Neutrino Oscillations: Issues
➔ why, how, … , what else…

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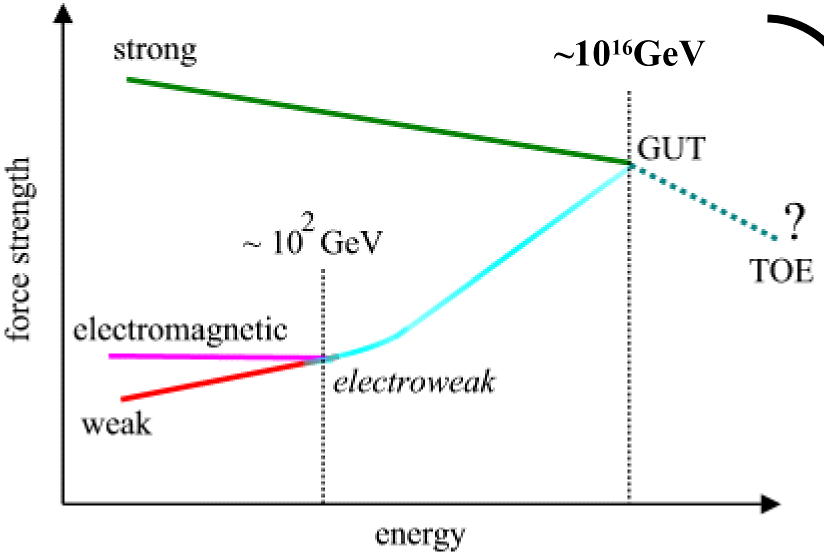
New Physics Beyond the SM

gauge bosons →



Higgs →

gauge hierarchy problem:

$\delta m_H^2 \sim \Lambda^2$

quarks leptons →

flavour problem: 3 generations

many parameters (m_i ,mixings)

unification into GUTs

$m_\nu = (m^D)^T M_R^{-1} m_D$

experimental facts:

limits on p decay

Dark Matter and Dark Energy

baryon asymetry ←→ $m_\nu > 0$

neutrino masses & mixings

indirect tests of GUT scale physics

➔ precision in the flavour sector

SUSY ~TeV

astrophysics & cosmology

$\sim\Lambda_{GUT}$ +seesaw

The Standard Model

➔ **success of renormalizable gauge field theories**

QED ⇒ QCD ⇒ SM

$U(1)_{em} \Rightarrow SU(3)_c \Rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$

- Singlet with respect to all symmetries
- Renormalizability
- Anomaly free combinations of chiral fermions

Many details fixed by Lagrangian: $\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{fermion}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$

$\mathcal{L}_{gauge} = -\frac{1}{2} Tr\left[G_{\mu\nu}G^{\mu\nu}\right] - \frac{1}{2} Tr\left[W_{\mu\nu}W^{\mu\nu}\right] - \frac{1}{4} B_{\mu\nu}B^{\mu\nu}$ (adjoint representations)

$\mathcal{L}_{fermion} = \sum_L \overline{L}\, i\gamma^\mu D_\mu L + \sum_r \overline{r}\, i\gamma^\mu D_\mu r$ (kinetic terms of all fermions)

$\mathcal{L}_{Higgs} = |D\Phi|^2 - V(\Phi^+\Phi)$ (Higgs potential ⇔ SSB)

$\mathcal{L}_{Yukawa} \simeq -g_Y \overline{L}\Phi r + h.c.$ (fermion masses, CKM–mixing, fermion–Higgs interaction)

Chiral Fermion Fields in the SM

- Left-handed quarks and leptons: $L = (3_c$ or $1_c,\ 2_L,\ Y = ...,\ Q = T_{3L} + Y/2)$
- Right-handed quarks and leptons: $r = (3_c$ or $1_c,\ 1_L,\ Y = ...,\ Q = Y/2$

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_Q = \begin{pmatrix} l_u \\ l_d \end{pmatrix}$	3	2	1/3
r_u	3	1	4/3
r_d	3	1	-2/3
$L_L = \begin{pmatrix} l_\nu \\ l_e \end{pmatrix}$	1	2	-1
r_ν ???	1	1	0
r_e	1	1	-2

- SM does **not contain** right-handed neutrinos $r_\nu \equiv \nu_R$
- Right-handed neutrinos make the table more symmetric!
- Fermions: Most diverse and the least constrains

SM speciality: No explicit fermion mass term L=m$\bar{\text{L}}$r ↔ no singlet can be formed

Majorana Mass Terms

Pair of left- and right-handed fields $L, R \Rightarrow$ $\boxed{\mathcal{L}_m = -m_D(\overline{L}R + \overline{R}L)}$

Charge conjugation for χ-ral fields: $\boxed{L_i = \text{left} \Leftrightarrow R_i = \text{right}}$

$$R' = L^c \; ; \quad L' = R^{\,c} \quad \Leftrightarrow \quad L = (R')^c \; ; \quad R = (L')^c$$

2 fields and 2 charge conjugate fields: ➔ 4 possible mass terms:

$$\mathcal{L}_m = m_D \overline{L}R + m_D \overline{L'}R' + M_L \overline{L}R' + M_R \overline{L'}R \quad +\text{h.c.}$$

<u>However:</u>

M_L and M_R only allowed for Q=0 particles

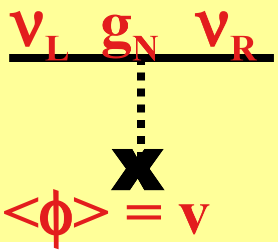
➔ neutrinos ➔ 2 new effects: L-violation, explicit mass terms

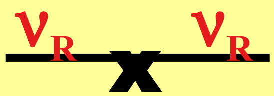
Neutrino Mass Operators

d=4 renormalizable mass operators

natural scale ⟷ symmetry

SM with ν_L only → $m_\nu=0$ → introduce $\nu_R = 1_L$

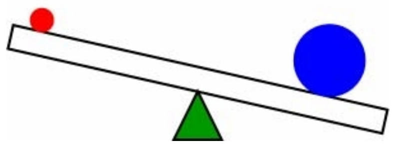




Majorana, $\cancel{L}$

→ $$\begin{pmatrix}\nu_L & \nu_R^c\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix}$$

seesaw mechanism (type I)



$$m_\nu=m_D M_R^{-1} m_D^T$$

$$m_h=M_R$$

For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim$ leptons → $M_R \sim 10^{11}$ - 10^{16}GeV

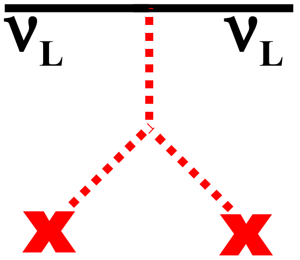
→ neutrinos are Majorana particles , m_ν probes ~ GUT scale physics!

→ smallness of neutrino masses ⟷ high scale of $\cancel{L}$, symmetries of m_D , M_R

More Mass Operators

$M_L \neq 0$ ⇔

$\sim \langle\Delta\rangle^2$



Seesaw type II

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

Further extensions:

→ SUSY

→ extra dimensions

→ …

In general:

- mass matrix for all neutrino-like fields
- every term has a natural scale ⇔ symmetries
  → GUT, flavour symmetry, lepton number, ...
- diagonalization → complicated dependence on all parameters

Neutrino Masses & Mixings

Some new physics to allow for neutrino mass terms $\Rightarrow$

- **Interaction states:**

  Active Flavour States ν_{e_f} $=$ 3 electro-weak partners of e, μ, τ (LEP: Z-line shape)
  Sterile States ν_{N_s} $=$ N electro-weak singlets

General mass matrix
$(\nu_e, \nu_\mu, \nu_\tau, \nu_{N_1}, \nu_{N_2}, \ldots)$

$$\begin{pmatrix} M_L & m_D \\ m_D^T & M_R \end{pmatrix}$$

$M_L \simeq 0$ with standard Higgs content
$m_D \simeq$ mass scale of charged leptons
$M_R \simeq$ embedding scale (LR, GUT, ...)

- **Physical states:** $\Leftrightarrow$ propagation as mass eigenstate ν_i with mass m_i

Diagonalization:$\Rightarrow$ See–Saw Mechanism

Heavy sterile ν's: $m_{heavy} \simeq M_R$ ($\simeq$ right-handed)
Light active ν's: $m_{light} \simeq M_L - m_D^T M_R^{-1} m_D$ ($\simeq$ left-handed)

For $\mathrm{m_{heavy}} \gg \mathrm{m_{light}}$: $\begin{pmatrix} \nu_{e_f} \\ \nu_{N_s} \end{pmatrix} = \begin{pmatrix} U_{\mathrm{mix}}^{\mathrm{light}} & \approx 0 \\ \approx 0 & U_{\mathrm{mix}}^{\mathrm{heavy}} \end{pmatrix} \cdot \begin{pmatrix} \nu_i^{\mathrm{light}} \\ \nu_j^{\mathrm{heavy}} \end{pmatrix}$

Mass hierarchy: $\Rightarrow$ Consider sub-space of light neutrinos $U_{\mathrm{mix}}^{\mathrm{light}} \simeq$ unitary

Leptonic mixing matrix in basis where charged leptons are diagonal:

$$\boxed{\mathbf{U_{MNS} := U_{mix}^{light} = U_{Dirac} \cdot diag\left(e^{i\alpha_1}, e^{i\alpha_2}, \ldots, e^{i\alpha_{n-1}}, 1\right)}}$$

Oscillations depend only on $\mathrm{U_{Dirac}}$:

2 Neutrinos: 1 angle + 0 phase (1 Majorana-phase; does not enter osc.)

3 Neutrinos: 3 angles + 1 phase $(\theta_{12}, \theta_{23}, \theta_{13}, \delta)$ (+2 further Majorana phases)

Warning: This contains various untested assumptions:

- **3 ν_R ➔ N could be different from 3 ⟷ flavour representation**
- **Rank(M_R=3) ⟷ more light ν´s ⟷ sterile ν´s**
- **ordinary QFT ⟷ CPT ⟷ identical neutrino-antineutrino parameters**
- **d=4, …**

Parameters for 3 Light Neutrinos

mass & mixing parameters: m_1 , Δm^2_{21}, $|\Delta m^2_{31}|$, sign(Δm^2_{31})

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

questions:

➔ Dirac or Majorana

➔ absolute mass scale: m_1

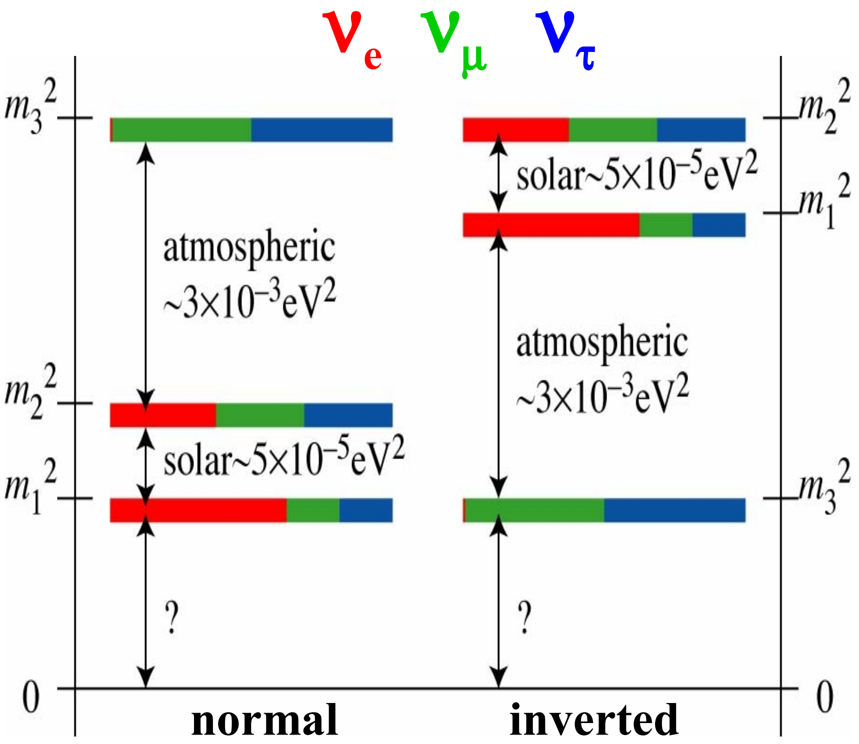
➔ mass ordering: sgn(Δm^2_{31})

➔ how small is θ_{13}, θ_{23} maximal?

➔ leptonic CP violation

➔ L/E pattern of oscillations

➔ LSND ⟵⟶ sterile neutrino(s)



hierarchical or degenerate

Four Methods of Mass Determination

- **Kinematical:** Mainz 2eV ➔ KATRIN ~0.2eV
- **lepton number violation ⟺ $0\nu 2\beta$ decay**

  ⟺ Majorana nature

  Heidelberg-Moscow ~0.5eV

  ➔ GERDA, Cuore: ~0.1eV
- **astrophysics & cosmology** ~0.5eV ➔ 0.1eV
- **Oscillations ➔**

  precision measurements of Δm^2 and mixings

The Future of Oscillation Physics

<u>Δm^2 and θ_{ij} regions</u> ➔ **improved oscillation experiments**

➔ **controlled sources & detectors**

➔ **long baseline experiments with neutrino beams**
➔ **reactor experiments with identical near & far detector**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1}&U_{e2}&U_{e3}\\ U_{\mu 1}&U_{\mu 2}&U_{\mu 3}\\ U_{\tau 1}&U_{\tau 2}&U_{\tau 3}\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\ 0&c_{23}&s_{23}\\ 0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\ 0&1&0\\ -s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\ -s_{12}&c_{12}&0\\ 0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

x Majorana-
CP-phases

θ_{23}

S_{13} ➔ 3 flavour effects
➔ CP phase δ

θ_{12}

matter effects

<u>Aims:</u> ➔ **improved precision of the leading 2x2 oscillations**
➔ **detection of generic 3-neutrino effects: θ_{13}, CP violation**

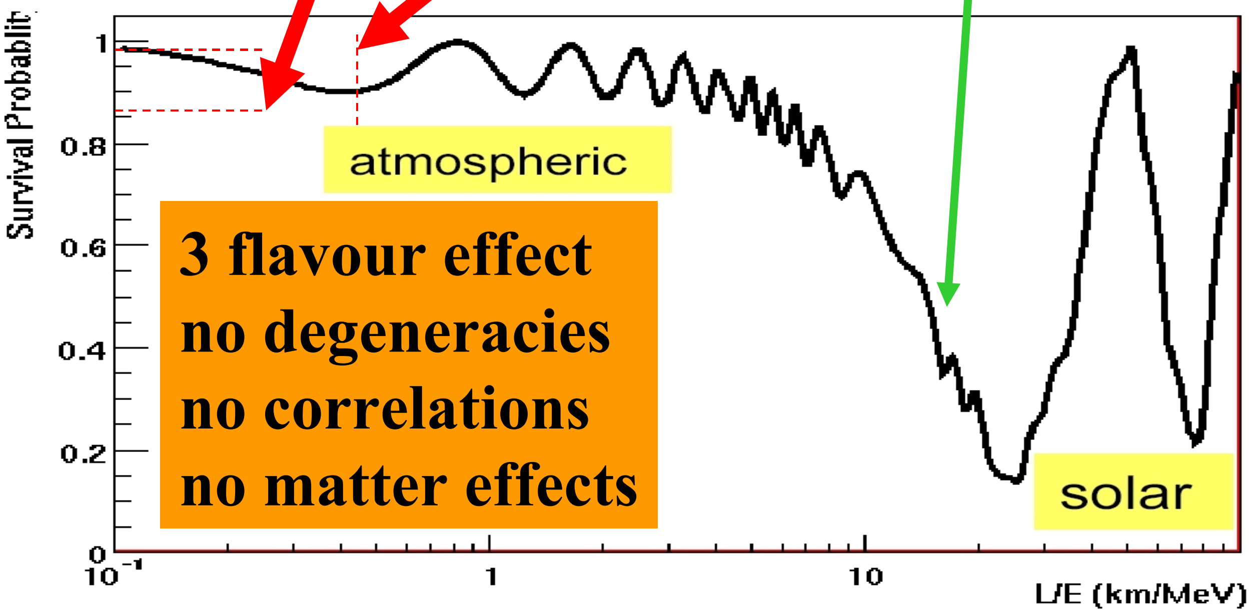
➔ **precision neutrino physics**

Future Precision with Reactor Experiments

$\xrightarrow{\bar{\nu}_e}$ **near detector** (170m) $\xrightarrow{\bar{\nu}_e}$ **far detector** (1700m)

identical detectors ➔ many errors cancel

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} - \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

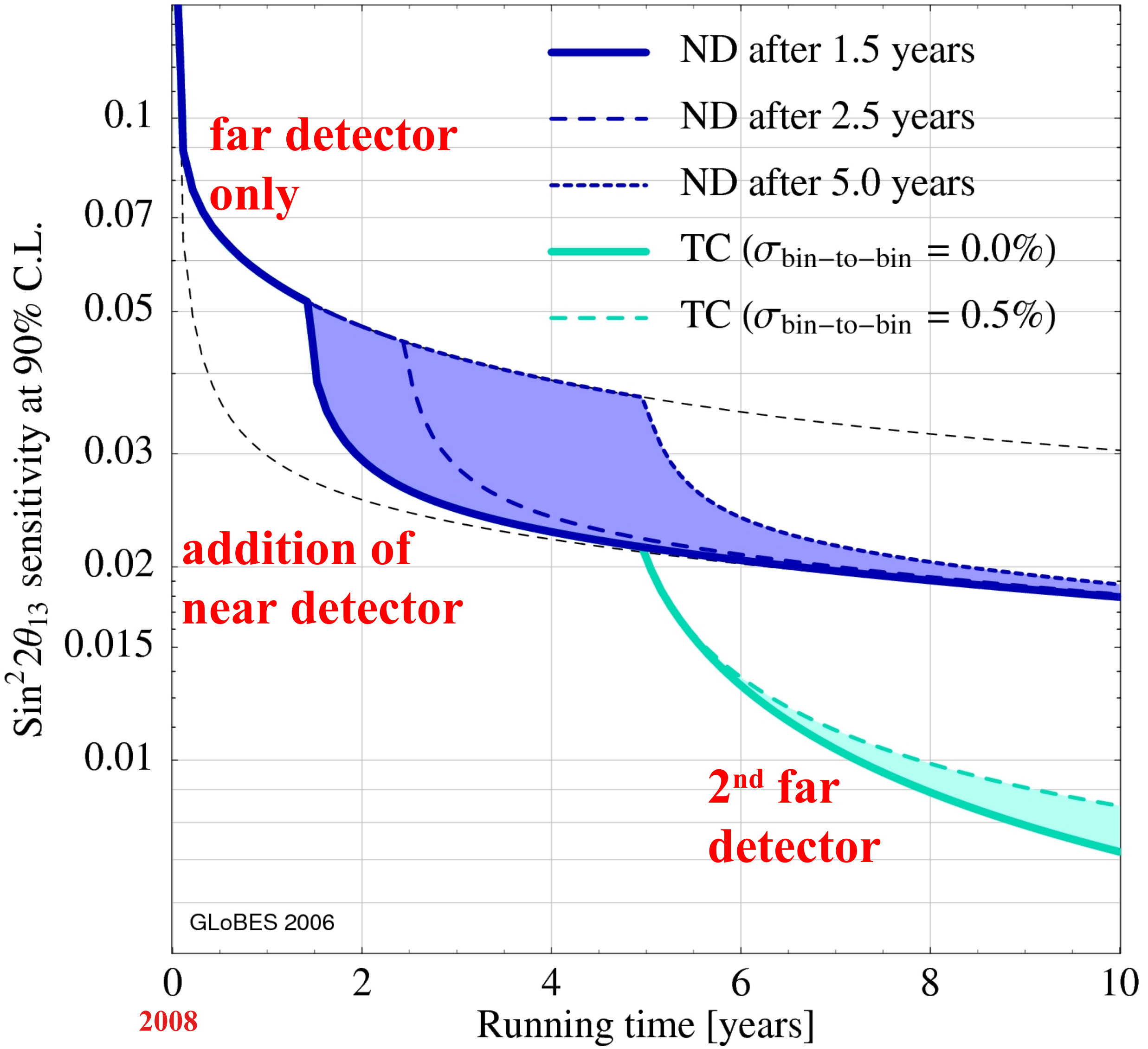


3 flavour effect
no degeneracies
no correlations
no matter effects

E=4MeV ➔ 2km 4km 40km 80km

- ➔ **Double Chooz**
- ➔ **Daya Bay**
- ➔ **Reno? Angra?**
- ➔ **Triple Chooz?**

Double Chooz and Triple Chooz



far detector only

addition of near detector

2nd far detector

$\sin^2 2\theta_{13}$ sensitivity

Chooz limit	< 0.20
Double Chooz	< 0.02
Triple Chooz ?	< 0.008

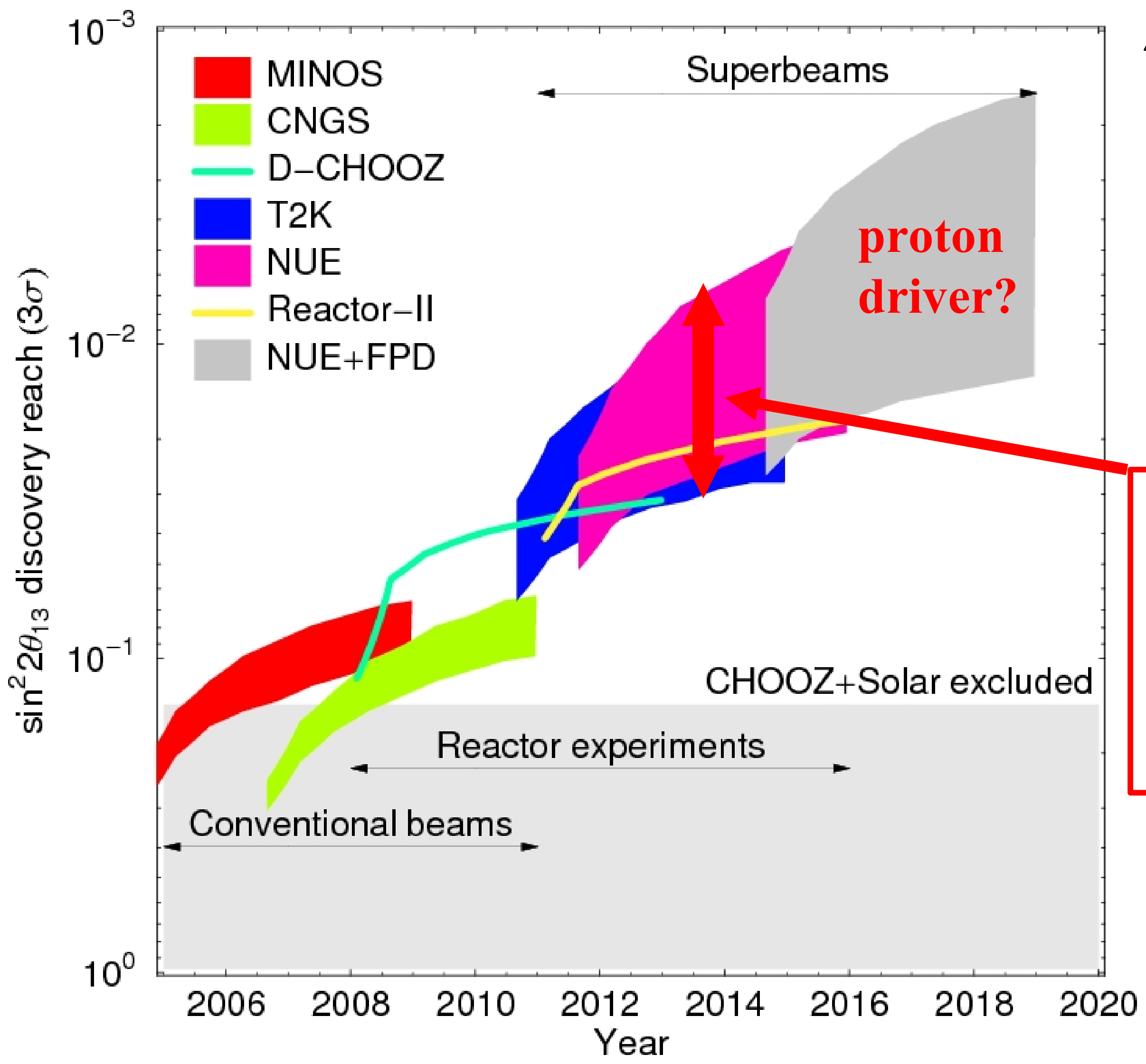
Future Precison with New Neutrino Beams

- conventional beams, superbeams
  - ➔ MINOS, CNGS, T2K, NOνA, T2H,…
- β-beams
  - ➔ pure ν_e and $\bar{\nu}_e$ beams from radioactive decays; $\gamma \simeq 100$
- neutrino factories
  - ➔ clean neutrino beams from decay of stored μ's

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\pm\ & \sin \delta_{CP}\ \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \cos \delta_{CP} \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

correlations & degeneracies, matter effects

Sensitivity Versus Time



proton driver?

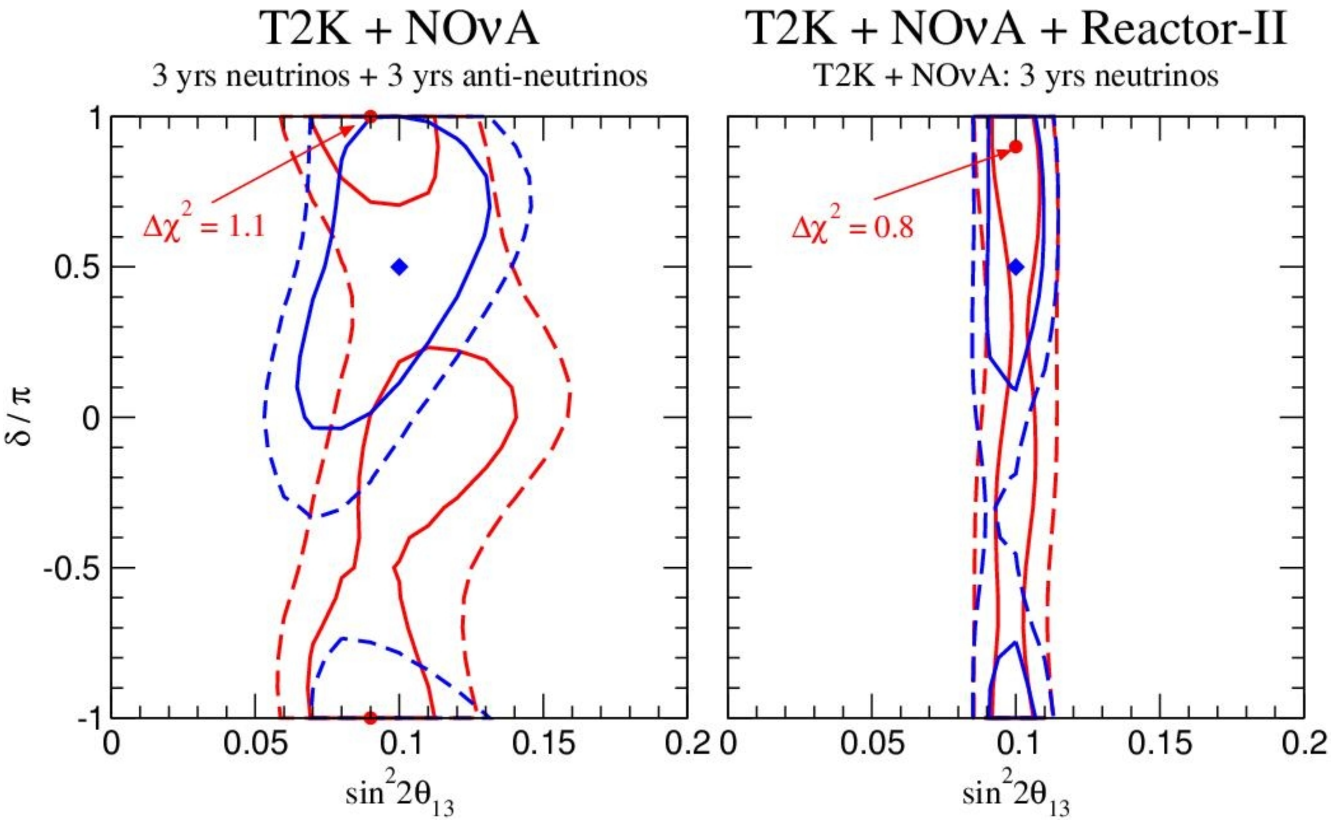
β-beams
neutrino factory

Range ↔
~unknown CP phase

combination with reactor
↔ synergies

Leptonic CP-Violation

<u>assume:</u> $\sin^2 2\theta_{13} = 0.1$, $\delta = \pi/2$ ➔ combine T2K+NOνA+reactor



$\Delta m^2 > 0$

$\Delta m^2 < 0$

━ 90%CL

⋯ 3σ

➔ **bounds or measurements of leptonic CP-violation**

➔ **leptonic CP-violation in M_R ⇔ baryon asymetry via leptogenesis**

The Value of Future Precision Experiments

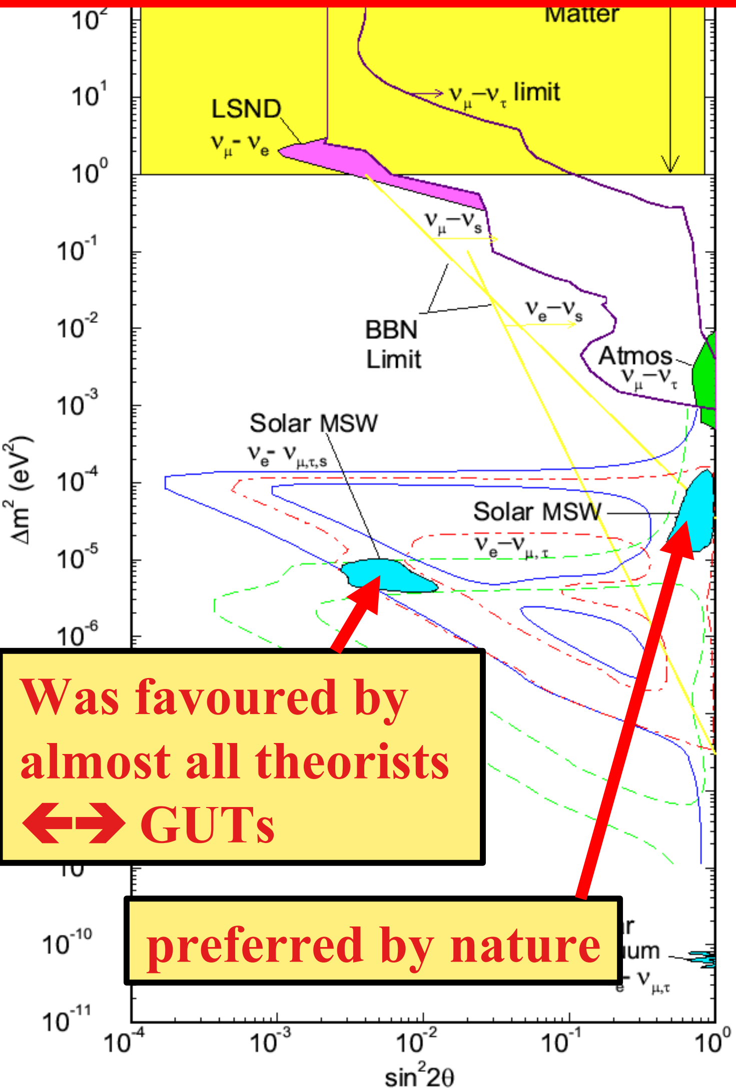
<u>Coming improvements:</u>

- **MINOS: improved oscillation parameters**
- **MiniBOONE ⇔ LSND**
- **L/E dependence of oscillations**
- **KATRIN**
- **Better 0ν2β limits / signals**
- **…**

But why do we need precision measurements?
➔ learn about the origin of flavour!

Learning about Flavour

History: Elimination of SMA



Was favoured by almost all theorists ⟺ GUTs

preferred by nature

Next: Smallness of θ_{13}

- models for masses & mixings
- input: known masses & mixings
  - ➔ distribution of θ_{13} „predictions“
  - ➔ θ_{13} often close to experimental bounds

What if $\sin^2 2\theta_{13} < 0.01$?

➔**is θ_{13} small or tiny?**

similar:

➔**is θ_{23} maximal or just large?**

numerical coincidence or symmetry

answering questions ➔precision

Further Implications of Precision

Precision allows to identify / exclude:

- special angles: $\theta_{13} = 0°$, $\theta_{23} = 45°$, ... ⇔ discrete f. symmetries?
- special relations: $\theta_{12} + \theta_C = 45°$? ⇔ quark-lepton relation?
- quantum corrections ⇔ renormalization group evolution

Provides also measurements or tests of:

- MSW effect (coherent forward scattering and matter profiles)
- cross sections
- 3 neutrino unitarity ⇔ sterile neutrinos with small mixings
- neutrino decay (admixture…)
- decoherence
- NSI
- MVN, ...

➔ various synergies with LHC and LFV

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

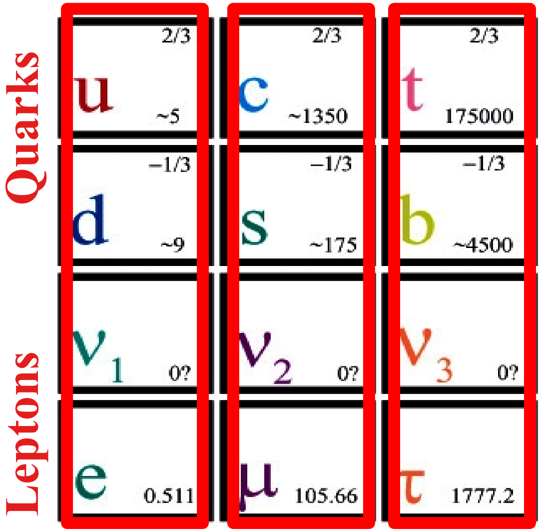
<u>Requirements:</u>

gauge unification

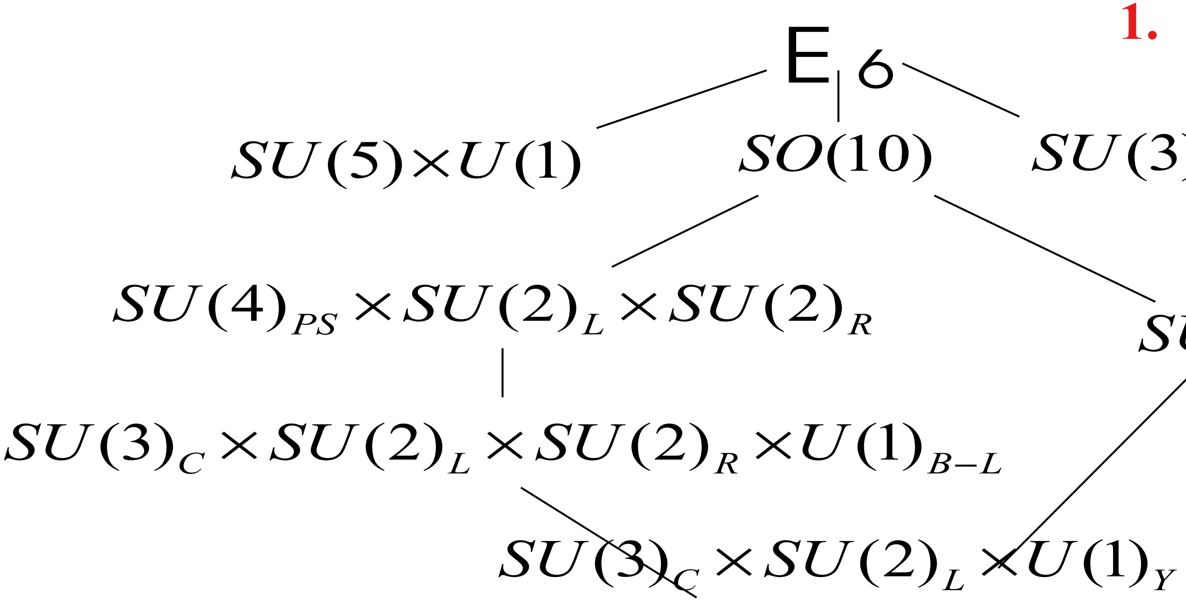
particle multiplets ⇔ ν_R

proton decay

…



	1.	2.	3. generation
Quarks	u 2/3 ~5	c 2/3 ~1350	t 2/3 175000
	d −1/3 ~9	s −1/3 ~175	b −1/3 ~4500
Leptons	ν_1 0?	ν_2 0?	ν_3 0?
	e 0.511	μ 105.66	τ 1777.2



$$E_6$$

$$SU(5)\times U(1) \qquad SO(10) \qquad SU(3)_C\times SU(3)_L\times SU(3)_R$$

$$SU(4)_{PS}\times SU(2)_L\times SU(2)_R \qquad SU(5)$$

$$SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$$

$$SU(3)_C\times SU(2)_L\times U(1)_Y$$

many models…

GUT Expectations and Requirements

Quarks and leptons sit in the same multiplets

- ➔ one set of Yukawa couplings for given GUT multiplet
- ➔ ~ tension: small quark mixings ⟷ large leptonic mixings
- ➔ this was in fact the reason for the `prediction' of small mixing angles (SMA) – ruled out by data

Mechanisms to post-dict large mixings:

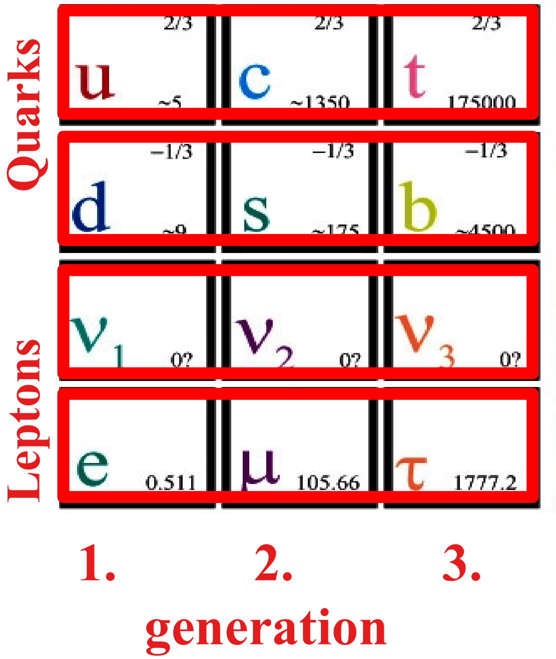
- ➔ sequential dominance
- ➔ type II see-saw
- ➔ Dirac screening
- ➔ …

Flavour Unification

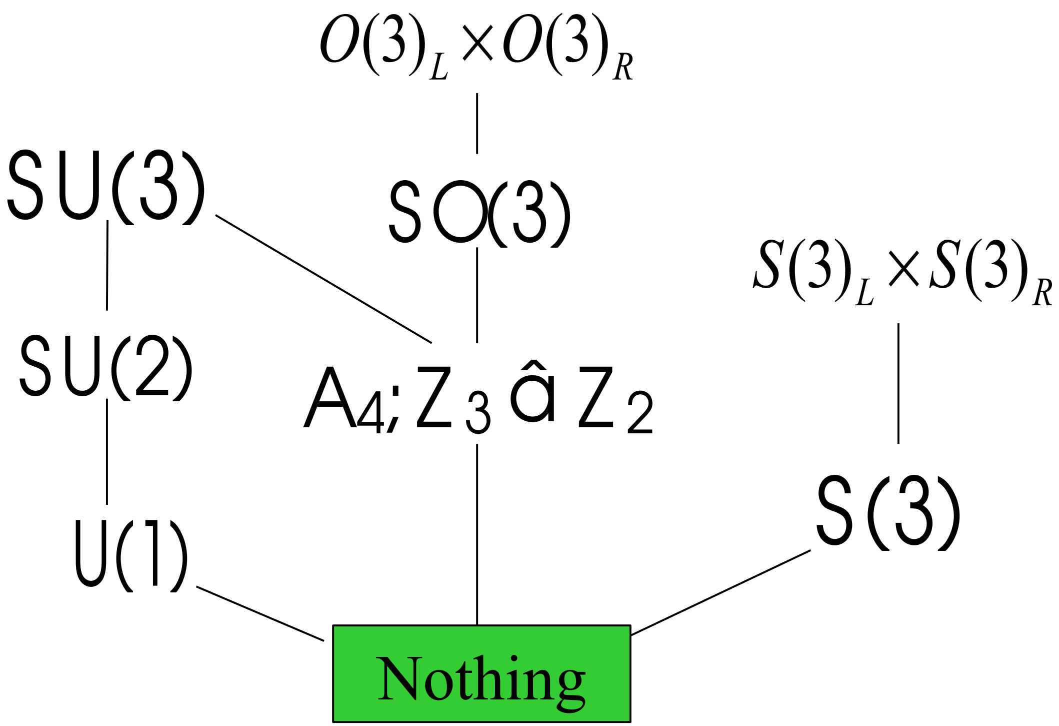
- so far no understanding of flavour, 3 generations
- apparant regularities in quark and lepton parameters

➔ flavour symmetries (finite number for limited rank)

➔ symmetry not texture zeros



Examples:


$O(3)_L \times O(3)_R$

SU(3)

SO(3)

$S(3)_L \times S(3)_R$

SU(2)

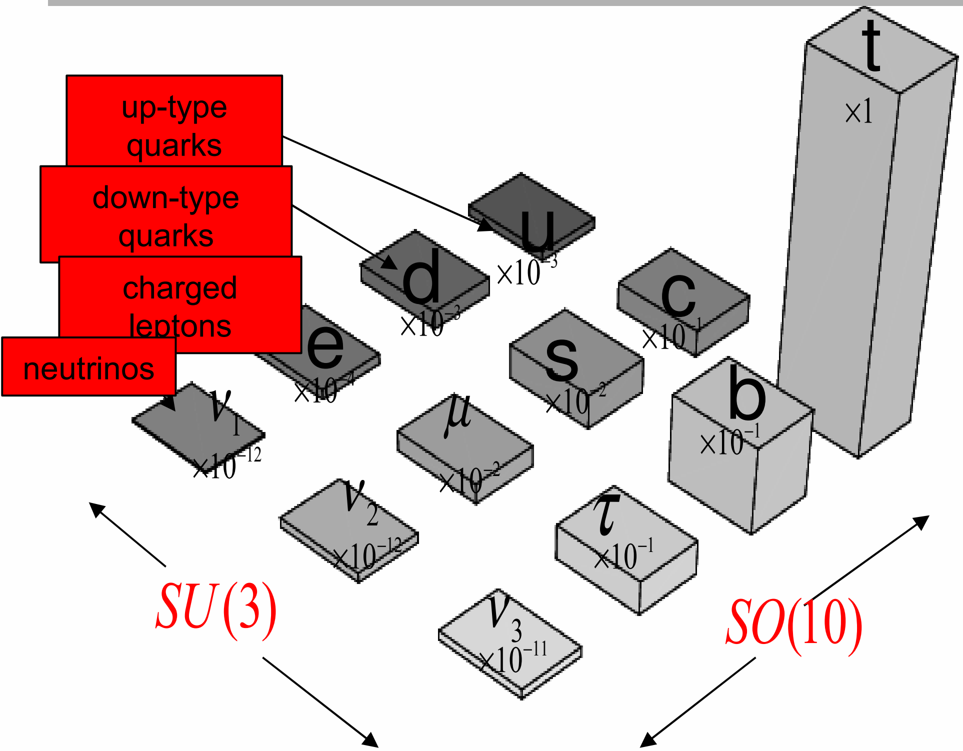
$A_4; Z_3$ â Z_2

S(3)

U(1)

Nothing

GUT 0 Flavour Unification



➔ GUT group 0 flavour group

<u>example:</u> SO(10) 0 SU(3)$_F$

- SSB of SU(3)$_F$ between Λ_{GUT} and Λ_{Planck}

- all flavour Goldstone Bosons eaten

- discrete sub-groups survive ↔SSB

e.g. Z2, S3, D5, A4

➔ structures in flavour space

➔ compare with data

GUT 0 flavour is rather restricted

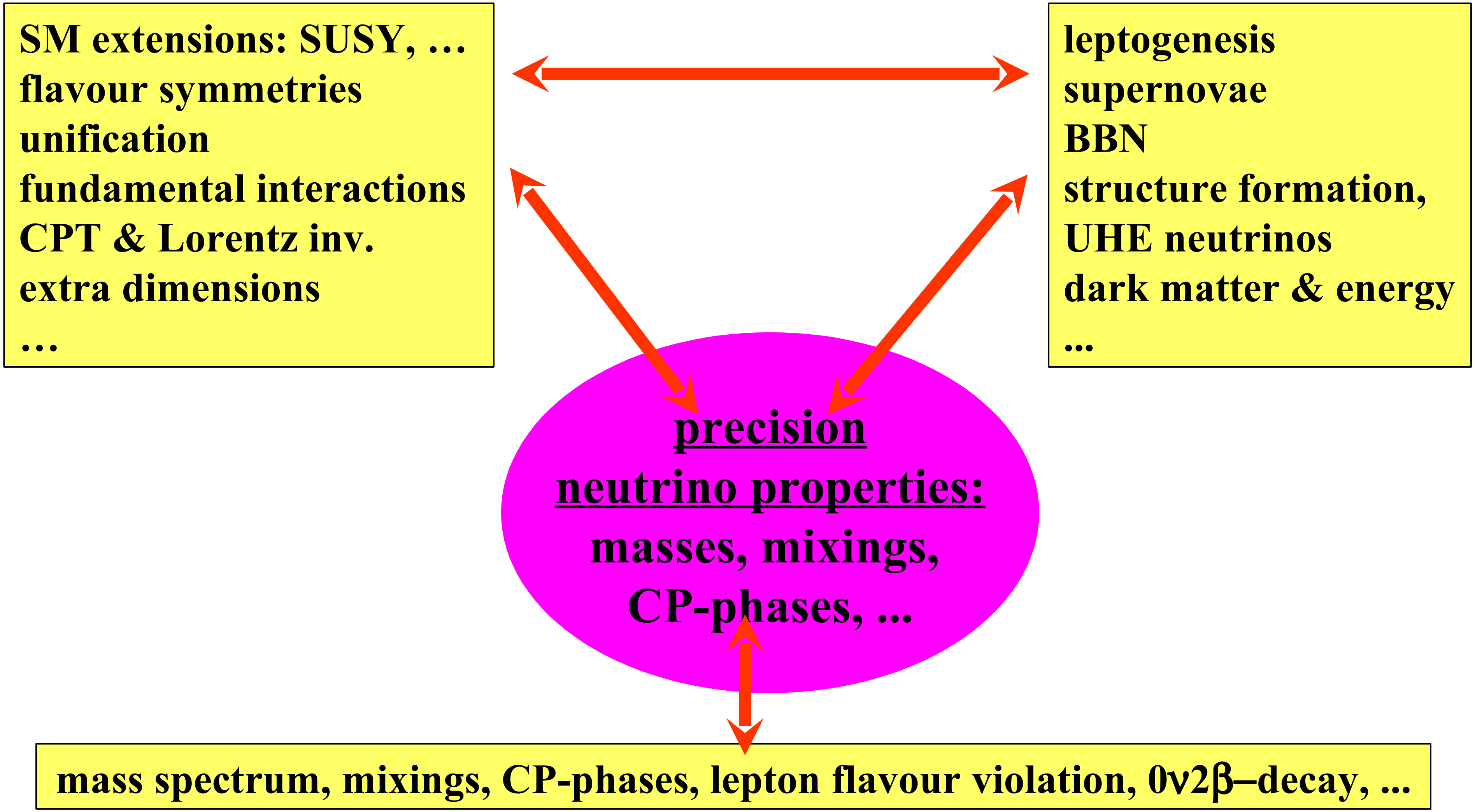
↔ small quark mixings *AND* large leptonic mixings ; quantum numbers

➔ so far only a few viable models; e.g. SO(10) 0 S4 Hagedorn, ML, Mohapatra

➔ rather limited number of possibilities; phenomenological success non-trivial

➔ aim: <u>distinguish models by future precision</u>

The Interplay of Topics



SM extensions: SUSY, …
flavour symmetries
unification
fundamental interactions
CPT & Lorentz inv.
extra dimensions
…

leptogenesis
supernovae
BBN
structure formation,
UHE neutrinos
dark matter & energy
...

precision
neutrino properties:
masses, mixings,
CP-phases, ...

mass spectrum, mixings, CP-phases, lepton flavour violation, $0\nu 2\beta$–decay, ...

LHC physics ↔ neutrino physics ↔ LFV ↔ astroparticle physics

3 Flavours and more

- **Physics motivation: origin of flavour**

  ➔ 3flavour oscillations ➔ precision neutrino physics

  ➔ compare models of flavour with precise data

- **Good reasons for physics beyond the SM**

  ⟺ 3 neutrinos? ➔ expect effects beyond 3flavours

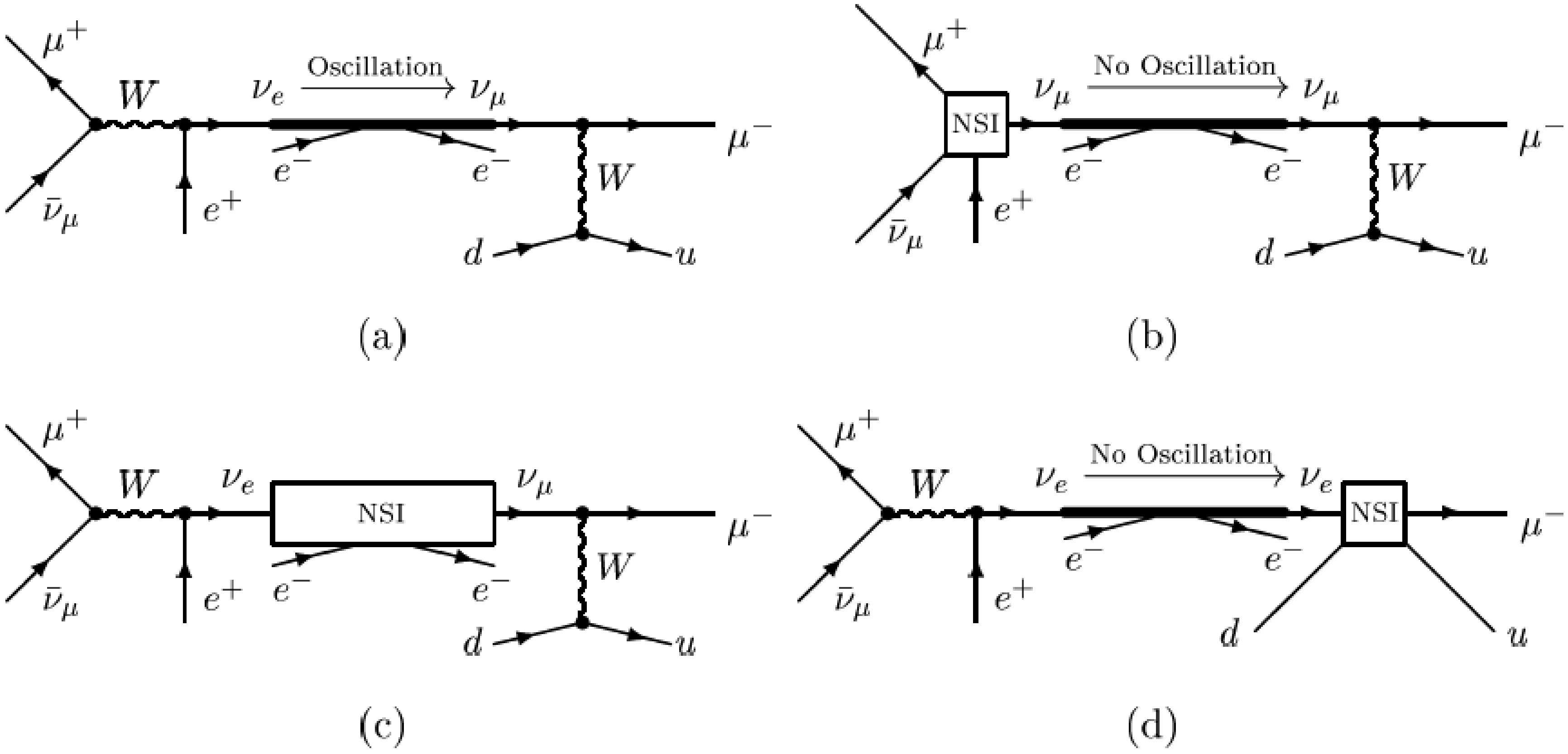
  ➔ example NSIs = flavour violationg interactions
  from new physics ≥ TeV

$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\ \gamma^\rho\ \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

∀ ε G_F from integrating out heavy physics (like G_F ⟺ M_W)

$$\rightarrow \epsilon \simeq \frac{M_W^2}{M_{new\ physics}^2} \leq \left(\frac{100\mathrm{GeV}}{1\mathrm{TeV}}\right)^2 = 0.01$$

NSIs interfere with Oscillations



(a) (b) (c) (d)

Figure 1: (a): The golden channel oscillation process in a neutrino factory; (b) – (d): Non-standard contributions to the golden channel.

NSIs & Future Oscillation Experiments

Source	⊗	**Oscillation**	⊗	**Detector**
- neutrino energy E		- oscillation channels		- effective mass, material
- flux and spectrum		- realistic baselines		- threshold, resolution
- flavour composition		- MSW matter profile		- particle ID (flavour, charge, event reconstruction, ...)
- contamination		- degeneracies		- backgrounds
- symmetric $\nu/\overline{\nu}$ operation		- correlations		- x-sections (at low E)

experiments with ≤ percent precision should be prepared

➔ Modification of 3f oscillation formulae

- small event rates ➔ offset in oscillation parameters

- spectral information ➔ poor goodness of fit

- ⇔ cf. LFV

Strategy Issues

Source ⊗ Oscillation ⊗ Detector

- 3f strategies:
  - best sources
  - best detector technologies
  - strategies to break degeneracies & correlations

  ➔ best physics potential / cost
- strategy with open boundary conditions:
  - most precise measurements
  - spectral resolution & redundancy
  - new ideas (e.g. Triple Chooz, Mössbauer ν's, …)?
  - keep an eye on LHC, LFV, astroparticle

➔ broad source and detector R&D
➔ theoretical support (phenomenology, theory)
➔ decide when time has come