MEG実験全データを用いた
荷電レプトンフレーバーを破る軽い新粒子の探索

Searching for a lepton flavour violating muon decay mediated by a new light particle with the MEG I full datasets

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Core-to-Core Program

Original: https://meg.web.psi.ch/docs/talks/JPS/2020s/nakao_jps2020s.pdf

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Abstract

- We have searched for a **lepton flavor violating muon decay** mediated by **a new light particle X**, $\mu^+ \to e^+X, X \to \gamma\gamma$, using the full datasets (2009–2013, $7.5 \times 10^{14} \mu^+ s$) of the MEG experiment.

- Statistics, reconstruction methods, and the decay search analysis are improved from the previous analysis in 2012 (2009, 2010 data was used).

- No significant excess was found in the mass region of 20–45 MeV, lifetime below 40 ps.
    - In particular, the upper limits are **pushed down to the level of $\mathcal{O}(10^{-11})$** for 20–30 MeV.

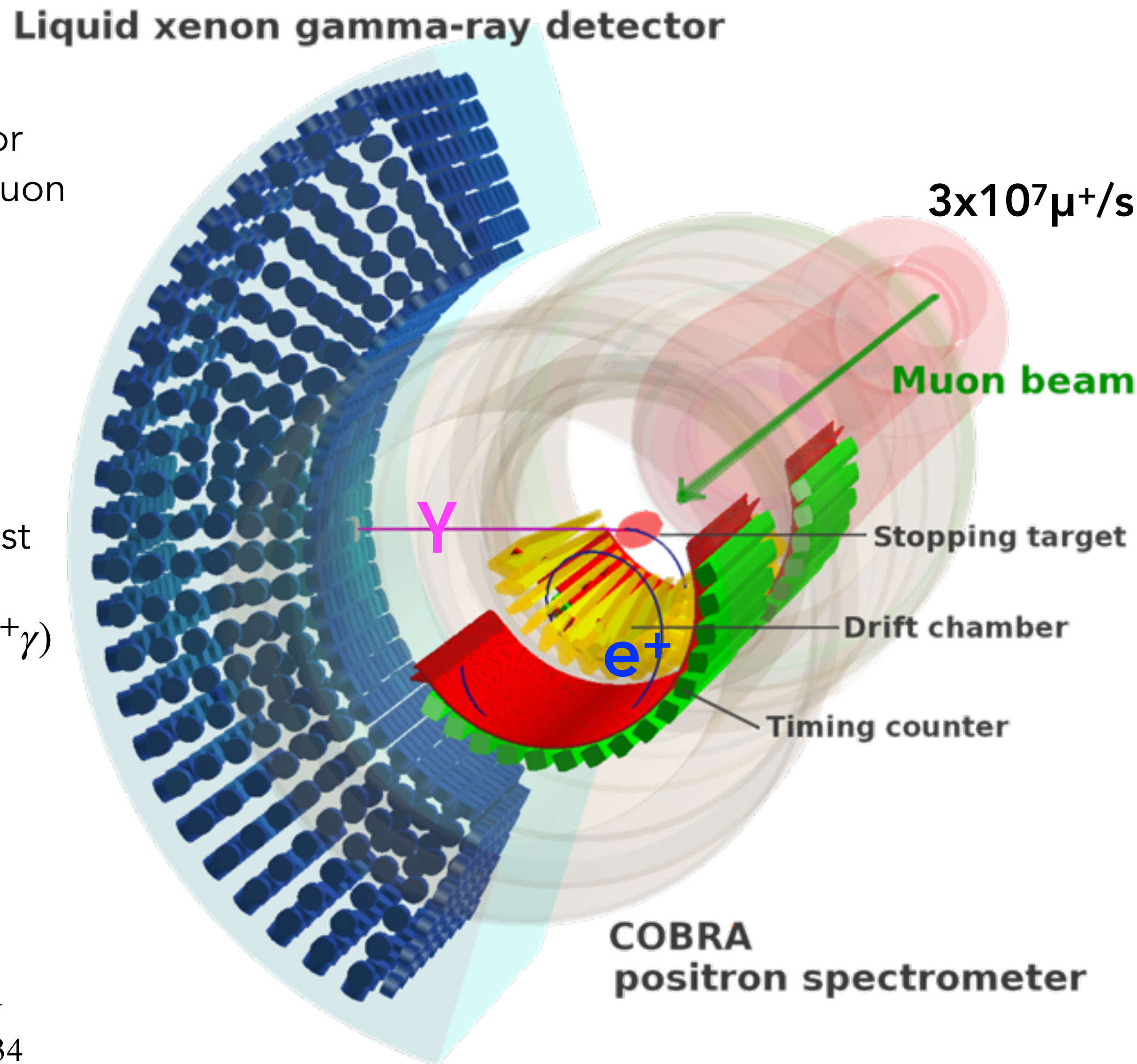
- It is at most **60 times more stringent** result than the bound from the Crystal Box experiment.

The MEG experiment

- The MEG experiment searched for charged lepton flavor violating muon decay ($\mu^+ \to e^+\gamma$).
- Physics data taking: **2009–2013**
  - 7.5x10^{14} stopped muons
- No excess was found and the most stringent upper limit, **4.2 x10^{-13} (90% C.L.)** was set on $\mathscr{B}(\mu^+ \to e^+\gamma)$ in 2016.

At Paul Scherrer Institut in Switzerland

The final results: A. M. Baldini et al. (MEG Collaboration), Eur. Phys. J. C 76 (2016) 434



Physics motivation

- There is no clear evidence of new physics beyond the standard model to date (except for some anomalies).

- We try to tackle this situation by combining two different directions: **charged lepton flavor violation** and **light new physics**.

Physics motivation: charged lepton flavor violation

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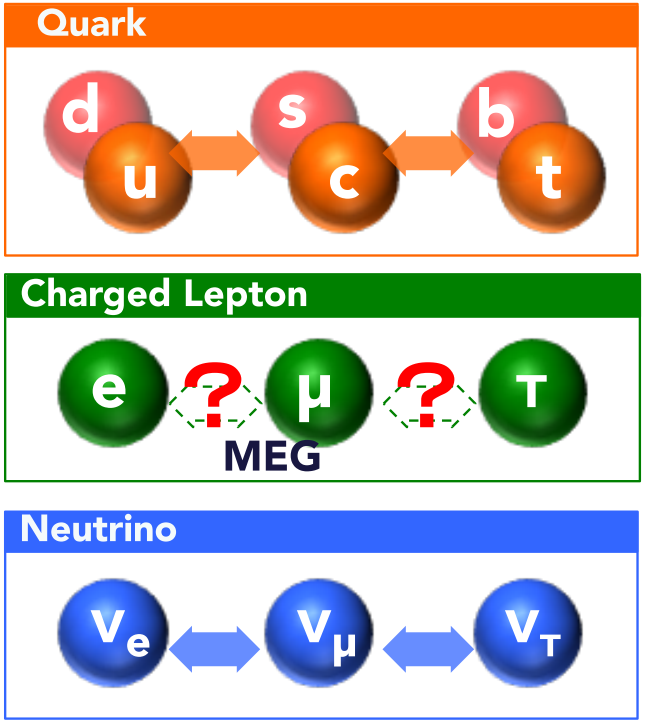
- We try to tackle this situation by combining two different directions: **charged lepton flavor violation** and **light new physics**.

- Inter-generational mixing in the charged lepton sector (= charged lepton flavor violation, CLFV) is clear evidence for new physics.

- The MEG experiment searched for charged lepton flavor violating muon decay ($\mu^+ \to e^+\gamma$).

- No excess was found and the most stringent upper limit, 4.2 x10^{-13} (90% C.L.) was set (2016*).



*A. M. Baldini et al. (MEG Collaboration), Eur. Phys. J. C 76 (2016) 434

Physics motivation: light new physics

- There is no clear evidence of new physics beyond the standard model to date (except for some anomalies).

- We try to tackle this situation by combining two different directions: **charged lepton flavor violation** and **light new physics**.

- LFV mediated by new light particle X $\sim \mathcal{O}(10\text{–}100)$ MeV might been left undiscovered as a loophole.

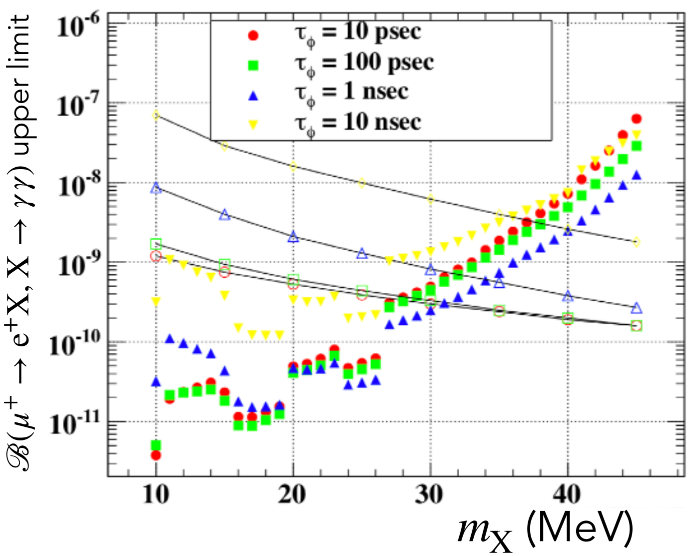
- A possible search in MEG: $\mu^+ \to \mathrm{e}^+\mathrm{X}, \mathrm{X} \to \gamma\gamma$ (hereafter we call it "MEx2G")
  - X is generated via LFV coupling and the on-shell X decays back into SM particles.
  - In this search, we assume decay width is narrow and X is long-lived.

- Possible candidates of X: axion-like particle, majoron, familon, flaxion, and strongly interacting DM (SIDM)

Previous studies (1/2)

- Direct search: MEG (2012) [1] (markers in bottom left plot)
  - $\mu^+ \to e^+X, X \to \gamma\gamma$ decay search using the MEG 2009/2010 datasets.
  - The first search in the world, available only in a Ph.D thesis [1].
- Inclusive search: Crystal Box (1988) [2] (solid lines in bottom left plot)
  - LFV μ decays including $\mu \to e\gamma\gamma$ were searched.
  - Limits on $\mu \to e\gamma\gamma$ can be converted to $\mu^+ \to e^+X, X \to \gamma\gamma$ [1].

[1] H. Natori, Ph.D. thesis (The University of Tokyo), 2012
[2] R. D. Bolton et al., Phys. Rev.D 38 (7) (1988) 2077–21
[3] J. Heeck et al., Phys. Lett. B 776 (2018) 385-390



[1]

Previous studies (2/2)

- Direct search: MEG (2012) [1] (markers in bottom left plot)
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- Inclusive search: Crystal Box (1988) [2] (solid lines in bottom left plot)
  - LFV μ decays including $\mu \to e\gamma\gamma$ were searched.
  - Limits on $\mu \to e\gamma\gamma$ can be converted to $\mu^+ \to e^+X, X \to \gamma\gamma$ [1].
- Constraints on X: beam dumps, SN1987A [3] (white area in bottom right plot)
  - "decay length <1 cm and m_X >20 MeV" is hot spot.

[1] H. Natori, Ph.D. thesis (The University of Tokyo), 2012
[2] R. D. Bolton et al., Phys. Rev.D 38 (7) (1988) 2077–21
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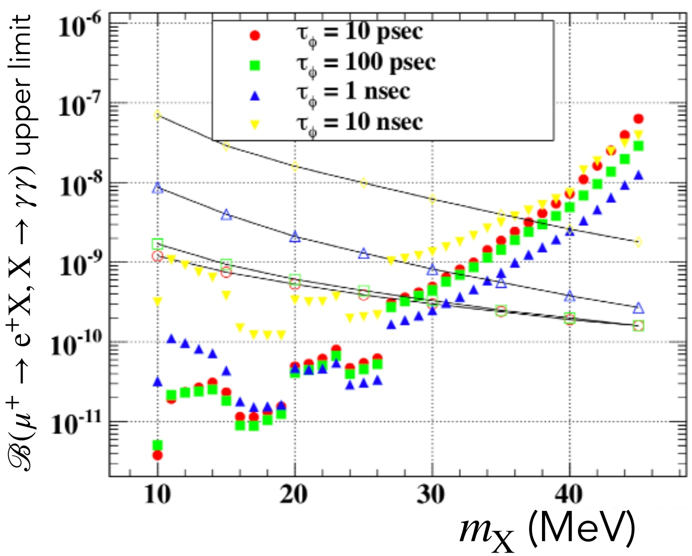
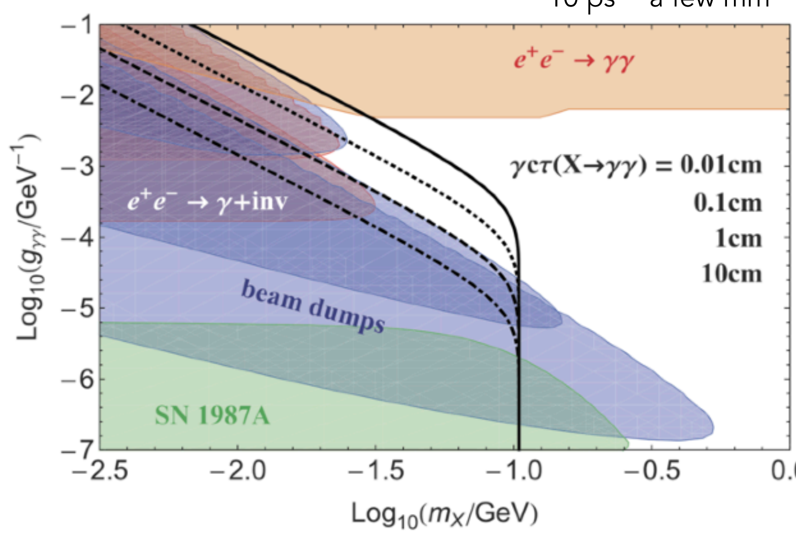


[1]

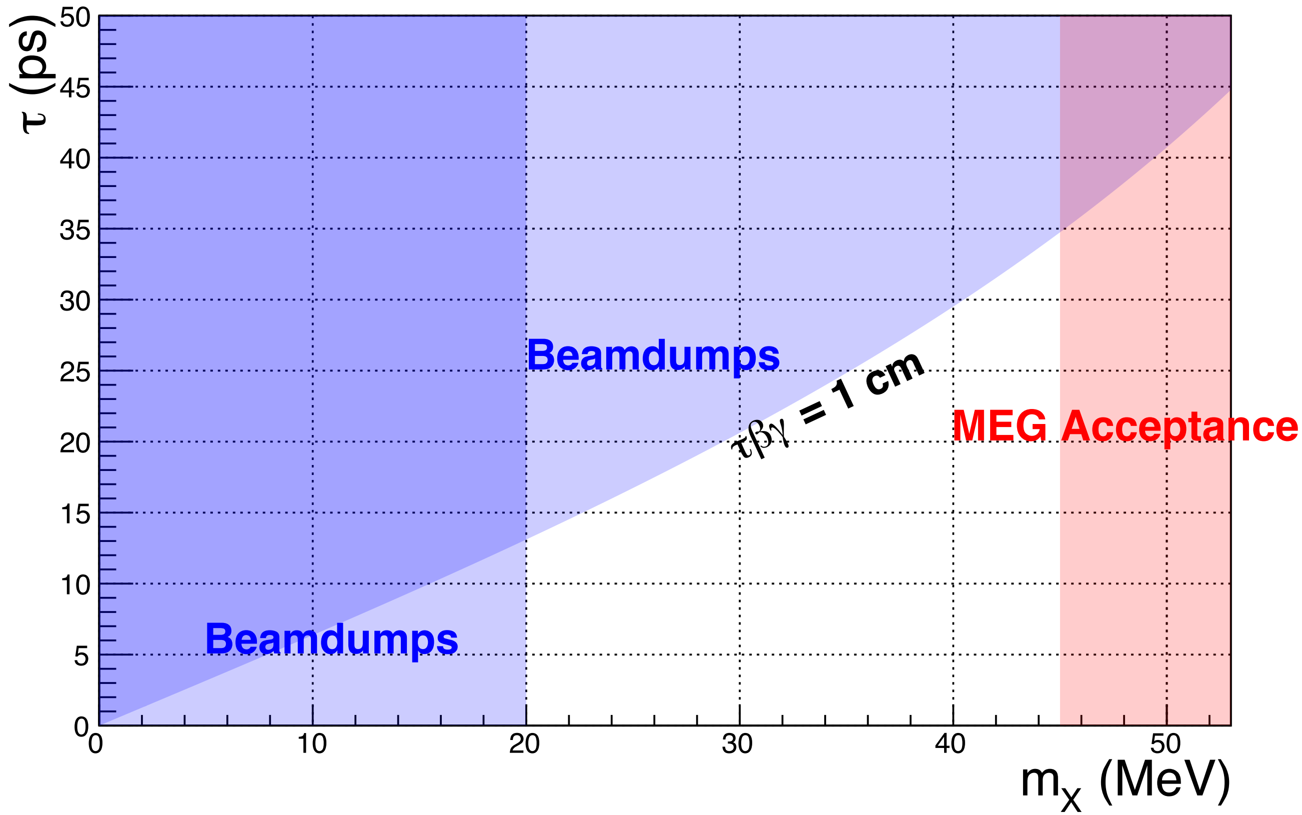
10 ps ~ a few mm



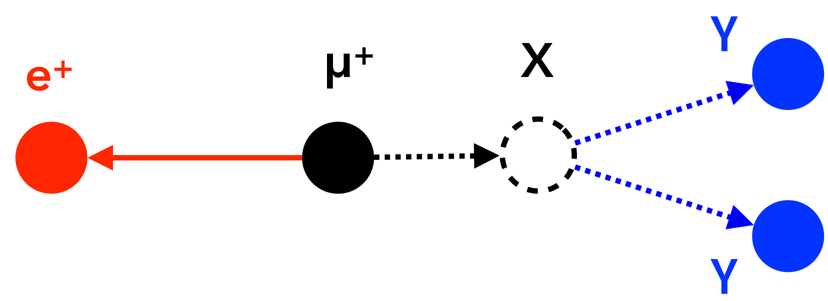
[3]

Target parameter space

- We have searched for the white region:
  - $m_X = 20 - 45\,\mathrm{MeV}$
  - $\tau < 40\,\mathrm{ps}$



Signal & Background



Signal

- p_X and p_{e^+} is less than $m_\mu/2 = 52.8\,\mathrm{MeV}$.
- $E_{\gamma_1} + E_{\gamma_2}$ is larger than $m_\mu/2$.
- 2γs are boosted and opening angle between them is less than 180°.
- $\mathrm{e}^+, \gamma, \gamma$ are coincident in time (at each vertex).

Background

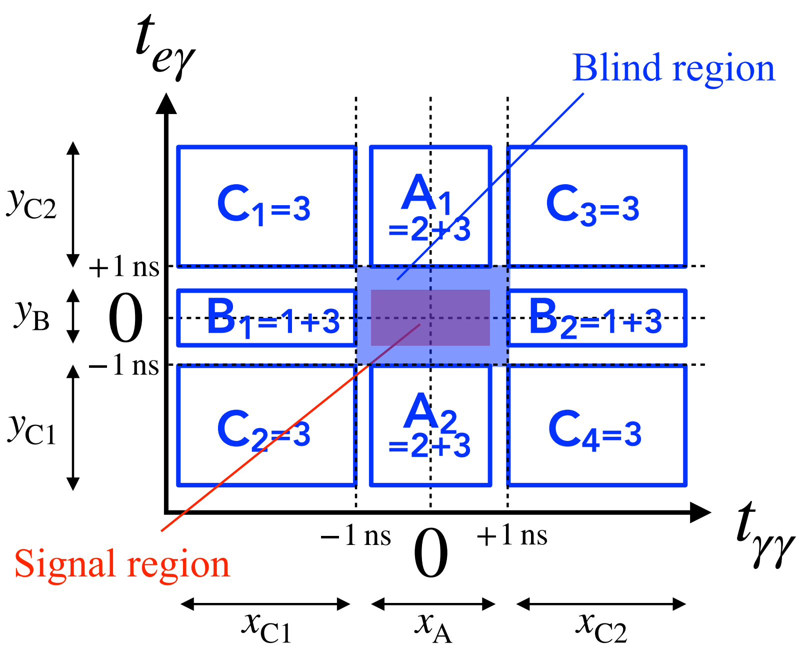
- one of γ is accidental
- e^+ is accidental
- e+, γ, and γ is accidental
- physics backgrounds are negligible

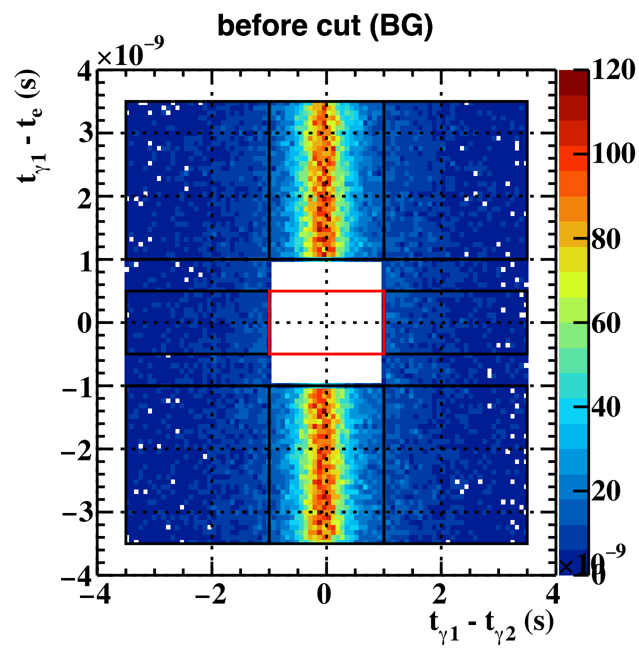
$\mu^+ \to e^+X, X \to \gamma\gamma$ decay search analysis

- Blind analysis
  - A blind analysis is used to reduce the experimenters's bias.
- Cut-counting-based analysis
  - We apply several cuts to reduce BGs while keeping the number of signal events.
  - The number of signals and BGs in the signal region are simultaneously estimated by a maximum likelihood fit.
- The confidence interval of the number of signal events and its significance are calculated in a frequentist approach.
- Branching ratio: $\mathscr{B}_{\mathrm{MEx2G}} = N_{\mathrm{Signal}} \times \dfrac{1}{k}$
  - N_{Signal}: the number of signal
  - k: normalization factor, $1/k$: single event sensitivity

Blind analysis

- Blind analysis
  - A blind analysis is used to reduce the experimenters's bias.
- Blind region: $|t_{e\gamma_1}| < 1\,\mathrm{ns} \wedge |t_{\gamma\gamma}| < 1\,\mathrm{ns}$
  - $t_{e\gamma_1}$: time difference between e^+ and γ_1.
  - $t_{\gamma\gamma}$: time difference between twoγs.



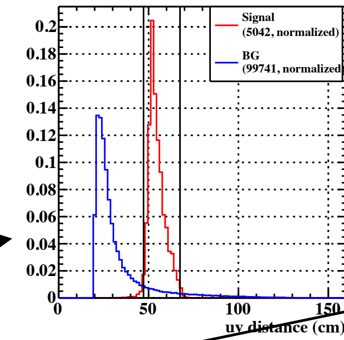


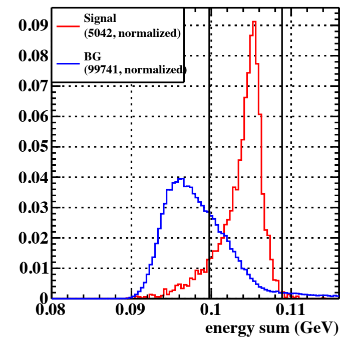
Signal selection

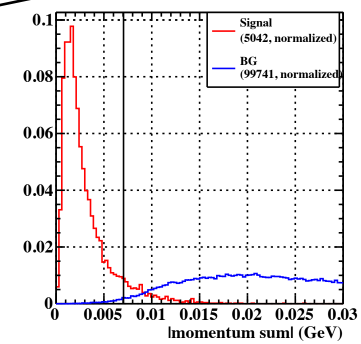
Red: signal (MC)
Blue: background (data)
Black: optimized thresholds

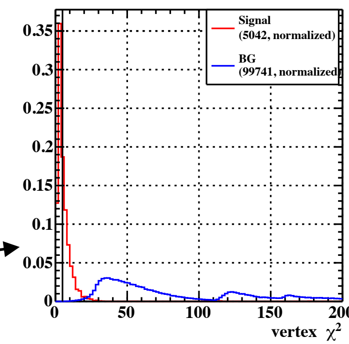
(20 MeV, 20 ps)

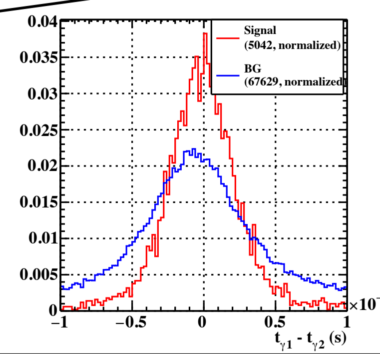
- Geometrical cuts
  - $|u_{\gamma 1,2}| < 25\,\mathrm{cm}$($\gamma$ acceptance), fixed
  - $|v_{\gamma 1,2}| < 71\,\mathrm{cm}$($\gamma$ acceptance), fixed
  - $\sqrt{(u_{\gamma 1} - u_{\gamma 2})^2 + (v_{\gamma 1} - v_{\gamma 2})^2}$
- Energy cuts
  - $E_{\mathrm{sum}} \equiv E_{\mathrm{e^+}} + E_{\gamma_1} + E_{\gamma_2}$
  - $E_{\gamma 1,2} > 10\,\mathrm{MeV}$, fixed
  - $|P_{\mathrm{e^+}} - P_{\mathrm{X}}| < 1\,\mathrm{MeV}$, fixed
- $\mathrm{X} \to \gamma\gamma$ vertex quality cuts
  - $\vec{P}_{\mathrm{sum}} \equiv \vec{P}_{\mathrm{e^+}} + \vec{P}_{\gamma_1} + \vec{P}_{\gamma_2}$
  - Vertex χ^2
- Time difference
  - $t_{\gamma\gamma} = (t_{\gamma_1} - \frac{r_1}{c}) - (t_{\gamma_2} - \frac{r_2}{c})$
  - $t_{\gamma_1 \mathrm{e}} = (t_{\gamma_1} - \frac{r_1}{c} - \frac{l}{\beta c}) - t_{\mathrm{e}}$

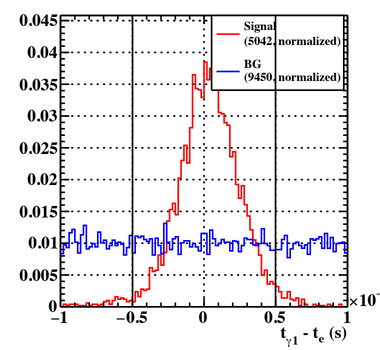












Signal estimation

- After the signal selections, we estimate the number of signal from the survived events.

normalization
k: true, k_0: estimated

- Likelihood function: $\mathscr{L}(N_{\mathrm{signal}}, \boxed{N_{\mathrm{BG}}}, k \,|\, N_{\mathrm{obs}}, \boxed{\text{Number of events in the sidebands}}, k_0)$

N_{BG} is calculated from time sidebands

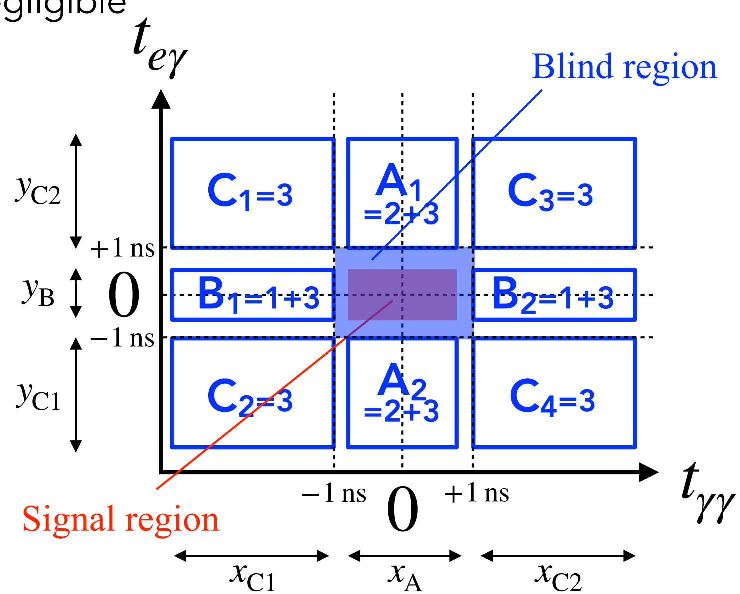
  - N_{signal}: number of signal
  - N_{BG}: number of background
  - N_{obs}: number of observed events in the analysis region (after unblinding).

- N_{BG} can be estimated from number of events in the sidebands (see next).

Background estimation

- N_{BG} can be estimated from number of events in the sidebands
- table: BG types. The same symbol indicates the same physics origin.

	type	e^+	γ_1	γ_2	source
Accidental	1	○	○	△	○: RMD △: RMD, AIF, brems.
	2	○	△	△	○: Michel △: AIF / RMD, AIF or brems. from RMD e^+
	3	○	△	◇	○: Michel △, ◇: RMD, AIF, or brems.
Physics →negligible	4	○	○	○	Doubly radiative muon decay, RMD accociated BG

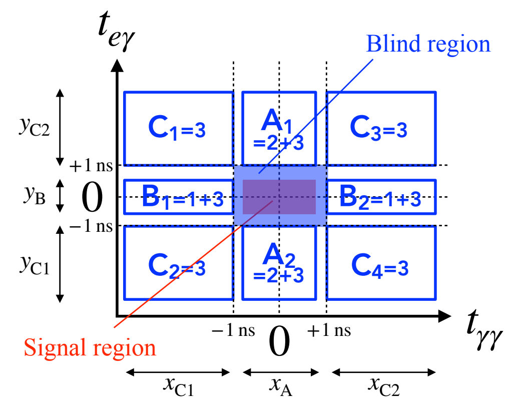


ex)
A_1 has contribution from BG type2 and type3.
→type2 component of N_{BG} can be estimated from A_1 and A_2.

Number of observed events in the signal region

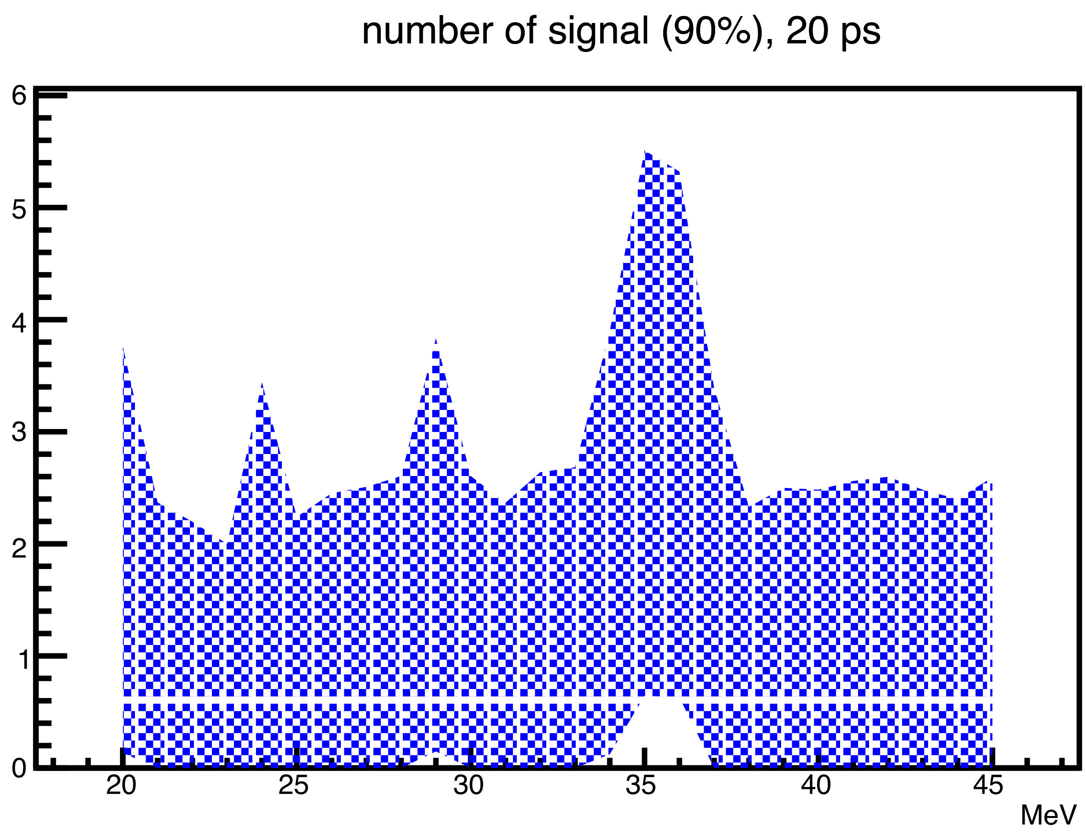
- We observed 1, 2 events in some mass regions:

mass (MeV)	sideband			expected N_{BG} in signal region	nObs
	$A(=A_1+A_2)$	$B(=B_1+B_2)$	$C(=C_1+C_2+C_3+C_4)$		
20	0	0	1	$0.048^{+0.202}_{-0.046}$	1
21	0	0	3	$0.146^{+0.198}_{-0.084}$	0
22	1	0	5	$0.292^{+0.211}_{-0.140}$	0
23	3	0	3	$0.622^{+0.425}_{-0.330}$	0
24	2	0	1	$0.414^{+0.346}_{-0.260}$	1
25	2	0	3	$0.414^{+0.346}_{-0.261}$	0
26	0	0	3	$0.150^{+0.189}_{-0.091}$	0
27	0	0	1	$0.050^{+0.200}_{-0.049}$	0
28	0	0	1	$0.048^{+0.202}_{-0.046}$	0
29	0	0	1	$0.048^{+0.202}_{-0.046}$	1
30	0	0	0	$0.000^{+0.170}_{-0.000}$	0
31	0	0	1	$0.048^{+0.202}_{-0.046}$	0
32	0	0	0	$0.000^{+0.170}_{-0.000}$	0
33	0	0	0	$0.000^{+0.210}_{-0.000}$	0
34	0	0	0	$0.000^{+0.210}_{-0.000}$	1
35	0	0	0	$0.000^{+0.210}_{-0.000}$	2
36	0	0	0	$0.000^{+0.210}_{-0.000}$	2
37	1	0	0	$0.400^{+0.517}_{-0.301}$	1
38	0	0	2	$0.168^{+0.183}_{-0.105}$	0
39	0	0	1	$0.084^{+0.201}_{-0.084}$	0
40	0	0	0	$0.000^{+0.210}_{-0.000}$	0
41	0	0	0	$0.000^{+0.210}_{-0.000}$	0
42	0	0	0	$0.000^{+0.210}_{-0.000}$	0
43	0	0	1	$0.084^{+0.201}_{-0.084}$	0
44	0	0	0	$0.000^{+0.210}_{-0.000}$	0
45	0	0	0	$0.000^{+0.210}_{-0.000}$	0



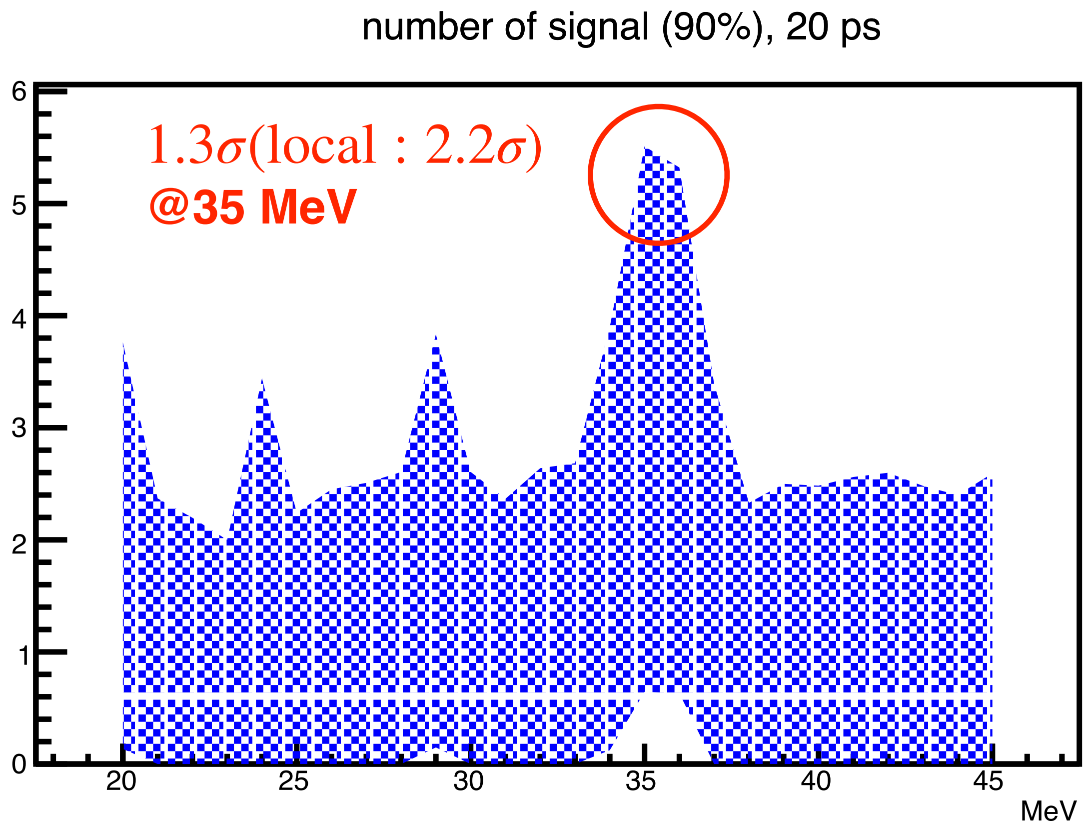
Number of signal (90% C.L.)

- The Feldman-Cousins approach is used to estimate the interval.
  - Note that Feldman-Cousins can give both upper and lower limits.
- Some masses have both upper and lower limits.



Number of signal (90% C.L.)

- The Feldman-Cousins approach is used to estimate interval.
- Some masses have both upper and lower limits.
- **The excess is not statistically significant.**



Normalization

- To get the relative normalization, Michel events ($\mathscr{B}(\mu^+ \to e^+\nu\bar{\nu})$~100%) are used.

$\mu^+ \to e^+\nu\bar{\nu}$: Michel decay, Br ~ 100%

$\mu^+ \to e^+X, X \to \gamma\gamma$: MEx2G signal

$$\mathscr{B}_{\mathrm{MEx2G}} = N_{\mathrm{Signal}} \times \frac{1}{k}$$

$$\frac{1}{k_0} = \frac{1}{N_{\mathrm{Michel}}} \times \overset{\sim 1}{\mathscr{B}_{\mathrm{Michel}}} \times f_{\mathrm{Michel}} \times \overset{\sim 10^{-7}}{\boxed{\text{ratio of trigger}}} \times \frac{\epsilon_{\mathrm{Michel}}}{\epsilon_{e^+}} \times \frac{1}{\epsilon_{\mathrm{MEx2G}/e^+}}$$

The number of Michel events

Fraction of Michel events (7%–10%)

Relative e+ efficiency (90%)

Efficiency of γ, direction match trigger, and cut. 0.2%–1.4%

*k_0: measured value of k

- By using Michel e$^+$s as a normalization, the estimation is independent of beam rate (stopped muons), and insensitive to absolute positron detection efficiency.

Uncertainty on normalization

20 MeV, 20 ps

- Main source: systematic uncertainty coming from MC smearing and γ detection efficiency.
  - MC smearing is estimated from differences of the efficiency with different smearing parameters (mean, mean±systematics).
  - γ detection efficiency from MEG1 study.
- The uncertainty is incorporated into the signal likelihood function;
  - normalization factor k is also fitted

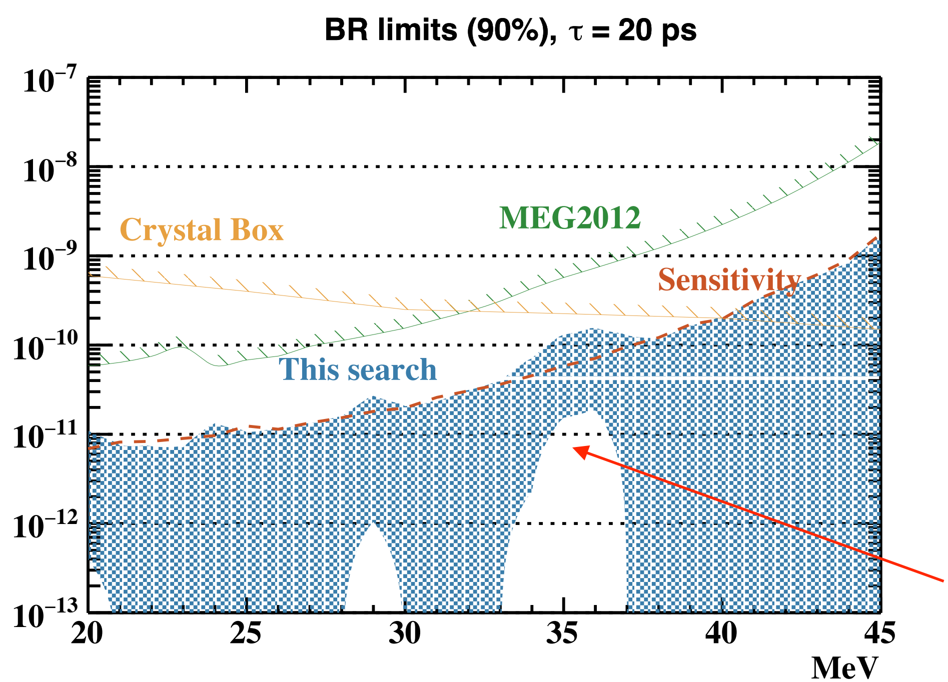
	(2013)	Relative uncertainty
# of Michel events	53841	0.43 % (stat)
branching ratio of Michel	1	0
energy fraction of Michel	0.104	0.01 % (sys)
prescale	10^7	0
prescale correction	1.12	0.89 % (stat)
Relative positron efficiency correction	1.024	1.3 % (sys)
Missing turn correction	0.957	0.21 % (sys)
Signal efficiency (γ, DM, selection)	0.0135	2.1 % (stat) 9.5 % (sys)

	Relative uncertainty
acceptance	1.3%
trigger efficiency	0.98%
pileup inefficiency	2.8%
detection efficiency	7.4%
MC Smearing	4.8%

γ

BR limits (1/2)

- BR limits is improved by a factor of 4.4–13 depending on m_X from MEG2012 (2009/2010 MEG data is used).
  - SES is improved by a factor of 5.6–13 depending on m_X
  - Statistics (and positron analysis updates) contributes (at most) ~5.
  - Optimization of selection efficiency at higher m_X contributes (at most) ~3.
    - ✓ In the previous analysis in MEG2012, selection conditions are not optimized.



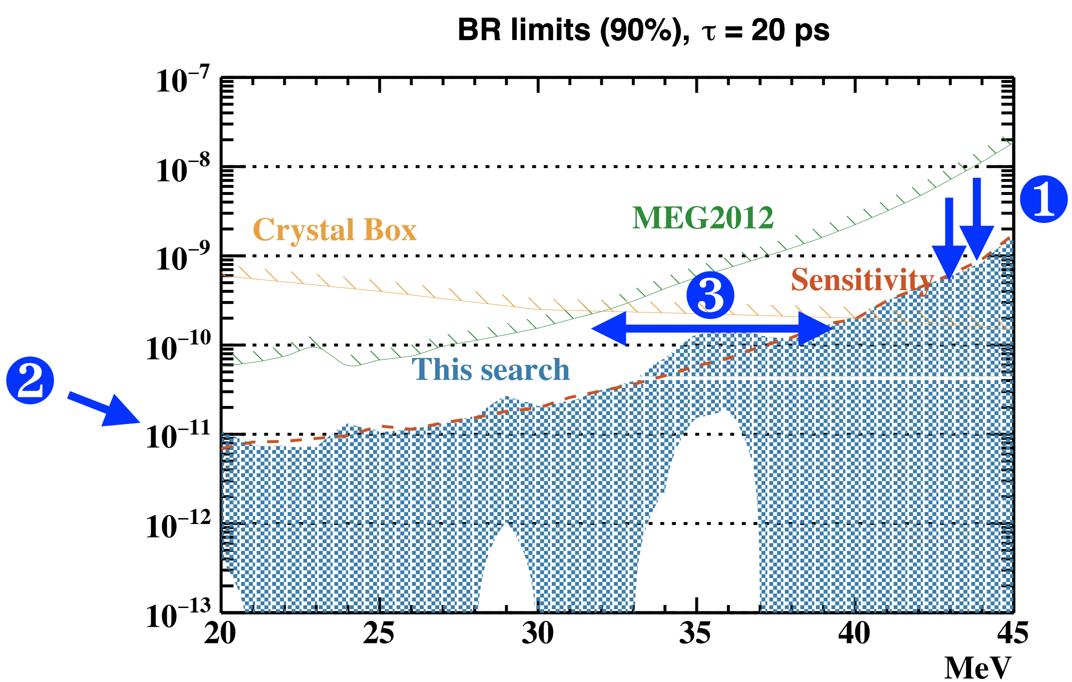
Lower limits of BR due to excess events.

BR limits (2/2): 3 key features

❶ Improved BR upper limits in all m_X from the previous analysis using 2009 and 2010 data (MEG2012).

❷ Set BR upper limits down to $\mathcal{O}(10^{-11})$.

❸ Improved BR upper limits in $m_X > 30\,\mathrm{MeV}$, which was not improved by MEG2012.

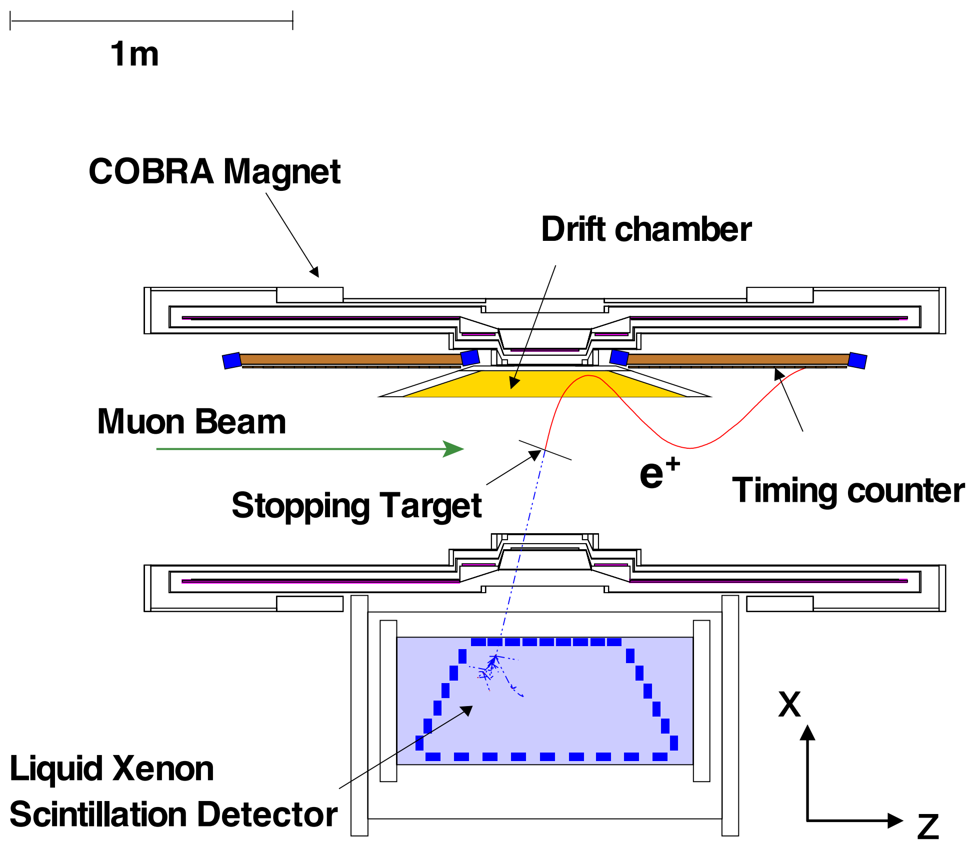


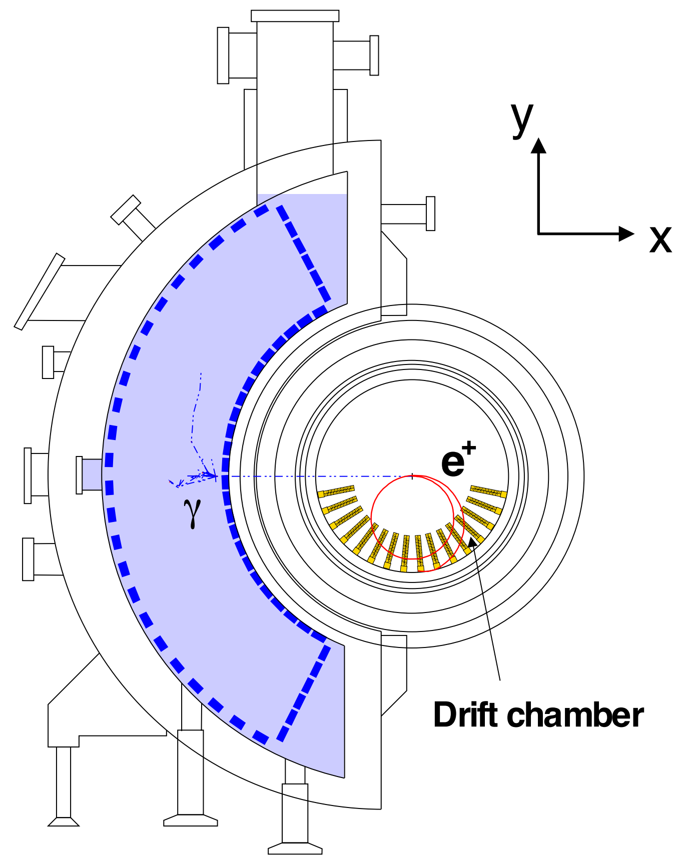
Conclusion

- We have searched for a **lepton flavor violating muon decay** mediated by **a new light particle X**, $\mu^+ \to \mathrm{e}^+\mathrm{X}, \mathrm{X} \to \gamma\gamma$, using the full datasets (2009–2013, $7.5 \times 10^{14} \mu^+\mathrm{s}$) of the MEG experiment.
- No significant excess was found in the mass region of 20–45 MeV, lifetime below 40 ps.
  - In particular, the upper limits are **pushed down to the level of $\mathscr{O}(10^{-11})$** for 20–30 MeV.
- It is at most **60 times more stringent** result than the bound from the Crystal Box experiment.
- The MEG II experiment is planned and the sensitivity is expected to be improved by one order of magnitude.
- A further update can be possible in the future CLFV experiments.

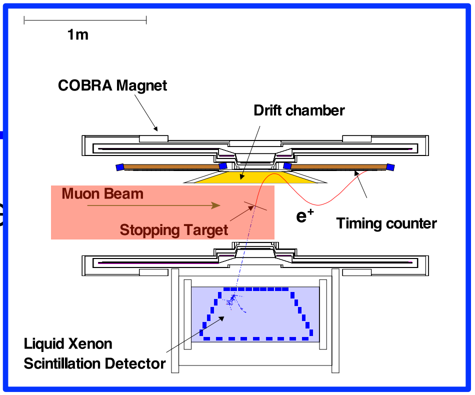
Backup slides

MEG Apparatus

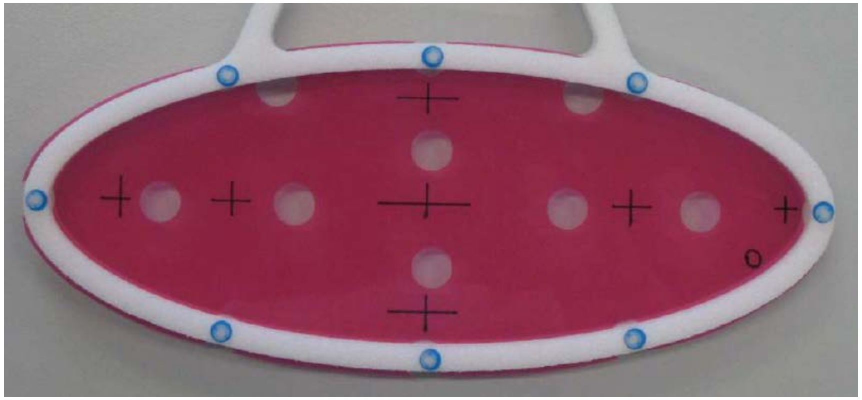


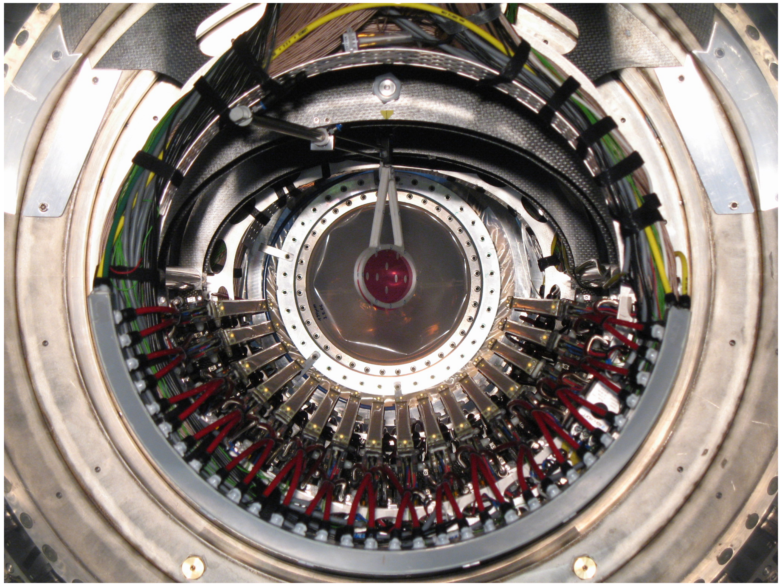


μ^+ Beam & target

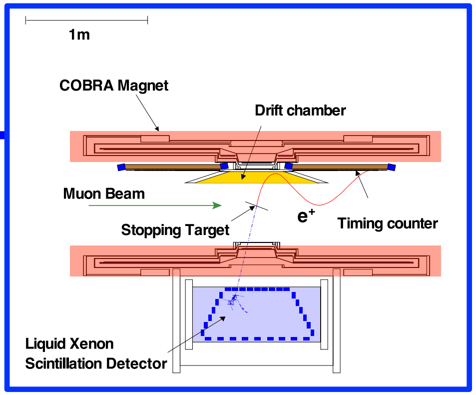


- The world most powerful proton ring cyclotron @PSI in Switze
  - 2.2-2.4 mA, 1.4 MW, 590 MeV proton, RF: 50.7 MHz.
- The πE5 beamline
  - provides $3 \times 10^8 \mu^+/\mathrm{s}$ at 28 MeV/c, operated at $3 \times 10^7 \mu^+/\mathrm{s}$ for the MEG data taking.
- Stopping target
  - 205 $\mu\mathrm{m}$ thick polyethylene and polyester sheet (density: 0.895 $\mathrm{g/cm^3}$).
  - Slanted angle of 20°

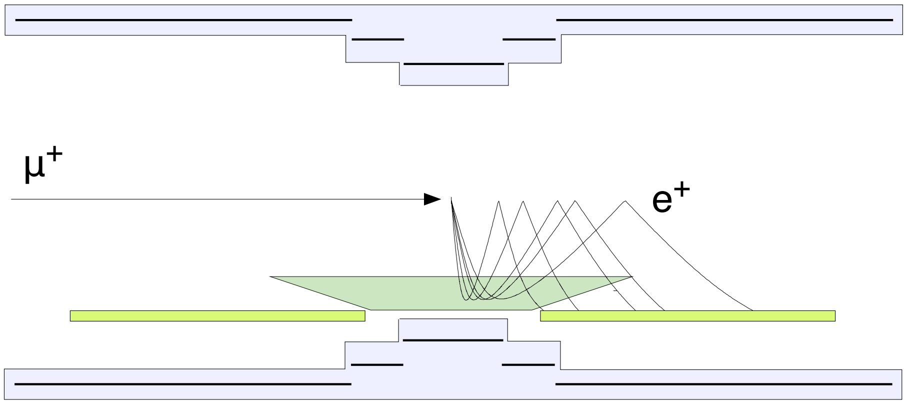




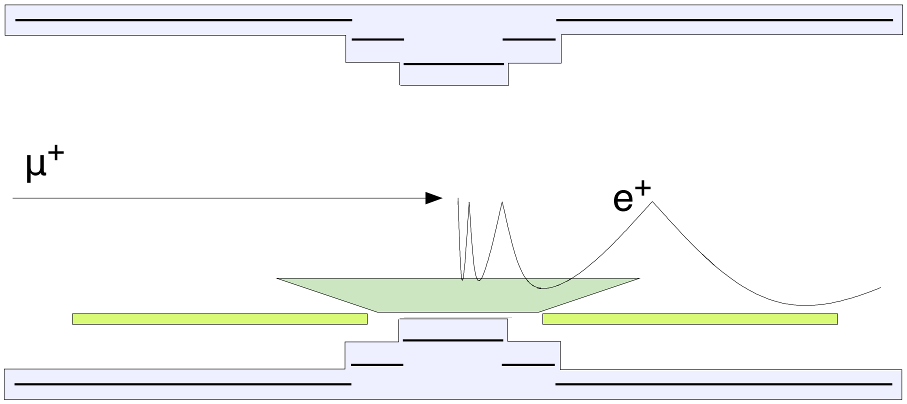
e^+: COBRA magnet



- COBRA = COnstant Bending RAdius
- Specially graded B field
  - The diameter of the trajectories depend on e^+ momenta independent of their emission angles.
  - Low momentum e^+s are quickly swept out
    - ✓ Low hit rate in the drift chambers
  - e^+s whose momenta are more than ~45 MeV come into the acceptance

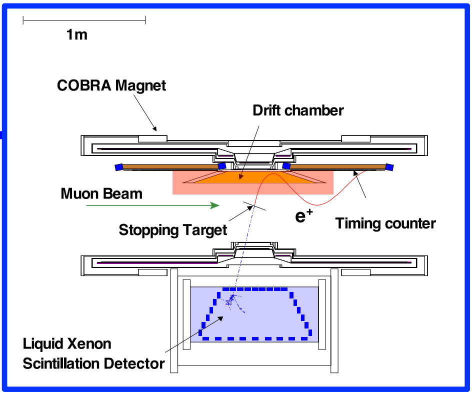


(a)

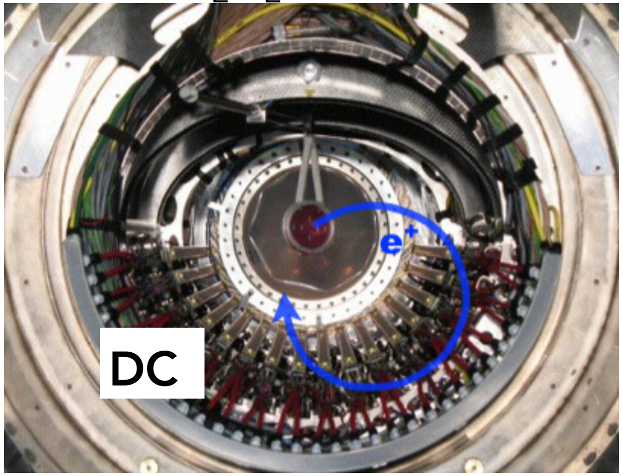


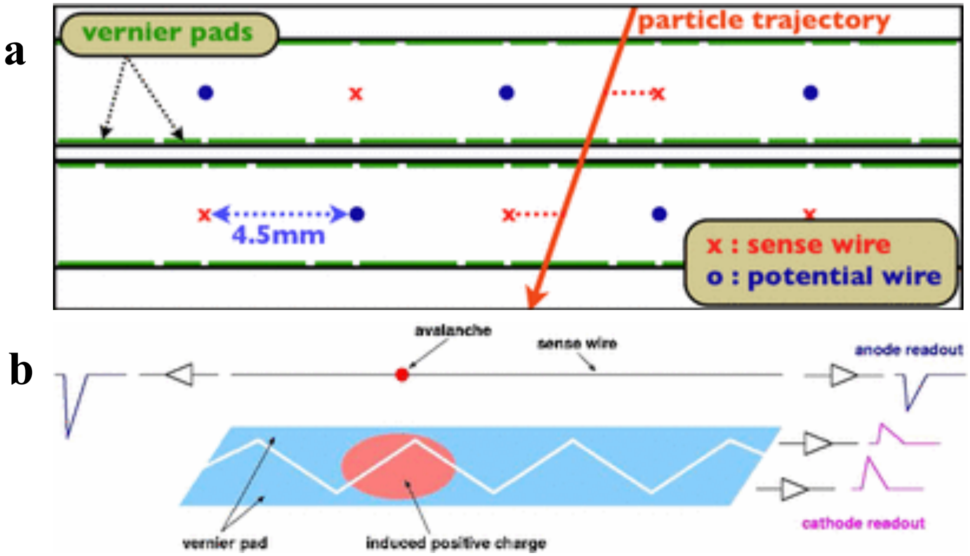
(b)

e^+: Drift Chamber

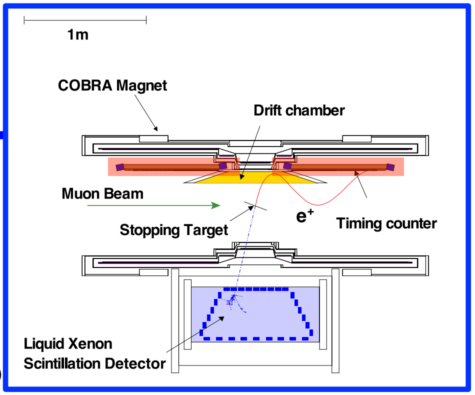


- Track e^+s.
- Made of ultra low mass materials
  - Minimize the multiple scattering.
  - Suppress γ BG.
  - in total, $2.6 \times 10^{-4} X_0$
- 16 modules consist of two staggered layers.
- Vernier method is used for z reconstruction.
- Helium-based chamber gas.
  - $He:C_2H_2=1:1$



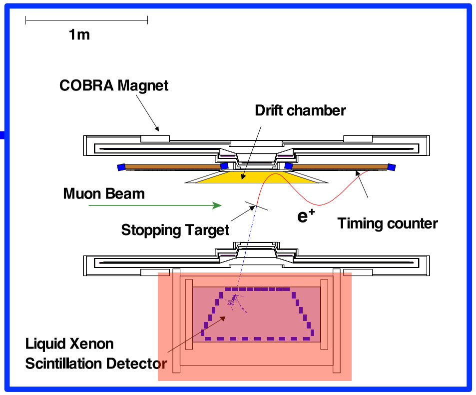


e^+: Timing Counter

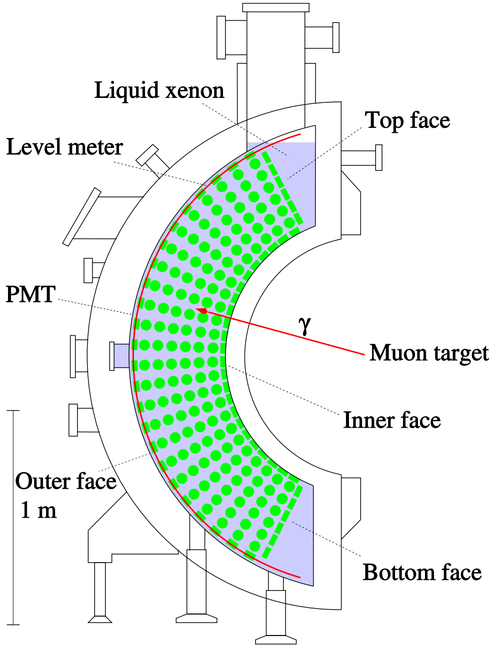


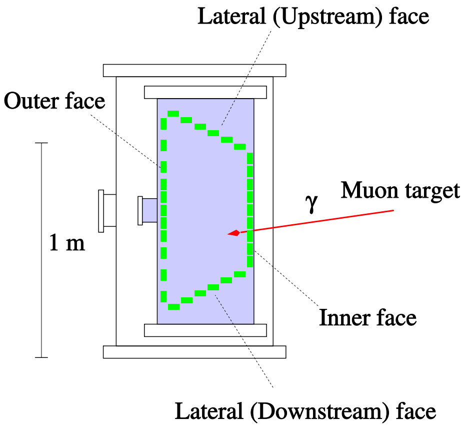
- Measure hit timing of e^+s.
- 15 scintillator bars for both upstream and downstream.
- Scintillation light are detected by using fine-mesh PMTs at bo

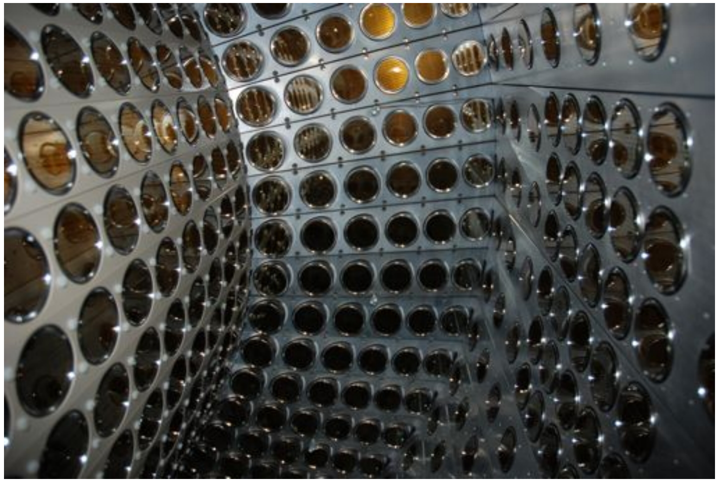
γ: Liquid xenon detector



- Detect γ using liquid xenon (active volume 800 L).
  - Determine timing, energy, and position of γ
- Good stopping power (Liquid xenon).
- Fast scintillation timing (Liquid xenon).
- VUV-sensitive (178 nm) PMTs (846 tubes).
  - Newly developed for MEG by Hamamatsu.







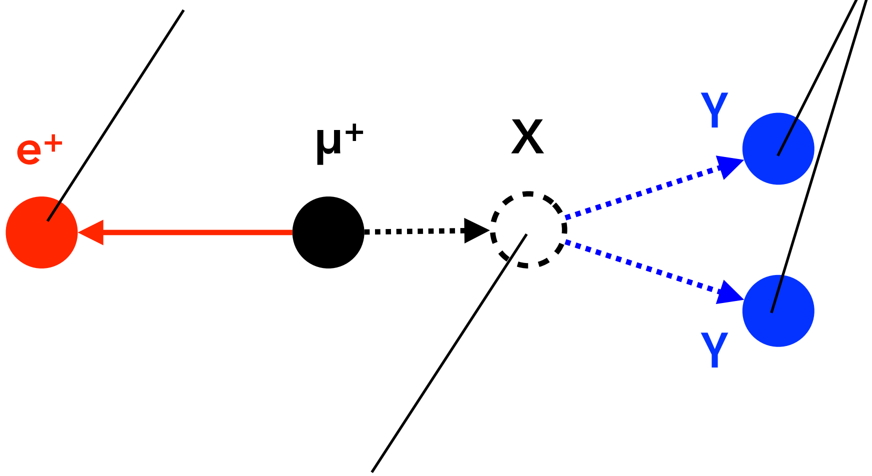
Event reconstruction

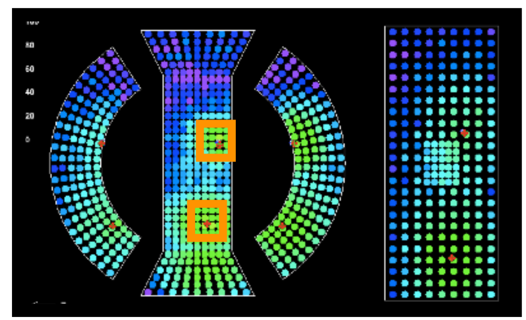
1. e^+ reconstruction

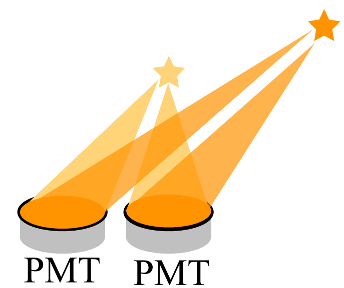
- TC: time
- DCH: momentum, position

2. 2γ reconstruction

- Energy & position: simultaneous least square fit using light yield of all PMTs.
- Time: least square fit using selected PMTs.







3. Combined reconstruction

- $X \to \gamma\gamma$ vertex position: maximum likelihood fit assuming m_X.
- Momentum: $\overrightarrow{P}_{\gamma_1}, \overrightarrow{P}_{\gamma_2} (, \overrightarrow{P}_X)$
- Time differences: $t_{\gamma 1} - t_{\gamma 2}, t_{\gamma 1} - t_{e^+}$

DAQ & Trigger

- DRS4 (Domino Ring Sampler)
  - Switched capacitor array specially developed at PSI.
  - Take the data from all detectors as waveforms.

- Trigger
  - Trigger rate below 10 Hz.
  - γ energy, time difference between e^+ and γ, and relative direction of e^+ and γ are used in the trigger algorithm.
  - Not optimized for the MEx2G search and the direction match trigger condition loses the MEx2G signal (down to 50–90 %).

Dataset

- $7.5 \times 10^{14} \mu^+$s stopped on the target in 5 years.
  - $1.8 \times 10^{14} \mu^+$ (2009 and 2010) was used for the previous MEx2G analysis in 2012.

- $\mu^+ \to e^+\gamma$ data is reused for the MEx2G search.