# Charged lepton flavor violating processes

## $\mu \to e\gamma$ Experimental Overview

**Hadley Santana Queiroz | April 10**

# Overview

Theory:

- Standard model
  - Michel Decay
- Neutrino mass - $\nu$SM
  - CLFV in $\nu$SM

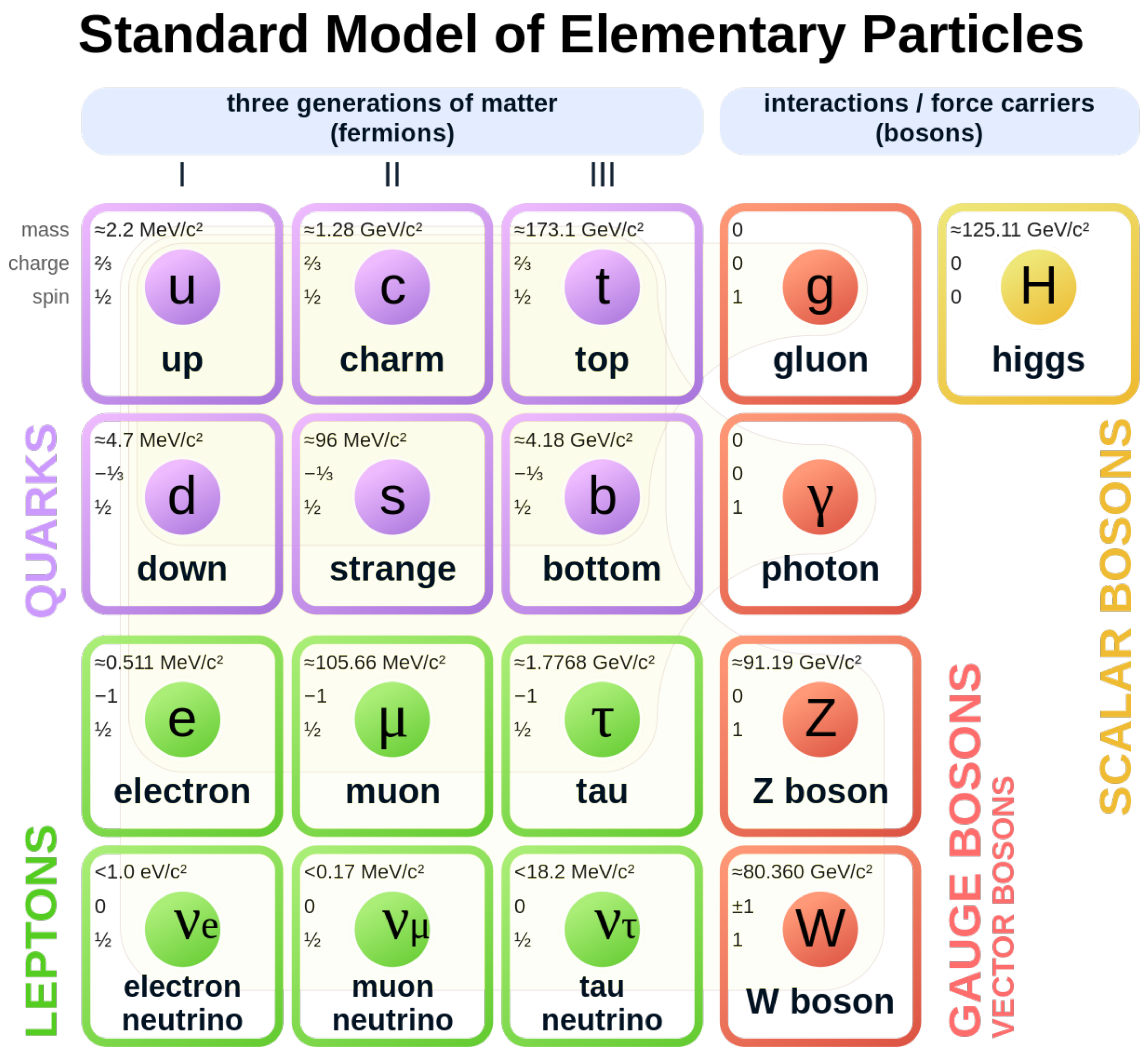
Experiment:

- Experimental candidates
- $\mu \rightarrow e\gamma$
  - Crystal Box
  - MEGA
  - MEG
  - MEG-II

# Theory

# The Standard Model

- Three generations of fermions
- Quark generations mix through weak interactions
- Leptons of different generations aren’t supposed to mix at all
    - Individual lepton-flavor numbers $(L_e, L_\mu, L_\tau)$ are conserved
- Muons decay to electrons without violating charged lepton flavor conservation



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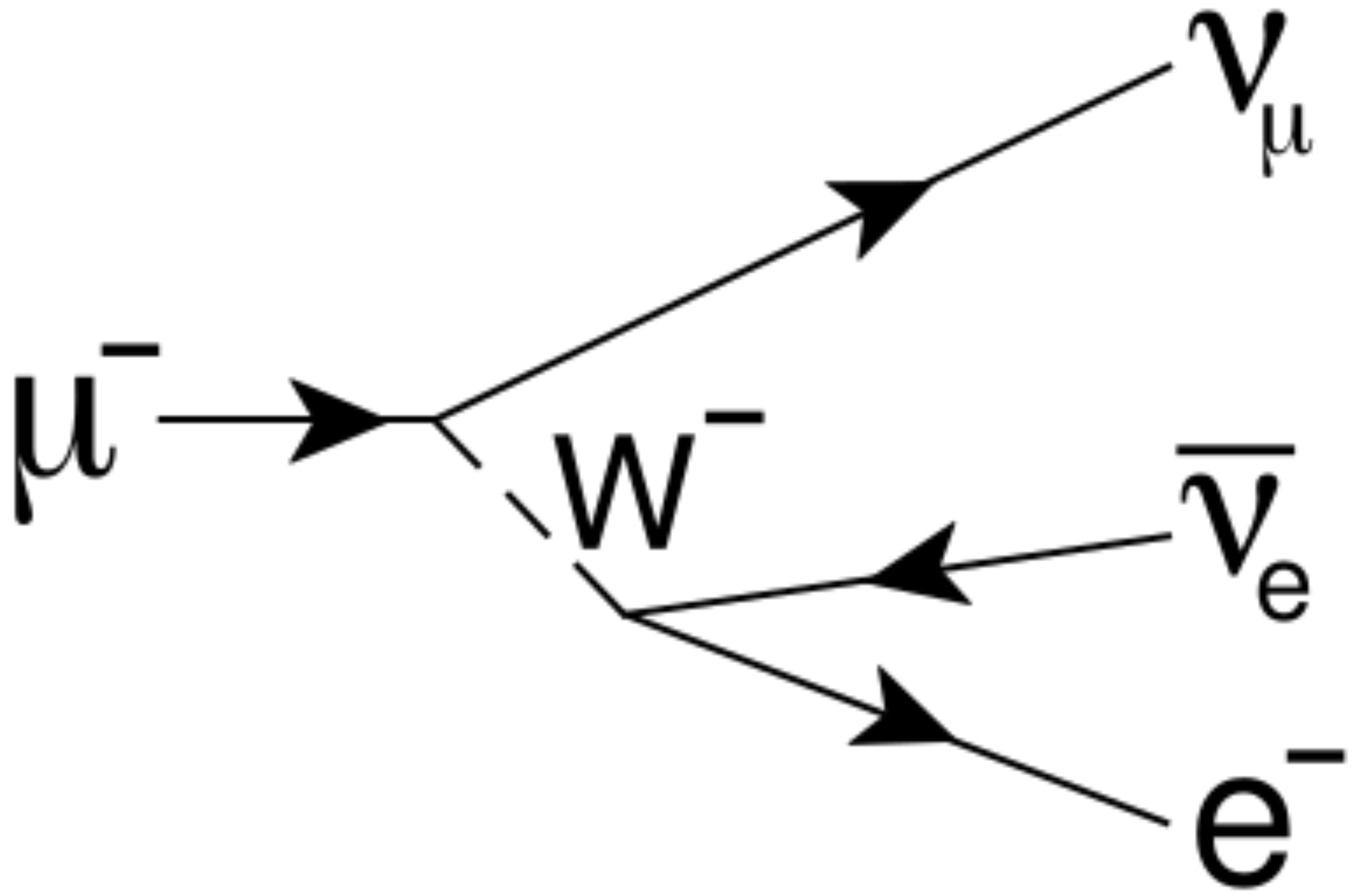
# Michel decay

$\mu \to e^- \bar{\nu}_e \nu_\mu$

- Dominant mode of muon decay under the Standard Model
- ~100% of muons decay this way
- Also possible to emit photon while decaying: Radiative Muon Decay (RMD)
- Does not violate lepton-flavor number conservation



$L_\mu = 1,$

$L_e = 0$

$L_\mu = 1,$

$L_e = (+1) + (-1) = 0$

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# Except actually…

- Super-Kamiokande Observatory and Sudbury Neutrino Observatory showed that neutrinos undergo flavor oscillations

- This is only possible if neutrinos have mass, and neutrino flavor states are not mass eigenstates

- 2015 Nobel Prize

- This requires a change to the Standard Model Lagrangian to add a neutrino mass term

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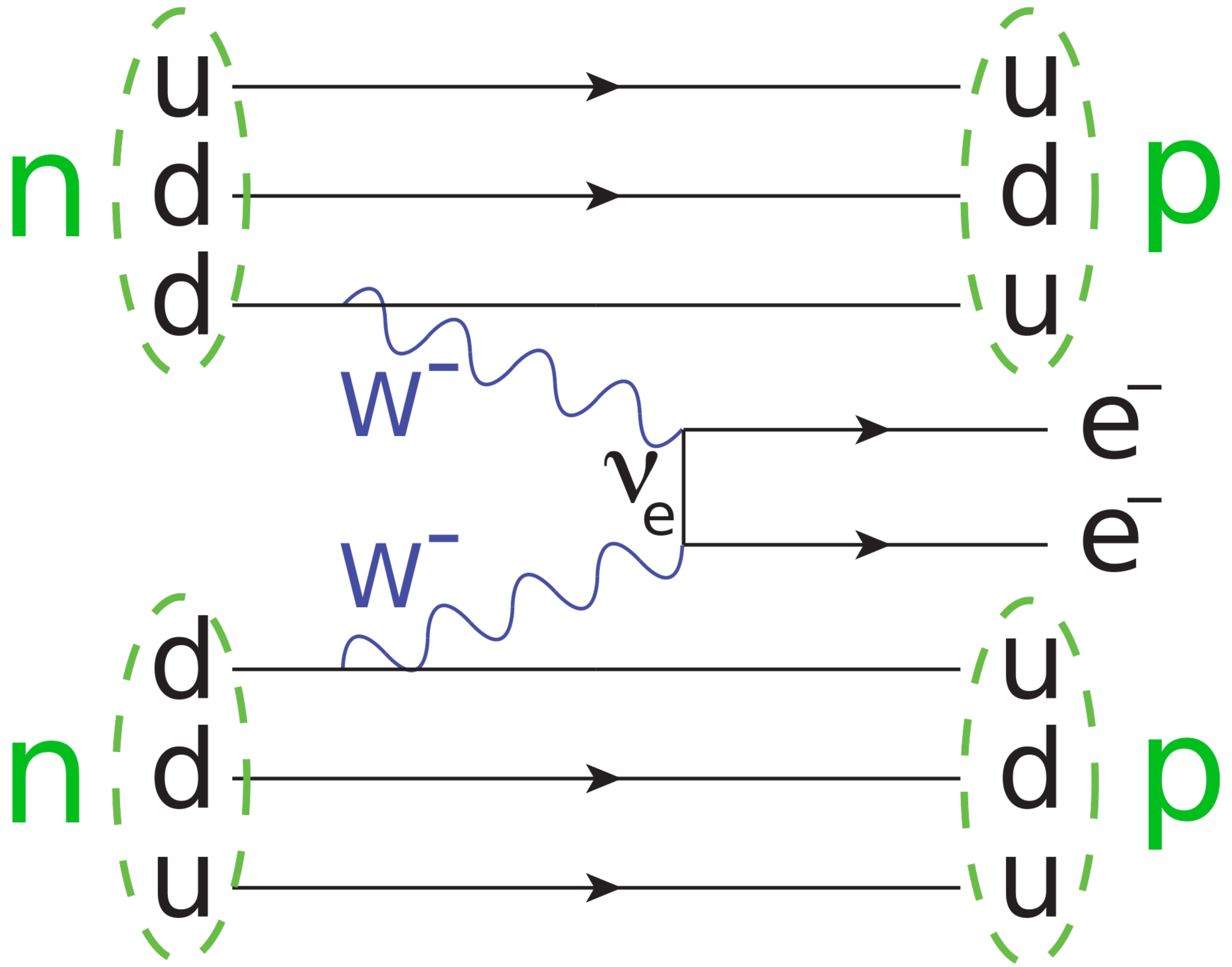
# Neutrino Mass

- $\nu$SM - Standard Model with neutrino mass
- Dirac fermions → total lepton number L conserved
- Majorana fermions → neutrinos are their own antiparticle → lepton number-violating processes allowed
  - E.g. neutrinoless double-beta decay



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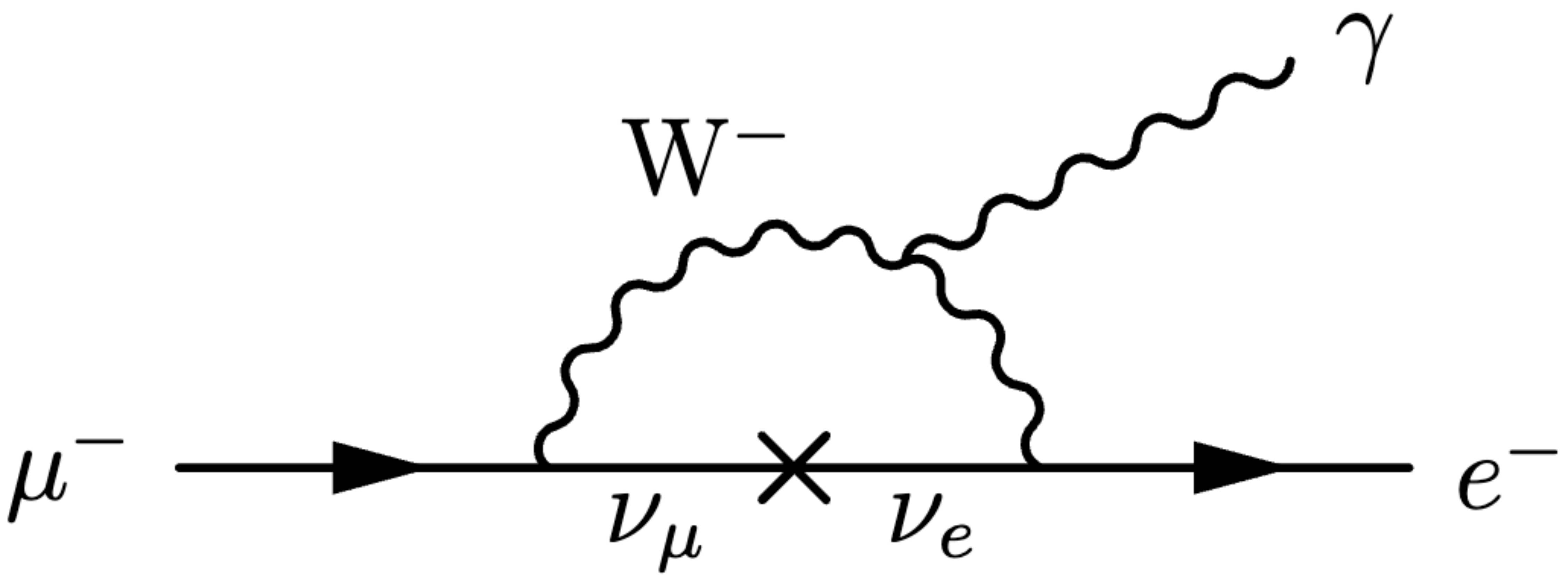
# CLFV in $\nu$SM

- Neutrino oscillation allows us to build CLFV processes
  - E.g. $\mu \to e\gamma$, shown right
  - The “$\times$” represents a process that changes neutrino flavor - CKM-like phase or BSM interaction
- BR ~ $10^{-54}$
  - Unmeasurable
- Then observing CLFV processes points to New Physics (NP)
  - Many new theories predict higher BR for these processes
- If CLFV not observed, can constrain energy scale of NP



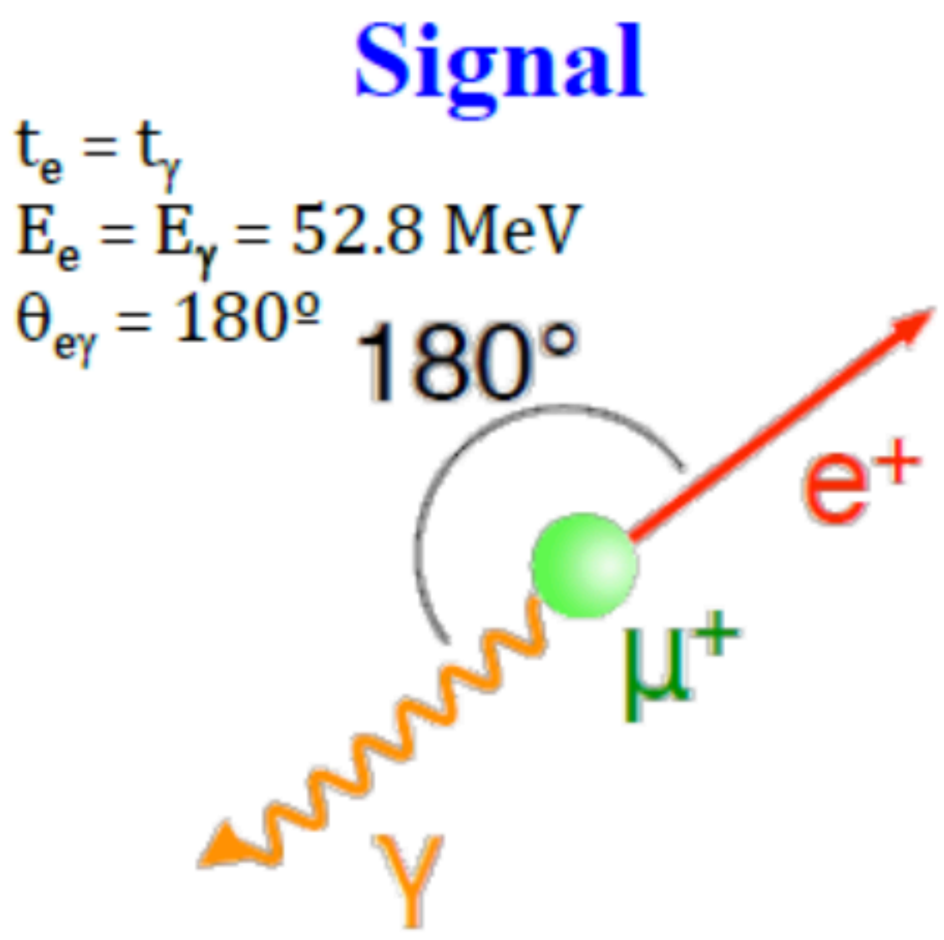
# Experiment

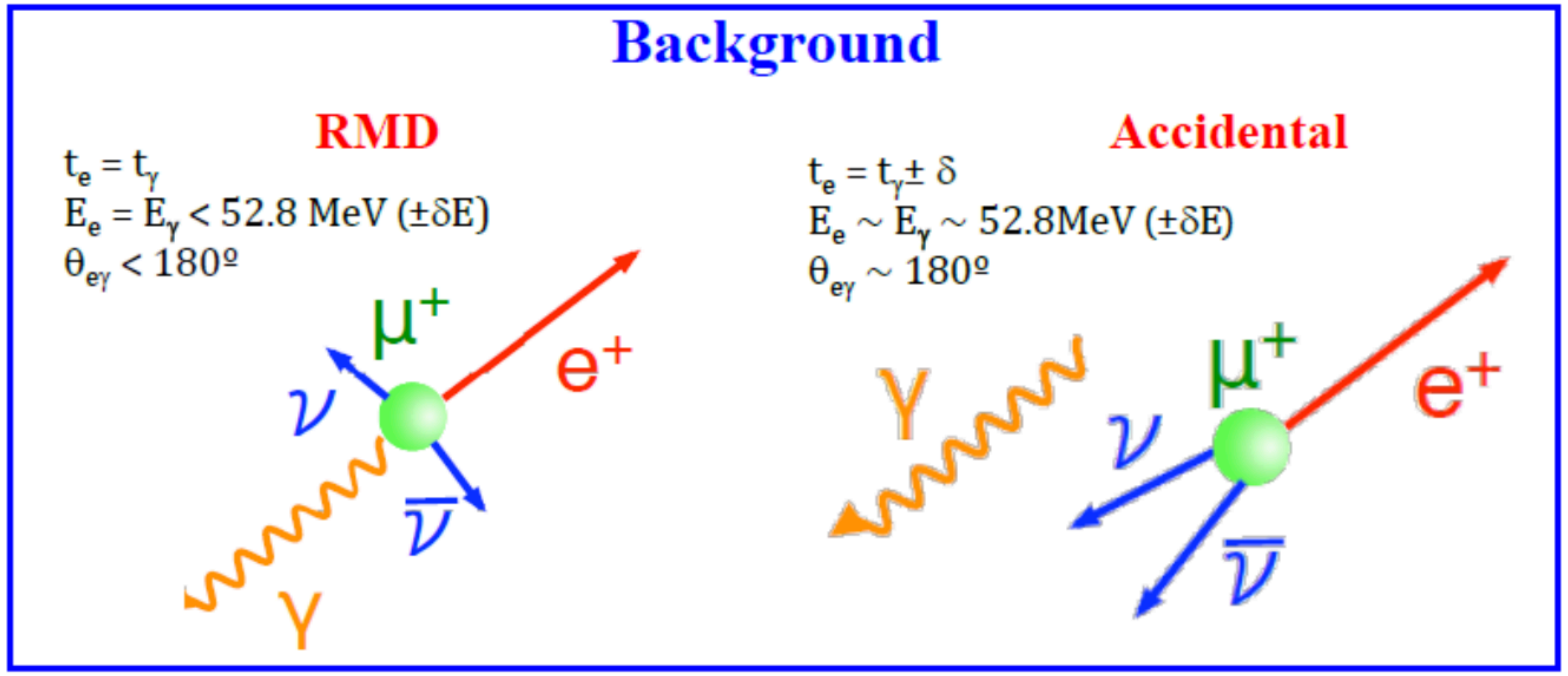
# CLFV Experimental Candidates

- $\mu \to e\gamma$
  - Crystal Box
  - MEGA
  - MEG
  - MEG-II
- $\mu \to eee$
  - Mu3e
- $\mu + N \to e + N$
  - SINDRUM-II
  - Mu2e
  - COMET

# $\mu \rightarrow e\gamma$

- Experimental setup: stop a muon on a target, wait for it to decay, then detect the outgoing electron and photon
  - use $\mu^+$ to avoid neutron capture
- Signal characteristics:
  - back-to-back gamma ray and positron
  - with energy 52.83 MeV
  - coming from same place at same time
- Backgrounds:
  - Radiative muon decay
  - “Accidentals” - positron from Michel decay + photon from another process happen to overlap within timing resolution to look like signal event (this is the dominant background)





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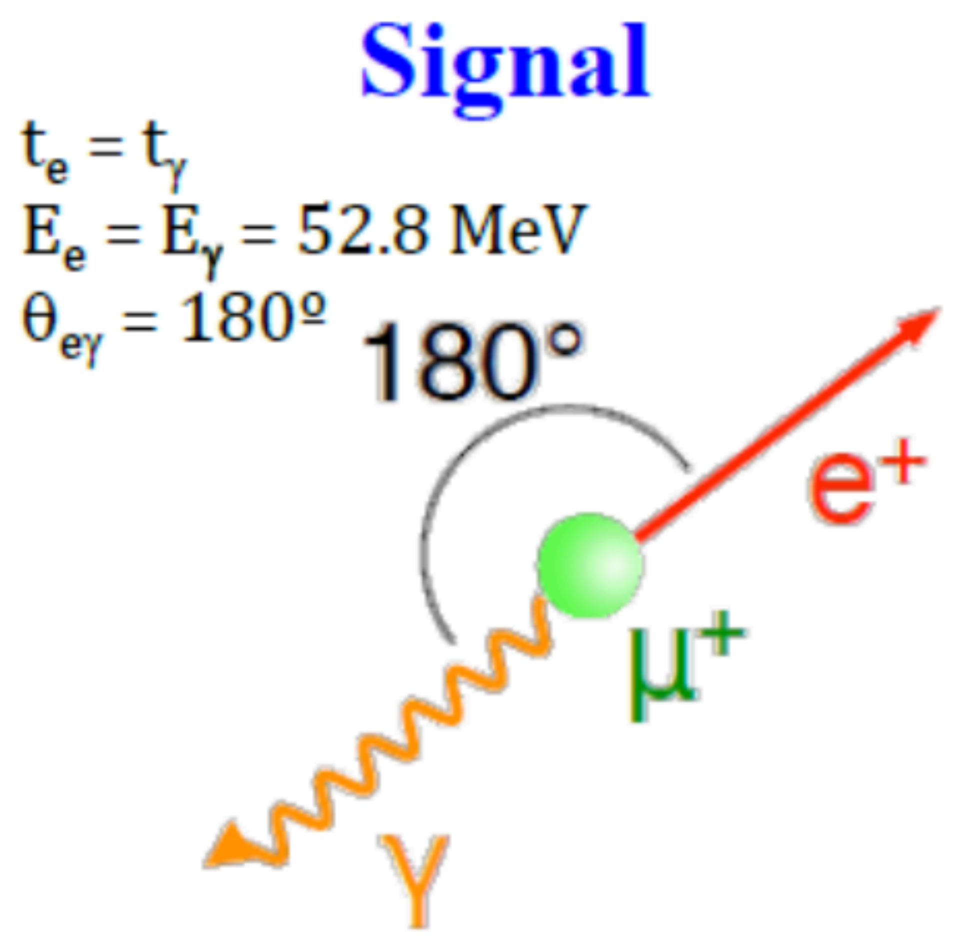
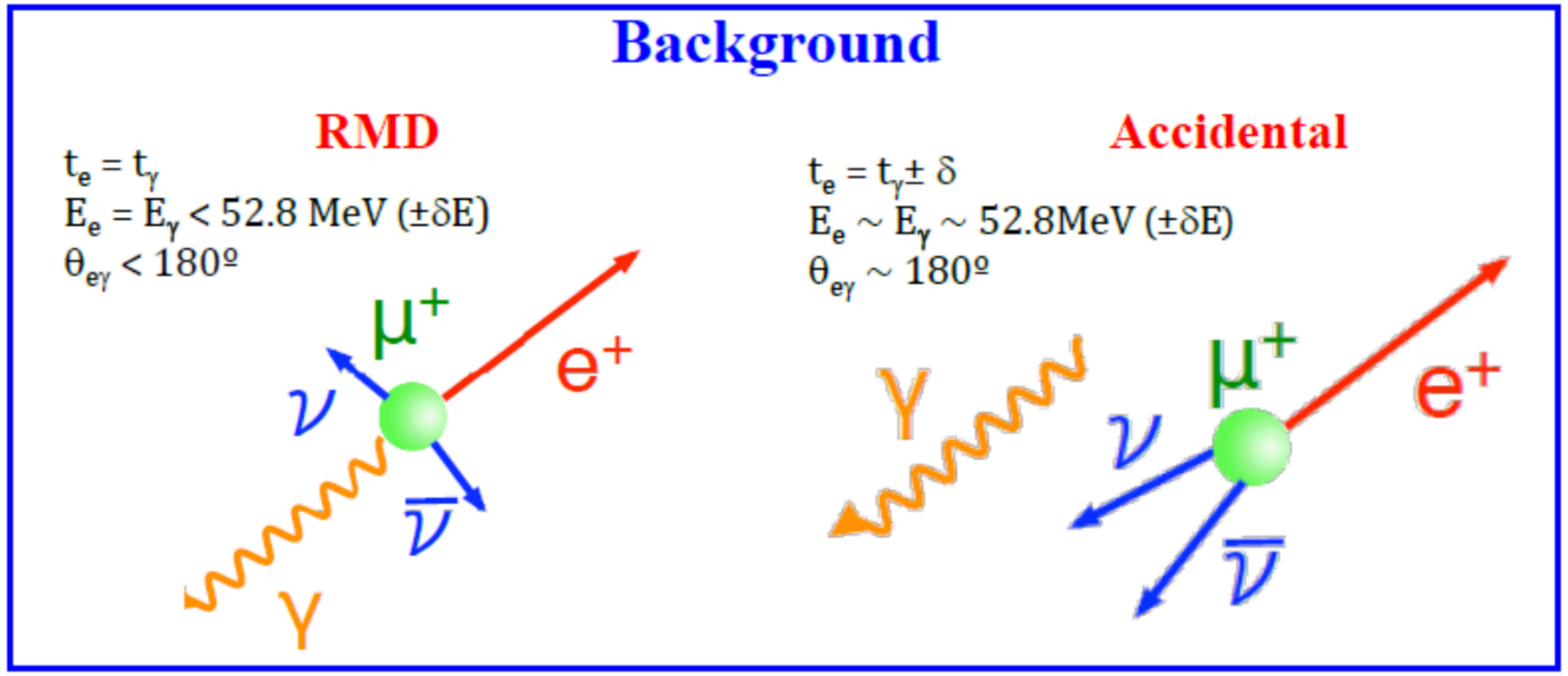
# $\mu \rightarrow e\gamma$

- Positron detection:
    - Tracking (usually with B field)
        - Great momentum resolution
        - Often coupled to scintillators for better timing resolution
    - Calorimetry
- Photon detection:
    - Calorimetry
        - high detection efficiency
    - Convert photon and measure momentum of $e^+e^-$ pair
        - better momentum/energy resolution





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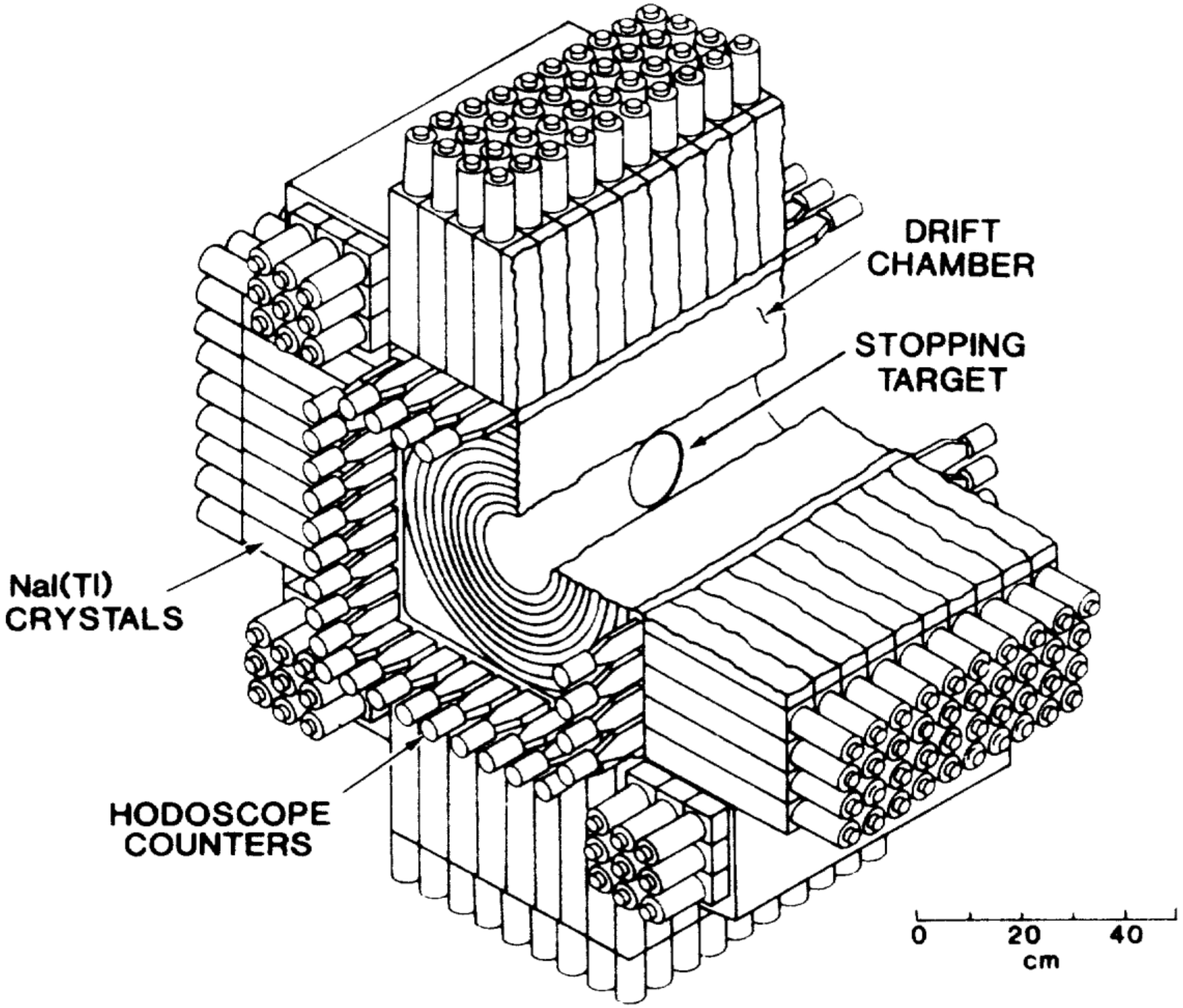
# $\mu \rightarrow e\gamma$ Experiments

## Crystal Box

- Detector:
  - Drift chamber to track charged particle trajectory (no applied B field)
  - Layer of scintillation hodoscope counters to differentiate charged and uncharged particles in calorimeter
  - 396 NaI(Tl) crystals coupled to PMTs act as a calorimeter for photons and positrons



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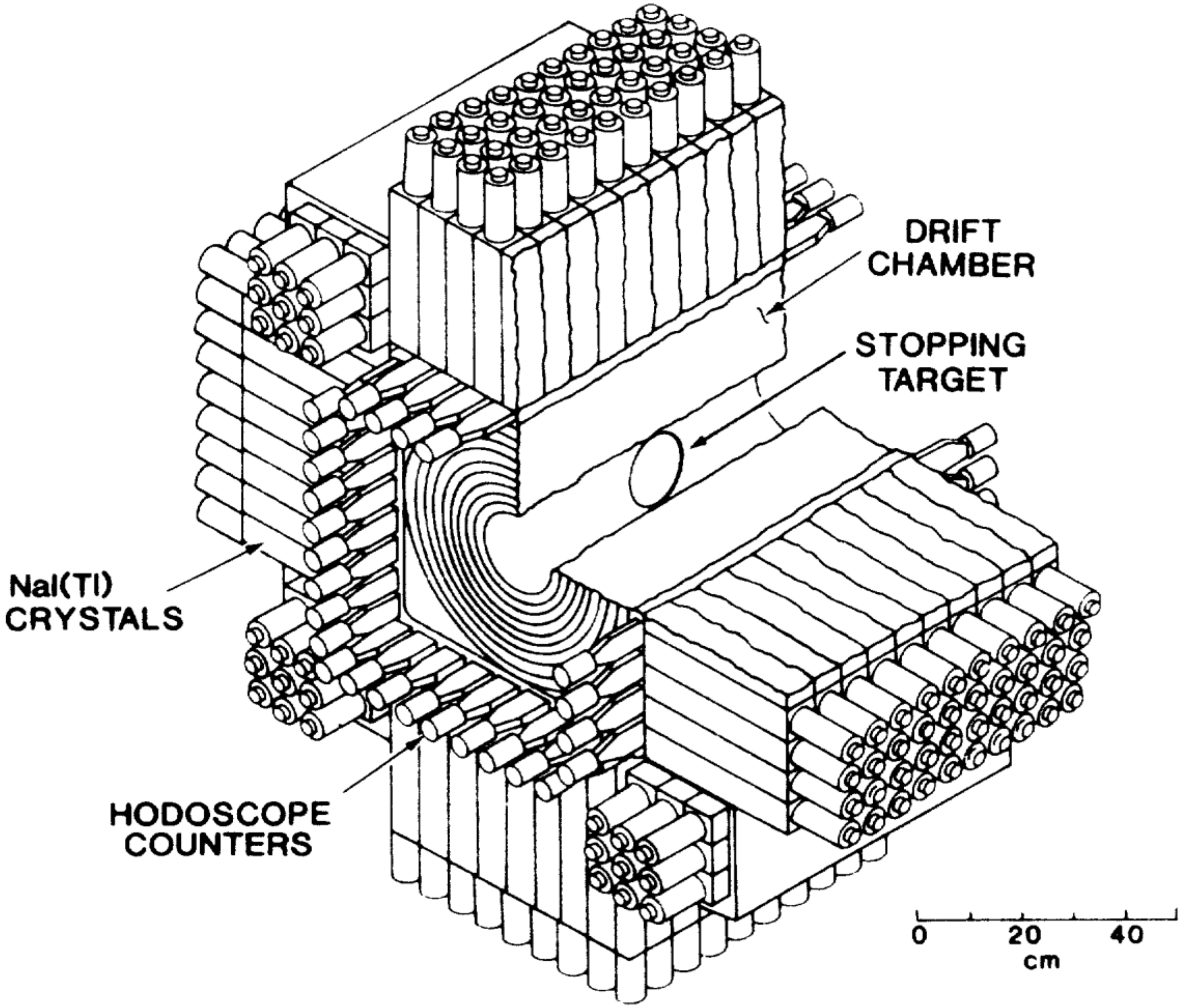
# $\mu \rightarrow e\gamma$ Experiments

## Crystal Box

- 90% CL upper limit for branching ratio to $e\gamma$ set at $4.9 \times 10^{-11}$ (1986)



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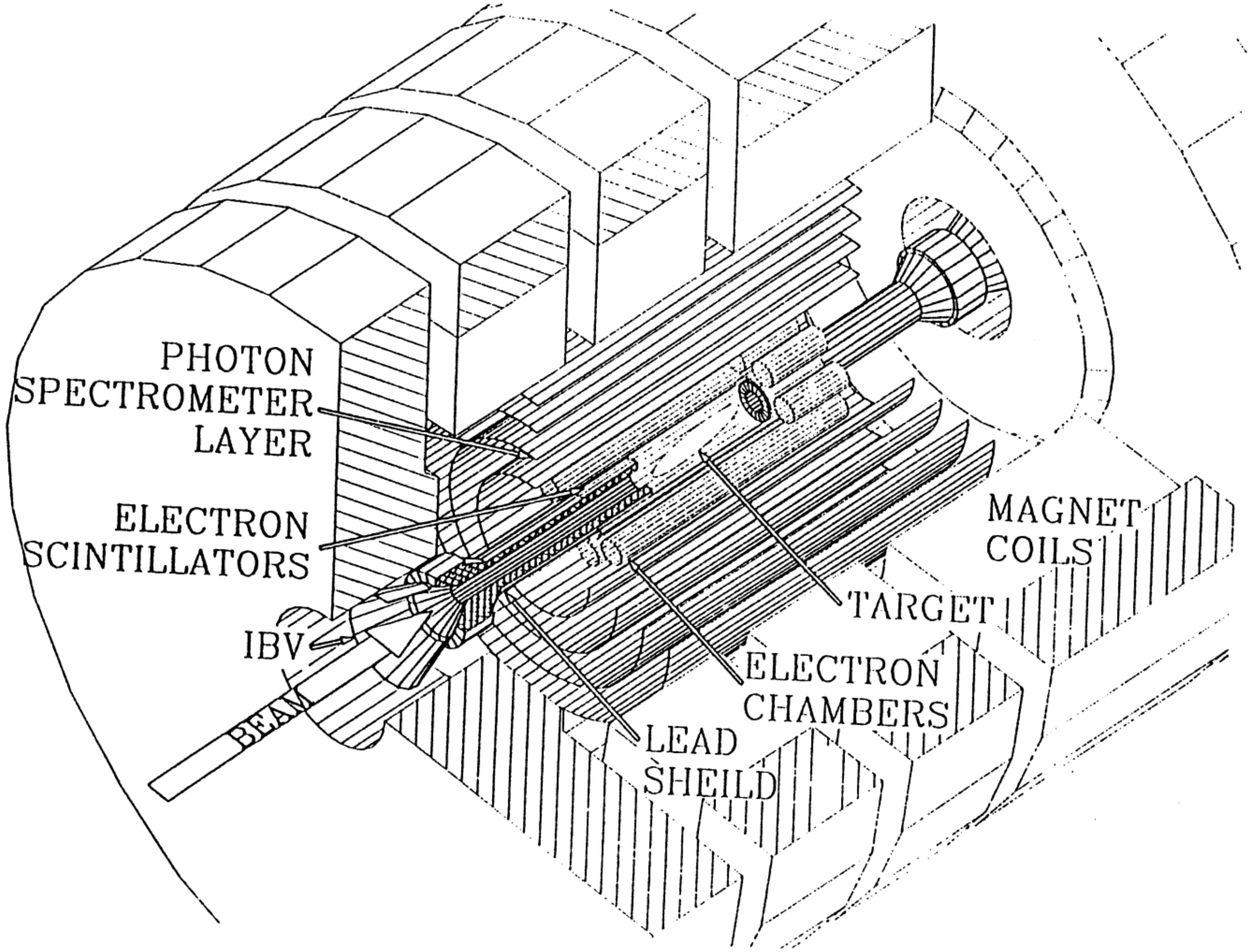
# $\mu \rightarrow e\gamma$ Experiments

## MEGA

- Detector:
  - 1.5T magnetic field (solenoid) - traps low energy positrons from Michel decay
  - Wire chambers to track positrons
  - 3 coaxial spectrometers to convert photons to electron-positron pair
    - Drift chambers, wire chambers, and scintillator to detect those pairs
    - Only 2.5% of photons convert



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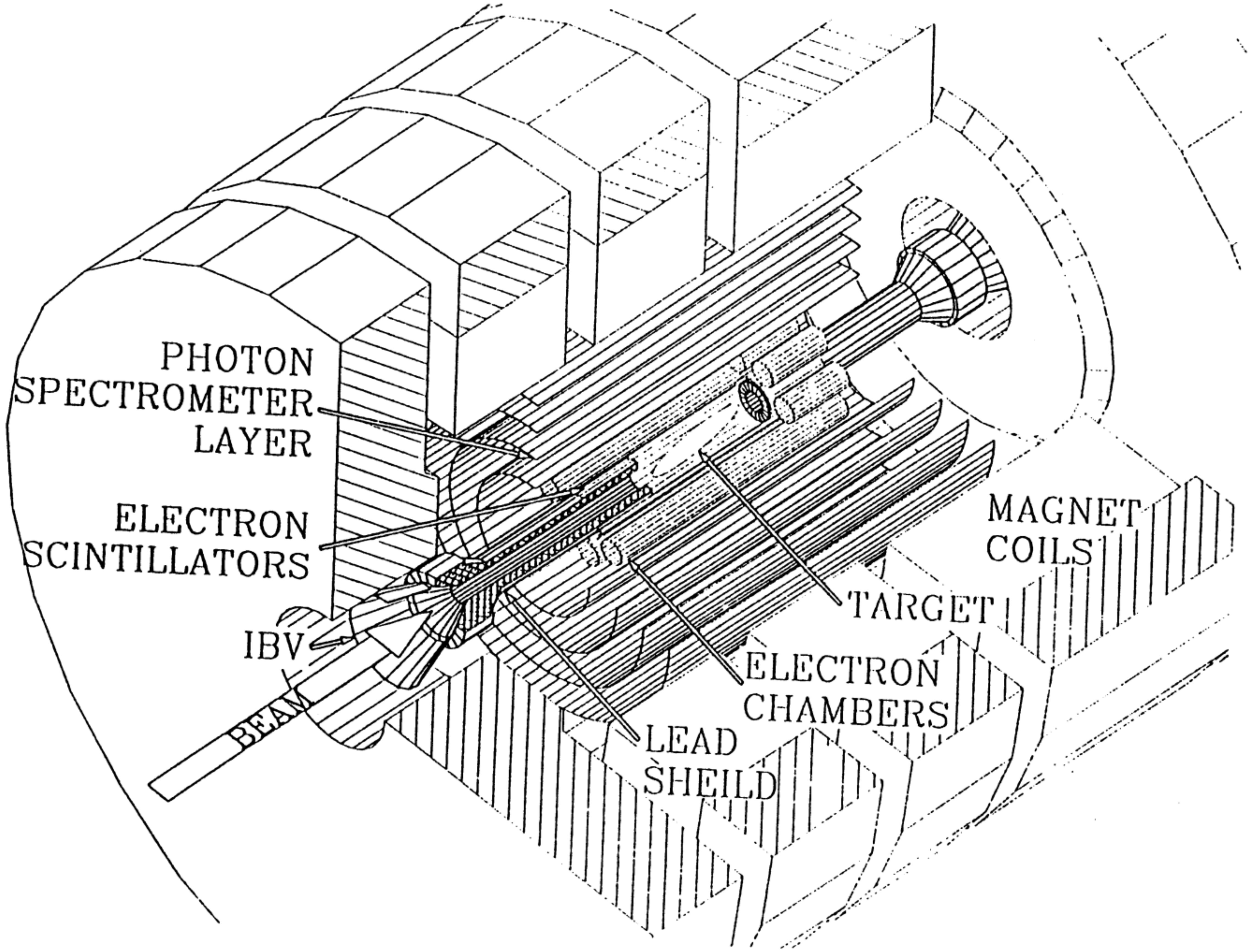
# $\mu \rightarrow e\gamma$ Experiments

## MEGA

- 90% CL upper lim for branching ratio to e gamma set at $1.2 \times 10^{-11}$ (1999)

- Only 4x better than previous result, 35x worse than written in proposal
  - Pileup in wire chambers severely reduced acceptance



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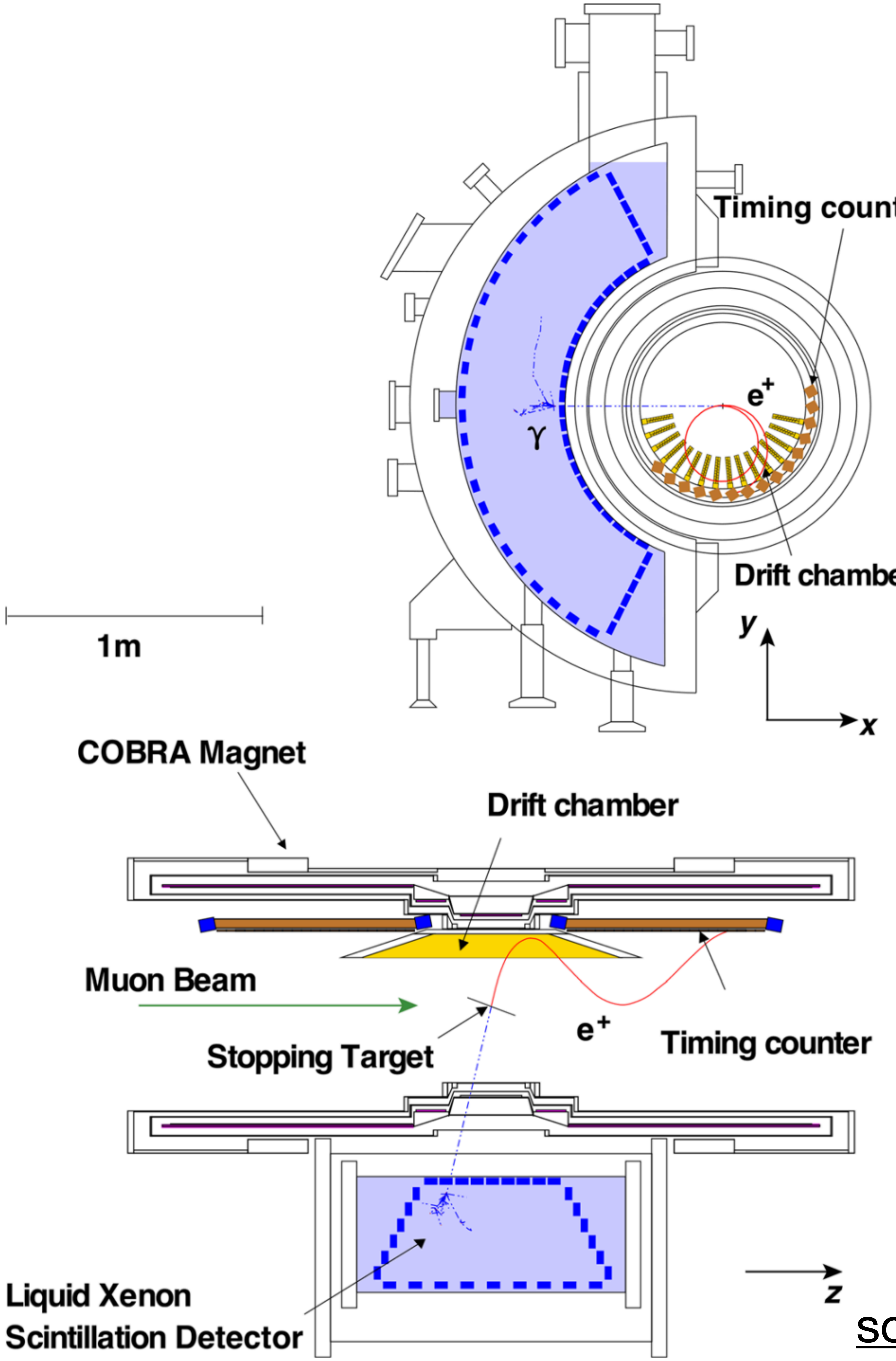
# $\mu \rightarrow e\gamma$ Experiments

## MEG

- Detector:
  - Liquid Xe calorimeter for photons
  - Innovative gradient magnetic field to keep constant bending radius for charged particles and to sweep away positrons emitted $90^\circ$ from field quicker than a solenoid would
  - Radial drift chambers to detect positrons
  - Covers only 10% solid angle



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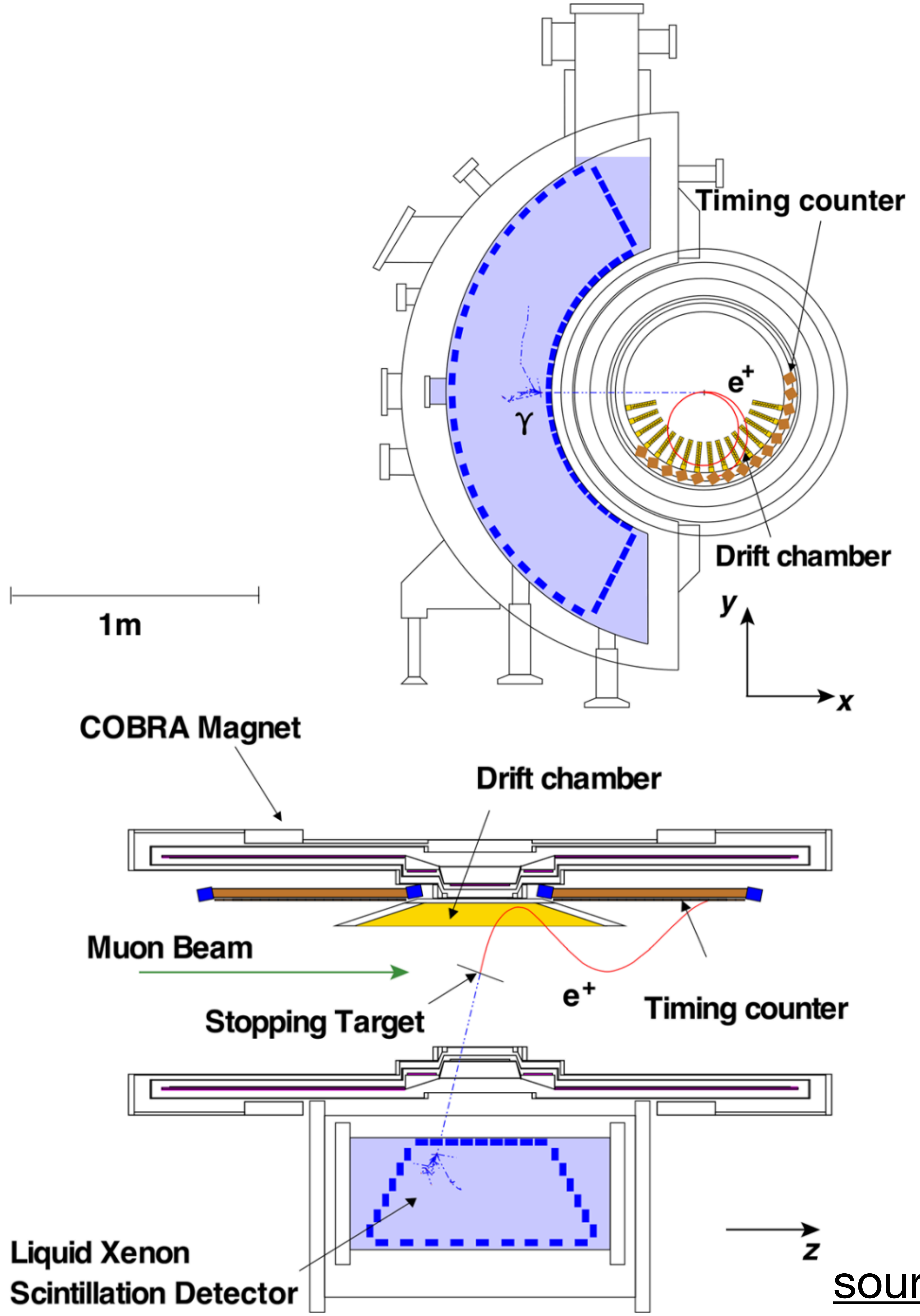
# $\mu \rightarrow e\gamma$ Experiments

## MEG

- 90% CL upper lim for branching ratio to e gamma set at $5.7 \times 10^{-13}$ (2013)



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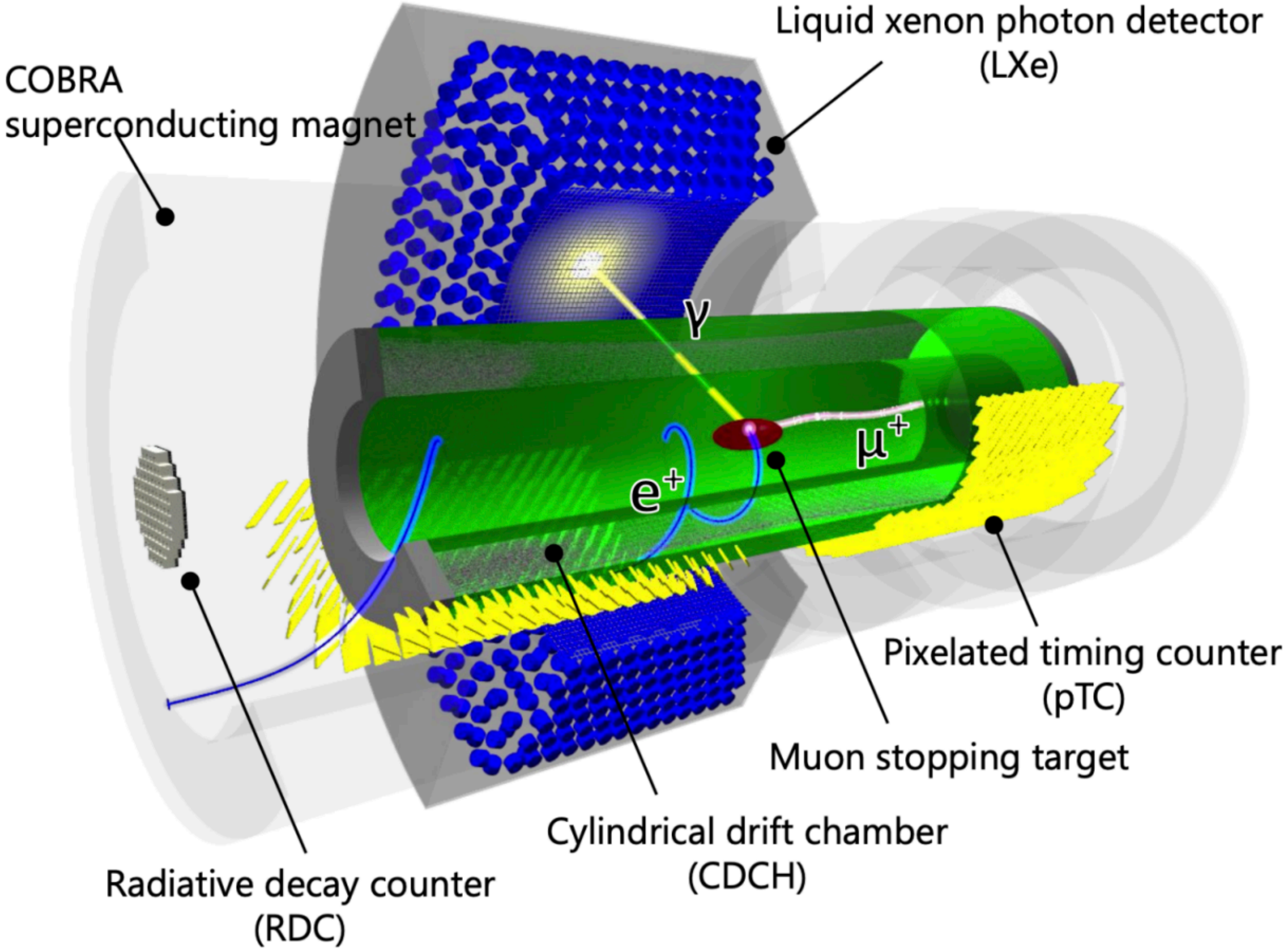
# $\mu \rightarrow e\gamma$ Experiments

## MEG-II

- Detector:
  - Single volume cylindrical drift chamber instead of multiple radial chambers, 2pi coverage
  - Radiative decay counter to veto high energy gamma rays from RMD



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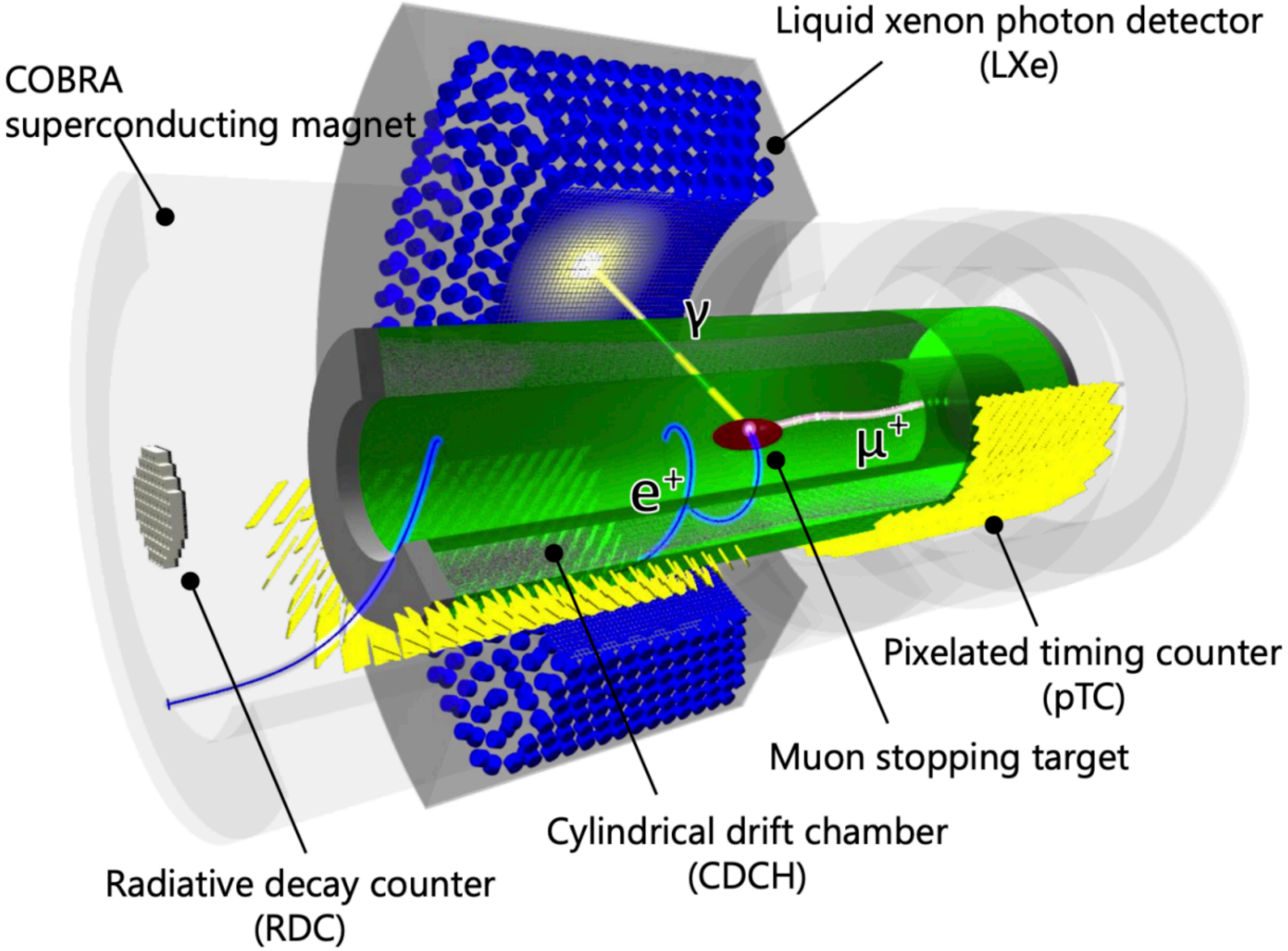
# $\mu \to e\gamma$ Experiments

## MEG-II

- 90% CL upper lim for branching ratio to e gamma reported at $7.5 \times 10^{-13}$ in 2023

- Combined with MEG, gives $3.1 \times 10^{-13}$
  - best limit to date!

- Predicted to reach $6 \times 10^{-14}$ by 2026



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# Conclusions

- Despite being allowed in the Standard Model with neutrino mass, CLFV is an interesting probe into new physics because of its unobservable branching ratios outside of BSM theories
- Experiments to measure $\mu \rightarrow e\gamma$ typically involve producing muons from pions, stopping them on a surface, waiting for them to decay, and then detecting the decay products, specifically looking for monochromatic back-to-back positron/gamma rays at ~53 MeV that originate from the same place and time
- Advances have been made in timing resolution, charged particle trackers, and electromagnetic calorimeters in order to reach the limits we are at today
- MEG-II is expecting exciting results in the next few years (depending on how excited you get about seeing nothing…)

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# Backup

# $\mu \to e\gamma$ Experiments

## MEG

- COBRA magnets:
  - Solves the issue that slow positrons emitted at ~90 degrees to field get “trapped” in solenoidal field, doing many revolutions before clearing detector, causing pileup in drift chambers
  - Thin-walled, so photons can get through easily
  - Compensation coils reduce field in LXe detector

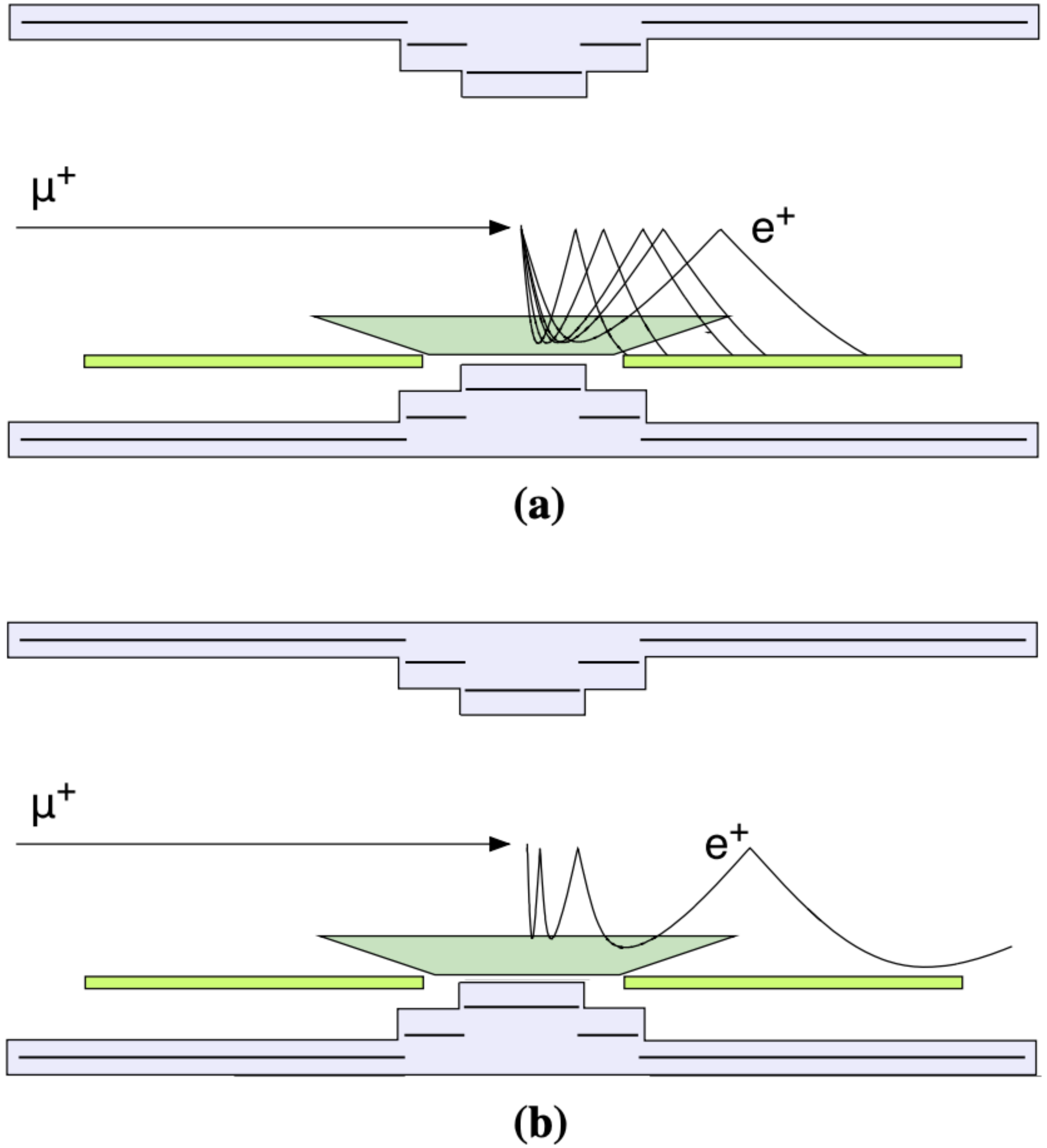

**Fig. 3** Concept of the gradient magnetic field of COBRA. The positrons follow trajectories at constant bending radius weakly dependent on the emission angle $\theta_{e+}$ (**a**) and those emitted from the target with small longitudinal momentum ($\theta_{e+} \approx 90°$) are quickly swept away from the central region (**b**)

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# $\mu^- + N \rightarrow e^- + N'$

- A muon slows to a stop and falls into the 1s (ground) state of some nucleus, emitting X-rays in a characteristic spectrum that allows it to be identified
- The muon is then either
    - Captured by the nucleus (producing a neutrino, neutron, and sometimes a photon),
    - Decays in orbit (Michel decay), or
    - Converts into an electron with enough energy to escape Coulomb potential
- The signal for muN -> eN’ is a monochromatic electron
    - Both muons that decay via Michel decay and muons that convert to electrons release electrons
    - The electron’s energy from muon conversion is higher than electrons produced by Michel decay, allowing for background rejection

# $\mu^- + N \rightarrow e^- + N'$

- The rate of muon to electron conversion is given in terms of the muon capture rate

- The number of muon captures is inferred using the number of stops (measured via their X-ray signature), the decay lifetime of the free muon, and the lifetime in the target nucleus

# $\mu^- + N \rightarrow e^- + N'$

- Muon capture produces a neutron and sometimes a photon, both of which can produce extra activity in the detector

- Cosmic rays can ionize electrons in the target atoms, which can fake a signal if they have the right momentum

    - Then a cosmic ray veto system is used to weed out fake signals by identifying the cosmic rays that originated them

    - However this poses problems, since muon captures can “self-veto” when their outgoing neutrons undergo capture by hydrogen and the subsequent photon undergoes pair production, creating electrons that can fake a cosmic ray signal

- Radiative Pion Capture

# $\mu^- + N \rightarrow e^- + N'$ Experiments

- Generally, proton beam hitting target produces pions, which decay to muons.
- SINDRUM-II
  - 590 MeV proton beam
  - 40 mm carbon production target
  - $10^8$ muons/sec at 52 MeV KE
  - $CH_2$ degrader - filters out pions from hitting stopping target
  - Gold stopping target
  - 90% CL: R $< 6 - 7 \times 10^{-13}$

# $\mu^- + N \rightarrow e^- + N'$ Experiments

- Generally, proton beam hitting target produces pions, which decay to muons.
- Mu2e and COMET
  - 8 GeV proton beam
  - $10^{11}$ muons/sec, at 40 MeV KE
  - Curved solenoid to transport muons to final detector (to eliminate neutral backgrounds)