A Novel μ → eee Experiment

André Schöning

Sebastian Bachmann, Rohin Narayan

Institute of Physics
University of Heidelberg

Seminar

University Heidelberg
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Shifting Stones in the Sierra Nevada

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Shifts were never directly seen

(like charged lepton flavor violation)

History

G.Feinberg, P.Kabir, S.Weinberg, PRL 3 527 (1959)

„Absence of:

- **Br ($\mu \rightarrow e\gamma$)**
- **Br ($\mu \rightarrow eee$)**
- **Br ($\mu N \rightarrow eN$)**

does not constitute a paradox there being no compelling reason why muons should transform into electrons, but it seems a **mystery** that processes which are allowed energetically and in every other known respect do not occur...“

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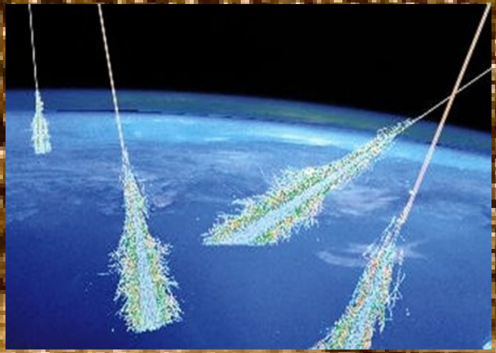
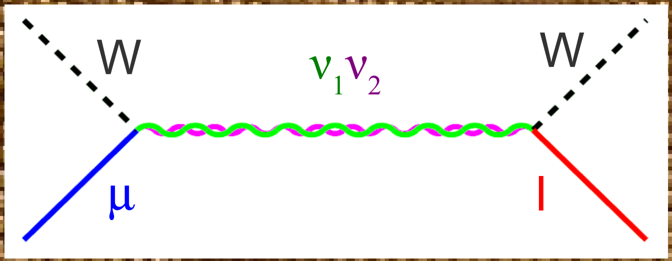
→ **Introduction of lepton flavor quantum number**

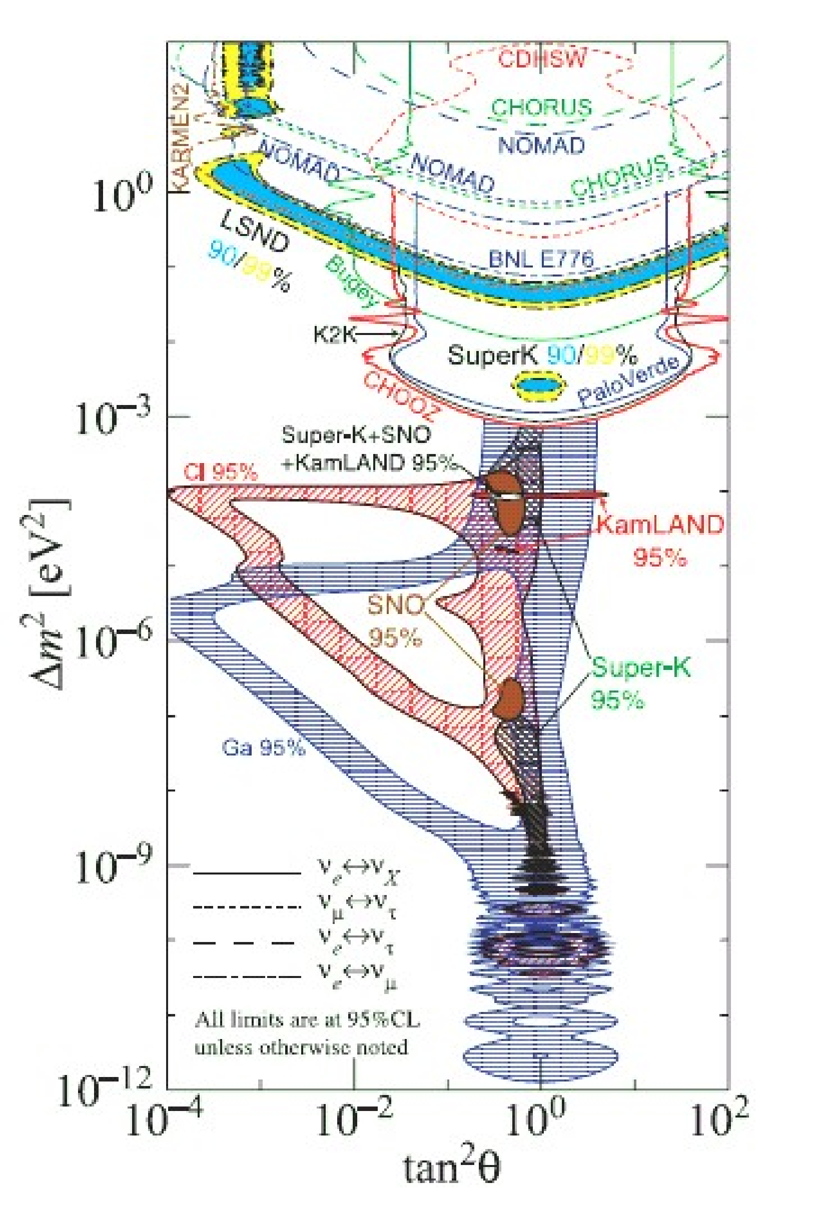
Standard Model: $\mu \to e\,\bar{\nu}_e\,\nu_\mu$

Discovery of Neutrino Oscillations

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







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

"Feinberg Kabir and Weinberg were wrong!"

Overview

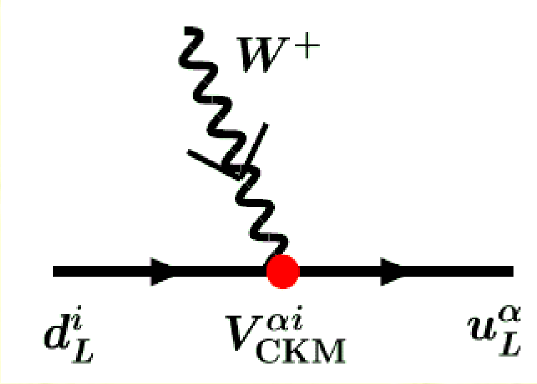
- Introduction to Lepton Flavor Violation
- Motivation to Search for $\mu \rightarrow eee$
- Backgrounds and Past Experiments
- (Novel) Detector Concept and Design
- Simulation Studies
- Summary

Fermion Mixing

Quarks

Cabibbo Kobayashi Maskawa (CKM)

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



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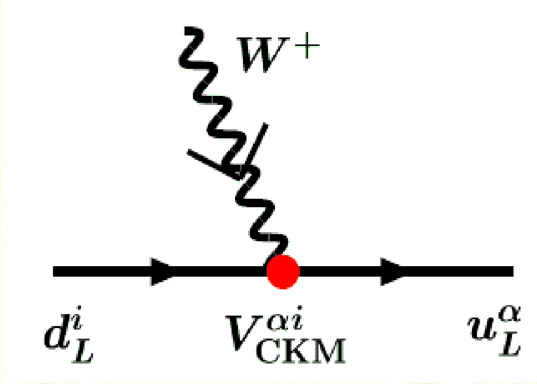
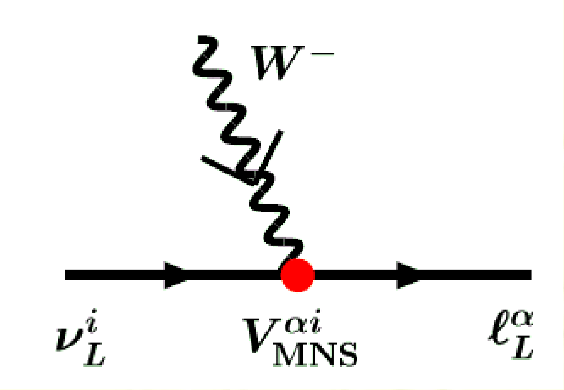


Leptons

Pontecorvo Maki Nakagawa Sakata (PMNS)

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



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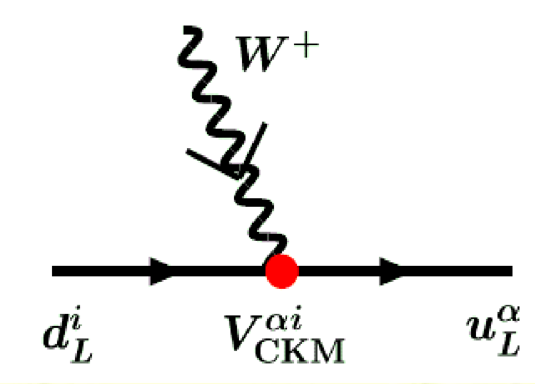

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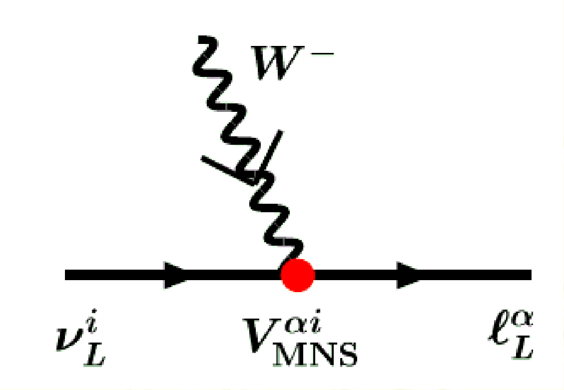


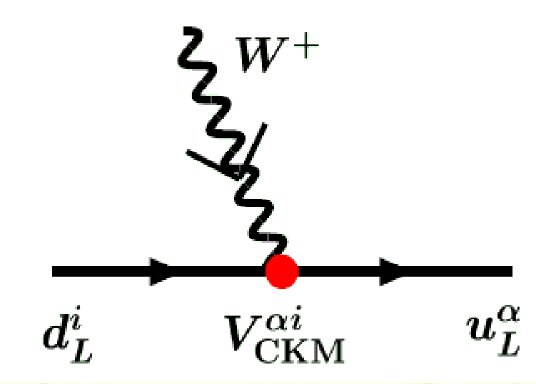
- **W bosons smell different flavors!**
- **other gauge bosons (γ, Z, g) do not (→ no FCNC)**

Fermion Mixing

Quarks

Cabibbo Kobayashi Maskawa (CKM)

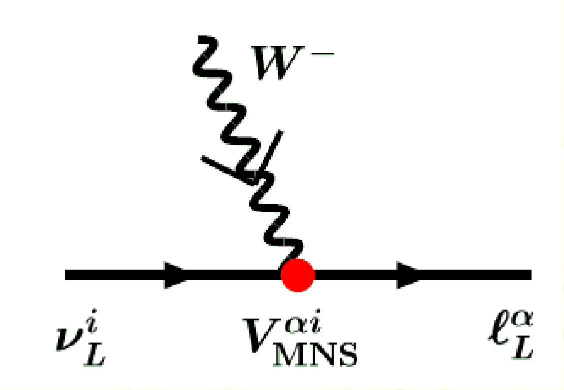
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Leptons

Pontecorvo Maki Nakagawa Sakata (PMNS)

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



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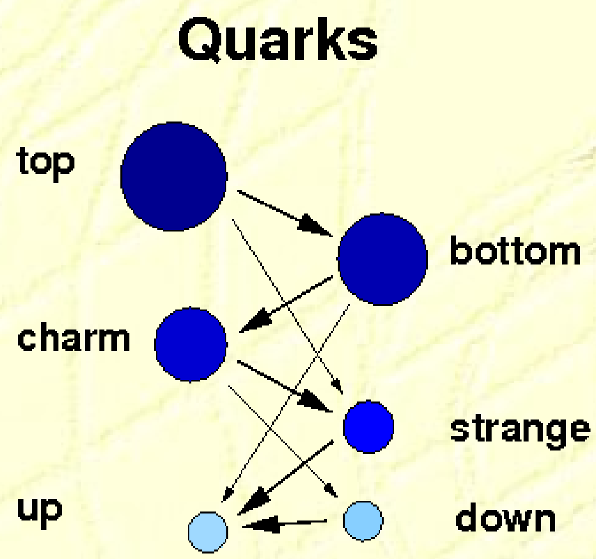
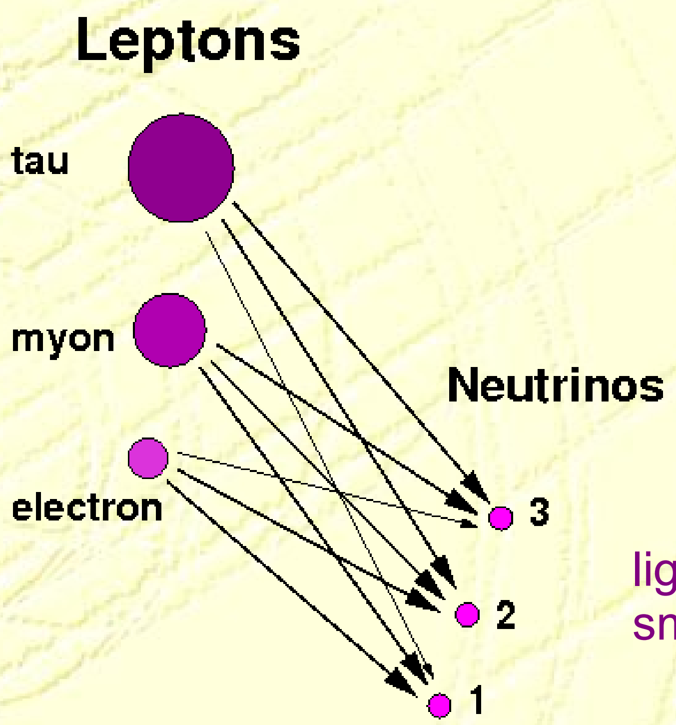
Family Number Violation

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





light
small mass splitting

quark flavor not conserved
(family number changes)

lepton flavor not conserved
but difficult to observe!

(concept of families right?)

Lepton Mixing, LFV and FCNC

U = Neutrino Mixing Matrix

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

weak eigenstates mass

W = Ch. Lepton Mixing Matrix

$$\begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} = \begin{pmatrix} w_{e1} & w_{e2} & w_{e3} \\ w_{\mu 1} & w_{\mu 2} & w_{\mu 3} \\ w_{\tau 1} & w_{\tau 2} & w_{\tau 3} \end{pmatrix} \begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix}$$

weak eigenstates mass

- **Charged Current:**

  PMNS matrix: $V_{ki} = \sum_{\alpha=1}^{3} W^{l^*}_{\alpha k} U^{\nu}_{\alpha i}$ only product measurable

  - product of lepton and neutrino mixing matrices (→ **flavor changing**)

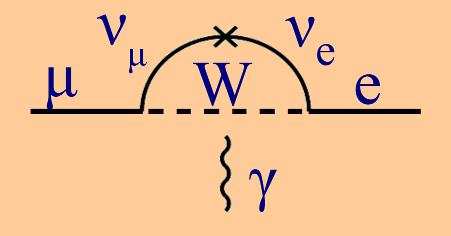
- **Neutral Current:**

  unit matrix: $\underline{1} = \sum_{\alpha=1}^{3} U^{\nu^*}_{\alpha k} U^{\nu}_{\alpha i} = \sum_{\alpha=1}^{3} W^{l^*}_{\alpha k} W^{l}_{\alpha i}$

  - unitary lepton and neutrino mixing matrices (→ **flavor conserving**)

Lepton Flavor Violation in the SM

Higher Order!



$\mu \rightarrow e\,\gamma$

Lepton Flavor Violation in the SM

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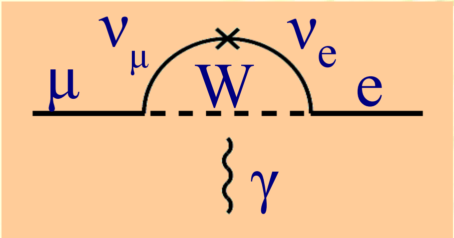

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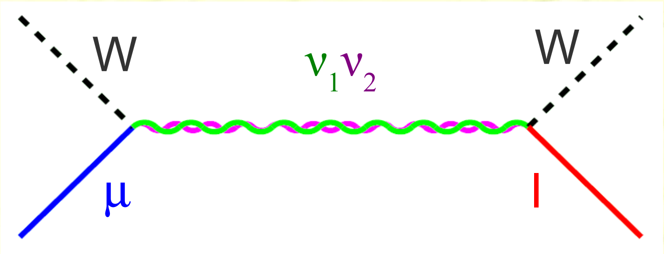

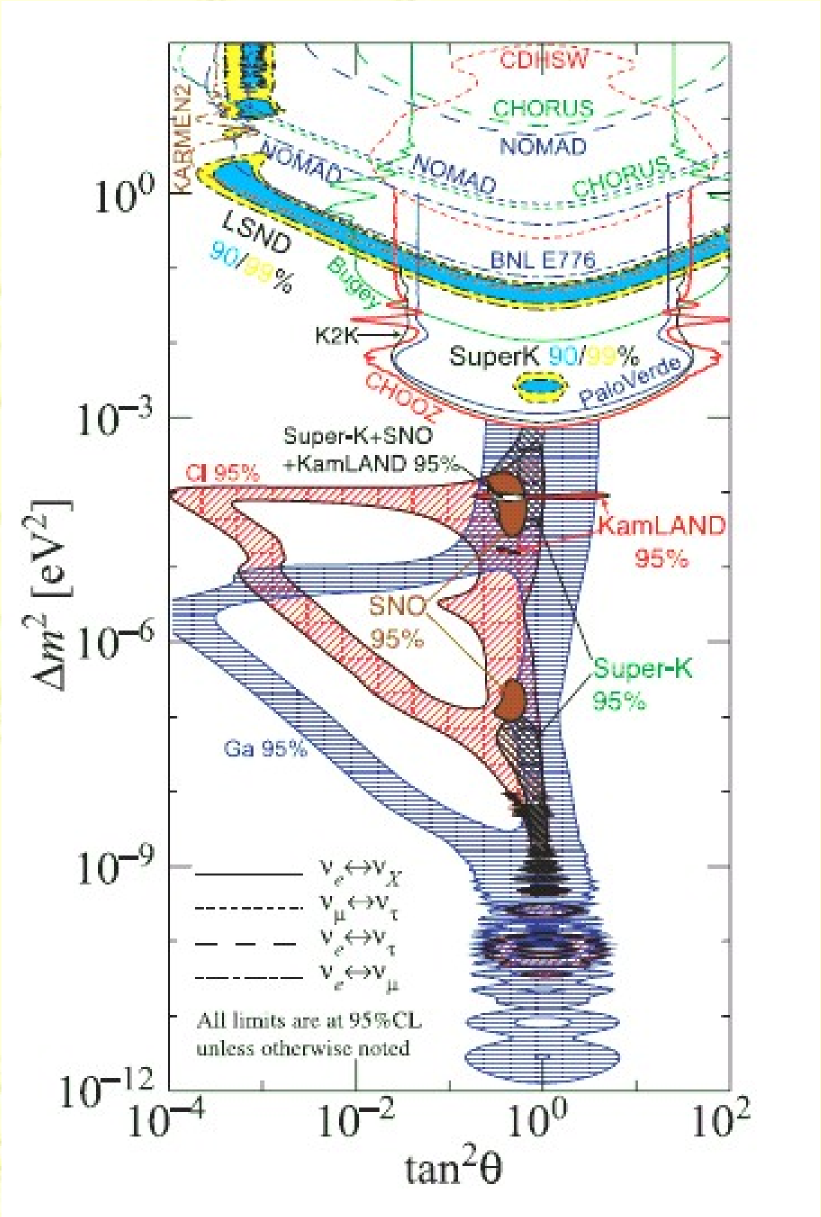

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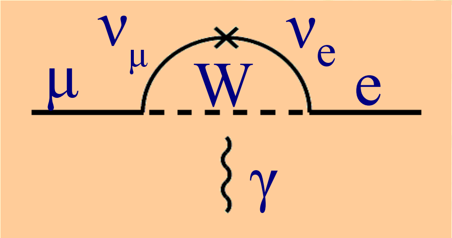

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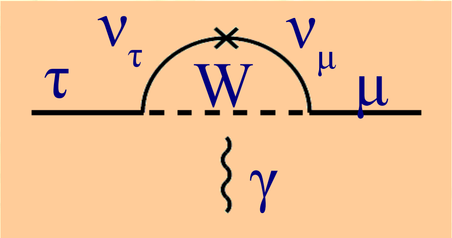
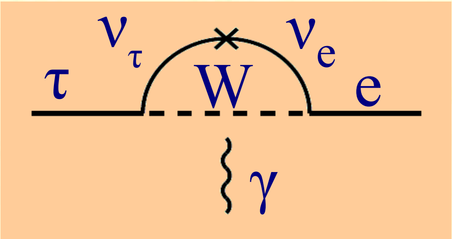


$\tau \rightarrow \mu\,\gamma$



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Lepton Flavor Violation in the SM

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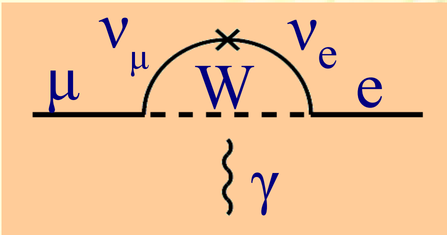

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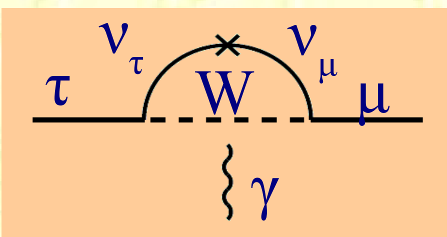

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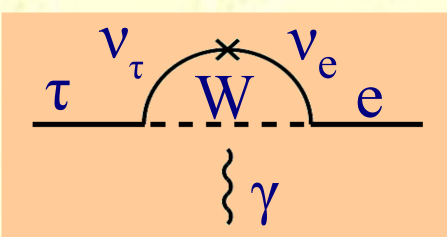

$\tau \rightarrow e\,\gamma$

<u>LFV in generated from lepton mixing:</u>

$$BR(l_j \rightarrow l_k \gamma) \propto \left| \sum_i V_{ij} V^*_{jk} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \sim \left| \frac{\Delta m^2_{\nu_{jk}}}{M^2_W} \right|^2$$

GIM – like suppression: $\sim 10^{-50}$

→ unobservable

→ high sensitivity to new physics!!!

<u>c.t. quark mixing:</u>

$$\left| \frac{\Delta m^2_{c-u}}{M^2_W} \right|^2 \sim 10^{-7}$$

→ FCNC in SM ~ 10^{-10}

Searches of Lepton$^{\pm}$ Flavor Violation

LFV

Lepton Decays:

- $\mu \rightarrow e\,\gamma$
- $\mu \rightarrow eee$
- $\tau \rightarrow e(\mu)\,\gamma$
- $\tau \rightarrow l\,l\,l$ $(l = e, \mu)$
- $\tau \rightarrow l\,h$

Meson Decays:

- Φ, K $\rightarrow$ ll'
- D, J/ψ $\rightarrow$ ll'
- B, Υ $\rightarrow$ ll'

Conversion (μ-Capture):

- $\mu\, N \rightarrow e\, N$

Collider Experiments:

- $e\,p \rightarrow \mu(\tau)\,X$ HERA
- $Z' \rightarrow l\,l'$ LHC
- $\chi^{0\,\pm} \rightarrow l\,l'\,X$

Fixed Target Experiments:

- $\mu\, N \rightarrow \tau\, N$ proposed
- $e\, N \rightarrow \mu(\tau)\, N$ proposed

Searches of Lepton$^{\pm}$ Flavor Violation

LFV

Lepton Decays:

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- $\mu \rightarrow eee$
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Fixed Target Experiments:

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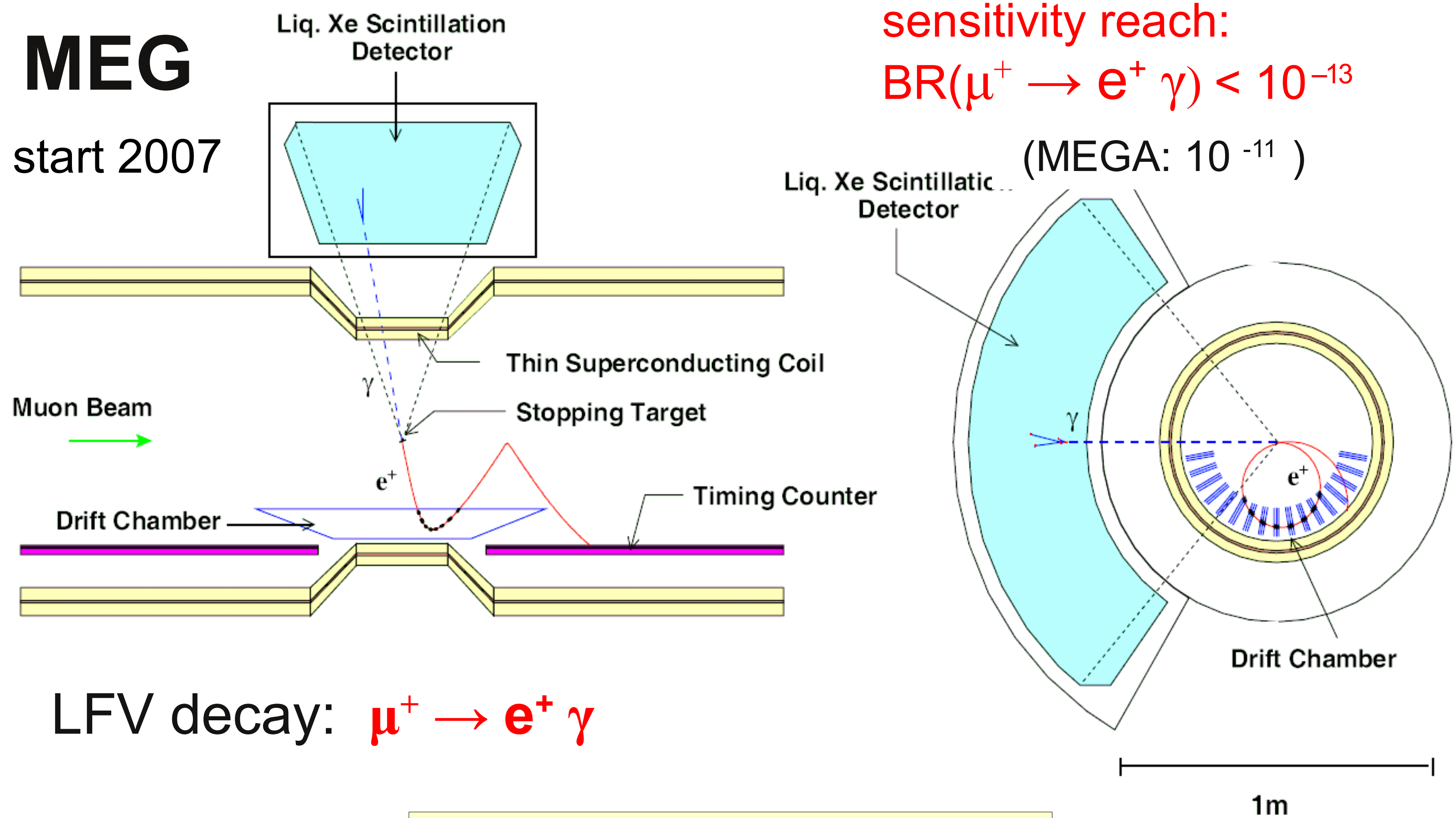
The MEG Experiment



sensitivity reach:

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

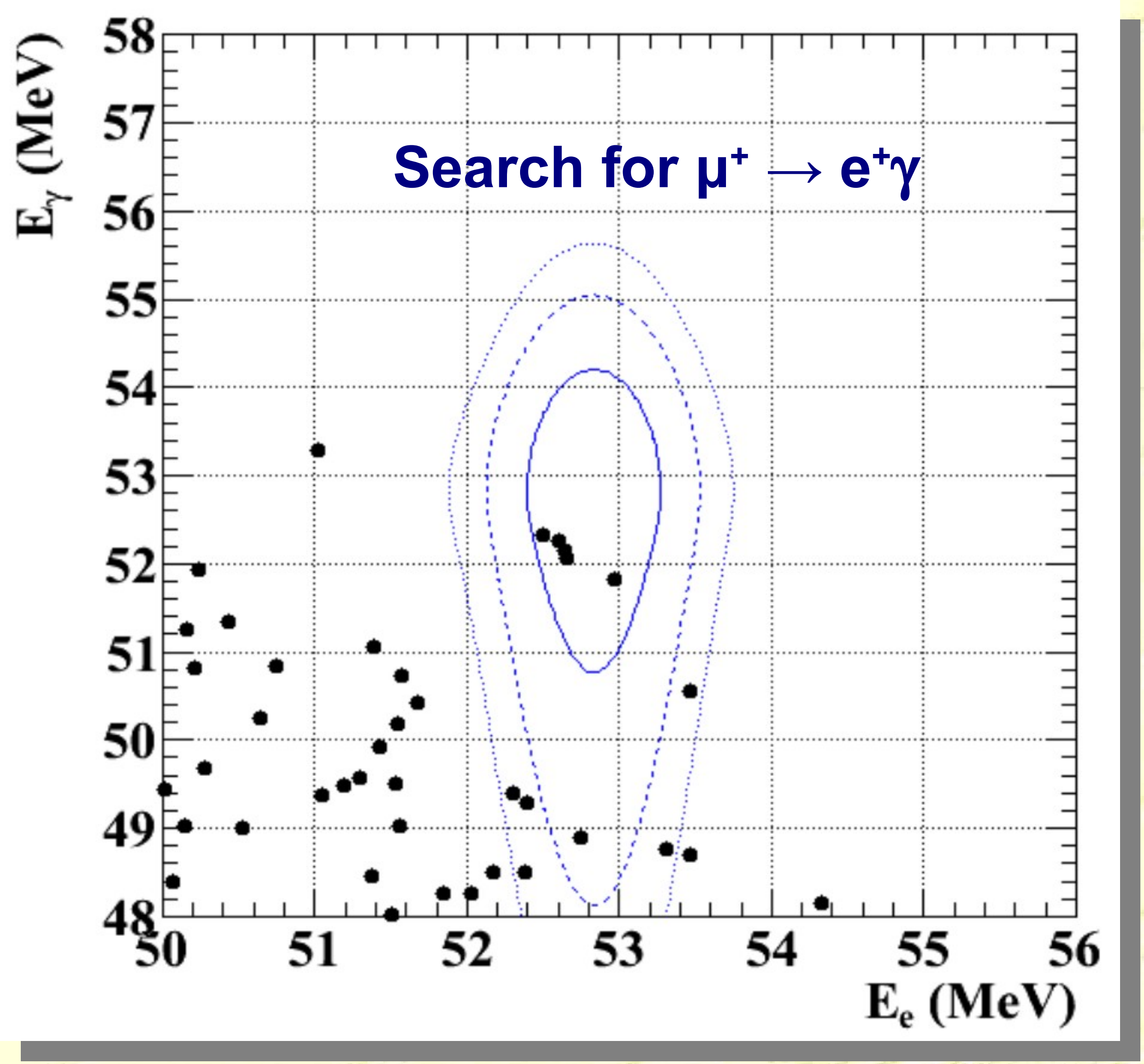
(MEGA: 10^{-11})

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

Limitation:

- accidental background
  - → better space resolution
  - → improve tracking

MEG Preliminary



MEG, ICHEP 2010

first indication of lepton flavor violation in muon decays?

Experimental LFV Results

Purely Leptonic LFV:

- **Br($\mu \to e\gamma$) < 10^{-11} [MEGA]**
  → 10^{-13} MEG
- Br($\tau \to \mu(e)\gamma$) < ~$4 \cdot 10^{-8}$ (B-factories)
- **Br($\mu \to eee$) < 10^{-12} [SINDRUM]**
  → 10^{-16} this talk
- Br($Z \to e\mu$) < 10^{-6} [LEP]

Semihadronic LFV:

- Br($K \to \pi\mu e$) < ≈ 10^{-11}
- **Br(μ_{capt} $N \to eN$) < ~ 10^{-12} [SINDRUM2]**
  → 10^{-17} Mu2e, Prism
- $\mu N \to eN'$ or $eN \to \mu(\tau)N'$ (DIS HERA):

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Experimental LFV Results

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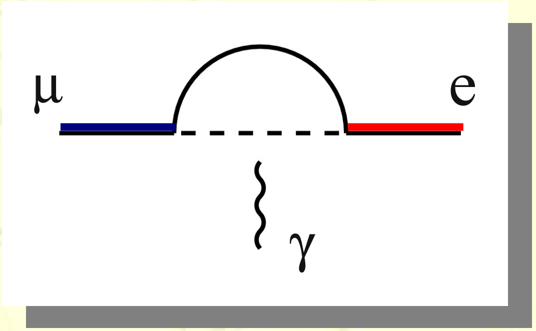

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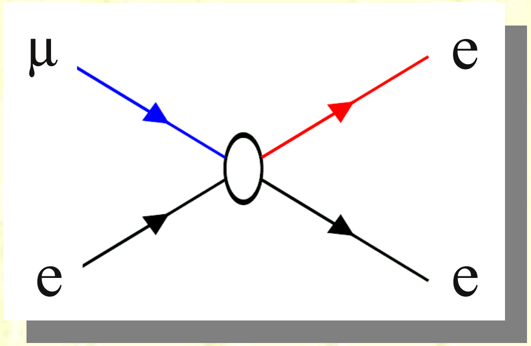

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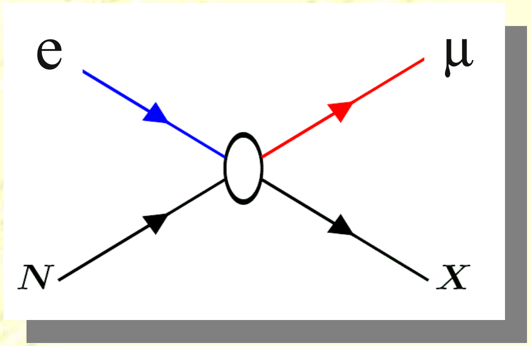
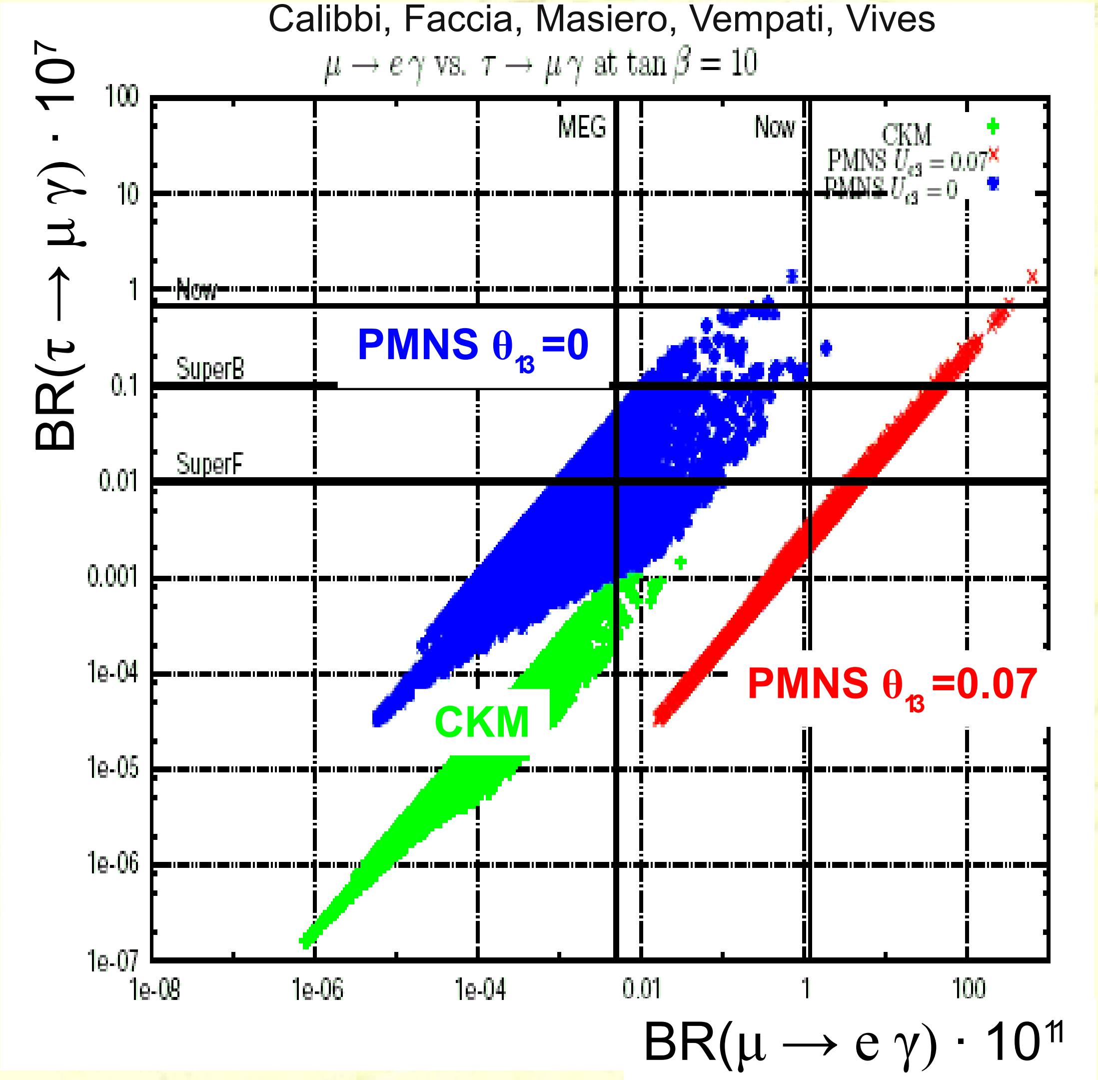


LFV in SUSY SO(10) GUT



points = SUSY LHC parameters

Yukawa coulings to neutrinos

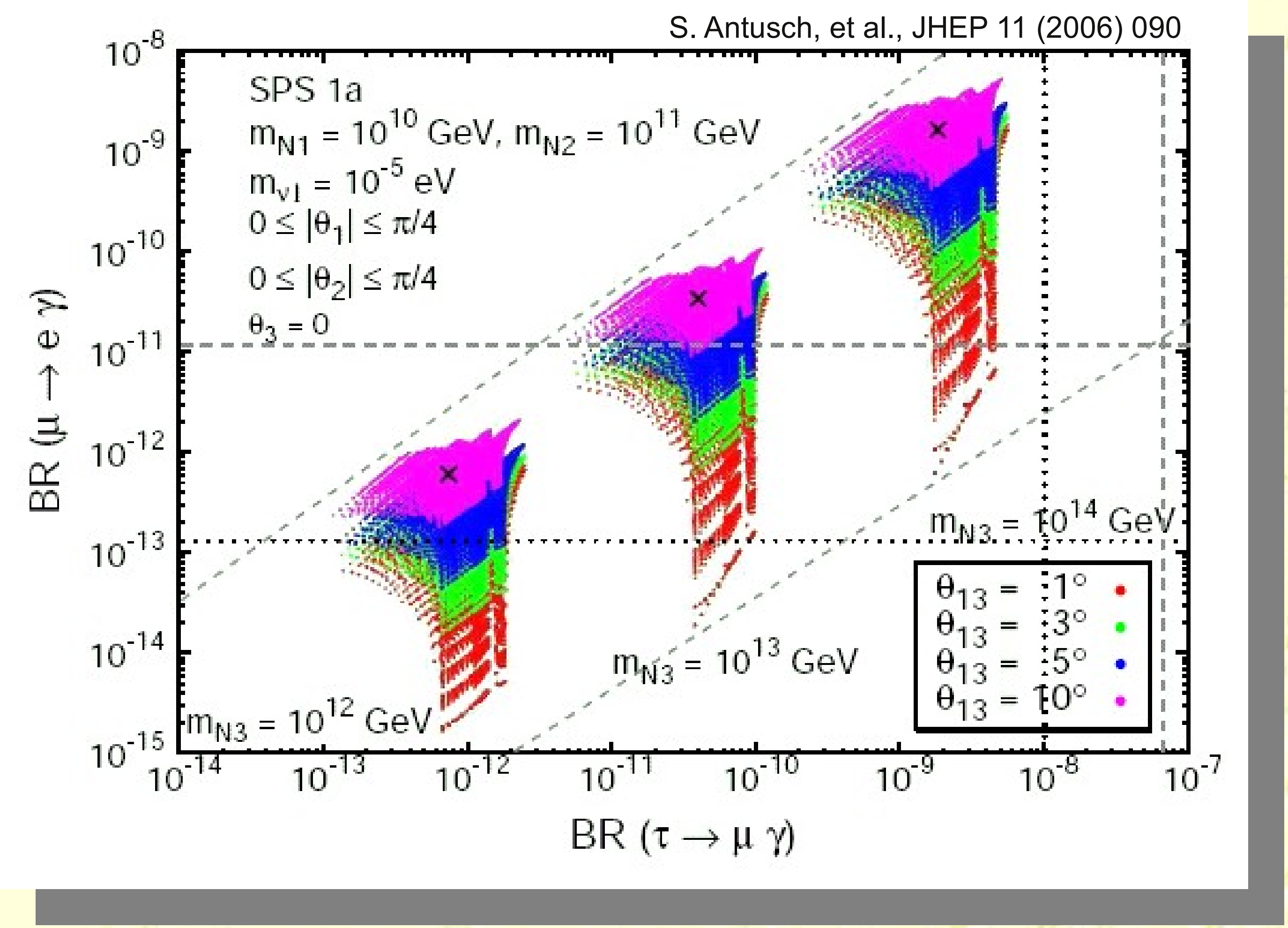
$h_\nu = h_u$ (CKM-case)

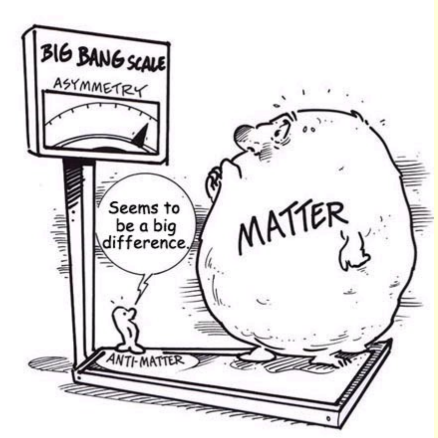
$h_\nu = U_{PMNS} h_u^{diag}$ (PMNS-case)

- quasi model-dependent preditions: (G. Isidori et al.)
  - CKM: BR(τ→ μ γ) : BR(τ→ e γ) : BR(μ→ e γ) : ~ 10^4 : 500 : 1
  - PMNS: BR(τ→ μ γ) : BR(τ→ e γ) : BR(μ→ e γ) : ~ 500-10 : 1 : 1

cMSSM Seesaw with Leptogenesis

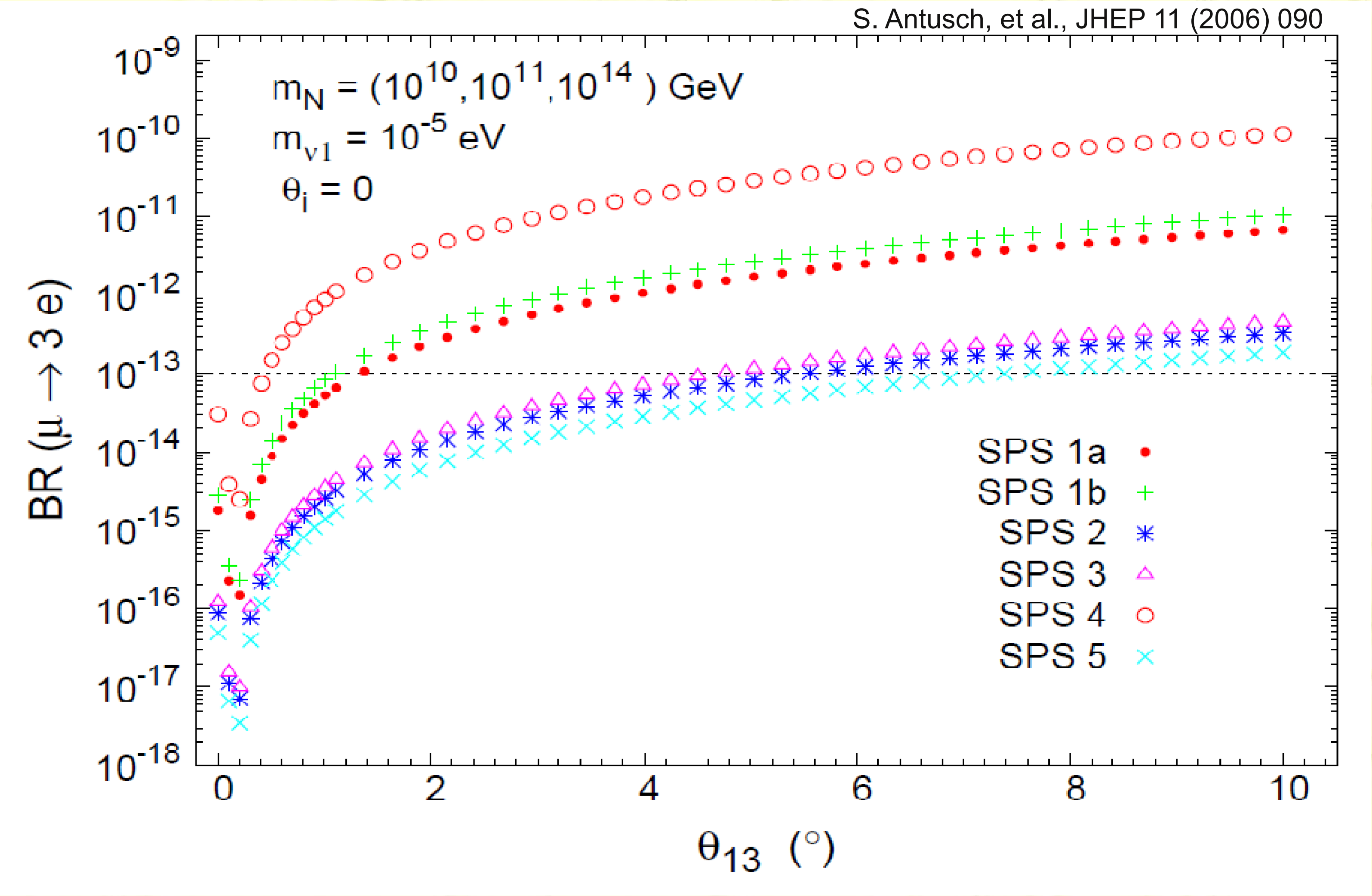
- SUSY SPS 1a
- require successfull BAU (baryon asymmetry in universe)





→ sensitivity to heavy Majorana Neutrino Masses

cMSSM Seesaw with Leptogenesis



$\sin^2 \Theta_{13} < 0.057$ (PDG)

Motivation to Search for $\mu^+ \rightarrow e^+e^+e^-$

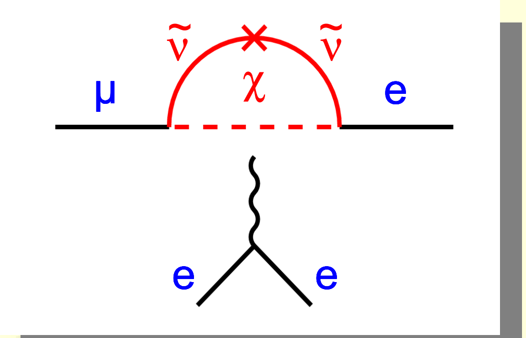
Effective Model for $\mu^+ \to e^+e^+e^-$

Effective charged LFV Lagrangian (Y. Kuno and Y Okada):

Tensor terms (dipole)

$$L_{\mu\to eee} = \frac{4G_F}{2}\left[m_\mu A_R \overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu} + m_\mu A_L \overline{\mu_L}\sigma^{\mu\nu}e_R F_{\mu\nu}\right.$$

dipole coupling



e.g. Supersymmetry

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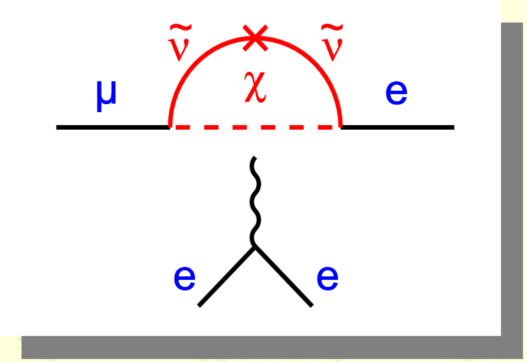
e.g. Supersymmetry

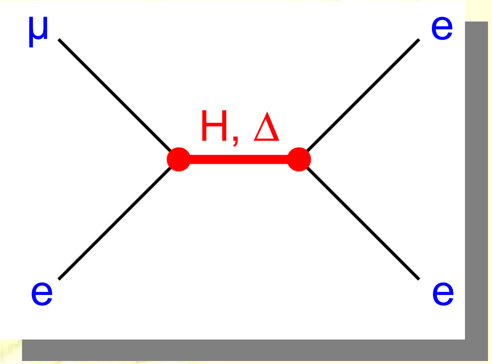
dipole coupling



Four-fermion terms

$$+ g_1 (\overline{\mu_R}e_L)(\overline{e_R}e_L) + g_2 (\overline{\mu_L}e_R)(\overline{e_L}e_R) \quad \text{(scalar)}$$
$$+ g_3 (\overline{\mu_R}\gamma e_R)(\overline{e_R}\gamma_\mu e_R) + g_4 (\overline{\mu_L}\gamma e_L)(\overline{e_L}\gamma_\mu e_L) \quad \text{(vector)}$$
$$\left. + g_5 (\overline{\mu_R}\gamma e_R)(\overline{e_L}\gamma_\mu e_L) + g_6 (\overline{\mu_L}\gamma e_L)(\overline{e_R}\gamma_\mu e_R) + H.c.\right]$$

tree diagram

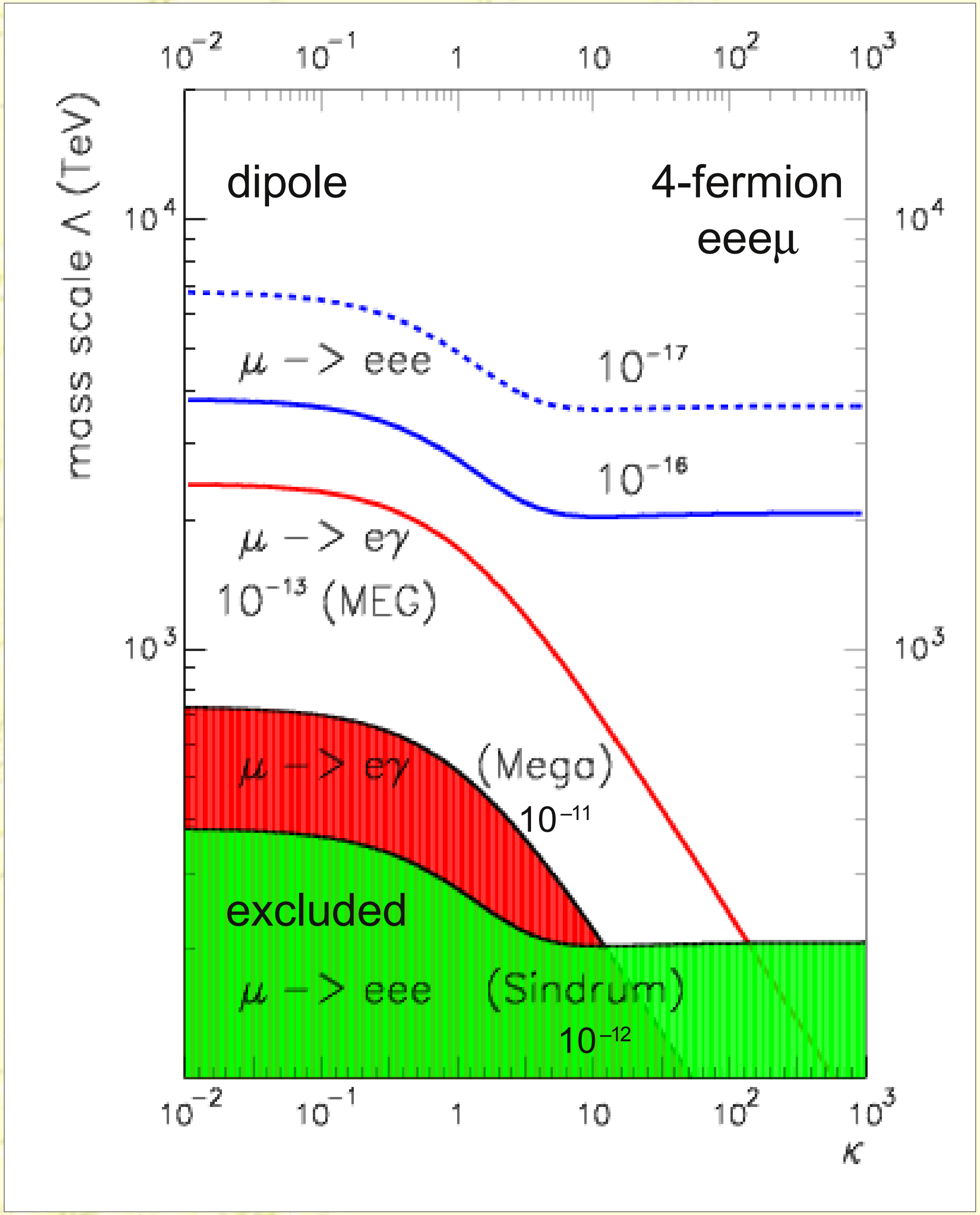


e.g. Higgs, Z', Doubly Charged Higgs

Testing new Mass Scales

Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\nu^{e\mu} J^{\nu, ee}$$



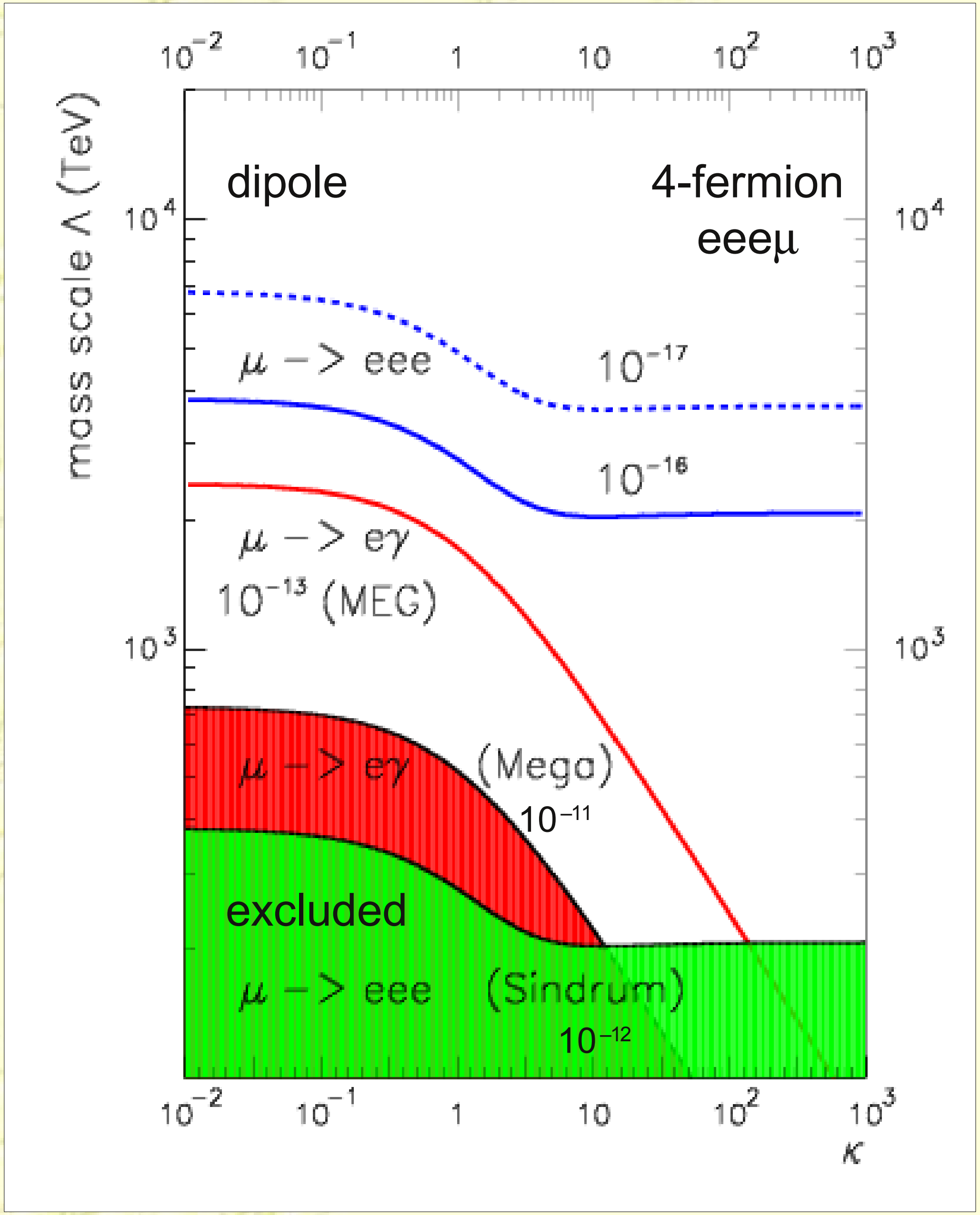
"André de Gouvêa"
plot for μeee

Testing new Mass Scales

Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2(1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2(1+\kappa)} J_\nu^{e\mu} J^{\nu,ee}$$

- **Almost factor 2 higher mass reach beyond MEG for LFV dipole couplings ($\Lambda = 4 \cdot 10^3$ TeV)**



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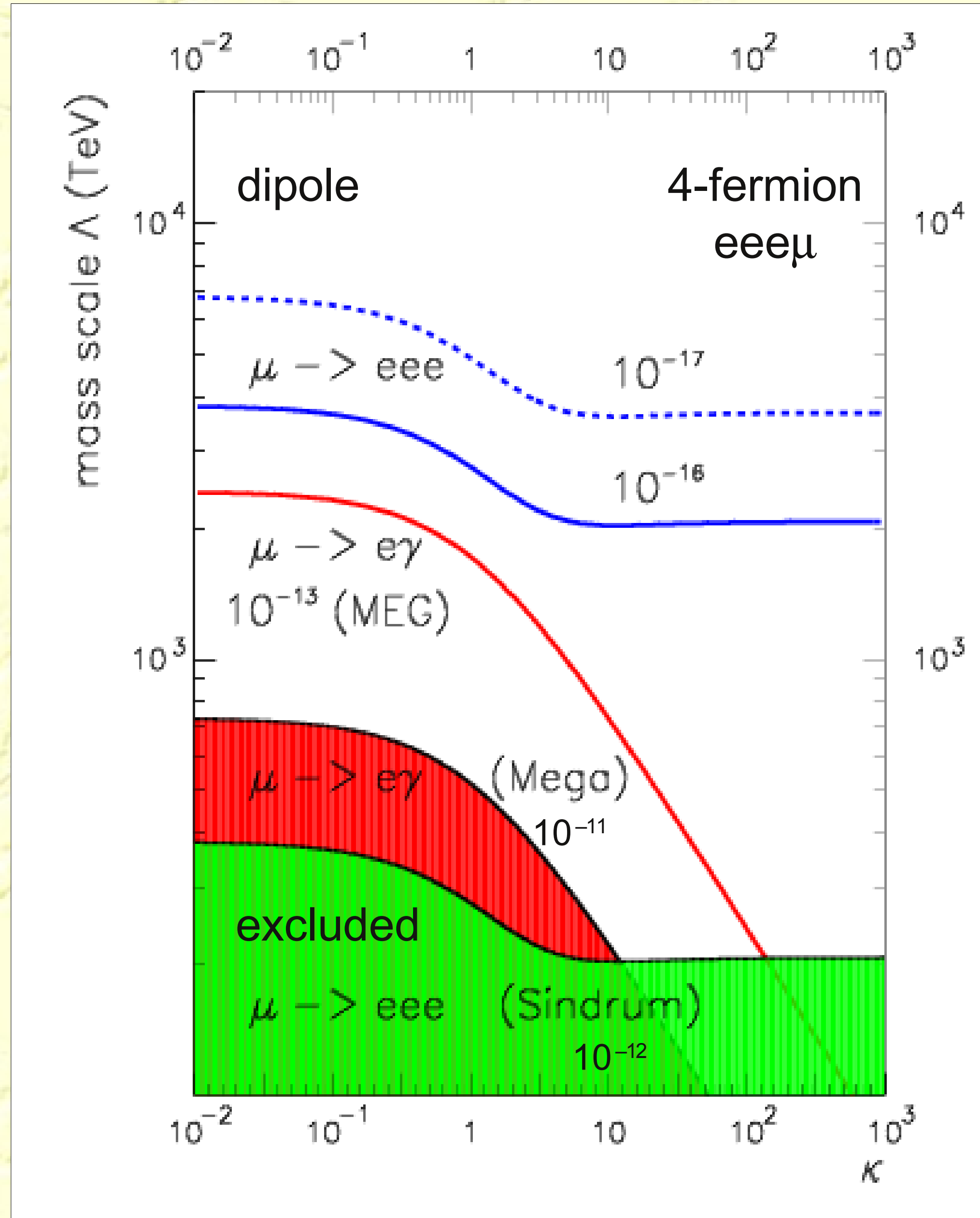
Testing new Mass Scales

Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\nu^{e\mu} J^{\nu,ee}$$

- **Almost factor 2 higher mass reach beyond MEG for LFV dipole couplings ($\Lambda = 4 \cdot 10^3$ TeV)**

- **x 10 mass reach beyond SINDRUM for LFV four-fermion couplings ($\Lambda = 2 \cdot 10^3$ TeV)**



"André de Gouvêa" plot for μeee

Predictions: $\mu \to eee$ versus $\mu \to e\gamma$

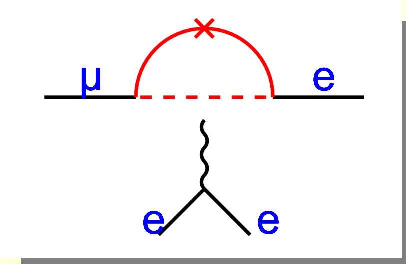
- In case of dominating LFV dipole couplings $\kappa = 0$ ($A_{L,R} >> g_i$)

$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} \approx 0.006$$

$B(\mu \to eee) = 10^{-15}$ corresponds to $B(\mu \to e\gamma) = \sim 10^{-13}$

$B(\mu \to eee) = 10^{-16}$ corresponds to $B(\mu \to e\gamma) = \sim 10^{-14}$

dipole coupling



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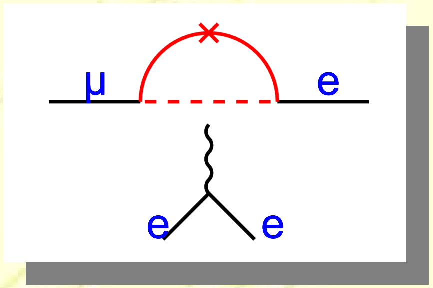
$B(\mu\to eee)=10^{-16}$ corresponds to $B(\mu\to e\gamma)=\sim10^{-14}$

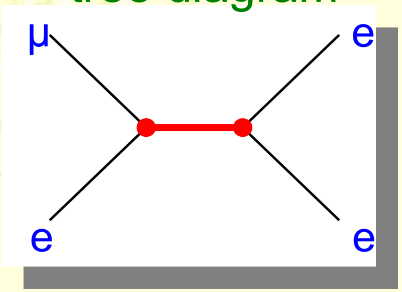
- **Specific Models**

Predictions	B(μ → eee) / B(μ → eγ)	B(μ → eee)
mSUGRA + seesaw	**$\sim10^{-2}$**	**$<10^{-13}$**
SUSY + SO(10)	**$\sim10^{-2}$**	**$< 10^{-13}$**
SUSY + Higgs	**$\sim10^{-2}$**	**$< 10^{-13}$**
Z', Kaluzza Klein	**>1**	
Little Higgs	**0.1 - 1**	**$< 10^{-13}$**
Higgs Triplet	**10^{-3} - 10^{+3}**	**$< 10^{-12}$**

dipole coupling



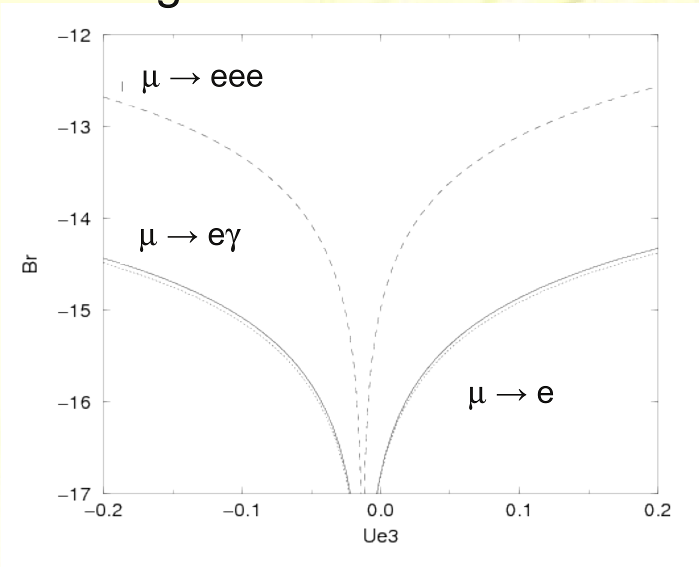
tree diagram



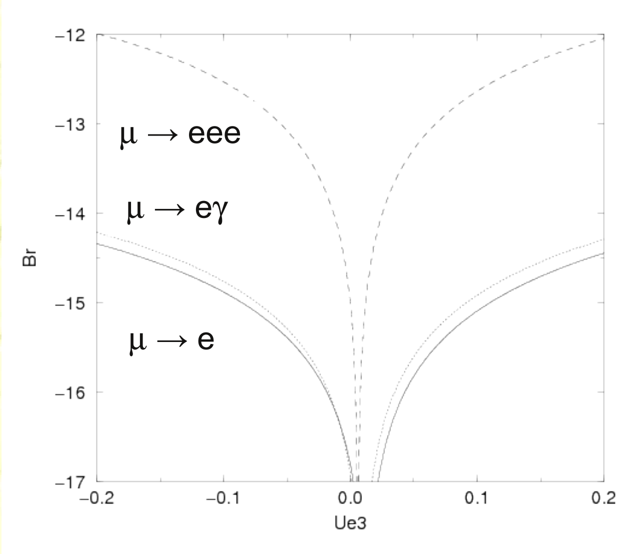
Higgs Triplet Models

M. Kakizaki et al., Phys. Lett. B 566 (2003) 210

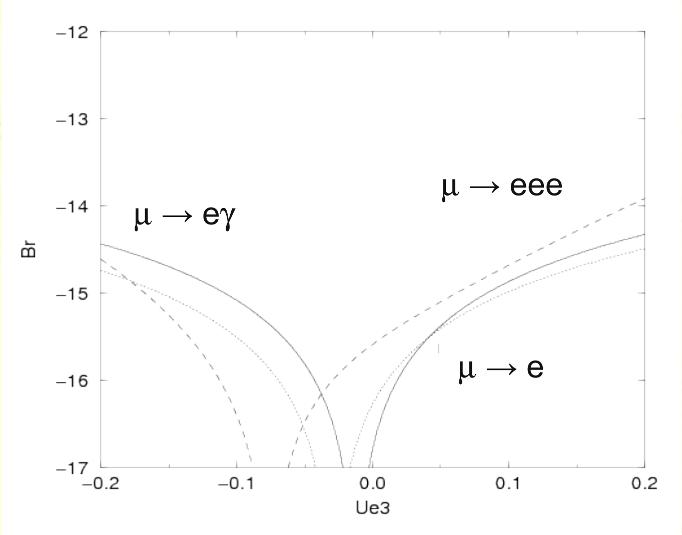
degenerate case

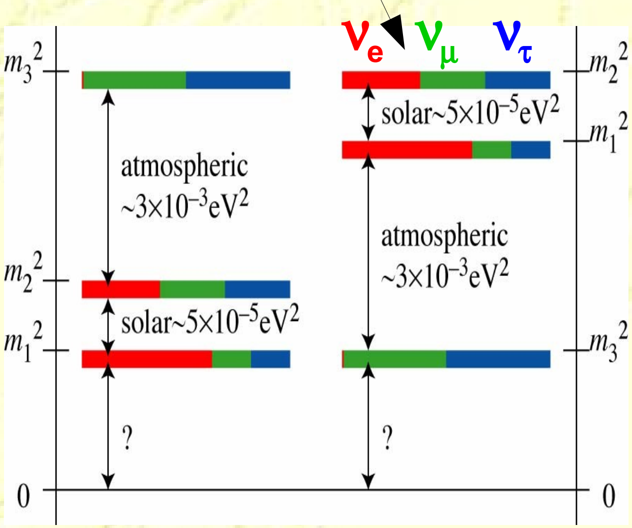


inverted case



hierarchical case





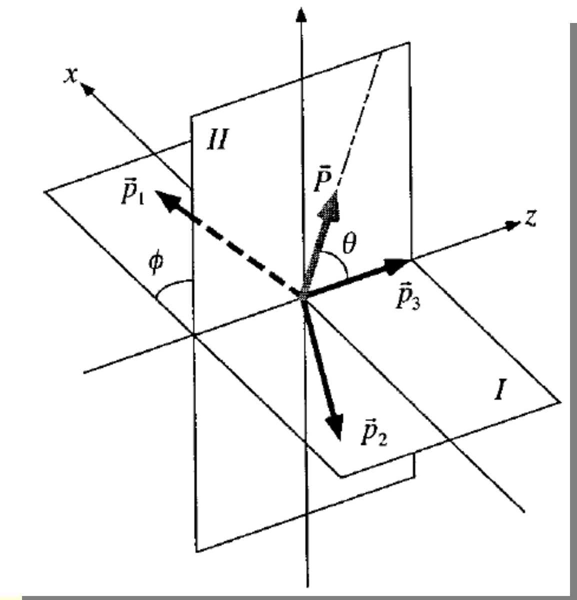
CP Violation in μ→eee

- Measurement of CP violation requires interference of diagrams
- 3-body decay kinematics allows for study of discrete symmetries!

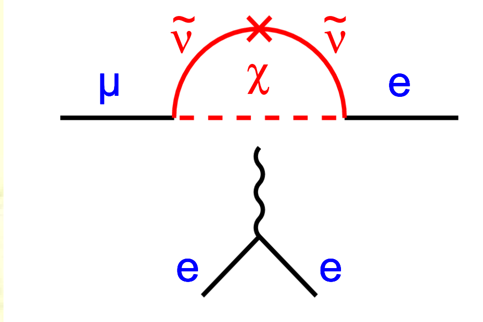
Okada et al. PRD 61, 094001 (2000)

$$\frac{dB}{dx_1 dx_2 d\cos\theta d\varphi} = \frac{3}{2\pi}[C_1\alpha_1(x_1,x_2)(1+P\cos\theta)+C_2\alpha_1(x_1,x_2)(1-P\cos\theta)$$
$$+C_3\{\alpha_2(x_1,x_2)+P\beta_1(x_1,x_2)\cos\theta+P\gamma_1(x_1,x_2)\sin\theta\cos\varphi\}$$
$$+C_4\{\alpha_2(x_1,x_2)-P\beta_1(x_1,x_2)\cos\theta-P\gamma_1(x_1,x_2)\sin\theta\cos\varphi\}$$
$$+C_5\{\alpha_3(x_1,x_2)+P\beta_2(x_1,x_2)\cos\theta+P\gamma_2(x_1,x_2)\sin\theta\cos\varphi\}$$
$$+C_6\{\alpha_3(x_1,x_2)-P\beta_2(x_1,x_2)\cos\theta-P\gamma_2(x_1,x_2)\sin\theta\cos\varphi\}$$
$$+C_7\{\alpha_4(x_1,x_2)(1-P\cos\theta)+P\gamma_3(x_1,x_2)\sin\theta\cos\varphi\}$$
$$+C_8\{\alpha_4(x_1,x_2)(1+P\cos\theta)-P\gamma_3(x_1,x_2)\sin\theta\cos\varphi\}$$
$$+C_9\{\alpha_5(x_1,x_2)(1+P\cos\theta)-P\gamma_4(x_1,x_2)\sin\theta\cos\varphi\}$$
$$+C_{10}\{\alpha_5(x_1,x_2)(1-P\cos\theta)+P\gamma_4(x_1,x_2)\sin\theta\cos\varphi\}$$
$$+C_{11}P\gamma_3(x_1,x_2)\sin\theta\sin\varphi-C_{12}P\gamma_4(x_1,x_2)\sin\theta\sin\varphi],$$

T-odd



dipole coupling



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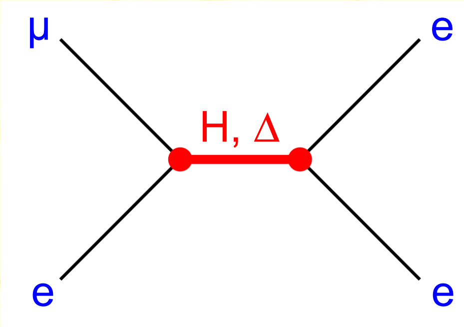

(can also distinguish e.g. SU(5) from SO(10) models)

Motivation for $\mu^+ \rightarrow e^+e^+e^-$ Search I

- **New Particles at the "Terascale" naturally induce LFV**

$$\left| \frac{\Delta_M^{\ 2}}{M^2} \right|^2$$

- **Search $\mu^+ \rightarrow e^+e^+e^-$ is complementary to other LFV searches**

Motivation for $\mu^+ \rightarrow e^+e^+e^-$ Search II

- Advances in detector technologies allow for
  high rate / high precision experiments at low energies

- Plans to improve PSI beamlines and targets: > 10^9 muon stops/s
  - would allow to test muon decay branching ratios at 10^{-16}
  - current exp. limit $B(\mu^+ \rightarrow e^+e^+e^-)=10^{-12}$ (Bellgard 1988)

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- **A search for $B(\mu^+ \rightarrow e^+e^+e^-) > 10^{-16}$ has a large potential to find LFV signal or to set very stringent bounds on new physics**

Backgrounds
and
Previous Experiments

Backgrounds for $\mu^+ \rightarrow e^+e^+e^-$

- **Combinatorial Background (Pile up):**
  - Two muon decays 2 x $(\mu^+ \rightarrow e^+ \nu\nu)$ and one fake e^- (wrong charge: reconstrution, Bhabha, back-curling $e^+ \rightarrow e^-$)
  - Radiative decay with internal conversion $\mu \rightarrow (e^+)\, e^+e^- \nu\nu$ and muon decay $\mu^+ \rightarrow e^+\nu\nu$
  - **Combinatorial BG can be largely reduced by imposing**
    - timing vetos
    - kinematic constraints
    - vertex requirements

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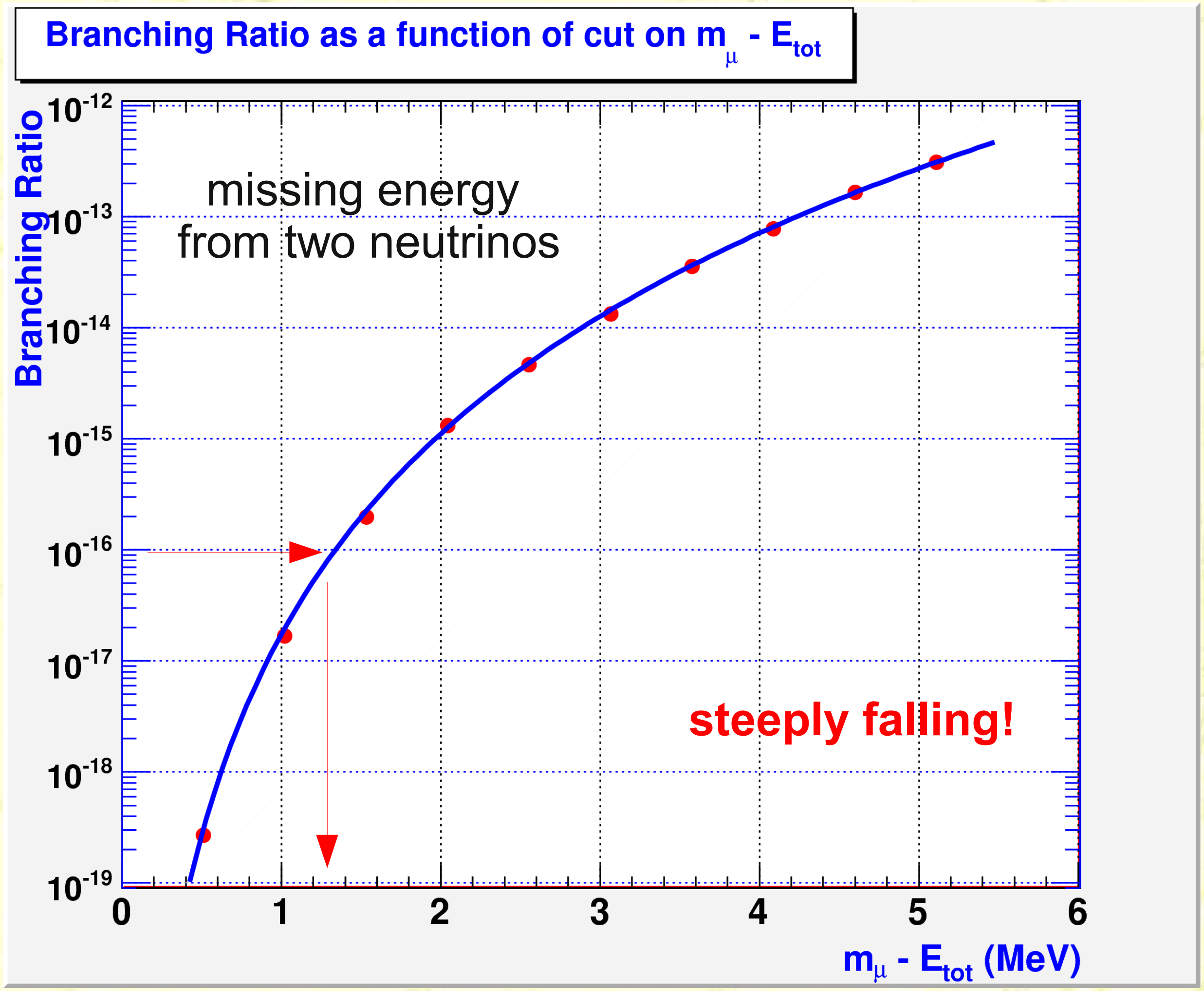
    - timing vetos
    - kinematic constraints
    - vertex requirements
- **Radiative decay with internal conversion $\mu^+ \rightarrow e^+e^+e^- \nu\nu$**

  irreducible background BR($\mu^+ \rightarrow e^+e^+e^- \nu\nu$) = $3.4 \cdot 10^{-5}$

Background from $\mu^+ \rightarrow e^+e^+e^- \nu\nu$



R.M.Djilkibaev and R.V.Konoplich PRD79 (2009)

Good energy (momentum) resolution $E_{tot} = \Sigma |E_i| \sim \Sigma |p_i|$ essential !!!

Comparison: μ-Decay Experiments

- **Sindrum 1988:**

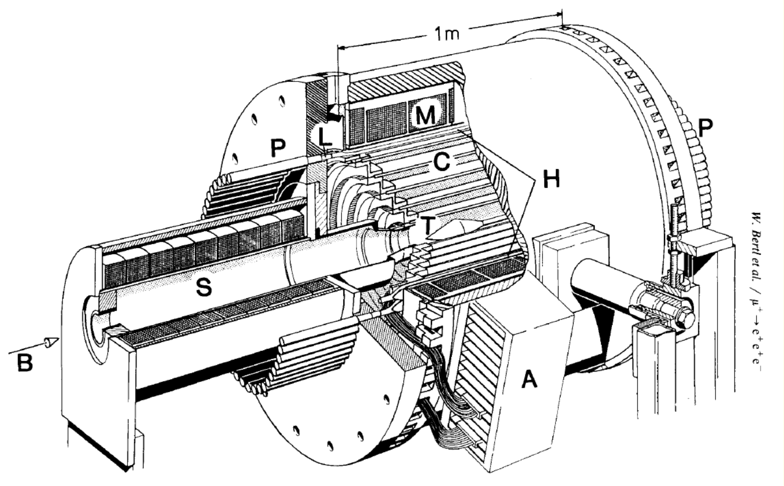
  σ_p/p (50 MeV/c) = 5.1%

  σ_p/p (20 MeV/c) = 3.6%

  σ_θ (20 MeV/c) = 28 mrad

  VTX: σ_d= ~ 1mm

  X0(MWPC) = 0.08% - 0.17% per layer



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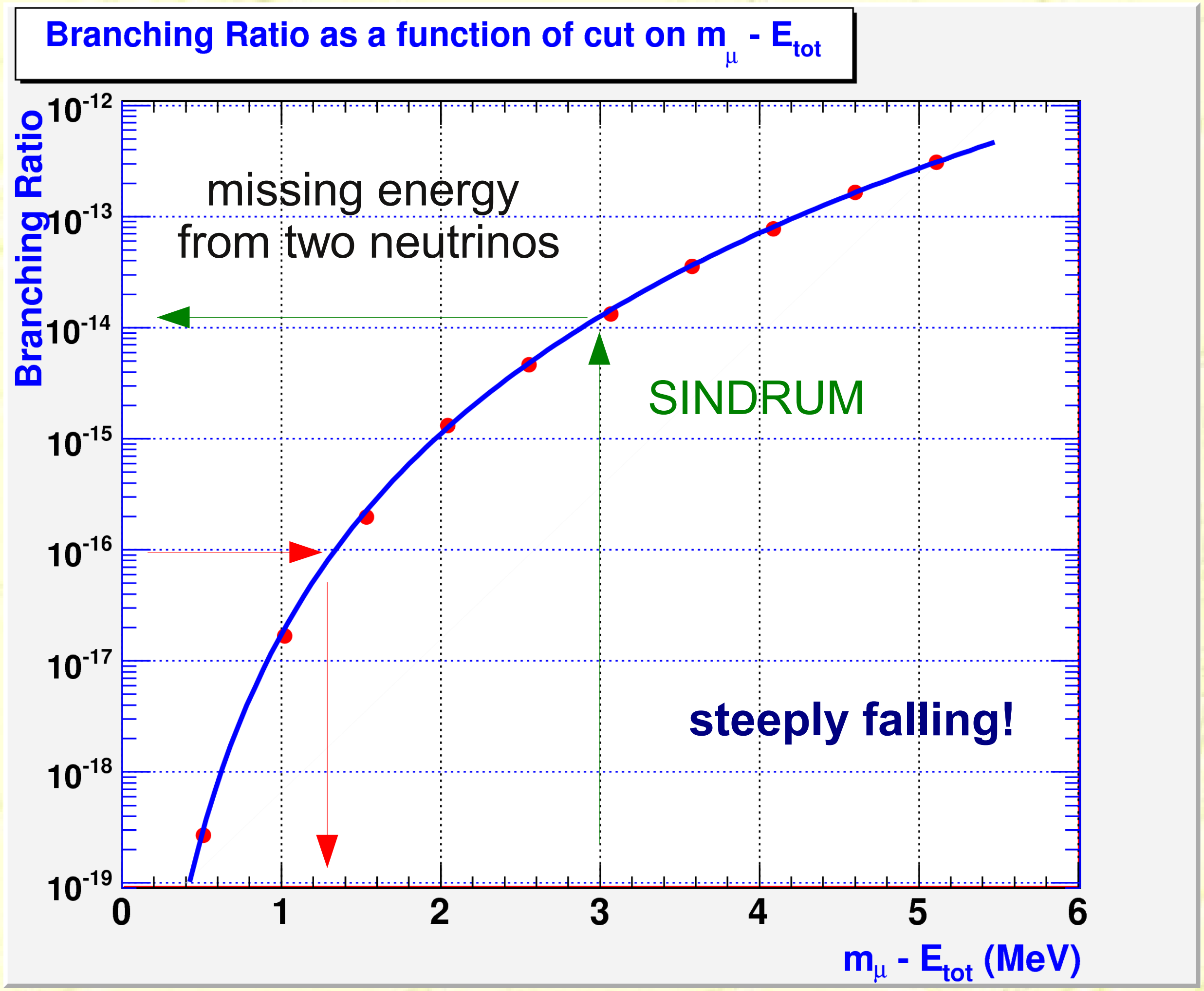

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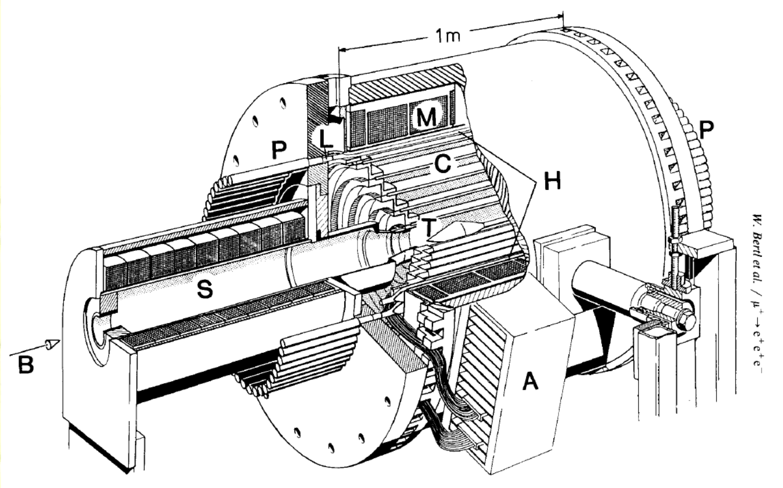


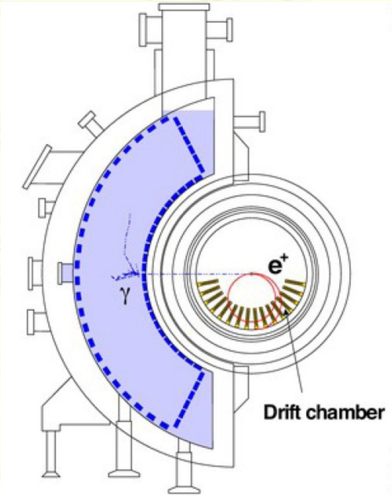
- **MEG 2010 (preliminary):**

  σ_p/p (53 MeV/c) = 0.7 %

  σ_θ (53 MeV/c) = 8 mrad

  σ_ϕ (53 MeV/c) = 8 mrad

  VTX: σ_R=1.4 mm, σ_Z=2.5 mm



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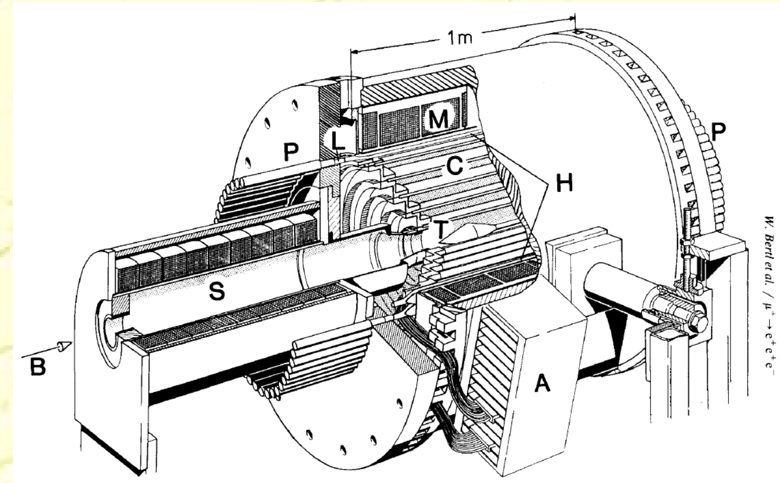

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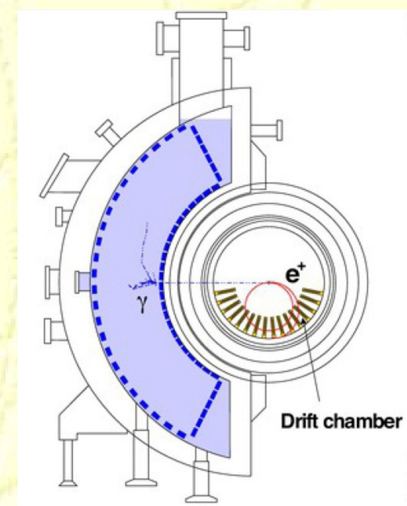


➜ **Aim for similar or better angular and momentum resolutions, high rates and better vertex resolution ~ 150 μm (combinatorial BG)**

Detector Concept and Design

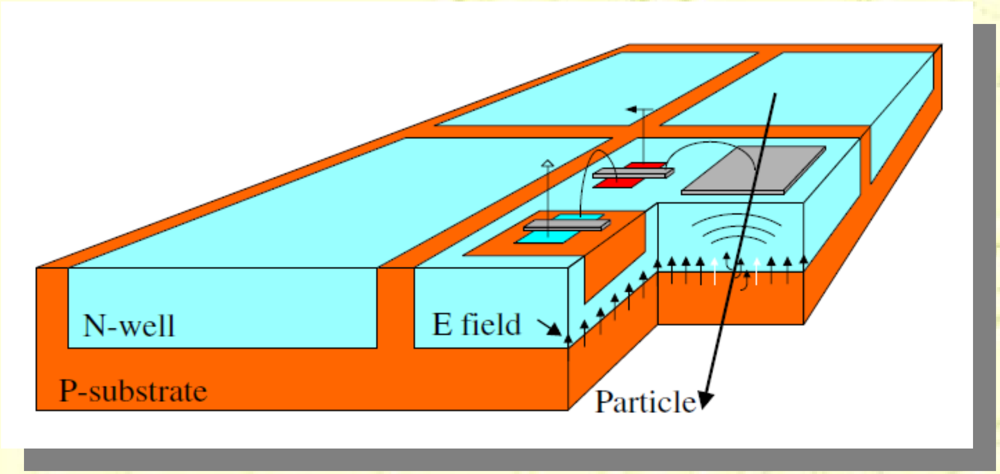
Requirements for $\mu^+ \rightarrow e^+e^+e^-$

- Aim for $B(\mu^+ \rightarrow e^+e^+e^-) = 10^{-16}$
  - need 10^9 stopped muons per second
  - high rate of electrons in detector!
- Tracking
  - gas detector disfavored → silicon detector
  - fast readout
- Momentum resolution
  - high precision detector → pixel sensor
  - low multiple scattering → thin sensors

Silicon Detectors Technologies

Technologies	Thickness	Speed	Readout
ATLAS pixel	260 μm	25 ns	extra RO chip
DEPFET	50 μm	slow (frames)	extra RO chip
MAPS	50 μm	slow (diffusion)	fully integrated
HV-MAPS	>30 μm	O(100ns)	fully integrated

High Voltage Monolithic CMOS Pixel



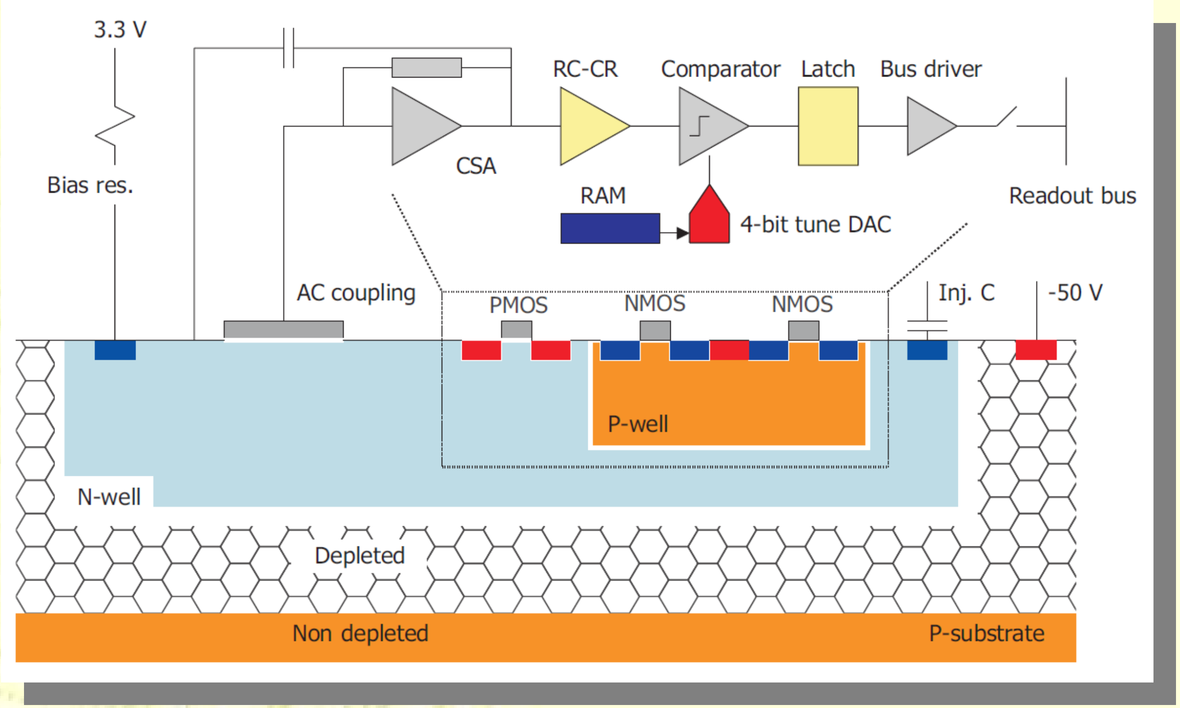
transistor logic embedded in N-well
("smart diode array")

New Technology!

I.Peric, P. Fischer et al., NIM A 582 (2007) 876 (ZITI Mannheim, Uni Heidelberg)

Sensors tested successfully :

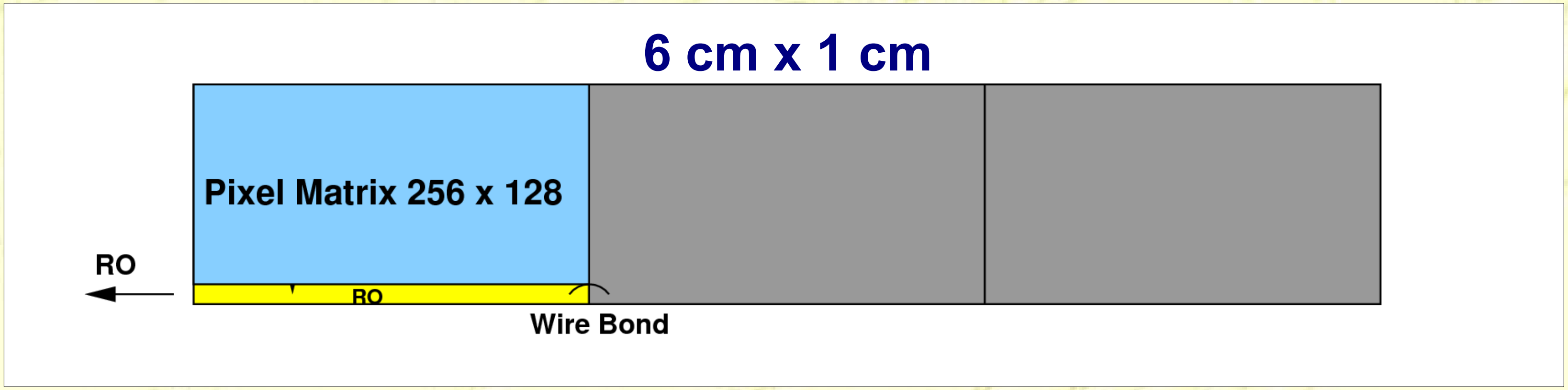
- radiation tolerant
- low noise: S/N>40
- tune DAC and zero suppression



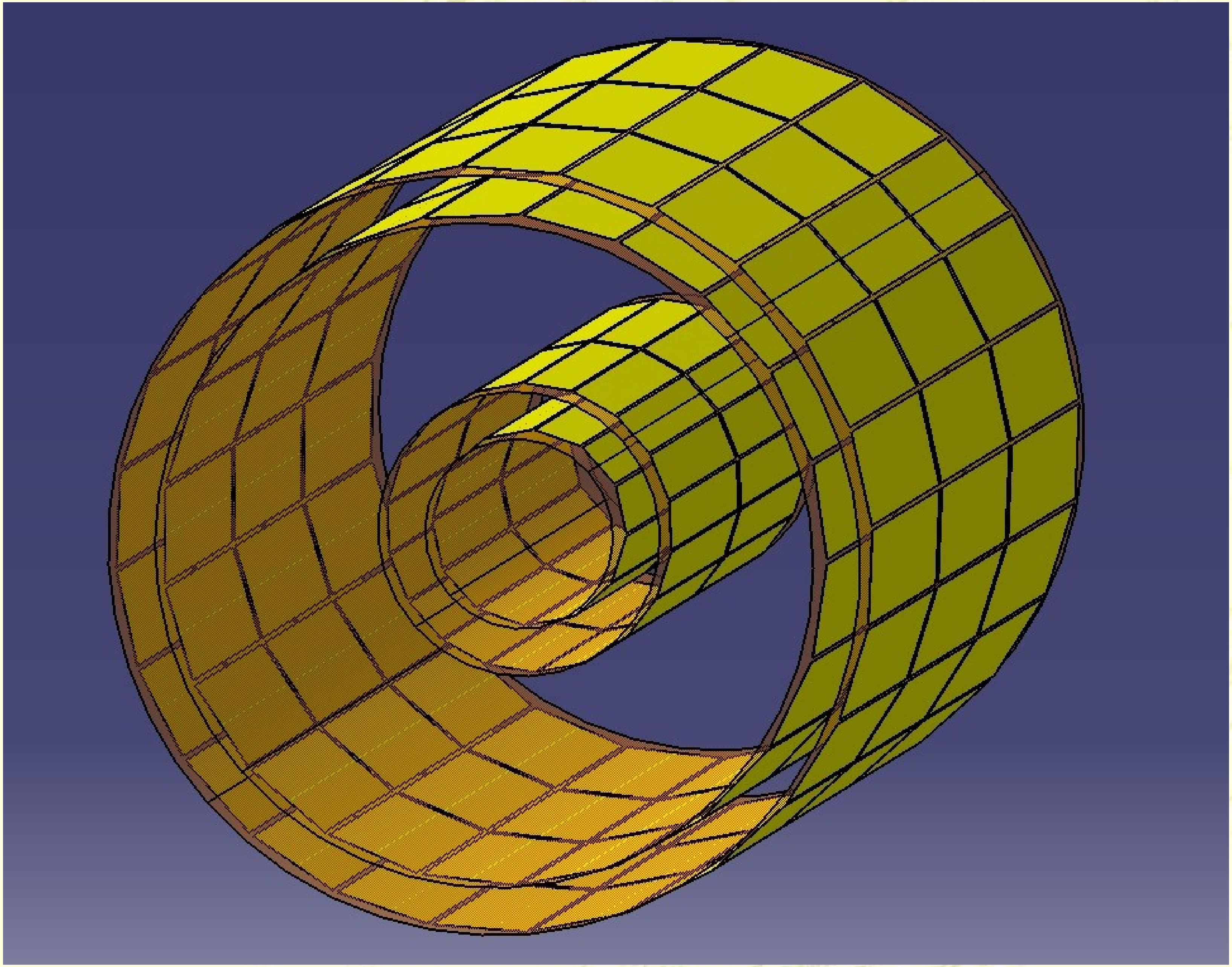
HV MAPS Sensor

- **Preliminary Sensor Specifications**
  - **Module Size 1 cm x 6 cm inner and 2 cm x 6 cm outer layer**
  - **Pixel Size 80 µm x 80 µm**
  - **98k (196k) pixels 128 (256) x 768**
  - **resolution 1 bit per pixel**
  - **power 150 mW/cm^2**
  - **zero suppression**
  - **data output 800 Mbit/s**
  - **time stamps every 100ns (10 MHz clock → power)**

first submission of test structures Feb. 2011
(AMS HV 0.18 micron)

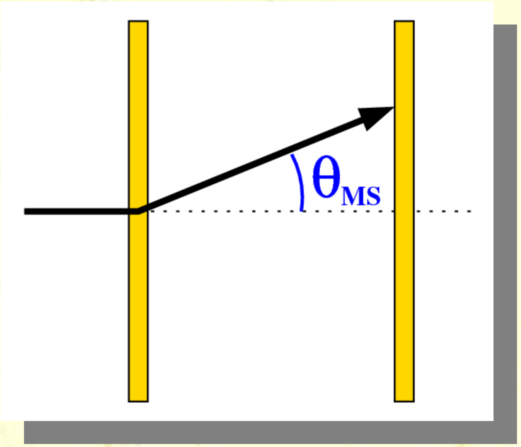


Possible Tracker Layout



30-50 μm Silicon
on
25 μm Kapton

Multiple Scattering in Silicon



Momentum range p = 15-53 MeV

- multiple scattering!

Example: p = 53 MeV/c

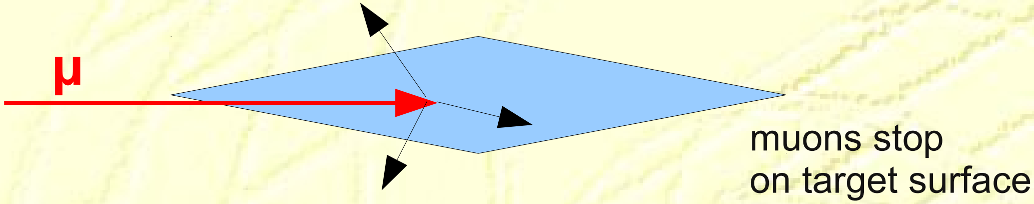
- **MEG: σ_θ^{MS} = 8 mrad**
  - multiple scatt. per layer X/X_0=0.1% → corresponds to 90 µm Silicon
- **µ → eee: σ_θ^{MS} = 5 mrad**
  - multiple scatt. per layer X/X_0=0.044% → corresponds to 40 µm Silicon

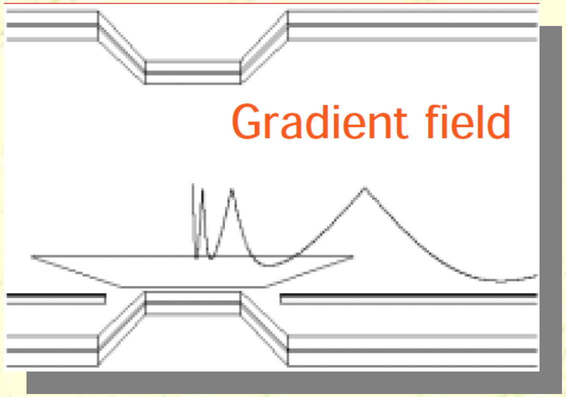
Pixel sensors can be thinned down to 30-50 µm

(examples CMOS MAPS, DEPFET 50 µm)

"Novel" Experimental Concept

- **Strong Magnet (e.g. Cobra from MEG)**
- **Hollow Double Cone Target (Sindrum)**





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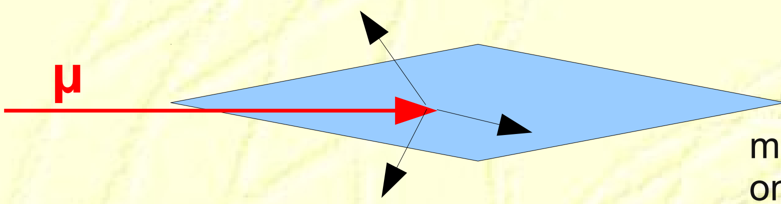
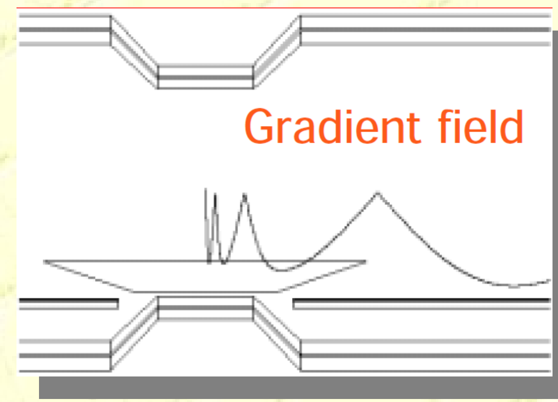
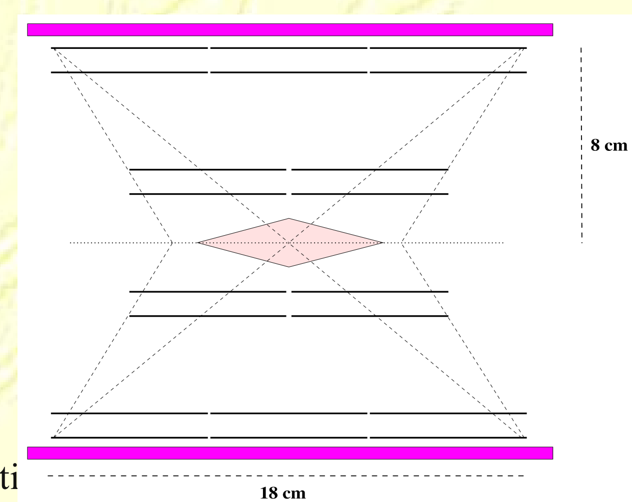




- **Silicon pixel detector for tracking**
  - high resolution
  - precise hit position 80 μm x 80 μm (c.t. multiple scattering σ_{MS} ~ 150 μm)



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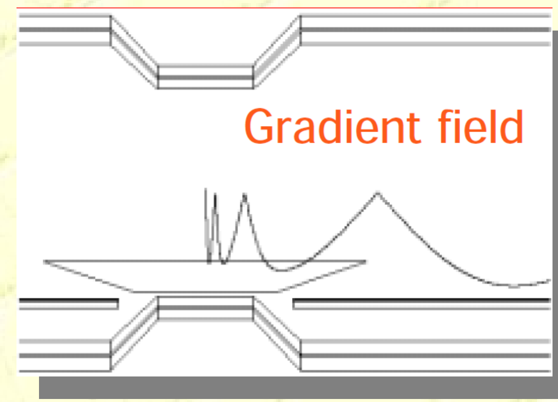

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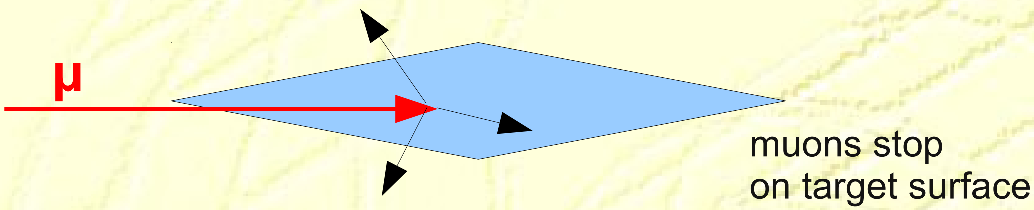
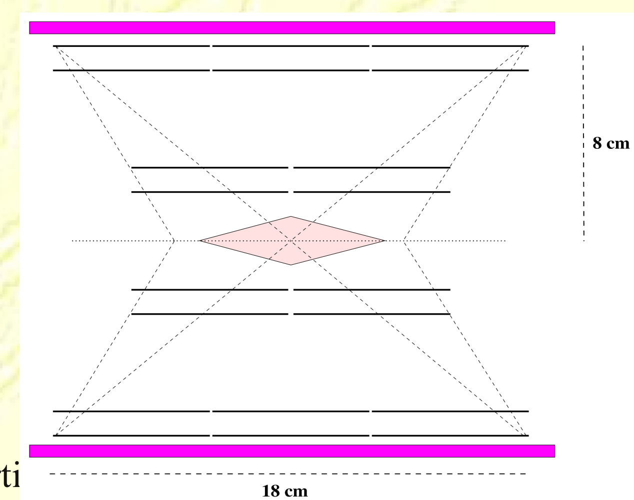


- **Silicon pixel detector for tracking**
  - high resolution
  - precise hit position **80 μm x 80 μm** (c.t. multiple scattering σ_{MS} ~ 150 μm)

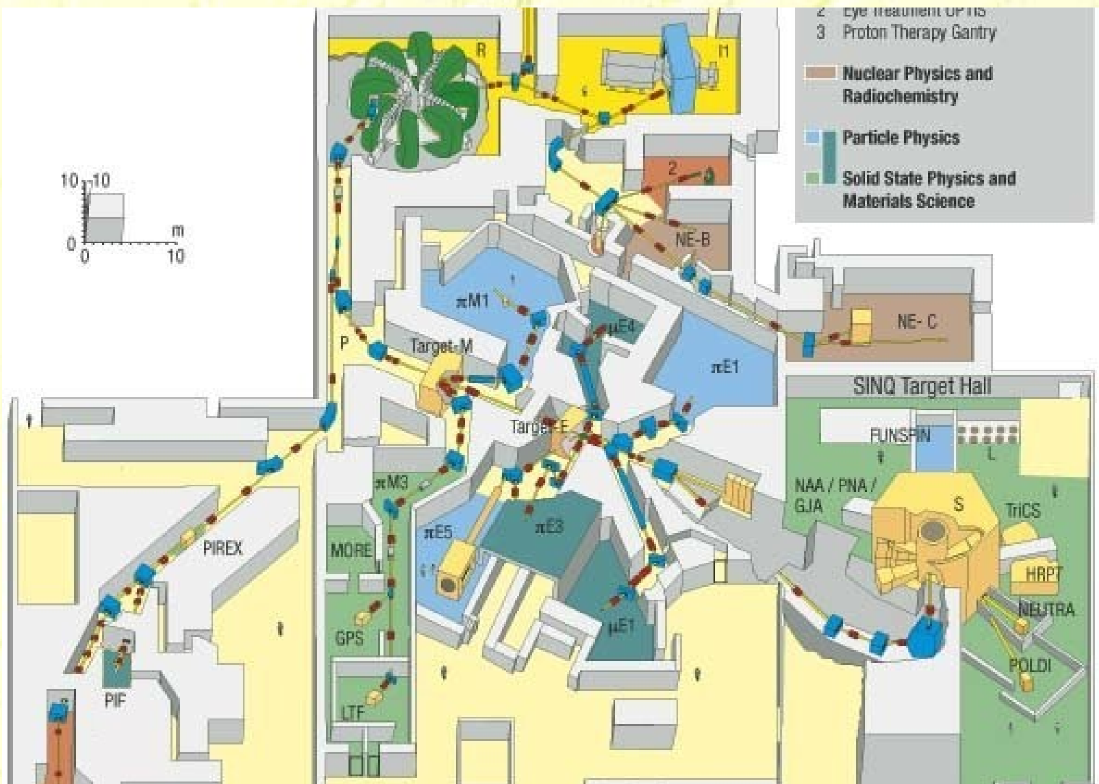
- **Scintillating fiber tracker for timing**
  - excellent timing **ΔT = 100 ps**
  - good spatial resolution
  - vector tracking (particle direction)



DC Muon Beams at PSI

- **μE1 beamline with rates up to** **~ 5 · 10^8 muons/s**
- **πE5 beamline (MEG experiment)** **~ 10^8 muons/s**
- **μE4 beamline** **~ 10^9 muons/s**
- **SINQ target could even provide** **~ 10^{10} muons/s**

- **New experiment (final stage) requires muon rates ≥ 1e9/s focussed and collimated on a spot with about d=2 cm diameter**

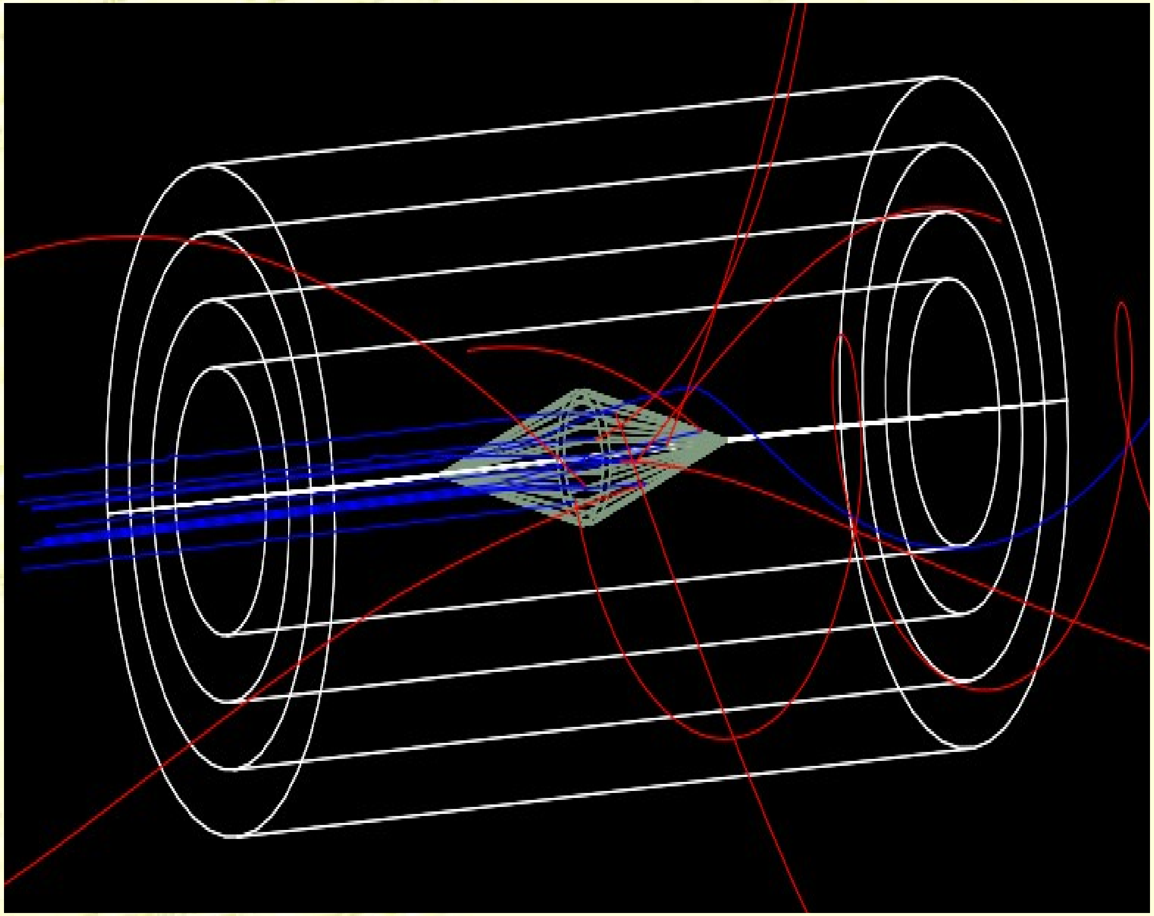


Target and Vertex Resolution

Sindrum-like Hollow Double Cone Target:

- total length of target: ~ 7 cm
- diameter: 2 cm
- thickness of hollow cone ~60 µm (Al)
- **vertex resolution: ~150 µm**

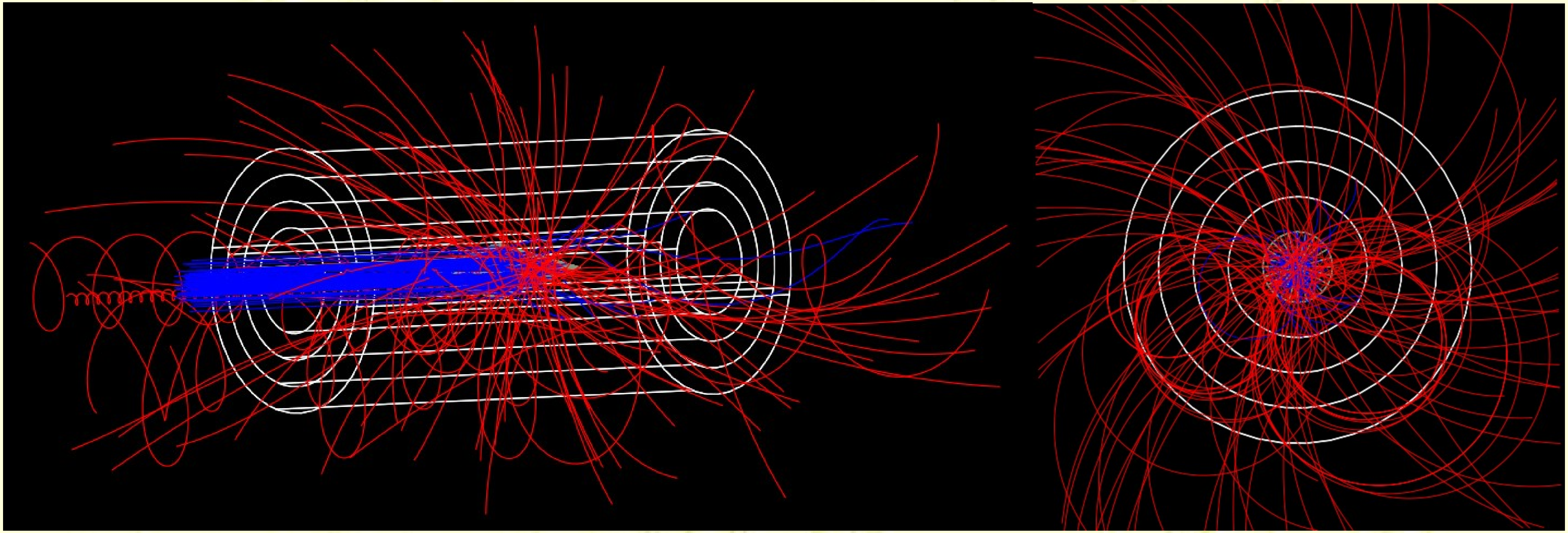
Simulation Model



allows to suppress combinatorial BG by factor $5 \cdot 10^{-5}$

Timing Resolution

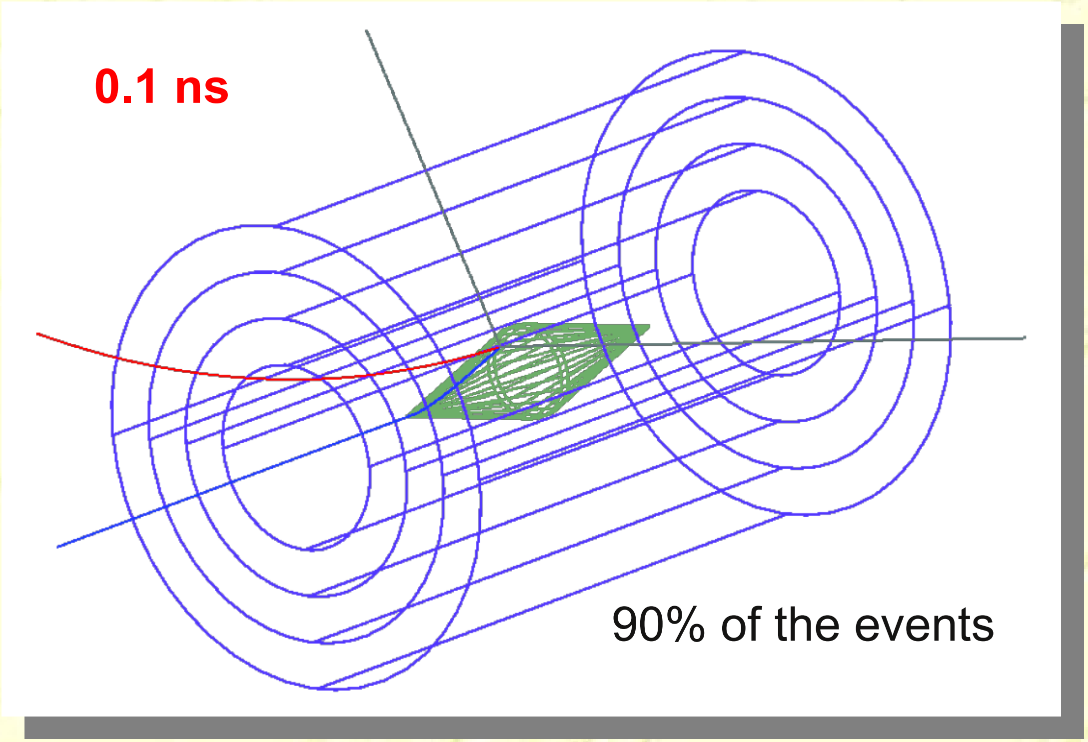
∫dt = 100 ns: 100 decays @ 10^9 muon stops/s



timing resolution silicon: 100 ns

Timing Resolution

$\int dt = 0.1$ ns: <1 decay @ 10^9 muon stops/s

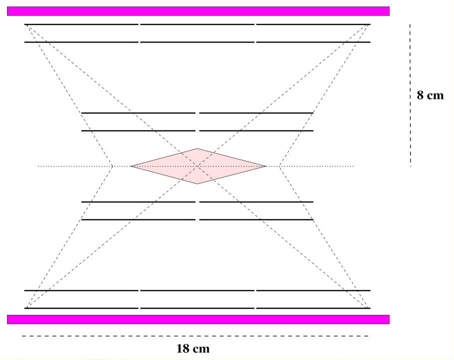


timing resolution silicon: 100 ns

timing resolution fiber tracker: ~0.1ns

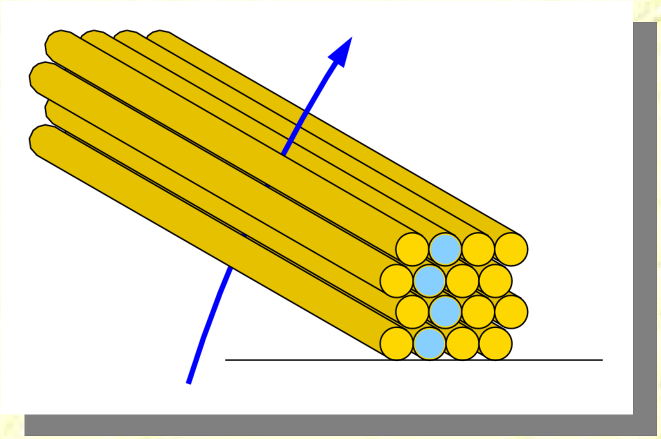
→ **allows to suppress combinatorial BG by factor 1000**

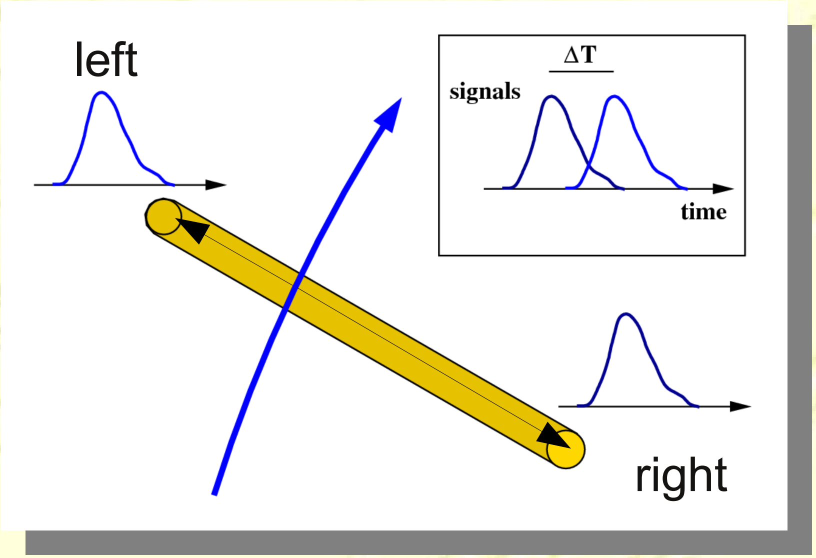
Scintillating Fiber Tracker



Purpose:

- **Measure timing of tracks precisely: σ_t = 50-100 ps**
- **Allows for unambiguous silicon hit assignment**
- **x-y plane: Ø = 0.25-1.0 mm fibers**
- **z-position: relative time difference both ends (precision 1-2 cm)**



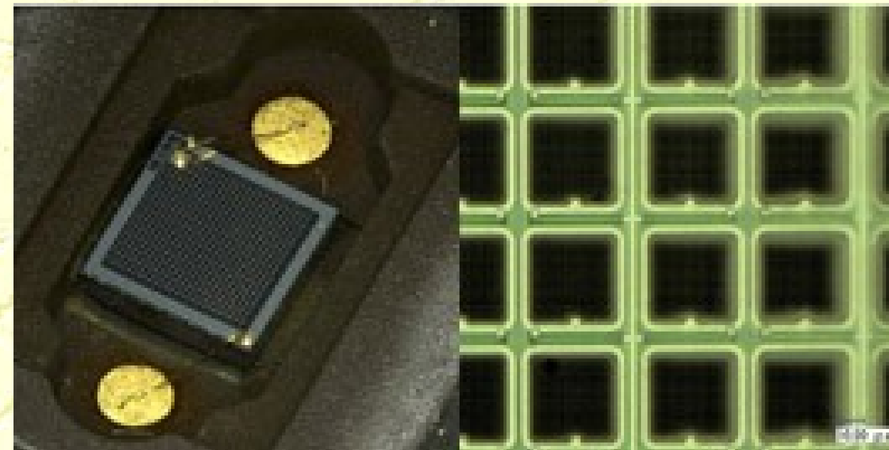


- **Photodetector: SiPM**

time difference between both ends

Silicon Photomultipliers

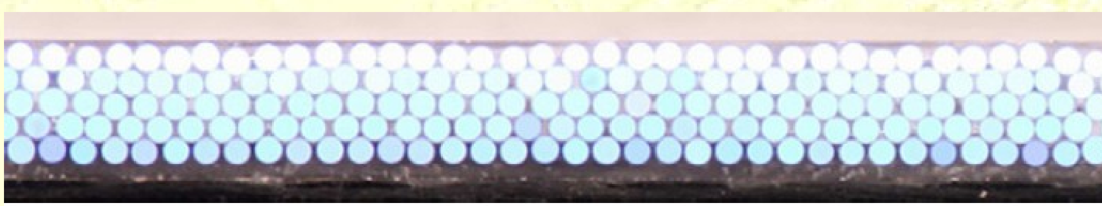
- **compact**
- **fast Δt < 100ps, f_{max} = 1-10 MHz**
- **high gain 1e5-1e6**
- **high efficiency**
- **radiation hard**
- **insensitive to magnetic fields**



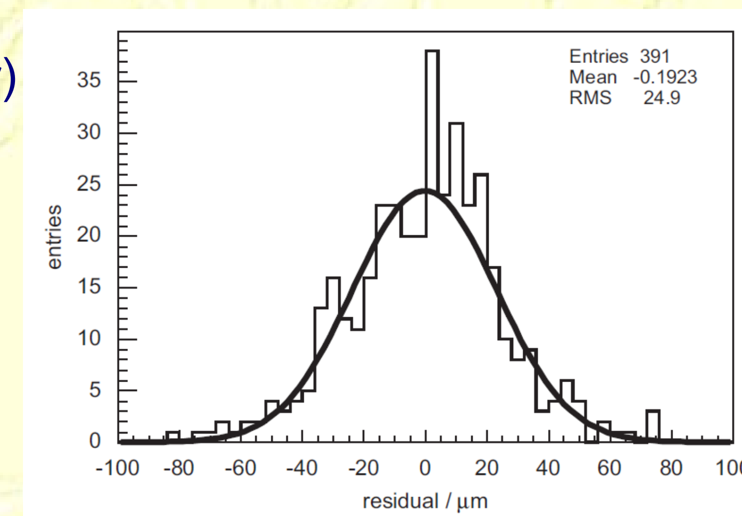
pixel array of avalanche photo diodes

used in various experiments:
- KEK T2K INGRID (photon detection)
- PEPS balloon-borne detector (scintillating fiber tracker)

Beischer at al., NIM A622(2010)542



5 layers of scintillating fibers 250µm diameter



spatial resolution 25 µm

Detector Acceptance $\mu^+ \rightarrow e^+e^+e^-$

Model Dependence:

$$\frac{dB(\mu \to eee)}{dx_1\, dx_2\, d\cos\theta\, d\phi} = \sum_{k=1}^{5} c_k\, \alpha_k(x_1, x_2)$$

four fermion

$$c_1 = \frac{g_1^2 + g_2^2}{16} + g_{34}^2$$

$$c_2 = g_{56}^2$$

acc ~ 80%

photon penguin

$$c_3 = e\, A^2$$

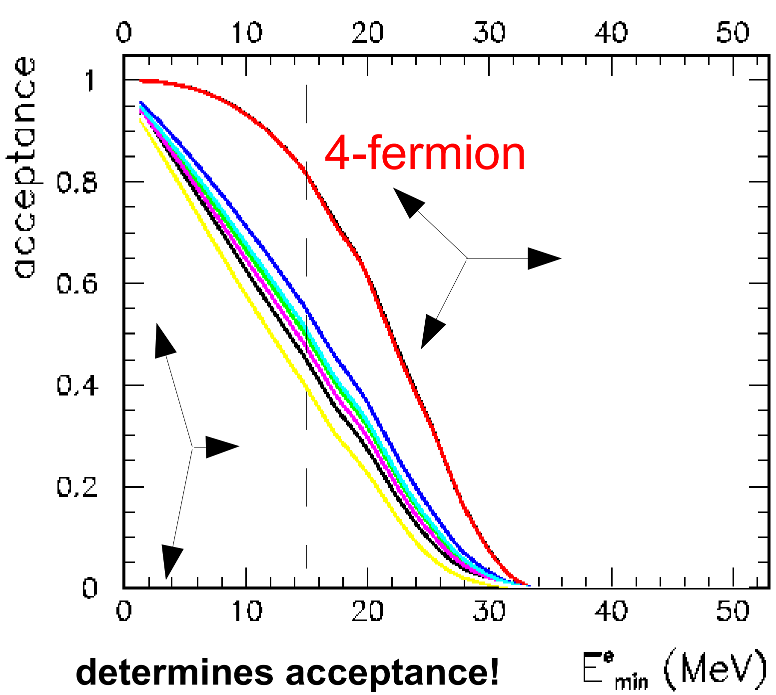
$$c_4 = e\, A g_{34}\, \eta$$

$$c_5 = e\, A g_{56}\, \eta'$$

acc ~ 40%

T-odd

Minimum electron energy:



determines acceptance!

measure momenta
in range: p=15-53 MeV/c

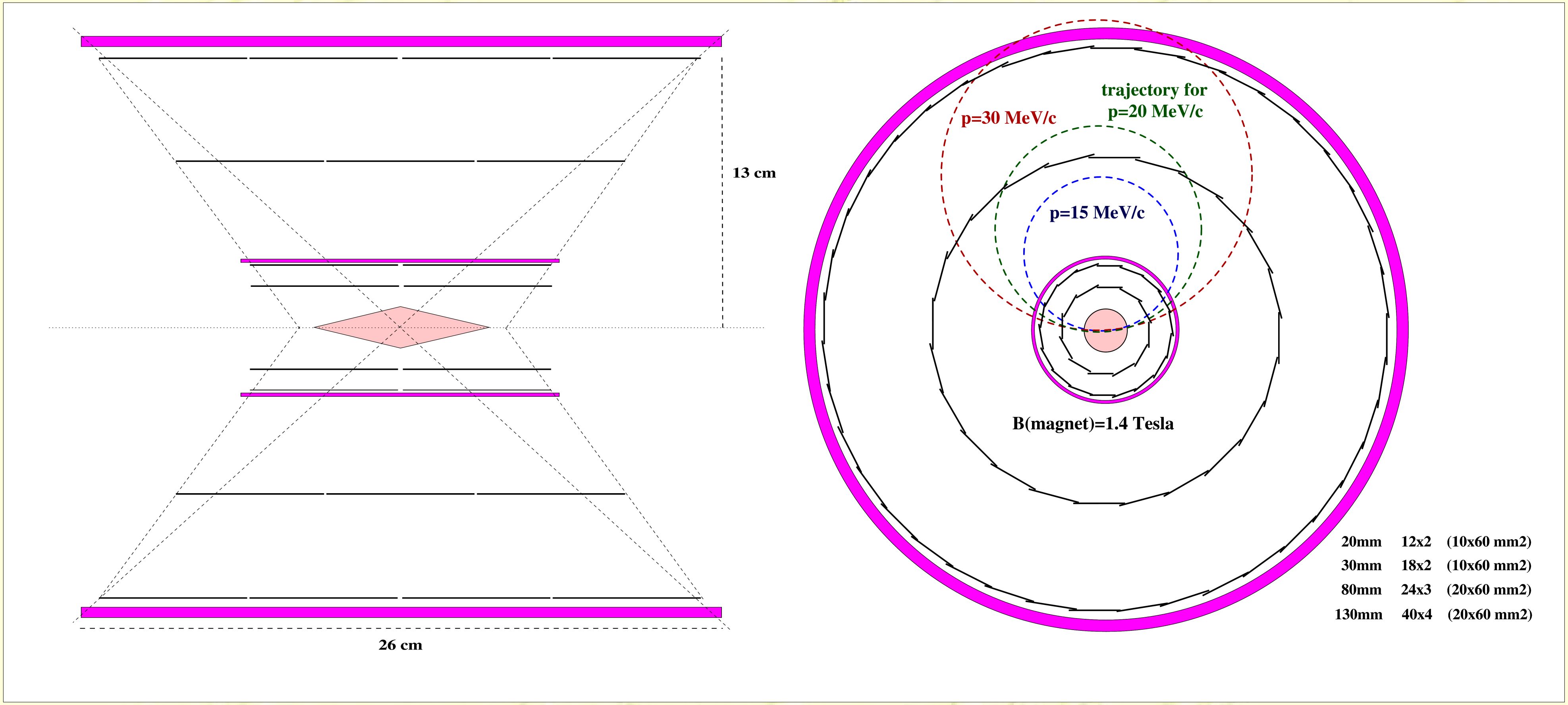
"Big Barrel" Design

momentum resolution:
(half-circle fit)

20 MeV/c: $\sigma_p/p=2.3\%$ → $\sigma_p=0.46$ MeV/c

35 MeV/c: $\sigma_p/p=1.3\%$ → $\sigma_p=0.45$ MeV/c

50 MeV/c: $\sigma_p/p=1.3\%$ → $\sigma_p=0.65$ MeV/c



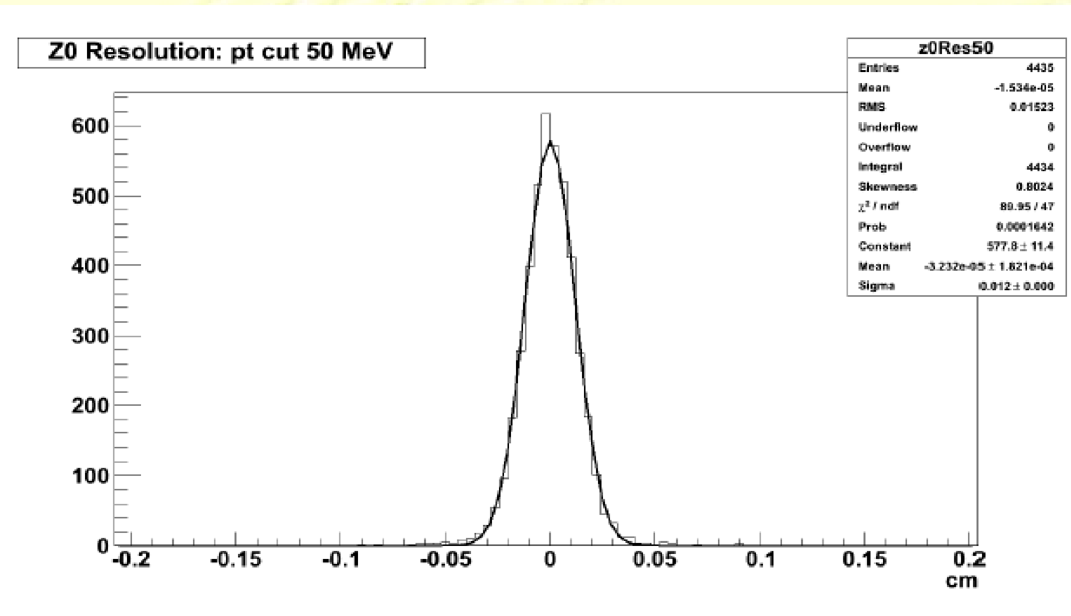
precise timing information for all tracks by second fiber tracker

Simulation Studies

Tracking Resolutions Studies

(R.Narayan)

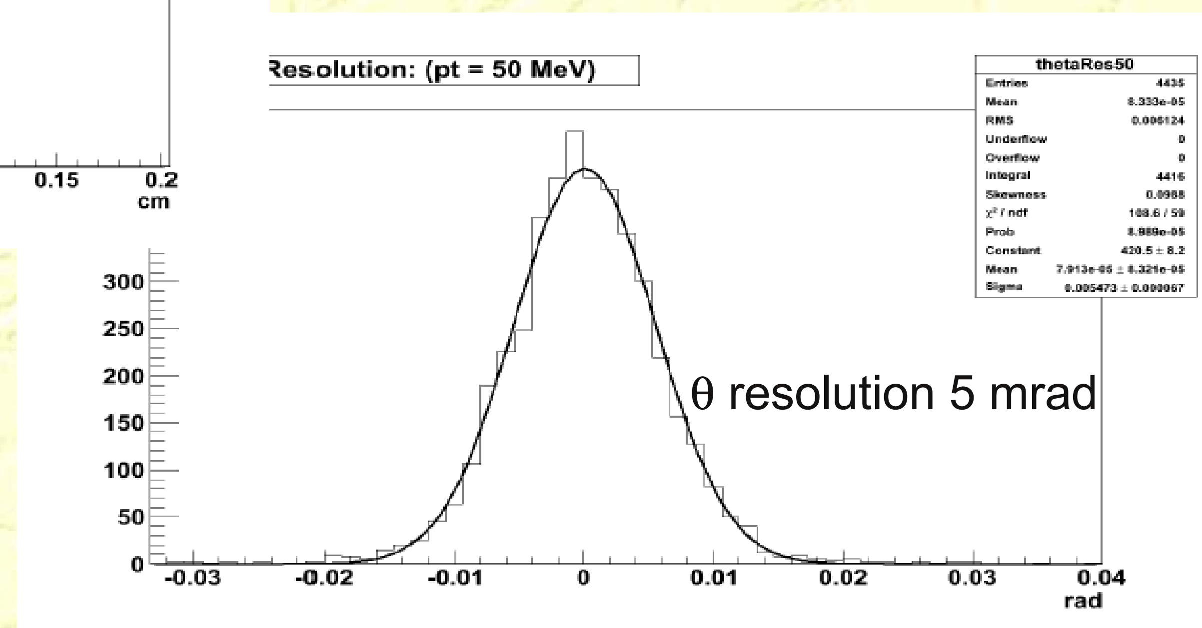
- **Preliminary results obtained using Geant4 by simulating a small scale detector (radial layers at 2, 3, 4, 5 cm)**



Z_0 (vertex) resolution 120 μm

results are from preliminary studies.

work in progress!



θ resolution 5 mrad

Possible Improvements

Momentum resolution

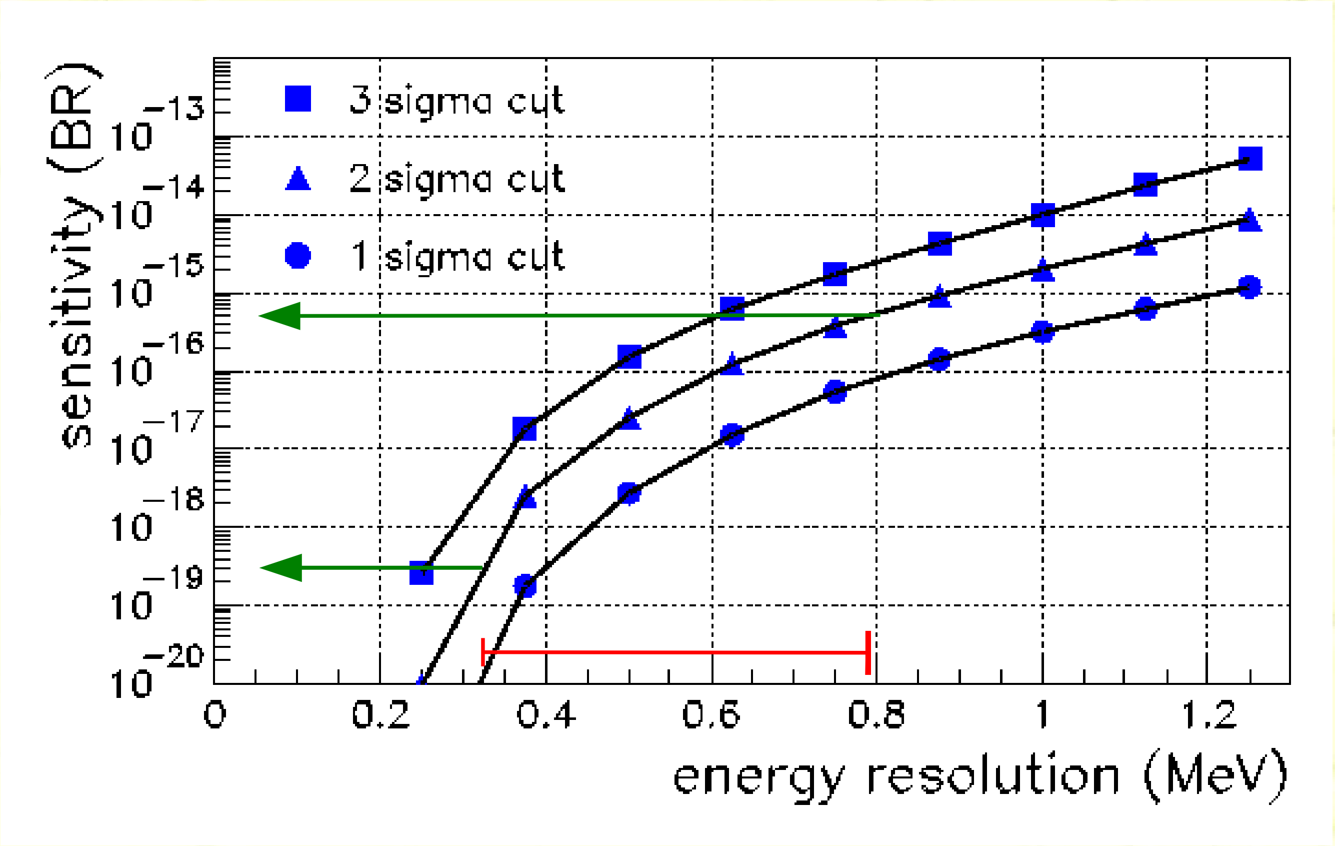
- factor ~0.7 fitting second track half
- factor ~0.8 primary vertex fit (3 tracks)
- factor ~0.8 from improved fitting (broken line fit)?
- factor ~0.9 no inner scintillating fiber tracker

➔ σ_E = 0.78-0.91 MeV → σ_E = 0.32-0.36 MeV

Simulated Sensitivity

Rate of $\mu \to eee\nu\nu$ as function of the energy resolution:

sensitivity ≡ background

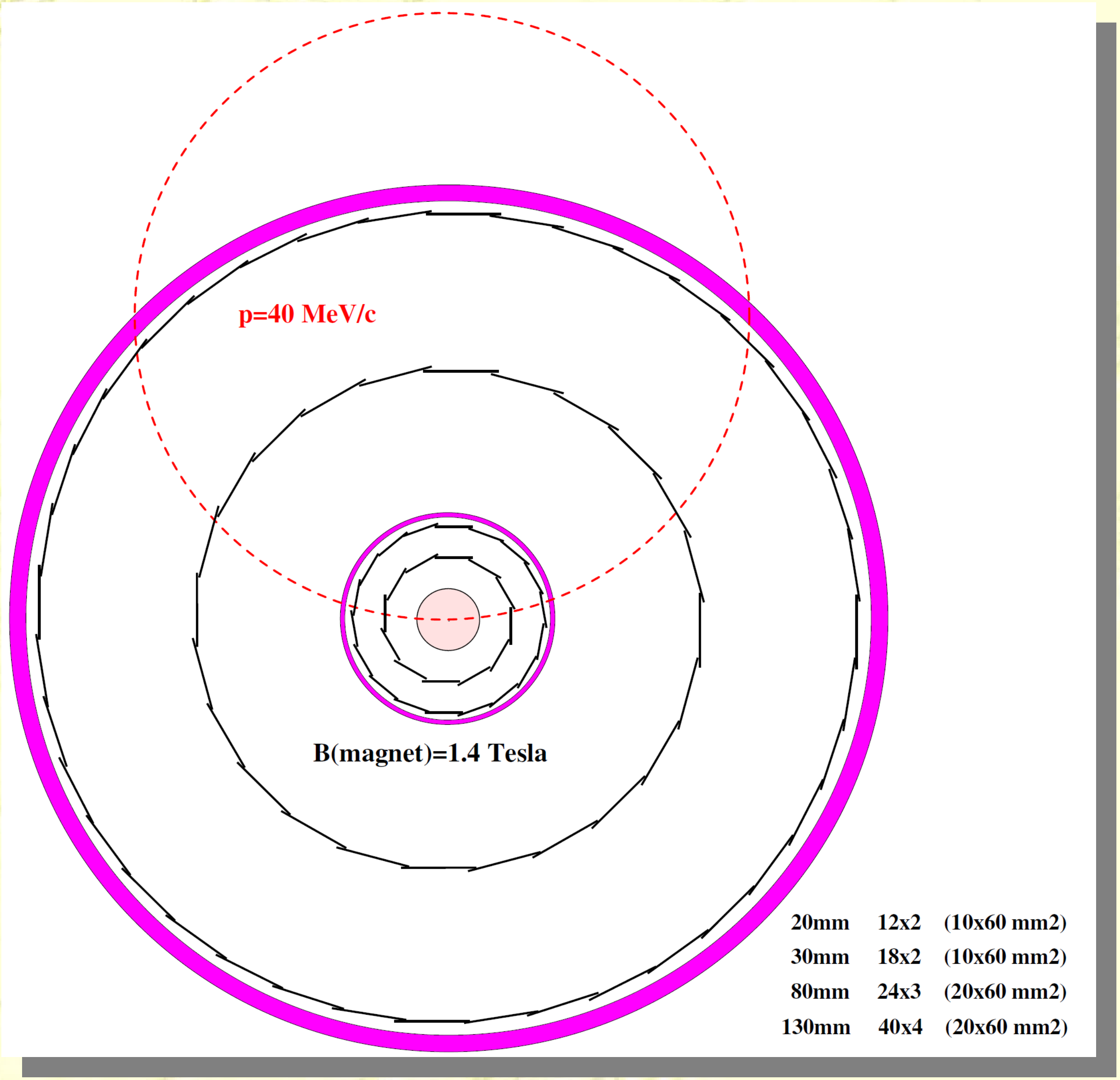


- good energy resolution suppresses $\mu \to eee\nu\nu$ BG effectively
- for σ_E = 0.3-0.6 MeV sensitivity even below 10^{-16}

Further Improvements?

Fit Recurling Track:

$\sigma_E \leq 0.1$ MeV ?



Mu3e Project

Status of Project

- interesting new ideas
- no name, looking for collaborators

Interested groups:

- Uni Zürich, ETH Zürich?
- Rome “La Sapienza”
- Paul Scherrer Institute
- Geneva
- Heidelberg/Mannheim

Status of Activites (Heidelberg / Mannheim)

- Tracker: Mechanical Stability / Construction studies
- Cooling studies
- MAPS HV CMOS design
  first funding (50k€) for sensor protoype submission
- Broken Line Fits and Fast Online Track Reconstruction

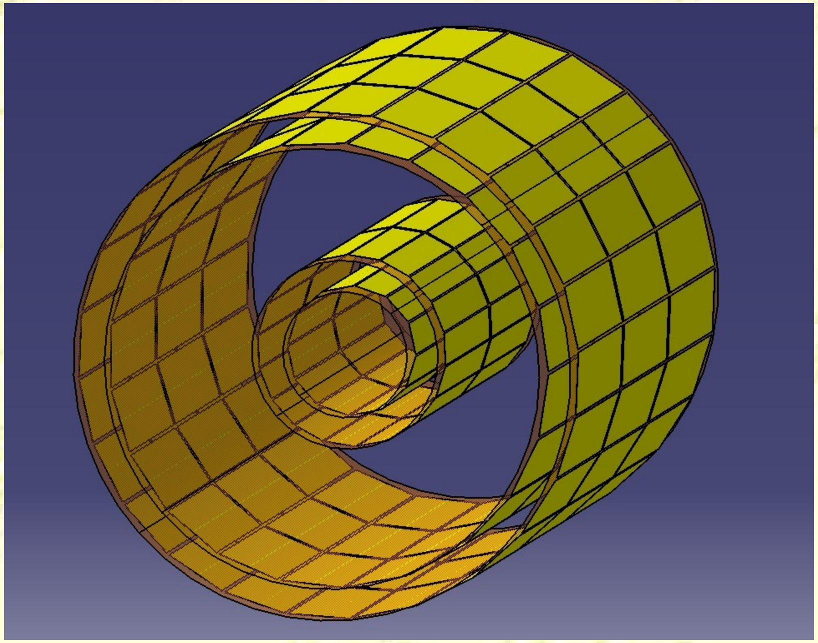
Summary

- Novel detector concept for $\mu \rightarrow eee$ experiment
- Technologies: Silicon Pixel and Scintillating Fibers Trackers
- sensitivity $BR(\mu \rightarrow eee) < 10^{-16}$ seems feasible
  but more detailed simulations are required

- first pixel tracker prototype for 2012?
- could replace completed MEG experiment (in 2-3 years)
- later go to an upgraded high intensity beamline

Conclusion

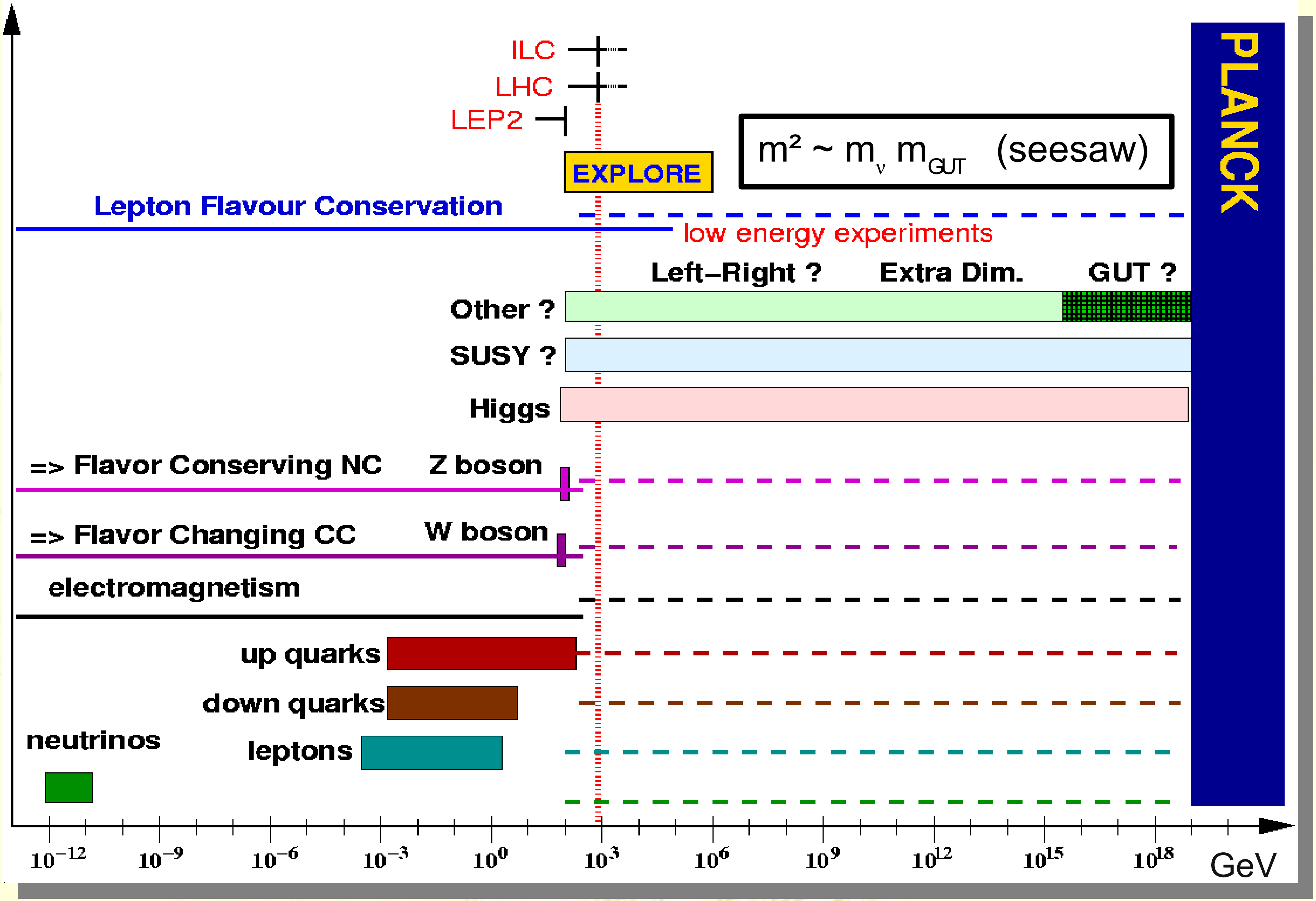
After more than 20 years time has come to repeat a search for $\mu \rightarrow eee$ and to repeat very a successful experiment (Sindrum)



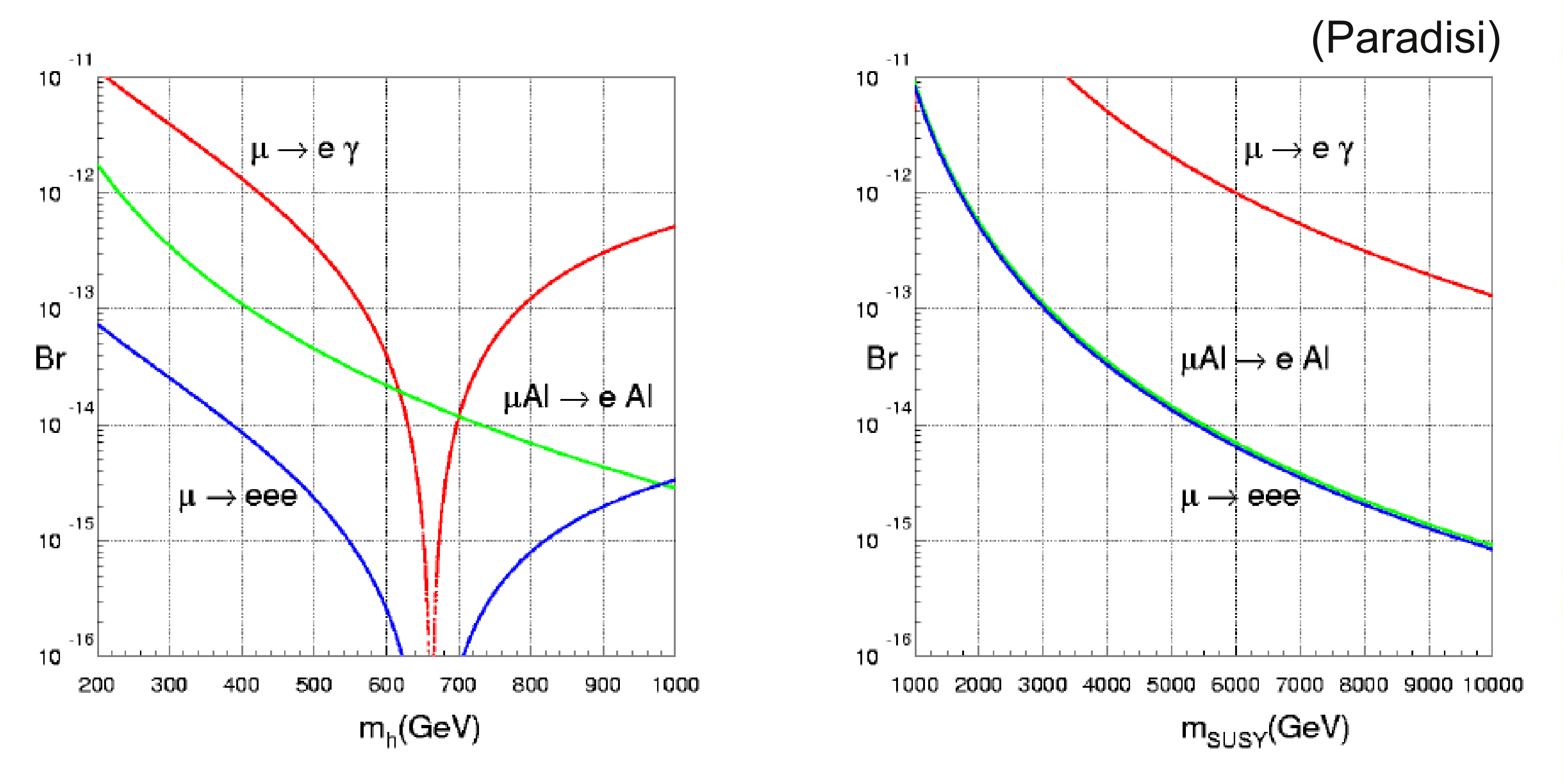
A good detector is needed to resolve mysteries!

Backup

Landscape of Mass Scales

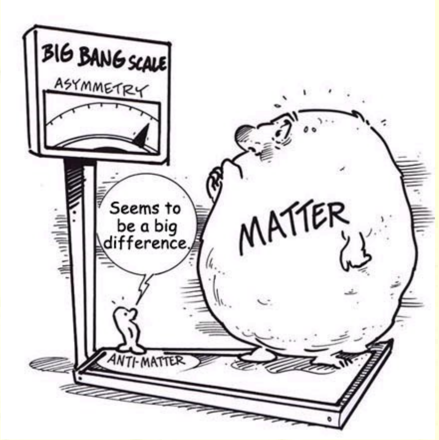


SUSY Higgs mediated LFV



Leptogenesis

Matter–anti matter asymmetry in the universe requires:



- Baryogenesis (Sacharov)
  - baryon number violation
  - CP (T) violation (measured but small)
  - non equilibrium process

- Leptogenesis (alternative)
  - lepton number violation (not observed)
  - CP phase in lepton matrix (might be measured by ν oscillation)
  - non equilibrium process

→ baryogenesis (sphaleron process)

- lepton flavor violation is a consequence of lepton number violation and CP phases

Optimum Momentum Resolution

- **minimum three layers → six coordinates**
- **momentum resolution multiple scattering dominated:**

3 layers equidistant: $$\frac{\sigma_p}{p} = 2\,\frac{b}{BL}$$

4 layers equidistant: $$\frac{\sigma_p}{p} = \frac{3}{\sqrt{2}}\,\frac{b}{BL} \approx 2.12\,\frac{2b}{BL}$$

b ~ 0.001 Tm
(for 40μm Silicon)

>4 equidistant layers: $$\frac{\sigma_p}{p} = \frac{N-3}{\sqrt{N-2}}\,\frac{b}{BL} \approx \sqrt{N}\,\frac{b}{BL}$$

- **resolution is given by 1/BL**
  - but minimum momentum given by $p_{min} \sim BL$

DAQ

- **Number of (zero supressed) channels in Silicon ~10-20 million**
- **Number of channels in Fiber Tracker 5-10k**
- **What matters is the events rate of ~10^9**
  - **data rate ~ 16 Gbyte/s**

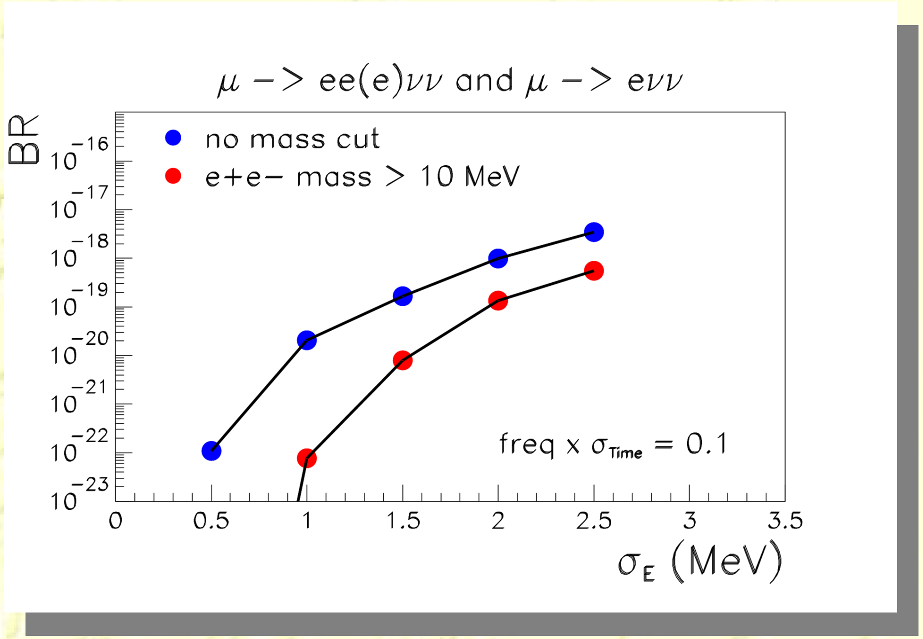
- **triggerless readout (software filter only)**

Combinatorial Background

Design Parameters:

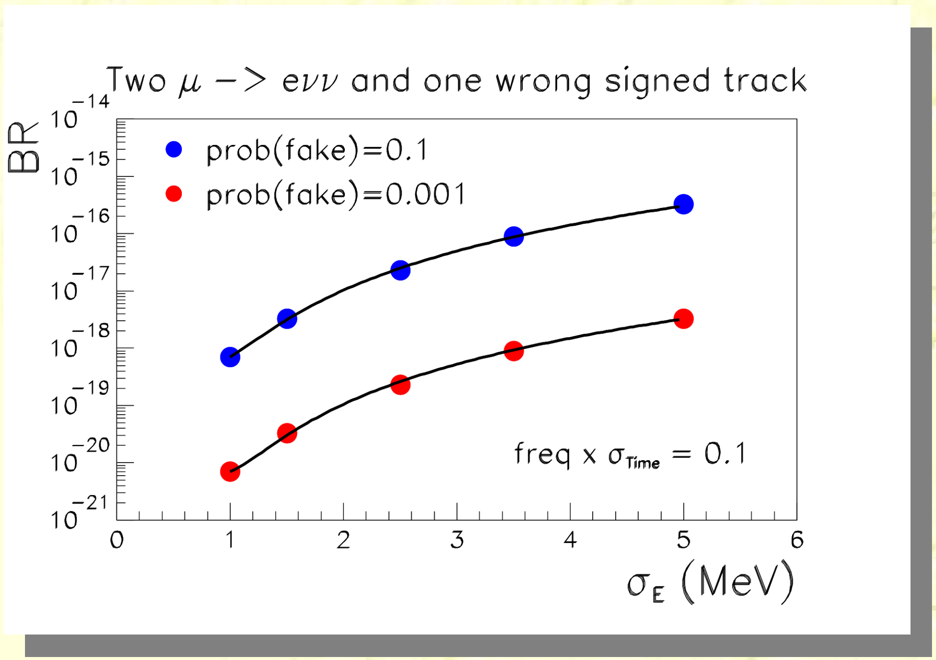
- prob (coincidence vertex) = $5 \cdot 10^{-5}$
- prob (coincidence time) = 0.1

internal conversion and muon decay



BG as function of E_{tot}

fake track and two muon decays

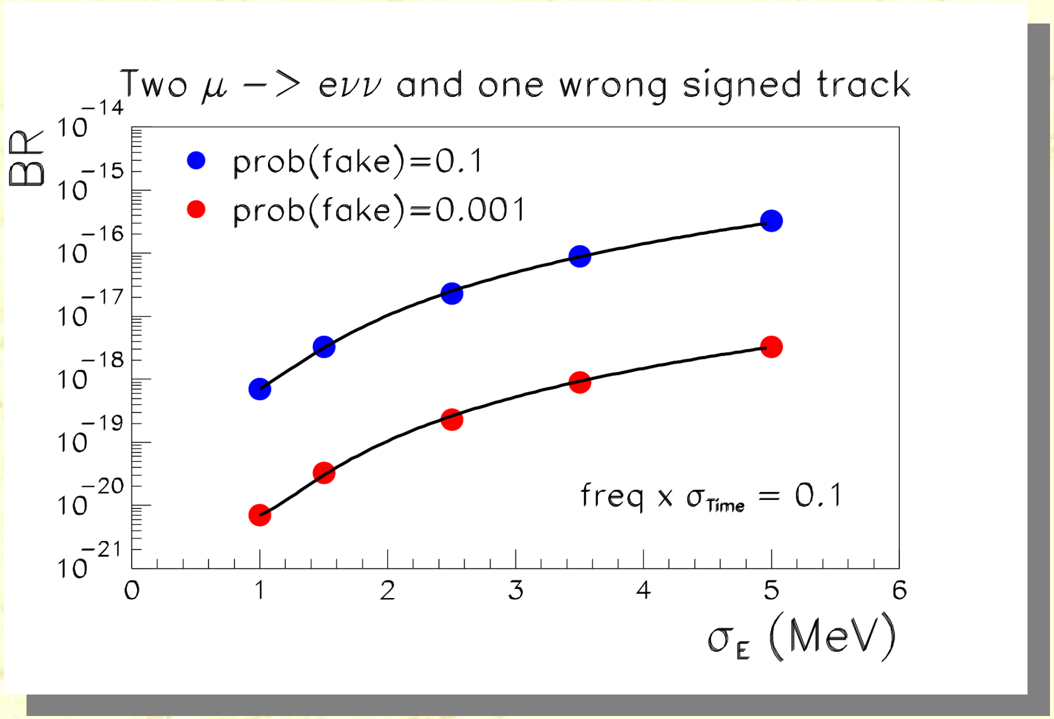


combinatorial BG can be ignored already for moderate energy resolution σ_E < 3 MeV

Maximum Muon Beam Intensity?

- **Combinatorial Background increases!**
- **The maximum tolerable muon intensity depends mainly on vertex, timing, and tracking resolution (also fake rate).**
- **assuming that the fake track reconstruction rate is small (0.001) a sensitivity of 10^{-17} could be achieved with beam intensities of $3 \cdot 10^{10}$ muon stops/s**

BG ~ rate^2



A new Silicon Detector for MEG?

Expected performance for electron p=53 MeV/c:

σ_p = 0.3-0.6 MeV/c (MEG 0.7 MeV/c)

σ_θ ~ 5 mrad (MEG 8 mrad)

σ_{vtx} ~ 0.15 mm (MEG 1.4-2.5 mm)

momentum resolution could be further improved by increasing the lever arm:
e.g. 13 cm → 20 - 25cm