Selected Topics in Majorana Neutrinos

Three lectures by

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SUMMARY

1. Higgs Mechanism, quark masses and mixing for three generations
2. FCNC processes today: Standard Theory
3. GIM mechanism and new physics at TeV scale
4. Minimal Flavor Violation
5. Neutrino oscillations with 3 neutrinos
6. Solar neutrinos
7. Atmospheric neutrinos
8. ν_τ appearence at LNGS
9. The last real angle: θ_{13} from the Daya Bay (China) experiment

1. Higgs Mechanism, quark masses and mixing for three generations

- Three generations

$$\begin{aligned}&\text{quarks :}\\&q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix}, \; U_R, \; D_R\\&U = (u, \; c, \; t), \; \text{etc.}\end{aligned}$$

- gauge interactions have a large global symmetry:
- $U(3)_q \otimes U(3)_U \otimes U(3)_D$ for independent trasfs. of q_L, U_R, D_R.
- the symmetry is broken by the Yukawa couplings to the Higgs doublet

$$\mathcal{L}_Y = \bar{q}_L Y_D H D_R + \bar{q}_L Y_U \tilde{H} U_R \qquad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, \; \tilde{H}_i = \epsilon_{ij} H_j = \begin{pmatrix} H^0 \\ -H^+ \end{pmatrix}$$

$$M_D = v Y_D \; , \; M_U = v Y_U \; , \qquad v = \langle 0 | H | 0 \rangle$$

Cabibbo-Kobayashi-Maskawa matrix

- Yukawa couplings are represented by the generally complex matrices, Y_D, Y_U, that can be diagonalized by bi-unitary transformations belonging to $U(3)_q \otimes U(3)_U \otimes U(3)_D$
- this is made possible by the following
  - ***theorem***: any complex matrix Y can be written as Y=W H, with W unitary and H hermitian
  - ***corollary***:any complex matrix Y can be written as Y=U m V, with U and V unitary and m diagonal, with real, positive or zero, elements
- I will simply assume all unitary matrices to have unit determinant
- transformations of fermion fields by an overall phase is a symmetry of the Yukawa interactons, which is in general affected by anomalies;
- Peccei&Quinn: we can use the symmetry to eliminate the CP violating QCD term $G_{\mu\nu}\tilde{G}^{\mu\nu}$
- if the symmetry is spontaneously broken, the phase is a Goldstone psuedoscalar field (axion), which takes a mass by the anomaly
- I will not elaborate further along this line.

$$\mathcal{L}_Y = \bar{q}_L Y_D H D_R + \bar{q}_L Y_U \tilde{H} U_R$$

- $Y_U = W m_U Z$: use Z to redefine U_R, W to redefine q_L
- $Y_D = U m_D V$: use V to redefine D_R
- the mass term is then:

$$\mathcal{L}_{mass} = \bar{D}_L U m_D D_R + \bar{U}_L m_U U_R$$

- up quark fields are at the same time mass and weak isospin eigenstates, but we have to define:

$$D^\dagger_{weak,L} U = D_{mass,L} \text{ i.e. } D_{weak,L} = U D_{mass,L}$$

- Charged current interactions acquire flavor violating components, while neutral current conserve flavor, since U is unitary:

$$\begin{aligned} &\mathcal{L}_{weak} = \bar{U}\gamma^\mu(1-\gamma_5)U_{CKM} D W_\mu \ + \\ &+ \left[\bar{U}\gamma^\mu(1-\gamma_5)U - \bar{D}(U^\dagger_{CKM}\gamma^\mu(1-\gamma_5)U_{CKM})D\right] W^3_\mu \end{aligned}$$

$(U = U_{CKM}, \text{ as usual})$

Fitting CKM

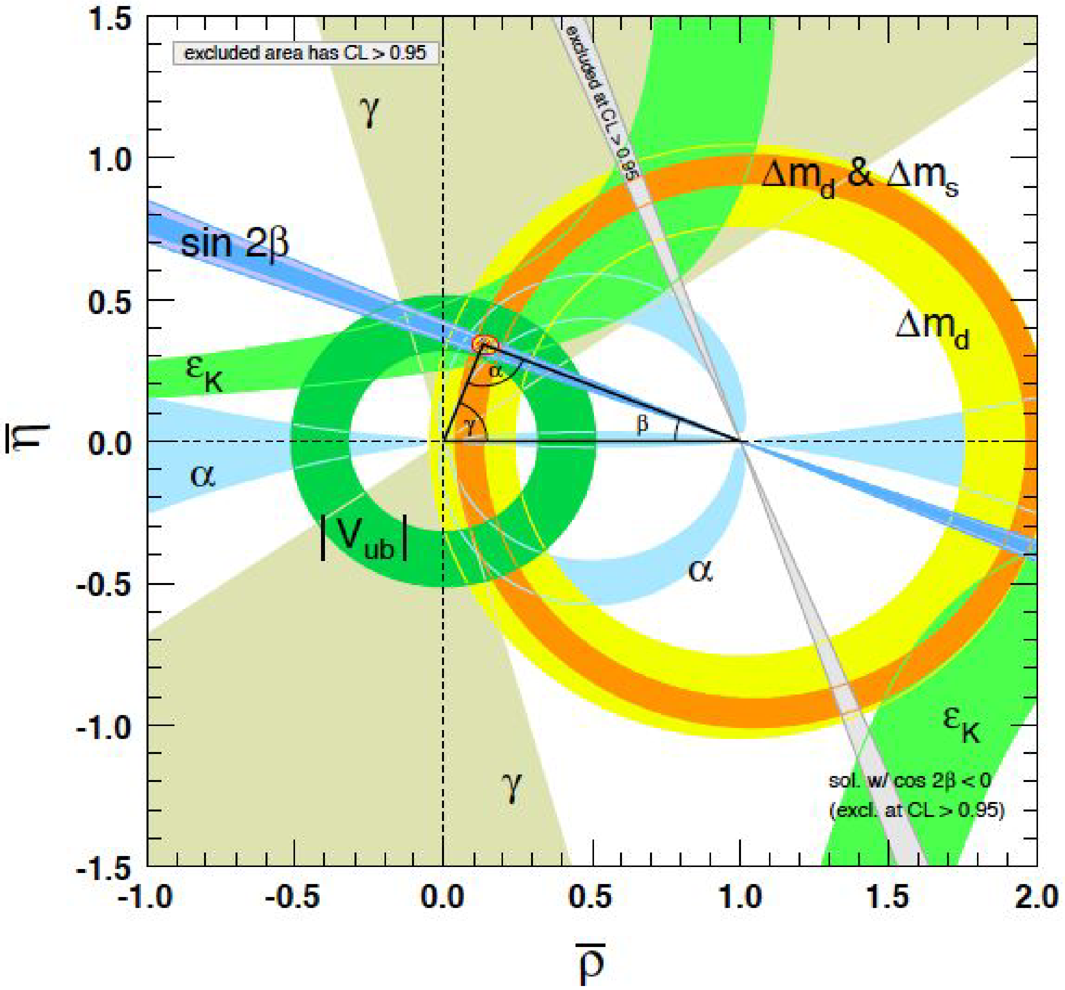
- CKM matrix in the Wolfenstein parametrization
- $\lambda = \sin\theta_C$

$$U_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = 0.2253 \pm 0.0007,\ \ A = 0.808^{+0.022}_{-0.015}$$
$$\rho = 0.132^{+0.022}_{-0.014},\ \ \eta = 0.341 \pm 0.013$$

Numerically:

$$U_{CKM} \approx \begin{pmatrix} 0.97462 & 0.2253 & 0.0012 - i0.0032 \\ -0.2253 & 0.9746 & 0.0410 \\ 0.0080 - i0.0032 & -0.04101 & 1 \end{pmatrix}$$



2. FCNC processes today:
Standard Theory

$$M_{12}(\bar{K}^0 \to K^0) =< K^0| - \mathcal{L}_{eff}|\bar{K}^0 >= \\ = \frac{(G_F M_W^2)(G_F f_K^2)}{12\pi^2} \times \sum_{i,j=c,t} C_iC_jE(x_i,x_j) \times m_K$$

Loop factors, x=$(m_q/M_W)^2$ (Inami & Lim)

CKM factors-squared

- in ΔF=2 transitions for K and B, quark loops with d ➞ s, b transitions are dominated by c and t quarks,
- leading QCD corrections are calculable multiplicative renormalizations to loop amplitudes, and are reliable for t-quark-dominated loops

$$M_{12}(\bar{K}^0 \to K^0)|_{corr} = \frac{(G_F M_W^2)(G_F f_K^2)}{12\pi^2} \times \\ \times [\eta_1 C_c^2 E(x_c,x_c) + \eta_2 C_t^2 E(x_t,x_t) + 2\eta_3 C_cC_tE(x_c,x_t)] \times m_K \times B_K$$

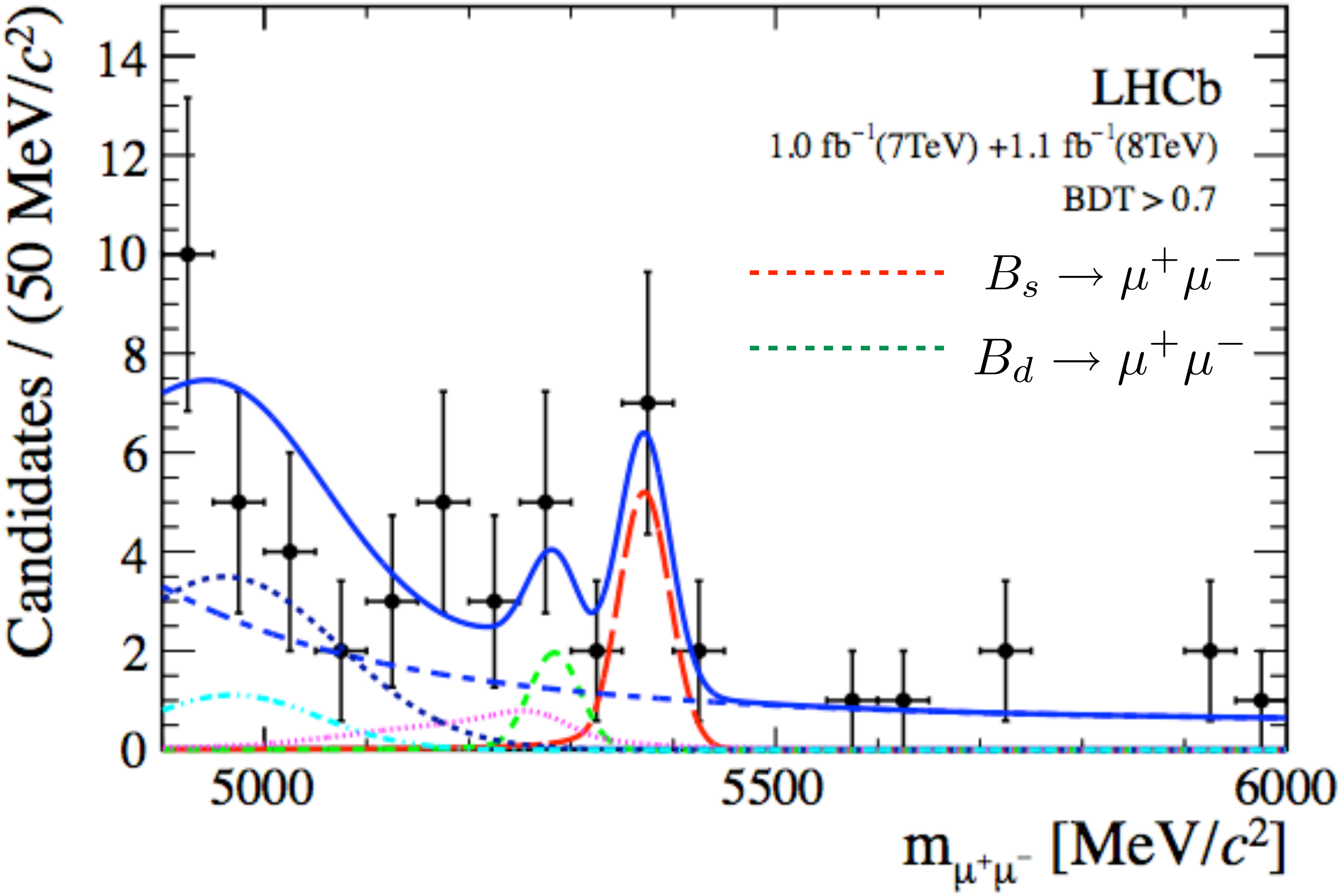
QCD corrections

- by comparison, ΔF=2 transitions for D-mesons are dominated by s and b quarks, but b is CKM suppressed much more than s and long-distance effects

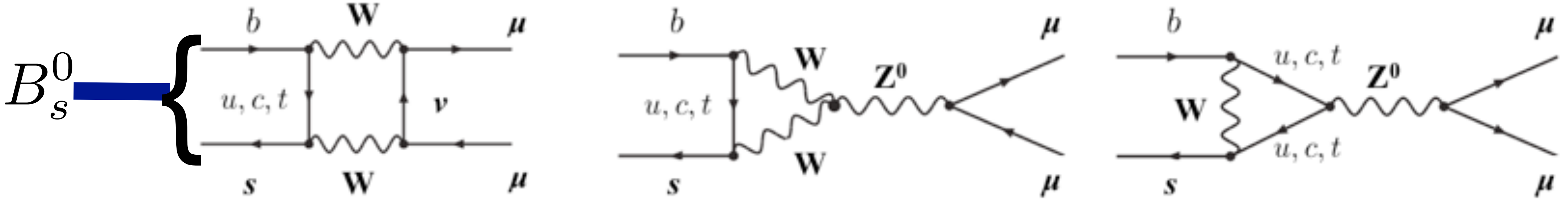
$$M_{12}(\bar{D}^0 \to D^0) = \frac{(G_F M_W^2)(G_F f_D^2)}{12\pi^2} \times \sum_{i,j=s,b} C_iC_jE(x_i,x_j) \times m_D$$

$$C_b \approx (\sin\theta_C)^5$$
$$C_s \approx (\sin\theta_C)$$

Remarkable last year result of LHCb: $B_s \to \mu^+\mu^-$

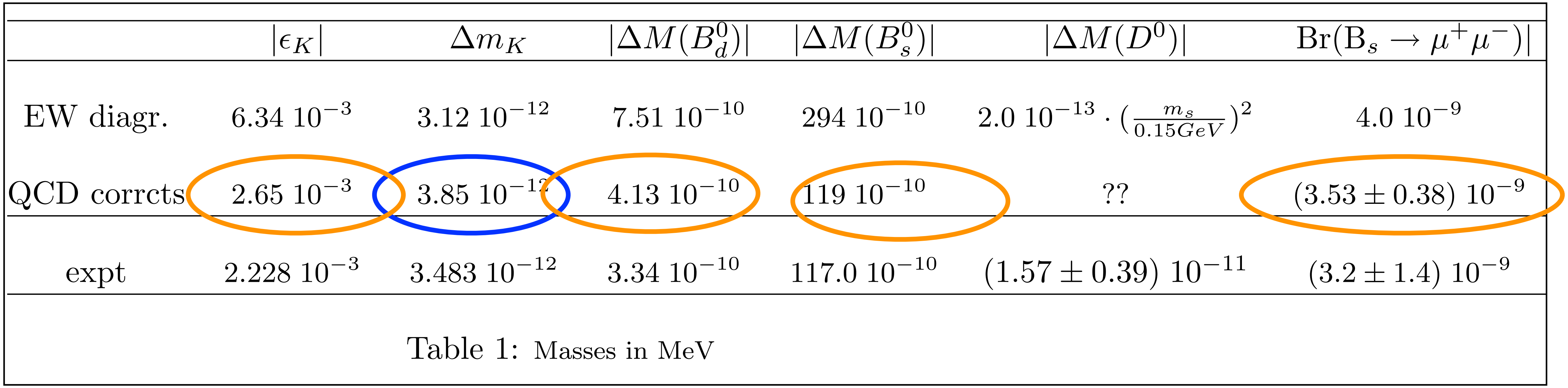


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$



see e.g. Buchalla, Buras, Lautenbacher, 1995

comparison of ST with data



	$\lvert\epsilon_K\rvert$	Δm_K	$\lvert\Delta M(B_d^0)\rvert$	$\lvert\Delta M(B_s^0)\rvert$	$\lvert\Delta M(D^0)\rvert$	$\mathrm{Br}(\mathrm{B}_s \to \mu^+\mu^-)\rvert$
EW diagr.	$6.34\ 10^{-3}$	$3.12\ 10^{-12}$	$7.51\ 10^{-10}$	$294\ 10^{-10}$	$2.0\ 10^{-13}\cdot(\frac{m_s}{0.15GeV})^2$	$4.0\ 10^{-9}$
QCD corrcts	$2.65\ 10^{-3}$	$3.85\ 10^{-12}$	$4.13\ 10^{-10}$	$119\ 10^{-10}$	??	$(3.53\pm0.38)\ 10^{-9}$
expt	$2.228\ 10^{-3}$	$3.483\ 10^{-12}$	$3.34\ 10^{-10}$	$117.0\ 10^{-10}$	$(1.57\pm0.39)\ 10^{-11}$	$(3.2\pm1.4)\ 10^{-9}$

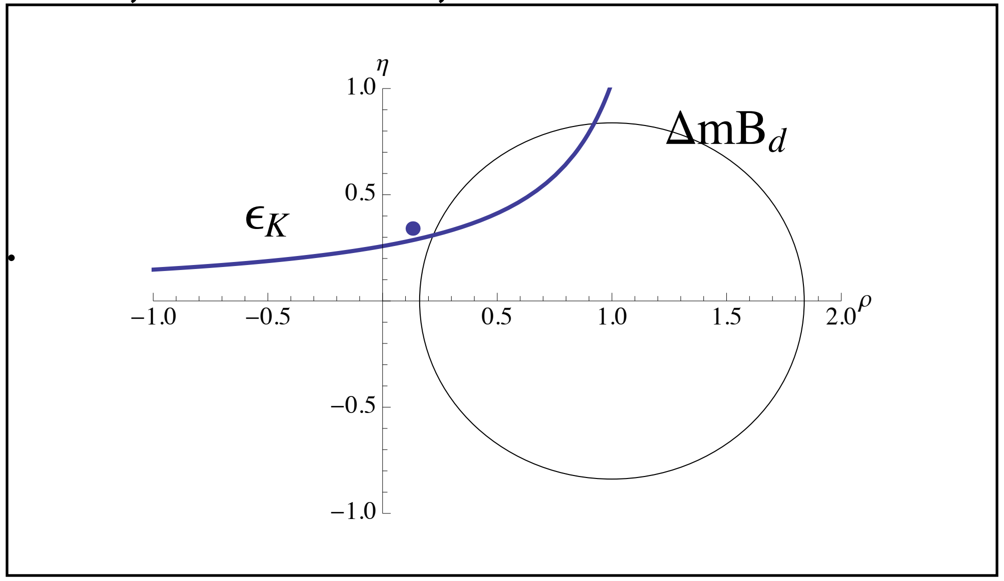
Table 1: Masses in MeV

dominated by the t-quark

dominated by the c-quark

Input data:
CKM coefficients (weak decays of s, c and b)
m_c=1.5, m_t=173, m_s=0.150, m_b=5.0

Simplified determination of the CKM coefficients ρ and η from the experimental values of $|\epsilon_K|$ and $|\Delta M(B_d^0)|$. The point corresponds to the values given in PDG



3. GIM mechanism and new physics at TeV scale

- A light Brout-Englert-Higgs scalar boson in the ST calls for new physics (NP) at TeV scale: SUSY, Composite Higgs, etc.;
- the new particles most likely carry flavor and will potentially add new FCNC effects: this is the so-called *flavor problem*.
- let's write, for example,

$$\mathcal{L}_{eff}(d\bar{s} \to \bar{d}s) =$$

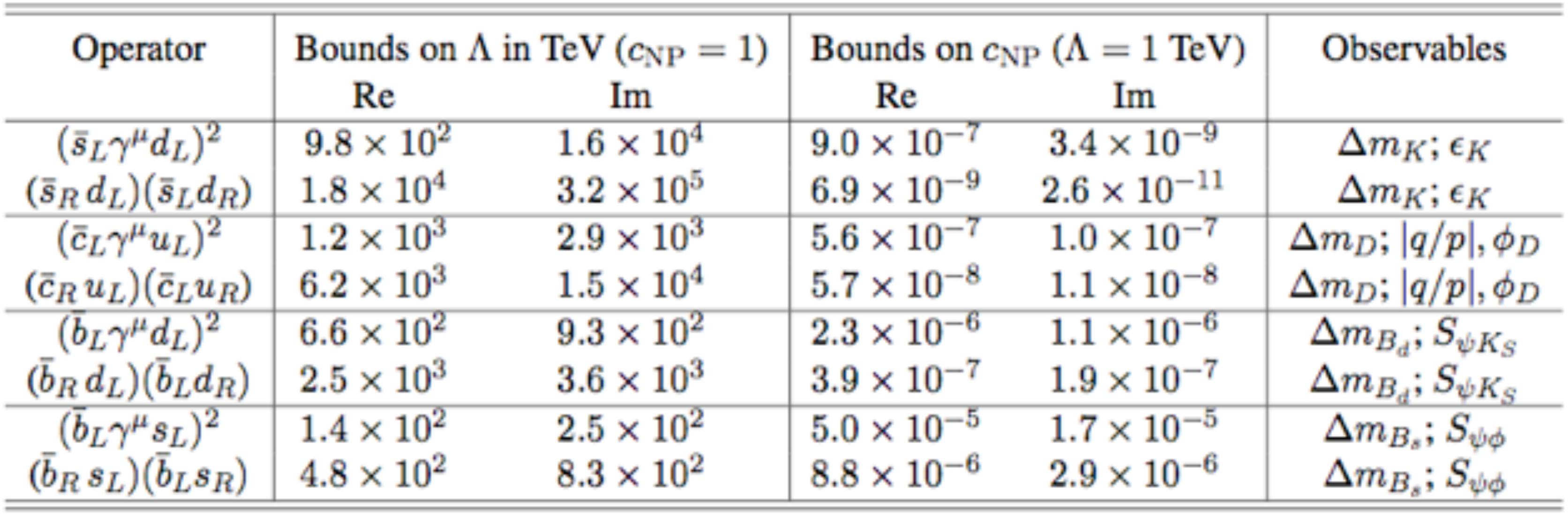
$$= -\frac{G_F^2 M_W^2}{16\pi^2} \times \sum_{i,j=c,t} (U_{id}^* U_{is})(U_{jd}^* U_{js}) E(x_i, x_j) \times (\bar{d}s)_{V-A} (\bar{d}s)_{V-A} +$$

$$+ \begin{pmatrix} +\frac{1}{\Lambda^2} \\ \\ +\frac{c_S}{\Lambda^2} \end{pmatrix} (\bar{d}s)_{S,P} (\bar{d}s)_{S,P}$$

Standard

New Physics at larger scale ?

- |NP|<|ST| ➪ very large Λ
- or very small coefficient:



Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Bounds on Λ in TeV ($c_{\rm NP}=1$) Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

Table 1.1: Bounds on representative dimension-six $\Delta F = 2$ operators, assuming an effective coupling $c_{\rm NP}/\Lambda^2$.

•Isidori, 2012 CERN HEP Summer School, arXiv:1302.0661v1 [hep-ph]

The simplest example of NP in TeV region: *Low Energy Supersymmetry*

(as seen by many)

- In the Standard Model, no increased symmetry is gained by letting the mass of the elementary scalar to vanish
- as a consequence, extraordinary fine-tuning of quantum corrections is needed to keep the Higgs boson mass to values so much smaller than the natural cutoff given by gravity (or grand unification)
- *low energy* supersymmetry relates scalars and fermions, whose mass is protected by chiral symmetry, and reduces the cutoff scale to M_{SUSY}.
- Alternative: there are no elementary scalars, the Higgs boson is composite by fermion fields, possibly a would-be-Goldstone boson of some symmetry.
- New physics of the strong-interaction type is not favoured by electroweak precision data (which are really becoming high-precision data).
- In addition, the value found for the Higgs boson mass speaks in favour of SUSY.

Rare processes and new physics at Tev scale

- If there is New Physics at TeV, it cannot be coupled to flavor ***genically***;
- many insights and many interesting papers (see G. Isidori@CERN School 2012)
- One idea is ***Minimal Flavor Violation***: *Yukawa couplings are the only source of flavor symmetry violation*
  - Chivukula and Georgi, *Composite Technicolor Standard Model*, PL **B188** (1987)
  - D'Ambrosio, Giudice, Isidori and Strumia, Minimal flavor violation: *An Effective field theory approach*, NP **B 645** (2002) 155 [hep-ph/0207036];
  - applies to technicolor and/or SUSY

4. Minimal Flavor Violation

$$\mathcal{L}_Y = \bar{q}_L Y_D H D_R + \bar{q}_L Y_U \tilde{H} U_R$$

- The lagrangian is formally invariant under a flavor group:

$$\mathcal{G}_{quark} = SU(3)_q \otimes SU(3)_{U_R} \otimes SU(3)_{D_R}$$

- if we apply the transformations to the quark fields and to the Yukawa couplings:

$$q_L \to U_L q_L;\ D_R \to V D_R;\ U_R \to W U_R$$

and :

$$Y_D \to U_L Y_D V^\dagger;\ Y_U \to U_L Y_U W^\dagger$$

- (in the old times, Ys would be called “spurions” and this was a usual trick to determine the effects of symmetry breaking)
- assume that
  - the new physics is made of particles at a scale Λ>> electroweak
  - the new particles transform under G_{quark} and
  - symmetry breaking in the new sector is decribed by the same Yukawa couplings Y_D and Y_U
  - the new physics gives rise to Flavor Changing Neutral Current effects described by dimension four operators, such as e.g. : $\frac{1}{\Lambda^2}\left[\bar{d}\gamma^\mu(1-\gamma_5)s\right]\cdot\left[\bar{d}\gamma_\mu(1-\gamma_5)s\right]$
- the coefficient must contain appropriate powers of Y_D and Y_U so as ***to make the overall operator invariant under transformations of the fields and the spurions***.

Minimal Flavor Violation (cont'd)

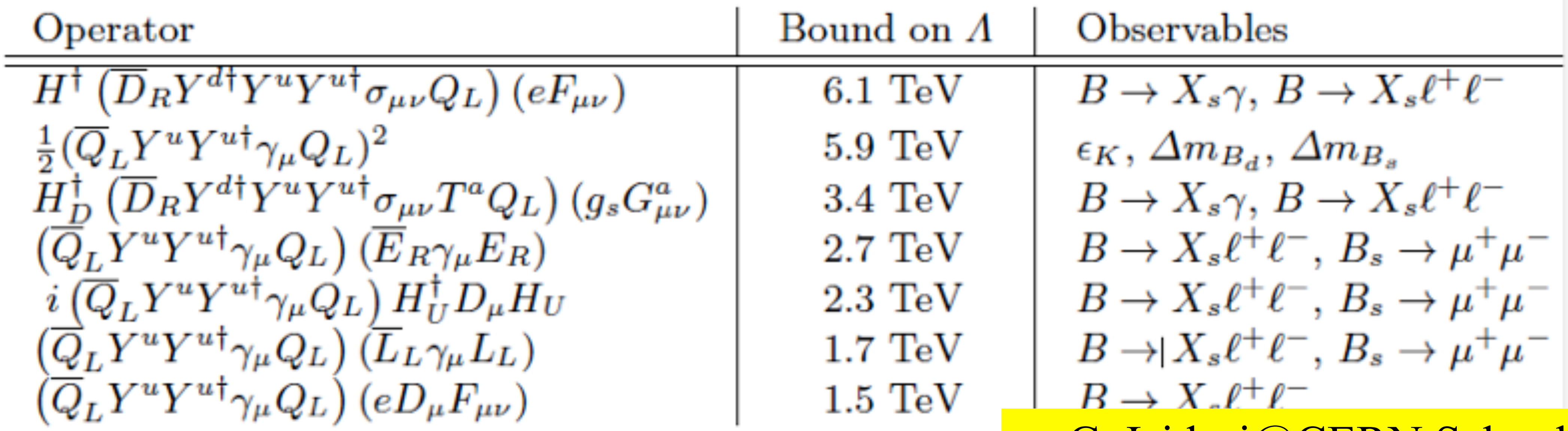
- In fact, Standard Model processes are sometime greatly suppressed by the CKM and mass coefficients which are in front of the effective lagrangian obtained from the loops at loww energy
- the suppression comes frm the small or very small CKM, intra-generation couplings,
- MFV makes so that similar couplings appear in front of the effective opertors from New Physics, releasing considerably the bounds to Λ
- for example, the operator
- must appear like:

$$\frac{1}{\Lambda^2}\left[\bar{d}\gamma^\mu(1-\gamma_5)s\right]\cdot\left[\bar{d}\gamma_\mu(1-\gamma_5)s\right]$$

$$\downarrow$$

$$\frac{1}{\Lambda^2}\left(\bar{Q}_L Y_U Y_U^\dagger \gamma_\mu Q_L\right)^2$$

- with remarkable effects on the present limits



Operator	Bound on Λ	Observables
$H^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)(eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H_D^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)\left(\overline{E}_R\gamma_\mu E_R\right)$	2.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$i\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)\left(\overline{L}_L\gamma_\mu L_L\right)$	1.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)(eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s\ell^+\ell^-$

G. Isidori@CERN School 2012)

CMSSM, bounds from $B_s \to \mu^+\mu^-$

Supersymmetric constraints from $B_s \to \mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$ observables

F. Mahmoudi[1,2,*] S. Neshatpour[2,†] and J. Orloff[2,‡]

arXiv:1205.1845v1 [hep-ph]

- The Constrained MSSM (CMSSM) is a SUSY model which satisfies the principles of Minimal Flavour Violation, thus the limits from FCNC are compatible with a relatively low energy scale for New Physics

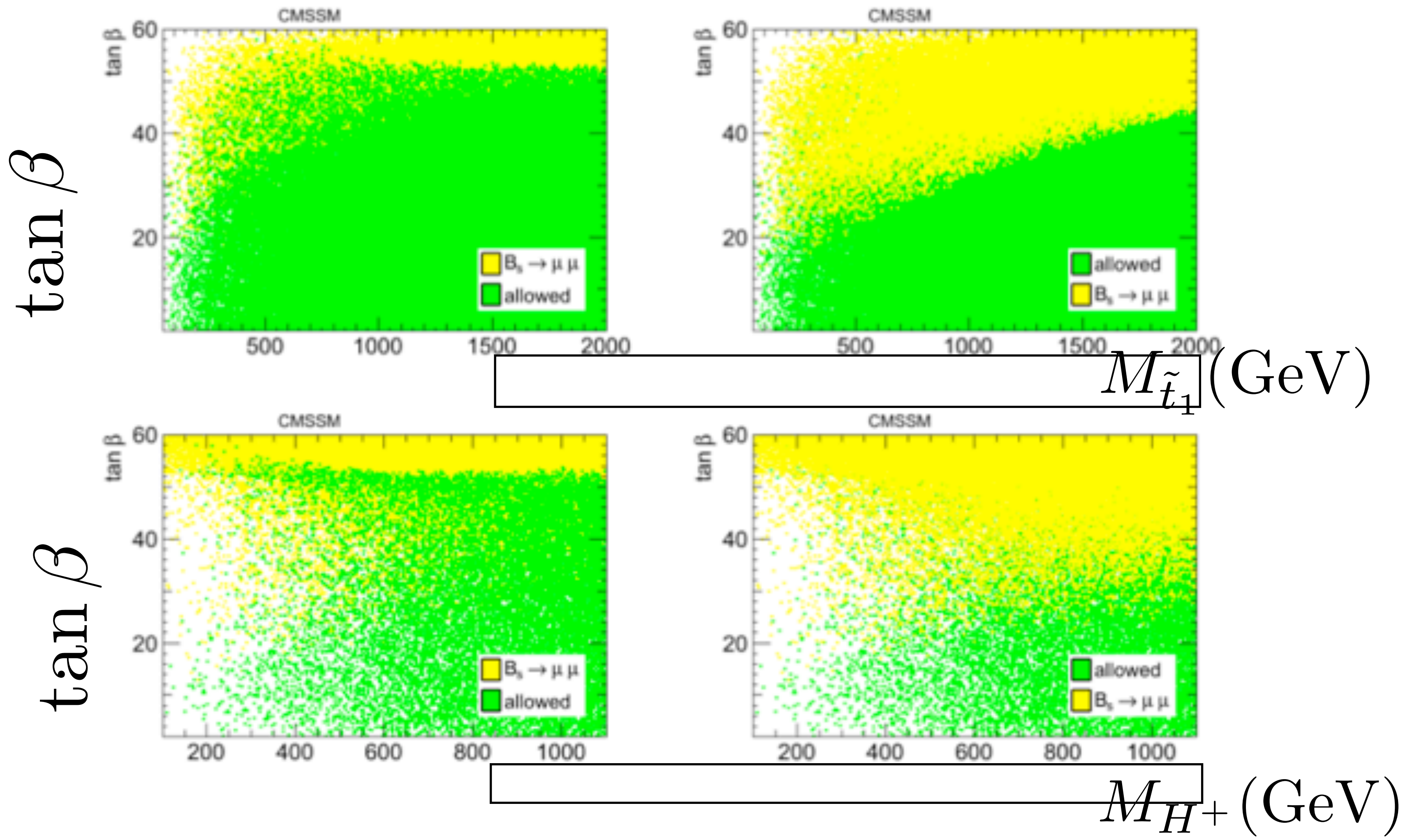
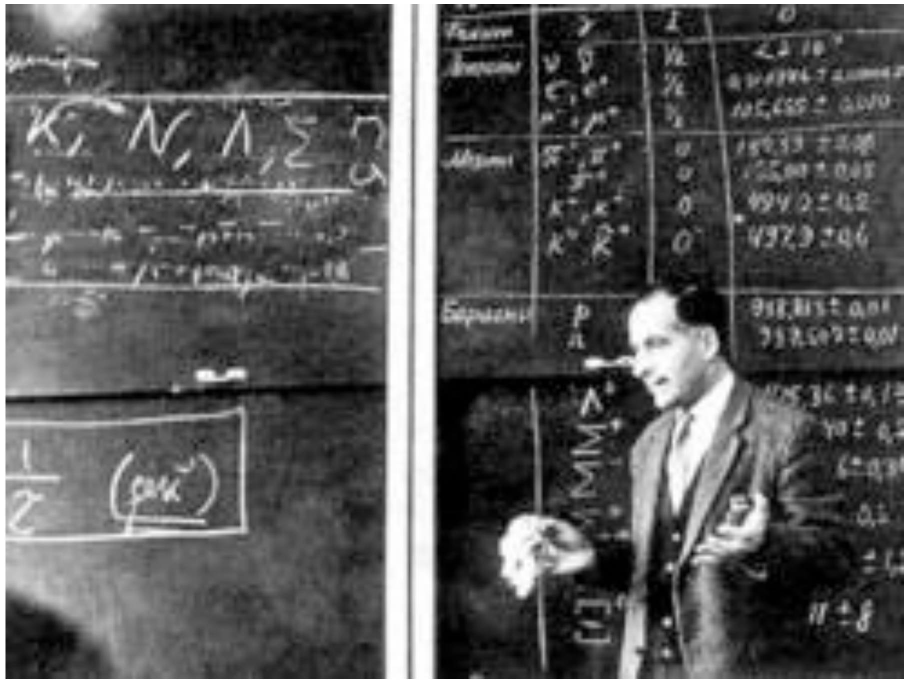


Figure 1: Constraint from BR($B_s \to \mu^+\mu^-$) in the CMSSM plane ($M_{\tilde{t}_1}$, $\tan\beta$) in the upper panel and ($M_{H^\pm}$, $\tan\beta$) in the lower panel, with the allowed points displayed in the foreground in the left and in the background in the right.

5. Neutrino oscillations with 3 neutrinos

- Neutrino mixing and oscillations have been introduced by Bruno Pontecorvo and Collaborators, with two neutrinos;
- neutrino oscillations with 3 flavours including CP and CPT violation: worked out for the first time by Nicola Cabibbo (N. Cabibbo, Phys. Lett. B72 (1978) 333);
- For an introduction see: L.Maiani, O.Benhar, *Meccanica Quantistica Relativistica*, Editori Riuniti University Press, 2012.



Bruno Pontecorvo in Dubna

- Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata (PNMS) mixing matrix (PMNS), with three real angles and one CP violating phase

$$J^\mu = (\bar{e},\ \bar{\mu},\ \bar{\tau})\ \gamma^\mu(1-\gamma_5)\ V\ \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- based on the latest data (note the large angles!!!):

$$V_{PMNS} \approx \begin{pmatrix} 0.825 & 0.545 & 0.15e^{i\delta} \\ -0.392+0.088e^{-i\delta} & 0.596+0.068e^{-i\delta} & -0.696 \\ 0.389+0.088e^{-i\delta} & -0.588+0.058e^{-i\delta} & -0.702 \end{pmatrix}$$

Neutrino mixing angles

- Treat neutrinos a Dirac particles, we'll see later that this is correct also for see-saw Majorana neutrinos.
- Define ν_e with respect to the fields which diagonalise the mass matrix, $\nu_{1,2,3}$, as:

$$\nu_e = \cos\theta_{13}\left[\cos\theta_{12}\nu_1 + \sin\theta_{12}\nu_2\right] + e^{i\delta}\sin\theta_{13}\nu_3$$

- Define further two ortho-normal fields with respect to ν_e:

$$\begin{aligned}\nu' &= -\sin\theta_{12}\nu_1 + \cos\theta_{12}\nu_2 \\ \nu'' &= e^{-i\delta}\sin\theta_{13}\left[\cos\theta_{12}\nu_1 + \sin\theta_{12}\nu_2\right] - \cos\theta_{13}\nu_3\end{aligned}$$

and the angle θ_{23} is defined according to:

$$\begin{aligned}\nu_\mu &= -\cos\theta_{23}\nu' + \sin\theta_{23}\nu'' \\ \nu_\tau &= -\sin\theta_{23}\nu' + \cos\theta_{23}\nu''\end{aligned}$$

... in total

$$J^\mu = (\bar{e},\ \bar{\mu},\ \bar{\tau})\ \gamma^\mu(1-\gamma_5)\ V\ \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$V = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & e^{i\delta}s_{13} \\ -c_{23}s_{12} + e^{-i\delta}s_{23}s_{13}c_{12} & c_{23}c_{12} + e^{-i\delta}s_{23}s_{13}s_{12} & -s_{23}c_{13} \\ s_{23}s_{12} + e^{-i\delta}c_{23}s_{13}c_{12} & -s_{23}c_{12} + e^{-i\delta}c_{23}s_{13}s_{12} & -c_{23}c_{13}\end{pmatrix}$$

Oscillations (two flavors)

- Amplitude, A, and probability, P, for the appearence of flavor ***j*** at a distance L from production of flavor ***i***

$$A(i \to j) = \sum_{a,b} \langle j|a\rangle\langle a|e^{-iHL}|b\rangle\langle b|i\rangle = e^{-iE_\nu} \sum_a \left(\langle j|a\rangle e^{-i\frac{m_a^2}{2E_\nu}L} \langle a|i\rangle \right)$$

$$P(\nu_e \to \nu_\mu; E, L) = |A(\nu_e \to \nu_\mu)|^2 = \cos^2\theta \sin^2\theta |1 - e^{-i\frac{\Delta m^2 L}{2E_\nu}}|^2$$

$$= \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

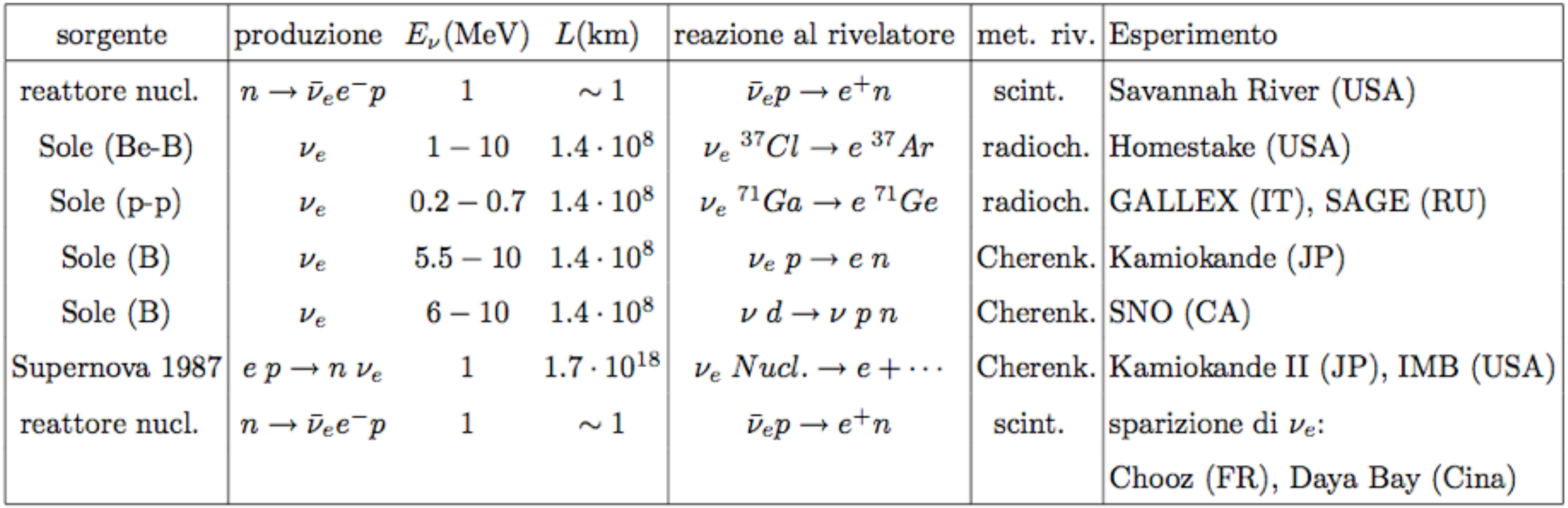
- probability of flavor non-oscillation:

$$P(\nu_e \to \nu_e; E, L) = 1 - P(\nu_e \to \nu_\mu; E, L)$$

- Numerically:

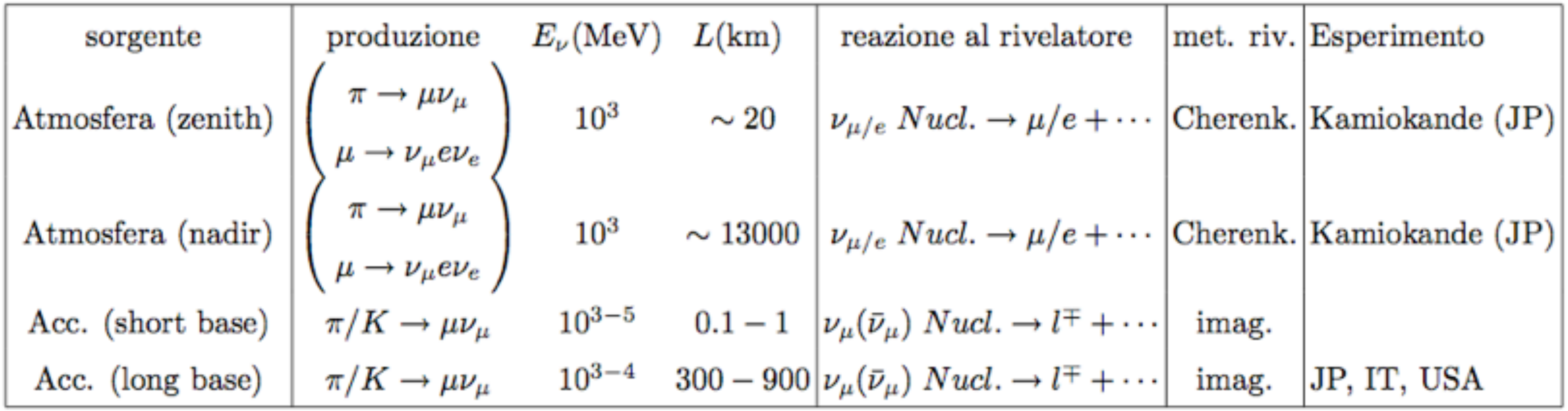
$$\frac{\Delta m^2 L}{4E_\nu} = \frac{\Delta m^2 L}{4\hbar c E_\nu} = 1.27\, \frac{\Delta m^2(\mathrm{eV}^2) L(\mathrm{km})}{E_\nu(\mathrm{GeV})} = 1.27\, \frac{\Delta m^2(\mathrm{eV}^2) L(\mathrm{m})}{E_\nu(\mathrm{MeV})}$$

Sorgenti e distanze



sorgente	produzione	E_ν(MeV)	L(km)	reazione al rivelatore	met. riv.	Esperimento
reattore nucl.	$n \to \bar{\nu}_e e^- p$	1	~ 1	$\bar{\nu}_e p \to e^+ n$	scint.	Savannah River (USA)
Sole (Be-B)	ν_e	$1 - 10$	$1.4 \cdot 10^8$	$\nu_e\, ^{37}Cl \to e\, ^{37}Ar$	radioch.	Homestake (USA)
Sole (p-p)	ν_e	$0.2 - 0.7$	$1.4 \cdot 10^8$	$\nu_e\, ^{71}Ga \to e\, ^{71}Ge$	radioch.	GALLEX (IT), SAGE (RU)
Sole (B)	ν_e	$5.5 - 10$	$1.4 \cdot 10^8$	$\nu_e\, p \to e\, n$	Cherenk.	Kamiokande (JP)
Sole (B)	ν_e	$6 - 10$	$1.4 \cdot 10^8$	$\nu\, d \to \nu\, p\, n$	Cherenk.	SNO (CA)
Supernova 1987	$e\, p \to n\, \nu_e$	1	$1.7 \cdot 10^{18}$	$\nu_e\, Nucl. \to e + \cdots$	Cherenk.	Kamiokande II (JP), IMB (USA)
reattore nucl.	$n \to \bar{\nu}_e e^- p$	1	~ 1	$\bar{\nu}_e p \to e^+ n$	scint.	sparizione di ν_e: Chooz (FR), Daya Bay (Cina)

TABLE I: Sorgenti e metodi di rivelazione dei neutrini naturali e artificiali di bassa energia.



sorgente	produzione	E_ν(MeV)	L(km)	reazione al rivelatore	met. riv.	Esperimento
Atmosfera (zenith)	$\begin{pmatrix} \pi \to \mu\nu_\mu \\ \mu \to \nu_\mu e \nu_e \end{pmatrix}$	10^3	~ 20	$\nu_{\mu/e}\, Nucl. \to \mu/e + \cdots$	Cherenk.	Kamiokande (JP)
Atmosfera (nadir)	$\begin{pmatrix} \pi \to \mu\nu_\mu \\ \mu \to \nu_\mu e \nu_e \end{pmatrix}$	10^3	~ 13000	$\nu_{\mu/e}\, Nucl. \to \mu/e + \cdots$	Cherenk.	Kamiokande (JP)
Acc. (short base)	$\pi/K \to \mu\nu_\mu$	10^{3-5}	$0.1 - 1$	$\nu_\mu(\bar{\nu}_\mu)\, Nucl. \to l^\mp + \cdots$	imag.	
Acc. (long base)	$\pi/K \to \mu\nu_\mu$	10^{3-4}	$300 - 900$	$\nu_\mu(\bar{\nu}_\mu)\, Nucl. \to l^\mp + \cdots$	imag.	JP, IT, USA

TABLE II: Sorgenti e metodi di rivelazione dei neutrini naturali e artificiali di alta energia.

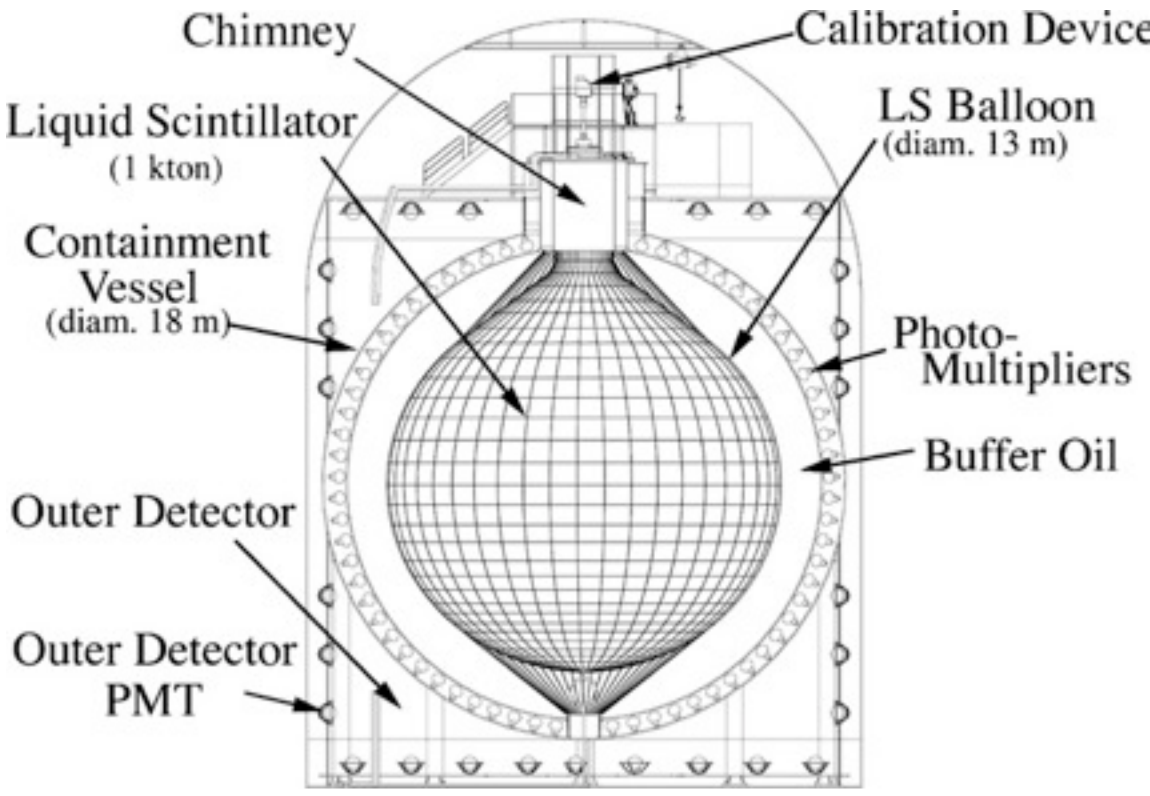
6. Solar neutrinos

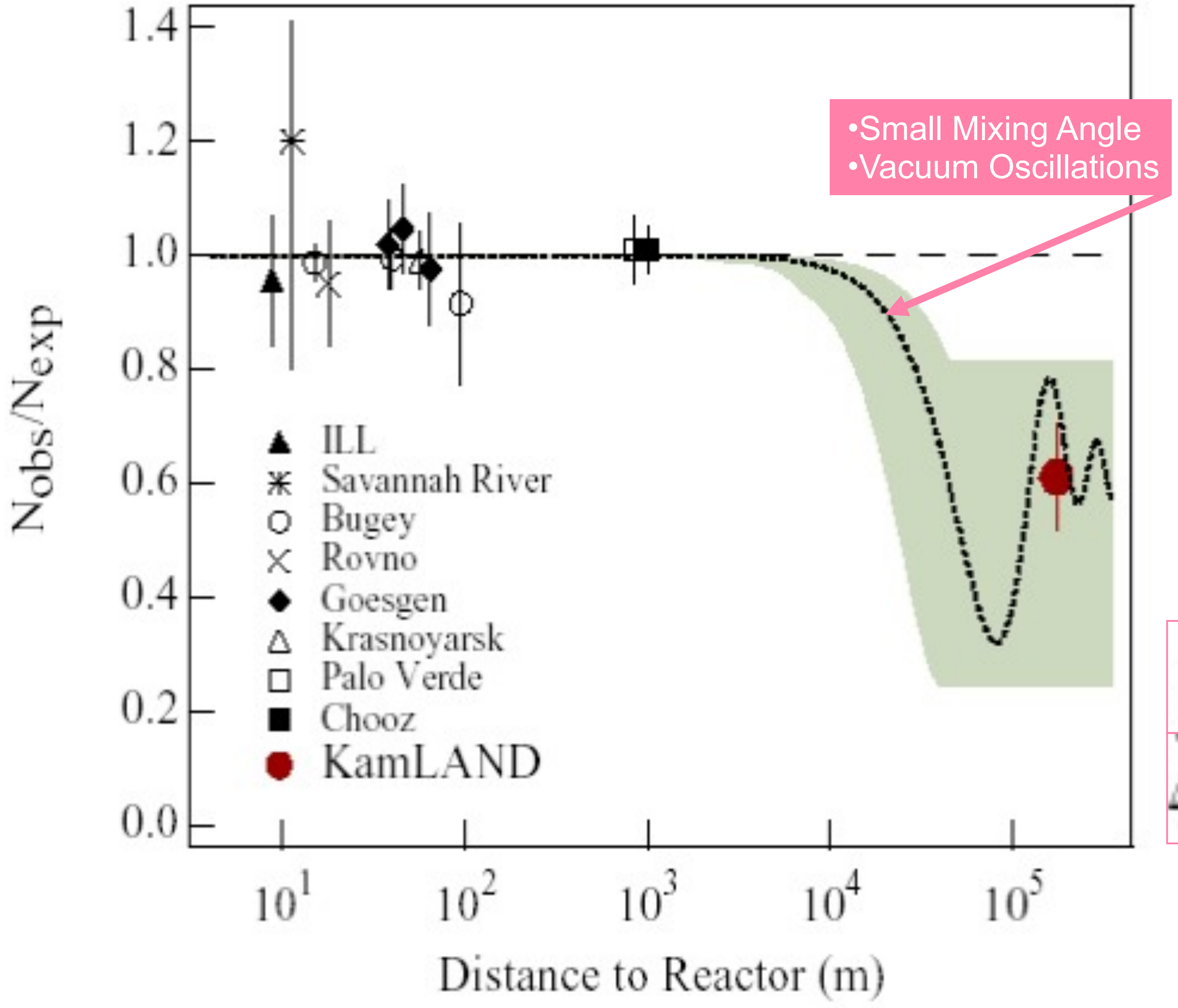
Deficit osservato negli esperimenti sui neutrini solari. Per SNO, vedi figura.

Esperimento	osservato/atteso	anni di osservazione
Homestake	$0.33 \pm 0.03 \pm 0.05$	1970 – 1995
Kamiokande	$0.54 \pm 0.08^{+0.10}_{-0.07}$	1986 – 1995
SAGE	$0.58 \pm 0.06 \pm 0.03$	1990 – 2006
GALLEX	$0.60 \pm 0.06 \pm 0.04$	1991 – 1996
Super- Kamiokande	$0.465 \pm 0.005^{+0.016}_{-0.015}$	1996–

- Pontecorvo:
  - I neutrini dal Sole partono come ν_e ed hanno energia bassa
  - se oscillano in ν_μ non hanno energia sufficiente per produrre un muone nei nostri rivelatori (con reazione di corrente carica)
  - in questo caso, una frazione di neutrini ci arriva come ***neutrini sterili per le reazioni di corrente carica*** e il flusso che misuriamo e' ridotto rispetto alle previsioni dei modelli solari
  - questo potrebbe spiegare il deficit visto a Homestake
  - deficit confermato negli anni da analoghi esperimenti (in particolare GALLEX con i neutrini pp, che hanno un flusso iniziale molto ben determinato)
  - e ormai consistente con una oscillazione in prevalenza ν_e - ν_μ .

KAMLAND





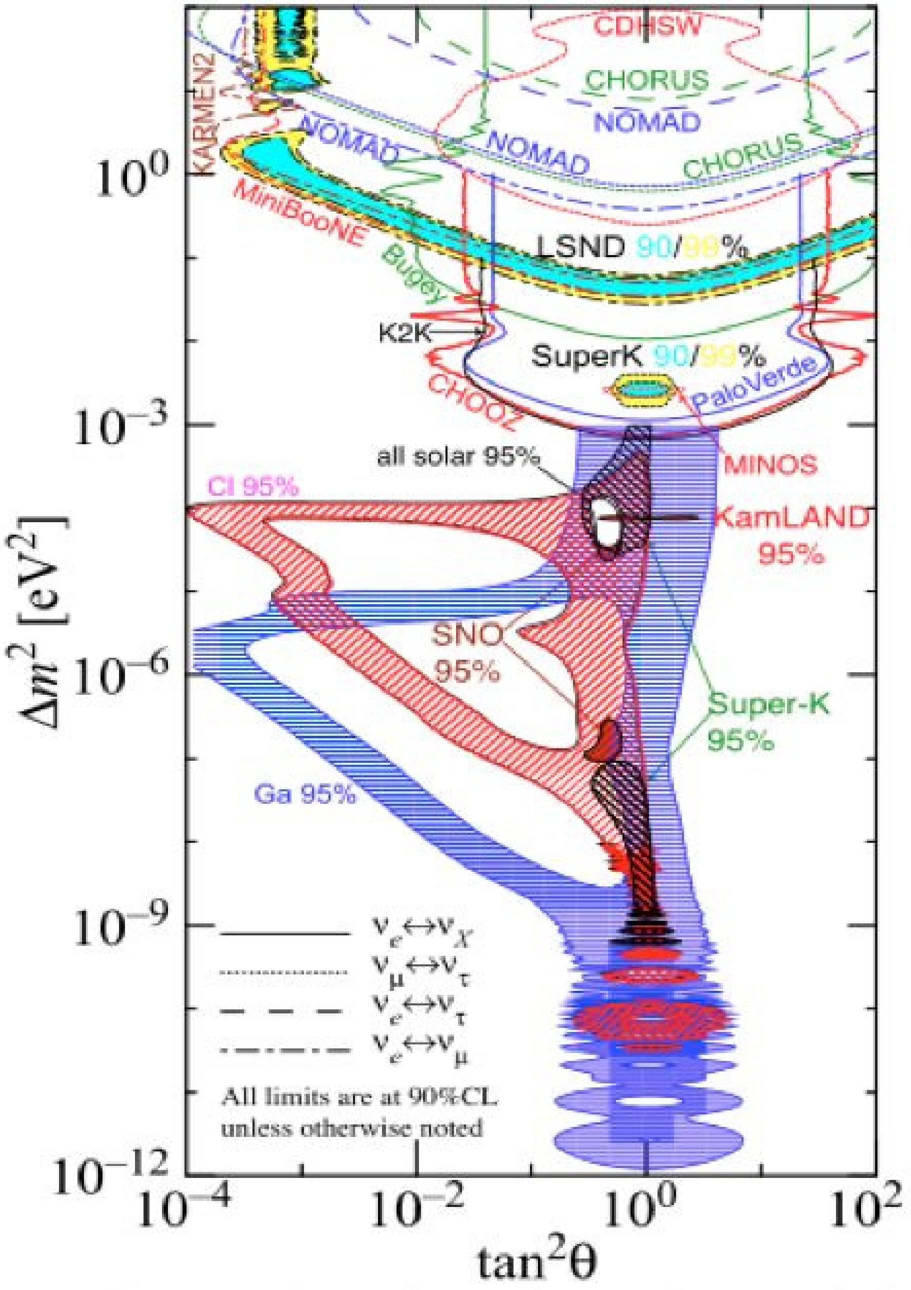
- Small Mixing Angle
- Vacuum Oscillations

KamLAND is surrounded by 55 Japanese nuclear power reactor units, each an isotropic νe source. The reactor operation records, ...are provided by a consortium of Japanese electric power companies. This information, combined with publicly available world reactor data, is used to calculate the instantaneous fission rates using a reactor model.

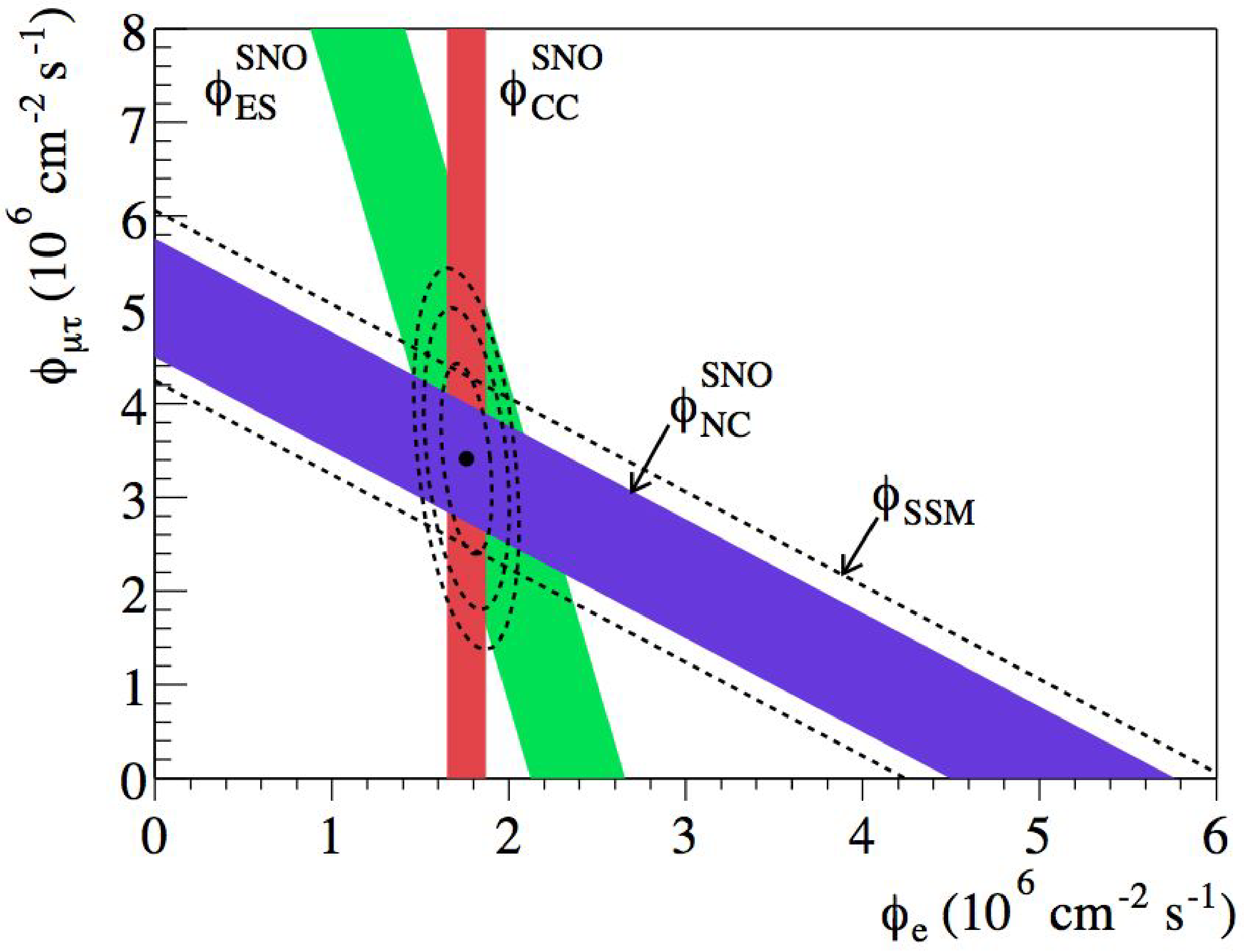
$$\sin^2 2\theta = 0.833$$

$$\Delta m^2 = 5.5 \times 10^{-5}\ \mathrm{eV}^2$$

Fits to solar neutrinos



KAMLAND result makes the definitive choice



SNO: No deficit in neutral currents: the reaction $\nu(\bar{\nu}) + p \to \nu(\bar{\nu}) + p$ is effective for all neutrino flavors

7. Atmospheric neutrinos

- $\Delta m_{23}^2 \approx 2.4\ 10^{-3}\ \mathrm{eV}^2$
- $\sin^2 2\theta_{23} \approx 1$

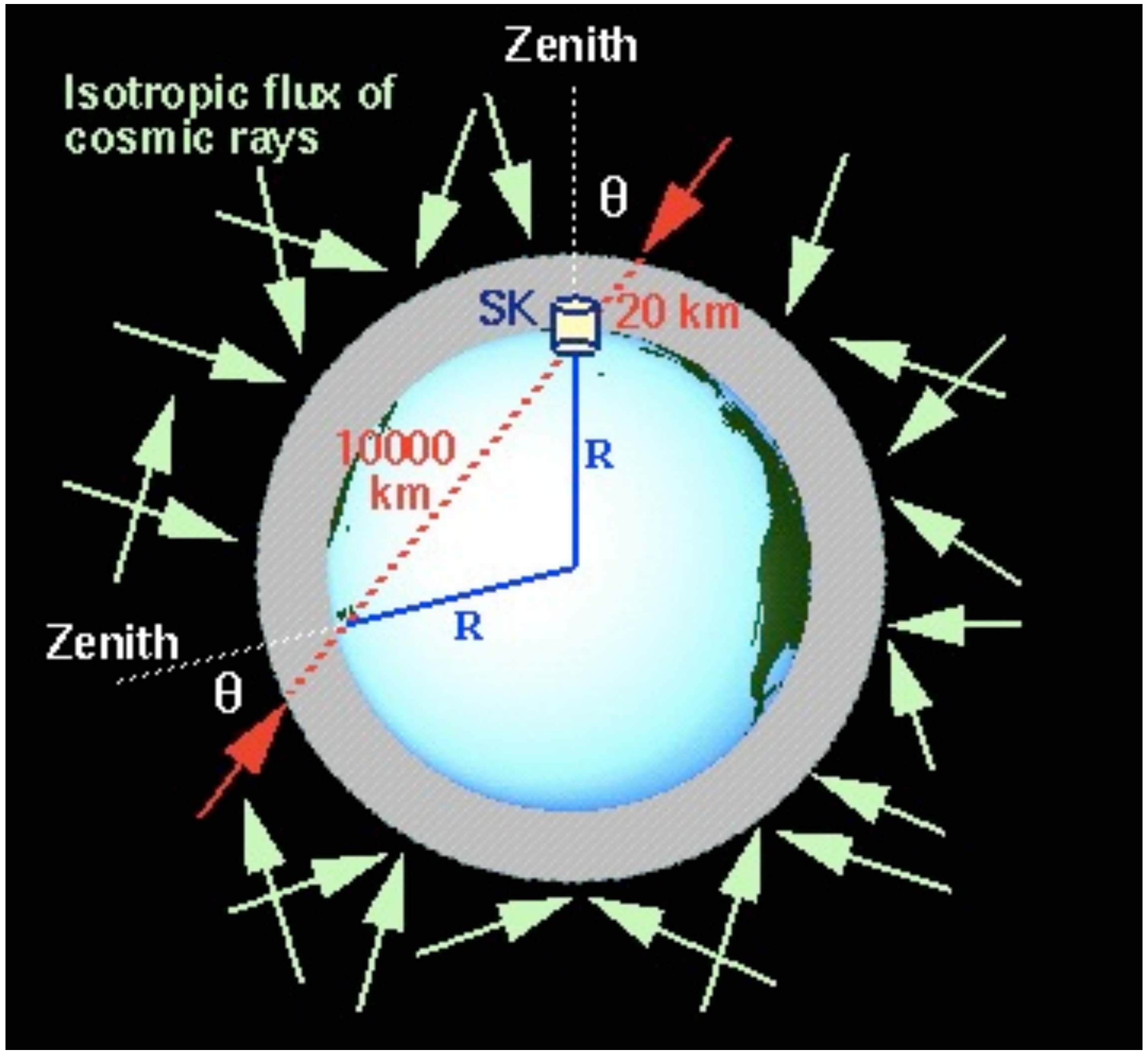
- Spectrum deformation indicated by K2K
- $\nu_\mu \Leftrightarrow \nu_\tau$ gives best fit to atmospheric neutrinos, but…
- Next generation long-baseline neutrino beams:
  - Spectrum deformation
  - NC/CC
  - τ appearance

NuMI-Minos

CNGS- OPERA and later ICARUS

- Super-Kamiokande studia i neutrini prodotti dai raggi cosmici che entrano nell'atmosfera terrestre.
- I neutrini attraversano la Terra senza attenuazione, quindi S-K puo' confrontare i neutrini che ***provengono dalla verticale*** con quelli che ***provengono dal basso***, dopo avere attraversato la Terra.
- I neutrini "dal basso" hanno percorso più strada: sono passati attraverso il nostro pianeta, percorrendo fino a 12.000 km, a seconda della direzione.

•Sorprendentemente, i neutrini di tipo muonico che vengono "dal basso" sono di meno di quelli che vengono "dal' alto".



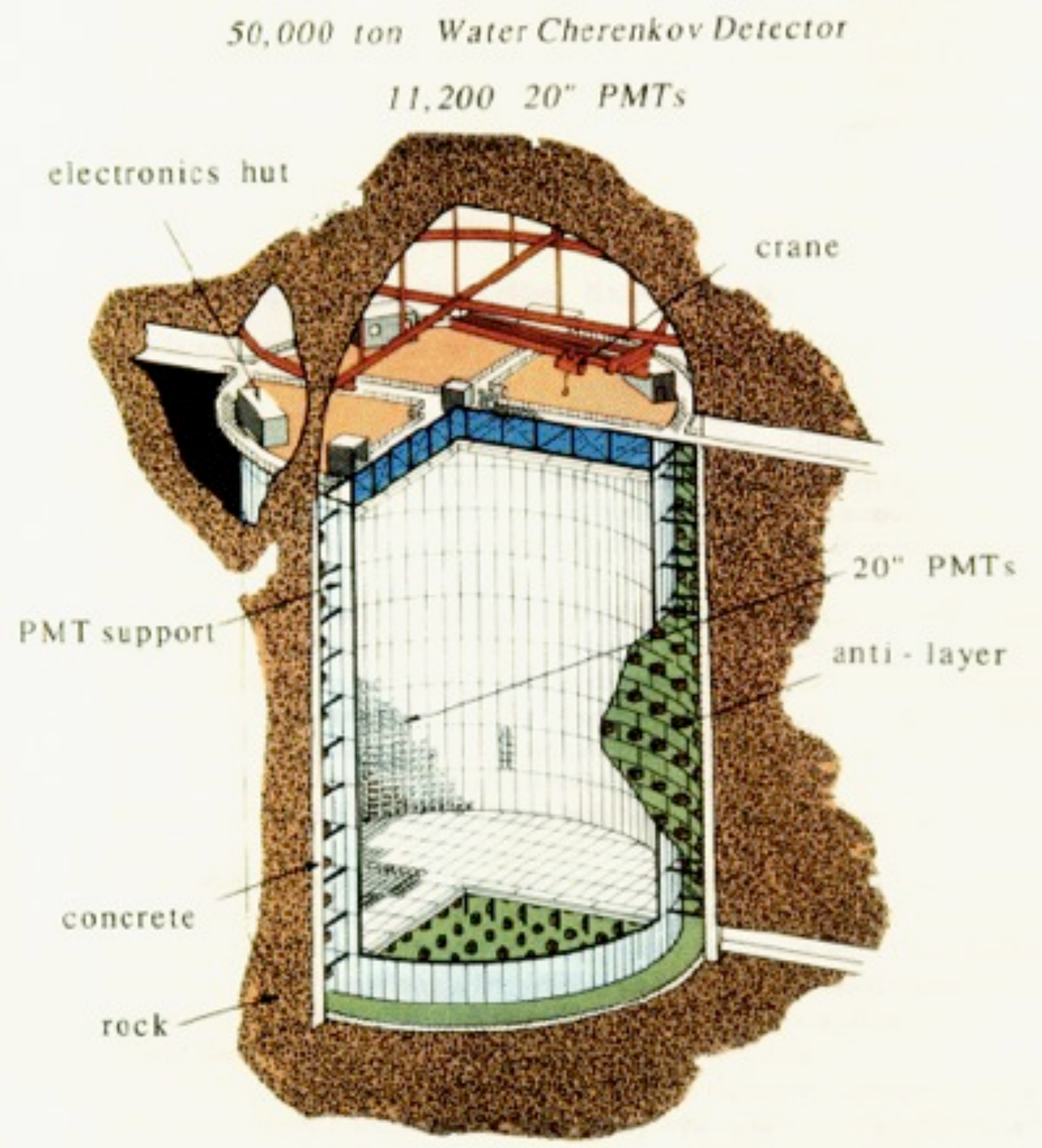
•Nel 1997, la sparizione di neutrini muonici nel caso in cui le particelle percorrono distanze dell'ordine del diametro della Terra, divenne una certezza.

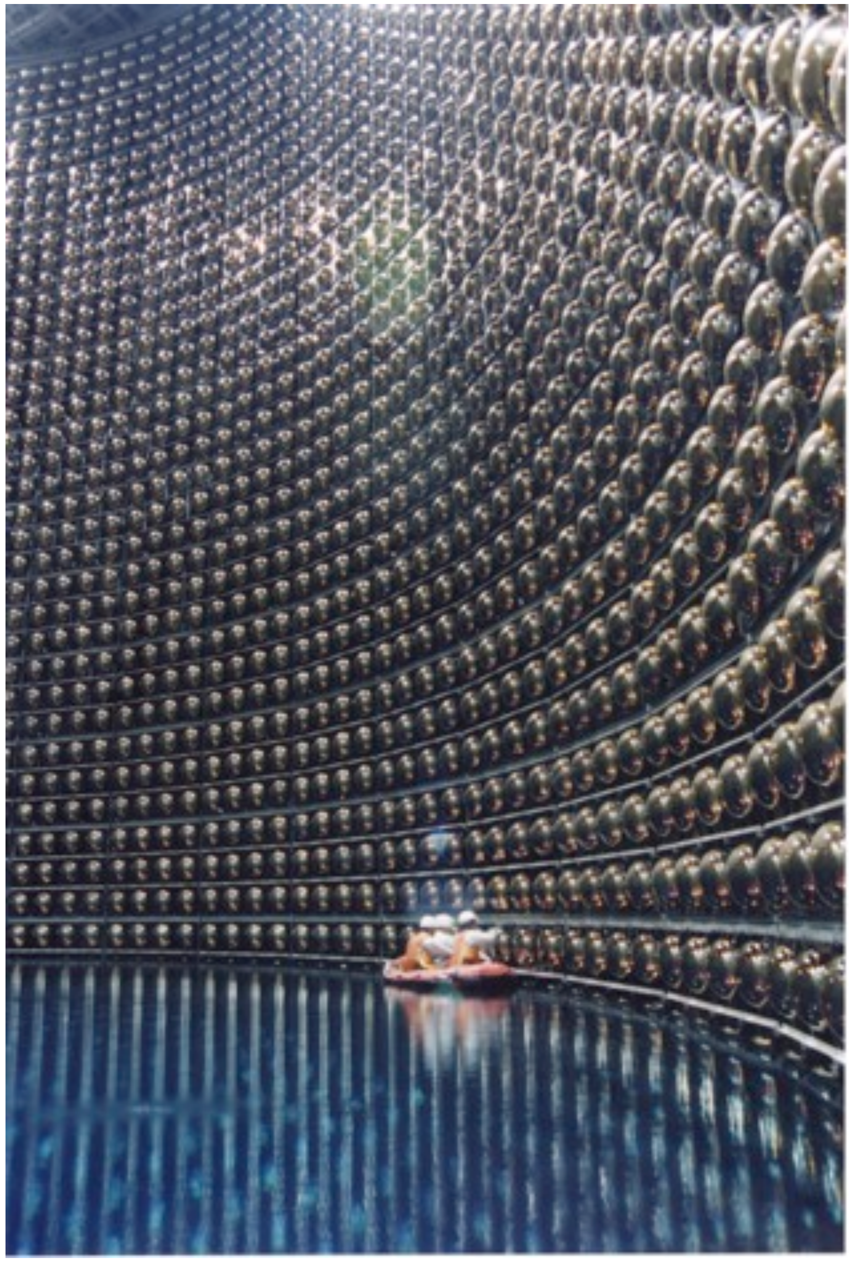
•Per i fisici di tutto il mondo era la prima prova sperimentale del fenomeno chiamato ***oscillazione dei neutrini***.

•La strada per CNGS poteva considerarsi aperta, ..ma sarebbe stata ancora molto in salita.

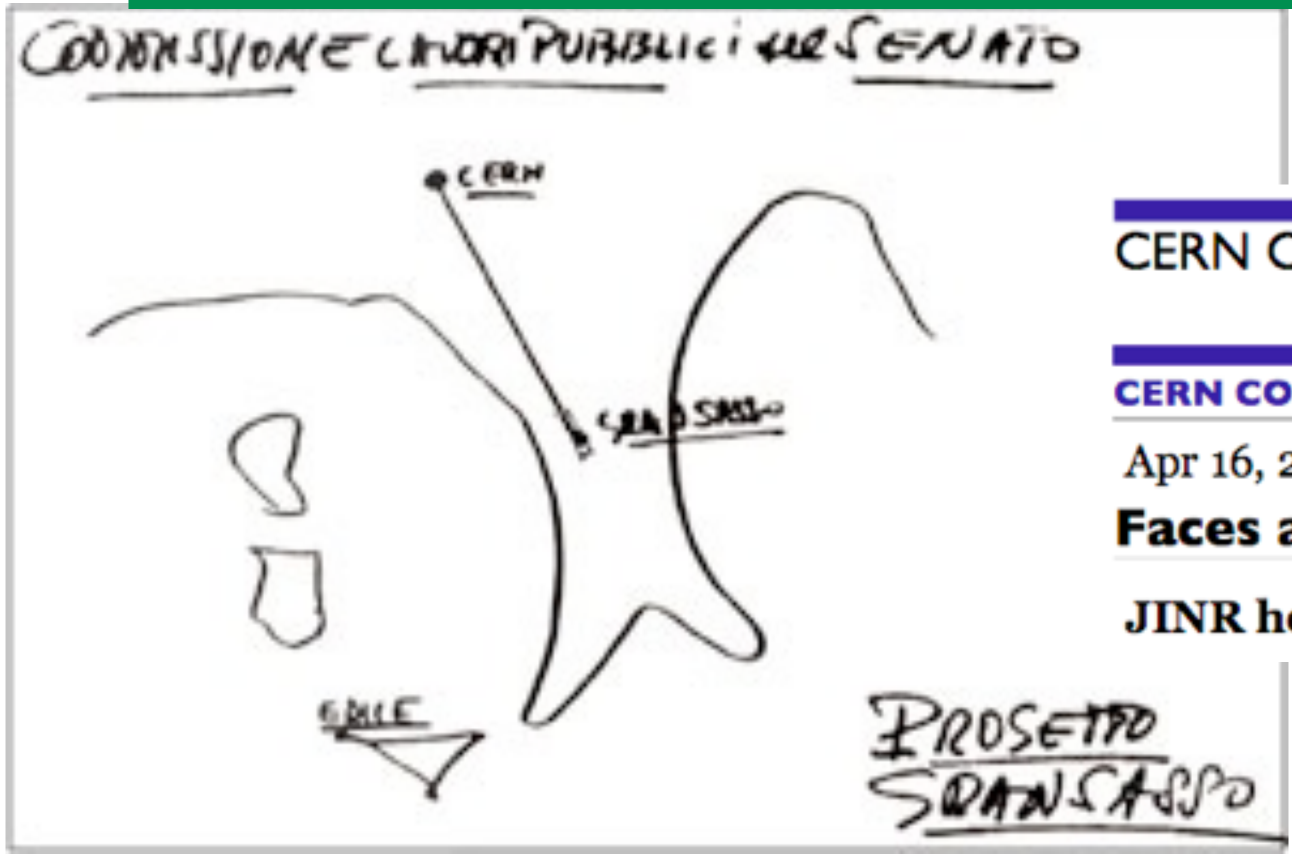
Oscillazioni a SuperKamiokande

- installazione nella miniera di Kamioka (Giappone) per osservare:
  - decadimento del protone (non visto finora
  - neutrini prodotti dai raggi cosmici nell' atmosfera (nu-atmosferici





8. ν_τ appearence at LNGS



CERN Courier

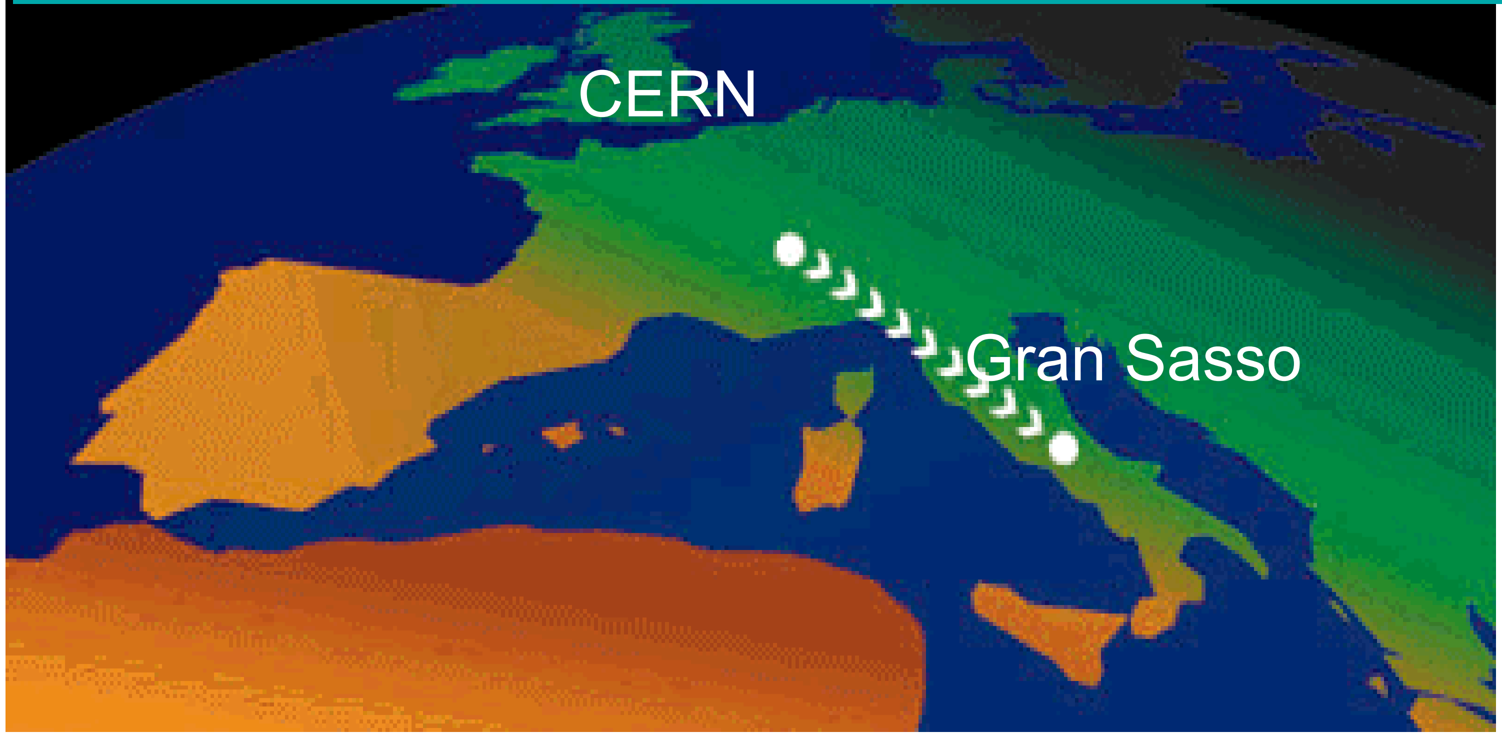
CERN COURIER

Apr 16, 2008

Faces and Places

JINR honours Zichichi with the 2007 Bruno Pontecorvo prize

The Long Baseline Neutrino Beam from CERN to Gran Sasso, to test $\nu_\mu \rightarrow \nu_\tau$ oscillations, 2000-2006



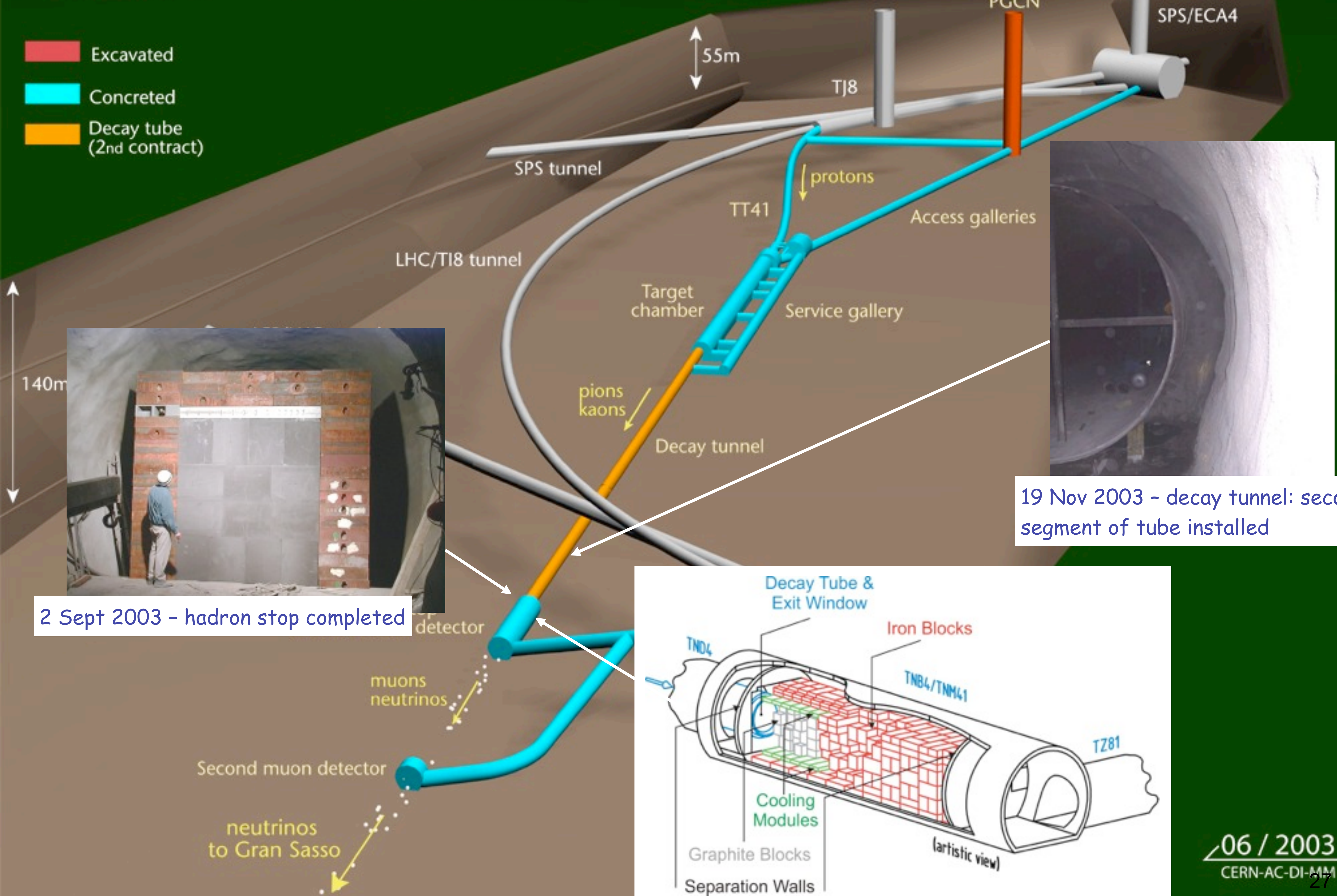
Ground-Breaking Ceremony, October 12, 2000

October 12, 2000

Madame Marie-Paule BARDECHE, *Sous-Préfet de Gex;*
Prof. Alessandro BETTINI, Direttore, Laboratori nazionali del Gran Sasso, INFN;
Prof. Luciano MAIANI, Director General, CERN.

CNGS, 11/09/2006 L. Maiani. Neutrini al Gran Sasso 16

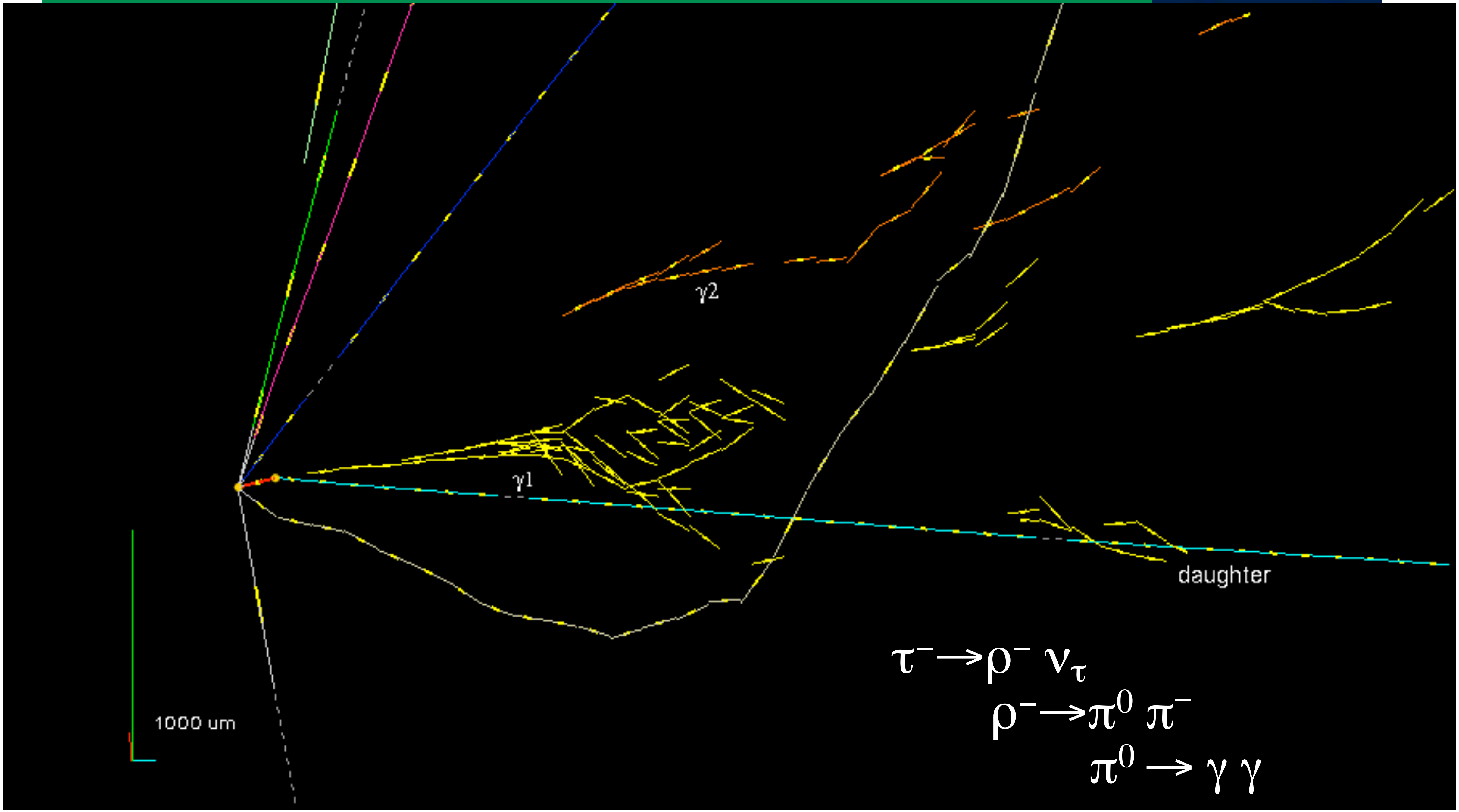
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN



2 Sept 2003 – hadron stop completed

19 Nov 2003 – decay tunnel: seco
segment of tube installed

OPERA, event 1



$$\tau^- \to \rho^- \nu_\tau$$

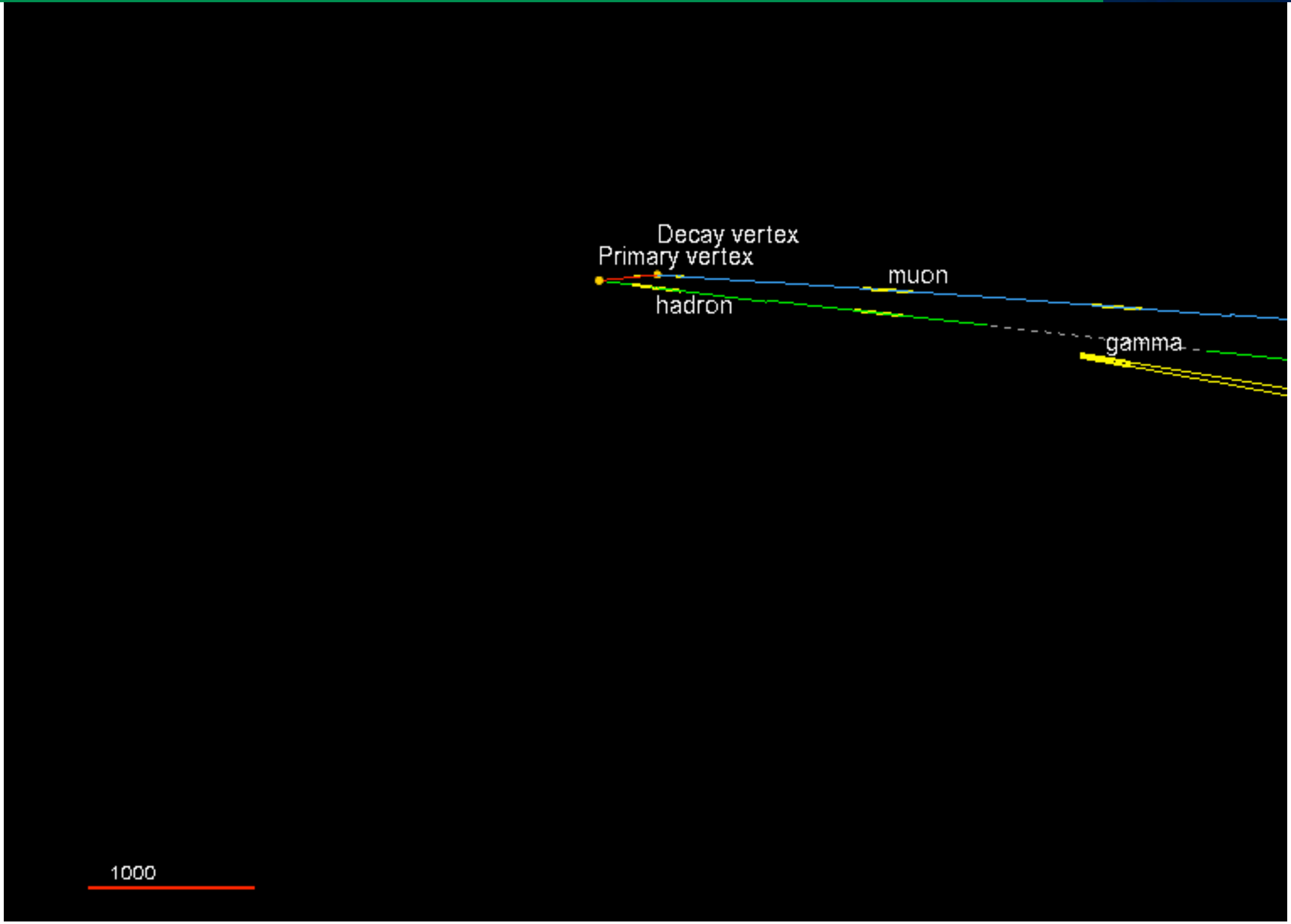
$$\rho^- \to \pi^0 \pi^-$$

$$\pi^0 \to \gamma\,\gamma$$

$\tau \rightarrow \nu_\tau + 2$ pi

Giovanni De Lellis, seminar at CERN, June 11 2013

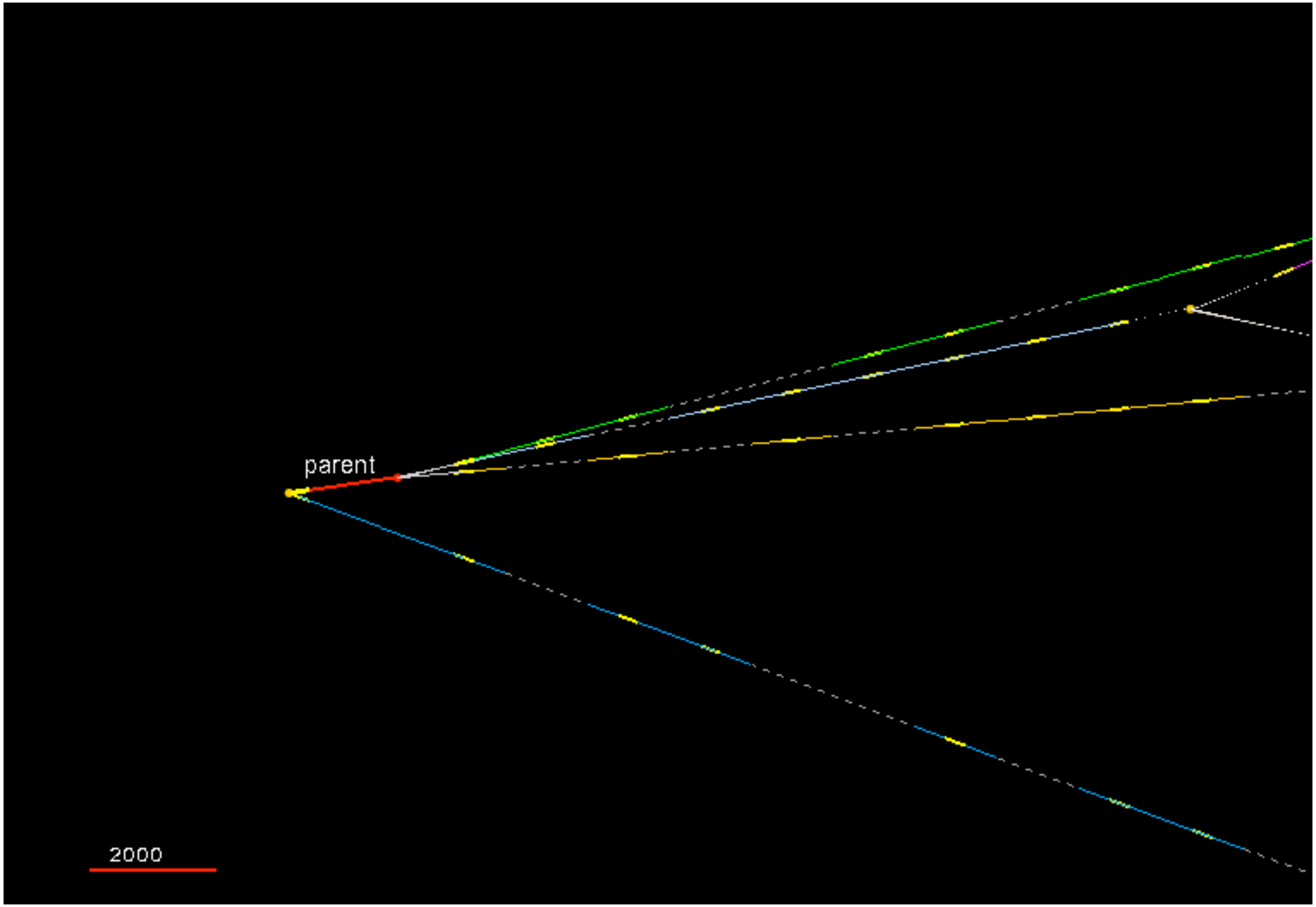
OPERA, event 2



$\tau \rightarrow \nu_\tau + \nu_\mu + \mu$

Giovanni De Lellis, seminar at CERN, June 11 2013

OPERA, event 1



$\tau \rightarrow \nu_\tau + 3$ hadrons

Giovanni De Lellis, seminar at CERN, June 11 2013

9. The last real angle: θ_{13} from the Daya Bay (China) experiment

- anti-ν_e non-oscillation experiment at a nuclear reactor
- L=1.6 km
- set $\Delta_{ij=}\ \Delta(m_i^2\text{-}m_j^2)\ L/(2E_\nu)$
- assume
  - $\Delta_{12} = -\Delta_{21} \approx 0,\ \Delta_{13} \approx \Delta_{23} = -\Delta_{31} \approx \Delta_{32}$
  - no CP violation
- compute $P(\nu_e \to \nu_e, L)$:

$$P(\nu_e \to \nu_e, L) = \sum_{a,b} e^{i\Delta_{ab}} |U_{ea}|^2\ |U_{eb}|^2 =$$

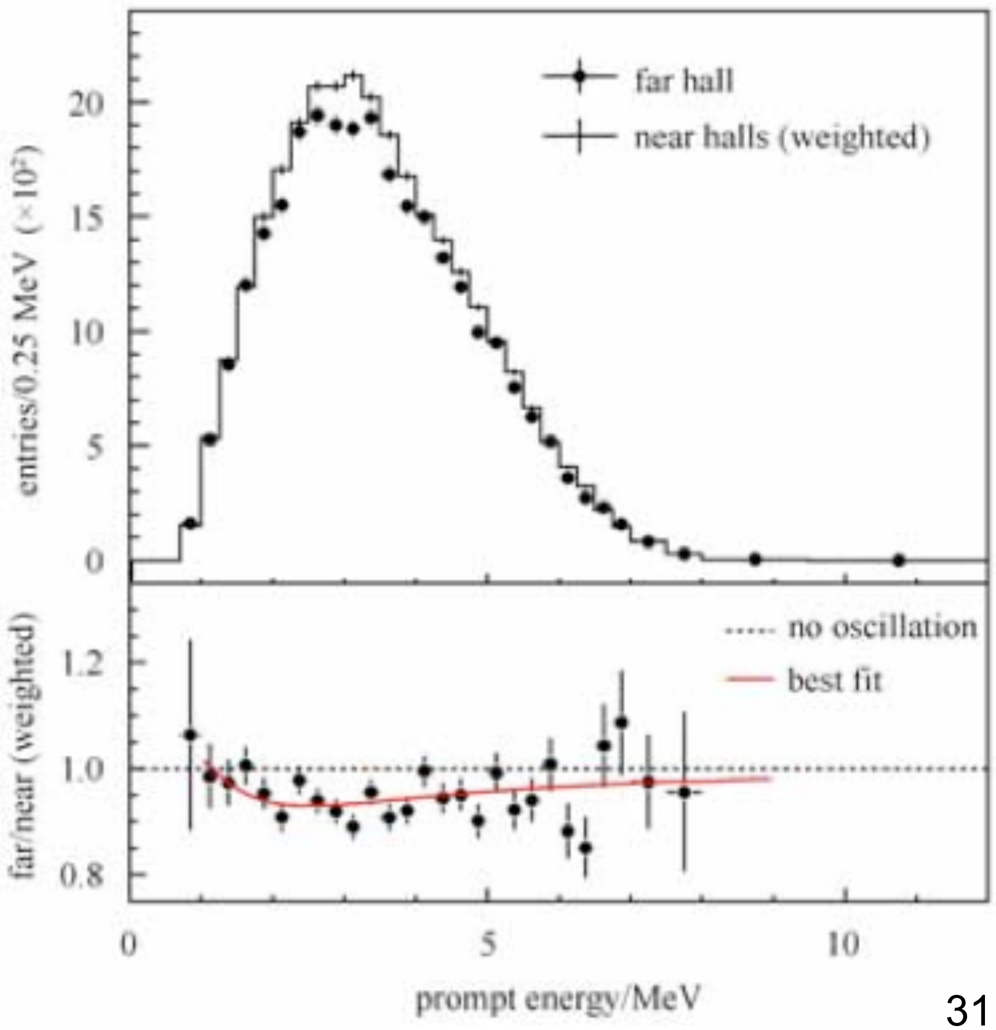
$$= \sum_a |U_{ea}|^4 + 2|U_{e1}|^2|U_{e2}|^2 +$$

$$+(e^{i\Delta_{13}} + e^{-i\Delta_{13}})\left[|U_{e1}|^2|U_{e3}|^2 + |U_{e2}|^2 U_{e3}|^2\right]$$

$$= c_{13}^4 + s_{13}^4 + s_{13}^2 c_{13}^2 \cdot 2\cos\Delta_{13}$$

- wherefrom:

$$P(\nu_e \to \nu_e, L) = 1 - \sin^2\theta_{13}\sin^2\frac{\Delta m_{23}^2 L}{4E_\nu}$$



Conclusions

- summary of oscillation data (S. Bilenky, Rome, Sept. 2013)

  - The situation with neutrino oscillations today
- Neutrino oscillation data are perfectly described by the three neutrino mixing

$$\Delta m^2_{23} = (2.41 \pm 0.10)\cdot 10^{-3}\,\mathrm{eV}^2, \quad \Delta m^2_{12} = (7.53 \pm 0.18)\cdot 10^{-5}\,\mathrm{eV}^2$$

$$0.407 < \sin^2\theta_{23} < 0.585, \quad \tan^2\theta_{12} = 0.436^{+0.029}_{-0.023}$$

atmospheric: $\nu_\mu \to \nu_\tau$

solar: $\nu_e \to \nu_{\mu,\tau}$

$$\sin^2 2\theta_{13} = 0.090 \pm 0.009$$

long base: $\nu_\mu \to \nu_e$ (Minos, USA)
ν_e disappearence (Daya Bay, China)

Nicola Cabibbo, as president of INFN, gave a great support to GALLEX (from T. Kirsten)

Conclusions (cont'd)

- What's next?
- signs of Δm^2 ?
- absolute masses ? from double beta decay or from Cosmological observation?
- CP violation: a relatively large θ_{13} helps
- Theory: can we "compute" the mixing matrices (Cabibbo's dream of the sixties)
- can we find an explanation why the textures of CKM and PMNS matrices so different ????

$$U_{CKM} \approx \begin{pmatrix} 0.97462 & 0.2253 & 0.0012 - i0.0032 \\ -0.2253 & 0.9746 & 0.0410 \\ 0.0080 - i0.0032 & -0.04101 & 1 \end{pmatrix}$$

$$V_{PMNS} \approx \begin{pmatrix} 0.825 & 0.545 & 0.15e^{i\delta} \\ -0.392 + 0.088e^{-i\delta} & 0.596 + 0.068e^{-i\delta} & -0.696 \\ 0.389 + 0.088e^{-i\delta} & -0.588 + 0.058e^{-i\delta} & -0.702 \end{pmatrix}$$