荷電レプトンフレーバーの破れの探索

大谷航 (東京大学素粒子物理国際研究センター)

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謝辞

今回のスライド作成にご協力頂いた以下の方々(順不同、敬称略)に深く感謝致します。

居波賢二(名古屋)、早坂圭司(名古屋KMI)、 三原智(KEK)、西口創(KEK)

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- Why is CLFV so important?
- Status and Prospects of CLFV experiments
- Summary

Charged Lepton Flavour Violation

- **Various CLFV experiments running, planned or proposed.**
  - $\mu \to e\gamma$ (MEG)
  - $\mu N \to eN$ (COMET, Mu2e, DeeMe)
  - τ LFV decay (Belle/BaBar)
  - $\mu \to eee$ (PSI, MUSIC?)
  - And many others
    - $K^+ \to \pi^+ \mu^+ e^-$, $K_L^0 \to \mu^\pm e^\mp$, collider searches, $\mu e \to ee$, fixed target ($lN \to l'N$)...
- **Why is CLFV so interesting?**

Charged Lepton Flavour Violation

- **Unambiguous evidence of new physics if observed!**
  - FCNC is highly suppressed by GIM mechanism in SM. No SM contamination!
  - Many new physics models predict sizable rates of CLFV processes within experimental reach.
- After discovery, measuring LFVs in various modes is quite important!
  - Correlations among different modes to discriminate new physics models
- Complementary to energy frontier experiments

Charged Lepton Flavour Violation

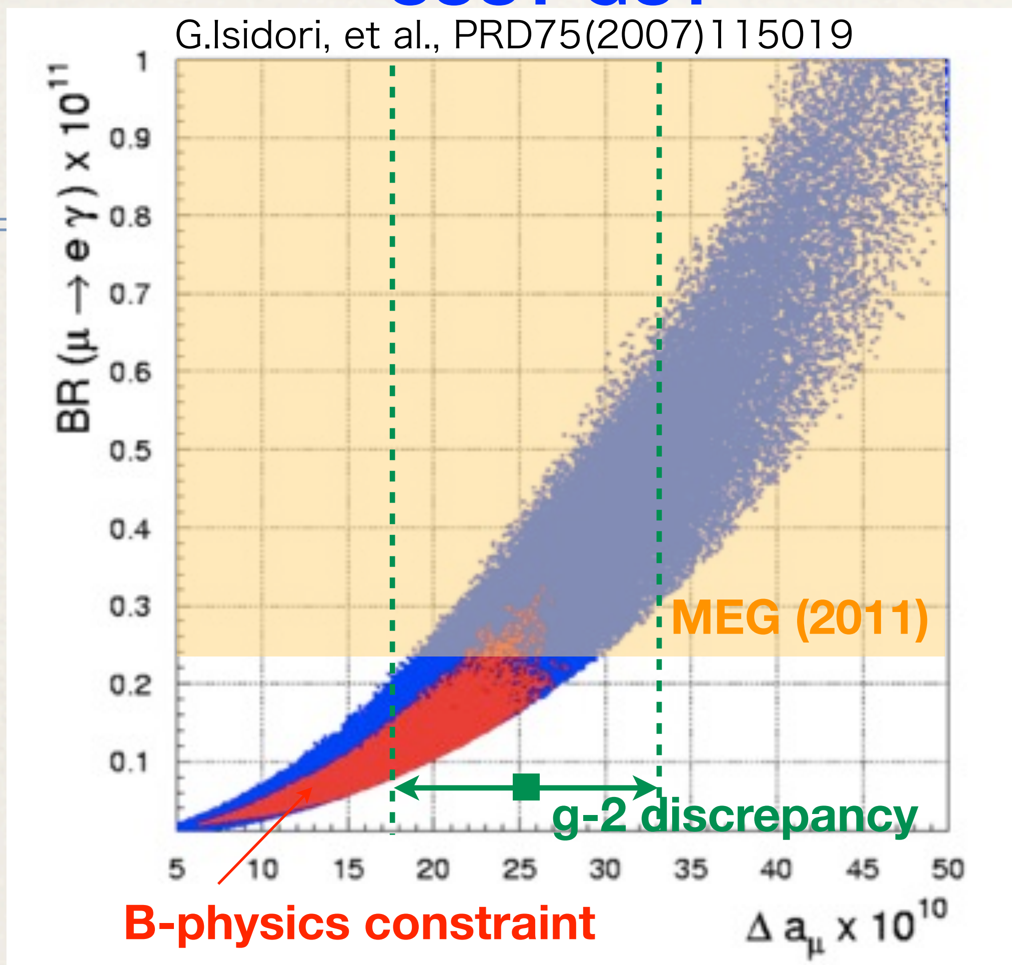
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

M.Blanke et al., Acta Phys.Polon.B41(2010)657

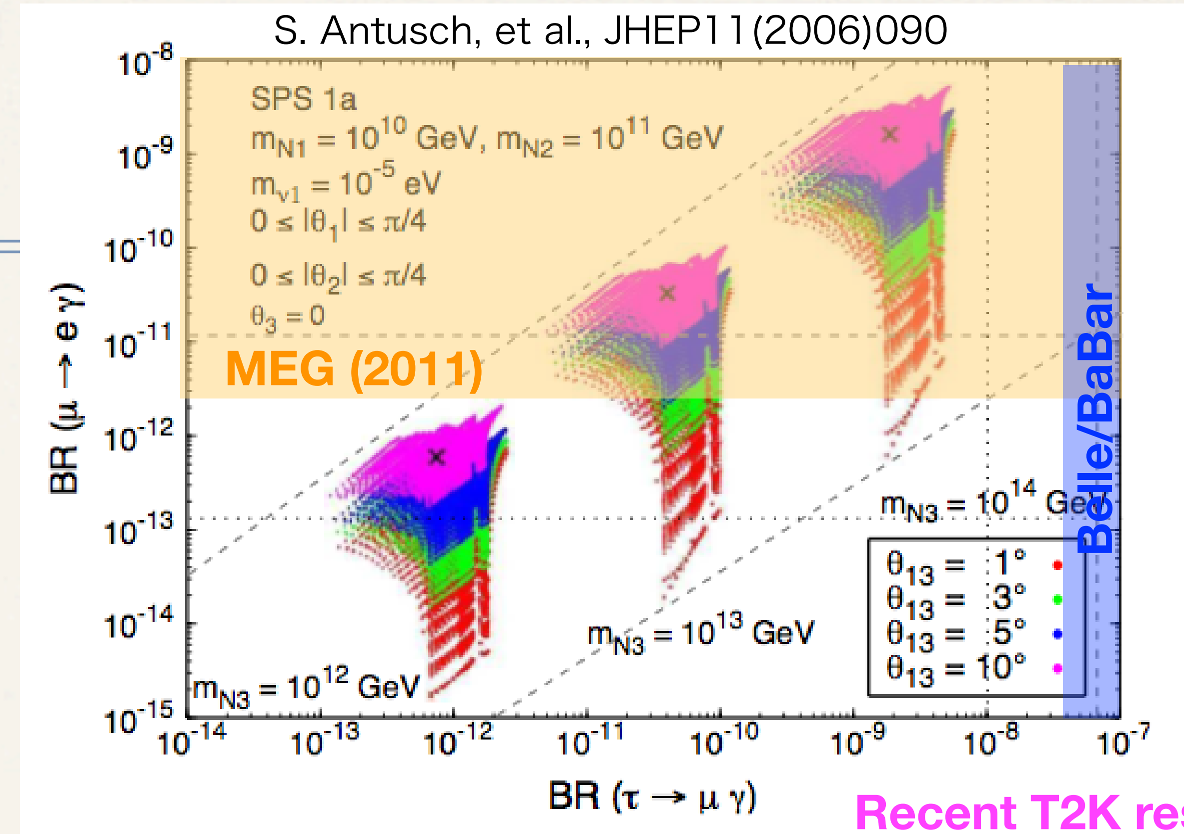
Correlations bw/ different CLFV modes depend on new physics models very much!

CLFV Searches Constrain NP Already!

SUSY-GUT

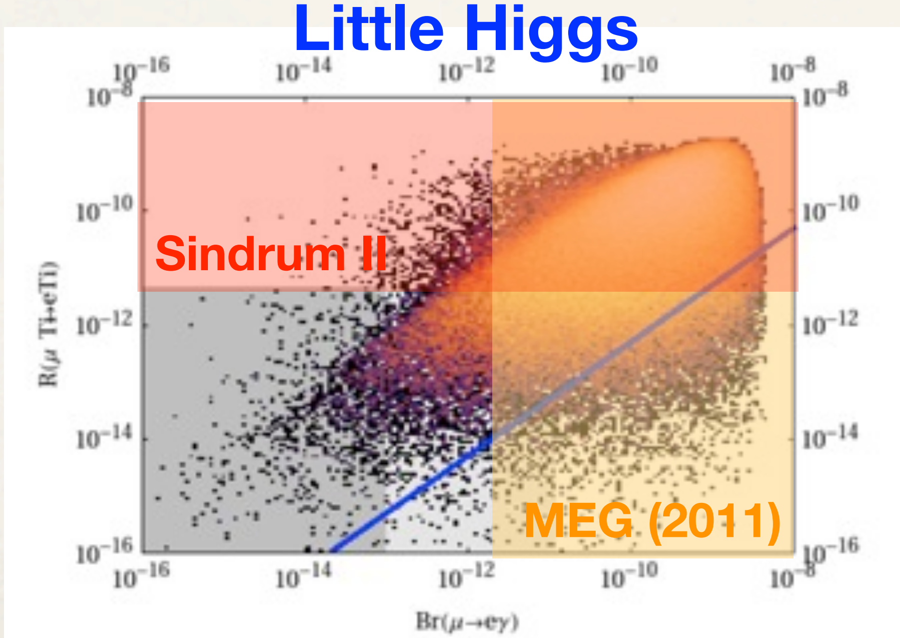


SUSY-Seesaw



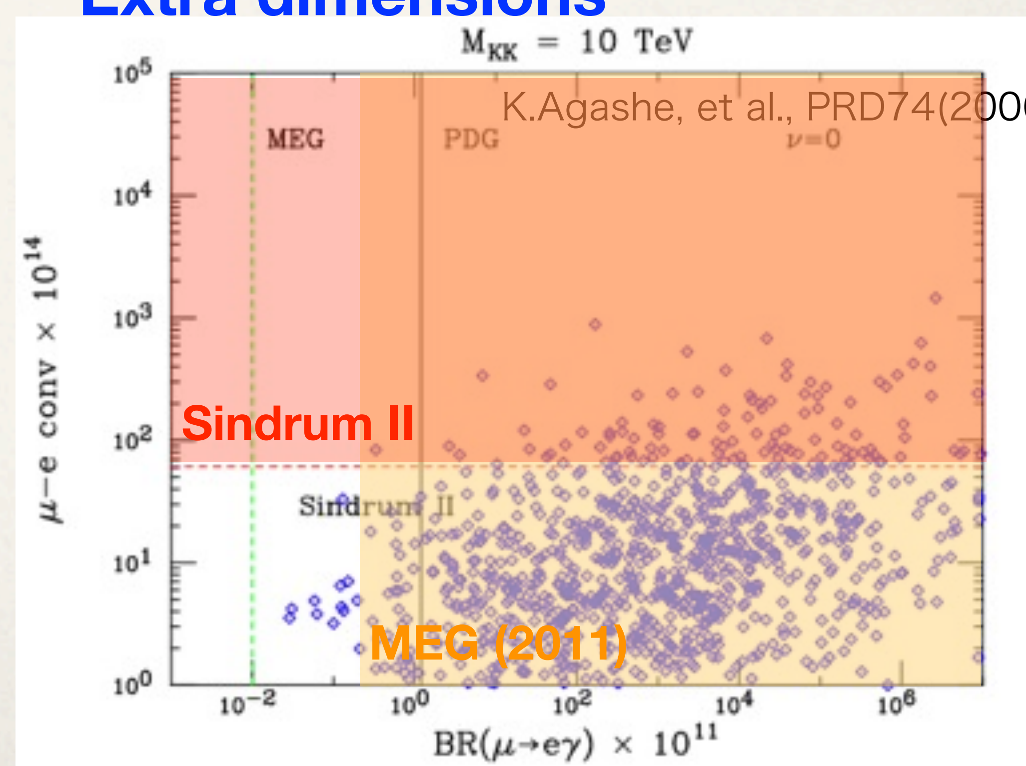
Recent T2K result favors large θ_{13}!

Little Higgs



M.Blanke et al., Acta Phys.Polon.B41(2010)657

Extra dimensions



Charged Lepton Flavour Violation

- **Various CLFV experiments running, planned or proposed.**
  - $\mu \to e\gamma$ (MEG)
  - $\mu N \to eN$ (COMET, Mu2e, DeeMe)
  - τ LFV decay (Belle/BarBar)
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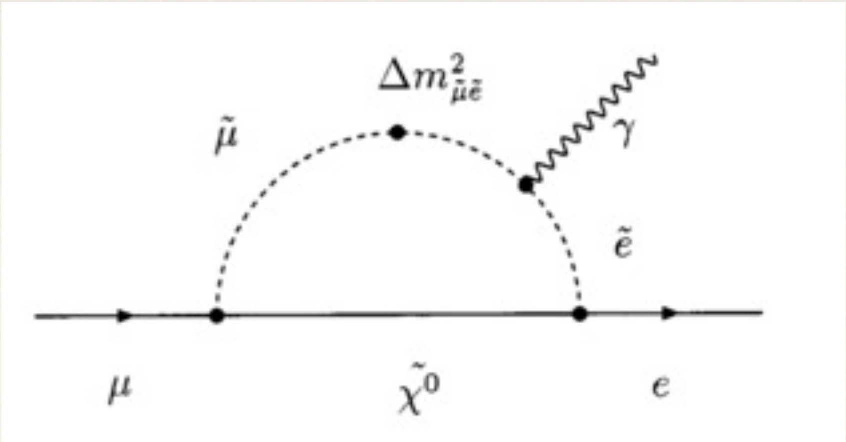
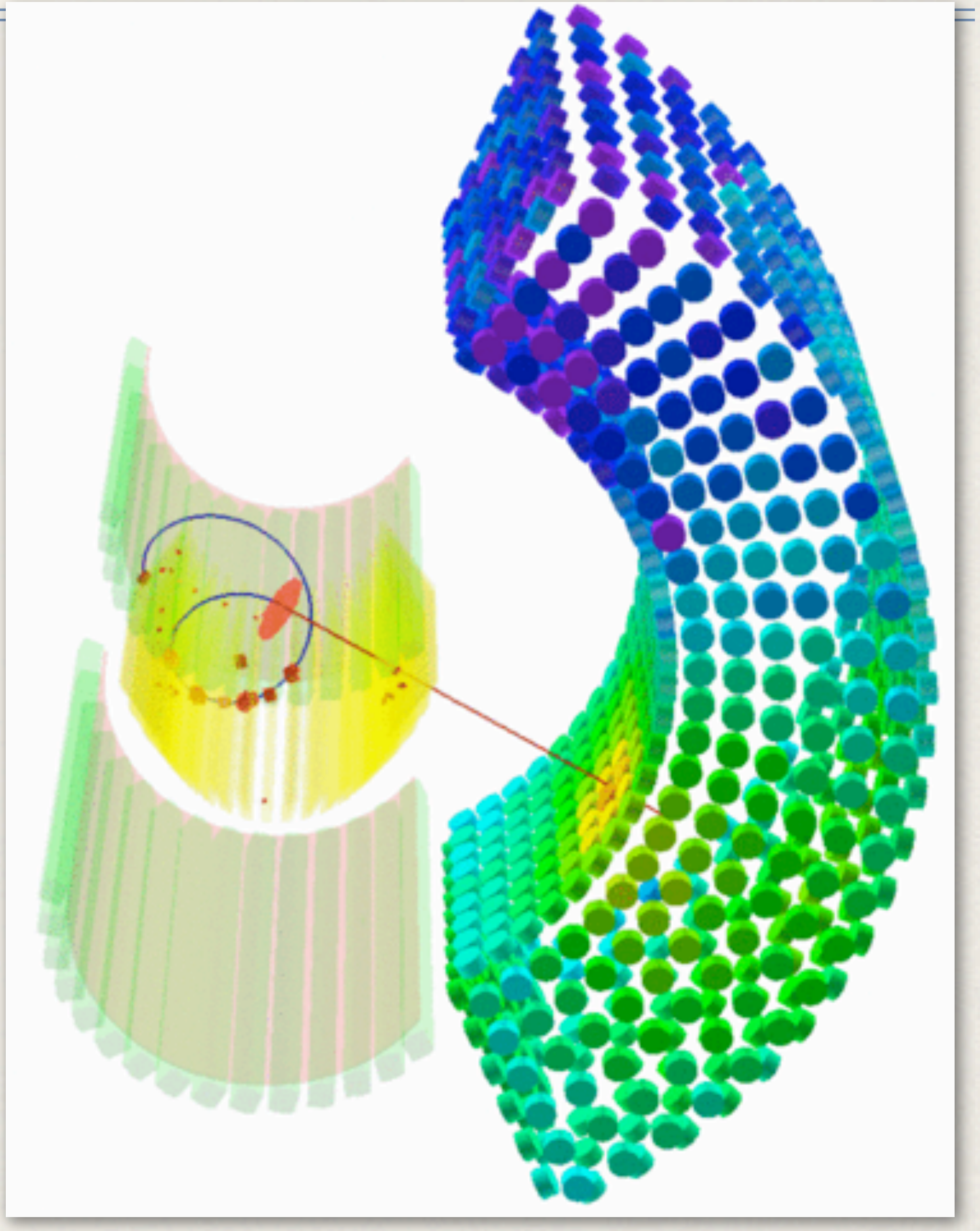
  - And many others
    - $K^+ \to \pi^+\mu^+e^-$, $K_L^0 \to \mu^\pm e^\mp$, collider searches, $\mu e \to ee$, fixed target ($lN \to l'N$)...
- **Why is CLFV so interesting?**

$\mu \rightarrow e\gamma$ at MEG



- MEG aiming at search for $\mu^+ \rightarrow e^+\gamma$ down to a few × 10^{-13} sensitivity
- World's most intense DC muon beam at PSI (>10^8 μ^+/s)
- MEG detectors
  - 900L-LXe gamma detector
  - Positron spectrometer with gradient magnetic field
- Physics data taking in progress since September in 2008.
- New result using data 2009+2010 recently published



Most signal-like event (Run2010)

MEG New Result

- Preliminary result on data 2009 was presented last summer in ICHEP2010 showing a small excess.
- Updates with new data (from run2010) and new analysis
  - Data 2010 (data statistics = 2 × data 2009)
  - Improve detector alignment
  - More detailed implementation of correlations in positron observables
  - Improve magnetic field map
  - Improve likelihood analysis tool
- New result from analysis on combined data sample for run 2009+2010
- 詳しくは明日の岩本(19aSD-7)、澤田(19aSD-8)の招待講演で

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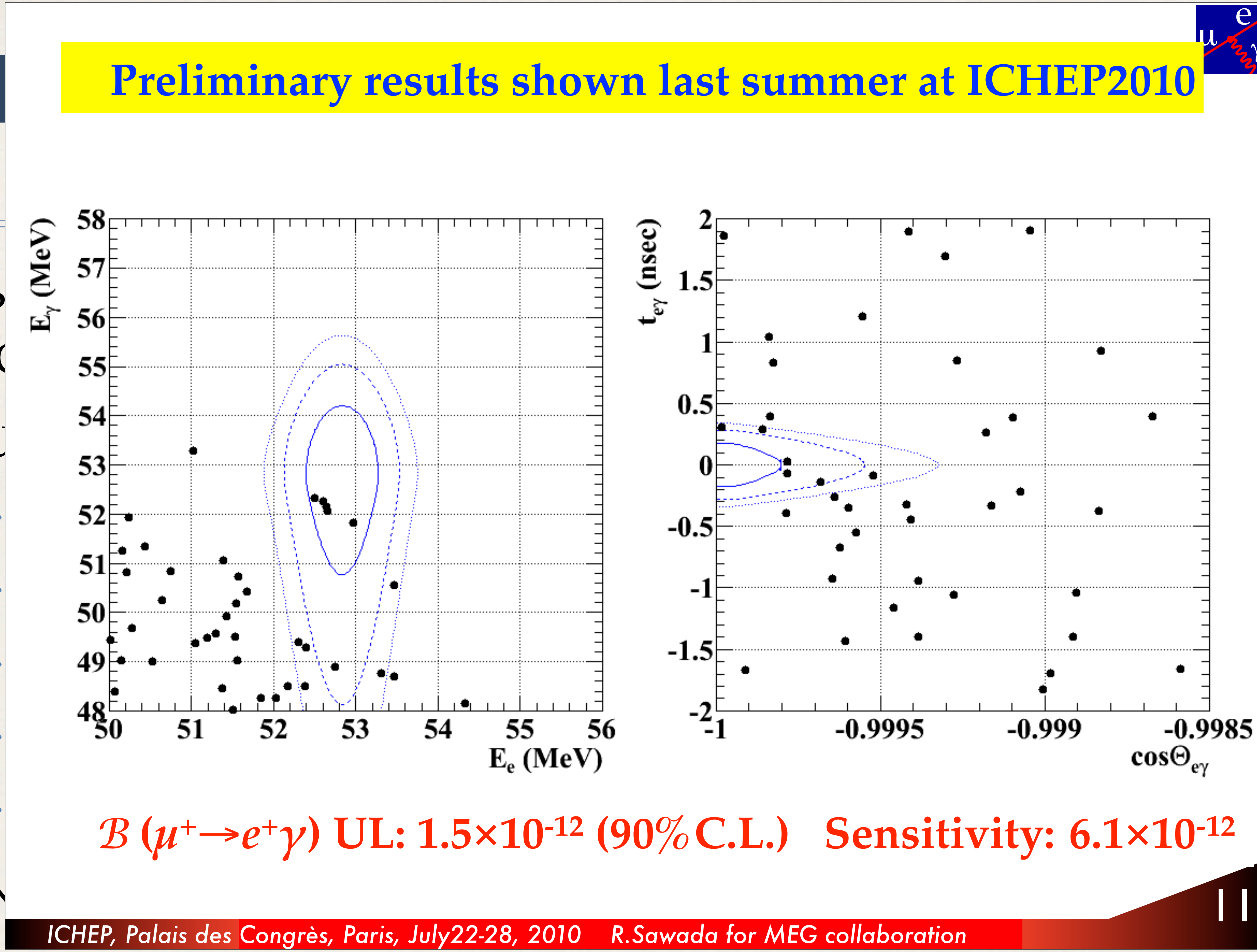

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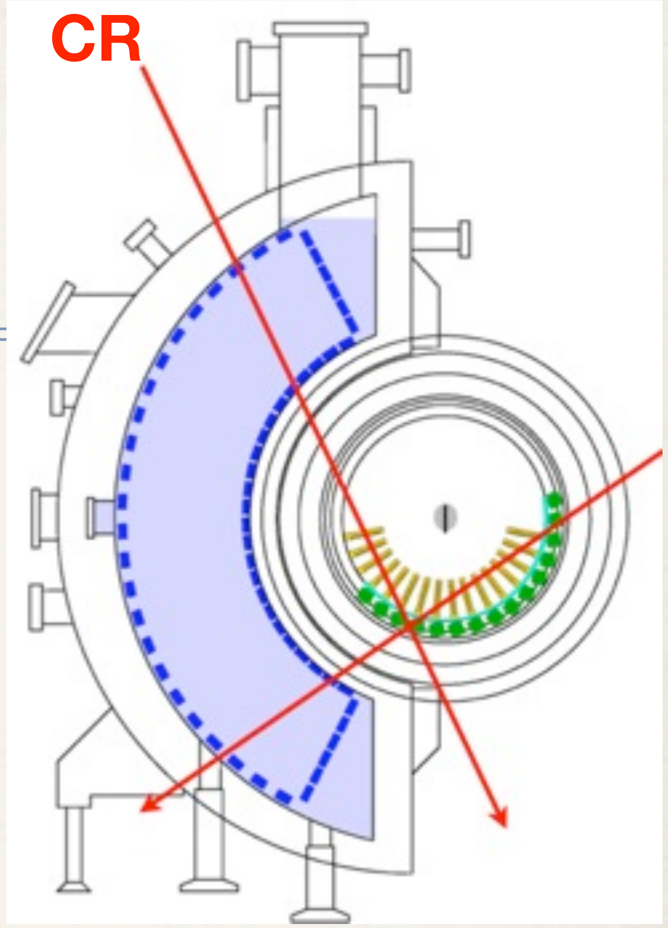
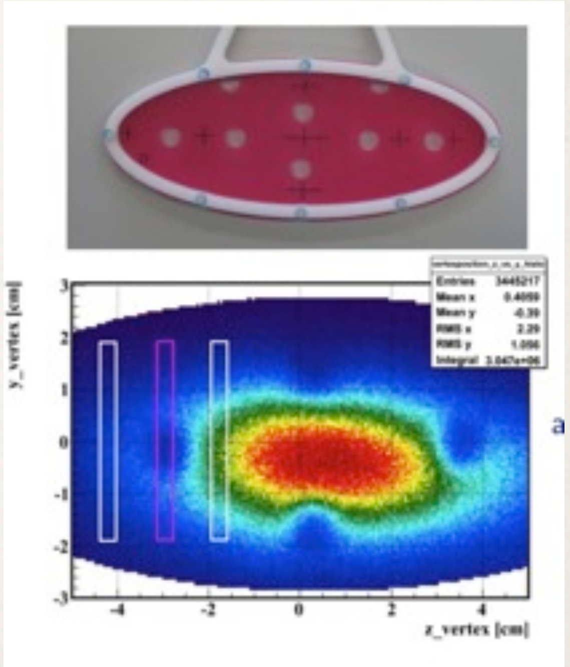
Detector Alignment



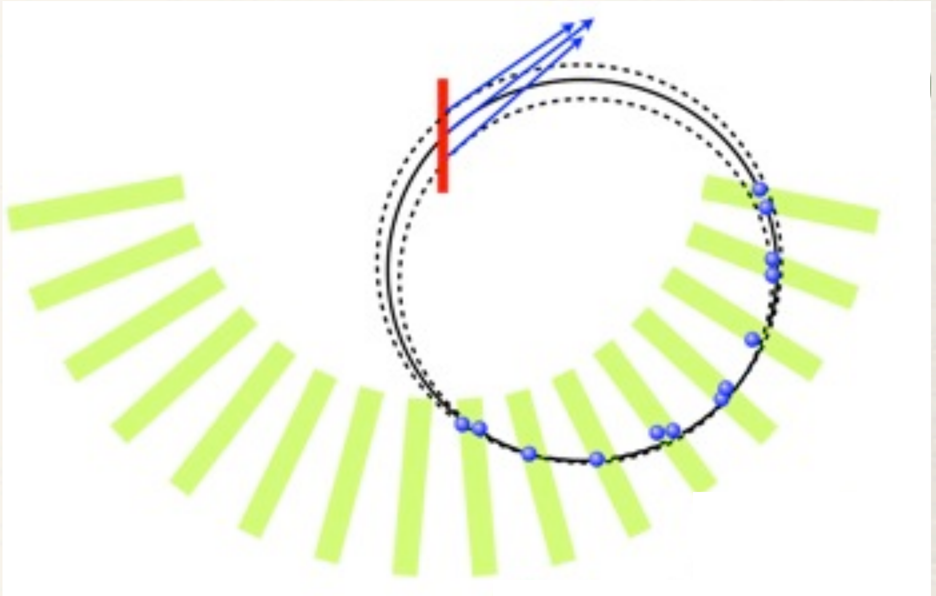
- Relative alignment bw/ LXe detector and drift chamber system
  - No direct calibration source for relative angle
  - Improve alignment combining various methods
    - optical surveying, cosmic ray, γ-ray((p-γ) reaction, AmBe)
- DC alignment
  - Optical surveying for global alignment
  - Cosmic ray + Millipede method for internal alignment
- Target alignment
  - Alignment using reconstructed positions of several holes on target

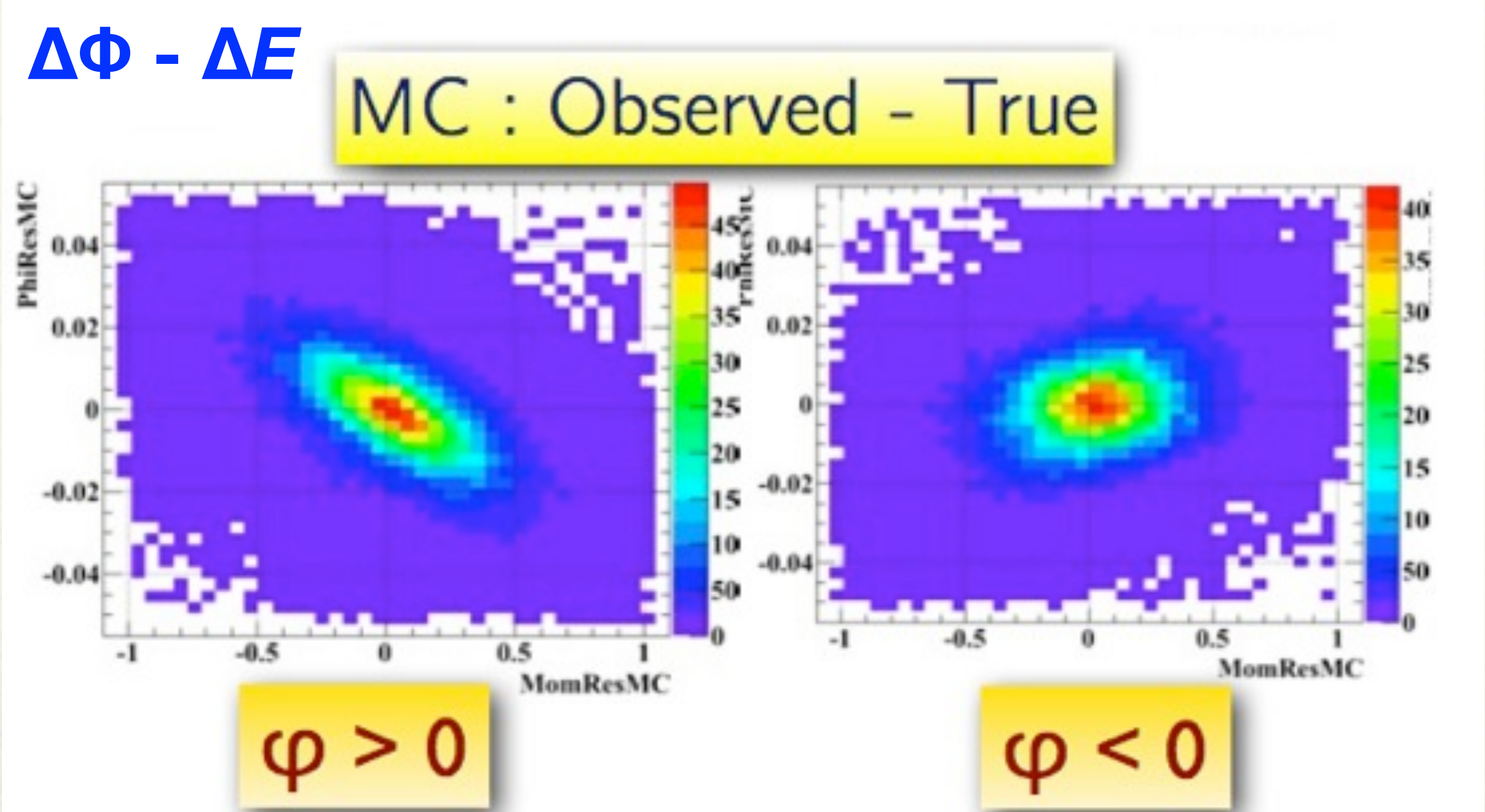


→ **Improve resolutions and systematic uncertainties**

Correlations

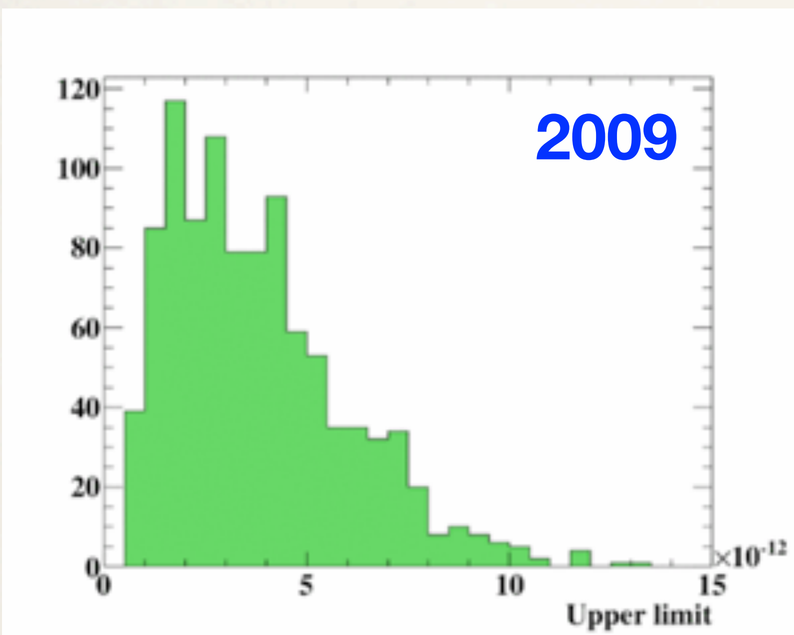
- Correlations bw/ positron observables due to geometrical constraint in track reconstruction
- Most of the correlations can be measured in data.
- Correlations are included in likelihood analysis in more detailed way.



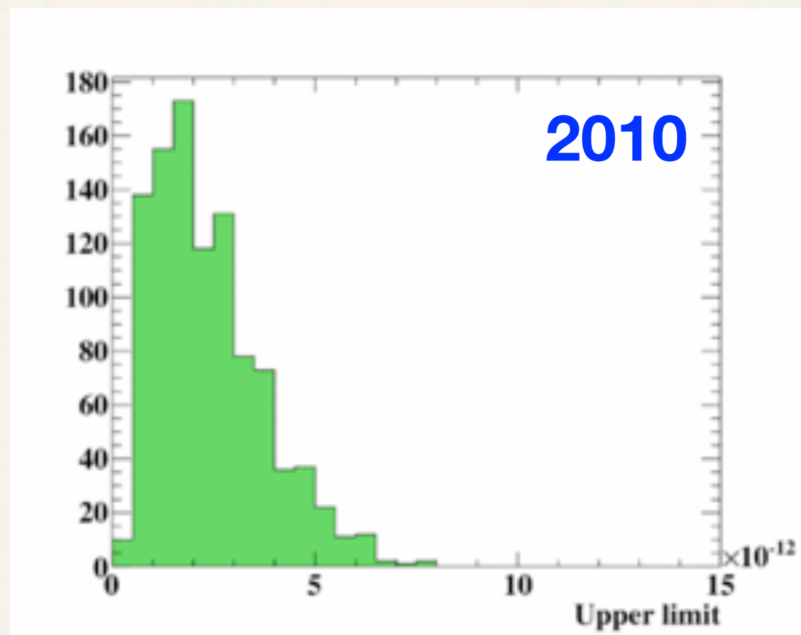


Sensitivity

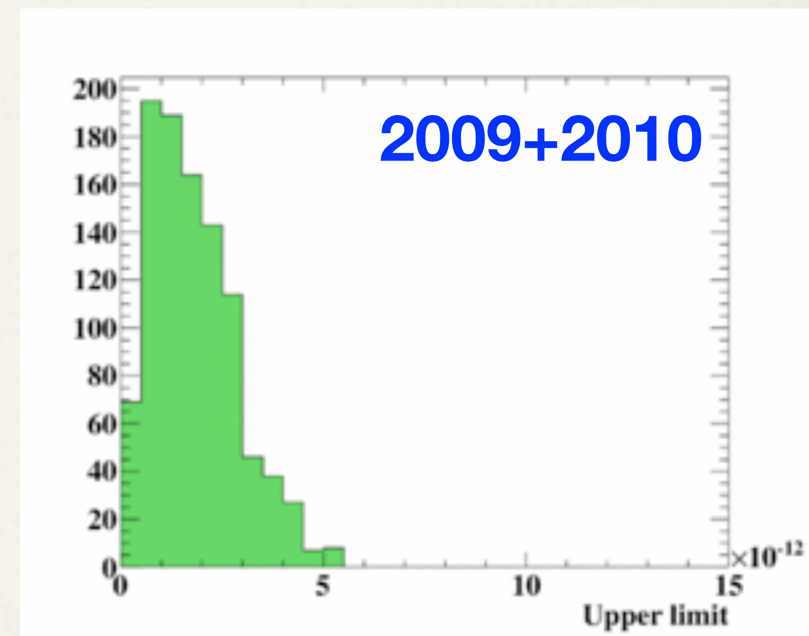
- **Sensitivity** = Upper limit averaged over an ensemble of many toy MC experiments with BG only hypothesis with BG rate measured in side-bands



$\mathcal{B}$= 3.3×10^{-12} (median)



$\mathcal{B}$ = 2.2×10^{-12} (median)

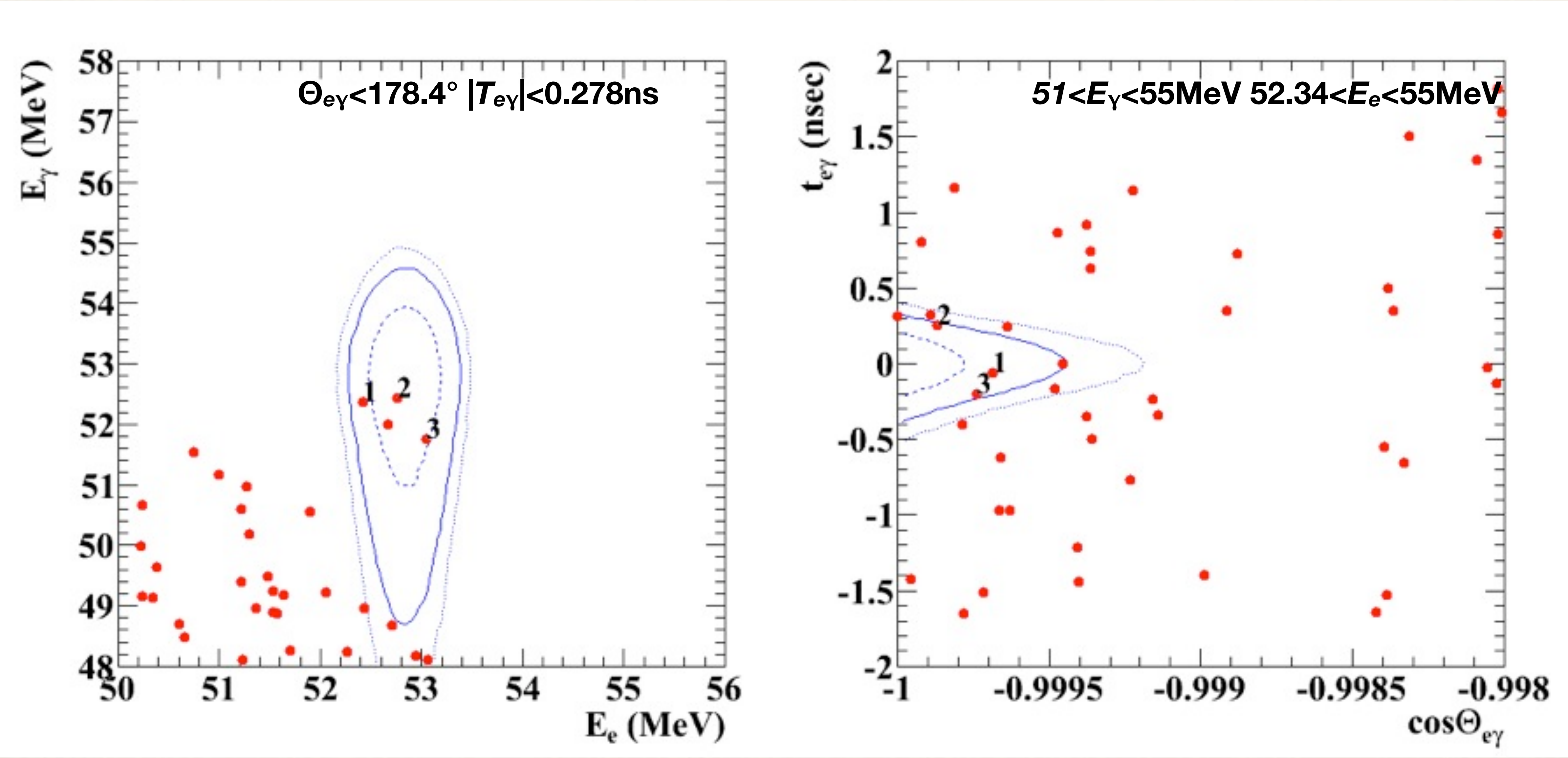


$\mathcal{B}$ = 1.6×10^{-12} (median)

Sensitivity(2009+2010) is ×8 better than previous best upper limit!

Run 2009 Event Distribution

Event distribution is not changed much compared to last sumer result



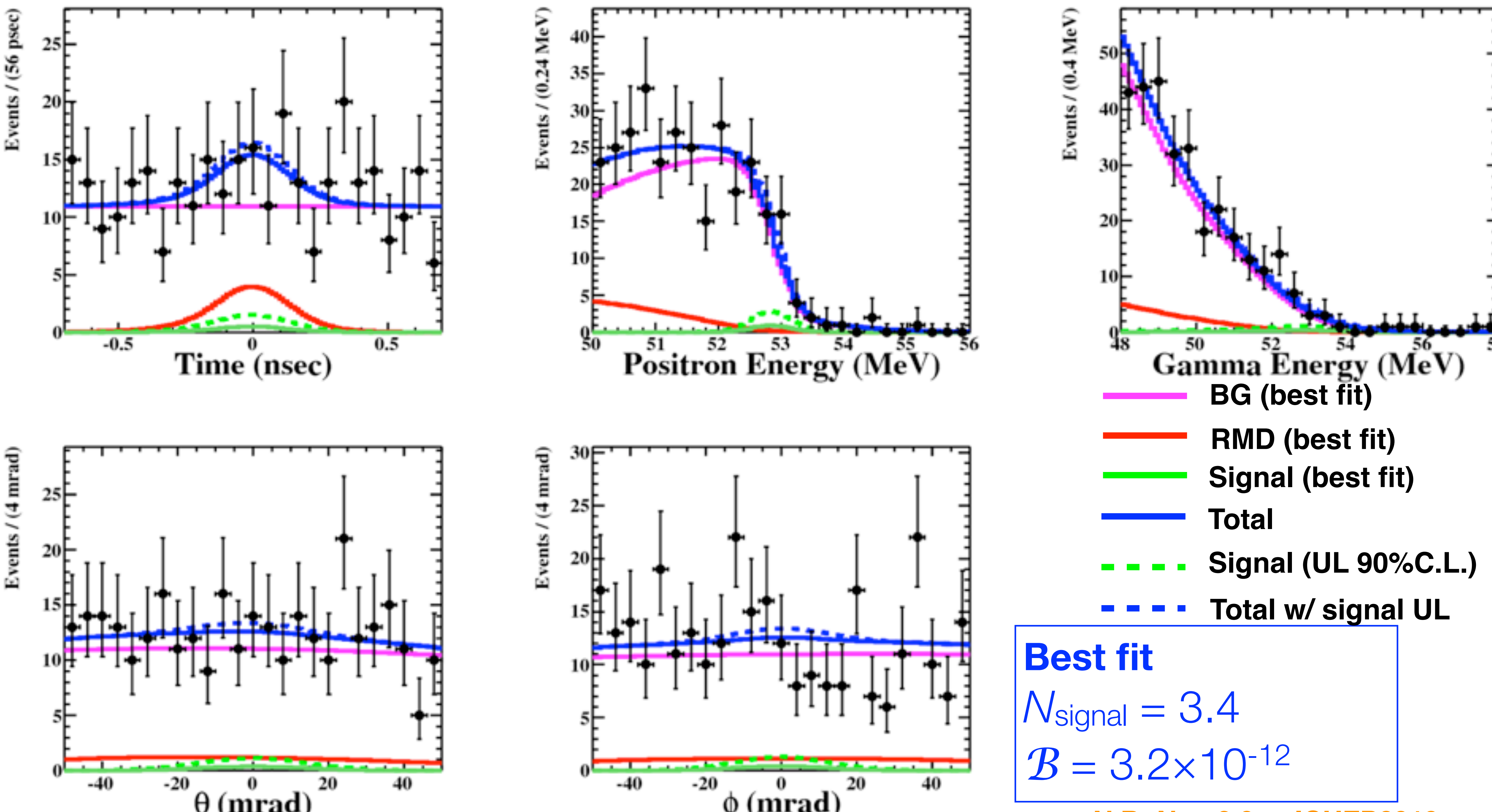
Blue curves: signal PDF contour (1, 1.64, 2-σ)

Events with highest signal likelihood (*S/(0.1R+0.9B)*) are numbered.

N.B.: These plots are just for reference, not used in the analysis

Run2009 Likelihood Fit

Fit region: **48<E_γ<58MeV, 50<E_e<56MeV, |$T_{e\gamma}$|<0.7ns, |$\theta_{e\gamma}$|<50mrad, |$\Phi_{e\gamma}$|<50mrad**



Best fit

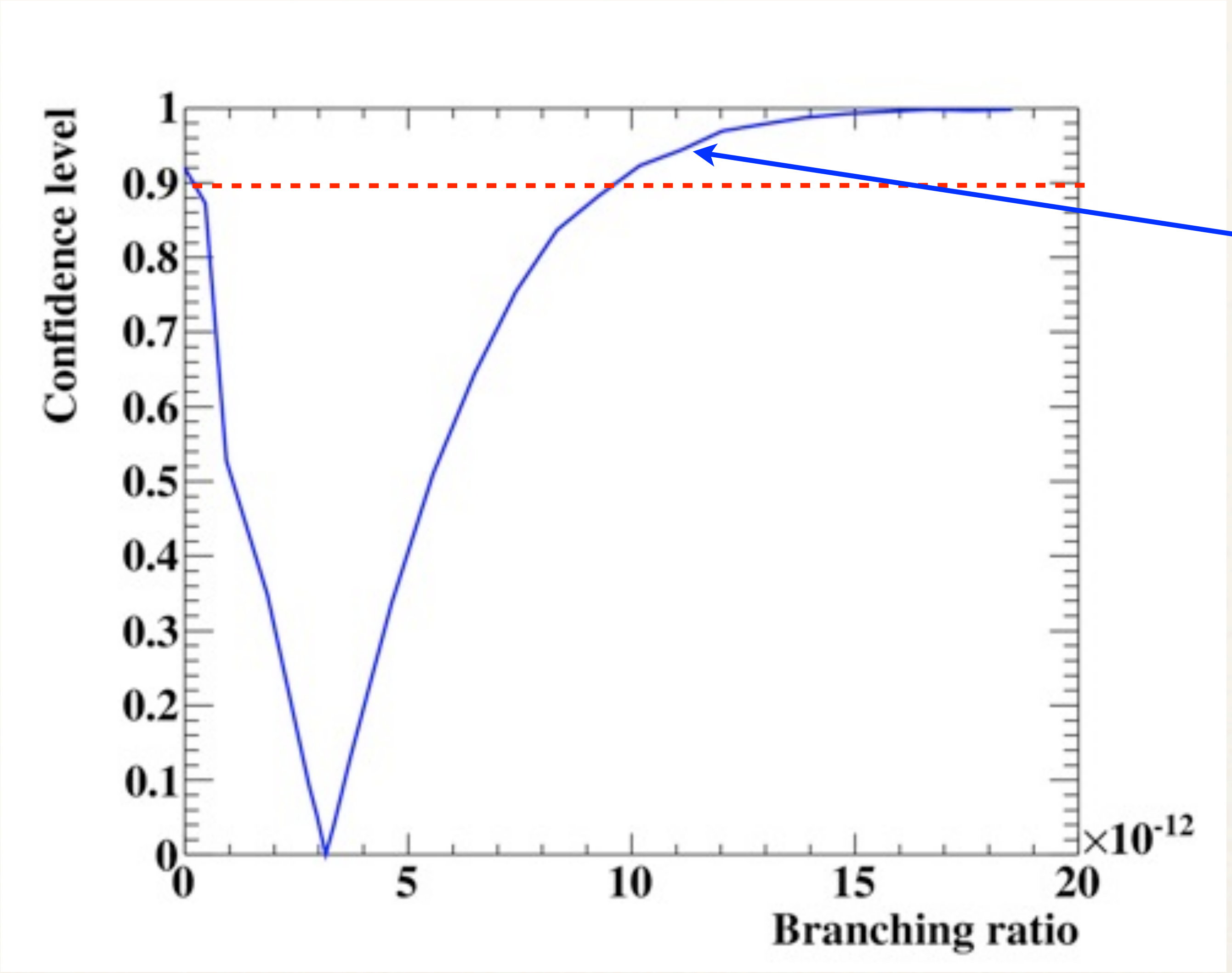
$N_{\mathrm{signal}} = 3.4$

$\mathcal{B} = 3.2\times10^{-12}$

N.B. N_{sig}=3.0 at ICHEP2010

Run 2009 Confidence Interval

$1.7\times10^{-13} < \mathcal{B} < 9.6\times10^{-12}$ (90%C.L., incl. sys.)

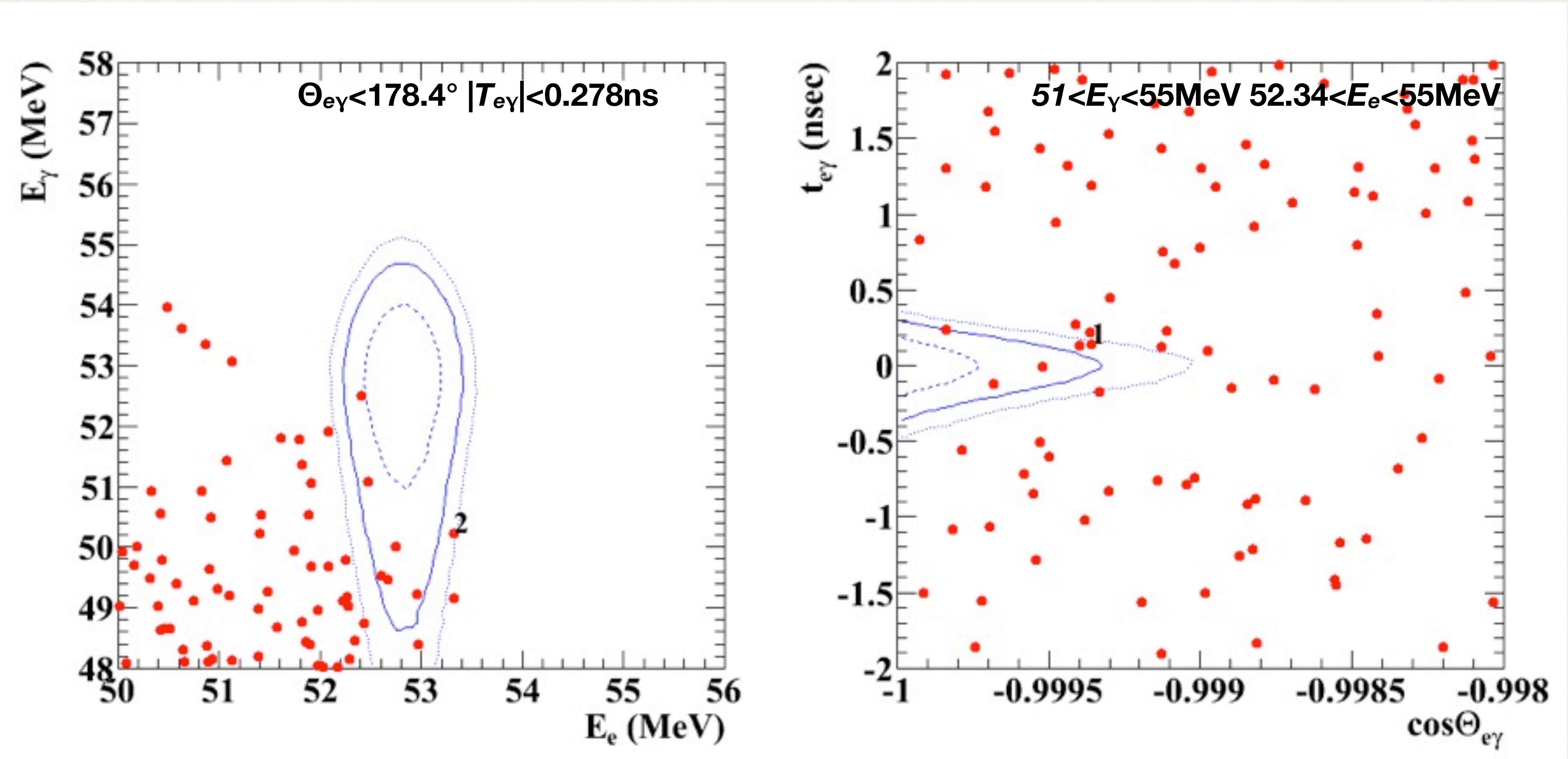


CL curve:

Allowed region of branching ratio can be read at any confidence level.

$\mathcal{B} = 0$ is marginally excluded, but significance is not high. (p-value is only 8%)

Run 2010 Event Distribution



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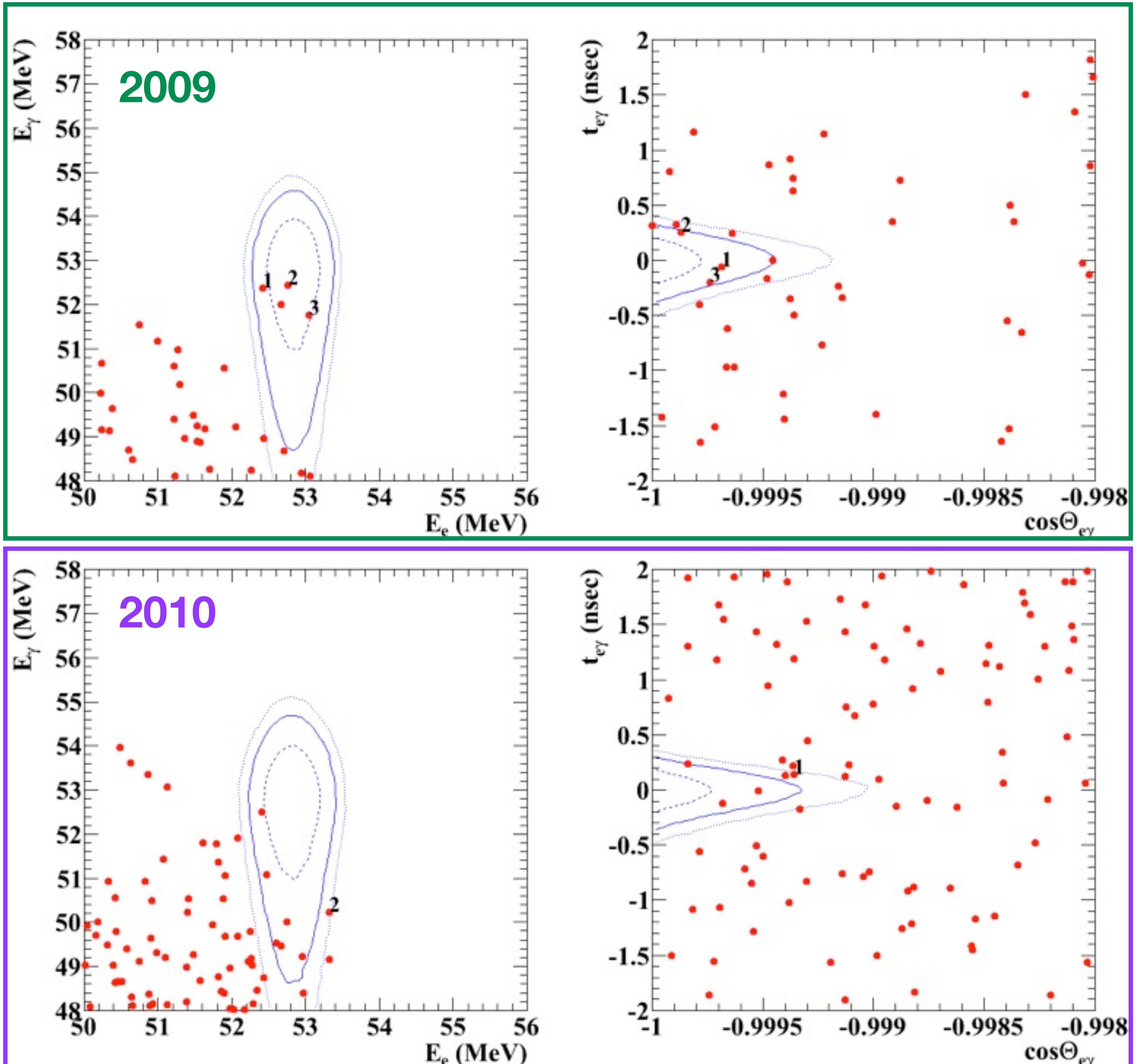
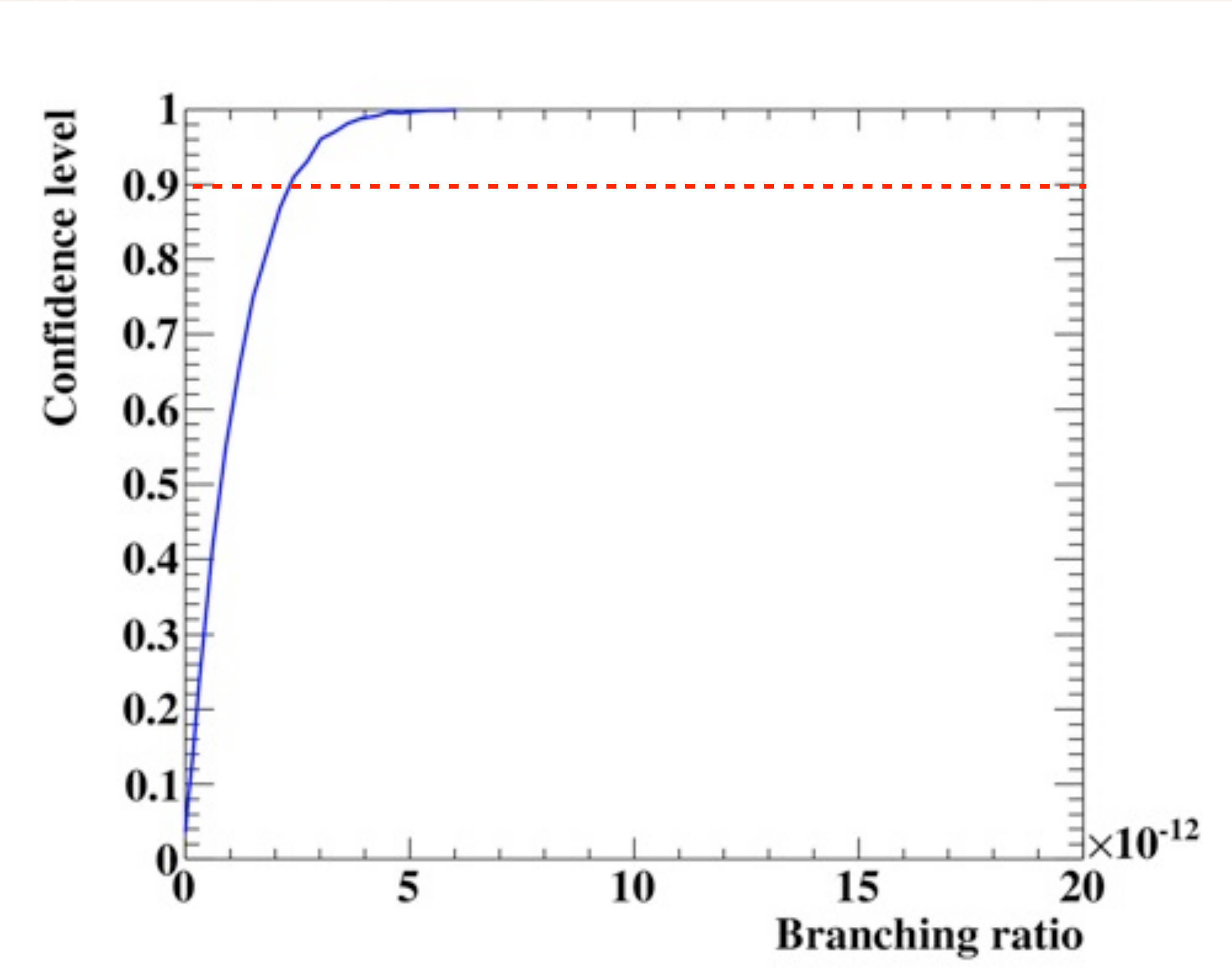

2009
2010
E_γ (MeV)
E_e (MeV)
$t_{e\gamma}$ (nsec)
$\cos\Theta_{e\gamma}$

Run 2009+2010 Combined

$\mathcal{B} < 2.4\times10^{-12}$ **(90%C.L., incl. sys.)**



Combined data set is analyzed as a single data set
(Note that PDF is on an even-by-event basis.)

MEG New Result Summary

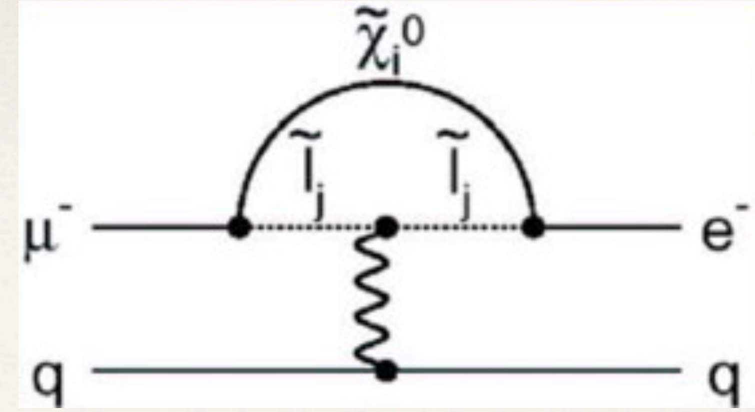
Data set	$\mathcal{B}_{fit}$	Sensitivity	LL	UL
2009	3.2×10^{-12}	3.3×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-12}	2.2×10^{-12}	-	1.7×10^{-12}
2009+2010	-1.5×10^{-12}	1.6×10^{-12}	-	2.4×10^{-12}

- New upper limit: **$\mathcal{B}(\mu^+\rightarrow e^+\gamma) < 2.4\times10^{-12}$ (90% C.L.)**
  - **×5 more stringent than the previous limit!**
  - arXiv:1107.5547, to appear in PRL

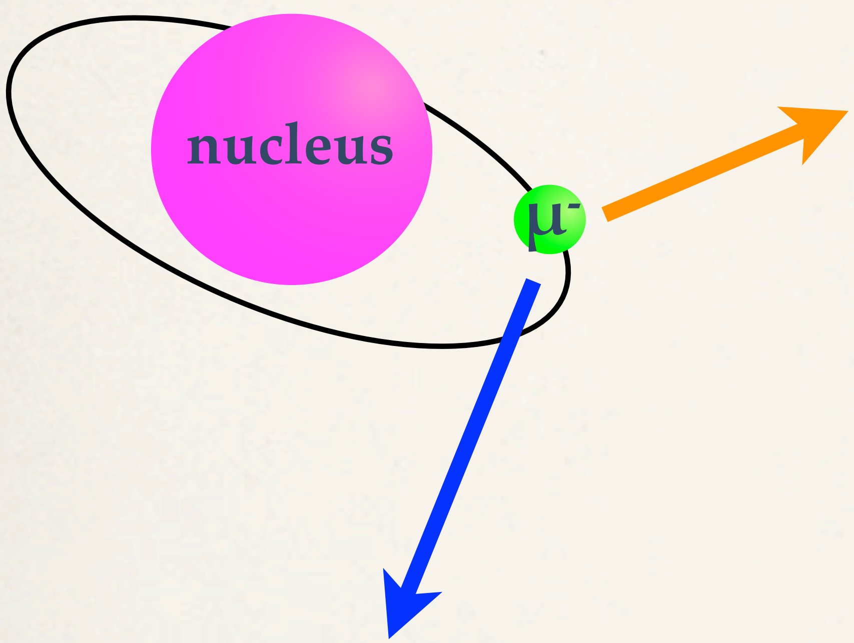
MEG Status & Prospects

- Run2011
  - Physics data taking is in progress since end-June.
    - Improvement of DAQ efficiency because of multi buffer scheme
    - New HV module reducing DC noise
    - TC fibre counters are in operation.
  - Expected data statistics ~ 2 × run2010
  - MEG is starting to explore sensitivity region below 10^{-12} this year!
- MEG will continue taking data to reach $O(10^{-13})$ in next few years.
- There's still good chance to discover $\mu \to e\gamma$.
- R&D for future upgrade for 10^{-14} sensitivity is starting.
  - Detector upgrade
  - Measure angular distribution with polarized muon beam

μ-e Conversion



1s-state in a muonic atom



Beyond standard model

μ-e conversion

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

Standard model

Muon decay in orbit (DIO)

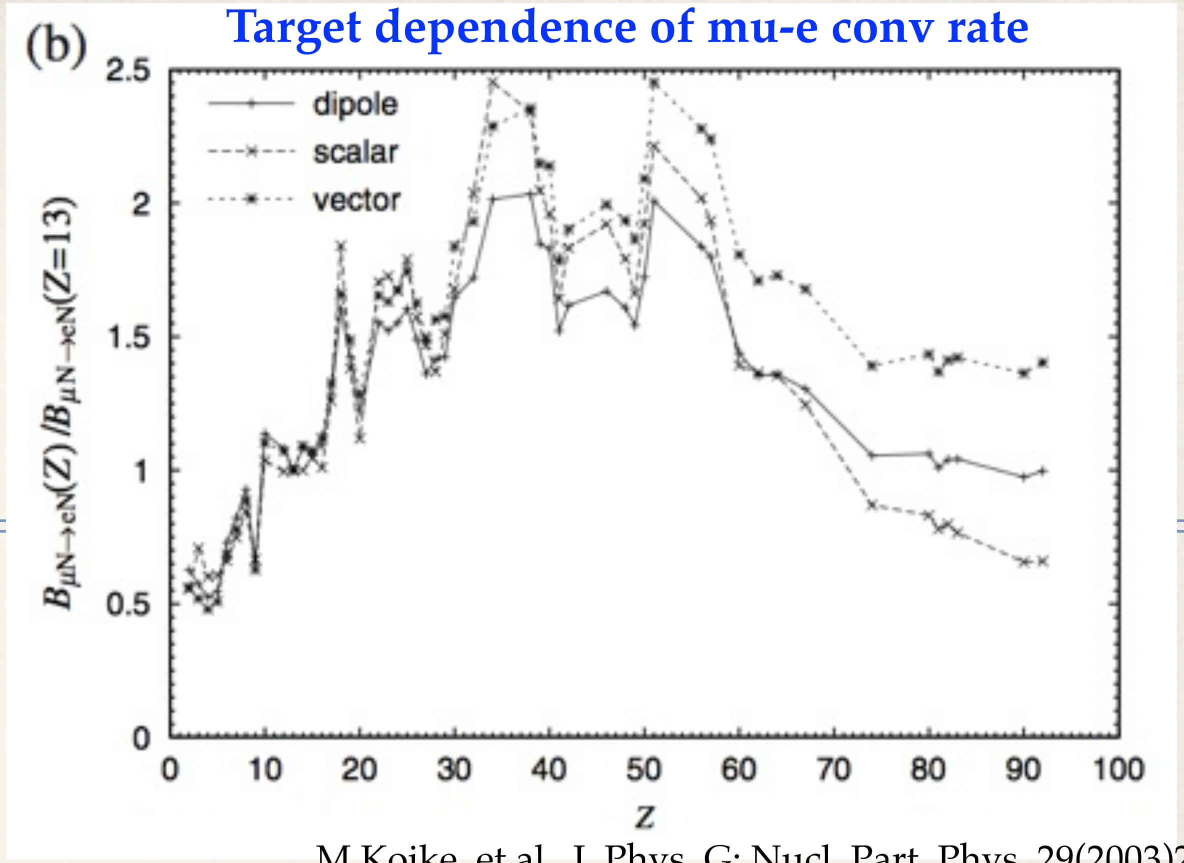
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Nuclear muon capture

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

- **Signal**
  - **A mono-energetic electron**
    - $E_e = m_\mu - B_\mu \sim 105\text{MeV}$
    - Delayed by ~1μs (Al target)
- **BG**
  - Muon decay in orbit (DIO)
  - Beam related
    - Radiative pion capture
    - Muon decay in flight (DIF)
  - Cosmic-ray
  - **No accidentals!**

μ-e Conversion

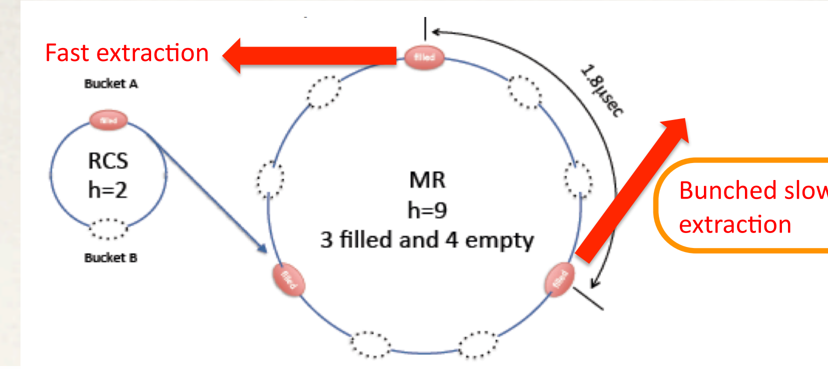


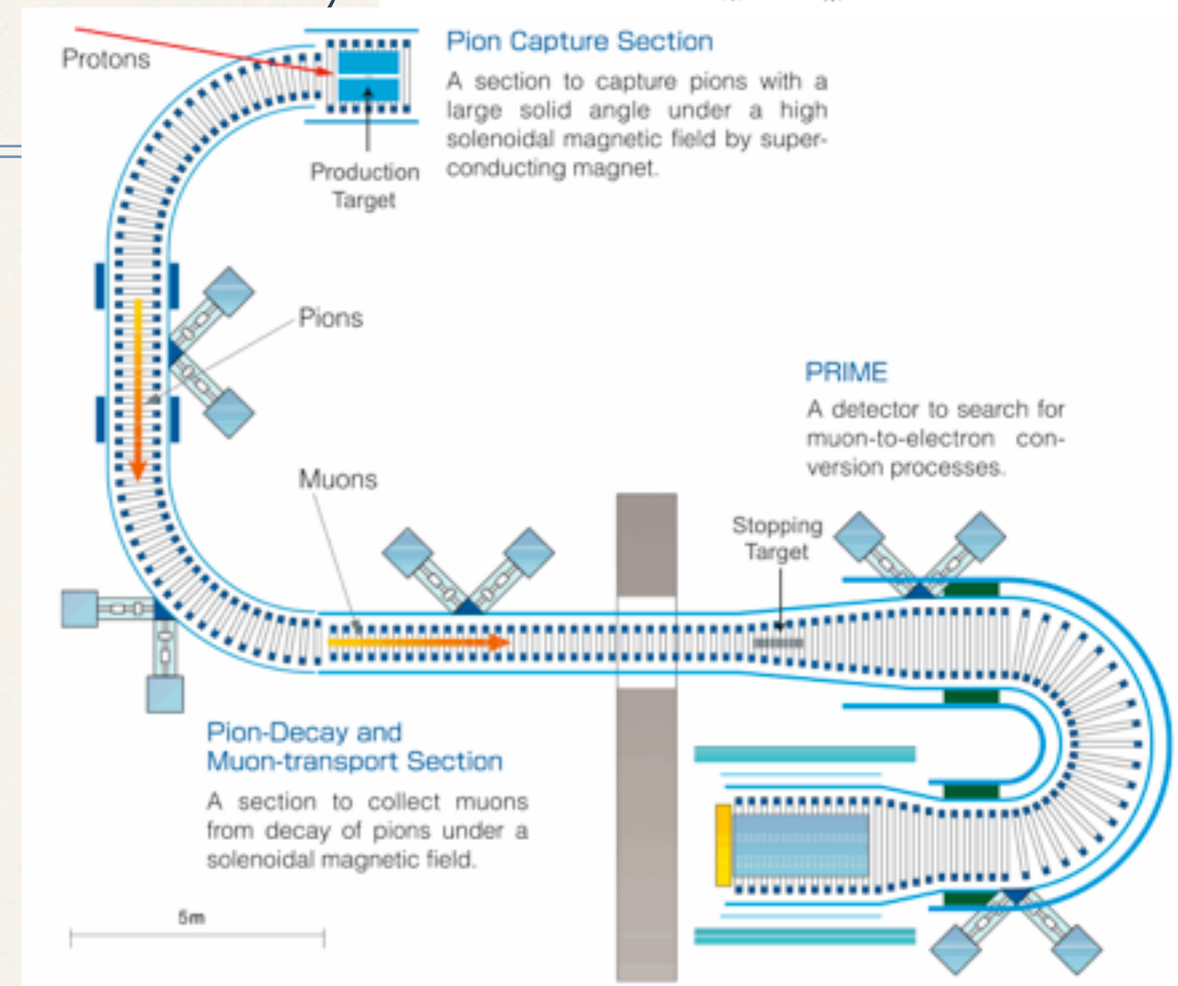
M.Koike, et al., J. Phys. G: Nucl. Part. Phys. 29(2003)2051

- *Pros*
  - Higher beam intensity is possible because of no accidentals → could greatly improve LFV sensitivity
  - Sensitive also to non-photonic process (n.b. only photonic process to $\mu \to e\gamma$)
  - Target dependence to discriminate interaction types
- *Cons*
  - Need high intensity and hight purity μ-beam of $O(10^{11})$ μ/s (n.b. present highest intensity $O(10^8)$ at PSI)

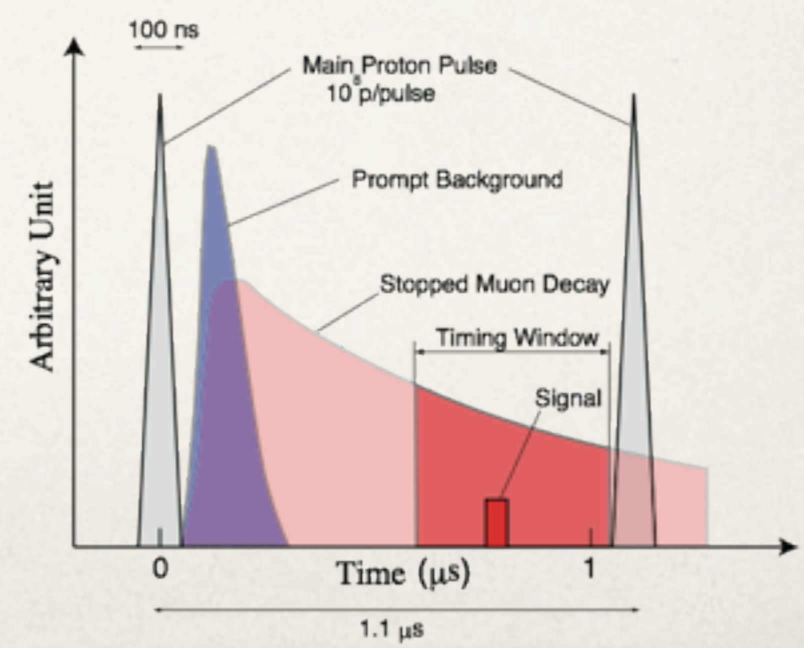
    → costly!

COMET (E21@J-PARC)



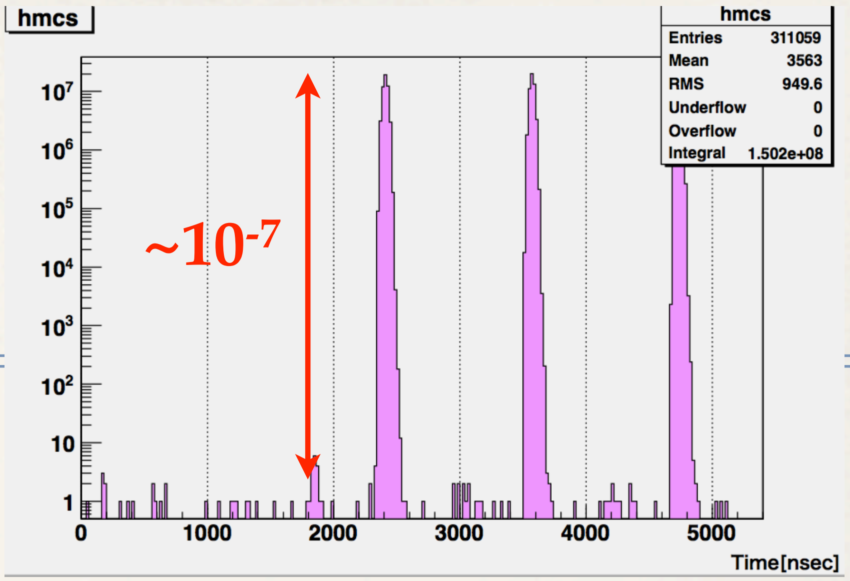


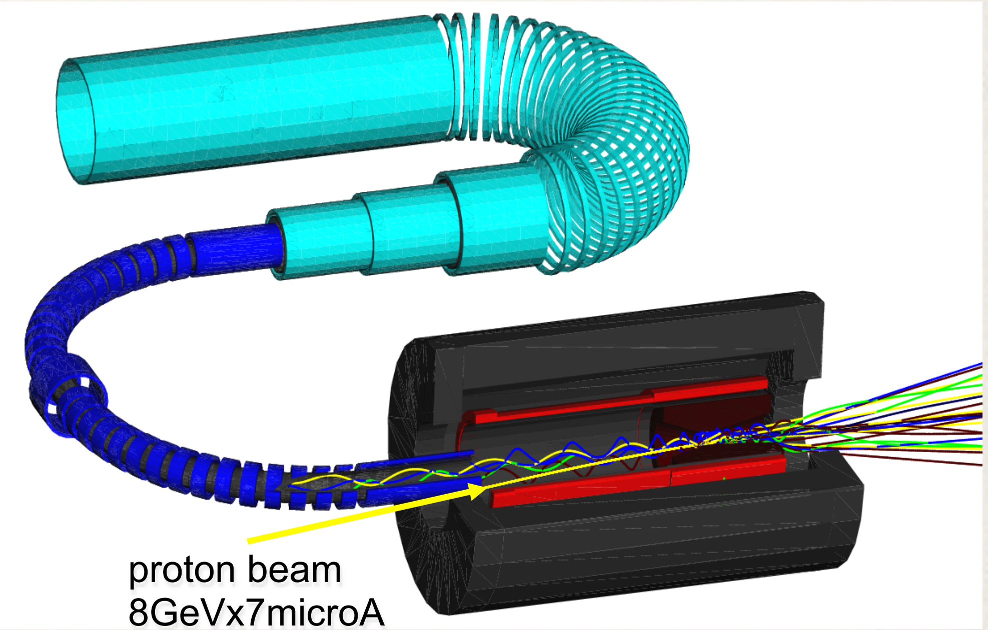
- **CO**herent **M**uon-to-**E**lectron **T**ransition experiment (E21@J-PARC)
- Target S.E.S.: **2.6×10^{-17}**
- Pulsed proton beam to reject beam related prompt BG
  - Pulse separation > 1μsec, pulse width < 100nsec
  - **Beam extinction = (# of protons bw/ pulse) / (# of protons in pulse) < 10^{-9}**
- Pion production target in novel superconducting magnet
- C-shaped solenoids for muon transport and electron momentum selection
- Tracker and calorimeter to measure electrons
- Next step: PRISM/PRIME with 10^{-18} sensitivity

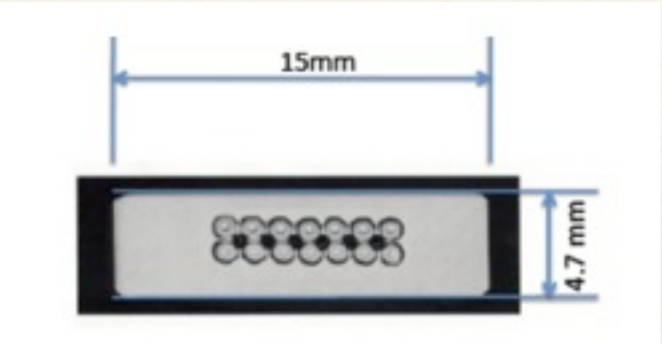


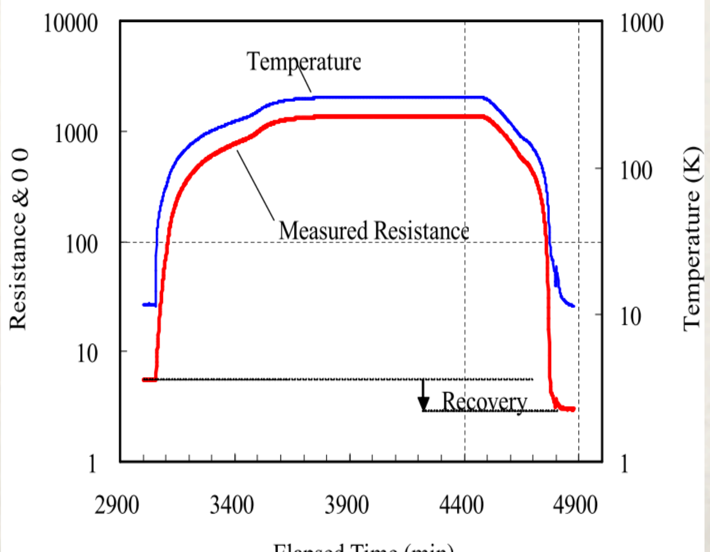
COMET R&D Status

- Proton beam extinction study
  - Measurements at MR abort line and secondary beam line give consistent result of O(10^{-7}) at MR
  - Confident of achieving requirement of extinction level ($O(10^{-9})$) together with
    - Double injection kicking ($O(10^{-6})$)
    - External extinction device (AC dipole) ($O(10^{-3})$)
- Design of pion capture solenoid in progress
  - Irradiation test of SC wire
- Design work on transport solenoid









COMET Status and Prospects

- Stage-1 approval in 2009 from J-PARC PAC
- TDR to complete in next months toward stage-2 approval

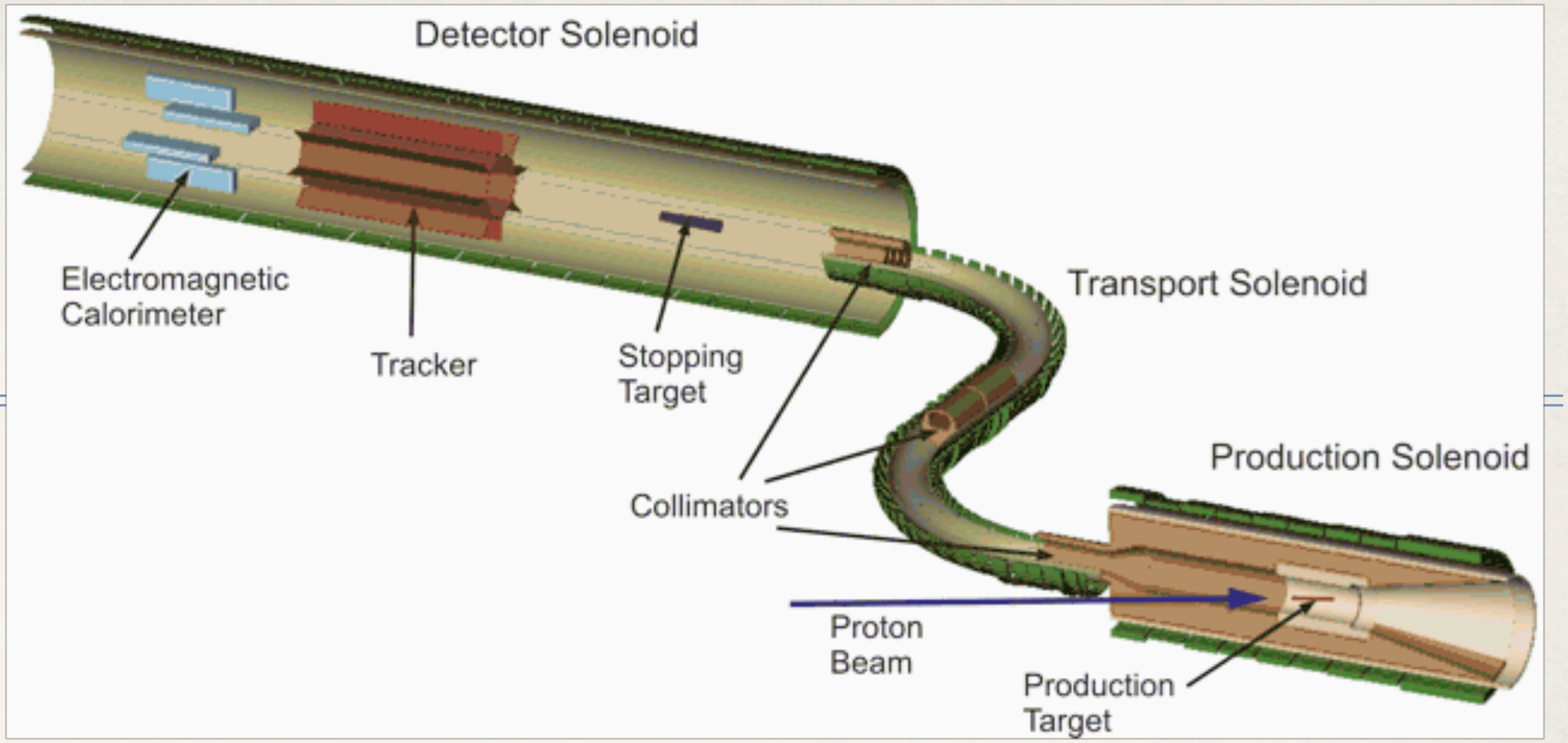
	2012	2013	2014	2015	2016	2017	2018	2019
MR studies	studies							
Proton beamline			construction					
Pion capture			construction			installation		
Muon transport				construction		installation		
Detector				construction		installation		
infrastructure				construction		installation		
data taking							engineer-ing	physics run

Latest costing ~ $80M

Mark Lancaster : COMET

APS/DPF 2011 : p28

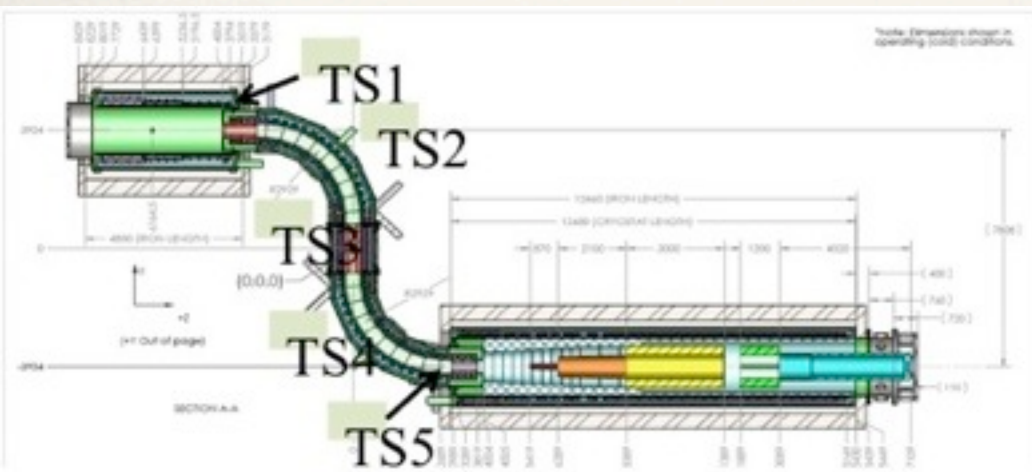
Mu2e



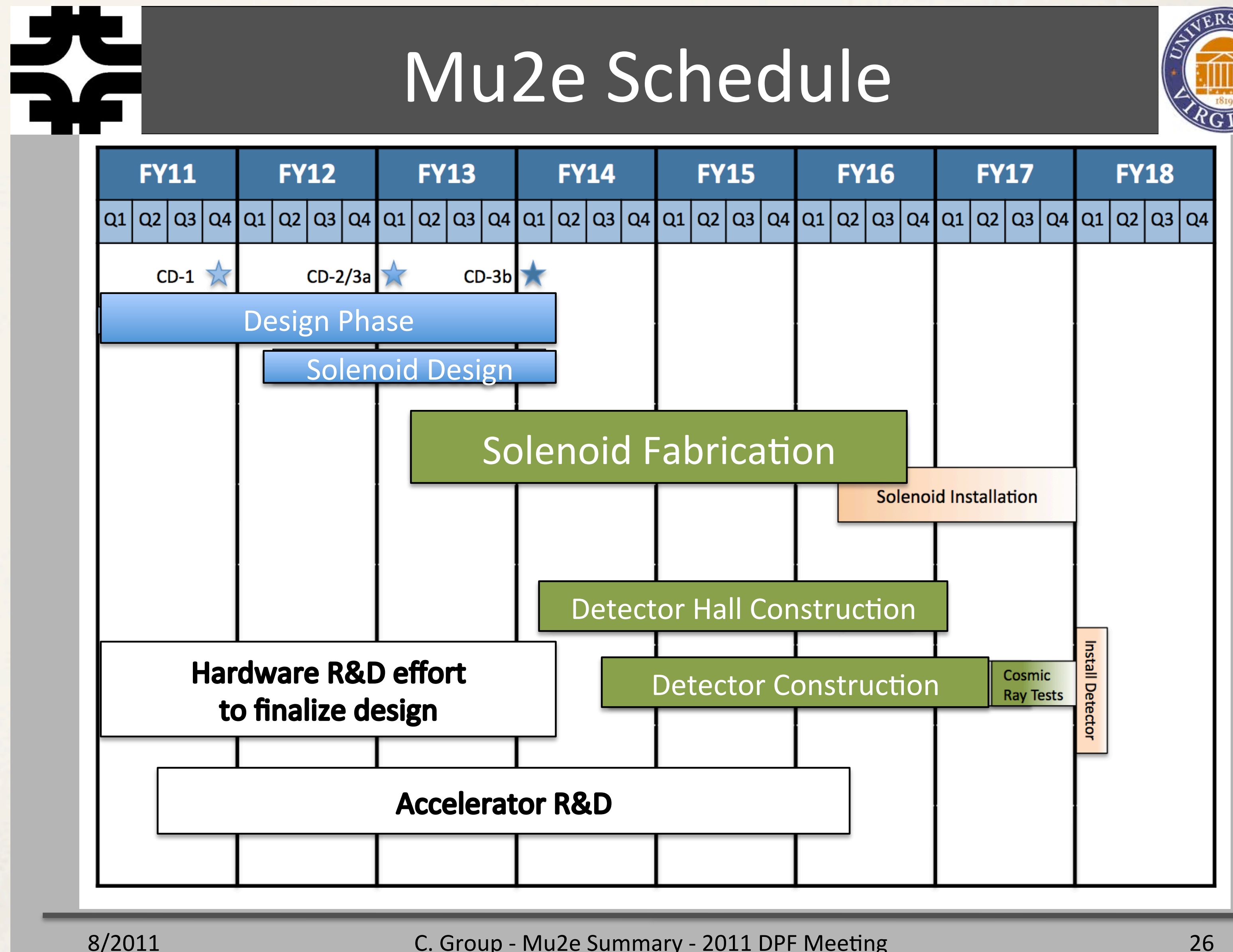
- Target S.E.S: **2×10^{-17} (similar to COMET sensitivity)**
- Planned at Fermilab
- Beam pulsing by using antiproton accumulator ring and debuncher ring after Tevatron shutdown
  - Beam extinction $< 10^{-10}$
  - No conflict with NOvA
- Pion production target in a solenoid magnet
- S-shaped solenoids for muon transport to eliminate BG and sign select
- Tracker and calorimeter to measure electrons
- Next step: ProjectX with 10^{-18} sensitivity

Mu2e R&D Status

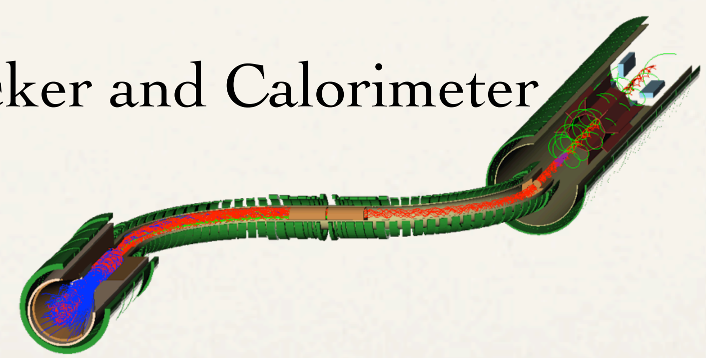
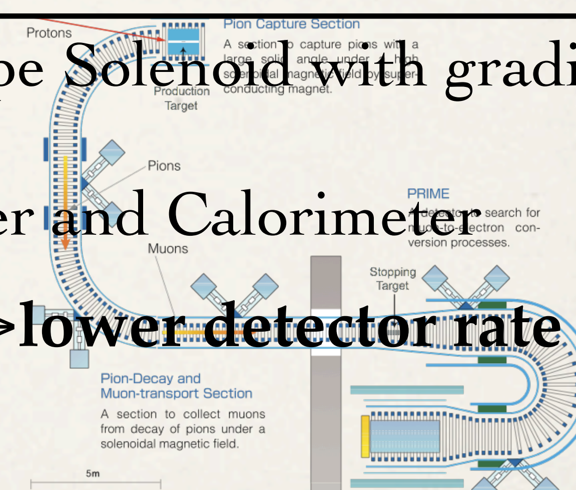
- Design work of solenoid system in progress.
- Civil an building design
- Detector R&D



- DOE CD-0 Approved in 2009
- DOE CD-1 this autumn, CD-2/3a about a year later



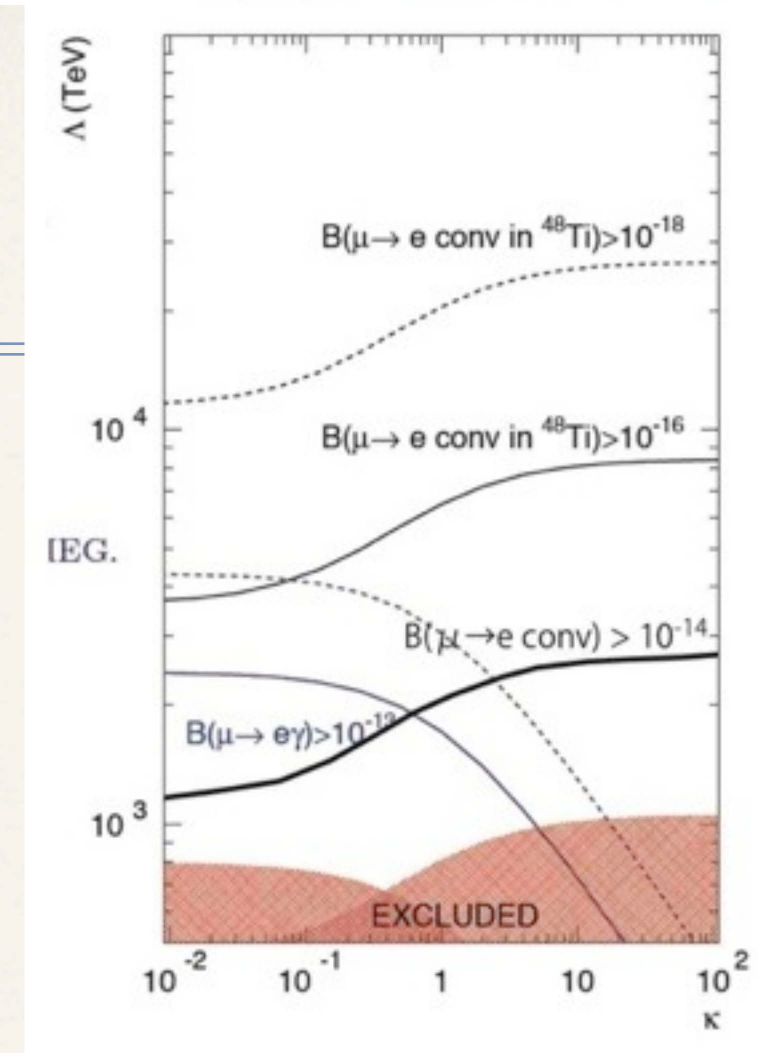
COMET vs. Mu2e

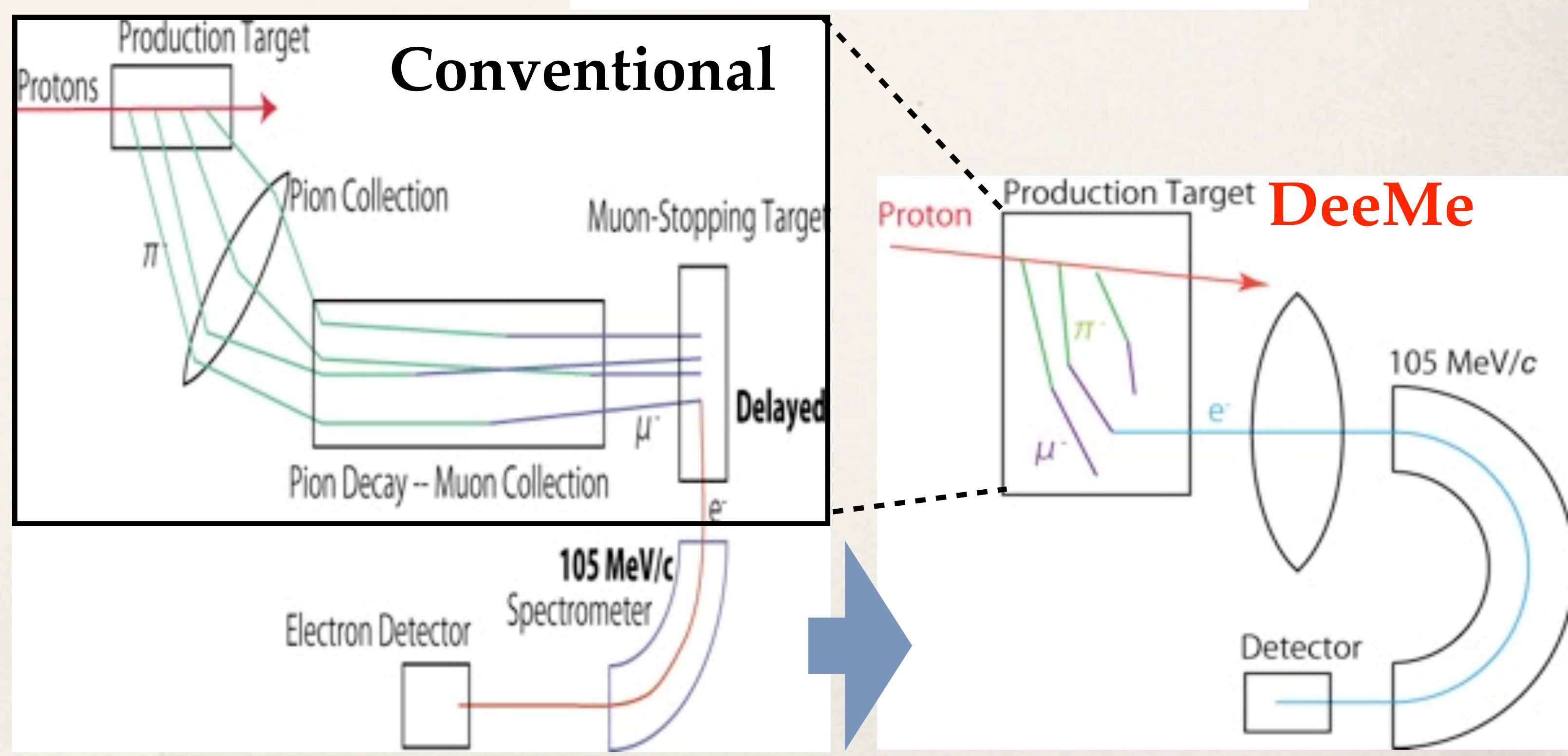
	Mu2e	COMET
Proton Beam	8GeV, 20kW bunch-bunch spacing 1.69 μsec **rebunching** Extinction: < **10^{-10}**	8GeV, 50kW bunch-bunch spacing 1.18-1.76 μsec **empty buckets** Extinction: < **10^{-9}**
Muon Transport	**S-shape** Solenoid	**C-shape** solenoid
Detector	Straight Solenoid with gradient field Tracker and Calorimeter 	C-shape Solenoid with gradient field Tracker and Calorimeter **→lower detector rate** 
Sensitivity	SES: 2×10^{-17} 90% CL UL: 6×10^{-17}	SES: 2.6×10^{-17} 90% CL UL: 6×10^{-17}

DeeMe

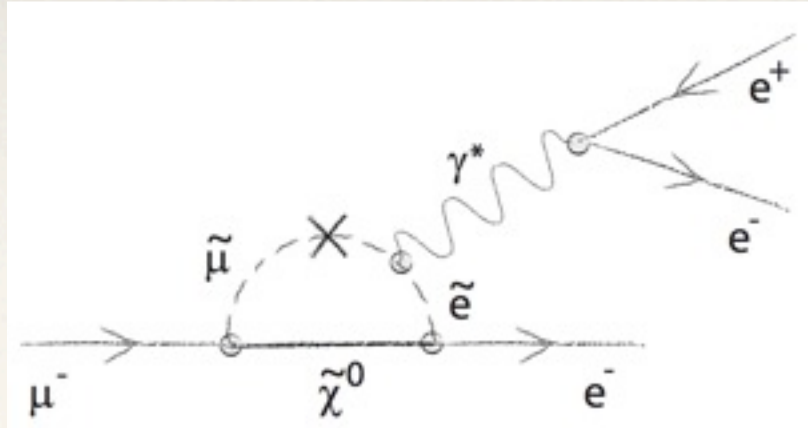
$$L_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

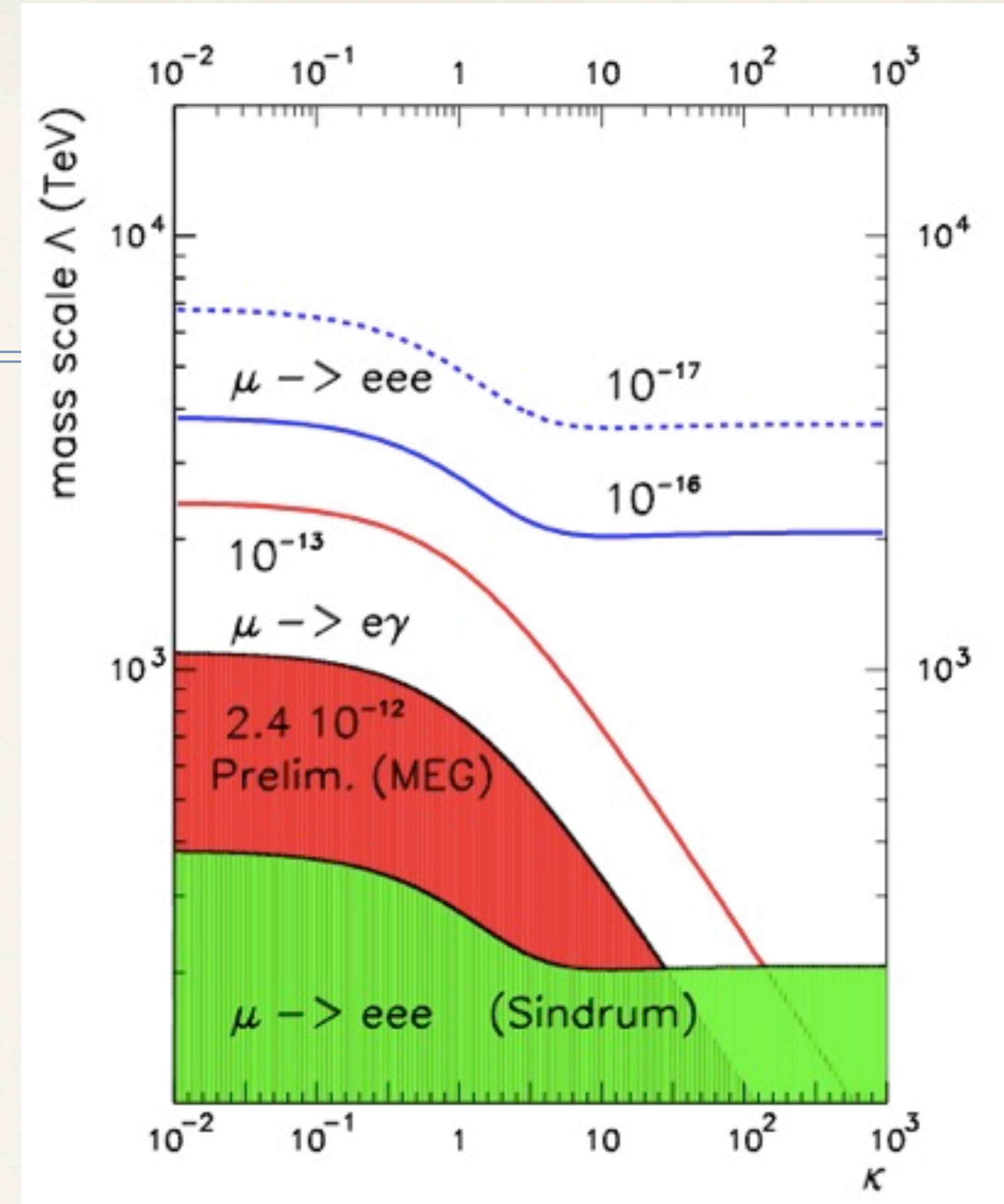
- Target S.E.S: 2×10^{-14}
- Moderate sensitivity, but in a timely fashion. (simple & low-cost)
- Aiming at obtaining first result by 2015
- Stage-1 approval at KEK/IMSS Muon PAC, under exam. at J-PARC PAC
- Possible beam line: H-line at J-PARC (which can be time-shared with other experiments such as HFS, g-2, EDM)



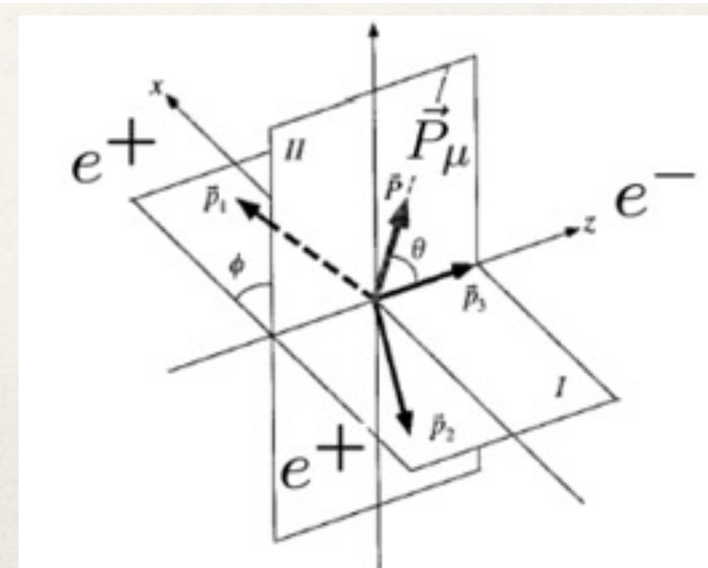


$\mu \rightarrow eee$

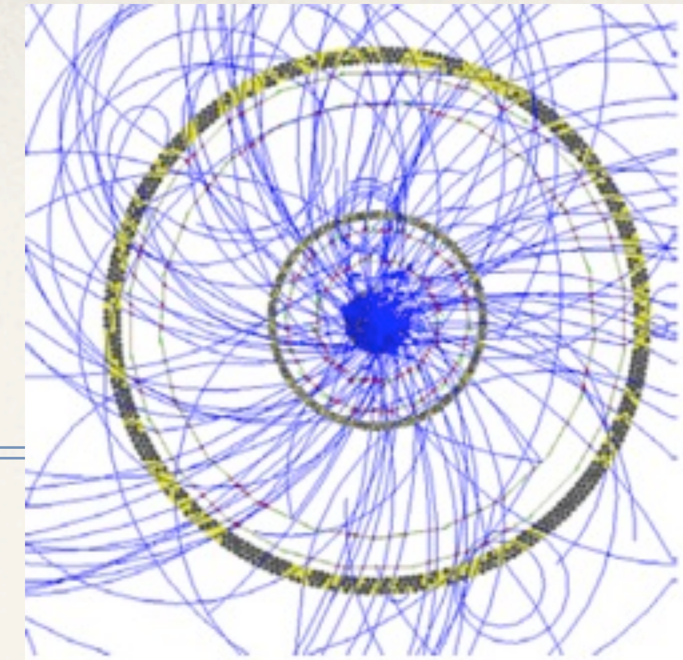


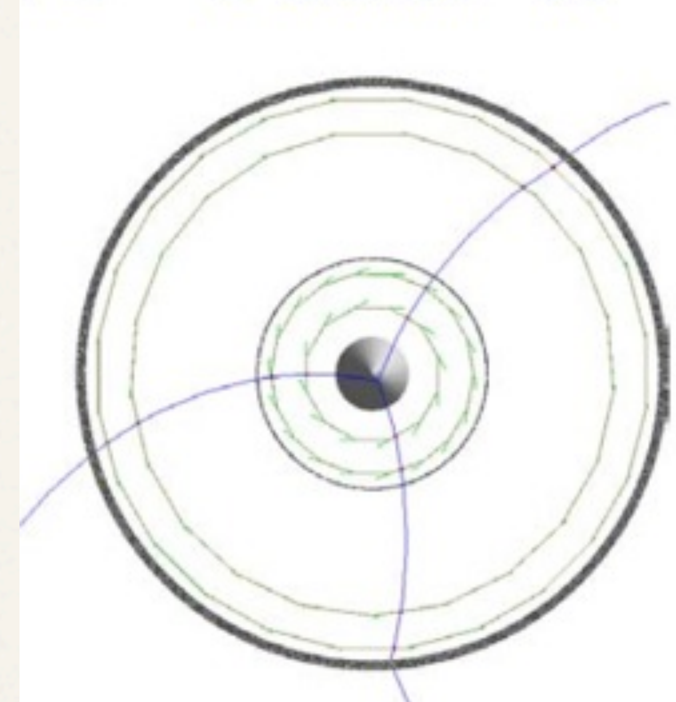


- Present limit B($\mu \rightarrow eee$) < 1.0×10^{-12} (SINDRUM at PSI, 1988)
- Large potential to discover at a search with $O(10^{-16})$ sensitivity
- Angular distribution with polarized muon to discriminate
  - P-odd and T-odd asymmetries
- Need 10^9 μ/s
- BG: Prompt and accidentals



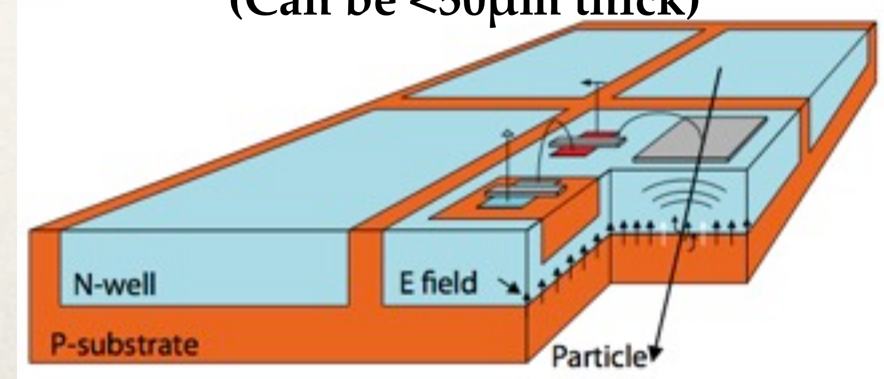
$\mu \to eee$ at PSI





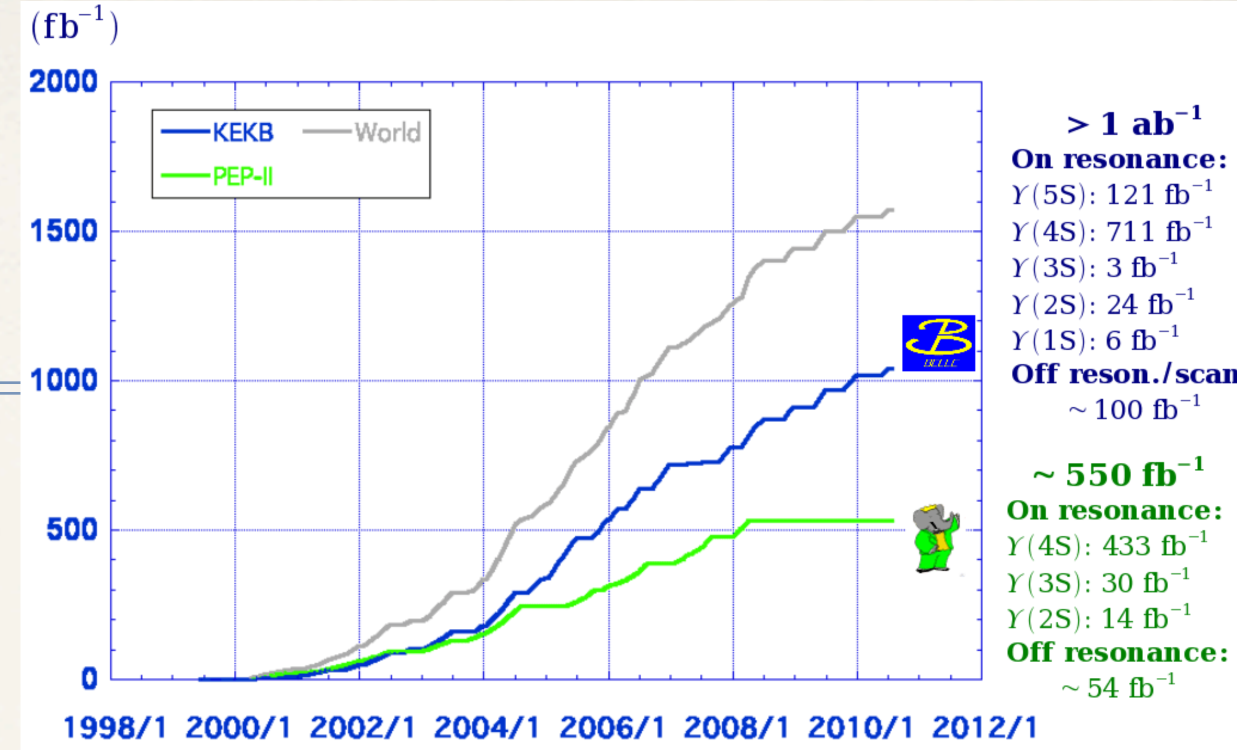
- **Sensitivity goal ~ 10^{-16}**
- HV monolithic pixel sensor and fibre tracker
- Background
  - Accidentals ← excellent vertex and timing resolutions
  - Internal conversion $\mu \to eee\nu\nu$ ← excellent mom resolution
- Thin silicon pixel tracker/scintillating fibre timing detector
- Kapton sensor support/hollow double cone target
- LOI planned for 2011

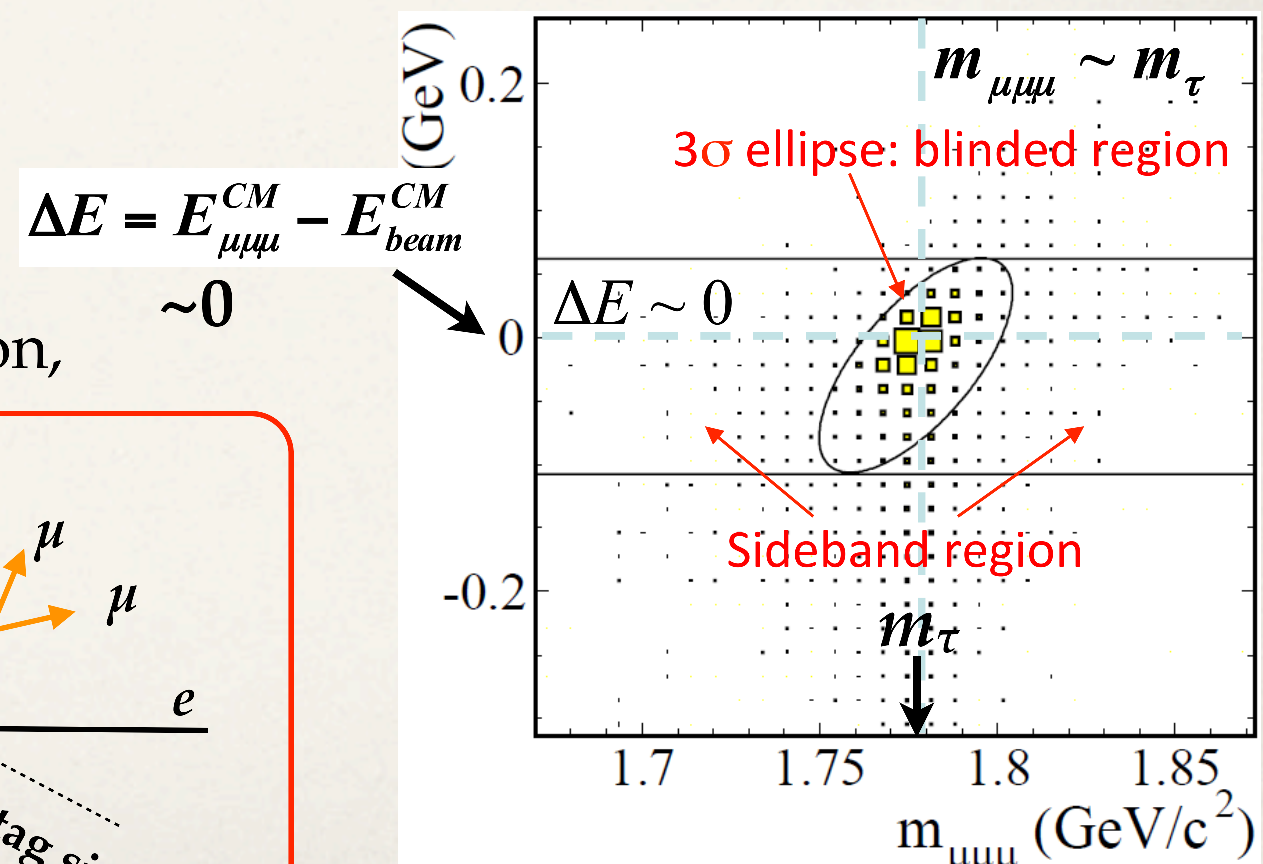
High voltage monolithic active pixel sensor (Can be <50μm thick)

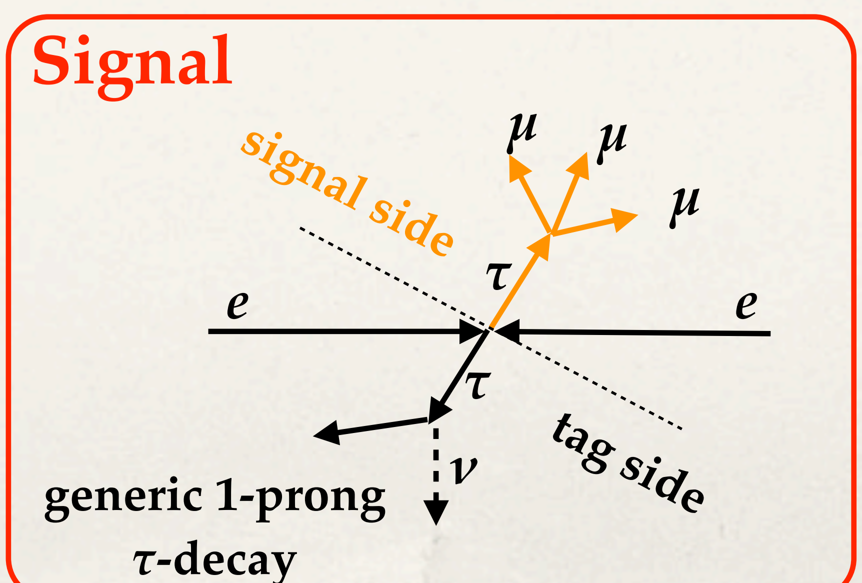


LFV τ Decays

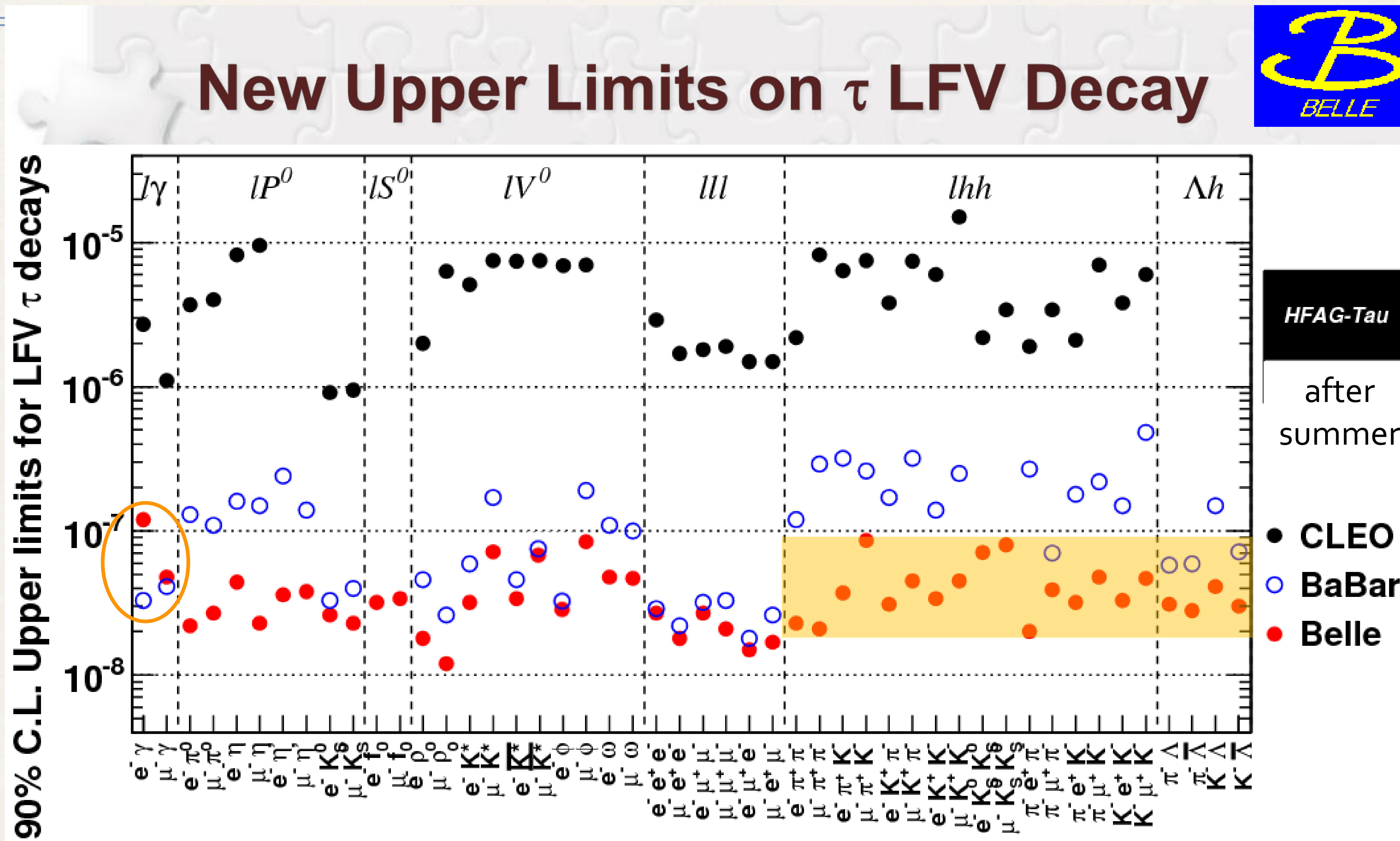
- Integrated luminosity > 1000fb^{-1} (Belle)
- B-factory is also an excellent τ-factory!
  - O(10^9) τ-pairs produced
- ~50 LFV τ decay processes are being searched for.
- BG
  - generic $\tau^+\tau^-$, continuum $e^+e^-\to qq$, two-photon, radiative Bhabha, ...







LFV τ Decays Status



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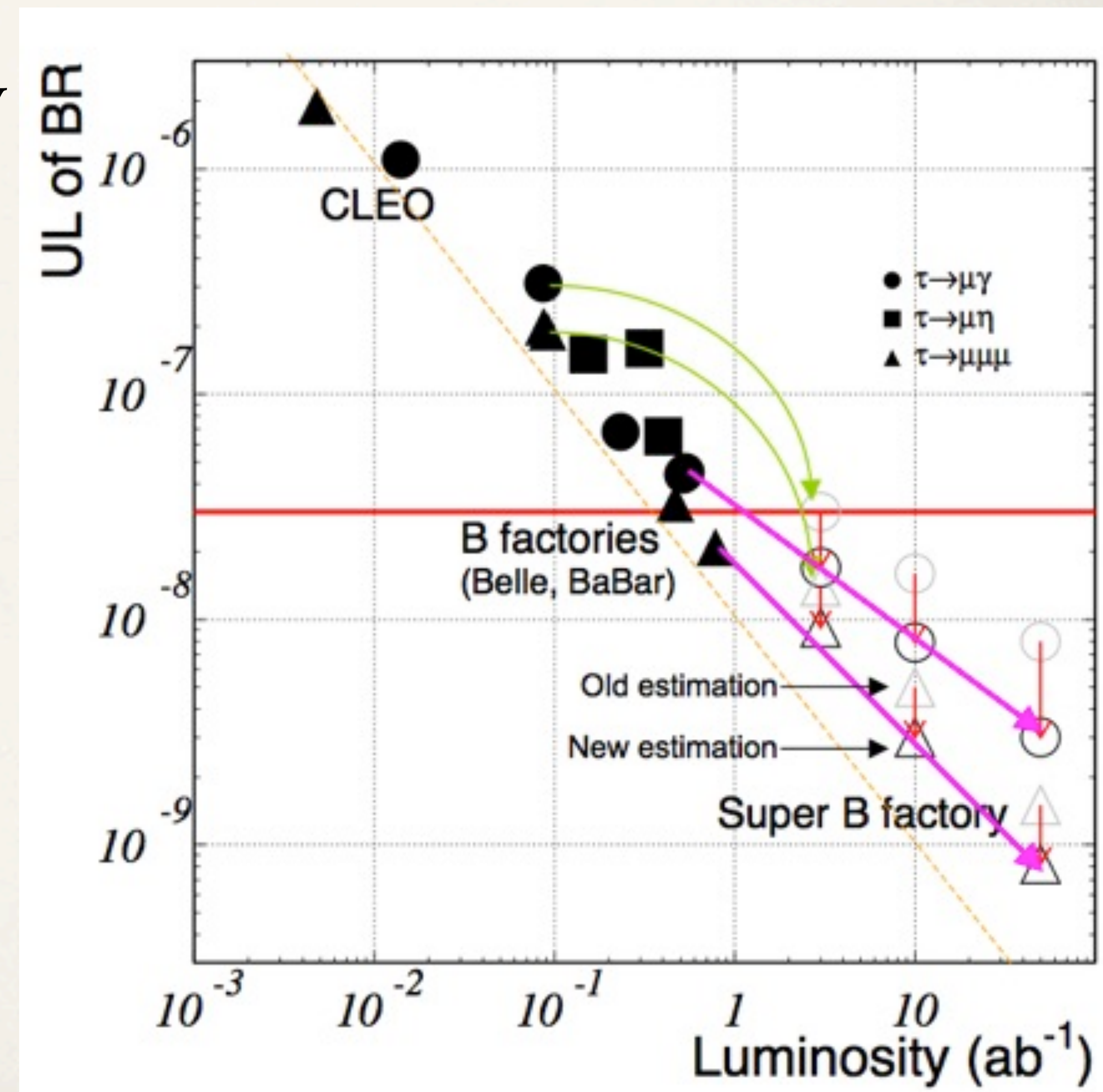
- Reached $O(10^{-8})$ sensitivity!
- $\tau \to l\gamma$ update with full data sample will arrive soon.

LFV τ Decays Prospects

- Super B-factories with >×10 luminosity will produce $O(10^{10})$ τ-pairs
- Need further optimization of BG reduction
- Sensitivity
  - $\tau \to \mu\gamma$: $O(10^{-(8\text{-}9)})$
  - $\tau \to lll$, $\tau \to l$+meson: $O(10^{-(9\text{-}10)})$

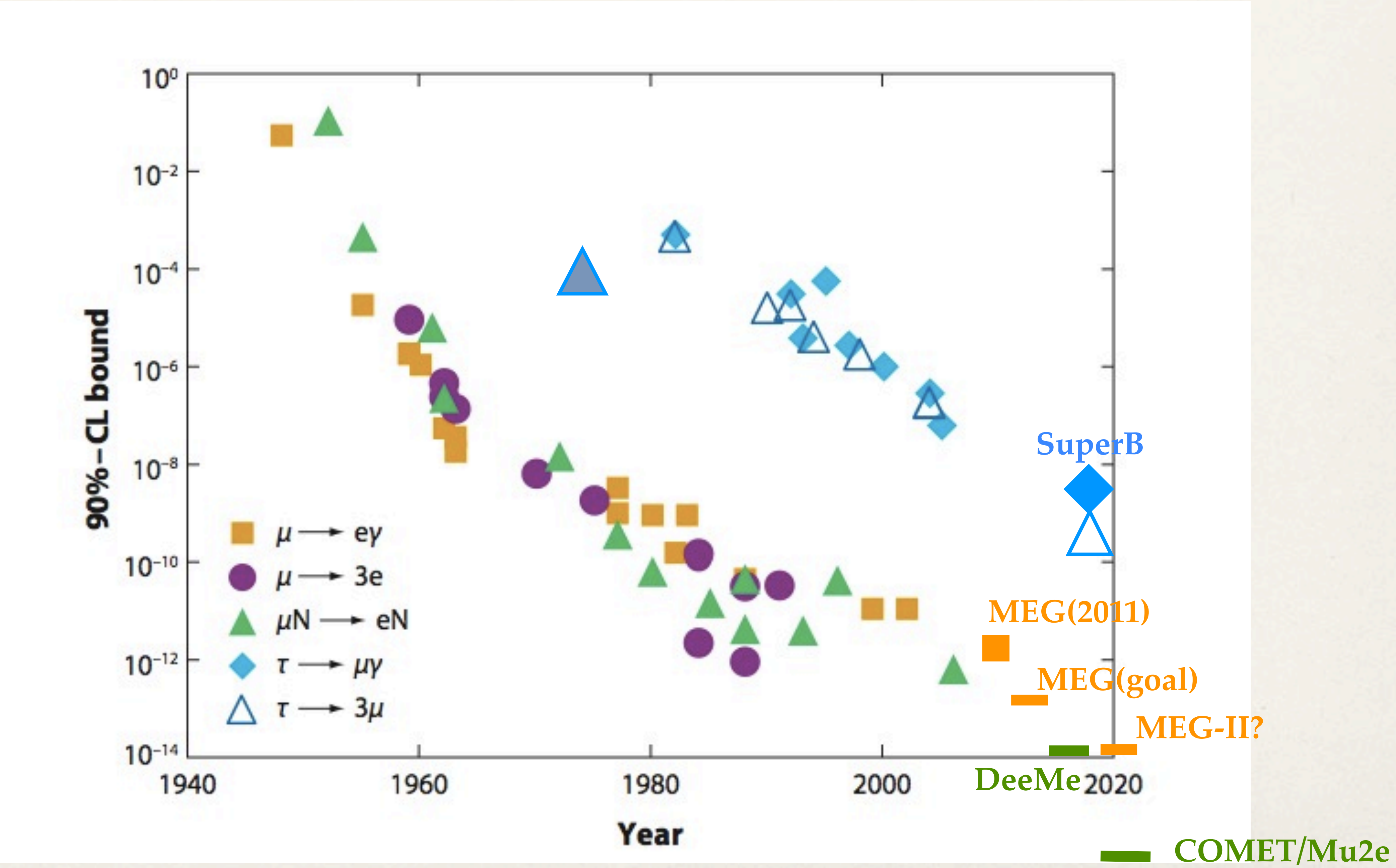
Improve as 1/sqrt(L) due to ISR BG

Improve as 1/L



K.Inami(Nagoya Univ.) @PANIC2011

CLFV Search Prospects



Original plot for past experiments from Annu. Ref. Nucl. Part. Sci. 2008. 58:315-41 W. J. Marciano, T.Mori, and J. M. Roney

Summary

- A wide variety of CLFV experiments are running, planned or proposed.
- Large potential to discover CLFV in the near future (maybe at MEG first?)
- "Discovery" is not the end of the story!
  - Various CLFV processes should offer possibility to pin-down new physics model.
    - Correlation between various processes
    - Target dependence in μ-e conversion, angular distribution in $\mu \to e\gamma / \mu \to eee$
- We should try to "measure" CLFV in as many processes as possible.