Quark Flavor Physics: Mixing & CPV

Outline:

- Quark Flavor Physics
- Neutral Meson Mixing
- CP Violation in Interference between Mixing and Decay
- CP Violation in Mixing
- A words to direct CPV and γ

Ulrich Uwer – Neckarzimmern 2019 – 20/03/2019

What is Flavor Physics?

Three generations carry the same charges under the Standard Model gauge group $SU(3)_c \times SU(2)_L \times U(1)$:

Leptons			Quarks		
e	μ	τ	uuu	ccc	ttt
ν_e	ν_μ	ν_τ	ddd	sss	bbb

Flavor is **the feature** that distinguishes the generations.

Quark Flavor within the Standard Model

Yukawa interaction couples fermions to Higgs. For the quarks:

$$\mathcal{L}_{\rm Y}^{\rm quarks} = -\frac{v}{\sqrt{2}}\left(\overline{d}_{\rm L}\, Y_d\, d_{\rm R} + \overline{u}_{\rm L}\, Y_u\, u_{\rm R}\right) + \text{h.c}$$

After electroweak symmetry breaking

Y_d, Y_u are 3×3 complex matrices in generation space

not diagonal → flavor structure

Mass eigenstates of the quarks obtained by unitary transformations:

$\tilde{u}_A = V_{A,u}\, u_A$ $\quad \tilde{d}_A = V_{A,d}\, d_A$ $\quad$ and $\quad A = L, R \quad$ where $\quad V_{A,q} V_{A,q}^{\dagger} = 1$

$V_{A,q}$ are determined by requiring that the matrices $M_{d,u}$ are diagonal:

$$M_d = \mathrm{diag}(m_d, m_s, m_b) = \frac{v}{\sqrt{2}} V_{\rm L,d}\, Y_d\, V_{\rm R,d}^{\dagger}$$

Quark masses

After this transformation quark masses appear as usual Dirac terms:

$$\mathcal{L}_{\mathrm{Y}}^{\mathrm{quarks}} = -\overline{\tilde{d}}_{\mathrm{L}} M_d \tilde{d}_{\mathrm{R}} - \overline{\tilde{u}}_{\mathrm{L}} M_u \tilde{u}_{\mathrm{R}} + \mathrm{h.c.}$$

Up-type and down-type quarks cannot be diagonalized by the same matrix, i.e. $V_{A,d} \neq V_{A,u} \rightarrow$ net effect on flavor structure of charged current.

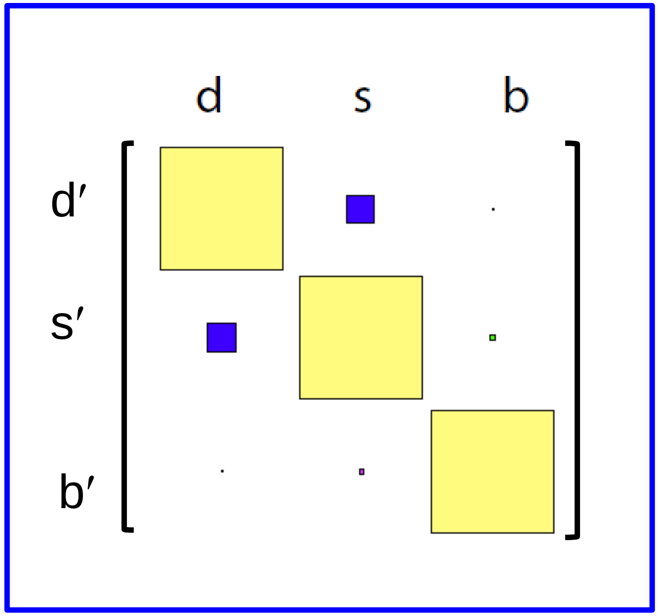
$$\mathcal{L}_{\mathrm{CC}} = -\frac{g_2}{\sqrt{2}} \left(\overline{\tilde{u}}_{\mathrm{L}} \gamma^\mu W_\mu^+ V_{\mathrm{CKM}} \tilde{d}_{\mathrm{L}} + \overline{\tilde{d}}_{\mathrm{L}} \gamma^\mu W_\mu^- V_{\mathrm{CKM}}^\dagger \tilde{u}_{\mathrm{L}} \right)$$

with $V_{\mathrm{CKM}} = V_{\mathrm{L},u} V_{\mathrm{L},d}^\dagger$ (must be unitary)

CKM Matrix

Complex and unitary 3×3 matrix:

$$\mathbf{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Complex 3×3 matrix: 18 parameters
+ unitarity condition (9 parameters)
+ removal of 5 unobservable quark phases
→ 4 free parameter:
3 Euler angles and one phase δ

Unobservable Phases

Absolute phases of quarks are unobservable: possible redefinition

$$u_L \to e^{i\phi(u)} u_L \qquad c_L \to e^{i\phi(c)} c_L \qquad t_L \to e^{i\phi(t)} t_L$$

$$d_L \to e^{i\phi(d)} d_L \qquad s_L \to e^{i\phi(s)} s_L \qquad b_L \to e^{i\phi(b)} b_L$$

Real numbers

Under phase transformation:

$$V \to \begin{pmatrix} e^{-i\phi(u)} & 0 & 0 \\ 0 & e^{-i\phi(c)} & 0 \\ 0 & 0 & e^{-i\phi(t)} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} e^{i\phi(d)} & 0 & 0 \\ 0 & e^{i\phi(s)} & 0 \\ 0 & 0 & e^{i\phi(b)} \end{pmatrix}$$

$$V\alpha j \to \exp[i(\phi(j) - \phi(\alpha))] V\alpha j$$

$L^{phys}(f, G)$ invariant

$L(f, H)$ affected …. rephasing q_R

CP violation

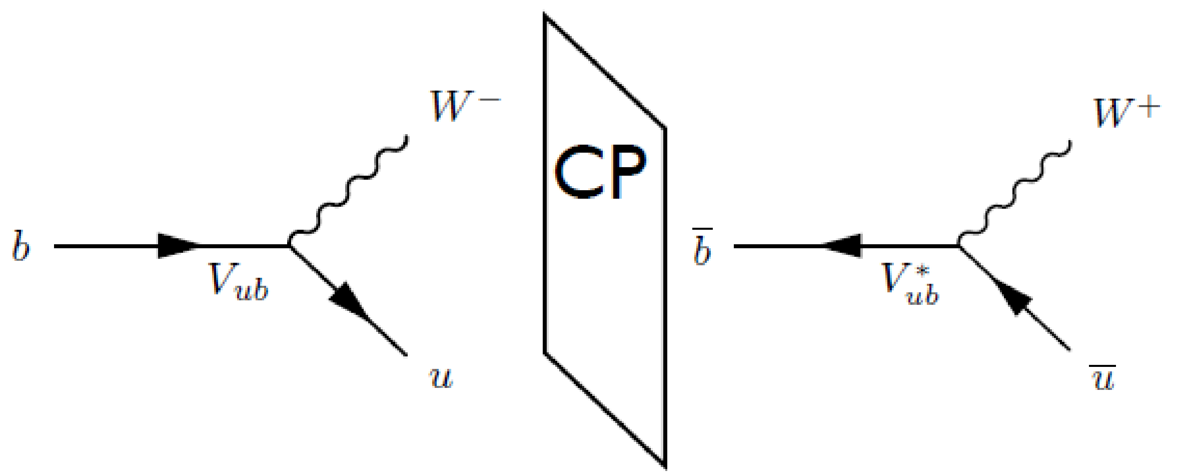
CP violation if $\boldsymbol{V_{CKM}}$ is complex:

$$\mathcal{L} = -\frac{g_2}{\sqrt{2}} \left[V_{ub}\, \overline{u}_L\, \gamma^\mu b_L\, W_\mu^+ + V_{ub}^*\, \overline{b}_L\, \gamma^\mu u_L\, W_\mu^- \right]$$

CP ↓

$$\mathcal{L}_{CP} = -\frac{g_2}{\sqrt{2}} \left[V_{ub}\, \overline{b}_L\, \gamma^\mu u_L\, W_\mu^- + V_{ub}^*\, \overline{u}_L\, \gamma^\mu b_L\, W_\mu^+ \right]$$

CP and T are anti-unitary operators → complex conjugation



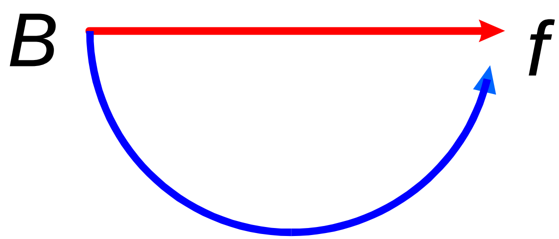
CP (T) violation possible if $V_{ji} \neq V_{ji}^*$

CP Violation in meson decays

CKM phase do not lead easily to measurable CPV asymmetries.

To observe CP violation needs at least two amplitudes with different weak (sign flip under CP) and different strong (invariant under CP) amplitudes:

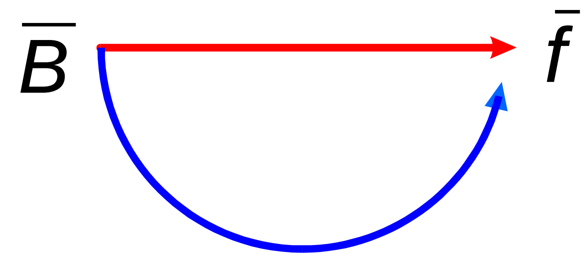
$$\mathcal{A}_1 = A_1 e^{i\phi_1} e^{i\delta_1}$$



$$\mathcal{A}_2 = A_2 e^{i\phi_2} e^{i\delta_2}$$

CP

$$\overline{\mathcal{A}}_1 = A_1 e^{-i\phi_1} e^{i\delta_1}$$



$$\overline{\mathcal{A}}_2 = A_2 e^{-i\phi_2} e^{i\delta_2}$$

$$\mathcal{A}(B \to f) = A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2} \qquad \overline{\mathcal{A}}(\bar{B} \to \bar{f}) = A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2}$$

$$\left|\overline{\mathcal{A}}\right|^2 - \left|\mathcal{A}\right|^2 = 4\, A_1 A_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

Wolfenstein Parametrization

Reflects the hierarchical structure of the CMK matrix

λ, A, ρ, η with λ= 0.22

$|V_{ub}| \times e^{-i\gamma}$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

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

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5\left(1/2-\rho-i\eta\right) & 1-\lambda^2/2-\lambda^4/8\left(1+4A^2\right) & A\lambda^2 \\ A\lambda^3\left(1-\bar{\rho}-i\bar{\eta}\right) & -A\lambda^2 + A\lambda^4\left(1/2-\rho-i\eta\right) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

$|V_{ts}| \times e^{-i\beta_s}$

Unitarity of CKM Matrix $V^{\dagger}_{CKM} V_{CKM} = 1$

$$\begin{pmatrix} V^*_{ud} & V^*_{cd} & V^*_{td} \\ V^*_{u\ldots} & & \\ V^*_{u\ldots} & & \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ & & \\ & & \end{pmatrix} \quad \begin{pmatrix} 1 & 0 & 0 \\ & & \\ & & \end{pmatrix}$$

Two definitions of β und γ. Which one is the correct definition, invariant aginst different phase conventions?

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

Im

Unitarity triangle „db“

CKM Phases **b→u**

$(\bar{\rho}, \bar{\eta})$

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \qquad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

$V_{cd} V_{cb}$

Re

CP Violation if Triangle has finite area !

More Triangles …

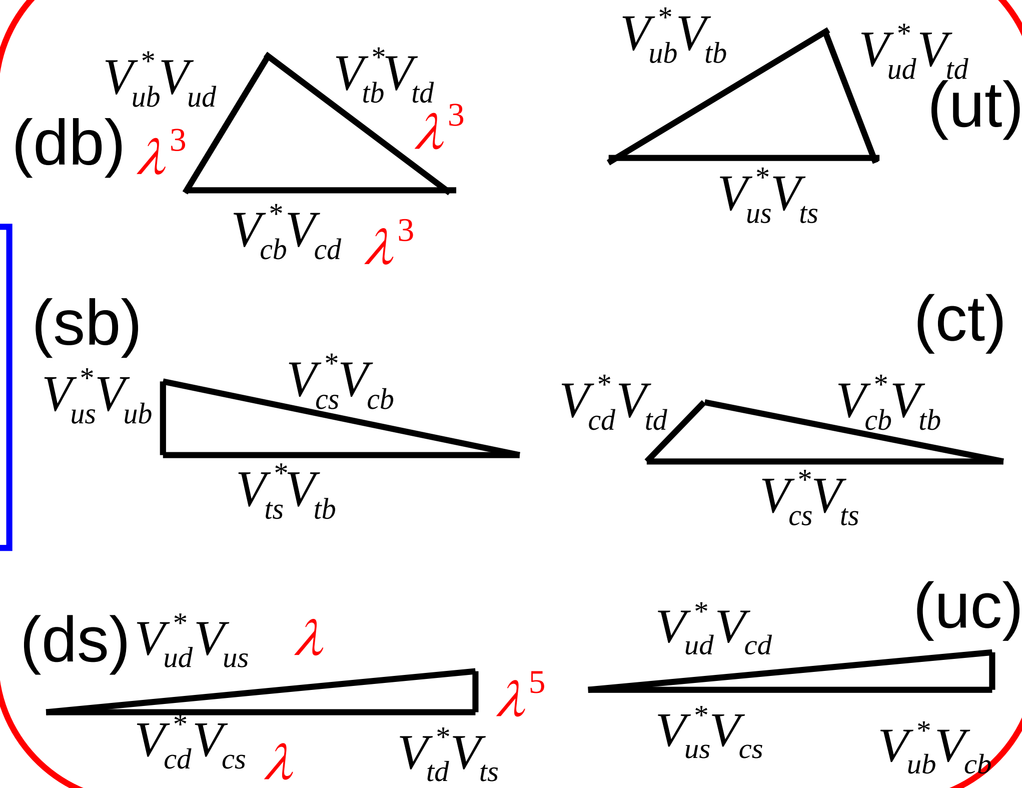
$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0 \text{ (db)}$$

$$V_{us}V_{ub}^{*}+V_{cs}V_{cb}^{*}+V_{ts}V_{tb}^{*}=0 \text{ (sb)}$$

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

$$V_{cd}V_{td}^{*}+V_{cs}V_{ts}^{*}+V_{cb}V_{tb}^{*}=0 \text{ (ct)}$$

$$V_{ud}V_{cd}^{*}+V_{us}V_{cs}^{*}+V_{ub}V_{cb}^{*}=0 \text{ (uc)}$$



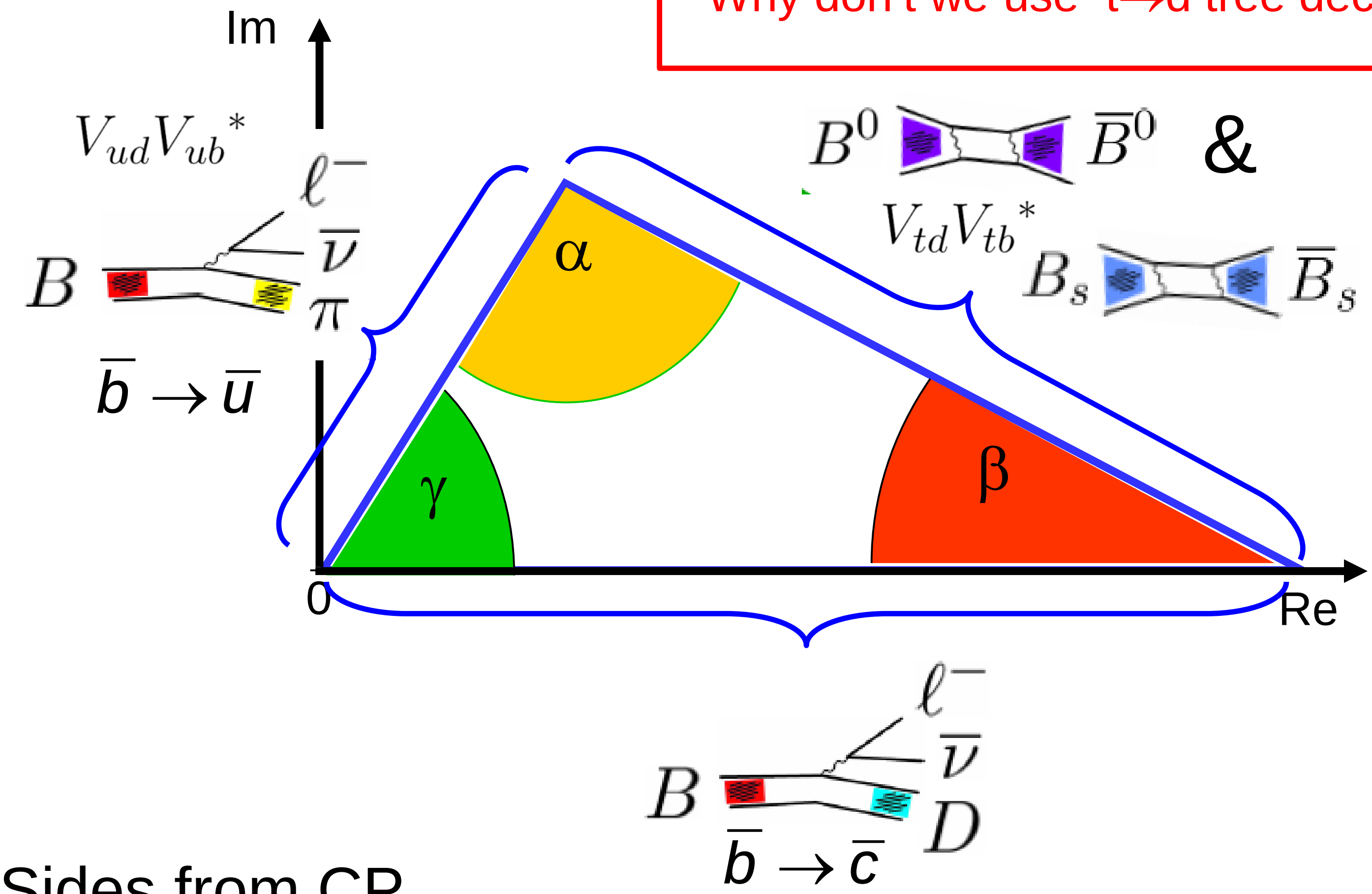
All 6 triangles have the same area: $J_{CP}/2$

J_{CP} is called Jarlskog invariant, it is a measure of CPV in Standard Model.

$$J_{CP} = \operatorname{Im}\left(V_{ij}\, V_{kl}\, V_{il}^{*} V_{kj}^{*} \right) \approx 3\cdot 10^{-5} \sim O(\lambda^{6})$$

Unitarity Triangle from B Decays

Why don't we use t→d tree decays?



Sides from CP conserving observables

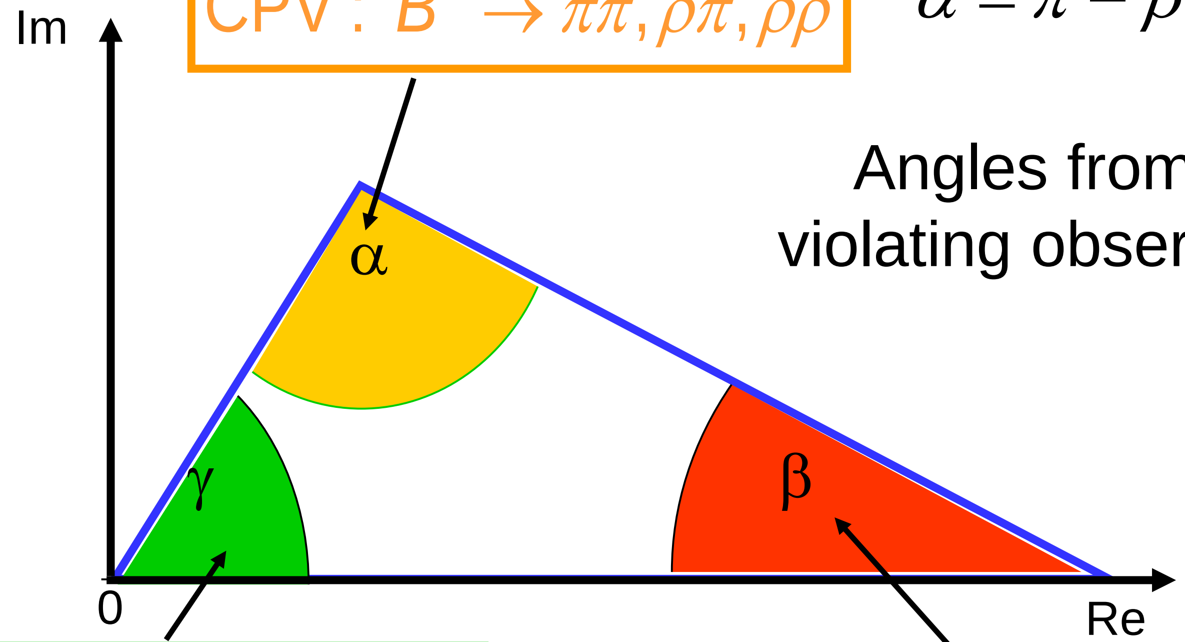
Unitarity Triangle from B Decays

(time-dependent)

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

$$\alpha = \pi - \beta - \gamma$$

Angles from CP violating observables



CPV : $B^0 \to DK^{(*)}, DK_S^0, K\pi, D^*\pi$

$B_s^0 \to D_s K, KK$

(time integrated)

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

(time-dependent)

Neutral Meson Mixing

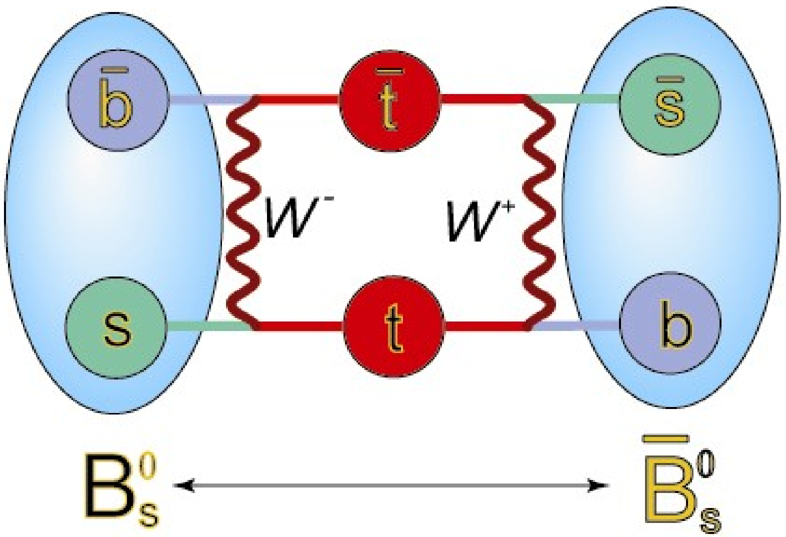
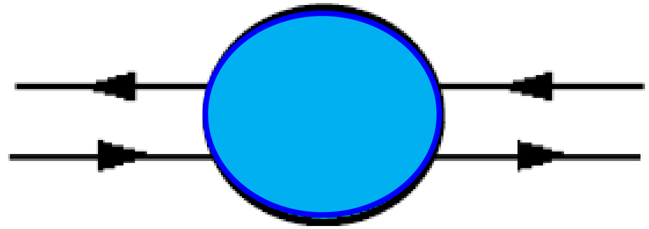


Figure from http://www.gridpp.ac.uk/news/?p=205

Mixing Phenomenology



$$i\frac{d}{dt}\begin{pmatrix} |P^0(t)\rangle \\ |\overline{P}^0(t)\rangle \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} |P^0(t)\rangle \\ |\overline{P}^0(t)\rangle \end{pmatrix}$$

No mass eigenstates

Non-hermitian $\rightarrow$ P^0 decays

CPT

$$m_{11} = m_{22} = m$$

$$\Gamma_{11} = \Gamma_{22} = \Gamma$$

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

M and **Γ** hermitian:

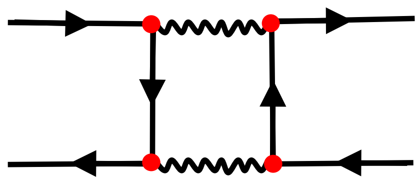
$$m_{21} = m_{12}^*$$

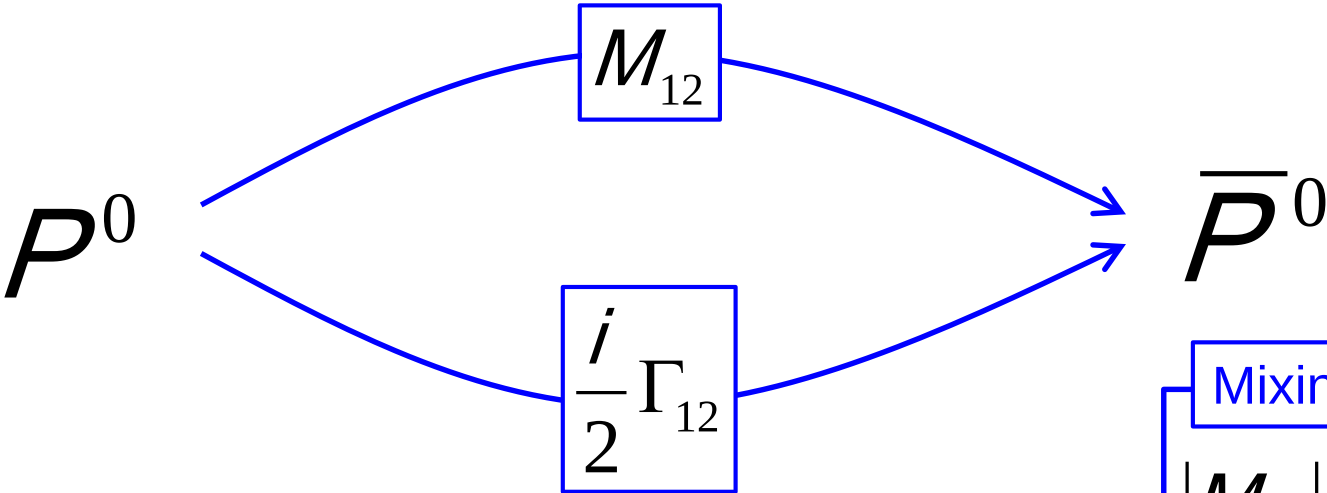
$$\Gamma_{21} = \Gamma_{12}^*$$

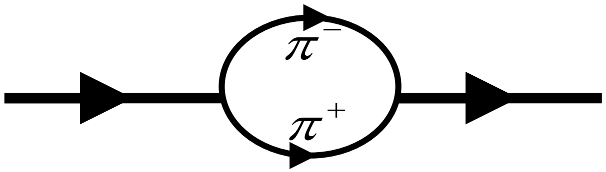
Off – diagonal elements describe the mixing.

Mixing Phenomenology

„short distant, virtual states“







„long distant, on-shell states“

for K^0 very important, for B^0 small

Mixing parameters

$$|M_{12}| \quad |\Gamma_{12}|$$

$$\phi_{M/\Gamma} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

Mass eigenstates

Mass eigenstates are obtained by diagonalizing the matrix:

$$|P_a\rangle = p|P^0\rangle + q|\overline{P^0}\rangle \quad \text{with } m_a, \Gamma_a \quad \Longrightarrow \quad |P_a(t)\rangle = e^{-im_a t} \cdot e^{-\frac{1}{2}\Gamma_a t}|P_a(0)\rangle$$

$$|P_b\rangle = p|P^0\rangle - q|\overline{P^0}\rangle \quad \text{with } m_b, \Gamma_b \quad \Longrightarrow \quad |P_b(t)\rangle = e^{-im_b t} \cdot e^{-\frac{1}{2}\Gamma_b t}|P_b(0)\rangle$$

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

P_a and P_b are not necessary orthogonal: $\langle P_b | P_a \rangle = |p|^2 - |q|^2 \neq 0$

The mass (physical) states are usually labeled by the properties which distinguish them the best: K_S, K_L; B_H, B_L; D_1, D_2;

For p = q = 1/√2: $P_a = P_1$ (CP +) , $P_b = P_2$ (CP -)

Mixing Parameters

$$\Delta m = m_b - m_a \qquad \Delta\Gamma = \Gamma_b - \Gamma_a \qquad \Delta\Gamma = \Gamma_a - \Gamma_b$$

H L H L L H

$$m = \frac{1}{2}(m_b + m_a) \qquad \Gamma = \frac{1}{2}(\Gamma_a + \Gamma_b)$$

$$\frac{q}{p} = \pm\sqrt{\frac{H_{21}}{H_{12}}} = \pm\sqrt{\frac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}}}$$

- The sign of q/p determines whether m_a or m_b is heavier: the usual choice is $\Delta m>0$: $q/p>0 \Rightarrow$ "+" sign.
- Attention: this conventions is not fixing the sign of $\Delta\Gamma$. The experiment has to tell whether CP even/odd lives longer.

for B mesons:
$\Gamma_{12} << M_{12}$:
$\Delta\Gamma$ small
$\Delta m = 2\,|M_{12}|$

$$\Delta m = 2\left|M_{12}\right|$$

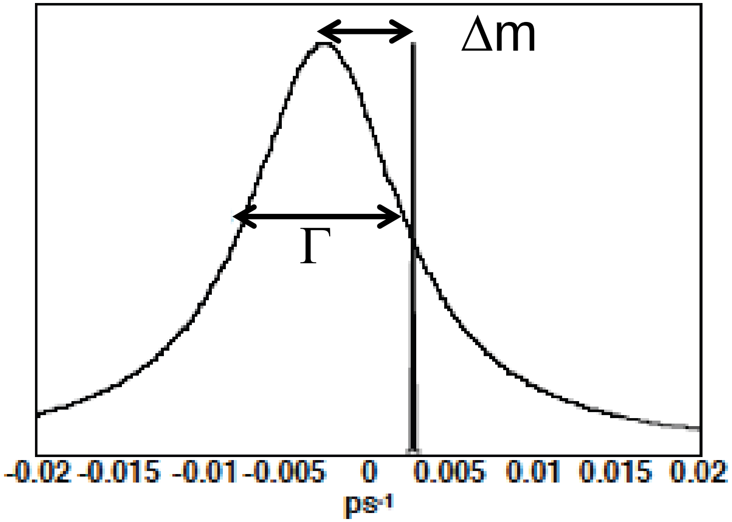
$$\Delta\Gamma = 2\left|\Gamma_{12}\right|\cos\varphi_{M/\Gamma}$$

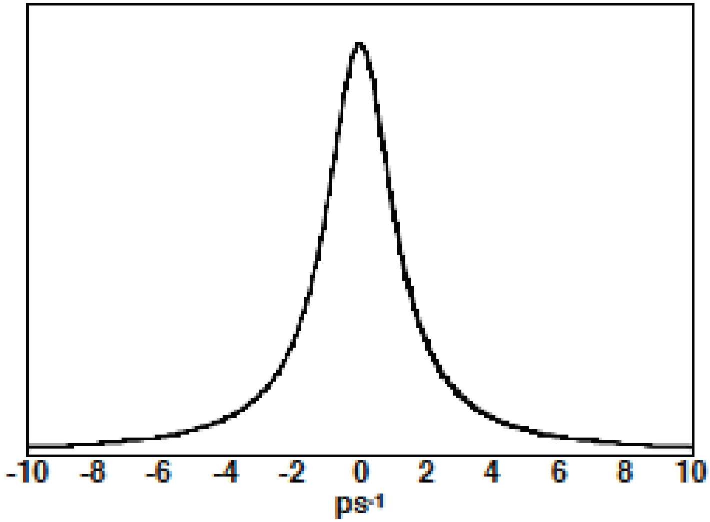
$$\left|q/p\right| \approx 1$$

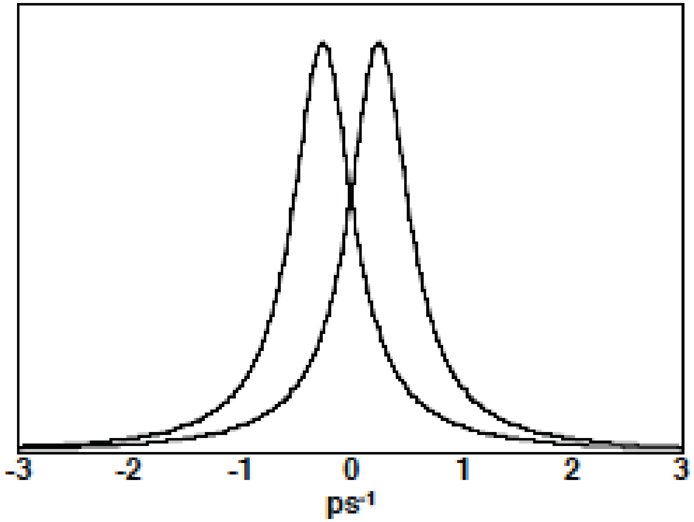
Neutral Mesons K^0, D^0, B^0, B_s ?

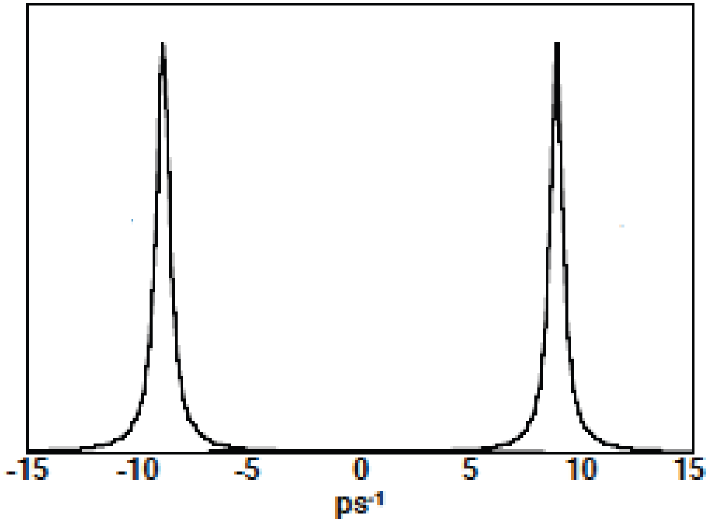
Slide from M. Gersabeck

Labeling of physical states: heavy/light, short/long, CP-even/CP-odd



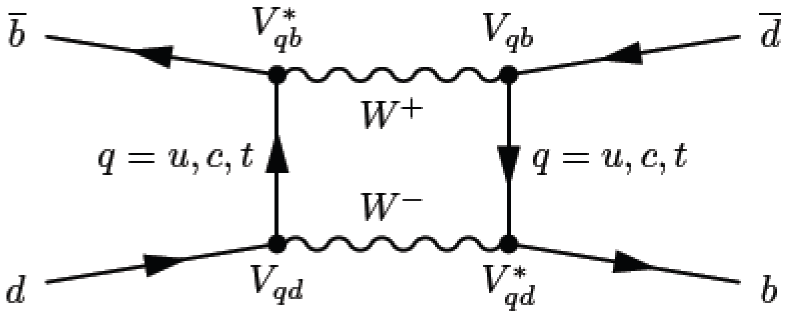






Theoretical predictions Δm_d

Question: What happens if quarks have the same mass?



$t-\bar{t}: \quad \propto m_t^2 \left|V_{tb}V_{td}^*\right|^2 \quad \propto m_t^2\lambda^6$

$c-\bar{c}: \quad \propto m_c^2 \left|V_{cb}V_{cd}^*\right|^2 \quad \propto m_c^2\lambda^6$

$c-\bar{t}, \bar{c}-t: \quad \propto m_c m_t V_{tb} V_{td}^* V_{cb} V_{cd}^* \quad \propto m_c m_t \lambda^6$

u quark can be replaced using unitarity V_{CKM}

$$M_{12} \approx \frac{G_F^2}{12\pi^2}\left(V_{td}^* V_{tb}\right)^2 M_W^2 S_0\left(x_t\right) B_B f_B^2 M_B \eta_B$$

$$\Delta m \approx 2\left|M_{12}\right|$$

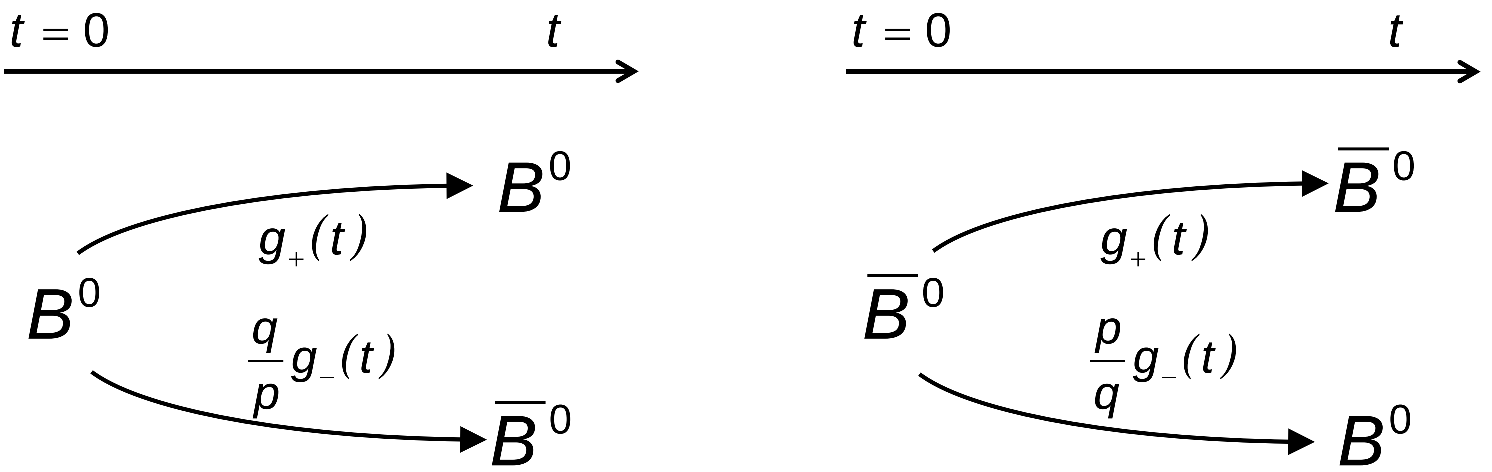
B_s: $(V^*_{ts}V_{tb})^2 \sim \lambda^4$ about $\times 25$ larger

$S_0\left(m_t^2/m_W^2\right)$ = Loop-function (Inami-Lim) = result of box diagramm.

$B_B f_B^2$ = non-perturbative hadronic effects

η_B = *perturbative QCD corrections*

Time evolution of B^0 (P^0)



$$\left|B^0\right\rangle = \frac{1}{2p}\left(\left|B_L\right\rangle + \left|B_H\right\rangle\right)$$

$$\left|\overline{B^0}\right\rangle = \frac{1}{2q}\left(\left|B_L\right\rangle - \left|B_H\right\rangle\right)$$

CP Violation in mixing: $\left|\frac{q}{p}\right| \neq 1$

Mixing phenomenology

Mixed/ unmixed probability: $\Delta\Gamma \approx 0$

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

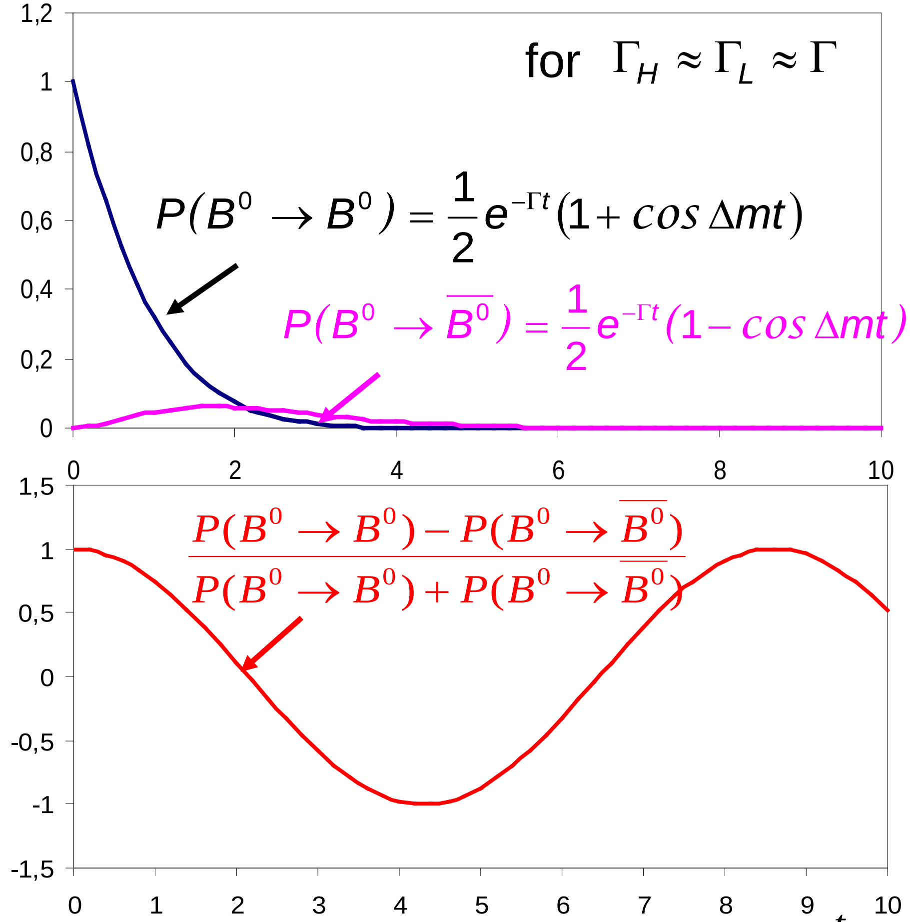
$$\mathcal{P}(B^0 \to \bar{B}^0, t) = \left|\left\langle B^0 | \bar{B}^0(t) \right\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}\left|\frac{q}{p}\right|^2(1 - \cos(\Delta m t))$$

Mixing asymmetry:

$$A(t) = \frac{unmixed(t) - mixed(t)}{unmixed(t) + mixed(t)} = \cos(\Delta m t)$$

If |q/p| =1

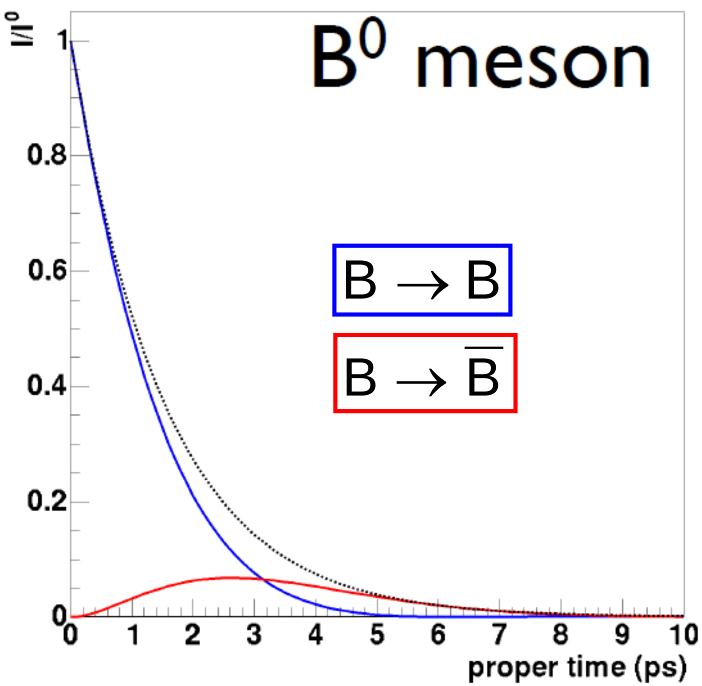
Time dependent mixing asymmetry

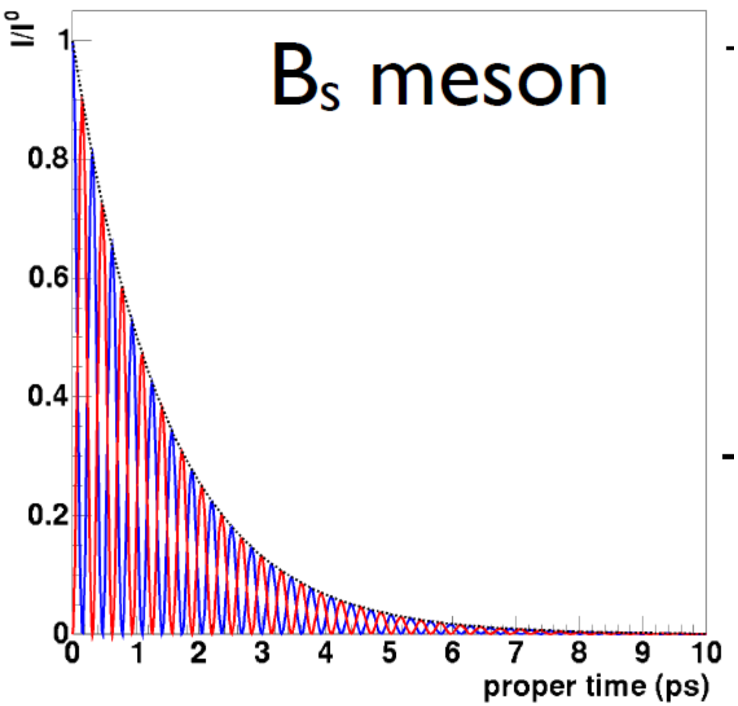


$\cos(\Delta m t)$

Lifetime (proper time) $\frac{t}{\tau_B}$

B meson mixing





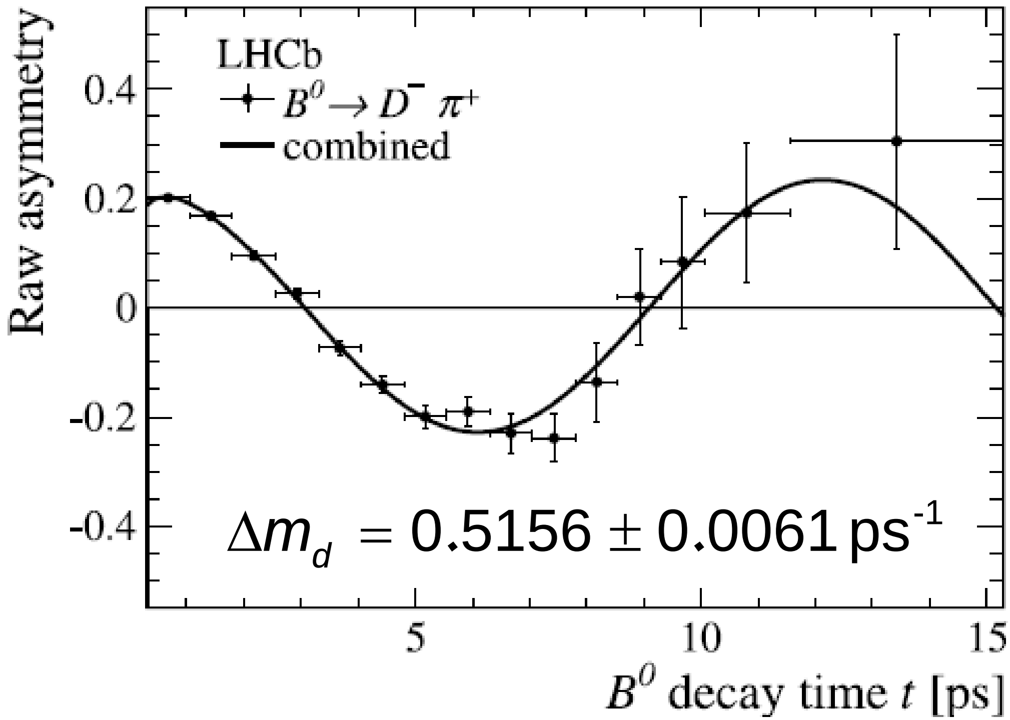
$$M_{12,q} = \frac{G_F^2}{12\pi^2}(V_{tq}^* V_{tb})^2 M_W^2 S_0(x_t) B_{B_q} f_{B_q}^2 M_{B_q} \hat{\eta}_B$$

$$\frac{\Delta m_d}{\Delta m_s} \approx \frac{|V_{td}|^2}{|V_{ts}|^2} \approx \frac{\lambda^6}{\lambda^4} = \lambda^2 \approx 0.04$$

B^0 Mixing *)

Phys. Lett. B 719 (2013) 318.

B^0 ↕ $\overline{B}^0$

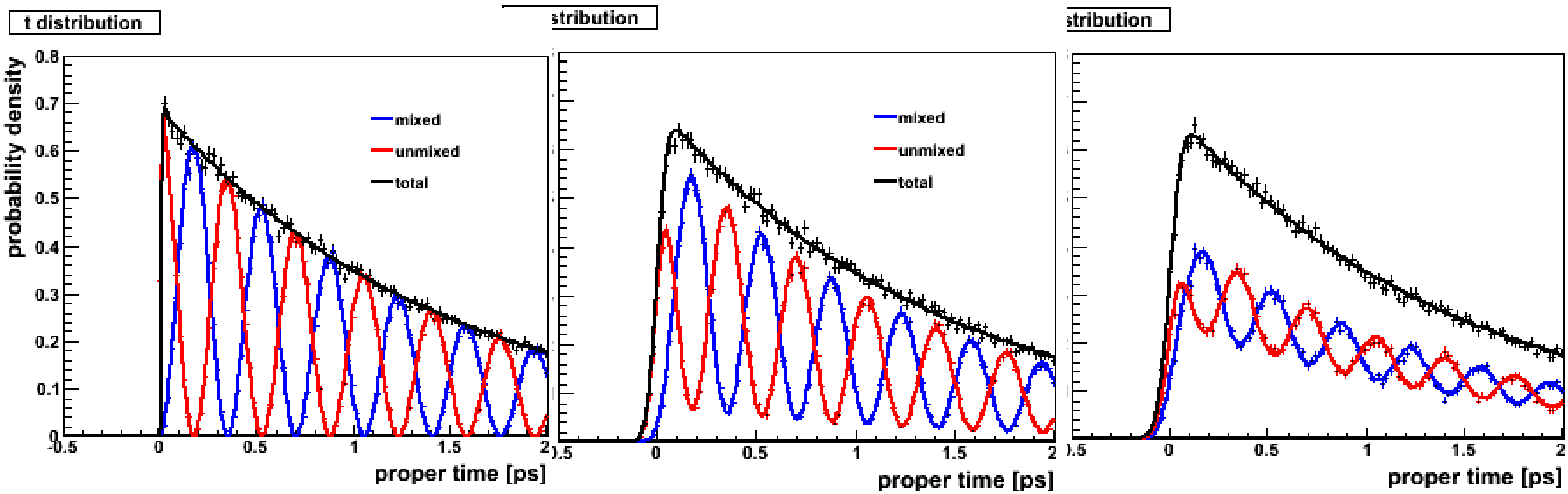


D=1-2ω

Question: Why is oscillation not from +1 to -1?

Question: ARGUS (DESY) in 1987: m_{top} > 50 GeV. Why???

Detector effects on B_s oscillation

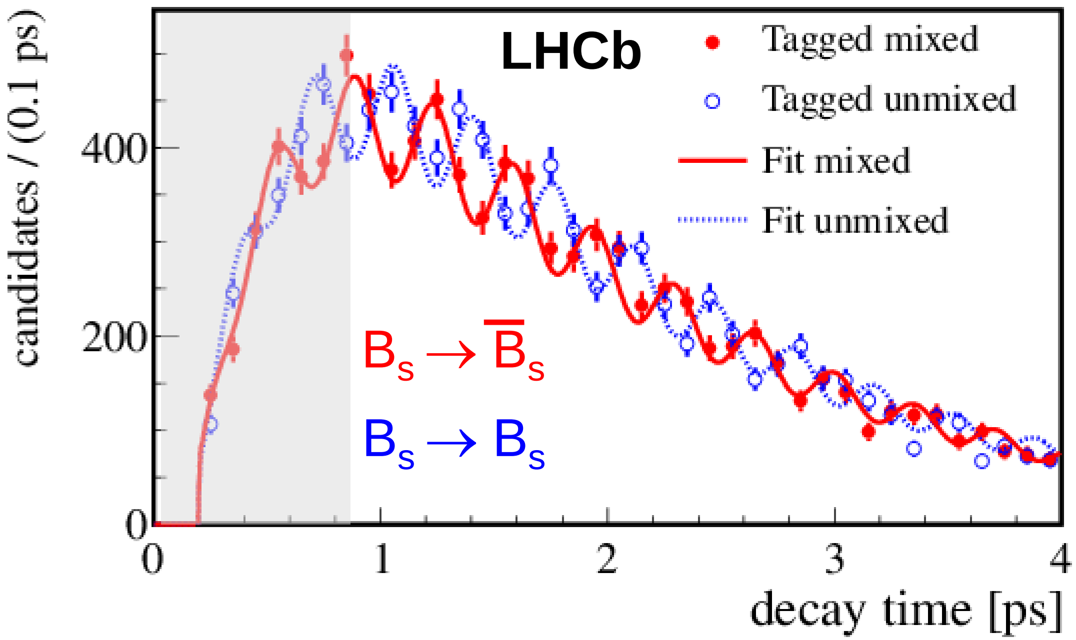


Finite time resolution: 44 fs

Realistic tagging

B_s-Mixing

New J. Phys. 15 (2013) 053021



$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ ps^{-1}$ ← **1 per mille** (syst: z & p scale)

Theorie *(M. Artuso et al., 2015)*
$\Delta m_s = 18.3 \pm 2.7\ ps^{-1}$

Precision tests of the Standard Model difficult:
Hadronic uncertainties limit the precision of the theoretical prediction

Parameters with better precision?

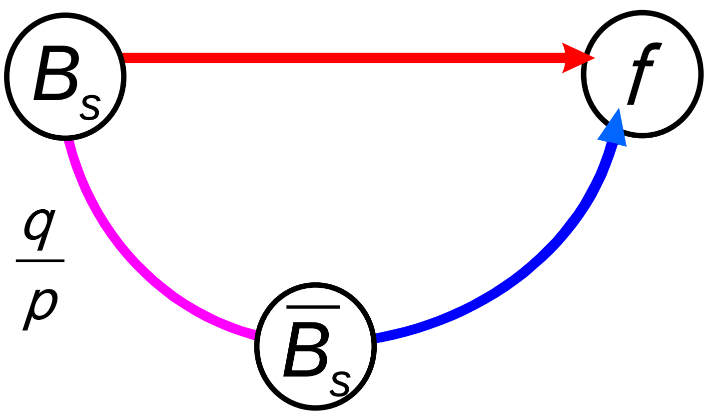
Phases have very small absolute theoretical uncertainties:

$$\phi_M = \arg(M_{12}) = \arg\left(\frac{q}{p}\right)$$ Mixing phase

Theory:

$$\phi_{M/\Gamma} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

Theory: $\phi_{M/\Gamma} = 0.0038 \pm 0.0010$



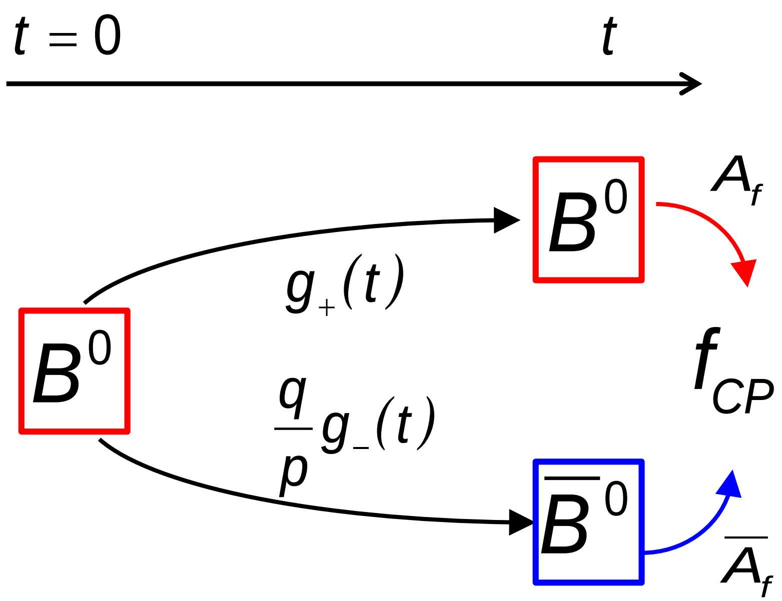
$$P(B^0 \longrightarrow \bar{B}^0) \neq P(\bar{B}^0 \longrightarrow B^0)$$

Time dependent CP-violation of B_s decaying to a CP eigenstate

CP-violation in mixing

Interference between Mixing and Decay

adapted from G. Raven



$$g_+(t) A_f + \frac{q}{p} g_-(t) \overline{A}_f$$

$$g_+(t) = e^{-i(m - i\frac{\Gamma}{2})t} \left[+ \cosh\frac{\Delta\Gamma t}{4} \cos\frac{\Delta m t}{2} - i \sinh\frac{\Delta\Gamma t}{4} \sin\frac{\Delta m t}{2} \right]$$

$$g_-(t) = e^{-i(m - i\frac{\Gamma}{2})t} \left[- \sinh\frac{\Delta\Gamma t}{4} \cos\frac{\Delta m t}{2} + i \cosh\frac{\Delta\Gamma t}{4} \sin\frac{\Delta m t}{2} \right]$$

Master Formula for t-dependent CPV

$$\Gamma(B^0 \to f)(t) = |A_f|^2 \left(1+|\lambda_f|^2\right)\frac{e^{-\Gamma t}}{2}\Big\{$$

$$\cosh\left(\frac{\Delta\Gamma}{2}t\right) + D_f \sinh\left(\frac{\Delta\Gamma}{2}t\right) + C_f \cos\left(\Delta m t\right) - S_f \sin\left(\Delta m t\right)\Big\}$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \quad D_f = \frac{2\Re A_f}{1+|\lambda_f|^2} \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \quad S_f = \frac{2\Im A_f}{1+|\lambda_f|^2}$$

$$\Gamma(\bar{B}^0 \to f)(t) = |A_f|^2 \left(1+|\lambda_f|^2\right)\frac{e^{-\Gamma t}}{2}\Big\{$$

$$\cosh\left(\frac{\Delta\Gamma}{2}t\right) + D_f \sinh\left(\frac{\Delta\Gamma}{2}t\right) - C_f \cos\left(\Delta m t\right) + S_f \sin\left(\Delta m t\right)\Big\}$$

Master Formula for t-dependent CPV

$$A_{CP}(t) = \frac{\Gamma(B^0 \to f)(t) - \Gamma(\bar{B}^0 \to f)(t)}{\Gamma(B^0 \to f)(t) + \Gamma(\bar{B}^0 \to f)(t)} = \frac{2C_f \cos(\Delta m\, t) - 2S_f \sin(\Delta m\, t)}{2\cosh\left(\frac{\Delta\Gamma}{2} t\right) + 2D_f \sinh\left(\frac{\Delta\Gamma}{2} t\right)}$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \quad D_f = \frac{2\Re A_f}{1+|\lambda_f|^2} \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \quad S_f = \frac{2\Im A_f}{1+|\lambda_f|^2}$$

Time-dependent CPV even if |q/p| = 1 (i.e. no CPV in mixing) and $\bar{A}_f$ / A_f = 1 (no direct CPV) if

$$|\lambda_f| = 1 \quad \text{and} \quad \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) = \phi_{weak} \neq 0$$

Time-dependent CP-Asymmetry $\Delta\Gamma\approx 0$

adapted from G. Raven

$t=0$	t	Rate
$B^0 \longrightarrow$	f_{CP}	$\propto e^{-\Gamma t}\,[1+\sin(\phi_{\text{weak}})\sin(\Delta m t)]$
$\overline{B^0} \longrightarrow$	f_{CP}	$\propto e^{-\Gamma t}\,[1-\sin(\phi_{\text{weak}})\sin(\Delta m t)]$

$$A_{CP}(t)=\frac{\Gamma(B^0\to f)(t)-\Gamma(\bar{B}^0\to f)(t)}{\Gamma(B^0\to f)(t)+\Gamma(\bar{B}^0\to f)(t)}=\frac{2C_f\cos(\Delta m t)-2S_f\sin(\Delta m t)}{2\cosh\left(\frac{\Delta\Gamma}{2}t\right)+2D_f\sinh\left(\frac{\Delta\Gamma}{2}t\right)}$$

$$=-S_f\sin(\Delta m t)=-\sin\phi_{weak}\sin(\Delta m t)$$

Time-dependent CP Asymmetry $\Delta\Gamma \neq 0$

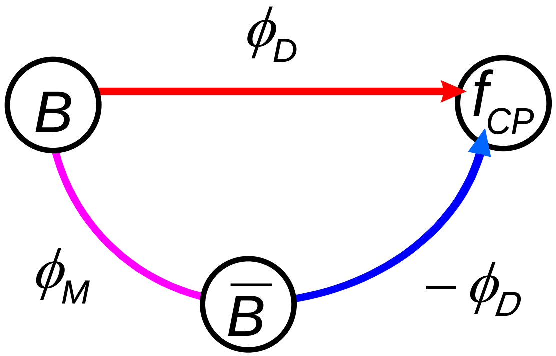
$$|\lambda_f| = \left|\frac{q}{p}\frac{\bar{A}_f}{A_f}\right| = 1$$

$$\mathcal{A}_{CP}(t) \equiv \frac{\Gamma(\overline{B^0} \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B^0} \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$

$$= \frac{-\Im\lambda_f \sin \Delta m t}{\cosh \frac{1}{2}\Delta\Gamma t + \Re\lambda_f \sinh \frac{1}{2}\Delta\Gamma t}$$

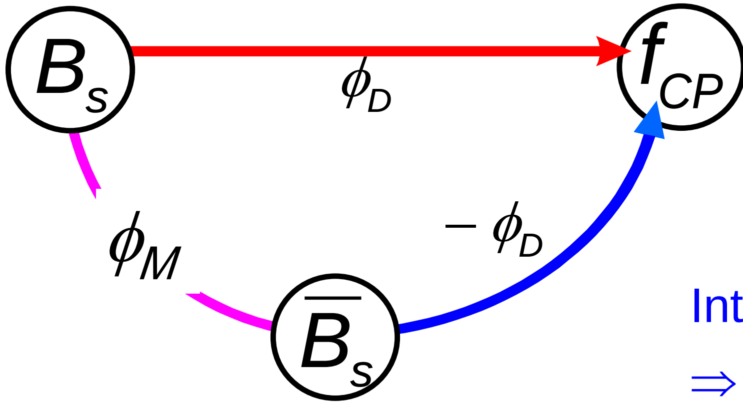
$$\approx -\sin\phi_{weak} \sin(\Delta m t)$$

Measurement of time dependent CP asymmetry of a process $B^0 \to f_{CP}$ measures the phase difference ϕ_{weak} between the two paths:



$$\phi_{weak} = \phi_M - 2\phi_{weak}$$

Measuring the B_s mixing phase



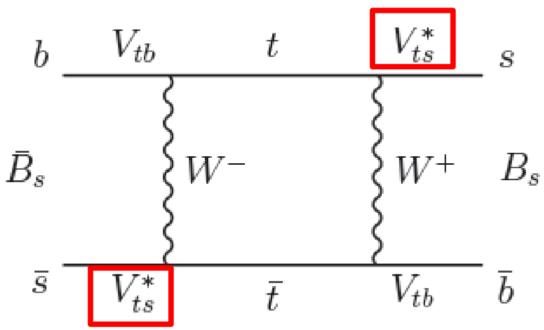
$B_s \rightarrow J/\psi\ \phi(KK)$

$$\phi_M = \arg(M_{12}) = \arg\left(\frac{q}{p}\right)$$

Interference of mixing & decay:

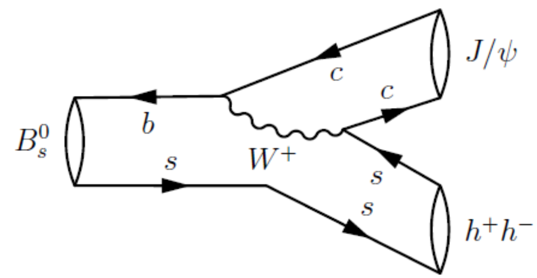
$$\Rightarrow \phi_{weak} = \phi_M - 2\phi_D \equiv \phi_s$$

Standard Model:



$$\phi_M \approx 2\arg(V_{ts}) \approx -2\beta_s$$

$$V_{ts} = |V_{ts}|e^{-i\beta_s}$$



+ small penguin pollution

$$\phi_D^{SM} = -2\arg(V_{cs}V_{cb}^*) \approx 0$$

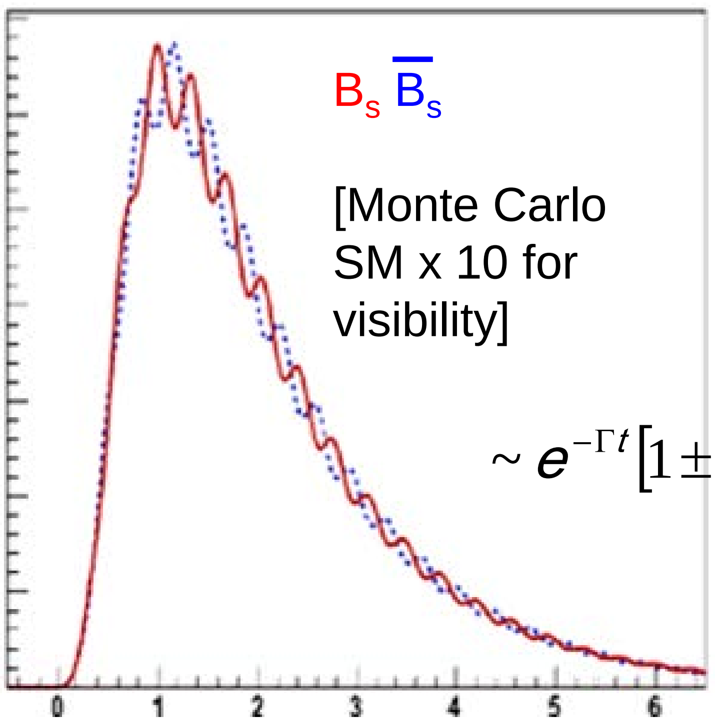
$$\phi_{weak,s}^{SM} = -0.0364 \pm 0.0016 \text{ rad} \quad \textit{(CKMFitter)}$$

$\rightarrow$ very small CPV

Standard Model Expectation

Precise Standard Model prediction:

$$\phi_s^{SM} = -0.0364 \pm 0.0016 \text{ rad}$$



B_s $\bar{B}_s$

[Monte Carlo SM x 10 for visibility]

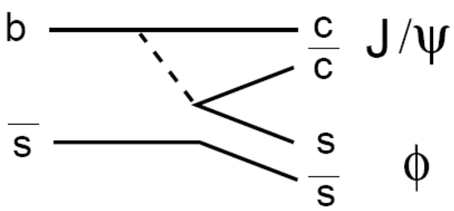
➡ ϕ_s small: expect very small CPV

$$\sim e^{-\Gamma t}\left[1 \pm \sin\phi_s \sin(\Delta m_s t)\right]$$

$B_s \rightarrow J/\psi\ (\mu\mu)\ \phi(KK)$

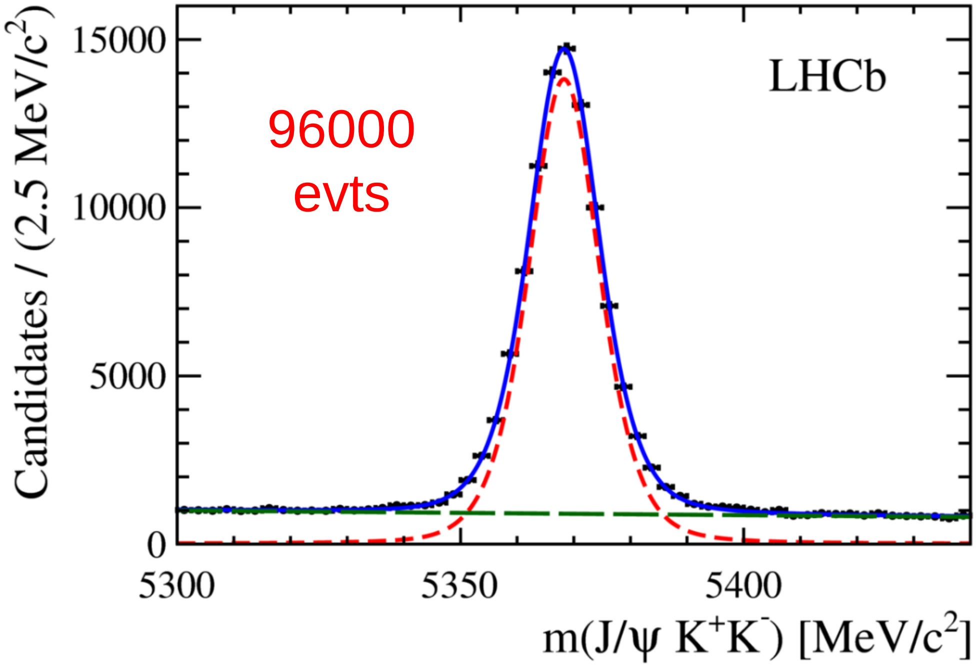
Phys. Rev. Lett. 114, 041801 (2015)

- experimentally clean
- VV final state:



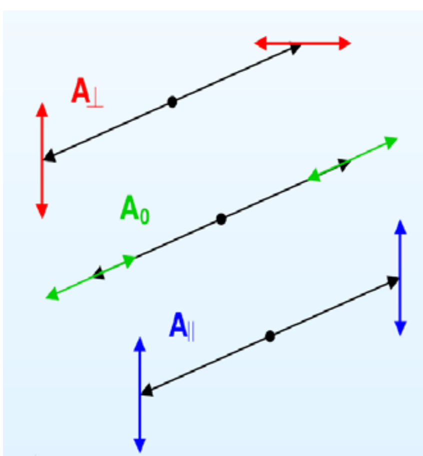
$J^{PC} = 1^{--}$

$J^{PC} = 1^{--}$

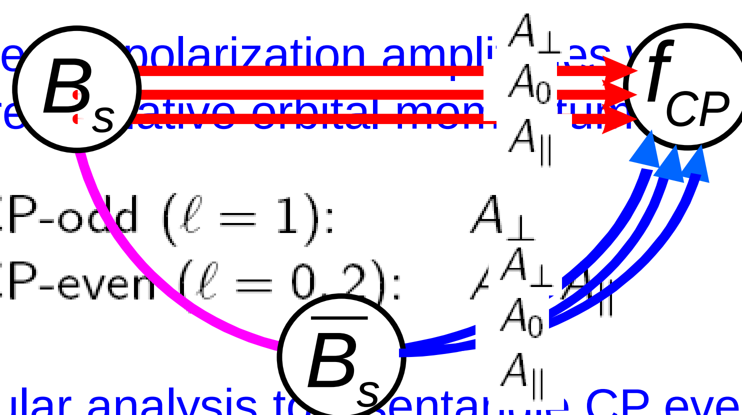


$CP(J/\psi\phi) = CP(J/\psi)CP(\phi)(-1)^L$

(L = 0, 1,2 = relative orbital momentu



3 diffe[illegible] polarization ampli[illegible]es w[illegible]
differe[illegible]lative orbital mom[illegible]tum



CP-odd ($\ell = 1$): $A_\perp$

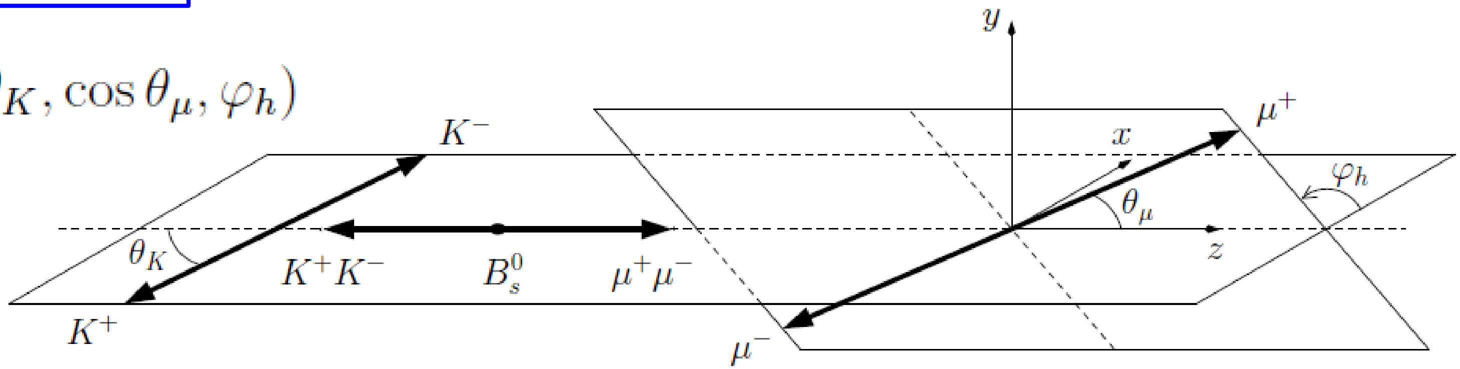
CP-even ($\ell = 0, 2$): A_0, $A_\parallel$

angular analysis to disentangle CP even/odd state

Angular dependent t distributions

Helicity frame

$$\Omega = (\cos\theta_K, \cos\theta_\mu, \varphi_h)$$



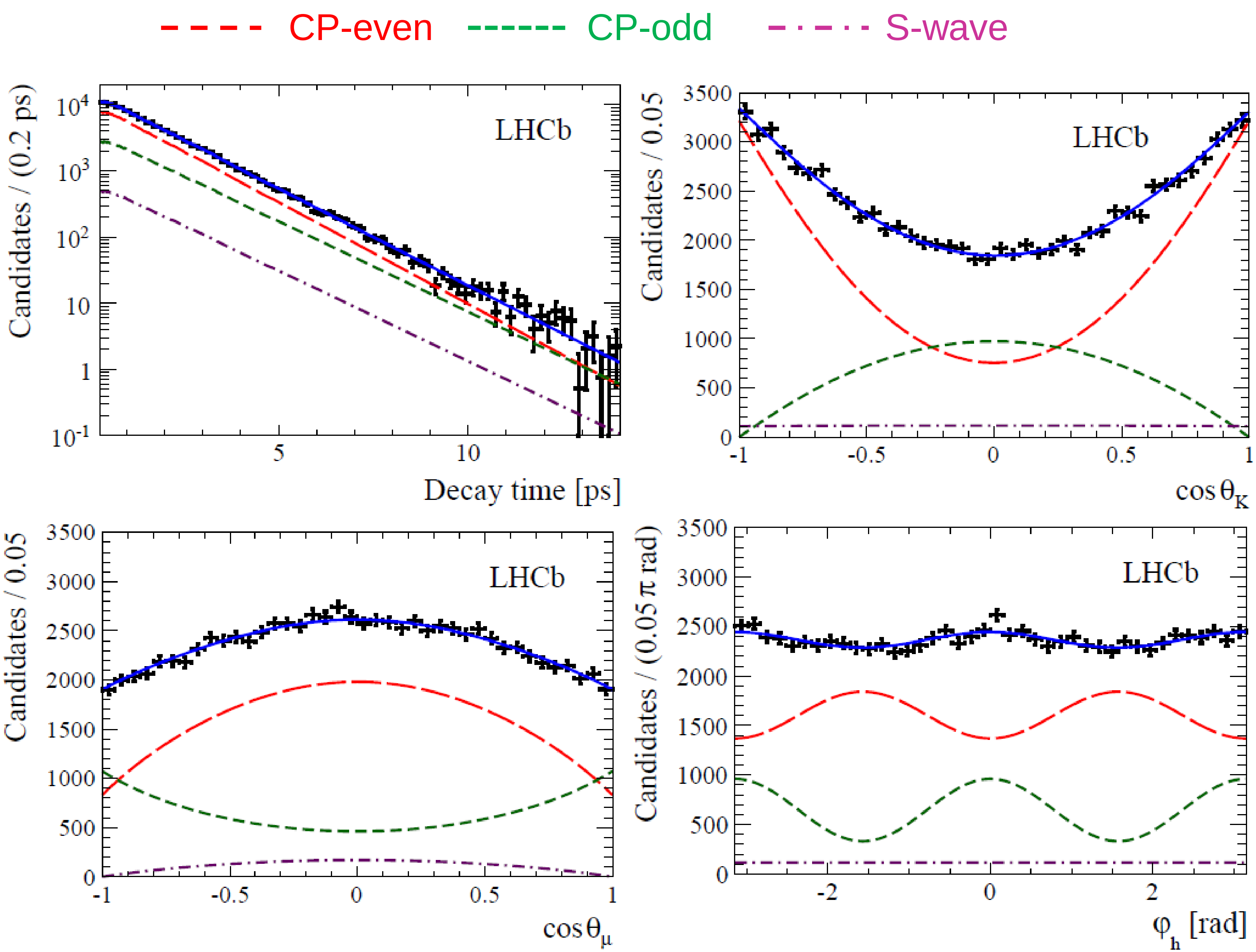
B_s

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

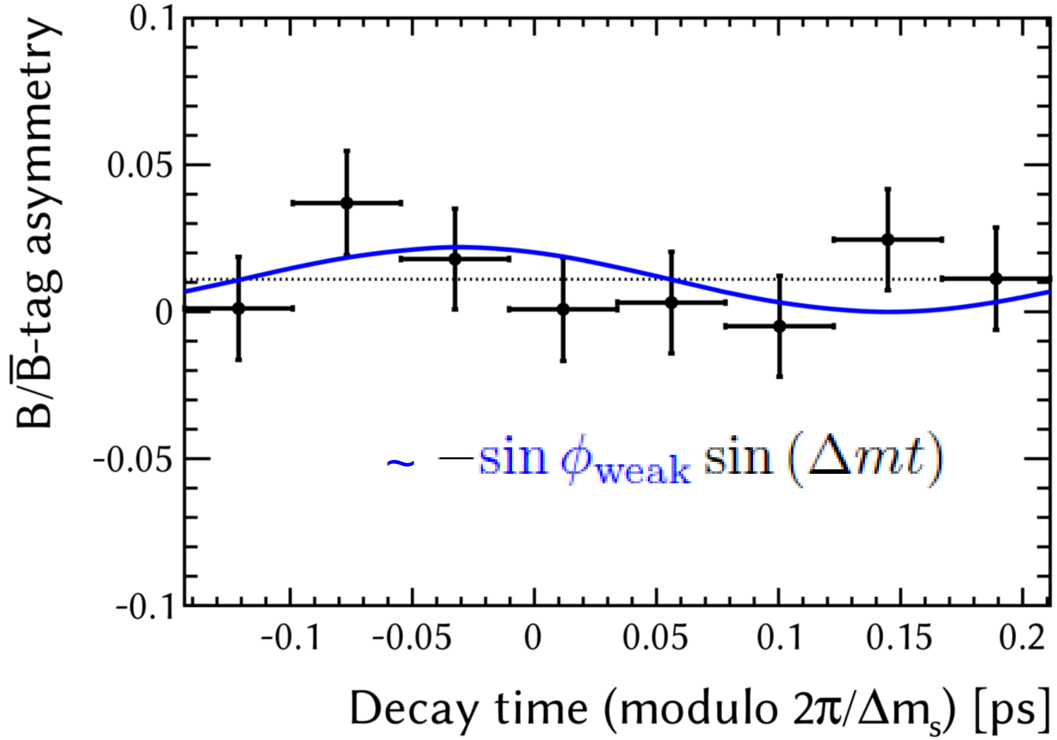
$\overline{B}_s$

$$\frac{d^4\Gamma(\overline{B}_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} \overline{h}_k(t)\, \overline{f}_k(\Omega)$$

Decay time and decay angles



Time-dependent CP Asymmetry for B_s



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$\phi_s = -0.058 \pm 0.049 \pm 0.006$

$\Gamma = 0.6603 \pm 0.0027 \pm 0.0015\ ps^{-1}$

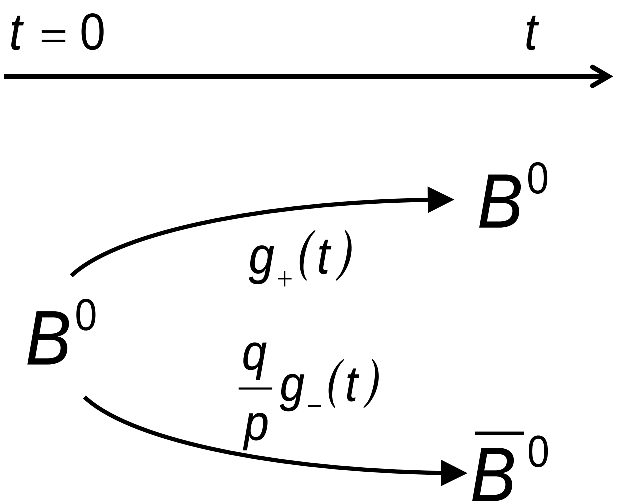
$\Delta\Gamma = 0.0805 \pm 0.0091 \pm 0.0032\ ps^{-1}$

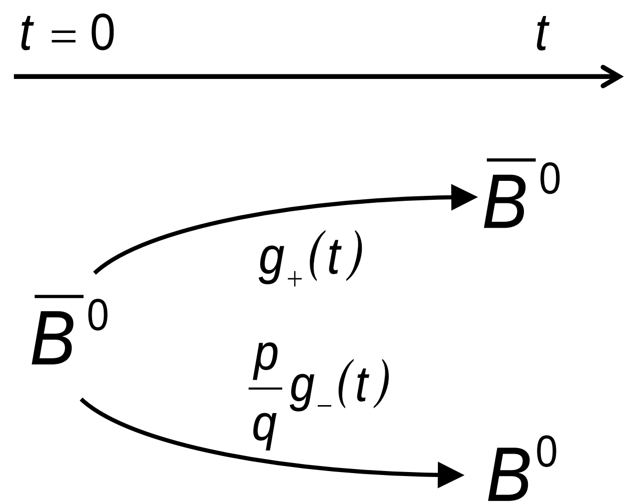
$|\lambda| = 0.964 \pm 0.019 \pm 0.007$

Consistent w/ =1:
no CPV

CP Violation in B mixing

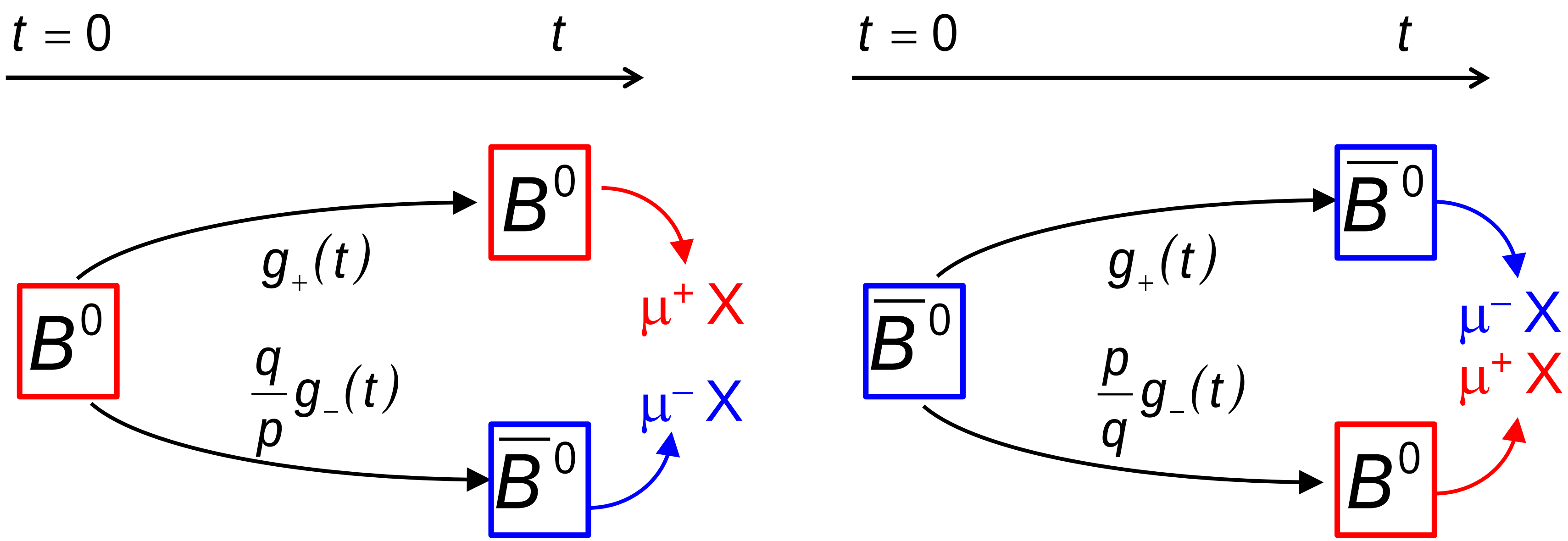
$$P(B^0_{d,s} \rightarrow \overline{B^0_{d,s}}) \neq P(\overline{B^0_{d,s}} \rightarrow B^0_{d,s})$$

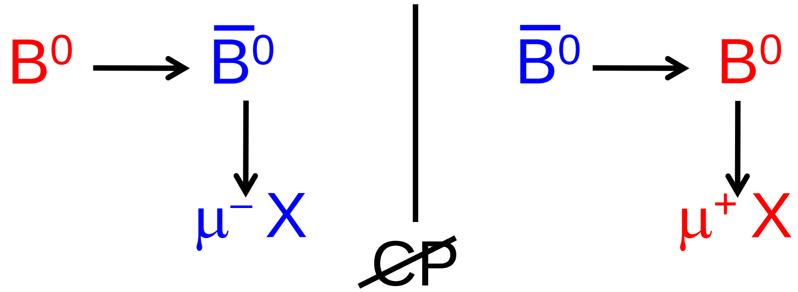




CP violation if $\left|\frac{q}{p}\right| \neq 1$

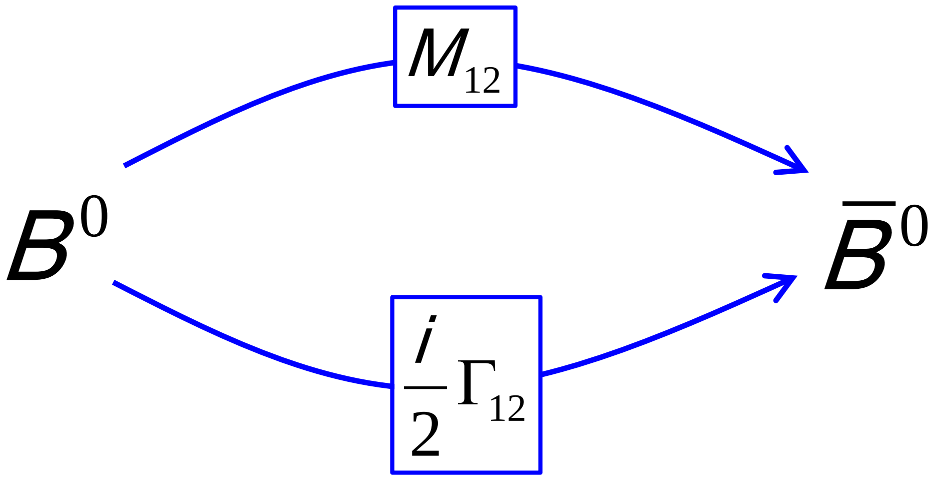
Semileptonic CP asymmetry





Question: Which amplitudes interfere?

Interference-Effect



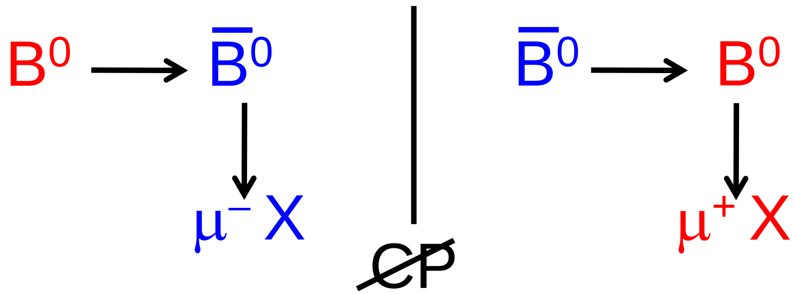
Weak phase difference:

$$\phi_{M/\Gamma} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

In case of CPV in mixing: $\left|\frac{q}{p}\right| = \left|\frac{1-\varepsilon}{1+\varepsilon}\right| \neq 1$ with $\varepsilon = \frac{p-q}{p+q}$ complex

Physical states (B_H, B_L) are not any longer pure CP states.

Time integrated asymmetry



$$a_{sl}^{q} \equiv \frac{\Gamma(\overline{B}_q^0 \to B_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \overline{B}_q^0 \to \mu^- X)}{\Gamma(\overline{B}_q^0 \to B_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \overline{B}_q^0 \to \mu^- X)}, \quad q = d, s$$

$$= \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_{M/\Gamma} \qquad \phi_{M/\Gamma} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

$$a_{fs}^{d,\mathrm{SM}} = (-4.5 \pm 0.8) \cdot 10^{-4} \qquad a_{fs}^{s,\mathrm{SM}} = (2.11 \pm 0.36) \cdot 10^{-5}$$

A.Lenz and U.Nierste

LHCb measurement of a_{SL}

- Tagging of the initial state reduces the statistical power drastically

- A untagged analysis is possible, reduction of stat. power only by factor 2. However this requires an excellent knowledge of the production asym.

$$A_P = \frac{\mathcal{P}(B^0) - \mathcal{P}(\overline{B}^0)}{\mathcal{P}(B^0) + \mathcal{P}(\overline{B}^0)}$$

- Moreover one needs to know the detection asymmetry for the final state

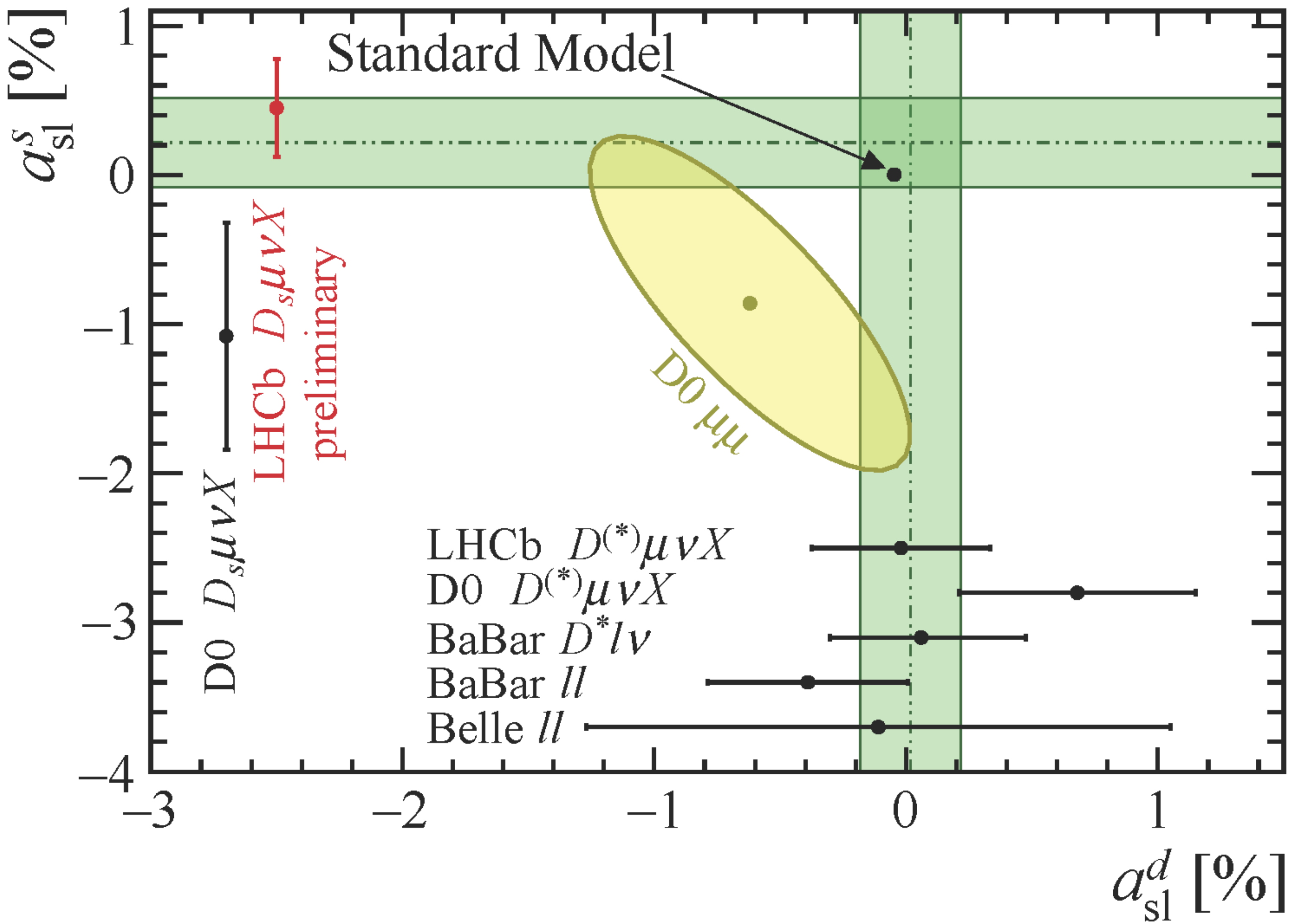
$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$

- Knowing the detection asymmetry, the production and semi-leptonic asymmetries can be determined in a time dependent analysis:

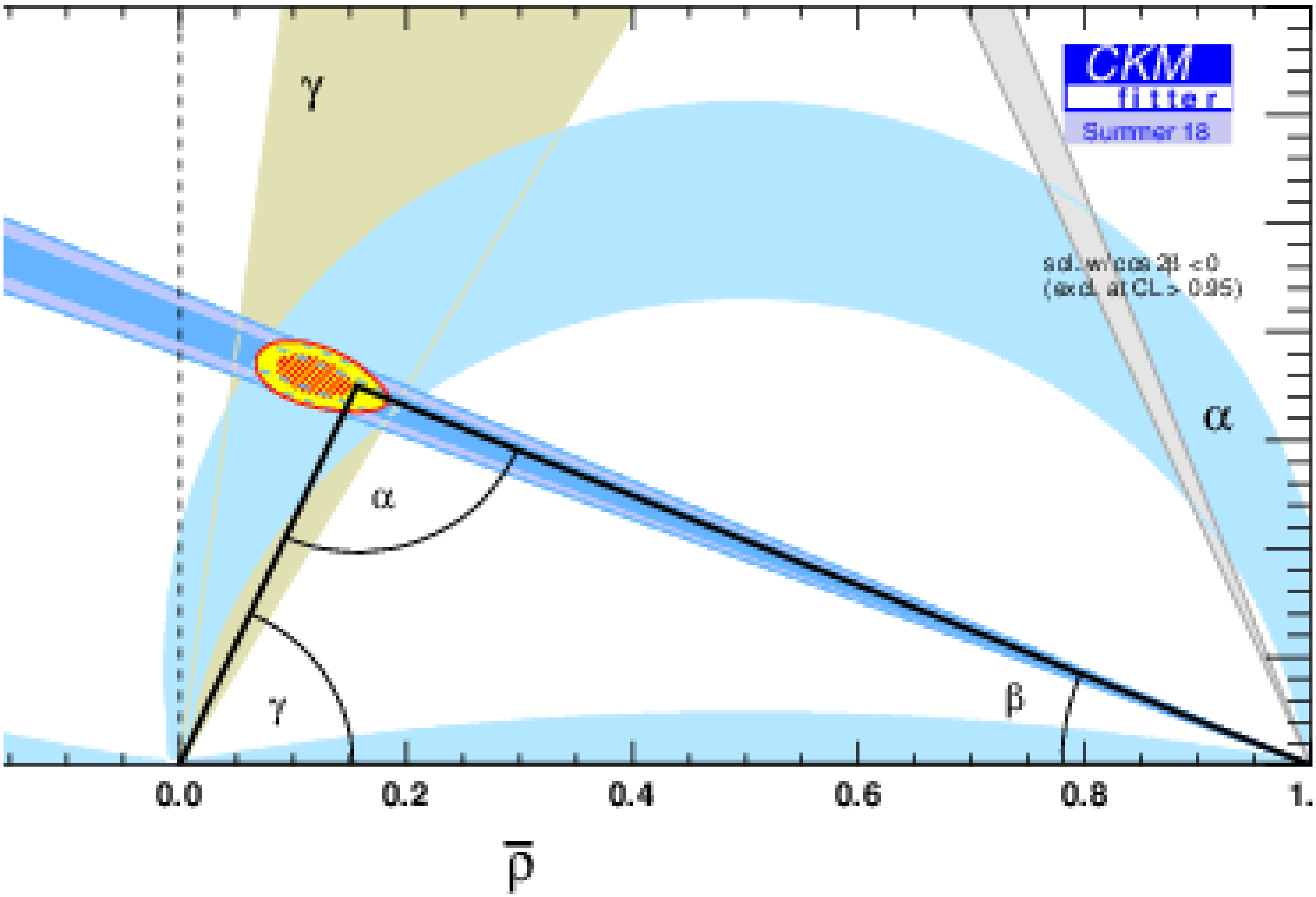
$$A_{\text{meas}}(t) = \frac{N(f,t) - N(\overline{f},t)}{N(f,t) + N(\overline{f},t)} \approx A_D + \frac{a_{sl}^d}{2} + \left(A_P - \frac{a_{sl}^d}{2}\right)\cos(\Delta m_d t)$$

- Due to the fast oscillation, the production asymmetry for B_s mesons is washed out and no time dependent measurement is necessary.

Experimental Status



Direct CP Violation & CKM angle γ

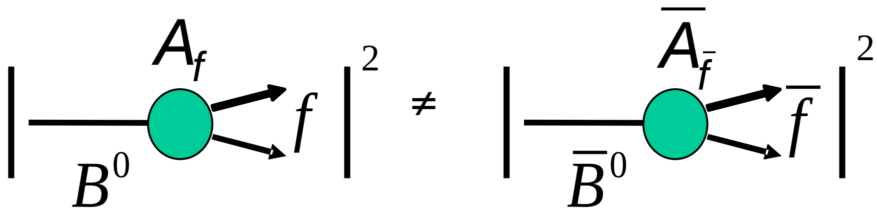


Direct CP Violation & CKM angle γ

- CP Violation in mixing
- CP Violation through interference between decay and mixing

} Indirect CPV

- CP violation in decay



$$P(B \to f) \neq P(\overline{B} \to \bar{f})$$

(time integrated)

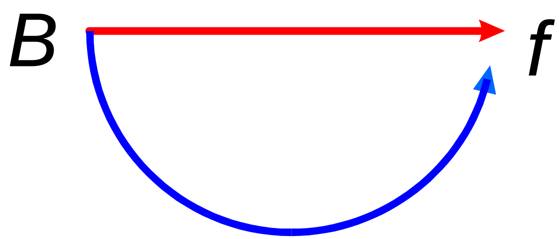
} direct CPV

CP Violation in meson decays

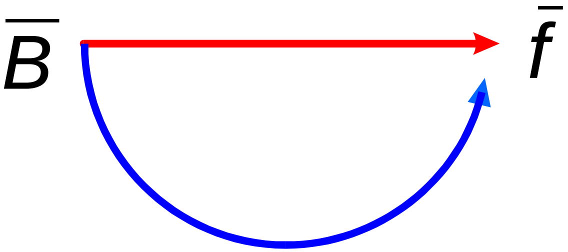
CKM phase do not lead easily to measurable CPV asymmetries.

To observe CP violation needs at least two amplitudes with different weak (sign flip under CP) and different strong (invariant under CP) amplitudes:

$$\mathcal{A}_1 = A_1\, e^{i\phi_1} e^{i\delta_1} \qquad\qquad \overline{\mathcal{A}}_1 = A_1\, e^{-i\phi_1} e^{i\delta_1}$$



CP



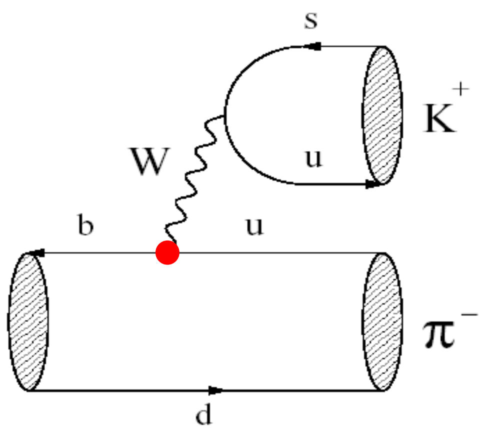
$$\mathcal{A}_2 = A_2\, e^{i\phi_2} e^{i\delta_2} \qquad\qquad \overline{\mathcal{A}}_2 = A_2\, e^{-i\phi_2} e^{i\delta_2}$$

$$\mathcal{A}(B \to f) = A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2} \qquad \overline{\mathcal{A}}(\bar{B} \to \bar{f}) = A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2}$$

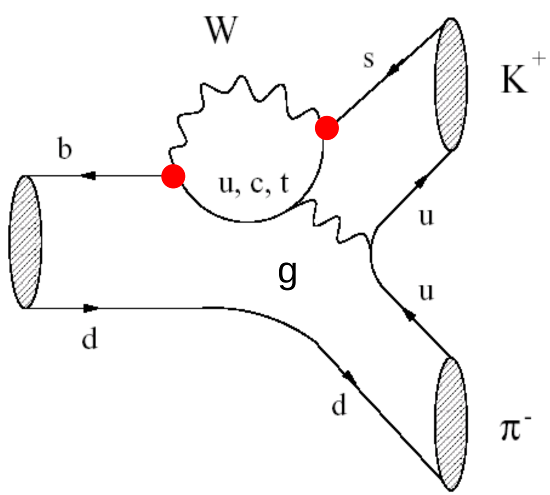
$$\left|\overline{\mathcal{A}}\right|^2 - \left|\mathcal{A}\right|^2 = 4\, A_1 A_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

Direct CP Violation in B→Kπ

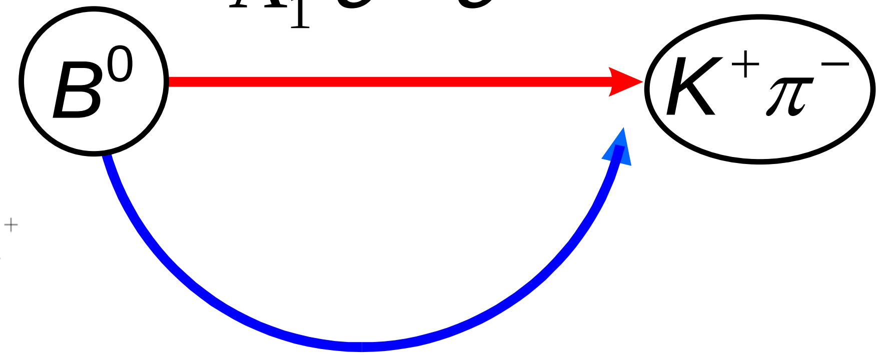
Tree **B^0**



Penguin **B^0**



$$A_1\, e^{i\varphi_1} e^{i\delta_2}$$



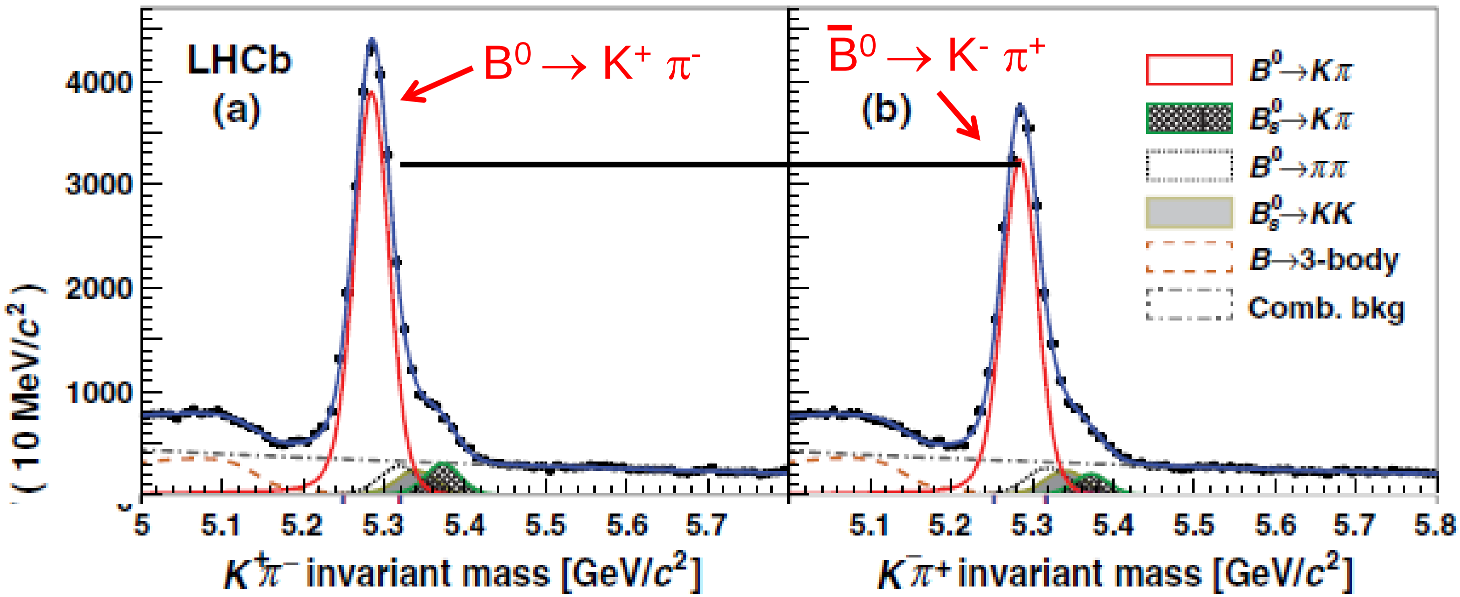
$$A_2\, e^{i\varphi_2} e^{i\delta_2}$$

Strong and weak phase difference

CP Asymmetrie $\left|\bar{A}\right|^2 - \left|A\right|^2 = 4\left|A_1\right|\left|A_2\right| \sin(\Delta\varphi) \sin\boxed{(\Delta\delta)}$ Strong phase difficult to predict

Direct CP asymmetries for $B^0_{d,s} \to K\pi$

PRL 110, 221601 (2013)



CP Observables

PRL 110, 221601 (2013)

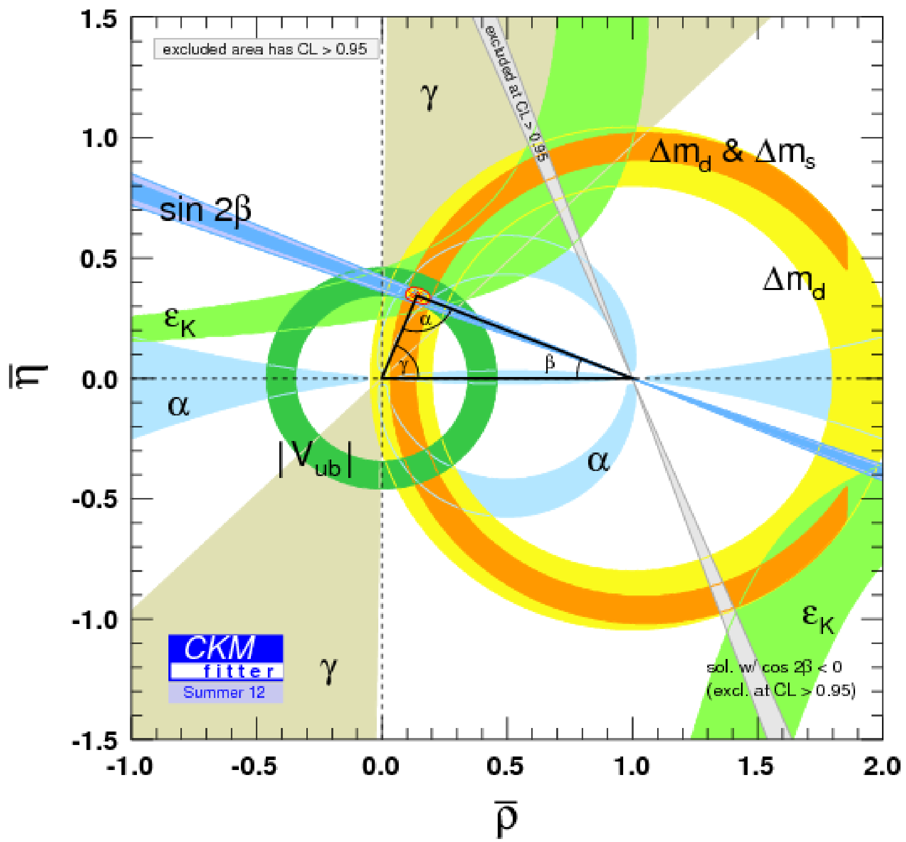
$$A_{CP}(B \to f) = \frac{\Gamma(\overline{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \bar{f}) + \Gamma(B \to f)}$$

Correction for detection / production asymmetry

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst})$$ [10.5σ]

$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}).$$ [6.5σ]

CKM Angle γ



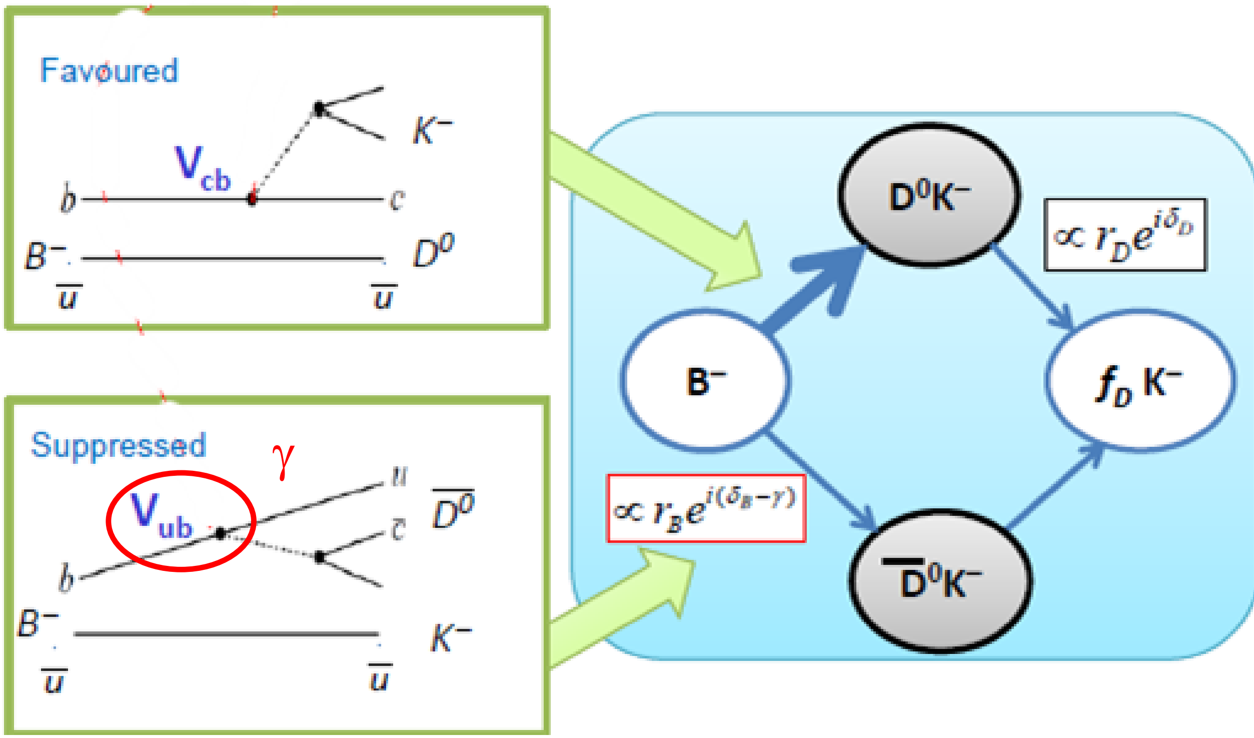
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

⇩

Exploit direct CPV in B→DK decays

Sensitivity of B→DK decays to γ

Adapted from S. Ricciardi



$$r_B e^{i(\delta_B-\gamma)} \equiv \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}$$

$$r_D e^{i\delta_D} \equiv \frac{A(D^0 \to f_D)}{A(\bar{D}^0 \to f_D)}$$

All unknowns from data

⇒ No hadronic uncertainties

Gronau, London, Wyler (GLW)

f_D = KK, ππ (CP state)

Atwood, Dunietz, Soni (ADS)

$f_D = K^+\pi^-$ and π^+K^-

Giri, Grossman, Soffer, Zupan (GGSZ)

Self conjugated Dalitz modes

LHCb:
- $B^\pm \to D(KK)\, K^\pm$
- $B^\pm \to D(\pi\pi)\, K^\pm$
- $B^\pm \to D(KK)\, \pi^\pm$
- $B^\pm \to D(\pi\pi)\, \pi^\pm$

LHCb:
- $B^\pm \to D(\pi^+K^-)\, K^\pm$
- $B^\pm \to D(\pi^+K^-)\, \pi^\pm$
- $B^\pm \to D(K_s\, K^+\pi^-)\, \pi^\pm$
- $B^\pm \to D(K_s\, K^+\pi^-)\, K^\pm$