Lepton Flavour Violation Experiments in the LHC Era

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On Behalf of the MEG Collaboration

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Outline

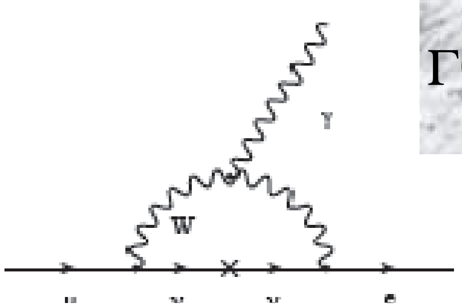
- LFV: what and why
- The muonic channel
  - $\mu \rightarrow e\gamma$ (MEG) (new preliminary results);
  - $\mu \rightarrow e\ e\ e$
  - $\mu \rightarrow e$ conversion (Mu2e, COMET, PRISM/PRIME);
- The tauonic channel
  - $\tau \rightarrow \mu\gamma$, $e\gamma$ (BABAR, BELLE);
  - $\tau \rightarrow lll$ (BABAR, BELLE);
  - Other decays ($\tau \rightarrow lh$, $\tau \rightarrow lhh$ …) briefly discussed.
- A look at the future
  - Possible improvements in the muonic sector;
  - Super-B factory
- Conclusions

LFV: what and why 1)

- In the **SM of electroweak interactions**, leptons are grouped in doublets and there is **no space for transitions where the lepton flavour is not conserved**.
- However, **lepton flavour is experimentally violated** in neutral sector (**neutrino oscillations**) ⇒ needed to **extend the standard model by including neutrino masses and coupling between flavours**.
- **cLFV indicates non conservation of lepton flavour in processes involving charged leptons**.

LFV: what and why 2)

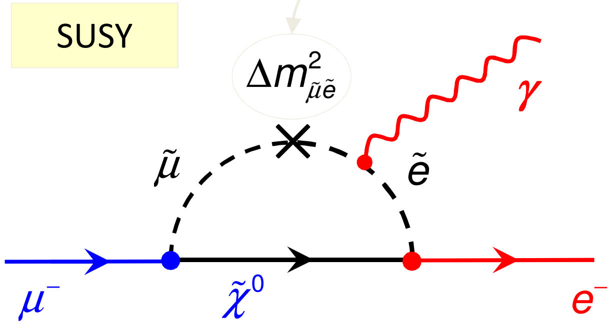
Including neutrino masses and oscillations:



$$\Gamma(\mu\to e\gamma)\approx\frac{G_F^2 m_\mu^5}{192\,\pi^3}\left(\frac{\alpha}{2\pi}\right)\sin^2(2\vartheta)\sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)\approx 10^{-55}$$

Experimentally not measurable !

However, huge rate enhancement in all SM extensions, expecially in SUSY/SUSY-GUT theories (mixing in high energy sector) ⇒ predicted rates experimentally accessible ! (Barbieri, Masiero, Ellis, Hisano ..)



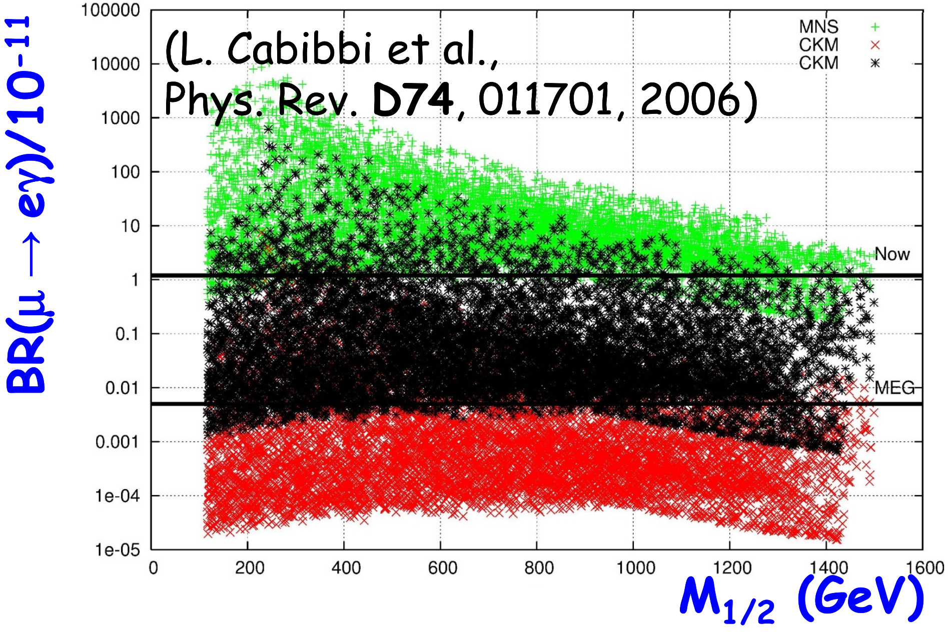
$$\approx 10^{-5}\,\frac{\Delta m^2_{\tilde e\tilde\mu}}{\bar m^2_{\tilde\ell}}\left(\frac{100\text{ GeV}}{m_{\text{SUSY}}}\right)^4\tan^2\beta\approx 10^{-12}$$

⇒ Observation of LFV clear evidence for physics beyond SM

LFV: what and why 3)

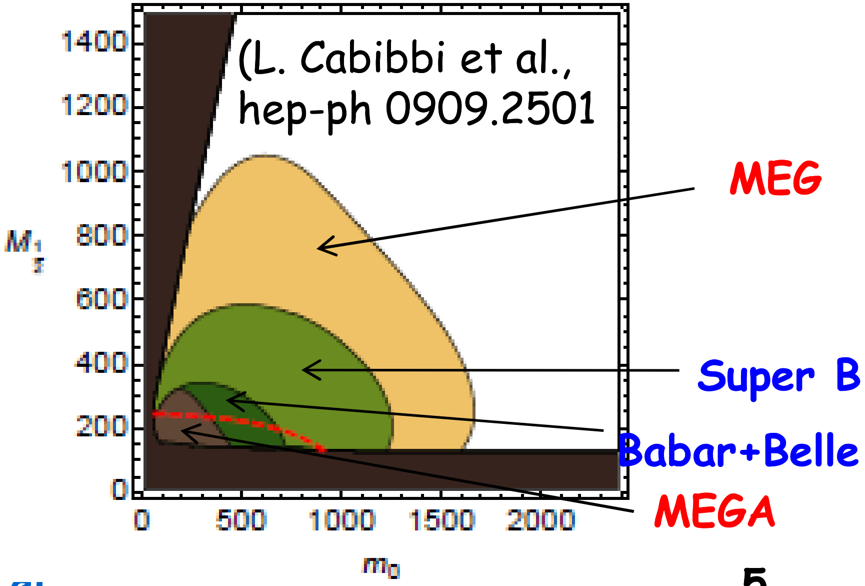
Strong impact of LFV searches in particle physics development:

- beginning of **lepton physics;** (Pontecorvo & Hincks, 1947)
- **universality** of Fermi interaction ⇒ **standard model;** (1955)
- **flavour physics** (> 1960)
- possibility to explore **high mass SUSY scale (> 1000 TeV)** and give insights about **large mass range, parity violation, number of generations** ... (now)



(L. Cabibbi et al., Phys. Rev. **D74**, 011701, 2006)

Examples of recent predictions



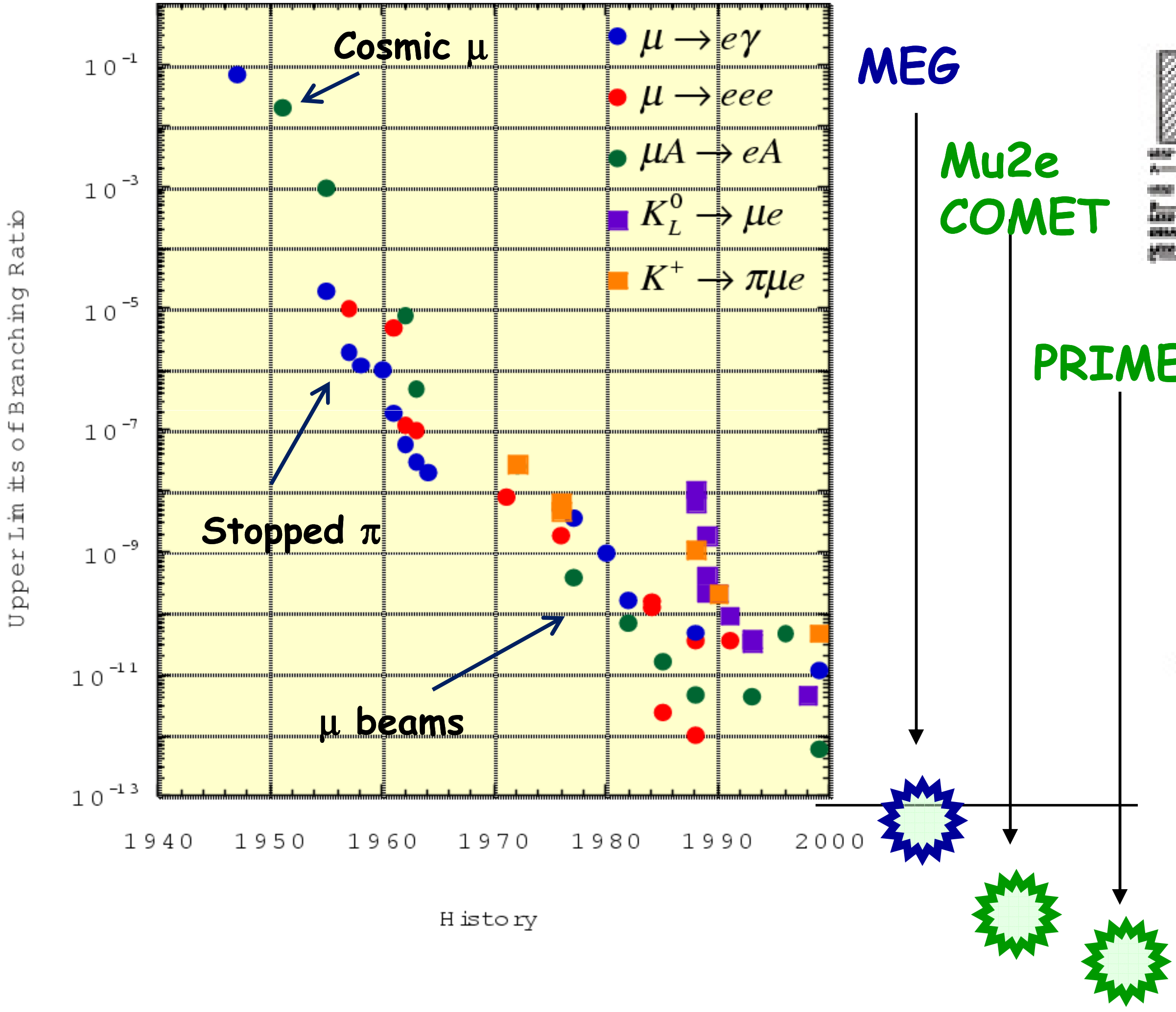
(L. Cabibbi et al., hep-ph 0909.2501

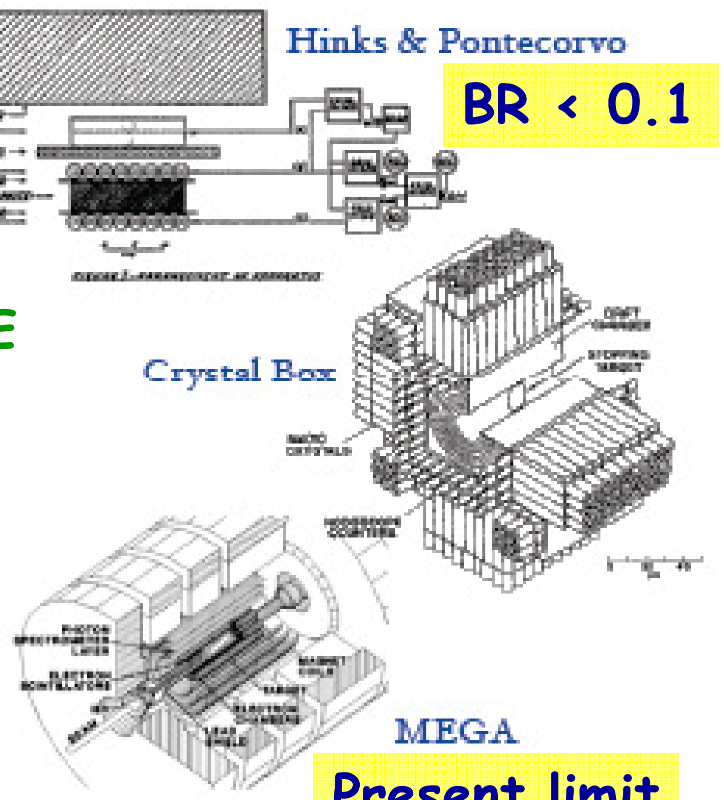
The muonic channel

Muons are very sensitive probes to study Lepton Flavour Violation:

- intense muon beams can be obtained at meson factories;
- muon lifetime is rather long (2.2 μs);
- final states are very simple and can be precisely measured

Experimental limits

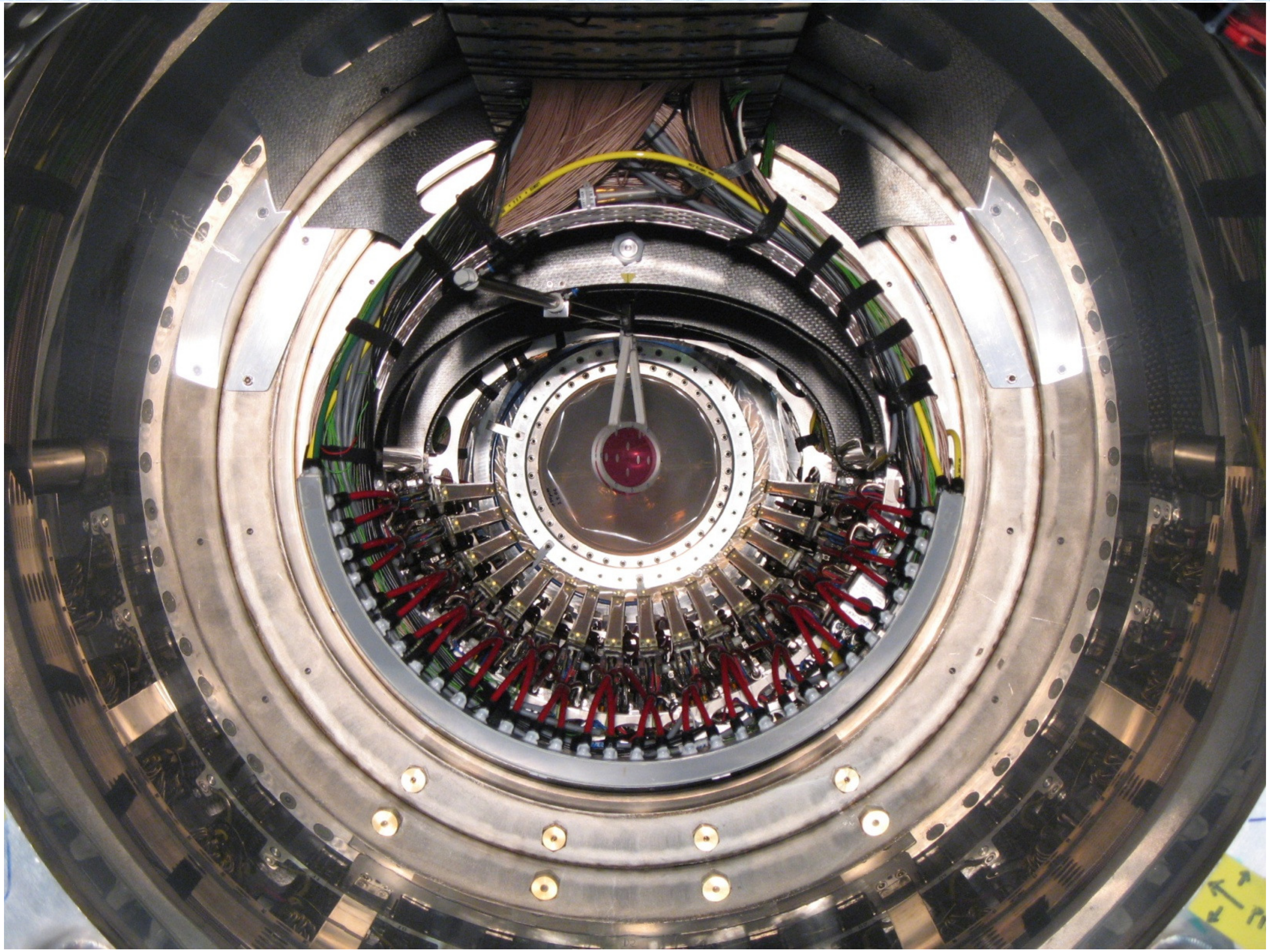




BR < 0.1

Present limit
1.2×10^{-11}

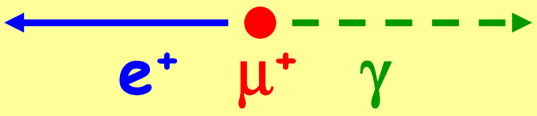
The MEG Experiment at PSI



$\mu \to e\gamma$ signal and background 1)

signal

$\mu \to e\,\gamma$



$\theta_{e\gamma} = 180°$

$E_e = E_\gamma = 52.8$ MeV

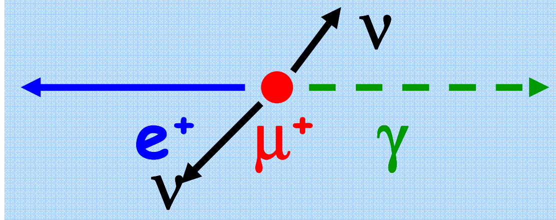
$T_e = T_\gamma$

background

physical

$\mu \to e\,\gamma\,\nu\,\nu$

(radiative decay)



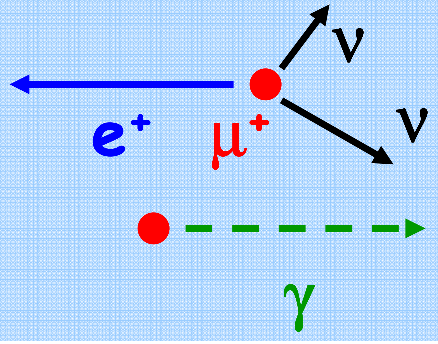
accidental

$\mu \to e\,\nu\,\nu$

$\mu \to e\,\gamma\,\nu\,\nu$

$ee \to \gamma\gamma$

$eZ \to eZ\gamma$



$\mu \to e\gamma$ signal and background 2)

- $R_{signal} = R_{\mu} * BR(\mu \to e\gamma)$
- $R_{RD} = R_{\mu} * BR(\mu \to e\nu\nu\gamma)$
- $R_{acc} \propto (R_{\mu})^2 * (\Delta\Theta)^2 * (\Delta E_{\gamma})^2 * \Delta T * \Delta E_e$

$$\Downarrow$$

- Muon rate to be used is a trade off between expected number of signal events and background level;
- Sensitivity is limited by accidental background;
- High resolution detectors are mandatory.

The MEG goal

FWHM

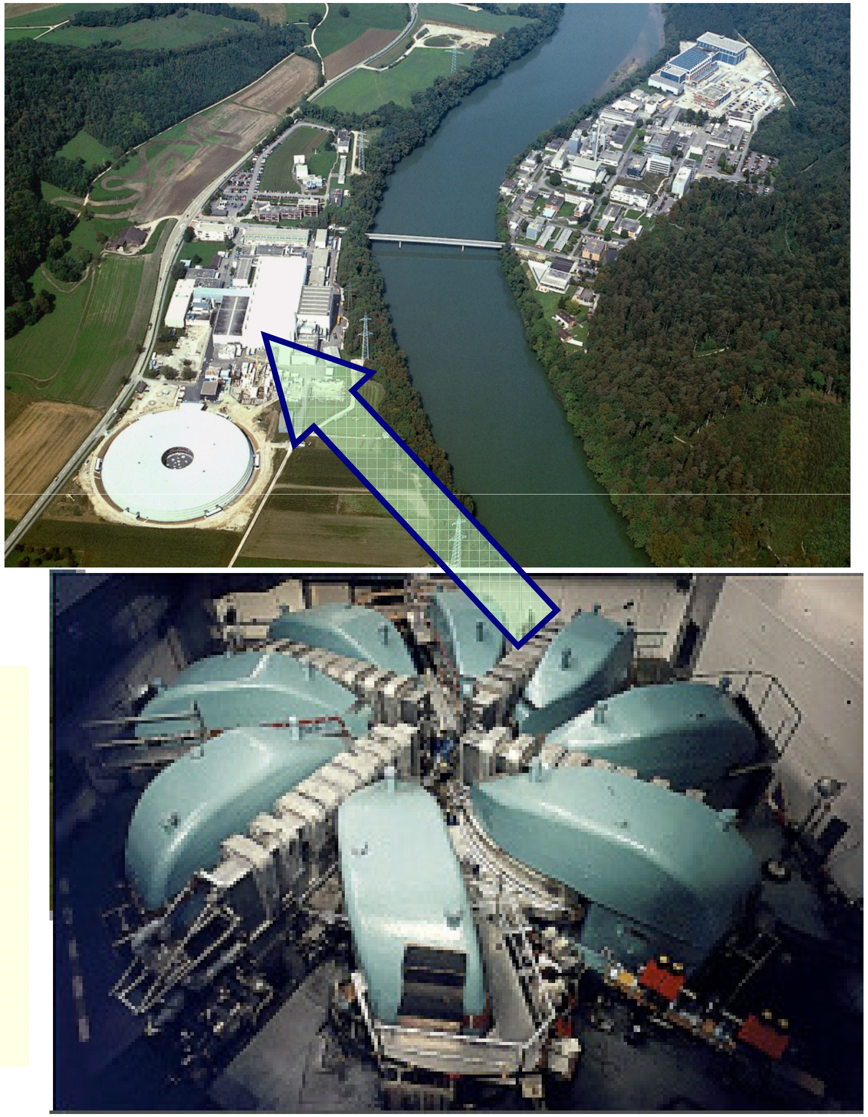
Need of a DC beam

Exp./Lab	Year	$\Delta E_e/E_e$ (%)	$\Delta E_\gamma/E_\gamma$ (%)	$\Delta t_{e\gamma}$ (ns)	$\Delta\theta_{e\gamma}$ (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	**2012**	**0.8**	**4**	**0.15**	**19**	**3.0×10^7**	**100**	**2×10^{-13}**

With these resolutions: BR(ACC) ~ $2 \cdot 10^{-14}$, BR(RD) ~ 10^{-15}

Improvement by two orders of magnitude ! A tough experimental challenge; possible, but excellent detector resolutions are needed.

The Paul Scherrer Institute (PSI)



- The **most powerful continuous machine** (proton cyclotron) in the world;
- **Proton energy** 590 MeV;
- Power 1.2 MW;
- **Nominal operational current** 2.2 mA.

MEG Detection Technique

- Stopped beam of 3 x 10^7 μ/sec in a 205 μm target.
- Liquid Xenon calorimeter for γ detection (scintillation).
- Solenoid spectrometer (COBRA) & drift chambers for e+ momentum measurement.
- Scintillation counters for e+ timing.

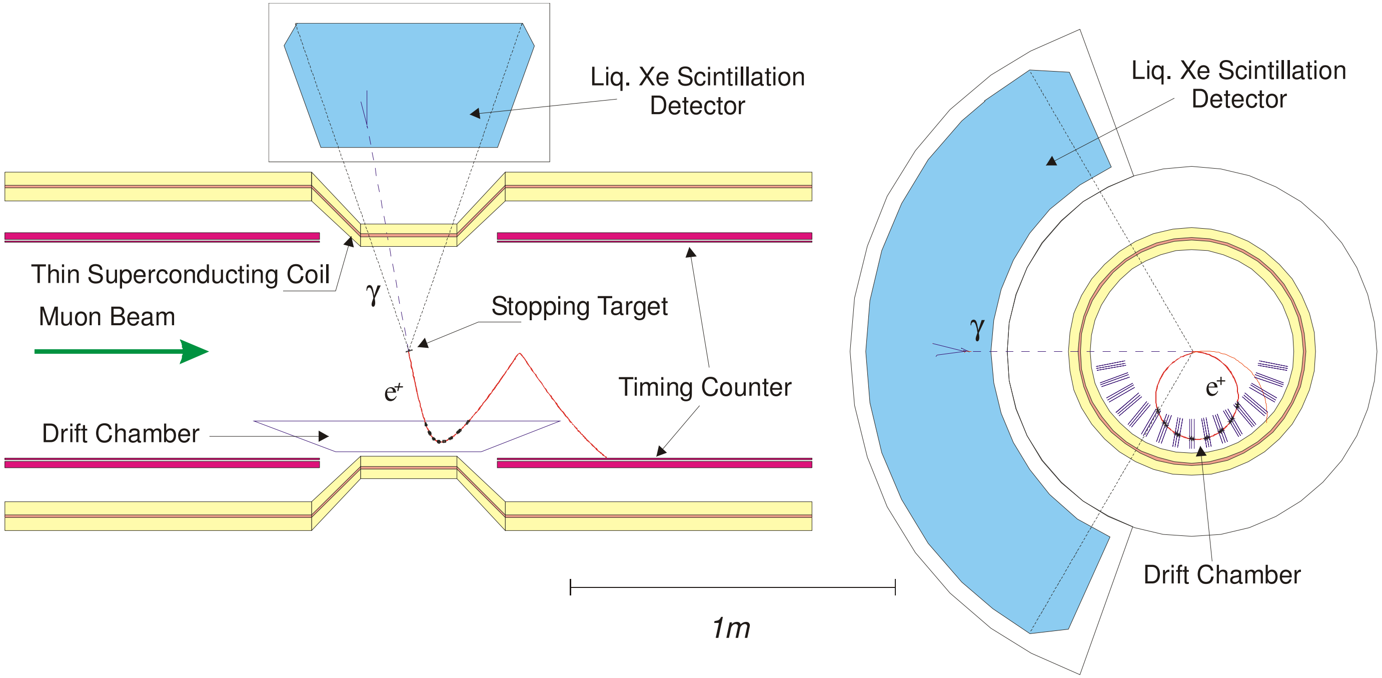
Method proposed in 1998; PSI-RR-99-05: 10^{-14} possibility

MEG proposal in 2002: 10^{-13} goal

A. Baldini and T. Mori spokespersons:

Italy, Japan, Switzerland, Russia, Usa.

≈ 60 physicists



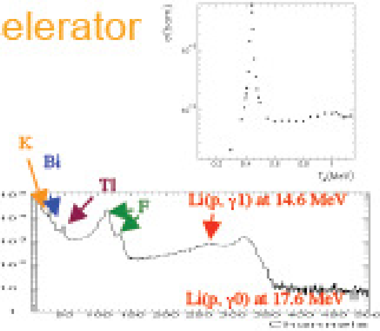
MEG Calibration

- MEG is a **precision experiment**;
- **High experimental resolutions** are mandatory (background level depends on resolutions);
- Good detector performances must **remain stable for a ~ 3 year scale**;
- Electromagnetic calorimeter uses an **innovative technology**;
- $\Rightarrow$ **Frequent and reliable calibration procedures represent one of the fundamental quality factors for MEG.**

Calibration tools 1)

Xenon Calibration

Proton Accelerator



Li(p,γ)Be

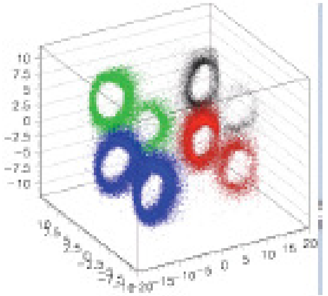
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

Alpha on wires

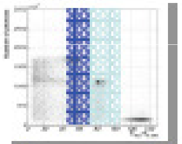


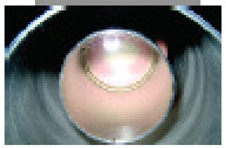
PMT QE & Att. L

Cold GXe

LXe

$\pi^0 \rightarrow \gamma\gamma$



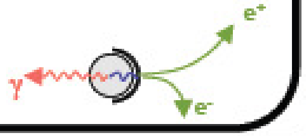


$\pi^- + p \rightarrow \pi^0 + n$

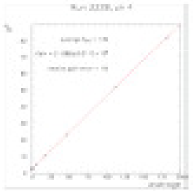
$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

$\pi^- + p \rightarrow \gamma + n$ (129MeV)

LH_2 target



LED

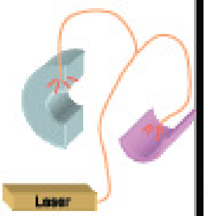


PMT Gain

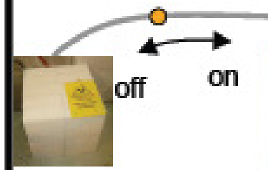
Higher V with light att.

Laser

relative timing calib.

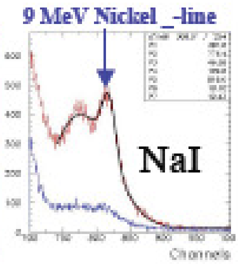


Nickel γ Generator

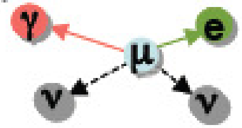


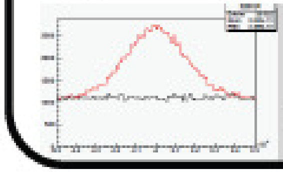
Illuminate Xe from the back

Source (Cf) transferred by comp air → on/off



μ radiative decay





Lower beam intensity < 10^7

Is necessary to reduce pile-ups

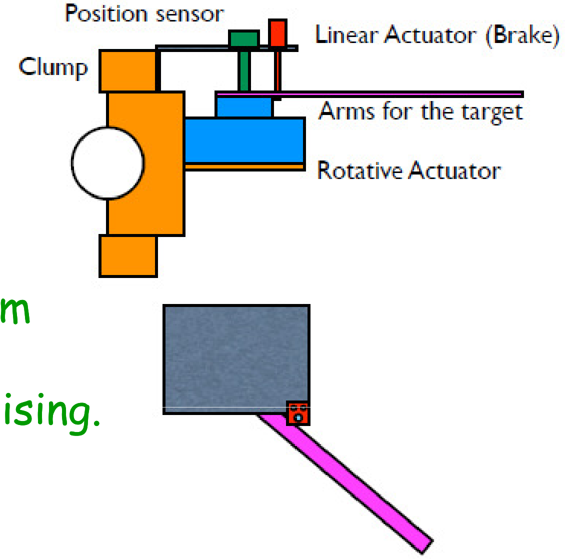
A few days ~ 1 week to get enough statistics

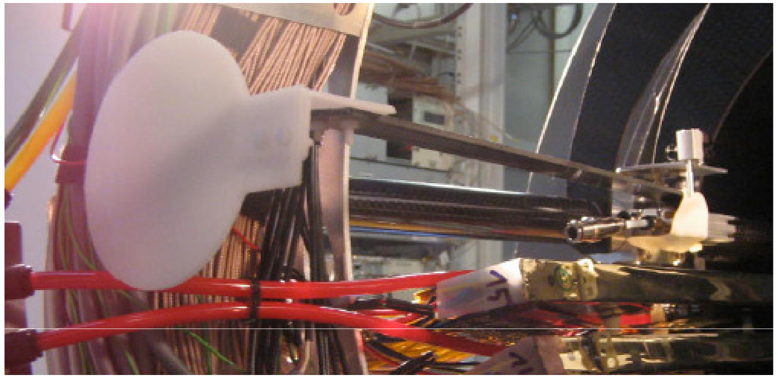
Calibration tools 2)

Positron monoergetic beam + CH_2 target for Mott scattering

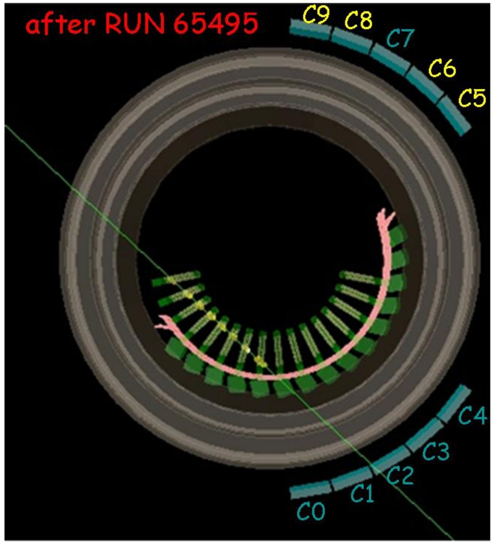
40 ÷ 60 MeV positron beam
Event rate ~ kHz for
10^8 e+/s. First tests promising.

NEW DEVICE !



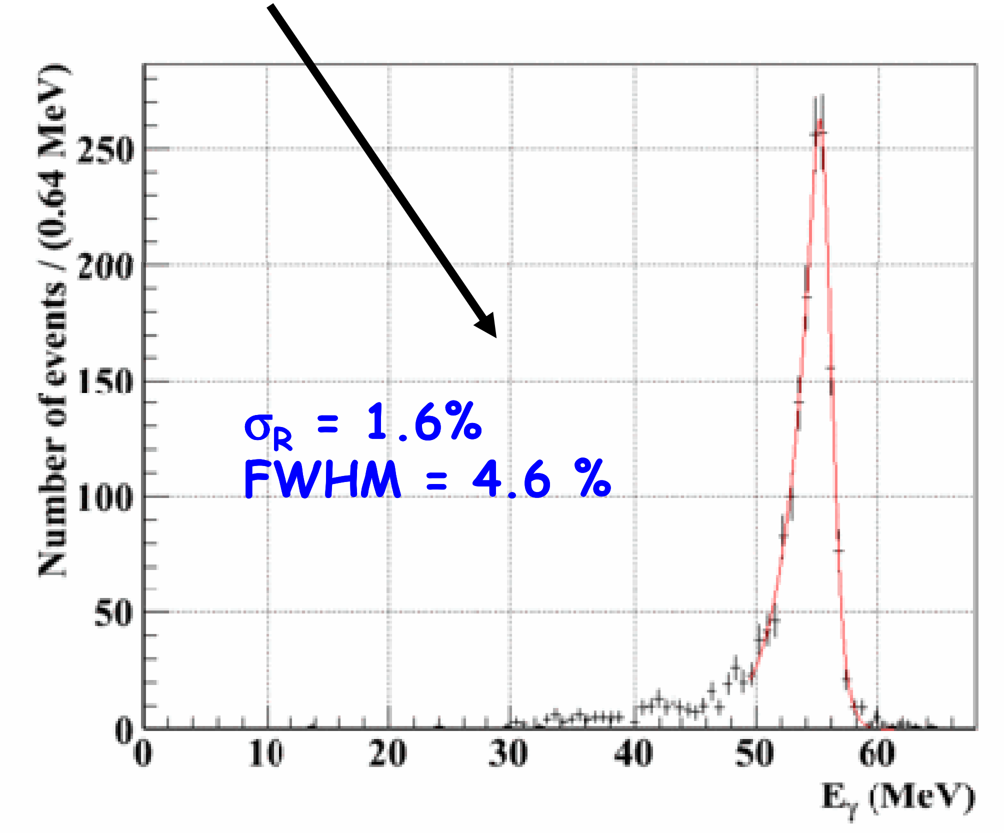


Cosmic rays triggered by Scintillation Counters and crossing several DCH chambers.
No magnetic field → straight line trajectories:
single hit chamber resolution and alignment.
Collected about **2 millions of cosmic muons**.

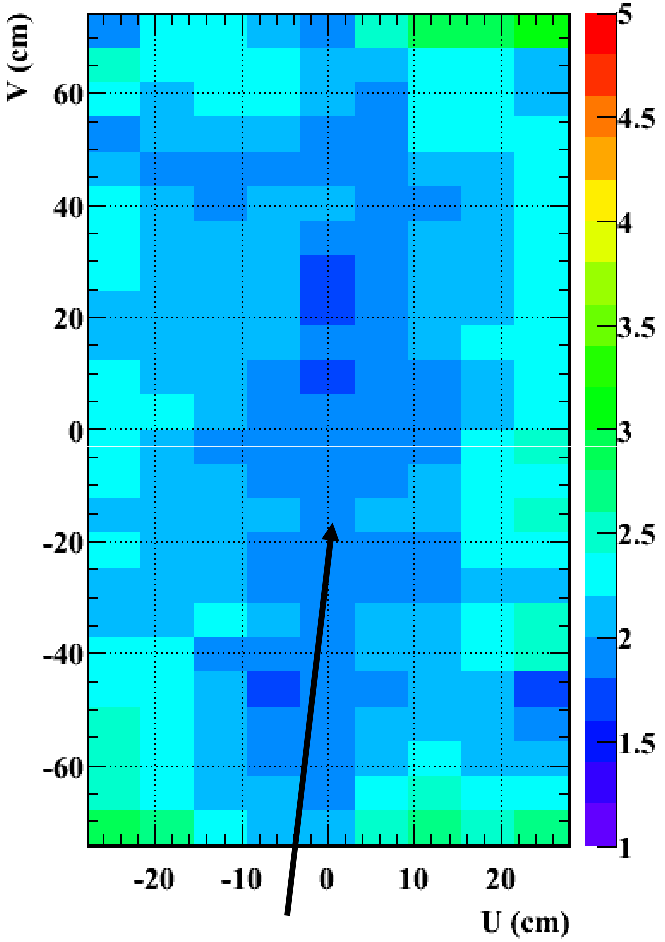


XEC performances 1)

55 MeV γ (from π^0 decay)



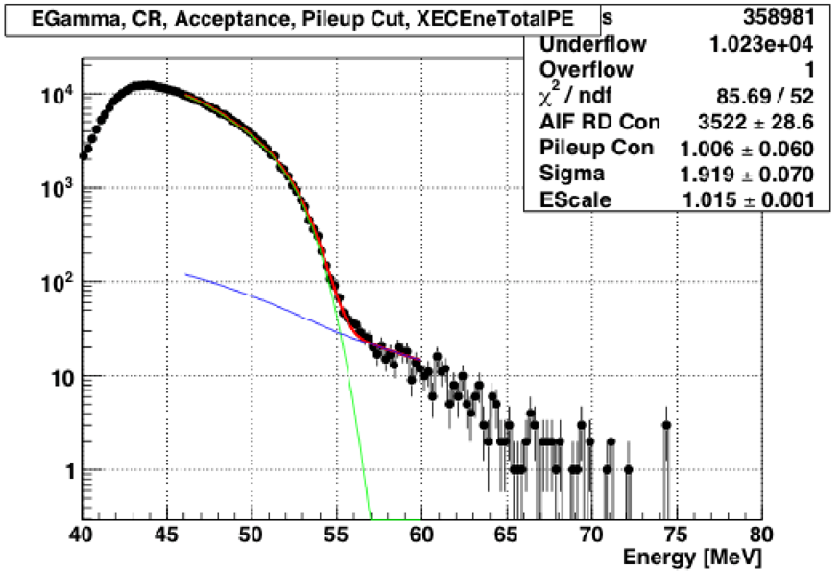
σ_R = 1.6%
FWHM = 4.6 %



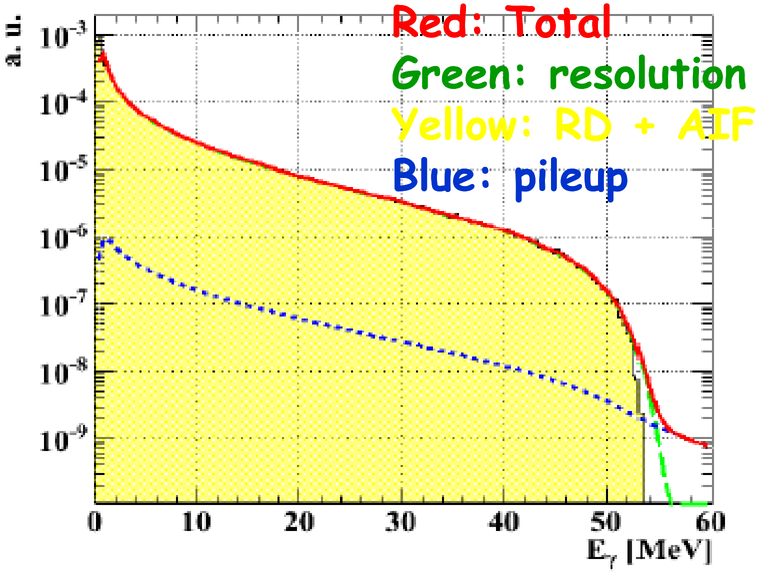
Spatial uniformity of energy resolution

XEC performances 2)

Photon BCK spectrum vs MC



Simulated components

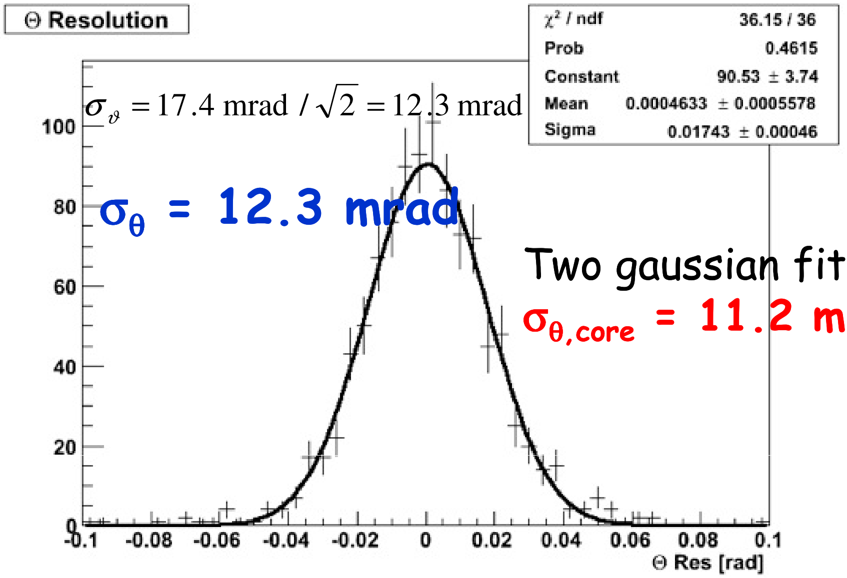


XEC performances summary:

σ_E/E = 2.1%, σ_x = (5 ÷ 6) mm, ε = 58 %

(averaged over detector surface)

Tracking Performances

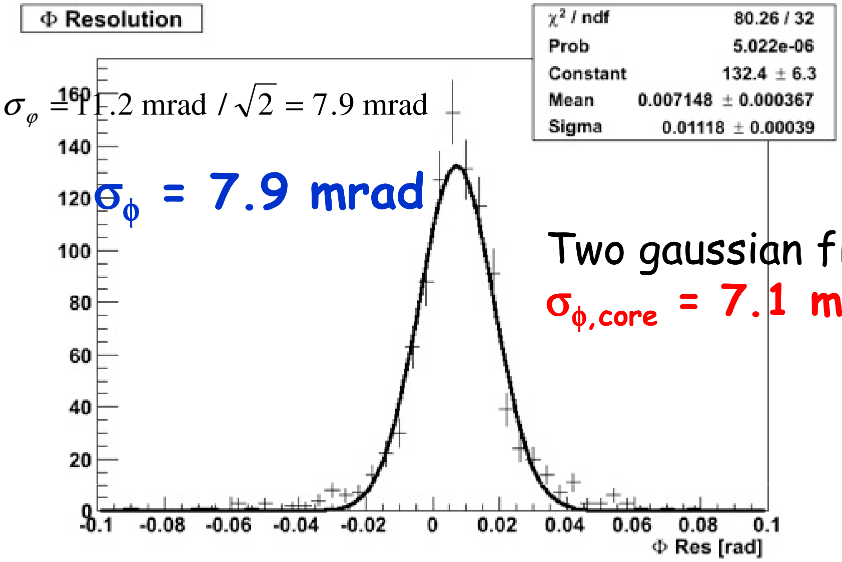


$\sigma_\vartheta = 17.4 \text{ mrad} / \sqrt{2} = 12.3 \text{ mrad}$

σ_θ = 12.3 mrad

Two gaussian fit:

$\sigma_{\theta,\text{core}}$ = 11.2 mrad



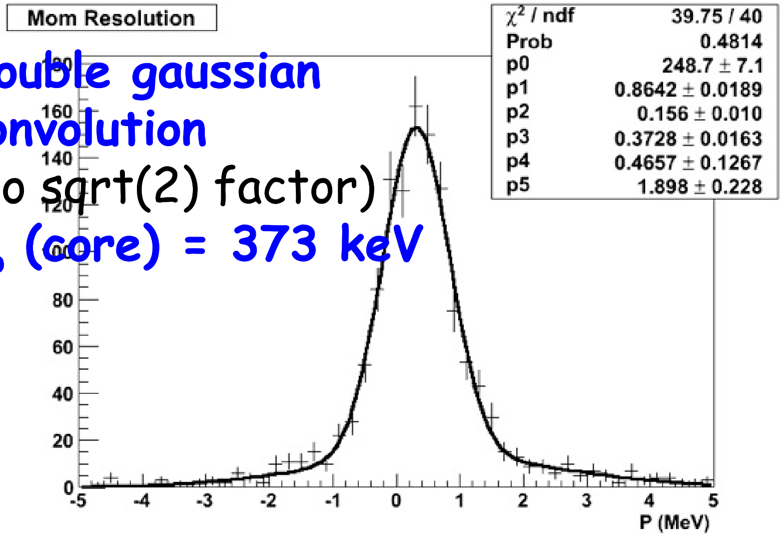
$\sigma_\varphi = 11.2 \text{ mrad} / \sqrt{2} = 7.9 \text{ mrad}$

σ_ϕ = 7.9 mrad

Two gaussian fit:

$\sigma_{\phi,\text{core}}$ = 7.1 mrad

DCH momentum and angular resolution measured by **double turn method** (two segments of track, making two turns in the spectrometer, treated as independent).

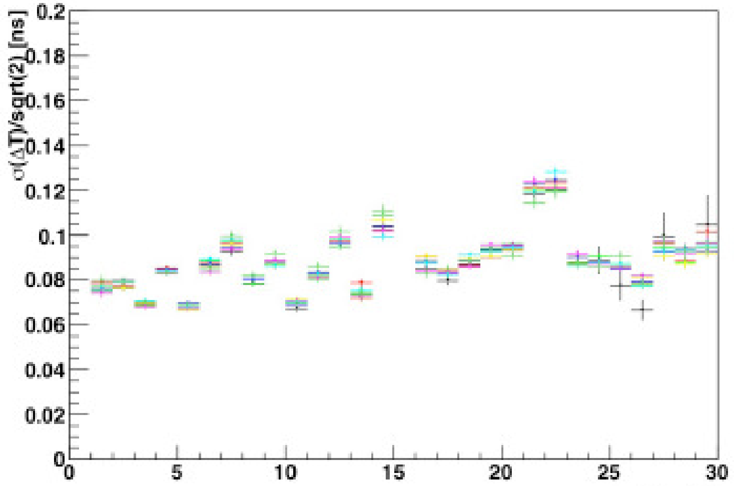


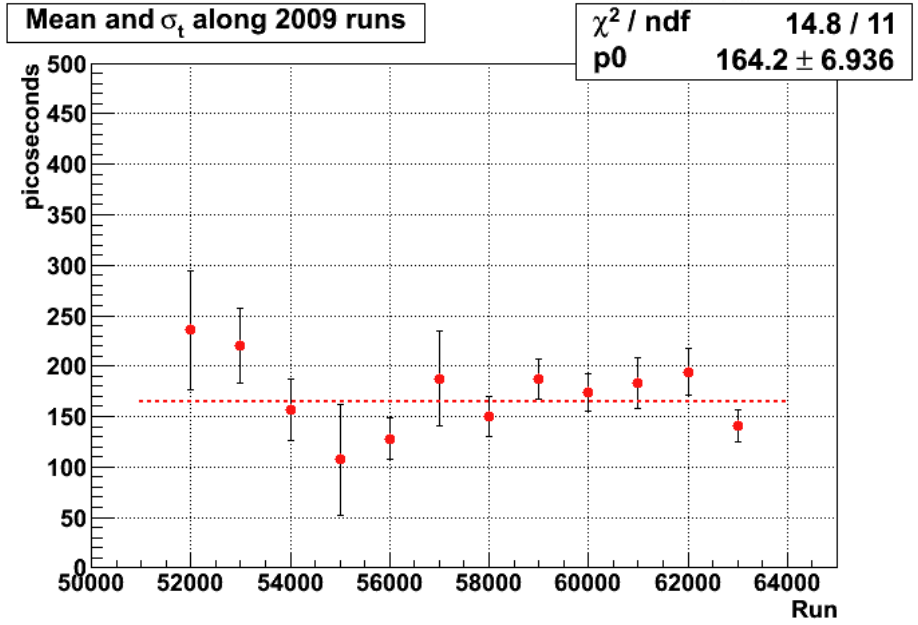
Double gaussian convolution

(no sqrt(2) factor)

σ_p (core) = 373 keV

Timing performances





Single bar timing resolution

- Different colors correspond to different weeks
- Average values ~ 80 ps

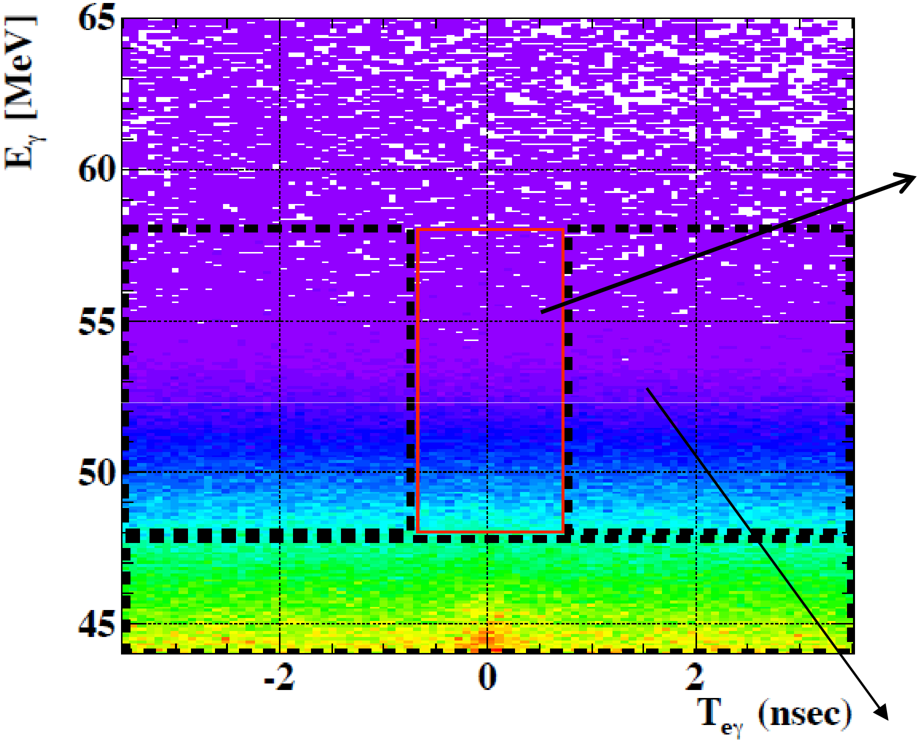
RD resolution as a function of time. Good stability

Average value ≈ 160 ps

For signal σ = 142 ps because of energy dependence.

Blind + likelihood analysis

Plane (E_γ, Δt) used for pre-selection + reconstructed track with associated TC hit



Blinded files: 0.2 % events

Open files: 16 % events

Open and blinded files reprocessed several times with improving calibrations and algorithms. Analysis box: ± 0.7 ns around zero (~ 10 $\sigma_{\Delta t}$).
2009 sample: 6 x 10^{13} stopped muons, 43 days of data taking.

Normalization

$$N_{e\gamma} = BR(\mu^+ \to e^+\gamma)\cdot k$$

where:

$$k \equiv N_{e\nu\nu} \times \left[\frac{f_{\mathrm{S}}}{f_{\mathrm{M}}}\right] \times \left[\frac{\varepsilon(TRG=0\,|\,e^+\gamma)}{\varepsilon(TRG=22\,|\,track \cap e^+_m \cap TC)}\right] \times A(\gamma\,|\,track)\cdot\varepsilon(\gamma)\cdot Psc(22)$$

$$f_S \equiv A(DC)\cdot\varepsilon(track, p_e > 50\mathrm{MeV}\,|\,DC)\cdot\varepsilon(TC\,|\,p_e > 50\mathrm{MeV})\big|_S$$

$$f_M \equiv \ldots\big|_M$$

10^7 pre-scaling factor

TRG = 22: Michel events trigger (only DCH track required)

TRG = 0: MEG events trigger

k = (1.0 ± 0.1) × 10^{12}

PRELIMINARY

Generalities on analysis

- **Three independent blind-likelihood analyses to evaluate systematics**
- RD and accidental event rates in the signal region fitted or estimated a priori by means of side-bands information.
- **Feldman-Cousins method for C.L. determination.**
- **Kinematical variables used:**
  - Positron and Gamma Energies;
  - Relative timing and relative angle;
- **Likelihood function:**

Signal PDF

RD PDF

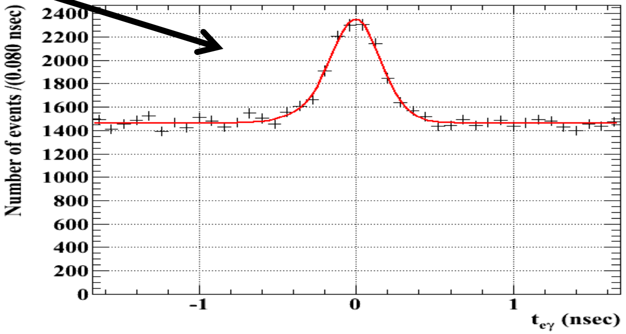
$$L(N_{Sig}, N_{RD}, N_{BG}) = \frac{N^{N_{obs}} \exp(-N)}{N_{obs}!} \prod_{i=1}^{N_{obs}} \left[\frac{N_{Sig}}{N} S + \frac{N_{RD}}{N} R + \frac{N_{BG}}{N} B \right]$$

Accidental BCK PDF

N_{obs} = number of observed events

PDF determination

- **Signal:**
  - **calibration data** (π^0, Michel edge, CW, XEC single events ...) for photon/positron energy and relative angle;
  - **RD data** for timing (corrected for energy dependence);
- **RD:**
  - **3-D theoretical distribution folded with detector response** to take into account kinematical constraints;
  - **direct measurement** for timing
- **Accidental background:**
  - Everything measured on sidebands



Important: the most dangerous background is measured !

Sensitivity evaluation

Expected sensitivity evaluated with two methods:

PRELIMINARY

- **Toy MC assuming zero signal**:
  - generated **1000 independent samples** of events using bck and RD pdf's (systematic effects not included);
  - upper bound on number of signal events evaluated for each sample;
  - average upper bound @90% C.L: **6.1 events** ⇒
  - average upper bound on **B.R.($\mu \rightarrow e\gamma$) = 6.1 x 10^{-12}**.

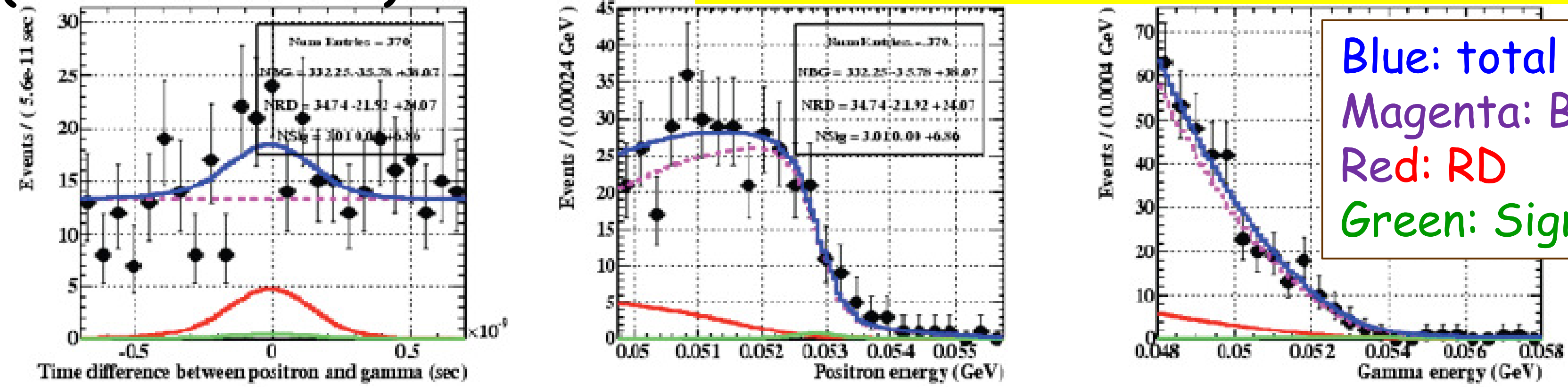
- **Fit to events in the sidebands:**
  - applied **same fitting procedure** used for data in the **signal region**;
  - upper bound: **B.R.($\mu \rightarrow e\gamma$) $\leq$ (4 ÷ 6) x 10^{-12}**.

Comparison: present upper bound from MEGA experiment: **1.2 x 10^{-11}**

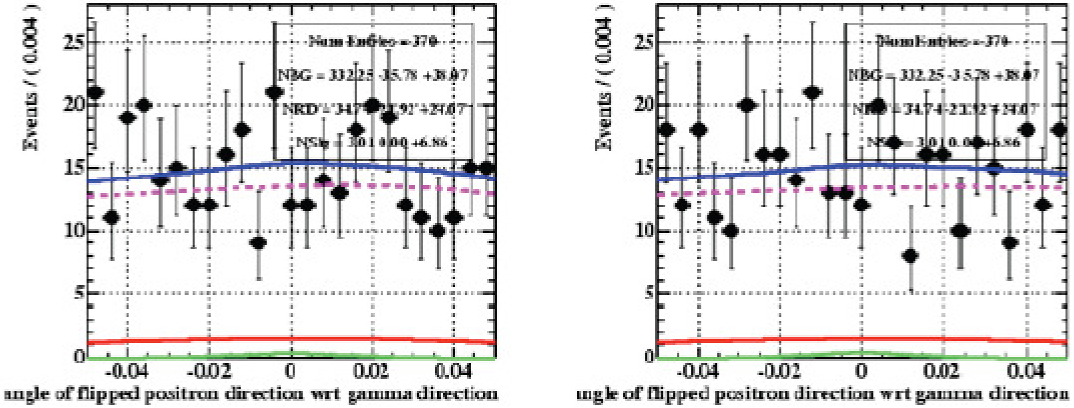
Likelihood analysis 1)

PRELIMINARY

Fit to events in analysis region
(370 total events)



Blue: total
Magenta: BCK
Red: RD
Green: Signal



Best fit: NSIG = 3.0

Depending on analysis technique this number varies in the range: 3 ÷ 4.5

Likelihood analysis 2)

- UL on signal: N_{sig} < 14.5 @90% C.L. (depending on analysis prescriptions varies between 12 and 14.5);
- **With this upper limit on Nsig:**

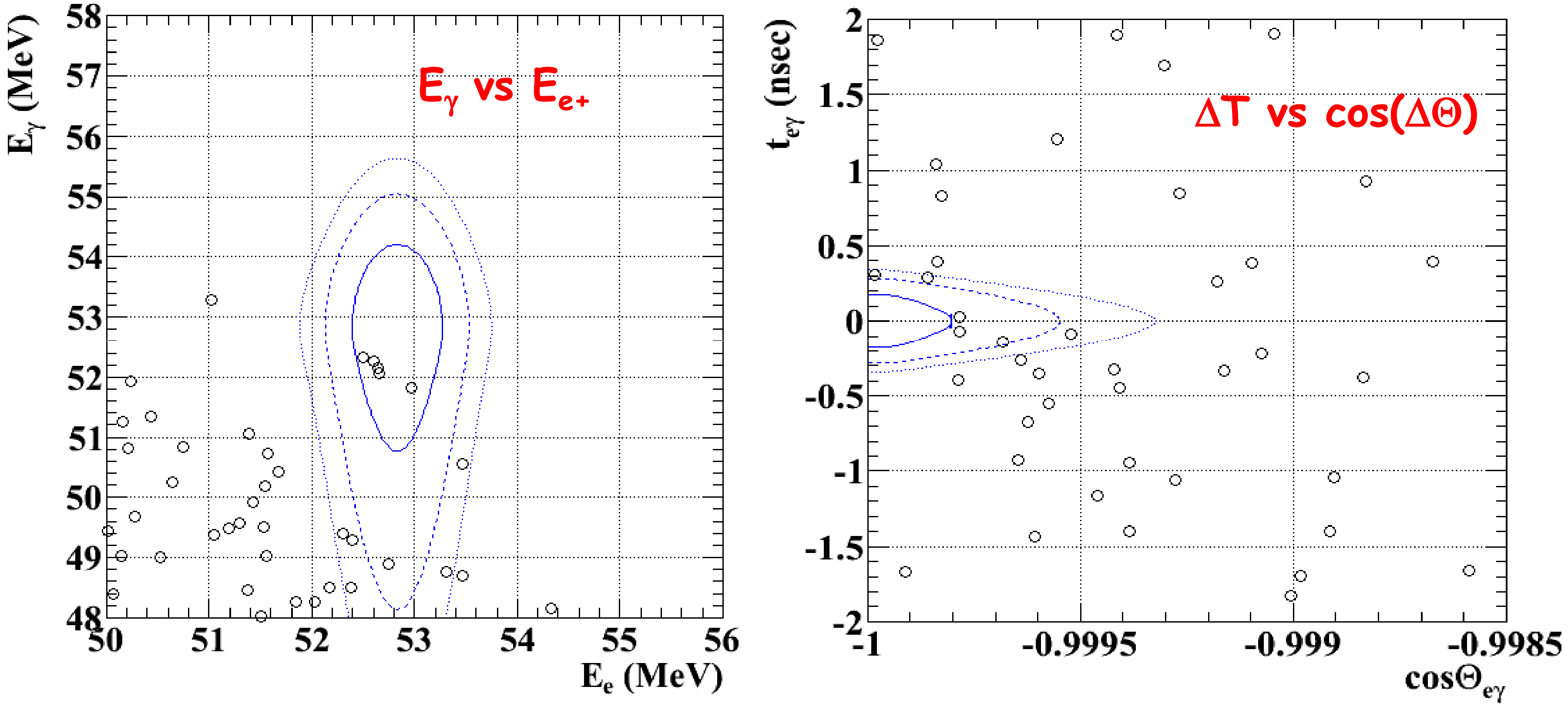
$$BR(\mu \to e\gamma)\ @90\%\ C.L. \leq 1.5 \times 10^{-11}$$

(previous result: BR < 2.8×10^{-11}, Nucl. Phys. **B834**, 1-12, 2010)

- Null hypothesis has a probability in the range (20 ÷ 60)% depending on analysis prescriptions.

PRELIMINARY

A look at events in signal region

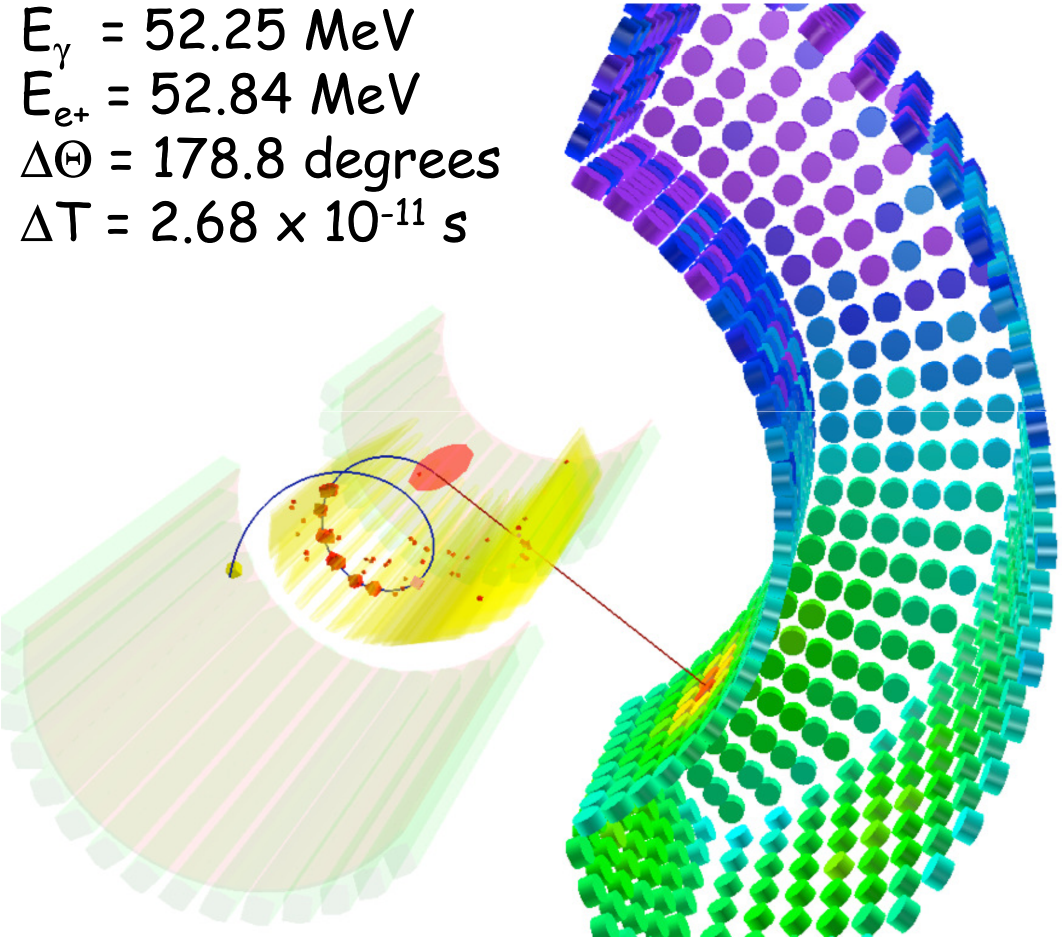


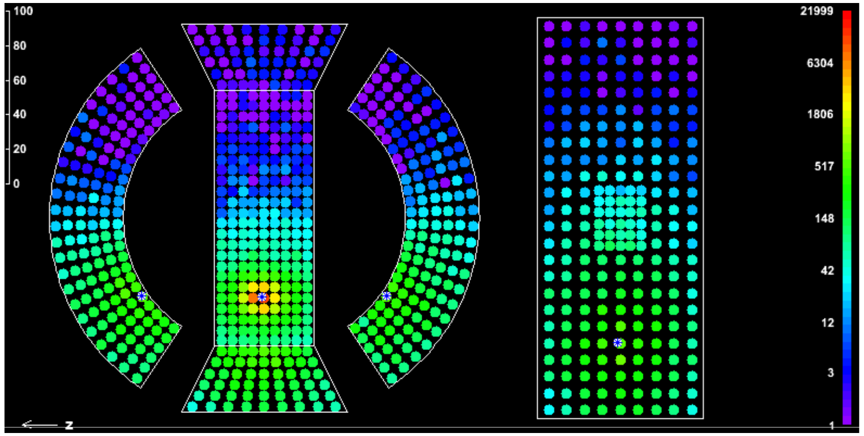
Cut at approximately 90% on other variables.

Probability contours PDFs correspond to 39.3%, 74.2%, 86.5% of signal events

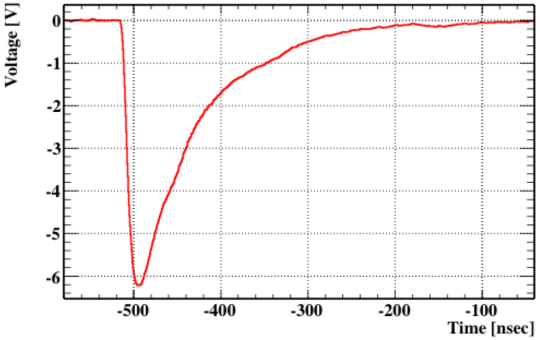
A picture of an interesting event

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



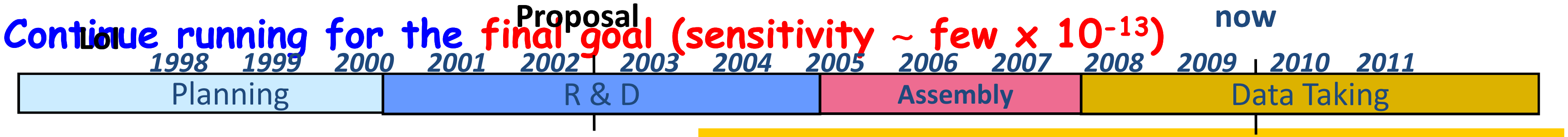


Calorimeter sum WF



MEG Perspectives

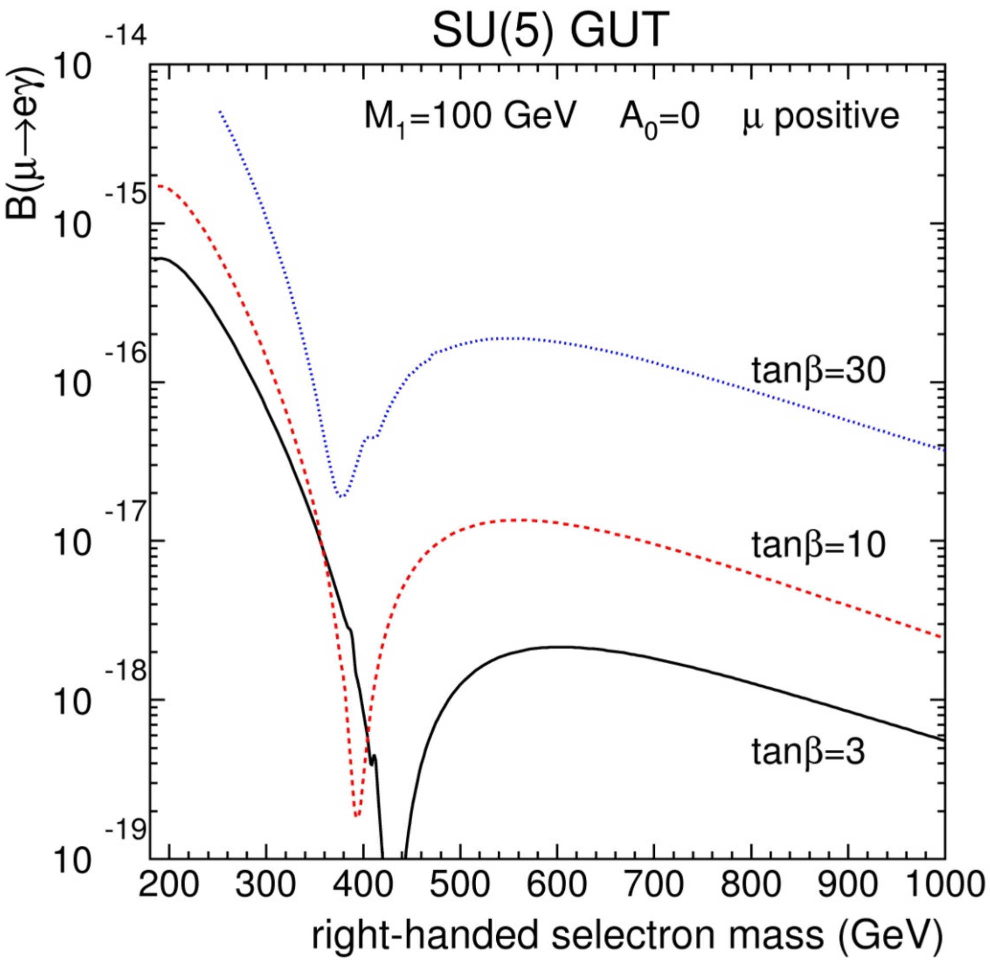
- Data taking will be **restarted at end of July**;
- Strategies to **combine 2008 and 2009 data** under discussion;
- We would have **3 years of stable data taking** from now until end of 2012 (large fluctuations expected to disappear);
- **Expected improvements:**
  - a factor 2 on electronic contribution to timing (hardware fine tuning);
  - possible better positron calibration (monocromatic beam) + DCH noise reduction $\Rightarrow$ σ_θ: 11 mrad $\rightarrow$ 8 mrad; σ_p: 0.85% $\rightarrow$ 0.7% (single gaussian);
  - relative timing resolution: 160 ps $\rightarrow$ 120 ps (timing + track length evaluation);
  - possible refinement in calorimeter analysis (σ_E/E = 2.0% $\rightarrow$ 1.5%).
- **Continue running for the final goal (sensitivity ~ few x 10^{-13})**



More details at

http://meg.psi.ch
http://meg.pi.infn.it
http://meg.icepp.s.u-tokyo.ac.jp

What next for $\mu \rightarrow e\gamma$? 1)



It should be very interesting to **explore lower BR's …**

Can we **gain order of magnitudes in sensitivity** by using **more intense muon beams** ($\geq 10^{10}$ μ/s) ?

J. Hisano et al., Phys. Lett. **B391** (1997) 341 and **B397** (1997) 357

What next for $\mu \rightarrow e\gamma$? 2)

Not an easy task ! Sensitivity limited by **accidental background**:

$$BR_{acc} \propto R_{\mu} \times \Delta E_{e} \times \Delta E_{\gamma}^{2} \times \Delta\theta_{e\gamma}^{2} \times \Delta t_{e\gamma}$$

⇨ **a simple increase of muon rate does not improve sensitivity !**

We need **much better detectors** to reach **BR ($\mu \rightarrow e\gamma$) $\leq 10^{-14}$**.

Some **possible suggestions** to reduce the background:

- use **high resolution beta spectrometers** ($\Delta E_e/E_e$ = 0.1 % feasible);
- **reduce the target thickness** to **improve $\Theta_{e\gamma}$ resolution** (possible because of higher intensity of muon beams);
- use a **finely segmented target** (it requires **good directional sensitivity** to distinguish adjacent targets);
- use **pixel detectors** to track **e^+ & e^+e^- pair** after photon conversion;
- some R&D studies under way …

$\mu \rightarrow$ eee

$BR(\mu \rightarrow 3e) \sim \alpha\ BR(\mu \rightarrow e\gamma) \sim 10^{-2}\ BR(\mu \rightarrow e\gamma)$

Present limit **$BR(\mu \rightarrow 3e) < 10^{-12}$**

(SINDRUM Coll., Nucl. Phys. **B260** (1985) 1)

Also limited by **accidental background** ⇒ **dc muon beam**

(Michel positron & e^+e^- pair from Bhabha scattering or γ conversion in detector)

Experimental advantage: no photons
→ **no need of e.m. calorimeter.**

However: expected **very high rate** in tracking system
→ **dead time, trigger & pattern recognition problems.**

$\mu^-A \rightarrow e^-A$: Conversion Mechanism

- Low energy negative muons are stopped in material foils (Al for MU2E & COMET, Al or Ti for PRIME), forming muonic atoms.
- Three possible fates for the muon:
  - Nuclear capture;
  - Three body decay in orbit;
  - **Coherent LFV decay** (extra factor of Z in the rates):

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

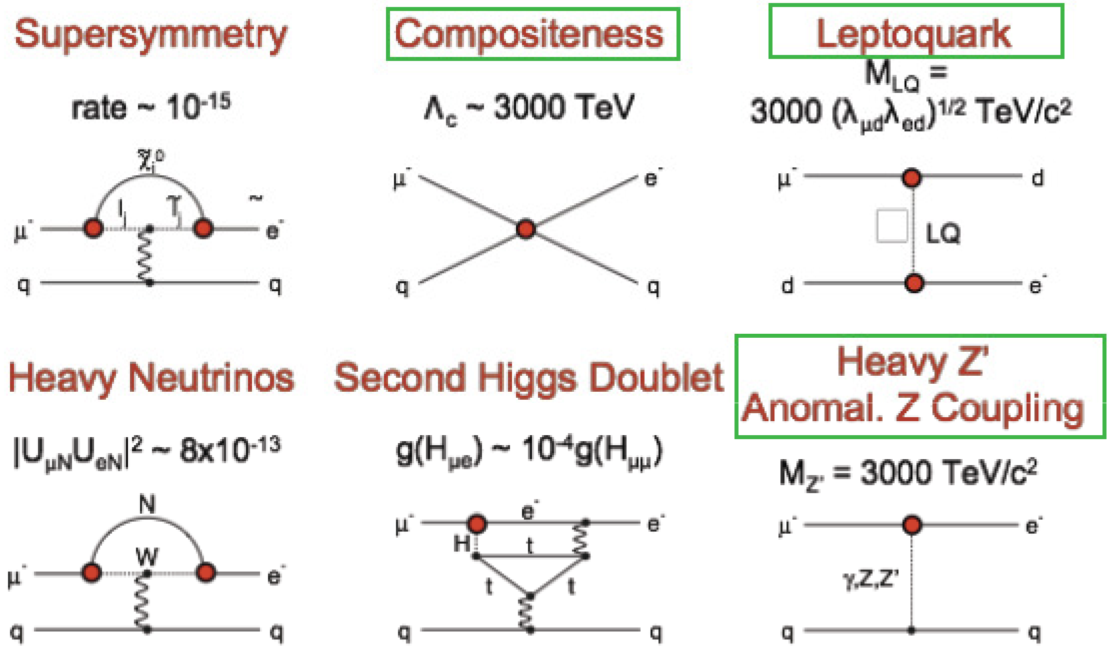
- Signal is a **single mono-energetic electron:**

$$E_e = m_\mu - E_{recoil} - E_{binding} \approx 105\,\mathrm{MeV}\ (\mathrm{Al}), 104.3\,\mathrm{MeV}\ (\mathrm{Ti})$$

- Muon lifetime in **Al ~ 0.86 μs**, in **Ti ~ 0.35 μs** (in vacuum: 2.2 μs).

- Present limit: **BR($\mu \rightarrow e$) $\leq 7 \times 10^{-13}$** in Au (SINDRUM II).

Muon Conversion physics

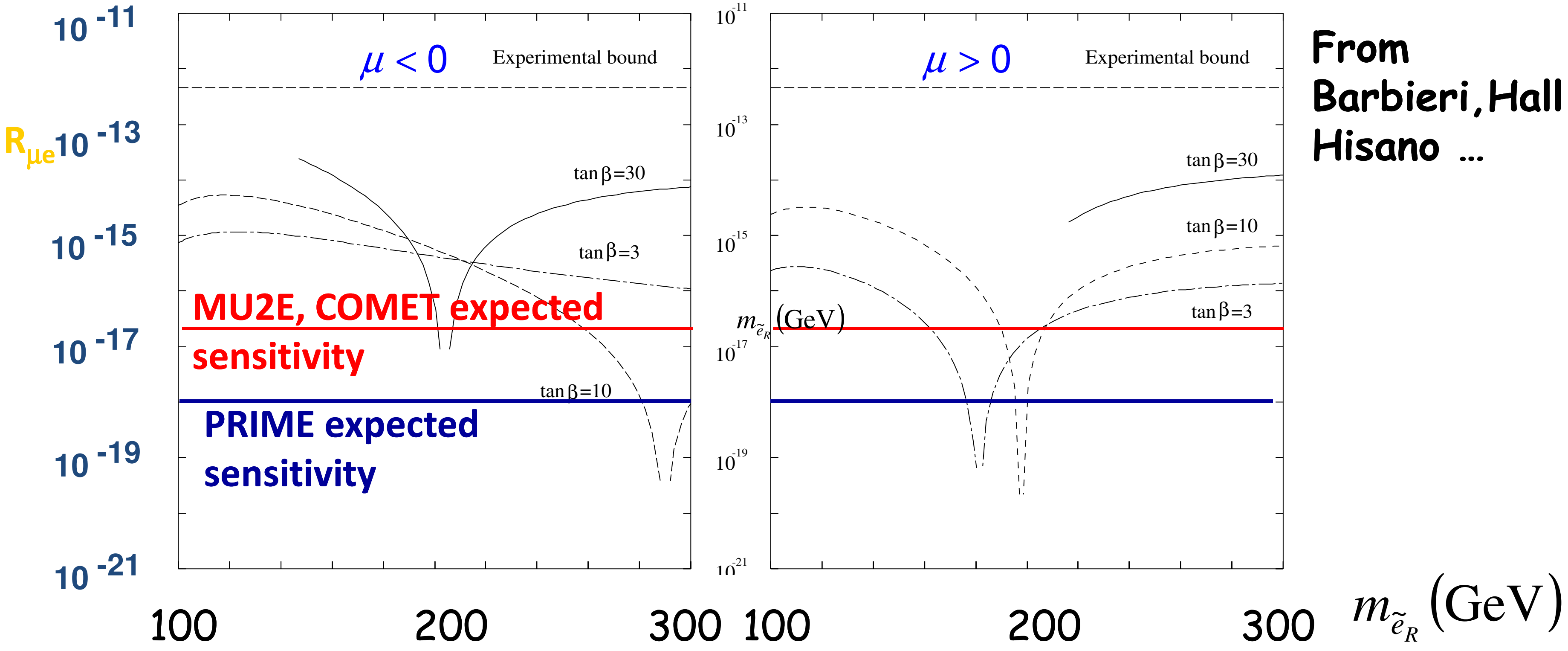


Sensitive to mass scales up to O(10,000 TeV)!

Do not contribute to μ→eγ

Muon conversion and μ → eγ are complementary measurements
(discrimination between SUSY models)

SUSY predictions for $\mu^- A \rightarrow e^- A$



From Barbieri, Hall, Hisano …

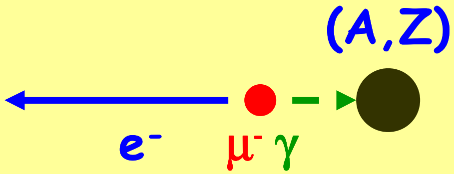
$\mu \rightarrow e\gamma$ & $\mu^- A \rightarrow e^- A$ Branching Ratios linearly correlated in photon dominated models

$$\frac{\mathrm{BR}(\mu \rightarrow e\gamma)}{\mathrm{BR}(\mu^- A \rightarrow e^- A)} \approx 200 \div 300$$

$\mu^- A \rightarrow e^- A$: Signal and Background

signal

$\mu\ (A,Z) \rightarrow e\ (A,Z)$



$$E_e = m_\mu - E_B - E_R$$

main backgrounds

MIO (muon decay in orbit)

$\mu\ (A,Z) \longrightarrow e\ \nu\ \nu\ (A,Z)$

RPC (radiative pion capture) $\pi\ (A,Z) \longrightarrow \gamma\ (A,Z-1)$

$\downarrow$

$e^+ e^-$

Beam related background

N.B. No coincidence → no accidental background

Reduction of beam background

1) Beam pulsing:

Muonic atoms have **some hundreds of ns lifetime** → use a pulsed beam with **buckets short compared to this lifetime**, leave pions decay and **measure in a delayed time window**.

2) Extinction factor:

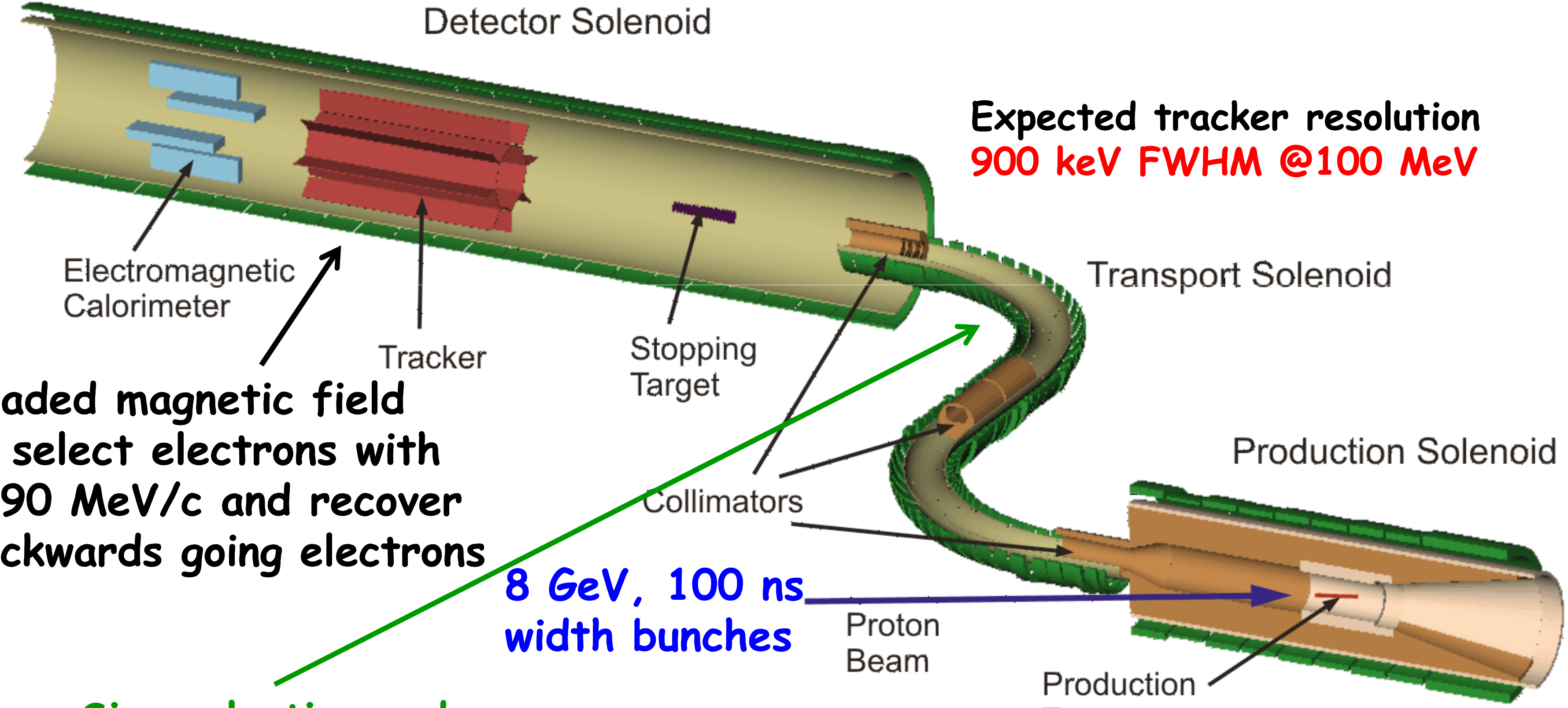
Protons arriving on target between the bunches can produce e^- or π in the signal timing window ⇒ **needed big extinction factor (~10^{-9})**

3) Beam quality:

- insert a **moderator** to **reduce the pion contamination** (pion range ≈ 0.5 muon range); a **10^6 reduction factor** obtained by SINDRUM II. **No more than 10^5 pions** may stop in the target during the full measurement ($\leq$ **1** background event);
- select **a beam momentum < 70 MeV/c** (muon decaying in flight produce low energy electrons).

Mu2e at Fermilab

Derived from original MECO project at AGS.



Expected tracker resolution
900 keV FWHM @100 MeV

Graded magnetic field to select electrons with P>90 MeV/c and recover backwards going electrons

8 GeV, 100 ns width bunches

Sign selection and antiprotons rejection

Mu2e background

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.225
	Radiative μ Capture	<0.002
Late Arriving	Radiative π Capture	0.072
	Beam electrons	0.036
	μ Decay in Flight	<0.063
	π Decay in Flight	<0.001
Miscellaneous	Long Transit	0.006
	Cosmic Ray	0.016
	Pat. Recognition Errors	<0.002
Total Background		0.42

(assuming 1E18 stopped muons in 2E7 s of run time)

- Designed to be nearly background free

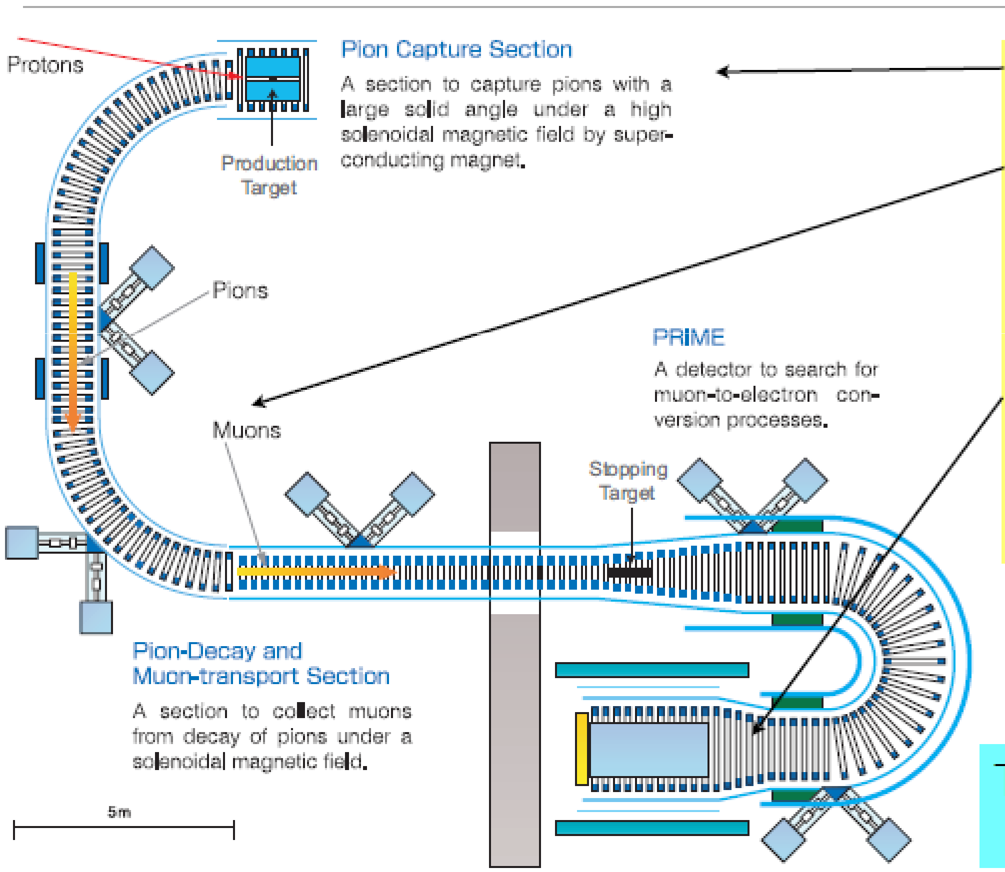
Assumed 10^{-9} extinction factor

Expected signal $\approx$ 40 events for $R_{\mu e} = 10^{-15}$

Expected upper Limit for no signal 6×10^{-17}

(D. Glezinsky, NuFact 09)

COMET at JPARC



Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by super-conducting magnet.

PRIME

A detector to search for muon-to-electron conversion processes.

Pion-Decay and Muon-transport Section

A section to collect muons from decay of pions under a solenoidal magnetic field.

Proton Beam

The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

Y. Kuno, Nufact 08

The beamline design is very important.

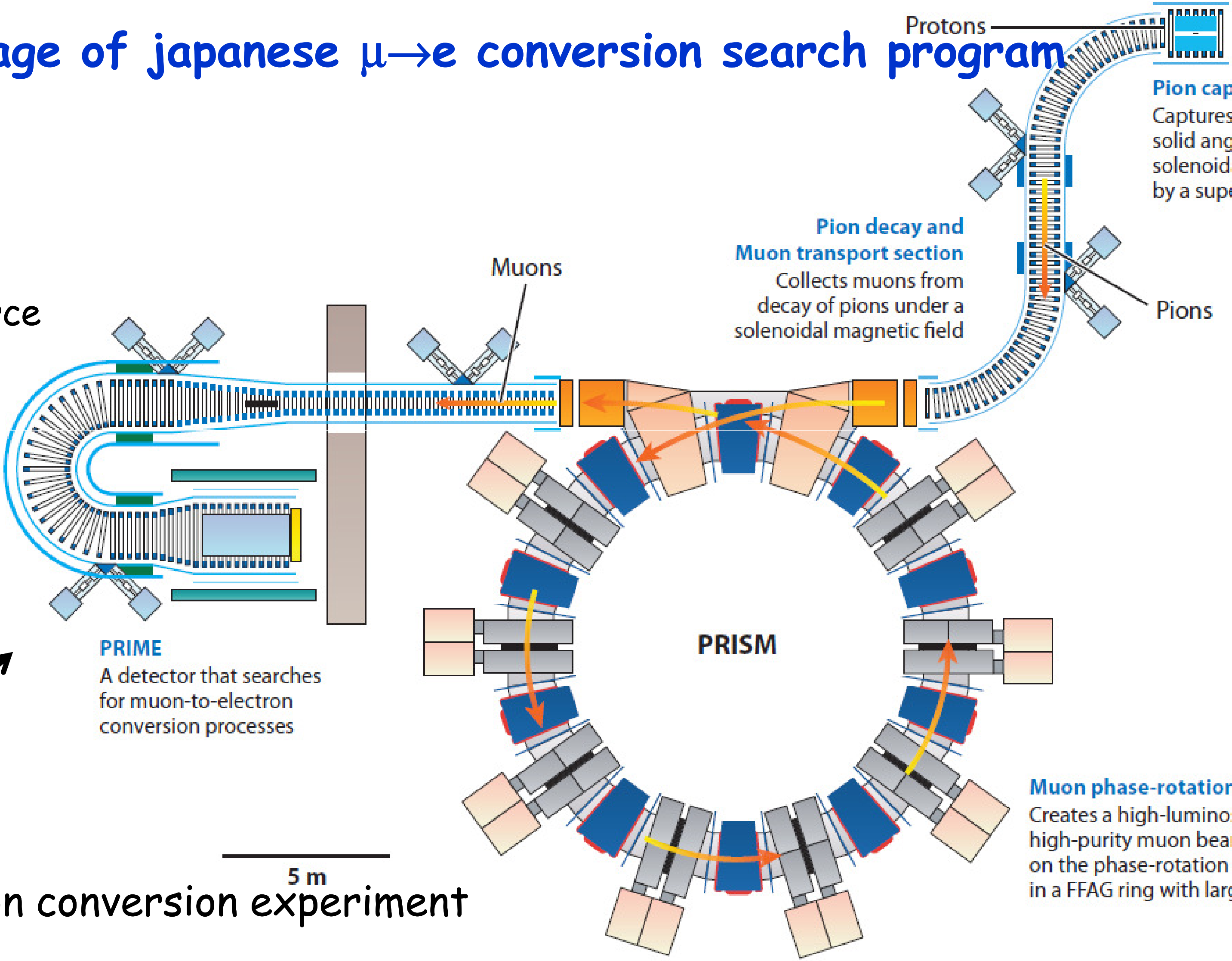
COMET features

- **Similar to Mu2e** for muon beam line and detector;
- Main differences:
  - **C-shaped** (180 degree bending) instead of S-shaped **solenoid beam line** (well matched with vertical magnetic field to perform **momentum selection**);
  - **curved solenoid spectrometer** to eliminate low energy electrons.
- **8 GeV proton beam**;
- Expected **1.5×10^{18} stopped muons in 2 years** running;
- Estimated **BCK 0.4 events** ⇒ **sensitivity 3×10^{-17}**.

PRISM/PRIME 1): Layout

2nd stage of japanese μ→e conversion search program

Phase
Rotated
Intense
Slow
Muon source



Pion capture section
Captures pions with a large solid angle under a high solenoidal magnetic field by a superconducting magnet

Pion decay and Muon transport section
Collects muons from decay of pions under a solenoidal magnetic field

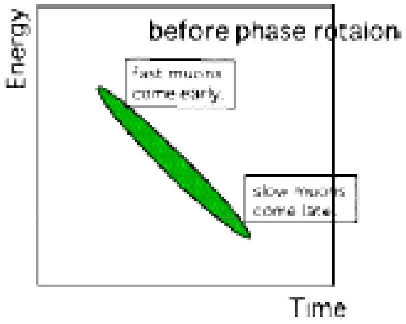
PRIME
A detector that searches for muon-to-electron conversion processes

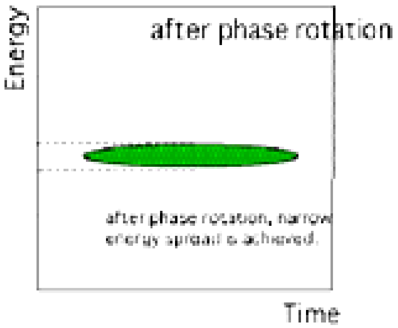
Muon phase-rotation section
Creates a high-luminosity and high-purity muon beam, based on the phase-rotation method in a FFAG ring with large acceptance

PRIsm
Muon
Electron conversion experiment

PRISM 2): concept

Phase rotation





- ➢ Muon energy spread reduction by means of a RF field ⇒ **3 % FWHM energy spread;**
- ➢ Intensity ≈ $10^{(11\div12)}$ μ/s (no pions);
- ➢ Muon momentum **68 MeV/c.**

Small energy spread essential to **stop enough muons** in **very thin targets**. If **a momentum resolution ≤ 350 keV (FWHM) is reached**, the experiment can be **sensitive** to $\mu \rightarrow e$ conversion **BRs down to 10^{-18}**.

Experimental demonstration of phase rotation in PRISM-FFAG ring underway.

A look at the future

High intensity machines under study (like **NUFACT** at CERN or **Project X** at Fermilab) should provide **proton beams at the level of 10^{15} protons/s of some GeV energy**. Secondary muon beams of intensity ~ **10^{14} muons/s** could be obtained from these machines.

The $\mu^{-}A \rightarrow e^{-}A$ conversion experiments are not limited by accidental background → in principle **they can benefit of the increased muon beam intensity better than $\mu \rightarrow e\gamma$ experiments.**

Can we hope to gain a couple of order of magnitudes in the experimental sensitivity for LFV muon decays with respect to present experiments ?

Beam requirements

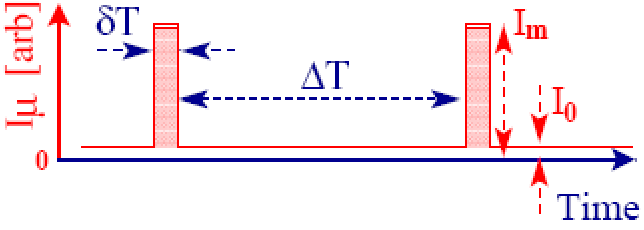
Total number of muons

The total number of muons looks **within the reach** of proposed high intensity machines

Experiment	$\int I_\mu dt$	I_0/I_m	δT [ns]	ΔT [μs]	p_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- A \rightarrow e^- A$	10^{21}	$< 10^{-10}$	< 100	> 1	< 80	< 5
$\mu \rightarrow e\gamma$	10^{17}	n/a	n/a	n/a	< 30	< 10
$\mu \rightarrow eee$	10^{17}	n/a	n/a	n/a	< 30	< 10

Surface muons

n/a = continuous beam



Various technical remarks:

- radiation, target heating → need of **cooling**;
- large momentum spread → need of a **PRISM-like ring**; beam intensity reduction;

(F. DeJongh, FERMILAB –TM-229 -E, CERN-TH 2001-231, J. Äystö et al., hep-ph/0109217)

The tauonic channel

The τ channel is in principle **very interesting** for studying LFV because of the τ **large mass ($m_\tau \approx 18\ m_\mu$)** ⇨

- ❖ Many **decay channels**;
- ❖ **BR's enhanced** wrt $\mu \to e\gamma$ by $(m_\tau/m_\mu)^\alpha$ with $\alpha \sim 3$

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

Experimental problem: **production & detection of τ large samples**.

To be **competitive with dedicated experiments** one must reach

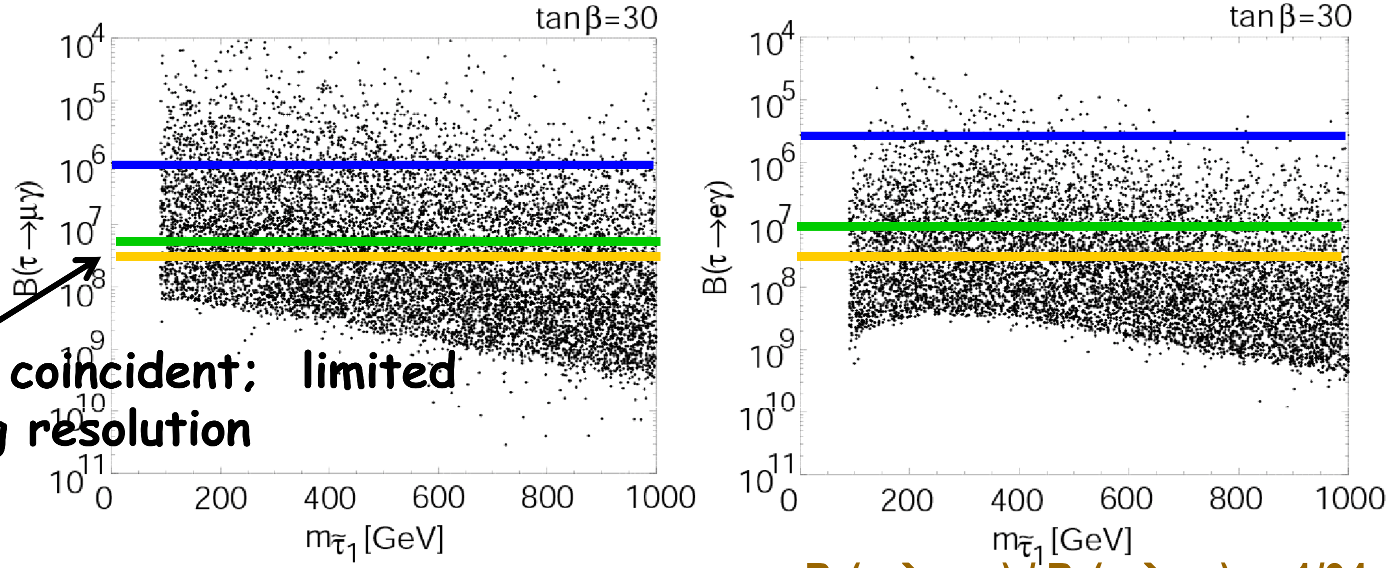
$$BR(\tau \to \mu\gamma) < 10^{-(9\div10)}$$

First significant results by **B-factories** (**BELLE,BABAR**).

SUSY predictions for LFV τ decays

J.Ellis, J.Hisano, M.Raidal and Y.Shimizu, PR **D66** (2002) 115013

τ → μγ



τ → eγ

Almost coincident; limited drawing resolution

Blue: old CLEO limit (2000)
Green: Belle
Yellow: BaBar

Br(τ→μee) / Br(τ→μγ) ≅ 1/94
Br(τ→μμμ)/ Br(τ→μγ) ≅ 1/440
Br(τ→eee) / Br(τ→eγ) ≅ 1/94
Br(τ→eμμ)/ Br(τ→eγ) ≅ 1/440

B-factories are τ-factories too:

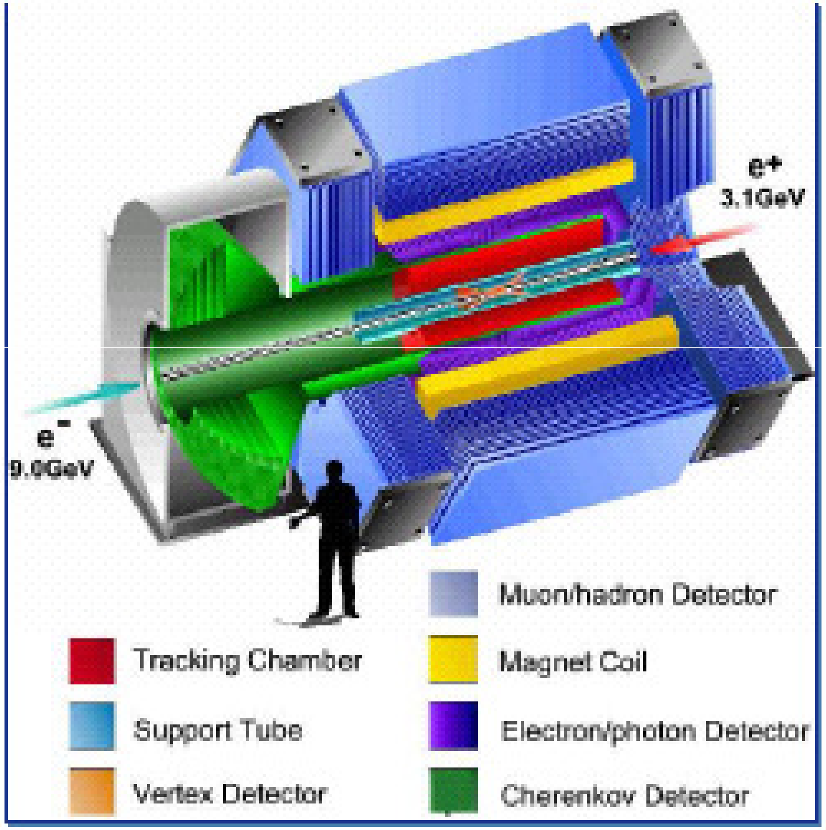
$$\sigma(e^+e^- \to \tau^+\tau^-) \approx 0.9\,\sigma(e^+e^- \to b\bar{b}) \approx 0.92\,\text{nb} \qquad \sqrt{s} = 10.54\,\text{GeV}$$

$\tau \rightarrow \mu\gamma/e\gamma$ BABAR 1)

The BABAR experiment at SLAC

PEP-II at SLAC

- Asymmetric collider at $\Upsilon(4S)$ peak
- $\Upsilon(4S)$ boost $\beta\gamma \approx 0.55$



Data sample:

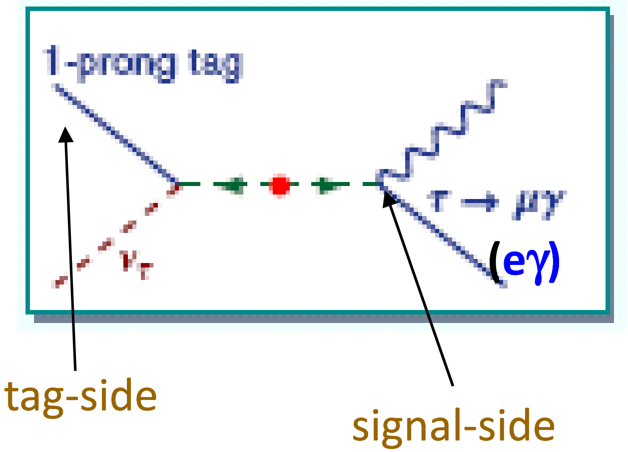
425.5 fb^{-1} @Υ(4S) +
90 fb^{-1} off-peak

$(963 \pm 7) \times 10^6$ τ decays

BABAR Collaboration (B. Aubert et al.), hep-ex/0908.2381v2

$\tau \to \mu\gamma/e\gamma$ BABAR 2)

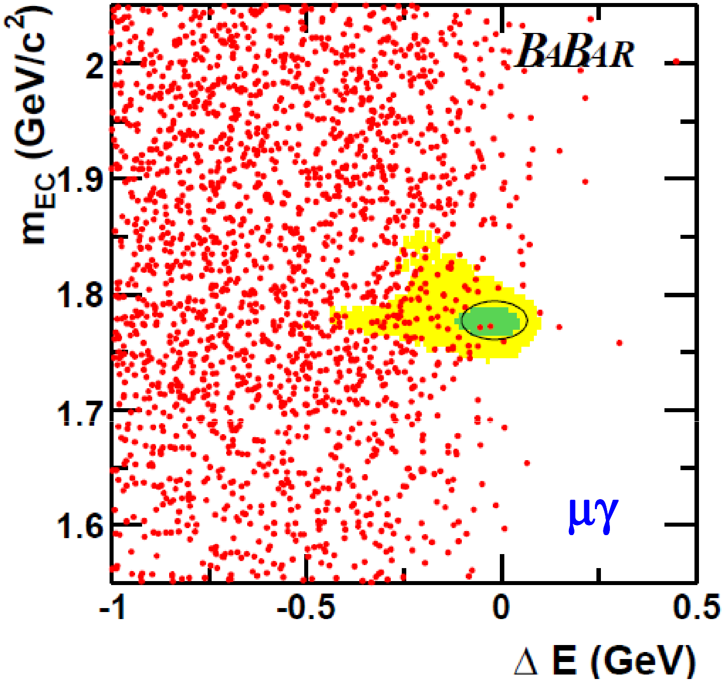
Search strategy: divide the "event world" in **two emispheres** and look for $\tau^+\tau^-$ **pairs**; **one candidate LFV decay** in the "signal side" and **one SM decay** in the "tag-side".

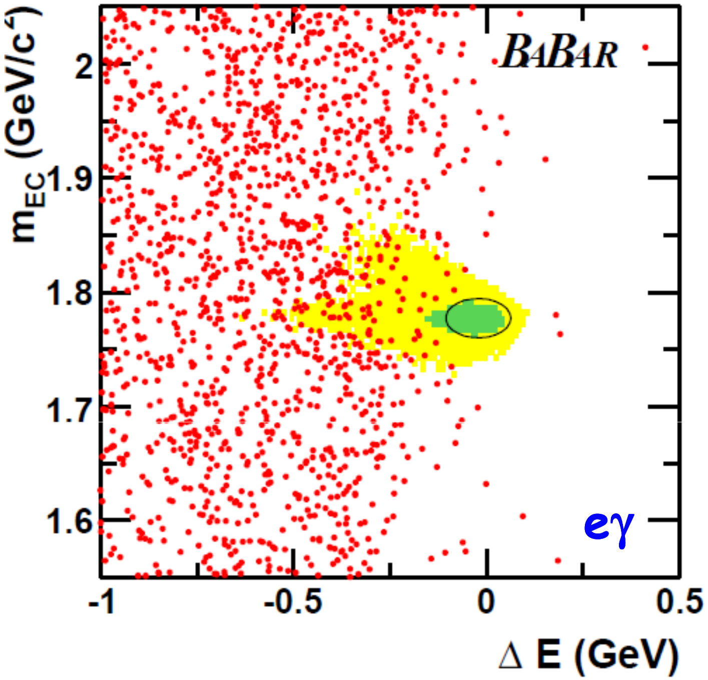


Main backgrounds from τ **decays**, $c\bar{c}$ **pairs**, **radiative processes (e.g.** $e^+e^- \to \mu^+\mu^-\gamma$).

In the signal side, look for **one single muon (electron)** plus **at least one photon**; then, look at the $\mu\gamma$ ($e\gamma$) **invariant mass** M_{EC} (it should be = m_τ) and to the energy difference in CM frame $\Delta E = (E_{\mu/e}+E_\gamma)_{CM} - E_{CM}/2$ (it should be zero).

$\tau \rightarrow \mu\gamma/e\gamma$ BABAR 3)





Green ellipse (2 σ's):

events observed 2 (μ), 0 (e)

events expected 3.6 (μ) 1.6 (e)

efficiency (6.1 ± 0.5) % (μ)
(3.9 ± 0.3) % (e)

⇒ **Upper Limit** @ 90% C.L.:

$BR(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$ $BR(\tau \rightarrow e\gamma) < 3.3 \times 10^{-8}$

$\tau \to \mu\gamma/e\gamma$ BELLE 1)

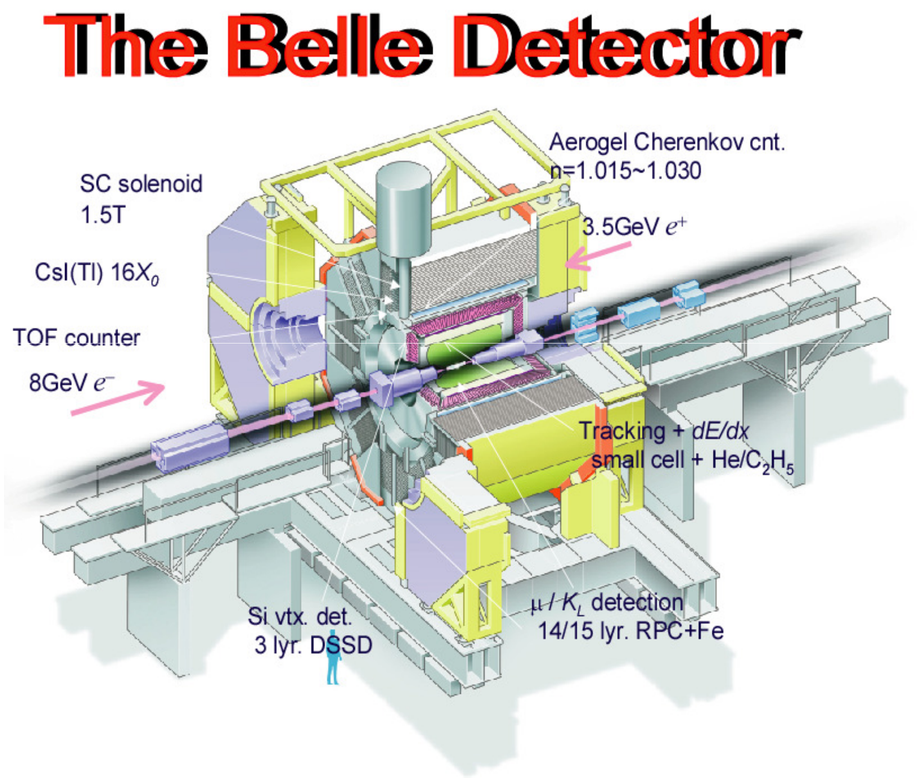
BELLE experiment at KEKB: asymmetric e^+e^- collider with energy peak at $\Upsilon(4S)$

Data sample:

- Integrated luminosity **535 fb^{-1}**
- **$\approx$ 4.77 x 10^8 $\tau^+\tau^-$ pairs**

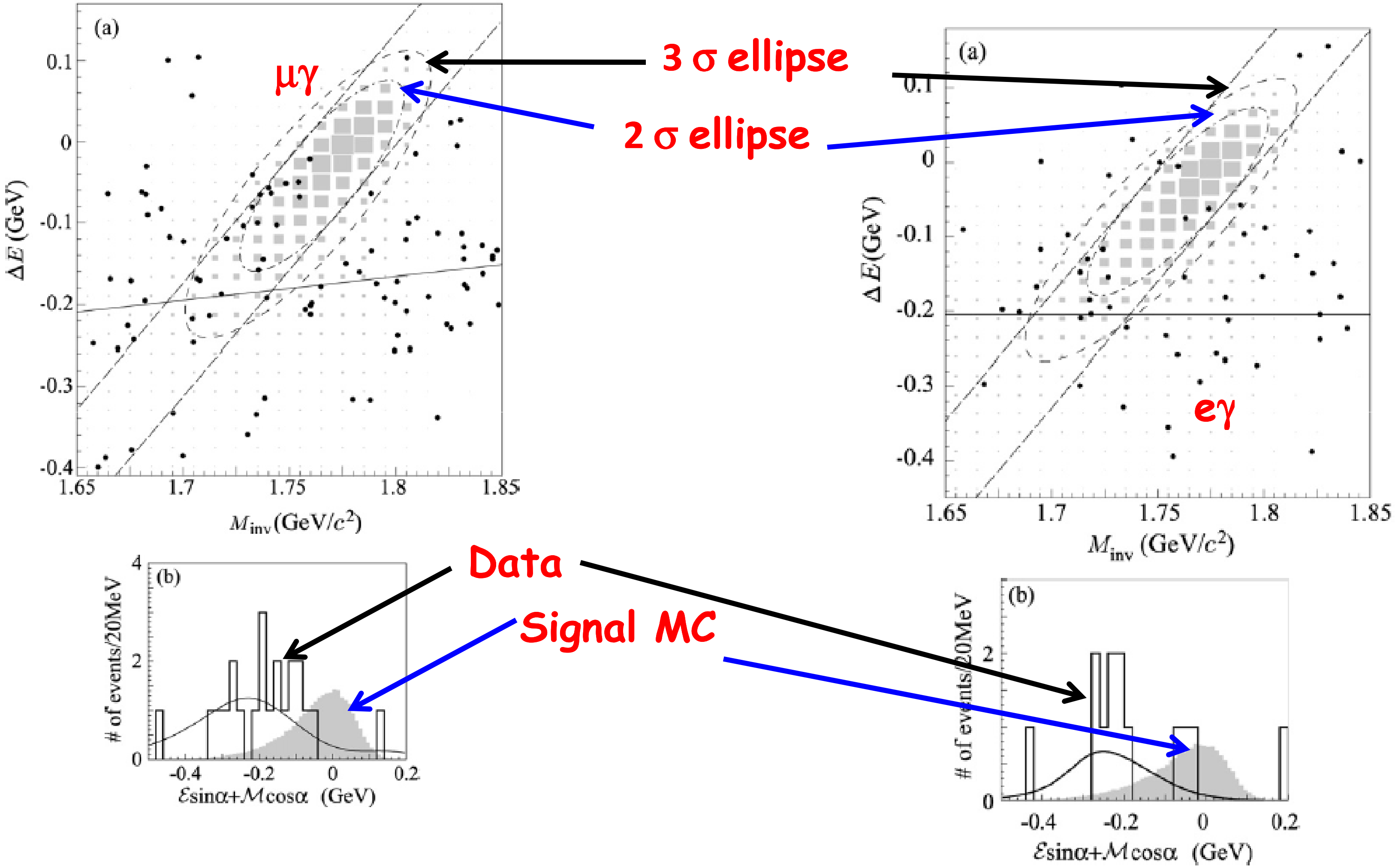
Similar search strategy:

☐ look for **two opposite charge tracks**, accompanied in **"signal-side"** by **one or more photons**; background from $e^+e^- \to \mu^+\mu^-$ (e^+e^-) γ and radiation in initial state;
☐ reduce other background by **cuts on missing quantities**;
☐ examine surviving events in the plane **(ΔE, $M_{\mu/e-\gamma}$)**;



BELLE Collaboration (K. Abe et al.), PL **B666** (2008) 16-22

$\tau \to \mu\gamma/e\gamma$ BELLE 2)



μγ

3 σ ellipse

2 σ ellipse

eγ

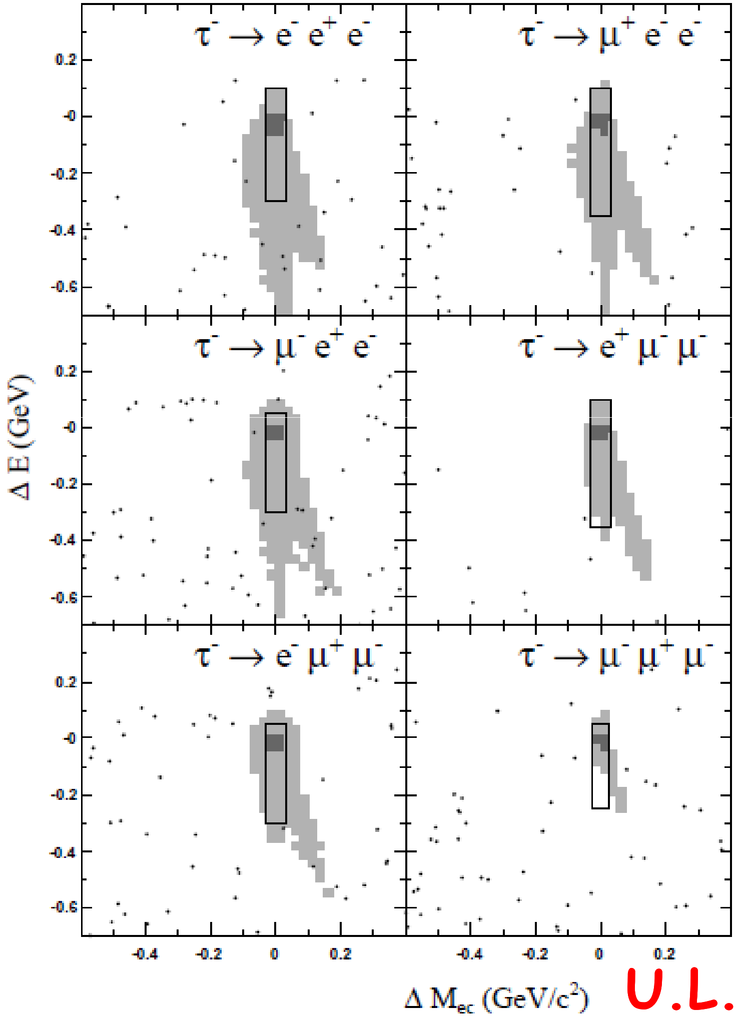
Data

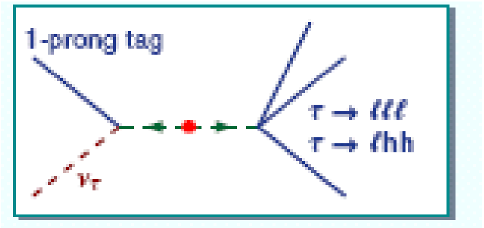
Signal MC

Maximum likelihood fit to signal & bck. UL: BR($\tau \to \mu\gamma$) < 4.5 x 10^{-8}, BR($\tau \to e\gamma$) < 1.2 x 10^{-7}

$\tau \to lll$ BABAR

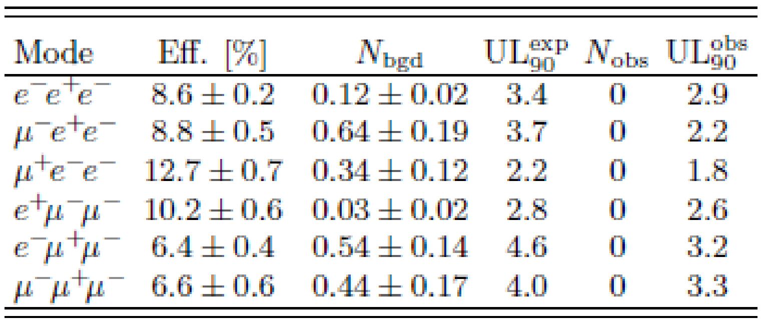
BABAR Collaboration: arXiv: 1002.4550v1





Same tag-side;
signal side with three charged tracks
Data sample **468 fb^{-1}**

Main backgrounds from $q\bar{q}$ and **Bhabha pairs**; **very low background in the search window**.
Search still based on **invariant mass** and ΔE; **no excess observed**.



Mode	Eff. [%]	$N_{\rm bgd}$	${\rm UL}_{90}^{\rm exp}$	$N_{\rm obs}$	${\rm UL}_{90}^{\rm obs}$
$e^-e^+e^-$	8.6 ± 0.2	0.12 ± 0.02	3.4	0	2.9
$\mu^-e^+e^-$	8.8 ± 0.5	0.64 ± 0.19	3.7	0	2.2
$\mu^+e^-e^-$	12.7 ± 0.7	0.34 ± 0.12	2.2	0	1.8
$e^+\mu^-\mu^-$	10.2 ± 0.6	0.03 ± 0.02	2.8	0	2.6
$e^-\mu^+\mu^-$	6.4 ± 0.4	0.54 ± 0.14	4.6	0	3.2
$\mu^-\mu^+\mu^-$	6.6 ± 0.6	0.44 ± 0.17	4.0	0	3.3

U.L. Range: (1.8 ÷ 3.3) × 10^{-8} (90% C.L.)

$\tau \to lll$ BELLE

BELLE Collaboration PL **B687** (2010) 139-143

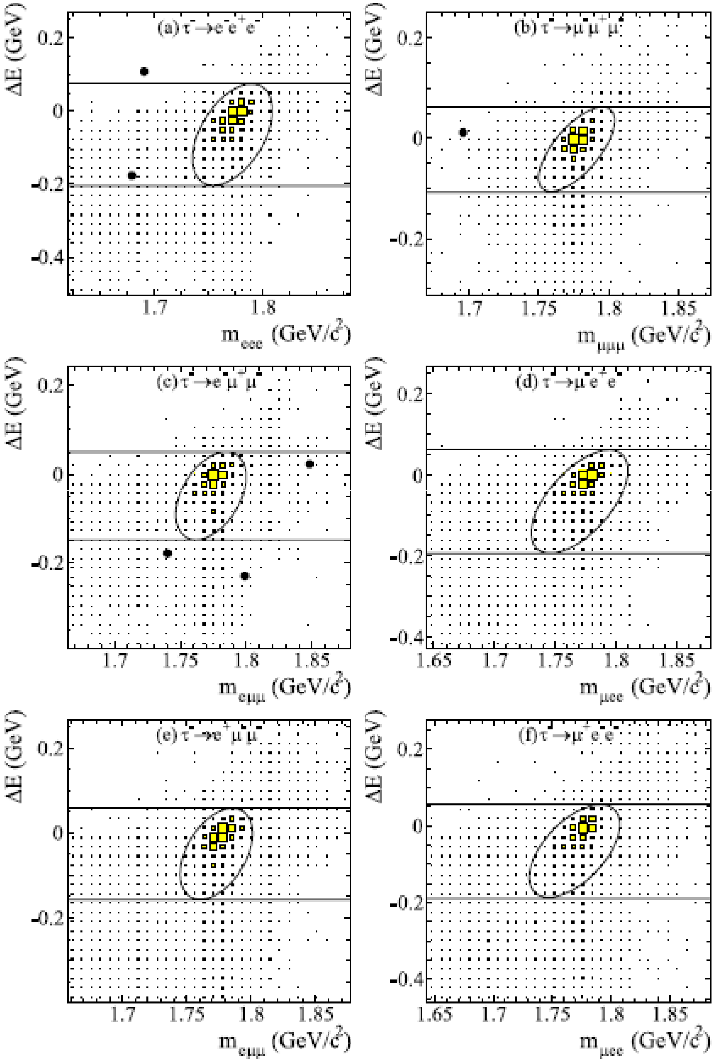
Data sample 782 fb^{-1}

Very low background as for BABAR.

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}$ ($\times 10^{-8}$)
$\tau^- \to e^- e^+ e^-$	6.0	0.21 ± 0.15	9.8	0	< 2.7
$\tau^- \to \mu^- \mu^+ \mu^-$	7.6	0.13 ± 0.06	7.4	0	< 2.1
$\tau^- \to e^- \mu^+ \mu^-$	6.1	0.10 ± 0.04	9.5	0	< 2.7
$\tau^- \to \mu^- e^+ e^-$	9.3	0.04 ± 0.04	7.8	0	< 1.8
$\tau^- \to e^+ \mu^- \mu^-$	10.1	0.02 ± 0.02	7.6	0	< 1.7
$\tau^- \to \mu^+ e^- e^-$	11.5	0.01 ± 0.01	7.7	0	< 1.5

U.L. Range: $(1.5 \div 2.7) \times 10^{-8}$ (90% C.L.)

$\tau \to 3l$ search as no irreducible bck
(no photons $\Rightarrow$ no problems with initial state radiation)



Very briefly: $\tau \rightarrow$ l+h (2h)

Both BELLE and BABAR reported results on **searches for LFV τ decays involving one lepton (e or μ) and one or two hadrons** (2006 – 2010).

Three cathegories:

- $\tau \rightarrow l + V$ (vector meson: ϕ, ω ...)
- $\tau \rightarrow l + h_0$ (pseudo-scalar meson: π^0, η, K_S^0 ...)
- $\tau \rightarrow l + h_1, h_2$ (charged mesons: $K^\pm$, $\pi^\pm$ ..)

Clean channels, without irreducible background.

No evidence found in any channel. Different data samples used.

90% C.L. Upper Limits on BR in the range:

$$(3 \div 20) \times 10^{-8}$$

A look at the future: SuperB

Projects of Super-B factories in Japan (KEKB upgrade) and Italy (Frascati).

Expected luminosities:

10^{35} cm^{-2} s^{-1} (SuperKEKB), 10^{36} cm^{-2} s^{-1} (SuperB)

SuperB would reach an **integrated luminosity L = 75 ab^{-1}**, a couple of orders of magnitude larger than the combined BELLE and BABAR sample.

To take advantage of this increasing in luminosity, **detector upgrades could be needed**, since the **expected B.R. scales as 1/L only for a background-free experiment** (otherwise, it scales as 1/sqrt(L)) ⇒ **$\tau \to 3l$ and $\tau \to l+h$ (2h) seems more promising than $\tau \to l\gamma$.**

Expected sensitivies:

Studies under way to reduce irreducible bck from ISR

- **BR($\tau \to l\gamma$) < 2×10^{-9}**
- **BR($\tau \to 3l$) < 2×10^{-10}**
- **BR($\tau \to l + h(2h)$) < $(2 \div 6) \times 10^{-10}$**

Conclusions

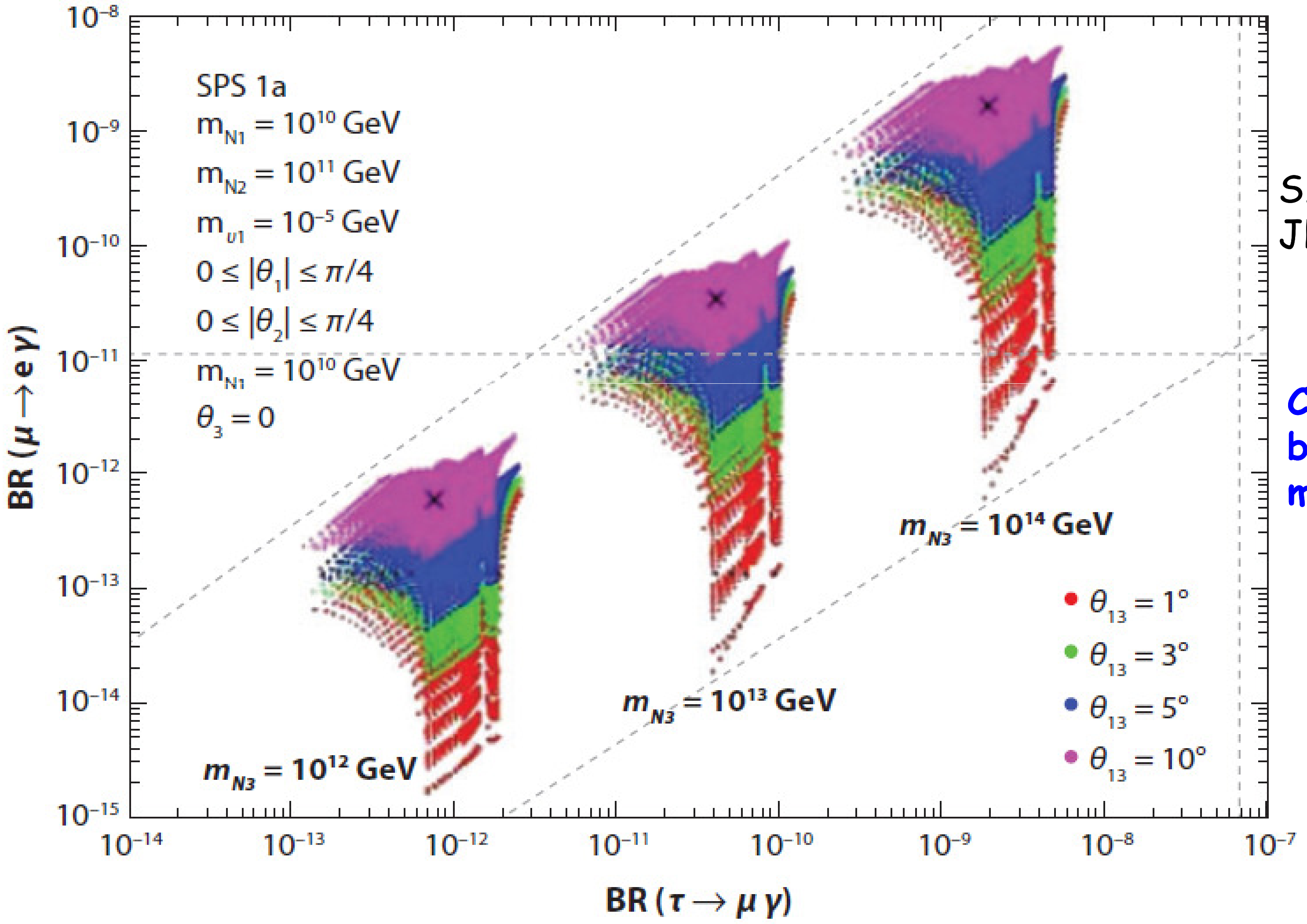
An exciting era for LFV searches:

- **MEG starting long term stable data taking**; sensitivity two times lower than present limit already reached. Projected sensitivity: **BR($\mu \to e\gamma$) $\leq$ few x 10^{-13}**.
- **New $\mu \to$ e conversion experiments (Mu2e & COMET)** should be installed in some years; **expected sensitivities $\leq 10^{-16}$**;
- **First significant results from B-factories for LFV τ decays** (BR Upper Limits ~ **few x 10^{-8}**);
- Expected **(10 ÷ 100) improvement from SuperB** projects.

Discovery of LFV just around the corner ???

Backup slides

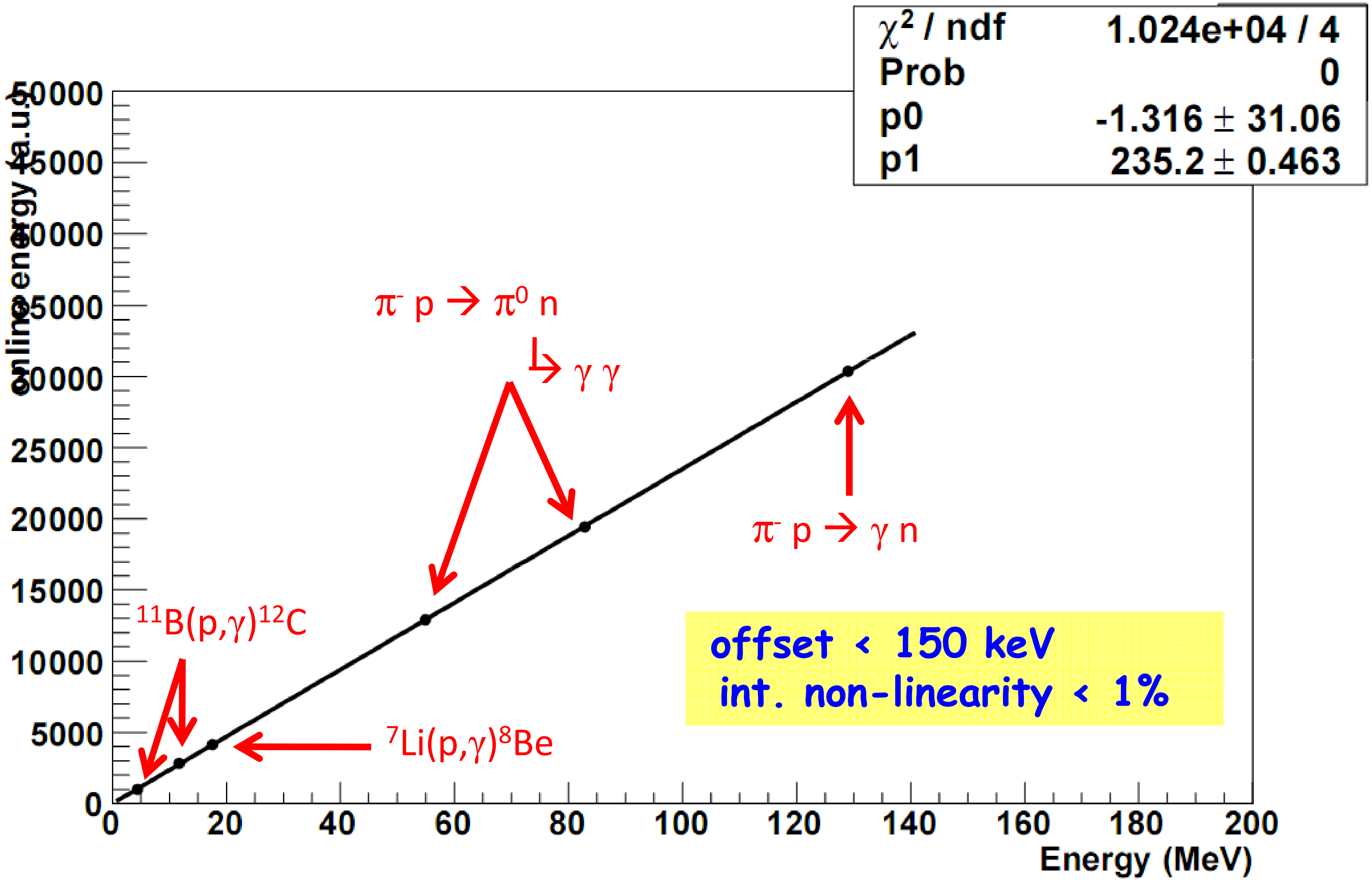
LFV Correlation



S. Antush et al.,
JHEP **11**(2006)90

Complementarity between measurements

XEC Linearity



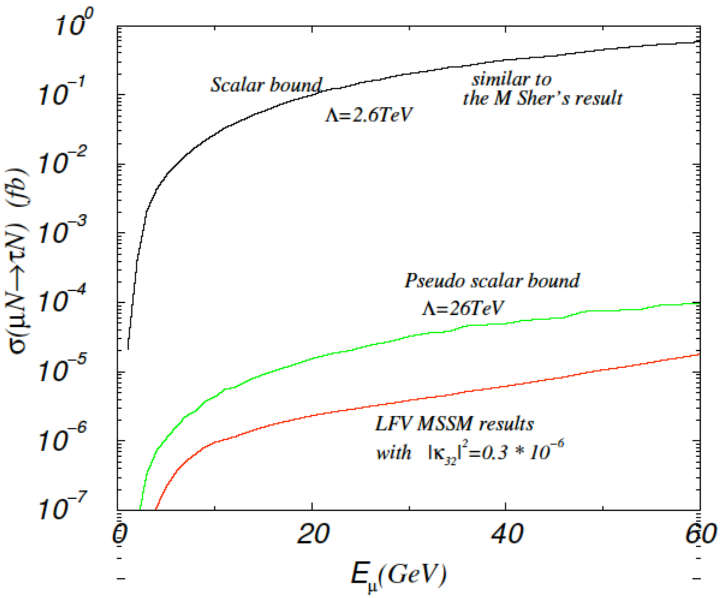
offset < 150 keV

int. non-linearity < 1%

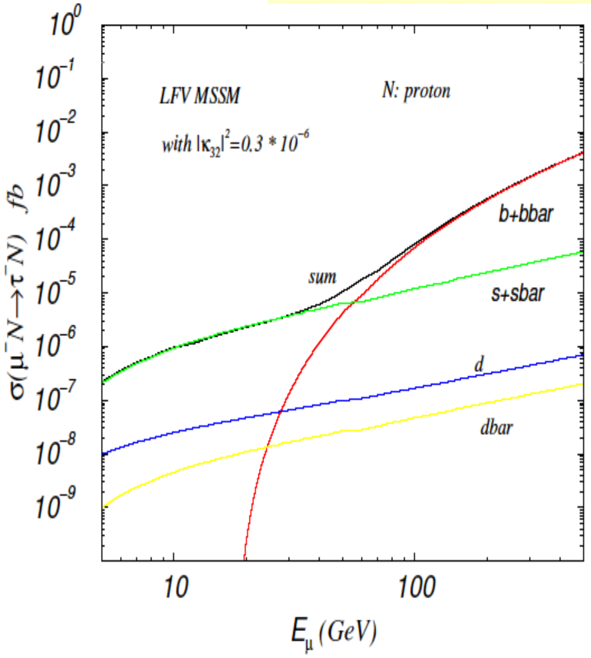
$\mu^-A \rightarrow \tau^-A,X$: a brief mention 1)

In recent years, some interest was devoted to the possibility of exploring the $\mu \rightarrow \tau$ **conversion** LFV channel. It could be a reasonable alternative to LFV t decays, as $\tau \rightarrow \mu\gamma$, $\tau \rightarrow e\gamma$ etc., not yet competitive with μ decays (M. Sher et al., Y. Kuno et al., …)

$\mu A \rightarrow \tau A$



$\mu A \rightarrow \tau X$



Largely enhanced at **E_μ > 50 GeV** for b-quark processes

(S.N. Gninenko et al.,
Mod. Phys. Lett.
A17 (2002) 1407,
M. Sher et al.,
Phys. Rev.
D69 (2004) 017302)

$\mu^- A \rightarrow \tau^- A, X$; a brief mention 2)

- **Different experimental approach**:
  need of an **intense high energy muon beam**:
  a) E_μ > 20 GeV b) 10^{20} muons/year
  (for instance at a muon/neutrino factory);
- Expected t production: **from hundreds to tens of thousands of τ's** (depending on muon energy);
- Signal selection based on **angular distribution of τ decay products** (hard hadrons) and **missing momentum**;
- Potential backgrounds from mis-identified hard muons from $\mu A \rightarrow \mu A'$ and from hard hadrons from target;
- Need of **realistic MC simulations and detector design !**

A look at the future: LHC

LHC (N. Ünel, talk at 40th Rencontres de Moriond, March 2005)

MC studies of possible detection of LFV violating processes at LHC . In the τ channel, with one year of data taking at low luminosity, ~ 10^{12} τ's will be produced and several hundred millions could be used to search for LFV τ decays.

Main τ sources: $W \to \tau\nu$, $Z \to \tau^+\tau^-$, $B \to \tau\nu D$

The predicted sensitivities in the $\tau \to \mu\gamma$ and $\tau \to 3$ muons BRs are ~ $10^{-7} \div 10^{-8}$, not competitive with present B-factories results (the $\tau \to 3$ muons channel has the best signal/noise ratio).

Potentially interesting are also LFV decays of SUSY particles, like

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \mu\tau$$