Rare K-meson and lepton decays

A.M. Baldini – INFN Pisa

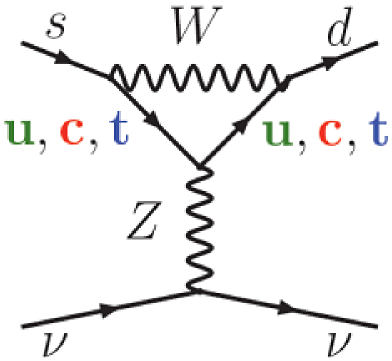
ICHEP PARIS 2010

OUTLINE

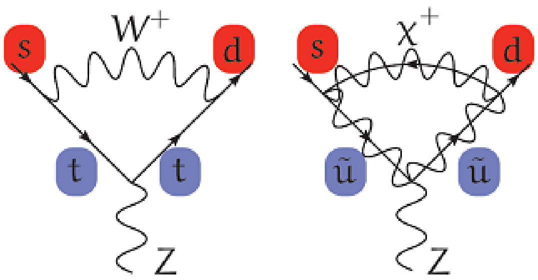
(Pardon!)

Ultra-rare K Decays

1) $K \to \pi \nu \bar{\nu}$



- The contribution to these processes due to the Standard Theory is strongly suppressed ($<10^{-10}$) and calculable with excellent precision (~%)
- They are very sensitive to possible contributions from New Physics



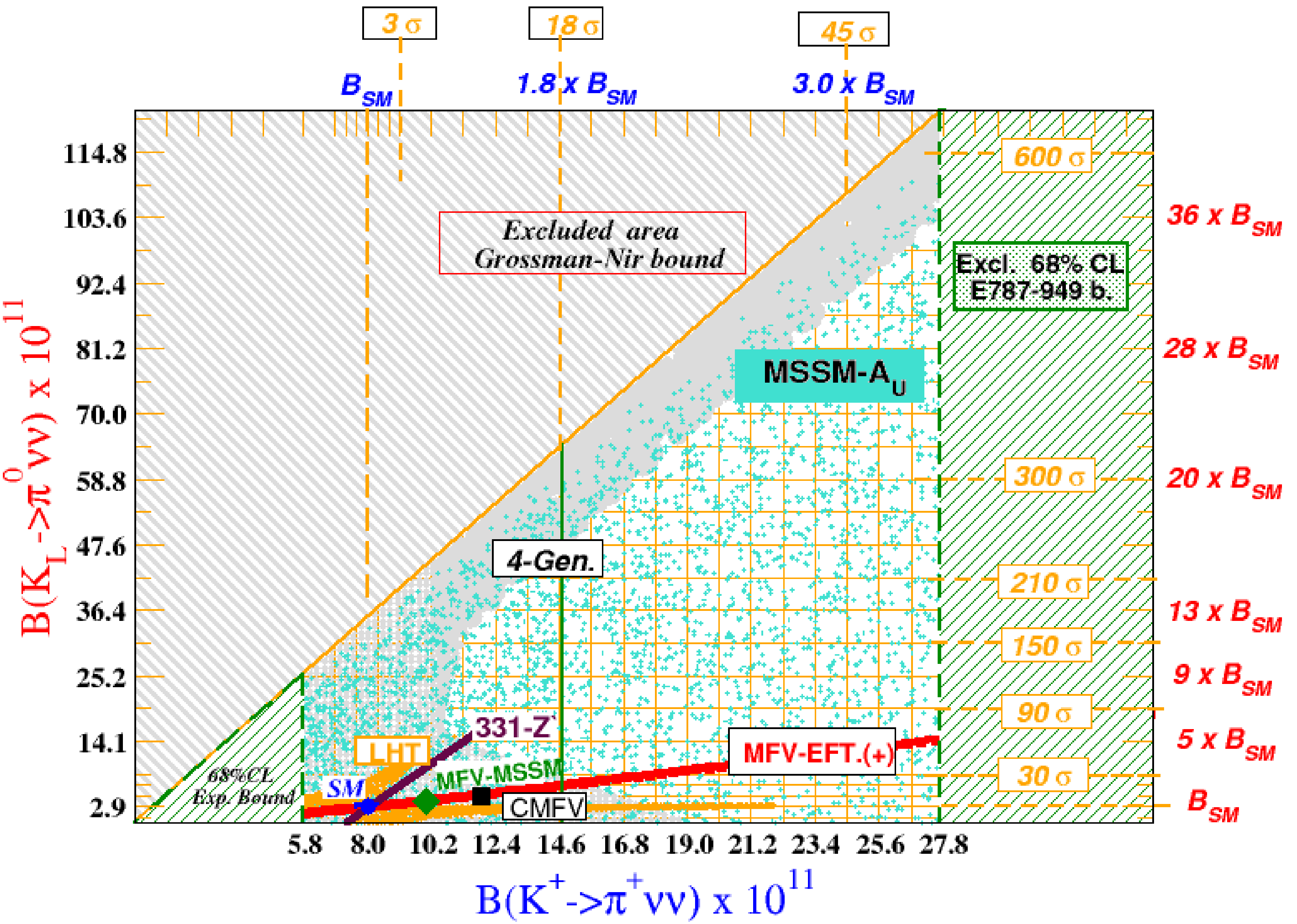
GGI March 24, 2010 Augusto Ceccucci 11

2)
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$
$$= (2.477 \pm 0.001) \times 10^{-5}$$
(V. Cirigliano, I. Rosell, JHEP 0710:005 (2007))

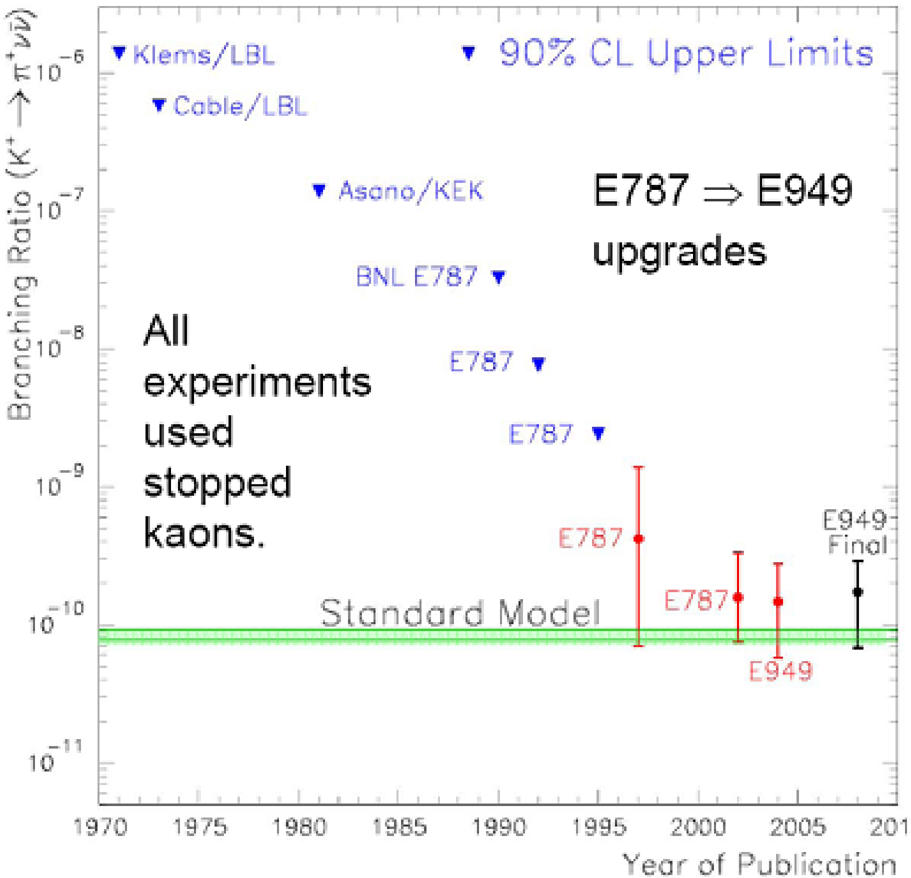
New Physics could contribute to up 1% (Masiero, Paradisi, Petronzio, PRD 74, 2006)

3) In the lepton case SM prediction unobservable! τ->lx, μ➔e γ

Observation = New Physics (Isidori's talk)


3 σ
18 σ
45 σ
B_{SM}
1.8 x B_{SM}
3.0 x B_{SM}
600 σ
300 σ
210 σ
150 σ
90 σ
30 σ
36 x B_{SM}
28 x B_{SM}
20 x B_{SM}
13 x B_{SM}
9 x B_{SM}
5 x B_{SM}
B_{SM}
Excluded area
Grossman-Nir bound
Excl. 68% CL
E787-949 b.
MSSM-A_U
4-Gen.
331-Z'
LHT
SM
MFV-MSSM
CMFV
MFV-EFT.(+)
68%CL
Exp. Bound
114.8
103.6
92.4
81.2
70.0
58.8
47.6
36.4
25.2
14.1
2.9
5.8
8.0
10.2
12.4
14.6
16.8
19.0
21.2
23.4
25.6
27.8
$B(K_L \to \pi^0 \nu\nu) \times 10^{11}$
$B(K^+ \to \pi^+ \nu\nu) \times 10^{11}$

$K^+ \to \pi^+ \nu\bar{\nu}$ History



J. Lewis Poster at this Conference

E787/E949 Final: 7 events observed

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$$

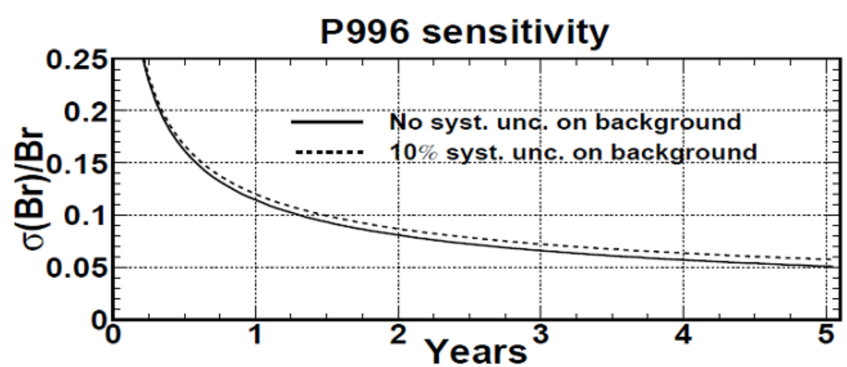
Standard Model:

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) x10^{-10}$$

Ratio P996/E949	
$11.3^{+3.3}_{-2.3}$	Detector acceptance
6.3 ± 2.1	Stopped kaons per hour
5.3	Hours per year

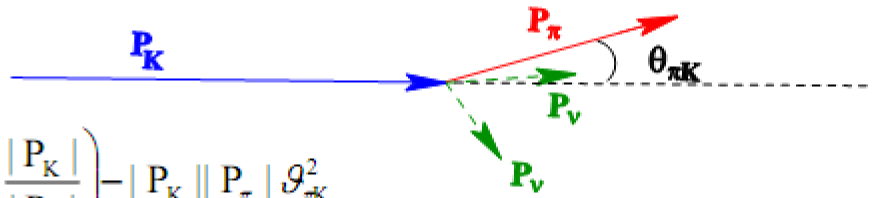
Tevatron used as a stretcher

200 events/year



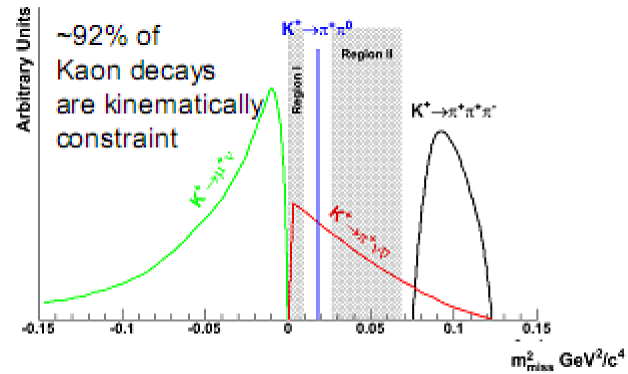
NA62 At CERN SPS

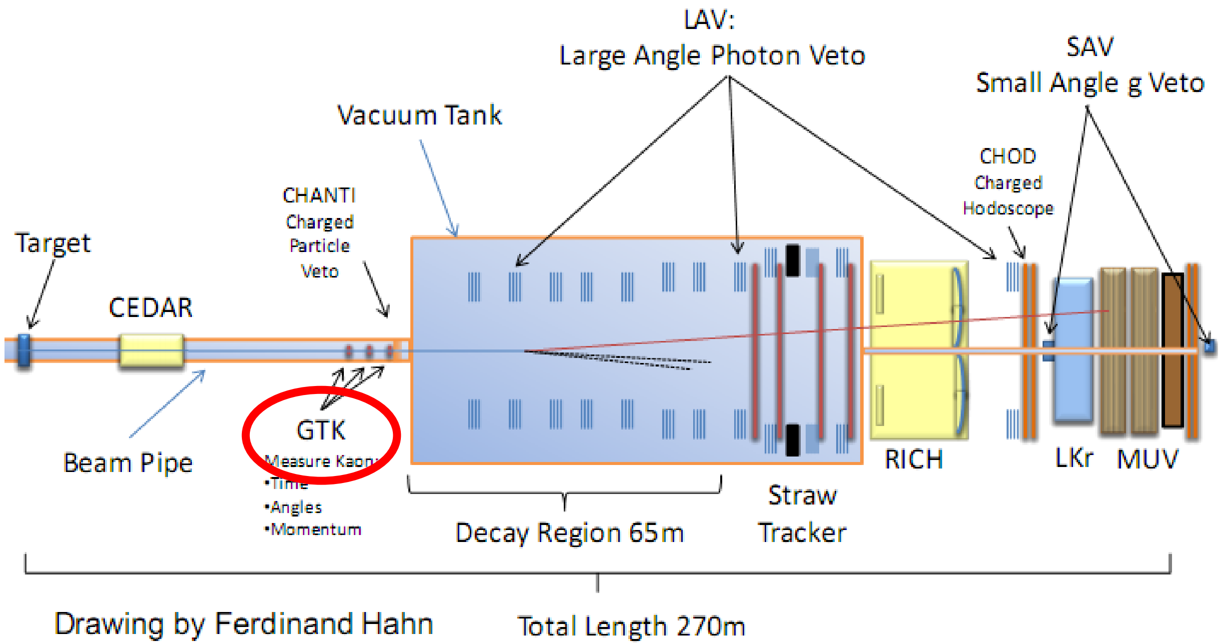
Unseparated K^+ (75 GeV/c) decay in flight



$$m^2_{miss} \approx m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta^2_{\pi K}$$

Decay	BR
$K^+\to\mu^+\nu$ ($K_{\mu2}$)	0.64
$K^+\to\pi^+\pi^0$ ($K_{\pi2}$)	0.21
$K^+\to\pi^+\pi^+\pi^-$ $K^+\to\pi^+\pi^0\pi^0$	0.07





- R&D/Construction phase
- Technical run: end of 2012

NA62 Sensitivity

Decay Mode	Events
Signal: $K^+ \to \pi^+ \nu \bar{\nu}$ SM [flux = 4.8×10^{12} decay/year]	55 *evt/year*
$K^+ \to \pi^+ \pi^0$ [$\eta_{\pi 0} = 2\times10^{-8}$ (3.5×10^{-8})]	4.3% (7.5%)
$K^+ \to \mu^+ \nu$	2.2%
$K^+ \to e^+ \pi^+ \pi^- \nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \to \pi^+ \pi^0 \gamma$	~2%
$K^+ \to \mu^+ \nu \gamma$	~0.7%
$K^+ \to e^+ (\mu^+) \pi^0 \nu$, others	negligible
Expected background	≤13.5% (≤17%)

Definition of "year" and running efficiencies based on NA48 experience:
~100 days/year; 60% overall efficiency

GGI March 24, 2010 Augusto Ceccucci 30

Meanwhile…from 48 to 62

$K \to e\nu / K \to \mu\nu$

Data taking:

Four months in 2007 (23/06 - 22/10):
~400k SPS spills, 300 TB of raw data (90 TB recorded), data preparation finished

Two weeks in 2008 (11/09 - 24/09):
Special data sets allowing reduction of systematic uncertainties

Magnetic spectrometer

Scintillator hodoscope

Liquid Kr EM calorimeter

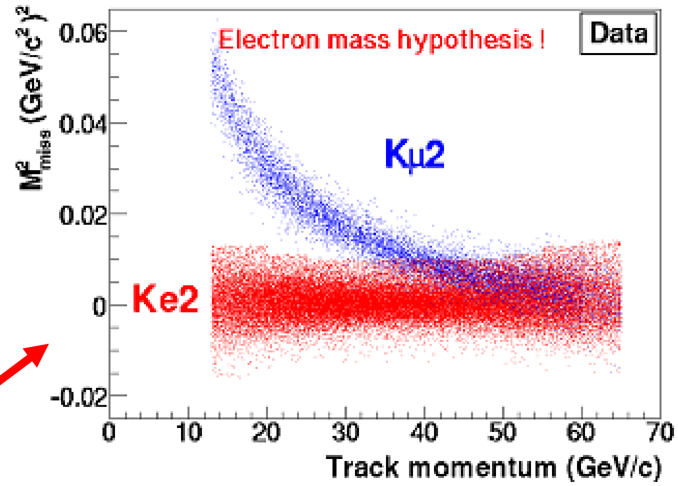
NA48

K_{e2} and $K_{\mu 2}$ selection

A. Winhart this Conference

Large common part (topological similarity)

- One reconstructed track
- Geometrical acceptance cuts
- Decay vertex defined as closest approach of track + nominal kaon axis
- Veto extra LKr energy deposition clusters
- Track momentum 13 - 65 GeV/c



Kinematic separation

Missing mass $M^2_{miss} = (P_K - P_l)^2$

P_K average measured with $K^{\pm} \longrightarrow 3\pi$ decays

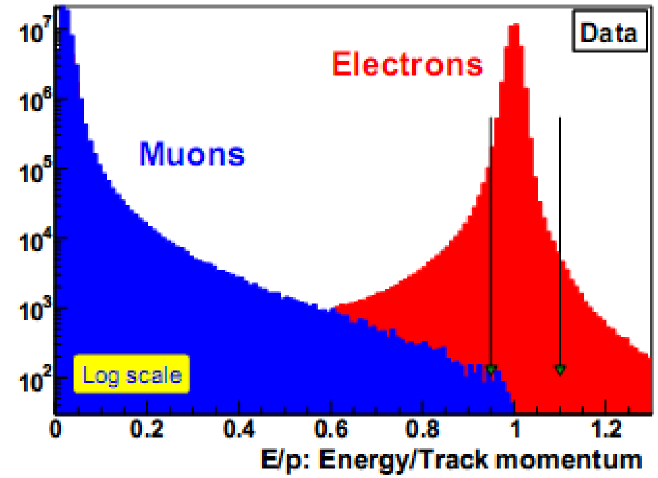
$\Rightarrow$ No $K_{\mu 2}$ background in K_{e2} only for momenta < 25 GeV/c (~ 15 % of data)

Particle identification

E/p LKr energy deposit / track momentum

<0.85 for muons, electrons: (0.90-0.95)<E/p <1.10

$\longrightarrow$ powerful $\mu^{\pm}$ suppression in $e^{\pm}$ sample ($\sim 10^6$)

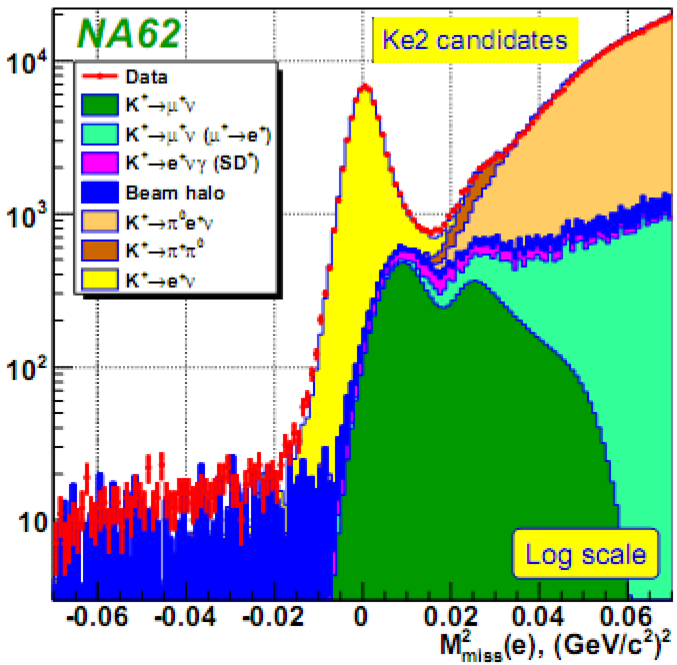


$P_{\mu e}$ / $R_K \sim 10\,\%$ $\Rightarrow$ $K_{\mu 2}$ decays represent the major background

Solution: direct measurement of $P_{\mu e}$

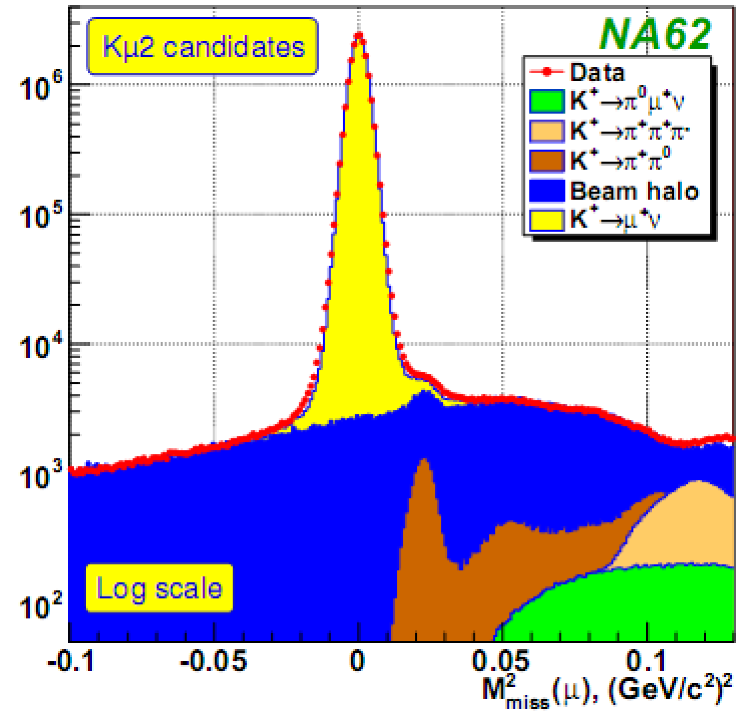
$\Rightarrow$ Lead wall ($9.2\ X_0$) in front of LKr (between the hodoscope planes)

40 % of data set



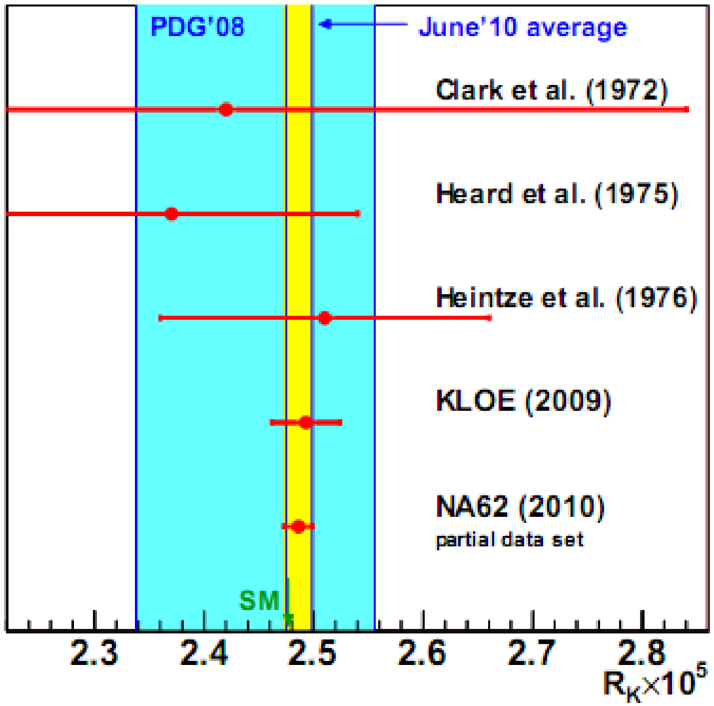
59963 $K^+ \to e^+\nu$ candidates
(99.27 ± 0.05) % electron ID efficiency
B/(S+B) = (8.8 ± 0.3) %

cf. KLOE: 13.8k candidates (both K^+ and K^-),
~ 90 % electron ID efficiency, 16 % bkg.



18.03M $K^+ \to \mu^+\nu$ candidates
with very low background
B/(S+B) = (0.38 ± 0.01) %

A. Winhart this Conference



World average	$R_K \times 10^5$	Precision
March 2009	2.467 ± 0.024	$0.97\,\%$
June 2010	2.487 ± 0.012	$0.48\,\%$

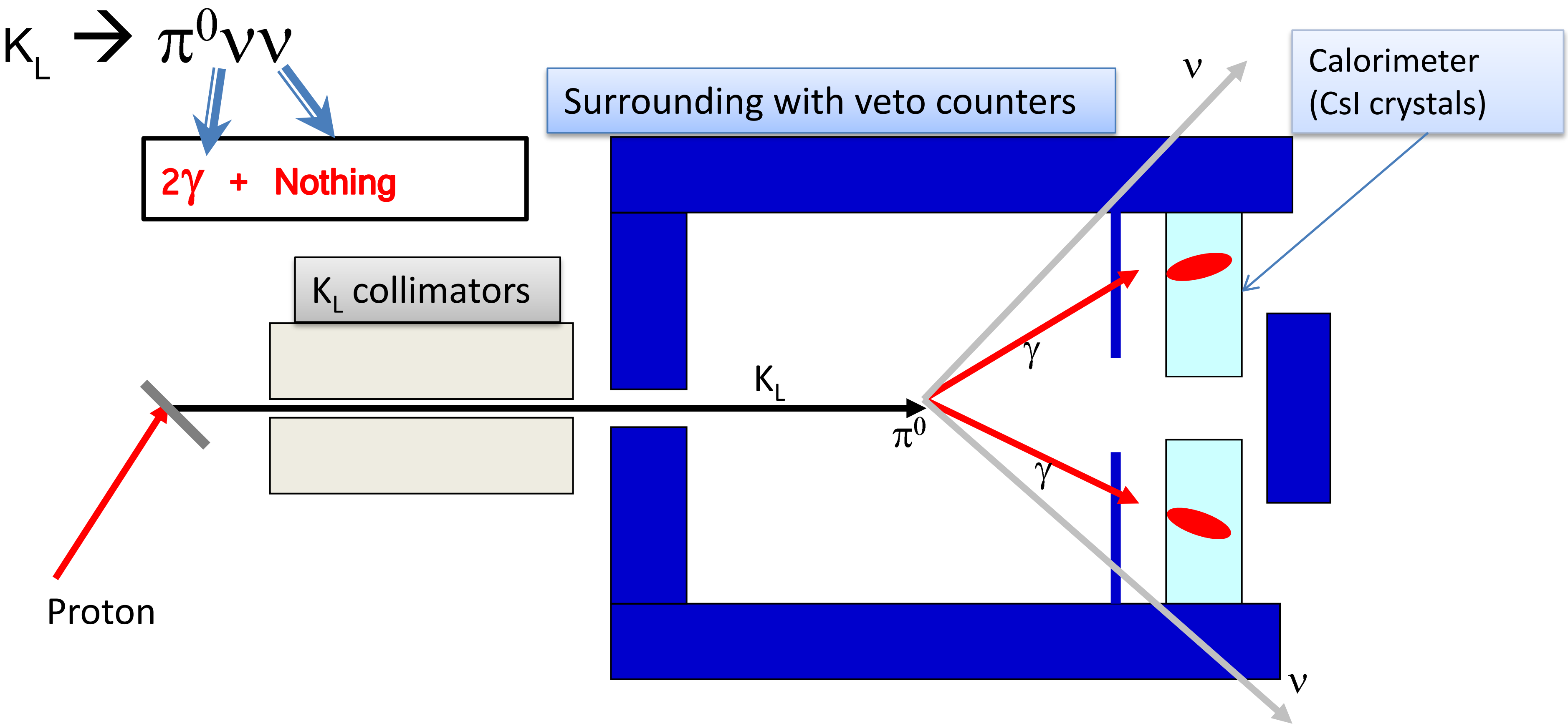
- Final result based on ($\sim 40\,\%$) of the NA62 K_{e2} sample: $R_K = (2.486 \pm 0.013) \times 10^{-5}$ with a record accuracy of $\sim 0.5\,\%$, being compatible with the SM prediction.
- With full data sample, overall uncertainty of 0.4 $\%$, as declared in the proposal, is within reach.
- Future experiments for further improvement: NA62 phase II (2013-2015) and KLOE-2 (> 2010) aim at ~0.2 $\%$ and ~0.4 $\%$ precision.

A. Winhart this Conference + Poster for $\pi\mu\mu$ and πee

Kloe: F. Archilli, Poster at this Conference

E391a (KEK) ➔KOTO (JPARC)

Experimental Method



1 . Hermetic veto with high detection efficiency: To count number of photons.
- $K_L \rightarrow \pi^0\pi^0$ ($\rightarrow 4\gamma$) is most serious background by missing 2 γ.

2. Pencil Beam : to obtain kinematical constraints. → K_L decay on Z-axis.
- reconstruction of decay vertex(Zvtx) and transverse momentum(P_T) of π^0.

H. Watanabe this Conference

Previous experiment: Sensitivity in KEK-E391a

Run	Run period	POT
Run-1	Feb.–Jun. 2004	2.1×10^{18}
Run-2	Feb.–Apr. 2005	1.4×10^{18}
Run-3	Oct.–Dec. 2005	1.1×10^{18}

→ PRD 74,051105(R) (2006)
→ PRL 100,201802 (2008)
→ PRD 81,072004 (2010)

- Number of K_L decay

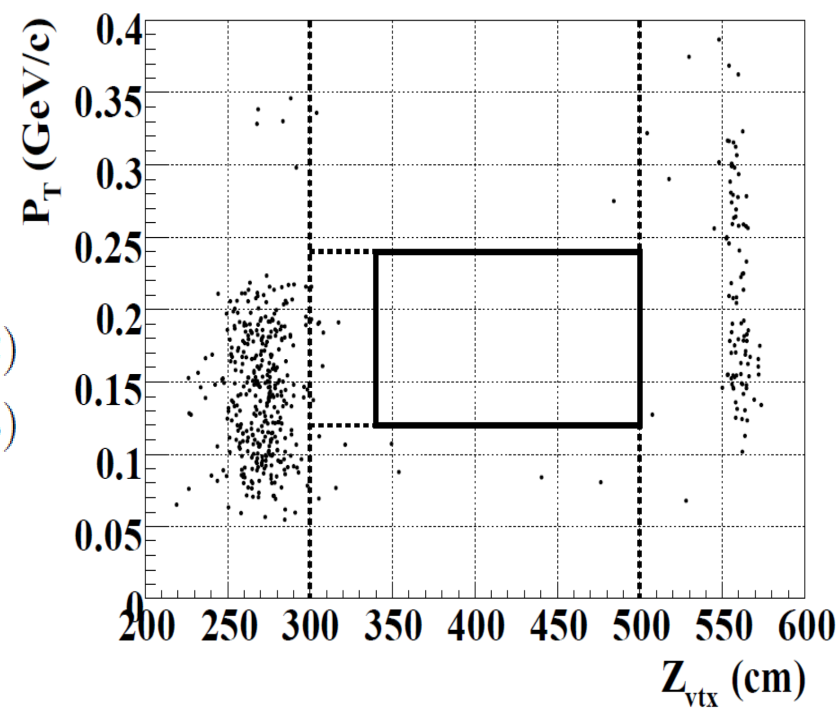
$$(8.70 \pm 0.17_{\mathrm{stat.}} \pm 0.59_{\mathrm{syst.}}) \times 10^9$$

- Signal Acceptance

$$A_{\mathrm{signal}} = (1.06 \pm 0.08)\% \quad (\text{for Run-2})$$
$$A_{\mathrm{signal}} = (1.01 \pm 0.06)\% \quad (\text{for Run-3})$$

- Single event sensitivity

$$(1.11 \pm 0.02_{\mathrm{stat.}} \pm 0.10_{\mathrm{syst.}}) \times 10^{-8}$$



$Br(K_L \rightarrow \pi^0 \nu\nu) < 2.6 \times 10^{-8}$

H. Watanabe this Conference

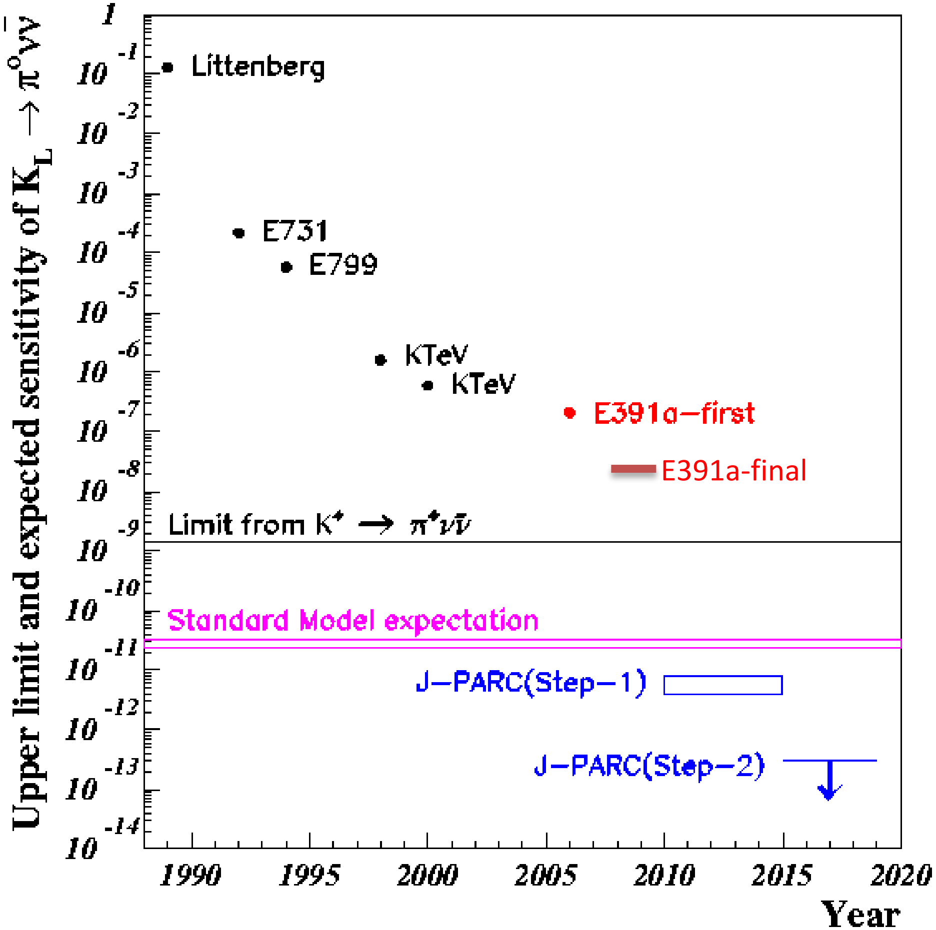
Strategy

✓ Step by Step approach.

✓KEK-E391a (previous experiment)
→Establishment of experimental method.

✓J-PARC Step-1 (E14 KOTO)
→ First observation.
→ Search for enhancement by New Physics.

✓J-PARC Step-2
→ > 100 events

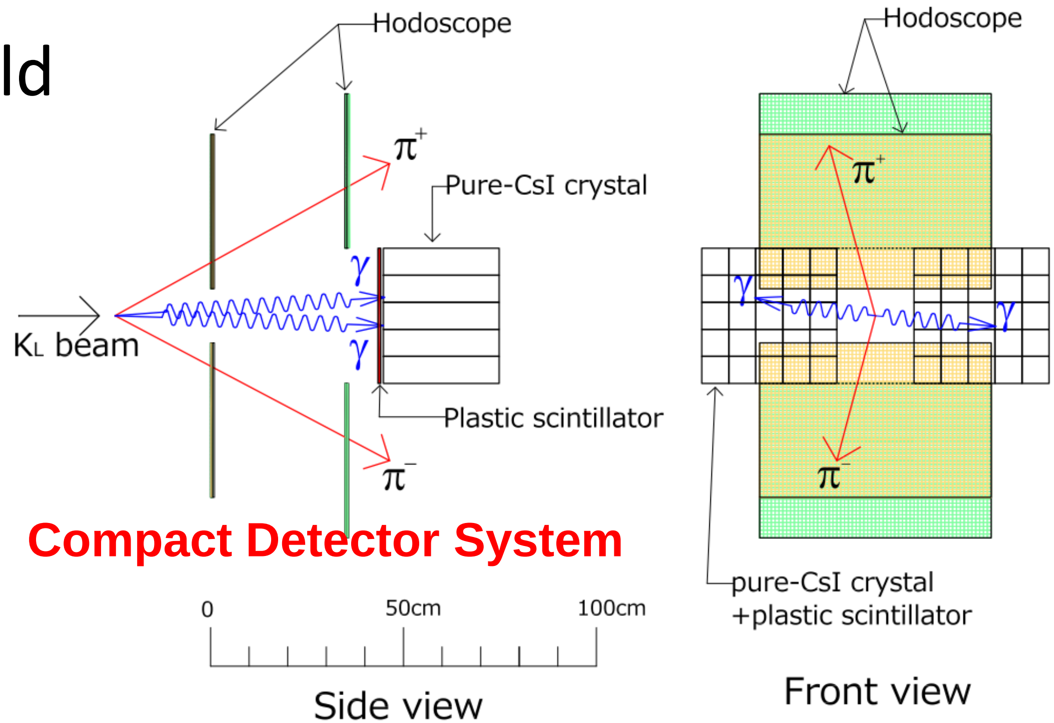


H. Watanabe this Conference

Measurement of K_L Yield by detecting $K_L \rightarrow \pi^+\pi^-\pi^0$

✓No data for 16° extraction at 30GeV.
✓Big differences betw. M.C. simulations.

MC package	#KL/2E+14pot
GEANT3	1.5×10^7
GEANT4(QGSP)	0.88×10^7
GENAT4(QBBC)	1.0×10^7
FLUKA	3.2×10^7

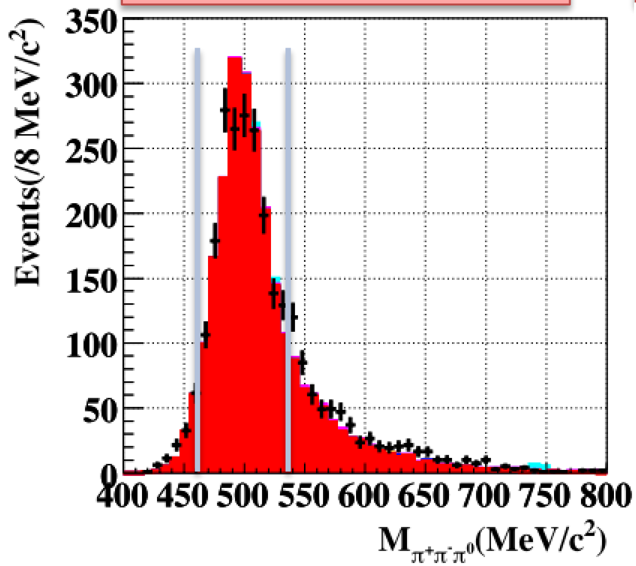


1905 events were observed.
→1.83×10^7 K_L's/2×10^{14} p.o.t.
(*preliminary number)

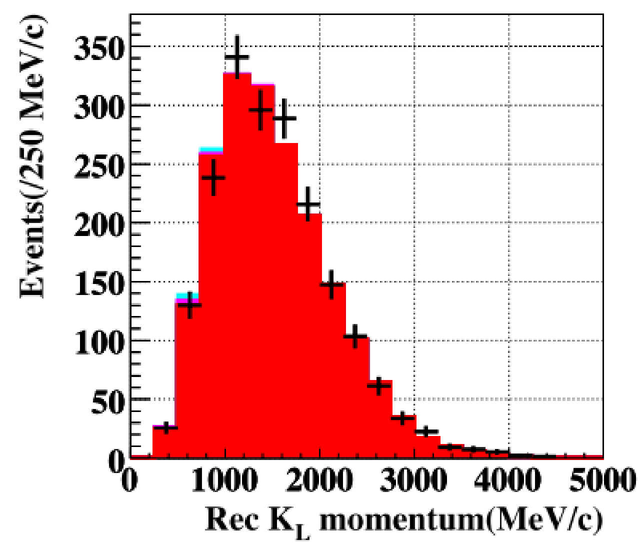
It corresponds to
- **Proposal-yield x 2.3**
  (*MR DCCT normalization)

Poster K. Shiomi at this Conference

Reconstructed Mass.



Reconstructed K_L Momentum



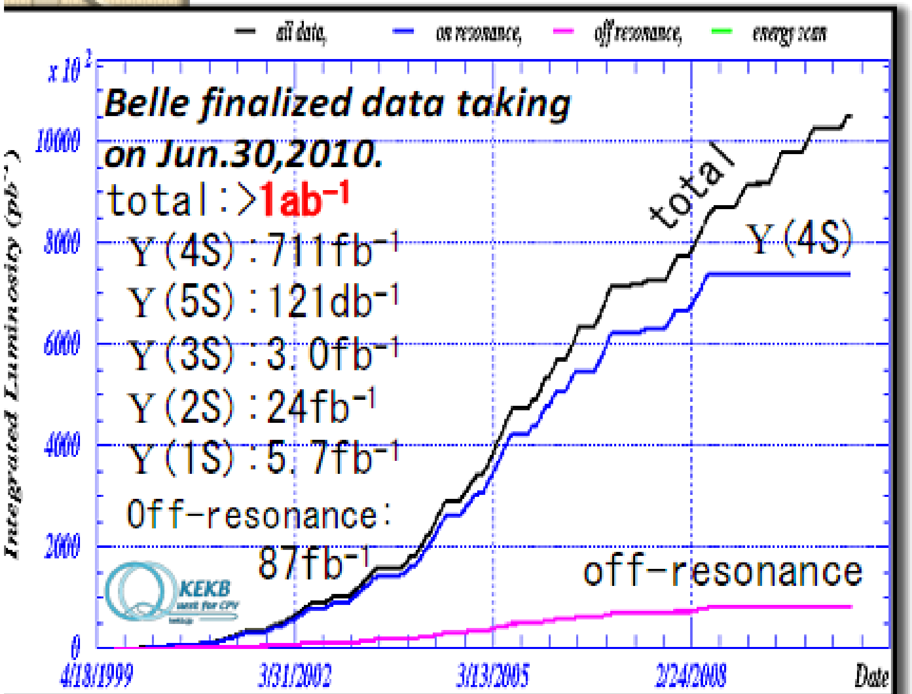
H. Watanabe this Conference

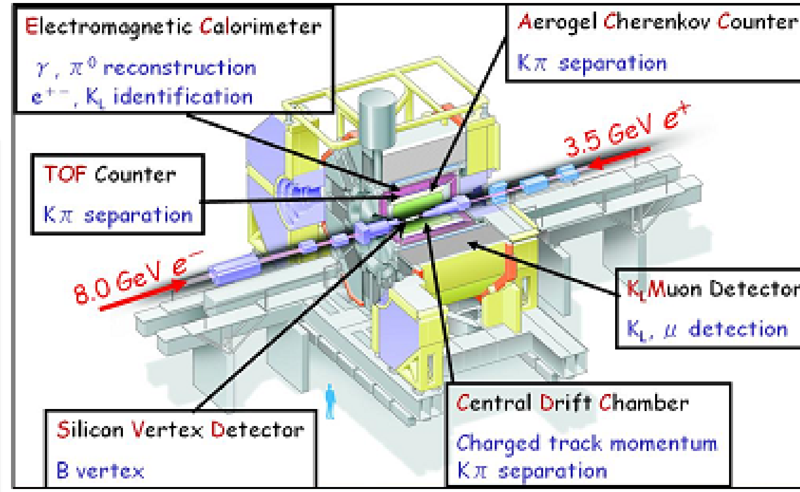
Leptons: $\tau \rightarrow l\ x$

KEKB/Belle

B-factory: E at CM = Υ(4S)

e^+(3.5 GeV) e^-(8 GeV)





Good track reconstruction and particle identification

Lepton ID ~ (80-90)%

Fake ID ~ (0.1-3)%

$\sigma(\tau\tau)$~0.9nb, $\sigma(b\bar{b})$~1.1nb

A B-factory is also a τ-factory!

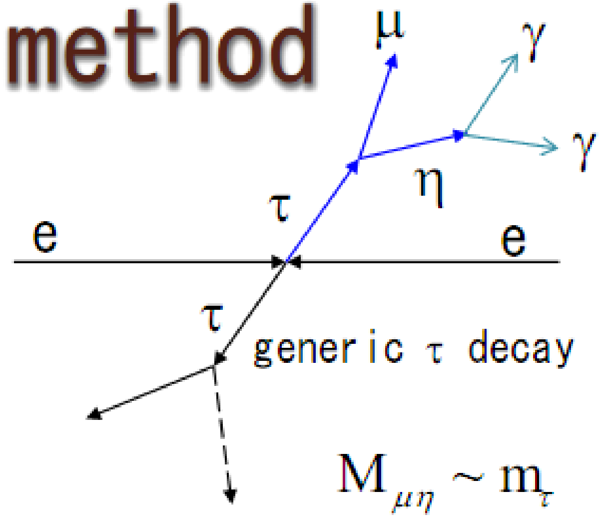
World-largest data sample!

~9×10^8 $\tau\tau$ at Belle

K. Hayasaka this Conference

2010/7/23 35th ICHEP2010, Paris 4

Analysis method



- $e^+e^- \rightarrow \tau^+\tau^-$
  - → 1 prong + missing (tag side)
  - → $\mu+\eta$ (signal side)
    - → $\gamma+\gamma$

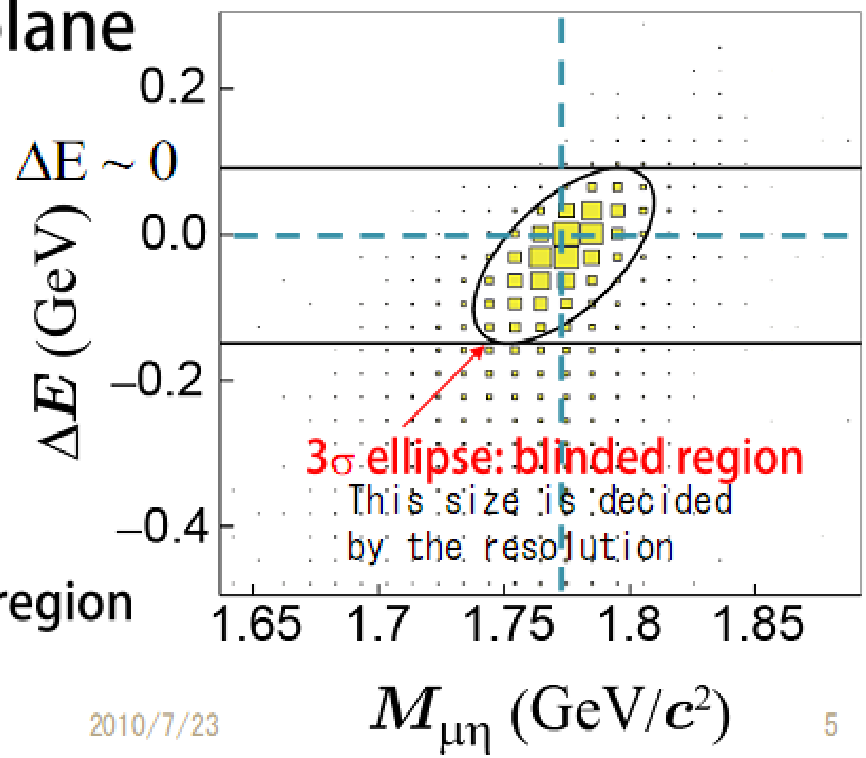
Signal extraction: $M_{\mu\eta}$-ΔE plane

$$M_{\mu\eta} = \sqrt{(E_{\mu\eta}^2 - p_{\mu\eta}^2)}$$

$$\Delta E = E_{\mu\eta}^{CM} - E_{beam}^{CM}$$

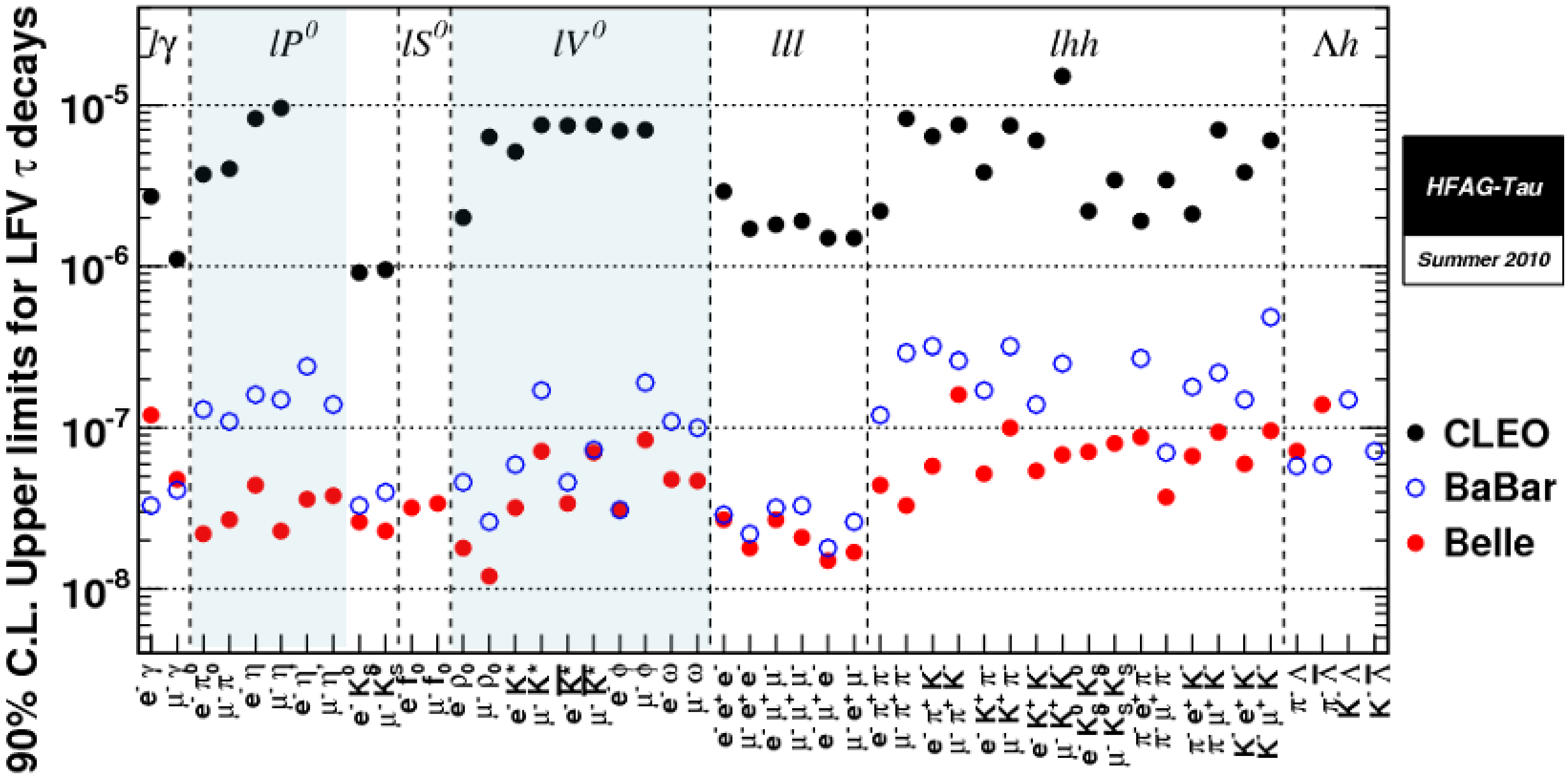
Blind analysis
⇒Blind signal region

Estimate number of BG in the singal region
using sideband data and MC



K. Hayasaka this Conference

New Upper Limits on LFV τ Decay



Our sensitivity reaches O(10^{-8})!

100x more sensitive than CLEO's

2010/7/23 35th ICHEP201

$$\left(\frac{BR(\tau \to \mu\gamma)}{BR(\mu \to e\gamma)}\right) \approx 10^{3\div5}$$

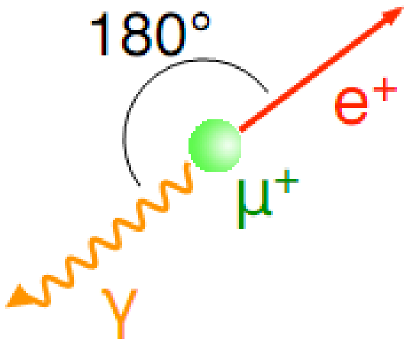
@ SuperB factories one order of magnitude improvement

K. Hayasaka this Conference

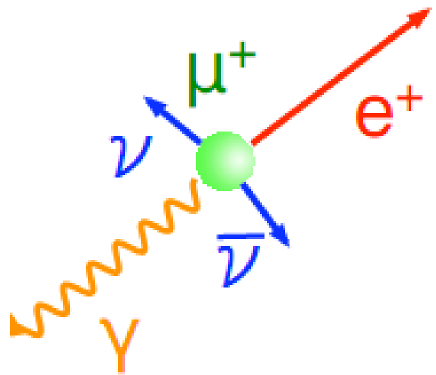
$\mu \rightarrow e\,\gamma$

Signal and Background

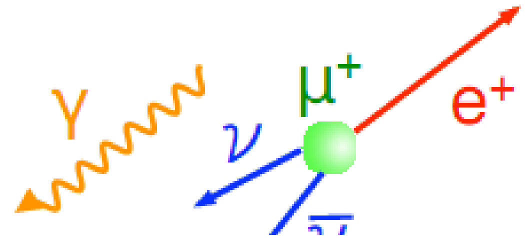
Signal



Prompt Background



Accidental Background



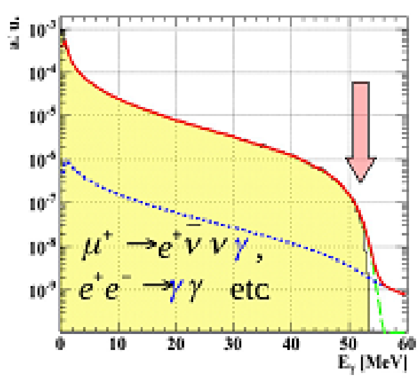
$$B_{acc} \propto \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \vartheta_{e\gamma})^2 \cdot \delta t_{e\gamma}$$

e γ	Signal	Radiative muon decay	Accidental pileup
Angle	Back-to-Back	Any angle	Any angle
Energy	52.8 MeV/c	< 52.8 MeV/c	< 52.8 MeV/c
Time	Same time	Same time	Flat

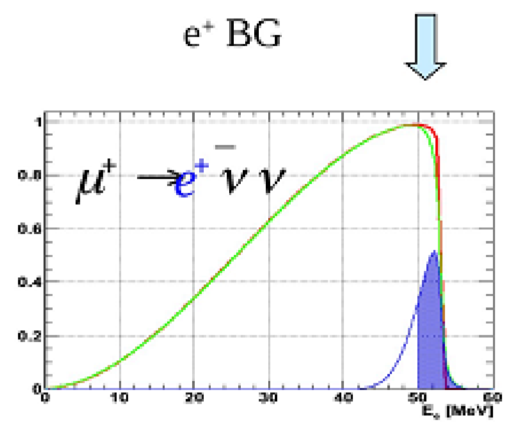
Dominant background is accidental.

Detector resolution is crucial.

γ BG



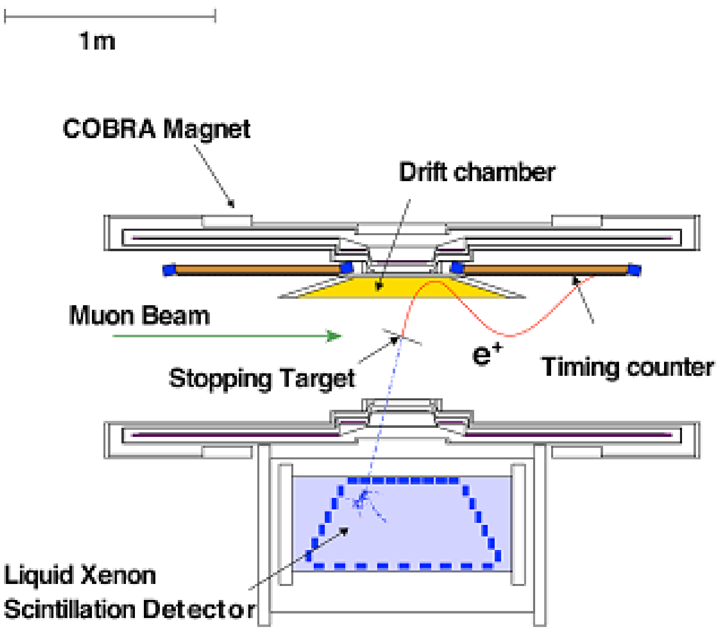
e+ BG

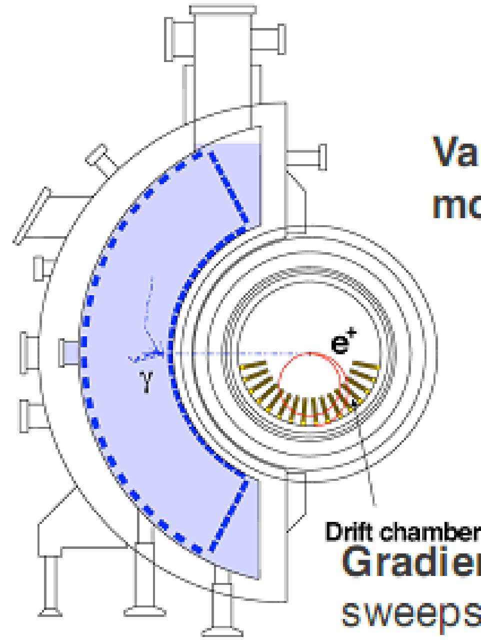


MEG: The Experiment

PSI : most intense DC muon

Beam transport system
stopping rate up to 10^8/sec on target





Various calibration and monitoring systems.

Gradient field SC magnet
sweeps out high rate e+ quickly
Constant bending radius of e+

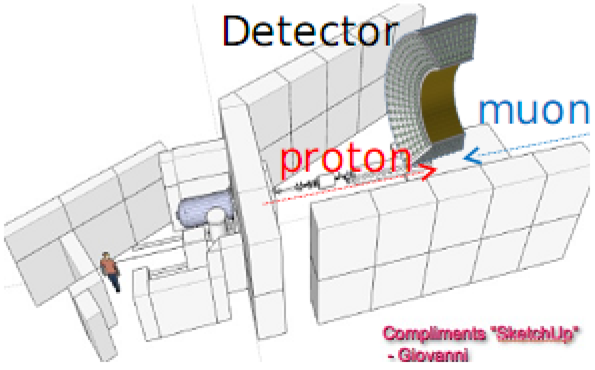
Drift chamber
Made of light materials
Precise measurement of positron tracks

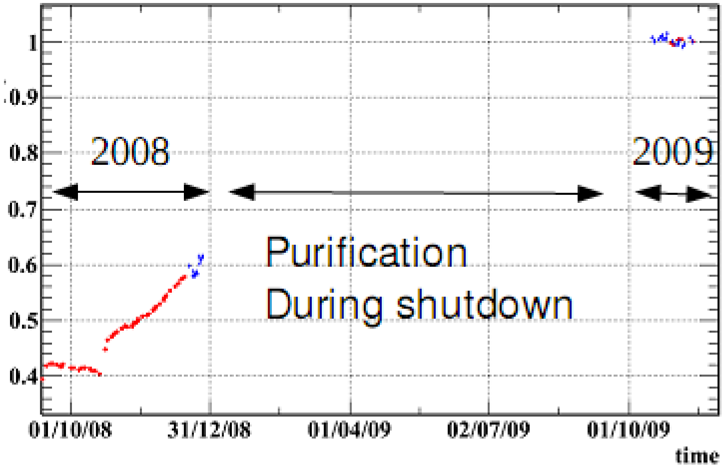
Timing counter
Good time resolution
Work in B-field

LXe gamma detector
2.7 tons of liquid xenon
Good time, position energy resolution
Fast signal : pileup identification

Calibration and Monitoring

- PMT gain monitored by LED, QE by α
- Light yield monitoring (CW, CR, AmBe etc.)
- Cockcroft-Walton proton accelerator
  - 17.6MeV γ by Li(p,γ)Be reaction
  - Light yield monitoring & σ_E at 17.6MeV





2008 physics run and shutdown:
gaseous purification to increase light yield

Light yield became as much as expected
And decay time of γ waveform changed

2009 physics run: no purification

Light yield monitoring: < 1% level

Time line and 2009 run

2008.sep-dec : **Physics data taking**
(lower efficiency and resolutions due to hardware problem)

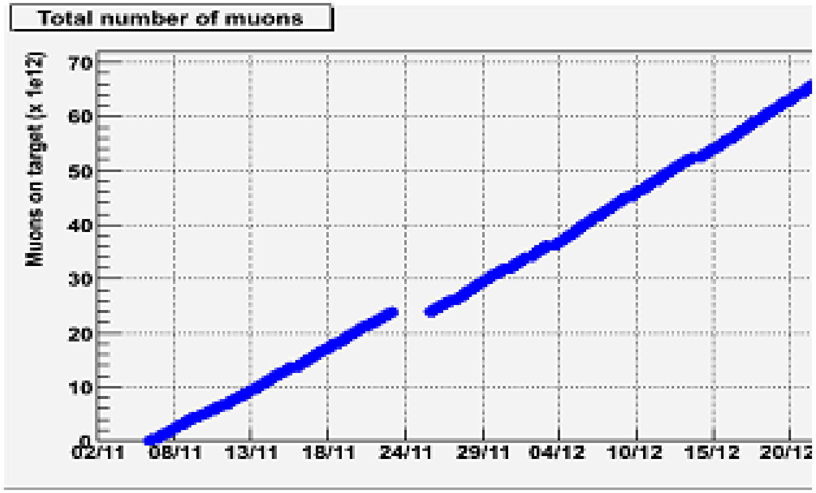
2008 run result : Sensitivity = 1.3×10^{-11}
90% U.L. = 2.8×10^{-11}

2009 : Analysis of 2008 data
Hardware upgrades

2009.nov-dec : **Physics data taking**

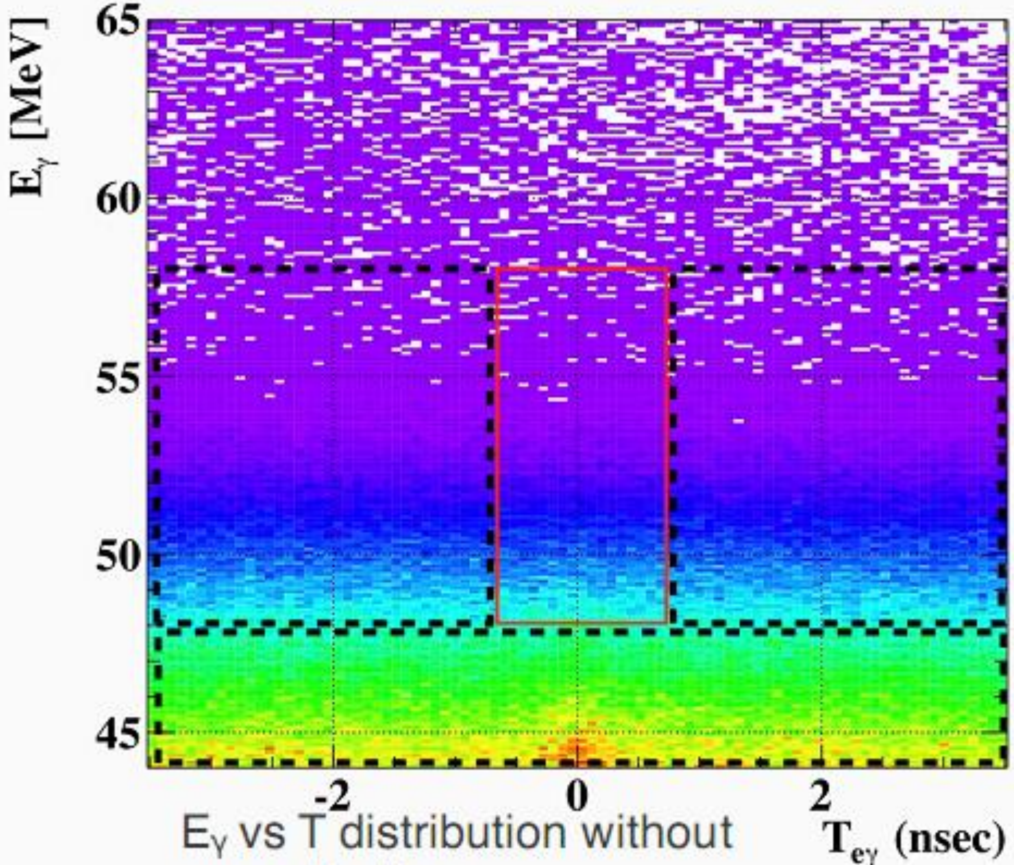
2009.dec- : Analysis of
2009 data
Hardware upgrades

2010.jul- : Physics data taking



43 days physics data taking

Data samples



E_γ vs T distribution without any selection.

Analysis box (~10σ width)

- $48 \leq E_\gamma \leq 58$ MeV
- $50 \leq E_e \leq 56$ MeV
- $| T_{e\gamma} | \leq 0.7$ ns
- $| \phi_{e\gamma} |, | \theta_{e\gamma} | \leq 50$ mrad*

Analysis box was blinded during calibration and optimization of physics analysis.

Time and E_γ sideband

- Accidental background PDF was made directly from sideband data. (Important because dominating background is accidentals)
- Positron detector response is studied by using Michel positrons.
- Time resolution is measured by using RMD peak in low gamma energy sideband.

* Angle is between gamma and flipped positron vectors.

Analysis Method

Extended unbinned maximum likelihood analysis on number of events

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

"BG" in this talk means accidental background.

Event types : Signal, RMD and Accidental background

Observables : E_γ, E_e, Relative time and Relative angle

- Fit is done for wide widow (about 10σ of each variable), and background events are fitted together.
- Fit is done by three independent likelihood analysis tools to check possible systematic effects.
- Event-by-event PDF
  - Position dependent PDF of gamma rays.
  - Two category PDF of positrons by reconstruction quality (fitting uncertainty etc.)
- Most of PDFs are made from data (next slide)
- RMD PDF is formed from theoretical shape and detecter response.

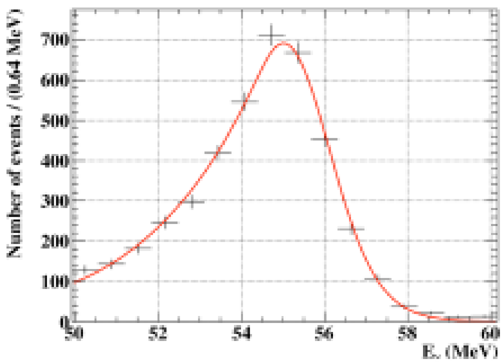
Normalization factor is obtained from number of observed Michel positrons taken simultaneously.

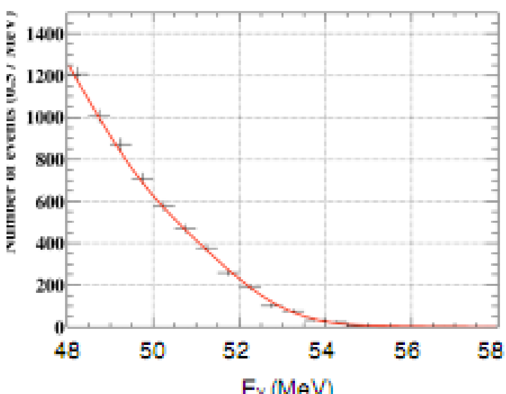
Preliminary

B.R. = Nsig / 1.0 ± 0.1 × 10^{12}

PDFs

55 MeV π^0 peak





Gamma

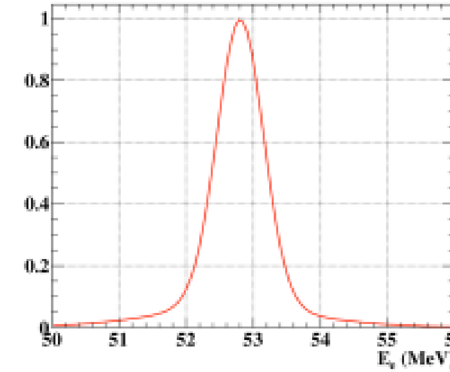
Signal PDF from 55MeV calibration gamma (π^0 decay)

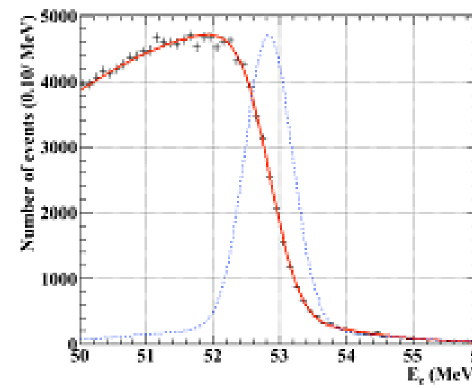
BG measured in sideband

Positron

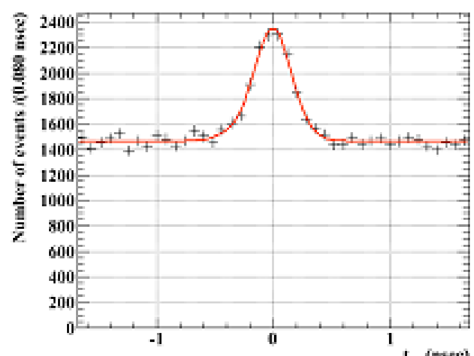
Signal PDF from Michel positrons

BG measured in sideband





RMD peak
mostly in low energy part



Relative time

Signal PDF from measured RMD peak

Relative angle

From measured double turn tracks

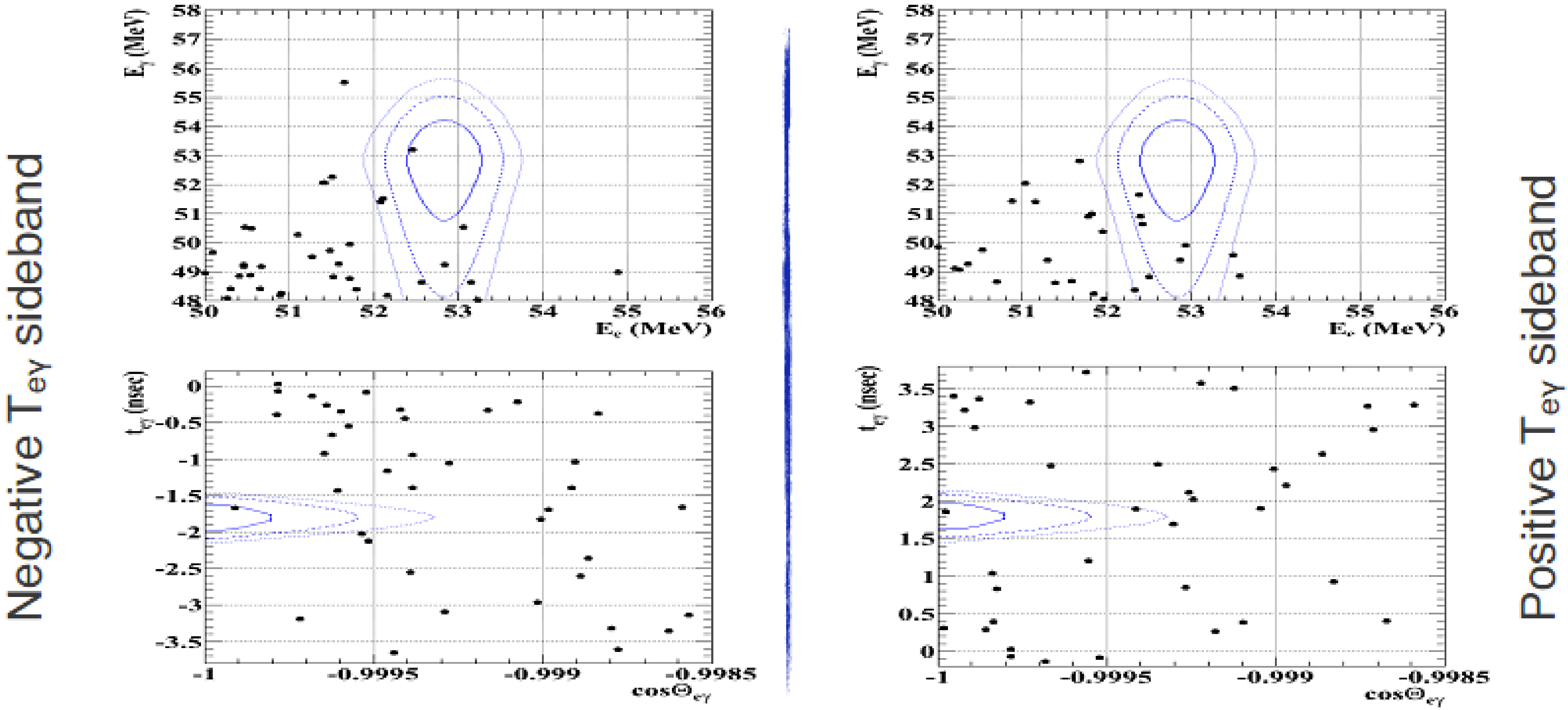
Sensitivity

Average 90% C.L. upper limit of toy MC with null signal.

Sensitivity : 6.1×10^{-12}

Preliminary

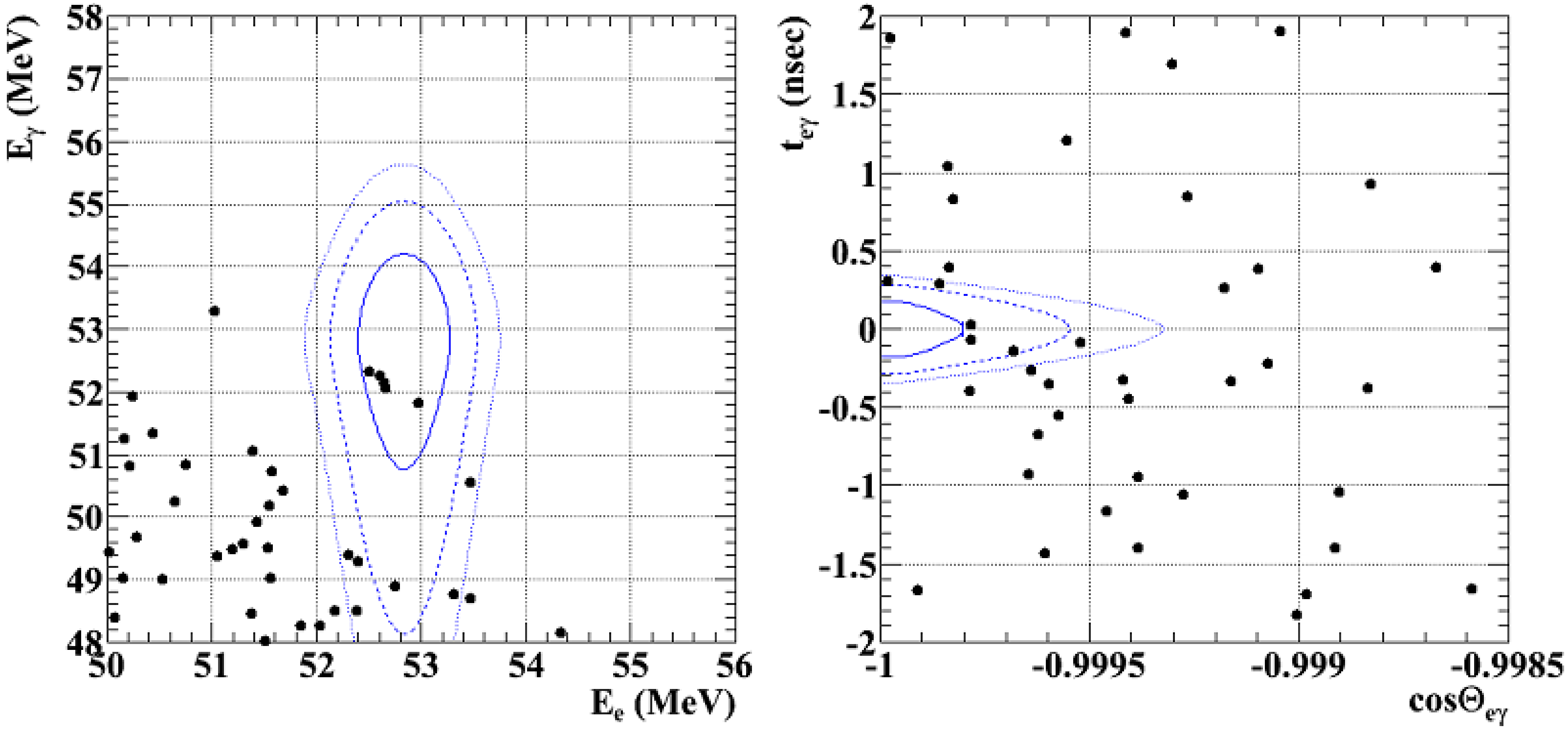
Sideband fit result is consistent. Br < $4 \sim 6\times10^{-12}$



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.

(Current B.R. upper limit is 1.2×10^{-11} by MEGA)

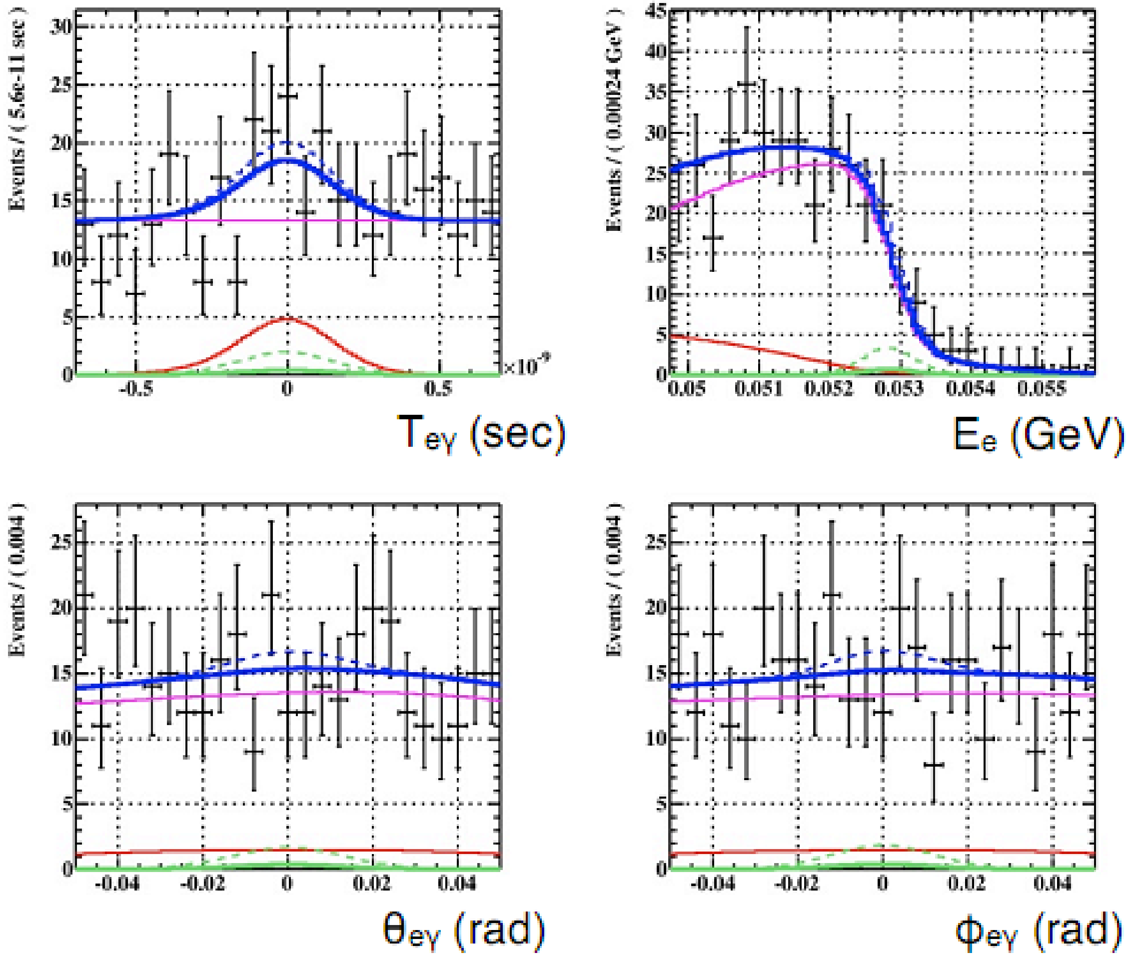
Event distribution after unblinding



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.

Fit Result

Preliminary



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**

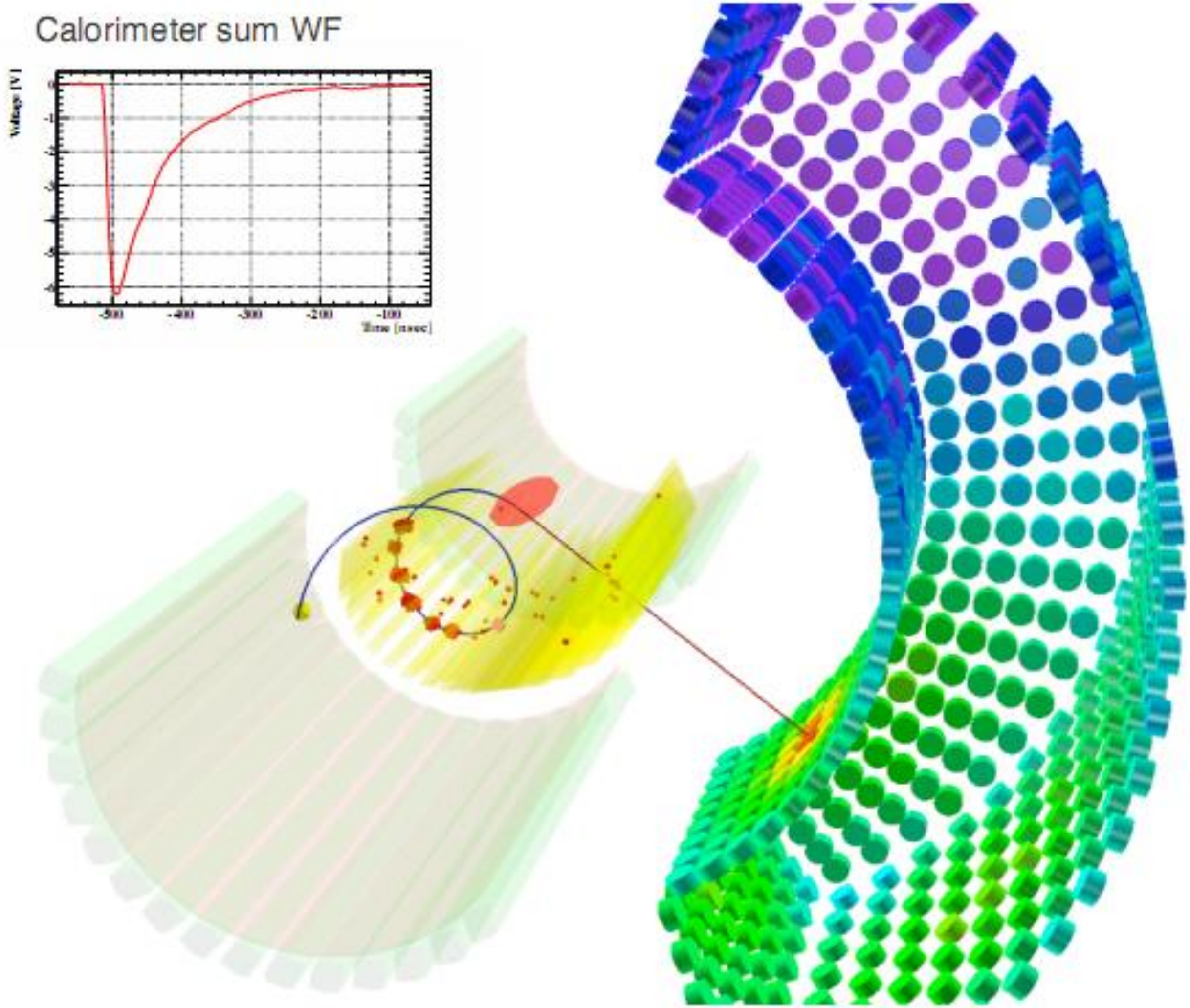
Fitting was done by three groups with different parametrization, analysis window and statistical approaches, and confirmed to be consistent (Nsig best fit = 3.0-4.5, UL = 1.2-1.5×10^{-11})

Event display

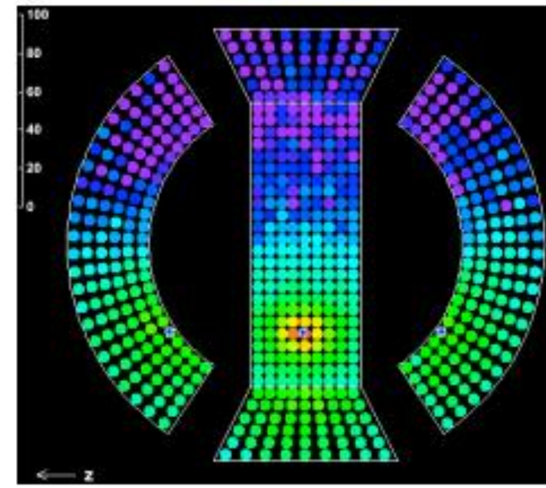
One of the most signal-like events.

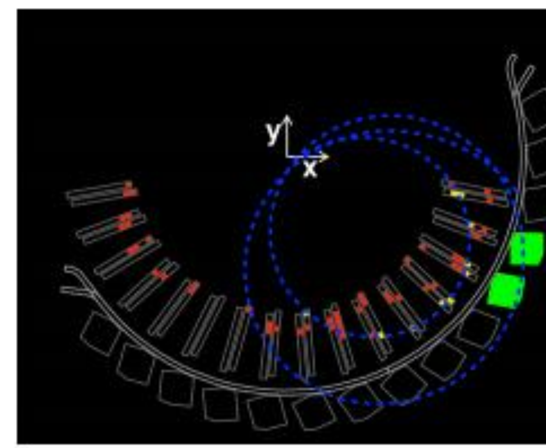
E_γ = 52.25 MeV
E_{e+} = 52.84 MeV
$\Delta\theta$ = 178.8 degrees
$\Delta T = 2.68 \times 10^{-11}$ s

Calorimeter sum WF



Calorimeter PMT hit map





Spectrometer hits and a track

Each highly ranked event is checked carefully.

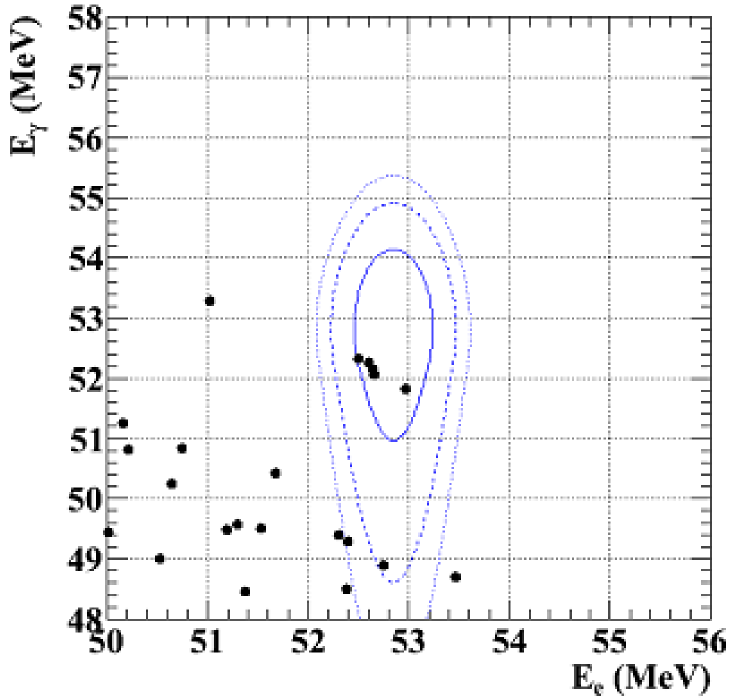
Check of events

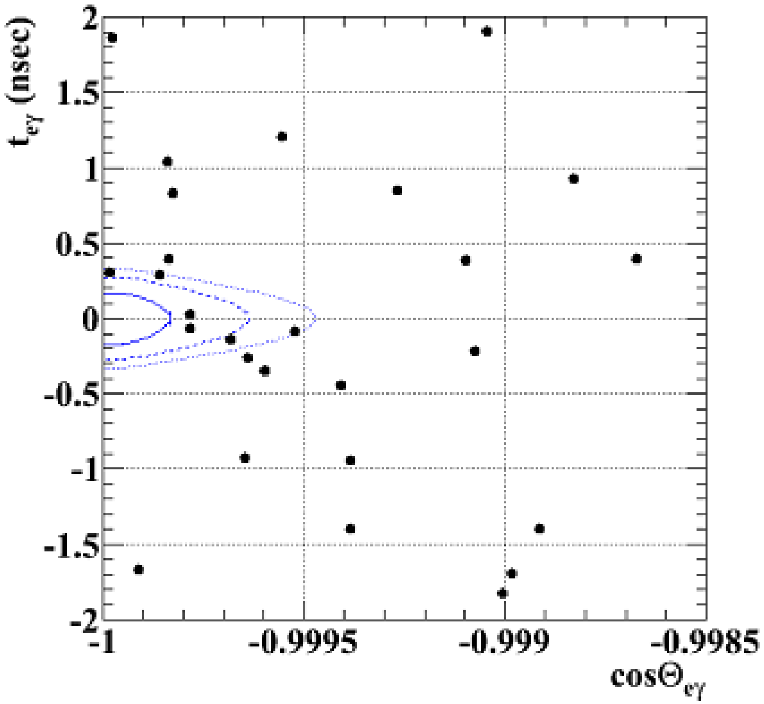
High quality e^+ track category events

Selected by number of drift chamber(DC) hits, E_e, θ_e, ϕ_e fitting uncertainties, track fitting χ^2, r and z difference between timing counter hit and extrapolation of a track.

Events around signal region do not disappear by selecting high quality track events.

High quality fraction = 59%





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.

Prospects

- Possible improvements
  - Improvement of synchronization of waveform digitizer (DRS4) improves σ_T
  - Possible better calibration with monochromatic positron beam and improve positron tracking
  - Noise reduction and electronics modification for DC
  - Refinement in calorimeter analysis
- 3 years physics data (2010-2012)
  - Sensitivity will reach our goal, a few x 10^{-13}
  - Each detector performance could be improved further!

	2010 (preliminary)
Gamma Energy (%)	1.5 (w>2cm)
Gamma Timing (psec)	67
Gamma Position (mm)	5(u,v)/6(w)
e^+ Timing (psec)	90
e^+ Momentum (%)	0.7
e^+ angle (mrad)	$8(\phi)/8(\theta)$
e^+ - gamma timing (psec)	120
Muon Decay Point (mm)	1.4(R)/2.5(Z)
Stopping Muon Rate (sec^{-1})	$3x10^7$
DAQ time / Real time (days)	95/117
Sensitivity	$2.0x10^{-12}$
BR upper limit	-

Summary

- Rare decay experiments are complementary to LHC in search of new physics
- New experiments in this field are (about) going to start data taking
- MEG will clarify the situation in its analysis box since it is now starting a long term stable data taking period
- Future experiments

COMET at JPARC ($\mu \rightarrow e$ conversion): Y. Kuno Poster
Mu2e at Fermilab: Y. Kolomensky Poster

Experiments at ProjectX

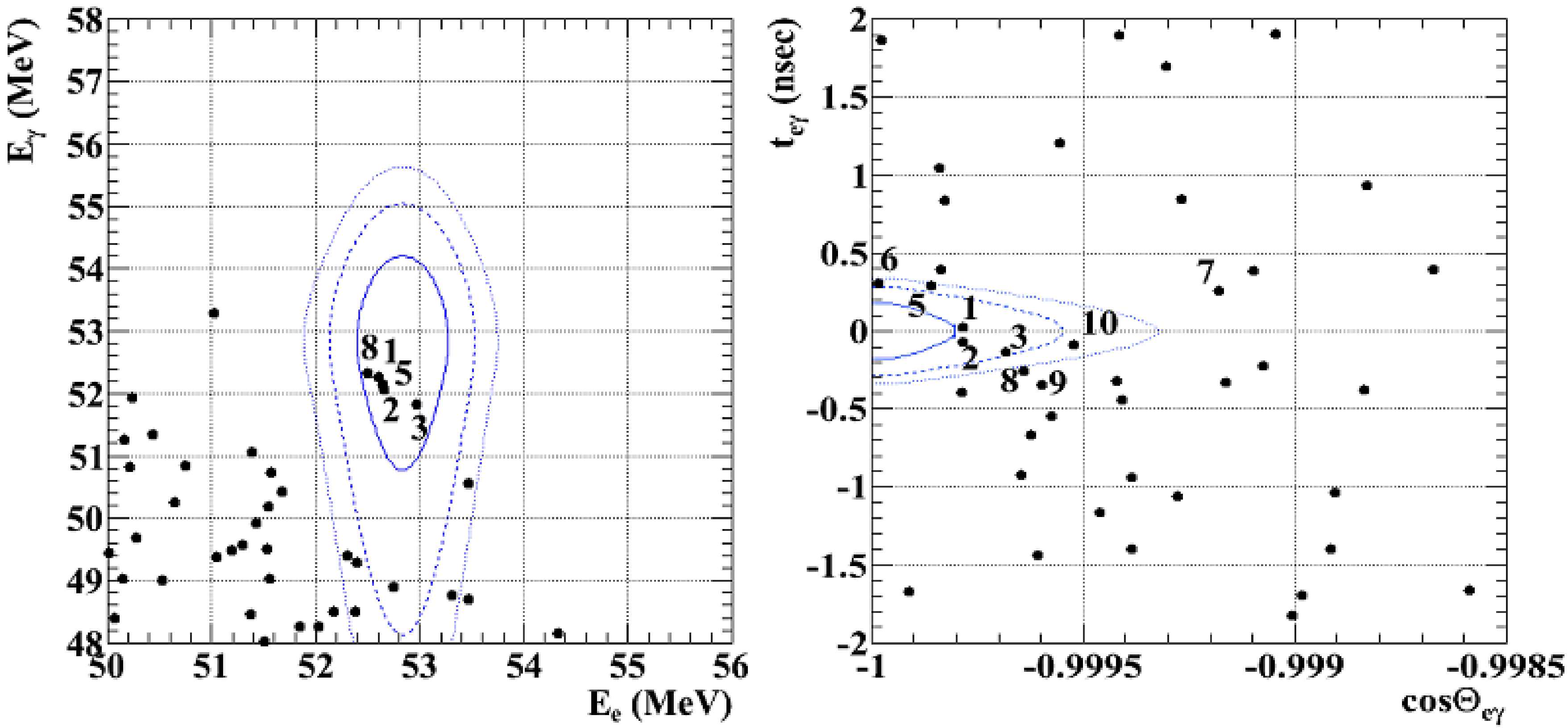
could maybe discriminate among different models

Performance

	2008	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	30~40%
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 (sec^{-1})	$3x10^7$	$2.9x10^7$(300μm)
DAQ time / Real time (days)	48/78	35/43
Sensitivity	$1.3x10^{-11}$	$6.1x10^{-12}$
BR upper limit (obtained)	$2.8x10^{-11}$	$1.5x10^{-11}$

- In 2008, sensitivity was $1.3x10^{-11}$, and our result was the BR UL $2.8x10^{-11}$ (90%C.L.)
- In 2009, our sensitivity reached $6.1x10^{-12}$, and the BR UL was $1.5x10^{-11}$ (90%C.L., these numbers are preliminary).

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.

Drift chamber

- 2008
  - Discharge problem reduced e^+ detection efficiency and resolution for positron measurement
    - ε ~14%(~1/3), σ_E, $\sigma_{\theta\phi}$ were worse
  - The problem was long term exposure to helium, fixed before physics run in 2009
- 2009
  - e^+ detection efficiency(30~40%, including TC matching) and resolutions improved