B mesons and CP violation

Tests of the Standard Model of Particle Physics II, SS 2020

Prof. Dr. H. Kroha

(updates by Dr. M. Spalla)

Flavor mixing in quarks (1)

- In quarks, the weak SU(2) eigenstates are different from the mass eigenstates
  - ➢Mass eigenstates: mass operator is diagonal, fixed masses
  - ➢Weak eigenstates: left-handed SU(2) doublet and right-handed SU(2) singlet

  - Experimental evidence from weak decays of K, D and B mesons

- The mass eigenstates U_L' and D_L' are connected to the weak eigenstates U_L and D_L by unitary transforms

$$U_L' = (u', c', t')_L \qquad \qquad U_L' = U_u^\dagger U_L$$

$$D_L' = (d', s', b')_L \qquad \Rightarrow \qquad D_L' = U_d^\dagger D_L$$

Flavor mixing in quarks (2)

- Charged weak interaction mediates transition between weak eigenstates within each generation

$$
\begin{aligned}
\mathcal{L}_{CC} &= -\frac{g}{\sqrt{2}}[j^{\mu+}_{CC}W^-_\mu + j^{\mu-}_{CC}W^+_\mu] \\
&= -\frac{g}{\sqrt{2}}\left[(\overline{U}_L\gamma^\mu 1 D_L)W^-_\mu + (\overline{D}_L\gamma^\mu 1 U_L)W^+_\mu\right] \\
&= -\frac{g}{\sqrt{2}}\left[(\overline{U}'_L U^\dagger_u\gamma^\mu U_d D'_L)W^-_\mu + (\overline{D}'_L U^\dagger_d\gamma^\mu U_u U'_L)W^+_\mu\right] \\
&= -\frac{g}{\sqrt{2}}\left[(\overline{U}'_L\gamma^\mu V_{CMK} D'_L)W^-_\mu + (\overline{D}'_L V^\dagger_{CKM}\gamma^\mu U'_L)W^+_\mu\right]
\end{aligned}
$$

- The unitary matrix $V_{CKM} = U_u^+ U_d$ (Cabibbo-Kobayashi-Maskawa matrix) describes charged weak interactions between quark mass eigenstates

Flavor mixing in quarks (3)

- V_{CKM} is responsible for flavor mixing in quarks

- Not diaginal: transition between different generations due to charged weak current

$$\begin{pmatrix} u' \\ c' \\ t' \end{pmatrix} \longleftrightarrow \begin{pmatrix} d_C \\ s_C \\ b_C \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

  - E.g.

$$u' \leftrightarrow d_C = V_{ud}d' + V_{us}s' + V_{ub}b'$$

Number of independent parameters in V_{CKM} (1)

- For n=2 generations (before discovery of *b*)
  - One real parameter (Cabibbo angle θ_C)
  - No complex phase

- Cabibbo matrix:

$$V = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

$$\Rightarrow \quad \sin\theta_C \approx 0.23$$

$$\Rightarrow \quad \cos\theta_C \approx 0.95$$

Number of independent parameters in V_{CKM} (2)

- For n=3 generations
  - 3 real parameters
    - ➢mixing angles θ_{ij} *(i,j = 1,2,3 with j>i)*
  - and 1 complex phase $e^{i\delta}$
    - ➢$V^*_{CKM} \neq V_{CKM}$ for at least 3 generations

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

With: $c_{ij} = \cos\theta_{ij} > 0, \ \ s_{ij} = \sin\theta_{ij} > 0$

V_{CKM} parameters

- The complex phase of V_{CKM} allows CP-violation within Standard Model
  - Occurs for weak interaction
  - Originates from fermion to Higgs coupling, i.e. the mass matrix

- Elements of V_{CKM} not predicted by Standard Model
  - Need to be determined experimentally
  - Very active field, particularly in heavy quarks physics (c, b, t)

Experimental information on V_{CKM} (1)

	Known from:
$\lvert V_{ud} \rvert$	nuclear β decays, neutron lifetime
$\lvert V_{us} \rvert$	semileptonic kaon decay ($K \to \pi \ell \nu_\ell$), also hyperon and τ decays
$\lvert V_{ub} \rvert$	semileptonic B decay ($B \to X_u \ell \nu_\ell : b \to u$)
$\lvert V_{cd} \rvert$	semileptonic D decays ($D \to \pi \ell \nu_\ell : c \to d$), c production in neutrino scattering
$\lvert V_{cs} \rvert$	semileptonic D decays ($D \to K \ell \nu_\ell : c \to s$)
$\lvert V_{cb} \rvert$	semileptonic B decays ($b \to c$)
$\lvert V_{td} \rvert$	$B_d^0 \bar{B}_d^0$ mixing
$\lvert V_{ts} \rvert$	$B_s^0 \bar{B}_s^0$ mixing
$\lvert V_{td} / V_{ts} \rvert$	combination of $B_d^0 \bar{B}_d^0$ and $B_s^0 \bar{B}_s^0$ mixing, $B \to X_s \gamma$ decay
$\lvert V_{ts} / V_{cb} \rvert$	$B \to X_s \gamma$ decay
$\lvert V_{tb} \rvert$	top quark decay ($t \to b W^+$)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Source: Particle Data Group (2019), http://pdg.lbl.gov/2019/reviews/rpp2019-rev-ckm-matrix.pdf

Experimental information on V_{CKM} (2)

- Best determination of V_{CKM} magnitudes comes from global fit to all measurements:

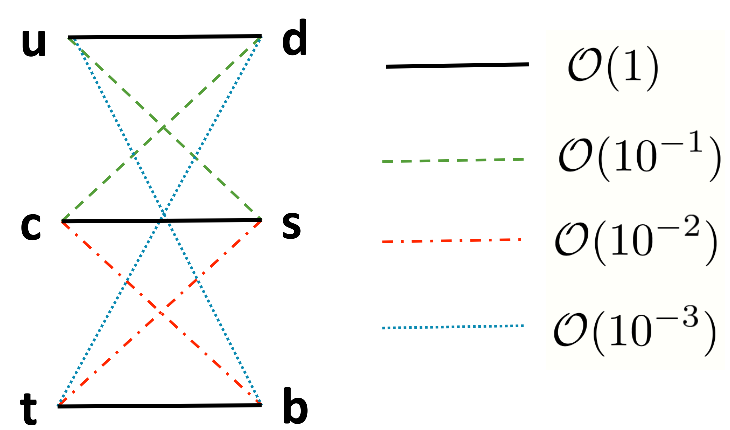
$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

Source: Particle Data Group (2019),
http://pdg.lbl.gov/2019/reviews/rpp2019-rev-ckm-matrix.pdf

- There's a clear hierarchy:

$$s_{12} = 0.22 \gg s_{23} = \mathcal{O}(10^{-2}) \gg s_{13} = \mathcal{O}(10^{-3})$$

$$m_t = 174\ \mathrm{GeV} \quad m_b = 5\ \mathrm{GeV} \quad m_c \approx 1.6\ \mathrm{GeV}$$



Wolfenstein parametrisation of V_{CKM}

- Useful tool for phenomenological considerations
- The hierarchical structure of V_{CKM} becomes very transparent

$$s_{12} \equiv \lambda = 0.22, \quad s_{23} \equiv A\lambda^2, \quad s_{13}e^{-i\delta_{13}} \equiv A\lambda^3(\rho - i\eta)$$

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

The Unitarity Triangle (1)

- Orthogonality condition of V_{CKM} columns defines triangles in the complex ρ-η plane

$$\begin{aligned} V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} &= 0, \\ V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} &= 0, \\ V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} &= 0, \end{aligned}$$

- The third triangle has nonzero surface if we have a nonzero complex phase: $\delta \neq 0$ (which implies $V_{ub} \neq 0$)
  - i.e. if there is CP-violation

V_{ub}

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

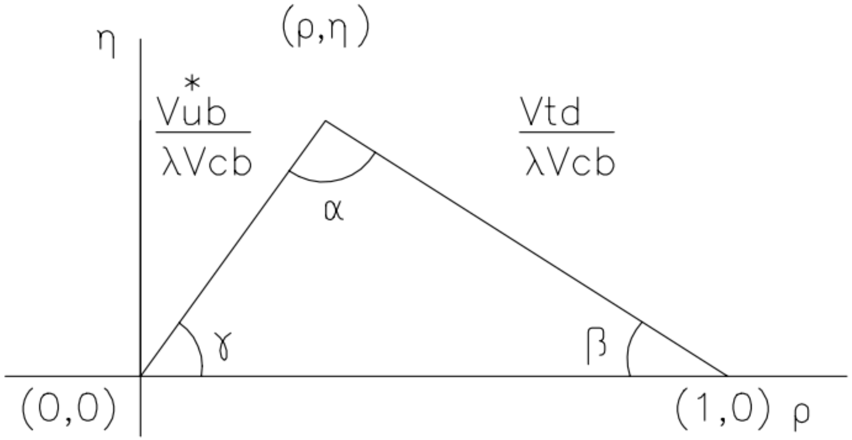
The Unitarity Triangle (2)

- Orthogonality condition of V_{CKM} columns defines triangles in the complex ρ-η plane

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

$$\frac{V_{ub}^*}{\lambda V_{cb}} + \frac{V_{td}}{\lambda V_{cb}} = 1$$

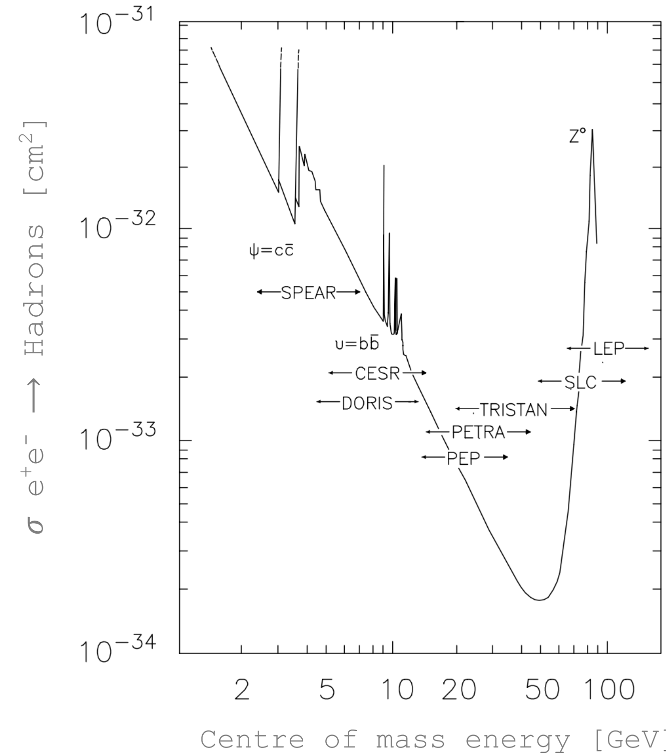
- The triangles have nonzero surface if the complex phase is different from 0: $\delta \neq 0$
  - i.e. if there is CP-violation



$$V_{td} = |V_{td}|e^{-i\beta},\ V_{ub} = |V_{ub}|e^{-i\gamma}$$

- The most useful, to study V_{CKM} unitarity, is the third equation
  - Describes CP-violation in B mesons decay
    - large $B^0\bar{B}^0$ mixing and V_{ub}/V_{cb} not so small imply large area, which imply strong CP violation in B's

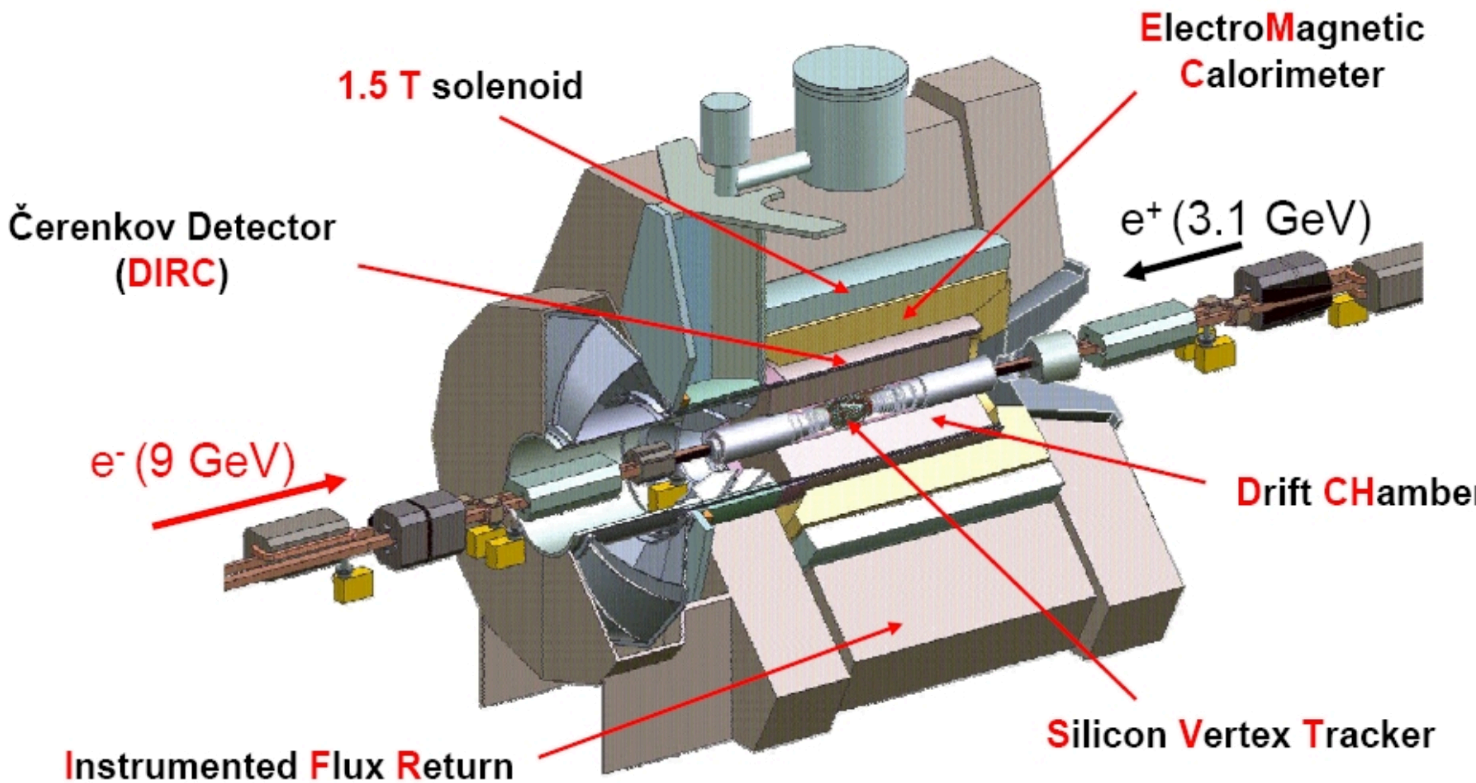
B mesons production



Exp.	Lifetime	$\sigma(b\bar{b})$	$N_{B\bar{B}}$	Process
LEP	1989 - 2000	7 nb	10^6 /Exp.	$e^+e^- \rightarrow Z^0 \rightarrow b\bar{b} \rightarrow B\bar{B} + X$
CLEO	1979 - 2008	1 nb	$2.0 \cdot 10^7$	$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
BaBar	1999 - 2008	1 nb	$2.5 \cdot 10^8$	$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
BELLE	1999 - 2010	1 nb	$4 \cdot 10^8$	$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
CDF/D0	1983 - 2011	0.1 mb	$1.5 \cdot 10^{10}$	$p\bar{p} \rightarrow b\bar{b} + X$
LHCb	2010 -	0.5 mb (14 TeV)	$\sim 10^{12}$ $b\bar{b}$/year (expected)	$pp \rightarrow b\bar{b} + X$
BELLE 2	2019 -	1 nb	$5 \cdot 10^{10}$ (expected)	$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

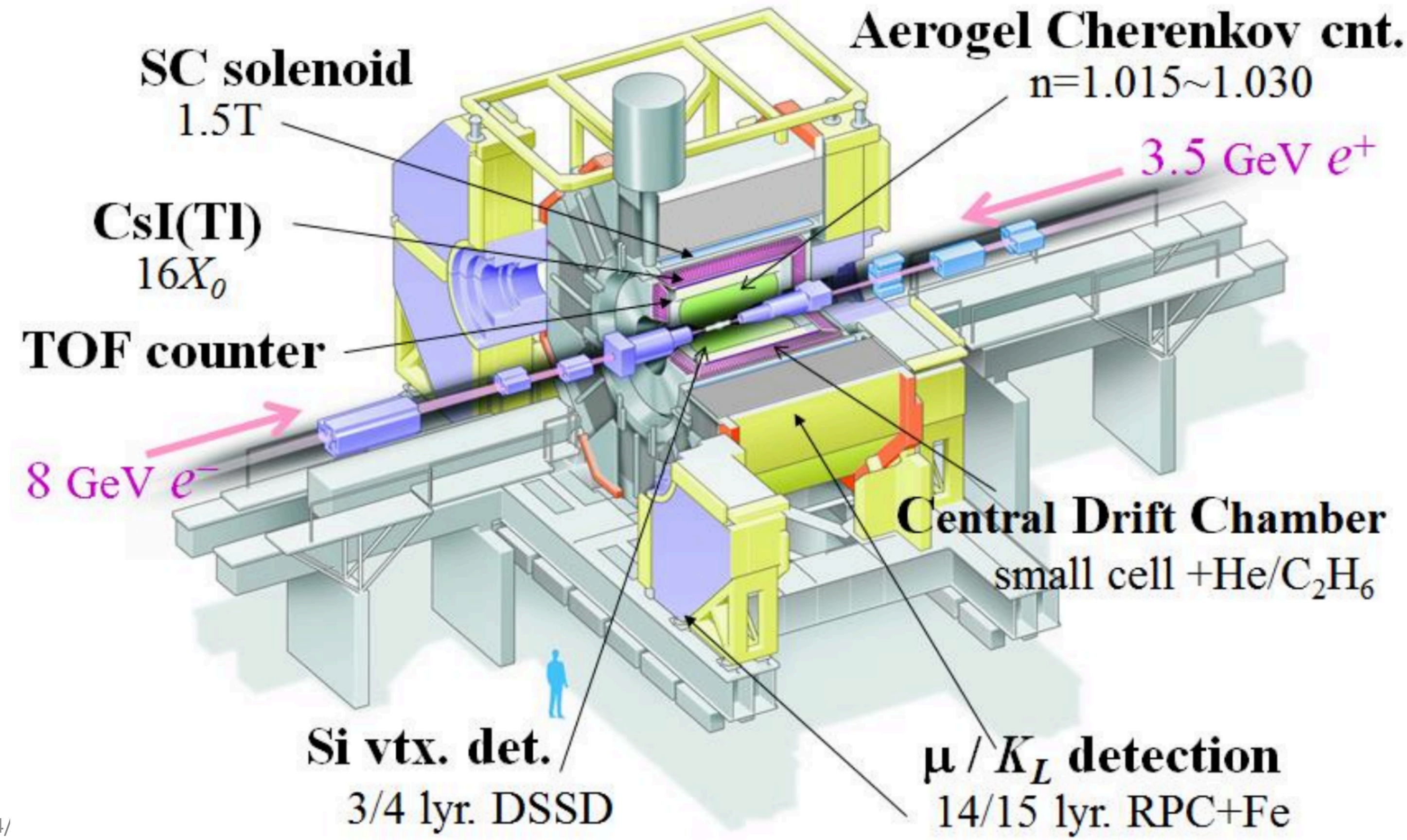
B factories: BaBar detector

- On PEP-II collider in SLAC



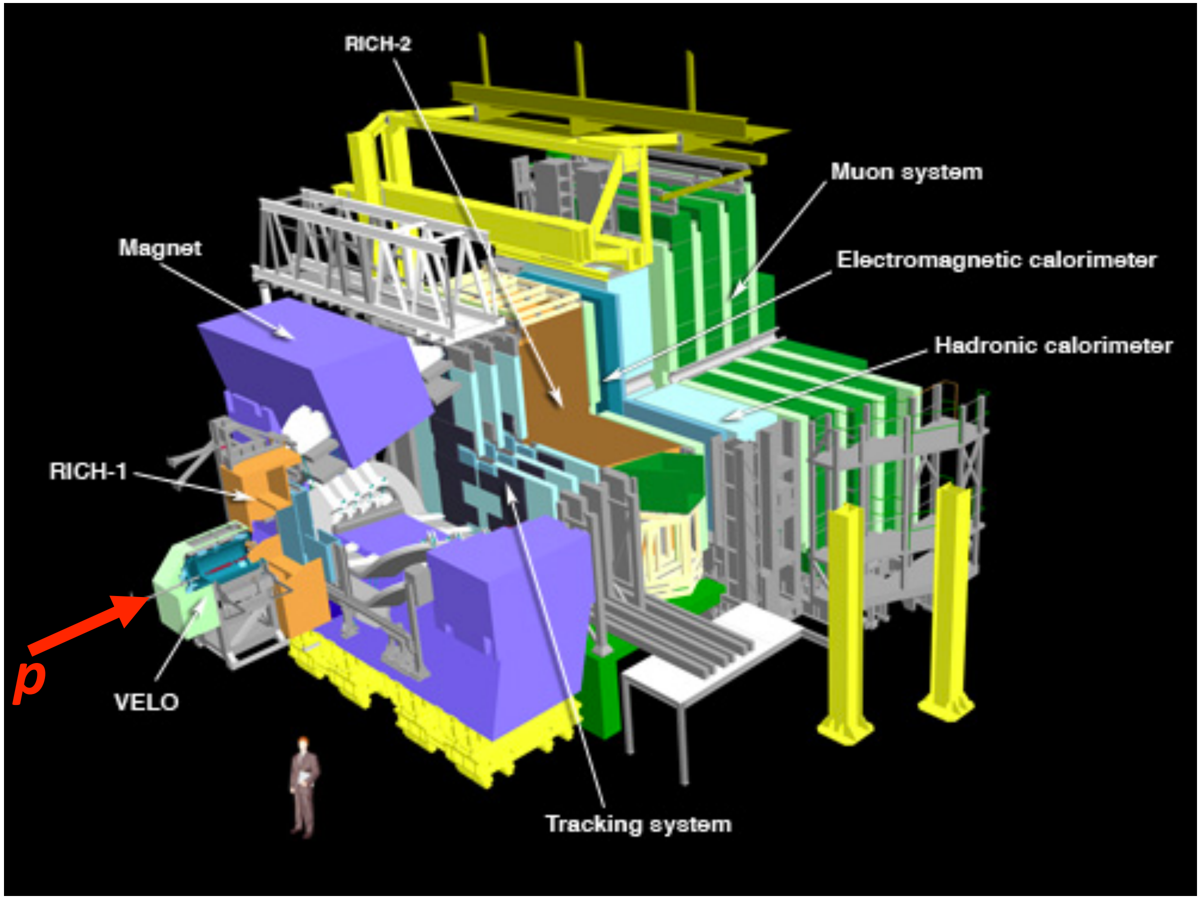
B factories: Belle detector

- On the KEK-B storage ring at the KEK Accelerator Center, Japan
- New detector (Belle 2) recently started operations



A B-dedicated detector at hadron colliders: LHCb

- On the LHC at CERN
  - 1-arm spectrometer: focusing on $b\bar{b}$ production in the forward direction



Weak decays of B mesons (1)

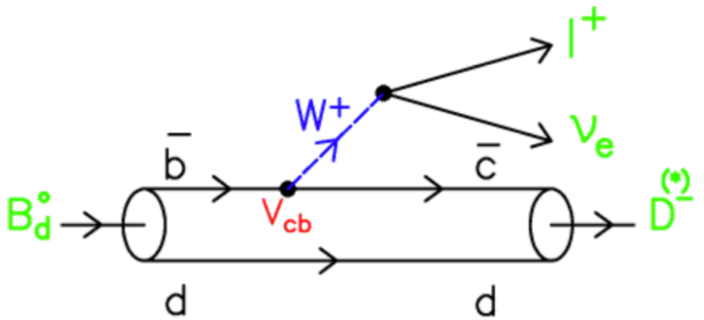
- B-mesons:

  $$B^+ = (\bar{b}u),\ B_d^0 = (\bar{b}d),\ B_s^0 = (\bar{b}s)$$

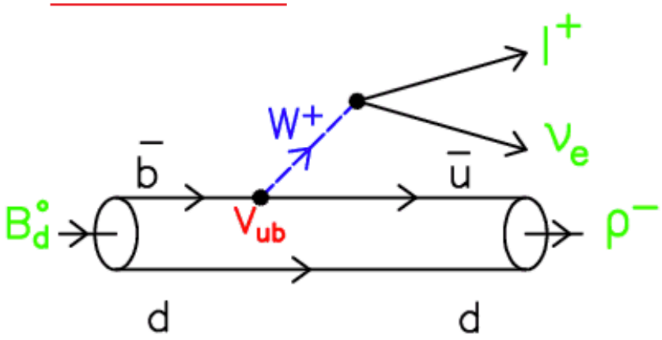
- Semileptonic decays
  - ➢BR ~ 20% ($\ell = e, \mu$)
  - $b \to c\ell\nu_\ell$ (e.g. $B^0 \to D^{(*)-}\ell^+\nu_\ell$)
  - $b \to u\ell\nu_\ell$ (e.g. $B^0 \to \rho^-\ell^+\nu_\ell$)

- Allow to access $|V_{cb}|$ and $|V_{ub}|$
  - by measuring BR of weak semileptonic decay

$b \to c\ell\nu$



$b \to u\ell\nu$



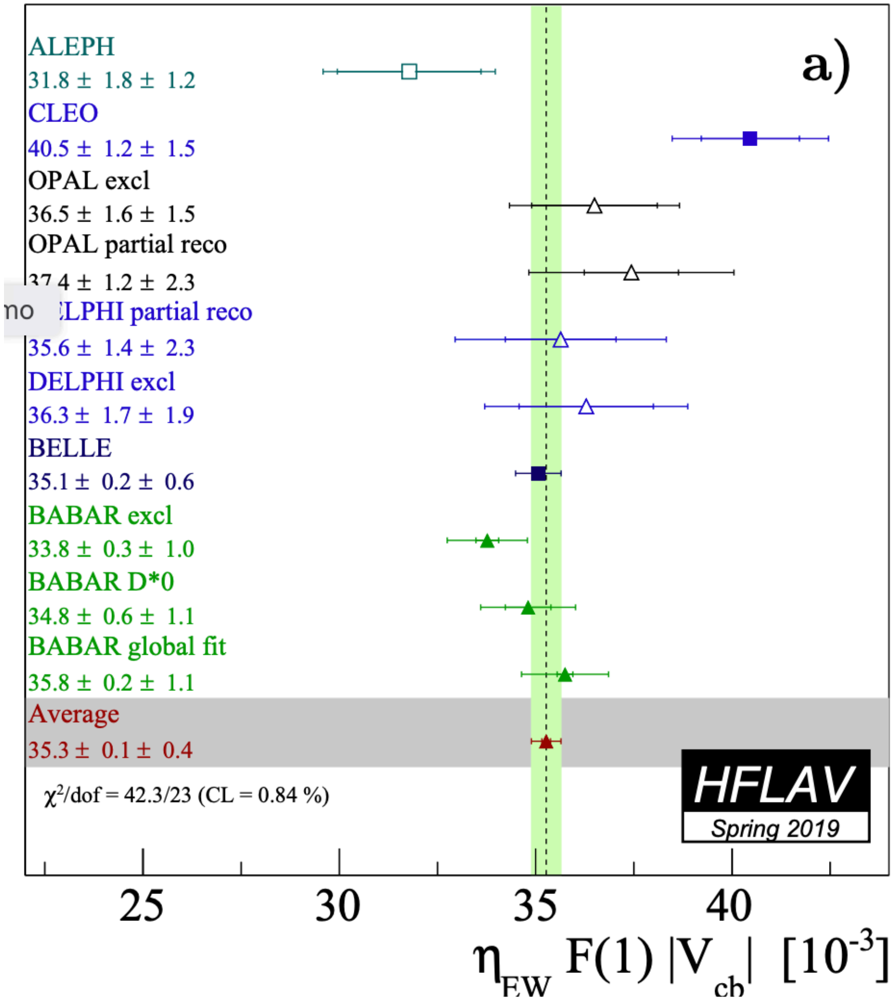
Weak decays of B mesons (2)

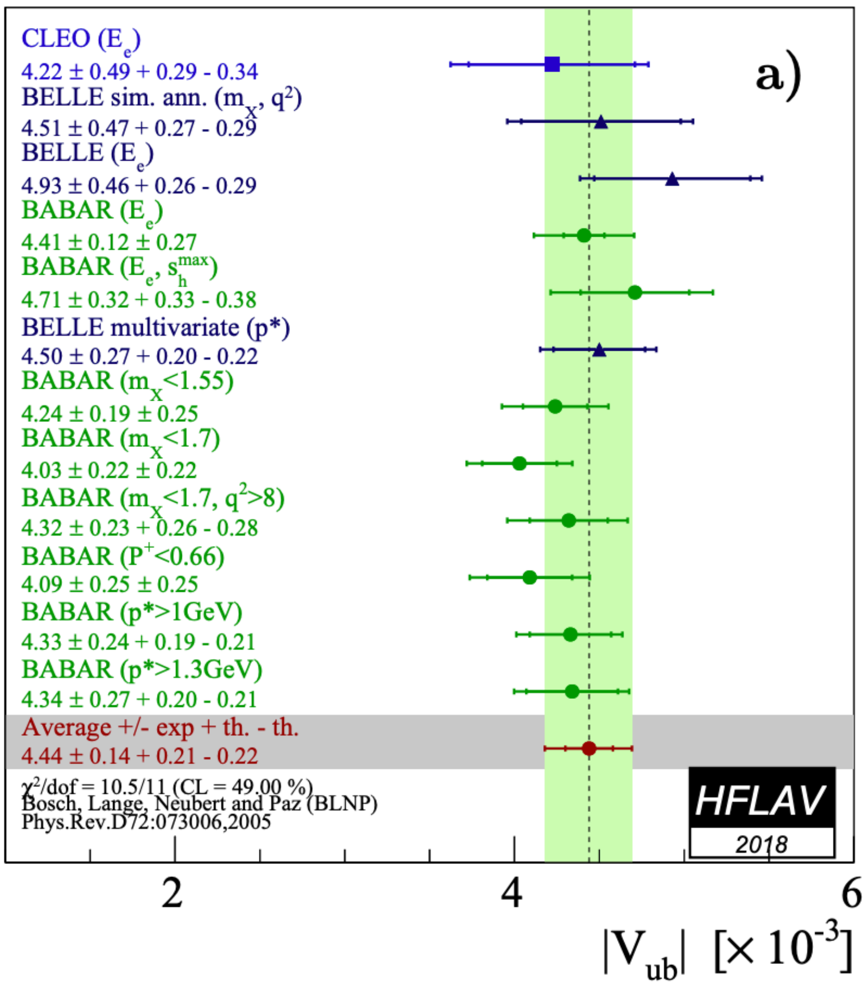
- Allow to access $|V_{cb}|$ and $|V_{ub}|$
  - by measuring BR of weak semileptonic decay

$$
\begin{aligned}
BR(B \to X\ell\nu_\ell) &= \frac{\Gamma(B \to X\ell\nu_\ell)}{\Gamma^B_{\mathrm{tot}}} \\
&= \frac{G_F^2 m_b^5}{192\pi^3}(r_c(x)|V_{cb}|^2 + r_u(x)|V_{ub}|^2) \\
&\cdot \quad (1 + \delta_{QCD}) \cdot \tau_B
\end{aligned}
$$

- $\Gamma^B_{\mathrm{tot}} = \tau_B^{-1}$
- $r_q(x)$ = phase space factor, with $x = m_q/m_b$ ($r_c \approx 0.5$, $r_u \approx 0.5$)
- δ_{QDC} is a model-dependent QCD correction factor

Measurements of $|V_{cb}|$ and $|V_{ub}|$





Quark flavour oscillation (1)

- Particle-antiparticle oscillation in neutral mesons.
  - Weak interaction violate flavour conservation.

$$
\begin{aligned}
K^0 = (d\bar{s}) &\longleftrightarrow \overline{K}^0 = (\bar{d}s) \quad (|\Delta S| = 2) \\
D^0 = (c\bar{u}) &\longleftrightarrow \overline{D}^0 = (\bar{c}u) \quad (|\Delta C| = 2) \\
B_d^0 = (d\bar{b}) &\longleftrightarrow \overline{B}_d^0 = (\bar{d}b) \quad (|\Delta B| = 2) \\
B_s^0 = (s\bar{b}) &\longleftrightarrow \overline{B}_d^0 = (\bar{s}b) \quad (|\Delta B| = 2).
\end{aligned}
$$

- Predicted by Gell-Mann and Pais in 1955 for the K^0 mesons

- Flavour eigenstates are different from mass/CP eigenstates
  - Flavour eigenstates: K^0 (S=-1) and $\overline{K}^0$ (S=1)
  - CP-eigenstates with defined masses and half-lives:
    - K_S^0 (K-short):

$$\tau_S \approx 10^{-10}\text{ s};\ K_S^0 \to \pi^+\pi^-,\ \pi^0\pi^0\ (CP = +1).$$

    - K_L^0 (K-long):

$$\tau_L \approx 10^{-7}\text{ s};\ K_L^0 \to \pi^+\pi^-\pi^0,\ \pi^0\pi^0\pi^0\ (CP = -1).$$

Quark flavour oscillation (2)

- Time evolution of $K^0\overline{K}^0$ system

$$\phi(t) >= a(t)|K^0 > + b(t)|\overline{K}^0 >= \begin{pmatrix} a(t) \\ b(t) \end{pmatrix},$$

$$|K^0 >= \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \overline{K}^0 = \begin{pmatrix} 0 \\ 1 \end{pmatrix},$$

- In Schrödinger formalism:

$$i\frac{\partial}{\partial t}|\phi >= H\phi >$$

  - Where H is an effective Hamiltonian ($H^+ \neq H$): $H = \hat{M} - i\hat{\Gamma}/2$
    - ➤ $\widehat{M}$ and $\widehat{\Gamma}$ being the mass and decay matrices
    - ➤ not diagonal, as $K^0\overline{K}^0$ are not mass eigenstates

$$\widehat{M} - \frac{i}{2}\widehat{\Gamma} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

Quark flavour oscillation (3)

- $K^0\overline{K}^0$ effective Hamiltonian: $H = \hat{M} - i\hat{\Gamma}/2$
  - CPT invariance implies: $m_{11} = m_{22},\ m_{21} = m_{12}^*$
  - While assuming CP invariance one has: $m_{12} = m_{21} = m_{12}^*$

$$\widehat{M} - \frac{i}{2}\widehat{\Gamma} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

$$= \begin{pmatrix} m_K & m_{12} \\ m_{12} & m_K \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_K & \Gamma_{12} \\ \Gamma_{12} & \Gamma_K \end{pmatrix}$$

Where:

$$m_K = \frac{m_S + m_L}{2}$$

$$\Gamma_K = \frac{\Gamma_S + \Gamma_L}{2}$$

➤CP-violation in mixing will be due to

$$m_{12} \neq m_{21}$$

i.e.

$$P(K^0 \to \overline{K}^0) \neq P(\overline{K}^0 \to K^0)$$

Quark flavour oscillation (4)

- Diagonalizing the Hamiltonian, the two mass states K_L and K_S are defined
  - Without CP violation, they are also eigenstates of CP

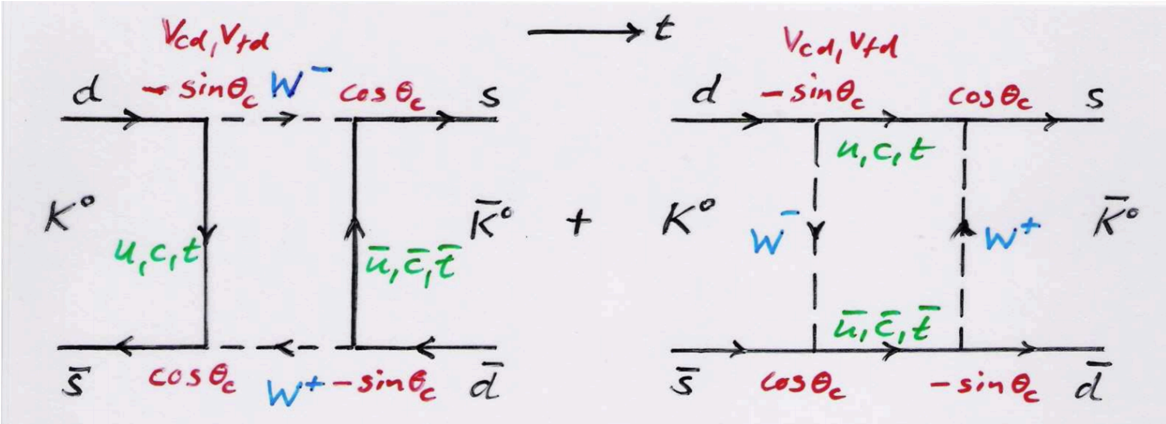
$$K_S^0 = \frac{1}{\sqrt{2}}(K^0 + \overline{K}^0);$$
$$K_L^0 = \frac{1}{\sqrt{2}}(K^0 - \overline{K}^0),$$

  - Masses and half-lives defined by:

$$m_{S,L} = m_K \pm \mathcal{R}e\sqrt{\left(m_{12} - \frac{i}{2}\Gamma_{12}\right)\left(m_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$
$$\Gamma_{S,L} = \Gamma_K \mp \mathcal{I}m\sqrt{\left(m_{12} - \frac{i}{2}\Gamma_{12}\right)\left(m_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)} = \tau_{S,L}^{-1}$$

Quark flavour oscillation (5)

- Interactions responsible for mixing (i.e. causing the nonzero m_{12} and Γ_{12} terms)
  - diagrams of second order in the weak interactions (ΔS=2)



- Interaction proportional to the mass of the up-type quark in the loop: *c* contribution dominates over *u* ($m_c >> m_u$)
- *t* contribution is CKM-suppressed (will dominate for $B^0\bar{B}^0$ oscillation)

Quark flavour oscillation (6)

- From diagrams, one can derive:

Cabibbo angle

$$\Delta m \approx \frac{G_F^2}{4\pi^2} f_K^2 m_K m_c^2 \cos^2\theta_C \sin^2\theta_C$$

f_K: kaon decay constant (QCD parameter)

$$\left(\Delta m = m_L - m_S \propto \sqrt{|m_{12}|^2 - |\Gamma_{12}|^2}\right)$$

- And compute the probability of a K^0 oscillating into a $\overline{K}^0$ and vice-versa
  - First, write time evolution for mass eigenstates:

$$K_S^0(t) = \mathcal{N} e^{-(im_S + \frac{\Gamma_S}{2})t} K_S(0)$$
$$K_L^0(t) = \mathcal{N} e^{-(im_L + \frac{\Gamma_L}{2})t} K_L(0).$$

  - then, in the approximation of $\Delta\Gamma = \Gamma_L - \Gamma_S = 0$:

$$K^0(t) = \mathcal{N} e^{-(im_K + \frac{\Gamma_K}{2})t} \left[\cos(\Delta m t/2) K^0 + \sin(\Delta m t/2) \overline{K}^0\right]$$
$$\overline{K}^0(t) = \mathcal{N} e^{-(im_K + \frac{\Gamma_K}{2})t} \left[\sin(\Delta m t/2) K^0 + \cos(\Delta m t/2) \overline{K}^0\right]$$

Quark flavour oscillation (7)

- Probability of a K^0 oscillating into a $\overline{K}^0$ and vice-versa:

$$
\begin{aligned}
\mathcal{P}(K^0 \to K^0(t)) &= |<K^0|K^0(t)>|^2 \\
&= \frac{1}{2\tau_K} e^{-t/\tau_K}(1 + \underline{\underline{\cos \Delta m\, t}}) \\
\mathcal{P}(K^0 \to \overline{K}^0(t)) &= |<\overline{K}^0|K^0>|^2 \\
&= \frac{1}{2\tau_K} e^{-t/\tau_K}(1 - \underline{\underline{\cos \Delta m\, t}})
\end{aligned}
$$

- <u>It oscillates as a function of time, with frequency *Δm*</u>

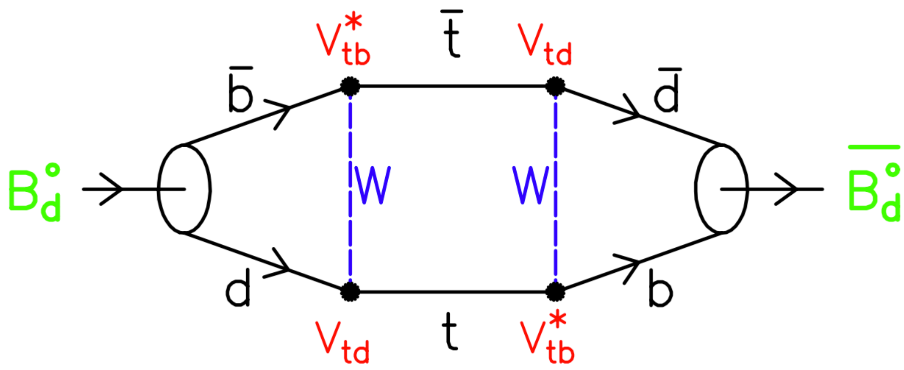
$$\Delta m = (3.489 \pm 0.008) \cdot 10^{-6}\,\mathrm{eV} = (0.530 \pm 0.001) \cdot 10^{10}\,\mathrm{Hz}.$$

  - First measurements in 1964 at BNL

Oscillations in $B^0\overline{B}^0$

$$B_d^0 = (d\bar{b}) \longleftrightarrow \overline{B}_d^0 = (\bar{d}b) \quad (|\Delta B| = 2)$$
$$B_s^0 = (s\bar{b}) \longleftrightarrow \overline{B}_d^0 = (\bar{s}b) \quad (|\Delta B| = 2).$$

- Mixing due to second order weak interaction as for $K^0\overline{K}^0$
  - Here t contribution is dominant (large m_t means large oscillation in B's)



$$\Delta m_d = \frac{G_F^2}{6\pi^2} M_{B_d} m_{\text{top}}^2 F\left(\frac{m_{\text{top}}^2}{M_W^2}\right) \eta_{QCD} (f_{B_d}^2 B_{B_d}) |V_{td} V_{tb}^*|^2$$

$$\Longrightarrow \frac{\Delta m_d}{\Delta m_s} = \frac{M_{B_d}}{M_{B_s}} \cdot \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}} \cdot \frac{|V_{td}|^2}{|V_{ts}|^2} \qquad |V_{ts}| \approx |V_{cb}|$$

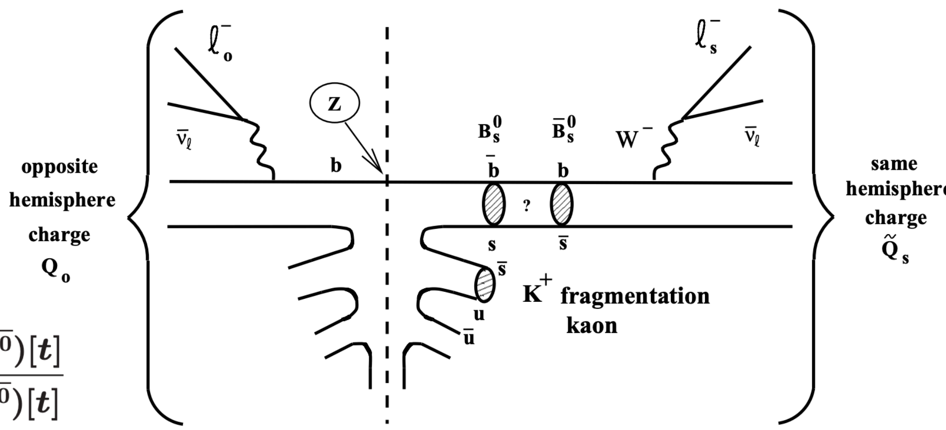
$$\approx (0.88 \pm 0.04)^2 \quad \frac{|V_{td}|^2}{|V_{cb}|^2}$$

$B^0\bar{B}^0$ oscillation measurement (1)

- Distinguish B^0 from $\bar{B}^0$ measuring the lepton charge in semileptonic B decays
- The signal for oscillations is then the fraction of same-charge lepton pairs as a function of the decay time
  - Measured as $t = d/\beta\gamma c$, d is the flight distance from production vertex

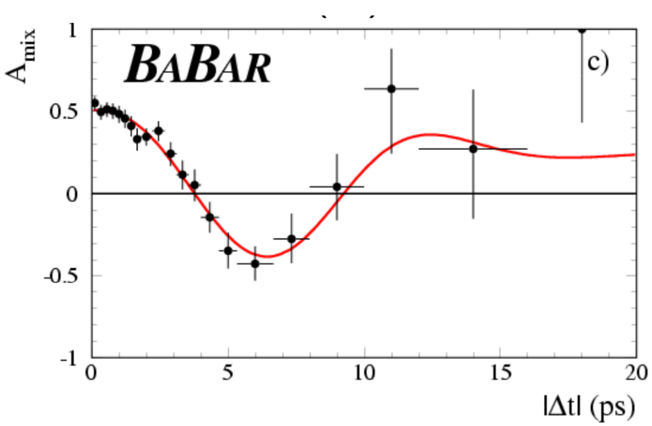
$$\frac{N(\ell^\pm\ell^\pm)[t]}{N_{\text{tot}}(\ell\ell)[t]} = \frac{\mathcal{P}(B^0 \to \overline{B^0})[t]}{\mathcal{P}(B^0 \to B^0)[t] + \mathcal{P}(B^0 \to \overline{B^0})[t]} = \sin^2(\Delta m \cdot t/2)$$

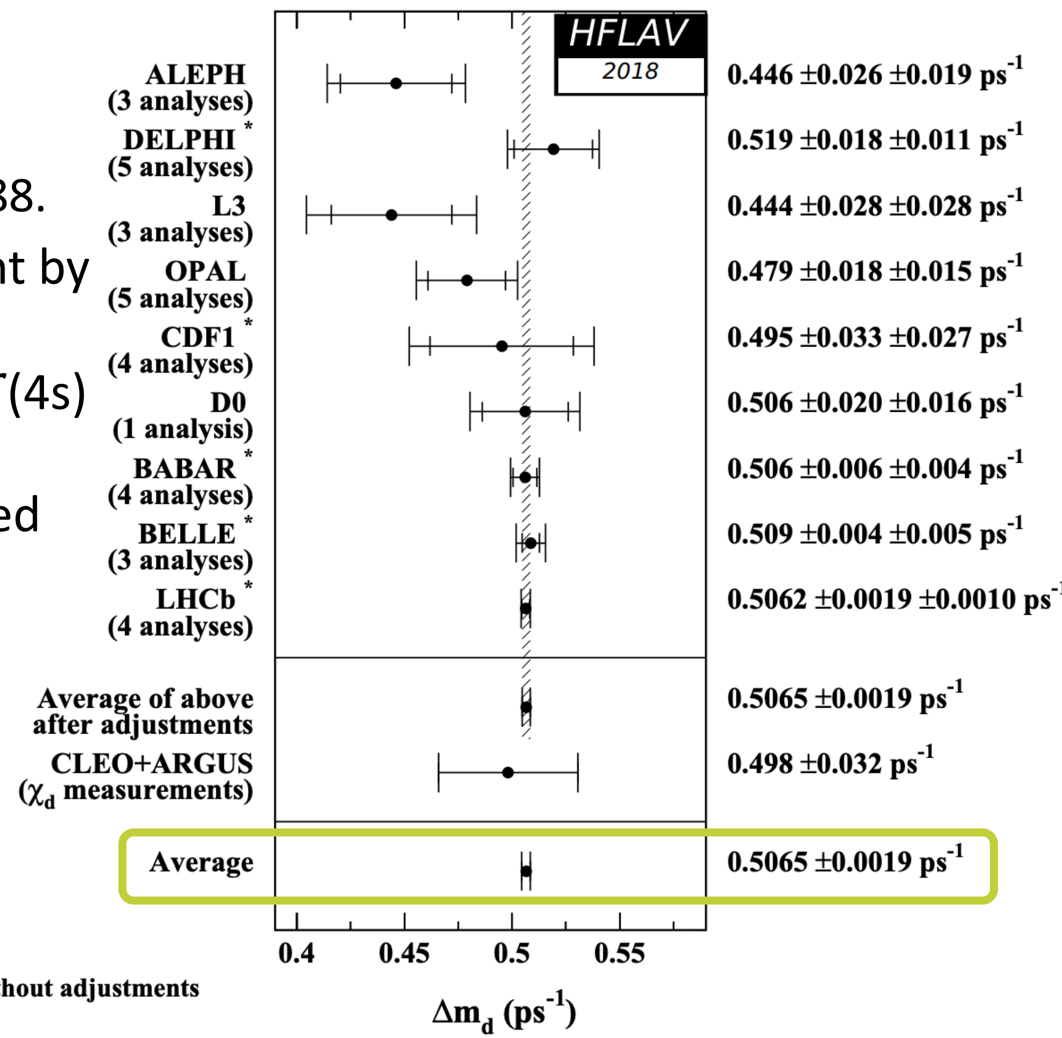
$$A_{\text{mix}}(\ell^\pm\ell^\mp - \ell^\pm\ell^\pm) = \frac{\mathcal{P}(B^0 \to B^0)[t] - \mathcal{P}(B^0 \to \overline{B^0})[t]}{\mathcal{P}(B^0 \to B^0)[t] + \mathcal{P}(B^0 \to \overline{B^0})[t]} = \cos(\Delta m \cdot t)$$



$B_d^0 \bar{B}_d^0$ oscillation

- First discovery:
  - UA1 Experiment at CERN ($Sp\bar{p}S$) 1987,
  - ARGUS Exp. at DESY (DORIS) 1988.
- First time-resolved measurement by ALEPH experiment at LEP
- Observed by B-factories at the Υ(4s) resonance
- Current world-average dominated by LHCb results



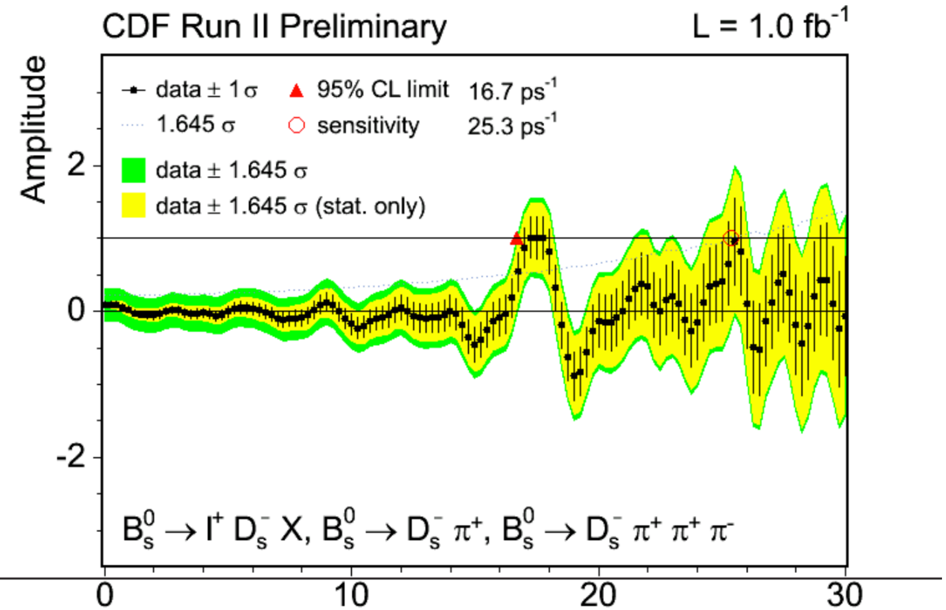


$B_s^0 \bar{B}_s^0$ oscillation measurement

$$\mathcal{P}(B_s^0 \to \overline{B_s^0}) = \frac{1}{2\tau} e^{-t/\tau}(1 - \mathcal{A} \cos \Delta m_s\, t)$$

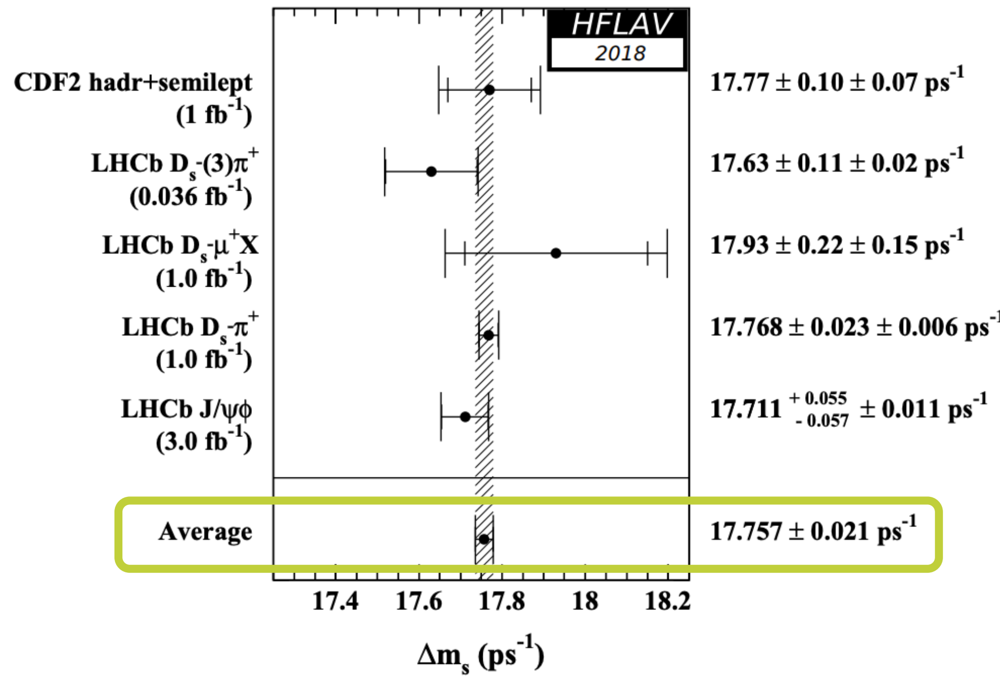
- Measure $\mathcal{P}(B_s^0 \to \overline{B_s^0})$
- One can then analyse A as a function of Δm_s: if oscillation is present, $A(\Delta m_s)=1$
- First measurement:

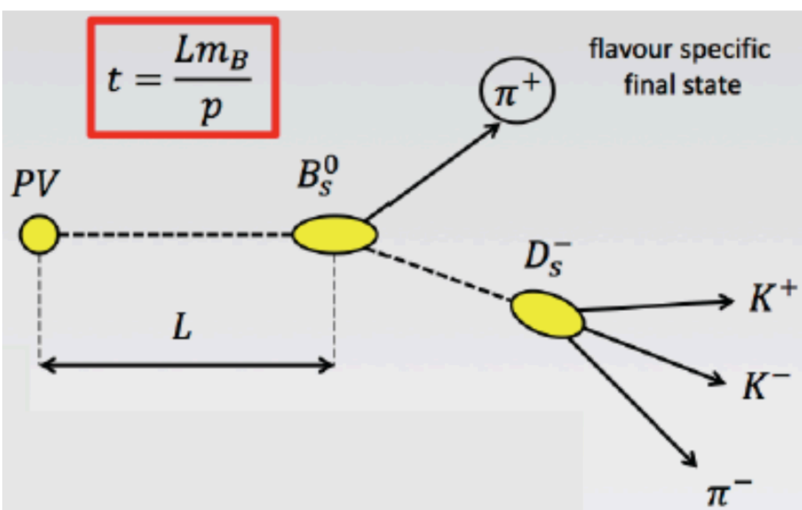
CDF (April 2006): $\Delta m_s = 17.77 \pm 0.12\ \mathrm{ps}^{-1}$

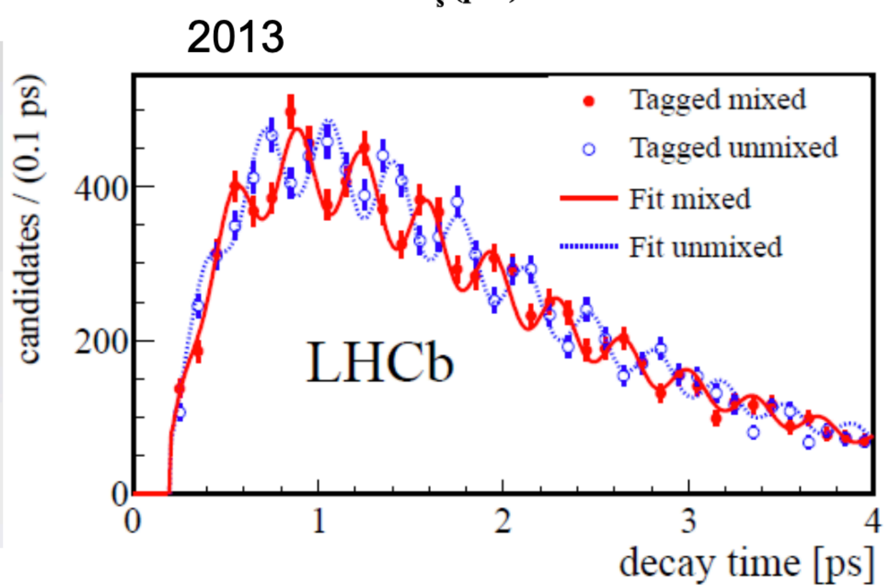


$B_s^0\bar{B}_s^0$ oscillation

- Later measured by LHCb with higher precision
  - Also with direct asymmetry measurement







$|V_{td} / V_{ts}|$

- Information on $|V_{td} / V_{ts}|$ combining B_s^0 and B_d^0
  - Many uncertainties cancel in the ratio
  - More effective in constraining CKM matrix than Δm_d alone

$$\frac{\Delta m_d}{\Delta m_s} \propto \frac{V_{td}}{V_{ts}}$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2053 \pm 0.0004(\text{exp}) \pm 0.0029(\text{lattice}) \, ,$$

- Also measured at B-factories from $b \to d\gamma$ and $b \to s\gamma$ decays
  - less precise measurement, although in agreement with the one from mixing

$$\frac{BR(\overline{B} \to (\rho,\omega)\gamma)}{BR(\overline{B} \to \overline{K}^*\gamma)} \Longrightarrow \frac{|V_{td}|}{|V_{ts}|} = 0.165 \pm 0.055$$

Belle, 2006

CP violation in mesons

CP violating phenomena in B (or K, or D) mesons

- CP (and T) violation in mixing (indirect)
  - probability of B^0 oscillating to $\bar{B}^0$ different from probability of $\bar{B}^0$ oscillating to B^0

$$B \to \bar{B} \neq \bar{B} \to B$$

- CP violation in decay (direct)
  - different decay rates between CP-conjugate states

$$B \to f \neq \bar{B} \to \bar{f}$$

where the final state $\bar{f} = \mathrm{CP}(f)$

- CP violation in interference between decay with and without mixing

  (direct + indirect)

$$B \to f + B \to \bar{B} \to f$$
$$\neq$$
$$\bar{B} \to f + \bar{B} \to B \to f$$

Discovery of CP violation: K^0 mixing

- Cronin-Fitch experiment, 1964: evicence of a small fraction of $K_L(\mathrm{CP}=-1) \rightarrow \pi^+\pi^-(\mathrm{CP}=+1)$

- The mass eigenstates K_L and K_S are then not eigenstates of CP, but a mixing of the CP eigenstates K_+^0, K_-^0
  - but the contribution from the 'other' CP eigenstate is very small

$$\boldsymbol{K_S^0 = pK^0 - q\overline{K}^0 = \frac{K_+^0 - \varepsilon K_-^0}{\sqrt{1+|\varepsilon|^2}} \approx K_+^0}$$

$$\boldsymbol{K_L^0 = pK^0 + q\overline{K}^0 = \frac{K_-^0 + \varepsilon K_+^0}{\sqrt{1+|\varepsilon|^2}} \approx K_-^0.}$$

With:

$$|p|^2 + |q|^2 = 1 \quad \text{and} \quad \frac{p}{q} = \sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}} = \frac{1-\varepsilon}{1+\varepsilon}$$

Discovery of CP violation: K^0 mixing (2)

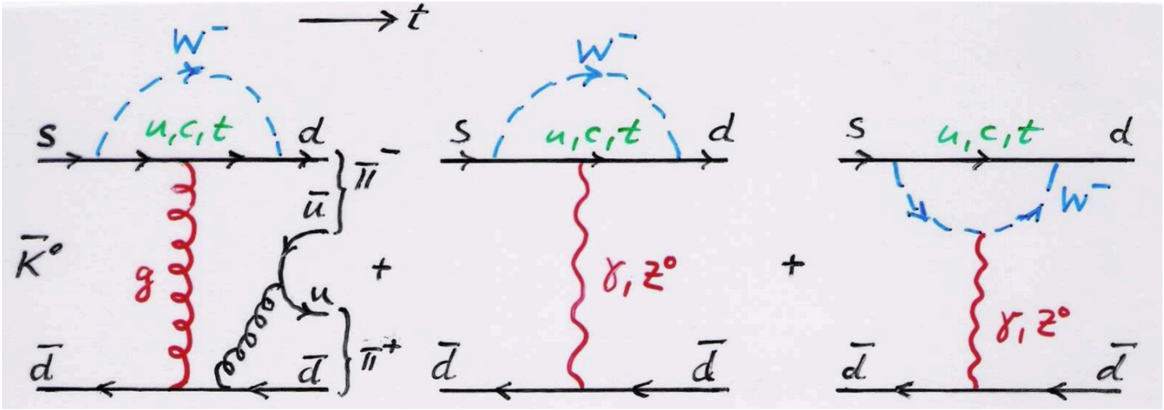
$$\frac{p}{q} = \sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}} = \frac{1-\varepsilon}{1+\varepsilon}$$

$$K_S^0 = pK^0 - q\overline{K}^0 = \frac{K_+^0 - \varepsilon K_-^0}{\sqrt{1+|\varepsilon|^2}} \approx K_+^0$$
$$K_L^0 = pK^0 + q\overline{K}^0 = \frac{K_-^0 + \varepsilon K_+^0}{\sqrt{1+|\varepsilon|^2}} \approx K_-^0.$$

- $\varepsilon \neq 0$ implies $M_{12}^* \neq M_{12}$ → CP violation in $K^0\overline{K}^0$ mixing
- Small effect: $\varepsilon = (2.228 \pm 0.011) \times 10^{-3}$
- In the Standard Model, caused by complex phase factor of CKM matrix
  - Alternative idea: new super-weak interaction

Direct CP violation in K^0 (1)

- In the decay of the CP eigenstate K_2^0 (CP=-1)
- Arises from interaction of the lowest order diagrams with higher order contributions leading to the same final state (Penguin diagram)



QCD Electroweak (2nd order)

- Contribution of direct CP violation expressed through additional parameter ε'

Direct CP violation in K^0 (2)

- Contribution of direct CP violation expressed through additional parameter ε'

- First evidence of $\varepsilon' \neq 0$ (1999):
  - CERN (NA48 Experiment)
  - FNAL (KTeV Experiment)

- $\varepsilon' \neq 0$ rules out the superweak interaction hypothesis
  - In Standard Model, both direct and indirect CP-violation caused by complex phase in V_{CKM}

- Direct CP violation even smaller effect than the one in mixing:

$$\left|\frac{\varepsilon'}{\varepsilon}\right| = (16.7 \pm 1.6) \cdot 10^{-4}$$

Indirect CP violation in B mesons (1)

- Same mechanism as in *K:*

$$B_H^0 = pB^0 - q\overline{B}^0 = \frac{B_+^0 - \varepsilon_B B_-^0}{\sqrt{1+|\varepsilon_B|^2}} \approx B_+^0$$

$$B_L^0 = pB^0 + q\overline{B}^0 = \frac{B_-^0 + \varepsilon_B B_+^0}{\sqrt{1+|\varepsilon_B|^2}} \approx B_-^0.$$

$\Rightarrow \frac{q}{p} = \left|\frac{q}{p}\right| e^{-i\phi_{\rm mix}}, \quad \phi_{\rm mix} \equiv arg(M_{12}/\Gamma_{12}),$ (mixing phase)

- In the Standard Model: $\left|\frac{q}{p}\right| = \left|\frac{1-\varepsilon_B}{1+\varepsilon_B}\right| = 1 + \frac{1}{2}\left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi_{\rm mix} \neq 1$
  - Meaning $\varepsilon_B \neq 0$

Indirect CP violation in B mesons (2)

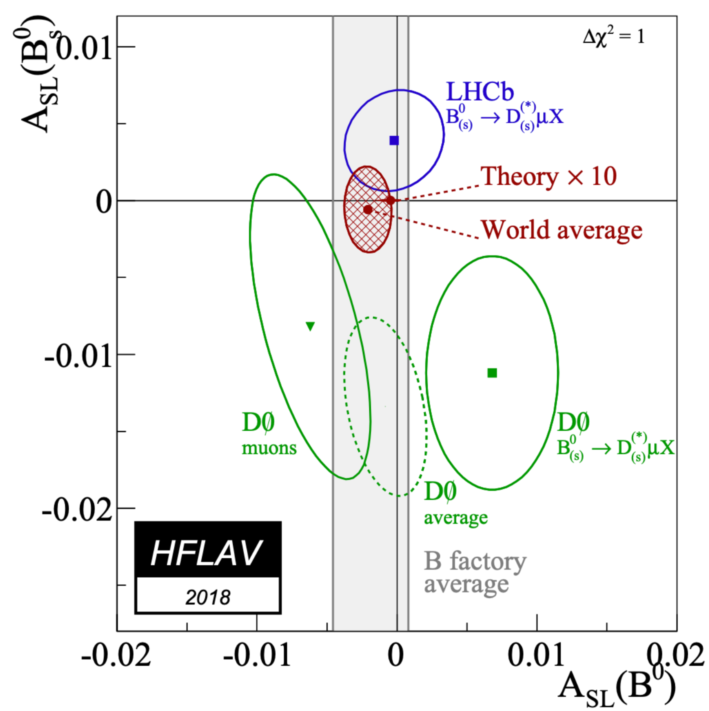
- CP violation in B meson's mixing can be observed using semileptonic B decays to distinguish B^0 from $\bar{B}^0$

$$A_{sl} = \frac{\Gamma(\overline{B}^0 \to B^0(t) \to \ell^+\nu X) - \Gamma(B^0 \to \overline{B}^0(t) \to \ell^-\nu X)}{\Gamma(\overline{B}^0 \to B^0(t) \to \ell^+\nu X) + \Gamma(B^0 \to \overline{B}^0(t) \to \ell^-\nu X)}$$

Note: time-independent asymmetry

$$= \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2} \approx 4\mathcal{R}e\,\varepsilon_B.$$

- Studied by multiple experiments
  - Definitive evidence still to be reached
  - Some tension between different measurements (D0 / LHCb)



Global fit results:

$$A_{sl}(B^0_d) = (-2.1 \pm 1.7) \times 10^{-3}$$
$$A_{sl}(B^0_s) = (-0.6 \pm 2.0) \times 10^{-3}$$

From: http://pdg.lbl.gov/2019/reviews/rpp2019-rev-b-bar-mixing.pdf

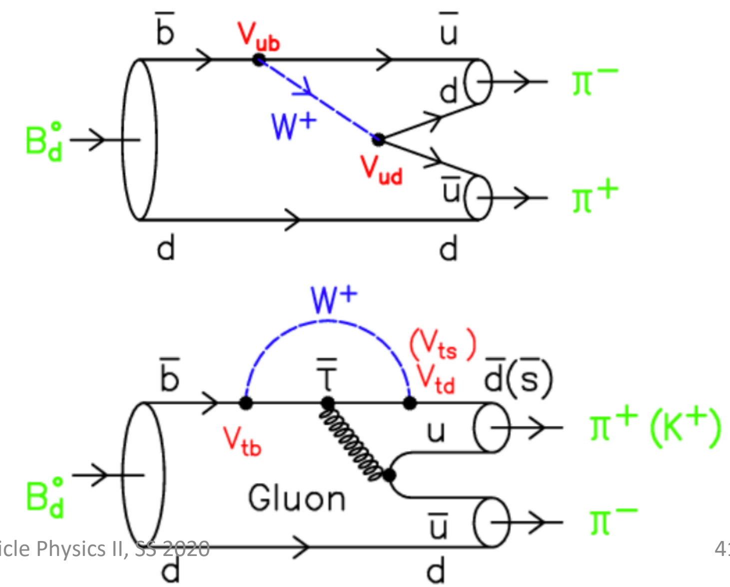
Direct CP violation in B mesons (1)

- Given the decay of B^0 ($\bar{B}^0$) to the final state f ($\bar{f}$), with $\bar{f}$ = CP(f)
  - consider the decay amplitudes: $A_f = A(B \to f)$
    $\overline{A}_{\overline{f}} = A(\overline{B} \to \overline{f})$

- Direct CP violation occurs if $|\bar{A}_{\bar{f}}| \neq |A_f|$:

$$|\overline{A}_{\overline{f}}/A_f|^2 = 1 - 4\mathcal{R}e\varepsilon'_B \neq 1.$$

- Originates from interference between Penguin and Tree diagrams.
  - E.g. for $B_d^0 \to \pi^+\pi^-$ (penguin diagram CKM-suppressed) or $B_d^0 \to K^+\pi^-$ (tree-diagram CKM-suppressed)



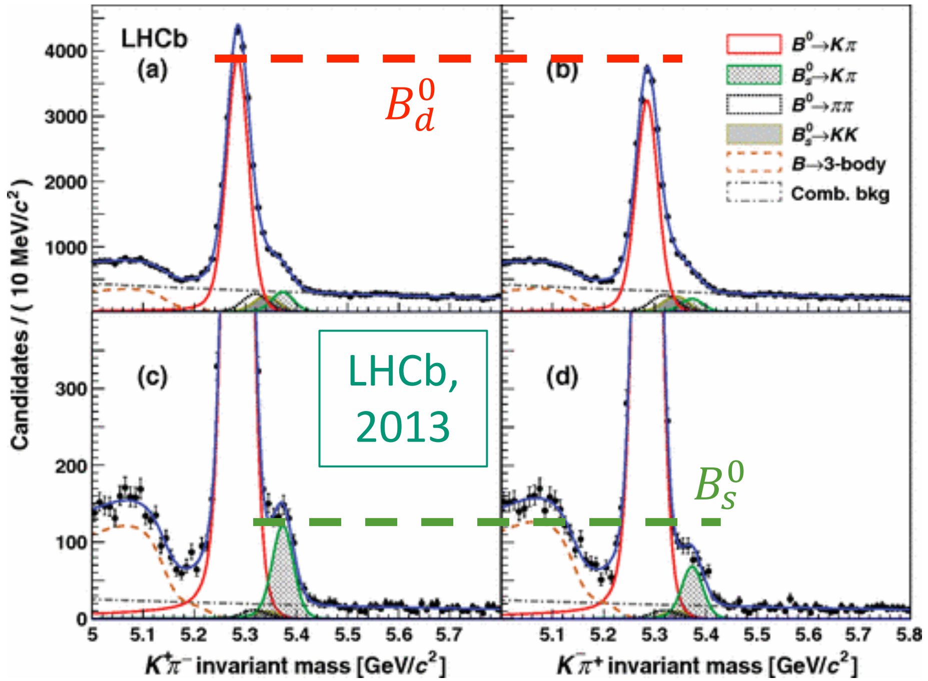
Direct CP violation in B mesons (2)

- First observed by BaBar and Belle in 2004 in the $B_d^0 \to K^+\pi^-$ channel
  - Later measured by CDF, LHCb

$$A_{K\pi} = \frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

$$\mathcal{A}_{\overline{B}^0 \to K^-\pi^+} = -0.084 \pm 0.004 \,.$$

$$\mathcal{A}_{\overline{B}^0_s \to K^+\pi^-} = +0.213 \pm 0.017 \,.$$



- Observed also in other channels, e.g.:

$$\Rightarrow \quad \mathcal{A}_{B^+ \to D_{K^-\pi^+} K^+} = -0.41 \pm 0.06 \,,$$

$$\Rightarrow \quad \mathcal{A}_{B^+ \to D_+ K^+} = +0.129 \pm 0.012 \,,$$

http://pdg.lbl.gov/2019/reviews/rpp2019-rev-cp-violation.pdf

Combination of direct and indirect CP violation (1)

- Interference between CP-violating effects in decay and mixing
- Resulting asymmetry has periodic time dependence
  - CP-violating asymmetries in both decay and mixing are time-independent when no interference occurs

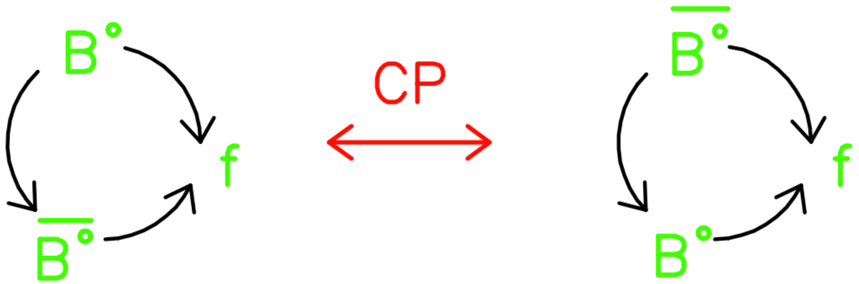
$$A_f(t) = \frac{\Gamma(B^0 \to \overline{B}^0(t) \to f) - \Gamma(\overline{B}^0 \to B^0(t) \to f)}{\Gamma(B^0 \to \overline{B}^0(t) \to f) + \Gamma(\overline{B}^0 \to B^0(t) \to f)} = S_f \underline{\sin \Delta m_d t} - C_f \underline{\cos \Delta m_d t}$$

$$S_f \neq 0 \;\Rightarrow\; \boxed{\text{indirect}}\ \text{CP violation}$$

$$C_f \neq 0 \;\Rightarrow\; \boxed{\text{direct}}\ \text{CP violation}$$

Combination of direct and indirect CP violation (2)

- Special case: *f* is a CP eigenstate: $\mathrm{CP}(f) = \eta_f \cdot f = \pm f \;\Leftrightarrow \overline{f} \equiv f$



- Calling: $A_f = A(B^0 \to f), \overline{A}_f = A(\overline{B}^0 \to f).$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}.$$

- It follows:

$$S_f = \frac{2\mathcal{I}m\lambda_f}{1+|\lambda_f|^2}$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

direct CP violation

$$\Updownarrow$$

$$|\lambda_f| \neq 1$$

Combination of direct and indirect CP violation (3)

- Can be further simplified if one decay diagram is dominant
  - Decay term:

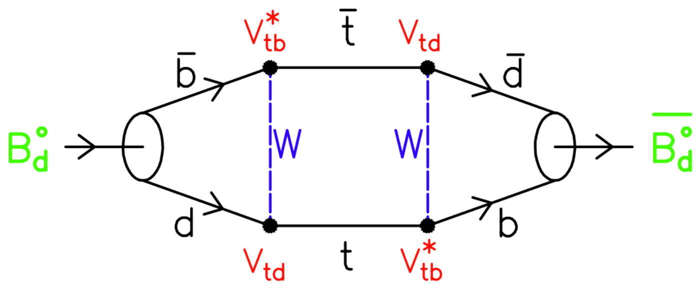
$$|\overline{A}_f/A_f| = 1, \quad \phi_f \equiv -arg(A_f) = arg(\overline{A}_f),$$
$$arg(\overline{A}_f/A_f) = -2\phi_f,$$

  - Mixing term:

$$\phi_{\rm mix} = 2\beta \Rightarrow \frac{q}{p} \simeq 2\beta$$

- Combining the two:

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}.$$
$$\Downarrow$$
$$\lambda_f = \eta_f e^{-2i(\beta+\phi_f)}, \; |\lambda_f| = 1$$
$$\Rightarrow C_f = 0$$



$$V_{td} = |V_{td}|e^{-i\beta}$$

$$B_H^0 = pB^0 - q\overline{B}^0 \approx \frac{1}{\sqrt{2}}[B^0 + e^{-2i\beta}\overline{B}^0]$$
$$B_L^0 = pB^0 + q\overline{B}^0 \approx \frac{1}{\sqrt{2}}[B^0 - e^{-2i\beta}\overline{B}^0],$$

Combination of direct and indirect CP violation (4)

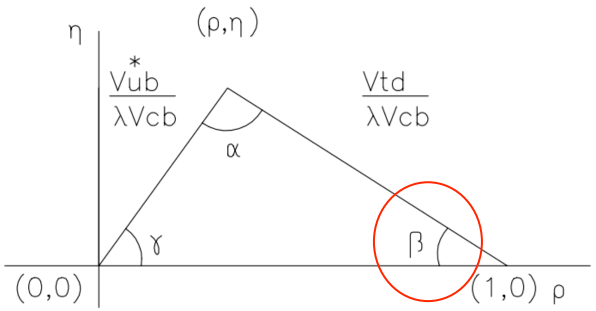
- Can be further simplified if one decay diagram is dominant

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

$$= \eta_f \cdot \sin 2(\beta + \phi_f) \underline{\underline{\sin \Delta m_d t}}$$

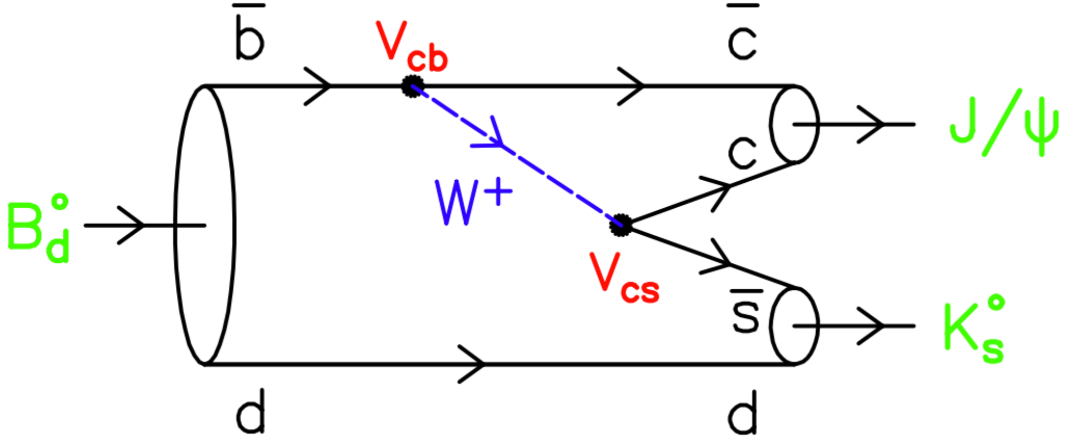
- We still have time dependence
- Provides direct measurement of the angles of unitarity triangle

B^0 decays to CP eigenstates: measuring β



- Most measurements in $b \to c\bar{c}s$ channel
  - Example:

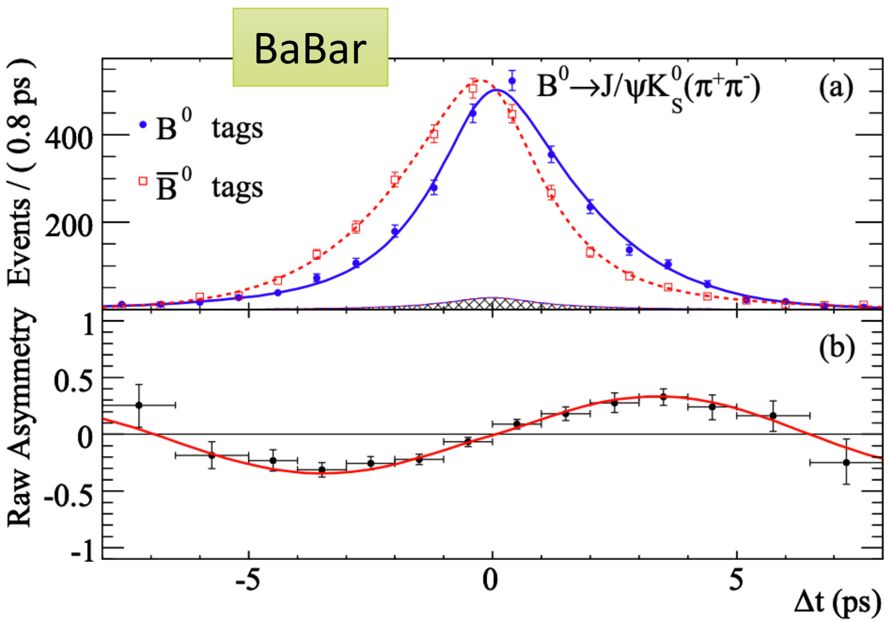
$$B_d^0 \to J/\psi K_s^0 : \quad \phi_f = 0,\ \eta_f = -1$$

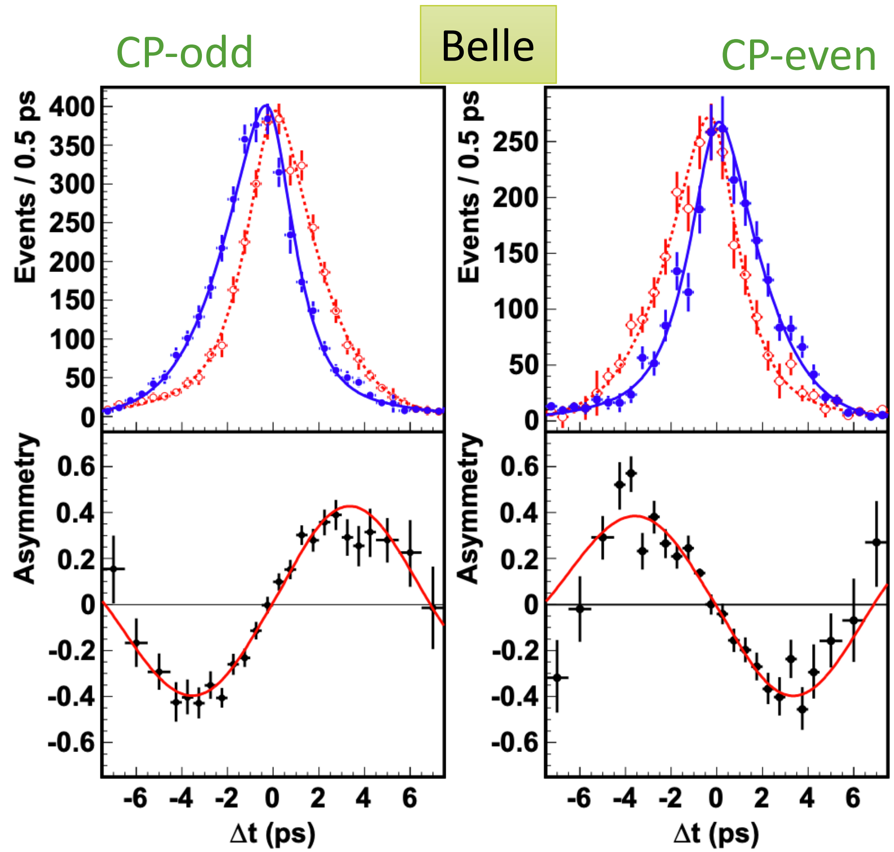


$$a_{CP}(t) = -\sin 2\beta \sin \Delta m\, t$$

Measurements of direct + indirect CP violation

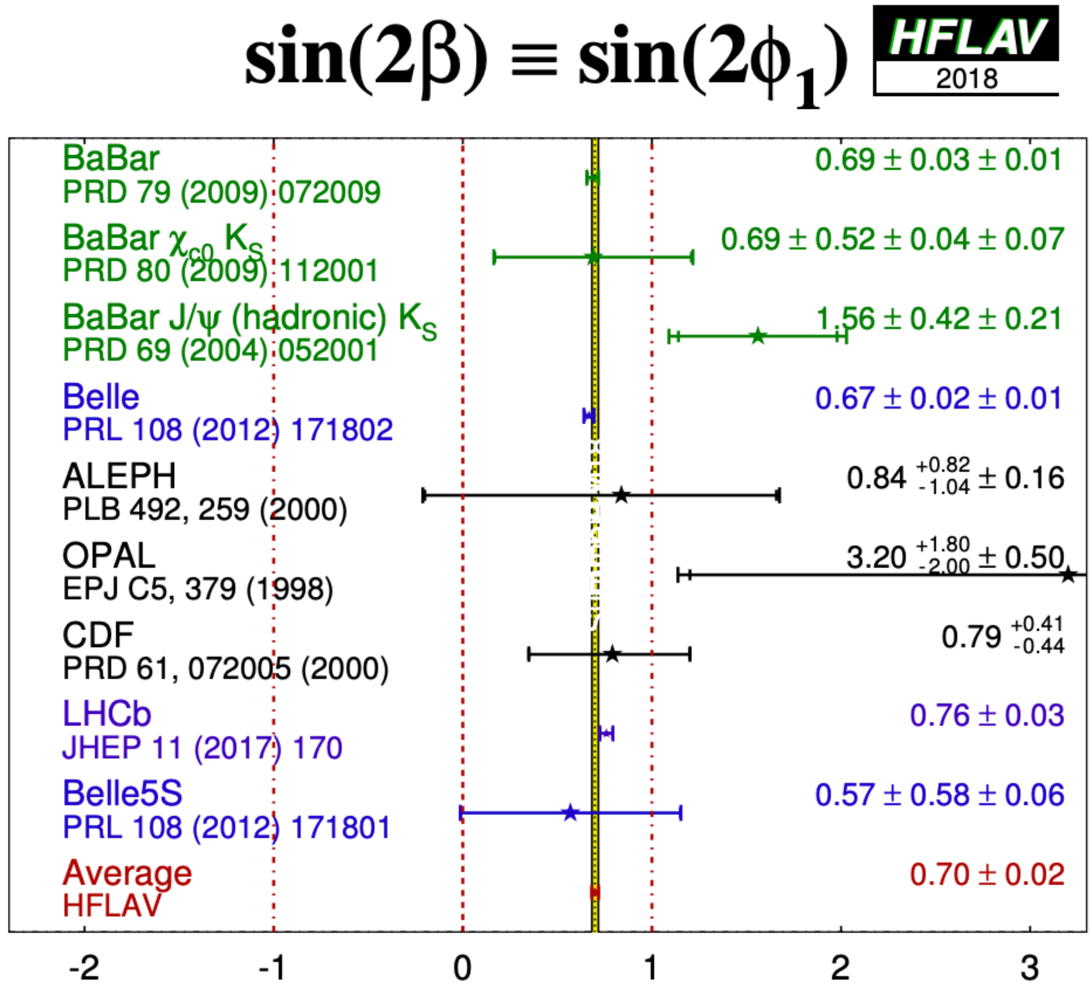
- First observation by B factories (2001) in $B_d^0 \to J/\Psi K^0$
  - ➤To be able to measure B decay length, a boosted $\Upsilon(4s)$ meson is needed
  - ➤Asymmetric beam energies allowed for this at B factories





β in $b \to c\bar{c}s$ channel: summary

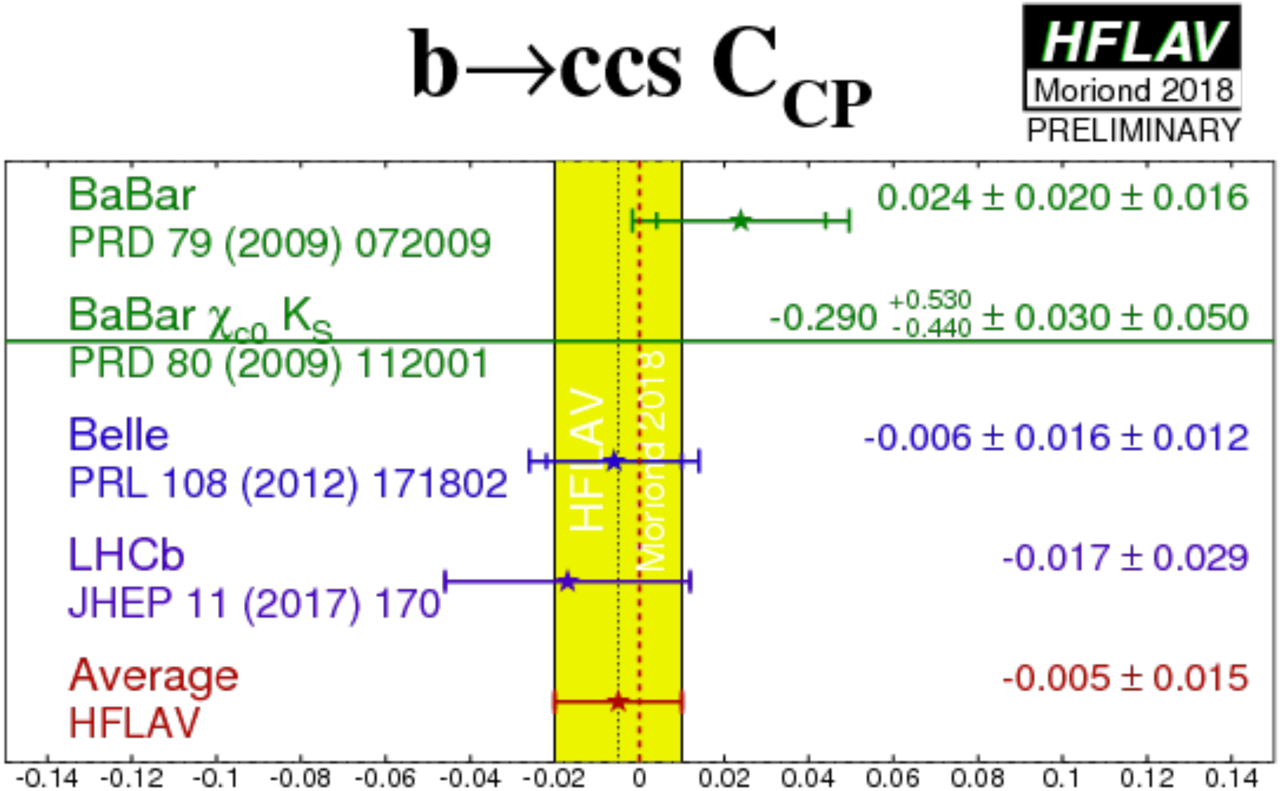
$$B \to J/\psi K_S^0,\ \psi(2S)K_S^0,\ \chi_{c1}K_S^0,\ \eta_c K_S^0$$



C_f in $b \to c\bar{c}s$: summary

$$B \to J/\psi K^0_S,\ \psi(2S)K^0_S,\ \chi_{c1}K^0_S,\ \eta_c K^0_S$$

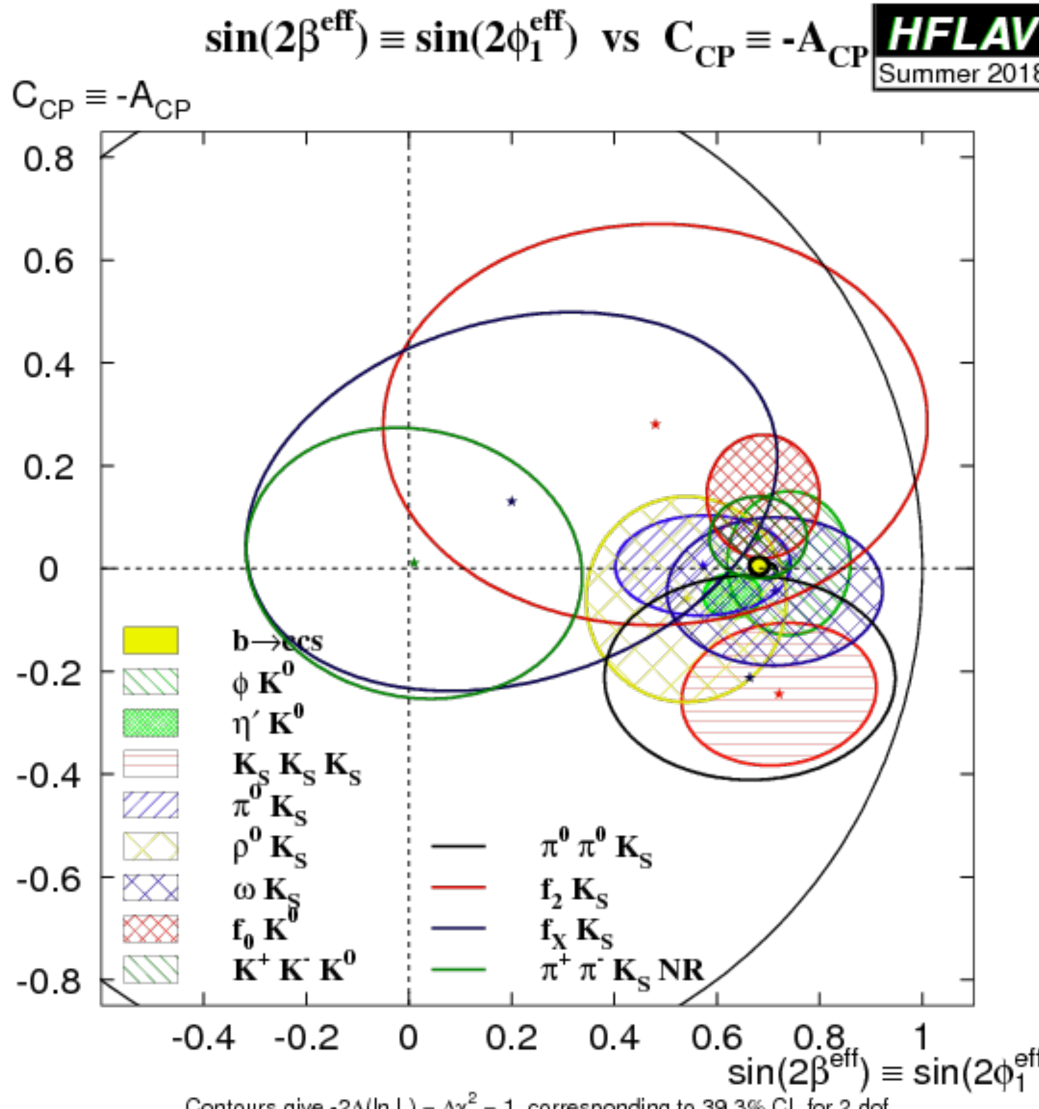
- Predicted to be 0 in the Standard Model



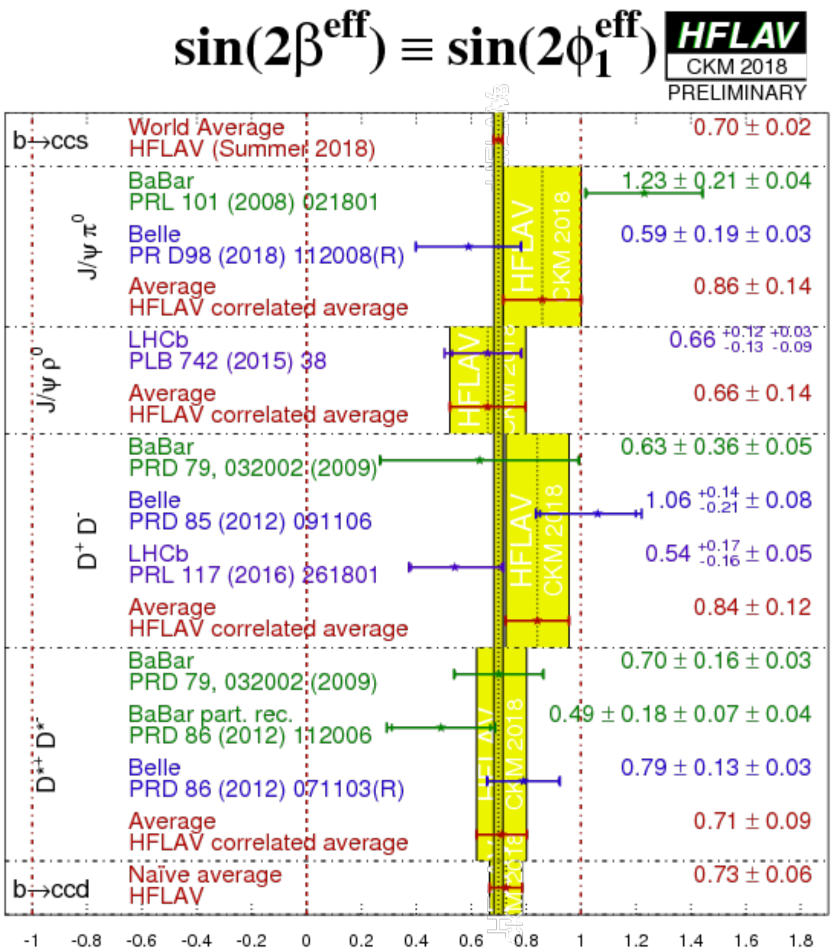
$S_f \propto \sin(2\beta)$ and C_f in $b \to q\bar{q}s$: summary

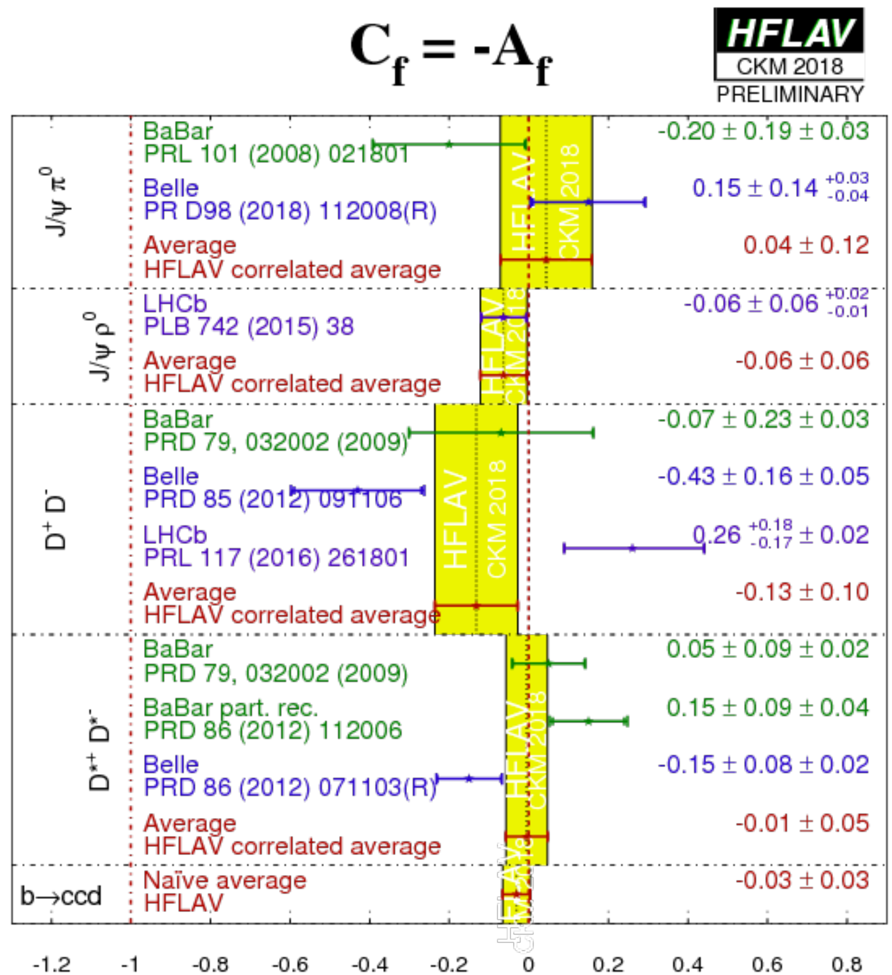
- Considering decays in
  - $b \to c\bar{c}s$ (tree)
  - $b \to q\bar{q}s$ (penguin)

- $b \to q\bar{q}s$ measurements all from BaBar and Belle



$S_f \propto \sin(2\beta)$ and C_f in $b \to c\bar{c}d$: summary



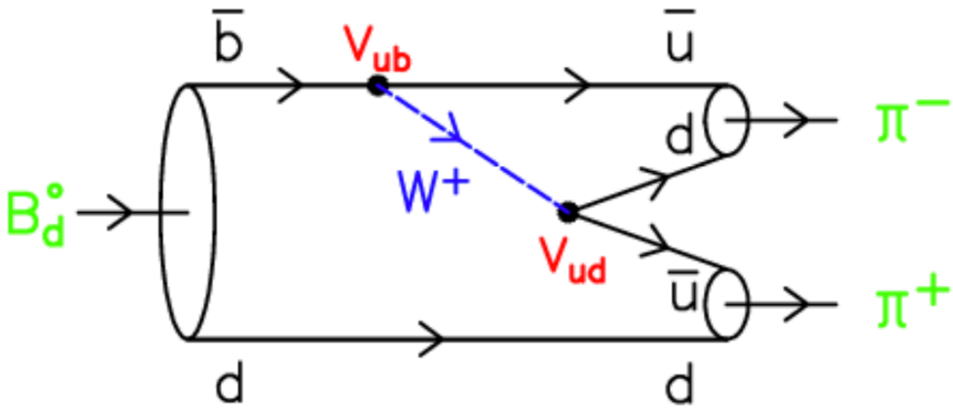


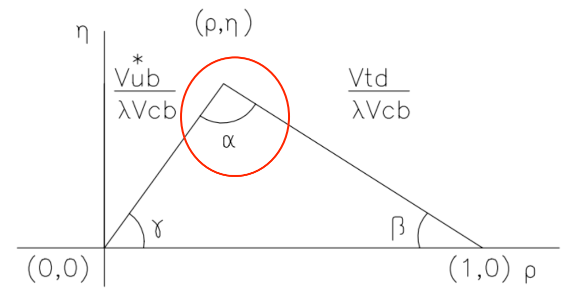
B^0 decays to CP eigenstates: measuring α

Example:

$B_d^0 \to \pi^+\pi^-$: $\quad \phi_f = \gamma, \; V_{ub} = |V_{ub}| e^{-i\gamma},$

$\eta_f = +1$





$$a_{CP}(t) = \sin 2(\beta + \gamma) \sin \Delta m \, t$$
$$= \sin 2\alpha \quad \sin \Delta m \, t$$

B^0 decays to CP eigenstates: measuring α

- Measuring α from $B_d^0 \to \pi\pi$ is much more difficult then measuring β
  - Smaller Branching Ratio ($b \to u$)
    - First observed by CLEO and LEP in 1994

$$
\begin{aligned}
BR(B_d^0 \to \pi^+\pi^-) &= (5.16 \pm 0.22) \cdot 10^{-6} \\
BR(B_d^0 \to \pi^0\,\pi^0\,) &= (1.55 \pm 0.19) \cdot 10^{-6} \\
BR(B^+ \to \pi^+\pi^0) &= (5.59 \pm 0.41) \cdot 10^{-6}
\end{aligned}
$$

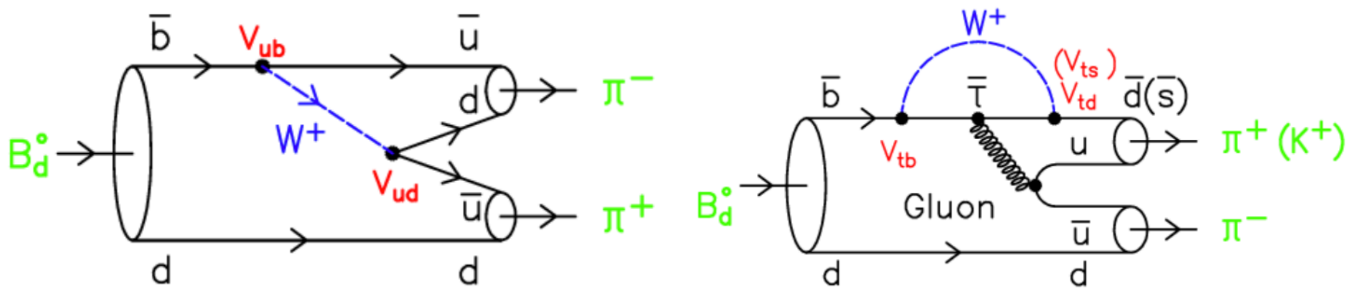
  - Must be distinguished from much more common $B_d^0 \to K\pi$

$$BR(B_d^0 \to K^+\pi^-) = (18.2 \pm 0.8) \cdot 10^{-6}$$

- Need good *K*-π separation. Done through:
  - Measuring the particle's Time Of Flight (ToF)
  - Measuring the energy loss by ionisation in track chambers or Cherenkov detectors

B^0 decays to CP eigenstates: measuring α

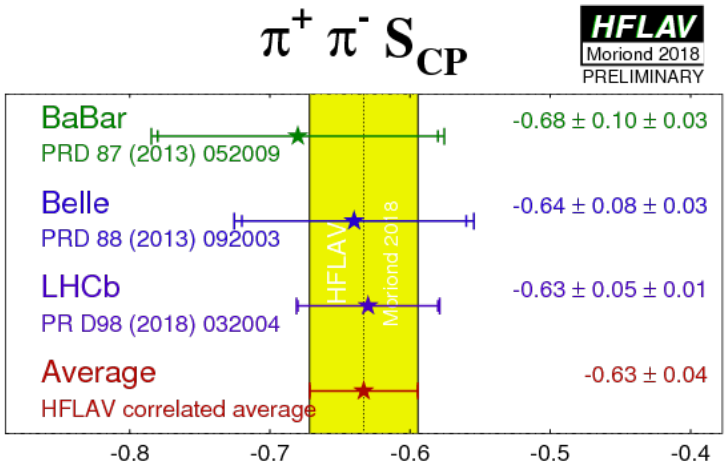
- In addition, here S_f and C_f are not directly proportional to α as those in $b \to c\bar{c}s$ channel are to β
  - Because $B_d^0 \to \pi\pi$ is not dominated by a single diagram
    - ➢Competing Penguin process is not negligible with respect to CKM-suppressed tree process

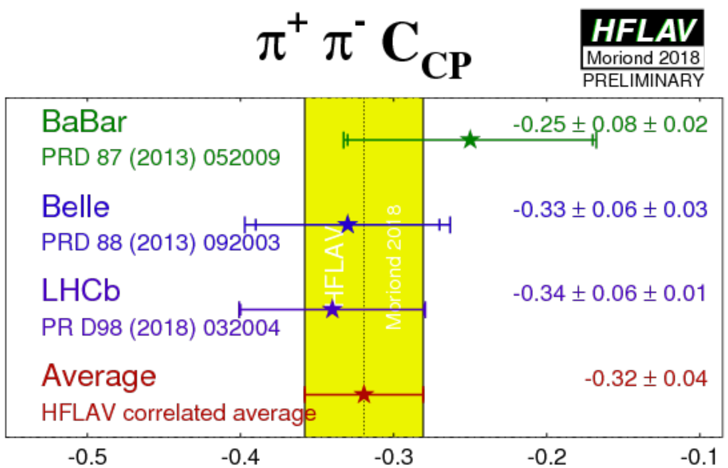


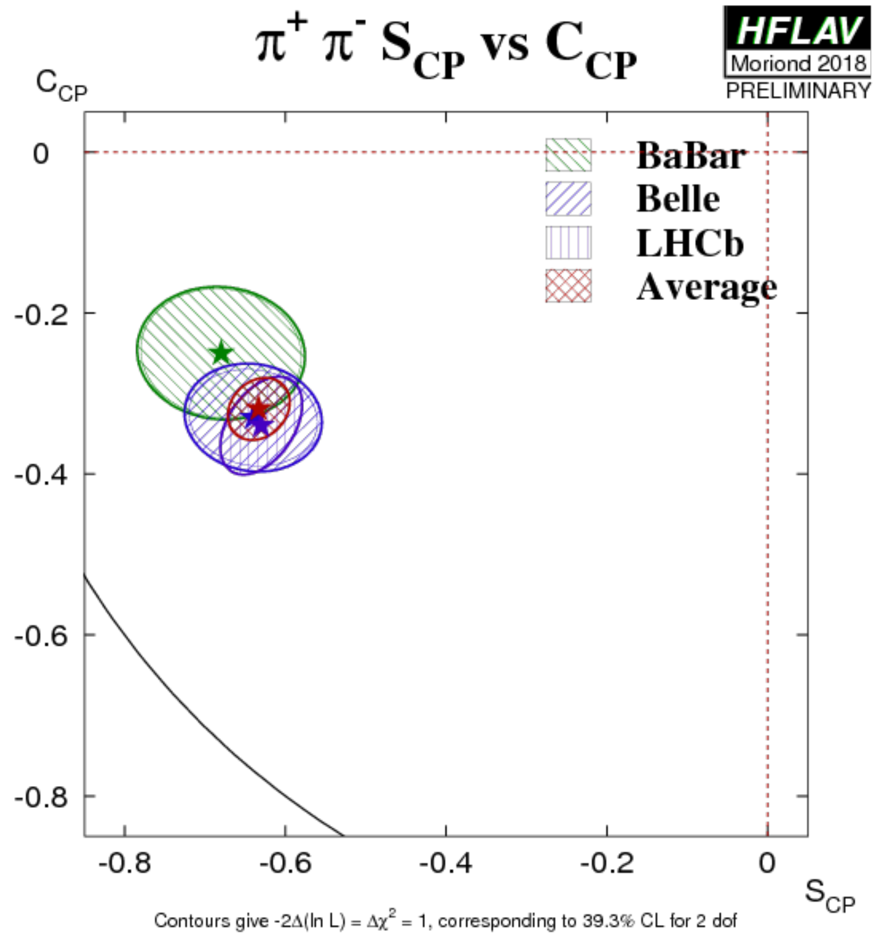
$$S_{\pi\pi} = \sin 2\alpha_{\text{eff}} \quad \Rightarrow \quad \alpha = \alpha_{\text{eff}} + \Delta\alpha.$$

- Correction can be derived by measuring decay rates and CP-asymmetries from $B_d^0 \to \pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ together

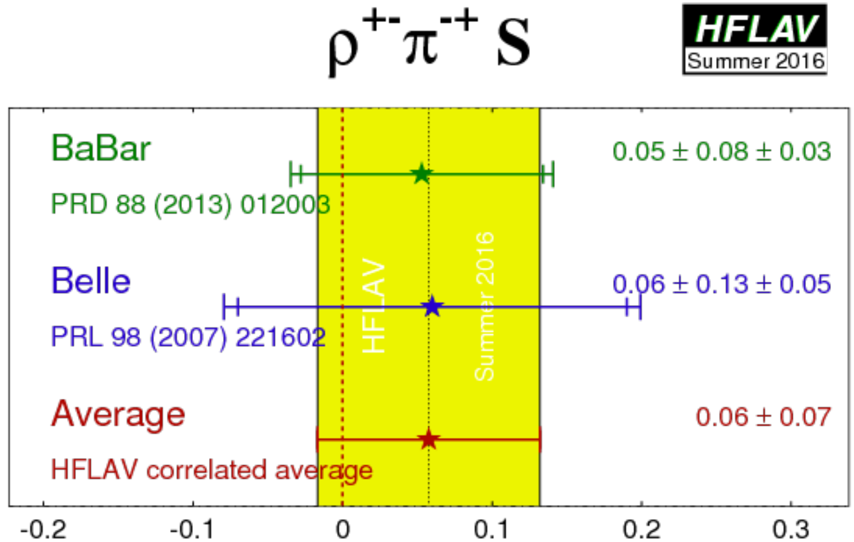
S_f and C_f in $B^0 \to \pi^+\pi^-$: summary

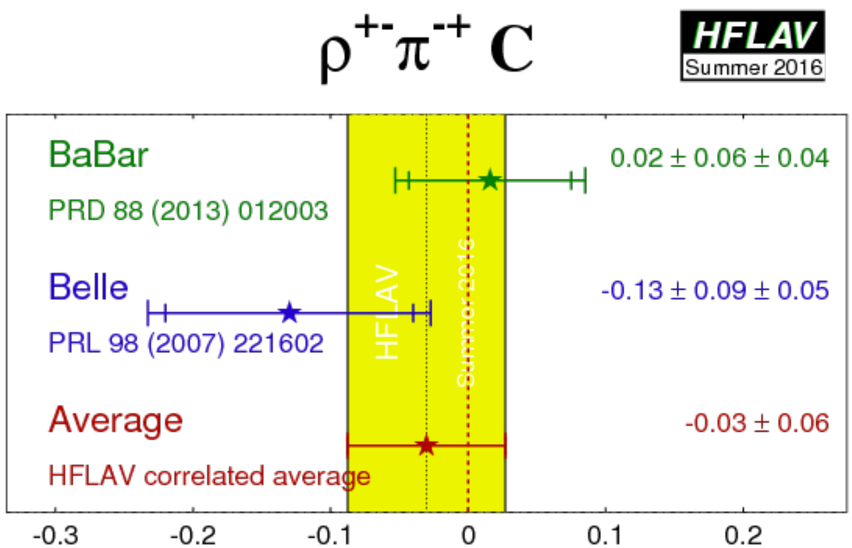


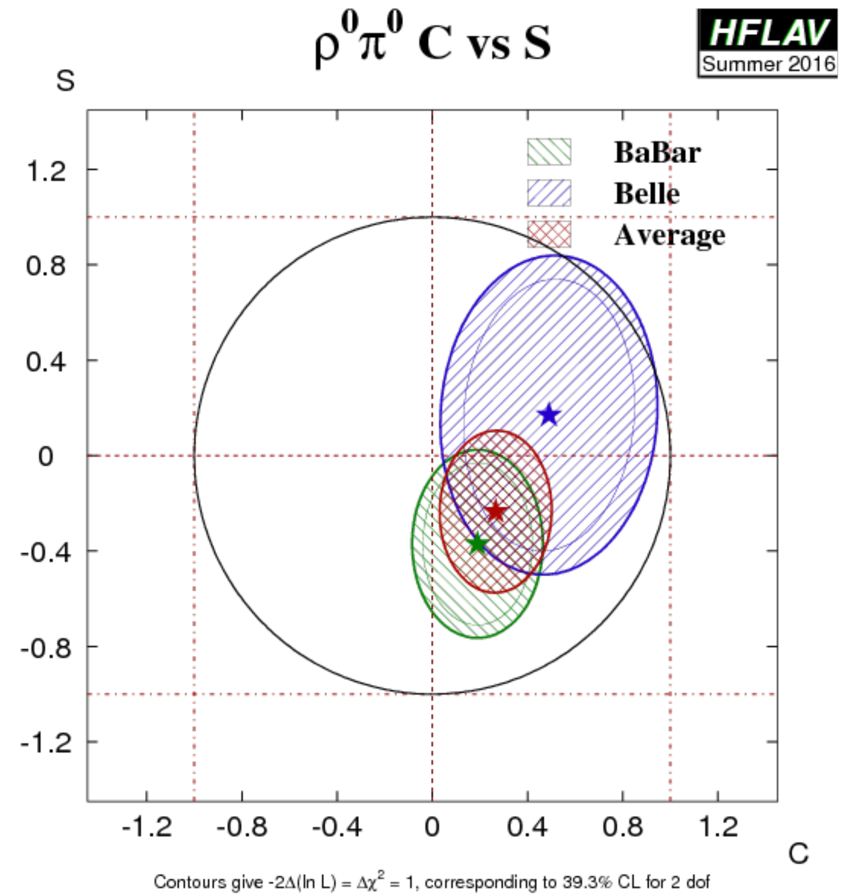




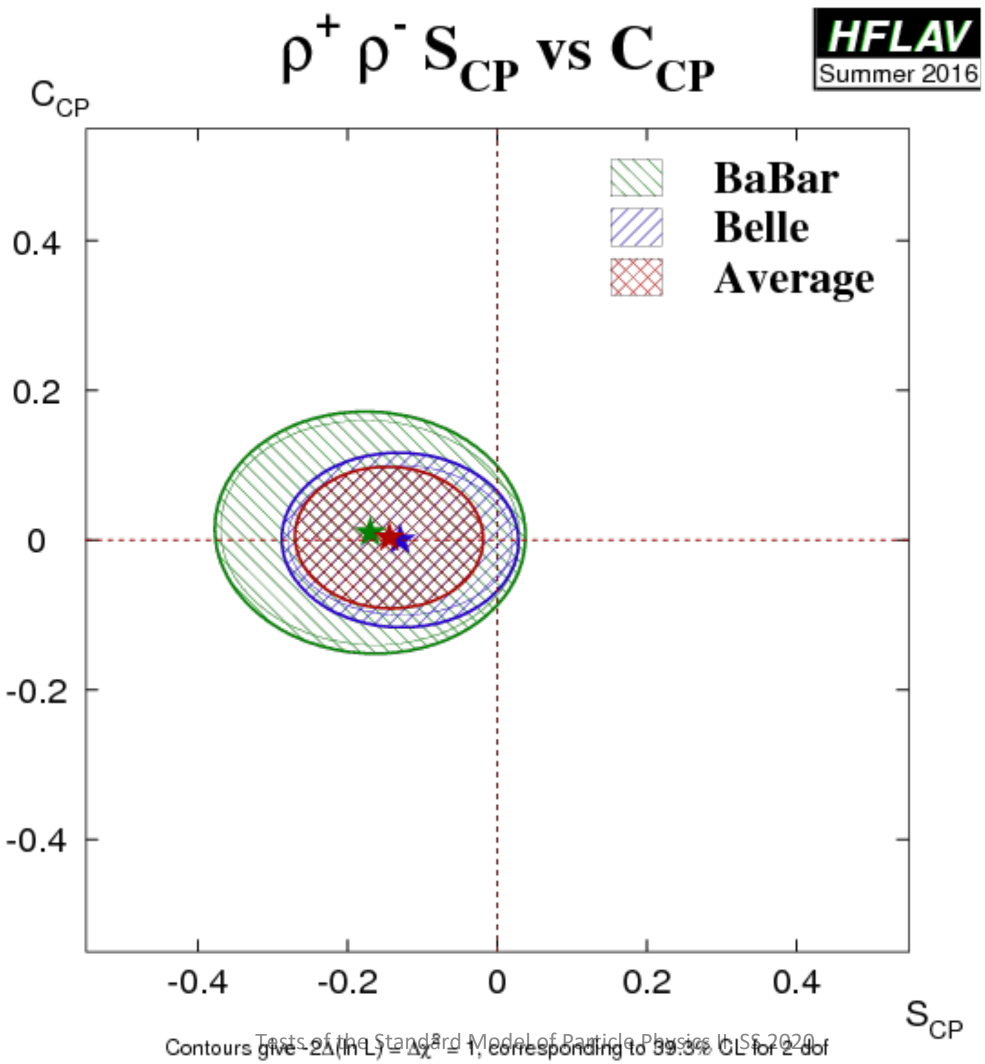
S_f and C_f in $B^0 \to \rho^{\pm,0}\pi^{\mp,0}$: summary





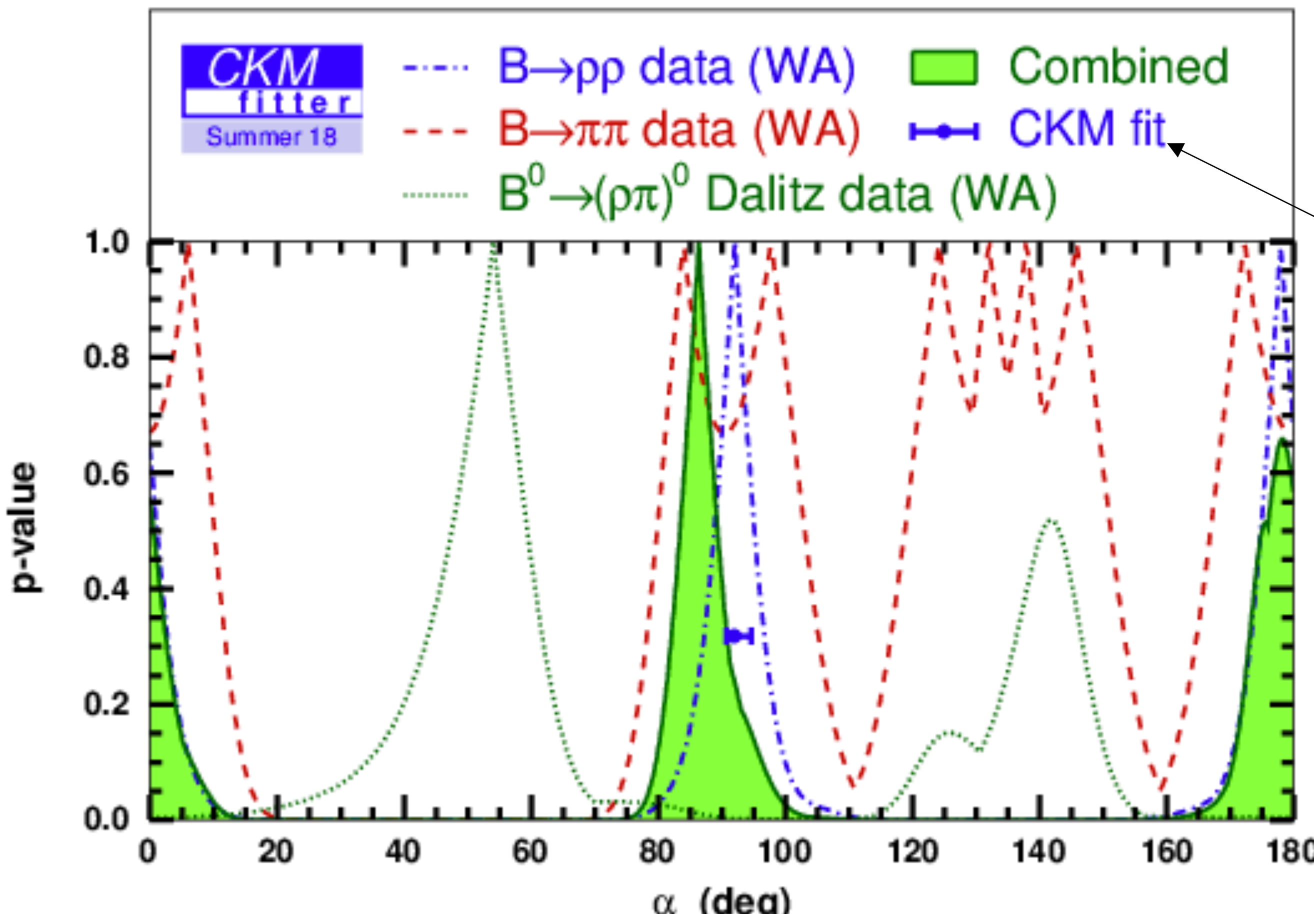


S_f and C_f in $B^0 \to \rho^{\pm}\rho^{\mp}$: summary



α world average: from combination of previous measurements

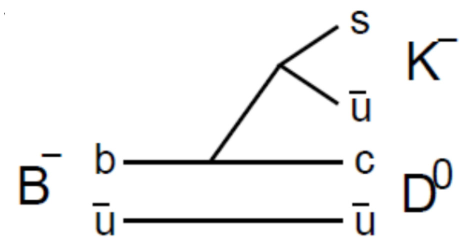
$$\alpha = (91.6^{+1.7}_{-1.1})^\circ$$

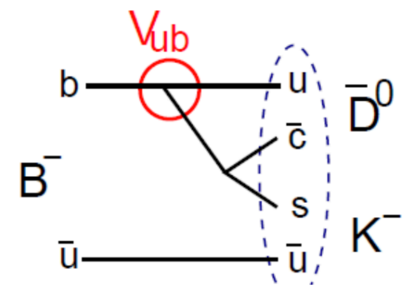


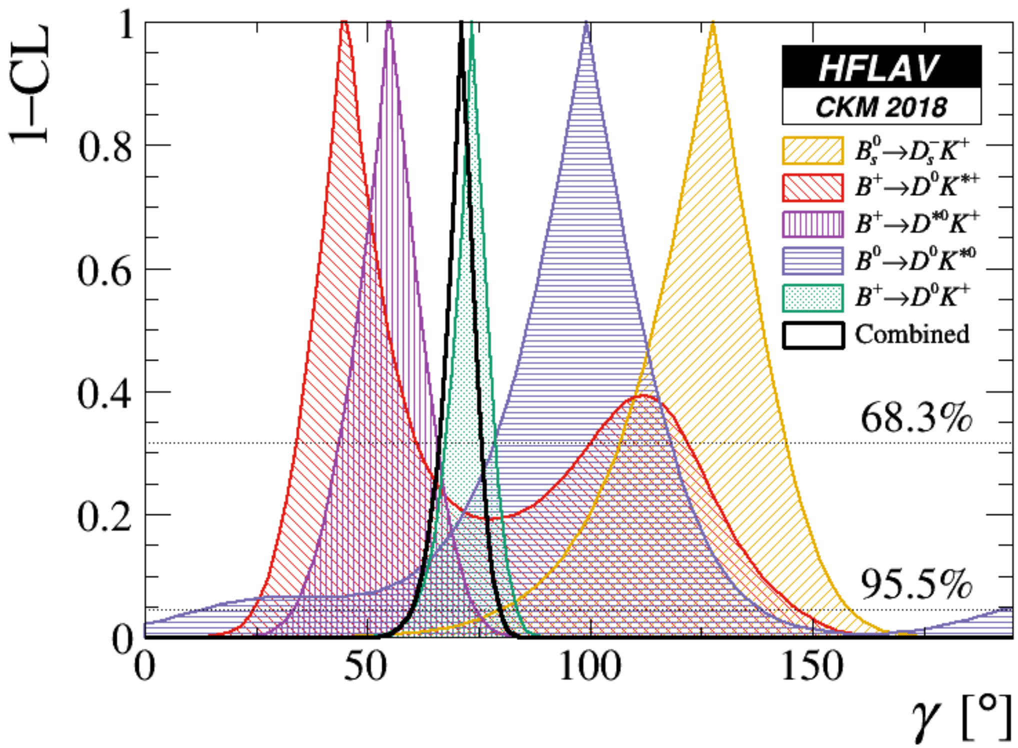
'CKM fit': fit to CKM parameters, direct α measurement not included.

Measuring γ

- From CP asymmetries and decay rates in $B^{\pm} \to DK^{\pm}$ with interference between:
  - $D = D^0 \to K^- \pi^+$ ($b \to c$, V_{cb})
  - $D = \overline{D}^0 \to K^- \pi^+$ ($b \to u$, $V_{ub} = |V_{ub}| e^{-i\gamma}$)







Belle: $\gamma = (68^{+15}_{-14})^\circ$

BaBar: $\gamma = (69^{+17}_{-16})^\circ$

LHCb (2018): $\gamma = (74.0^{+5.0}_{-5.8})^\circ$

Fit: $\gamma = (71.1^{+4.6}_{-5.3})^\circ$

Unitarity triangle: summary

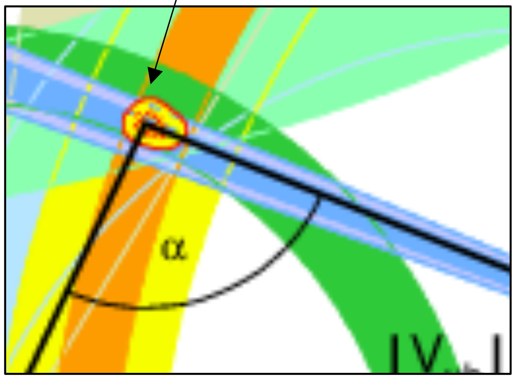
- By constraining the unitarity triangle we test the Standard Model consistency

- Physics beyond the Standard Model might create discrepancies
- e.g. $\alpha + \beta + \gamma \neq 180°$
  - unitarity violation: new generation of weak fermions?
- difference between direct angle measurements and those derived from the sides' measurements
  - new phase angle by exchanging new particles in loop process?

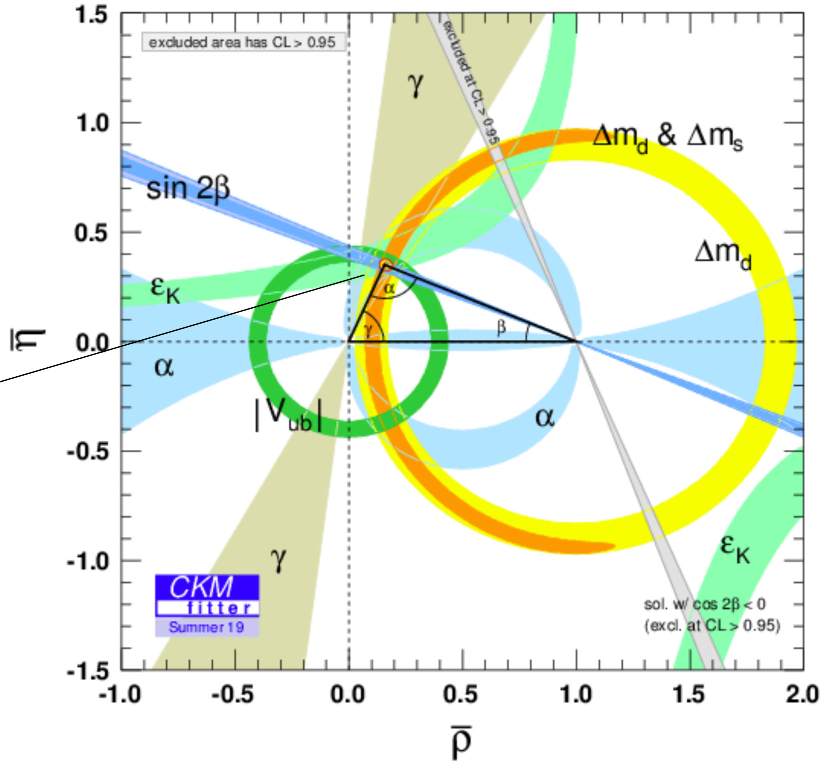
Unitarity triangle: summary

- Vast variety of measurements providing inputs (more than those discussed here)
  - From B, K and D mesons (charm sector)
- All measurements appear consistent with one another

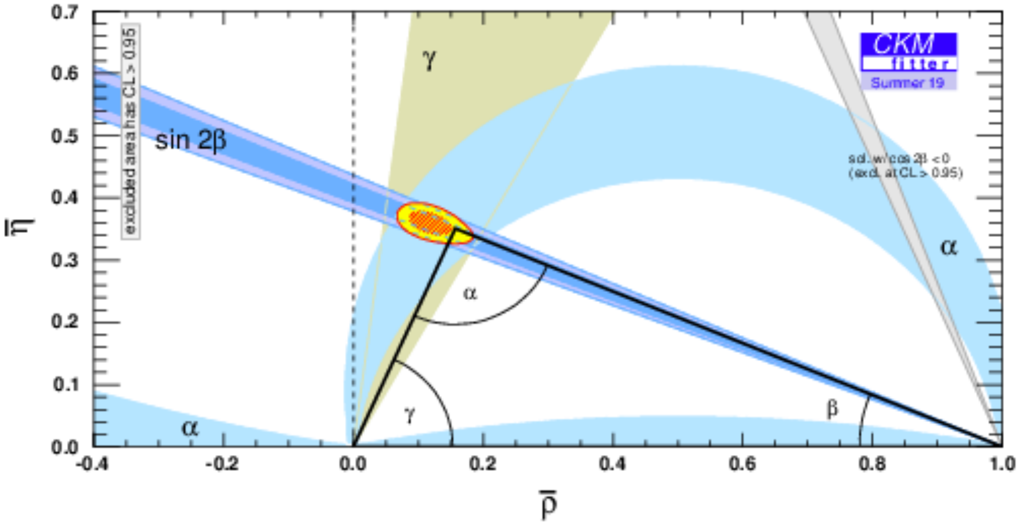
Location of vertex from the complete fit (yellow contour)



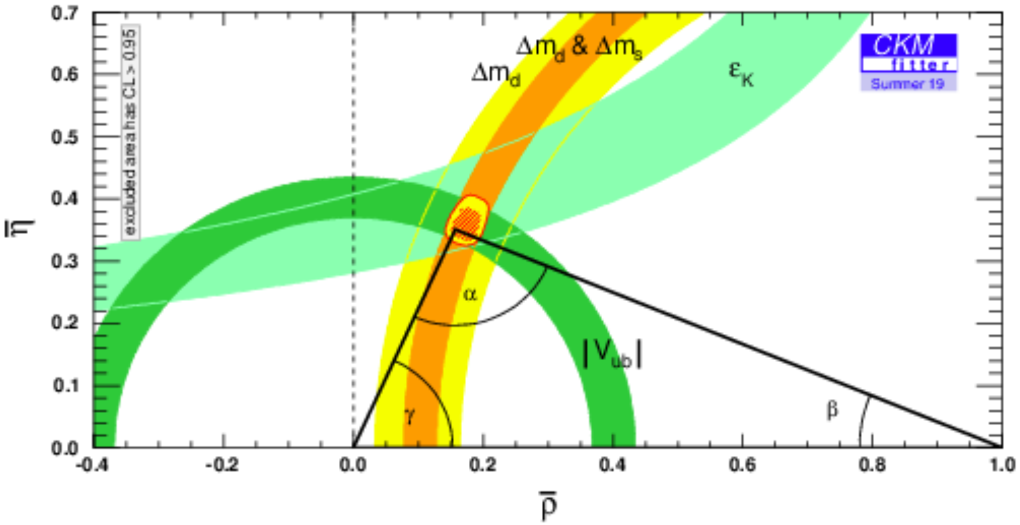
ZOOM



Unitarity triangle: summary



Angles only



Sides only

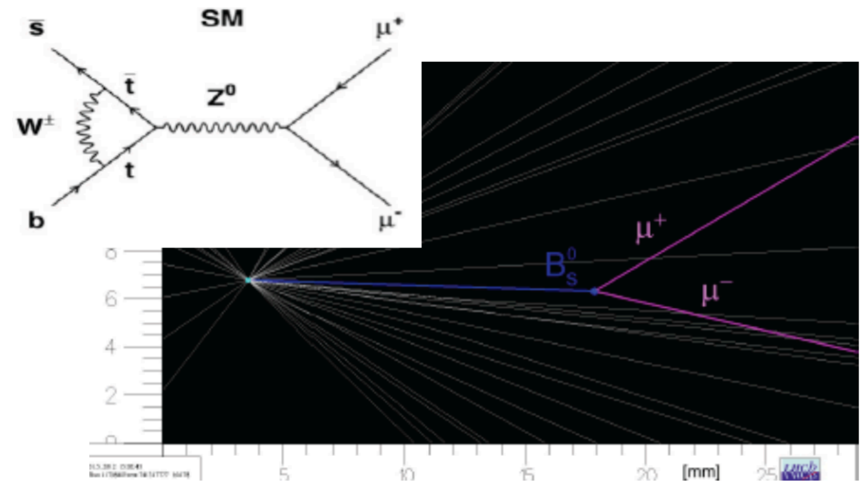
More from B physics: rare decays

- Measurements of very rare *B* decays
  - Test for excess over Standard Model
  - Can be useful to improve precision of unitarity triangle fit
  - Other Standard Model constraints (e.g. lepton flavour universality)

- Some examples:
  - $B_d^0 \to \mu^+\mu^-$, $B_s^0 \to \mu^+\mu^-$ (LHCb + CMS, 2013)
  - $B \to K\ell^+\ell^-$ (LHCb)

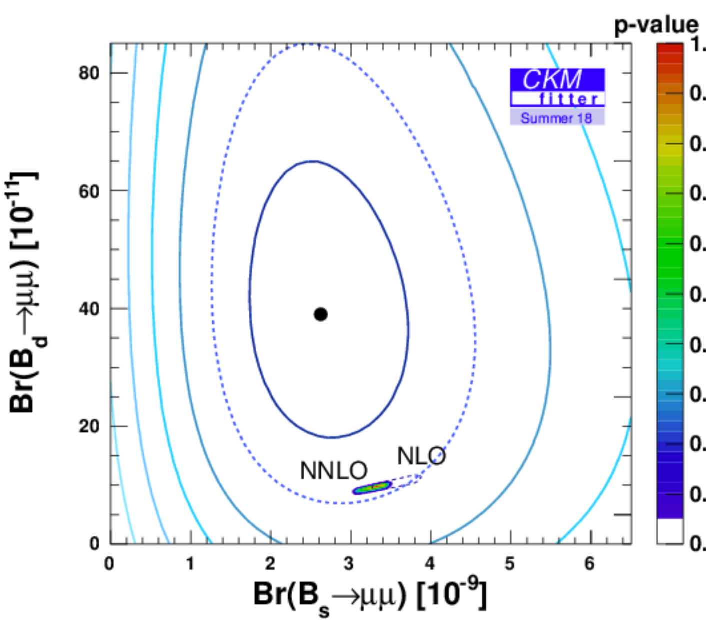
$B_d^0 \to \mu^+\mu^-, B_s^0 \to \mu^+\mu^-$

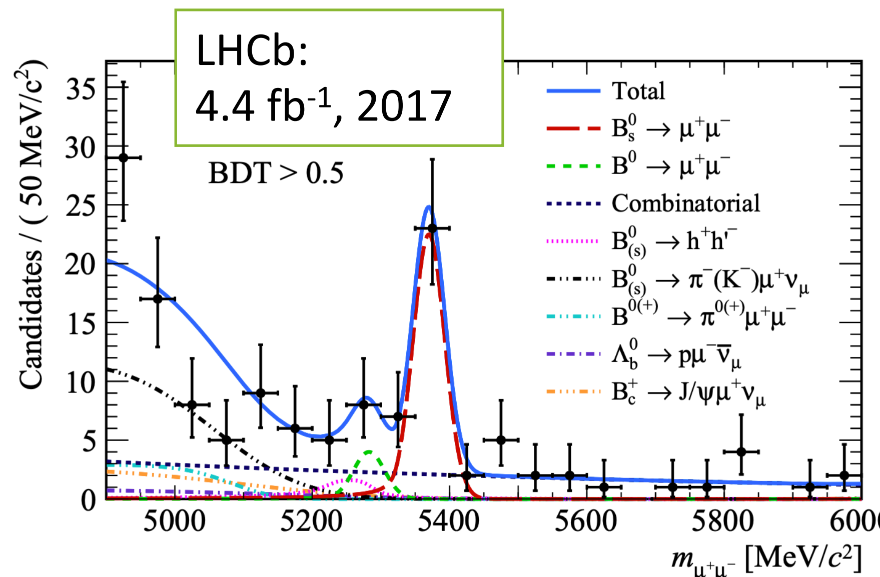
- 2nd order loop process, FCNC and helicity suppressed
- First measurement by LHCb + CMS in 2013
- Results show good compatibility with Standard Model
  - Not much room for new physics



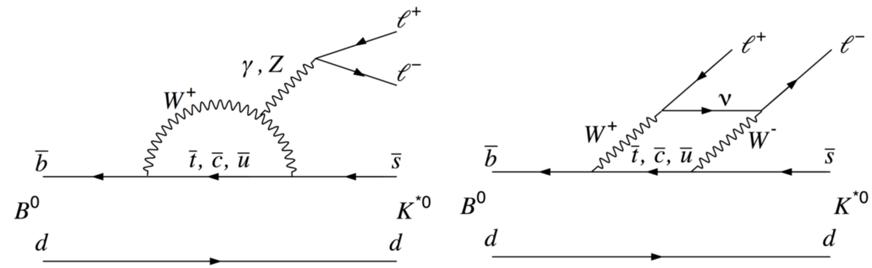
$\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.34 \pm 0.27 \times 10^{-9}$

$\mathrm{BR}(B^0 \to \mu^+\mu^-) = 1.07 \pm 0.10 \times 10^{-10}$

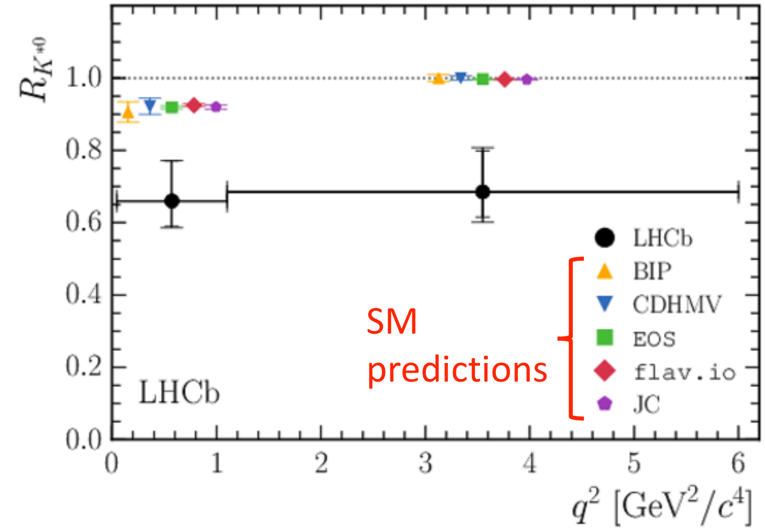




$B^0 \to K^{0*}\ell^+\ell^-$



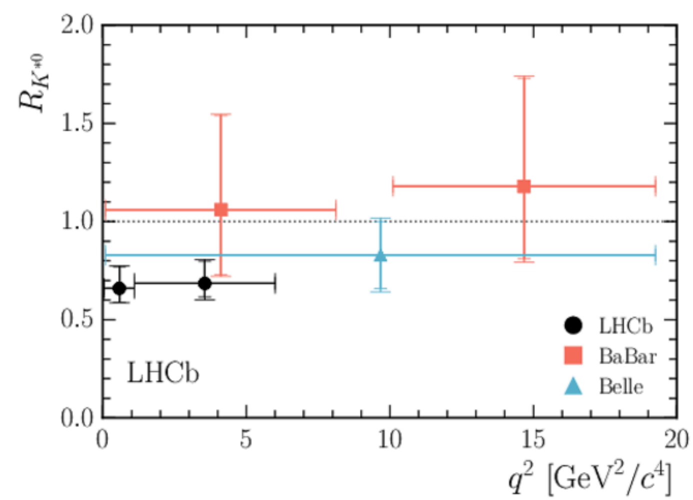
- Second order process (penguin+box diagram)
  - Potentially sensitive to new physics contributions



- Test of lepton flavour universality: $\ell = e$ vs $\ell = \mu$
  - double ratio of decay rates, systematic uncertainties cancel

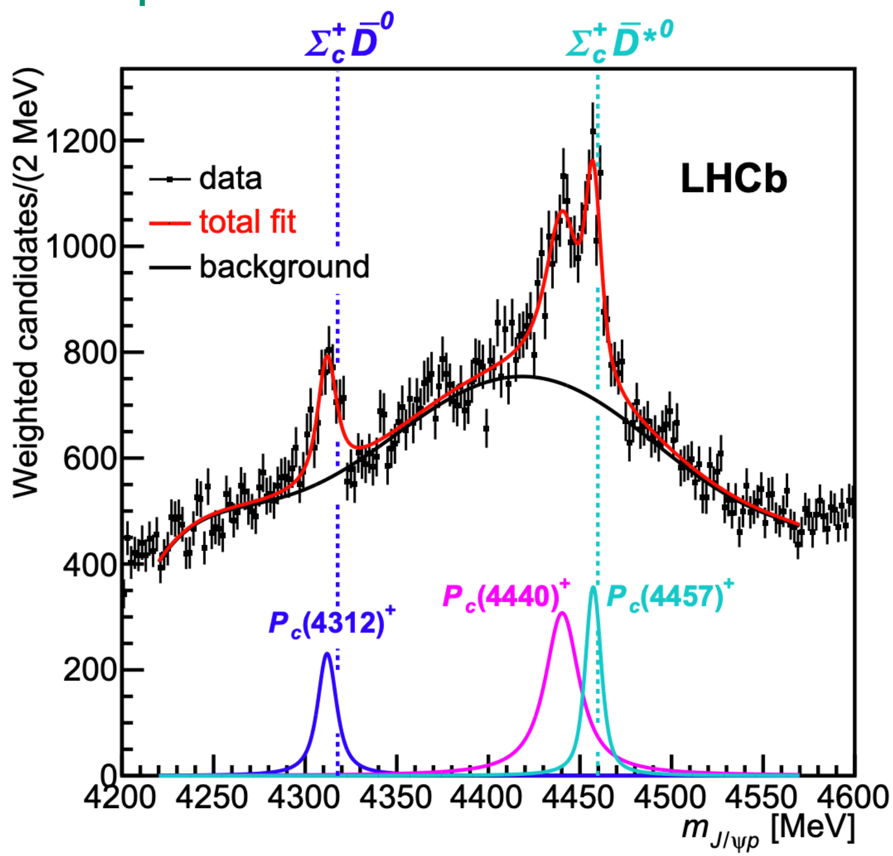
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to e^+e^-))},$$

- LHCb (2017) ome tension with Standard Model (2-2.5 σ)
  - Similar analysis in $B^+ \to K^+\ell^+\ell^-$ also shows a ~2 σ tension (LHCb, 2019)



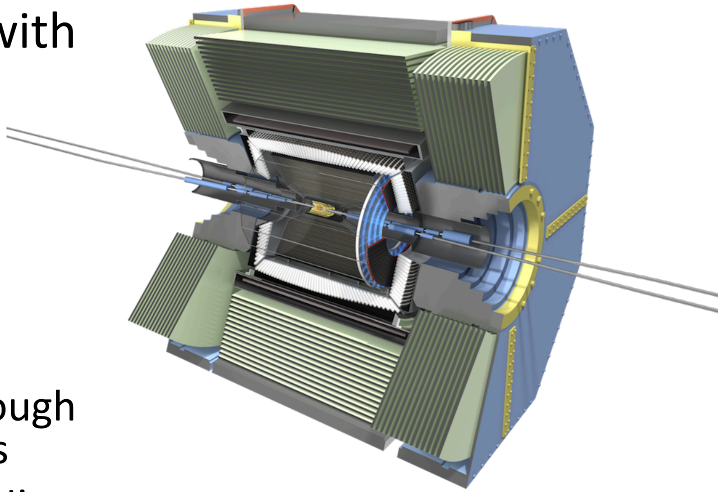
More from B physics: pentaquarks

- Baryonic states made of 5 quarks
  - Allowed by SU(3), have been searched for for ~50 years
- 3 pentaquarks structures observed by LHCb in $\Lambda_b^0 \to J/\Psi p K^-$ channel
  - ➤in 2015 and later in 2019
  - Complex amplitude analysis to confirm interpretation as pentaquarks
- Currently no observation by other experiments or in other channels



State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$

Coming soon: super B-factories



- Similar concept to (asymmetric) B-factories, with higher luminosity
  - Belle 2 started operations in 2019
- (Some) physics questions in agenda
  - New physics search at 'intensity frontier'
    - Search for deviations from Standard Model through very precise measurements of known processes
    - e.g. $B \to \tau\nu$ / $B \to D^{(*)}\tau\nu$ sensitive to charged Higgs models
  - Test for additional CP-violating phases in the quark sector
  - Search for Lepton Flavor Violation
  - …