NuFact 07

New Physics Searches with Beta Beams

Sanjib Kumar Agarwalla

Harish-Chandra Research Institute, Allahabad, India

work done in collaboration with

Rathin Adhikari, Subhendu Rakshit and Amitava Raychaudhuri

Phys.Lett.B642:111-118,2006

Phys.Lett.B647:380-388,2007

An ask : new motivation for LBL

Can upcoming long baseline neutrino experiments probe non-standard interactions (NSI) like $\not{R}$ supersymmetry?

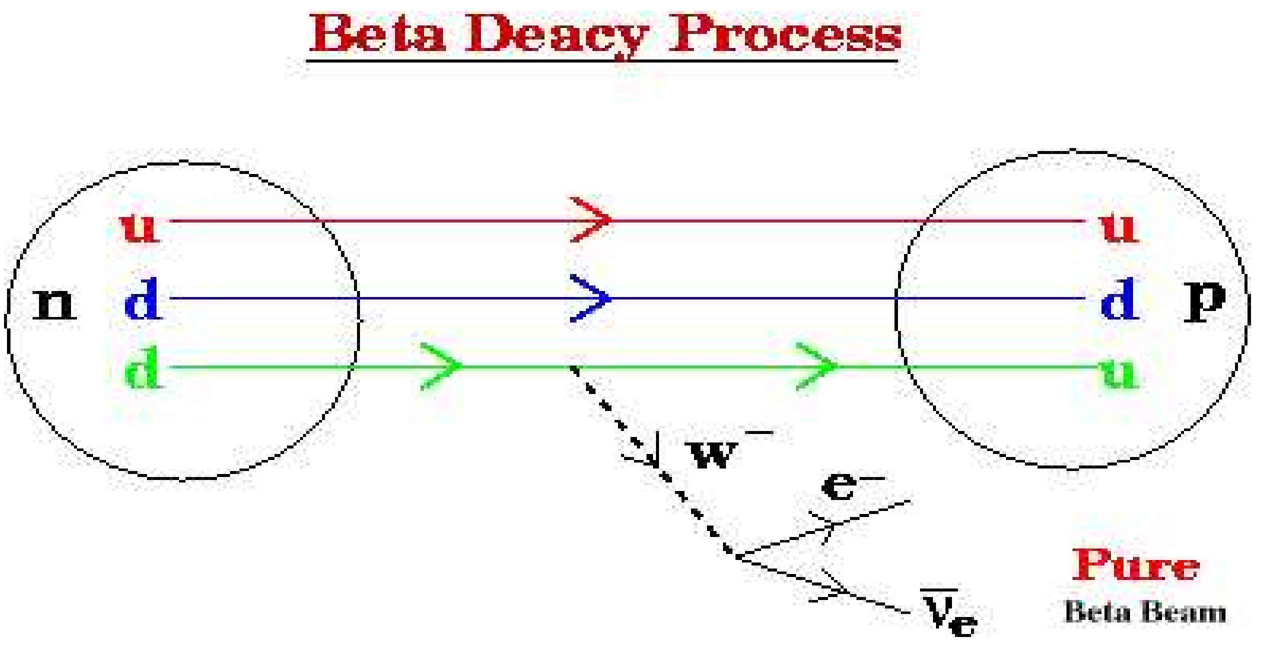
Can they become fatal in attempts to further sharpen the neutrino properties?

Can new physics leave its imprints at the production, detection or propagation stage of neutrinos?

Can a near or far detector play a crucial role in this direction?

What is Beta Beam?

A pure, intense, collimated beam of ν_e or $\bar{\nu}_e$, essentially background free



P. Zucchelli, Phys. Lett. B 532 (2002) 166

Beta decay of completely ionized, radioactive ions circulating in a storage ring. No contamination of other types of neutrinos

Some positive features

- **Known energy spectrum**
- **High intensity and low systematic errors**
- **High Lorentz boost of the parent ions $\Rightarrow$ better collimation and higher energy of beam**

Some positive features

- Known energy spectrum
- High intensity and low systematic errors
- High Lorentz boost of the parent ions ⇒ better collimation and higher energy of beam
- Can be produced with existing CERN facilities or planned upgrades
- It can be operated simultaneously in the ν_e as well as $\bar{\nu}_e$ mode. The boost factors are fixed by the e/m ratio of the respective ions

Beta Beam : Ion sources

Ion	τ (s)	E_0 (MeV)	f	Decay fraction	Beam
$^{18}_{10}$Ne	2.41	3.92	820.37	92.1%	ν_e
$^{6}_{2}$He	1.17	4.02	934.53	100%	$\bar{\nu}_e$
$^{8}_{5}$B	1.11	14.43	600684.26	100%	ν_e
$^{8}_{3}$Li	1.20	13.47	425355.16	100%	$\bar{\nu}_e$

Comparison of different source ions

Low-γ design, useful decays in case of anti-neutrinos can be 2.9×10^{18}/year and for neutrinos 1.1×10^{18}/year

Larger total end-point energy, E_0 is preferred

A possible experiment

CERN based β-beam neutrino source

+

The proposed India-based Neutrino Observatory (INO)

A baseline of $\sim$ 7152 Km (close to magic)

ν interacts with earth matter $\Rightarrow$

a possible test bed for NSI

!!! Matter does matter !!!

The India-based Neutrino Observatory

The INO/ICAL will be the world's first magnetized large mass iron calorimeter with interleaved Glass RPC detectors

Funding considerations in final stage

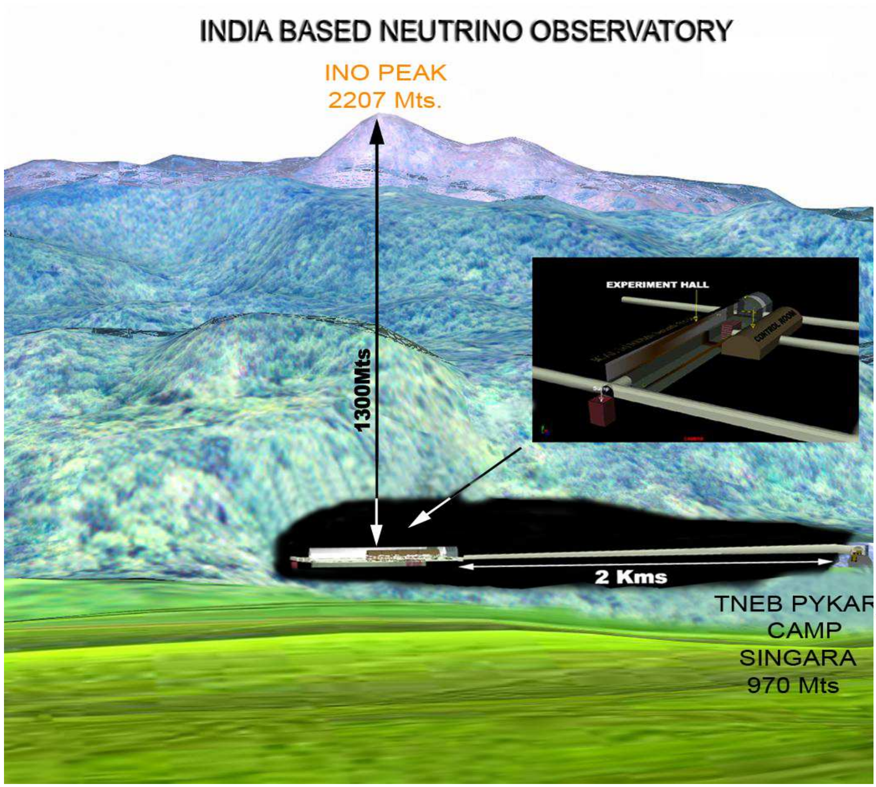
Location of INO

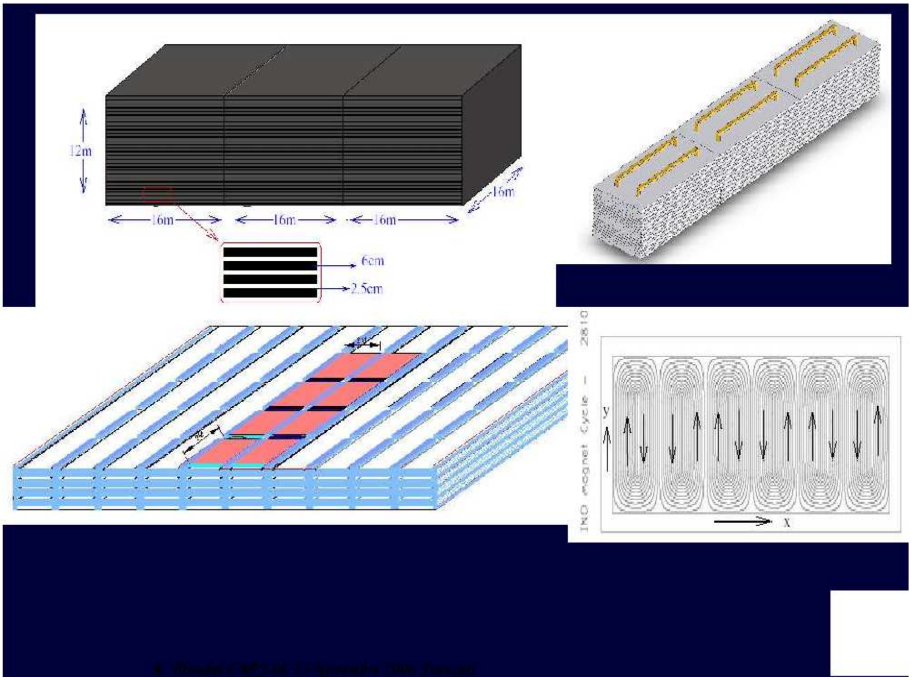
PUSHEP Site (Lat: N11.5°, Long: E76.6°)

PUSHEP-Bangalore: 250km

http://www.imsc.res.in/∼ino/

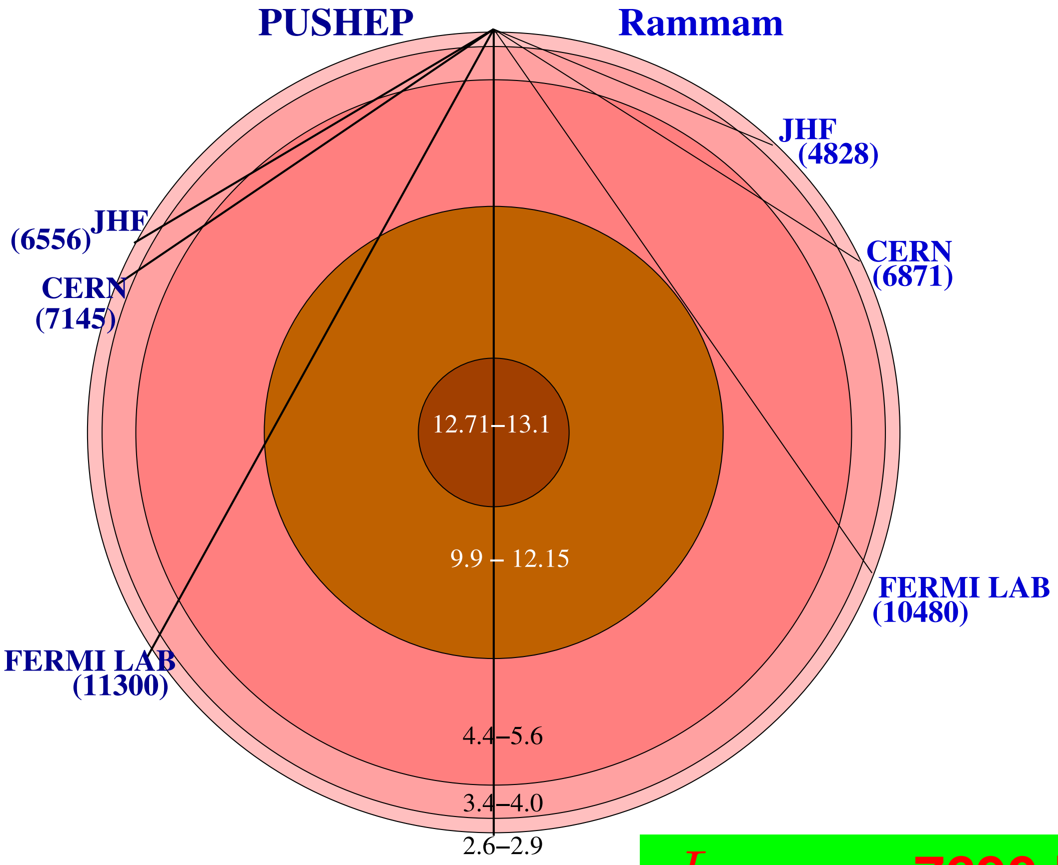
ICAL Design





Spokesperson: Prof. N.K. Mondal, TIFR

INO : 2nd Phase



L_{magic} = 7690 km

Artificial Source

Beta Beam ?

Neutrino Factory ?

INO

- A magnetized Iron calorimeter (ICAL) detector with excellent efficiency of charge identification ($\sim$ 95%) and good energy determination

- Preferred location is Singara (PUSHEP) in the Nilgiris (near Bangalore), 7152 km from CERN

- A (50+50) Kton Iron detector

- Oscillation signal is the muon track ($\nu_e \longrightarrow \nu_\mu$ channel)

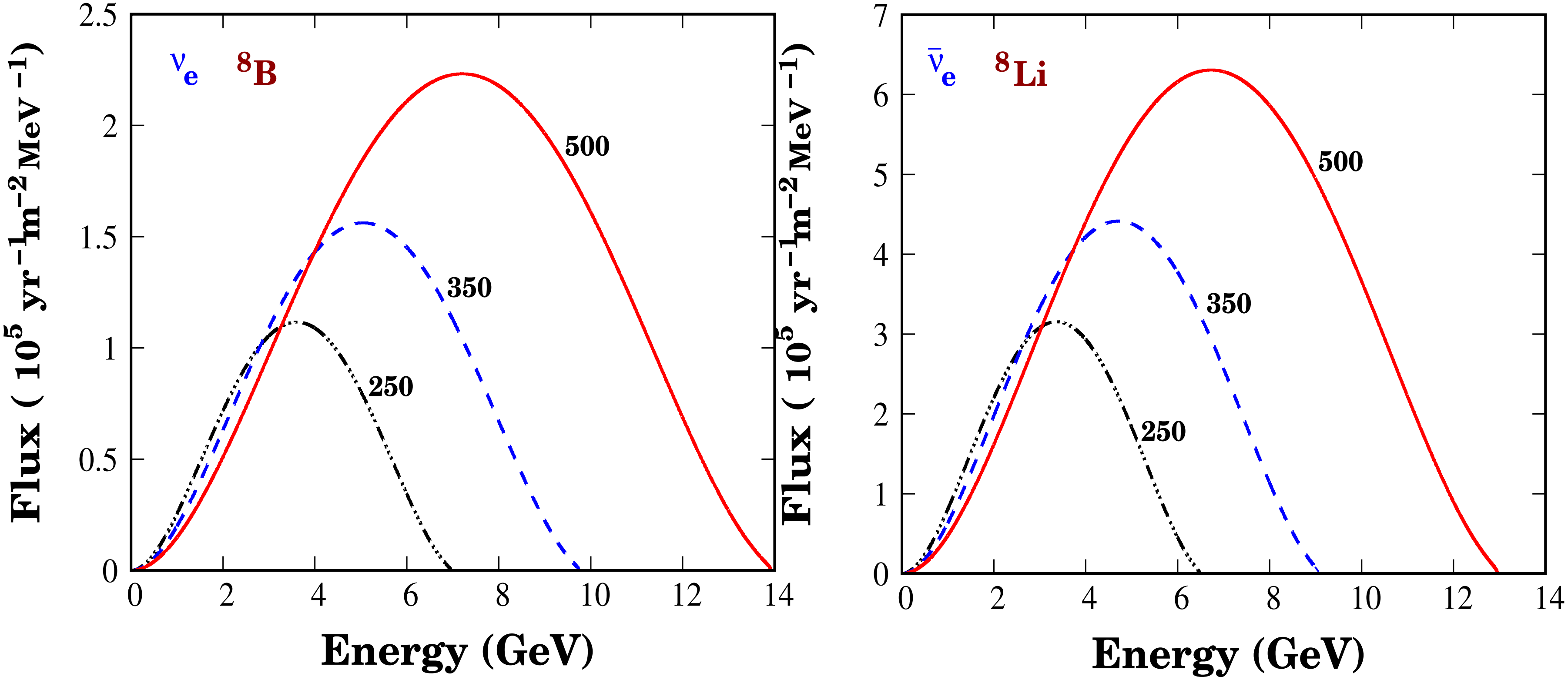
Detector assumptions

Total Mass	50 kton
Energy threshold	1.5 GeV
Detection Efficiency (ϵ)	60%
Charge Identification Efficiency (f_{ID})	95%

Detector characteristics used in the simulations

We assume a Gaussian energy resolution function with $\sigma = 0.15E$

β-beam flux at INO-ICAL



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Boosted on-axis spectrum of ν_e and $\bar{\nu}_e$ at the far detector assuming no oscillation. We take γ = 350

$\not{R}$ SUSY

- In the SM, lepton number (L) conservation is only accidental
- Neutrino oscillation experiments indicate non-zero neutrino mass. SM should be viewed as a low energy effective theory
- Indeed, a Majorana mass term for the neutrinos violates total lepton number
- In minimal supersymmetric standard model, gauge invariance does not imply lepton number (L) conservation

In general, R-parity (R $= (-1)^{3B+L+2S}$) is violated.
B is the baryon number $\&$ S is the spin

Discrete Z_2 symmetry, SM particles even, superpartners odd

$\not{R}$ SUSY continued..

In $\not{R}$ MSSM, we have the superpotential :

$$W_{\not{L}} = \sum_{i,j,k} \left(\tfrac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \mu_i L_i H_u\right)$$

(Suppressing colour and $SU(2)$ indices)

- $i,\ j,\ k$ are generation indices
- L_i and Q_i are $SU(2)$-doublet lepton and quark superfields respectively
- E_i, D_i denote the right-handed $SU(2)$-singlet charged lepton and down-type quark superfields respectively
- H_u, Higgs superfield which gives masses to up-type quarks

$\not{R}$ SUSY

Focus on the trilinear L-violating term with λ' couplings

==

Expanding in standard four-component Dirac notation,

the quark-neutrino interaction lagrangian :

$$\mathcal{L}_{\lambda'} = \lambda'_{ijk}\left[\,\tilde{d}^j_L\,\bar{d}^k_R\nu^i_L + (\tilde{d}^k_R)^*(\bar{\nu}^i_L)^c d^j_L\right] + h.c.$$

The sfermion fields are characterized by the tilde sign

$\Rightarrow$ All the couplings are real, can be +ve or -ve

SM versus $\not R$ SUSY

- ν **interacts with electrons and** d, u**-quarks during propagation**

In Standard Model

(i) $\nu_i + d(u) \longrightarrow \nu_i + d(u)$ & **(ii)** $\nu_i + e \longrightarrow \nu_i + e$

(i) ***via*** Z **exchange** **(ii)** ***via*** W **and** Z **exchange**

In $\not R$ SUSY

$$\nu_i + d \rightarrow \nu_j + d$$

Through λ' **couplings** ***via*** **squark exchange for all** i, j

Three-flavour oscillations

Neutrino flavour states $|\nu_\alpha\rangle$ $(\alpha = e, \mu, \tau)$ **are related to the mass eigenstates** $|\nu_i\rangle$ $(i$ **= 1, 2, 3)** **with masses** m_i **:**

$\Rightarrow$ $|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$ **;** U **is a** 3×3 **unitary (PMNS) matrix**

The neutrino flavour eigenstates evolve in time as :

$$i\frac{d}{dt}\begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \\ \nu_\tau(t) \end{pmatrix} = H \begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \\ \nu_\tau(t) \end{pmatrix},$$

$$where\ \ H = E \times \mathbf{1}_{3\times 3} + U\left(\frac{M^2}{2E}\right)U^\dagger + R$$

Here E **is the neutrino energy,** R **is a** 3×3 **matrix reflecting the matter effect** $\&$ $M^2 = \mathrm{diag}(m_1^2, m_2^2, m_3^2)$

NSI in Matter effect

$$\boxed{R_{ij} = R_{ij}(SM) + R_{ij}(\lambda')}$$

$$R_{ij}(SM) = \sqrt{2} G_F n_e \delta_{ij}(i,j=1) + \frac{G_F n_n}{\sqrt{2}} \delta_{ij},$$

$$R_{ij}(\lambda') = \sum_m \left(\frac{\lambda'_{im1}\lambda'_{jm1}}{4m^2(\tilde{d}_m)} n_d + \frac{\lambda'_{i1m}\lambda'_{j1m}}{4m^2(\tilde{d}_m)} n_d \right)$$

$\Rightarrow$ R **is a symmetric matrix**

$\Rightarrow$ n_e, n_n **and** n_d **respectively are the electron, neutron and down-quark densities in earth matter**

$\Rightarrow$ **Isoscalar earth matter,** $n_e = n_p = n_n$ **and** $n_d = 3n_e$

$\Rightarrow$ **Current bounds on the** $\not{R}$ **couplings imply,** λ' **induced contributions to** R_{11}, R_{12} **and** R_{13} **are several orders less than** $\sqrt{2} G_F n_e$

NSI in Matter effect

$\Rightarrow$ **In addition to the Standard Model contribution, we consider**

$$R_{23} = R_{32} = \frac{n_d}{4m^2(\tilde{d}_m)} \left(\lambda'_{2m1}\lambda'_{3m1} + \lambda'_{21m}\lambda'_{31m}\right),$$

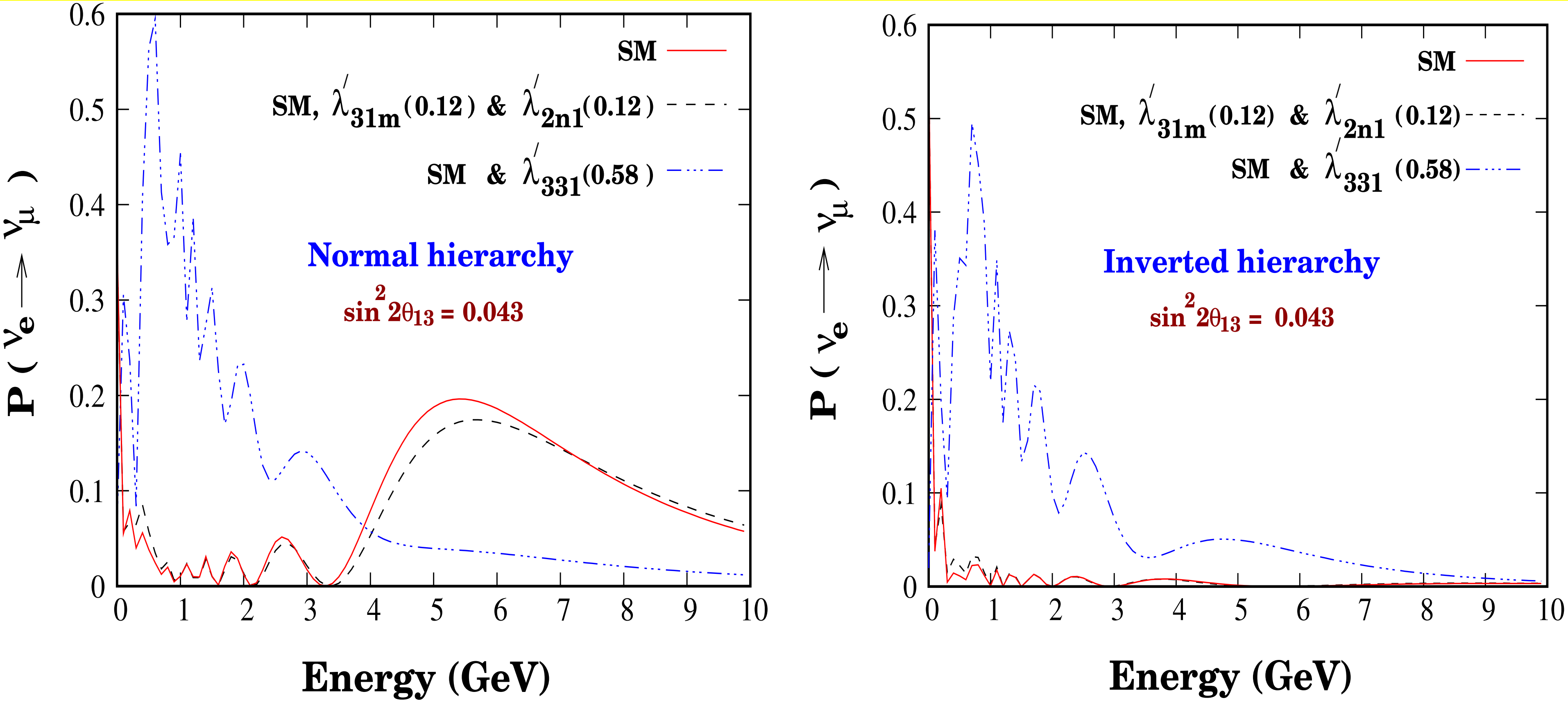
$$R_{22} = \frac{n_d}{4m^2(\tilde{d}_m)} \left(\lambda'^{\,2}_{2m1} + \lambda'^{\,2}_{21m}\right), \quad R_{33} = \frac{n_d}{4m^2(\tilde{d}_m)} \left(\lambda'^{\,2}_{3m1} + \lambda'^{\,2}_{31m}\right)$$

which are comparable to $\sqrt{2}G_F n_e$. One can see that $R_{23} \neq 0$ implies both R_{22} and R_{33} are non-zero

Current bounds : $|\lambda'_{221}, \lambda'_{231}| < 0.18$; $|\lambda'_{21m}| < 0.06$; $|\lambda'_{331}| < 0.58$; $|\lambda'_{321}| < 0.52$; $|\lambda'_{31m}| < 0.12$ **for down squark mass** $m_{\tilde{d}} = 100$ **GeV**

Recent BELLE data puts tight constrains on $|\lambda'_{21m}\lambda'^{*}_{31m}|$ and $|\lambda'_{2m1}\lambda'^{*}_{3m1}|$. This effectively makes R_{23} negligible

Golden Channel versus E_ν

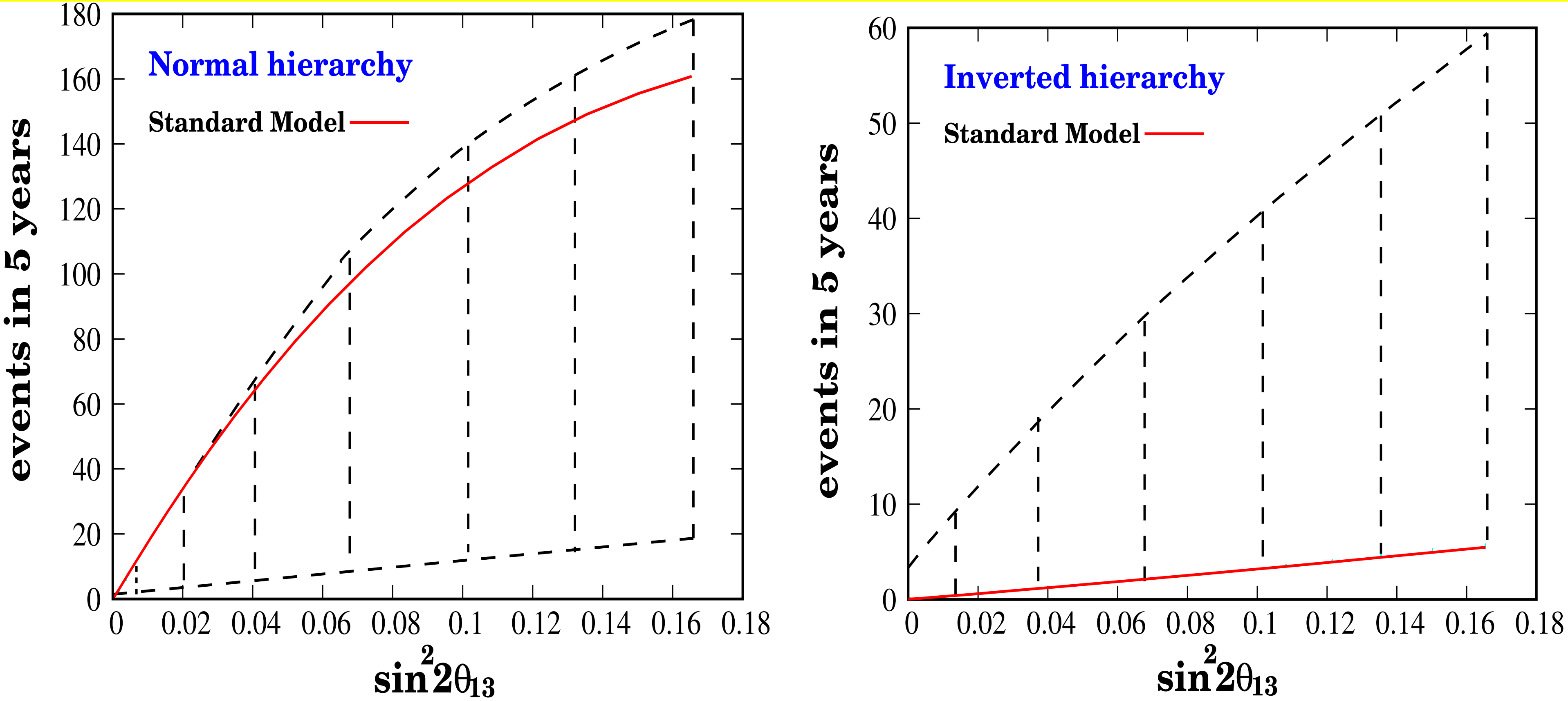


Adhikari, Agarwalla, Raychaudhuri, hep-ph/0608034

$P_{e\mu}$ **for NH and IH**

m **can take any value,** $n = 2$ **or 3**

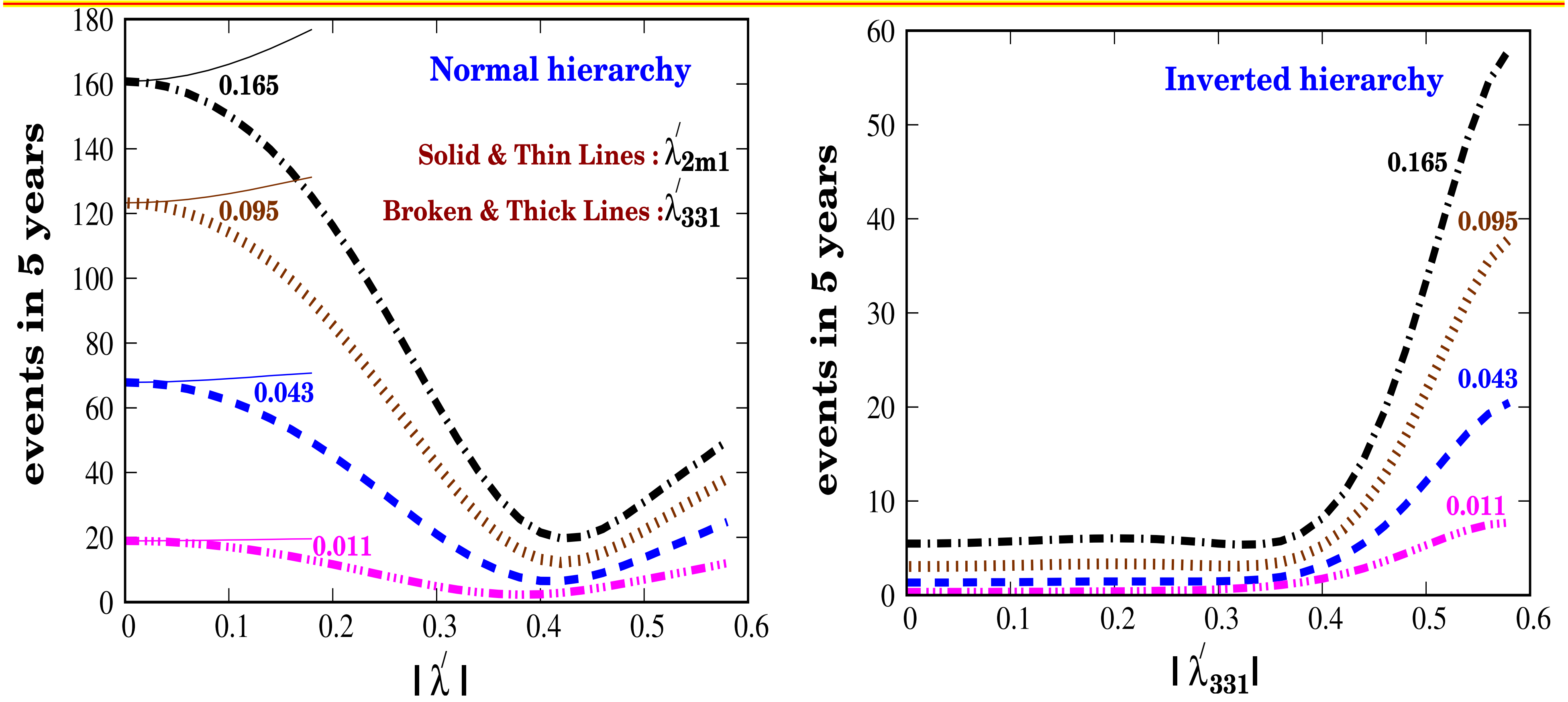
Extracting θ_{13} & $sgn(\Delta m^2_{31})$



Adhikari, Agarwalla, Raychaudhuri, hep-ph/0608034

Muon events .vs. $\sin^2 2\theta_{13}$ for NH and IH. The solid lines correspond to the SM. The shaded area is covered if the λ' couplings are varied over their entire allowed range

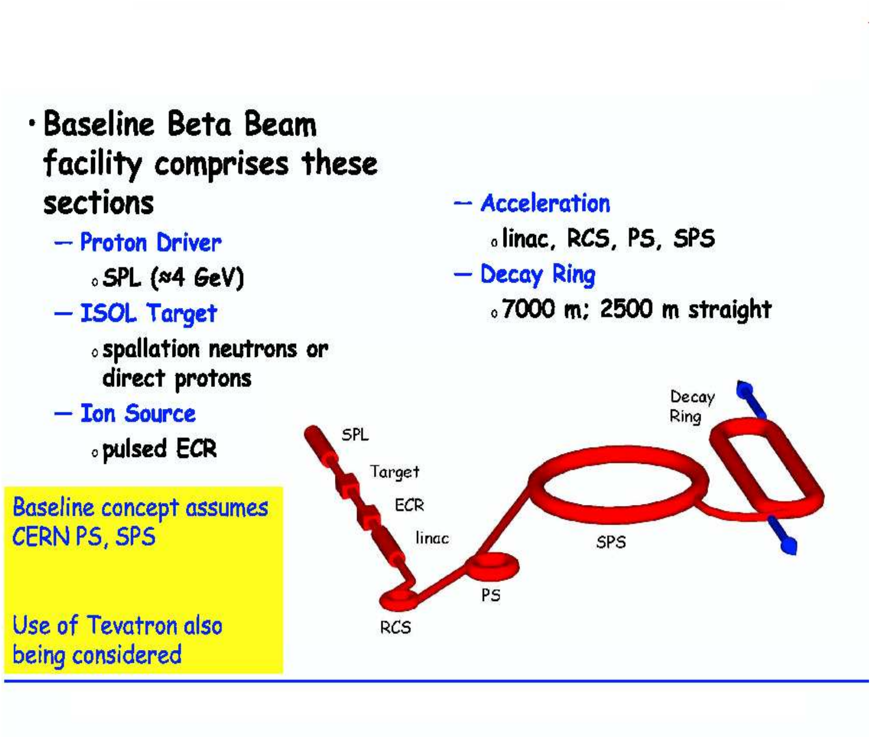
Constraining λ'



Adhikari, Agarwalla, Raychaudhuri, hep-ph/0608034

Event rates .vs. $|\lambda'|$, present singly, for NH and IH. The thick (thin) lines are for $|\lambda'_{331}|$ ($|\lambda'_{2m1}|$, $m=$2,3). The chosen $\sin^2 2\theta_{13}$ are indicated next to the curves

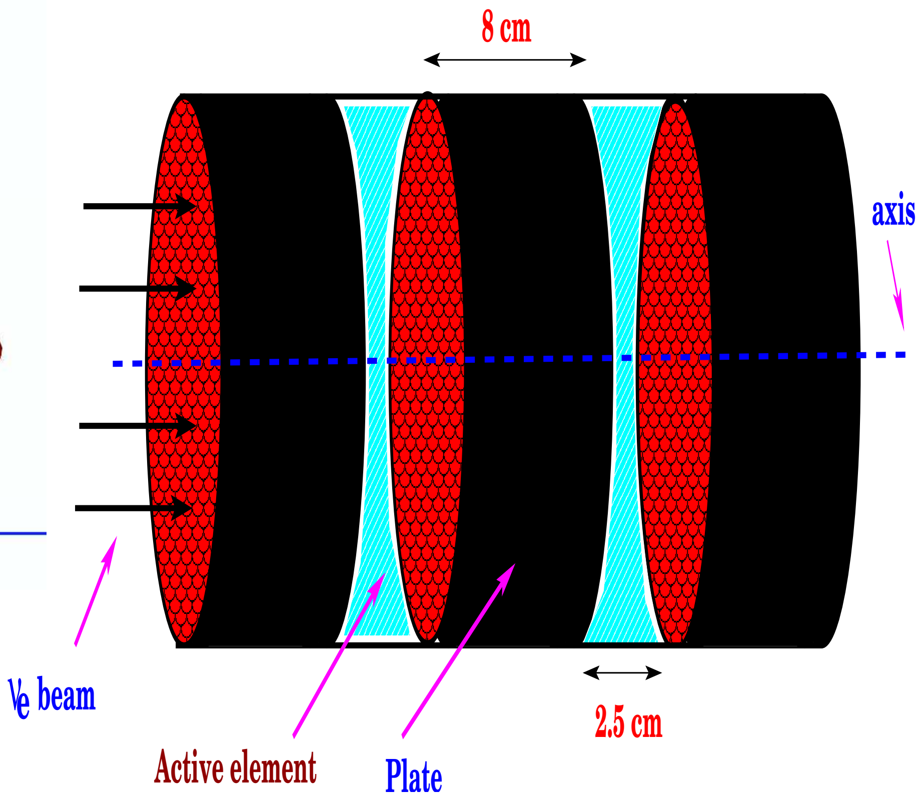
NSI at Near Detector



- Baseline Beta Beam facility comprises these sections
  - Proton Driver
    - SPL (≈4 GeV)
  - ISOL Target
    - spallation neutrons or direct protons
  - Ion Source
    - pulsed ECR
  - Acceleration
    - linac, RCS, PS, SPS
  - Decay Ring
    - 7000 m; 2500 m straight

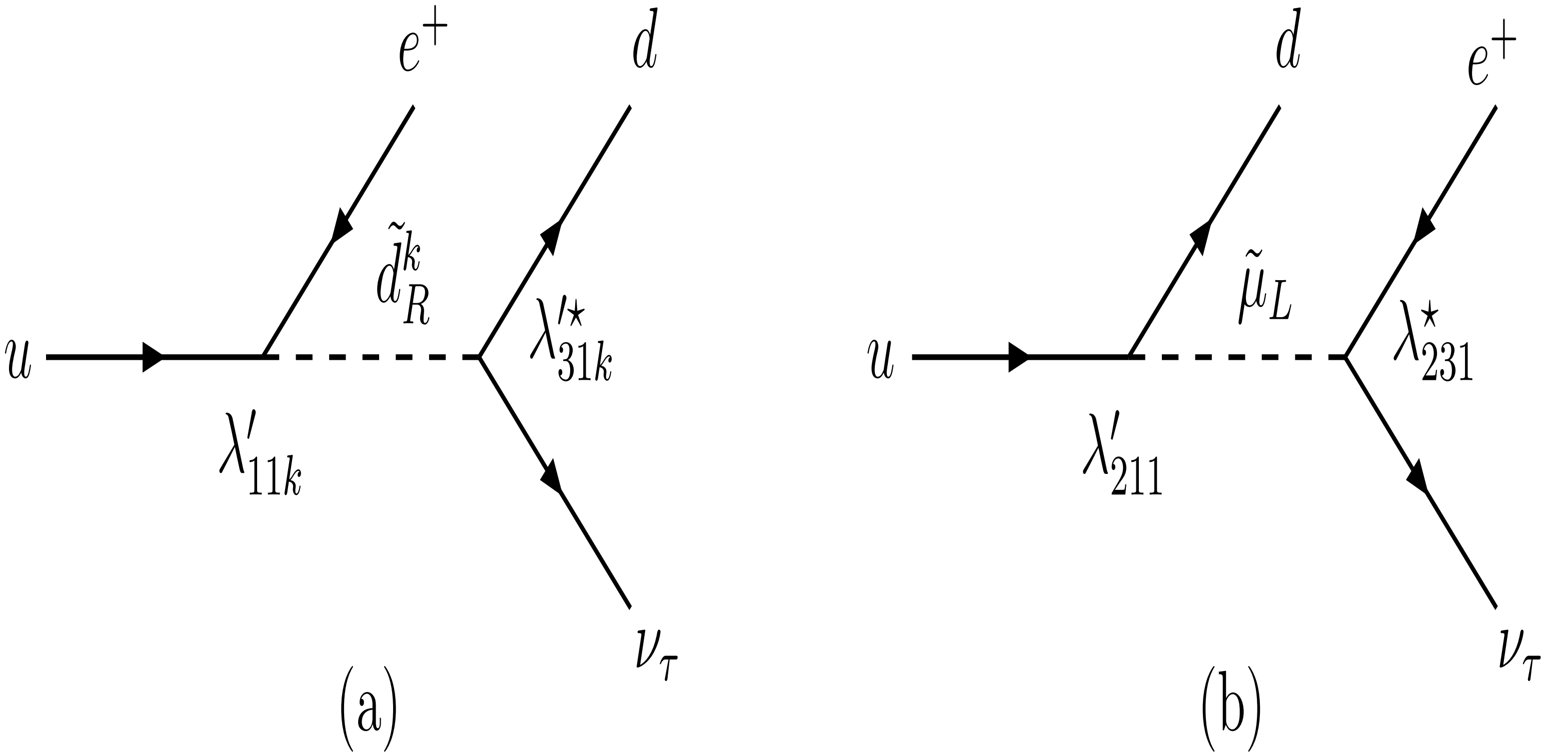
Baseline concept assumes CERN PS, SPS

Use of Tevatron also being considered



β-beam flux at a near detector

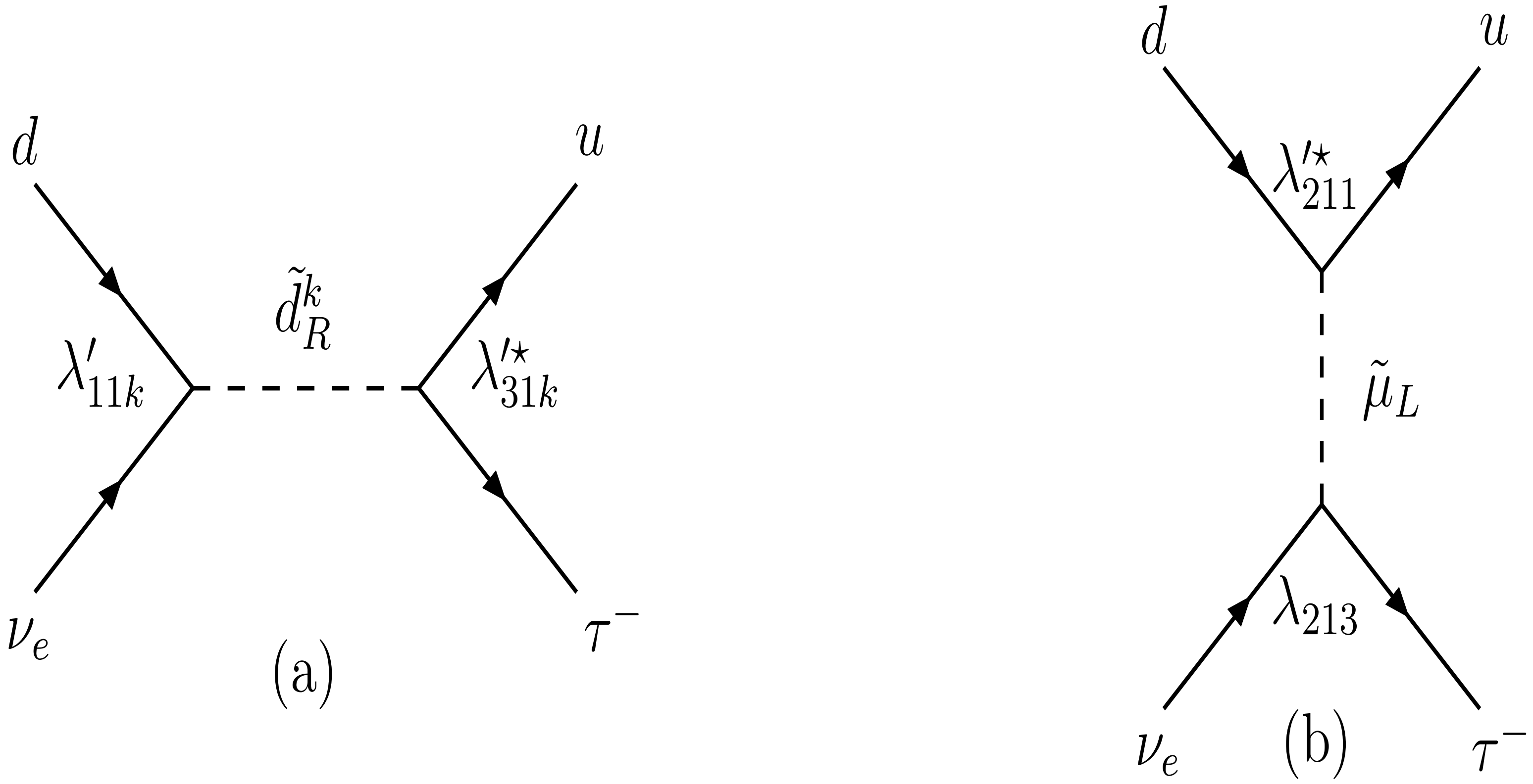
RPV and ν_τ production in β-decay



Agarwalla, Rakshit, Raychaudhuri, hep-ph/0609252

Feynman diagrams for RPV driven β-decay through (a) $\lambda'\lambda'$ and (b) $\lambda\lambda'$ type trilinear product couplings. Substantial event rates are obtained in (a) when $k = 2, 3$.

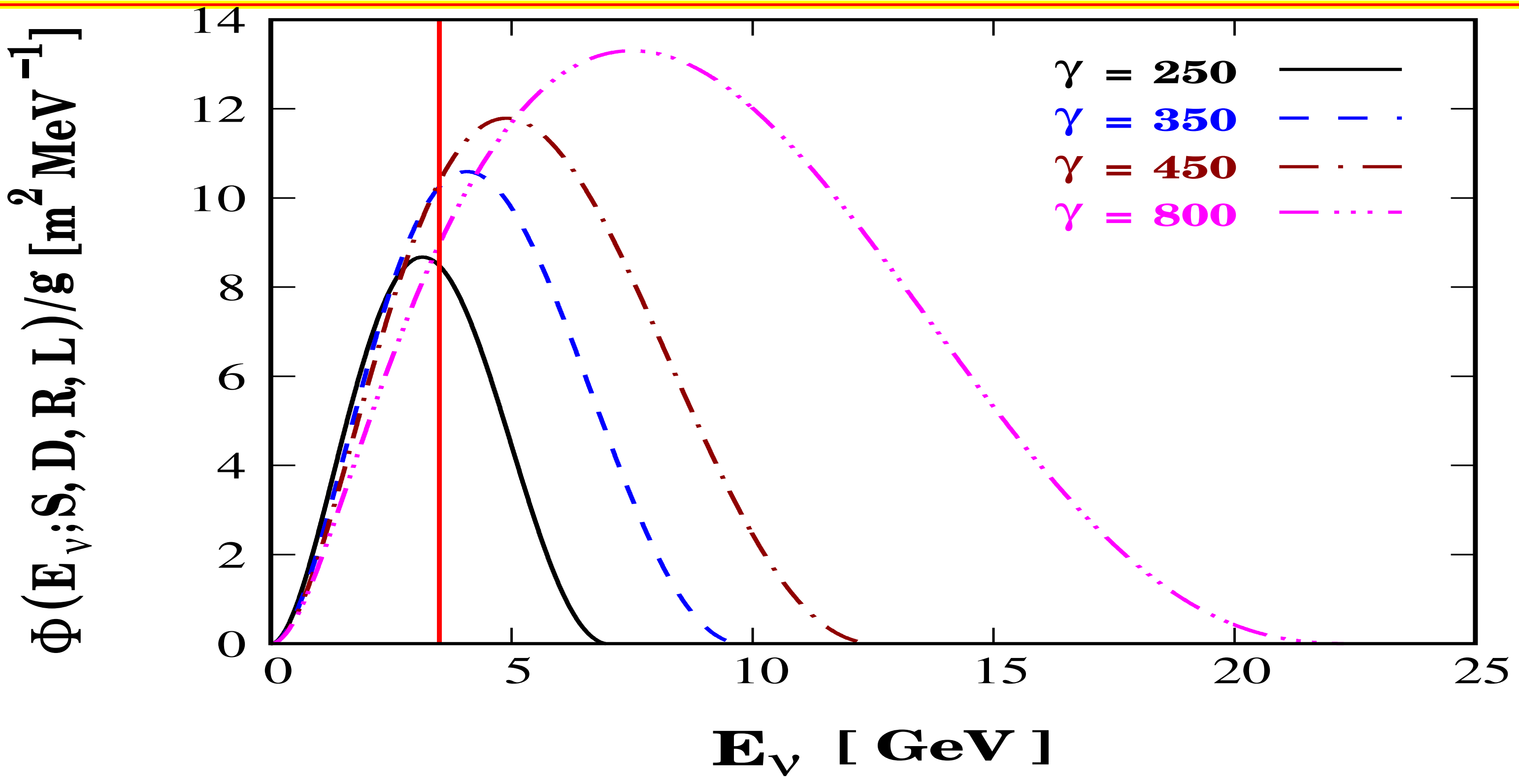
RPV in tau production from ν_e



Agarwalla, Rakshit, Raychaudhuri, hep-ph/0609252

Feynman diagrams for tau production from an incoming ν_e beta-beam through (a) $\lambda'\lambda'$ and (b) $\lambda\lambda'$ type trilinear product couplings. Substantial event rates are obtained in (a) when $k = 2, 3$.

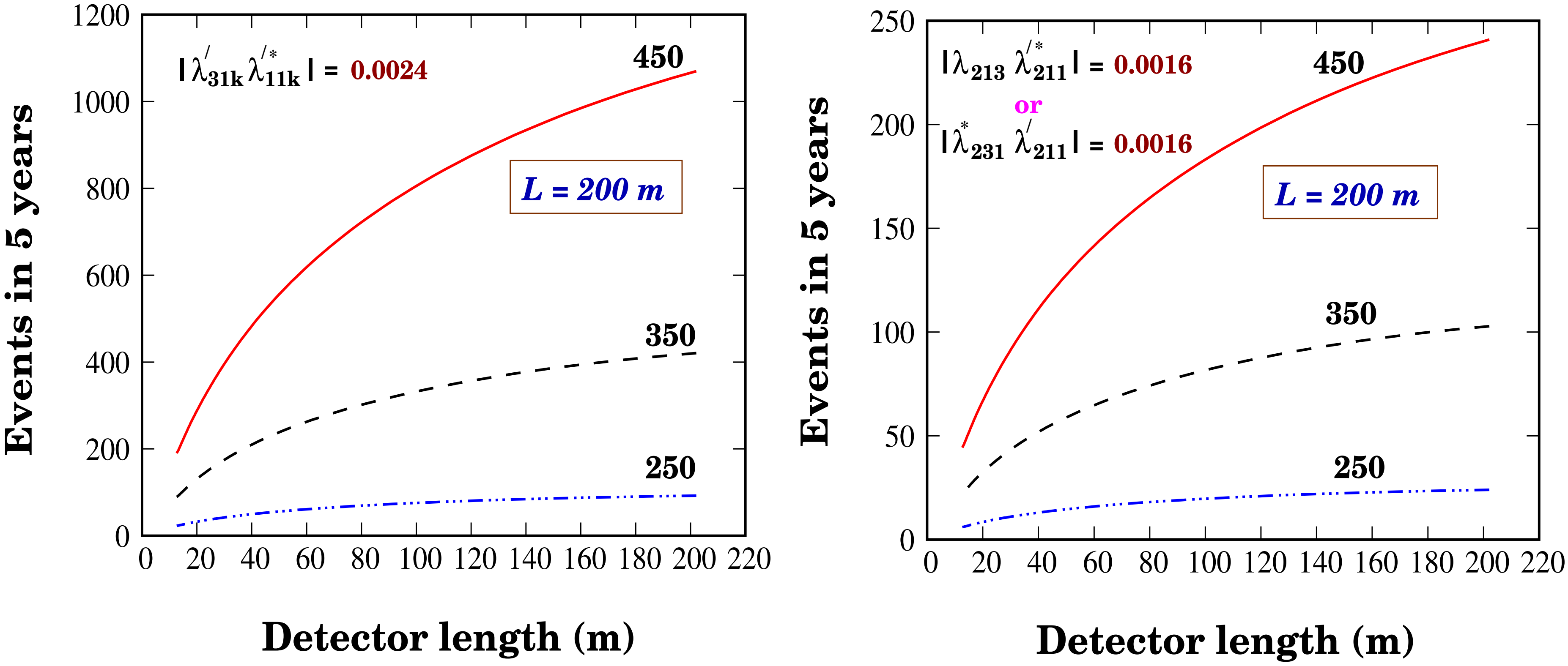
Geometry integrated flux



Agarwalla, Rakshit, Raychaudhuri, hep-ph/0609252

Geometry integrated flux $\Phi(E_\nu; S, D, R, L)/g$ taking ^{8}B as the decaying ion is plotted against neutrino energy E_ν for different γ for $S = 2500$ m, $D = 202.13$ m, $R = 1$ m, and $L = 200$ m. The vertical line at 3.5 GeV indicates the tau production threshold energy.

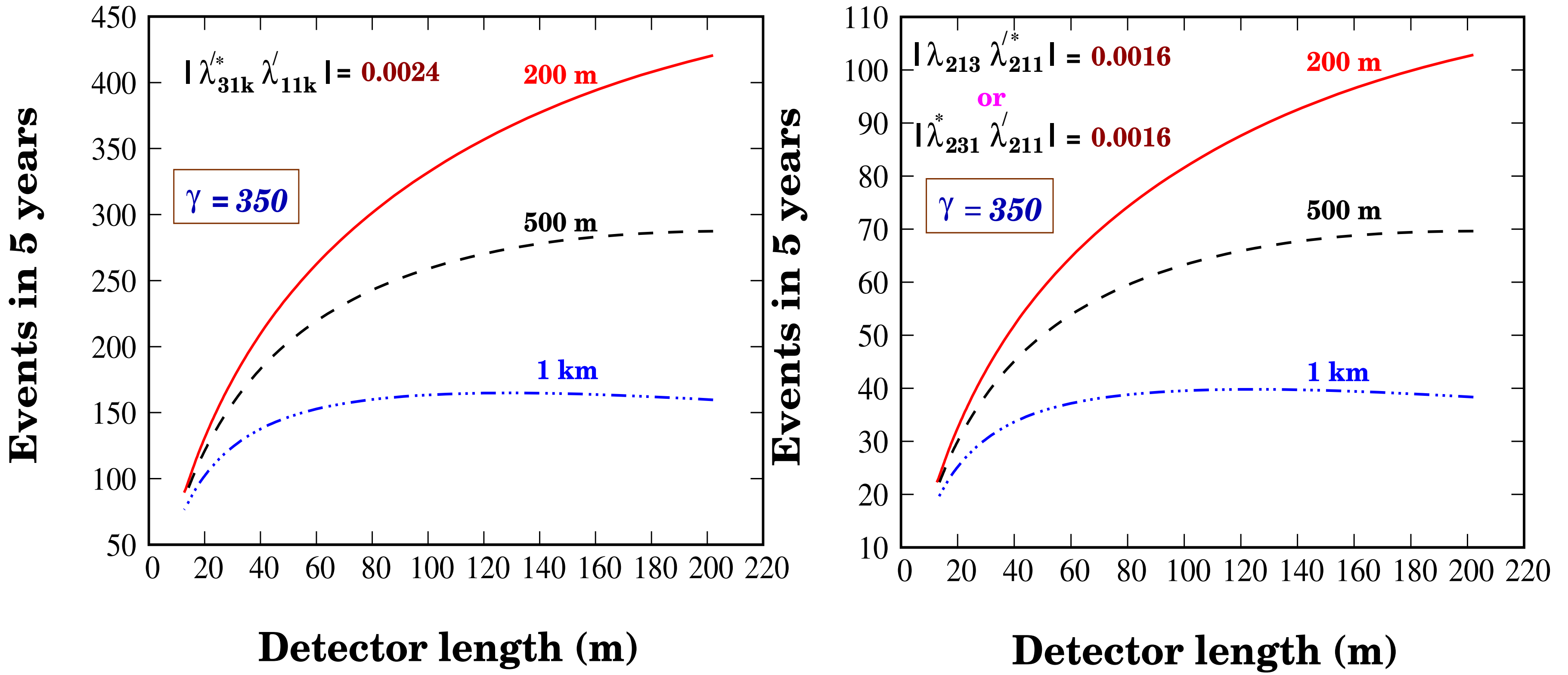
Effect of Boost



Agarwalla, Rakshit, Raychaudhuri, hep-ph/0609252

Expected number of RPV muon events in five years for a 5 kT iron detector vs. the detector length for γ = 250, 350, and 450 for ^{8}B beta-beam flux. The left (right) panel is for the $\lambda'\lambda'$ ($\lambda\lambda'$) driven process. $k = 2, 3$.

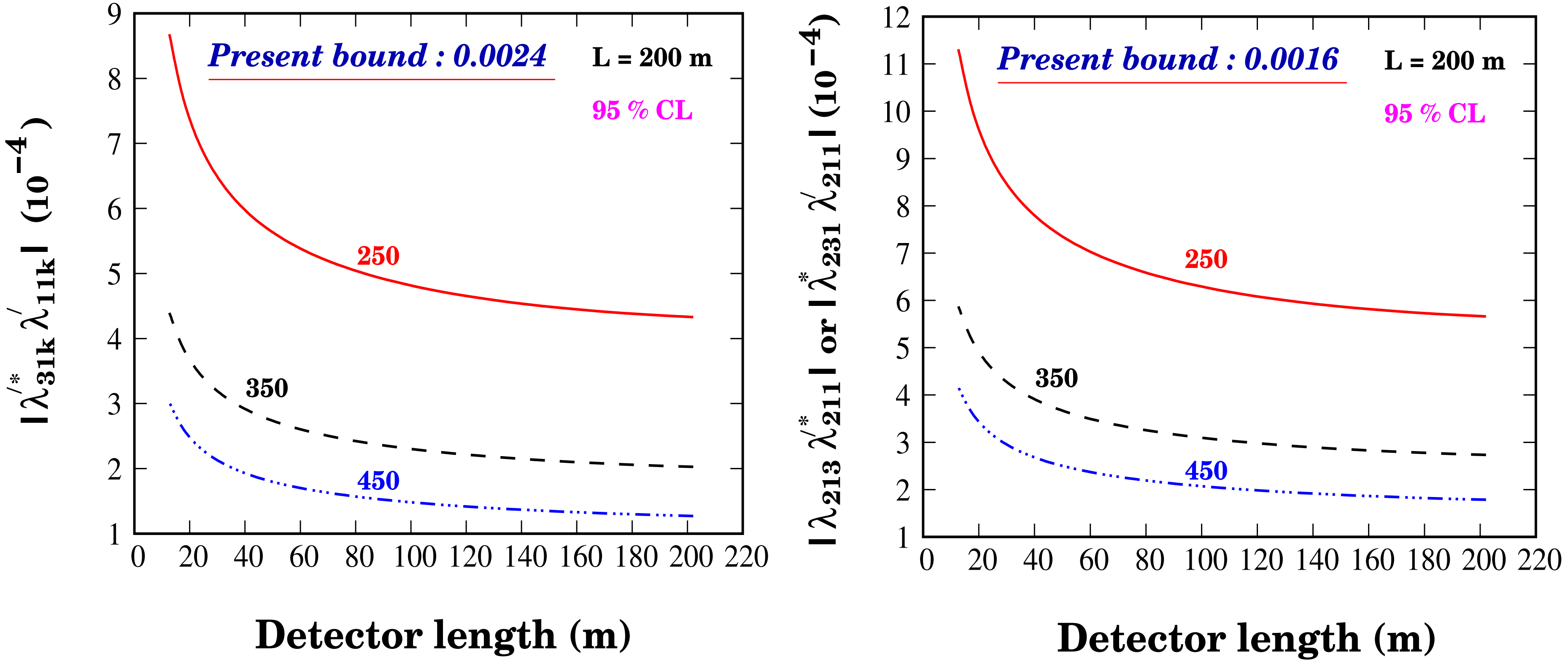
Effect of Baseline



Agarwalla, Rakshit, Raychaudhuri, hep-ph/0609252

Muon signal event rate in 5 years as a function of the detector (Fe) length for three different choices of base-length have been shown for ^{8}B beta-beam flux. The left (right) panel corresponds to the $\lambda'\lambda'$ ($\lambda\lambda'$) driven process. $k = 2, 3$.

Constraining RPV couplings



Agarwalla, Rakshit, Raychaudhuri, hep-ph/0609252

Bounds on $|\lambda'^{\star}_{31k}\lambda'_{11k}|$, $k = 2, 3$ ($|\lambda^{\star}_{231}\lambda'_{211}|$ or $|\lambda_{213}\lambda'^{\star}_{211}|$) versus detector size at 95% CL for zero observed events in left (right) panel for $\gamma = 250, 350, 450$. Results with a 5-yr run for a 5 kT Fe detector placed at a distance of 200 m from the front end of the ring for ^{8}B β-beam flux.

Conclusions

- $\not{R}$ SUSY is among several extensions of the SM crying out for experimental verification. It has FDNC and FCNC, affect neutrinos at their production, detection and propagation stage and leave their imprints in LBL expts

This is the focus of this work

- We consider a β-beam experiment with CERN-INO baseline. $\not{R}$ interactions may obstruct a clean extraction of the mixing angle θ_{13} or determination of the mass hierarchy unless the bounds on the λ' couplings are tightened
- one might see a clean signal of new physics and put tighter constraints on the λ' couplings
- A near detector might be a smart candidate in exploring new physics signal