Lecture:

Standard Model of Particle Physics

Heidelberg SS 2013

Flavour Physics I + **II**

Contents

PART I

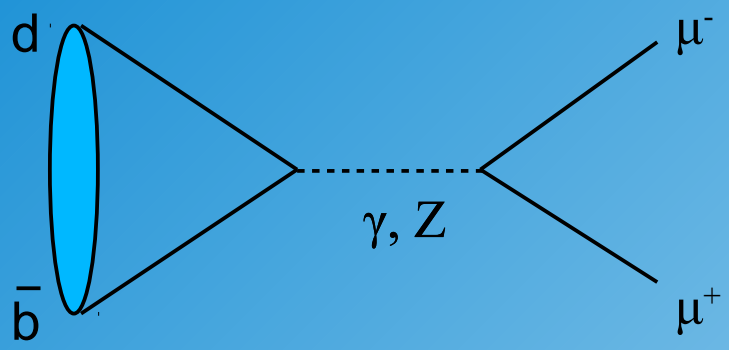
- Determination of the CKM Matrix
- CP Violation in Kaon system
- CP violation in the B-system

PART II

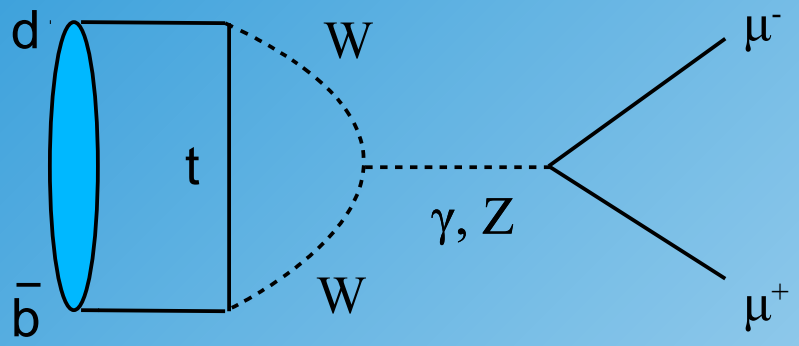
- Search for Flavor Violating Neutral Currents (Lepton Flavor Violation)
- Search for Lepton/Baryon Number Violation

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 enhanced 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

Recent Results from LHCB

PRL **110,** 021801 (2013)

Search for

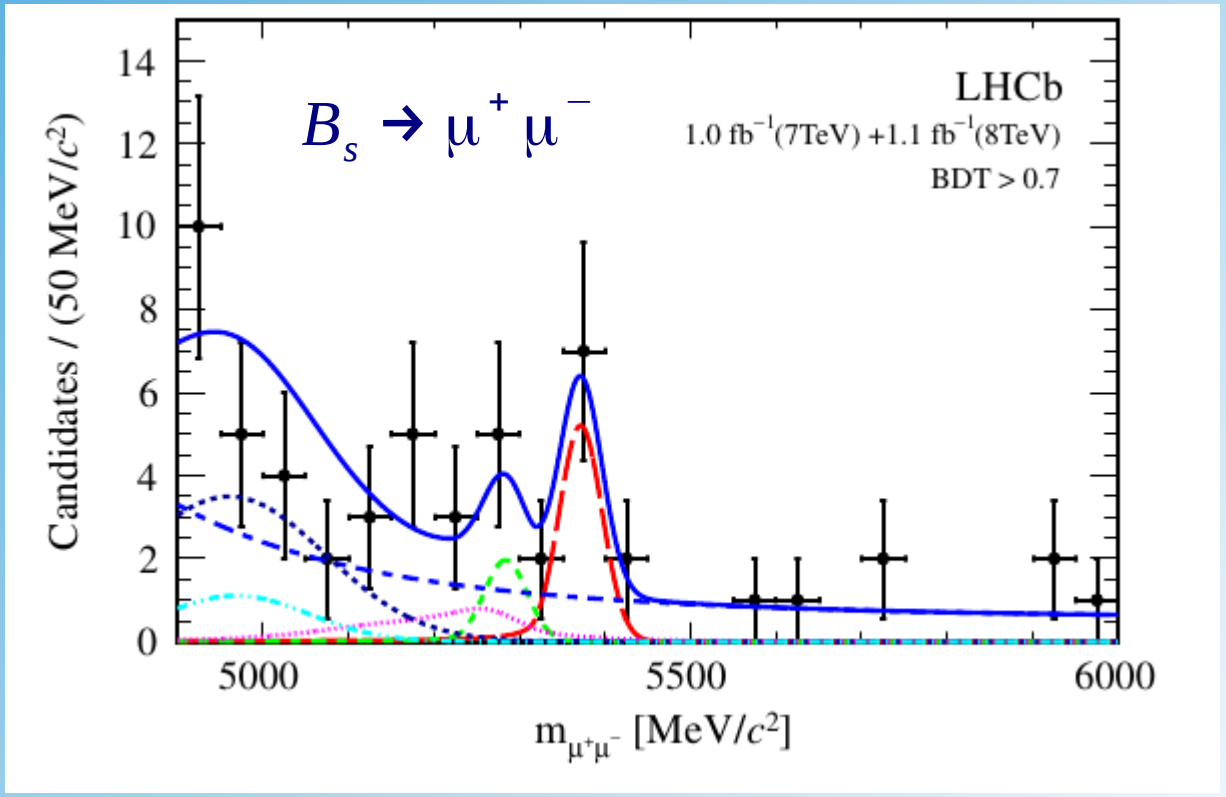
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ (95% CL)

$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$

SM expected 1.1 x 10^{-10}

SM expected 3.2 x 10^{-9}

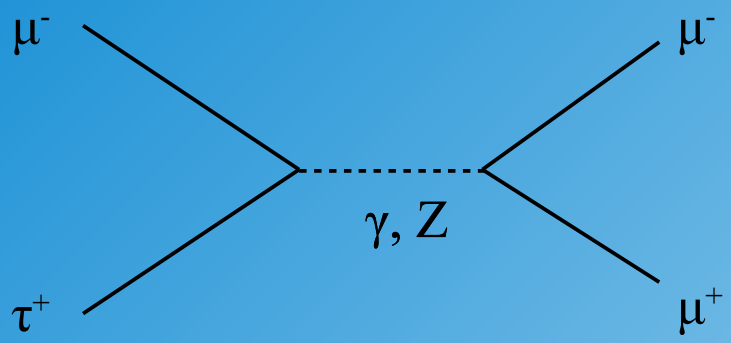
- well compatible with SM expectation
- not much room for physics beyond the SM



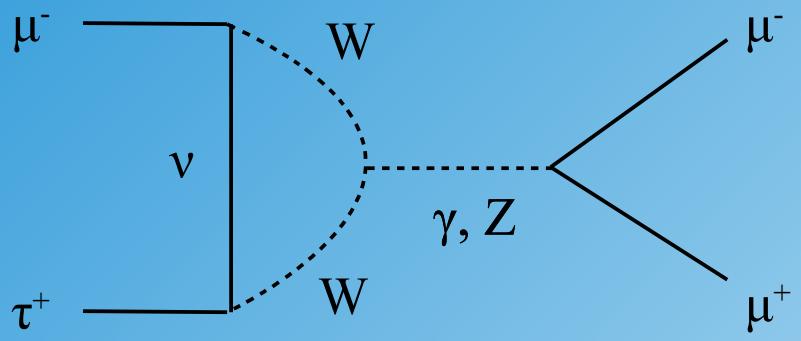
ATLAS and CMS also looking into this channel

Lepton Flavor Violation (FCNC)

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



branching ratio=0



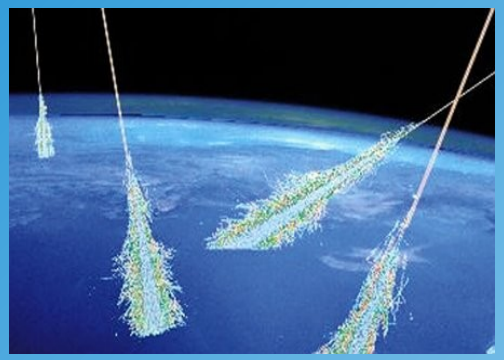
penguin diagram

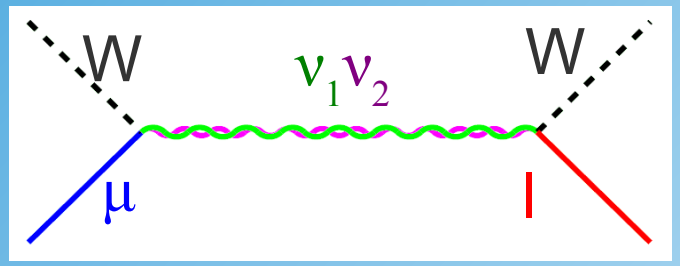
suppressed $\frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

branching ratio largely enhanced by new physics (40 orders of magnitude)!

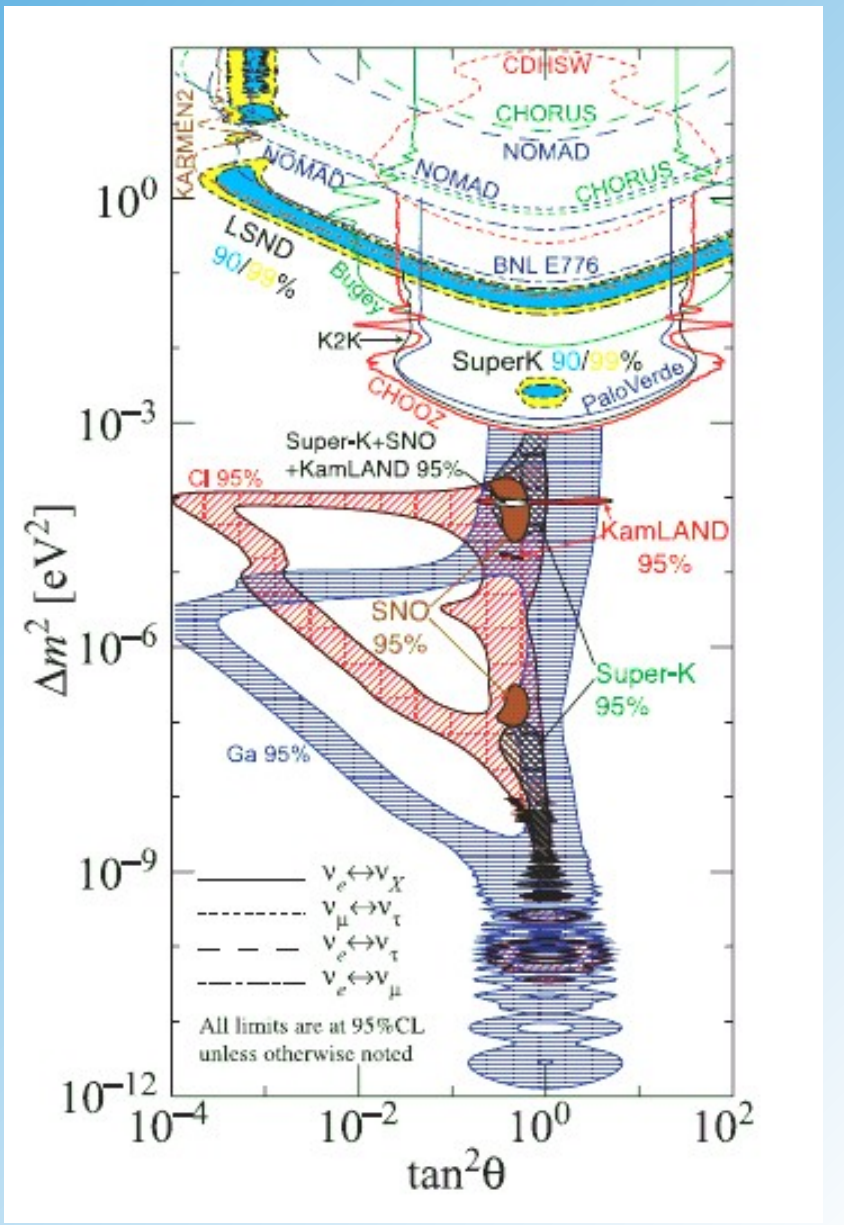
Discovery of Neutrino Oscillations

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





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

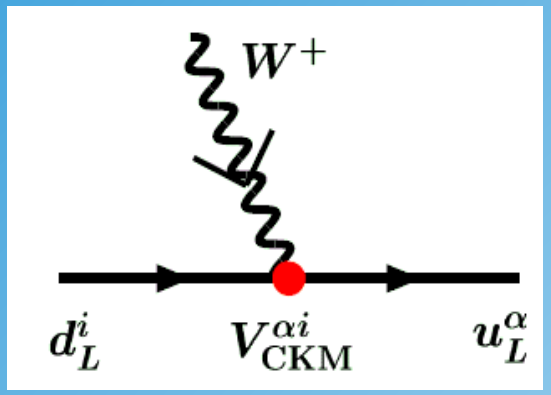


Fermion Mixing

Quarks

Cabibbo Kobayashi Maskawa (CKM)

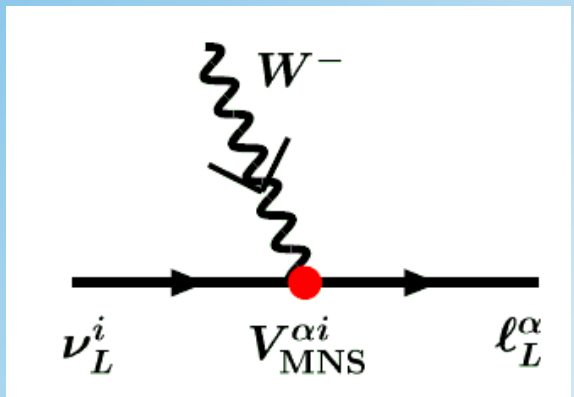
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Leptons

Pontecorvo Maki Nakagawa Sakata (PMNS)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



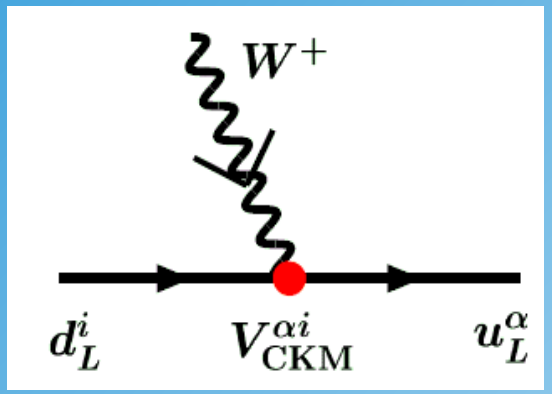
- **W bosons smell different flavors!**
- **other gauge bosons (γ, Z, g) do not (→ no FCNC)**

Fermion Mixing

Quarks

Cabibbo Kobayashi Maskawa (CKM)

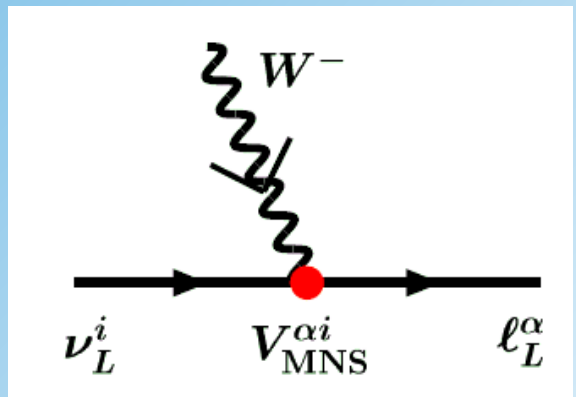
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Leptons

Pontecorvo Maki Nakagawa Sakata (PMNS)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \approx \begin{pmatrix} 0.816 & 0.577 & <0.2 \\ 0.408 & 0.577 & 0.707 \\ 0.408 & 0.577 & 0.707 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- **W bosons smell different flavors!**
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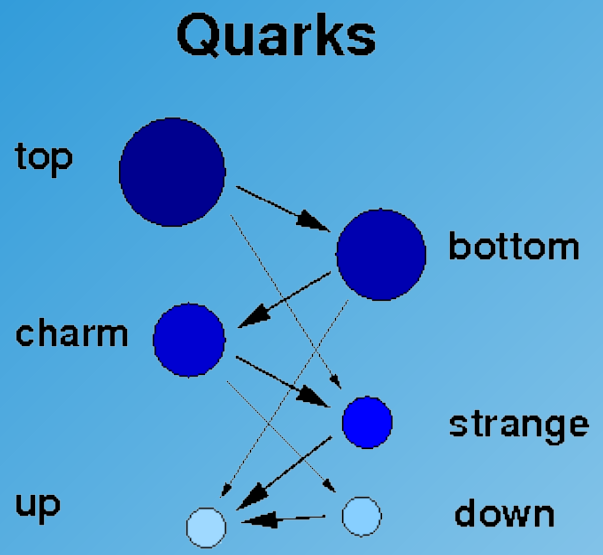
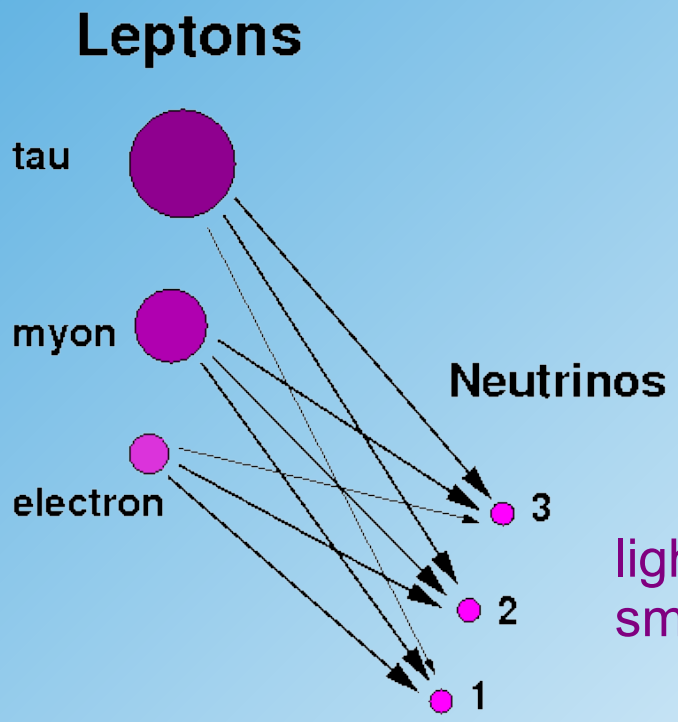
Family Number Violation

- **Flavor Changing neutral currents are forbidden!**
- **Lepton Flavor Number in Charged Currents is an “adhoc” concept**





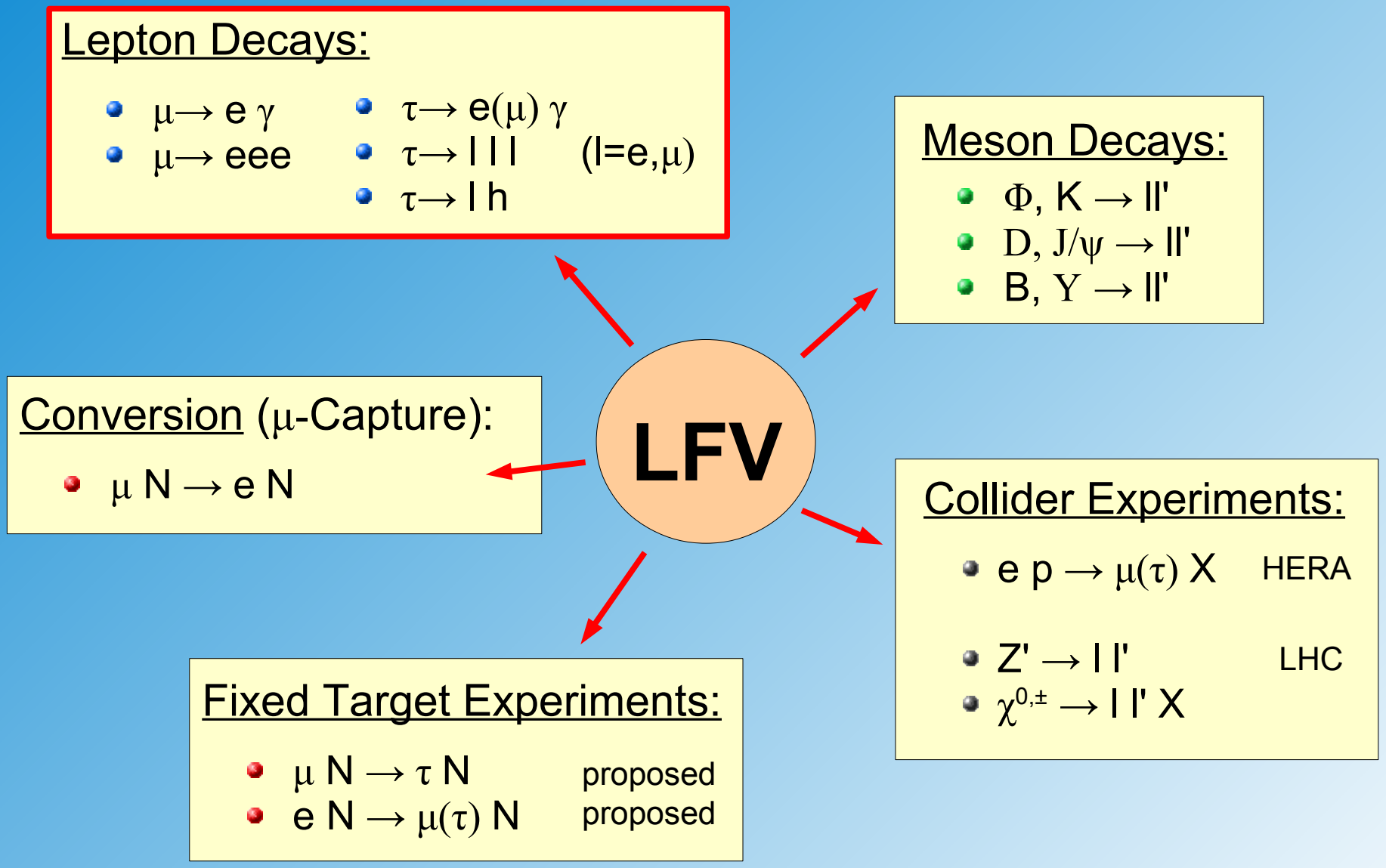
light and
small mass splitting

quark flavor not conserved
(family number changes)

lepton flavor not conserved
but difficult to observe!

(concept of families right?)

Overview LFV Experiments



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

muon to electron conversion experiments

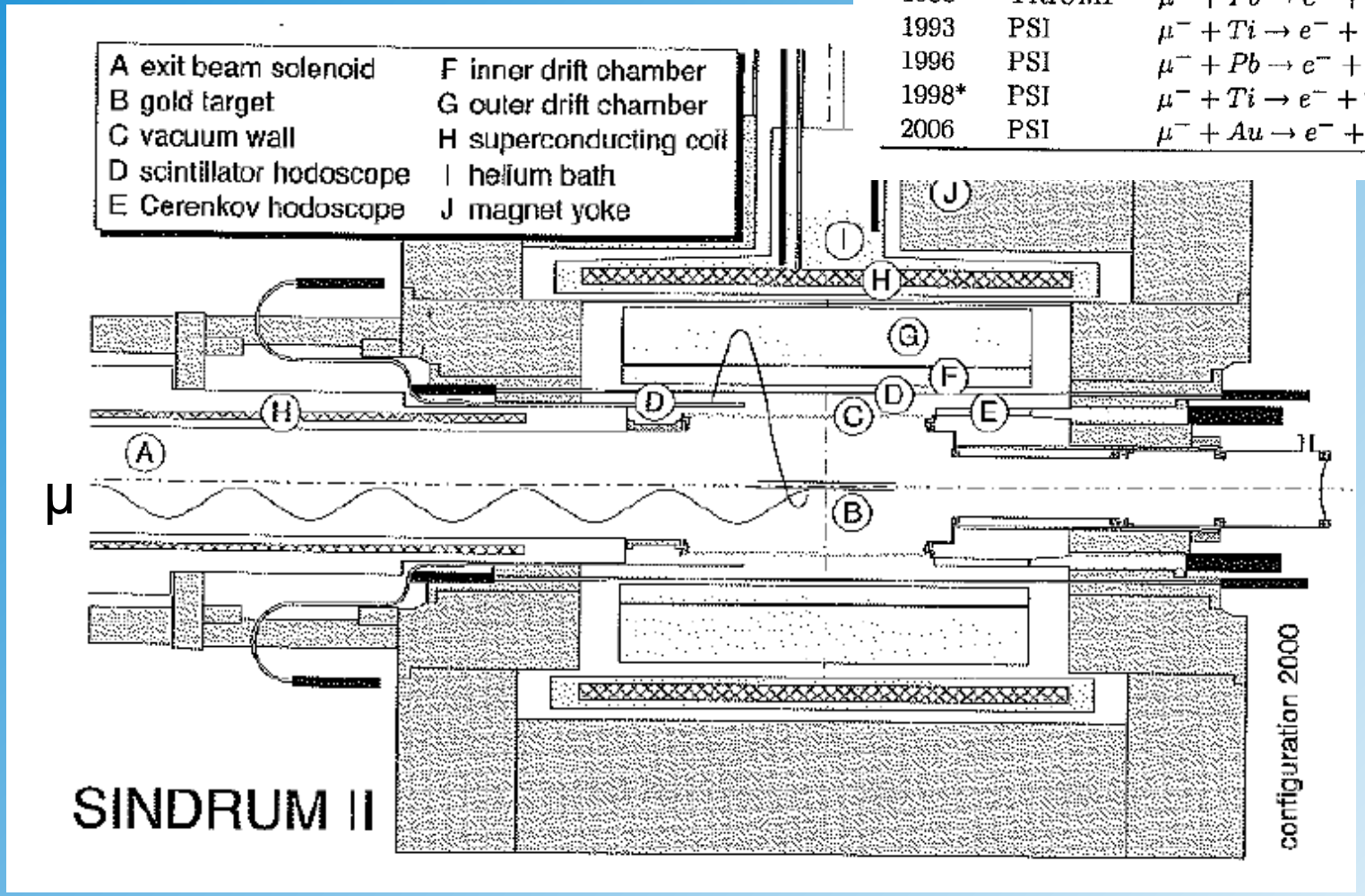
Muon-Electron Conversion

μ N ⟶ e N conversion

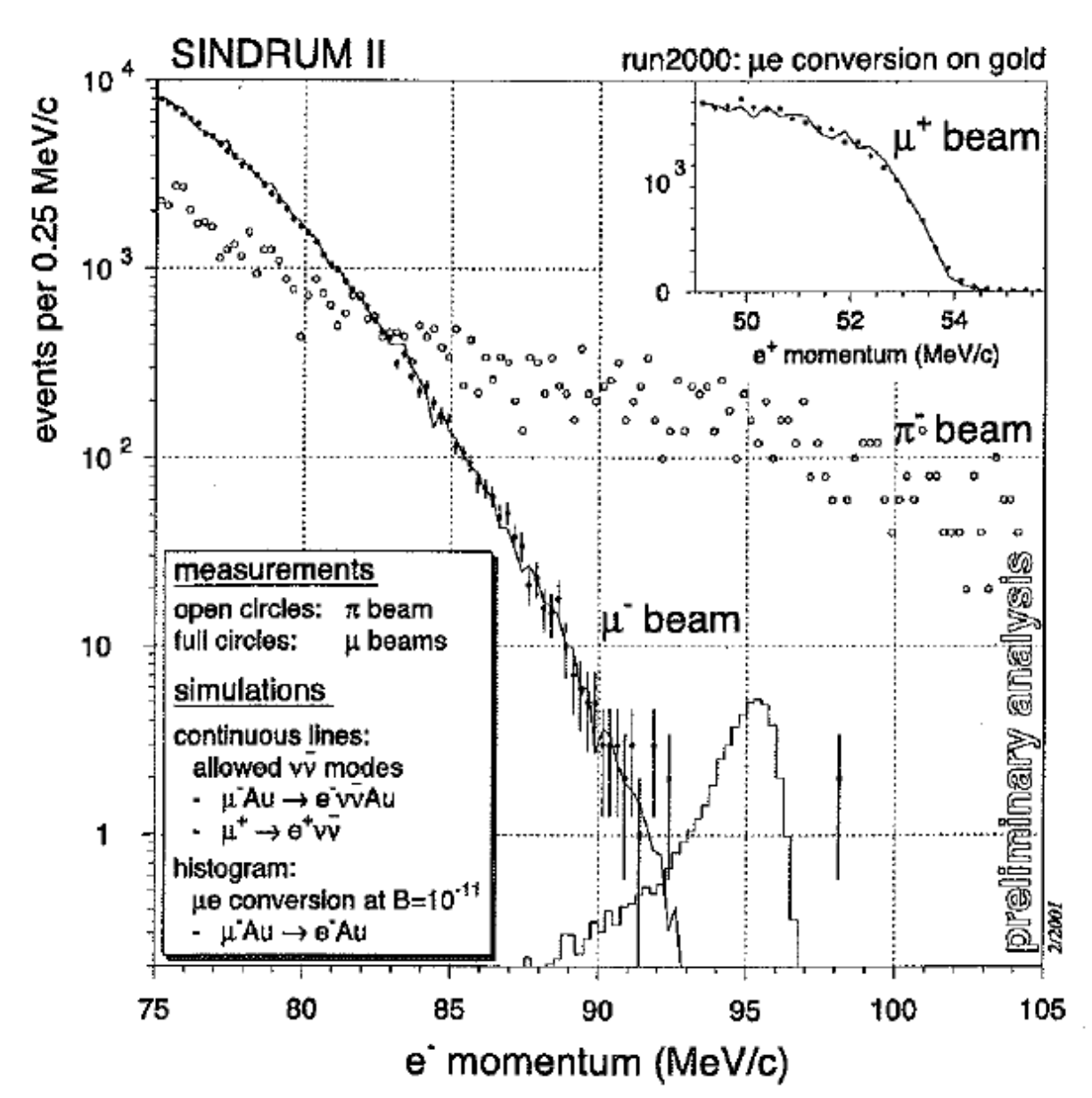
- muon capture in nucleons
- muon decays in orbit

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]

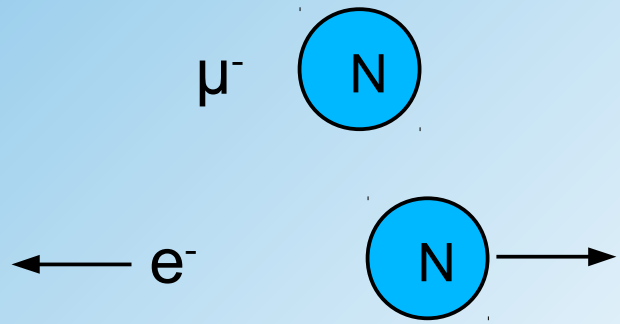


SINDRUM II Result



μ N → e N conversion

electron receives kinetic energy from muon mass minus nuclear recoil energy



no sign of a signal!

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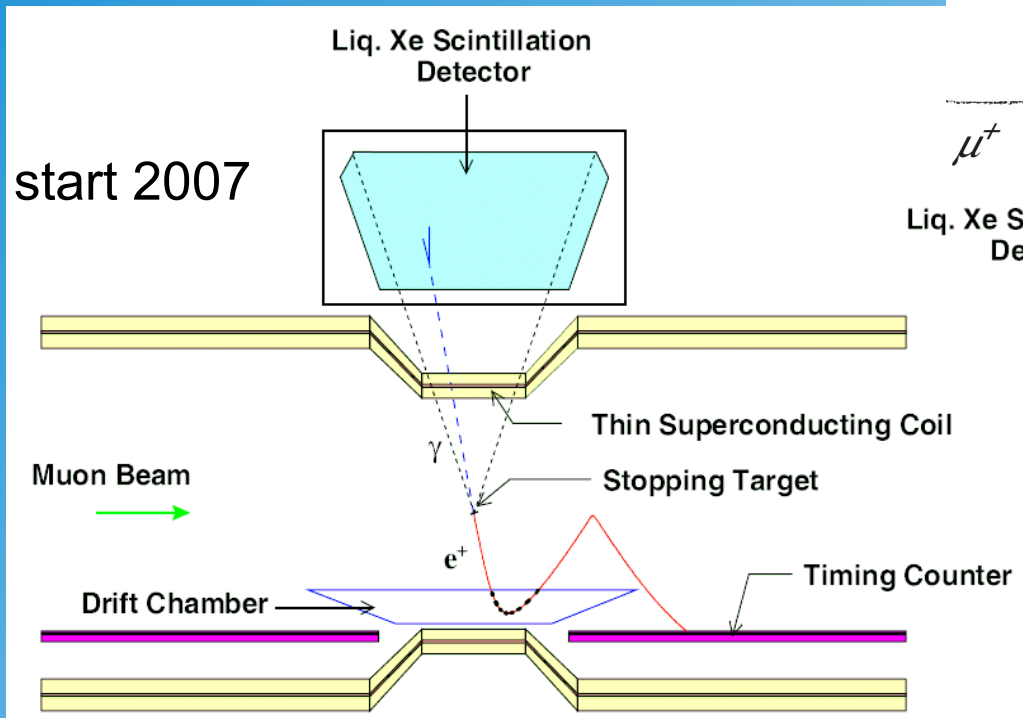
muon to electron conversion experiments

The MEG Experiment

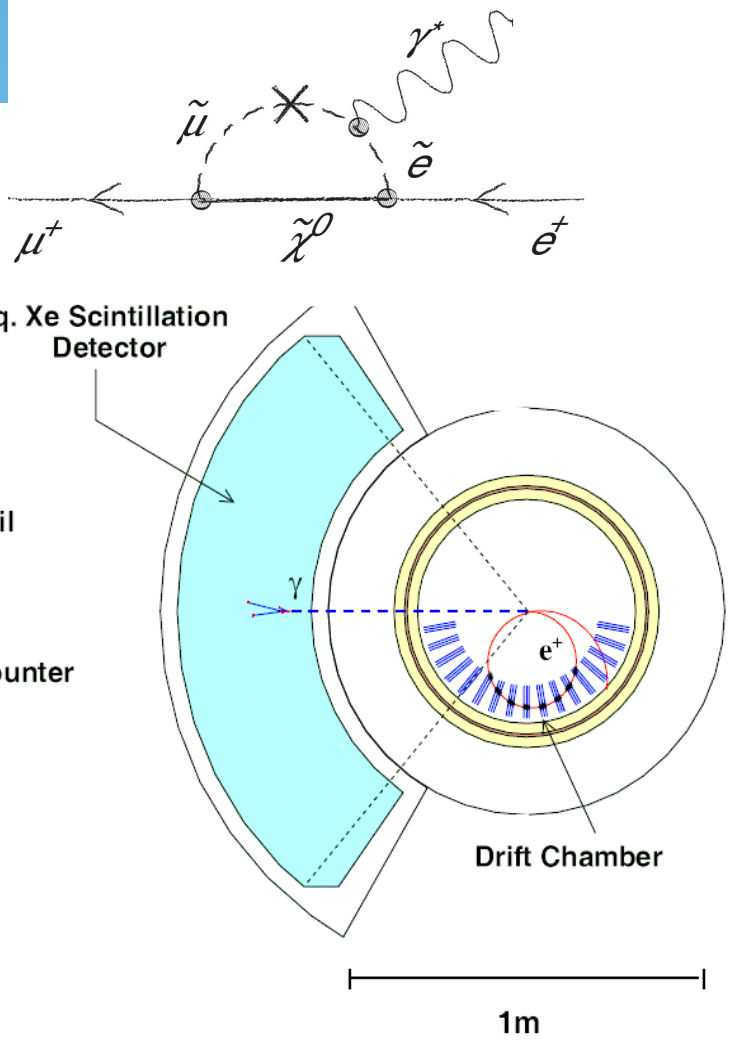
current limit:

$BR(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13}$

start 2007



LFV decay: $\mu^+ \rightarrow e^+ \gamma$



Limitation:

- accidental background
  - better space resolution
  - improve tracking

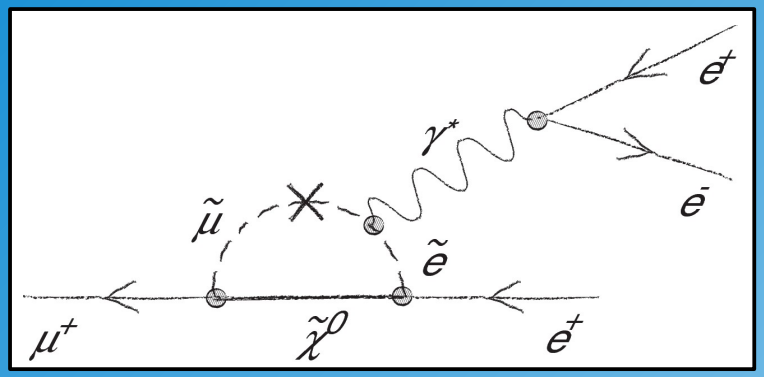
- still taking data
- upgrade planned starting next year

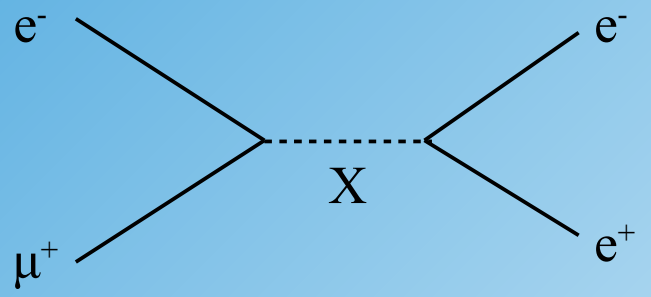
Mu3e Experiment

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

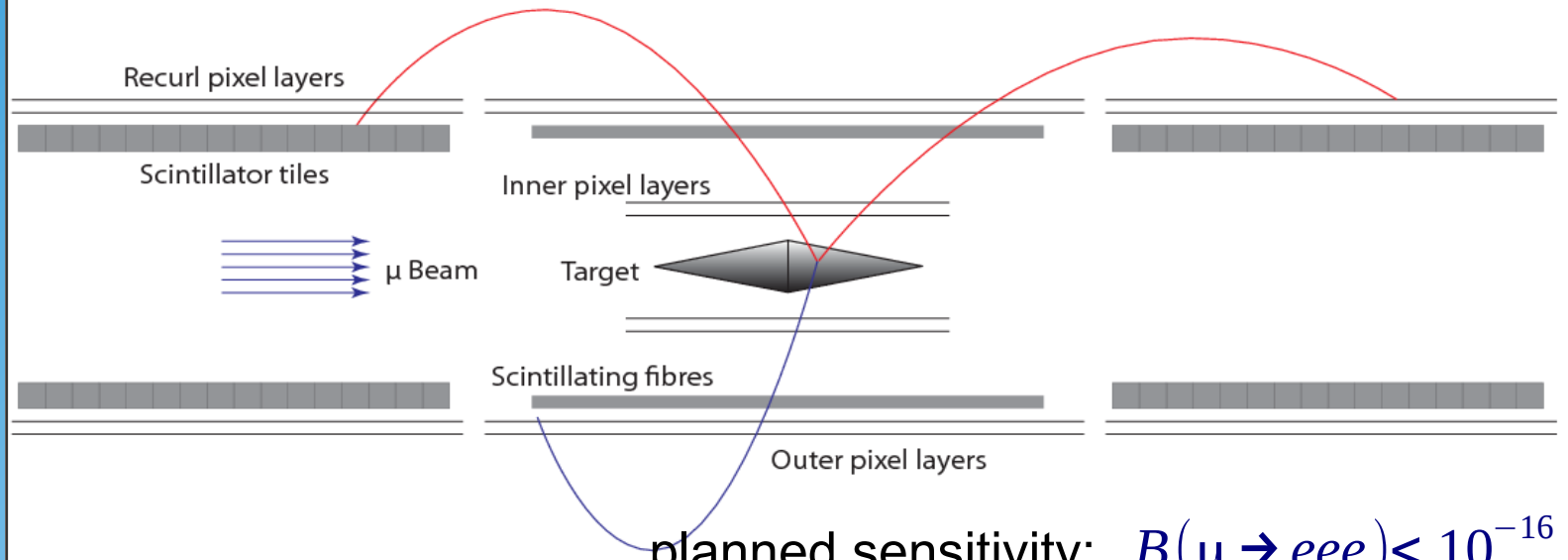
SM prediction: $B(\mu \to eee) \ll 10^{-50}$

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





Design and construction: Heidelberg



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

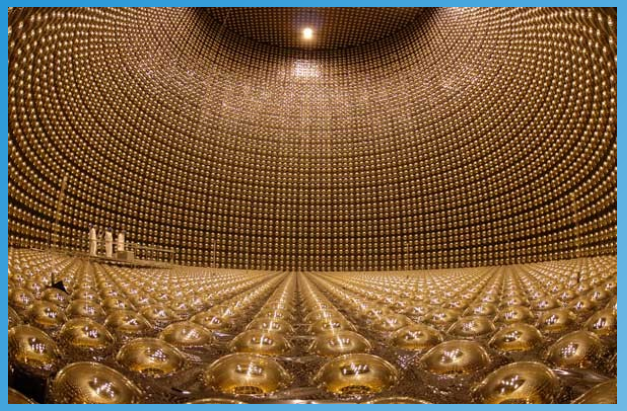
will be performed at the Paul Scherrer Institute (PSI) in 2014+

Baryon and Lepton Number Violation

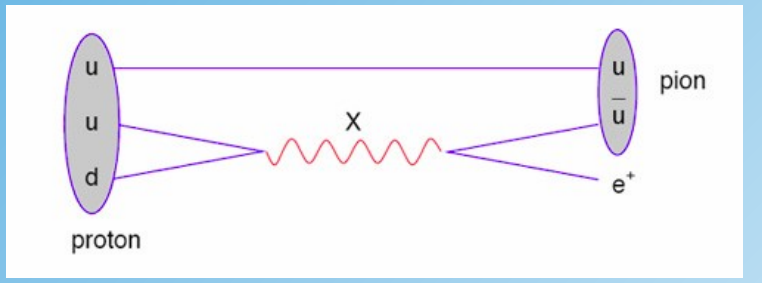
Proton is stable: $\tau > 10^{31} - 10^{33}$ *years*

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!