Recent Result of the MEG Experiment

Satoshi MIHARA

Seminar at Kyoto Univ.

1/Dec/2010

Outline

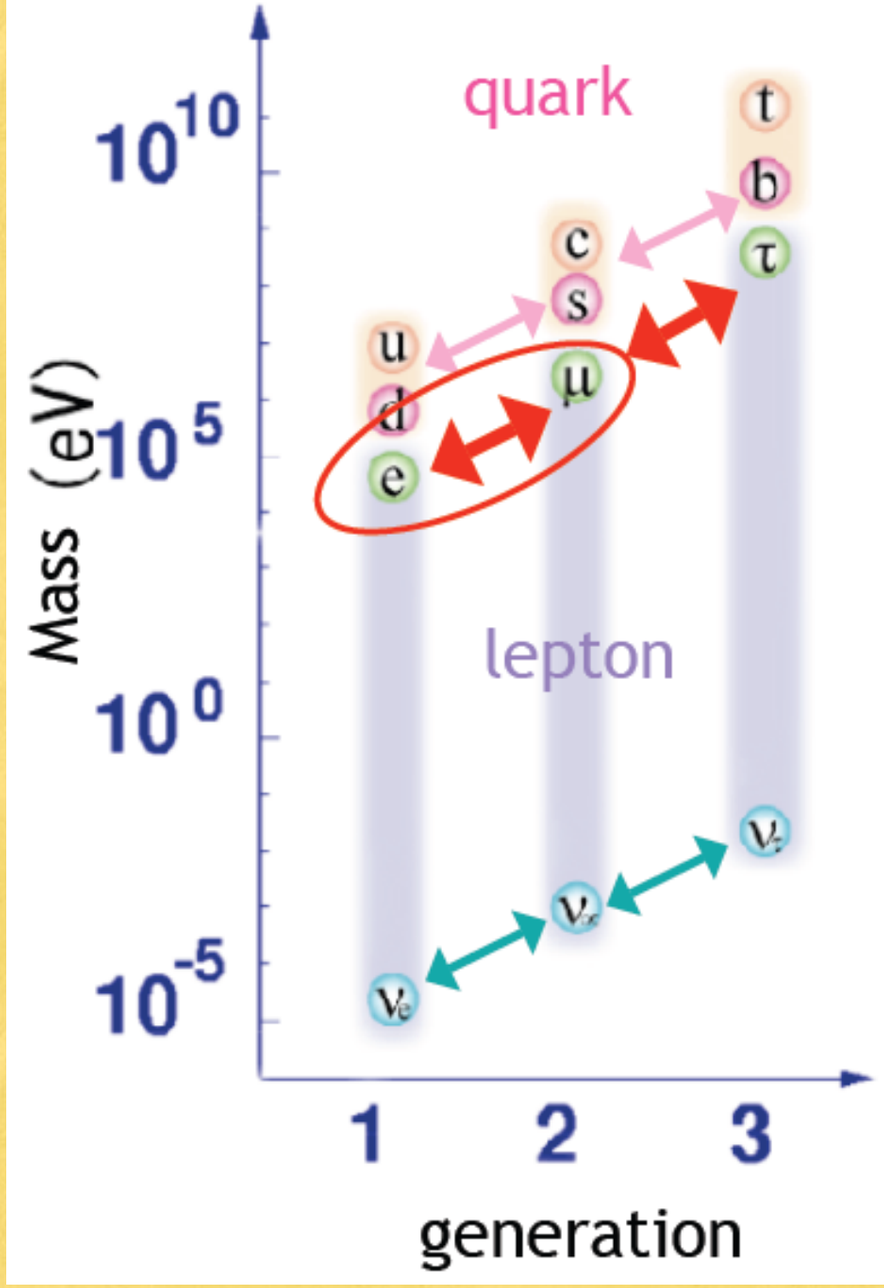
- Introduction
- MEG History
- 2009 Run
- 2009 Data Analysis and Result
- New cLFV experiments at J-PARC
- Summary

Important Remark

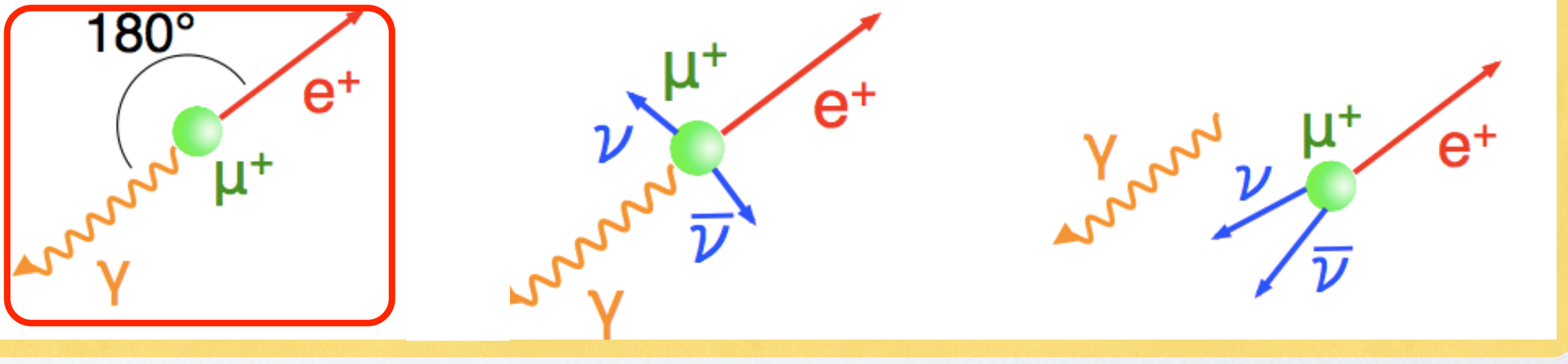
- All results presented in this presentation are preliminary

$\mu \rightarrow e\,\gamma$ Introduction

- Muon discovery in 1937
- Order of 10 improvement in 50 years
- Current best limit set by MEGA collaboration
  - BR($\mu \rightarrow e\,\gamma$) < 1.2×10^{-11} @ 90%C.L.
- Strong physics motivation
  - Neutrino oscillation
  - SUSY GUT

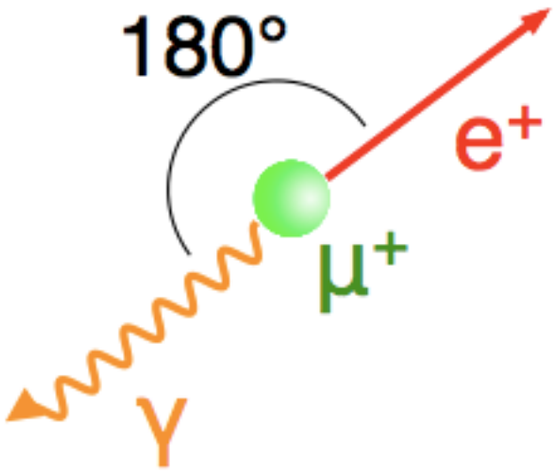


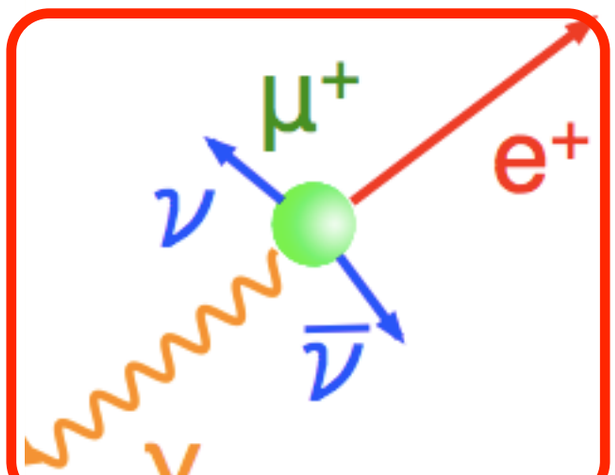
Signal and Background

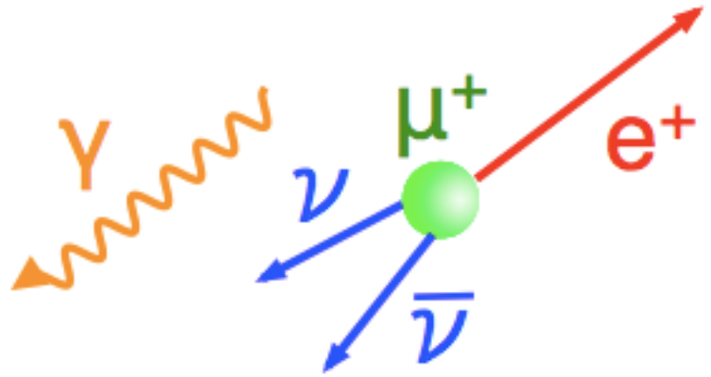


- Signal
  - Gamma and positron with 52.8MeV
  - Back to back
  - Time coincidence

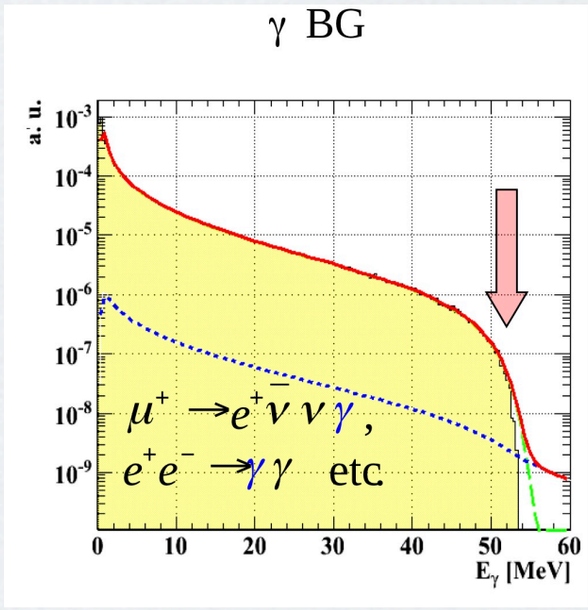
Signal and Background



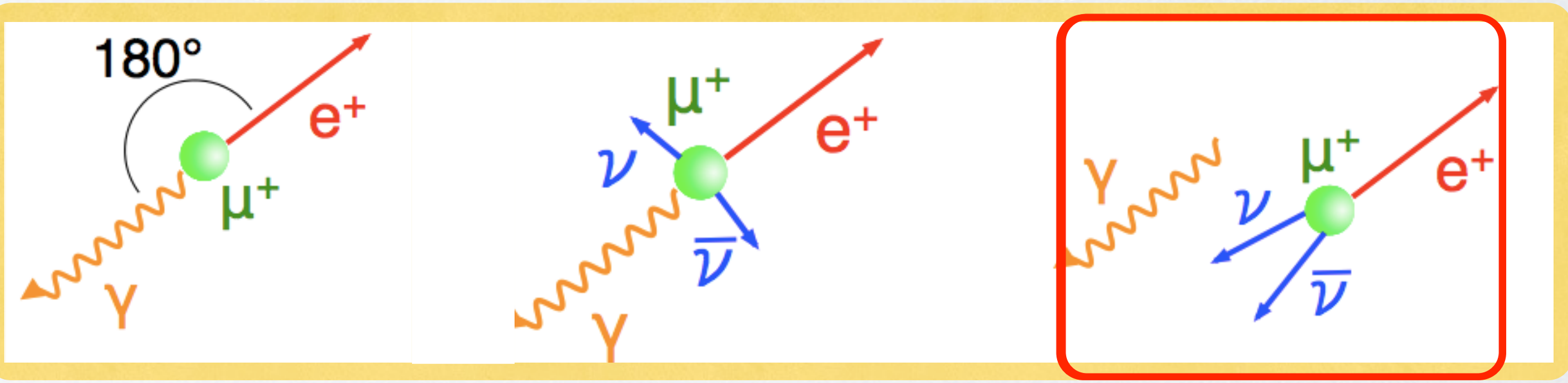




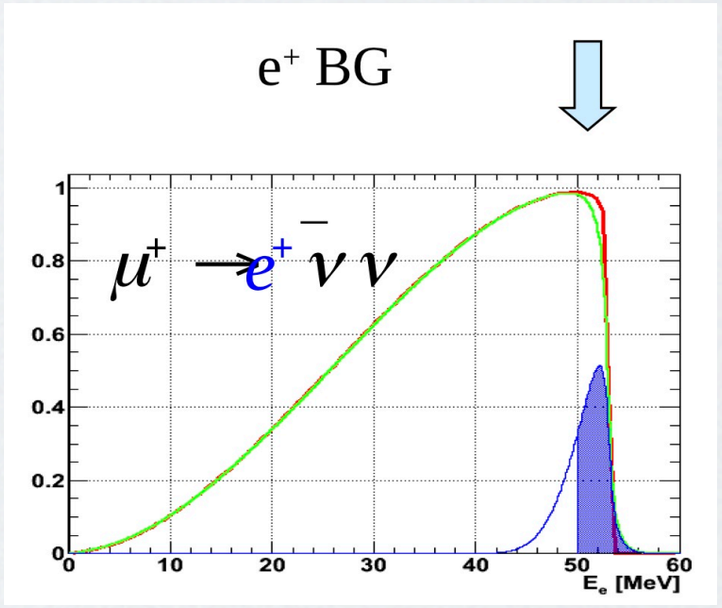
- Prompt background - Radiative muon decay
  - Gamma and positron < 52.8MeV
  - Any angle < 180°
  - Time coincidence



Signal and Background



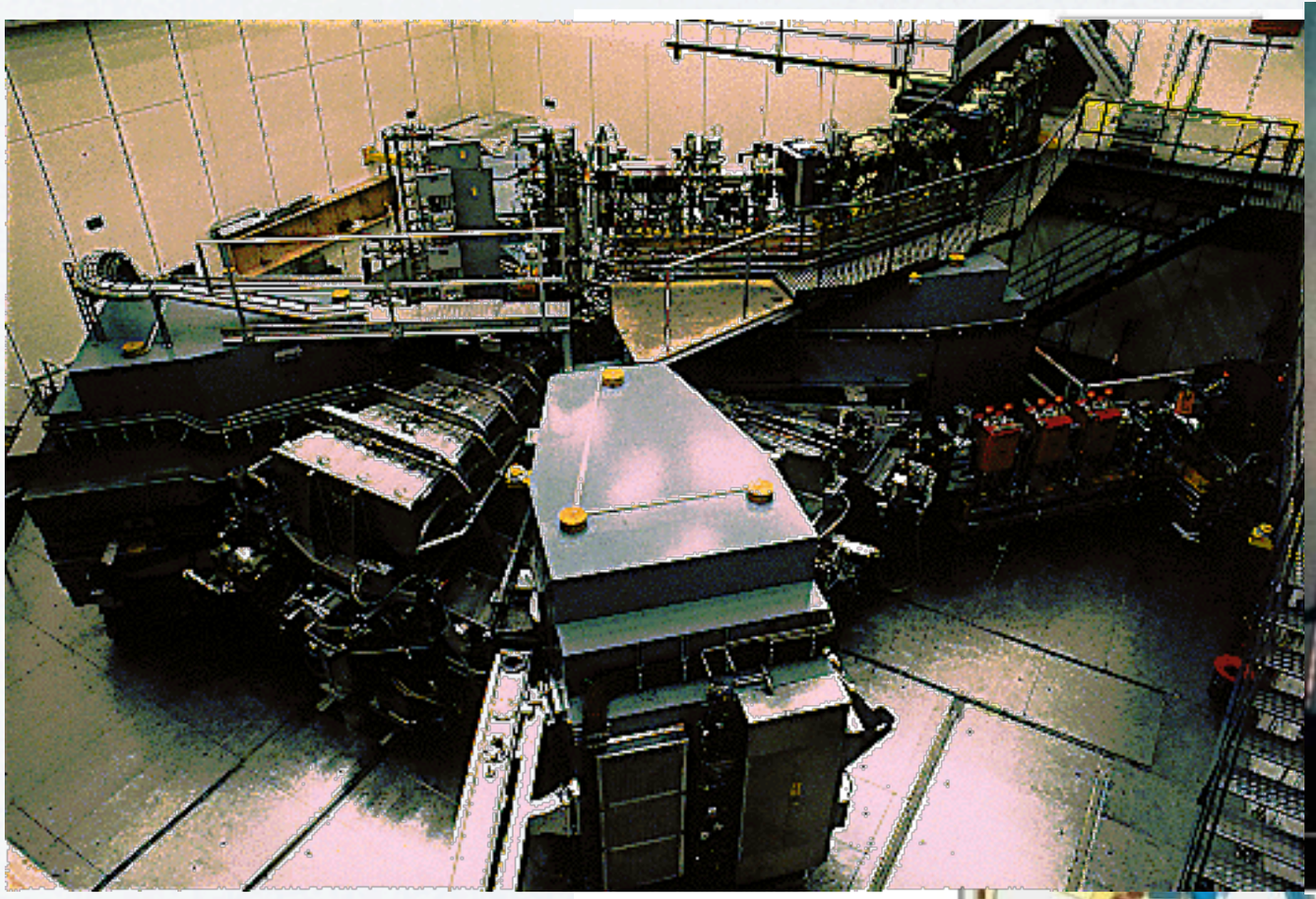
- Accidental background
  - Gamma and positron < 52.8MeV
  - Any angle
  - Random

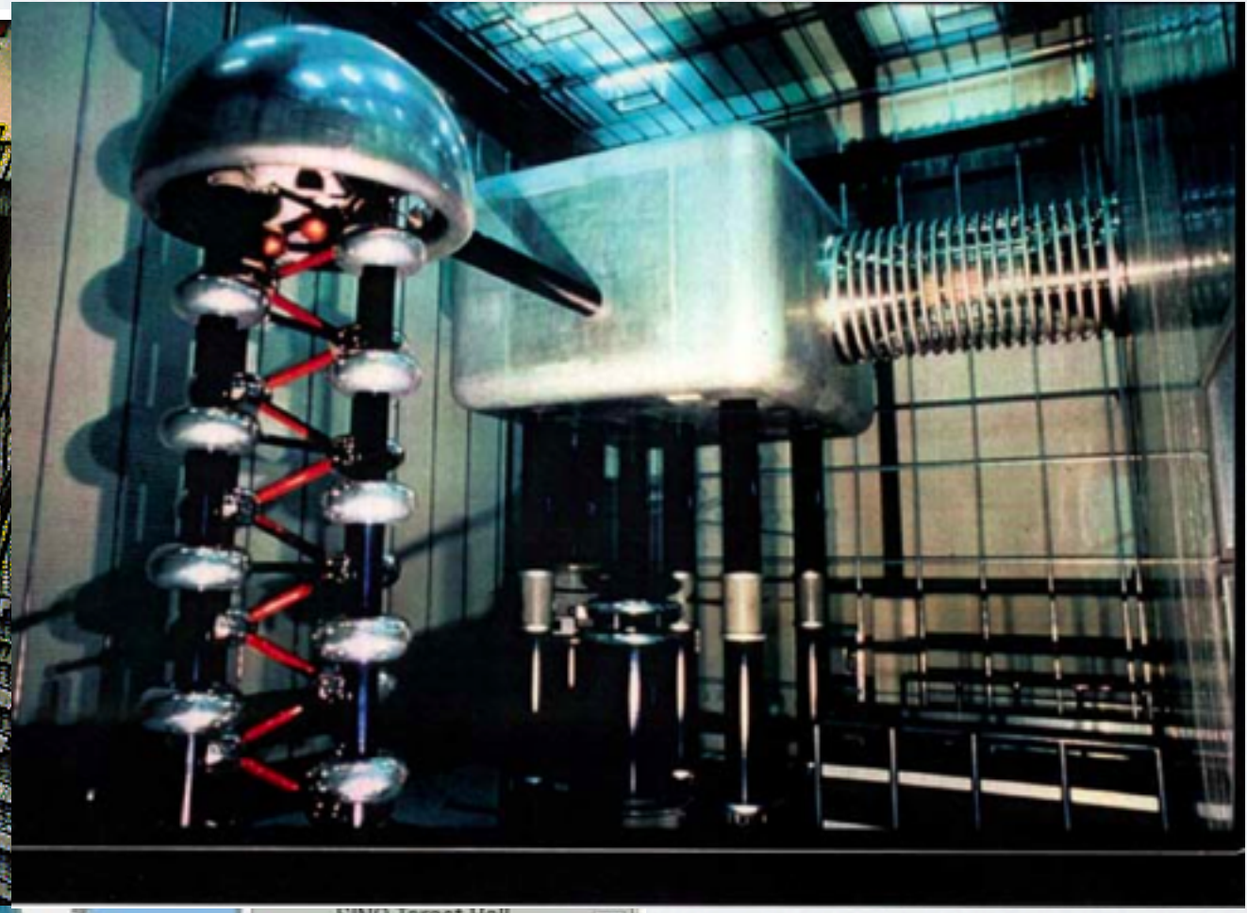


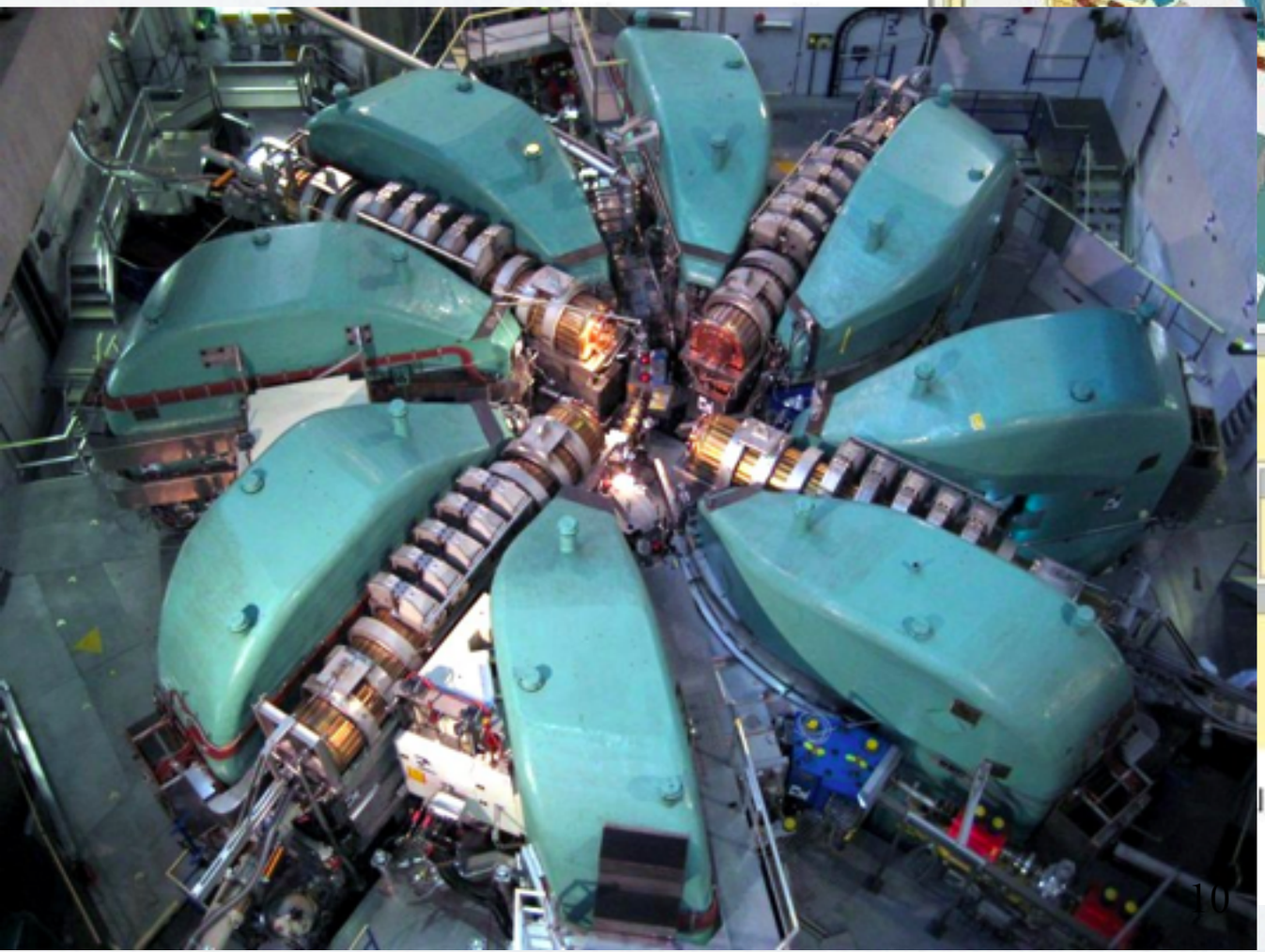
Signal and Background

- Accidental background dominates in MEG
  - DC muon beam is necessary
- Good detector resolution is crucial to suppress the background

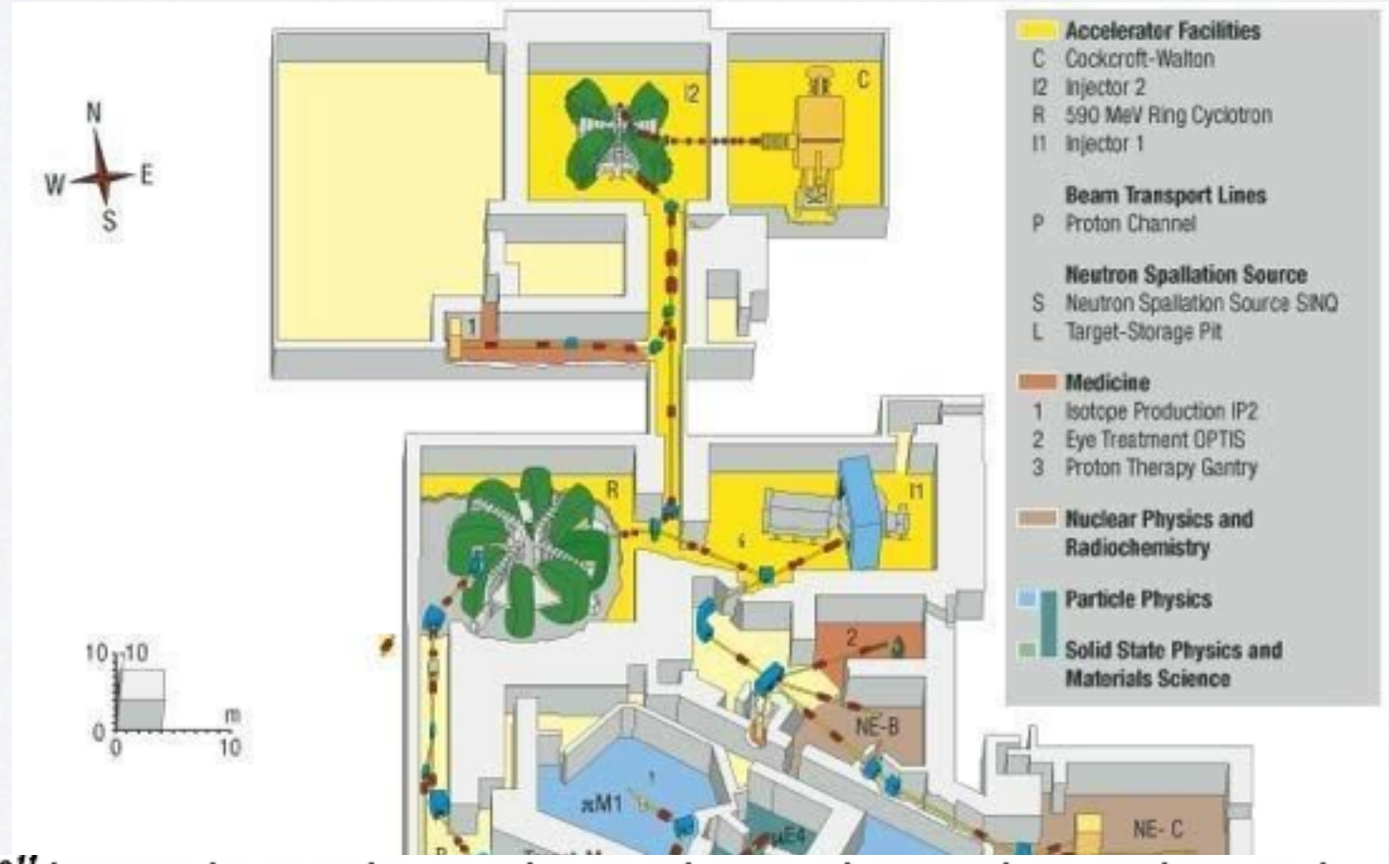
PSI Surface Muon Beam

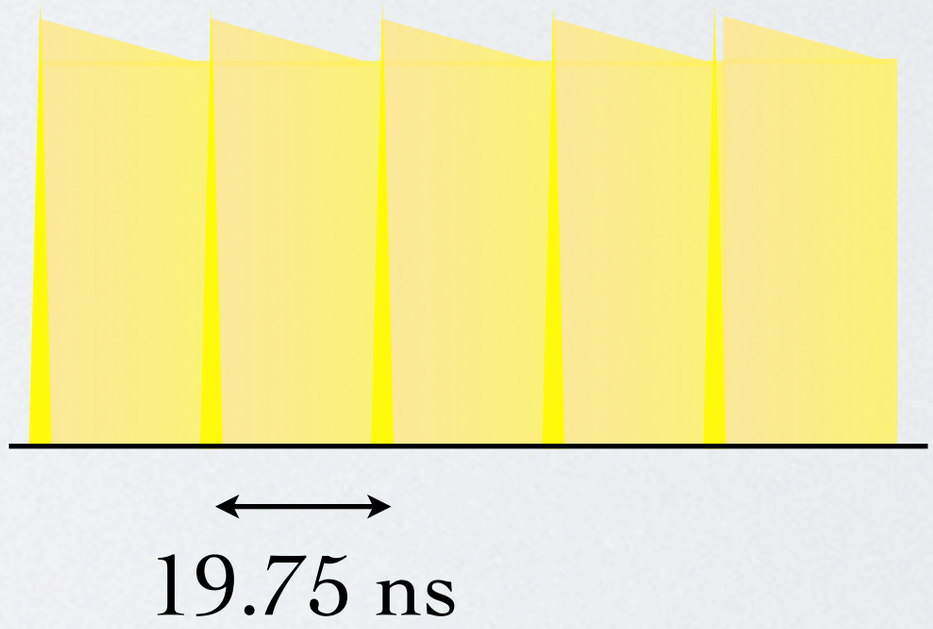


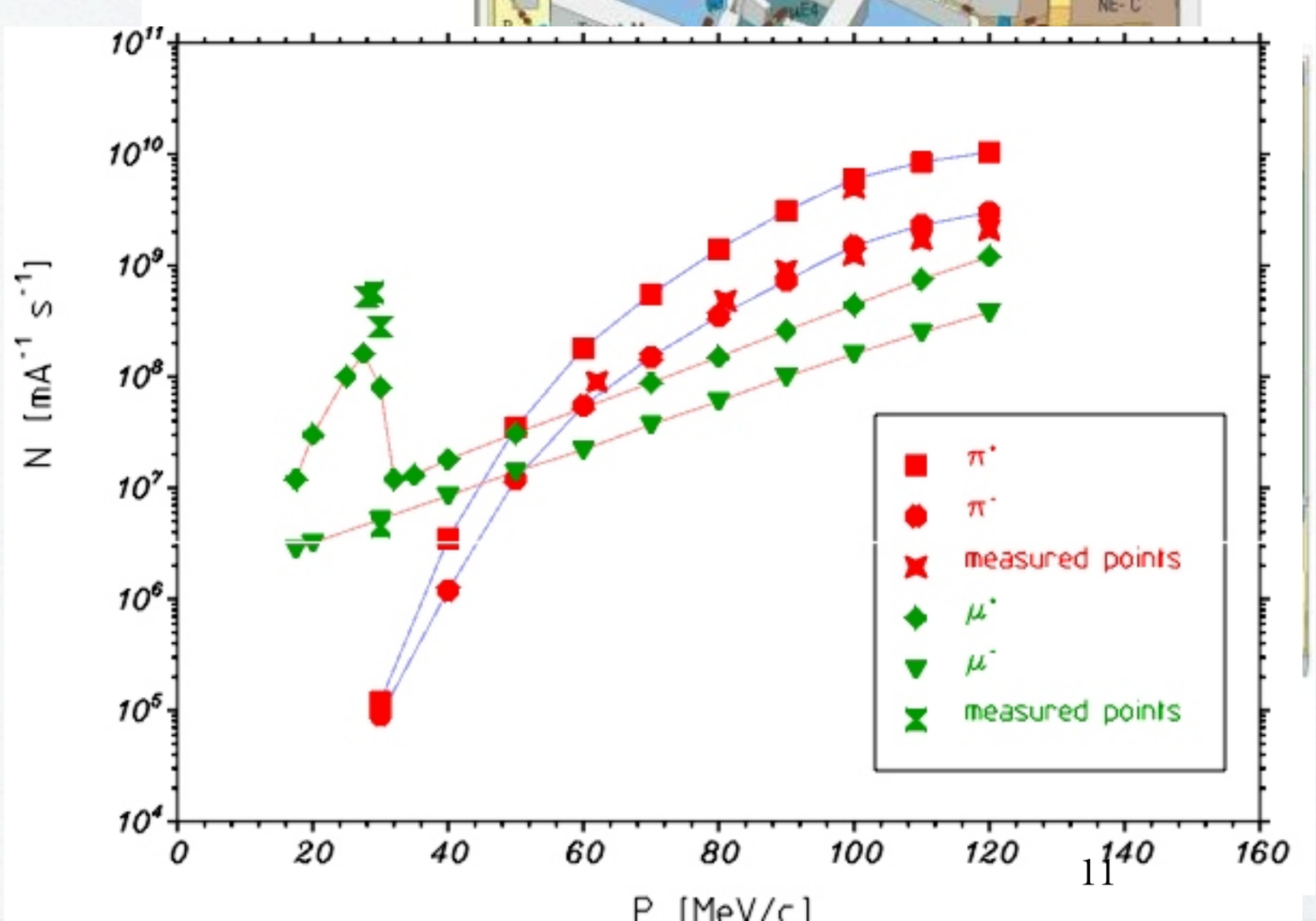


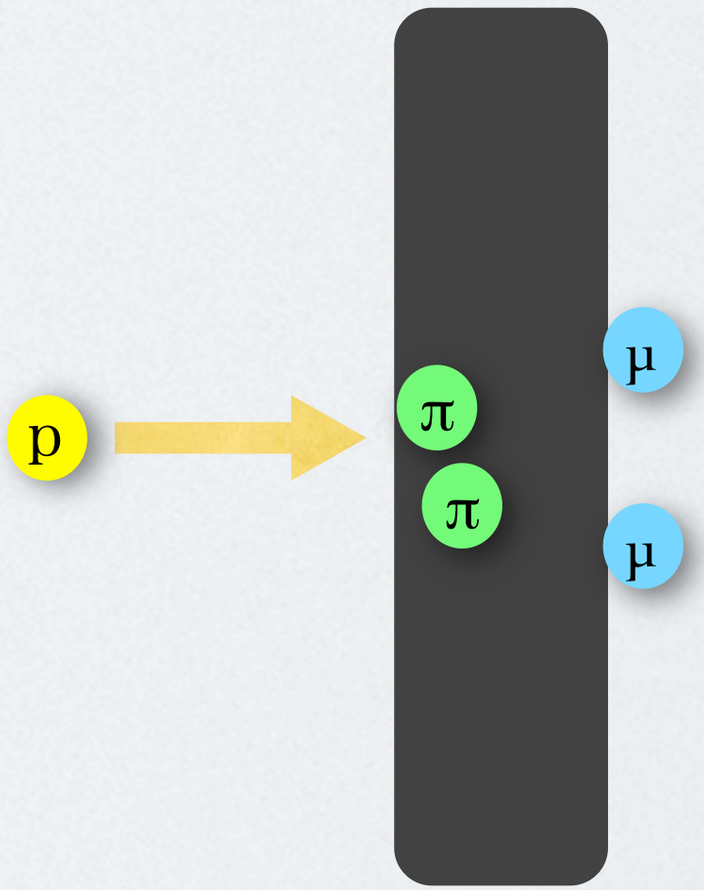


Injection Energy	72 MeV
Extraction Energy	590 MeV
Extraction Momentum	1.2 GeV/c
Energy spread (FWHM)	ca. 0.2 %
Beam Emittance	ca. 2π mm×mrad
Beam Current	2.0 mA DC
Accelerator Frequency	50.63 MHz
Time Between Pulses	19.75 ns
Bunch Width	ca. 0.3 ns
Extraction Losses	ca. 0.03%


N
W
E
S
C
I2
I1
R
2
NE-B
NE- C
πM1
10
0
m
Accelerator Facilities
C Cockcroft-Walton
I2 Injector 2
R 590 MeV Ring Cyclotron
I1 Injector 1
Beam Transport Lines
P Proton Channel
Neutron Spallation Source
S Neutron Spallation Source SINQ
L Target-Storage Pit
Medicine
1 Isotope Production IP2
2 Eye Treatment OPTIS
3 Proton Therapy Gantry
Nuclear Physics and Radiochemistry
Particle Physics
Solid State Physics and Materials Science

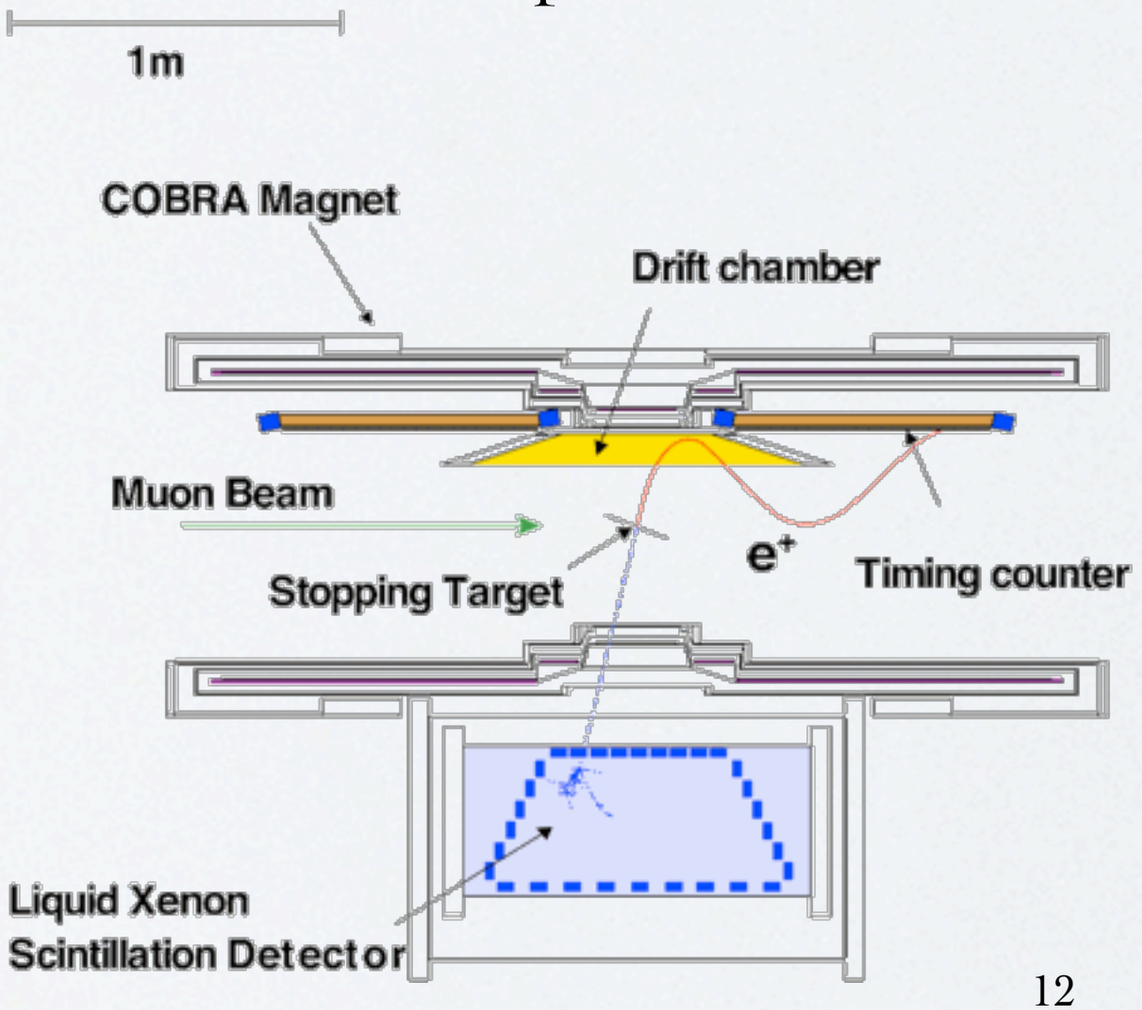

19.75 ns

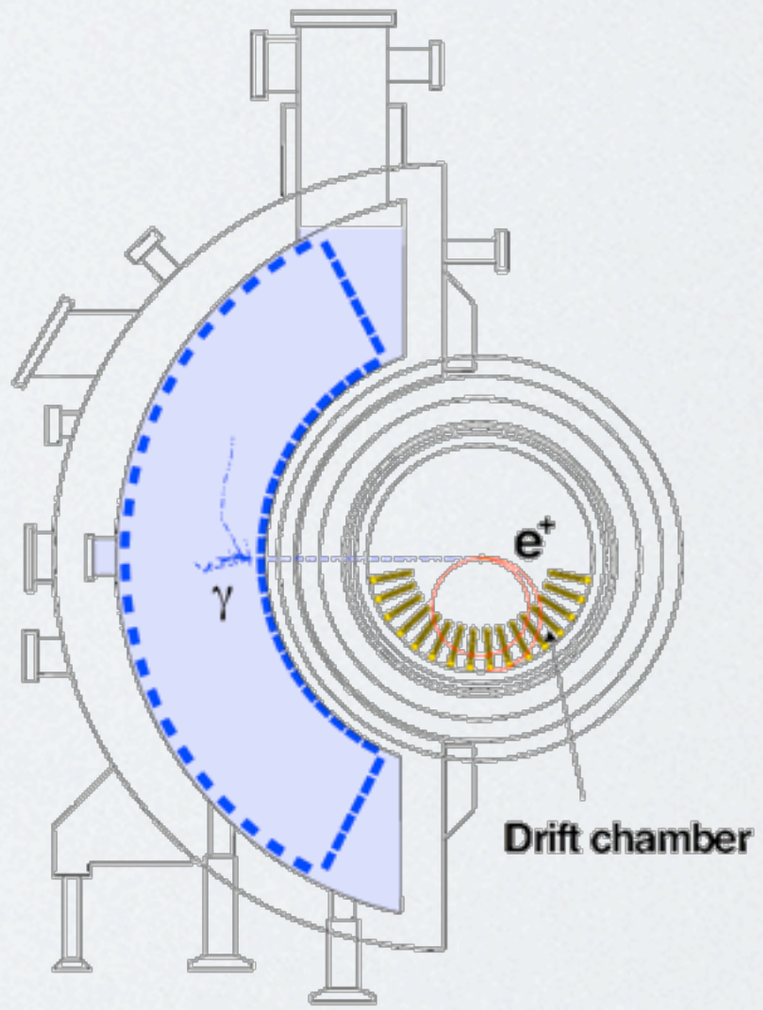

N [mA⁻¹ s⁻¹]
P [MeV/c]
π⁺
π⁻
measured points
μ⁺
μ⁻
measured points


p
π
π
μ
μ

MEG Detector

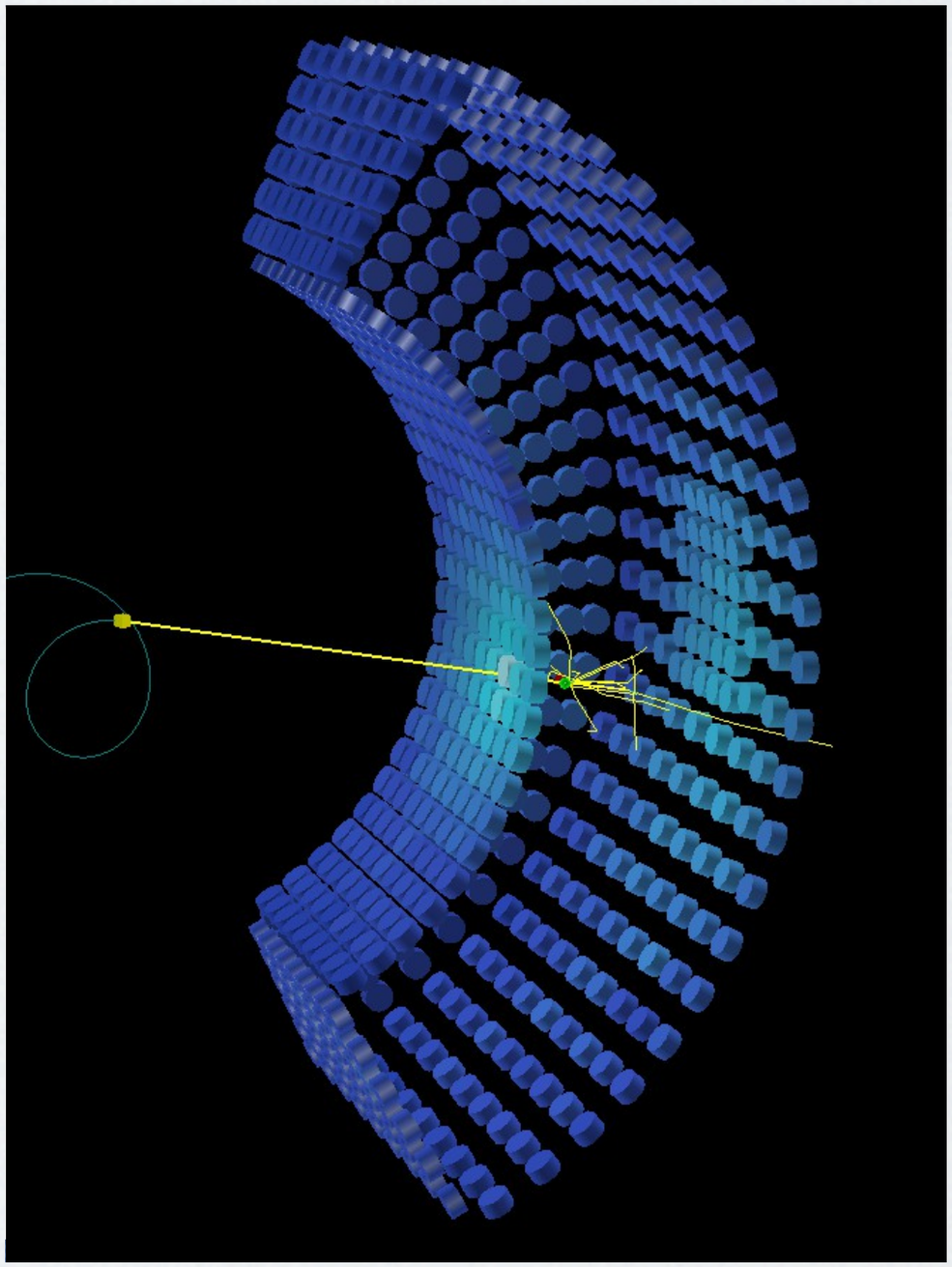
- Beam Transport System
- Liquid Xenon Gamma-ray Detector
- Positron Spectrometer





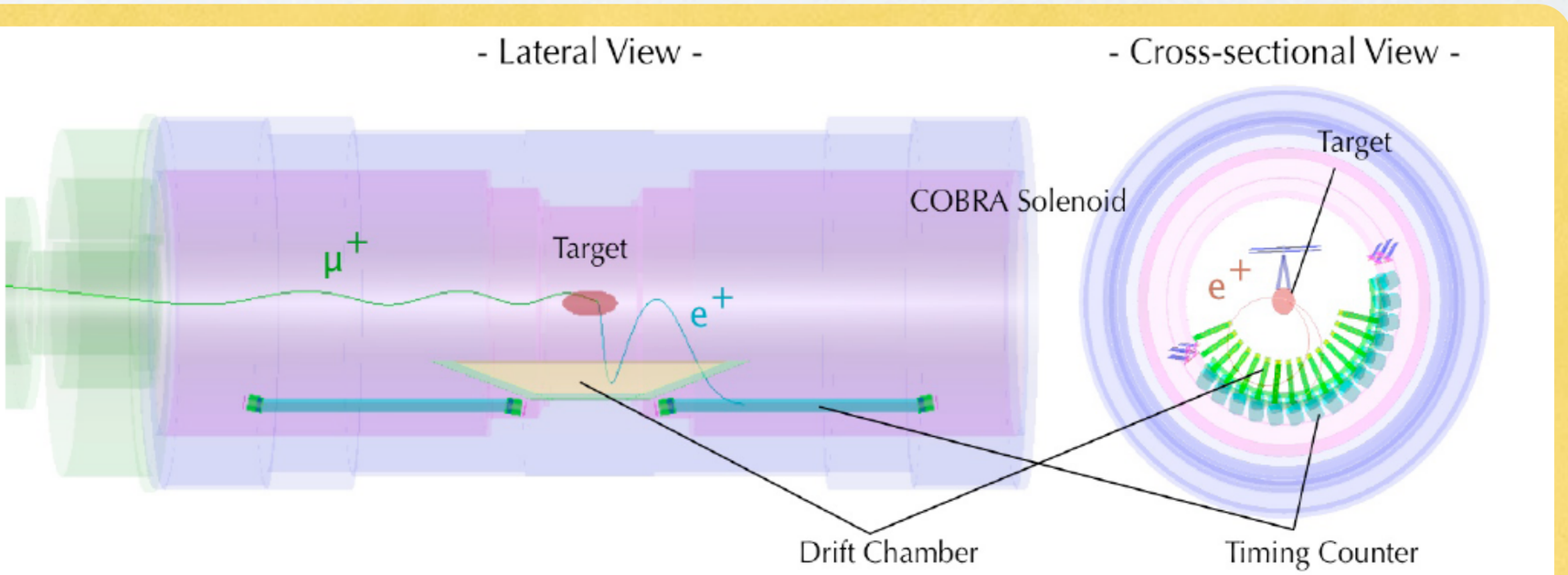
Liquid Xenon Gamma-ray Detector

- 900 liter liquid xenon
- 846 photomultipliers submersed in liquid
  - Hamamatsu R9869
- Uses only scintillation light information
  - High light output
  - Short decay time
  - High density
- Purification system implemented to remove impurity like H_2O, O_2 and N_2



Positron Spectrometer

- COBRA magnet
- Drift chamber system
- Timing counter



Solenoid

superconducting solenoid
gradient B-field (0.5-1.7 T)
very thin conductor and
cryostat wall ($0.2X_0$)

Drift Chamber

segmented radially (16 sectors)
helium:ethane (50:50)
opened-frame
very thin cathode foil with pads

Timing Counter

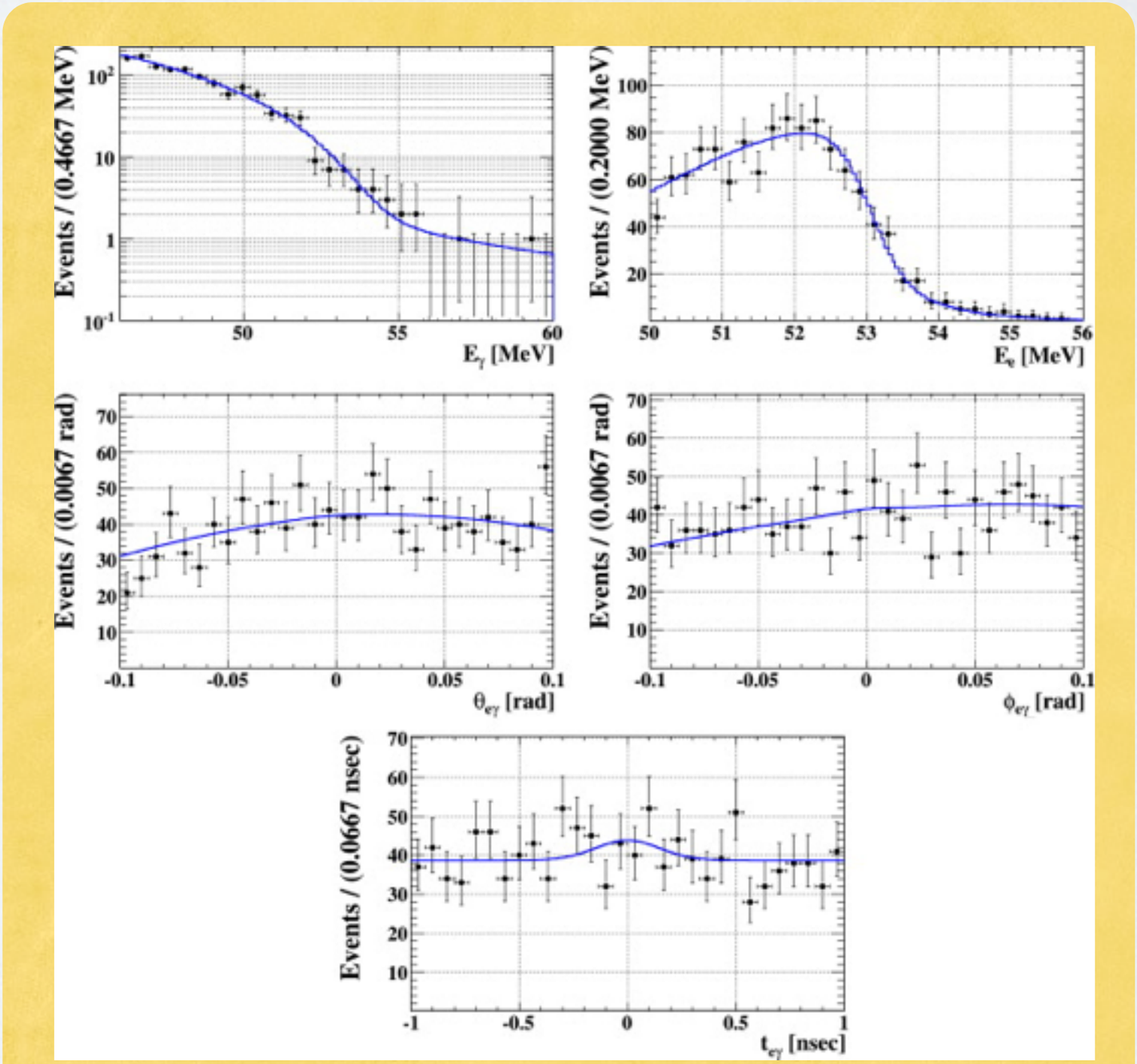
2-layers of scintillators
- scintillator bars (outer)
- scintillator fibres (inner)

MEG History

1999		Proposal
		...
2007	Dec.	Engineering run
2008	Sep.-Dec.	1st physics data acquisition
2009		Analysis of 2008 data
		Hardware upgrade
	Nov.-Dec.	2nd physics data acquisition
	Dec.-	Analysis of 2009 data
2010	Jul.-	3rd physics data acquisition

2008 Result Summary

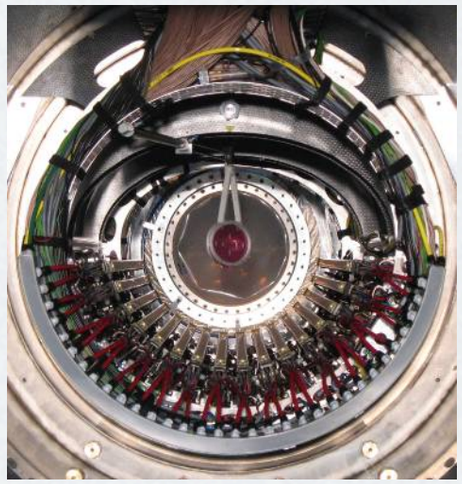
- NP B834(2010) 1-12
- Sensitivity: 1.3×10^{-11}
- 90% C.L. upper limit: 2.8×10^{-11}
- Toy MC study → 5%

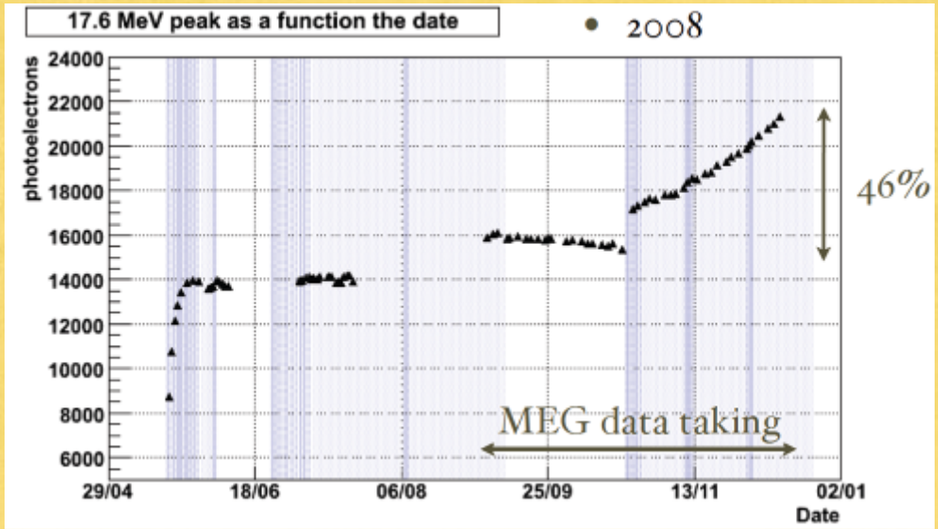


2009 Run

Review 2009 Run

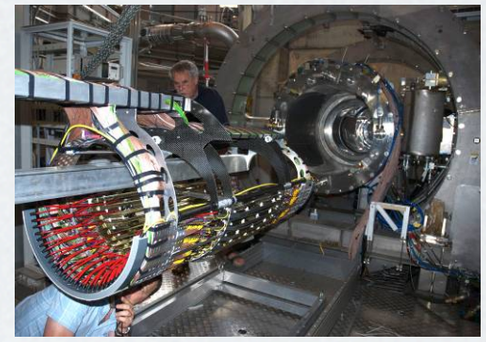
- Successfully finished 1st MEG physics run in 2008
- However - Major issues to be investigated before starting 2009 run
  - DC HV stability (He diffusion problem)
  - LXe light yield (unexpected impurity contamination)



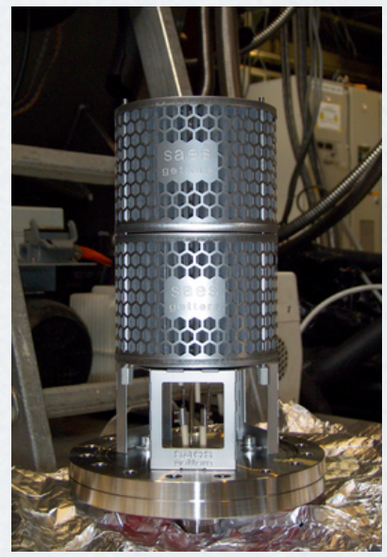


Situation Spring 2009

- Back to “Square One”
  - Total detector DISMANTLED for Maintenance/Repair/Improvement during shutdown 2008/2009

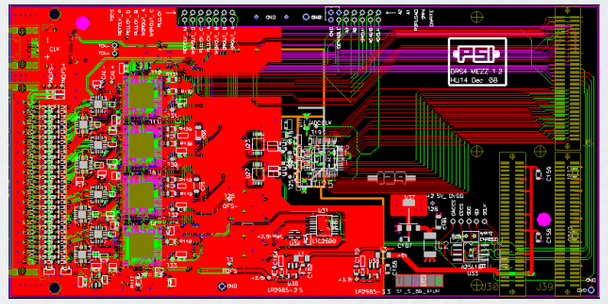


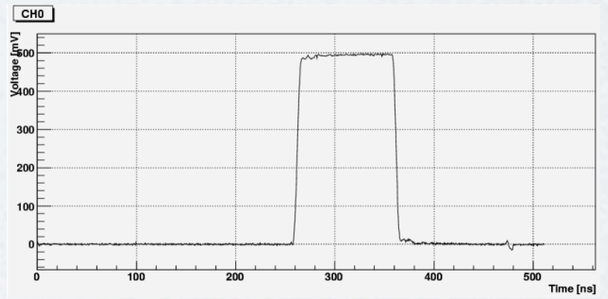
- DC
  - Dismantled all modules
  - New anode-prints+wires+extensive test in the lab
- LXe
  - Exchange the suspicious LN_2 cooling pipe
  - New NEG pump installation
  - New purifier tower installation

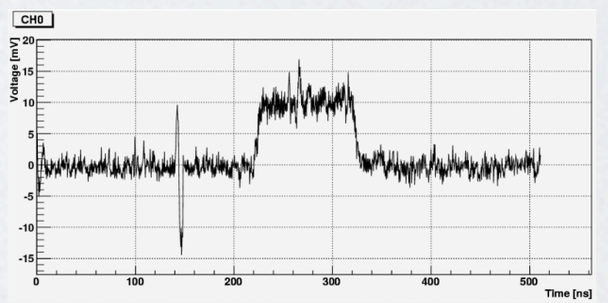


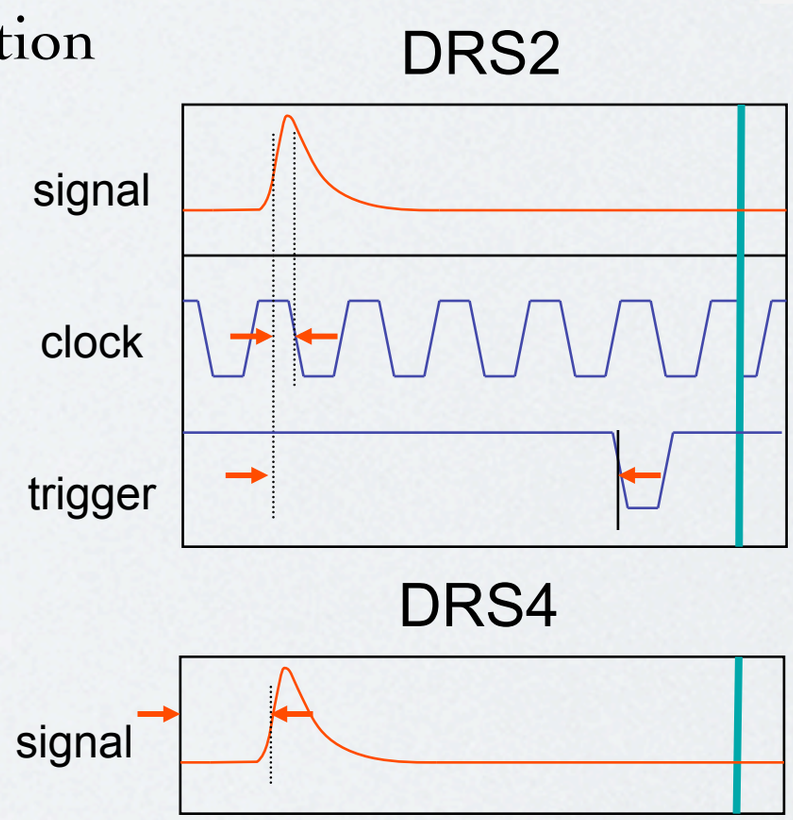
Further Implementation Sprig 2009

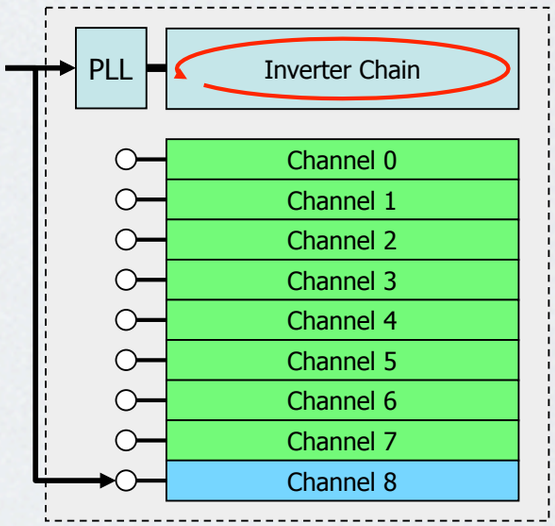
- Update from DRS2 to DRS4
  - Differential I/P
  - Internal clock & synchronization
  - On-board timing calibration
  - 3.2 GSPS possible
    - XEC1.6GHz
    - DC 0.7GHz
  - Fix the “ghost pulse” problem





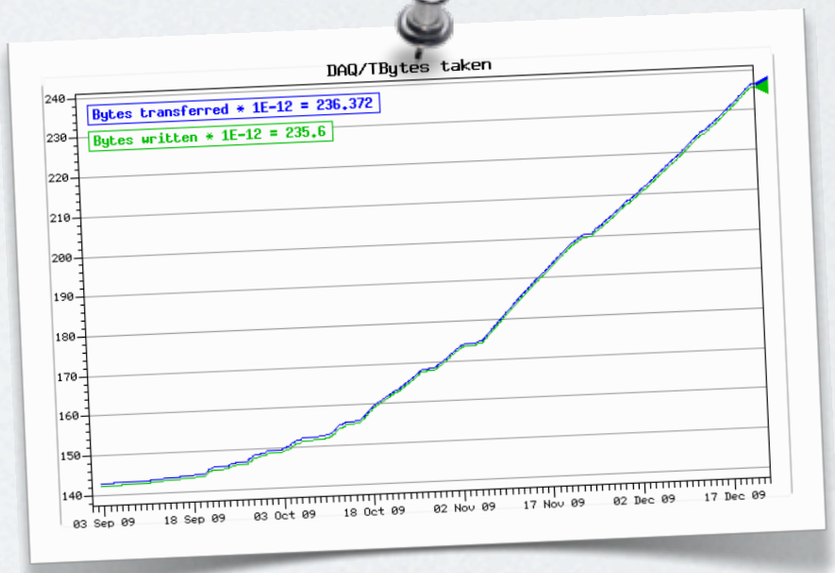


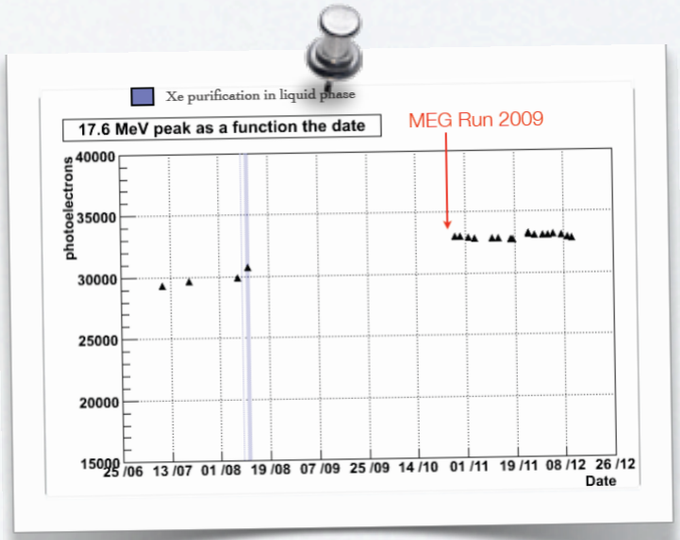


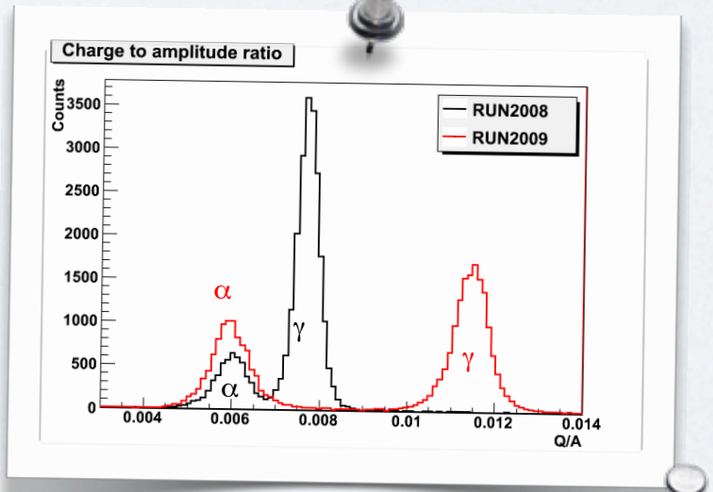


Run 2009 Summary

- 8½ weeks physics DAQ
  - 25th/Oct - 22nd/Dec
- 93 TB data on disk

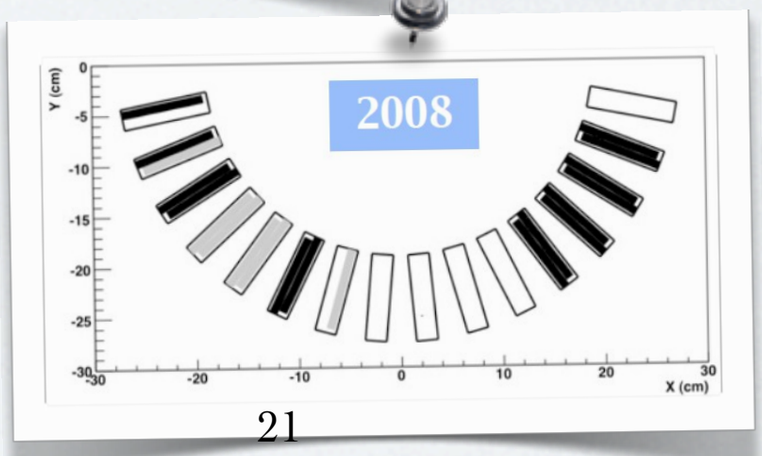


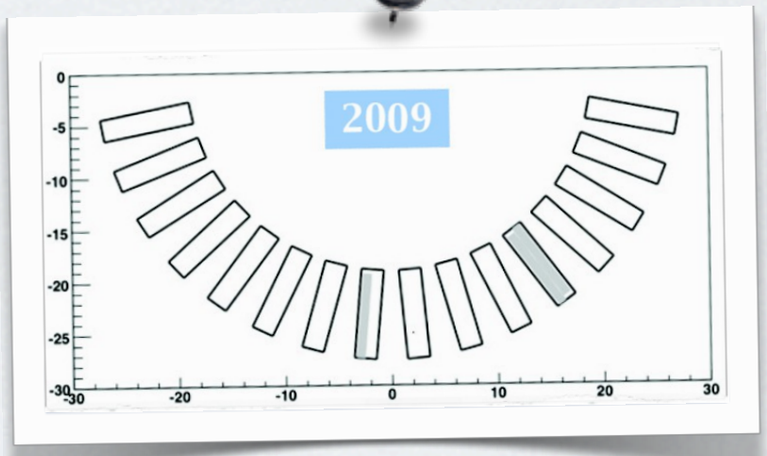




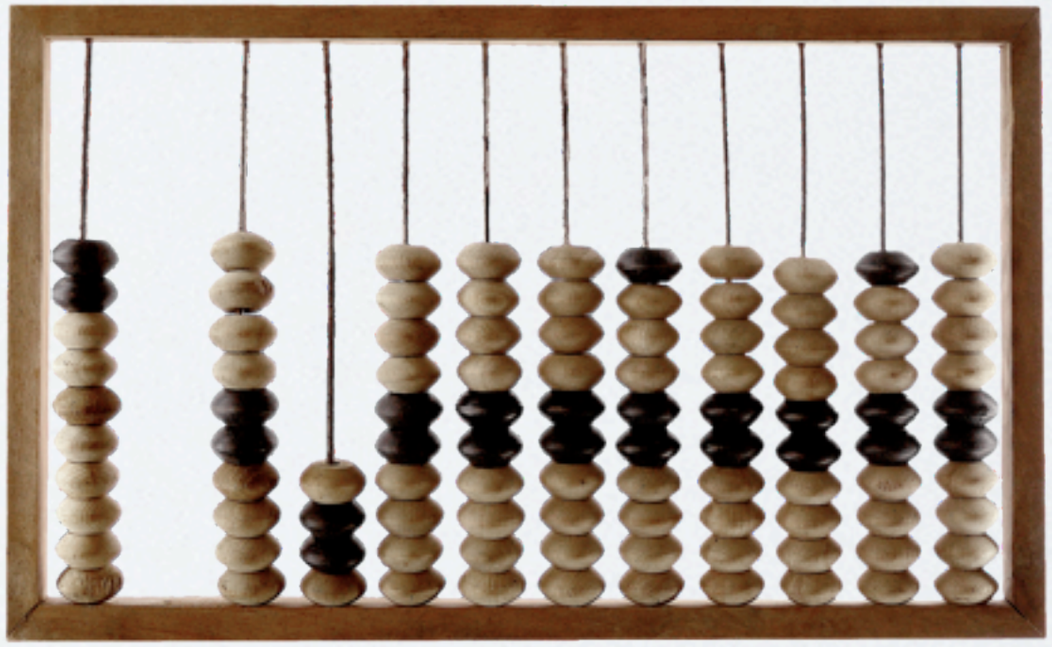
- LXe
  - Light yield as expected
  - Good α/γ separation
  - Precise calibrations

- DC
  - HV instability solved
  - Ran with "full efficiency"



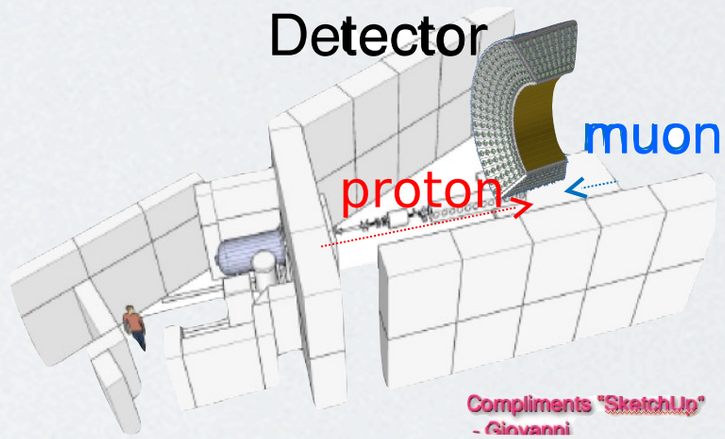


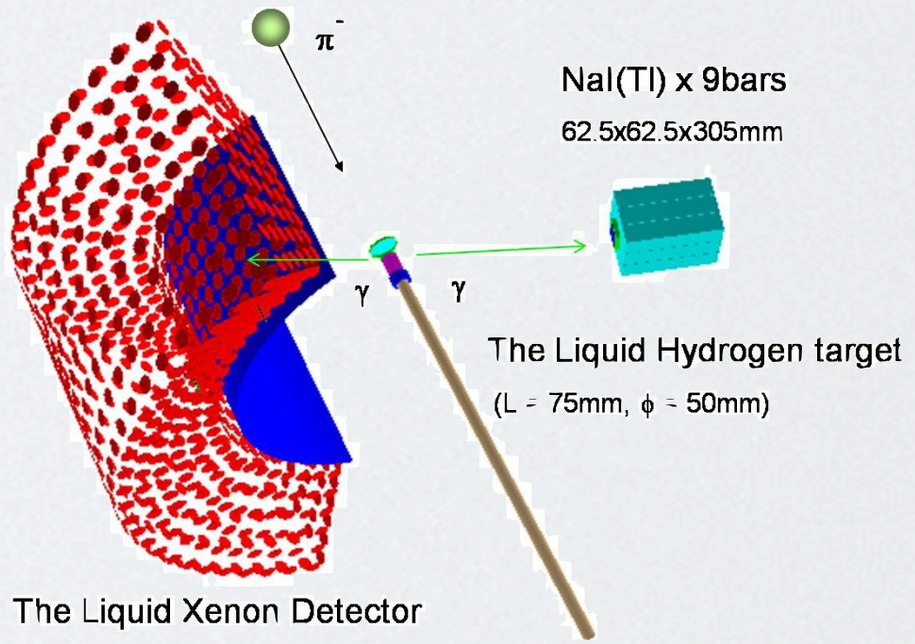
2009 Data Analysis



LXe Calibration

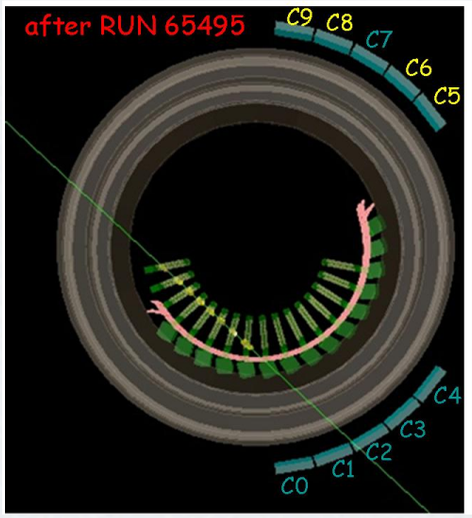
- PMT Gain by LED & QE by α
- Light yield by CW, CR, Am-Be
- Cockcroft-Walton proton accelerator at the rear end of the experimental area
  - 17.6 MeV γ through Li(p, γ)Be reaction
- Energy calibration by CEX
  - $\pi^- p \rightarrow \pi^0 n$, $\pi^0 \rightarrow \gamma\gamma$
    - 55-MeV - 83-Me Gamma ray
    - Close to our 52.8 MeV signal
  - Check by the RMD edge

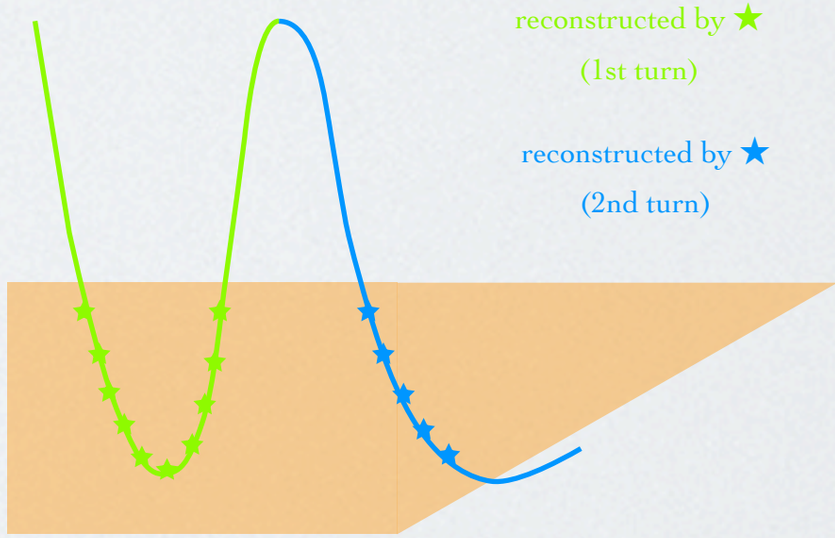




Positron Calibration

- Calibration using cosmic ray events triggered by scintillation counters located outside COBRA
- Resolutions evaluated using residuals of two turn tracks
  - Momentum
  - Angle
    - ϕ and θ





Performance Summary

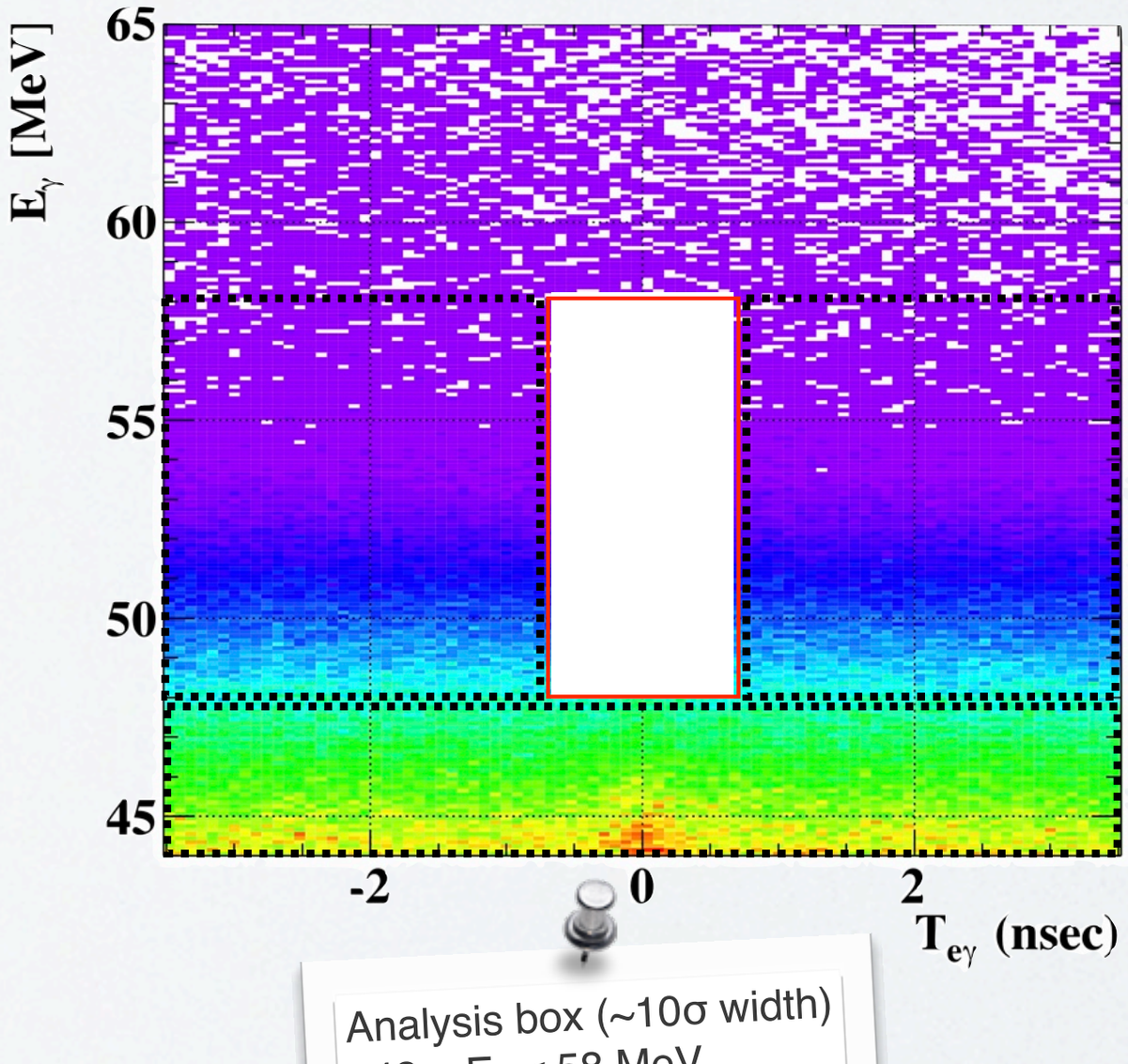
- Resolutions in sigma
- 2009 performance is preliminary
- Further improvement foreseen after detailed calibration

	2008 published	2009 Preliminary
Gamma Energy (%)	2.0 (w>2cm)	2.1 (w>2cm)
Gamma Timing (psec)	80	> 67
Gamma Position (mm)	5(u,v)/6(w)	←
Gamma Efficiency (%)	63	58
e^+ Timing (psec)	<125	←
e^+ Momentum (%)	1.6	0.74 (core)
e^+ Efficiency (%)	14	~40%
e^+ Angle (mrad)	10(ϕ)/18(θ)	7.1(ϕ core)/11.2(θ)
e^+-gamma Timing (psec)	148	142 (core)
Muon Decay Point (mm)	3.2(R)/4.5(Z)	3.3(R)/3.4(Z)
Trigger Efficiency (%)	66	83.5
Stopping Muon Rate (Hz)	3×10^7	2.9×10^7
DAQ Time / Real Time (days)	48/78	35/43
Sensitivity	1.3×10^{-11}	6.1×10^{-12}

MEG Data Analysis Principle

- Blind analysis
  - E_γ - $T_{e\gamma}$
- Likelihood analysis
  - Probability Density Function (PDF) from data

Data Sample



Analysis box (~10σ width)
$48 \le E_\gamma \le 58$ MeV
$50 \le E_e \le 56$ MeV
$|T_{e\gamma}| \le 0.7$ ns
$|\phi_{e\gamma}|, |\theta_{e\gamma}| \le 50$ mrad

- Analysis box (containing 0.2% data) was blinded during calibration and optimization of physics analysis
- Side band data (16%) to study background
- Michel positrons for positron detector response study
- RMD with low gamma energy to evaluate timing resolutions

Likelihood Analysis

$$L(N_{SIG}, N_{RMD}, N_{BG}) = \frac{N^{N_{obs}} \exp^{-N}}{N_{obs}!} \prod_{i=1}^{N_{obs}} \left[\frac{N_{SIG}}{N} S + \frac{N_{RMD}}{N} R + \frac{N_{BG}}{N} B \right]$$

- $N_{obs} = N_{SIG} + N_{RMD} + N_{BG}$
- N_{sig}, N_{RMD} and N_{BG} are evaluated based on the maximum likelihood analysis method
  - Input: E_γ, E_e, $T_{e\gamma}$, Relative angles (ϕ,θ)
- Three independent likelihood analysis tools are employed to check possible systematic effects

- PDF evaluated (mostly) from data
  - Except RMD

Normalization

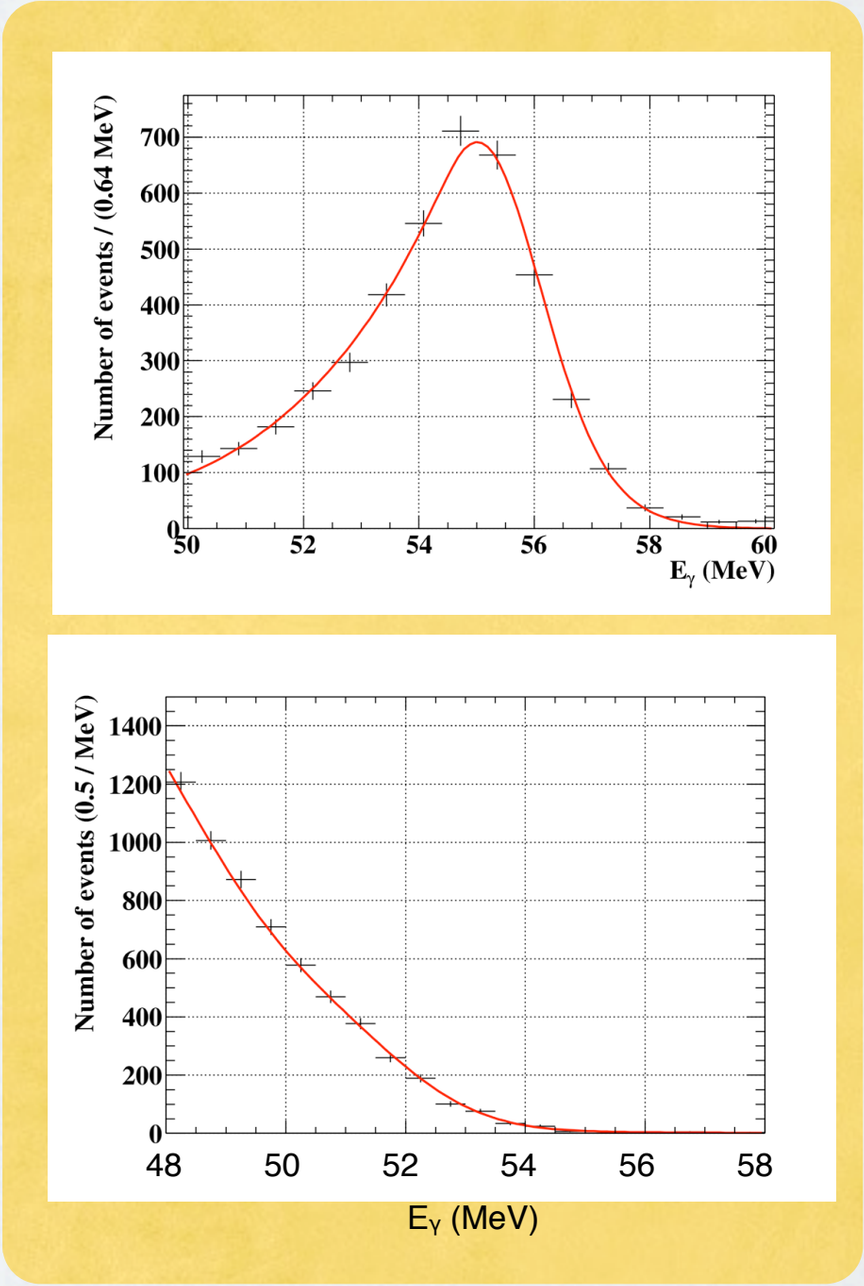
- The normalization factor is evaluated from the number of observed Michel positrons

$$k \equiv N_{evv} \times \left[\frac{f_S}{f_M}\right] \times \left[\frac{\varepsilon(TRG=0 \mid e^+\gamma)}{\varepsilon(TRG=22 \mid track \cap e_m^+ \cap TC)}\right] \times A(\gamma \mid track) \cdot \varepsilon(\gamma) \cdot Psc(22)$$

- $k=(1.0\pm0.1)\times10^{12}$
- $BR = N_{SIG}/k$

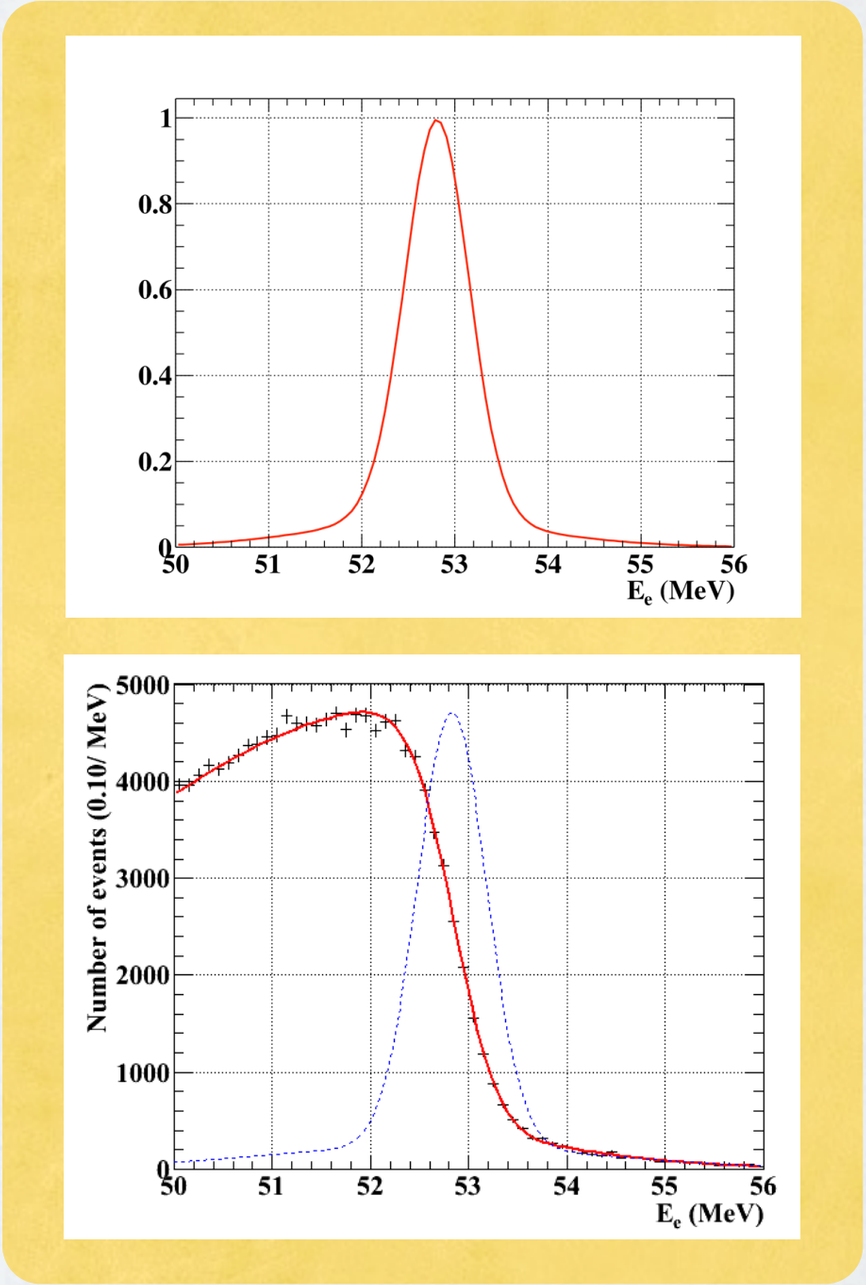
Gamma PDF

- Signal PDF
  - CEX π^0 data, 55MeV
- Background PDF
  - Sideband data



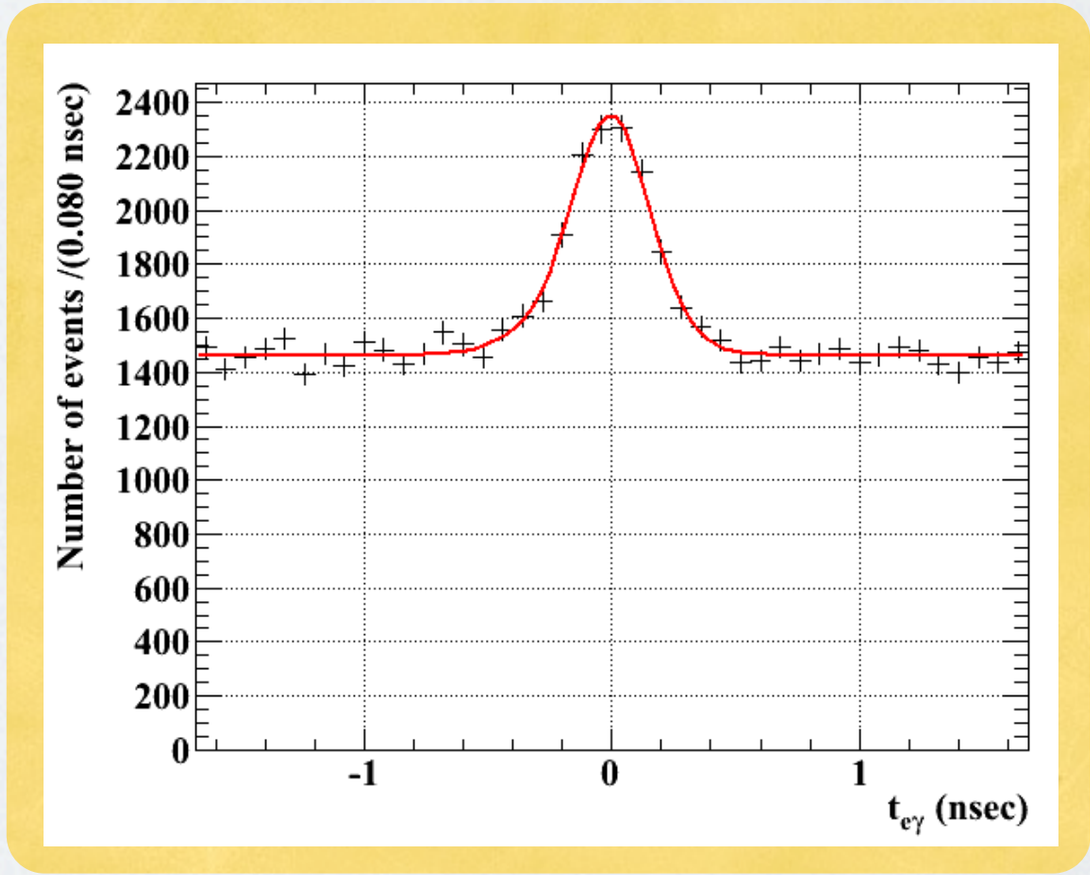
Positron PDF

- Signal PDF
  - Measured resolution
- Background PDF
  - Sideband data



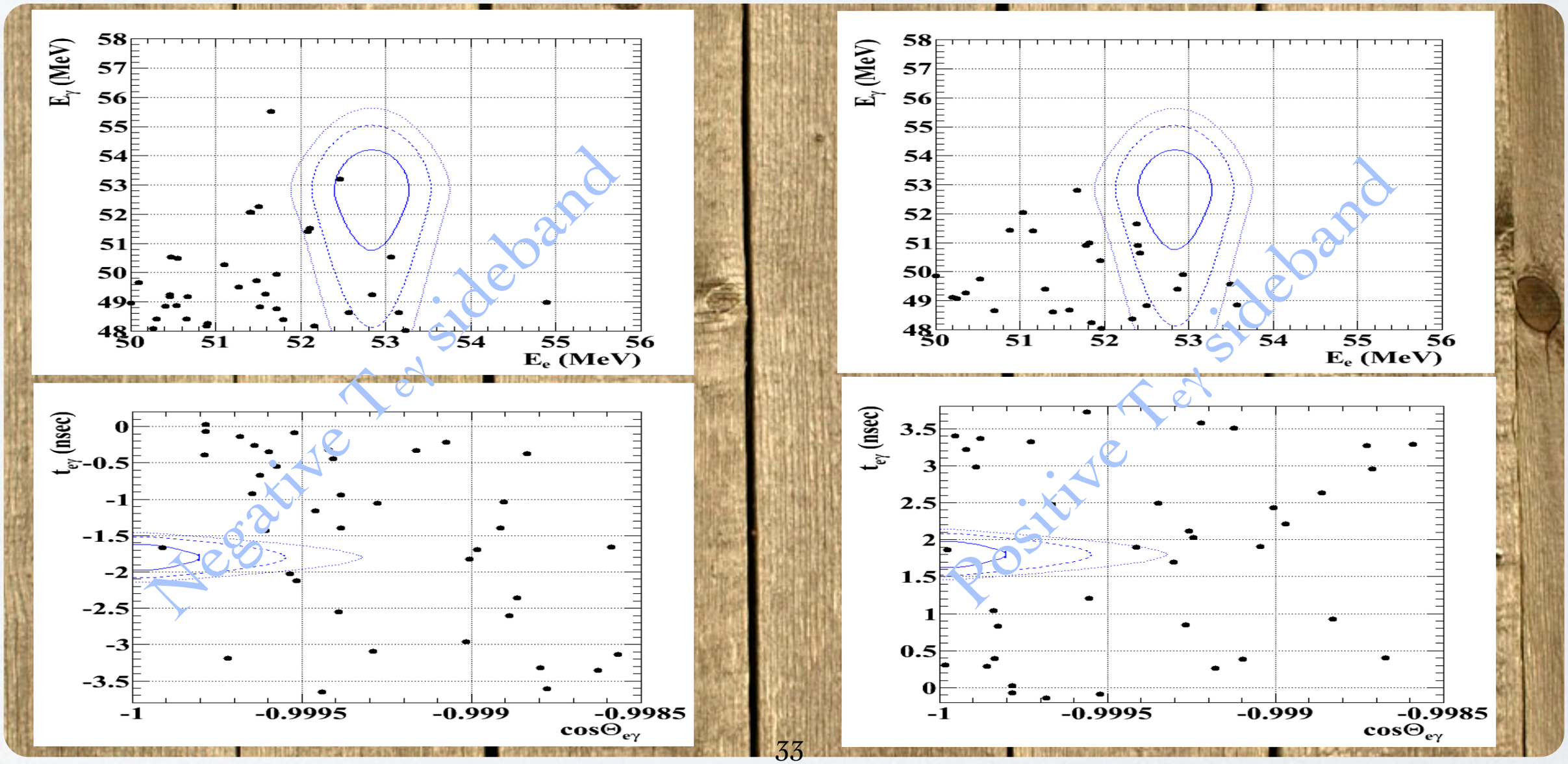
Relative Time/Angle PDFs

- Relative Time
  - Signal PDF from RMD
- Relative Angle
  - Signal PDF from measured resolutions
- Flat distributions as background PDFs



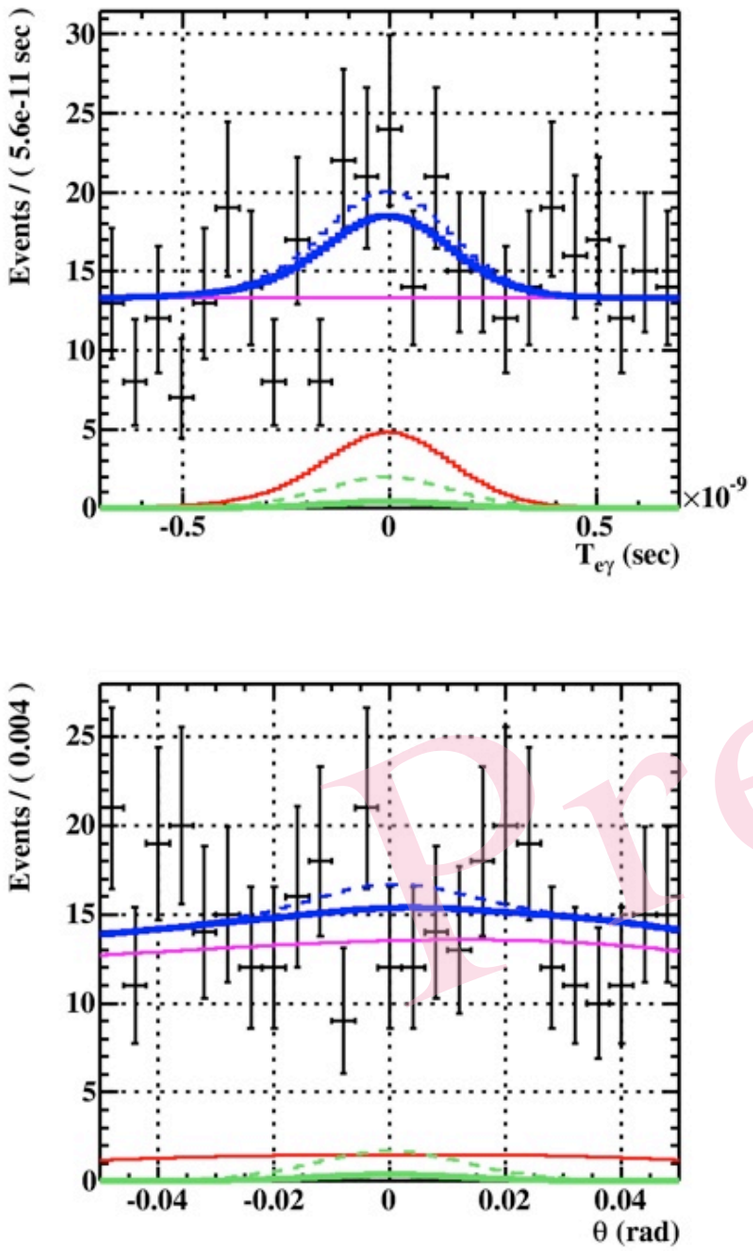
Sensitivity

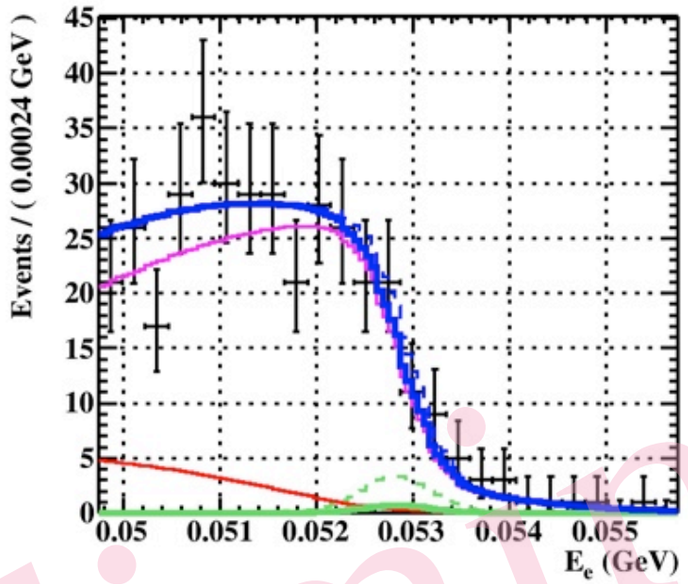
- Average 90% C.L. estimated with toy MC with null signal is **6.1×10^{-12}**
- Consistent with evaluation with sideband data fitting: ***4-6*×10^{-12}**

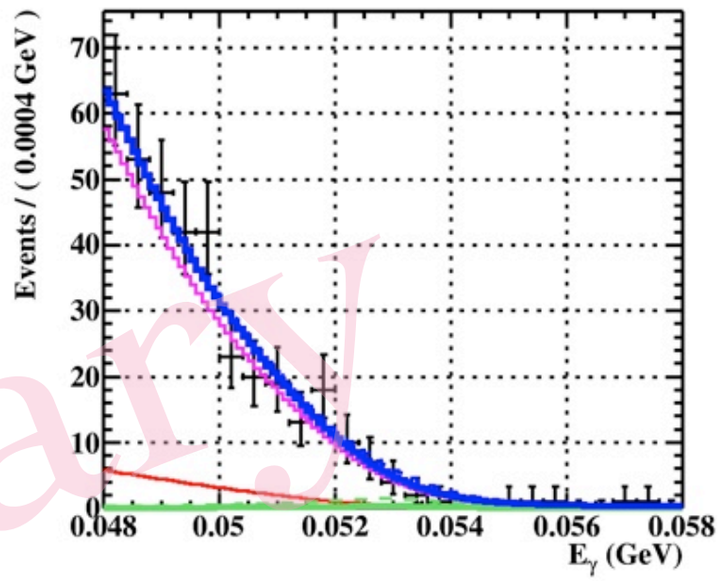


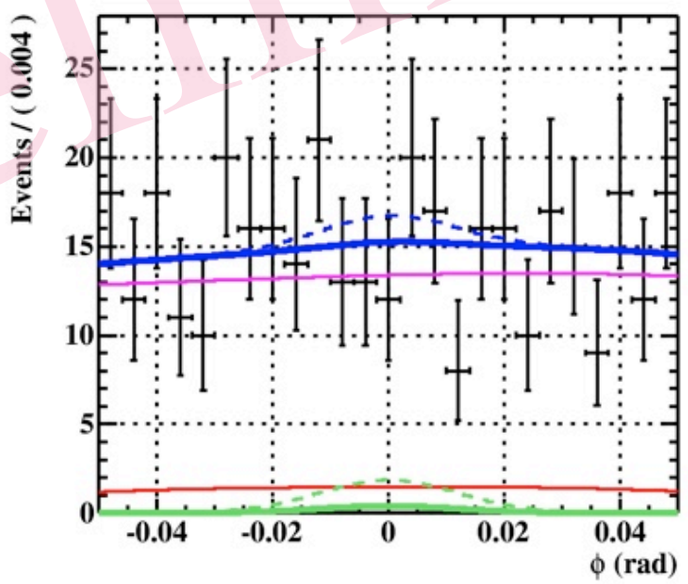
Unblinding

Likelihood Fit Result









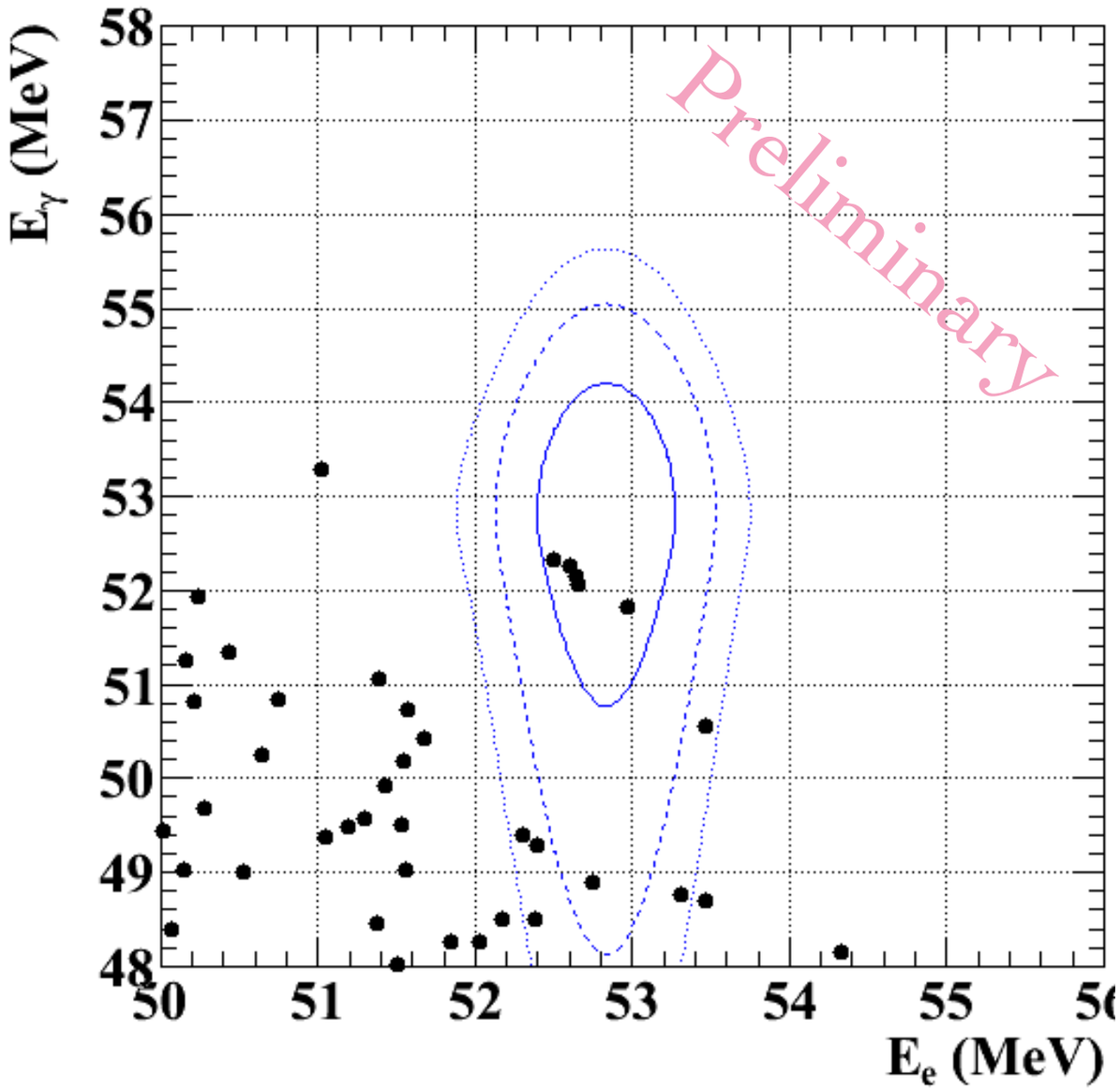
Accidental BG
RMD
Signal
Total
Dashed lines for 90% CL UL for N_{SIG}

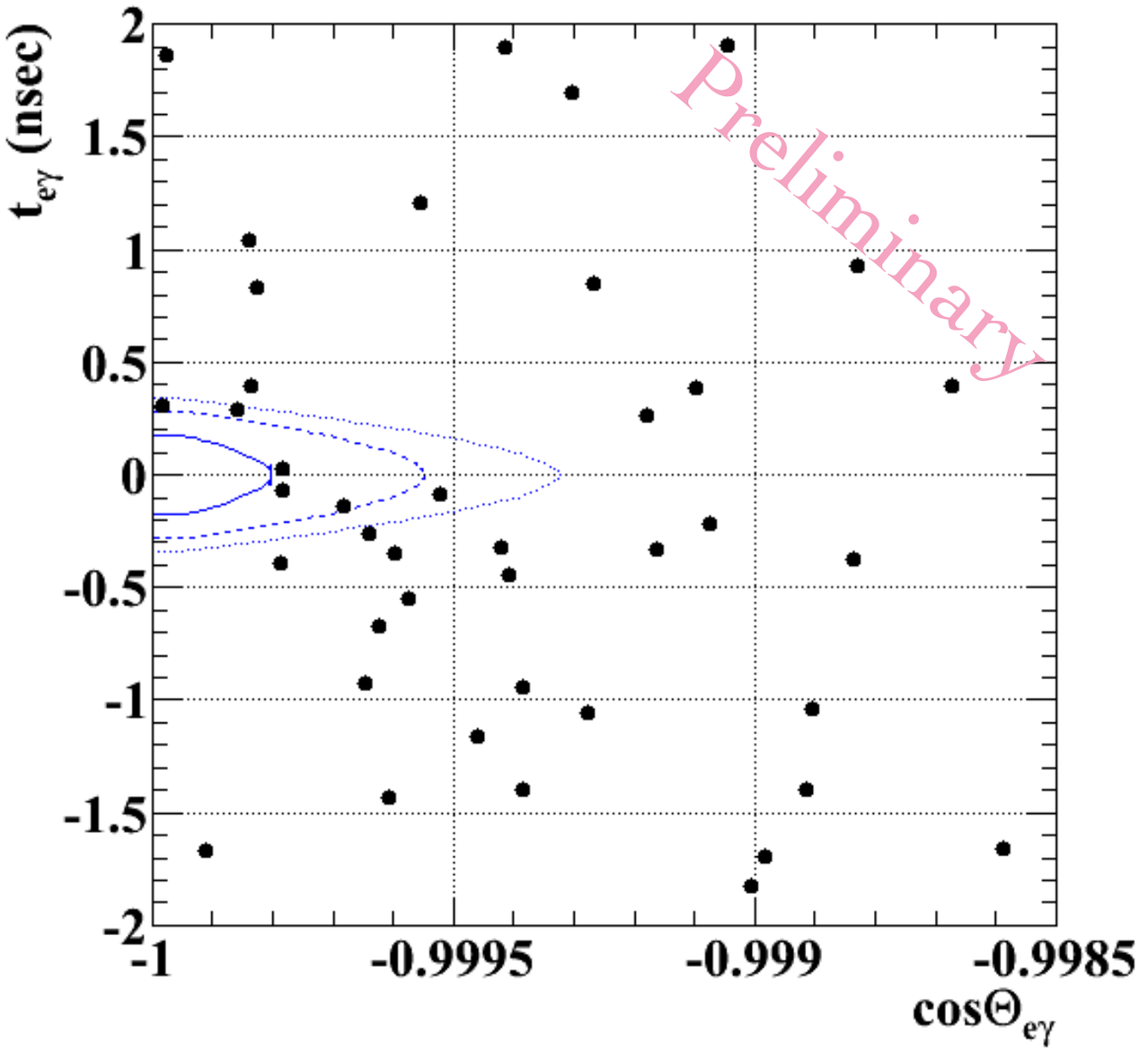
Summary of Likelihood Analysis

- **N_{SIG} limit = 14.5 @ 90% C.L.**
  - varies between 12 to 14.5 depending on the analysis
- N_{SIG}=0 in the 90% C.L. region
  - varies between 20% to 60% depending on the analysis

- N_{SIG} best fit = 3.0
  - varies between 3.0 to 4.5 depending on the analysis

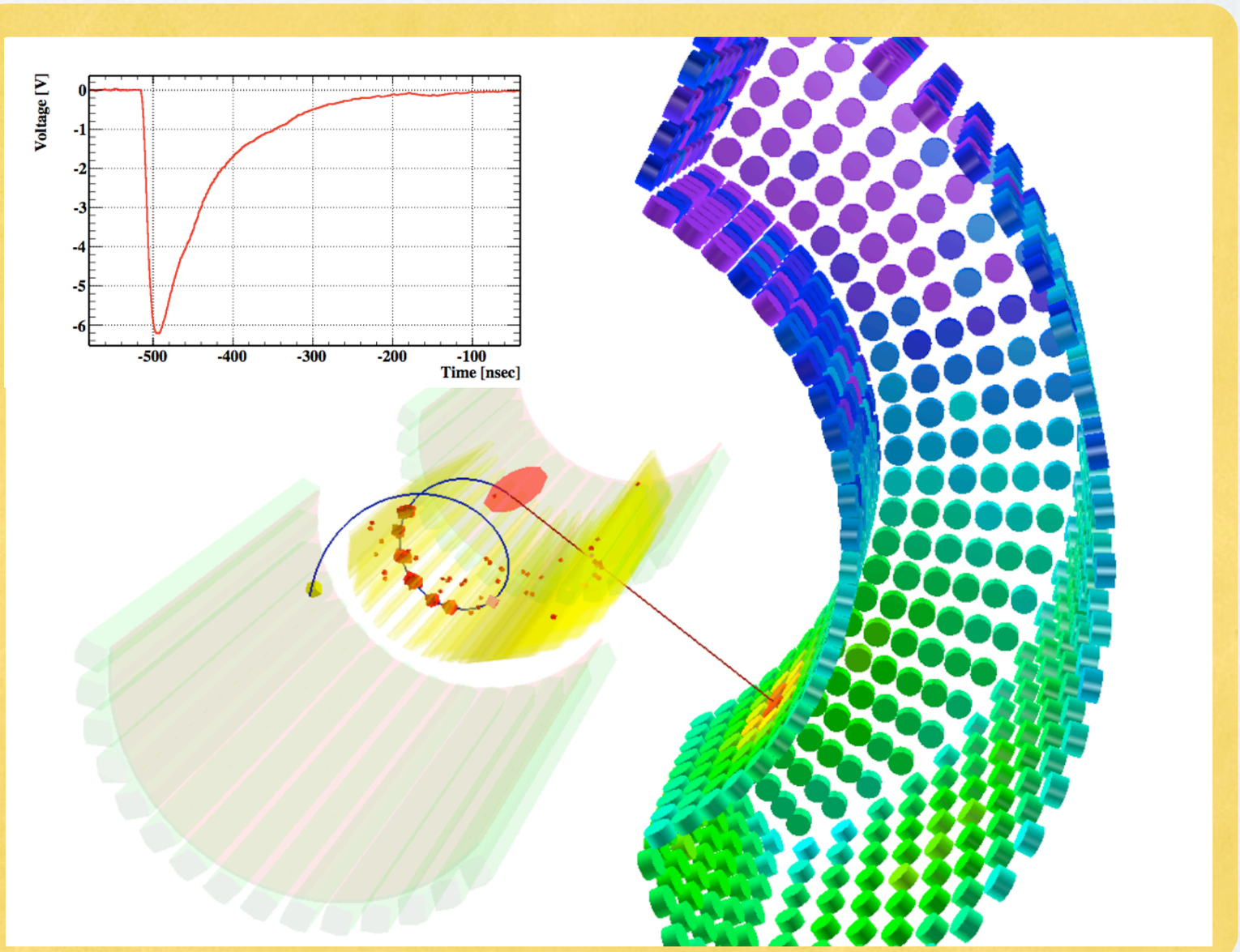
Event Distribution after unblinding

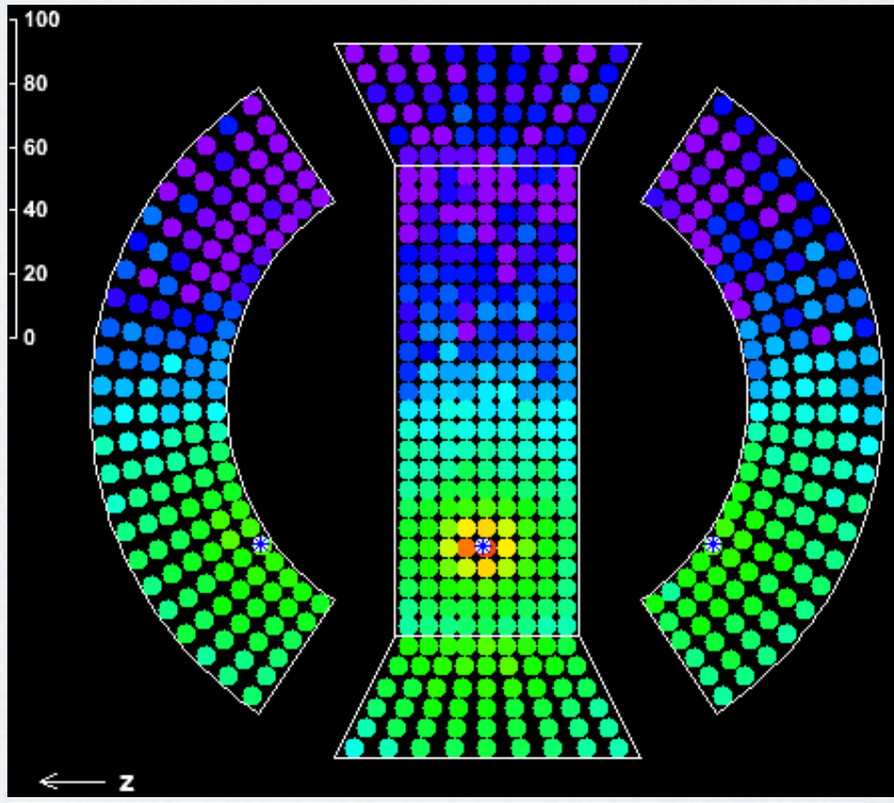


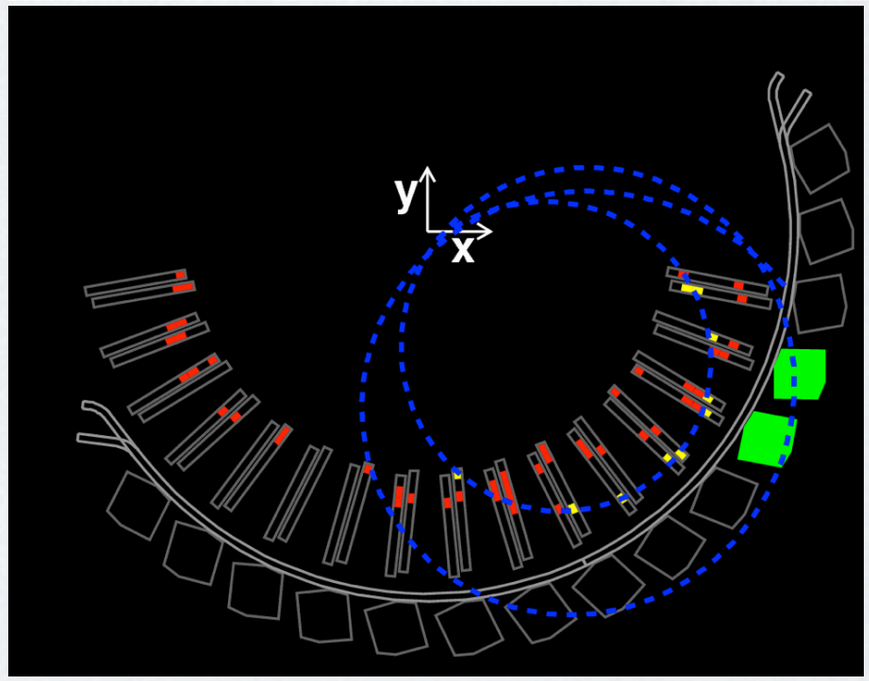


E_γ = 52.25 MeV
E_{e+} = 52.84 MeV
$\Delta\theta$ = 178.8 degrees
$\Delta T = 2.68 \times 10^{-11}$ s

Event Display

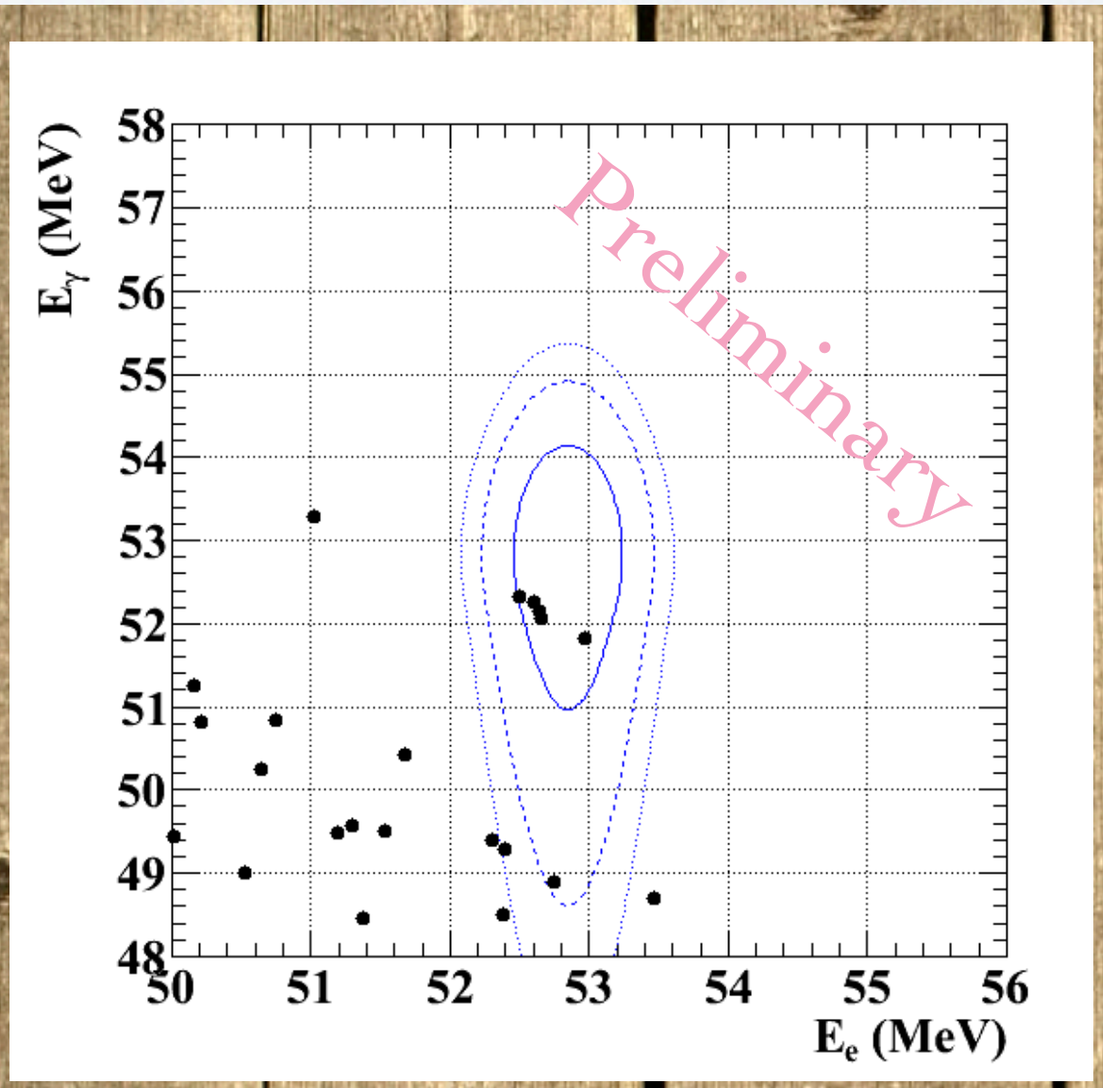


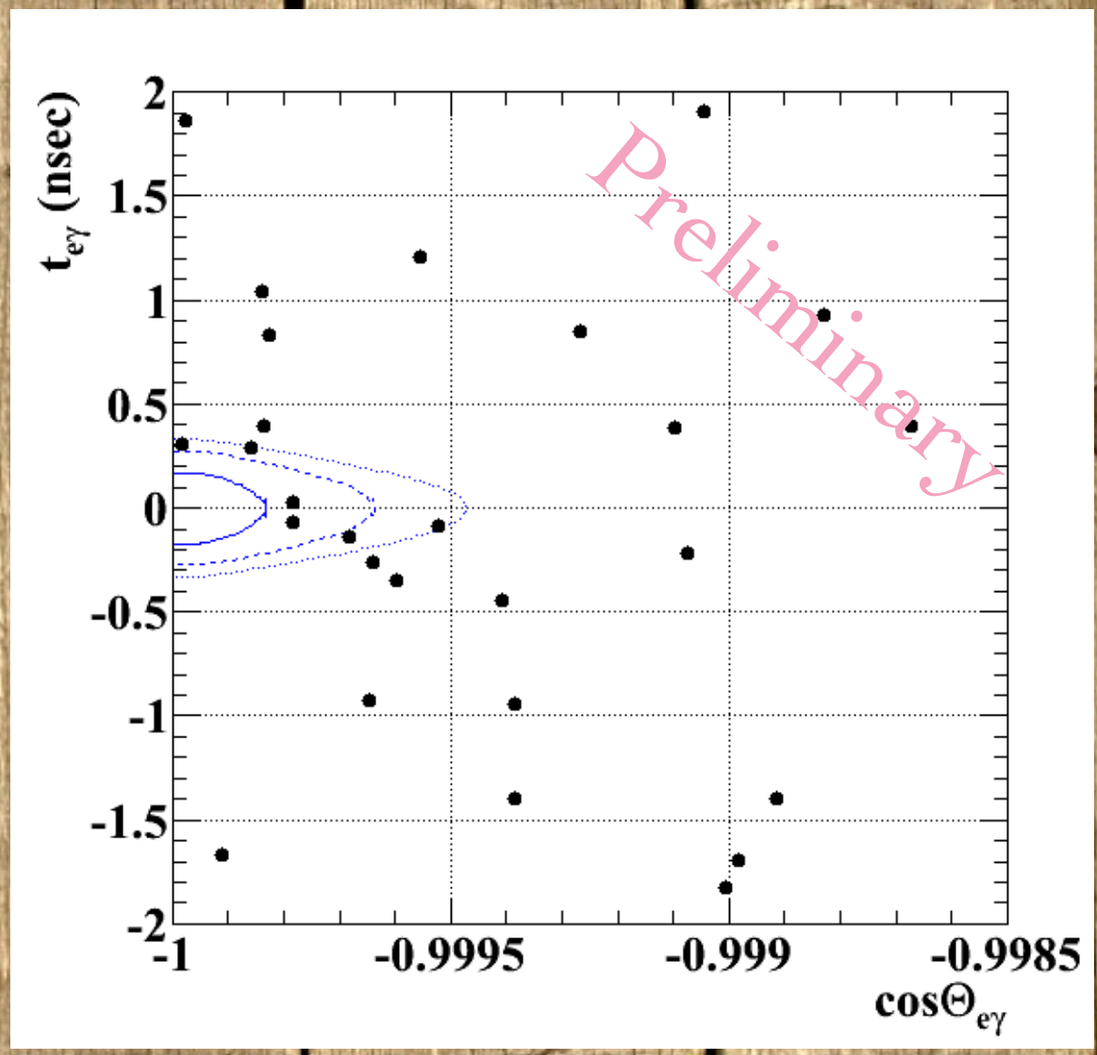




Further Check

- High quality e^+ track category events (59%)





Consideration

- Improved upper limit on Br($\mu \rightarrow e\,\gamma$)
  - 1.5×10^{-11} at 90% C.L. (previous result 2.8×10^{-11})
    - Toy MC/Sideband C.L. evaluation, *4*-6×10^{-12}
    - cf. MEGA limit 1.2×10^{-11}

- Events around the signal region do not disappear by selecting high quality tracks

Prospects

- Expected Detector/Analysis improvement
  - Improve of synchronization of DRS4 provides better $\sigma_{e\gamma}$
  - Noise reduction and electronics modification of DC
  - Better calibration with monochromatic positron Mott scattering
  - Refinement of LXe analysis

	2010 Preliminary
Gamma Energy (%)	1.5 (w>2cm)
Gamma Timing (psec)	67
Gamma Position (mm)	5(u,v)/6(w)
Gamma Efficiency (%)	58
e^+ Timing (psec)	90
e^+ Momentum (%)	0.7
e^+ Efficiency (%)	40%
e^+ Angle (mrad)	8(ϕ)/8(θ)
e^+-gamma Timing (psec)	120
Muon Decay Point (mm)	1.4(R)/2.5(Z)
Trigger Efficiency (%)	94
Stopping Muon Rate (Hz)	3×10^7
DAQ Time / Real Time (days)	95/117
Sensitivity	1.8×10^{-12}

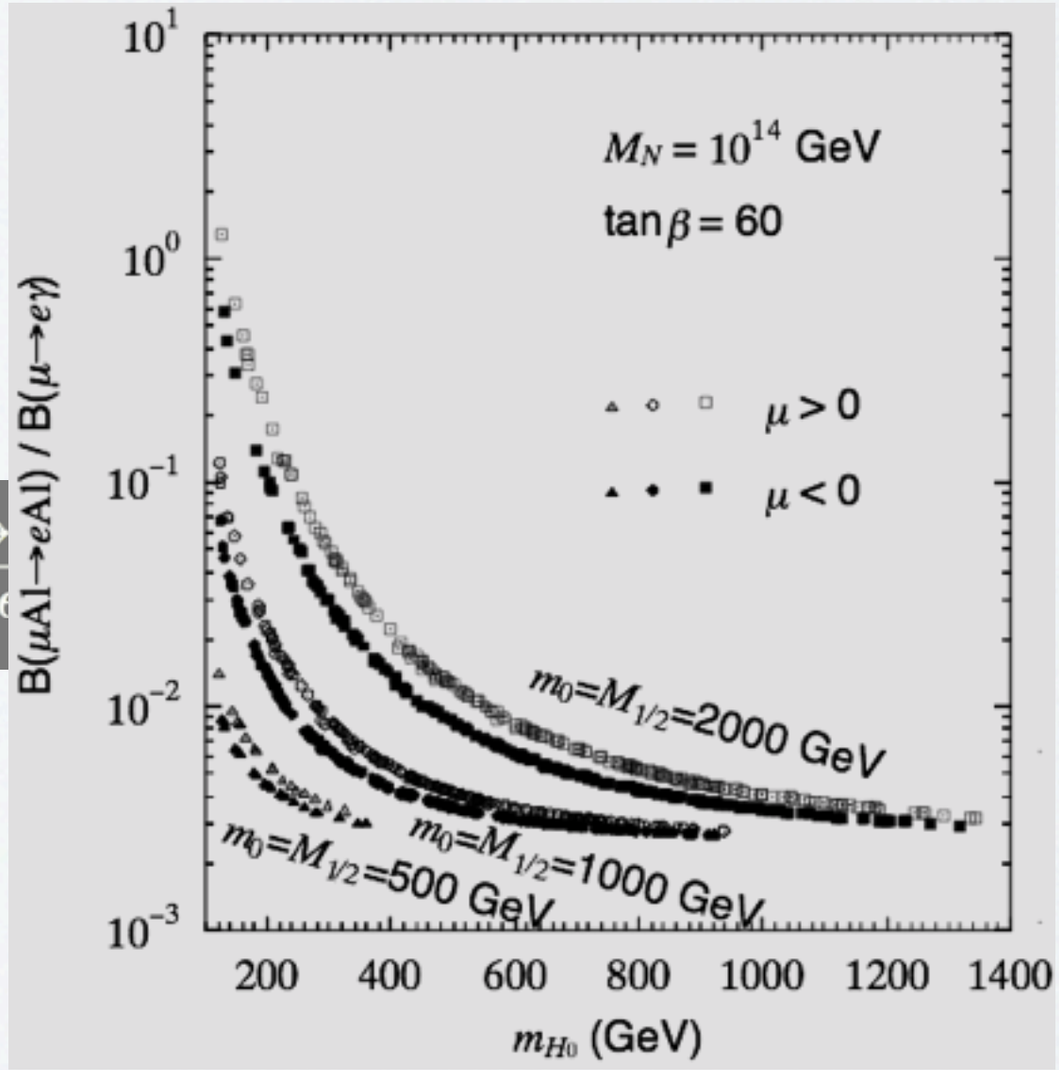
DAQ Prospects

- 2010 DAQ restarted at the end of July
- 3 years DAQ until the end of 2012
- Final goal sensitivity ~ a few×10^{-13}

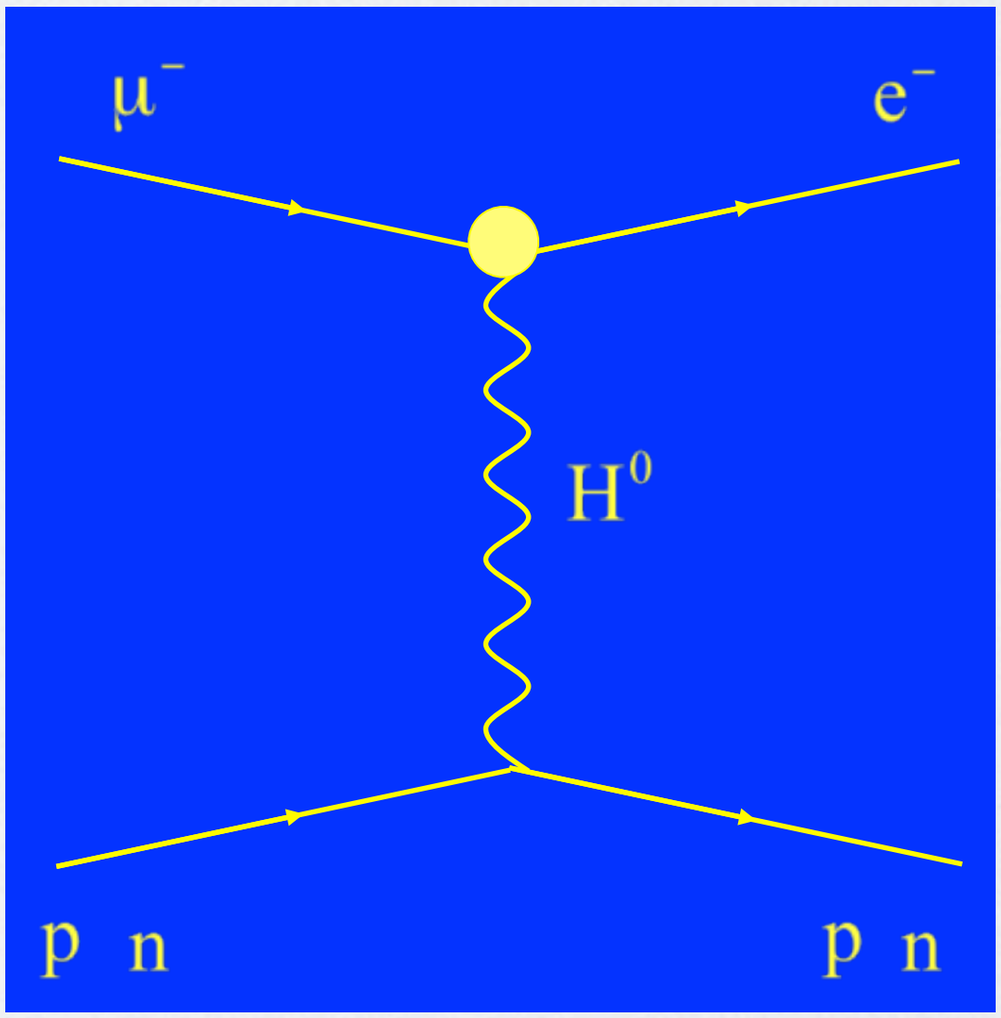
What should we do after MEG?

Short introduction to mu-e conversion search experiments at J-PARC

μ→eγ and μ-e conversion



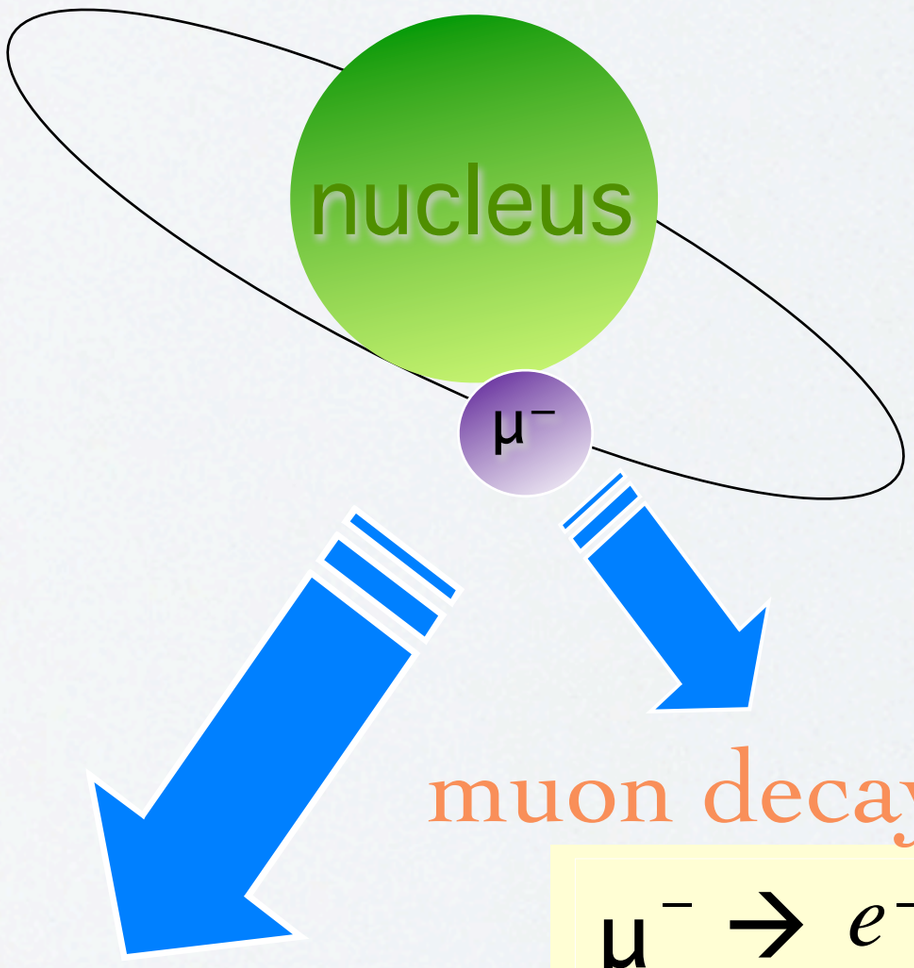
$$\frac{B(\mu N \to \quad)}{B(\mu \to e}$$



- If μ→eγ exits, μ-e conv. must be
- Even if μ→eγ is not observed, μ-e conv may be
  - Loop vs Tree
  - Searches at LHC

What is a μ-e Conversion ?

1s state in a muonic atom



Neutrino-less muon nuclear capture (=μ-e conversion)

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

lepton flavors changes by one unit

muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

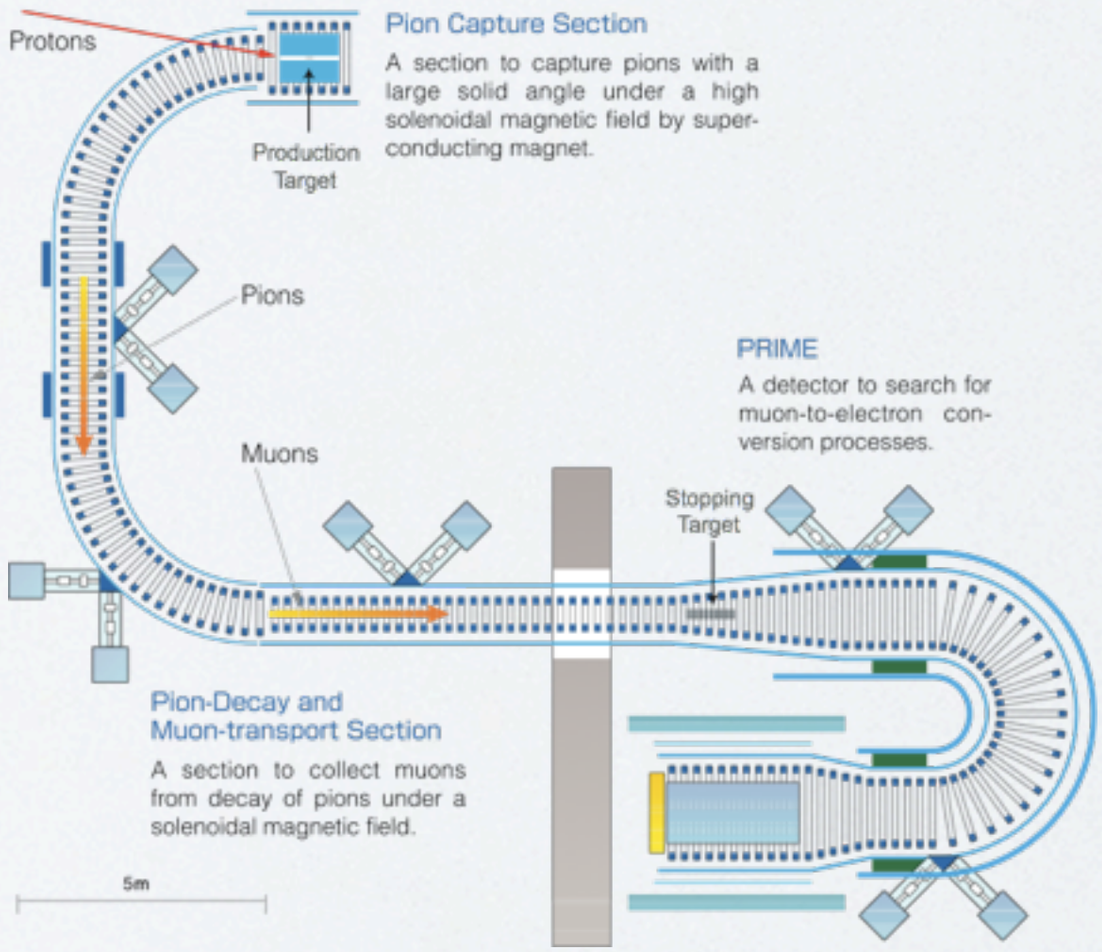
nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

mu-e conversion search experiment at J-PARC

COMET 10^{-16} for 2 years running

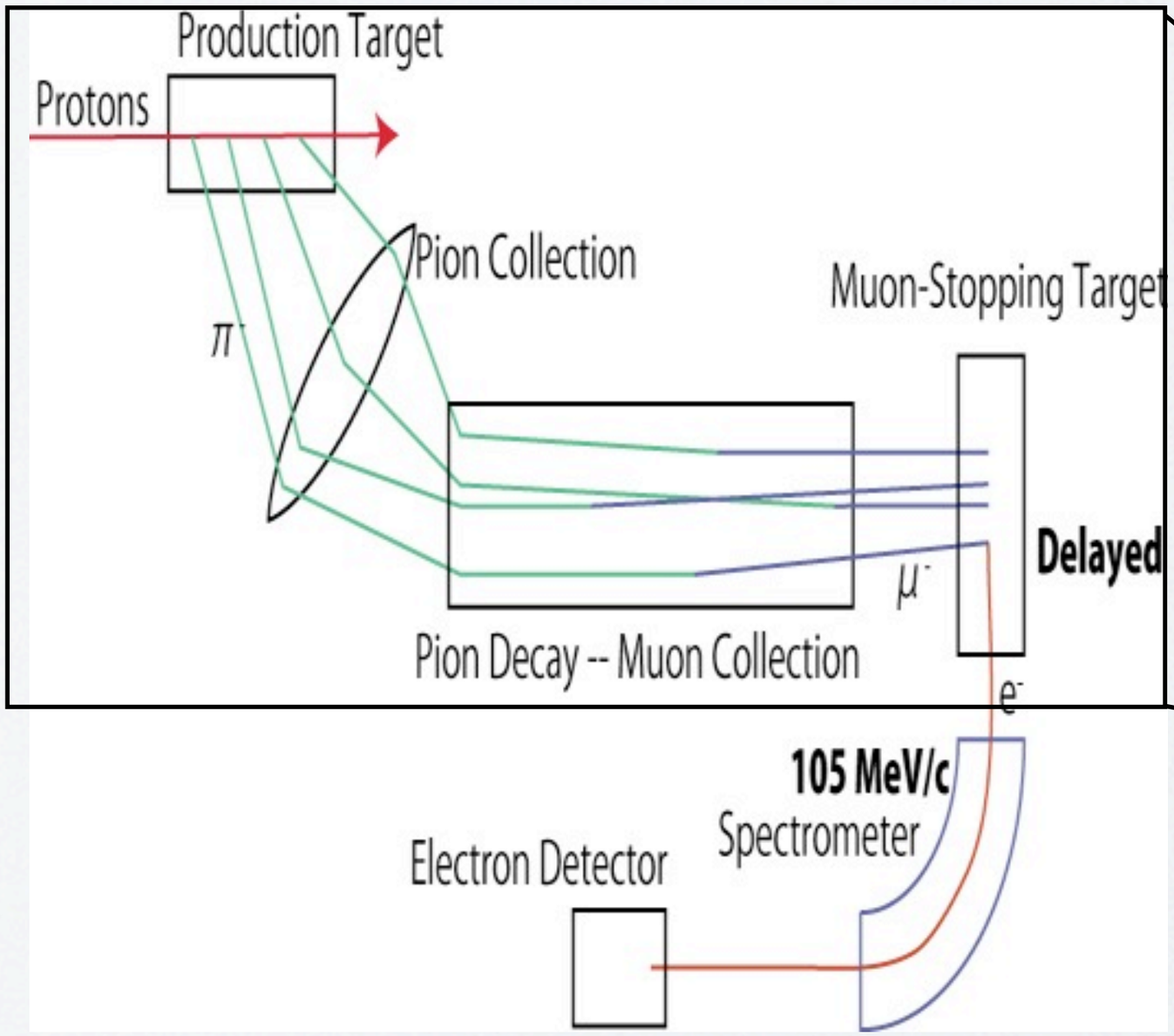


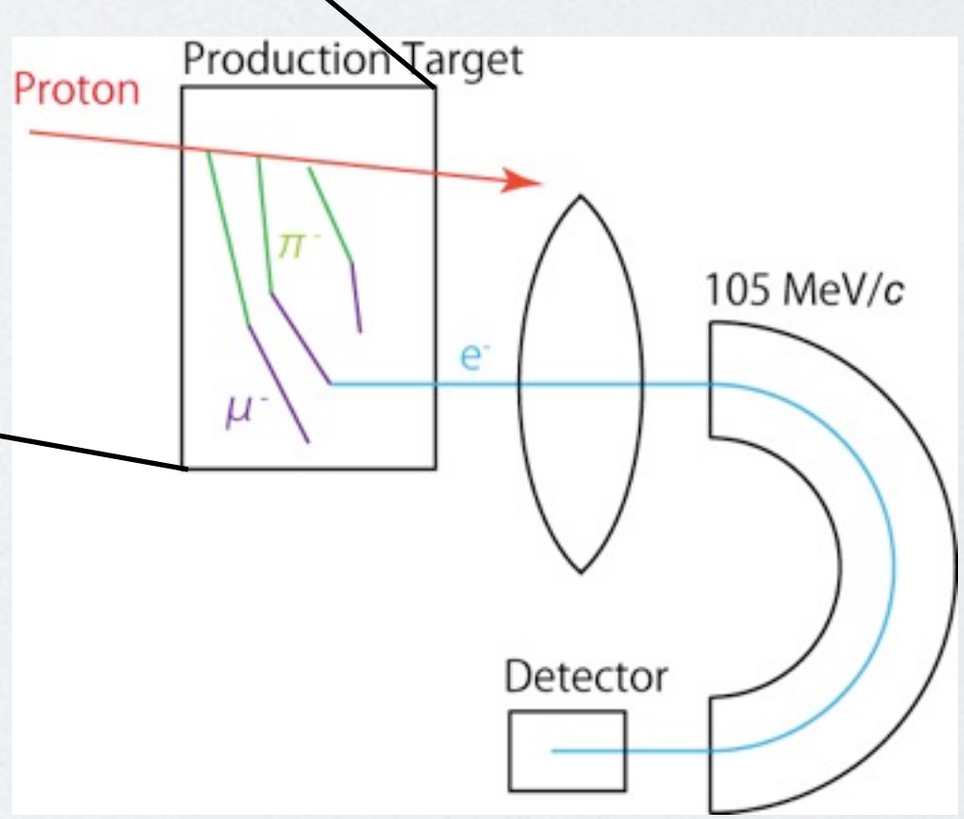
- **Proton Beam**
  - **p→π→μ**
- **The Muon Source**
  - **Proton Target**
  - **Pion Capture**
  - **Muon Transport**
- **The Detector**
  - **Muon Stopping Target**
  - **Electron Transport**
  - **Electron Detection**

Mu2e, competing experiment at FNAL

μ-e electrons may directly coming from a production target

→ DeeMe





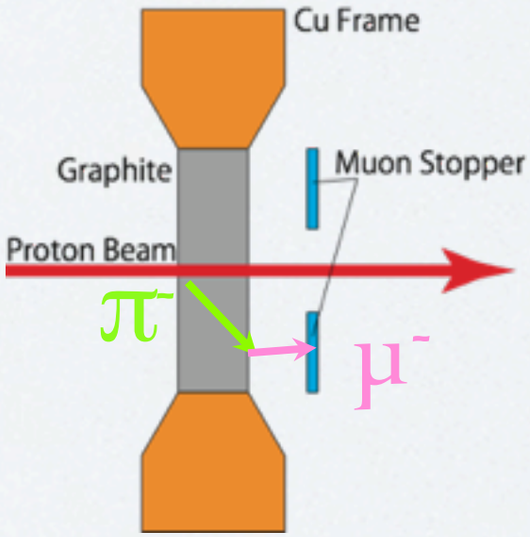
- An electron analogue of the surface muon.
- Experiment could be very simple, quick and low-cost.

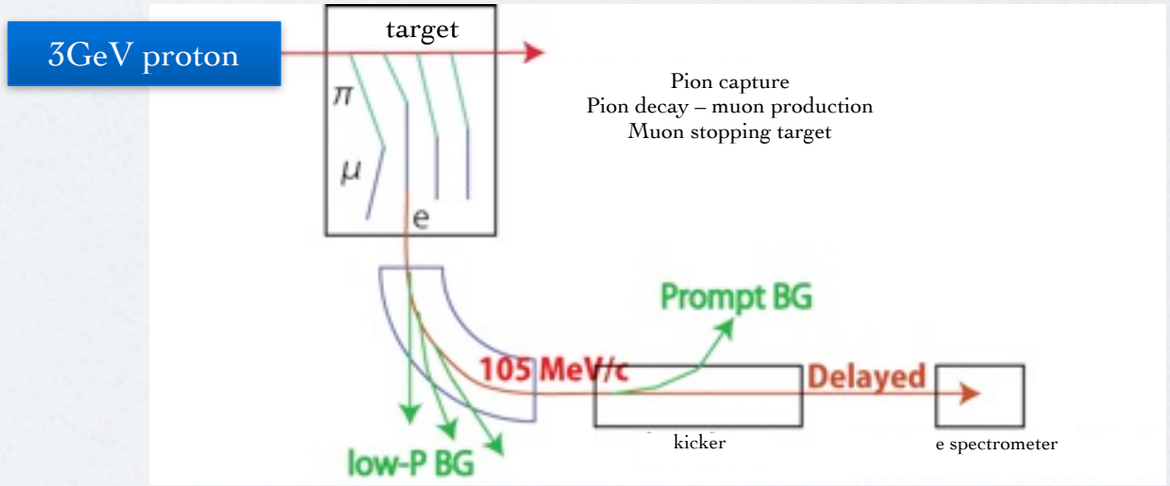
DeeMe

Another m-e conversion search at J-PARC

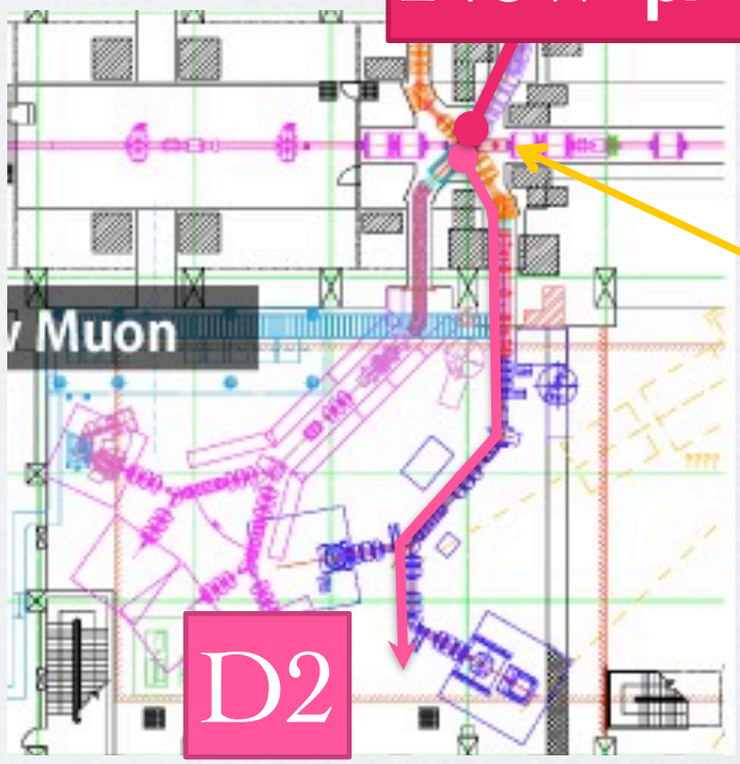
- Mu-e conversion electron directly comes from the target?
- 10^{10} muon stops/sec/MW
- Transport 105MeV/c delayed electrons
- Expected reach (crude)
  - D2 beam line (40msr)
    - 8×10^{-13} for C (10^7 sec)
    - 2×10^{-13} for Al (10^7 sec)
  - New beam line (150msr)
    - 10^{-14} for Al (2×10^7 sec)
  - cf SINDRUM II limit: 7×10^{-13}

Capture rate
0.08 → 0.60
(C) (Al)





New μ beam line



Graphite target with water cooling

Summary

- MEG is not at the edge of a cliff yet!
  - 2 months DAQ in 2009 with stable detector operation
  - Preliminary result from 2009 data
    - Sensitivity : 6.1×10^{-12}
    - 90% C.L. upper limit:1.5×10^{-11}
    - $N_{SIG}=0$ is in the 90% C.L. region
  - 3 years DAQ until the end of 2012
- Two new experiments searching for mu-e conversion at J-PARC to confirm MEG result
  - COMET and DeeMe

Event Distribution after unblinding