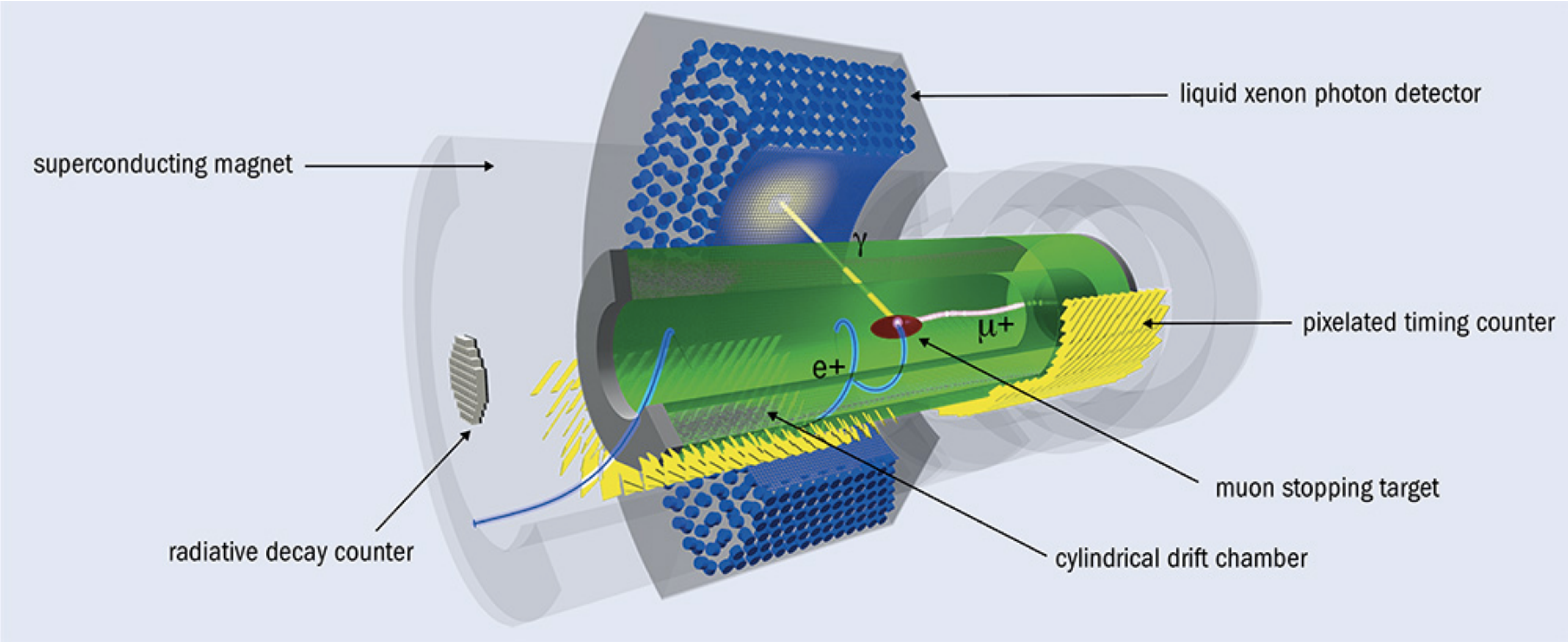


Chasing muon decays: recent results from MEG II

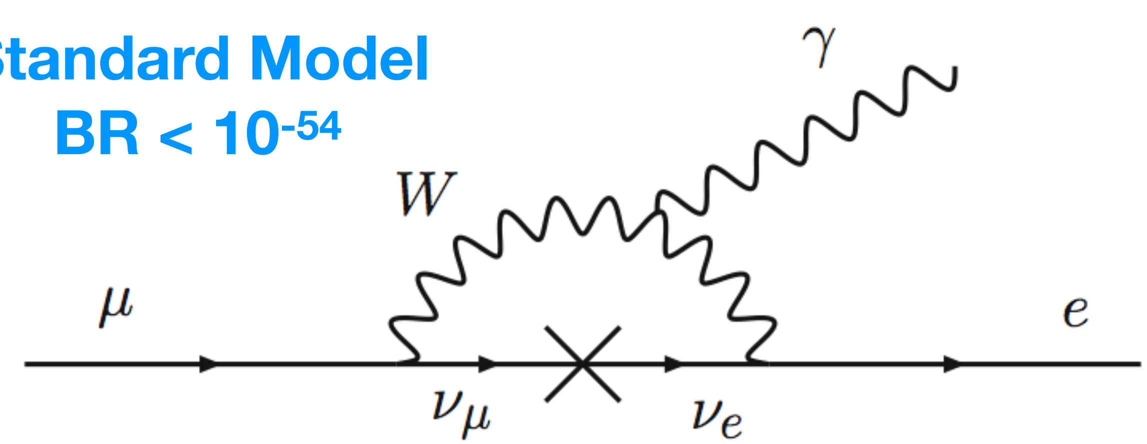
Francesco Renga, INFN Roma

Lepton Flavor Conservation

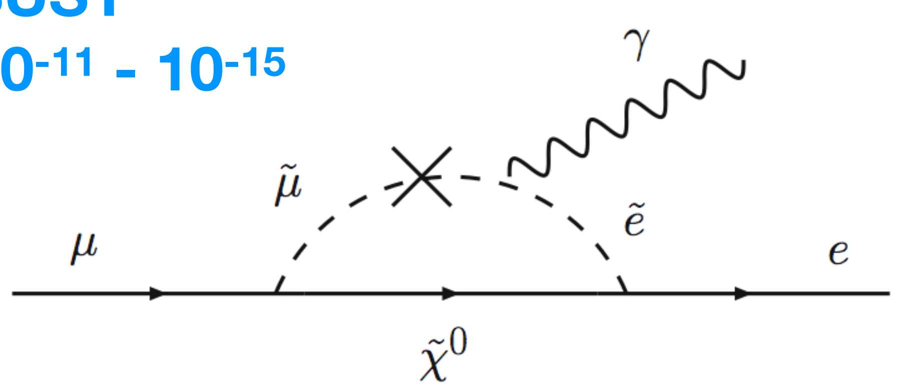
- Lepton Flavor conservation in the Standard Model is an *accidental symmetry*, arising from the particle content of the model

- Generally violated in most of New Physics models

Standard Model
BR < 10^{-54}



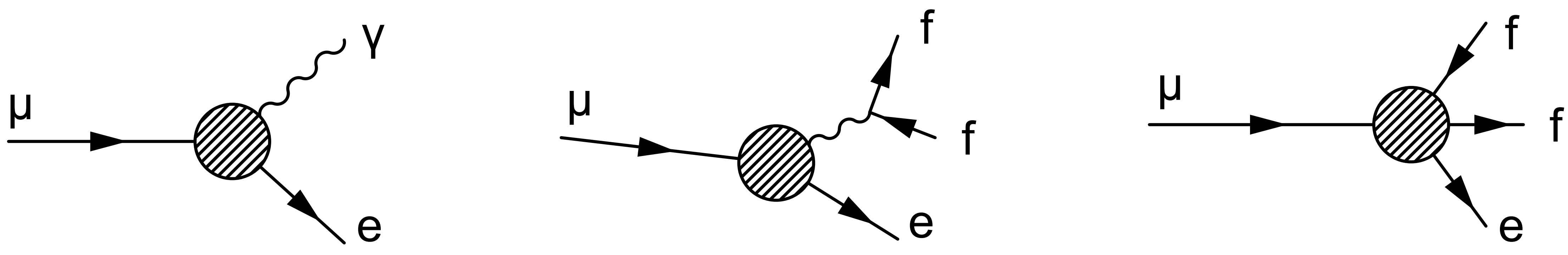
SUSY
BR ~ 10^{-11} - 10^{-15}

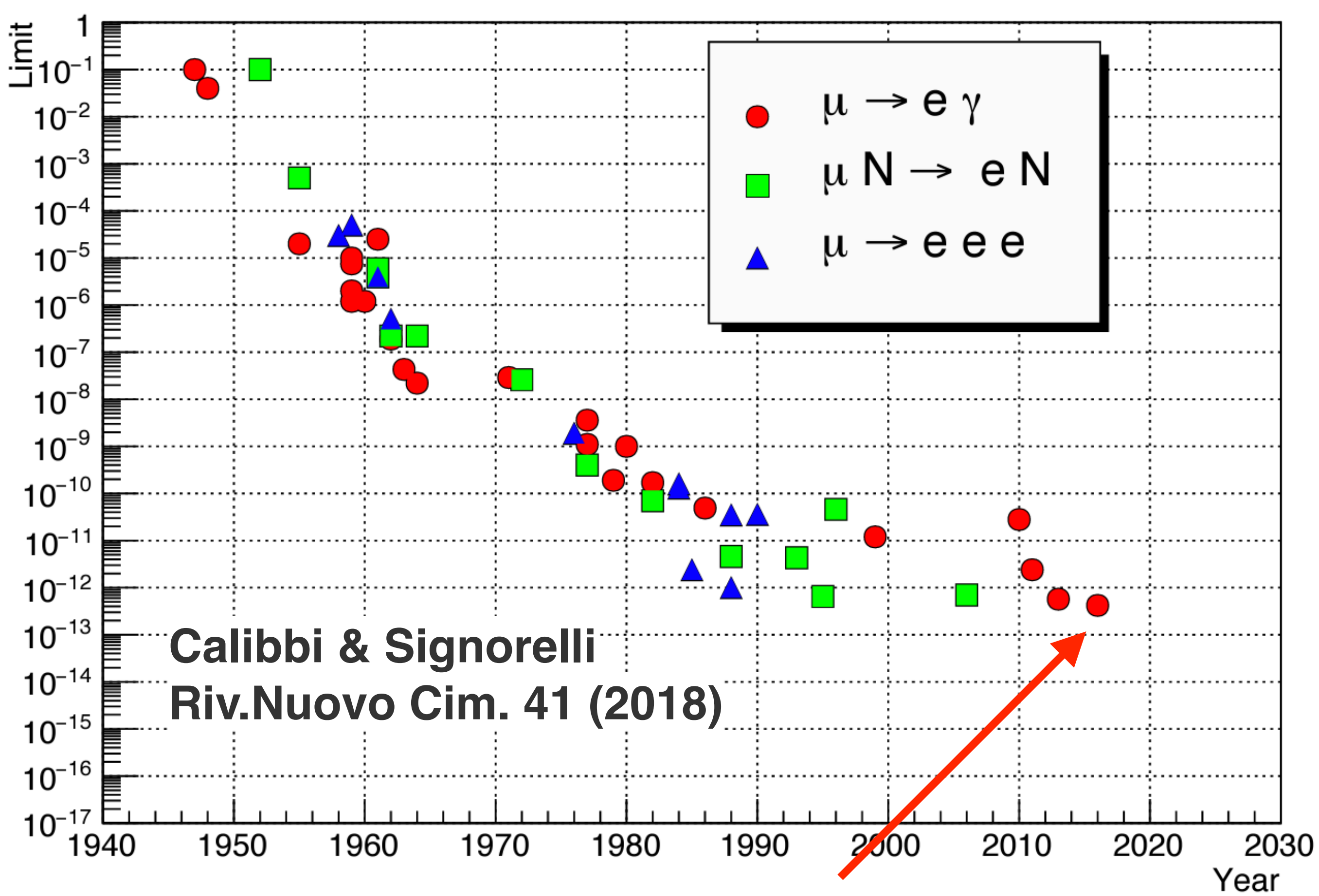


"Charged Lepton Flavor Violation (cLFV) is THE signature for New Physics"

— A. Schöning

cLFV in the muon sector





Final result of the MEG experiment

BR < 4.2 x 10^{-13} @ 90% C.L.

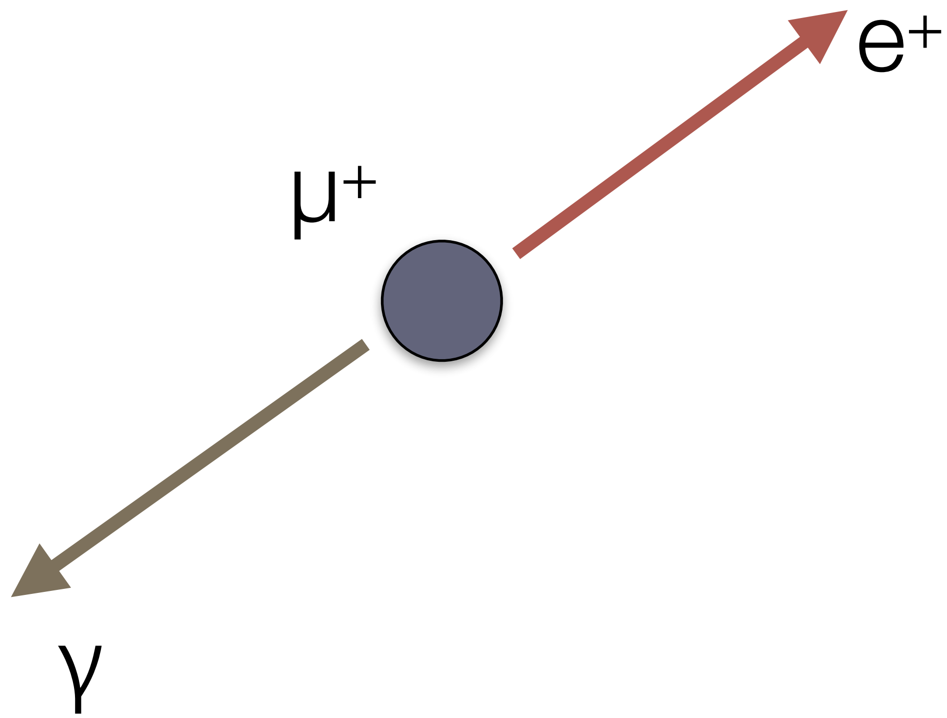
Eur. Phys. J. C76 (2016)

In a naive interpretation, $\mu \rightarrow e\gamma$ is only sensitive to the dipole-like vertex

In reality, loops mix dipole and 4-fermion operators, creating event rate patterns that are specific to each NP model

Strong complementarity between experiments

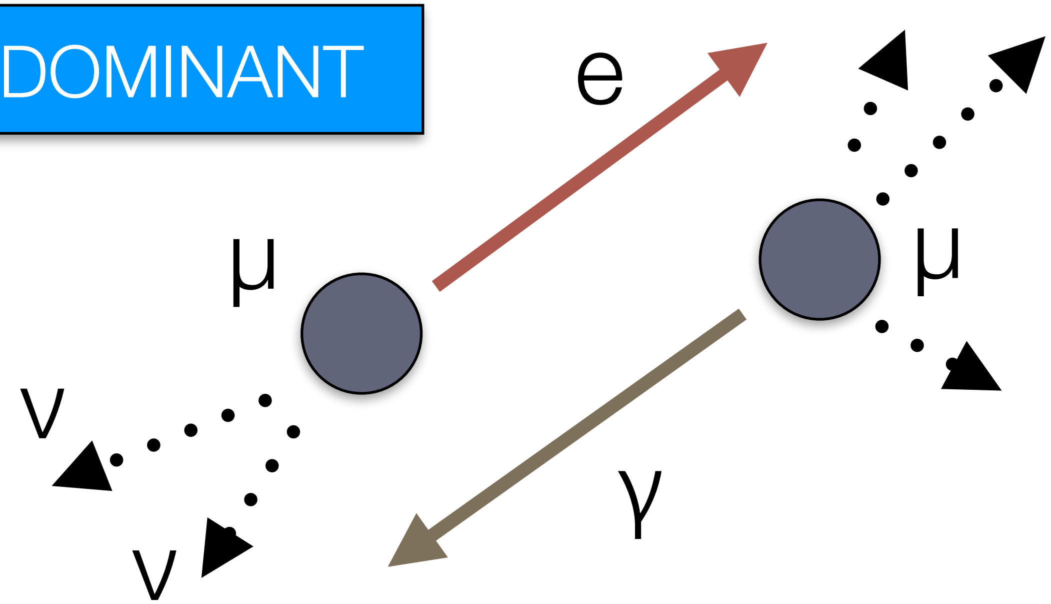
$\mu \to e\gamma$ searches



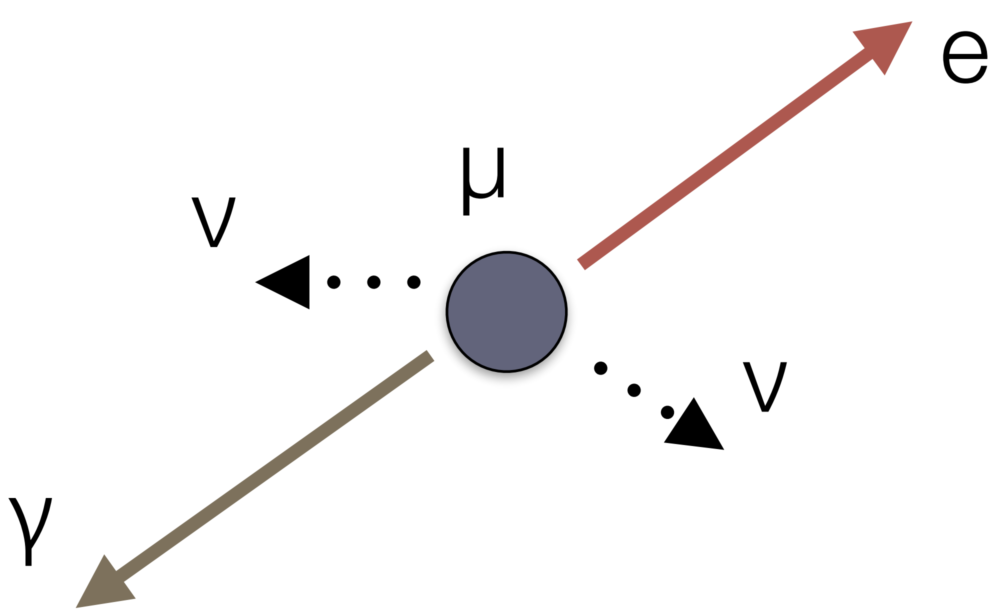
Positron and photon are **monochromatic** (52.8 MeV), **back-to-back** and produced at the **same time**

Accidental Background

DOMINANT



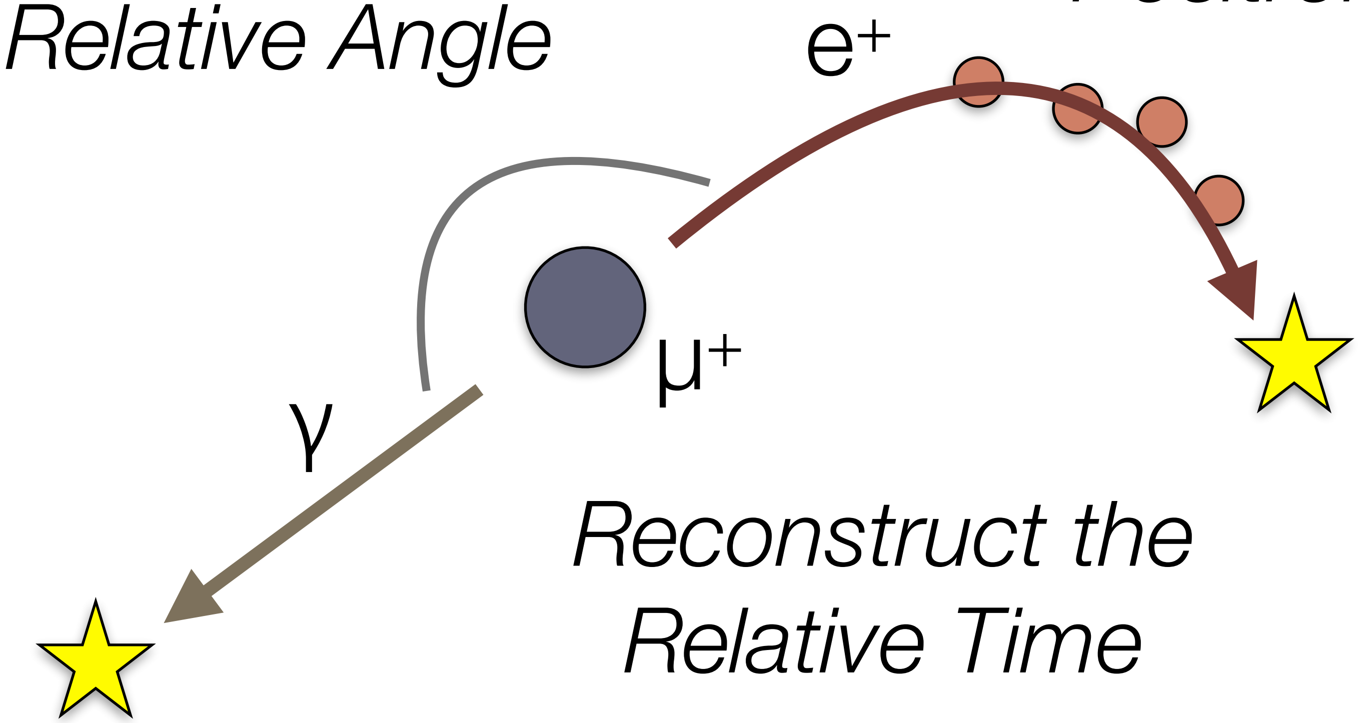
Radiative Muon Decay (RMD)



The MEG II quest for $\mu \to e\gamma$

Reconstruct the Relative Angle

Reconstruct the Positron Energy



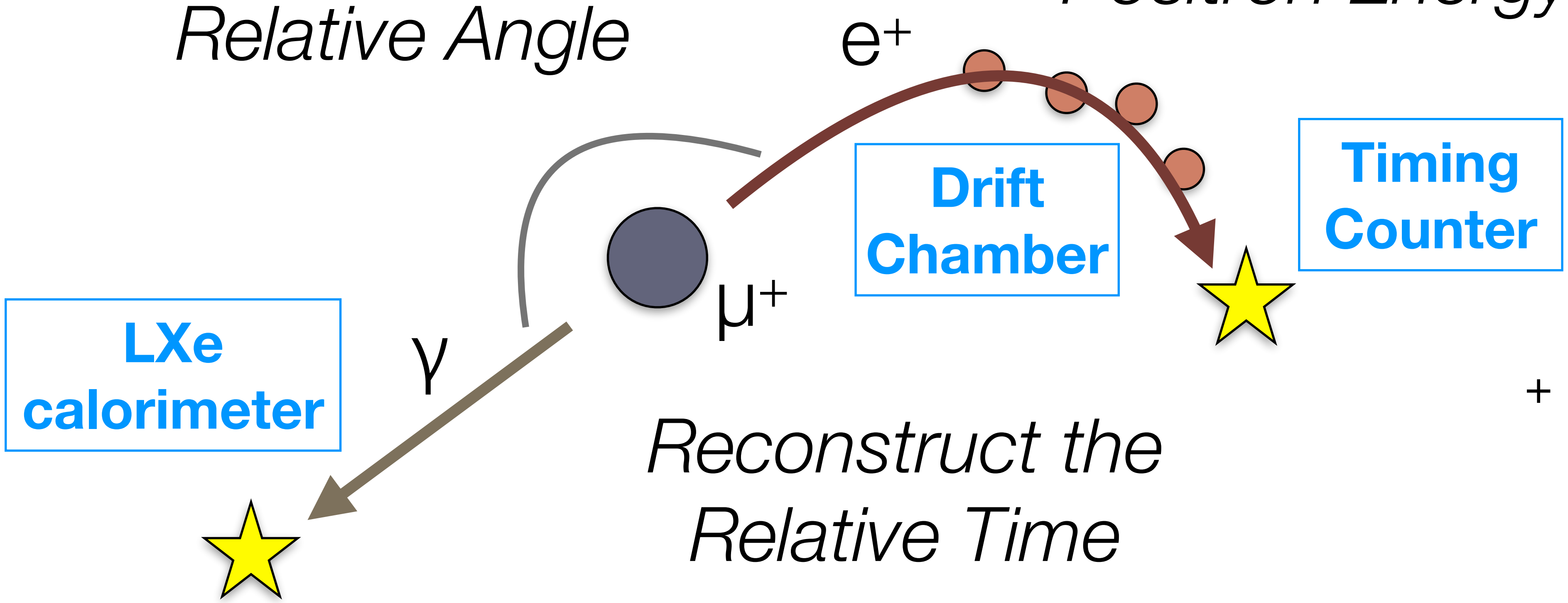
Reconstruct the Relative Time

Reconstruct the Photon Energy

The MEG II quest for $\mu \to e\gamma$

Reconstruct the Relative Angle

Reconstruct the Positron Energy

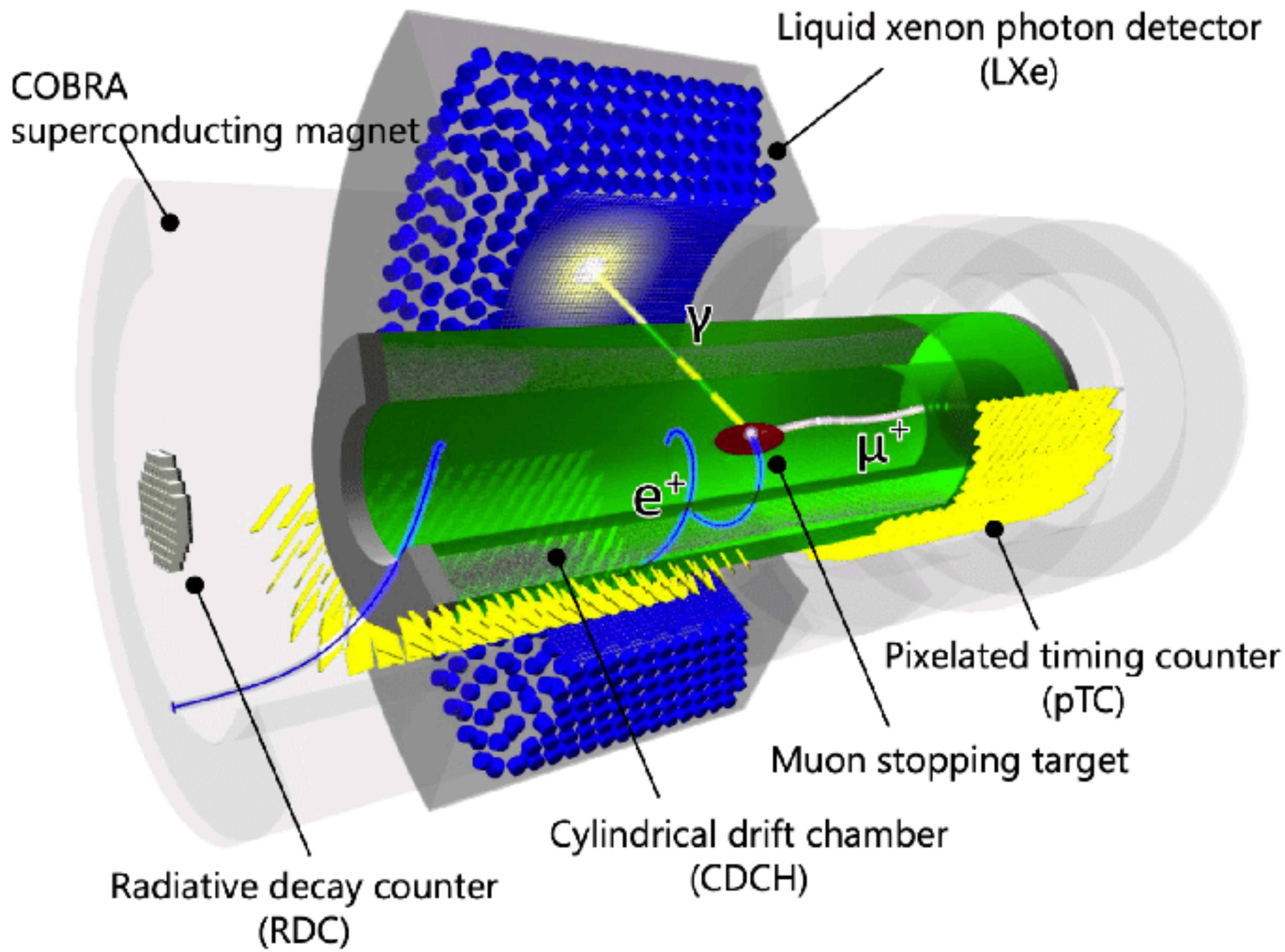


Reconstruct the Relative Time

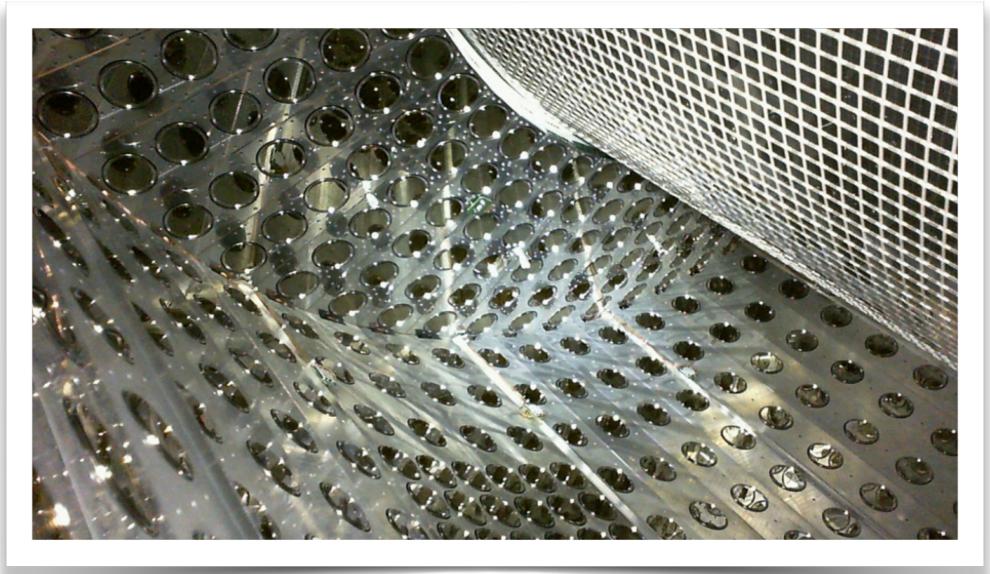
Reconstruct the Photon Energy

- *Highly selective trigger & acquisition of full waveforms for all sensors (**WaveDAQ**)*
- *Radiative Decay Counters (**RDC**) to reject high energy RMD photons in the XEC by tagging the associated low-energy positron*

The MEG II detector



The MEG II detector

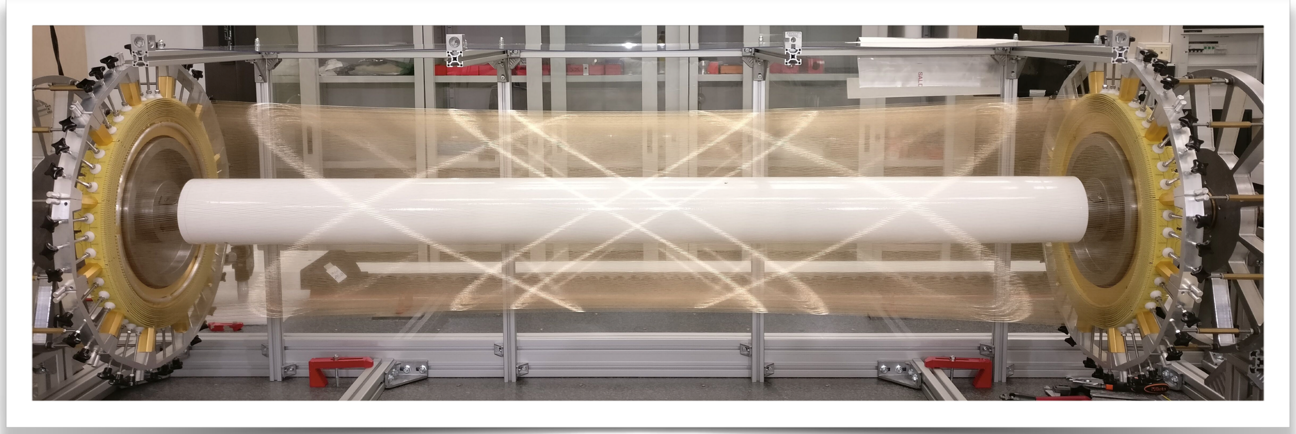


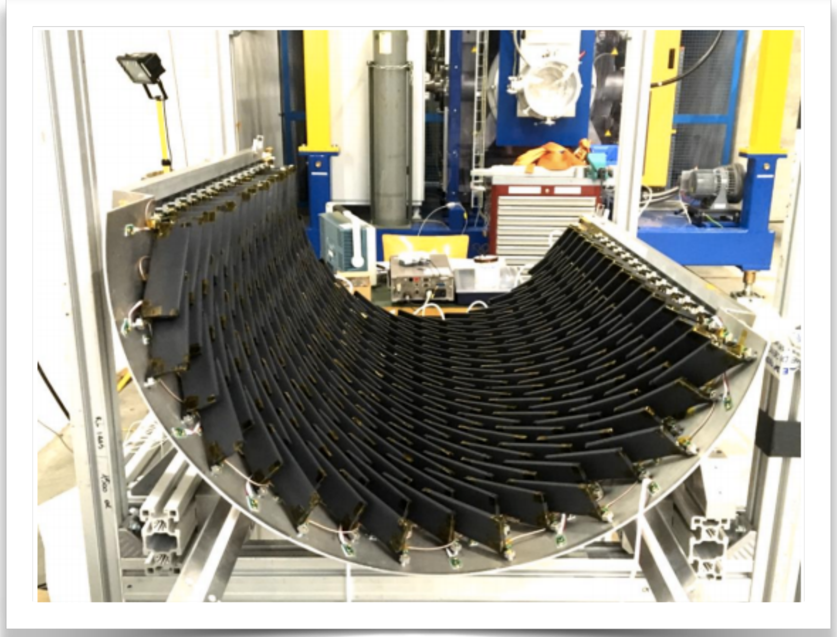
LXe calorimeter (XEC)

- 800 liter LXe readout by PMTs and VUV-sensitive MPPCs

Cylindrical Drift Chamber (CDCH)

- Unique-volume cylindrical drift chamber in a graded magnetic field
- Full-stereo geometry
- High granularity with extremely thin wires



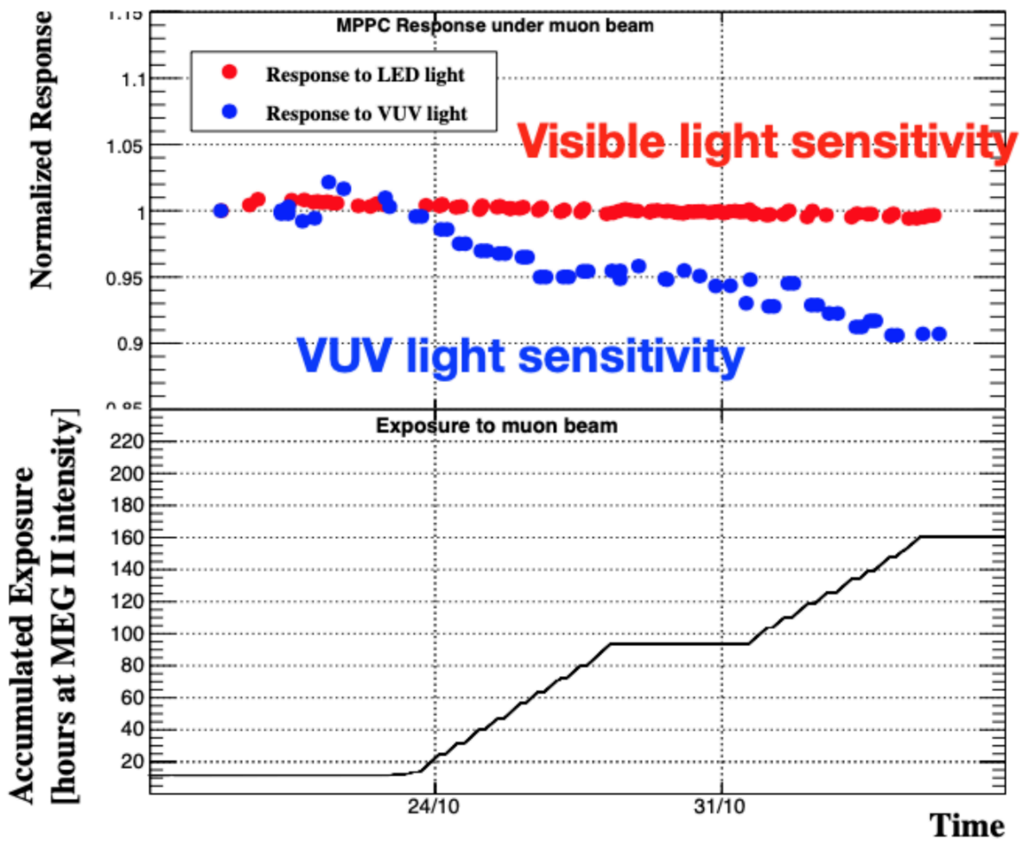


Pixelatred timing counter (pTC)

- 2 x 256 scintillating tiles readout by SiPMs

UL ~ 6 x 10^{-14} in a 3-year run

Detector operations



Degradation speed ~0.08%/hour

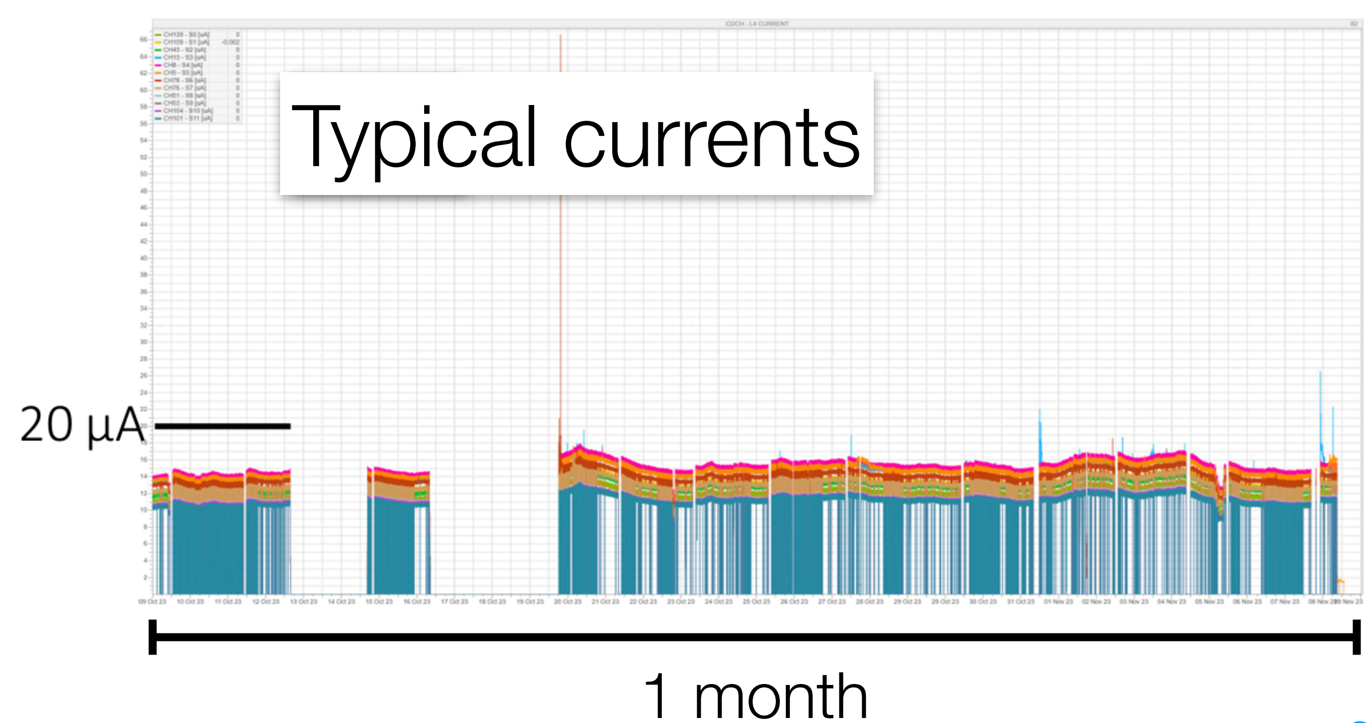
LXe calorimeter

We observe a degradation of the PDE of MPPCs under beam

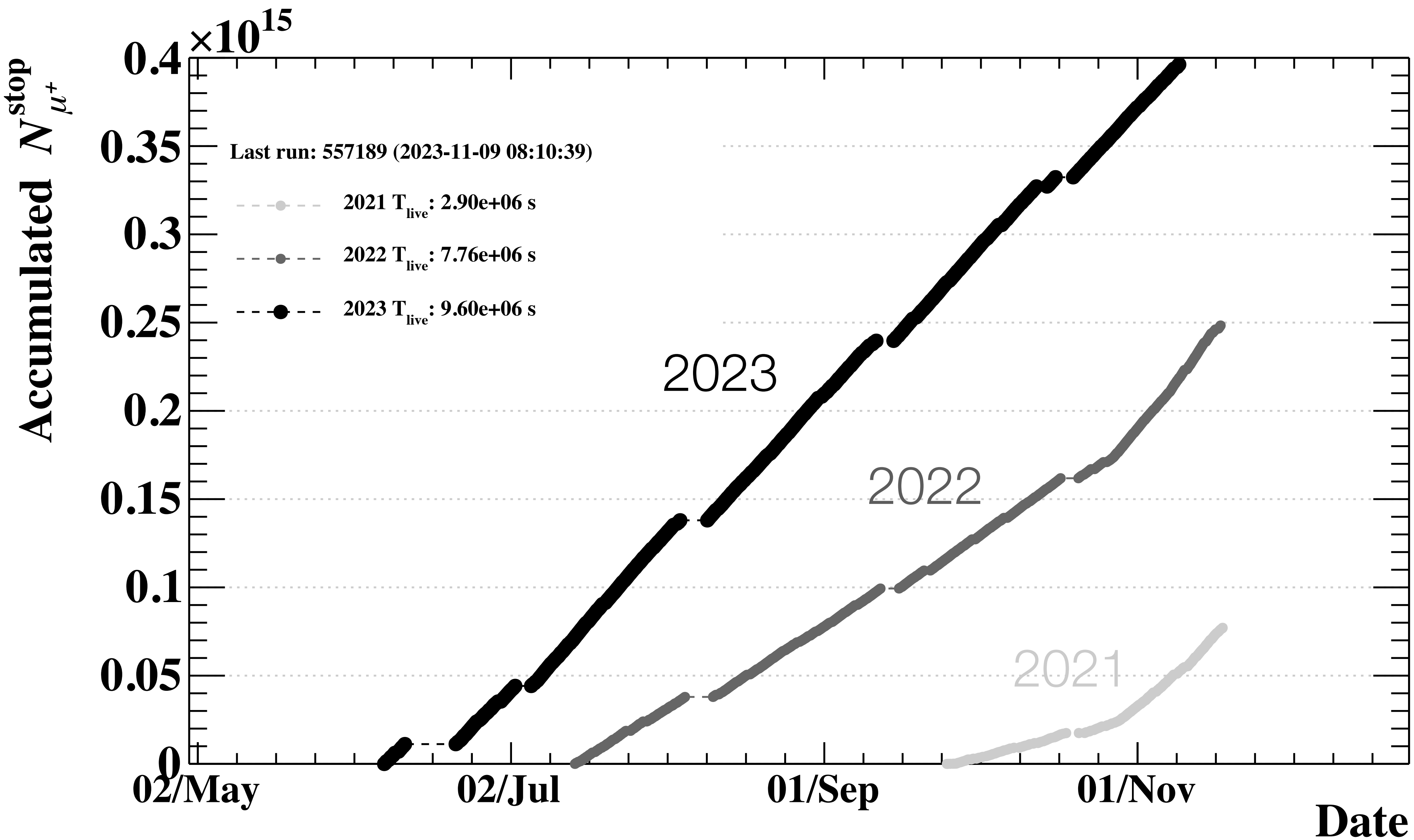
We successfully developed a recovery procedure, to be repeated periodically
(annealing by heat: we let the MPPCs draw a large current when illuminated by LEDs, so to heat them by Joule effect up to 70 ºC for several hours)

Drift Chamber

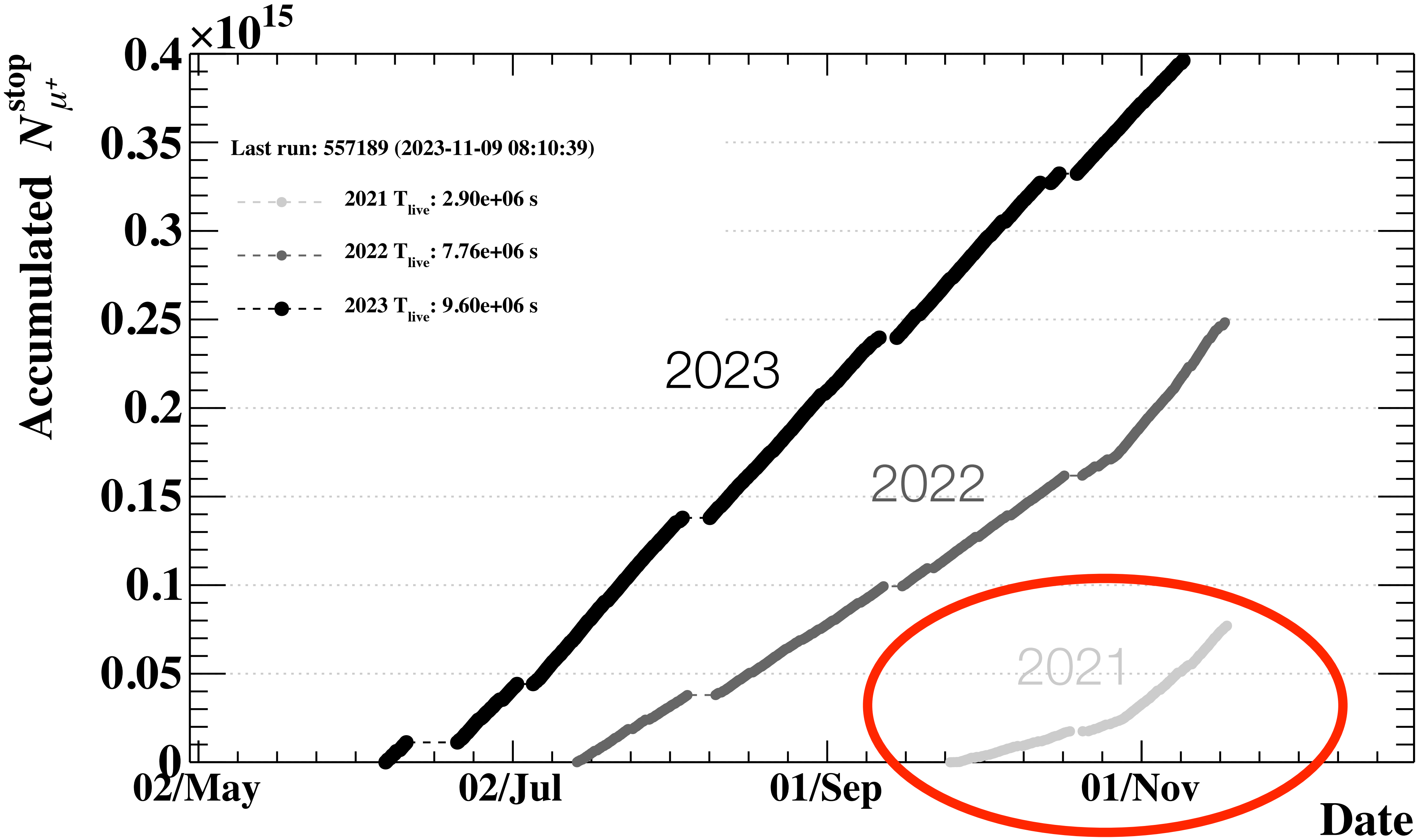
After a complicated commissioning phase, affected by wire corrosion and discharges (due to imperfections of the wire surfaces), the chamber has been operating stably since Dec. 2020, with no evident sign of aging



The MEG II dataset (so far...)

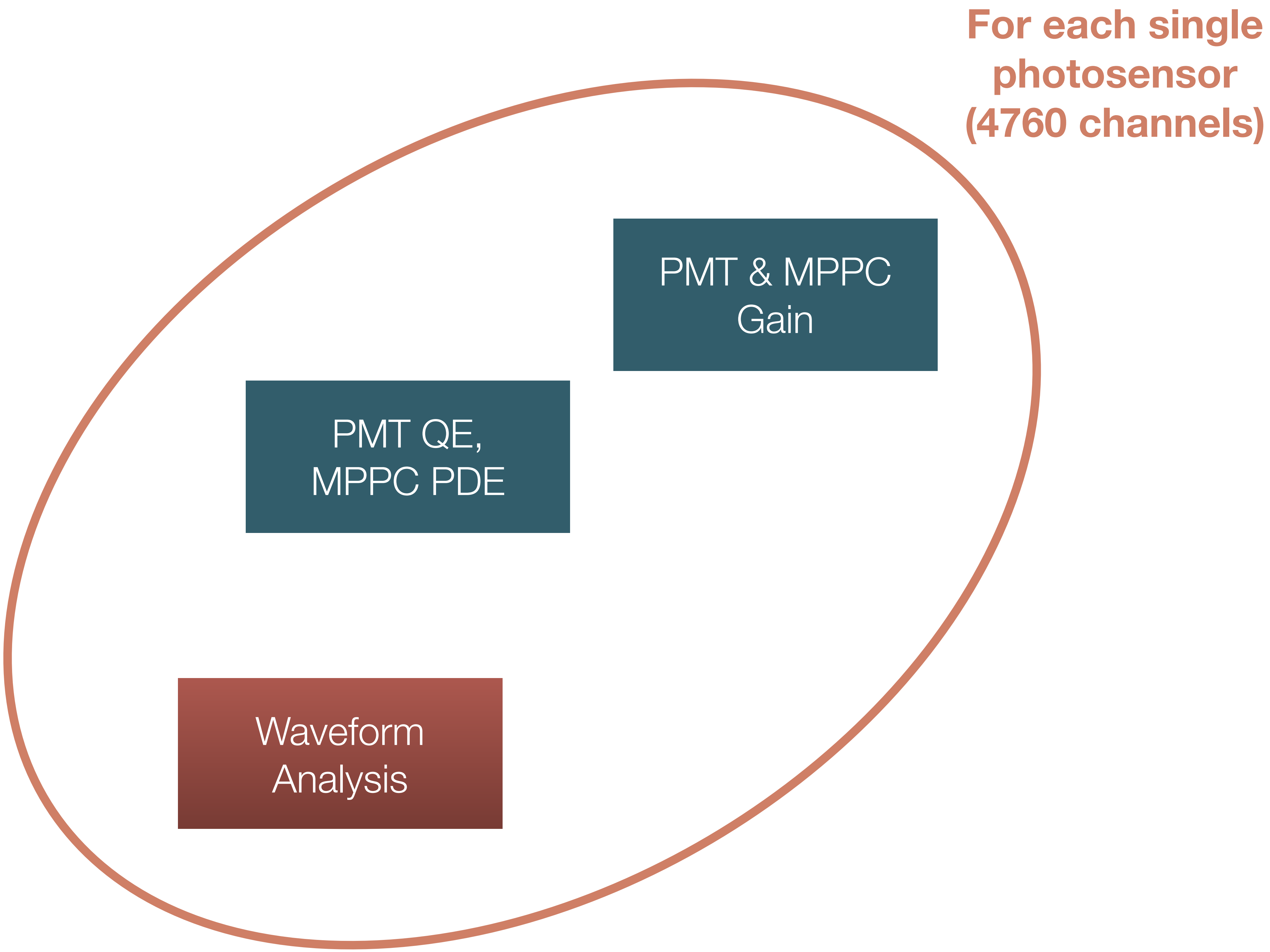


The MEG II dataset (so far...)

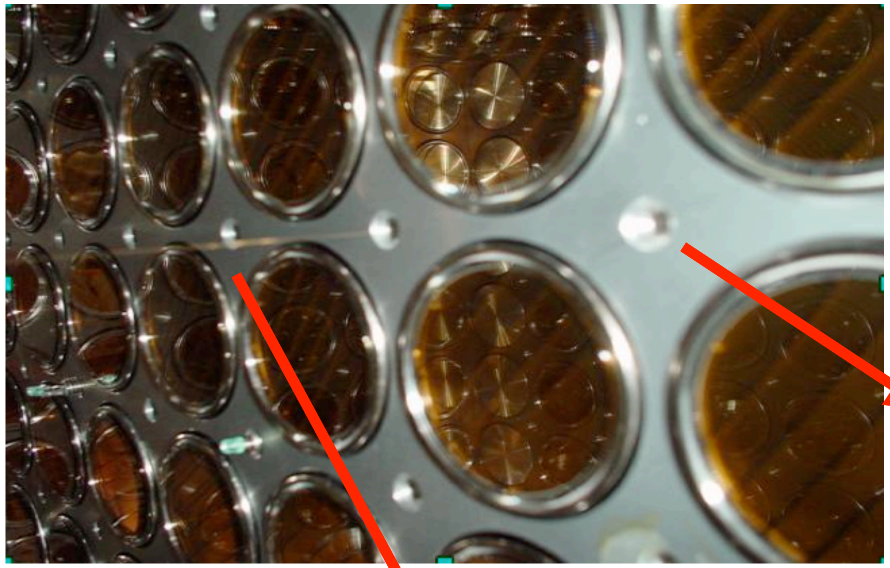


Published data

Event reconstruction — photon



Event reconstruction — photon



Calibration sources (α, LED)

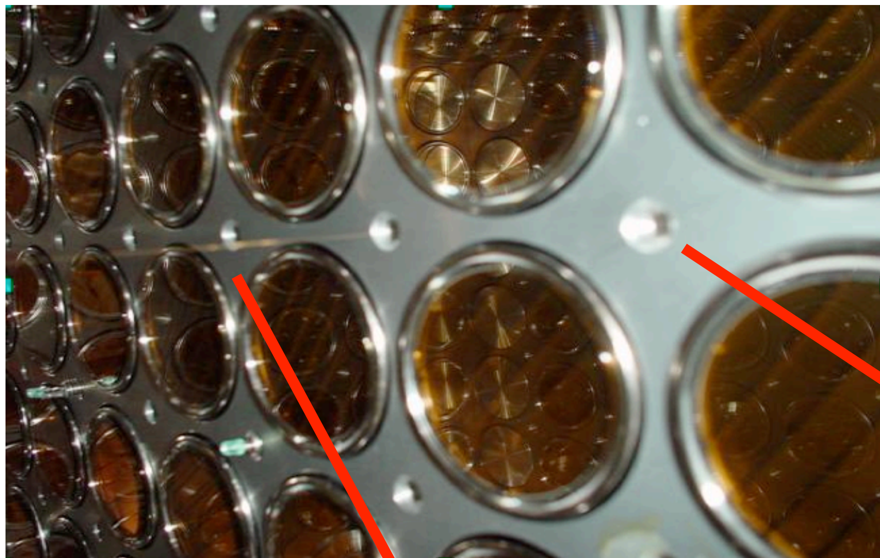
installed inside the XEC

PMT & MPPC Gain

PMT QE, MPPC PDE

Waveform Analysis

Event reconstruction — photon



Calibration sources (α, LED)

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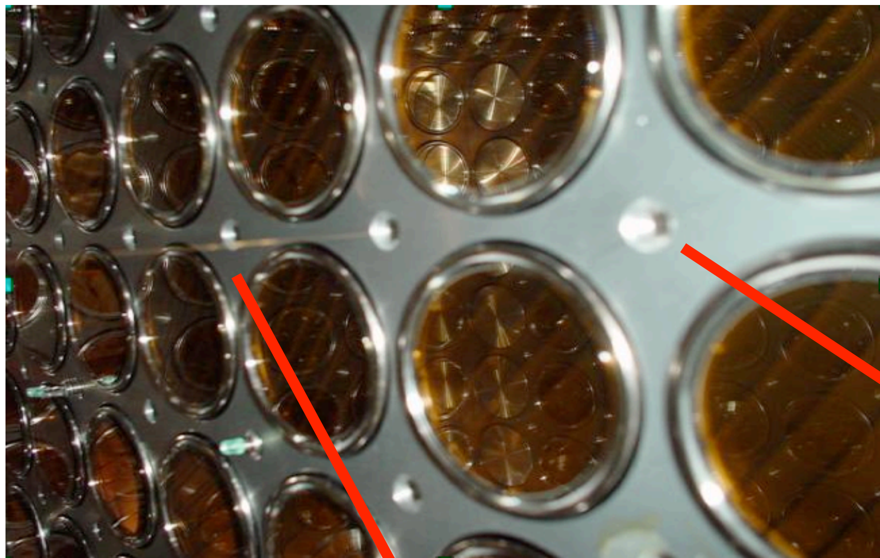
PMT QE, MPPC PDE

Waveform Analysis

Energy, time, position reconstruction

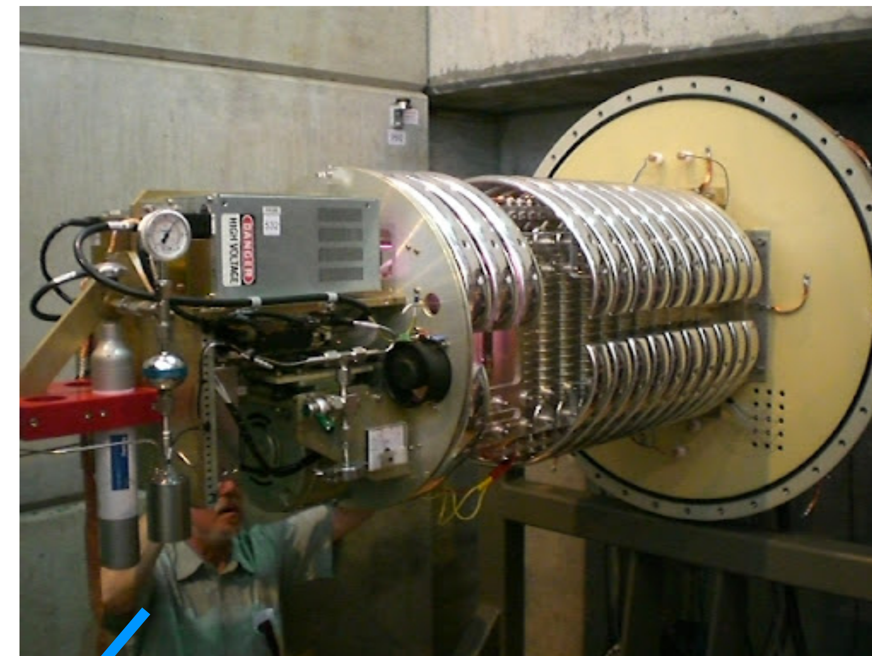
Event reconstruction — photon



Calibration sources (α, LED) installed inside the XEC

PMT & MPPC Gain

PMT QE, MPPC PDE



Periodic correction of time-dependences with dedicated Cockroft-Walton

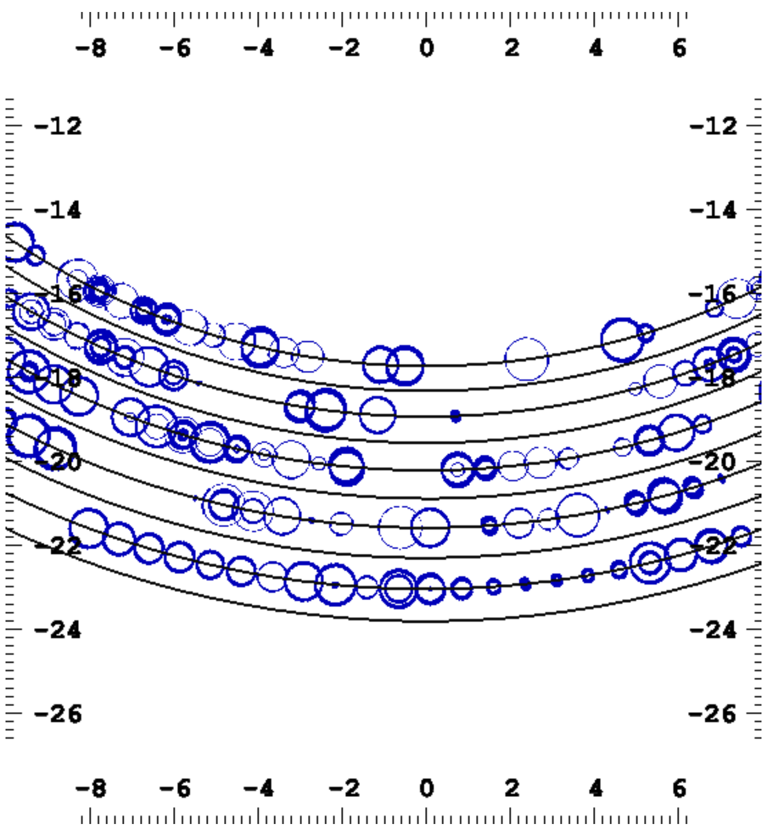
Energy, time, position reconstruction

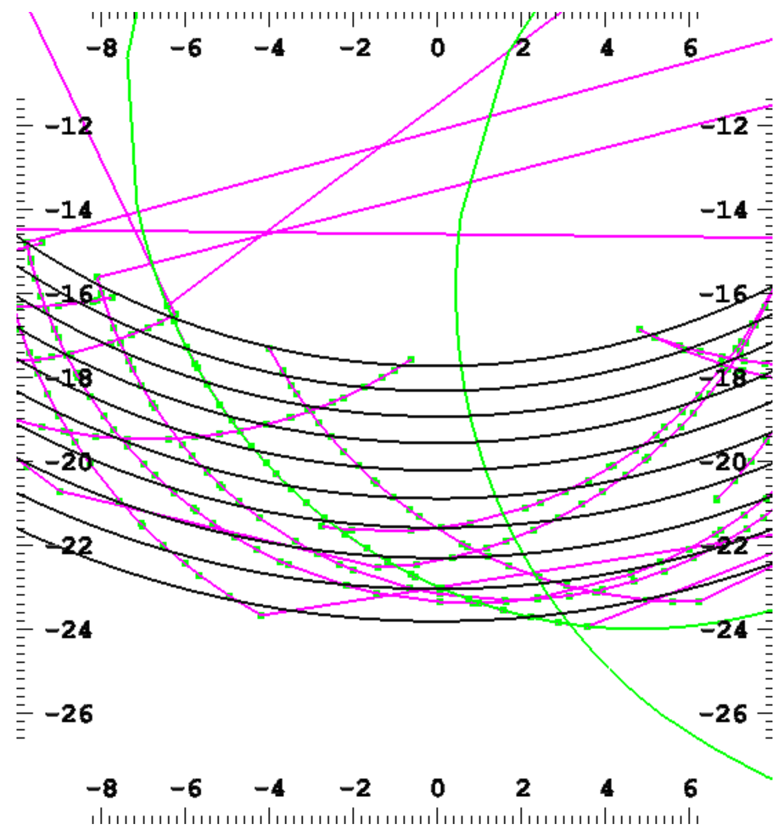
Waveform Analysis

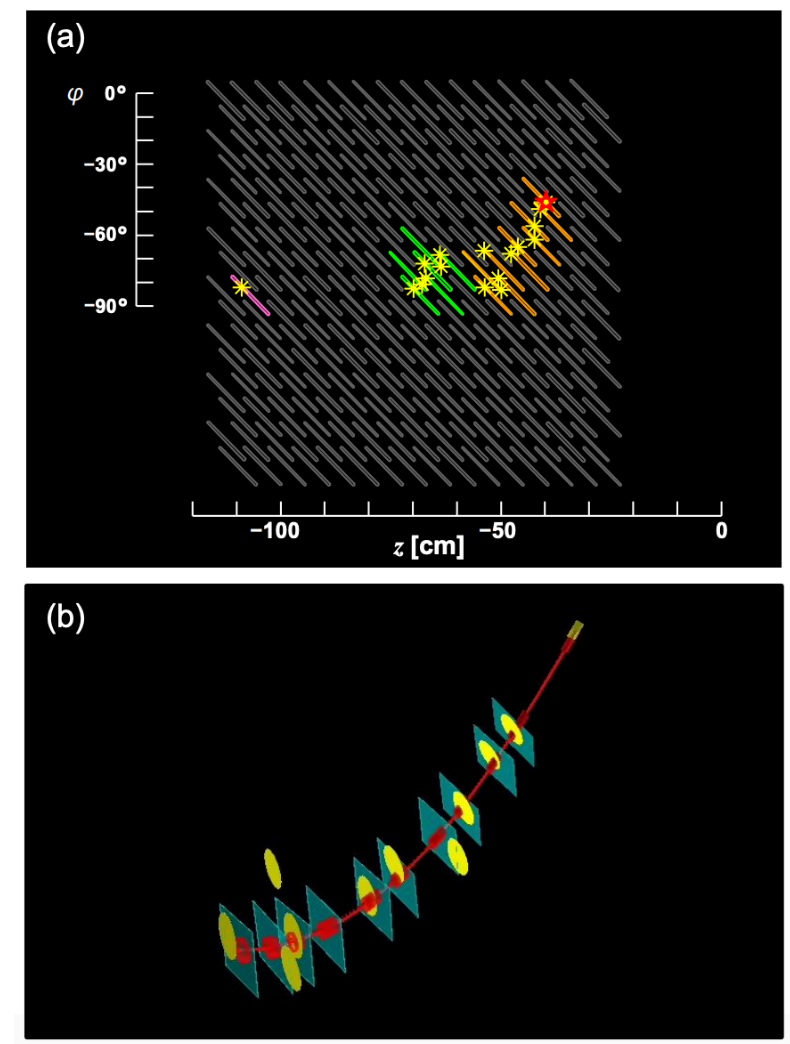
Absolute calibrations with 55 MeV photons from charge-exchange reactions

$$\pi^- + p \rightarrow \pi^0(\gamma\gamma) + n$$

Event reconstruction — positron

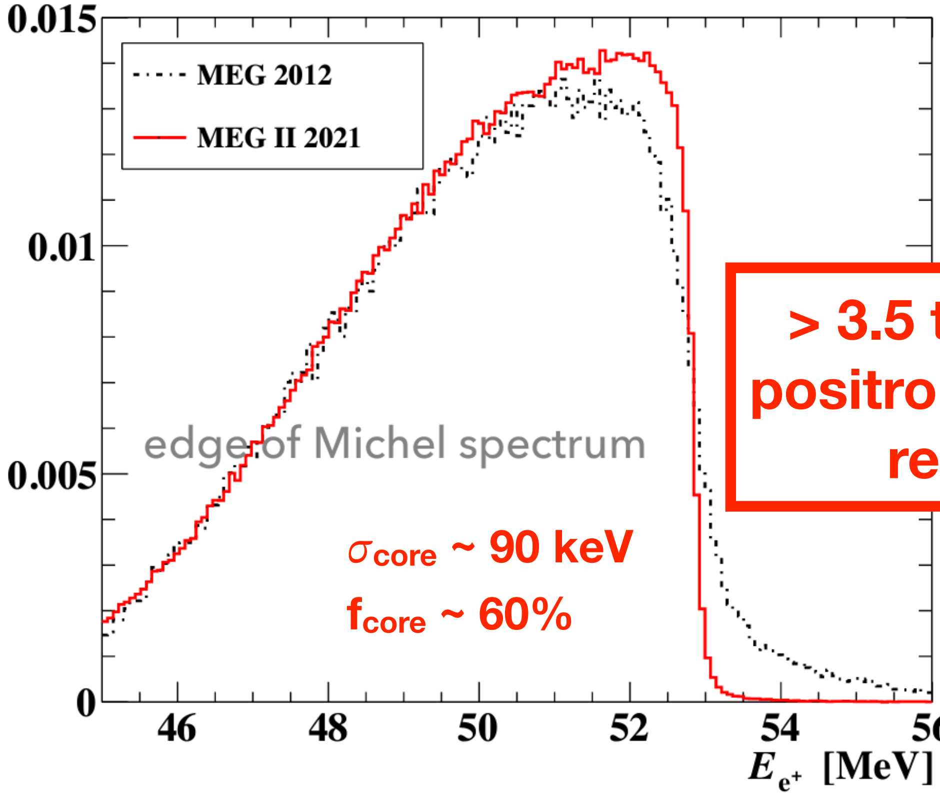






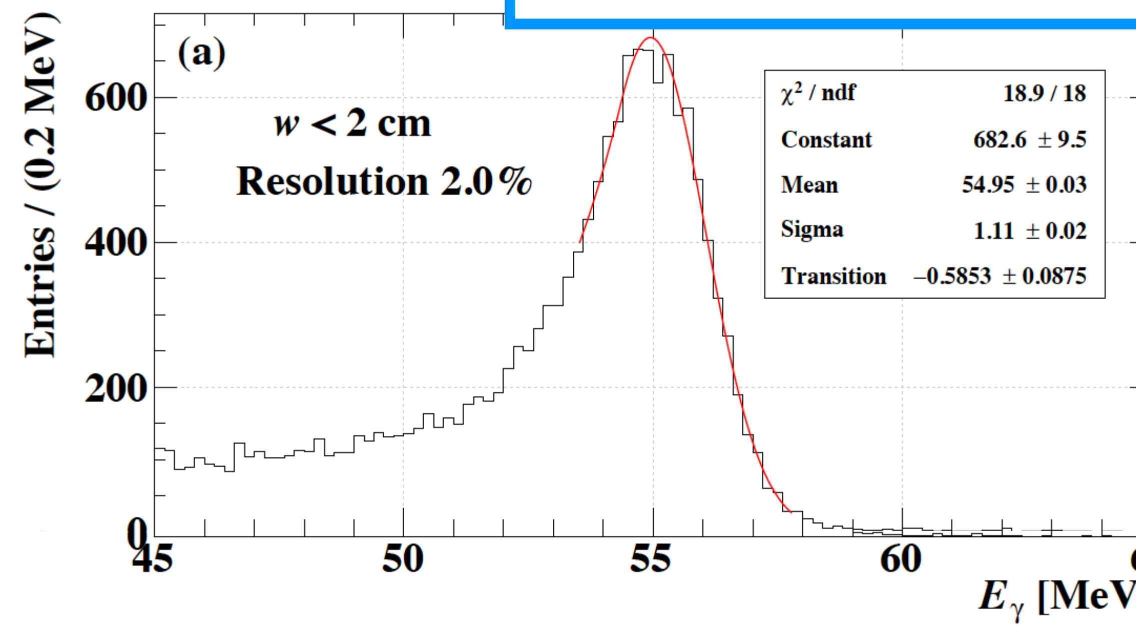
Pattern recognition in a high occupancy environment exploiting the high granularity of CDCH and pTC

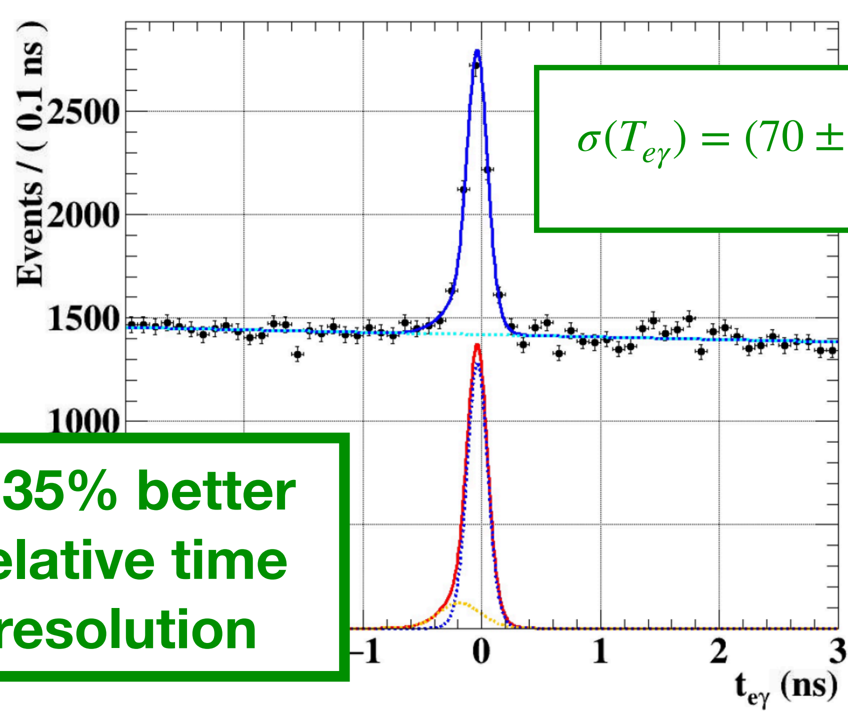
Detector Performance (vs. MEG)



> 3.5 times better positron momentum resolution

20% better photon energy resolution for shallow events





$$\sigma(T_{e\gamma}) = (70 \pm 3) \oplus \frac{112}{\sqrt{n_{TC}}}$$

~ 35% better relative time resolution

Resolutions	Foreseen	Achieved
E_{e^+} (keV)	100	89
ϕ_{e^+} [a], θ_{e^+} (mrad)	3.7/6.7	4.1/7.2
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.74/2.0
E_γ(%) (w<2 cm)/(w>2 cm)	1.7/1.7	2.0/1.8
$u_\gamma, v_\gamma, w_\gamma$ (mm)	2.4/2.4/5.0	2.5/2.5/5.0
$t_{e^+\gamma}$ (ps)	70	78
Efficiency (%)		
ε_γ	69	62
ε_{e^+}	65	67
ε_{TRG}	≈99	80

Likelihood analysis

- We construct fully frequentistic confidence intervals using the **Feldman-Cousins prescription** with **profile likelihood ordering** for the treatment of nuisance parameters
  - proper treatment of physics limit $N_{sig} > 0$, in particular when the best fit gives $\hat{N}_{sig} < 0$
  - Optimal treatment of the most relevant systematics

$$\lambda_p(N_{\rm sig}) = \begin{cases} \dfrac{\mathcal{L}(N_{\rm sig},\hat{\hat{\boldsymbol{\theta}}}(N_{\rm sig}))}{\mathcal{L}(0,\hat{\hat{\boldsymbol{\theta}}}(0))} & \text{if } \hat{N}_{\rm sig} < 0 \\ \dfrac{\mathcal{L}(N_{\rm sig},\hat{\hat{\boldsymbol{\theta}}}(N_{\rm sig}))}{\mathcal{L}(\hat{N}_{\rm sig},\hat{\boldsymbol{\theta}})} & \text{if } \hat{N}_{\rm sig} \geq 0 \end{cases}$$

Nuisance parameters

$$\boldsymbol{\theta} = (N_{\rm RMD}, N_{\rm ACC}, x_{\rm T})$$

Target alignment parameter

Blind analysis

- Analysis developed and tested in sidebands of $T_{e\gamma}$ and E_γ

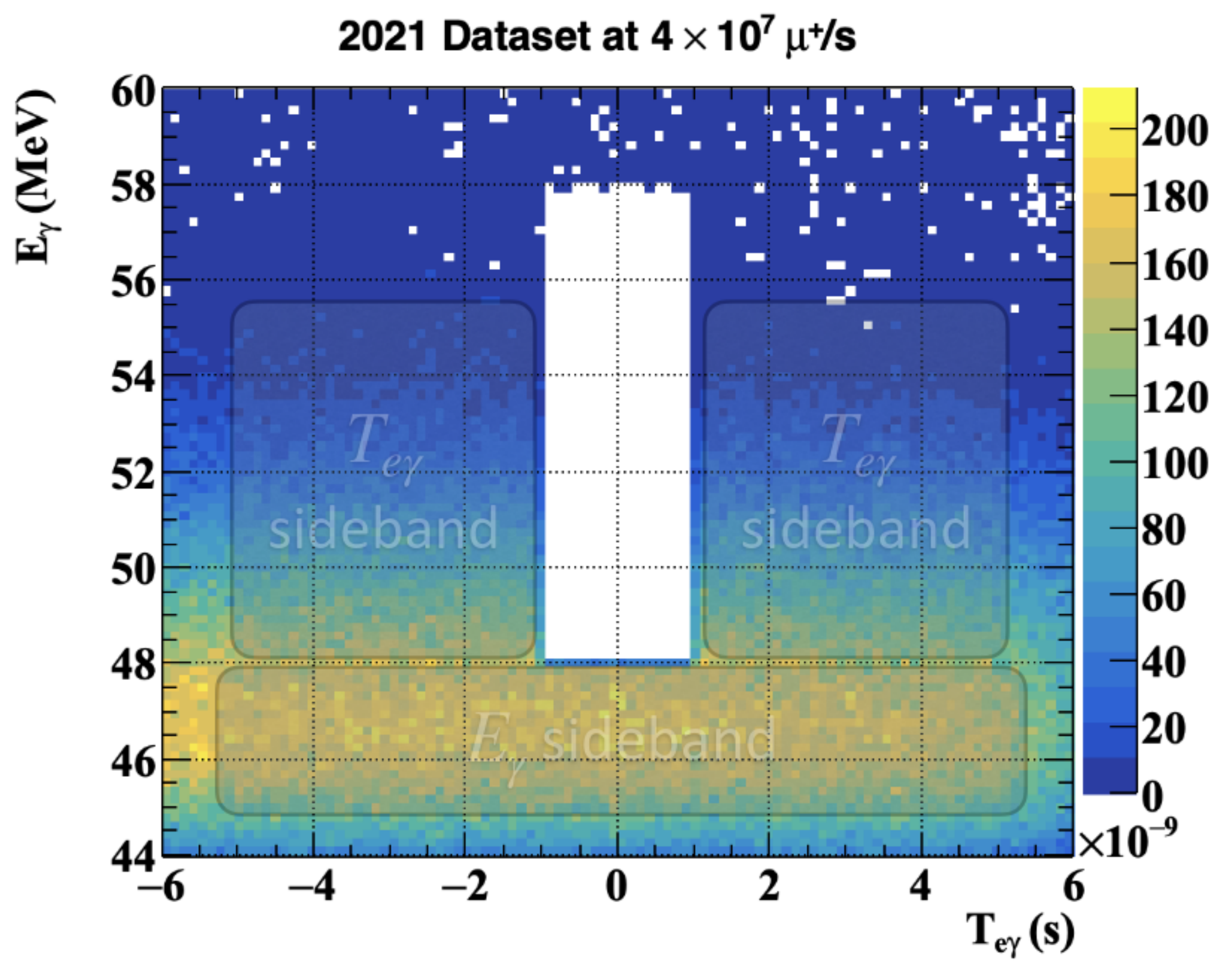
Development of reconstruction algorithms

Selection

Normalization

Extraction of PDFs

Estimate of background yields (used as a constraint for the analysis in the analysis region)



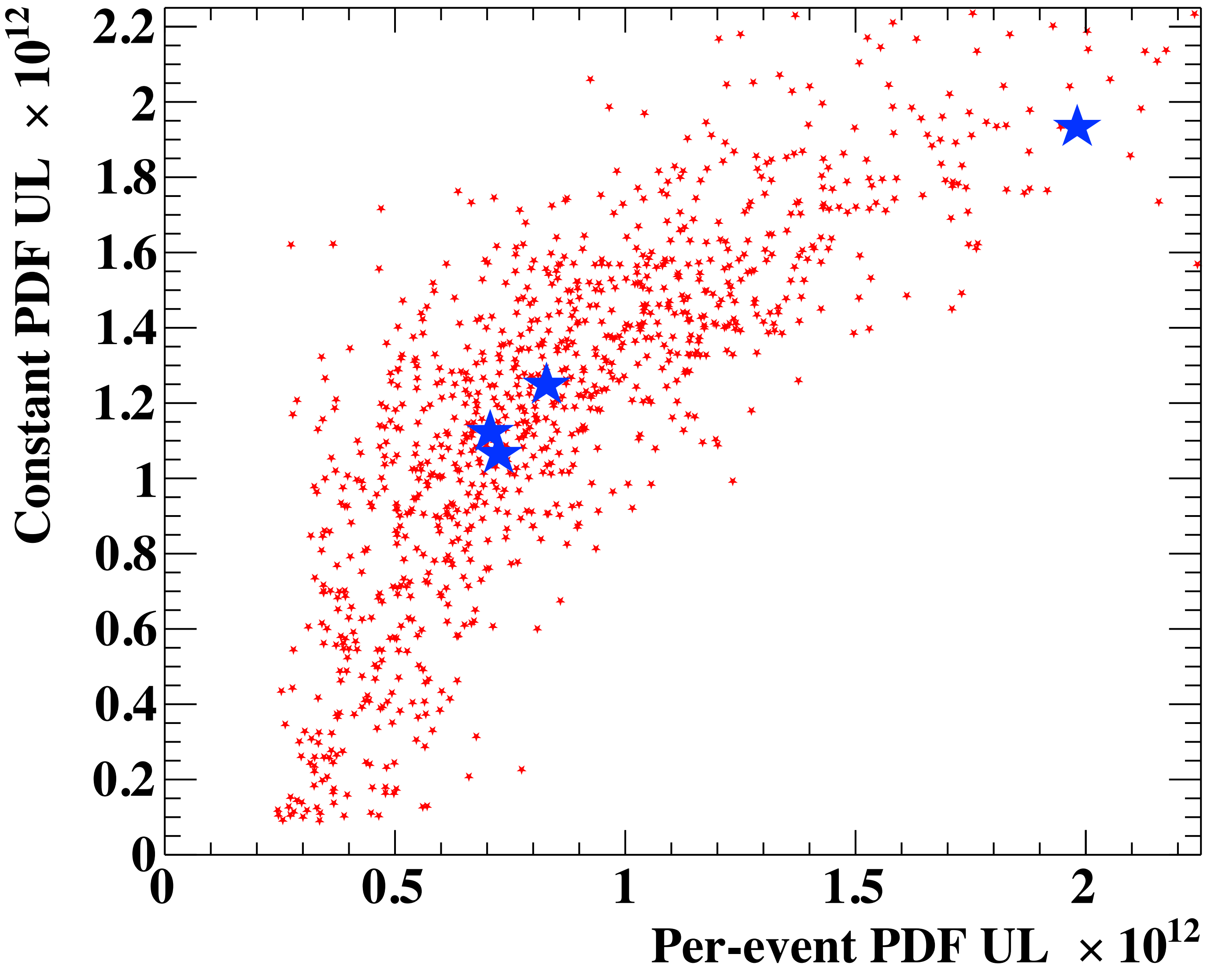
Comparison of two analyses

- The final analysis uses event-by-event PDFs and correlations
  - a careful investigation of their reliability is needed

Constant PDFs vs. Per-event PDFs

on the same set of toy MC experiments with null signal

on 4 fictitious analysis regions in the $T_{e\gamma}$ sidebands

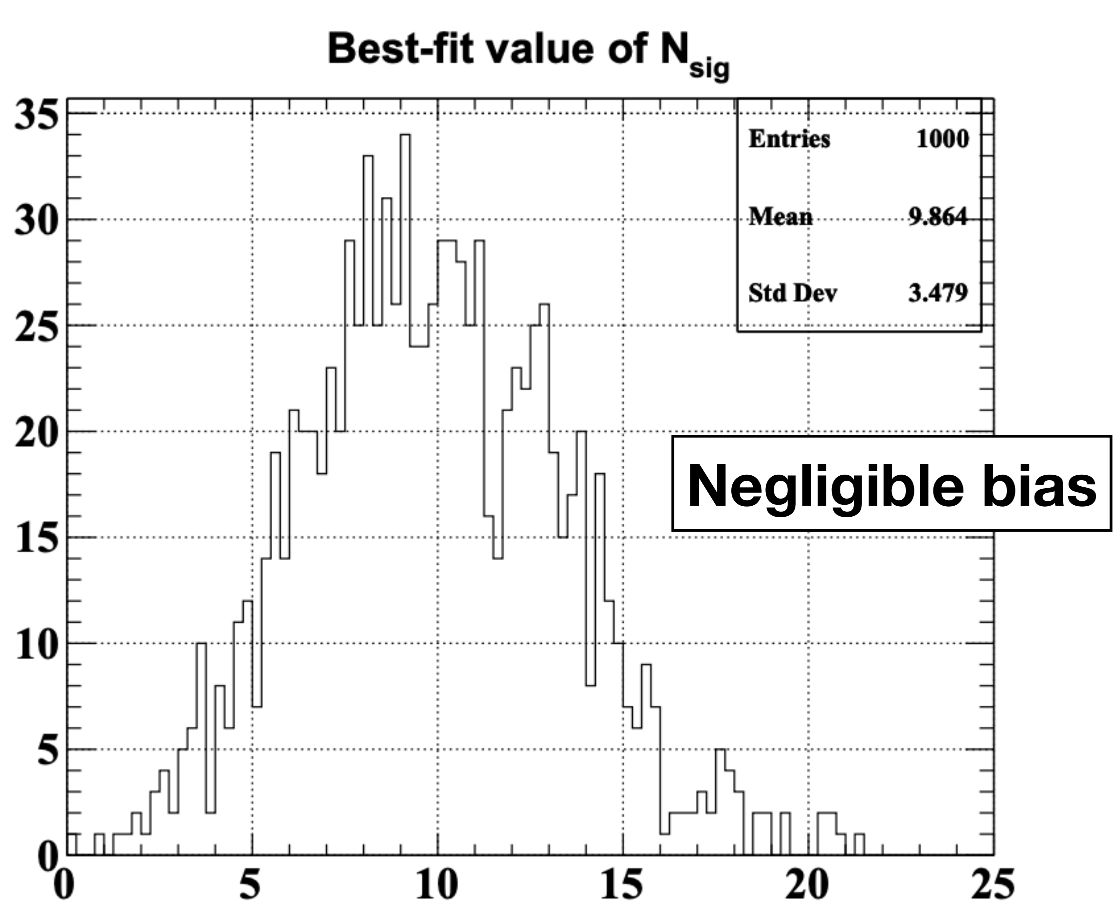


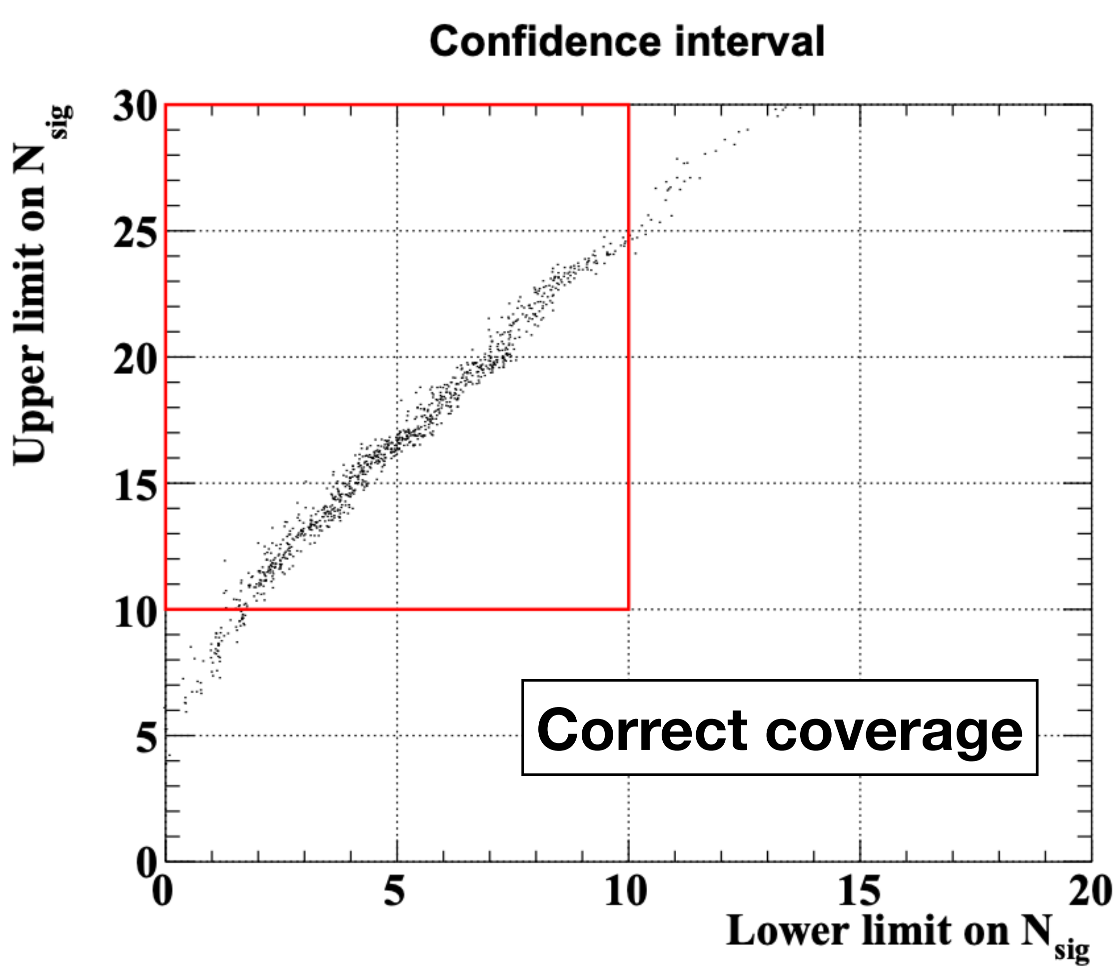
Consistency checks

- The final analysis uses event-by-event PDFs and correlations
  - a careful investigation of their reliability is needed

Fit to toy MC background + non-null signal ($\langle N_{sig} \rangle = 10$) from full simulation ("embedded toys")

—> critical test for resolution and correlation models

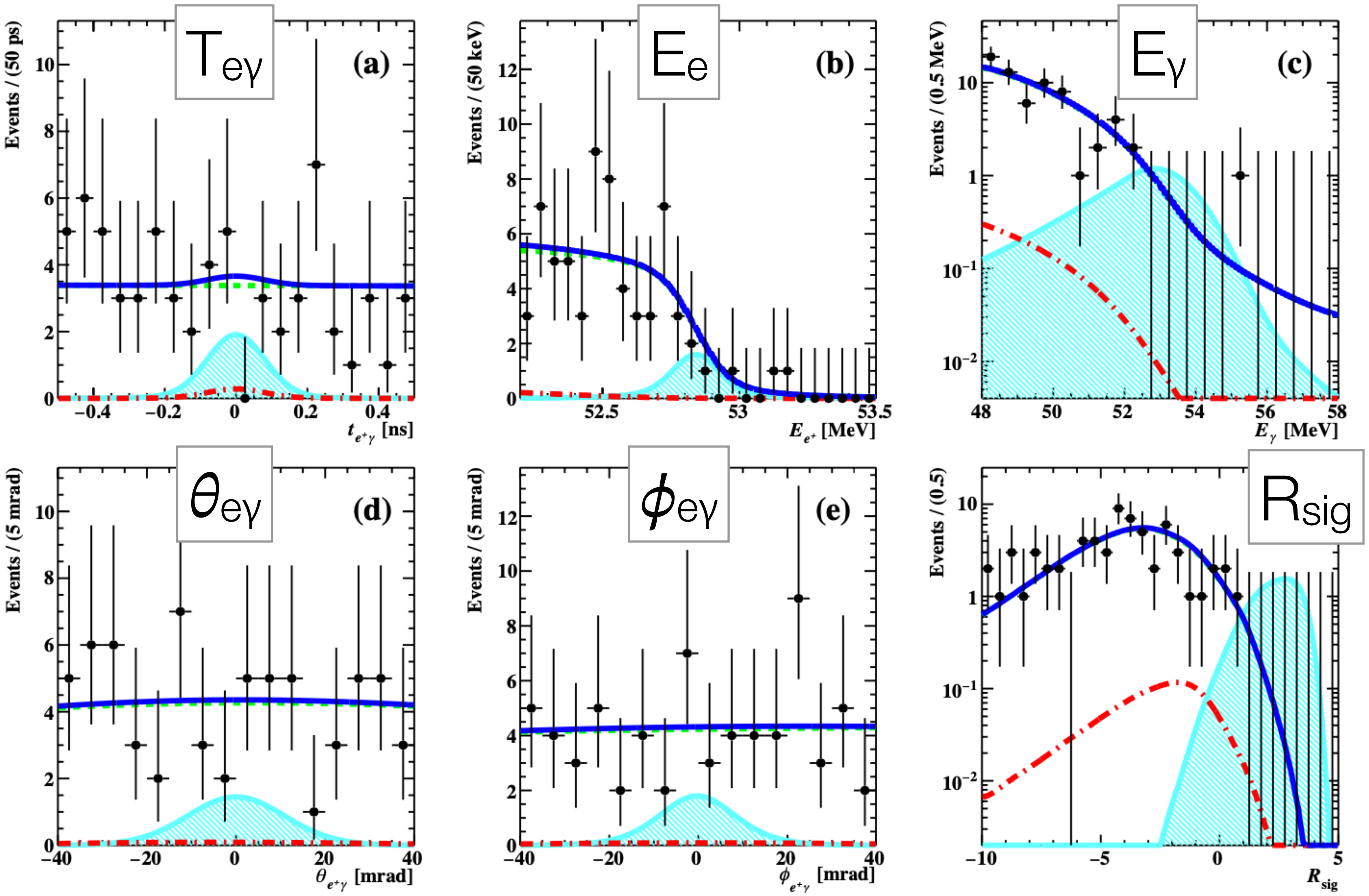




Results

Relative signal likelihood

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



$N_{\mathrm{obs}} = 66$

$N_{\mathrm{sig}} < 2$

$N^{\mathrm{exp}}_{\mathrm{ACC}} = 68.0 \pm 3.5$

$N^{\mathrm{exp}}_{\mathrm{RMD}} = 1.2 \pm 0.2$

$BR_{\mathrm{sig}} < 7.5 \times 10^{-13}$
at 90% C.L.

Results

Relative signal likelihood

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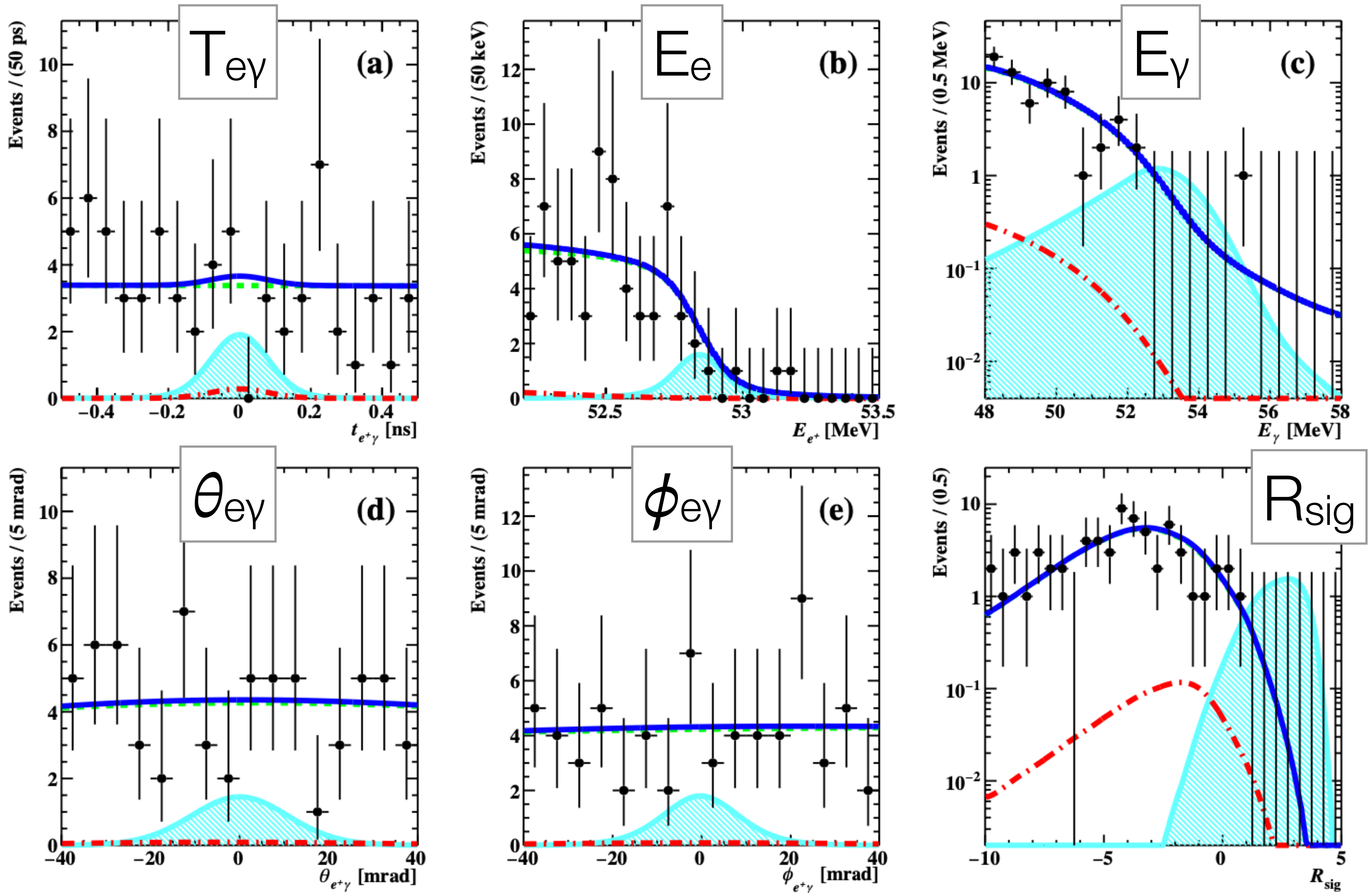

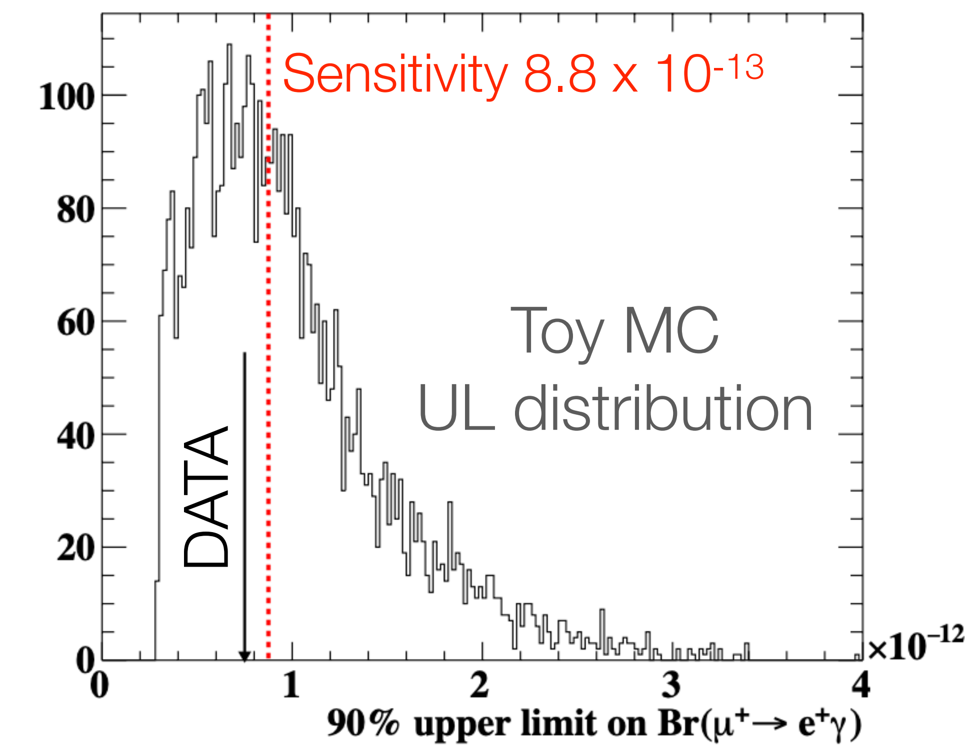

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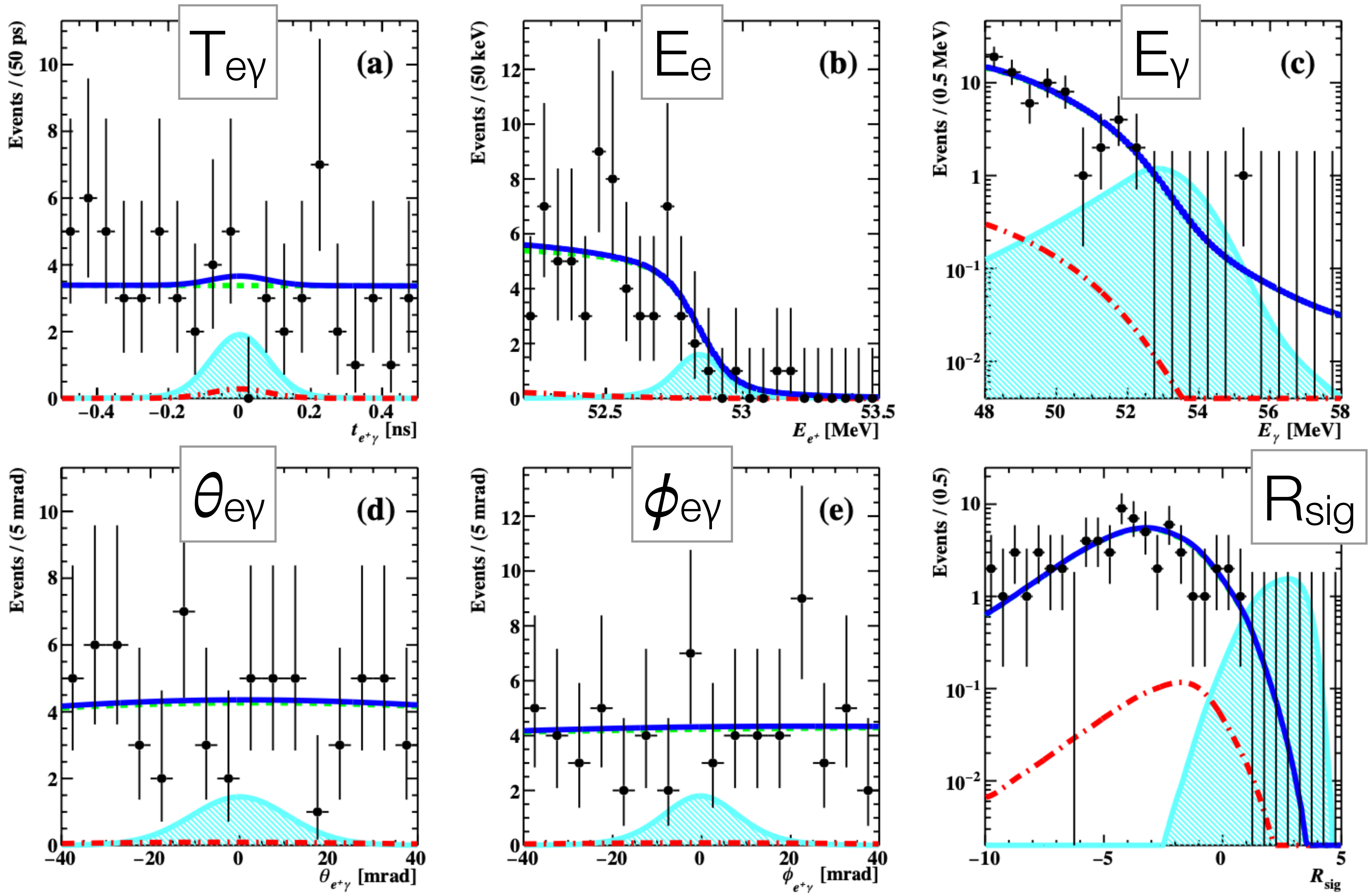

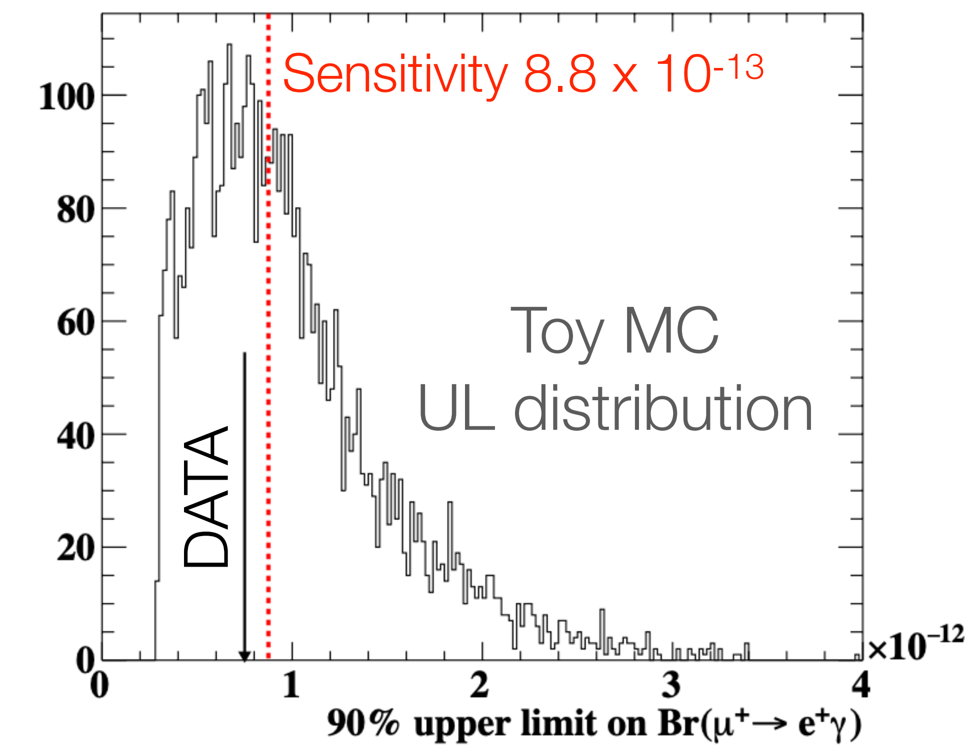

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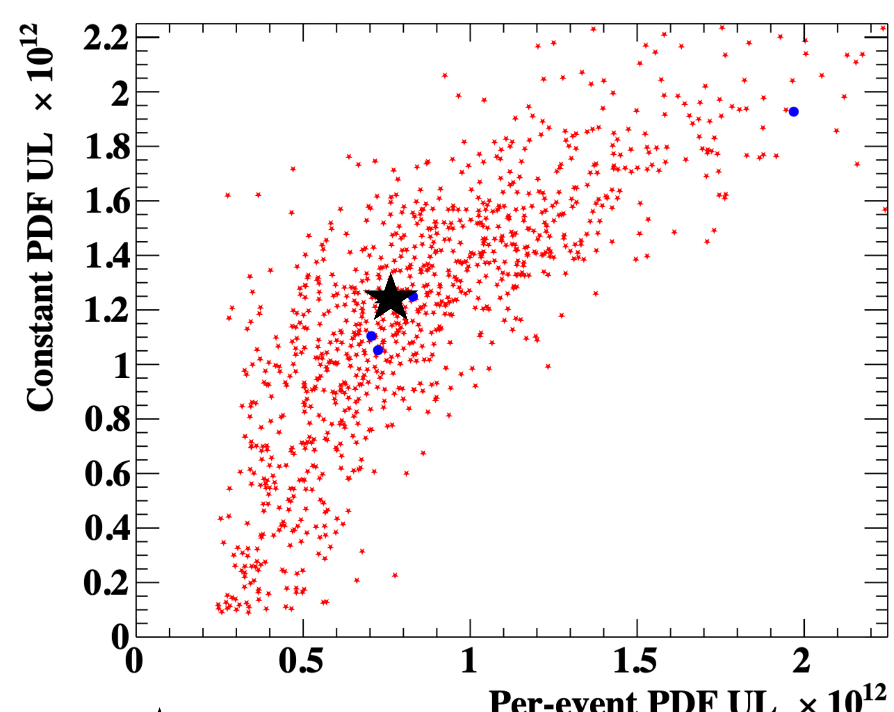
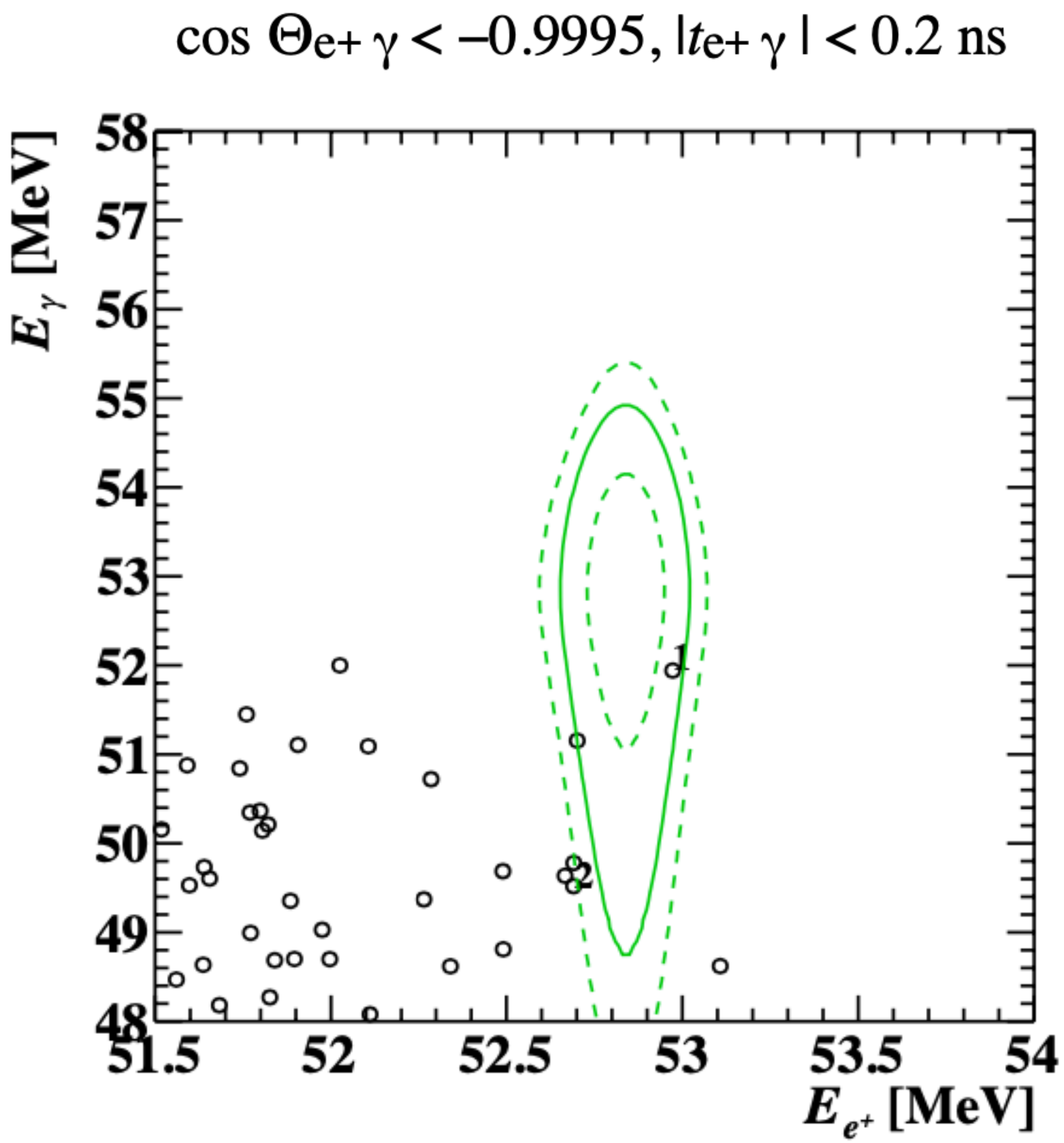
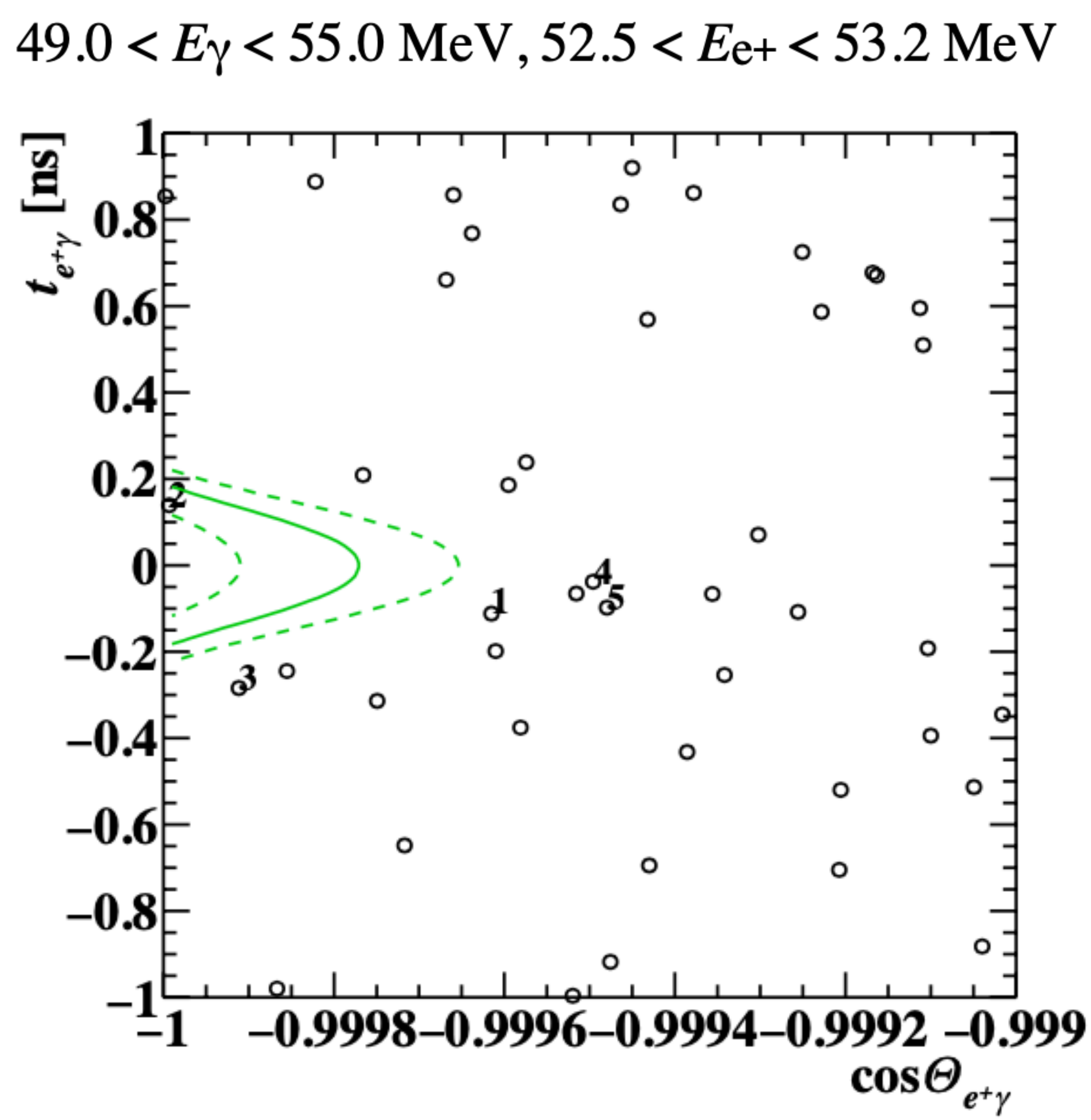


A closer look inside the box

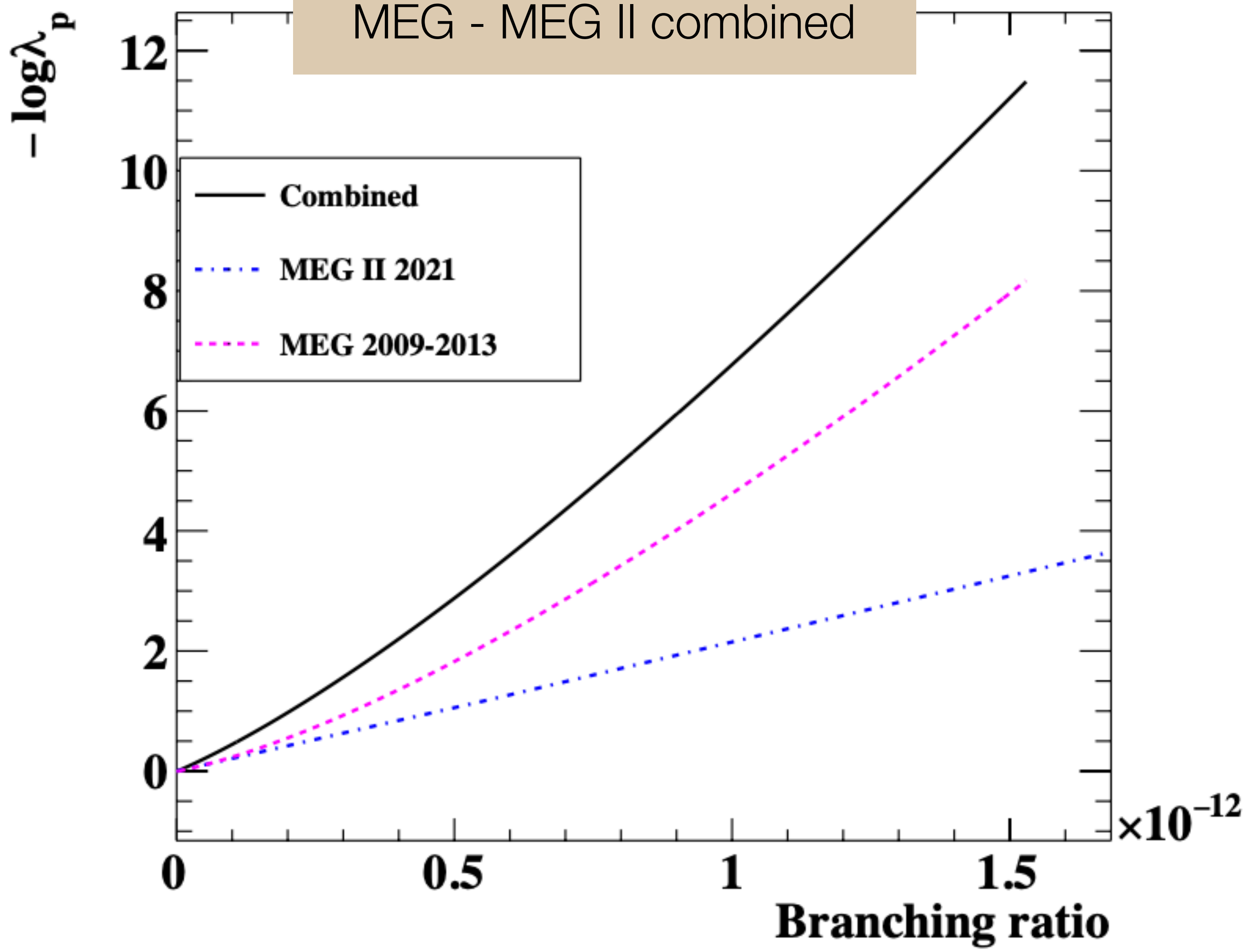


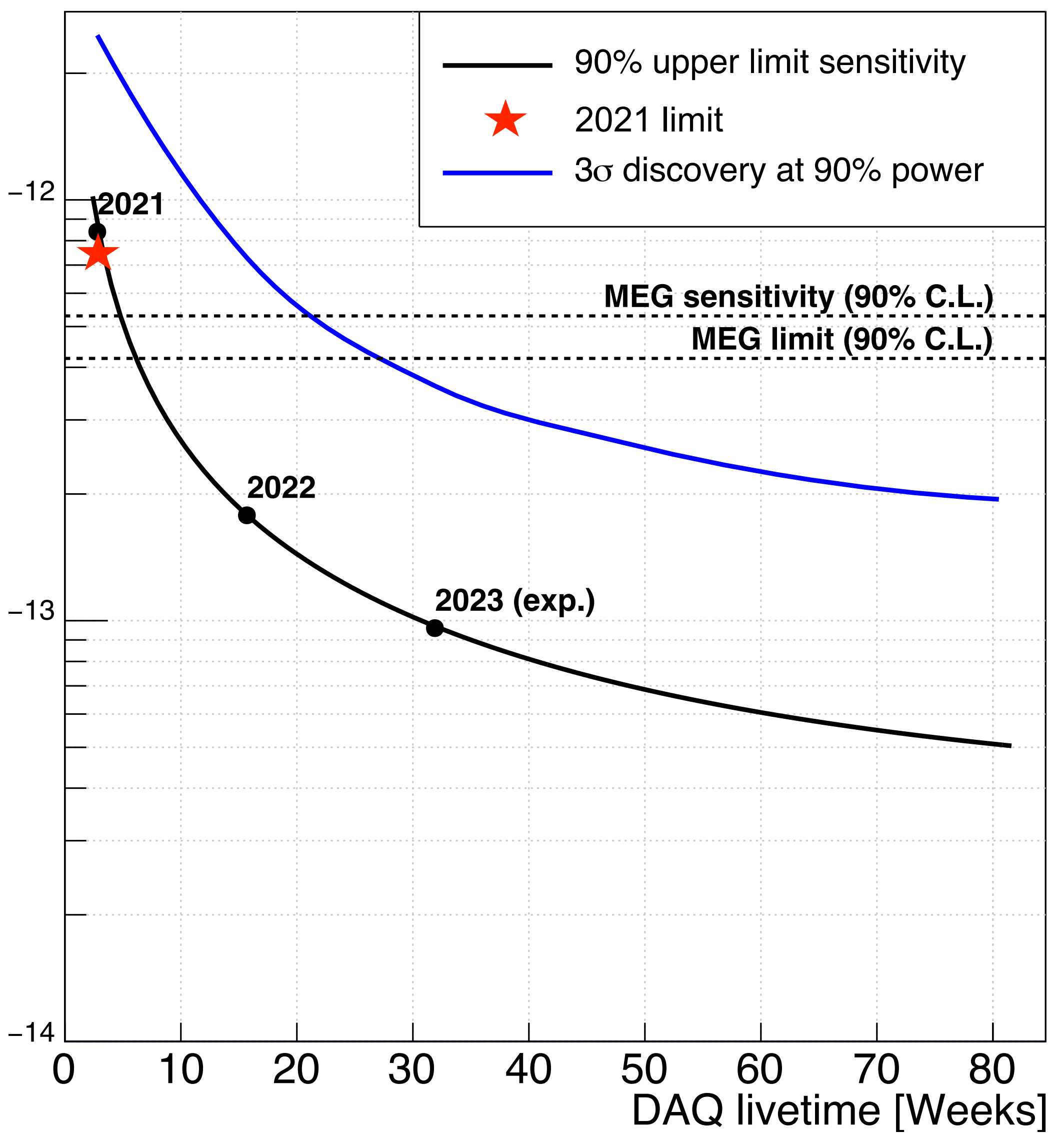


Combined limit and sensitivity prospects

$BR_{sig} < 3.1 \times 10^{-13}$

MEG - MEG II combined





Other physics opportunities at MEG II

Search for μ -> e a γ

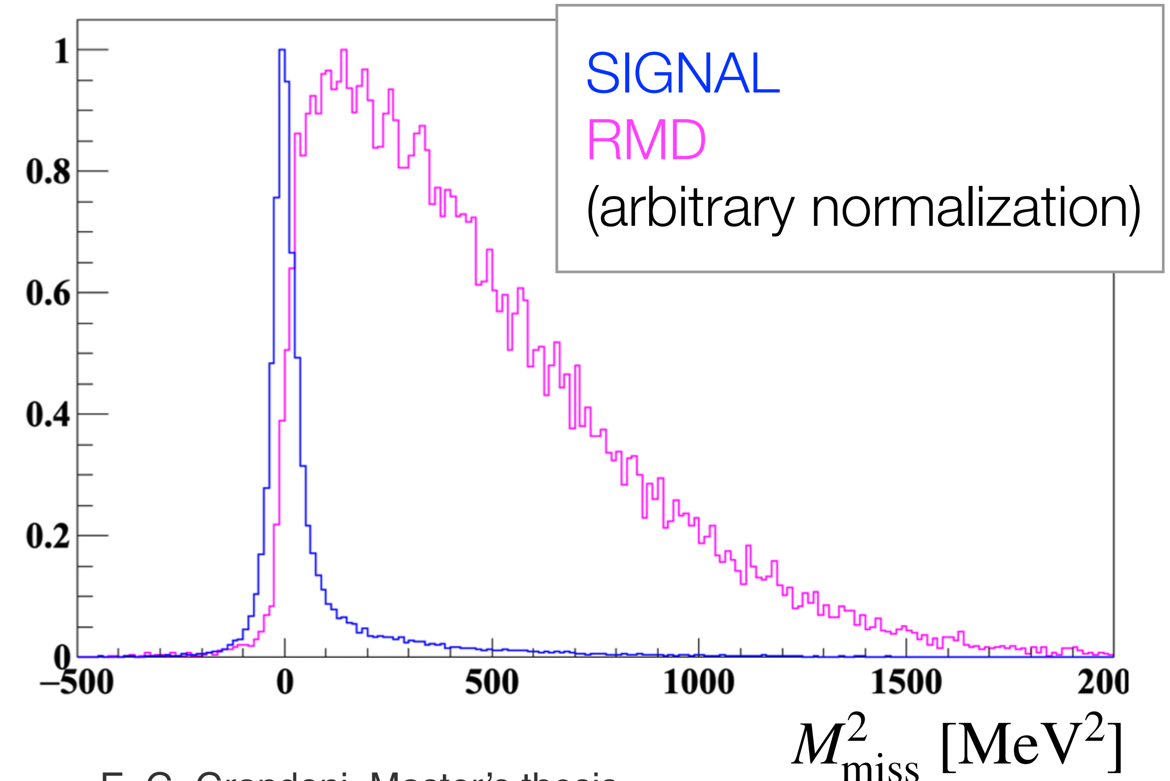
- Search for pseudo Goldstone bosons from spontaneous symmetry breaking of global symmetries (axion-like particles):

$$\mathscr{L}_{ALP} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 + \boxed{\frac{\partial_\mu a}{f_a}\sum_f c_f \overline{\Psi}_f \gamma^\mu \psi_f} + h.c.$$

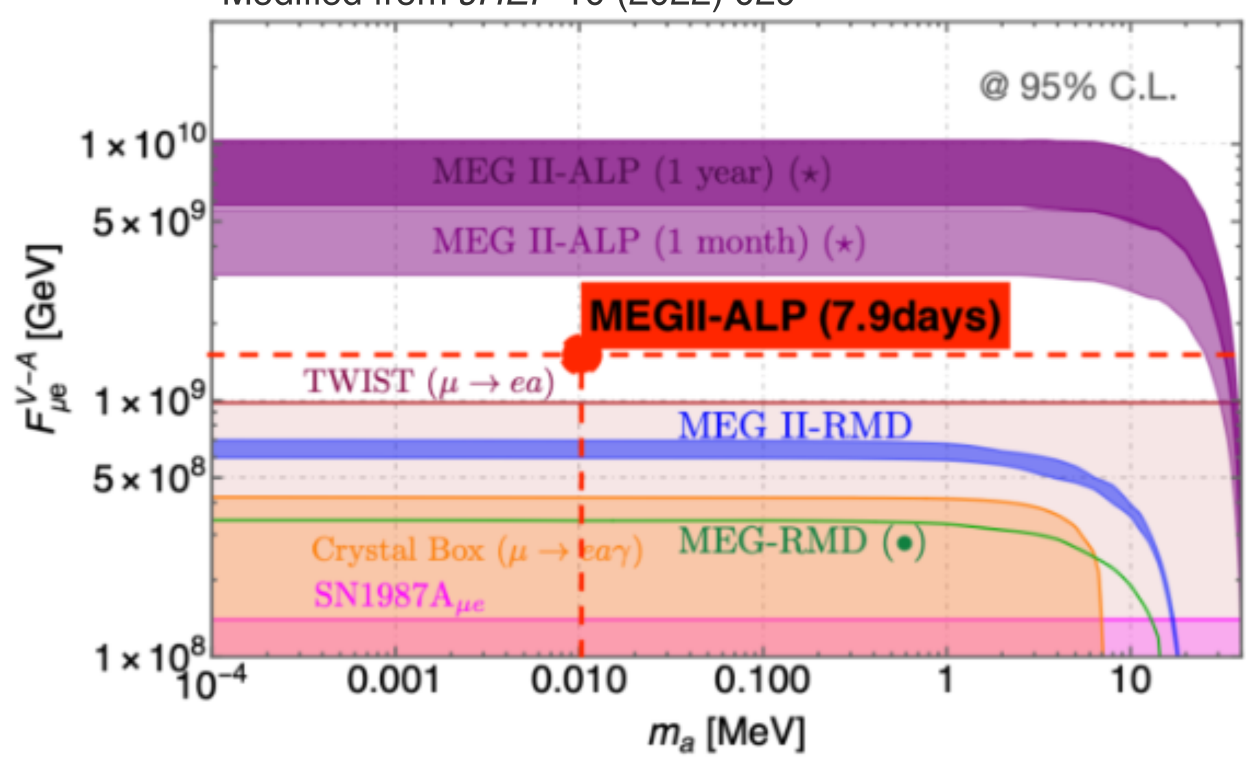
- The most natural cLFV muon decay to ALPs, $\mu^+ \to e^+ a$, is very difficult at MEG:
    - limited e^+ acceptance in the CDCH if the ALP is massive
    - large systematics from e^+ energy scale if the ALP is massless
- Following discussions between the Italian group and Redigolo et al. (**Jho, Knapen & Redigolo, *JHEP* 10 (2022) 029**) we are concentrating our attention on the radiative counterpart, **$\mu^+ \to e^+ a \gamma$**
    - μ -> e γ + invisible

Search for μ -> e a γ

- Experimental strategy:
  - trigger on **e⁺ γ coincidence** with very low E_γ threshold (~ 10 MeV)
  - dedicated run at very low beam intensity (1 to few weeks around 10^6 μ/s) to suppress accidentals
    - ➡ manageable trigger rate and better S/N ratio
  - search for a peak in **missing mass distribution** (fighting against radiative muon decays)
- A few days of low intensity data are already on disk
- Other could be taken with minimal impact on the MEG plans

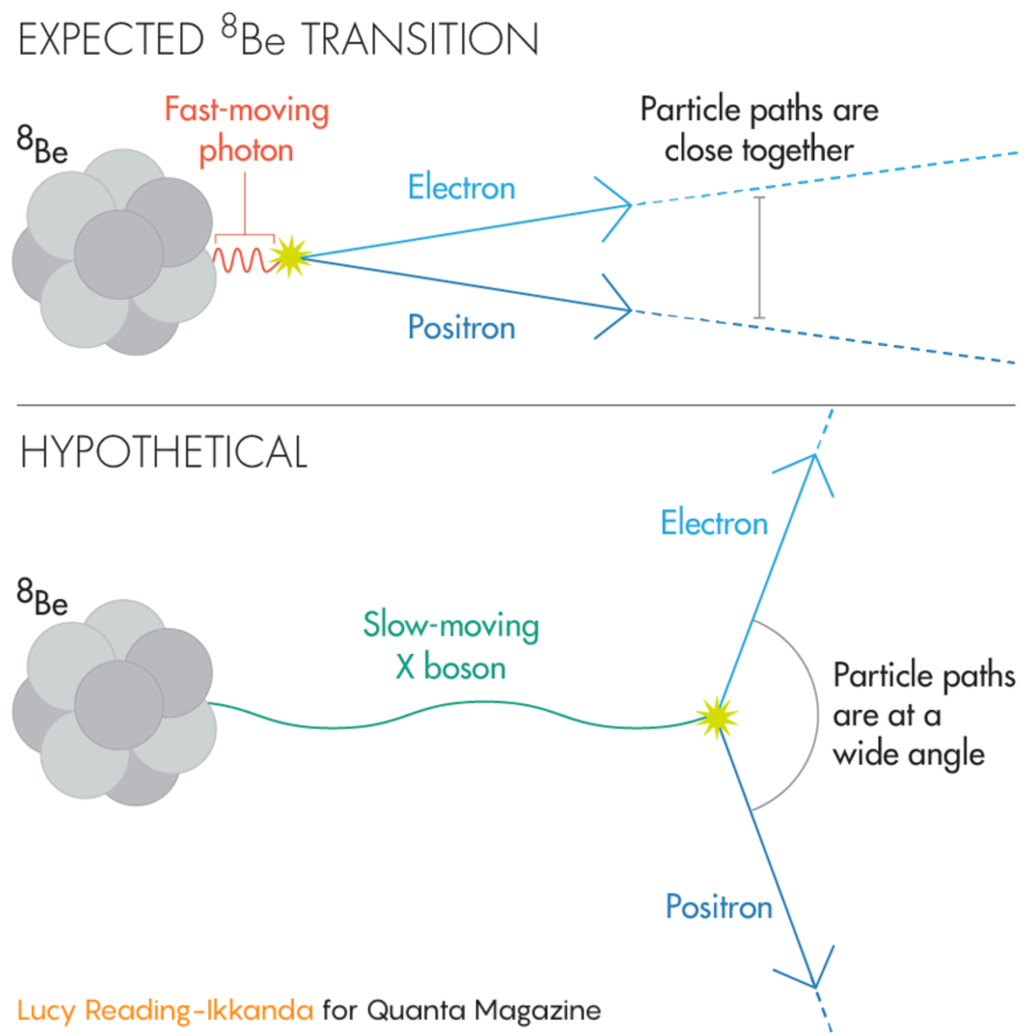


E. G. Grandoni, Master's thesis,
Modified from *JHEP* 10 (2022) 029

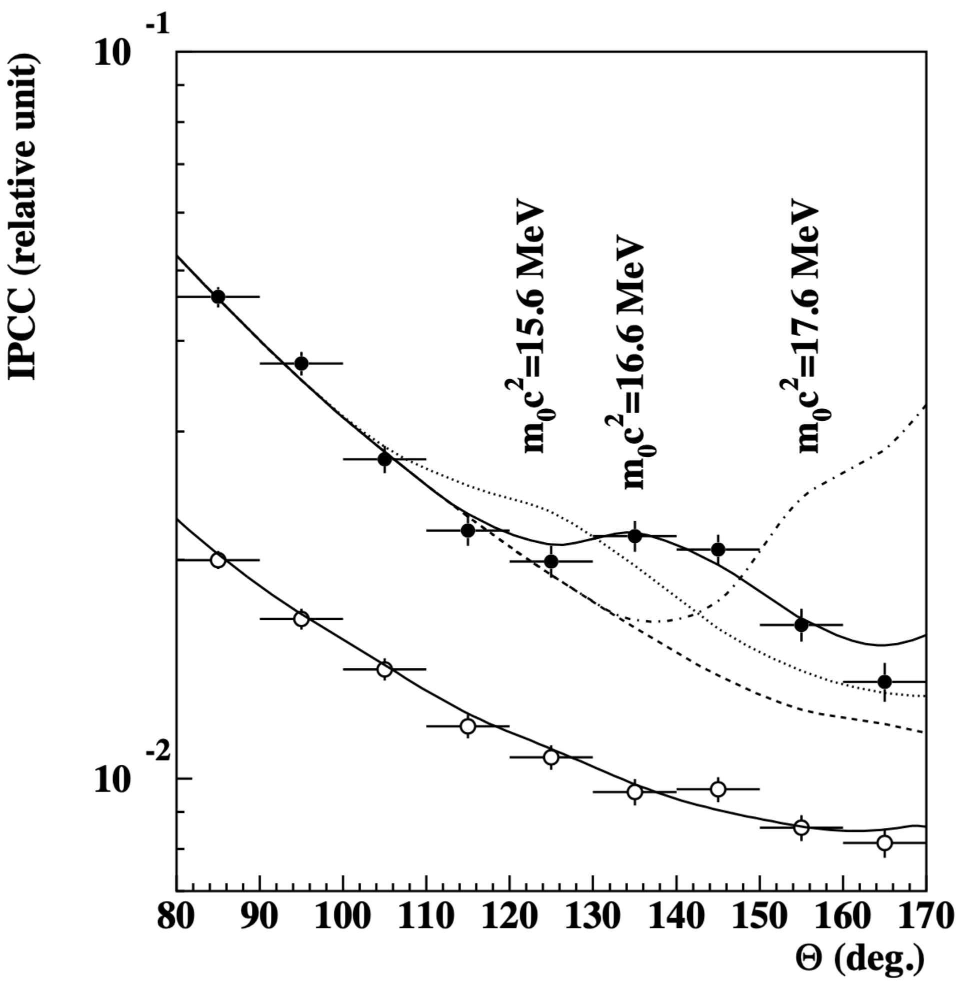


Search for the X17 boson

- Attempt to confirm/exclude the excess observed at ATOMKI (Hungary) in the angular spectrum of e^+e^- pairs from Internal Pair Conversion (IPC) in $^8Be^*$ (and other nuclei) transitions

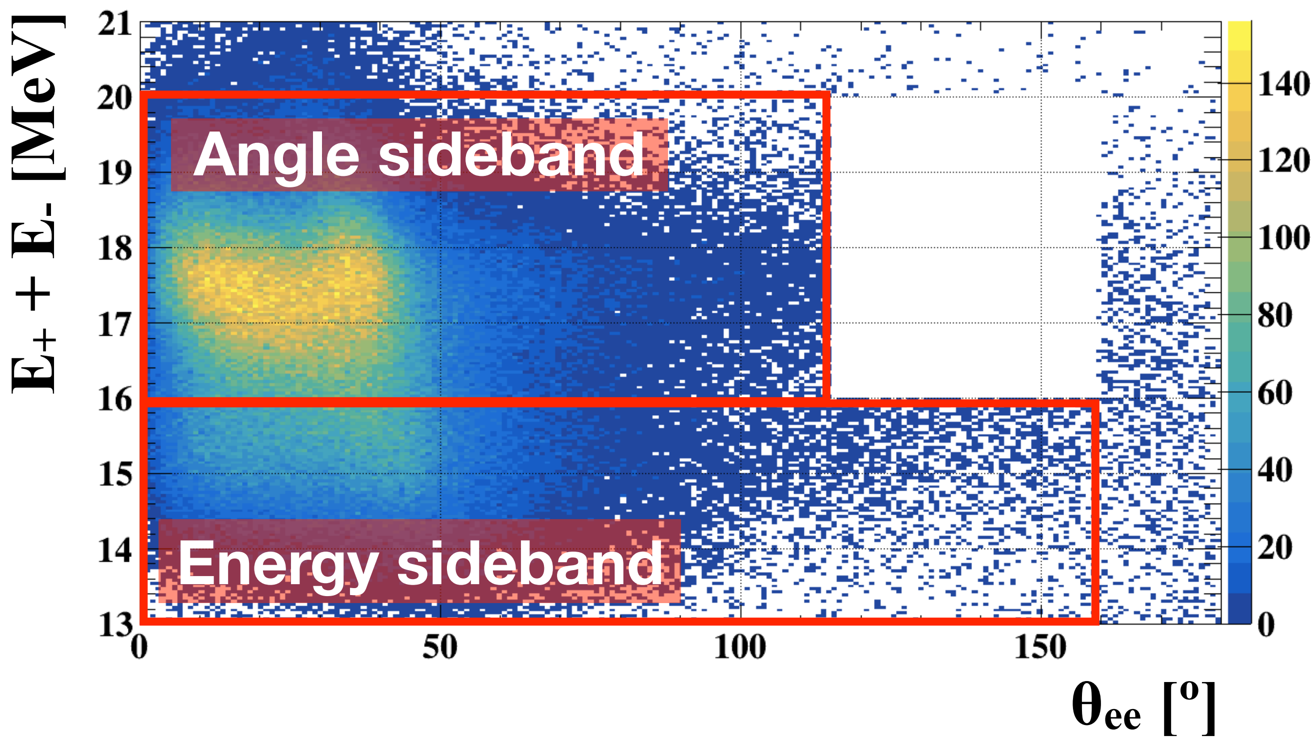


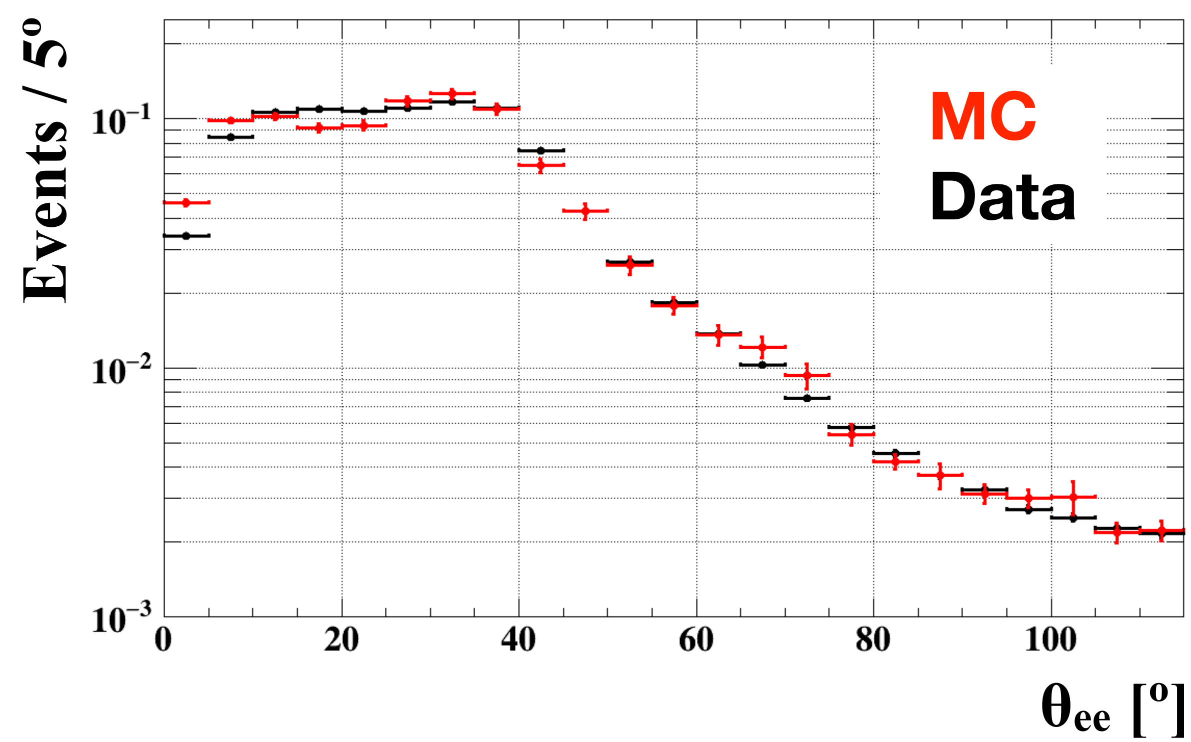
A.J. Krasznahorkay, Phys. Rev. Lett. 116, 042501 (2016)



Data taking and analysis

- 4 weeks of DAQ in February 2023
- ~ 300k reconstructed e^+e^- pairs





- Aiming at unblinding at the beginning of 2024 (3-5σ signal expected)
- Options for additional data taking to be evaluated after completing the analysis of 2023 data

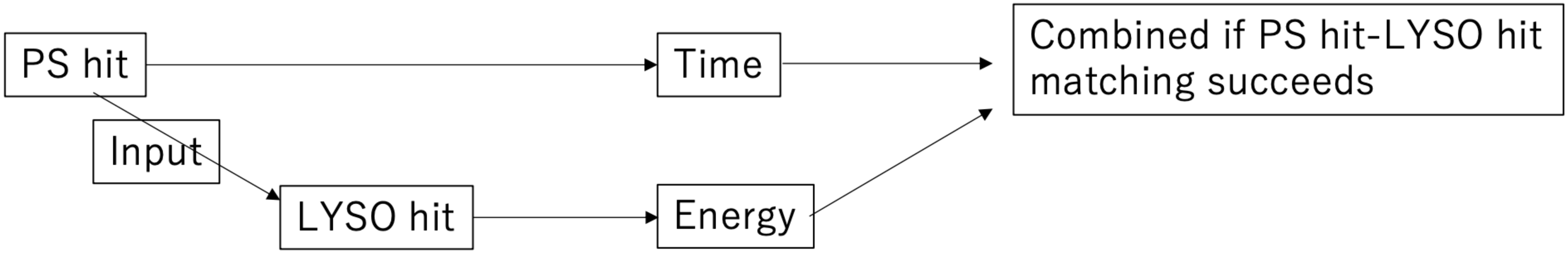
Conclusions

- MEG II published his first physics result
  - Search for **$\mu \to e \gamma$ with data from the first physics run** (2021)
  - Demonstrated readiness for effectively analyzing data already taken (**~ 10x more statistics**) and to come
- We are enriching our physics reach with searches for (even more) exotic processes:
  - Search for **ALPs in muon decays**
  - Search for the **X17** boson in $p + {}^{7}Li \to {}^{8}Be^{*}$ reactions

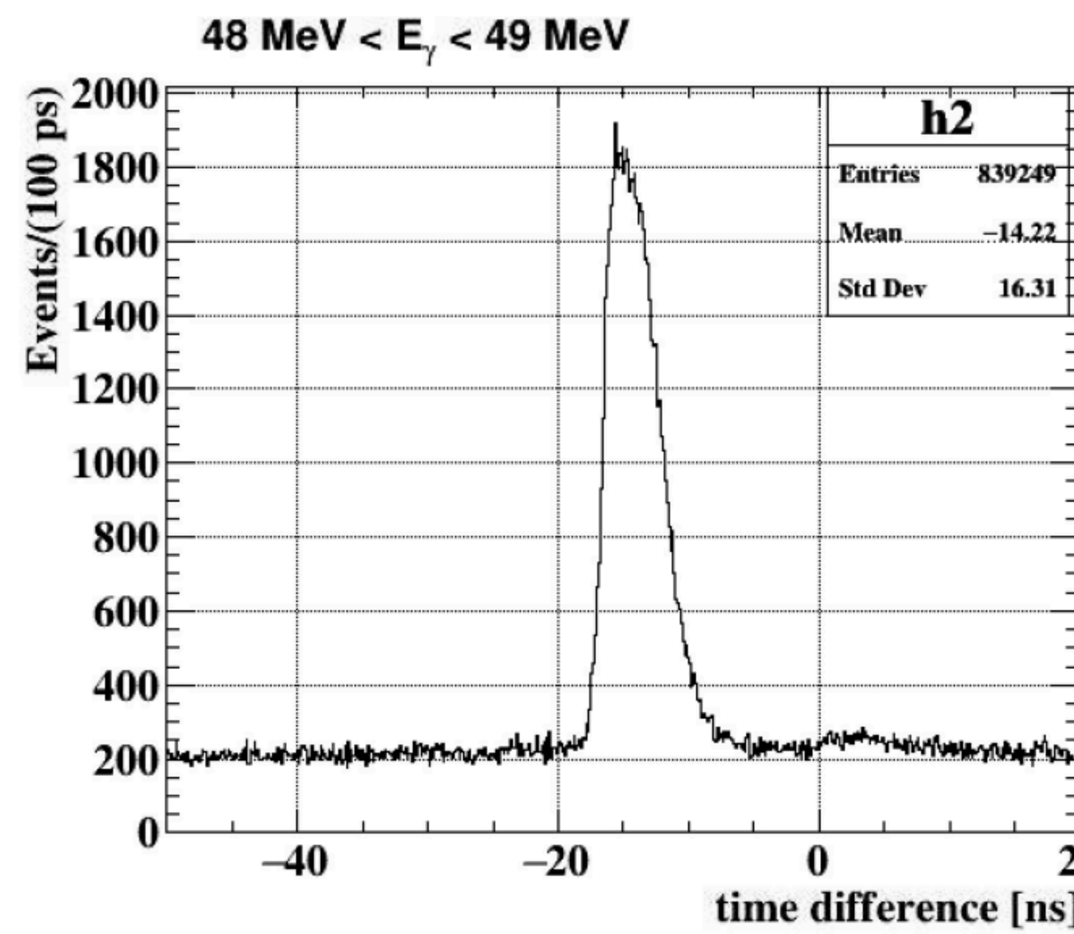
Backup

RDC Analysis

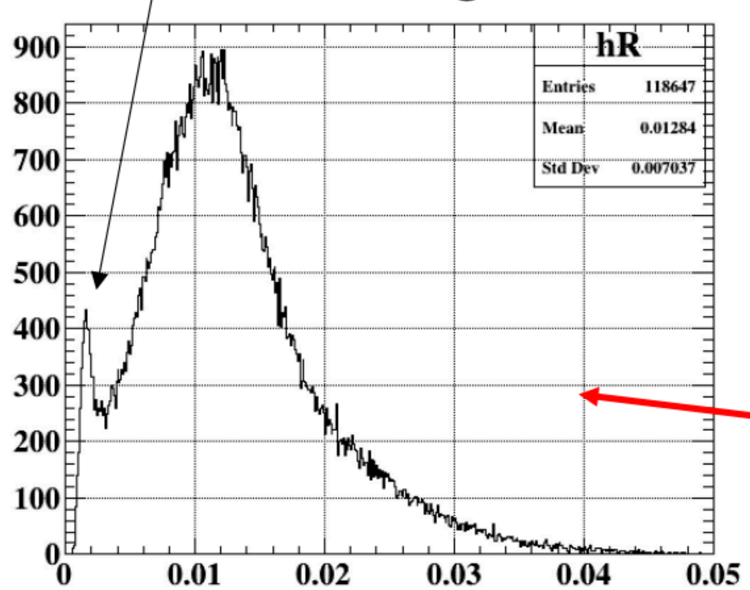
Analysis strategy

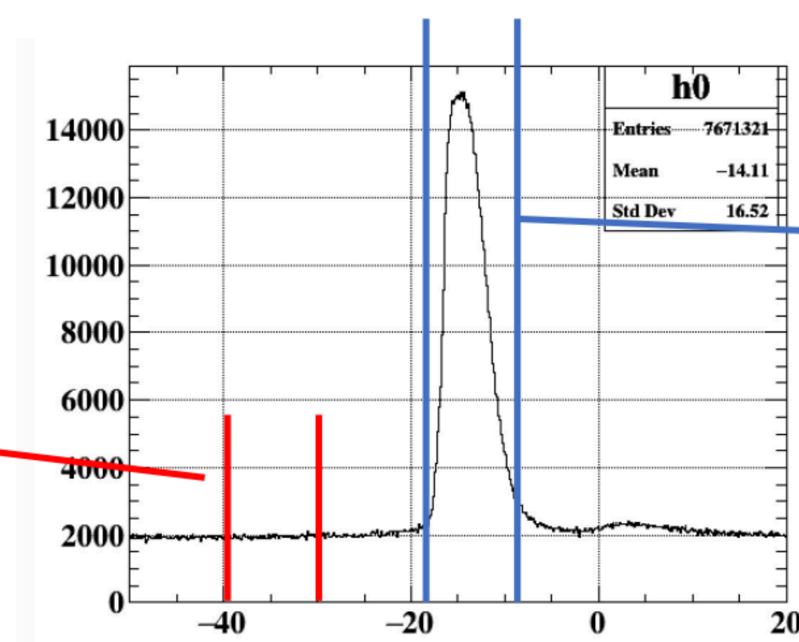


- RDC-XEC pair selection based on smallest $|t_{RDC} - t_{XEC}|$
- **Time difference and energy** are used to discriminate events where the RDC signal can be interpreted as an RMD positron associated to the photon in the XEC

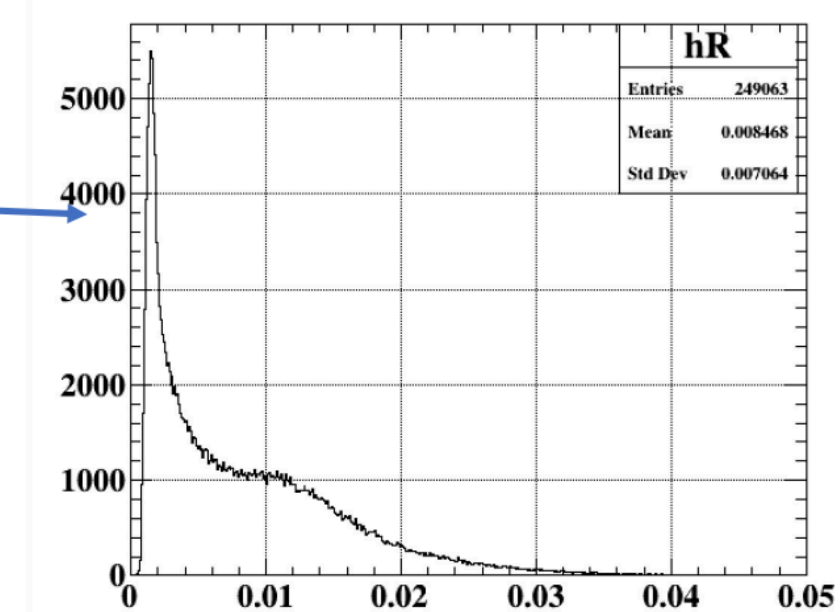


Energy distribution for
off-timing RDC hits



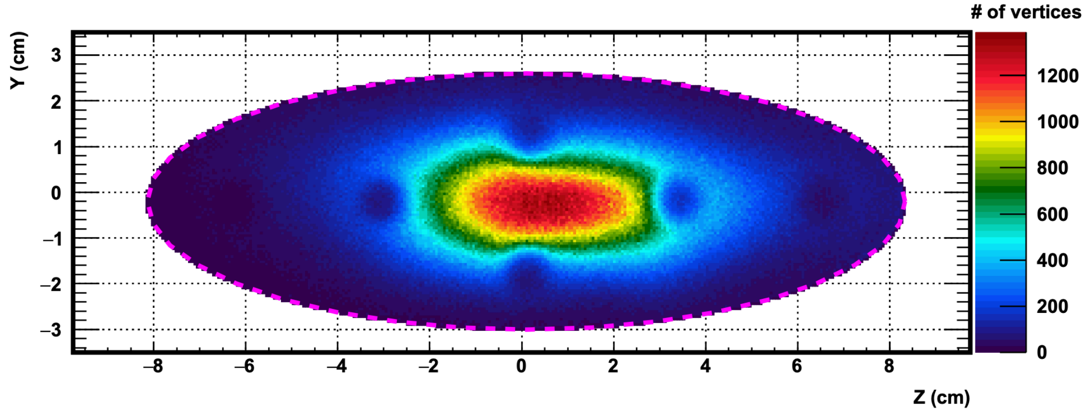


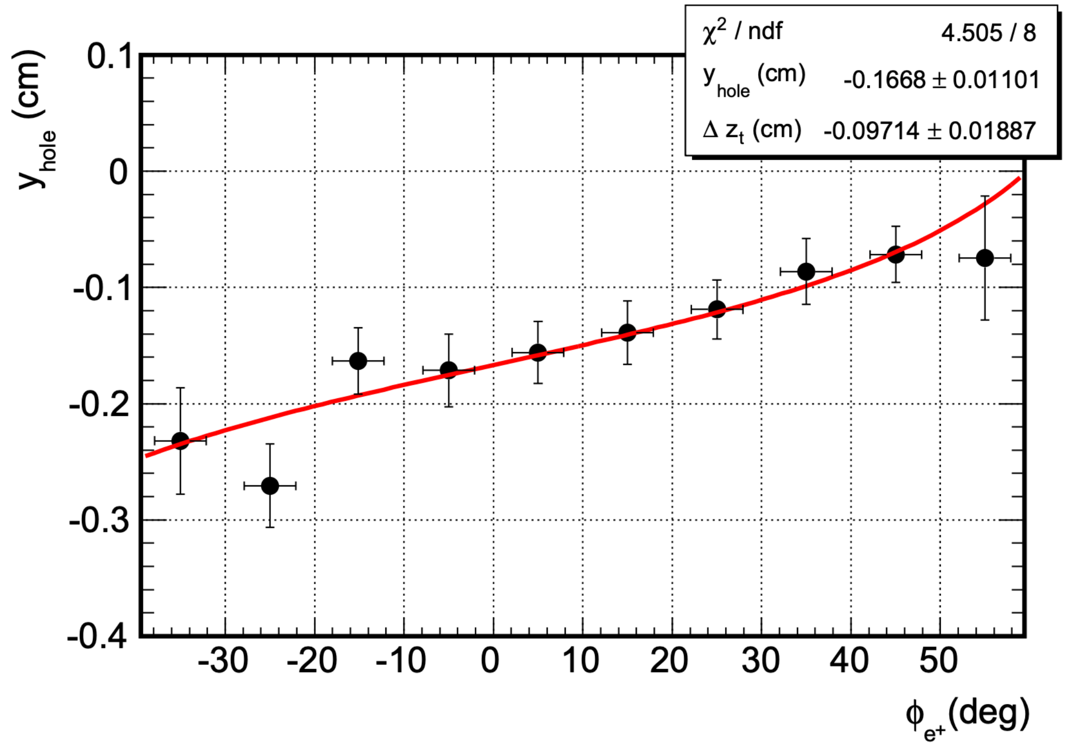
Energy distribution for
on-timing RDC hits



Target alignment

- Severe criticalities in the MEG I (target deformation, time evolution, etc.)
- Relative CDCH-target alignment exploiting holes in the target
  - reconstructed position of holes vs. track angles reveals misalignments
  - high statistics needed —> **cannot be used to track movements during the run**





MEG I

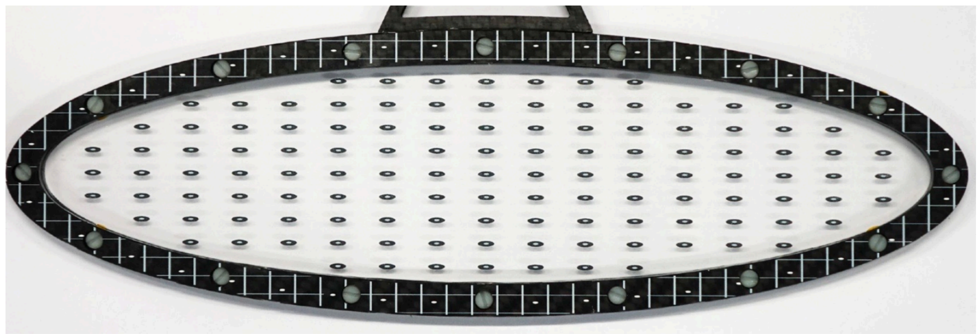
D. Palo *et al.*, *Nucl. Instrum. Meth.A* 944 (2019) 162511
G. Cavoto *et al.*, *Rev. Sci. Instrum.* 92 (2021) 4, 043707

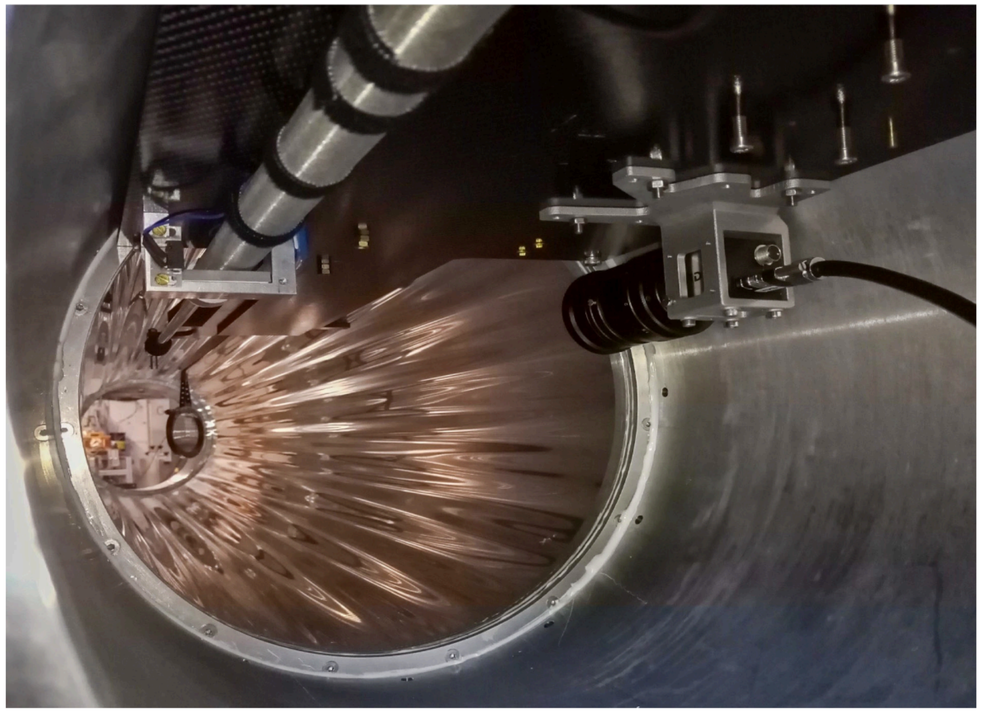
Target alignment

- Severe criticalities in the MEG I (target deformation, time evolution, etc.)

- In MEG II, a set of photo cameras was installed to monitor the target position and deformation during the run

    - photogrammetric approach based on the imaging of dots printed in the target





D. Palo *et al.*, *Nucl. Instrum. Meth.A* 944 (2019) 162511
G. Cavoto *et al.*, *Rev. Sci. Instrum.* 92 (2021) 4, 043707

Target alignment

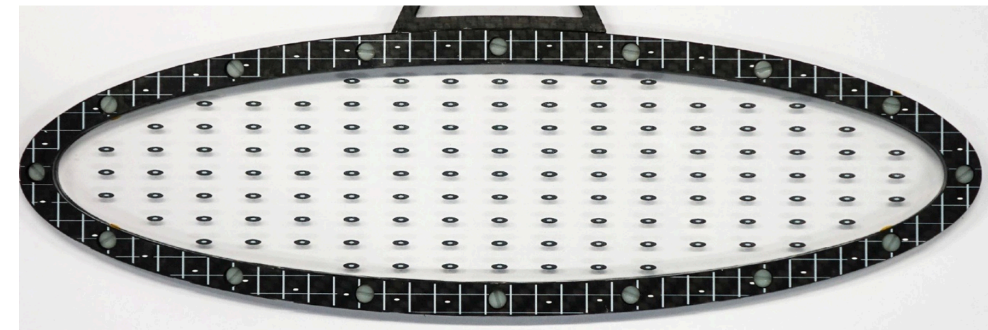
- Severe criticalities in the MEG I (target deformation, time evolution, etc.)

- Strategy:

    1. tentative alignment with optical surveys at the beg. of the run

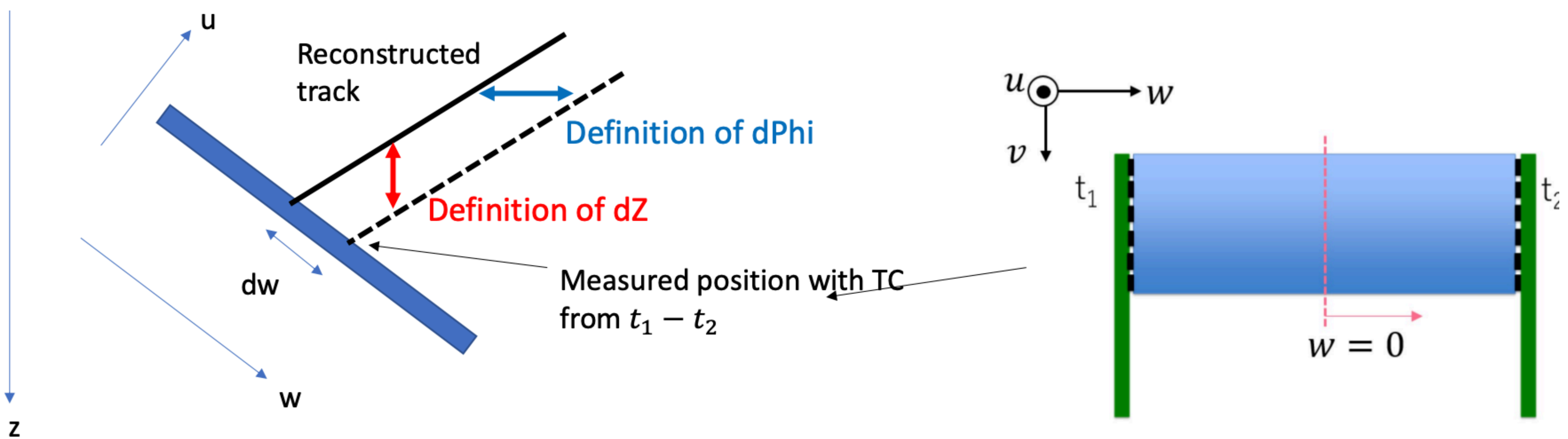
    2. time-dependent correction of alignment and deformations with photo cameras

    3. final global alignment with target holes



pTC vs. CDCH alignment

- The pTC is sensitive to the longitudinal position *w* of the hit along the scintillating tiles (via time difference at the two ends)
  - the difference between *w* from pTC and tracks can be used to align the pTC to the CDCH



pTC vs. CDCH alignment

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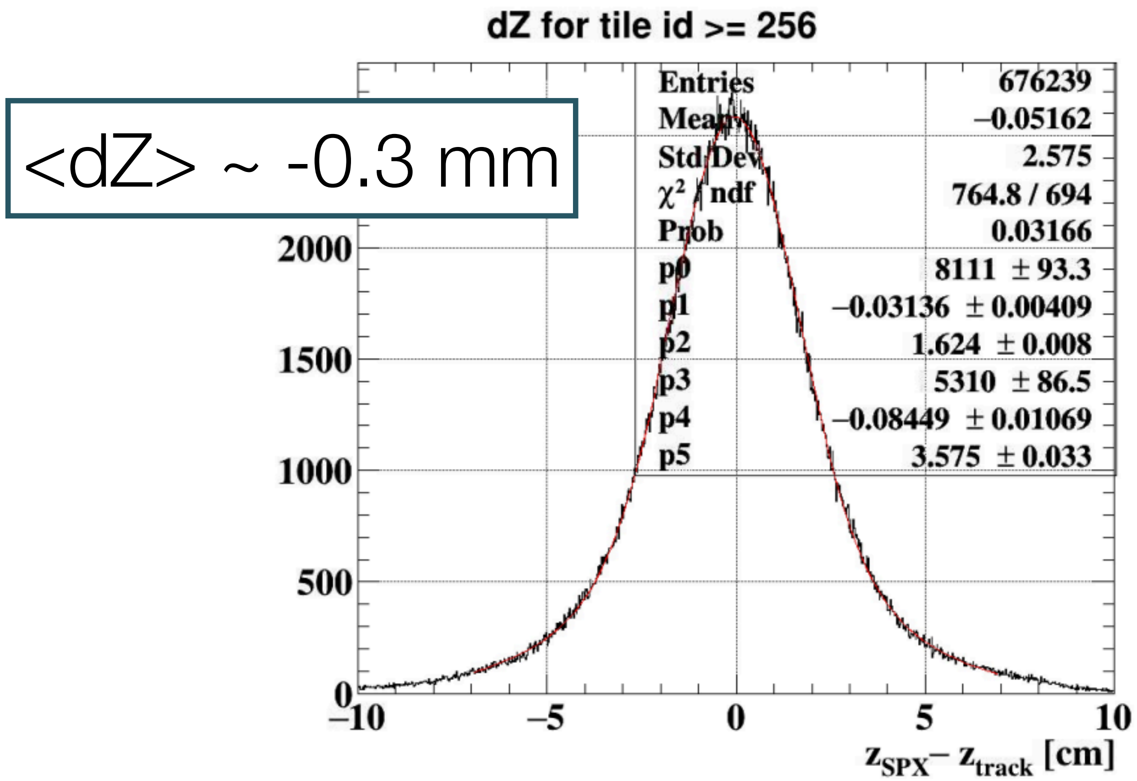
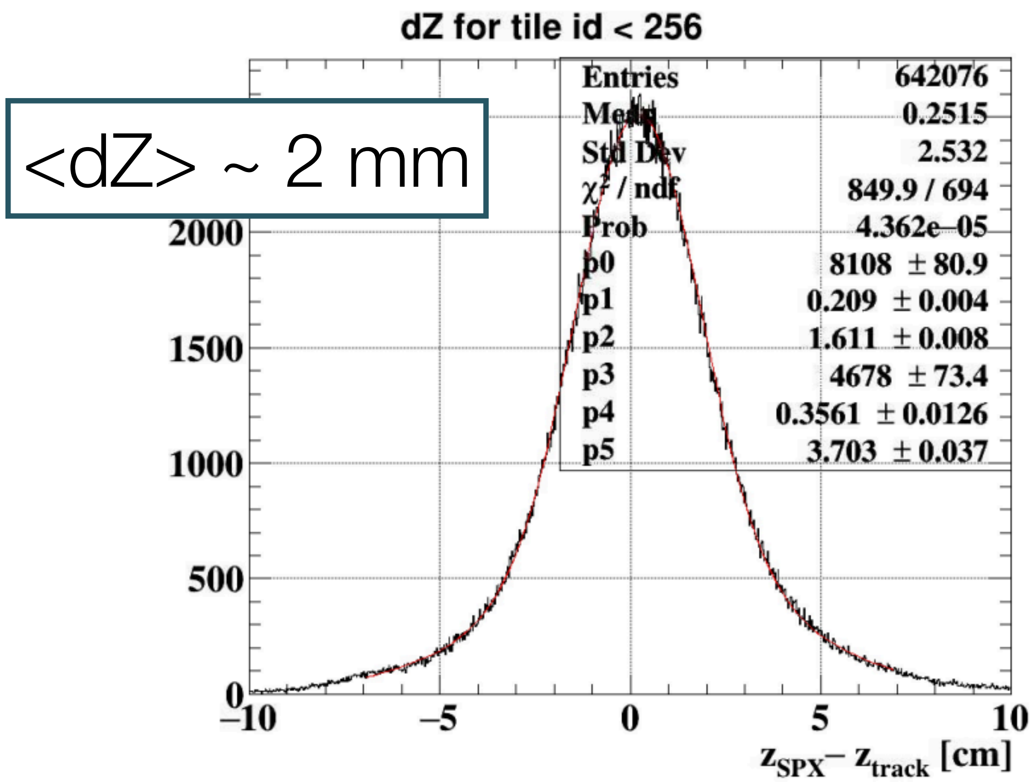
US

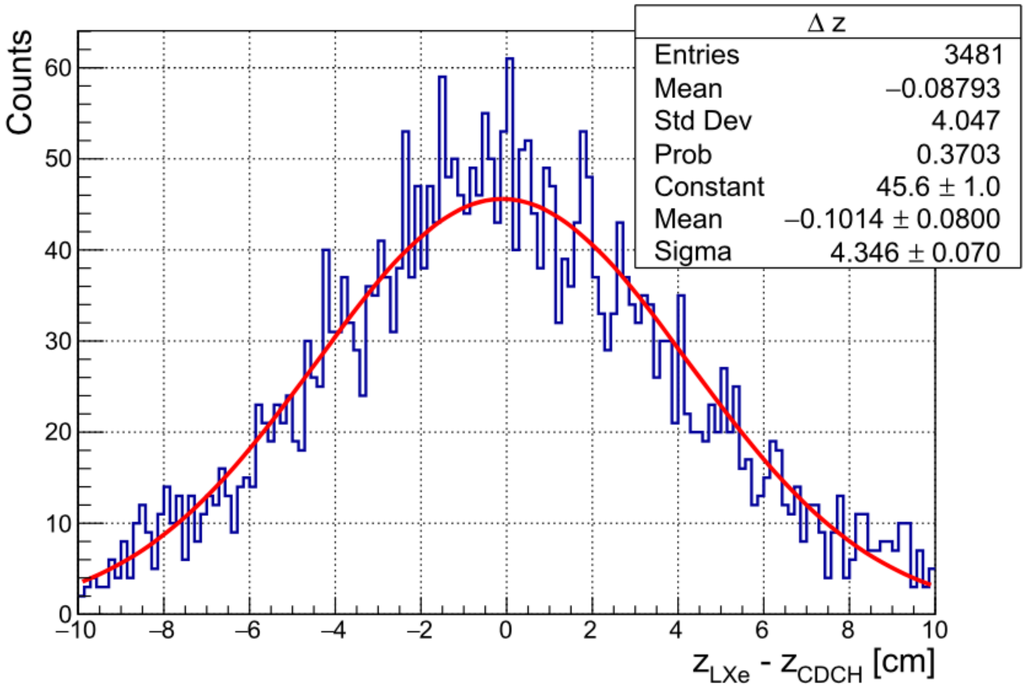


DS

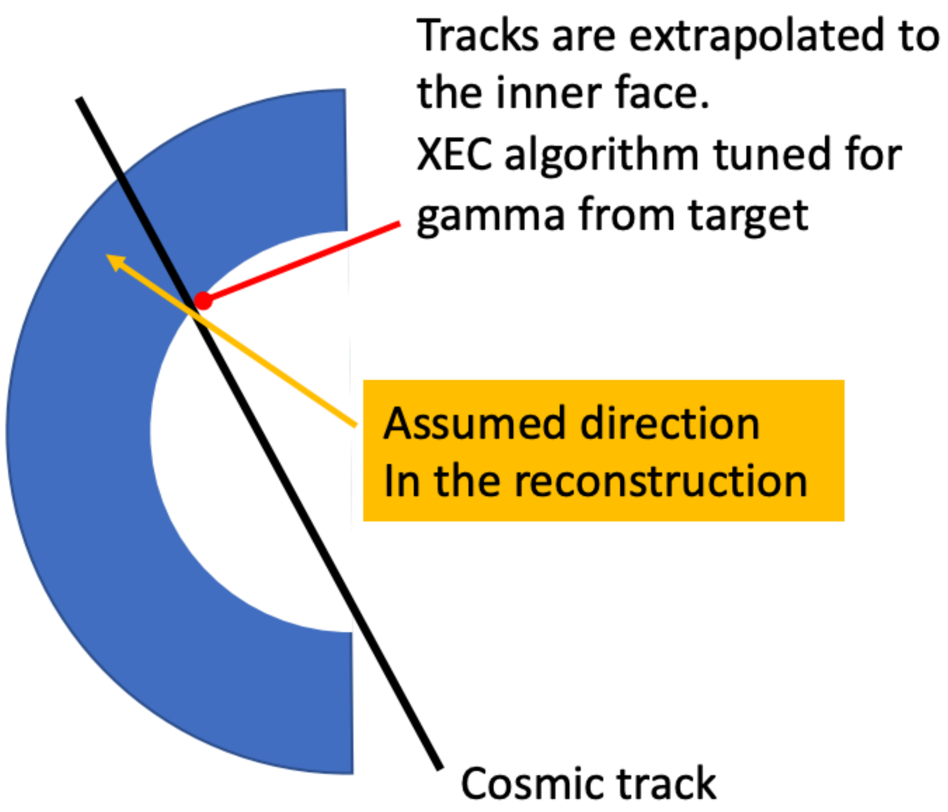


XEC vs. CDCH alignment

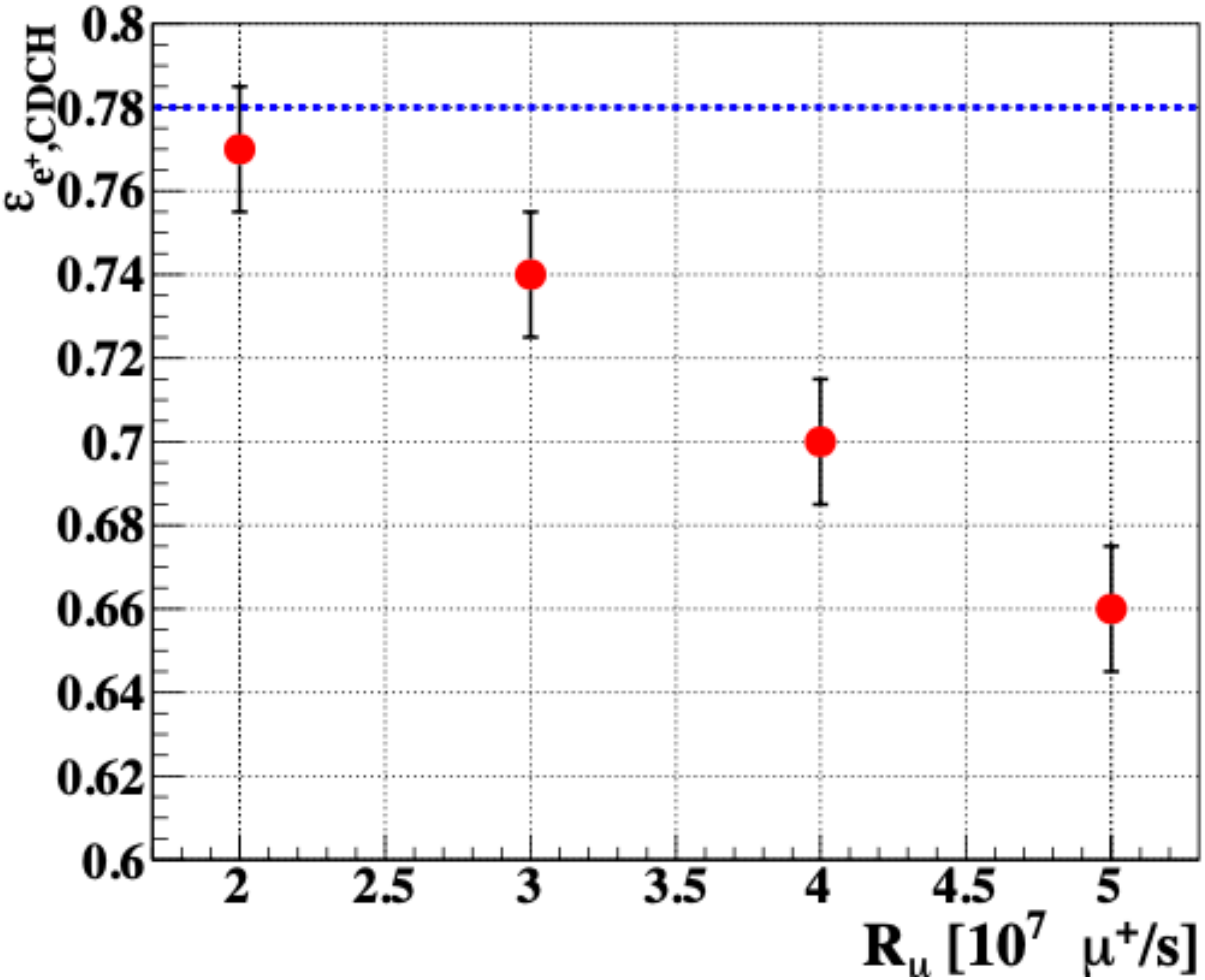
- XEC vs. CDCH alignment performed using cosmic rays as in MEG I
- Some bias because the XEC reconstruction is tuned for photons
  - but bias should cancel in z direction thanks to symmetry
- Disagreement to be understood w.r.t. MPPC positions measured with collimated X-rays (Nucl. Instrum. Meth. A 1048 (2023) 167901)



1 mm z shift



Positron performance vs. beam intensity



Track selection

Parameter	Condition
Track quality	
Number of fitted hits	$N_{\mathrm{hit}} \geq 18$
Those in the first half turn	$N_{\mathrm{hit,first}} \geq 5$
Chisquare of the fit	$\chi^2_{\mathrm{fit}}/N_{\mathrm{dof}} < 4.33 - 0.0167 N_{\mathrm{hit}}$
Energy fit uncertainty	$\mathrm{cov}(E_{\mathrm{e}}, E_{\mathrm{e}}) < (300\,\mathrm{keV})^2$
Angular fit uncertainties	$\mathrm{cov}(\theta_{\mathrm{e}}, \theta_{\mathrm{e}}) < (50\,\mathrm{mrad})^2$
	$\mathrm{cov}(\phi_{\mathrm{e}}, \phi_{\mathrm{e}}) < (12\,\mathrm{mrad})^2$
Position fit uncertainties	$\mathrm{cov}(y_{\mathrm{e}}, y_{\mathrm{e}}) < (5\,\mathrm{mm})^2$
	$\mathrm{cov}(z_{\mathrm{e}}, z_{\mathrm{e}}) < (5\,\mathrm{mm})^2$
Matching with pTC[a)]	
Timing	$\lvert \Delta T \rvert < 15\,\mathrm{ns}$
Distance	$\Delta v^2 + \Delta w^2 < (10\,\mathrm{cm})^2$
	$\lvert \Delta w \rvert < 5\sigma_{w,\mathrm{pTC}} \approx 6\,\mathrm{cm}$
Fiducial volume	$+3\,\mathrm{cm}$
Extrapolation length	$l_{\mathrm{pTC}} < 80\,\mathrm{cm}$
Extrapolation to target	
Fiducial volume	$-2\sigma_{y,z}$
Extrapolation length	$l_{\mathrm{target}} < 45\,\mathrm{cm}$
Multivariate analysis	
NN output	$O_{\mathrm{NN}} < 0.1$

Systematics

Parameter	Impact on limit
$\phi_{e\gamma}$ 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 %

Table 4: Sumamry of uncertain parameters

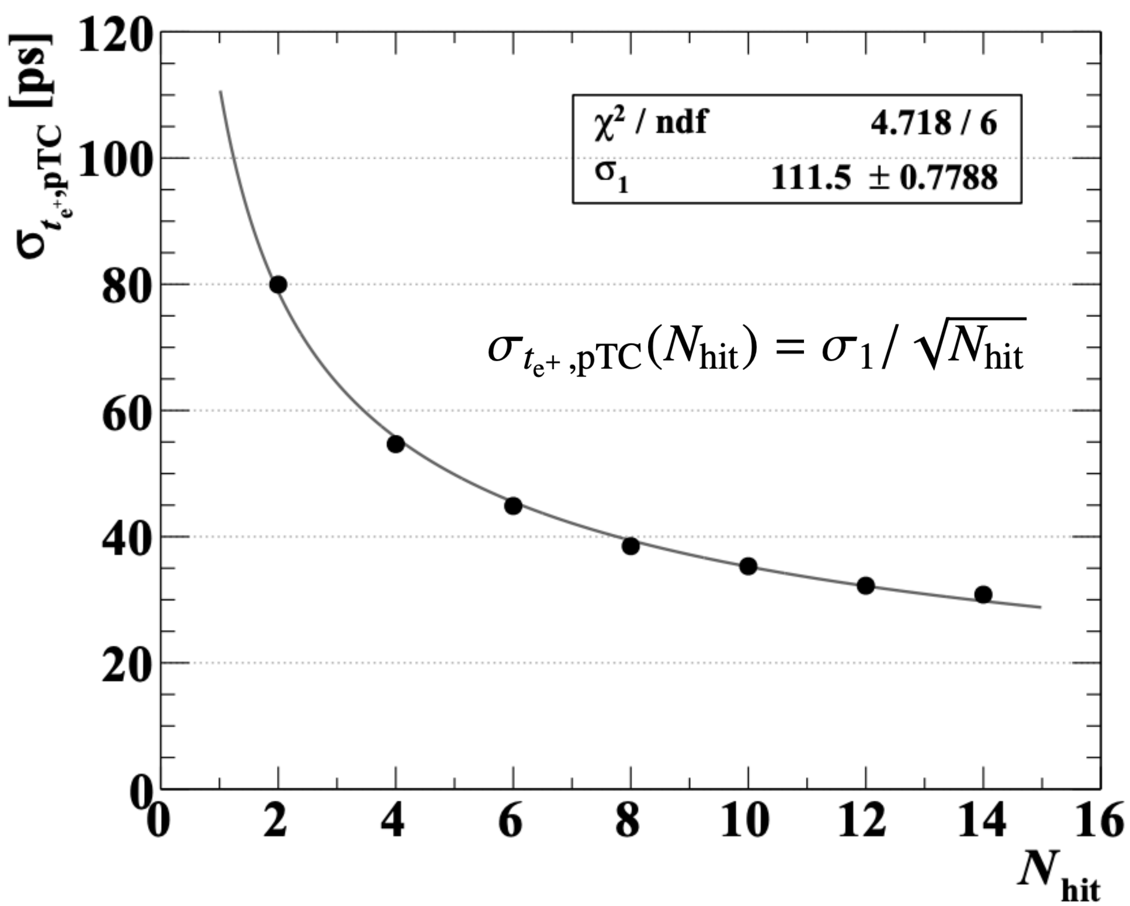
Parameter	Uncertainty
Target alignment	100 μm
LXe global shift	1 mm
Normalization	5 %
E_γ energy scale	0.3 %
E_e energy scale	6 keV
$t_{e\gamma}$ center	4 ps
Positron correlation	5 – 10 %

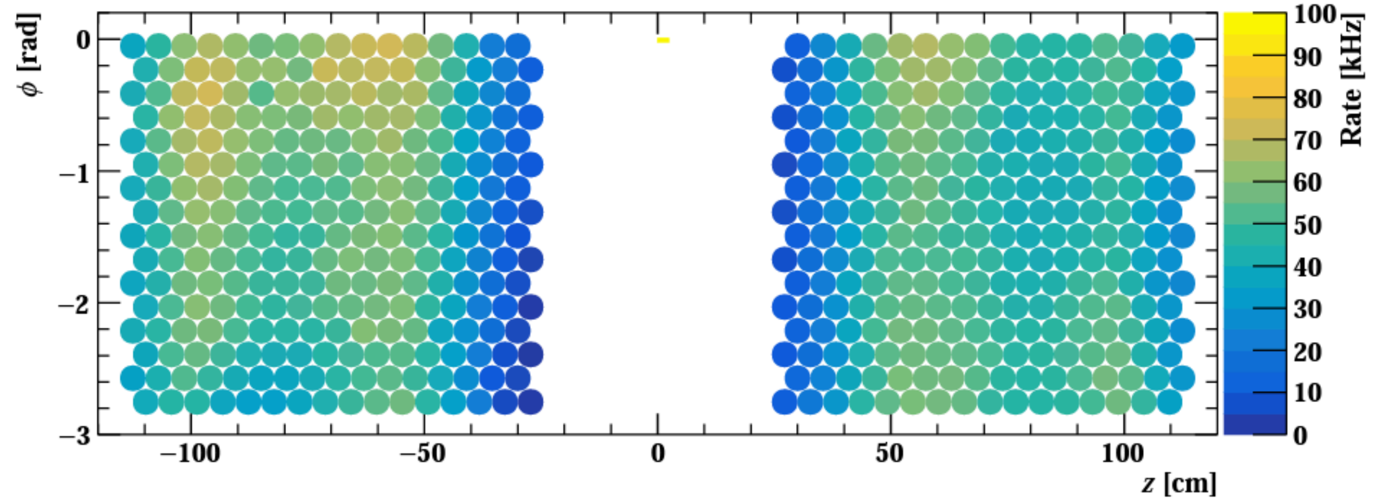
pTC analysis

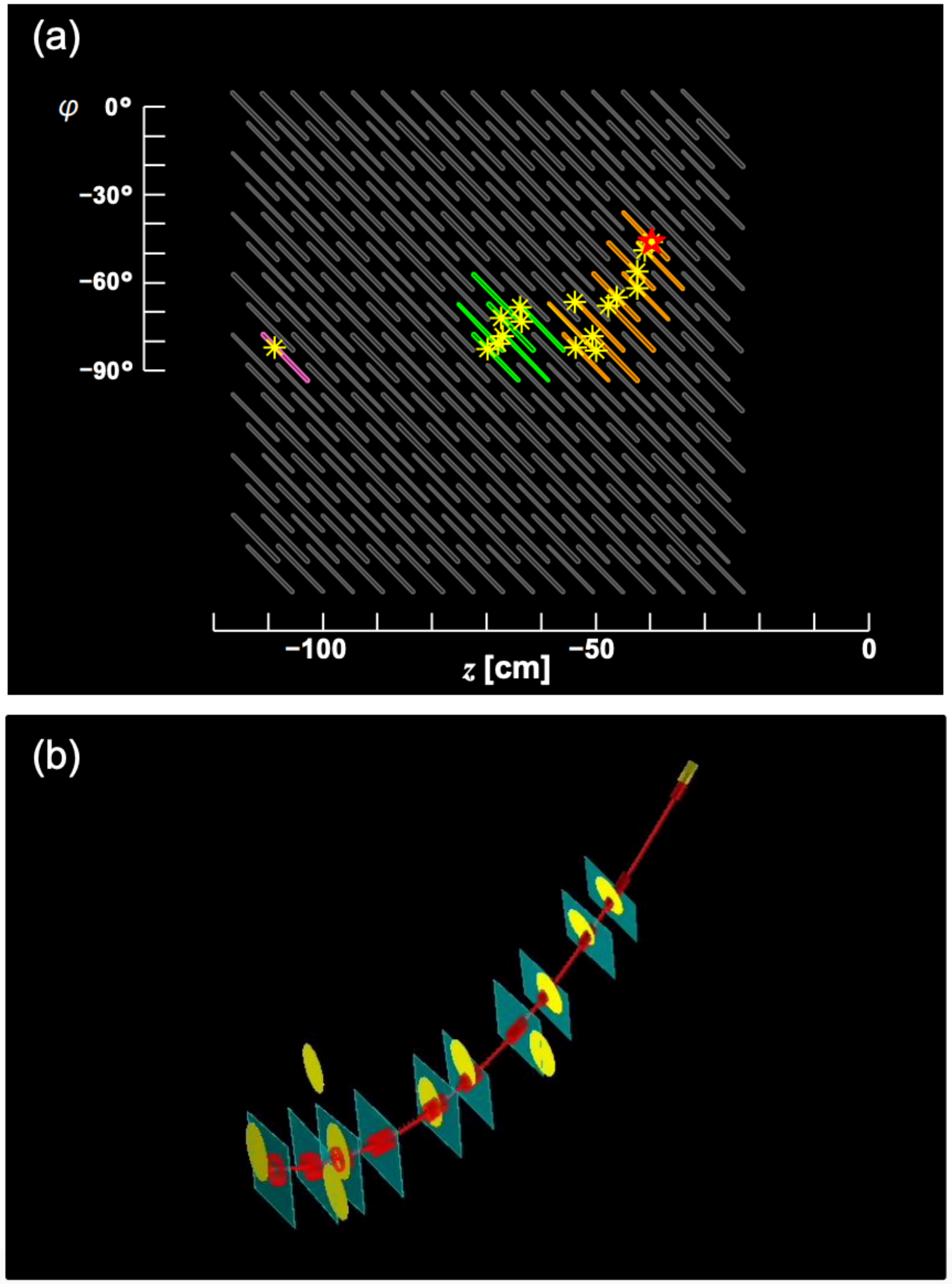
- Positron time from the combination of multiple tiles

$$t_{e^+,\mathrm{pTC}} = \sum_{i=1}^{N_{\mathrm{hit}}} \left(t_{\mathrm{hit},i} - f_{1,i}\right) / N_{\mathrm{hit}}$$

TOF







Likelihood Analysis

- **Likelihood analysis** with either 6 or 7 discriminating variables:
  - Positron Energy
  - Photon Energy
  - Relative time $t_{e\gamma}$
  - $\phi_{e\gamma}$
  - $\theta_{e\gamma}$

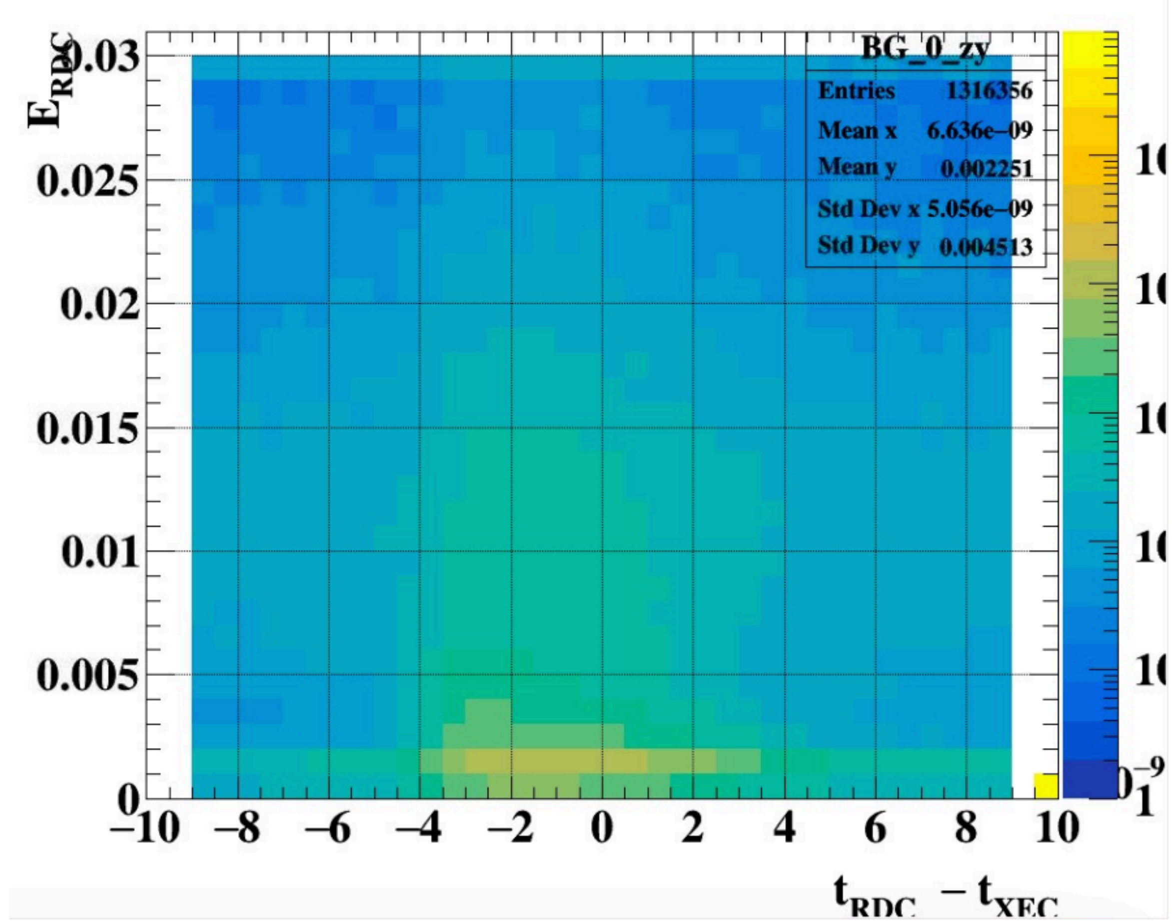
  $\left.\begin{matrix}\phi_{e\gamma} \\ \theta_{e\gamma}\end{matrix}\right\}$ or $\boldsymbol{\Theta}_{e\gamma}$
  - t_{RDC} - t_{XEC}
  - E_{RDC}

Likelihood Analysis

- **Likelihood analysis** with either 6 or 7 discriminating variables:
  - Positron Energy
  - Photon Energy
  - Relative time $t_{e\gamma}$
  - $\phi_{e\gamma}$
  - $\theta_{e\gamma}$ } or $\boldsymbol{\Theta}_{e\gamma}$
  - t_{RDC} - t_{XEC}
  - E_{RDC} **NEW**

The RDC look for positrons in time coincidence with the XEC (t_{RDC} - t_{XEC} ~ 0) and low energy (E_{RDC} ~ few MeV), indicating that the photon in the XEC comes from a RMD, not from μ -> e γ

2D binned PDF with one bin reserved for events w/o RDC hits



Likelihood Analysis

- **Likelihood analysis** with either 6 or 7 discriminating variables:
  - Positron Energy
  - Photon Energy
  - Relative time $t_{e\gamma}$
  - $\phi_{e\gamma}$ } or $\boldsymbol{\Theta}_{e\gamma}$
  - $\theta_{e\gamma}$ }
  - t_{RDC} - t_{XEC}
  - E_{RDC}

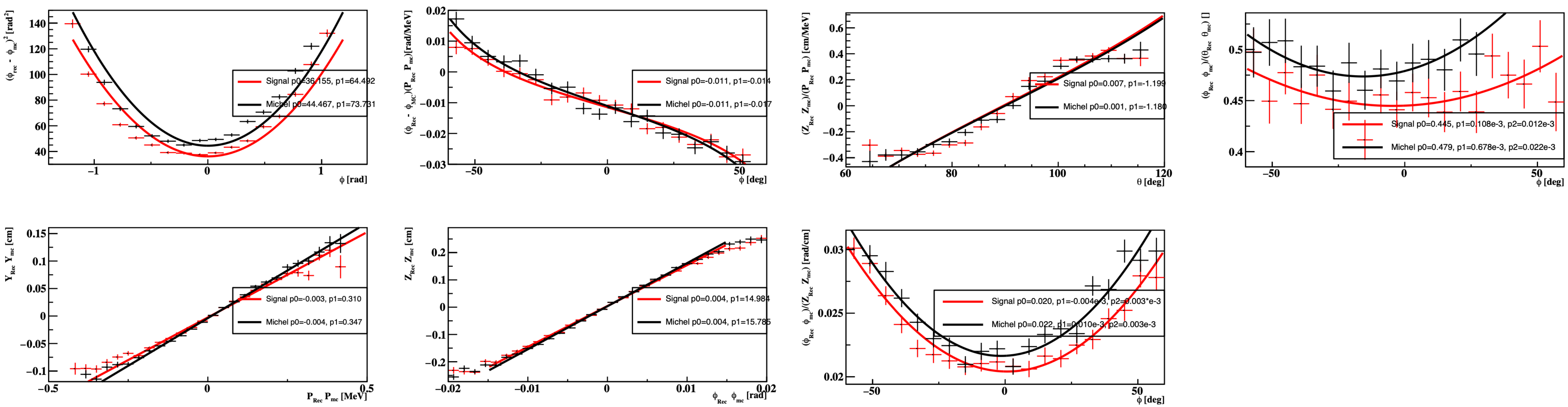
2 different strategies:

1. Use fully **event-dependent PDFs** (i.e. event by event resolution estimate) wherever possible —> more sensitive
2. Use **a few sets of PDFs** for events categorized by reconstruction quality —> less prone to systematics

Correlations

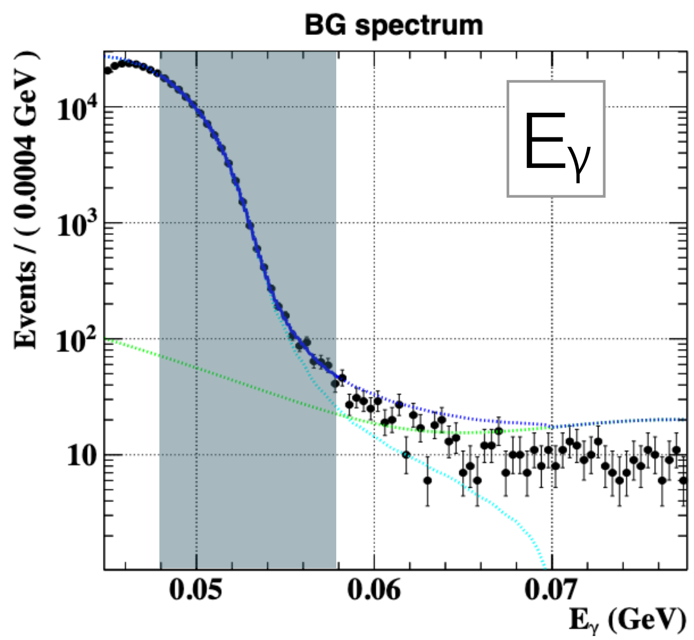
- There are correlations between likelihood observables to be carefully studied and modeled event-by-event

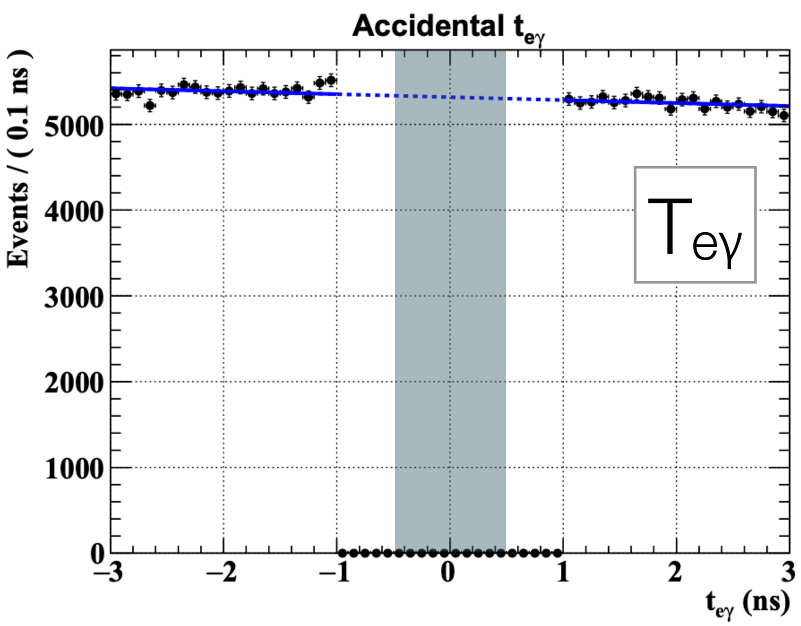
POSITRON CORRELATIONS in double-turn tracks

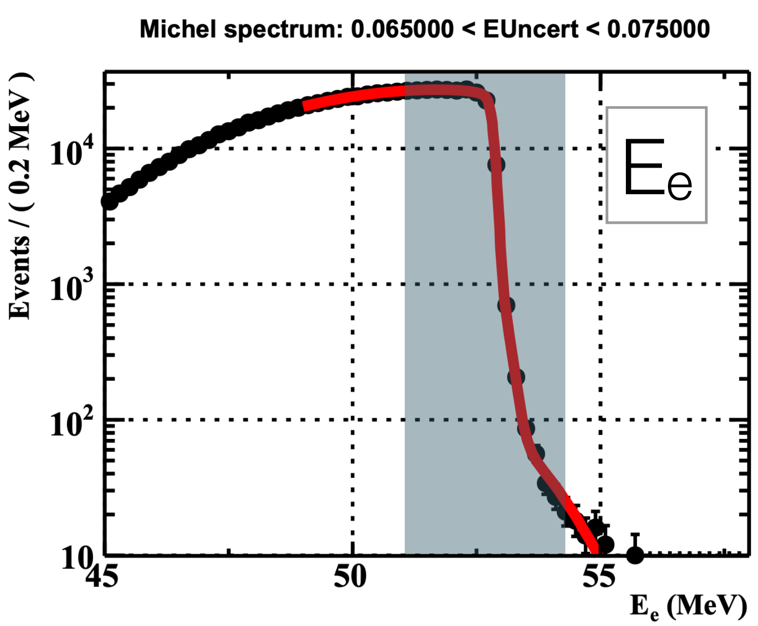


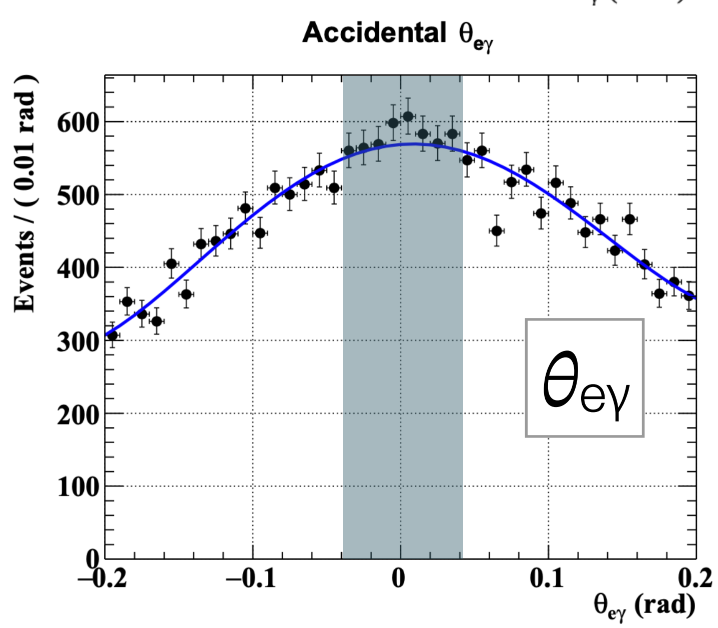
Extraction of PDFs

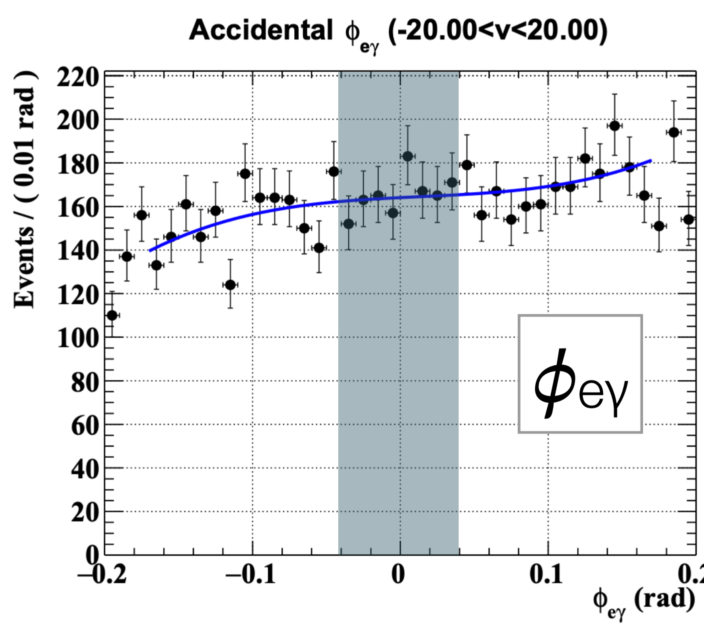
- Signal and RMD PDFs from resolution measurements
  - Positron multiple turn technique, positron Michel spectrum fit, CEX energy spectrum…
- Acc. Bkg PDFs from **sidebands** (fully data-driven)









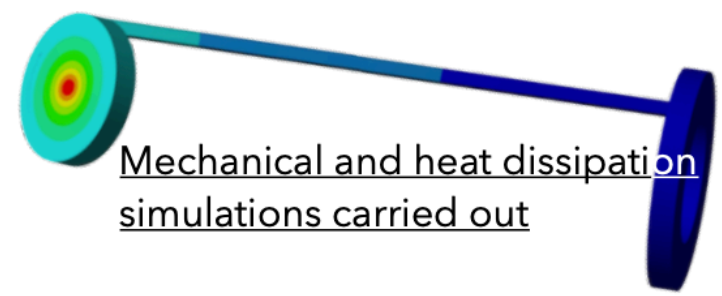


MEG II Pros & Contra

- Exploit MEG-II Cockroft-Walton accelerator to excite $p + {}^{7}Li \rightarrow {}^{8}Be^{*}$ resonances, and reconstruct the $e^{+}e^{-}$ pair in the magnetic spectrometer (CDCH + pTC)
- Pros:
  - same physics process as ATOMKI, but different detectors and analysis strategy (complementary test w.r.t. PADME)
  - larger θ acceptance (ATOMKI limited to $\theta \sim 90°$ w.r.t. the proton beam)
  - superior energy resolution of the spectrometer w.r.t. scintillators
  - IPC predictions based on a more robust theoretical model
  - blind analysis strategy
- Cons:
  - limited momentum and ϕ acceptance in the spectrometer —> low efficiency
  - thicker target to compensate for the low efficiency —> difficulties in target production and quality control

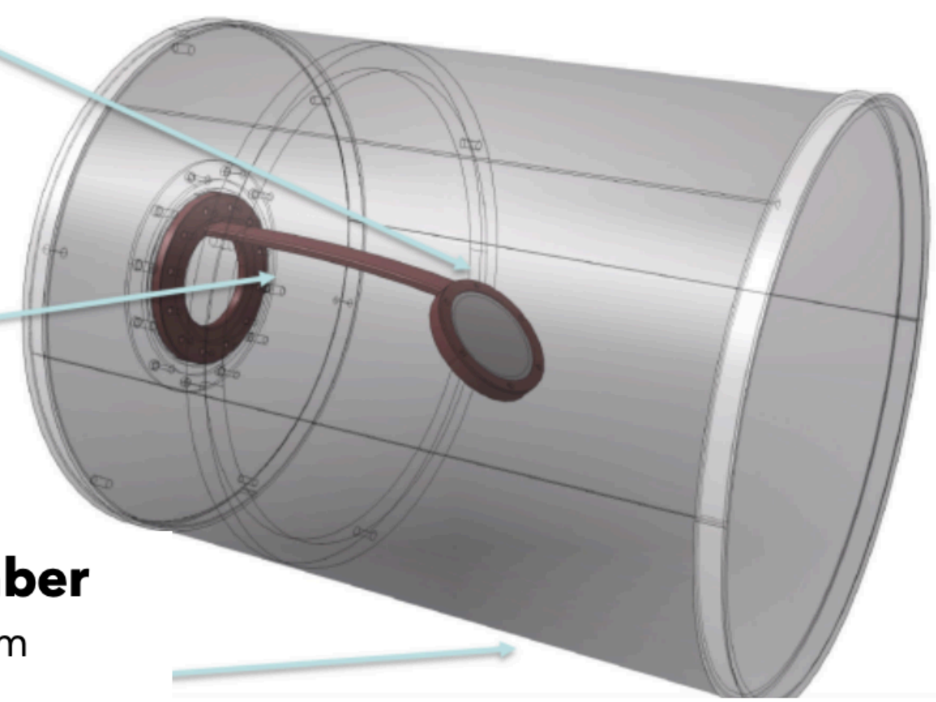
Dedicated target region

- 400 μm-thickness carbon fiber vacuum chamber to minimize multiple scattering
- 5 μm LiF on 10 μm copper (@ INFN Legnaro)
- > 2 μm LiPON on 25 μm copper (@ PSI)



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 ($Li_{3-x}PO_{4-Y}N_{x+Y}$)