The final result of $\mu^+ \to e^+ + \gamma$ decay with the MEG experiment

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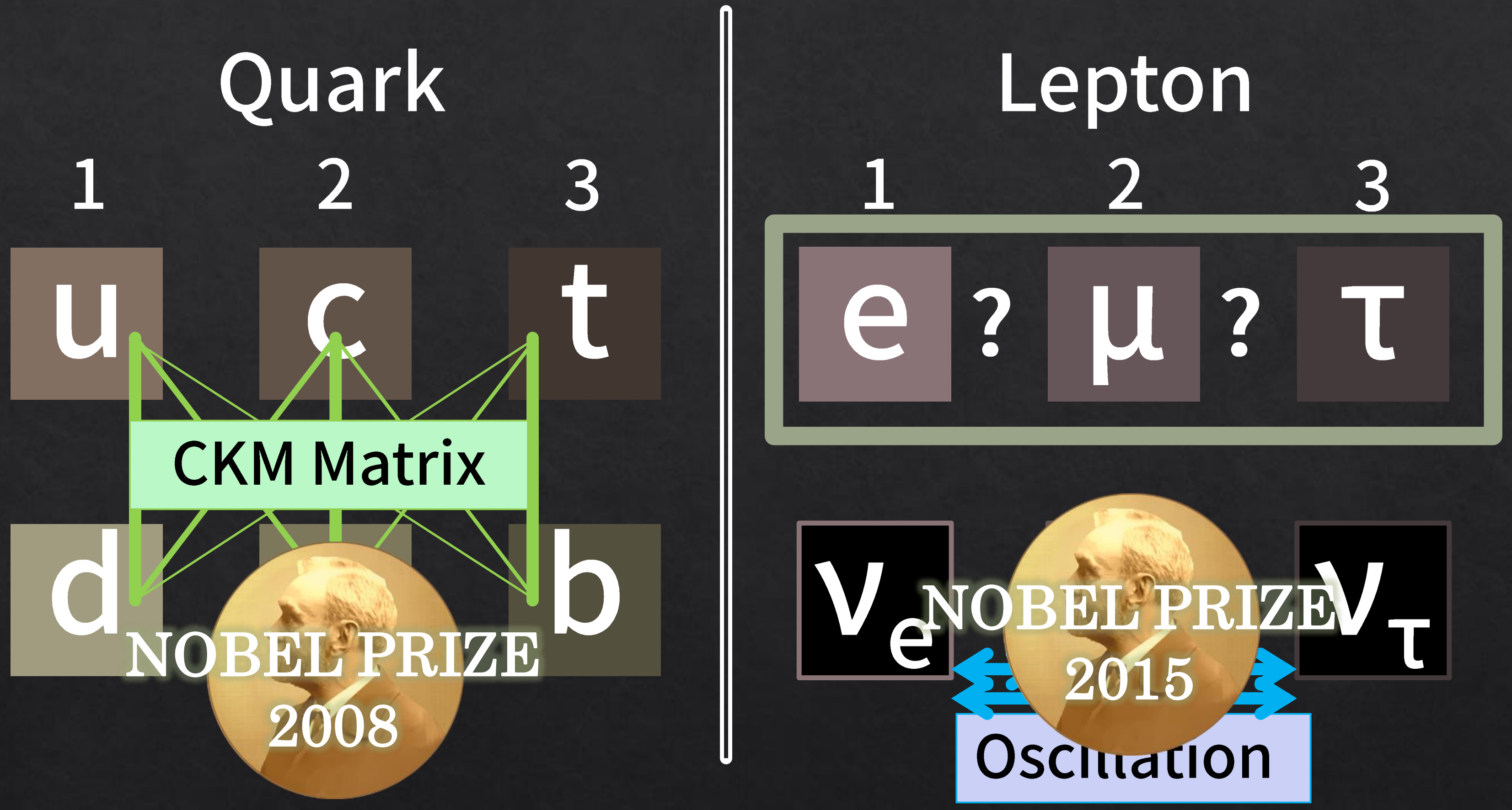
ICEPP The University of Tokyo → KAVLI IPMU

Contents

1. What is $\mu \rightarrow e\gamma$ Decay

Flavor of Particles



μ : who ordered that?

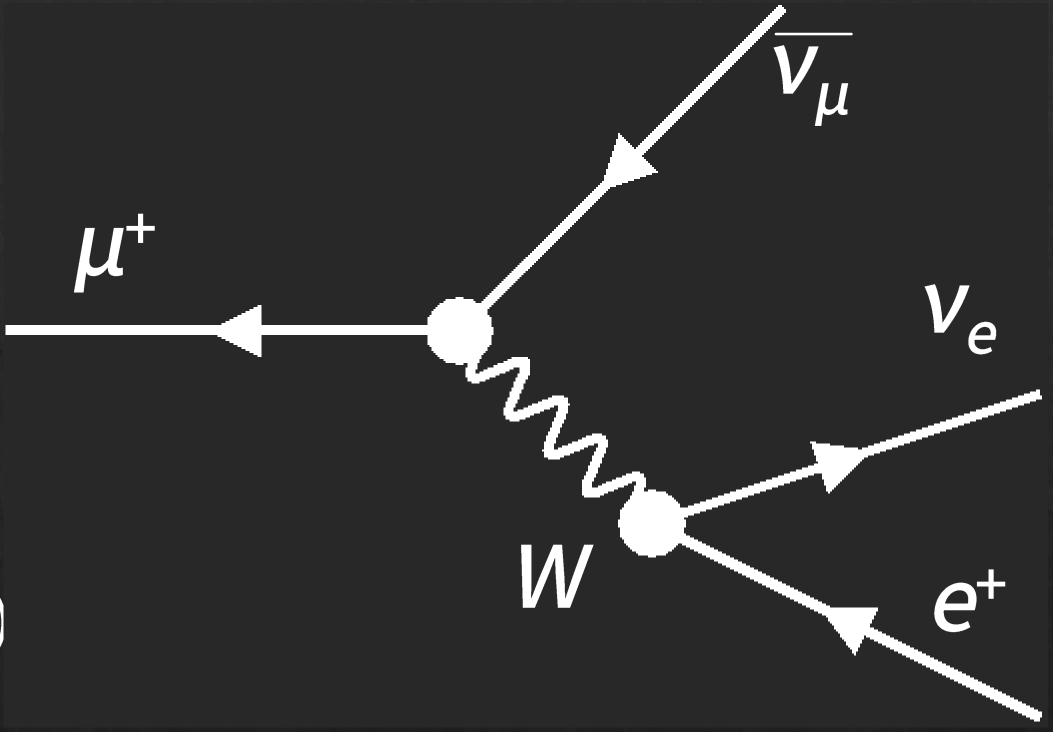
Charge : -e

Spin : 1/2

Rest mass : 105.6 MeV

Mean life : 2.197 μs

Decay :
- mode (branching ratio)
  - $e^+\overline{\nu_\mu}\nu_e$ (≈100%)
  - $e^+\overline{\nu_\mu}\nu_e\gamma$ (1.4% (Eγ>10MeV))



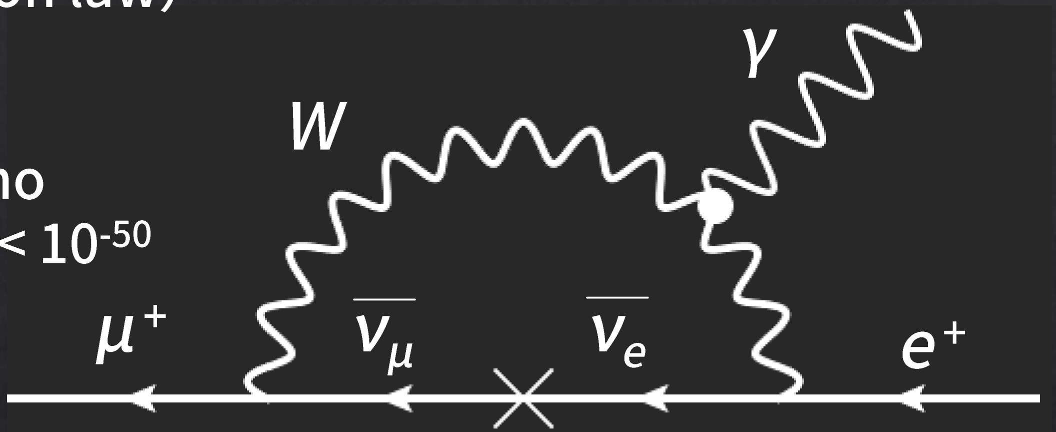
Lepton flavor violating modes have never been observed !

LFV decay : μ→e γ

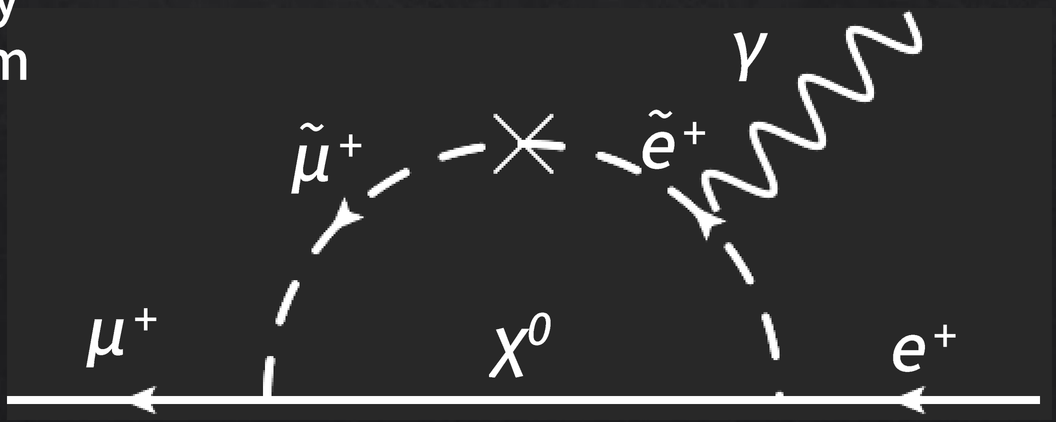
- Forbidden in Standard Model
  (Lepton flavor conservation law)

- It is possible, with neutrino oscillation, probability is $< 10^{-50}$
  no exist practically

- New theories beyond the SM predict sizable probability
  - see-saw mechanism
  - SUSY-GUT
  - etc.



μ→e γ via ν-oscillation



μ→e γ via SUSY particle

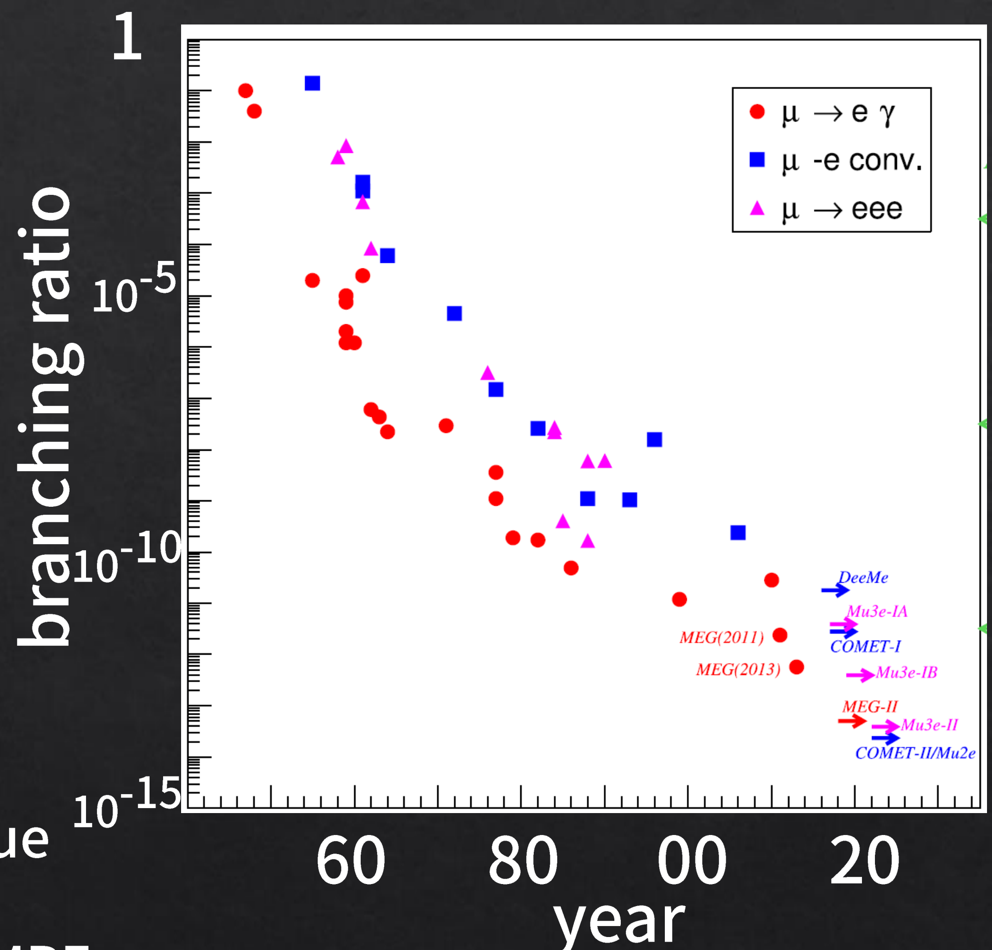
History of μ→e γ search

1936
 Discovery of μ

1947
 First search with cosmic-ray
 "μ is not an excited state of e"

1950s
 μ→eγ search with accelerator

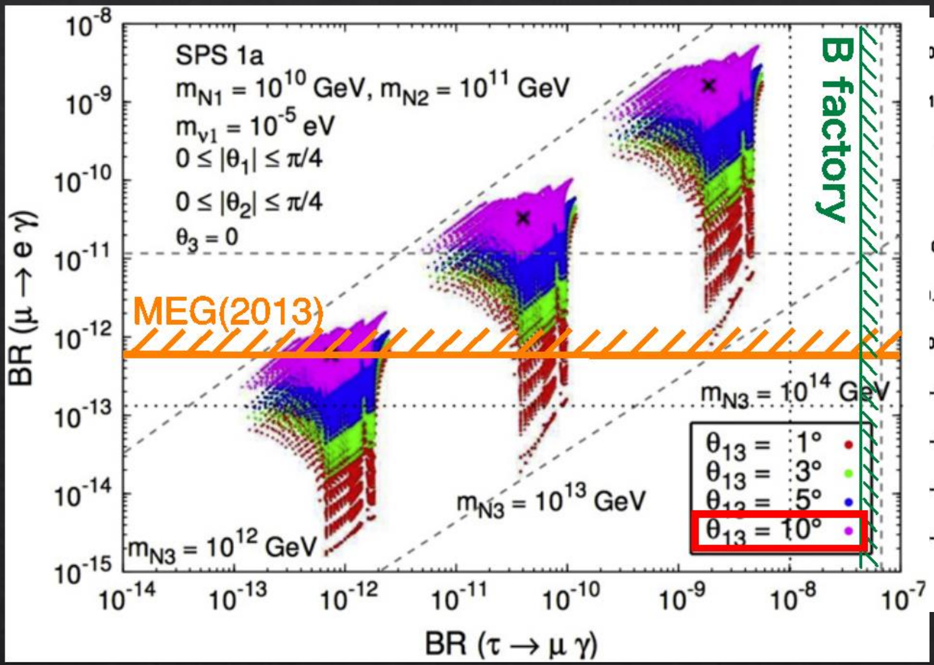
1970s
 Search with meson factories
 "Concept of lepton flavor"
 Rumor of discovery, but not true

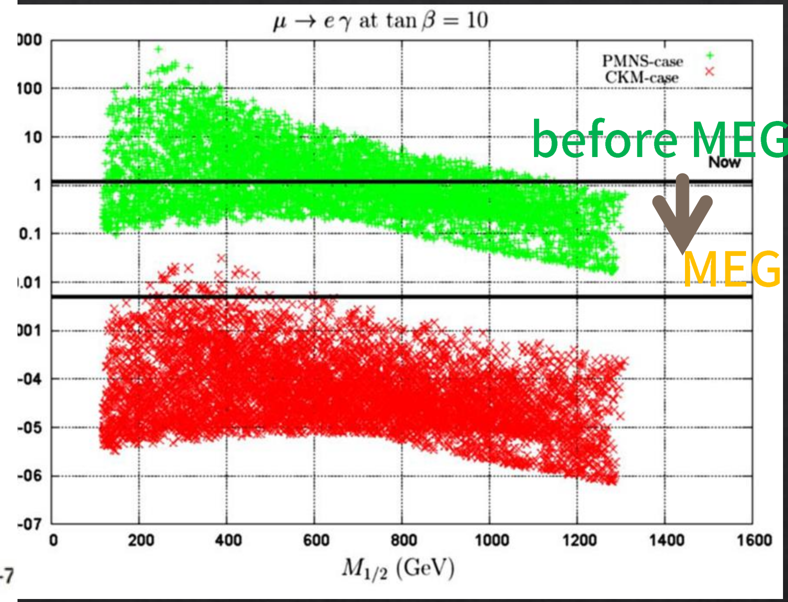


Crystal Box: 1.7×10^{-10} 1984 @LAMPF

MEGA: 1.2×10^{-11} 1999 @ LAMPF

$10^{-12} \sim 10^{-14}$ is predicted





Antusch et al.,
J. HEP **2006**(11), 090 (2006)

SUSY SU(5) + seesaw
different colors correspond
different θ_{13} value
(already discovered to be ~9°)

L. Calibbi et al.
Phys. Rev. D **74,** 116002 (2006)

SO(10) + seesaw
green : PMNS case, red : CKM case
tanβ = 10, as function of $M_{1/2}$

Signal & BackGround

★ Signal

52.8 MeV = m_μ /2, back-to-back, at the same time.

● BackGrounds

○ Radiative Muon Decay (RMD) $\mu^+ \rightarrow e^+\overline{\nu_\mu}\nu_e\gamma$

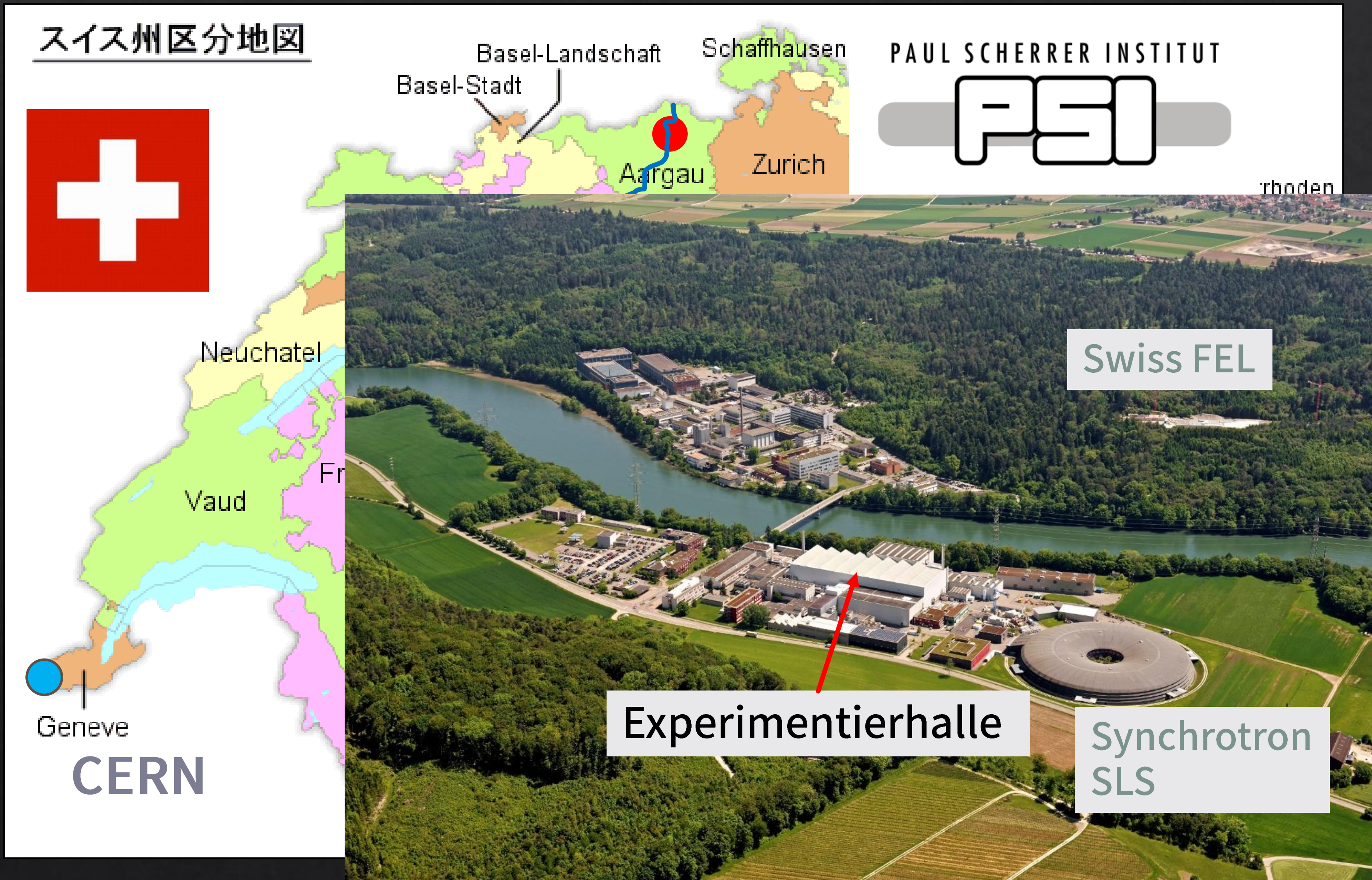
○ ACCidental BG (ACC)

- e^+ from normal μ+ decay
- γ from RMD or annihilation of e^+

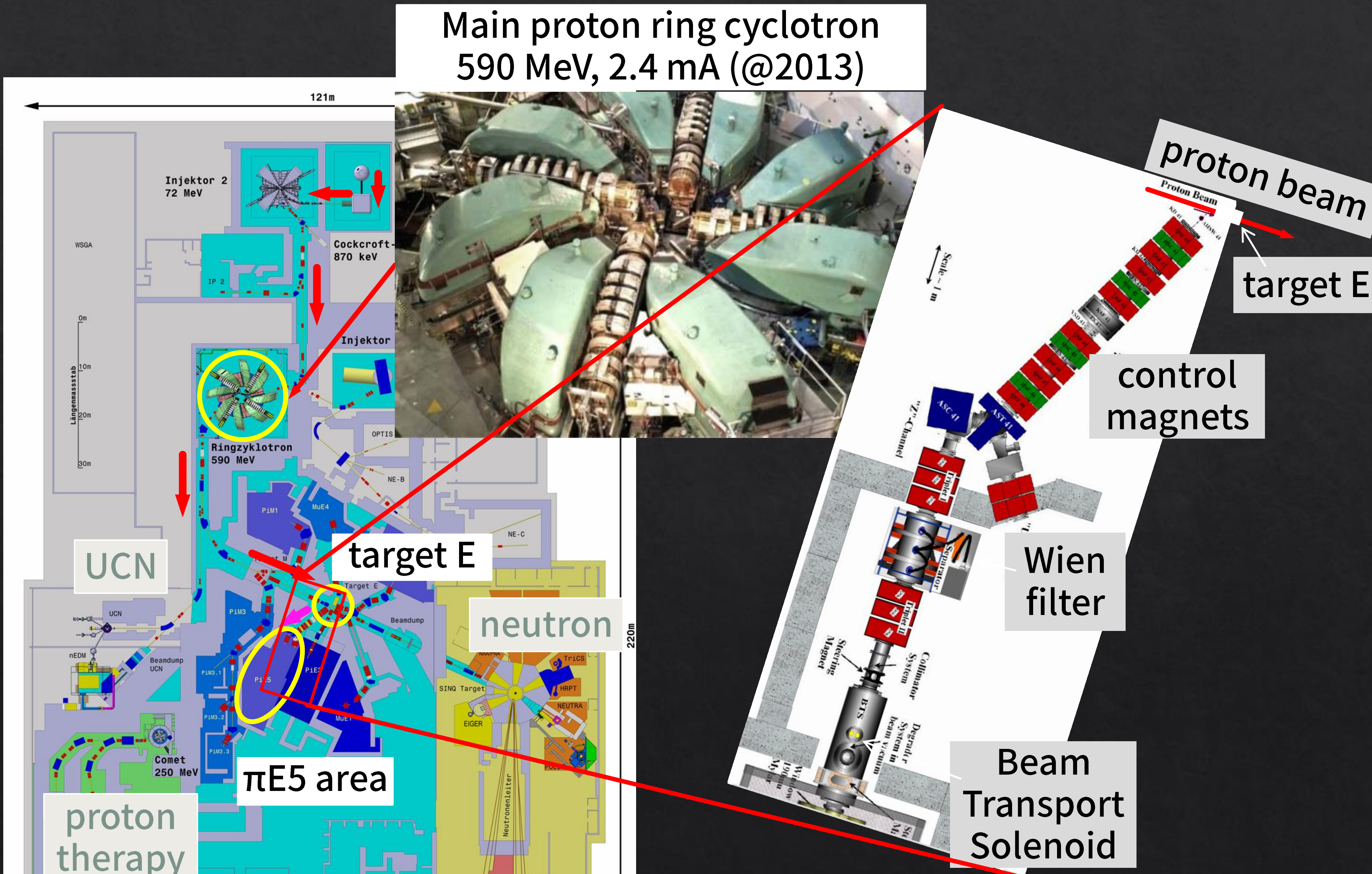
Type	Eγ	Ee+	Time	Angle
Signal	52.8 MeV	52.8 MeV	Te = Tγ	180°
RMD	<52.8 MeV	<52.8 MeV	Te = Tγ	≦180°
ACC	<52.8 MeV	≦52.8 MeV	uniform	no correlate

2. MEG Instruments

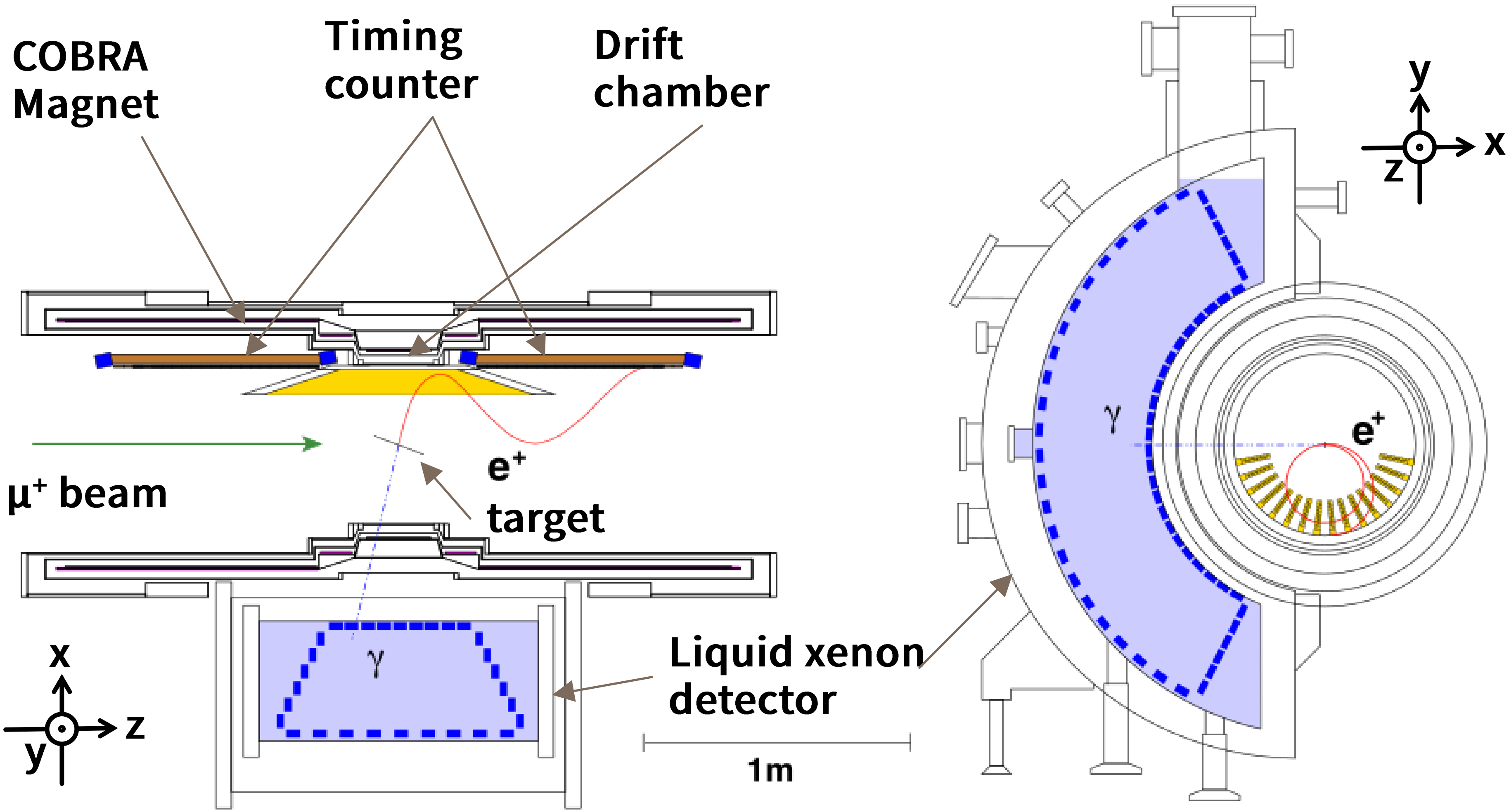
Location of experiment



PSI experimental hall

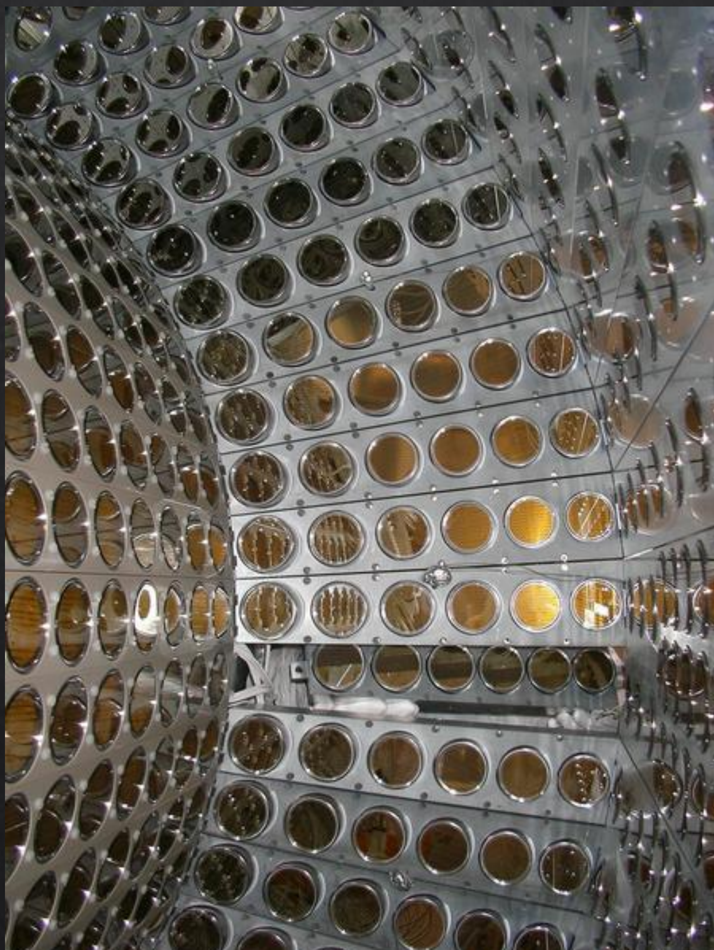


MEG detector



Liquid Xenon detector

Inside of the detector



Characteristics

- Total 900 l liquid Xe
- C-shaped cryostat
- 846 PMTs on 6 faces
- Honey-comb window at γ-ray entrance face
- Cooled with pulse tube refrigerator
- 2 kinds of purification systems equipped

200 W pulse tube refrigerator

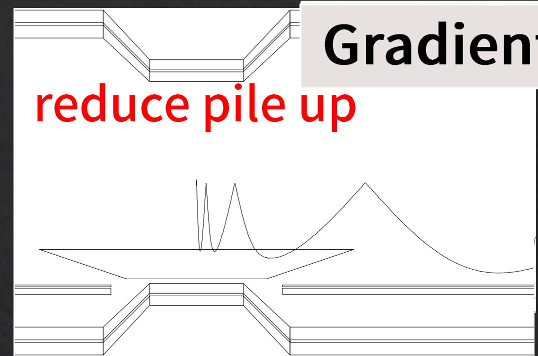
Liquid purifier

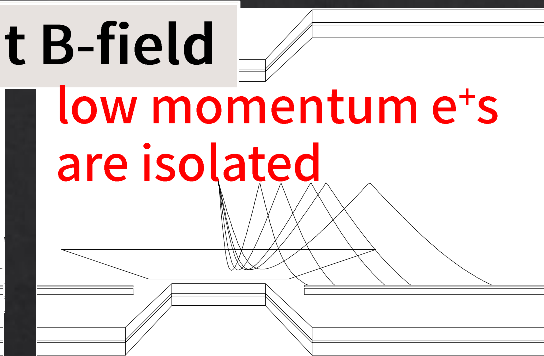
COBRA magnet

e$^+$ emitted in θ~90

θ vs radius of track

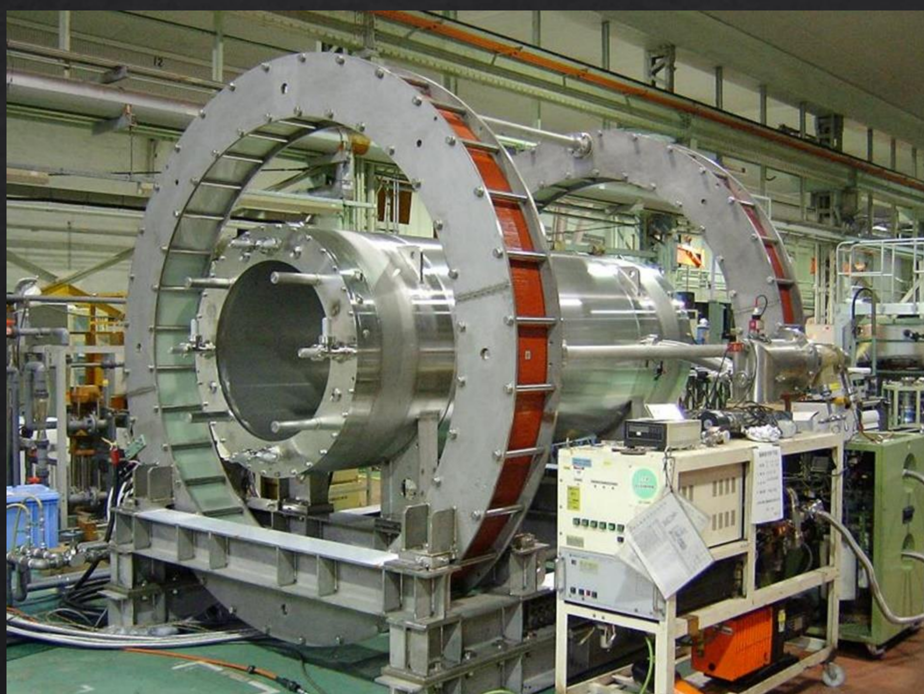
Gradient B-field

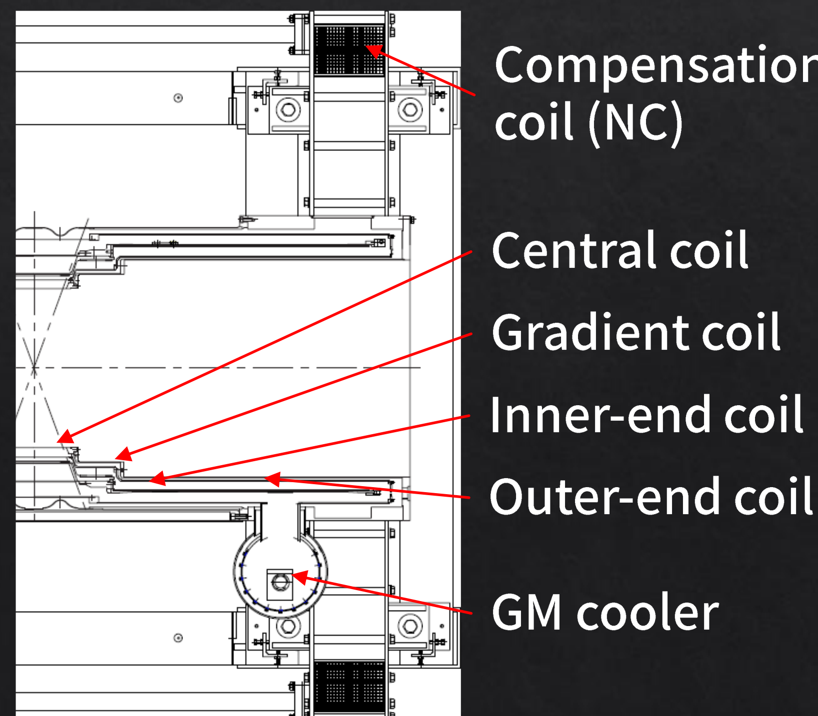




Design

- Gradient field
- NbTi/Cu SC magnet
- Thin for γ-ray transmission
- Cooled by GM refrigerator





Drift chamber: e^+ tracker

Interaction of e^+ and matter：

Multiple scattering → Worsens angular resolution
Pair annihilation → Generate γ-ray background

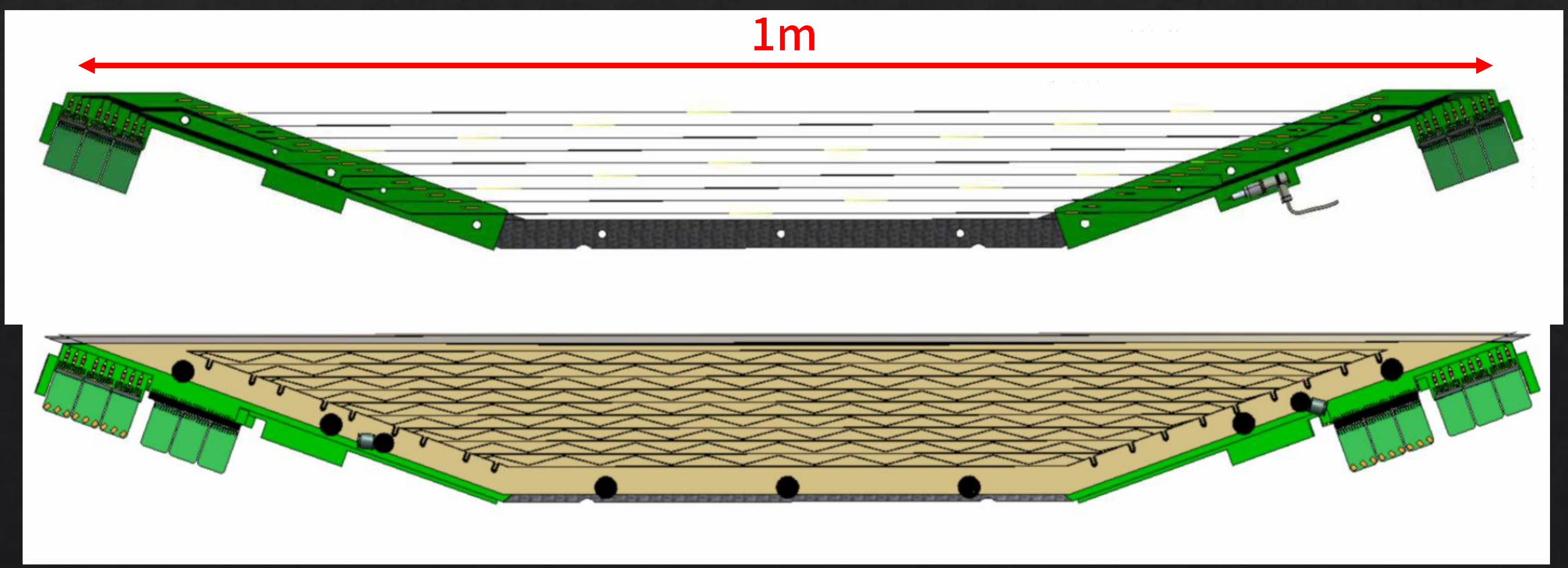
→ Ultra-low mass tracker

High-rate tolerance：

High rate μ^+s in beam eventually decay into e^+s.

→ 16 modularized detector in ϕ direction

Detector locate only at large R



e^+ timing counter

ϕ counter

- BC404 scintillator
  4×4×79.6 cm^3
  15 bars on each side
- PMT read-out on both end
  (Fine mesh type)

z counter

- BCF-20 scintillation fiber
  Total 256 pcs.
- APD readout at one end

(※z counter is not used)

Assembled ϕ counter (one of two)

Roll of timing counter

- Precise measurement of e^+ hit time
- Provide information for trigger

Electronics

Typical chain

data size
～1 MB/event

Trigger :

Make trigger information with FPGA by fast event reconstruction

- γ energy
- timing γ-e^+
- angle γ-e^+

trigger rate ～13 Hz

DRS :

Waveform digitizer developed in PSI
Sampling speed 1.4GHz (DCH: 0.7GHz, Max. 5GHz)

MIDAS system:

System to control DAQ and slow-control with Ethernet, by PSI.

3. Analysis and Result

History of MEG

2000 2004 2008 2012 2016

design | construction | data taking

1999
PSI proposal
Approval

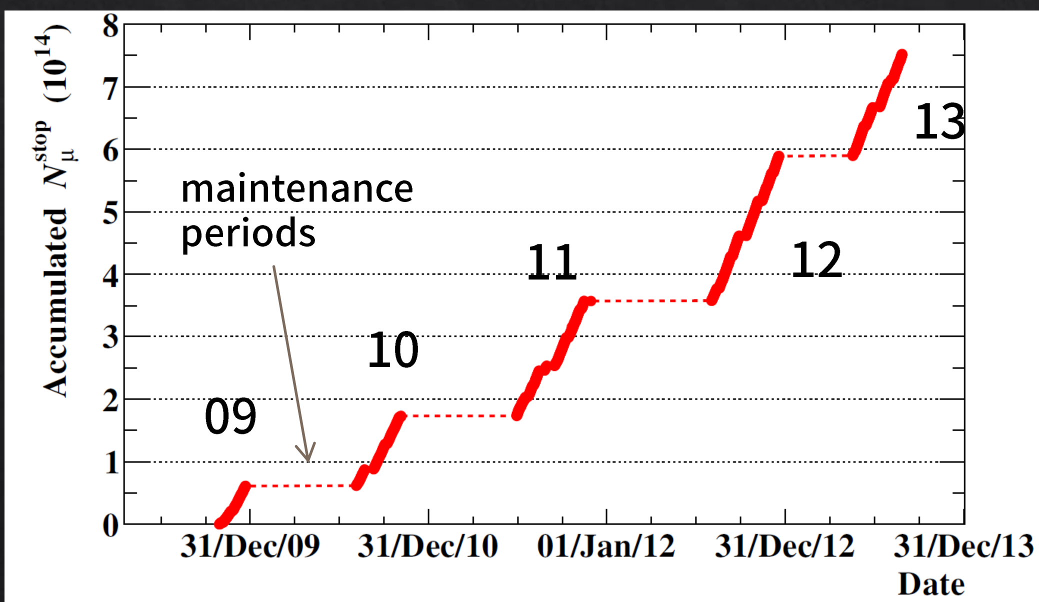
2007
Detector
Complete

2010
Nucl. Phys. B
834 1
2.8×10^{-11}
(90%CL)

2011
Phys. Rev. Lett.
107, 171801
2.4×10^{-12}
(90%CL)

2013
Phys. Rev. Lett.
110, 201801
5.7×10^{-13}
(90%CL)

final



data amount 93 TB
DAQ time 288days
# of run 124156
(~2000 event/run)
# of stopped μ^{+} 7.5×10^{14}

Event selection

Firstly, apply pre-selection in order to obviously accidental events.

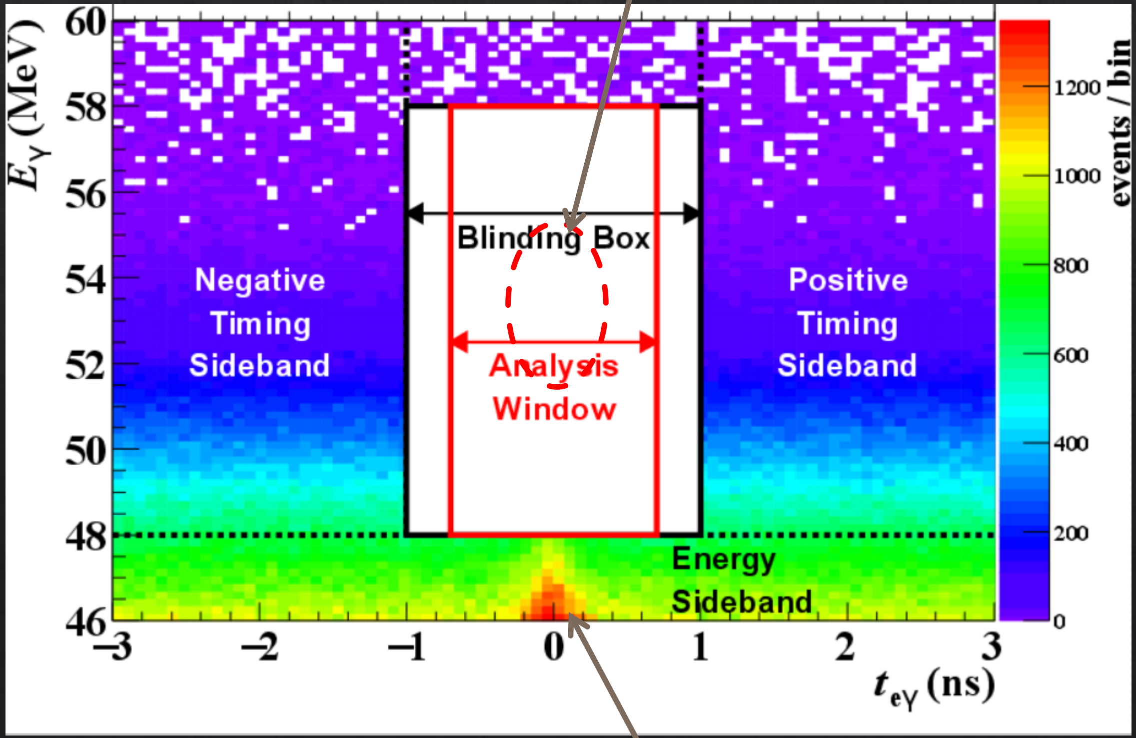
Then, detailed calibration is done on passed events

Event selection is defined as,

$48 < E\gamma < 58$ MeV
$50 < Ee < 56$ MeV
$|te\gamma| < 0.7$ ns
$|\theta e\gamma| < 50$ mrad
$|\phi e\gamma| < 75$ mrad

Region $|te\gamma| < 1.0$ ns is blinded at first. Parameter for physics analysis is determined by outside (sideband) events.

Signal events will concentrate around here, if exist.



RMD

Likelihood analysis

Definition of MEG likelihood function

extended likelihood — constraint term

$$\mathcal{L}(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{ACC}}) = \frac{e^{-N}}{N_{\mathrm{obs}}!} C(N_{RMD}, N_{ACC})$$
$$\times \prod_{i=1}^{N_{\mathrm{obs}}} (N_{\mathrm{sig}} S(\overrightarrow{x_i}) + N_{\mathrm{RMD}} R(\overrightarrow{x_i}) + N_{\mathrm{ACC}} A(\overrightarrow{x_i}))$$

$N = N_{sig} + N_{\mathrm{RMD}} + N_{\mathrm{ACC}}$

N_{obs}: Event number in window

$\vec{x}$: $(E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}; t)$

S, R, A: (Probability Density Function)

C : Constrain N_{RMD} N_{ACC} around expectation in side band

Best fit value is defined by such that maximized likelihood function
Confidence interval is determined with Feldman-Cousins approach, setting Nsig as the main parameter, and profiling out the others.

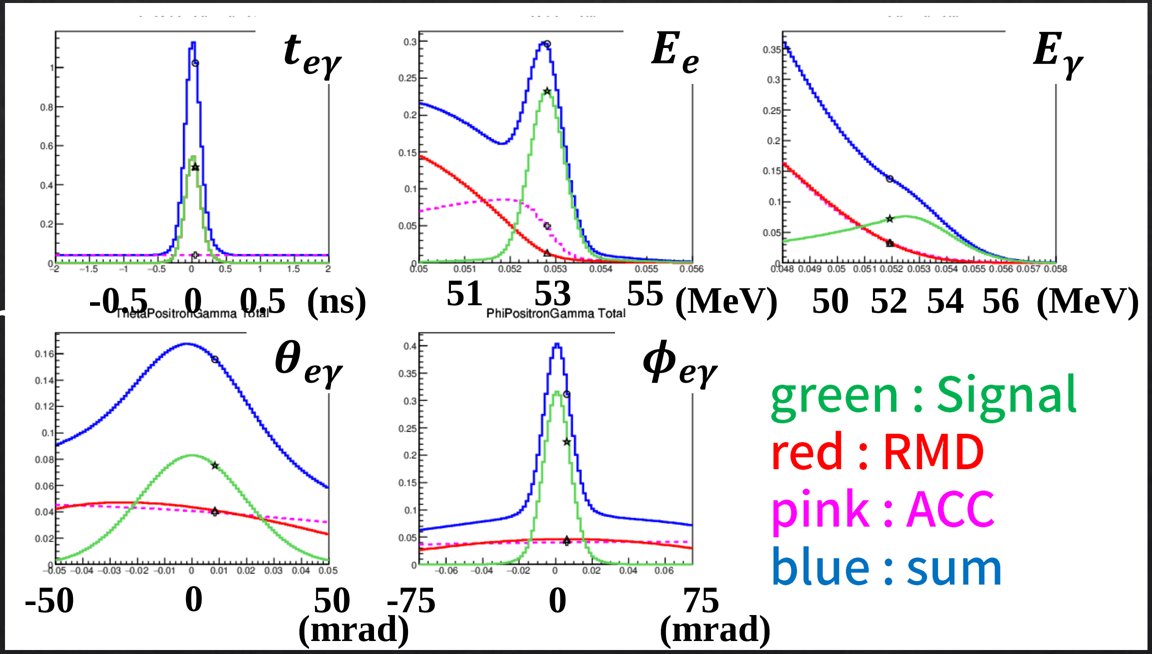
PDF

Probability to find the observable to be the value when each type of event happens.

Determined from sideband data (partially Monte Carlo simulation)

All known correlations between observables, detector position etc. are corrected.

event-by-event PDF
- Shape of function changes, according to
  - Error in reconstruction
  - Position in detector
  - Correlation



Examples in certain events

Normalization

A constant to convert event number into $\mu^+ \to e^+\gamma$ branching ratio

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

Norm. factor

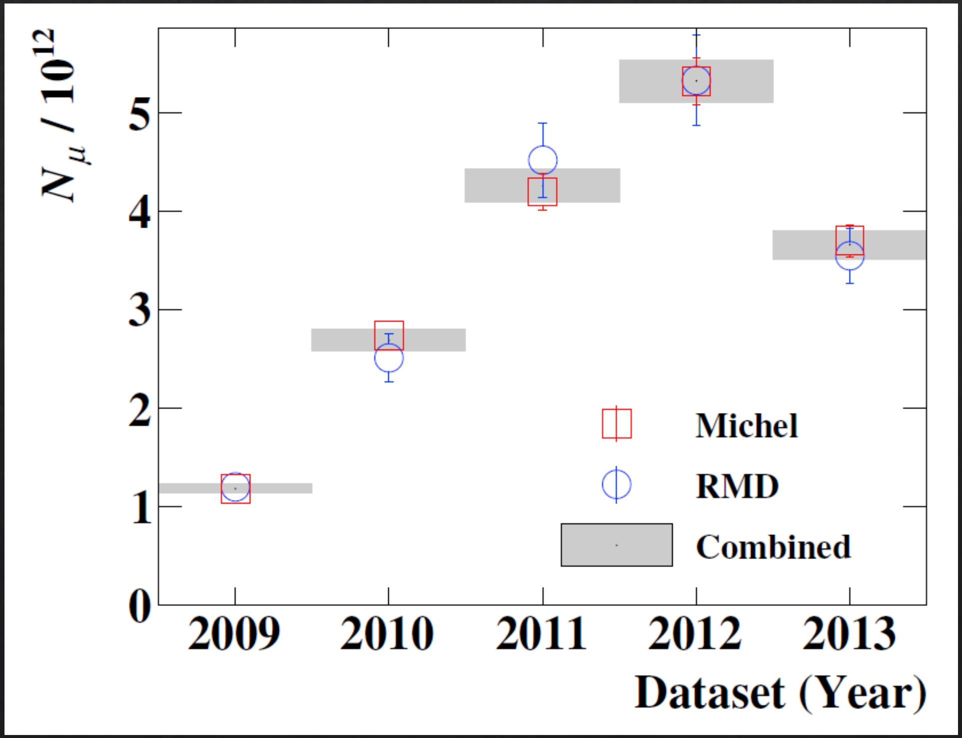
k is considered to be a number of events multiplied with detector acceptance and detection efficiency,

There are independent 2 ways, Michel positron way and RMD way. Final value is given by combining two.

Both ways do not need e^+ detection efficiency.

For all statistics of MEG data,

$$k = 1.71 \pm 0.06 \times 10^{13}$$

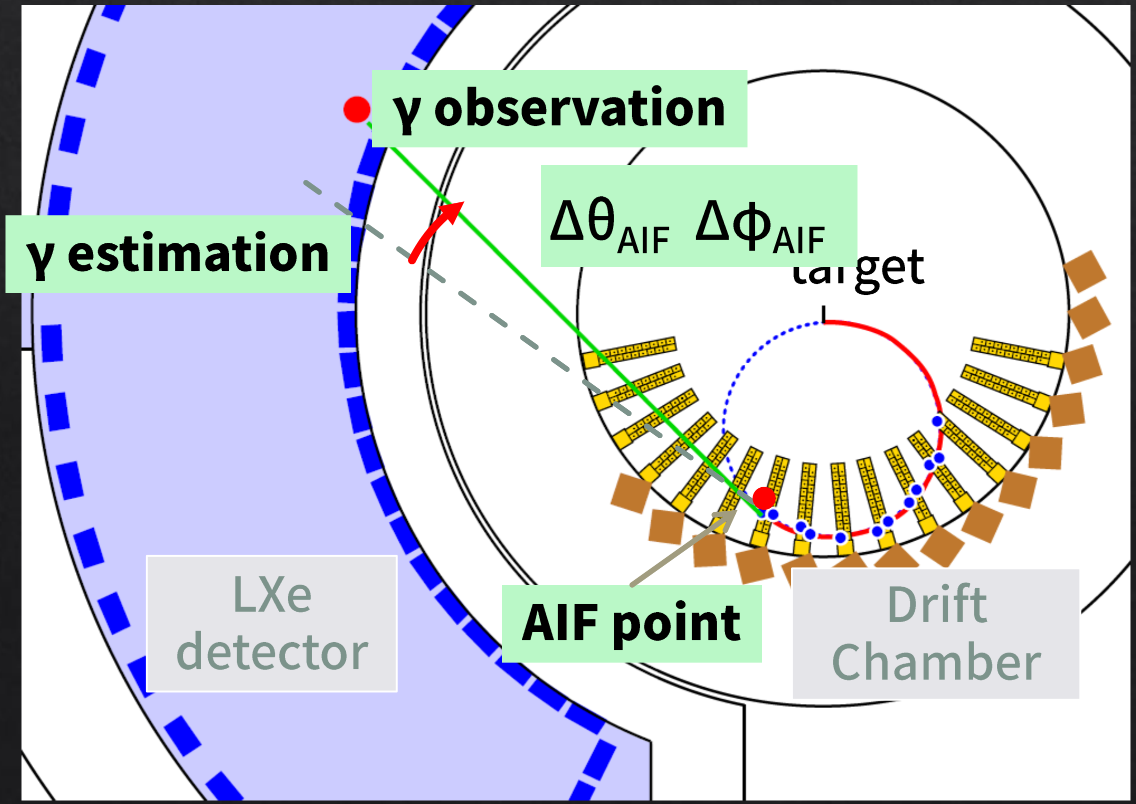


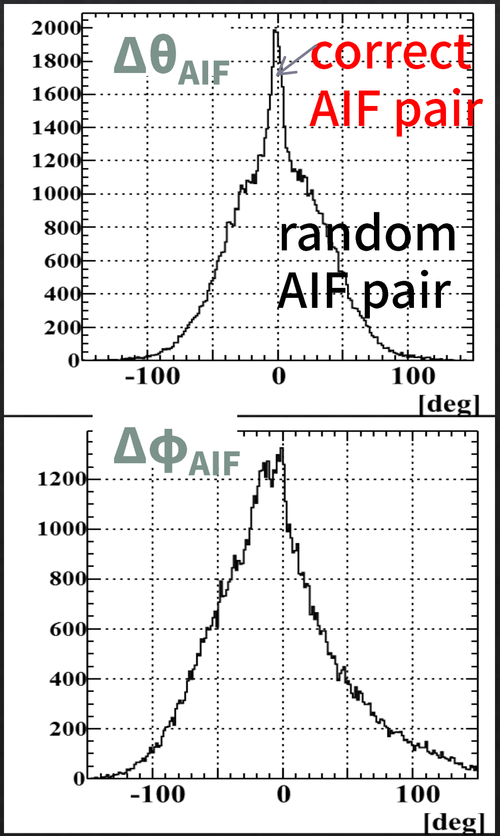
positron AIF recognition

(Annihilation in Flight)

Tag one of the sources of γ-ray, "positron AIF"

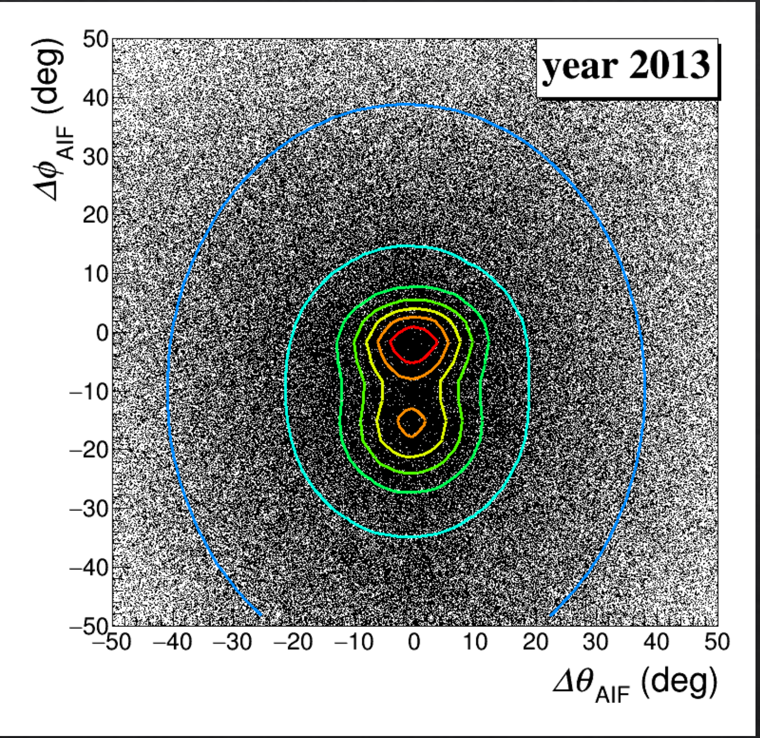
A. Recognize interrupted e^+ track in drift chamber
B. Estimate γ-ray momentum from the track
C. Calculate angle difference between estimation and observation





AIF reduction and impact

Sharp peak in $\Delta\theta_{AIF}$, $\Delta\phi_{AIF}$ distribution is really tagged AIF events.
Cut events near peak.



Method :

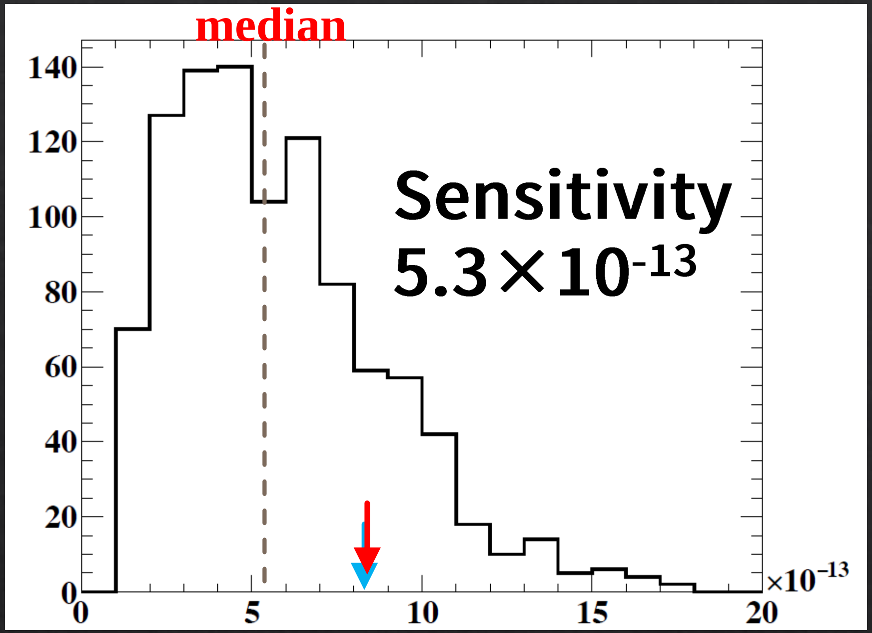
1. Fit 2D distribution $\Delta\theta_{AIF}$, $\Delta\phi_{AIF}$ with combination of 2D Gaussian function. (2 peak and 1 base component.)

2. Remove events within 0.7σ from either of the peaks, as they are likely to be AIF Accidental BG.

Impact :

No significant improvement in sensitivity.
Insurance for AIF event to come near center of window.

Search sensitivity



←Histogram of upper limits of many Toy MCs which do not contain signal.

(90% CL)

Data set	2009-2011	2012-2013	2009-2013
k ($\times 10^{12}$)	8.15	8.95	17.1
Sensitivity ($\times 10^{-13}$)	8.0	8.2	5.3

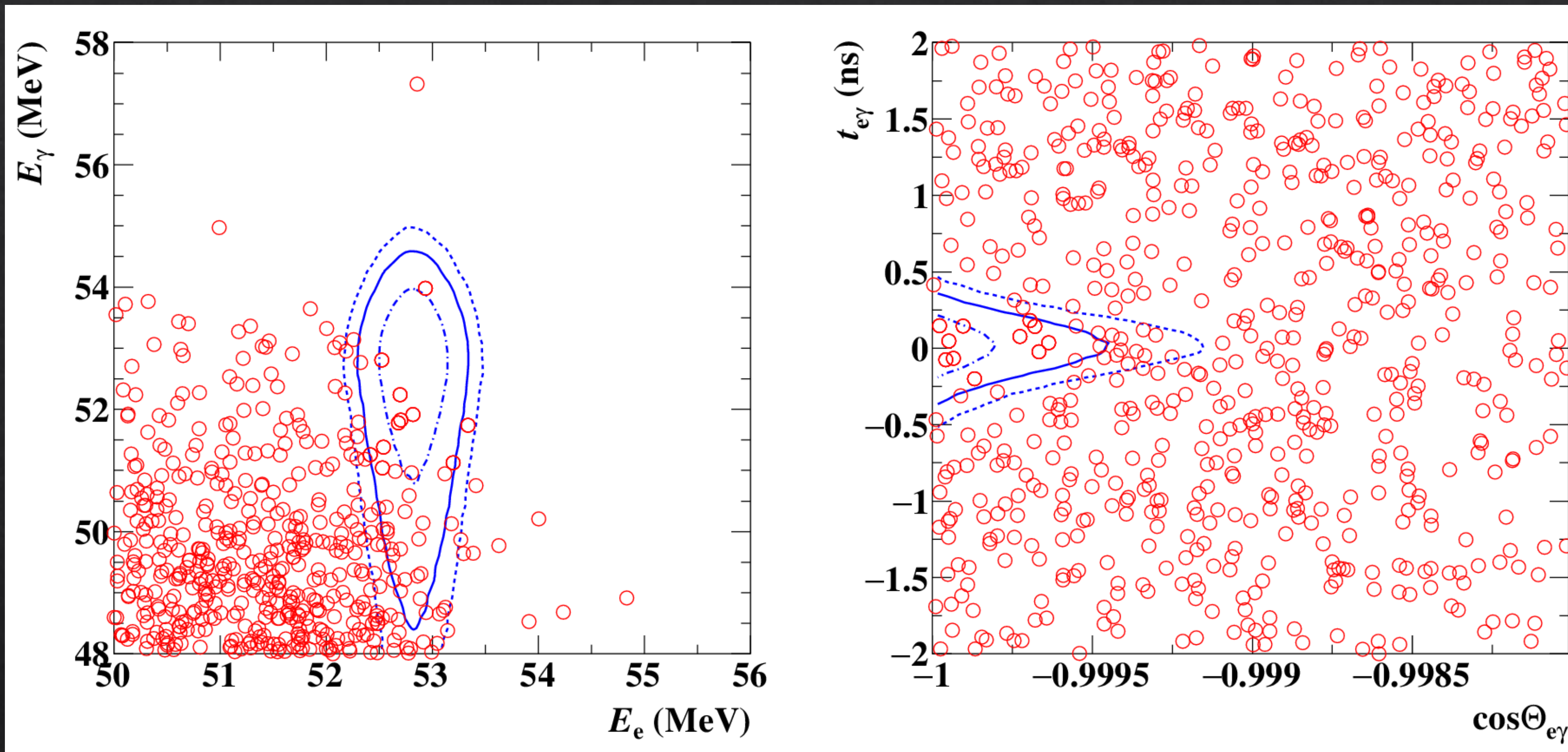
Arrows are limit from time sideband (-2.0ns, +2.0ns)
8.4×10^{-13}, 8.3×10^{-13}

Previous publication(2009-2011)
Sensitivity was 7.7×10^{-13}
Understandable, considering the changes in analysis.

Event distribution

Excess of the signal is not seen.

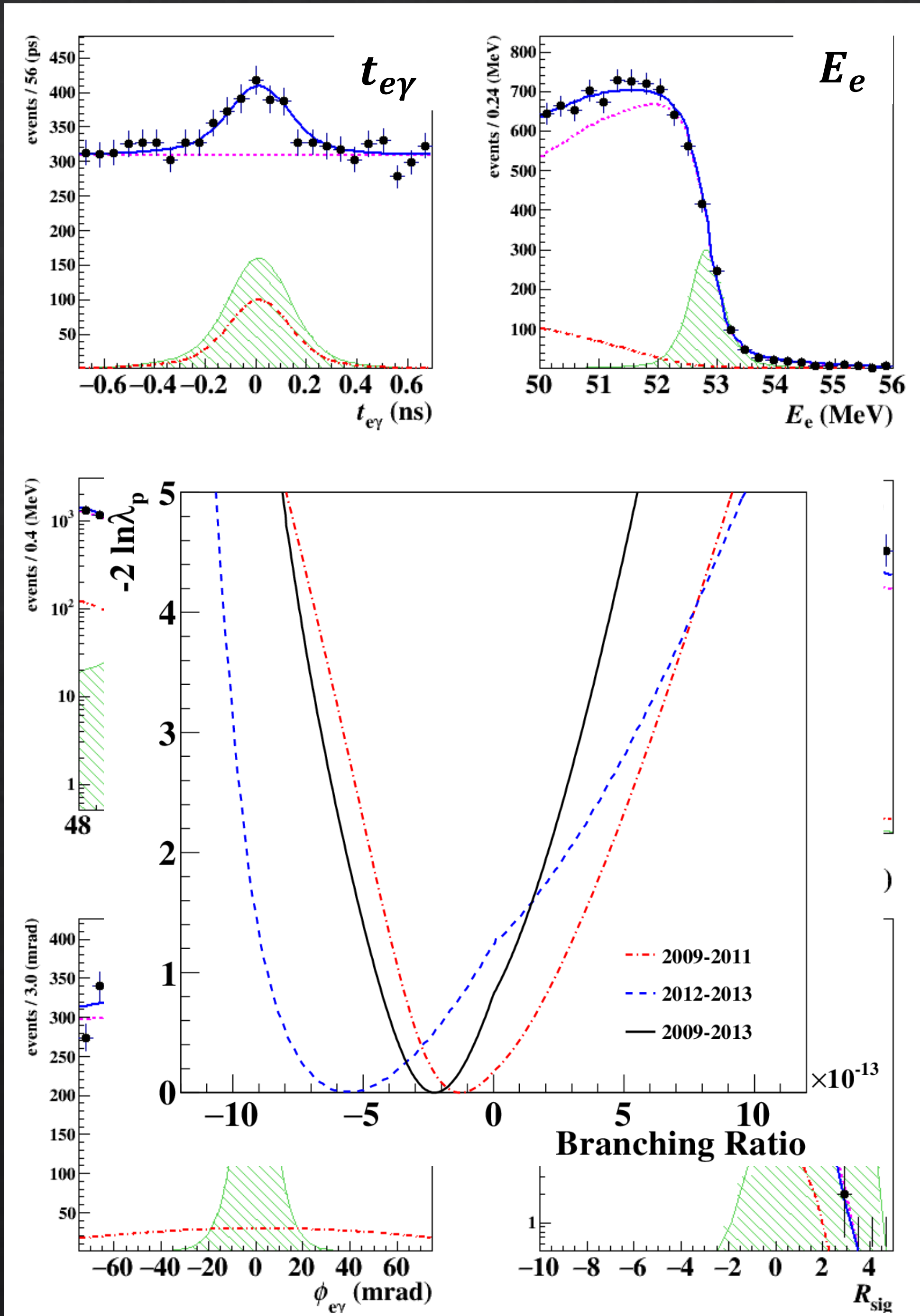
2009-2013 full data



$\cos\Theta < -0.99963$ (90% ε_{signal})
$|t_{e\gamma}| < 0.2443$ns (90% ε_{signal})

$51 < E_\gamma < 55.5$ MeV (74% ε_{signal})
$52.385 < E_e < 55$ MeV (90% ε_{signal})

Contours show averaged signal PDF (1σ, 1.64σ, 2σ)



Fit result

2009-2013 full data

● data   ACC   signal (500events)

sum   RMD

Data and projected PDF agree well.

Data set	2009-2011	2012-2013	2009-2013
best fit $\mathcal{B}$ (×10^{-13})	-1.3	-5.5	-2.2

←Indication for signal-likelihood R sig

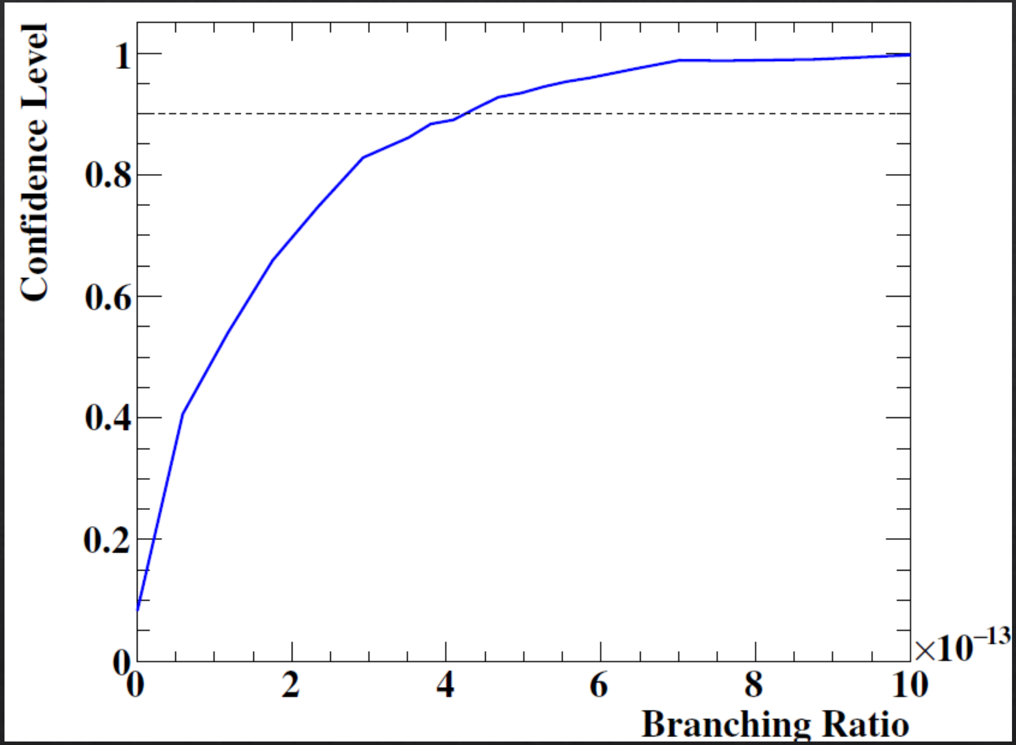
$$R_{\rm sig} = \frac{S(\vec{x_i})}{0.07R(\vec{x_i}) + 0.93A(\vec{x_i})}$$

Confidence interval

Consistent with no signal assumption

Data set	2009-2011	2012-2013	2009-2013
$\mathcal{B}$ 90% UL ($\times 10^{-13}$)	6.1	7.9	4.2
Sensitivity ($\times 10^{-13}$)	8.0	8.2	5.3

In previous result, 5.7×10^{-13} with 2009-2011 data. Consistent including change in analysis.

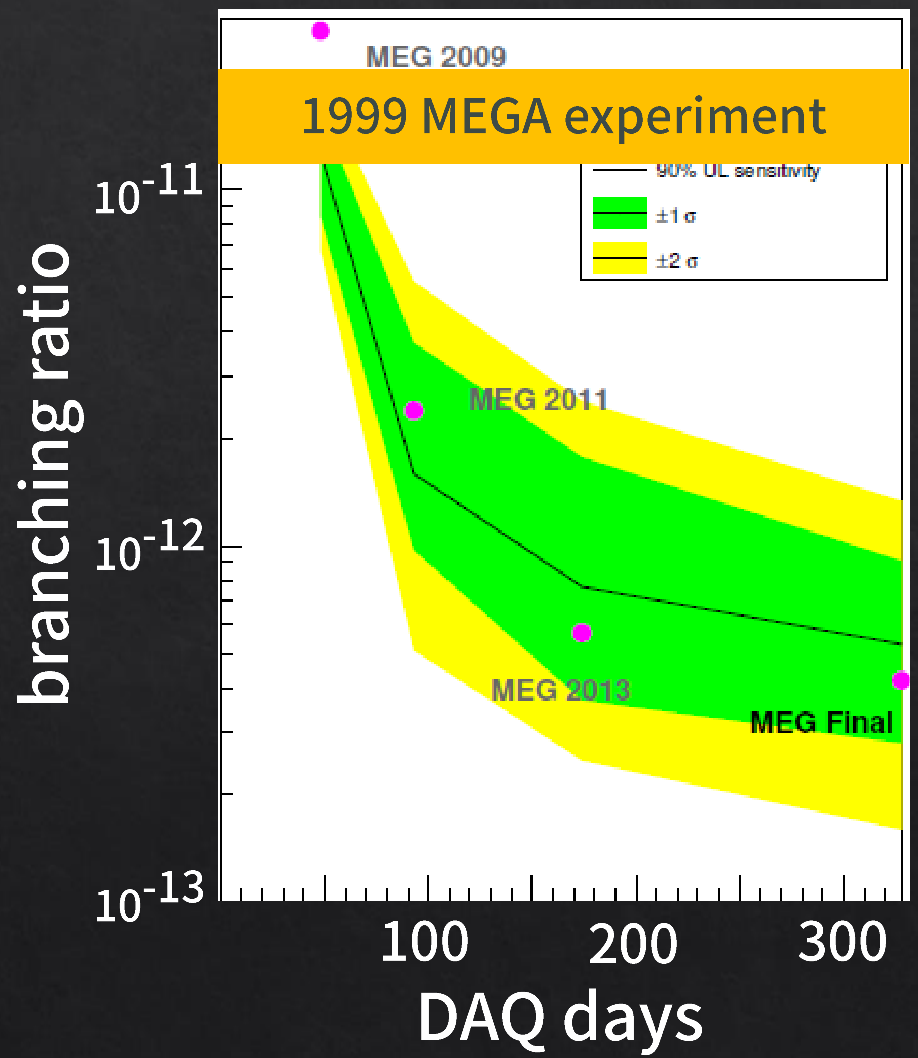


CL curve with 2009-2013 data (Ratio of ToyMC with $\lambda_p^{\mathrm{MC}} < \lambda_p^{\mathrm{data}}$)

MEG I summary

MEG experiment has searched in regime of new physics.

New upper limit for μ→eγ is 30 times better than that before MEG.



4. MEG II experiment

MEG II experiment

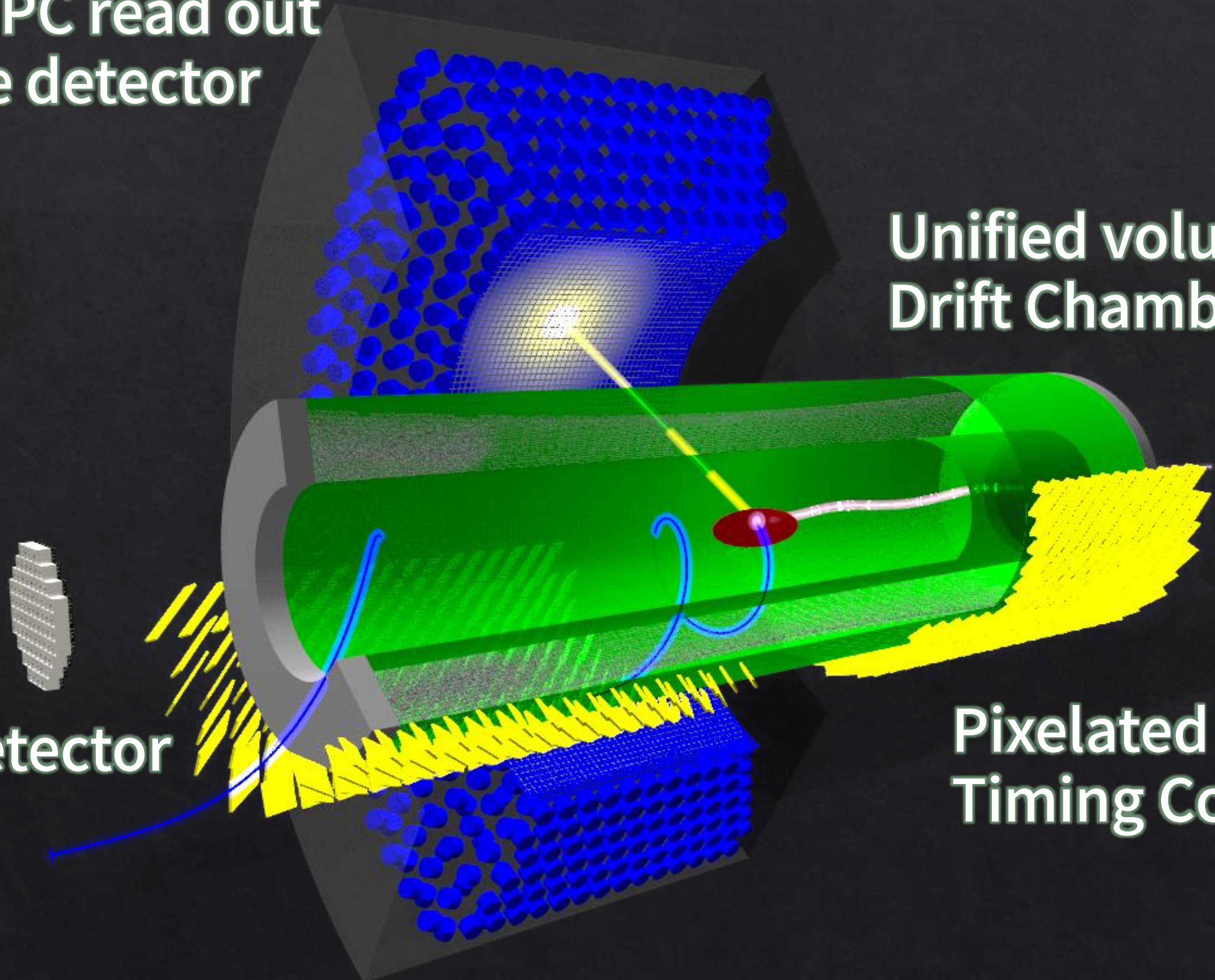
MEG was no linger BG-free experiment,
how to go further?

A. Increase statistics
   A-1 Increase beam intensity ×2
   A-2 Improve detector efficiency ×2

B. Improve detector resolutions
   Eγ, Ee, Angle, Timing ÷2 for all components

Aiming at one order of magnitude higher sensitivity.

MEG II detectors



MEG II status

Please listen to talks in this JPS meeting!

MEG II general : 22pL402 4 (yesterday)
内山

LXe detector : 25aK206 1–3
小川、松澤、小林

Timing counter : 25aL401 2–5
宇佐美、中尾、西村、恩田

MEG II prospects

Specification	MEG I	MEG II
Beam intensity (/s)	3×10^7	7×10^7
Resolutions		
Eγ(%, w>2 / w<2)	2.4/1.7	1.1/1.0
γ pos. (mm, u/v/w)	5/5/6	2.6/2.2/5
Ee (keV)	380	130
E pos. (mm, z/y)	2.4/1.2	1.6/0.7
θeγ/φeγ (mrad)	9.4/8.7	5.3/3.7
teγ (ps)	122	84
Efficiencies (%)		
trigger	>99	>99
γ	63	69
e^+	30	70

R&D

←2012

2013 Upgrade proposal approve

Assembly

←2016

2018 upgrade complete

DAQ

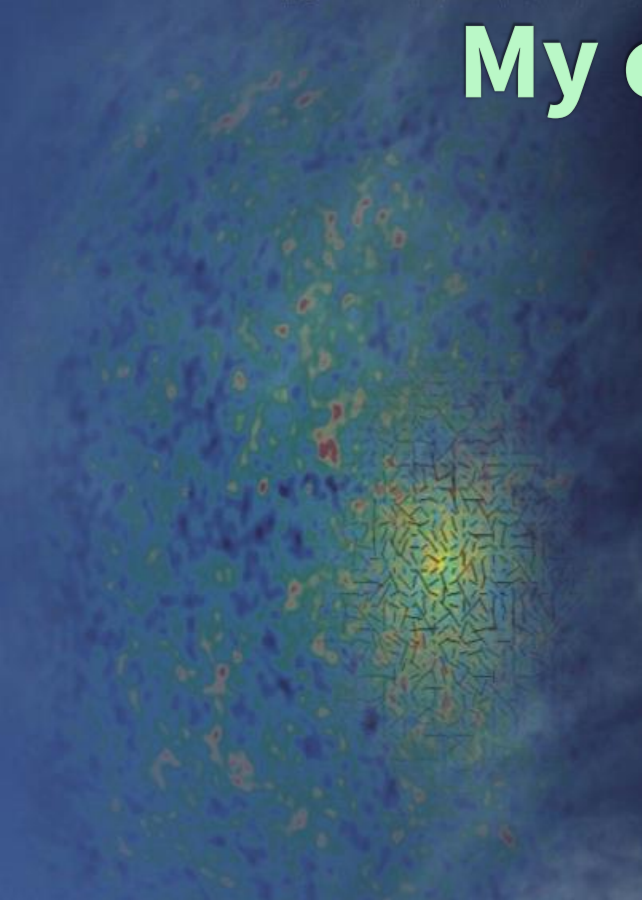
3 years

←2020

sensitivity 6×10^{-14}

5. My Current Project

My current project is

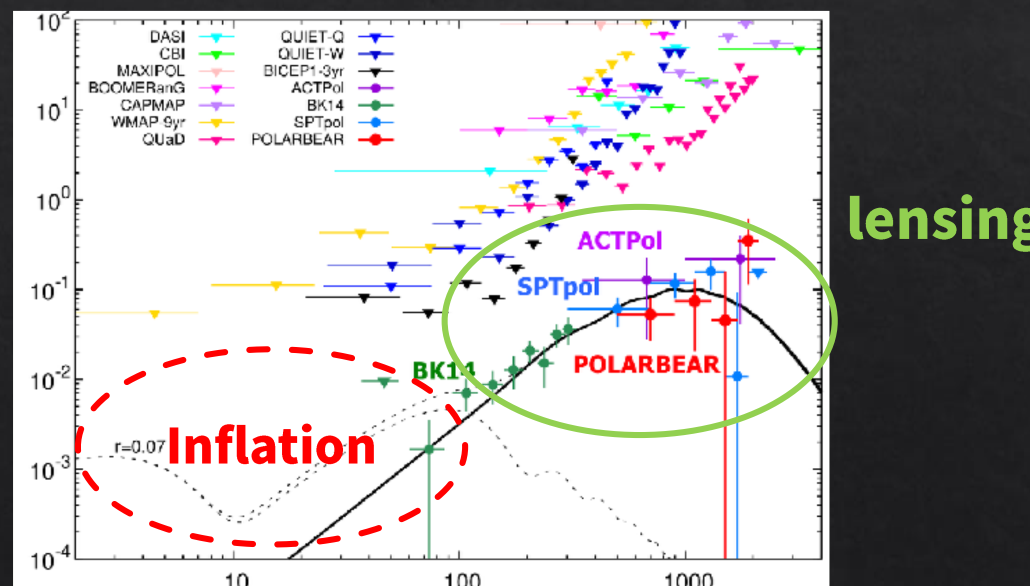


POLARBEAR

Cosmic Microwave Background

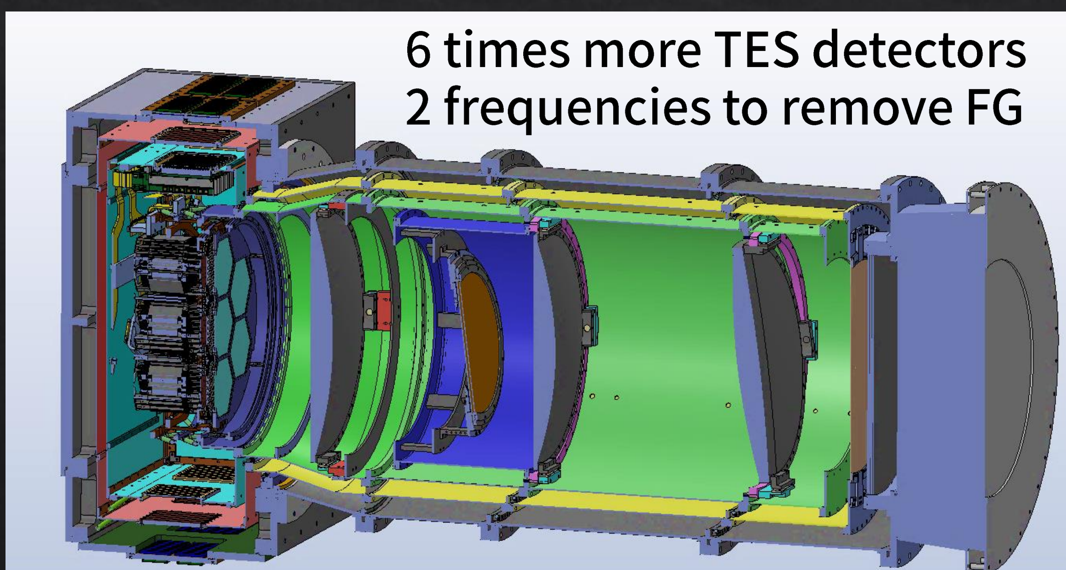
If low-ℓ B-mode polarization is found, it's a decisive evidence of the Inflation theory!

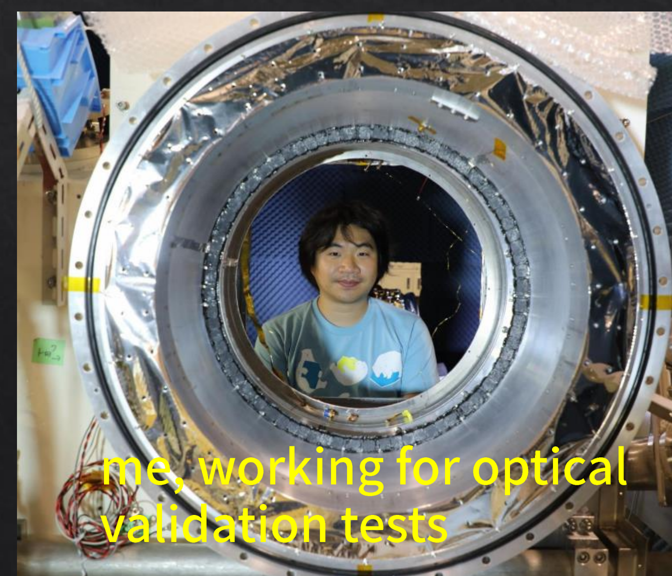
B-mode strength



Multipole moment ℓ
(Fineness of the patterns)

POLARBEAR-2 / Simons Array





Differences (personal feeling)

	MEG	PB/SA
Collab. size	~100 people	~100 people
Goal	Beyond SM (of particle)	Beyond SM (of cosmology)
Site	Switzerland (German)	Chile (Spanish)
Energy	MeV	meV
Time	ns	ms
Temperature	100K	100mK
Data type	Triggered	Continuous
Coding	C++	python

Many differences, but I hope more people from high-energy.

Summary

MEG experiment is searching for $\mu^+ \rightarrow e^+ \gamma$, evidence of the physics beyond the standard model of particle.

MEG experiment has been finished and we published final result. **(Eur. Phys. J. C, 76(8), 1-30)**
New limit 4.2×10^{-13} is 30 times more stringent than previous experiment.

Preparation for MEG II experiment is underway, aiming at one order of magnitude better sensitivity.
(arXiv :1801.04688)

Please look forward the results from CMB experiment.
Today's afternoon, 23pK 307

Thank you for your listening