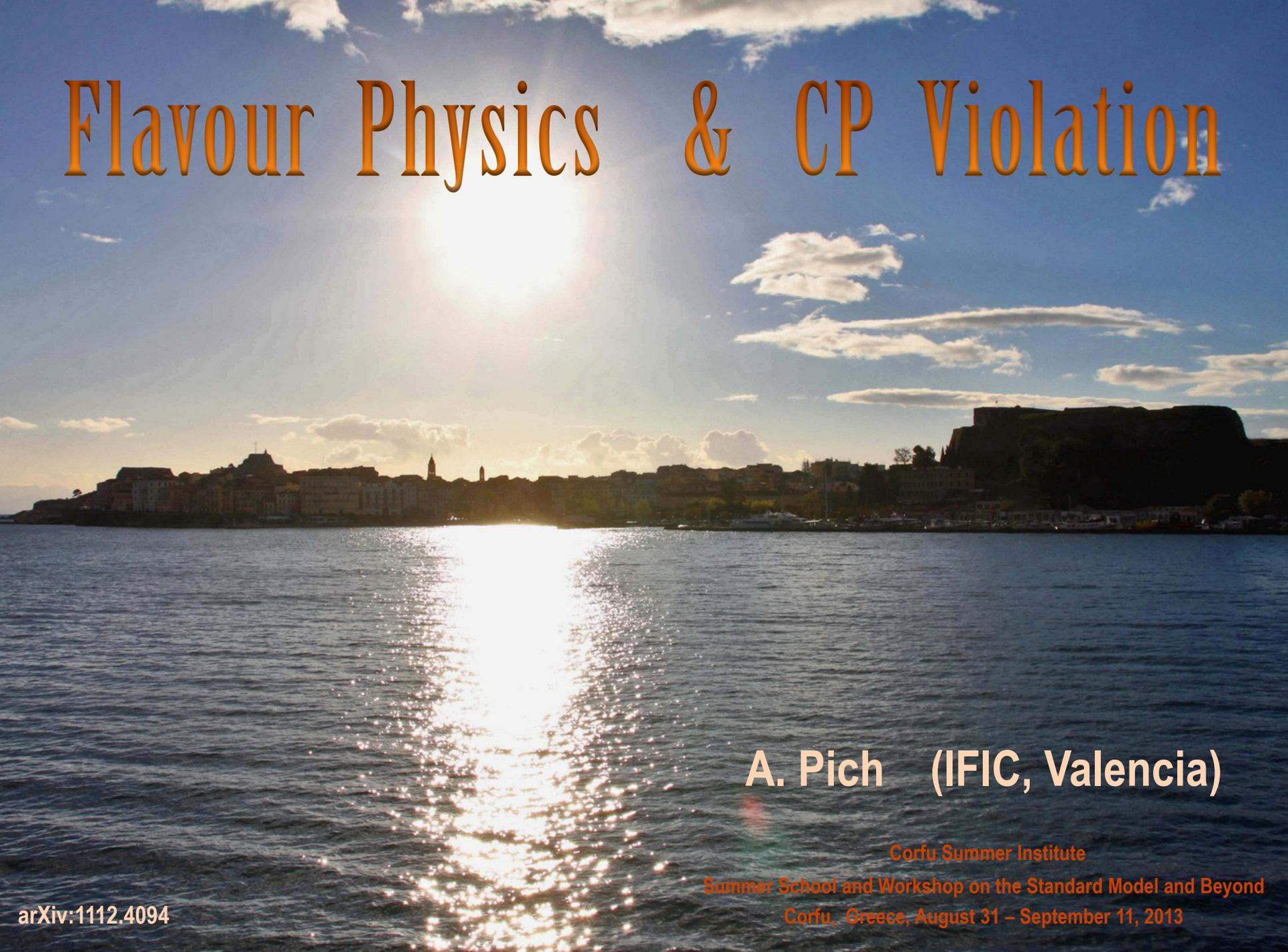


Flavour Physics & CP Violation



A. Pich (IFIC, Valencia)

Corfu Summer Institute

Summer School and Workshop on the Standard Model and Beyond
Corfu, Greece, August 31 – September 11, 2013

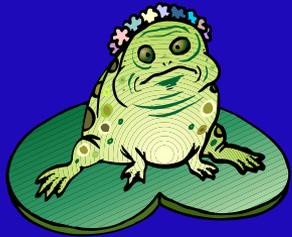
Quarks



up



down



charm



strange



top



beauty

Leptons



electron



neutrino e



muon



neutrino μ



tau



neutrino τ

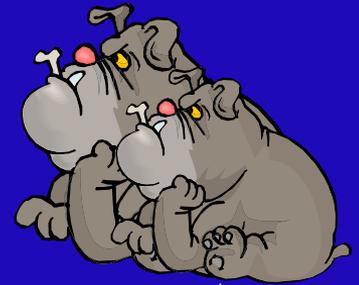
Bosons



photon



gluon



Z^0 W^\pm



Higgs

Flavour Structure of the Standard Model

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



- Pattern of masses
- Flavour Mixing
- ~~CP~~



Related to SSB
Scalar Sector (Higgs)

• **Kaon Factories** : u, d, s

• **τ CF** : c, τ

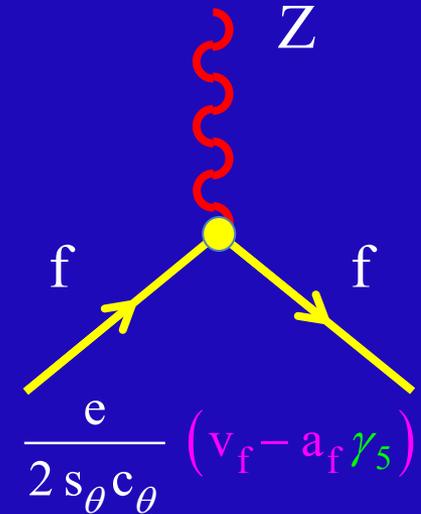
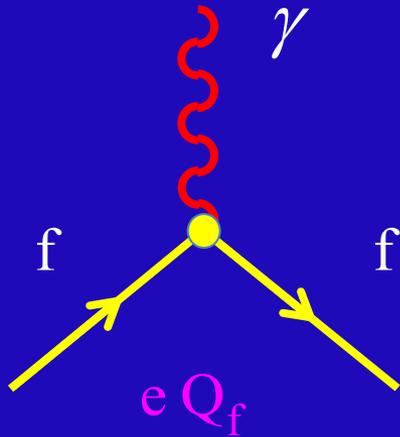
• **BF, S-BF** : b, c, τ

• **LHC** : t, b, c

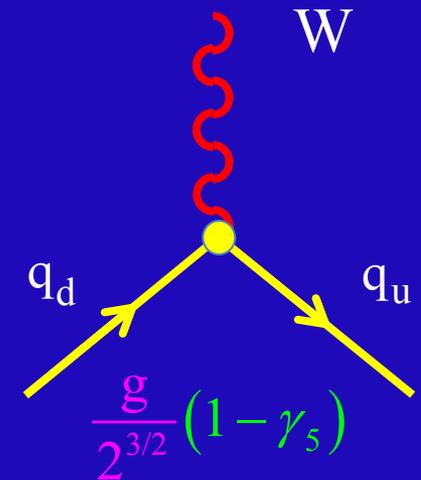
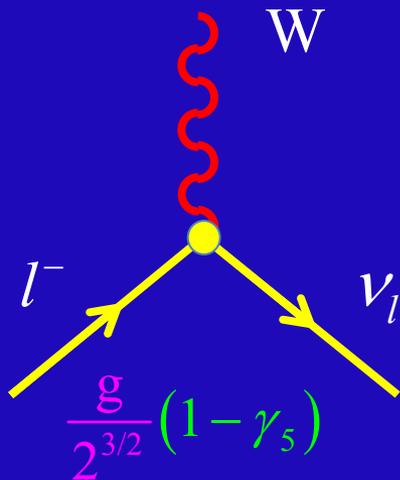
• **LC** : t, \dots

• **ν F** : ν_e, ν_μ, ν_τ

NEUTRAL CURRENTS



CHARGED CURRENTS



Three Families

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

Family Structure

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

Charged Currents

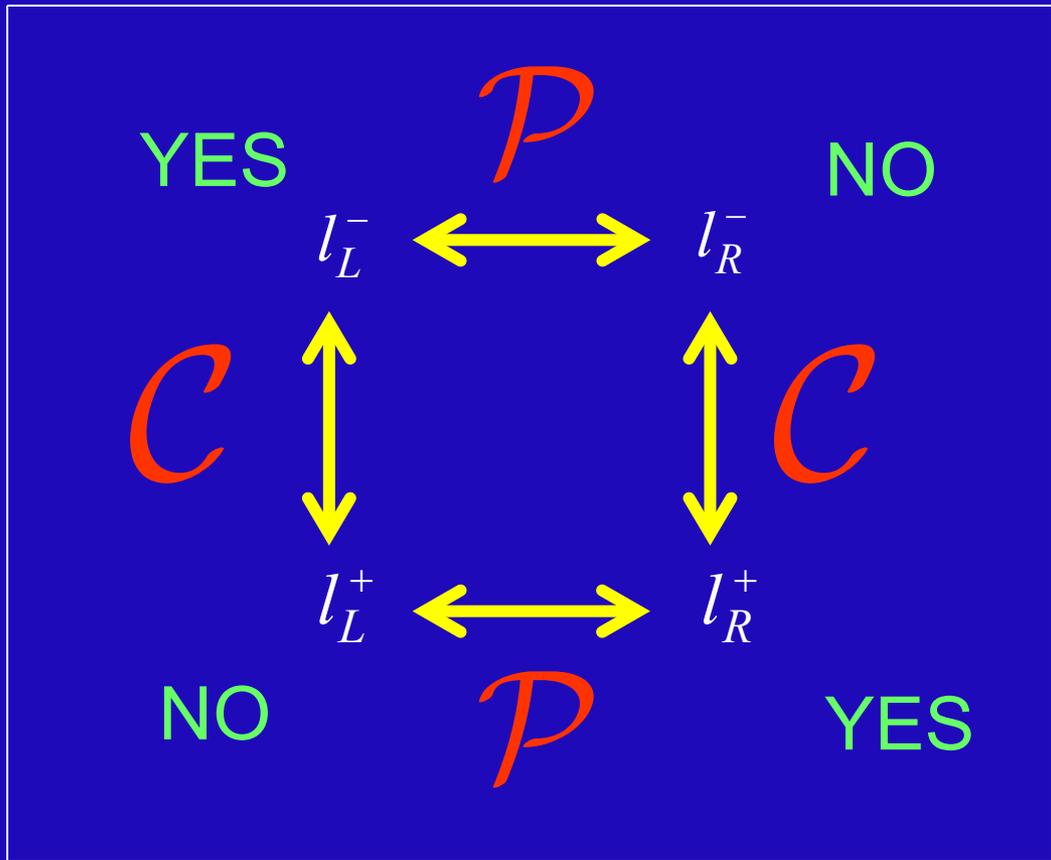
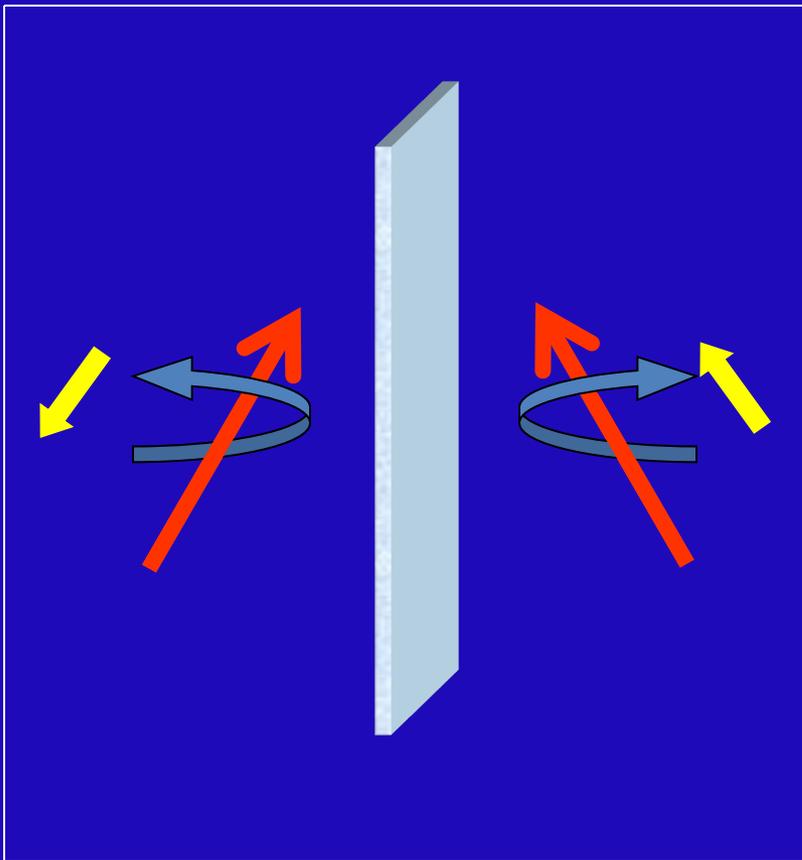
$$W^\pm \begin{cases} \text{Left-handed Fermions only} \\ \text{Flavour Changing: } \nu_l \Leftrightarrow l, q_u \Leftrightarrow q_d \end{cases}$$

Neutral Currents

$$\gamma, Z \quad \text{Flavour Conserving}$$

Universality

Family – Independent Couplings



~~\mathcal{P}~~ and ~~\mathcal{C}~~ in Weak Interactions

CP still a good symmetry (1 family)

FERMION MASSES

Scalar – Fermion Couplings allowed by Gauge Symmetry

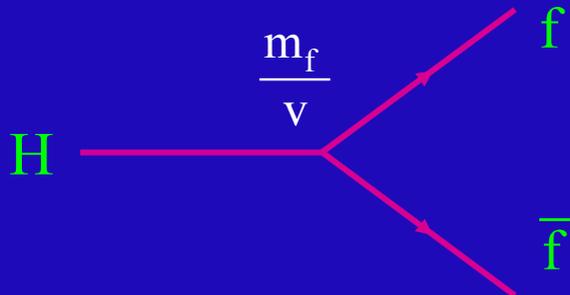
$$\mathcal{L}_Y = - (\bar{q}_u, \bar{q}_d)_L \left[c^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} (q_d)_R + c^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} (q_u)_R \right] - (\bar{\nu}_l, \bar{l})_L c^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix}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

↓ SSB

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

**Fermion Masses are
New Free Parameters**

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



Couplings Fixed: $g_{Hf\bar{f}} = \frac{m_f}{v}$

FERMION GENERATIONS

$N_G = 3$ **Identical Copies**

Masses are the only difference

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

WHY ?

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



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

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

DIAGONALIZATION OF MASS MATRICES

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

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

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

$$\mathbf{H}_f = \mathbf{H}_f^\dagger$$

$$\mathbf{U}_f \cdot \mathbf{U}_f^\dagger = \mathbf{U}_f^\dagger \cdot \mathbf{U}_f = 1$$

$$\mathbf{S}_f \cdot \mathbf{S}_f^\dagger = \mathbf{S}_f^\dagger \cdot \mathbf{S}_f = 1$$



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

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

$$\begin{aligned} \mathbf{d}_L &\equiv \mathbf{S}_d \cdot \mathbf{d}'_L & ; & & \mathbf{u}_L &\equiv \mathbf{S}_u \cdot \mathbf{u}'_L & ; & & \mathbf{l}_L &\equiv \mathbf{S}_l \cdot \mathbf{l}'_L \\ \mathbf{d}_R &\equiv \mathbf{S}_d \cdot \mathbf{U}_d \cdot \mathbf{d}'_R & ; & & \mathbf{u}_R &\equiv \mathbf{S}_u \cdot \mathbf{U}_u \cdot \mathbf{u}'_R & ; & & \mathbf{l}_R &\equiv \mathbf{S}_l \cdot \mathbf{U}_l \cdot \mathbf{l}'_R \end{aligned}$$

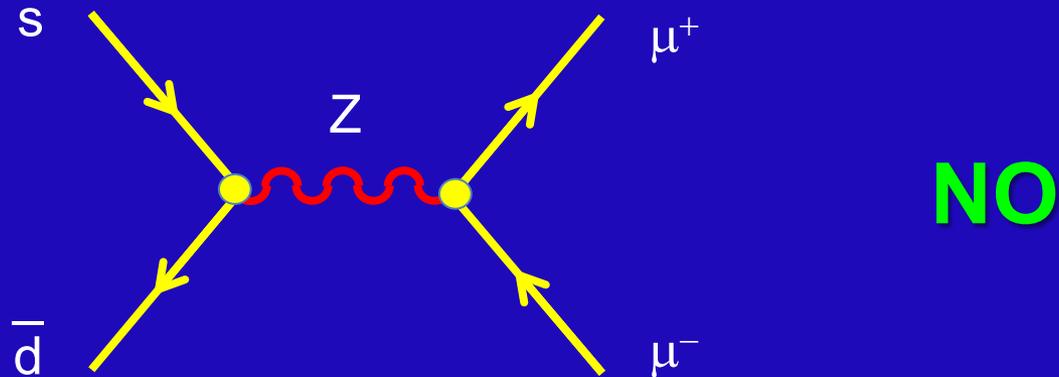
Mass Eigenstates
 \neq
Weak Eigenstates

$$\begin{aligned} \bar{\mathbf{f}}'_L \mathbf{f}'_L = \bar{\mathbf{f}}_L \mathbf{f}_L & \quad ; \quad \bar{\mathbf{f}}'_R \mathbf{f}'_R = \bar{\mathbf{f}}_R \mathbf{f}_R & \quad \longrightarrow & & \mathcal{L}'_{\text{NC}} = \mathcal{L}_{\text{NC}} \\ \bar{\mathbf{u}}'_L \mathbf{d}'_L = \bar{\mathbf{u}}_L \cdot \mathbf{V} \cdot \mathbf{d}_L & \quad ; \quad \mathbf{V} \equiv \mathbf{S}_u \cdot \mathbf{S}_d^\dagger & \quad \longrightarrow & & \mathcal{L}'_{\text{CC}} \neq \mathcal{L}_{\text{CC}} \end{aligned}$$

QUARK MIXING

Flavour Conserving Neutral Currents (GIM)

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



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

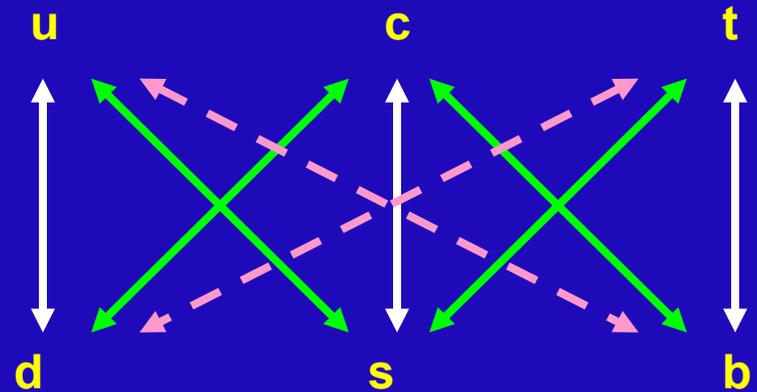
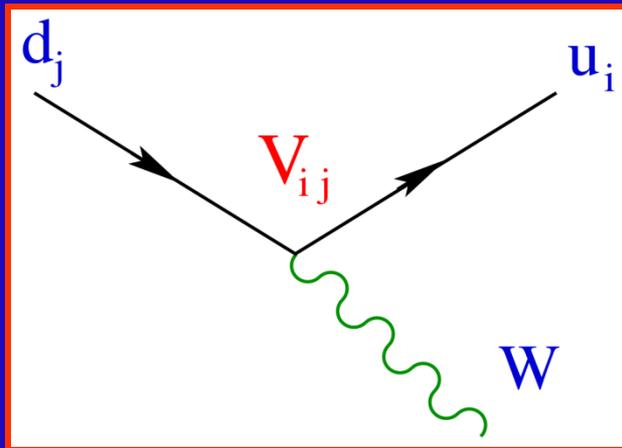
$$K_L \rightarrow \pi^{0*} \rightarrow (\gamma\gamma)^* \rightarrow \mu^+ \mu^-$$

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

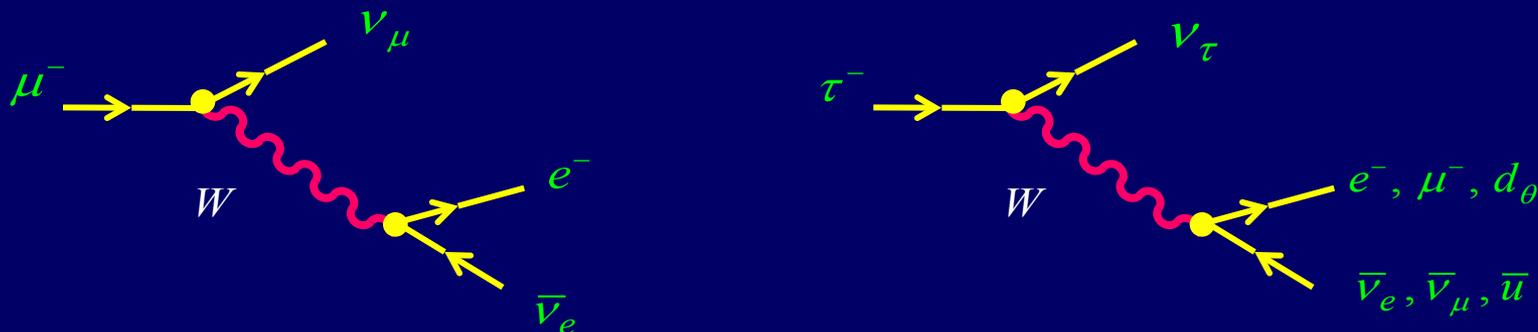
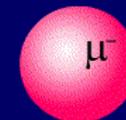
Flavour Changing Charged Currents

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

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



Weak Decays



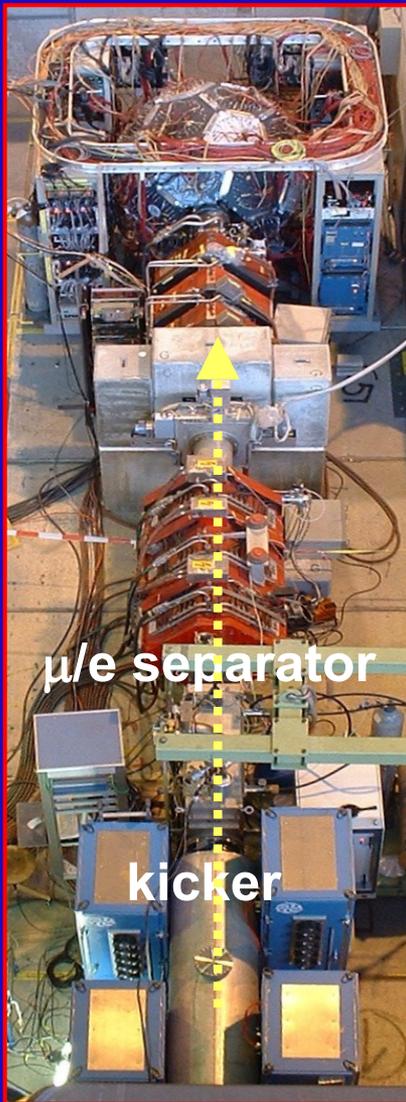
$$T(l \rightarrow \nu_l l' \bar{\nu}_{l'}) \sim \frac{g^2}{M_W^2 - q^2} \xrightarrow{q^2 \ll M_W^2} \frac{g^2}{M_W^2} = 4\sqrt{2} G_F$$

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

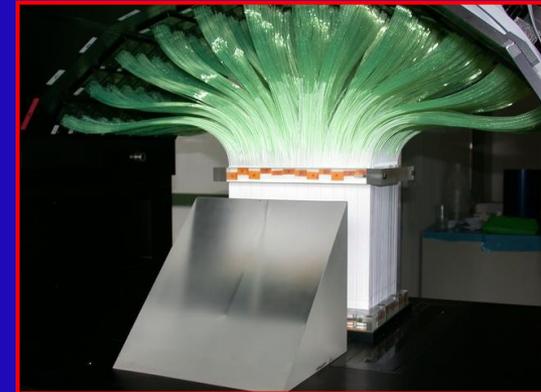
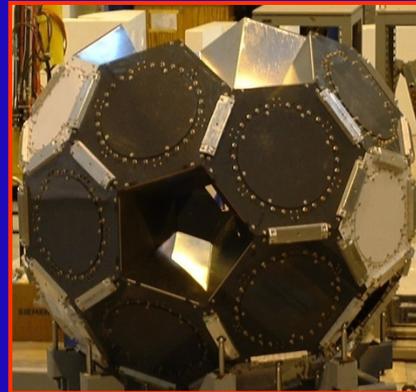
$$r_{EW} = \left[1 + \frac{\alpha(m_\mu)}{2\pi} \left(\frac{25}{4} - \pi^2 \right) + C_2 \frac{\alpha(m_\mu)^2}{\pi^2} \right] = 0.9958 \quad ; \quad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$$

Muon Lifetime

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



M
U
L
A
N



F
A
S
T

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

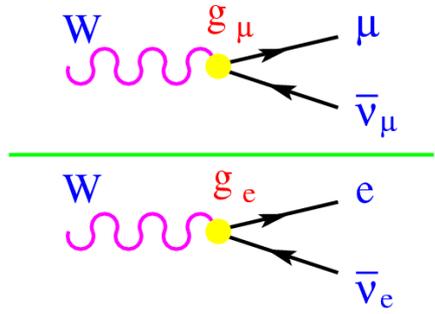
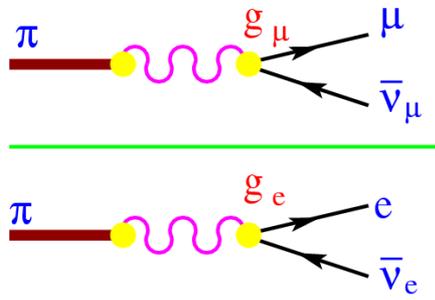
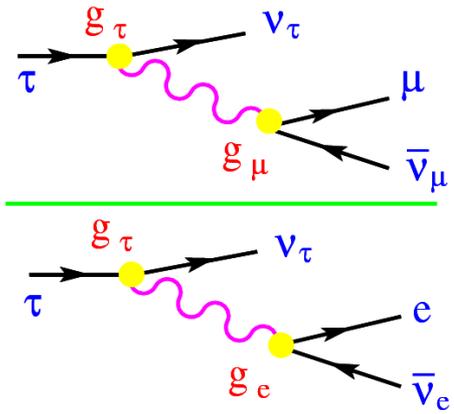
δ_{QED} known to 0.3 ppm
(van-Ritbergen & Stuart)

New World Average:

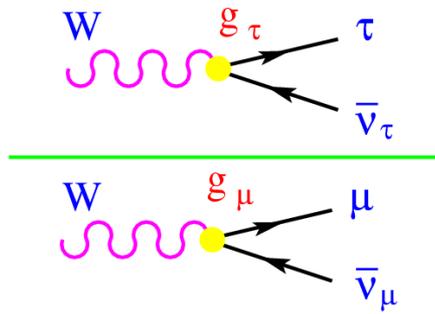
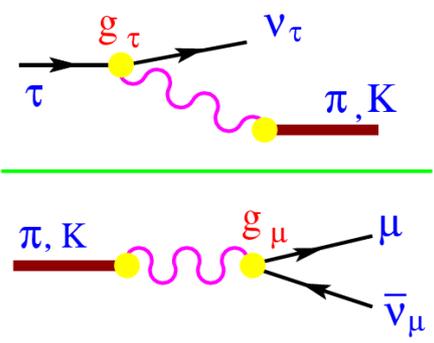
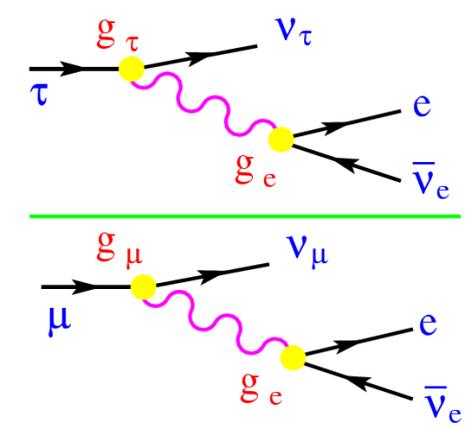
$$\tau_\mu = 2.196\,981\,1 (22) \mu s \quad \longrightarrow \quad G_F = 1.166\,378\,7 (6) \times 10^{-5} \text{ GeV}^{-2} \quad (0.5 \text{ ppm})$$

LEPTON UNIVERSALITY

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



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



CHARGED CURRENT UNIVERSALITY

$$|g_\mu / g_e|$$

$B_{\tau \rightarrow \mu} / B_{\tau \rightarrow e}$	1.0018 ± 0.0014
$B_{\pi \rightarrow \mu} / B_{\pi \rightarrow e}$	1.0021 ± 0.0016
$B_{K \rightarrow \mu} / B_{K \rightarrow e}$	0.9978 ± 0.0020
$B_{K \rightarrow \pi\mu} / B_{K \rightarrow \pi e}$	1.0010 ± 0.0025
$B_{W \rightarrow \mu} / B_{W \rightarrow e}$	0.991 ± 0.009

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

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

$$|g_\tau / g_e|$$

$B_{\tau \rightarrow \mu} \tau_\mu / \tau_\tau$	1.0024 ± 0.0021
$B_{W \rightarrow \tau} / B_{W \rightarrow e}$	1.023 ± 0.011

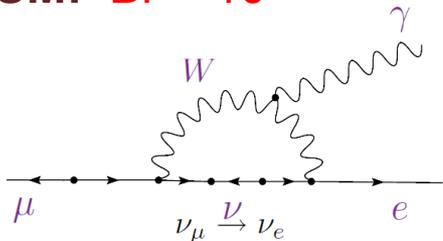
LEPTON FLAVOUR VIOLATION

90% CL Upper Limits on $\text{Br}(l^- \rightarrow X^-)$ [MEG'13, SINDRUM'88, Bolton'88, BABAR, BELLE]

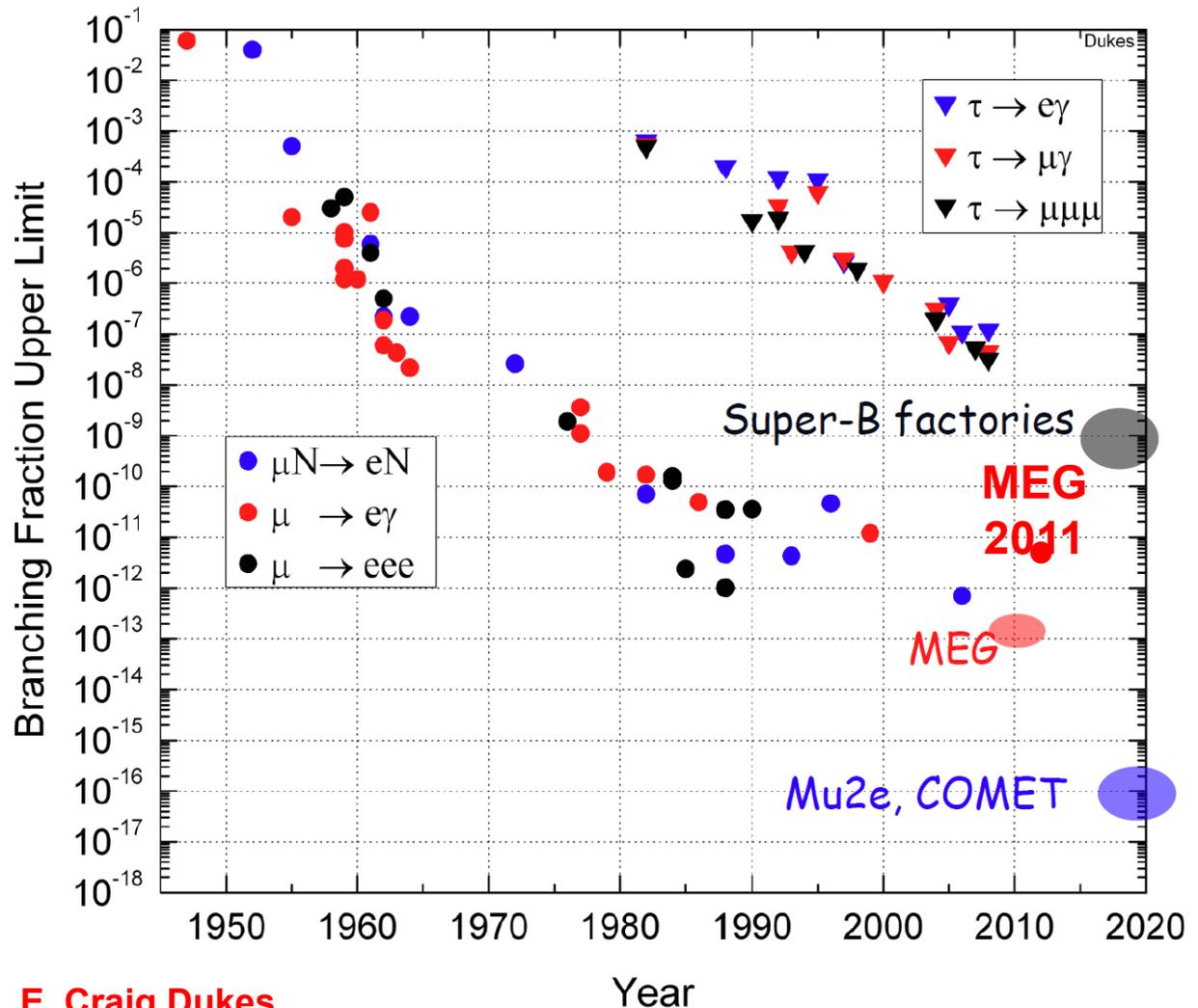
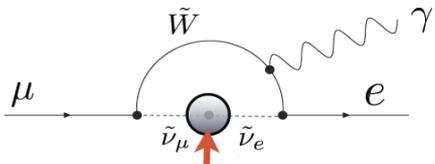
Decay	U.L.	Decay	U.L.	Decay	U.L.
$\mu^- \rightarrow e^- \gamma$	$5.7 \cdot 10^{-13}$	$\mu^- \rightarrow e^- e^+ e^-$	$1.0 \cdot 10^{-12}$	$\mu^- \rightarrow e^- \gamma \gamma$	$7.2 \cdot 10^{-11}$
$\tau^- \rightarrow e^- \gamma$	$3.3 \cdot 10^{-8}$	$\tau^- \rightarrow e^- e^+ e^-$	$2.7 \cdot 10^{-8}$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

Exciting Prospects

SM: $Br < 10^{-54}$



New Physics ?

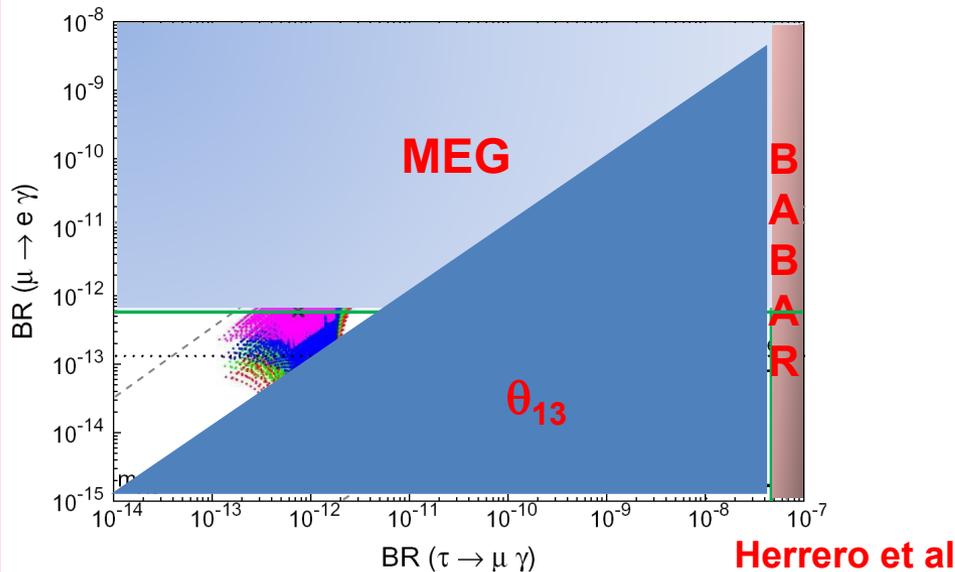


E. Craig Dukes

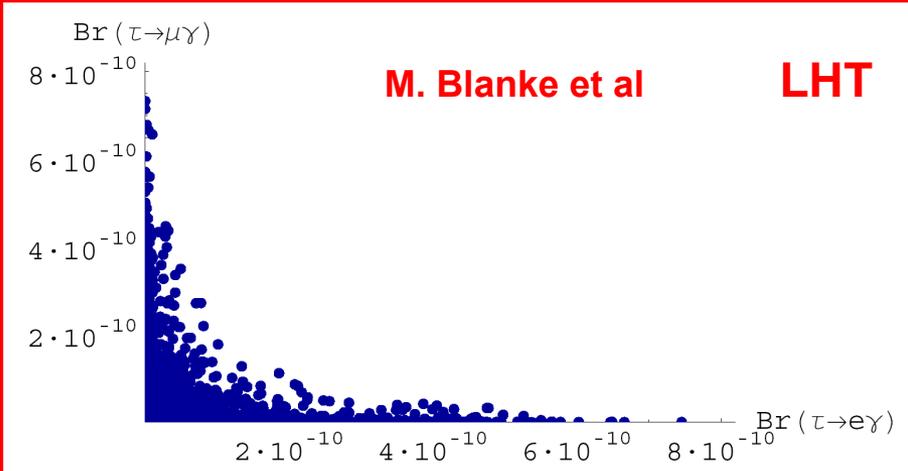
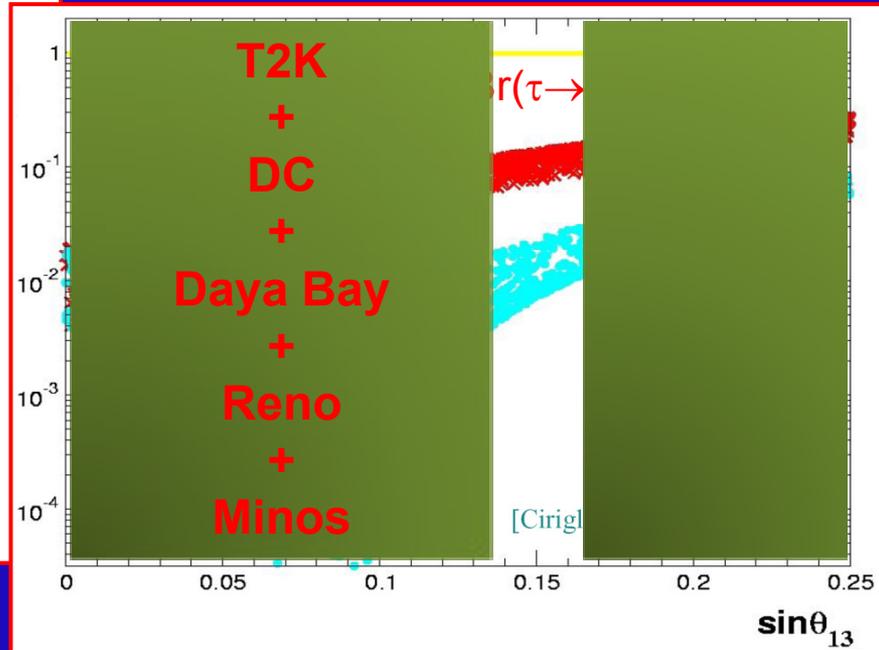
Impact of θ_{13} on LFV processes

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



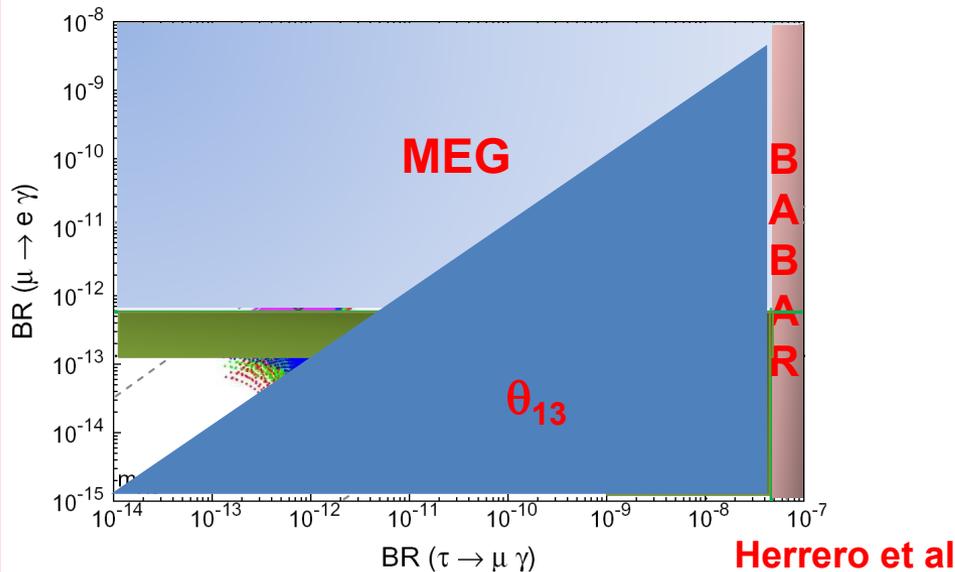
Kicking out Models



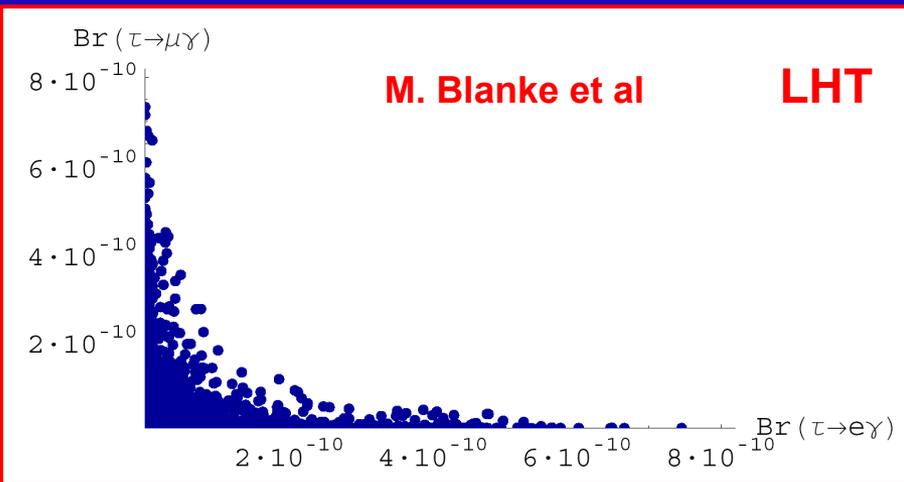
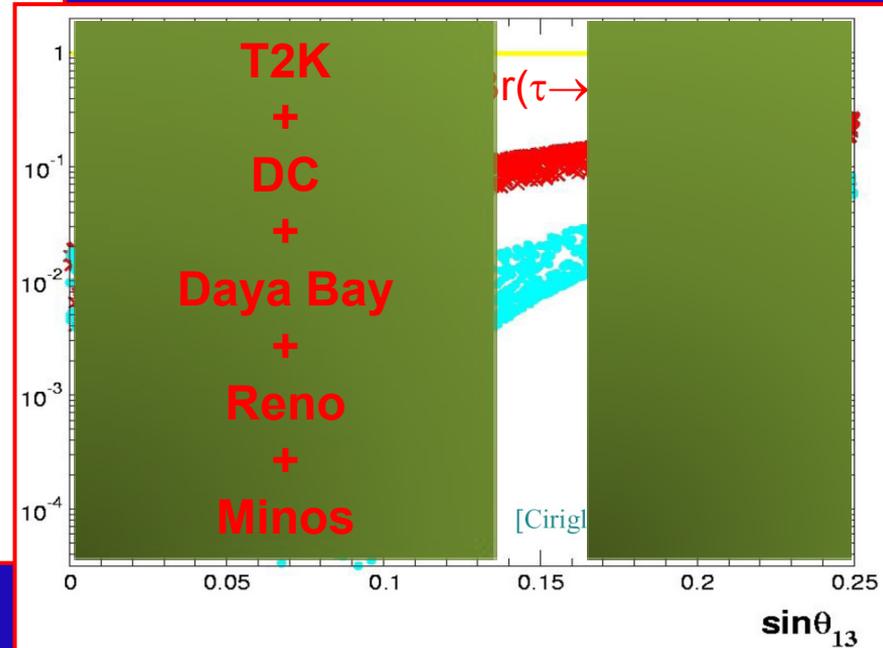
Impact of θ_{13} on LFV processes

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



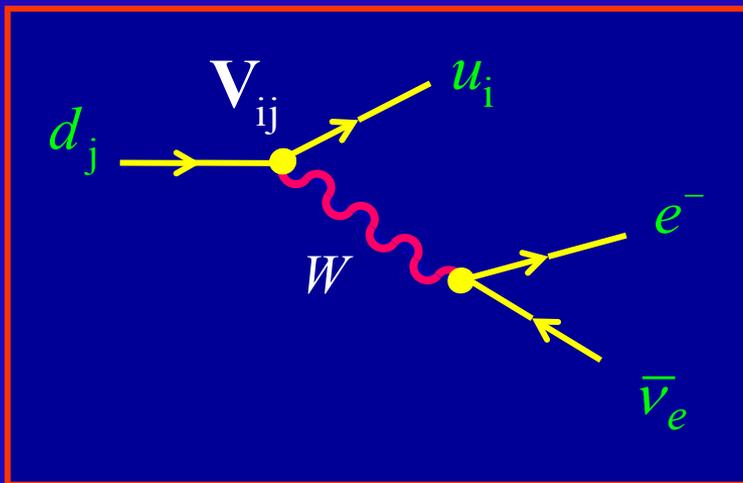
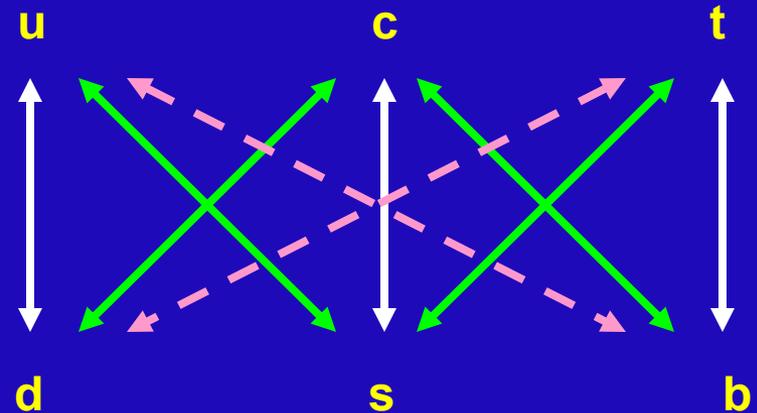
MEG: $Br(\mu \rightarrow e \gamma) \sim 10^{-13}$
Prism: $Pr(\mu \rightarrow e) \sim 10^{-18}$
S-BF: $Br(\tau \rightarrow \mu \gamma) \sim 10^{-9}$



Kicking out Models



Flavour Changing Charged Currents



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

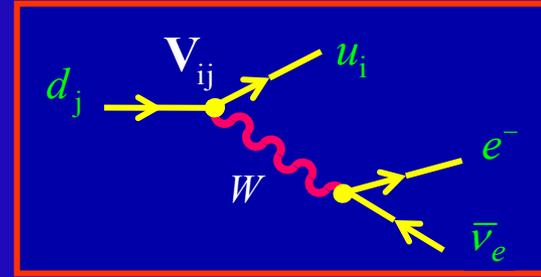
We measure decays of hadrons (no free quarks)

Important QCD Uncertainties

V_{ij} Determination

$(0^- \rightarrow 0^-)$

$K \rightarrow \pi l \nu, D \rightarrow K l \nu \dots$



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

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

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

$f_-(q^2)$ suppressed
($m_{u_i} - m_{d_j}, m_l$)

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

Theory is always needed: Symmetries

$|V_{ud}|$

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

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

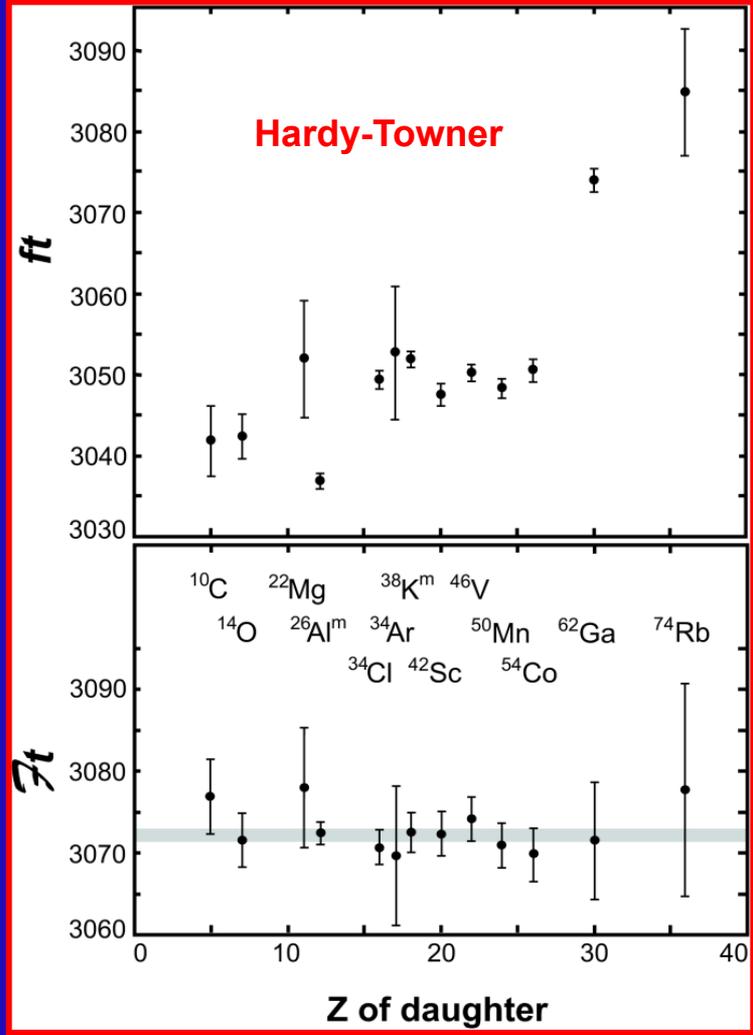
$$|V_{ud}|^2 = \frac{\pi^3 \ln 2}{ft G_F^2 m_e^5 (1 + \delta_{RC})} = \frac{(2984.48 \pm 0.05) \text{ s}}{ft (1 + \delta_{RC})}$$

(Marciano – Sirlin)



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

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



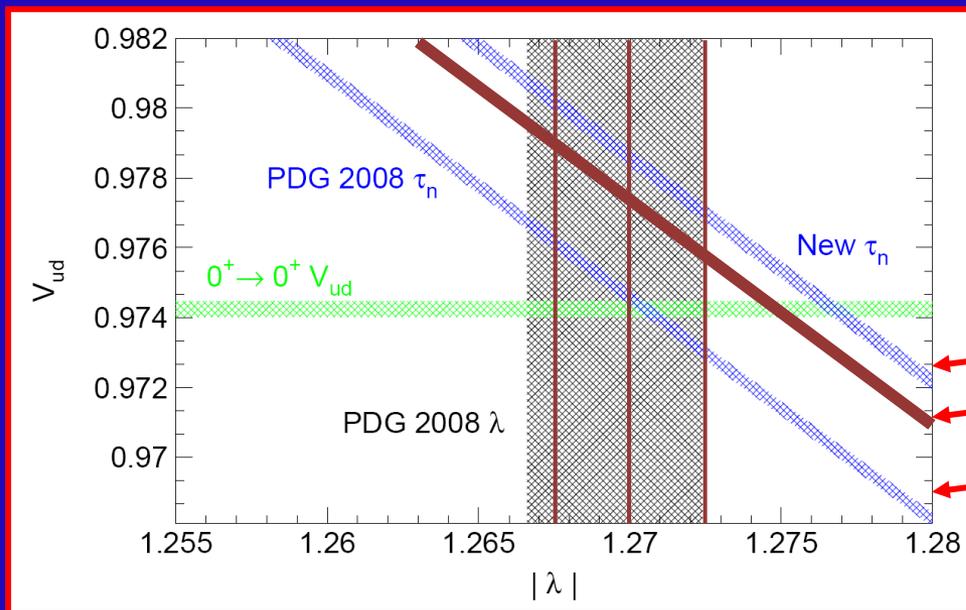
● Neutron Decay:

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

(Czarnecki – Marciano – Sirlin)

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

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



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

$$\tau_n = (878.5 \pm 0.7 \pm 0.3) \text{ s}$$

(Serebrov et al, 2005)

PDG12

PDG10

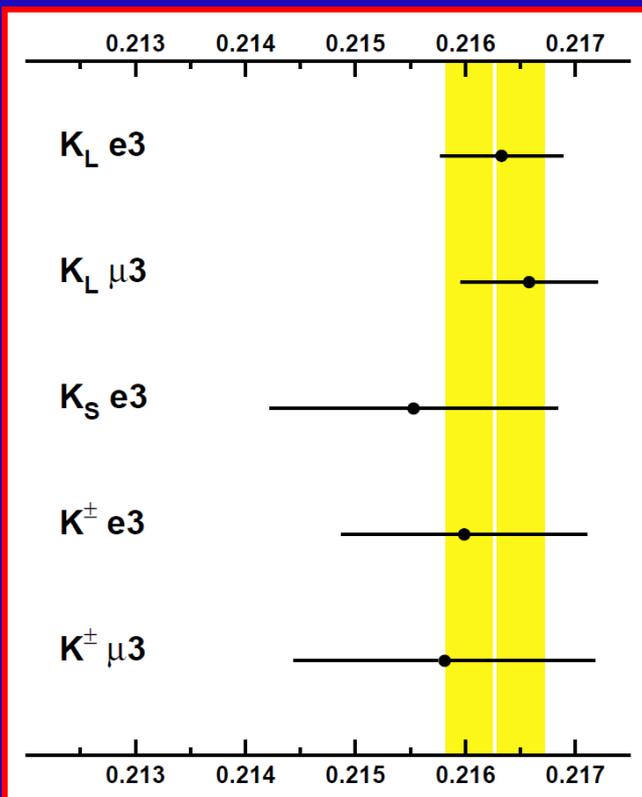
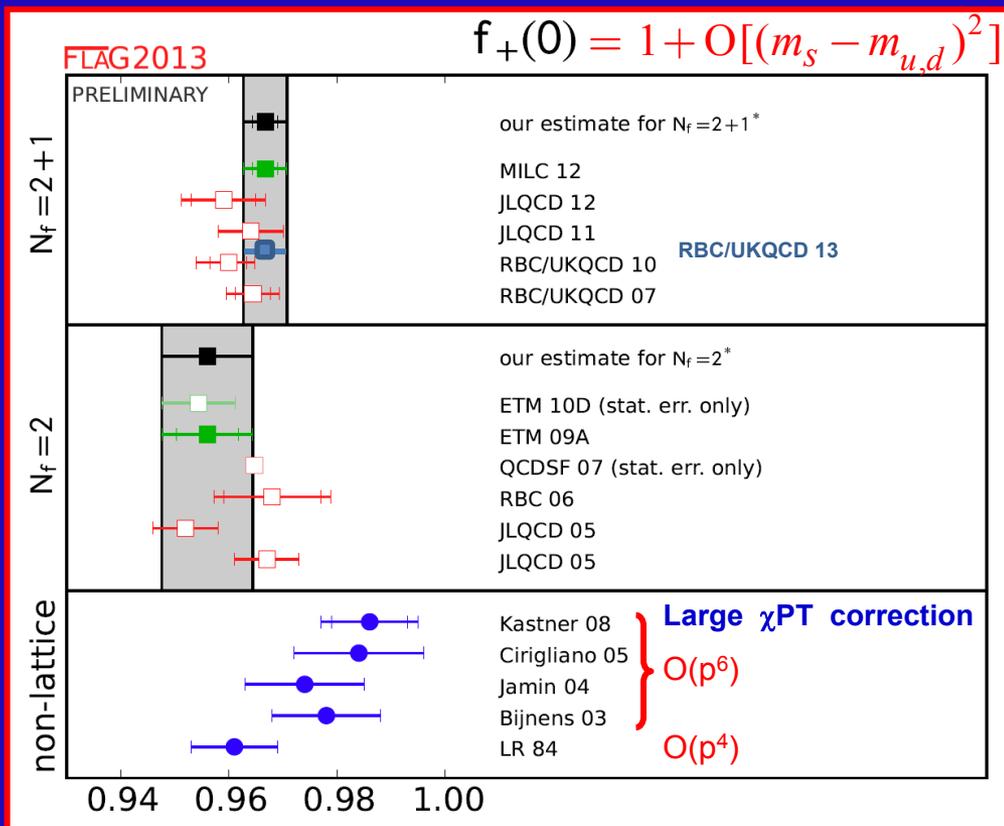
● Pion Decay:

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

(PIBETA)

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

K → πlν Decays



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

2012: $f_+(0) = 0.959 \pm 0.005$ \Rightarrow $|V_{us}| = 0.2255 \pm 0.0014$

2013: $f_+(0) = 0.967 \pm 0.004$ \Rightarrow $|V_{us}| = 0.2238 \pm 0.0011$

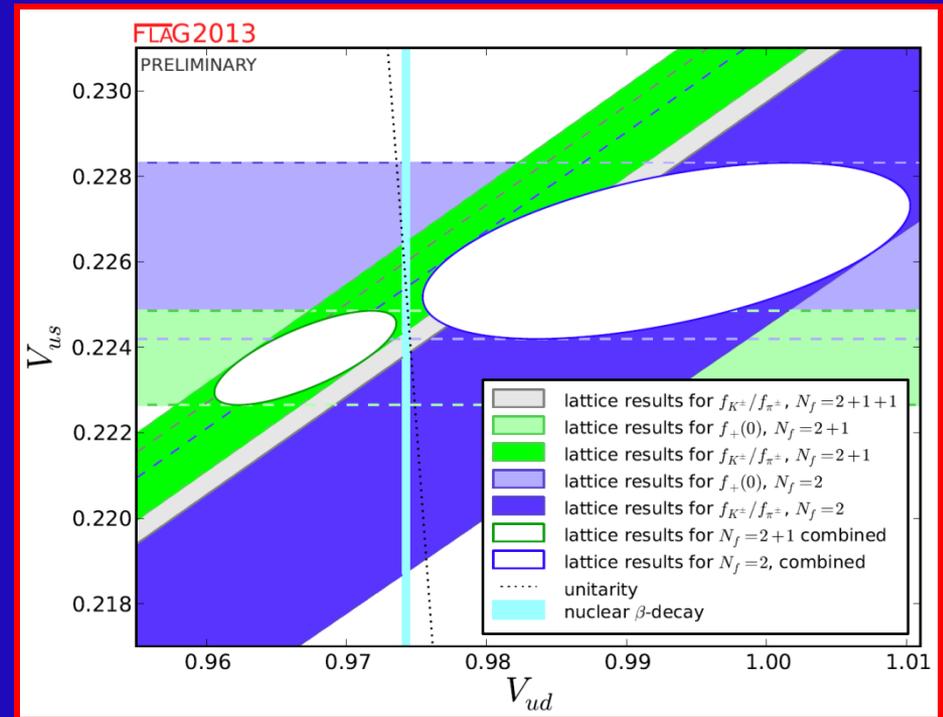
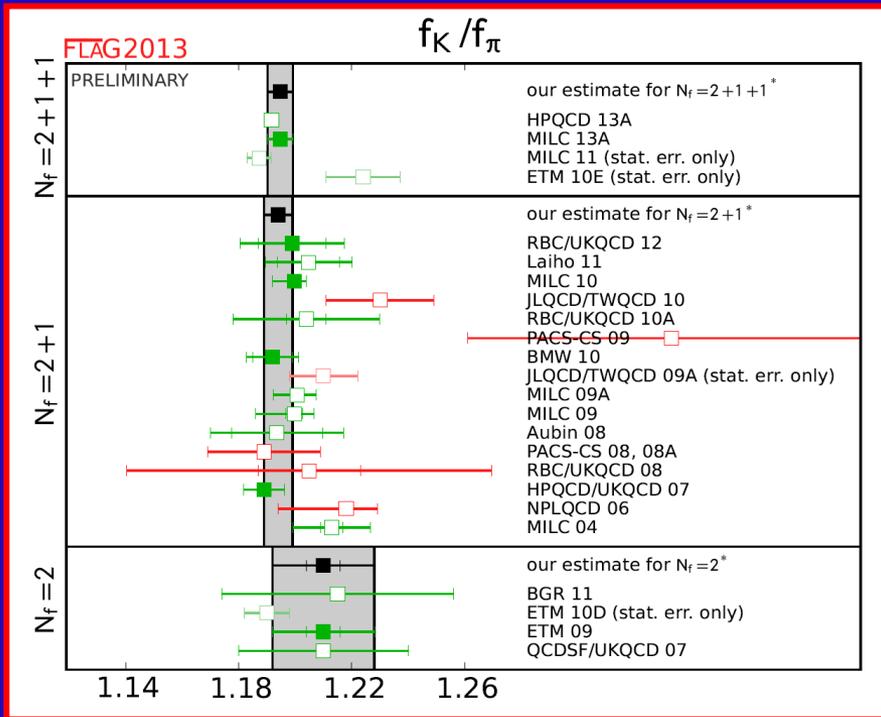
$$\Gamma(\text{K}^+ \rightarrow \mu^+ \nu_\mu) / \Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu)$$

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



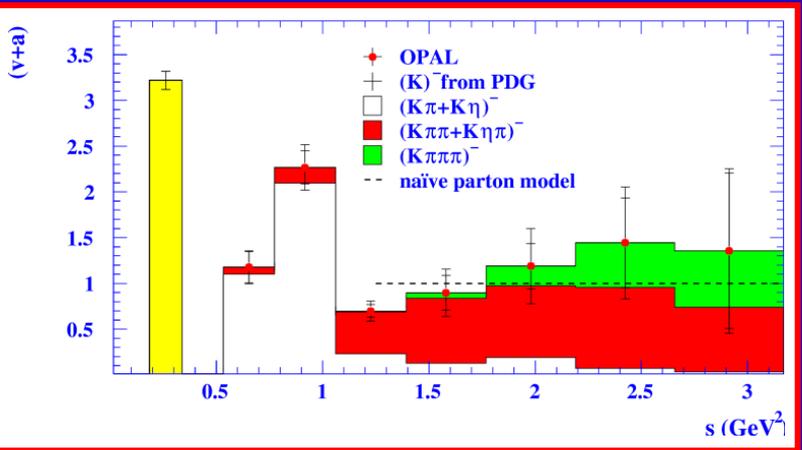
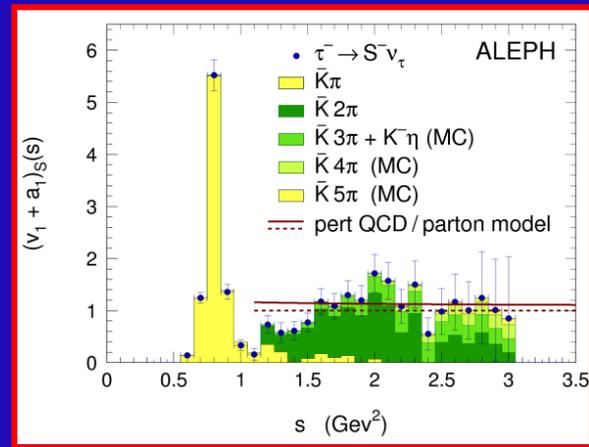
$$\frac{|V_{us}|}{|V_{ud}|} = 0.2314 \pm 0.0011$$

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



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

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



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

Gámiz-Jamin-Pich-Prades-Schwab

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

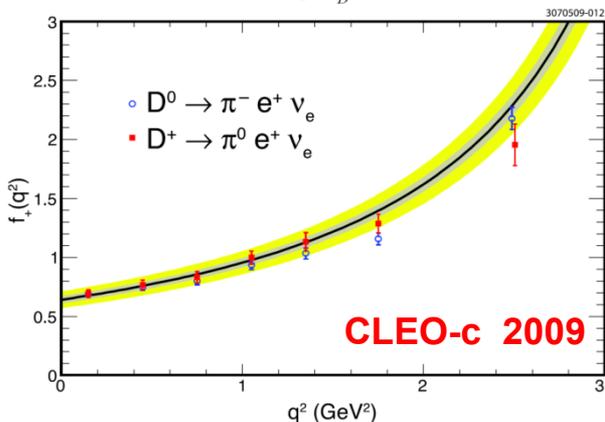
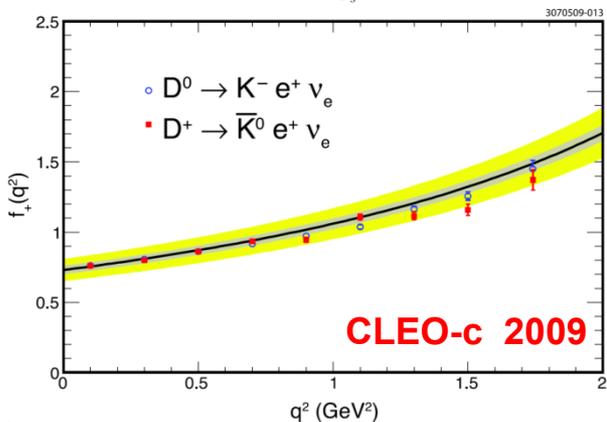
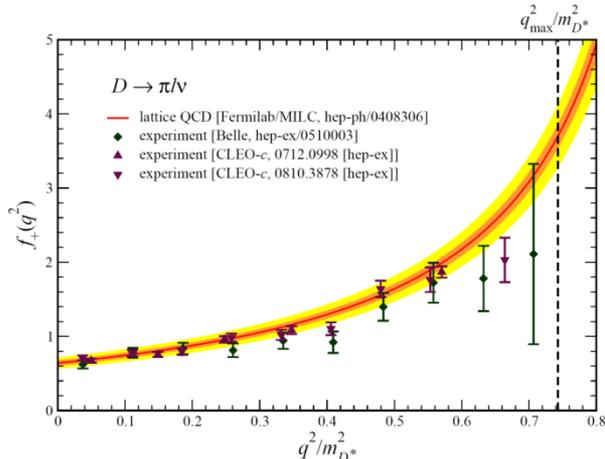
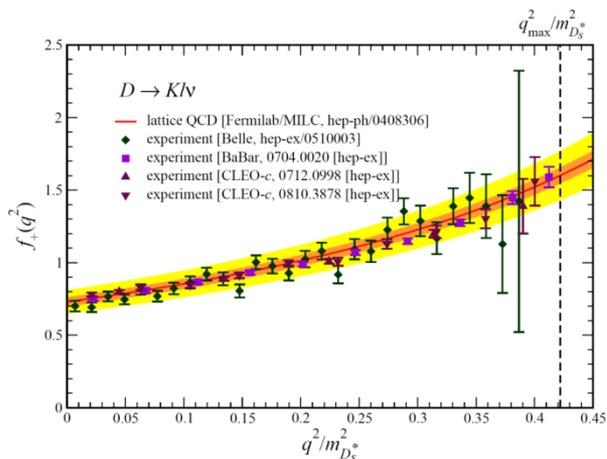
$$m_s(2 \text{ GeV}) = 94 \pm 6 \text{ MeV}$$

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

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

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

D → K/π l ν



Lattice input

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

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

PDG 2012:

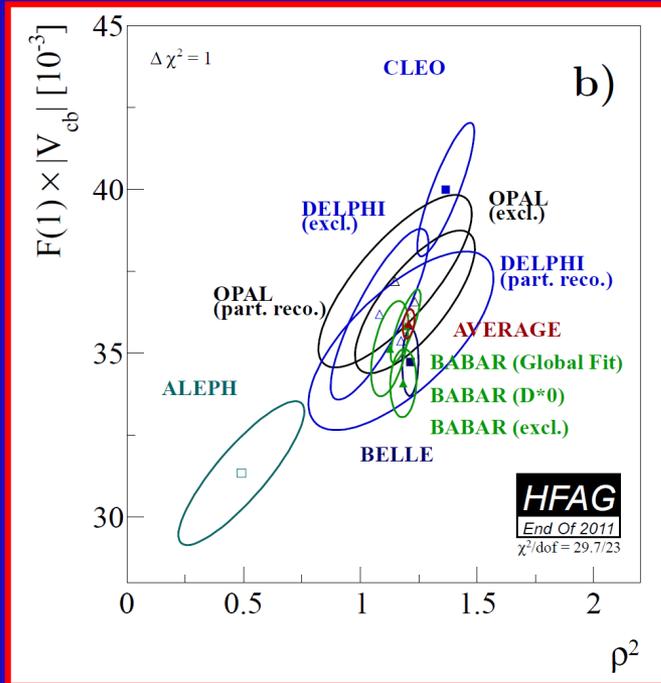
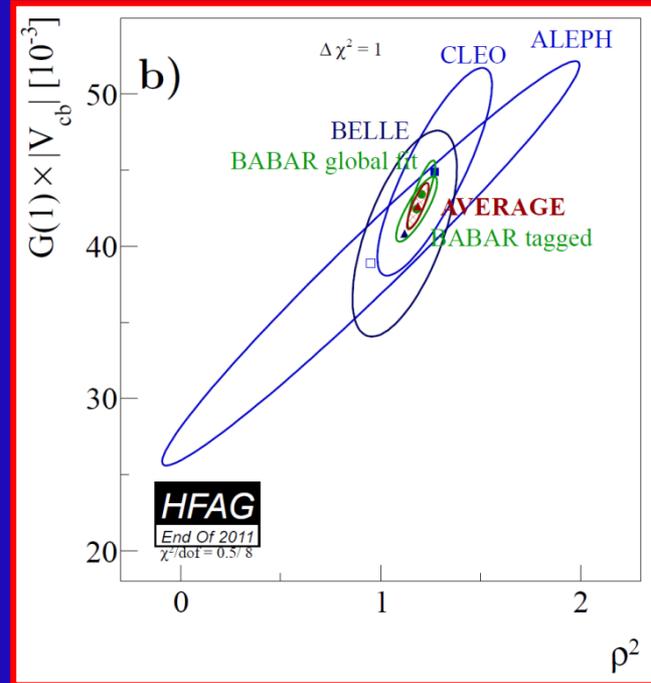
$$|V_{cd}|_{D \rightarrow \mu e} = 0.230 \pm 0.011$$

$$|V_{cs}|_{D \rightarrow Kl\nu, D_s \rightarrow l\nu} = 1.006 \pm 0.023$$

B → D l ν

B → D* l ν

QCD Symmetries at 1/M_Q → 0 HQET



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

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

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

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

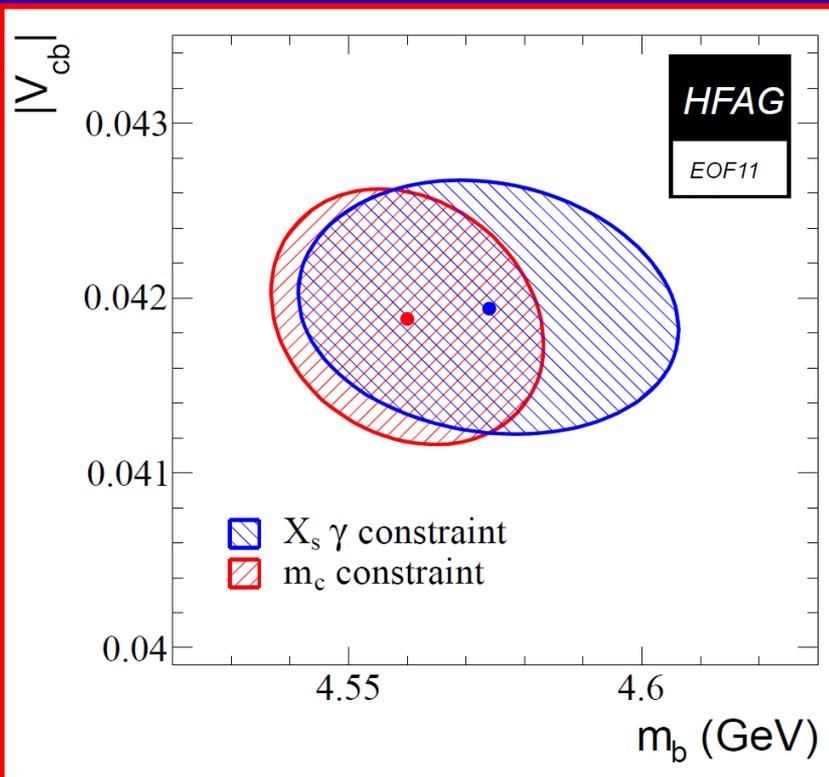


$$|V_{cb}|_{\text{excl}} = (39.6 \pm 0.9) \cdot 10^{-3}$$

Inclusive B Decays

(OPE, HQET)

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



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

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

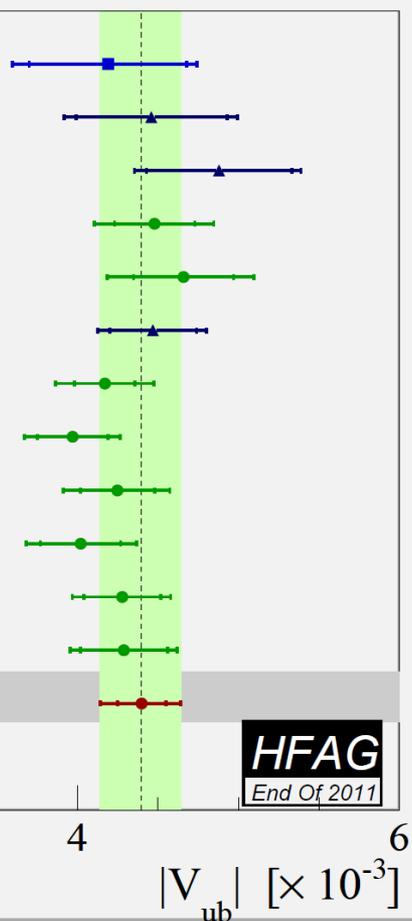
1.9 σ discrepancy with exclusive measurement



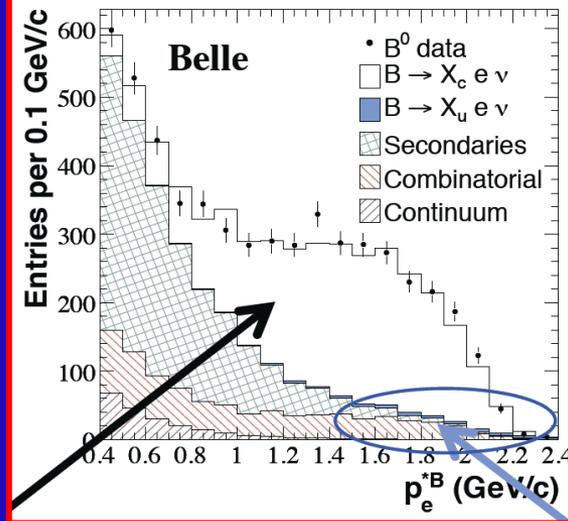
$$|V_{cb}| = (40.9 \pm 1.1) \cdot 10^{-3}$$

$B \rightarrow X_u l \nu$

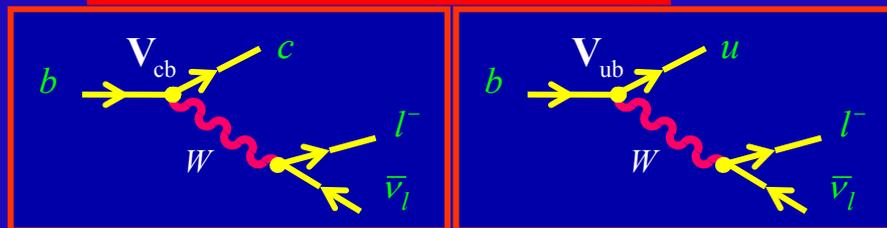
CLEO (E_c)
 $4.19 \pm 0.49 + 0.26 - 0.34$
 BELLE sim. ann. (m_{X_c}, q^2)
 $4.46 \pm 0.47 + 0.25 - 0.27$
 BELLE (E_c)
 $4.88 \pm 0.45 + 0.24 - 0.27$
 BABAR (E_c)
 $4.48 \pm 0.25 + 0.27 - 0.28$
 BABAR (E_c, s_h^{\max})
 $4.66 \pm 0.31 + 0.31 - 0.36$
 BELLE multivariate (p^*)
 $4.47 \pm 0.27 + 0.19 - 0.21$
 BABAR ($m_{X_c} < 1.55$)
 $4.17 \pm 0.19 \pm 0.24$
 BABAR ($m_{X_c} < 1.7$)
 $3.97 \pm 0.22 \pm 0.20$
 BABAR ($m_{X_c} < 1.7, q^2 > 8$)
 $4.25 \pm 0.23 + 0.23 - 0.25$
 BABAR ($P^+ < 0.66$)
 $4.02 \pm 0.25 + 0.24 - 0.23$
 BABAR (m_{X_c}, q^2 fit, $p^* > 1\text{GeV}$)
 $4.28 \pm 0.24 + 0.18 - 0.20$
 BABAR ($p^* > 1.3\text{GeV}$)
 $4.29 \pm 0.27 + 0.19 - 0.20$
 Average +/-exp + theory - theory
 $4.40 \pm 0.15 + 0.19 - 0.21$
 $\chi^2/\text{dof} = 11.0/11$ (CL = 44.00 %)
 Bosch, Lange, Neubert and Paz (BLNP)
 Phys.Rev.D72:073006,2005



HFAG
 End Of 2011



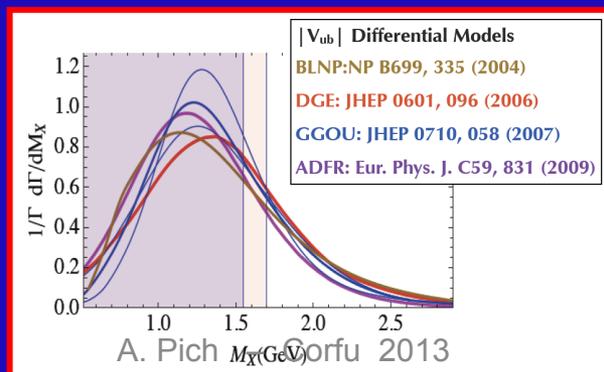
$$\left| \frac{V_{ub}}{V_{cb}} \right|^2 \approx \frac{1}{50}$$



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

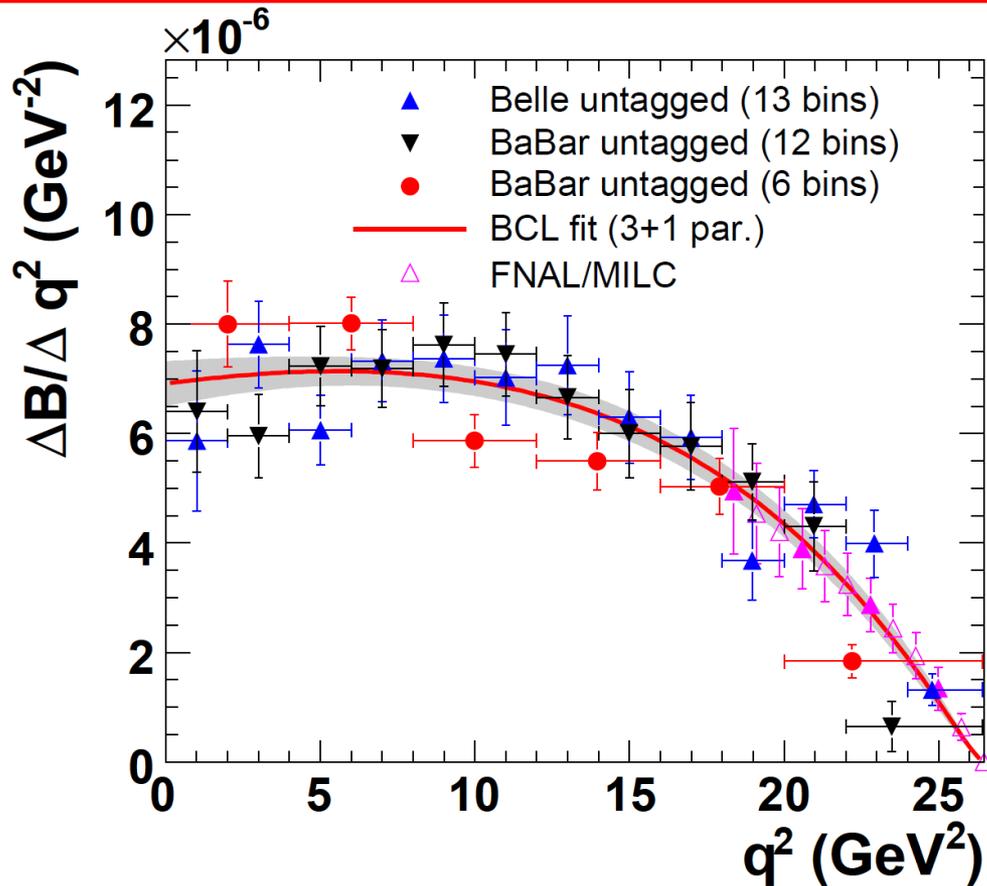
PDG 2012:

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



$B \rightarrow \pi l \nu$

Large theoretical uncertainties



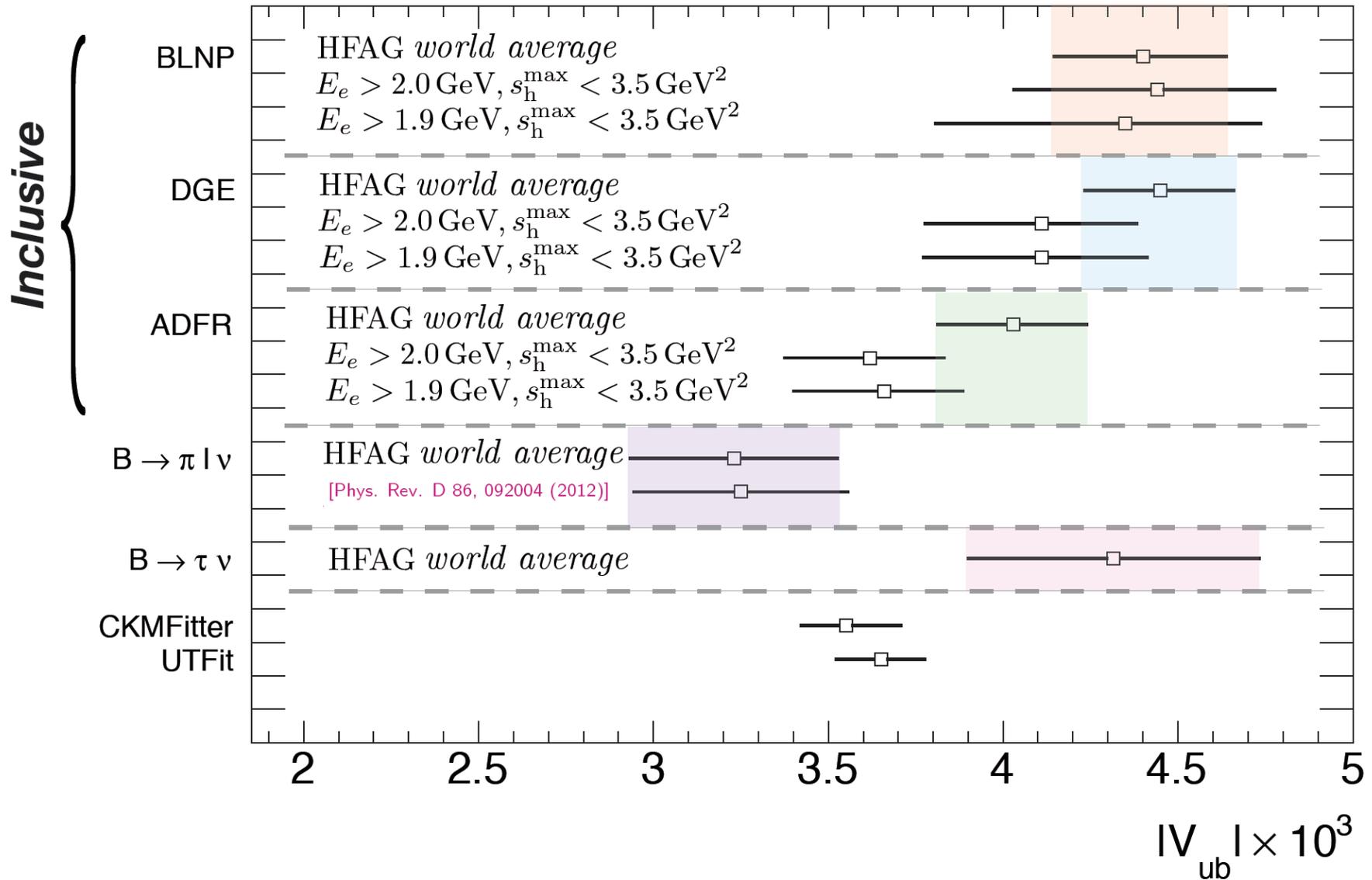
PDG 2012:

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

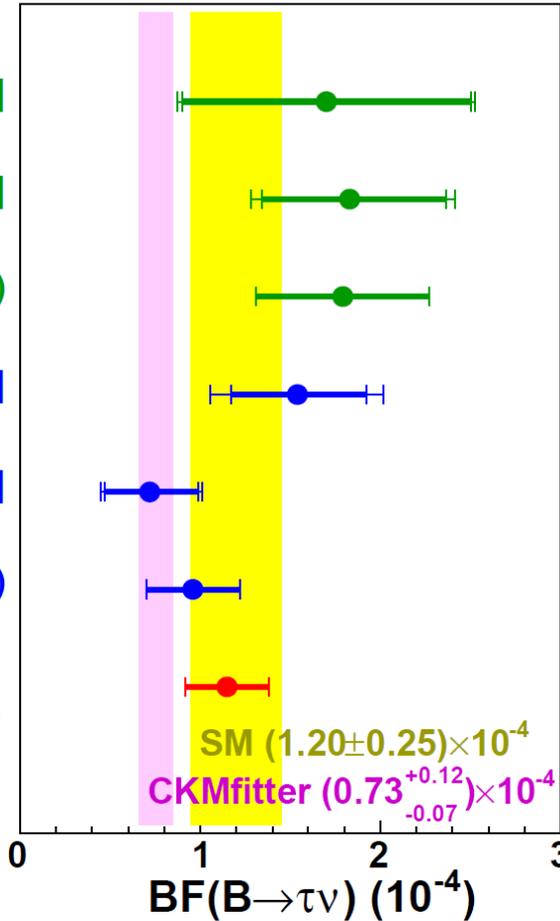


$$|V_{ub}| = (4.15 \pm 0.49) \cdot 10^{-3}$$

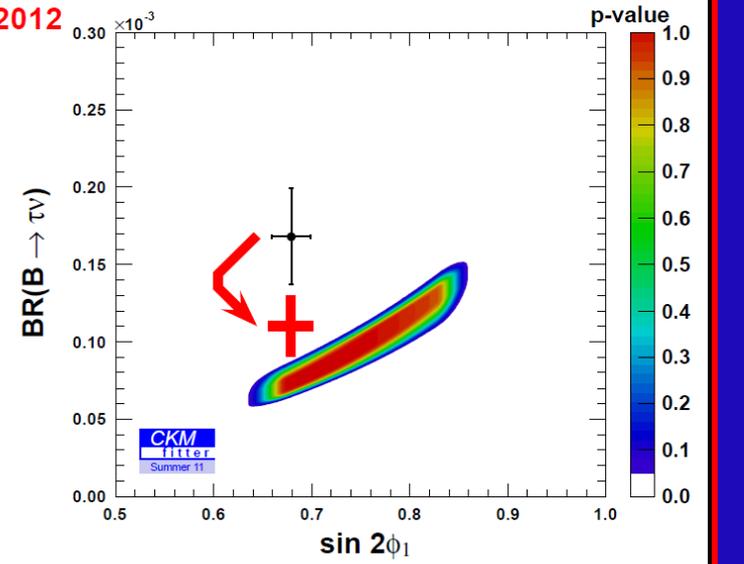
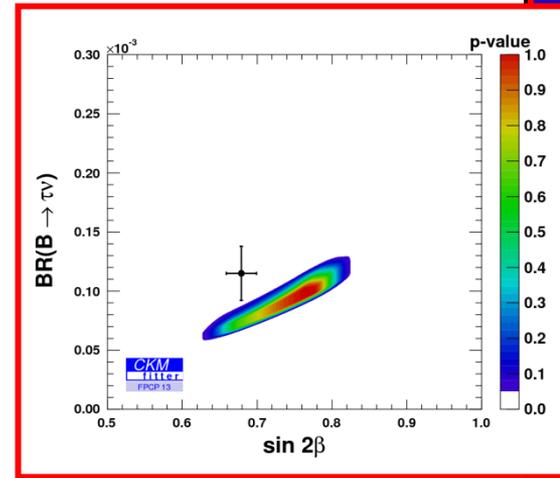
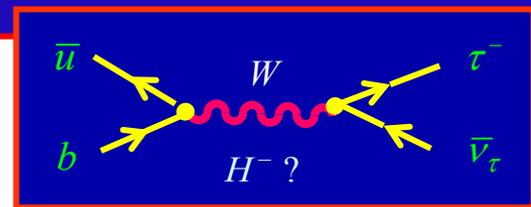
Summary for $|V_{ub}|$



- BaBar [468M] (2010) semilep-tag
- BaBar [468M] (2012) hadronic-tag
- BaBar (combined) with correlations
- Belle [657M] (2010) semilep-tag
- Belle [772M] (2012) hadronic-tag
- Belle (combined) with correlations
- W.A. private average (MN)



- $(1.70 \pm 0.80 \pm 0.20) \times 10^{-4}$
PRD81,051101
- $(1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$
arxiv:1207.0698
- $(1.79 \pm 0.48) \times 10^{-4}$
arxiv:1207.0698
- $(1.54^{+0.38+0.29}_{-0.37-0.31}) \times 10^{-4}$
PRD82,071101
- $(0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$
ICHEP 2012
- $(0.96 \pm 0.26) \times 10^{-4}$
ICHEP 2012
- $(1.15 \pm 0.23) \times 10^{-4}$
ICHEP 2012



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

CKM

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

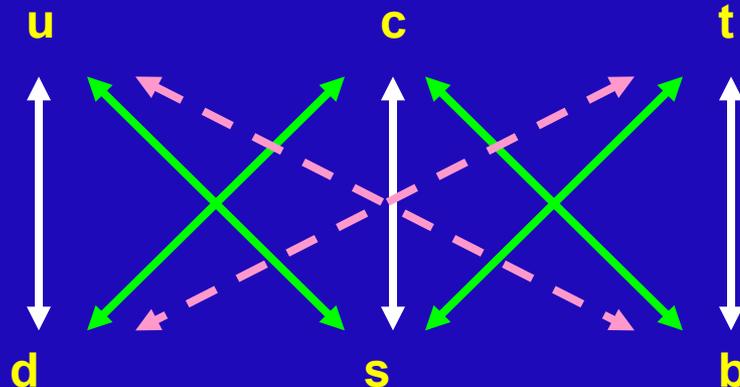
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9993 \pm 0.0009$$

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

Hierarchical Structure

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

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



QUARK MIXING MATRIX

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

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

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

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



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

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

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

$$\mathbf{V} = \begin{bmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{bmatrix} \quad \longrightarrow \quad \text{No } \cancel{CP}$$

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

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

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

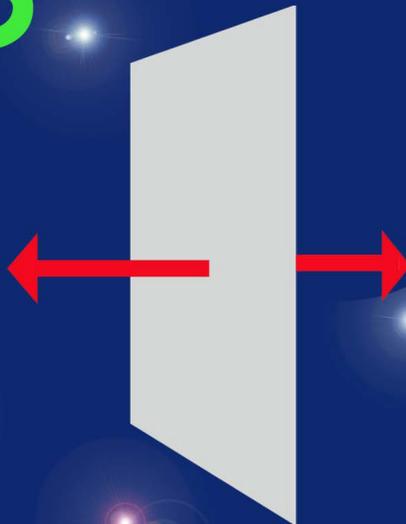
$$\lambda \approx \sin \theta_C \approx 0.226 \quad ; \quad A \approx 0.80 \quad ; \quad \sqrt{\rho^2 + \eta^2} \approx 0.45$$

$$\delta_{13} \neq 0 \quad (\eta \neq 0) \quad \longrightarrow \quad \cancel{CP}$$

C



P



- C, P : Violated maximally in weak interactions
- CP : Symmetry of nearly all observed phenomena
- Slight ($\sim 0.2\%$) CP in K^0 decays (1964)
- Sizeable CP in B^0 decays (2001)
- Huge Matter—Antimatter Asymmetry
in our Universe \longrightarrow Baryogenesis

CPT Theorem: $CP \longleftrightarrow T$

- Thus, CP requires:
- Complex Phases
 - Interferences

Standard Model \mathcal{CP} : 3 fermion families needed

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

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

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

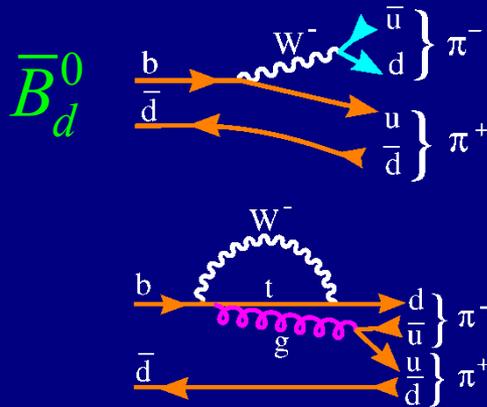
$$\mathbf{J} = c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin \delta_{13} = |A^2 \lambda^6 \eta| < 10^{-4}$$

- Low-Energy Phenomena
- Small Effects $\sim \mathbf{J}$
- Big Asymmetries \iff Suppressed Decays
- B Decays are an optimal place for \mathcal{CP} signals

DIRECT

\cancel{CP}

$$|\mathbf{T}(P \rightarrow f)| \neq |\mathbf{T}(\bar{P} \rightarrow \bar{f})|$$



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

\downarrow CP

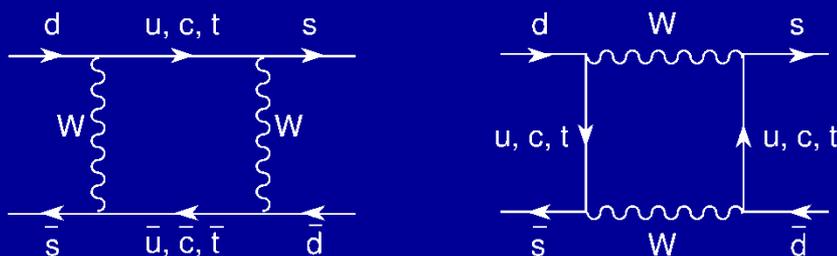
$$\mathbf{T}(\bar{P} \rightarrow \bar{f}) = T_1 e^{-i\phi_1} e^{i\delta_1} + T_2 e^{-i\phi_2} e^{i\delta_2}$$

$$A_{P \rightarrow f}^{CP} \equiv \frac{\Gamma(P \rightarrow f) - \Gamma(\bar{P} \rightarrow \bar{f})}{\Gamma(P \rightarrow f) + \Gamma(\bar{P} \rightarrow \bar{f})} = \frac{-2 T_1 T_2 \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1)}{T_1^2 + T_2^2 + 2 T_1 T_2 \cos(\phi_2 - \phi_1) \cos(\delta_2 - \delta_1)}$$

One needs:

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

INDIRECT CP : $K^0 - \bar{K}^0$ MIXING



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

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

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

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

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

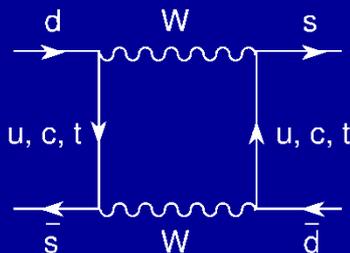
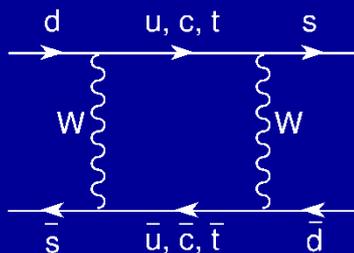
- **GIM Mechanism:** $\lambda_u + \lambda_c + \lambda_t = 0$

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

- **CP:** $\text{Im} \lambda_t = -\text{Im} \lambda_c \simeq \eta \lambda^5 A^2$

- **Hard GIM Breaking:** $S(r_i, r_i) \sim r_i \rightarrow$ **t quark**

INDIRECT \mathcal{CP} : $K^0 - \bar{K}^0$ MIXING



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

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

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

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

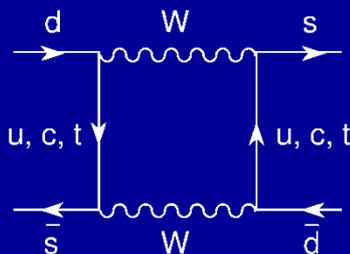
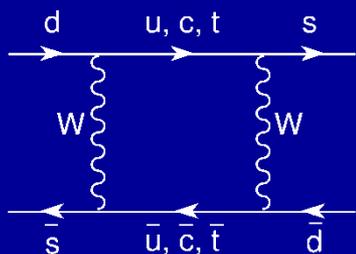
$$\lambda_i \equiv V_{id} V_{is}^* \quad ; \quad r_i \equiv m_i^2 / M_W^2 \quad (i = u, c, t)$$

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

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

$$|K_S^0\rangle \simeq |K_1^0\rangle + \bar{\epsilon}_K |K_2^0\rangle \quad , \quad |K_L^0\rangle \simeq |K_2^0\rangle + \bar{\epsilon}_K |K_1^0\rangle$$

INDIRECT CP : $K^0 - \bar{K}^0$ MIXING



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

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

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

$$\frac{\Gamma(K_L^0 \rightarrow \pi^- l^+ \nu_l) - \Gamma(K_L^0 \rightarrow \pi^+ l^- \bar{\nu}_l)}{\Gamma(K_L^0 \rightarrow \pi^- l^+ \nu_l) + \Gamma(K_L^0 \rightarrow \pi^+ l^- \bar{\nu}_l)} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = \frac{2 \operatorname{Re}(\bar{\varepsilon}_K)}{1 + |\bar{\varepsilon}_K|^2} = (0.332 \pm 0.006)\%$$

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

$$\eta_{+-} \equiv \frac{T(K_L \rightarrow \pi^+ \pi^-)}{T(K_S \rightarrow \pi^+ \pi^-)} \approx \varepsilon_K$$

$$\eta_{00} \equiv \frac{T(K_L \rightarrow \pi^0 \pi^0)}{T(K_S \rightarrow \pi^0 \pi^0)} \approx \varepsilon_K$$

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

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

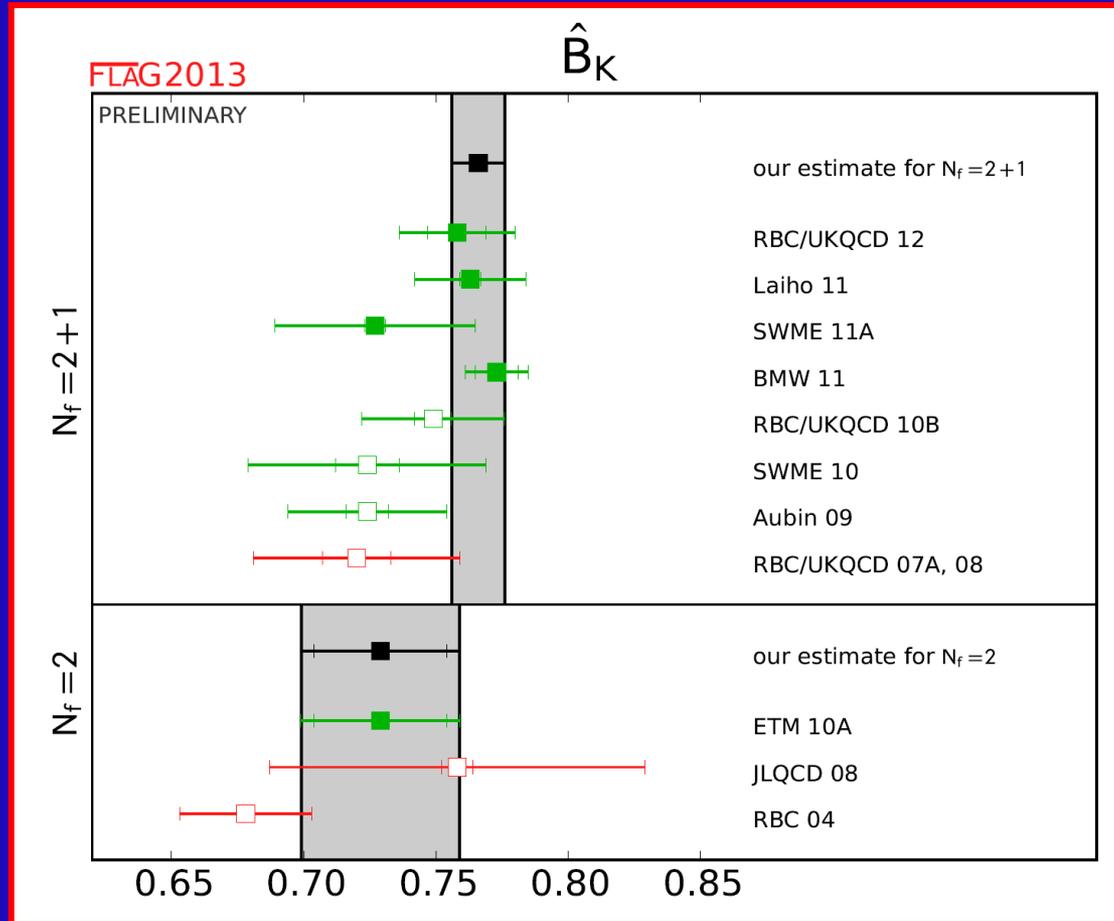


Buras et al

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

Lattice Results for \hat{B}_K

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



Flavianet Lattice Averaging Group

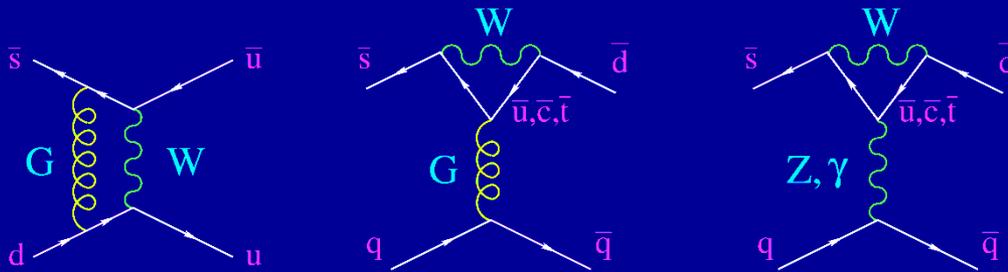
DIRECT CP in $K \rightarrow \pi \pi$

$$\eta_{+-} \equiv \frac{T(K_L \rightarrow \pi^+ \pi^-)}{T(K_S \rightarrow \pi^+ \pi^-)} \approx \varepsilon_K + \varepsilon'_K$$

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

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

NA48, NA31
KTeV, E731



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

- Short-distance OPE

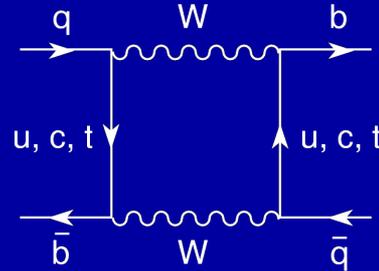
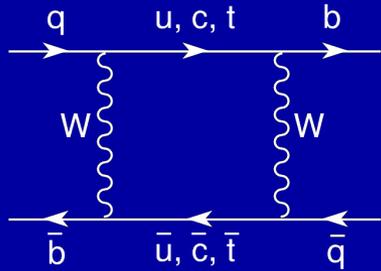
Ciuchini et al, Buras et al

- Long-distance χ PT

Pallante-Pich-Scimemi

Cirigliano-Ecker-Neufeld-Pich

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



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

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

$$\Delta M_{B_d^0} = (0.510 \pm 0.004) \text{ ps}^{-1}$$



$$|V_{td}|$$

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

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

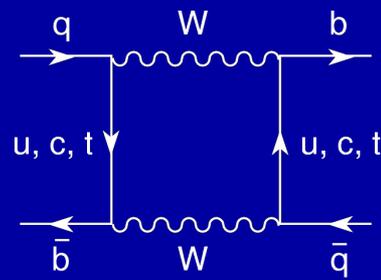
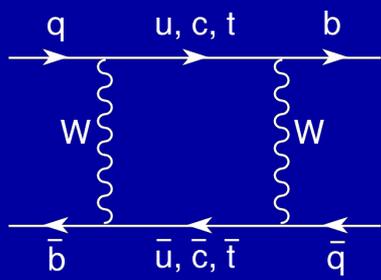
$$|V_{ts}|^2 \gg |V_{td}|^2$$

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

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

\mathcal{CP} very small

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



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

$$|B_{\mp}^0\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}} \left(p |B^0\rangle \mp q |\bar{B}^0\rangle \right)$$

$$\frac{q}{p} \equiv \frac{1 - \varepsilon_B}{1 + \varepsilon_B} = \left(\frac{M_{12}^* - \frac{i}{2} \Gamma_{12}^*}{M_{12} - \frac{i}{2} \Gamma_{12}} \right)^{1/2}$$

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

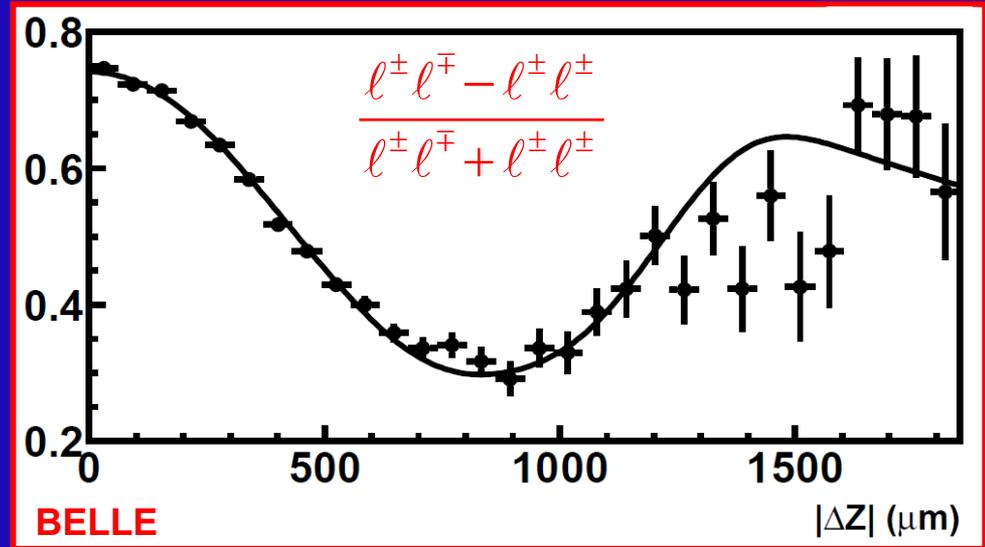
$$\Delta M \equiv M_{B_+} - M_{B_-}$$

$$\Delta\Gamma \equiv \Gamma_{B_+} - \Gamma_{B_-}$$

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

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

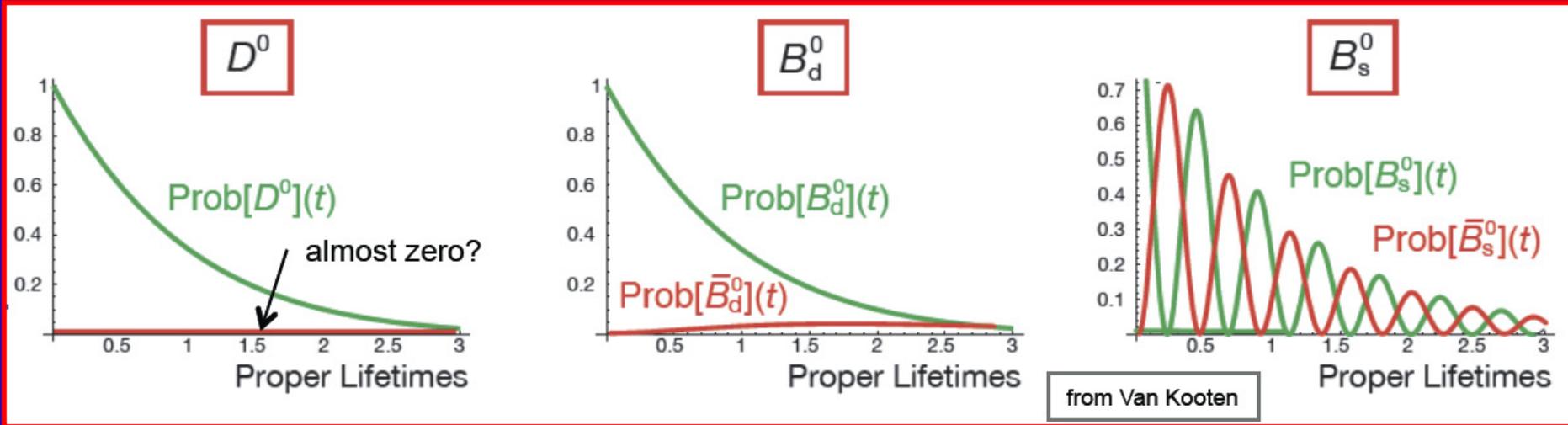
$$x \equiv \frac{\Delta M}{\Gamma} \quad , \quad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$



- 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)

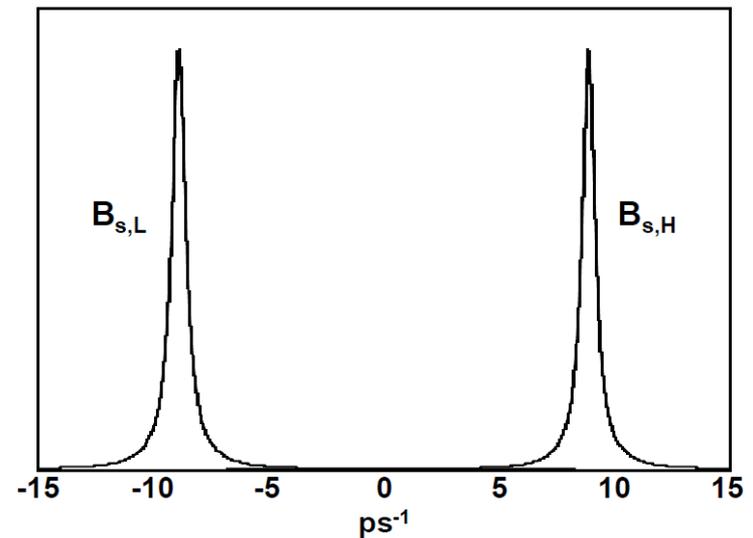
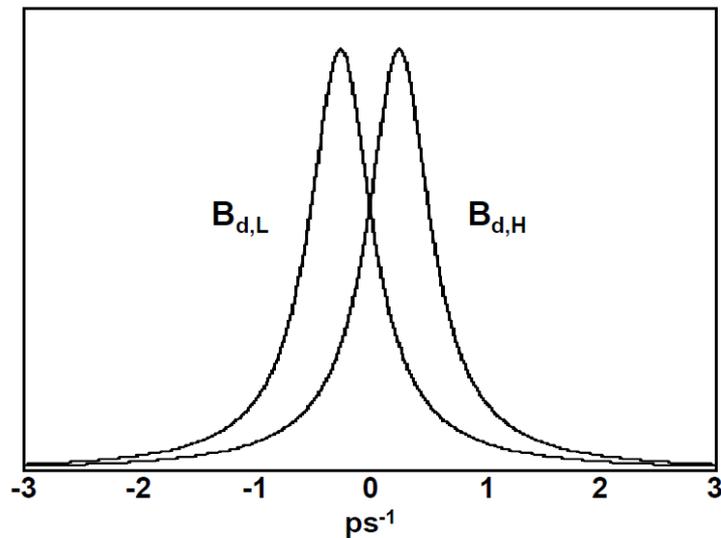
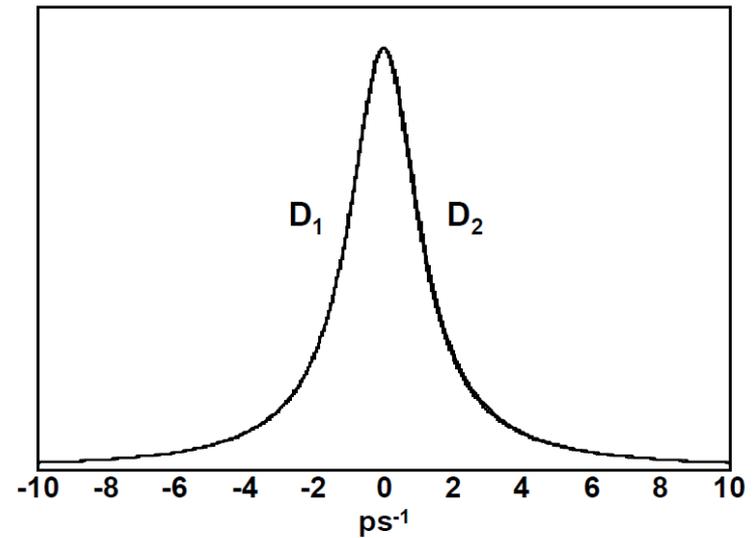
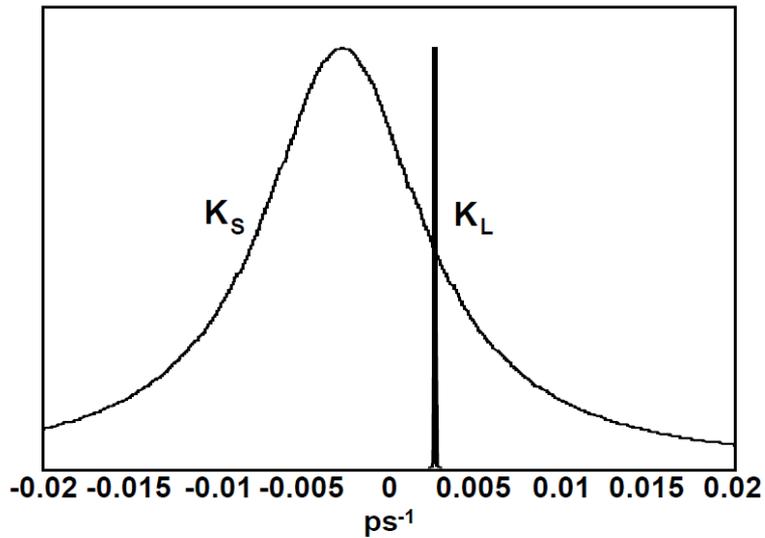
Time Scales: Oscillation $\sim \sin\left[(x - iy)\Gamma t / 2\right]$

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



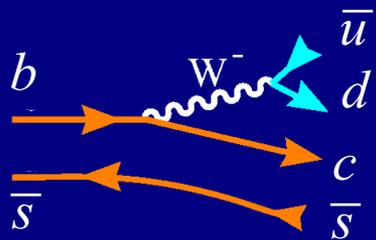
- K^0 : $x \sim y \sim 1$
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- B_d : $x \sim 1$, $y \sim 0.01$
- B_s : $x \sim 25$, $y \leq 0.01$ Fast oscillation (averages out to 0)

Widths & Mass Differences

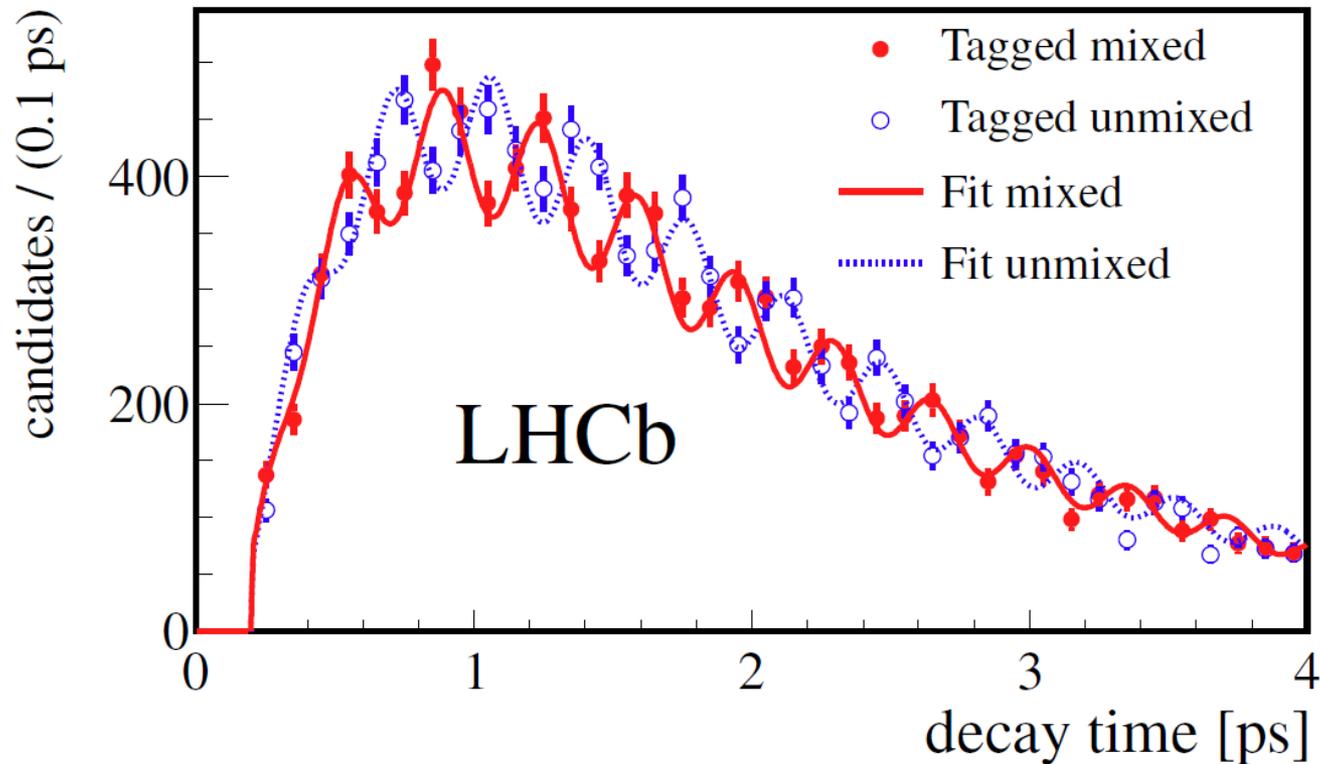


M. Gersabeck

B_s Mixing @ LHCb



$\bar{B}_s^0 \rightarrow D_s^+ \pi^-$

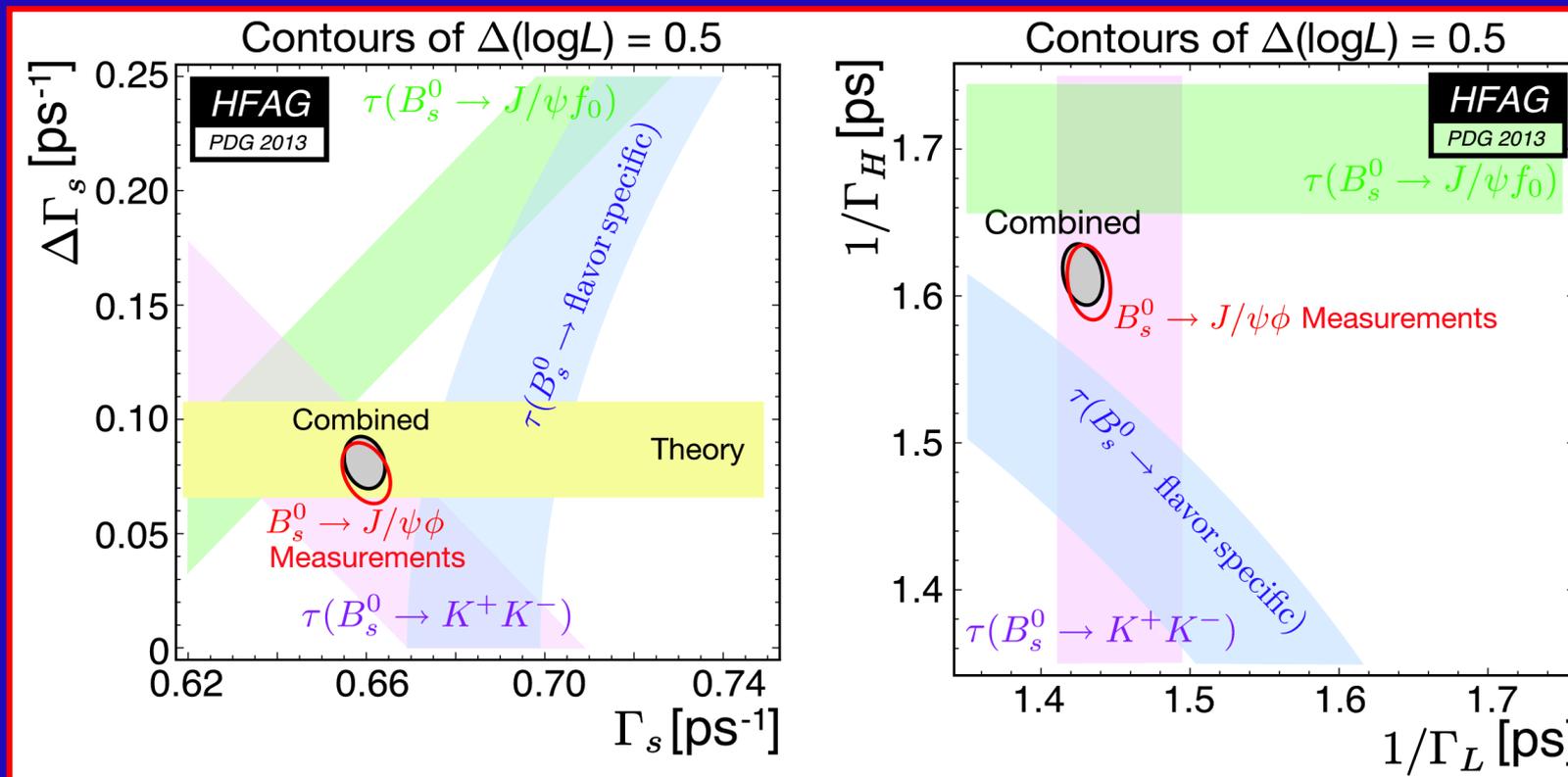


$$\Delta m_s = 17.768 \pm 0.023 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1}$$

B_s Lifetimes

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

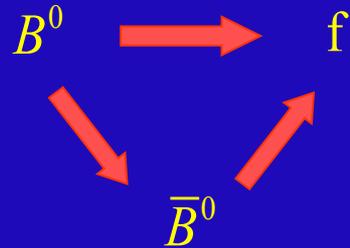
$$\Delta\Gamma \equiv \Gamma_L - \Gamma_H$$



CP (K⁺K⁻) = +

CP (J/ψ f₀) = -

$B^0 - \bar{B}^0$ MIXING AND DIRECT \mathcal{CP}



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

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

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

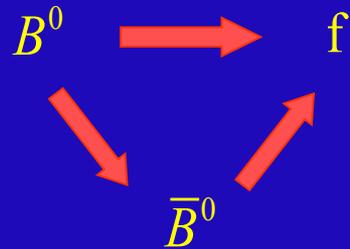
$$\Gamma[B^0(t) \rightarrow f] \sim \frac{1}{2} e^{-\Gamma t} (|T_f|^2 + |\bar{T}_f|^2) \left\{ 1 + \mathbf{C}_f \cos(\Delta M t) - \mathbf{S}_f \sin(\Delta M t) \right\}$$

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

$$\mathbf{C}_f \equiv \frac{1 - |\bar{\rho}_f|^2}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{S}_f \equiv \frac{2 \operatorname{Im}\left(\frac{q}{p} \bar{\rho}_f\right)}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{C}_{\bar{f}} \equiv -\frac{1 - |\rho_{\bar{f}}|^2}{1 + |\rho_{\bar{f}}|^2} \quad ; \quad \mathbf{S}_{\bar{f}} \equiv \frac{-2 \operatorname{Im}\left(\frac{p}{q} \rho_{\bar{f}}\right)}{1 + |\rho_{\bar{f}}|^2}$$

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

$B^0 - \bar{B}^0$ MIXING AND DIRECT \mathcal{CP}



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

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

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

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

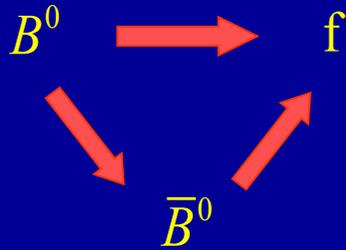
$$\Gamma[\bar{B}^0(t) \rightarrow \bar{f}] \sim \frac{1}{2} e^{-\Gamma t} \left(|\bar{T}_{\bar{f}}|^2 + |T_{\bar{f}}|^2 \right) \left\{ 1 - \mathbf{C}_{\bar{f}} \cos(\Delta M t) + \mathbf{S}_{\bar{f}} \sin(\Delta M t) \right\}$$

$$\mathbf{C}_f \equiv \frac{1 - |\bar{\rho}_f|^2}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{S}_f \equiv \frac{2 \operatorname{Im} \left(\frac{q}{p} \bar{\rho}_f \right)}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{C}_{\bar{f}} \equiv -\frac{1 - |\rho_{\bar{f}}|^2}{1 + |\rho_{\bar{f}}|^2} \quad ; \quad \mathbf{S}_{\bar{f}} \equiv \frac{-2 \operatorname{Im} \left(\frac{p}{q} \rho_{\bar{f}} \right)}{1 + |\rho_{\bar{f}}|^2}$$

CP self-conjugate: $\bar{f} = \eta_f f \quad \longrightarrow \quad T_{\bar{f}} = \eta_f T_f \quad ; \quad \bar{T}_{\bar{f}} = \eta_f \bar{T}_f \quad ; \quad \rho_{\bar{f}} \equiv 1 / \bar{\rho}_f$

$$\mathbf{C}_{\bar{f}} = \mathbf{C}_f \quad ; \quad \mathbf{S}_{\bar{f}} = \mathbf{S}_f$$

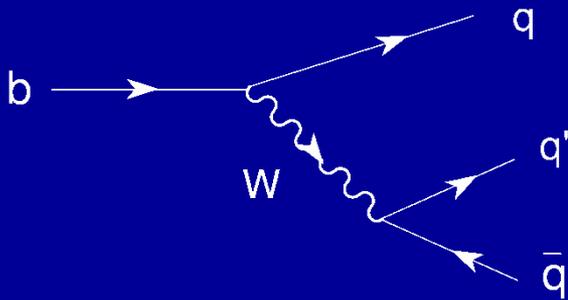
$B^0 - \bar{B}^0$ MIXING AND DIRECT CP



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

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

Assumption: Only 1 decay amplitude



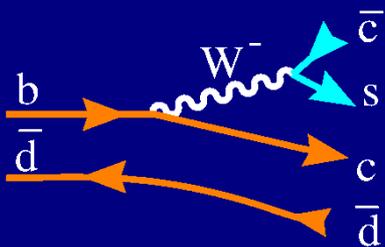
$$\frac{A_{b \rightarrow q\bar{q}q'}}{A_{\bar{b} \rightarrow \bar{q}q\bar{q}'}} = \frac{V_{qb} V_{qq'}^*}{V_{qb}^* V_{qq'}} = e^{-2i\phi_D}$$

$$\frac{\Gamma(\bar{B}^0 \rightarrow \bar{f}) - \Gamma(B^0 \rightarrow f)}{\Gamma(\bar{B}^0 \rightarrow \bar{f}) + \Gamma(B^0 \rightarrow f)} = -\eta_f \sin(2\phi) \sin(\Delta M t) \quad ; \quad \phi = \phi_M + \phi_D$$

Direct information on the CKM matrix

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

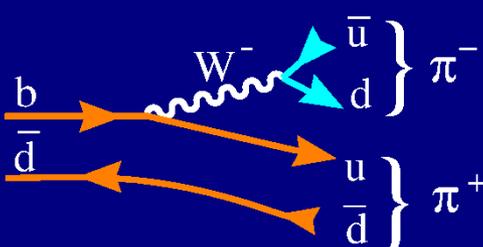
$$\phi \simeq \beta$$



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

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

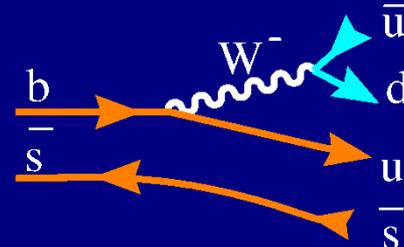
$$\phi \simeq \beta + \gamma = \pi - \alpha$$



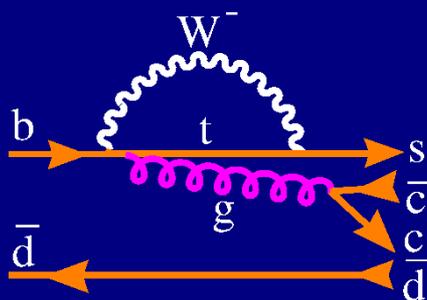
$$V_{ub} V_{ud}^* \sim A\lambda^3 (\rho - i\eta)$$

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

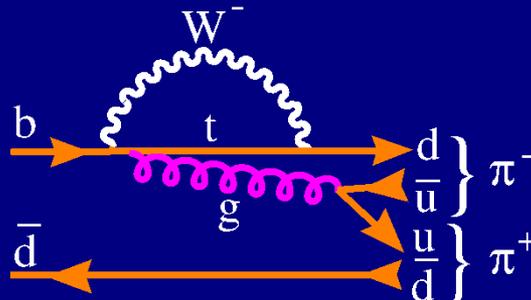
$$\phi \neq \gamma$$



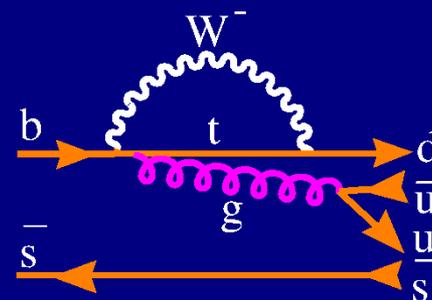
$$V_{ub} V_{ud}^* \sim A\lambda^3 (\rho - i\eta)$$



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



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

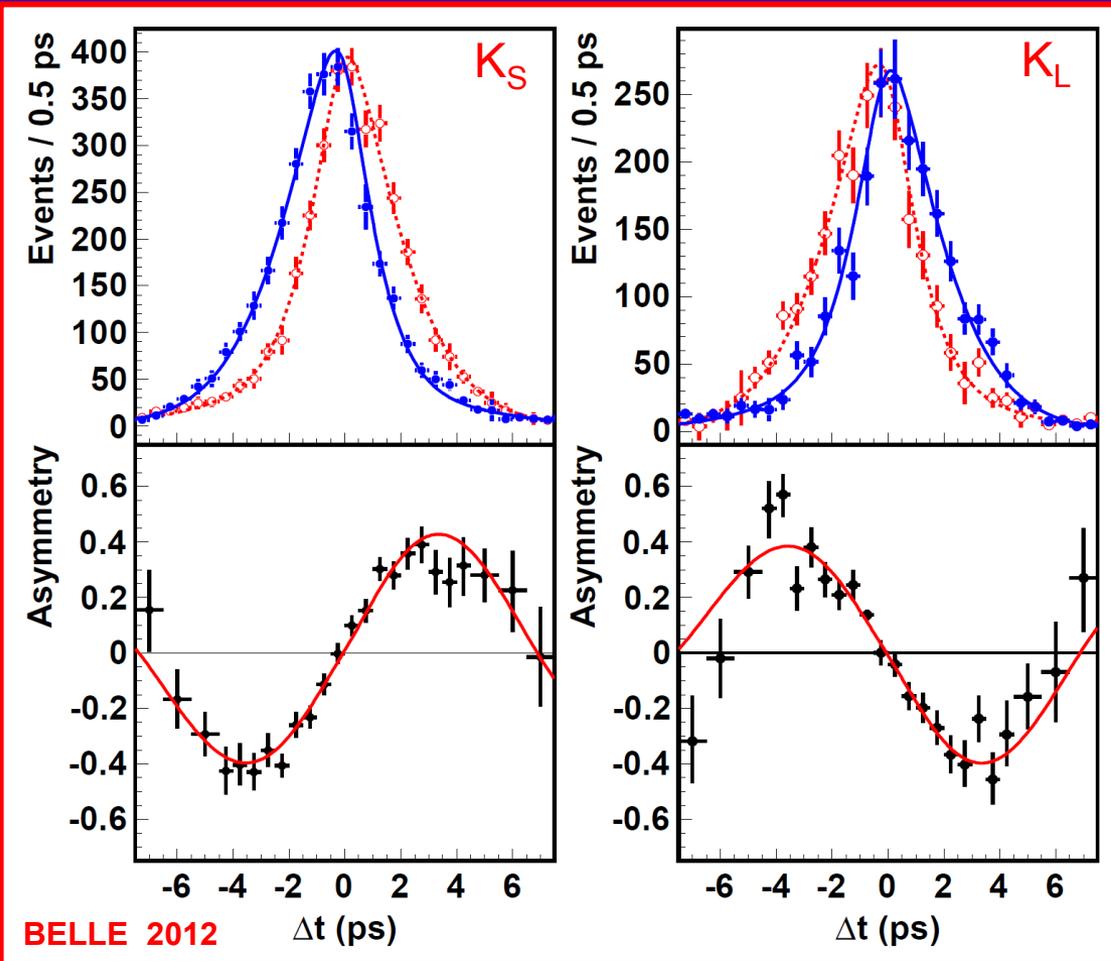


$$V_{tb} V_{td}^* \sim A\lambda^3 (1 - \rho + i\eta)$$

**

BAD

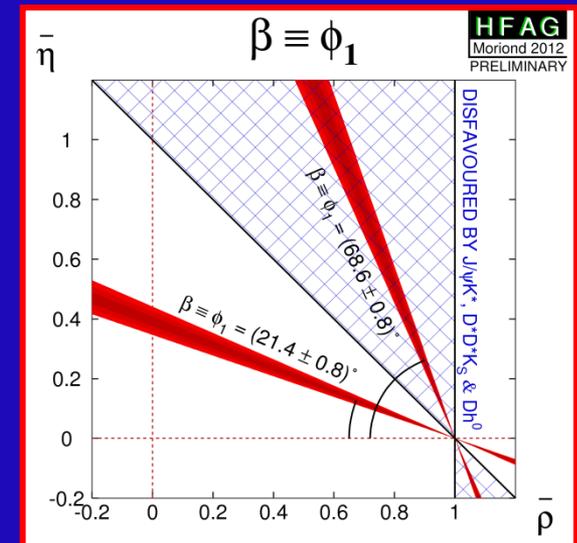
$$\frac{\Gamma(\bar{B}^0 \rightarrow J/\psi K_S) - \Gamma(B^0 \rightarrow J/\psi K_S)}{\Gamma(\bar{B}^0 \rightarrow J/\psi K_S) + \Gamma(B^0 \rightarrow J/\psi K_S)} = -\eta_f \sin(2\beta) \sin(\Delta M t)$$



HFAG:

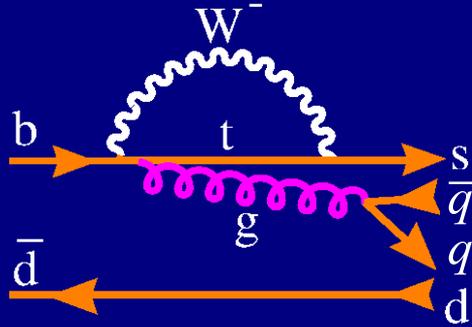
$$\sin(2\beta) = 0.682 \pm 0.019$$

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



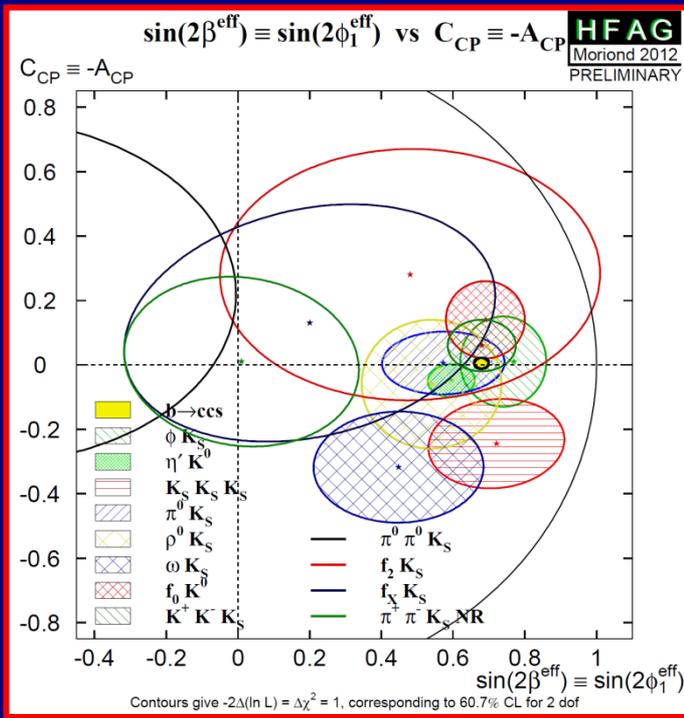
CP Signal

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



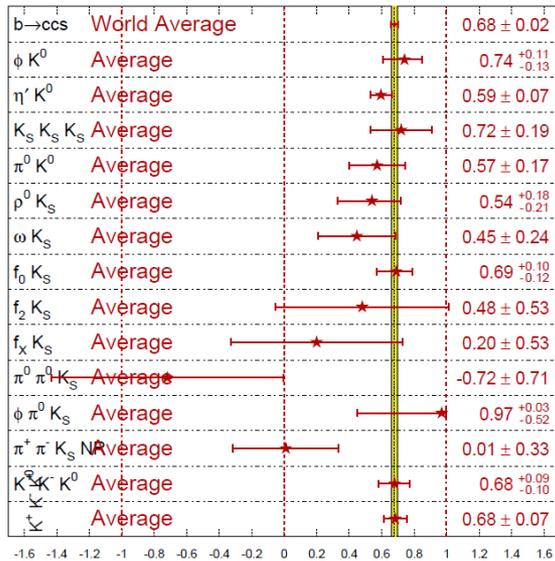
$$V_{tb} V_{ts}^* \sim -A\lambda^2$$

Sensitive to New Physics in Penguin diagram

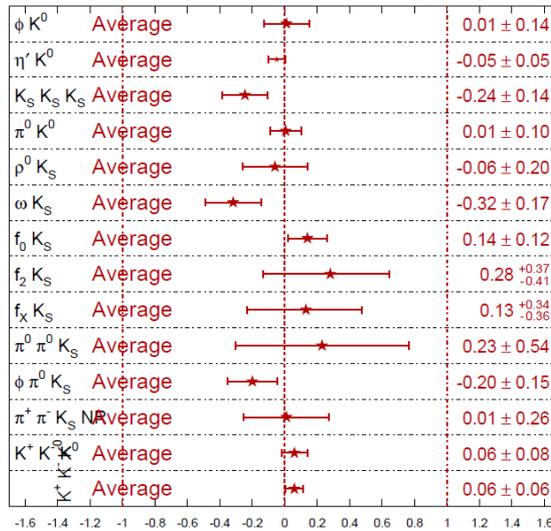


HFAG
Moriond 2012
PRELIMINARY

$$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$$



$$C_f = -A_f$$

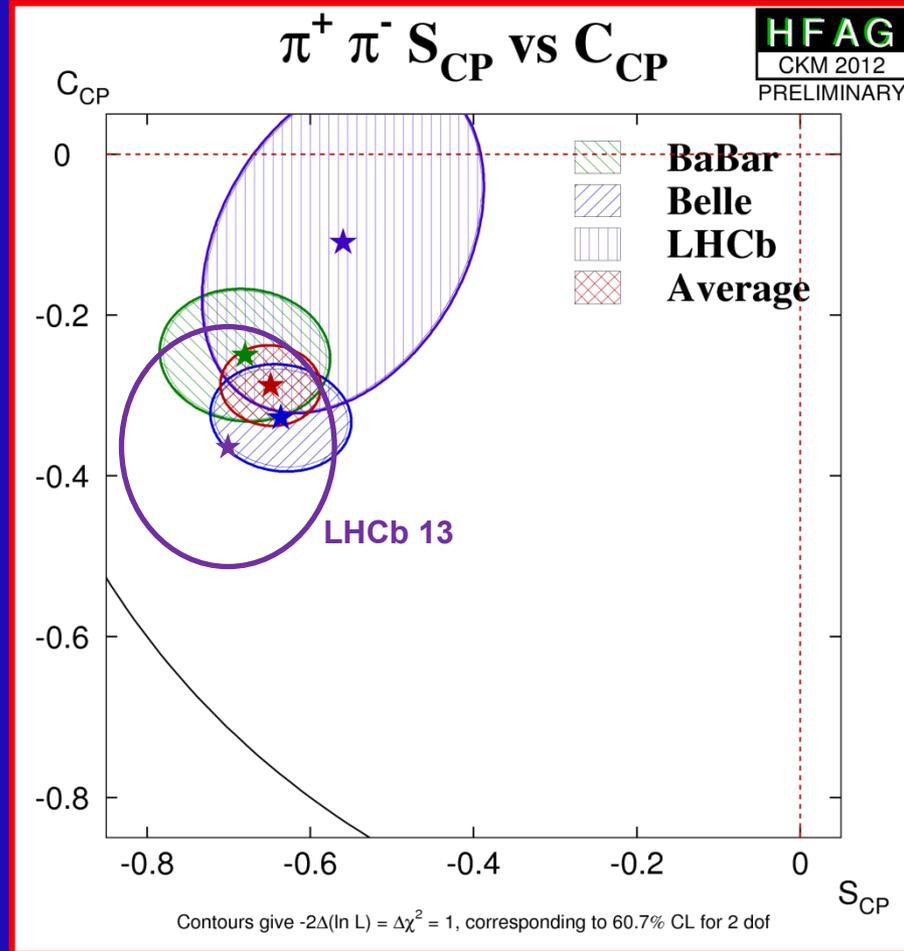
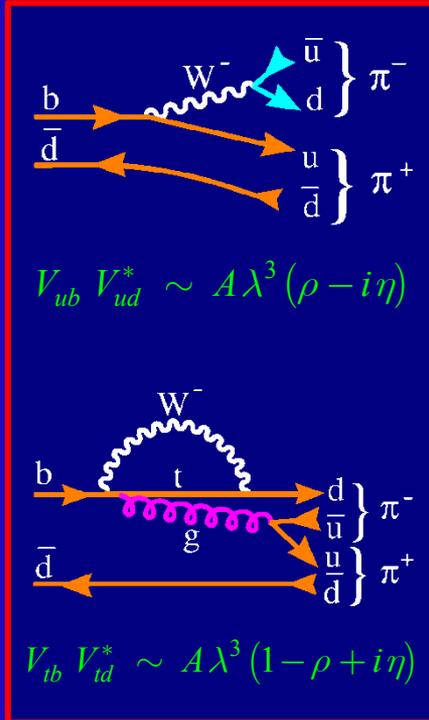


Agreement with $B^0 \rightarrow J/\Psi K_S$ ($b \rightarrow c\bar{c}s$)

No signal of direct CP

$B^0 \rightarrow \pi\pi$

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



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



Direct CP

Penguins



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

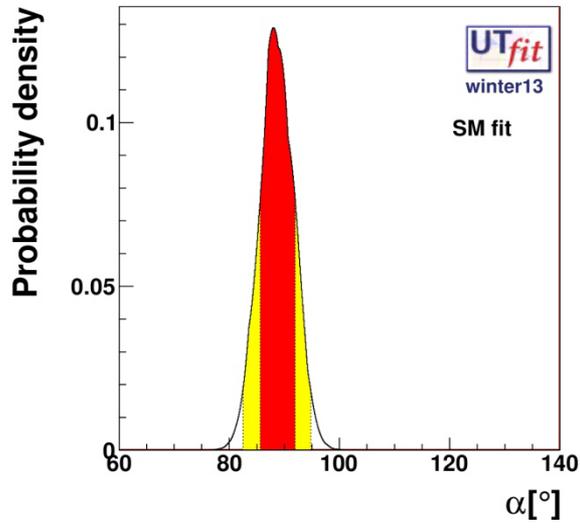
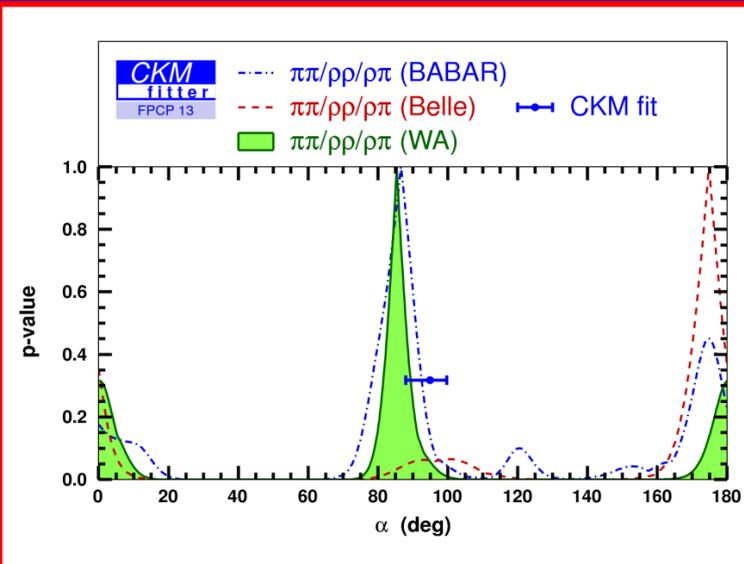
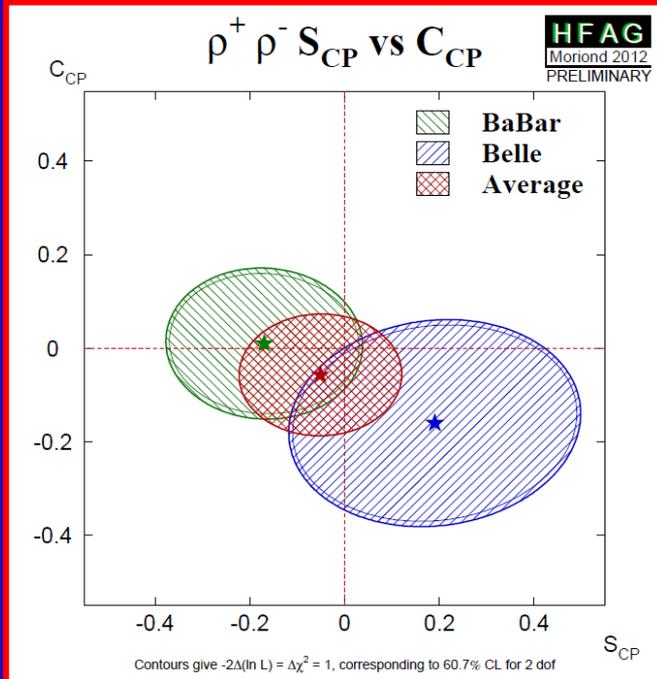
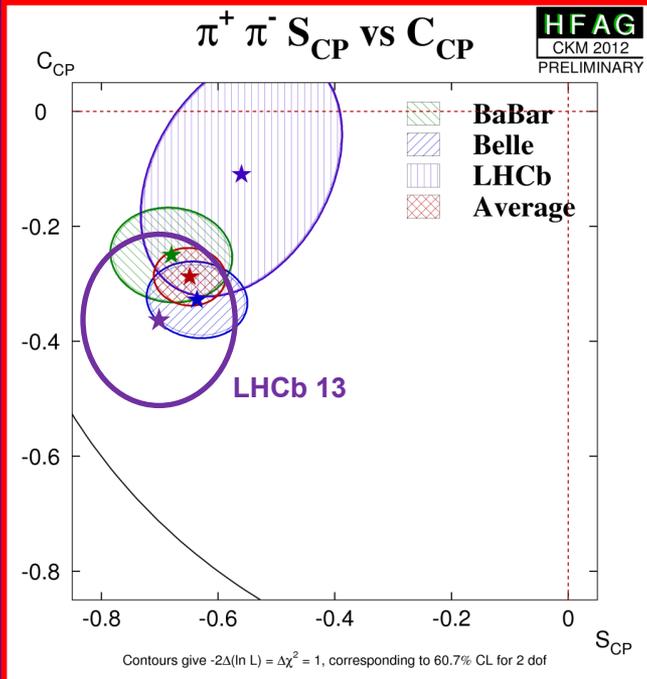
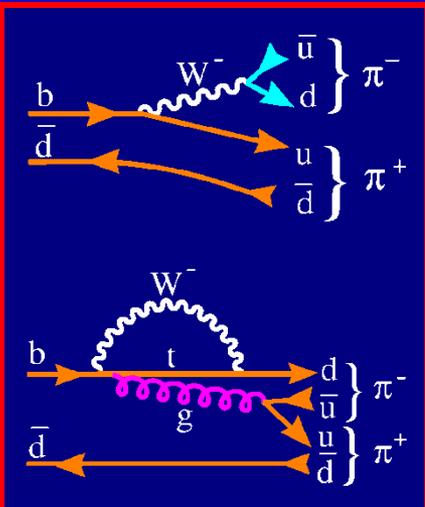
$B^0 \rightarrow \pi\pi, \rho\rho, \rho\pi$

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



Direct CP

Penguins



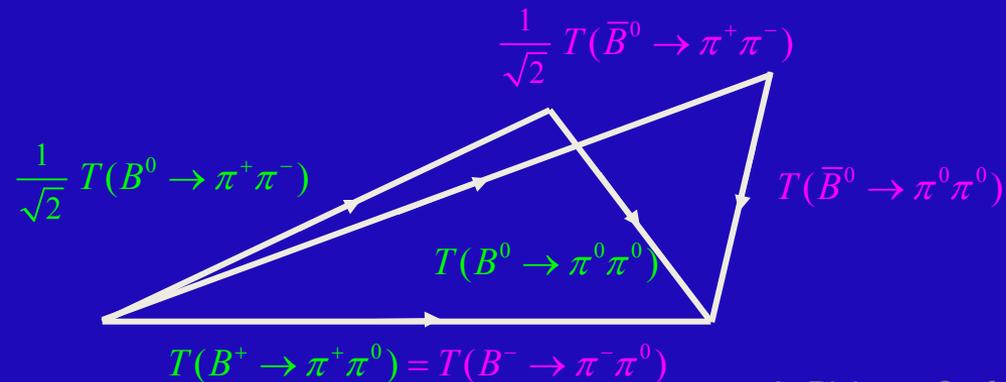
MEASURING HADRONIC CONTAMINATIONS

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

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

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

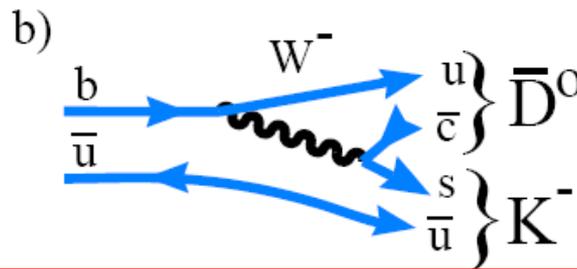
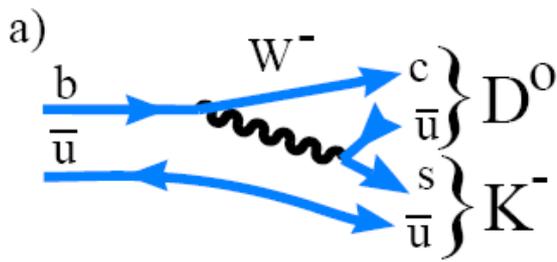
- Dalitz Analysis
- SU(3) Relations: $B \rightarrow \pi K, \pi \pi, \dots$
- ...



D⁰-D̄⁰ Mixing

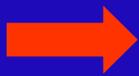
Gronau-London-Wyler

Atwood-Dunietz-Soni

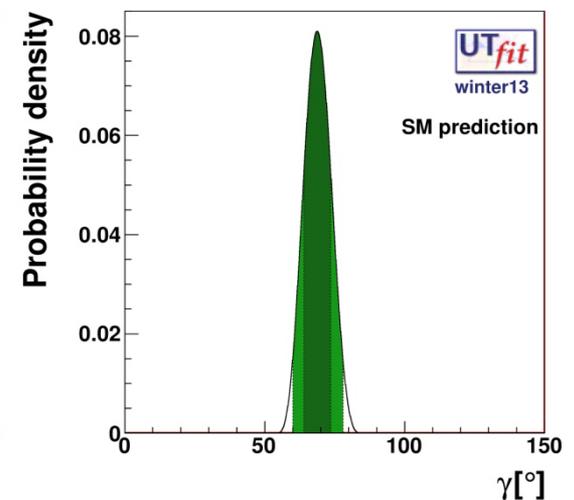
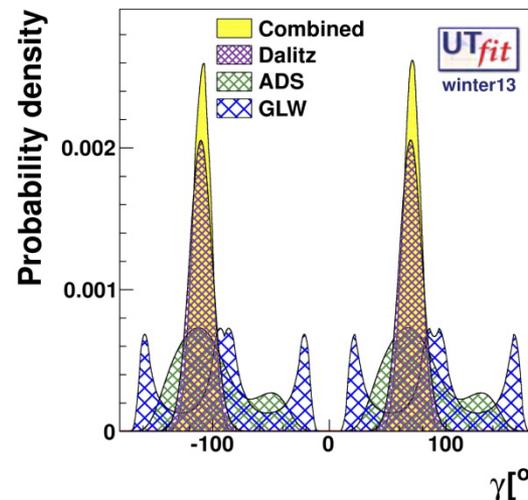
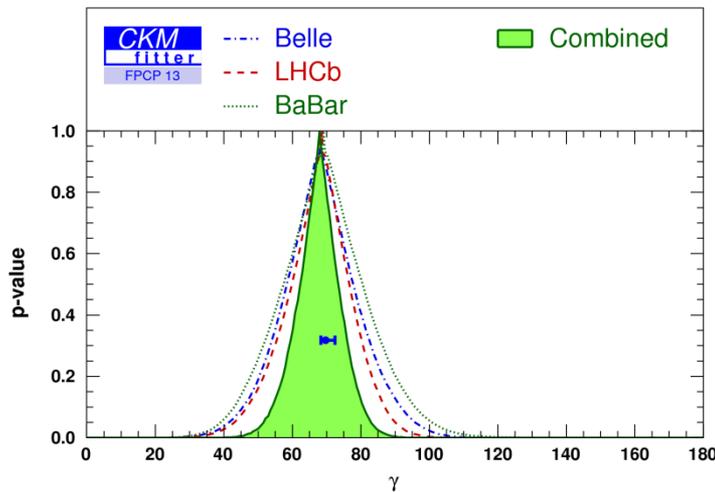


$$\sqrt{2} T(B^+ \rightarrow D_+^0 K^+) = T(B^+ \rightarrow D^0 K^+) + T(B^+ \rightarrow \bar{D}^0 K^+)$$

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

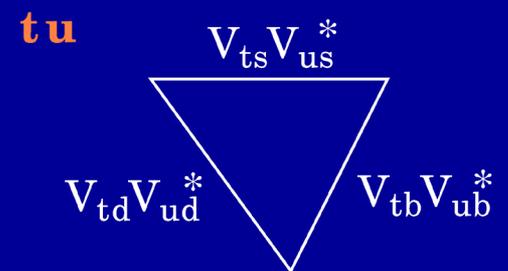
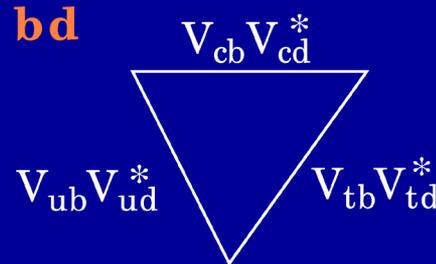
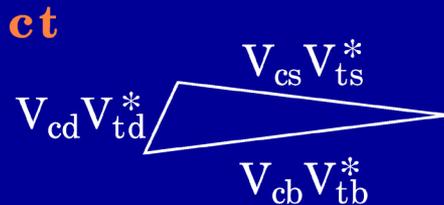
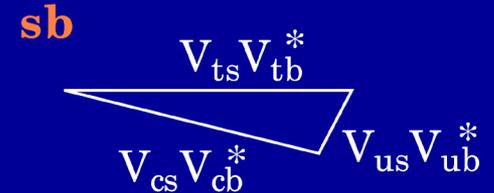
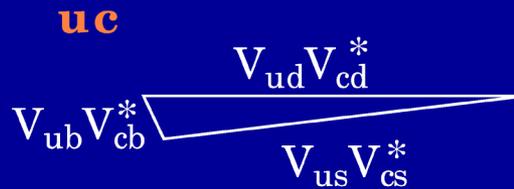
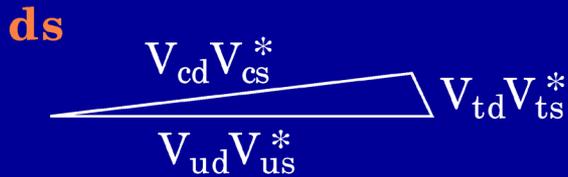


$$\gamma \equiv \arg \left[-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right] = (68.0^{+8.0}_{-8.5})^\circ$$



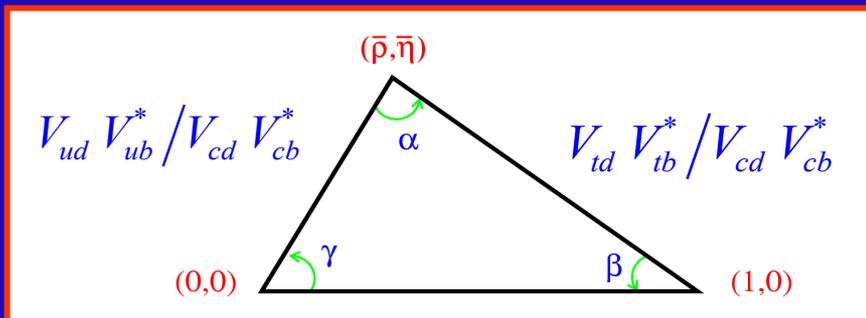
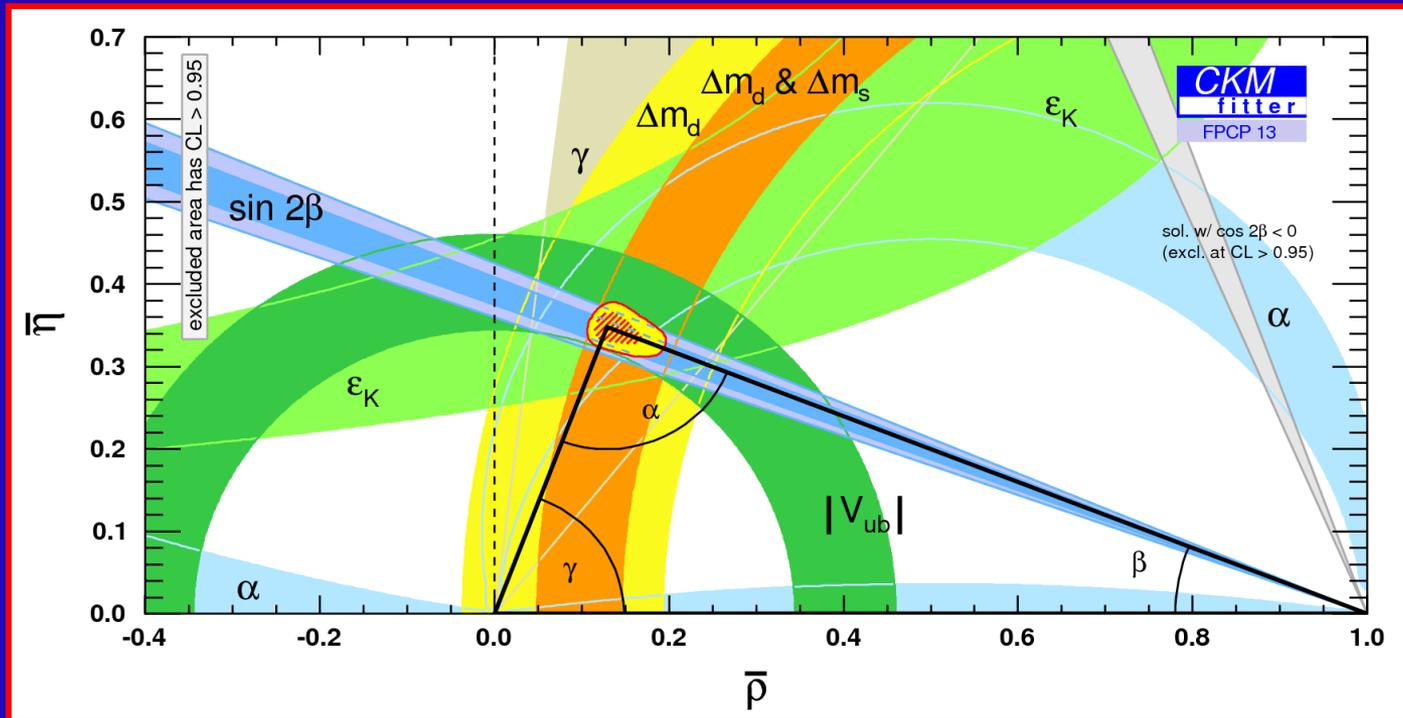
UNITARITY TRIANGLES

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



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

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



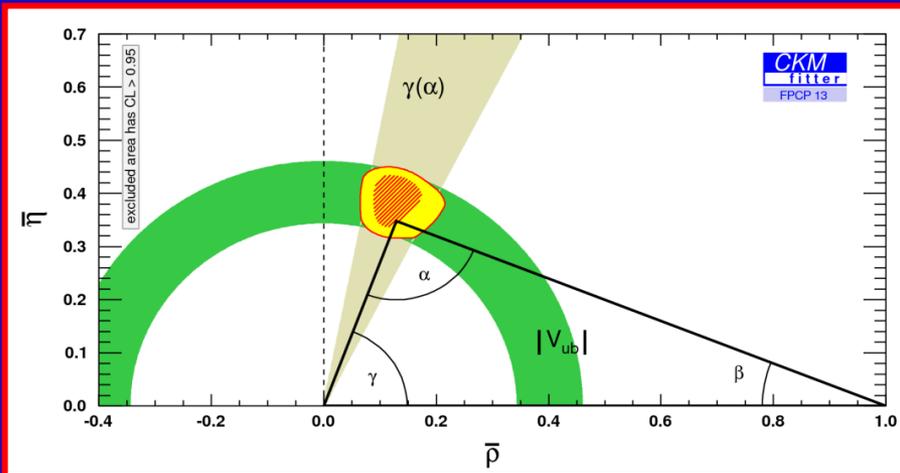
UT_{fit}

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

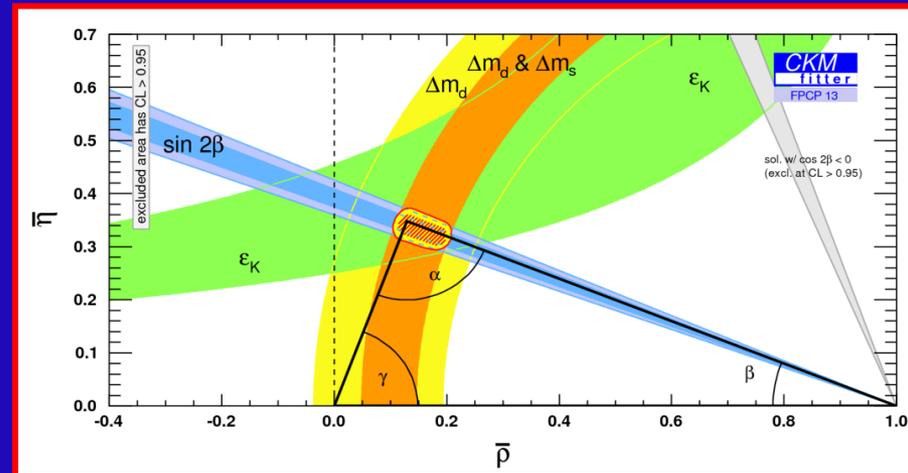
$$\bar{\rho} \equiv \rho \left(1 - \frac{1}{2} \lambda^2 \right) = 0.132 \pm 0.021$$

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

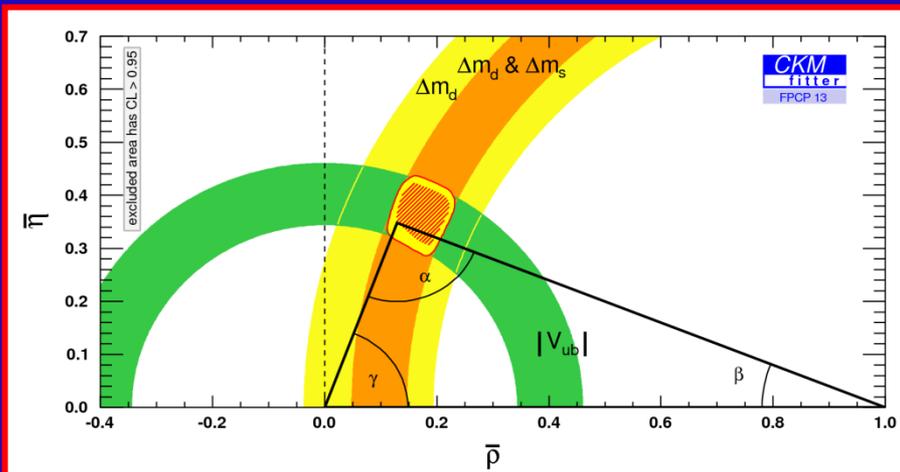
Tree-level determinations



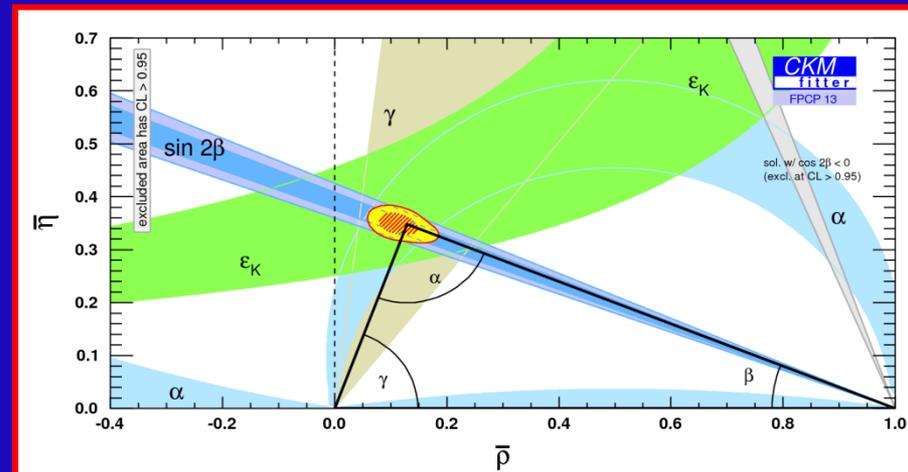
Loop processes

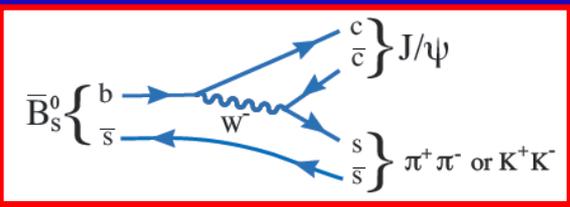


CP Conserving



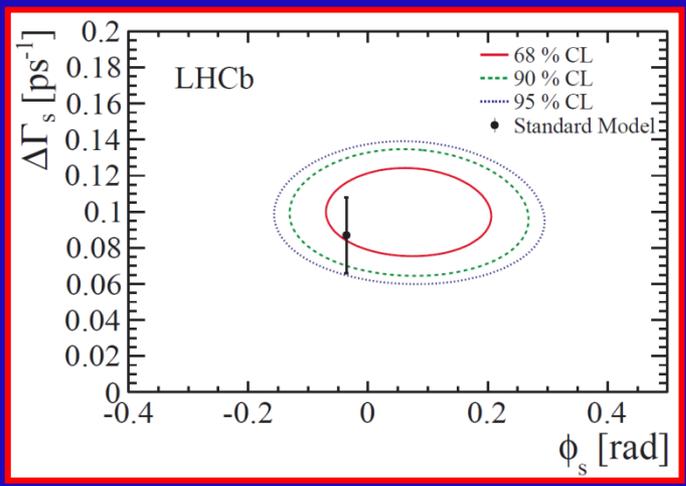
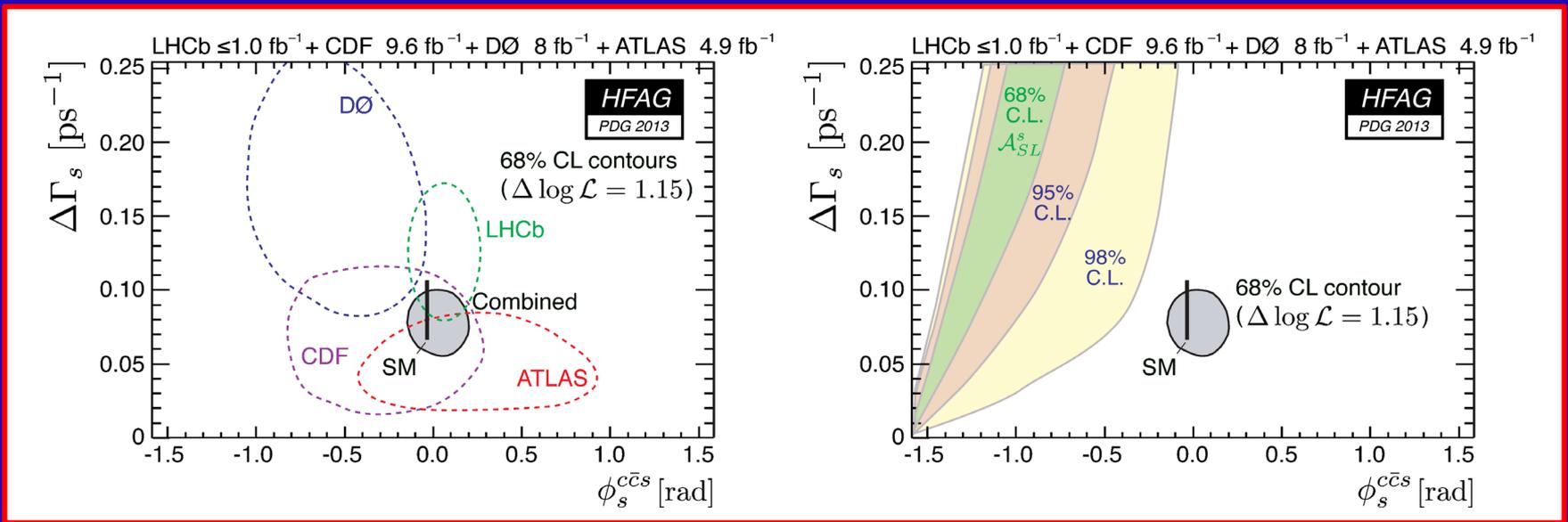
CP Violating





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

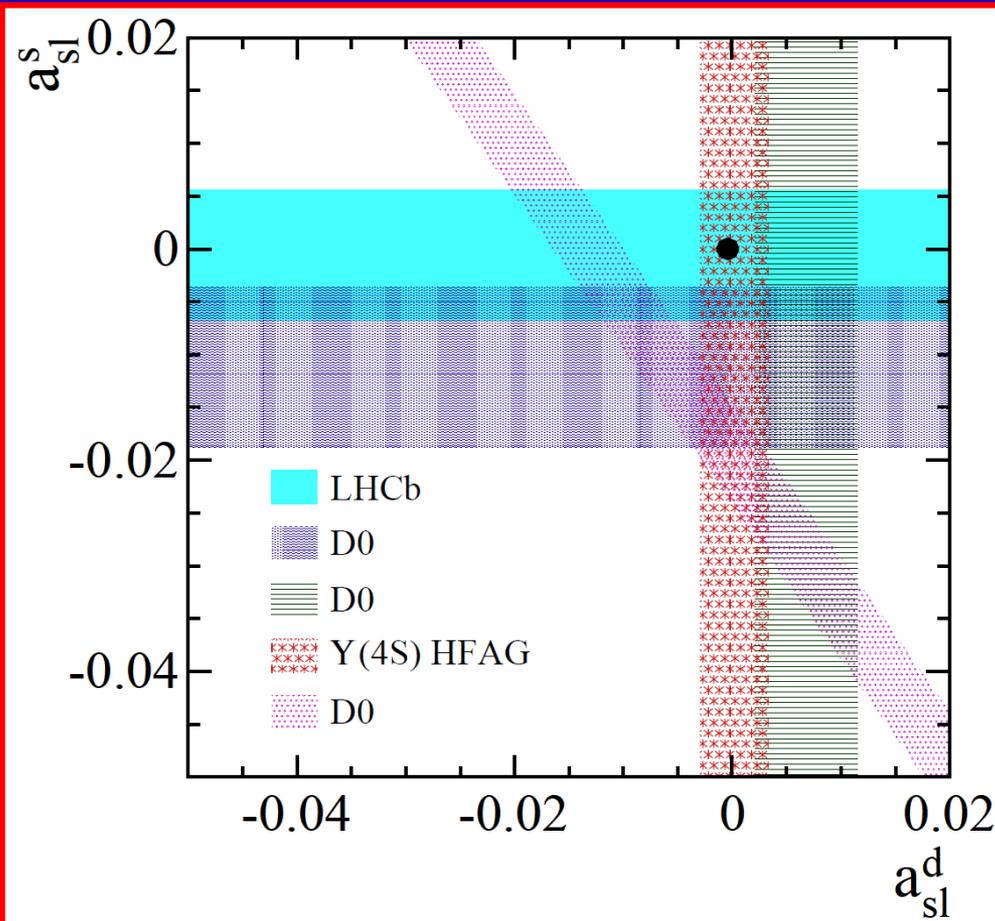
$$\phi_s^{c\bar{c}s} \Big|_{\text{SM}} = \begin{pmatrix} -0.0363^{+0.0016} \\ -0.0015 \end{pmatrix} \text{ rad} \quad (\text{CKMfitter})$$



PDG 2013: $\phi_s^{c\bar{c}s} = \begin{pmatrix} 0.04^{+0.10} \\ -0.13 \end{pmatrix} \text{ rad}$

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

B_s Semileptonic Asymmetry



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

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

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

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

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

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

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

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

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

DIRECT CP in B_s Decays

6.5 σ signal

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

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

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

DIRECT

~~CP~~

$$A_{\bar{B}_d^0 \rightarrow K^- \pi^+}^{CP} = -0.087 \pm 0.008$$

,

$$A_{\bar{B}_d^0 \rightarrow \bar{K}^{*0} \eta}^{CP} = 0.19 \pm 0.05$$

$$A_{\bar{B}_d^0 \rightarrow K^{*-} \pi^+}^{CP} = -0.22 \pm 0.06$$

,

$$C_{B_d^0 \rightarrow \pi^- \pi^+} = -0.38 \pm 0.15$$

$$A_{B^- \rightarrow K^- \rho^0}^{CP} = 0.37 \pm 0.10$$

,

$$A_{B^- \rightarrow K^- \eta}^{CP} = -0.37 \pm 0.08$$

$$A_{B^- \rightarrow \pi^- \eta}^{CP} = -0.14 \pm 0.07$$

,

$$A_{B^- \rightarrow K^- D_{CP(+1)}}^{CP} = 0.170 \pm 0.0033$$

$$A_{B^- \rightarrow K^- f_2(1270)}^{CP} = -0.68^{+0.19}_{-0.17}$$

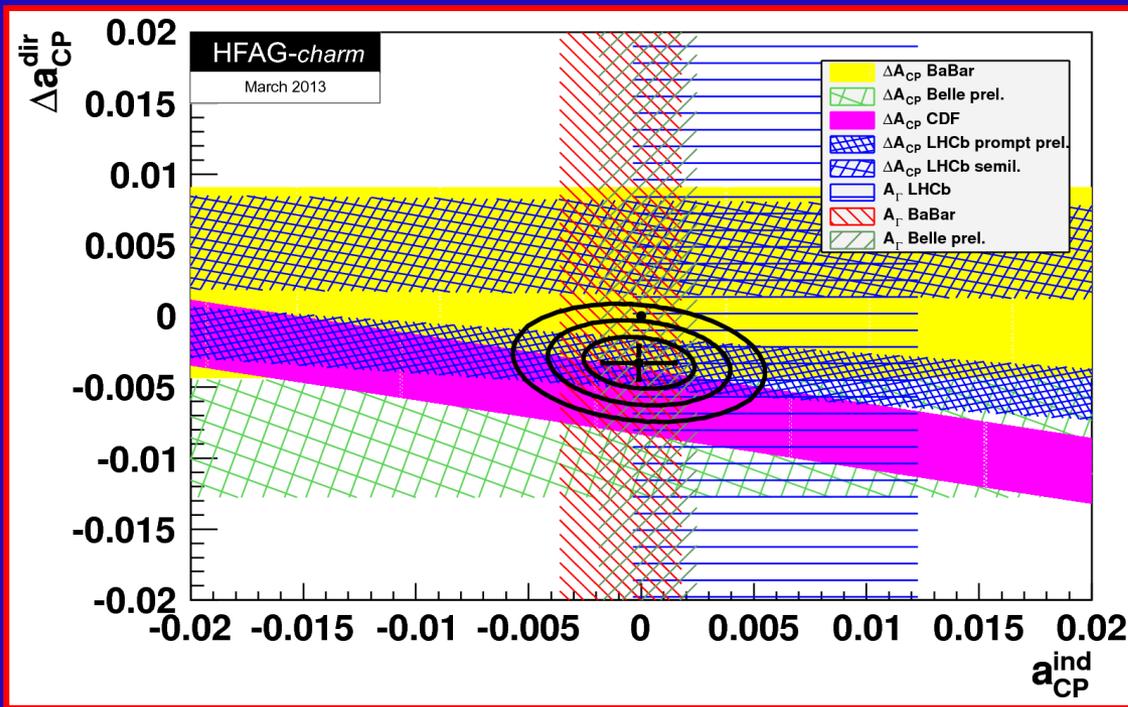
,

$$A_{B^- \rightarrow \pi^- f_0(1370)}^{CP} = 0.72 \pm 0.22$$

$$A_{D^0 \rightarrow K^+ K^-}^{CP} - A_{D^0 \rightarrow \pi^+ \pi^-}^{CP} = -0.0068 \pm 0.0016$$

DIRECT CP in D decays

$$A_{D^0 \rightarrow K^+ K^-}^{CP} - A_{D^0 \rightarrow \pi^+ \pi^-}^{CP} = -0.0068 \pm 0.0016$$



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

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

$$\Delta A^{CP} \equiv A_{D^0 \rightarrow K^+ K^-}^{CP} - A_{D^0 \rightarrow \pi^+ \pi^-}^{CP} = \Delta a_{CP}^{\text{dir}} \left(1 + y_{CP} \frac{\langle t \rangle}{\tau} \right) + a_{CP}^{\text{ind}} \frac{\Delta \langle t \rangle}{\tau}$$

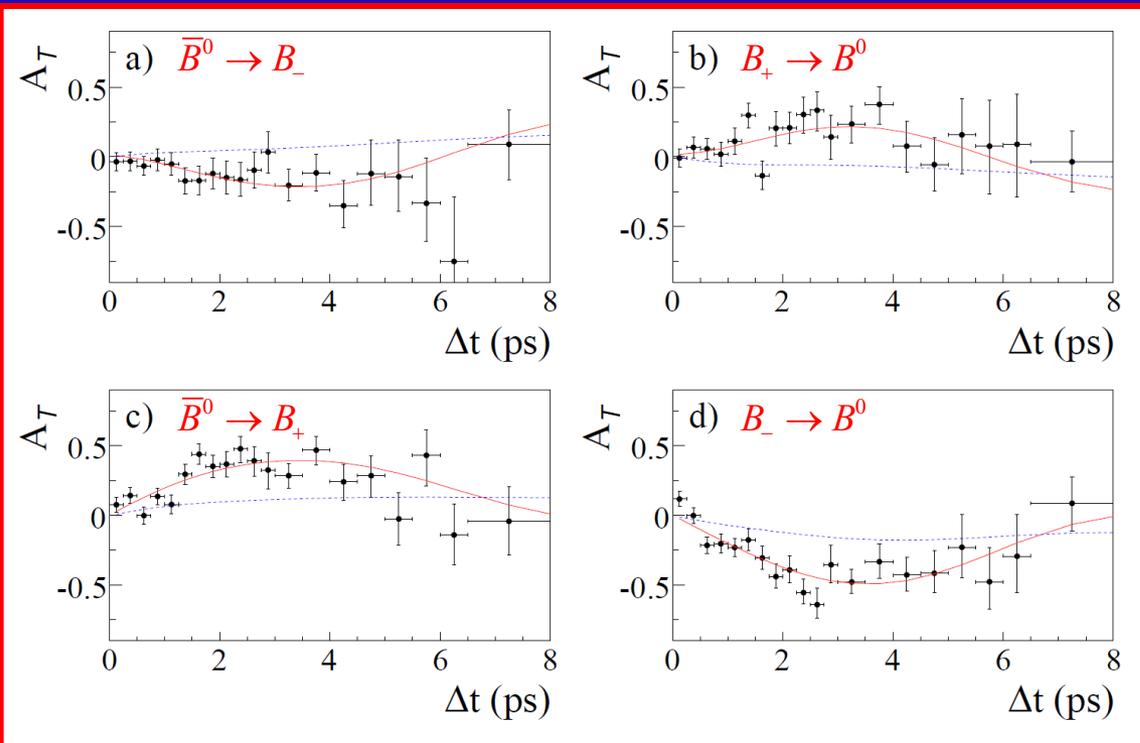
T Violation @ Babar

Quantum Entanglement

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

(Bañuls-Bernabeu-Martínez-Villanueva)

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

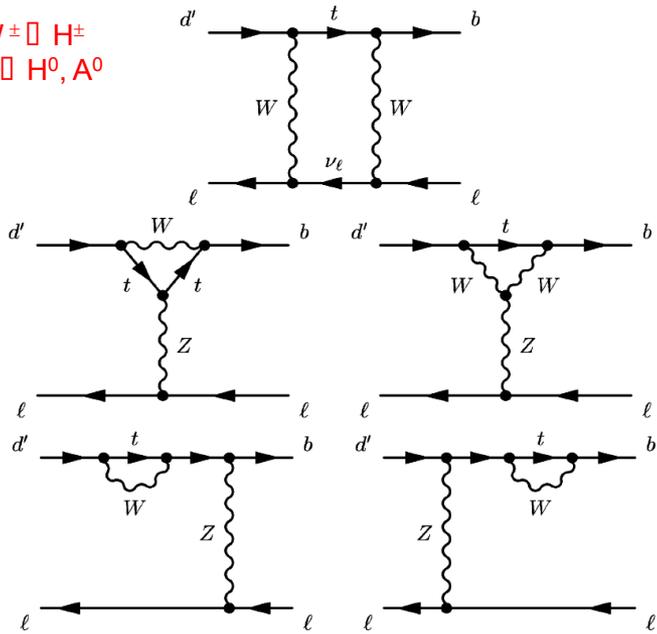


$$S_{B_- \rightarrow \bar{B}^0} - S_{\bar{B}^0 \rightarrow B_-} = -1.37 \pm 0.14 \pm 0.06$$

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

$\not\tau$ established at 14σ

$W^\pm \rightarrow H^\pm$
 $Z \rightarrow H^0, A^0$



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

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

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

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

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

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

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

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

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

Sensitive to (pseudo) scalar contributions

$$\begin{aligned} \text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} &= \frac{\tau_{B_s}}{2} \langle \Gamma(B_s(t) \rightarrow \mu^+ \mu^-) \rangle \Big|_{t=0} \\ &= \frac{\tau_{B_s} G_F^4 M_W^4 \sin^4 \theta_W}{8\pi^5} |C_{10}^{\text{SM}} V_{ts} V_{tb}^*|^2 F_{B_s}^2 m_{B_s} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} \end{aligned}$$

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

Experimental Branching Ratio:

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

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

(Fleischer et al)

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



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

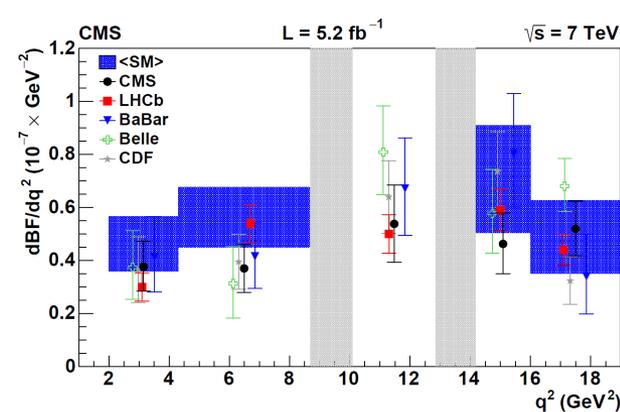
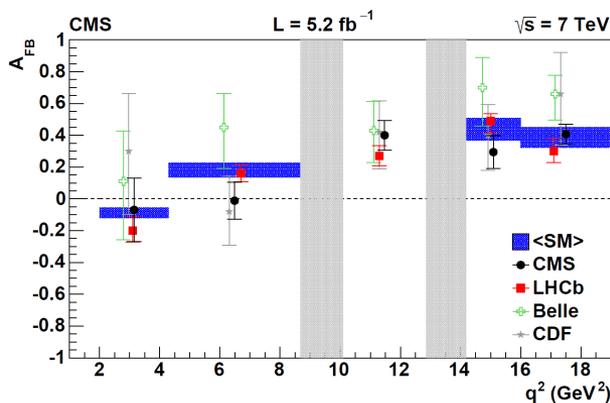
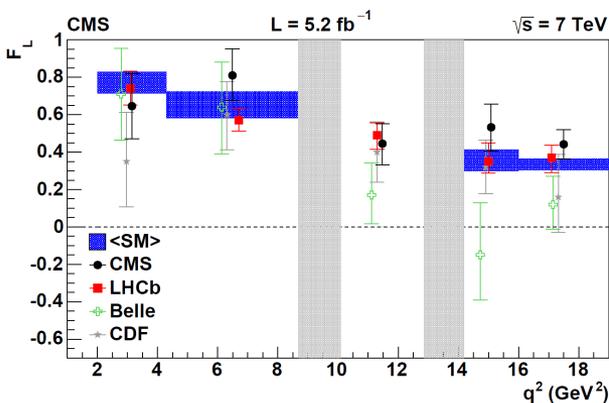
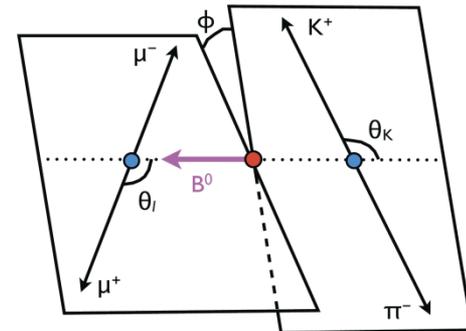
$$\text{LHCb: } \overline{\text{Br}}(B_s^0 \rightarrow \mu^+\mu^-) = \left(2.9^{+1.1}_{-1.0} \right) \cdot 10^{-9} \quad ; \quad \text{Br}(B_d^0 \rightarrow \mu^+\mu^-) < 7.4 \cdot 10^{-10} \quad (95\% \text{ CL})$$

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

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

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

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



Good agreement with SM

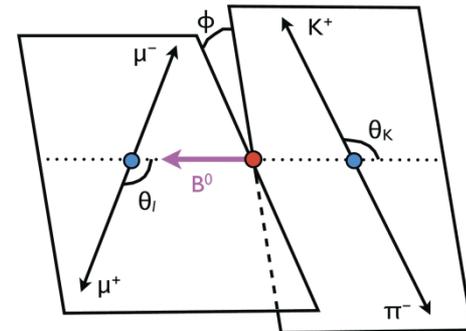
(Bobeth et al)

Large hadronic uncertainties

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

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

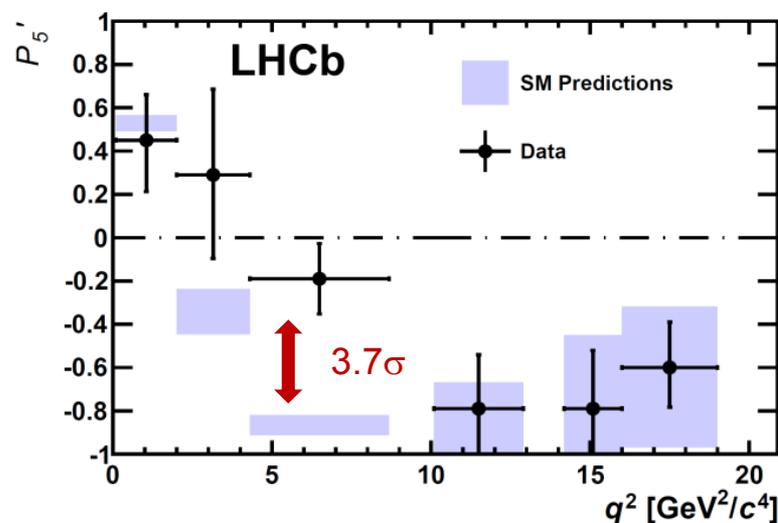
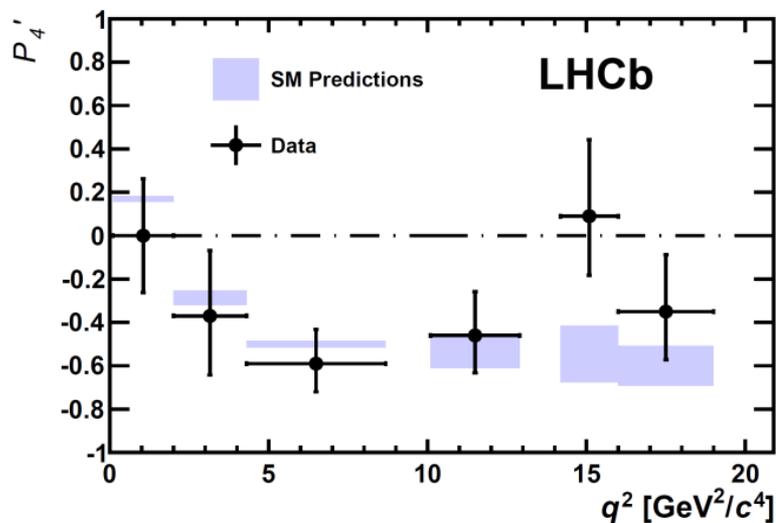
$$q^2 = s_{\mu^+ \mu^-}$$



Improved observables (Descotes-Genon et al)

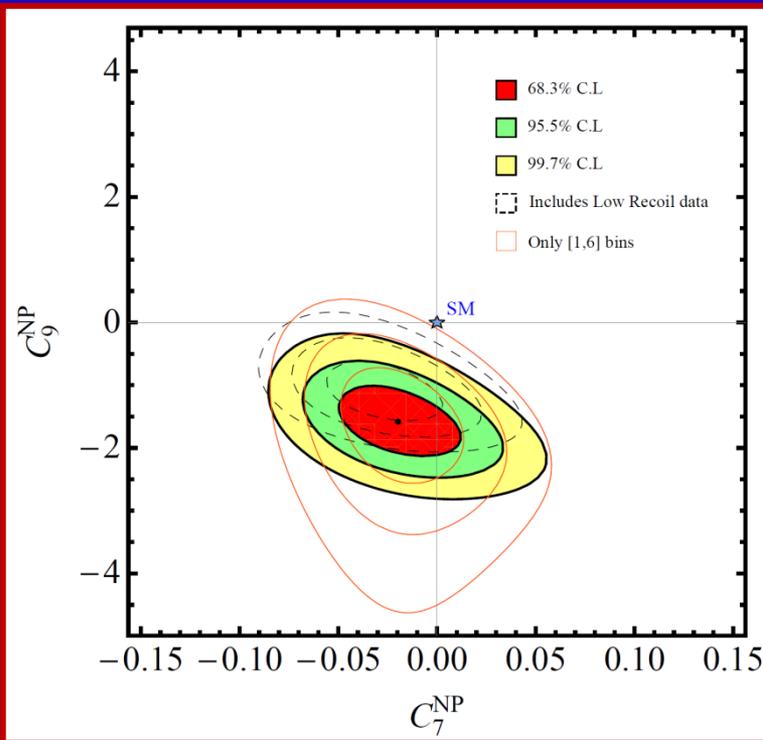
Largely free from FF uncertainties

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



23 of 24
measur.
agree with
the SM

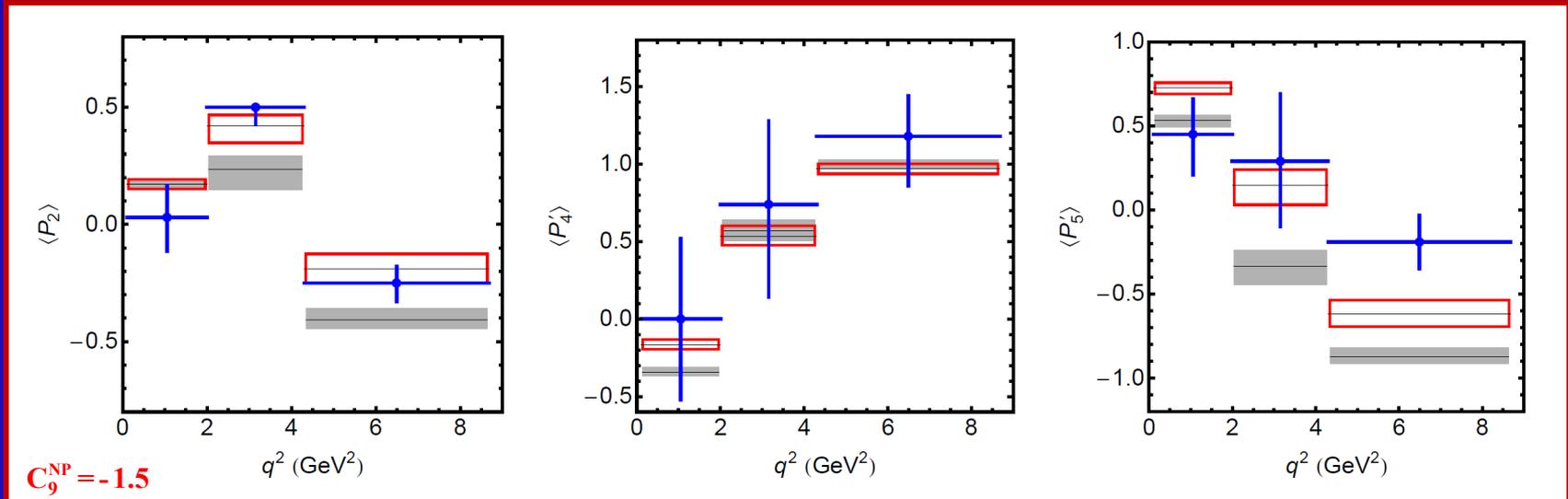
Observed pattern consistent with New Physics contributions to $C_{7,9}$



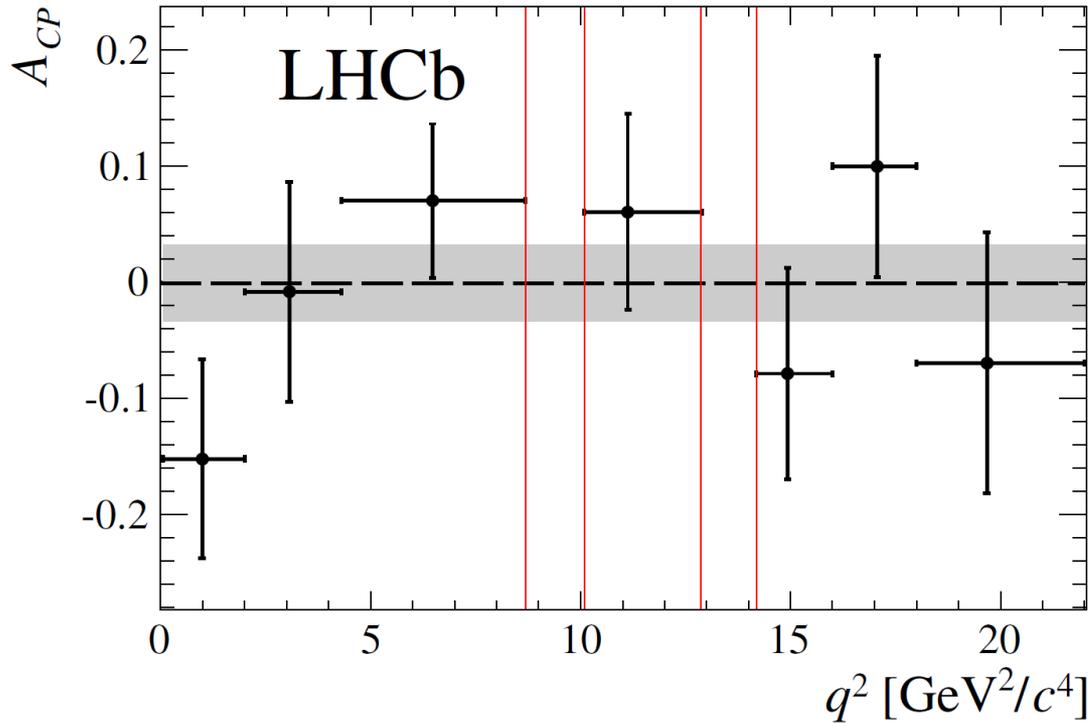
$$\mathcal{O}_7 = e/(16\pi^2) m_b (\bar{s}\sigma_{\mu\nu}P_R b) F^{\mu\nu}$$

$$\mathcal{O}_9 = e^2/(16\pi^2) (\bar{s}\gamma_\mu P_L b) (\bar{\ell}\gamma^\mu \ell)$$

Z' boson ?



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



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

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

$$-0.03 \pm 0.14$$

Babar

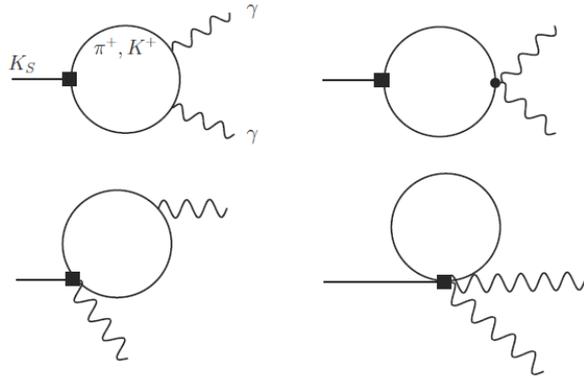
$$-0.04 \pm 0.10$$

Belle

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

Rare K Decays

$$K^0 \rightarrow \gamma\gamma$$



Finite loop:

$$\text{Br}_{\text{LO}} = 2.0 \cdot 10^{-6}$$

(D'Ambrosio-Espriu, Goity)

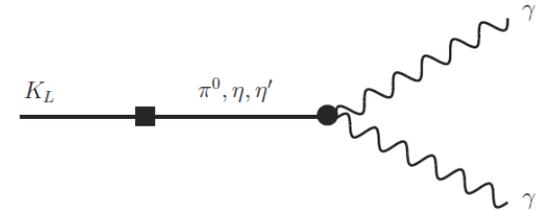
$$\text{Br}(K_S \rightarrow \gamma\gamma) = (2.63 \pm 0.17) \cdot 10^{-6}$$

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

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

(Kambor-Holstein, Buchalla et al)

Long-distance dynamics



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

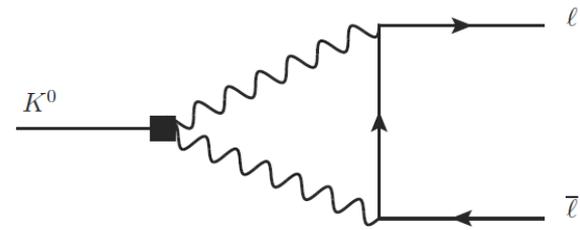
WZW Anomaly

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

$O(p^6)$: SU(3) breaking, η - η' mixing

Well understood

$$K^0 \rightarrow l^+ l^-$$



$$K_S \rightarrow l^+ l^-$$

Long-distance dynamics

Finite 2-loop amplitude: (Ecker-Pich)

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

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

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

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

(90% CL)

$$K_L \rightarrow l^+ l^-$$

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

$$\text{Br}(K_L \rightarrow e^+ e^-) = (9 \pm 6) \cdot 10^{-12}$$

Saturated by absorptive contrib.

Local counterterm \longleftrightarrow **SD**

LD extracted from $\pi^0, \eta \rightarrow l^+ l^-$

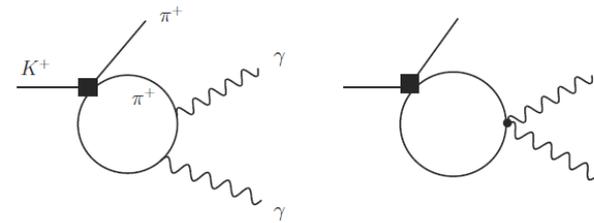
(Gomez-Dumm, Pich)

Fitted SD contrib. agrees with SM

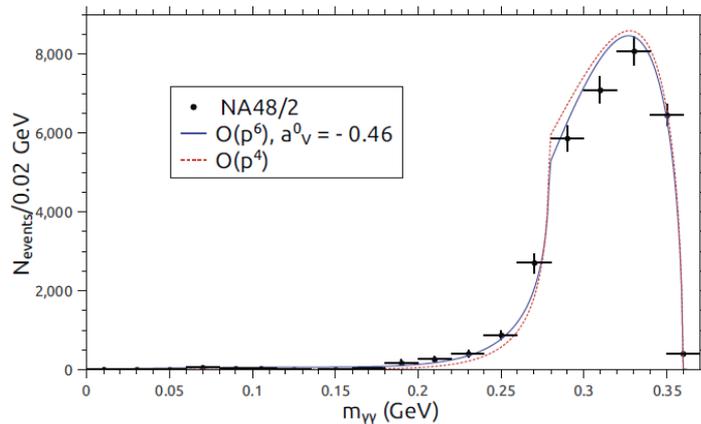
Longitudinal Polarization: (Ecker-Pich)

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

$$K \rightarrow \pi \gamma \gamma$$



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



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

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

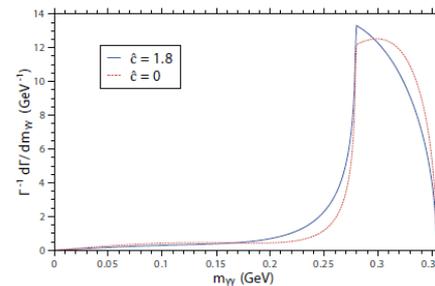
(Ecker-Pich-de Rafael, Capiello-D'Ambrosio, Sehgal)

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

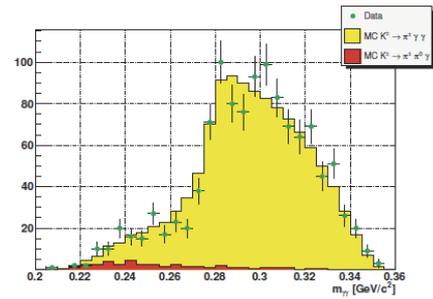
(Cohen et al, Capiello et al, D'Ambrosio-Portolés)

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

(BNL-E787)



NA48



Local $\mathcal{O}(p^4)$ LEC:

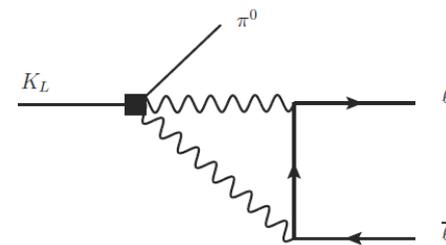
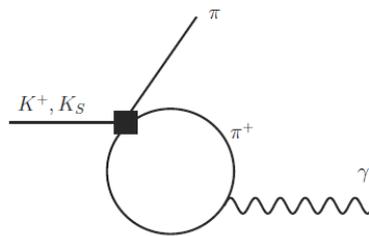
(Ecker-Pich-de Rafael)

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

Small higher-order corrections

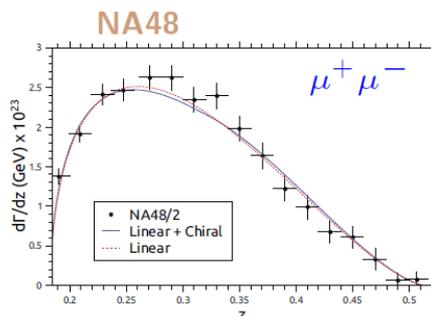
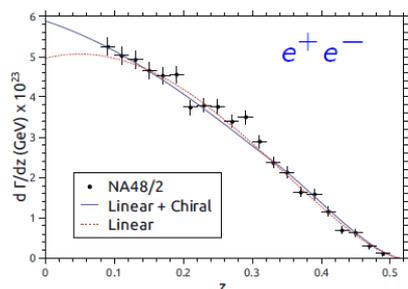
(D'Ambrosio-Portolés)

$$K \rightarrow \pi \ell^+ \ell^-$$



$$\text{Br}(K^\pm \rightarrow \pi^\pm e^+ e^-) = 3.14 (10) \cdot 10^{-7}$$

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



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

Electromagn. transition form factor
 $\mathcal{O}(p^6)$ corrections (D'Ambrosio et al)

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

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

(KTeV, 90% CL)

3 contributions: (Ecker-Pich-de Rafael)

- Direct C/P
- Indirect C/P
- CP conserving (2γ)

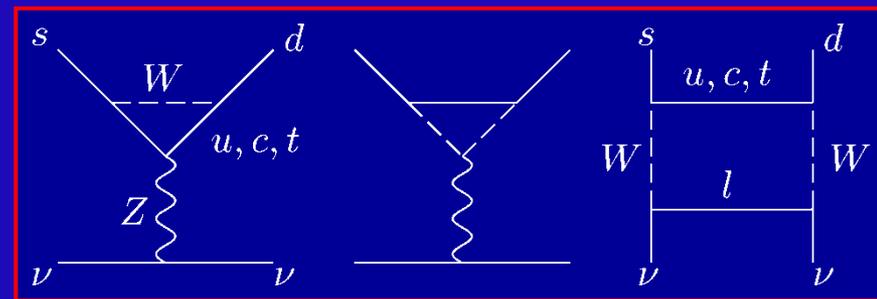
C/P dominates for $e^+ e^-$:

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

(Buchalla et al)

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

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



$$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.8 \pm 0.8) \times 10^{-11} \sim A^4 [\eta^2 + (1.4 - \rho)^2]$$

$$\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (2.4 \pm 0.4) \times 10^{-11} \sim A^4 \eta^2$$

Buras et al

Long-distance contributions are negligible

$$\mathbf{T}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \neq 0 \quad \longrightarrow \quad \cancel{CP}$$

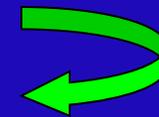
- **BNL-E949:** few events! \longrightarrow $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \cdot 10^{-10}$
- **KEK-E391a:** $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L.)

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

Standard Model Mechanism of \mathcal{CP}

Complex phases in Yukawa couplings only:

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

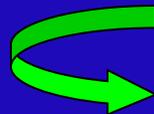


SSB

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

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

$c_{jk}^{(q)}$ diagonalization



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

$$L_{CC} = \frac{g}{2\sqrt{2}} W_\mu^\dagger \sum_{ij} \bar{u}_i \gamma^\mu (1 - \gamma_5) V_{ij} d_j + \text{h.c.}$$

The CKM matrix V_{ij} is the only source of \mathcal{CP}

SUMMARY

- **Flavour Structure** and CP are major pending questions
- Related to **SSB**  **Scalar Sector (Higgs)**
- Important cosmological implications (**Baryogenesis**)
- Sensitive to **New Physics**
- CP is highly constrained in the **SM**: **1 phase only**
- Many interesting CP signals within experimental reach
- Better control of **QCD** effects **urgently needed**
- Challenging future ahead:
BES-III, LHCb, NA62, J-Parc, Super-Belle, τ CF, ...

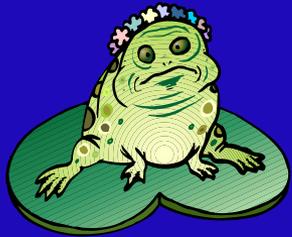
Quarks



up



down



charm



strange



top



beauty

Leptons



electron



neutrino e



muon



neutrino μ



tau



neutrino τ

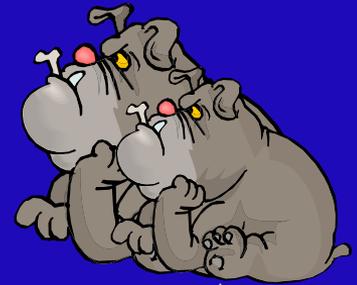
Bosons



photon



gluon

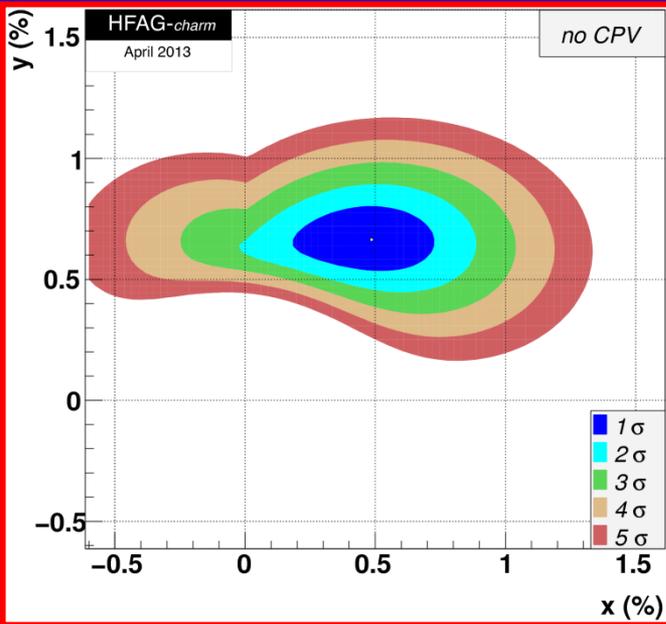


$Z^0 W^\pm$



Higgs

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

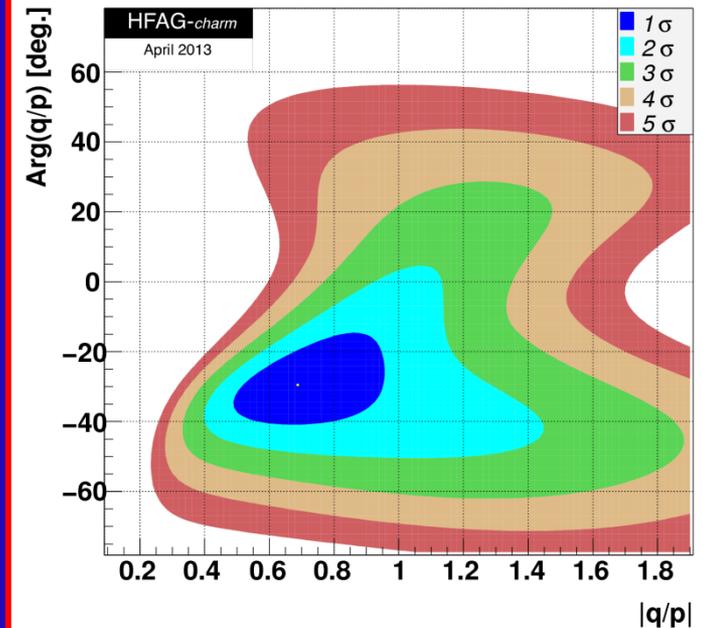
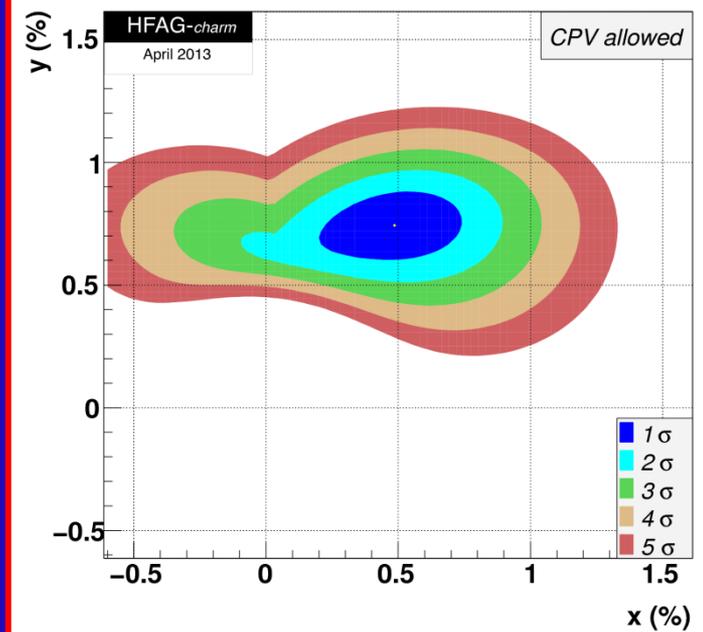


$$x = (0.49^{+0.17}_{-0.18})\%$$

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

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

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



Long-distances Dominate

- No-mixing excluded at $> 5\sigma$
- $\tau_{D_-} < \tau_{D_+}$, $M_{D_-} > M_{D_+}$
- No evidence of CP in mixing



Direct CP Asymmetry in τ Decay

$$A_\tau \equiv \frac{\Gamma(\tau^+ \rightarrow \pi^+ K_S \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow \pi^- K_S \nu_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K_S \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow \pi^- K_S \nu_\tau)} = (-3.6 \pm 2.3 \pm 1.1) \cdot 10^{-3} \quad \text{BaBar'11} \\ (\geq 0 \pi^0)$$

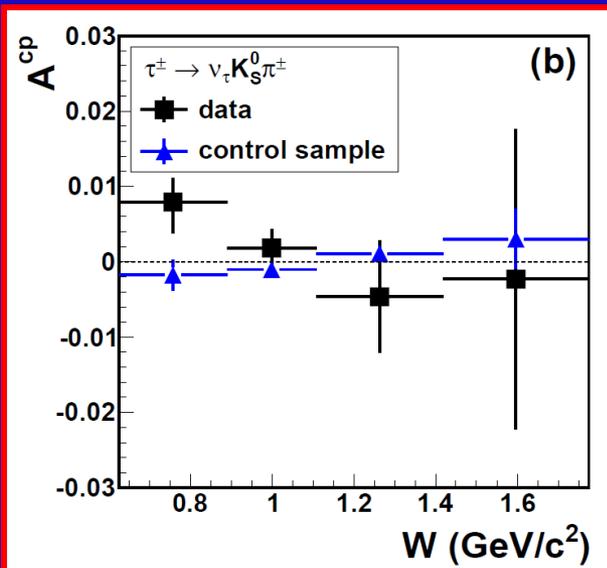
$$A_\tau^{\text{SM}}(\tau^+ \rightarrow \pi^+ K_S \bar{\nu}_\tau) = (3.6 \pm 0.1) \cdot 10^{-3}$$

2.8 σ discrepancy

Bigi-Sanda, Grossman-Nir



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



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

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

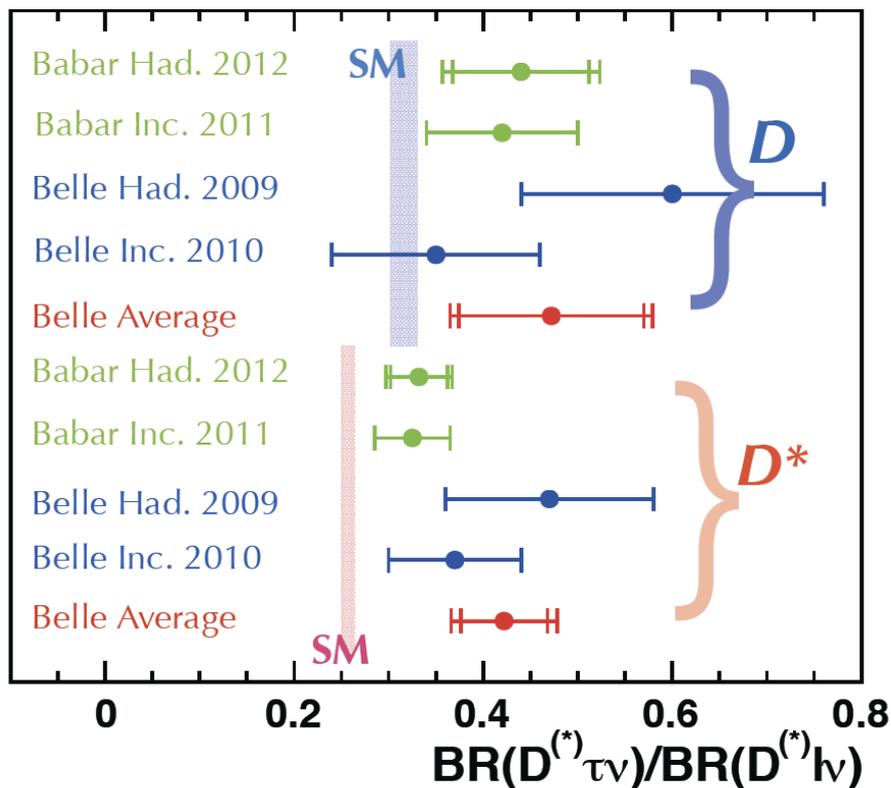
$\beta = K_S$ direction in hadronic rest frame

$\psi = \tau$ direction

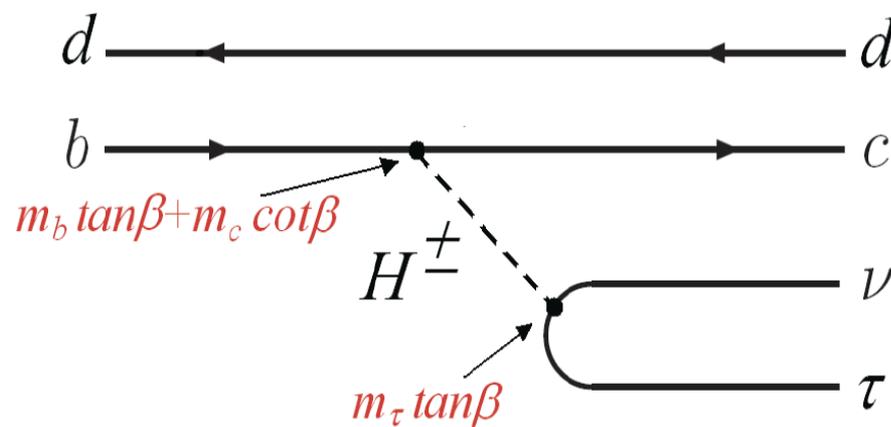
A word on tauonic modes: $B \rightarrow D^{(*)} \tau^+ \nu_l$

- Higher values than expected from the SM

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

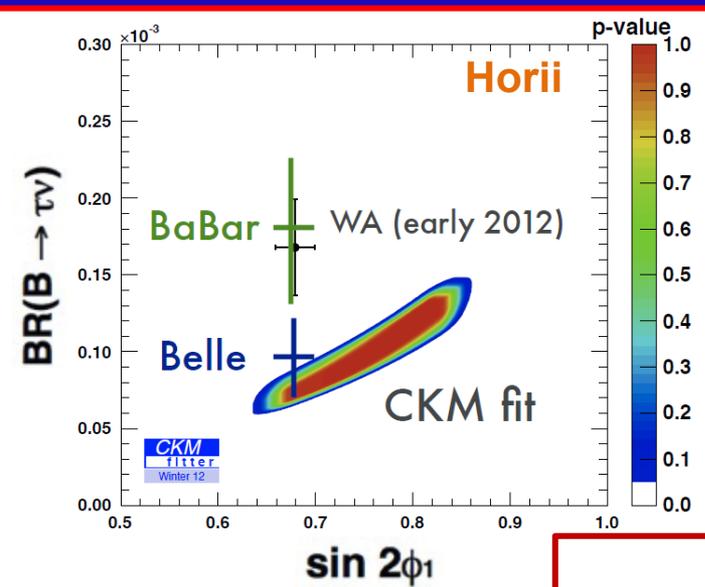


Isospin invariance assumed



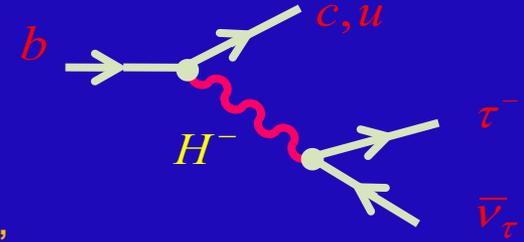
Belle hadronic tag update coming soon!

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



Sensitivity to scalar exchange

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



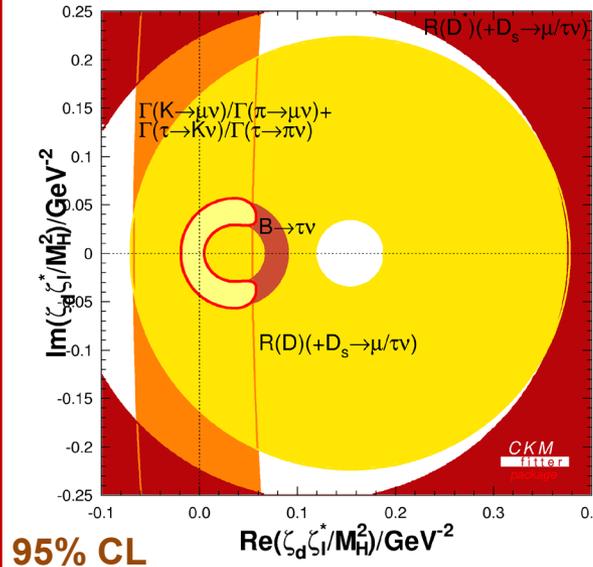
Type II 2HDM excluded

Celis-Jung-Li-Pich

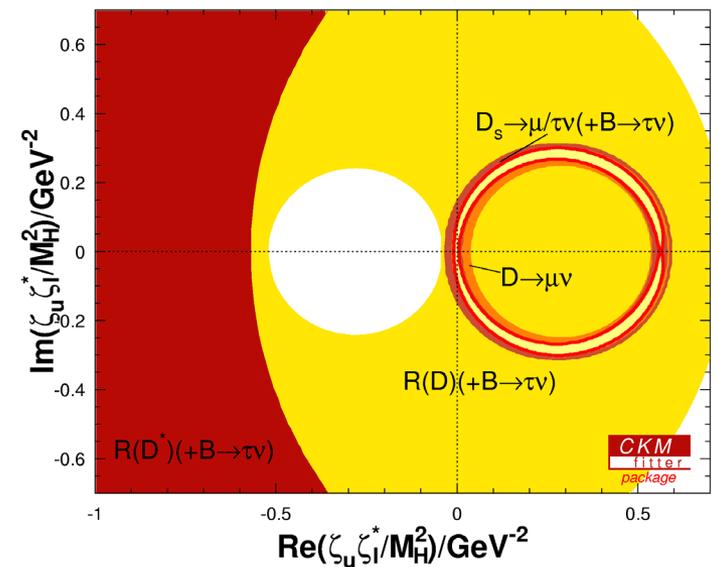
B data fitted within
Aligned 2-Higgs
Doublet Model

But tensions with charm

$$\mathcal{L}_Y^{H^\pm} = -\frac{\sqrt{2}}{v} H^\pm \{ \bar{u} [s_d V M_d \mathcal{P}_R - s_u M_u^\dagger V \mathcal{P}_L] d + s_l \bar{\nu} M_l \mathcal{P}_{R/L} \} + \text{h.c.}$$



95% CL



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

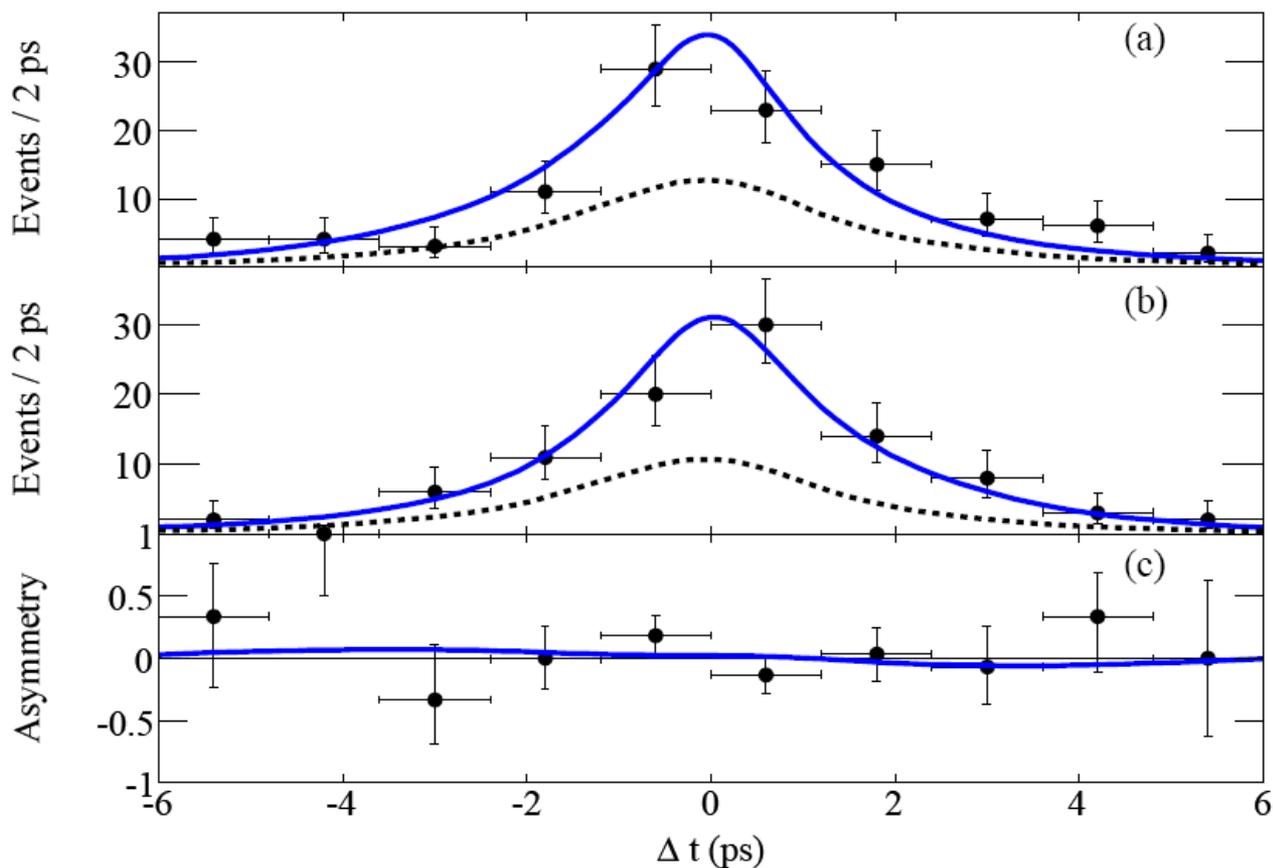
 B^0
 \bar{B}^0


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