Lecture:

Standard Model of Particle Physics

Heidelberg SS 2012

Flavour Physics I + **II**

Contents

PART I

- Determination of the CKM Matrix
- CP Violation in Kaon system
- CP violation in the B-system

PART II

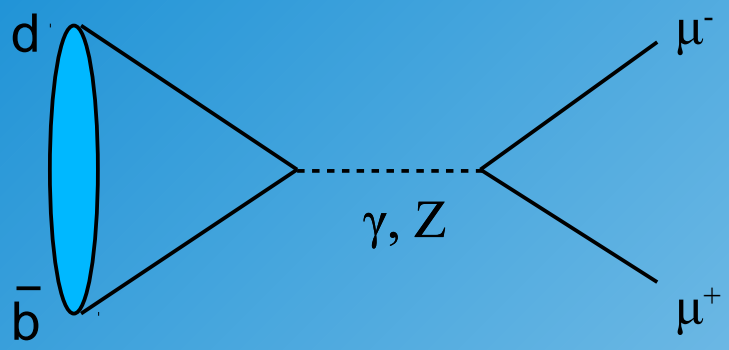
- Search for Flavor Violating Neutral Currents (Lepton Flavor Violation)
- Search for Lepton/Baryon Number Violation

PART III (W.R)

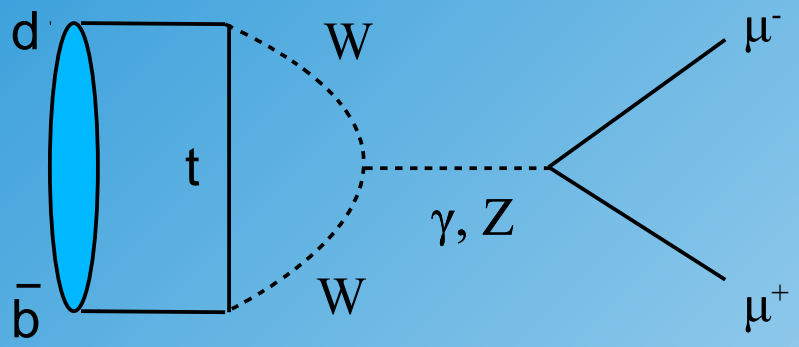
- Massive Neutrinos

Flavour Changing Neutral Currents

...are forbidden in the SM at tree level (GIM mechanism)



branching ratio=0



penguin diagram

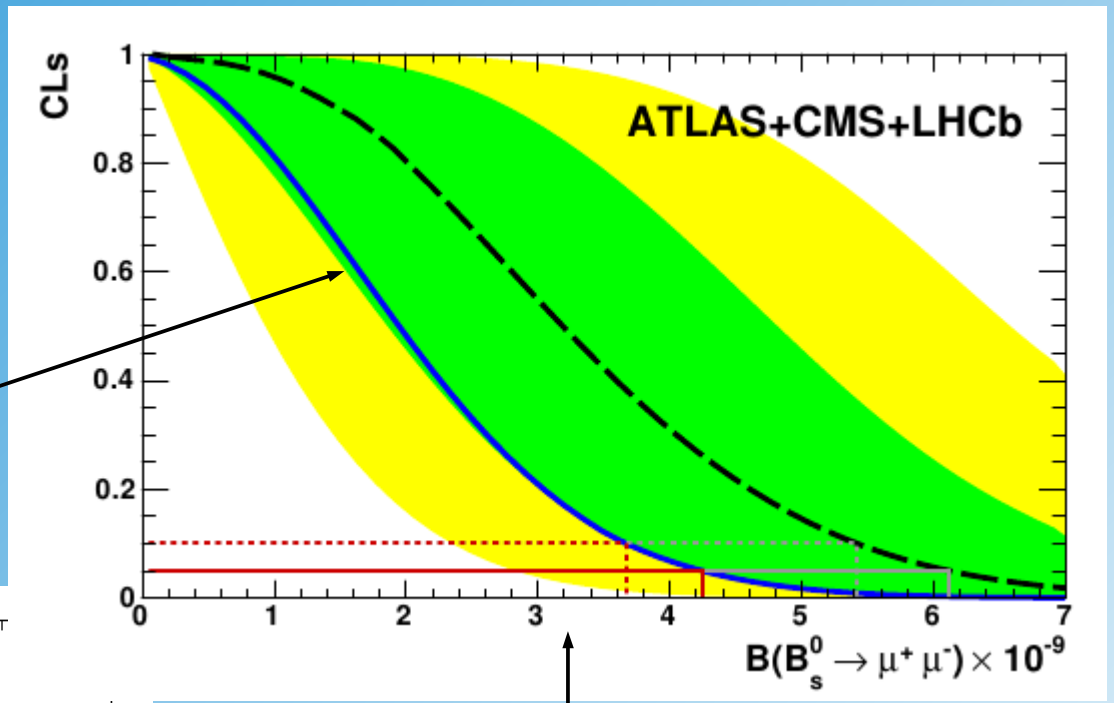
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.0 \pm 0.1) \times 10^{-10}.$$

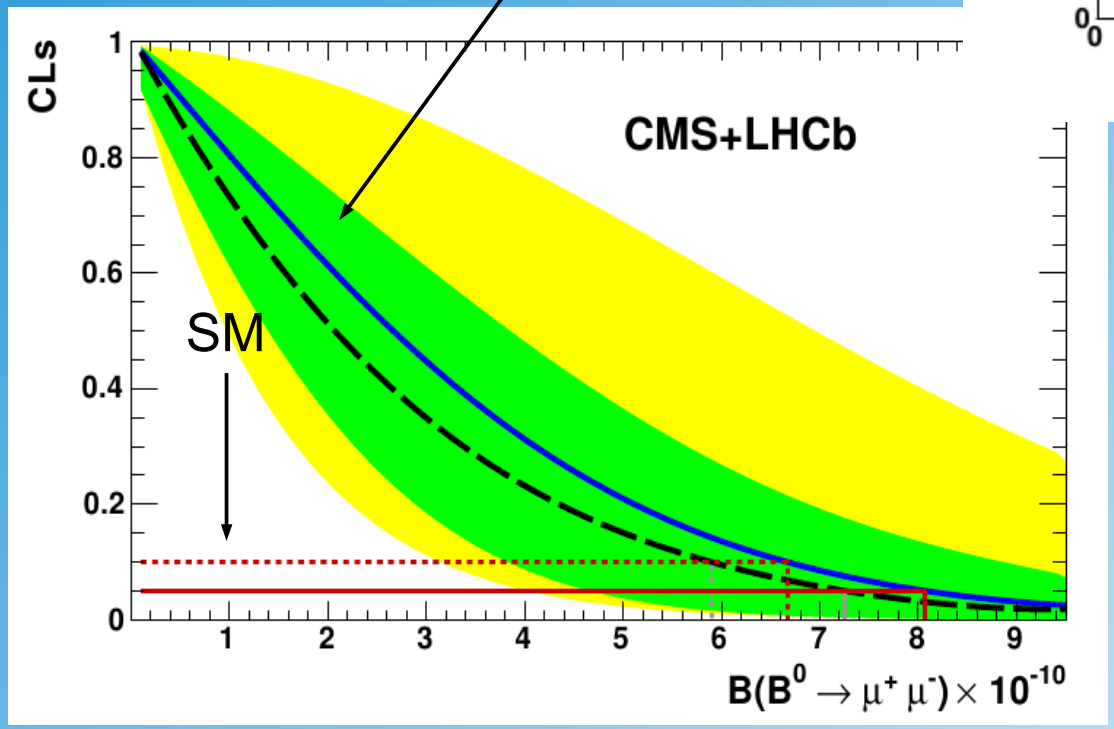
branching ratio easily anhanced by new physics!

$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm CMSSM}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM}} \approx 1.2^{+0.8}_{-0.2}$$

arXiv:1112.3564

Curent Limits (LHC)





no sign of new physics

Charged Lepton Flavour Violation

- Leptons mix in a similar way as quarks (→ PMNS matrix, W.R next week)
- Lepton mixing discovered in neutrino oscillations

But (Charged) Lepton Flavor Violation not seen:

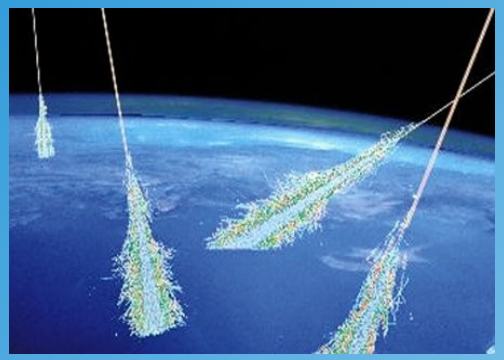
Reaction	Present limit	Reference
$\mu^+ \to e^+\gamma$	$< 1.2 \times 10^{-11}$	Brooks *et al.* [49]
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$	Bellgardt *et al.* [55]
$\mu^- Ti \to e^- Ti$	$< 4.3 \times 10^{-12}$	C. Dohmen *et al.* [70]
$\mu^- Ti \to e^- Ti$	$< 6.1 \times 10^{-13}$	Wintz [72] *
$\mu^- Au \to e^- Au$	$< 7 \times 10^{-13}$	Bert *et al.* [73]
$\mu^- Pb \to e^- Pb$	$< 4.6 \times 10^{-11}$	Honecker *et al.* [71]
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	Willmann *et al.* [23]
$\tau \to e\gamma$	$< 1.1 \times 10^{-7}$	Aubert *et al.* [24]
$\tau \to \mu\gamma$	$< 4.5 \times 10^{-8}$	Hayasaka *et al.* [25]
$\tau \to \mu\mu\mu$	$< 3.2 \times 10^{-8}$	Miyazaki *et al.* [26]
$\tau \to eee$	$< 3.6 \times 10^{-8}$	Miyazaki *et al.* [26]
$\pi^0 \to \mu e$	$< 8.6 \times 10^{-9}$	Edwards *et al.* [27]
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	Ambrose *et al.* [28]
$K^+ \to \pi^+\mu^+e^-$	$< 2.1 \times 10^{-10}$	Lee *et al.* [29]
$K_L^0 \to \pi^0\mu^+e^-$	$< 3.1 \times 10^{-9}$	Arisaka *et al.* [30]
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$	Akers *et al.* [31]
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$	Akers *et al.* [31]
$Z^0 \to \tau\mu$	$< 1.2 \times 10^{-5}$	Abreu *et al.* [32]

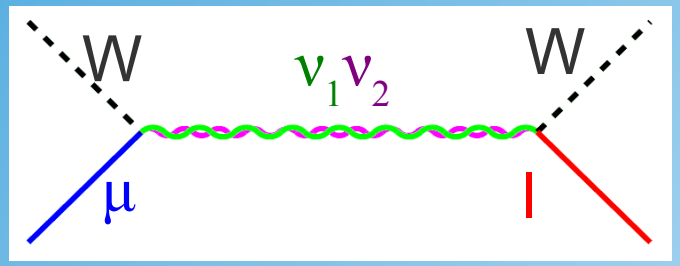
The SM prediction for Lepton Flavor Violating (LFV) Processes is negligible (GIM-like suppression)

Any sign of LFV would manifest New Physics

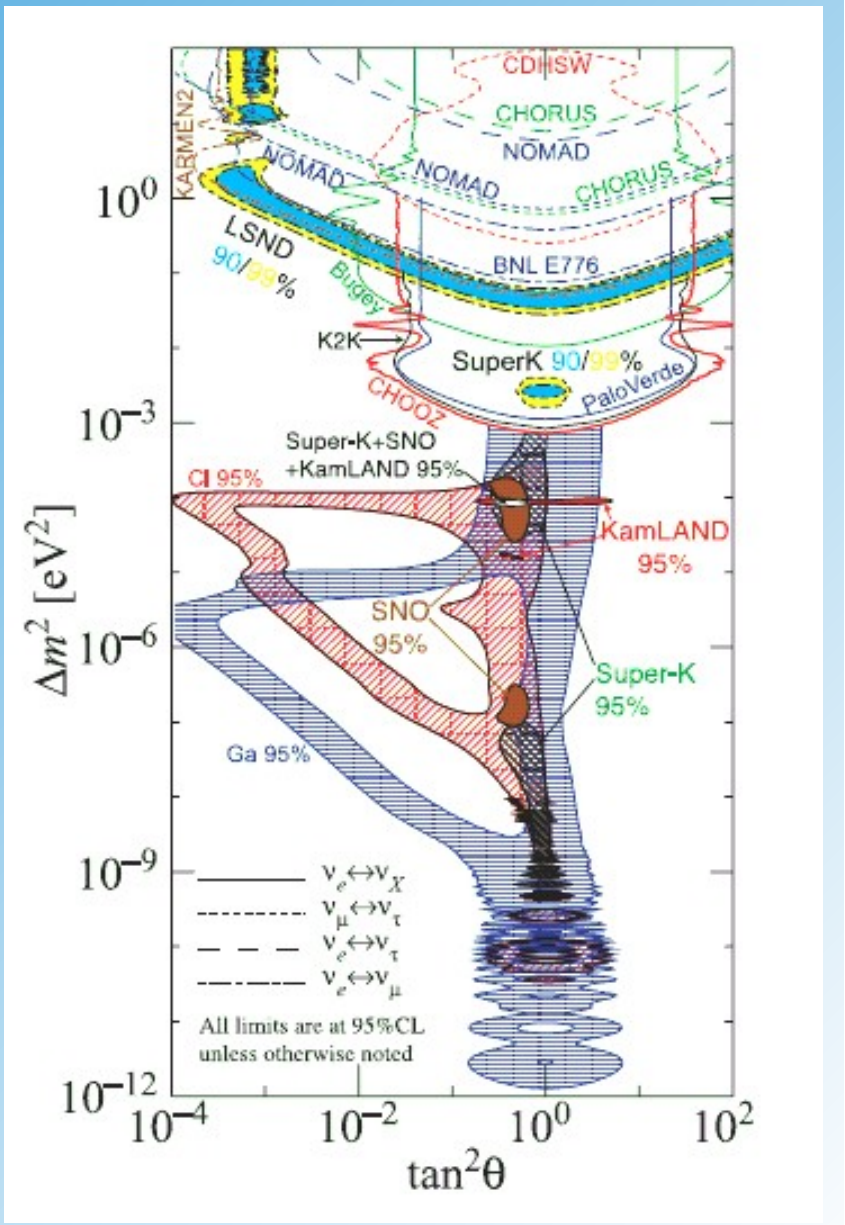
Discovery of Neutrino Oscillations

- Neutrino Oscillations:
  - solar neutrinos
  - reactor neutrinos
  - atmospheric neutrinos
  - neutrino beams





$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2_{\alpha\beta}\frac{L}{E}\right)$$

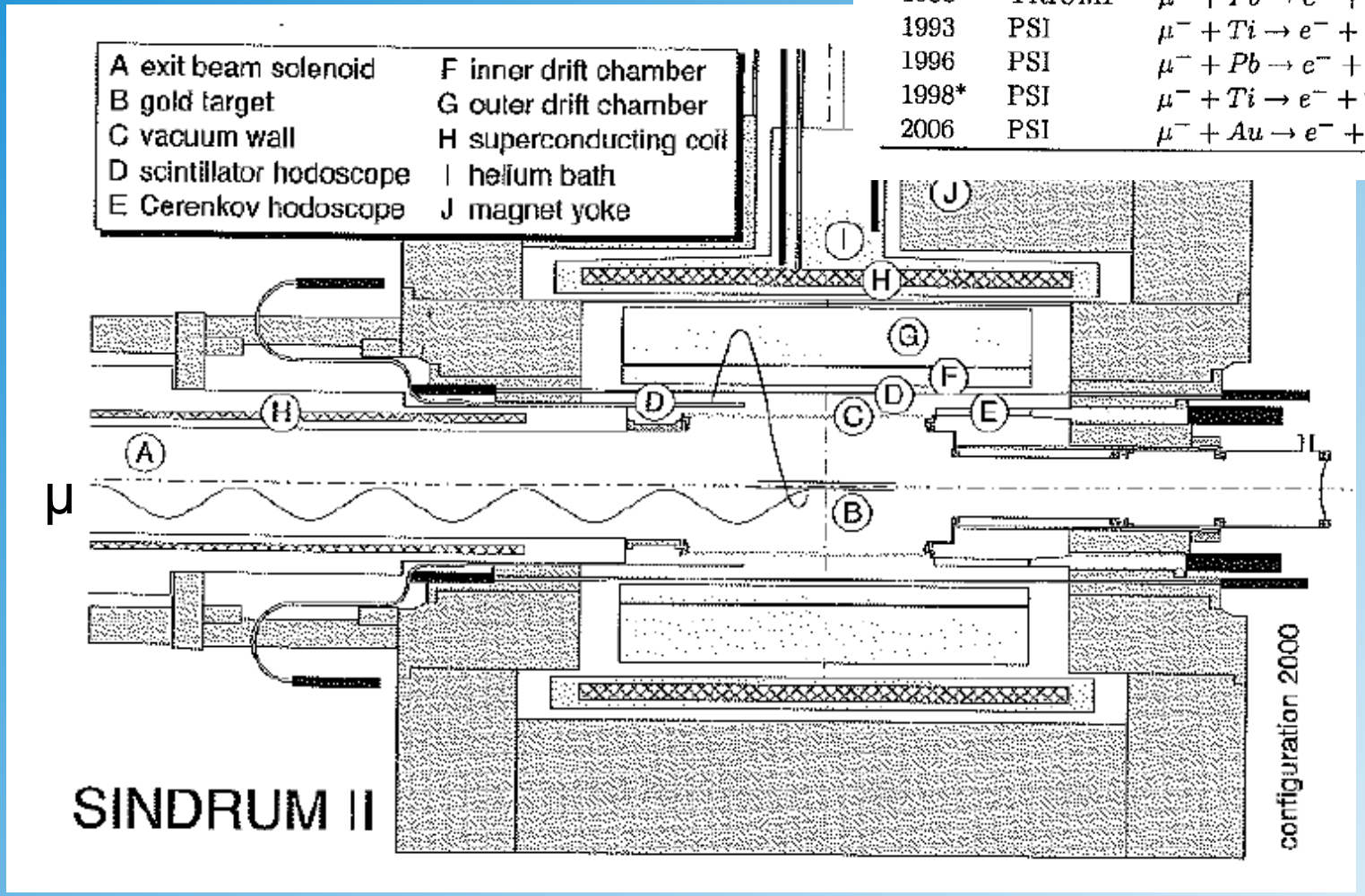


Muon-Electron Conversion

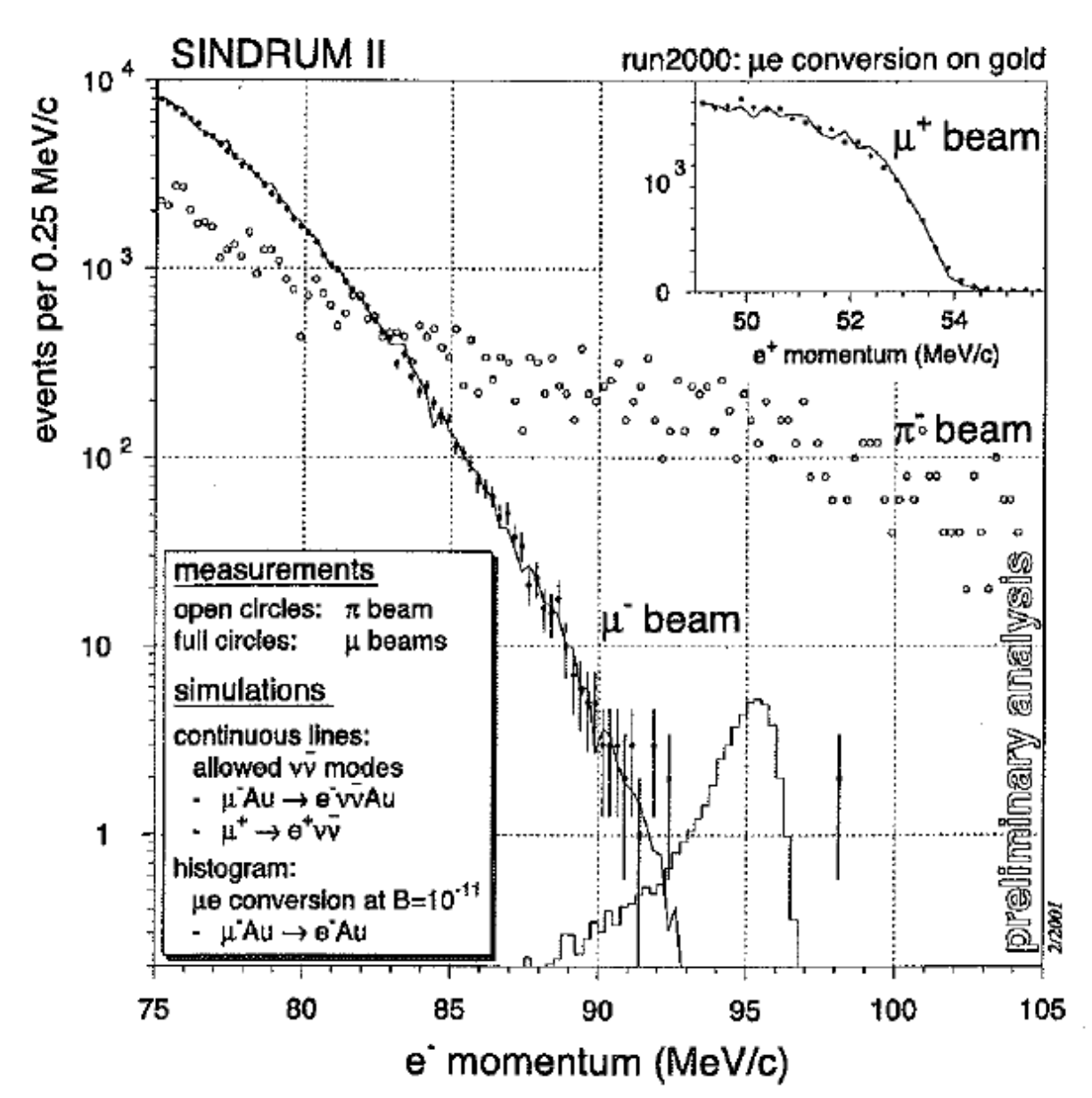
μ N ⟶ e N conversion

Table 19.6. Past experiments on $\mu^- - e^-$ conversion. (*Reported only in conference proceedings.)

Year	Location	Process	Upper Limit	Reference
1972	SREL	$\mu^- + Cu \to e^- + Cu$	$< 1.6 \times 10^{-8}$	[66]
1982	SIN	$\mu^- + {}^{32}S \to e^- + {}^{32}S$	$< 7 \times 10^{-11}$	[67]
1985	TRIUMF	$\mu^- + Ti \to e^- + Ti$	$< 1.6 \times 10^{-11}$	[68]
1988	TRIUMF	$\mu^- + Ti \to e^- + Ti$	$< 4.6 \times 10^{-12}$	[69]
1988	TRIUMF	$\mu^- + Pb \to e^- + Pb$	$< 4.9 \times 10^{-10}$	[69]
1993	PSI	$\mu^- + Ti \to e^- + Ti$	$< 4.3 \times 10^{-12}$	[70]
1996	PSI	$\mu^- + Pb \to e^- + Pb$	$< 4.6 \times 10^{-11}$	[71]
1998*	PSI	$\mu^- + Ti \to e^- + Ti$	$< 6.1 \times 10^{-13}$	[72]
2006	PSI	$\mu^- + Au \to e^- + Au$	$< 7 \times 10^{-13}$	[73]

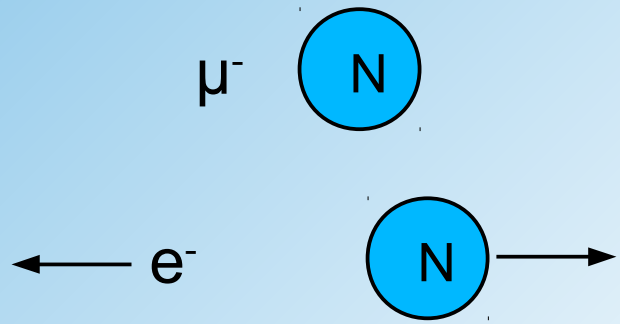


SINDRUM II Result



μ N → e N conversion

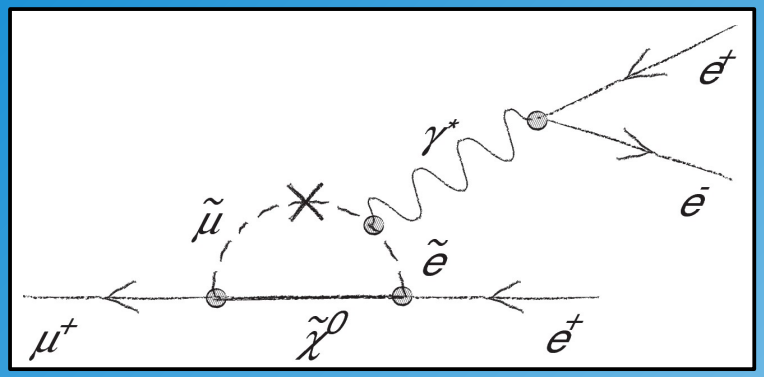
electron receives kinetic energy from muon mass minus nuclear recoil energy



no sign of a signal!

Mu3e Experiment

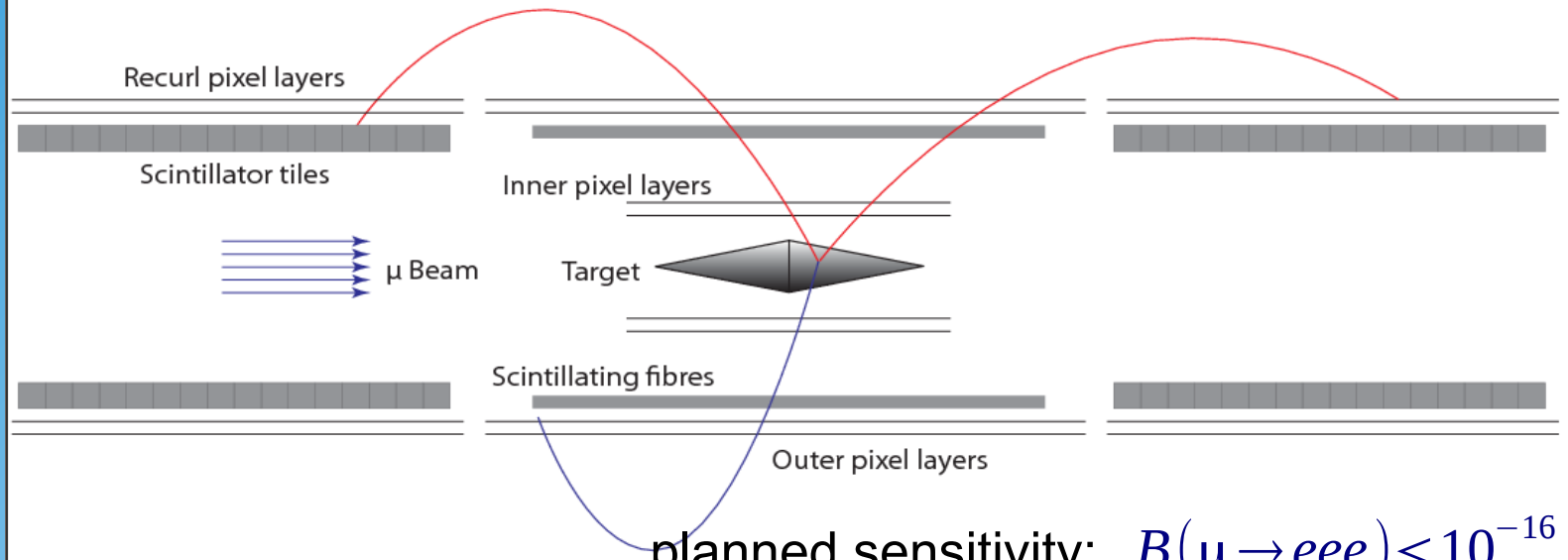
Search for the decay: $\mu \to eee$



SM prediction: $B(\mu \to eee) \ll 10^{-50}$

current limit $B(\mu \to eee) < 10^{-12}$

Design and construction: Heidelberg



planned sensitivity: $B(\mu \to eee) < 10^{-16}$

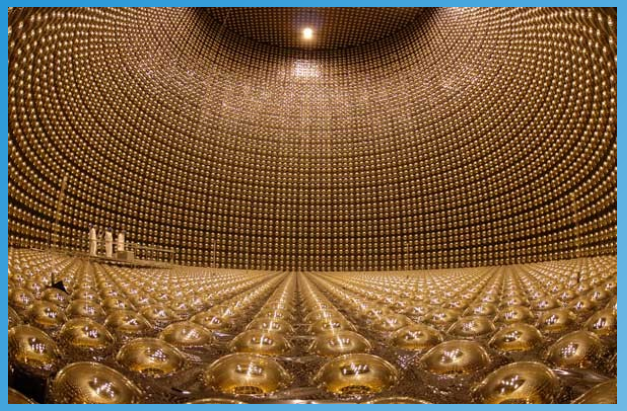
will be performed at the Paul Scherrer Institute (PSI) in 2014+

Baryon and Lepton Number Violation

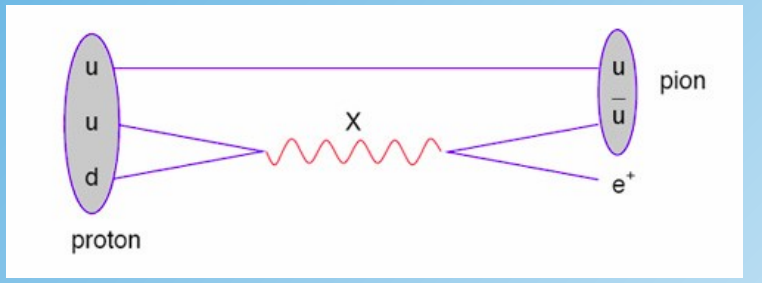
Proton is stable: $\tau > 10^{31} - 10^{33}$ *years*

Not seen:

$$p \not\to \pi^0 e^+$$
$$p \not\to \pi^+ \gamma$$
$$\pi^+ \not\to e^+ \gamma$$



Super Kamiokande



No observation of Baryon or Lepton Number Violation!

The fact the humans and life exists on earth (no radiation damage) excludes already BSM scenarios!

However, baryon or lepton number violating processes are required to explain matter antimatter asymmetry in universe

New BSM Physics is required!