

Revisiting Froggatt-Nielsen mechanism

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Work in progress

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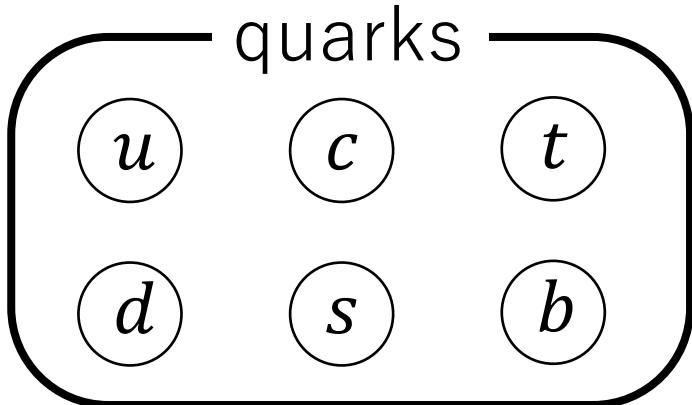
Contents

- 1. Flavor puzzles and FN mechanism**
- 2. Good FN charge and phenomenology**
- 3. Summary**

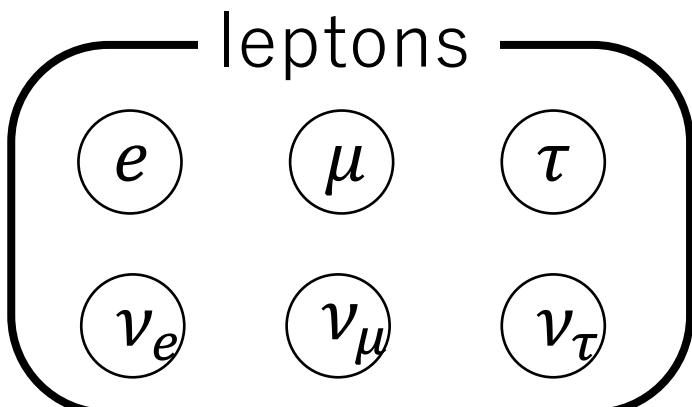
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The standard model



- Repetitive structure of quarks and leptons



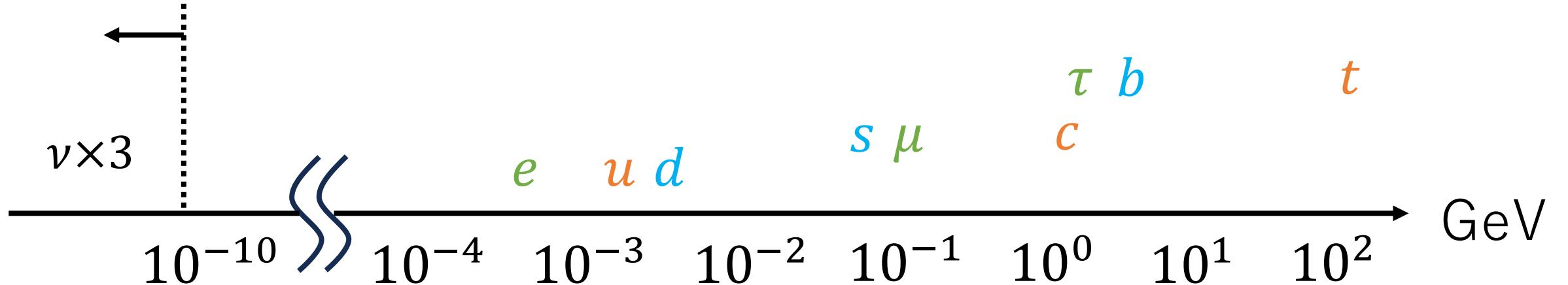
- Very successful

1st 2nd 3rd

Situation

There exist flavor puzzles in the SM !

Fermion mass structure



$$\text{e.g., } \frac{m_t}{m_u} = O(10^5)$$

There is hierarchical mass structure.

Structure of mixings

$$|V_{\text{CKM}}| = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \quad \text{hierarchical}$$

$$|V_{\text{PMNS}}| = \begin{pmatrix} |V_{e1}| & |V_{e2}| & |V_{e3}| \\ |V_{\mu 1}| & |V_{\mu 2}| & |V_{\mu 3}| \\ |V_{\tau 1}| & |V_{\tau 2}| & |V_{\tau 3}| \end{pmatrix} \quad \text{anarchical}$$

Mixing matrices have distinctive structures.

Froggatt-Nielsen (FN) mechanism

C.D.Froggatt and H.B.Nielsen, Nucl.Phys.B 147 (1979)

- SM fermions have charges under new U(1) symmetry

$$f_i : q(f_i), \quad (i: \text{generation})$$

- We cannot write ordinary Yukawa interactions

$$f_i f_j H \longrightarrow \cancel{f_i f_j H}$$

- If we introduce new scalar $S : -1$, new operators can be written

$$\kappa_{ij} f_i f_j H \left(\frac{S}{M_{\text{Pl}}}\right)^{|q(f_i)+q(f_j)|} \quad \kappa_{ij} = O(1)$$

FN mechanism (sequel)

- If S obtains VEV, Yukawa interactions arise,

$$\kappa_{ij} f_i f_j H \left(\frac{S}{M_{\text{Pl}}} \right)^{|q(f_i) + q(f_j)|} \xrightarrow{S \rightarrow \langle S \rangle} \kappa_{ij} f_i f_j H \left(\frac{\langle S \rangle}{M_{\text{Pl}}} \right)^{|q(f_i) + q(f_j)|},$$

$$y_{ij} = \kappa_{ij} \times \delta^{|q(f_i) + q(f_j)|}, \quad \delta = \langle S \rangle / M_{\text{Pl}} < 1$$

- **Hierarchy is realized naturally by this mechanism.**

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How to find good charges

- Compare the plausibility of multiple different FN charge assignments
- We adopt **the Bayes factor**

(J. Bergstrom, D. Meloni and L. Merlo, PRD 89 (2014) 9, 093021)

Bayes theorem

$$\begin{aligned} P(M_i | Data) &\propto P(Data | M_i) \times P(M_i) \\ &= \int d\theta P(Data | \theta, M_i) \times P(\theta | M_i) \times P(M_i) \end{aligned}$$

$P(M_i)$: prior probability of models

$P(\theta | M_i)$: prior distribution of model parameters

$P(Data | \theta, M_i)$: likelihood function

Bayes factor

$$\frac{P(M_i | Data)}{P(M_j | Data)} \propto \boxed{\frac{P(Data | M_i)}{P(Data | M_j)}} \times \frac{P(M_i)}{P(M_j)}$$

Bayes factor: Comparison of the plausibility of two models

Set up

$$\begin{aligned}-\mathcal{L}_Y = & y_{u,ij} Q_i \bar{u}_j H + y_{d,ij} Q_i \bar{d}_j H^\dagger \\ & + y_{e,ij} L_i \bar{e}_j H^\dagger + y_\nu (L_i H)(L_j H)/(2M_R) + h.c..\end{aligned}$$

$$y_{ij} = \kappa_{ij} \times \delta^{|q(f_i) + q(f_j)|},$$

Concrete functions

$$\begin{aligned} P(M_i | Data) &\propto P(Data | M_i) \times P(M_i) \\ &= \int d\theta P(Data | \theta, M_i) \times P(\theta | M_i) \times P(M_i) \end{aligned}$$

$$P(\theta = \kappa_{ij}, \delta | M_i) \propto \exp(-\text{tr}(\kappa^\dagger \kappa)), \quad (y_{ij} = \kappa_{ij} \times \delta^{|f_i + f_j|})$$

$$P(M_i) = P(M_j) \text{ for } i \neq j$$

$$P(Data = x_a | \theta, M_i) \propto \delta(x_a(\theta) - x_a^{\text{obs}})$$

Parameters

Fermion Yukawas

$$y_u, y_c, y_t, y_d, y_s, y_b, y_e, y_\mu, y_\tau$$

CKM and PMNS
parameters

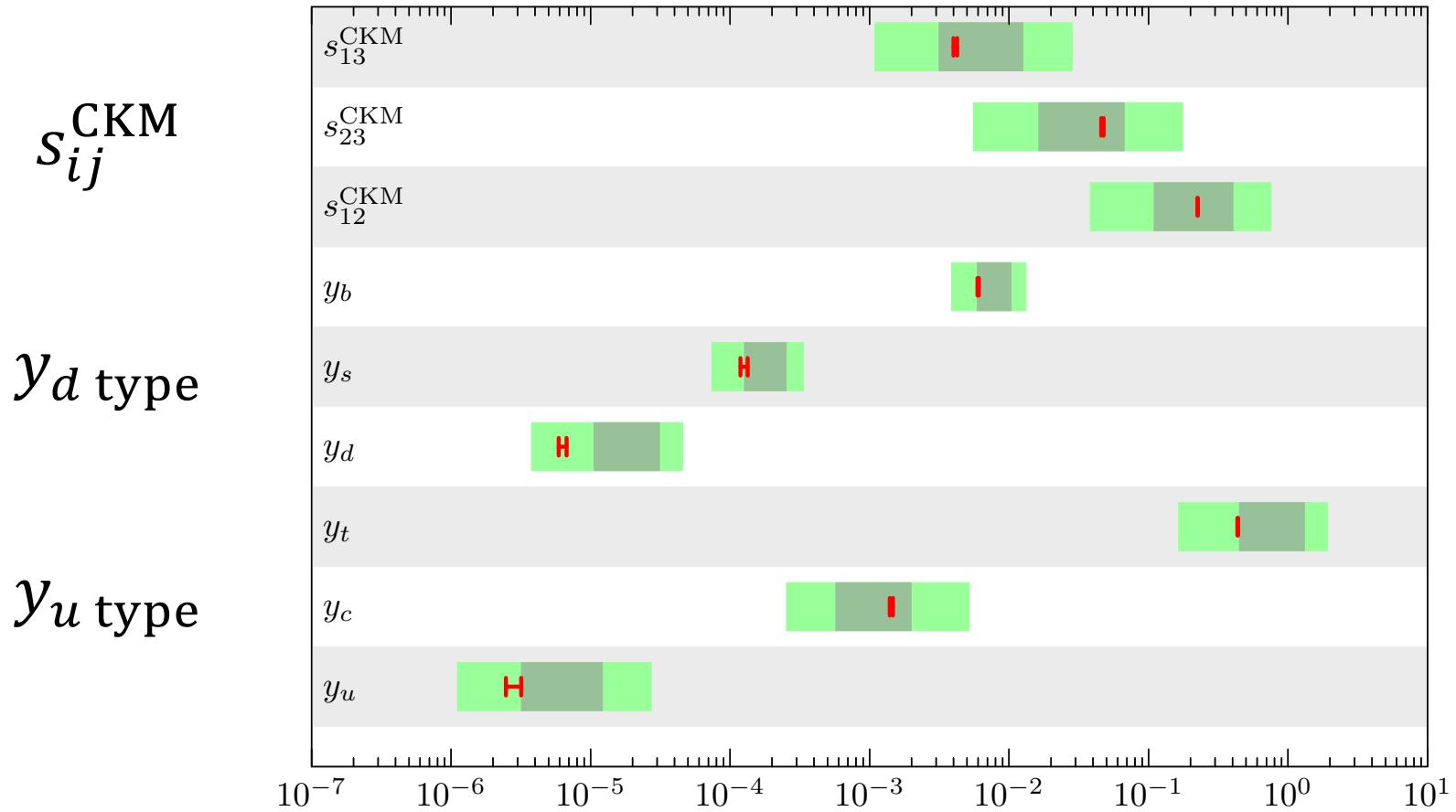
$$s_{12}^{\text{CKM}}, s_{23}^{\text{CKM}}, s_{13}^{\text{CKM}}, \delta^{\text{CKM}}, \\ s_{12}^{\text{PMNS}}, s_{23}^{\text{PMNS}}, s_{13}^{\text{PMNS}}$$

Neutrino mass ratio

$$\Delta m_{12}^2 / \Delta m_{13}^2 = m_1^2 - m_2^2 / m_1^2 - m_3^2$$

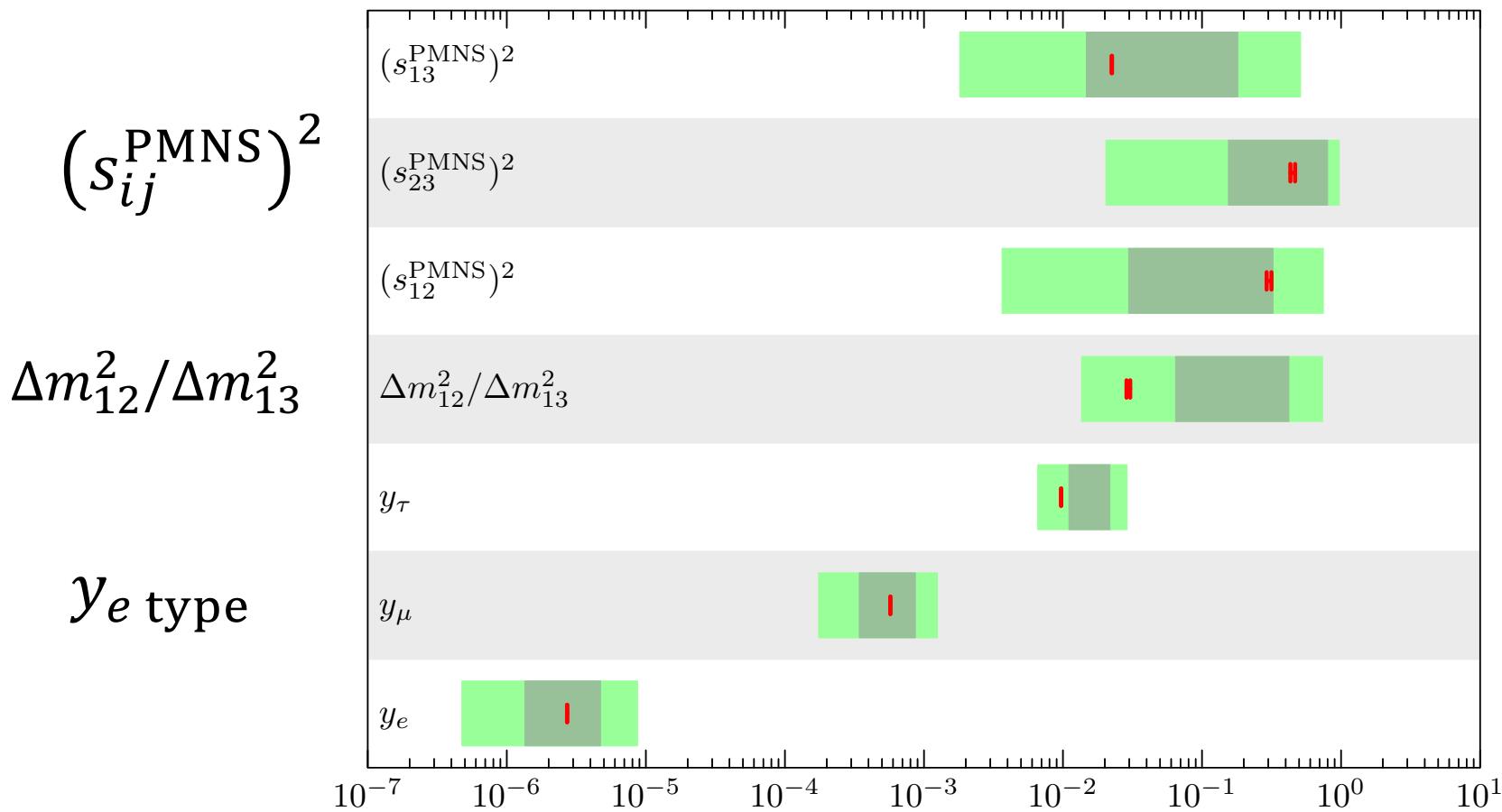
Results(quarks)

$$\delta = 0.17, \quad q(Q) = (3, 2, 0), \quad q(\bar{u}) = (4, 2, 0), \quad q(\bar{d}) = (3, 3, 3)$$



Results(leptons)

$$\delta = 0.23, \quad q(L) = (4, 4, 3), \quad q(\bar{e}) = (5, 2, 0)$$



How to explore flavor

- We have studied proton decay
- Proton decay is a probe of high energy physics
- Branching fractions of proton decay
 - Details of flavor structure

Proton decay

- Dim-6 operators relevant to proton decay S. Weinberg, PRL 43 (1979)

$$O_{ijkl}^{(1)} = \frac{1}{M^2} (\bar{u}_i^\dagger \bar{e}_j^\dagger)(\bar{u}_k^\dagger \bar{d}_l^\dagger), \quad O_{ijkl}^{(2)} = \frac{1}{M^2} (Q_i Q_j)(Q_k L_l),$$

$$O_{ijkl}^{(3)} = \frac{1}{M^2} (\bar{u}_i^\dagger \bar{d}_j^\dagger)(Q_k L_l), \quad O_{ijkl}^{(4)} = \frac{1}{M^2} (\bar{e}_i^\dagger \bar{u}_j^\dagger)(Q_k Q_l),$$

(i, j, k, l) : flavor indices, M : an energy scale

FN charge dependence of operators

$$C_{ijkl}^{(1)} \propto \delta^{|-q(\bar{u}_i) - q(\bar{e}_j) - q(\bar{u}_k) - q(\bar{d}_l)|} \quad (\bar{u}_i^\dagger \bar{e}_j^\dagger)(\bar{u}_k^\dagger \bar{d}_l^\dagger)$$

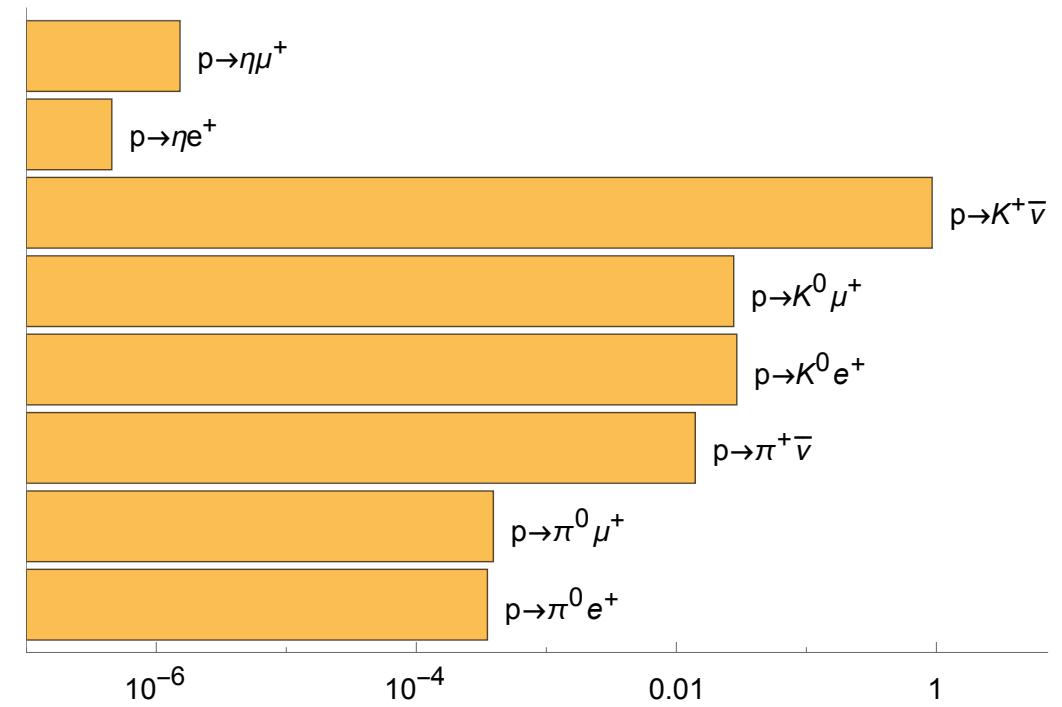
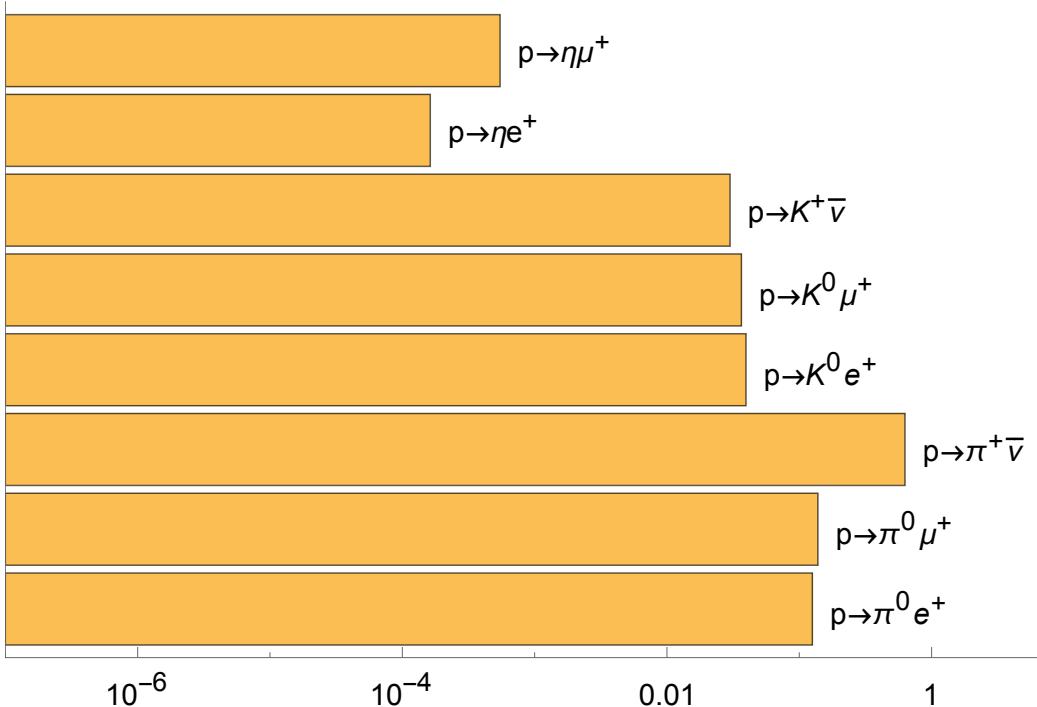
$$C_{ijkl}^{(2)} \propto \delta^{|q(Q_i) + q(Q_j) + q(Q_k) + q(L_l)|} \quad (Q_i Q_j)(Q_k L_l)$$

$$C_{ijkl}^{(3)} \propto \delta^{|-q(\bar{u}_i) - q(\bar{d}_j) + q(Q_k) + q(L_l)|} \quad (\bar{u}_i^\dagger \bar{d}_j^\dagger)(Q_k L_l)$$

$$C_{ijkl}^{(4)} \propto \delta^{|-q(\bar{e}_i) - q(\bar{u}_j) + q(Q_k) + q(Q_l)|} \quad (\bar{e}_i^\dagger \bar{u}_j^\dagger)(Q_k Q_l)$$

Branching fraction

$$(\bar{u}_i^\dagger \bar{d}_j^\dagger)(Q_k L_l)$$



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Summary

- The FN mechanism is a promising mechanism to explain the flavor puzzles
- We are searching for good FN charge assignments which can explain the flavor puzzles
- We need to find good FN charge assignments to search for new physics

Thank you for your attention!

Integral measure

$$A = U_L \Sigma U_R^\dagger \quad \Sigma = \text{diag}(\sigma_1, \sigma_2, \sigma_3)$$

$$\begin{aligned} & \prod_{i,j} d \operatorname{Re}(A_{ij}) d \operatorname{Im}(A_{ij}) \\ &= (\sigma_1^2 - \sigma_2^2)^2 (\sigma_2^2 - \sigma_3^2)^2 (\sigma_3^2 - \sigma_1^2)^2 d\sigma_1^2 d\sigma_2^2 d\sigma_3^2 \frac{dU_L dU_R}{d\phi_1 d\phi_2 d\phi_3} \end{aligned}$$

Prior function

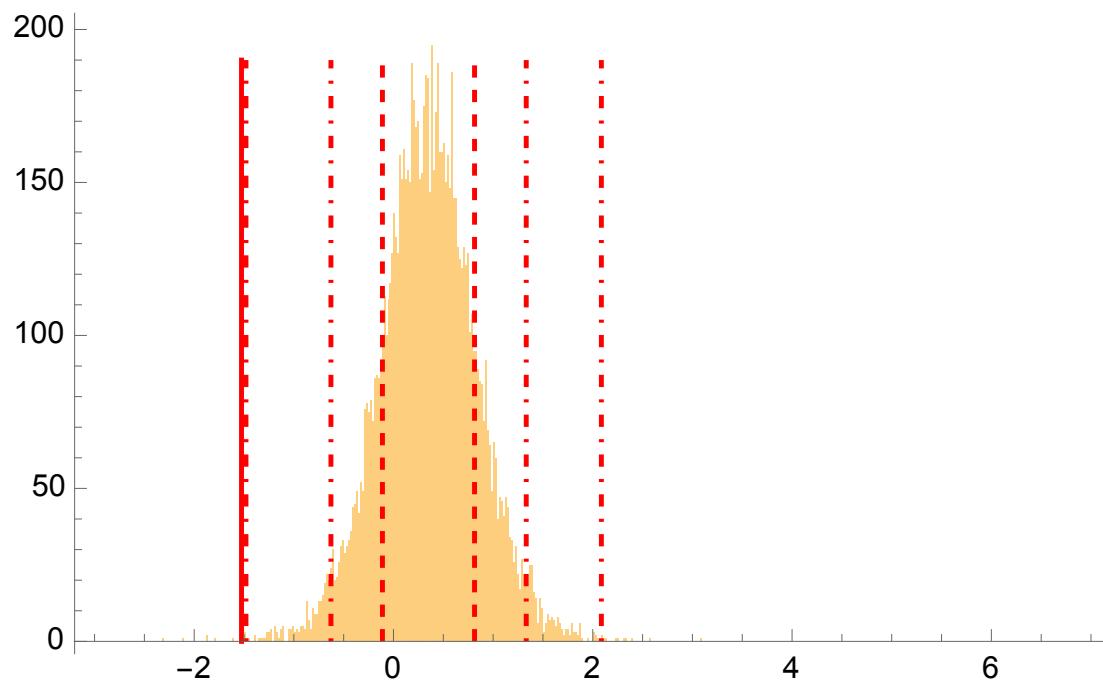
$$\begin{aligned}\pi(\kappa_u) &= \pi\left(y_u \circ \delta^{-|q_i+u_j|}\right) \\ &= \exp(-\text{tr}[\left(y_u \circ \delta^{-|q_i+u_j|}\right)^\dagger (y_u \circ \delta^{-|q_i+u_j|})]/2)\end{aligned}$$

$$y_u = U_{uL} \Sigma_u U_{uR}^\dagger, \quad \Sigma = \text{diag}(\sigma_{u1}, \sigma_{u2}, \sigma_{u3})$$

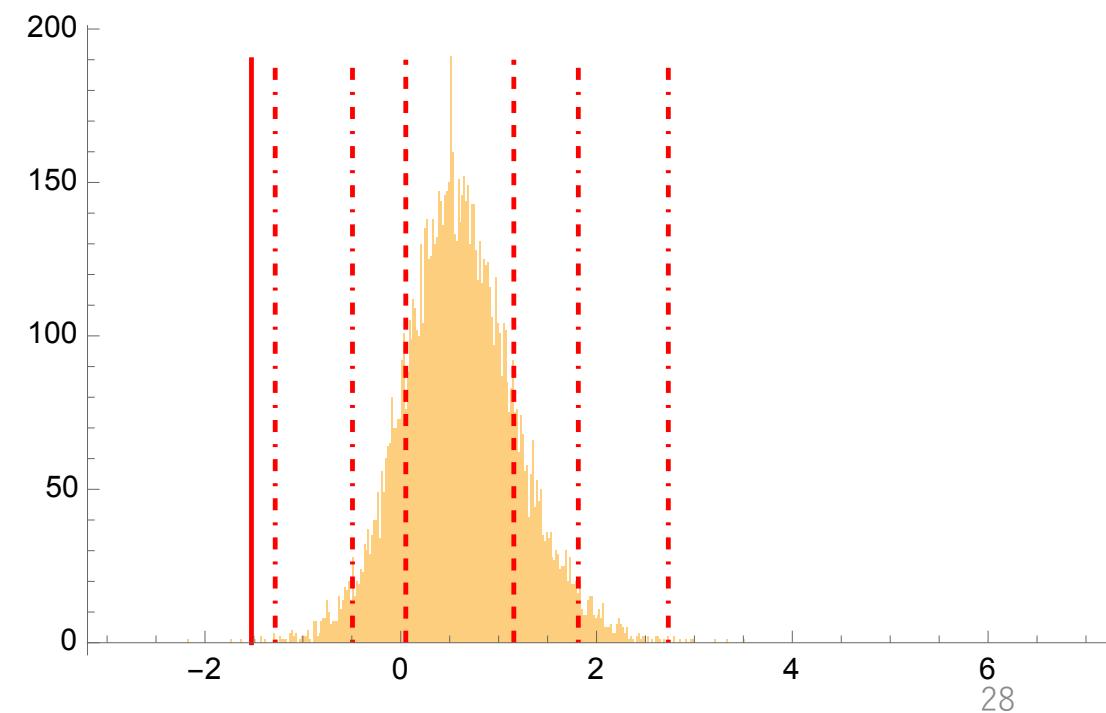
Neutrino ordering(inverted)

Histogram of $R (= \Delta m_{21}^2 / \Delta m_{13}^2)$

$$q(L) = (0, 0, 0)$$

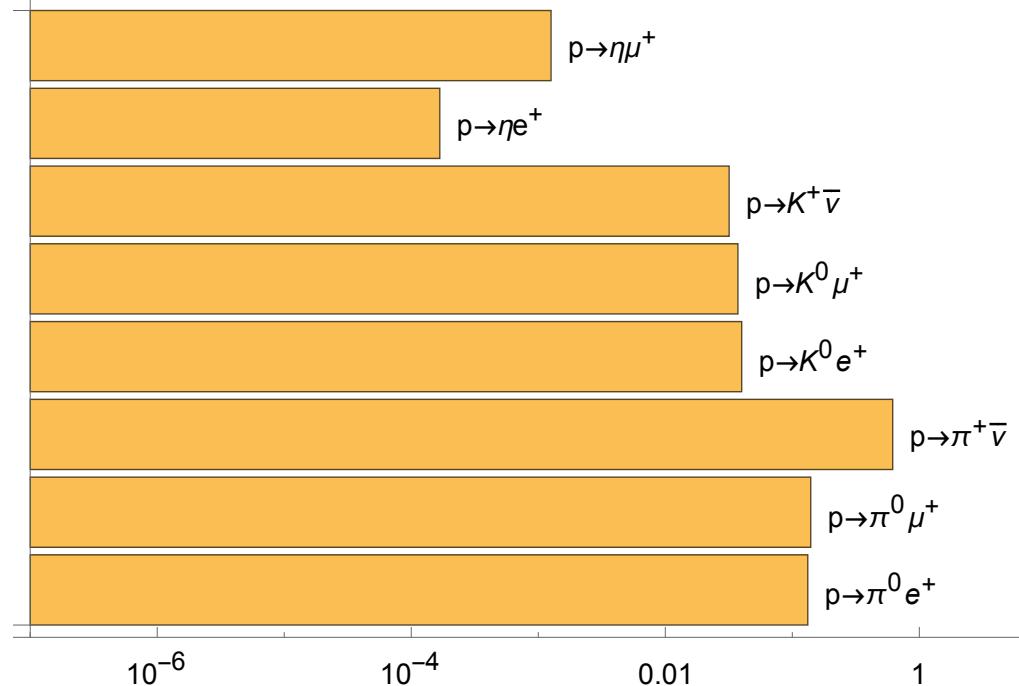


$$q(L) = (0, 0, 1)$$

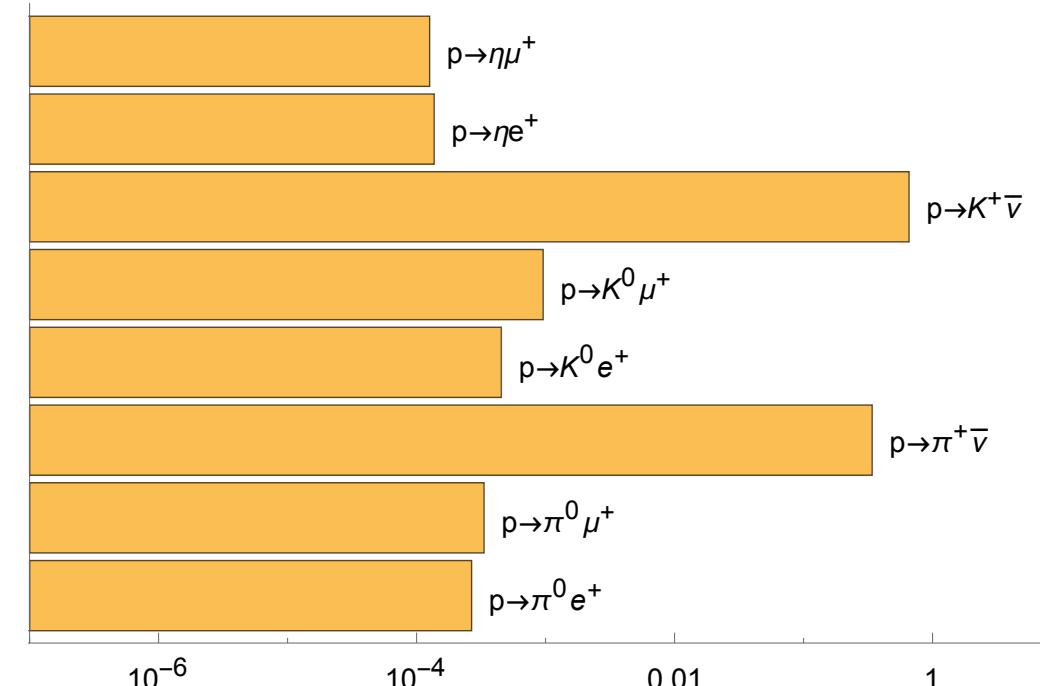


Branching fraction

$$(\bar{u}_i^\dagger \bar{d}_j^\dagger)(Q_k L_l)$$

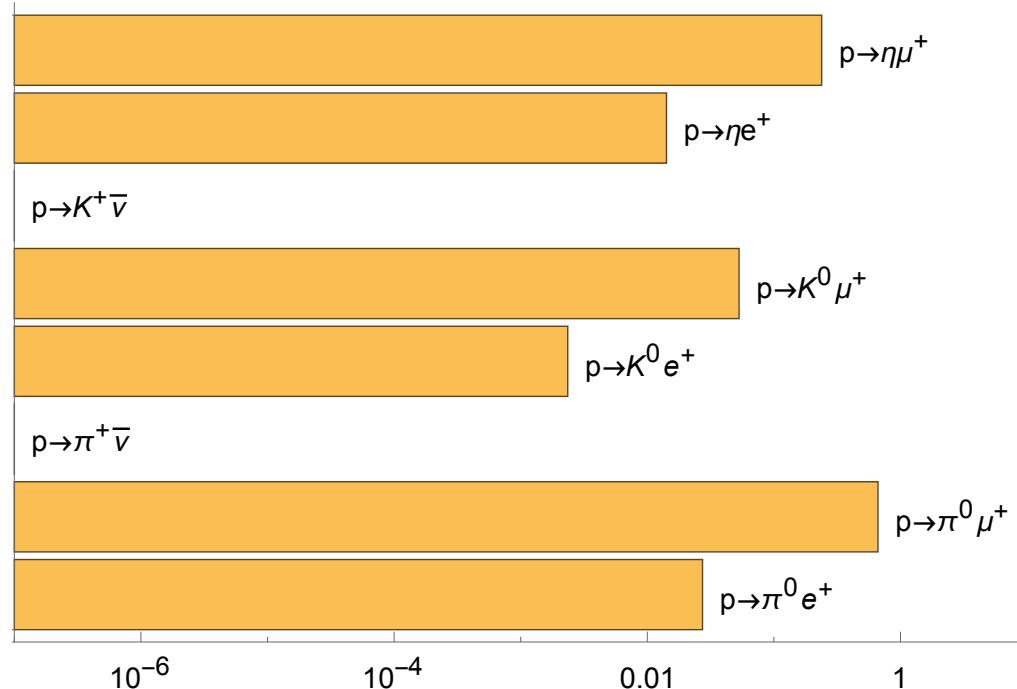


$$(Q_i Q_j)(Q_k L_l)$$



Branching fraction

$$(\bar{u}_i^\dagger \bar{e}_j^\dagger)(\bar{u}_k^\dagger \bar{d}_l^\dagger)$$



$$(\bar{e}_i^\dagger \bar{u}_j^\dagger)(Q_k Q_l)$$

