Flavor Physics V

Chaehyun Yu

Aug 10 2017, IBS, Korea

Outline

- Flavor Physics and the Standard Model
- Discrete Symmetry and CKM matrix
- Renormalization and Muon g-2
- RG and Effective Field Theory
- CP Violation and BSM Flavor Physics
  - CP Violation
  - BSM Flavor Physics

Neutral meson mixing

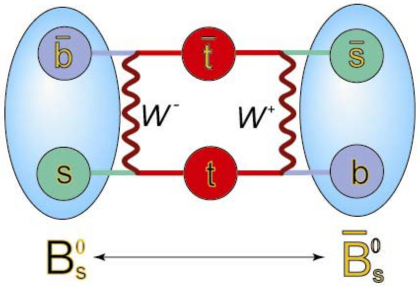
- Mixing can appear when the flavor eigenstates are different from the mass eigenstates

- Four neutral meson mixing: $K^0(\bar{s}d)\bar{K}^0(s\bar{d}), D^0(c\bar{u})\bar{D}^0(\bar{c}u), B^0(\bar{b}d)\bar{B}^0(b\bar{d}), B_s^0(\bar{b}s)\bar{B}_s^0(b\bar{s})$

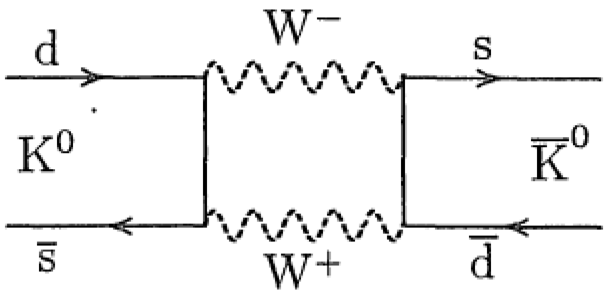
- The top quark decays before hadronization becasue its lifetime is smaller than the hadronization scale

- QED and QCD preserve the flavor symmetry but weak interactions can break flavor symmetry

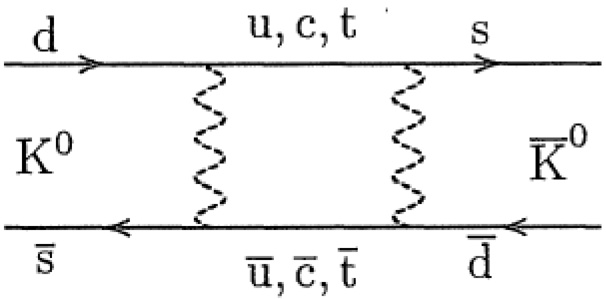
- In other words, without weak interactions there will be no neutral meson mixing in the SM



ΔF=2 effective operator



(a)



(b)

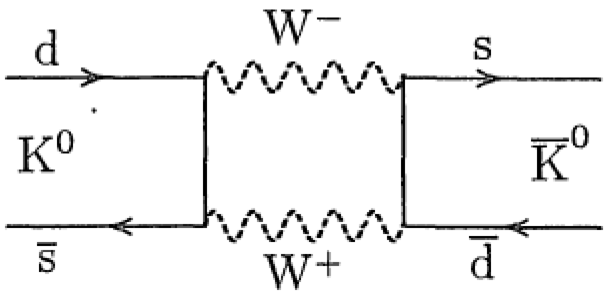
$\mathcal{M}_a = \mathcal{M}_b$

- all external momenta are taken to be zero compared to M_W

$$\mathcal{M}_a = \mathrm{i}\left[\frac{-\mathrm{i}g}{2\sqrt{2}}V_{\mathrm{ud}}^*\right]^2\left[\frac{-\mathrm{i}g}{2\sqrt{2}}V_{\mathrm{us}}\right]^2\int\frac{\mathrm{d}^4k}{(2\pi)^4}\bar{u}(\mathrm{s})\gamma_\lambda(1-\gamma_5)\frac{\mathrm{i}(\not{k}+m_i)}{k^2-m_i^2}\gamma_\rho(1-\gamma_5)v(\mathrm{d})$$
$$\times\,\bar{v}(\mathrm{s})\gamma_\alpha(1-\gamma_5)\frac{\mathrm{i}(\not{k}+m_j)}{k^2-m_j^2}\gamma_\sigma(1-\gamma_5)u(\mathrm{d})\,\frac{-\mathrm{i}g^{\lambda\sigma}}{k^2-M_{\mathrm{W}}^2}\;\frac{-\mathrm{i}g^{\alpha\rho}}{k^2-M_{\mathrm{W}}^2}$$

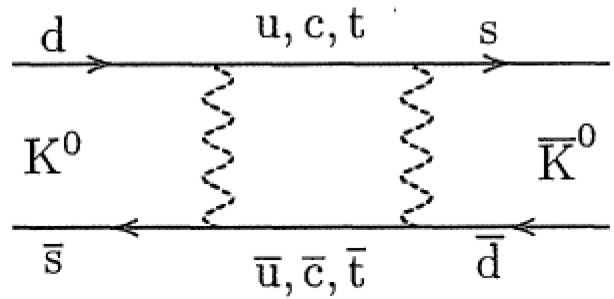
$\mathrm{i},\mathrm{j} = \mathrm{u},\mathrm{c},\mathrm{t}$

ΔF=2 effective operator



(a)

$\mathcal{M}_a = \mathcal{M}_b$



(b)

- all external momenta are taken to be zero compared to M_W

$$\mathcal{M}_a = i \left[\frac{-ig}{2\sqrt{2}}\right]^4 V_{id}^* V_{is} V_{jd}^* V_{js} \int \frac{d^4k}{(2\pi)^4} \bar{u}(s)\gamma_\lambda(1-\gamma_5)\frac{i(\not{k} + m_i)}{k^2 - m_i^2}\gamma_\rho(1-\gamma_5)v(d)$$

$$\times \bar{v}(s)\gamma_\alpha(1-\gamma_5)\frac{i(\not{k} + m_j)}{k^2 - m_j^2}\gamma_\sigma(1-\gamma_5)u(d) \frac{-ig^{\lambda\sigma}}{k^2 - M_W^2} \frac{-ig^{\alpha\rho}}{k^2 - M_W^2}$$

i, j = u, c, t

- The relevant integral is

$$I_{\alpha\beta}(i,j) \equiv \int \frac{d^4k\, k_\alpha k_\beta}{(k^2 - M_W^2)^2(k^2 - m_i^2)(k^2 - m_j^2)} = \frac{1}{4} g_{\alpha\beta} I(i,j)$$

ΔF=2 effective operator

$$I(i,j)=\frac{1}{4}\int\frac{k^2d^4k}{(k^2-M_W^2)^2(k^2-m_i^2)(k^2-m_j^2)}=-\frac{i}{4M_W^4}\int\frac{k^5dkd\Omega_3}{(k^2+1)^2(k^2+x_i)(k^2+x_j)}$$

$$=-\frac{i\pi^2}{2M_W^4}\int\frac{k^5dk}{(k^2+1)^2(k^2+x_i)(k^2+x_j)}$$

$$I_{\alpha\beta}(i,j)\equiv\int\frac{d^4k\,k_\alpha k_\beta}{(k^2-M_W^2)^2(k^2-m_i^2)(k^2-m_j^2)}=\frac{-i\pi^2}{4M_W^2}A(x_i,x_j)g_{\alpha\beta}$$

$$A(x_i,x_j)=\frac{J(x_i)-J(x_j)}{x_i-x_j}\qquad J(x_i)=\frac{1}{1-x_i}+\frac{x_i^2\ln x_i}{(1-x_i)^2}\qquad x_i=\frac{m_i^2}{M_W^2}$$

- By using the relation and replace the spinors by the quark fields

$$\gamma^\mu\gamma^\alpha\gamma^\nu=g^{\mu\alpha}\gamma^\nu+g^{\nu\alpha}\gamma^\mu-g^{\mu\nu}\gamma^\alpha-i\varepsilon^{\mu\alpha\nu\beta}\gamma_5\gamma_\beta$$

$$\varepsilon^{\mu\alpha\nu\beta}\varepsilon_{\mu\alpha\nu\delta}=-6_\delta^\beta$$

$$[\gamma^\mu\gamma^\alpha\gamma^\nu(1-\gamma_5)/2]\ldots[\gamma_\nu\gamma_\alpha\gamma_\mu(1-\gamma_5)/2]=4[\gamma^\alpha(1-\gamma_5)/2]\ldots[\gamma_\alpha(1-\gamma_5)/2]$$

$$\Theta^{|\Delta S|=2}\equiv[\bar{s}\gamma_\lambda(1-\gamma_5)d]\,[\bar{s}\gamma^\lambda(1-\gamma_5)d]$$

$$g^2/8M_W^2=G_F/\sqrt{2}$$

- The effective Hamiltonian is

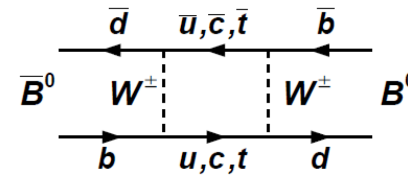
$$H^{(2)}=2H_a^{|\Delta S|=2}=\frac{G_F^2}{4\pi^2}(V_{id}^*V_{js})^2M_W^2A(x_i,x_j)\Theta^{|\Delta S|=2}$$

The story is not over for the transition amplitude (Goldstone boson contribution, vacuum insertion, …)

$B^0 - \overline{B}^0$ Mixing

- Neutral meson systems: $K^0\overline{K}^0, D^0\overline{D}^0, B^0\overline{B}^0, B_s^0\overline{B}_s^0$

  - flavor mixing through box diagrams → coupled system



$$|\psi(t)\rangle = a(t)\,|B^0\rangle + b(t)\,|\overline{B}^0\rangle$$

  - time evolution can be described by a two-component Schrödinger equation with an effective Hamiltonian H

$$-i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = H\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

  - mesons can decay → unitarity not conserved → H is not Hermitian

  - decompose H into two Hermitian parts

$$\left.\begin{aligned} M &\equiv \frac{1}{2}\left(H + H^\dagger\right) \\ \frac{\Gamma}{2} &\equiv \frac{1}{2i}\left(H - H^\dagger\right) \end{aligned}\right\} \Rightarrow H = M - \frac{i}{2}\Gamma = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix} = \begin{pmatrix} \langle B^0 | H^{(0)} | B^0 \rangle & \langle B^0 | H^{(2)} | \overline{B^0} \rangle \\ \langle \overline{B^0} | H^{(2)} | B^0 \rangle & \langle \overline{B^0} | H^{(0)} | \overline{B^0} \rangle \end{pmatrix}$$

  - off-diagonal elements of M and Γ describes meson-antimeson mixing

$B^0 - \overline{B}^0$ Mixing

- M and Γ are Hermitian → $M_{21} = M_{12}^*$ and $\Gamma_{21} = \Gamma_{12}^*$
- Assume CPT conservation (i.e. meson and its antimeson have the same mass and lifetime)

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

$$\begin{matrix} M & \equiv & M_{11} & = & M_{22} \\ \Gamma & \equiv & \Gamma_{11} & = & \Gamma_{22} \end{matrix}$$

- diagonalize H to determine Eigenvalues and Eigenstates

$$\lambda_{L,H} = M_{L,H} - i\frac{\Gamma_{L,H}}{2} = \frac{H_{11} + H_{22}}{2} \pm \sqrt{H_{12}H_{21}}$$

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle = \frac{1}{\sqrt{1+|\tilde{\epsilon}|^2}}\left[(1+\tilde{\epsilon})|B^0\rangle + (1-\tilde{\epsilon})|\overline{B}^0\rangle\right]$$

$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle = \frac{1}{\sqrt{1+|\tilde{\epsilon}|^2}}\left[(1+\tilde{\epsilon})|B^0\rangle - (1-\tilde{\epsilon})|\overline{B}^0\rangle\right]$$

$$|p|^2 + |q|^2 = 1$$

$$\frac{q}{p} = \frac{1-\tilde{\epsilon}}{1+\tilde{\epsilon}} = \sqrt{\frac{H_{21}}{H_{12}}} = \sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}}$$

$$\bar{\epsilon} = \frac{p-q}{p+q}$$

- B_H and B_L have well-defined masses and decay widths

$$|B_H(t)\rangle = \left(p \cdot |B^0\rangle - q \cdot |\overline{B}^0\rangle\right) \cdot e^{-im_H t} \cdot e^{-\Gamma_H t/2}$$

$$|B_L(t)\rangle = \left(p \cdot |B^0\rangle + q \cdot |\overline{B}^0\rangle\right) \cdot e^{-im_L t} \cdot e^{-\Gamma_L t/2}$$

$B^0 - \overline{B}^0$ Mixing

- Time evolution of initially pure flavour states
  - mesons are not produced in mass eigenstates, but in pure flavour states

$$|B^0\rangle \text{ or } |\overline{B}^0\rangle \text{ at } t=0$$

  - They are decomposed into a super position of mass eigenstates

$$|B^0_{t=0}\rangle = \frac{1}{2p}\left(|B_H\rangle + |B_L\rangle\right) \quad \text{and} \quad |\overline{B}^0_{t=0}\rangle = \frac{1}{2q}\left(|B_L\rangle - |B_H\rangle\right)$$

$$a_H(t) = a_H(0)e^{-iM_H t}e^{-\frac{1}{2}\Gamma_H t} \qquad a_L(t) = a_L(0)e^{-iM_L t}e^{-\frac{1}{2}\Gamma_L t}$$

  - propagate according to the solution of the Schrödinger equation

$$|B^0_{t=0}(t)\rangle = \frac{1}{2p}\left(|B_H\rangle e^{-im_H t}e^{-\Gamma_H t/2} + |B_L\rangle e^{-im_L t}e^{-\Gamma_L t/2}\right)$$

$$|\overline{B}^0_{t=0}(t)\rangle = \frac{1}{2q}\left(|B_L\rangle e^{-im_L t}e^{-\Gamma_L t/2} - |B_H\rangle e^{-im_H t}e^{-\Gamma_H t/2}\right)$$

  - time evolution of initially pure flavour states

$$|B^0_{t=0}(t)\rangle = g_+(t)\cdot|B^0\rangle + \frac{q}{p}\cdot g_-(t)\cdot|\overline{B}^0\rangle$$

$$|\overline{B}^0_{t=0}(t)\rangle = g_+(t)\cdot|\overline{B}^0\rangle + \frac{p}{q}\cdot g_-(t)\cdot|B^0\rangle$$

$$\overline{m} \equiv (m_H + m_L)/2$$
$$\overline{\Gamma} \equiv (\Gamma_H + \Gamma_L)/2$$
$$\Delta m \equiv m_H - m_L > 0$$
$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L$$

with $g_\pm(t) = \frac{1}{2}e^{-i\overline{m}t}e^{-\frac{\overline{\Gamma}t}{2}}\left(e^{i\frac{\Delta m t}{2}}e^{+\frac{\Delta\Gamma t}{4}} \pm e^{-i\frac{\Delta m t}{2}}e^{-\frac{\Delta\Gamma t}{4}}\right)$

$B^0 - \overline{B}^0$ Mixing

- mixing probabilities

$$P(B^0 \to B^0, t) = \frac{1}{2} \cdot e^{-\Gamma t} \cdot \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) + \cos(\Delta m\, t) \right\}$$

$$P(\overline{B}^0 \to \overline{B}^0, t) = P(B^0 \to B^0, t)$$

$$P(B^0 \to \overline{B}^0, t) = \frac{1}{2} \cdot \left|\frac{q}{p}\right|^2 \cdot e^{-\Gamma t} \cdot \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) - \cos(\Delta m\, t) \right\}$$

$$P(\overline{B}^0 \to B^0, t) = \frac{1}{2} \cdot \left|\frac{p}{q}\right|^2 \cdot e^{-\Gamma t} \cdot \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) - \cos(\Delta m\, t) \right\}$$

- Time-dependent asymmetries

$$a_{\text{mix}}(t) \equiv \frac{N(B^0 \to B^0) - N(B^0 \to \overline{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \overline{B}^0)} = \frac{\cos(\Delta m \cdot t) + \delta \cdot \cosh(\Delta\Gamma \cdot t/2)}{\cosh(\Delta\Gamma \cdot t/2) + \delta \cdot \cos(\Delta m \cdot t)}$$

$$\overline{a}_{\text{mix}}(t) \equiv \frac{N(\overline{B}^0 \to \overline{B}^0) - N(\overline{B}^0 \to B^0)}{N(\overline{B}^0 \to \overline{B}^0) + N(\overline{B}^0 \to B^0)} = \frac{\cos(\Delta m \cdot t) - \delta \cdot \cosh(\Delta\Gamma \cdot t/2)}{\cosh(\Delta\Gamma \cdot t/2) - \delta \cdot \cos(\Delta m \cdot t)}$$

$\delta \neq 0 \Leftrightarrow$ *CP* violation in mixing

$$\delta \equiv \frac{1 - |q/p|^2}{1 + |q/p|^2}$$

CP violation in K decay

- Two kinds of neutral K mesons and make isospin doublet with charged K

$$K^0 = d\bar{s}\,(S=+1) \qquad \bar{K}^0 = s\bar{d}\,(S=-1)$$

$$K^+ = u\bar{s} \qquad K^- = s\bar{u}$$

- CP properties of neutral K mesons are

$$\mathrm{CP}\left|K^0\right\rangle = e^{i\xi_{\mathrm{CP}}}\left|\bar{K}^0\right\rangle = \eta_{\mathrm{CP}}\left|\bar{K}^0\right\rangle$$

$$\mathrm{CP}\left|\bar{K}^0\right\rangle = e^{-i\xi_{\mathrm{CP}}}\left|K^0\right\rangle = \eta^*_{\mathrm{CP}}\left|K^0\right\rangle$$

$\xi_{\mathrm{CP}} = 0$ by convention

- If CP is conserved in weak interactions, CP is a good quantum number and CP eigenstates can be defined by

$$\left|K_1\right\rangle = \left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right)/\sqrt{2}$$

$$\left|K_2\right\rangle = \left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right)/\sqrt{2}$$

$$\mathrm{CP}\left|K_1\right\rangle = \left|K_1\right\rangle$$

$$\mathrm{CP}\left|K_2\right\rangle = -\left|K_2\right\rangle$$

- They decay to 2π or 3π, whose CP is +1 and -1, respectively.

$$K_1 \to 2\pi,\ K_2 \to 3\pi$$

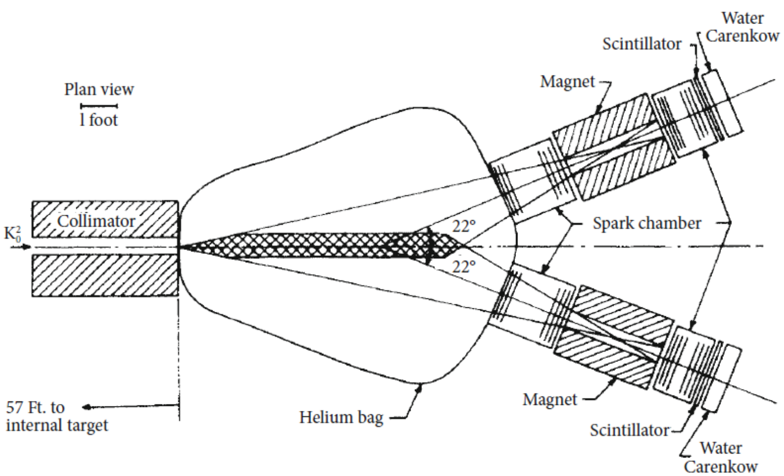
$$K_1 \sim K_S,\ K_2 \sim K_L$$

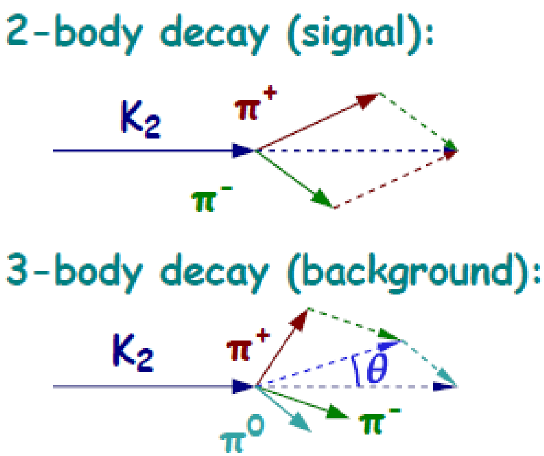
$m_K \sim 497$ MeV

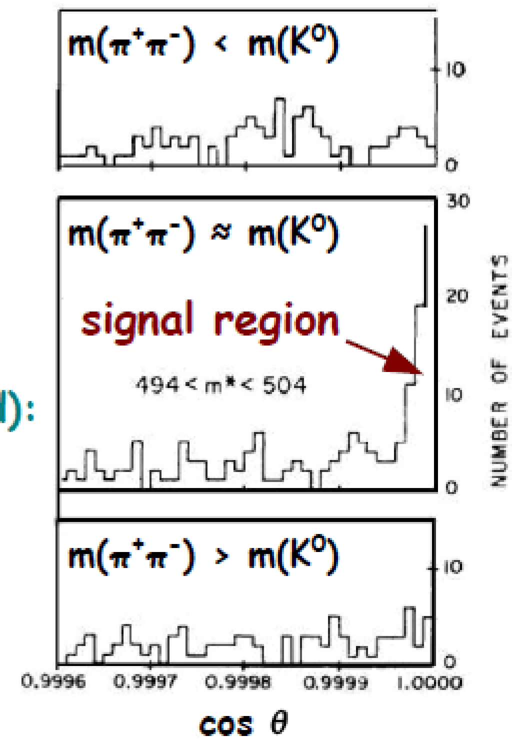
$m_\pi \sim 140$ MeV

Discovery of CP violation

- Observation of $K_2 \to \pi^+\pi^-$ (Christension,Cronin,Fitch,Turlay,1964)
  - produce K^0 (mix of K_1 and K_2) and let them propagate in vacuum tube long enough for K_1 component to decay away → pure K_2 beam
  - search for CP-forbidden decay, $K_2 \to \pi^+\pi^-$







- find excess of 48 events ⇒ BR $(K_2 \to \pi^+\pi^-) \approx 2 \times 10^{-3}$

Kaon CP-violation observables

- Observed neutral Kaons are not eigenstates of CP.

$$|K_S\rangle = \frac{1}{\sqrt{1+|\tilde{\epsilon}|^2}}\left(|K_1\rangle + \tilde{\epsilon}|K_2\rangle\right) \longrightarrow \pi\pi$$

$$|K_L\rangle = \frac{1}{\sqrt{1+|\tilde{\epsilon}|^2}}\left(|K_2\rangle + \tilde{\epsilon}|K_1\rangle\right) \longrightarrow \pi\pi\pi$$

K_S	$\rightarrow$	$\pi^+\pi^-$	$BR = 69.2\%$
	$\rightarrow$	$\pi^0\pi^0$	$BR = 30.7\%$
	$\rightarrow$	$\pi^-e^+\nu_e$	$BR = 0.03\%$
	$\rightarrow$	$\pi^+e^-\overline{\nu}_e$	$BR = 0.03\%$
	$\rightarrow$	$\pi^-\mu^+\nu_\mu$	$BR = 0.02\%$
	$\rightarrow$	$\pi^+\mu^-\overline{\nu}_\mu$	$BR = 0.02\%$

K_L	$\rightarrow$	$\pi^+\pi^-\pi^0$	$BR = 12.6\%$
	$\rightarrow$	$\pi^0\pi^0\pi^0$	$BR = 19.6\%$
	$\rightarrow$	$\pi^-e^+\nu_e$	$BR = 20.2\%$
	$\rightarrow$	$\pi^+e^-\overline{\nu}_e$	$BR = 20.2\%$
	$\rightarrow$	$\pi^-\mu^+\nu_\mu$	$BR = 13.5\%$
	$\rightarrow$	$\pi^+\mu^-\overline{\nu}_\mu$	$BR = 13.5\%$

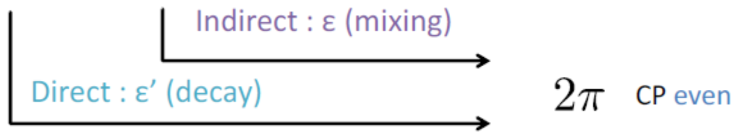
Question. Br($K_S \rightarrow 2\pi$)~0.998, but Br($K_L \rightarrow 3\pi$)~0.32. In the K_L decays, the semileptonic decay modes are dominant. Why is the branching ratio of the semileptonic decay of K_S quite small?

CP violation in Kaon decays

- direct CP violation in the K_L decay

CP odd CP even

$$|K_L\rangle = |K_2\rangle + \epsilon\, |K_1\rangle$$

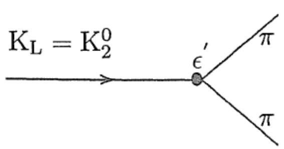


– direct CP violation can occur only if the transition violates CP symmetry

$$|\Delta S| = 1 \text{ transition}$$

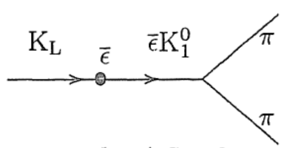
– indirect CP violation occurs through the mixing

$$|\Delta S| = 2 \text{ transitions}$$



milliweak : $\Delta S = 1$

Direct CP violation in amplitude



superweak : $\Delta S = 2$

CP violation in mass matrix

Kaon CP-violation observables

$$\eta_{+-} \equiv \frac{\mathcal{A}\left(K_L \to \pi^+\pi^-\right)}{\mathcal{A}\left(K_S \to \pi^+\pi^-\right)} = \varepsilon + \varepsilon'$$

$$\eta_{00} \equiv \frac{\mathcal{A}\left(K_L \to \pi^0\pi^0\right)}{\mathcal{A}\left(K_S \to \pi^0\pi^0\right)} = \varepsilon - 2\,\varepsilon'$$

- Indirect : ε (mixing)

$$\epsilon_K = \frac{p-q}{p+q} = \frac{p^2 - q^2}{4pq + (p-q)^2} \approx \frac{p^2 - q^2}{4pq} \simeq \frac{\mathrm{Im} M_{12}^K}{\Delta M^K}$$

$$\varepsilon = f\left(\hat{B}_K, V_{\mathrm{CKM}}, m_c, m_t, \ldots\right) \xrightarrow{\text{Theory}} |\varepsilon| = 1.90(26) \times 10^{-3}$$

$$|\varepsilon|_{\mathrm{exp}} = 2.228(11) \times 10^{-3} \qquad \arg(\varepsilon)_{\mathrm{exp}} = 44(7)^\circ$$

- Direct : ε' (decay)

$$\left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 \simeq 1 - 6\,\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

$$(\epsilon'/\epsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \times 10^{-4}$$

2.9σ difference

SM
$$\left(\frac{\epsilon'}{\epsilon}\right)_{\mathrm{SM}} = \begin{cases} (1.38 \pm 6.90) \times 10^{-4}, & \text{[RBC-UKQCD]} \\ (1.9 \pm 4.5) \times 10^{-4}, & \text{[Buras et al.]} \\ (1.06 \pm 5.07) \times 10^{-4}. & \text{[Kitahara et al.]} \end{cases}$$

Importance of B physics

- Large mass m_b
  - Variety of final states to decay to
  - determination of several CKM elements
  - allows us to use expansion in $1/m_b$ to estimate non-perturbative effects systematically

- CPV phase in V_{ub} → CPV effects

- Rare decays of B mesons due to loop suppression
  - sensitive to New Physics

- K and D physics have relatively large theoretical uncertainties

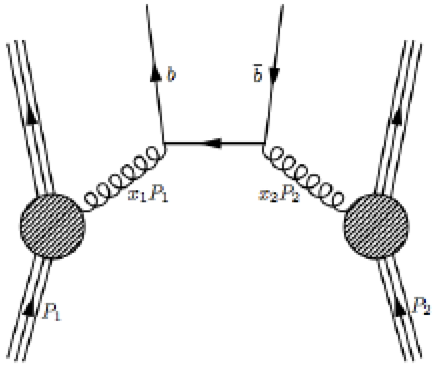
$b\bar{b}$ production mechanism

Hadron colliders: *e.g.* Tevatron, LHC

$b\bar{b}$ from QCD mediated process

incoherent production of *b* hadrons

not defined hadron energy



gluon-gluon fusion is the leading mechanism at LHCb

Tevatron $\sigma(b\bar{b}) \sim 10\mu\text{b at } p\bar{p} \text{ collisions, } E_{CM} = 1.96 \text{ TeV}$

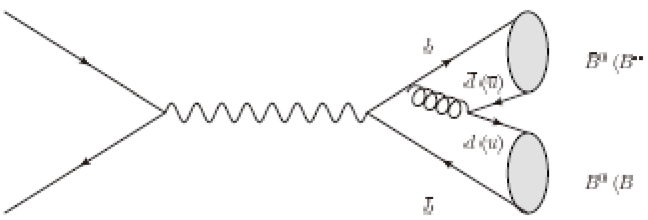
LHCb $\sigma(b\bar{b}) \sim 150\mu\text{b at } pp \text{ collisions, } E_{CM} = 14 \text{ TeV}$

Electron colliders: *e.g.* *B* factories

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

coherent production of $B\bar{B}$ at E_{CM}=10.58 GeV

well defined *B* meson energy



$$\sigma(B\bar{B}) \sim 1.1\text{nb at } e^+e^- \text{ collisions, } E_{CM} = 10.58 \text{ GeV}$$

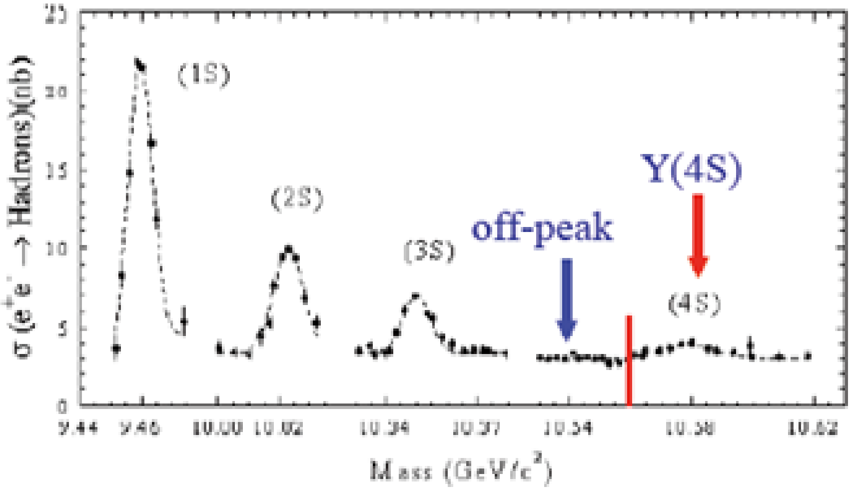
B meson production at B factories

- Collide electrons and positrons at $\sqrt{s}$=10.58 GeV/c²

resonance at q=m $\sim \frac{1}{q^2 - m^2 + im\Gamma}$

$e^+e^- \to$	Cross-section (nb)
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$d\bar{d}$	0.35
$u\bar{u}$	1.39
$\tau^+\tau^-$	0.92
$\mu^+\mu^-$	1.16
e^+e^-	~ 40

many types of interaction occur.



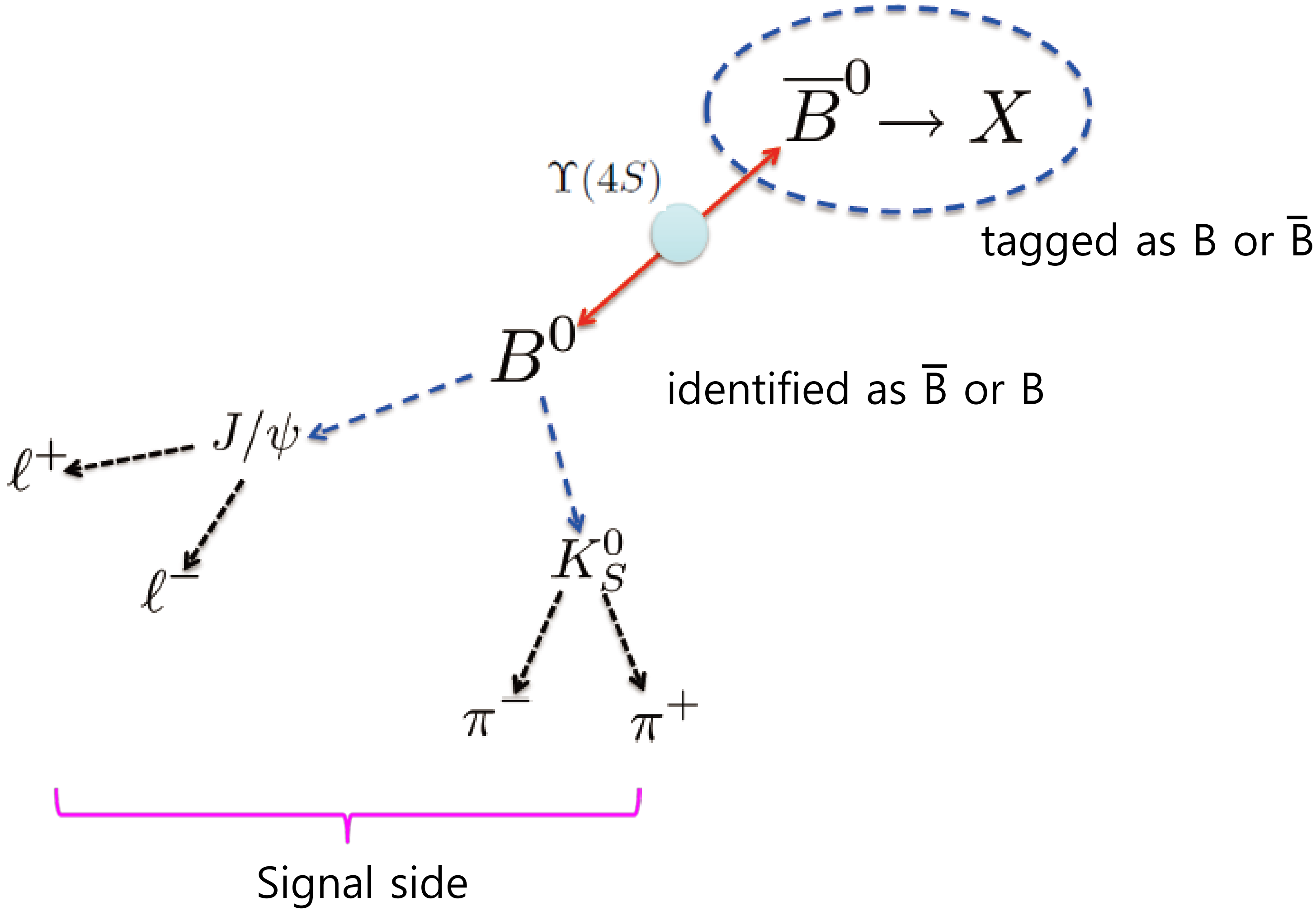
- We are interested in $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for B physics

$$B(\Upsilon(4S) \to B\bar{B}) \sim 100\% \qquad \frac{\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)}{\mathcal{B}(\Upsilon(4S) \to B^+B^-)} \simeq 1$$

$\sigma_{b\bar{b}} \approx$ 1 nb ⇒ with 1 fb^{-1} produce 10^6 $B\bar{B}$ pairs

N.B. $\Upsilon(5S) \to B_s\bar{B}_s$ is possible, but it is not the main target of B factories

How to identify B or $\bar{B}$



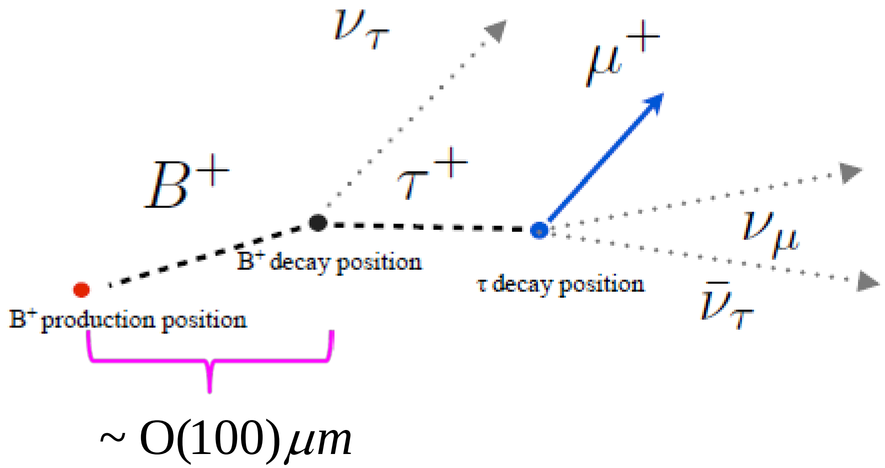
Travel distance of B meson

For a relativistic particle, the travel distance:

$$d = (\beta c\ \tau)\gamma \approx (300\ \mu m)(\frac{\tau}{10^{-12}\ s})\ \gamma$$

The lifetime of B meson $\tau_B \sim 10^{-12} s$

$$B^+ \rightarrow \tau^+ \nu_\tau$$
$$\searrow \mu^+ \nu_\mu \bar{\nu}_\tau$$



b-hadrons:

$\tau \approx 1.5$ ps, $c\tau \approx 450\ \mu m$

at p = 20 GeV → dist ≈ 1.8 mm

$m_b \approx 4.2$ GeV

c-hadrons:

D^+: ≈ 312 μm, D^0: ≈ 123 μm

$m_c \approx 1.9$ GeV

Why need asymmetric B factories?

- Many observables require measurement of time-dependent asymmetries
- But, B mesons are produced almost at rest in the $\Upsilon(4S)$ rest frame

  $\Longrightarrow$ difficult to resolve the vertex of B decays

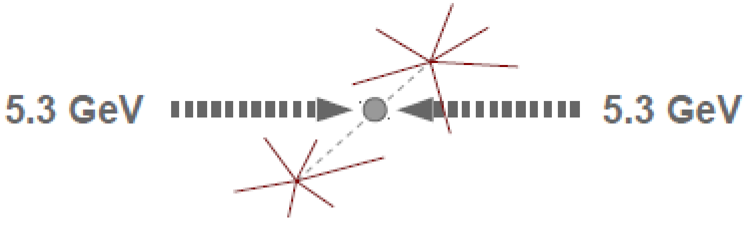
- $\Upsilon(4S)$ decays produce $B\bar{B}$ pairs in a coherent quantum state

  $J_{\Upsilon(4s)} = 1$, $J_B = 0 \Rightarrow L_{B\bar{B}} = 1 \Rightarrow$ **wave function anti-symmetric**

- Bose-Einstein statistics implies flavour wave-function must be anti-symmetric

  $\Longrightarrow$ $B\bar{B}$ must oscillate in phase until one of them decays

- $\Upsilon(4S)$ is produced at rest at a symmetric collider



back-to-back
cannot construct production vertex

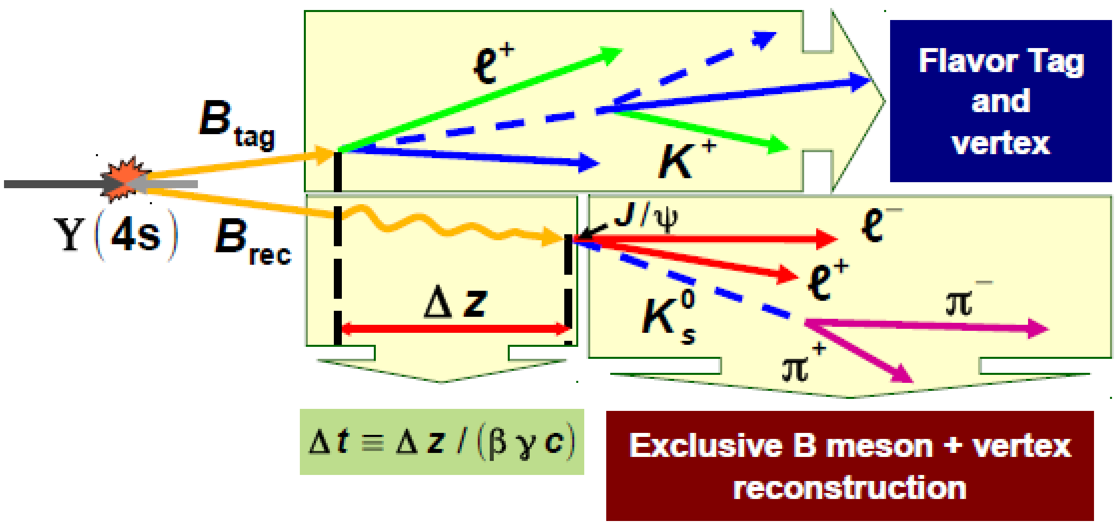
Asymmetric B factories

- PEP-II: 9 GeV e^- + 3.1 GeV e^+

$$\beta\gamma = 0.56$$
$$\langle \Delta z \rangle \approx 260\ \mu m$$

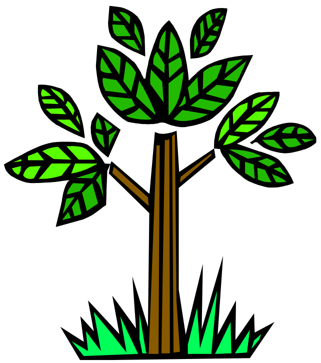
- KEKB: 8 GeV e^- + 3.5 GeV e^+

$$\beta\gamma = 0.425$$
$$\langle \Delta z \rangle \approx 200\ \mu m$$



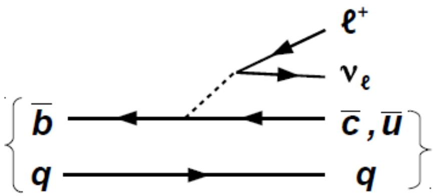
This is a counter example of the famous EPR paradox

Classification of B decays



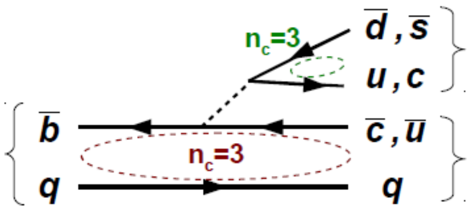
Tree decays

- semileptonic



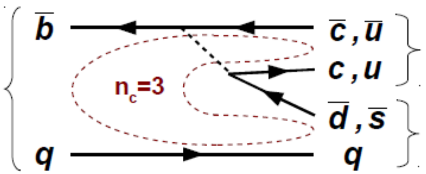
$Br \sim 11\%$ per each lepton(e, μ, τ)

- color-allowed tree



$Br \sim$ up to a few %

- color-suppressed tree



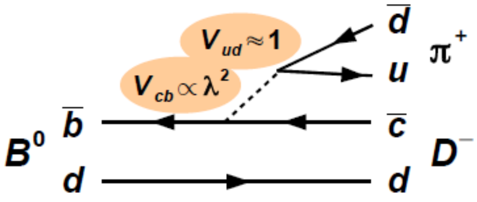
$Br \sim 1/10$ of color-allowed tree

nonleptonic

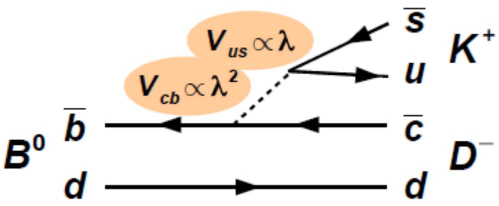
Classification of B decays

Tree decays by orders of λ

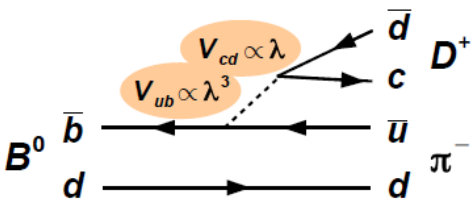
- Cabibbo-favored (λ^2)



- Cabibbo-suppressed (λ^3)



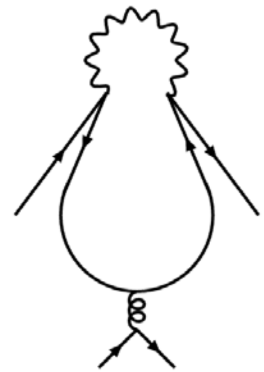
- doubly Cabibbo-suppressed (λ^4)

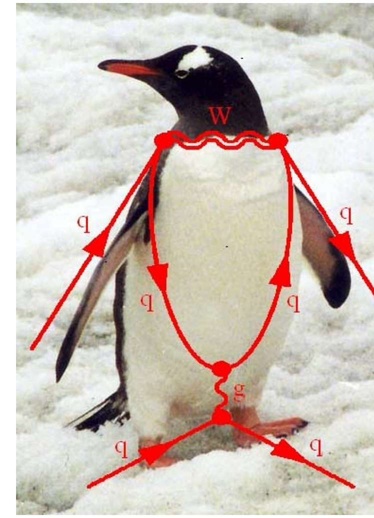


Classification of B decays

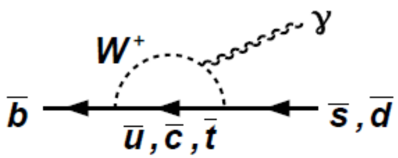
Penguin decays

~FCNC, loop suppressed, sensitive to new physics

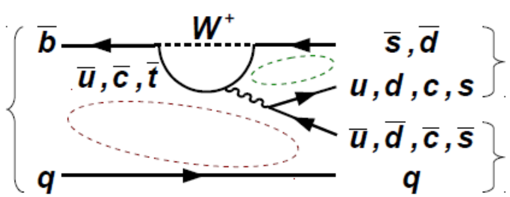




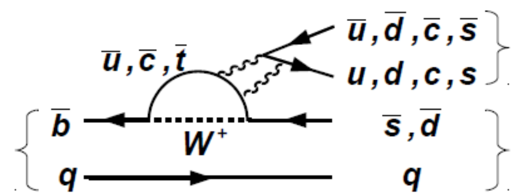
- radiative



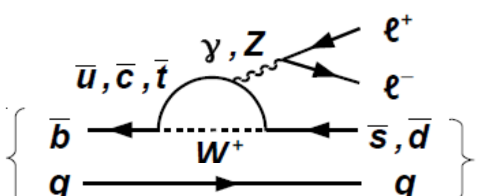
- (internal) gluonic penguin



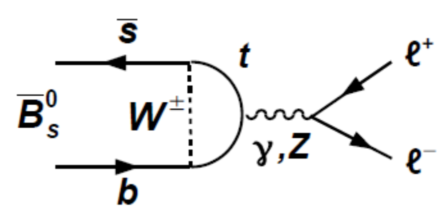
- external gluonic penguin



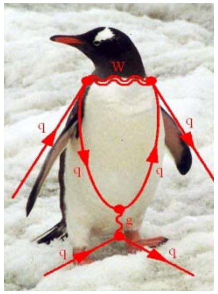
- electroweak penguin



- leptonic



Penguin diagram

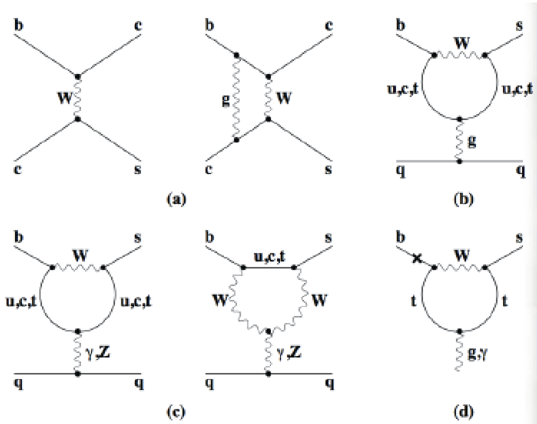


Origin of the name [edit]

John Ellis was the first to refer to a certain class of Feynman diagrams as **penguin diagrams**, due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis:[2]

> Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.

Effective Hamiltonian



- many scales (m_b,m_W,Λ_{QCD}) are involved in B decays
- large logarithms appear in the calculation

$$\ln\frac{M_W^2}{\mu^2},\left(\ln\frac{M_W^2}{\mu^2}\right)^2,\ldots$$

- perturbative calculation might be broken because of the large logarithms

- go to the M_W scale, where the logarithms disappers
- Physical process should be calculated at the m_b scale
- use the operator product expansion (OPE)
- the large logarithms are summed up in Wilson coefficients (RGE required)

$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}} V_{us}^* V_{cb} \left[C_1(\mu)O_1 + C_2(\mu)O_2\right]$$

$$\langle K^- D^+|\mathcal{H}_{\rm eff}|\bar{B}_d^0\rangle = \frac{G_{\rm F}}{\sqrt{2}} V_{us}^* V_{cb}\Big[a_1\langle K^- D^+|(\bar{s}_\alpha u_\alpha)_{\rm V\text{-}A}(\bar{c}_\beta b_\beta)_{\rm V\text{-}A}|\bar{B}_d^0\rangle$$
$$+\,2\,C_1\langle K^- D^+|(\bar{s}_\alpha\, T^a_{\alpha\beta}\, u_\beta)_{\rm V\text{-}A}(\bar{c}_\gamma\, T^a_{\gamma\delta}\, b_\delta)_{\rm V\text{-}A}|\bar{B}_d^0\rangle\Big],$$

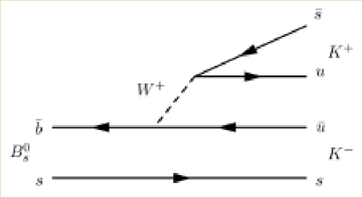
- short distance physics and long distance physics are well seperated

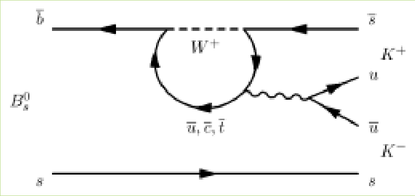
- how to calculate the matrix elements?
→Naïve Factorization,QCDF,PQCD,SCET,...

Three types of CP violation

CPV in decay

(“direct *CP* violation”)



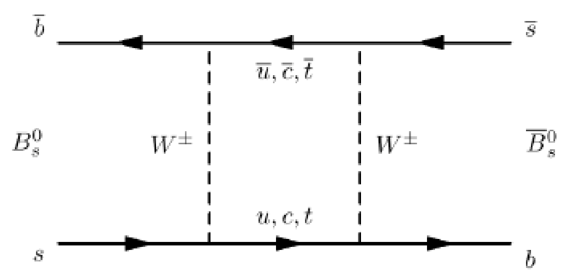


- interference of decay diagrams with different weak and strong phases
- different decay rates

  $B \to f$ vs $\overline{B} \to \overline{f}$
- beware of strong phases

CPV in mixing

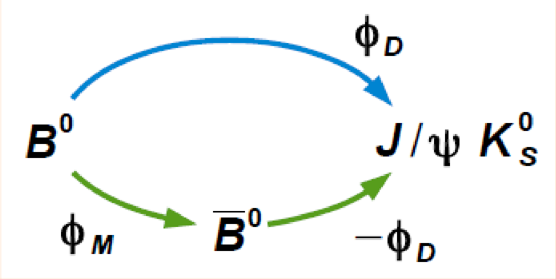
(“indirect *CP* violation”)



- interference of absorp-tive and dispersive part of mixing amplitude
- different mixing rate

  $B^0_{(s)} \to \overline{B}^0_{(s)}$ vs $\overline{B}^0_{(s)} \to B^0_{(s)}$
- small in Standard Model

CPV in interference of mixing and decay



- interference between direct decay and decay after mixing
- different decay rates

  $B^0_{(s)} \to f_{CP}$ vs $\overline{B}^0_{(s)} \to f_{CP}$
- “golden modes”

Direct CP violation

- CP violation in decays if $A(\overline{B} \to \overline{f}) \neq A(B \to f)$

  • requires interference of at least two decay amplitudes with different weak phase and different strong phase, which lead to the same final state

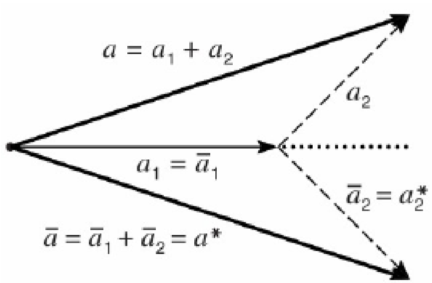
$$A_f \equiv A(B \to f) = \sum_i a_i e^{i(\delta_i + \phi_i)}$$

$$\overline{A}_{\overline{f}} \equiv A(\overline{B} \to \overline{f}) = \sum_i a_i e^{i(\delta_i - \phi_i)}$$

ϕ_i: weak phase, changes sign under *CP*

δ_i: strong phase, does not change sign under *CP*

$$|A_f|^2 - |\overline{A}_{\overline{f}}|^2 = -2 \sum_{ij} a_i a_j \cdot \sin(\phi_i - \phi_j) \cdot \sin(\delta_i - \delta_j)$$

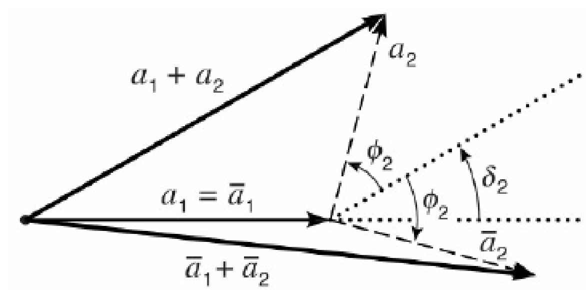


$\phi_2 \neq \phi_1$

$\delta_2 = \delta_1$

$\Rightarrow |\bar{a}| = |a|$

$(\phi_1 = \delta_1 = 0)$



$\phi_2 \neq \phi_1$

$\delta_2 \neq \delta_1$

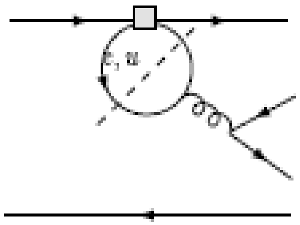
$\Rightarrow |\bar{a}| \neq |a|$

$(\phi_1 = \delta_1 = 0)$

- at least two amplitudes with different weak phase but also strong phase are required.

Sources of strong phase

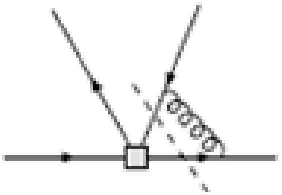
- The weak phase is the phase in the Lagrangian, but what is the origin of the strong phase?



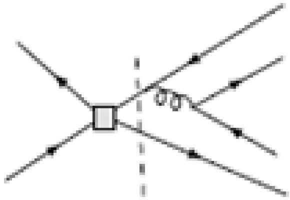
Bander-Silverman-Soni (BSS) mechanism

It gives a small phase.
Only source?
Important source?

⇒ Insufficient to explain large direct CP asymmetries



Vertex correctoins in QCDF



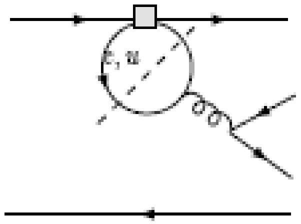
Annihilation diagram in PQCD

Final state interaction (long-range interaction)

BSS mechanism, vertex corrections in QCDF, annihilation diagram in PQCD: only account for perturbative strong phase

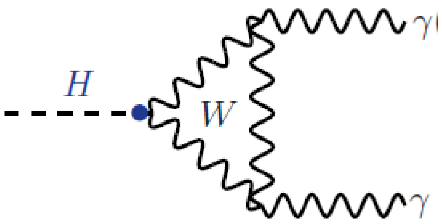
Vertex corrections in QCDF, annihilation diagram in PQCD, final state interaction: model-dependent

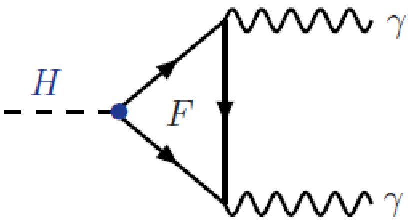
BSS mechanism



Bander-Silverman-Soni (BSS) mechanism

c.f. H→$\gamma\gamma$ decay





$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \, \alpha^2 \, M_H^3}{128\,\sqrt{2}\,\pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

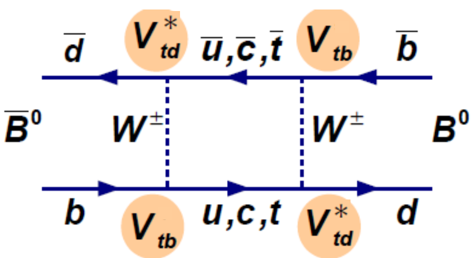
$$\begin{aligned} A_{1/2}^H(\tau) &= 2[\tau + (\tau-1) f(\tau)]\,\tau^{-2} \\ A_1^H(\tau) &= -[2\tau^2 + 3\tau + 3(2\tau-1) f(\tau)]\,\tau^{-2} \end{aligned}$$

$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \le 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$

$\tau_i = M_H^2/4M_i^2$ with $i = f, W$

Indirect CP violation

- CP violation induced by mixing



$$H_{12} = M_{12} - (i/2)\,\Gamma_{12}$$

$\Gamma_{12} \ll M_{12} \Rightarrow$ **interference term small**

$\Rightarrow$ ***CP* violation in mixing small**

New physics can enter in box and may have significant effects

CP

$$P\left(B^0(0) \to \bar{B}^0(t)\right) = \left|\frac{q}{p}\right|^2 \left|g_-(t)\right|^2$$

$$P\left(\bar{B}^0(0) \to B^0(t)\right) = \left|\frac{p}{q}\right|^2 \left|g_-(t)\right|^2$$

CP violation is present if $|q/p| \neq 1$

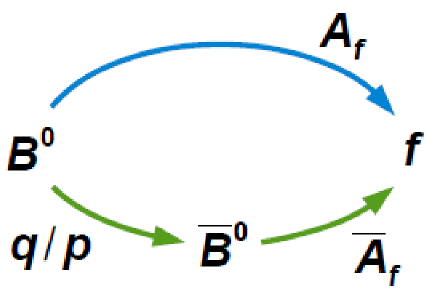
- In experiments, one can define

$$a_{sl} = \frac{P\left(\bar{B}^0(0) \to B^0(t)\right) - P\left(B^0(0) \to \bar{B}^0(t)\right)}{P\left(\bar{B}^0(0) \to B^0(t)\right) + P\left(B^0(0) \to \bar{B}^0(t)\right)} = \frac{1 - \left|\frac{q}{p}\right|^4}{1 + \left|\frac{q}{p}\right|^4} \Rightarrow$$

Does not depend on time anymore

CP violation in interference of mixing and decay

- For decay into a CP eigenstate f that is accessible to both B^0 and $\overline{B}^0$



$$\left|B^0_{t=0}\right\rangle = g_+(t)\left|B^0\right\rangle + \frac{q}{p} g_-(t)\left|\overline{B}^0\right\rangle$$

$$\left|\overline{B}^0_{t=0}\right\rangle = g_+(t)\left|\overline{B}^0\right\rangle + \frac{p}{q} g_-(t)\left|B^0\right\rangle$$

$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m_B t/2)$$

$$g_-(t) = e^{-iMt}e^{-\Gamma t/2} i \sin(\Delta m_B t/2)$$

N.B. $\Delta\Gamma \simeq 0$

- time-dependent decay rate asymmetry

$$a_f(t) = \frac{\Gamma(B^0(t)\to f) - \Gamma(\overline{B}^0(t)\to f)}{\Gamma(B^0(t)\to f) + \Gamma(\overline{B}^0(t)\to f)}$$

- decay amplitudes are defined by

$$A_f = \left\langle f \mid H \mid B^0 \right\rangle \qquad A_{\overline{f}} = \left\langle \overline{f} \mid H \mid B^0 \right\rangle$$

$$\overline{A}_f = \left\langle f \mid H \mid \overline{B}^0 \right\rangle \qquad \overline{A}_{\overline{f}} = \left\langle \overline{f} \mid H \mid \overline{B}^0 \right\rangle$$

CP violation in interference of mixing and decay

$$\Gamma(B^0(t)\to f)\sim\left|g_+(t)\left\langle f\,|\,H\,|\,B^0\right\rangle+\frac{q}{p}g_-(t)\left\langle f\,|\,H\,|\,\bar{B}^0\right\rangle\right|^2$$

$$=\left|g_+(t)\right|^2\left|A_f\right|^2+\left|\frac{q}{p}\right|^2\left|g_-(t)\right|^2\left|\bar{A}_f\right|^2+2\,\mathrm{Re}\left(g_+(t)\left(\frac{q}{p}g_-(t)\right)^*A_f\bar{A}_f^*\right)$$

$$\Gamma(\bar{B}^0(t)\to f)\sim\left|g_+(t)\left\langle f\,|\,H\,|\,\bar{B}^0\right\rangle+\frac{p}{q}g_-(t)\left\langle f\,|\,H\,|\,B^0\right\rangle\right|^2$$

$$=\left|g_+(t)\right|^2\left|\bar{A}_f\right|^2+\left|\frac{p}{q}\right|^2\left|g_-(t)\right|^2\left|A_f\right|^2+2\,\mathrm{Re}\left(g_+(t)\left(\frac{p}{q}g_-(t)\right)^*\bar{A}_fA_f^*\right)$$

$$\Gamma(B^0(t)\to f)\sim\left|A_f\right|^2\left(1+\left|\lambda_f\right|^2\right)\left[1-S\sin\Delta m_Bt+C\cos\Delta m_Bt\right]$$

$$\Gamma(\bar{B}^0(t)\to f)\sim\left|A_f\right|^2\left|\frac{p}{q}\right|\left(1+\left|\lambda_f\right|^2\right)\left[1+S\sin\Delta m_Bt-C\cos\Delta m_Bt\right]$$

$$C_f=\frac{1-\left|\lambda_f\right|^2}{1+\left|\lambda_f\right|^2}\qquad S_f=\frac{2\,\mathrm{Im}\,\lambda_f}{1+\left|\lambda_f\right|^2}\qquad \lambda_f=\frac{q}{p}\frac{\bar{A}_f}{A_f}=\eta_f\frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_f}$$

CP violation in interference of mixing and decay

- In the SM, it is known that

$$1-\left|\frac{q}{p}\right|^2 \simeq \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right) \sim \begin{cases} O(10^{-3}) & \text{for } B_d^0-\bar{B}_d^0 \\ \lesssim O(10^{-4}) & \text{for } B_s^0-\bar{B}_s^0 \end{cases}$$

- time-dependent decay rate asymmetry

$$a_f(t)=\frac{\Gamma(B^0(t)\to f)-\Gamma(\bar{B}^0(t)\to f)}{\Gamma(B^0(t)\to f)+\Gamma(\bar{B}^0(t)\to f)}=C\cos(\Delta m_B t)-S\sin(\Delta m_B t)$$

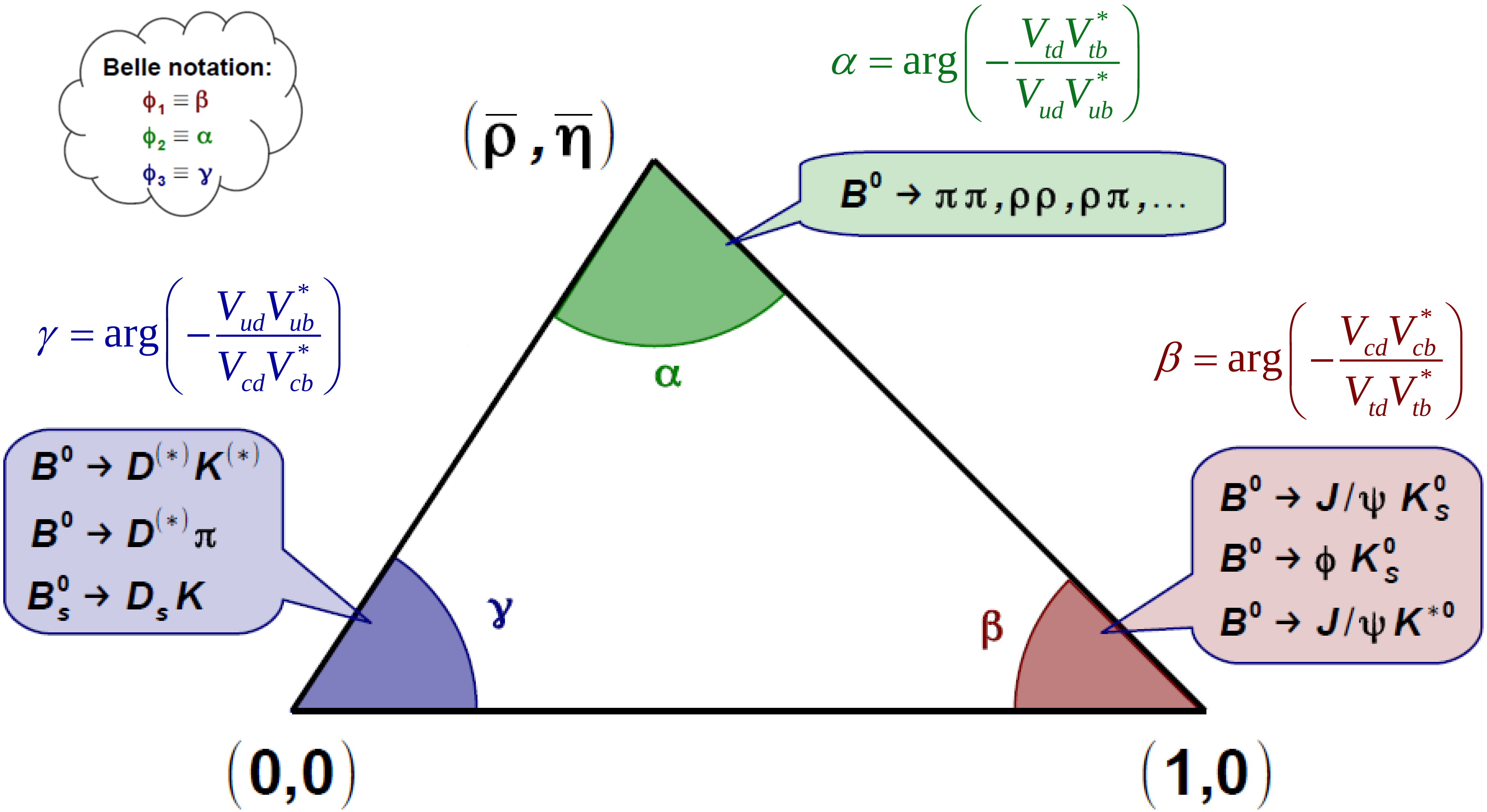
- CP is violated if

$$\left|\lambda_f\right| \neq 1 \quad \text{and/or} \quad \mathrm{Im}\,\lambda_f \neq 0$$

- *C* is called sometimes “direct CP violation”, but in this case nontrivial strong phases are necessary, unlike CP violation in decays.

- *S* corresponds to the “mixing-induced CP violation”

Determination of CKM angles



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

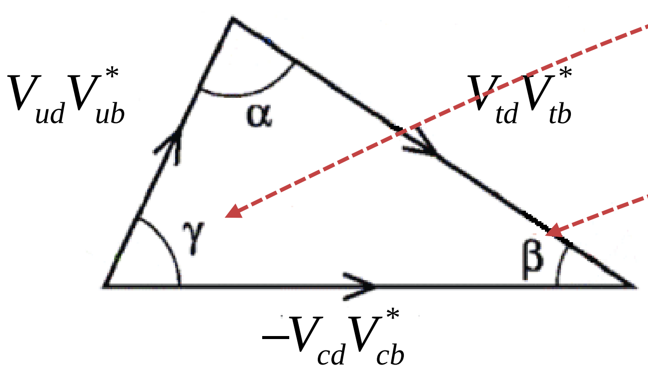
Useful notation for the CKM matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

complex

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

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



$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}| & |V_{tb}| \end{pmatrix}$$

$\sin 2\beta$

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

$B^0 \to J/\psi K_L^0$

$B^0 \to J/\psi K_S^0$

$B^0 \to \psi(2S) K_S^0$

$B^0 \to \chi_{1c} K_S^0$

$B^0 \to \eta_c K_S^0$

$B^0 \to J/\psi K^{*0}$

$B \to J/\psi \pi^0$

$B \to D^{(*)+} D^{(*)-}$

$B \to \eta' K^0$

$B \to \rho K^0$

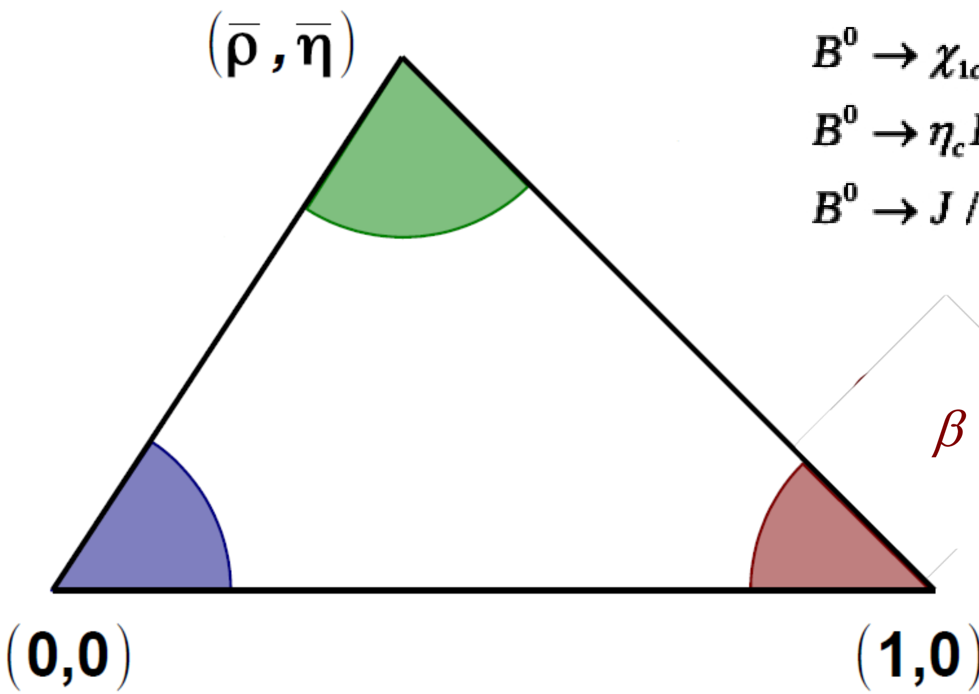
$B \to \omega K^0$

$B \to \pi^0 K^0$

$B \to \phi K^{(*)0}$

$B \to K K K^0$

$B \to f^0(980) K^0$



$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

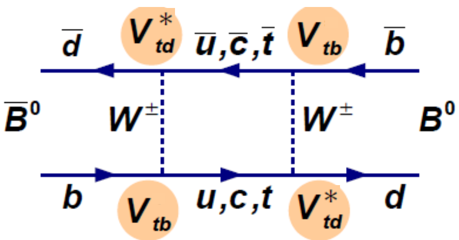
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

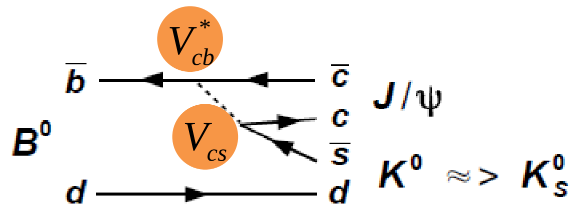
$\sin 2\beta$: Golden decay $B^0 \to J/\psi K_s^0$

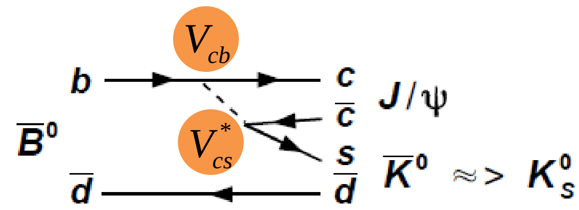
$J^P(K_s^0) = 0^-$

$J^{PC}(J/\psi) = 1^{--}$

- $CP(J/\psi K_s^0) = -1$ and both B^0 and $\bar{B}^0$ can decay to $J/\psi K_s^0$







- time-dependent decay rate asymmetry

$$a_f(t) = \frac{\Gamma(B^0(t) \to f) - \Gamma(\bar{B}^0(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\bar{B}^0(t) \to f)} = C\cos(\Delta m_B t) - S\sin(\Delta m_B t)$$

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \qquad S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1 + |\lambda_f|^2}$$

$$\lambda_{J/\psi K_s^0} = -\left(\frac{q}{p}\right)_{B^0} \left(\frac{\bar{A}_{J/\psi K_s^0}}{A_{J/\psi K_s^0}}\right) \left(\frac{q}{p}\right)_{K^0}$$

- define $\dfrac{\Gamma_{12}}{M_{12}} = re^{i\xi} \quad (r \sim 10^{-3})$

$$\left(\frac{q}{p}\right)_{B^0} = \sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}} \simeq \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)$$

(leading order in r and t-t contribution is dominant in M_{12})

$\sin 2\beta$: Golden decay $B^0 \to J/\psi K_S^0$

$J^{P}(K_s^0) = 0^-$

$J^{PC}(J/\psi) = 1^{--}$

- $\text{CP}(J/\psi K_s^0) = -1$ and both B^0 and $\bar{B}^0$ can decay to $J/\psi K_s^0$

$$\lambda_{J/\psi K_s^0} = -\left(\frac{q}{p}\right)_{B^0}\left(\frac{\bar{A}_{J/\psi K_s^0}}{A_{J/\psi K_s^0}}\right)\left(\frac{q}{p}\right)_{K^0} = -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)\left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)$$

- In the SM,

$$1 - \left|\frac{q}{p}\right|^2 \simeq \text{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right) \sim \begin{cases} O(10^{-3}) & \text{for } B_d^0 - \bar{B}_d^0 \\ \lesssim O(10^{-4}) & \text{for } B_s^0 - \bar{B}_s^0 \end{cases} \Rightarrow \left|\frac{q}{p}\right| \sim 1$$

- Then we obtain

$$\lambda_{J/\psi K_s^0} \cong \eta_{J/\psi K_s^0} e^{-2i\beta} = -e^{-2i\beta}$$

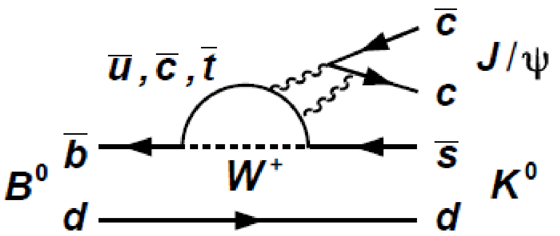
$$a_{J/\psi K_s^0}(t) \cong \eta_{J/\psi K_s^0} \sin 2\beta \sin \Delta m_B t$$

opposite oscillation for CP even final states

- this holds if tree amplitude dominates

$\sin 2\beta$: Golden decay $B^0 \to J/\psi K_s^0$

- contamination from penguin amplitudes



From unitary condition

$$V_{tb}^* V_{ts} = -V_{cb}^* V_{cs} - V_{ub}^* V_{us}$$

$$A_{J/\psi K^0} = P_t \cdot (V_{tb}^* V_{ts}) + (T + P_c) \cdot (V_{cb}^* V_{cs}) + P_u \cdot (V_{ub}^* V_{us})$$

$$= \underbrace{(T + P_c - P_t)}_{\approx 0.1 \cdot T} \cdot \underbrace{(V_{cb}^* V_{cs})}_{\propto \lambda^2} + \underbrace{(P_u - P_t)}_{\approx 0.1 \cdot T} \cdot \underbrace{(V_{ub}^* V_{us})}_{\propto \lambda^4}$$

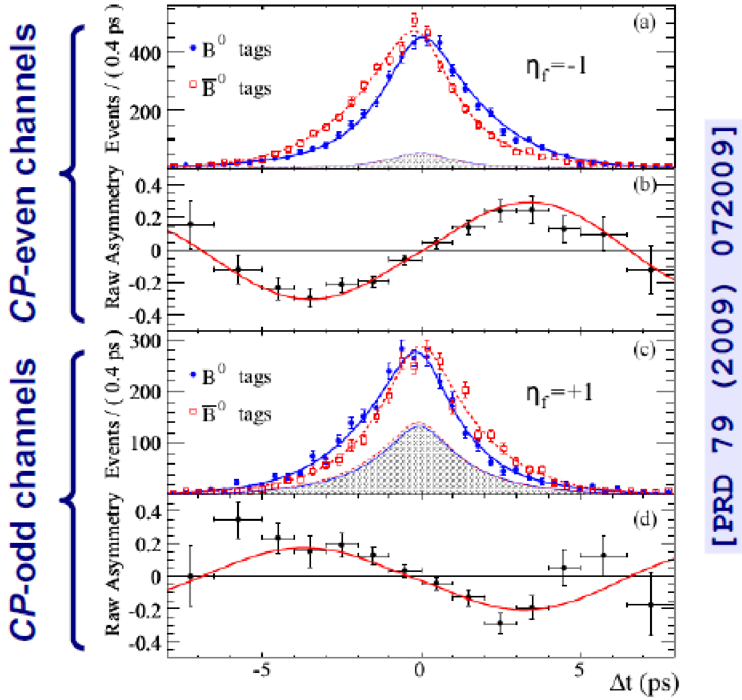
contamination is smaller than 1%

$\Longrightarrow$ Golden decay mode to measure $\sin 2\beta$

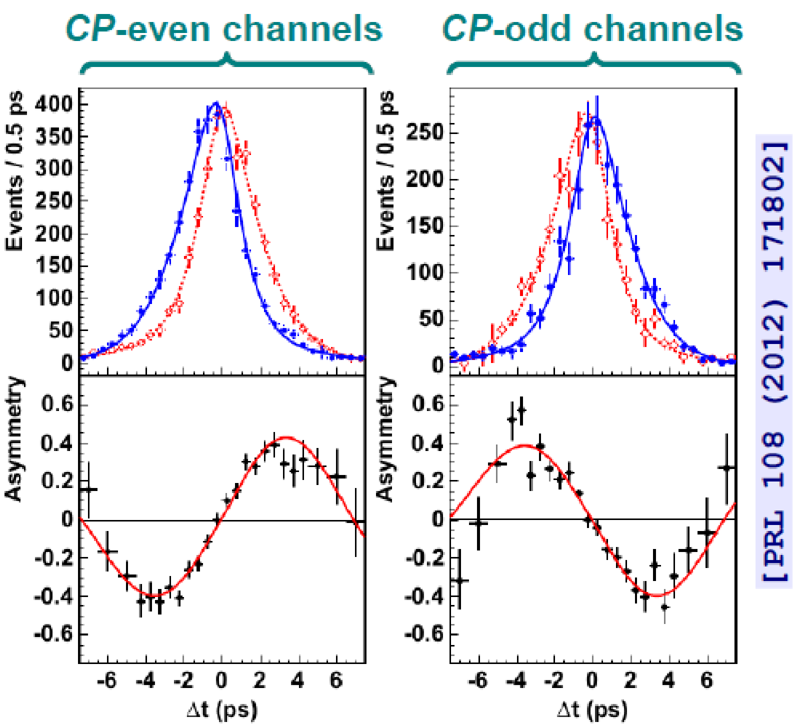
$B^0 \to J/\psi K_L^0$
$B^0 \to J/\psi K_S^0$
$B^0 \to \psi(2S) K_S^0$
$B^0 \to \chi_{1c} K_S^0$
$B^0 \to \eta_c K_S^0$
$B^0 \to J/\psi K^{*0}$

$\sin 2\beta$ from $b \to c\bar{c}s$

Babar (465M $B\bar{B}$ pairs):



Belle (772M $B\bar{B}$ pairs):



$\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$

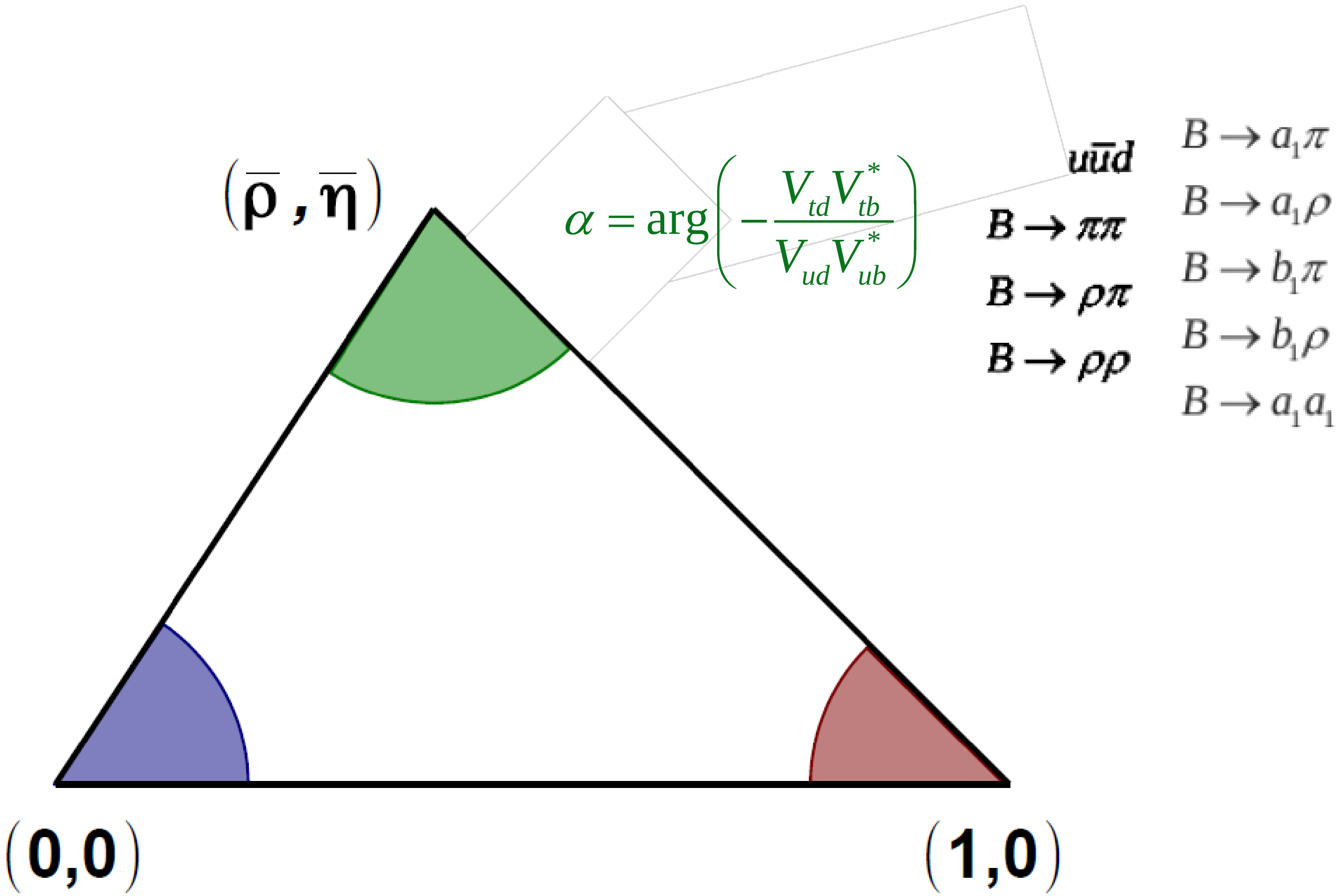
$\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$

- direct CP asymmetry is consistent with zero as expected

$C_f = 0.024 \pm 0.020 \pm 0.016$

$C_f = 0.006 \pm 0.019 \pm 0.012$

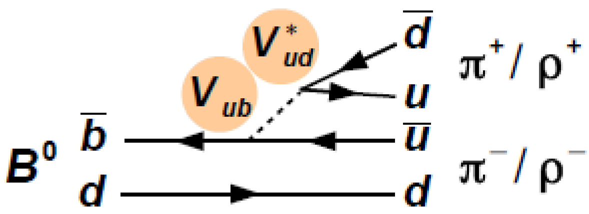
$\sin 2\alpha$

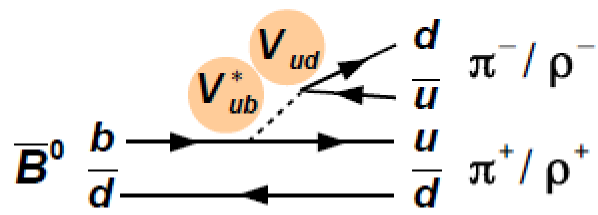


$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$\sin 2\alpha$ in $B^0 \to \pi^+\pi^-$

- $\pi^+\pi^-$ is a CP even eigenstate and B^0 and $\bar{B}^0$ can decay to $\pi^+\pi^-$



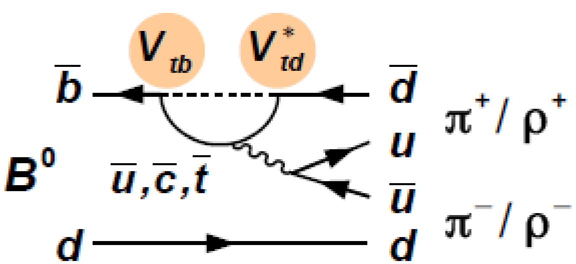


- If the tree-level amplitudes dominate, easy to measure α

$$\lambda_{\pi\pi} = \eta_{\pi\pi}\left(\frac{q}{p}\right)_{B^0}\left(\frac{\bar{A}_{\pi\pi}}{A_{\pi\pi}}\right) = \left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\right)\left(\frac{V^*_{ud}V_{ub}}{V_{ud}V^*_{ub}}\right) = e^{-2i(\beta+\gamma)} = e^{2i\alpha}$$

$$a_{\pi\pi}(t) \sim \eta_{\pi\pi}\sin 2\alpha \sin \Delta m_B t$$

- but significant penguin contamination with different weak phase exists



$$A_{\pi\pi} = P_t \cdot (V^*_{tb}V_{td}) + P_c \cdot (V^*_{cb}V_{cd}) + (T + P_u)\cdot(V^*_{ub}V_{ud})$$

$$= (P_t - P_c)\cdot\underbrace{(V^*_{tb}V_{td})}_{\propto\lambda^3} + \underbrace{(T + P_u - P_c)}_{\approx T}\cdot\underbrace{(V^*_{ub}V_{ud})}_{\propto\lambda^3}$$

$$V^*_{cb}V_{cd} = -V^*_{ub}V_{ud} - V^*_{tb}V_{td}$$

$\Rightarrow$ measure effective angle $\alpha_{eff} = \alpha_{CKM} + \Delta\alpha$

$P/T \sim 30\ \%$

γ

$B \to D^{(*)} K^{(*)}$

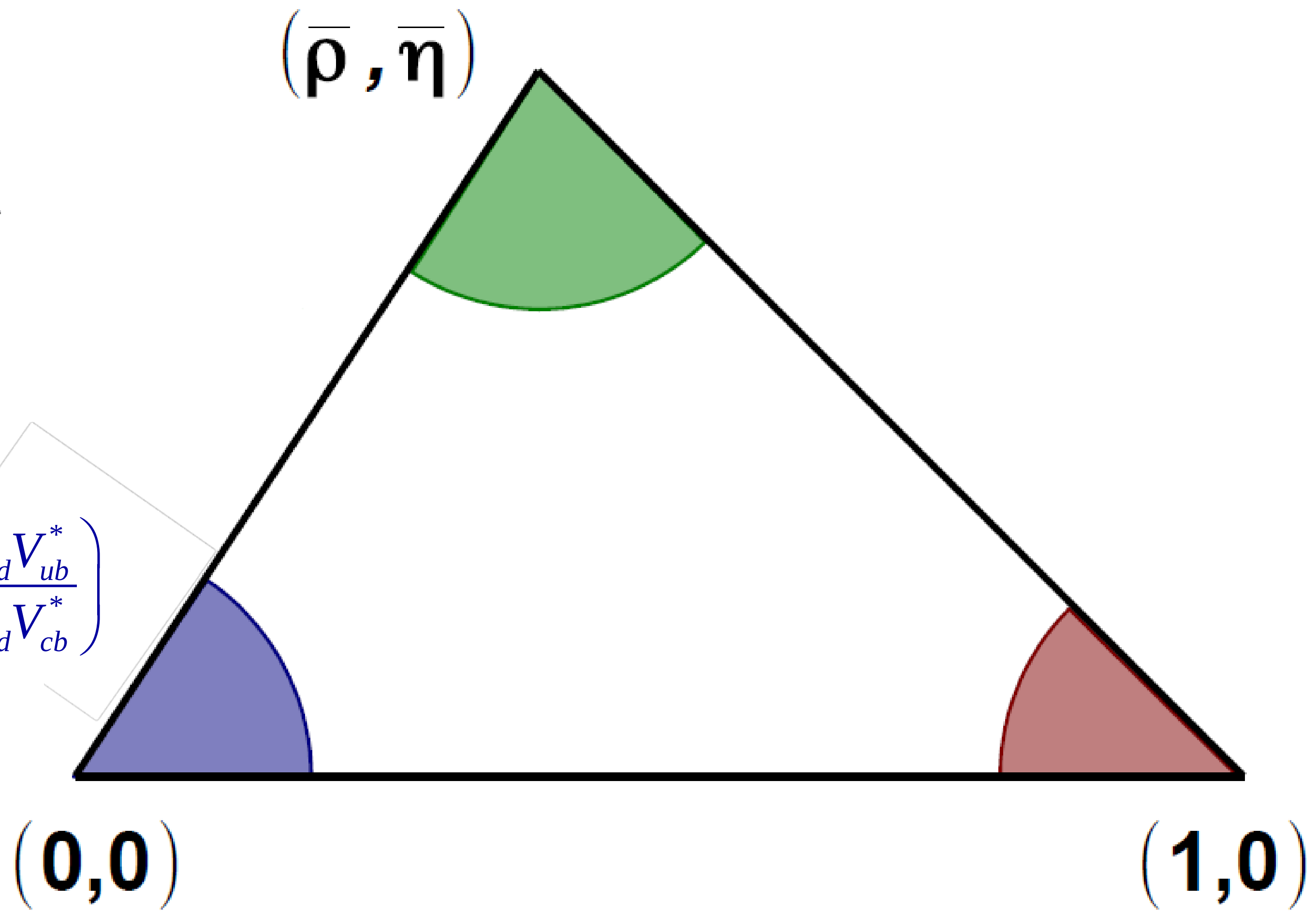
$B^0 \to D^- K^0 \pi^+$

$B^0 \to D^{(*)} \pi$

$B^0 \to D^{(*)} \rho$

$+$ *charmless*

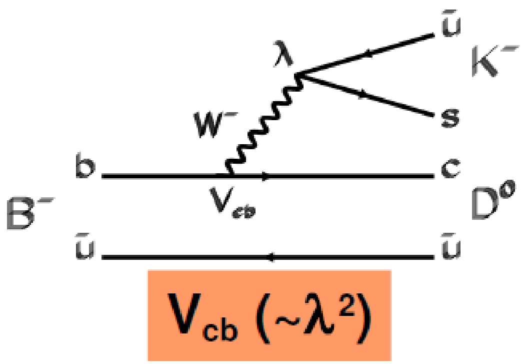
$$\gamma = \arg\left(-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)$$

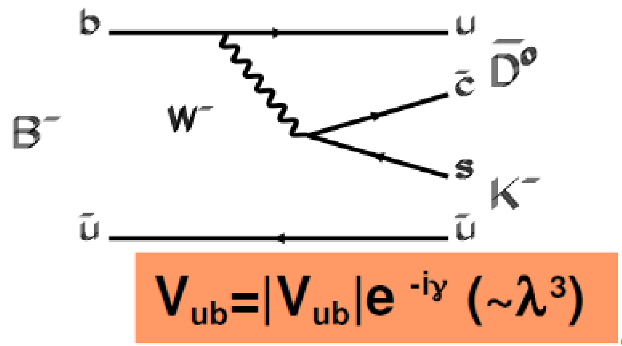


$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

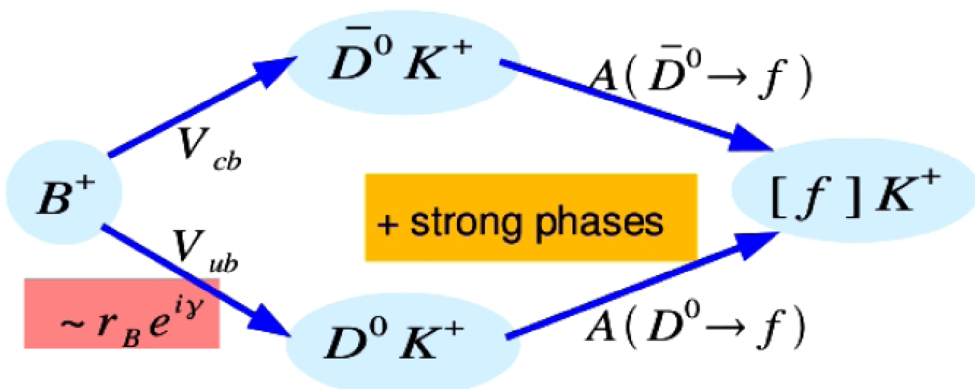
γ measurement in $B \to D^{(*)}K^{(*)}$

- interference of tree diagrams: theoretically clean (no penguin pollution)





- direct CP violation used ~ no time-dependent CP asymmetry, just rates



- not sensitive to New Physics ~ theoretically clean determination of γ
- theory uncertainties from hadronic parameters

Flavour physics beyond the SM

$$\mathscr{L}_{eff} = \mathscr{L}_{gauge}(A_a, \psi_i) + \mathscr{L}_{Higgs, Yukawa}(\phi, A_a, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$$M(B_d - \bar{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP} \frac{1}{\Lambda^2}$$

Λ = *effective scale of new physics*

Isidori (2012)

c_{NP}:

- ~ 1 — tree/strong + generic flavor → $\Lambda \gtrsim 2\times 10^4$ TeV [K]
- $\sim 1/(16\pi^2)$ — loop + generic flavor → $\Lambda \gtrsim 2\times 10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ — tree/strong + “alignment” → $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2)$ — loop + “alignment” → $\Lambda \gtrsim 0.5$ TeV [K & B]

New flavor-breaking sources at the TeV scale (if any) are highly tuned

Minimal Flavor Violation

- Global $U(3)^5$ flavor symmetry in the SM

$$G_{\text{global}} = U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$$

  – the symmetry is already broken by Yukawa couplings
  – Generic flavor-violating interactions at $\Lambda \simeq$ TeV are already excluded

- The hypothesis of minimal flavor violation (MFV)

  – The Yukawa couplings are the only source of the flavor and CP violation in and beyond the SM

- The Effective Field Theory approach with MFV

$$\mathcal{L}_{SM} + \frac{c_{\alpha\beta}}{\Lambda_{NP}^2} \overline{Q}_\alpha \gamma^\mu Q_\beta \overline{E}_R \gamma_\mu E_R + \ldots$$

$$\text{MFV} \;\rightarrow\; c_{\alpha\beta} = (Y_U)_{\alpha\gamma} \left(Y_U^\dagger\right)_{\gamma\beta} \simeq V_{ti}^* V_{tj} y_t^2$$

  – The predictions have the SM flavor structure

$$\mathcal{A}(d^i \to d^j)_{MFV} = (V_{ti}^* V_{tj}) \mathcal{A}_{SM}^{(\Delta F=1)} \left(1 + \frac{(4\pi)^2 y_t^2 M_W^2}{\Lambda_{NP}^2}\right)$$

Minimal Flavor Violation

- MFV is not a theory of flavor but a simple framework for flavor structure of NP from EFT point of view

Minimally flavour violating dimension six operator	main observables	Λ [TeV] $-$	$+$
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	ϵ_K, Δm_{B_d}	6.4	5.0
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi$, $\epsilon'/\epsilon, \ldots$	~ 1	

- MFV framework can be implemented for a given BSM scenario (e.g. SUSY, 2HDM,…)

- The bound for flavor cutoff scale is reduced from O(1000) TeV to O(1) TeV

- MFV is very predictive but its justification in the new physics scenario is questionable

Quo vadis flavour physics?

From precision tests of the SM

- CKM determination
- FCNC processes

to New Physics Discoveries?

- ε'/ε and rare kaon decays
- B physics anomalies and lepton flavour universality
- lepton flavour violation and $(g-2)_\mu$

➢ **NP sensitivity well beyond the TeV scale**

Recent anomalies in the flavour sector

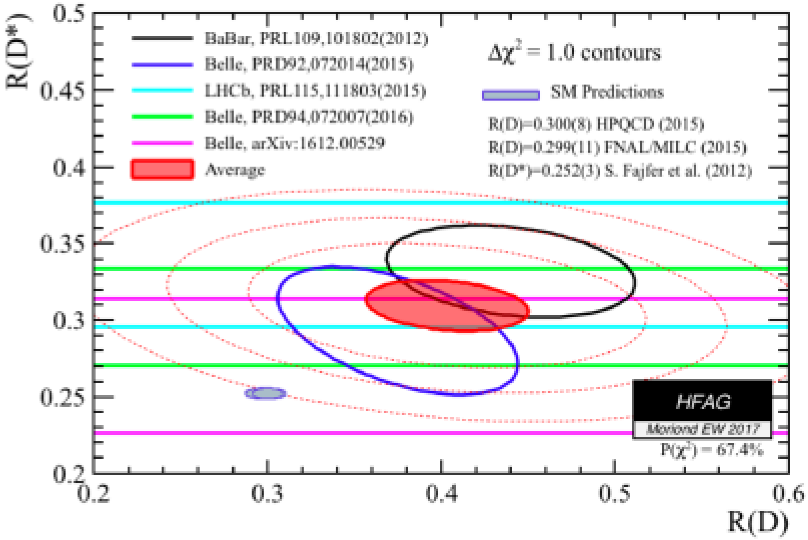
- tension in CP violation in $K \to \pi\pi$ decays
- 3.9σ anomaly in semi-tauonic B decays
- various $2-3\sigma$ tensions in $b \to s\mu^+\mu^-$ transitions and $R_{K^{(*)}}$

Monika Blanke FPCP 2017

Semi-tauonic decays $B \to D^{(*)}\tau\nu$

Test of lepton flavour universality (LFU) in semi-leptonic B decays

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$



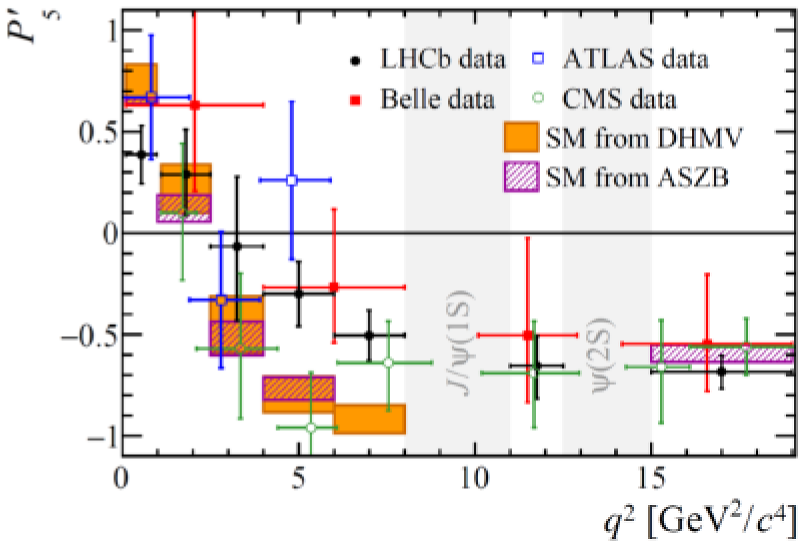
- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb ($R(D^*)$ only)
- 3.9σ tension between HFAG fit and SM value

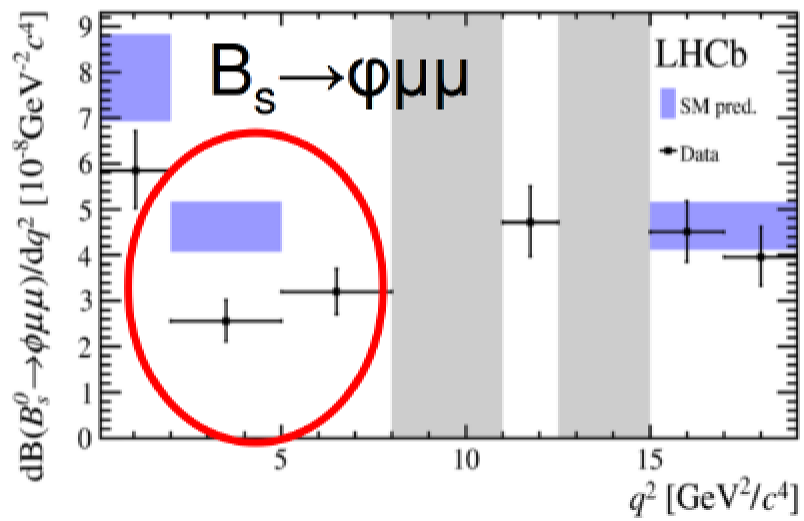
Note: anomaly mainly driven by leptonic τ decays

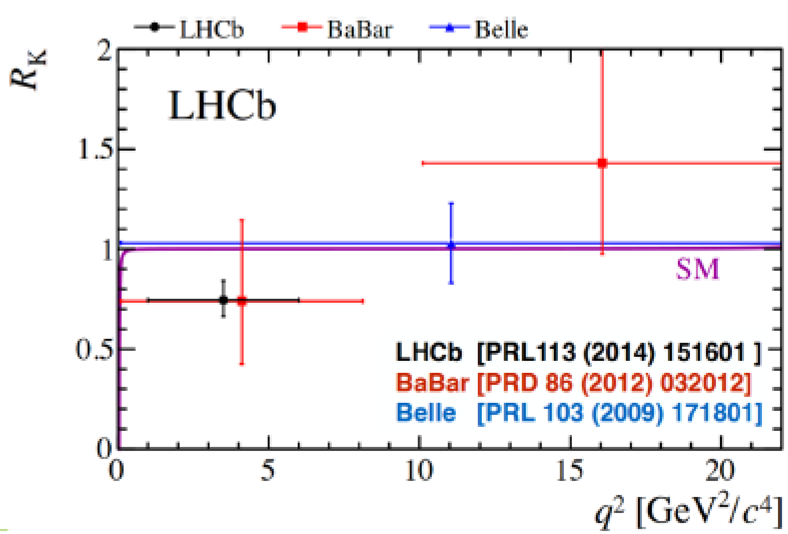
Semileptonic $b \to s$ transitions

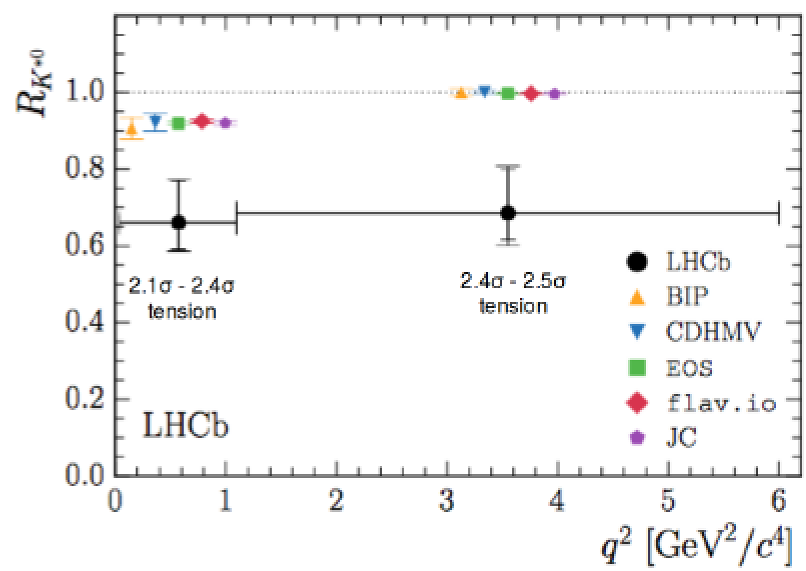
anomalous penguins

The $b \to s\mu^+\mu^-$ transitions and LFU



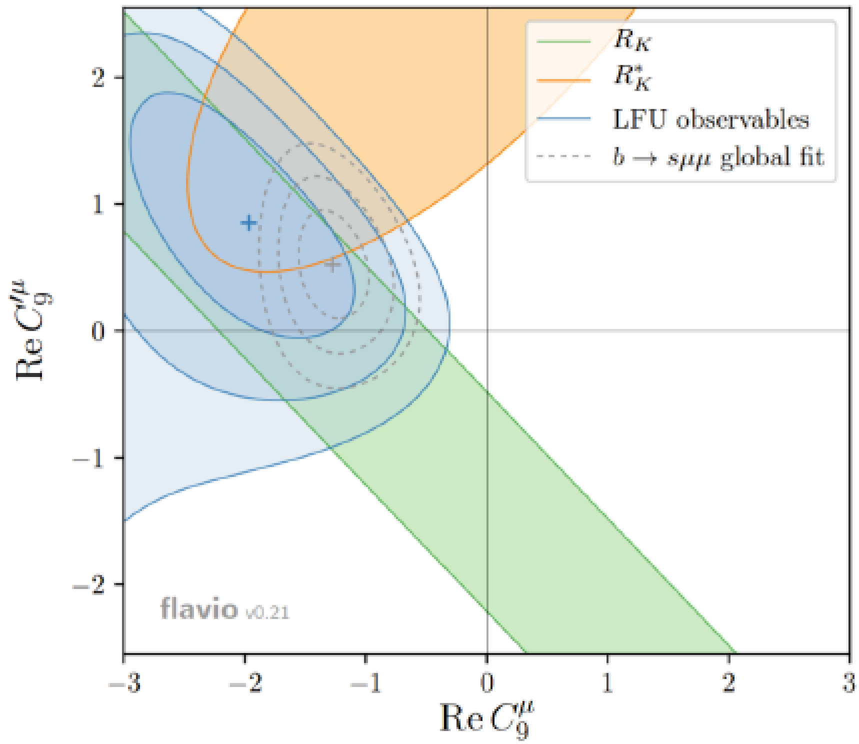






Global analysis

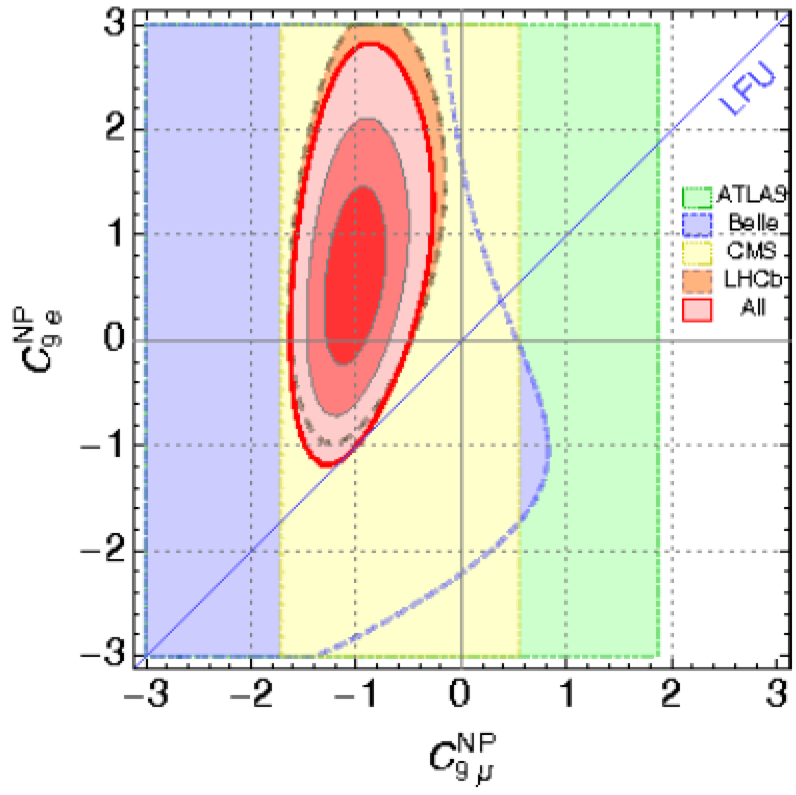
Altmannshofer, Stangl, Straub (2017)
see also Capdevila et al. (2017)



➢ **consistent fit for $C_9^{\mathrm{NP}} \simeq -1$**, non-zero $C_9'^{\mathrm{NP}}$, C_{10}^{NP} possible
$\sim 4-5\sigma$ deviation from SM

Yet not quite global experimentally

Capdevila et al. (2017)
see also Altmannshofer, Stangl, Straub (2017)



➢ **dominated by LHCb – we need independent cross-check!**