MEG: Status of $\mu \to e\gamma$ Search

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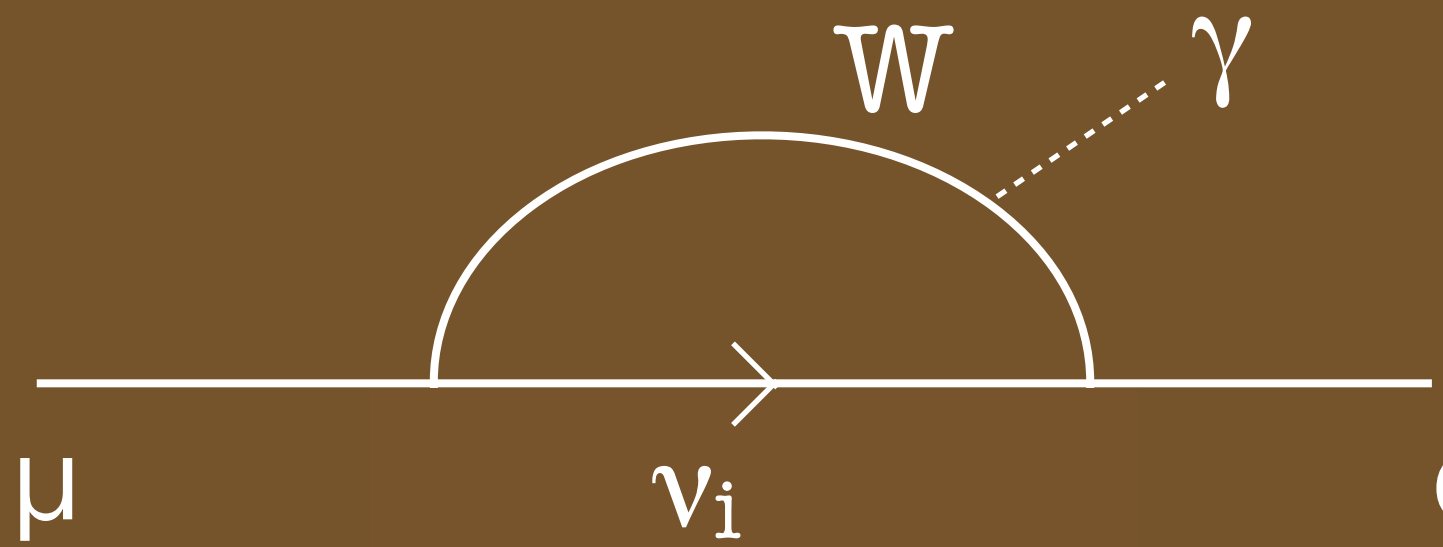
Why search for $\mu \rightarrow e\gamma$?

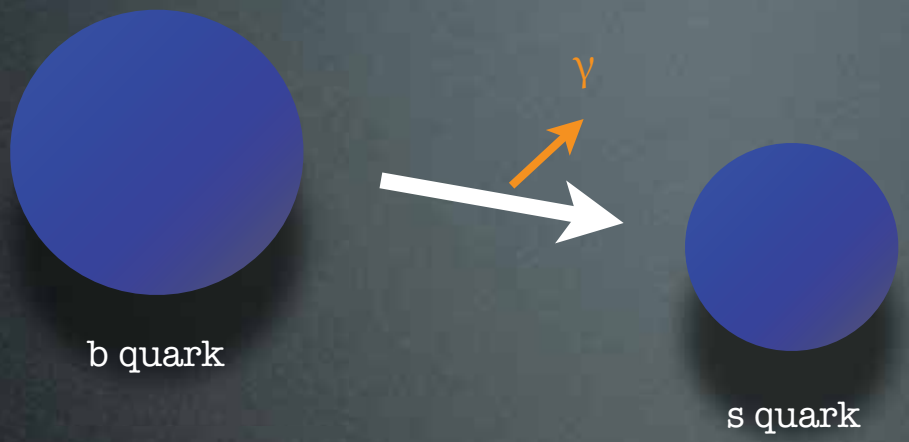
Neutrinos mix, so Charged leptons must also mix !

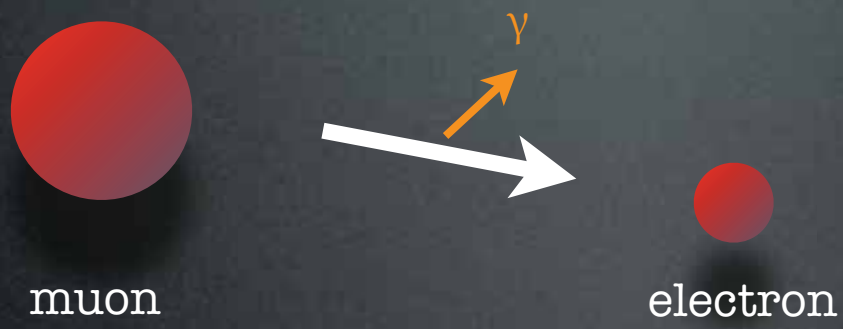


$$\frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}\left(\frac{m^2_{\nu_i}}{M^2_W}\right)U_{ei}\right|^2 \leq 10^{-45}$$

practically no mixing

Flavors are Violated!



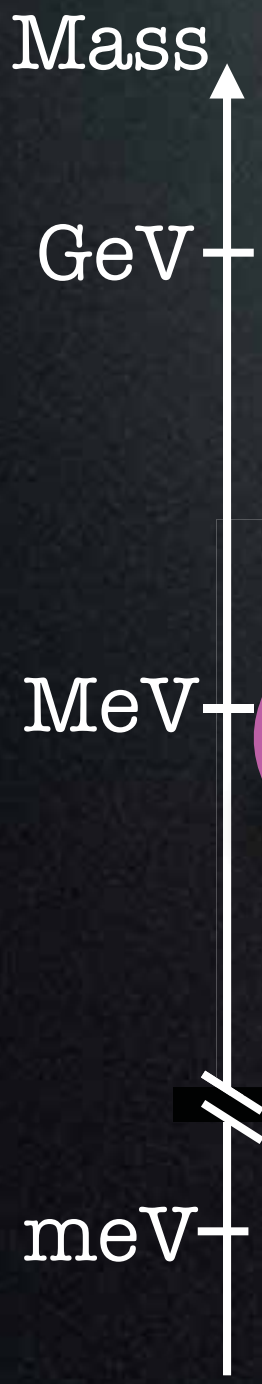


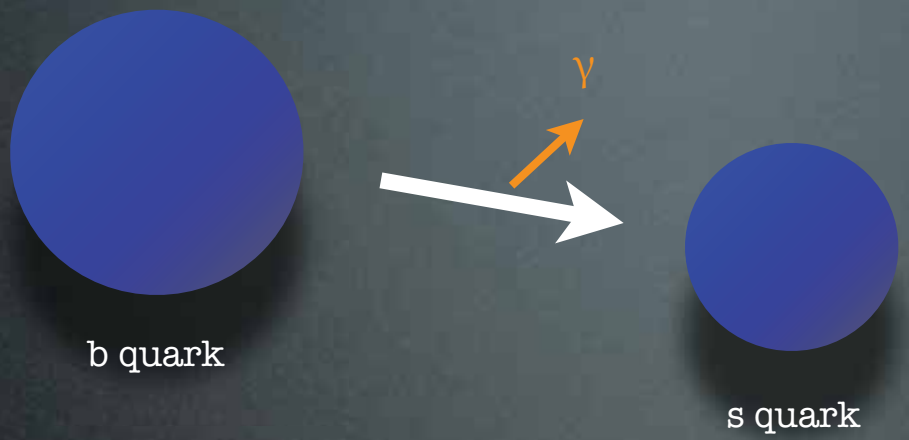
Standard Model
CKM matrix
verified at B factories

definite proof of "Beyond SM"

a possible hint of new physics
(seesaw mechanism?)

Flavors are Violated!





Standard Model
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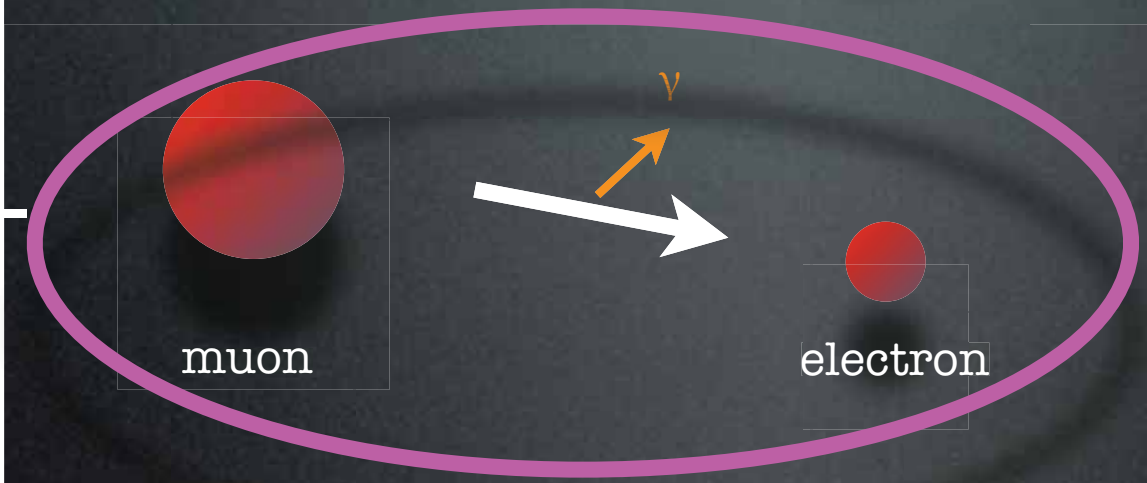
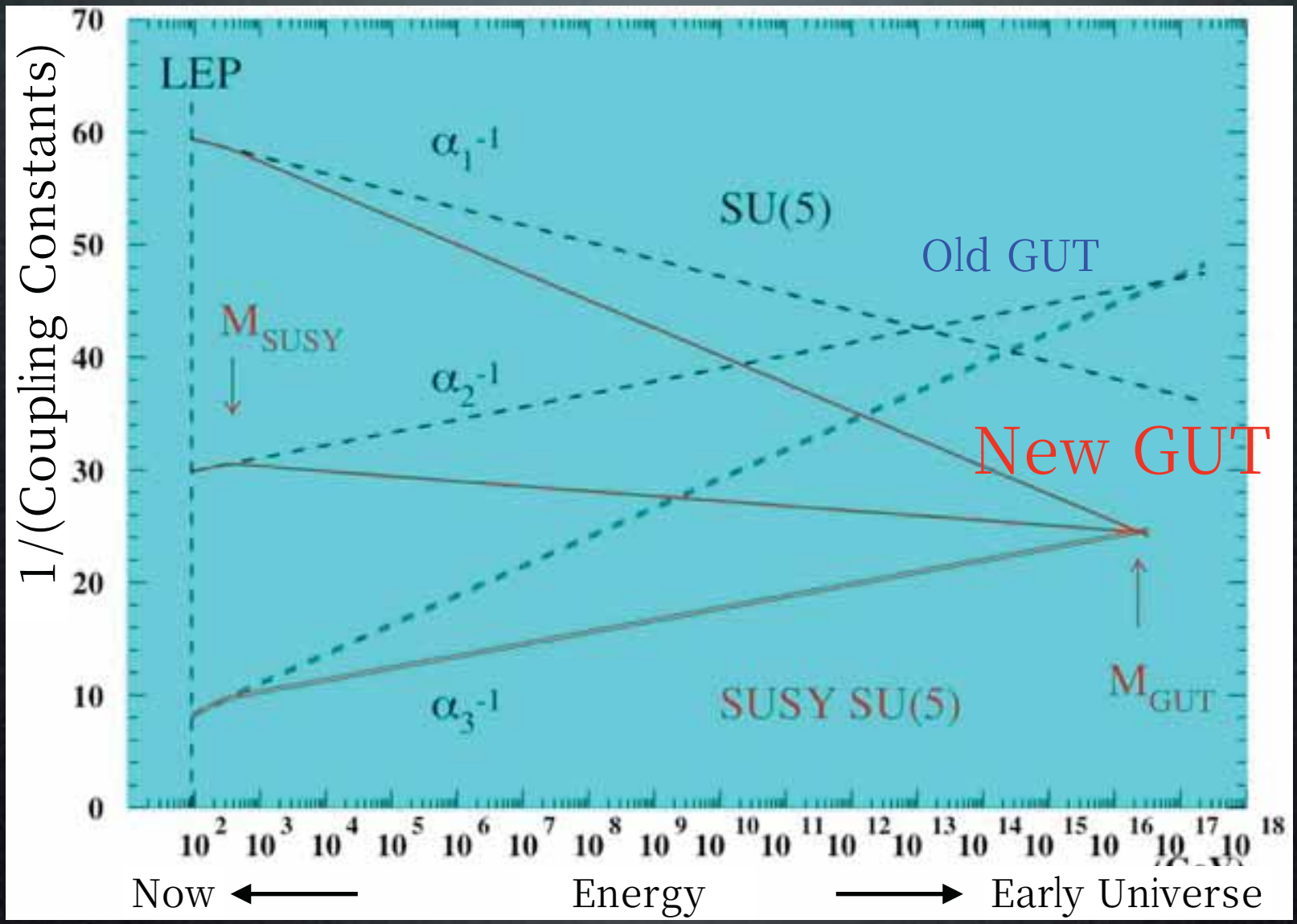


μ → e γ

definite proof of "Beyond SM"

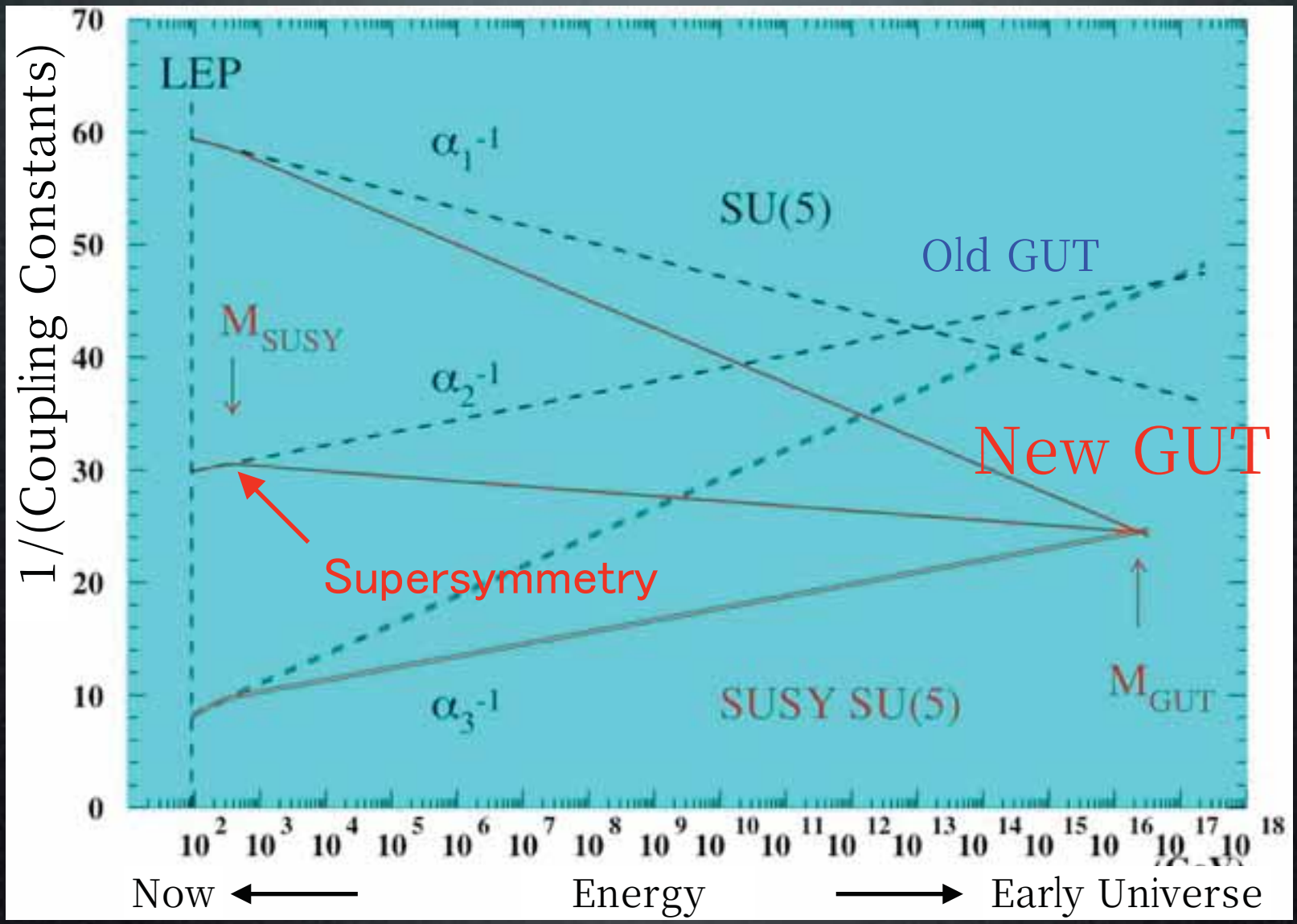
a possible hint of new physics
(seesaw mechanism?)

New GUTs Revived by LEP



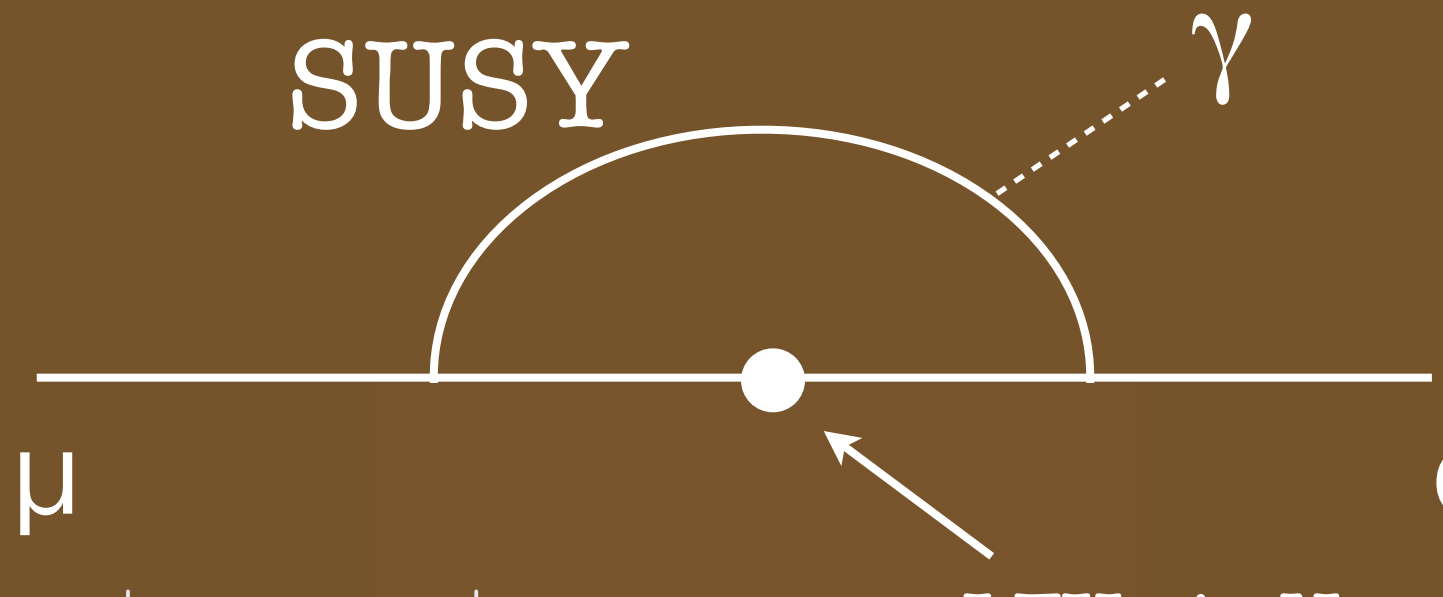
The key is a new symmetry called "supersymmetry" (SUSY)

New GUTs Revived by LEP



The key is a new symmetry called "supersymmetry" (SUSY)

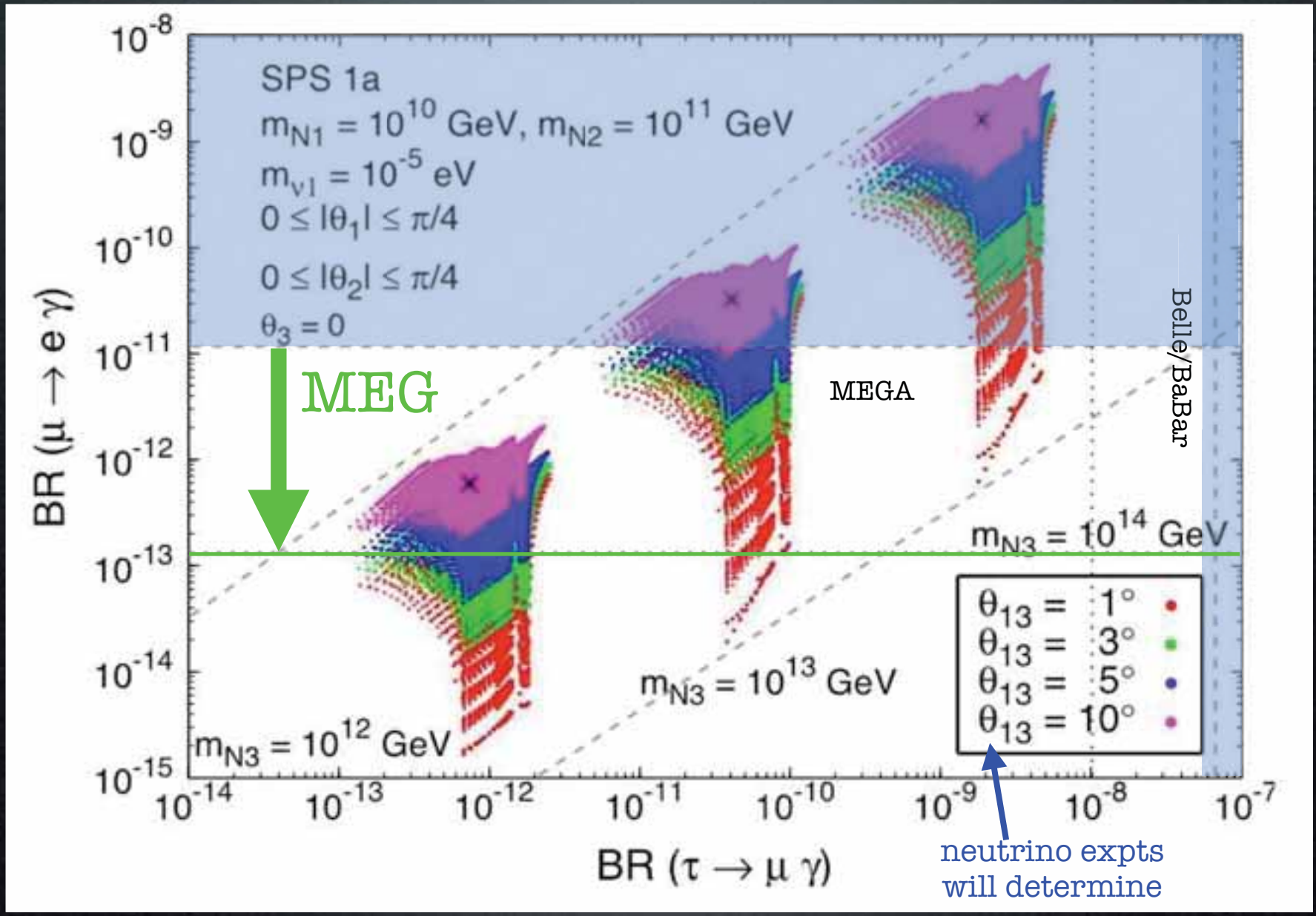
SUSY seesaw & GUT help them mix !



$$\left| \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{M^2_{SUSY}} \right| \rightarrow \sim 10^{-12}$$

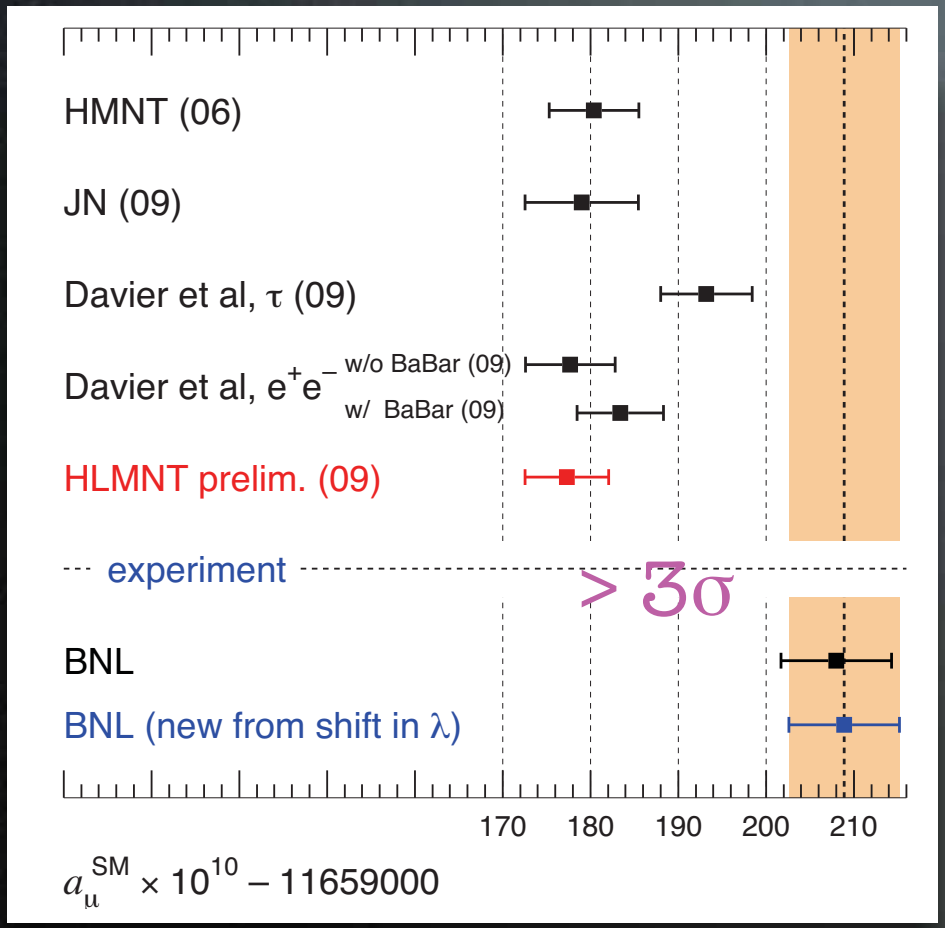
Perhaps you can observe!

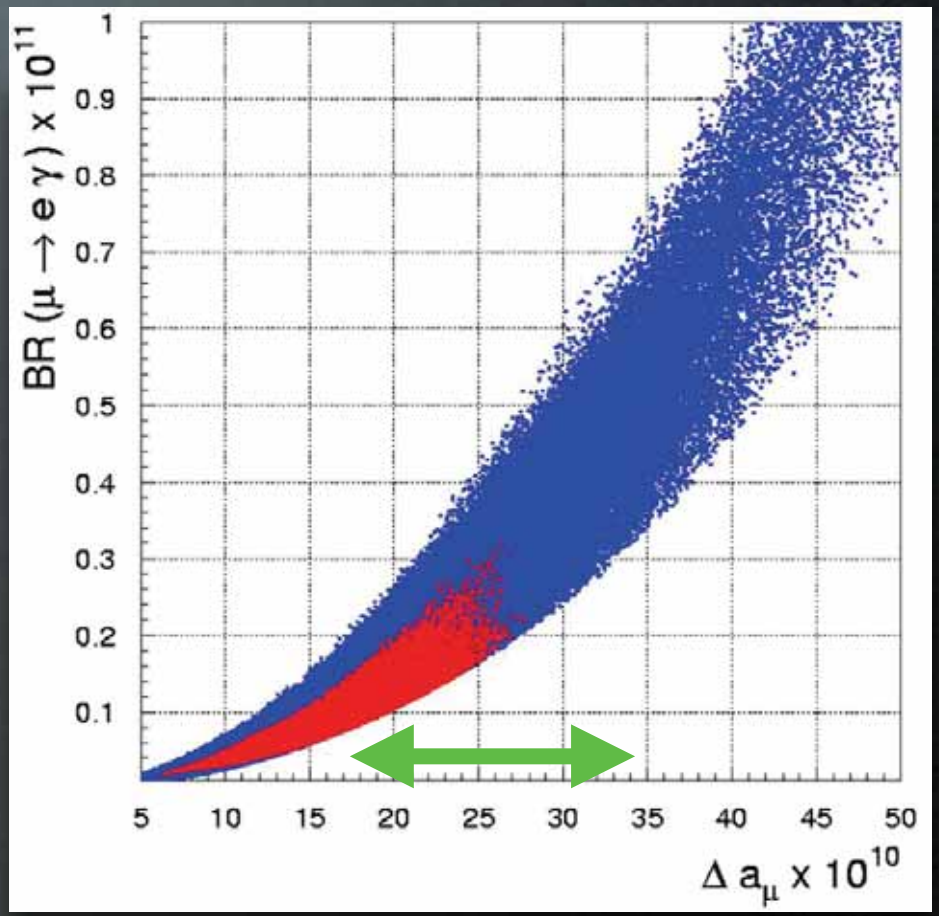
SUSY GUT & Seesaw Prediction



S.Antusch et al, JHEP11 (2006) 090

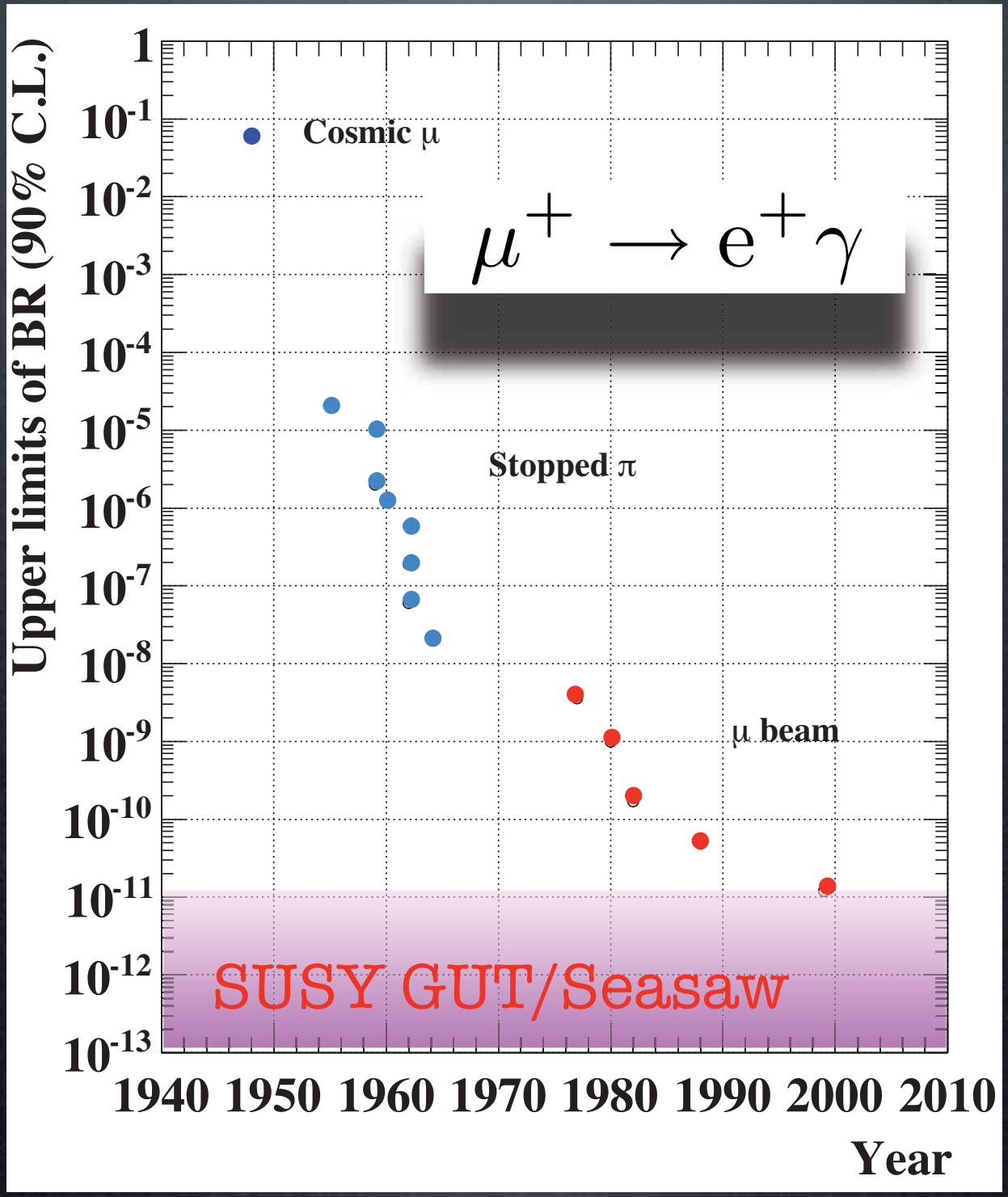
muon (g-2) anomaly

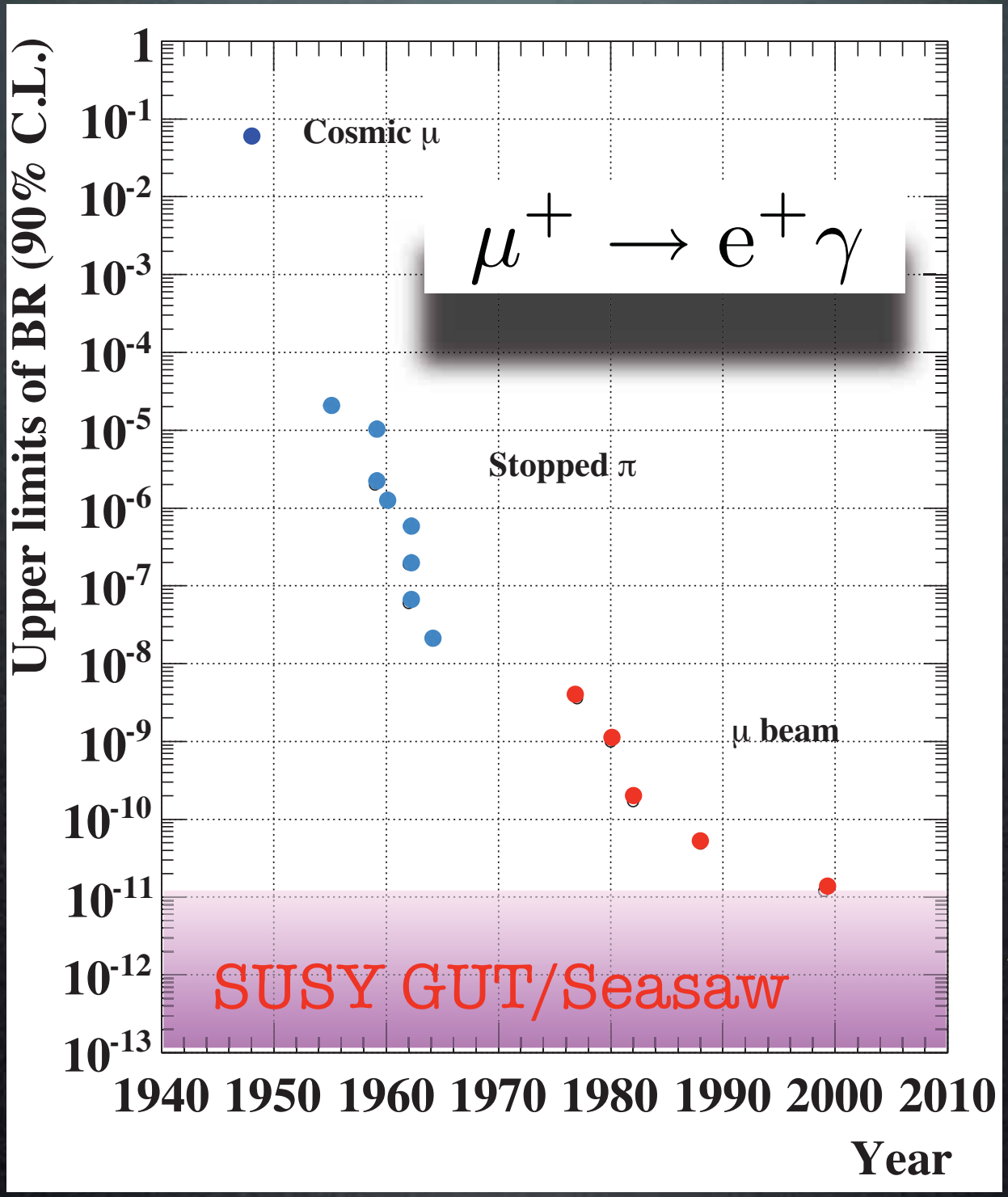




G.Isidori et al. PRD75, 115019

muon's anomalous magnetic moment


Upper limits of BR (90% C.L.)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
Cosmic μ
$\mu^+ \rightarrow e^+\gamma$
Stopped π
μ beam
SUSY GUT/Seasaw
1940 1950 1960 1970 1980 1990 2000 2010
Year


Upper limits of BR (90% C.L.)
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
Cosmic μ
μ+ → e+γ
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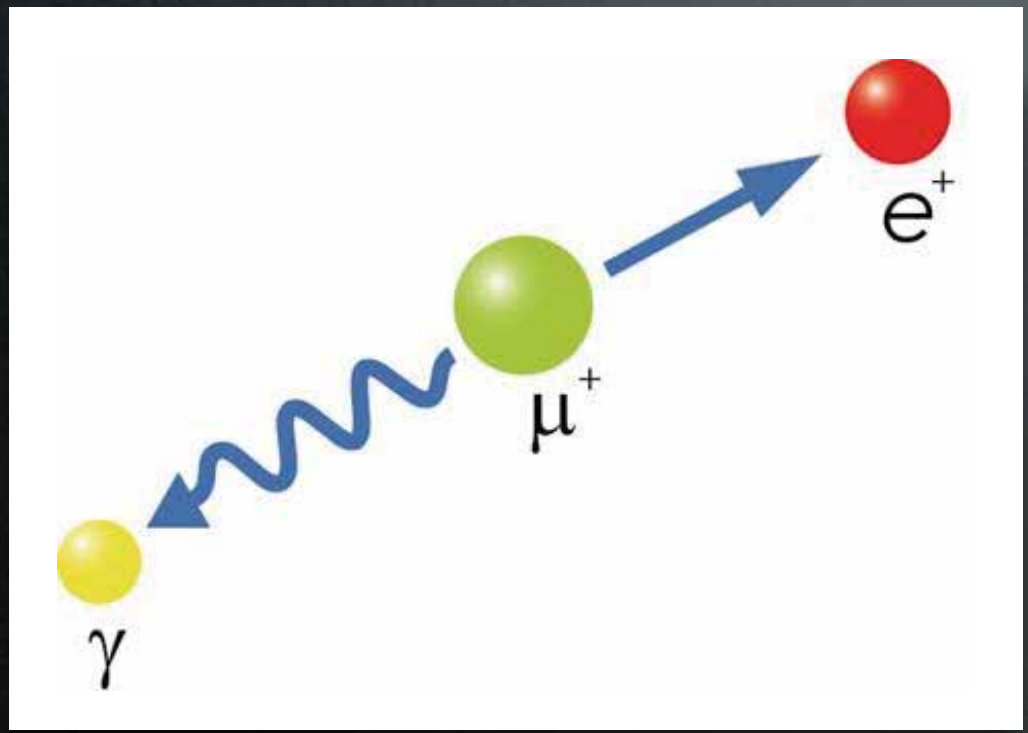
SUSY GUT/Seasaw
MEG
1940 1950 1960 1970 1980 1990 2000 2010
Year

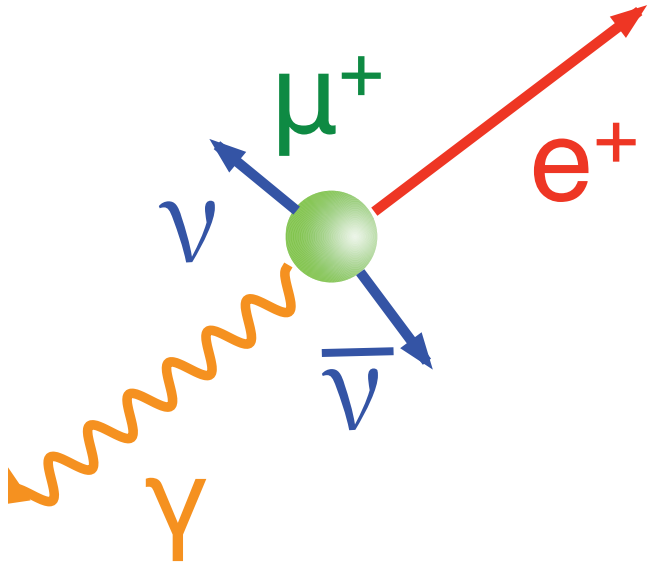
The $\mu^+ \to e^+\gamma$ process



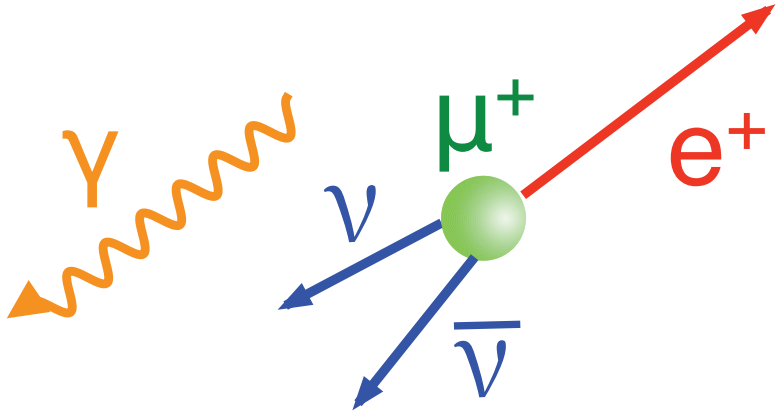
- clear 2-body kinematics
- need positive muons to avoid formation of muonic atoms
- accidental background limits the experiment
  - DC beam, rather than pulsed beam, gives lowest instantaneous rate and thus lowest background

Background

Prompt Background

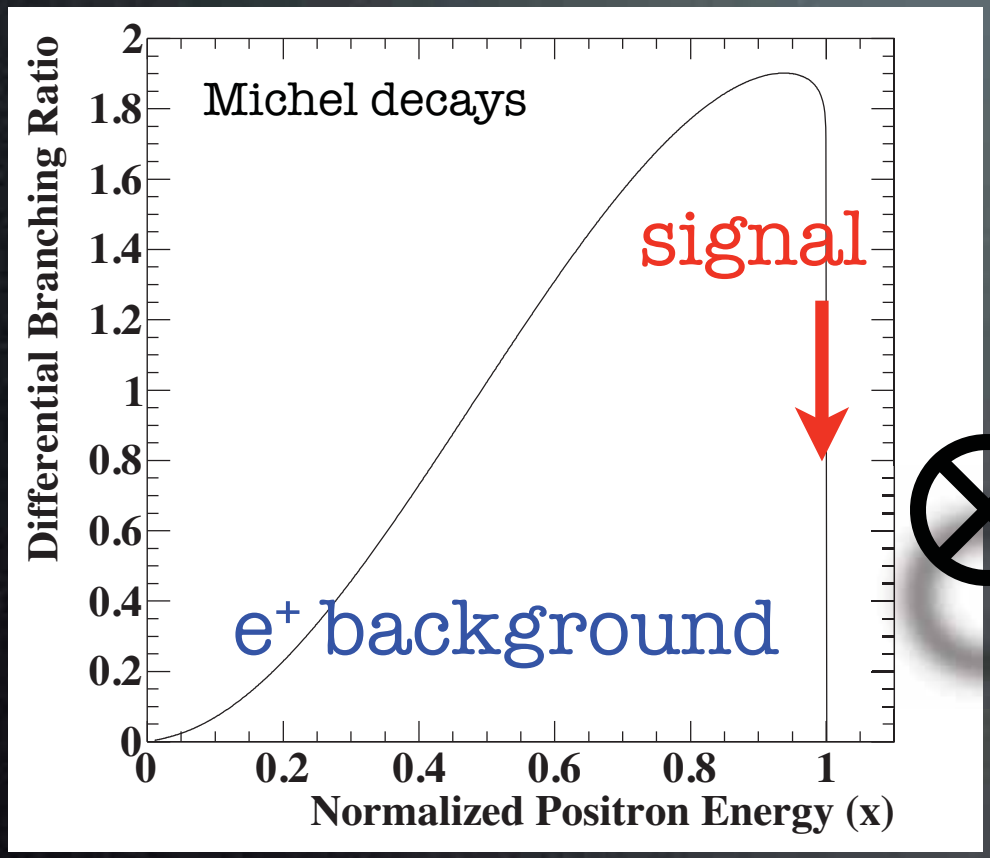


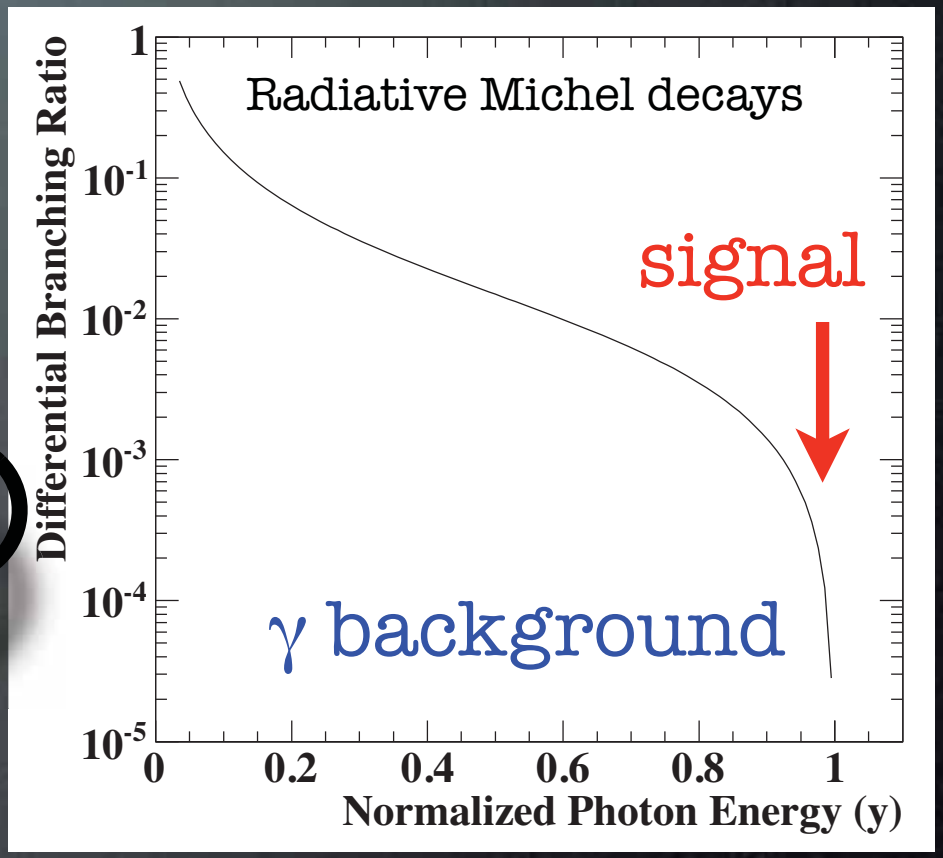
Accidental Background



Radiative muon decay	Accidental pileup
Any angle	Any angle
< 52.8 MeV/c	< 52.8 MeV/c
Same time	Flat

Accidental Background Distribution





must manage high rate e^+

good γ resolution is most important !

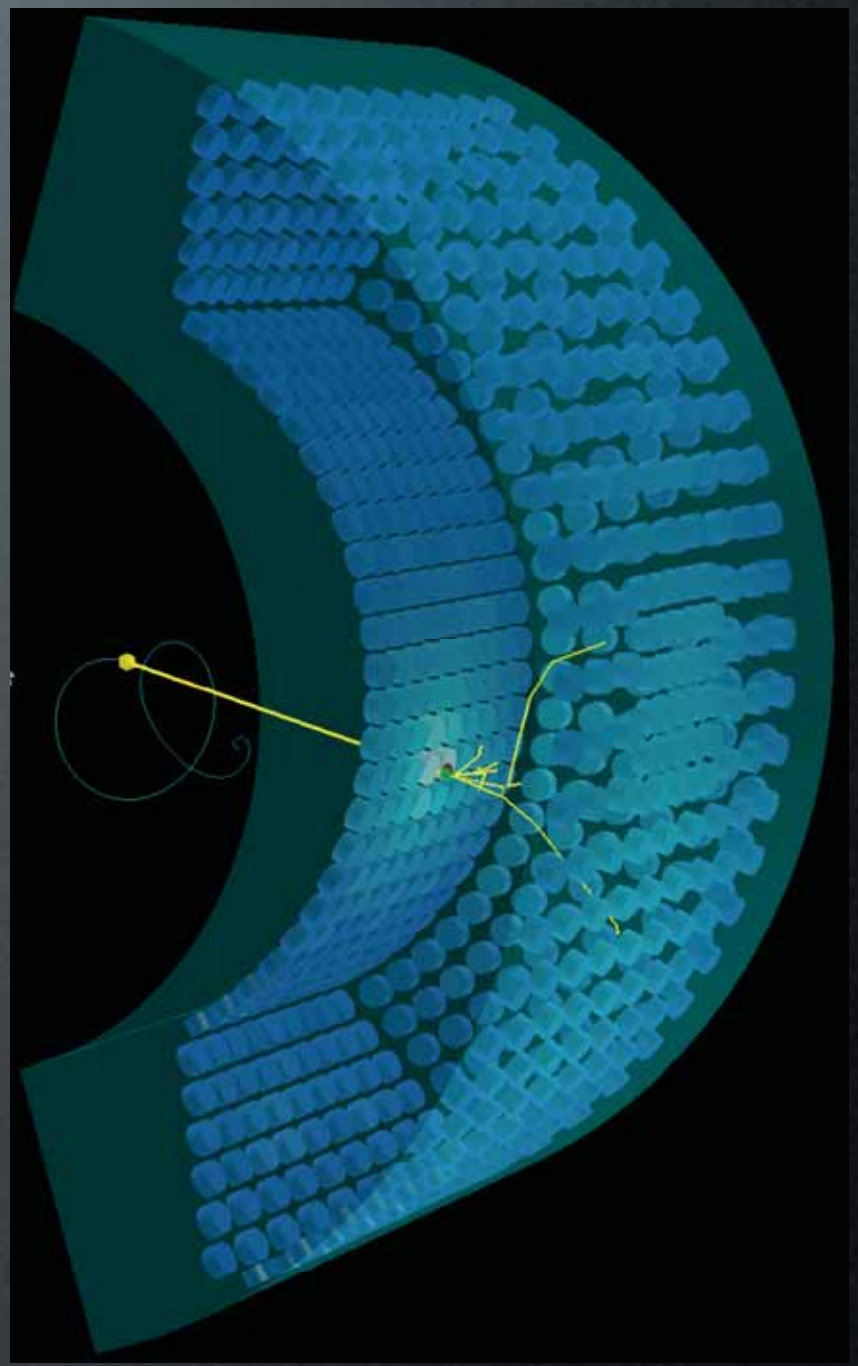
- ✓ High intensity (~10^7/sec) DC muon beam
  - ➡ Paul Scherrer Institute's 1.3MW Cyclotron
- ✓ e^+ spectrometer that can manage high rate
  - ➡ Gradient Magnetic Field Spectrometer
- ✓ High resolution gamma-ray detector
  - ➡ Liquid Xenon Scintillation Detector

→ **MEG Experiment**

The MEG Experiment

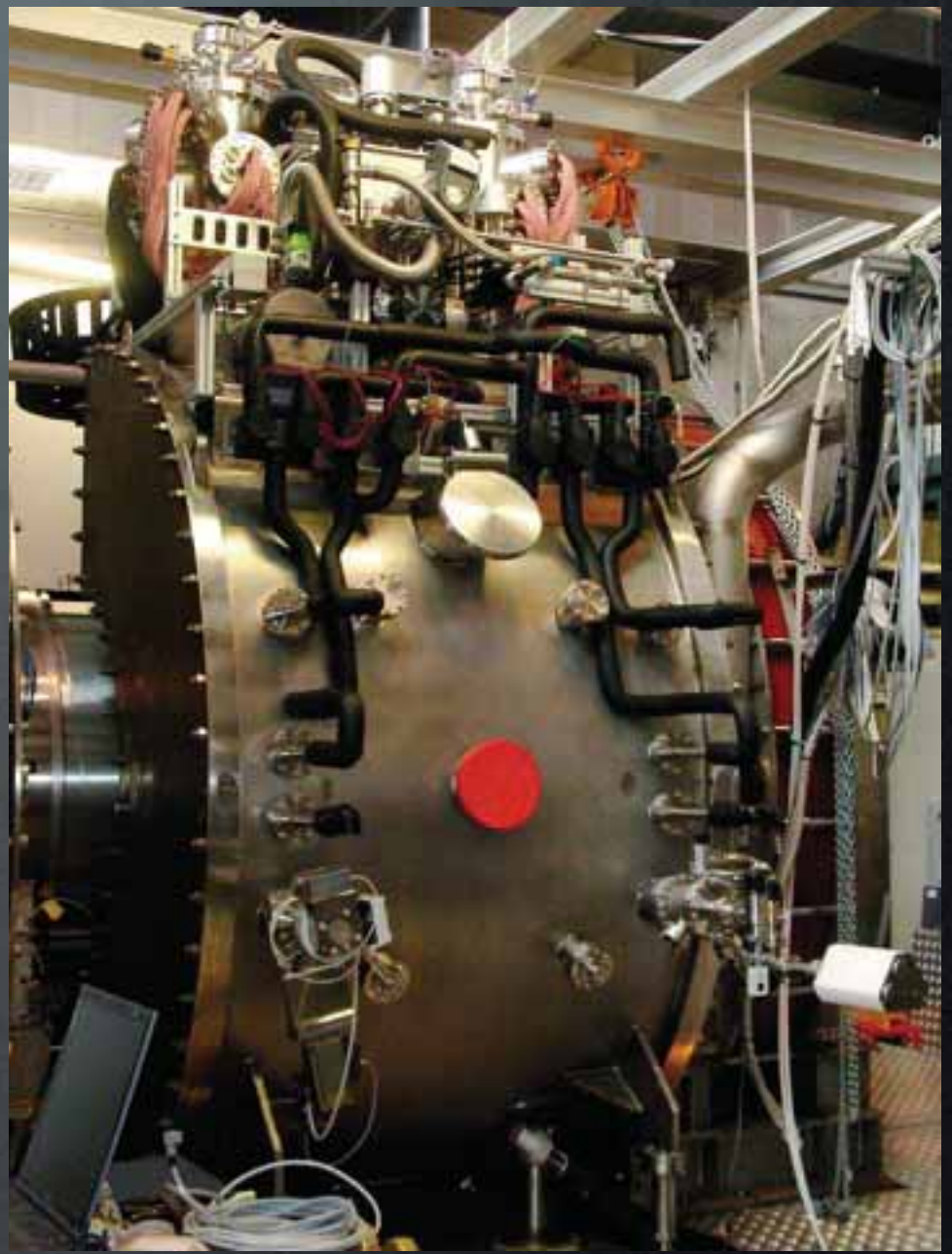
2.7t Liquid Xenon Photon Detector

- Scintillation light from 900 liter liquid xenon is detected by 846 PMTs mounted on all surfaces and submerged in the xenon
- fast response & high light yield provide good resolutions of E, time, position
- kept at 165K by 200W pulse-tube refrigerator
- gas/liquid circulation system to purify xenon to remove contaminants

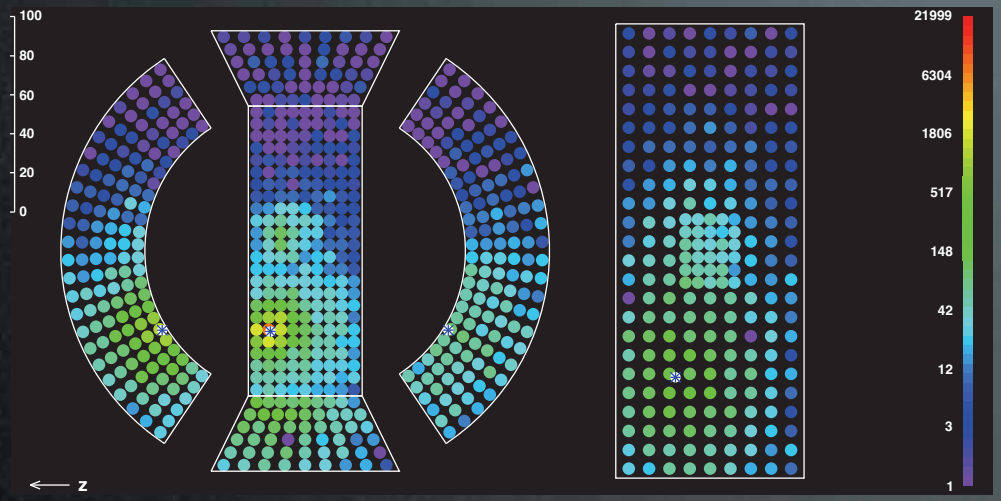


assembling
the detector

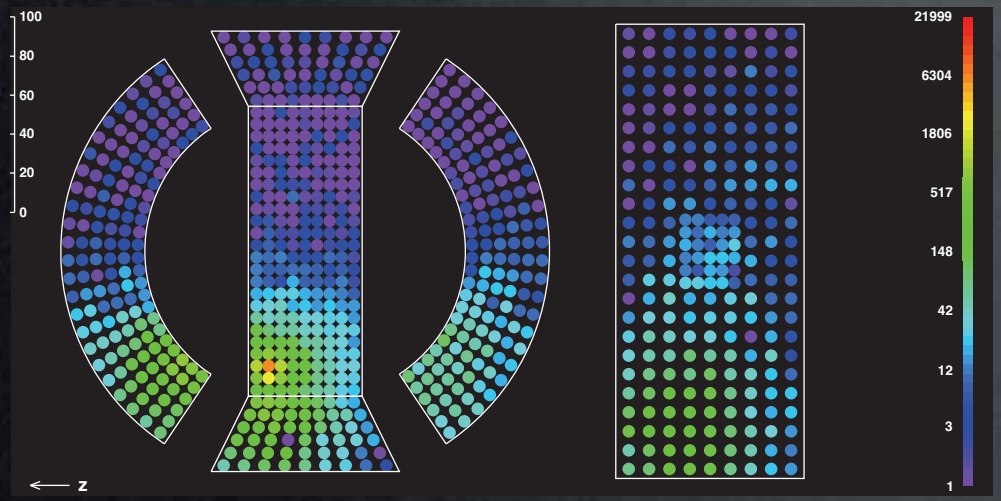
placed at
the beam line



Pile-up Photon Removal

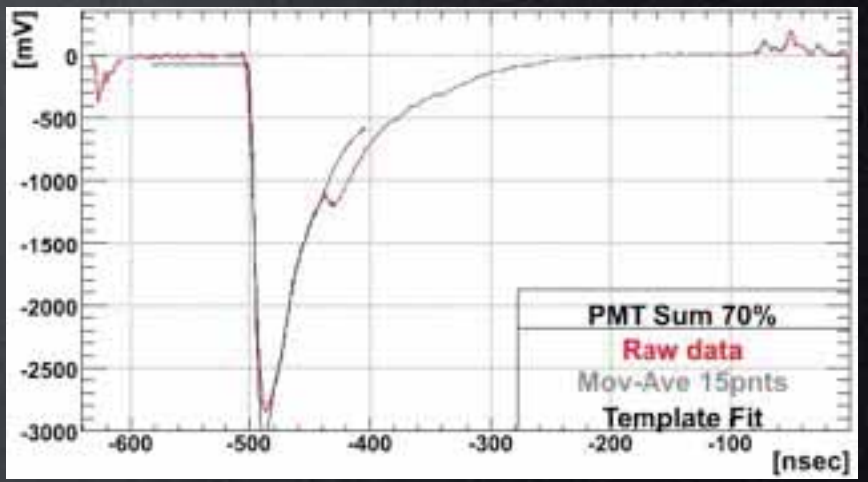


before

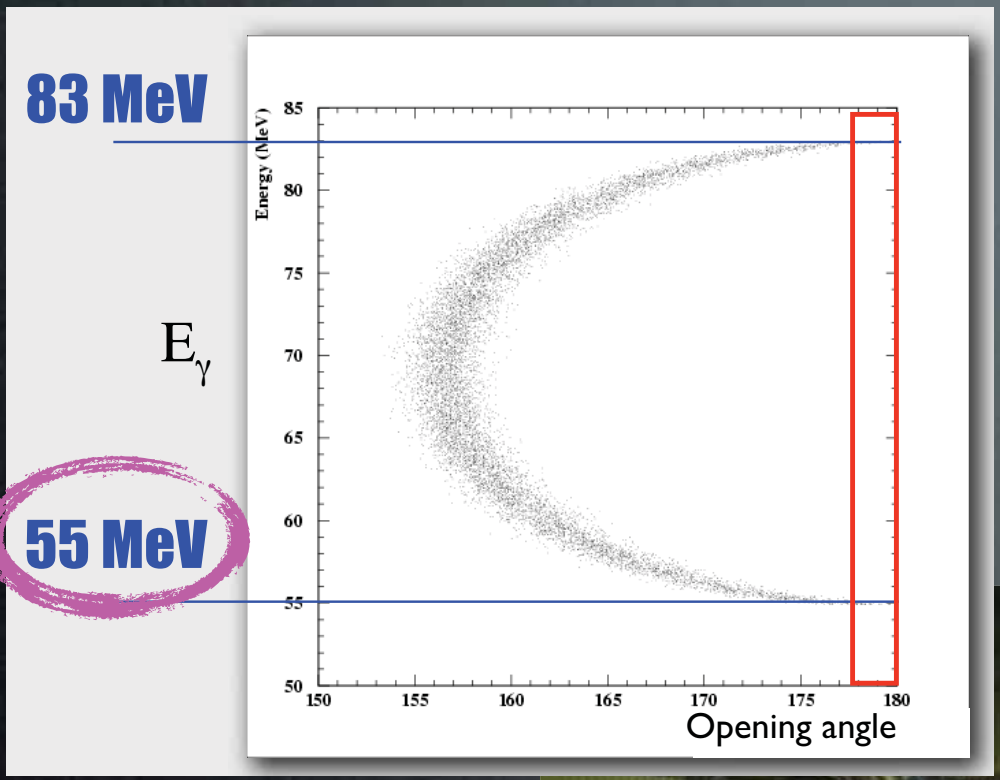


after

- Good position/timing resolutions enable to remove pile-up photons
- All the PMTs are read out by waveform digitizers (DRS)
- Events are not thrown away

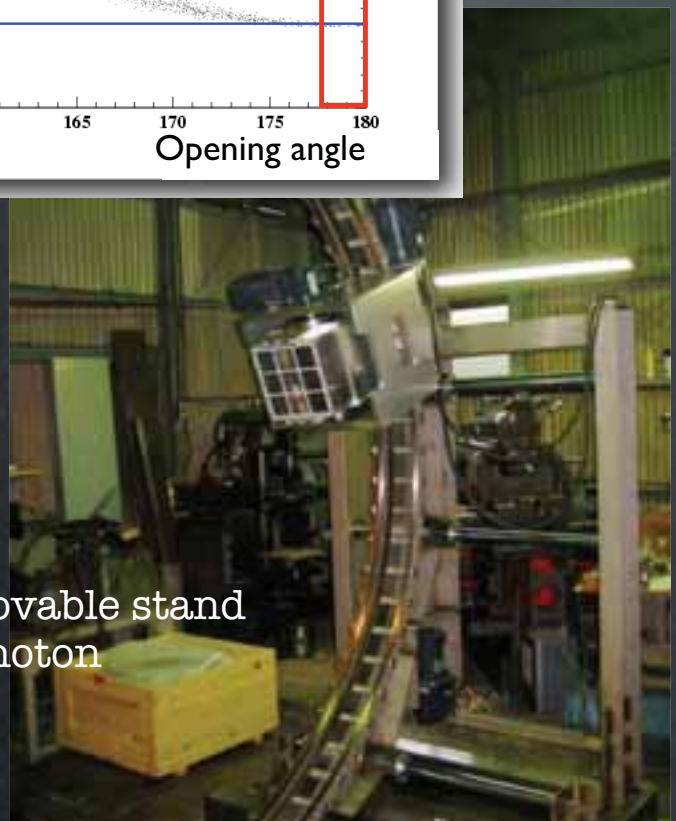


Absolute E_γ Calibration



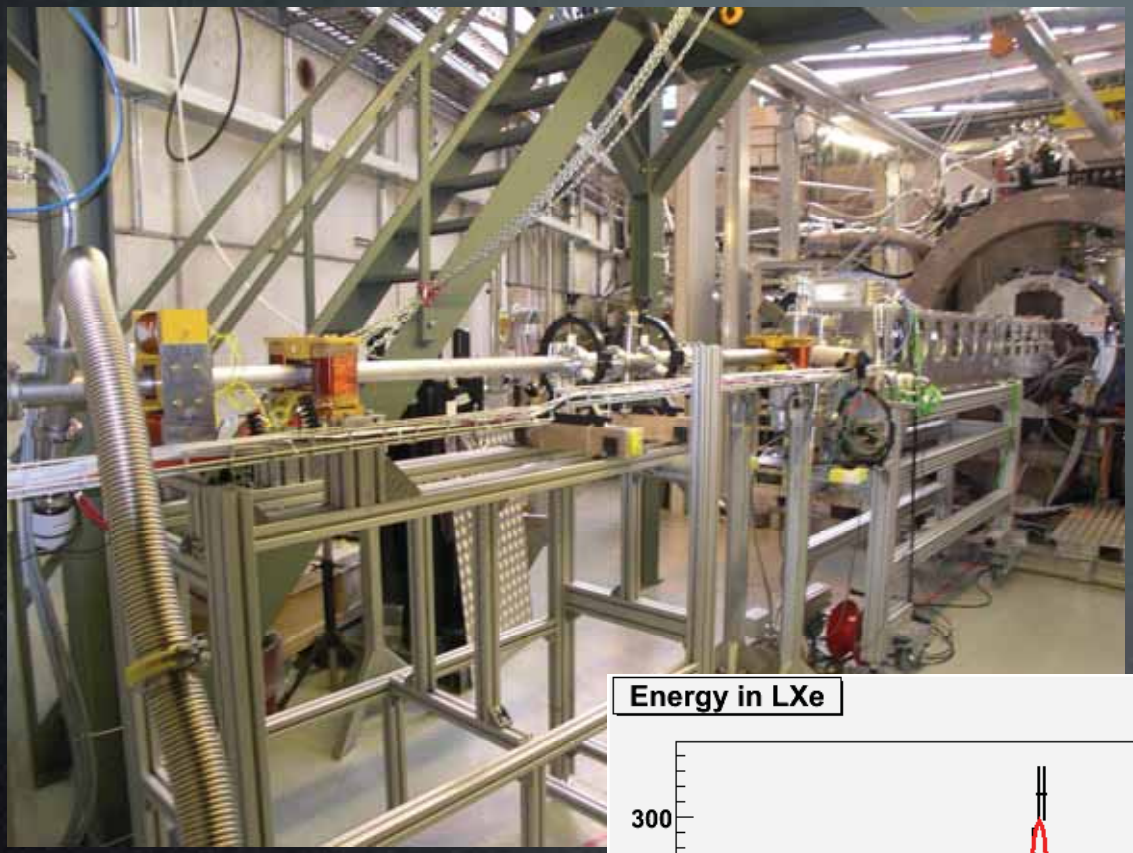
$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$$

- negative pions stopped in liquid hydrogen target
- Tagging the other photon at 180° provides monochromatic photons
- Dalitz decays were used to study positron-photon synchronization and time resolution: $\pi^0 \rightarrow \gamma e^+ e^-$

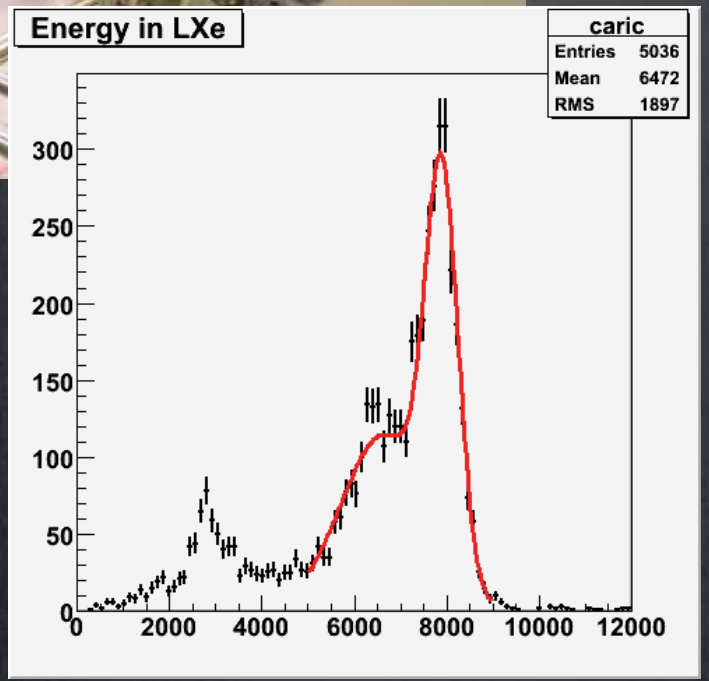


NaI crystal array on a movable stand to tag the other photon

Monitor E_γ during Run



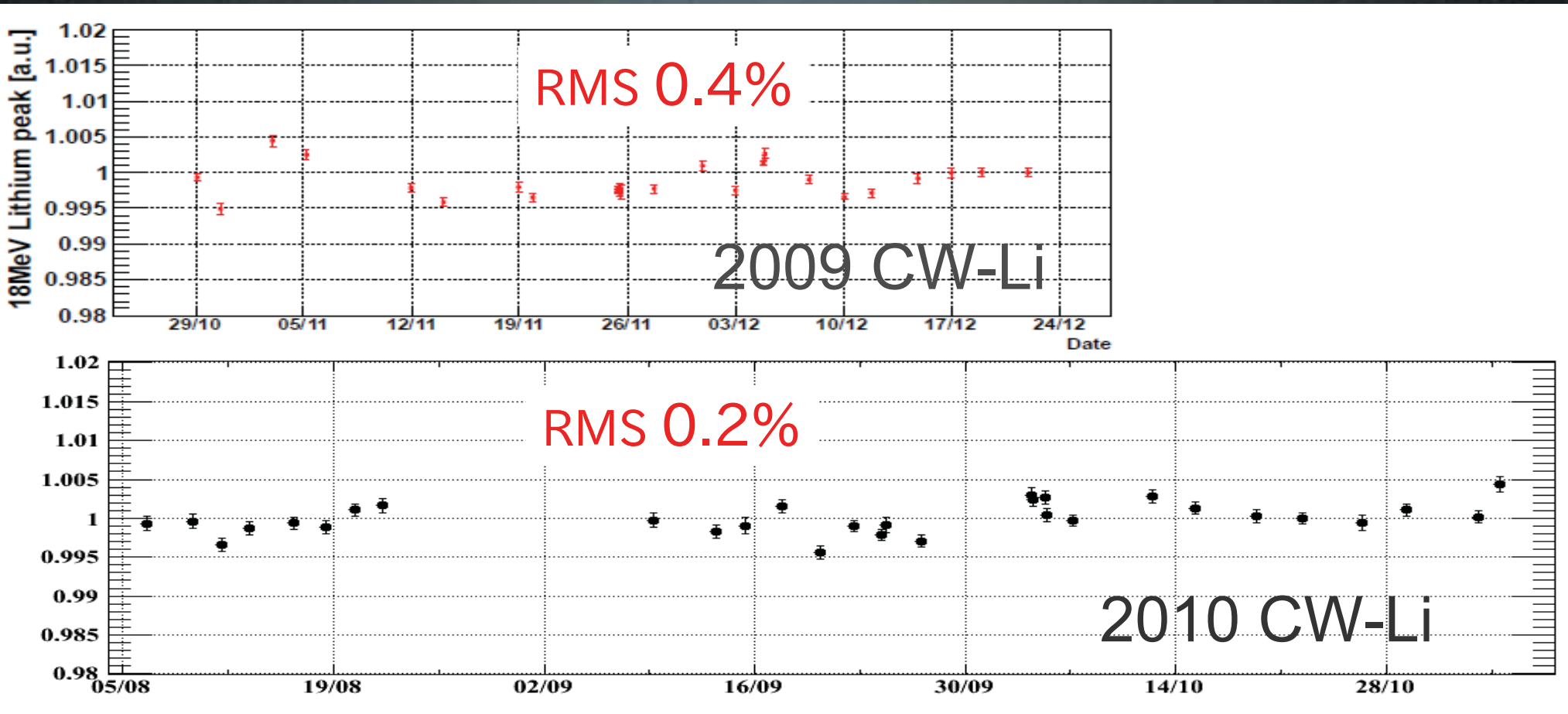
remotely extendable beam pipe of CW proton beam (downstream of muon beam line)



17.67MeV Li peak

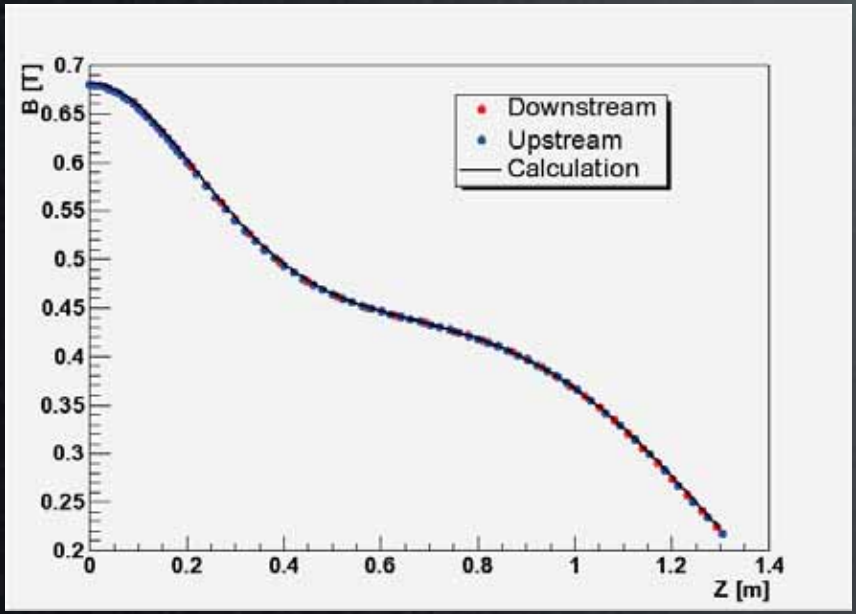
- sub-MeV proton beam produced by a dedicated Cockcroft-Walton accelerator (CW) are bombarded on $Li_2B_4O_7$ target.
- 17.67MeV from ^7Li
- 2 coincident photons (4.4, 11.6) MeV from ^{11}B: synchronization of LXe and TC
- Short runs two-three times a week

Stability of E_γ Scale

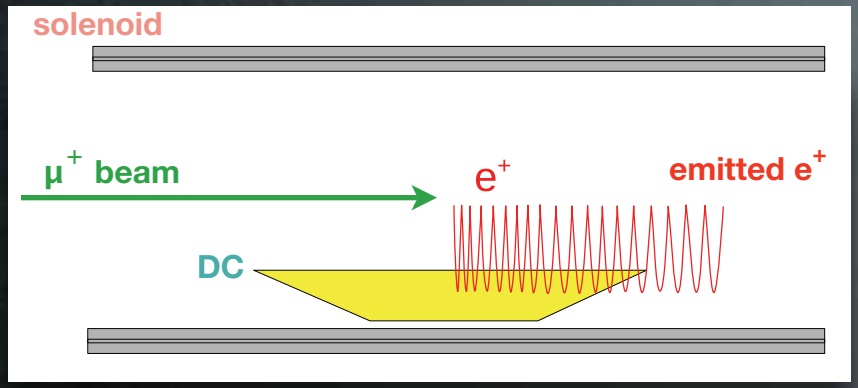


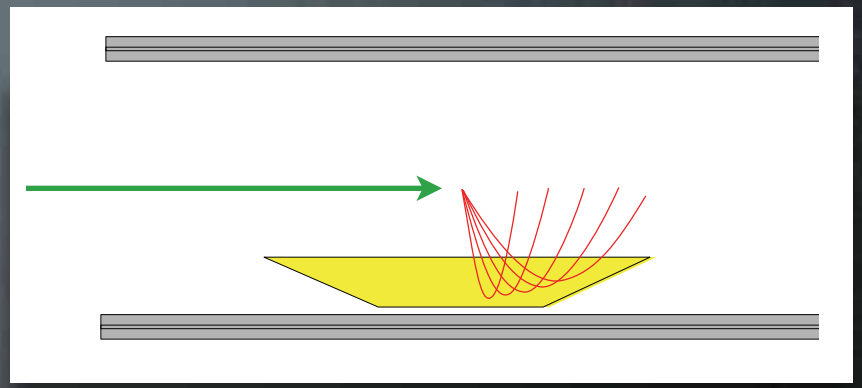
COBRA Positron Spectrometer

- thin-walled SC solenoid with a gradient magnetic field: 1.27 - 0.49 Tesla

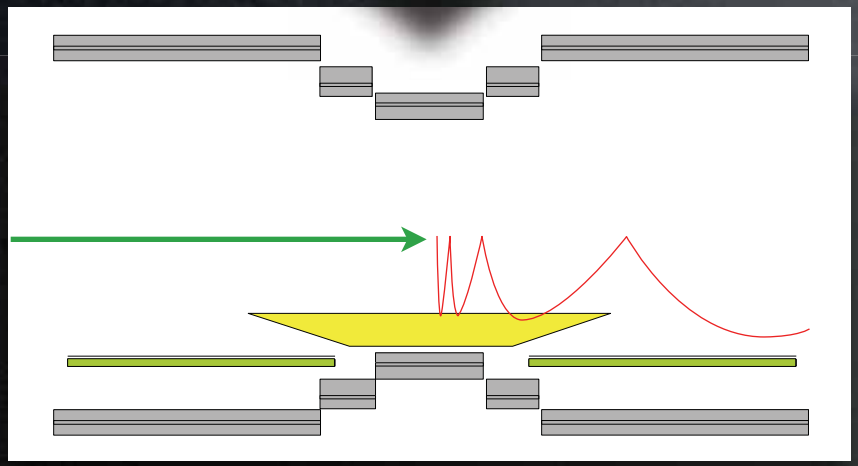


uniform
B-field

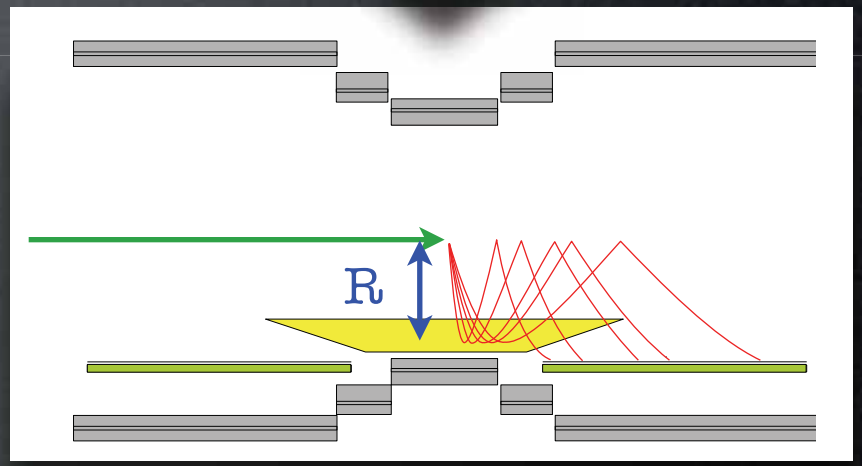




gradient
B-field

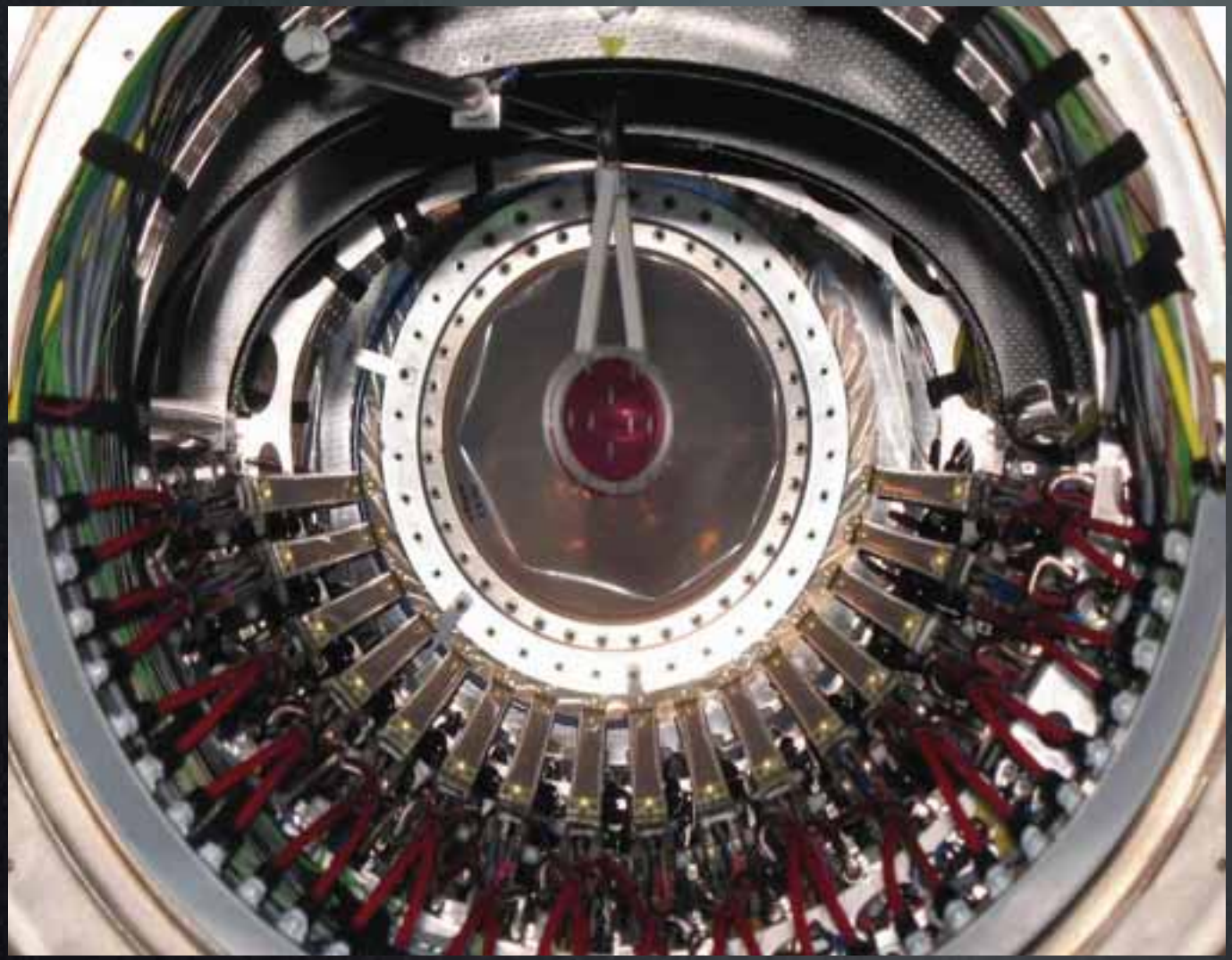


Low energy positrons
quickly swept out



Constant bending radius
independent of emission angles

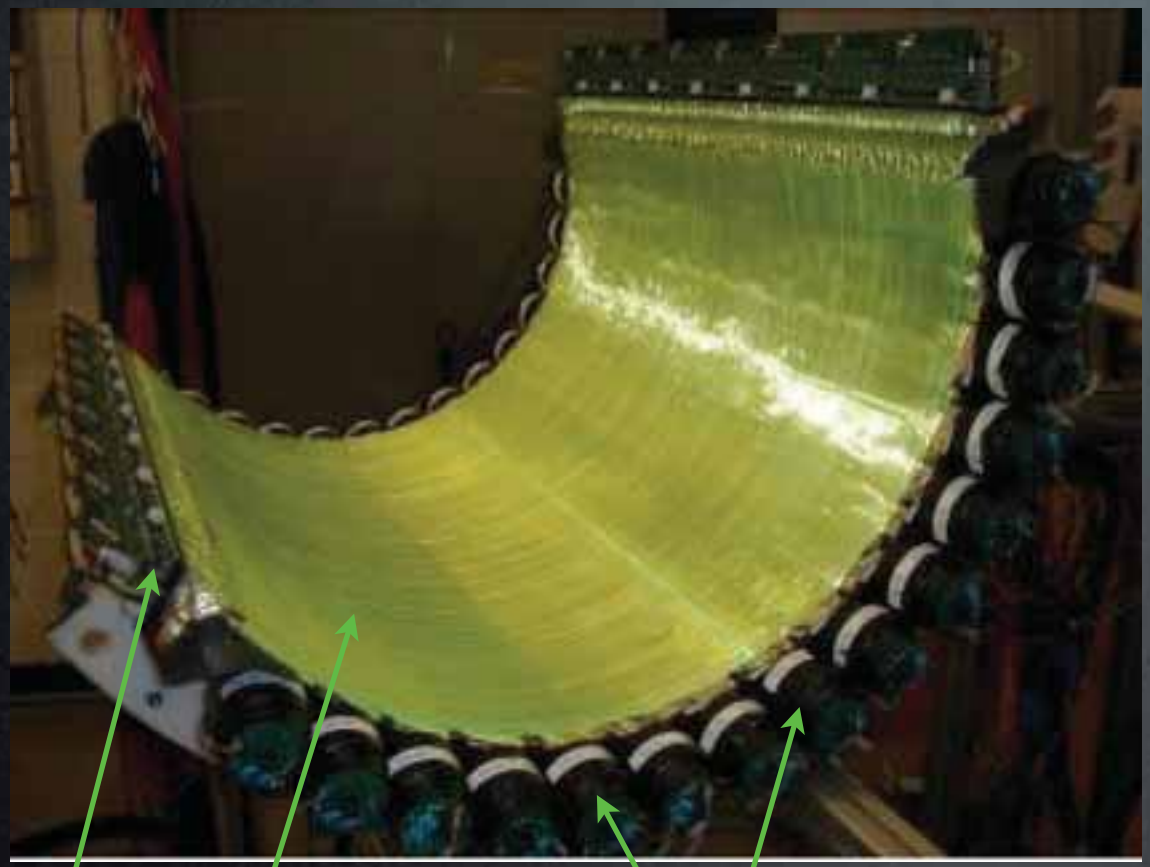
Drift Chambers



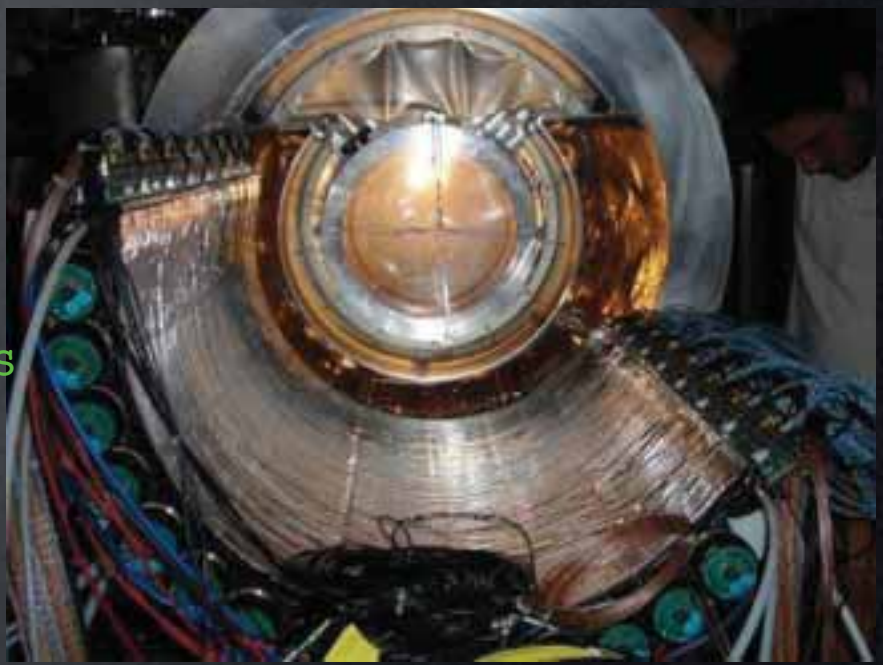
filled with He inside COBRA

- 16 radially aligned modules, each consists of two staggered layers of wire planes
- 12.5um thick cathode foils with a Vernier pattern structure
- He:ethane = 50:50 differential pressure control to COBRA He environment
- ~2.0 x 10^{-3} X_0 along the positron trajectory

Timing Counters



- Scintillator arrays placed at each end of the spectrometer
- Measures the impact point of the positron to obtain precise timing



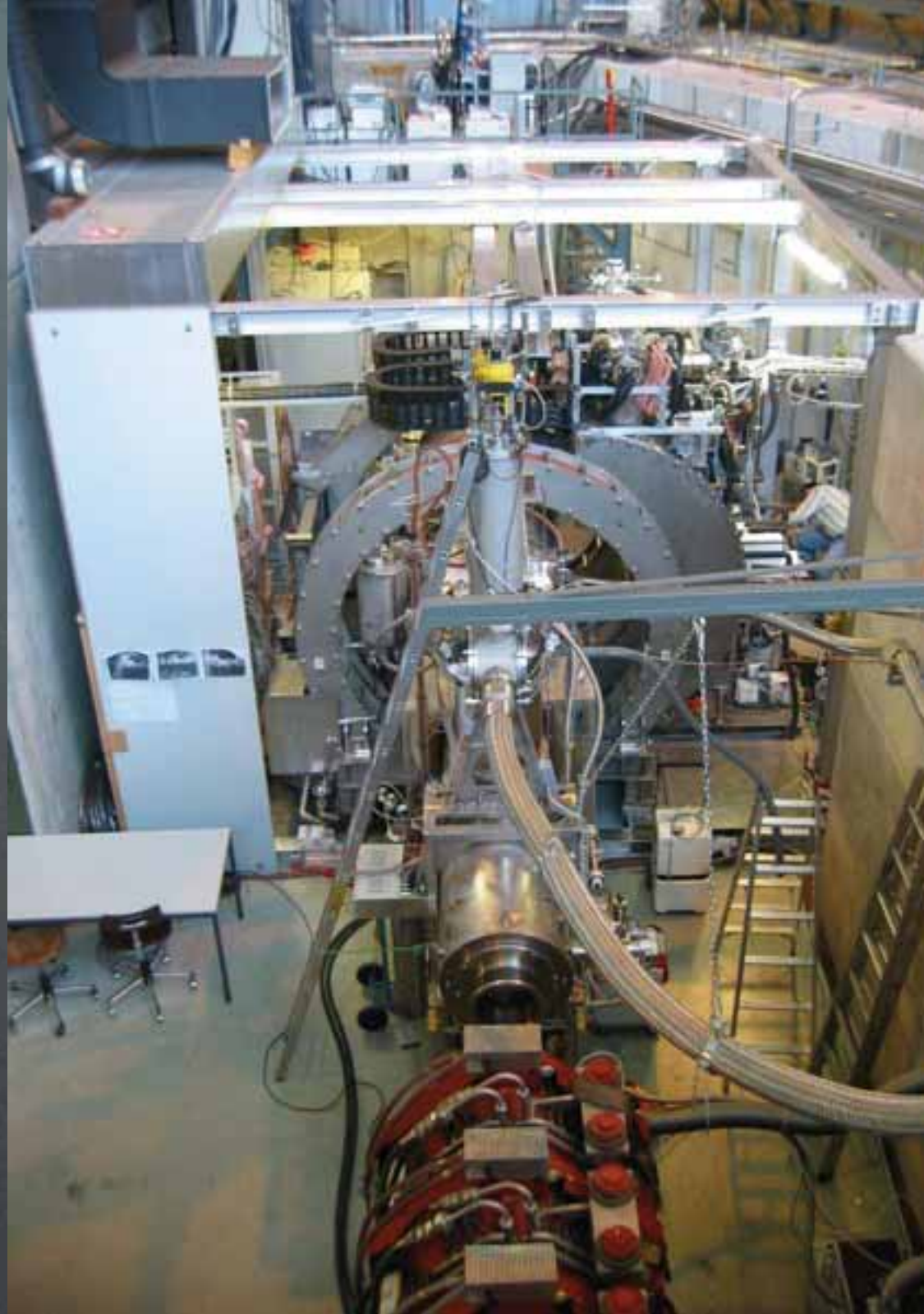
installing inside COBRA

Physics Runs

- 2008: 3 month run w/ low DC efficiencies & low LXe light yield
  sensitivity: $1.3 * 10^{-11}$
  90% CL UL: $2.8 * 10^{-11}$
  (published)

- 2009: 2 month stable run
  2* more data than 2008
  preliminary result
  presented at ICHEP, Paris

- 2010: 3 month stable run
  early end by BTS accident
  1.9* more data than 2009

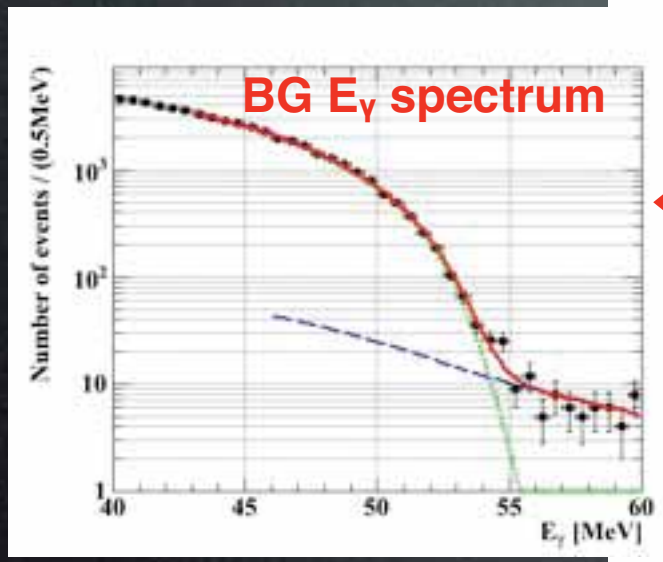


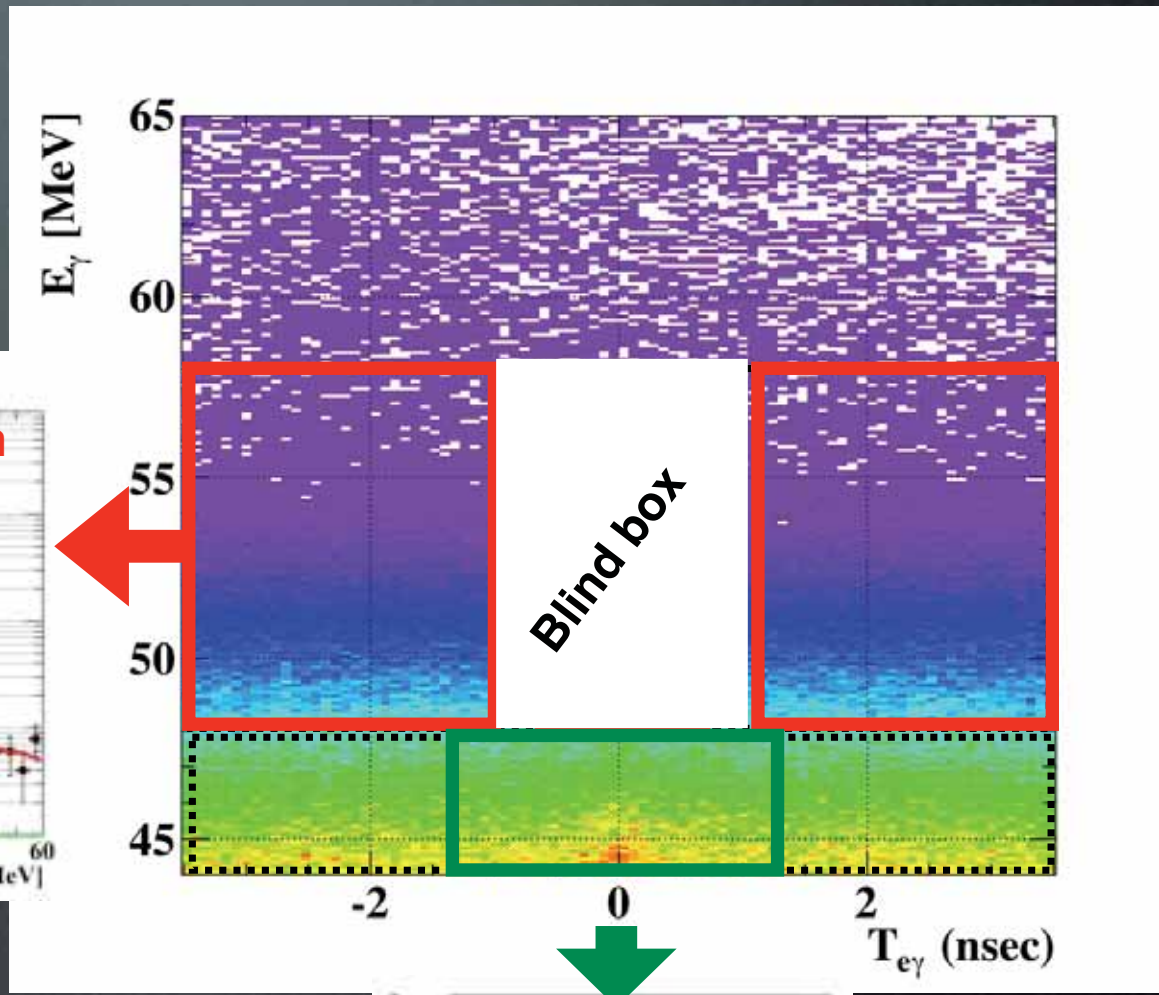
2009 Data Analysis

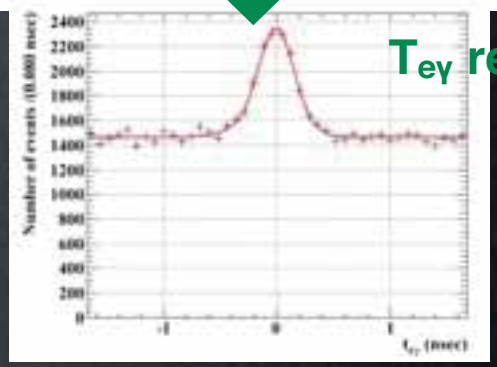
Blind & Likelihood Analysis

$(E_\gamma, E_e, T_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$

→ signal, acc BG, RD BG





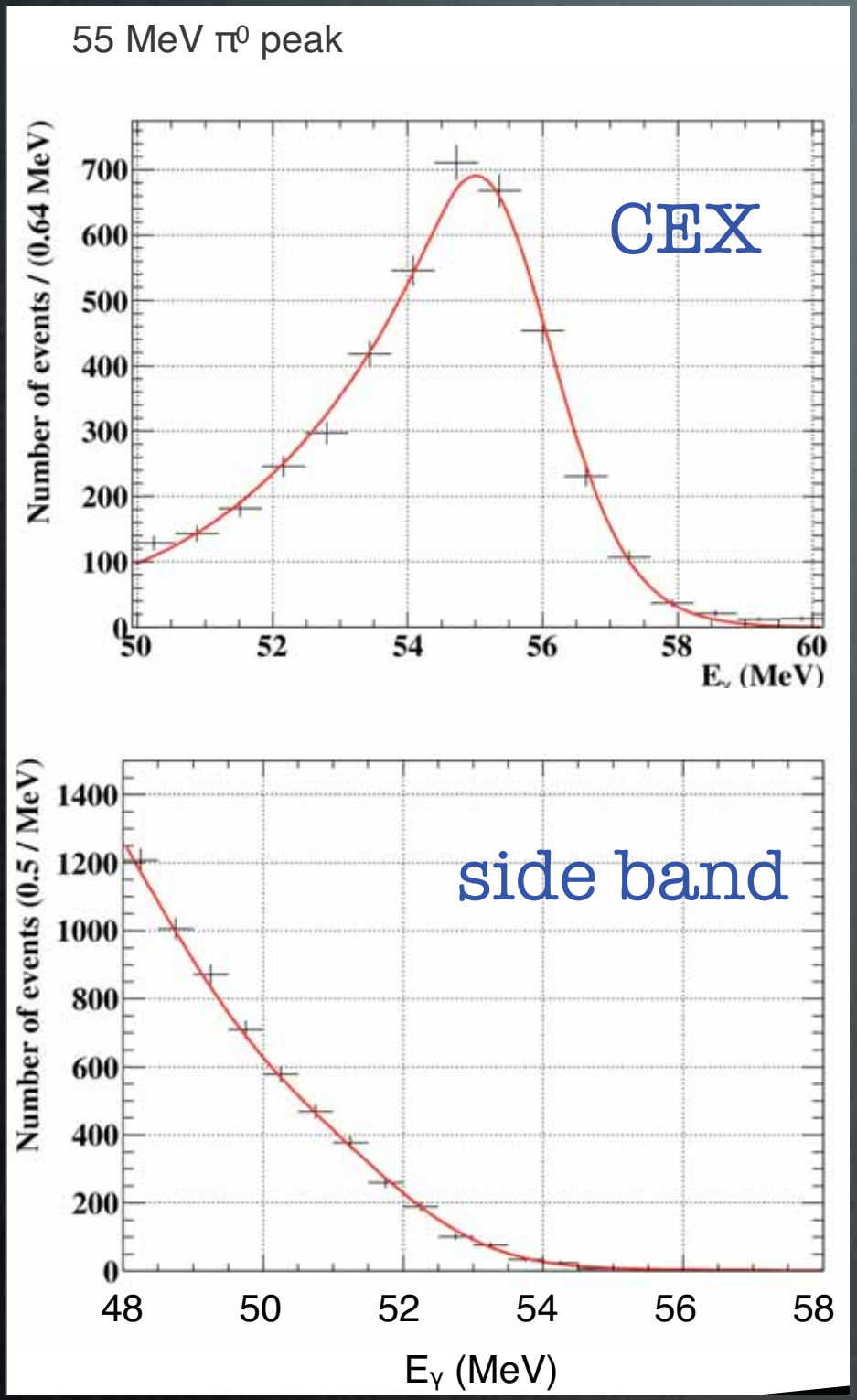


PDFs mostly from data

accidental BG: side bands

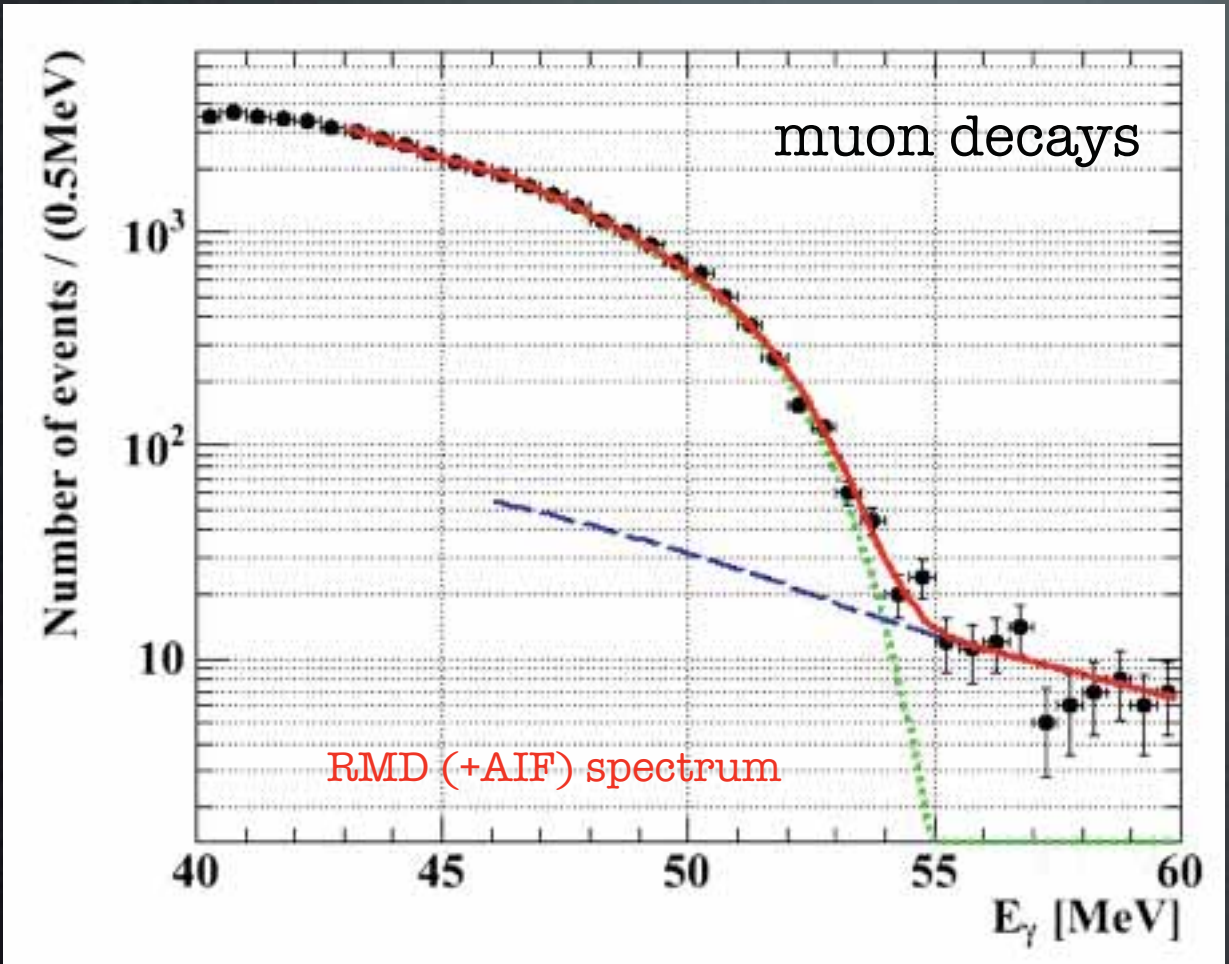
signal: measured resolution

radiative BG: theory + resolution

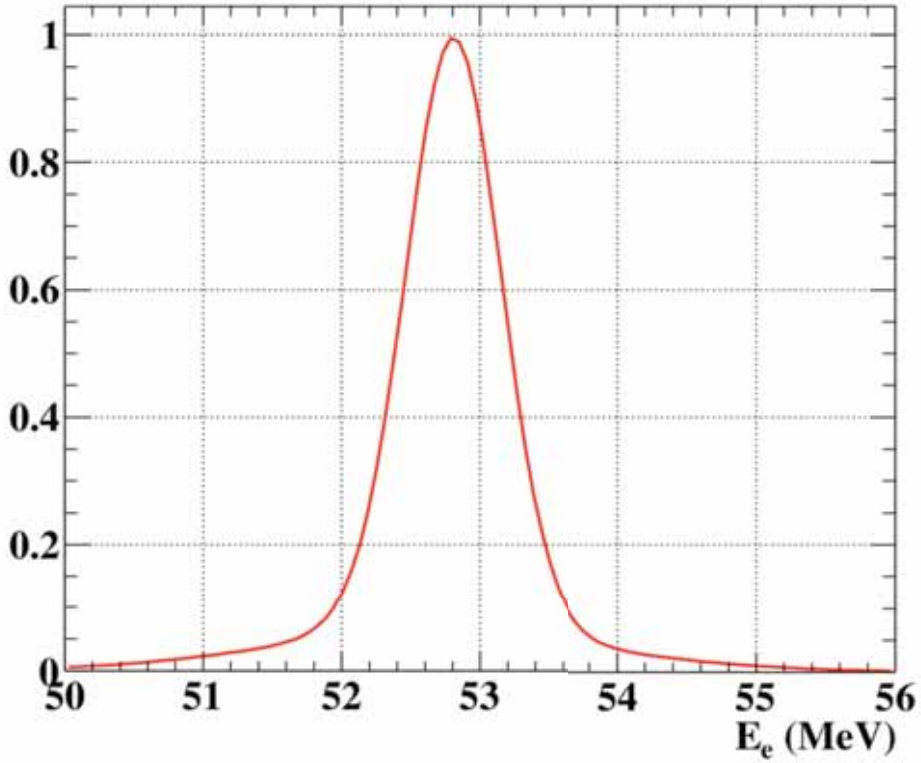


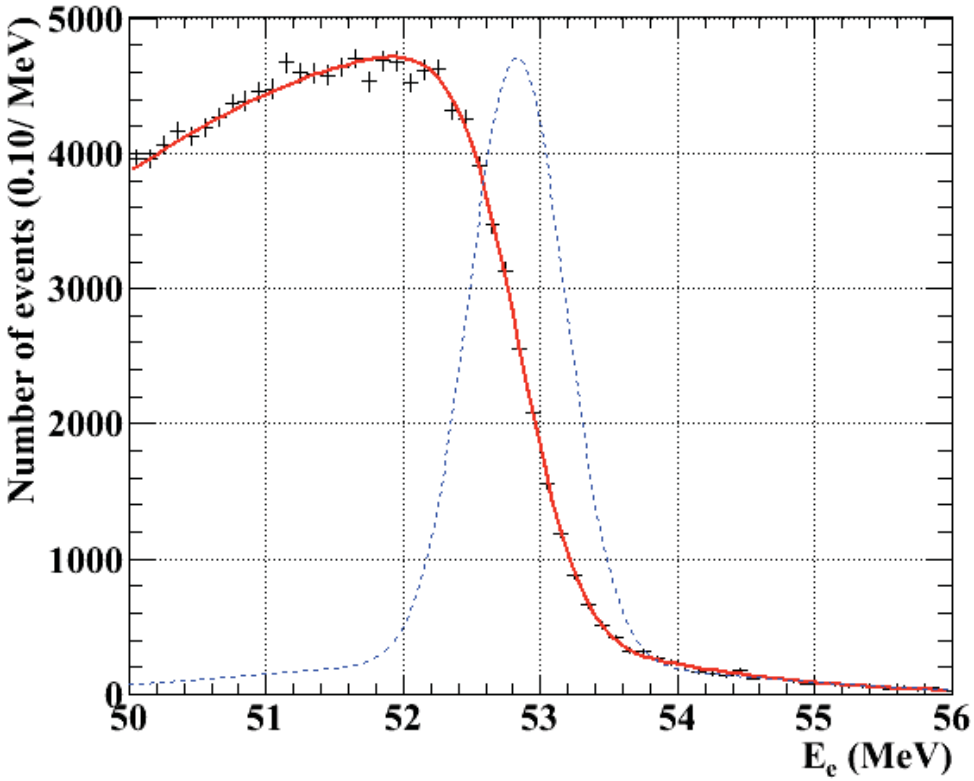
- Gamma ray energy
  - Signal PDF from the CEX data
  - Accidental PDF from the side bands

Photon Energy



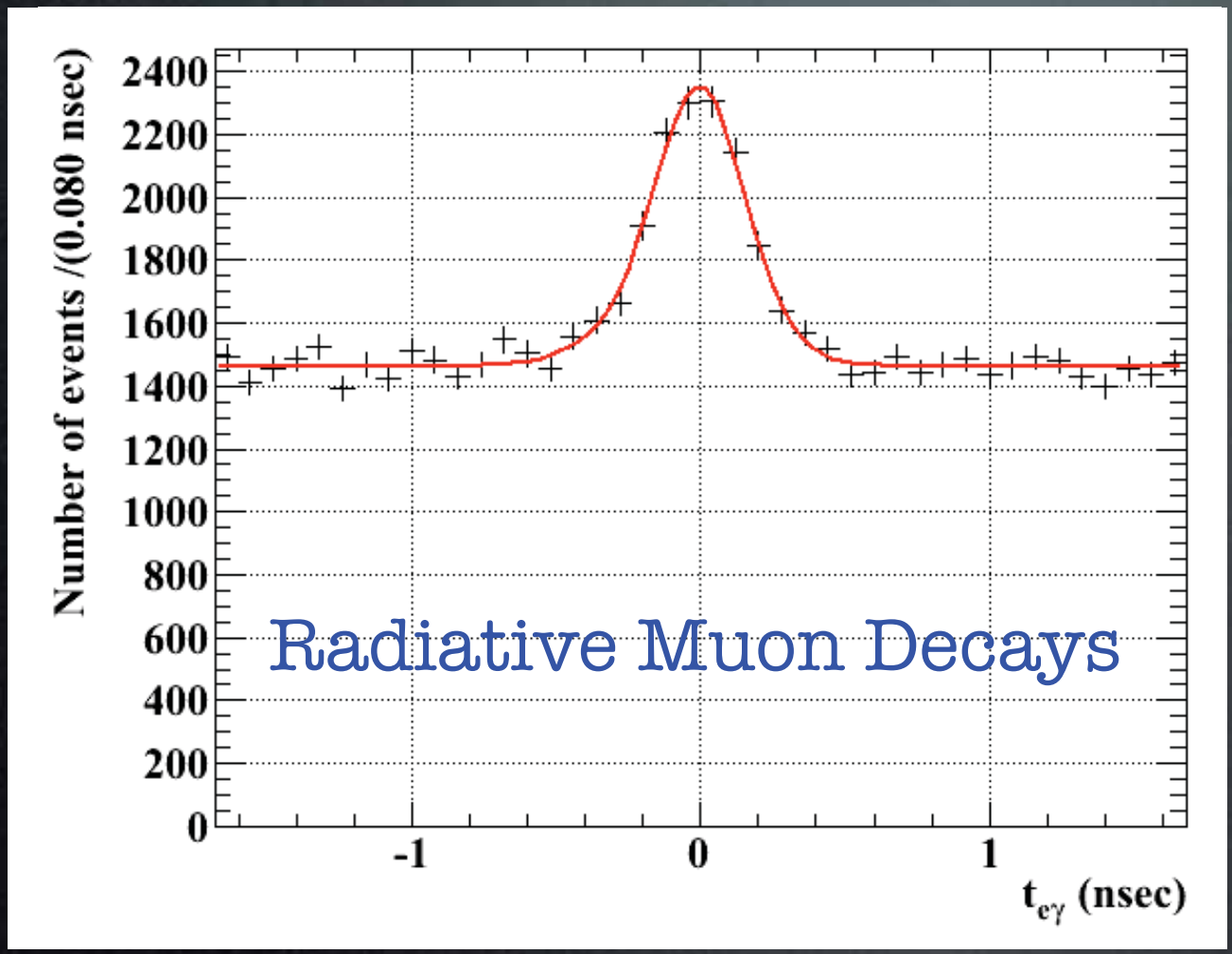
- Scale & resolutions verified by radiative decay spectrum
- systematic uncertainty on energy scale: 0.5%





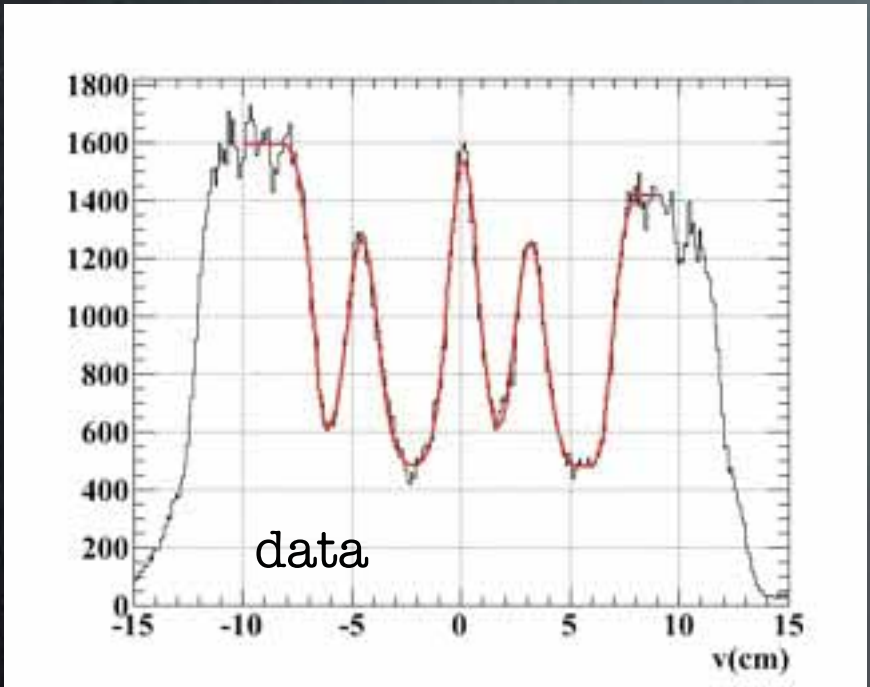
- Positron energy scale and resolution are evaluated by fitting the kinematic edge of the Michel positron spectrum at 52.8MeV

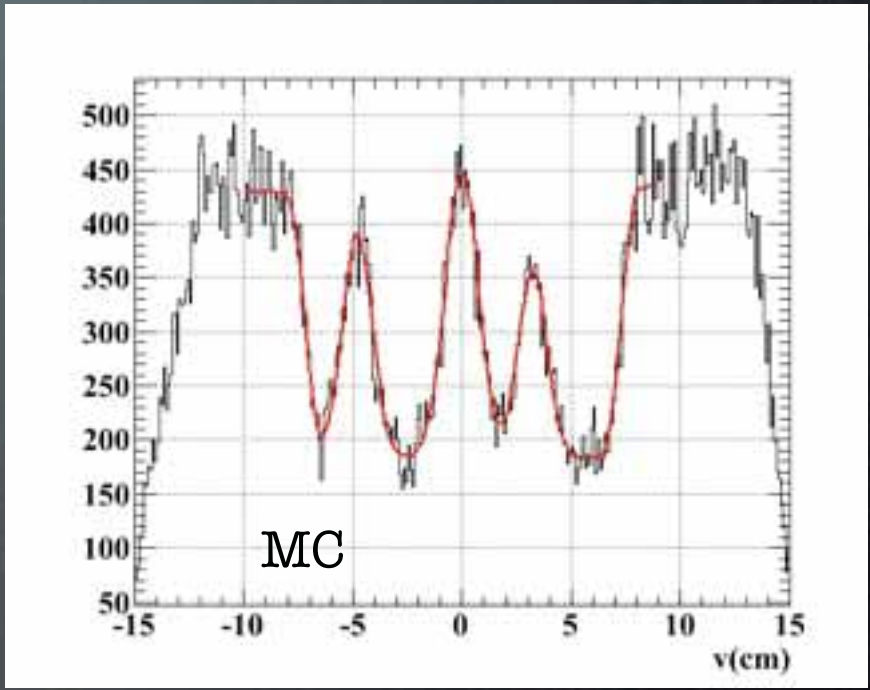
Positron - Photon Timing

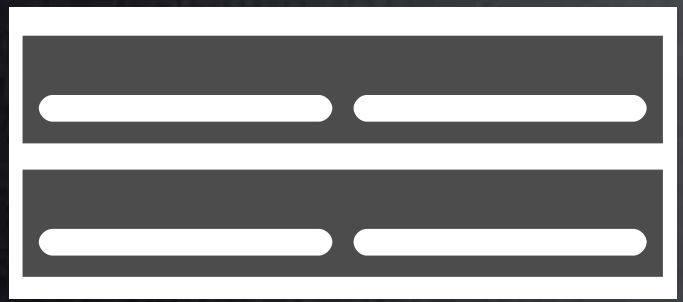


- Positron time measured by TC and corrected by ToF (DC trajectory)
- LXe time corrected by ToF to the conversion point
- RMD peak in a normal physics run corrected by small energy dependence; stable < 20ps

Photon Conversion Position



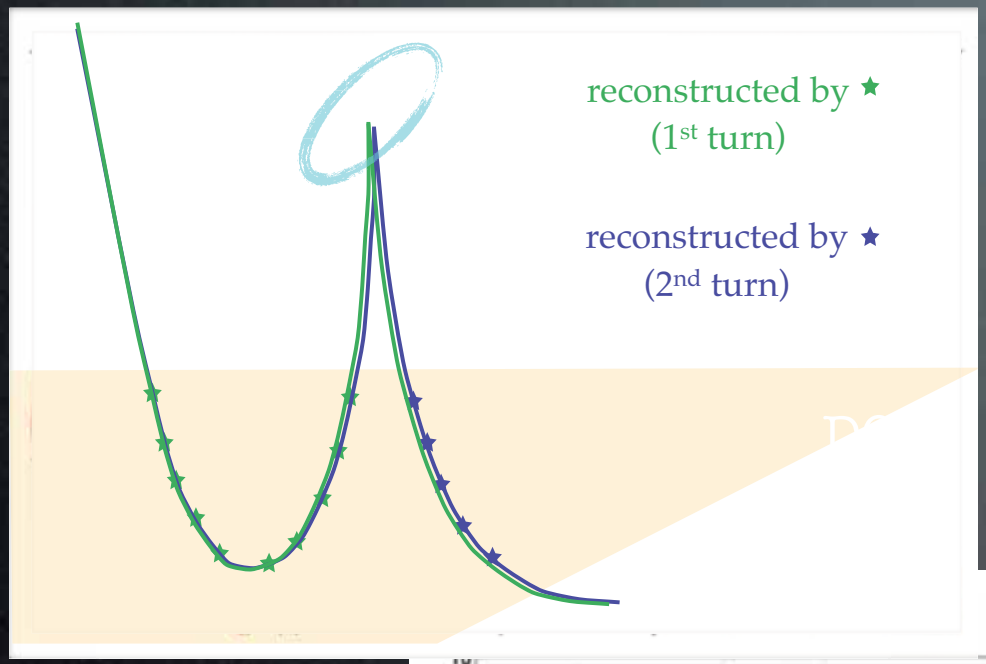




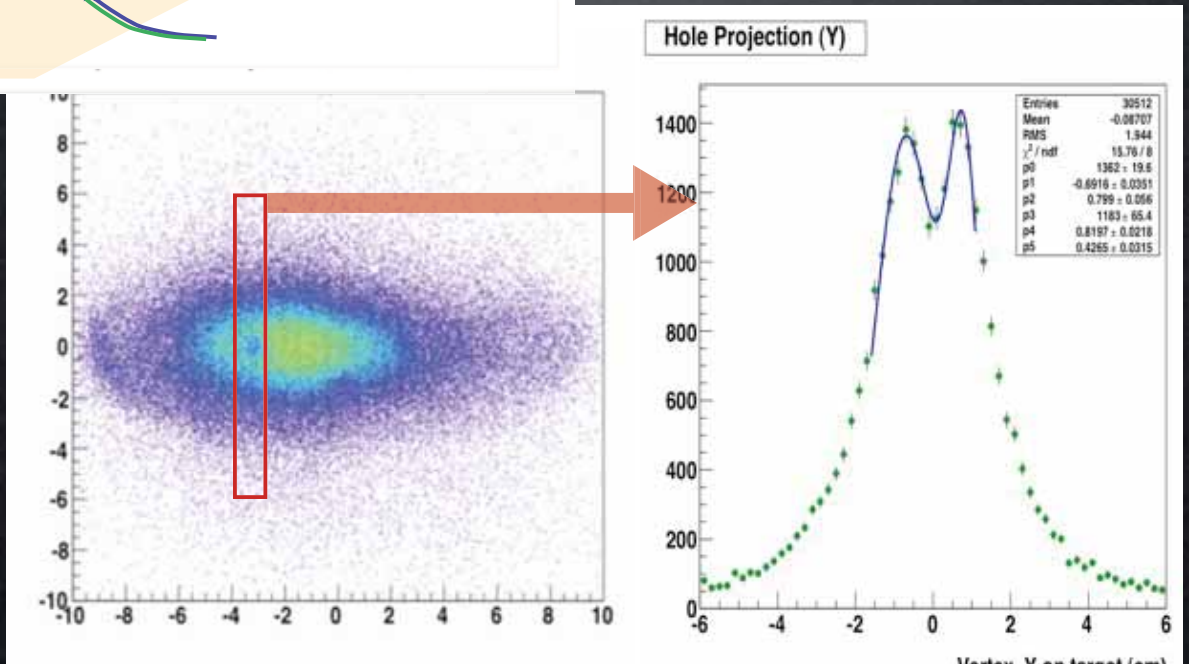
Pb collimator

- Resolution for photon conversion position was evaluated by CEX run with Pb collimators
- ~ 5mm

Positron Angle & Muon Decay Point



- Angular resolutions were evaluated by the double turn tracks inside the DC
- holes of the muon stopping target



Performance in 2009

Stable detector operation in 2009

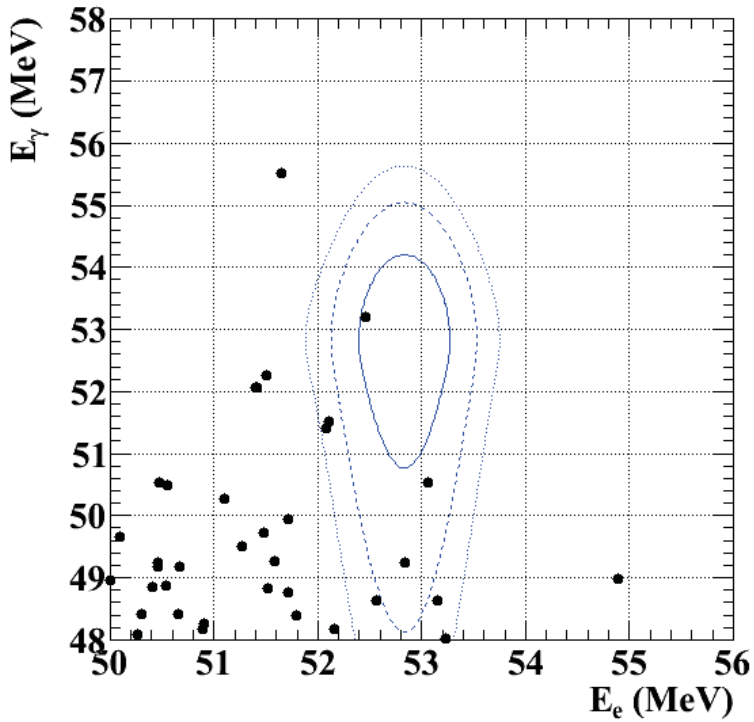
in sigma	
Gamma Energy (%)	2.1 (w>2cm)
Gamma Position (mm)	5(u,v) / 6(w)
e+ Momentum (%)	0.74 (core)
e+ Angle (mrad)	7.1(ϕ core),11.2(θ)
Vertex position (mm)	3.4 (Z), 3.3 (Y)
Gamma - e+ Timing (psec)	142 (core)
Gamma Efficiency (%)	58
Trigger Efficiency (%)	83.5

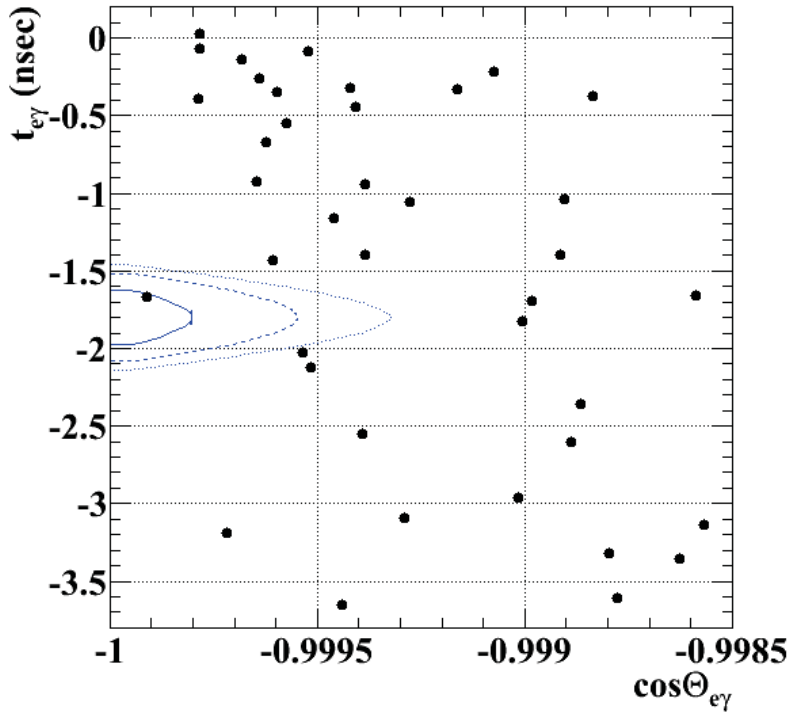
preliminary

Expected Sensitivity

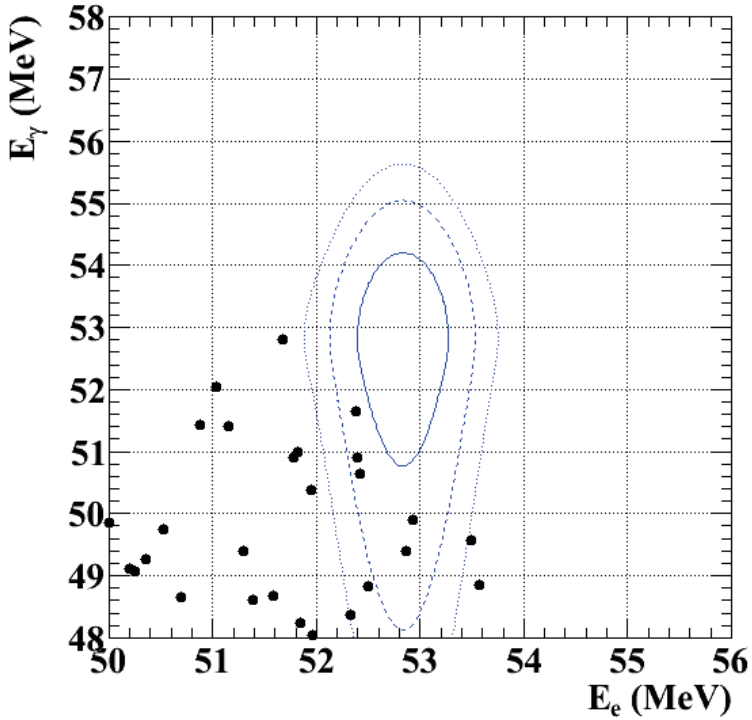
- Average 90% CL upper limit for toy MC with no signal event:
  - $6.1 * 10^{-12}$
- 90% CL upper limits for the side bands:
  - $(4 - 6) * 10^{-12}$
  - Note: RD BG is much smaller than accidental BG

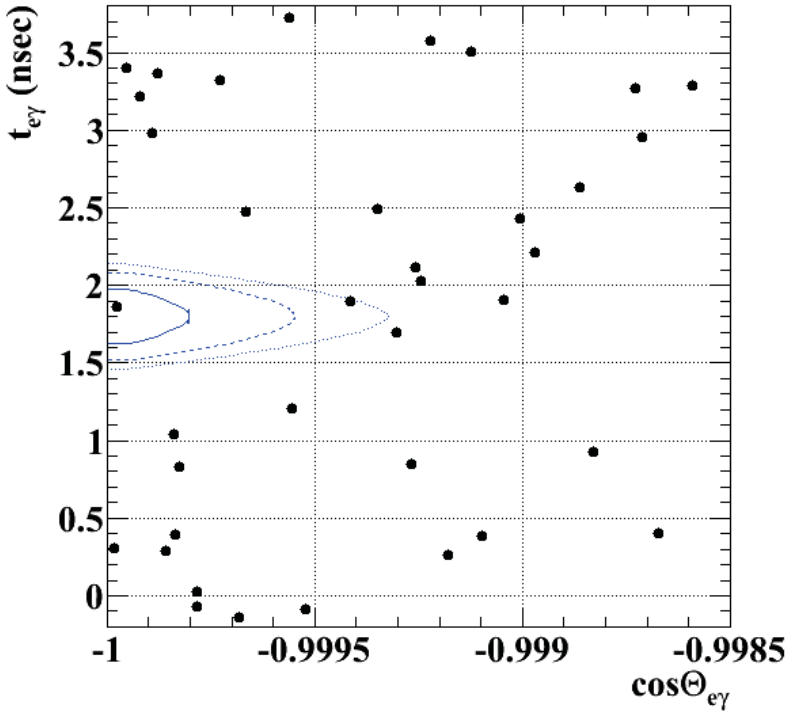
Left sideband



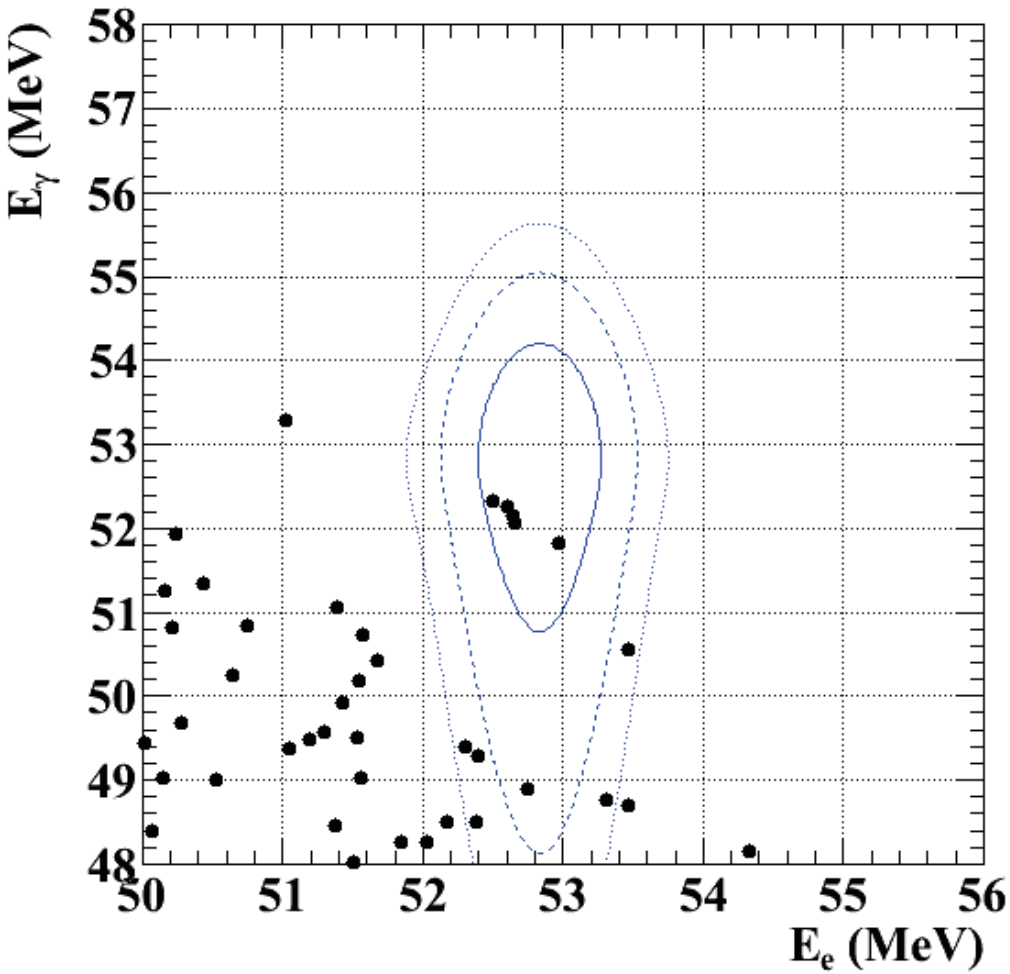


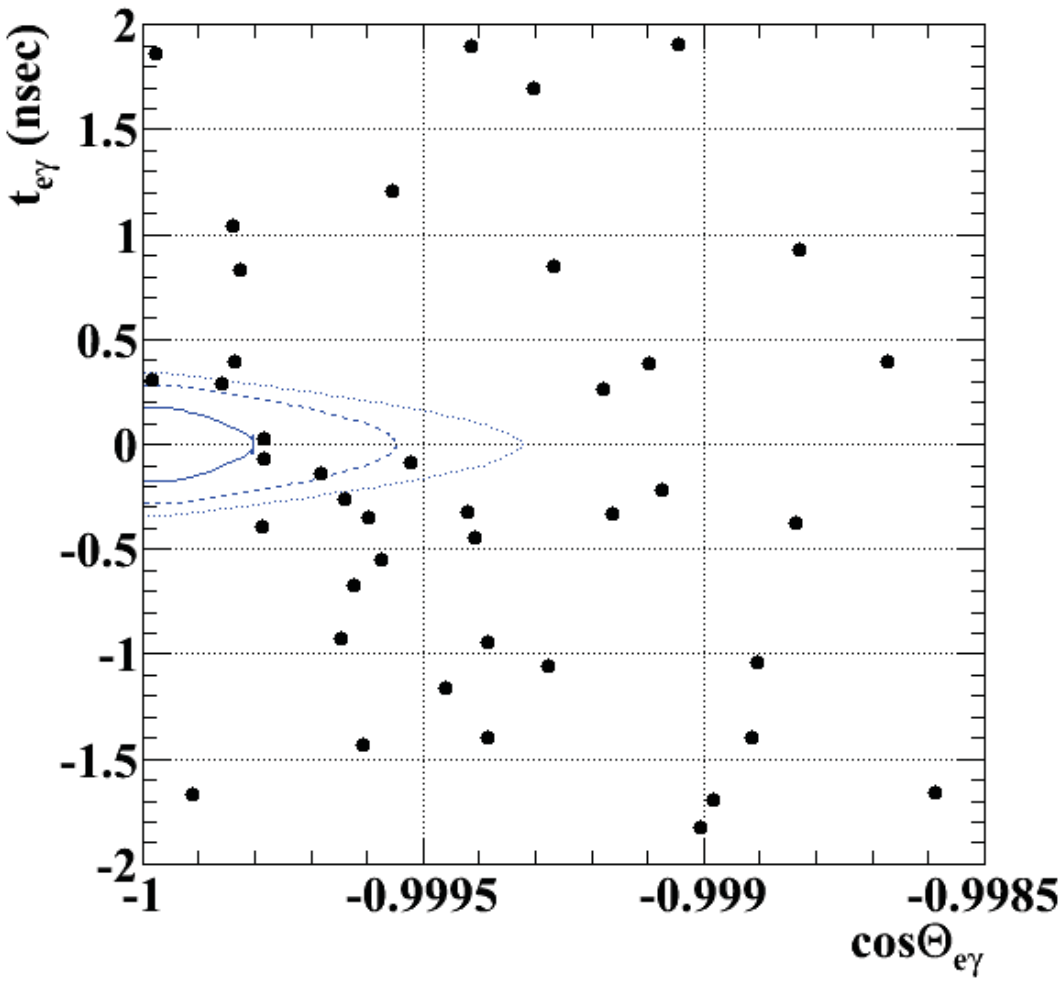
Right sideband





Event distribution after unblinding

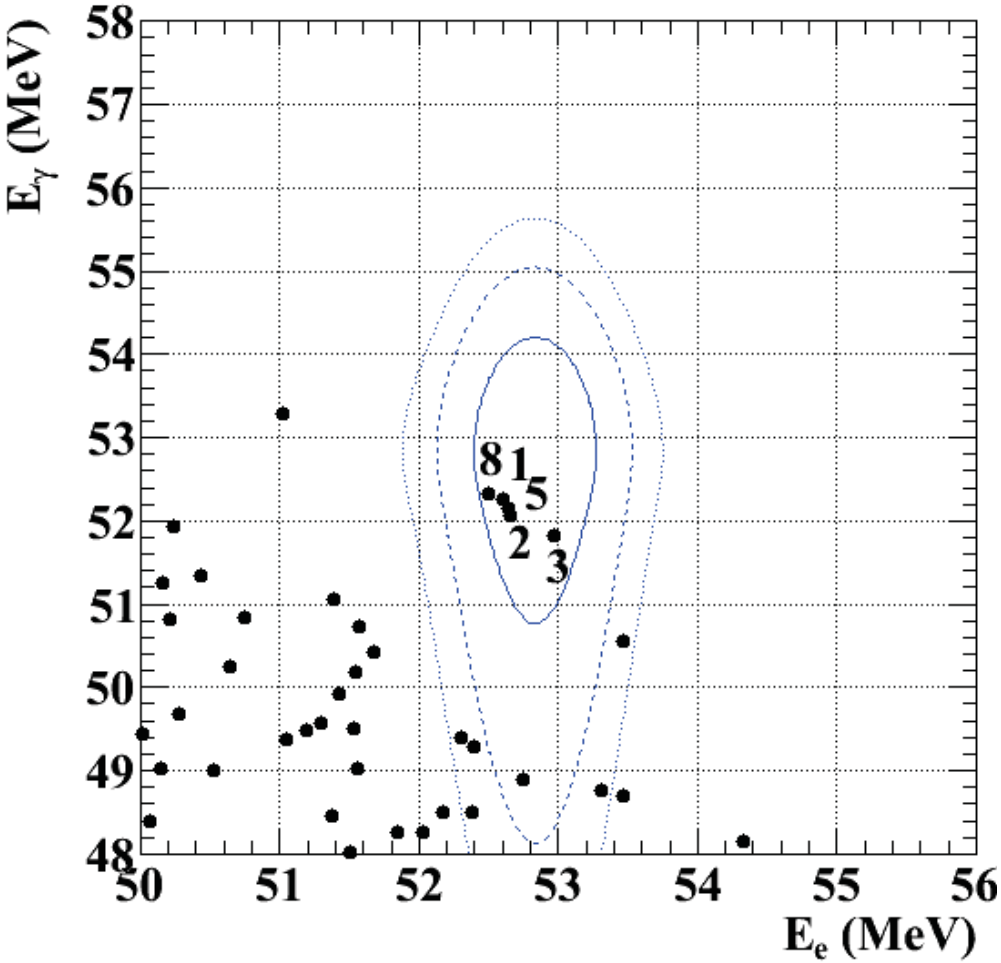


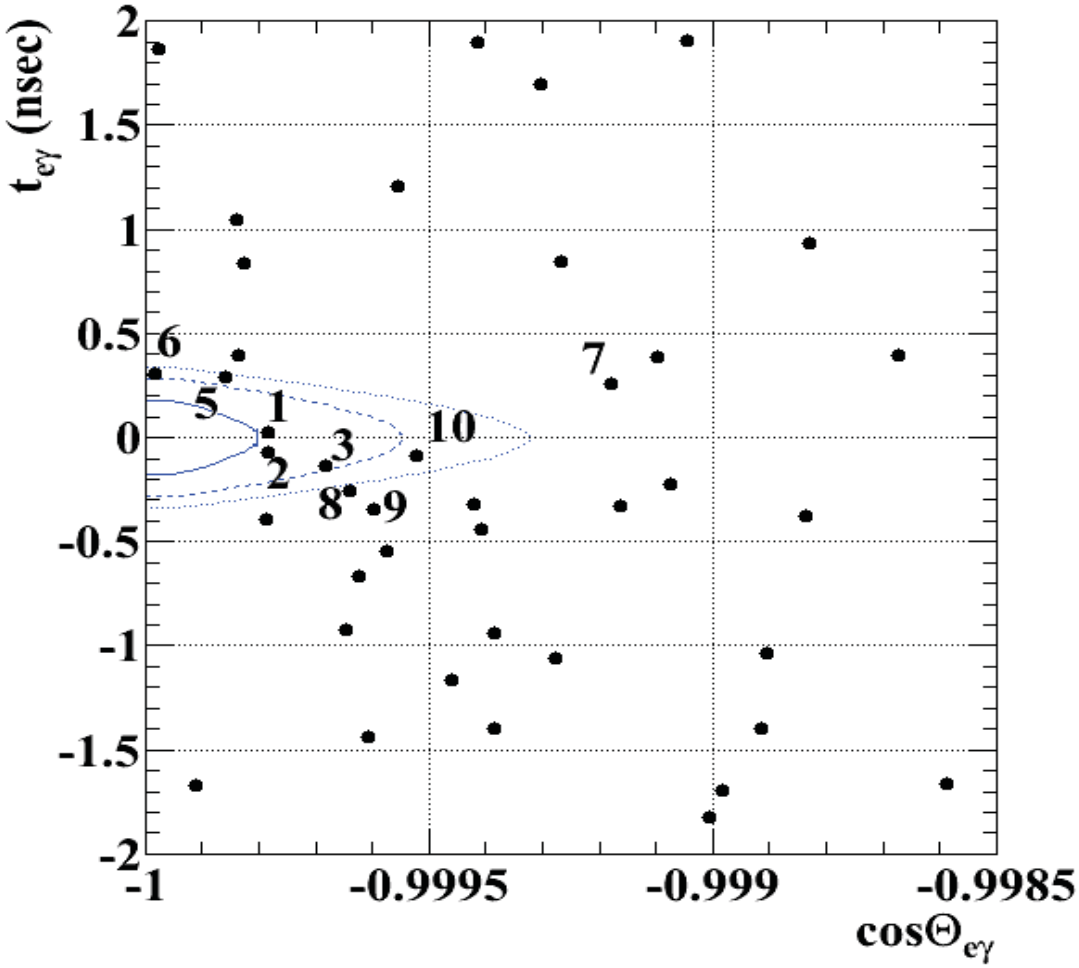


Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.

For each plot, cut on other variables for roughly 90% window is applied.

Event distribution after unblinding



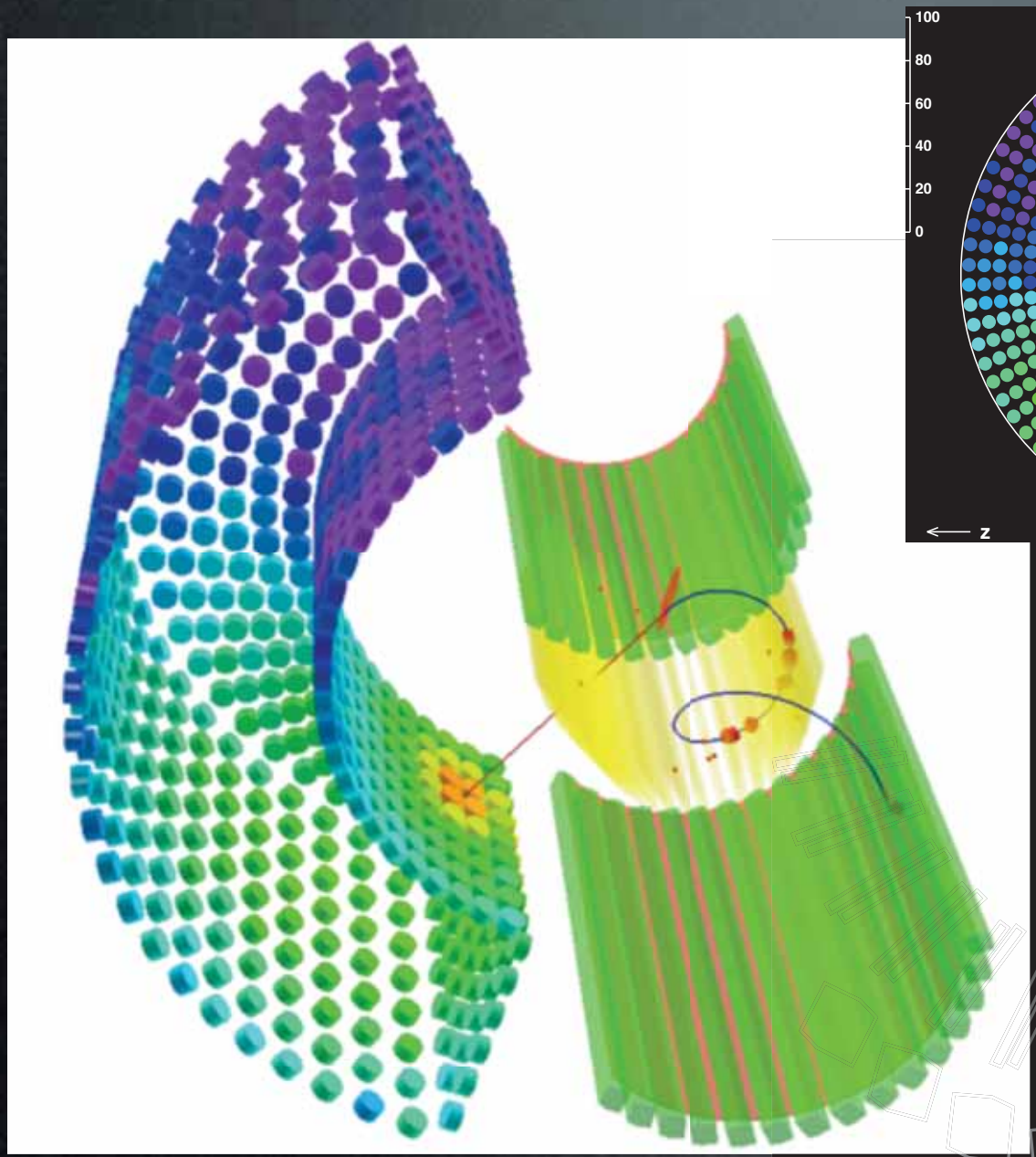


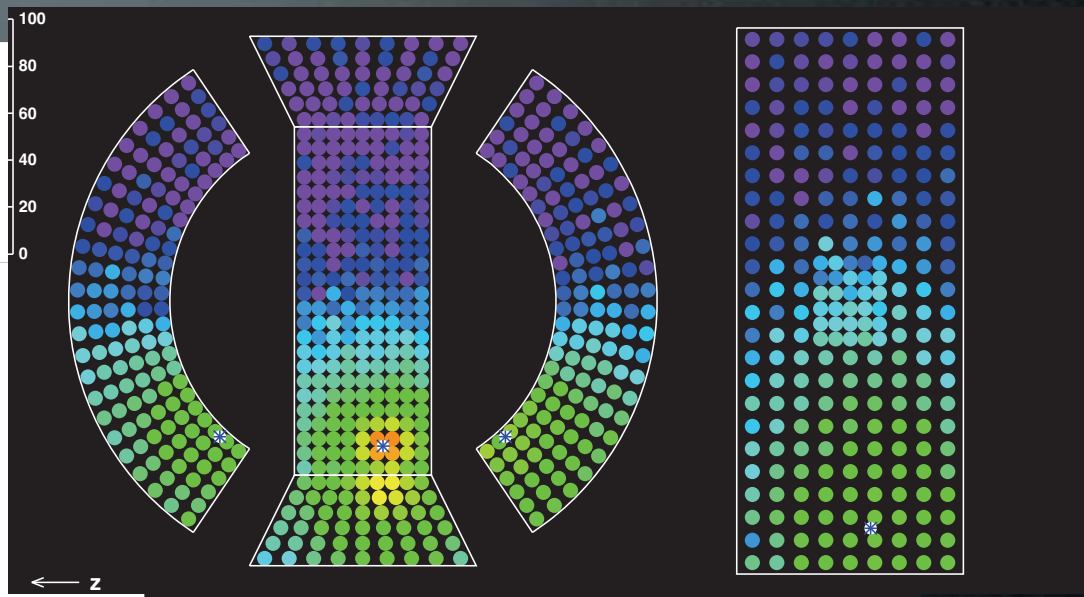
Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.

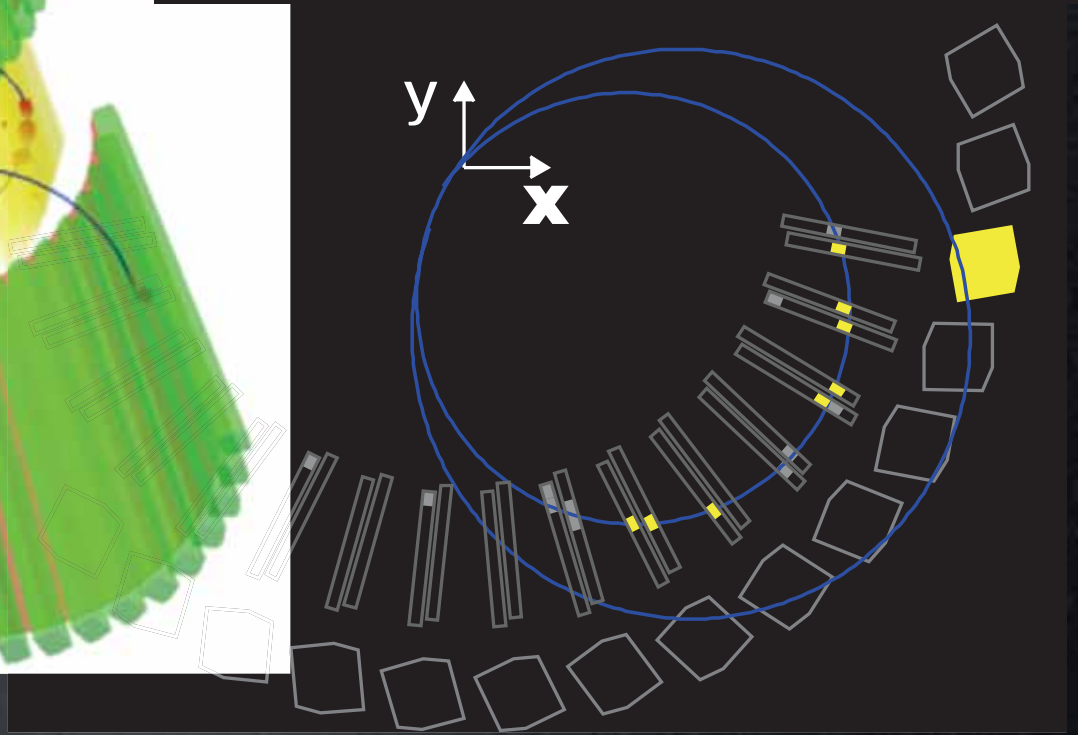
For each plot, cut on other variables for roughly 90% window is applied.

Numbers in figures are ranking by $L_{sig}/(L_{RMD}+L_{BG})$. Same numbered dots in the right and the left figure are an identical event.

A Signal Candidate

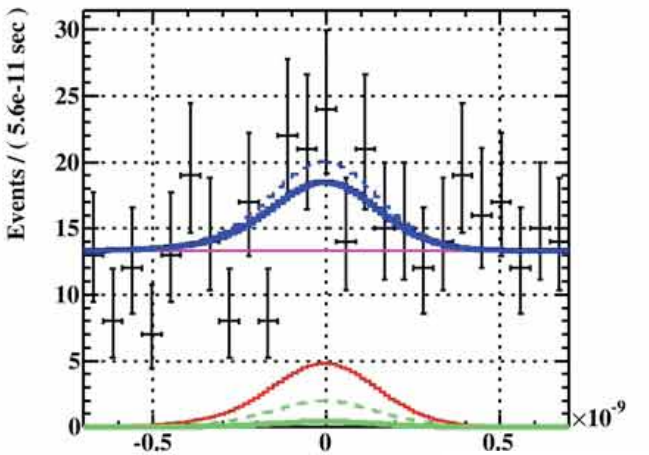




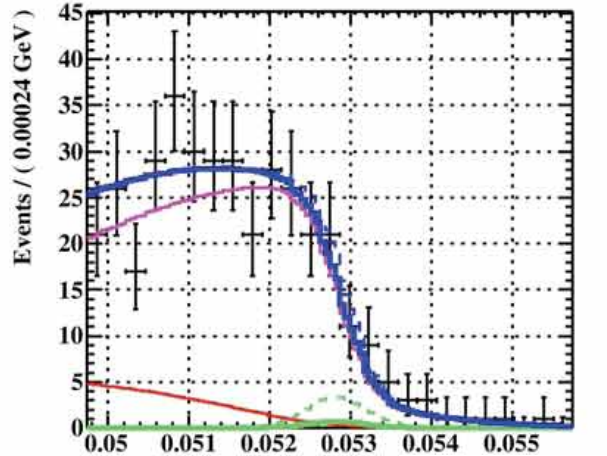


Fit Result

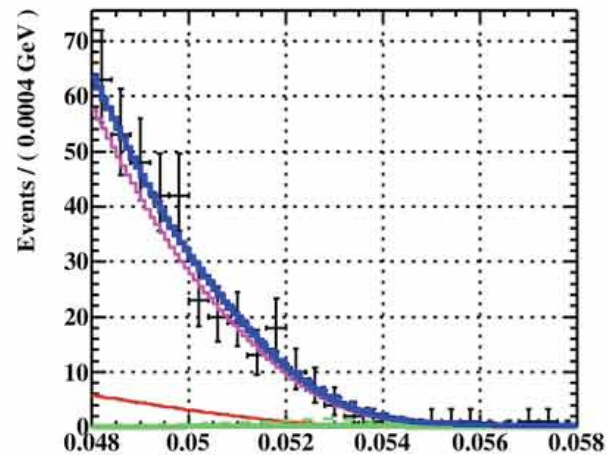
Preliminary



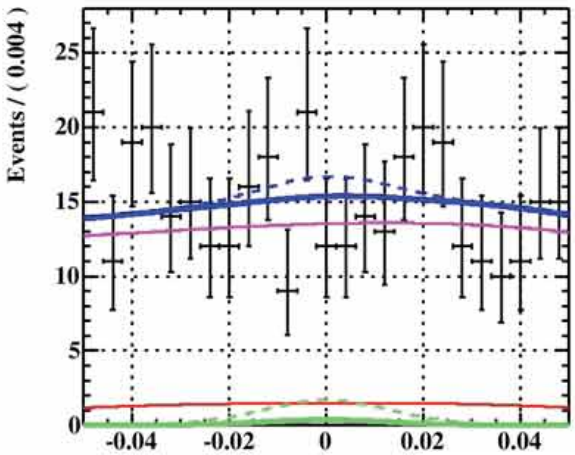
$T_{e\gamma}$ (sec)



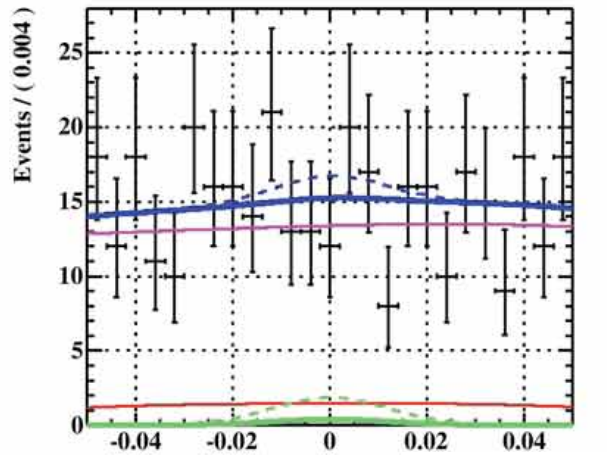
E_e (GeV)



E_γ (GeV)



$\theta_{e\gamma}$ (rad)



$\phi_{e\gamma}$ (rad)

Accidental BG
RMD
Signal
Total

$N_{RMD}=35^{+24}_{-22}$
(Expectation from sideband = 32±2)

Dashed lines : 90% C.L. UL of Nsig

Nsig < 14.5 @ 90% C.L

Nsig=0 is in 90% confidence region

Nsig best fit = 3.0

Fitting was done by three groups with different parametrization, analysis window and statistical approaches, and confirmed to be consistent (Nsig best fit = 3.0-4.5, UL = 1.2-1.5×10^{-11})

Systematic Uncertainty

	Uncertainty	
Normalization	8 %	e^+ mementum dep. $\oplus$ γ det. ε $\oplus$ trigger ε
E_γ scale	0.4 %	Light yield stability, gain shift
E_γ resolution	7 %	
E_e scale	50 keV	From Michel edge
E_e resolution	15 %	
$t_{e\gamma}$ center	15 ps	
$t_{e\gamma}$ resolution	10 %	RD peak
Angle	7.5 mrad	Tracking $\oplus$ LXe position
Angle resolution	10 %	
E_e-ϕ_e correlation	50%	MC evaluation

$\Delta N_{sig} \sim 1$

μ→eγ Branching Ratio

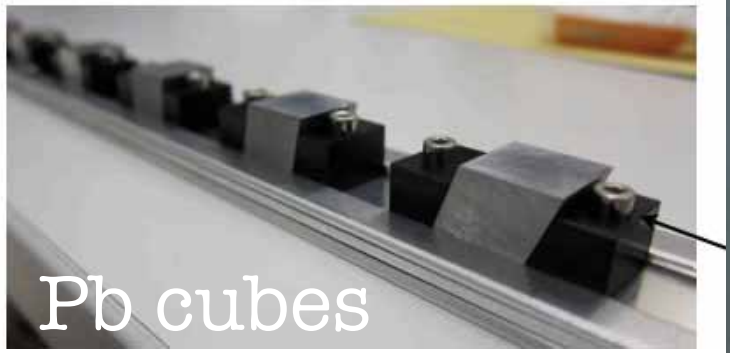
$$\frac{\mathcal{B}(\mu^+ \to e^+\gamma)}{\mathcal{B}(\mu^+ \to e^+\nu\bar{\nu})} = \frac{N_{\rm sig}}{N_{e\nu\bar{\nu}}} \times \frac{f^e_{e\nu\bar{\nu}}}{P \cdot \epsilon_{\rm pu}} \times \frac{\epsilon^{\rm trig}_{e\nu\bar{\nu}}}{\epsilon^{\rm trig}_{e\gamma}} \times \frac{\epsilon^{\rm DC}_{e\nu\bar{\nu}}}{\epsilon^{\rm DC}_{e\gamma}} \times \frac{1}{A^{\rm geo}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}}$$

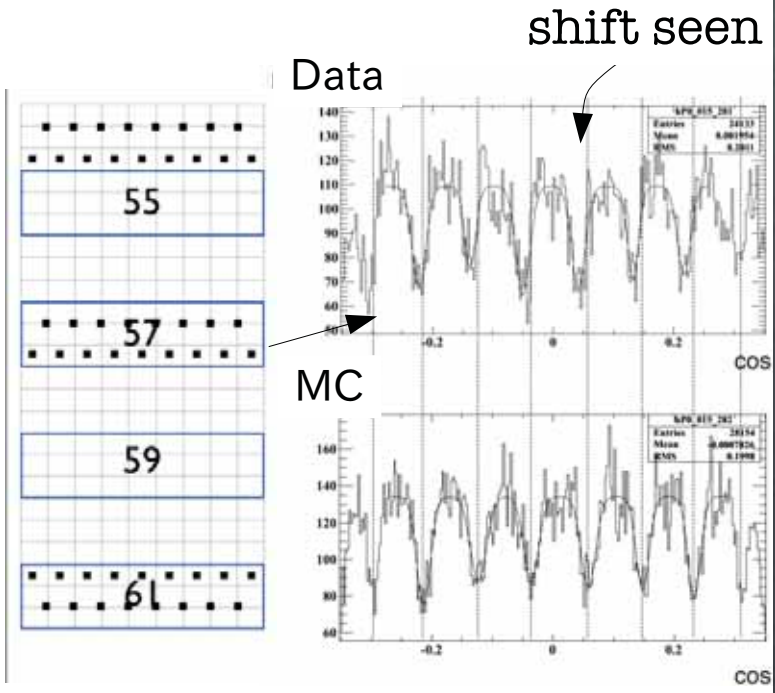
- Normalized to # Michel decays
  - e+ efficiency & instability canceled
  - BR = N_{sig} *(1.01+-0.08)* 10^{-12}
- BR < 1.5 * 10^{-11} @90% C.L. (preliminary)

Systematics resolved & improved

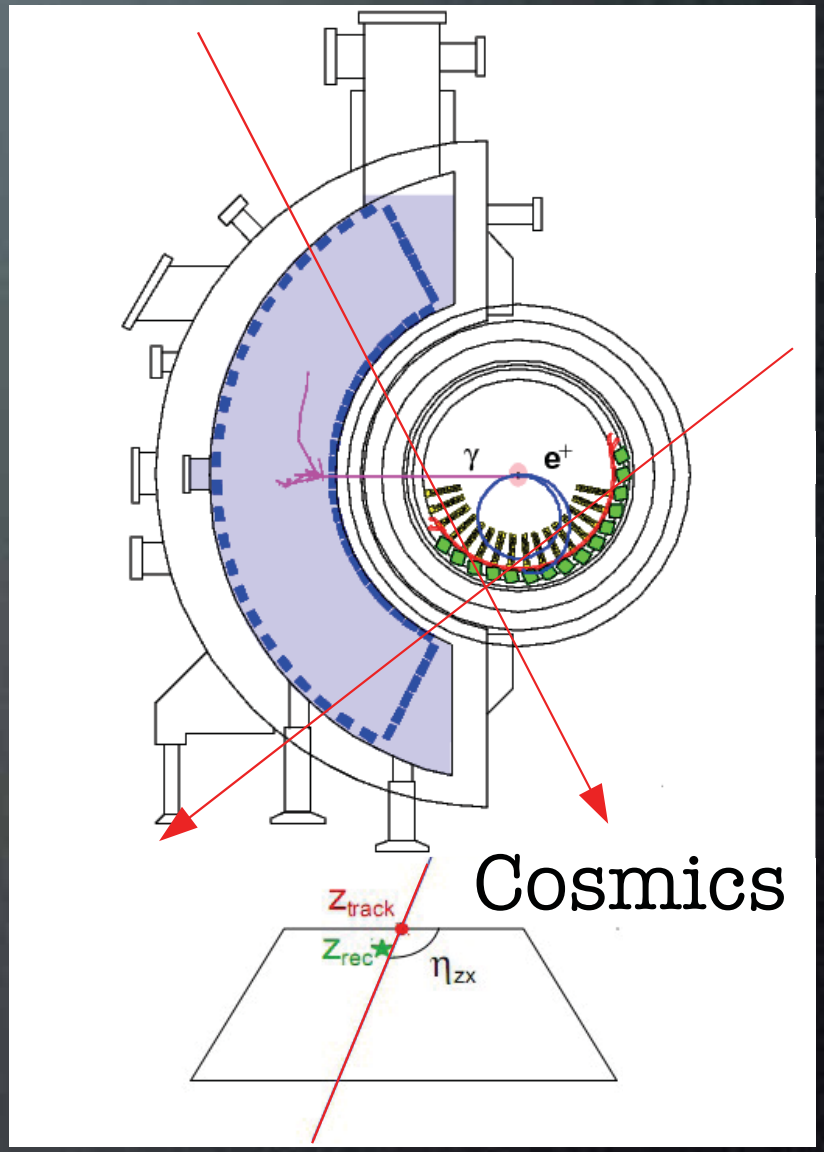
- Better understanding of e+ reconstruction and B field systematics
  - σ_p= 0.74 → 0.61%
  - $\sigma_{\phi,\theta}$= 7.4, 11.2 → 6.1, 9.4mrad
- Reduction of systematics in alignments among LXe, DC and target
- Improved Likelihood approach: FC+profile

Alignments





PMT position inside vessel



matching γ - e+

Updated 2009 Result

- In view of the progress in ongoing 2010 data analysis, we decided not to publish the updated 2009 result alone but to present the 2009 and 2010 results in a combined way in order to get a clearer picture of the origin of what we observed in 2009
- 2010 data = 1.9 times 2009 data

2010 Runs & Data Analysis

2010 Physics Run

- Delay at start-up
  - DC construction, LHe transfer line vacuum leak, muon target accident, injector problem, etc
- BTS quench on November 5
  - Premature end of physics run
  - ~67 days of physics DAQ
  - 1.9 times more statistics than 2009

2010 Physics Run

- Trigger
  - better online resolutions
  - better direction match: ~92% efficiency
- Electronics
  - less inter-board jitter: 130 -> 48ps
- Calibration
  - nNi 9MeV gamma, BGO for CEX, Mott
- LXe requires no LN_2 for operation

2010 Data Analysis

- in full progress
- already reaching the 2009 level resolutions

Preparation for 2011 Physics Run

- BTS
  - final full cold test successful
- Drift Chambers
  - chamber construction, new HV power supply to reduce noise, test of cell 0 problem
- TC Fiber Detectors for trigger
- DAQ Multiple buffer
  - tested, live time >99% @5Hz
  - trigger >99% w/ relaxed D-match & fiber

Improvements to come

- DC resolutions
  - noise reduction; Mott calibration
  - better understanding of B field
- Timing
  - positron TOF - DC resolutions, material effects
- Gamma-ray energy resolutions
- Angles
  - relative alignments < O(mm)
- Positron efficiency - DC material

Summary

- Hope to publish 2009 + 2010 combined result later this year:
  Sensitivity ~$1.5 * 10^{-12}$
- Starting 2011 run soon: Much more statistics to come!