Flavour Physics & CP Violation

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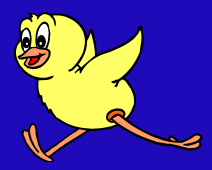
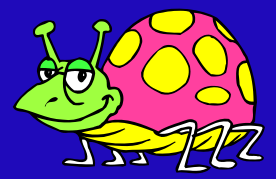
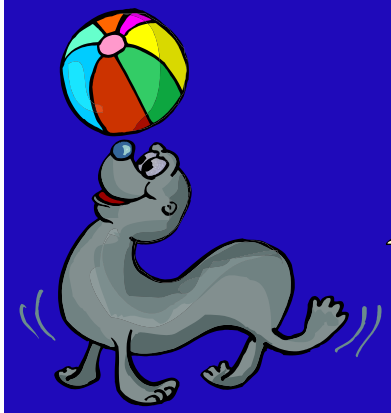
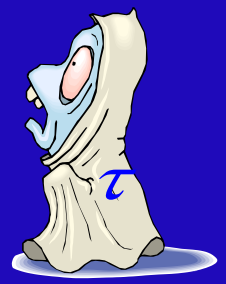
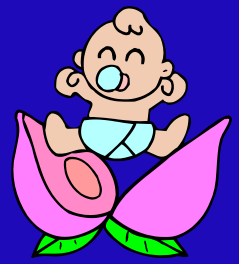
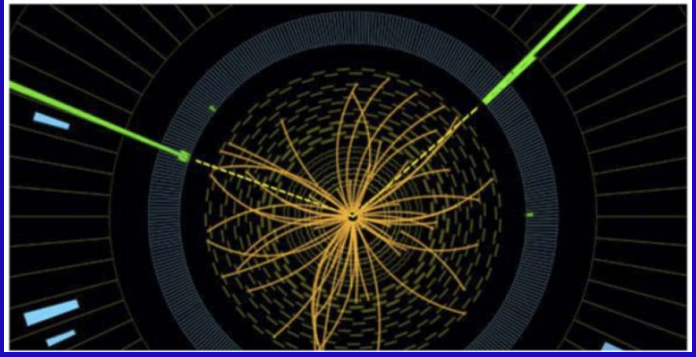
arXiv:1112.4094

2012 School of
High-Energy Physics
(TAE 2012)
Madrid, 16 – 27 July 2012

Quarks		Leptons		Bosons
 up	 down	 electron	 neutrino e	 photon
 charm	 strange	 muon	 neutrino μ	 gluon
 top	 beauty	 tau	 neutrino τ	 Z^0 $W^{\pm}$
				 Higgs

New particle found, consistent with Higgs boson: CERN

ArabNews



BBC NEWS

SCIENCE & ENVIRONMENT

4 July 2012 Last updated at 07:35 GMT

Higgs boson-like particle discovery LHC

El portavoz de la Conferencia Episcopal: "Bienvenida sea la partícula de Dios"

'La partícula de Dios' no derrumbará la teología, según los obispos

La Conferencia Episcopal Española manifiesta que el posible descubrimiento de la existencia del Bosón de Higgs no supondrá ningún dogma a la doctrina de la Iglesia.

EUROPA PRESS,

FINANCIAL TIMES

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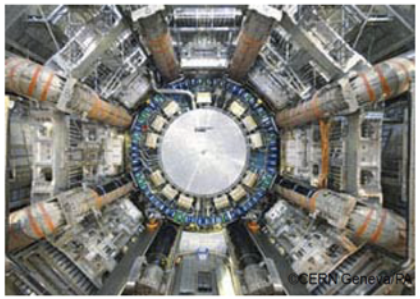
Last updated: July 4, 2012 11:18 pm

Scientists bask in 'god particle' discovery

By Clive Cookson, Science Editor



The most anticipated discovery in the history of physics – known officially as the Higgs boson and informally as the god particle – has been announced at Cern, the European nuclear physics centre near Geneva.

Two scientific teams have detected a subatomic particle that matches the predicted characteristics of the Higgs, after analysing the debris of trillions of collisions at the $8bn Large Hadron Collider (LHC), the world's most powerful atom smasher.

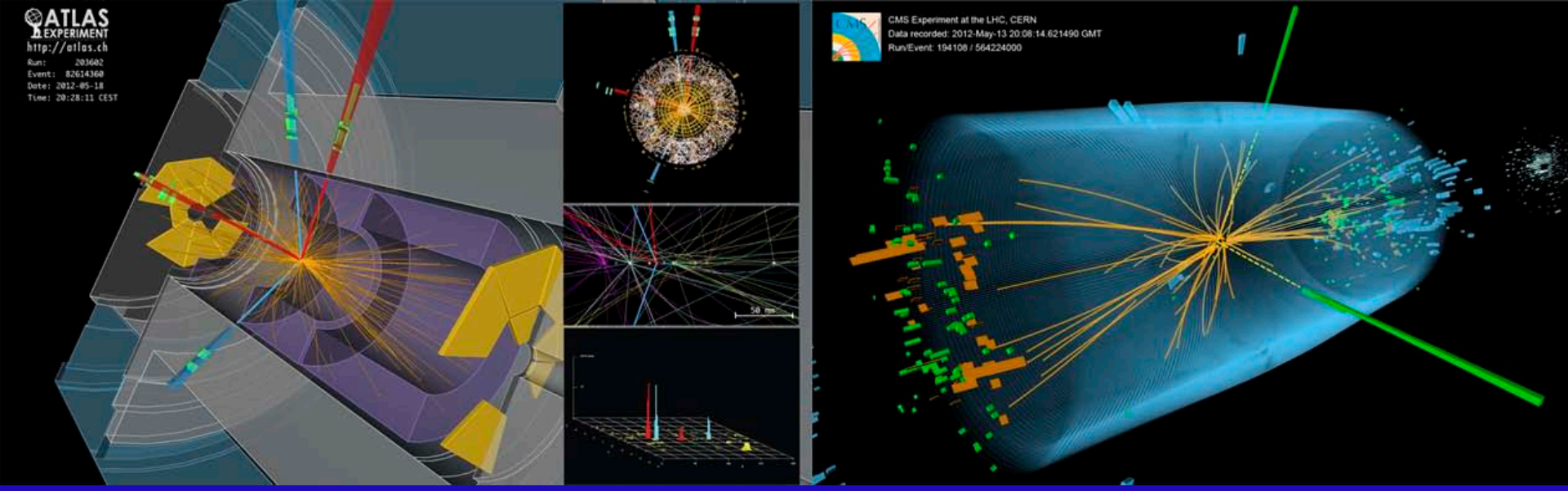
中国日报网 Wed, July 11, 2012

CHINADAILY Europe

Higgs boson-like 'God particle' discovered

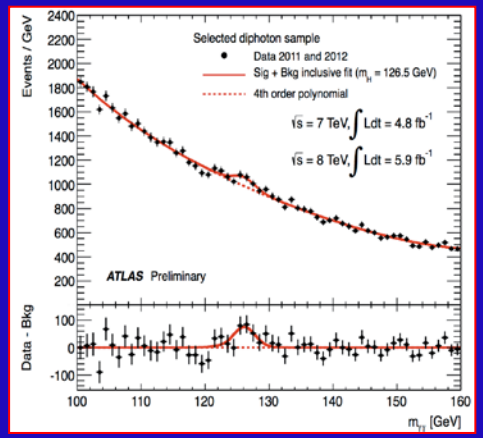
Updated: 2012-07-07 08:08

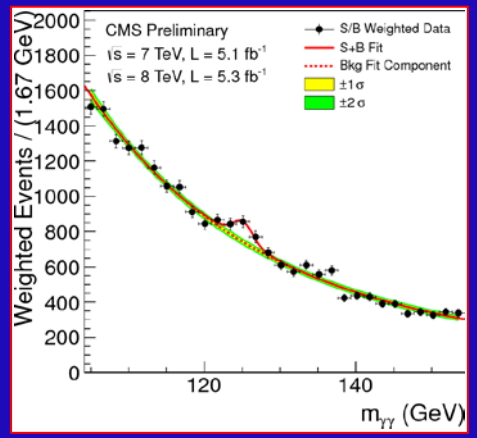
(Agencies in London and Beijing)

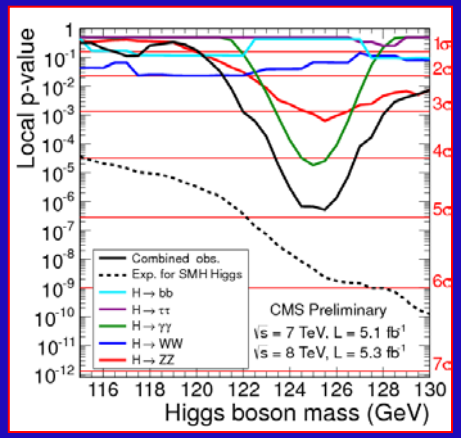


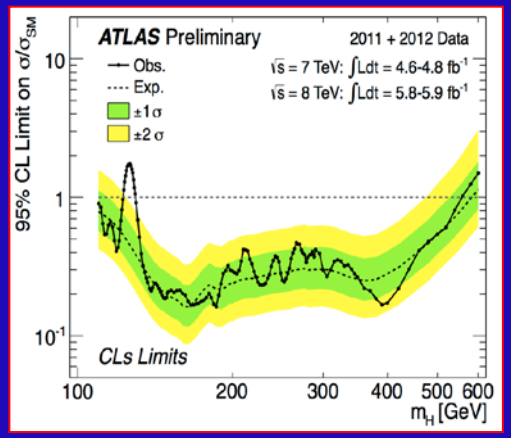
A boson with $M_H = 125$ GeV and $J \neq 1$

5.0 σ both ATLAS & CMS

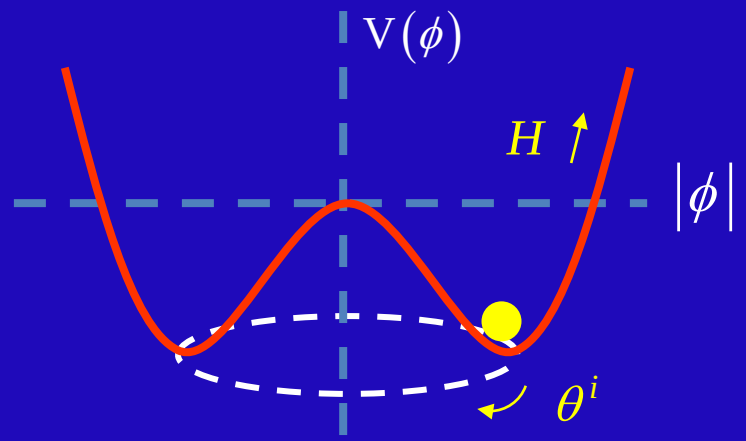






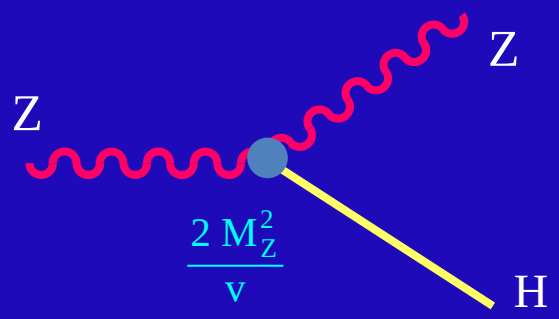


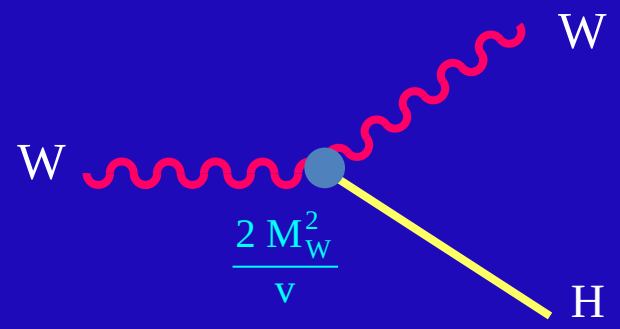
HIGGS MECHANISM



$$\phi(x) \;=\; \exp\left\{ i\,\frac{\vec{\tau}}{2}\cdot\vec{\theta}\,(x)\right\}\;\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \mathrm{v} + H(x)\end{pmatrix}$$

$$(\mathrm{D}_\mu\phi)^\dagger\,\mathrm{D}^\mu\phi \;\;\rightarrow\;\; \frac{1}{2}\,\partial_\mu H\,\partial^\mu H \;+\; \frac{g^2}{4}\,(\mathrm{v}+H)^2\left\{ W^\dagger_\mu W^\mu + \frac{1}{2\cos^2\theta_W}\,Z_\mu Z^\mu\right\}$$





$$M_Z\;\cos\theta_W \;=\; M_W \;=\; \frac{1}{2}\,\mathrm{v}\,g$$

Massive Gauge Bosons

Flavour Structure of the Standard Model

$$\begin{pmatrix} u & \nu_e \\ d & e^- \end{pmatrix}, \begin{pmatrix} c & \nu_\mu \\ s & \mu^- \end{pmatrix}, \begin{pmatrix} t & \nu_\tau \\ b & \tau^- \end{pmatrix}$$

Why 3 ?

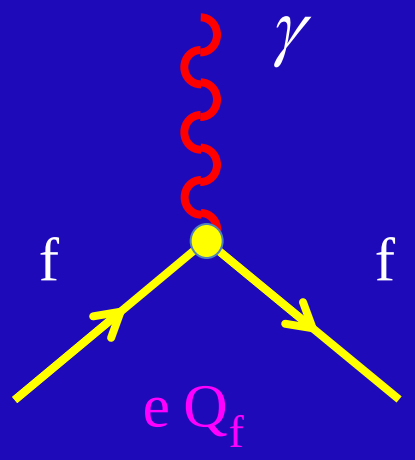
- Pattern of masses
- Flavour Mixing
- $\not{CP}$

$\Longleftrightarrow$

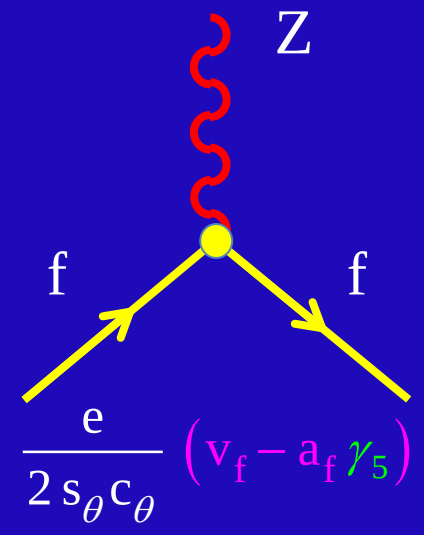
Related to SSB

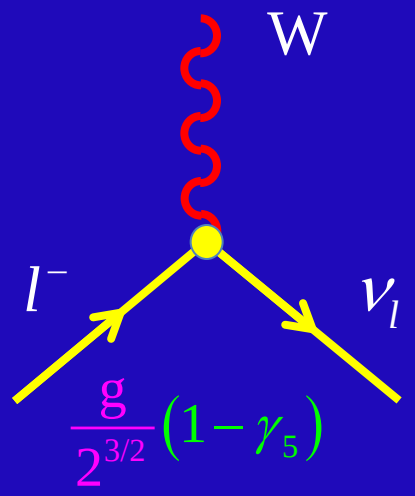
Scalar Sector (Higgs)

- **Kaon Factories :** u , d , s
- **τcF :** c , τ
- **BF, SuperB :** b , c , τ
- **LHC :** t , b
- **LC :** t , ...
- **νF :** ν_e , ν_μ , ν_τ

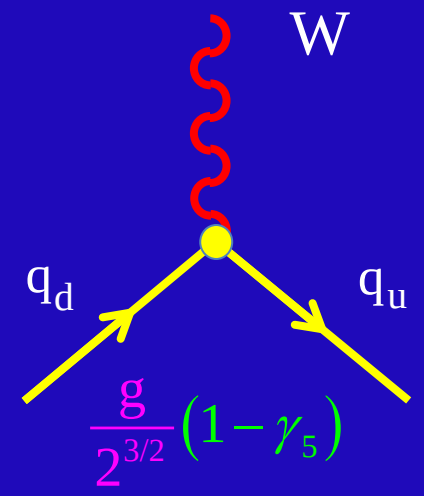


NEUTRAL CURRENTS





CHARGED CURRENTS



Three Families $\begin{bmatrix} \nu_e & u \\ e^- & d' \end{bmatrix} , \begin{bmatrix} \nu_\mu & c \\ \mu^- & s' \end{bmatrix} , \begin{bmatrix} \nu_\tau & t \\ \tau^- & b' \end{bmatrix}$

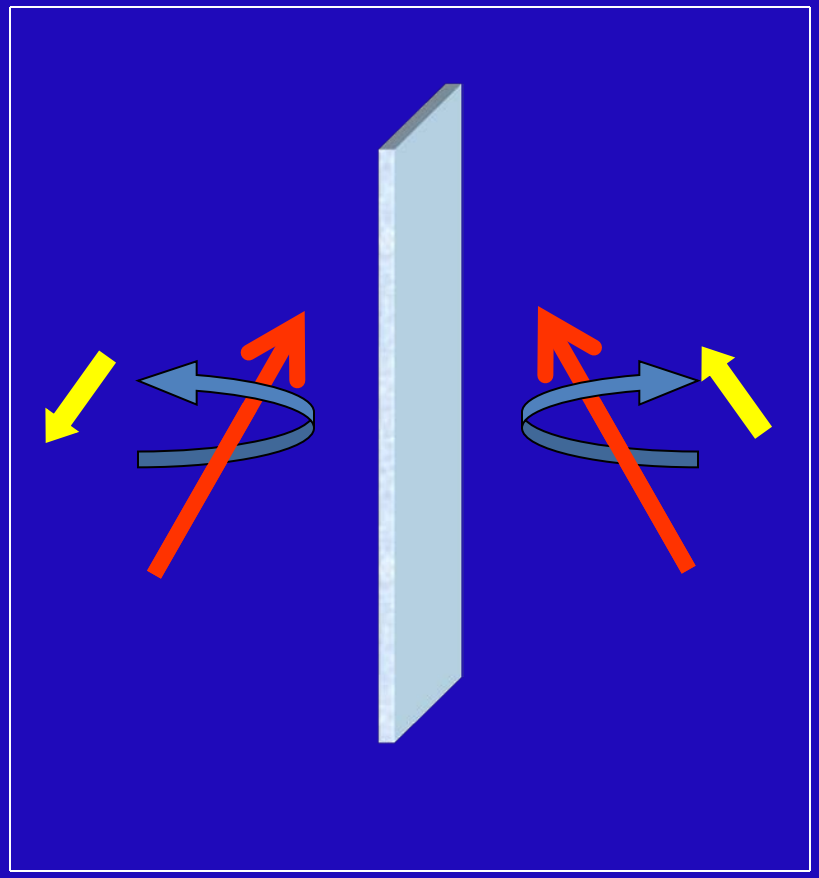
Family Structure

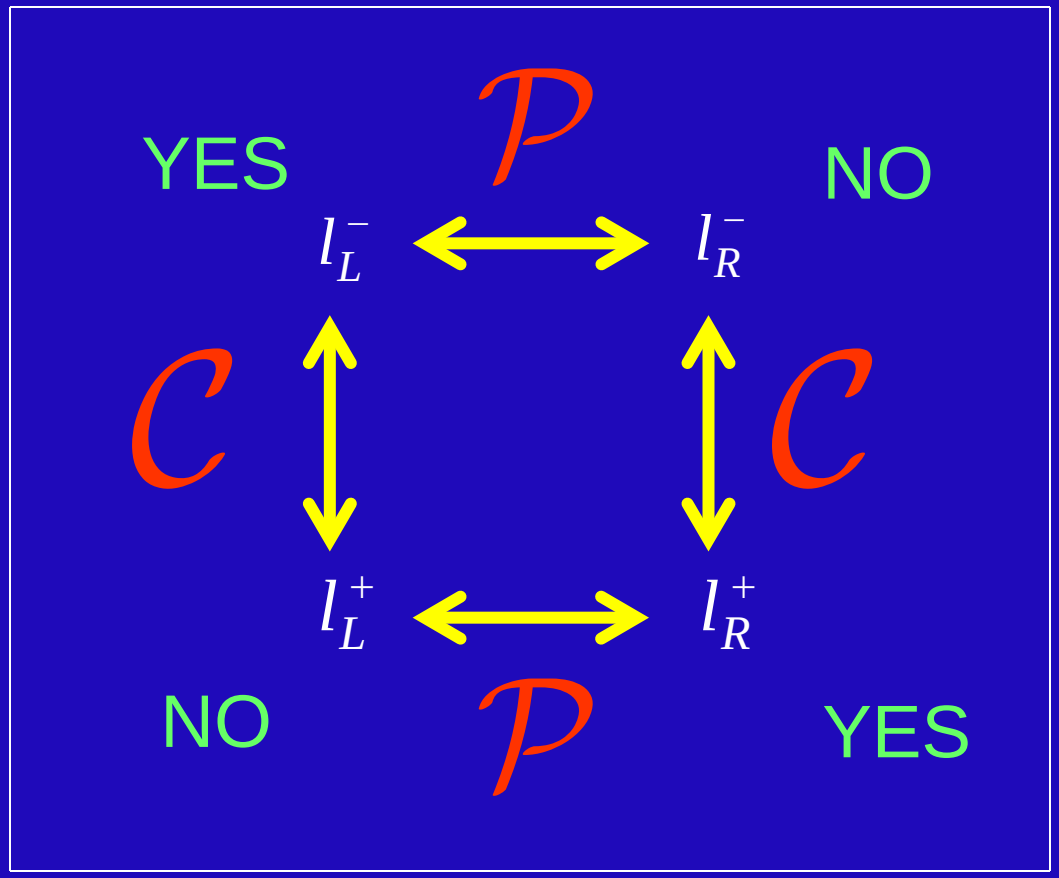
$$\begin{bmatrix} \nu_l & q_u \\ l^- & q_d \end{bmatrix} \equiv \left\{ \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L , (\nu_l)_R , l^-_R \right\} ; \left\{ \begin{pmatrix} q_u \\ q_d \end{pmatrix}_L , (q_u)_R , (q_d)_R \right\}$$

Charged Currents $W^\pm$ $\begin{cases} \text{Left–handed Fermions only} \\ \text{Flavour Changing: } \nu_l \Leftrightarrow l \ , \ q_u \Leftrightarrow q_d \end{cases}$

Neutral currents γ , Z Flavour Conserving

Universality Family – Independent Couplings





$\not{\mathcal{P}}$ **and** $\not{\mathcal{C}}$ **in Weak Interactions**

$\mathcal{CP}$ **still a good symmetry** **(1 family)**

FERMION MASSES

Scalar – Fermion Couplings allowed by Gauge Symmetry

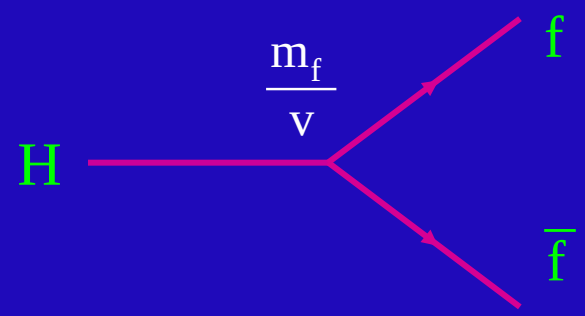
$$\mathcal{L}_Y = -(\bar{q}_u, \bar{q}_d)_L \left[c^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} (q_d)_R + c^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} (q_u)_R \right] - (\bar{\nu}_l, \bar{l})_L \; c^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l_R + \text{h.c.}$$

SSB

$$\mathcal{L}_Y = -\left(1 + \frac{H}{\mathrm{v}}\right) \left\{ m_{q_d} \; \bar{q}_d \, q_d + m_{q_u} \; \bar{q}_u \, q_u + m_l \; \bar{l} \, l \right\}$$

Fermion Masses are New Free Parameters

$$\left[m_{q_d} \, , \; m_{q_u} \, , \; m_l \right] = \left[c^{(d)} \, , \; c^{(u)} \, , \; c^{(l)} \right] \frac{\mathrm{v}}{\sqrt{2}}$$



Couplings Fixed: $g_{H f \bar{f}} = \dfrac{m_f}{\mathrm{v}}$

FERMION GENERATIONS

$N_G = 3$ **Identical Copies** **Masses are the only difference**

$$\begin{matrix} Q=0 \\ Q=-1 \end{matrix} \qquad \begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix} \qquad \begin{matrix} Q=+2/3 \\ Q=-1/3 \end{matrix} \qquad (j=1,\cdots,N_G)$$

WHY ?

$$\mathcal{L}_Y = -\sum_{jk} \left\{ \left(\bar{u}'_j, \bar{d}'_j\right)_L \left[c^{(d)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c^{(u)}_{jk} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} u'_{kR} \right] - \left(\bar{\nu}'_j, \bar{l}'_j\right)_L c^{(l)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l'_{kR} \right\} + \text{h.c.}$$

SSB

$$\mathcal{L}_Y = -\left(1+\frac{H}{\mathrm{v}}\right) \left\{ \bar{d}'_L \cdot \mathbf{M}'_d \cdot d'_R + \bar{u}'_L \cdot \mathbf{M}'_u \cdot u'_R + \bar{l}'_L \cdot \mathbf{M}'_l \cdot l'_R + \text{h.c.} \right\}$$

Arbitrary Non-Diagonal Complex Mass Matrices

$$\left[\mathbf{M}'_d \,,\, \mathbf{M}'_u \,,\, \mathbf{M}'_l \right]_{jk} = \left[c^{(d)}_{jk} \,,\, c^{(u)}_{jk} \,,\, c^{(l)}_{jk} \right] \frac{\mathrm{v}}{\sqrt{2}}$$

DIAGONALIZATION OF MASS MATRICES

$$\mathbf{M}'_d = \mathbf{H}_d \cdot \mathbf{U}_d = \mathbf{S}_d^\dagger \cdot \boldsymbol{\mathcal{M}}_d \cdot \mathbf{S}_d \cdot \mathbf{U}_d$$
$$\mathbf{M}'_u = \mathbf{H}_u \cdot \mathbf{U}_u = \mathbf{S}_u^\dagger \cdot \boldsymbol{\mathcal{M}}_u \cdot \mathrm{S}_u \cdot \mathbf{U}_u$$
$$\mathbf{M}'_l = \mathbf{H}_l \cdot \mathbf{U}_l = \mathbf{S}_l^\dagger \cdot \boldsymbol{\mathcal{M}}_l \cdot \mathbf{S}_l \cdot \mathbf{U}_l$$

$$\mathbf{H}_\mathrm{f} = \mathbf{H}_\mathrm{f}^\dagger$$
$$\mathbf{U}_\mathrm{f} \cdot \mathbf{U}_\mathrm{f}^\dagger = \mathbf{U}_\mathrm{f}^\dagger \cdot \mathbf{U}_\mathrm{f} = 1$$
$$\mathbf{S}_\mathrm{f} \cdot \mathbf{S}_\mathrm{f}^\dagger = \mathbf{S}_\mathrm{f}^\dagger \cdot \mathbf{S}_\mathrm{f} = 1$$

$$\mathcal{L}_Y = -\left(1+\frac{H}{\mathrm{v}}\right)\left\{\bar{\mathrm{d}}\cdot\boldsymbol{\mathcal{M}}_d\cdot\mathrm{d} + \bar{\mathrm{u}}\cdot\boldsymbol{\mathcal{M}}_u\cdot\mathrm{u} + \bar{l}\cdot\boldsymbol{\mathcal{M}}_l\cdot l\right\}$$

$$\boldsymbol{\mathcal{M}}_u = \mathrm{diag}\,(m_u, m_c, m_t) \;;\; \boldsymbol{\mathcal{M}}_d = \mathrm{diag}\,(m_d, m_s, m_b) \;;\; \boldsymbol{\mathcal{M}}_l = \mathrm{diag}\,(m_e, m_\mu, m_\tau)$$

$$\mathrm{d}_L \equiv \mathbf{S}_d \cdot \mathrm{d}'_L \;;\; \mathrm{u}_L \equiv \mathbf{S}_u \cdot \mathrm{u}'_L \;;\; l_L \equiv \mathbf{S}_l \cdot l'_L$$
$$\mathrm{d}_R \equiv \mathbf{S}_d \cdot \mathbf{U}_d \cdot \mathrm{d}'_R \;;\; \mathrm{u}_R \equiv \mathbf{S}_u \cdot \mathbf{U}_u \cdot \mathrm{u}'_R \;;\; l_R \equiv \mathbf{S}_l \cdot \mathbf{U}_l \cdot l'_R$$

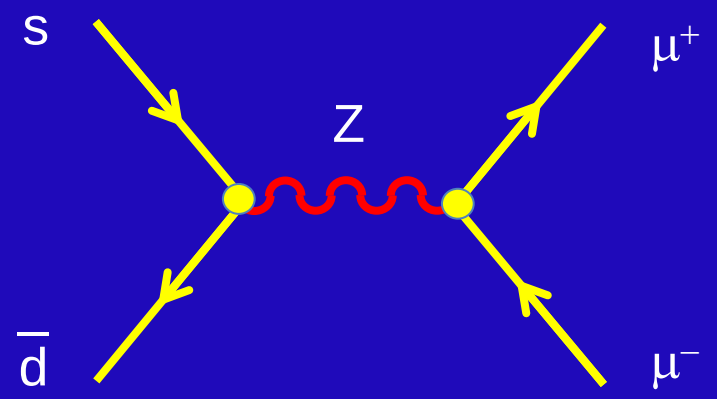
Mass Eigenstates
$\neq$
Weak Eigenstates

$$\bar{\mathrm{f}}'_L\,\mathrm{f}'_L = \bar{\mathrm{f}}_L\,\mathrm{f}_L \;;\; \bar{\mathrm{f}}'_R\,\mathrm{f}'_R = \bar{\mathrm{f}}_R\,\mathrm{f}_R \;\Rightarrow\; \mathcal{L}'_{\mathrm{NC}} = \mathcal{L}_{\mathrm{NC}}$$
$$\bar{\mathrm{u}}'_L\,\mathrm{d}'_L = \bar{\mathrm{u}}_L \cdot \mathbf{V} \cdot \mathrm{d}_L \;;\; \mathbf{V} \equiv \mathbf{S}_u \cdot \mathbf{S}_d^\dagger \;\Rightarrow\; \mathcal{L}'_{\mathrm{CC}} \neq \mathcal{L}_{\mathrm{CC}}$$

QUARK MIXING

Flavour Conserving Neutral Currents (GIM)

$$\mathcal{L}^{Z}_{\mathrm{NC}} = -\frac{e}{2\sin\theta_W\,\cos\theta_W}\, Z_\mu \sum_{\mathrm{f}} \bar{\mathrm{f}}\,\gamma^\mu\left[\mathrm{v_f} - \mathrm{a_f}\,\gamma_5\right]\mathrm{f}$$



NO

$$\mathrm{Br}(K_L \to \mu^+\mu^-) = (6.84 \pm 0.11)\times 10^{-9} \quad , \quad \mathrm{Br}(K_S \to \mu^+\mu^-) < 3.2\times 10^{-7}$$

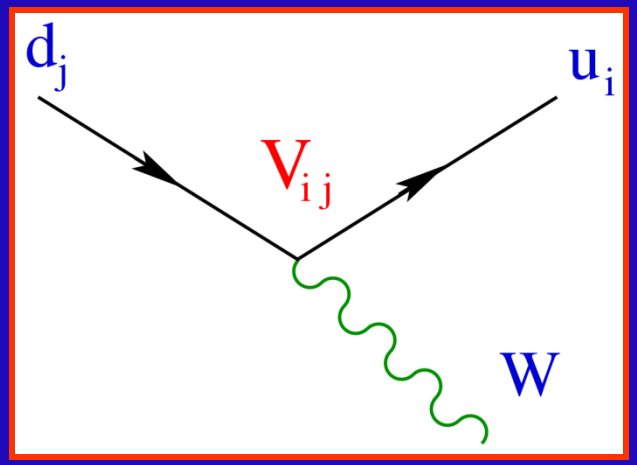
$$K_L \to \pi^{0*} \to (\gamma\gamma)^* \to \mu^+\mu^-$$

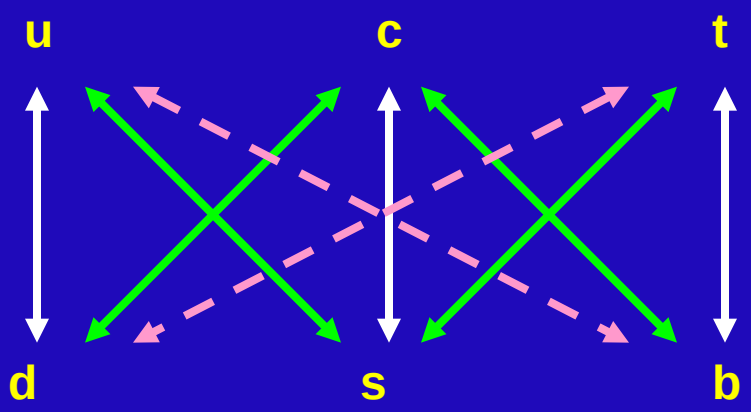
$$K_S \to (\pi^+\pi^-)^* \to (\gamma\gamma)^* \to \mu^+\mu^-$$

Flavour Changing Charged Currents

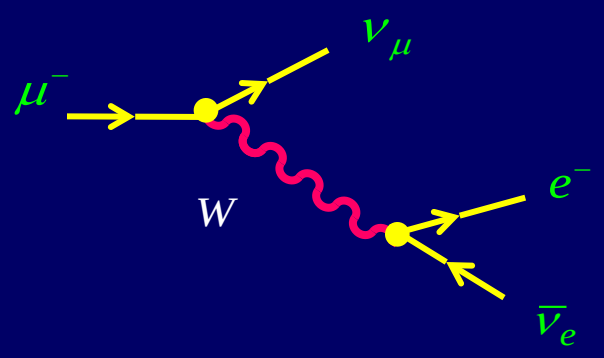
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5) \mathbf{V}_{ij} d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5) l \right] + \text{h.c.}$$

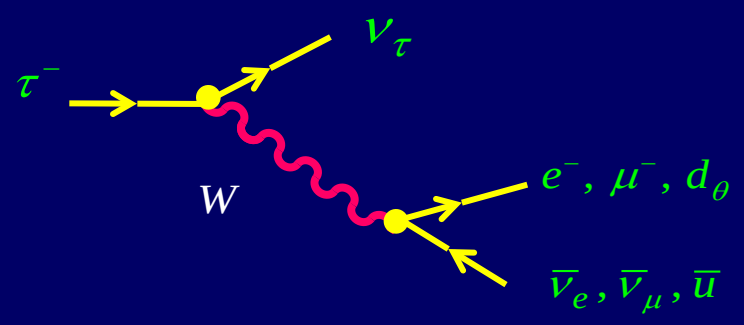
$$\left(\bar{\nu}_{l_j} \equiv \bar{\nu}_i \; \mathbf{V}_{ij}^{(l)} \right)$$





Weak Decays



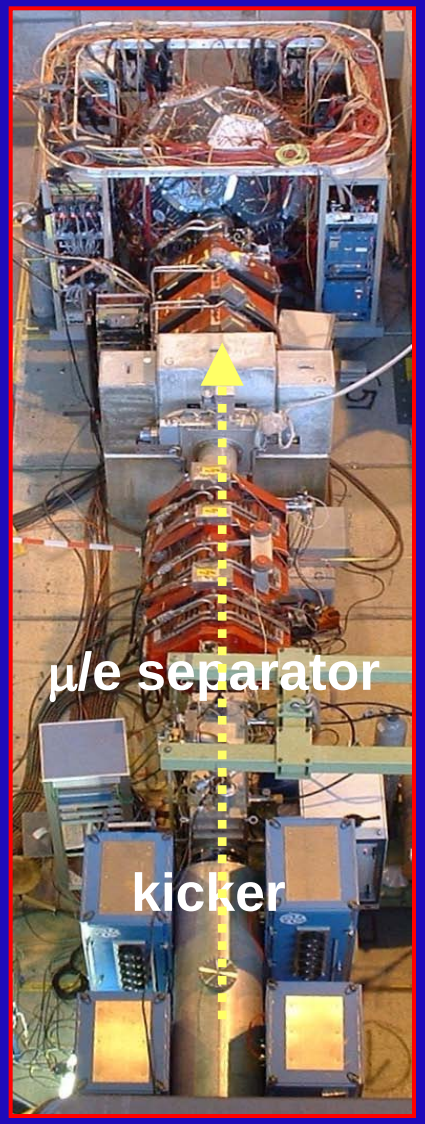


$$T(l \to \nu_l\, l' \bar{\nu}_{l'}) \sim \frac{g_W^2}{M_W^2 - q^2} \xrightarrow{q^2 << M_W^2} \frac{g_W^2}{M_W^2} = 4\sqrt{2}\, G_F$$

$$\frac{1}{\tau_\mu} = \frac{G_F^2\, m_\mu^5}{192\,\pi^3}\, f(m_e^2/m_\mu^2)\, r_{EW} \quad \Rightarrow \quad G_F = (1.166\,378\,8 \pm 0.000\,000\,7) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

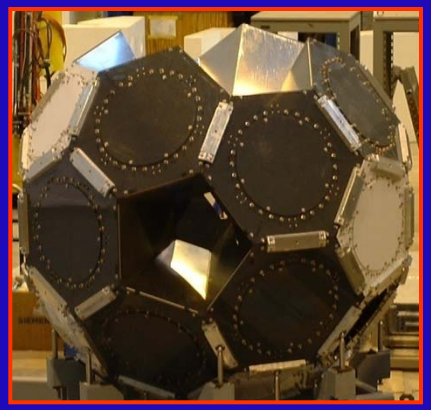
$$r_{EW} = \left[1 + \frac{\alpha(m_\mu)}{2\pi}\left(\frac{25}{4} - \pi^2\right) + C_2\,\frac{\alpha(m_\mu)^2}{\pi^2}\right]\left[1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2} - 2\frac{m_e^2}{M_W^2}\right] = 0.9958 \quad ; \quad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$$

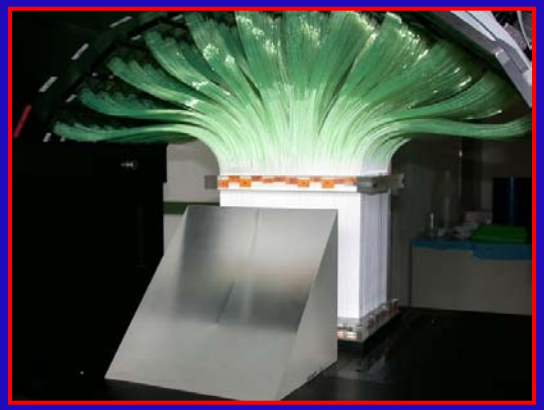
Muon Lifetime



$$\tau_\mu\,(\mu s) = \begin{cases} 2.197\,03 \pm 0.000\,04 & \text{PDG '06} \\ 2.197\,013 \pm 0.000\,024 & \text{MuLan '07} \\ 2.197\,083 \pm 0.000\,035 & \text{FAST '08} \\ 2.196\,980\,3 \pm 0.000\,002\,2 & \text{MuLan '10} \end{cases}$$

MULAN





FAST

$$\frac{1}{\tau_\mu} = \frac{G_F^2\, m_\mu^5}{192\,\pi^3}\,(1+\delta_{\text{QED}})$$

δ_{QED} known to 0.3 ppm (van-Ritbergen & Stuart)

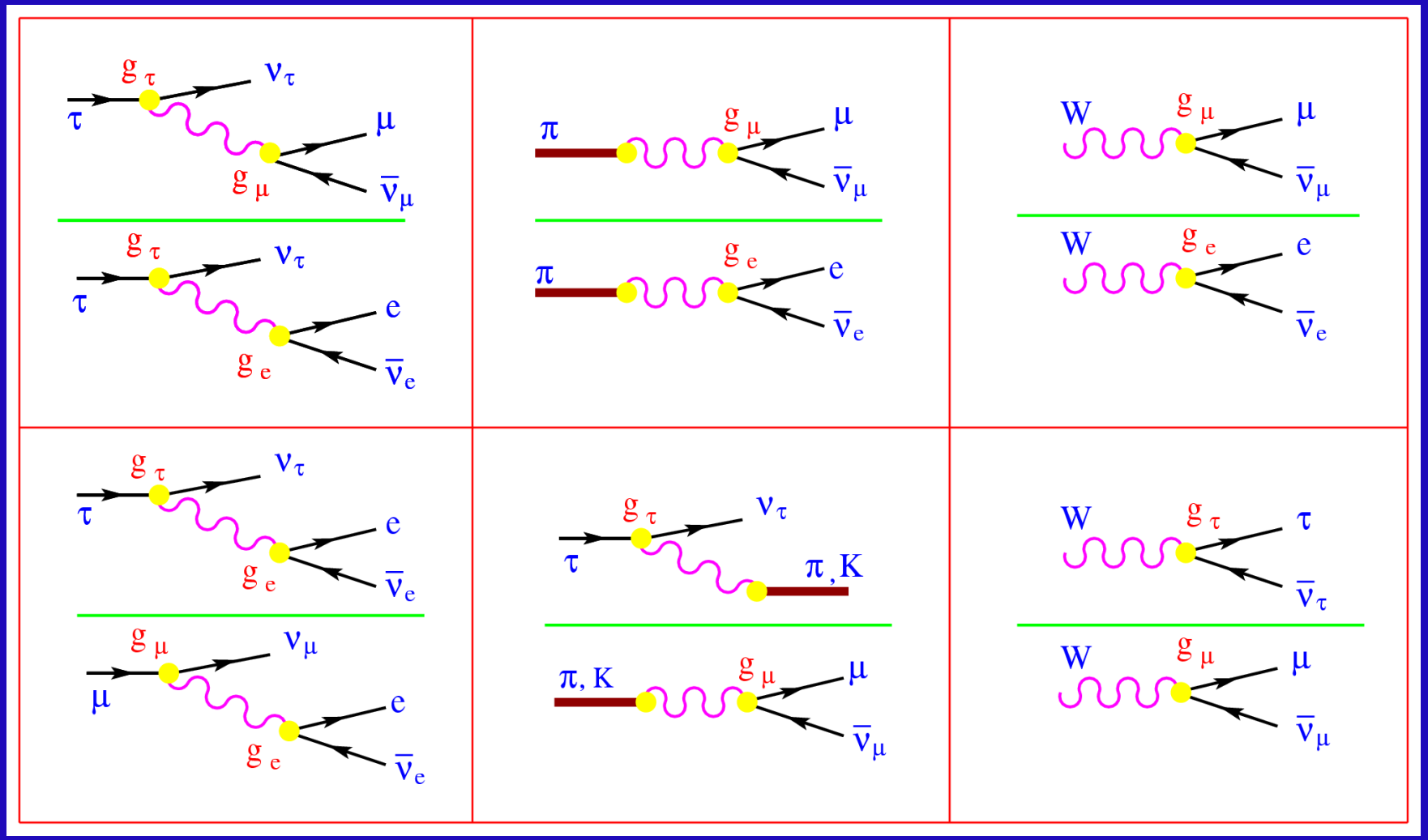
New World Average:

τ_μ = 2.196 981 1 (22) μs → G_F = 1.166 378 7 (6) x 10^{-5} GeV^{-2} (0.5 ppm)

LEPTON UNIVERSALITY

$\frac{g_\mu}{g_e}$

$\frac{g_\tau}{g_\mu}$



CHARGED CURRENT UNIVERSALITY

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0018 ± 0.0014
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0021 ± 0.0016
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0024
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	0.997 ± 0.010

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0007 ± 0.0022
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.992 ± 0.004
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.982 ± 0.008
$B_{W\to\tau}/B_{W\to\mu}$	1.032 ± 0.012

$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0016 ± 0.0021
$B_{W\to\tau}/B_{W\to e}$	1.023 ± 0.011

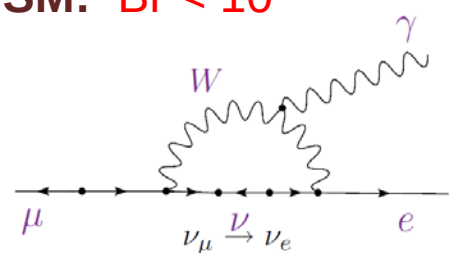
LEPTON FLAVOUR VIOLATION

90% CL Upper Limits on $Br(l^- \to X^-)$ [MEG'11,SINDRUM'88, Bolton'88, BABAR / BELLE]

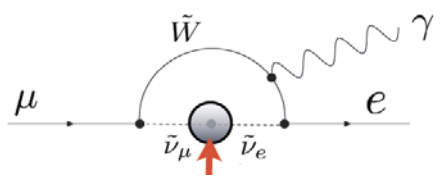
Decay	U.L.	Decay	U.L.	Decay	U.L.
$\mu^- \to e^-\gamma$	$2.4 \cdot 10^{-12}$	$\mu^- \to e^-e^+e^-$	$1.0 \cdot 10^{-12}$	$\mu^- \to e^-\gamma\gamma$	$7.2 \cdot 10^{-11}$
$\tau^- \to e^-\gamma$	$3.3 \cdot 10^{-8}$	$\tau^- \to e^-e^+e^-$	$2.7 \cdot 10^{-8}$	$\tau^- \to e^-e^+\mu^-$	$1.8 \cdot 10^{-8}$
$\tau^- \to \mu^-\gamma$	$4.4 \cdot 10^{-8}$	$\tau^- \to e^-\mu^+\mu^-$	$2.7 \cdot 10^{-8}$	$\tau^- \to \mu^-e^+\mu^-$	$1.7 \cdot 10^{-8}$
$\tau^- \to e^-e^-\mu^+$	$1.5 \cdot 10^{-8}$	$\tau^- \to \mu^-\mu^+\mu^-$	$2.1 \cdot 10^{-8}$	$\tau^- \to e^-\pi^0$	$8.0 \cdot 10^{-8}$
$\tau^- \to \mu^-\pi^0$	$1.1 \cdot 10^{-7}$	$\tau^- \to e^-\eta'$	$1.6 \cdot 10^{-7}$	$\tau^- \to \mu^-\eta'$	$1.3 \cdot 10^{-7}$
$\tau^- \to e^-\eta$	$9.2 \cdot 10^{-8}$	$\tau^- \to \mu^-\eta$	$6.5 \cdot 10^{-8}$	$\tau^- \to e^-K^{*0}$	$3.2 \cdot 10^{-8}$
$\tau^- \to e^-K_S$	$2.6 \cdot 10^{-8}$	$\tau^- \to \mu^-K_S$	$2.3 \cdot 10^{-8}$	$\tau^- \to \mu^-\rho^0$	$1.2 \cdot 10^{-8}$
$\tau^- \to e^-K^+K^-$	$3.4 \cdot 10^{-8}$	$\tau^- \to e^-K^+\pi^-$	$3.1 \cdot 10^{-8}$	$\tau^- \to e^-\pi^+K^-$	$5.8 \cdot 10^{-8}$
$\tau^- \to \mu^-K^+K^-$	$4.4 \cdot 10^{-8}$	$\tau^- \to \mu^-K^+\pi^-$	$4.5 \cdot 10^{-8}$	$\tau^- \to \mu^-\pi^+K^-$	$1.6 \cdot 10^{-7}$
$\tau^- \to e^-\pi^+\pi^-$	$2.3 \cdot 10^{-8}$	$\tau^- \to \mu^-\pi^+\pi^-$	$2.1 \cdot 10^{-8}$	$\tau^- \to \Lambda\pi^-$	$7.2 \cdot 10^{-8}$
$\tau^- \to e^+K^-K^-$	$3.3 \cdot 10^{-8}$	$\tau^- \to e^+K^-\pi^-$	$3.2 \cdot 10^{-8}$	$\tau^- \to e^+\pi^-\pi^-$	$2.0 \cdot 10^{-8}$
$\tau^- \to \mu^-K^{*0}$	$5.9 \cdot 10^{-8}$	$\tau^- \to e^-\phi$	$3.1 \cdot 10^{-8}$	$\tau^- \to \mu^-\omega$	$4.7 \cdot 10^{-8}$
$\tau^- \to \mu^+K^-K^-$	$4.7 \cdot 10^{-8}$	$\tau^- \to \mu^+K^-\pi^-$	$4.8 \cdot 10^{-8}$	$\tau^- \to \mu^+\pi^-\pi^-$	$3.7 \cdot 10^{-8}$

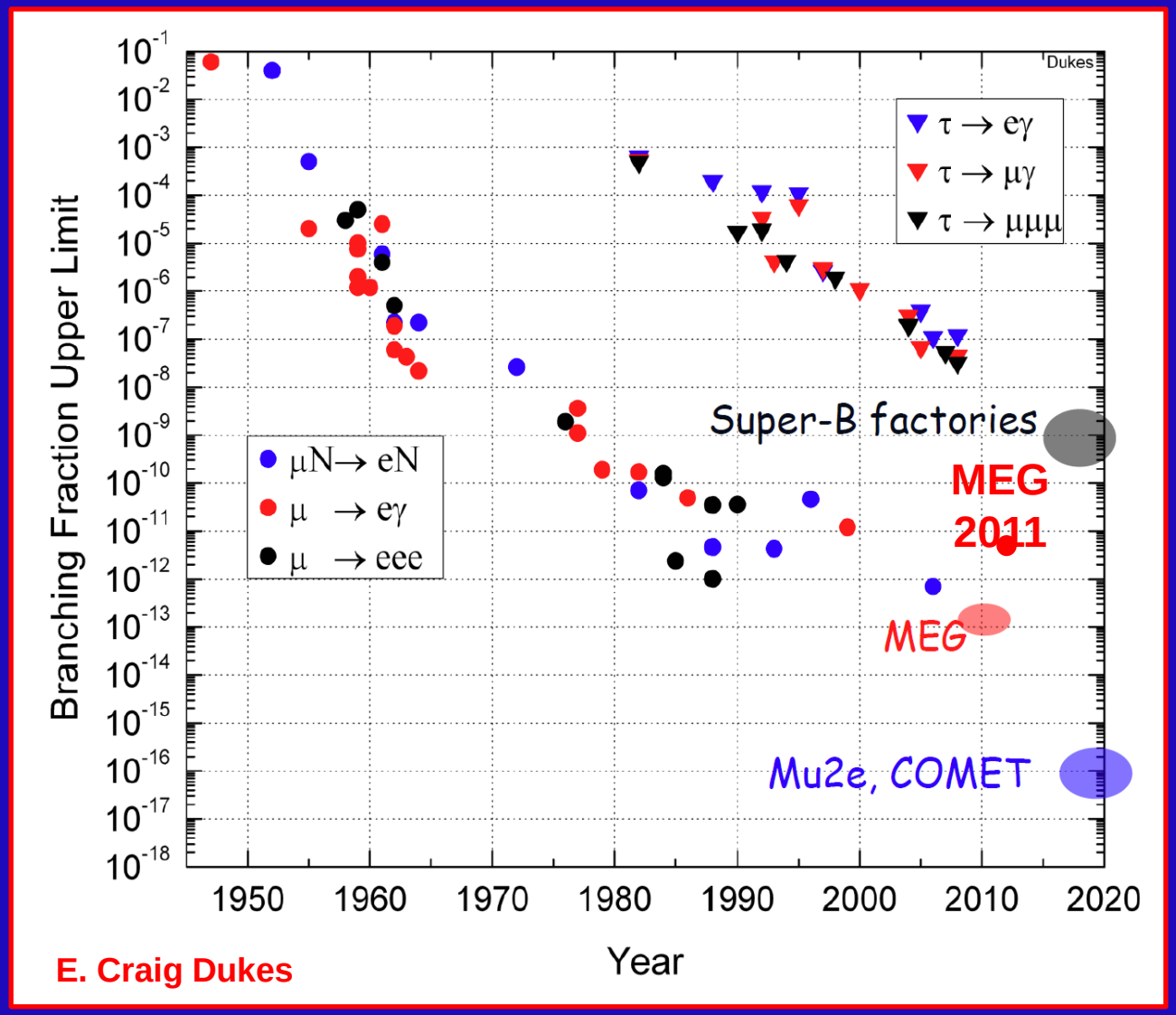
Exciting Prospects

SM: Br < 10^{-51}



New Physics ?

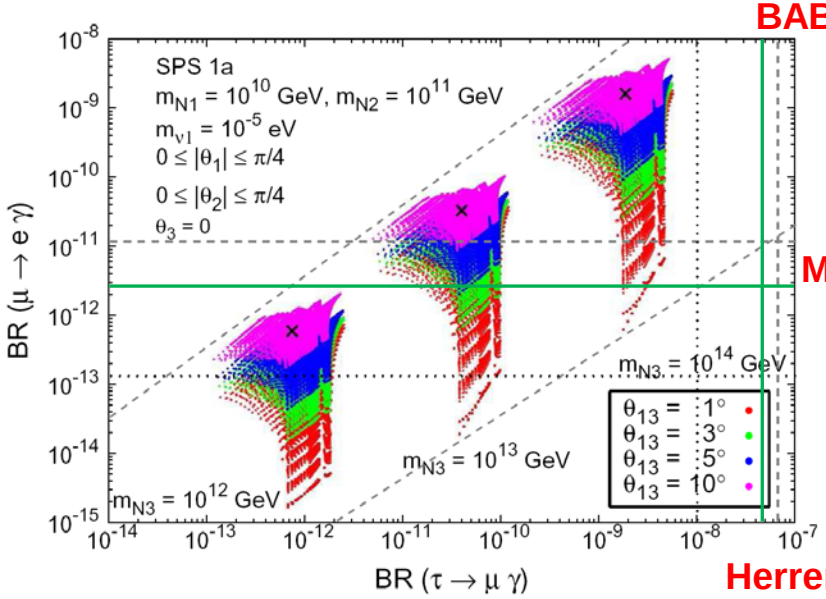




Impact of θ_{13} on LFV processes

(All plotted points lead to 'viable BAU' and respect EDM bounds)

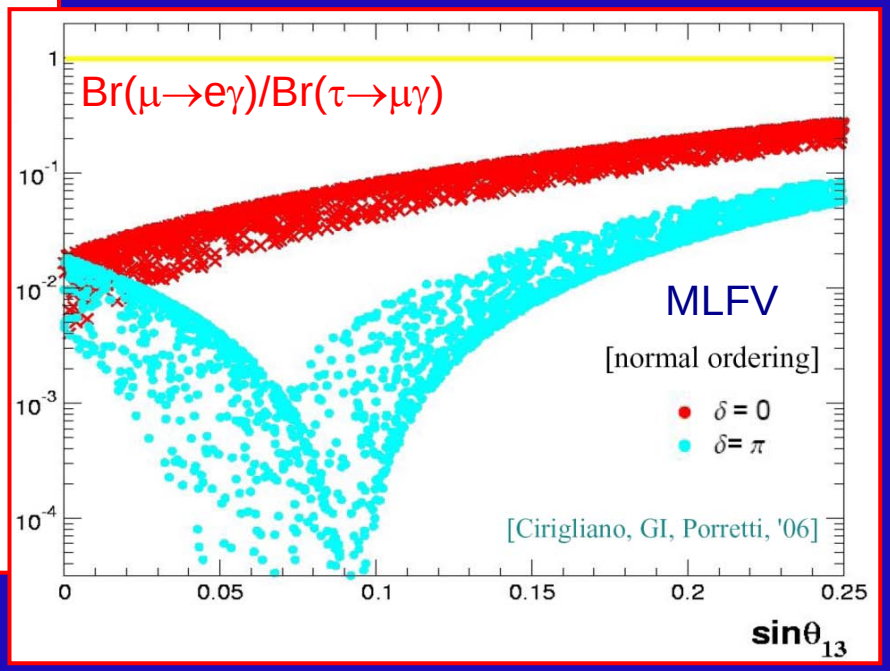
$(-\pi/4 \lesssim \arg\theta_1 \lesssim \pi/4,\ 0 \lesssim \arg\theta_2 \lesssim \pi/4)$

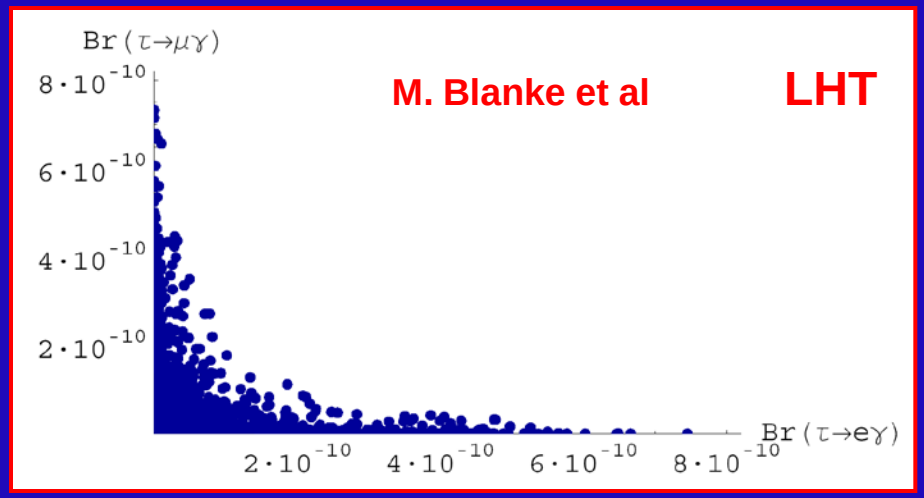


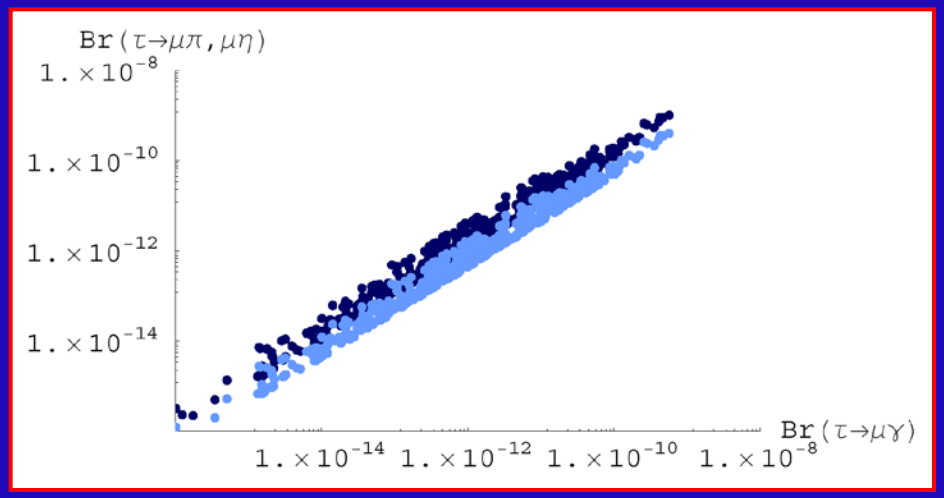
MEG: $Br(\mu\to e\gamma) \sim 10^{-13}$

Prism: $Pr(\mu\to e) \sim 10^{-18}$

SuperB: $Br(\tau \to \mu\gamma) \sim 10^{-9}$







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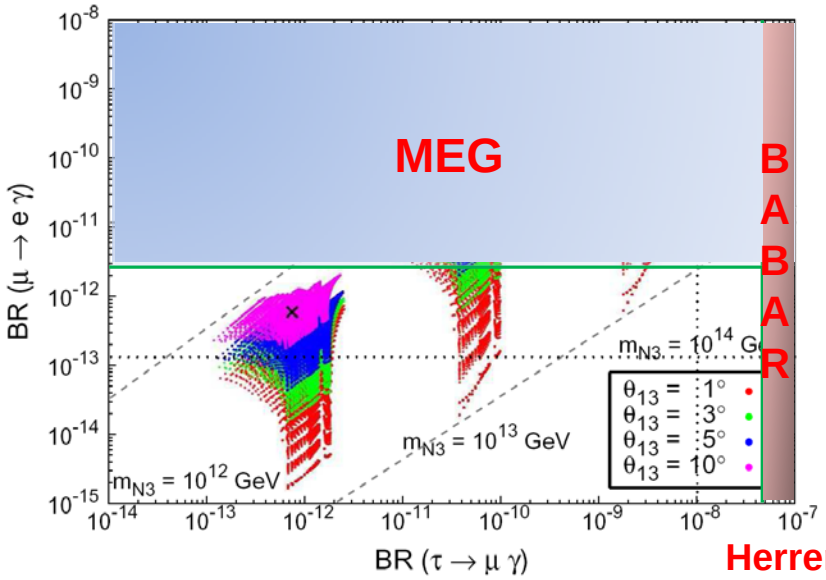

Herrero et al

MEG: $Br(\mu \to e\gamma) \sim 10^{-13}$

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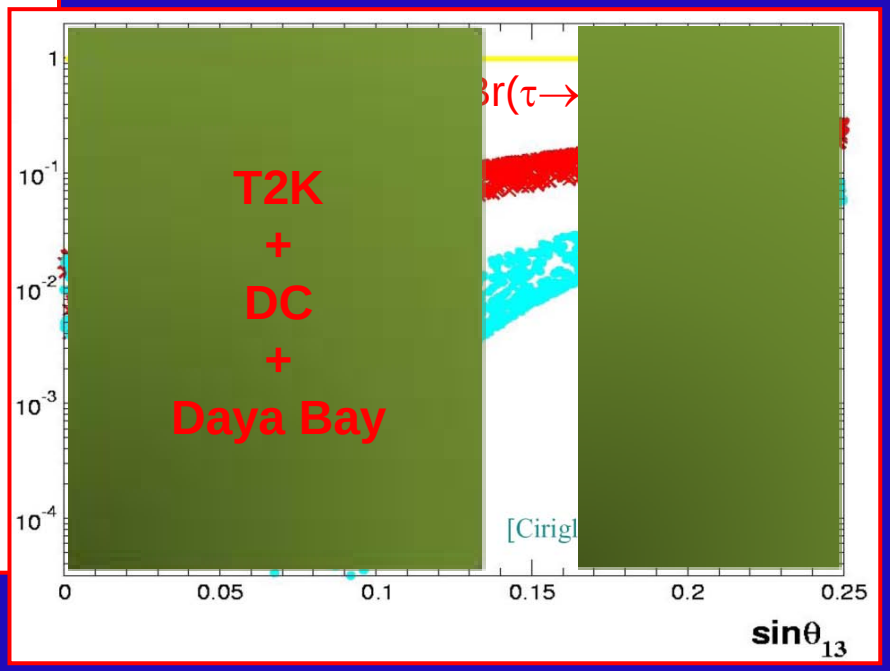
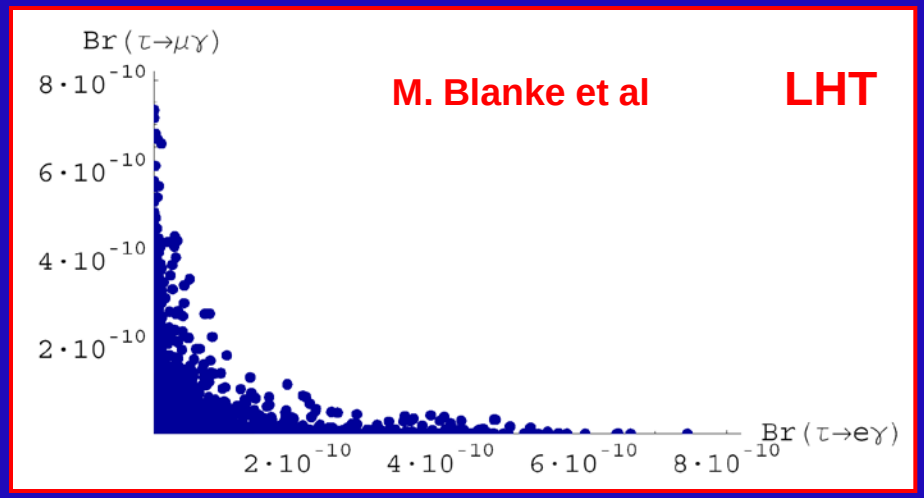
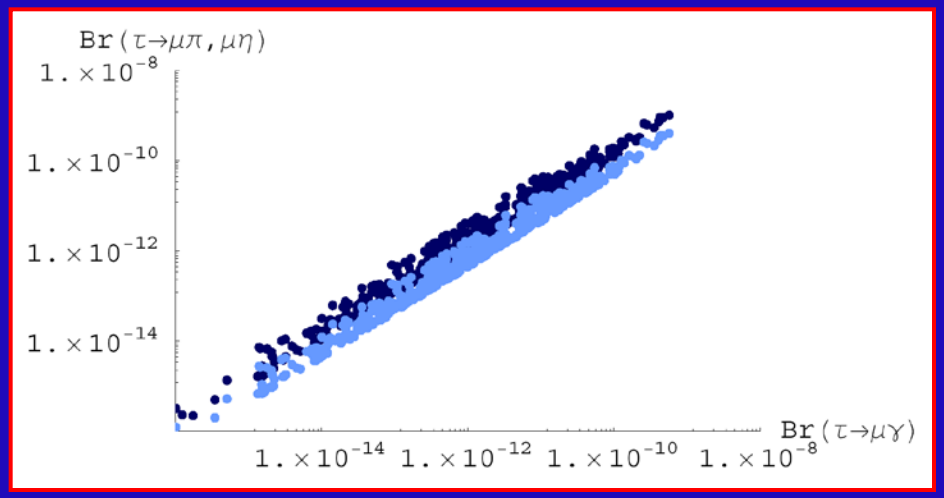
SuperB: $Br(\tau \to \mu\gamma) \sim 10^{-9}$





M. Blanke et al

LHT



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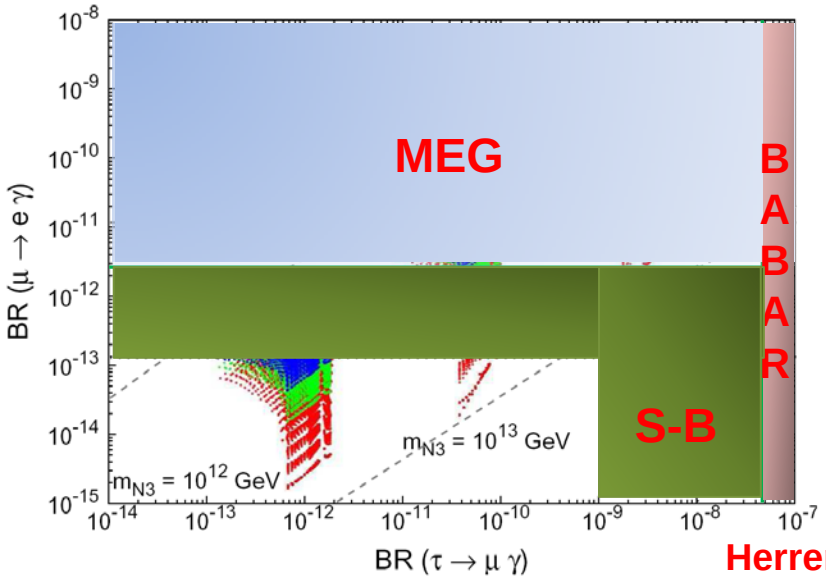

Herrero et al

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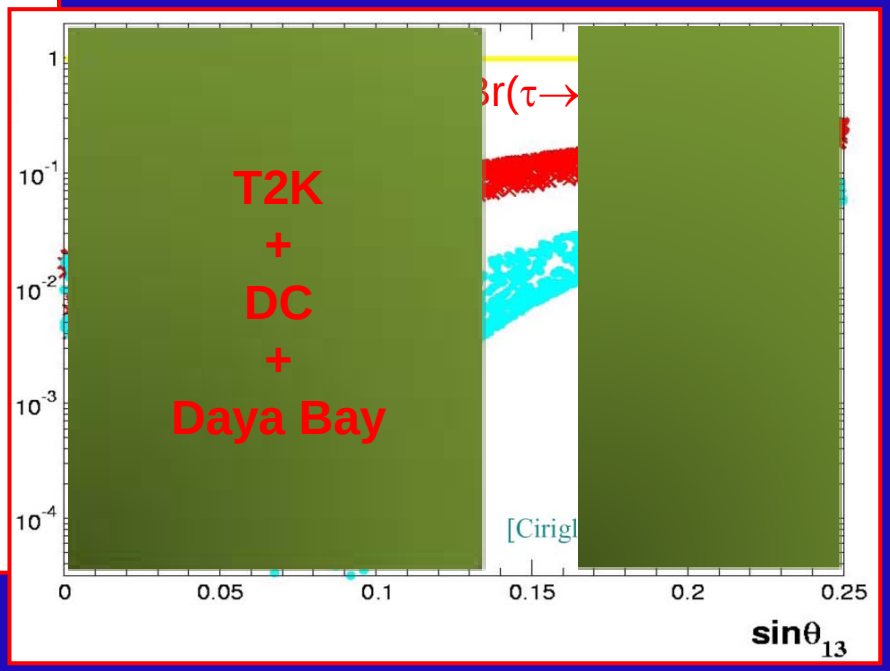
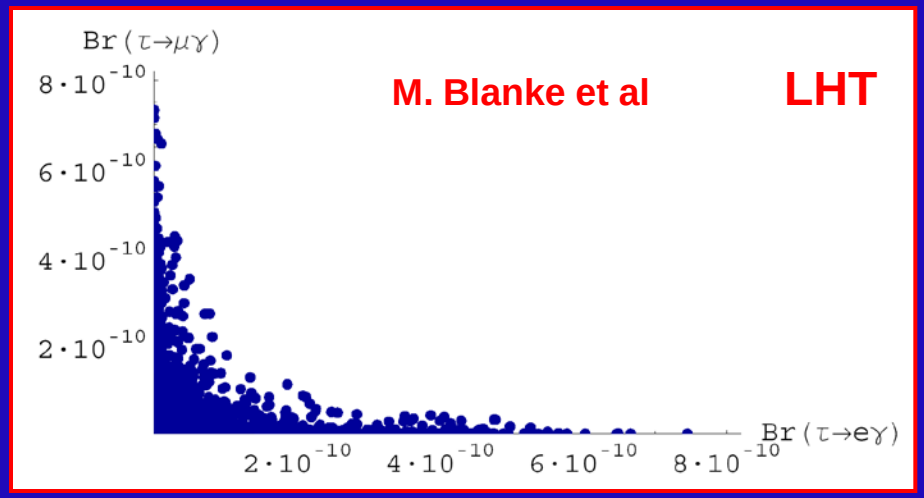
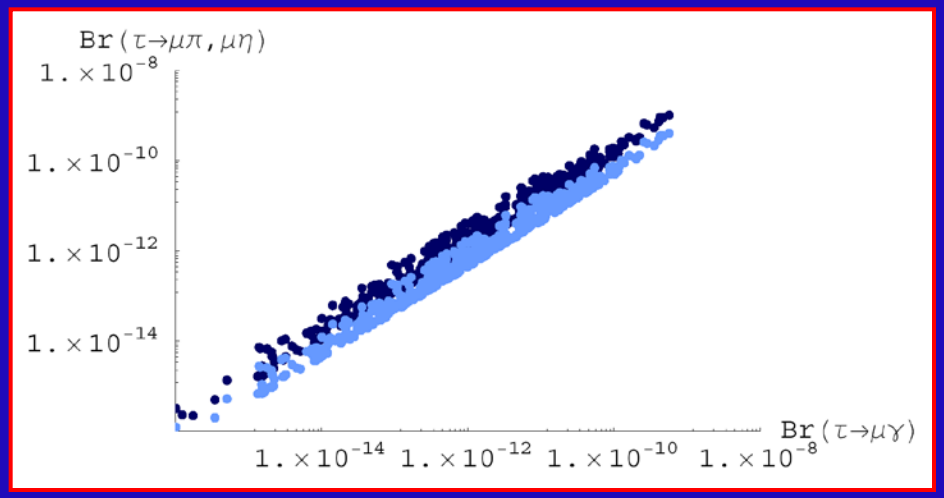
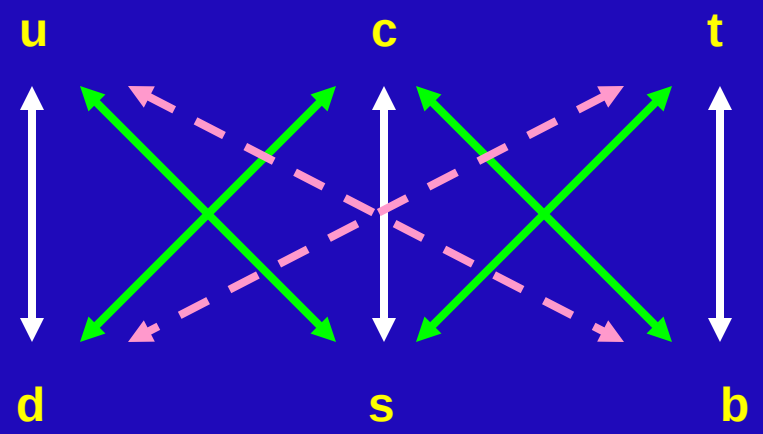
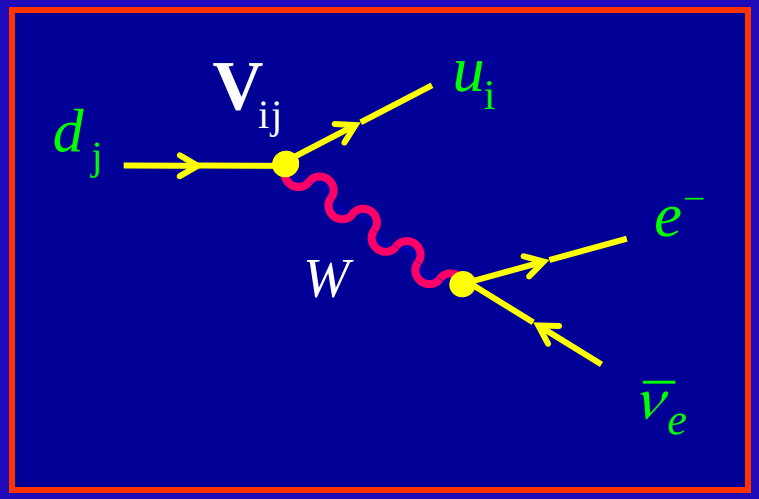






Flavour Changing Charged Currents





$$\Gamma(d_j \to u_i\, e^-\, \bar{\nu}_e) \propto \left|V_{ij}\right|^2$$

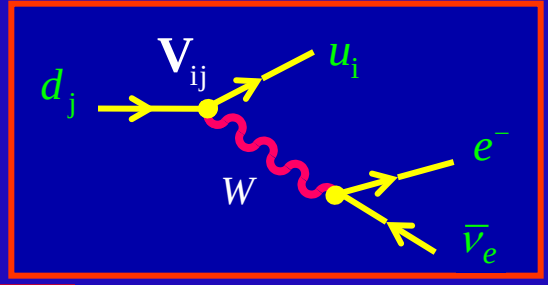
We measure decays of hadrons (no free quarks)

Important QCD Uncertainties

V_{ij} Determination

$(0^- \to 0^-)$

$K \to \pi l \nu$, $D \to K l \nu$ ...



$$\langle P'(k')|\bar{u}_i \gamma^\mu d_j|P(k)\rangle = C_{PP'}\left\{(k+k')^\mu \; f_+(q^2) + (k-k')^\mu \; f_-(q^2)\right\}$$

$$\Gamma(P \to P' l \nu) = \frac{G_F^2 M_P^5}{192\pi^3} \, |\mathbf{V_{ij}}|^2 \, C_{PP'}^2 \, |f_+(0)|^2 \, \mathbf{I} \; (1+\delta_{RC})$$

$$\mathbf{I} \approx \int_0^{(M_P - M_{P'})^2} \frac{dq^2}{M_P^8} \, \lambda^{3/2}(q^2, M_P^2, M_{P'}^2) \left|\frac{f_+(q^2)}{f_+(0)}\right|^2$$

$f_-(q^2)$ suppressed

$(m_{u_i} - m_{d_j}, m_l)$

- Measure the q^2 distribution ➡ $\mathbf{I}$
- Measure Γ ➡ $f_+(0) \; |\mathbf{V_{ij}}|$
- Get a theoretical prediction for $f_+(0)$ ➡ $|\mathbf{V_{ij}}|$

Theory is always needed: Symmetries

$|V_{ud}|$

$$f_+(0) = 1 + O[(m_u - m_d)^2]$$

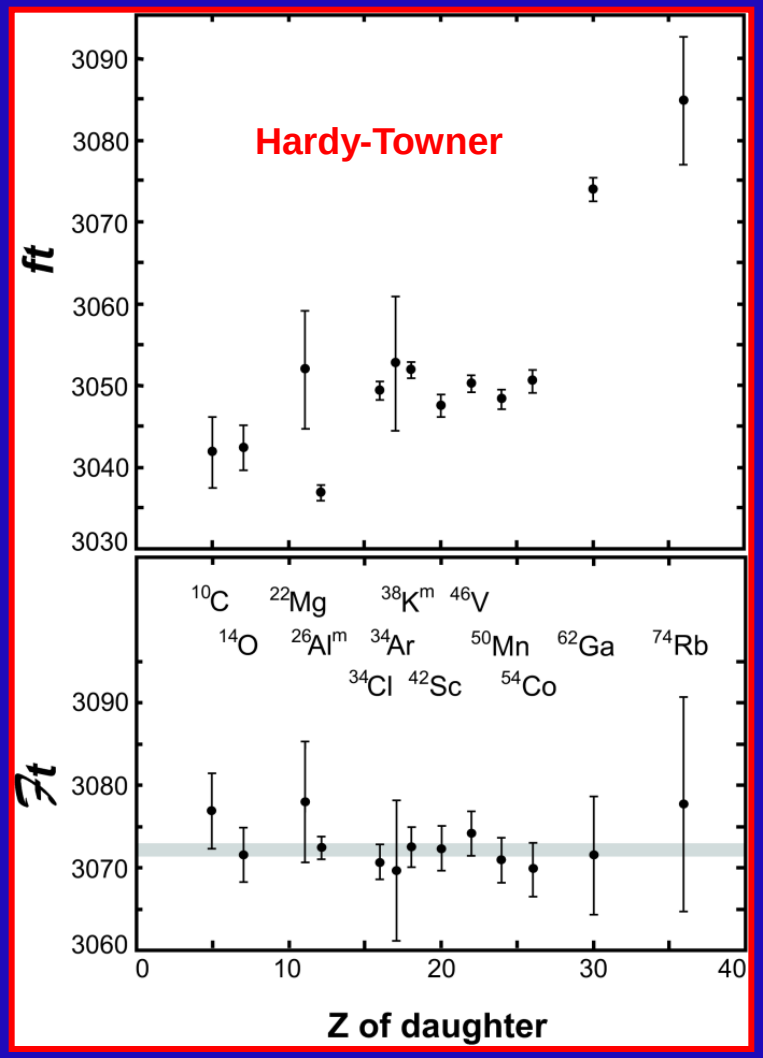
Superallowed Nuclear β Transitions $(0^+ \to 0^+)$

$$|V_{ud}|^2 = \frac{\pi^3 \ln 2}{ft\, G_F^2 m_e^5 (1+\delta_{RC})} = \frac{(2984.48 \pm 0.05)\ \mathrm{s}}{ft\,(1+\delta_{RC})}$$

(Marciano – Sirlin)

$$|V_{ud}| = 0.97425 \pm 0.00022$$

$|V_{ud}| = 0.97377 \pm 0.00027$ (PDG 06)



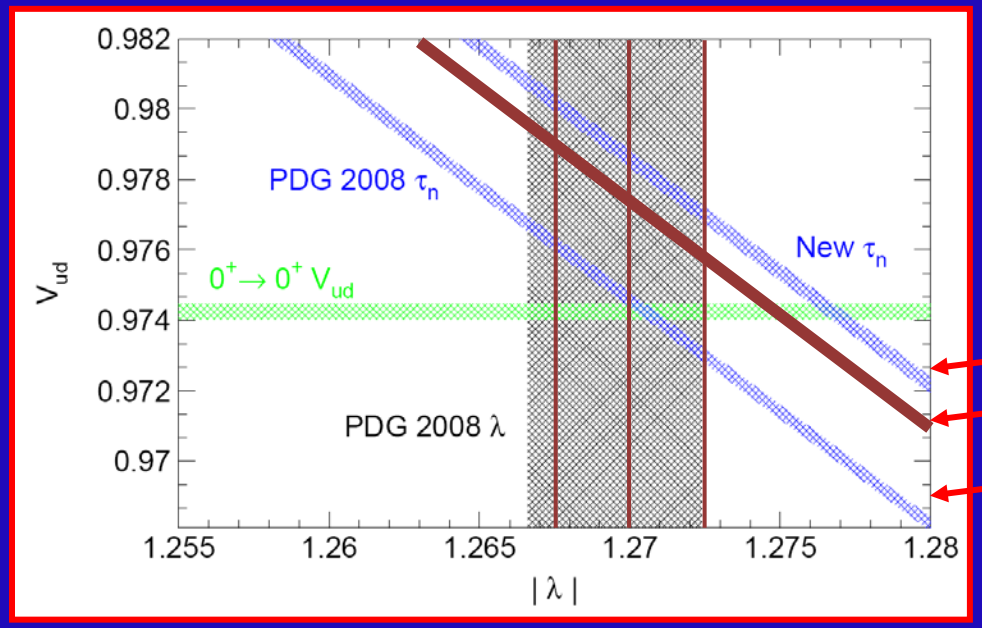
• Neutron Decay:

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)\ \mathrm{s}}{\tau_n (1+3\lambda^2)}$$

(Czarnecki – Marciano – Sirlin)

PDG10: $\tau_n = (885.7 \pm 0.8)$ s , $\lambda \equiv g_A / g_V = -1.2694 \pm 0.0028$

PDG12: $\tau_n = (880.1 \pm 1.1)$ s , $\lambda \equiv g_A / g_V = -1.2701 \pm 0.0025$



$|V_{ud}| = 0.9773 \pm 0.0017$

$\tau_n = (878.5 \pm 0.7 \pm 0.3)$ s

(Serebrov et al, 2005)

PDG12

PDG10

• Pion Decay:

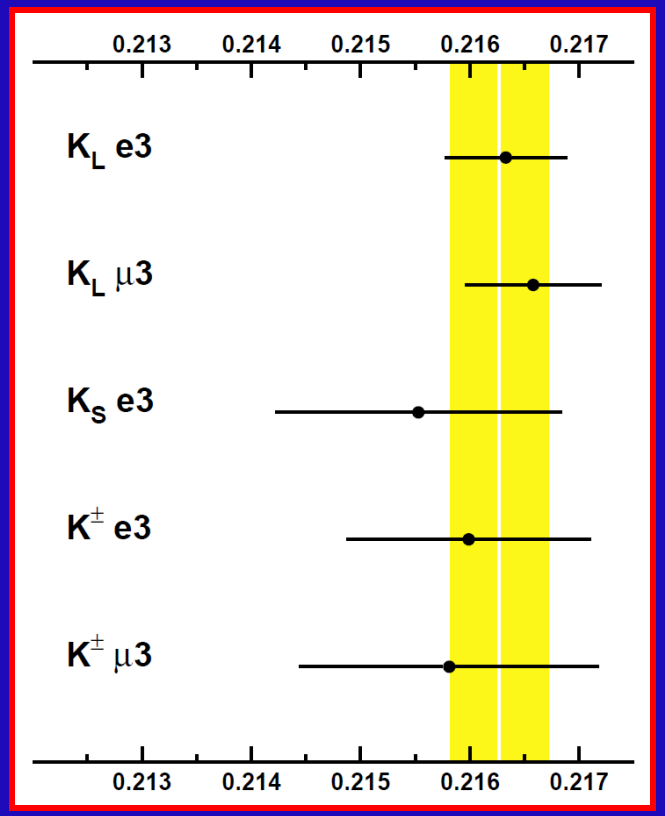
$$\mathrm{Br}(\pi^+ \to \pi^0 e^+ \nu_e) = (1.036 \pm 0.006) \times 10^{-8}$$

(PIBETA)

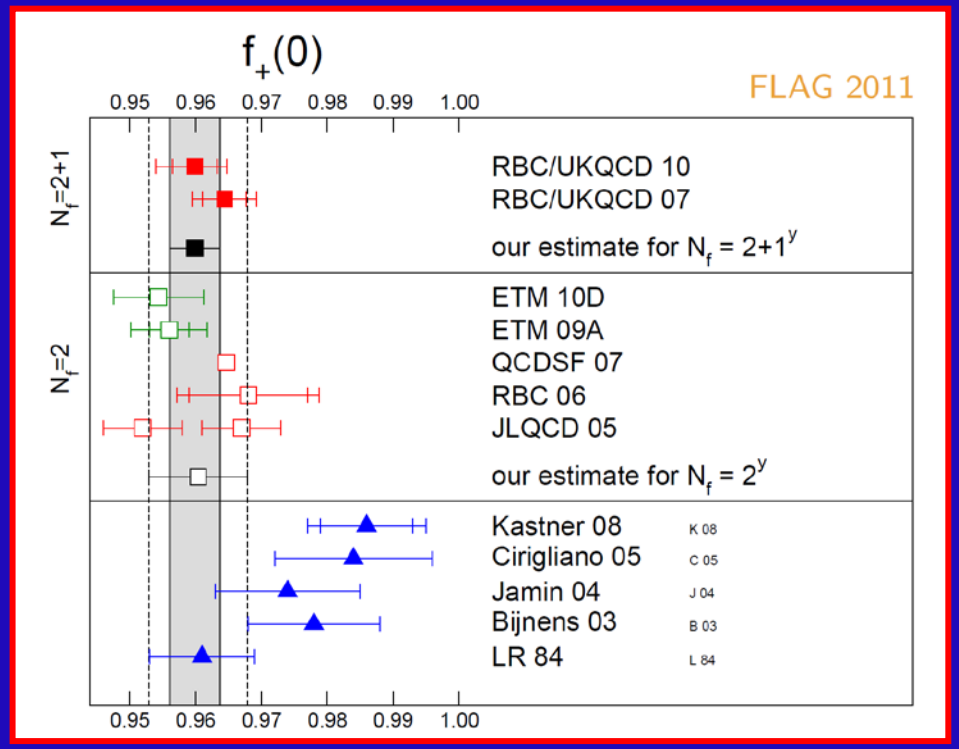
$|V_{ud}| = 0.9741 \pm 0.0026$

$K \to \pi l \nu$ Decays

Flavianet, arXiv:1005.2323 [hep-ph]



Large $O(p^6)$ χPT correction (Bijnens-Talavera)



$O(p^6)$

$O(p^4)$

$$|f_+(0)\,\mathbf{V_{us}}| = 0.2163 \pm 0.0005$$

$$f_+(0) = 0.959 \pm 0.005 \quad \Rightarrow \quad |\mathbf{V_{us}}| = \mathbf{0.2255 \pm 0.0014}$$

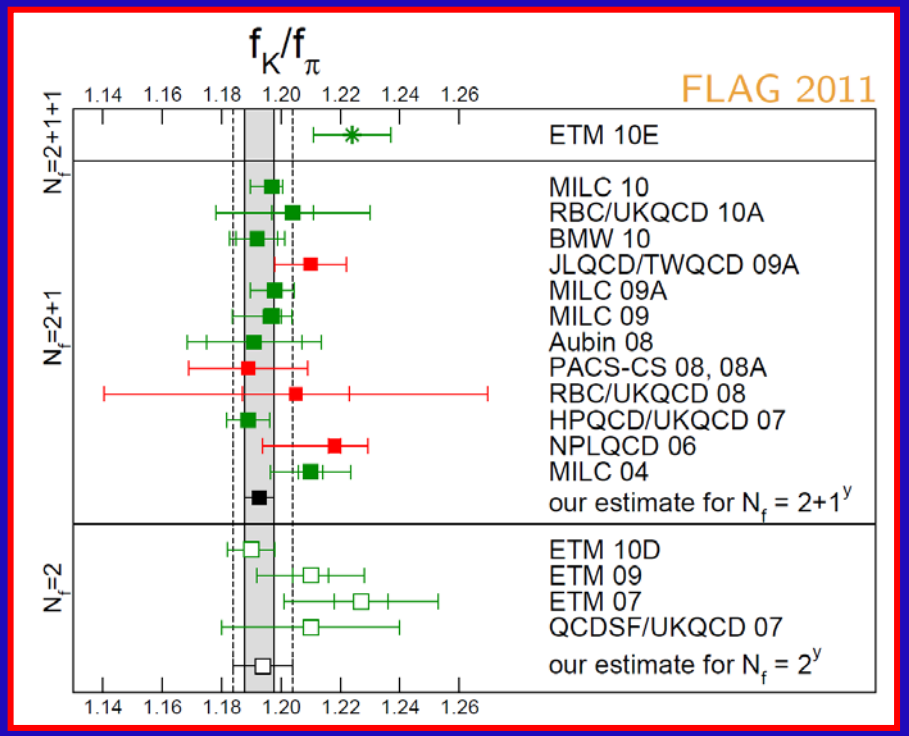
$$f_+(0) = 0.97 \pm 0.01 \quad \Rightarrow \quad |\mathbf{V_{us}}| = 0.2230 \pm 0.0024$$

$\Gamma(K^+ \to \mu^+ \nu_\mu) / \Gamma(\pi^+ \to \mu^+ \nu_\mu)$

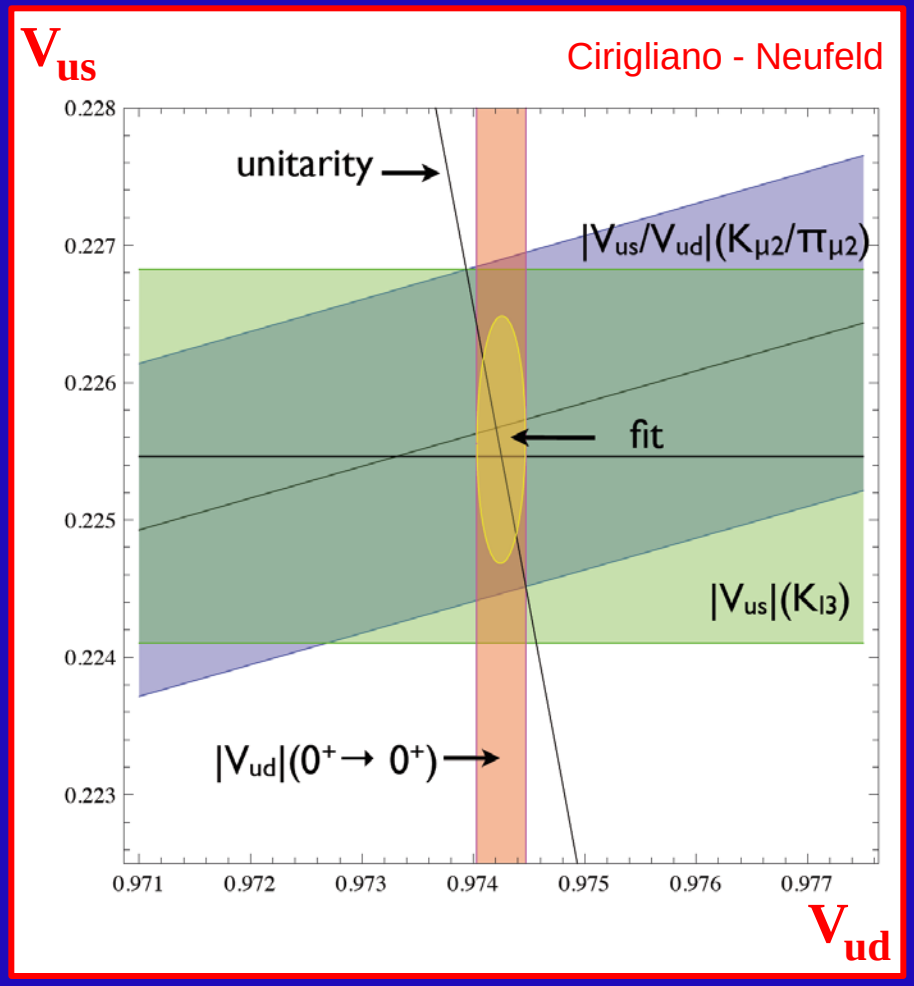
(Marciano 04)

$$\frac{f_K}{f_\pi}\frac{|V_{us}|}{|V_{ud}|} = 0.2763 \pm 0.0005 \quad \Rightarrow \quad \frac{|V_{us}|}{|V_{ud}|} = 0.2316 \pm 0.0012$$

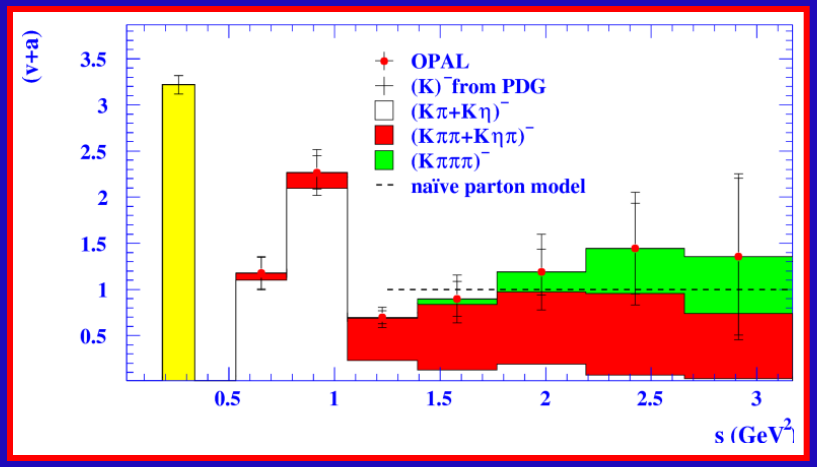
$$\langle 0 | \bar{d}_i \gamma^\mu \gamma_5 u_j | P(k) \rangle = i\, f_P\, k^\mu$$

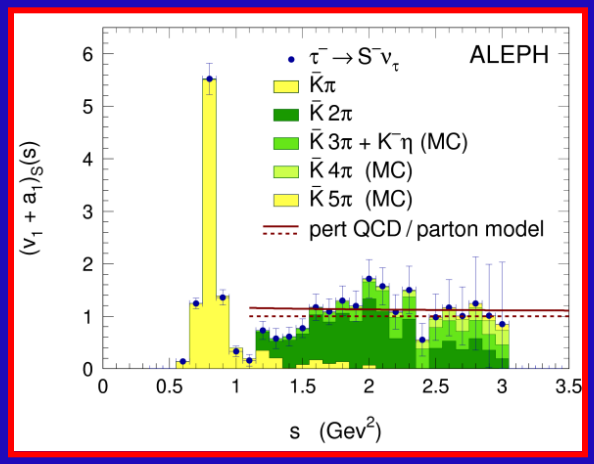


$f_K / f_\pi = 1.193 \pm 0.005$ (FLAG 2011)



$R_{\tau,S} = \Gamma(\tau^- \to \nu_\tau S^-) / \Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)$





$$\delta R_\tau \equiv \frac{R_{\tau,ud}}{|\mathbf{V_{ud}}|^2} - \frac{R_{\tau,S}}{|\mathbf{V_{us}}|^2} \approx 24\,\frac{m_s^2(m_\tau^2)}{m_\tau^2}\,\Delta(\alpha_s)$$

$$|\mathbf{V_{us}}|^2 = \frac{R_{\tau,S}}{\dfrac{R_{\tau,ud}}{|\mathbf{V_{ud}}|^2} - \delta R_\tau^{\text{th}}}$$

$$m_s(2\,\text{GeV}) = 96 \pm 10\ \text{MeV}$$

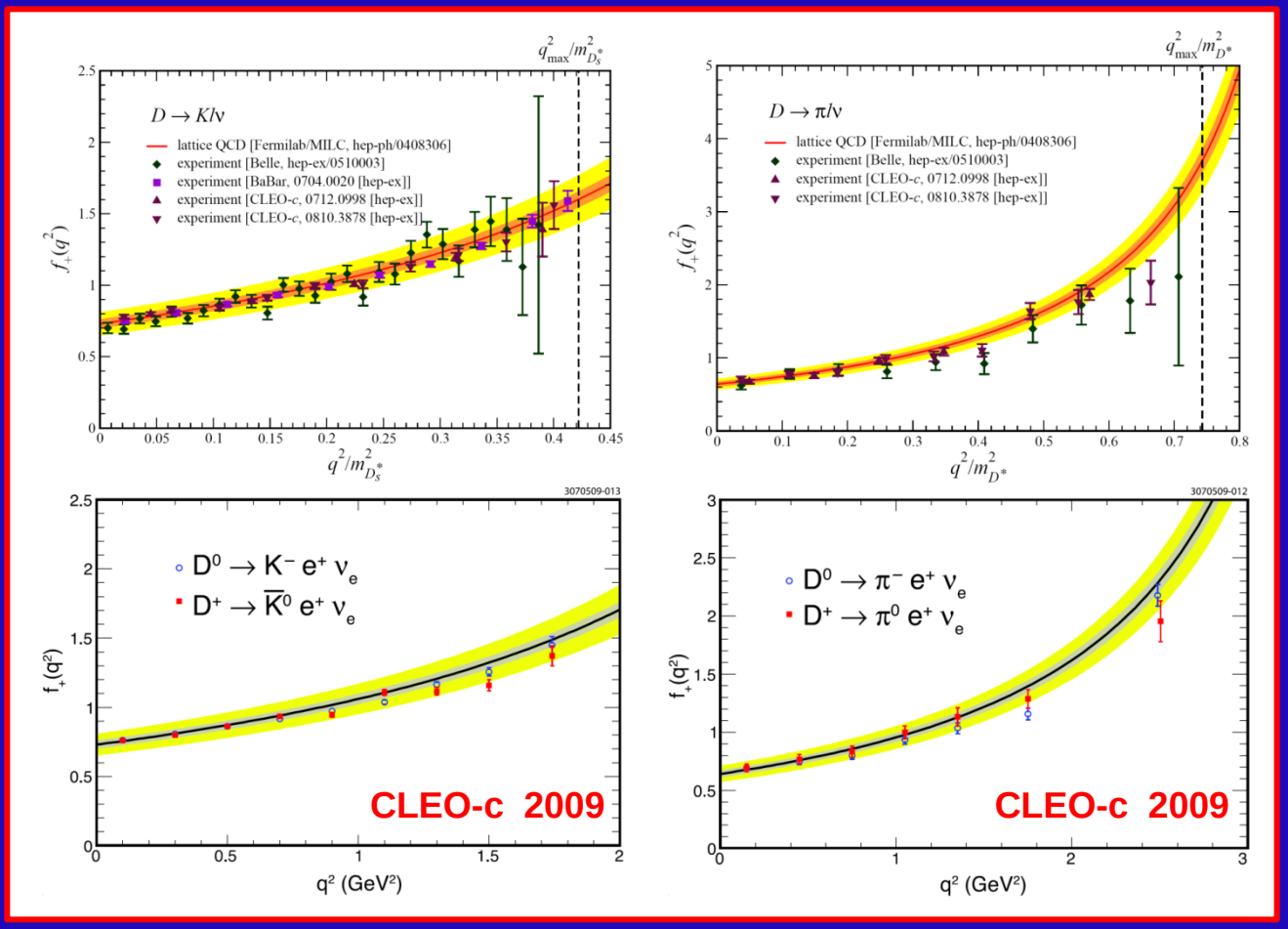
Gámiz-Jamin-Pich-Prades-Schwab

$$|\mathbf{V_{us}}| = 0.2166 \pm 0.0019_{\text{exp}} \pm 0.0005_{\text{th}}$$

Simultaneous m_s & V_{us} fit possible with better data

The τ could give the most precise V_{us} determination

$D \to K/\pi\, l\, \nu$



Lattice input

$$|V_{cs}|_{D\to Kl\nu} = 0.98 \pm 0.10$$

$$|V_{cd}|_{D\to \pi l\nu} = 0.229 \pm 0.025$$

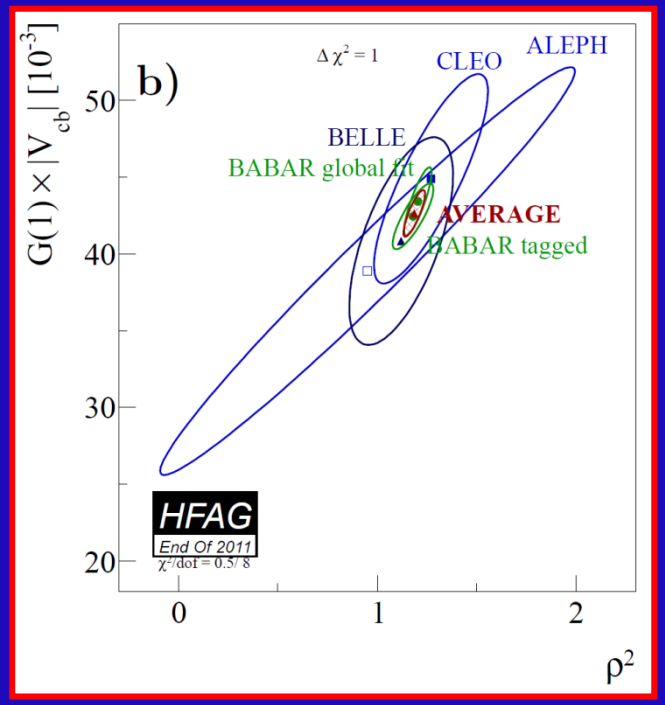
PDG 2012:

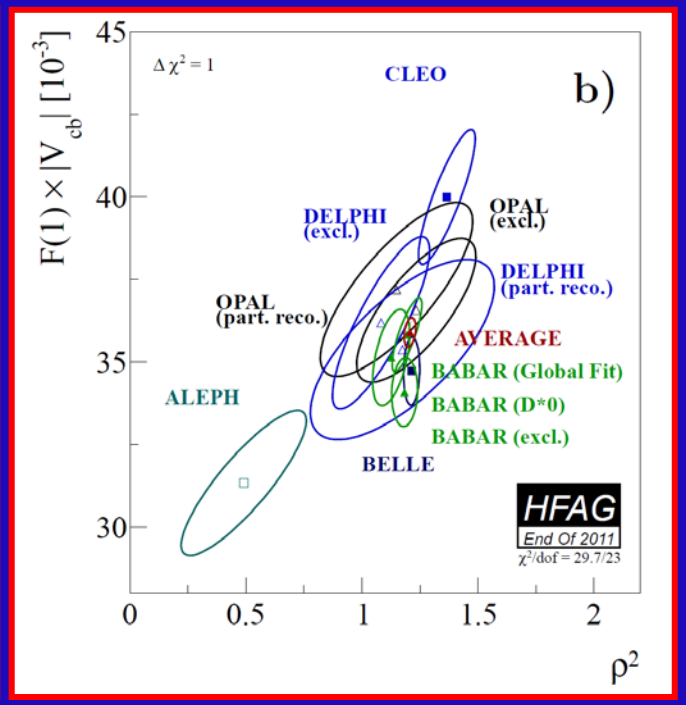
$$|V_{cd}|_{\nu c\to \mu d} = 0.230 \pm 0.011 \qquad |V_{cs}|_{D\to Kl\nu, D_s\to l\nu} = 1.006 \pm 0.023$$

$B \to D\, l\, \nu$ $\quad$ $B \to D^*\, l\, \nu$

QCD Symmetries at $1/M_Q \to 0$

HQET





$$G(1)\ |\mathbf{V_{cb}}| = (42.64 \pm 1.53) \times 10^{-3}$$

$$F(1)\ |\mathbf{V_{cb}}| = (35.90 \pm 0.45) \times 10^{-3}$$

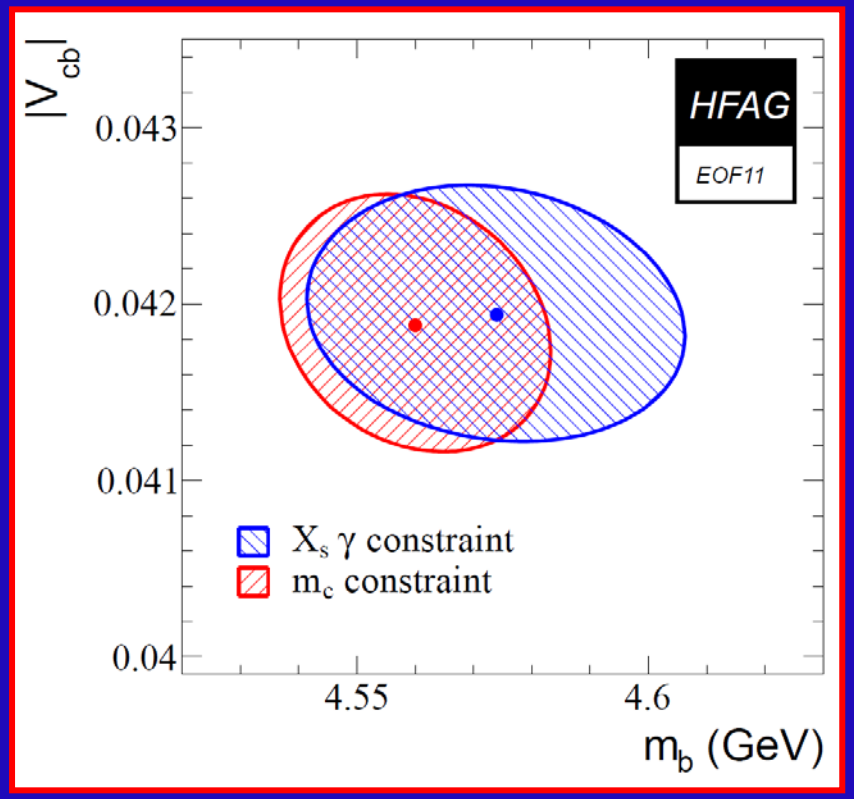
$G(1) = 1.074 \pm 0.024$ (FNAL / MILC) $\Rightarrow$ $|\mathbf{V_{cb}}| = (39.70 \pm 1.42_{\text{exp}} \pm 0.89_{\text{th}}) \cdot 10^{-3}$

$F(1) = 0.908 \pm 0.017$ (MILC) $\Rightarrow$ $|\mathbf{V_{cb}}| = (39.54 \pm 0.50_{\text{exp}} \pm 0.74_{\text{th}}) \cdot 10^{-3}$

$$\Rightarrow \quad \boxed{|\mathbf{V_{cb}}|_{\text{excl}} = (39.6 \pm 0.8) \cdot 10^{-3}}$$

Inclusive B Decays (OPE, HQET)

$$\Gamma(\bar{B} \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3} \left\{ f(\rho) + k(\rho)\frac{\mu_\pi^2}{2m_b^2} + g(\rho)\frac{\mu_G^2}{2m_b^2} \right\}$$



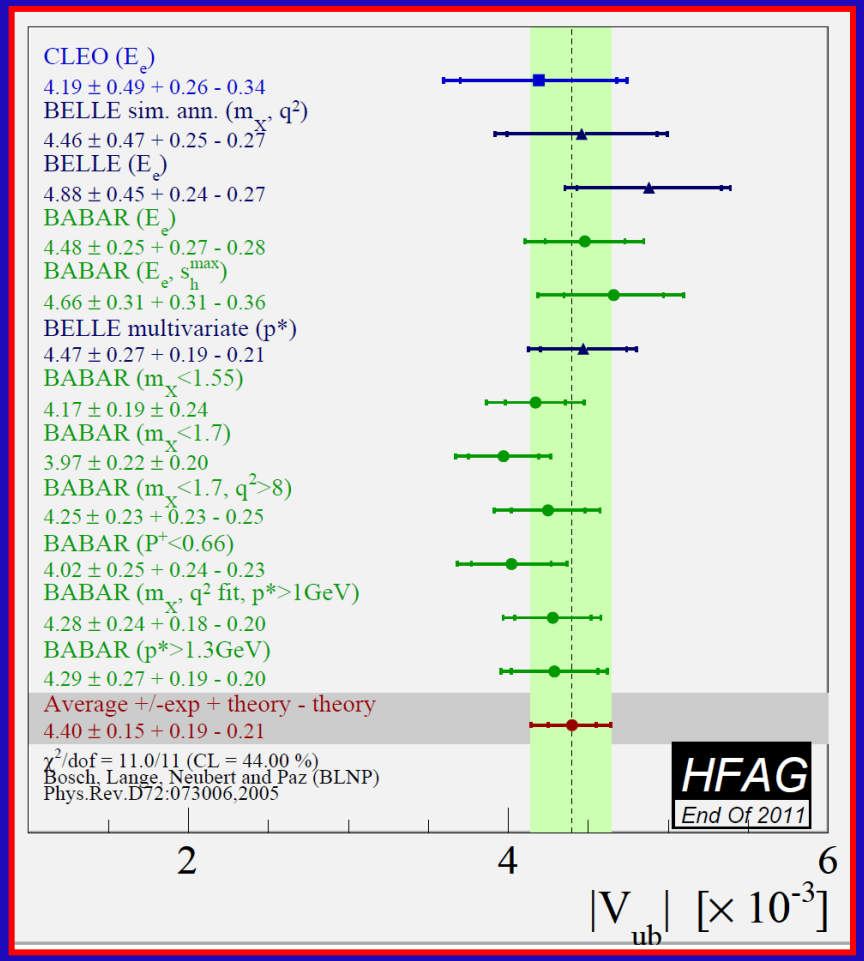
Fits to lepton energy, hadronic invariant mass and photon energy moments

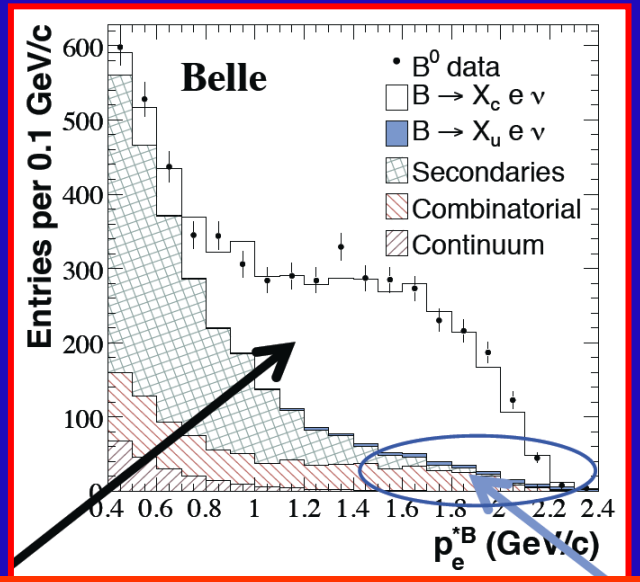
$$|\mathbf{V_{cb}}|_{\text{incl}} = (41.9 \pm 0.7) \cdot 10^{-3}$$

1.9 σ discrepancy with exclusive measurement

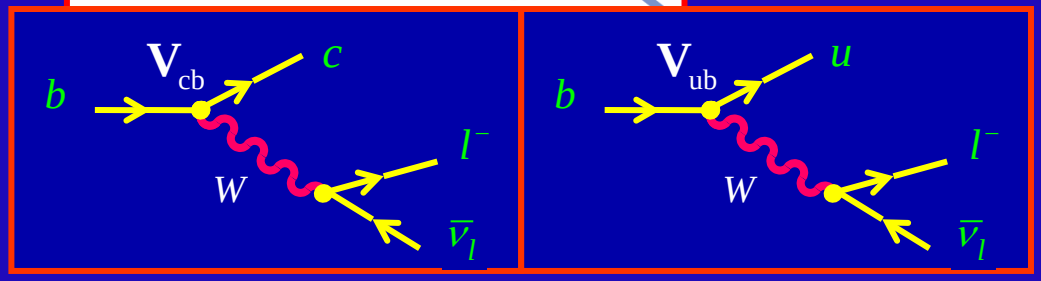
$$|\mathbf{V_{cb}}| = (40.9 \pm 1.1) \cdot 10^{-3}$$

$B \to X_u\, l\, \nu$





$$\left|\frac{V_{ub}}{V_{cb}}\right|^2 \approx \frac{1}{50}$$



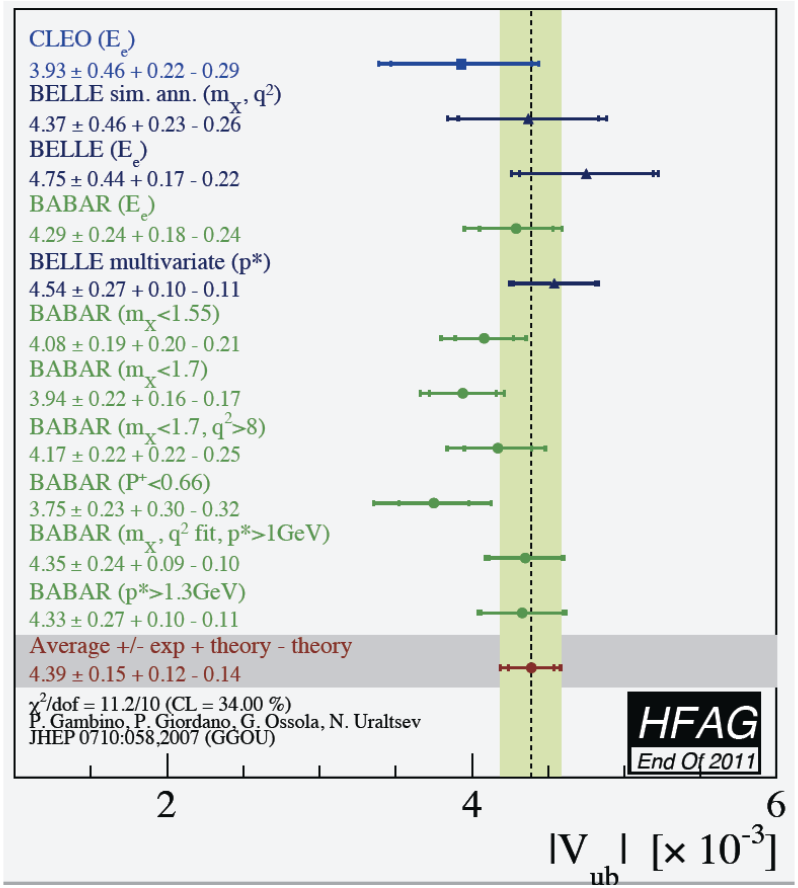
- Large backgrounds from $B \to X_c l \nu$
- Strong experimental cuts
- Large theoretical uncertainties

PDG 2012:

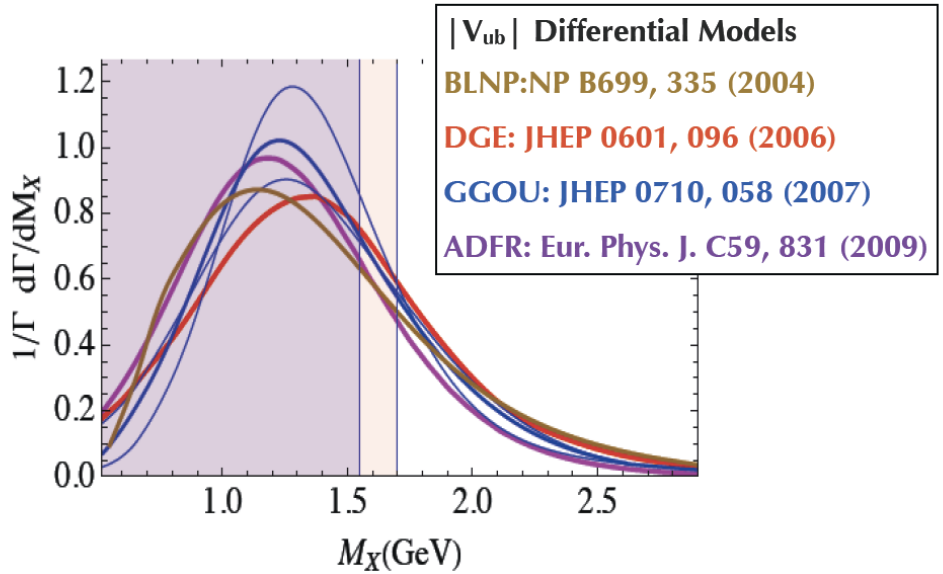
$$\left|V_{ub}\right|_{incl} = \left(4.41 \pm 0.15\,^{+0.15}_{-0.17}\right)\cdot 10^{-3}$$

Inclusive $|V_{ub}|$

Use m_c, m_b, μ_π^2 from $B \to X_c l \nu$ and $B \to X_s \gamma$



- Agreement between experiments!
- **Theory:** Error **(5-7%)** dominated by m_c, m_b, μ_π^2
- **Experiment**: Error from $B \to \rho/\omega/\eta\, l\nu$, non-resonant. & high X_u mass region (**unmeasured**)

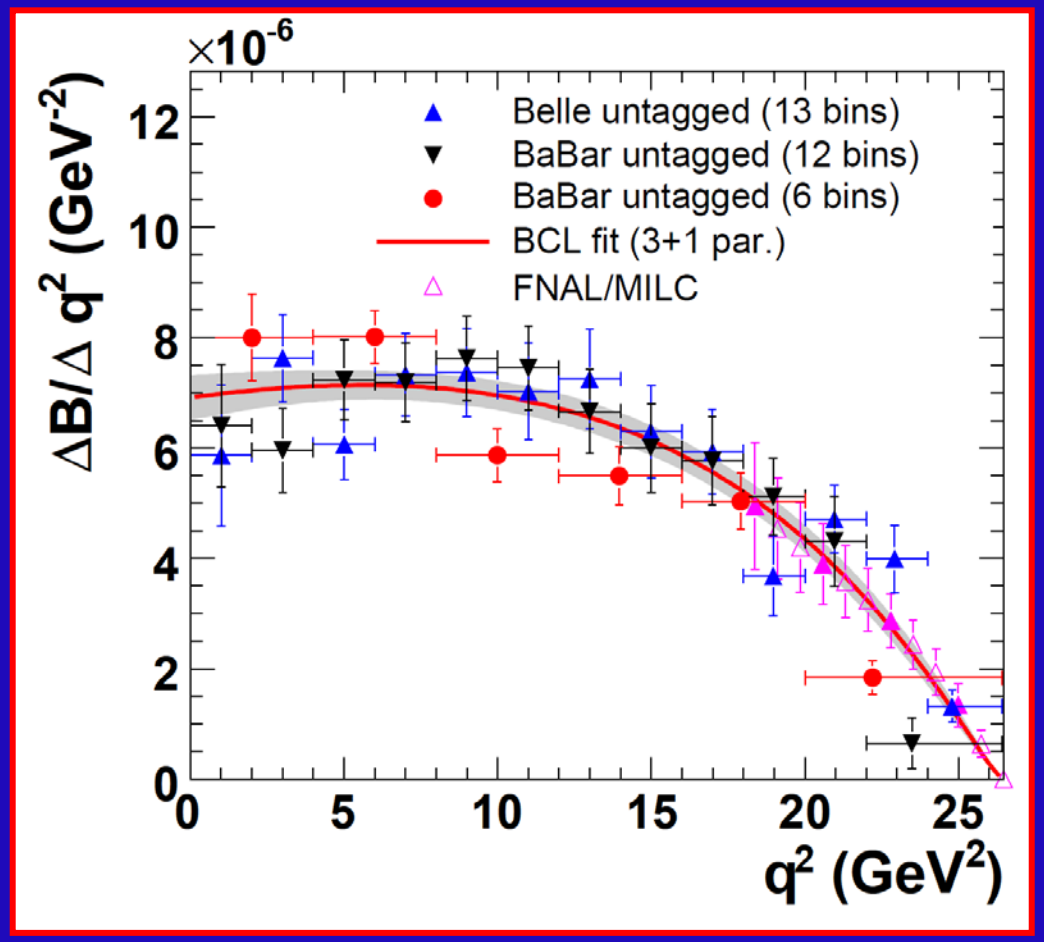


4 approaches:

BLNP, DGE, GGOU (above), ADFR

$B \to \pi\, l\, \nu$

Large theoretical uncertainties

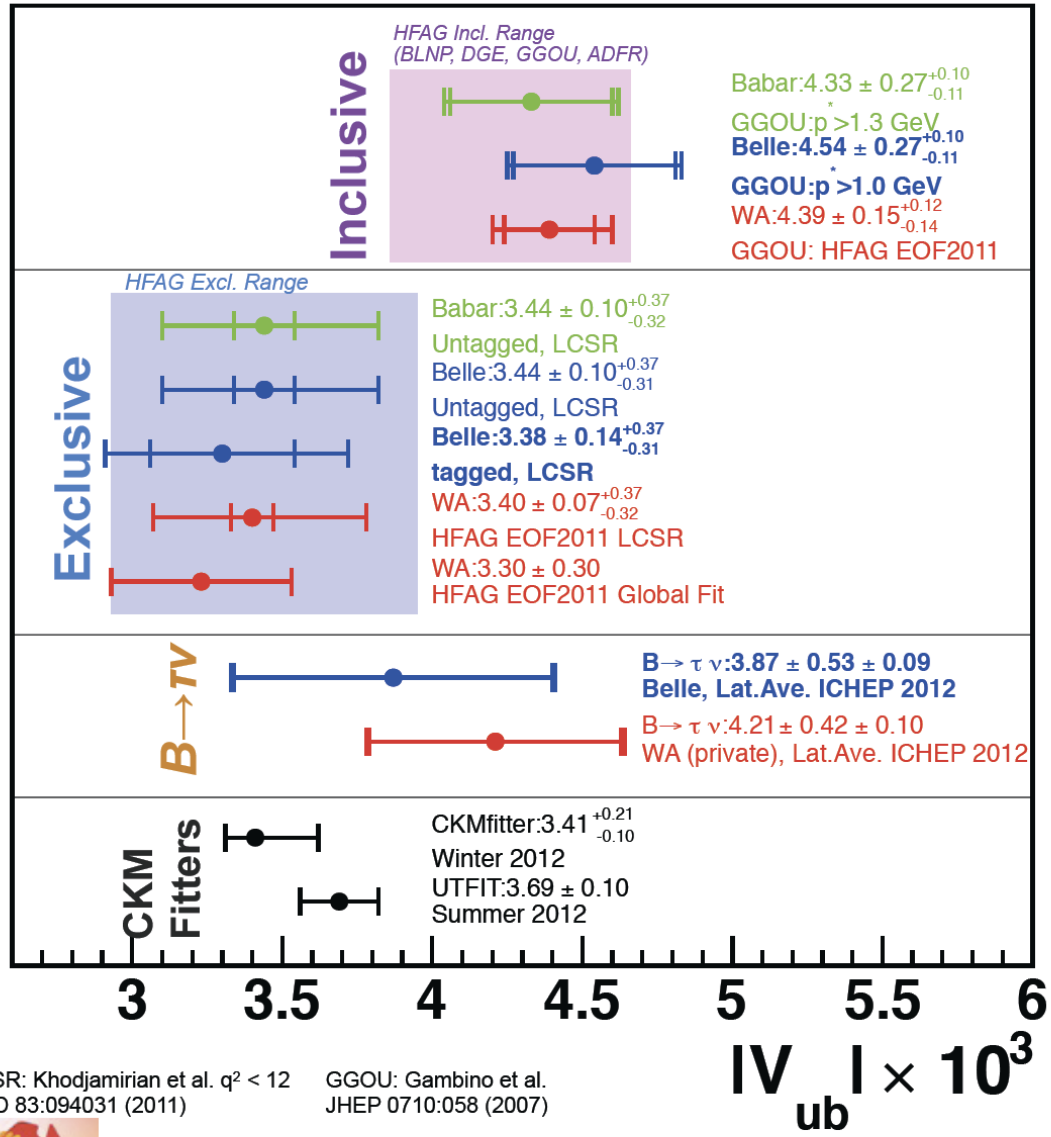


PDG 2012:

$$\left|V_{ub}\right|_{excl} = (3.23 \pm 0.31) \cdot 10^{-3}$$

$$\left|V_{ub}\right| = (4.15 \pm 0.49) \cdot 10^{-3}$$

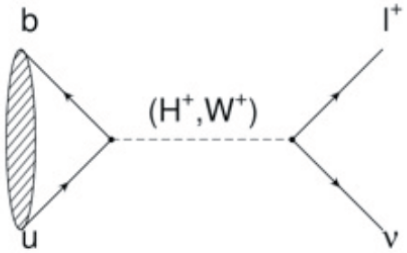
$|V_{ub}|$ Summary

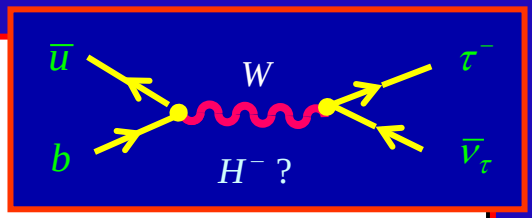


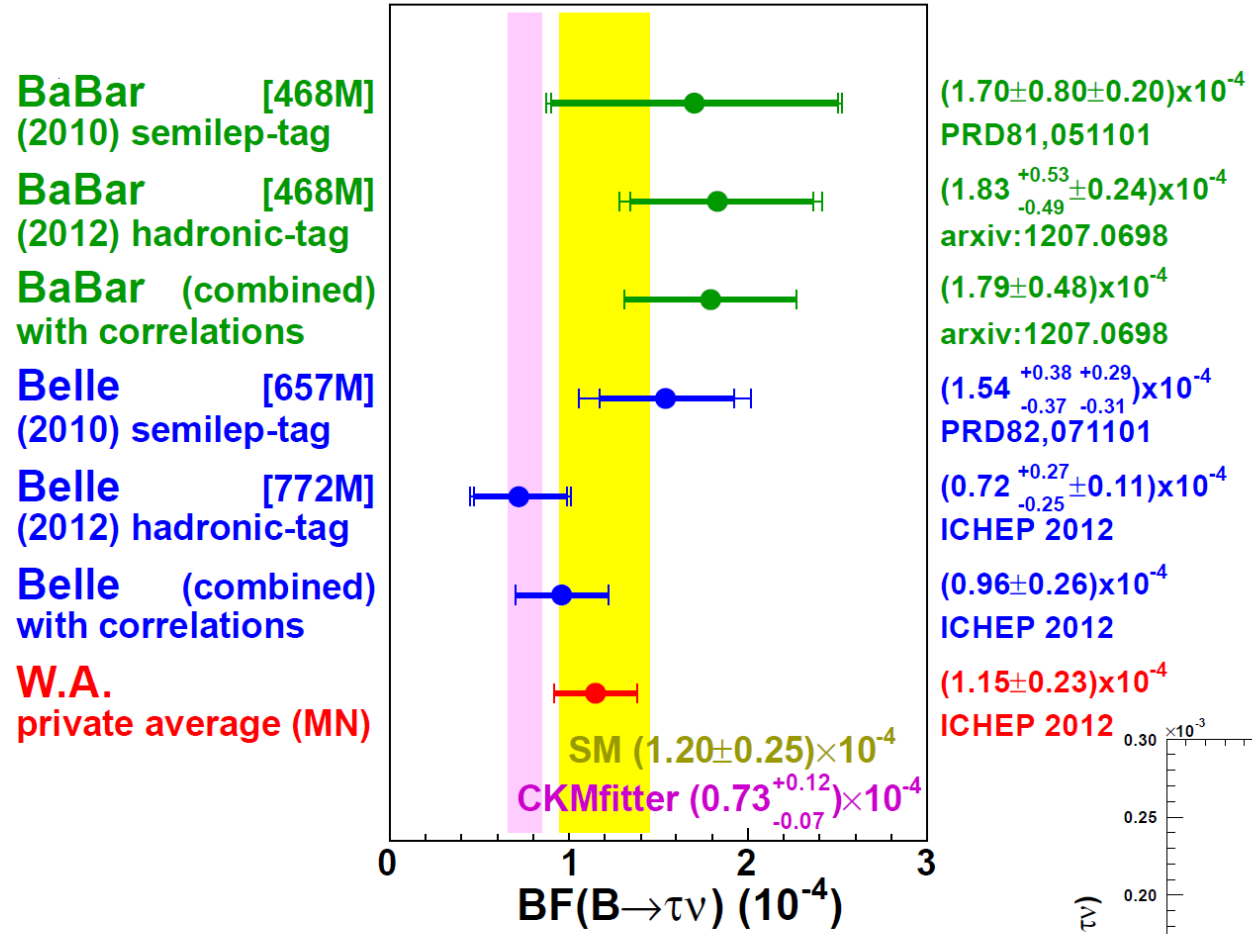
LCSR: Khodjamirian et al. $q^2 < 12$ PRD 83:094031 (2011)

GGOU: Gambino et al. JHEP 0710:058 (2007)

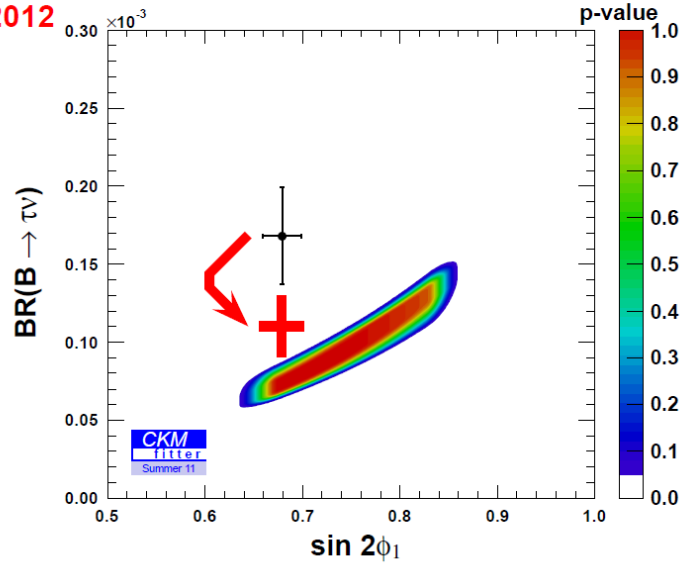
- ΔIncl.~6% (↓from 18% in 2004) ΔExcl.~10%
  Up to 2-3 σ difference between Excl.-Incl.
- Variation on WA in inclusive is substantial, but theory agrees very well for p>1.0 measurements (pure **OPE**)
- **New** Belle results on **B→τν @ICHEP 2012** in agreement with both methods. (See M.Nakao's talk).
  ΔLeptonic.~10%!!







Tension between $B^+ \to \tau^+\nu$ world average and CKM fit becomes much smaller



V_{ij} DETERMINATION

CKM entry	Value	Source
$\lvert V_{ud}\rvert$	$\mathbf{0.97425 \pm 0.00022}$ 0.9773 ± 0.0017 0.9741 ± 0.0026	Nuclear β decay $n \to p e^- \bar{\nu}_e$ $\pi^+ \to \pi^0 e^+ \nu_e$
$\lvert V_{us}\rvert$	$\mathbf{0.2255 \pm 0.0014}$ 0.2166 ± 0.0020 0.2256 ± 0.0012	$K \to \pi e^- \bar{\nu}_e$ τ decays $K/\pi \to \mu\nu$, Lattice
$\lvert V_{cd}\rvert$	$\mathbf{0.230 \pm 0.011}$ 0.229 ± 0.025	$\nu d \to c X$ $D \to \pi l \nu$, Lattice
$\lvert V_{cs}\rvert$	$\mathbf{1.006 \pm 0.023}$	$D \to K l \nu$, $D_s \to l \nu$, Lattice
$\lvert V_{cb}\rvert$	0.0396 ± 0.0008 0.0419 ± 0.0007 $\mathbf{0.0409 \pm 0.0011}$	$B \to D^*/D\, l\, \bar{\nu}_l$ $b \to c\, l\, \bar{\nu}_l$
$\lvert V_{ub}\rvert$	0.00323 ± 0.00031 0.00441 ± 0.00032 $\mathbf{0.00415 \pm 0.00049}$	$B \to \pi\, l\, \bar{\nu}_l$ $b \to u\, l\, \bar{\nu}_l$
$\lvert V_{tb}\rvert \Big/ \sqrt{\sum_q \lvert V_{tq}\rvert^2}$ $\lvert V_{tb}\rvert$	> 0.92 (95% CL) $\mathbf{0.89 \pm 0.07}$	$t \to bW / t \to qW$ $p\bar{p} \to tb + X$

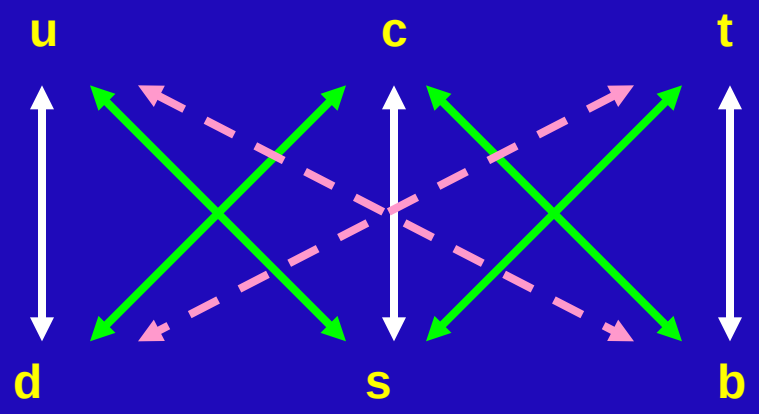
$$\lvert V_{ud}\rvert^2 + \lvert V_{us}\rvert^2 + \lvert V_{ub}\rvert^2 = \mathbf{1.0000 \pm 0.0007}$$

$$\sum_j \left(\lvert V_{uj}\rvert^2 + \lvert V_{cj}\rvert^2 \right) = 2.002 \pm \mathbf{0.027} \quad \text{(LEP)}$$

Hierarchical Structure

$$\mathbf{V} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

$$\lambda \approx \sin\theta_C \approx 0.226 \quad ; \quad A \approx 0.80 \quad ; \quad \sqrt{\rho^2+\eta^2} \approx 0.45$$



QUARK MIXING MATRIX

- **Unitary** $N_G \times N_G$ **Matrix:** N_G^2 **parameters**

$$\mathbf{V} \cdot \mathbf{V}^\dagger = \mathbf{V}^\dagger \cdot \mathbf{V} = \mathbf{1}$$

- $2\,N_G - 1$ **arbitrary phases:**

$$u_i \to e^{i\phi_i}\, u_i \quad ; \quad d_j \to e^{i\theta_j}\, d_j \quad \Rightarrow \quad \mathbf{V}_{ij} \to e^{i(\theta_j - \phi_i)}\, \mathbf{V}_{ij}$$

$\mathbf{V}_{ij}$ **Physical Parameters:**

$\frac{1}{2} N_G (N_G - 1)$ **Moduli** ; $\frac{1}{2}(N_G - 1)(N_G - 2)$ **phases**

- **$N_f = 2$: 1 angle, 0 phases (Cabibbo)**

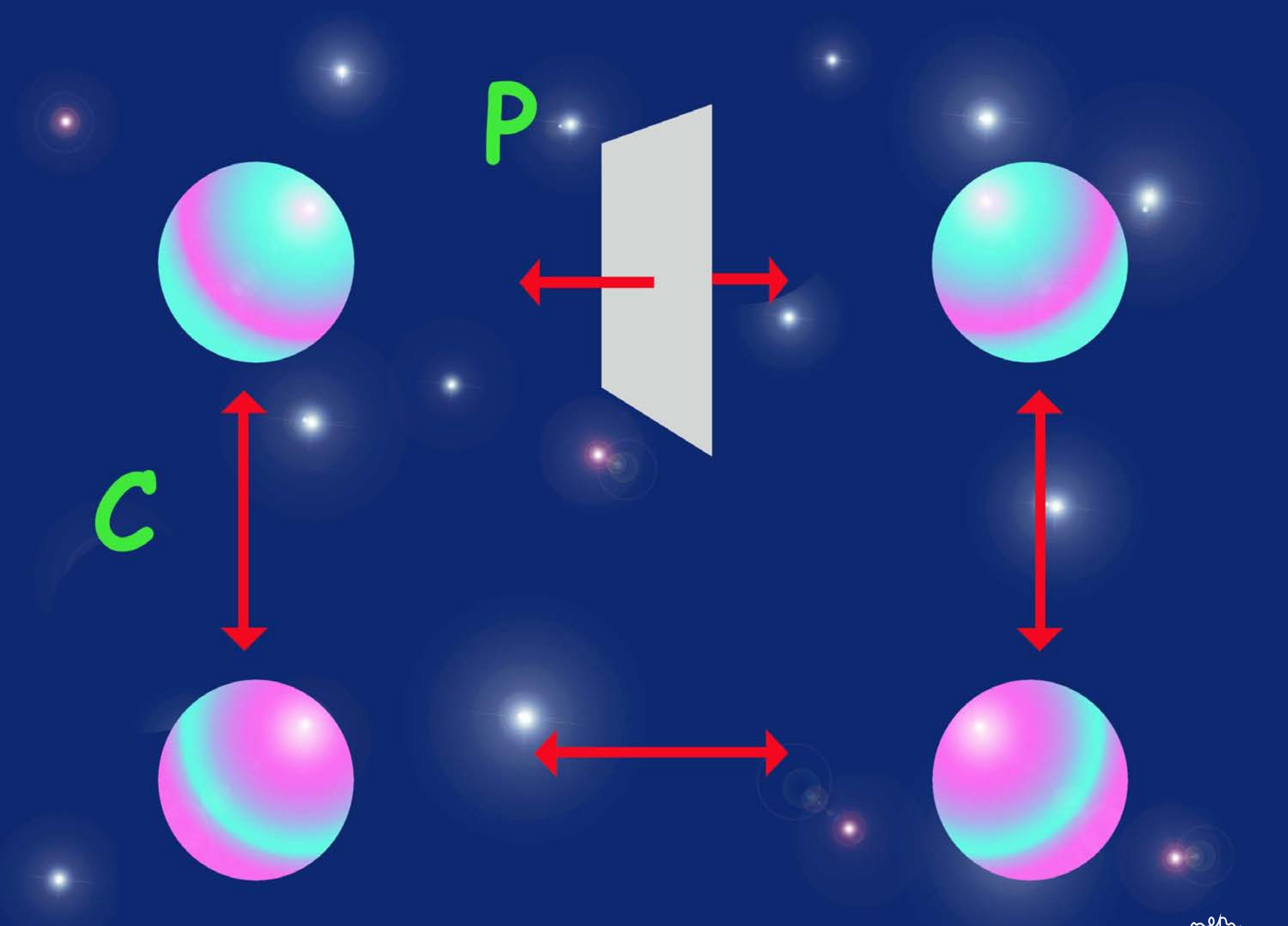
$$\mathbf{V} = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \quad \Rightarrow \quad \text{No } \not{CP}$$

- **$N_f = 3$: 3 angles, 1 phase (CKM)** $c_{ij} \equiv \cos\theta_{ij}$; $s_{ij} \equiv \sin\theta_{ij}$

$$\mathbf{V} = \begin{bmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{13}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & c_{23}\, c_{13} \end{bmatrix}$$

$$\approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\,(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\,(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

$\lambda \approx \sin\theta_C \approx 0.226$; $A \approx 0.80$; $\sqrt{\rho^2+\eta^2} \approx 0.45$ $\quad \delta_{13} \neq 0 \quad (\eta \neq 0) \Rightarrow \not{CP}$


P
C

- $\mathcal{C}$, $\mathcal{P}$: Violated maximally in weak interactions
- $\mathcal{CP}$: Symmetry of nearly all observed phenomena
- Slight (~ 0.2 %) $\not{\mathcal{CP}}$ in K^0 decays (1964)
- Sizeable $\not{\mathcal{CP}}$ in B^0 decays (2001)
- Huge Matter — Antimatter Asymmetry in our Universe $\Longrightarrow$ Baryogenesis

$\mathcal{CPT}$ **Theorem:** $\not{\mathcal{CP}} \Longleftrightarrow \not{\mathcal{T}}$

Thus, $\not{\mathcal{CP}}$ requires:

- Complex Phases
- Interferences

Standard Model $\not{CP}$: 3 fermion families needed

$$\not{CP} \quad \Longleftrightarrow \quad \mathbf{H}(M_u^2) \cdot \mathbf{H}(M_d^2) \cdot \mathbf{J} \neq 0$$

$$\mathbf{H}(M_u^2) \equiv (m_t^2 - m_c^2)\,(m_c^2 - m_u^2)\,(m_t^2 - m_u^2)$$

$$\mathbf{H}(M_d^2) \equiv (m_b^2 - m_s^2)\,(m_s^2 - m_d^2)\,(m_b^2 - m_d^2)$$

$$\mathbf{J} = c_{12}\, c_{13}^2\, c_{23}\, s_{12}\, s_{13}\, s_{23} \sin\delta_{13} = \left| A^2 \lambda^6 \eta \right| < 10^{-4}$$

- Low-Energy Phenomena
- Small Effects ~ J
- Big Asymmetries $\Longleftrightarrow$ Suppressed Decays
- B Decays are an optimal place for $\not{CP}$ signals