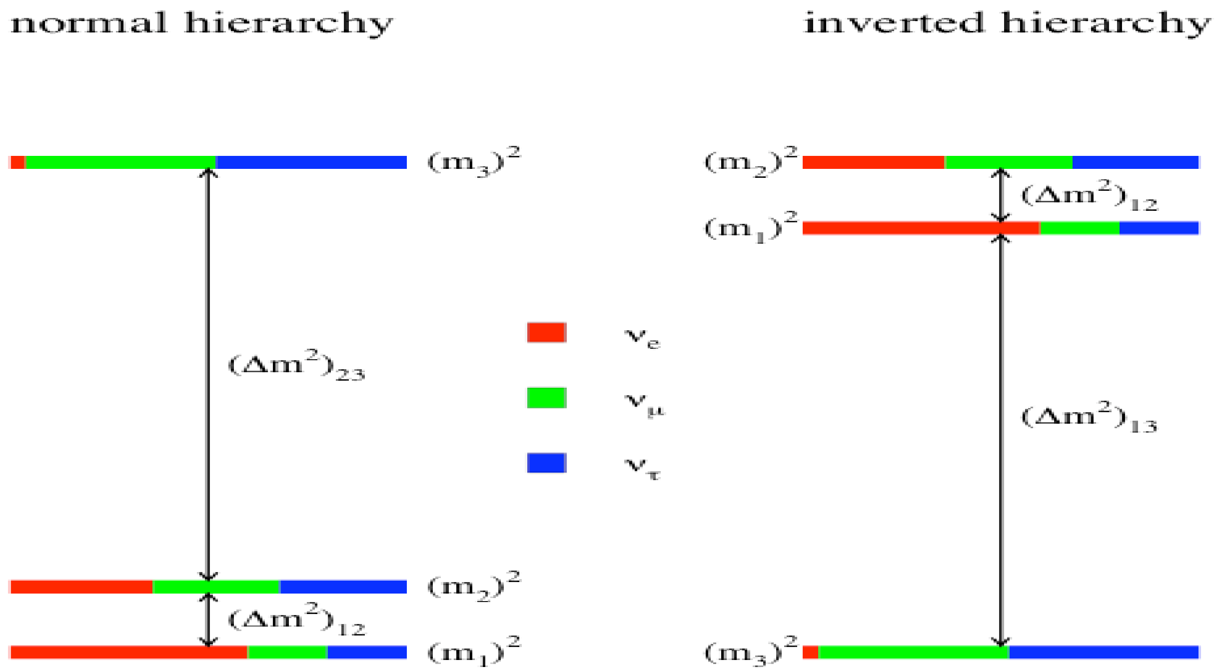
Lecture III

- Prospects in ν physics
- Leptogenesis
- Theory outlook

Prospects in ν physics

Standard 3ν scenario

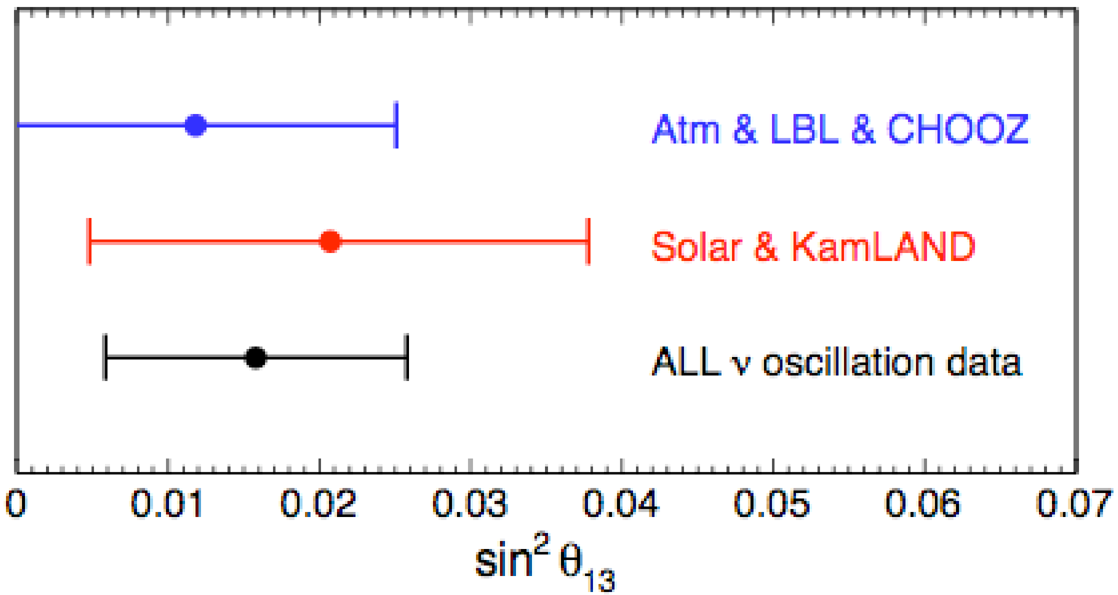


The flavour observables:

Masses	Angles	CP-phases
$m_1^2 < m_2^2, m_3^2$	$\theta_{12}, \theta_{23}, \theta_{13}$	$\delta, \alpha_1, \alpha_2$

$\Theta_{13} \neq 0$ …wishfull thinking

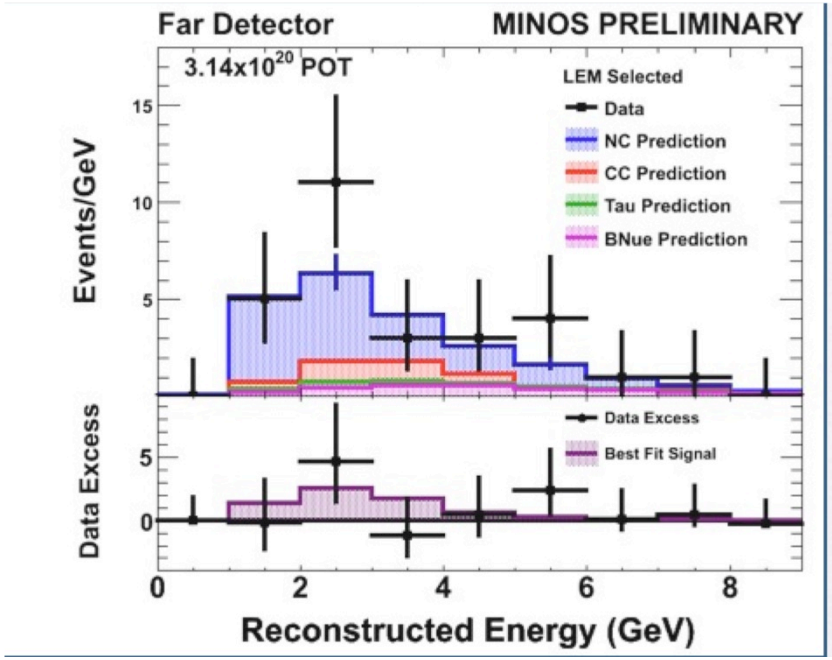
3ν analysis after the Neutrino 08 conference…

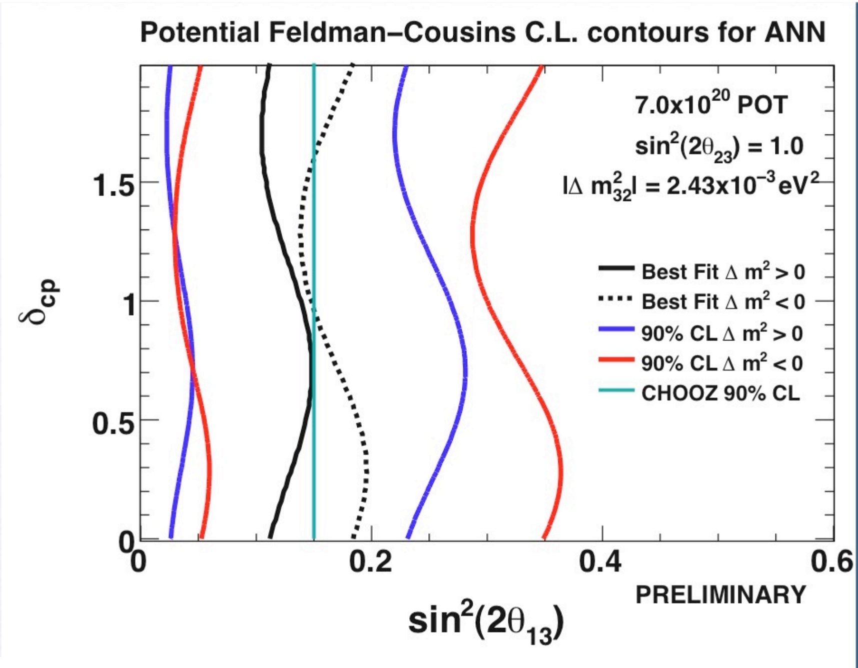


Fogli et al

Out of the oven

MINOS experiment first appearance search…





Prospects in ν physics

The fundamental questions that can and should be answered:

- Dirac or Majorana ?
- Lepton number conserved or violated ?
- What is the absolute ν mass scale ? New physics scale!
- What is the ν mass spectrum ?
- CP violation in the lepton sector ?
- θ_{13} ?

How to measure the unknowns...

θ_{13}

δ

Hierarchy

$\text{sign}(\cos\theta_{23})$

Precise ν oscillations experiments

α_1, α_2

$\beta\beta 0\nu$

m^2_1, m^2_3

$\beta\beta 0\nu$, $\beta\beta$

Cosmology

Majorana & L

$\beta\beta 0\nu$

ββ0ν and Cosmology

Plethora of forthcoming experiments: CUORE, EXO, GENIUS

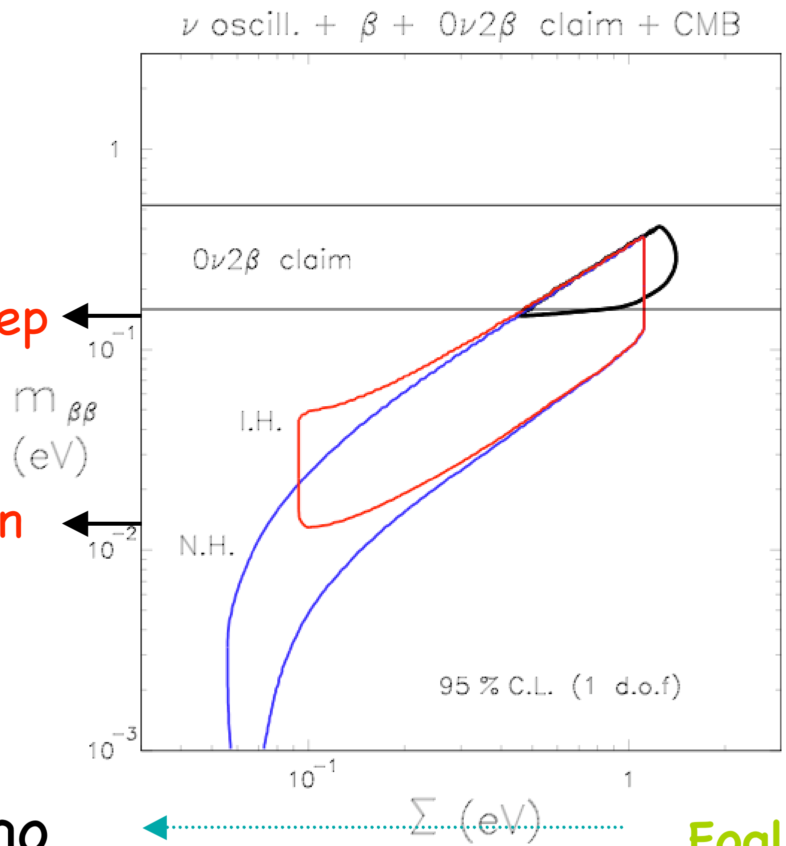
Almost warrantied if hierarchy inverse !

$$m_{\beta\beta} \equiv |m_{ee}|$$

$$\Sigma \equiv \sum_i m_i$$

Next step

Next generation



Cosmo

Fogli, et al

$$|m_{ee}| = |c_{13}^2(m_1 c_{12}^2 + m_2 e^{i\alpha} s_{12}^2) + m_3 e^{i\beta} s_{13}^2|$$

CP violation in ν oscillations

$$P_{\nu_\alpha \nu_\beta(\bar\nu_\alpha \bar\nu_\beta)} = \delta_{\alpha\beta} - 4 \sum_{k>j} \mathrm{Re}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin^2\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}}\,\mathrm{L}}{4\mathrm{E}_\nu}\right)$$

$$\pm\ 2 \sum_{k>j} \mathrm{Im}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}}\,\mathrm{L}}{2\mathrm{E}_\nu}\right)$$

CP violation shows up in a difference between

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar\nu_\alpha \to \bar\nu_\beta)$$

CPT implies: $P(\nu_\alpha \to \nu_\beta) = P(\bar\nu_\beta \to \bar\nu_\alpha)$

CP asymmetry only in appearance measurements $\alpha \neq \beta$

CP and T asymmetries

$$A_{\alpha\beta}^{CP} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$$ CP

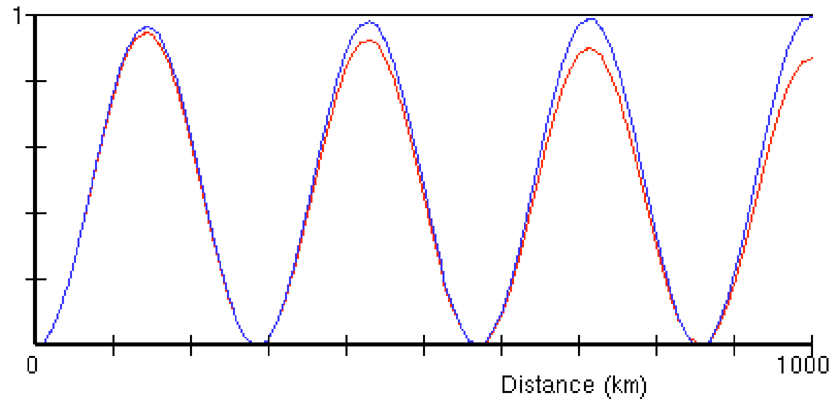
T: $$A_{\alpha\beta}^{T} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\nu_\beta \to \nu_\alpha)}{P(\nu_\alpha \to \nu_\beta) + P(\nu_\beta \to \nu_\alpha)}$$

CP and T-odd asymmetries are the same in the standard scenario:

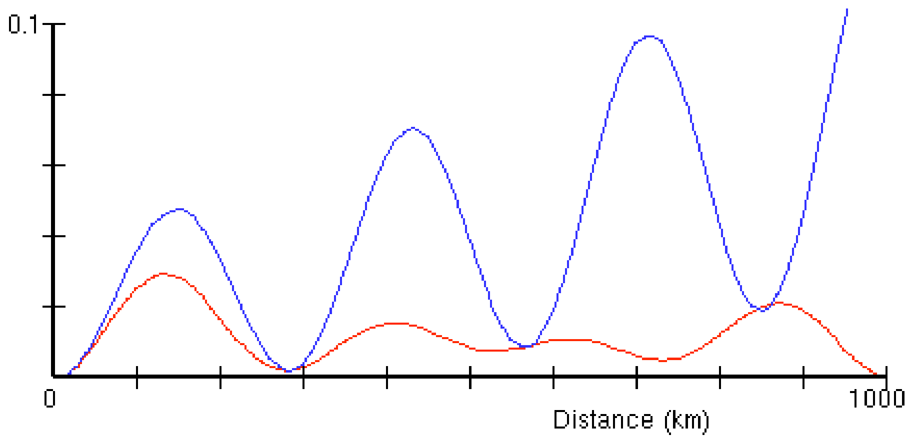
$$A_{\nu_\alpha\nu_\beta}^{\mathrm{CP(T)}} = \frac{2\sin\delta c_{13}\sin 2\theta_{13}\overbrace{\sin 2\theta_{12}\frac{\Delta m_{12}^2 L}{4E_\nu}}^{\mathrm{solar}}\overbrace{\sin 2\theta_{23}\sin^2\frac{\Delta m_{13}^2 L}{4E_\nu}}^{atmos}}{P_{\nu_\alpha\nu_\beta}^{\mathrm{CP-even}}}$$

Suppressed in mass differences (GIM) and angles

$P(\nu_\mu \to \nu_\tau)$ vs $P(\bar{\nu}_\mu \to \bar{\nu}_\tau)$



$P(\nu_e \to \nu_\mu)$ vs $P(\bar{\nu}_e \to \bar{\nu}_\mu)$



θ_{13} and δ

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} \quad &= \quad s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23}\,L}{2}\right) \quad \equiv P^{atmos} \\
&+ \quad c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}\,L}{2}\right) \quad \equiv P^{solar} \\
+\tilde{J} \quad & \cos\left(\pm\delta - \frac{\Delta_{23}\,L}{2}\right) \frac{\Delta_{12}\,L}{2} \sin\left(\frac{\Delta_{23}\,L}{2}\right) \quad \equiv P^{inter}
\end{aligned}
$$

$$\tilde{J} \equiv c_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}$$

$$P^{atmos} \gg P^{solar} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\Delta_{12}L}{\sin 2\theta_{13}}$$

$$P^{solar} \gg P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\sin 2\theta_{13}}{\Delta_{12}L}$$

$$P^{solar} \simeq P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} = O(1)$$

Matter effects matter

At second order in $\varepsilon = \theta_{13}$ or Δm^2_{12} $\quad A \equiv \sqrt{2} G_F N_e$

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$
$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$
$$+ \tilde{J} \frac{\Delta_{12}}{A} \sin\left(\frac{AL}{2}\right) \frac{\Delta_{13}}{B_\pm} \sin\left(\frac{B_\pm L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

$$B_\pm = |A \pm \Delta_{13}| \qquad \Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

MSW effect for ν or $\bar{\nu}$ depending on sign(Δm^2_{13}) :

$$2E_\nu A \sim |\Delta m^2_{13}|, \qquad E_\nu \sim 10 - 20 GeV$$

Sensitivity to unknows at $E_\nu/L \sim |\Delta m^2_{23}|$ in matter

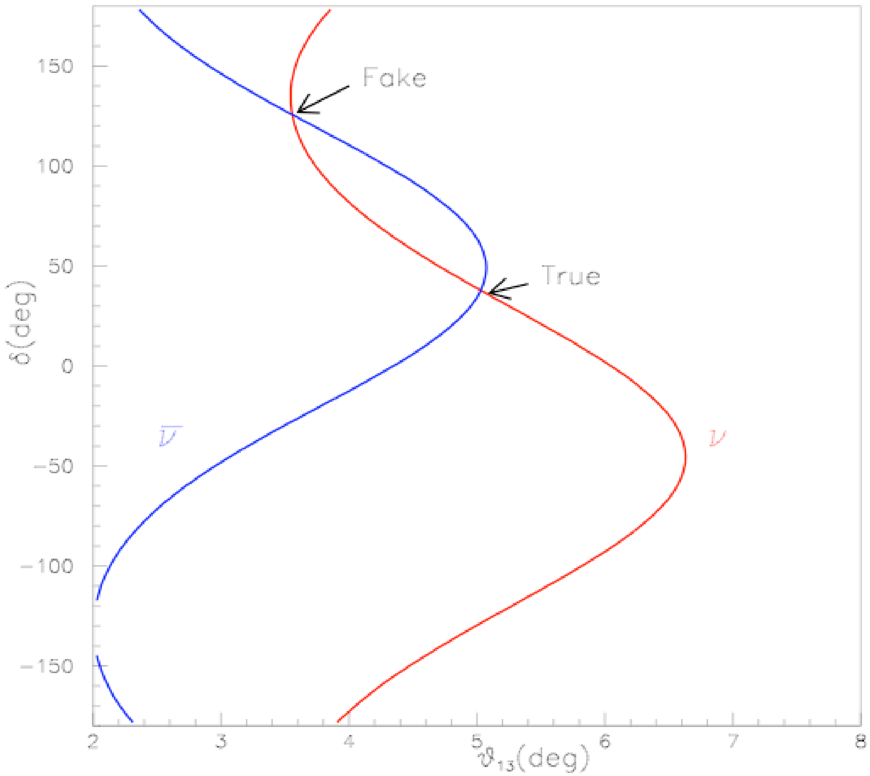
	ee	eμ	μμ	eτ	μτ
θ_{13}	ε^2	1	ε^2	1	ε^2
δ	–	1	ε^2	1	ε^2
sign(Δ_{23})	–/ε^2	–/1	ε	–/1	ε
sign($\cos 2\theta_{23}$)	–	1	ε^2	1	ε^2

↓ *Golden* (eμ) ↓ *Silver* (eτ)

$\varepsilon \rightarrow$ small parameters $\theta_{13}, \Delta_{12}/\Delta_{23}$

vac/matter

Correlations and degeneracies



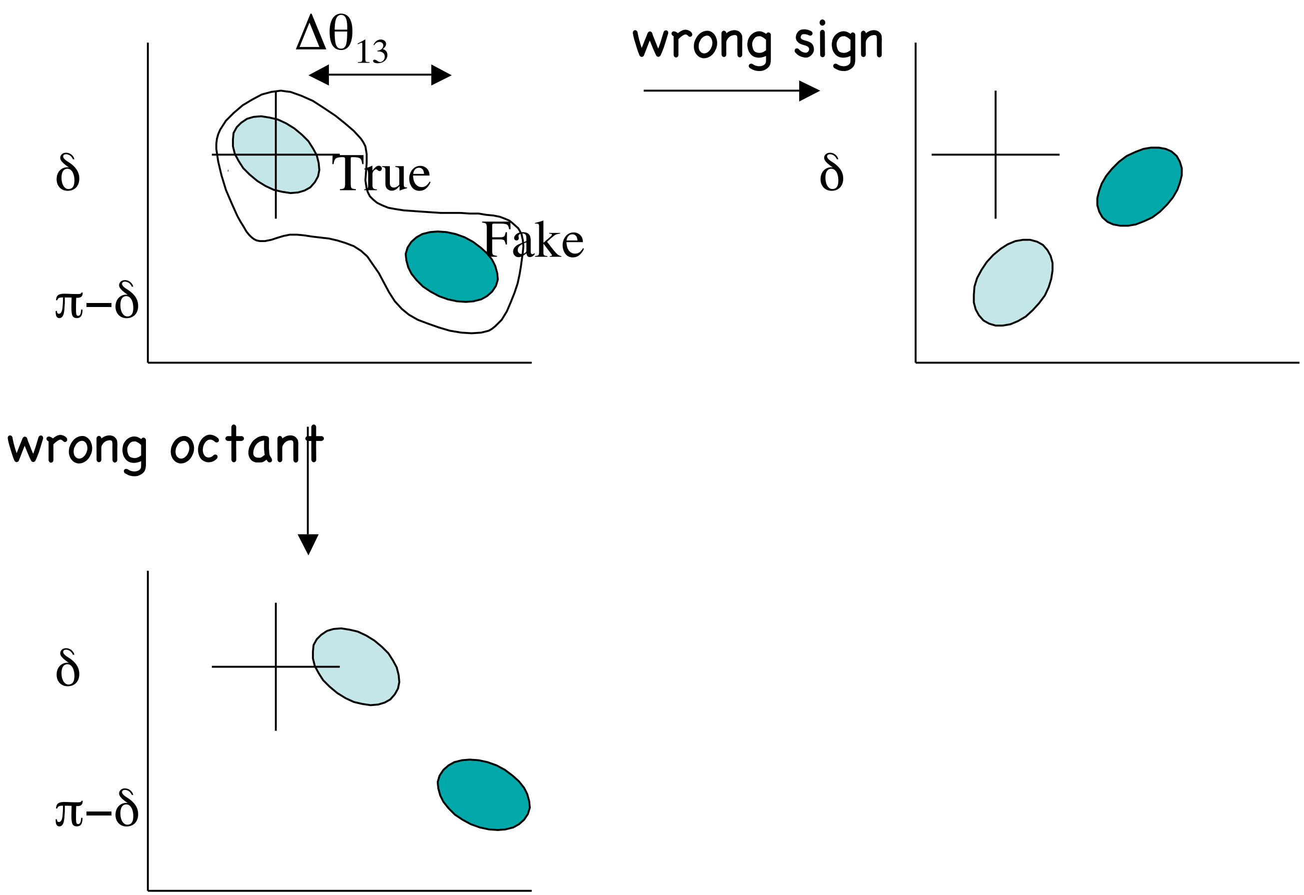
At fixed $E_{\nu,}$ L:

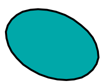
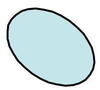
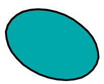
$$\left.\begin{array}{l} P^{\nu}_{\alpha\beta}(\theta_{13},\delta) = Meas_1 \\ P^{\bar{\nu}}_{\alpha\beta}(\theta_{13},\delta) = Meas_2 \end{array}\right\}$$

Generically two solutions: true and intrinsic degeneracy

Including the discrete ambiguities eight-fold

$$\left.\begin{array}{l} P^{\nu}_{\alpha\beta}(\theta_{13},\delta,\pm\Delta_{23},\pm\cos 2\theta_{23}) = Meas_1 \\ P^{\bar{\nu}}_{\alpha\beta}(\theta_{13},\delta,\pm\Delta_{23},\pm\cos 2\theta_{23}) = Meas_2 \end{array}\right\}$$



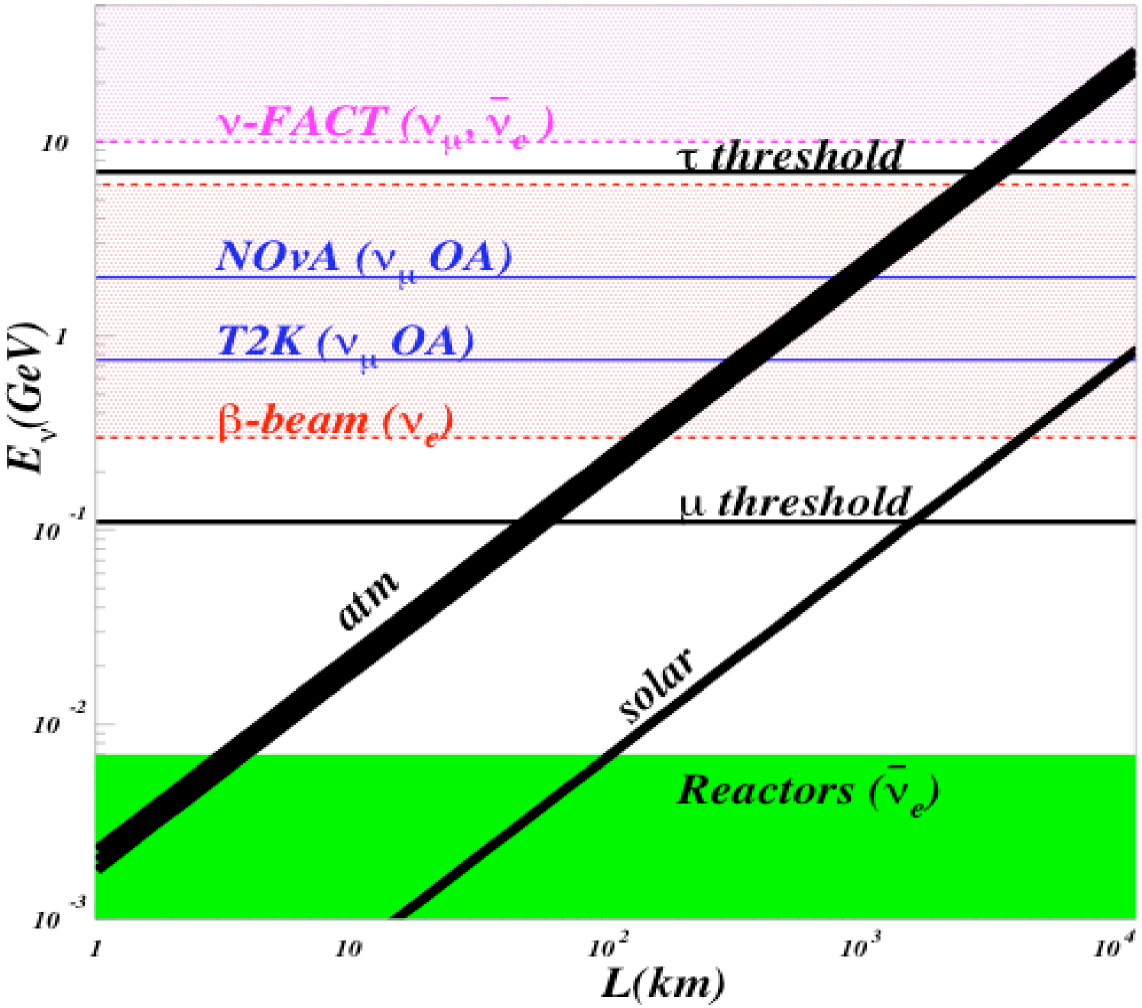
- Position of  depend strongly on the E,L and channel
- Fake  do not depend on E and L
-  are the ones that increase the error on $\theta_{13,}\delta$
- In vacuum all are CP violating or all CP conserving: $\delta^{fake}=\pi-\delta$

Towards precision lepton flavour physics

- Need more intense and pure ν beams
- Resolve degeneracies by significant
  - energy dependence
  - combining baselines
  - combining channels

Many ideas and proposals in the market…

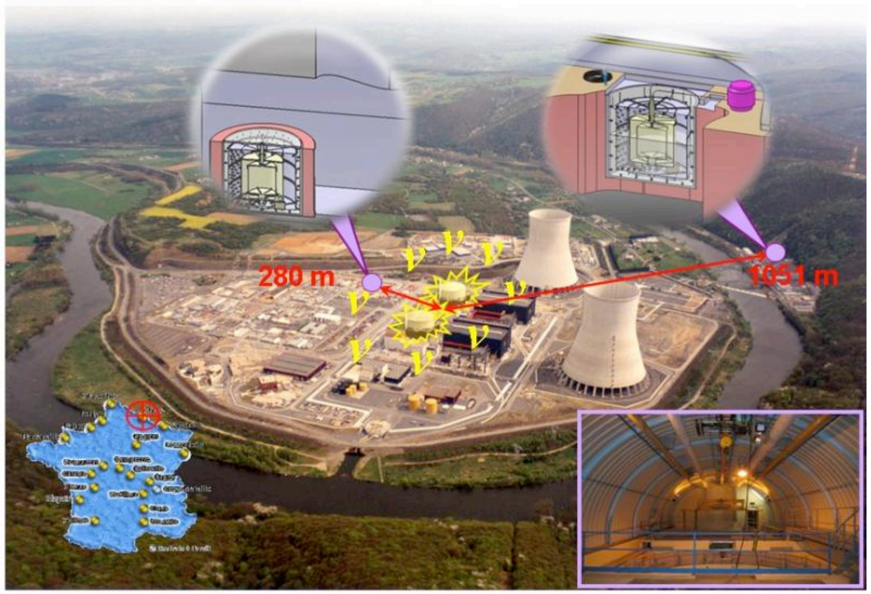
Long baselines are required ...



Future reactor ν experiments

$$\bar{\nu}_e \longrightarrow \bar{\nu}_e$$

Double-chooz



Reach:

$\sin^2(2\theta_{13}) > 0.03$

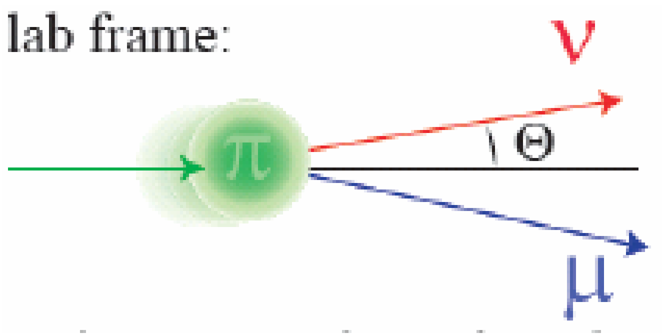
It is a disappearance measurement:

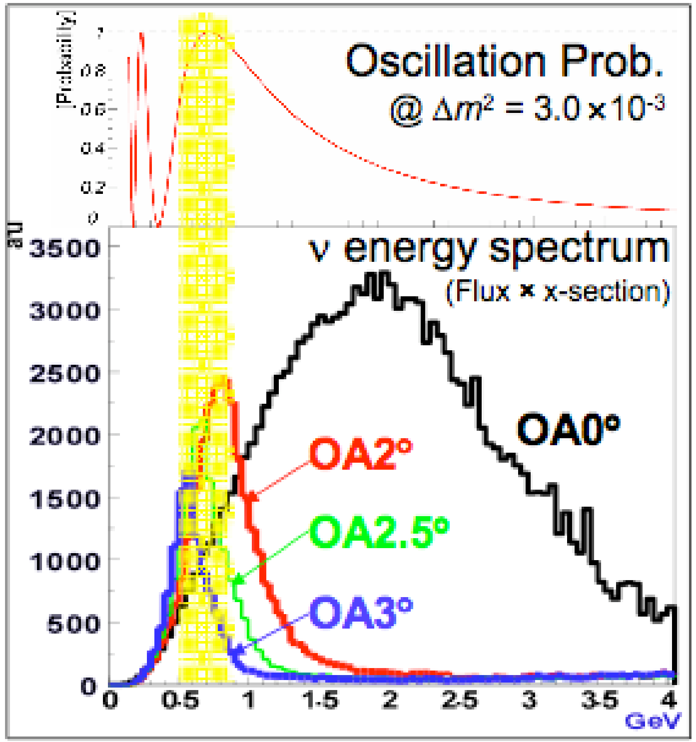
θ_{13} without ambiguities !

Future Superbeams

Use more intense conventional ν beams off-axis

$p \rightarrow \text{Target} \rightarrow K,\pi\ \ \nu_\mu,\ \%\ \nu_e \qquad\qquad \nu_\mu \longrightarrow \nu_e$

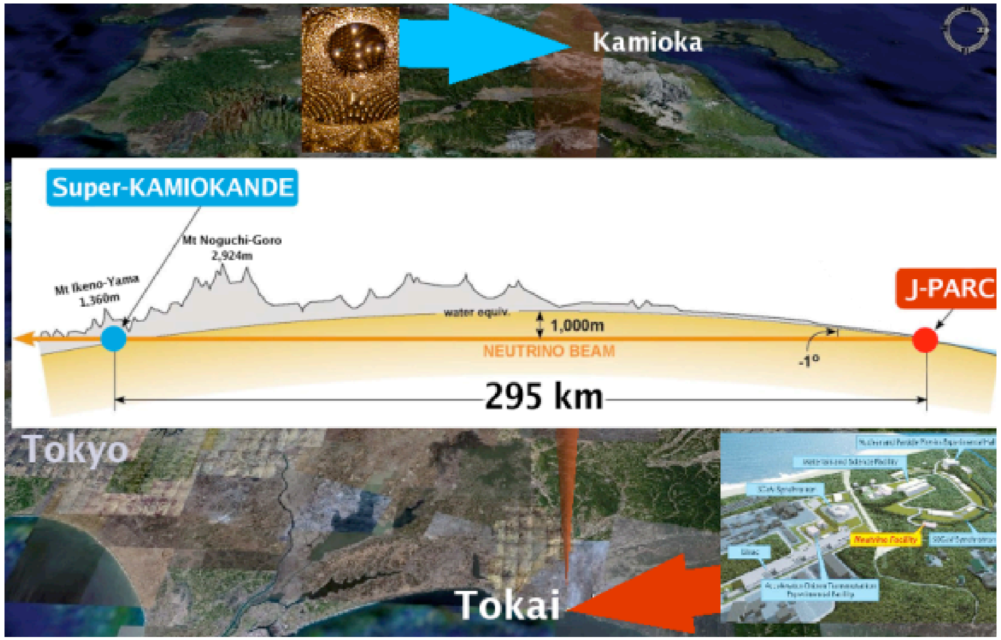


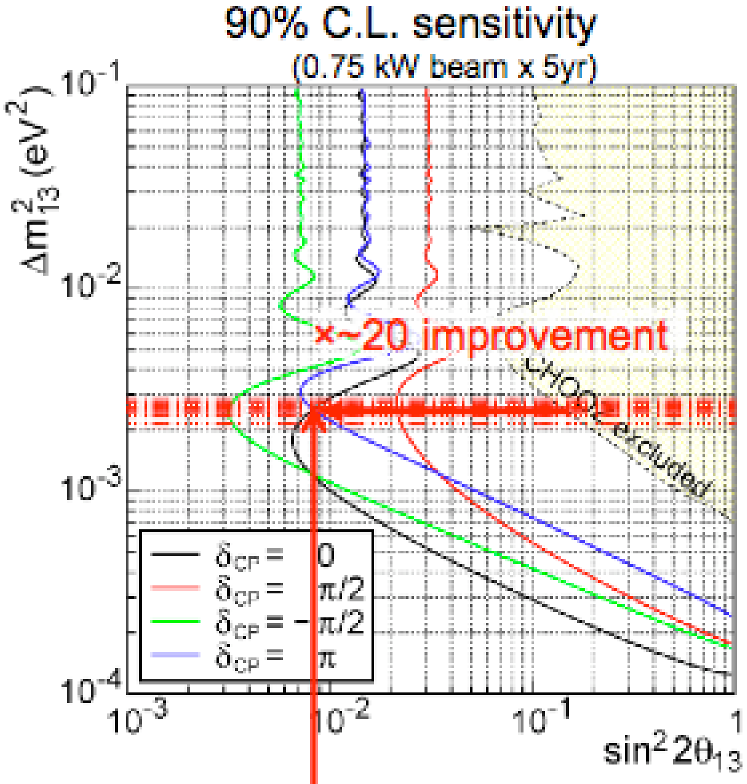


ν_e contamination in beam below 1%

T2K

Again SuperKamiokande !





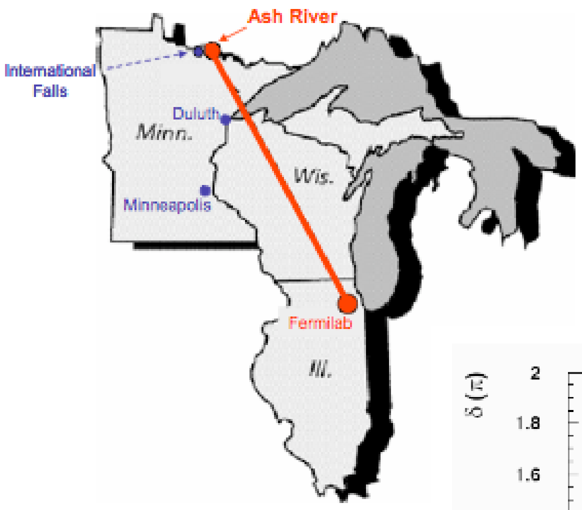
$\sin^2 2\theta_{13} \sim 0.008$ ($\delta_{CP} = 0,\pi$)

$\sin^2(2\theta_{13}) > 0.01\text{-}0.02$ no sensitivity to hierarchy or CP

Will start taking data in 2009...

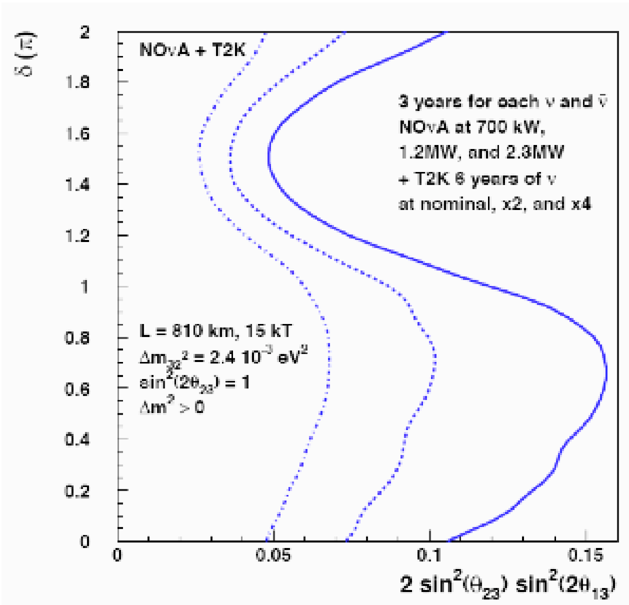
NOνA

First superbeam with sensitivity to the hierarchy

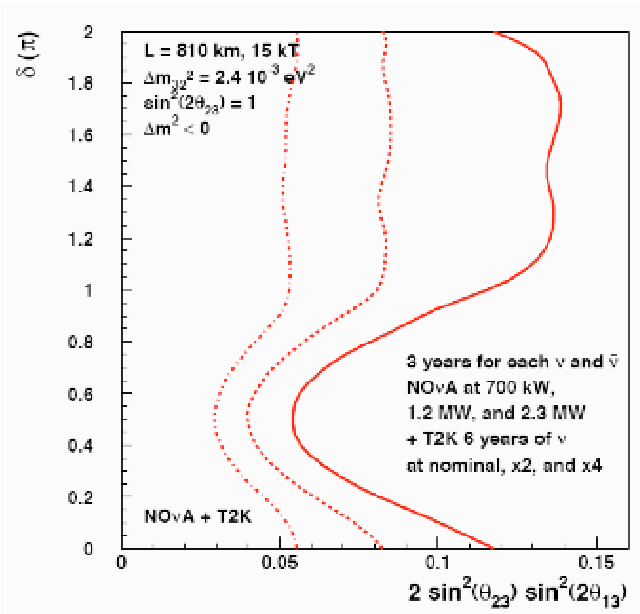


$\sin^2(2\theta_{13}) > 0.005\text{-}0.015$

Hierarchy for $\sin^2(2\theta_{13}) > 0.05$



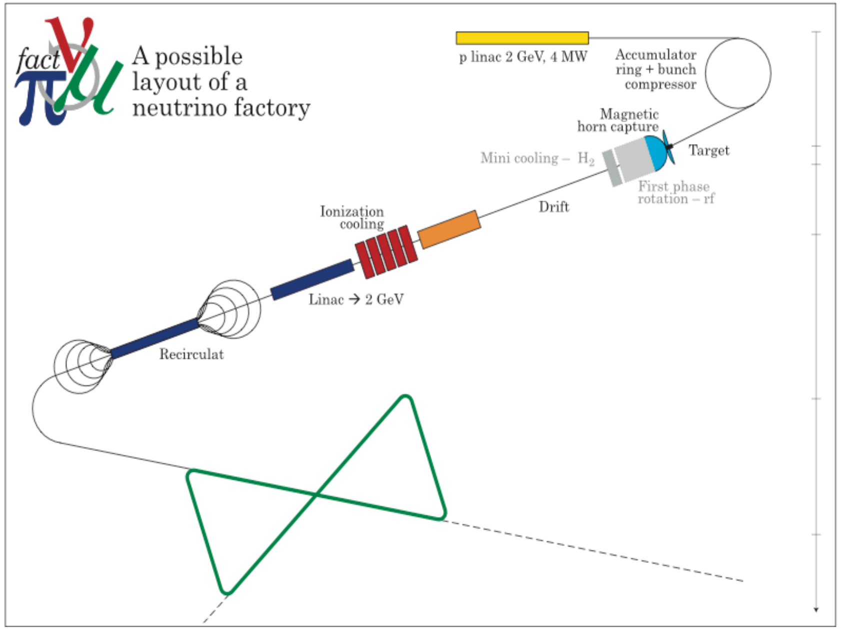
Normal Ordering



Inverted Ordering

Next generation: CP violation

Neutrino factory



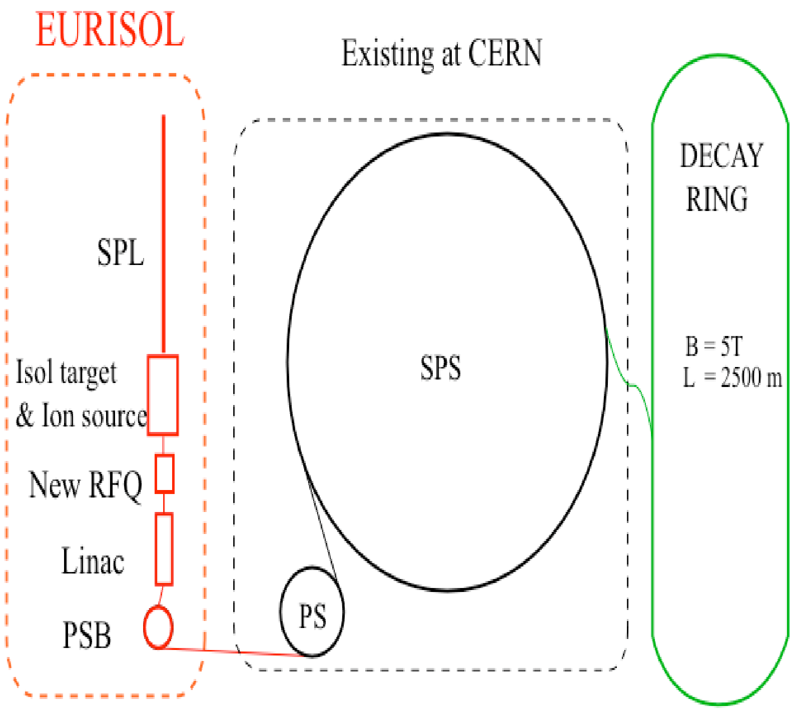
From μ decays

$$\mu^- \rightarrow e^- \quad \nu_\mu \quad \bar{\nu}_e\,;$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$$

$$\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$$

β beam

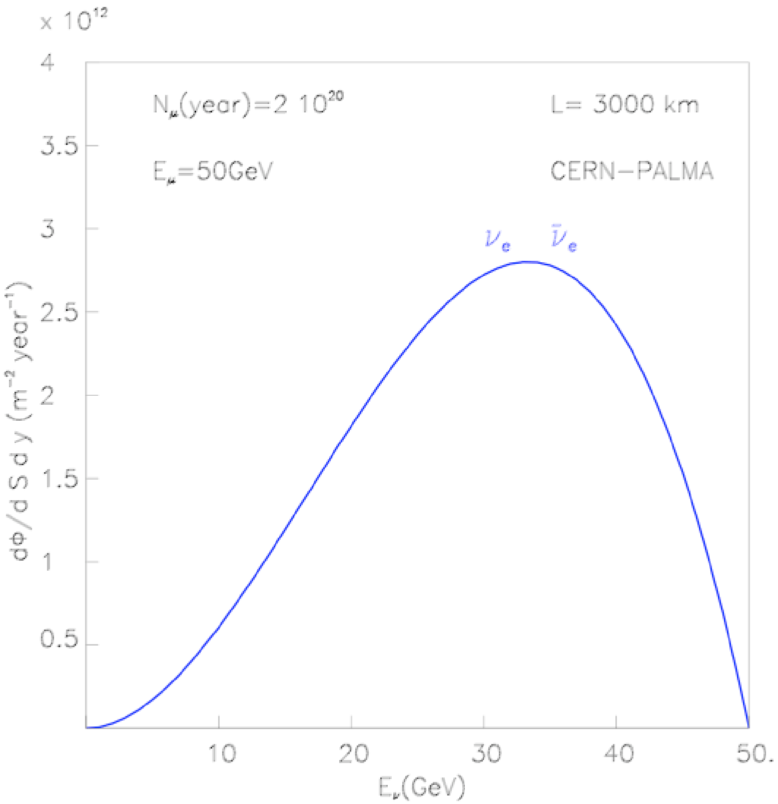


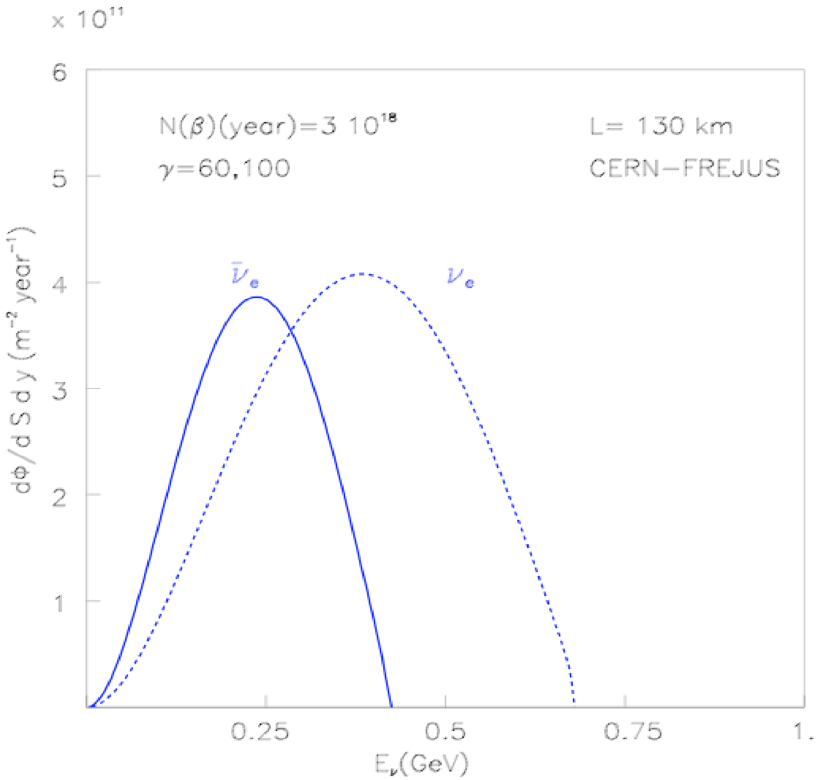
From radioactive ions

$$^6He^{++} \rightarrow ^6_3 Li^{+++}\ e^- \qquad \bar{\nu}_e$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$$

Pure beams

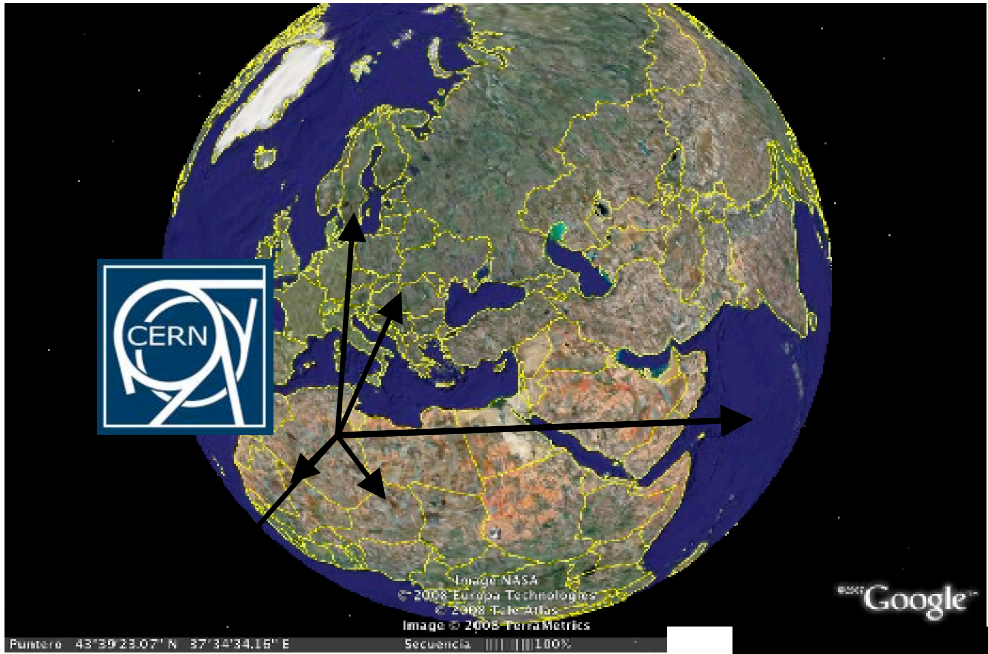




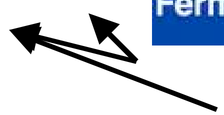
$$\left.\frac{d\Phi^{\rm NF}}{dSdy}\right|_{\theta\simeq 0} \simeq \frac{N_\mu}{\pi L^2} 12\gamma^2 y^2 (1-y)$$

$$\left.\frac{d\Phi^{\rm BB}}{dSdy}\right|_{\theta\simeq 0} \simeq \frac{N_\beta}{\pi L^2}\frac{\gamma^2}{g(y_e)} y^2 (1-y)\sqrt{(1-y)^2 - y_e^2}$$

Optimization of γ, L for physics output takes out far…



Fermilab



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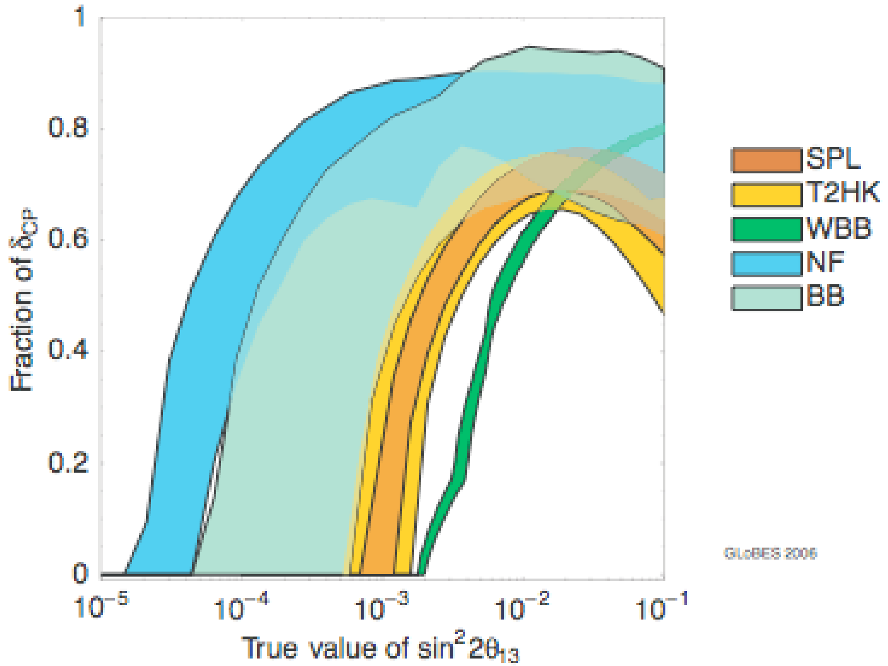
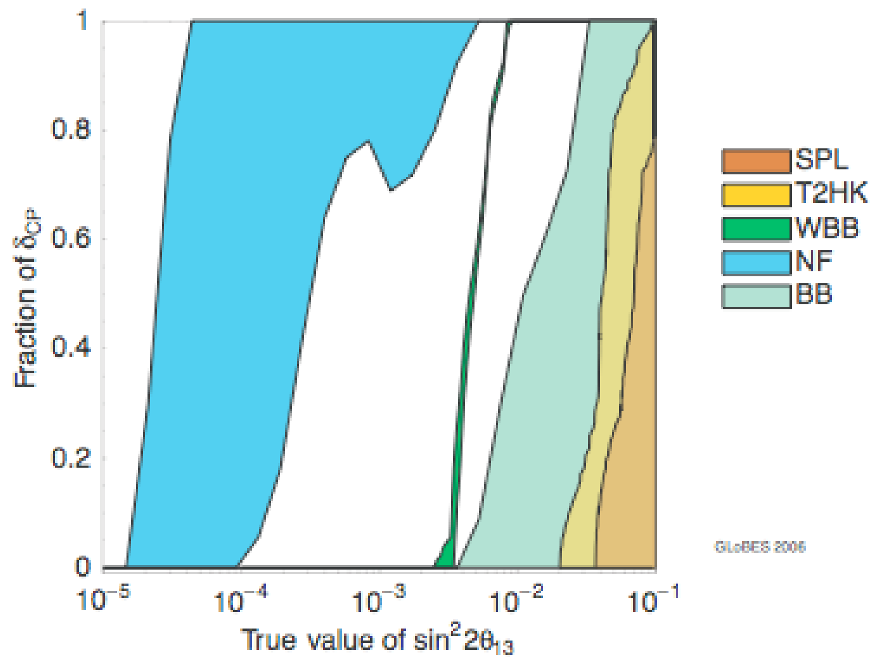
Physics potential

CP phase



Hierarchy



The realm of $\sin^2 2\theta_{13}$~10^{-4} can be reached !

ν in cosmology

You will see in the cosmology lectures why neutrinos are revelant

Big-Bang nucleosynthesis: N_ν

Contribution to Ω_m, structure formation $\Sigma\, m_{\nu\iota}$

The most interesting contribution of ν to the Universe could be the generation of the matter-antimatter asymmetry

leptogenesis

Fukuyita, Yanagida

Leptogenesis

The Universe seems to be made of matter

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.15(25) \times 10^{-10}$$

Generating this from a symmetric initial condition with same ammount of matter as antimatter: baryogenesis

Sakharov's necessary conditions

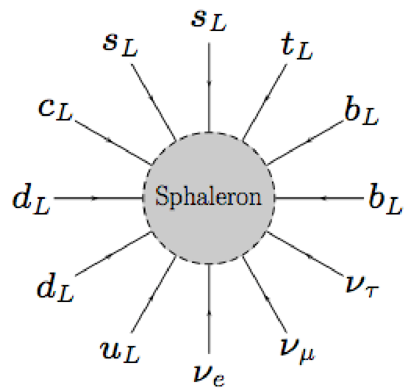
- ✓ Baryon number violation
- ✓ C and CP violation
- ✓ Deviation from thermal equilibrium

Baryon number violation

In the SM there is violation of B+L, preserve B-L

These processes are strongly suppressed at $T < T_{EW}$ and in equilibrium at $T > T_{EW}$

$$\Delta Q_B = \int d^4x \frac{3g^2}{32\pi^2} \epsilon^{\mu\nu\alpha\beta} W^a_{\mu\nu} W^a_{\alpha\beta}$$



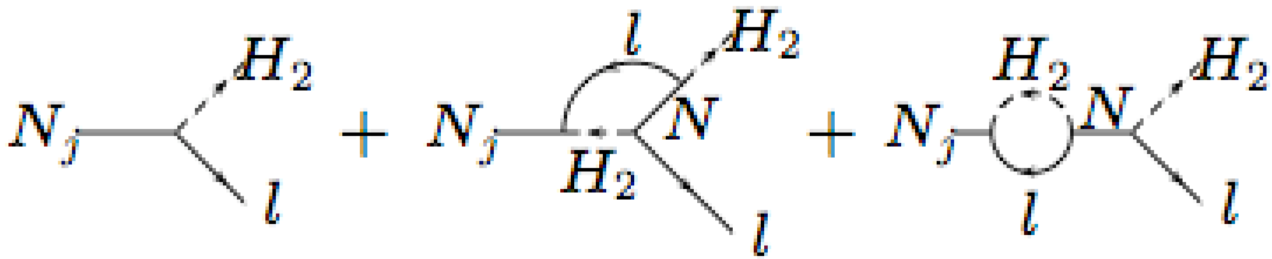
If B-L is generated above T_{EW} sphalerons produce B

$$Y_B \simeq \frac{12}{37} Y_{B-L}$$

L can be violated by presence of heavy Majorana ν (see-saw)

C, CP, L violation

New sources of CP violation in lepton sector can induce CP asymmetries in decays of heavy Majorana ν



$$\epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})}$$

Can this quantity be related to ν masses ?

Unfortunately…no $\epsilon_1 = -\frac{3}{16\pi} \sum_i \frac{Im[(\lambda_\nu^\dagger \lambda_\nu)^2_{i1}]}{(\lambda^\dagger \lambda)_{11}} \frac{M_1}{M_i}$

While $m_\nu = \lambda_\nu^T \frac{1}{M} \lambda_\nu$

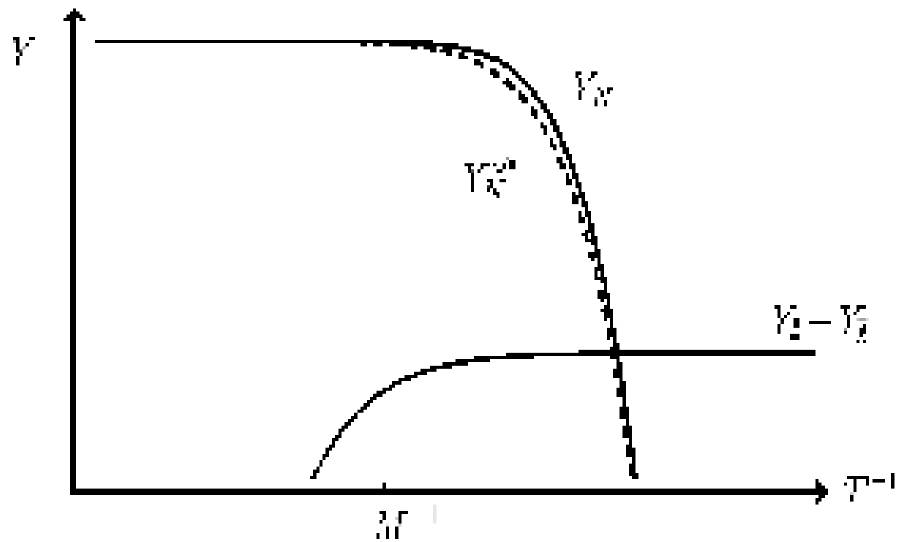
The two combinations are different, the model has 6 masses+6 angles + 6 phases, while in m_ν there are only 3+3+3

Generically not connected …

Out-of-equilibrium

The Majorana neutrinos decay out-of-equilibrium

$$\Gamma_N < \text{expansion rate} \quad \Rightarrow N_N > N_N^{\text{thermal}}$$



Baryon asymmetry

$M_{2,3} >> M_1$

$$Y_B = 4 \times 10^{-3} \overbrace{\epsilon_1}^{\mathrm{CP-asym}} \overbrace{\kappa}^{\mathrm{eff.\ factor}}$$

There is an upper limit on ε_1 $$|\epsilon_1| \leq \frac{8}{16\pi} \frac{M_1}{v^2} \left|\Delta m^2_{\mathrm{atm}}\right|^{1/2}$$

Davidson, Ibarra

$M_1 \geq 10^9$ GeV

Sufficiently large wash-out factor κ

$m_{\nu(\mathrm{min})} < \mathcal{O}(\mathrm{eV})$

If you want to learn more about leptogenesis ask the local organizers: Marta y Enrico !

Extensive recent review by Davidson, Nardi, Nir

Theory outlook

Neutrino masses imply a new physics scale ? Which ?

If $\Lambda > v$ low-energy effects should be well described by an effective field theory:

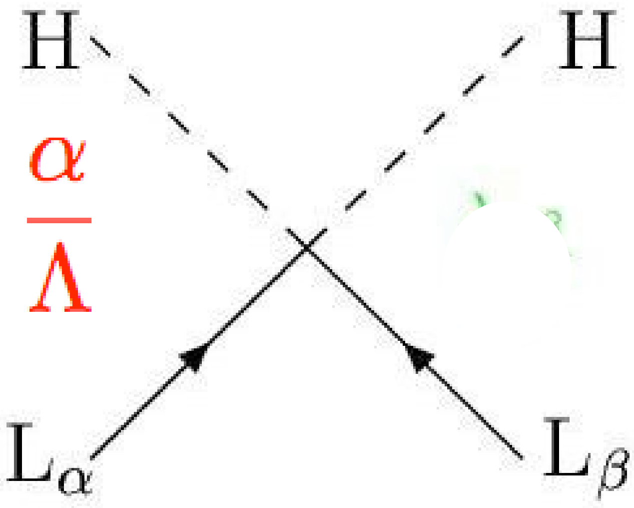
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha_i}{\Lambda} O_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda^2} O_i^{d=6} + \ldots$$

O_i^d built from SM fields satisfying the gauge symmetries

Weinberg; Buchmuller, Wyler;...

New physics scale

d=5 only Weinberg's operator! { Majorana ν masses
lepton number violation

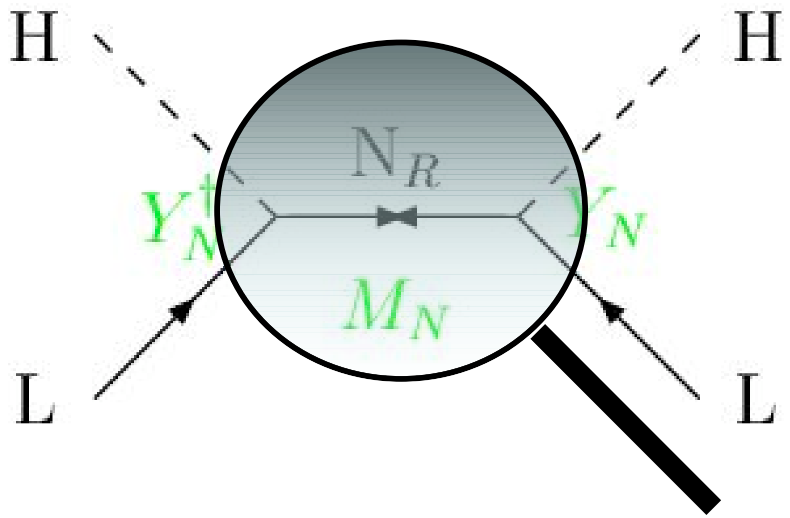


$$O^{d=5} = \bar{L}^c \Phi \Phi L$$

$$m_\nu = \frac{\alpha}{\Lambda} v^2$$

New physics scale

Type I see-saw: interchange a heavy singlet fermion



$$O^{d=5} = \bar{L}^c \Phi \Phi L$$

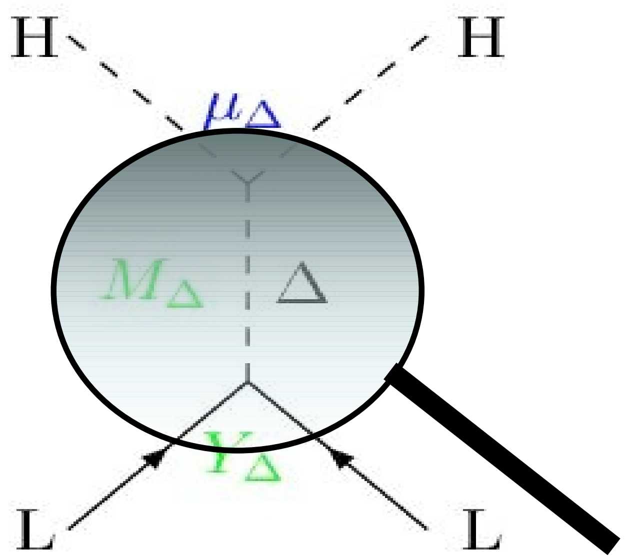
$$m_\nu = \frac{\alpha}{\Lambda} v^2$$

$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow...

New physics scale

Type II see-saw: interchange a heavy triplet scalar

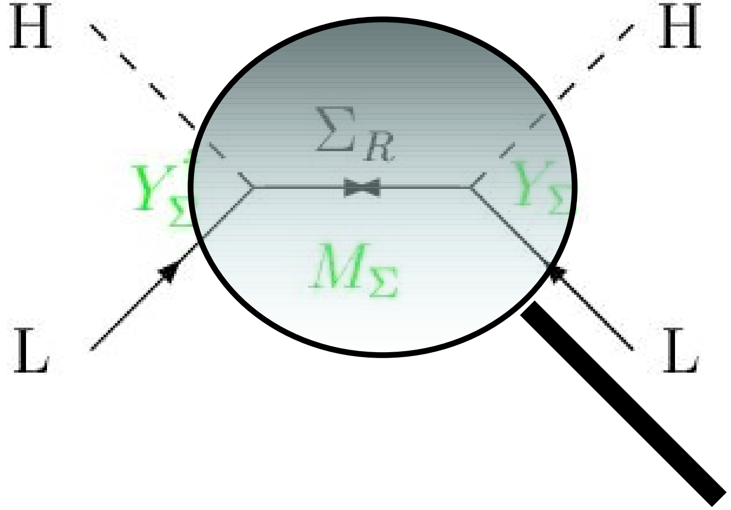


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Konetschny, Kummer; Cheng, Li; Lazarides, Shafi, Wetterich ...

New physics scale

Type III see-saw: interchange a heavy triplet fermion



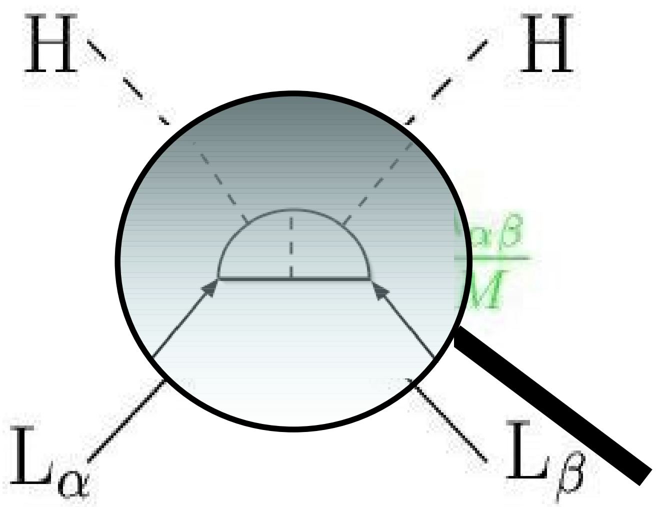
$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

Foot et al; Ma; Bajc, Senjanovic...

New physics scale

Also from loops !

Zee-Babu



$$m_\nu \sim \mathcal{O}\left(\frac{1}{(16\pi^2)^2} \times \frac{\mu m_l^2}{M^2}\right)$$

Effective see-saw theories

The measurement of m_ν not enough…

$\alpha \longleftrightarrow \Lambda$ "degeneracy"

All these models induce also d=6 operators:

Type I $$O^{d=6} = Y_N^\dagger \frac{1}{M_N^2} Y_N (\bar{L}\Phi) \not{\partial} (\Phi L)$$

Type III $$O^{d=6} = Y_\Sigma^\dagger \frac{1}{M_\Sigma^2} Y_\Sigma (\bar{L}\Phi) \not{D} (\Phi L)$$

Type II $$O^{d=6} = Y_\Delta^\dagger \frac{1}{M_\Delta^2} (\bar{L}L)(\bar{L}L) + \frac{\mu_\Delta^2}{M_\Delta^4} (\Phi^\dagger \Phi)^3 + \ldots$$

Can we test this?

Gavela, et al; Abada, et al

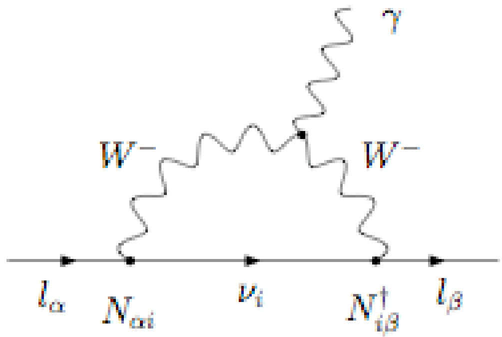
d=6 operators

Do not violate L and provide a rich phenomenology...

- rare lepton decays: $\mu \to e\,\gamma$
- Z, W decays
- rho parameter
- W mass, ...
- violations of universality, unitarity,...

$l_\alpha \to l_\beta \gamma$

$$Br(\mu \to e\gamma)_{exp} \leq 1.2 \cdot 10^{-11}$$



If just neutrino masses:

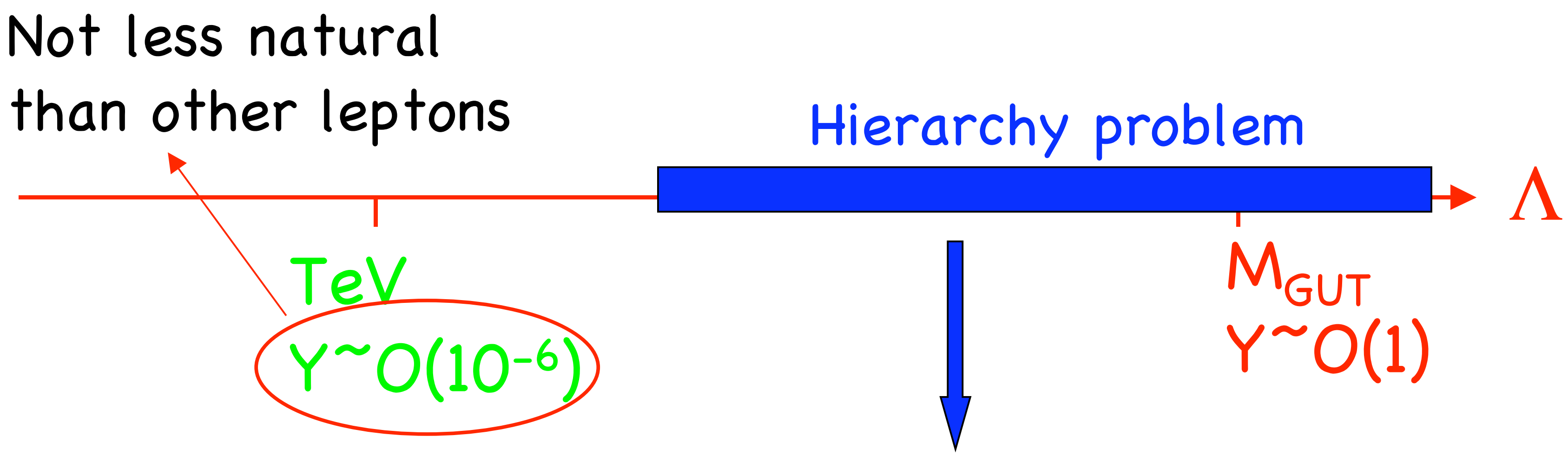
$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i V^*_{\mu i} V_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 \leq 10^{-56}$$

$$m_i \sim \frac{1}{\Lambda}$$

If also d=6 operators:

$$Br(\mu \to e\gamma) \sim \frac{100\alpha}{96\pi} \left| \frac{\beta_{\mu e}}{\Lambda^2} \right|^2$$

What we expect for Λ ?



Generically, naturalness problem

$$\delta m_H^2 \sim \frac{\lambda}{16\pi^2}\Lambda^2 \log\left(\frac{\Lambda}{\mu}\right)$$

Vissani;Casas, et al

Can $\Lambda \sim$ TeV and large d=6 effects beyond ν masses ?

Could d=6 be stronger ?

Yes if two independent scales in d=5, d=6 from a symmetry principle: lepton number

Cirigliano et al; Kersten,Smirnov; Abada et al

$\Lambda_5 \sim \Lambda_{LN} > \Lambda_6 \sim \Lambda_{LFV} \sim$ TeV

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha}{\Lambda_{LN}} O_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda_{LFV}^2} O_i^{d=6} + \ldots$$

- Origin of lepton/quark flavour violation linked to the Λ_{LFV}
- Lepton number breaking scale higher and responsible for the gap between ν and remaining fermions

Many interesting consequences if so...

- LFV could be measurable beyond neutrino oscillations

  Eg: μ -> e γ

- Scale of LFV within LHC reach:

Keung, Senjanovic;...

same-charge lepton pairs !

Eg: Type II see-saw

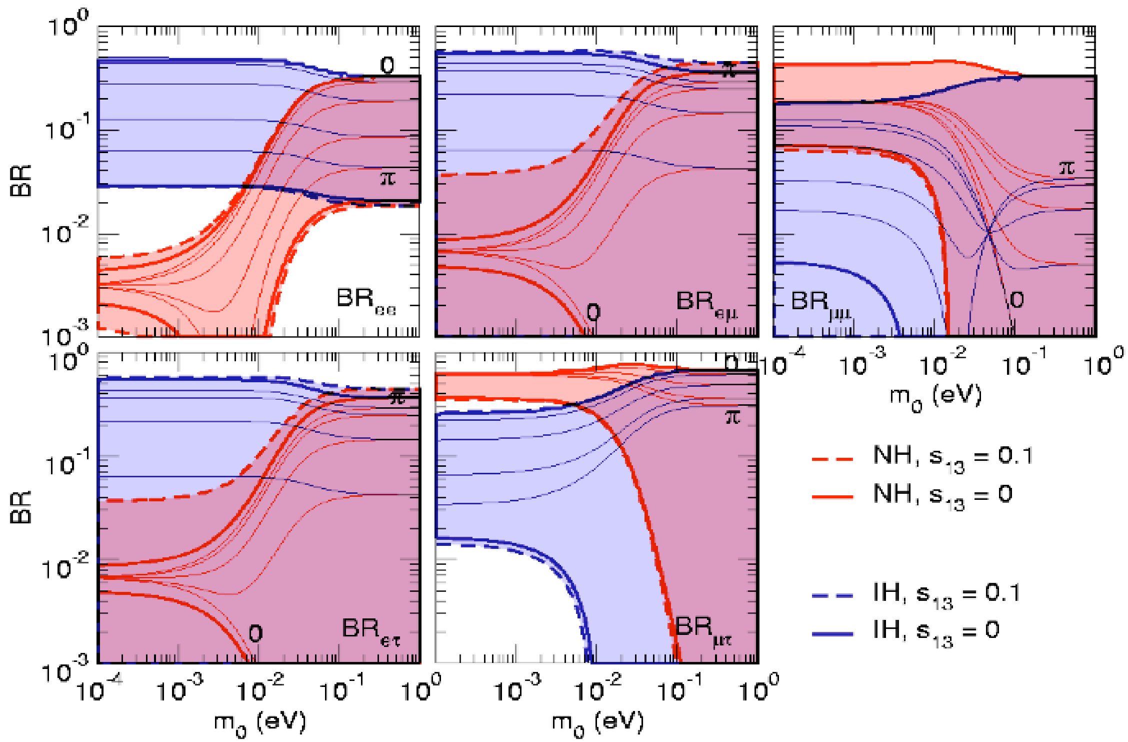
$$\Lambda_{LN} = M_{\Delta}^{2}/\mu \qquad \Lambda_{LFV} = M_{\Delta}$$

$\Lambda_{LFV} \sim$ TeV: direct searches at LHC ?

See-saw II:Pair-production of charged triplet scalars

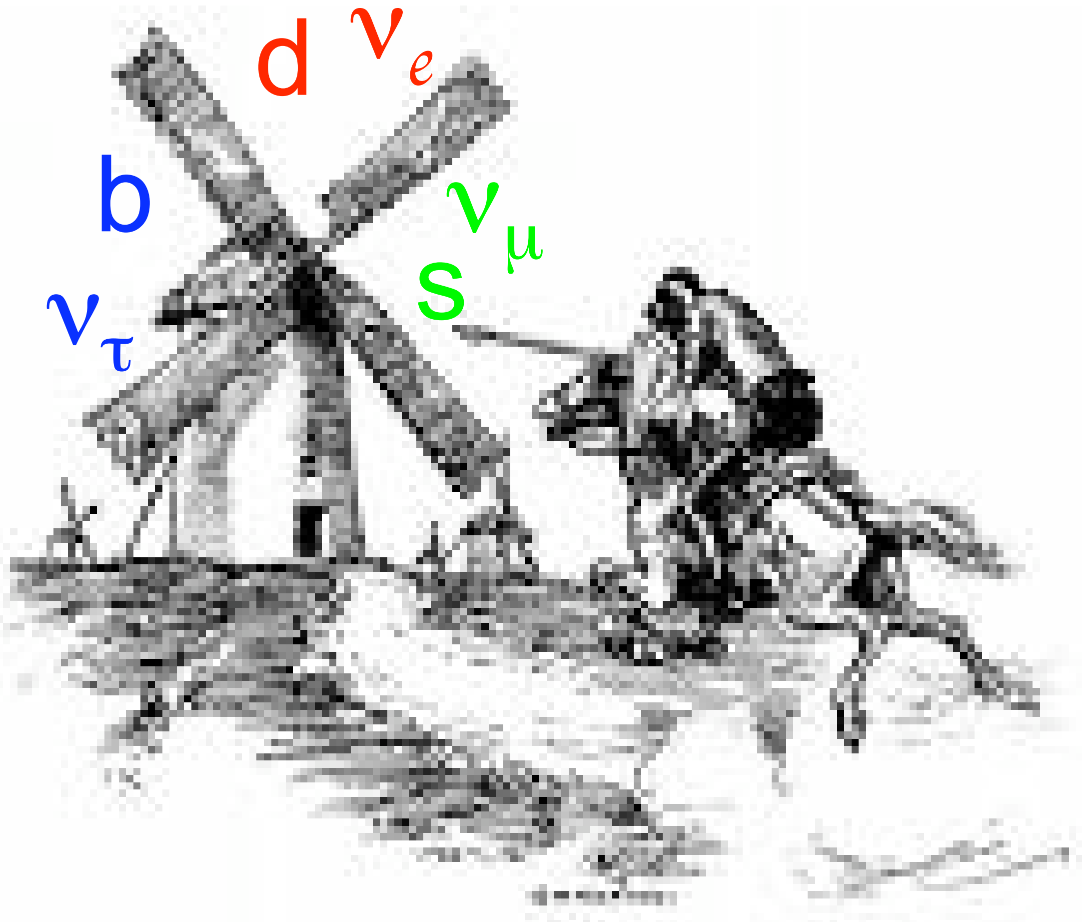
$pp \to H^{++} H^{--} \to l^+ l^+ l^- l^-$

Flavour structure one-to-one to m_n ! $BR(H^{++} \to l_a^+ l_b^+) \sim |M_{ab}|^2$



Garayoa, Schwetz

The flavour problem



Quixotic enterprise…we need as many approaches as possible

LHC, lepton and quark flavour factories

Conclusions

- The results of many beautiful experiments have demonstrated beyond doubt that ν are massive and mix

- Standard 3ν scenario can explain in terms of 4 fundamental parameters all available data, except LSND

- The lepton flavour sector looks quite different to the quark one: a complementary approach to flavour puzzle

- Many fundamental questions remain to be answered however: Majorana nature of neutrinos and scale of new physics? CP violation in the lepton sector? Source of the matter-antimatter asymmetry ?

A rich experimental programme lies ahead where fundamental physics discoveries are very likely (almost warrantied) ....

Maybe ν will keep their tradition and bring in surprises that will give us a clue of what lies Beyond the SM