Neutrino Factory - a Manifesto

1 - Neutrino masses and oscillations

what we 'know', the BIG ISSUES

2 - Programme of work for a ν factory

→ Pilar H et al.

3 - Concept for a ν factory

superconducting linac → μ storage rings

4 - Charged lepton flavour violation

$\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion on nuclei

other stopped (slow) μ physics

5 - Deep Inelastic ν scattering

short-baseline beam

6 - High-intensity kaon physics

$K \to \pi \bar{\nu} \nu$, $K_L^0 \to \pi^0 e^+ e^-$, $K_L^0 \to \mu e$

1 Neutrino Masses & Oscillations

Why not? there is no good reason why $m_\nu = 0$

vanishing masses $\Leftrightarrow$ exact symmetries

e.g.: photon — e.g.: gauge invariance, Q_{em}

There is no massless gauge boson coupling to lepton number

$\Rightarrow$ do not expect lepton number conserved

cf string theory

$\Rightarrow$ ν mass possible

e.g. $m_\nu \, \nu \cdot \nu$ $\Delta L = 2$

- generic feature of Grand Unified Theories
- even possible in the Standard Model:

(Barbieri + JE + Gaillard

$$\frac{1}{M} \nu H \cdot \nu H \Rightarrow m_\nu = \frac{\langle 0|H|0\rangle^2}{M}$$

M: some heavy mass scale $\gg m_W$

H: Higgs field

very small?

not so small in M theory

$M \ll m_P$

Generic GUT Seesaw Model

no new gauge int^{us} needed

$$(\nu_L , \nu_0)\begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_0 \end{pmatrix}$$

Dirac mass $= O(m_q, m_l)$

singlet ✓

Majorana mass

diagonalization:

$$m_\nu = m_D \frac{1}{M_M} m_D^T \qquad \ll m_{q,l} \text{ if } M_M \gg m_W$$

each mass matrix in flavour space

flavour diagonalization:

$$V_{MNS} = V_l V_\nu^\dagger$$

diagonalize l_L $\quad \nu_L \leftarrow m_D \frac{1}{M} m_D^T$

different structure from quark mixing

$$V_{CKM} = V_d V_u^\dagger \leftarrow m_q$$

ν mixing might be very different from q

U(1) models? $\begin{pmatrix} \epsilon^m & \epsilon^q & \epsilon^p \\ \epsilon^{q'} & \epsilon^r & \epsilon^s \\ \epsilon^{p'} & \epsilon^{s'} & \epsilon^t \end{pmatrix}$ GUTs? extra dimensions?

Neutrino Masses in Extra Dimensions

(Dienes

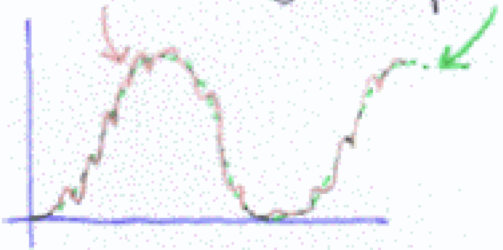
- many excited Kaluza-Klein states coupled to ν_L?

$$\left(\begin{array}{c|cccc} 0 & m & m & m & \cdots \\ \hline m & M_1 & 0 & 0 & \\ m & 0 & M_2 & 0 & \\ m & 0 & 0 & M_3 & \\ \vdots & & & & \ddots \end{array}\right) \otimes \text{flavour}$$

- naturally light neutrinos

small Yukawa coupling? related to R_{extra}?

- possible deviation from periodic oscillation:



much new parameter space to explore!

- multiple MSW effects

in String-Inspired/Derived Models

← intermediate $\underbrace{\hspace{1em}}_{\text{GUT}}$ extra

- many singlet massive states

$$\begin{array}{cc} & \\ 3 & \\ N \gg 3 & \\ & \end{array}\left(\begin{array}{c|c} 0 & 1, \epsilon, \epsilon^2, \ldots \\ \hline 1, \epsilon, \epsilon^2, \ldots & \mathcal{M} \end{array}\right)$$

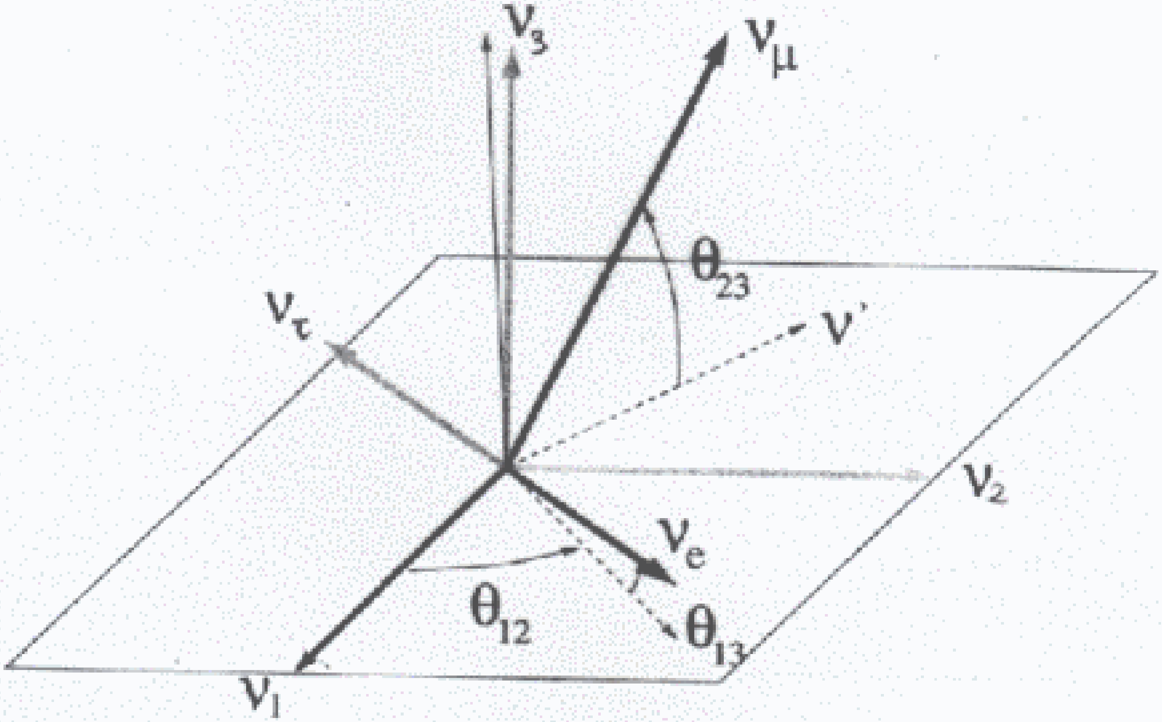
$$\qquad 3 \qquad\qquad N \gg 3$$

(J.E. + Leontaris + Lola + Nanopoulos

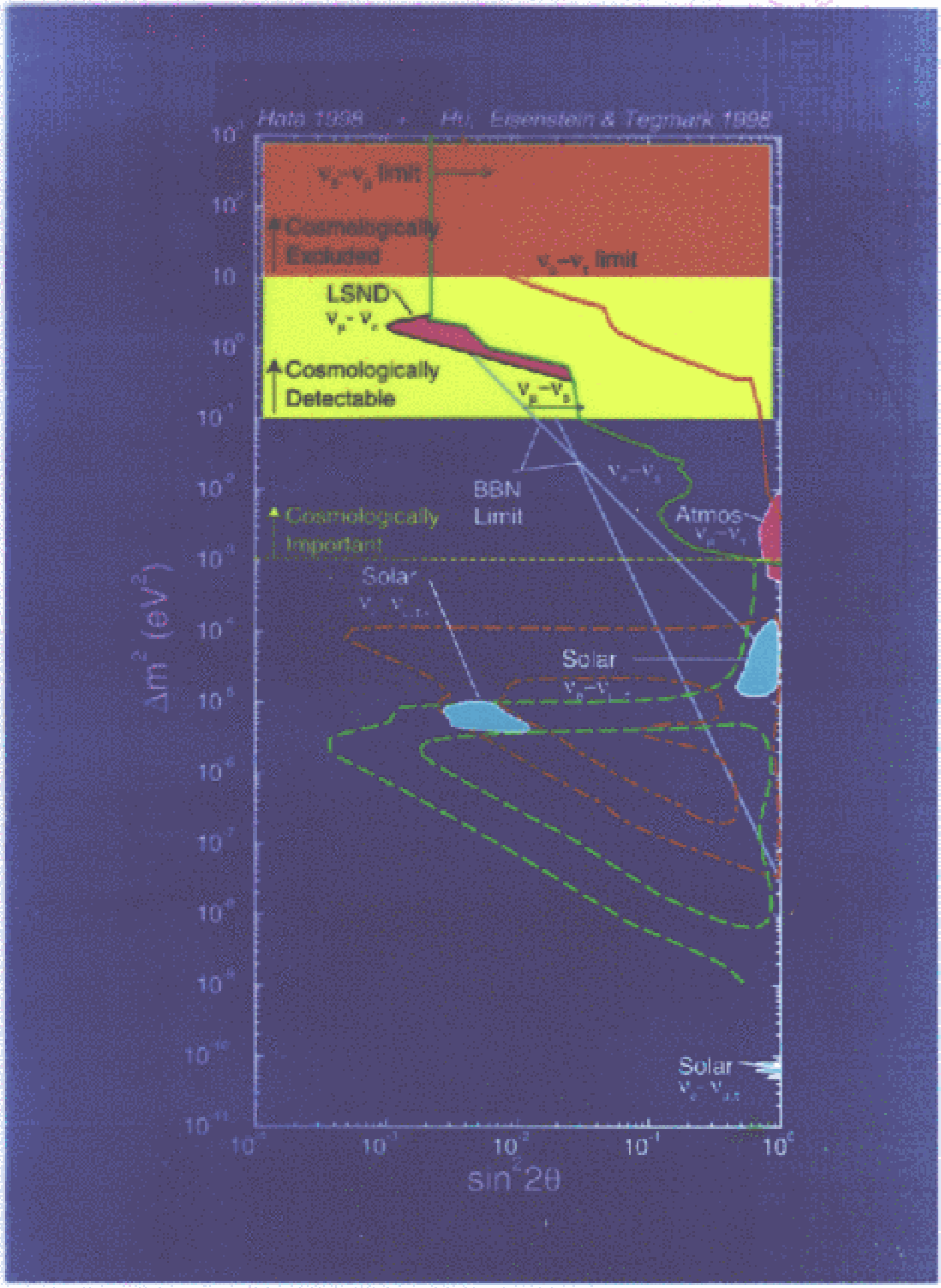
- more possibilities for large mixing?

Geometry of 3-Flavour Mixing

$$(\nu_e, \nu_\mu, \nu_\tau)^T = U \cdot (\nu_1, \nu_2, \nu_3)^T$$



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$


Hata 1998 • Hu, Eisenstein & Tegmark 1998
$\nu_e - \nu_\mu$ limit
Cosmologically Excluded
$\nu_e - \nu_\tau$ limit
LSND
$\nu_\mu - \nu_e$
Cosmologically Detectable
$\nu_\mu - \nu_s$
BBN Limit
$\nu_e - \nu_s$
Atmos
$\nu_\mu - \nu_\tau$
Cosmologically Important
Solar
$\nu_e - \nu_{\mu,\tau}$
Solar
$\nu_e - \nu_s$
Solar
$\nu_e - \nu_{\mu,\tau}$
10^3
10^2
10
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Δm^2 (eV^2)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
$\sin^2 2\theta$

Can neutrinos be degenerate?

(hep-ph/9904279)

$m_{1,2,3}$ ~ upper limit from $\left\{ \begin{array}{l} \text{tritium } \beta \text{ decay} \\ \text{astrophysics / cosmology} \end{array} \right.$

$$m \sim 2\,\text{eV} \gg \sqrt{\Delta m^2_{\text{Atmo}}} \gg \sqrt{\Delta m^2_{\text{solar}}}$$

strong constraint from absence of $\beta\beta_{0\nu}$ decay:

$$\langle m_\nu \rangle_e \simeq m \times \Big| \underbrace{c_2^2 c_3^2 e^{i\phi} + s_2^2 c_3^2 e^{i\phi'}}_{\text{cancel!}} + \overset{\uparrow \text{ neglect: CHOOZ}}{s_3^2} e^{2i\phi''} \Big|$$

$$\lesssim 0.2\,\text{eV}$$

$$c_2^2 - s_2^2 = \cos 2\theta_2 \lesssim 0.1 \Rightarrow \sin^2 2\theta_2 \gtrsim 0.99$$

maximal mixing necessary!

$\underbrace{\times \text{ SMA , also } \times \text{ LMA}}$? ✓ vacuum oscillations

$\leftarrow \sin^2 2\theta_2 \lesssim 0.97$

⇒ extreme degeneracy: $m \sim 10^{10} \times \sqrt{\Delta m^2_{\text{solar}}}$!

is this compatible with renormalization ?

$$\swarrow$$

$$\propto m_\mu^2 , m_\tau^2 , m_e^2$$

⇒ excessive breaking of degeneracy;
lose maximal mixing

Texture fixed @ 10^{13} GeV

generation-dependent factors:

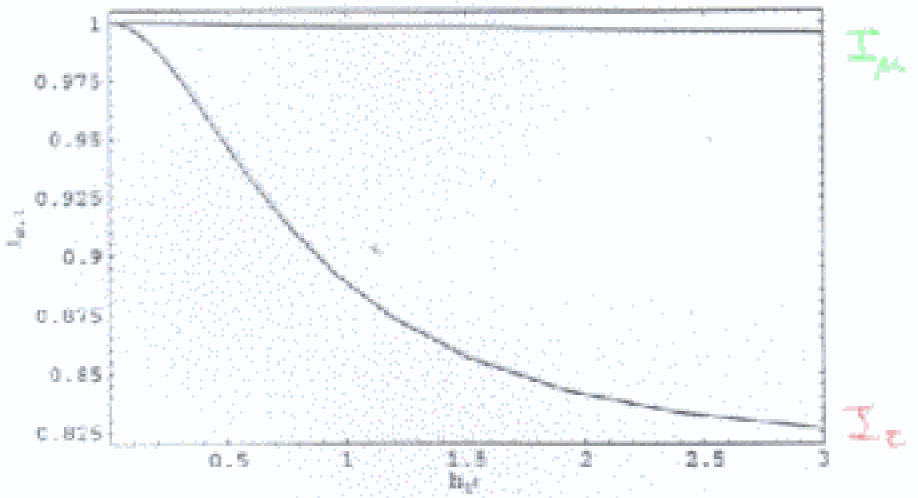


Figure 1: *Numerical values of I_μ and I_τ for different initial values of h_τ, assuming $M_N = 10^{13}$ GeV. The values of h_τ^2 = 0.013, 0.03, 0.05 and 0.5 to 3 in steps of 0.5 correspond to tanβ 1, 2.2, 6.5, 42.8, 53.6, 56.3, 57.4, 57.9 and 58.2, respectively.*

breaking of mass degeneracies:

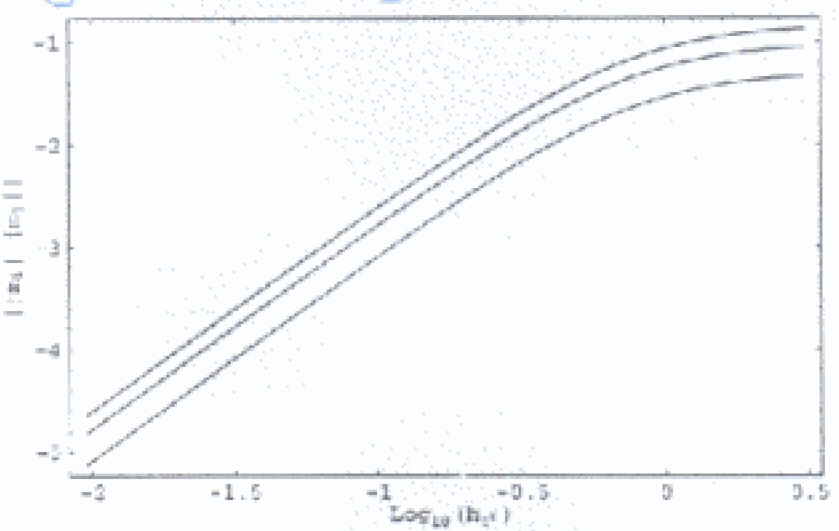
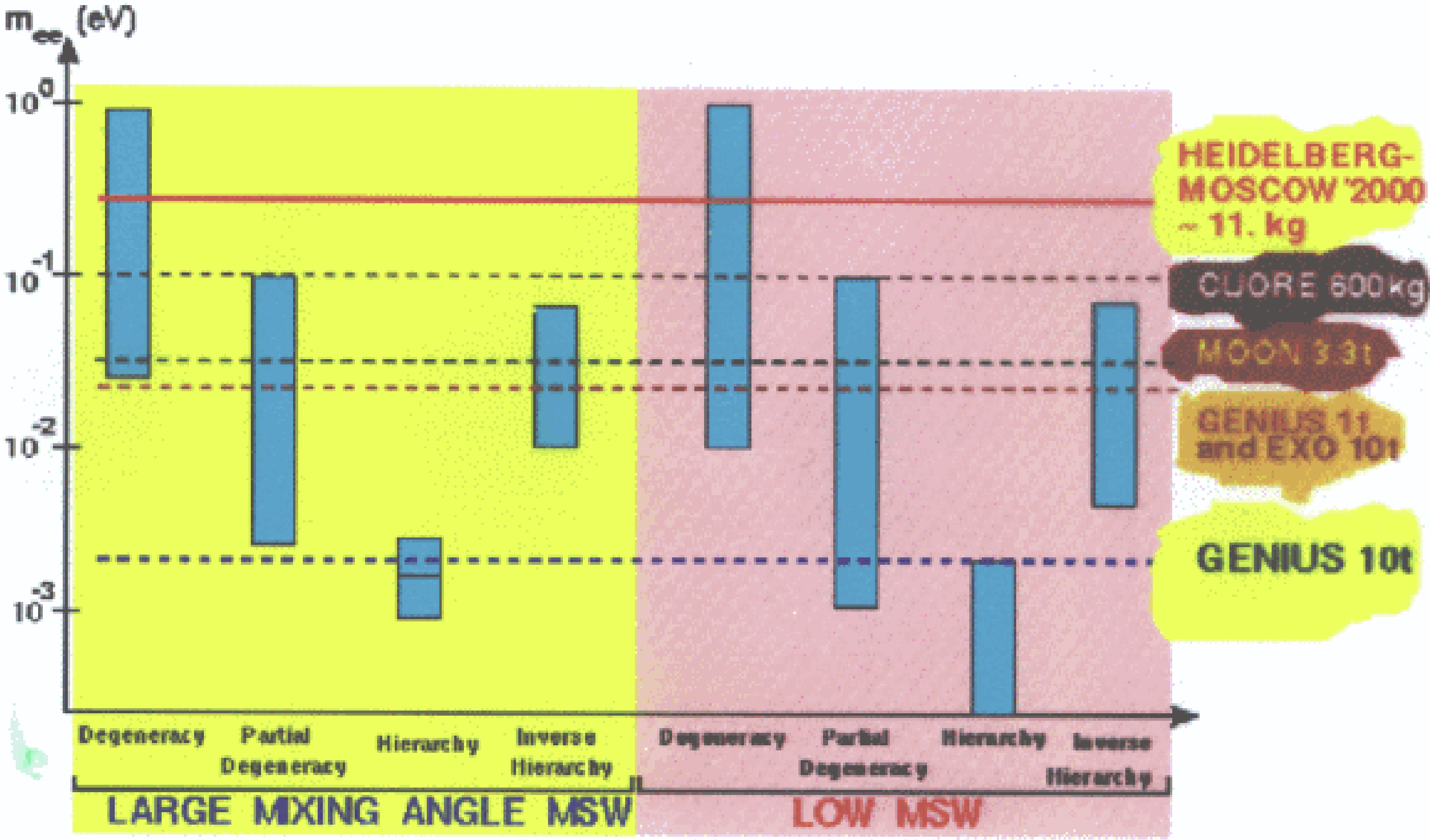


Figure 2: *Renormalization of m_{eff} eigenvalues for different initial values of h_τ corresponding to values of tanβ in the range 1 to 58, assuming the particular neutrino-mass texture (5) and $M_N = 10^{13}$ GeV. We see that the vacuum-oscillation scenario is never accommodated.*

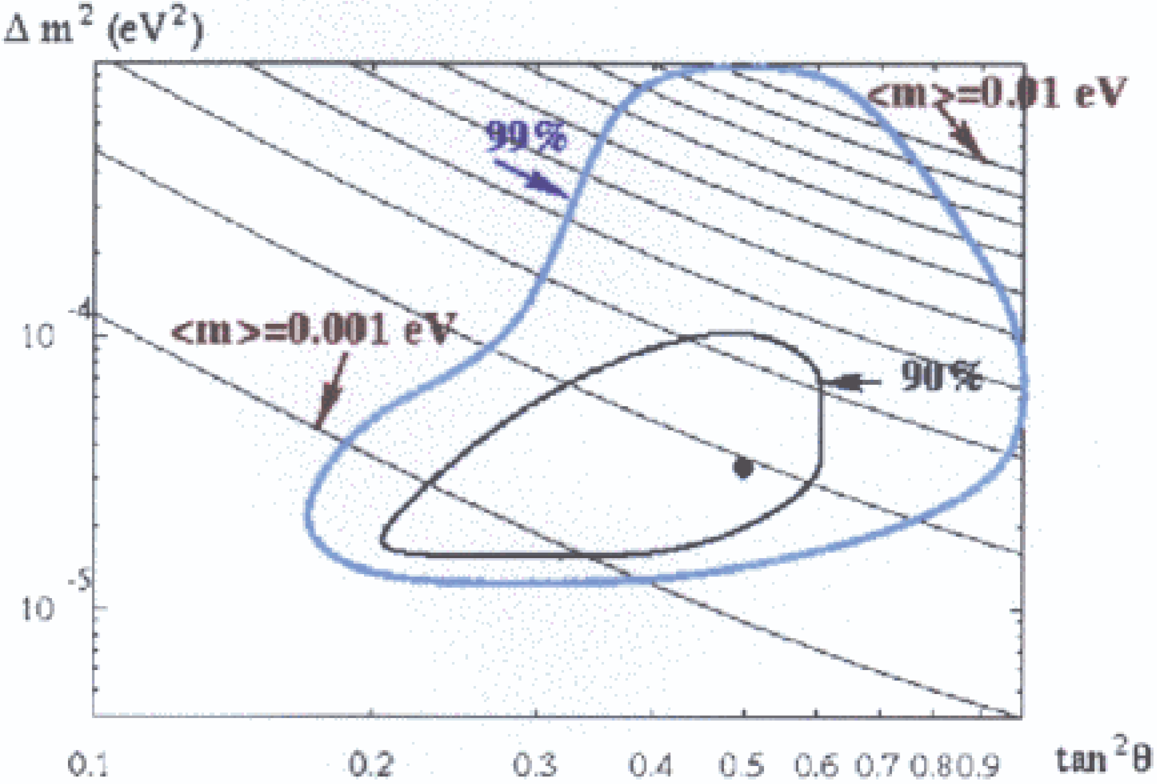
(J.E. + Lola:
hep-ph/9904279)

$\beta\beta_{0\nu}$ Experiments vs Models

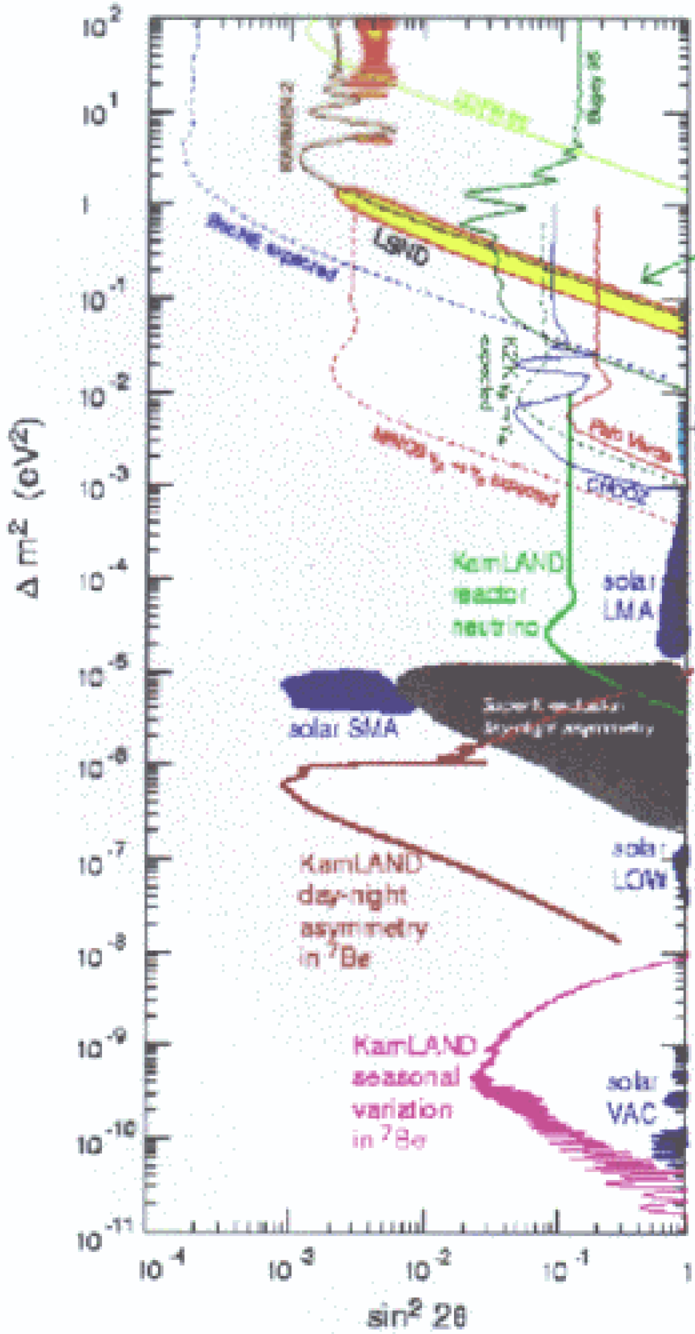


(Klapdor Kleingrothaus)

Required Sensitivity in $\beta\beta_{0\nu}$ Experiment



(Klapdor-Kleingrothaus



ignore at our peril!

soon much new information: SNO, KamLAND

Likely Scenario for Atmospheric ν Oscillations:

$\nu_\mu \to \nu_e$ not dominant

Super-K, Chooz

$\nu_\mu \to \nu_{\text{sterile}}$ not dominant

Super-K azimuthal angle

near-maximal $\nu_\mu \to \nu_\tau$ favoured

evidence soon from Super-K?

prospects at MINOS?

proof with OPERA?

assume:

θ_{13} small how small?

θ_{23} large

Likely Scenario for Solar ν Oscillations?

- Rates do not discriminate:

  LMA ↔ SMA ↔ LOW ↔ VO

- Day-Night/spectra favour LMA?

  if so, is this yet significant?

ν factory physics case strongest for LMA

- Answer to be provided by SNO, KamLAND

- Accessible to $\beta\beta_{0\nu}$ measurements?

  if sensitivity: $\langle m \rangle \sim 0.2\,\mathrm{eV}$

  ↳ 0.001 eV

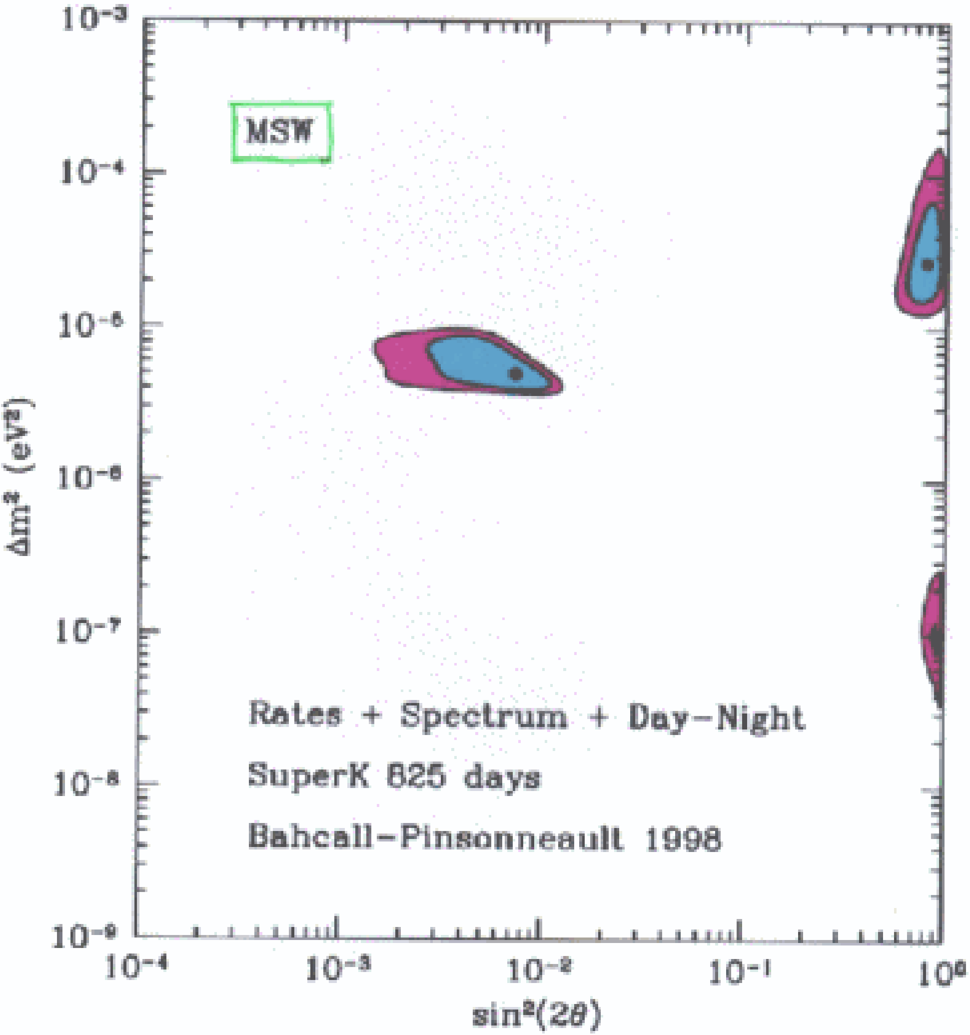
assume LMA:

θ_{12} large

$\Delta m^2_{12} \sim \text{few} \times 10^{-5}\,\mathrm{eV}^2 \rightarrow 10^{-4}\,\mathrm{eV}^2$

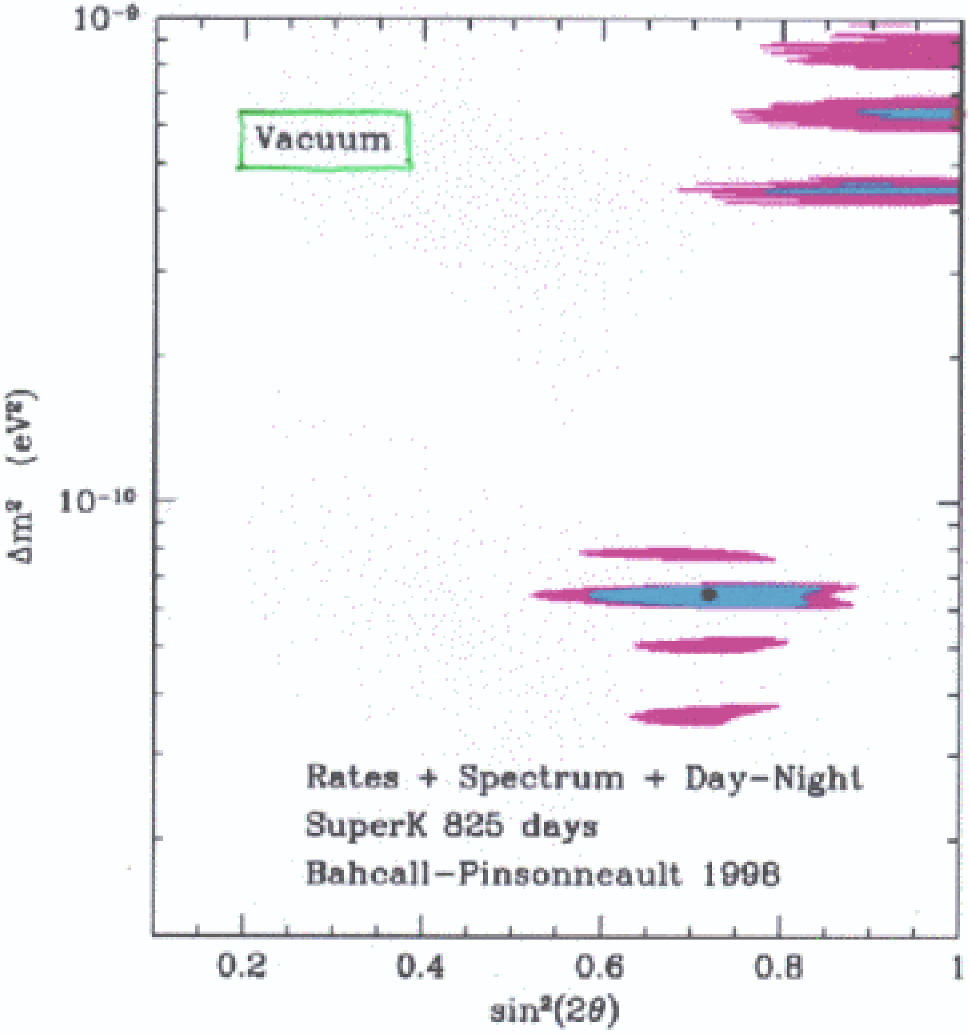
almost too good to be true?

Best Oscillation fits to Solar ν Data



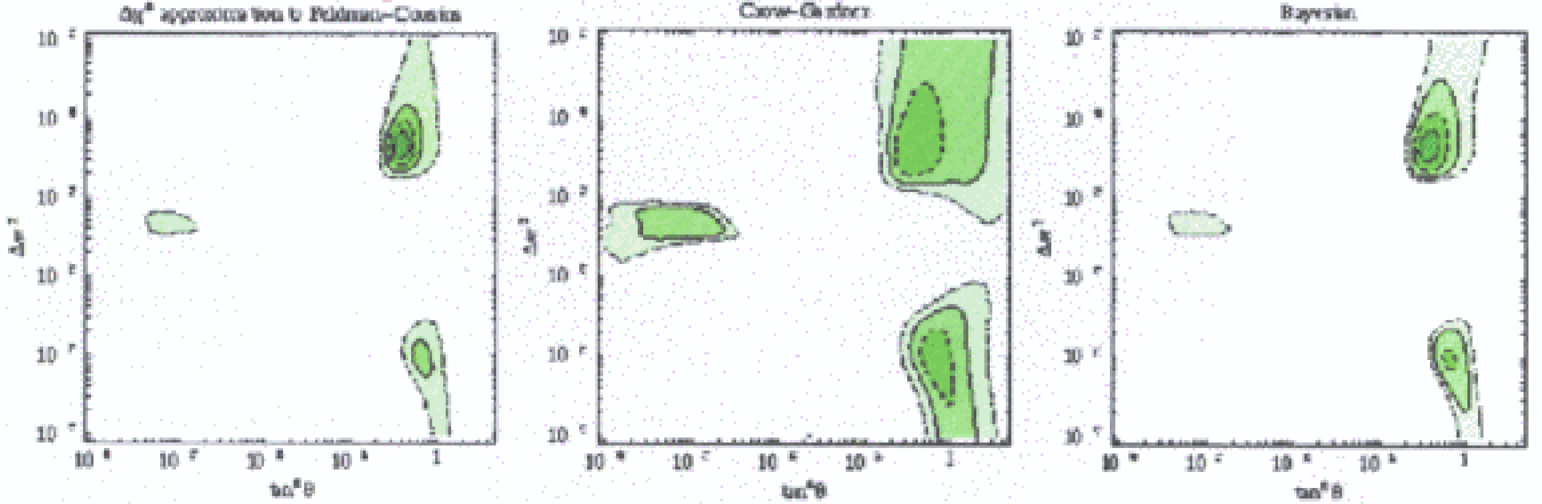
(Bahcall + Krastev + Smirnov)

Best Oscillation Fits to Solar ν Data



(Bahcall + Krastev
+ Smirnov)

Comparing Statistical Treatments of Solar ν Data



↑
too much weight
to inessential
data

(Creminelli +
Signorelli +
Strumia
hep-ph/010

The Emerging Default Option ⇒ ISSUES

- 3 light ν — Can we exclude ν_s?
- hierarchical masses — { degenerate? / which order? }
- ~ bimaximal mixing — are SMA, VO allowed?

$$\begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

how to discriminate LMA, LOW

size of θ_{13}? CP?

- masses mainly Majorana — fixed by $\beta\beta_{0\nu}$?
- small dipole moments — measure?
- $\tau_\nu \gg$ age of Universe — see oscillation pattern?

How do we prove $m_\nu \neq 0$?

plenty of work for the ν factory!

2– Programme of Work for a ν Factory

ν oscillation studies

magnitude of θ_{13}

CP violation

MSW effects

sign of Δm^2_{23}

⋮

other physics

slow (stopped) μ physics

deep-inelastic ν (μ?) scattering

neutron physics

kaon physics

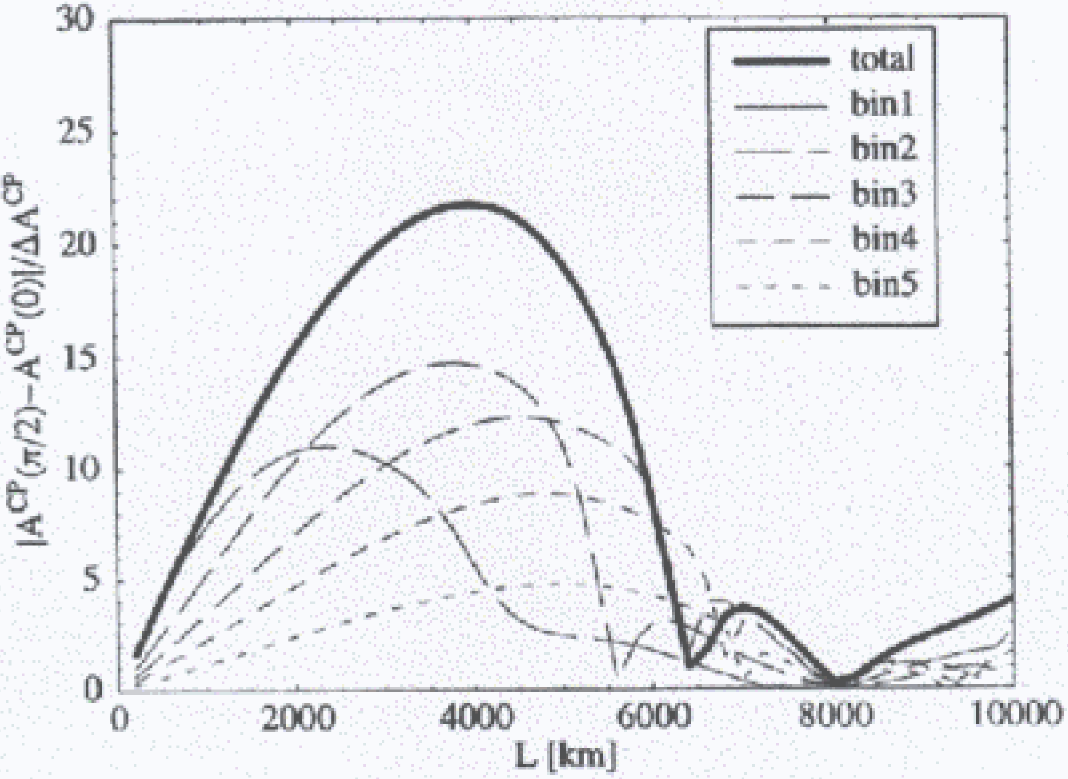
⋮

Signal/Noise for CP-Violating Asymmetry

@ ν factory

$\Delta m^2_{23} = 2{\cdot}8 \times 10^{-3}\ eV^2$ $\theta_{12} = 22{\cdot}5^\circ$ $\theta_{13} = 13^\circ$

$\Delta m^2_{12} = 1 \times 10^{-4}\ eV^2$ $\theta_{23} = 45^\circ$ $\delta = 90^\circ$

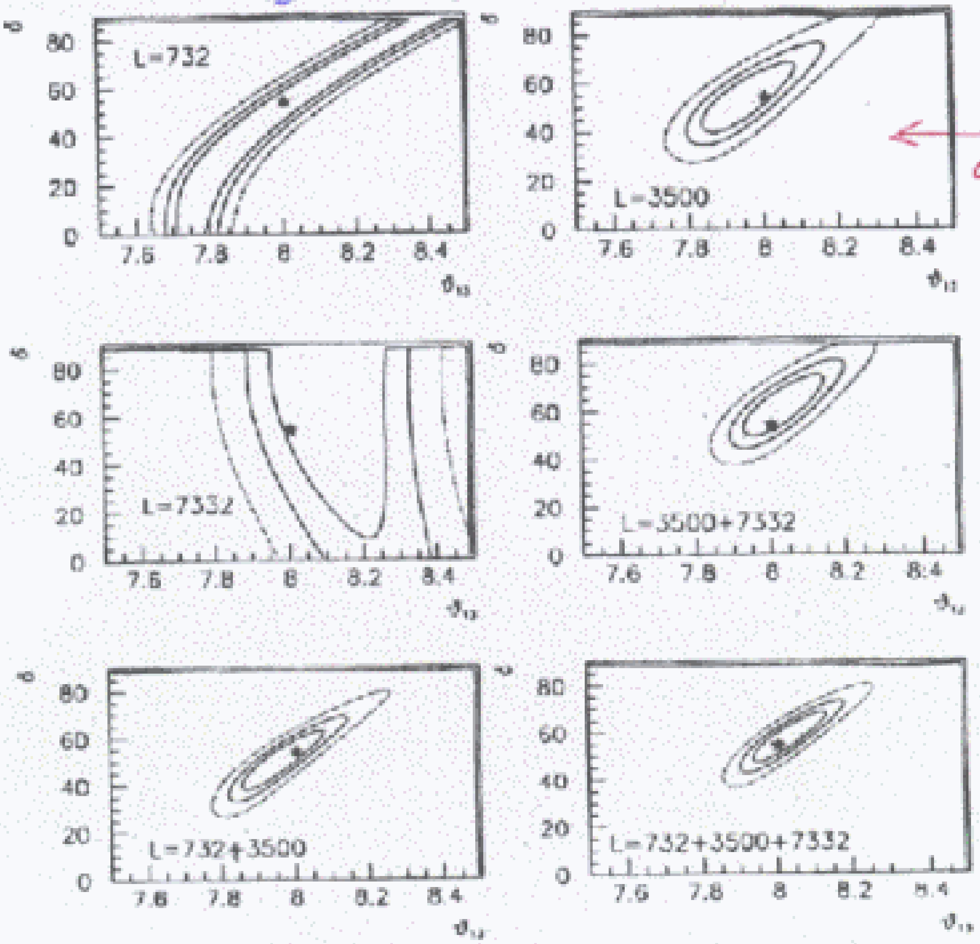


(Cervera et al.

CP-Violating Phase Measurements

@ ν factory

$\Delta m_{12}^2 = 10^{-4} eV^2$, $\Theta_{13} = 8°$, $\delta = 54°$



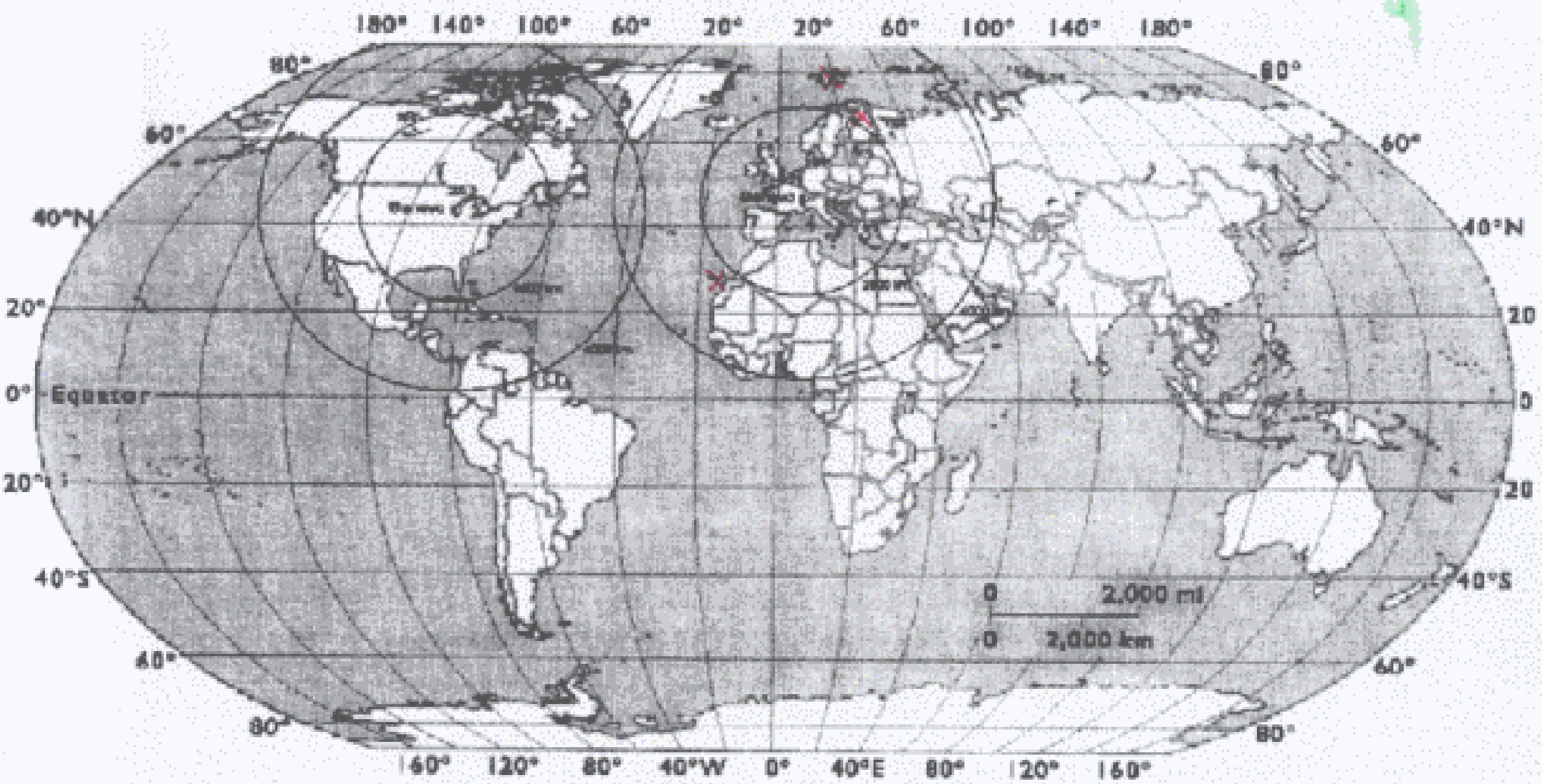
← good distance

including backgrounds, efficiencies

(Cervera et al.

Geography of Long-Baseline ν Beams

→ Canary Islands? Spitzbergen? N. Finland?



(Cervera et al.

5 Concept for a ν Factory

- intense proton source
    - linac @ 2GeV → rapid-cycling synchrotron
- accumulator/compressor ring
    - modify time structure
- target + horn system
    - $p \rightarrow \pi \rightarrow \mu$
- cooling and phase rotation
    - 'tame' μ beam
- recirculating linacs
    - accelerate μ → 20 to 50 GeV
- store and allow to decay
    - SBL + LBL + VLBL ?
- more cooling for muon collider?
    - Higgs factory: CP violation?
    - high-energy frontier?

A possible layout of a neutrino factory

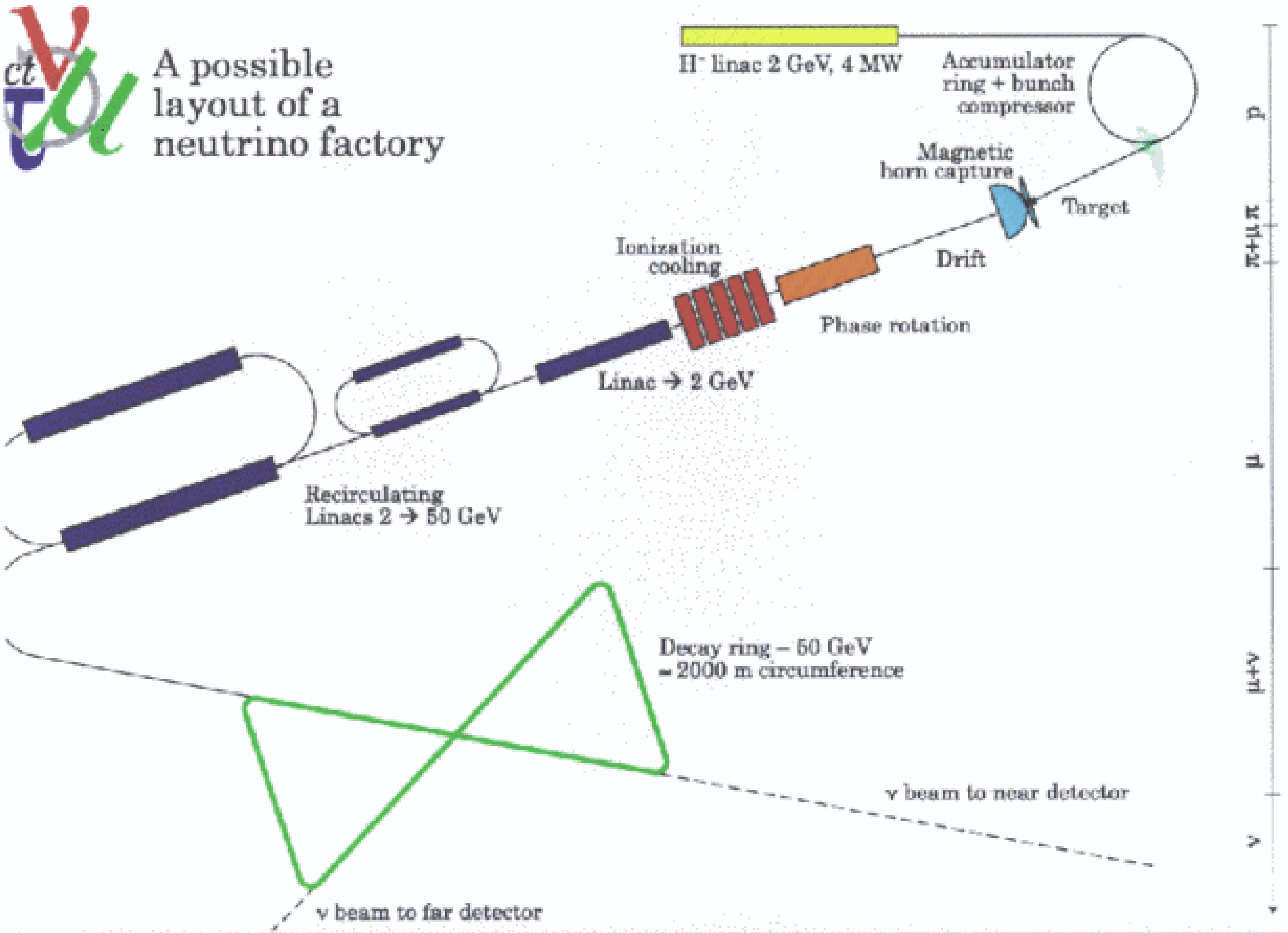
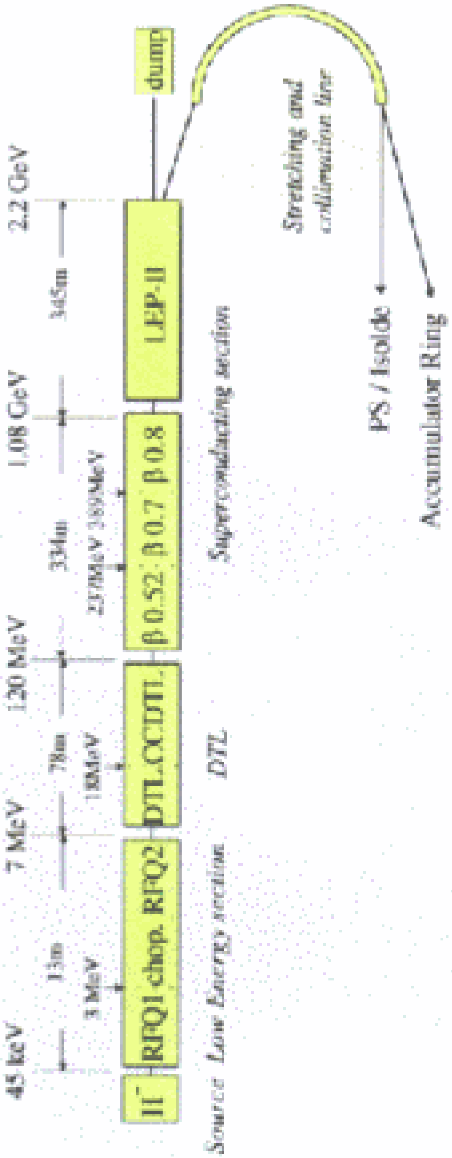


Table 4: Main linac design parameters.

Particles	H⁻
Kinetic energy	2.2 GeV
Mean current during pulse	11 mA
Repetition rate	75 Hz
Beam pulse duration	2.2 ms
Number of particles per pulse	1.5×10^{14}
Number of particles per second	1.1×10^{16}
Duty cycle	16.5%
Mean beam power	4 MW
RF and bunch frequency	352.2 MHz
Chopping factor	40%
Mean bunch current	18.4 mA
Overall length	799 m
Peak RF power	32 MW
Total main power	38 MW
Transverse r.m.s. emittance (norm.)	< 0.6 μm
Longitudinal r.m.s. emittance	< 0.6 π ° MeV < 15 μeVs
Bunch length at accumulator, total	0.5 ns
Energy spread at accumulator, total	0.4 MeV
Energy jitter at accumulator, between pulses (max.)	±2 MeV

(CERN report 2000-012, B. Autin et al.

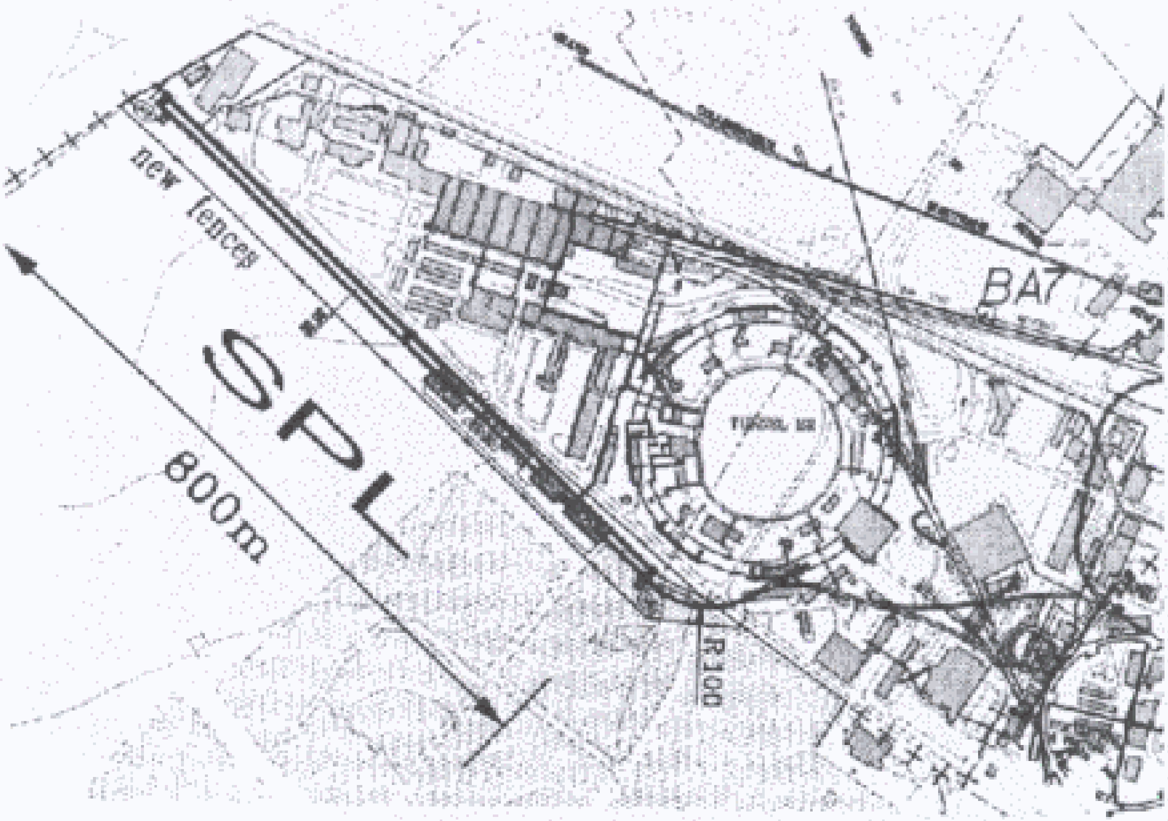
reuse LEP s.c. RF



(B.Autin et al.

Layout of the SPL.

Possible Layout of Proton Driver @ CERN

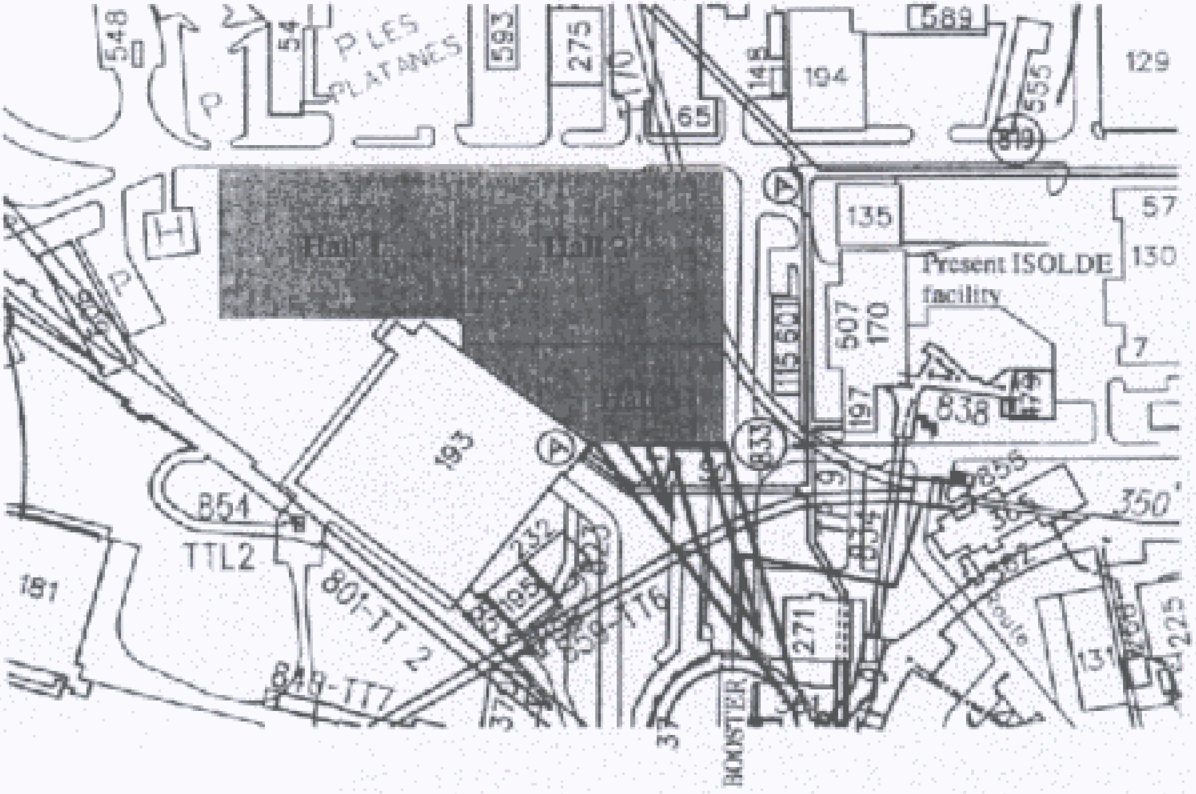


- better PS beams
- ISOLDE current x 5, new radioactive beam facility?
- better SPS beams: CNGS, ...
- better beams for LHC, shorter filling time

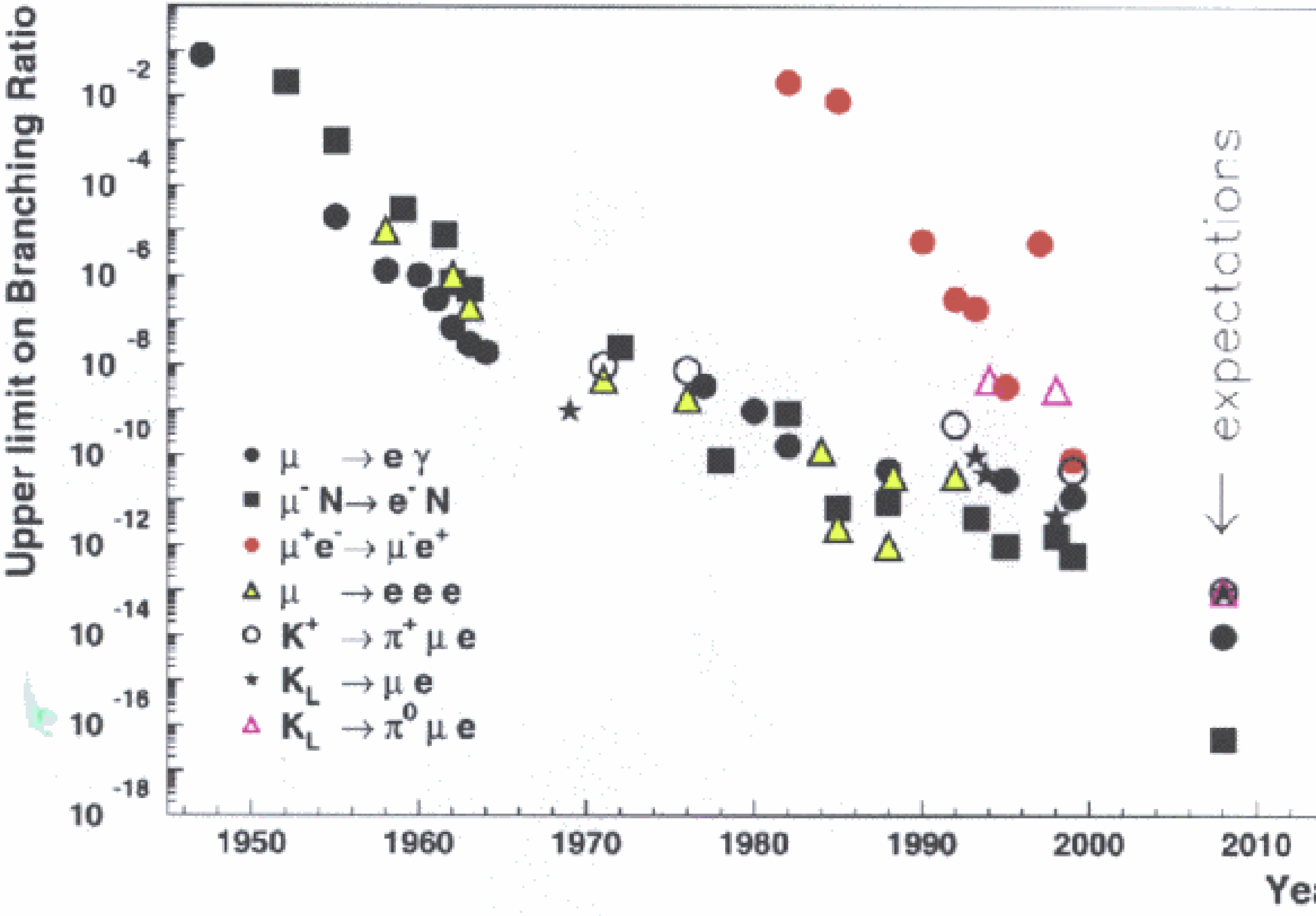
(B. Autin et al.

Possible Successor to ISOLDE

second-generation radioactive nuclear beam facility



(CERN 2000-012, Autin et al.



Searches for Lepton Number Violation

in the light of Super-K

mechanism in supersymmetric GUT:

renormalization of slepton mass matrix:

$$\delta\tilde{m}^2_L \simeq \frac{1}{16\pi^2}(3+A^2)\ln\left(\frac{M_{GUT}}{M_N}\right)\lambda_D^{+}\lambda_D m_0^2$$

trilinear coupling

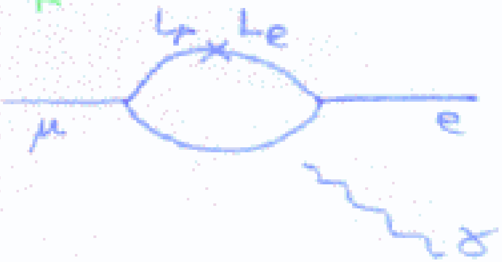
scales between M_{GUT}, M_{ν_R}

Dirac ν Yukawa coupling

contribution to

$\mu \to e\gamma$

$(\tau \to \mu\gamma, \tau \to e\gamma)$



and related processes:

$$\frac{\Gamma(\mu\to 3e)}{\Gamma(\mu\to e\gamma)} \simeq \frac{\alpha}{3\pi}\left[\ln\left(m_\mu^2/m_e^2\right)-\frac{11}{4}\right] = 0.007$$

$\mu N \to e N$ conversion

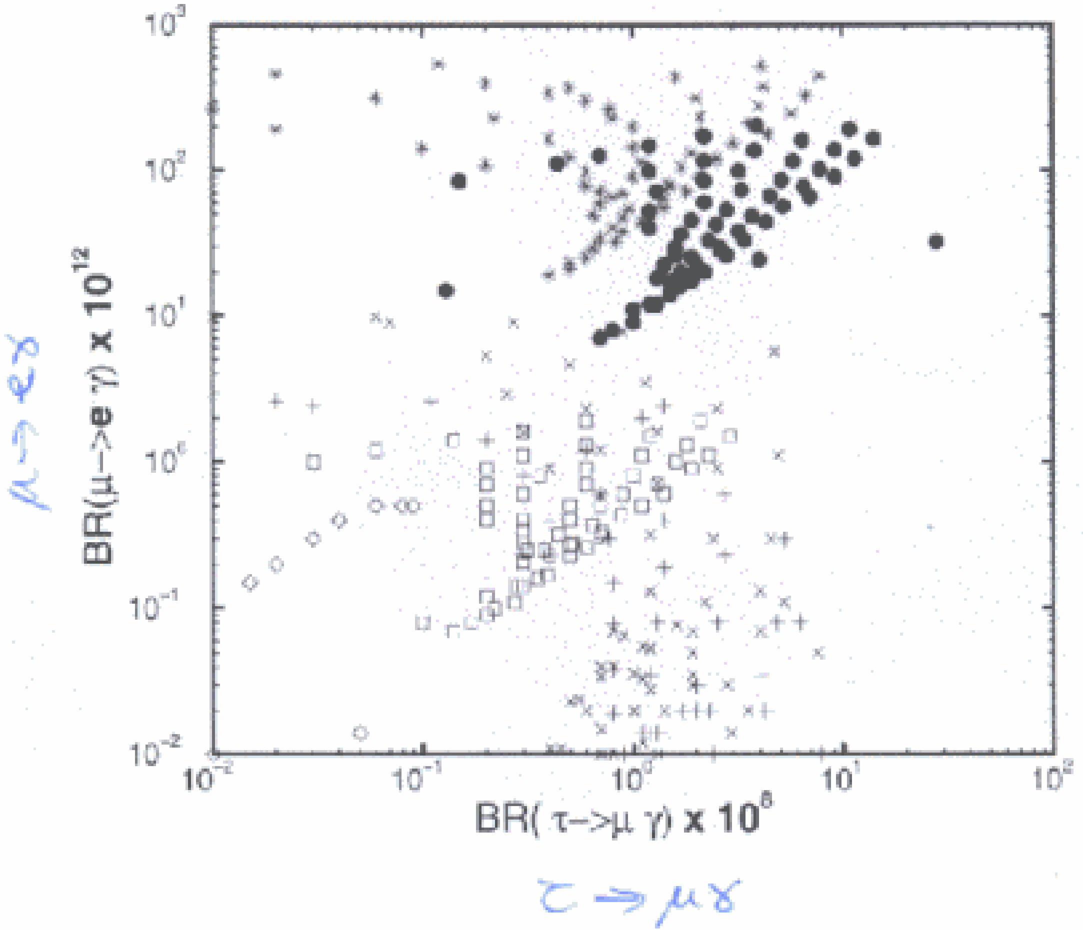
$\mu \to e\gamma$ may occur close to present experimental limit

within reach of next generation?

$\tau \to \mu\gamma$ may occur at rate $\gtrsim 10^{-9}$

accessible to ATLAS, CMS@LHC?

Charged-Lepton-Flavour Violation
in models inspired by Super-K

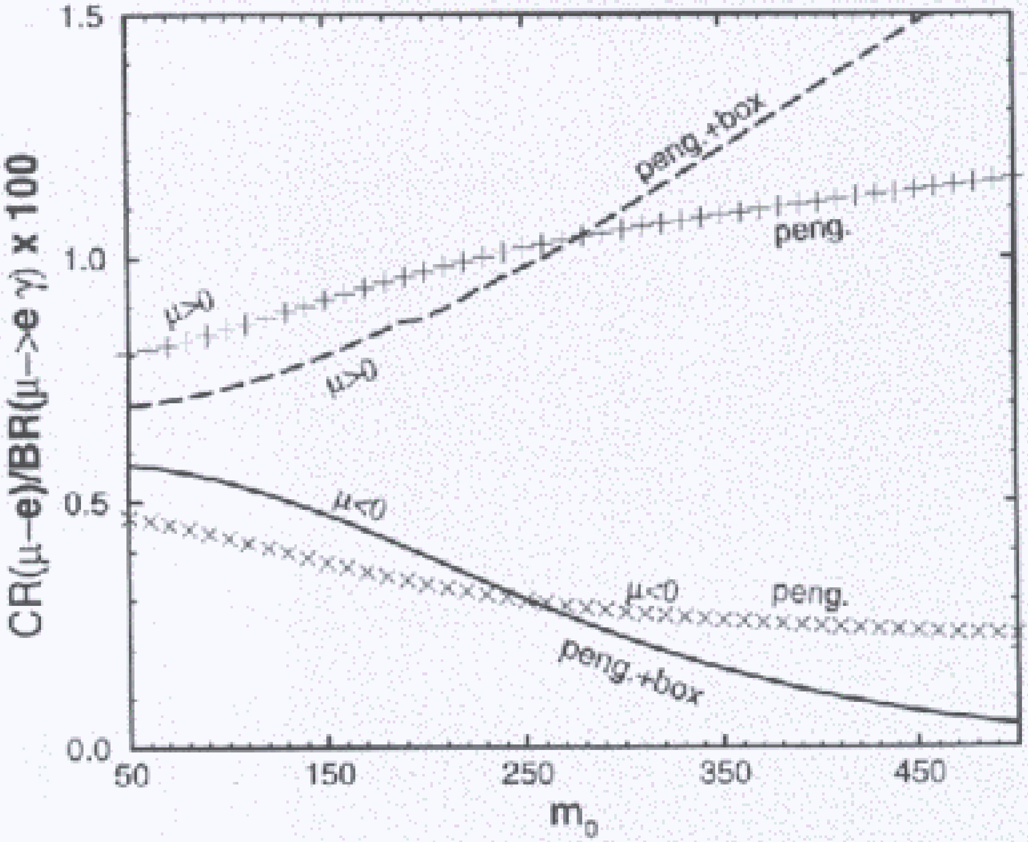


(J.E. + Gomez + Leontaris +
Lola + Nanopoulos:
hep-ph/9911459

$\mu \to e$ Conversion on nuclei vs $\mu \to e\gamma$

ratio depends on model parameters

typically ~ few x 10^{-3}



(J.E. + Gomez + Lola + Nanopoulos

Encouragement from $g_\mu - 2$

non-trivial vertex  @ scale ≤ 1 TeV

made by particles carrying L_μ 

ν oscillations ⇒ $\Delta L_\mu \neq 0$

⇒ expect analogous vertex 

concrete example: supersymmetry

(J.E.+Nanopoulos+Olive

⇒ measurement of $(g_\mu - 2)$ fixes sparticle mass scale ⇒ fix $\Gamma(\mu \to e\gamma)$ within given flavour texture

$g_\mu - 2$ within $\frac{1}{2}\sigma$

⇒ $B(\mu \to e\gamma)$ within $\frac{1}{2}$ order of magnitude

(Carvalho+J.E.+Gomez+Lola

$\mu \to 3e$, $\mu \to e$ conversion on nuclei

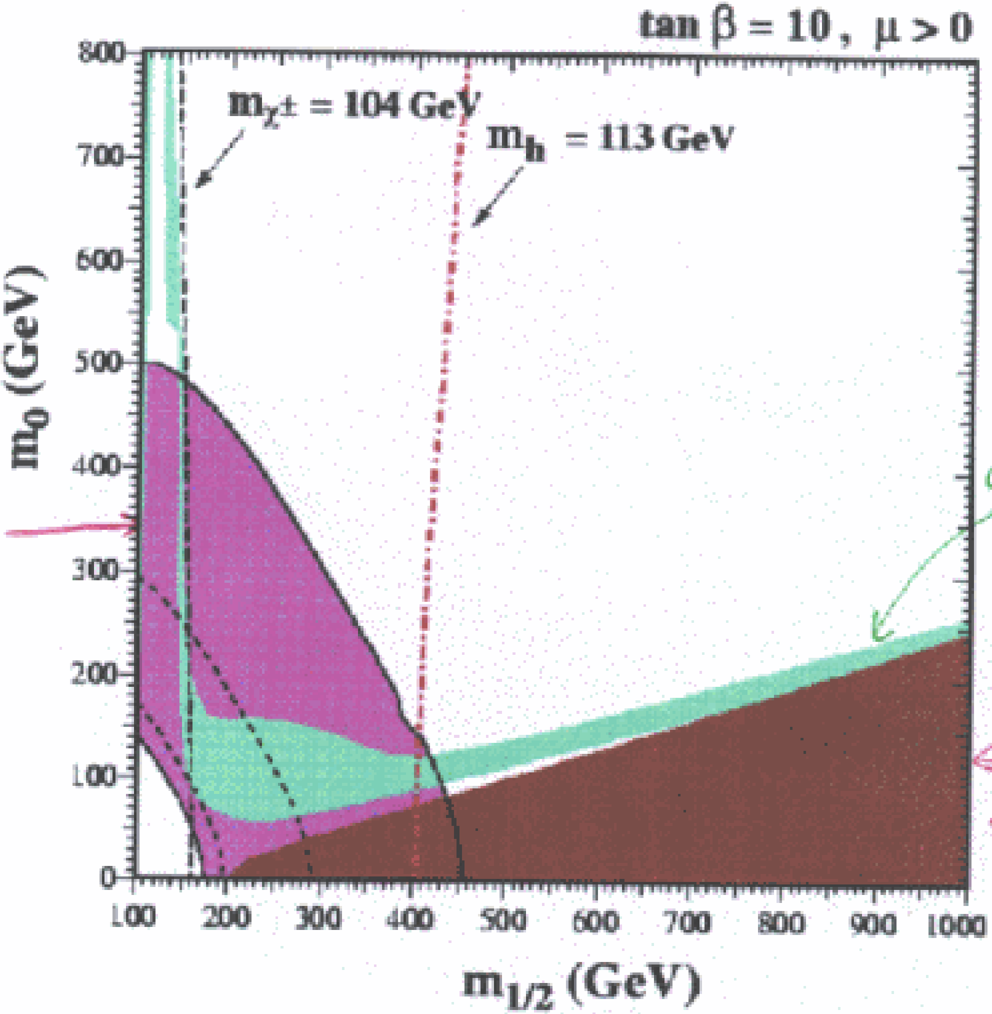
more opportunities to search for $\Delta L_\mu \neq 0$

theory, experimental problems different

$g_\mu - 2$ in CMSSM

universal susy× parameters

$m_0, m_{1/2}$ (A)

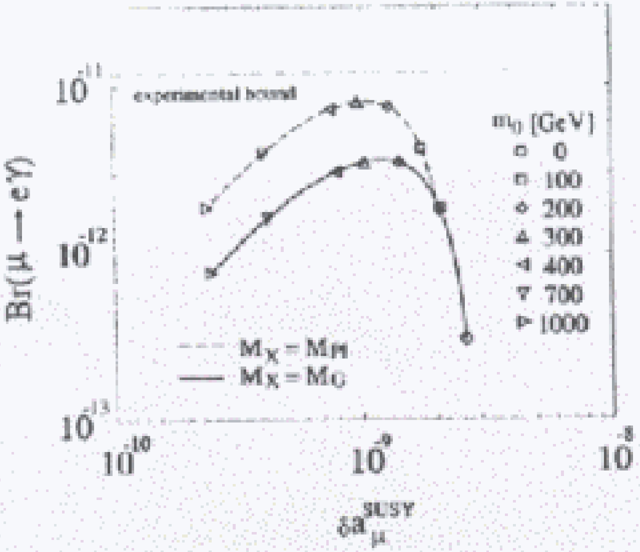


$g_\mu - 2$ →

cosmology

← $m_{\tilde\tau} < m_\chi$ excluded

(J.E.+Nanopoulos+Olive



sample flavour texture

Figure 1: $Br(\mu \to e\gamma)$ and δa_μ^{SUSY} as a function of universal mass m_0. Here we take $V_{13} = 0.01$, $V_{23} = 1/\sqrt{2}$, $\tan\beta = 10$ and $M_2 = 250$ GeV. We assume unification between the top-quark and tau-neutrino Yukawa couplings ($m_t = 175$ GeV and $m_{\nu_\tau} = 0.055$ eV). The solid and dashed lines are for cases where the scale for the generation of the SUSY-breaking terms in the SUSY SM (M_X) are the GUT scale and the reduced Planck scale, respectively.

dependence on texture →

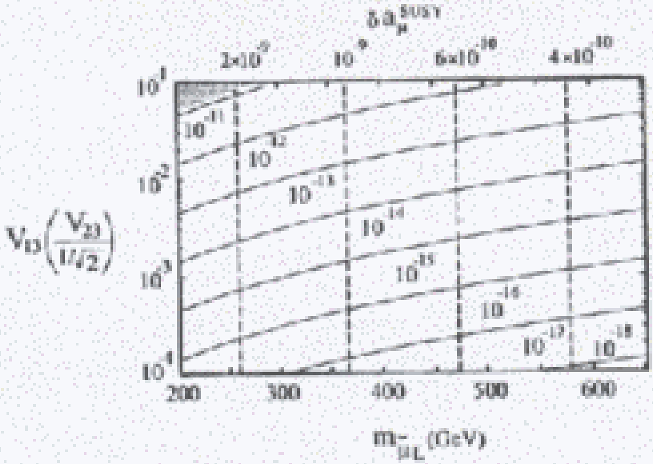
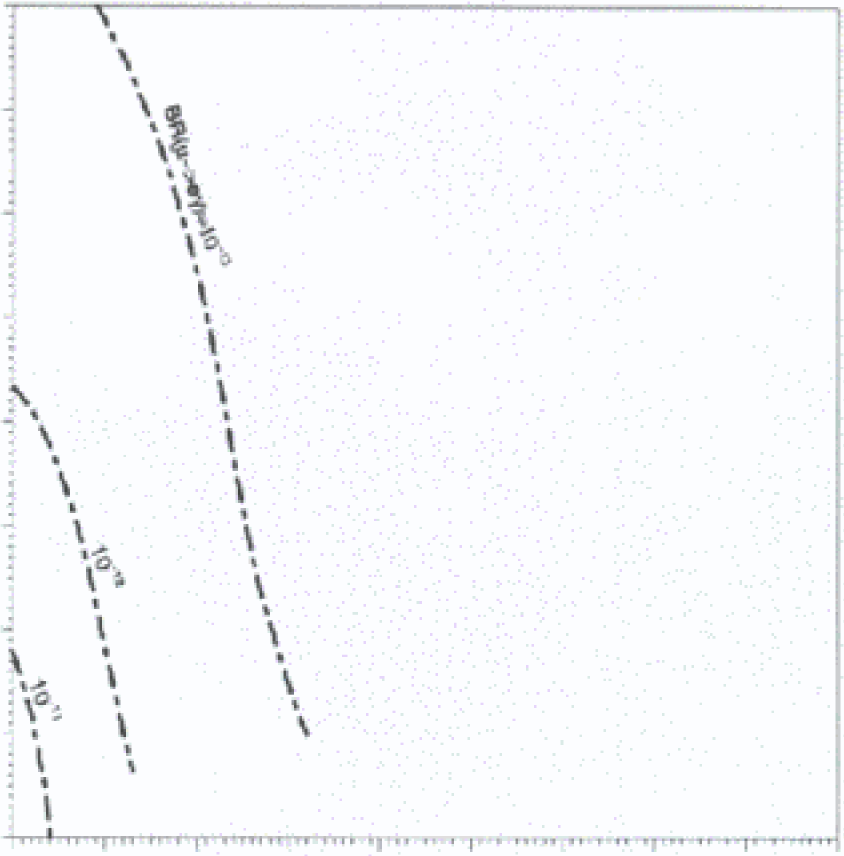


Figure 3: $Br(\mu \to e\gamma)$ as a function of $V_{13}V_{23}$ and the left-handed smuon mass or δa_μ^{SUSY} assuming $\tan\beta = 10$. We impose the no-scale condition ($m_0 = 0$) at the GUT scale. Unification between the top-quark and tau-neutrino Yukawa couplings is assumed as in Fig. 1. In typical models, $V_{13} \gtrsim 10^{-2}$, as listed in Table 1.

(Hisano+Tobe

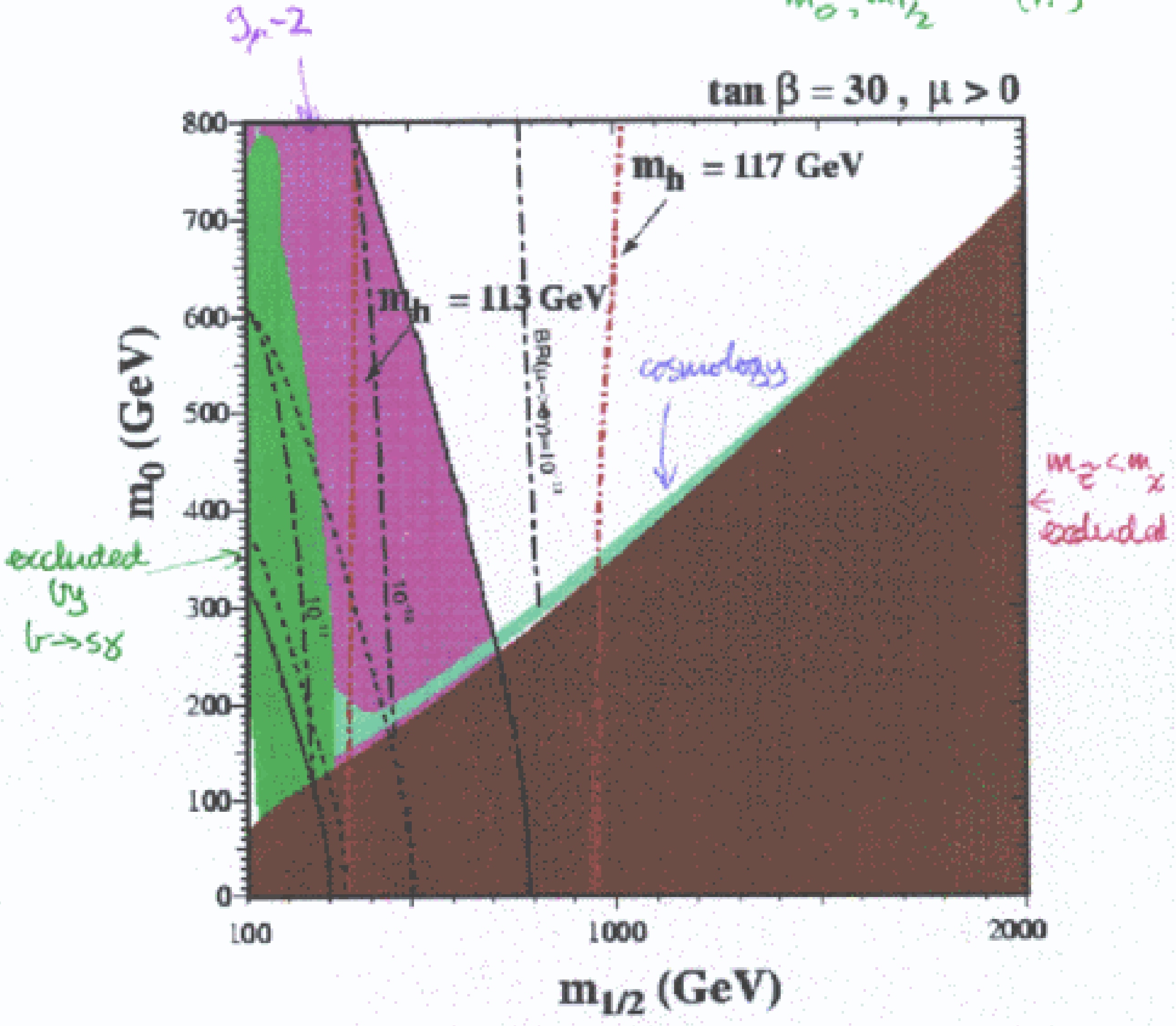


contours of $\mu \to e \gamma$ in
SK-motivated ν mass texture

(Carvalho + J.E. + Gomez + Lola

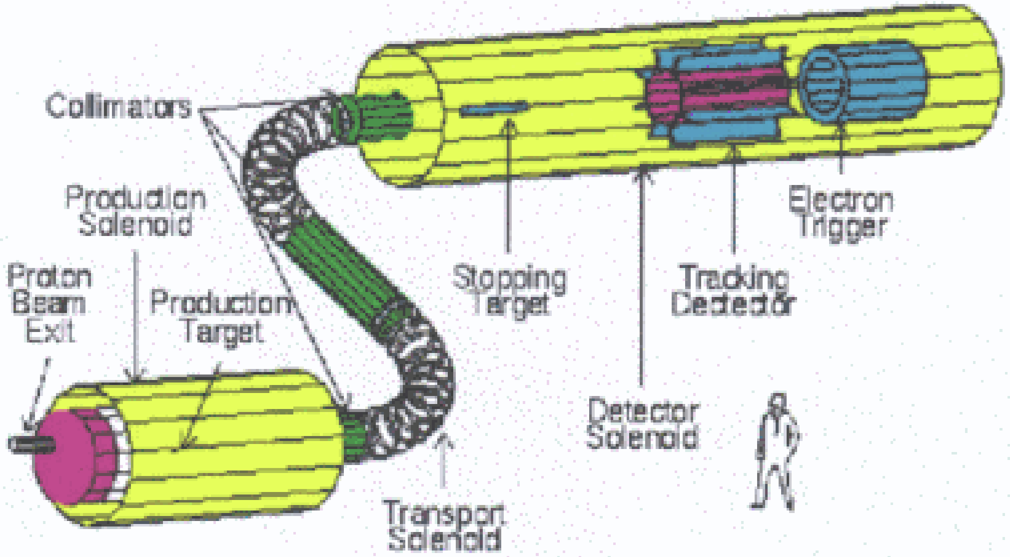
g_μ-2 and $\mu \to e\gamma$ in CMSSM

universal susy x parameters
m_0, $m_{1/2}$ (A)



(Carvalho + J.E. + Gomez + Lola

Next-Generation $\mu \to e$ Conversion Expt



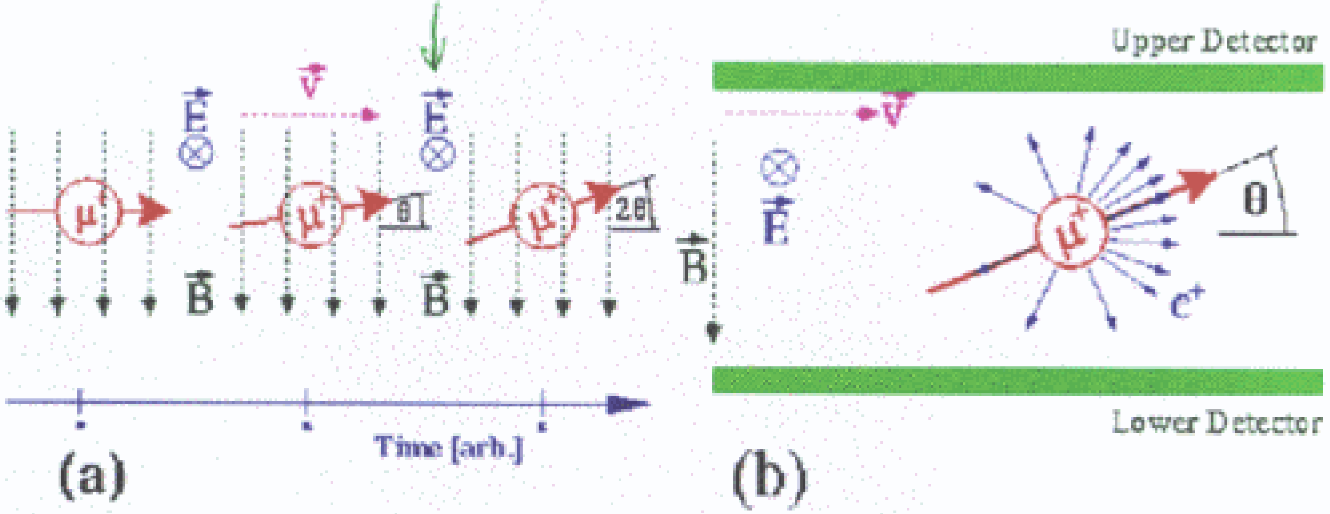
$$\frac{\mu N \to e N}{\mu N \to \nu N} \longrightarrow 10^{-16}$$

(MECO @ BNL

Principle of Experiment to Measure Electric Dipole Moment of μ

$\underline{E}$ causes precession of μ spin

decay asymmetry



(Giudice et al.

Physics of Muonic Atoms

TABLE 1. Some possibilities for laser spectroscopy of muonic atoms. The potential is given for line centers determined to 1 part in 10^5. (From [10]).

System & Transition	Laser System & Frequency	Physics Interest and Potential
Muonium $1S-2S$	CW dye/diode laser with an enhancement cavity 2×1228.5 THz	Measures Lamb shift (without nuclear structure effects), QED recoil, μ^+ mass. Improve current 0.8 % Lamb shift and 5 ppm μ^+ mass determinations by several orders of magnitude.
Muonic ^{4}He ion $2S-2P$	Dye or Ti:Sapphire 369.6, 334.2 THz	Test QED vacuum polarization. Improve current 0.2% α-particle charge radius measurement by two orders of magnitude.
Muonic ^{4}He ion $3D-3P$	Carbon dioxide 30.4 THz	Probes QED vacuum polarization (insensitive to nuclear structure). Sensitivity of 1/5 of linewidth would provide new test of vacuum polarization. Potential for factor 200 more.
Muonic Hydrogen $2S-2P$	Carbon monoxide or nonlinear mixing 48.4 THz	Measures proton charge radius, polarizability, QED vacuum polarization. PSI aims at a 500 MHz measurement, giving $\langle r_p^2\rangle^{1/2}$ to a few parts in 10^4.
Muonic Hydrogen $1S, F=0, F=1$	Difference frequency generation 43.9 THz	Measures proton charge radius and polarizability. A 10 GHz uncertainty determines $\langle r_p^2\rangle^{1/2}$ to about 2%. Potential for five more orders of magnitude.
Muonic Hydrogen $3D-3P$	Free electron laser 1.6 THz	Probes QED vacuum polarization (insensitive to nuclear structure). Potential for 6 ppm test of vacuum polarization, an improvement of 1000 over current tests.

(Kawall et al.: AIP 435)

Beam Requirements for Low-Energy μ Experiments

possible at front end of ν factory

Experiment	q_μ	$\int I_\mu dt$	I_0/I_μ	δT [ns]	ΔT [ns]	E_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- N \to e^- N^\dagger$	$-$	10^{19}	$< 10^{-9}$	≤ 100	≥ 1000	< 20	1...5
$\mu^- N \to e^- N^\ddagger$	$-$	10^{19}	n/a	continuous	continuous	< 20	1...5
$\mu \to e\gamma$	$+$	10^{17}	n/a	continuous	continuous	1...4	1...5
$\mu \to eee$	$+$	10^{17}	n/a	continuous	continuous	1...4	1...5
$\mu^+ e^- \to \mu^- e^+$	$+$	10^{18}	$< 10^{-4}$	< 1000s	≥ 20000	1...4	1...2
τ_μ	$+$	10^{14}	$< 10^{-4}$	< 100	≥ 20000	4	1...10
transvers.polariz.	$+$	10^{16}	$< 10^{-4}$	< 0.5	> 20	430-40	1...3
$g_\mu - 2$	$\pm$	10^{15}	$< 10^{-7}$	≤ 50	$\geq 10^6$	3100	10^{-4}
edm_μ	$\pm$	10^{16}	$< 10^{-6}$	≤ 50	$\geq 10^6$	≤ 1000	$\leq 10^{-5}$
M_{HFS}	$+$	10^{15}	$< 10^{-4}$	≤ 1000	≥ 20000	4	1...3
M_{1s2s}	$+$	10^{14}	$< 10^{-3}$	≤ 500	$\geq 10^6$	1...4	1...2
μ^- atoms	$-$	10^{14}	$< 10^{-3}$	≤ 500	≥ 20000	1...4	1...5
condensed matter (incl.bio sciences)	$\pm$	10^{14}	$< 10^{-3}$	< 50	≥ 20000	1...4	1...5

$\mu \to e$ conv^n (

$\mu \to e\gamma$

$\mu \to 3e$

$g_\mu - 2$

d^e_μ

μSR

pulse length

pulse separation

(Giudice et a

5- Neutrino Deep-Inelastic Scattering

needs μSR , at short baselines

Very large rates in small detectors

↖ polarized target?
Si vertex detectors?

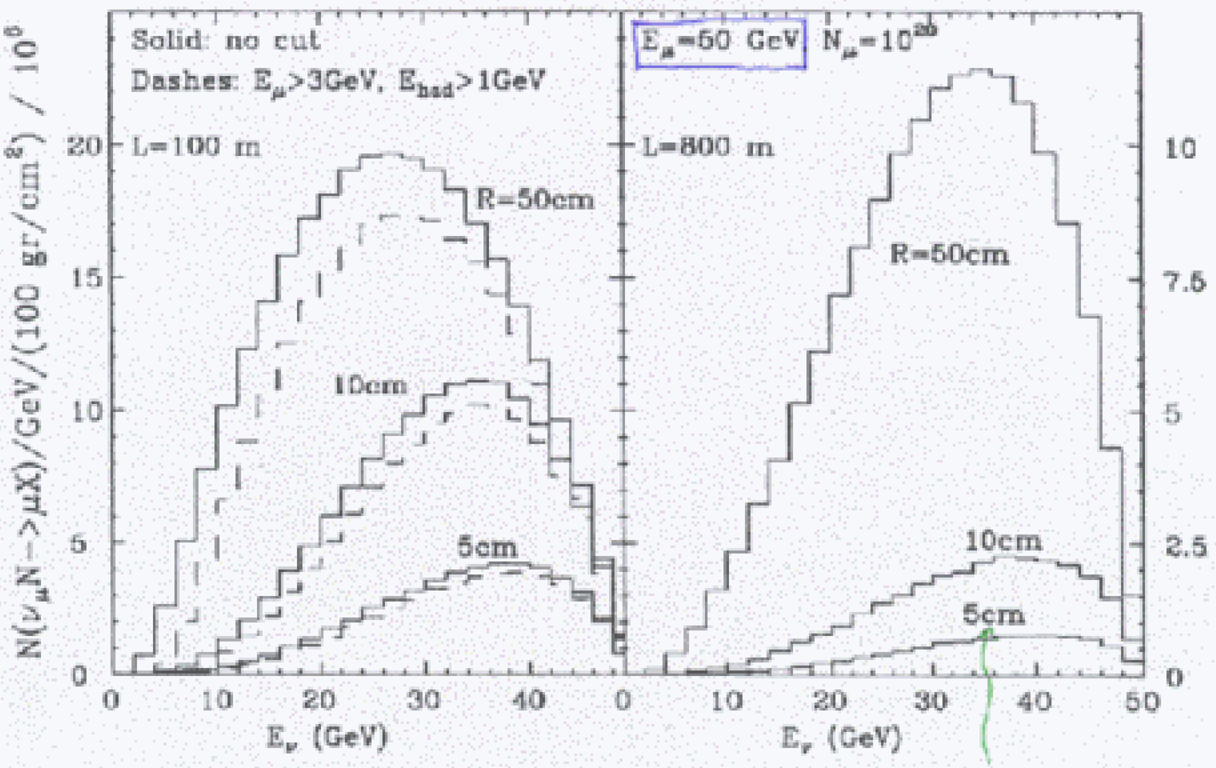
- $> 10^8$ events , all x, y
- measure 'difficult' structure functions
  ↳ e.g. $s(x) - \bar{s}(x)$
- polarized structure functions

$$\sigma^{\nu,\bar{\nu}}_{p\uparrow, p\downarrow} \Rightarrow g_1, g_2, g_3, g_4, g_5$$

$$(g_1^{\nu})_p = \Delta u + \Delta d + \Delta s \, (+\Delta c) \qquad (g_5)^{\nu-\bar{\nu}}_{p+n} = \Delta s \, (-\Delta c)$$

- tag heavy quark production
  measure V_{cs} , V_{cd}
- measure α_s stat $\pm$ 0.0003
- measure $\sin^2\theta_W$ stat $\pm$ 0.0002

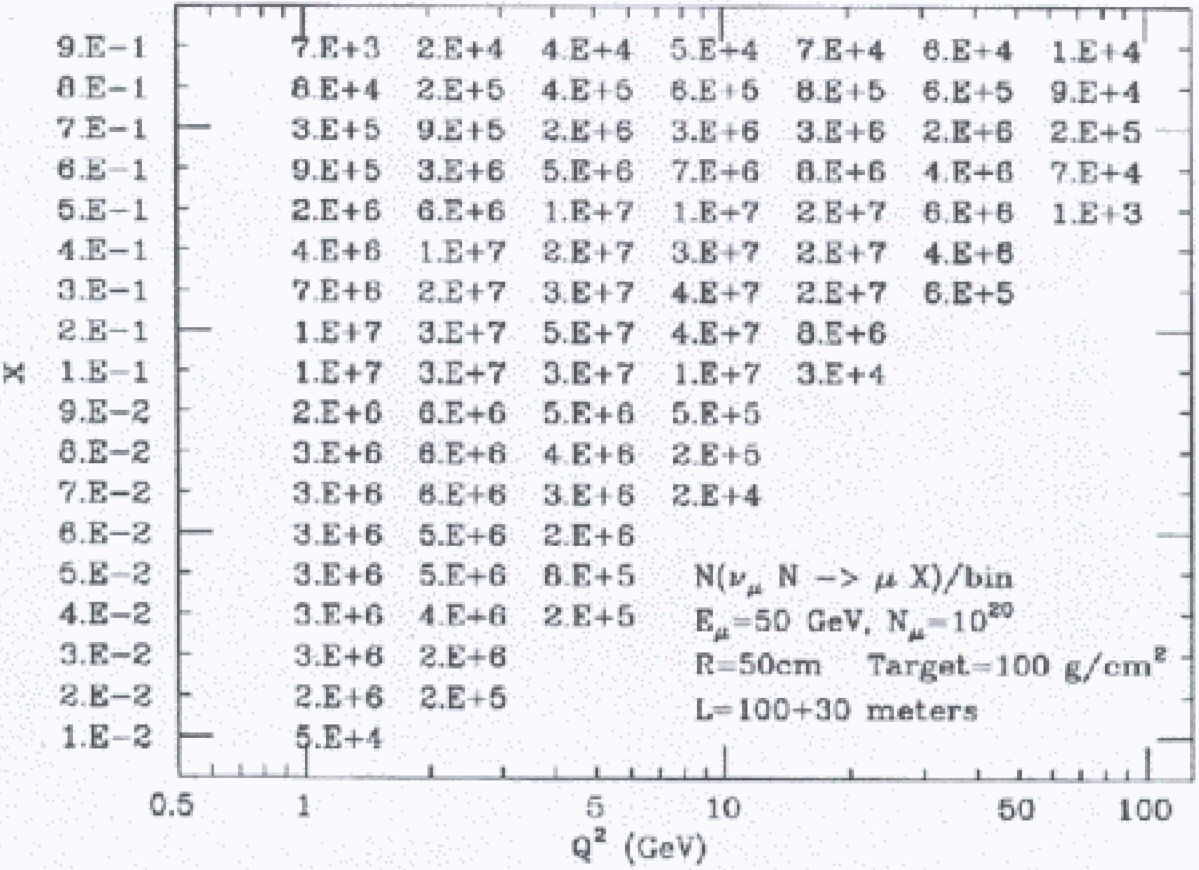
Deep-Inelastic Scattering Rates



radius of detector

(Mangano et al.

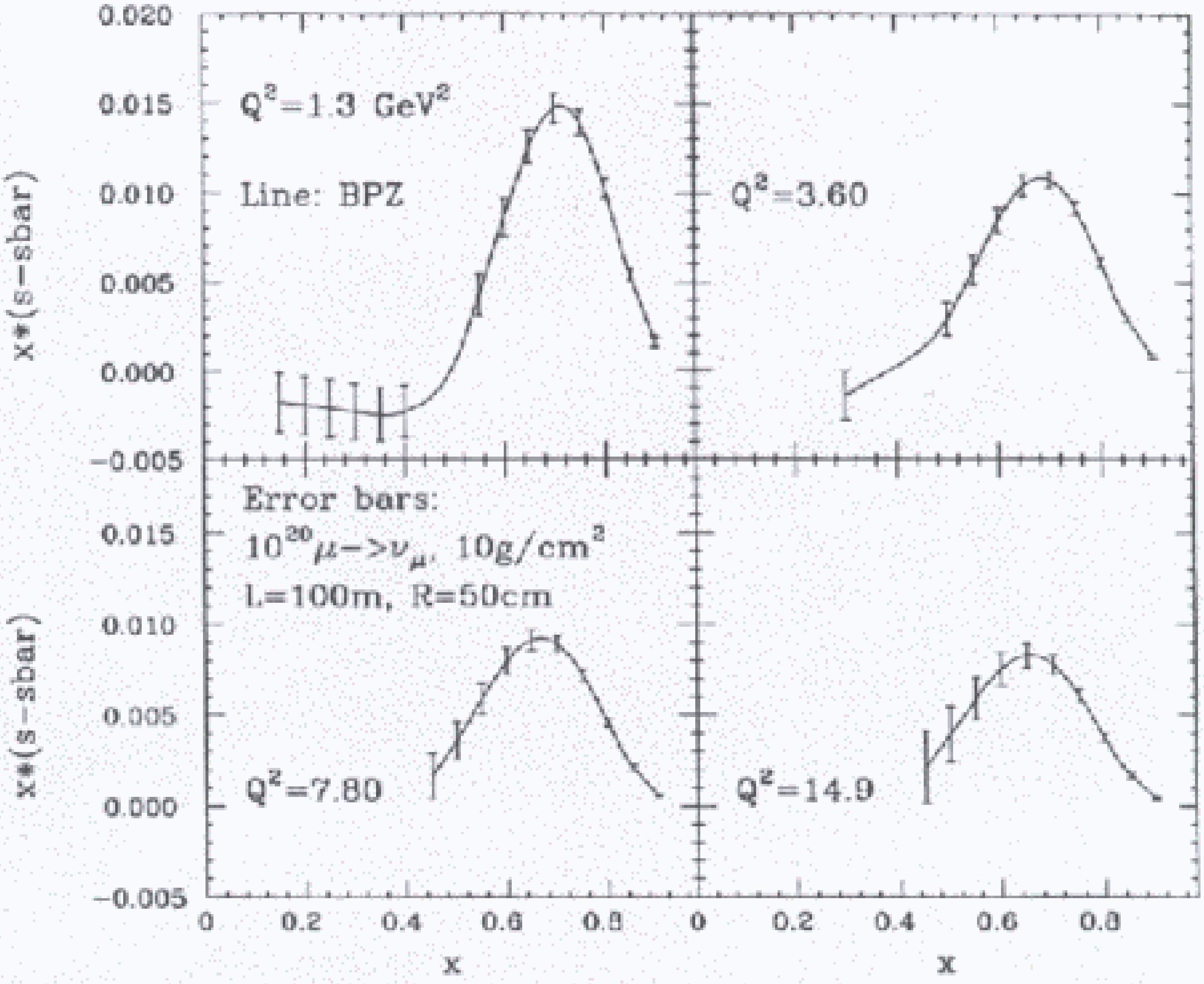
Differential Scattering Rates



9.E−1	7.E+3	2.E+4	4.E+4	5.E+4	7.E+4	6.E+4	1.E+4
8.E−1	8.E+4	2.E+5	4.E+5	6.E+5	8.E+5	6.E+5	9.E+4
7.E−1	3.E+5	9.E+5	2.E+6	3.E+6	3.E+6	2.E+6	2.E+5
6.E−1	9.E+5	3.E+6	5.E+6	7.E+6	8.E+6	4.E+6	7.E+4
5.E−1	2.E+6	6.E+6	1.E+7	1.E+7	2.E+7	6.E+6	1.E+3
4.E−1	4.E+6	1.E+7	2.E+7	3.E+7	2.E+7	4.E+6	
3.E−1	7.E+6	2.E+7	3.E+7	4.E+7	2.E+7	6.E+5	
2.E−1	1.E+7	3.E+7	5.E+7	4.E+7	8.E+6		
1.E−1	1.E+7	3.E+7	3.E+7	1.E+7	3.E+4		
9.E−2	2.E+6	6.E+6	5.E+6	5.E+5			
8.E−2	3.E+6	6.E+6	4.E+6	2.E+5			
7.E−2	3.E+6	6.E+6	3.E+6	2.E+4			
6.E−2	3.E+6	5.E+6	2.E+6				
5.E−2	3.E+6	5.E+6	6.E+5				
4.E−2	3.E+6	4.E+6	2.E+5				
3.E−2	3.E+6	2.E+6					
2.E−2	2.E+6	2.E+5					
1.E−2	5.E+4						

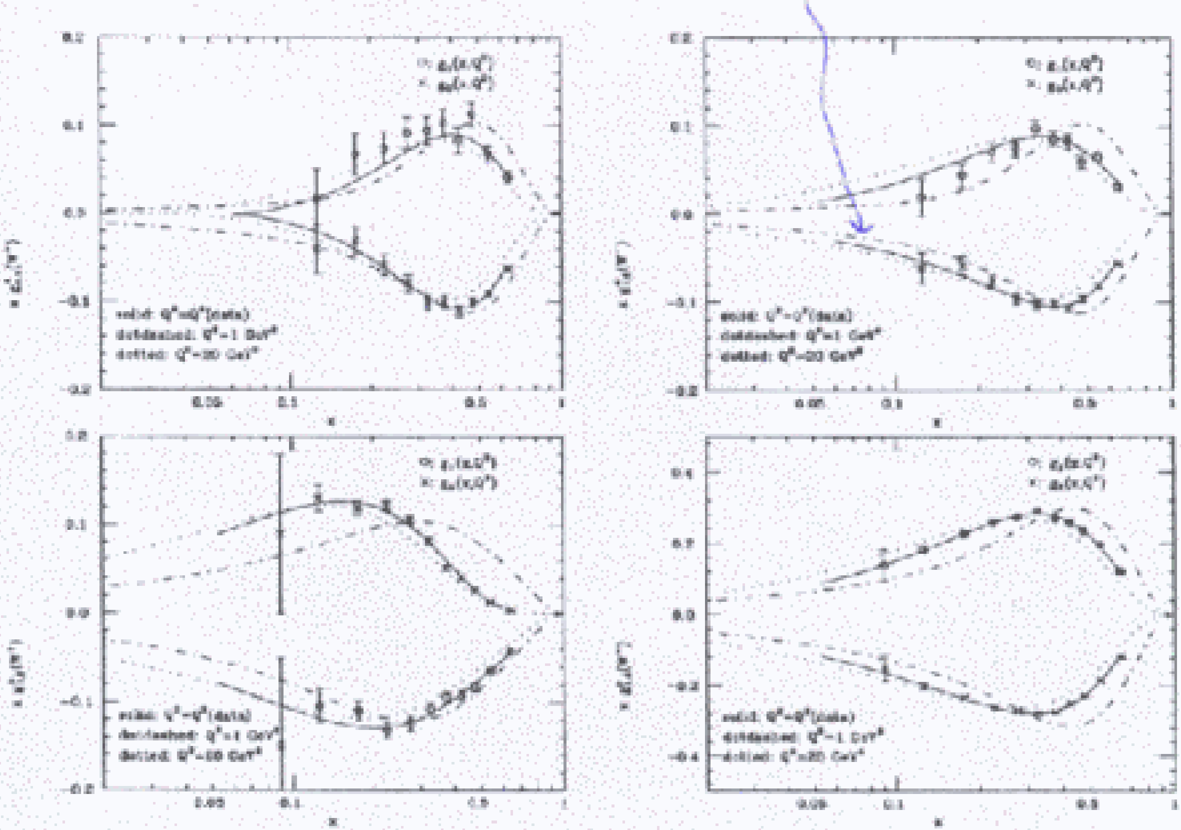
(Mangano et al.

Measuring $s(x) - \bar{s}(x)$



Polarized Structure Functions

g_4, g_5



6 High-Intensity Kaon Physics

needs high-E driver, or p post-accelerator

(Buchalla et al.

$K_L^0 \to \pi^0 \bar{\nu} \nu$

measures $\mathrm{Im}\, V_{ts}^* V_{td}$, complementary to $\sin 2\beta$

expect $BR = (2{\cdot}8 \pm 1{\cdot}1) \times 10^{-11}$

aim at 10% measurement

$K^+ \to \pi^+ \bar{\nu} \nu$

measures $|V_{td}|$

combination $\Rightarrow \Delta(\sin 2\beta) = \pm 0{\cdot}07$

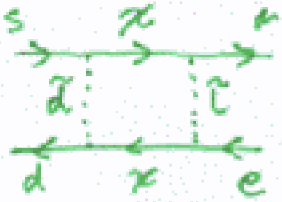
$K_L^0 \to \pi^0 e^+ e^-$

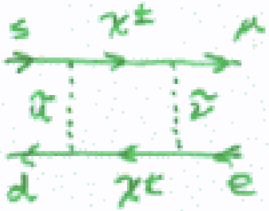
direct CP×, indirect CP×, CP conserving

$\mathrm{Im}\, V_{ts}^* V_{td}$ $\quad K_S \to \pi^0 e^+ e^-$ $\quad K_L^0 \to \pi^0 \gamma^* \gamma^* \to \pi^0 e^+ e^-$

← 10% measurement?

$K_L^0 \to \mu e$





expected in MSSM with $\boxed{\nu \text{ masses}}$

may not be negligible!

Charged-Lepton-Flavour Violation

$\tan\beta = 10$ $\tan\beta = 20$

$K \to \mu e$

$\mu \to e\gamma$

$\mu \to e$ conv^{n}

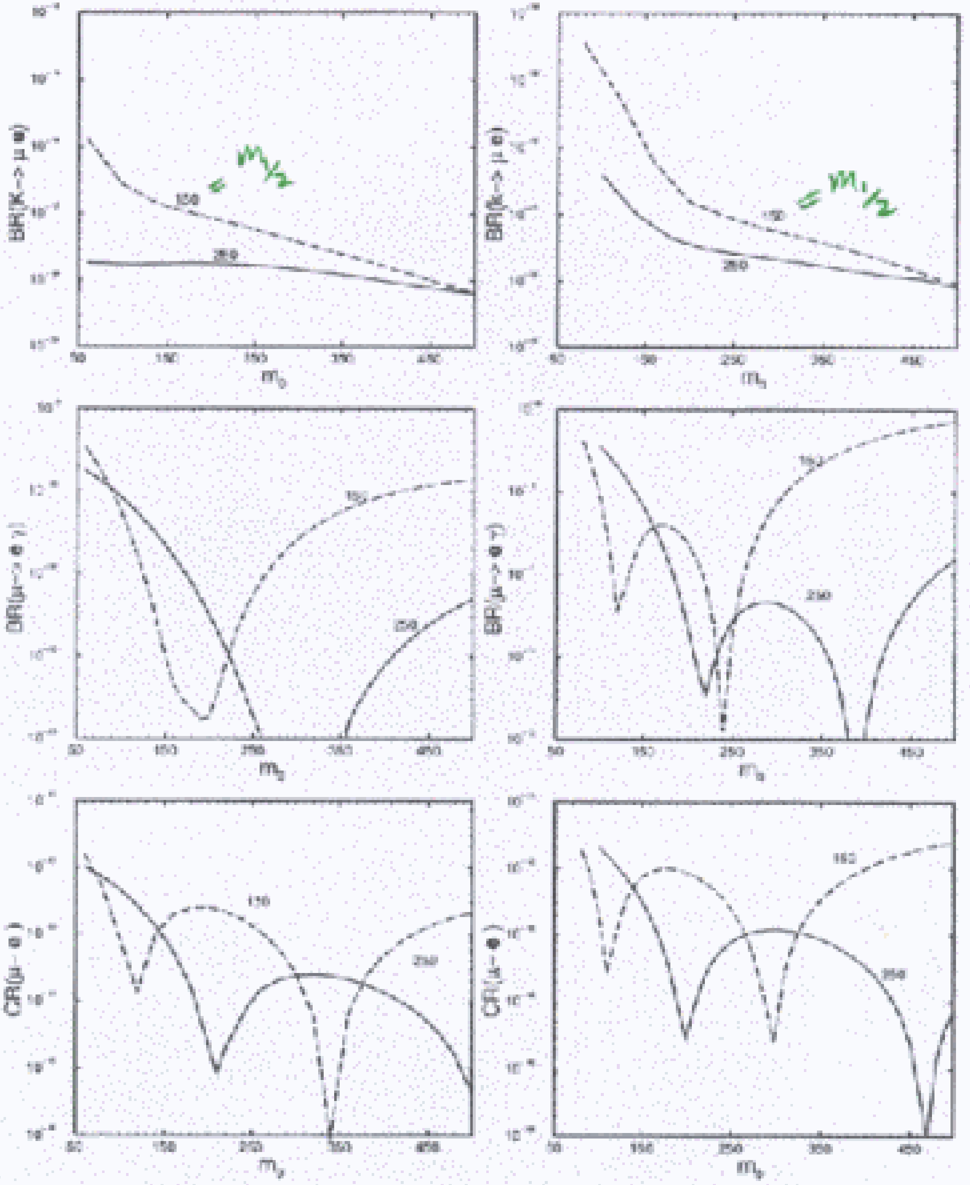


Figure 2: *Illustrative predictions for $BR(K \to \mu e)$, $BR(\mu \to e\gamma)$ and $BR(\mu - e)$ for different values of* $\tan\beta = 10$ *(left column), 20 (right column) and* $m_{1/2} = 150$ *(dashed lines), 250 GeV (solid lines), as functions of* m_0 *(in GeV).*

(Belyaev + Chizhov + Dorokhov + J.E + Gomez + Lola

Concluding Remarks

- LBL ν oscillation experiments are the 'core business' of a ν factory

  bears on fundamental theoretical issues

  possibilities for exciting experiments

- Many other exciting prospects

  (muon colliders Higgs factories, H.E. frontier)

- Low-energy μ physics @ front end

  $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion,

  $g_\mu - 2$, d^e_μ, ...

- Short-baseline neutrino physics

  DIS, ν-e ; deep-inelastic μ-N?

A ν factory is a complex (& expensive) project

ν physicicists likely to need support of others

We must work with other communities