Sergio Tostado
Universidad Santiago de Cali

“MEZCLAS DE SABOR”

INICIOS

- 2010 — Cinvestav
- 2012 — Tesis de Maestría
- 2013–2017 — Doctorado

MATRIZ DE MEZCLA DE LOS QUARKS

Corriente cargada:

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

$$V_{\rm CKM} = V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- Unitaria

$$V_{CKM} V_{CKM}^\dagger = \mathbb{1}$$

- Violación CP

$$V_{CKM} \neq V_{CKM}^*$$

- Patrón jerárquico

$$s_{13} \ll s_{23} \ll s_{12} \ll 1$$

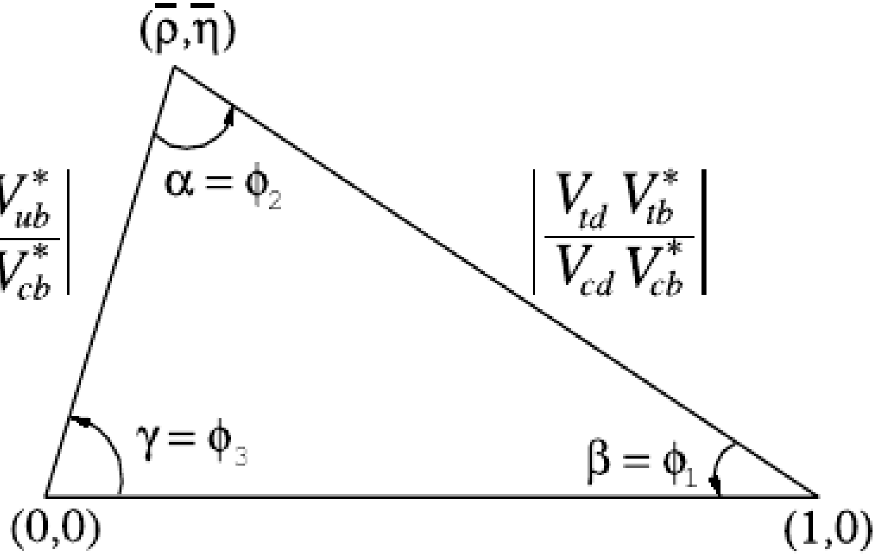
[Cabbibo, PRL 10, 531 (1963); Kobayashi and Maskawa, Prog. Theor. Phys. 49, 652 (1973)]

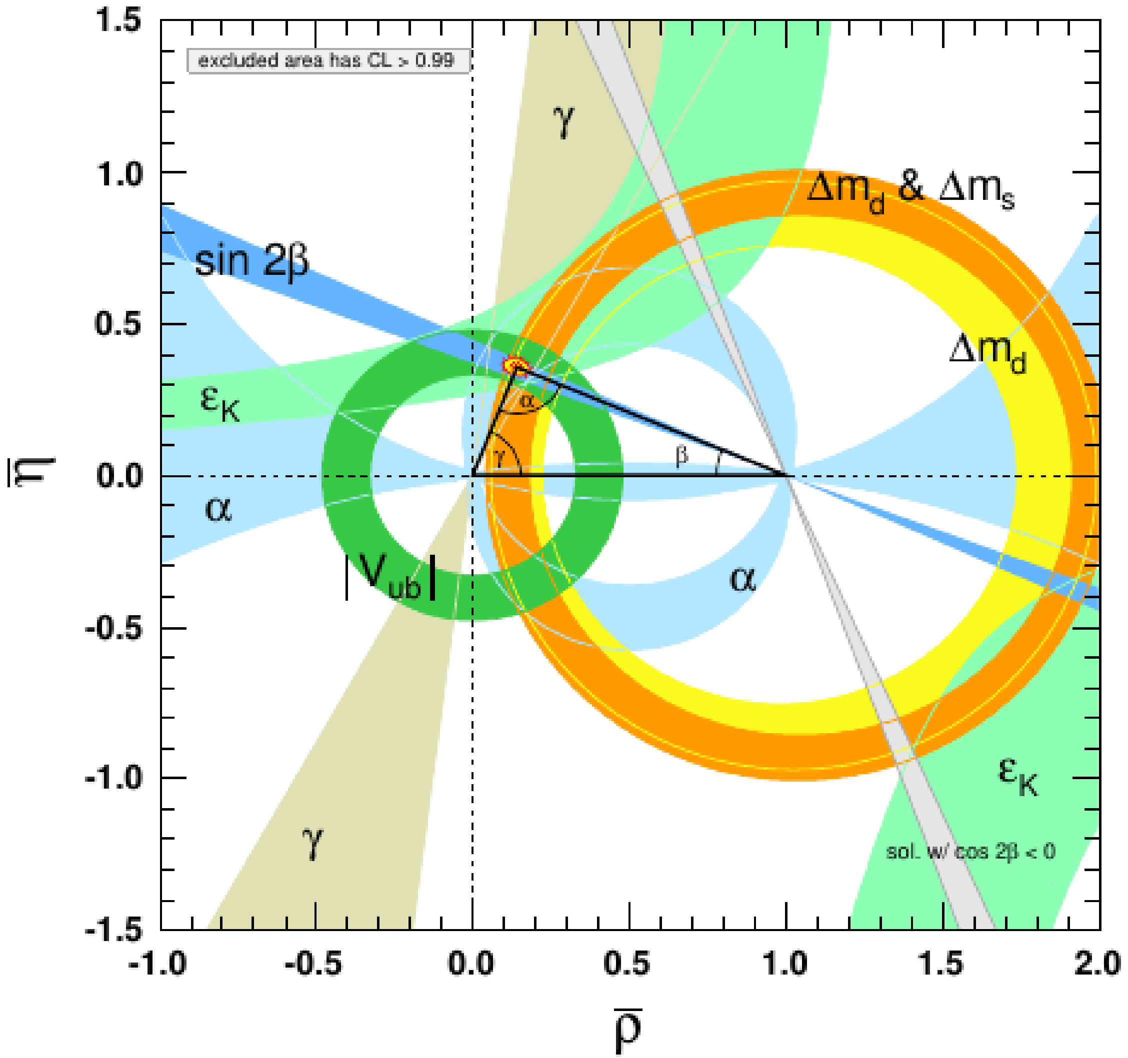
TRIÁNGULOS UNITARIOS

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

$$\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} + 1 + \frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}} = 0\,,$$

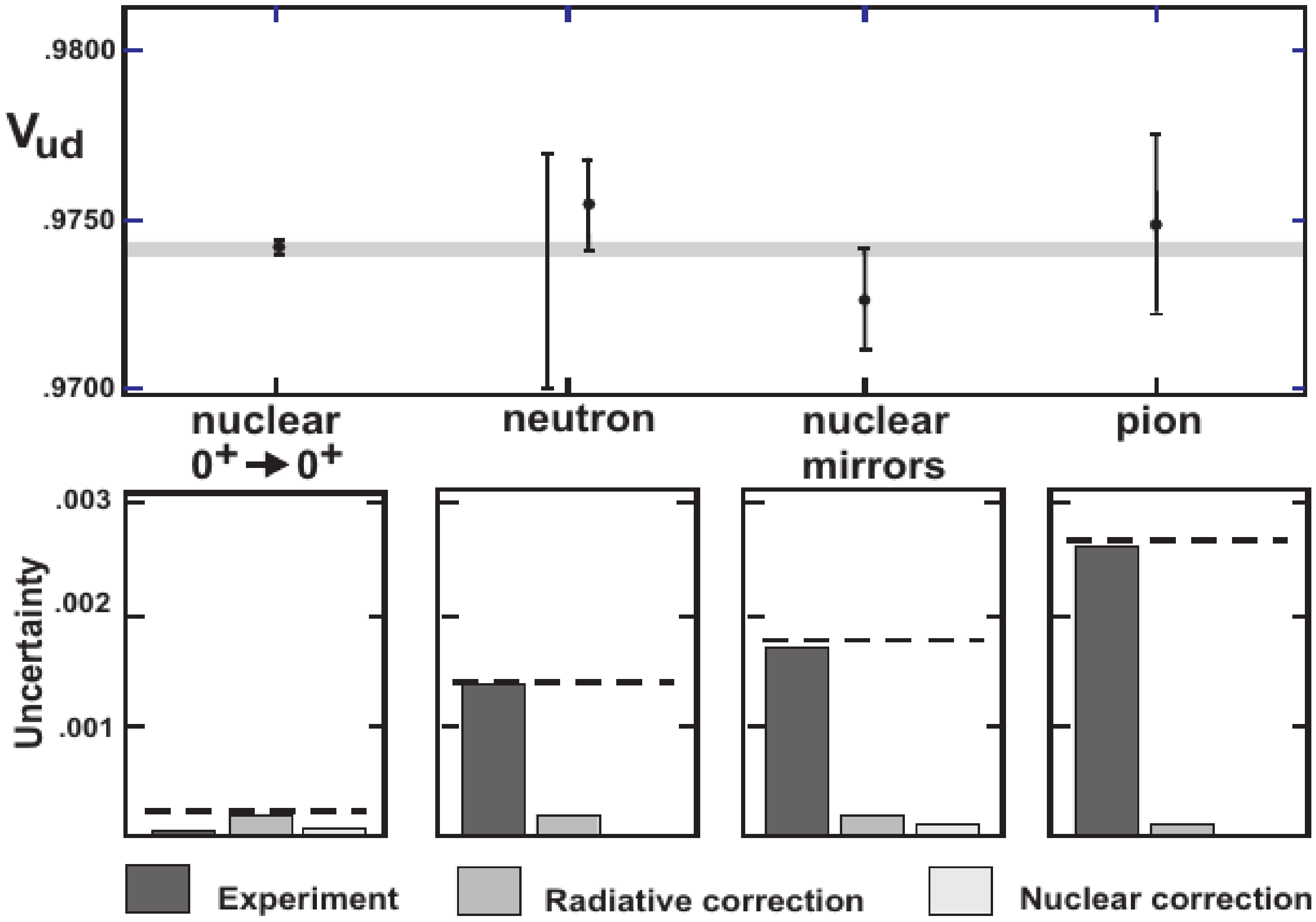
$$-(\bar{\rho} + i\bar{\eta}) + 1 - (1 - \bar{\rho}) + i\bar{\eta} = 0$$





P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2021) and 2021 update
1st December, 2021 8:52am

CORRECCIONES RADIATIVAS



Hardy and Towner, CIPANP 2018 (arXiv: 1807.01146)

Neutrón

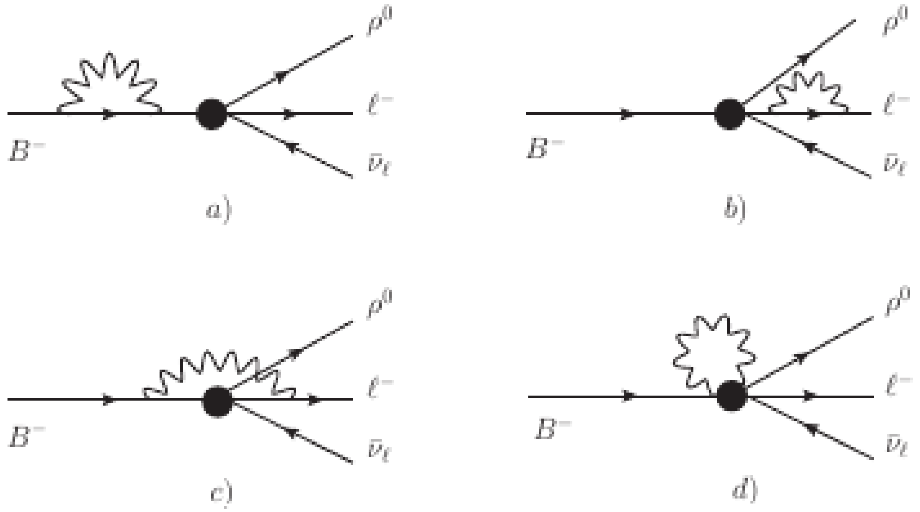
$$\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{\rm ud}|^2}{2\pi^3} m_e^5 \left(1 + 3g_A^2\right)\left(1 + \rm{RC}\right) f$$

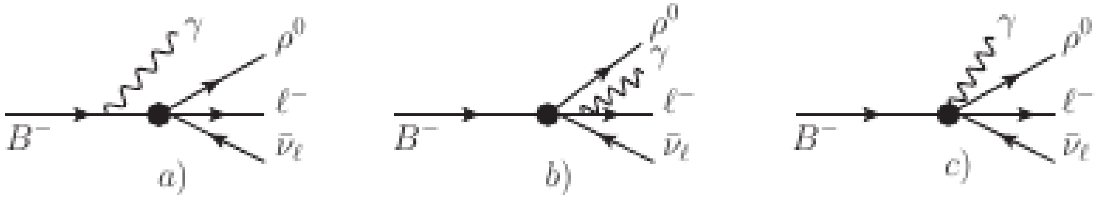
Czarnercki, Marciano and Sirlin *PRD* 100 (2019) 7, 073008

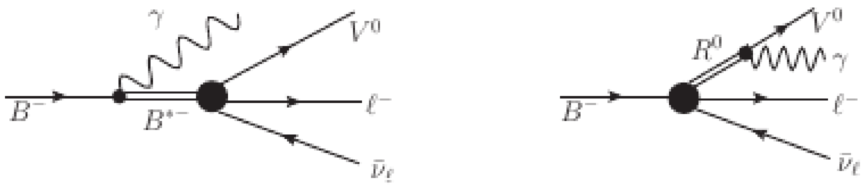
- Incertidumbres: factores de forma y del tiempo de vida
- Resultados más precisos para el neutrón → Factorizar adecuadamente las RC (~1%)

ST, Tesis de Maestría, Cinvestav 2011.

CORRECCIONES RADIATIVAS: Vub, Vcb







$$B^- \to (\rho^0, \omega)\ell^- \bar{\nu}_\ell$$

$$\delta_T^1(\ell) = \begin{cases} (1.62 \pm 0.10 \pm 0.04)\% \,, & \text{for } \ell = \mu \\ (1.63 \pm 0.11 \pm 0.04)\% \,, & \text{for } \ell = e \end{cases}$$

$$B^- \to D^{*0}\ell^- \bar{\nu}$$

$$\delta_T^1(\ell) = \begin{cases} (1.53 \pm 0.06 \pm 0.04)\%, & \text{for } \ell = \mu \\ (1.53 \pm 0.08 \pm 0.04)\%, & \text{for } \ell = e \end{cases}$$

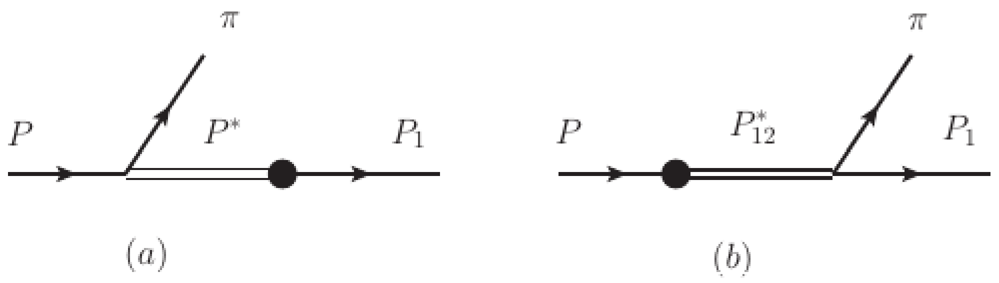
hasta 10% en Dalitz Plot

- **Importante para extracción precisa de FFs**

G. López-Castro and ST, EPJC 76, 495 (2016)

OTRAS CORRECCIONES

$$P \to P_2 P^* \to P_1 P_2 \ell \nu_\ell$$



$$|V_{ub}| = \sqrt{\frac{B(B \to (\pi\pi)_\rho \ell \nu_\ell)}{\tau_B \cdot \Delta\zeta \cdot (1 + \delta_{P^*}) B(\rho \to \pi\pi)}}$$

Neutro (cargado)

$\delta_{B^*} = 1.7\ (6.4)\%$

δ_{D^*} =1.9(8.2)%

$$|V_{ub}| = (3.73 \pm 0.30) \times 10^{-3}$$

$$|V_{cd}|_{\rho + D^*} = 0.224 \pm 0.011$$

$|V_{cb}|$ Sin cambios

Incertidumbre dominada por los factores de forma

C.S. Kim, G. López-Castro, ST, PRD 95, 073003 (2017)

PANORAMA ACTUAL

$$V_{\rm CKM} = \begin{pmatrix} 0.97401 \pm 0.00011 & 0.22650 \pm 0.00048 & 0.00361^{+0.00011}_{-0.00009} \\ 0.22636 \pm 0.00048 & 0.97320 \pm 0.00011 & 0.04053^{+0.00083}_{-0.00061} \\ 0.00854^{+0.00023}_{-0.00016} & 0.03978^{+0.00082}_{-0.00060} & 0.999172^{+0.000024}_{-0.000035} \end{pmatrix}$$

$$\lambda = 0.22650 \pm 0.00048\,, \qquad A = 0.790^{+0.017}_{-0.012}\,,$$
$$\bar\rho = 0.141^{+0.016}_{-0.017}\,, \qquad \bar\eta = 0.357 \pm 0.011\,.$$

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2021) and 2021 update
1st December, 2021 8:52am

MEZCLA DE NEUTRINOS

La corriente cargada:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \overline{(e \quad \mu \quad \tau)_L} \gamma^\mu U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} W_\mu^- + h.c.$$

- $U_\nu^\dagger M_\nu U_\nu^* = \text{Diag}(m_1, m_2, m_3) \equiv M_\nu^{diag}$
- U_ℓ esta asociada con la diagonalización M_ℓ.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad \begin{matrix} m_1 \\ m_2 \\ m_3 \end{matrix}$$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} P_\nu .$$

$c_{ij} \equiv \cos\theta_{ij}, s_{ij} \equiv \sin\theta_{ij}$

Fases de Majorana

$$P_\nu = Diag(e^{-i\frac{\beta_1}{2}}, e^{-i\frac{\beta_2}{2}}, 1).$$

B. Pontecorvo, Zh. Eksp. Teor. Fiz. 33 (1957) 549, and 34 (1958) 247.
Z. Maki, M. Nakagawa, S. Sakata, Prog. Theor. Phys. 28 (1962) 870.
B. Pontecorvo, Sov. Phys. JETP 26 (1968) 984, Zh. Eksp. Teor. Fiz. 53 (1967) 1717.

SIMETRIA MU-TAU

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Primeros Experimentos → $U_{PMNS}|_{\theta_{13}=0,\ \theta_{23}=45^\circ}$

$$U = U^{\mu-\tau} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ \frac{-s_{12}}{\sqrt{2}} & \frac{c_{12}}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ \frac{-s_{12}}{\sqrt{2}} & \frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \quad |U_{\mu i}| = |U_{\tau i}|$$

Dado que: $M\nu = U M_\nu^{diag} U^T$.

$$M_\nu^{\mu-\tau} = \begin{pmatrix} m_1 c_{12}^2 + m_2 s_{12}^2 & (m_2 - m_1)\frac{s2_{12}}{\sqrt{8}} & (m_2 - m_1)\frac{s2_{12}}{\sqrt{8}} \\ (m_2 - m_1)\frac{s2_{12}}{\sqrt{8}} & \frac{1}{2}(m_1 s_{12}^2 + m_2 c_{12}^2 + m_3) & \frac{1}{2}(m_1 s_{12}^2 + m_2 c_{12}^2 - m_3) \\ (m_2 - m_1)\frac{s2_{12}}{\sqrt{8}} & \frac{1}{2}(m_1 s_{12}^2 + m_2 c_{12}^2 - m_3) & \frac{1}{2}(m_1 s_{12}^2 + m_2 c_{12}^2 + m_3) \end{pmatrix}$$

$M_\nu^{\mu-\tau}$ invariante ante el intercambio de etiquetas $\nu_\mu \leftrightarrow \nu_\tau$.

DESVIACIONES AL PATRÓN TBM

Cuando $\sin^2\theta_{12} = 1/3$

$$U_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

Se puede de generar en algunas extensiones del ME.

S.T. Petcov, Nucl. Phys. B 892 (2015) 400.
P.P. Novichkov, et.al.,PLB 793 (2019) 247.

Se han explorado algunas correcciones de la forma

$$U_{\text{PMNS}} = U_{TBM} U_{\text{Corr}}$$

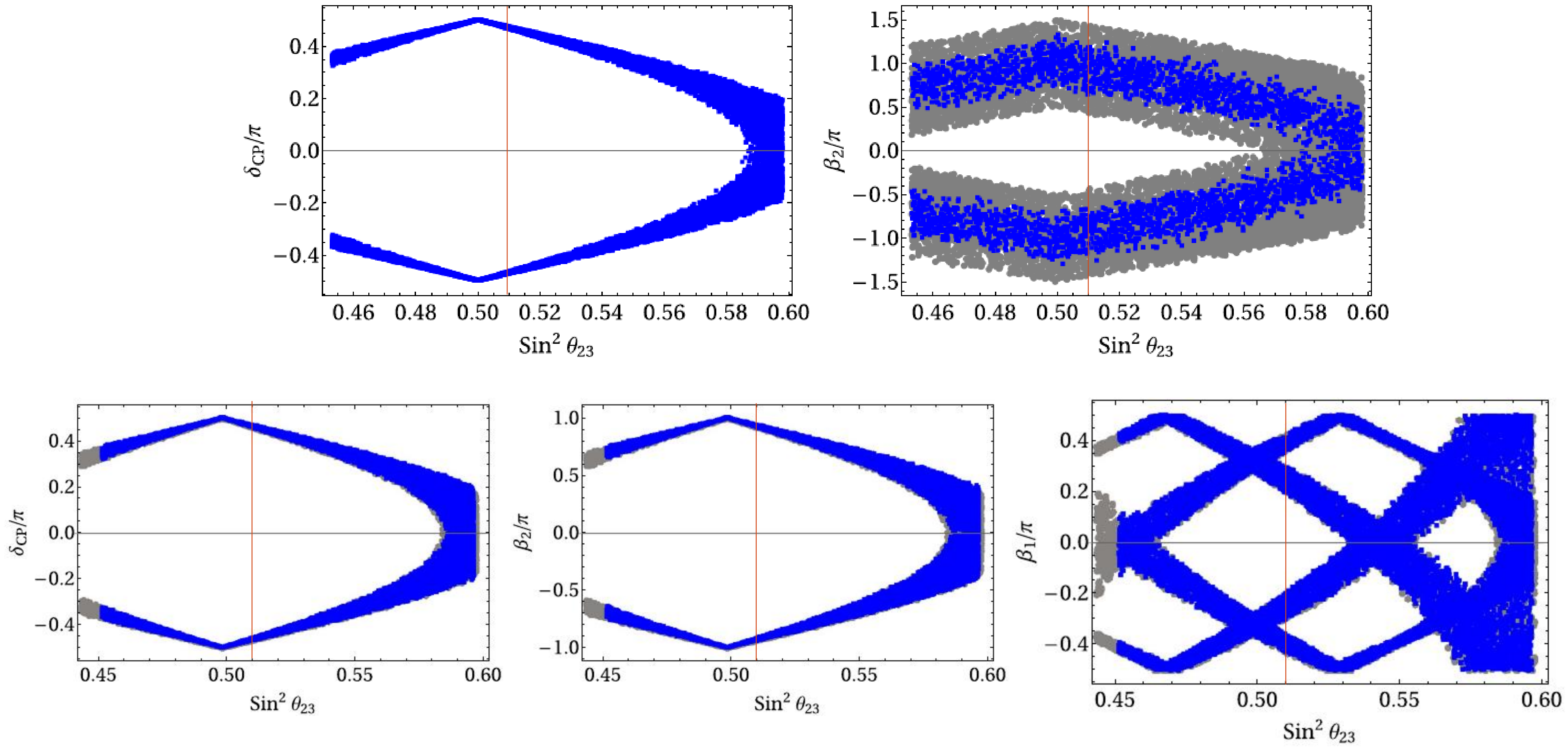
Ucorr Real:

S.K. Garg, S. Gupta,J. High Energy Phys. 10 (2013) 128.
Y. Shimizu, M. Tanimoto, K. Yamamoto, Mod. Phys. Lett. A 30 (2015) 1550002.

Ucorr Compleja (fases CP Majorana)

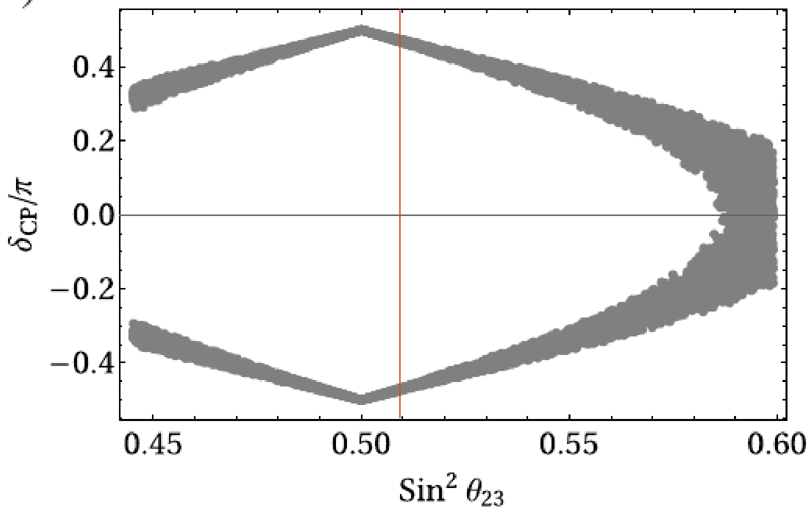
D.C. Rivera-Agudelo, A. Pérez-Lorenzana, ST, PLB 794, 89(2019).
D.C. Rivera-Agudelo, ST, NPB 965, 115359 (2021).

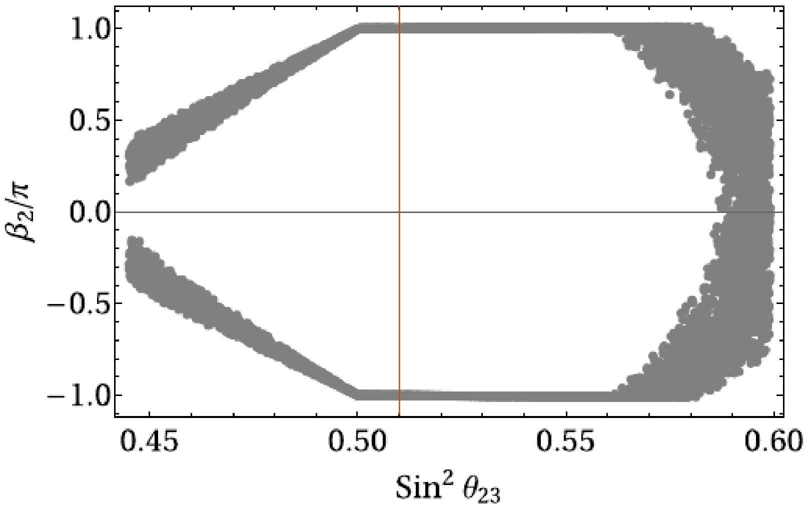
$U_{12}(\phi, \sigma)U_{13}(\phi', \sigma')$



$\sigma' = 0$

$U_{12}(\phi, \sigma) U_{13}(\phi', \sigma')$

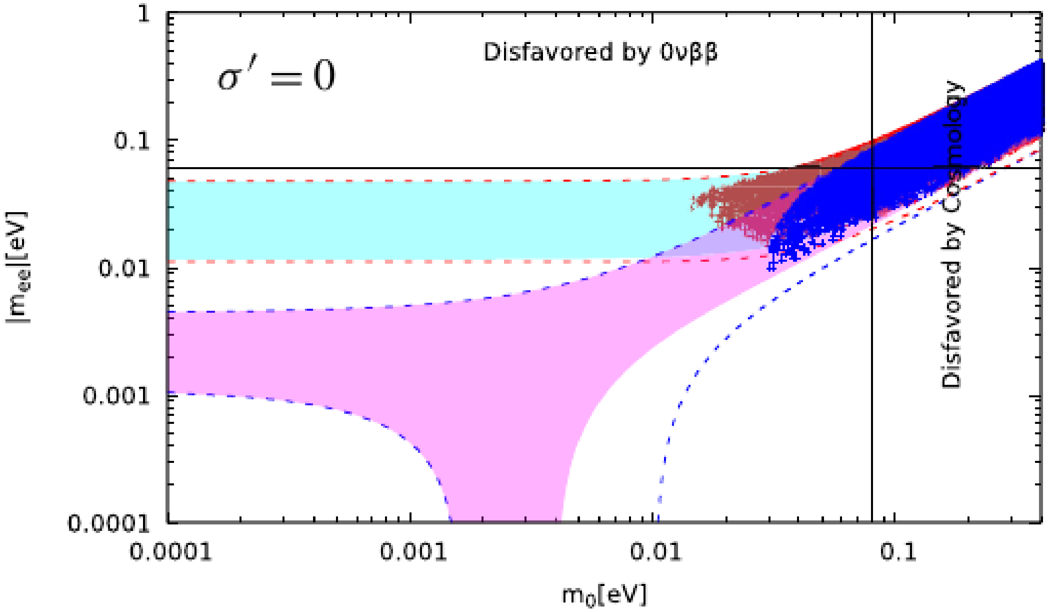


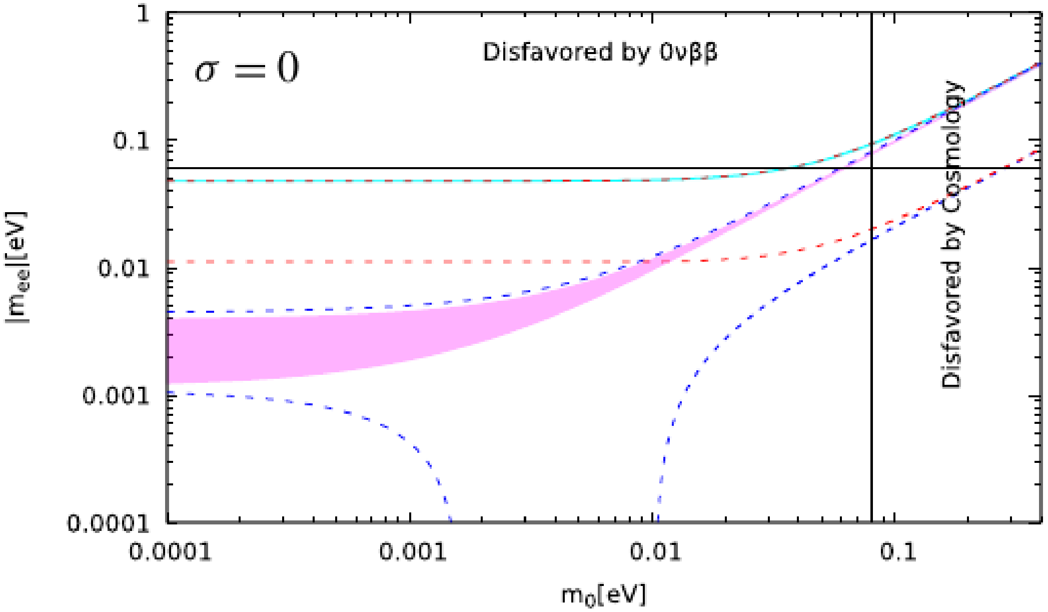


$\beta_1 = 0$

$0\nu\beta\beta$

$$m_{ee} = \left| \sum_i m_i U_{ei}^2 \right|$$

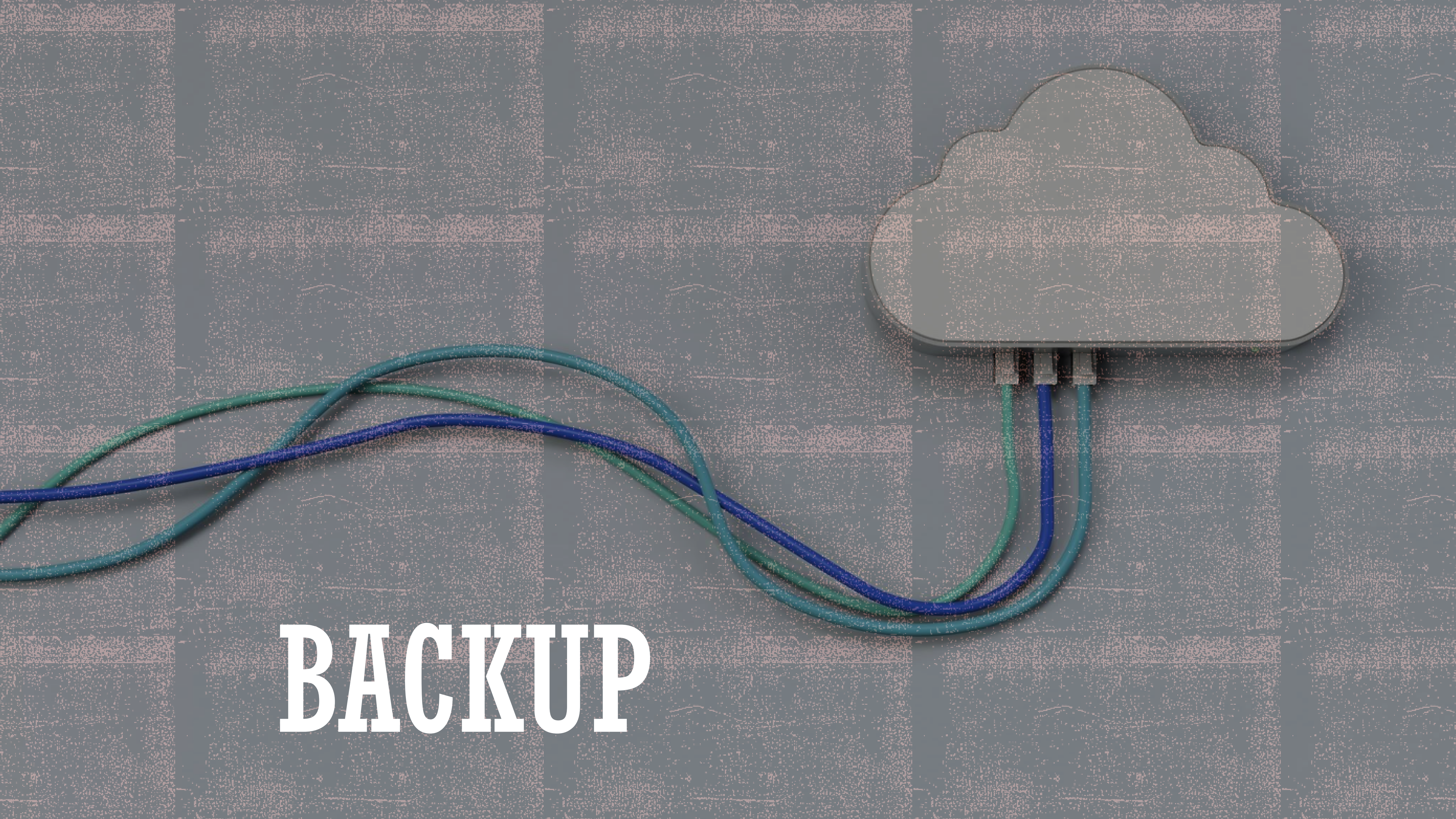




CONCLUSIONES Y PERSPECTIVAS

- Las pruebas de precisión en el sector de mezclas son indispensables en las búsquedas indirectas de nueva física.
- Los patrones de masas y mezclas de quarks y leptones se pueden relacionar en algunos modelos de sabor.
- Hay fuentes de violación CP adicionales en el sector de neutrinos.

GRACIAS

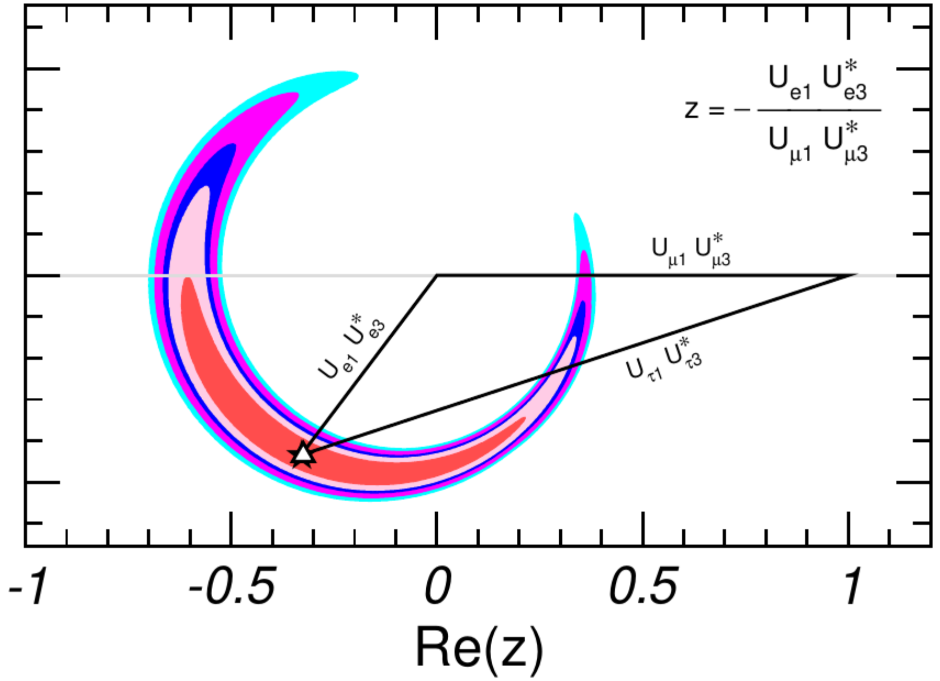

BACKUP

ESTATUS DE LOS NEUTRINOS

	Ref. [188] w SK-ATM			
	Best Fit Ordering (NO)		IO	
Param	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.63^{+0.18}_{-0.24}$	$4.33 \to 6.09$	$5.65^{+0.17}_{-0.22}$	$4.36 \to 6.10$
$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.237^{+0.066}_{-0.065}$	$2.044 \to 2.435$	$2.259^{+0.065}_{-0.065}$	$2.064 \to 2.457$
$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$
$\delta_{CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$	$2.454^{+0.029}_{-0.031}$	$2.362 \to 2.544$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$

NO

IO



I. Esteban *et al.*, JHEP **01**, 106 (2019), [arXiv:1811.05487].

I. Esteban *et al.*, "Nufit4.1 at nufit webpage," http://www.nu-fit.org.

RELACIÓN CON LOS PARÁMETROS DE MEZCLA

$$\sin^2\theta_{12} = \frac{|U_{e2}|^2}{1-|U_{e3}|^2}, \qquad \sin^2\theta_{23} = \frac{|U_{\mu 3}|^2}{1-|U_{e3}|^2}, \qquad \sin^2\theta_{13} = |U_{e3}|^2$$

Invariantes de CP:

$$\begin{aligned} J_{CP} &= \mathrm{Im}\left[U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}\right] \\ &= (1-s^2\theta_{13})\sqrt{s^2\theta_{13}s^2\theta_{12}s^2\theta_{23}(1-s^2\theta_{12})(1-s^2\theta_{23})}\,\sin\delta_{CP} \end{aligned}$$

$$\begin{aligned} I_1 &= \mathrm{Im}\left[U^2_{e2}U^{*2}_{e1}\right] = -\cos^2\theta_{12}\cos^4\theta_{13}\sin^2\theta_{12}\sin\beta_1\ , \\ I_2 &= \mathrm{Im}\left[U^2_{e3}U^{*2}_{e1}\right] = -\cos^2\theta_{12}\cos^2\theta_{13}\sin^2\theta_{13}\sin(\beta_2+2\delta_{CP}) \end{aligned}$$

Desviaciones en la matriz de masa

$$M_\nu = M_{\mu-\tau} + \delta M\,(\delta, \epsilon)$$

$$\hat{\delta} \equiv \frac{\delta}{m_{e\mu}} = \frac{\sum_i (U_{ei}U_{\tau i} - U_{ei}U_{\mu i})m_i}{\sum_i U_{ei}U_{\mu i}m_i} \,,$$

$$\hat{\epsilon} \equiv \frac{\epsilon}{m_{\mu\mu}} = \frac{\sum_i (U_{\tau i}U_{\tau i} - U_{\mu i}U_{\mu i})m_i}{\sum_i U_{\mu i}U_{\mu i}m_i} \,.$$

Lo parámetros de rompimiento dependen del ordenamiento de masas.

$$|m_2| = \sqrt{m_0^2 + \Delta m_{21}^2} \,, \quad |m_3| = \sqrt{m_0^2 + |\Delta m_{31}^2|} \text{ for NH,}$$

$$|m_1| = \sqrt{m_0^2 + |\Delta m_{31}^2|} \,, \quad |m_2| = \sqrt{m_0^2 + |\Delta m_{31}^2| + \Delta m_{21}^2} \text{ for IH}$$

Solar

$$\Delta m_{21}^2 = m_2^2 - m_1^2$$

Atmosférica

$$\Delta m_{31}^2 = m_3^2 - m_1^2$$

Vus

Decay Mode	$\lvert V_{us}\rvert f_+(0)$
$K^{\pm}e3$	0.21714 ± 0.00091
$K^{\pm}\mu3$	0.21703 ± 0.00114
$K_L e3$	0.21617 ± 0.00047
$K_L \mu3$	0.21664 ± 0.00058
$K_S e3$	0.21530 ± 0.00122
$K_S \mu3$	0.21265 ± 0.00467
Average (including correlation effects [44])	0.21635 ± 0.00038

$$|V_{us}| = 0.2244(5)$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(6)(4)$$

$$|V_{ub}| = (4.13 \pm 0.12 \,{}^{+\,0.13}_{-\,0.14} \pm 0.18) \times 10^{-3} \quad \text{(inclusive)},$$

$$|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3} \quad \text{(exclusive)},$$

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \quad \text{(inclusive)}$$

$$|V_{cb}| = (39.4 \pm 0.8) \times 10^{-3} \quad \text{(exclusive)}.$$

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2021) and 2021 update
1st December, 2021 8:52am

$P \to V$ and $P^* \to P_1$ Form Factors

$$F_i(q^2) = \frac{F_i(0)}{1 - q^2/m_i^2(J^P)} .$$

Transition	$A'_0(0)$	$A'_1(0)$	$A'_2(0)$	$V'(0)$	$m(0^-)$	$m(1^-)$	$m(1^+)$
$D^* \to K$ [139]	0.78	1.02	0.40	0.90	1.97	2.11	2.53
$D^* \to \pi$ [139]	0.75	1.08	0.37	0.76	1.87	2.01	2.42
$B^* \to \pi$ [170]	0.34	0.38	0.29	0.34	5.27	5.32	5.71
$B^* \to D$ [170]	0.63	0.66	0.56	0.70	6.30	6.34	6.73

Table 5.1. Form factors of the weak transition $P^* \to P_1$ at $q^2 = 0$ in the Wirbel-Stech-Bauer model [153, 154]. Values of pole masses are given in GeV units.

$B \to \rho$ **Lattice**

UKQCD Collaboration, L. Del Debbio, J. M. Flynn, L. Lellouch, and . Nieves, Phys. Lett. **B416** (1998) 392–401.

$D \to K^*$ and $D \to \rho$ **Experiment**

BESIII Collaboration, M. Ablikim *et al.*, Phys. Rev. **D94** (2016) 032001.