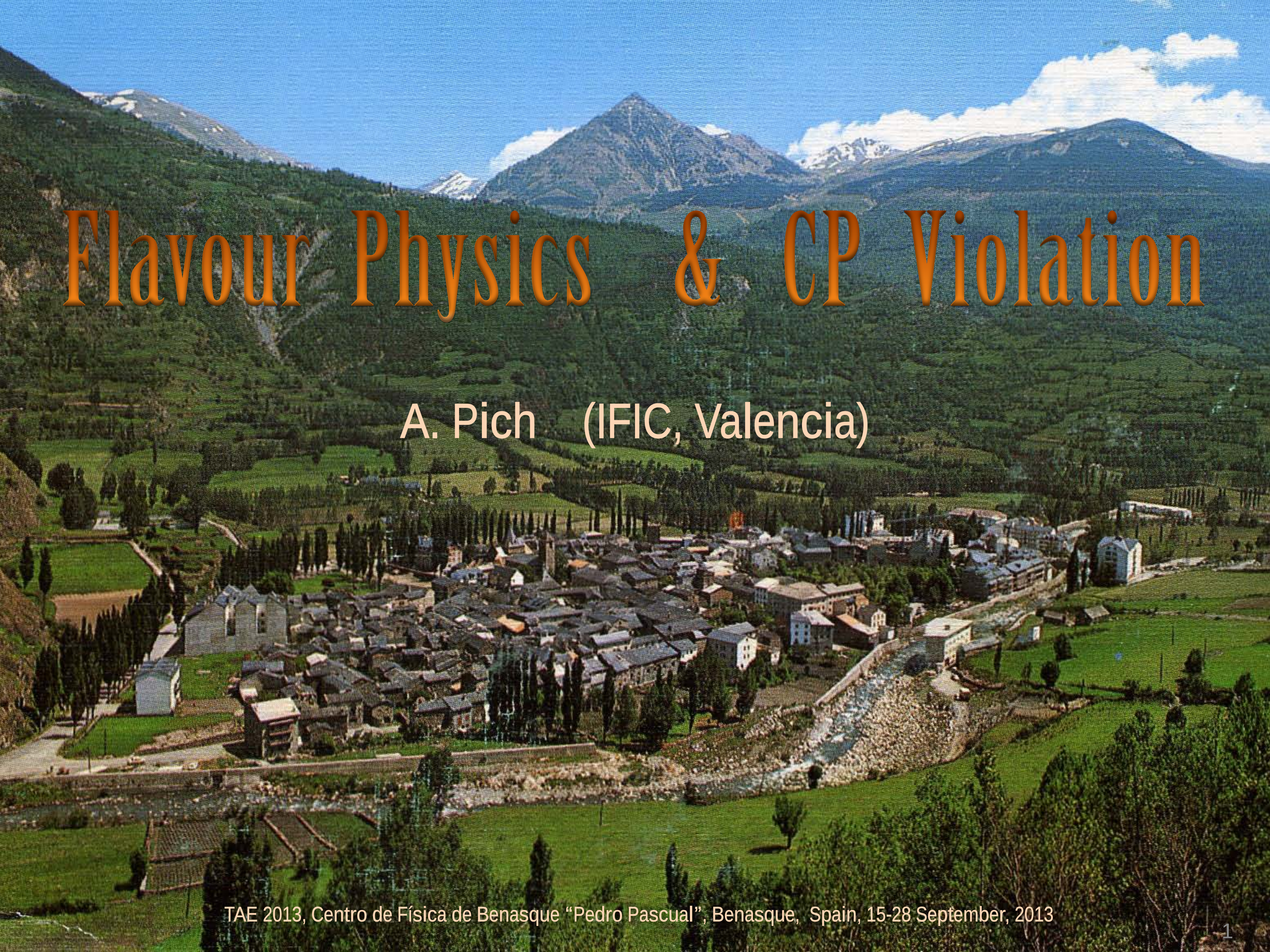


Flavour Physics & CP Violation

A. Pich (IFIC, Valencia)

TAE 2013, Centro de Física de Benasque "Pedro Pascual", Benasque, Spain, 15-28 September, 2013


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

Flavour Structure of the Standard Model

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

Why 3 ?

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

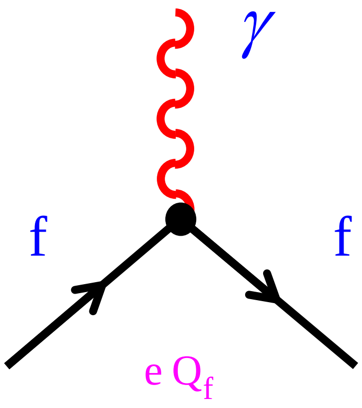
↔

Related to SSB

Scalar Sector (Higgs)

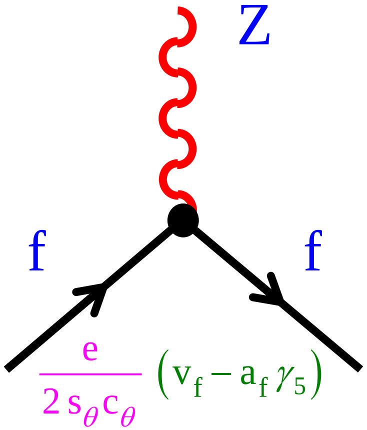
- **Kaon Factories :** u , d , s
- **τcF :** c , τ
- **BF, S-BF :** b , c , τ
- **LHC :** t , b, c
- **LC :** t , …
- **νF :** ν_e , ν_μ , ν_τ

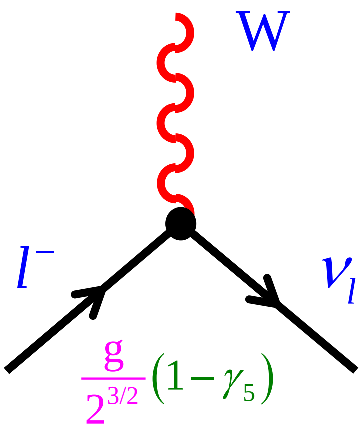
Universality: Family–Independent Couplings



NEUTRAL CURRENTS

Flavour Conserving

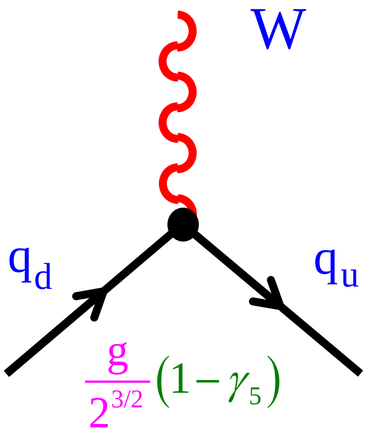


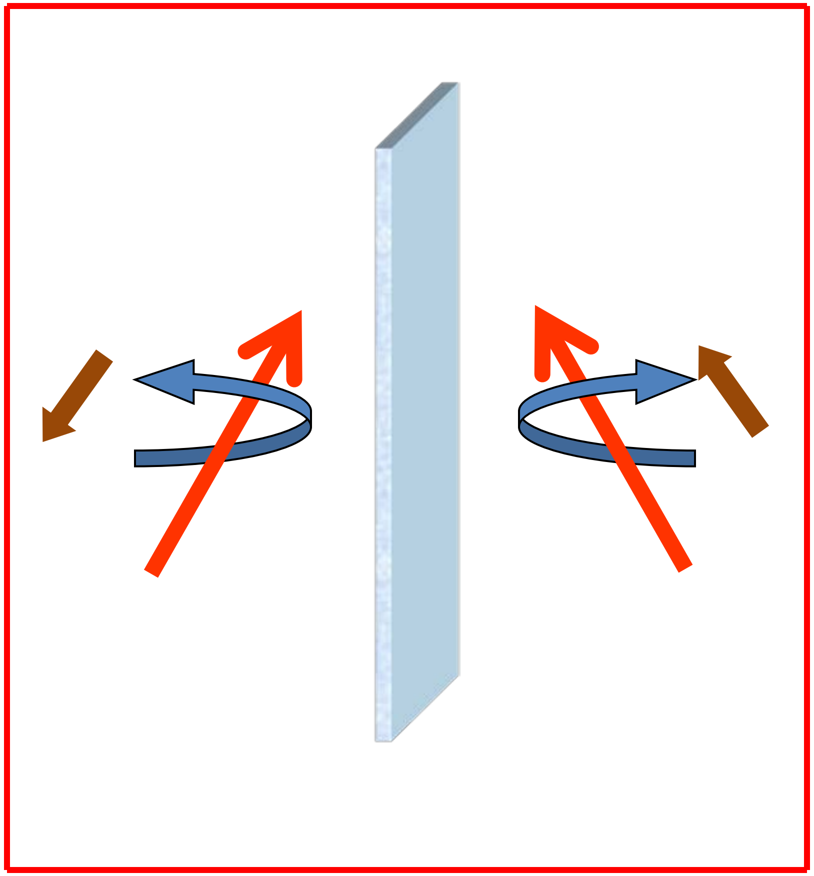


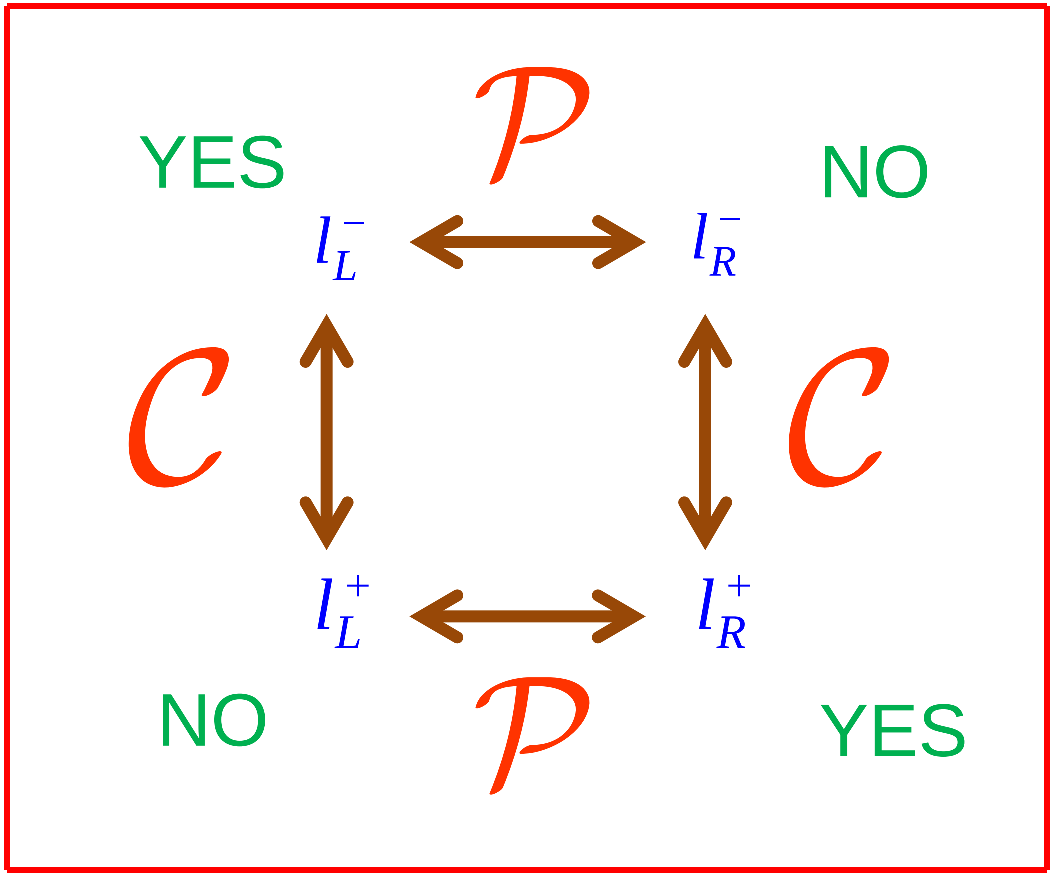
CHARGED CURRENTS

Flavour Changing

Left Handed







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

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

FERMION MASSES

Scalar – Fermion Couplings allowed by Gauge Symmetry

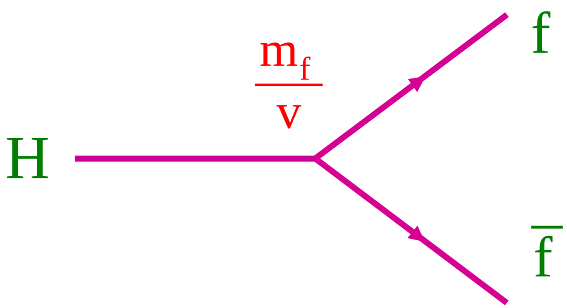
$$\mathcal{L}_Y = -\,(\bar{q}_u\,,\bar{q}_d\,)_L \left[c^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} (q_d)_R + c^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} (q_u)_R \right] - (\bar{\nu}_l , \bar{l}\,)_L \; c^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)}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

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: $\quad g_{Hf\bar{f}} = \dfrac{m_f}{\mathrm{v}}$

FERMION GENERATIONS

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

$$Q = 0 \qquad \begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix} \qquad Q = +2/3$$
$$Q = -1 \qquad\qquad\qquad\qquad Q = -1/3$$

$$(j = 1, \cdots, N_G)\, a$$

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

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

Arbitrary Non-Diagonal Complex Mass Matrices

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

DIAGONALIZATION OF MASS MATRICES

$$\mathbf{M}'_d = \mathbf{H}_d \cdot \mathbf{U}_d = \mathbf{S}_d^\dagger \cdot \mathcal{M}_d \cdot \mathbf{S}_d \cdot \mathbf{U}_d \qquad \mathbf{H}_f = \mathbf{H}_f^\dagger$$

$$\mathbf{M}'_u = \mathbf{H}_u \cdot \mathbf{U}_u = \mathbf{S}_u^\dagger \cdot \mathcal{M}_u \cdot \mathrm{S}_u \cdot \mathbf{U}_u \qquad \mathbf{U}_f \cdot \mathbf{U}_f^\dagger = \mathbf{U}_f^\dagger \cdot \mathbf{U}_f = 1$$

$$\mathbf{M}'_l = \mathbf{H}_l \cdot \mathbf{U}_l = \mathbf{S}_l^\dagger \cdot \mathcal{M}_l \cdot \mathbf{S}_l \cdot \mathbf{U}_l \qquad \mathbf{S}_f \cdot \mathbf{S}_f^\dagger = \mathbf{S}_f^\dagger \cdot \mathbf{S}_f = 1$$

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

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

$$d_L \equiv \mathbf{S}_d \cdot d'_L \quad ; \quad u_L \equiv \mathbf{S}_u \cdot u'_L \quad ; \quad l_L \equiv \mathbf{S}_l \cdot l'_L$$

$$d_R \equiv \mathbf{S}_d \cdot \mathbf{U}_d \cdot d'_R \quad ; \quad u_R \equiv \mathbf{S}_u \cdot \mathbf{U}_u \cdot u'_R \quad ; \quad l_R \equiv \mathbf{S}_l \cdot \mathbf{U}_l \cdot l'_R$$

Mass Eigenstates ≠ Weak Eigenstates

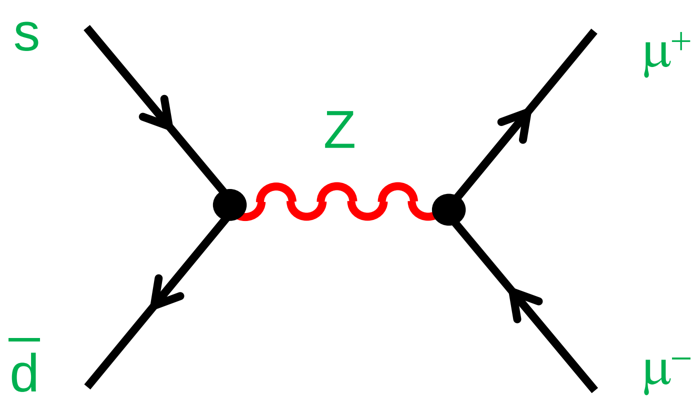
$$\bar{f}'_L f'_L = \bar{f}_L f_L \quad ; \quad \bar{f}'_R f'_R = \bar{f}_R f_R \quad \Longrightarrow \quad \mathcal{L}'_{NC} = \mathcal{L}_{NC}$$

$$\bar{u}'_L d'_L = \bar{u}_L \cdot \mathbf{V} \cdot d_L \quad ; \quad \mathbf{V} \equiv \mathbf{S}_u \cdot \mathbf{S}_d^\dagger \quad \Longrightarrow \quad \mathcal{L}'_{CC} \neq \mathcal{L}_{CC}$$

QUARK MIXING

Flavour Conserving Neutral Currents (GIM)

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



NO

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

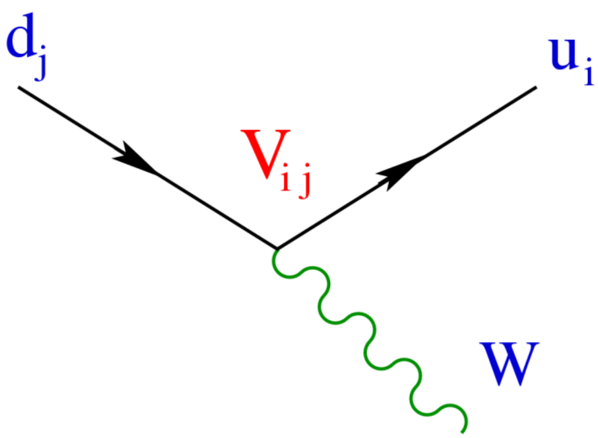
$$K_L \to \pi^{0*} \to (\gamma\gamma)^* \to \mu^+\mu^-$$

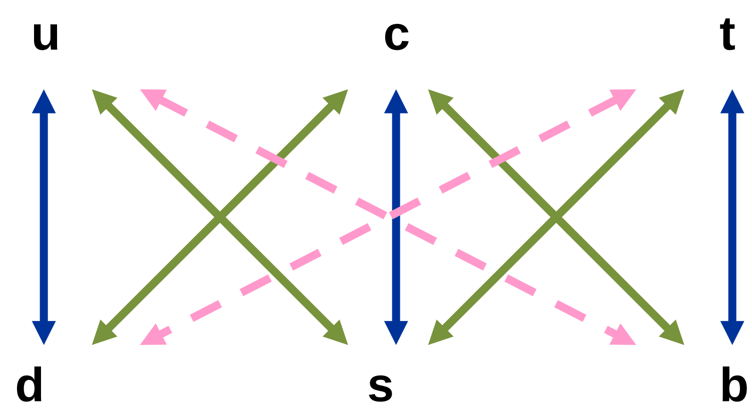
$$K_S \to (\pi^+\pi^-)^* \to (\gamma\gamma)^* \to \mu^+\mu^-$$

Flavour Changing Charged Currents

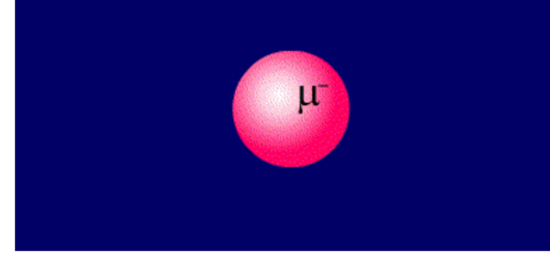
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}\, W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5)\, \mathbf{V}_{ij}\, d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5)\, l \right] + \text{h.c.}$$

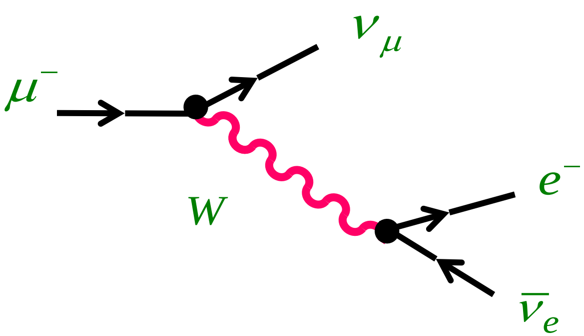
$$\left(\bar{\nu}_{l_j} \equiv \bar{\nu}_i \;\; \mathbf{V}_{ij}^{(l)} \right)$$

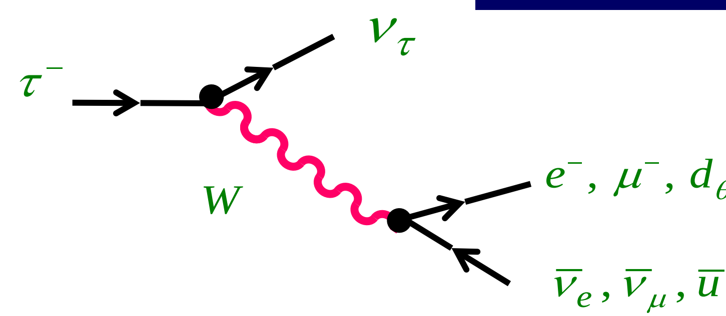




Weak Decays





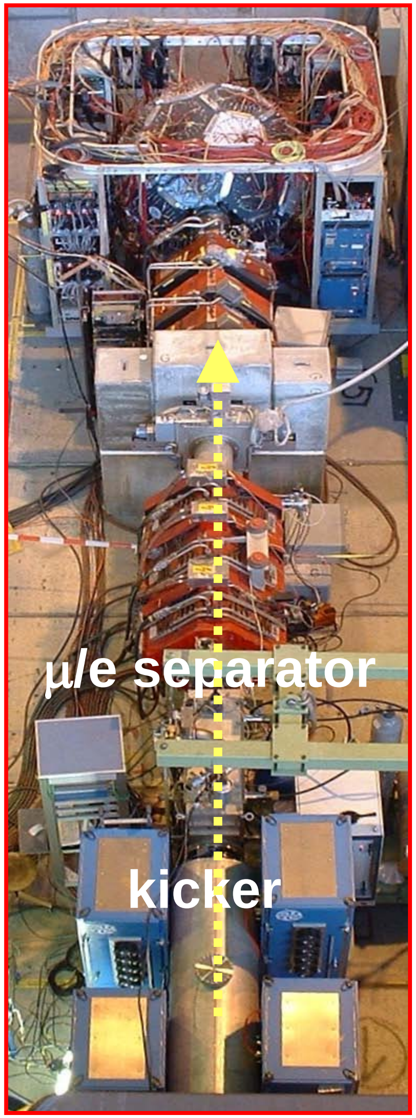


$$T(l \to \nu_l\, l' \bar{\nu}_{l'}) \sim \frac{g^2}{M_W^2 - q^2} \quad \xrightarrow{q^2 \ll M_W^2} \quad \frac{g^2}{M_W^2} = 4\sqrt{2}\, G_F$$

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

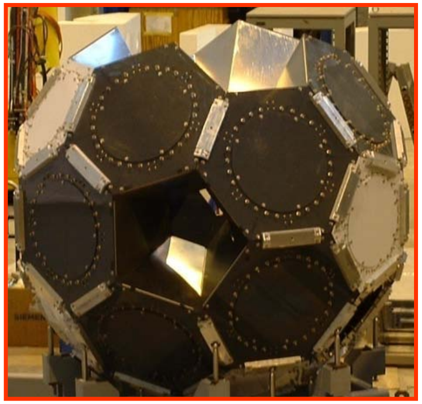
$$r_{EW} = \left[1 + \frac{\alpha(m_\mu)}{2\pi} \left(\frac{25}{4} - \pi^2 \right) + C_2\, \frac{\alpha(m_\mu)^2}{\pi^2} \right] = 0.9958 \qquad ; \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$$

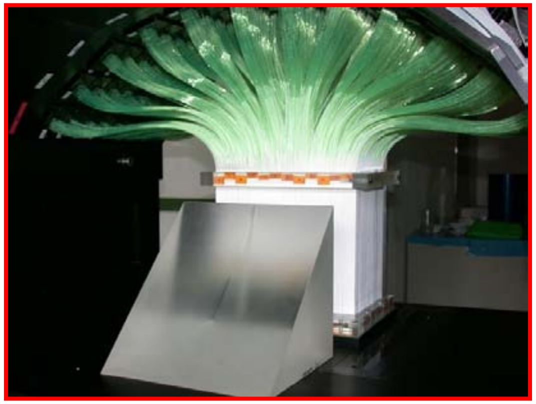
Muon Lifetime



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

MULAN





FAST

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

δ_{QED} known to 0.3 ppm

(van-Ritbergen & Stuart)

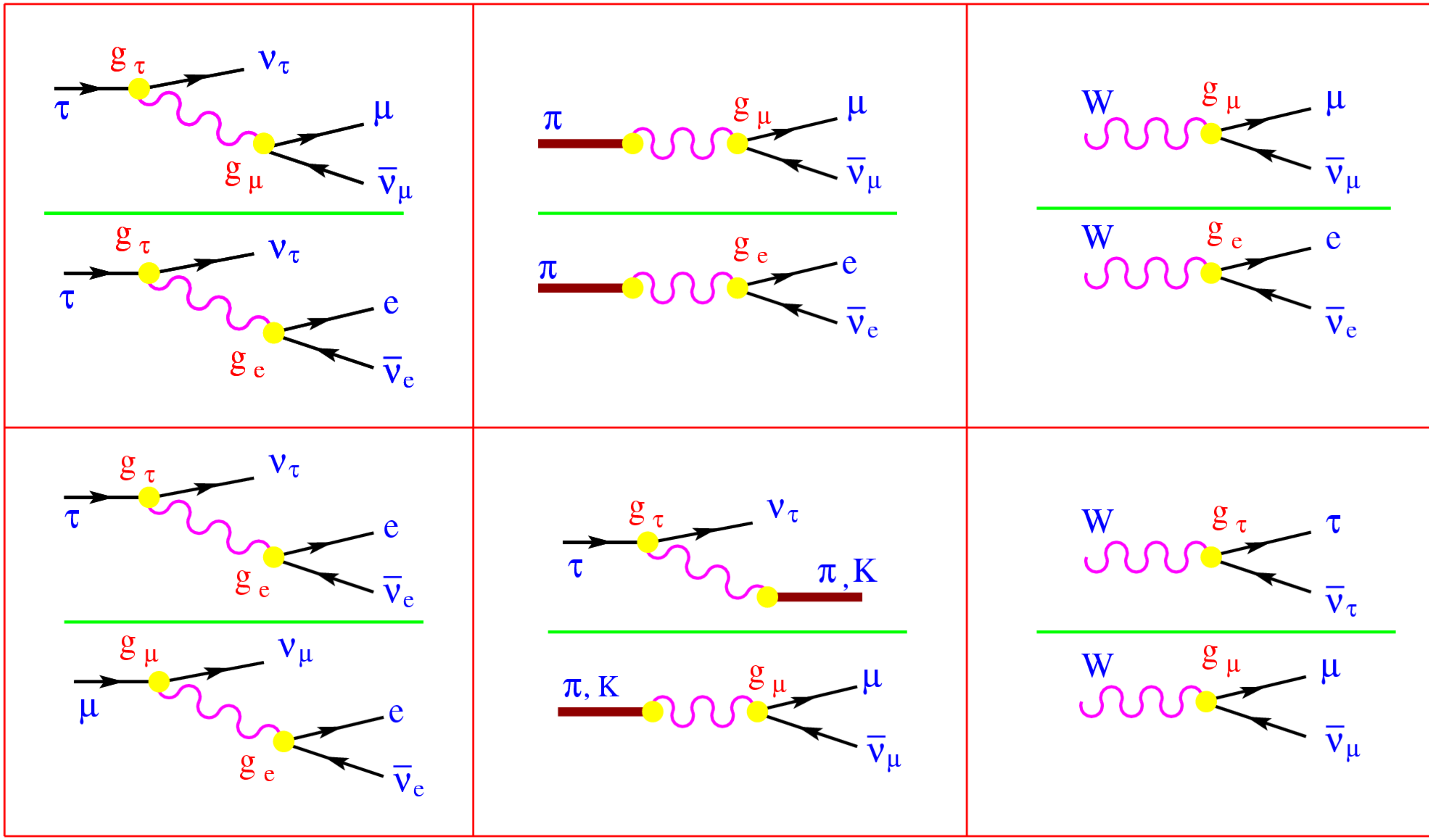
New World Average:

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 ± 0.0020
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	0.991 ± 0.009

$$|g_\tau / g_\mu|$$

$B_{\tau\to e}\;\tau_\mu/\tau_\tau$	1.0006 ± 0.0021
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9956 ± 0.0031
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.9852 ± 0.0072
$B_{W\to\tau}/B_{W\to\mu}$	1.032 ± 0.012

$$|g_\tau / g_e|$$

$B_{\tau\to\mu}\;\tau_\mu/\tau_\tau$	1.0024 ± 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'13, SINDRUM'88, Bolton'88, BABAR , BELLE]

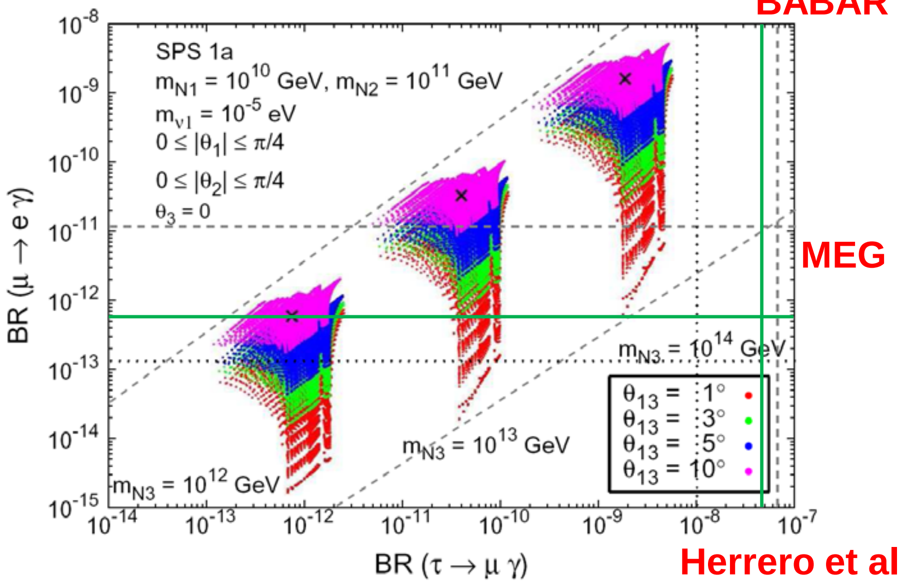
Decay	U.L.	Decay	U.L.	Decay	U.L.
$\mu^- \to e^-\gamma$	$5.7 \cdot 10^{-13}$	$\mu^- \to e^-e^+e^-$	$1.0 \cdot 10^{-12}$	$\mu^- \to e^-\gamma\gamma$	$7.2 \cdot 10^{-11}$
$\tau^- \to e^-\gamma$	$3.3 \cdot 10^{-8}$	$\tau^- \to e^-e^+e^-$	$2.7 \cdot 10^{-8}$	$\tau^- \to e^-e^+\mu^-$	$1.8 \cdot 10^{-8}$
$\tau^- \to \mu^-\gamma$	$4.4 \cdot 10^{-8}$	$\tau^- \to e^-\mu^+\mu^-$	$2.7 \cdot 10^{-8}$	$\tau^- \to \mu^-e^+\mu^-$	$1.7 \cdot 10^{-8}$
$\tau^- \to e^-e^-\mu^+$	$1.5 \cdot 10^{-8}$	$\tau^- \to \mu^-\mu^+\mu^-$	$2.1 \cdot 10^{-8}$	$\tau^- \to e^-\pi^0$	$8.0 \cdot 10^{-8}$
$\tau^- \to \mu^-\pi^0$	$1.1 \cdot 10^{-7}$	$\tau^- \to e^-\eta'$	$1.6 \cdot 10^{-7}$	$\tau^- \to \mu^-\eta'$	$1.3 \cdot 10^{-7}$
$\tau^- \to e^-\eta$	$9.2 \cdot 10^{-8}$	$\tau^- \to \mu^-\eta$	$6.5 \cdot 10^{-8}$	$\tau^- \to e^-K^{*0}$	$3.2 \cdot 10^{-8}$
$\tau^- \to e^-K_S$	$2.6 \cdot 10^{-8}$	$\tau^- \to \mu^-K_S$	$2.3 \cdot 10^{-8}$	$\tau^- \to \mu^-\rho^0$	$1.2 \cdot 10^{-8}$
$\tau^- \to e^-K^+K^-$	$3.4 \cdot 10^{-8}$	$\tau^- \to e^-K^+\pi^-$	$3.1 \cdot 10^{-8}$	$\tau^- \to e^-\pi^+K^-$	$3.7 \cdot 10^{-8}$
$\tau^- \to \mu^-K^+K^-$	$4.4 \cdot 10^{-8}$	$\tau^- \to \mu^-K^+\pi^-$	$4.5 \cdot 10^{-8}$	$\tau^- \to \mu^-\pi^+K^-$	$8.6 \cdot 10^{-8}$
$\tau^- \to e^-\pi^+\pi^-$	$2.3 \cdot 10^{-8}$	$\tau^- \to \mu^-\pi^+\pi^-$	$2.1 \cdot 10^{-8}$	$\tau^- \to \mu^-\omega$	$4.7 \cdot 10^{-8}$
$\tau^- \to \mu^-K^{*0}$	$5.9 \cdot 10^{-8}$	$\tau^- \to e^-\phi$	$3.1 \cdot 10^{-8}$	$\tau^- \to \Lambda\pi^-$	$7.2 \cdot 10^{-8}$
$\tau^- \to e^+K^-K^-$	$3.3 \cdot 10^{-8}$	$\tau^- \to e^+K^-\pi^-$	$3.2 \cdot 10^{-8}$	$\tau^- \to e^+\pi^-\pi^-$	$2.0 \cdot 10^{-8}$
$\tau^- \to \mu^+K^-K^-$	$4.7 \cdot 10^{-8}$	$\tau^- \to \mu^+K^-\pi^-$	$4.8 \cdot 10^{-8}$	$\tau^- \to \mu^+\pi^-\pi^-$	$3.7 \cdot 10^{-8}$

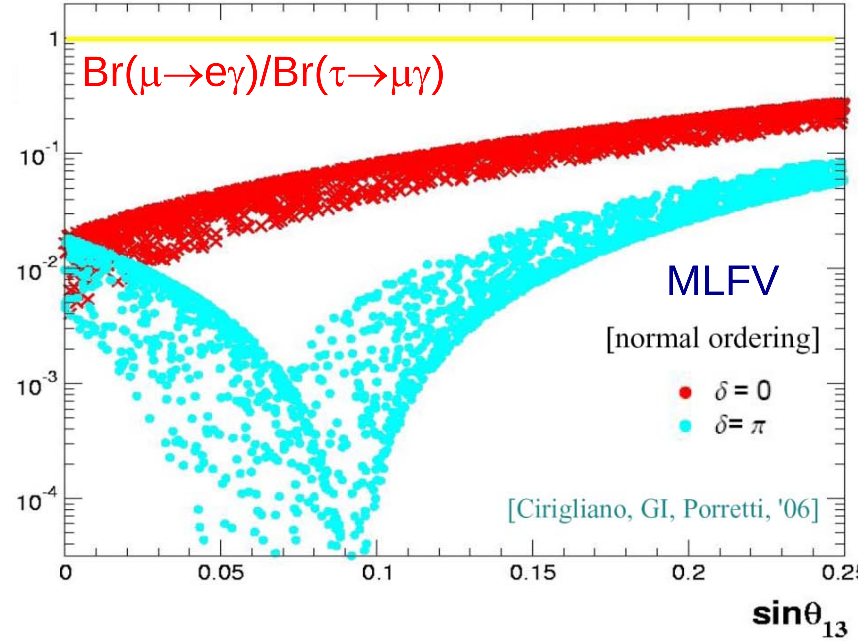
Impact of θ_{13} on LFV processes

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

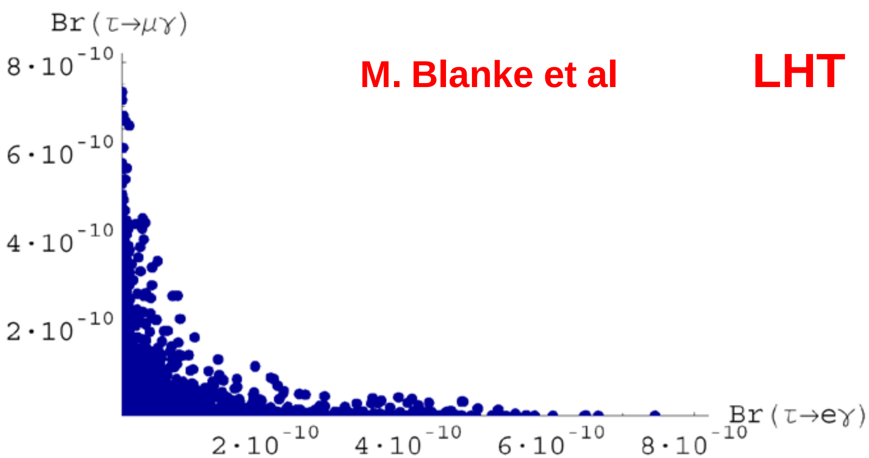
$(-\pi/4 \lesssim \arg\theta_1 \lesssim \pi/4,\ 0 \lesssim \arg\theta_2 \lesssim \pi/4)$

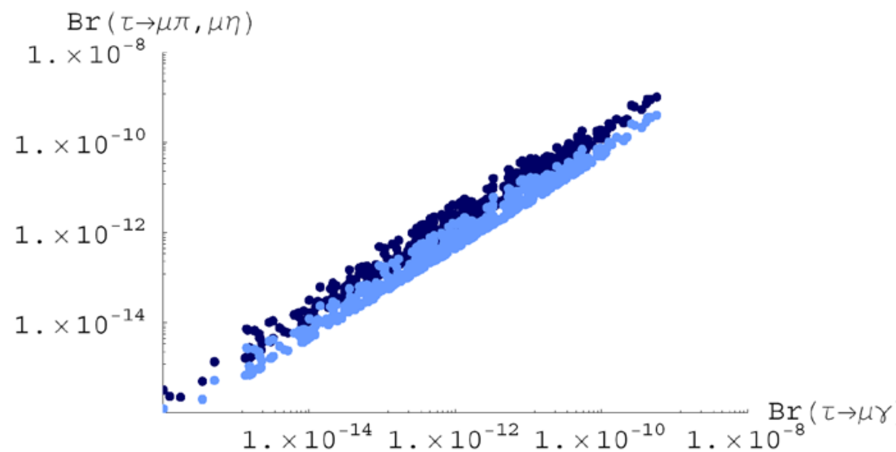
MEG:	**$Br(\mu\to e\gamma) \sim 10^{-13}$**
Prism:	**$Pr(\mu\to e) \sim 10^{-18}$**
S-BF:	**$Br(\tau\to\mu\gamma) \sim 10^{-9}$**





M. Blanke et al **LHT**



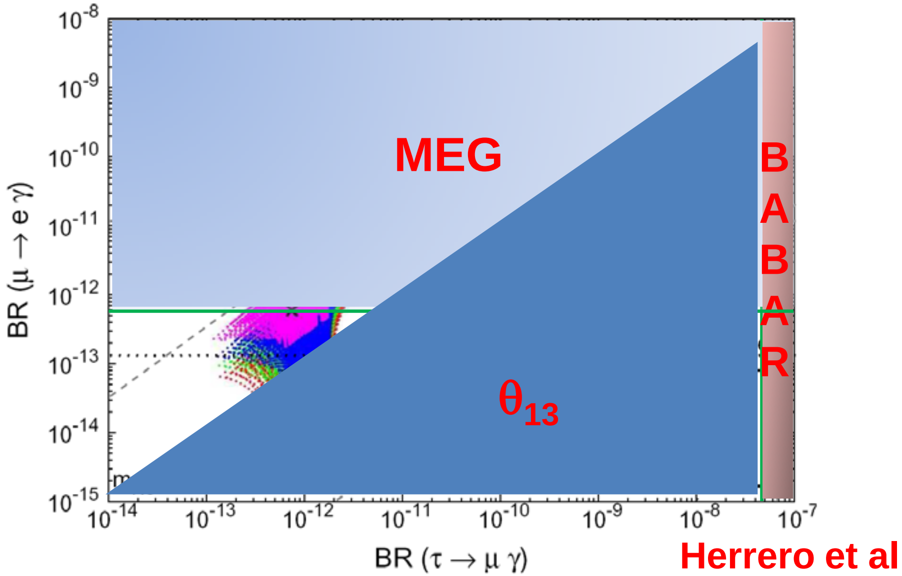


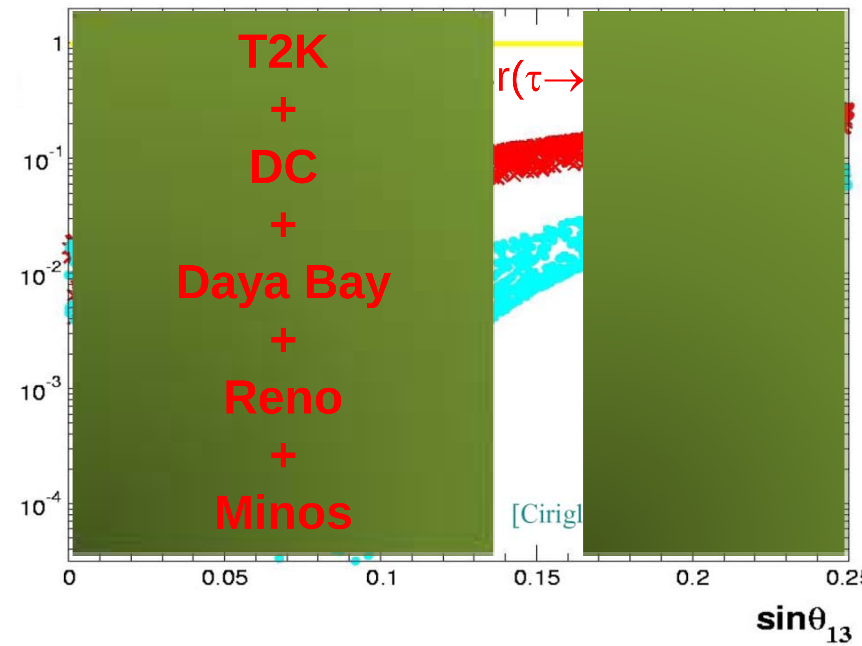
MEG: Br(μ→eγ) ~ 10^{-13}
Prism: Pr(μ→e) ~ 10^{-18}
S-BF: Br(τ →μγ) ~ 10^{-9}

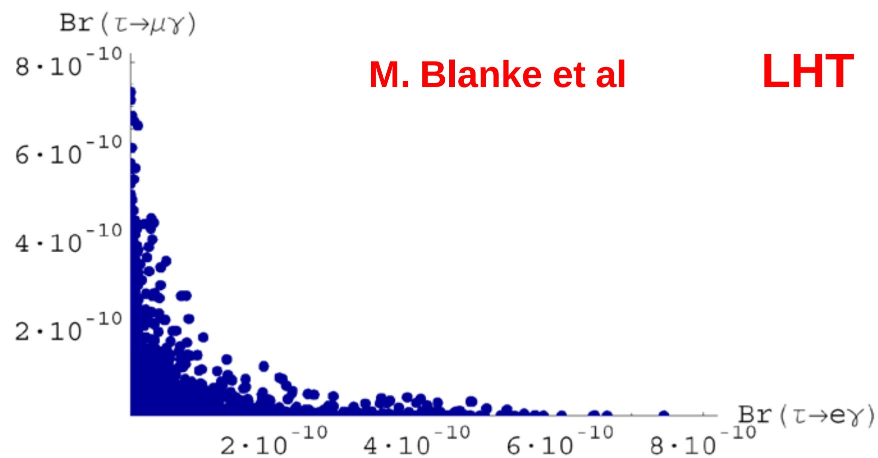
Impact of θ_{13} on LFV processes

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

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







Kicking out Models

Impact of θ_{13} on LFV processes

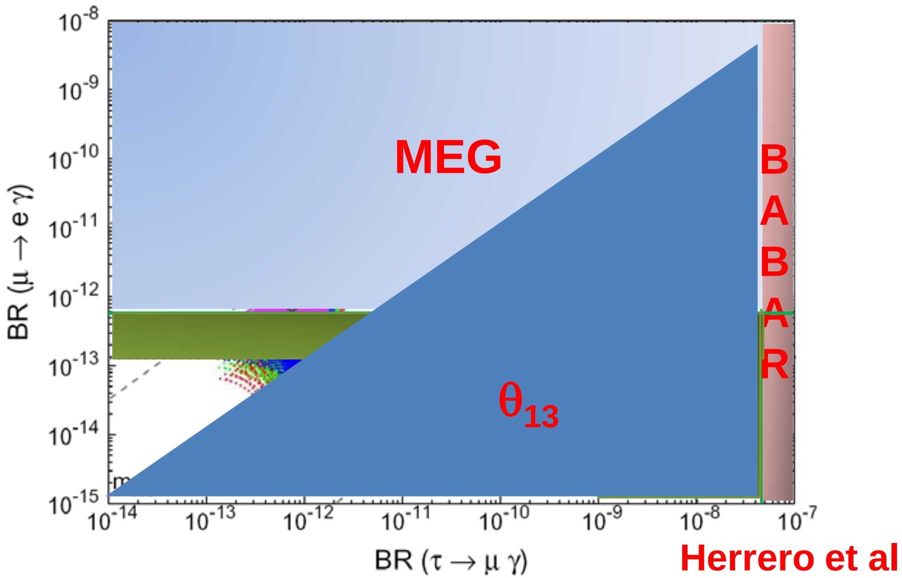
(All plotted points lead to 'viable BAU' and respect EDM bounds)

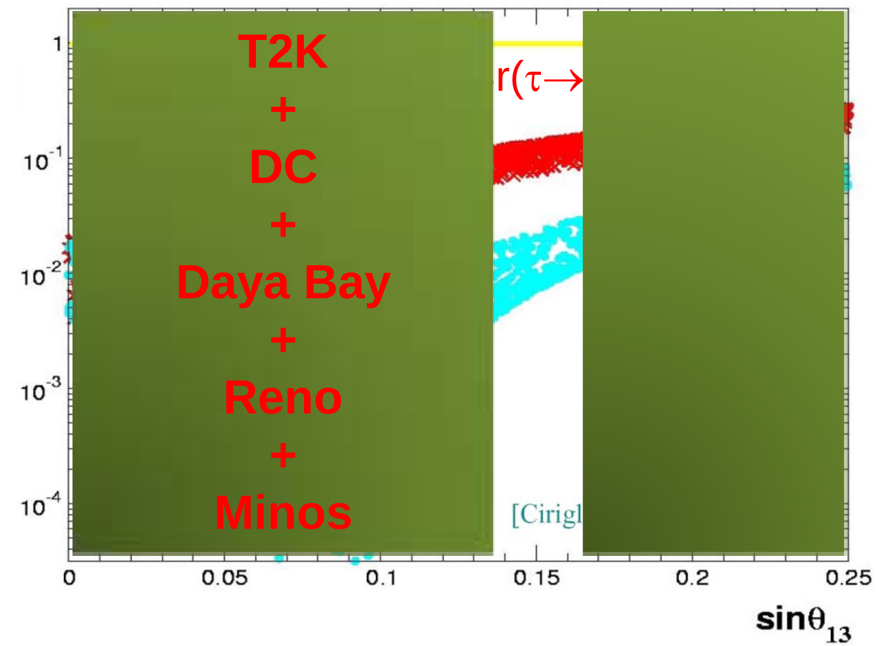
$(-\pi/4 \lesssim \arg\theta_1 \lesssim \pi/4,\ 0 \lesssim \arg\theta_2 \lesssim \pi/4)$

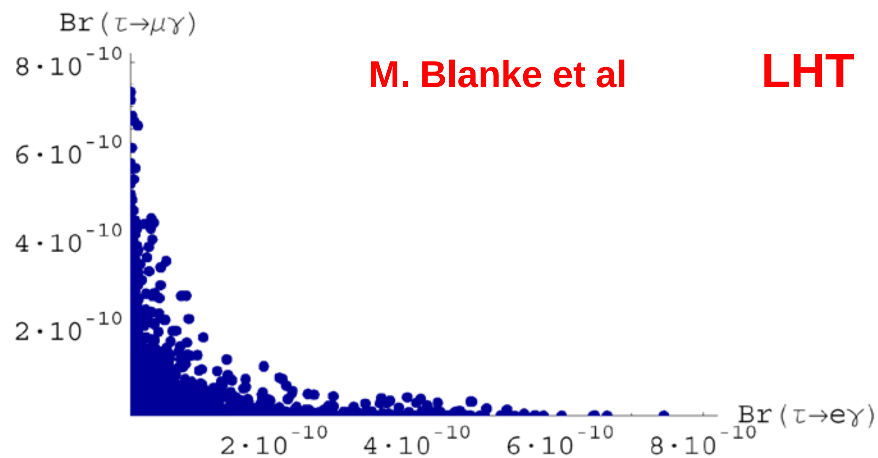
MEG: $Br(\mu \to e\gamma) \sim 10^{-13}$

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

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

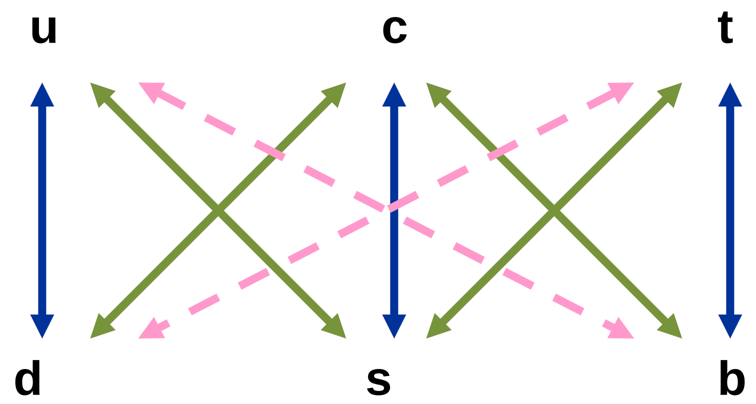


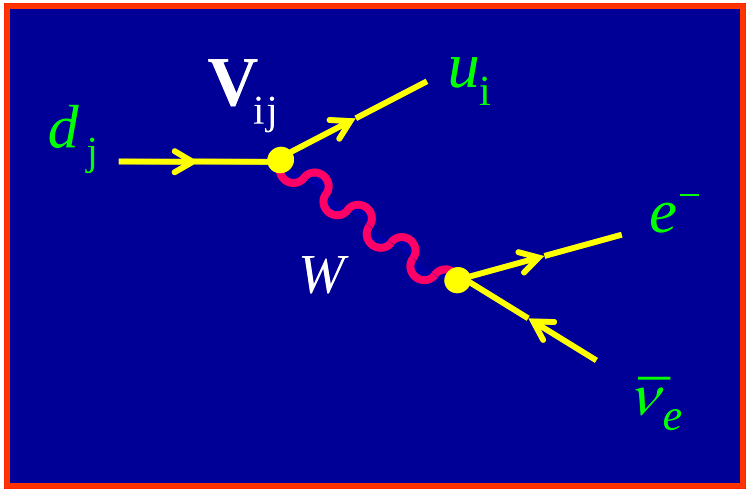




Kicking out Models

Flavour Changing Charged Currents



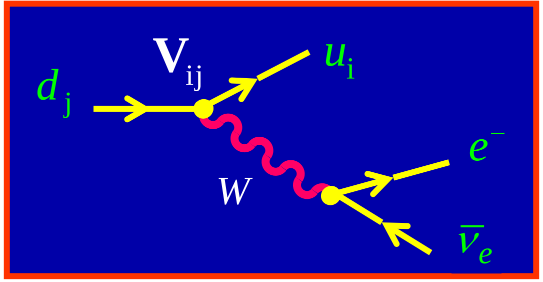


$$\Gamma(d_j \to u_i\, e^-\, \bar{\nu}_e) \propto \left|\mathbf{V}_{ij}\right|^2$$

We measure decays of hadrons (no free quarks)

Important QCD Uncertainties

V_{ij} Determination $(0^- \to 0^-)$



K→πlν , D→Klν ...

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

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

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

$f_-(q^2)$ 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

$|V_{ud}|$

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

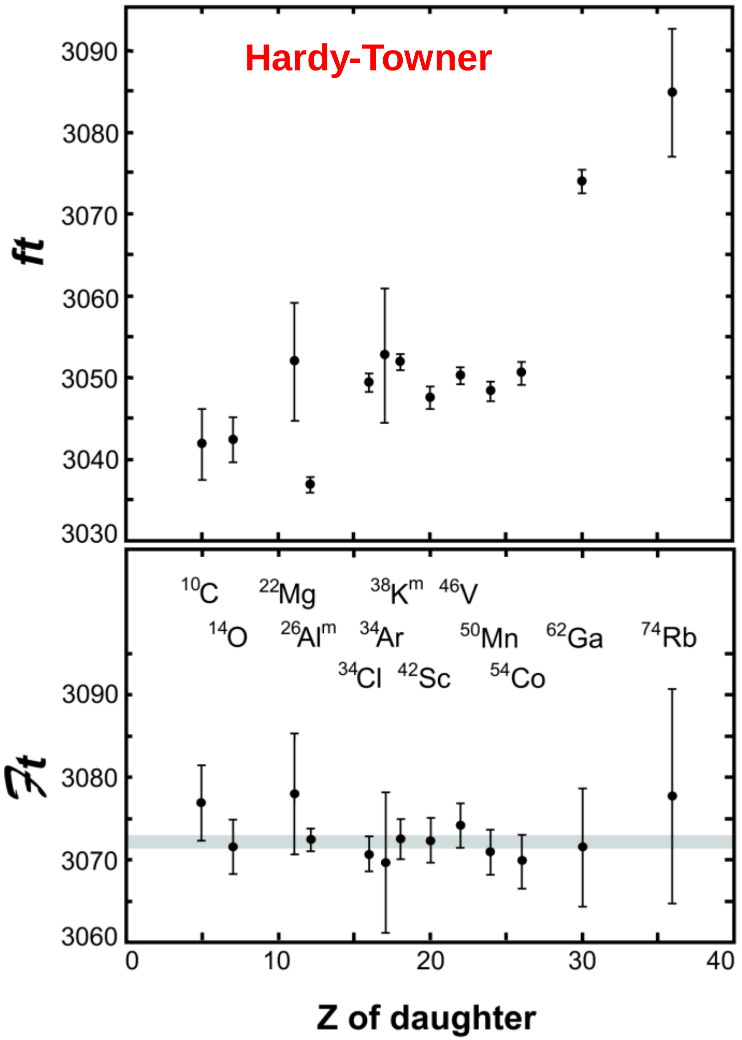
Superallowed Nuclear β Transitions $(0^+ \to 0^+)$

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

(Marciano – Sirlin)

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

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



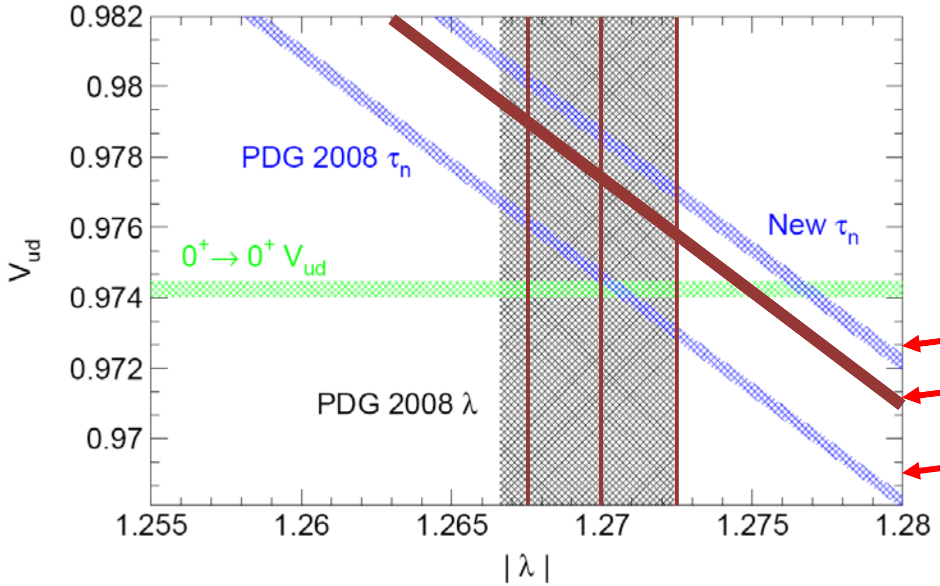
• Neutron Decay:

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

(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:

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

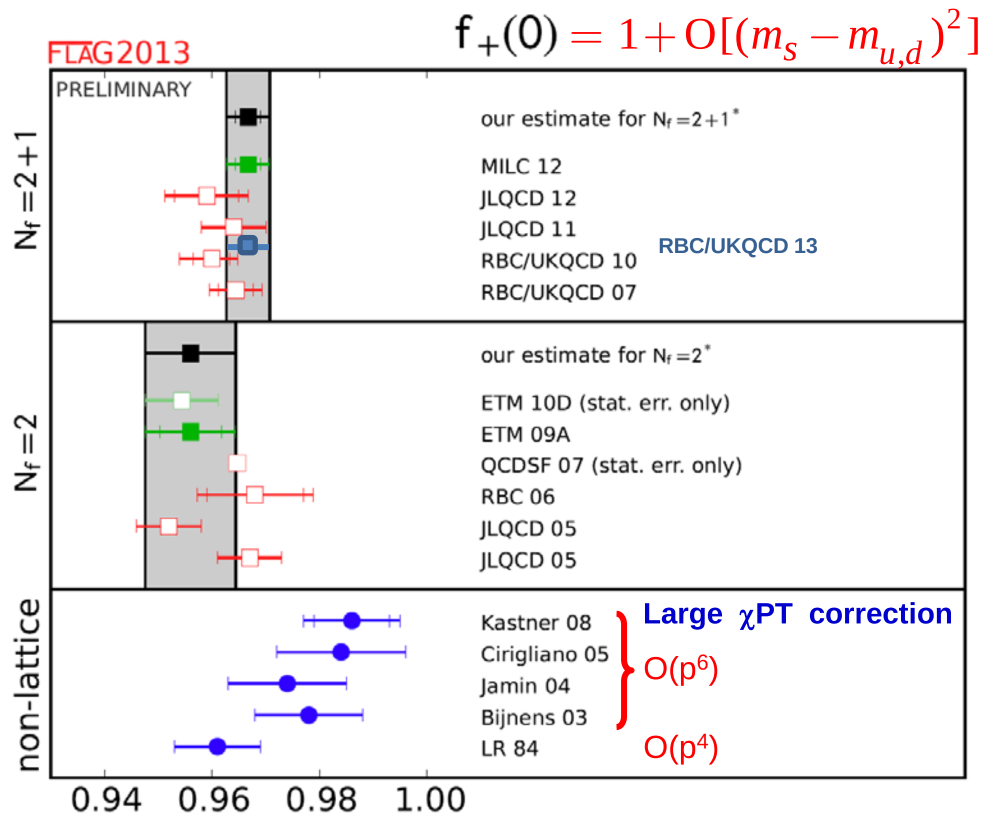
(PIBETA)

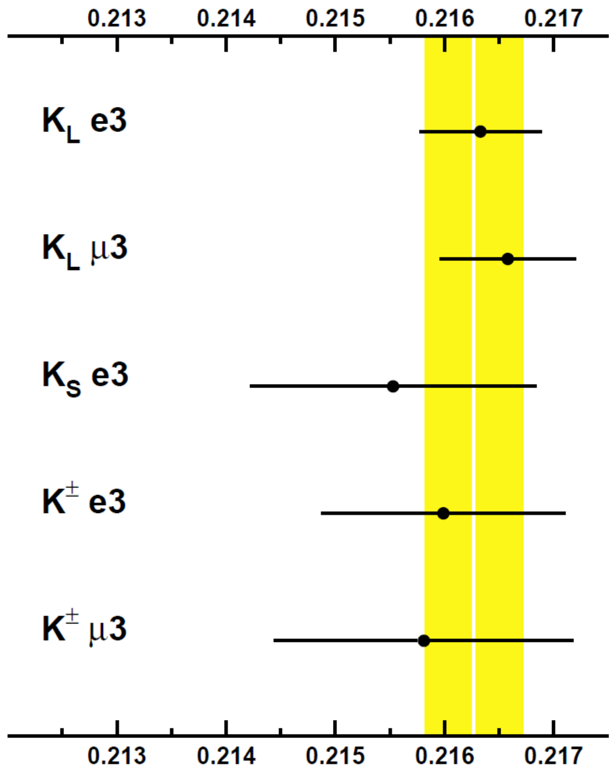
$|V_{ud}| = 0.9741 \pm 0.0026$

$K \to \pi l \nu$ Decays

Flavianet, arXiv:1005.2323 [hep-ph]

$f_+(0) = 1 + O[(m_s - m_{u,d})^2]$





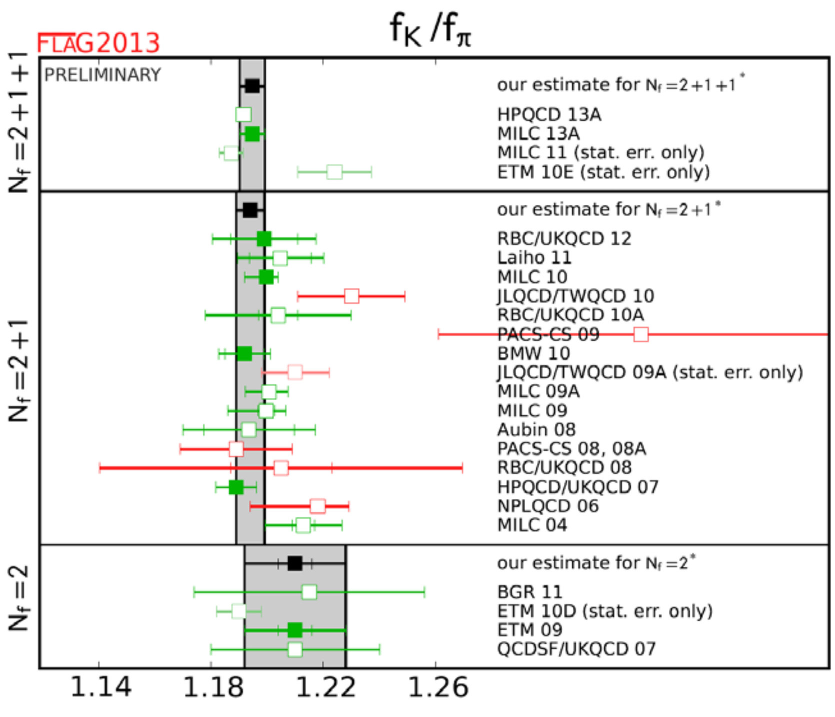
$|f_+(0)\, \mathbf{V_{us}}| = 0.2163 \pm 0.0005$

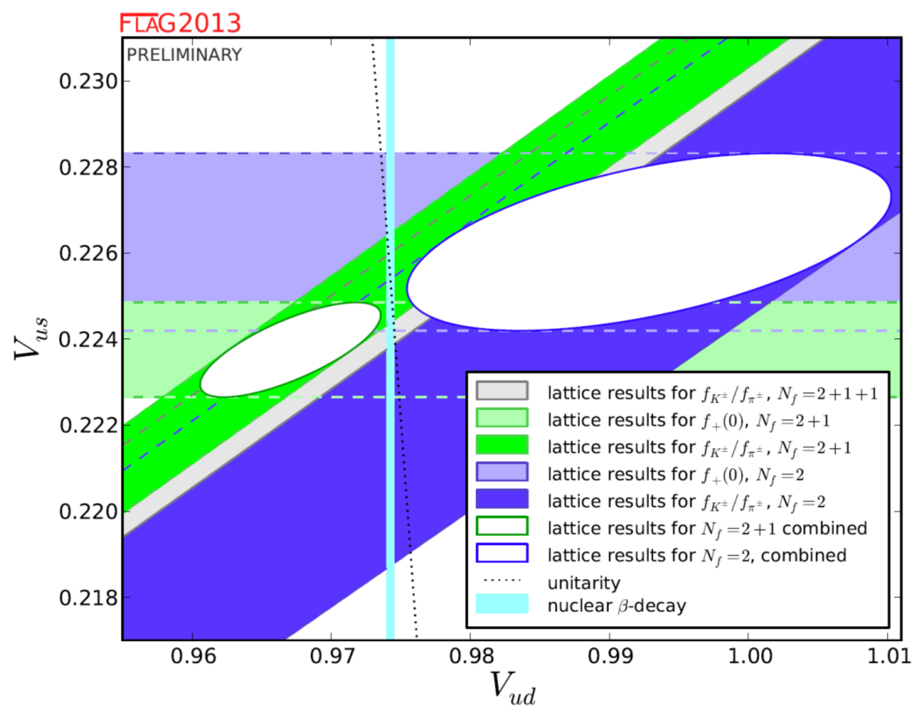
2012 :	$f_+(0) = 0.959 \pm 0.005$ →	$\mathbf{|V_{us}| = 0.2255 \pm 0.0014}$
2013 :	$f_+(0) = 0.967 \pm 0.004$ →	$\mathbf{|V_{us}| = 0.2238 \pm 0.0011}$

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

$$\frac{f_K}{f_\pi} \frac{|V_{us}|}{|V_{ud}|} = 0.2763 \pm 0.0005 \quad \Longrightarrow \quad \frac{|V_{us}|}{|V_{ud}|} = 0.2314 \pm 0.0011$$

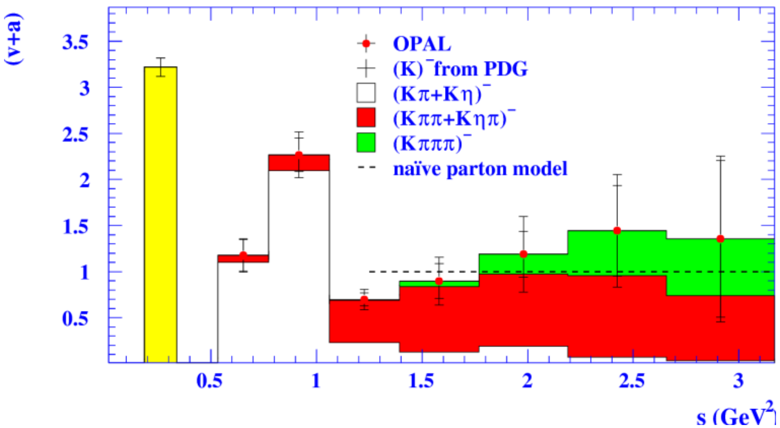
$$\langle 0 | \bar{d}_i \gamma^\mu \gamma_5 u_j | P(k) \rangle = i \, f_P \, k^\mu$$

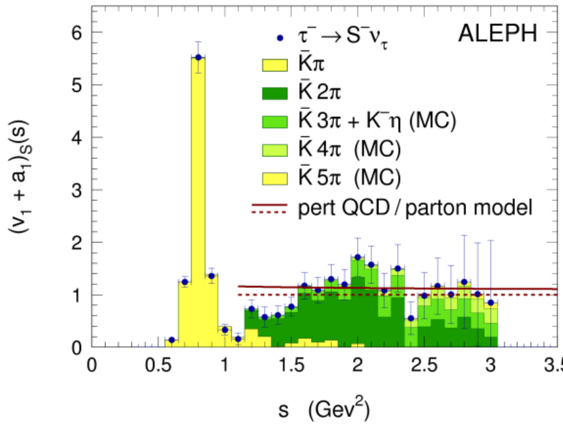




$$f_K / f_\pi = 1.194 \pm 0.005 \qquad \text{(FLAG 2013)}$$

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





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

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

$$m_s(2\,\text{GeV}) = 94 \pm 6\ \text{MeV}$$

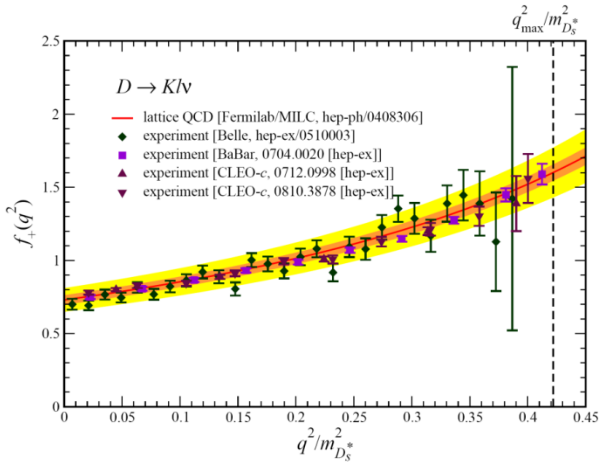
Gámiz-Jamin-Pich-Prades-Schwab

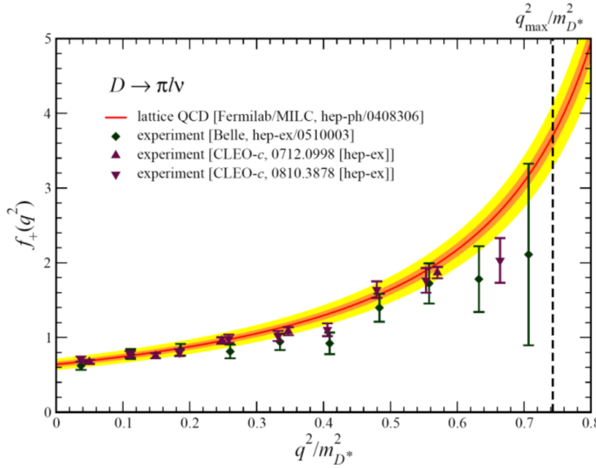
$$|\mathbf{V_{us}}| = 0.2173 \pm 0.0020_{\text{exp}} \pm 0.0010_{\text{th}}$$

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

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

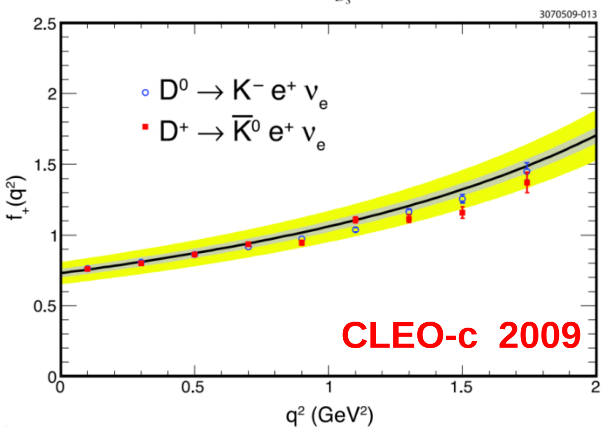
$D \to K/\pi\, l\, \nu$

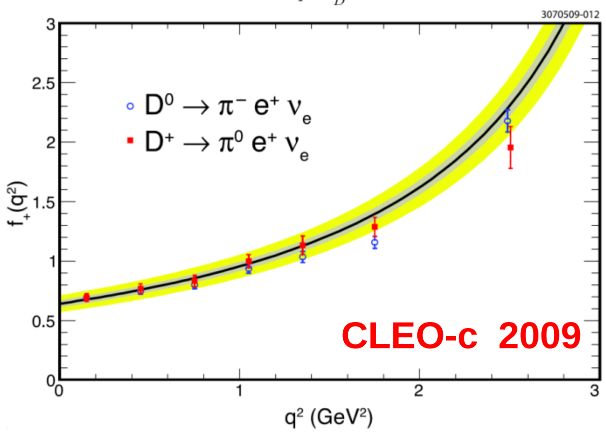




Lattice input

$$\left|\mathbf{V_{cs}}\right|_{D\to K l\nu} = 0.98 \pm 0.10$$



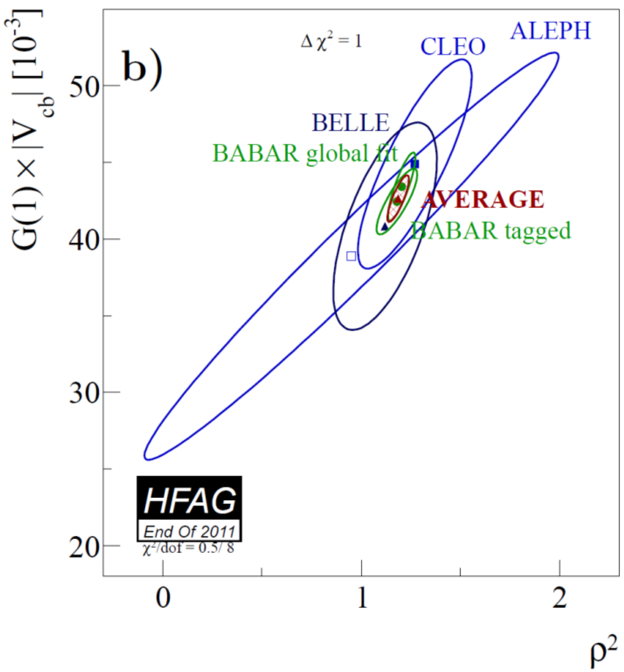


$$\left|\mathbf{V_{cd}}\right|_{D\to \pi l\nu} = 0.229 \pm 0.025$$

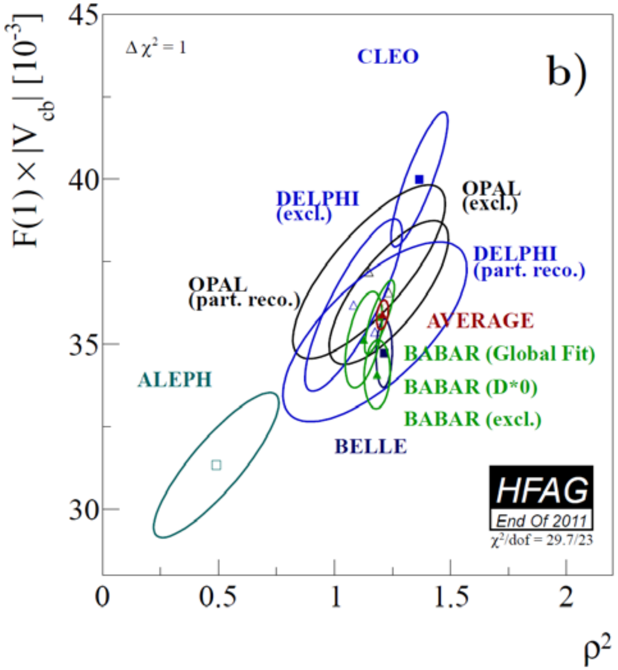
PDG 2012:

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

$B \to D\, l\, \nu$



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



QCD Symmetries at $1/M_Q \to 0$
HQET

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

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

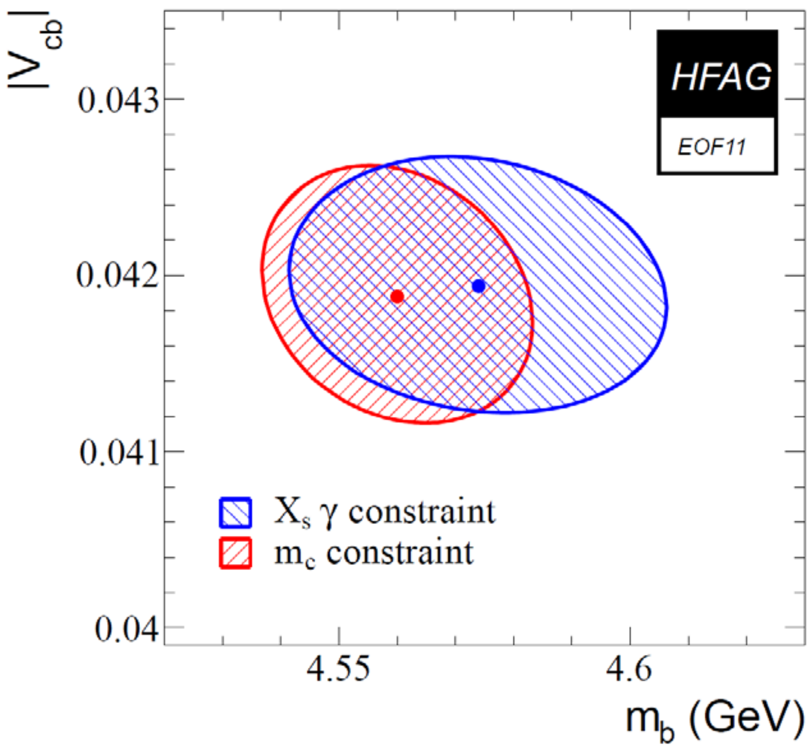
$G(1) = 1.074 \pm 0.024$ (FNAL / MILC) ➡ $|\mathbf{V_{cb}}| = (39.70 \pm 1.42_{\text{exp}} \pm 0.89_{\text{th}}) \cdot 10^{-3}$

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

➡ $$\left|\mathbf{V_{cb}}\right|_{\text{excl}} = (39.6 \pm 0.9) \cdot 10^{-3}$$

Inclusive B Decays (OPE, HQET)

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



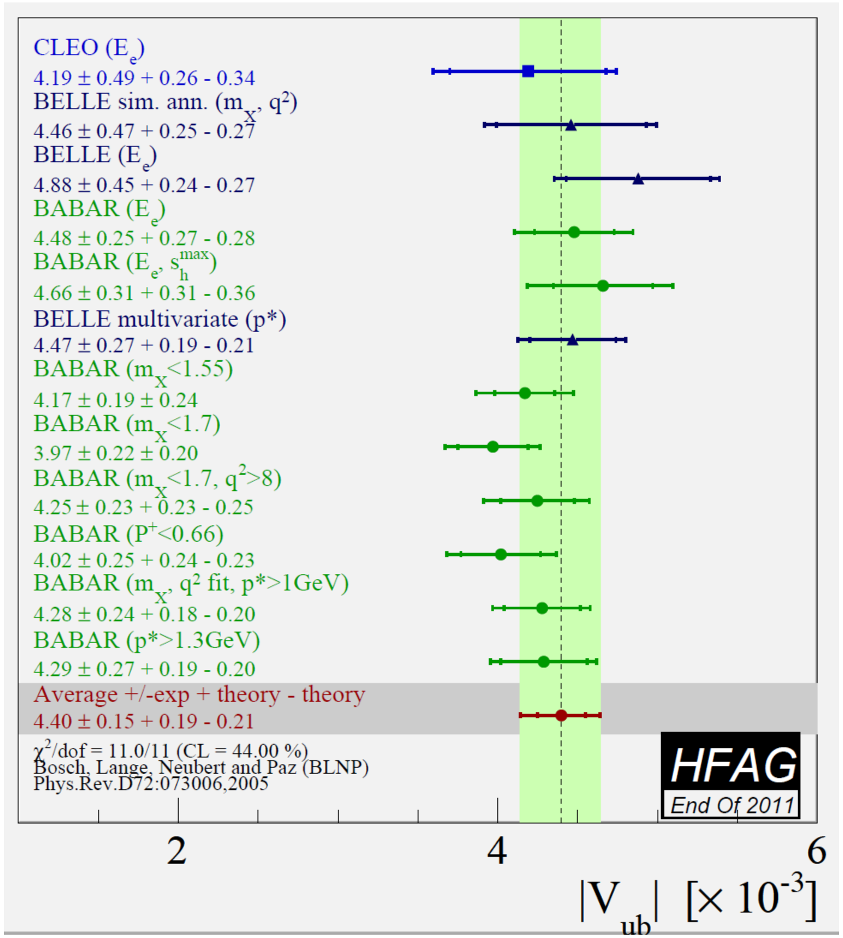
Fits to lepton energy, hadronic invariant mass and photon energy moments

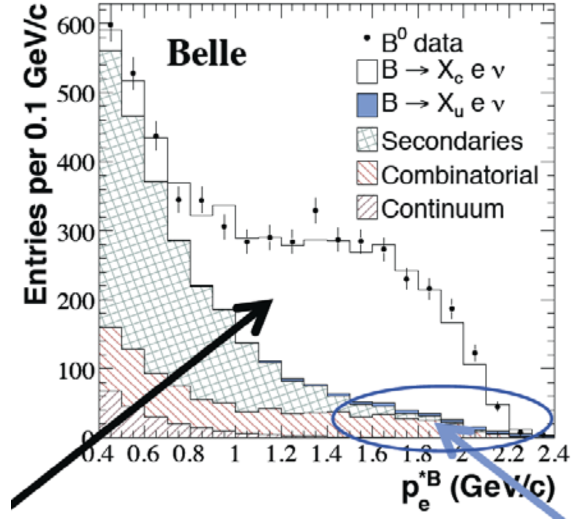
$$|V_{cb}|_{incl} = (41.9 \pm 0.7) \cdot 10^{-3}$$

1.9 σ discrepancy with exclusive measurement

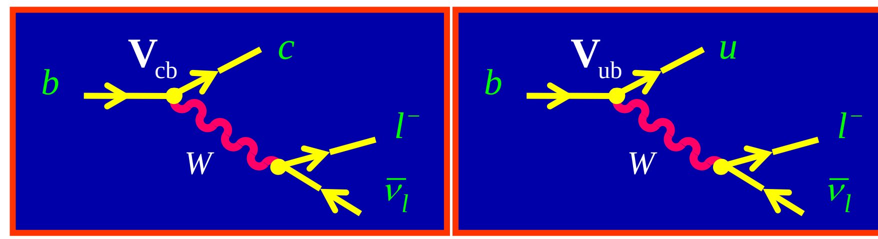
$$\Rightarrow \quad |V_{cb}| = (40.9 \pm 1.1) \cdot 10^{-3}$$

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

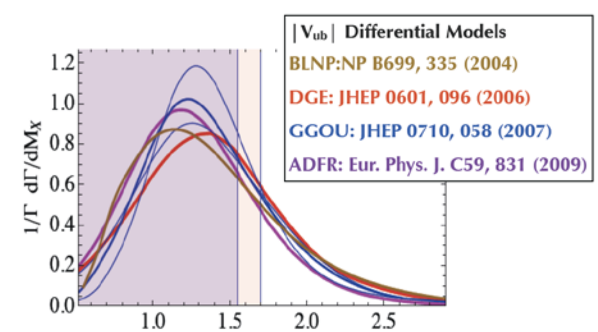




$$\left|\frac{V_{ub}}{V_{cb}}\right|^2 \approx \frac{1}{50}$$



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

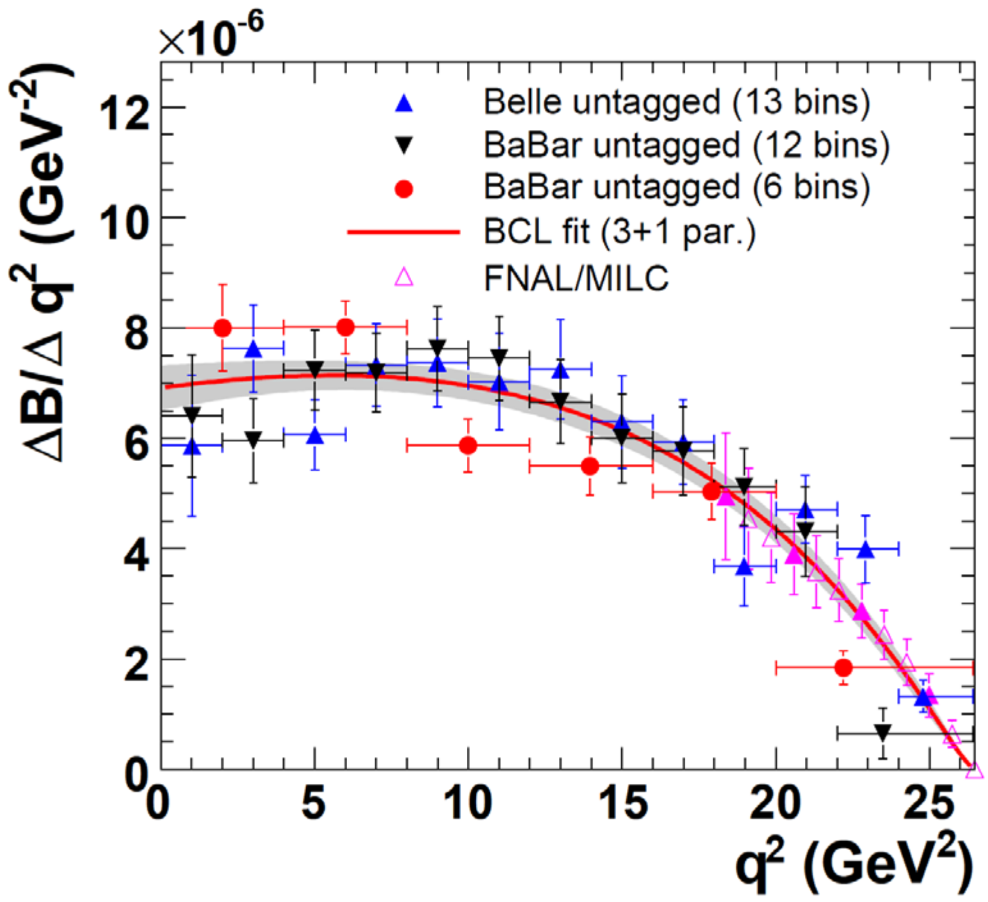


PDG 2012:

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

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

Large theoretical uncertainties



PDG 2012:

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

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

V_{ij}

DETERMINATIONS

CKM entry	Value	Source
$\|V_{ud}\|$	$\mathbf{0.97425 \pm 0.00022}$ 0.9773 ± 0.0017 0.9741 ± 0.0026	Nuclear β decay $n \to p e^- \bar{\nu}_e$ $\pi^+ \to \pi^0 e^+ \nu_e$
$\|V_{us}\|$	$\mathbf{0.2238 \pm 0.0011}$ 0.2256 ± 0.0012 0.2173 ± 0.0012	$K \to \pi e^- \bar{\nu}_e$ $K/\pi \to \mu\nu$, Lattice τ decays
$\|V_{cd}\|$	$\mathbf{0.230 \pm 0.011}$ 0.229 ± 0.025	$\nu d \to c X$ $D \to \pi l \nu$, Lattice
$\|V_{cs}\|$	$\mathbf{1.006 \pm 0.023}$	$D \to K l \nu$, $D_s \to l \nu$, Lattice
$\|V_{cb}\|$	0.0396 ± 0.0009 0.0419 ± 0.0007 $\mathbf{0.0409 \pm 0.0011}$	$B \to D^* / D l \bar{\nu}_l$ $b \to c l \bar{\nu}_l$
$\|V_{ub}\|$	0.00323 ± 0.00031 0.00441 ± 0.00032 $\mathbf{0.00415 \pm 0.00049}$	$B \to \pi l \bar{\nu}_l$ $b \to u l \bar{\nu}_l$
$\|V_{tb}\| / \sqrt{\sum_q \|V_{tq}\|^2}$ $\|V_{tb}\|$	> 0.97 (95% CL) $\mathbf{0.89 \pm 0.07}$	$t \to bW / t \to qW$ $p\bar{p} \to tb + X$

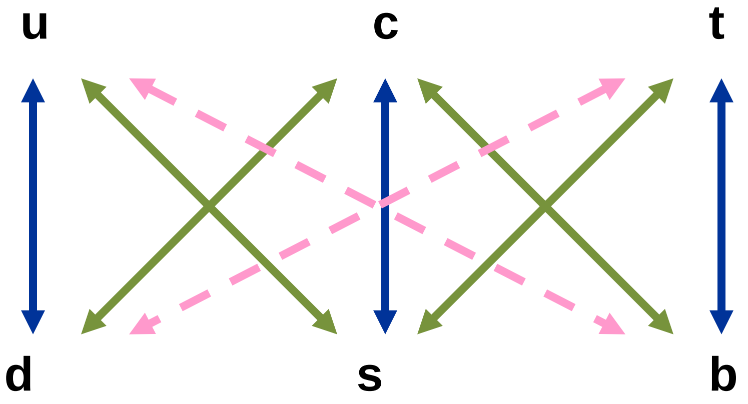
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = \mathbf{0.9993 \pm 0.0009}$$

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

Hierarchical Structure

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

$$\lambda \approx \sin\theta_C \approx 0.224 \quad ; \quad A \approx 0.82 \quad ; \quad \sqrt{\rho^2+\eta^2} \approx 0.45$$



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:**

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

$\Downarrow$

$\mathbf{V}_{ij}$ 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)**

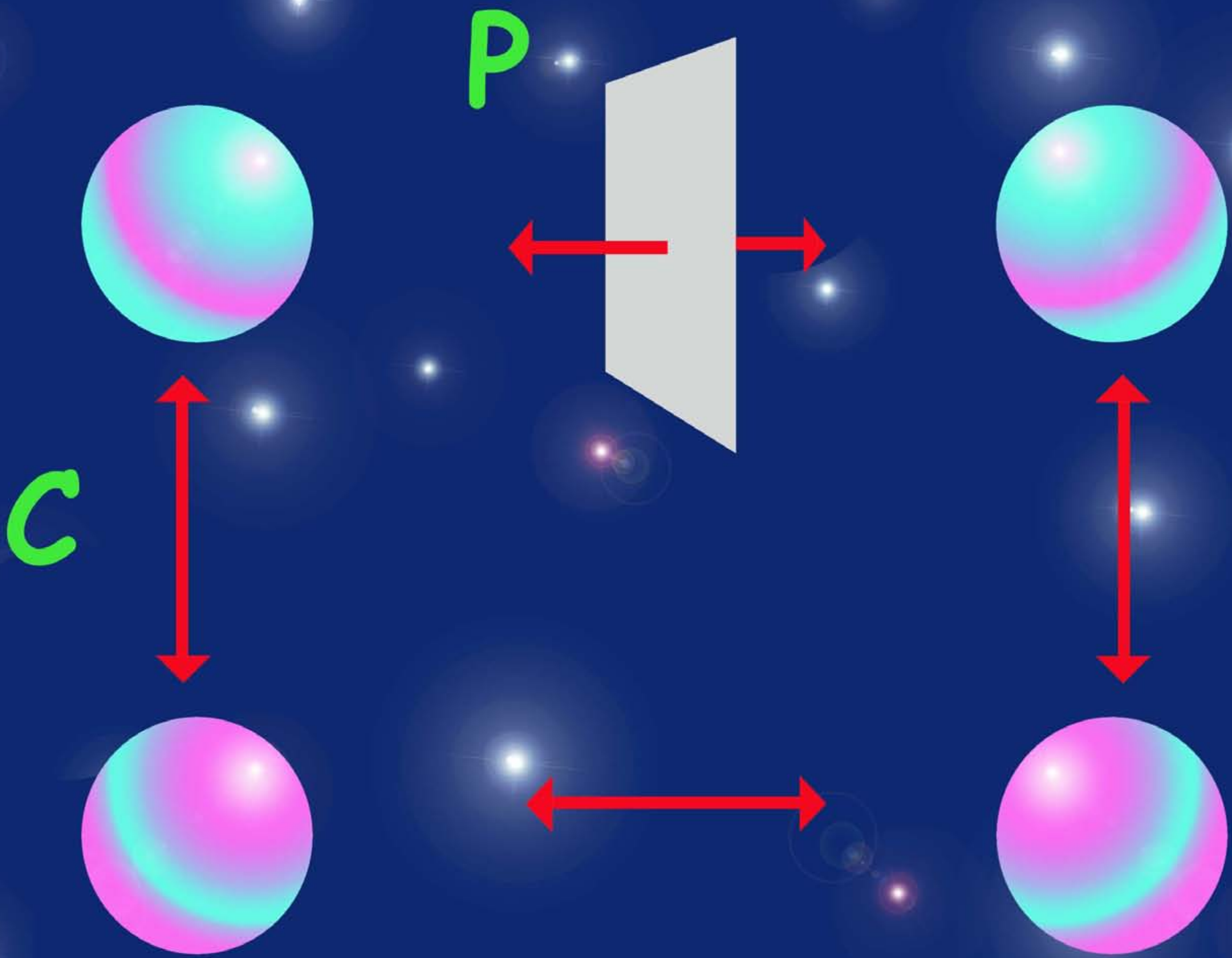
$$\mathbf{V} = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \quad \Rightarrow \quad \text{No } \not{CP}$$

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

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

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

$\lambda \approx \sin\theta_C \approx 0.224 \;;\; A \approx 0.82 \;;\; \sqrt{\rho^2+\eta^2} \approx 0.45$ $\qquad \delta_{13} \neq 0 \;\; (\eta \neq 0) \;\Rightarrow\; \not{CP}$


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 → Baryogenesis

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

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

- Complex Phases
- Interferences

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

$$\mathcal{CP} \quad \Longleftrightarrow \quad \mathbf{H}(M_u^2) \cdot \mathbf{H}(M_d^2) \cdot \mathbf{J} \neq 0$$

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

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

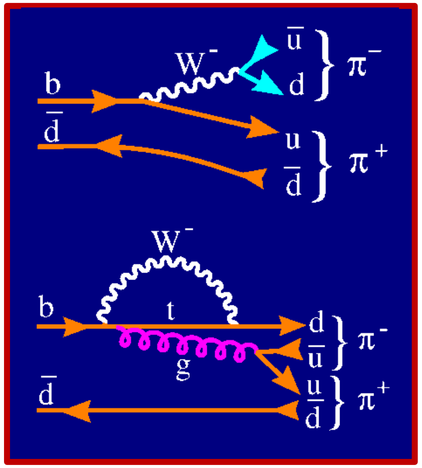
$$\mathbf{J} = c_{12}\, c_{13}^2\, c_{23}\, s_{12}\, s_{13}\, s_{23} \sin\delta_{13} = \left|A^2 \lambda^6 \eta\right| < 10^{-4}$$

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

DIRECT $\not{CP}$

$$\left|\mathbf{T}\left(P\to f\right)\right| \neq \left|\mathbf{T}\left(\overline{P}\to \overline{f}\right)\right|$$

$\overline{B}_d^0$



$$\mathbf{T}\left(P\to f\right) = T_1\, e^{i\phi_1}\, e^{i\delta_1} + T_2\, e^{i\phi_2}\, e^{i\delta_2}$$

$\mathcal{CP}$

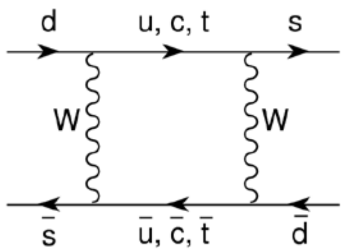
$$\mathbf{T}\left(\overline{P}\to \overline{f}\right) = T_1\, e^{-i\phi_1}\, e^{i\delta_1} + T_2\, e^{-i\phi_2}\, e^{i\delta_2}$$

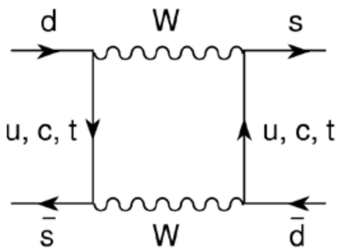
$$A^{CP}_{P\to f} \equiv \frac{\Gamma\left(P\to f\right)-\Gamma\left(\overline{P}\to \overline{f}\right)}{\Gamma\left(P\to f\right)+\Gamma\left(\overline{P}\to \overline{f}\right)} = \frac{-2\, T_1\, T_2\, \sin(\phi_2-\phi_1)\, \sin(\delta_2-\delta_1)}{T_1^{\,2}+T_2^{\,2}+2\, T_1\, T_2\, \cos(\phi_2-\phi_1)\, \cos(\delta_2-\delta_1)}$$

One needs:

- **2 Interfering Amplitudes**
- **2 Different Weak Phases** $\left[\sin(\phi_2-\phi_1)\neq 0\right]$
- **2 Different FSI Phases** $\left[\sin(\delta_2-\delta_1)\neq 0\right]$

INDIRECT $\not{CP}$: $K^0 - \bar{K}^0$ MIXING





$$\left|K^0_{S,L}\right\rangle \sim p\left|K^0\right\rangle \mp q\left|\bar{K}^0\right\rangle$$

$$q/p \equiv (1-\bar{\varepsilon}_K)/(1+\bar{\varepsilon}_K)$$

$$\left\langle \bar{K}^0 \right| \mathbf{H} \left| K^0 \right\rangle \sim \sum_{ij} \lambda_i \lambda_j \, S(r_i, r_j) \, \eta_{ij} \quad \left\langle O_{\Delta S=2} \right\rangle$$

$$\left\langle O_{\Delta S=2} \right\rangle = \alpha_s(\mu)^{-2/9} \left\langle \bar{K}^0 \right| \left(\bar{s}_L \gamma^\alpha d_L\right)\left(\bar{s}_L \gamma_\alpha d_L\right) \left| K^0 \right\rangle \equiv \left(\frac{4}{3} M_K^2 f_K^2\right) \hat{B}_K$$

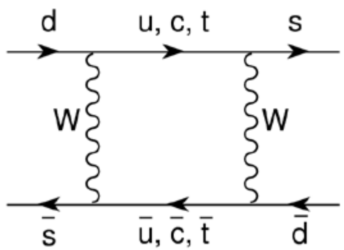
$$\lambda_i \equiv V_{id} V_{is}^* \quad ; \quad r_i \equiv m_i^2 / M_W^2 \quad (i = u, c, t)$$

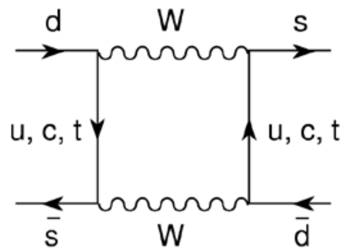
- **GIM Mechanism:** $\lambda_u + \lambda_c + \lambda_t = 0$

$$\left(M_{K_L} - M_{K_S}\right)/M_{K^0} = (7.00 \pm 0.01) \times 10^{-15}$$

- $\not{CP}$ **:** $\mathrm{Im}\,\lambda_t = -\mathrm{Im}\,\lambda_c \simeq \eta \lambda^5 A^2$
- **Hard GIM Breaking:** $S(r_i, r_i) \sim r_i$ ➡ **t quark**

INDIRECT $\not{CP}$: $K^0 - \bar{K}^0$ MIXING





$$|K^0_{S,L}\rangle \sim p\,|K^0\rangle \mp q\,|\bar{K}^0\rangle$$

$$q/p \equiv (1-\bar{\varepsilon}_K)/(1+\bar{\varepsilon}_K)$$

$$\langle \bar{K}^0 | \mathbf{H} | K^0 \rangle \sim \sum_{ij} \lambda_i \lambda_j\, S(r_i, r_j)\, \eta_{ij} \quad \langle O_{\Delta S=2} \rangle$$

$$\langle O_{\Delta S=2} \rangle = \alpha_s(\mu)^{-2/9} \langle \bar{K}^0 | (\bar{s}_L \gamma^\alpha d_L)(\bar{s}_L \gamma_\alpha d_L) | K^0 \rangle \equiv \left(\frac{4}{3} M_K^2 f_K^2\right) \hat{B}_K$$

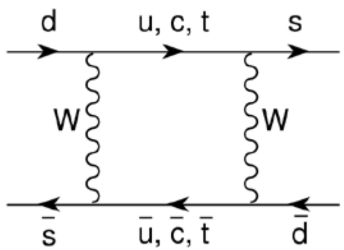
$$\lambda_i \equiv V_{id} V_{is}^* \quad ; \quad r_i \equiv m_i^2 / M_W^2 \quad (i = u, c, t)$$

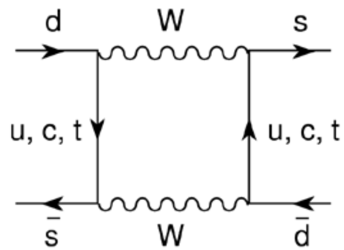
$$\mathcal{C}\,|K^0\rangle = |\bar{K}^0\rangle \quad , \quad \mathcal{P}\,|K^0\rangle = -|K^0\rangle \quad , \quad \mathcal{CP}\,|K^0\rangle = -|\bar{K}^0\rangle$$

$$|K^0_{1,2}\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle \mp |\bar{K}^0\rangle\right) \quad , \quad \mathcal{CP}\,|K^0_{1,2}\rangle = \pm\,|K^0_{1,2}\rangle$$

$$|K^0_S\rangle \simeq |K^0_1\rangle + \bar{\varepsilon}_K\,|K^0_2\rangle \quad , \quad |K^0_L\rangle \simeq |K^0_2\rangle + \bar{\varepsilon}_K\,|K^0_1\rangle$$

INDIRECT $\not{C}\not{P}$: $K^0 - \bar{K}^0$ MIXING





$$|K^0_{S,L}\rangle \sim p\,|K^0\rangle \mp q\,|\bar{K}^0\rangle$$

$$q/p \equiv (1-\bar{\varepsilon}_K)/(1+\bar{\varepsilon}_K)$$

$$K^0 \to \pi^- l^+ \nu_l \quad (\bar{s} \to \bar{u}) \qquad ; \qquad \bar{K}^0 \to \pi^+ l^- \bar{\nu}_l \quad (s \to u)$$

$$\frac{\Gamma(K^0_L \to \pi^- l^+ \nu_l) - \Gamma(K^0_L \to \pi^+ l^- \bar{\nu}_l)}{\Gamma(K^0_L \to \pi^- l^+ \nu_l) + \Gamma(K^0_L \to \pi^+ l^- \bar{\nu}_l)} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = \frac{2\,\mathrm{Re}(\bar{\varepsilon}_K)}{1+|\bar{\varepsilon}_K|^2} = (0.332 \pm 0.006)\%$$

➡ $\mathbf{Re(\bar{\varepsilon}_K) = (1.66 \pm 0.03) \cdot 10^{-3}}$

$$\eta_{+-} \equiv \frac{T(K_L \to \pi^+\pi^-)}{T(K_S \to \pi^+\pi^-)} \approx \varepsilon_K \qquad\qquad \eta_{00} \equiv \frac{T(K_L \to \pi^0\pi^0)}{T(K_S \to \pi^0\pi^0)} \approx \varepsilon_K$$

$$\varepsilon_K = (2.228 \pm 0.011) \cdot 10^{-3}\, e^{i\phi_\varepsilon}$$

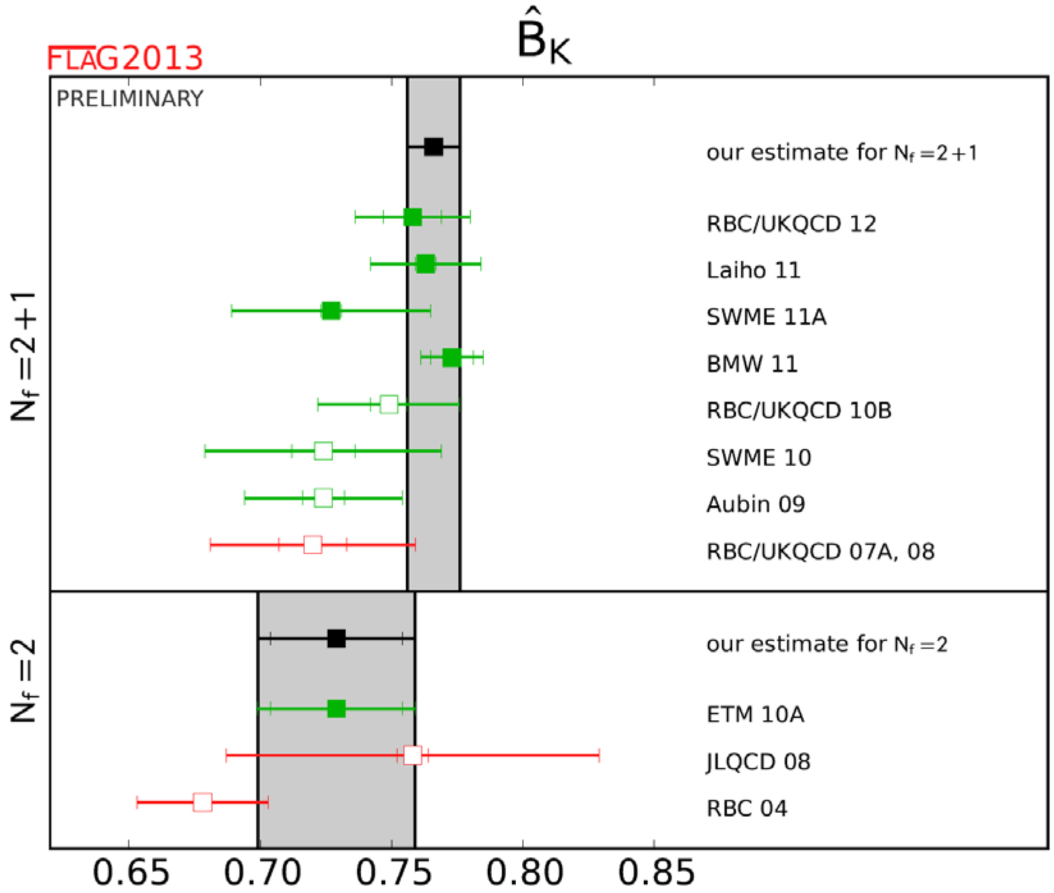
$$\phi_\varepsilon = (43.5 \pm 0.5)^\circ$$

➡ $\eta\,\left[(1-\rho)\,A^2 + 0.22\right] A^2\, \hat{B}_K = 0.143$

Buras et al

Lattice Results for $\hat{B}_K$

$$B_K^{\overline{\rm MS}}(2\,{\rm GeV}) = 0.560 \pm 0.007 \qquad , \qquad \hat{B}_K = 0.766 \pm 0.010$$



Flavianet Lattice Averaging Group

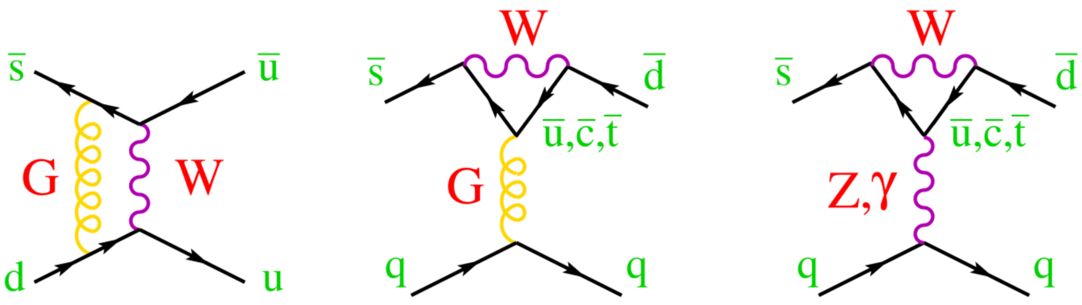
DIRECT $\not{CP}$ in $K \to \pi\pi$

$$\eta_{+-} \equiv \frac{T(K_L \to \pi^+\pi^-)}{T(K_S \to \pi^+\pi^-)} \approx \varepsilon_K + \varepsilon'_K \qquad \eta_{00} \equiv \frac{T(K_L \to \pi^0\pi^0)}{T(K_S \to \pi^0\pi^0)} \approx \varepsilon_K - 2\,\varepsilon'_K$$

$$\mathrm{Re}(\varepsilon'_K/\varepsilon_K) \approx \frac{1}{6}\left\{1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right\} = (16.8 \pm 1.4)\cdot 10^{-4}$$

NA48, NA31

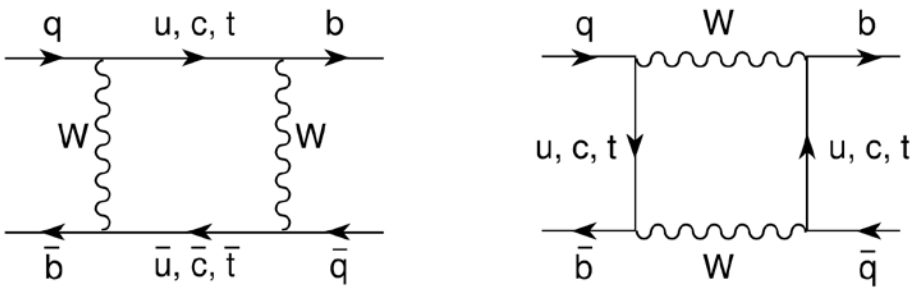
KTeV, E731



$$\mathrm{Re}(\varepsilon'_K/\varepsilon_K)_{\mathrm{Th}} = \left(19\,{}^{+11}_{-9}\right)\cdot 10^{-4}$$

- Short-distance OPE
  Ciuchini et al, Buras et al
- Long-distance χPT
  Pallante-Pich-Scimemi
  Cirigliano-Ecker-Neufeld-Pich

$B^0 - \bar{B}^0$ MIXING



$$V_{ud}\, V_{ub}^* \sim V_{cd}\, V_{cb}^* \sim V_{td}\, V_{tb}^* \sim A\lambda^3$$

$$\langle \bar{B}^0 | \mathrm{H} | B^0 \rangle \sim |V_{td}|^2\; S(r_t, r_t)\; \left(\frac{4}{3} M_B^2\, f_B^2\right)\; \hat{B}_B$$

$$\Delta M_{B_d^0} = (0.510 \pm 0.004)\ \mathrm{ps}^{-1} \quad \longrightarrow \quad |V_{td}|$$

- $\Delta M_{B_d^0} / \Gamma_{B_d^0} = 0.775 \pm 0.006$
- $\Delta M_{B_s^0} = (17.768 \pm 0.024)\ \mathrm{ps}^{-1}$
- $\Delta\Gamma_{B^0} / \Delta M_{B^0} \sim m_b^2 / m_t^2 \ll 1$
- $\mathrm{Re}\left(\varepsilon_{B_d^0}\right) = -0.0002 \pm 0.0007$

$$\Delta M_{B_s^0} / \Gamma_{B_s^0} = 26.74 \pm 0.22$$

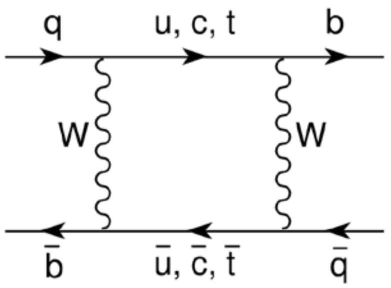
$$|V_{ts}|^2 \gg |V_{td}|^2$$

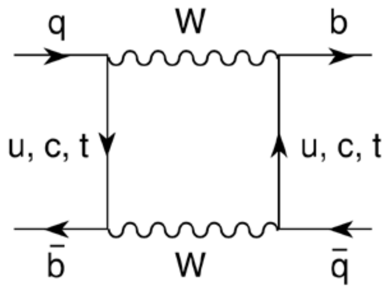
$$\Delta\Gamma_{B_s^0} / \Gamma_{B_s^0} = -0.123 \pm 0.017$$

$$\mathrm{Re}\left(\varepsilon_{B_s^0}\right) = -0.0043 \pm 0.0014$$

$\not{CP}$ very small

$$|q/p| - 1 \sim m_c^2 / m_t^2$$





$$\mathbf{M} = \begin{pmatrix} M & M_{12} \\ M_{12} & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12} & \Gamma \end{pmatrix}$$

$$|B^0_{\mp}\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}} \left(p\,|B^0\rangle \mp q\,|\bar{B}^0\rangle \right) \qquad , \qquad \frac{q}{p} \equiv \frac{1-\varepsilon_B}{1-\varepsilon_B} = \left(\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}} \right)^{1/2}$$

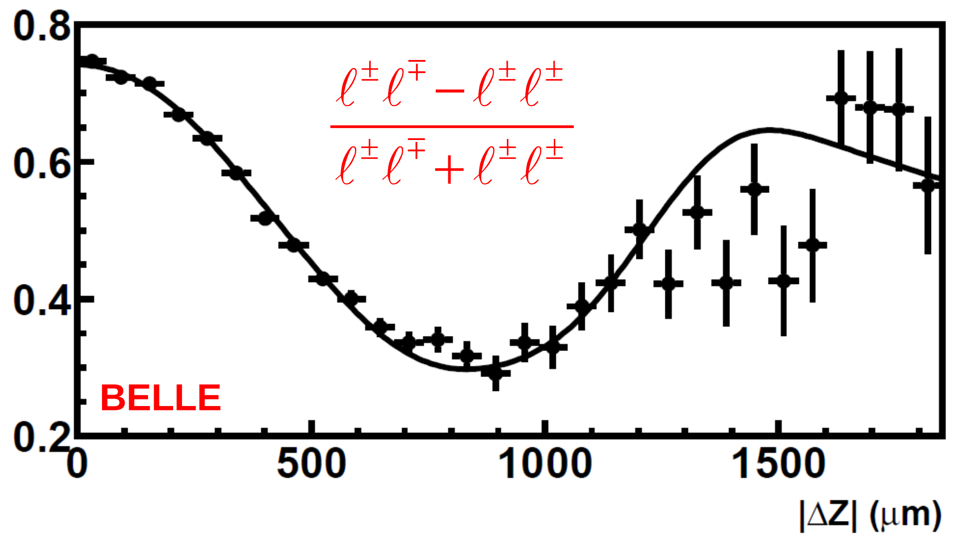
$$\Delta\Gamma/\Delta M \approx \Gamma_{12}/M_{12} \sim m_b^2/m_t^2 \ll 1 \quad \Rightarrow \quad \left|\frac{q}{p}\right| \approx 1 + \frac{1}{2}\left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi_{\Delta B=2} \qquad , \qquad \phi_{\Delta B=2} \equiv \arg\left(M_{12}/\Gamma_{12}\right)$$

$$\Delta M \equiv M_{B_+} - M_{B_-} \qquad , \qquad \Delta\Gamma \equiv \Gamma_{B_+} - \Gamma_{B_-}$$

$$\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \begin{pmatrix} g_1(t) & \frac{q}{p} g_2(t) \\ \frac{p}{q} g_2(t) & g_1(t) \end{pmatrix} \begin{pmatrix} |B^0\rangle \\ |\bar{B}^0\rangle \end{pmatrix} \qquad , \qquad \begin{pmatrix} g_1(t) \\ g_2(t) \end{pmatrix} = e^{-iMt}\, e^{-\Gamma t/2} \begin{pmatrix} \cos\left[\left(\Delta M - \frac{i}{2}\Delta\Gamma\right)\frac{t}{2}\right] \\ -i\sin\left[\left(\Delta M - \frac{i}{2}\Delta\Gamma\right)\frac{t}{2}\right] \end{pmatrix}$$

Time Scales: Oscillation $\sim \sin\left[(x - iy)\,\Gamma t/2\right]$

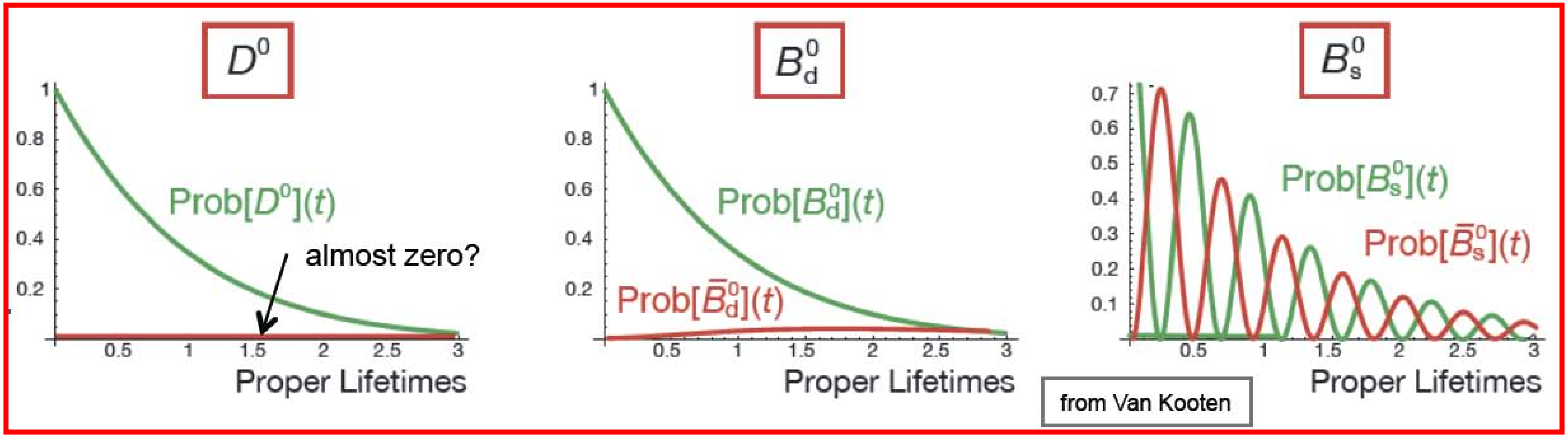
$$x \equiv \frac{\Delta M}{\Gamma} \qquad , \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$



- **K^0 :** $x \sim y \sim 1$
- **D^0 :** $x \sim y \sim 0.01$ Slow oscillation (decays faster)
- **B_d :** $x \sim 1$, $y \sim 0.01$
- **B_s :** $x \sim 25$, $y \leq 0.01$ Fast oscillation (averages out to 0)

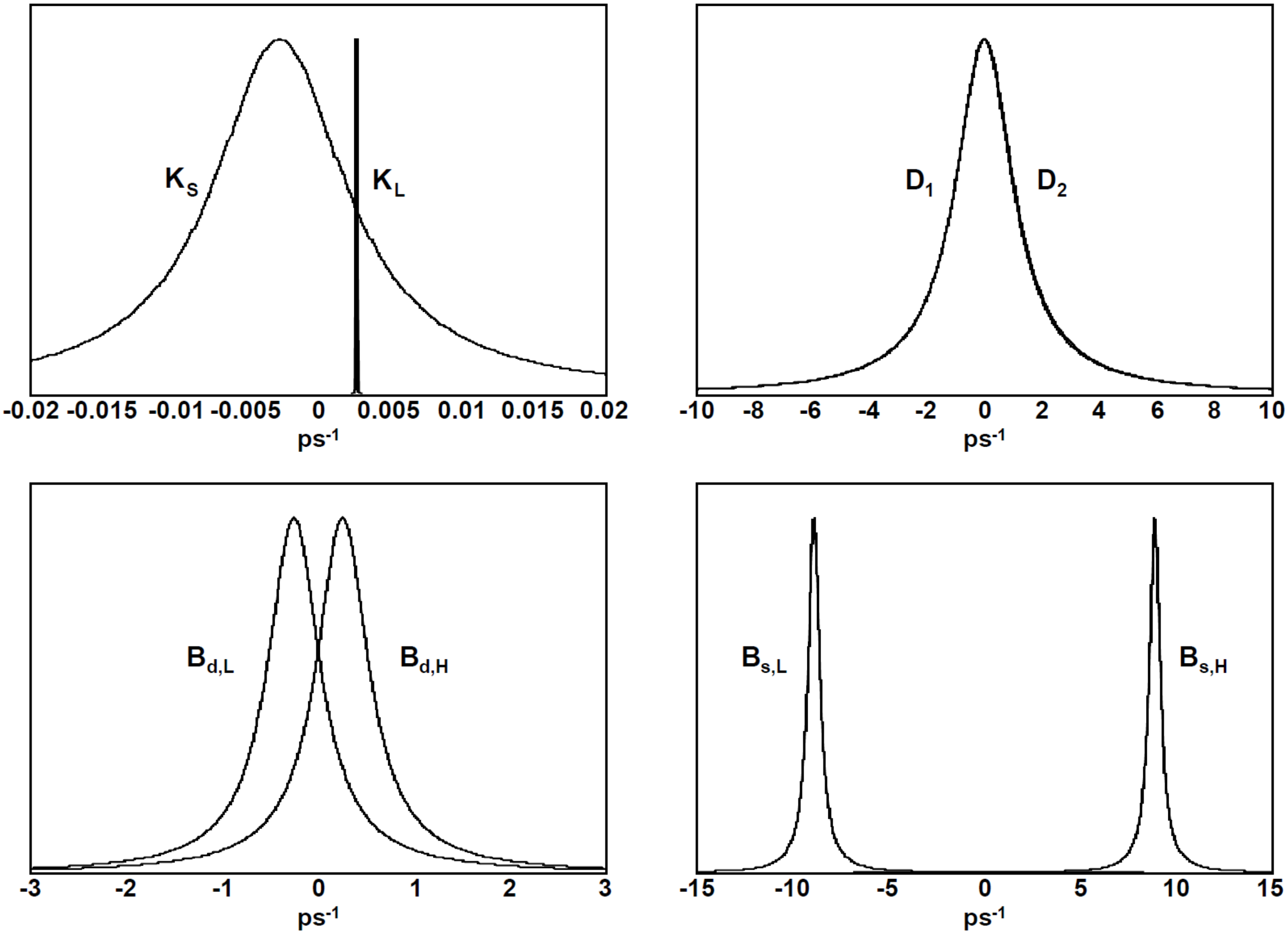
Time Scales: Oscillation ~ $\sin\left[\left(x - iy\right)\Gamma t/2\right]$

$$x \equiv \Delta M/\Gamma \qquad , \qquad y \equiv \Delta\Gamma/2\Gamma$$



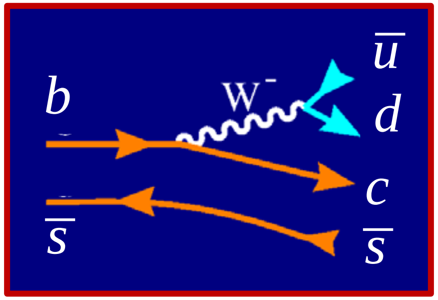
- **K^0 :** x ~ y ~ 1
- **D^0 :** x ~ y ~ 0.01 Slow oscillation (decays faster)
- **B_d :** x ~ 1 , y ~ 0.01
- **B_s :** x ~ 25 , y ≤ 0.01 Fast oscillation (averages out to 0)

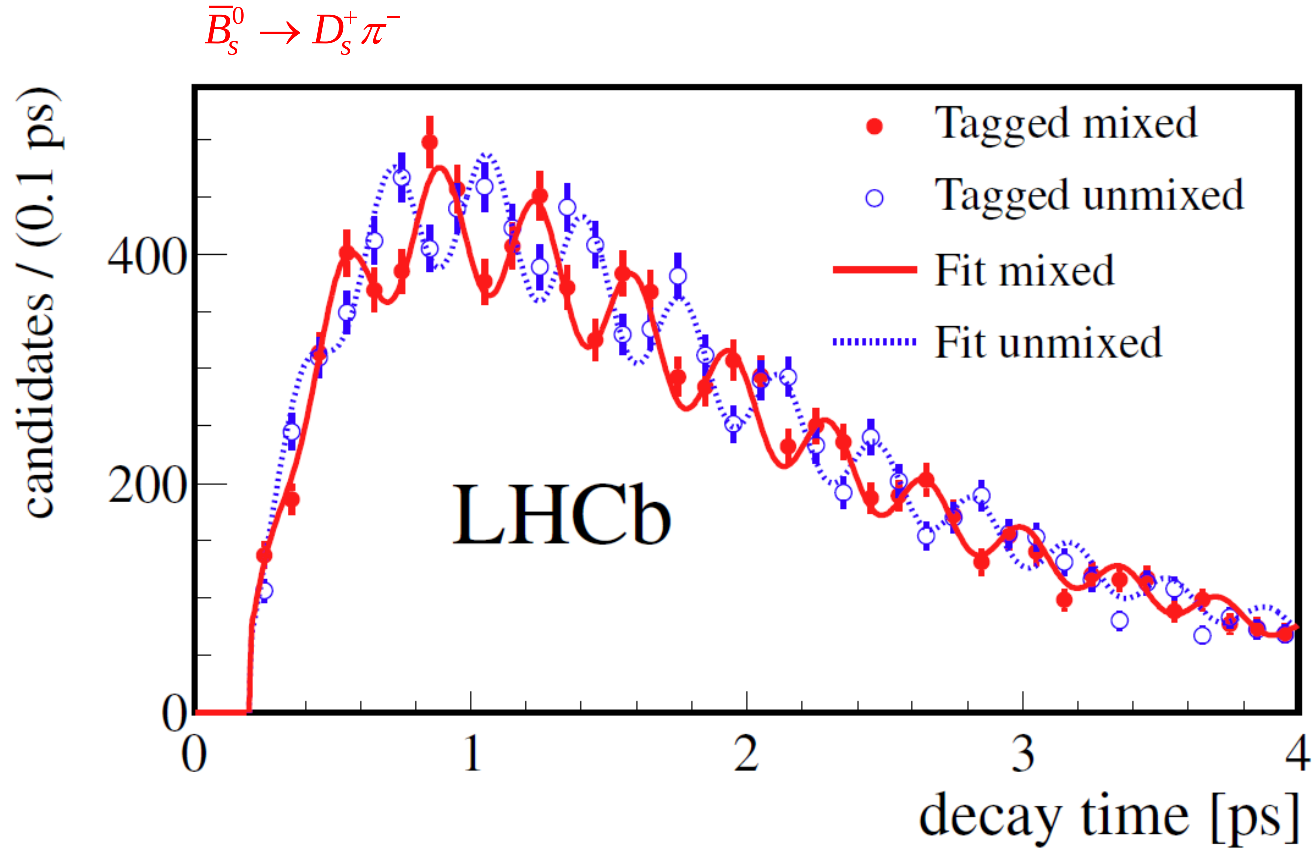
Widths & Mass Differences



M. Gersabeck

B_s Mixing @ LHCb



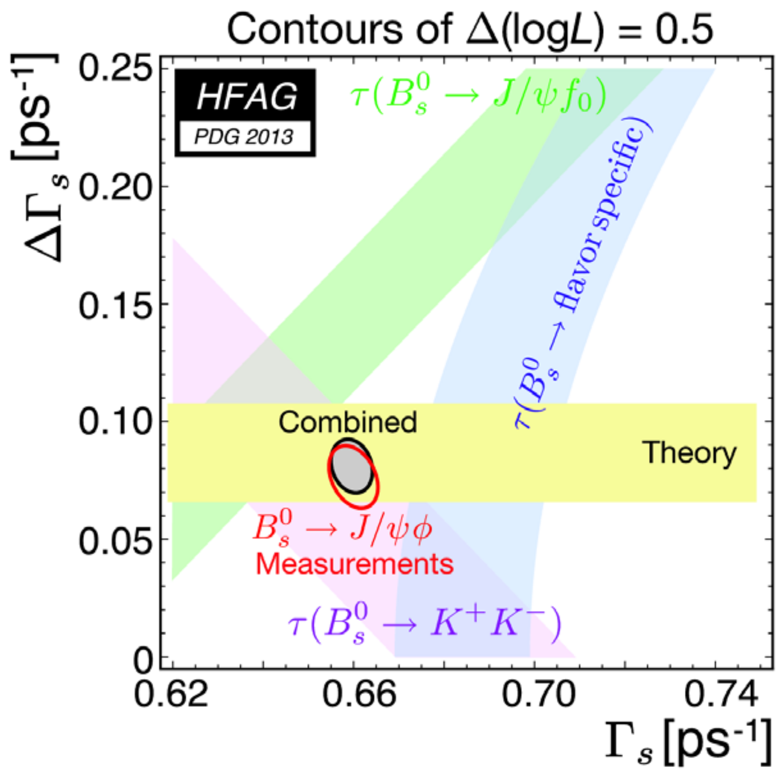


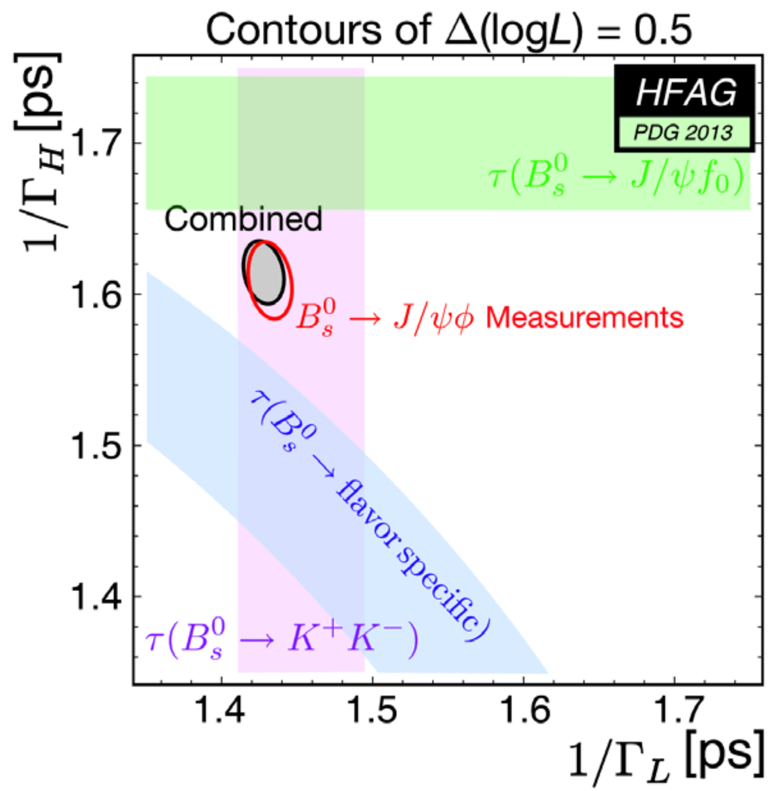
$$\Delta m_s = 17.768 \pm 0.023\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})\ \mathrm{ps}^{-1}$$

B_s Lifetimes

Γ_s	**0.6596 ± 0.0046 ps^{-1}**
$1/\Gamma_s$	**1.516 ± 0.011 ps**
$\tau_{Short} = 1/\Gamma_L$	**1.428 ± 0.013 ps**
$\tau_{Long} = 1/\Gamma_H$	**1.615 ± 0.021 ps**
$\Delta\Gamma_s$	**+0.081 ± 0.011 ps^{-1}**
$\Delta\Gamma_s/\Gamma_s$	**+0.123 ± 0.017**

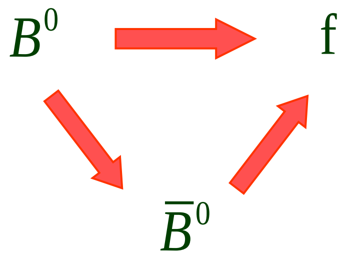
$\Delta\Gamma \equiv \Gamma_L - \Gamma_H$





CP (K^+K^-) = + **CP ($J/\psi\ f_0$) = –**

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\not{\mathcal{CP}}$



$$T_f \to T[B^0 \to f] \quad ; \quad \bar{T}_f \to -T[\bar{B}^0 \to f] \quad ; \quad \bar{\rho}_f \equiv \bar{T}_f / T_f$$

$$T_{\bar{f}} \to T[B^0 \to \bar{f}] \quad ; \quad \bar{T}_{\bar{f}} \to -T[\bar{B}^0 \to \bar{f}] \quad ; \quad \rho_{\bar{f}} \equiv T_{\bar{f}} / \bar{T}_{\bar{f}}$$

$$\mathcal{CP}\; B^0 = -\bar{B}^0 \qquad ; \qquad \mathcal{CP}\; f = \bar{f}$$

$$\Gamma[B^0(t) \to f] \sim \frac{1}{2}\, e^{-\Gamma t} \left(|T_f|^2 + |\bar{T}_f|^2 \right) \left\{ 1 + \mathbf{C_f} \cos(\Delta M\, t) - \mathbf{S_f} \sin(\Delta M\, t) \right\}$$

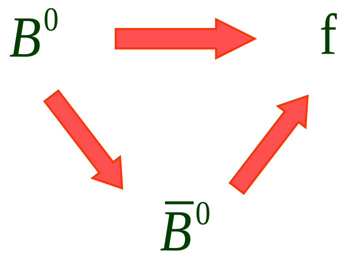
$$\Gamma[\bar{B}^0(t) \to \bar{f}] \sim \frac{1}{2}\, e^{-\Gamma t} \left(|\bar{T}_{\bar{f}}|^2 + |T_{\bar{f}}|^2 \right) \left\{ 1 - \mathbf{C_{\bar{f}}} \cos(\Delta M\, t) + \mathbf{S_{\bar{f}}} \sin(\Delta M\, t) \right\}$$

$$\mathbf{C_f} \equiv \frac{1 - |\bar{\rho}_f|^2}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{S_f} \equiv \frac{2\, \mathrm{Im}\left(\frac{q}{p}\, \bar{\rho}_f \right)}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{C_{\bar{f}}} \equiv -\frac{1 - |\rho_{\bar{f}}|^2}{1 + |\rho_{\bar{f}}|^2} \quad ; \quad \mathbf{S_{\bar{f}}} \equiv \frac{-\,2\, \mathrm{Im}\left(\frac{p}{q}\, \rho_{\bar{f}} \right)}{1 + |\rho_{\bar{f}}|^2}$$

$\Delta\Gamma \ll \Delta M$ ⟹

$$\frac{q}{p} \approx \frac{\mathbf{V}_{tb}^*\, \mathbf{V}_{tq}}{\mathbf{V}_{tb}\, \mathbf{V}_{tq}^*} = e^{-2i\phi_M} \quad ; \quad \phi_M \approx \begin{cases} \beta & (B_d^0) \\ -\beta_s \approx -\lambda^2 \eta & (B_s^0) \end{cases}$$

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\not{C}\not{P}$



$$T_{\mathrm{f}} \to T[B^0 \to \mathrm{f}\,] \quad ; \quad \bar{T}_{\mathrm{f}} \to -T[\bar{B}^0 \to \mathrm{f}\,] \quad ; \quad \bar{\rho}_{\mathrm{f}} \equiv \bar{T}_{\mathrm{f}} / T_{\mathrm{f}}$$

$$T_{\bar{\mathrm{f}}} \to T[B^0 \to \bar{\mathrm{f}}\,] \quad ; \quad \bar{T}_{\bar{\mathrm{f}}} \to -T[\bar{B}^0 \to \bar{\mathrm{f}}\,] \quad ; \quad \rho_{\bar{\mathrm{f}}} \equiv T_{\bar{\mathrm{f}}} / \bar{T}_{\bar{\mathrm{f}}}$$

$$\mathcal{CP}\; B^0 = -\bar{B}^0 \qquad ; \qquad \mathcal{CP}\; \mathrm{f} = \bar{\mathrm{f}}$$

$$\Gamma[B^0(t) \to \mathrm{f}\,] \;\sim\; \frac{1}{2}\, e^{-\Gamma t} \left(|T_{\mathrm{f}}|^2 + |\bar{T}_{\mathrm{f}}|^2 \right) \left\{ 1 + \mathbf{C_f}\, \cos(\Delta M\, t) - \mathbf{S_f}\, \sin(\Delta M\, t) \right\}$$

$$\Gamma[\bar{B}^0(t) \to \bar{\mathrm{f}}\,] \;\sim\; \frac{1}{2}\, e^{-\Gamma t} \left(|\bar{T}_{\bar{\mathrm{f}}}|^2 + |T_{\bar{\mathrm{f}}}|^2 \right) \left\{ 1 - \mathbf{C_{\bar{f}}}\, \cos(\Delta M\, t) + \mathbf{S_{\bar{f}}}\, \sin(\Delta M\, t) \right\}$$

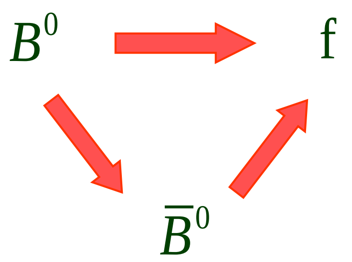
$$\mathbf{C_f} \equiv \frac{1 - |\bar{\rho}_{\mathrm{f}}|^2}{1 + |\bar{\rho}_{\mathrm{f}}|^2} \quad ; \quad \mathbf{S_f} \equiv \frac{2\,\mathrm{Im}\left(\frac{q}{p}\, \bar{\rho}_{\mathrm{f}} \right)}{1 + |\bar{\rho}_{\mathrm{f}}|^2} \quad ; \quad \mathbf{C_{\bar{f}}} \equiv -\frac{1 - |\rho_{\bar{\mathrm{f}}}|^2}{1 + |\rho_{\bar{\mathrm{f}}}|^2} \quad ; \quad \mathbf{S_{\bar{f}}} \equiv \frac{-\,2\,\mathrm{Im}\left(\frac{p}{q}\, \rho_{\bar{\mathrm{f}}} \right)}{1 + |\rho_{\bar{\mathrm{f}}}|^2}$$

CP self-conjugate: $\bar{\mathrm{f}} = \eta_{\mathrm{f}}\; \mathrm{f}$ ⟹

$$T_{\bar{\mathrm{f}}} = \eta_{\mathrm{f}}\; T_{\mathrm{f}} \quad ; \quad \bar{T}_{\bar{\mathrm{f}}} = \eta_{\mathrm{f}}\; \bar{T}_{\mathrm{f}} \quad ; \quad \rho_{\bar{\mathrm{f}}} \equiv 1 / \bar{\rho}_{\mathrm{f}}$$

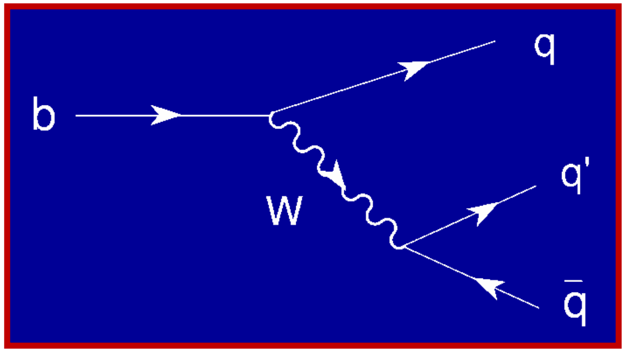
$$\mathbf{C_{\bar{f}}} = \mathbf{C_f} \qquad ; \qquad \mathbf{S_{\bar{f}}} = \mathbf{S_f}$$

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\not{CP}$



CP self-conjugate: $\bar{\mathrm{f}} = \eta_{\mathrm{f}}\ \mathrm{f}$

$$\frac{q}{p} \approx \frac{\mathbf{V}_{tb}^{*}\ \mathbf{V}_{tq}}{\mathbf{V}_{tb}\ \mathbf{V}_{tq}^{*}} = e^{-2i\phi_M} \quad ; \quad \phi_M \approx \begin{cases} \beta & \left(B_d^0\right) \\ -\beta_s \approx -\lambda^2\eta & \left(B_s^0\right) \end{cases}$$



Assumption: **Only 1 decay amplitude**

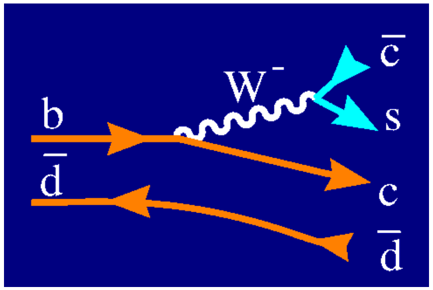
$$\frac{\mathrm{A}_{b\to q\bar{q}q'}}{\mathrm{A}_{\bar{b}\to \bar{q}q\bar{q}'}} = \frac{\mathbf{V}_{qb}\ \mathbf{V}_{qq'}^{*}}{\mathbf{V}_{qb}^{*}\ \mathbf{V}_{qq'}} = e^{-2i\phi_D}$$

$$\frac{\Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right) - \Gamma\left(B^0 \to \mathrm{f}\right)}{\Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right) + \Gamma\left(B^0 \to \mathrm{f}\right)} = -\eta_{\mathrm{f}}\ \sin(2\phi)\ \sin(\Delta M\, t) \quad ; \quad \phi = \phi_M + \phi_D$$

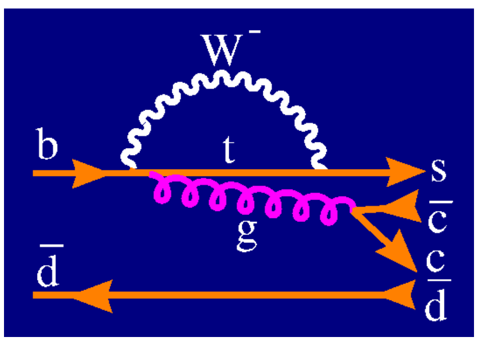
Direct information on the CKM matrix

$\bar{B}_d^0 \to J/\Psi\, K_S^0$

$\phi \simeq \beta$



$V_{cb}\, V_{cs}^* \sim A\lambda^2$

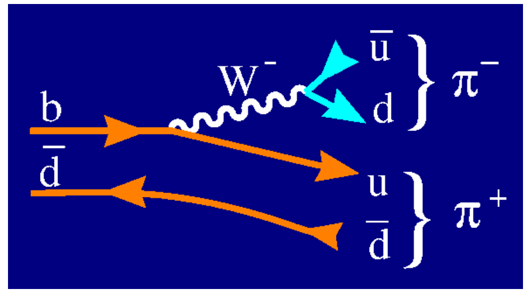


$V_{tb}\, V_{ts}^* \sim -A\lambda^2$

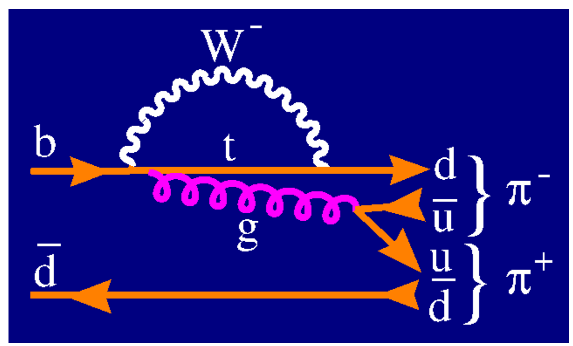
***

$\bar{B}_d^0 \to \pi^+\pi^-$

$\phi \simeq \beta+\gamma = \pi-\alpha$



$V_{ub}\, V_{ud}^* \sim A\lambda^3(\rho - i\eta)$

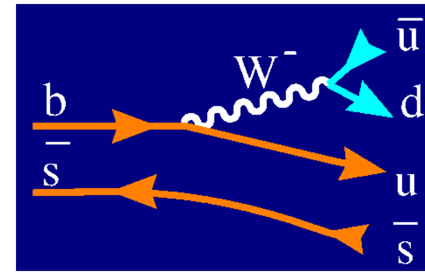


$V_{tb}\, V_{td}^* \sim A\lambda^3(1-\rho+i\eta)$

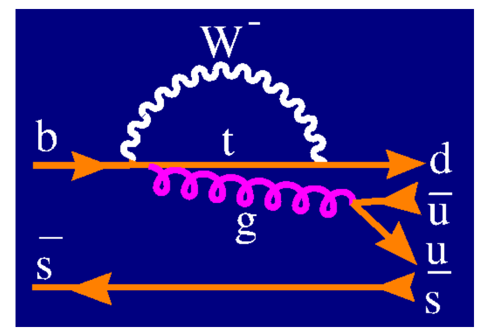
**

$\bar{B}_s^0 \to \rho^0 K_S^0$

$\phi \neq \gamma$



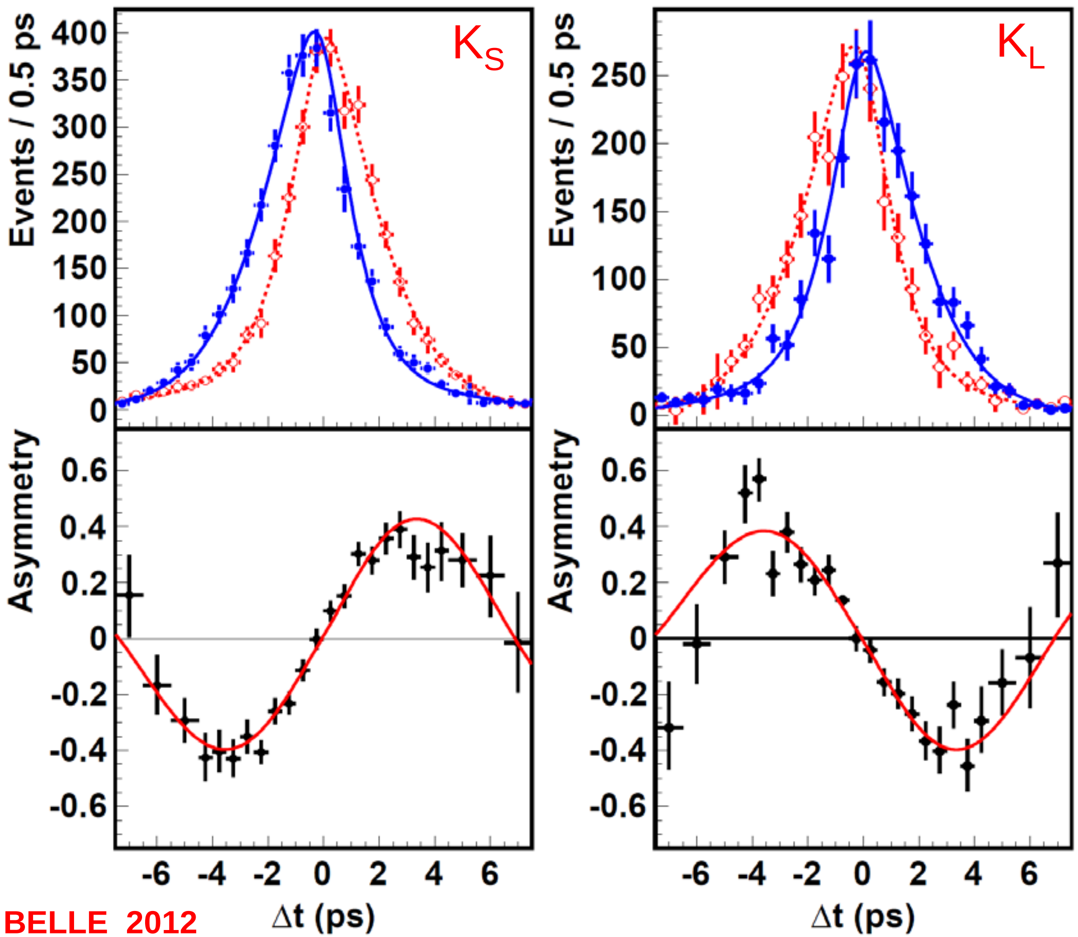
$V_{ub}\, V_{ud}^* \sim A\lambda^3(\rho - i\eta)$



$V_{tb}\, V_{td}^* \sim A\lambda^3(1-\rho+i\eta)$

BAD

$$\frac{\Gamma(\bar{B}^0 \to J/\psi\, K_S) - \Gamma(B^0 \to J/\psi\, K_S)}{\Gamma(\bar{B}^0 \to J/\psi\, K_S) + \Gamma(B^0 \to J/\psi\, K_S)} \;=\; -\eta_f\; \sin(2\beta)\; \sin(\Delta M\, t)$$

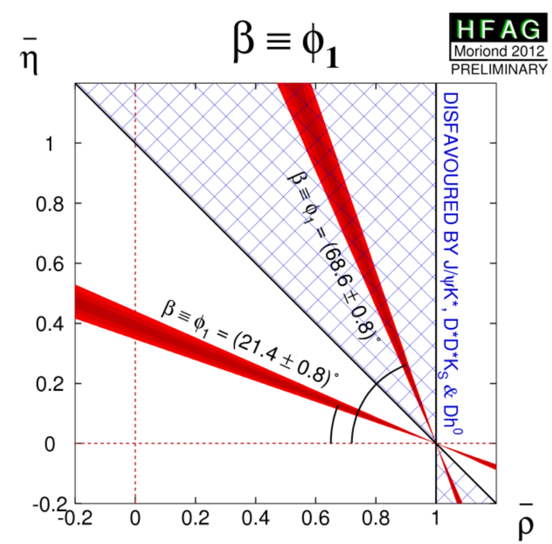


BELLE 2012

HFAG:

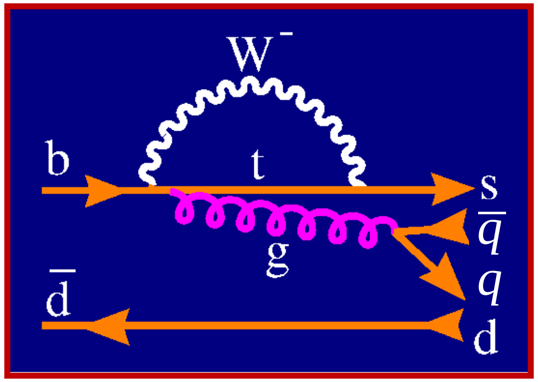
sin(2β) = 0. 682 ± 0.019

$B^0 \to J/\psi\, K_{S,L}\,,\, \psi(2S)\, K_S\,,\, \chi_c\, K_S\,,\, \eta_c\, K_S$



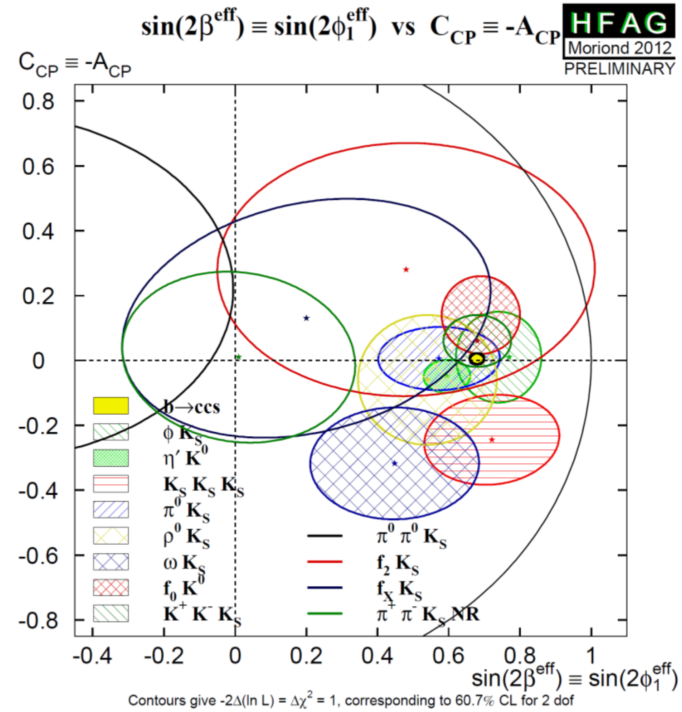
$\not{CP}$ Signal

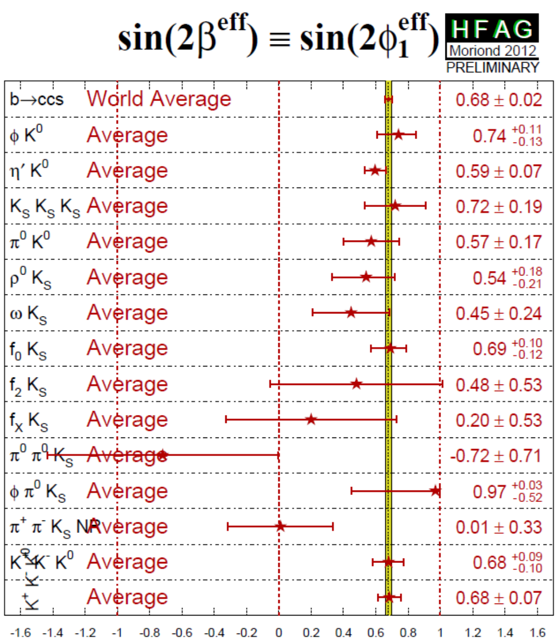
$b \to q\bar{q}s$

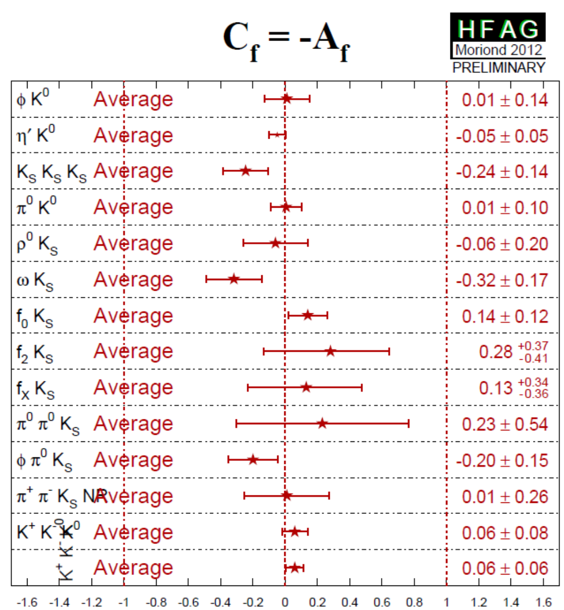


$$V_{tb}\, V_{ts}^{*} \sim -A\lambda^{2}$$

Sensitive to New Physics in Penguin diagram







Agreement with

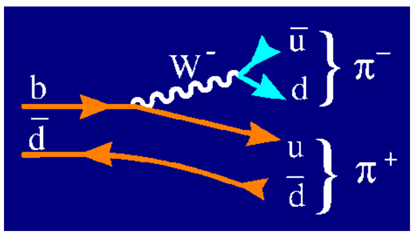
$$B^0 \to J/\Psi\, K_S \qquad (b \to c\bar{c}s)$$

No signal of direct $\not{C}\!\not{P}$

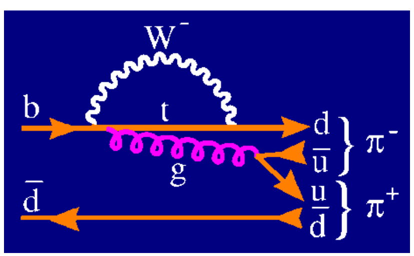
$B^0 \to \pi\pi$

$$\frac{\Gamma\left(\bar{B}^0 \to \bar{f}\right) - \Gamma\left(B^0 \to f\right)}{\Gamma\left(\bar{B}^0 \to \bar{f}\right) + \Gamma\left(B^0 \to f\right)} = -C_f \cos(\Delta M\, t) + S_f \sin(\Delta M\, t)$$

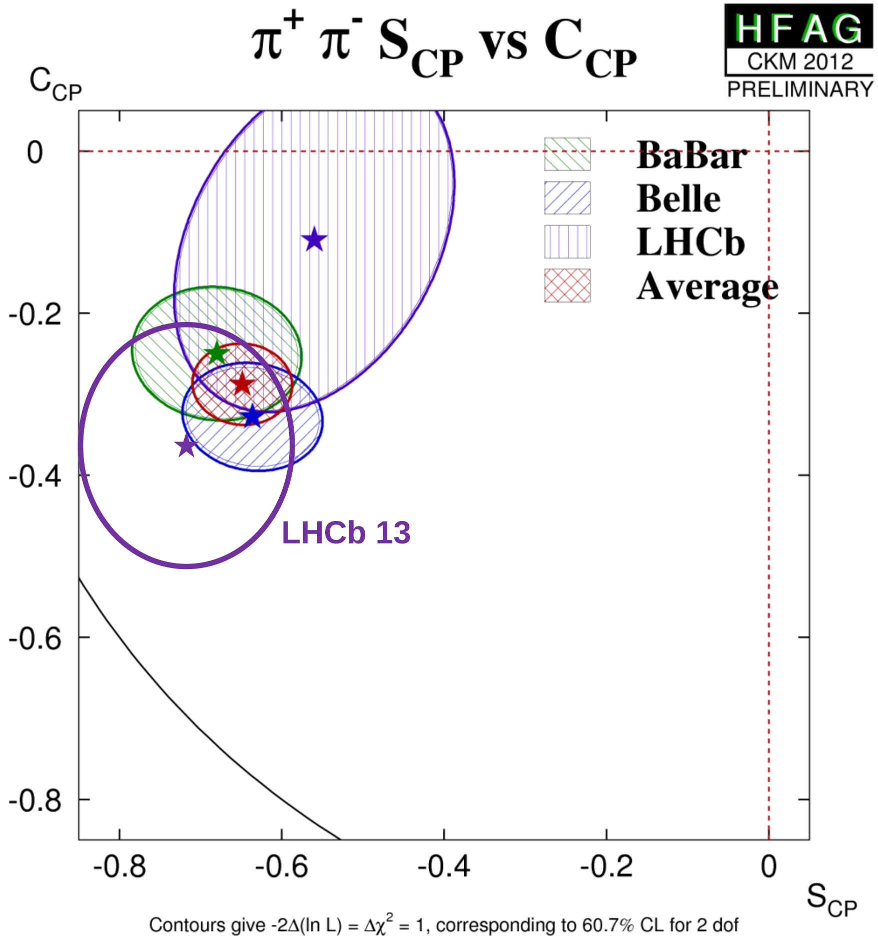
$$\alpha \equiv \arg\left[-\frac{\mathbf{V}_{td}\,\mathbf{V}_{tb}^*}{\mathbf{V}_{ud}\,\mathbf{V}_{ub}^*}\right]$$



$$V_{ub}\,V_{ud}^* \sim A\lambda^3(\rho - i\eta)$$



$$V_{tb}\,V_{td}^* \sim A\lambda^3(1-\rho+i\eta)$$



$$C_f \equiv \frac{1-|\bar{\rho}_f|^2}{1+|\bar{\rho}_f|^2} \neq 0$$

Direct $\not{CP}$

Penguins

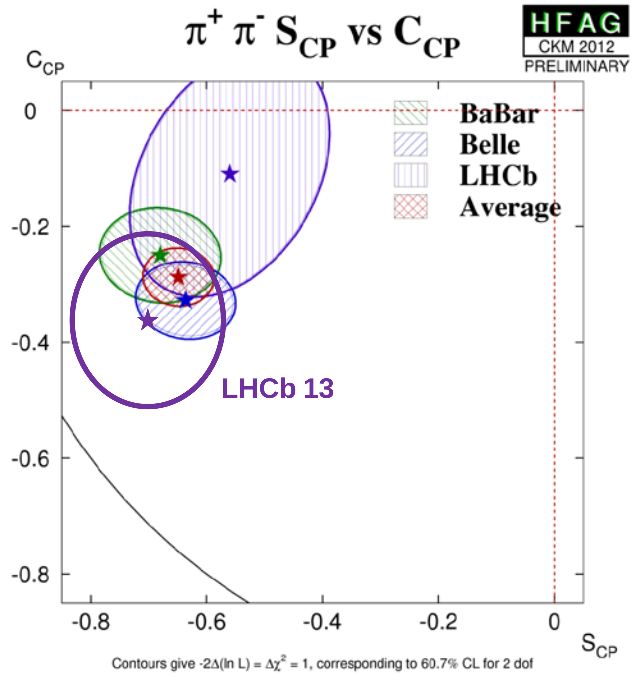
$$S_f \approx -\sin(2\alpha) \quad ?$$

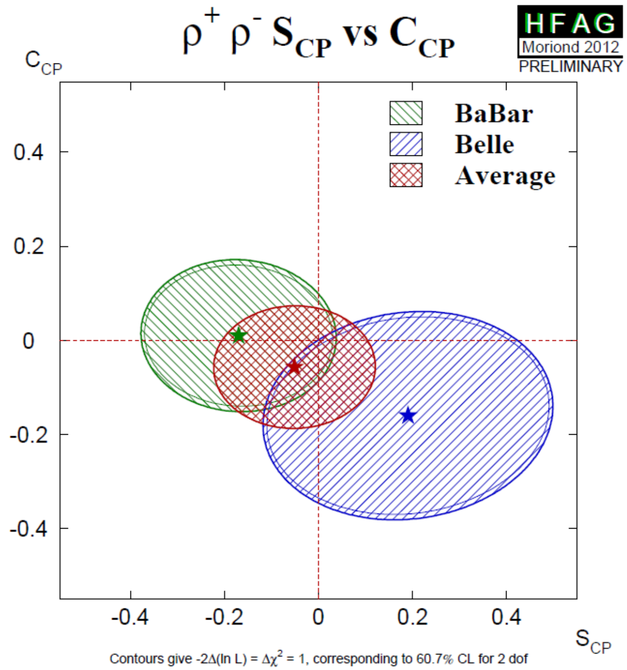
$B^0 \to \pi\pi, \rho\rho, \rho\pi$

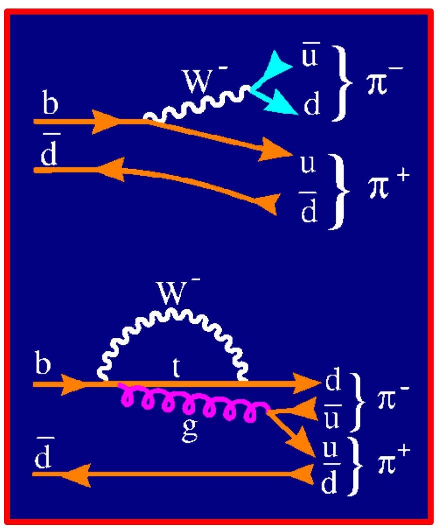
$$C_f \equiv \frac{1-|\bar{\rho}_f|^2}{1+|\bar{\rho}_f|^2} \neq 0$$

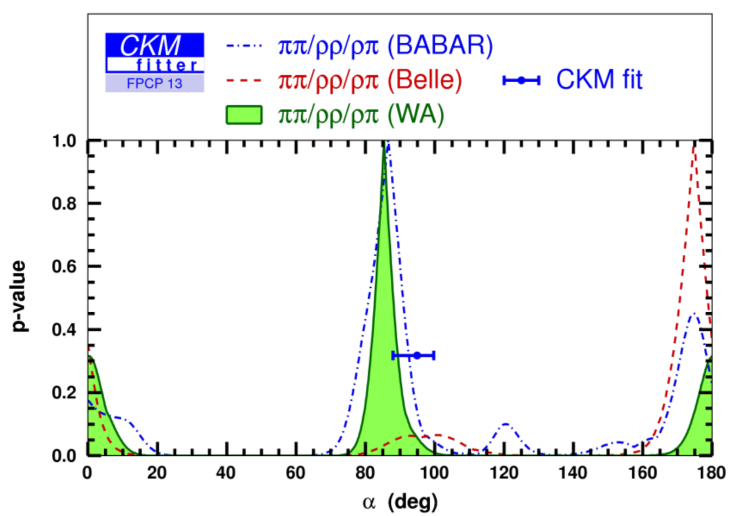
Direct $\not{CP}$

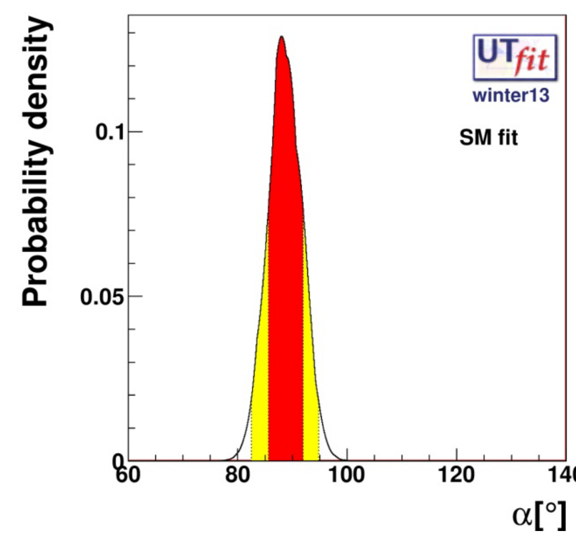
Penguins











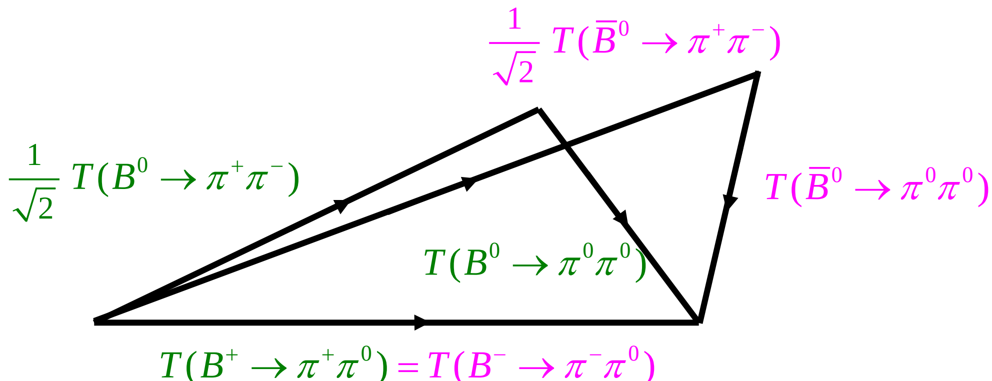
MEASURING HADRONIC CONTAMINATIONS

- **Time Evolution**
- **Transversity Analysis:** $B \to V\, V$
- **Isospin Relations** (Gronau-London)
- D^0-$\bar{D}^0$ **Mixing** (Gronau-London-Wyler, Atwood-Dunietz-Soni)

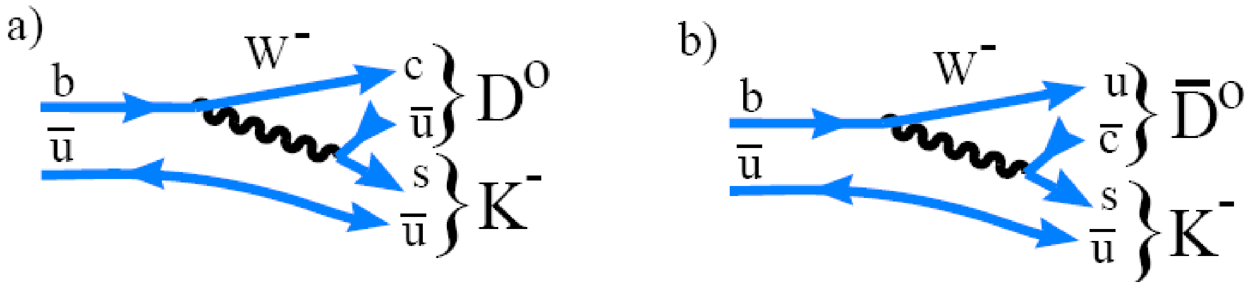
$$\sqrt{2}\, T(B^+ \to D_+^0 K^+) = T(B^+ \to D^0 K^+) + T(B^+ \to \bar{D}^0 K^+)$$

$$\sqrt{2}\, T(B_d^0 \to D_+^0 K_S) = T(B^+ \to D^0 K_S) + T(B^+ \to \bar{D}^0 K_S)$$

- **Dalitz Analysis**
- **SU(3) Relations:** $B \to \pi K\, ,\ \pi\pi\, ,\ \ldots$
- …



D^0-$\bar{D}^0$ Mixing



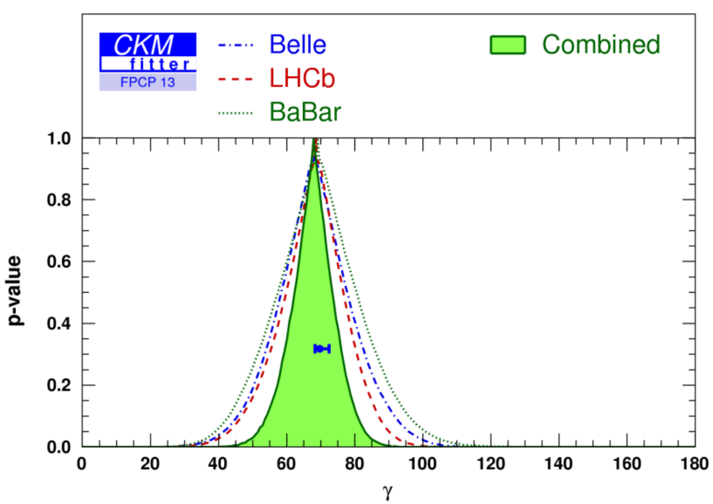
Gronau-London-Wyler

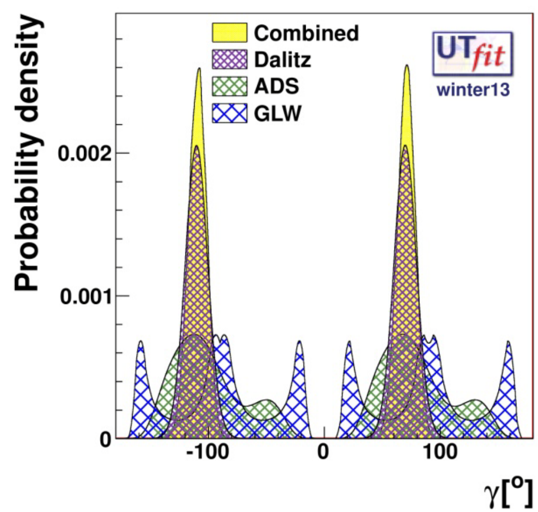
Atwood-Dunietz-Soni

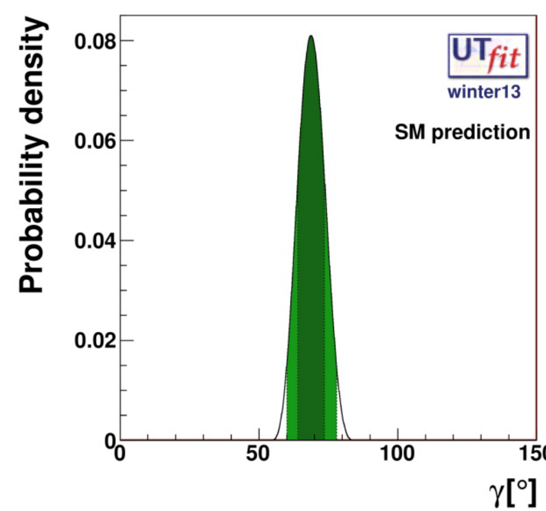
$$\sqrt{2}\,\mathrm{T}(B^+ \to D^0_+ K^+) = \mathrm{T}(B^+ \to D^0 K^+) + \mathrm{T}(B^+ \to \bar{D}^0 K^+)$$

$$\sqrt{2}\,\mathrm{T}(B^0_d \to D^0_+ K_S) = \mathrm{T}(B^+ \to D^0 K_S) + \mathrm{T}(B^+ \to \bar{D}^0 K_S)$$

$$\Rightarrow \quad \gamma \equiv \arg\left[-\frac{\mathbf{V}_{ud}\,\mathbf{V}_{ub}^*}{\mathbf{V}_{cd}\,\mathbf{V}_{cb}^*}\right] = \left(68.0\,{}^{+8.0}_{-8.5}\right)^\circ$$

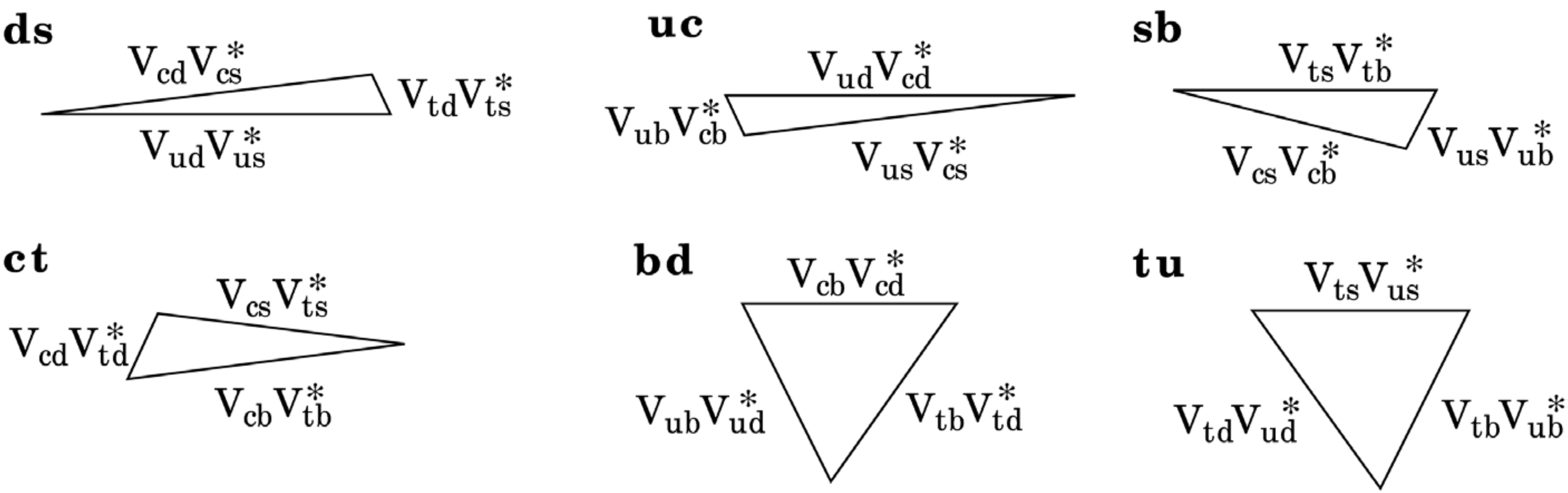






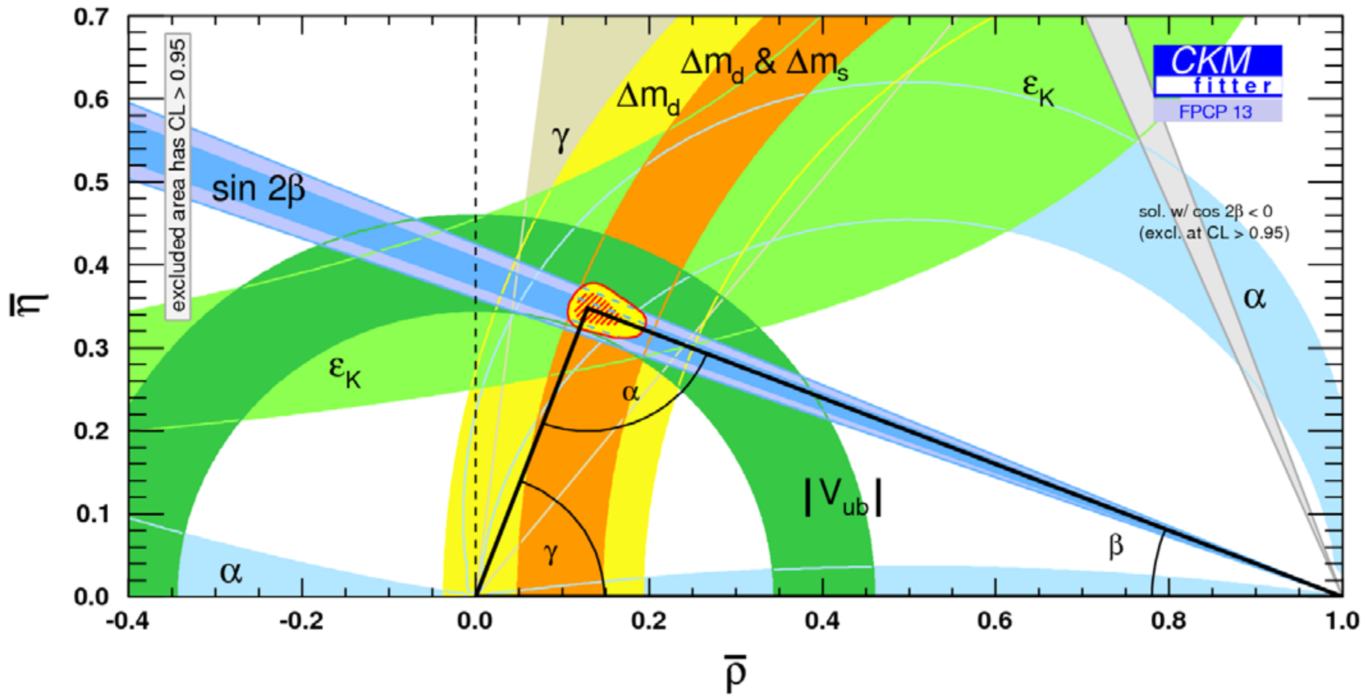
UNITARITY TRIANGLES

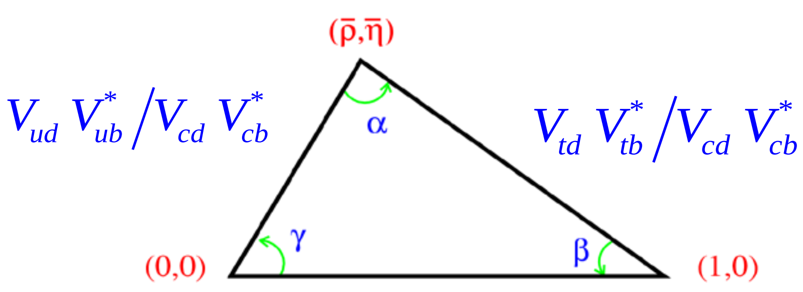
$$\mathbf{V_{ui}\,V_{uj}^* + V_{ci}\,V_{cj}^* + V_{ti}\,V_{tj}^*} = 0 \qquad (i \neq j)$$



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

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





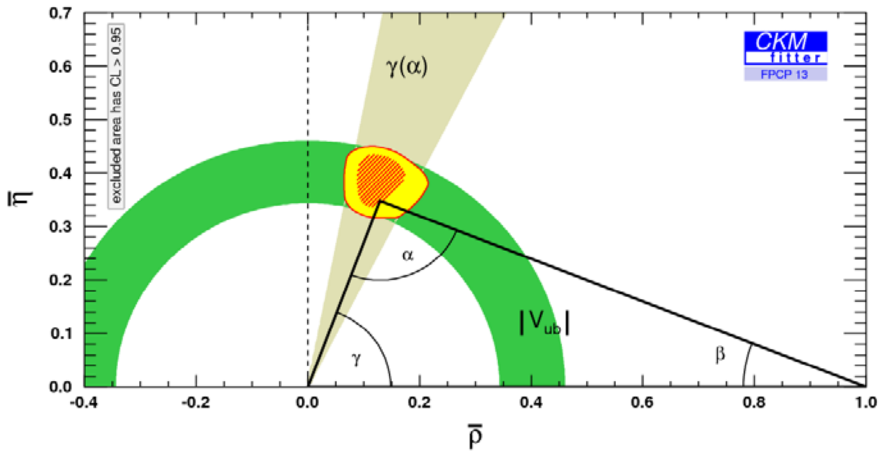
UT*fit*

$$\bar{\eta} \equiv \eta \left(1 - \frac{1}{2}\lambda^2\right) = 0.350 \pm 0.014$$

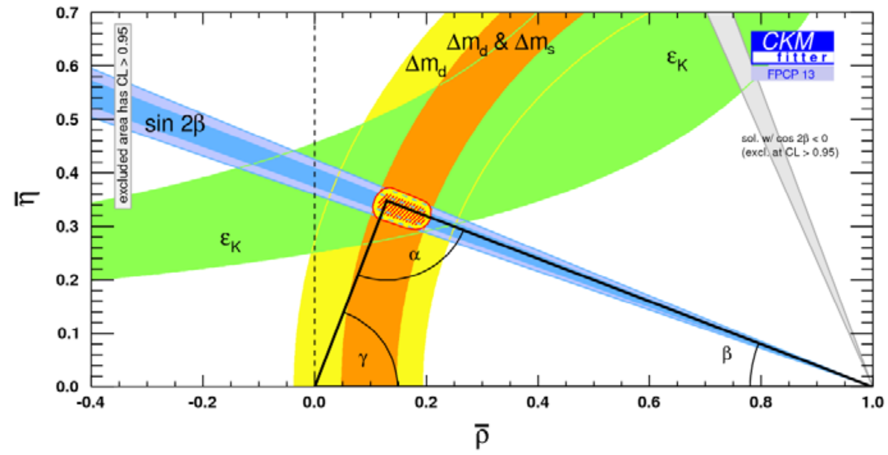
$$\bar{\rho} \equiv \rho \left(1 - \frac{1}{2}\lambda^2\right) = 0.132 \pm 0.021$$

$\alpha = 88.7 \pm 3.1°$; $\beta = 21.95 \pm 0.86°$; $\gamma = 69.2 \pm 3.2°$

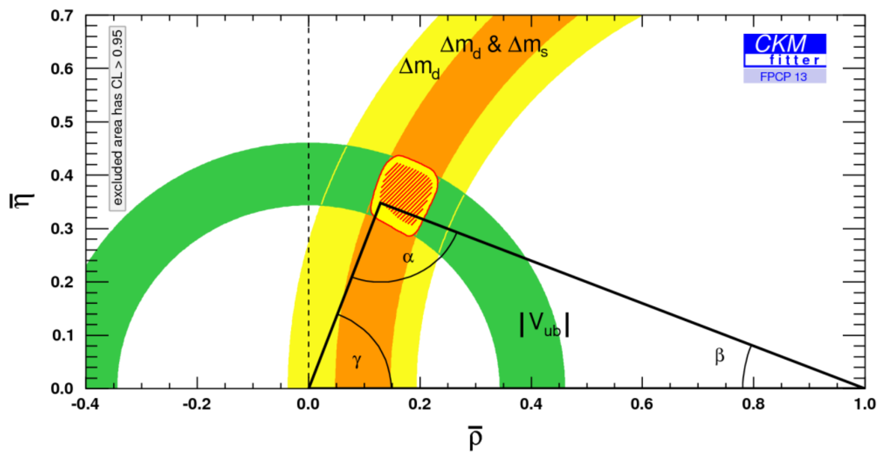
Tree-level determinations



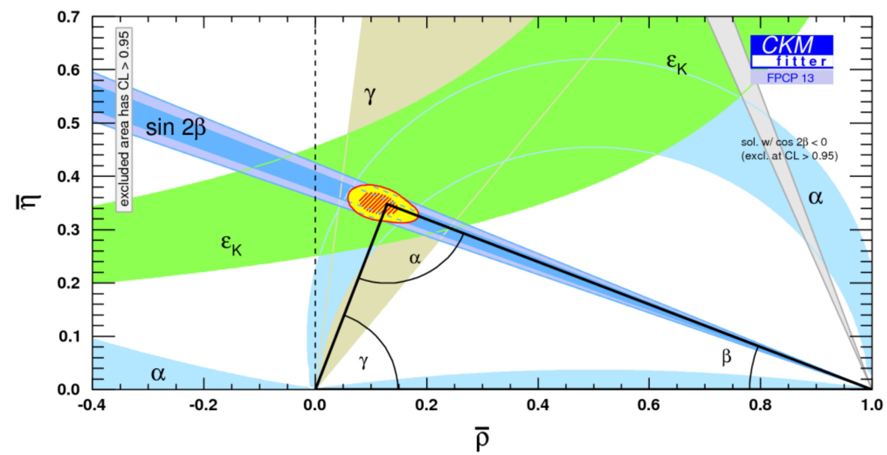
Loop processes

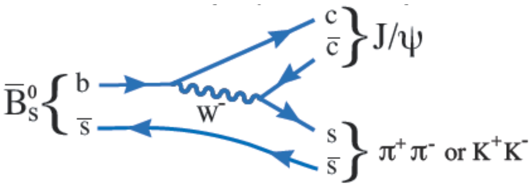


CP Conserving



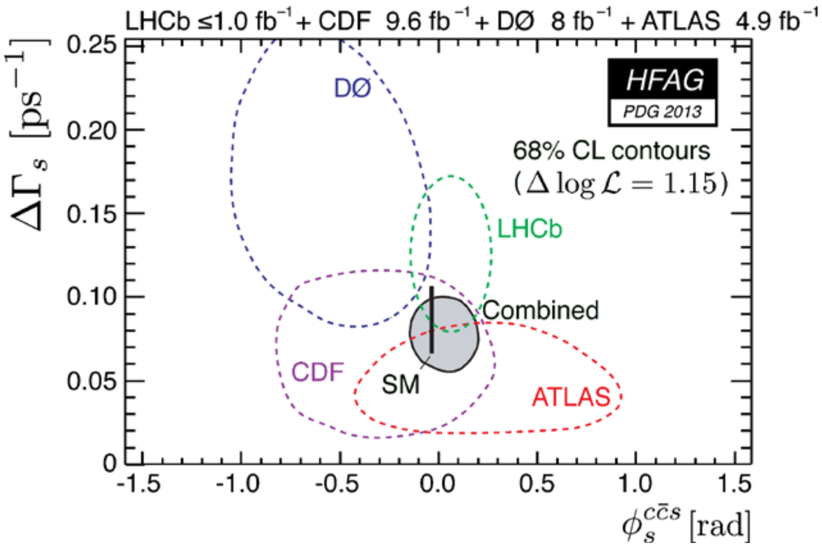
CP Violating

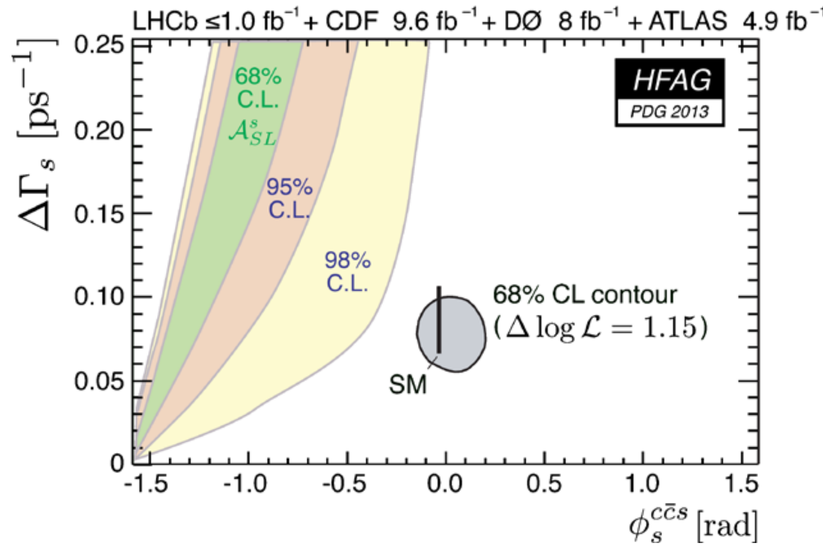


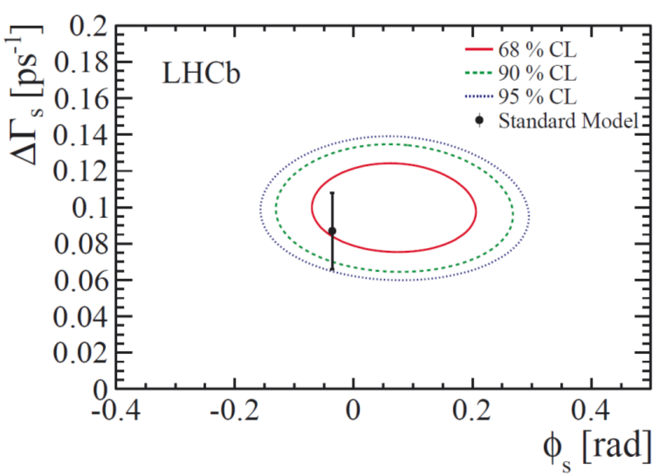


$$\phi_s^{c\bar{c}s} \equiv 2\left(\phi_s^M + \phi_s^D\right) \qquad ; \qquad \phi_s^{c\bar{c}s}\Big|_{SM} \approx -2\beta_s \equiv -2\,\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

$$\phi_s^{c\bar{c}s}\Big|_{SM} = \left(-0.0363\,^{+0.0016}_{-0.0015}\right)\ \text{rad} \qquad \text{(CKMfitter)}$$



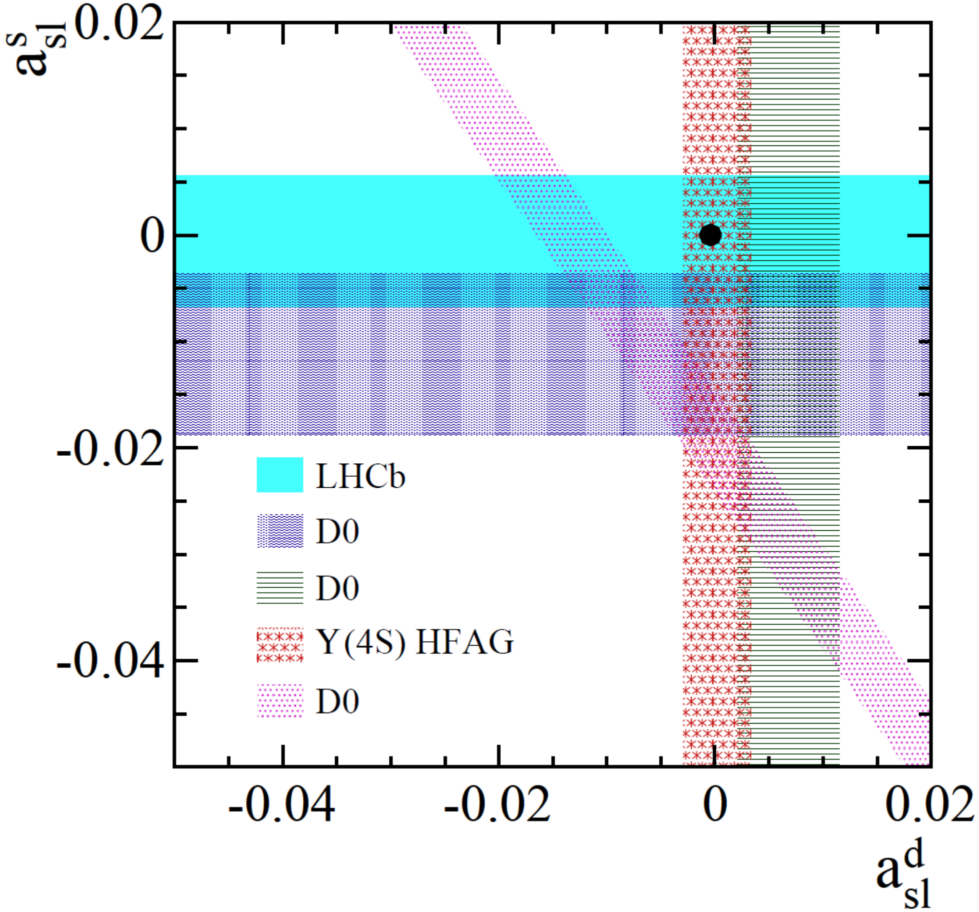




PDG 2013: $\phi_s^{c\bar{c}s} = \left(0.04\,^{+0.10}_{-0.13}\right)$ rad

LHCb 2013: $\phi_s^{c\bar{c}s} = \left(0.01 \pm 0.07\right)$ rad

B_s Semileptonic Asymmetry



$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$$a_{sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\bar{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)}$$

$$= \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

$$\phi_q \equiv \arg\left(-M_{12}^q/\Gamma_{12}^q\right) \sim \frac{m_c^2}{m_b^2}$$

DIRECT $\not{CP}$ 10.9 σ signal

$$A(\bar{B}_d^0 \to \pi^+ K^-) \equiv \frac{\mathrm{Br}(\bar{B}_d^0 \to \pi^+ K^-) - \mathrm{Br}(B_d^0 \to \pi^- K^+)}{\mathrm{Br}(\bar{B}_d^0 \to \pi^+ K^-) + \mathrm{Br}(B_d^0 \to \pi^- K^+)} = -0.087 \pm 0.008$$

$$A(B^- \to \pi^0 K^-) \equiv \frac{\mathrm{Br}(B^- \to \pi^0 K^-) - \mathrm{Br}(B^+ \to \pi^0 K^+)}{\mathrm{Br}(B^- \to \pi^0 K^-) + \mathrm{Br}(B^+ \to \pi^0 K^+)} = 0.037 \pm 0.021$$

$$A(\bar{B}_d^0 \to \pi^+ K^-) - A(B^- \to \pi^0 K^-) = -0.124 \pm 0.022$$

Difficult to accommodate in the Standard Model **(but huge uncertainties)**

$$A(\bar{B}_d^0 \to \pi^+ K^-) = \begin{cases} -0.080 \pm 0.008 & \text{LHCb 2013} \\ -0.083 \pm 0.013 & \text{CDF 2013} \end{cases}$$

DIRECT $\not{CP}$ in B_s Decays   6.5 σ signal

$$A(\bar{B}_s^0 \to \pi^- K^+) = \begin{cases} 0.27 \pm 0.04 \pm 0.01 & \text{LHCb 2013} \\ 0.22 \pm 0.07 \pm 0.02 & \text{CDF 2013} \end{cases}$$

$$\Delta \equiv \frac{A(\bar{B}_d^0 \to \pi^+ K^-)}{A(\bar{B}_s^0 \to \pi^- K^+)} + \frac{\Gamma(\bar{B}_s^0 \to \pi^- K^+)}{\Gamma(\bar{B}_d^0 \to \pi^+ K^-)} = -0.02 \pm 0.05 \pm 0.04 \qquad \text{LHCb 2013}$$

SM prediction (Lipkin): $\Delta \approx 0$

DIRECT $\not{CP}$

$$A^{CP}_{\bar{B}^0_d\to K^-\pi^+} = -0.087 \pm 0.008 \quad , \quad A^{CP}_{\bar{B}^0_d\to \bar{K}^{*0}\eta} = 0.19 \pm 0.05$$

$$A^{CP}_{\bar{B}^0_d\to K^{*-}\pi^+} = -0.22 \pm 0.06 \quad , \quad C_{B^0_d\to \pi^-\pi^+} = -0.38 \pm 0.15$$

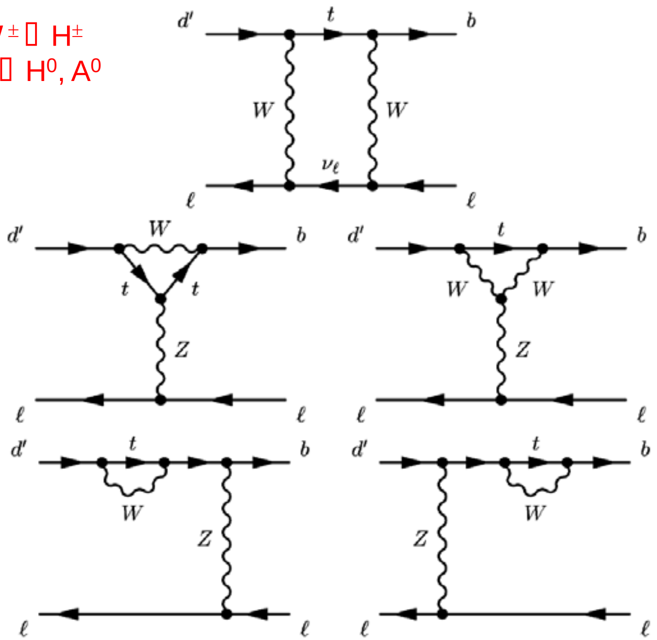
$$A^{CP}_{B^-\to K^-\rho^0} = 0.37 \pm 0.10 \quad , \quad A^{CP}_{B^-\to K^-\eta} = -0.37 \pm 0.08$$

$$A^{CP}_{B^-\to \pi^-\eta} = -0.14 \pm 0.07 \quad , \quad A^{CP}_{B^-\to K^- D_{CP(+1)}} = 0.170 \pm 0.0033$$

$$A^{CP}_{B^-\to K^- f_2(1270)} = -0.68\ {}^{+\,0.19}_{-\,0.17} \quad , \quad A^{CP}_{B^-\to \pi^- f_0(1370)} = 0.72 \pm 0.22$$

$B_{s,d} \to \mu^+\mu^-$

$W^{\pm} \to H^{\pm}$
$Z \to H^0, A^0$



$$\mathcal{H}_{\rm eff} = -\frac{G_F\,\alpha}{\sqrt{2}\pi}\left\{V_{ts}^* V_{tb} \sum_i^{10,S,P} \left(C_i\,\mathcal{O}_i + C_i'\,\mathcal{O}_i'\right) + \text{h.c}\right\}$$

SM: $C_{10} = -4.134$; $C_i' \approx C_{P,S} \approx 0$ (Buras et al)

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu\gamma_5 l), \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\mu P_R b)(\bar{l}\gamma^\mu\gamma_5 l)$$

$$\mathcal{O}_S = m_b(\bar{s}P_R b)(\bar{l}l), \qquad \mathcal{O}_S' = m_b(\bar{s}P_L b)(\bar{l}l)$$

$$\mathcal{O}_P = m_b(\bar{s}P_R b)(\bar{l}\gamma_5 l), \qquad \mathcal{O}_P' = m_b(\bar{s}P_L b)(\bar{l}\gamma_5 l)$$

Sensitive to (pseudo) scalar contributions

$$\text{BR}(B_s \to \mu^+\mu^-)_{\rm SM} = \frac{\tau_{B_s}}{2}\langle\Gamma(B_s(t) \to \mu^+\mu^-)\rangle\Big|_{t=0}$$

$$= \frac{\tau_{B_s}\,G_F^4\,M_W^4\,\sin^4\theta_W}{8\pi^5}\left|C_{10}^{\rm SM} V_{ts} V_{tb}^*\right|^2 F_{B_s}^2\, m_{B_s} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$

$\text{Br}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.35 \pm 0.28)\cdot 10^{-9}$; $\text{Br}(B_d^0 \to \mu^+\mu^-)_{\rm SM} = (1.07 \pm 0.10)\cdot 10^{-10}$

Experimental Branching Ratio:

$\Delta\Gamma_s/(2\Gamma_s) = 0.0615 \pm 0.0085$

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) \equiv \frac{1}{2}\int_0^\infty \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle\, dt$$

$$\langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle \equiv \Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)$$

(Fleischer et al)

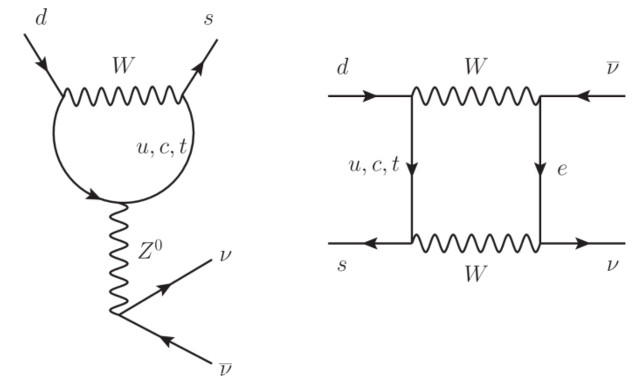
$$\overline{\mathrm{Br}}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (3.56 \pm 0.30)\cdot 10^{-9} \quad ; \quad \mathrm{Br}(B_d^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (1.07 \pm 0.10)\cdot 10^{-10}$$

LHCb: $\overline{\mathrm{Br}}(B_s^0 \to \mu^+\mu^-) = \left(2.9\,{}^{+1.1}_{-1.0}\right)\cdot 10^{-9}$; $\mathrm{Br}(B_d^0 \to \mu^+\mu^-) < 7.4 \cdot 10^{-10}$ (95% CL)

CMS: $\overline{\mathrm{Br}}(B_s^0 \to \mu^+\mu^-) = \left(3.0\,{}^{+1.0}_{-0.9}\right)\cdot 10^{-9}$; $\mathrm{Br}(B_d^0 \to \mu^+\mu^-) < 1.1 \cdot 10^{-9}$ (95% CL)

$K \to \pi \nu \bar{\nu}$

$$\mathbf{T} \sim F\left(V_{is}^{*} V_{id}, m_i^2/M_W^2\right) \left(\overline{\nu}_L \gamma_\mu \nu_L\right) \left\langle \pi \middle| \overline{s}_L \gamma_\mu d_L \middle| K \right\rangle$$



$$\mathrm{Br}\left(K^+ \to \pi^+ \nu \overline{\nu}\right) = (7.8 \pm 0.8) \times 10^{-11} \sim A^4 \left[\eta^2 + (1.4 - \rho)^2\right]$$

$$\mathrm{Br}\left(K_L \to \pi^0 \nu \overline{\nu}\right) = (2.4 \pm 0.4) \times 10^{-11} \sim A^4 \eta^2$$

Buras et al

Long-distance contributions are negligible

$$\mathbf{T}\left(K_L \to \pi^0 \nu \overline{\nu}\right) \neq 0 \quad \Longrightarrow \quad \not{CP}$$

- **BNL-E949:** **few events!** ⟹ $\mathrm{Br}\left(K^+ \to \pi^+ \nu \overline{\nu}\right) = \left(1.73\,^{+1.15}_{-1.05}\right) \cdot 10^{-10}$
- **KEK-E391a:** $\mathrm{Br}\left(K_L \to \pi^0 \nu \overline{\nu}\right) < 2.6 \times 10^{-8}$ (90% C.L.)

New Experiments Needed: **NA62, K0TO** **(ORKA, Project-X)**

Standard Model Mechanism of $\not{\mathcal{CP}}$

Complex phases in Yukawa couplings only:

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

SSB $\left[\langle \phi^{(0)} \rangle = \mathrm{v}/\sqrt{2} \right]$

$$\mathcal{L}_Y = -\left(1+\frac{H}{\mathrm{v}}\right) \frac{\mathrm{v}}{\sqrt{2}} \left\{ \bar{d}'_{jL}\, c^{(d)}_{jk}\, d'_{kR} + \bar{u}'_{jL}\, c^{(u)}_{jk}\, u'_{kR} + \text{h.c.} \right\}$$

$c^{(q)}_{jk}$ **diagonalization**

$$\mathcal{L}_Y = -\left(1+\frac{H}{\mathrm{v}}\right) \left\{ \bar{d}_{jL}\, m_{d_j}\, d_{jR} + \bar{u}_{jL}\, m_{u_j}\, u_{jR} + \text{h.c.} \right\}$$

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}}\, W^{\dagger}_{\mu} \sum_{ij} \bar{u}_i \gamma^{\mu} (1-\gamma_5)\, \mathbf{V}_{ij}\, d_j + \text{h.c.}$$

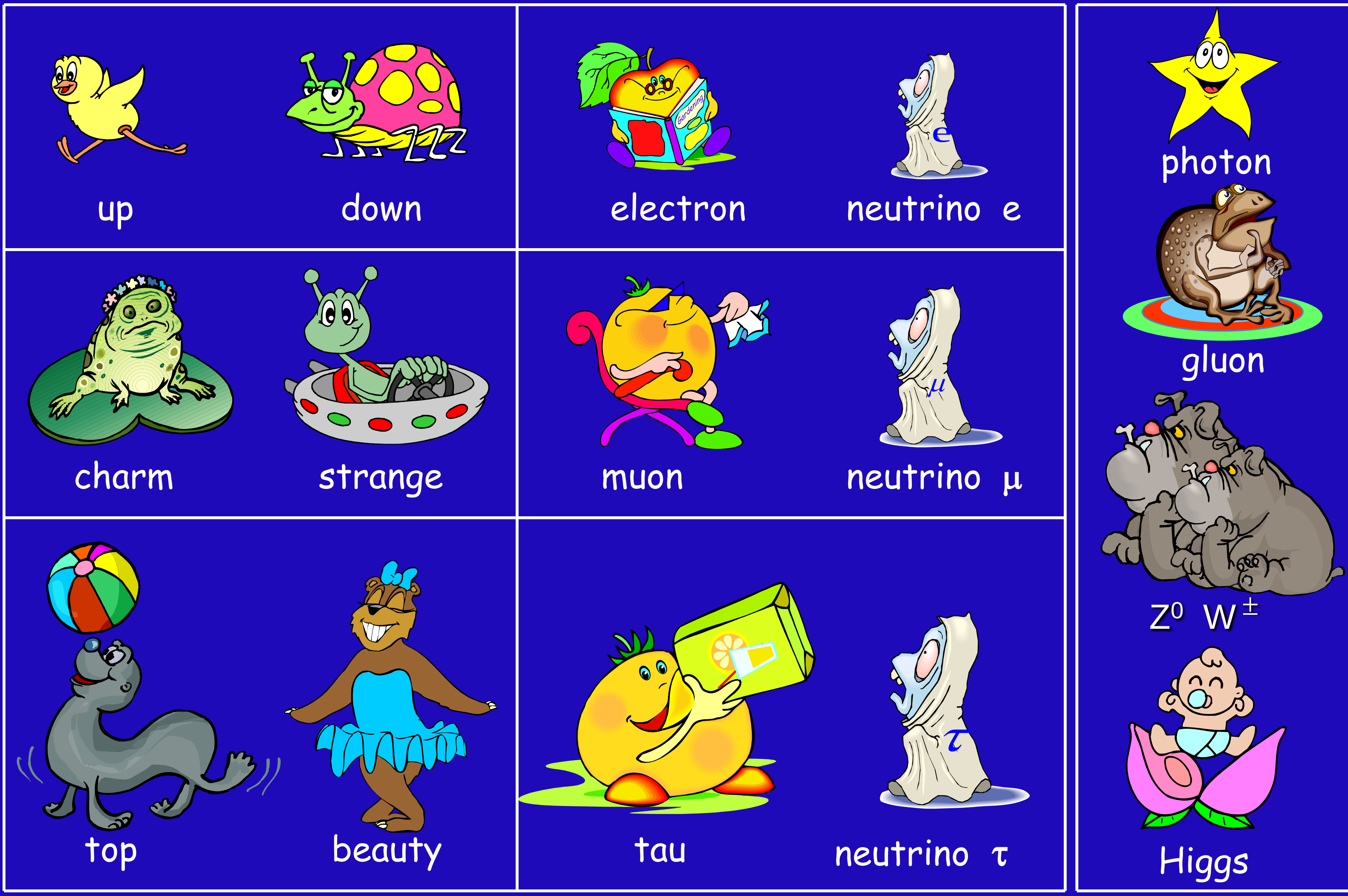
The CKM matrix $\mathbf{V}_{ij}$ is the only source of $\not{\mathcal{CP}}$

SUMMARY

- **Flavour Structure and** $\not{CP}$ are major pending questions
- **Related to SSB** ➡ **Scalar Sector** (Higgs)
- Important **cosmological implications** (Baryogenesis)
- Sensitive to **New Physics**
- $\not{CP}$ is highly constrained in the SM: **1 phase only**
- Many interesting $\not{CP}$ signals within experimental reach
- Better control of **QCD** effects urgently needed
- **Challenging future ahead:**

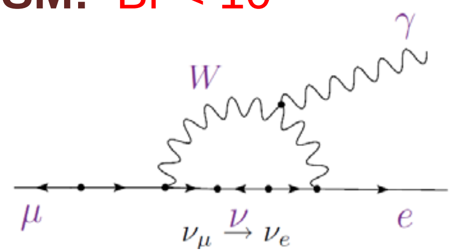
  BES-III, LHCb, NA62, J-Parc, Super-Belle, τcF, …

Quarks Leptons Bosons

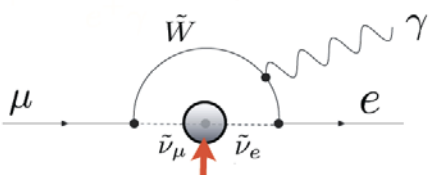


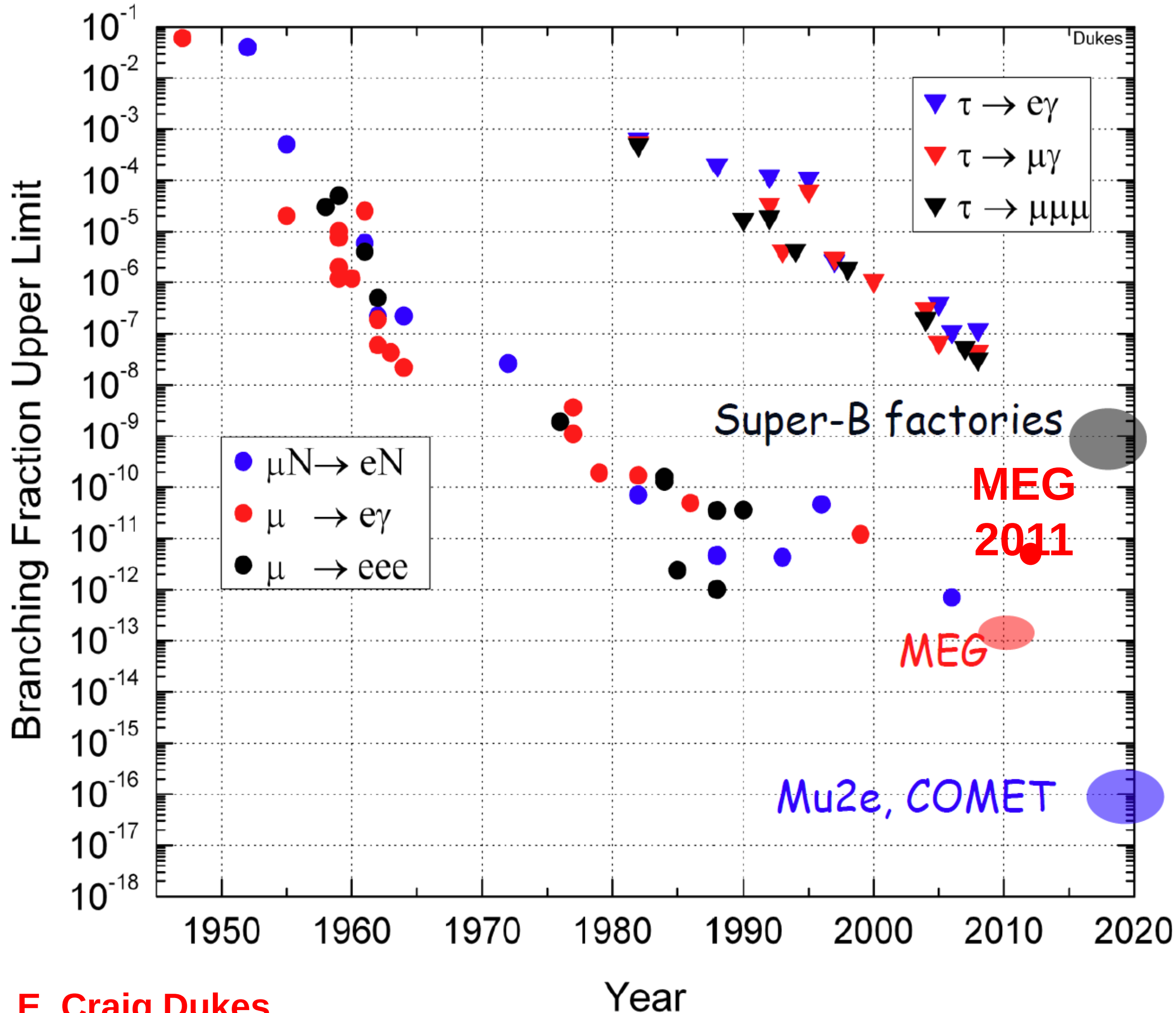
Exciting Prospects

SM: Br < 10^{-54}



New Physics ?

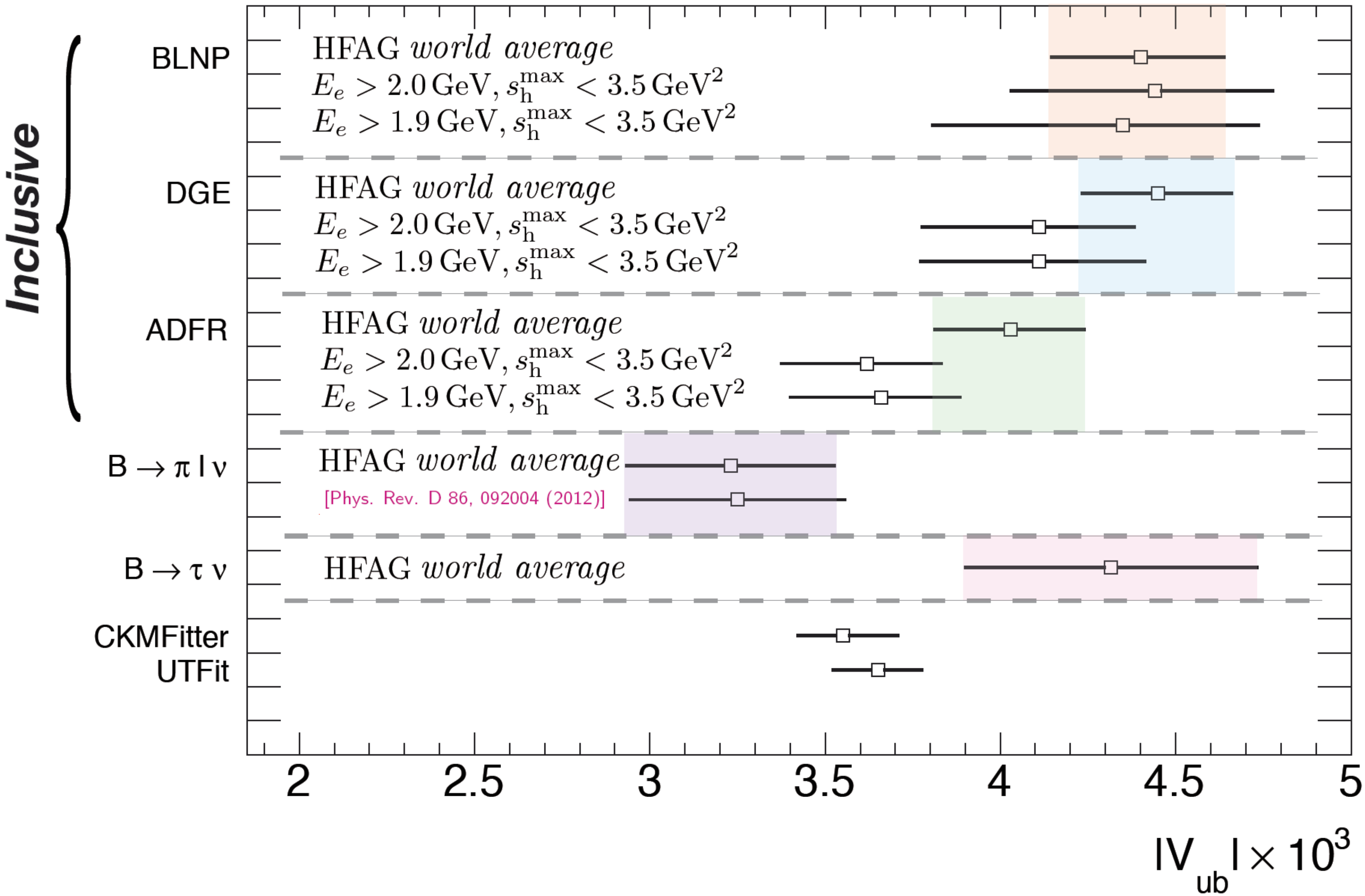




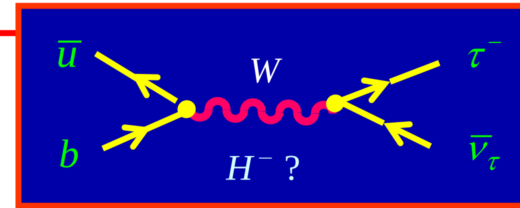
E. Craig Dukes

F. Bernlochner, EPS-HEP-2013

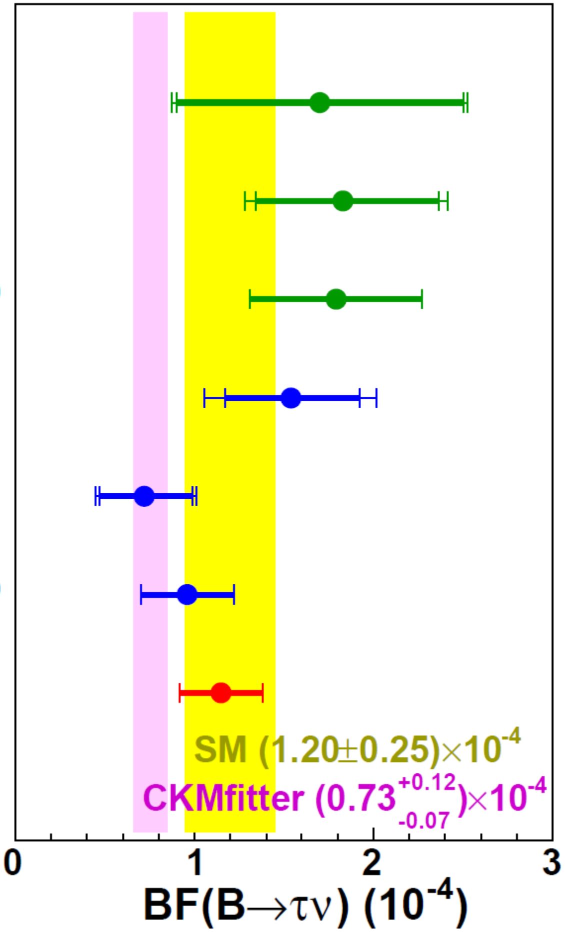
Summary for $|V_{ub}|$

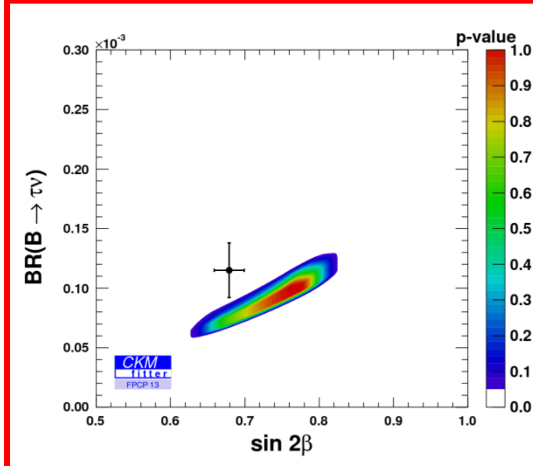


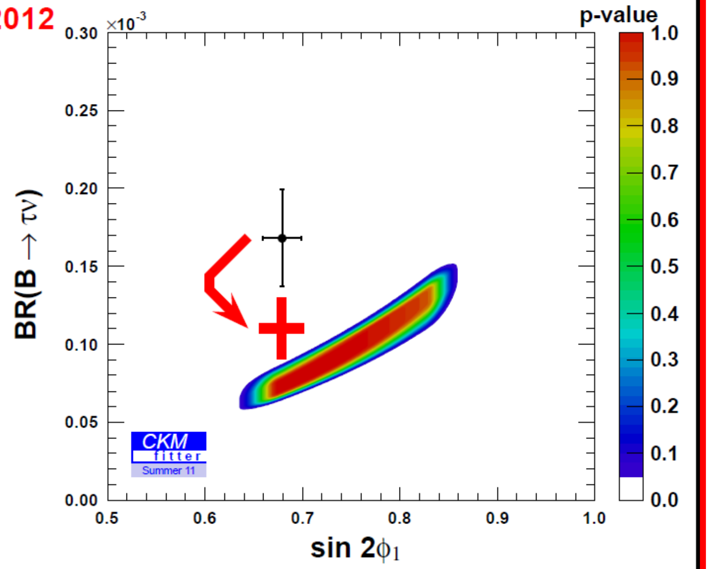
CP Violation and CKM Measurements — Mikihiko Nakao — p.24



Experiment	$BF(B\to\tau\nu)$	Reference
BaBar [468M] (2010) semilep-tag	$(1.70\pm0.80\pm0.20)\times10^{-4}$	PRD81,051101
BaBar [468M] (2012) hadronic-tag	$(1.83\,^{+0.53}_{-0.49}\pm0.24)\times10^{-4}$	arxiv:1207.0698
BaBar (combined) with correlations	$(1.79\pm0.48)\times10^{-4}$	arxiv:1207.0698
Belle [657M] (2010) semilep-tag	$(1.54\,^{+0.38}_{-0.37}\,^{+0.29}_{-0.31})\times10^{-4}$	PRD82,071101
Belle [772M] (2012) hadronic-tag	$(0.72\,^{+0.27}_{-0.25}\pm0.11)\times10^{-4}$	ICHEP 2012
Belle (combined) with correlations	$(0.96\pm0.26)\times10^{-4}$	ICHEP 2012
W.A. private average (MN)	$(1.15\pm0.23)\times10^{-4}$	ICHEP 2012

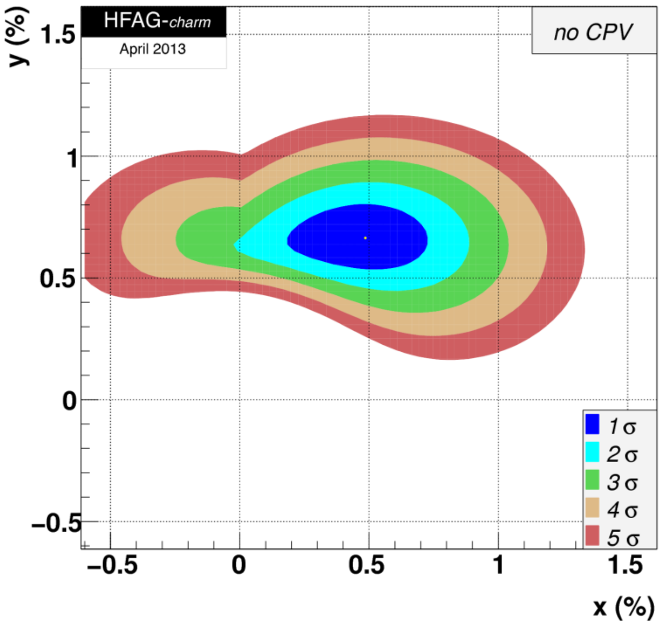






Tension between $B^+\to\tau^+\nu$ world average and CKM fit becomes much smaller

$D^0 - \bar{D}^0$ MIXING

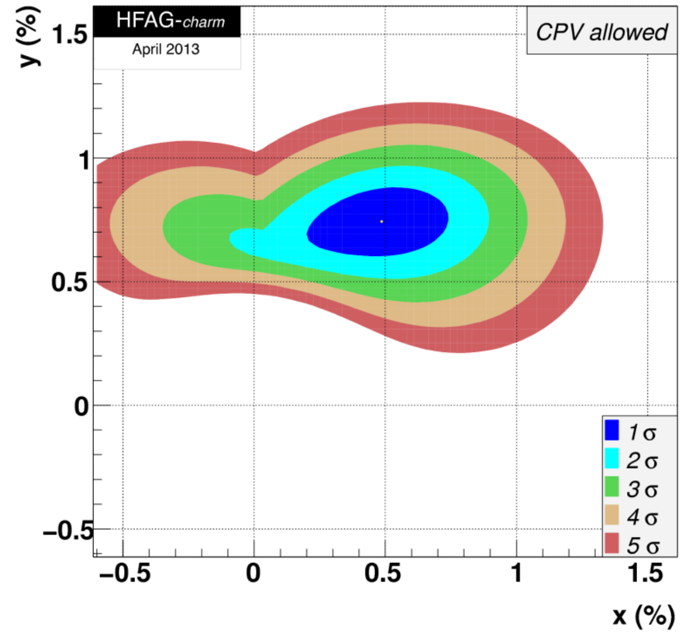


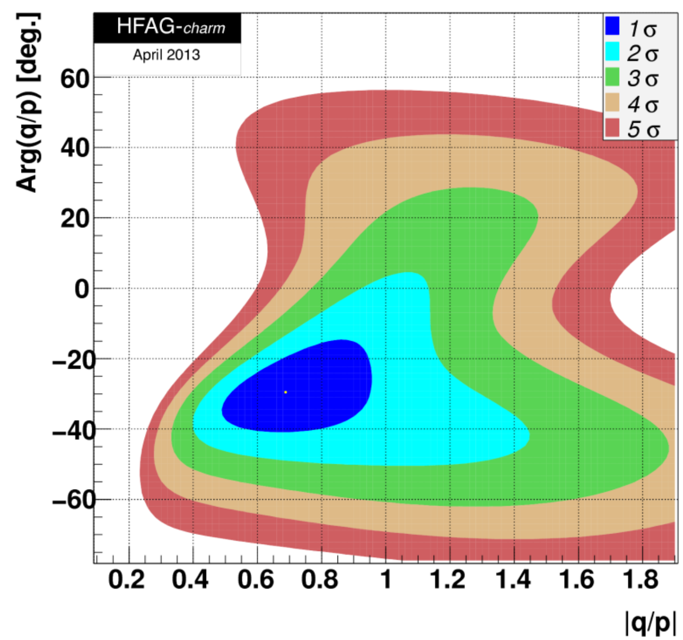
$$x = \left(0.49\ {}^{+0.17}_{-0.18}\right)\%$$

$$y = \left(0.74 \pm 0.09\right)\%$$

$$|q/p| = 0.69\ {}^{+0.17}_{-0.14}$$

$$\phi = \left(-29.6\ {}^{+8.9}_{-7.5}\right)^\circ$$





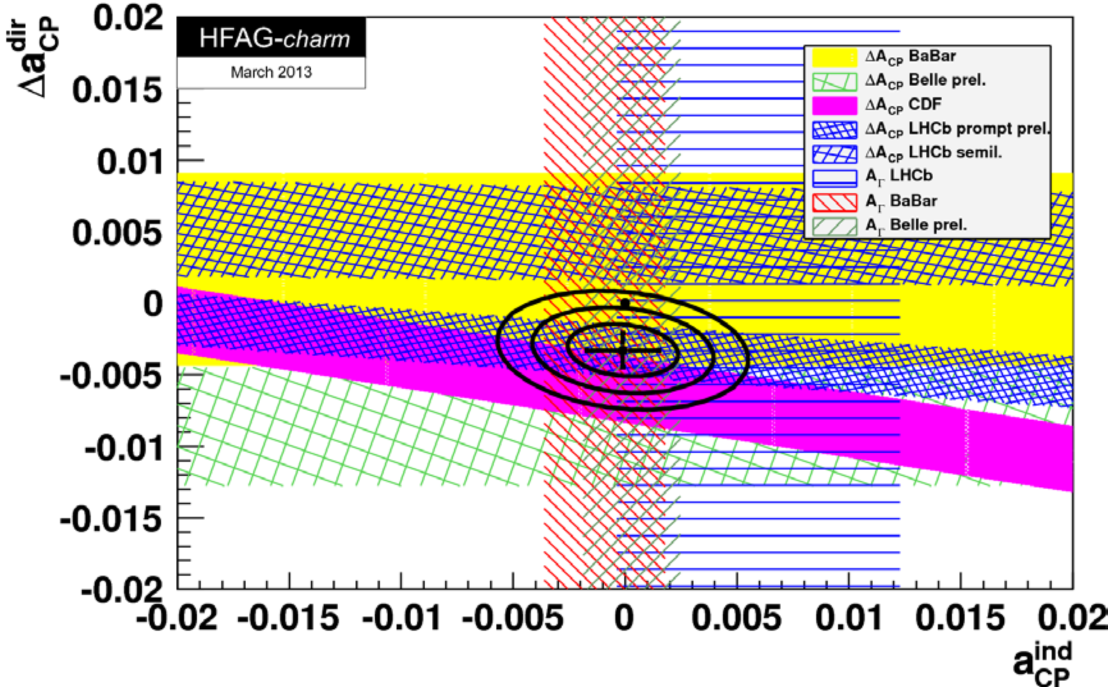
Long-distances Dominate

- No-mixing excluded at $> 5\sigma$
- $\tau_{D_-} < \tau_{D_+}$, $M_{D_-} > M_{D_+}$
- No evidence of $\not{CP}$ in mixing

CP conservation disfavoured at 1.8 σ

DIRECT $\not{CP}$ in D decays

$$\Delta A^{CP} \equiv A^{CP}_{D^0\to K^+K^-} - A^{CP}_{D^0\to\pi^+\pi^-} = -0.0068 \pm 0.0016$$



$$\Delta A^{CP} = \Delta a_{CP}^{\text{dir}} \left(1 + y_{CP} \frac{\langle t\rangle}{\tau}\right) + a_{CP}^{\text{ind}} \frac{\Delta\langle t\rangle}{\tau}$$

$$\Delta a_{CP}^{\text{dir}} = (-0.329 \pm 0.121)\%$$

$$a_{CP}^{\text{ind}} = (-0.010 \pm 0.162)\%$$

$$\text{LHCb 2013:} \qquad \Delta A^{CP} = -0.0015 \pm 0.0016$$

Direct CP Asymmetry in τ Decay

$$A_\tau \equiv \frac{\Gamma\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) - \Gamma\left(\tau^- \to \pi^- K_S \nu_\tau\right)}{\Gamma\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) + \Gamma\left(\tau^- \to \pi^- K_S \nu_\tau\right)} = \left(-3.6 \pm 2.3 \pm 1.1\right) \cdot 10^{-3}$$

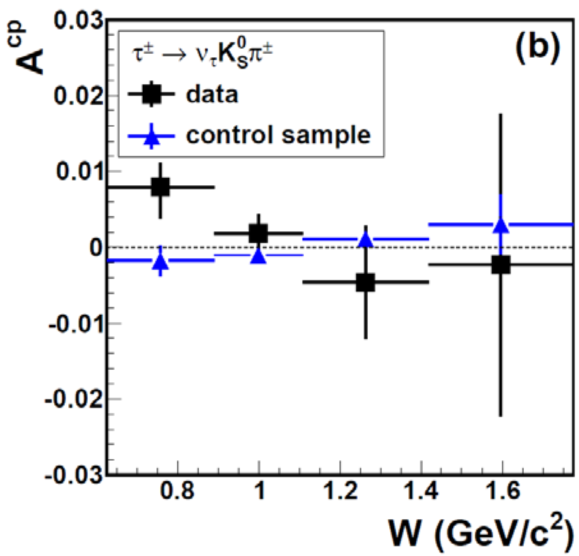
BaBar'11
$\left(\geq 0\ \pi^0\right)$

$$A_\tau^{\rm SM}\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) = \left(3.6 \pm 0.1\right) \cdot 10^{-3}$$

2.8 σ discrepancy

Bigi-Sanda, Grossman-Nir

Belle does not see any asymmetry at the 0.2-0.3% level



$$A_i^{CP} \simeq \langle \cos\beta \cos\psi \rangle_i^{\tau^-} - \langle \cos\beta \cos\psi \rangle_i^{\tau^+}$$

bins (i) of $W = \sqrt{Q^2}$

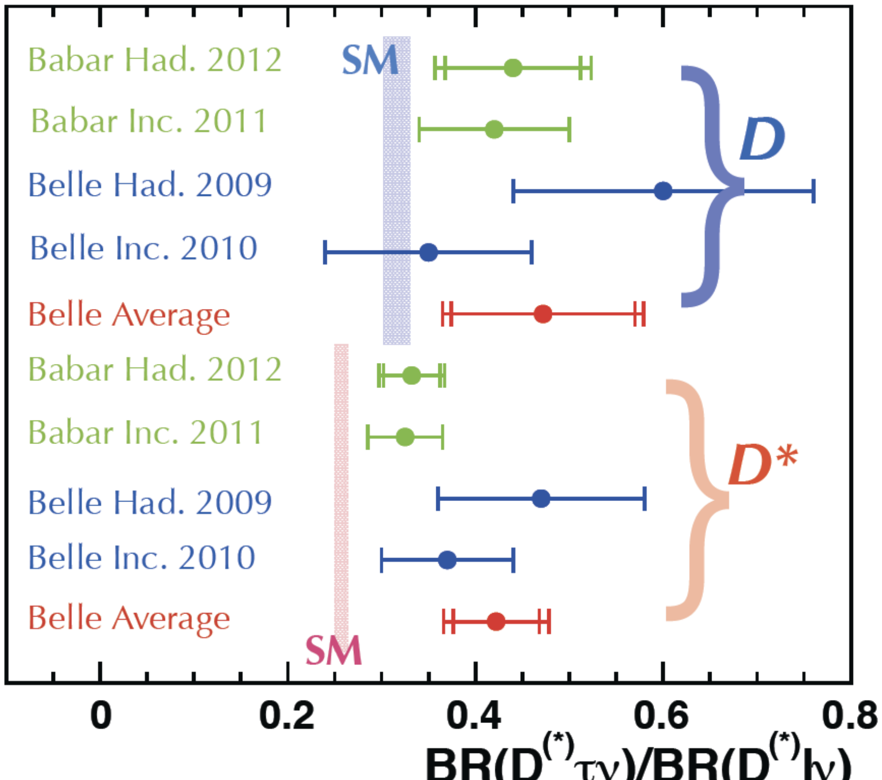
$\beta = K_S$ direction in hadronic rest frame

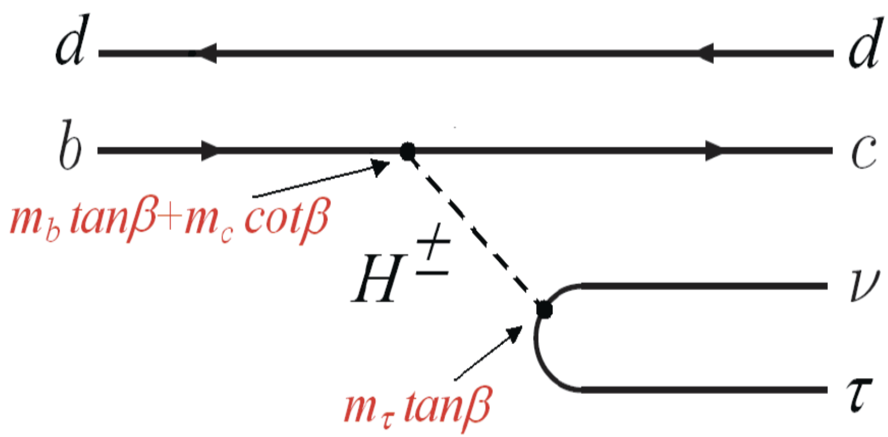
$\psi = \tau$ direction

A word on tauonic modes: $B \to D^{(*)}\tau^+\nu_l$

- Higher values than expected from the SM

But, no indications in favour of a Type II charged Higgs.



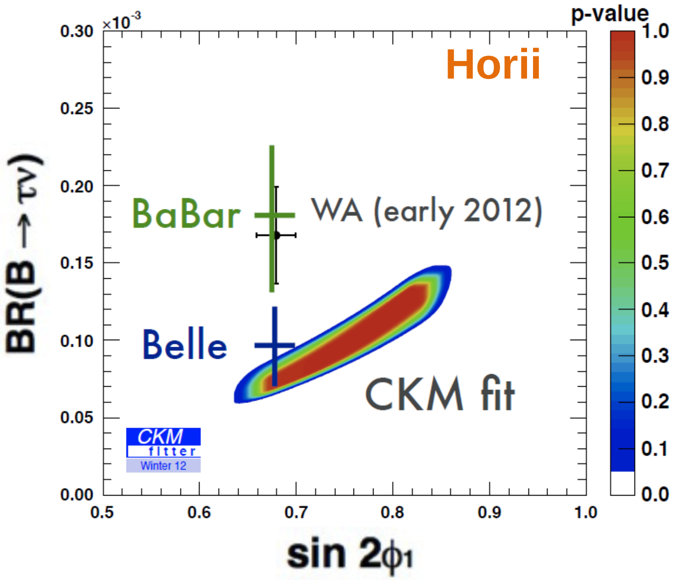


Belle hadronic tag update coming soon!

Isospin invariance assumed

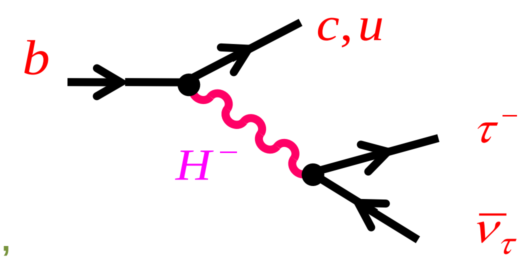
Semileptonic *B* decays, IUPAP Prize, ICHEP 2012 Phillip URQUIJO 37

$B \to \tau\nu_\tau$, $B \to D^{(*)}\tau\nu_\tau$



Sensitivity to scalar exchange

(Fajfer et al, Sakai-Tanaka, Crivellin et al, Datta et al, Becirevic et al, Bailey et al …)



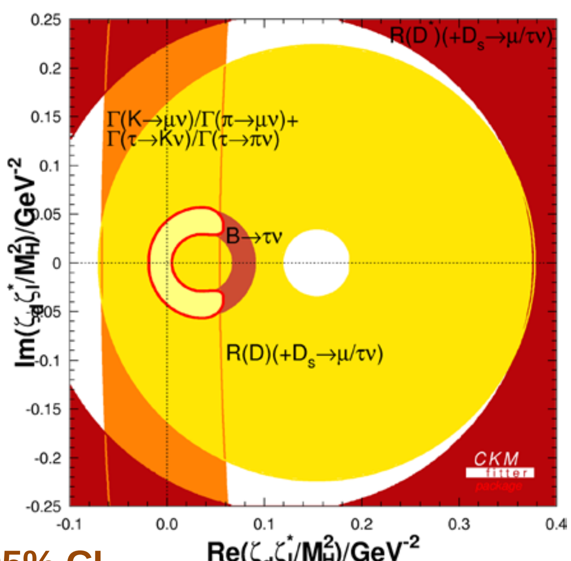
Type II 2HDM excluded

$$\mathcal{L}_Y^{H^\pm} = -\frac{\sqrt{2}}{v}\, H^+ \left\{ \bar{u} \left[\varsigma_d\, V M_d \mathcal{P}_R - \varsigma_u\, M_u^\dagger V \mathcal{P}_L \right] d \,+\, \varsigma_l\, \bar{\nu} M_l \mathcal{P}_R l \right\} \,+\, \text{h.c.}$$

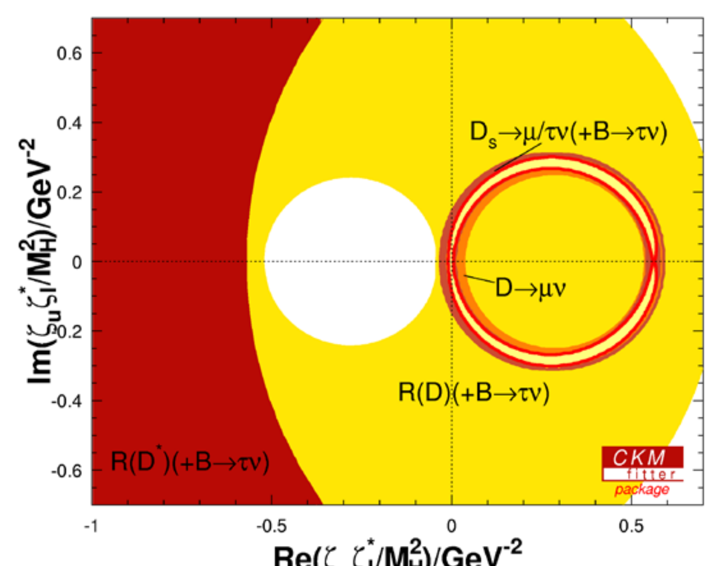
Celis-Jung-Li-Pich

B data fitted within Aligned 2-Higgs Doublet Model

But tensions with charm



95% CL



$B^0 \to \rho^+ \rho^-$

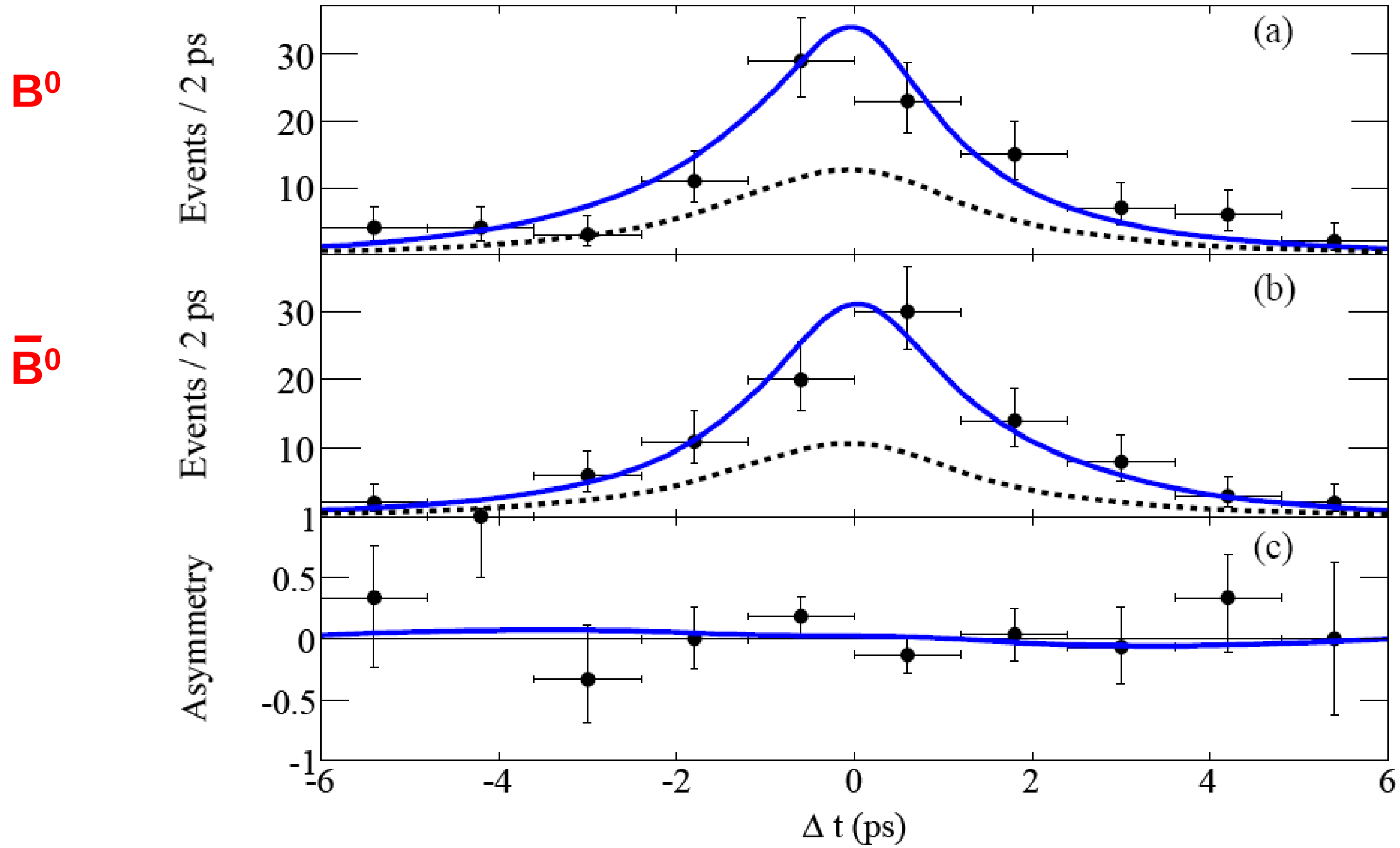


Fig. 86. Decay time distributions from *BABAR* [1110]. *(a)* $\overline{B}^0 \to \rho^+\rho^-$ decays *(b)* $B^0 \to \rho^+\rho^-$ decays, and *(c)* the asymmetry $(\overline{N} - N)/(\overline{N} + N)$, where $\overline{N}$ (N) is the number of signal $\overline{B}^0 \to \rho^+\rho^-$ $(B^0 \to \rho^+\rho^-)$ decays. The dashed curve shows the fit result for all backgrounds, and the solid curve shows the fit result for the total.

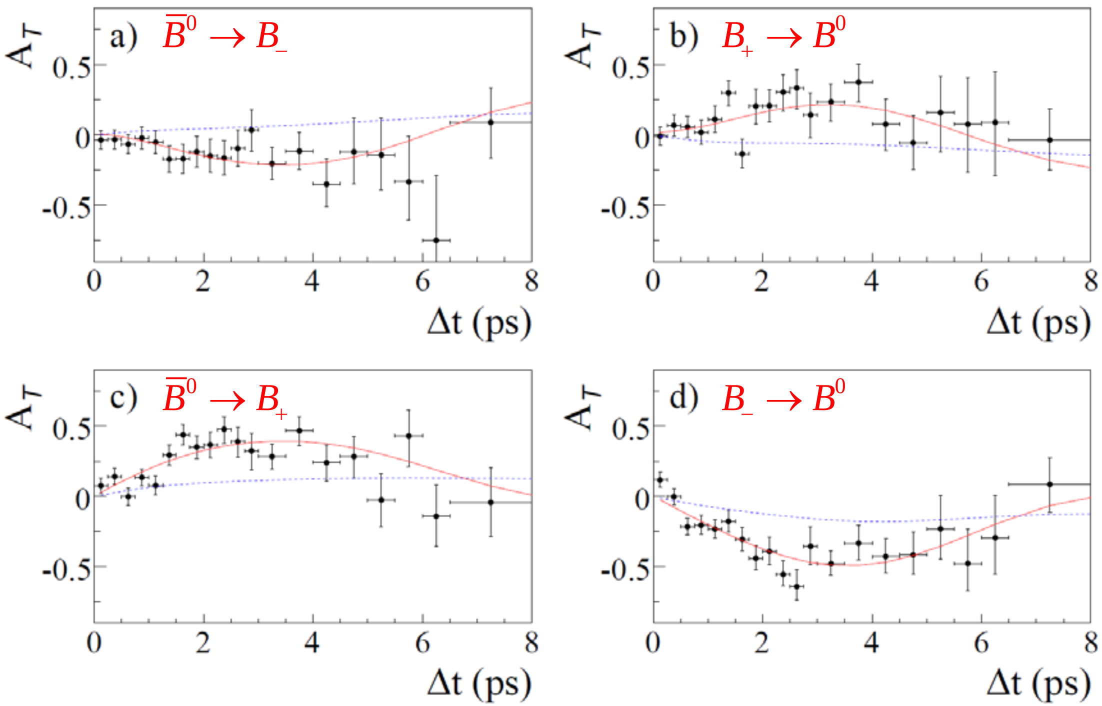
T Violation @ Babar

Quantum Entanglement

Flavour $\left(B^0 \to l^+ X\,,\; \bar{B}^0 \to l^- X\right)$ and CP $\left(B_+ \to J/\psi K_L\,,\; B_- \to J/\psi K_S\right)$ tags

(Bañuls-Bernabeu-Martínez-Villanueva)

$e^+ e^- \to \Upsilon(4S) \to (B_1(t_1) \to f_1\,,\, B_2(t_2) \to f_2) \equiv (f_1\,,\, f_2)$; $t_2 > t_1$



$$S_{B_- \to \bar{B}^0} - S_{\bar{B}^0 \to B_-} = -1.37 \pm 0.14 \pm 0.06$$

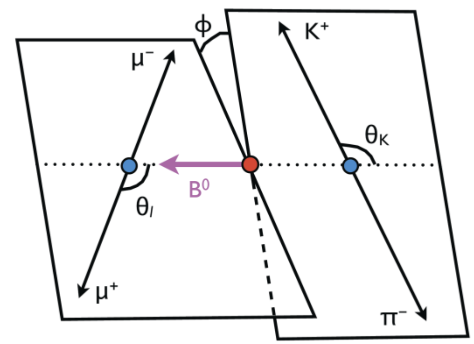
$$S_{B^0 \to B_+} - S_{B_+ \to B^0} = 1.17 \pm 0.18 \pm 0.11$$

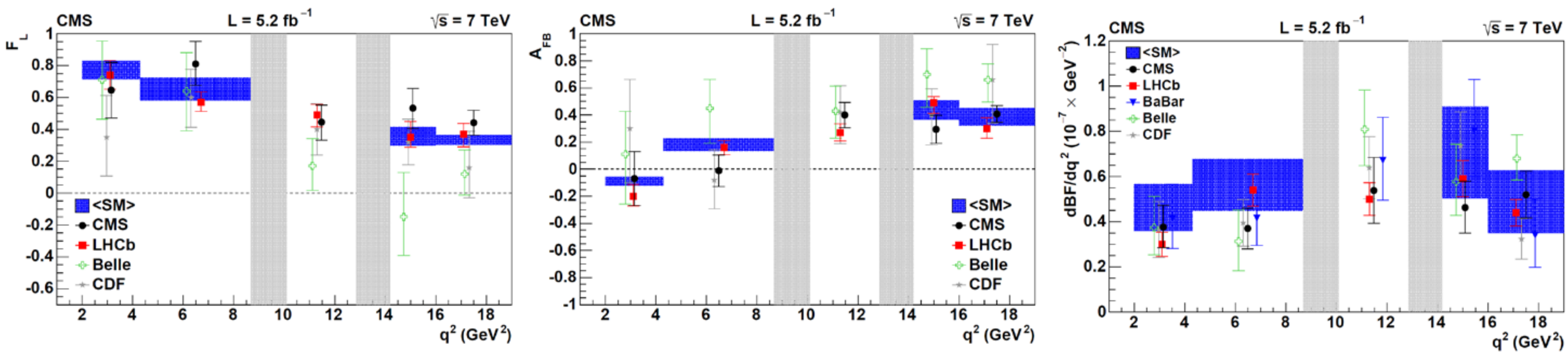
$\not{T}$ established at $14\,\sigma$

$B^0 \to K^{*0}\mu^+\mu^- \to K^+\pi^-\mu^+\mu^-$

$$\frac{1}{d\Gamma/dq^2}\,\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$q^2 = s_{\mu^+\mu^-}$





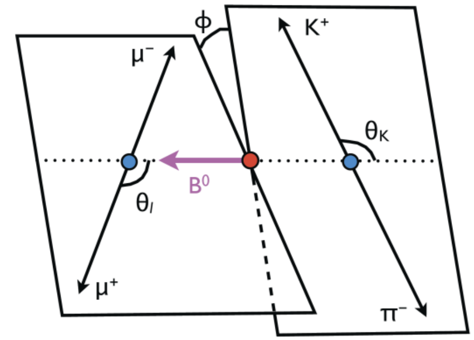
Good agreement with SM (Bobeth et al)

Large hadronic uncertainties

$B^0 \to K^{*0}\mu^+\mu^- \to K^+\pi^-\mu^+\mu^-$

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\,\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

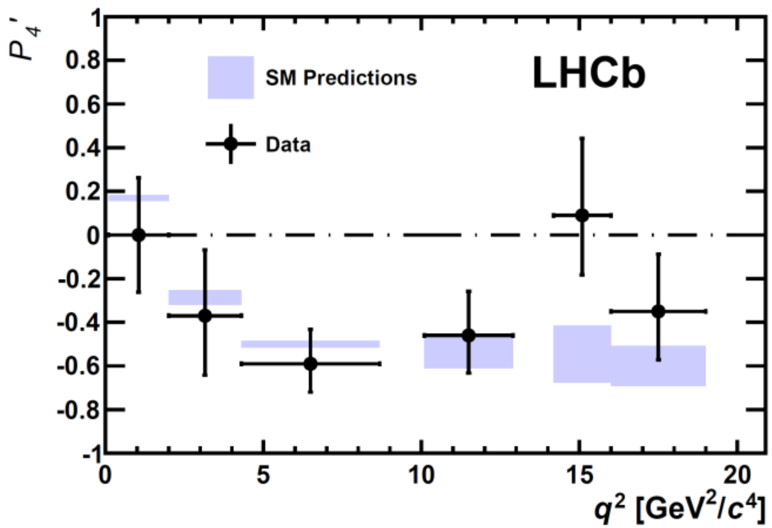
$q^2 = s_{\mu^+\mu^-}$

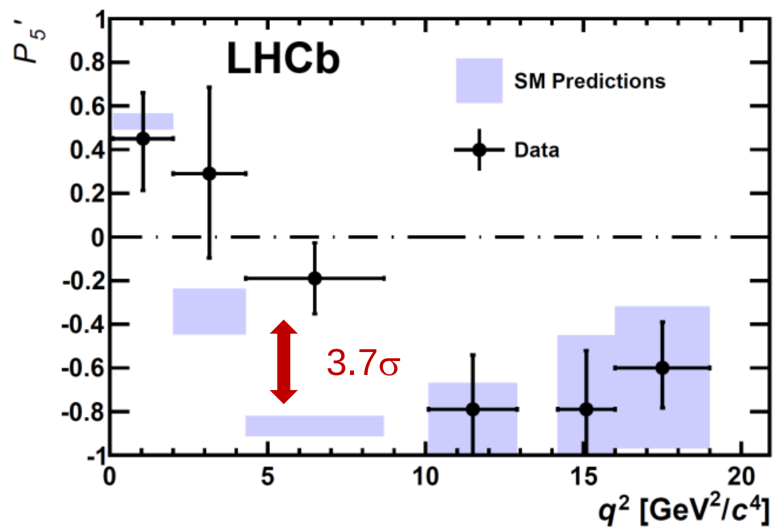


Improved observables (Descotes-Genon et al)

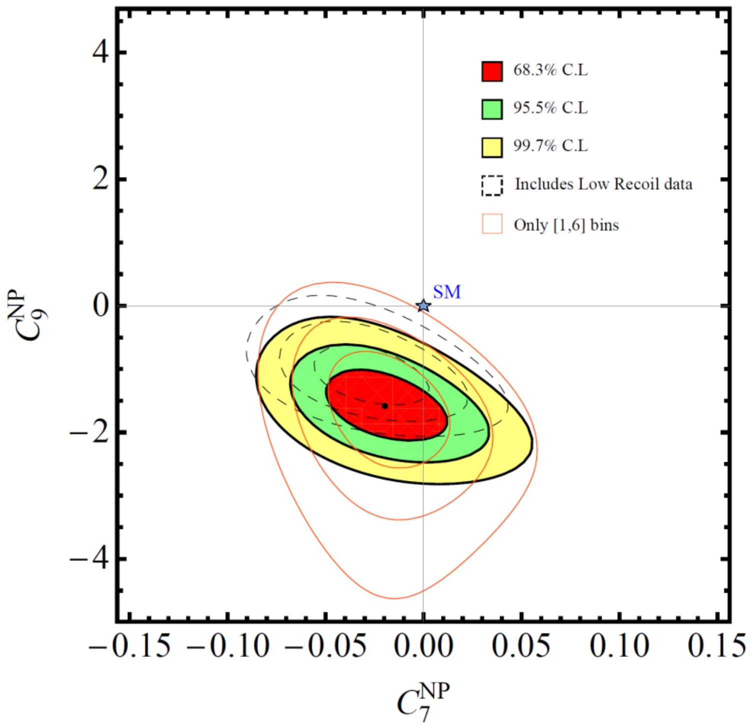
Largely free from FF uncertainties

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$$





23 of 24 measurem. agree with the SM

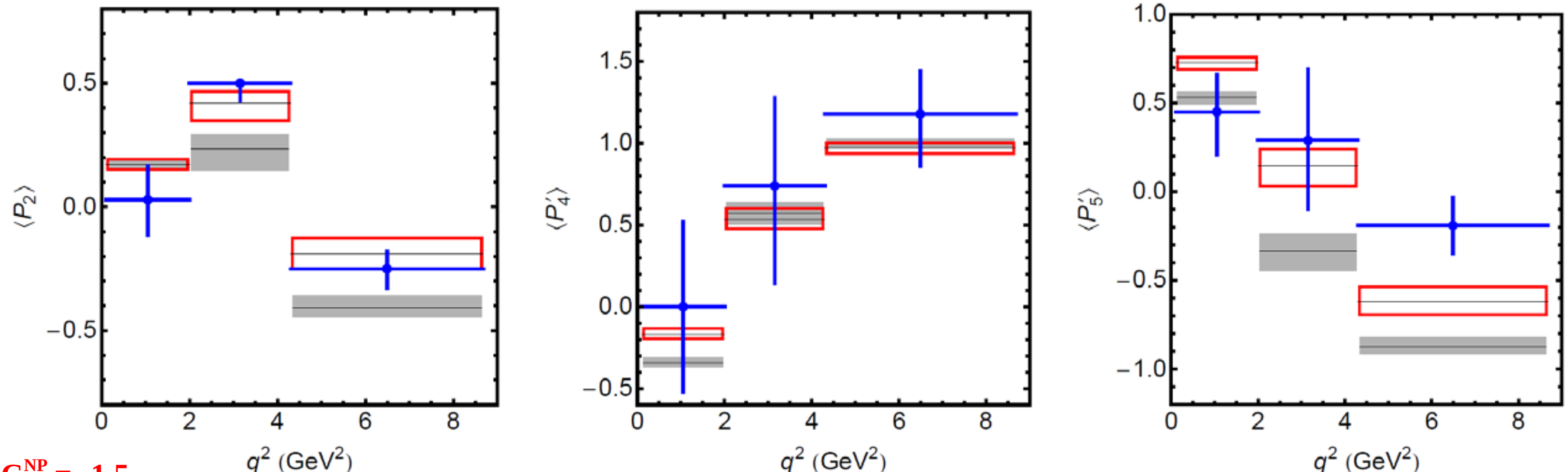


Descotes-Genon et al, 1307.5683

Observed pattern consistent with New Physics contributions to $C_{7,9}$

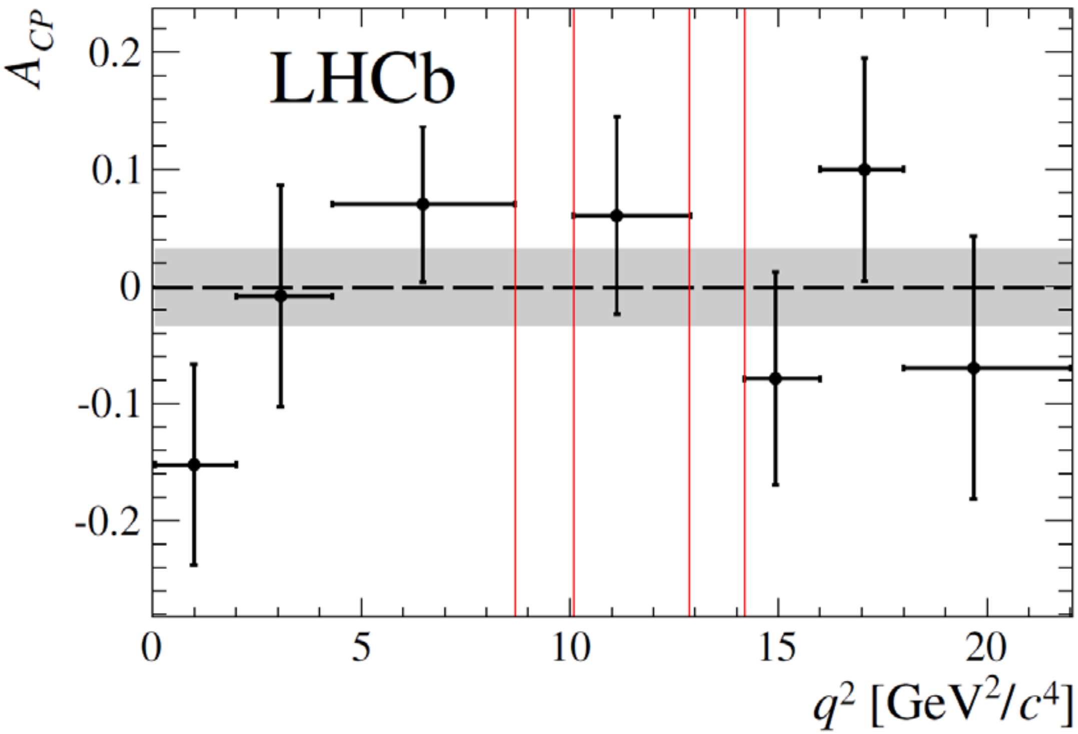
$$\mathcal{O}_7 = e/(16\pi^2)\, m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$$
$$\mathcal{O}_9 = e^2/(16\pi^2)\, (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

Z' boson ?



$C_9^{NP} = -1.5$

$$\mathcal{A}_{CP} = \frac{\Gamma(B^- \to K^-\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^- \to K^-\mu^+\mu^-) + \Gamma(B^+ \to K^+\mu^+\mu^-)} = 0.000 \pm 0.033 \text{ (stat.)} \pm 0.005 \text{ (syst.)} \pm 0.007 \; (J/\psi K^+)$$



SM: $A_{CP} \sim 10^{-4}$

$A_{CP}(B^+ \to K^+ l^+ l^-) =$

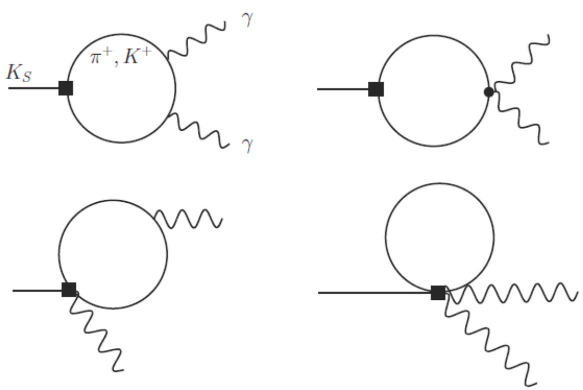
-0.03 ± 0.14 **Babar**

-0.04 ± 0.10 **Belle**

LHCb: $A_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.072 \pm 0.040$

Rare K Decays

$K^0 \to \gamma\gamma$ — Long-distance dynamics



Finite loop: $\mathrm{Br}_{\mathrm{LO}} = 2.0 \cdot 10^{-6}$

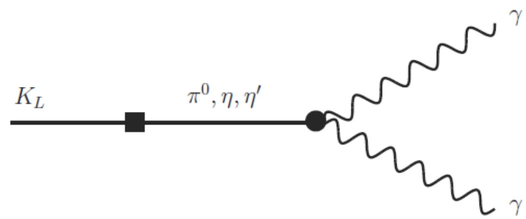
(D'Ambrosio-Espriu, Goity)

$\mathrm{Br}(K_S \to \gamma\gamma) = (2.63 \pm 0.17) \cdot 10^{-6}$

Agreement at $O(p^6)$ (FSI)

$K_S \to \pi\pi \to \pi^+\pi^- \to \gamma\gamma$

(Kambor-Holstein, Buchalla et al)



$\mathrm{Br}(K_L \to \gamma\gamma) = (5.47 \pm 0.04) \cdot 10^{-4}$

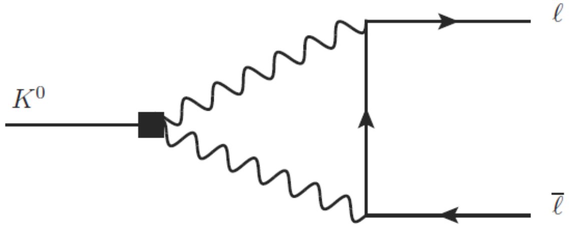
WZW Anomaly

$\mathbf{T}_{\mathrm{LO}} = \mathbf{0}$ $[\mathcal{O}(p^4)$, GMO cancel.]

$\mathcal{O}(p^6)$: SU(3) breaking, η–η' mixing

Well understood

$K^0 \to \ell^+\ell^-$



$K_S \to \ell^+\ell^-$

Long-distance dynamics

Finite 2-loop amplitude: (Ecker-Pich)

$$\mathrm{Br}(K_S \to e^+e^-)_{\mathrm{LO}} = 2.1 \cdot 10^{-14}$$

$$\mathrm{Br}(K_S \to \mu^+\mu^-)_{\mathrm{LO}} = 5.1 \cdot 10^{-12}$$

$$\mathrm{Br}(K_S \to e^+e^-)_{\mathrm{exp}} < 9 \cdot 10^{-9}$$

$$\mathrm{Br}(K_S \to \mu^+\mu^-)_{\mathrm{exp}} < 3.2 \cdot 10^{-7}$$

(90% CL)

$K_L \to \ell^+\ell^-$

$$\mathrm{Br}(K_L \to \mu^+\mu^-) = (6.84 \pm 0.11) \cdot 10^{-9}$$

$$\mathrm{Br}(K_L \to e^+e^-) = (9\,^{+6}_{-4}) \cdot 10^{-12}$$

Saturated by absorptive contrib.

Local countertem ⟷ **SD**

LD extracted from $\pi^0, \eta \to \ell^+\ell^-$

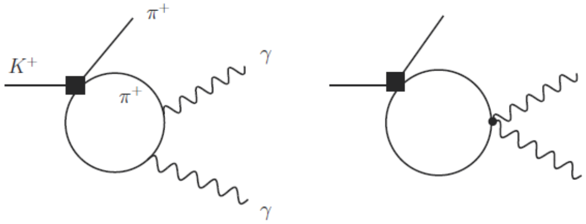
(Gomez-Dumm, Pich)

Fitted SD contrib. agrees with SM

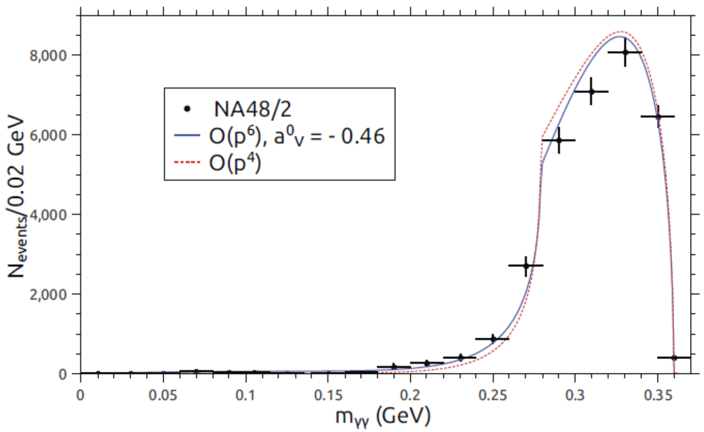
Longitudinal Polarization: (Ecker-Pich)

$$|\mathcal{P}_L| = (2.6 \pm 0.4) \cdot 10^{-3}$$

$K \to \pi\gamma\gamma$



$$\mathrm{Br}(K_L \to \pi^0\gamma\gamma) = (1.27 \pm 0.03) \cdot 10^{-6}$$



Finite 1-loop amplitude $[\mathcal{O}(p^4)]$**:**

$$\mathrm{Br}(K_L \to \pi^0\gamma\gamma)_{\mathrm{LO}} = 6.8 \cdot 10^{-7}$$

(Ecker-Pich-de Rafael, Cappiello-D'Ambrosio, Sehgal)

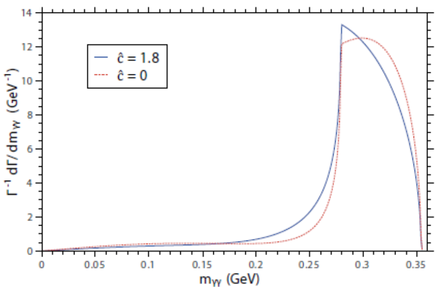
$\mathcal{O}(p^6)$ unitarity corrections needed

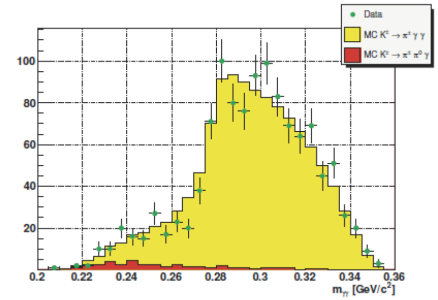
(Cohen et al, Cappiello et al, D'Ambrosio-Portolés)

$$\mathrm{Br}(K^+ \to \pi^+\gamma\gamma) = (1.1 \pm 0.3) \cdot 10^{-6}$$

(BNL-E787)

NA48





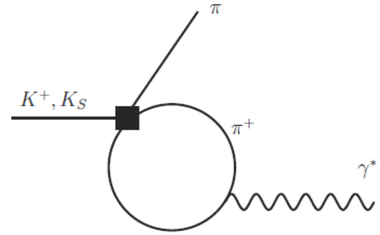
Local $\mathcal{O}(p^4)$ **LEC:** (Ecker-Pich-de Rafael)

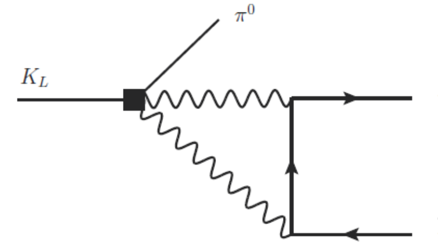
$\hat{c} = 1.6\,(1.8) \pm 0.6$ at $\mathcal{O}(p^4)$ (p^6)

Small higher-order corrections

(D'Ambrosio-Portolés)

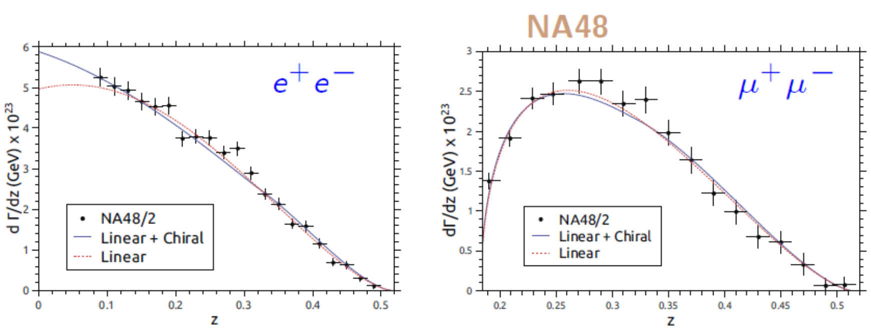
$K \to \pi\, \ell^+ \ell^-$





$$\mathrm{Br}(K^\pm \to \pi^\pm e^+ e^-) = 3.14\;(10) \cdot 10^{-7}$$

$$\mathrm{Br}(K^\pm \to \pi^\pm \mu^+ \mu^-) = 9.62\;(25) \cdot 10^{-8}$$



Local $\mathcal{O}(p^4)$ LECs (Ecker-Pich-de Rafael)

Electromagn. transition form factor

$\mathcal{O}(p^6)$ corrections (D'Ambrosio et al)

$$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) < 2.8 \cdot 10^{-10}$$

$$\mathrm{Br}(K_L \to \pi^0 \mu^+ \mu^-) < 3.8 \cdot 10^{-10}$$

(KTeV, 90% CL)

3 contributions: (Ecker-Pich-de Rafael)

- **Direct** $\not{\!\!CP}$
- **Indirect** $\not{\!\!CP}$
- **CP conserving** (2γ)

$\not{\!\!CP}$ **dominates for e^+e^-:**

$$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) = 3.1\;(0.9) \cdot 10^{-11}$$

(Buchalla et al)