Muon physics and searches for new physics at MEG

Marco Francesconi
on behalf of MEG II collaboration

Workshop on status and perspectives of physics at high intensity, LNF, 09/11/2022

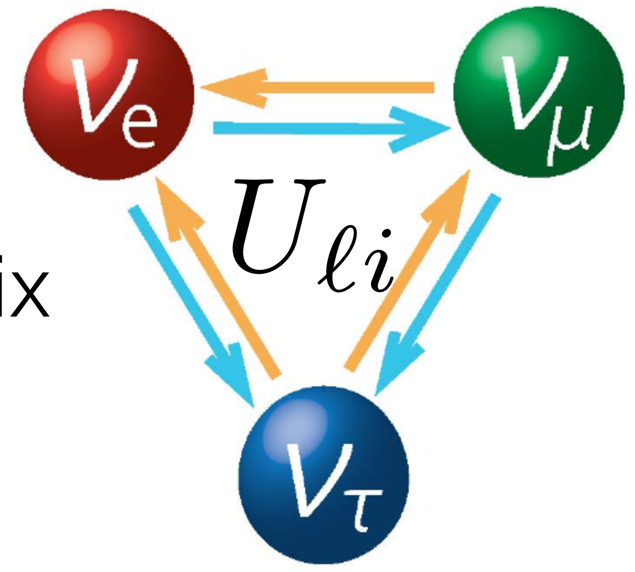
Overview

- Few words on Charged Lepton Flavour Violation (CLFV) and $\mu^+ \to e^+\gamma$ decay
- The detectors of the MEG II experiment
- MEG II experiment status for $\mu^+ \to e^+\gamma$ search
- Other "Exotic" physics at MEG II

Neutrino oscillation and (Charged) Lepton Flavour violation

Evidence of neutrino oscillation explicitly violates Lepton Flavor (LFV processes)

PMNS Matrix



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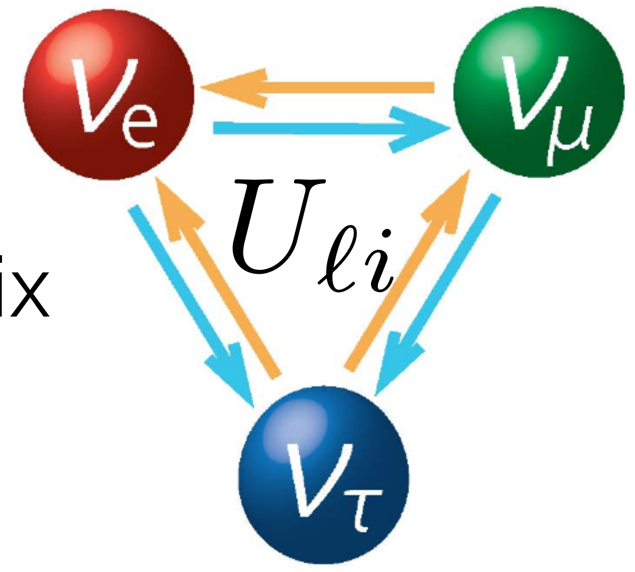

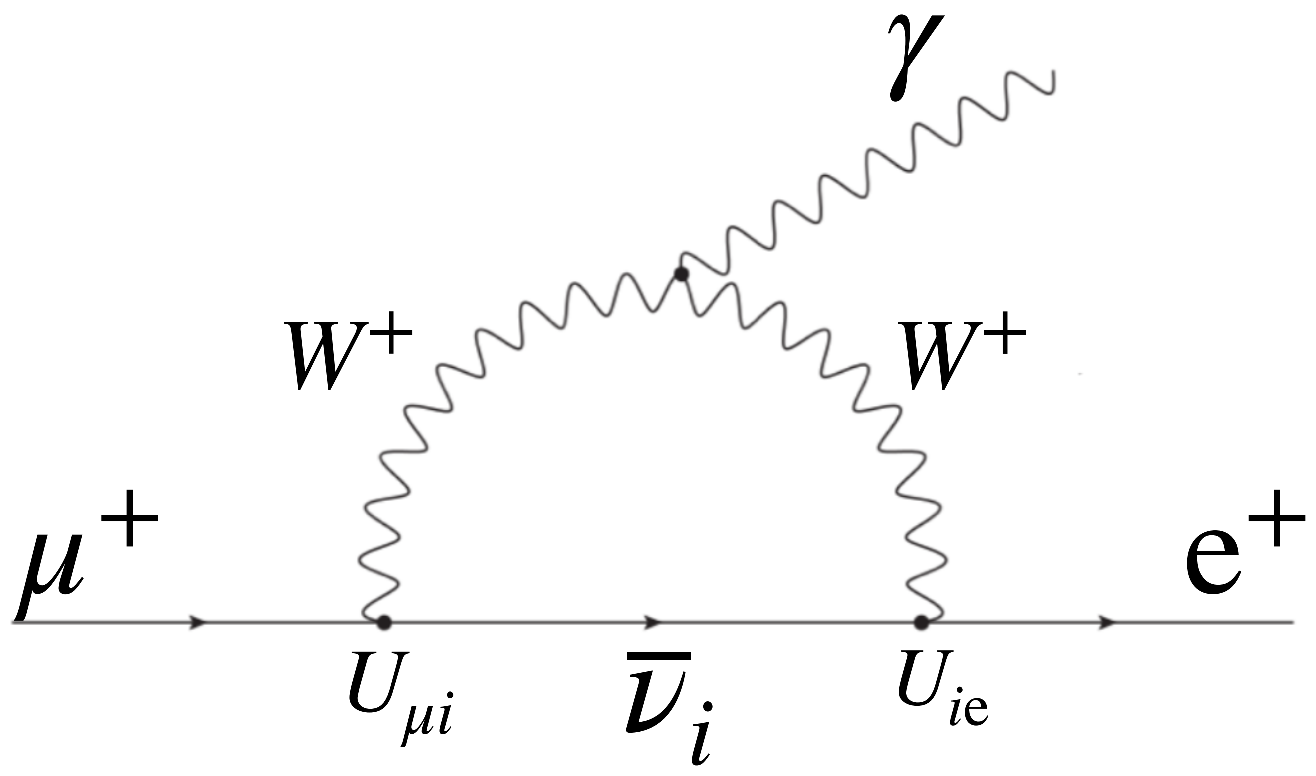

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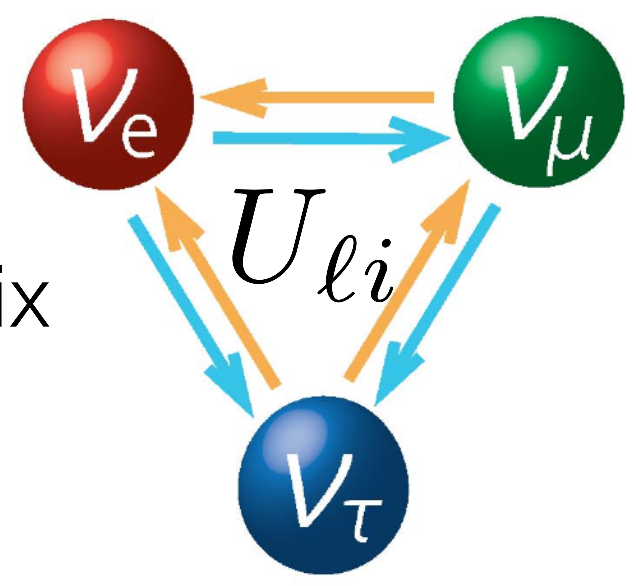

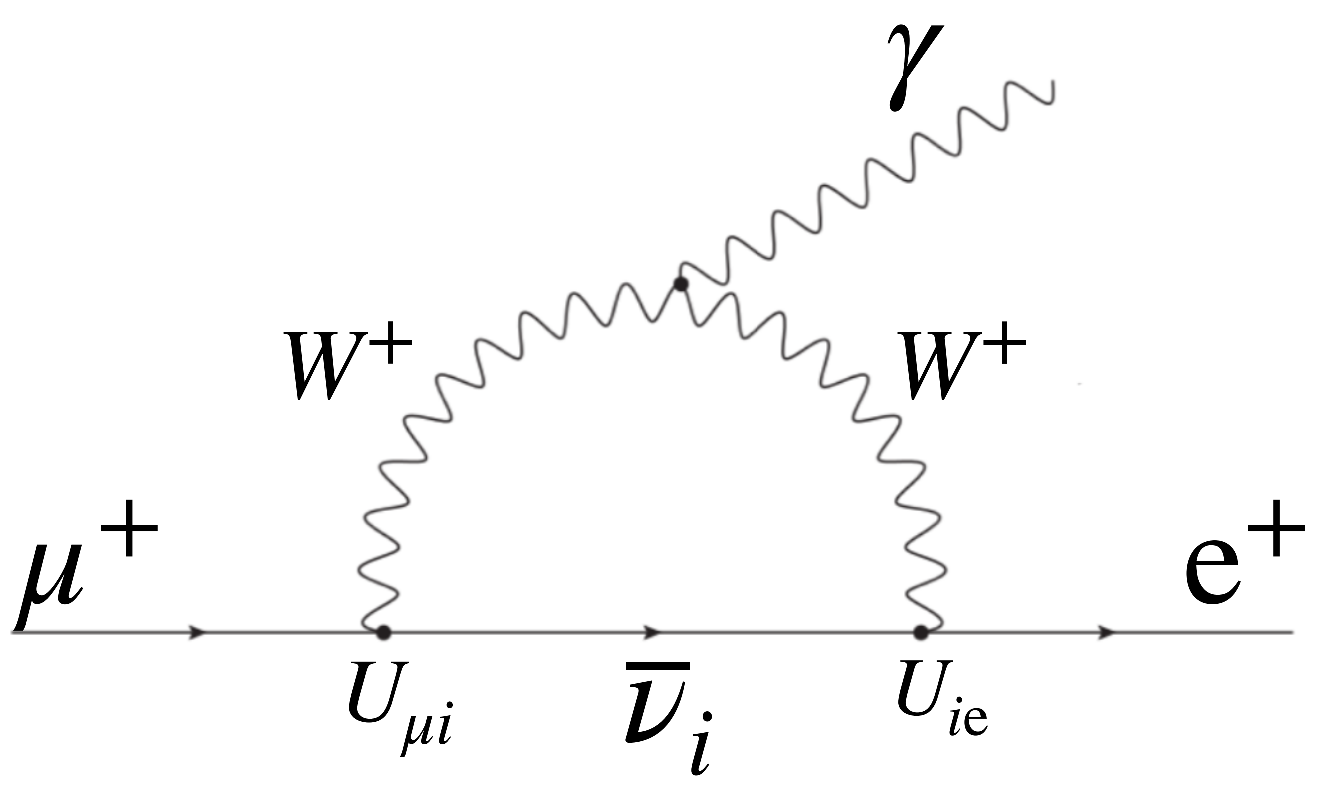

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$$\mathrm{BR}(\mu \to \mathrm{e} + \gamma) = \frac{\Gamma_{\mu \to \mathrm{e}+\gamma}}{\Gamma_{TOT}} = \frac{3\alpha}{32\pi} \left| \sum_{i=1}^{3} U_{\mu i} U^*_{\mathrm{e}i} \frac{m_i^2}{m_W^2} \right|^2 \approx 10^{-55 \leftrightarrow -50}$$

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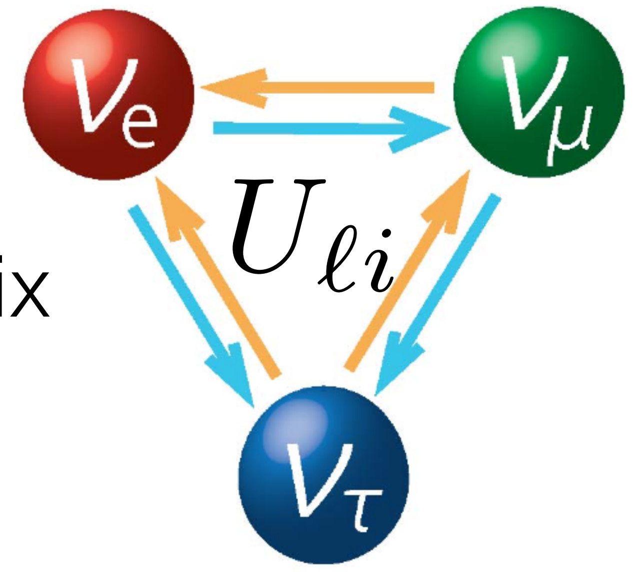

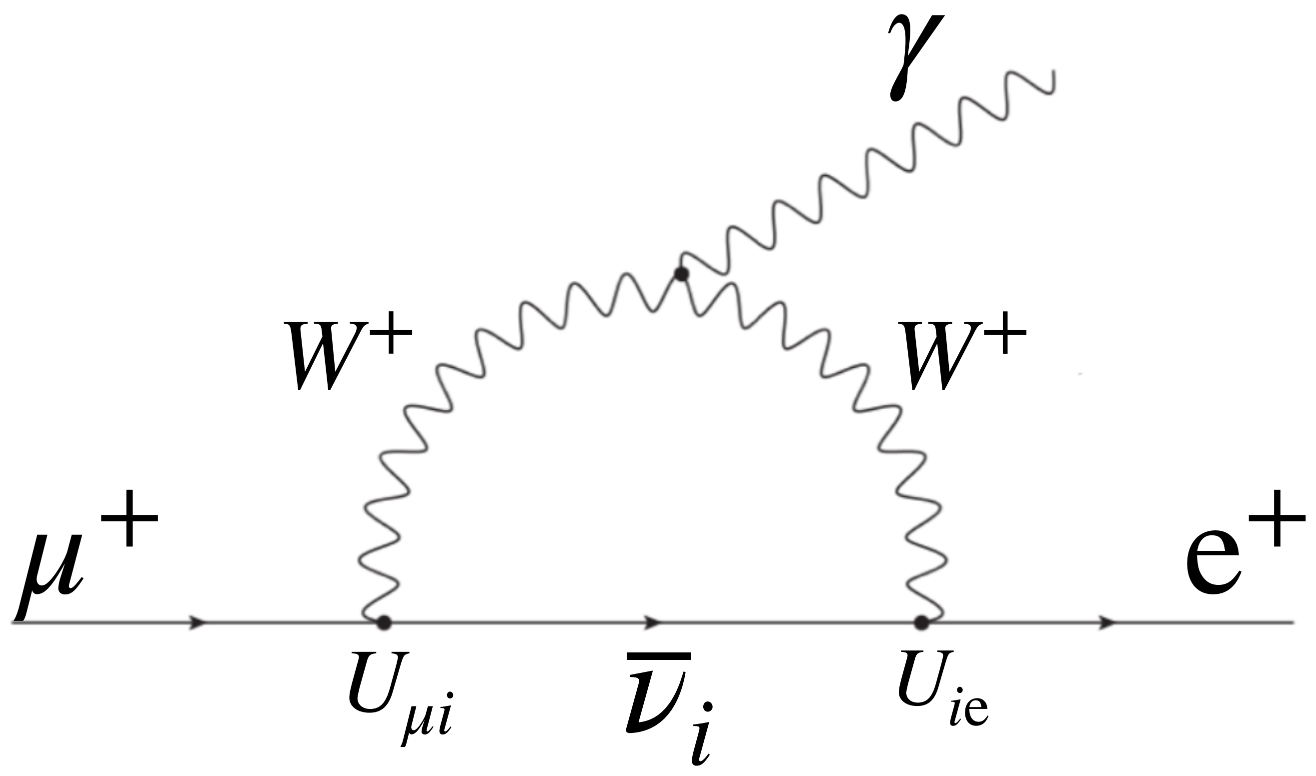

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(C)LFV Golden channel for Beyond SM physics:

- not forbidden by other conservation laws
- SM contribution is beyond reach
- Model agnostic

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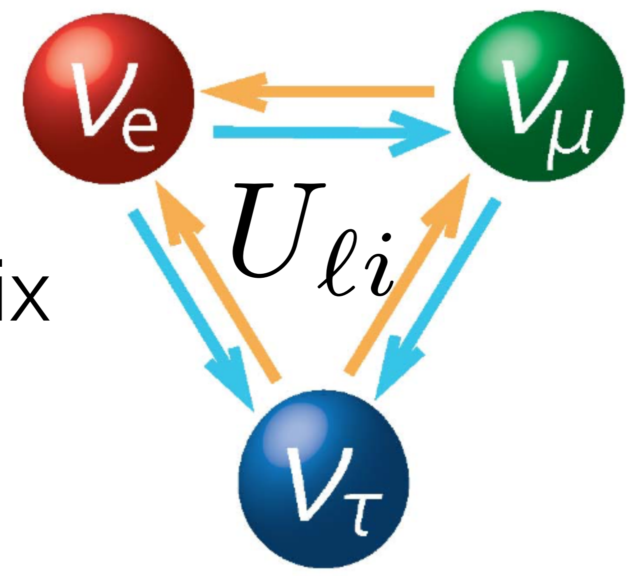

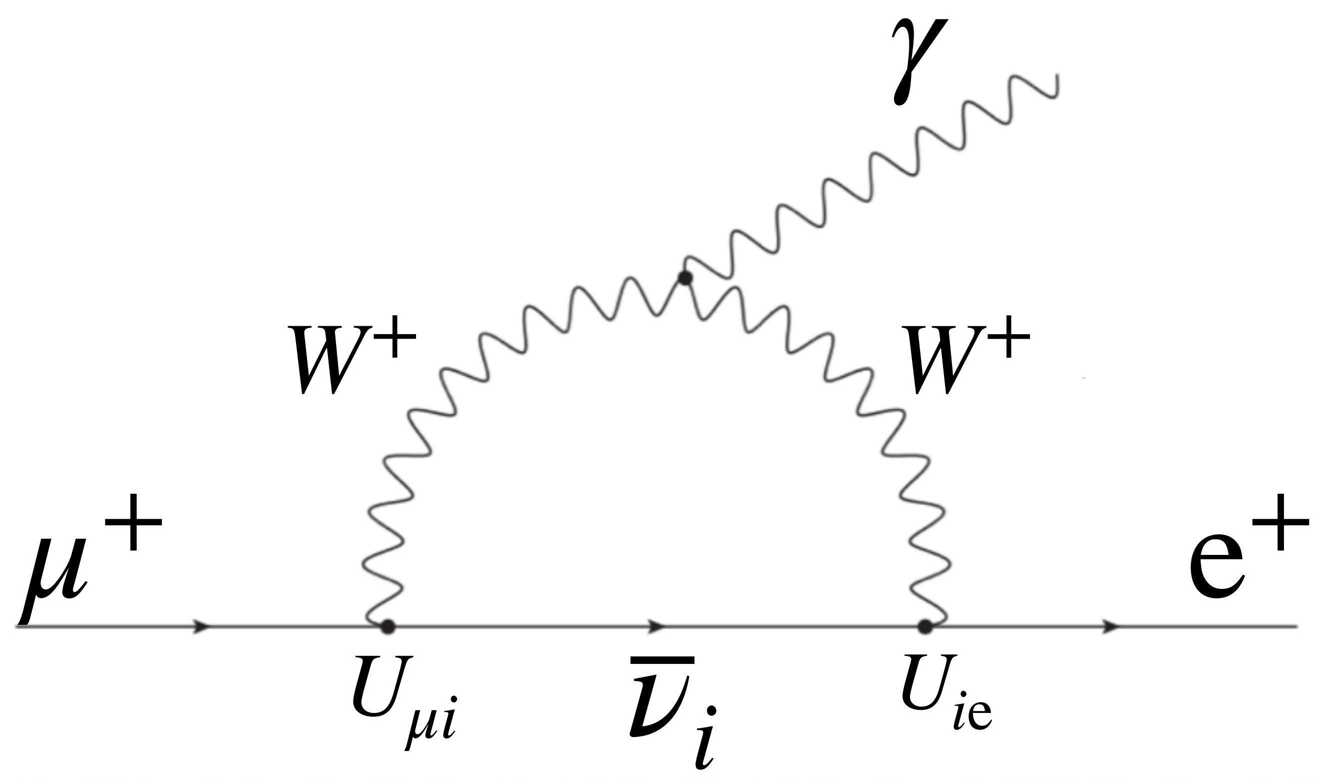

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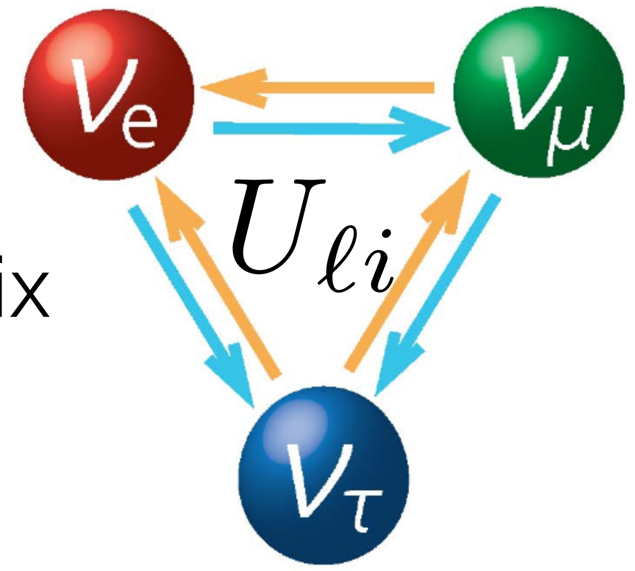

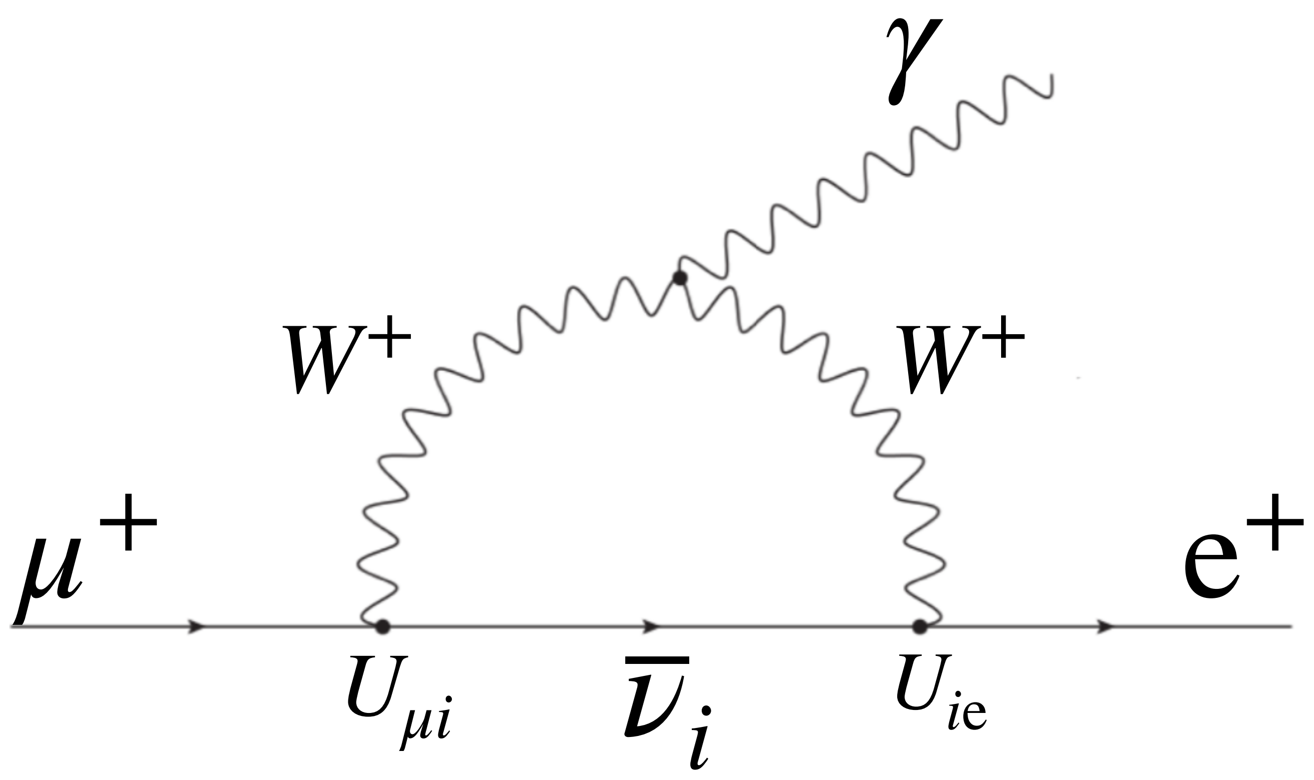

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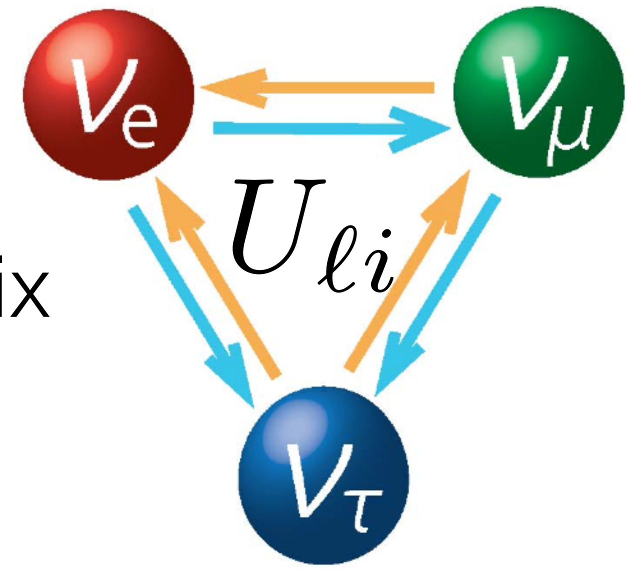

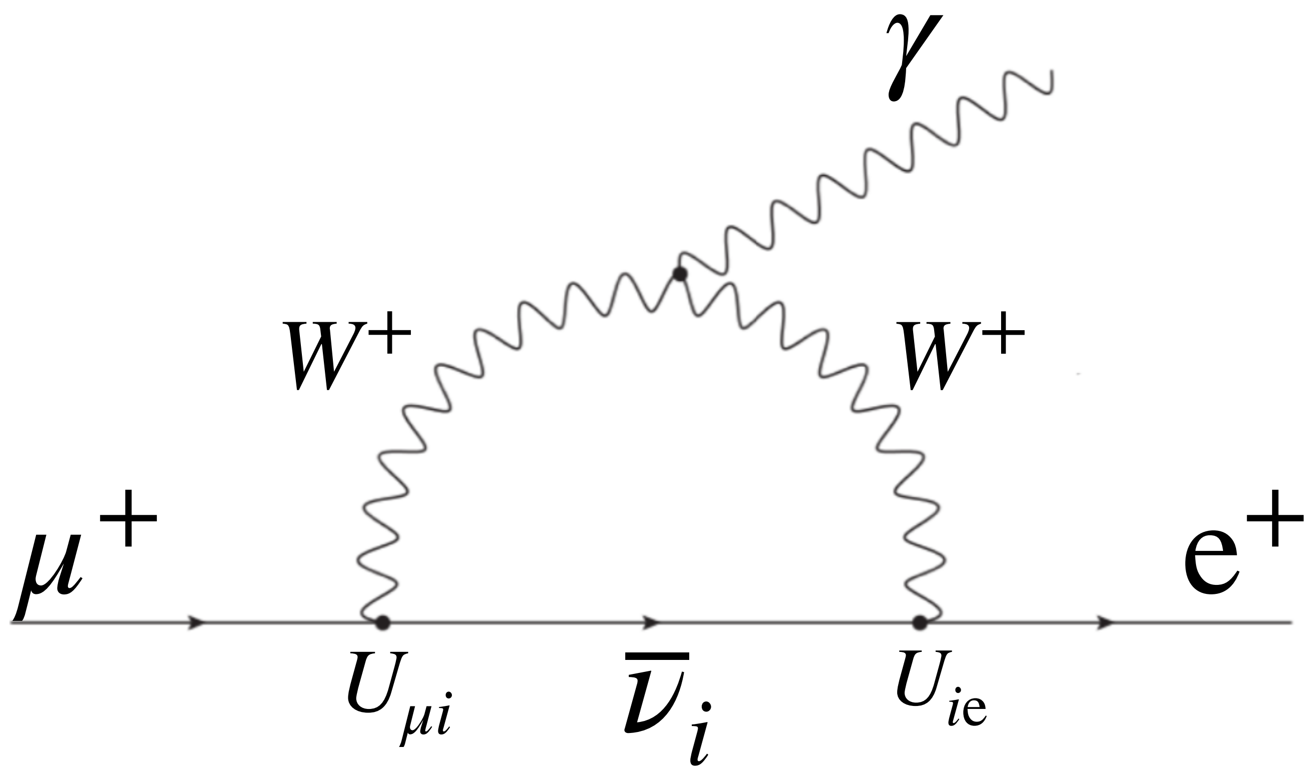

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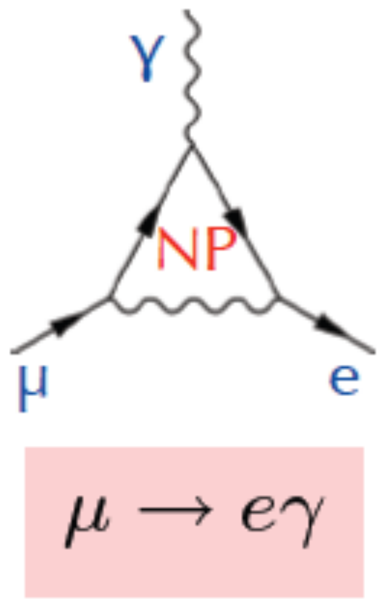
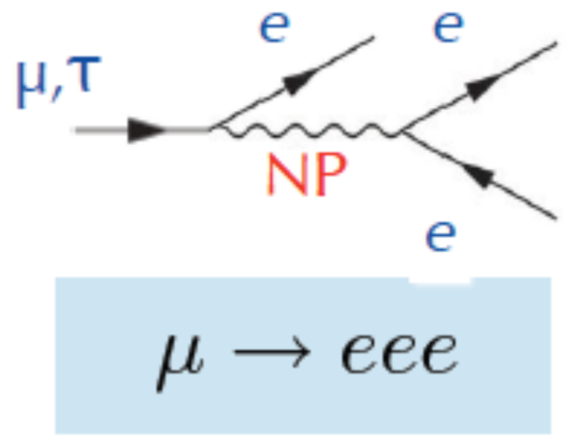
Interplay between measurements

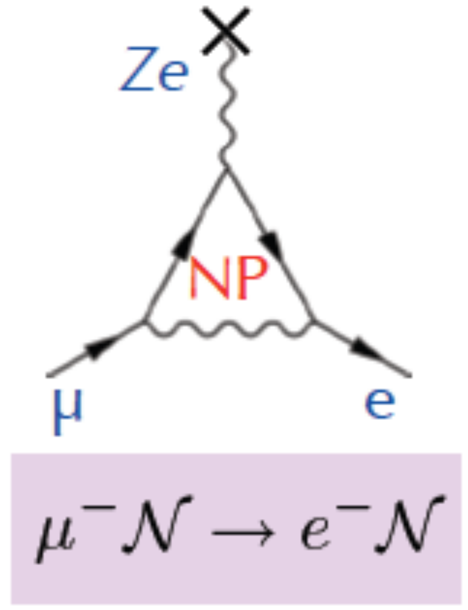
In particular within the muon sector



MEG



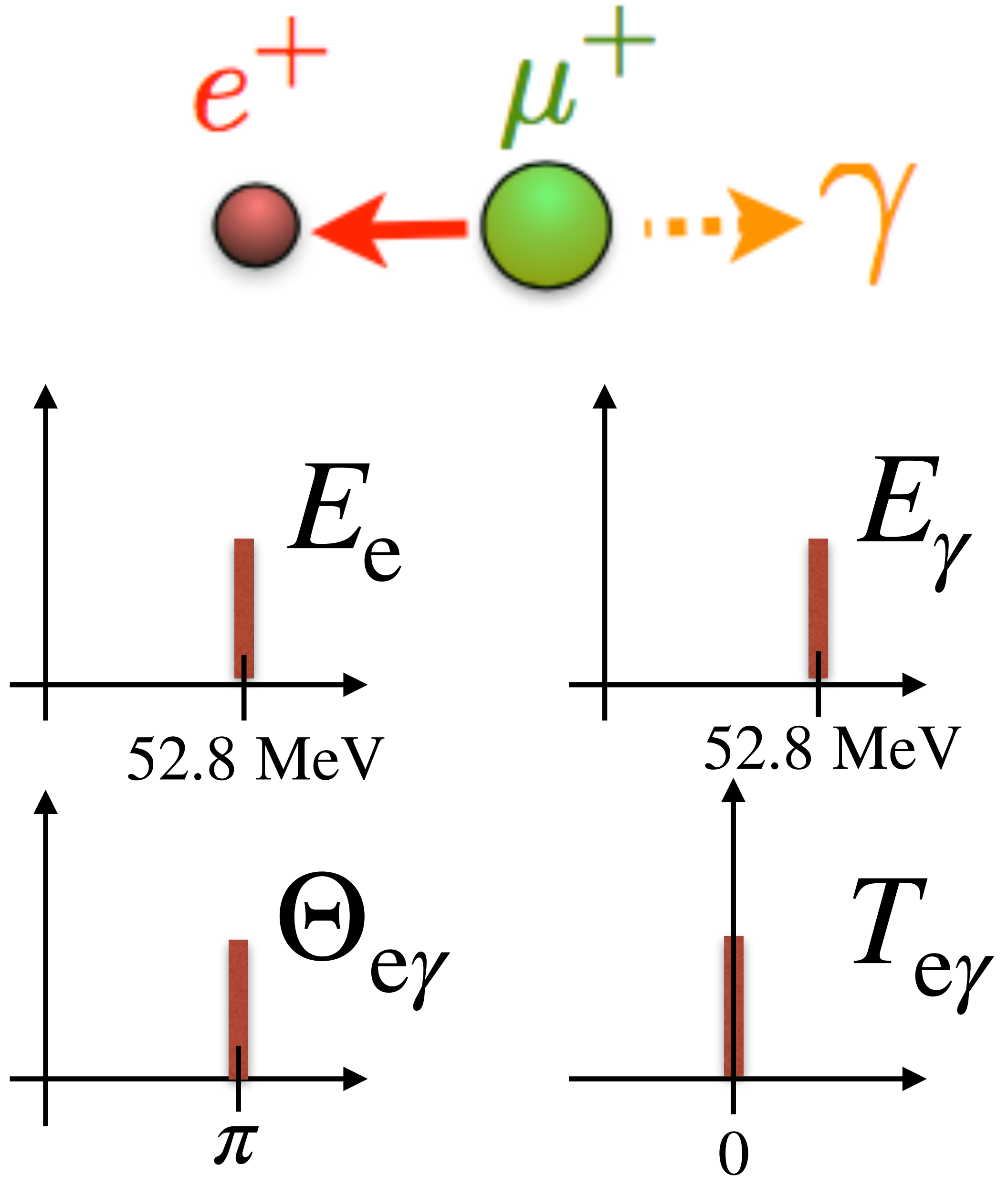
Mu3e



Mu2e, COMET

MEG experiment: signature and backgrounds

Signal



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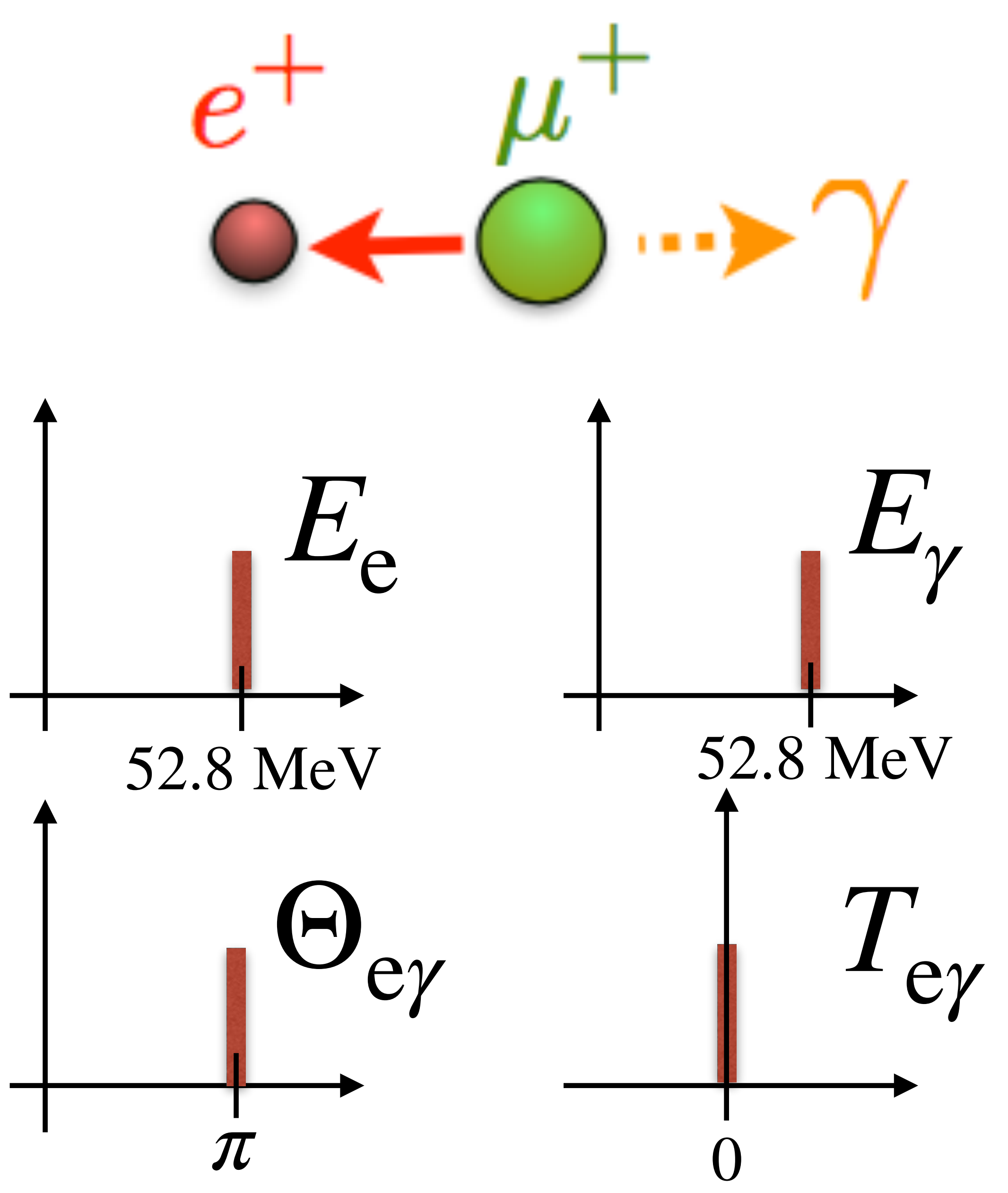
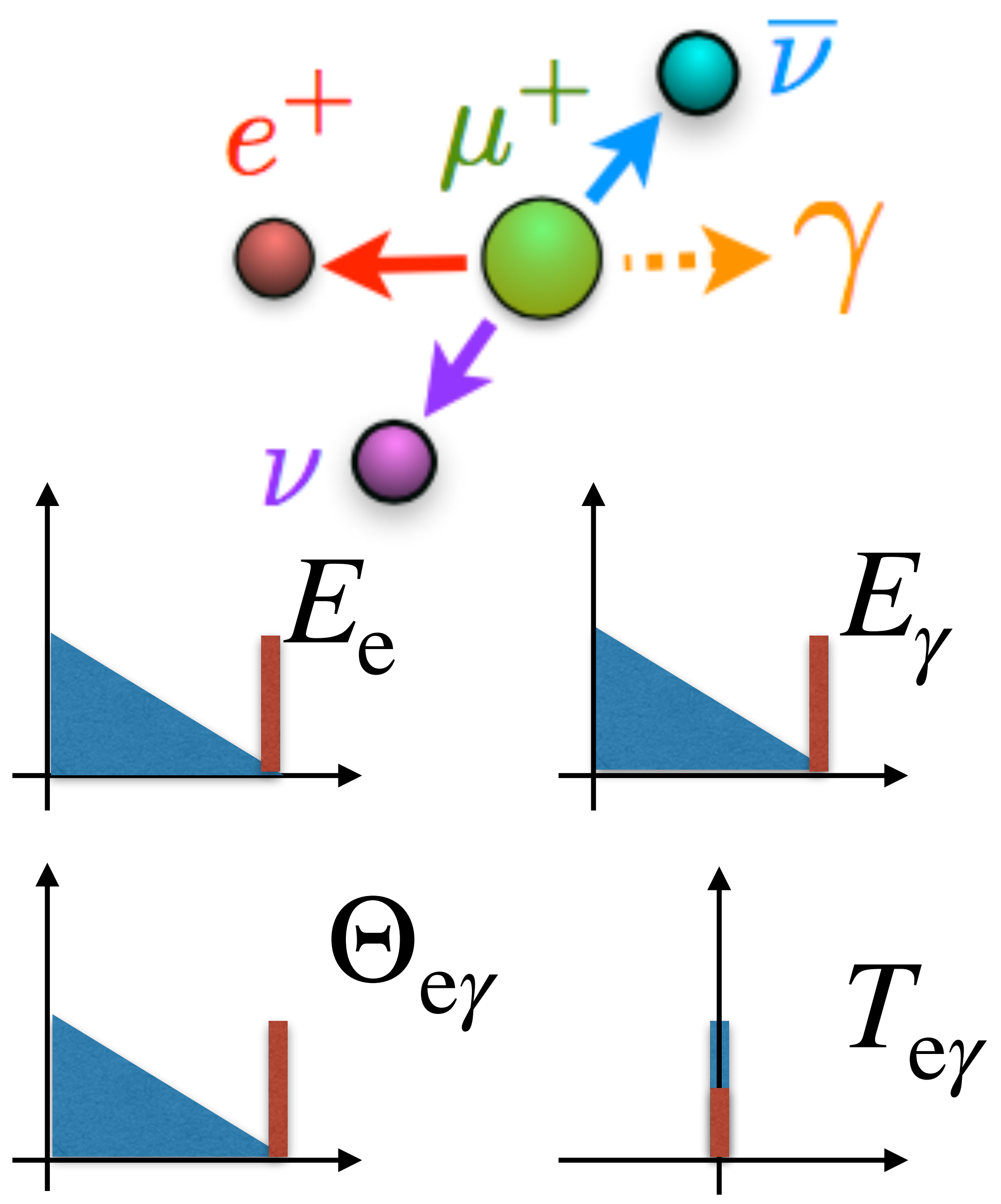


Physics Background:



$$R_{\mathrm{Rad}} = R_\mu \, \mathrm{BR}(\mu \to e\nu\bar{\nu}\gamma \,|\, \Delta E_\gamma, \Delta E_e, \Delta\Theta_{e\gamma})$$

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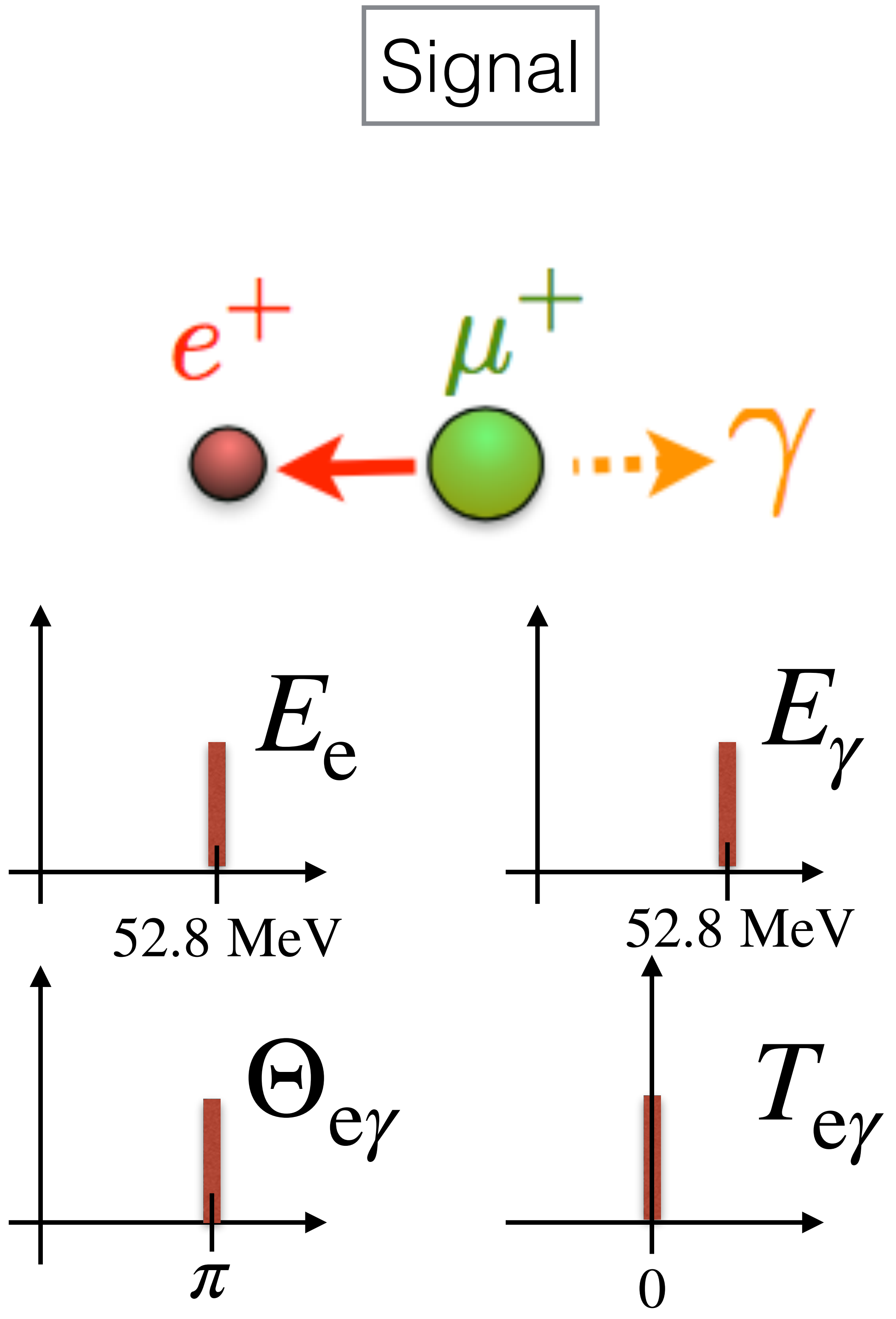

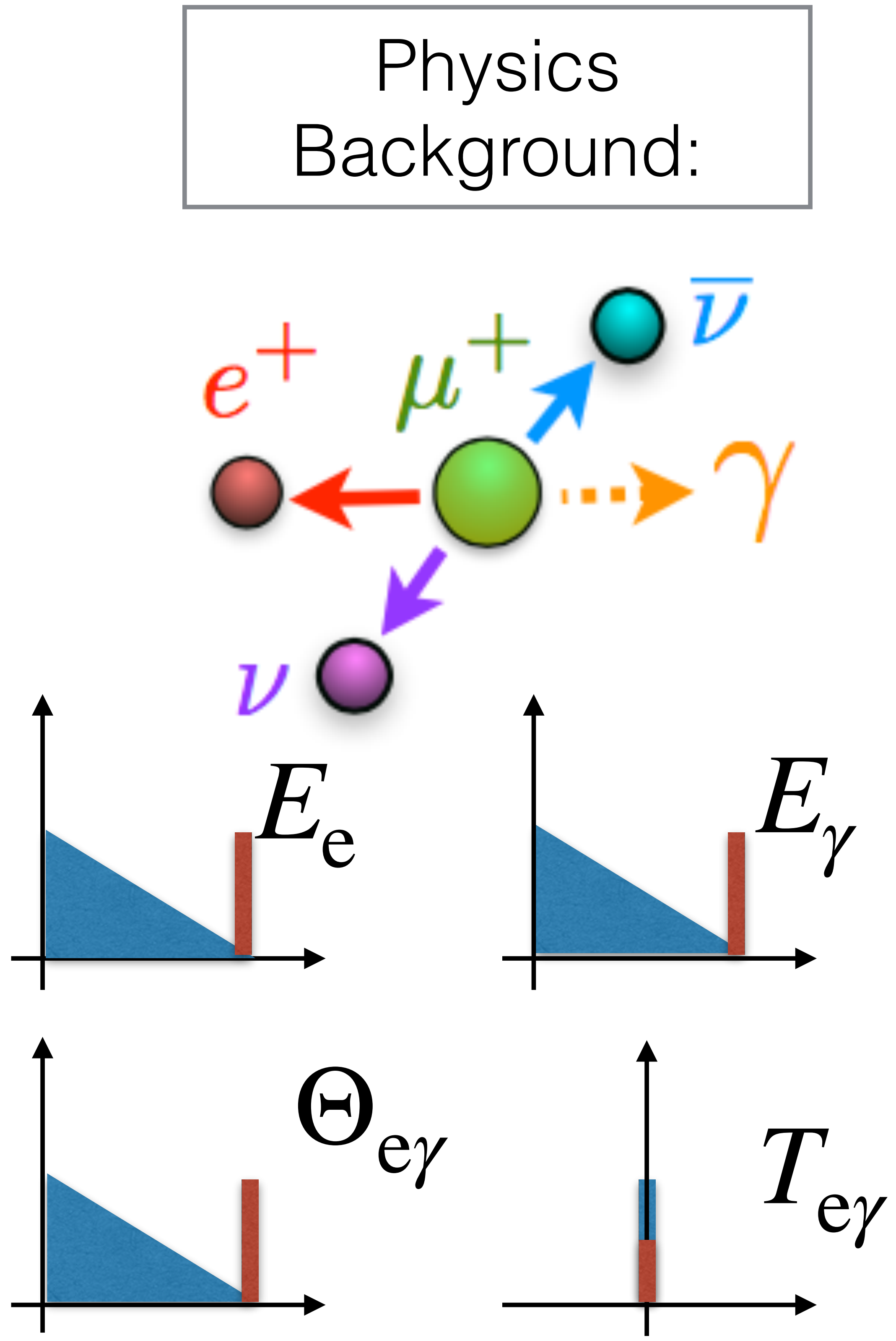

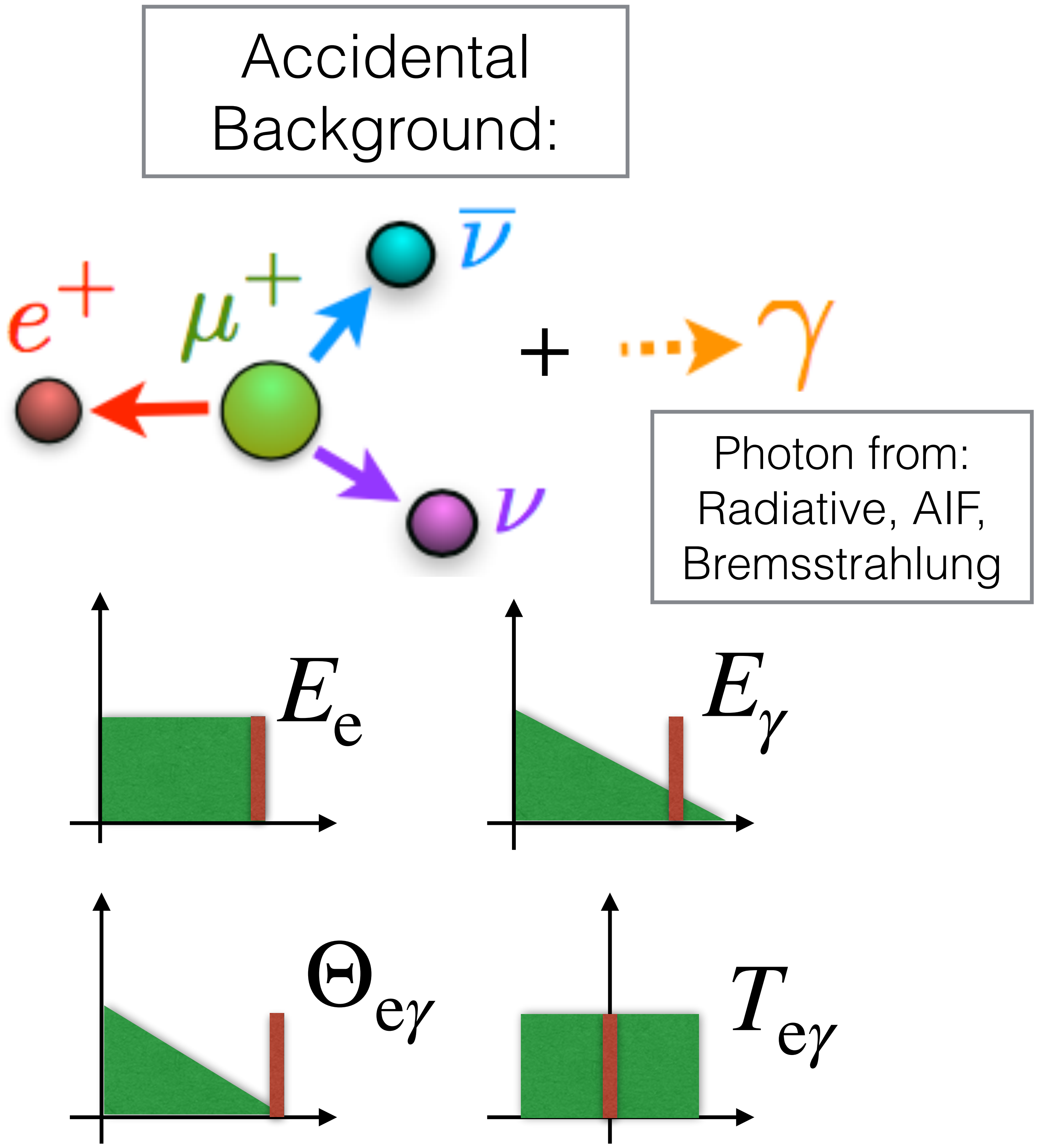

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$$R_{\text{Acc}} \approx R_\mu^2 \cdot \Delta E_e \cdot \Delta E_\gamma^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

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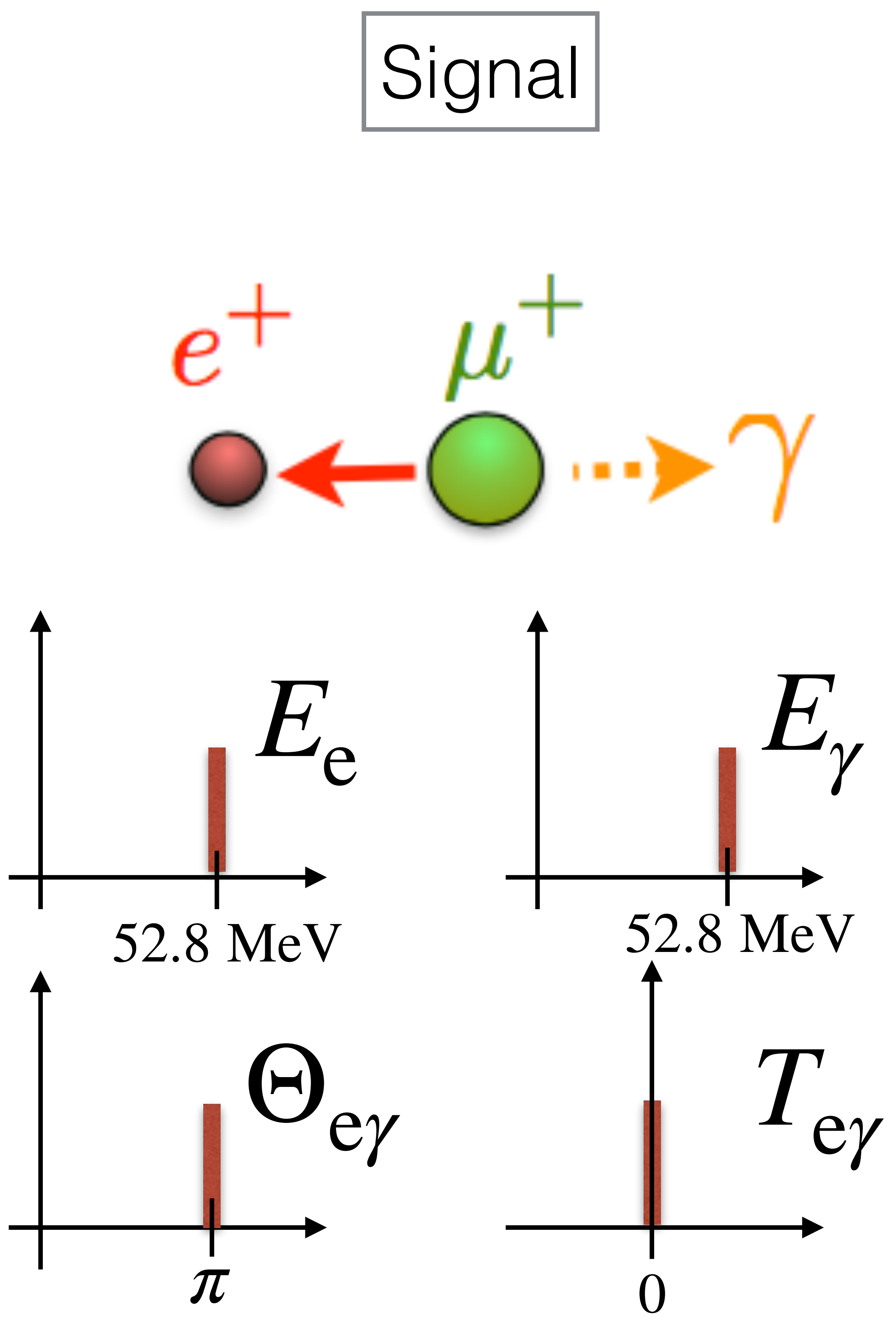

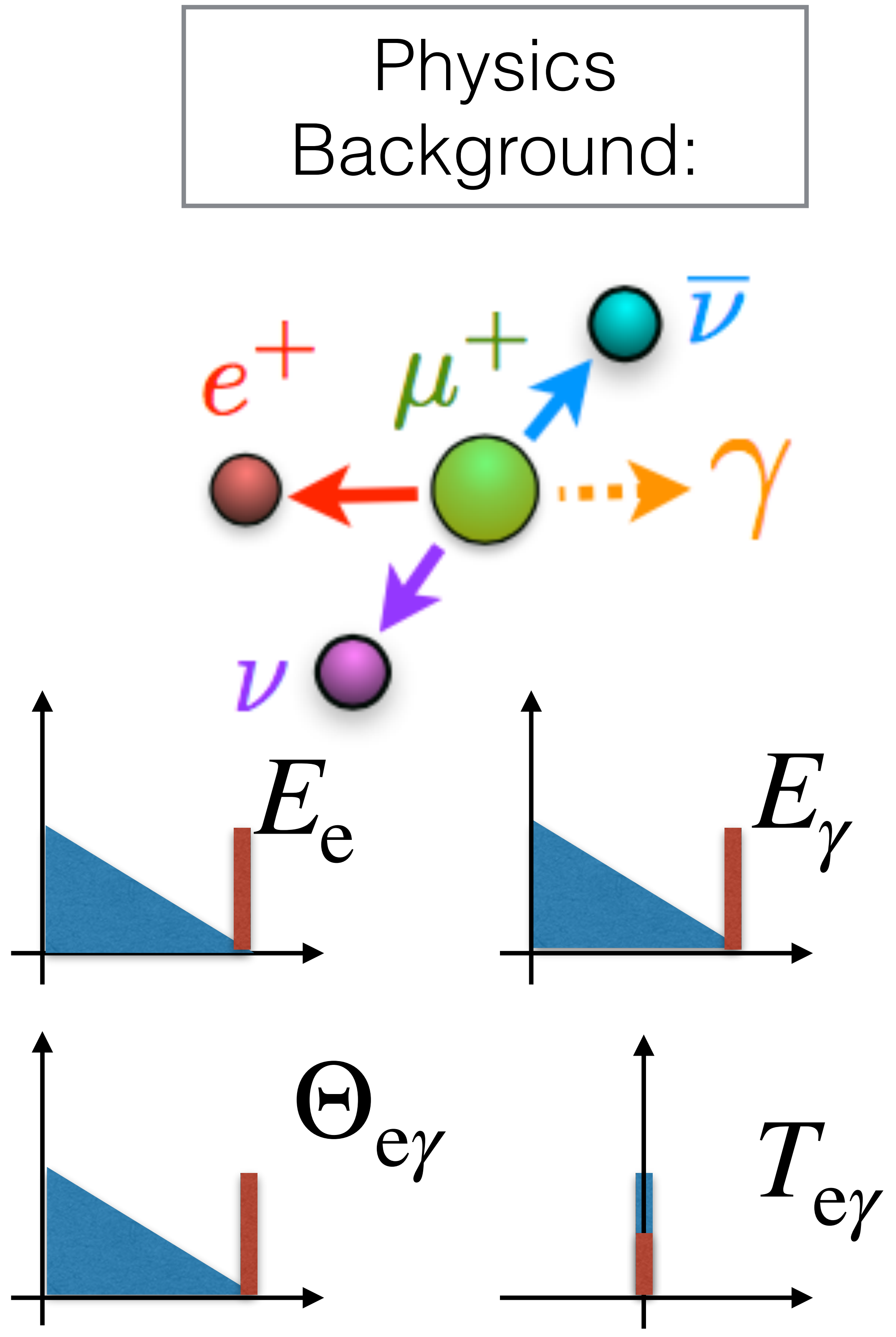

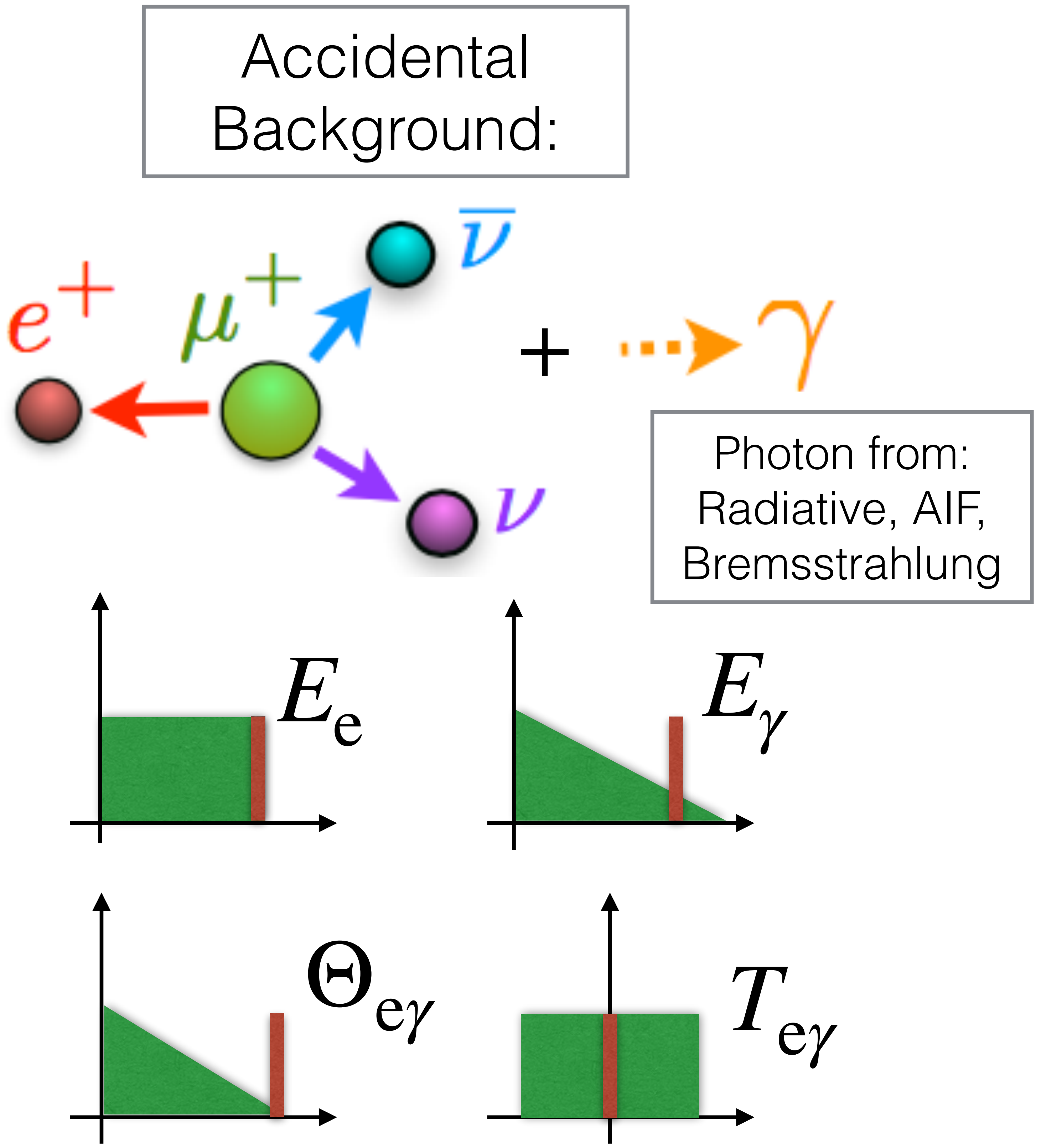

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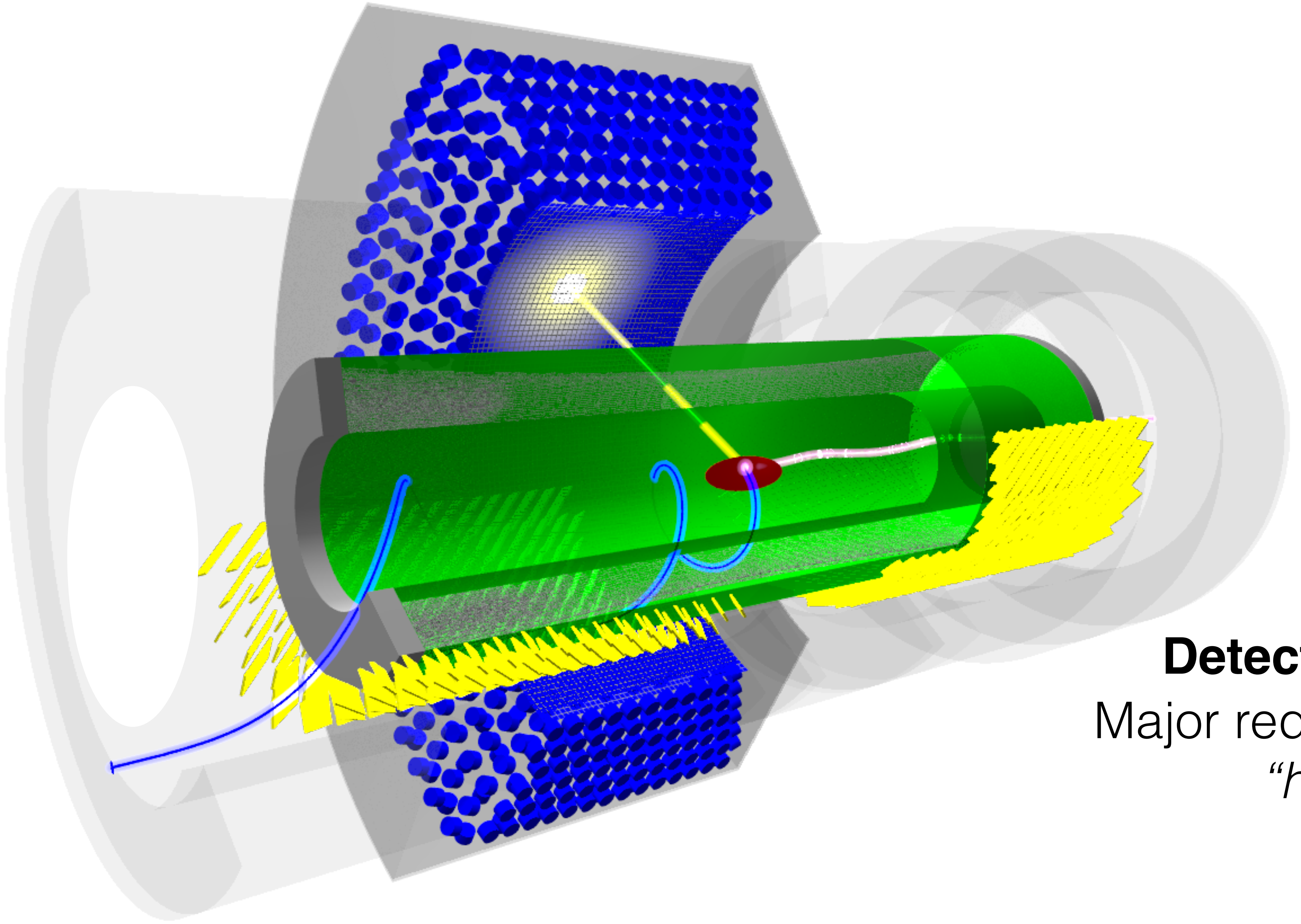
← **Dominating for high muon rates R_μ**

The MEG II Experiment



Detection strategy is the same of MEG
Major redesign or completely new detectors
“higher rate & increased resolutions”

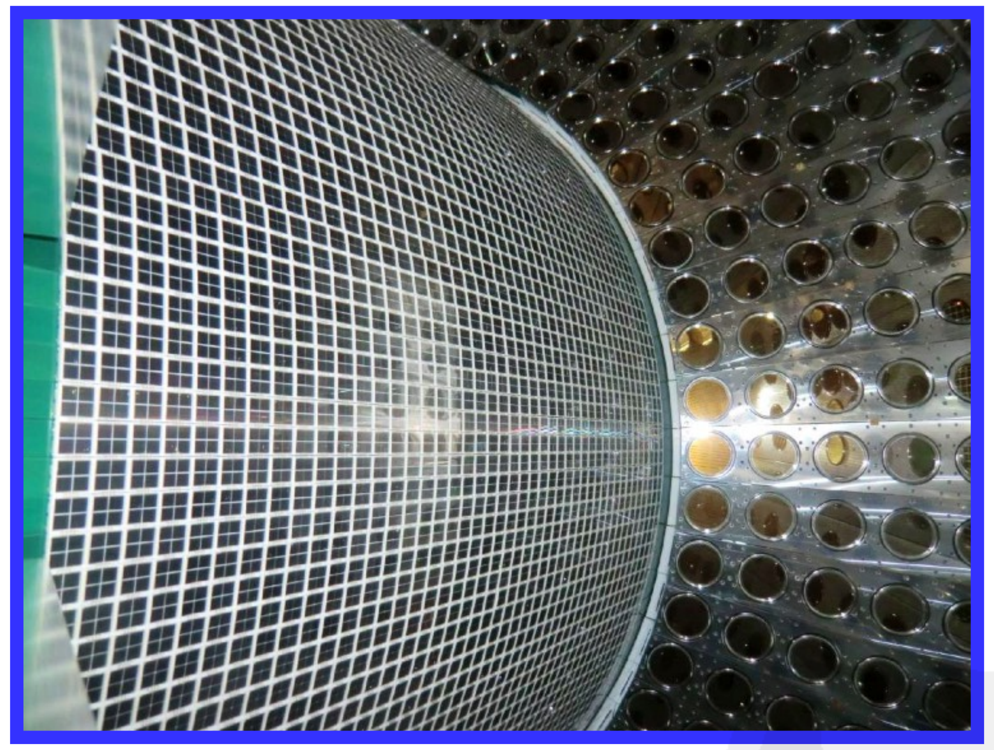
The MEG II Experiment

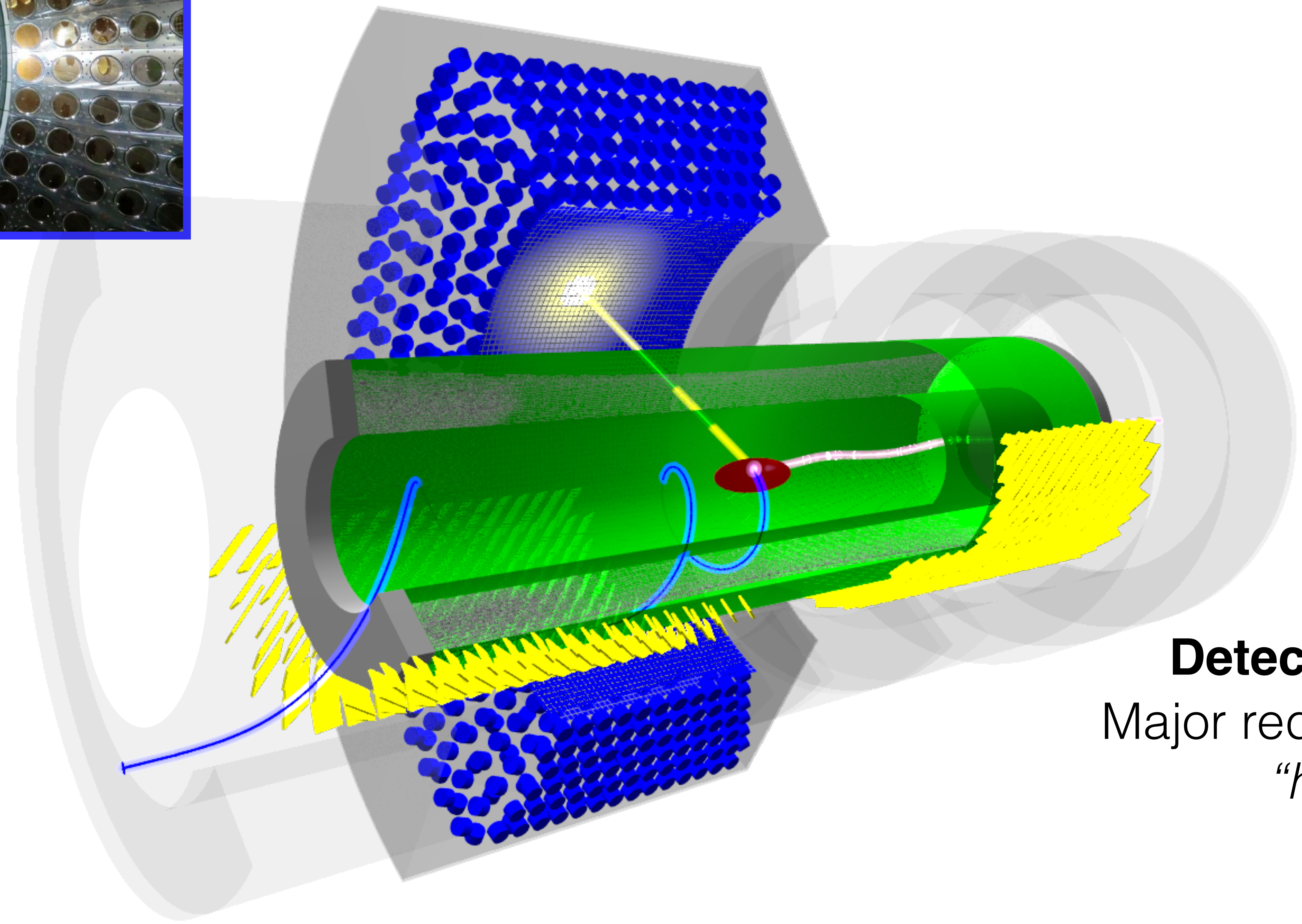
LXe

Scintillation Detector

4092 **SiPMs** +
668 **PMTs**

$E_\gamma, \Theta_\gamma, T_\gamma$





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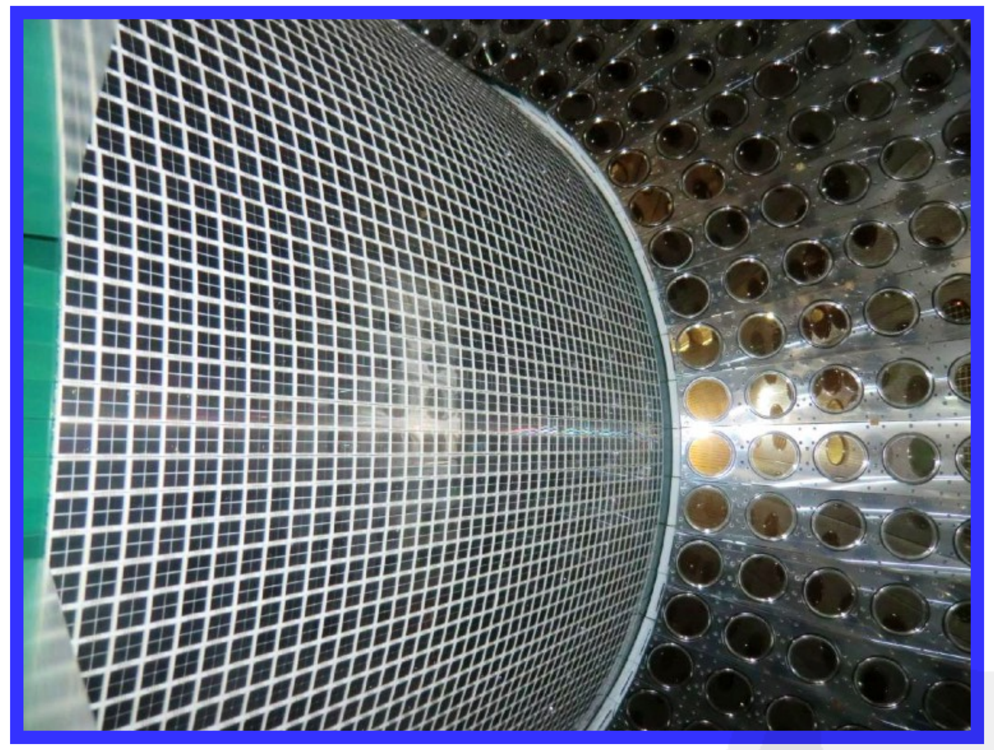
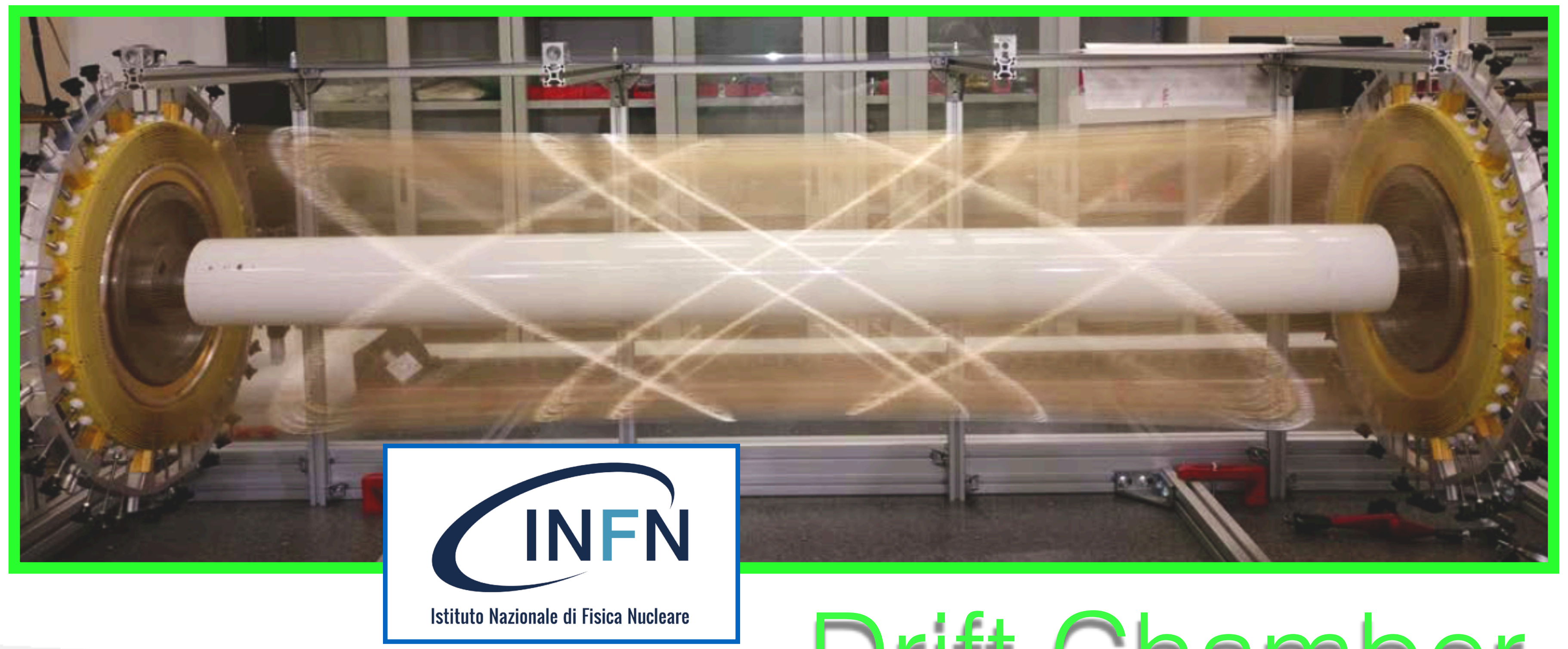
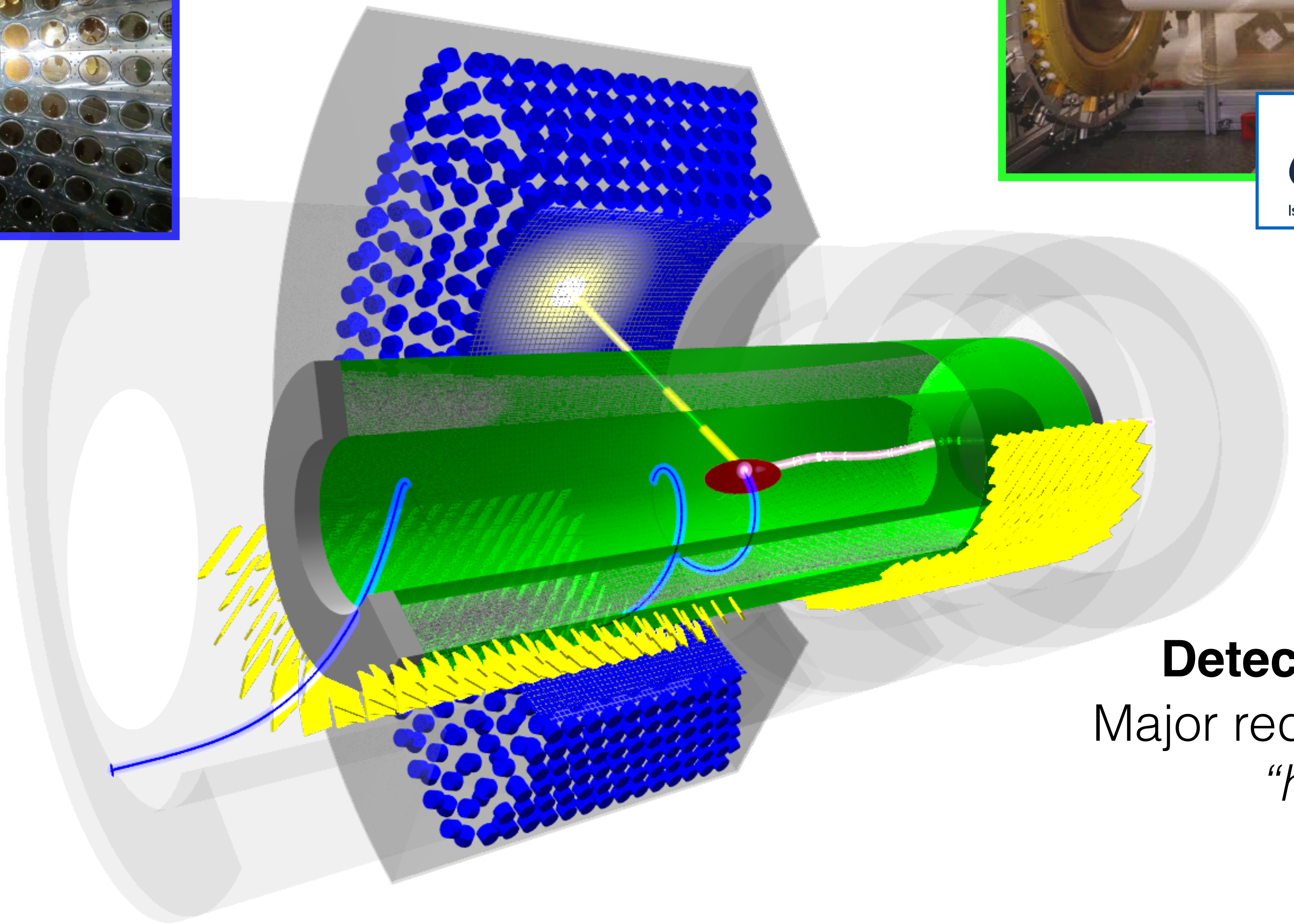




Drift Chamber

1728 square **drift cells**
More than 60 hits per track with
~110um spatial resolution

Θ_e, P_e



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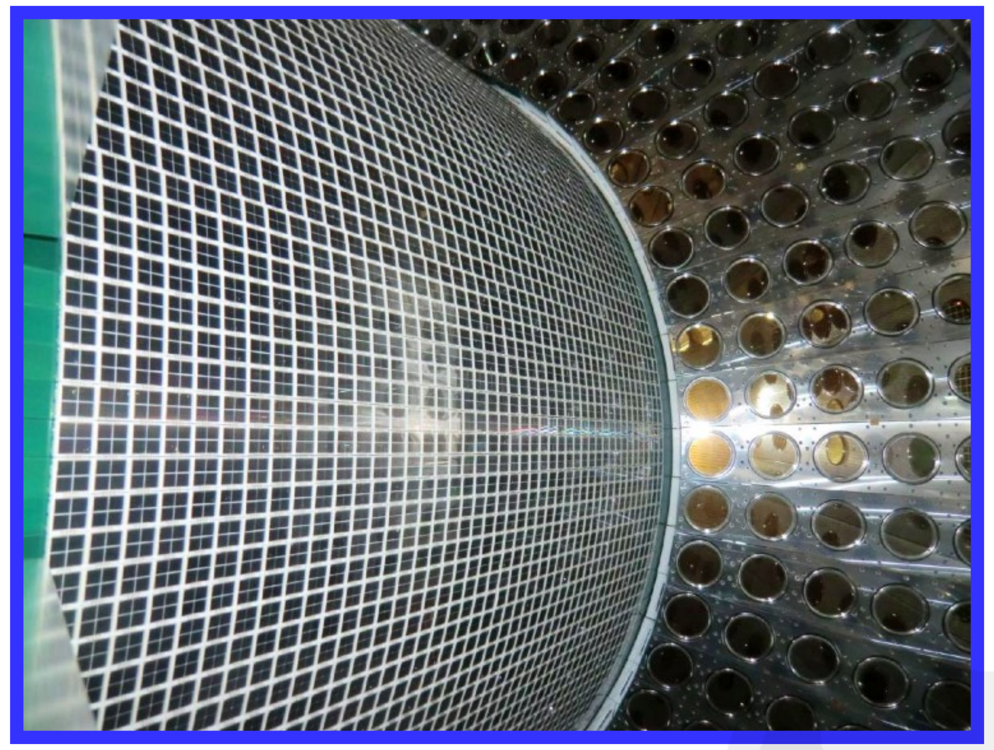

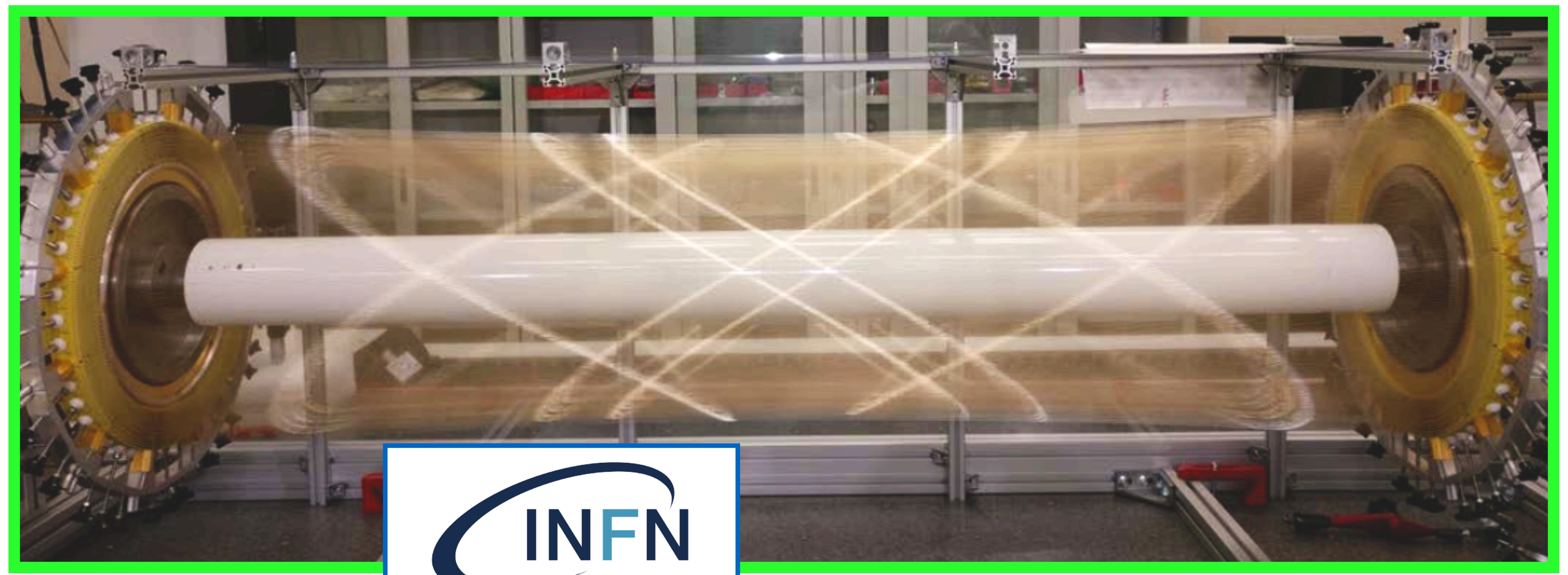

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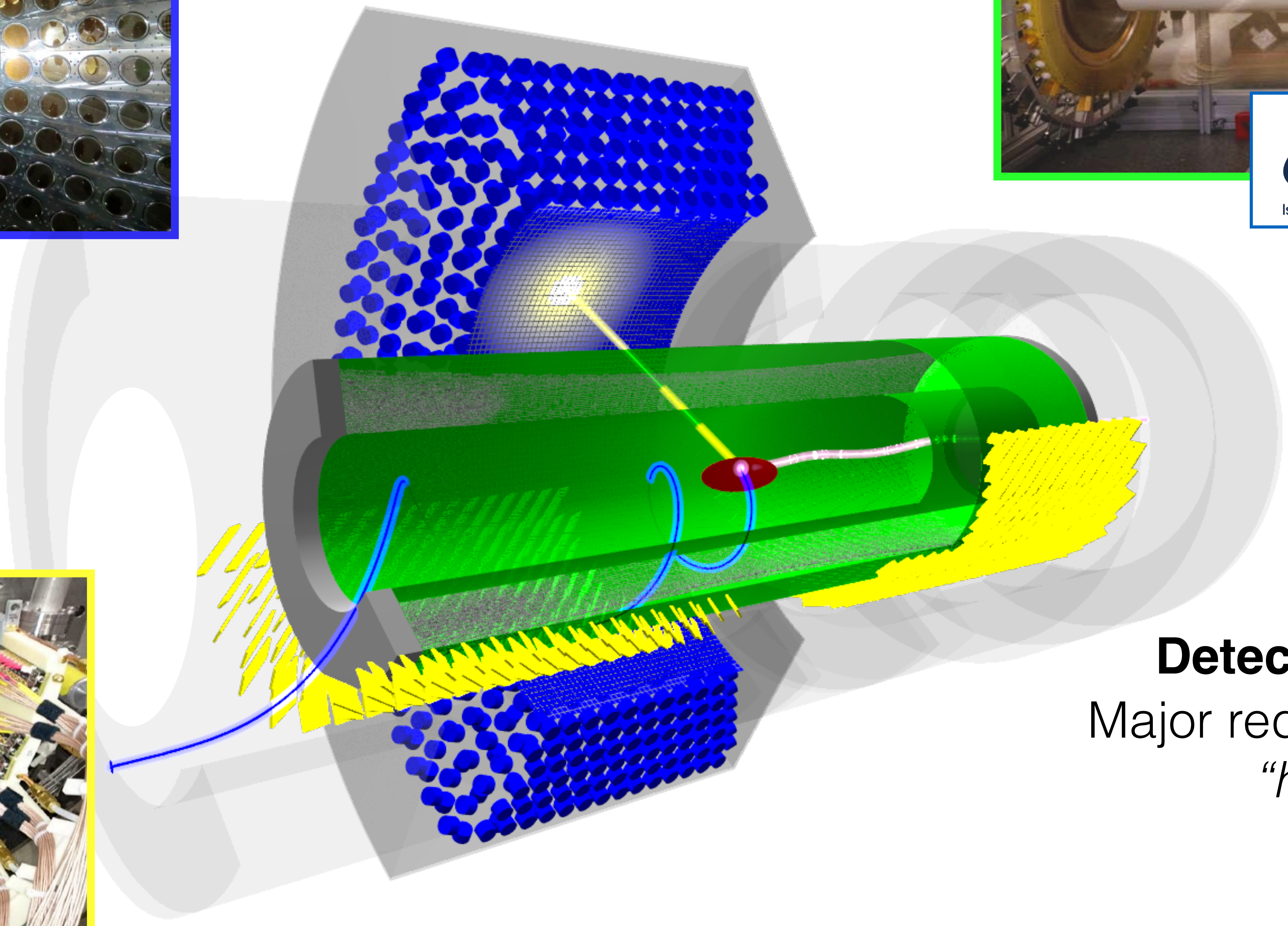

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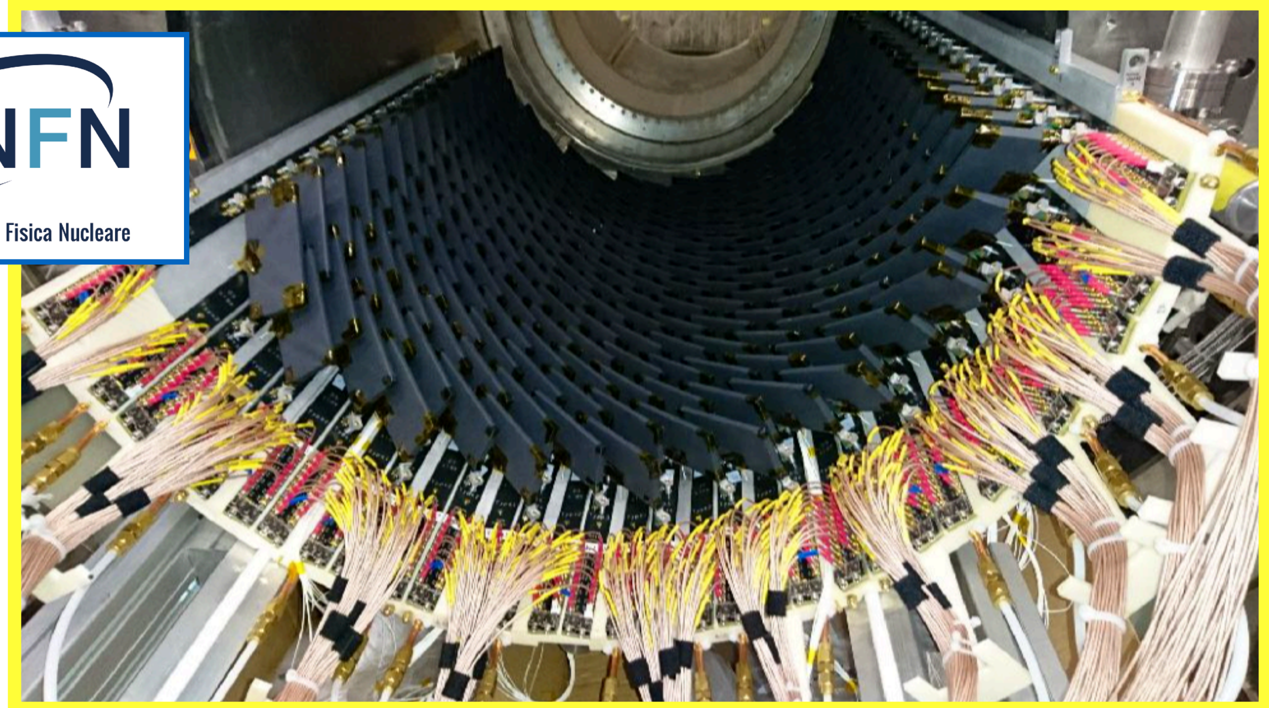
Timing Counter



512 **plastic scintillator** tiles with SiPMs.

T_e

The MEG II Experiment

LXe

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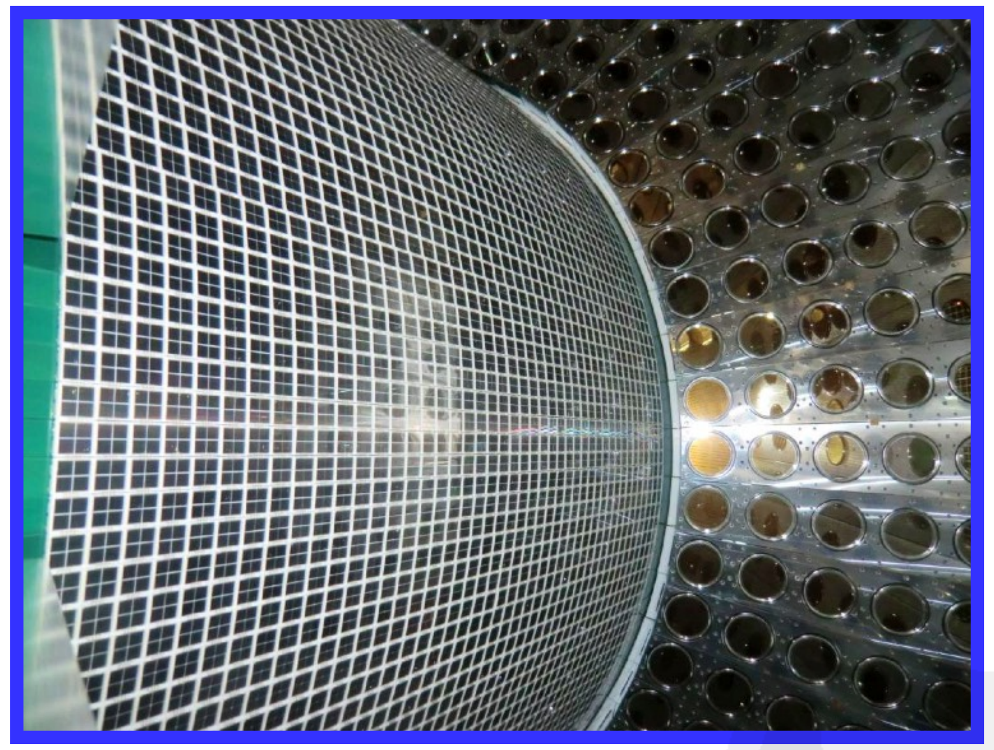

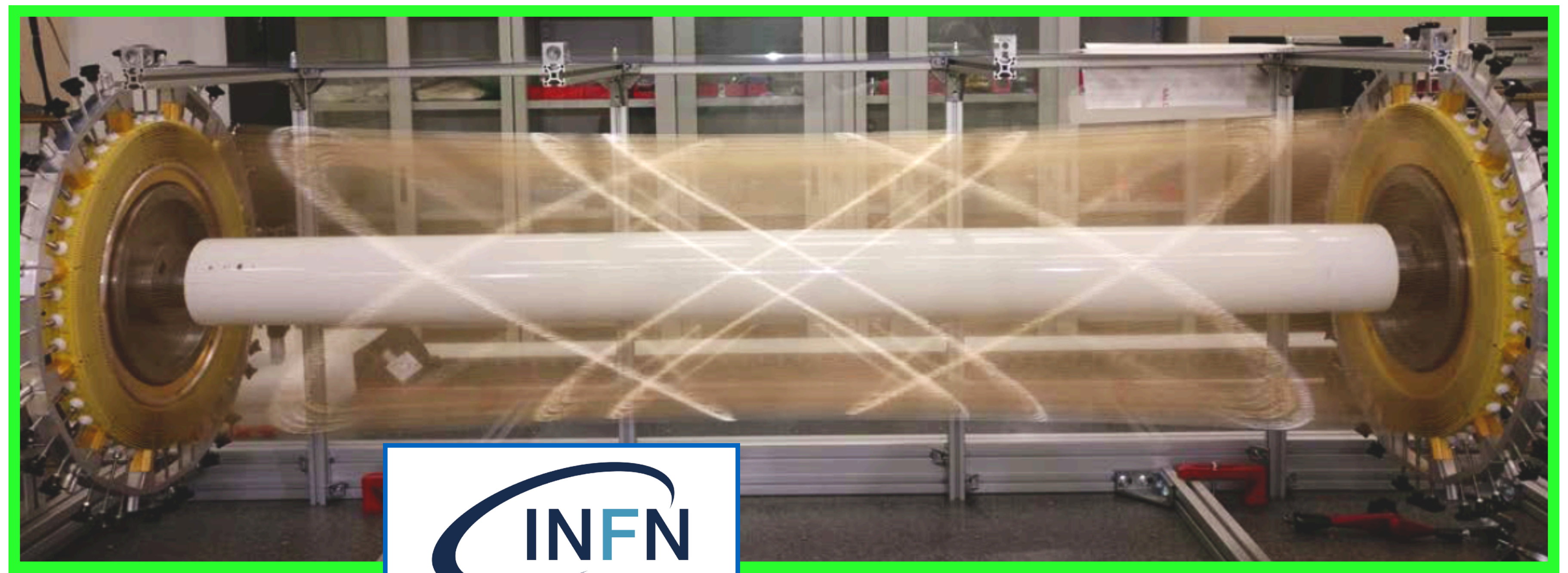

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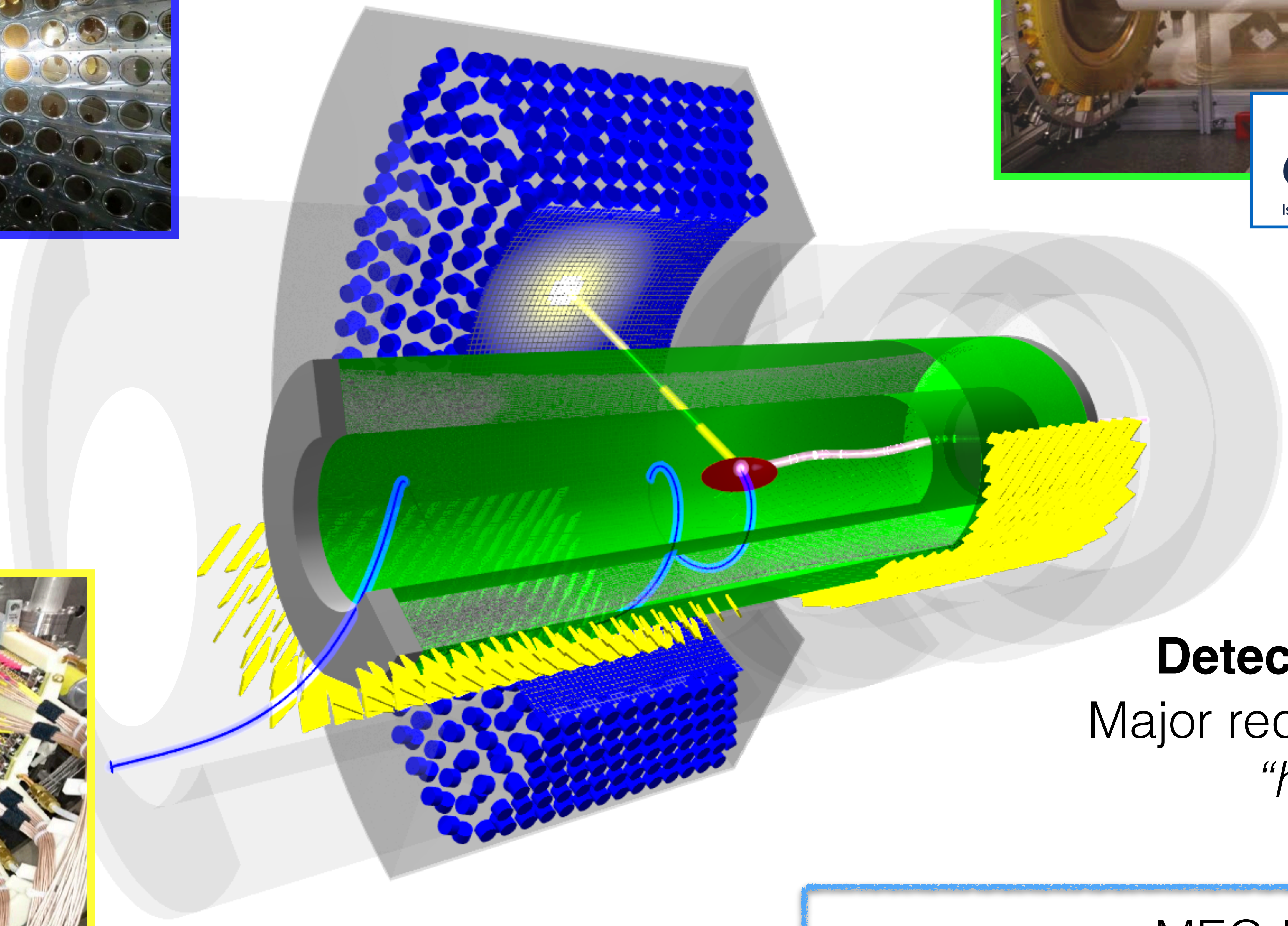

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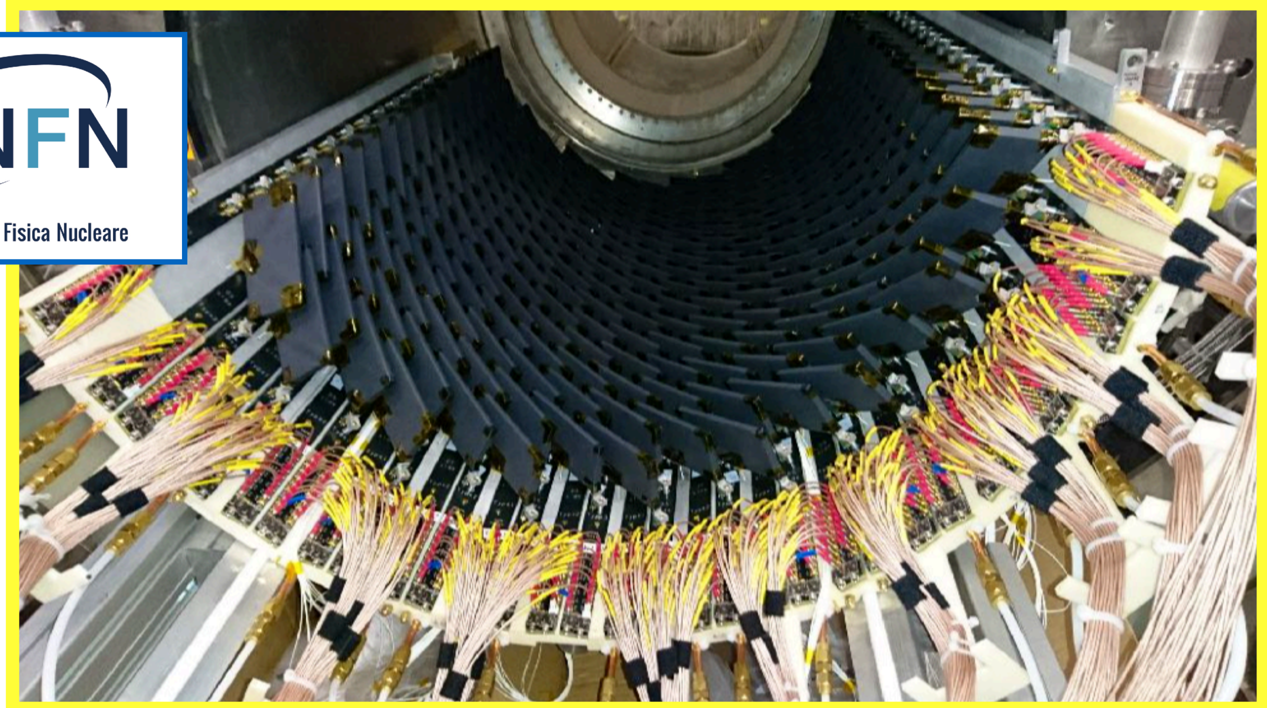

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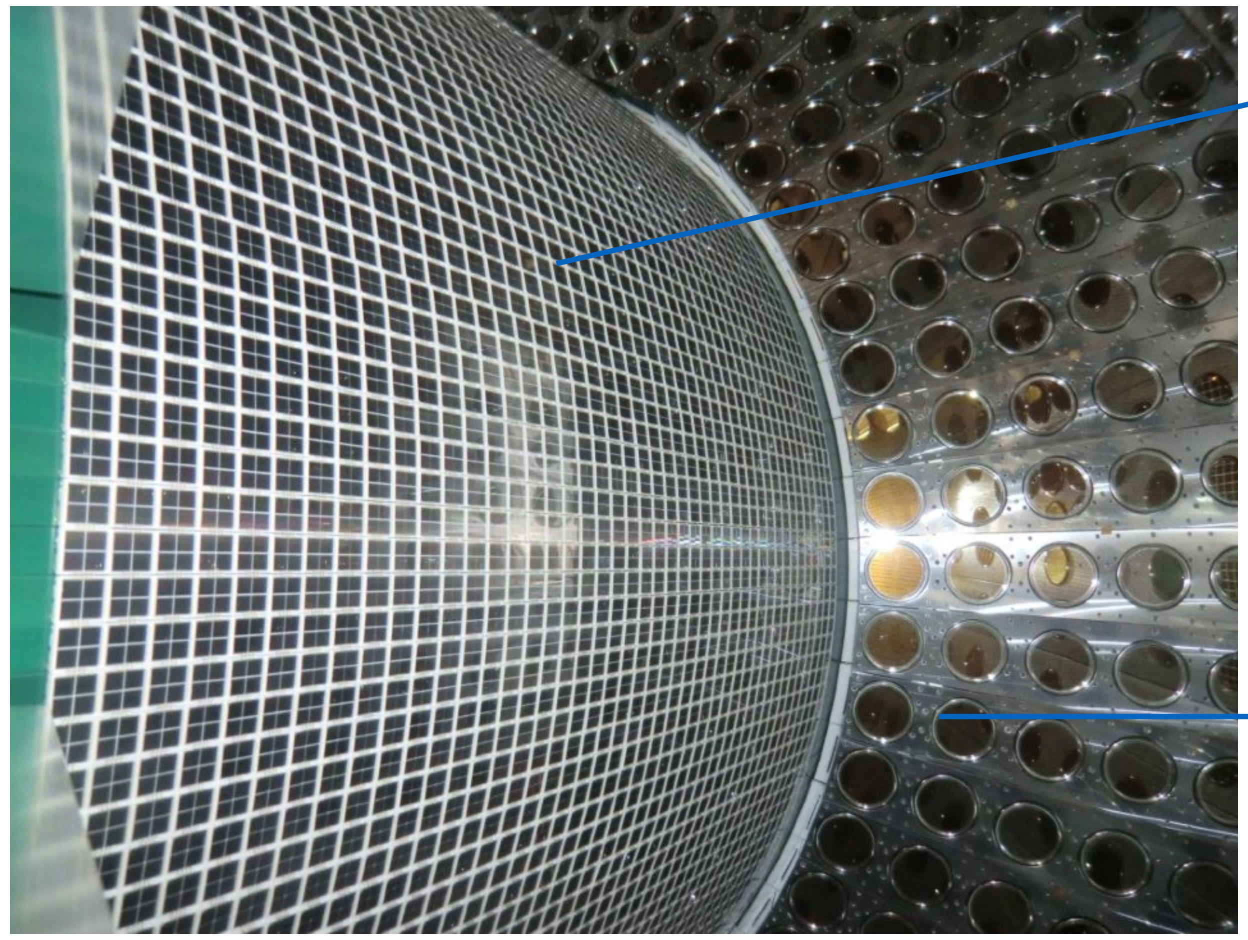
MEG II final Sensitivity

$$\mathrm{BR}(\mu^+ \rightarrow e^+ + \gamma) \leq 6 \cdot 10^{-14}\ (@\ 90\,\%\ C.L.)$$

Photon detector: the Liquid Xenon detector

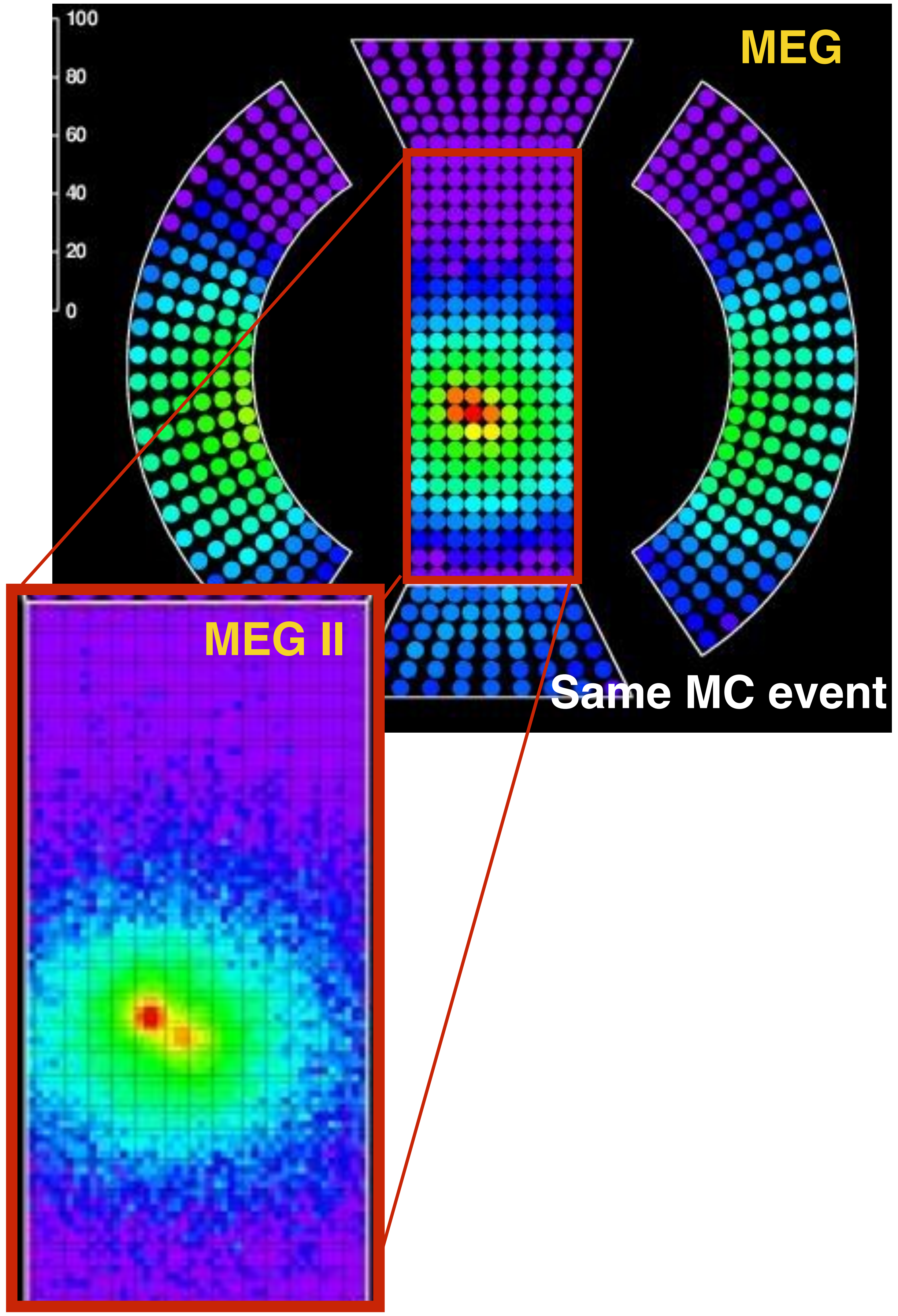


4092 VUV-sensitive SiPMs 12mmx12mm

optimised positions of the remaining 668 PMTs

Key factors:
- High granularity
- Pileup rejection capability
- Energy reconstruction uniformity

	MEG	MEG II design	MEG II current
Position	5 mm	2.4 mm	2.4 mm
Energy	2.4%-1.7%	1.1%-1.0%	1.7%
Timing	67 ps	50 ps	62 ps



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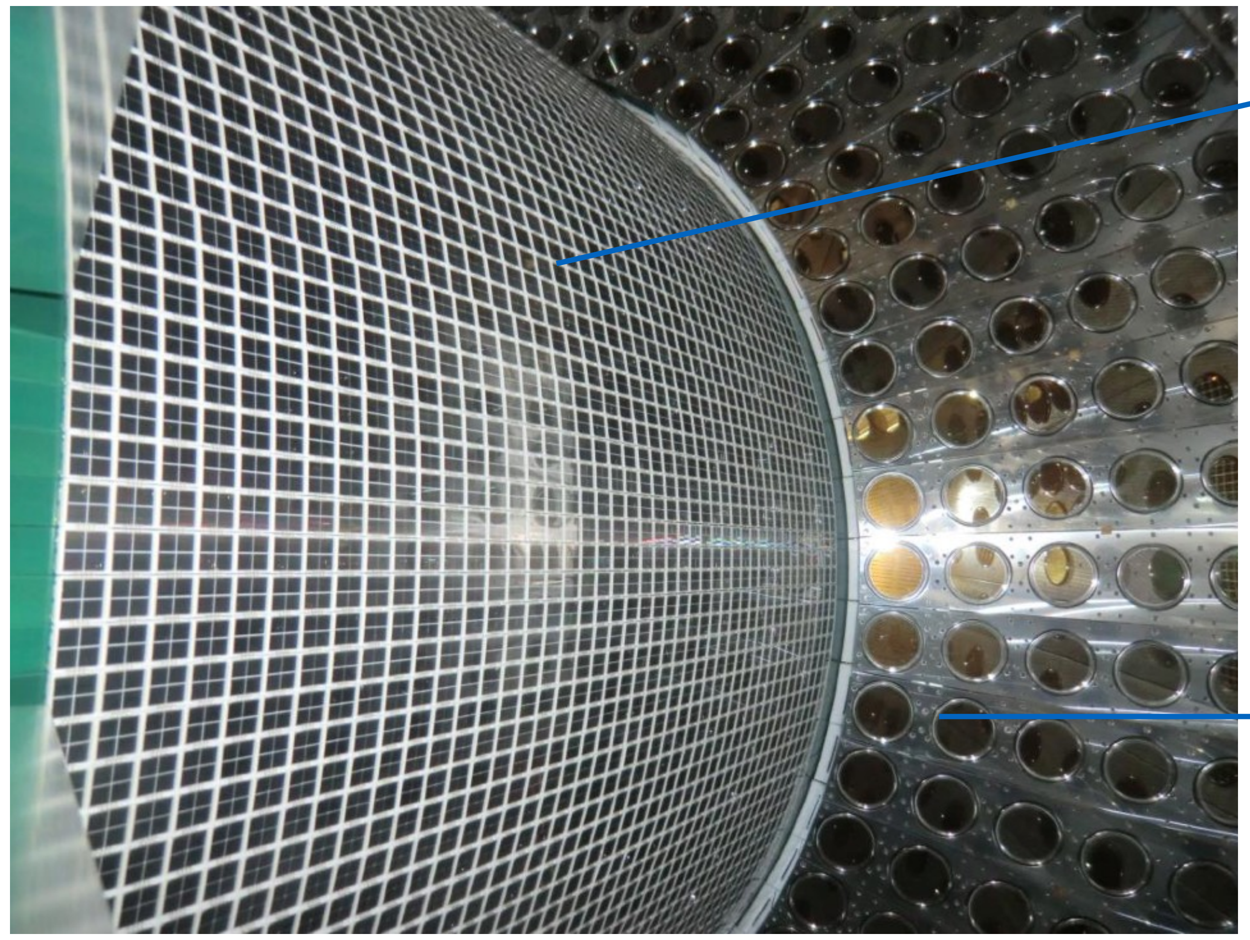

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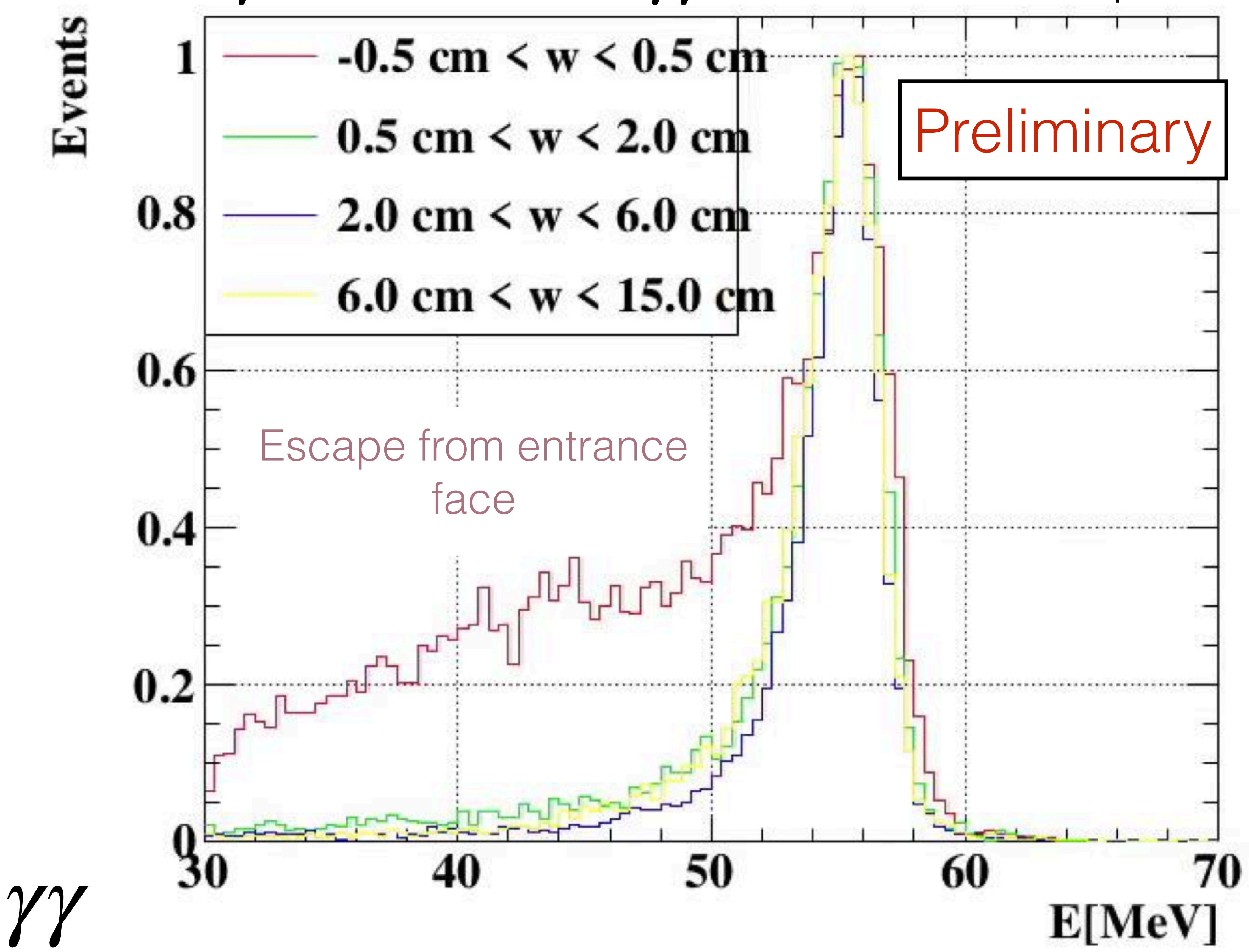
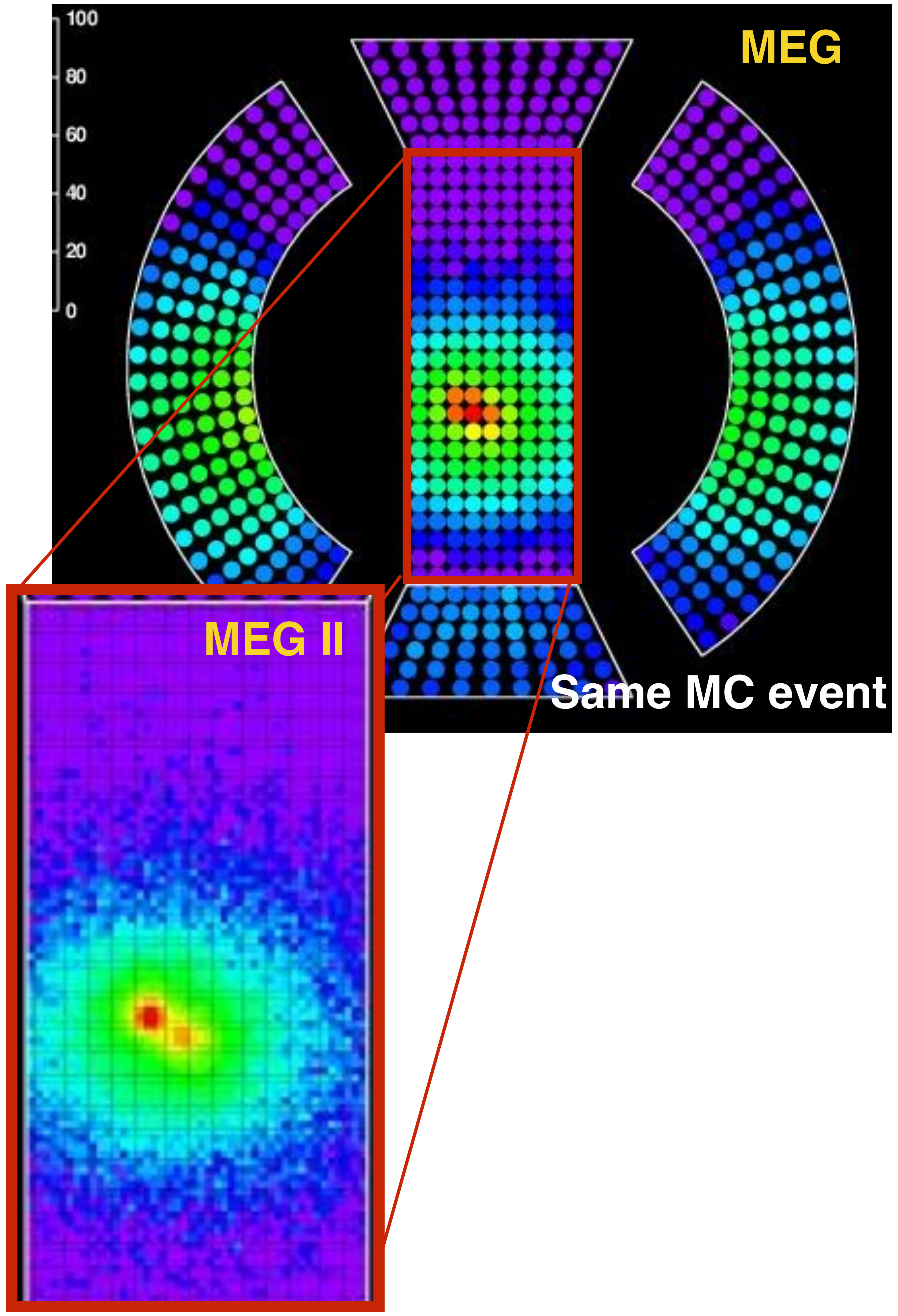
Measure energy response through
Charge Exchange reaction

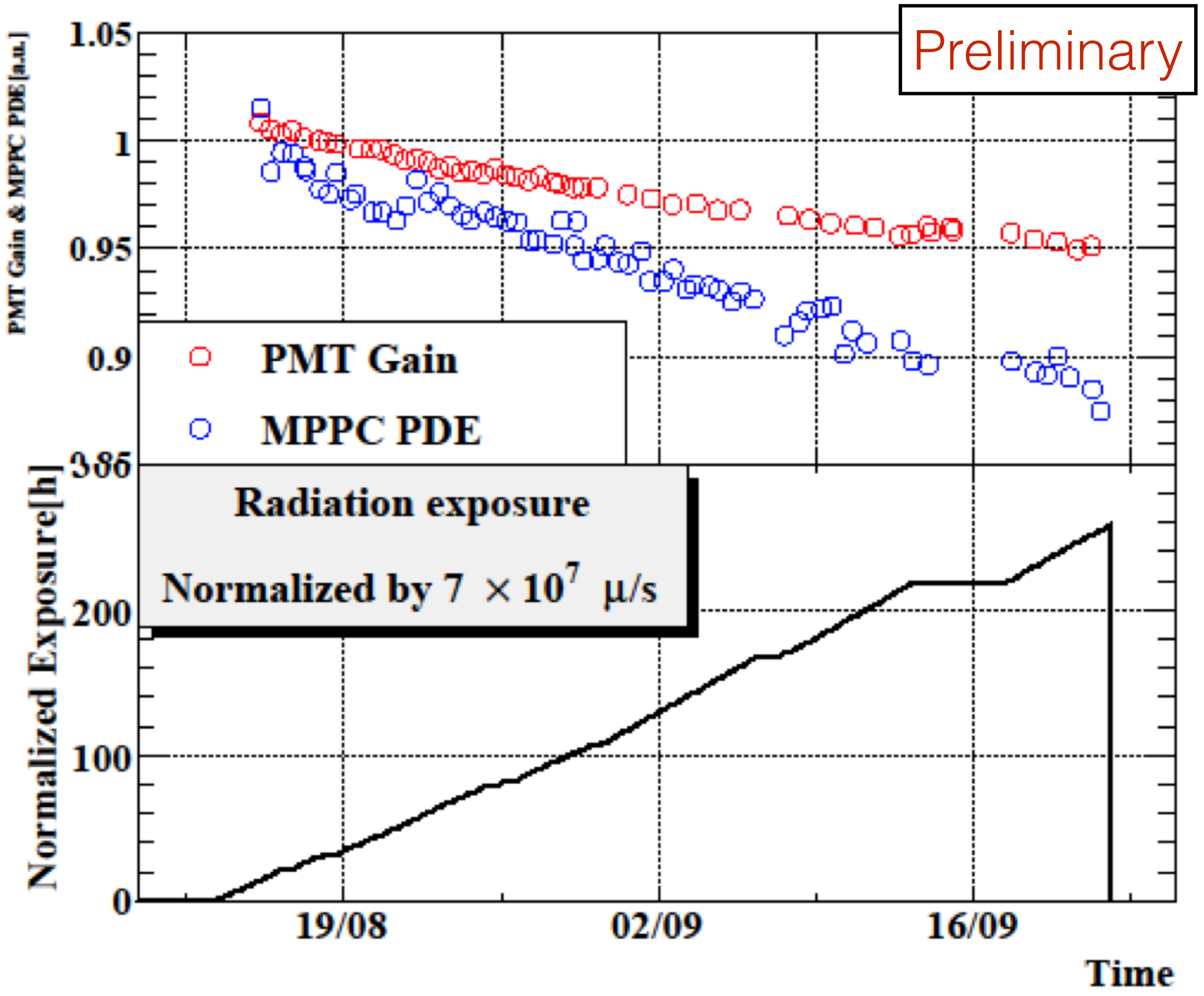
$$\pi^- p \rightarrow \pi^0 n$$
$$\hookrightarrow \pi^0 \rightarrow \gamma\gamma$$

γ line from $\pi^0 \rightarrow \gamma\gamma$ vs interaction depth



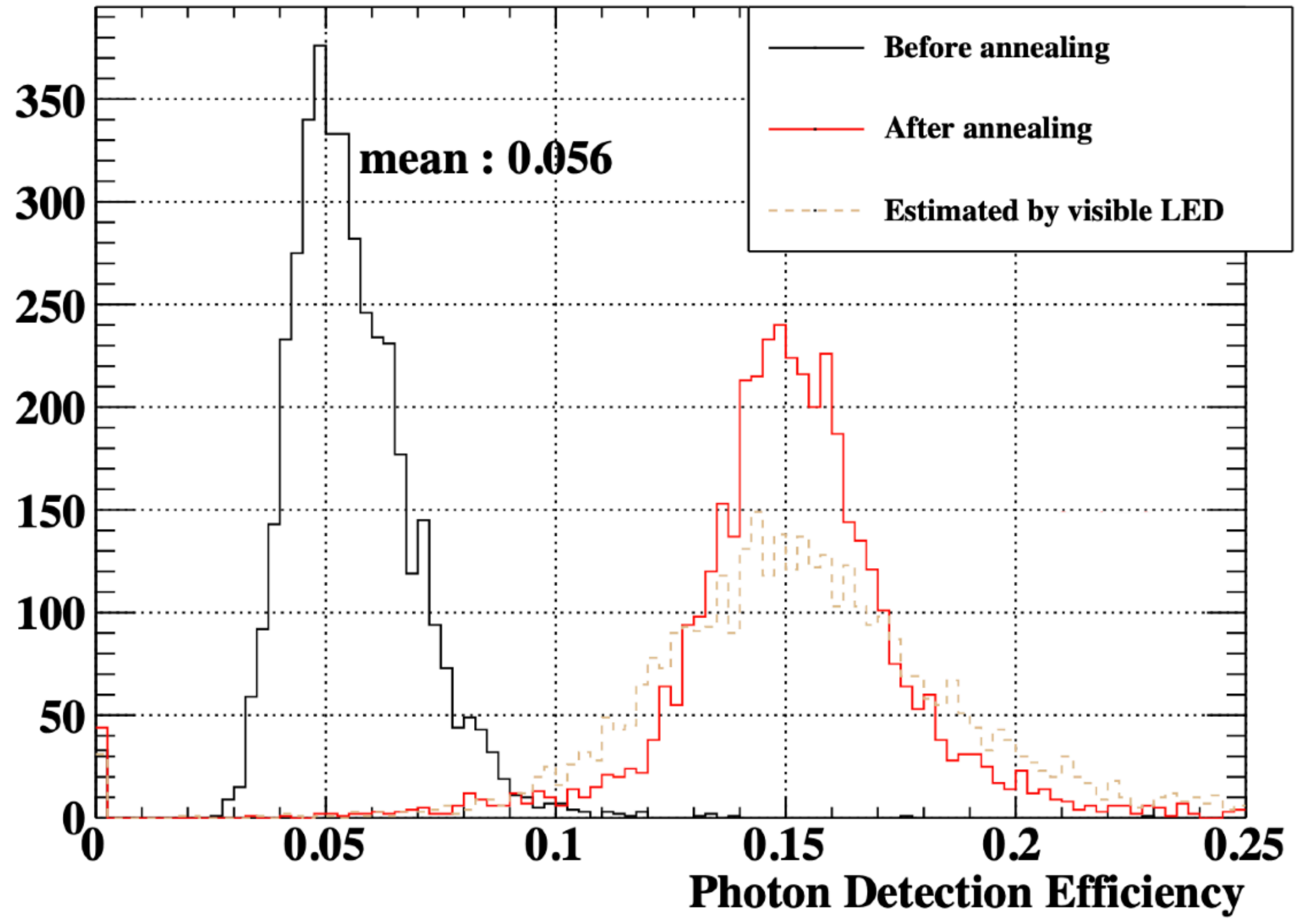


Liquid Xenon detector calibrations



Loss of SiPM Photon Detection Efficiency and PMT Gain due to **ageing effects**

MPPC PDE: -0.04%/beam hour
PMT Gain: -0.02%/beam hour
at 7 10^7 mu/s



PDE is recovered after thermal annealing

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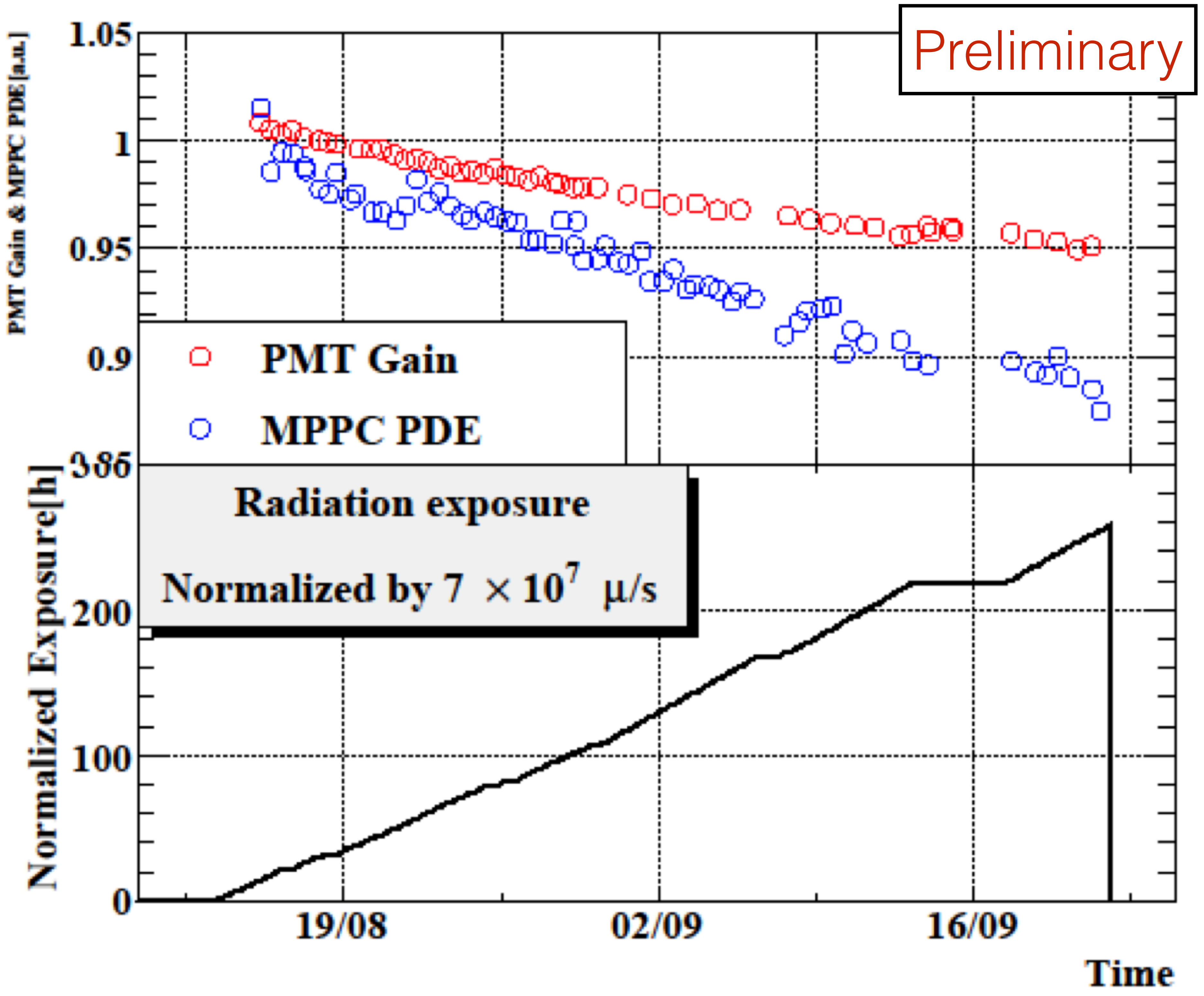

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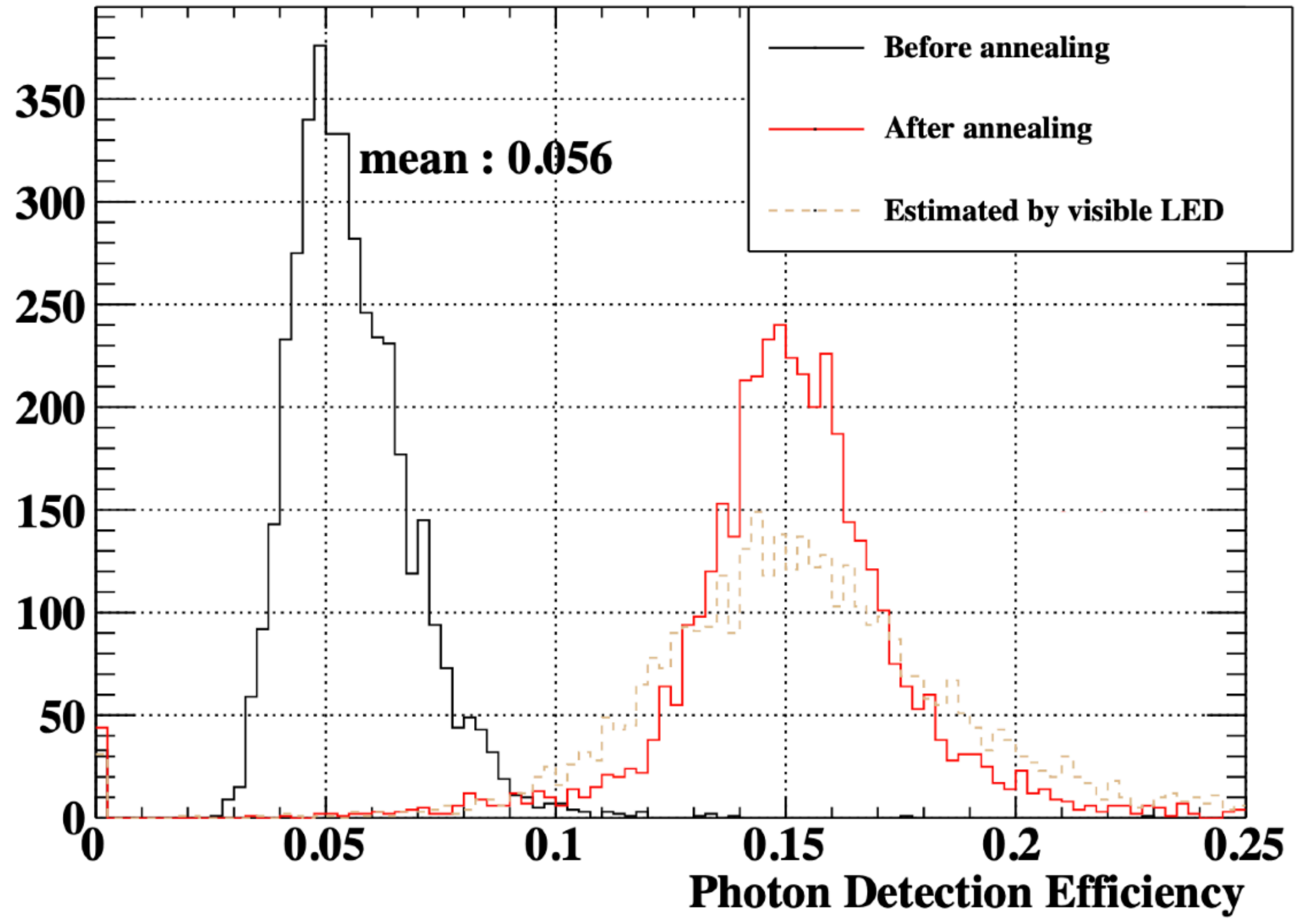
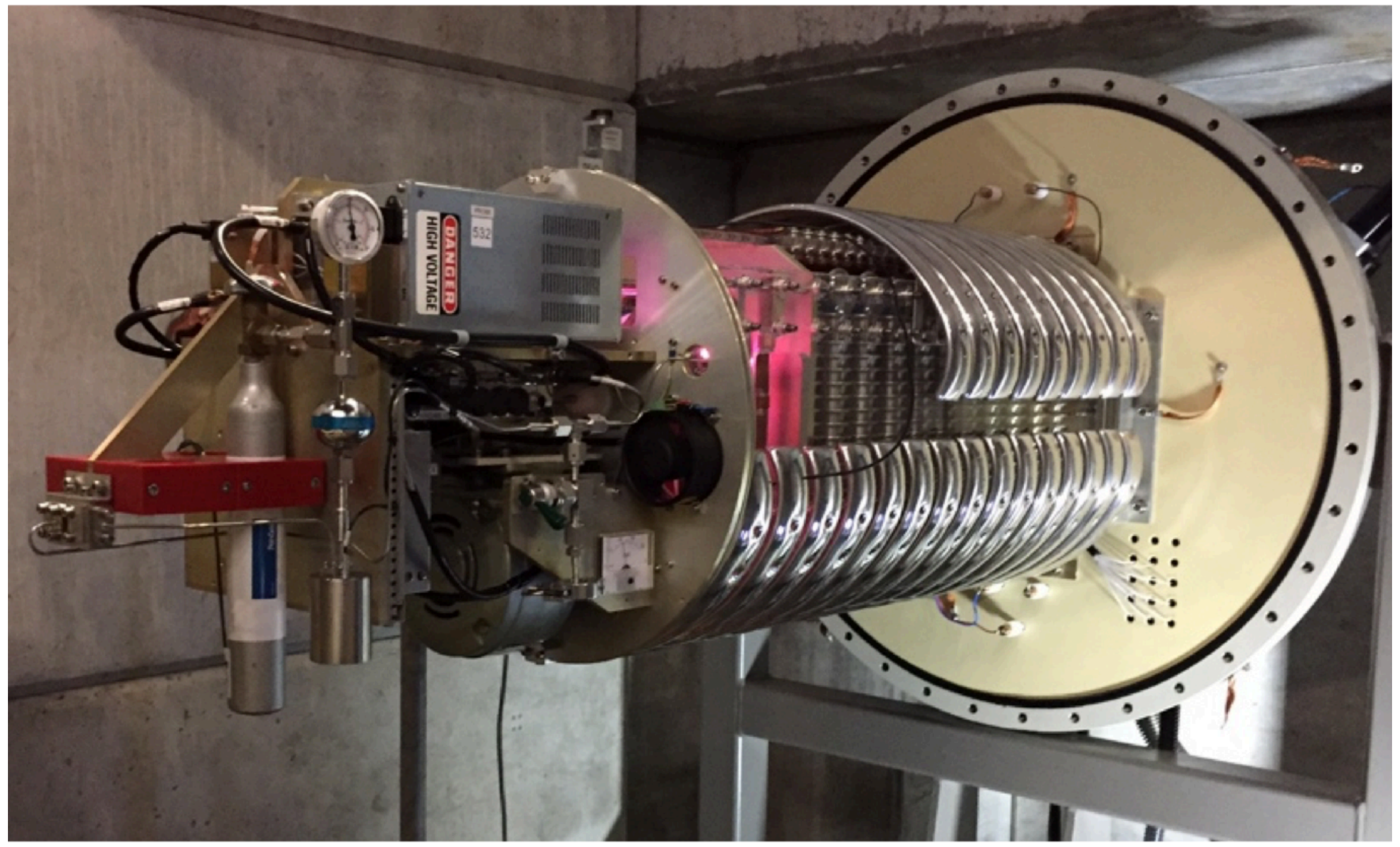


PDE is recovered after thermal annealing

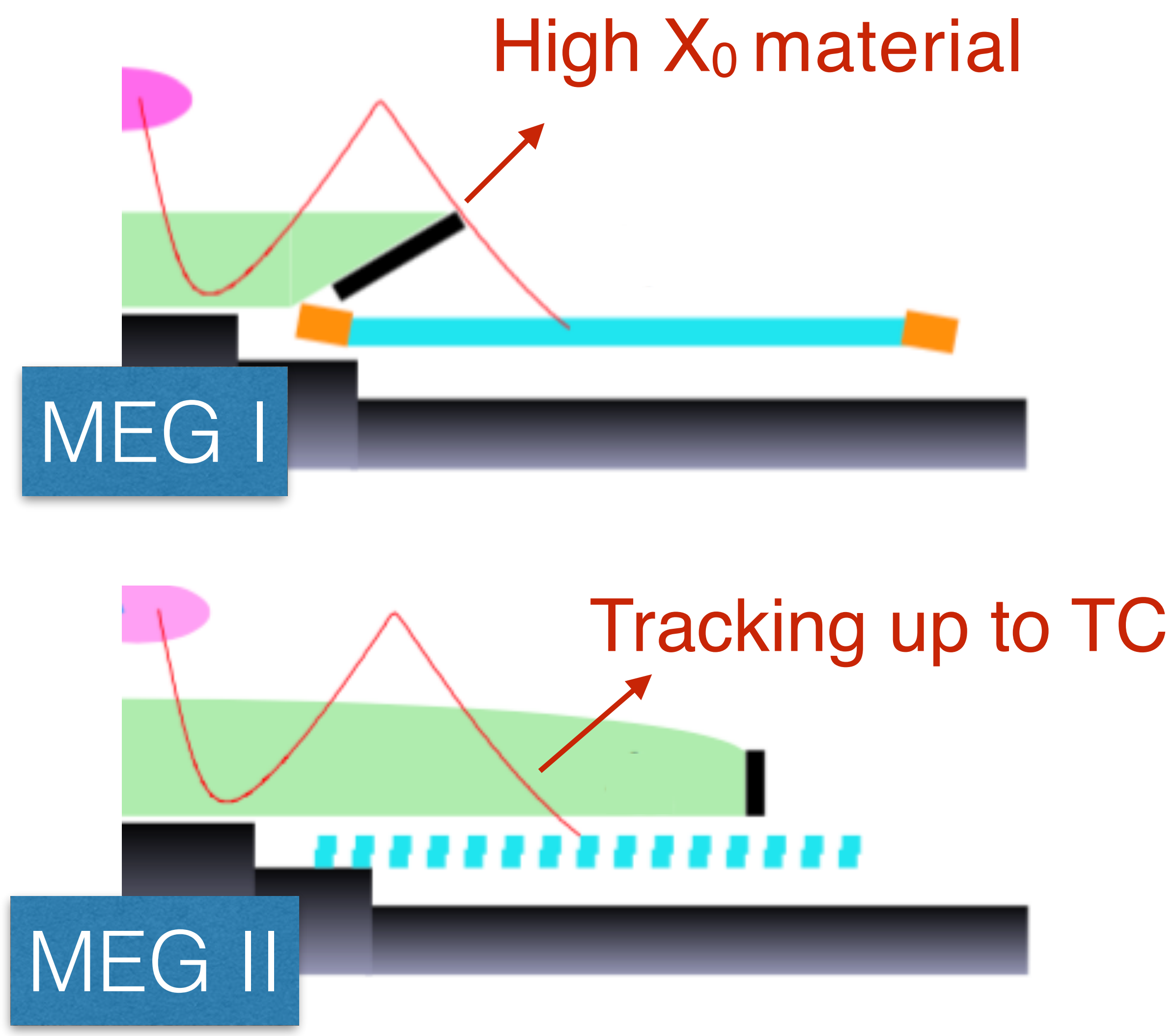
Continuous monitoring and calibration is needed

Can be provided through daily **Cockroft-Walton calibration** runs

$$p\ {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be}\ \gamma(17.6\ \mathrm{MeV})$$
$$p\ {}^{11}\mathrm{B} \rightarrow {}^{12}\mathrm{C}\ \gamma(11.6\ \mathrm{MeV})\ \gamma(4.4\ \mathrm{MeV})$$

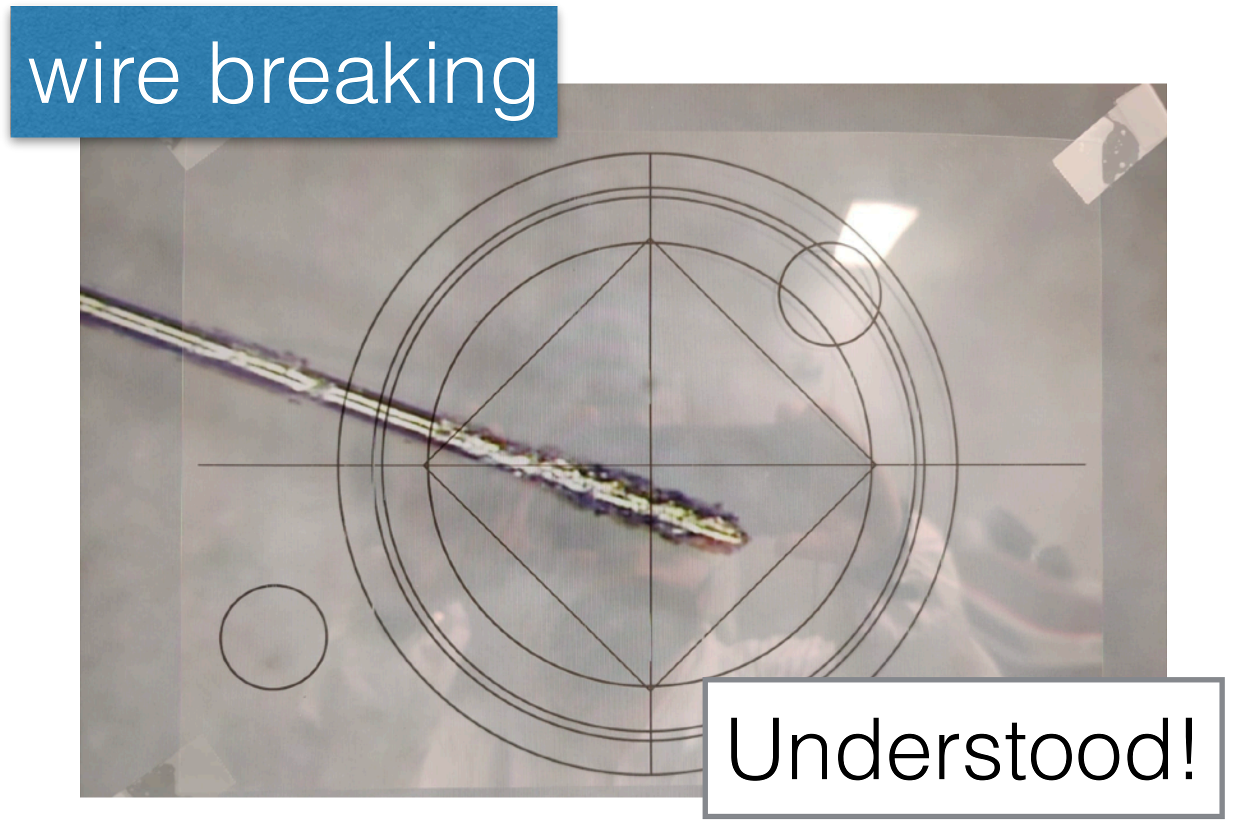


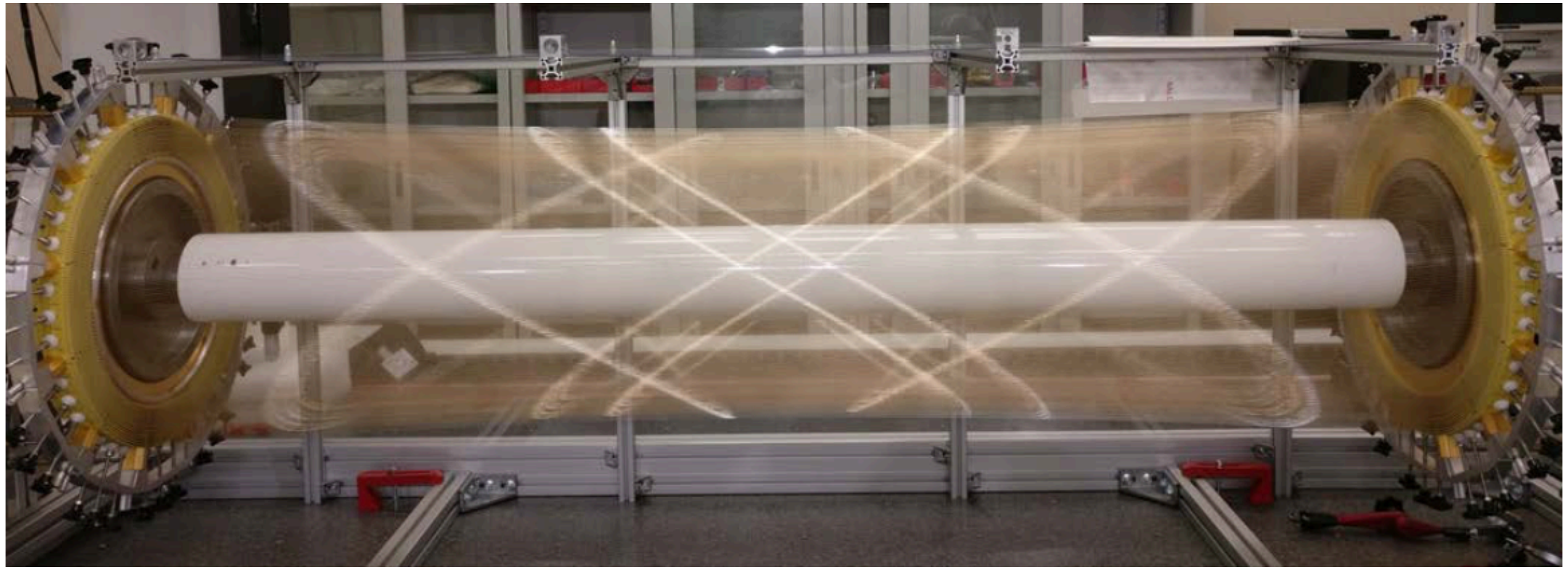
The Cylindrical Drift Chamber



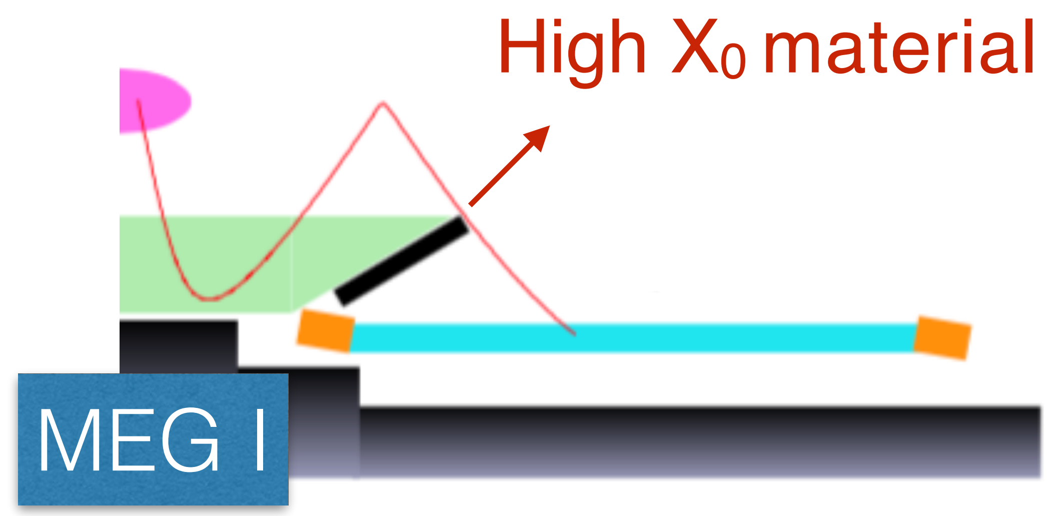
Single volume stereo drift chamber with He:Isobutane

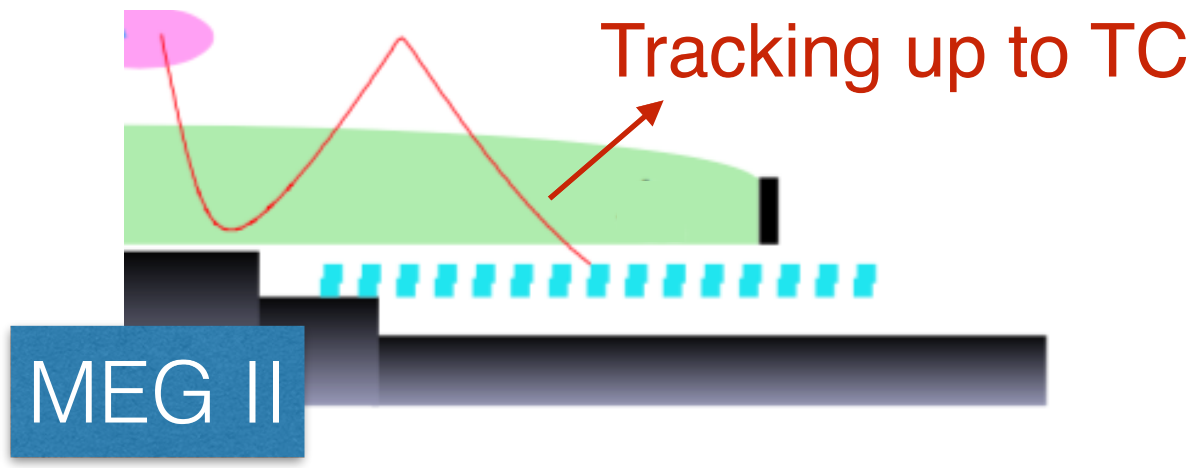
- 1.5 10^{-3} X_0 per turn
- Drift cells 6mm x 6mm to cope with pileup. (PCB-based construction)
- ~65 hits per track (MEG: ~12)





The Cylindrical Drift Chamber

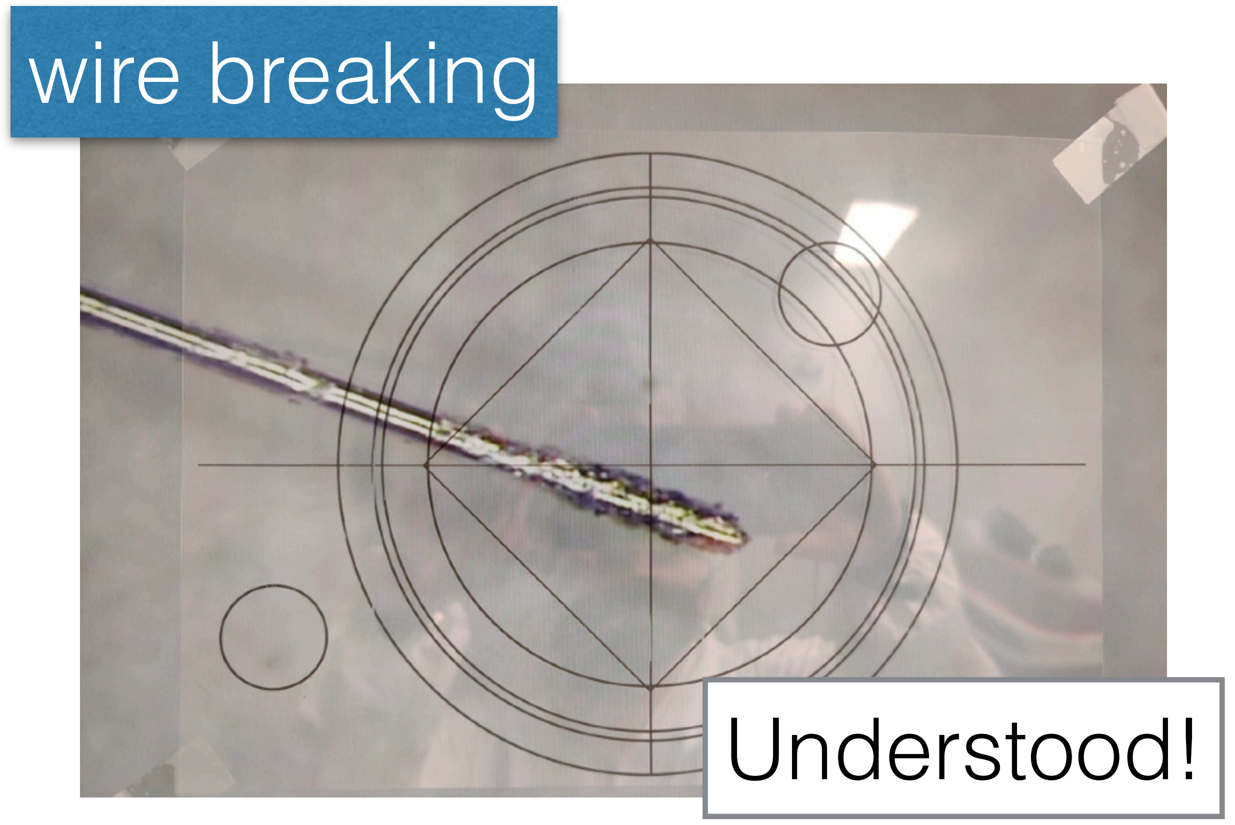




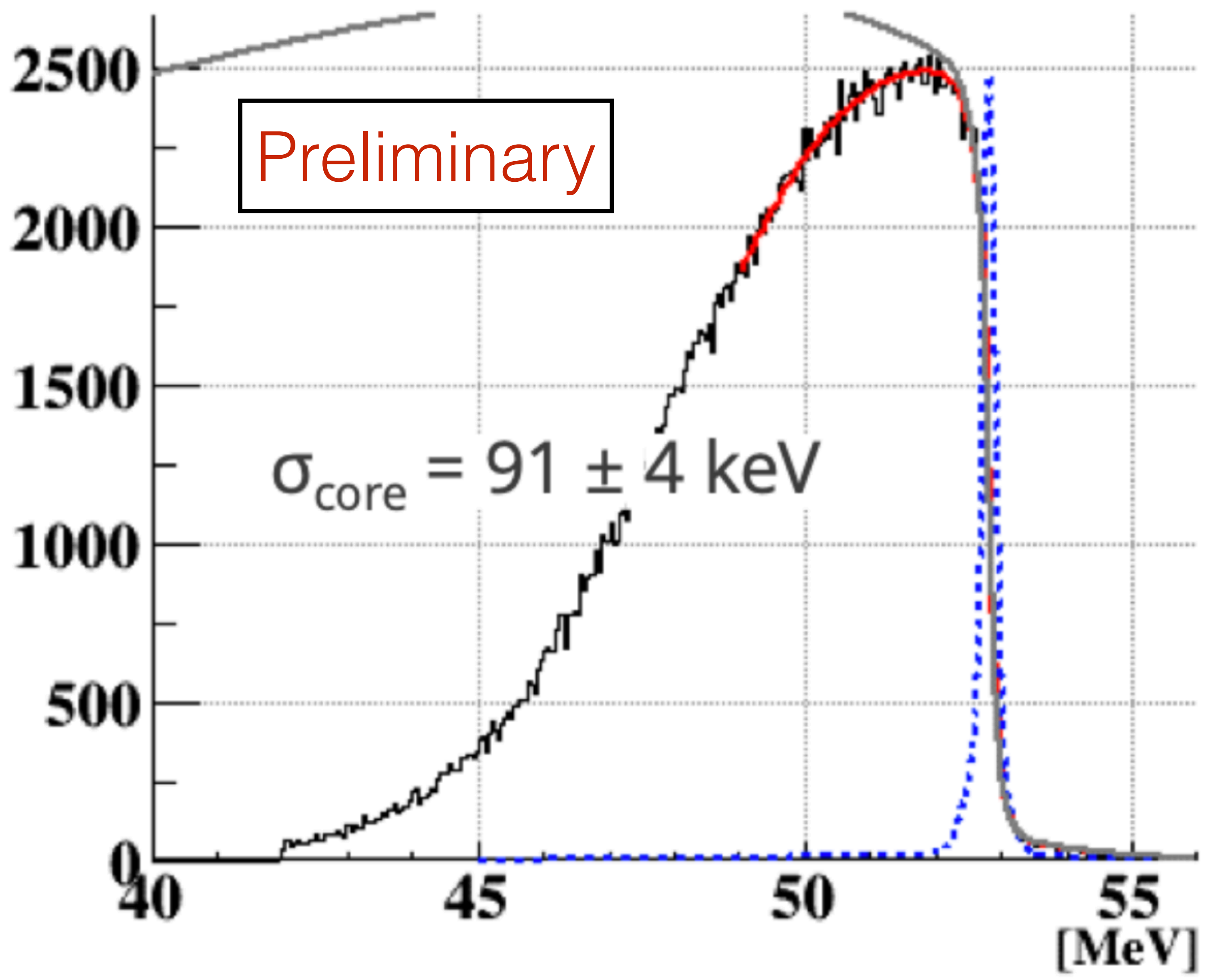
Single volume stereo drift chamber with He:Isobutane

- 1.5 10^{-3} X_0 per turn
- Drift cells 6mm x 6mm to cope with pileup. (PCB-based construction)
- ~65 hits per track (MEG: ~12)

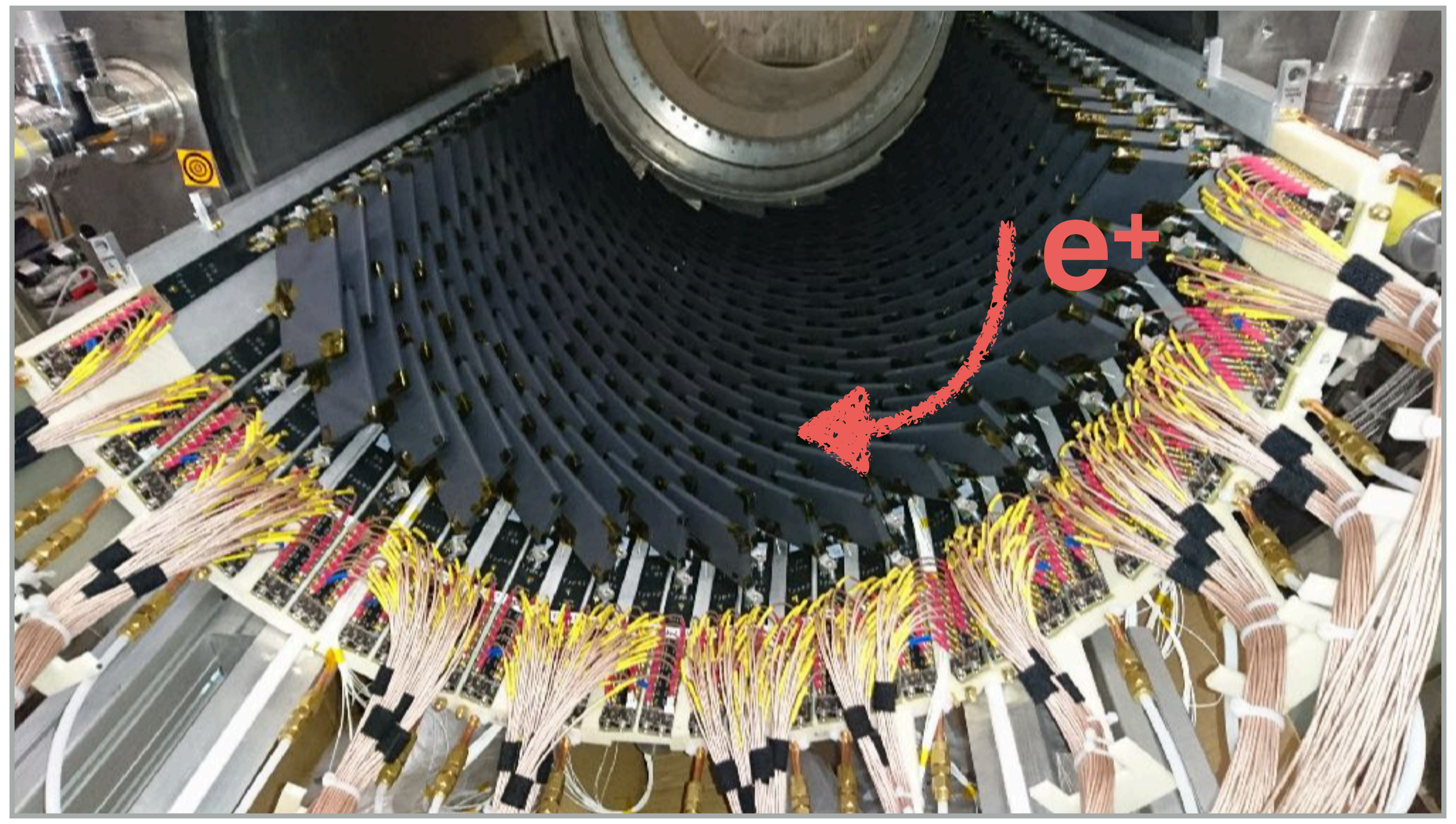
	MEG	MEG II design	MEG II current
Efficiency	29%	70%	65%
Theta	9.4 mrad	5.3 mrad	6.7 mrad
Momentum	306 keV/c	130 keV/c	100 keV/c

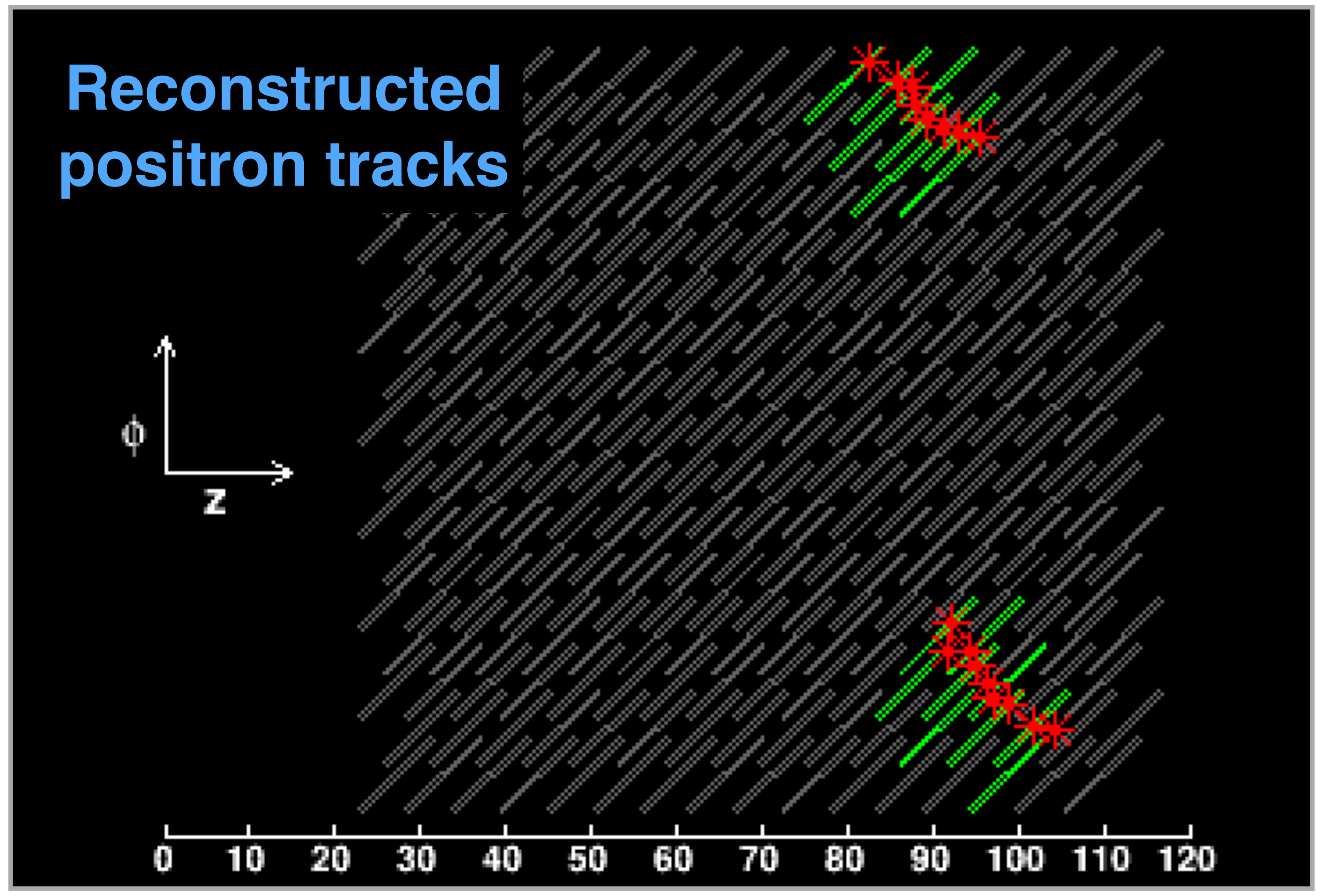


$\mu^+ \rightarrow e^+\nu\bar{\nu}$ kinematic edge fit



The pixelated Timing Counter





Final detector fully tested with **full beam intensity** (7 10^7 μ/s):

- 256 scintillating “Tiles” per module
- Multiple hits belonging to the same **positron track**
- Tracking capability to seed CDCH tracks
- Auxiliary Laser for stability monitoring

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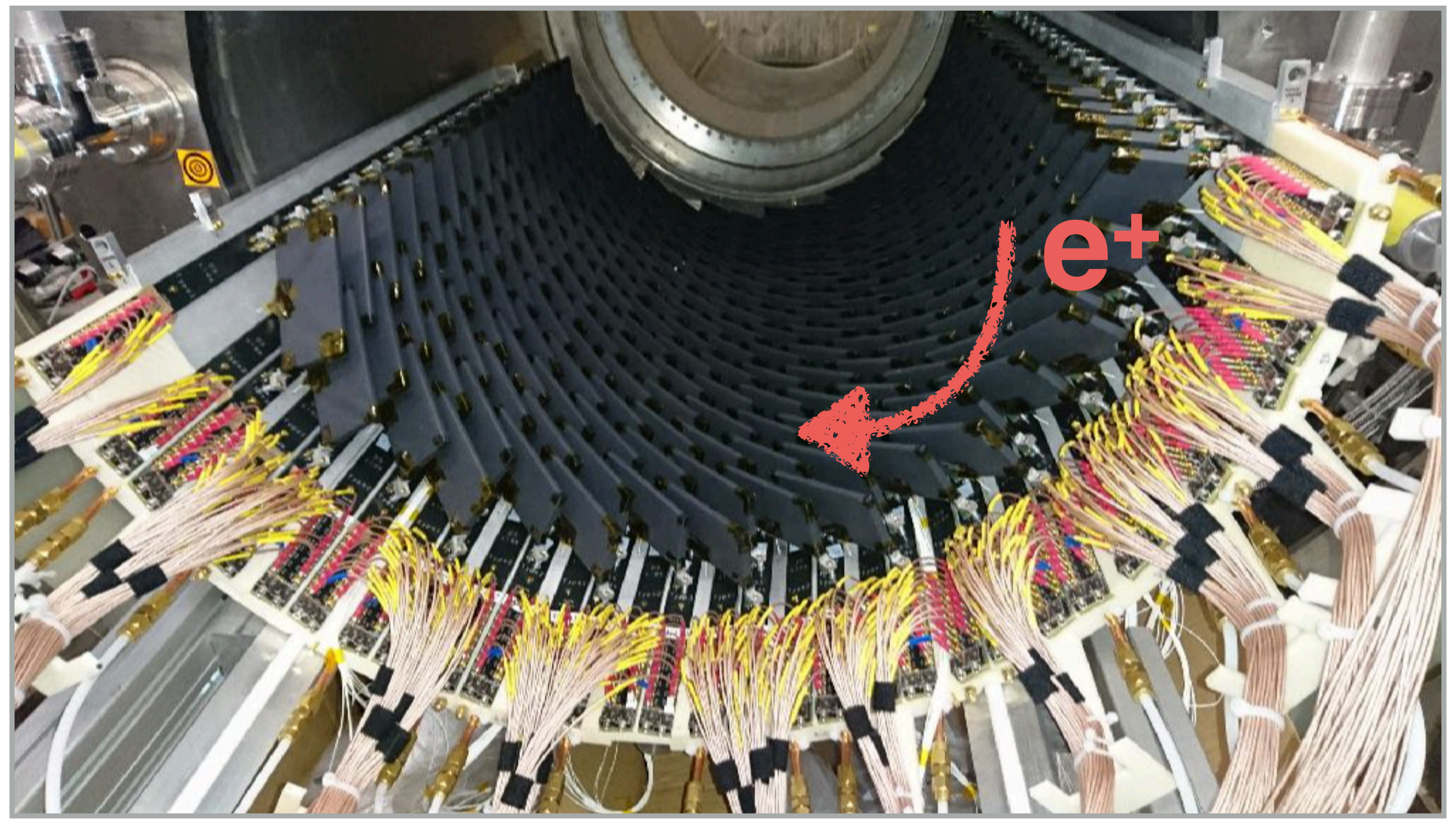

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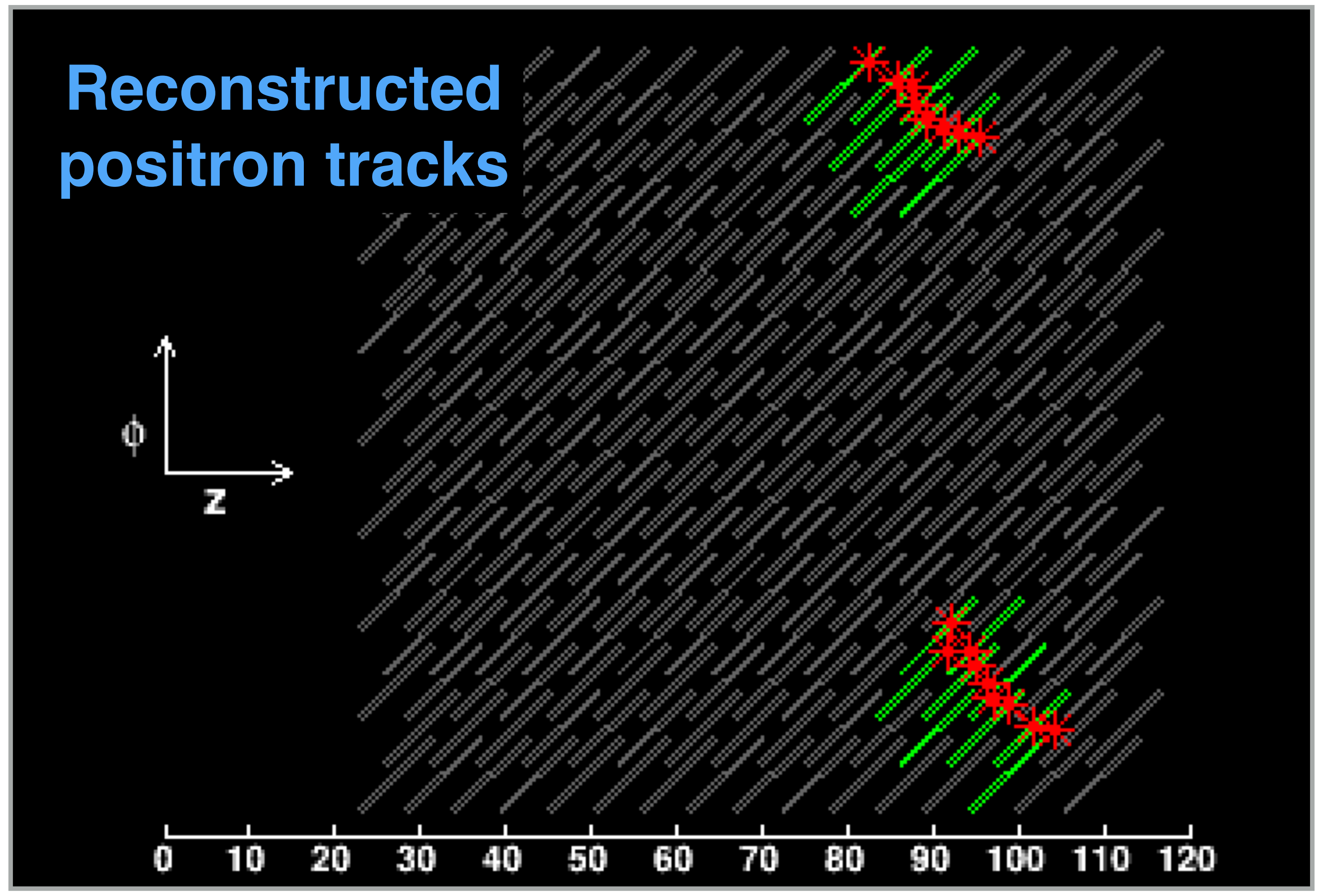

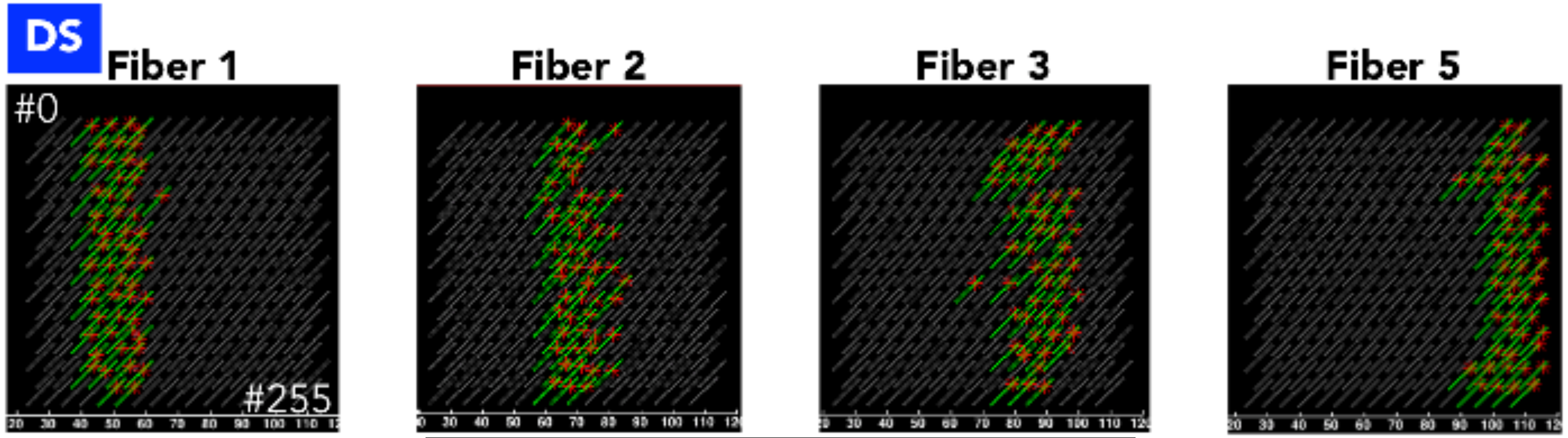

Laser calibration events

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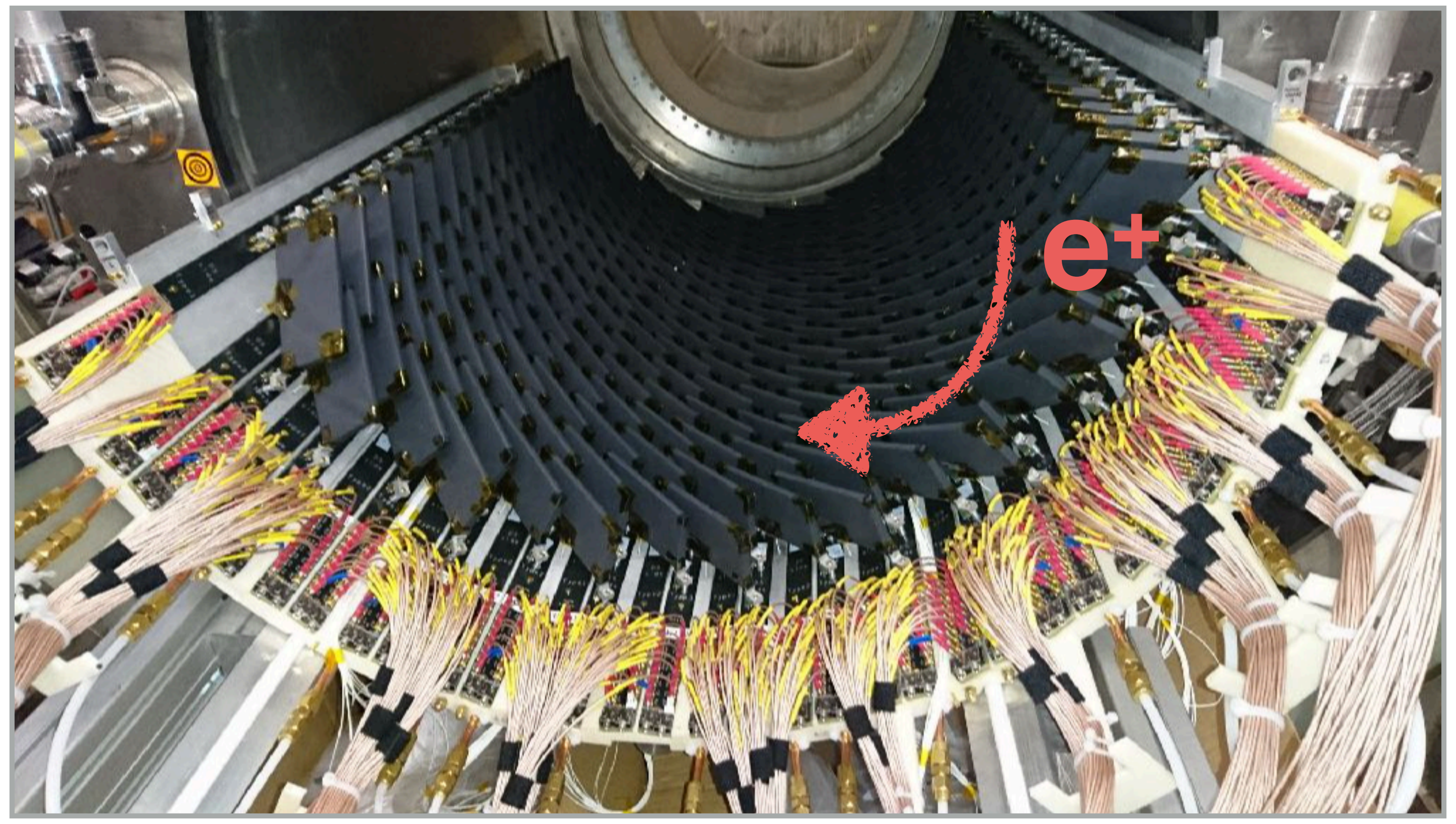

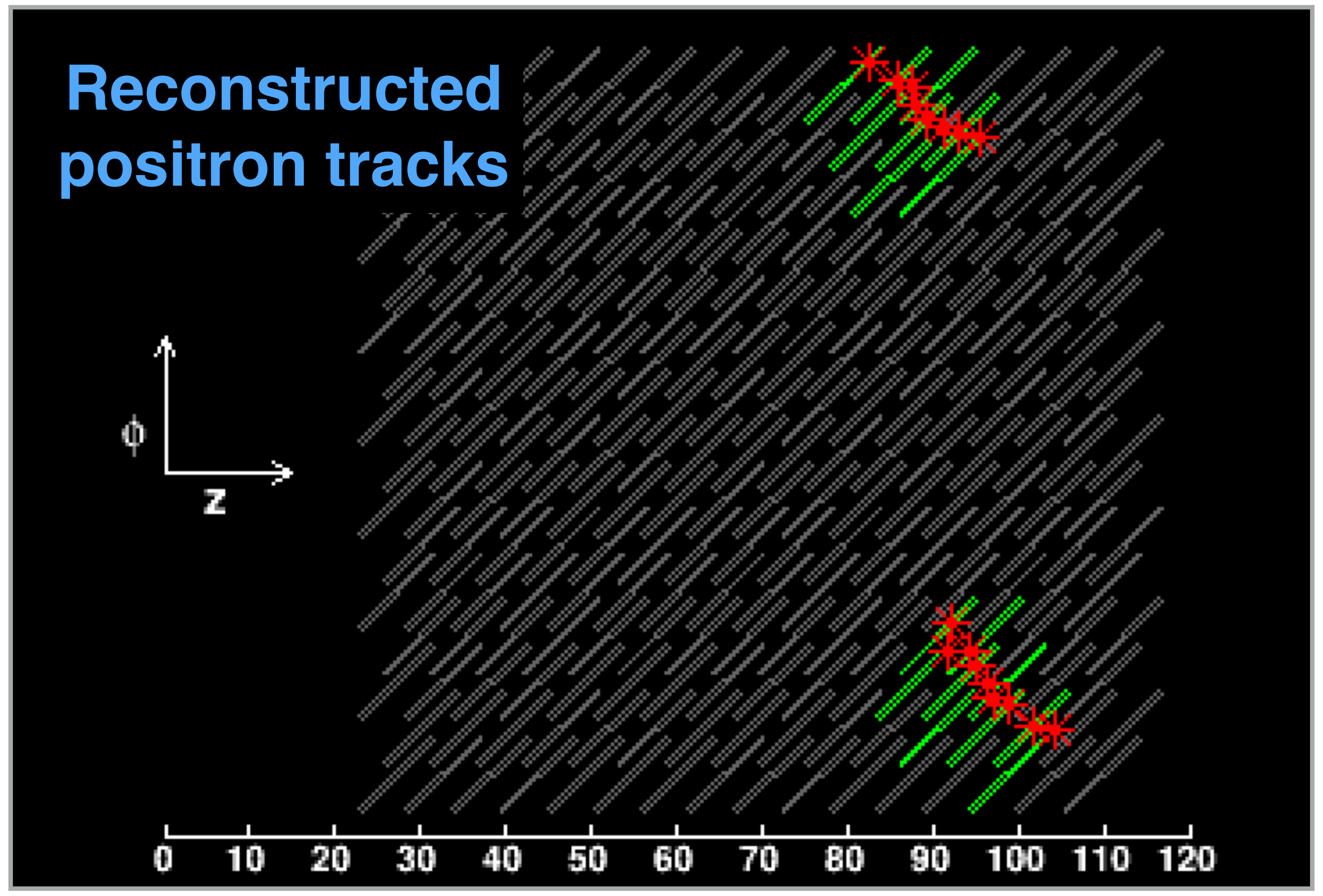

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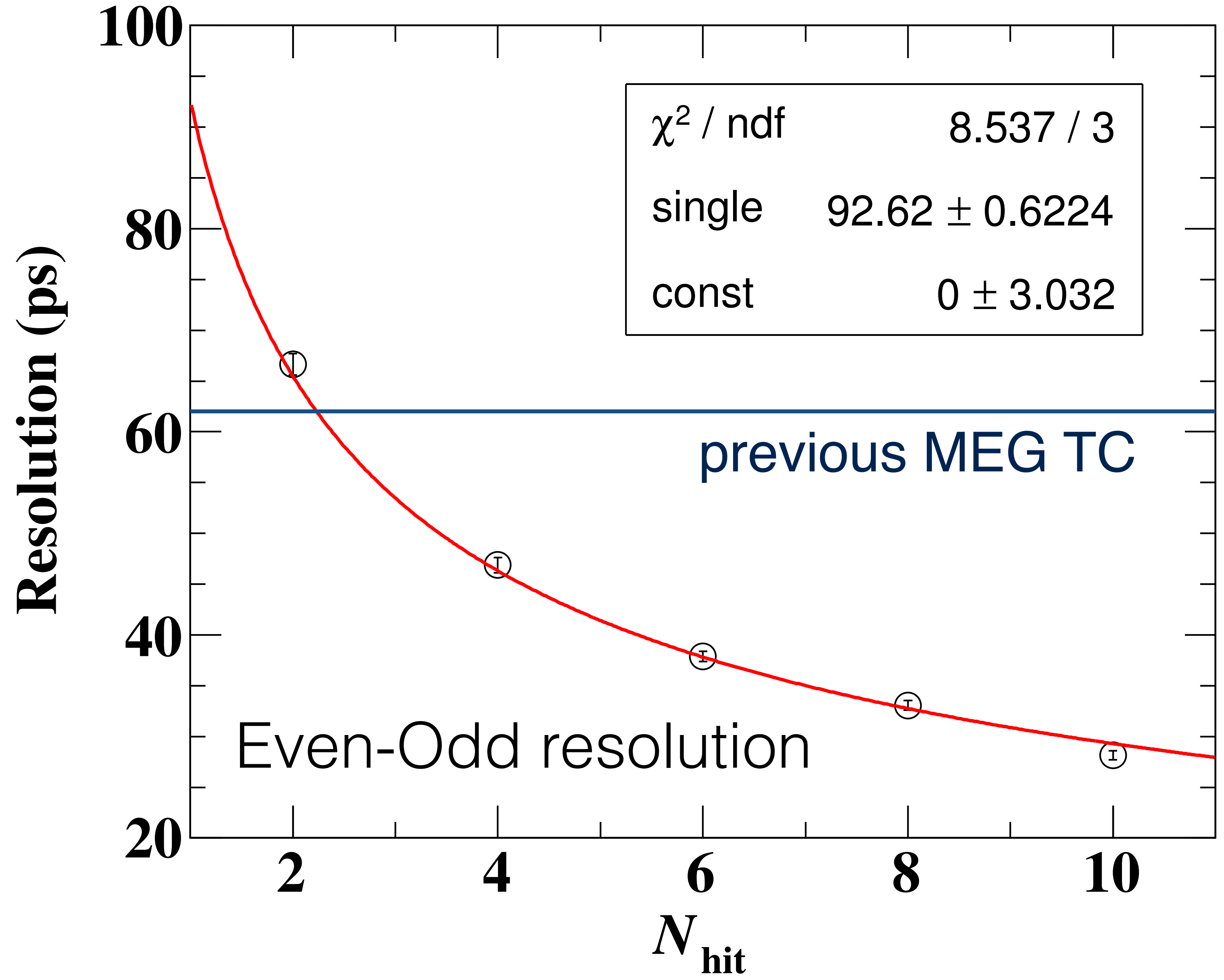
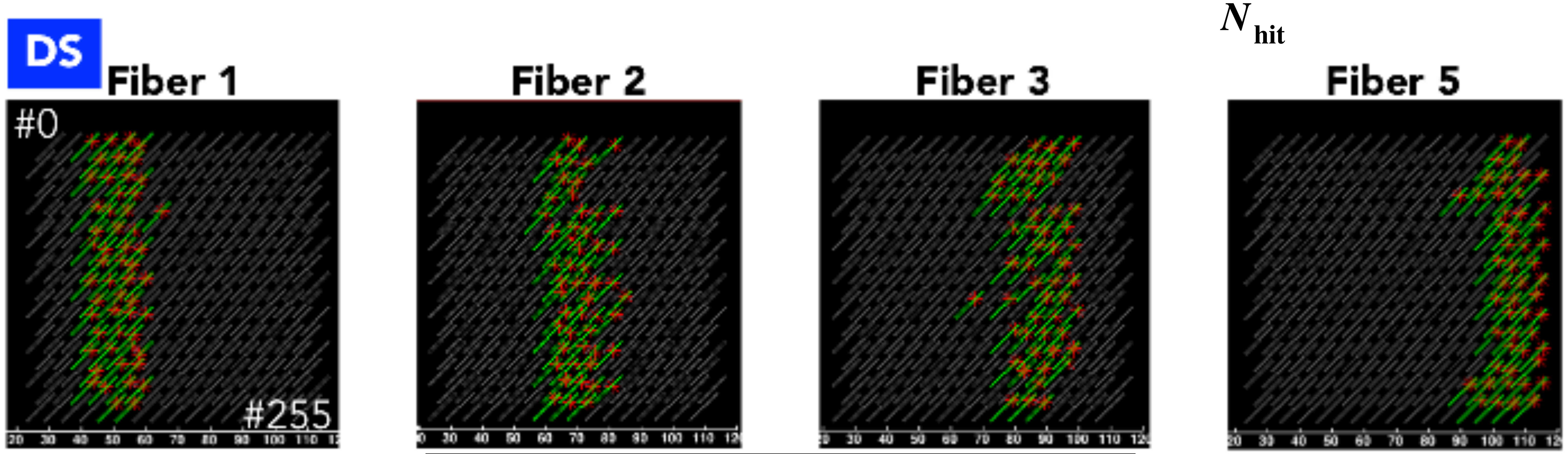
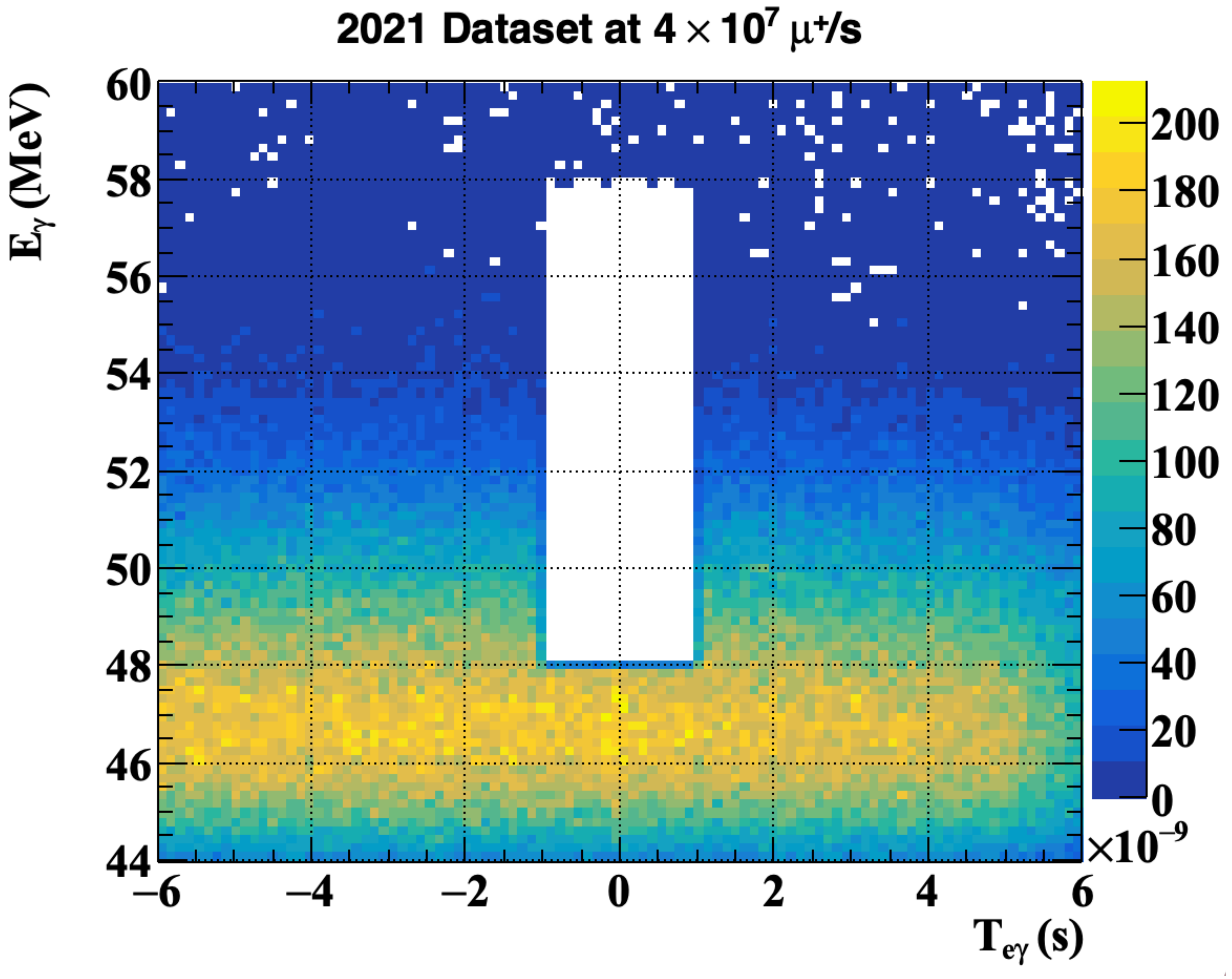




Laser calibration events

2021 Analysis: Blinding Box



Blinding in the $E_\gamma - T_{e\gamma}$ plane applied to 2021 data

Offline reconstruction tuning ongoing

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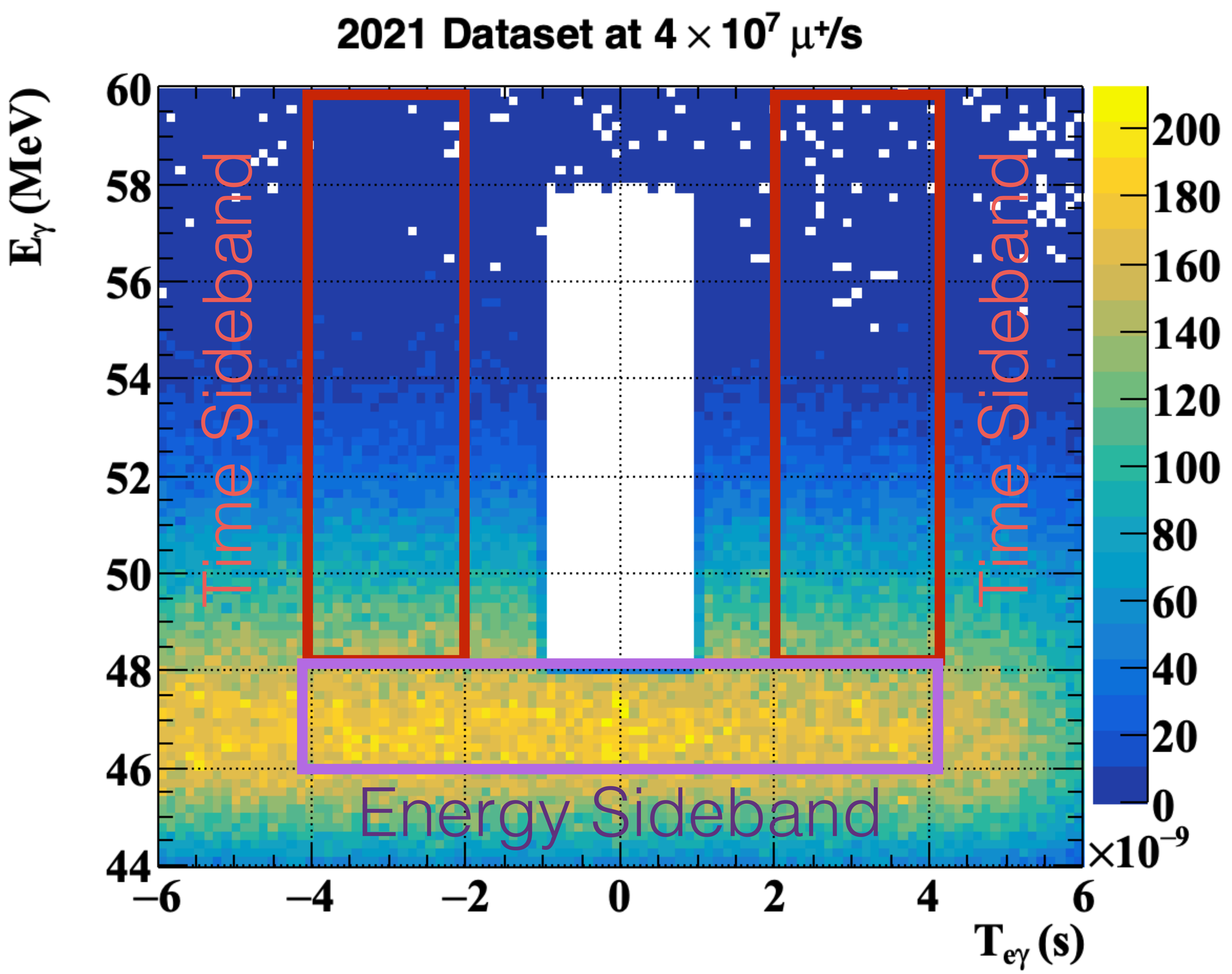

Caveat: Final analysis sidebands defined
when analysis will be frozen

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Signal & Background PDFs fully data-drien:
Will be extracted using **Sidebands** and dedicated **calibration runs**

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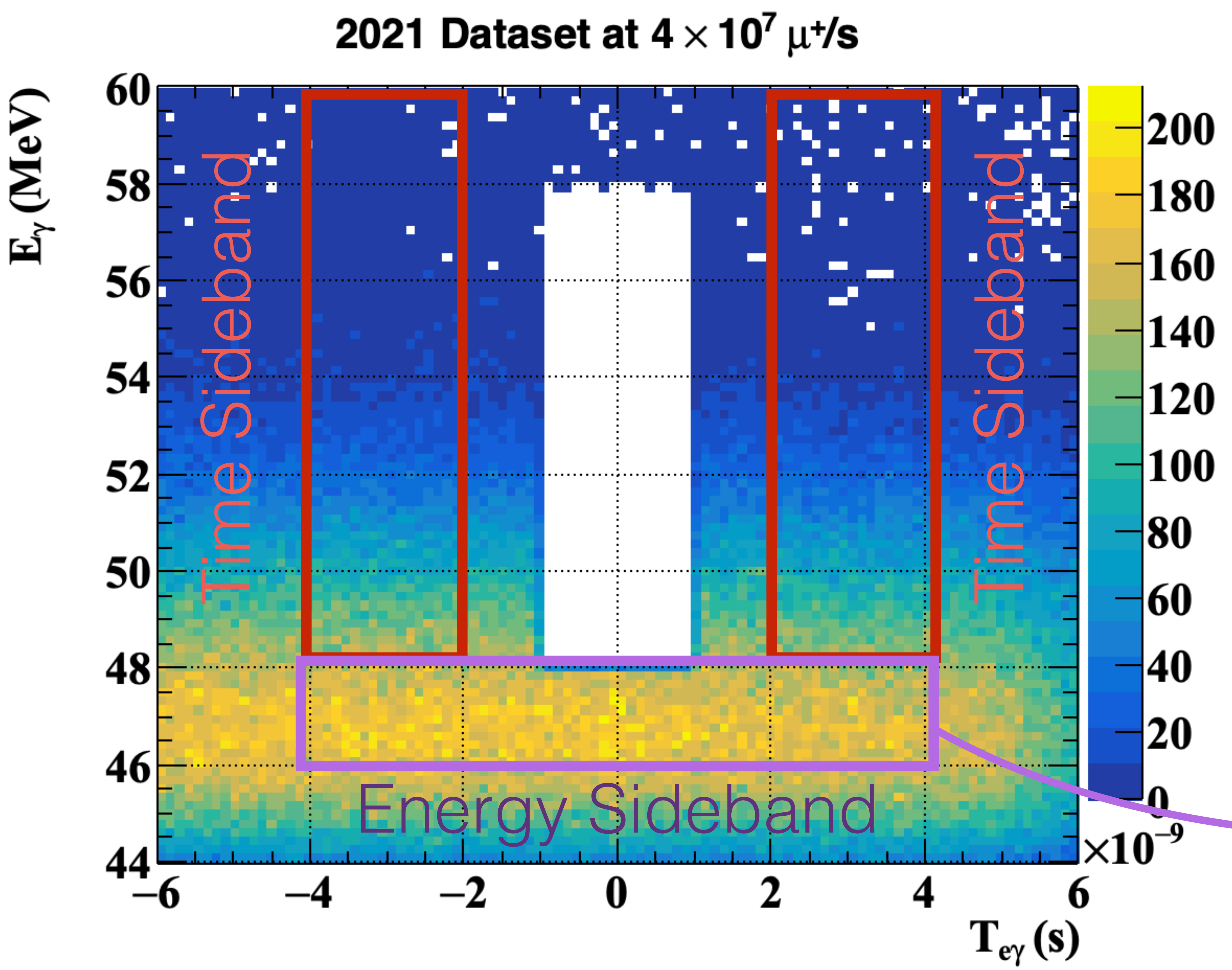

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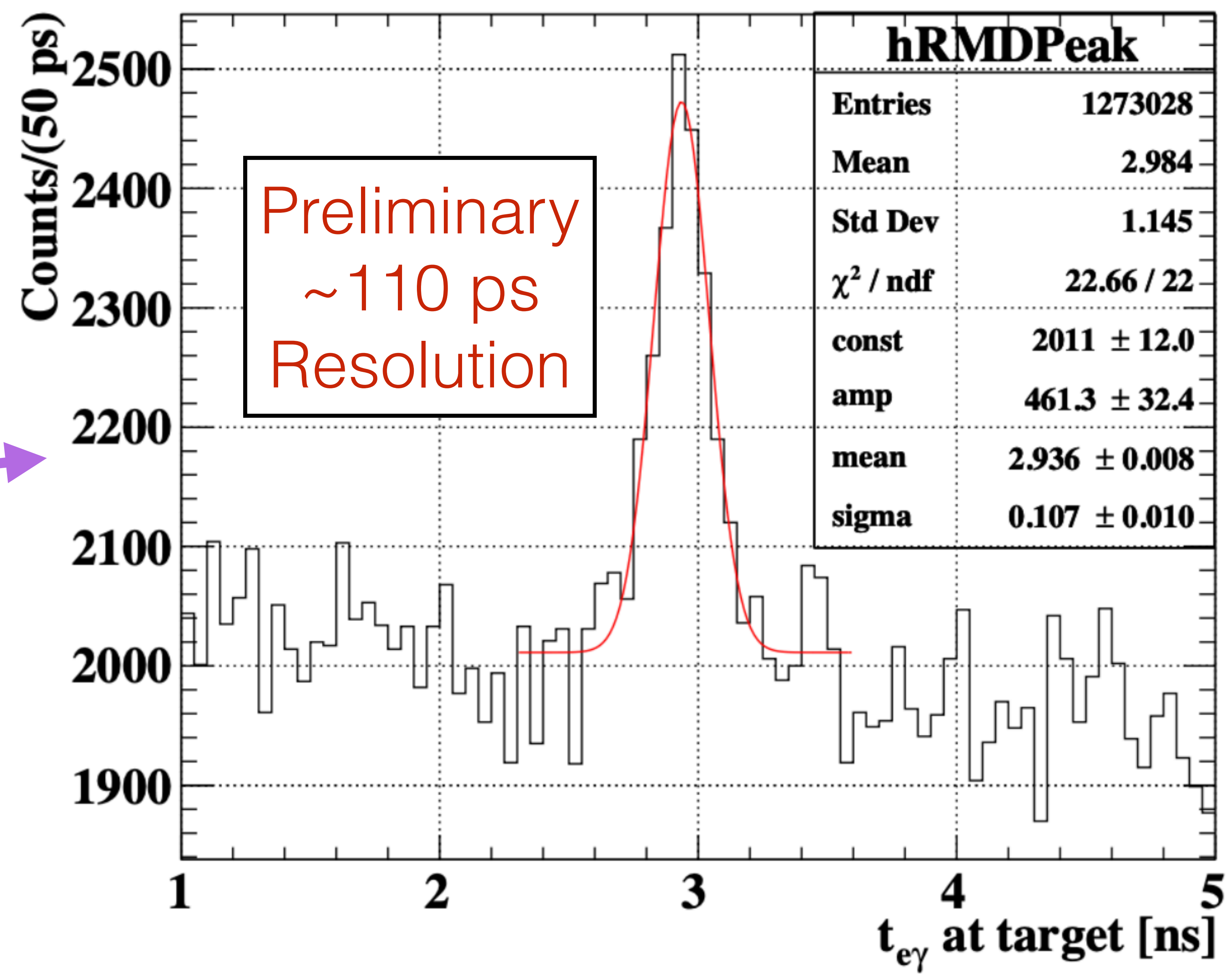


Caveat: Final analysis sidebands defined when analysis will be frozen

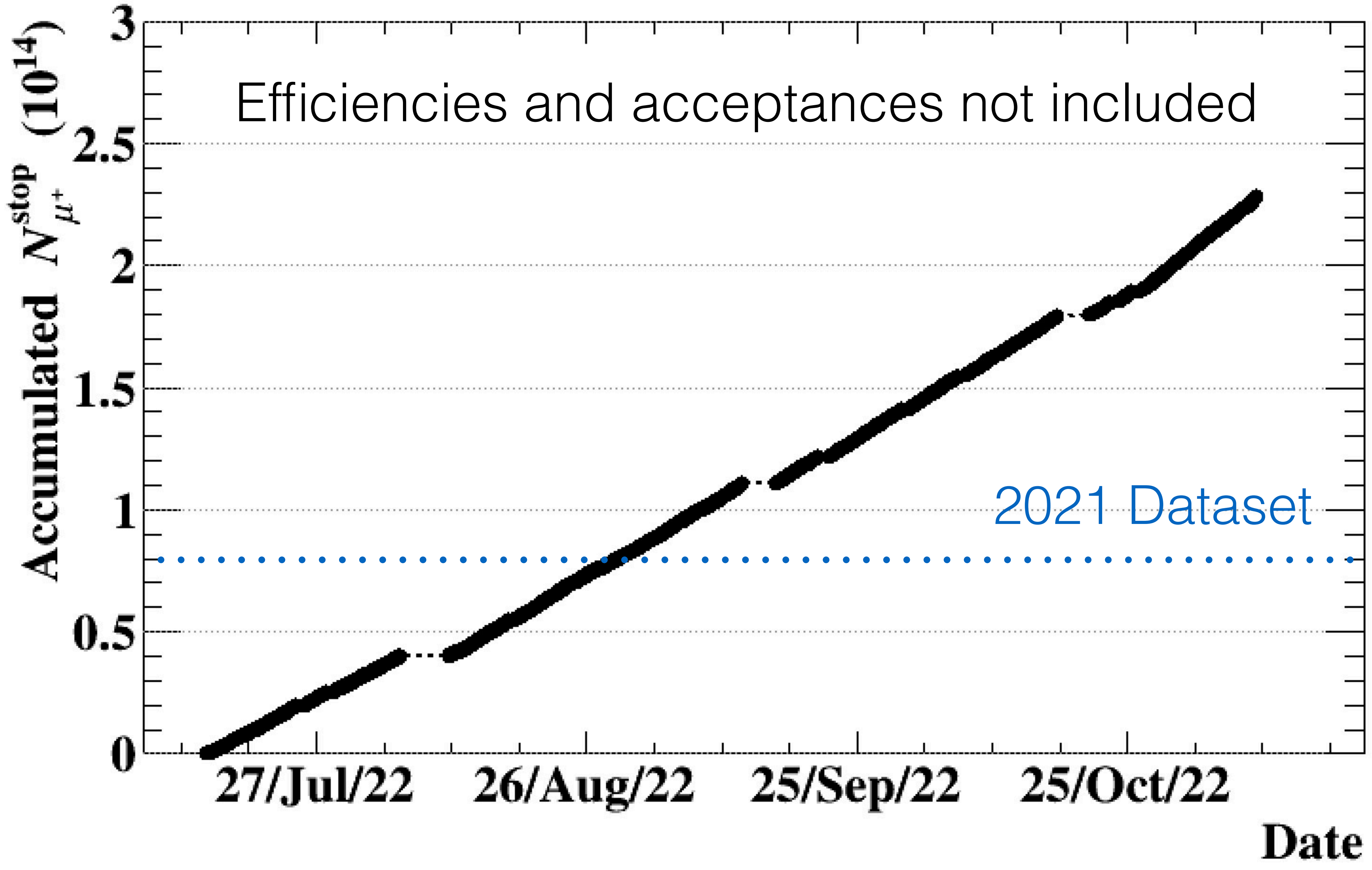
Example: $\mu \rightarrow e\nu\bar{\nu}\gamma$ time PDF from energy sideband

Data Acquisition ongoing: physics run 2022

Run2022 DAQ ongoing: already 2.4 10^{14} mu stopped

MEG I full dataset: 7.5 10^{14} mu stopped

End Physics run when $\pi^- p \rightarrow \pi^0 n$ calibration begins on next 13th November



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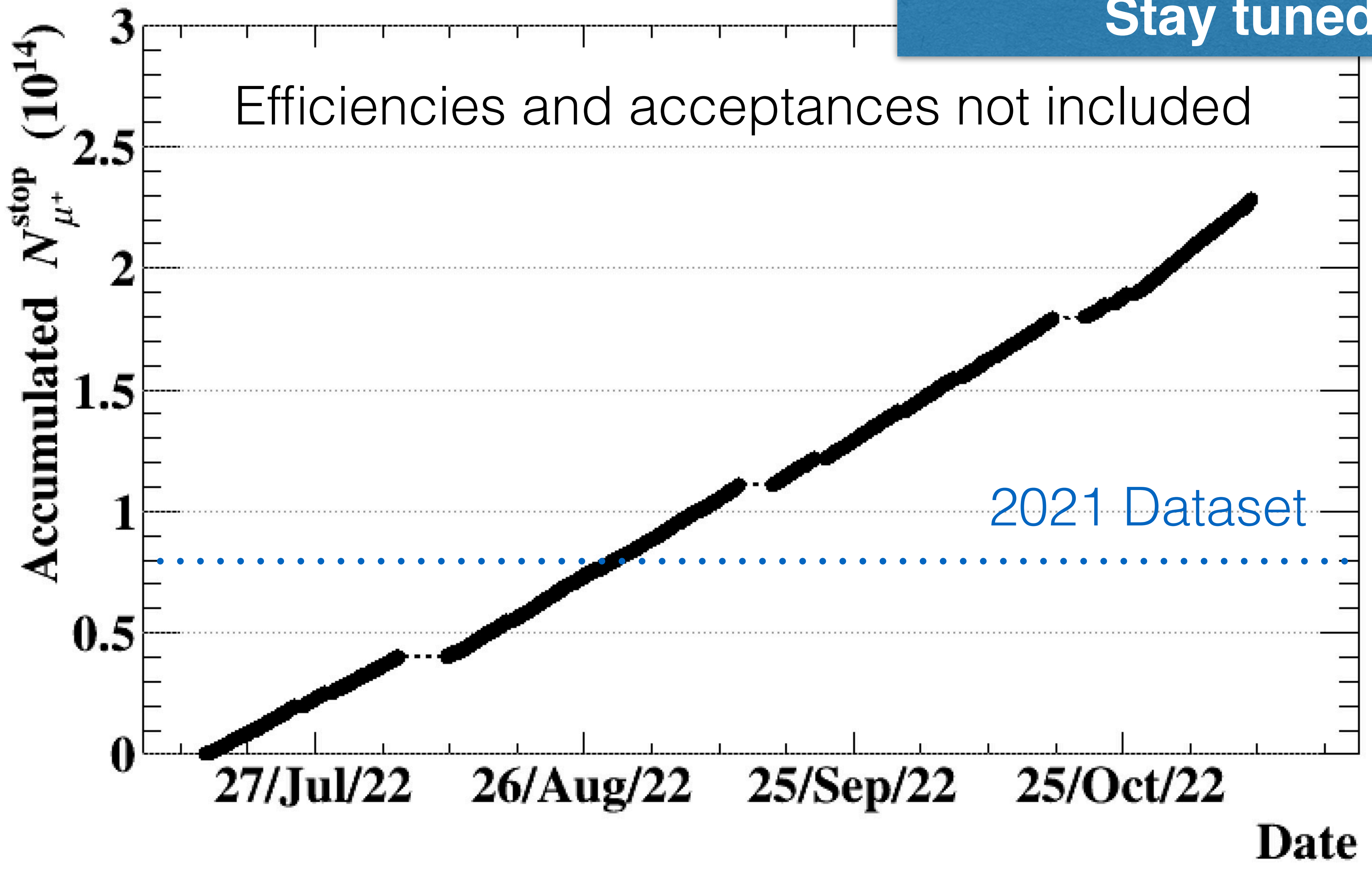
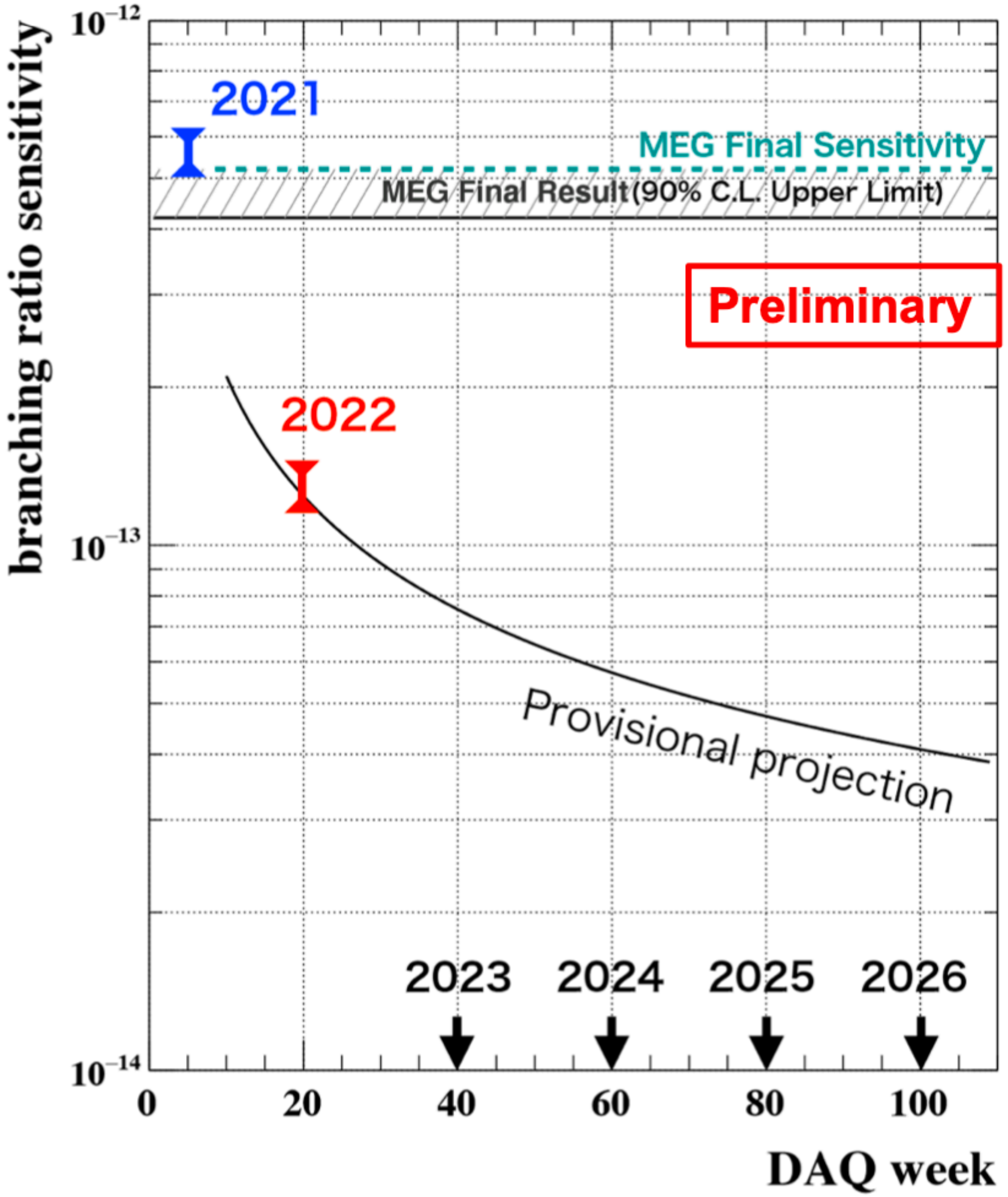
Preliminary sensitivity on 2021+2022: 1.2-1.4 10^{-13}

x3 better than MEG !!!
Stay tuned!





Looking at “Exotic” physics in MEG II

Sensitivities for $\mu^+ \to e^+X$ at MEG II

Strong theoretical interest in long-lived light particles coupling across lepton families

https://arxiv.org/abs/2006.04795

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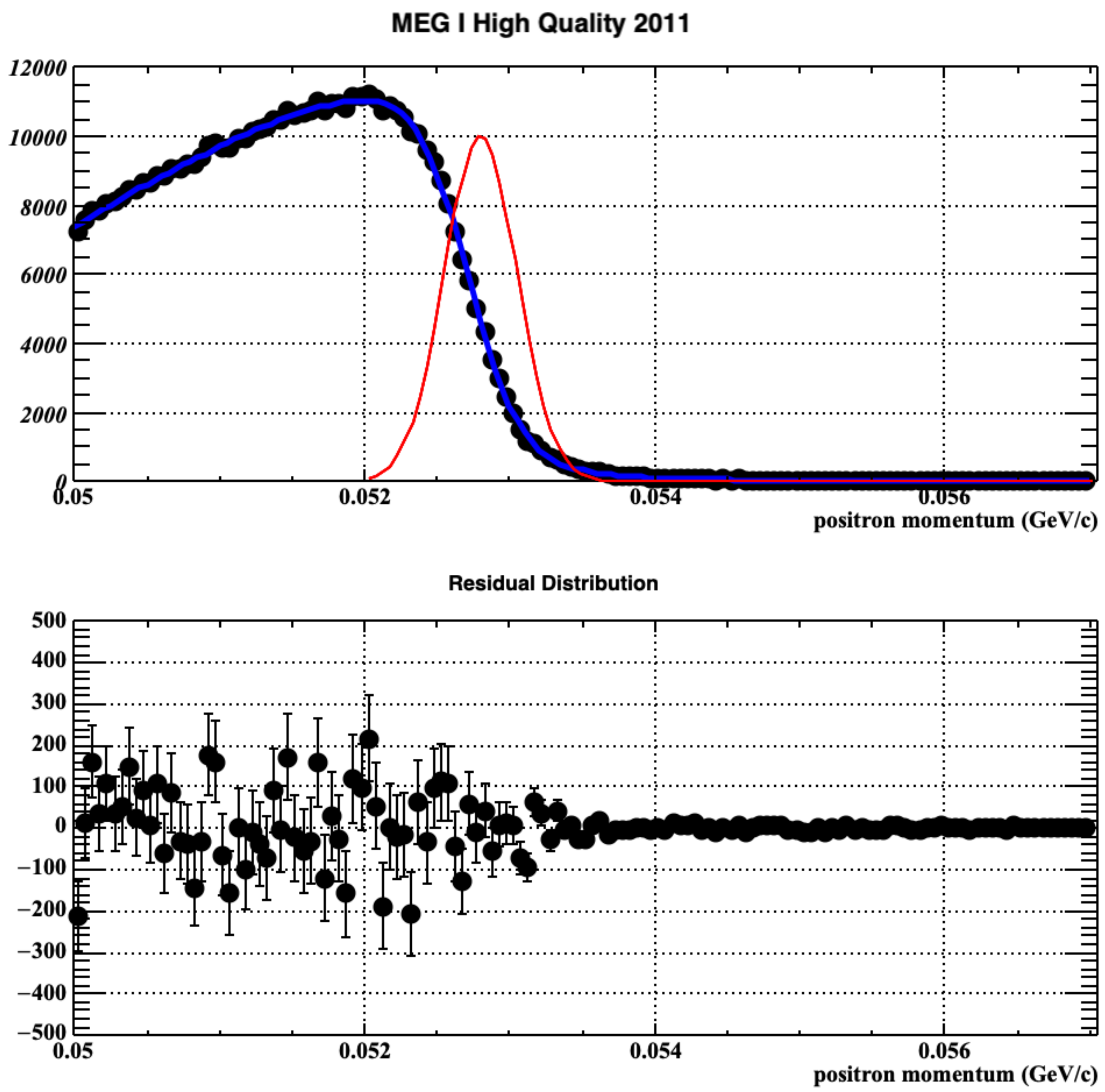

Search for $\mu^+ \to e^+ X$ (X invisible)

Monochromatic positron similar MEG signal for $m_X \ll m_\mu$

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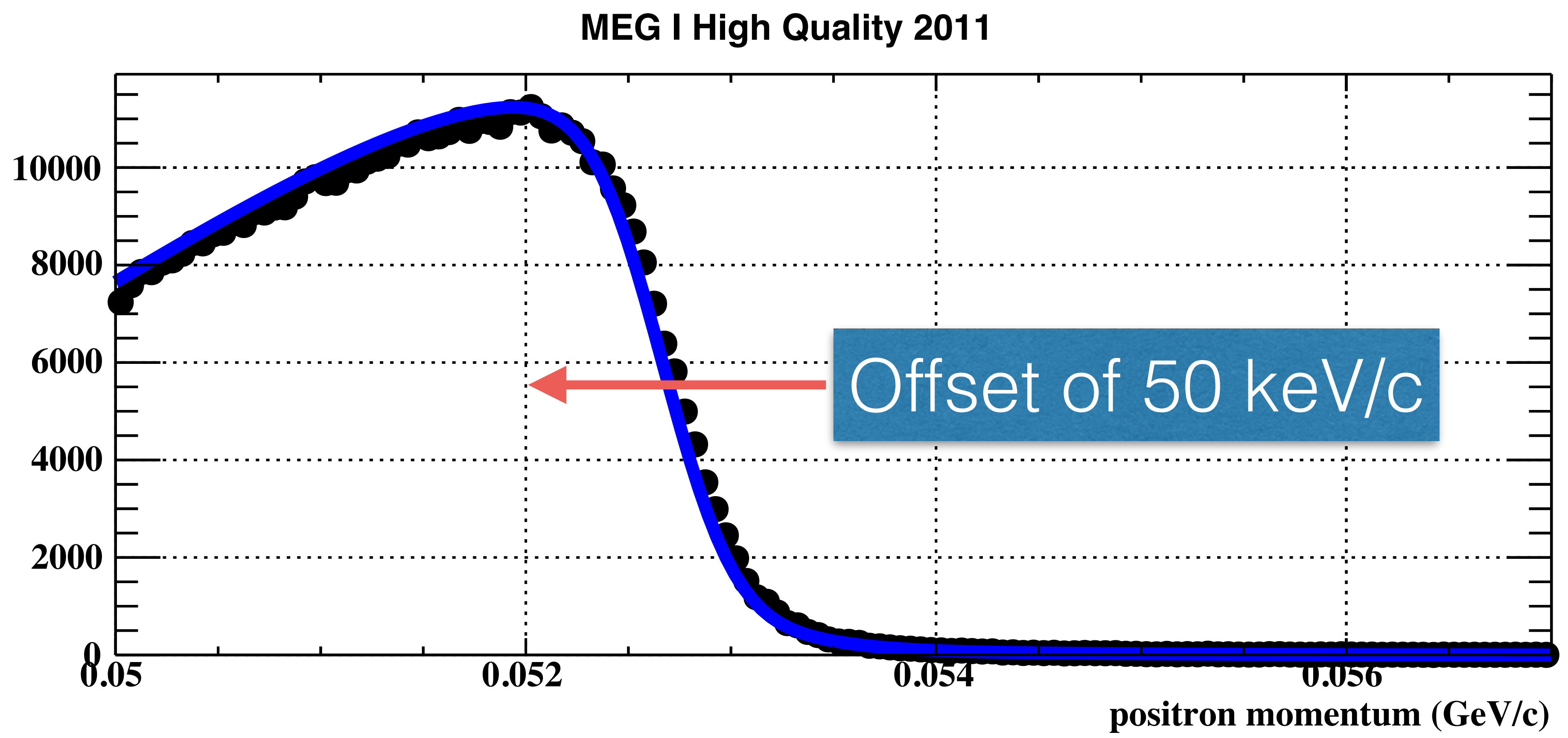

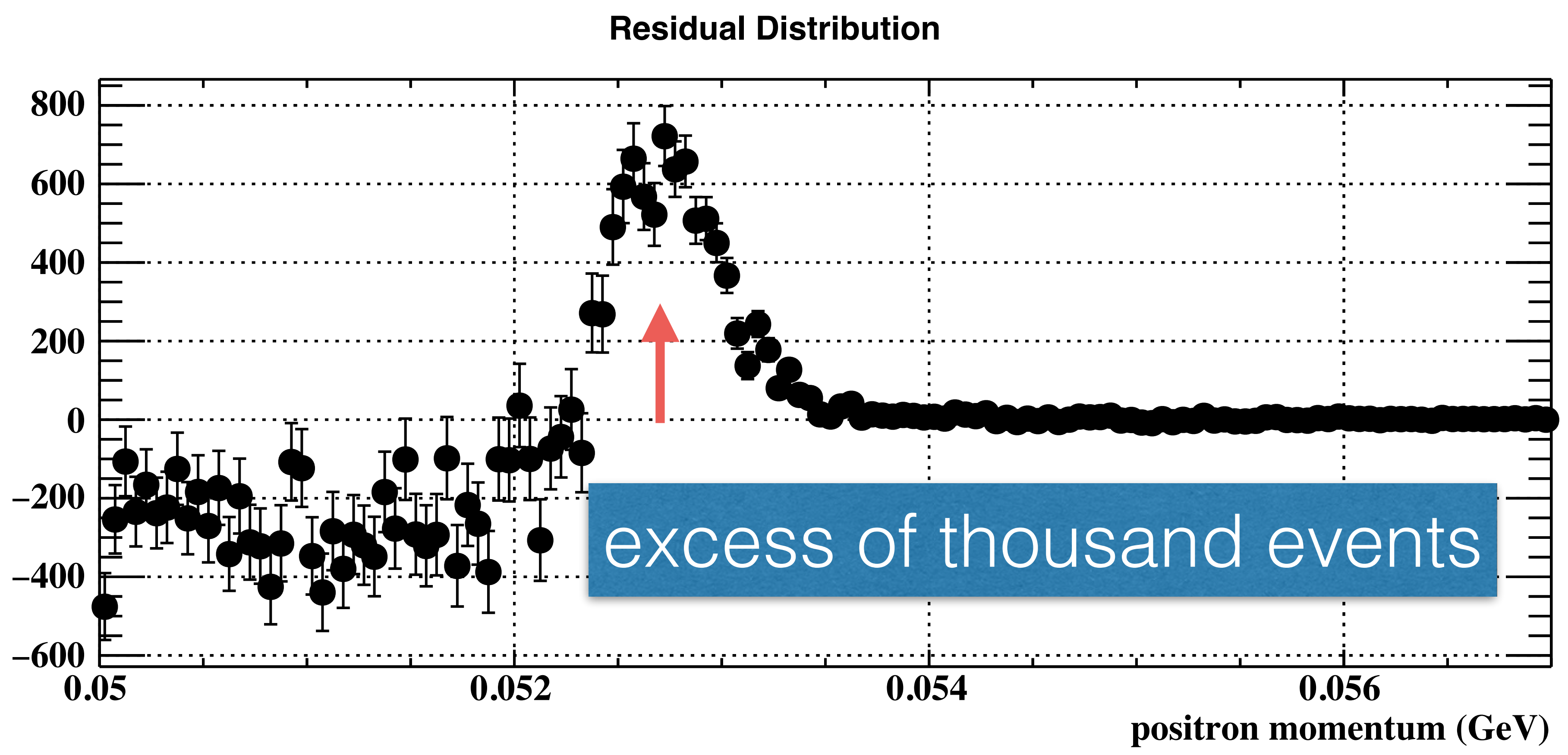

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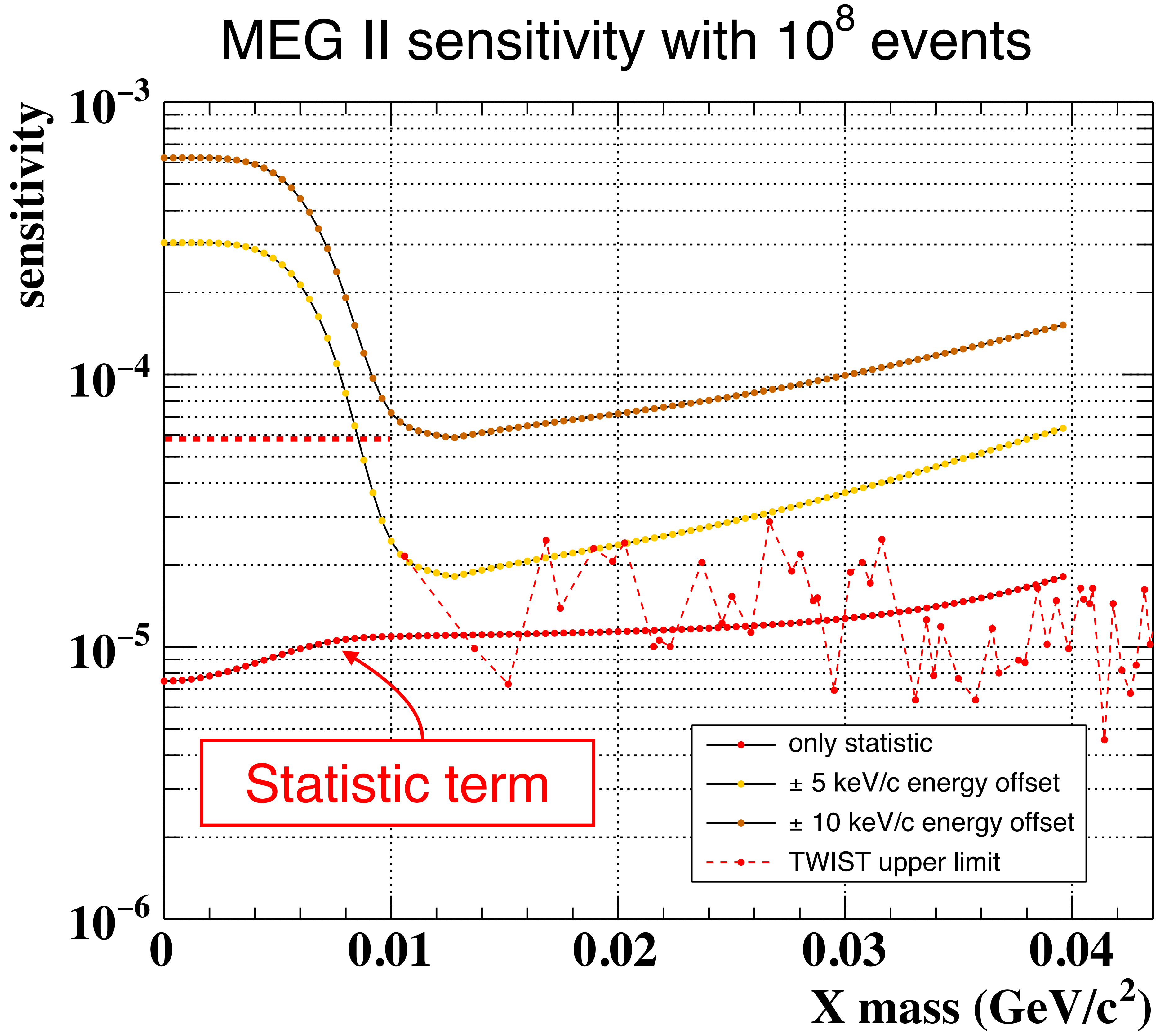
Monochromatic positron similar MEG signal for $m_X \ll m_\mu$

Biggest systematic from momentum scale: spectrometer response needs to be calibrated at 5 keV/c level to be competitive with existing limits.



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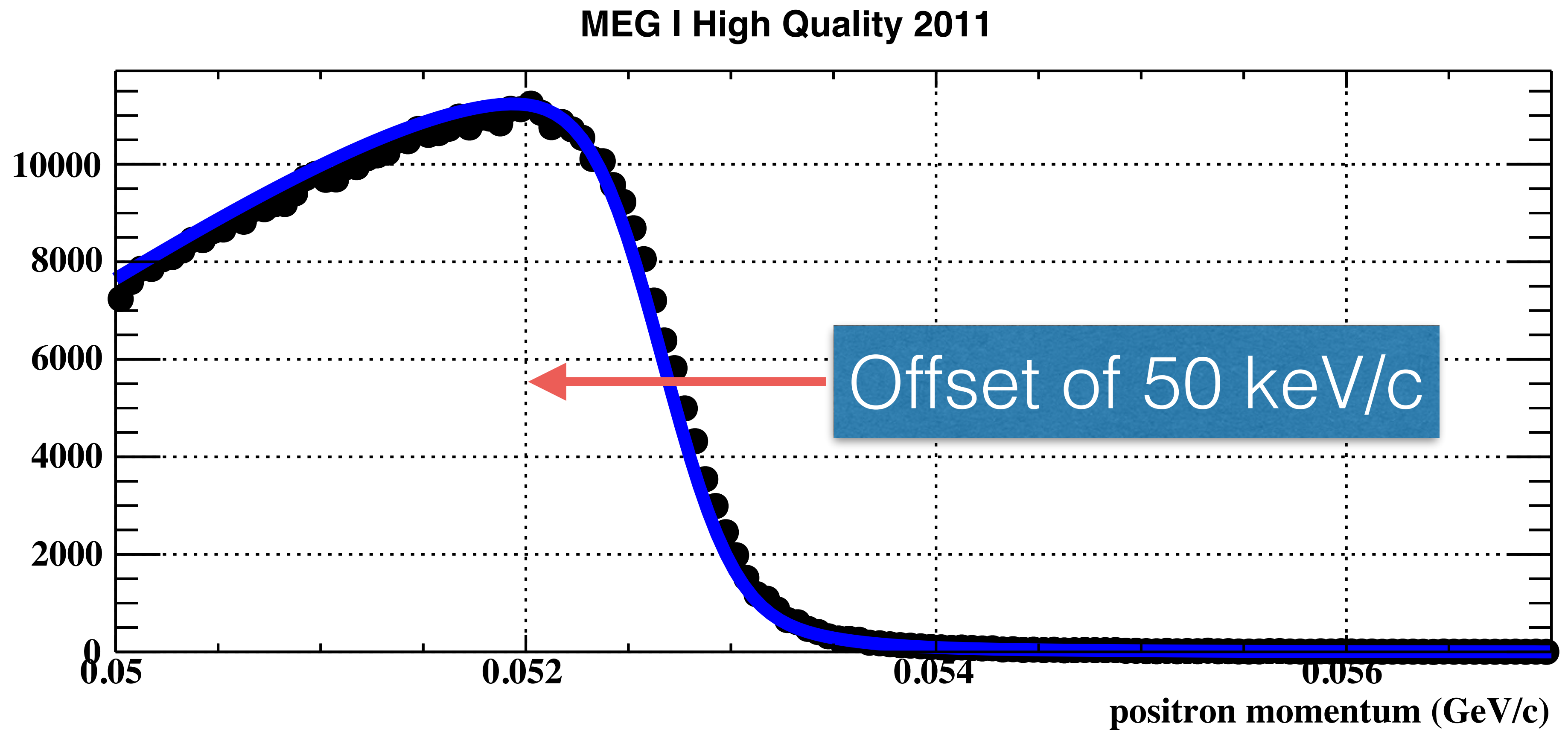

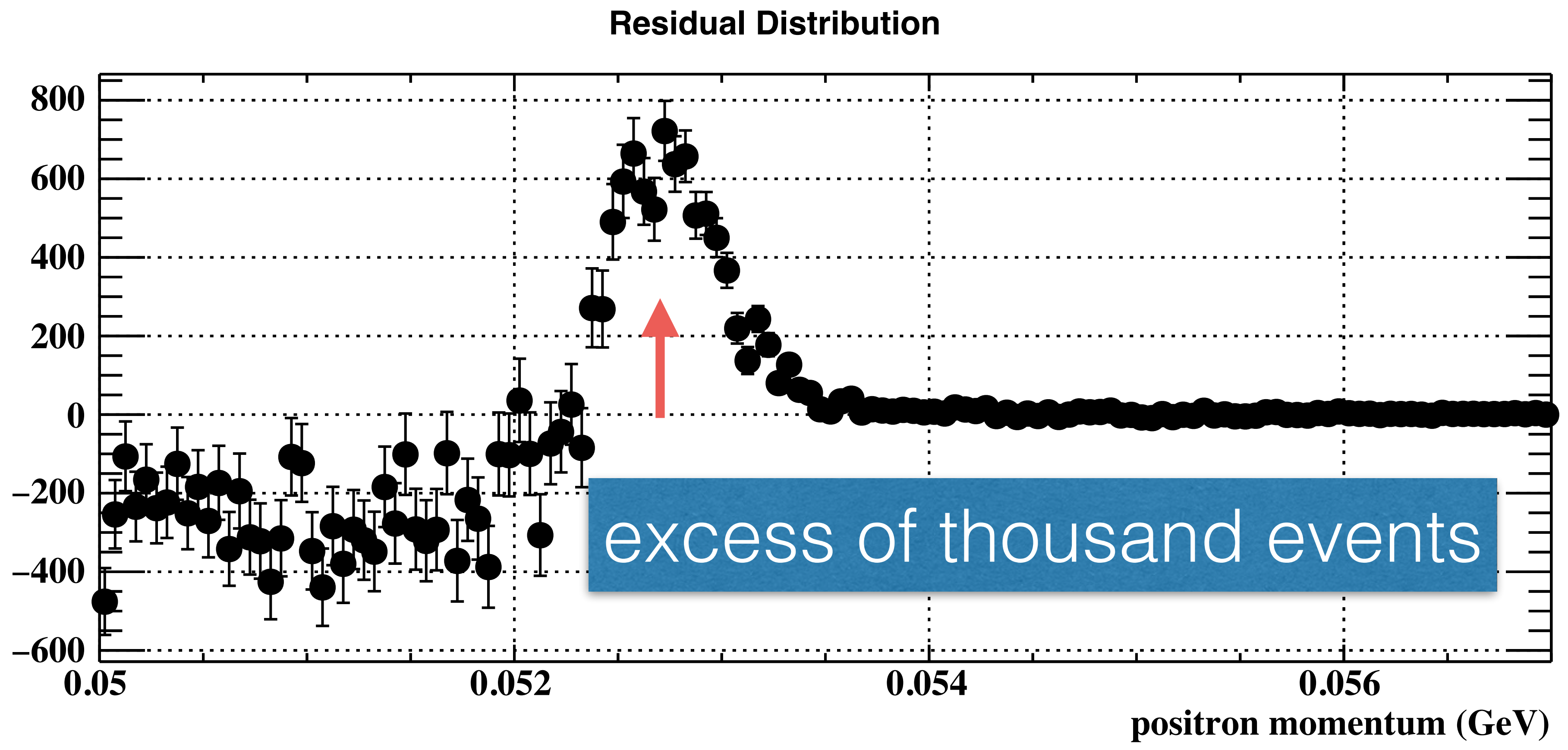

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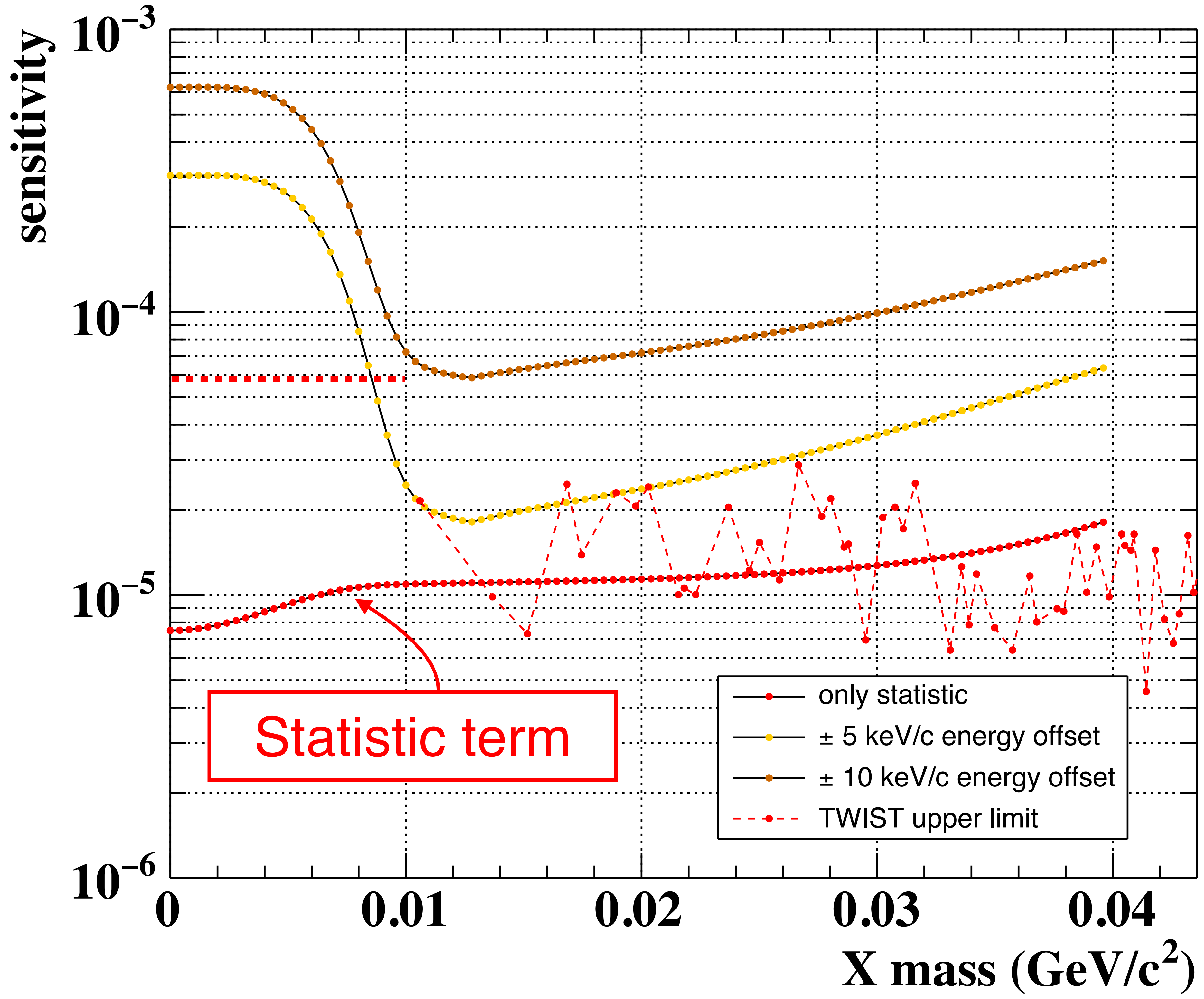
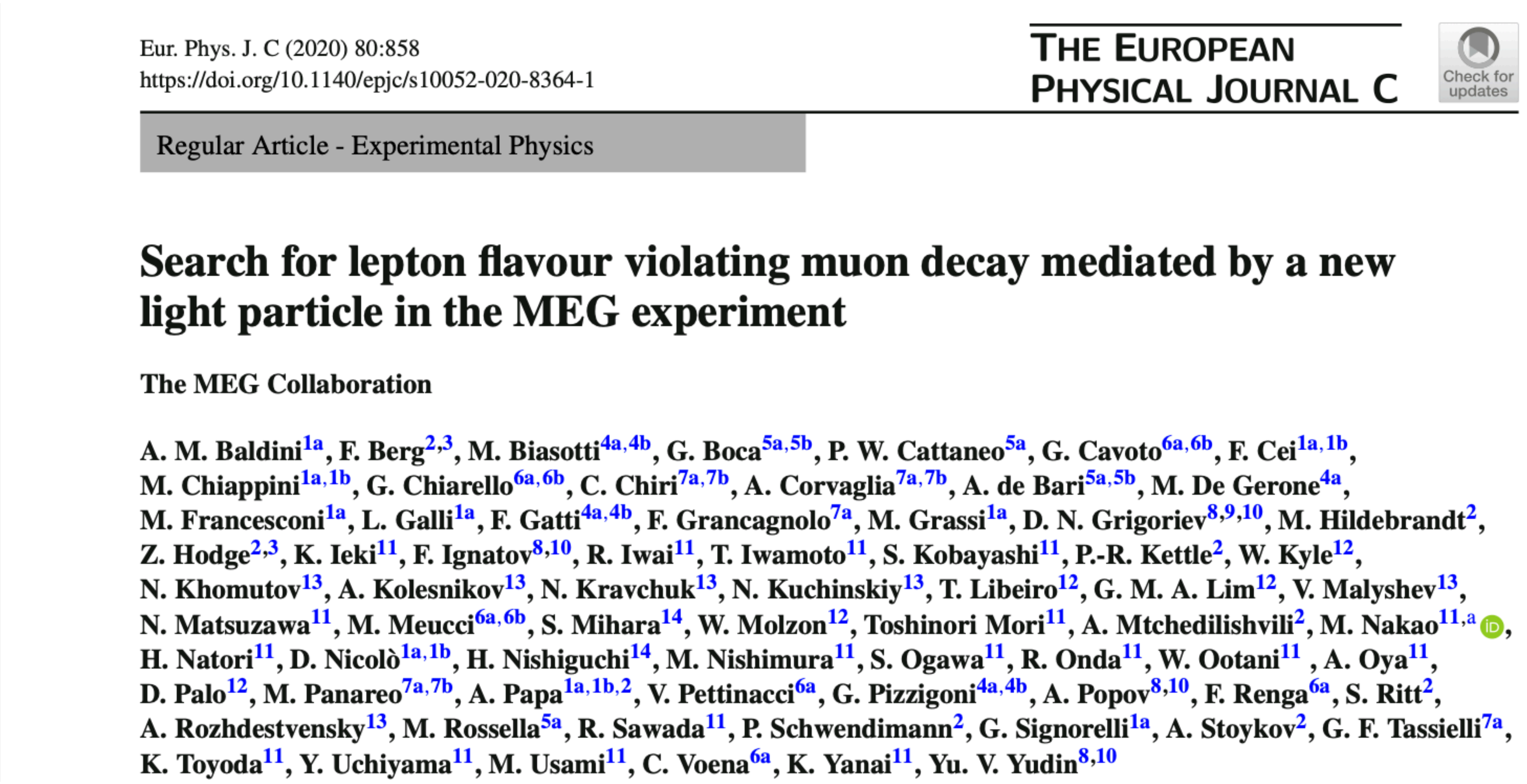
MEG II sensitivity with 10^8 events



Calibration issue less important for the $\mu^+ \to e^+ \gamma X$ process, **sensitivity studies underway**

$\mu^+ \to e^+X(X \to \gamma\gamma)$ in MEG

Looking to **two-photon events** in the final **MEG I** dataset


Eur. Phys. J. C (2020) 80:858
https://doi.org/10.1140/epjc/s10052-020-8364-1

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

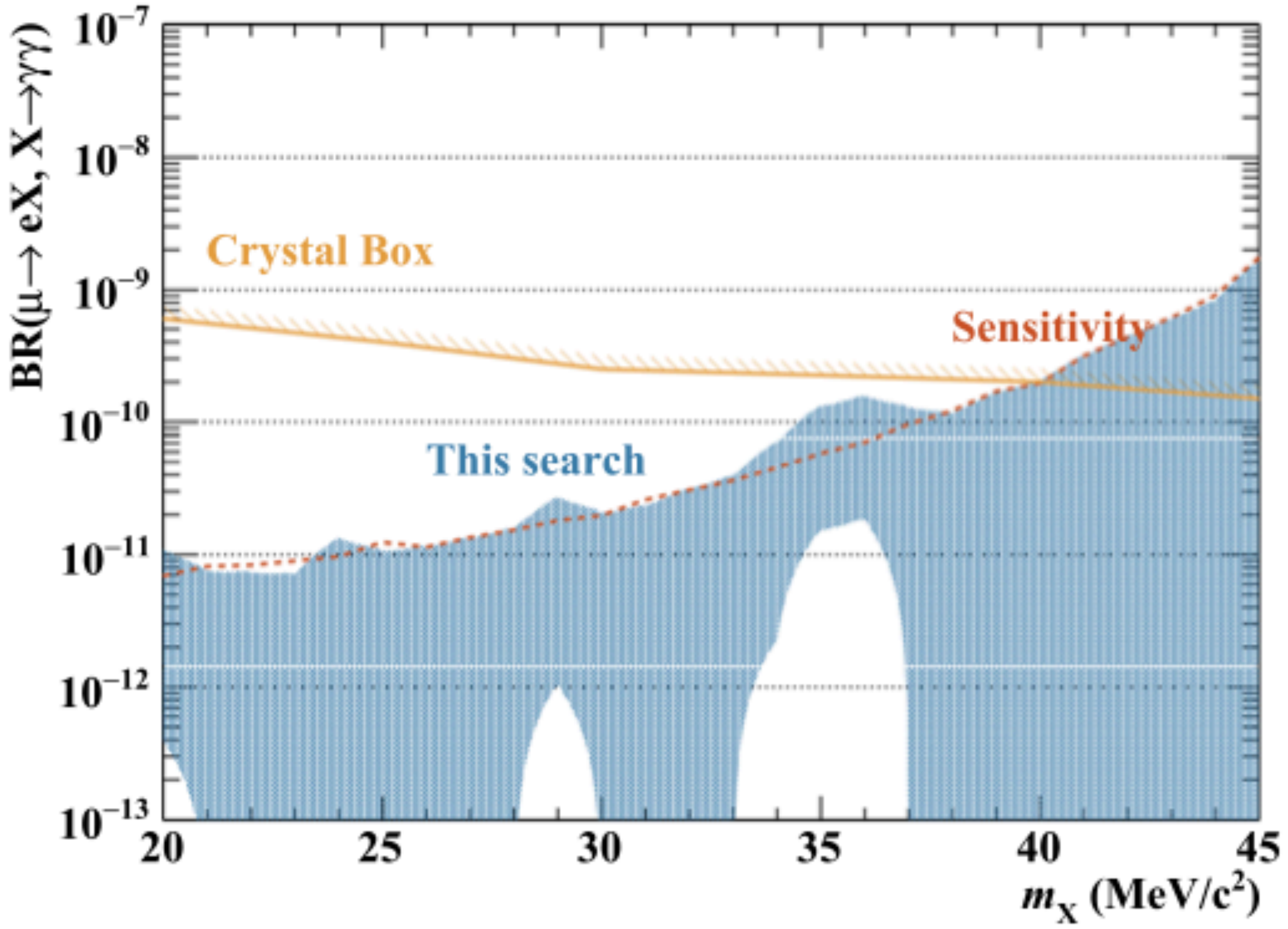
Regular Article - Experimental Physics

Search for lepton flavour violating muon decay mediated by a new light particle in the MEG experiment

The MEG Collaboration

A. M. Baldini[1a], F. Berg[2,3], M. Biasotti[4a,4b], G. Boca[5a,5b], P. W. Cattaneo[5a], G. Cavoto[6a,6b], F. Cei[1a,1b], M. Chiappini[1a,1b], G. Chiarello[6a,6b], C. Chiri[7a,7b], A. Corvaglia[7a,7b], A. de Bari[5a,5b], M. De Gerone[4a], M. Francesconi[1a], L. Galli[1a], F. Gatti[4a,4b], F. Grancagnolo[7a], M. Grassi[1a], D. N. Grigoriev[8,9,10], M. Hildebrandt[2], Z. Hodge[2,3], K. Ieki[11], F. Ignatov[8,10], R. Iwai[11], T. Iwamoto[11], S. Kobayashi[11], P.-R. Kettle[2], W. Kyle[12], N. Khomutov[13], A. Kolesnikov[13], N. Kravchuk[13], N. Kuchinskiy[13], T. Libeiro[12], G. M. A. Lim[12], V. Malyshev[13], N. Matsuzawa[11], M. Meucci[6a,6b], S. Mihara[14], W. Molzon[12], Toshinori Mori[11], A. Mtchedilishvili[2], M. Nakao[11,a], H. Natori[11], D. Nicolò[1a,1b], H. Nishiguchi[14], M. Nishimura[11], S. Ogawa[11], R. Onda[11], W. Ootani[11], A. Oya[11], D. Palo[12], M. Panareo[7a,7b], A. Papa[1a,1b,2], V. Pettinacci[6a], G. Pizzigoni[4a,4b], A. Popov[8,10], F. Renga[6a], S. Ritt[2], A. Rozhdestvensky[13], M. Rossella[5a], R. Sawada[11], P. Schwendimann[2], G. Signorelli[1a], A. Stoykov[2], G. F. Tassielli[7a], K. Toyoda[11], Y. Uchiyama[11], M. Usami[11], C. Voena[6a], K. Yanai[11], Yu. V. Yudin[8,10]

Photon energy,
opening angle
and event acceptance
depends on m_X



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THE EUROPEAN PHYSICAL JOURNAL C

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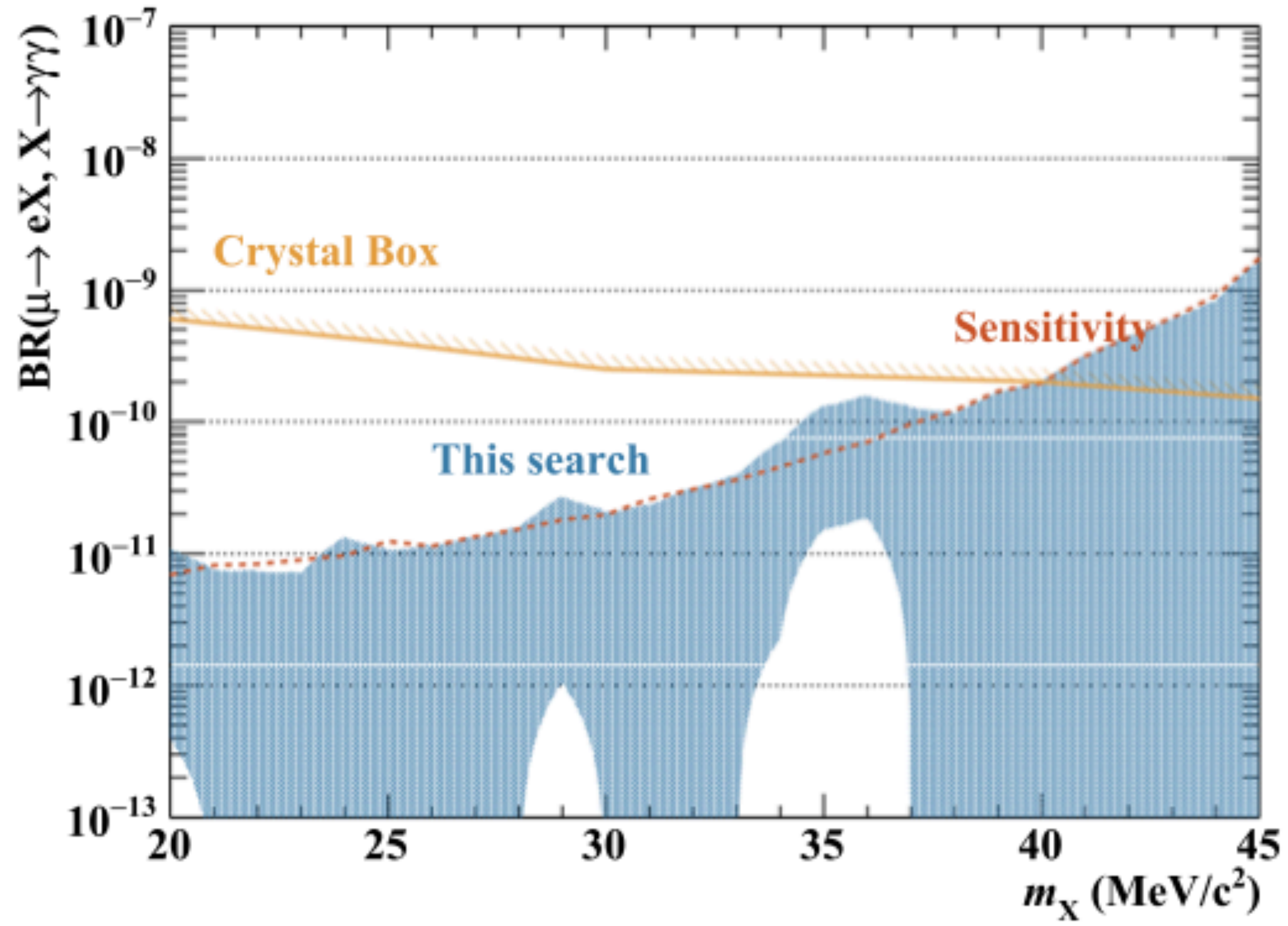
Photon energy, opening angle and event acceptance depends on m_X

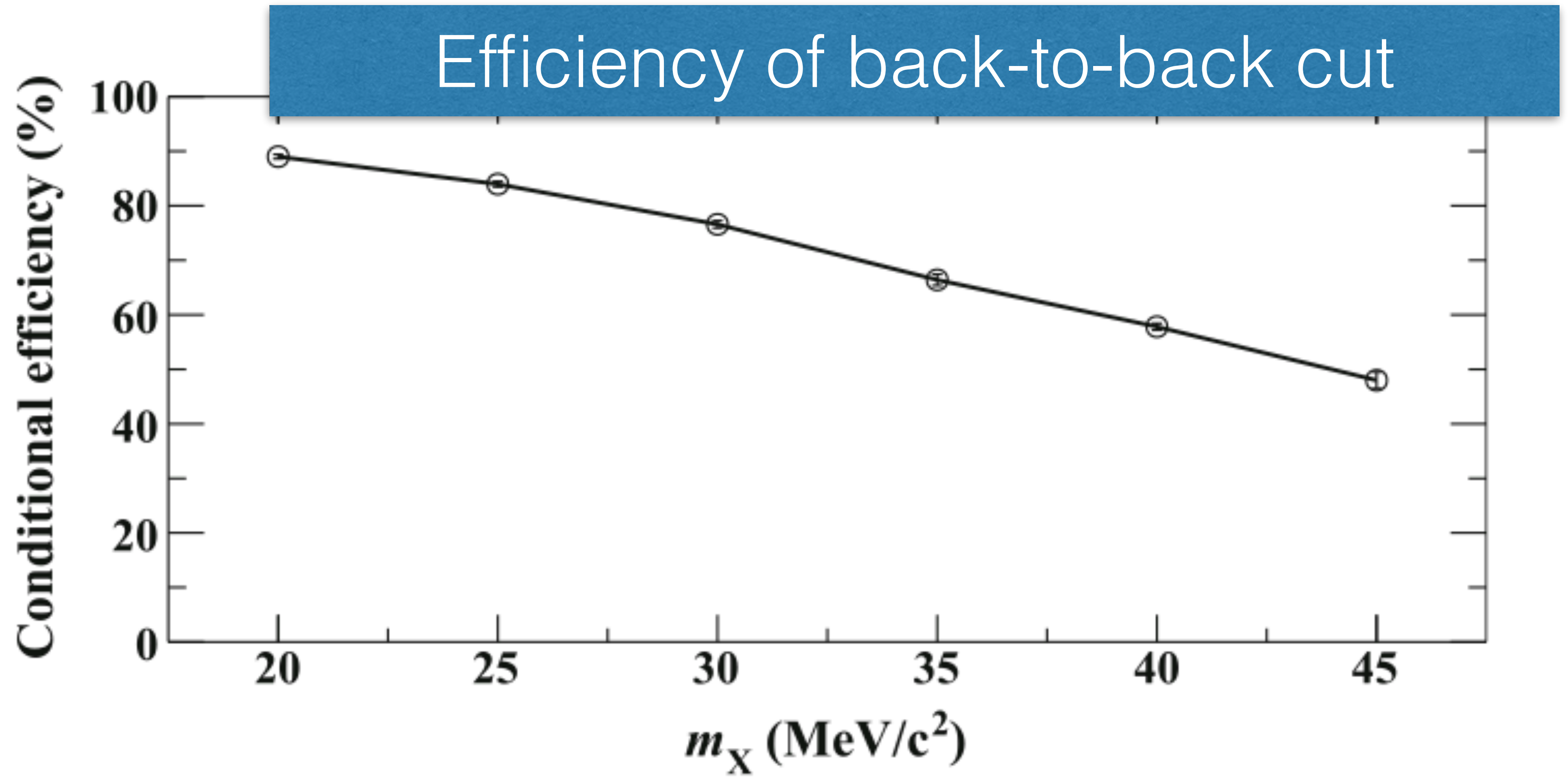


Non trivial effect of trigger used in MEG I:

- Online back-to-back cut
- Photon energy veto threshold

Keep an higher veto threshold (~90 MeV) in 2021-2022 while MEG II sensitivities are investigated

Improved spatial resolution of MEG II Liquid Xenon Detector expected to play an important role



Atomki $^8\mathrm{Be}^\star$ anomaly

Atomki collaboration observed an
excess of e^+e^- production from proton beam in ^{7}Lithium (BR~3 10^{-3})

$$p\ {}^7\mathrm{Li} \to {}^8\mathrm{Be}^\star \to {}^8\mathrm{Be}\ X$$
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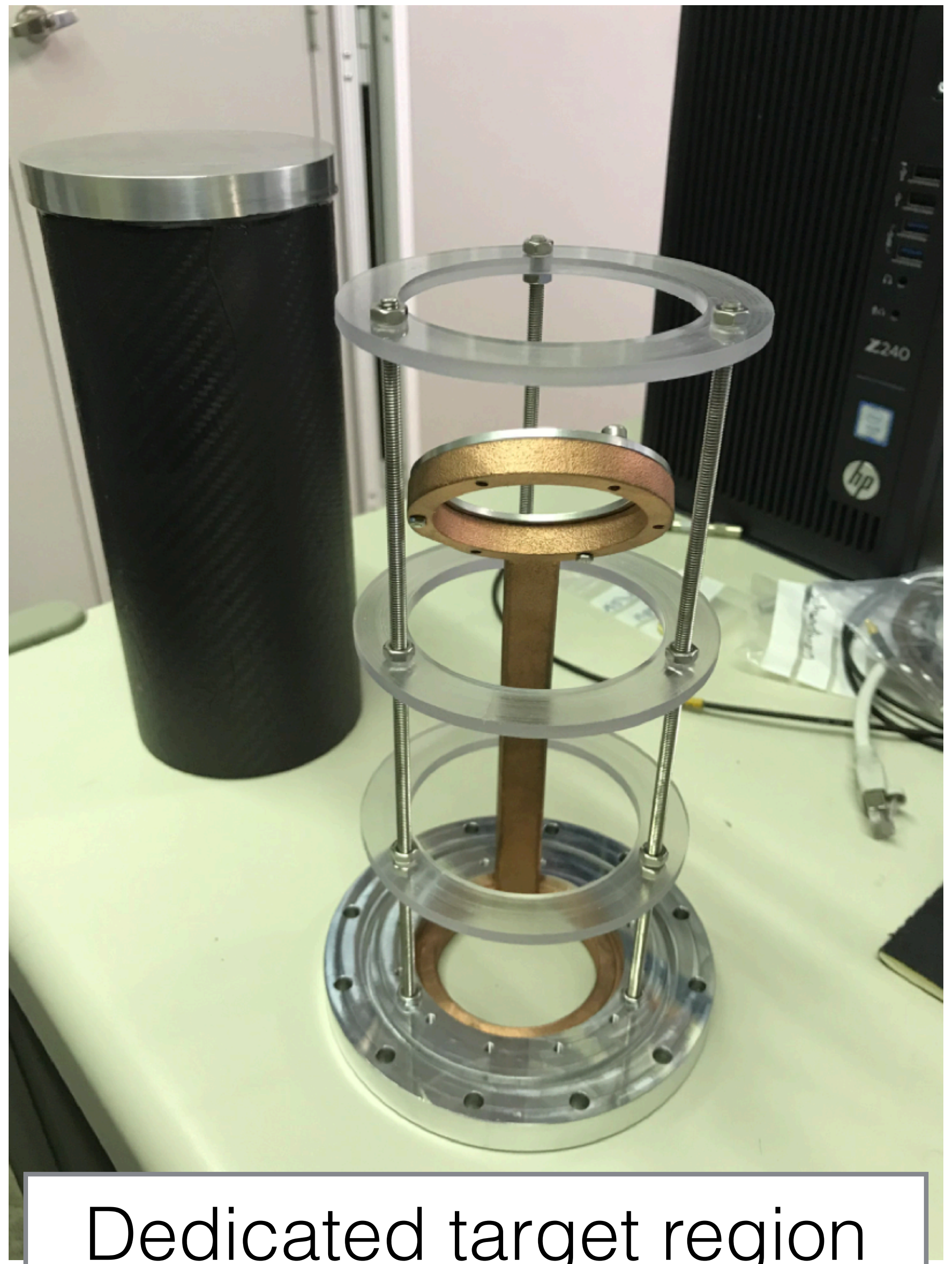
MEG II can reproduce Atomki experiment using existing items:
Cockroft-Walton accelerator and magnetic spectrometer + new target region



Dedicated target region

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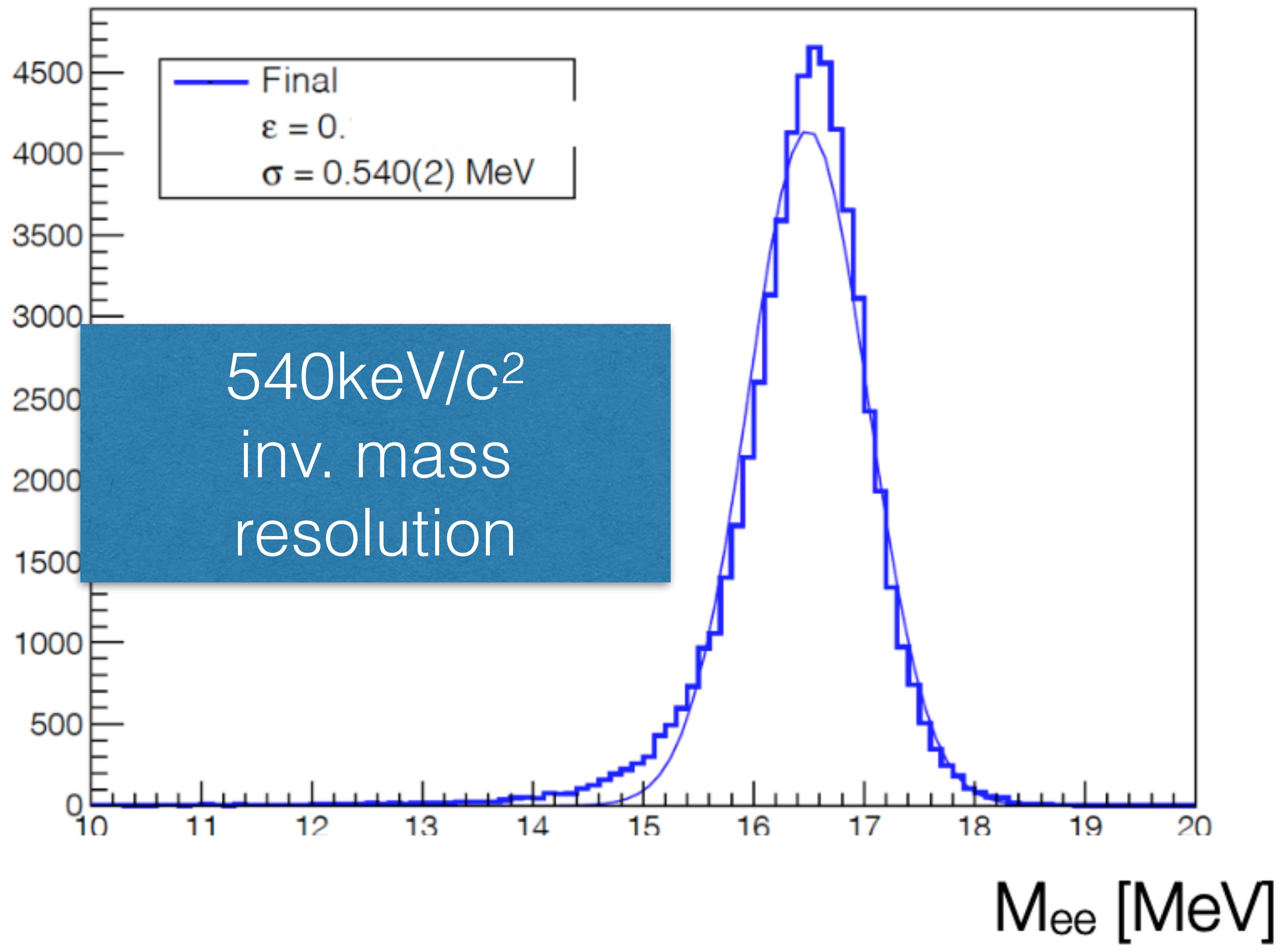
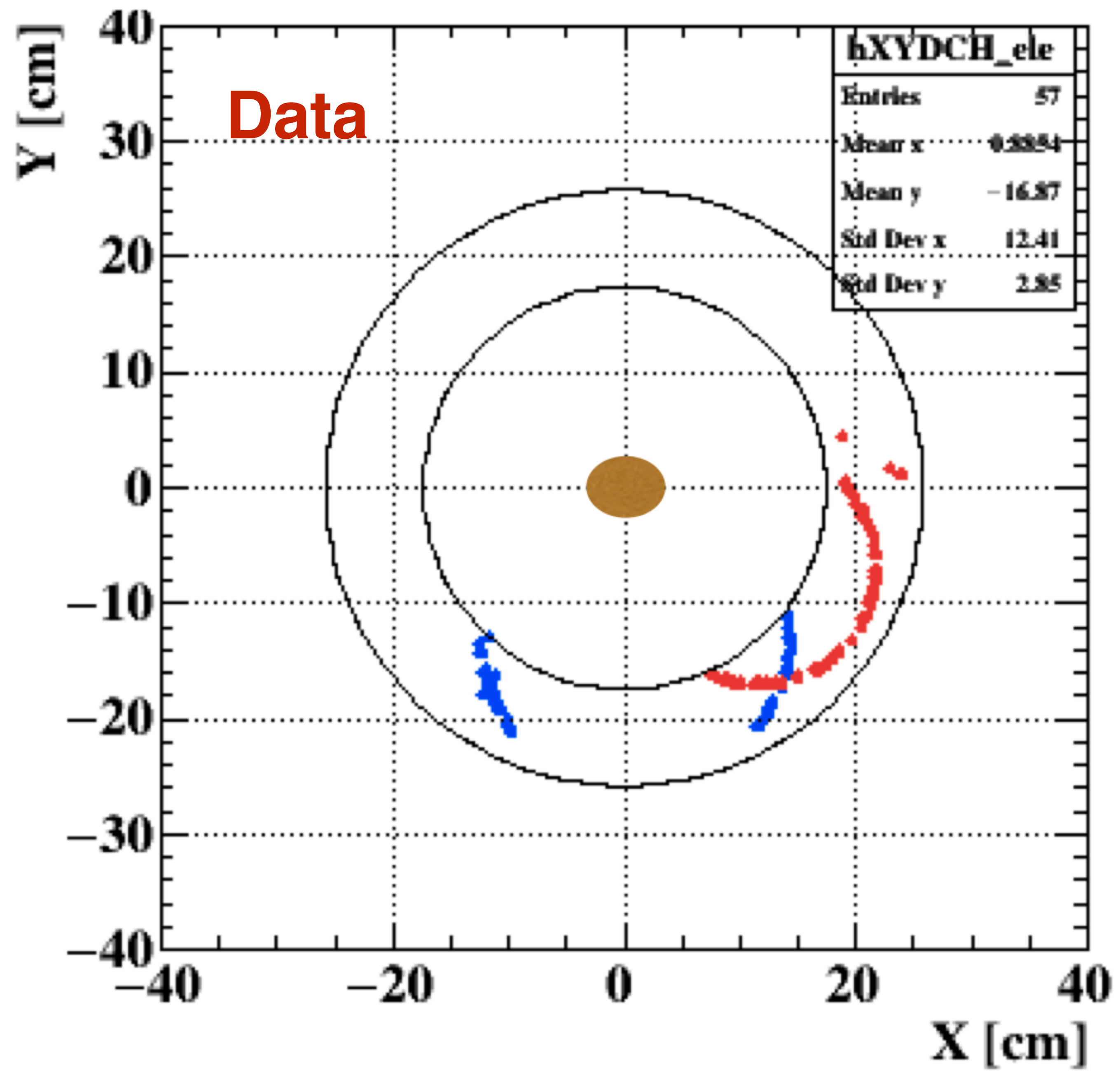
Goals:
- Validate Montecarlo external pair conversions
- Develop negative sign reconstruct algorithm
- Investigate Trigger and DAQ schemes

90M Events collected in February 2022:
with LiF (55M) and LiPON (35M) targets

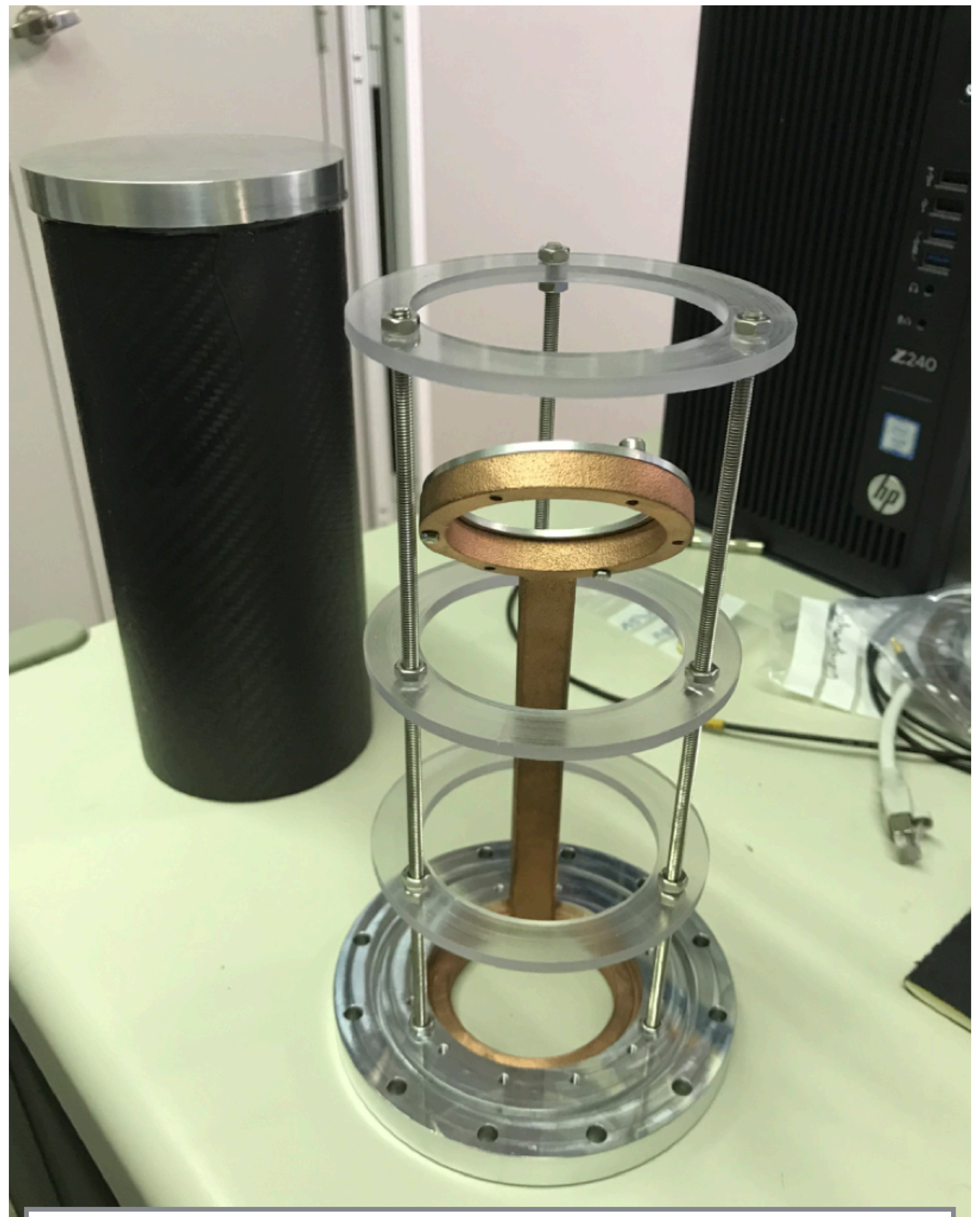
Montecarlo





- **e+ hit**
- **e- hit**

p^- = 6.7MeV
p^+ = 8.3 MeV
Angle = 141°



Dedicated target region

Conclusions and prospects

MEG II entered its **Physics run** period in spite of detector history and pandemic

Currently focusing efforts in providing some physics analysis results:
2021+2022 expected to achieve higher sensitivity than MEG I

Improvements in detector reconstruction will impact also **other physics channels** under consideration:
$\mu^+ \to e^+ X$, $\mu^+ \to e^+ \gamma\, X$, $\mu^+ \to e^+ X\, (X \to \gamma\gamma)$, Atomki $^8\mathrm{Be}^\star$ anomaly

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At the same time **CDCH2** *"Backup Drift Chamber"* is being assembled in Pisa

Backup

The Lepton Flavour in SM

Started with Hincks & Pontecorvo searches of $\mu \to e\gamma$ in **1948**

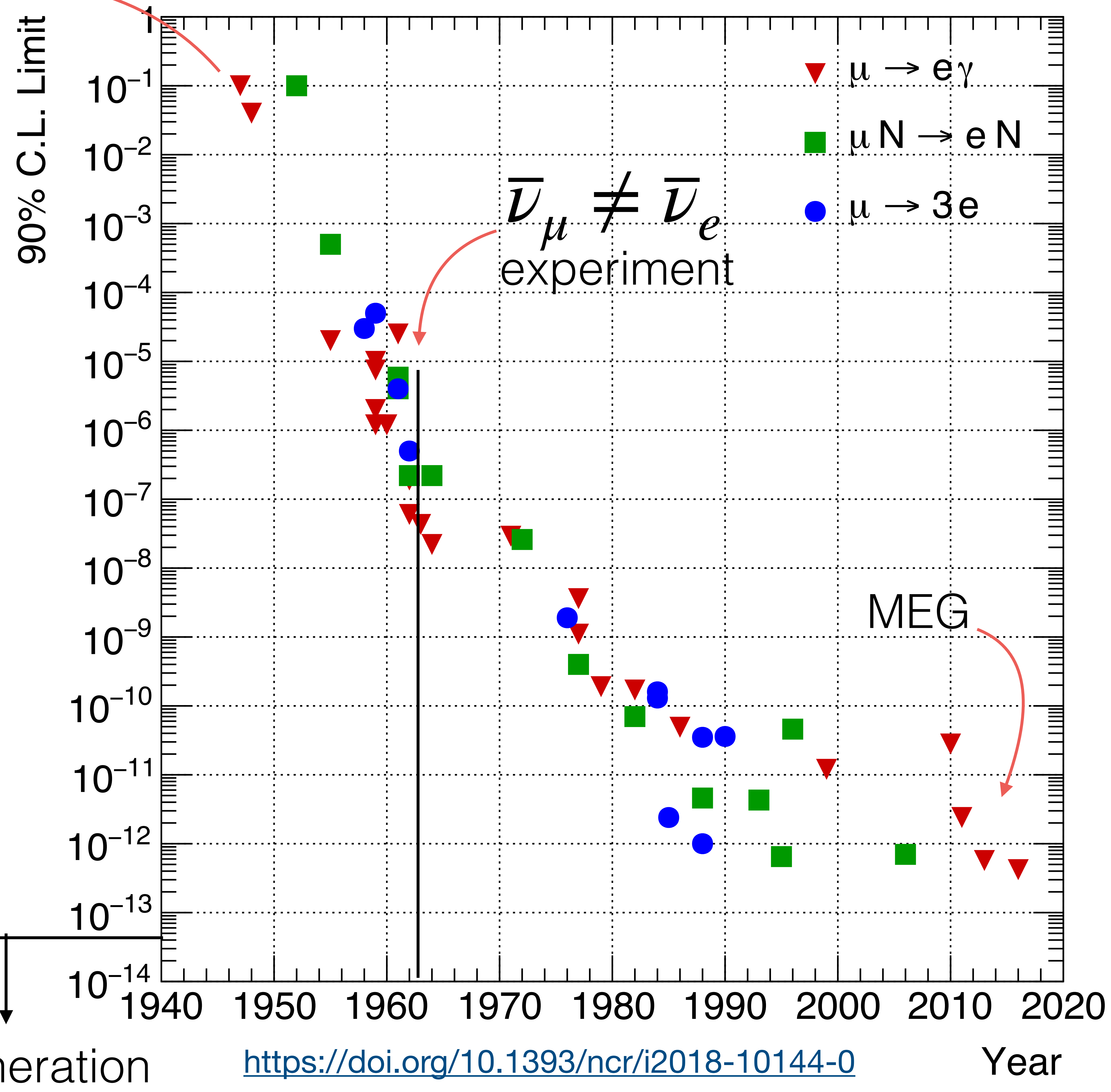
Key ingredient in SM:
lepton interactions can only couple within the same family

$$\overset{(-)}{\nu}_e \leftrightarrow e^{\pm}$$
$$\overset{(-)}{\nu}_\mu \leftrightarrow \mu^{\pm}$$
$$\overset{(-)}{\nu}_\tau \leftrightarrow \tau^{\pm}$$

Non observation of $\mu \to e\gamma$ was a key ingredient in $\bar{\nu}_\mu \neq \bar{\nu}_e$ hypothesis

Experiment sensitivity follows accelerator evolution:
First limits with cosmic rays → pion beams → muon beams

History of CLFV experiments with muons



Next generation experiments

https://doi.org/10.1393/ncr/i2018-10144-0

Effective theories

Huge theoretical effort on combining results from various processes

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_{\alpha} C_{\alpha}^{(5)} O_{\alpha}^{(5)} + \frac{1}{\Lambda^2}\sum_{\alpha} C_{\alpha}^{(6)} O_{\alpha}^{(6)} + \ldots$$

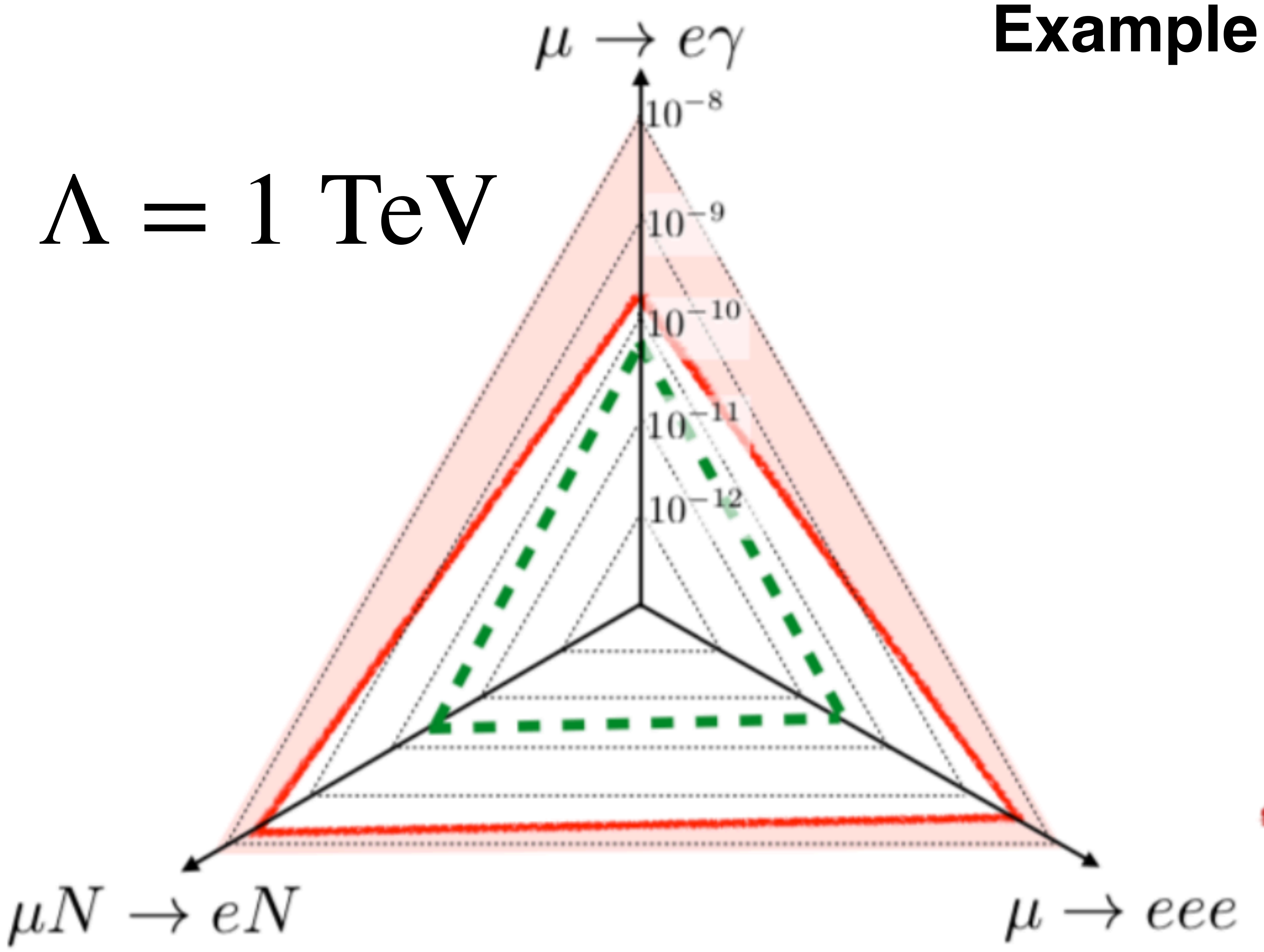
$O_{\alpha}^{(i)}$ = operator of i-th order in SM field

Λ = scale of physics being integrated

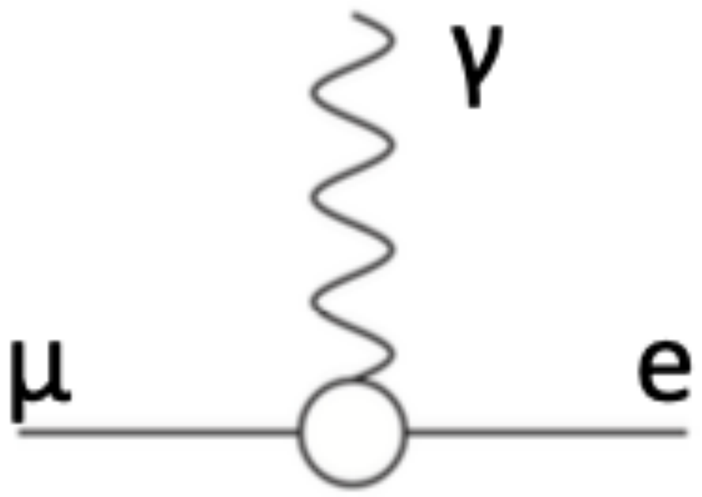
$C_{\alpha}^{(i)}$ = coupling associated to operator $O_{\alpha}^{(i)}$

Example with $C_{e\gamma}^{\mu e}$

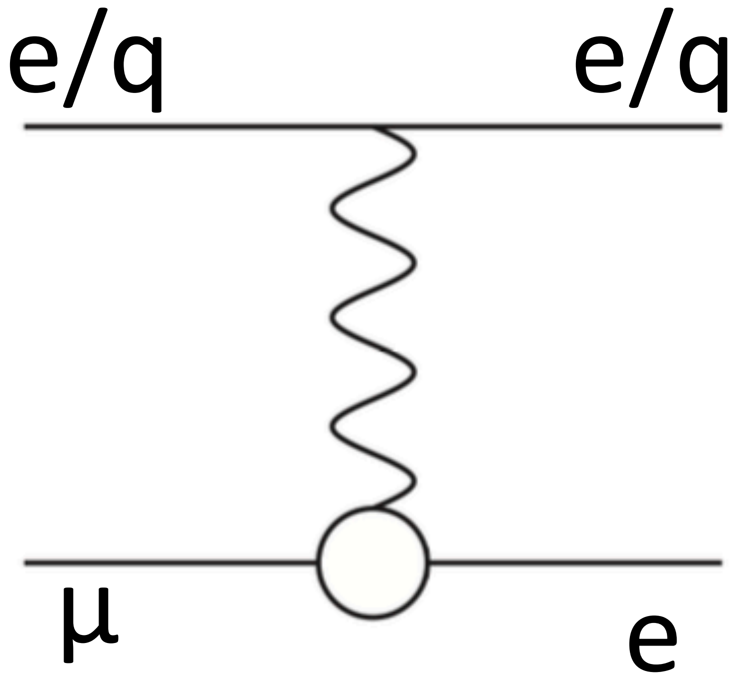
$\Lambda = 1$ TeV



https://doi.org/10.1393/ncr/i2018-10144-0



$\mu \to e\gamma$



$\mu \to eee$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$

$C_{e\gamma}^{\mu e}$ from present limits

$C_{e\gamma}^{\mu e}$ from future experiments

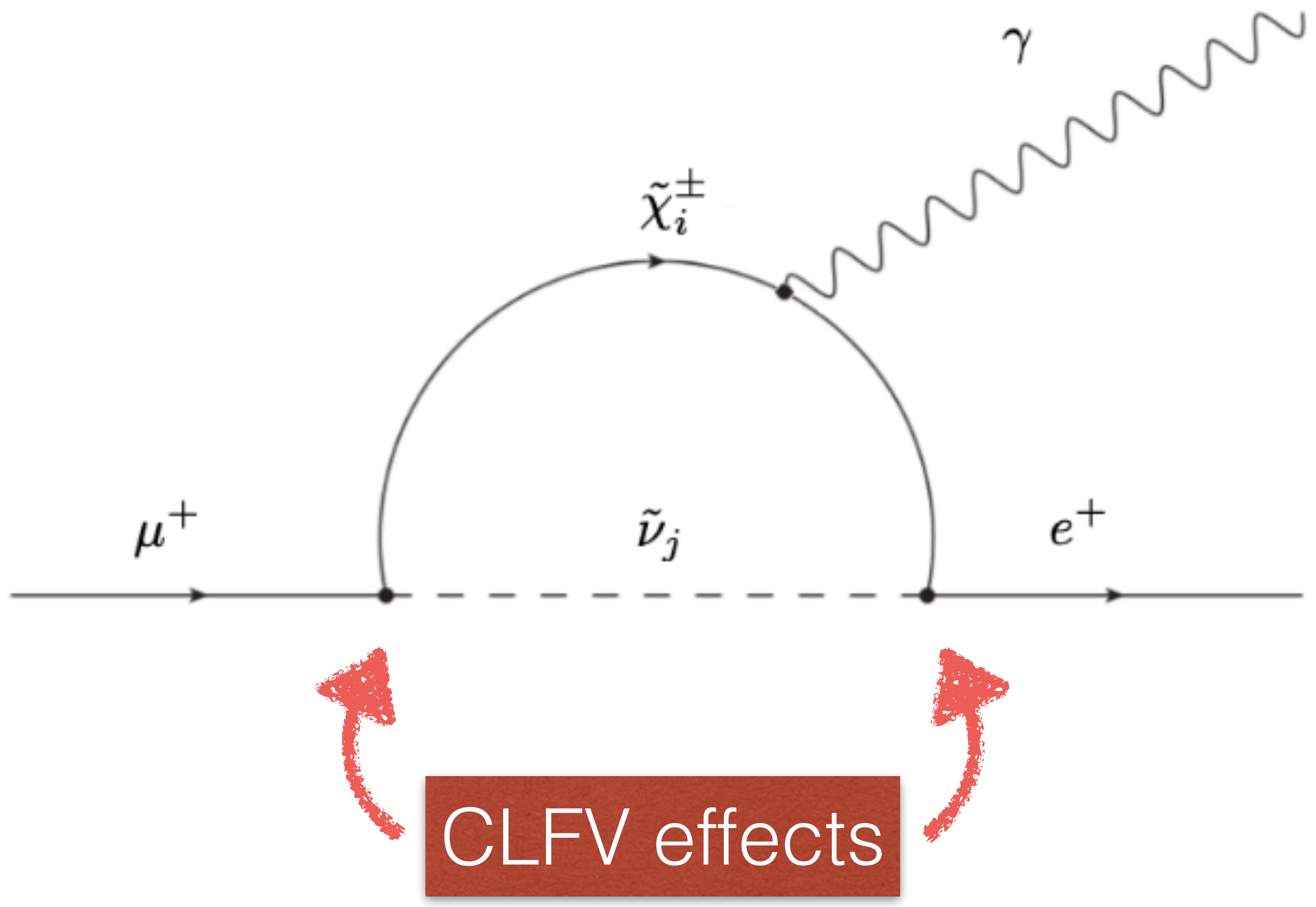
μ→eγ and SUSY theories

Additional fields for each SM particle

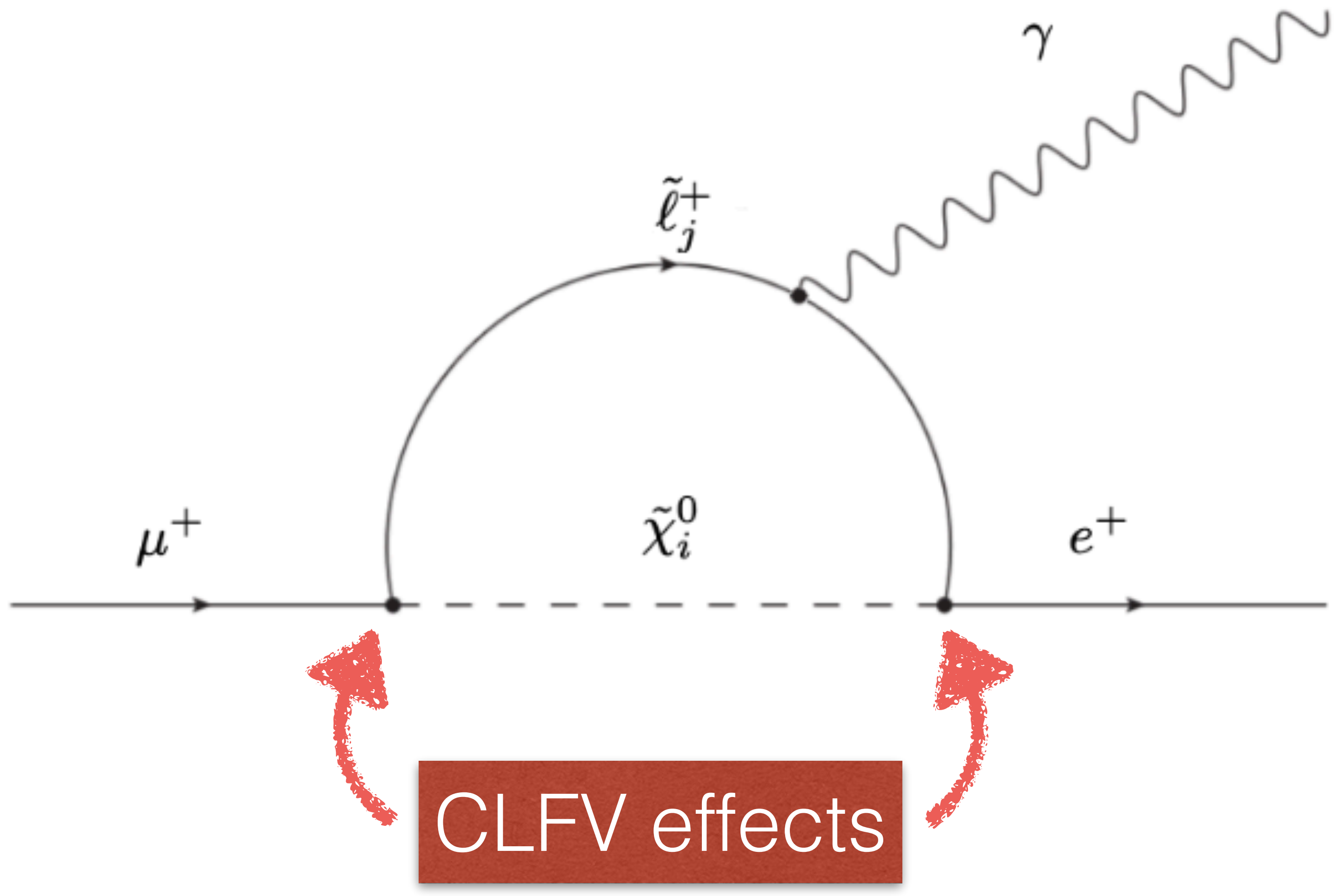
bosons
↕
fermions

SM particle	**SUSY associated**	**SUSY spin**
charged leptons (e, μ, τ)	sleptons ($\tilde{\ell}_i$)	1
neutrinos (ν_e, ν_μ, ν_τ)	sneutrinos ($\tilde{\nu}_i$)	1
quarks	squark	1
neutral gauge bosons (γ, Z^0, h)	neutralinos ($\tilde{\chi}_i^0$)	1/2
charged gauge bosons ($W^\pm$)	charginos ($\tilde{\chi}_i^\pm$)	1/2

Chargino-sneutrino

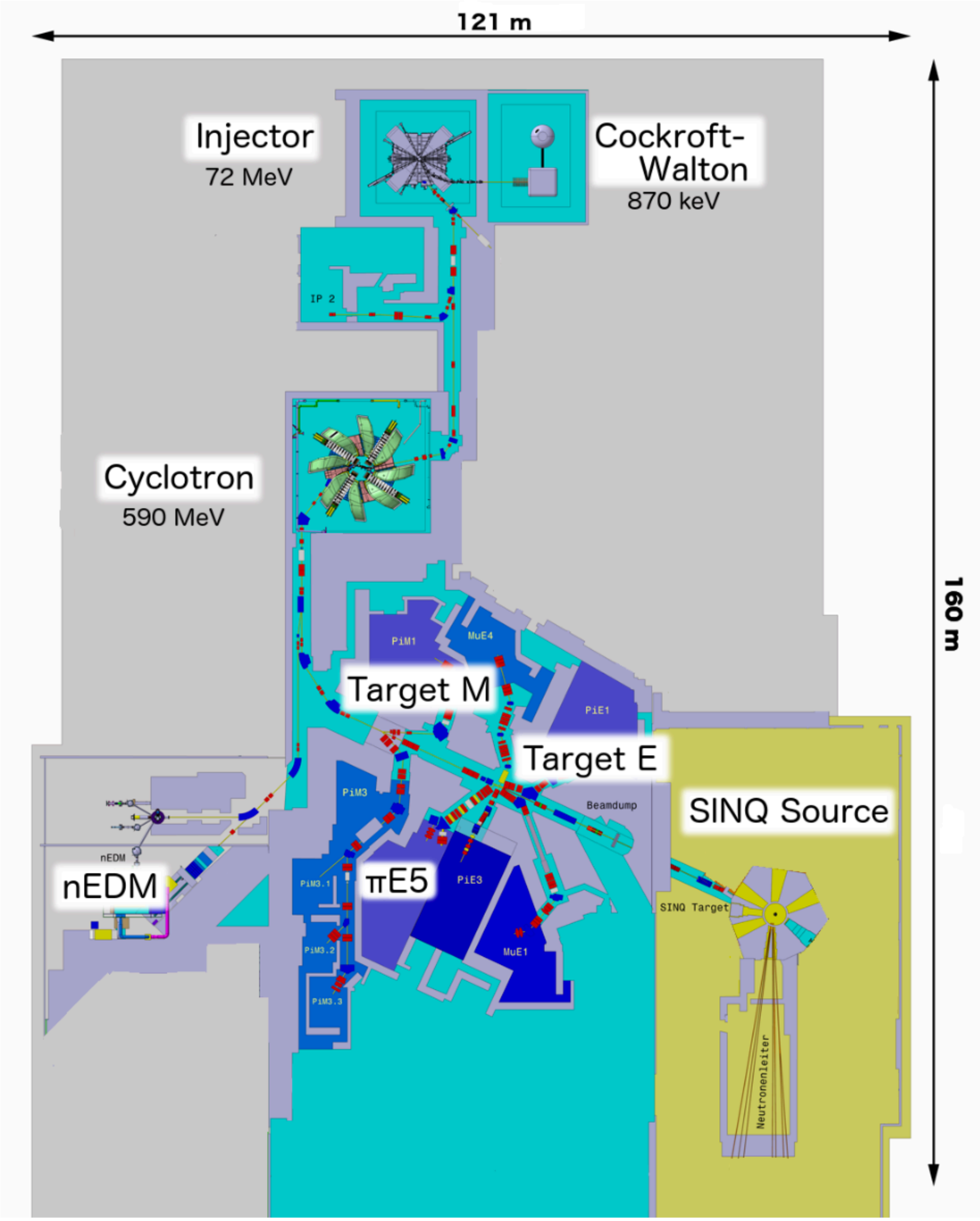


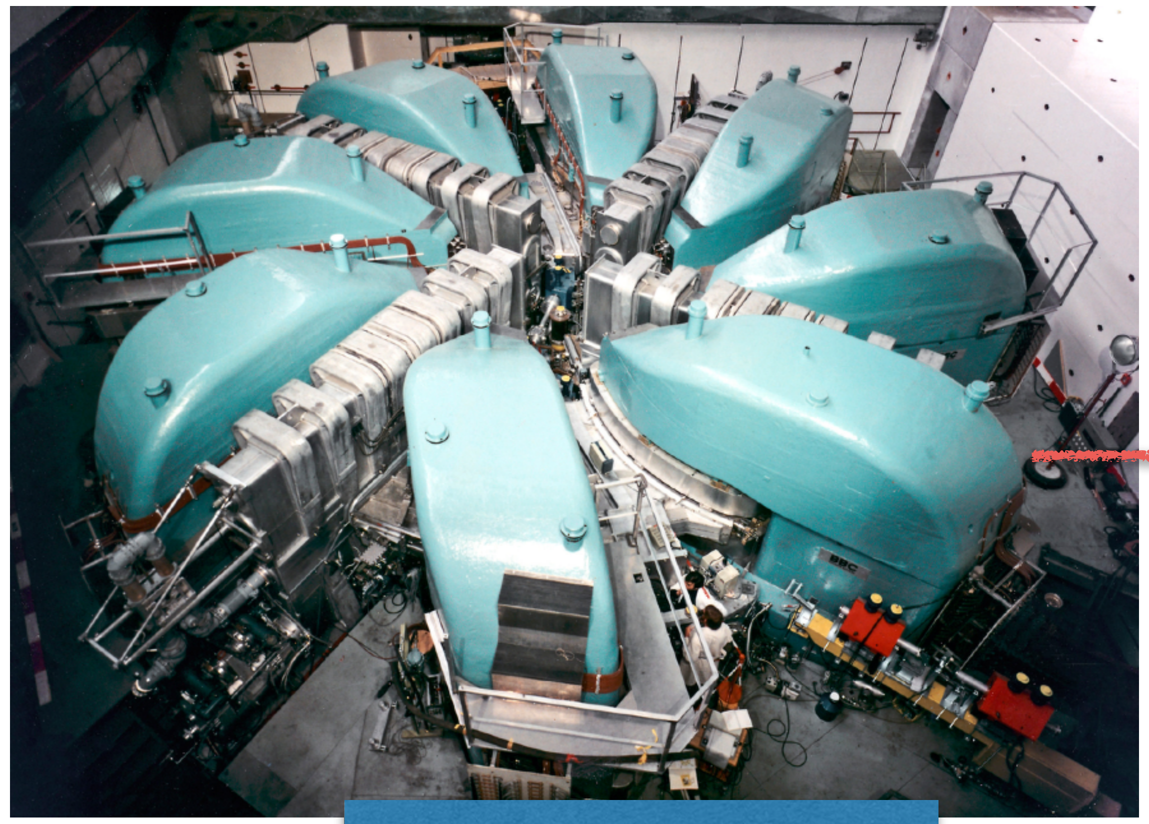
Neutralino-slepton

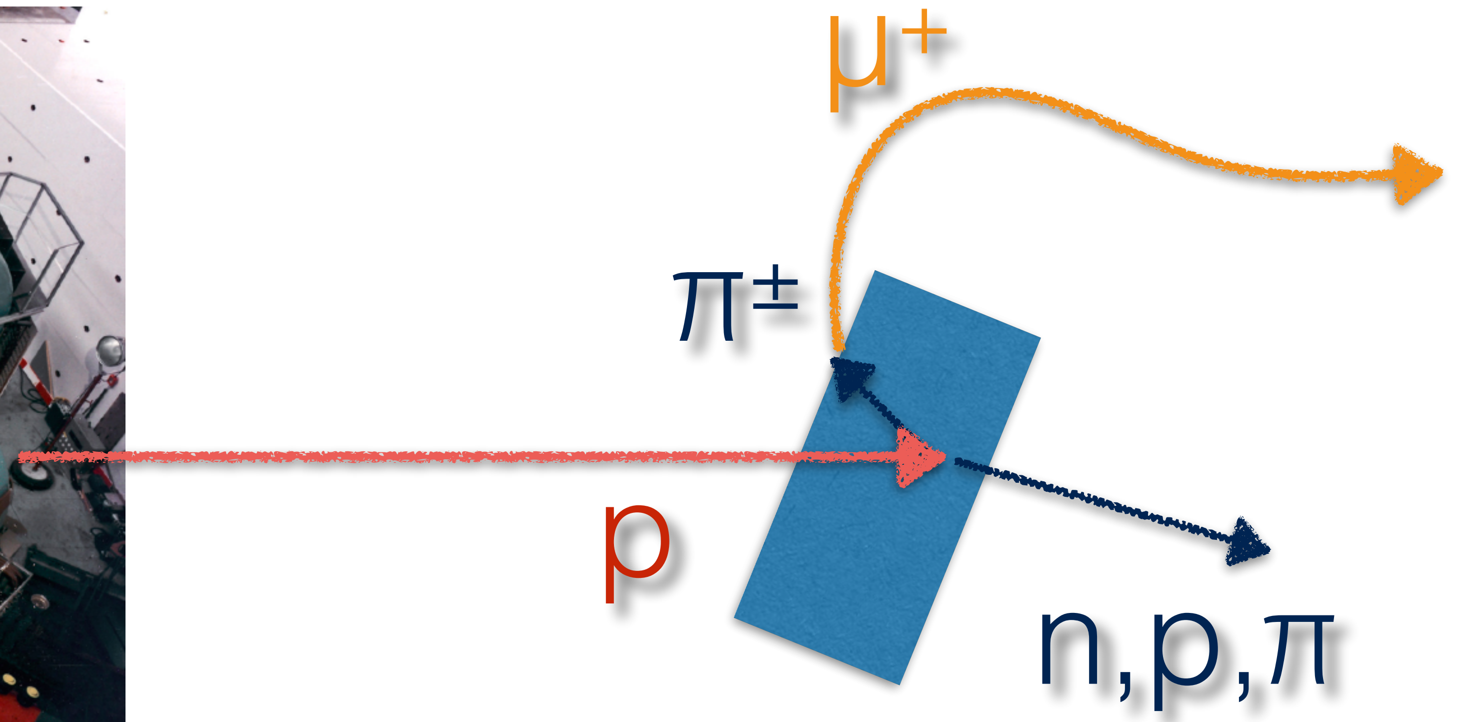


δ_{RR} = normalized off-diagonal component of slepton mass matrix

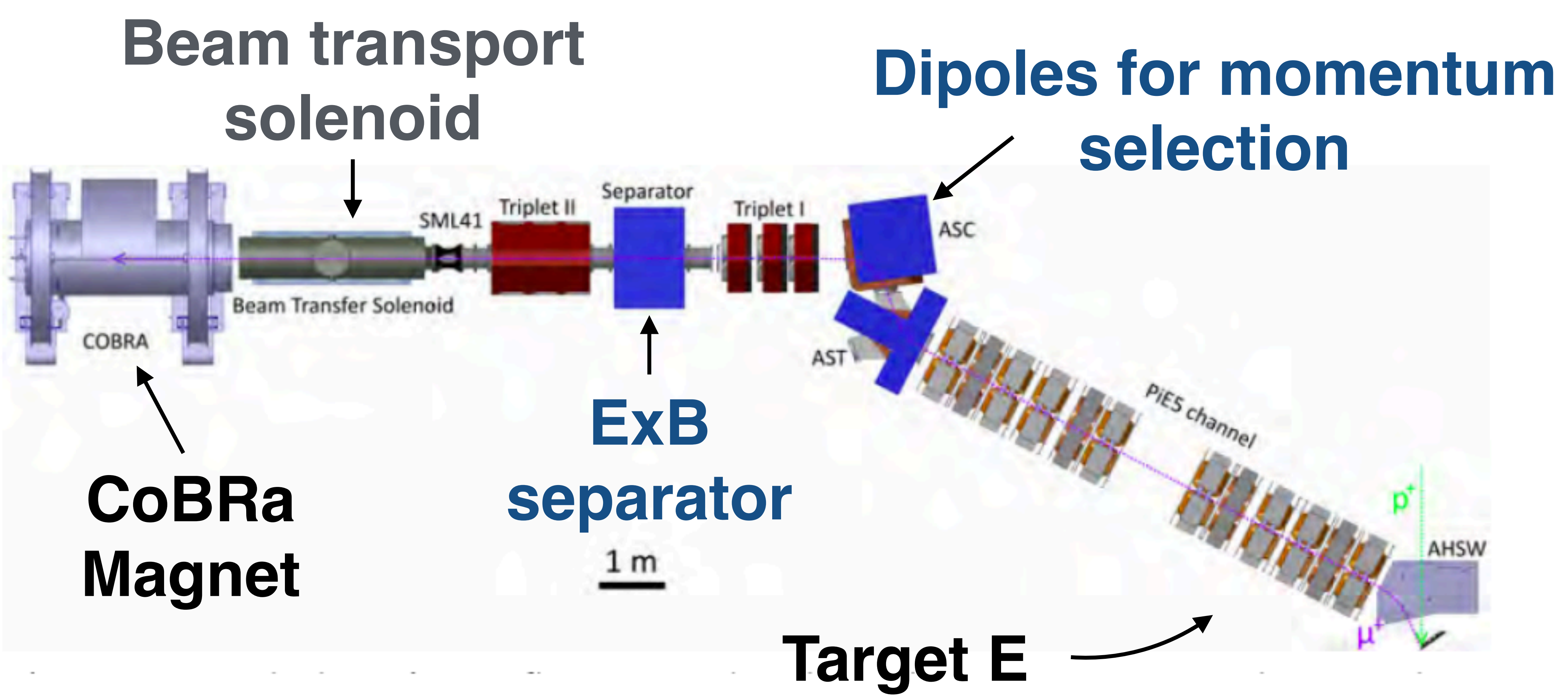
muon beams at PSI



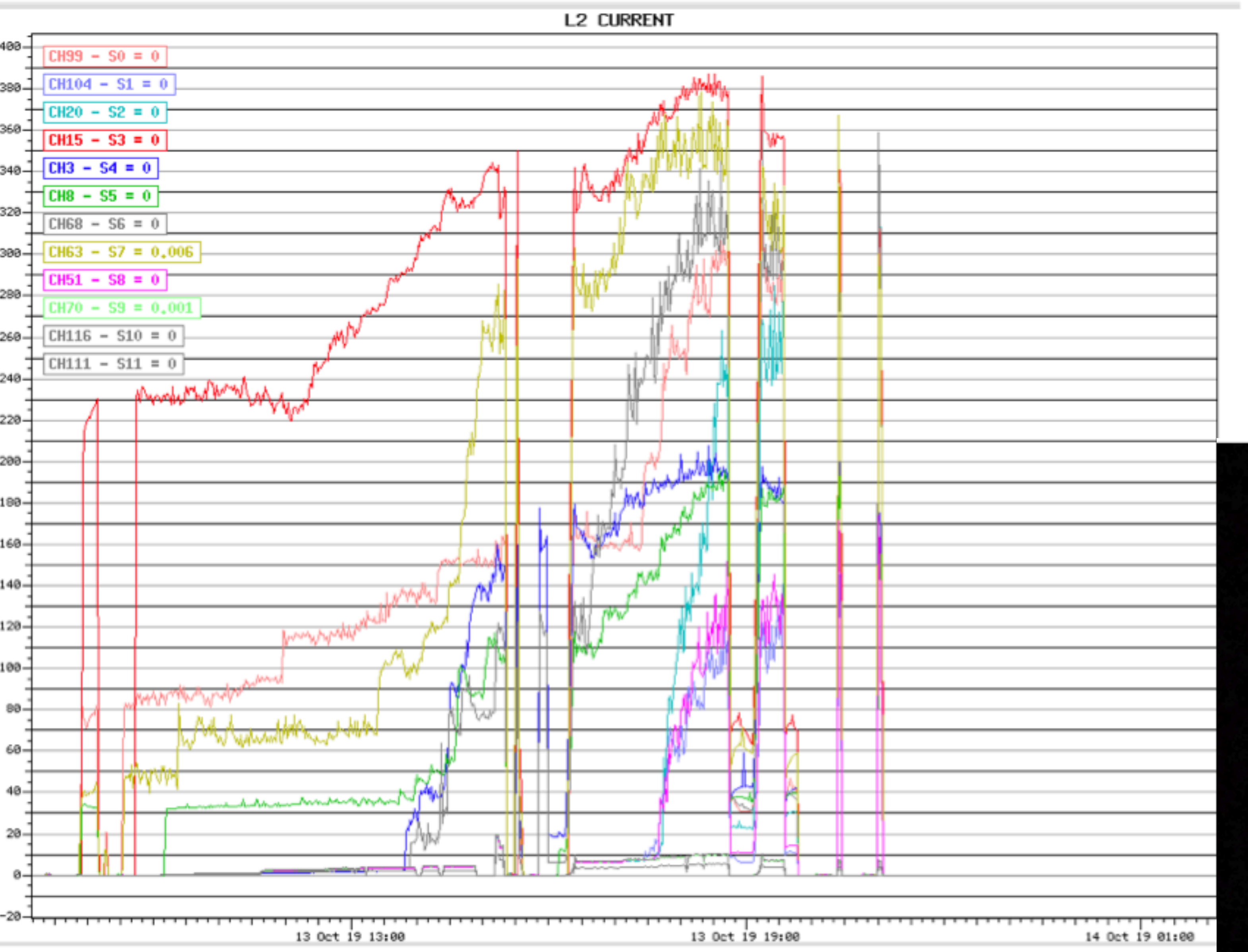




590 MeV protons, 2.2mA current
below kaon production threshold

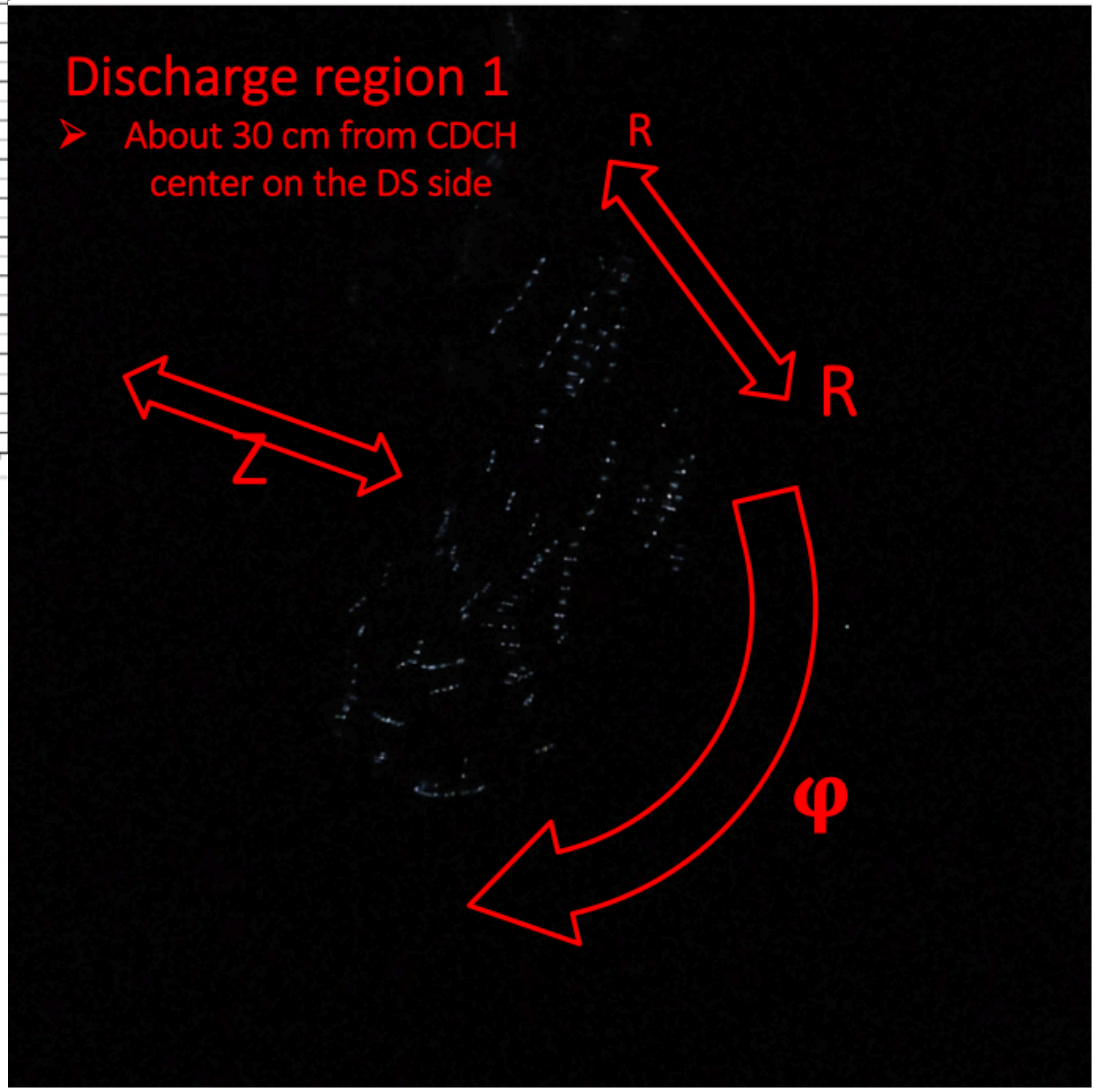


CDCH abnormal currents



Currents up to 300uA

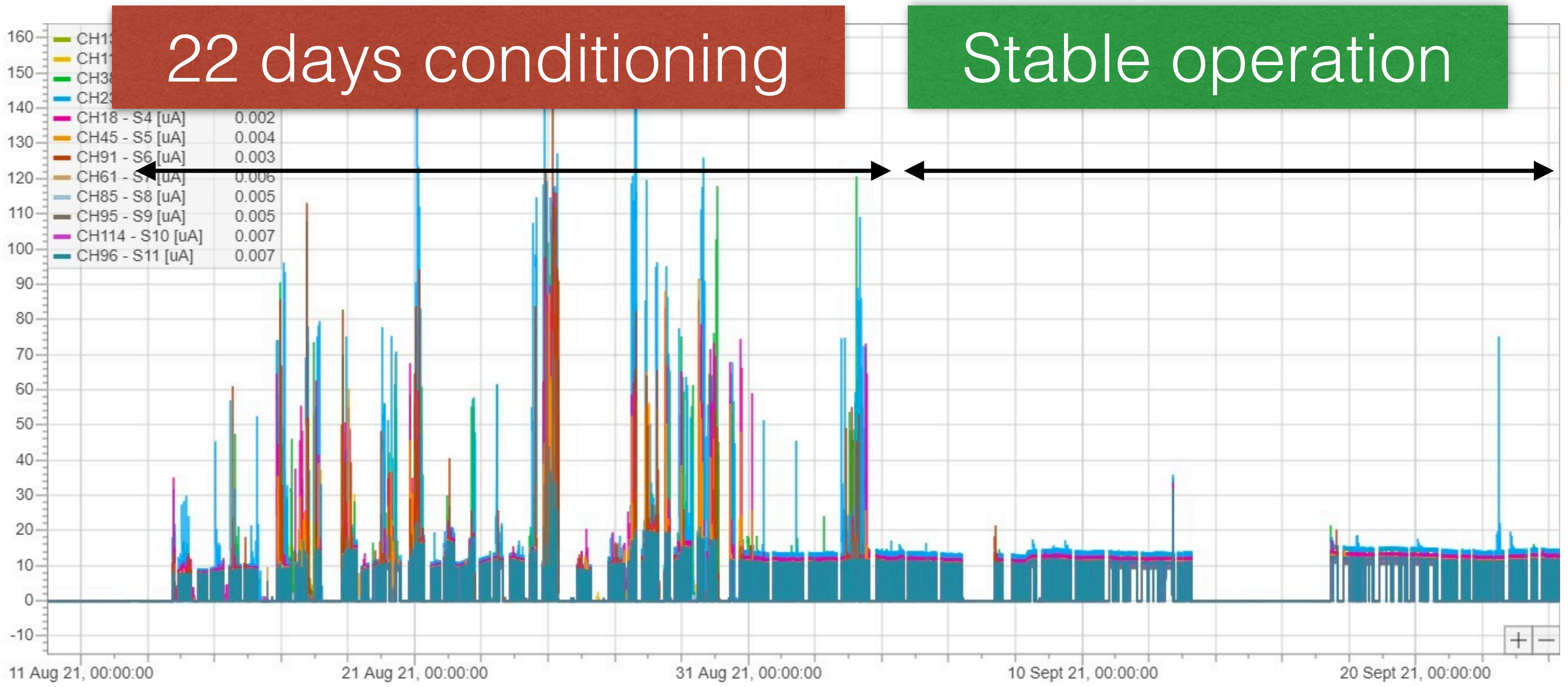
Also at HV levels with no gas amplification



Faint **flickering** (Corona discharges) observed inside the gas volume

in correspondence of white deposits on the wire

Solution:



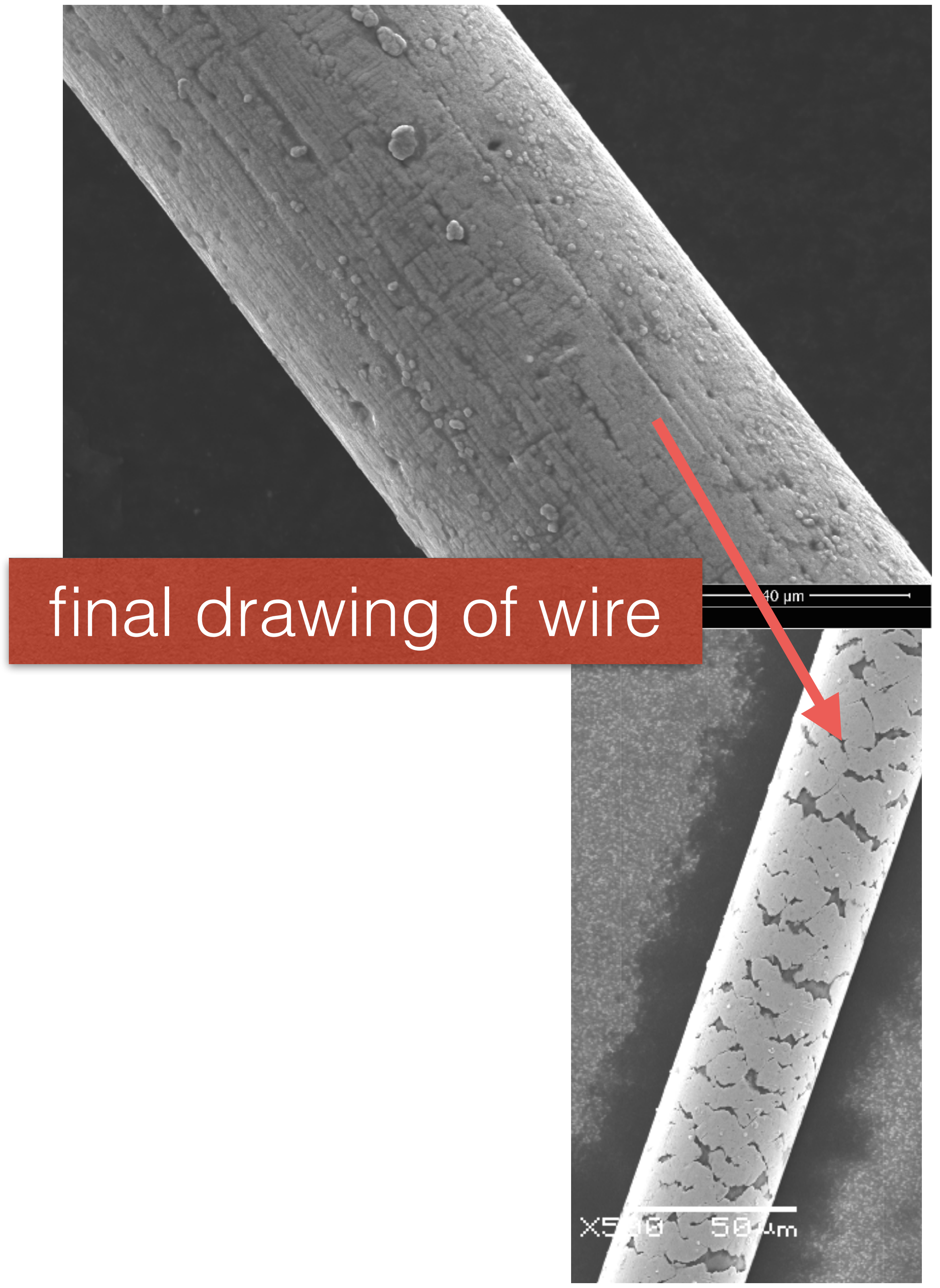
CDCH stable after a period of conditioning with gas mixture with high oxygen volume (>2%)

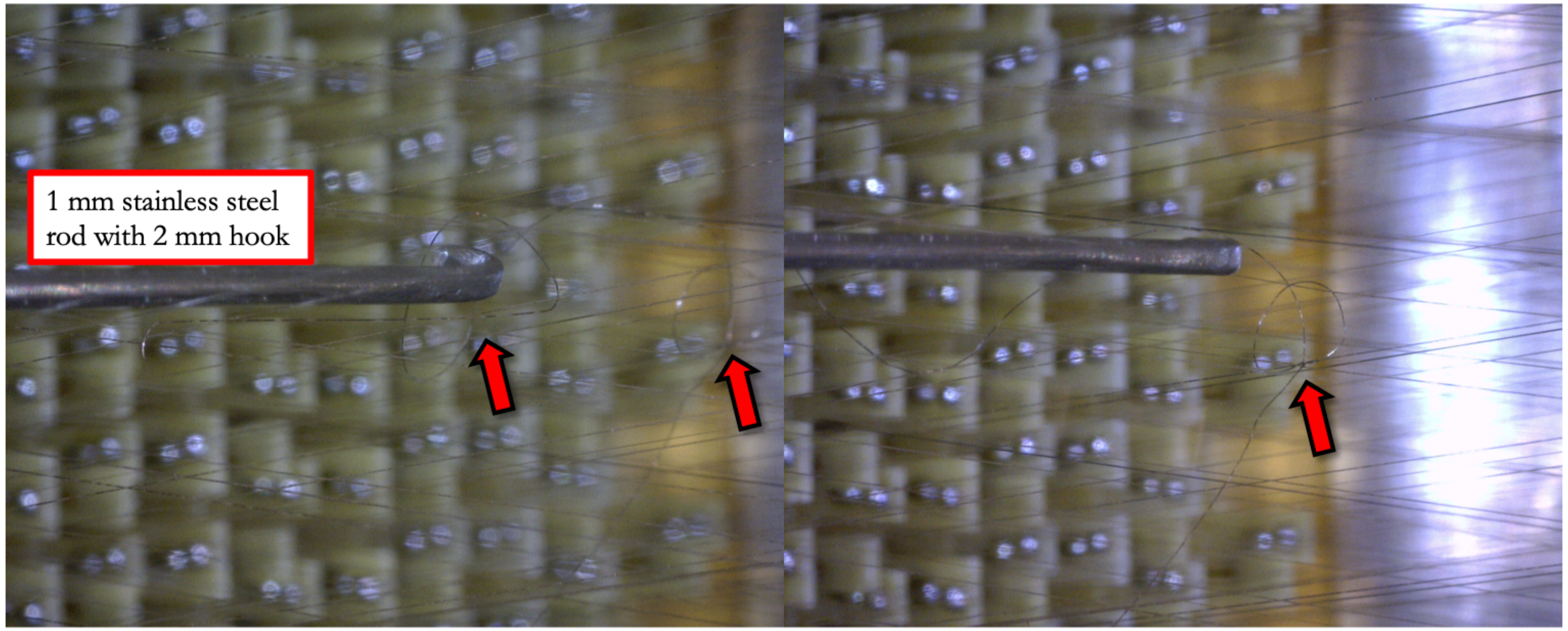
Final 2021 gas mixture:

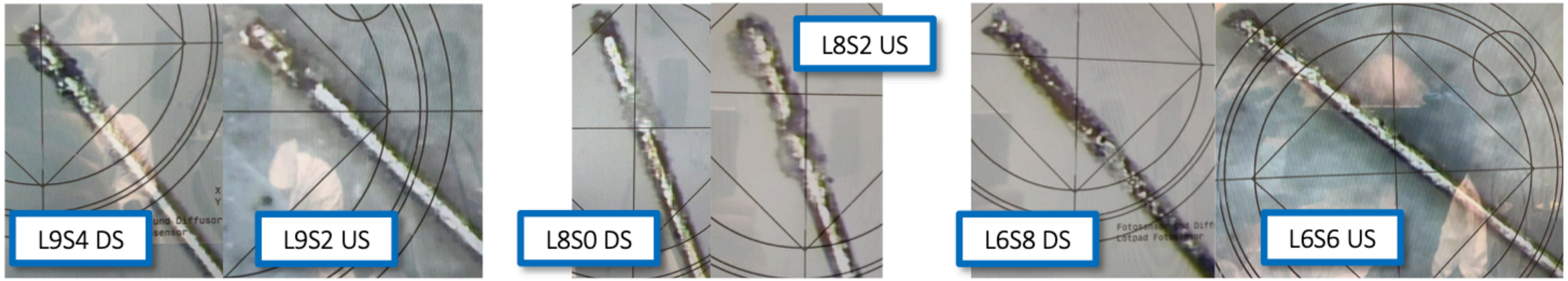
(90%He/10%Isobutane) + 0.5% O2 + 1.2% IsoPropyl alcol

CDCH broken wire removal

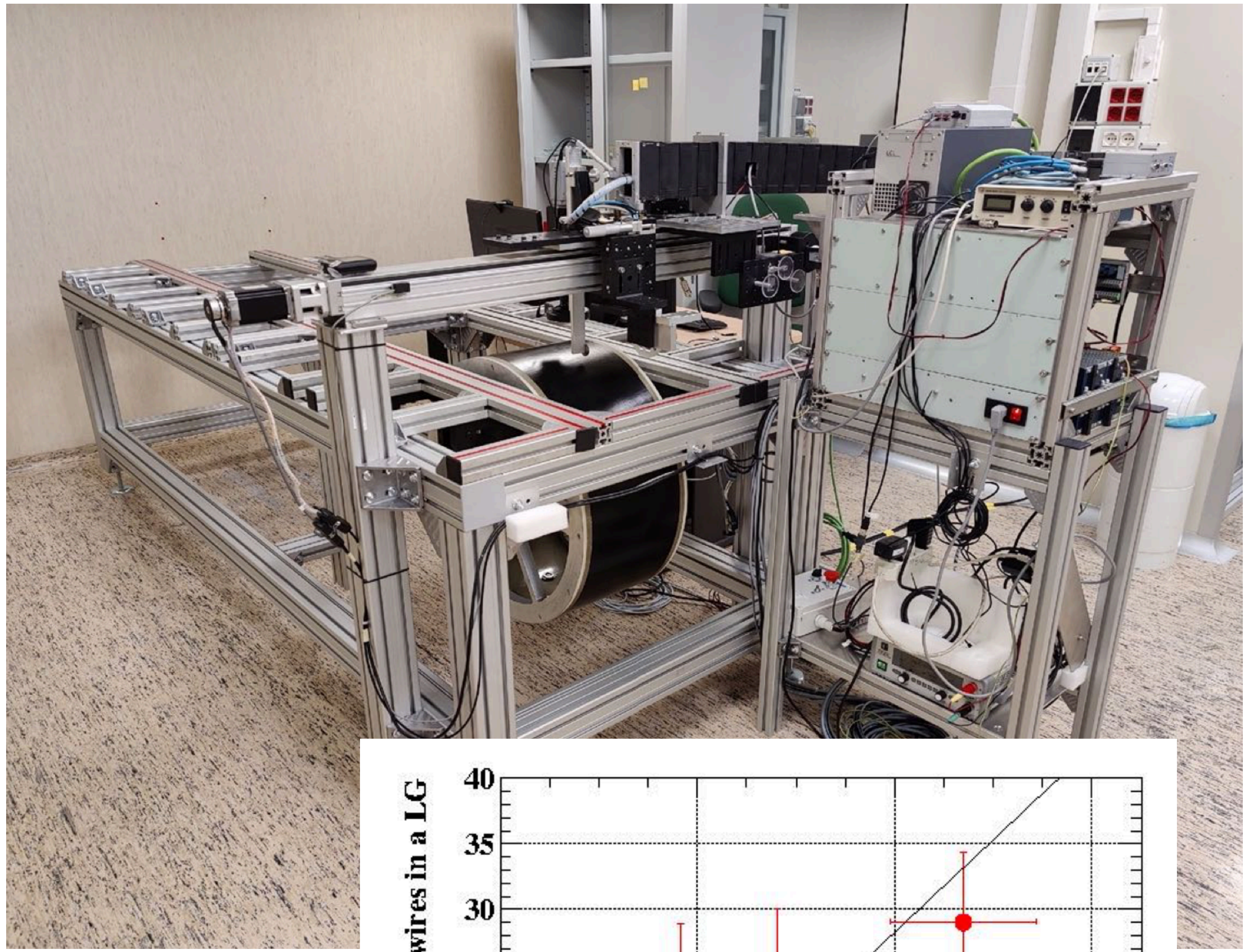
50-40um Al(Ag) cathode wires found to corrode in **humid** environment because of cracks in coating

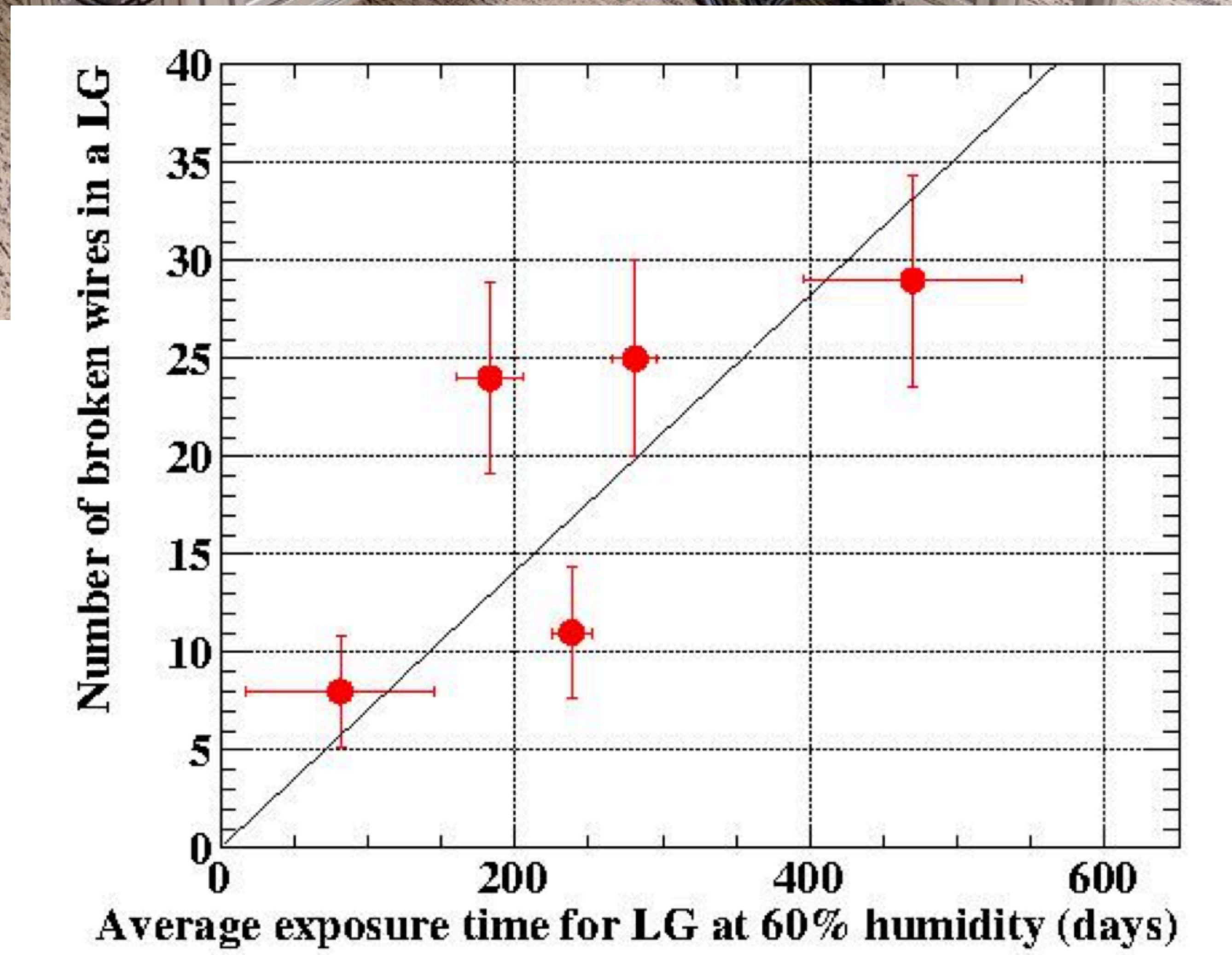






CDCH2: “Backup Drift Chamber”





CDCH2 construction in Pisa: avoid transportation

- Cathode wires ~~without last drawing~~
  - Pure aluminum + glueing
  - Production company not able to reproduce samples
- Avoid unnecessary exposure to humid environment
- Additives from the beginning
- 10th tracking layer

Safety net solution in case of issues
with the first CDCH

Wiring robot ready, Pure Al wire delivered,
Assembly starts soon

Prepared for submission to JINST

Detailed analysis of chemical corrosion of ultra-thin wires used in drift chamber detectors.

A.M.Baldini,[a] G.Cavoto,[d] F.Cei,,[b,1] M.Chiappini,[a] G.Chiarello,[d] C.Chiri,[f] G.Cocciolo,[g] A.Corvaglia,[f] F.Cuna,[g] M.Francesconi,[b] L.Galli,[a] F.Grancagnolo,[f] M.Grassi,[a] R.Ishak,[e] M.Meucci,[d] D.Nicoló,[b] M.Panareo,[g] A.Papa,[b] A.Pepino,[g] F.Raffaelli,[a] F.Renga,[c] E.Ripiccini,[d] G.Signorelli,[a] G.F.Tassielli,[f] R.Valentini,[e] C.Voena.[c]

arXiv:2108.13948v1

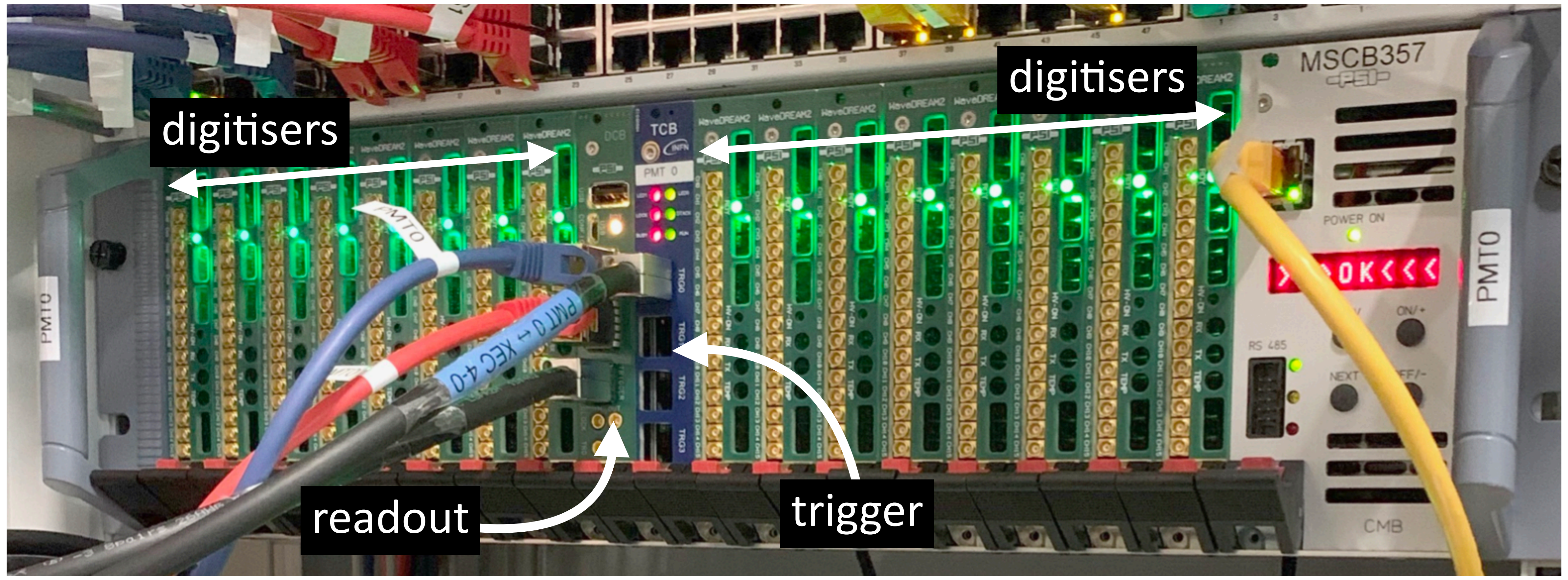
Trigger and Data acquisition

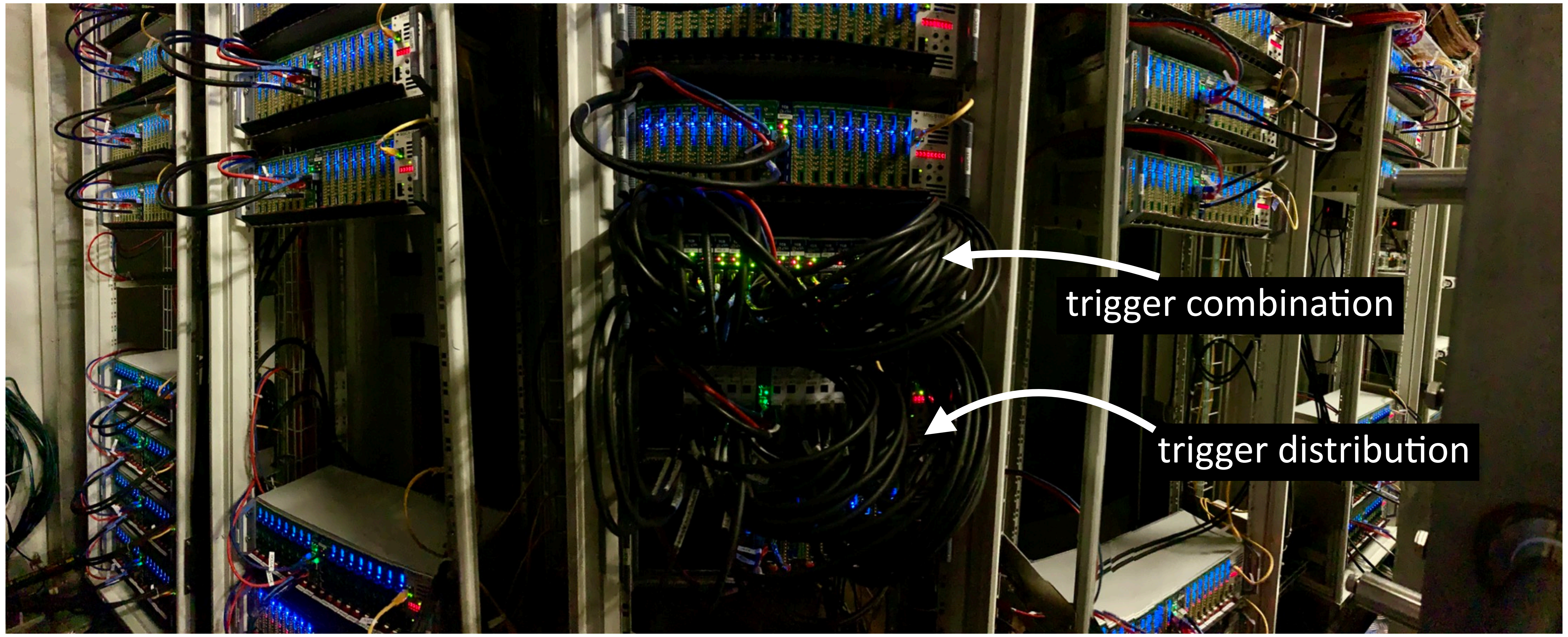
Integrated trigger and data acquisition system, with **high speed digitizers** (up to 5GSPS) on all 9000 channels

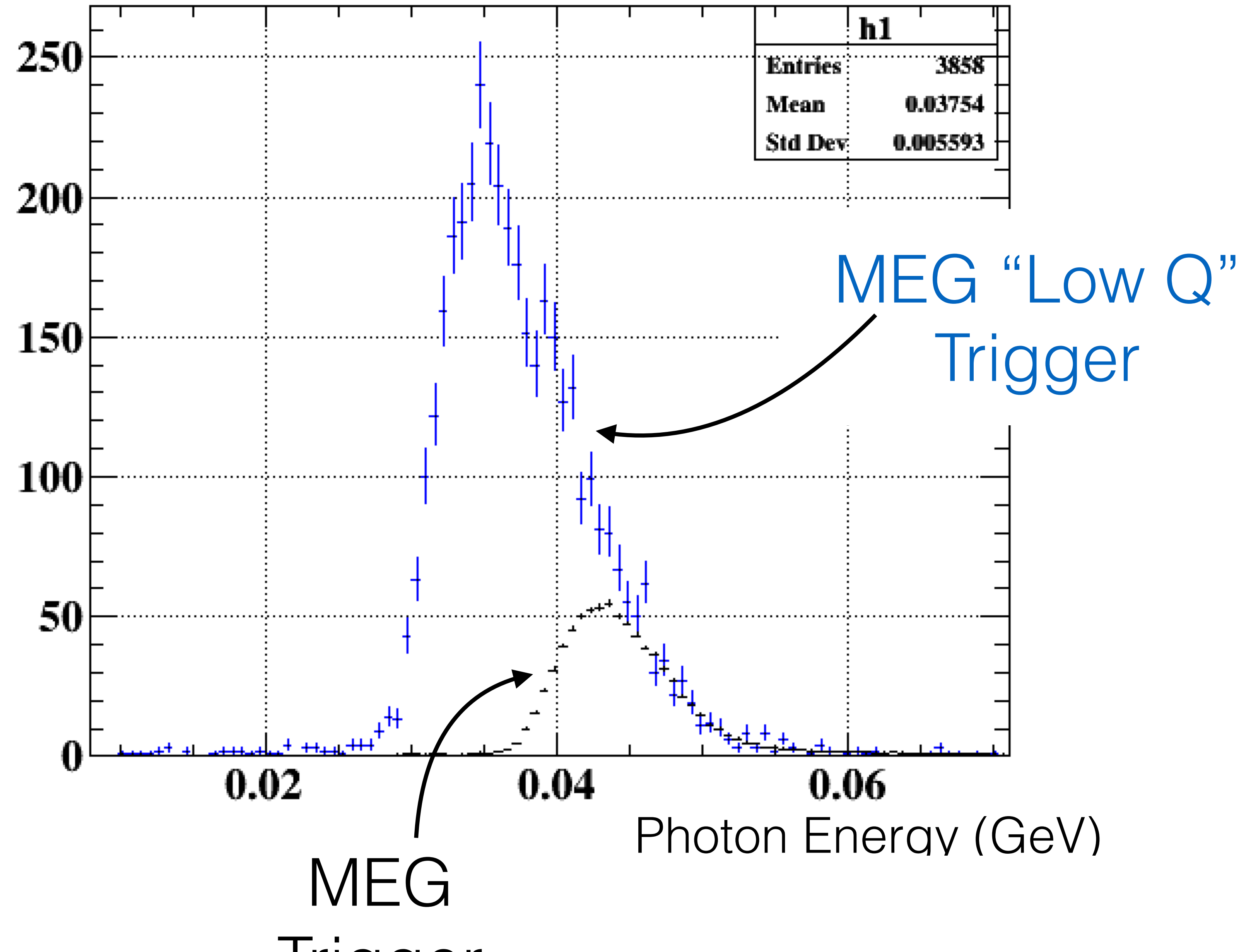
Very large event size (~12 MB)

↓

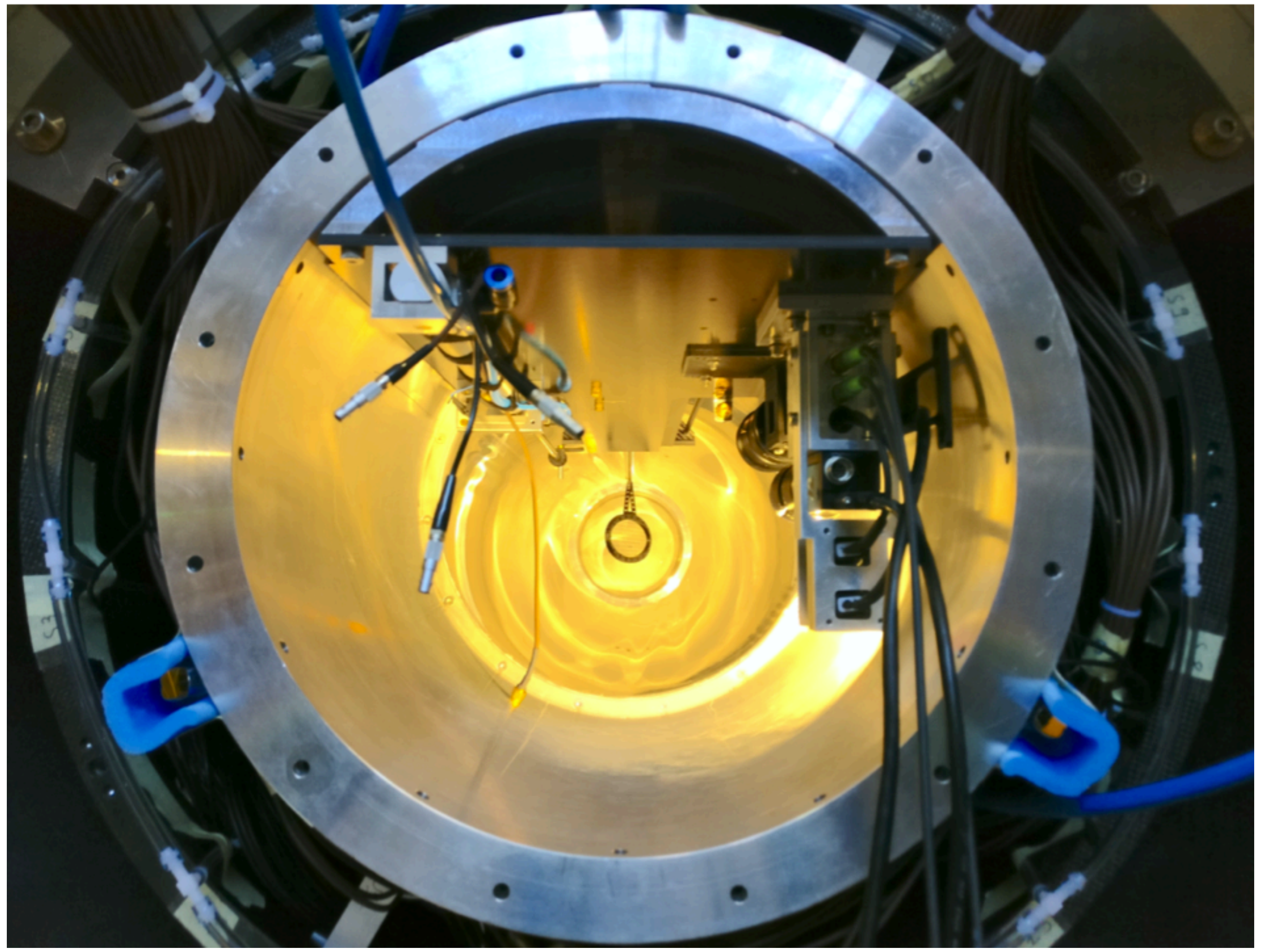
Complex triggers in FPGA to reduce event rate down to ~20 Hz







MEG II Target and monitoring CCDs

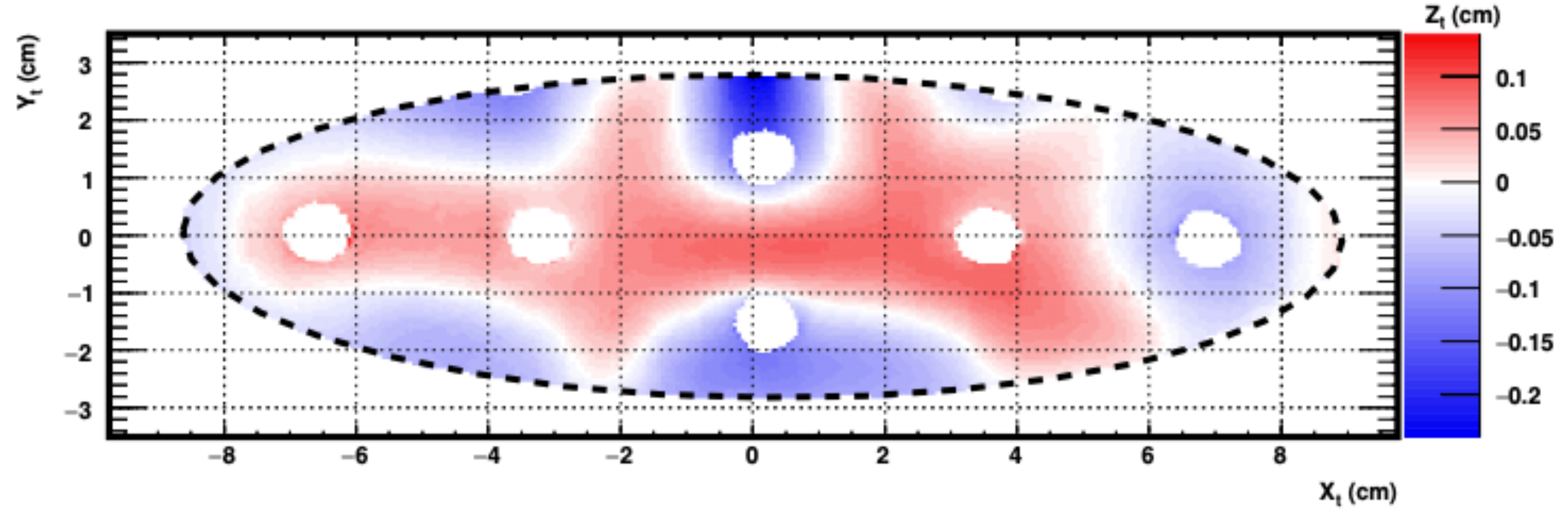


BC400 scintillating target

Markers (dots) for position monitoring using CCDs

Optional UV-sensitive CCD for beam centering monitoring

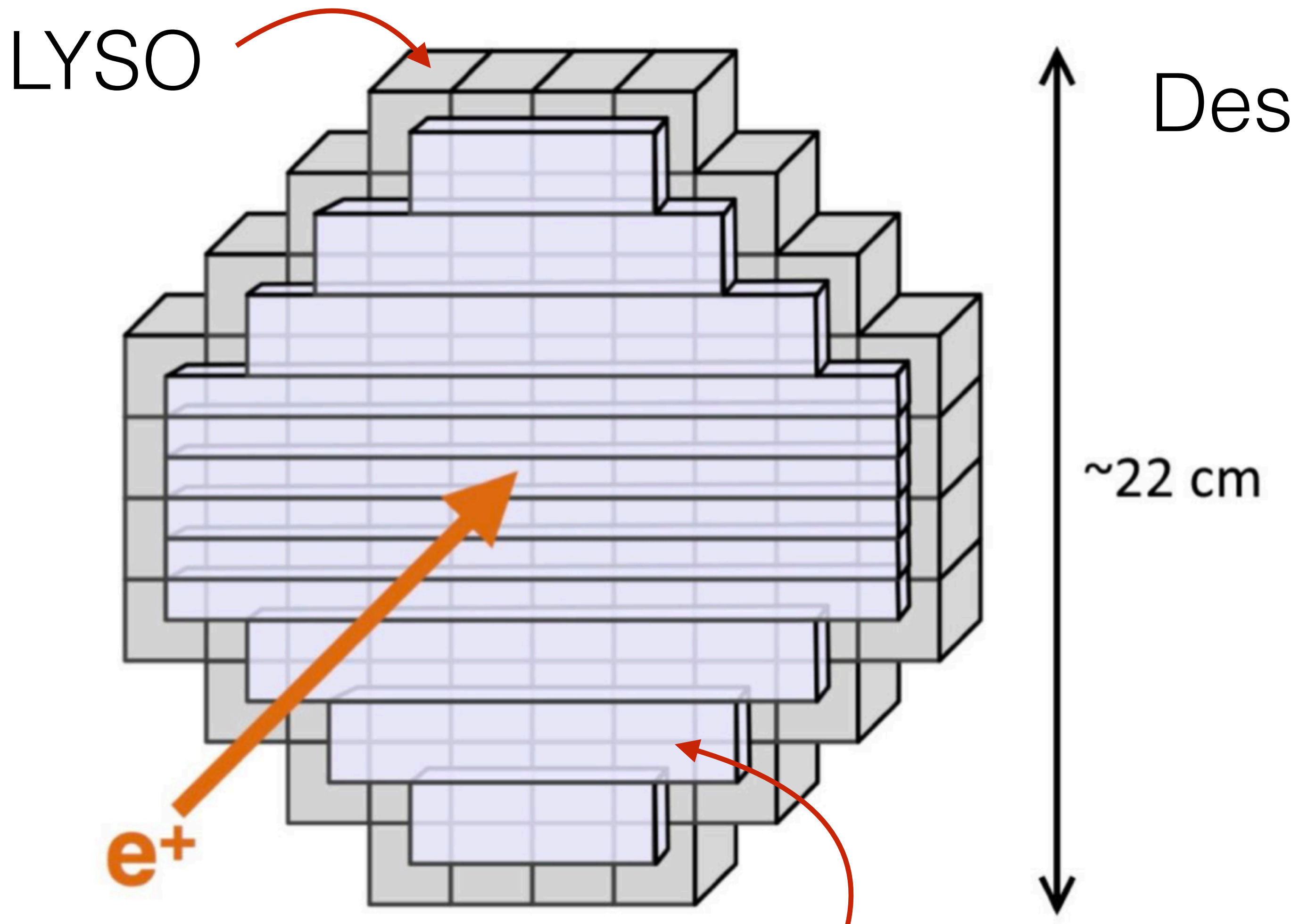
Polyethylene 205μm thickness



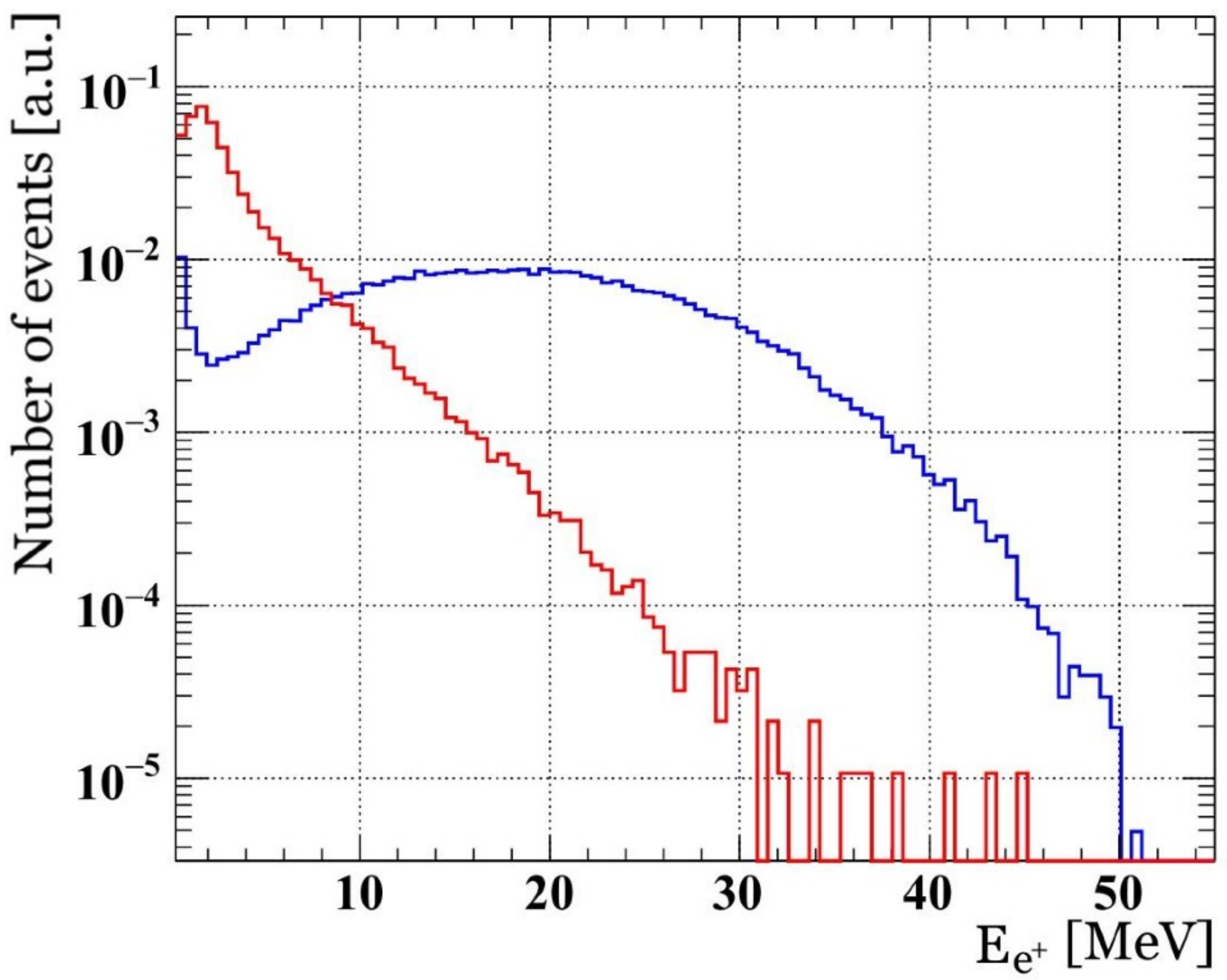
mm-level deformations discover **after** data taking

130μm thickness

RMD detection: the Radiative Decay Counter



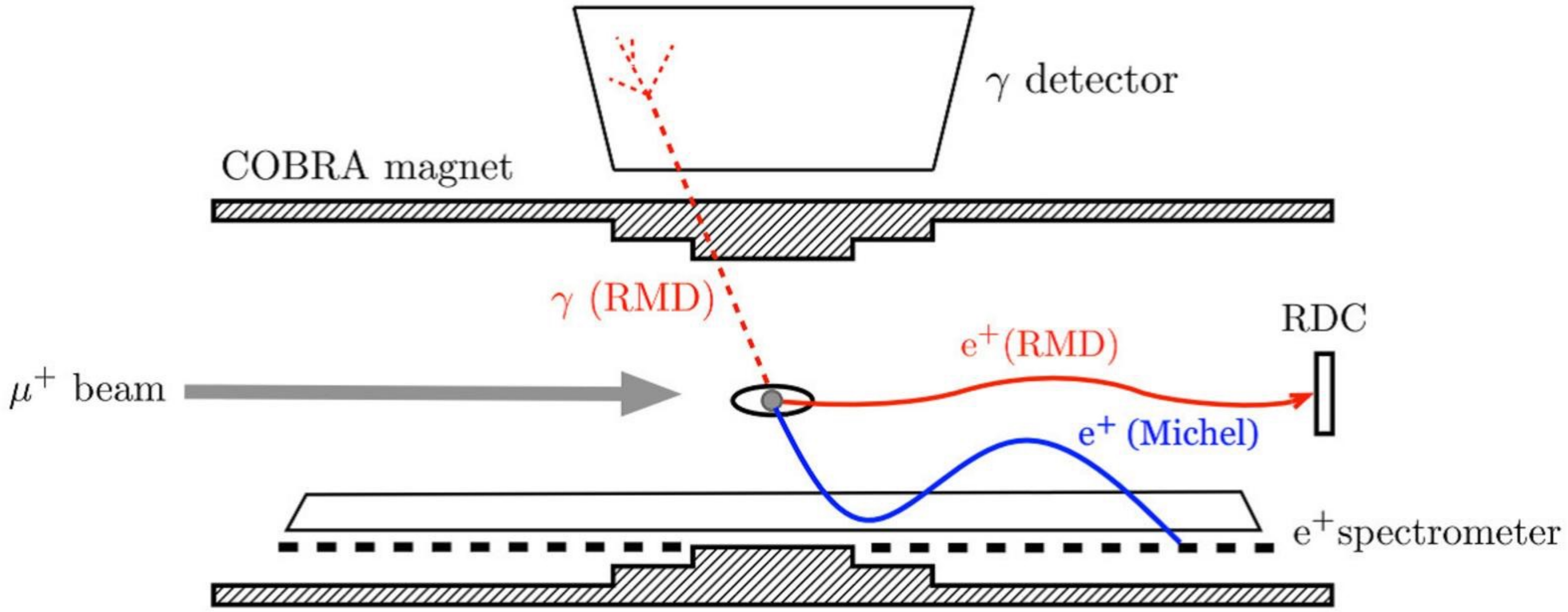
Designed to detect **low energy positron** associated to high energy Radiative Michel decays

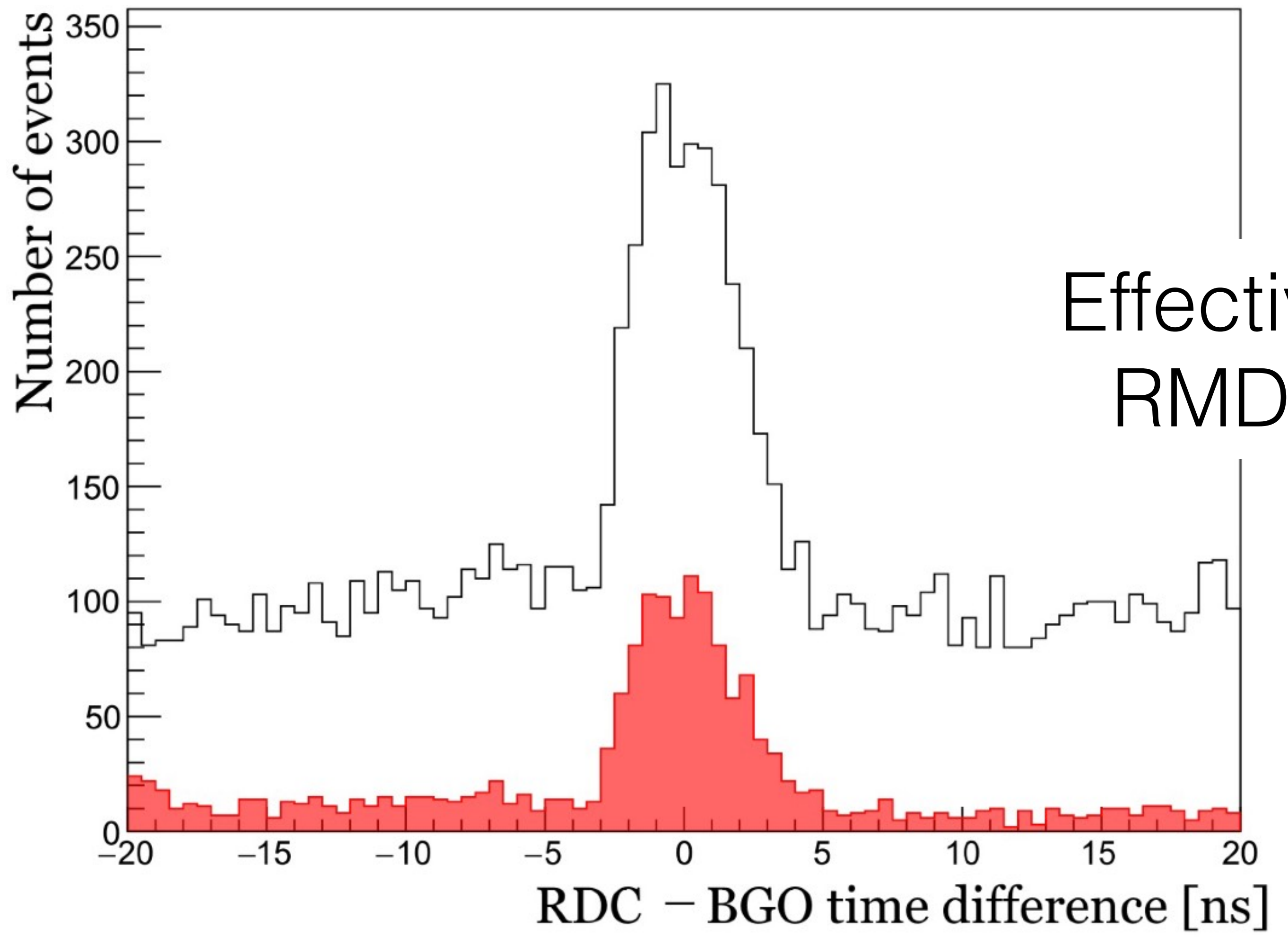


Identification based on energy deposit in plastic scintillator

RMD (1-4 MeV)
Michel (>48 MeV)

High timing precision to provide anti-coincidence to main gamma reconstruction





Effective to select RMD positrons

MEG II Calibrations

C-W proton accelerator

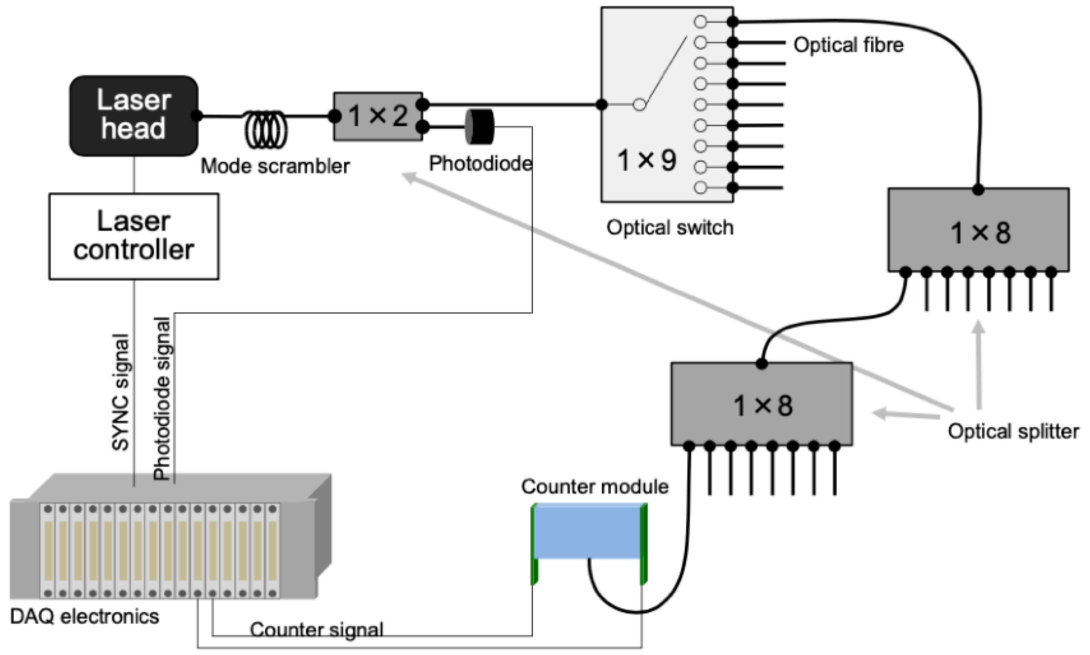
Up to 1 MeV proton on $LiBO_4$ target

Energy calibration line :

$$p\ ^{7}\mathrm{Li} \rightarrow\ ^{8}\mathrm{Be}\ \gamma(17.6\ \mathrm{MeV})$$

XEC-pTC time alignment with line :

$$p\ ^{11}\mathrm{B} \rightarrow\ ^{12}\mathrm{C}\ \gamma(11.6\ \mathrm{MeV})\ \gamma(4.4\ \mathrm{MeV})$$



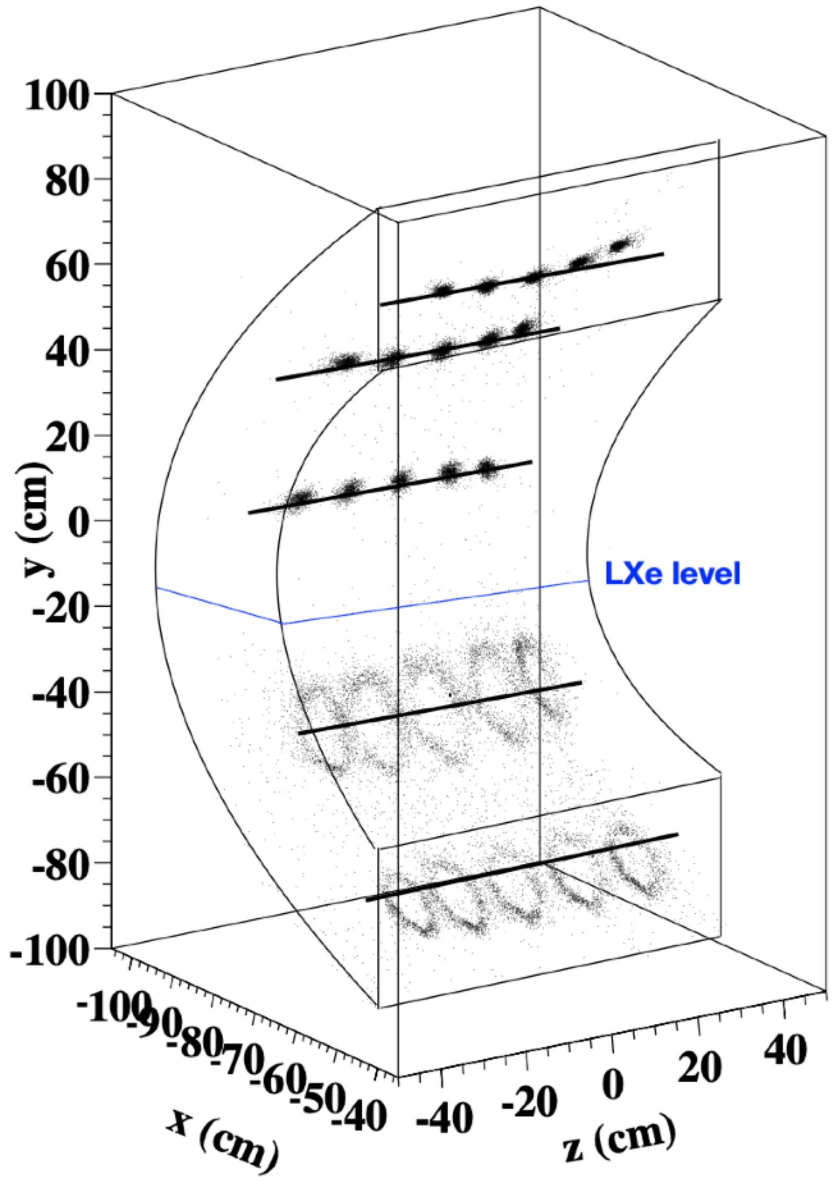
Laser system

401 nm laser

Distribution to a big part of pTC Tiles

Time offset monitoring

α particle sources in Liquid Xenon



25 point-like sources on wires

Localized energy deposit (40 μm range in LXe)

For detection efficiency monitoring calibration

Charge Exchange reaction

Energy & time calibration at signal energy

$$\pi^{-} p \rightarrow \pi^{0} n$$
$$\pi^{0} \rightarrow \gamma\gamma$$

Movable array of BGO Crystals

Energy in 55-83 MeV range

Other calibrations

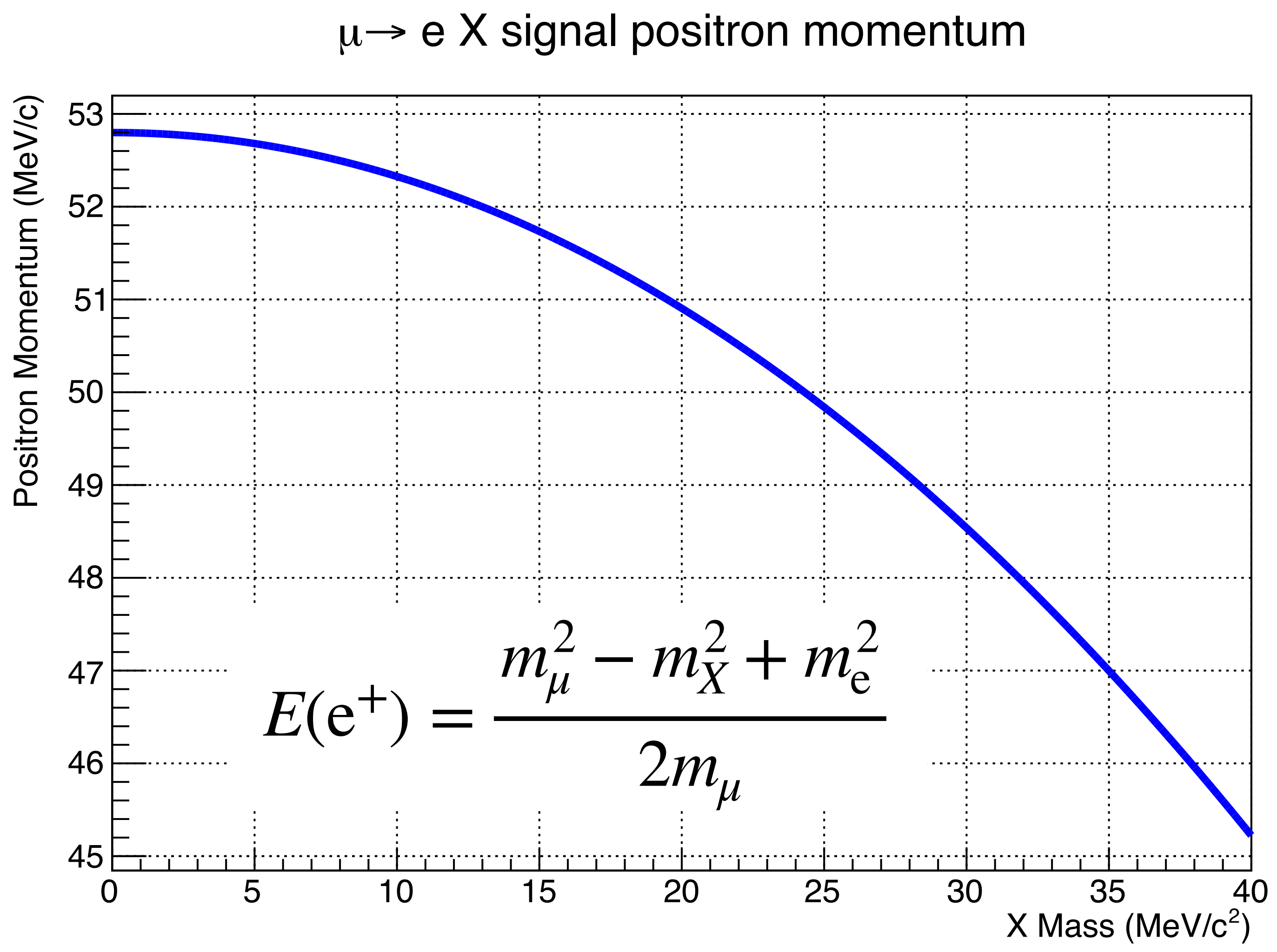
Drift chamber:
- Cosmic rays
- Mott scattering
- B-field mapping

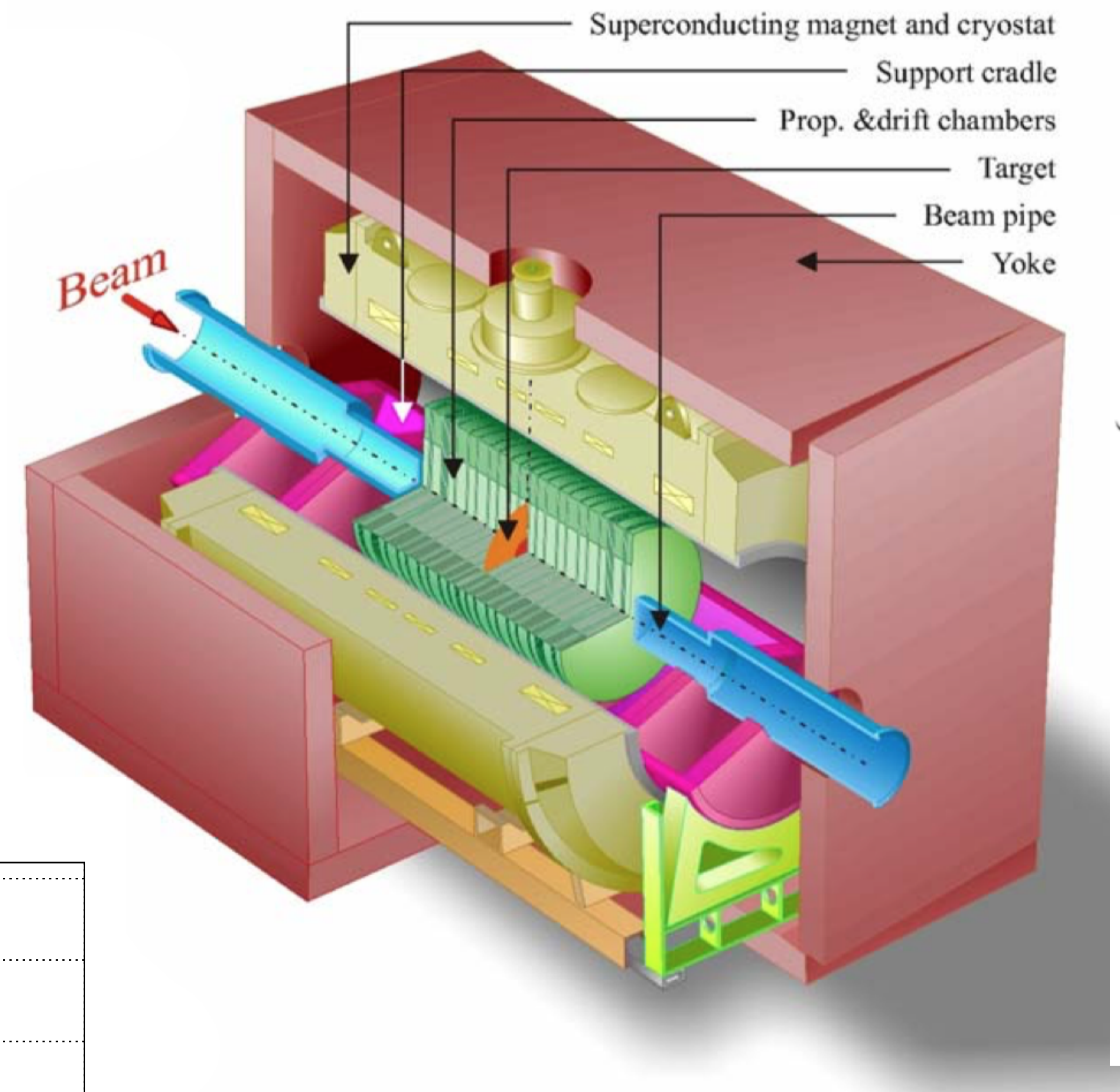
Liquid Xenon detector:
- LED
- AmBe γ(4.4 MeV)
- Neutron-Nicke γ(9 MeV)
- ^{57}Co X-Ray position survey

$\mu^+ \to e^+ X$ and TWIST Experiment

μ→eX peculiarities:

- Monocromatic
- Possible angle dependencies
  - Not in MEG
- mX <25MeV/c^2
  - Pe>50 MeV/c



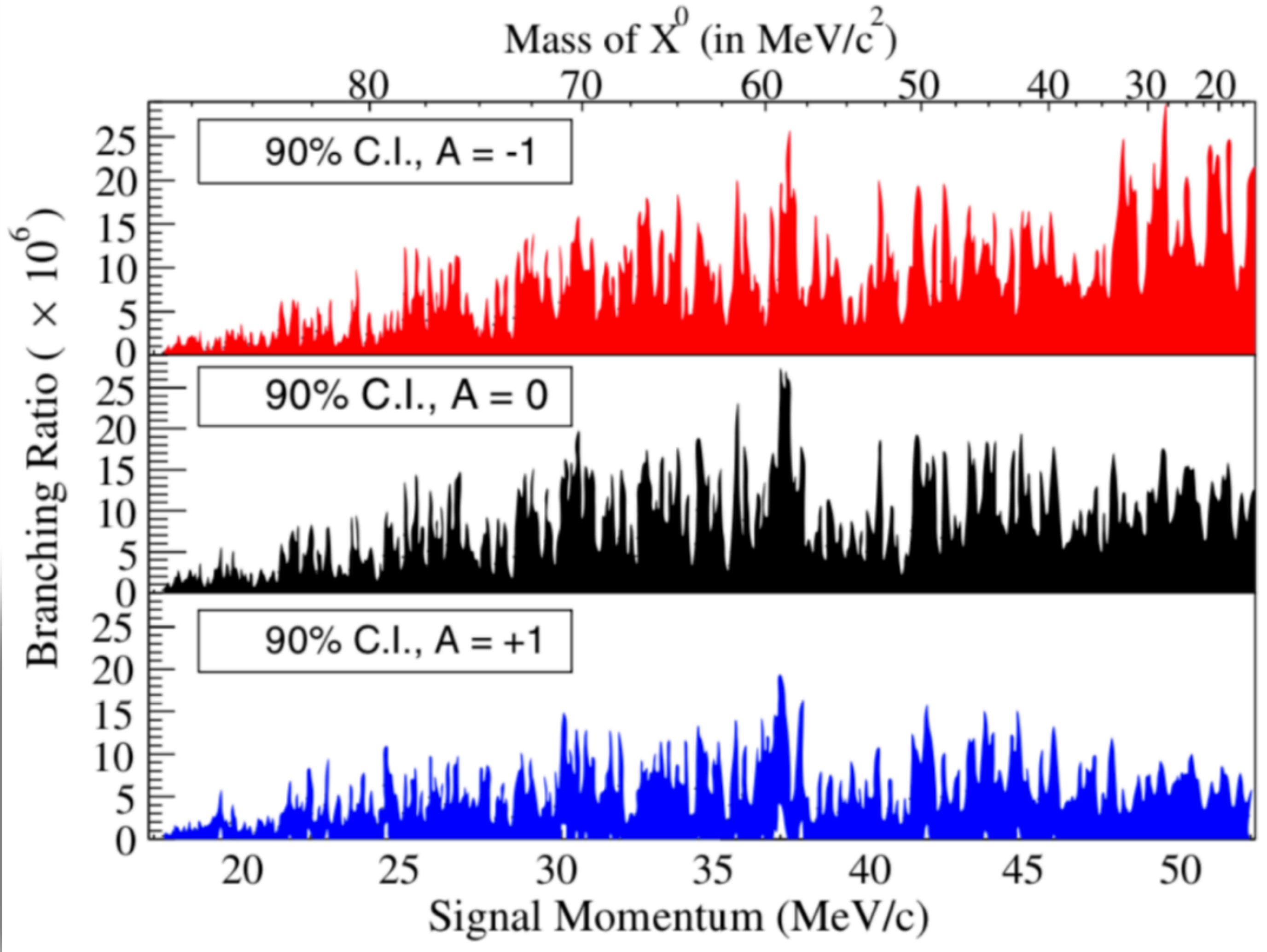


Target:
75 μm aluminium
30 μm silver

2T solenoid **magnetic field**

95 keV/c momentum resolution in signal region (|cosθ|>0.6)

Forward-backward spectrometer designed to measure Michel parameters of muon decay



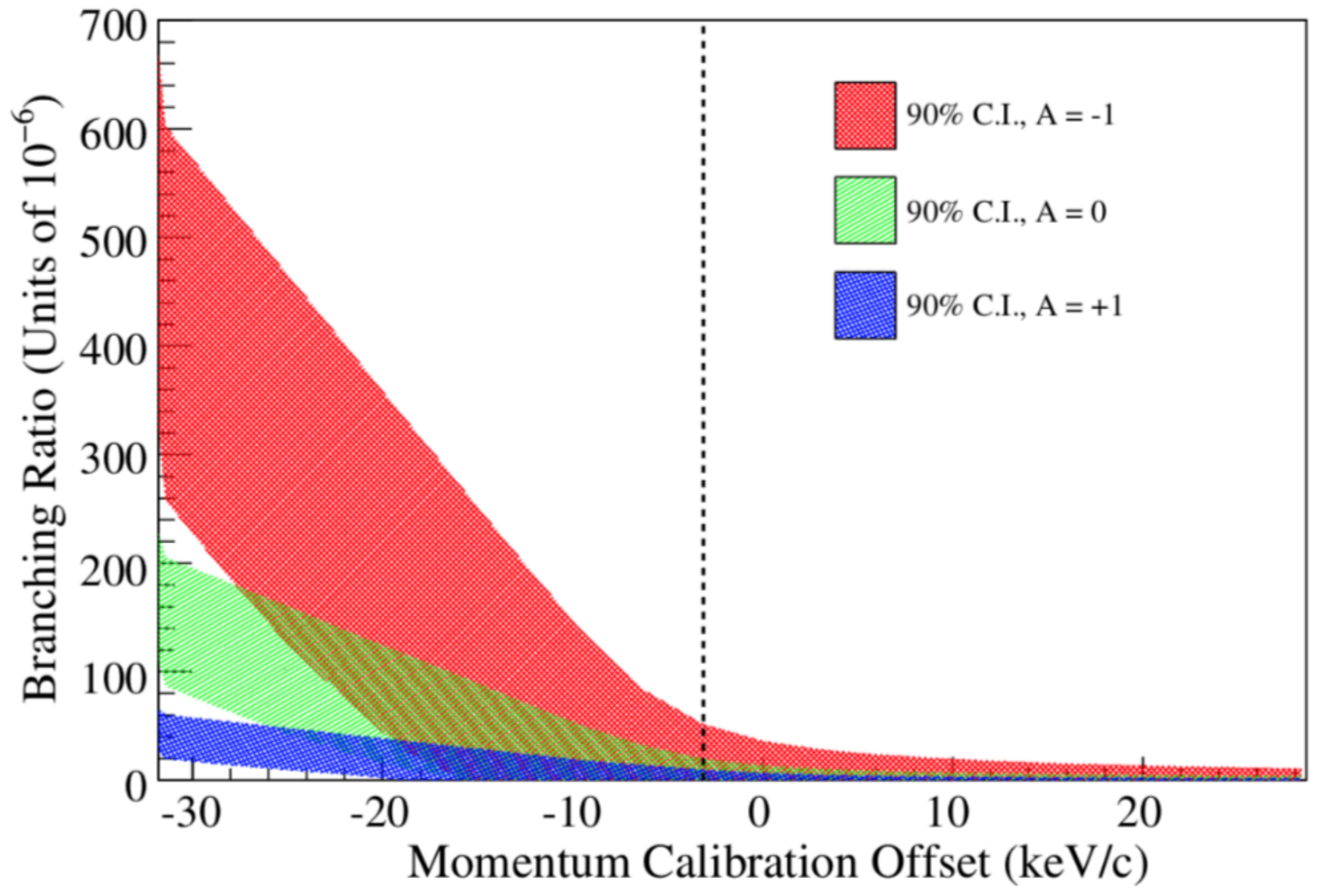
$m_X > 13$ MeV/c^2 $\leftrightarrow E_e < 52$ MeV

Kinematic endpoint of background Michel spectrum can be used to establish a momentum scale

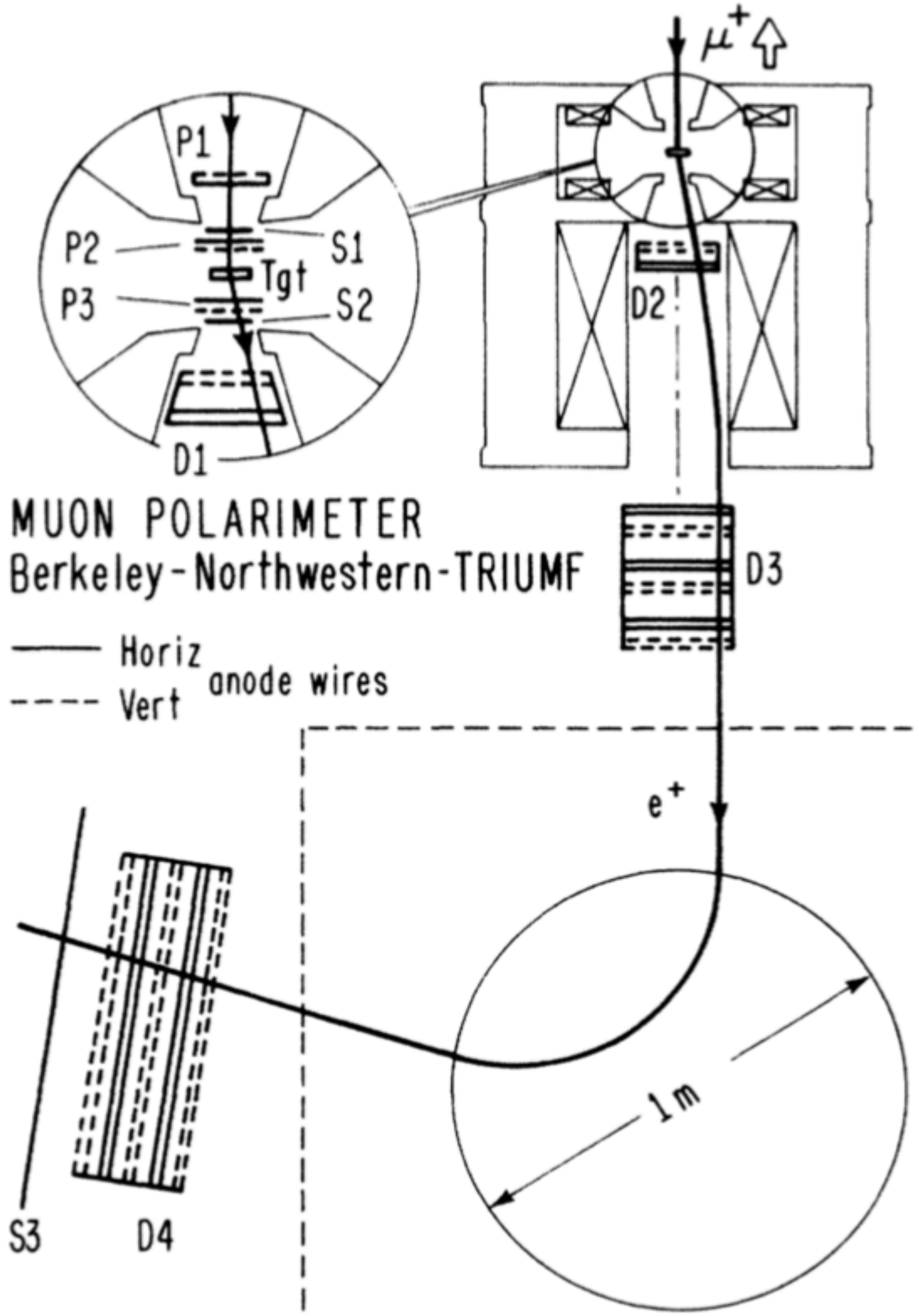
$m_X < 13$ MeV/c^2 $\leftrightarrow E_e > 52$ MeV

External momentum scale used

-4.3 ± 6.1 keV/c



$\mu^+ \to e^+ X$ and A. Jodidio setup



Single arm spectrometer 1T field

Use **spin rotation technique**:
rotate muon spin keeping apparatus fixed

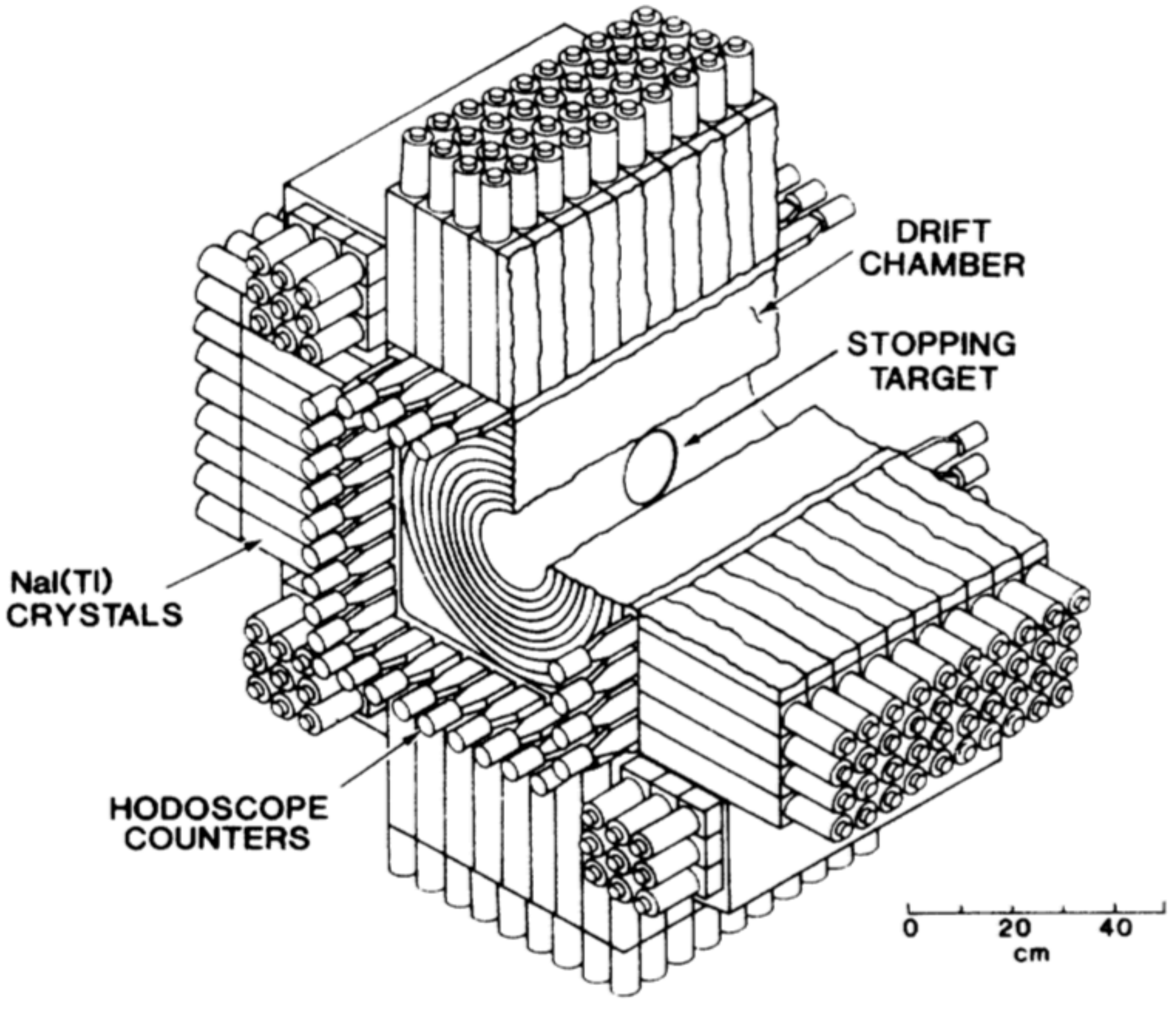
Use Michel endpoint to calibrate and look for signals in the opposite direction

BR(μ→eX) < 2.6 10^{-6} A=0 $\frac{d\Gamma}{d\Omega} \propto 1 - AP\cos\theta$

Best limit on isotropic decay

cannot be used with A=-1 (same distrubution to $\mu^+ \to e^+ \nu\bar{\nu}$):
signal acceptance goes to 0

Crystal Box detector: $\mu^+ \to e^+\gamma\, X$ and $\mu^+ \to e^+\gamma\gamma$



Apparatus originally designed for $\mu^+ \to e^+\gamma$ searches

$\mu^+ \to e^+\gamma\, X$ BR < 1.1 10^{-9}

Physical Review D 38.7 (1988): 2077

No magnetic field: positron momentum from calorimetry

Segmented calorimeter: granularity from crystal size

Timing also obtained from NaI(TI) signal

observable	Crystal Box	MEG II
tracking resolution	130 μm	110 μm
positron momentum/energy	3.7 MeV	130 keV/c
photon position	1.8 cm @ R=23 cm	2 mm @ R=58 cm
photon energy	7% @ 55 MeV	1% @55 MeV
relative time	488 ps	84 ps

Detector acceptance larger than MEG (II)

Teoretical interest in $\mu^+ \to e^+\gamma\, X$: Jho, Y., Knapen, S. & Redigolo, D. Lepton-flavor violating axions at MEG II. *J. High Energ. Phys.* **2022**, 29 (2022)

Sensitivity study needed (ongoing) to evaluate the time needed to accumulate the required dataset

$\mu^{\pm} \to e^{\pm}\nu\bar{\nu}(\gamma)$ SM spectra