崩壊分岐比感度 10^{-15} の新しい $\mu^+ \to e^+\gamma$ 探索実験の検討

18/September/2014

日本物理学会2014年秋季大会@佐賀大学

東京大学
THE UNIVERSITY OF TOKYO

東大ICEPP，東大理[A], PSI[B]　内山雄祐，
家城佳[B], 岩本敏幸，大谷航，小川真治[A], 金子大輔[A], 澤田龍，柴田直哉[A],
中浦正太[A], 西村美紀[A], 森俊則，吉田昂平[A], Elisabetta Baracchini

Abstract

1. A project to make a new muon beamline is progressing at PSI to provide **10–100 times higher continuous muon beam.**

2. Study possibilities of carrying out **a new $\mu \rightarrow e\gamma$ experiment with a sensitivity of 10^{-15}**, an order of magnitude better than MEG-II.

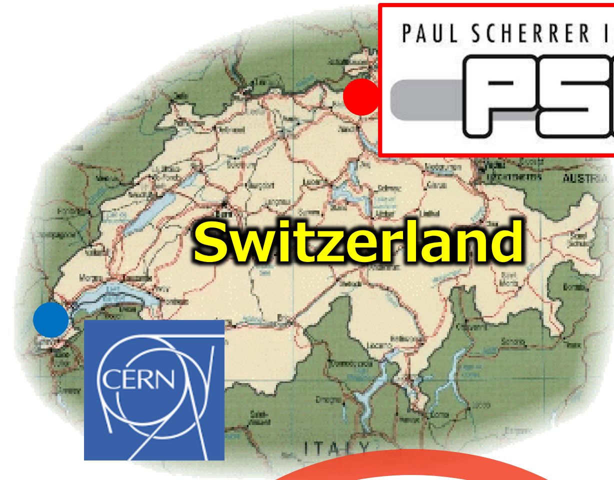
3. Consider **converting photon spectrometer** for the gamma-ray detector.

PSI

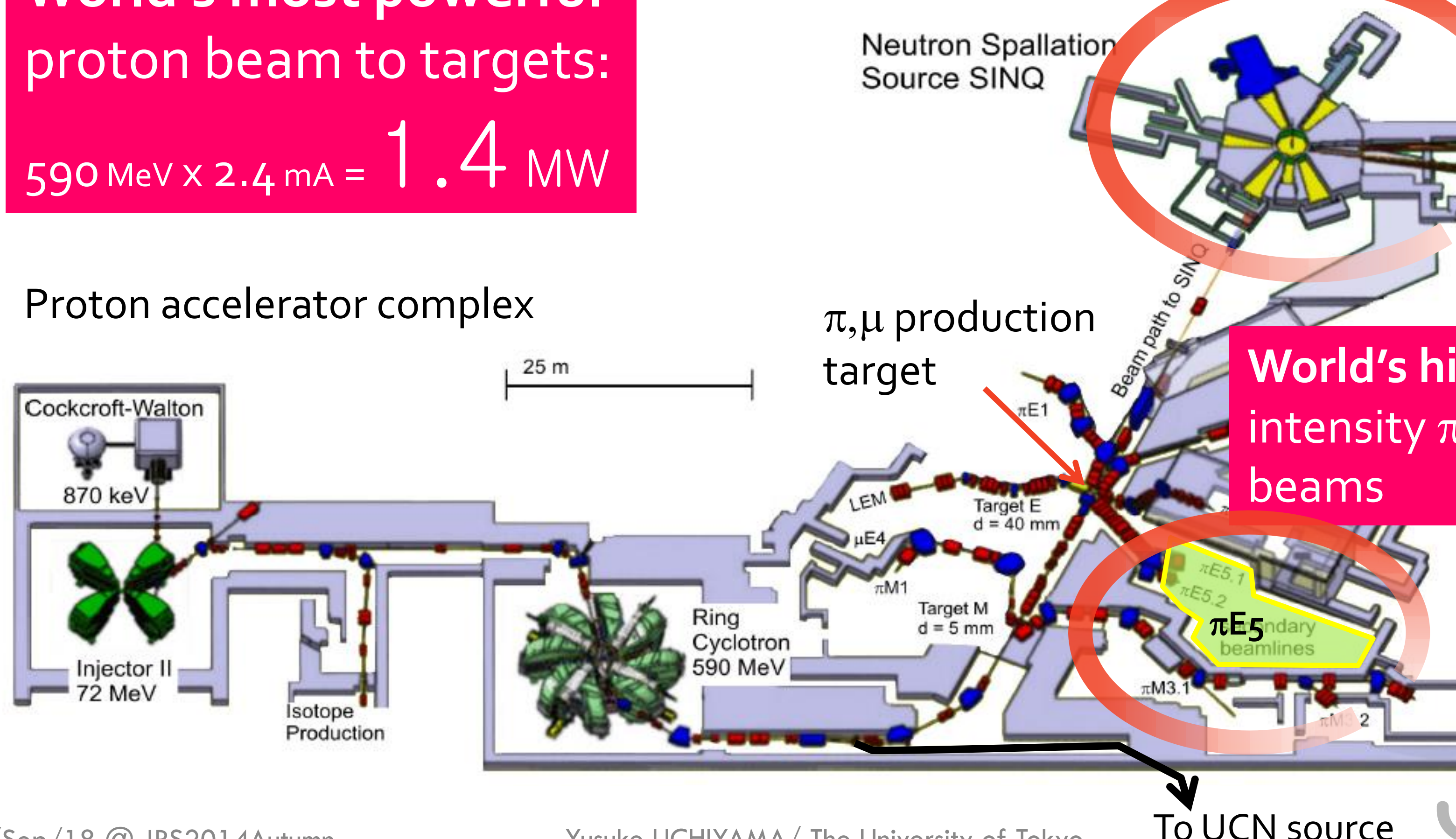
- Paul Scherrer Institut

World's most powerful proton beam to targets:

590 MeV x 2.4 mA = 1.4 MW



Proton accelerator complex

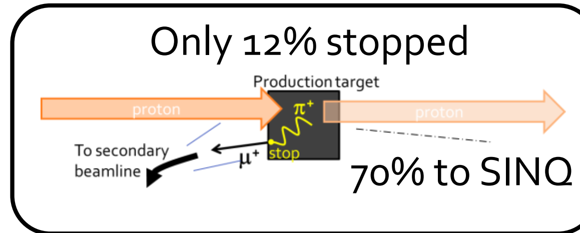


PAUL SCHERRER INSTITUT PSI

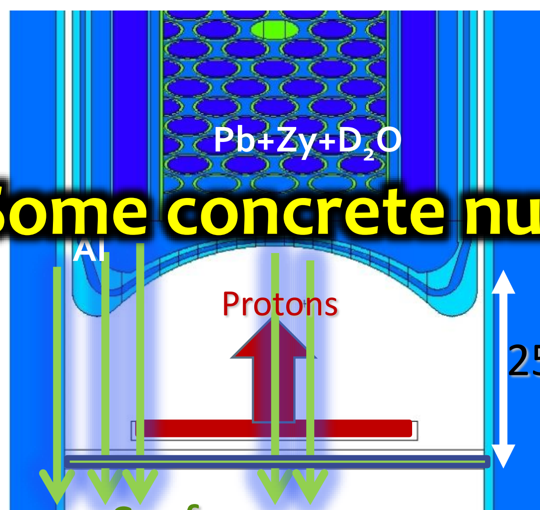
HiMB project

- Next generation **H**igh **I**ntensity **M**uon **B**eam project

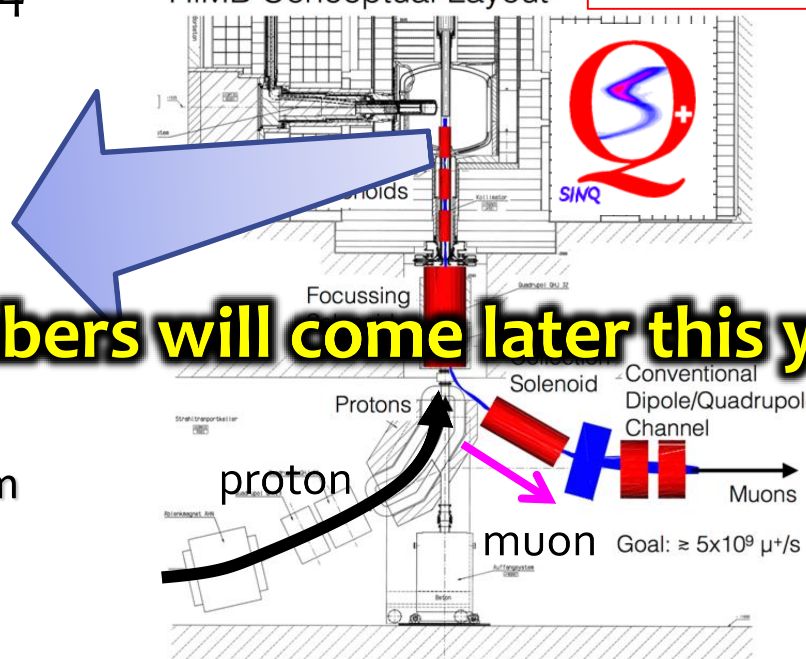
- Extract muon produced at the target of spallation neutron (SINQ)
  - High intensity proton (70% of primary proton stop here)
  - Wide pion energy-range (<150MeV)
  - Large production volume (9000 times larger than E-target at PiE5)
- $O(10^{10})$ surface μ^+/s (estimate)
- Feasibility study in 2013 – 2014
- **Operation from ~2019 (?)**



Keep PSI as the intensity frontier



HiMB Conceptual Layout

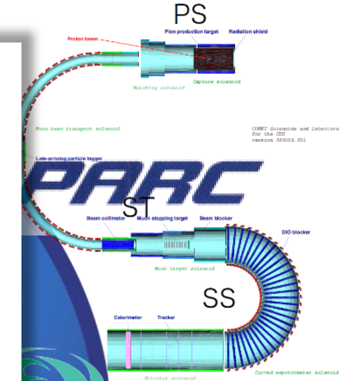


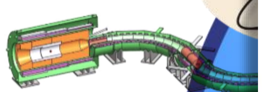
Some concrete numbers will come later this year

$\mu \to e\gamma$ status (from MEG to MEG II)

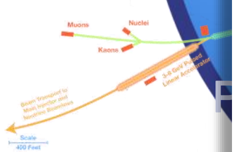
- **MEG completed data taking**
  - Set limit $\mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ @90%CL
  - Final result with ~40% improved sensitivity coming soon.
- **MEG II construction has been started**
  - Aim at x10 better sensitivity ($< 5\text{x}10^{-14}$)
  - By exploiting full beam intensity available today
    - ~10^8 μ^+/s at the PSI πE5
  - By upgrading the MEG detector
    - Keep experimental concept
    - In short (~5 years), at low cost

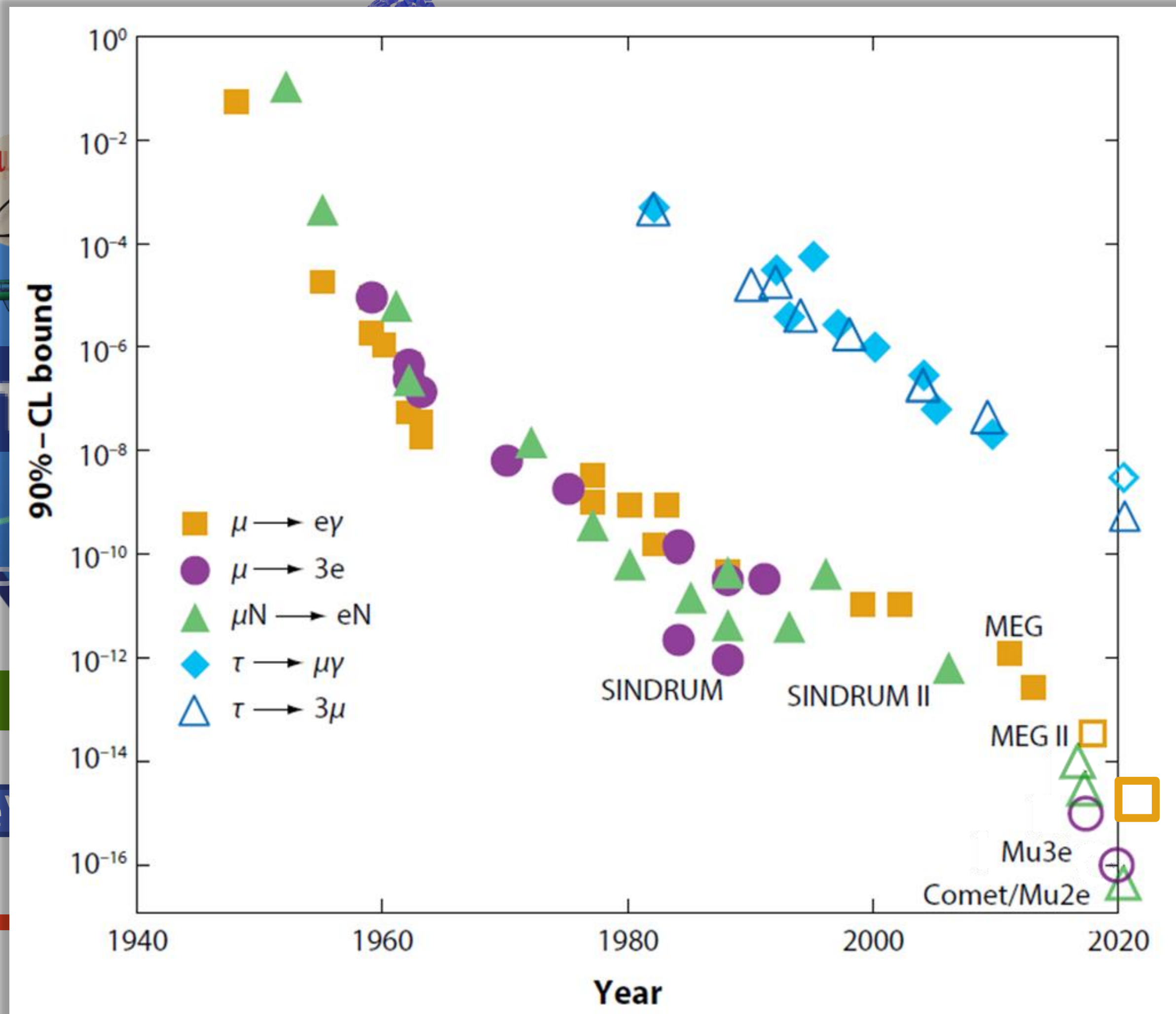
Next decade





Fern





2010 … 022

7–8 Te

HL-LHC

MEG

new μ→eγ?

Now

Mu3e phase I

Mu3e phase II

DeeMe

Mu2e

COMET phase I

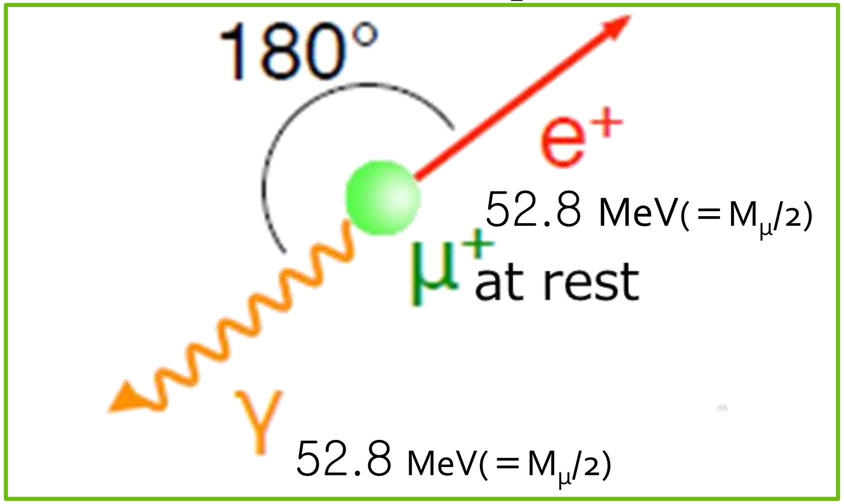
COMET phaseII

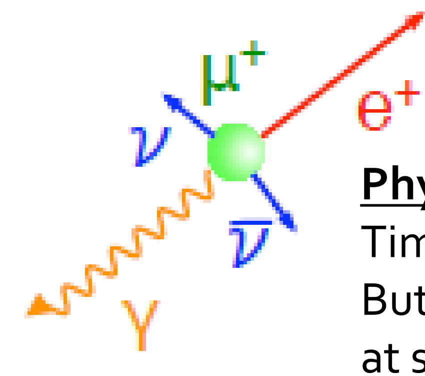
FNAL/PIP II

PRISM?

Belle II

$\mu^+ \to e^+\gamma$

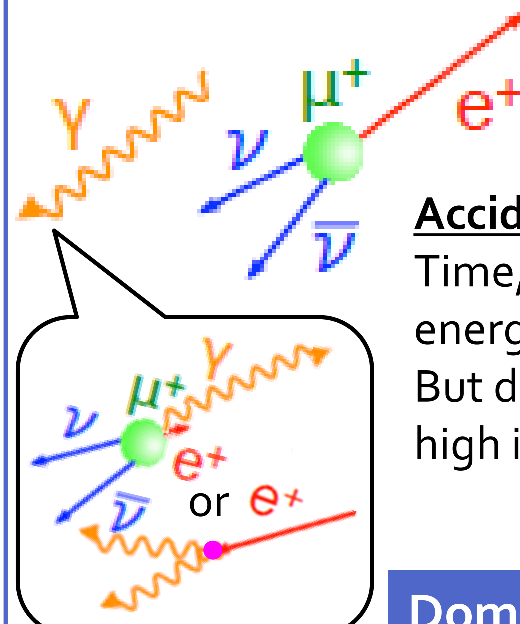




1

Physics BG

Time coincident
But highly suppressed at signal region by energies & angle



100

Accidental BG

Time, direction & energies are random
But dangerous at high intensity

Dominant in MEG

Two-body decay

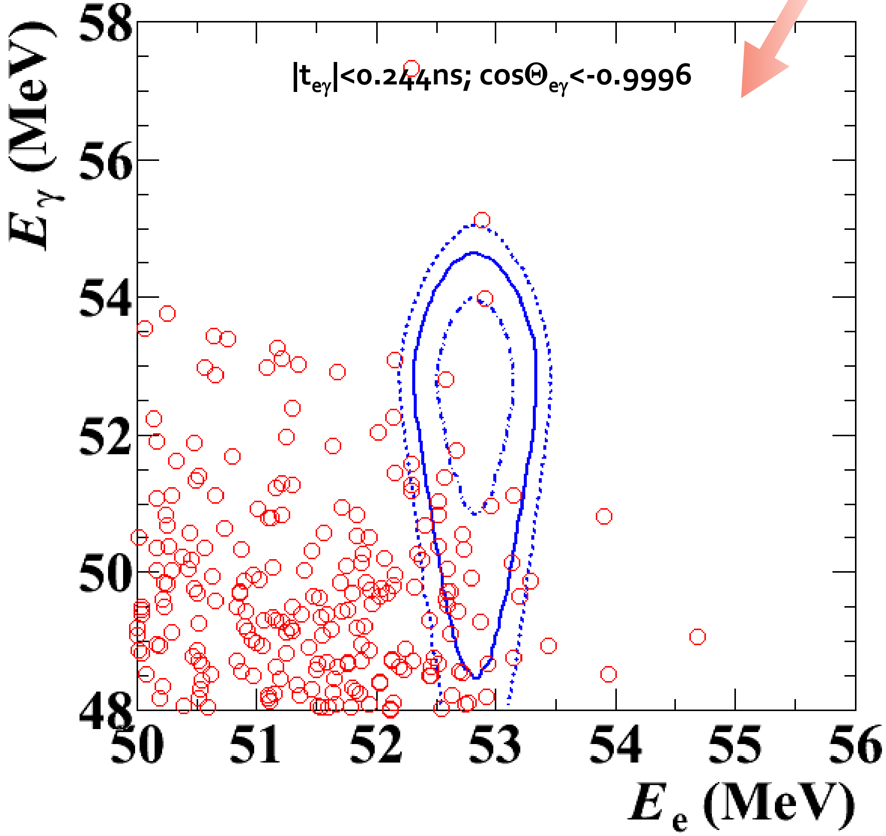
- Clear signature
- Easy to gain acceptance (solid angle & momentum)

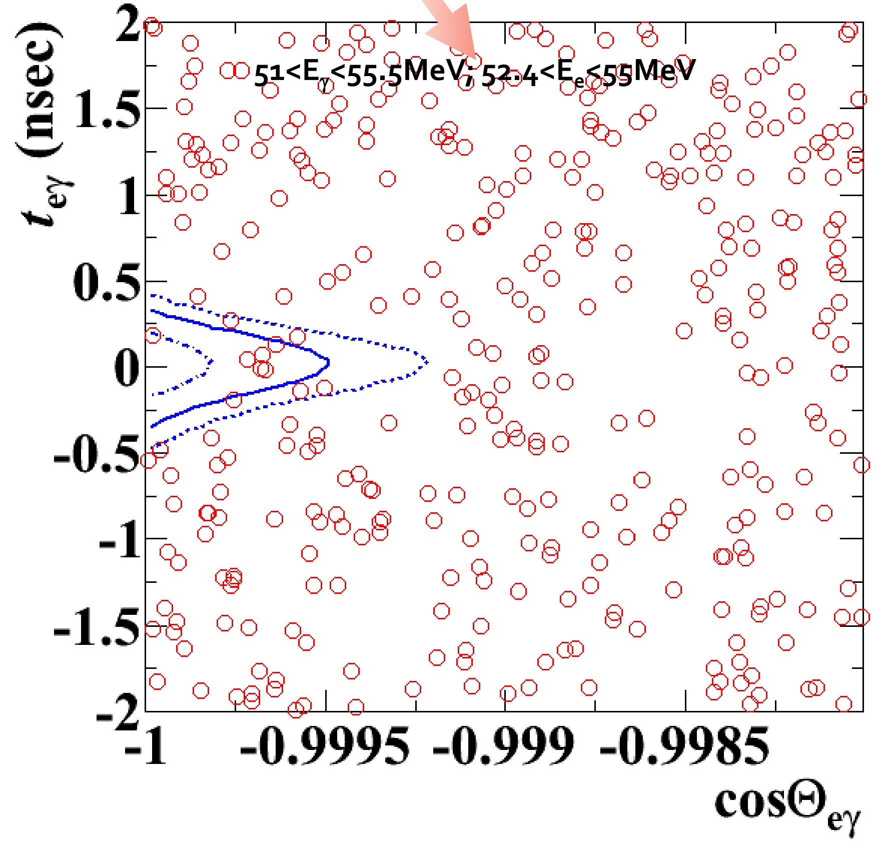
Neutral particle (γ)

- Difficult in high precision & high efficiency detection
- No (or very little) info of direction
- Not able to test vertex matching

MEG data

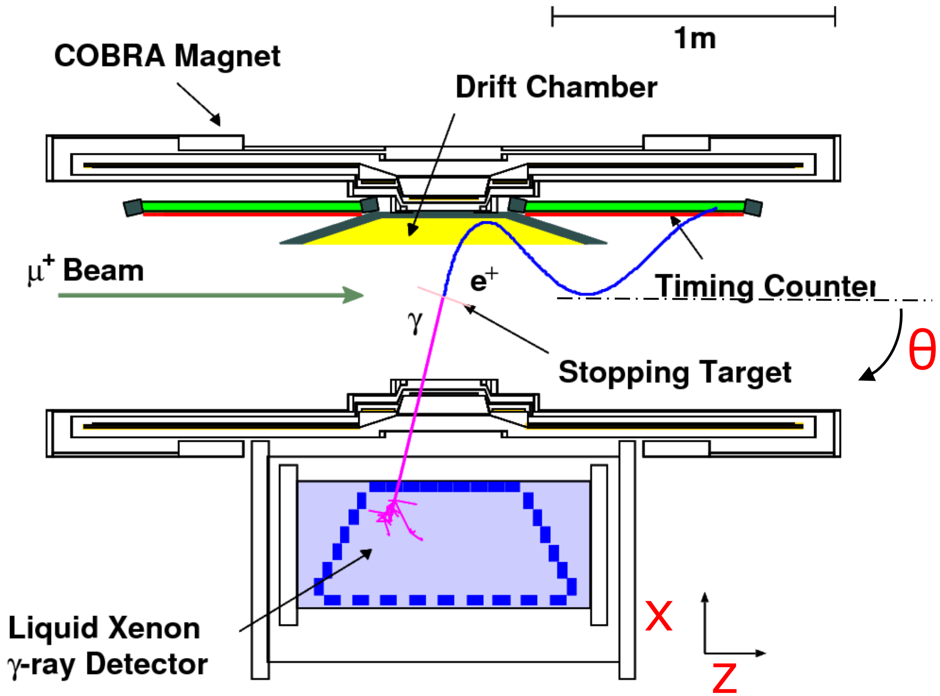
$$N_{BG} \propto (R_\mu)^2 \cdot \epsilon \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \vartheta_{e\gamma})^2 \cdot (\delta t_{e\gamma})$$

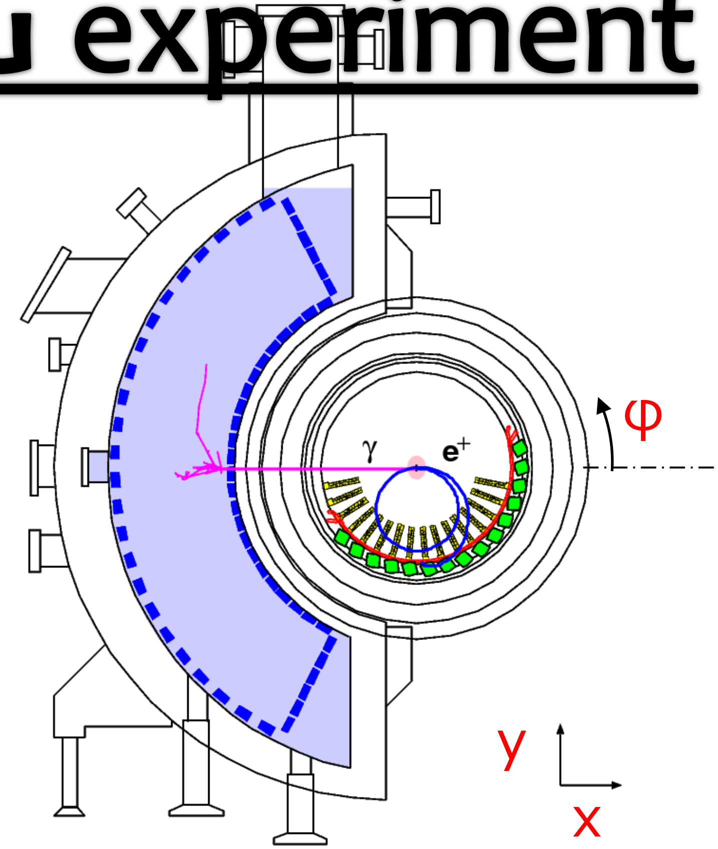


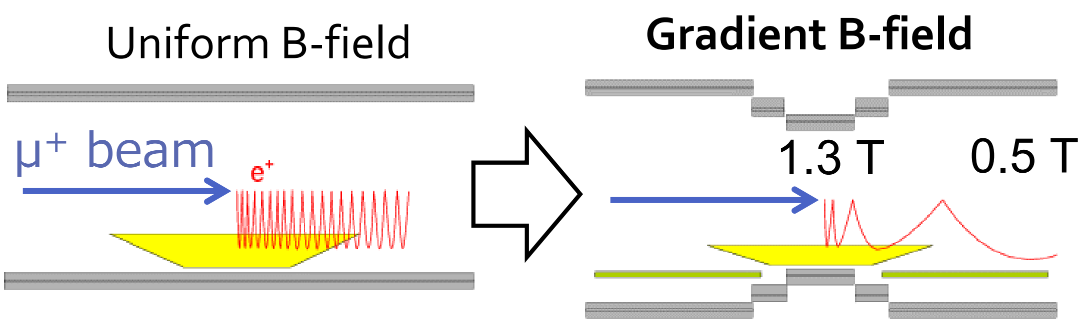


2009 – 2011 data
No excess of signal-like events observed

MEG experiment







1. LXe γ-ray detector
2. Gradient field e^+ spectrometer

MEG features

1. **Liquid xenon γ detector**
   - ○ High eff. γ detection ($\varepsilon > 50\%$)
   - ○ Total absorption w/o any dead material, with good uniformity and high light yield ($\sigma_E \sim 1\%$)
   - ○ High time resolution ($\sigma_t \sim 60$ ps)
   - × Difficult operation, need massive cryostat
   - × Weak to pileup due to single volume
   - × No power of direction reconstruction
2. **Gradient B-field for efficient e^+ measurement**
3. **Relatively small solid angle (geometrical acceptance) ~ 10%**

From MEG II

- **To improve x10 (a few dozens?) sensitivity, we need at least x10 statistics. How to gain?**

Higher beam intensity $\times$ 3, 5, 10, 100 ?	Increase acceptance $\times$ 3, 5, 10 ?
MEG II $7\times10^{7}\ \mu^{+}/s$	MEG II ~5%

- **Then, we have to reduce increased BG.**
  – How much do we have to reduce?

Statistics & BG

$$N_{BG} \propto (R_\mu)^2 \cdot \epsilon \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \vartheta_{e\gamma})^2 \cdot (\delta t_{e\gamma})$$

S: Increase factor of the statistics ($\propto R_\mu \cdot \epsilon$)

B: Increase factor of number of BG events ($\propto N_{BG}$)

	ε x 1		ε x 3		ε x 5		ε x 10	
	S	B	S	B	S	B	S	B
Rμ x 1	MEG II		3	3	5	5	10	10
Rμ x 3	3	9	9	27	15	45	30	90
Rμ x 5	5	25	15	75	25	125	50	250
Rμ x 10	10	100	30	300	50	500	100	1000
Rμ x 100	100	10000	300	30000	500	50000	1000	10^5

*Assuming same running time as MEG II

Converting Photon Spectrometer

Concept

- Measure e^+e^- pair from incident photon converted in conversion layer.
- Previous experiment, MEGA, used this type detector.

0.045 X0

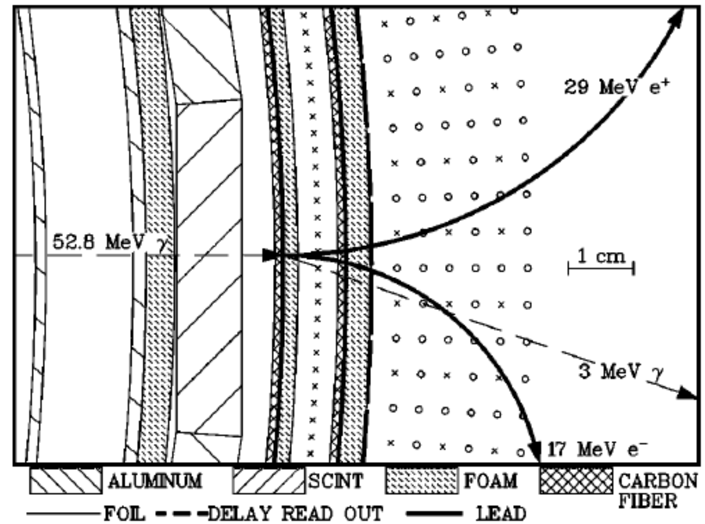


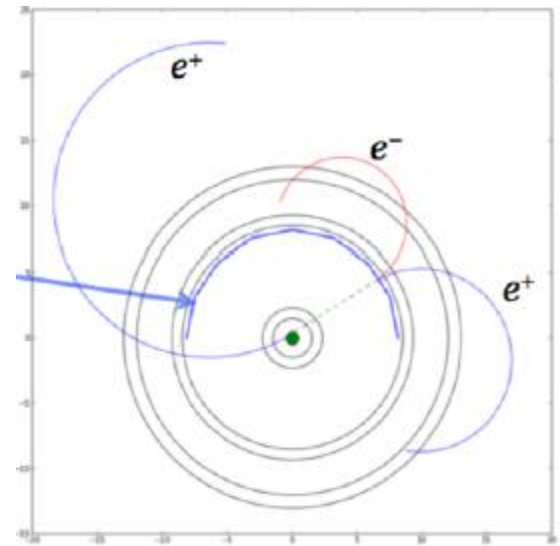
FIG. 5. A cross section of a pair spectrometer layer, showing the aluminum support cylinder for an inner layer, and the timing scintillators, conversion cylinders, MWPC and drift detectors for the next outer layer. A typical conversion in the first conversion cylinder is shown.

- **Merits**
  - Good position resolution
  - Direction of γ reconstructed
  - Strong against pileup
  - Low cost (?)
  - Better energy resolution possible but trade off b/w efficiency
- **Challenge: How to gain efficiency**
  - ~a few %
  - Complicated pattern recognition and tracking

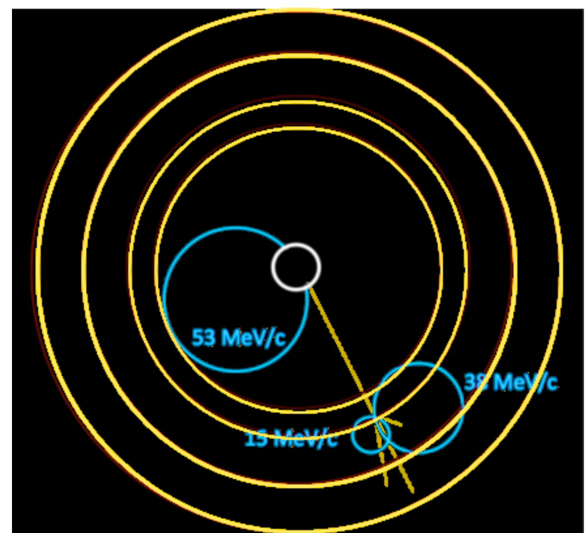
Preceding studies

arXiv 1309.7679 & Snowmass 2013 report

- **There are a few preceding studies of new μ→eγ experiments using the converting photon spectrometer.**
  - Mainly in US snowmass process for ProjectX
  - They conclude that it is possible to go to O(10^{-15})
- **However, there are several points suspicious**
  - Unreasonable assumptions,
  - Not proper (or lack) simulation



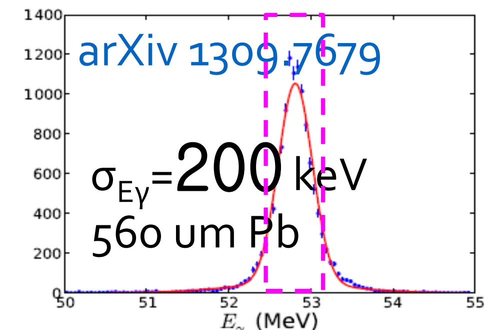
A **0.56 mm Pb** (0.1 X0) conversion layer.
Si strip for detector



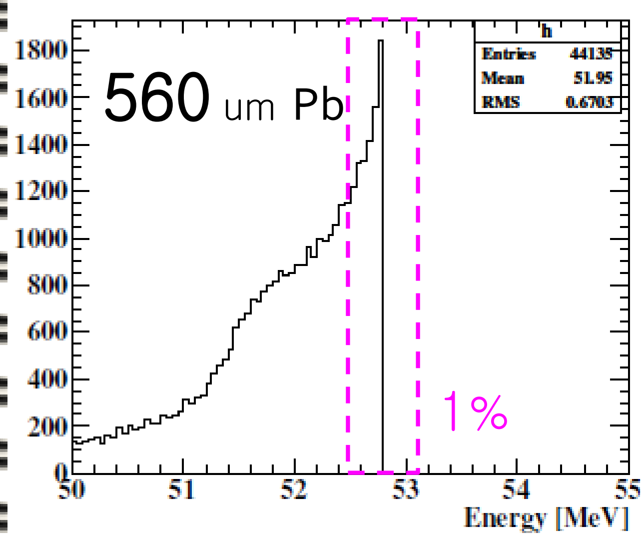
multi layers of **0.5 mm W** (0.14 X0) conversion layer.
~100 layers of drift chamber

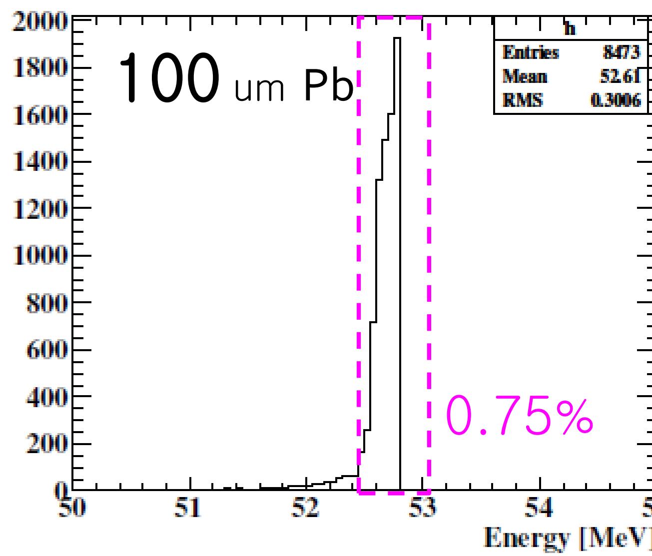
Resolution vs Thickness

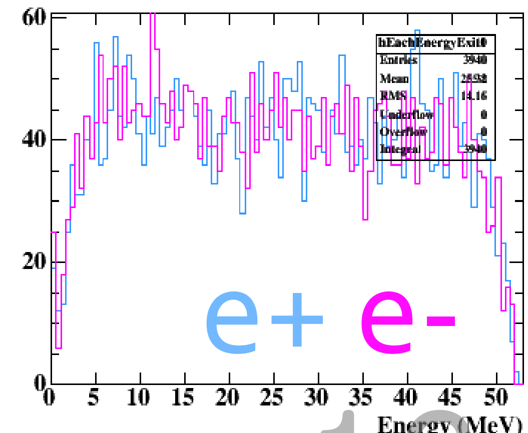
- **Perform simple MC study**
  - shoot 52.8 MeV γ perpendicular to the Pb plate
  - Calculate out-coming e+e- energies
- **Need to track particle as low as <10 MeV to get good efficiency**



Energy loss inside the converter (dominant) was not simulated!

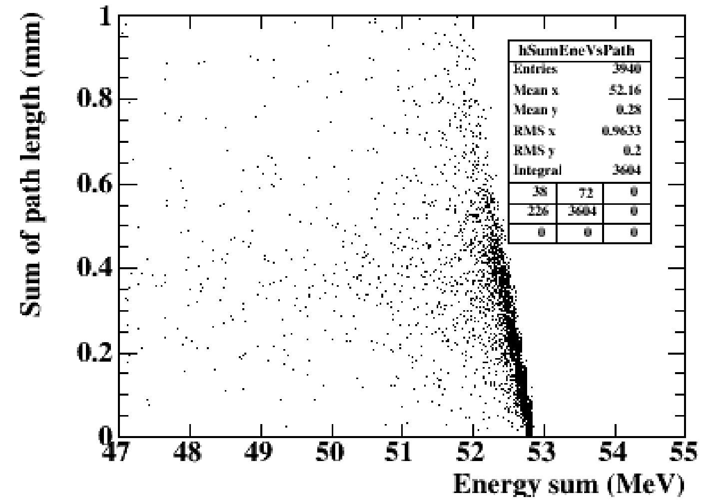






52.8 MeV ± 200keV * 1.64

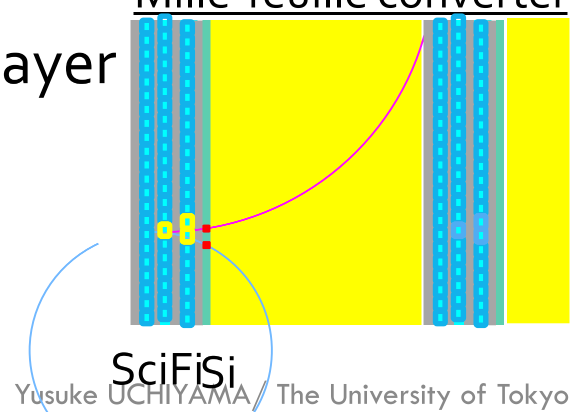
- **Energy reso. is limited by energy loss in converter**
  - Energy loss clearly correlates with path length inside the converter
  - However, reconstruct the depth of conversion seems difficult



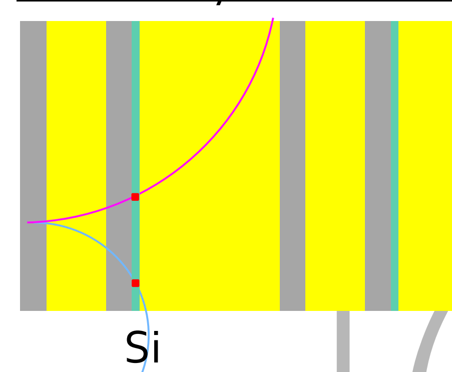
- **As thin as 100 um necessary.**
- **Efficiency is <0.75% per layer.**

- **Able to solve the dilemma by sub-layers**
  - Fill the gap with active device, or
  - Just gap
  - can disentangle sub layer

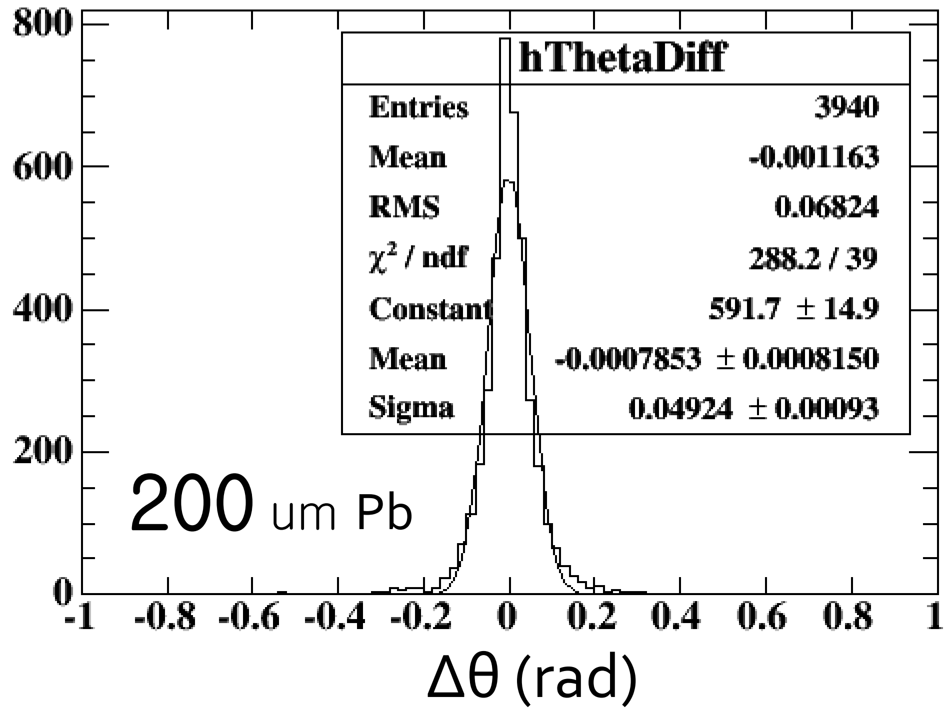
Mille-feuille converter

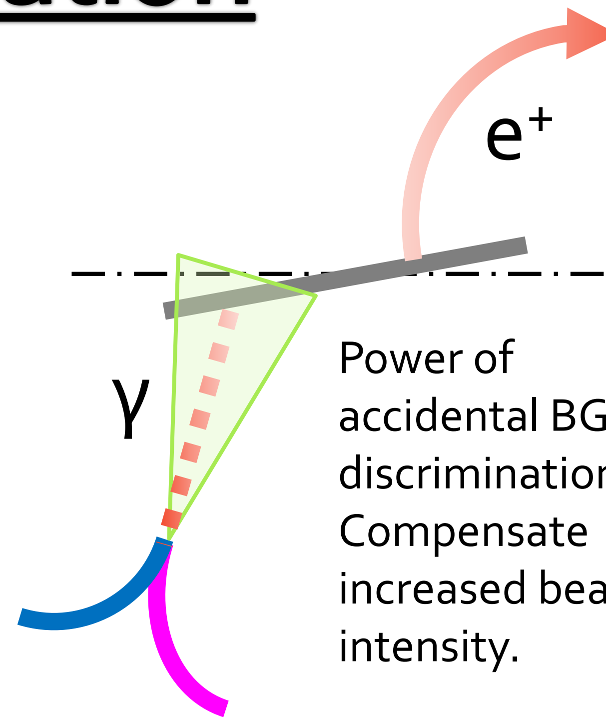


Double-layer converter



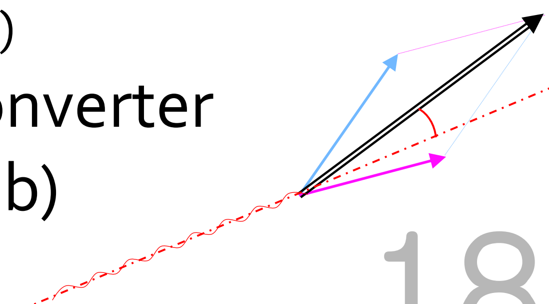
γ angular resolution



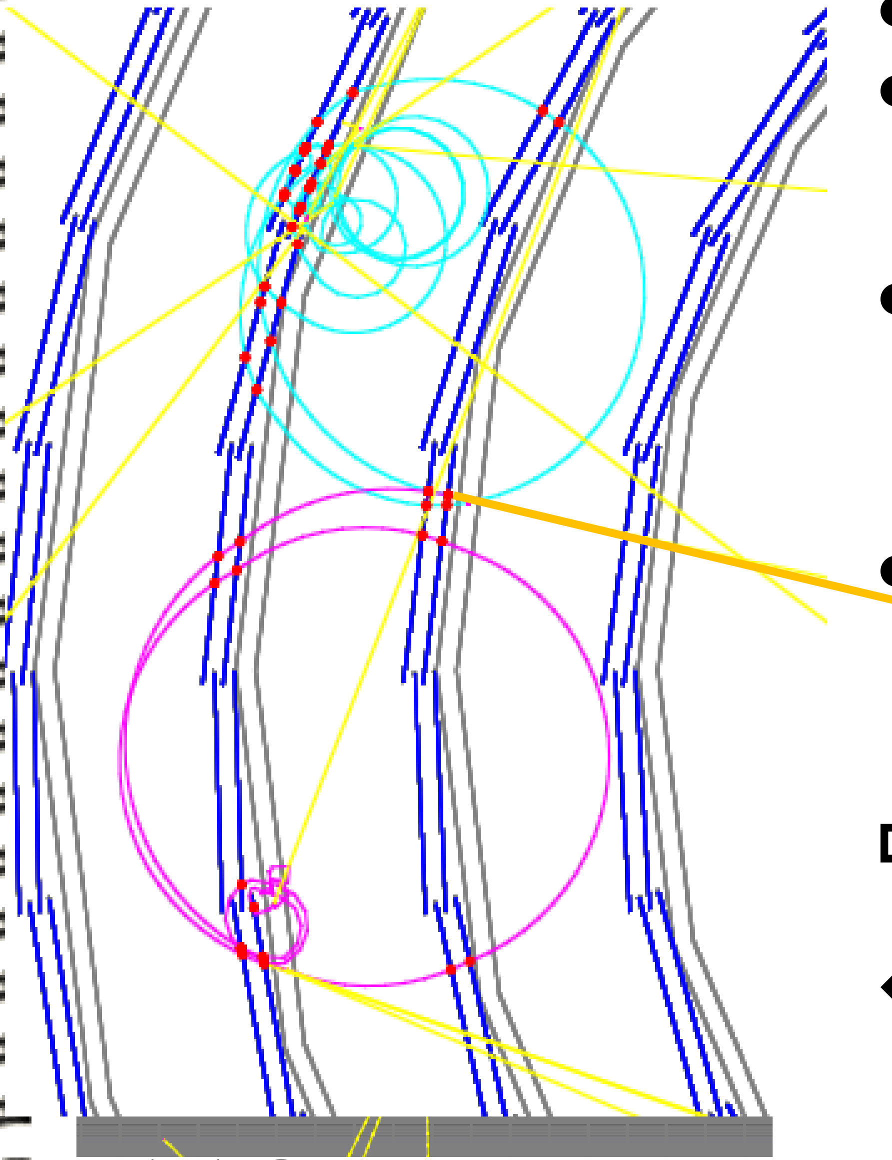


Power of accidental BG discrimination. Compensate increased beam intensity.

- **γ direction can be reconstructed from momenta of the pair**
- **Resolution: ~50 mrad** (<10 mrad in ProjectX study)
  – Limited by multiple scattering in the converter
  – Similar to MEGA's resolution (250 um Pb)



Possible configuration



- In 1.5 T uniform B-field
- 10 super layers
  - first layer from r=26 cm
  - at 5 cm radial distance
- A super layer consists of
  - two 100 um Pb converters
  - two Si pixel layers put both outside the conversion double layer
- Target
  - 100 um plastic sheet
  - slant angle of 10° to spread vertex distribution

□ **~15% conversion eff.**
assuming 50% rec. eff. ⇒ 7–8% eff.

◆ **Need active area of 160 m²**
CMS level!
⇒ Increase B-field, increase sub-layers

Detector requirement

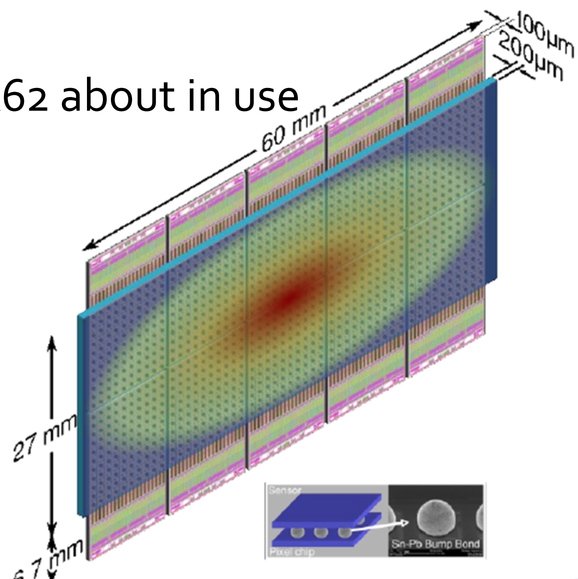
- **Si pixel tracker with**
  - Large area
  - High time resolution (O(100 ps))
  - Ultra thin (~50 um)
    - If build e^+ side as well, <50 um important

- **No available device today**

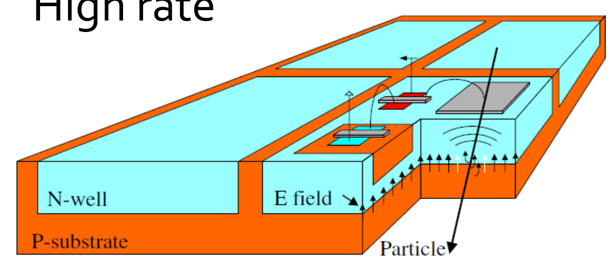
  Need device development

Giga-tracker for NA62 about in use

Hybrid pixel
σt = 200 ps
200 um thick



HV-MAPS for Mu3e
50 um thick
High rate



(High voltage monolithic active pixel sensors)
I. Peric et.al. NIMA 582 (2007) 876

New technologies open new physics!

Summary

Toward $\mu \to e\gamma$ $O(10^{-15})$

- **10 times larger statistics achievable by**
  - 5 times higher intensity beam
  - twice higher signal acceptance (compared to MEG II)
- **with multi-layer converting photon spectrometer**
  - multi layers to gain efficiency
  - sub layers for good resolution retaining efficiency
- **Suppress increased BG by**
  - Vertex matching (compensate increased beam rate)
  - Better γ energy resolution (3 times better)

◆ **However, realization seems really challenging**
  - Need further detailed studies
  - Need technological development
  - Need more or completely different idea

To be studied

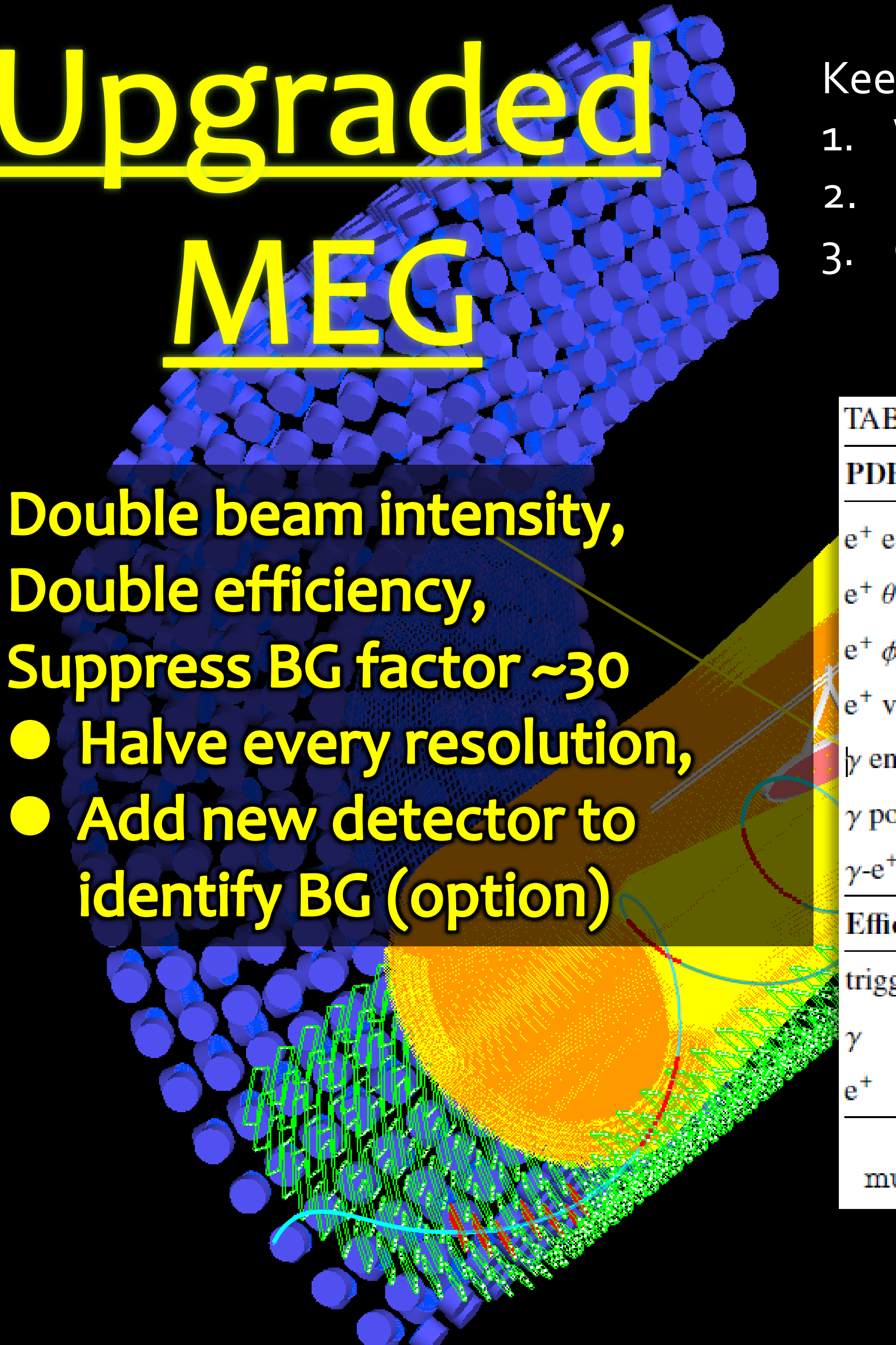
- Reconstruction (pattern recognition & tracking)
- Event overlap

- BG study

- e^+ side (no study yet)

Upgraded MEG

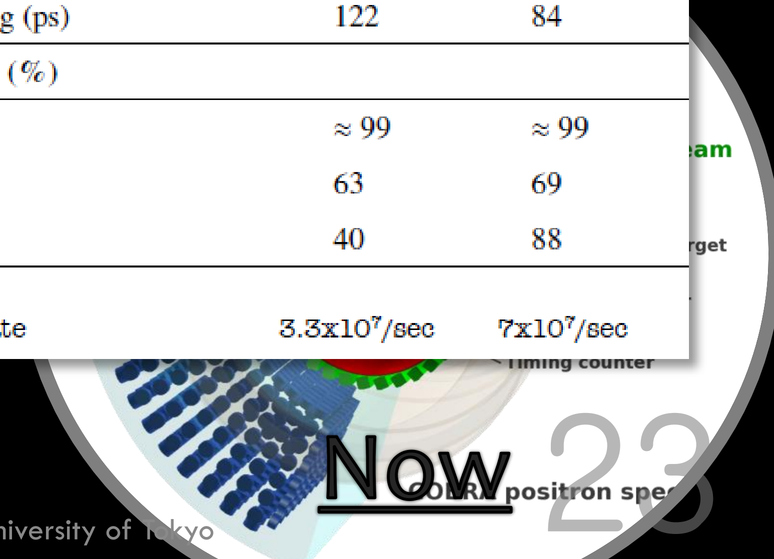
Keep 3 keys of MEG
1. World's most intensity DC μ beam @ PSI
2. Innovative liquid xenon γ-ray detector
3. Gradient B-field e^+-spectrometer



Double beam intensity,
Double efficiency,
Suppress BG factor ~30
- **Halve every resolution,**
- **Add new detector to identify BG (option)**

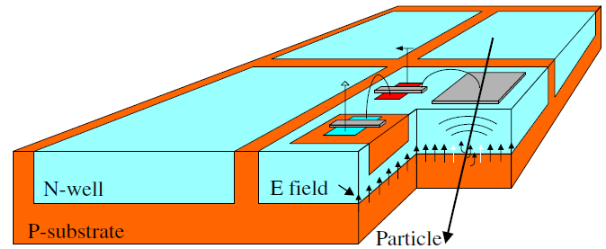
TABLE XI: Resolution (Gaussian σ) and efficiencies for MEG up

PDF parameters	Present MEG	Upgrade scen
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88
muon rate	3.3×10^7/sec	7×10^7/sec

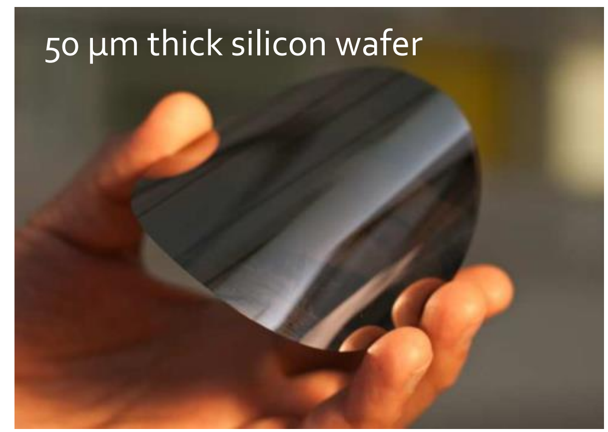


Detector technology

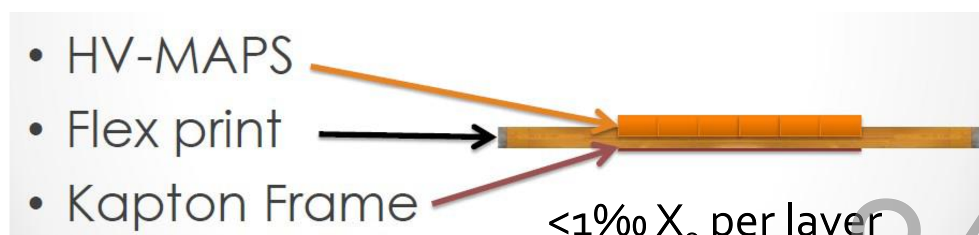
- **Ultra thin device necessary to suppress multiple scattering.**
- **HV-MAPS**
  - Thinned down to 30–50 μm
  - Amp, digitization on chip
  - Fast readout: <50 ns timestamp



(High voltage monolithic active pixel sensors)
I. Peric et.al. NIMA 582 (2007) 876



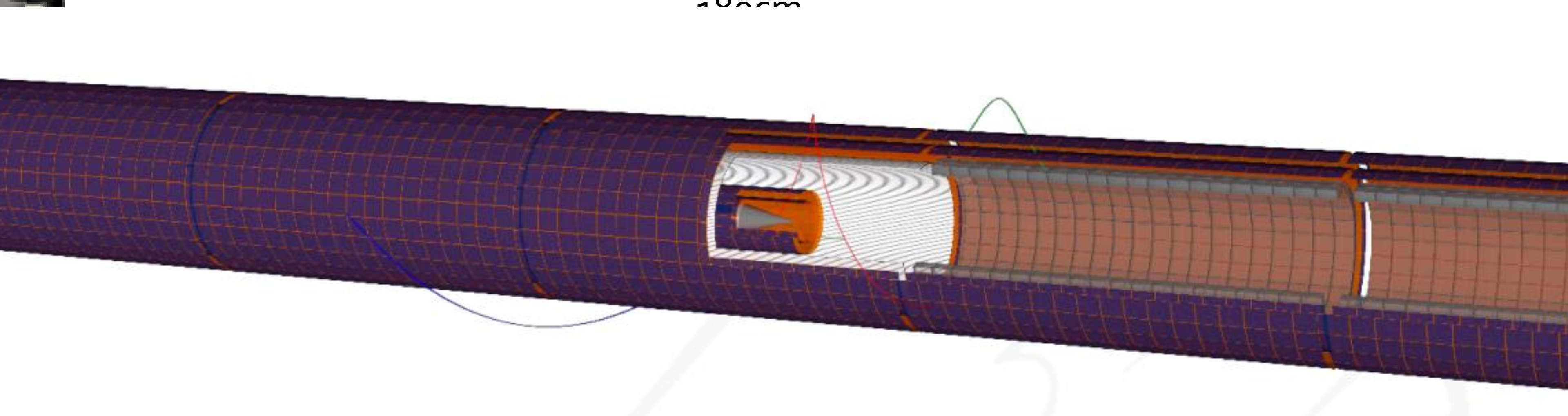
2013:Extensive beam test campaign

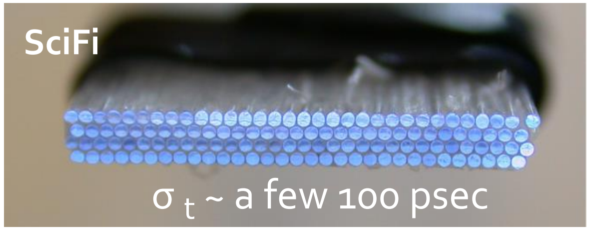


<1‰ X_0 per layer

Mu3e Experiment

Tackle with new technologies





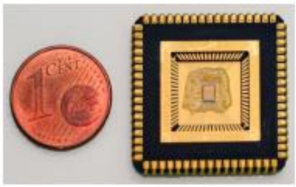
Cone-shape target
disperse vertices into large surface

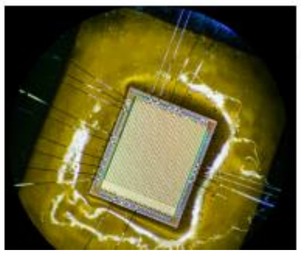
- Geometrical acceptance ~70%

HV-MAPS Prototypes

Design Specifications

- 80 µm × 80 µm pixel size
- 1 cm × 2 cm active area



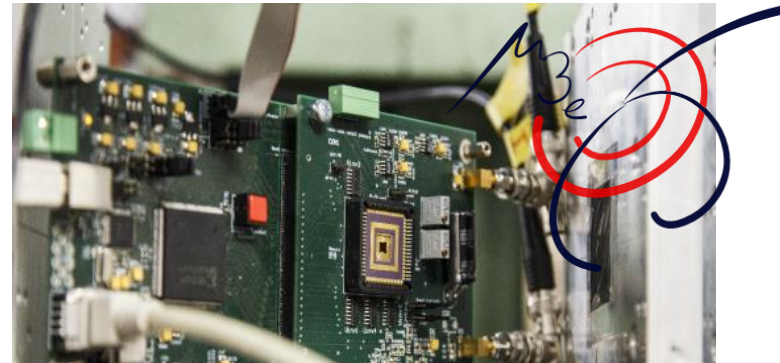


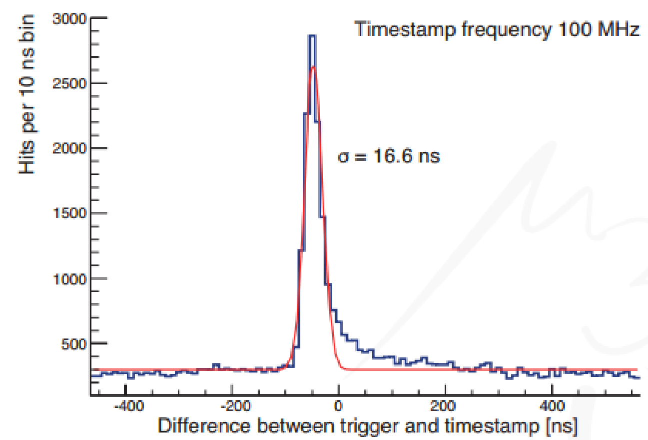
MuPix2

- 39 µm × 30 µm pixel size
- 1.8 mm × 1 mm active area
- Proof of Concept

MuPix3/4

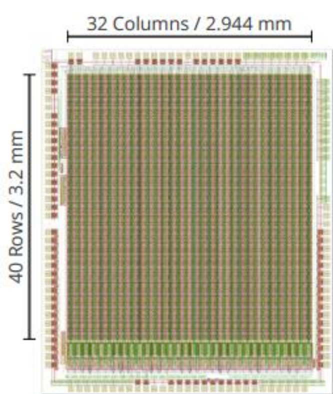
- 92 µm × 80 µm pixel size
- 2.9 mm × 3.2 mm active area





MuPix4 HV-MAPS Prototype

16



- 92 µm × 80 µm pixel size
- Global threshold
- Zero-suppressed digital readout
- Timestamps
- Additional readout FPGA