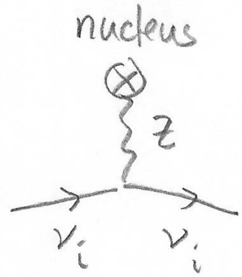
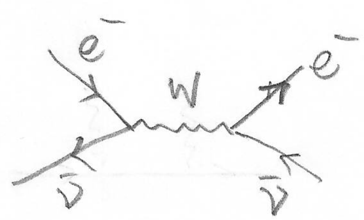
Notes: 1. $\sin^2\left(\frac{(E_1 - E_2)L}{2}\right)$

if neutrinos travel in background, then E_i are affected by "matter effects"



universal $\Rightarrow$ no contribution to ΔE



singles out ν_e because only electrons exist in matter.

proportional to n_{e^-}, electron number density.

$\Rightarrow$ MSW effect.

2. $L_{osc} \sim \frac{E}{\Delta m^2}$ depends on neutrino energy and type

$\Rightarrow$ different distances probe different physics

solar ν's:

main fusion reaction: $4p \to {}^4He + 2e^+ + 2\nu_e + 2\gamma$

Figure 14.1 pdg review

98.5% of heat of sun

⇒ well-known flux

$E_\nu \lesssim 0.42$ MeV

small, hard to detect

$$L_{osc} \sim \frac{10^6 \text{ eV}}{10^{-4} \text{ eV}^2} \cdot 2 \cdot 10^{-7} \text{ eV m} \sim \text{km}$$

(10^6 eV ← E, 10^{-4} eV² ← Δm^2)

Earth-Sun = 1 AU ≃ 10^{10} m

⇒ oscillations averaged out ⇒ $P_{ee} \sim 1/2$

Experiment:

Homestake:

$\nu_e + {}^{37}Cl \to {}^{37}Ar + e^-$

↑ chemically separated, half life 35 days

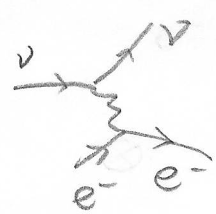
Expected: 8.46 ± 0.88 SNU

Obs: 2.56 ± 0.22 SNU

≈ 30%

SAGE + GALLEX 65 obs 130 exp. in SNU

SUPER-K real-time



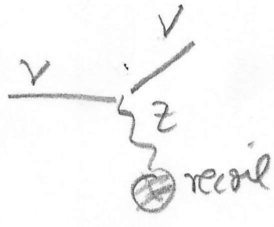
Čerenkov rings directional!

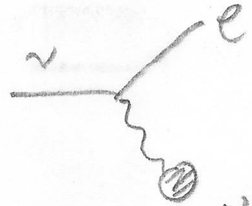
sensitive to ^8B neutrinos (8 MeV)

2.345 obs 5.46 exp.

Picture of sun in ν's

SNO measured both CC & NC



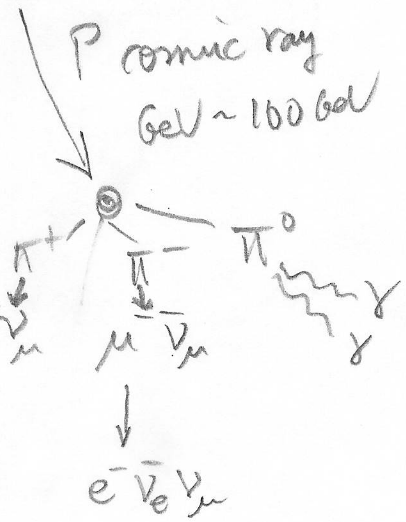


$\Rightarrow$ confirms both total flux (✓ $\nu_e + \nu_\mu + \nu_\tau$) and depletion of ν_e.

solution is MSW adiabatic conversion in solar matter.

$\Delta m^2 \sim 0.75\, 10^{-4}\, eV^2$, $\sin^2\theta \sim 0.3$.

Atmospheric:



$\Longrightarrow \sim \frac{2}{3}\nu_\mu + \frac{1}{3}\nu_e$

Super-K:

Cerenkov ring

- zenith angle varies L
- energy of p^+ varies E

Fig 14.4.

$\Rightarrow$ can explore $\sin^2\left(\frac{\Delta m^2}{E} L\right)$ dependence

$\Delta m^2_{atm} \sim 2.45 \pm 0.03 \; 10^{-3} \, eV^2$ (Δm^2_{32})

$\sin^2\theta_{12} = 0.31 \pm 0.01$ solar

$\sin^2\theta_{23} = 0.55 \pm 0.02$ atmosph.

$\sin^2\theta_{13} = 0.022 \pm 0.001$ "

$\delta^{CP} \sim 280° \pm 20°$

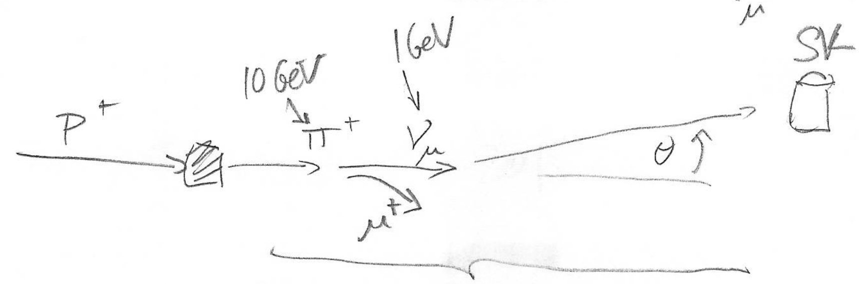
<u>Reactors</u> $\bar{\nu}_e$ from β decays $p^+ \to n e^- \bar{\nu}_e$

$\bar{\nu}_e$ disappearance — $L_1 \sim 1.5\,km \Rightarrow \Delta m^2 \sim 10^{-2}\,eV^2$

$E \sim MeV$ — $L_2 \sim 200\,km$ $\Delta m^2 \sim 10^{-4}\,eV^2$ solar

T2K 2017

Accelerator make $\pi^\pm \to \mu^\pm \nu_\mu / \bar{\nu}_\mu$

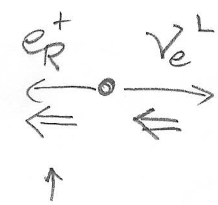


$L = 300$ km

"off axis" to select more monochromatic beam

Q: why $\pi^+ \to \mu^+ \nu_\mu$ (not $e^+ \nu_e$?)

A: π is spin 0 $\Rightarrow$ in rest frame



chiralities

need helicity flip $\propto m_e$

$\Rightarrow \Gamma \propto m_f^2$

$$\Rightarrow \frac{\Gamma_{\mu\nu}}{\Gamma_{e\nu}} \propto \left|\frac{m_\mu}{m_e}\right|^2 \sim 10^4$$

ν_μ disappearance

~ 100 μ^- events expected (no oscillation)

~ 30 μ^- observed

~ 4 e^- "

SHOW formula fit δ_{CP}, θ_{13}

What do we not know?

- CP phase
- ordering of neutrino masses

} DUNE — FNAL → Sanford, 1300 km, Beam in 2026

- LSND anomaly
- are there more than 3?
- majorana vs. Dirac } SNO+

Quark flavor

$$V_{CKM} = \begin{pmatrix} ud & us & ub \\ cd & cs & cb \\ td & ts & tb \end{pmatrix} \equiv \begin{pmatrix} 1 & & \\ & \theta_{23} & \\ & & \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} \theta_{12} & & \\ & & \\ & & \end{pmatrix}$$

Rephasing invariant J_{CKM}

$$\mathrm{Im}\left(V_{ij} V^{\dagger}_{jk} V_{kl} V^{\dagger}_{li}\right) = J_{CKM} \sum_{mn} \epsilon_{ikm} \epsilon_{jln} \quad (\text{no sum } ijkl)$$

$$J_{CKM} = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta$$

- V_{CKM} can be made real if $\theta_{ij} = 0, \pi/2, \pi$
- 2 (quark) masses equal $m_i = m_j \Rightarrow \theta_{ij}$ unphysical

e.g. $\begin{pmatrix} M & & \\ & m & \\ & & m \end{pmatrix} \Rightarrow \theta_{23}$ arbitrary because 2-3 submatrix diagonal in any basis

Unitarity triangle

in SM V_{CKM} is unitary i.e. $V^\dagger V = \mathbb{1} \iff V_{ij} V^*_{ik} = \delta_{jk}$

in BSM it may not be

e.g. down quarks mix with TeV extra quark

$$\begin{array}{c} \\ d^c \end{array} \begin{pmatrix} \overset{d}{\begin{matrix} 4\times 3 \\ \lambda_{\alpha j} \end{matrix}} & \Bigg| \overset{d'}{M_j} \end{pmatrix}$$

$$\lambda_{\alpha j}\, d^c_\alpha \tilde{H} Q_j + M_\alpha d^c_\alpha d'$$

$j \in 1 \dots 3$

$\alpha \in 1 \dots 4$

$\Rightarrow$ M^D diagonalized by unitary 4×4 matrices

$$\Rightarrow V_{CKM} = V_u V_D^\dagger \Big|_{3\times 3}$$

$\uparrow$ not unitary

$$V_D^{4\times 4} = \left(\begin{array}{c|c} V_D^{3\times 3} & \\ \hline & \end{array} \right)$$

$$\sum_{i=1}^{4} V_{D_{ij}} V^*_{D_{ik}} = \sum_{i=1}^{3} V_{D_{ij}} V^*_{D_{ik}} + \underbrace{V_{D4j} V^*_{D4k}}_{\text{deviation of } 3\times 3 \text{ unitarity}} = \delta_{jk}$$

unitarity: $\sum_i V_{ik} V_{il}^* = \delta_{kl}$ 9 relations (rephase invariant!)

- 3 diagonal ones $\sum_i |V_{ik}|^2 = 1$ dominated by $V_{kk} \approx 1$

  $\Rightarrow$ not a precision test.

- 6 off-diagonal e.g.

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

$$\lambda^3 \qquad \lambda^3 \qquad \lambda^3$$

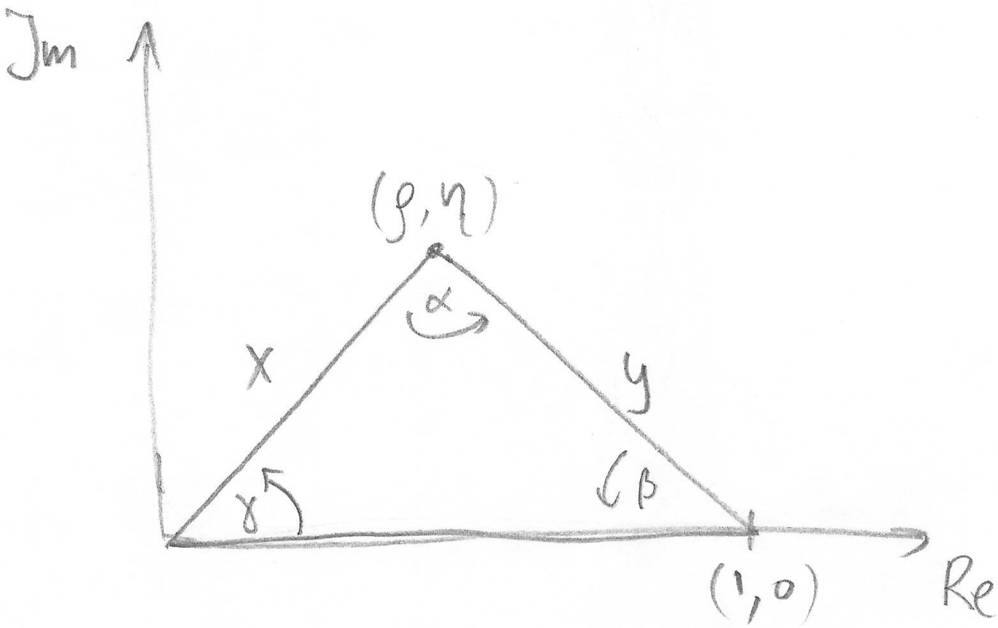
nice because 3 terms of similar size

divide by $V_{cd} V_{cb}^*$

$$1 = -\overbrace{\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}}^{x} - \overbrace{\frac{V_{tb}V_{tb}^*}{V_{cd}V_{cb}^*}}^{y}$$

↑ (first fraction) $\sim \rho + i\eta$ in Wolfenstein parametrization

$1 = x + y$ triangle in complex plane



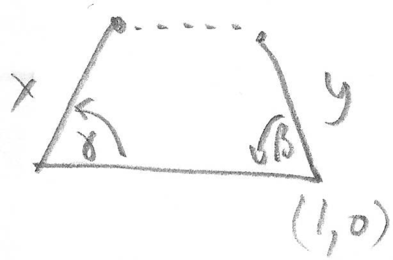
$$|X| = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \qquad \gamma = \arg(X)$$

$$|y| = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| \qquad \beta = \arg(1/y)$$

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

idea: measure sides & angles in as many ways as possible to overconstrain △ to check consistency with SM.

BSM could have



goals: measure CKM

1. assuming unitarity, only need 4 measurements

$$\theta_{12}\ \theta_{23}\ \theta_{13}\ \delta \iff \lambda\ A\ \eta\ \rho$$

$$\iff |V_{td}|, |V_{ts}|, |V_{tb}|, |V_{cs}| \quad \text{(e.g.)}$$

2. SM may be wrong $\Rightarrow$ measure more than 4 to test consistency

a.) measure same quantity in different ways

b.) over constrain triangle

PLOT unitarity triangle