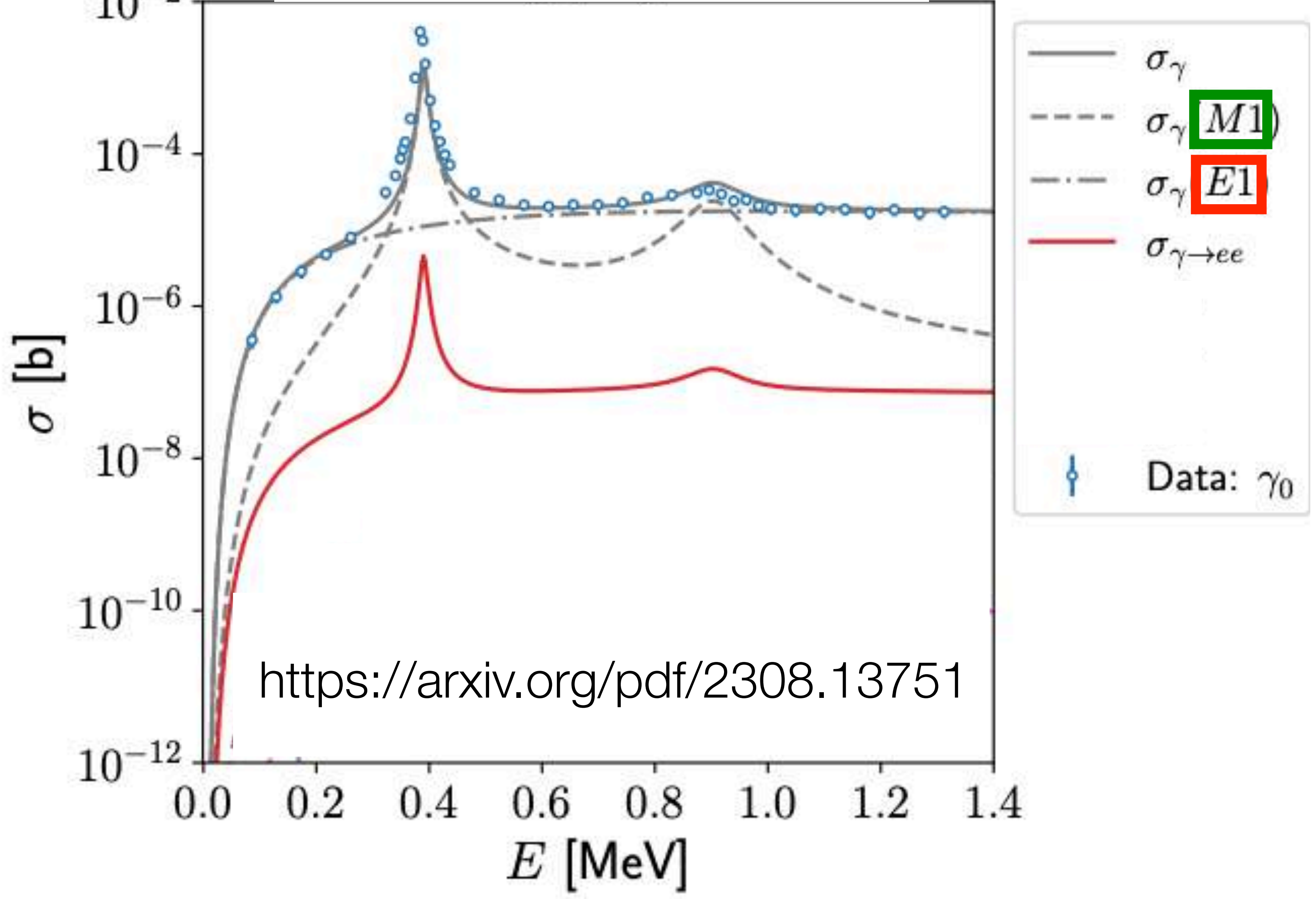
Back-up: Useful plots (results 2021+2022)

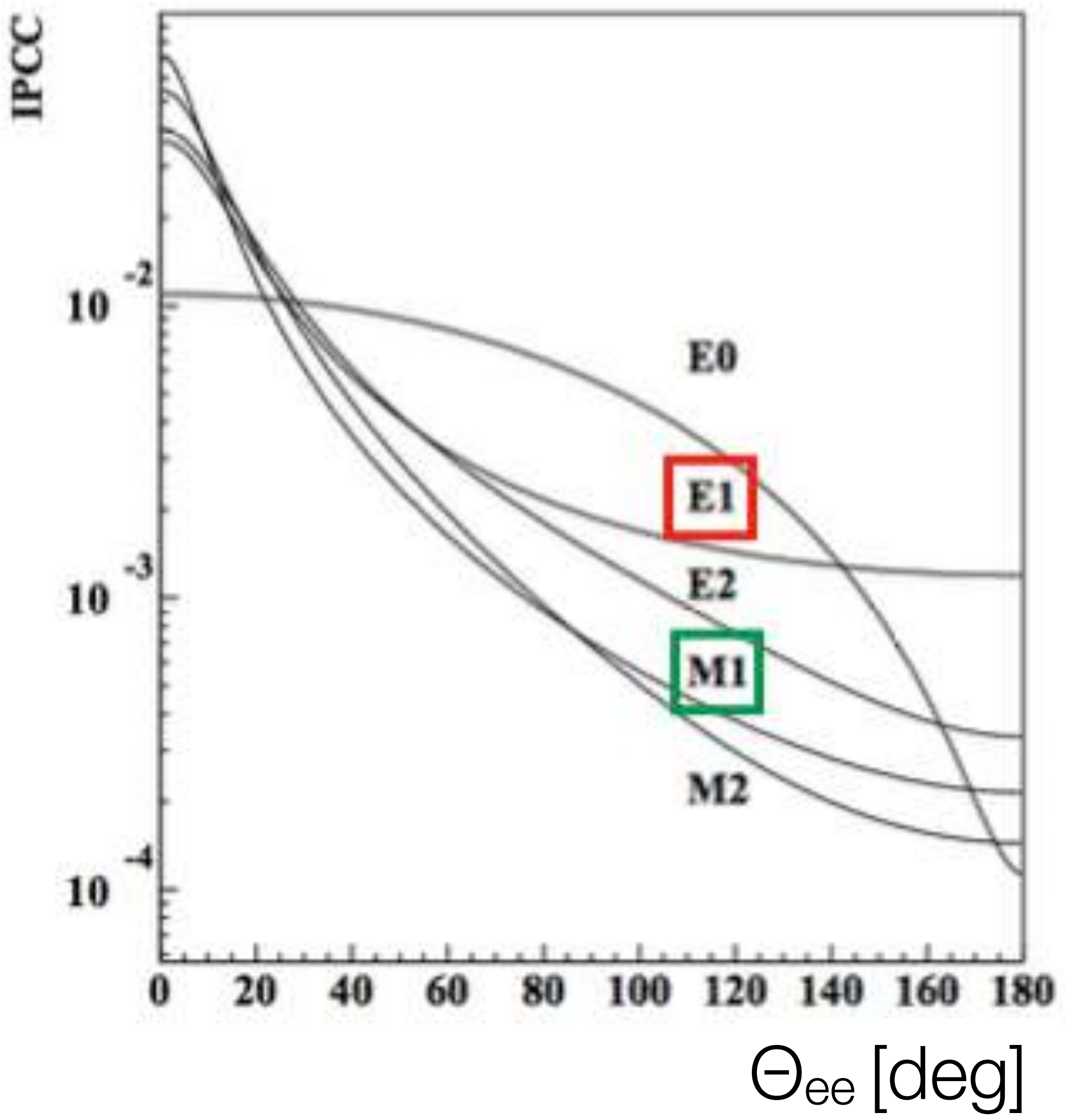


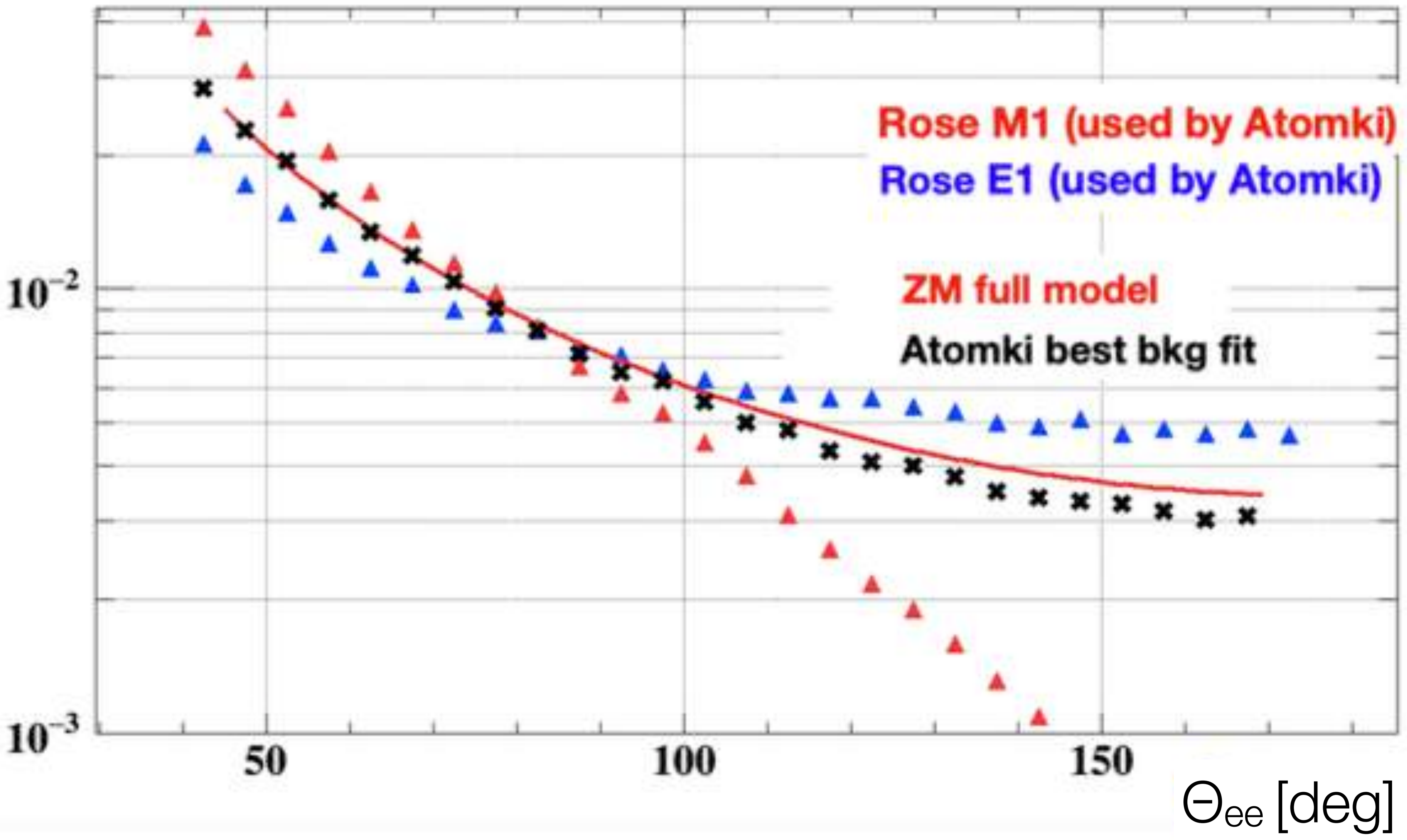
MC simulation for the signal and background studies: IPC

- Starting point: Electromagnetic transition cross section as a function of the proton energy in multipole decomposition
- Internal Pair Conversion (**IPC**) background:
  - 1 IPC every 1000 gammas (when energy > 2 m_e)
  - IPC angular opening Θ_{ee} changes accordingly with the multipole transition type, Rose (1949) - first model, Zhang-Miller Z-M (2017) - including gamma anisotropy and interferences among transitions [Z-M used in our MC] (recently available calculation *ab initio*: https://arxiv.org/pdf/2308.13751)
    - Different Θ_{ee} distribution for E1 and M1 ➝ separate IPC Q=17.6 MeV from IPC Q=18.1 MeV
    - With interferences and anisotropy the IPC background shape in Θ changes
  - IPC dominant in the signal region

$^7Li(p, \gamma$ or $\gamma \rightarrow e^+e^-)^8Be$

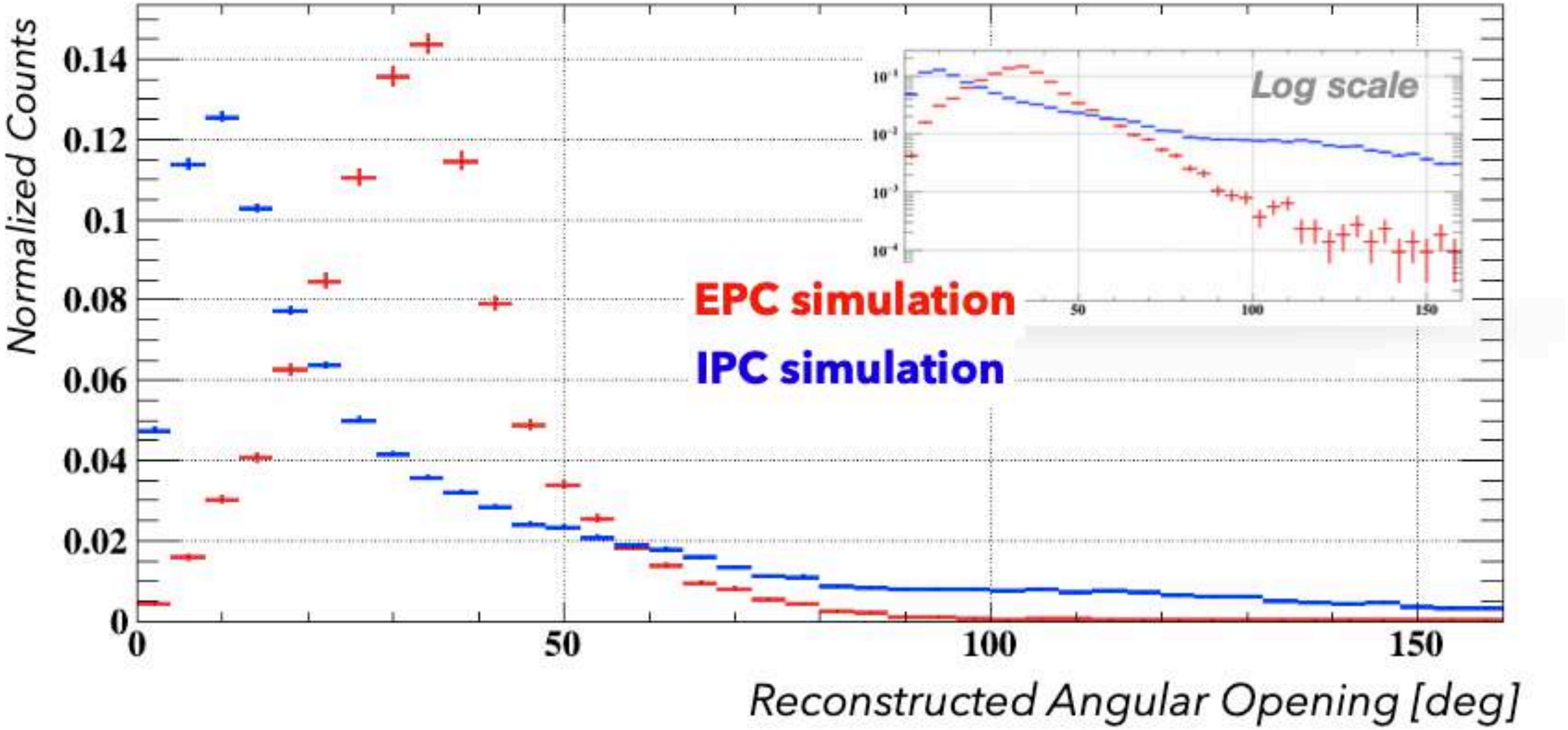






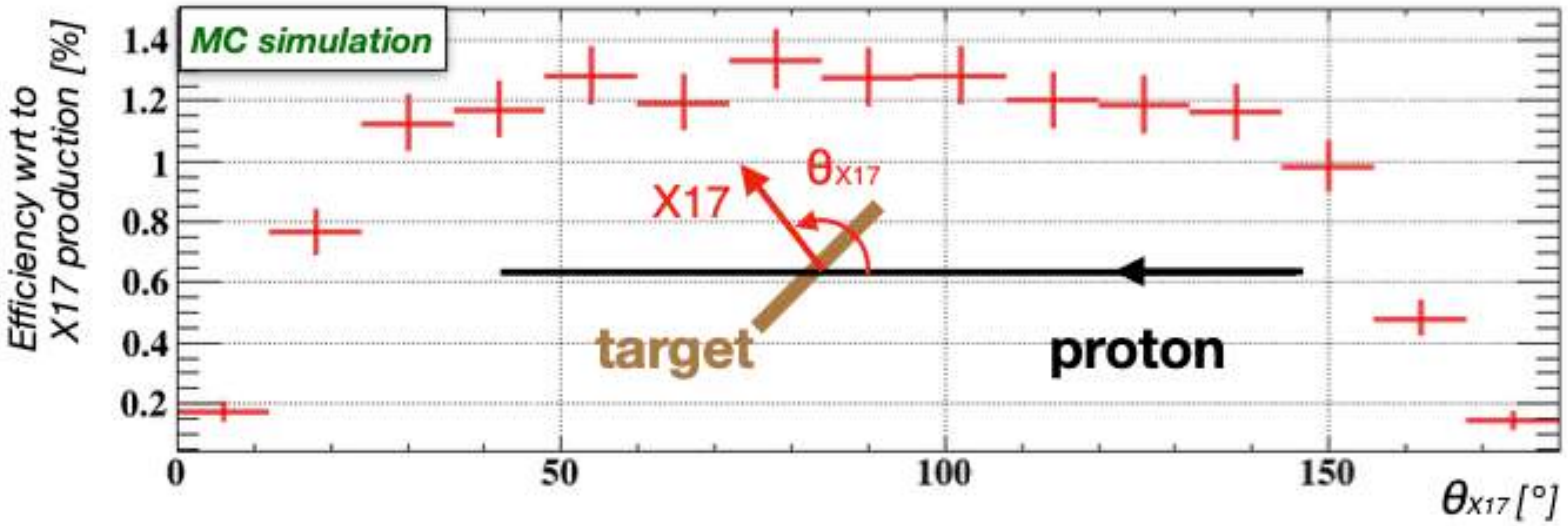
MC simulation for the signal and background studies: EPC and Compton

- External pair conversion (EPC) and Compton
  - Strongly depends on the specific apparatus: It calls for a detailed MC simulation
  - Main source: material around the target region (i.e. target support)
    - All photon conversion events included in full simulation
    - Almost 2 orders of magnitude below IPC in signal region



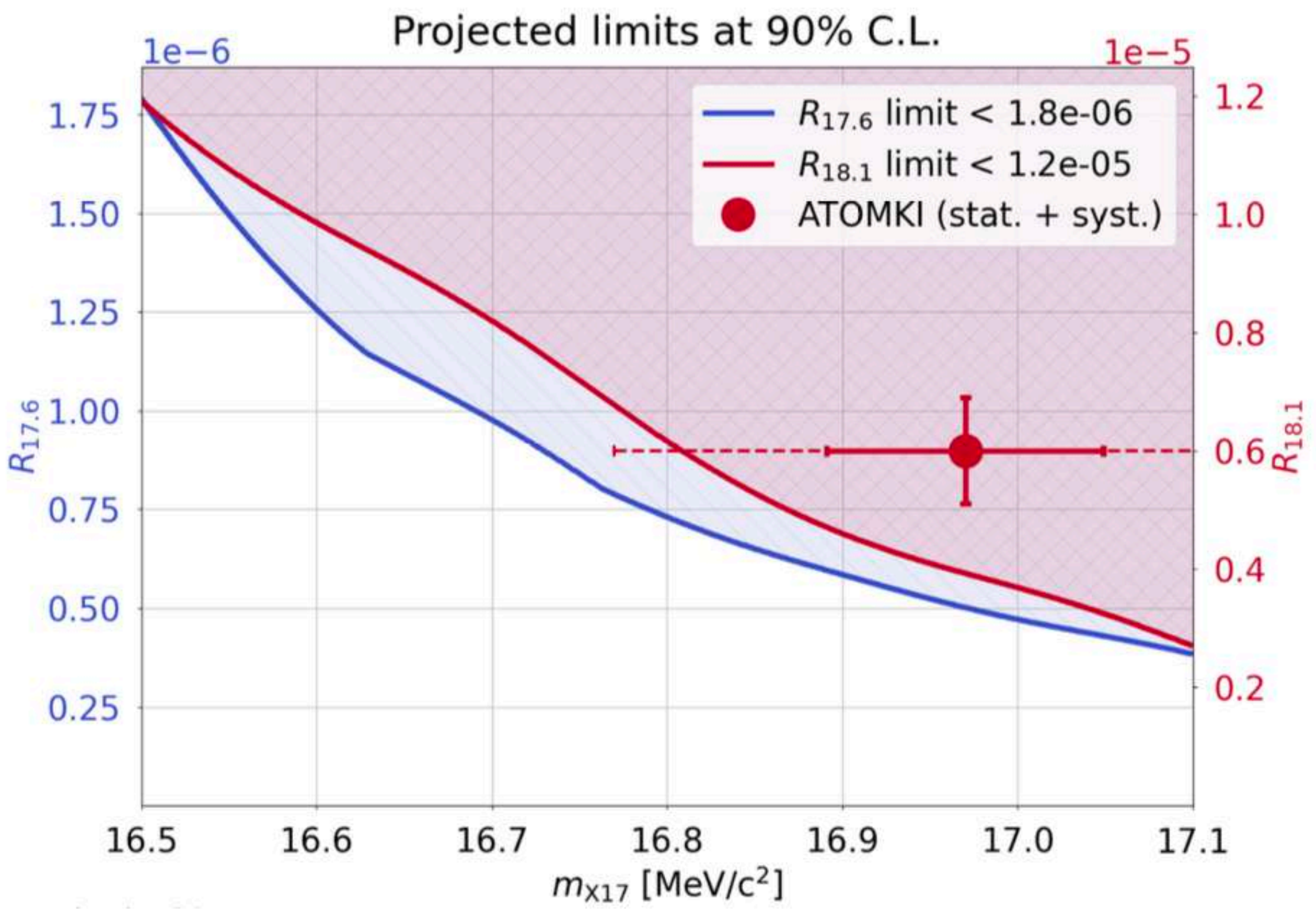
MC simulation for the signal and background studies: Signal

- Study of the signal events looking at both resonances (440 and 1030 keV)
- X17 assumed isotropically produced



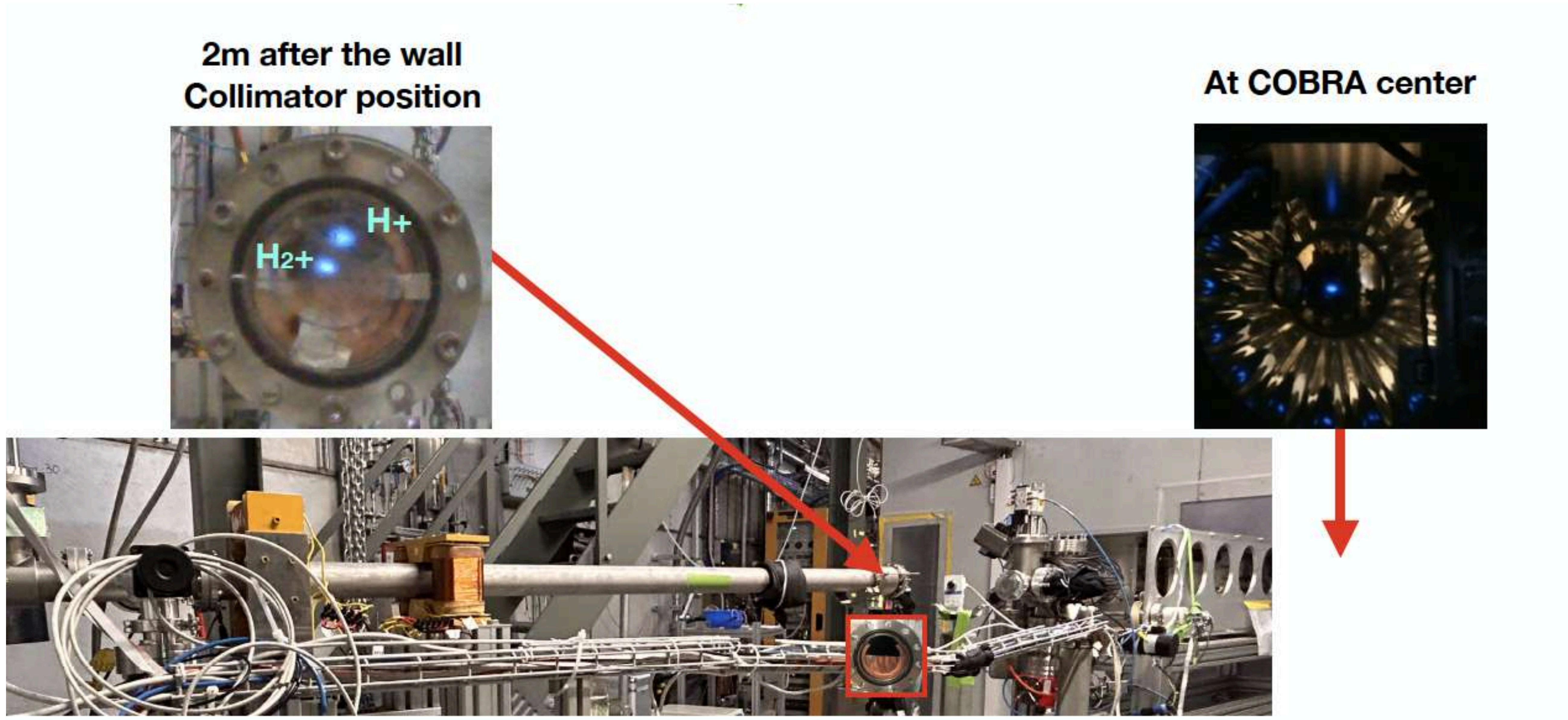
Hypothesis testing

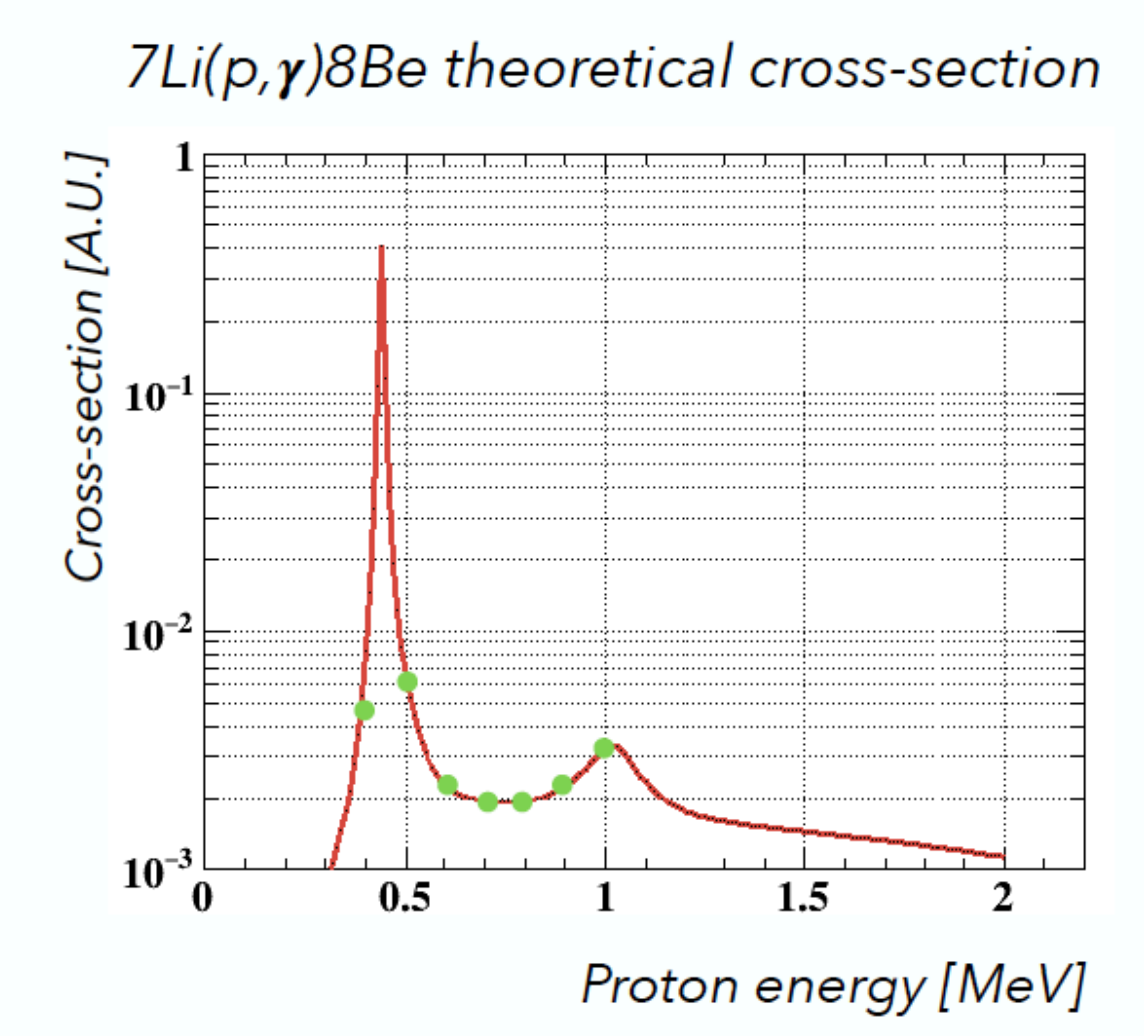
- Using:
  - M_{X17} = 16.97(22) MeV and $R_{18.1}$ = 6 10^{-6}
  - Scaling $R_{17.6}$ = 0.46 $R_{18.1}$
- ATOMKI: X17 produced at 1.030 MeV **and not** at 0.440 MeV
  - → *p*-value : 6.2% (1.5σ)
  - **ATOMKI observation excluded at 94%**
- J.L.Feng et al.: X17 produced **both** at 1.030 MeV **and** at 0.440 MeV
  - → *p*-value : 1.8% (2.1σ)



In view of a next run: Pure proton beam and new target

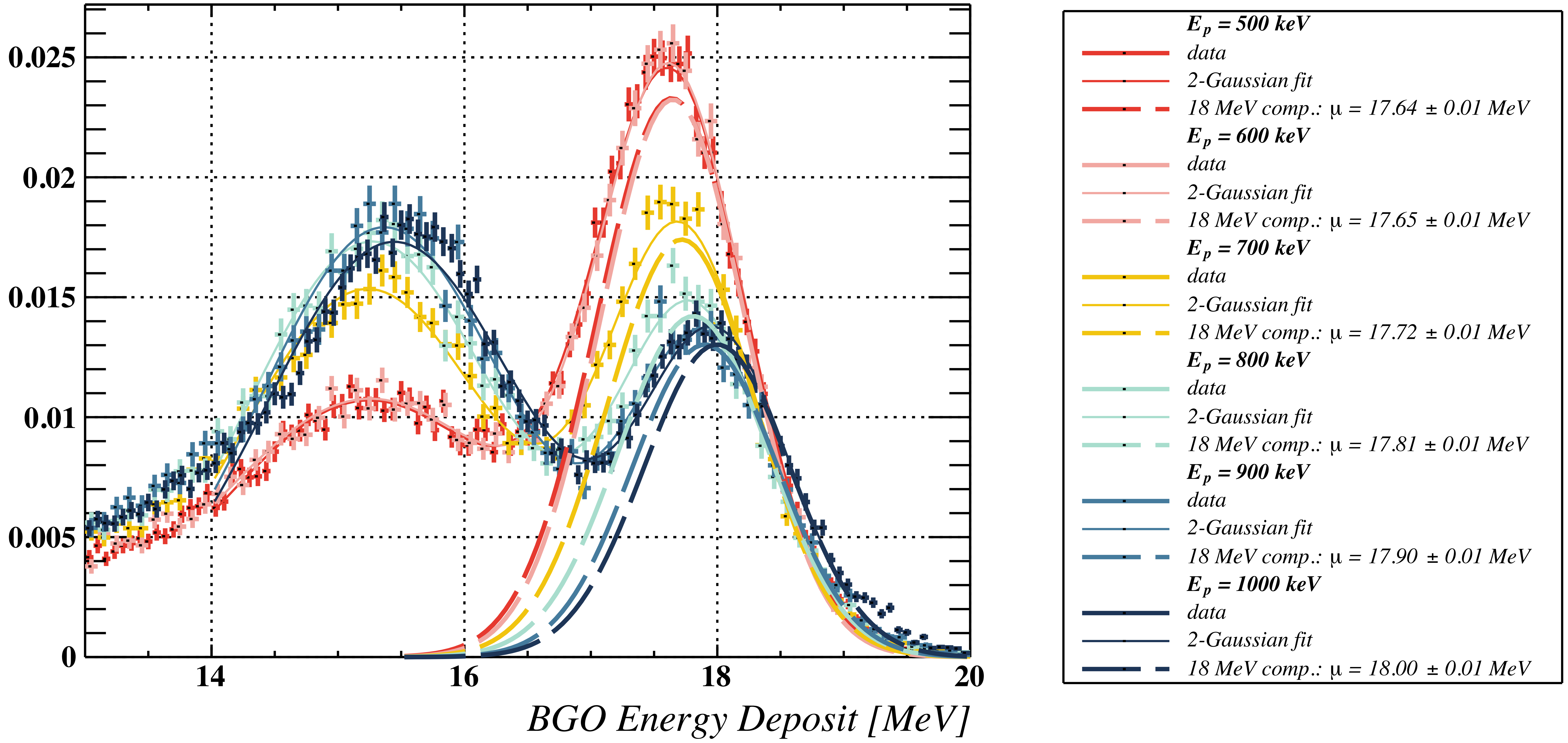
- Exploiting only the 1030 keV resonance
  - **Pure** H+ beam: Delivered
  - **New** thin (1.2 um) and uniform targets: Produced and tested
  - Measurements fully in line with **expected** H+ cross-section





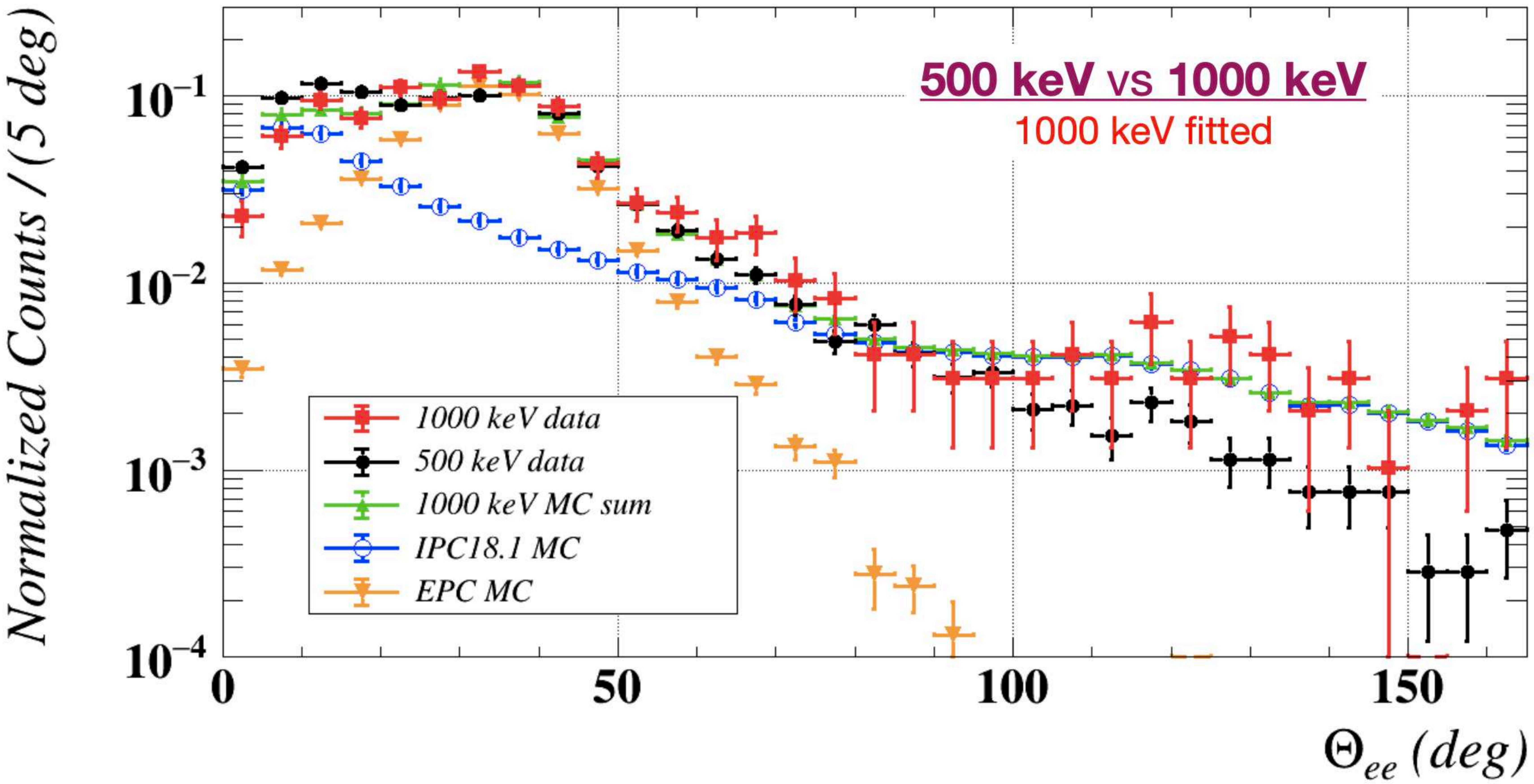
In view of a next run: Gamma spectra

- **Observed** pure 18.1 MeV gamma line
    - Clear shift of a few hundred keV
    - Increased proportion of « 15 MeV gamma line » wrt to « 18 MeV gamma line »



In view of a next run: First Zhang-Miller IPC model test at 1000 keV

- Although referring only to < 1 day of data taking, looking at the $e^+ e^-$ angular opening distribution
  - **First test** of the Zhang-Miller IPC model **at 1000 keV** (previously only at 500 keV)



X17 search: Next steps

- Excite only the resonance at 1030 keV
  - Target: LiPON 1.2 um
  - Beam: H^+ only
  - Energy: 1000 KV
- Minimal data set to achieve the aimed sensitivity:
  - 40 days of live time assuming to be able to run at 30 uA
    - Taking into account that σ(at 440 keV) ~ 10 σ(at 1030 keV)

Signal hypothesis Significance @1000 keV	No signal hypothesis Exclusion @1000 keV
0,005 % 3,9 σ	0,4 % 2,7 σ

*Quoted numbers are medians