Quark Flavor Physics

<u>Outline:</u>

- Quark Flavor Physics und New Physics Searches
- Neutral Meson Mixing
- CP Violation in Interference between Mixing and Decay
- CP Violation in Mixing
- One Word to Direct CPV (no γ)

Ulrich Uwer – Neckarzimmern 2017 – 22/03/2017

What is Flavor Physics?

Fundamental matter comes in three generations carrying 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	$\boxed{ccc}$	ttt
ν_e	ν_μ	ν_τ	ddd	sss	$\boxed{bbb}$

Heavy mesons:

K^0 ($\bar{s}d$), D^0 ($\bar{c}u$), D^+($\bar{c}d$)

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

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

Flavor physics studies the complex phenomenology:

- masses ranging over 12 orders of magnitude (sub-eV neutrino - 173 GeV top)
- flavor transitions (mixing)
- CP Violation

Flavor within the Standard Model

Yukawa interaction couples fermions to Higgs. For the quarks:

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

After electroweak symmetry breaking

$$\underbrace{Y_d,\ Y_u \text{ are } 3\times 3 \text{ complex matrices in generation space}}_{\text{not diagonal } \rightarrow \text{ flavor structure}}$$

Mass eigenstates of the quarks obtained by unitary transformations:

$\tilde{q}_A = V_{A,q}\,q_A$ for $q = u, d$ and $A = L, R$ where $\boxed{V_{A,q}V_{A,q}^{\dagger} = 1}$

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

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

Quark masses

After this transformation quark masses appear as usual Dirac terms:

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

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

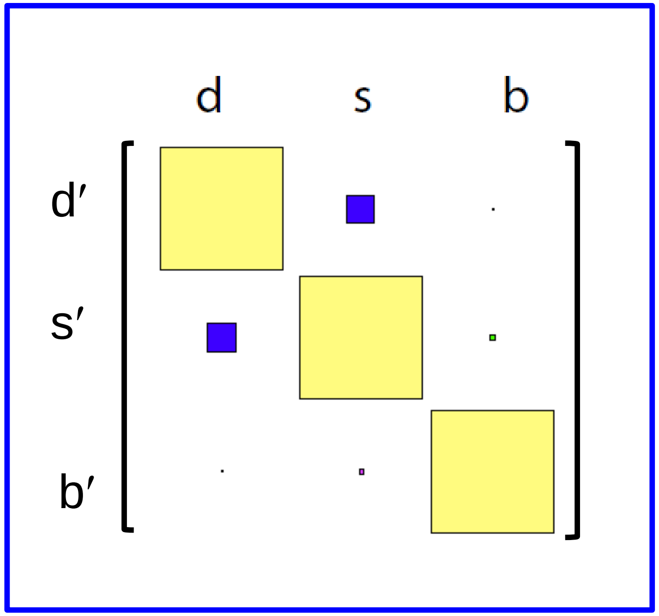
$$\mathcal{L}_{\mathrm{CC}} = -\frac{g_2}{\sqrt{2}} \left(\overline{\tilde{u}}_{\mathrm{L}} \gamma^{\mu} W_{\mu}^{+} V_{\mathrm{CKM}} \tilde{d}_{\mathrm{L}} + \overline{\tilde{d}}_{\mathrm{L}} \gamma^{\mu} W_{\mu}^{-} V_{\mathrm{CKM}}^{\dagger} \tilde{u}_{\mathrm{L}} \right)$$

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

CKM Matrix

Complex and unitary 3×3 matrix:

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



Complex 3×3 matrix: 18 parameters
+ unitarity condition (9 parameters)
+ removal of 5 unobservable phases results into
→ 4 free parameter:

3 Euler angles and one phase δ:

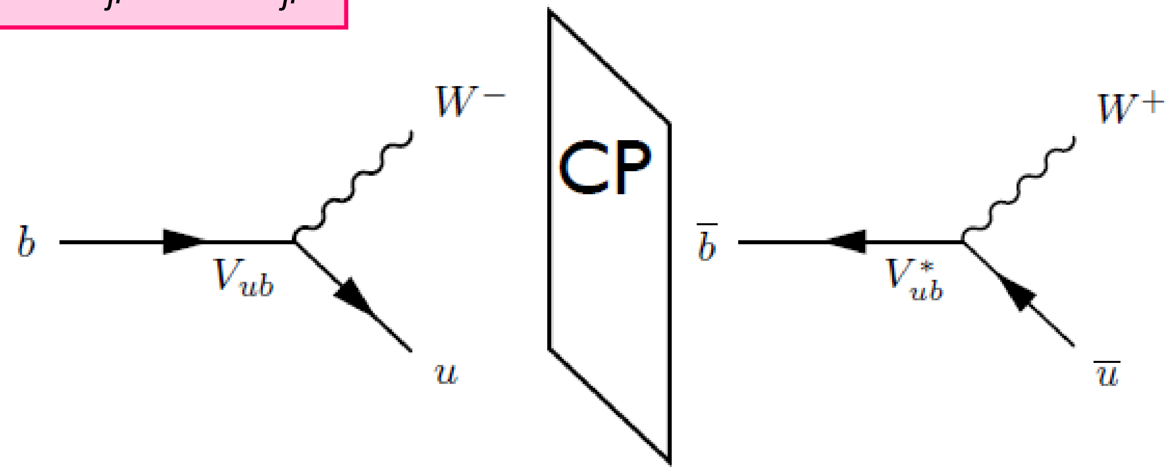
CP violation

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

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

$$\mathcal{L}_{CC}^{CP} = -\frac{g_2}{\sqrt{2}}\left(\bar{\tilde{d}}_L \gamma^\mu W_\mu^- V_{CKM}^T \tilde{u}_L + \bar{\tilde{u}}_L \gamma^\mu W_\mu^+ V_{CKM}^* \tilde{d}_L\right) .$$

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



Wolfenstein Parametrization

Reflects the hierarchical structure of the CMK matrix

λ, A, ρ, η with $\lambda = 0.22$

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

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

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

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

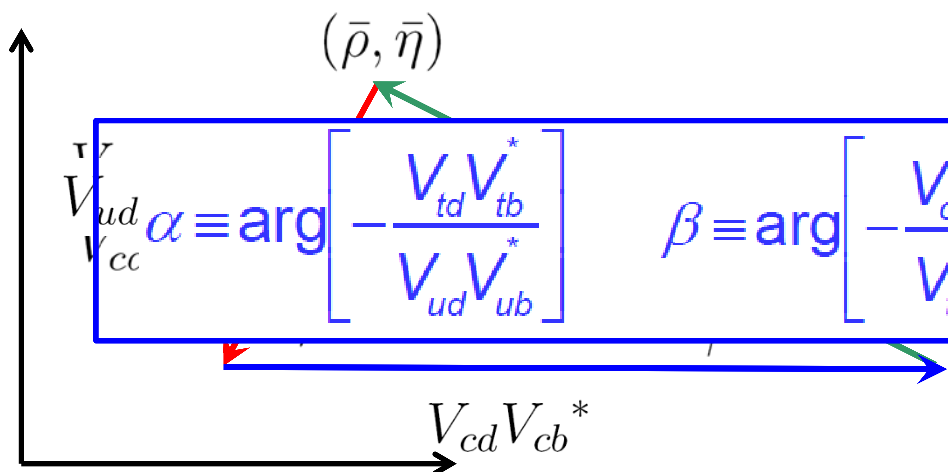
$-|V_{ts}| \times e^{i\beta_s}$

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

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ \boxed{V_{td}} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Unitarity triangle „db“



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

CKM Phases **b→u** $e^{-i\gamma}$ **t→d**

CP Violation if Triangle has finite area !

More Triangles ...

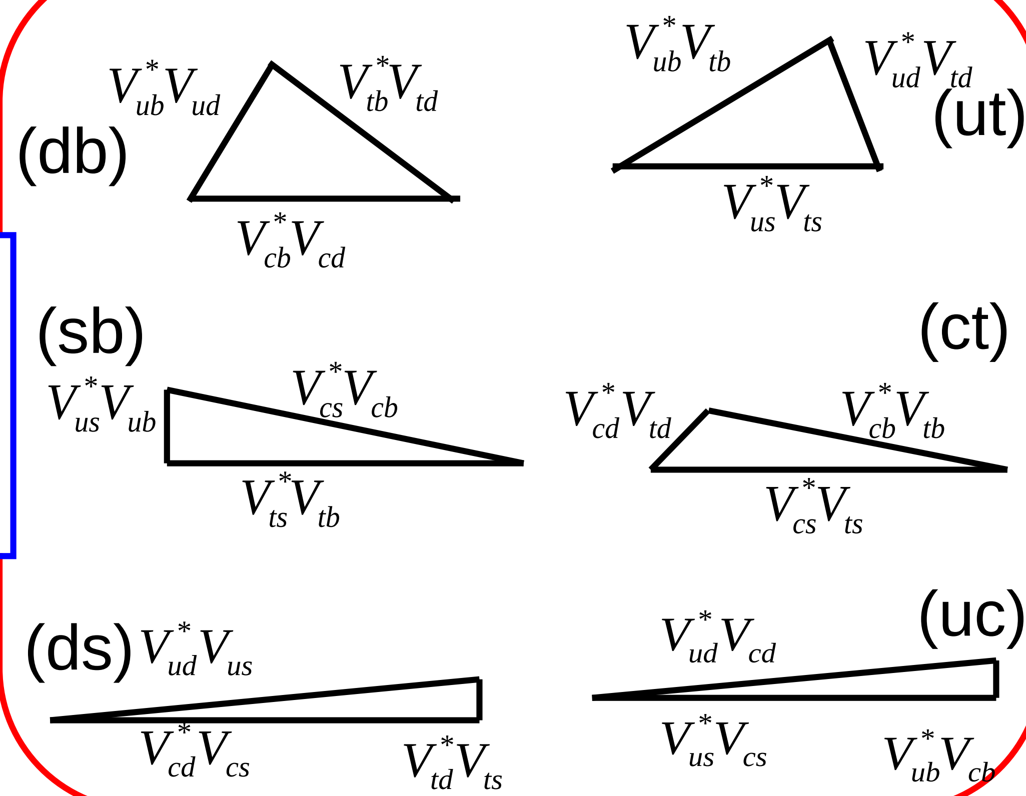
$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0 \text{ (db)}$$

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

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

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

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

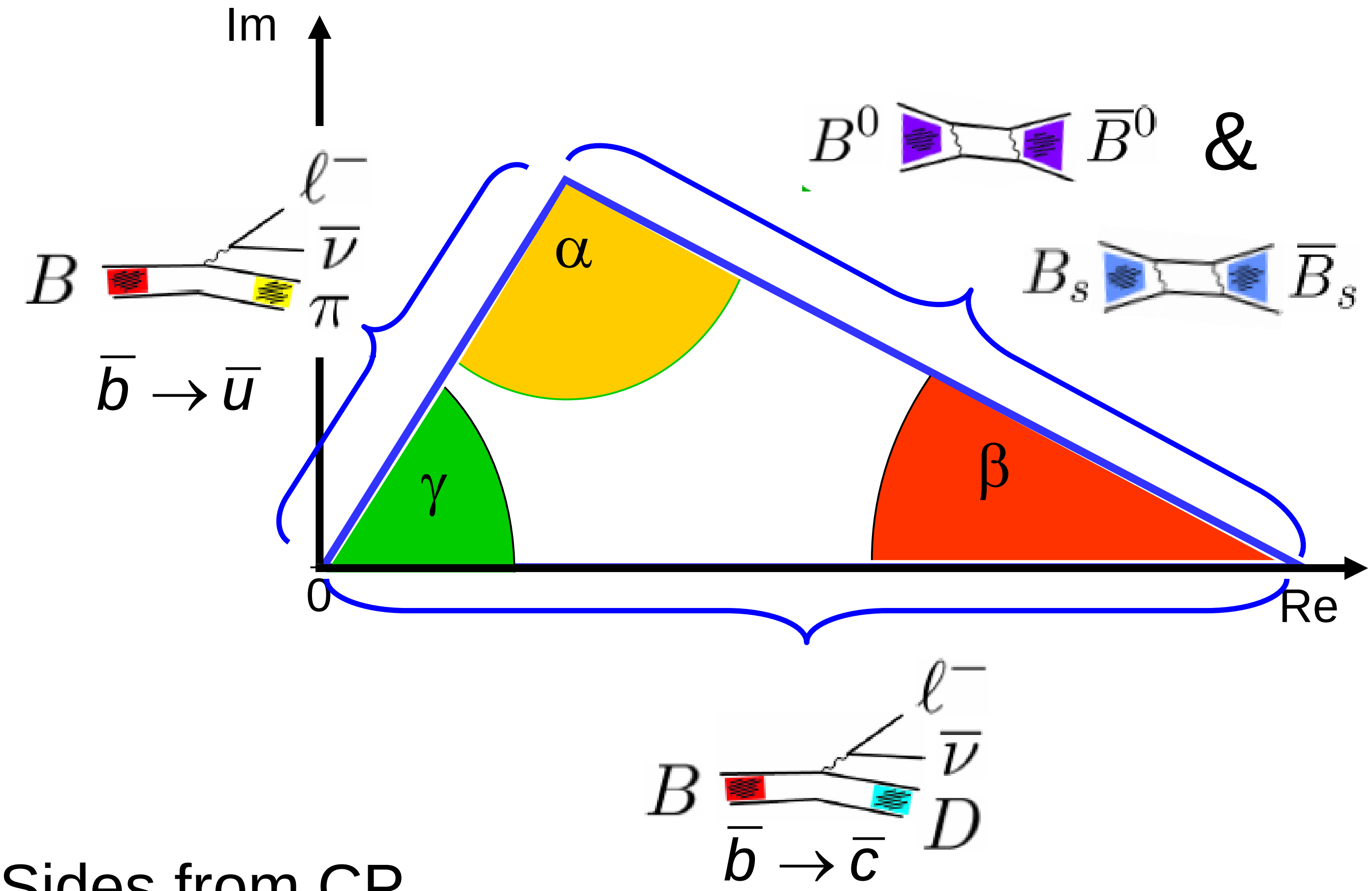


All 6 triangles have the same area: $J_{CP}/2$

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

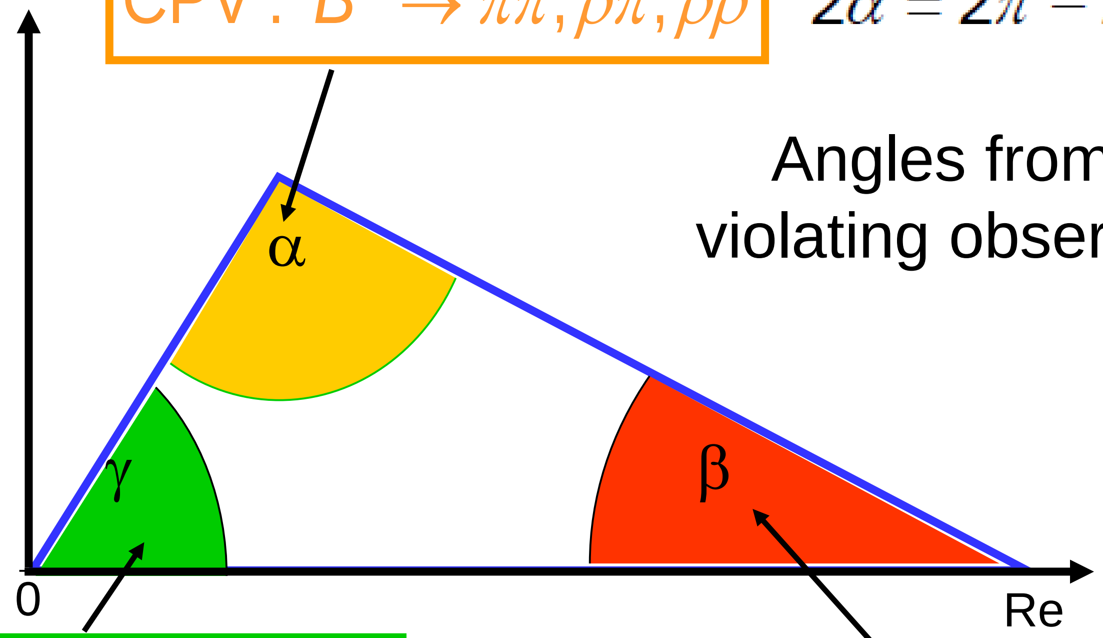
$$J_{CP} = \mathcal{Im}\left(V_{ij}\,V_{kl}\,V_{il}^{*}V_{kj}^{*}\right) \approx 3\cdot 10^{-5}$$

Unitarity Triangle from B Decays



Sides from CP
conserving observables

Unitarity Triangle from B Decays



$\text{CPV}: B^0 \to \pi\pi, \rho\pi, \rho\rho$

$2\alpha = 2\pi - 2\beta - 2\gamma$

Angles from CP violating observables

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

$B_S^0 \to D_S K, KK$

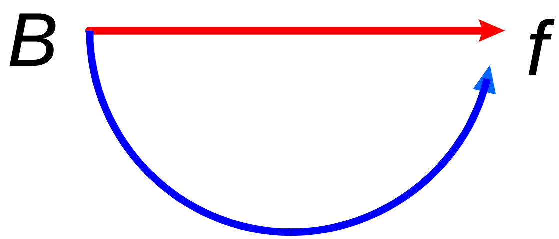
$\text{CPV}: B^0 \to J/\psi K_S^0$

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:

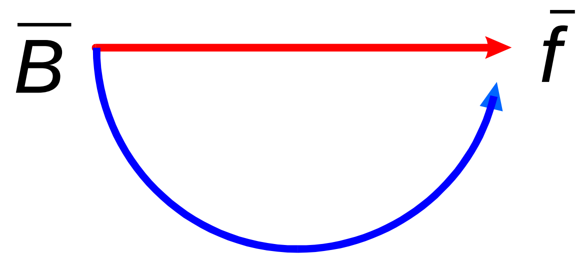
$$\mathcal{A}_1 = \mathrm{A}_1\, e^{i\phi_1} e^{i\delta_1}$$



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

CP

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

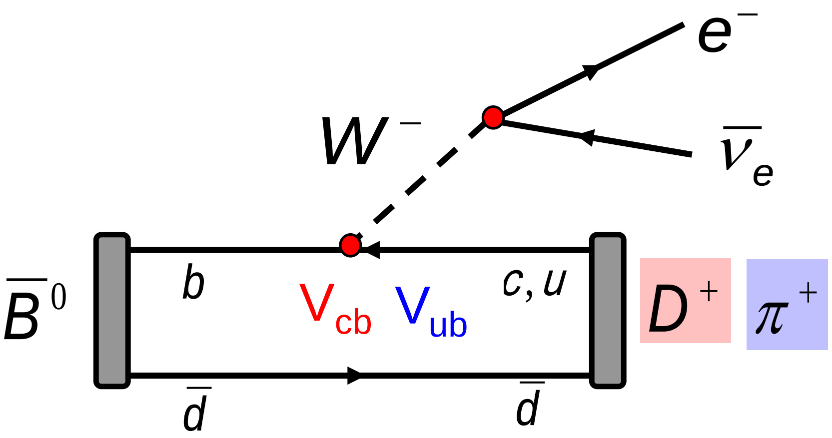


$$\overline{\mathcal{A}}_2 = \mathrm{A}_2\, e^{-i\phi_2} e^{i\delta_2}$$

$$\mathcal{A}(B \to f) = \mathrm{A}_1 \mathrm{e}^{i\phi_1} \mathrm{e}^{i\delta_1} + \mathrm{A}_2 \mathrm{e}^{i\phi_2} \mathrm{e}^{i\delta_2} \qquad \overline{\mathcal{A}}(\bar{B} \to \bar{f}) = \mathrm{A}_1 \mathrm{e}^{-i\phi_1} \mathrm{e}^{i\delta_1} + \mathrm{A}_2 \mathrm{e}^{-i\phi_2} \mathrm{e}^{i\delta_2}$$

$$\boxed{\left|\overline{\mathcal{A}}\right|^2 - \left|\mathcal{A}\right|^2 = 4\,\mathrm{A}_1 \mathrm{A}_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)}$$

Weak b hadron hecays



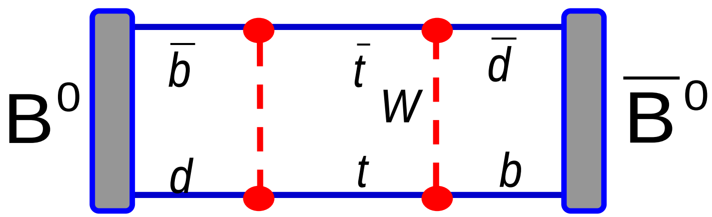
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

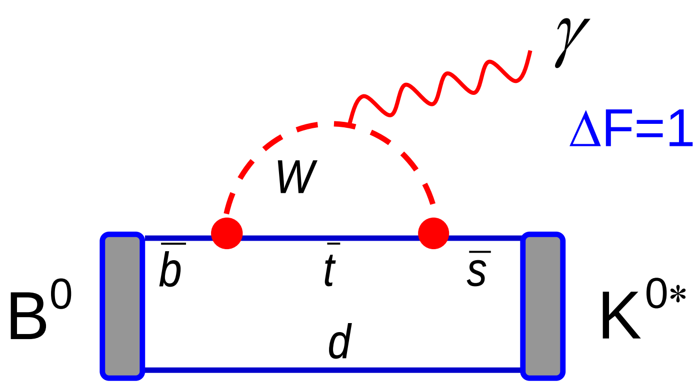
b cannot decay into top quark

Tree decays “CKM” suppressed:
→ Loop corrections important.

Flavor Changing Neutral Current (FCNC) Processes:

ΔF=2

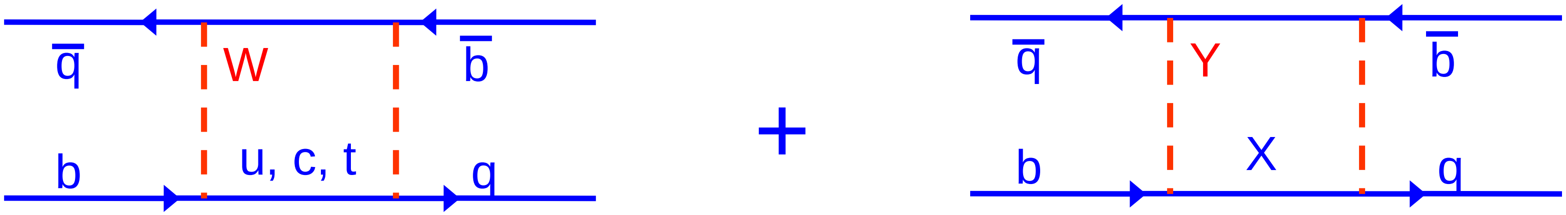




New Physics in Quantum Loops

If the precision of the measurements is high enough we can discover NP due to effect of "virtual" new particles in quantum loops,

Standard Model New Physics



$$\mathcal{A}_{SM} \quad + \quad \mathcal{A}_{NP}$$

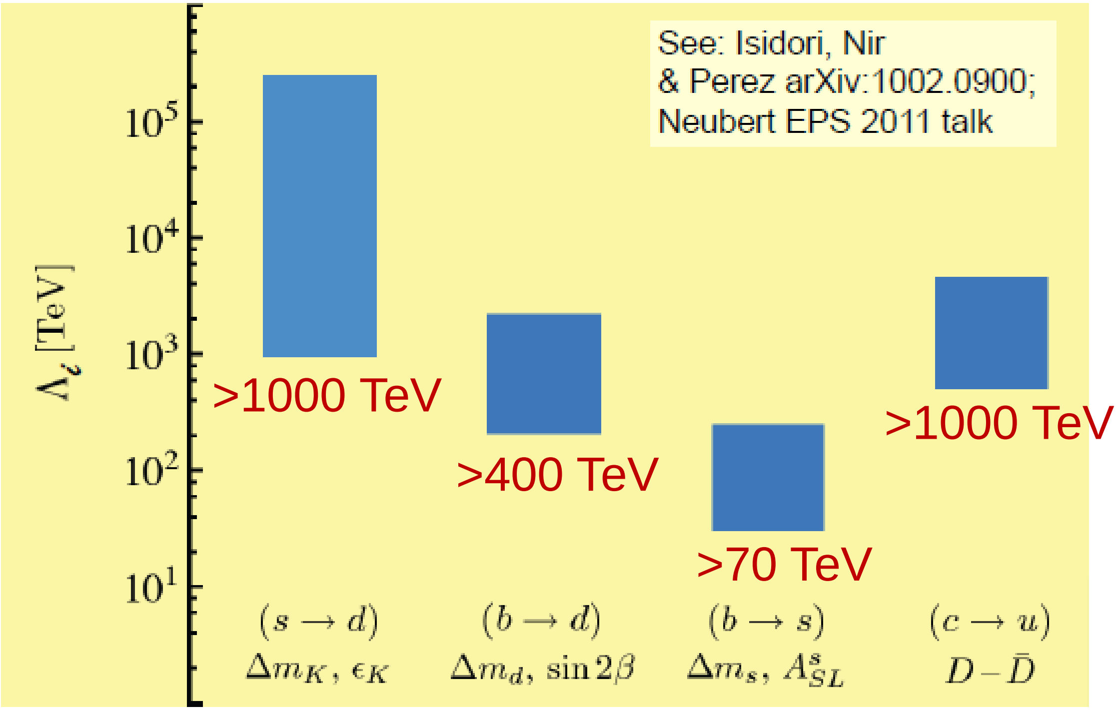
$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \boxed{\frac{c_{NP}}{\Lambda_{NP}^2}} \right)$$

What is the scale of Λ_{NP}? Size of C_{NP} and alignment w/r to C_{SM} ?

The Flavor Problem

excluded NP scales
for generic flavor
models $C_{NP}=1$
from mixing

Numbers by T.Mannel
(FPCP 2016)



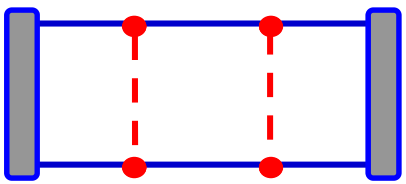
Possible scenarios:
- new particles indeed have very large masses.
- new particles have degenerated masses
- mixing angles in new flavor sector are small, similar to SM

Flavor Problem: Absence of NP effects in flavor physics implies non-natural "fine tuning" if NP at TeV scale exists: Minimal flavor violation (MFV)

LHCb – Strategies to Probe New Physics

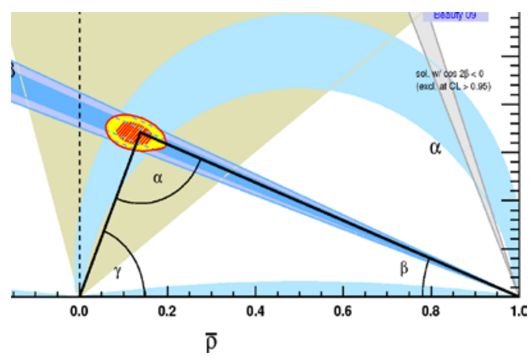
Meson - Mixing

$$A_{mix} = \left|A_{mix}\right| e^{-i\phi_{mix}}$$

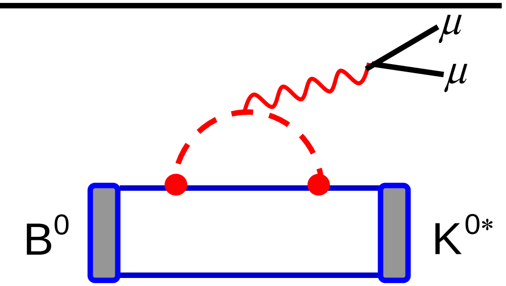


~~CP~~ to get mixing phase

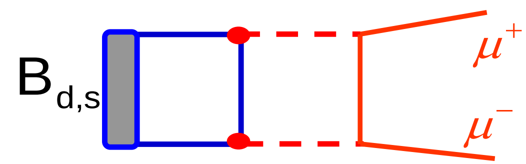
CKM Metrology: γ



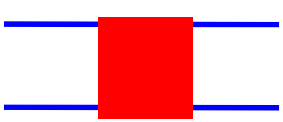
Rare decays



angular distribution



Rates



magnitude ↔ rates
phase ↔ CP-violation
Lorentz-structure ↔ angular distrib.

Neutral Meson Mixing

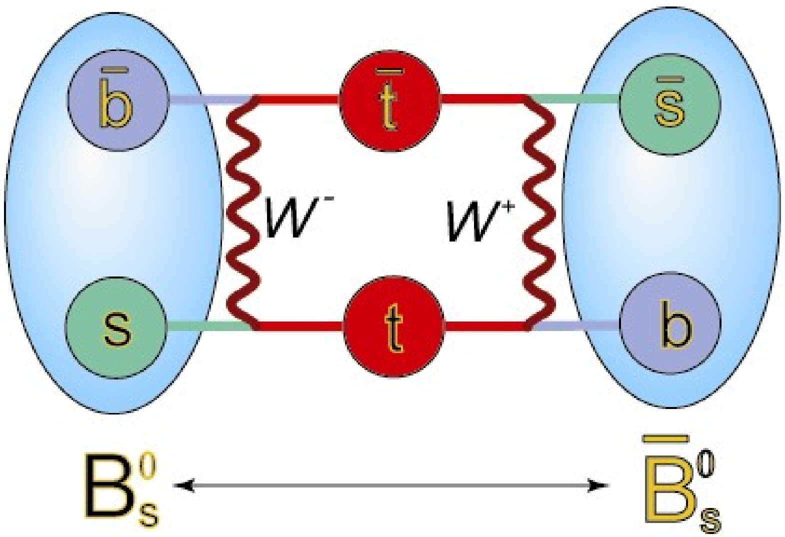
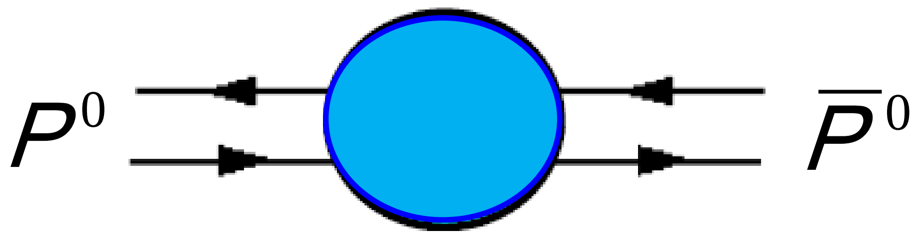


Figure from http://www.gridpp.ac.uk/news/?p=205

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

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

CPT

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

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

M and **Γ** hermitian:

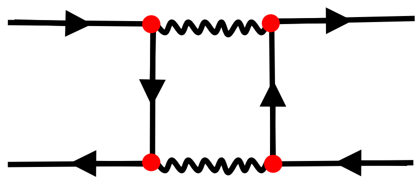
$$m_{21} = m_{12}^*$$

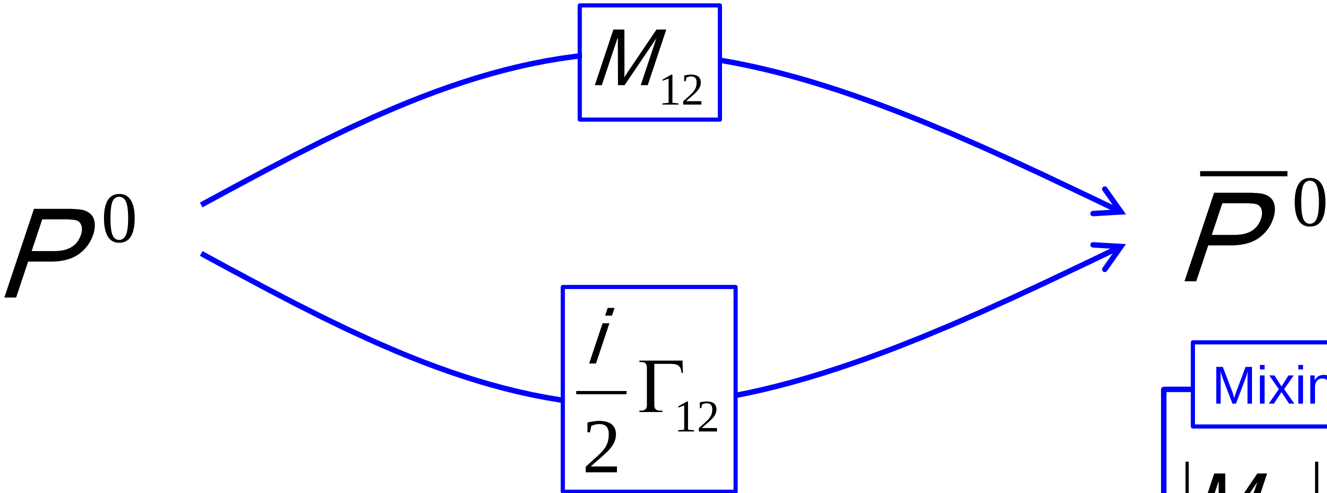
$$\Gamma_{21} = \Gamma_{12}^*$$

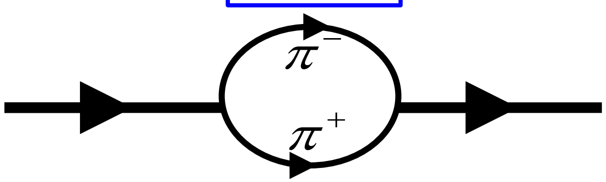
Off – diagonal elements describe the mixing.

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:

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

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

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

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;

Mixing Parameters

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

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

One finds:

$$(\Delta m)^2 - \frac{1}{4}(\Delta\Gamma)^2 = 4\,|M_{12}|^2 - |\Gamma_{12}|^2$$

$$\Delta m\,\Delta\Gamma = -4\,\mathrm{Re}\,(M_{12}\Gamma_{12}^*)\,,$$

$$\boxed{\begin{aligned} &\Delta m \approx 2|M_{12}| \\ &\Delta\Gamma \approx 2|\Gamma_{12}|\cos\phi_{M/\Gamma} \\ &|q/p| \approx 1 \end{aligned}}$$

And q/p:

$$\frac{q}{p} = -\frac{\Delta m + i\,\Delta\Gamma/2}{2M_{12} - i\,\Gamma_{12}} = -\frac{2M_{12}^* - i\,\Gamma_{12}^*}{\Delta m + i\,\Delta\Gamma/2}$$

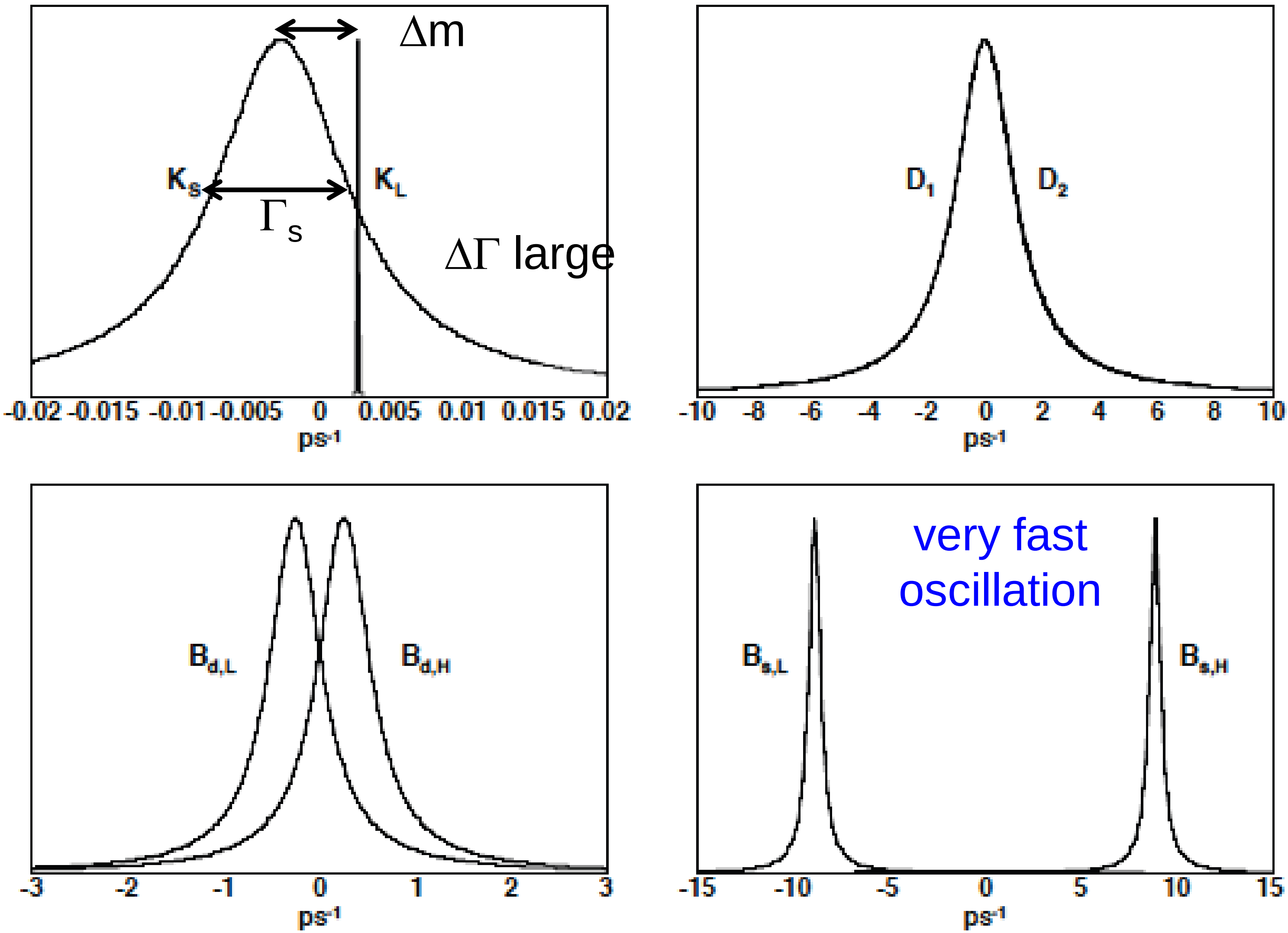
for B mesons: $\Gamma_{12} < M_{12}$, $\Delta\Gamma$ small: $\Delta m = 2\,|M_{12}|$

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

Neutral Mesons

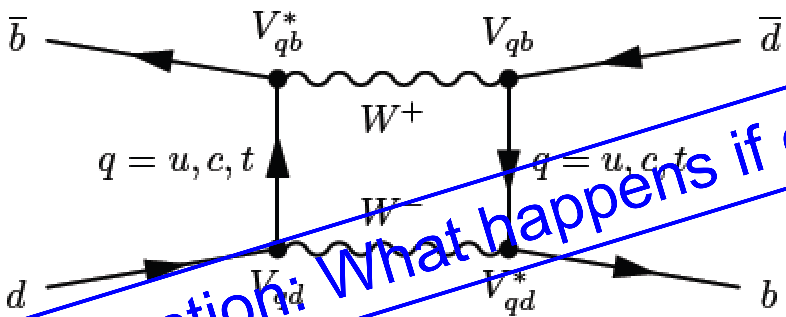
Slide from M. Gersabeck

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



Theoretical predictions

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}

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

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

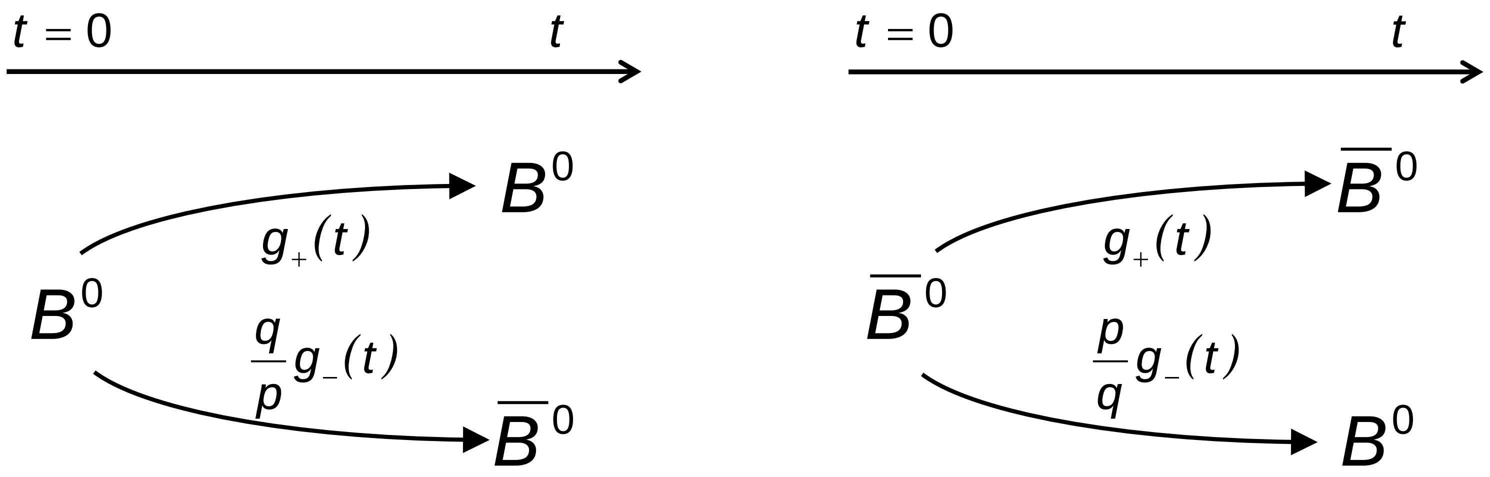
$$\langle B | Q(\Delta B = 2) | \bar{B} \rangle$$

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

B_B = bag factor, f_B = decay constant: non-perturbative effects

η_B = *perturbative QCD corrections*

Time evolution of B^0 (P^0)



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

$$g_+(t) = e^{-i(m-i\frac{\Gamma}{2})t}\left[+\cancelto{1}{\cosh\frac{\Delta\Gamma t}{4}}\cos\frac{\Delta m t}{2} - i\cancel{\sinh\frac{\Delta\Gamma t}{4}}\sin\frac{\Delta m t}{2}\right]$$

$$g_-(t) = e^{-i(m-i\frac{\Gamma}{2})t}\left[-\cancel{\sinh\frac{\Delta\Gamma t}{4}}\cos\frac{\Delta m t}{2} + i\cancelto{1}{\cosh\frac{\Delta\Gamma t}{4}}\sin\frac{\Delta m t}{2}\right]$$

$\Delta\Gamma \approx 0$

Mixing phenomenology

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

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

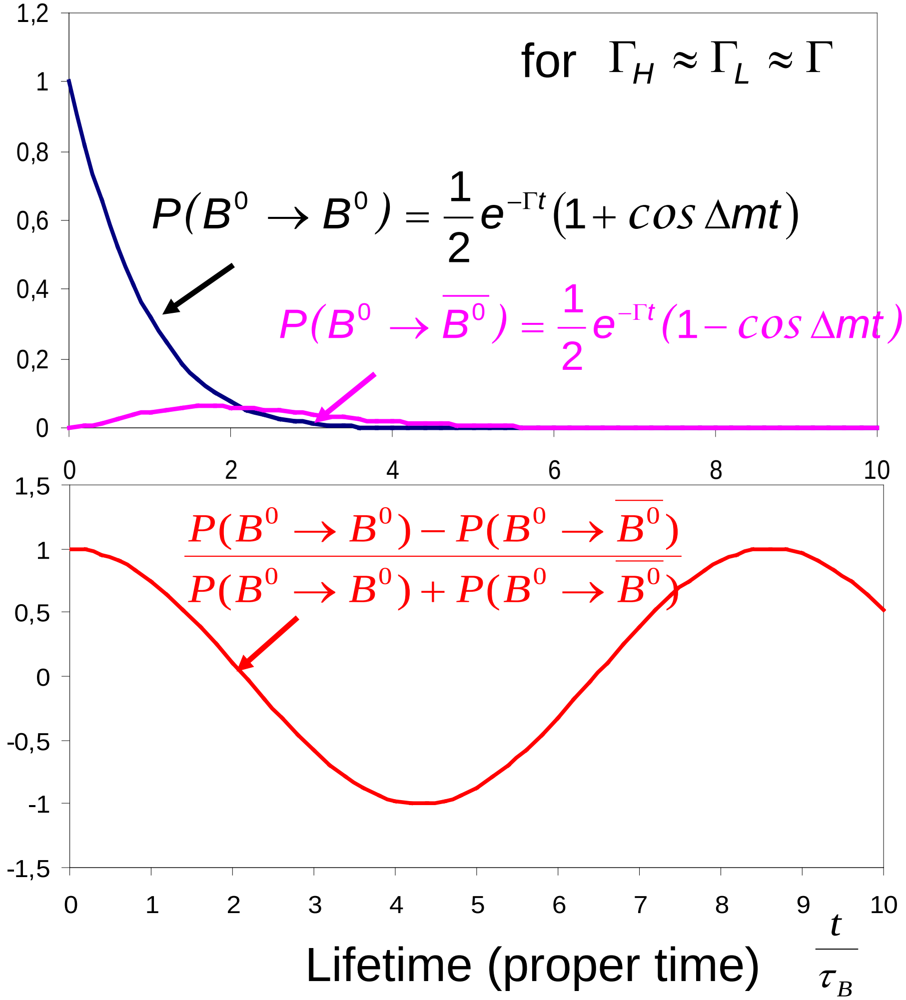
$$\mathcal{P}(B^0 \to \bar{B}^0, t) = \left|\left\langle B^0 | \bar{B}^0(t) \right\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}\left|\frac{q}{p}\right|^2(1 - \cos(\Delta m t))$$

Mixing asymmetry:

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

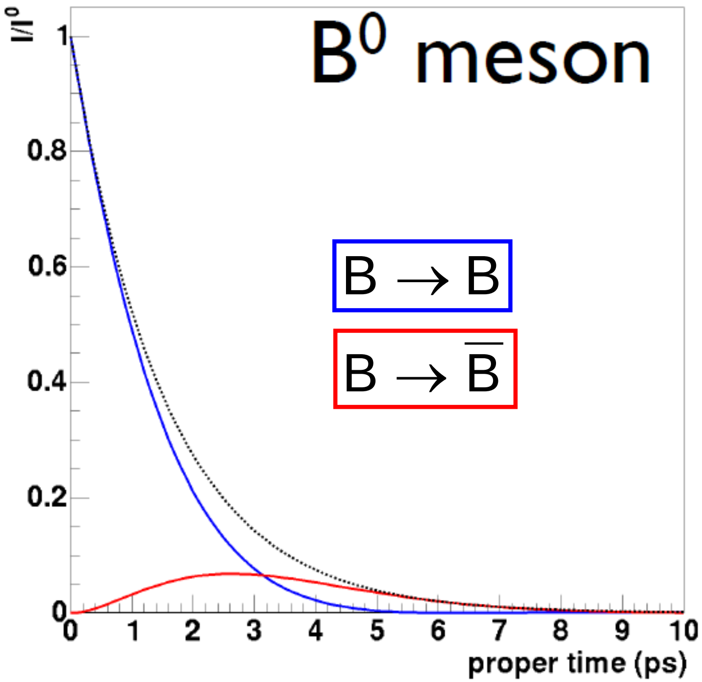
If |q/p| =1

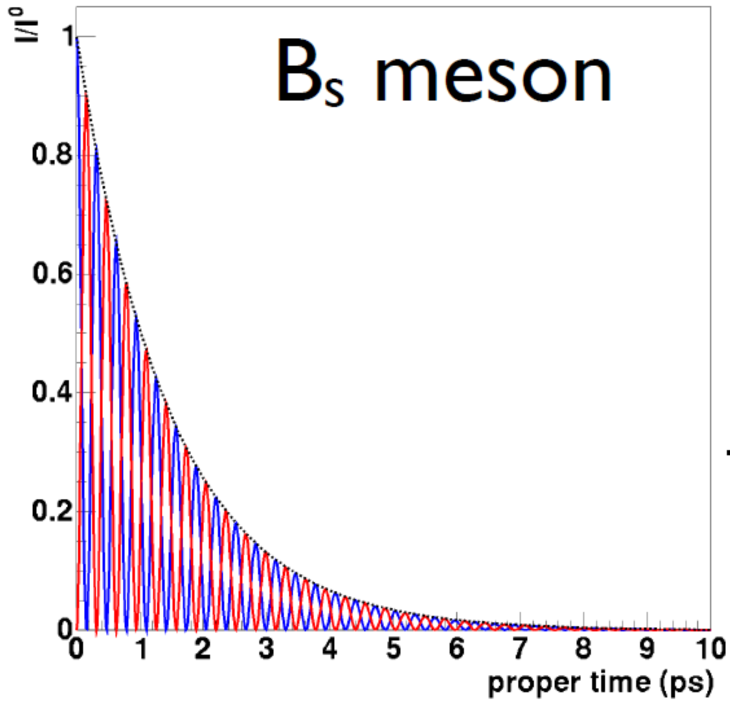
Time dependent mixing asymmetry



$\cos(\Delta m t)$

B meson mixing





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

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

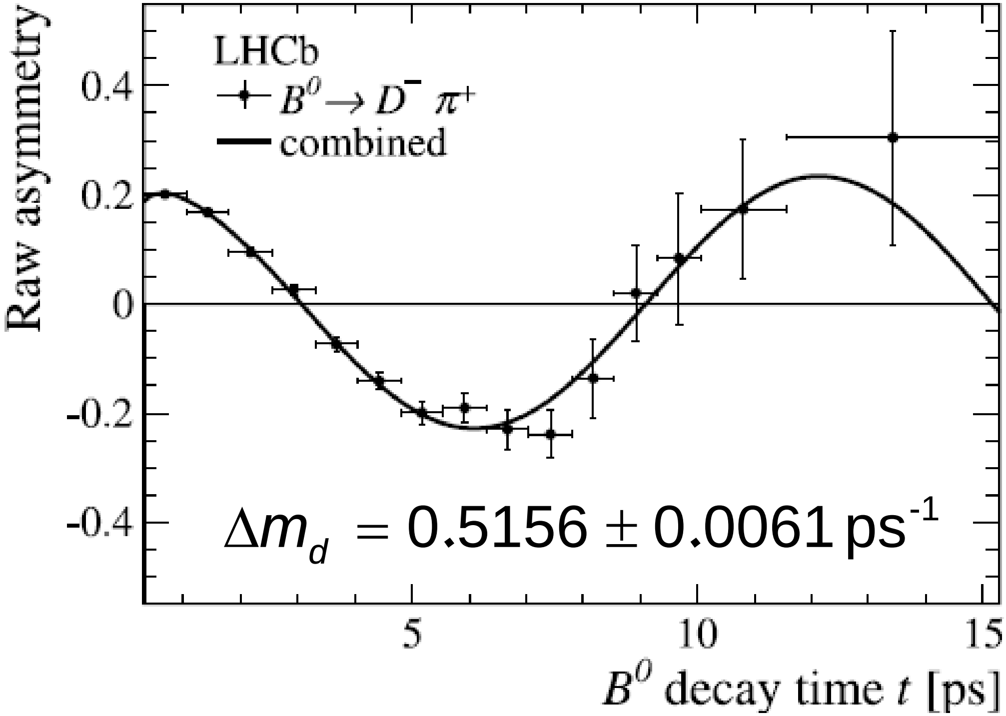
B^0 Mixing *)

Phys. Lett. B 719 (2013) 318.

B^0

$\updownarrow$

$\overline{B}^0$



$D=1-2\omega$

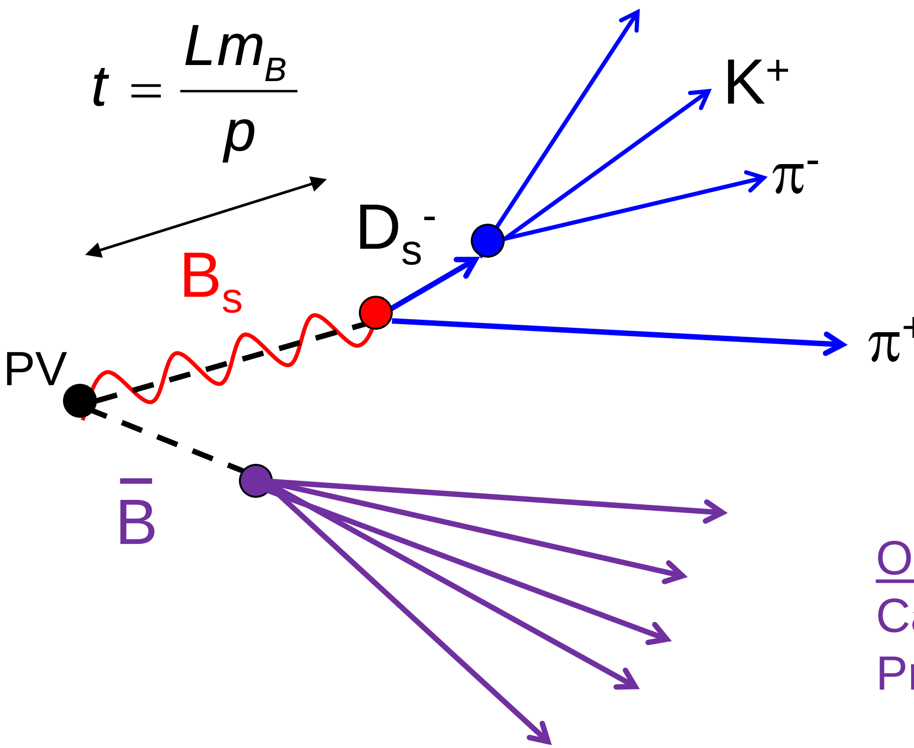
Question: Why is oscillation not from +1 to -1?

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

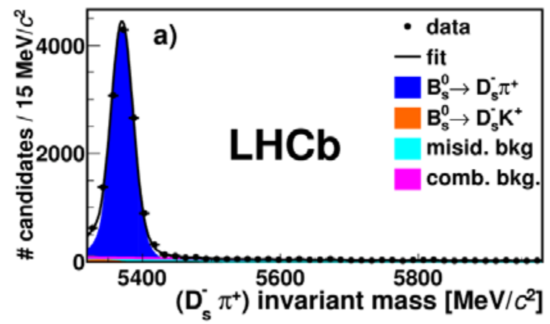
B_s Mixing Measurement

$L = \beta\gamma\, ct$

$t = \dfrac{L m_B}{p}$



Signal B
(flavor specific decay)



Need production flavor

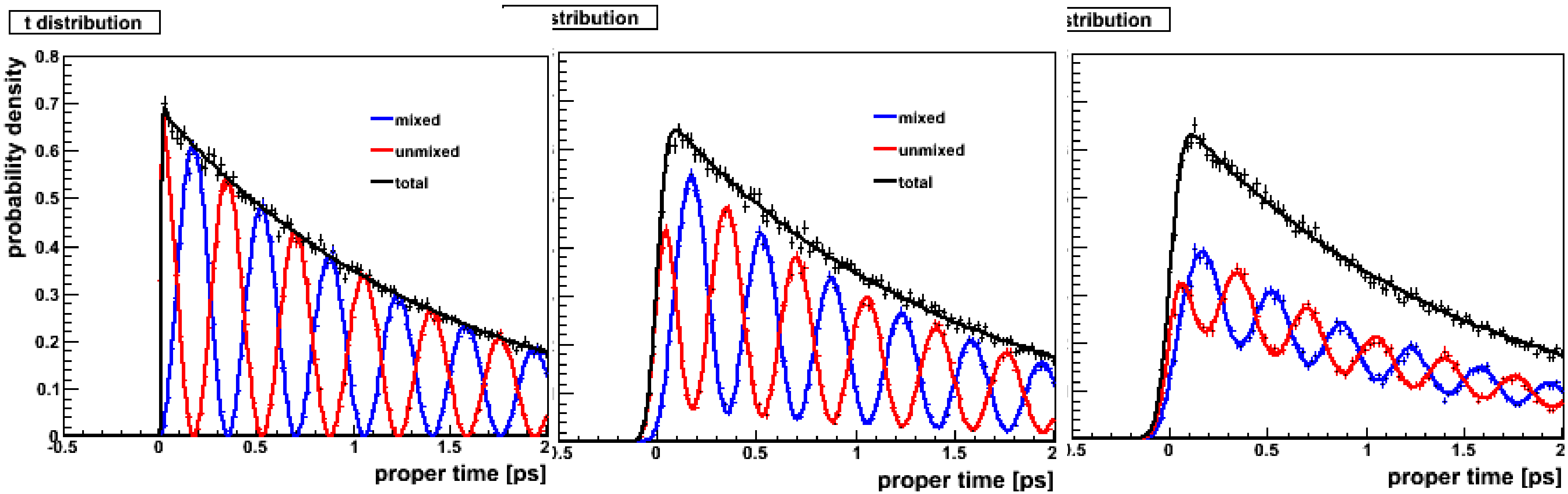
Opposite B
Can be used for flavor tagging
Problem w/ neutral B's (→mixing)

$$PDF \propto \left[e^{-\Gamma t} \cdot \left(1 \pm \cos(\Delta m \cdot t) \right) \right]$$

Production flavour from tagging algorithms

resolution

Detector effects on B_s oscillation

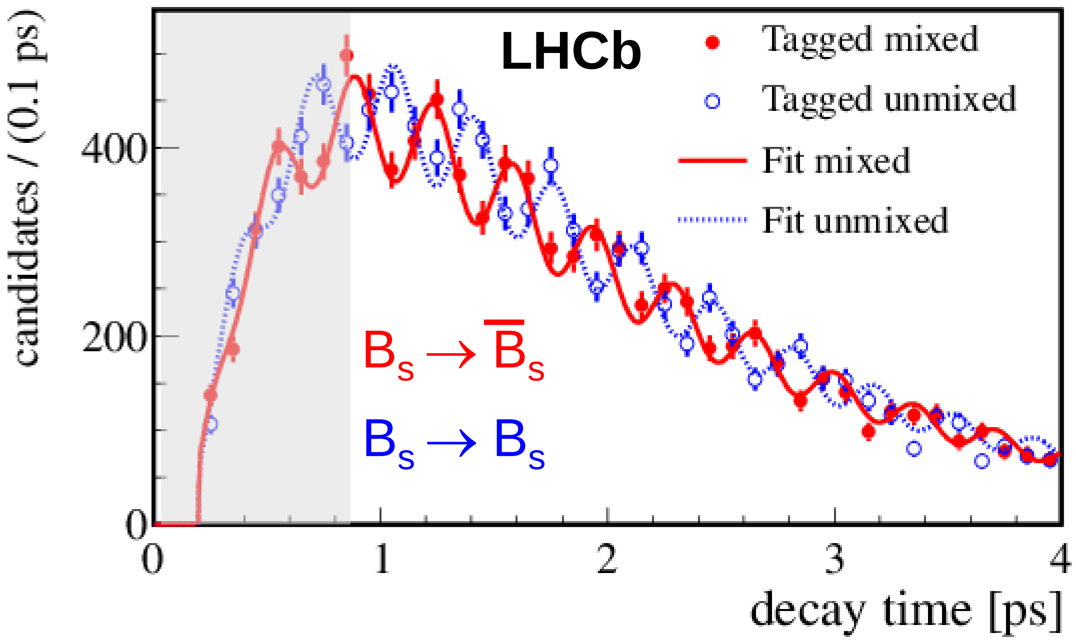


Finite time resolution: 44 fs

Realistic tagging

B_s-Mixing

New J. Phys. 15 (2013) 053021



Δm_s = 17.768± 0.023 ± 0.006 ps^{-1} ← 1 per mille (syst: z & p scale)

Theorie *(U.Nierste, 2012)*

Δm_s = 17.3± 1.5 ps^{-1}

Unsatisfying: Hadronic uncertainties limit the precision of theoretical prediction

Can we do better?

Parameters with better precision?

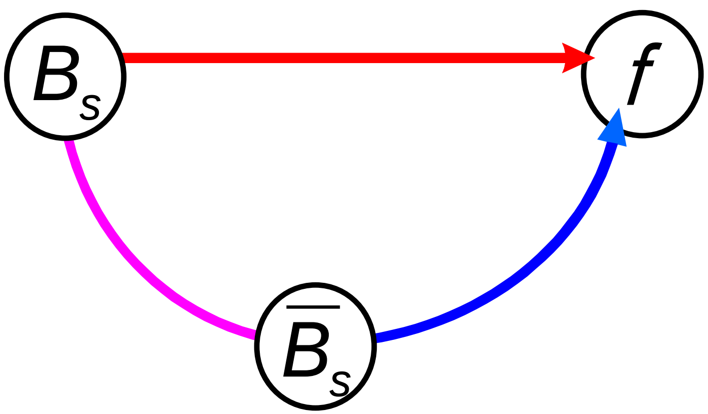
Phases have very small absolute theoretical uncertainties:

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

Theory: $\phi_M = -0.0364 \pm 0.0016$

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

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



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

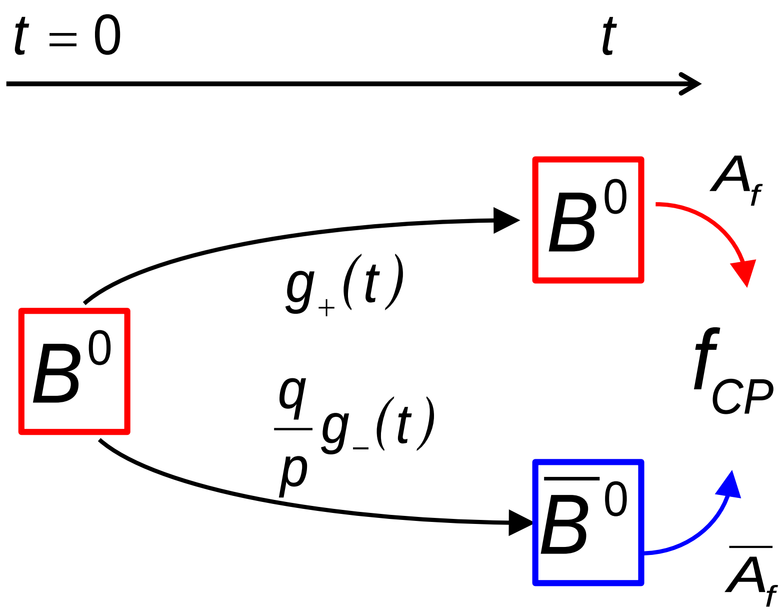
$$P(B^0 \longrightarrow \overline{B}^0) \neq P(\overline{B}^0 \longrightarrow B^0)$$

CP-violation in mixing

Phases are very sensitive to new effects in the loops.

Interference between Mixing and Decay

adapted from G. Raven



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

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

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

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}	$\propto e^{-\Gamma t}\,[1-\sin(\phi_{\text{weak}})\sin(\Delta m t)]$

$$\boxed{\begin{aligned} \mathcal{A}_{CP}(t) \equiv & \frac{\Gamma(\overline{B^0}\to f_{CP})-\Gamma(B^0\to f_{CP})}{\Gamma(\overline{B^0}\to f_{CP})+\Gamma(B^0\to f_{CP})} \\ = & -\sin\phi_{\text{weak}}\sin(\Delta m t) \end{aligned}}$$

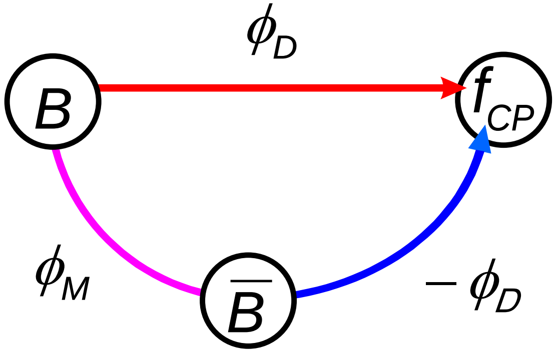
Time-dependent CP Asymmetry $\Delta\Gamma\neq 0$

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

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

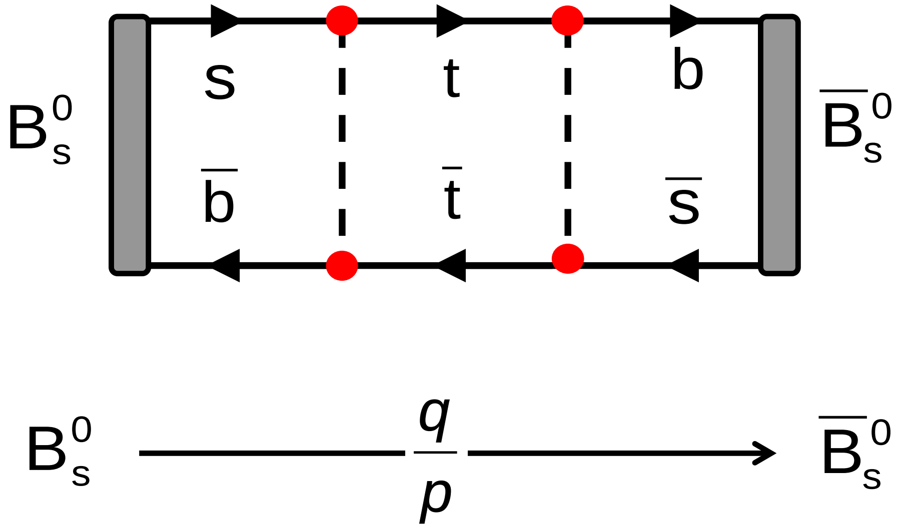
For $\Delta\Gamma\approx 0$ (B_d): $\quad = \quad -\sin\phi_{\text{weak}} \sin(\Delta m t)$

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



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

B_s mixing Phase ϕ_s

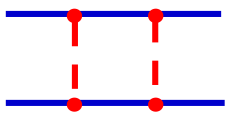


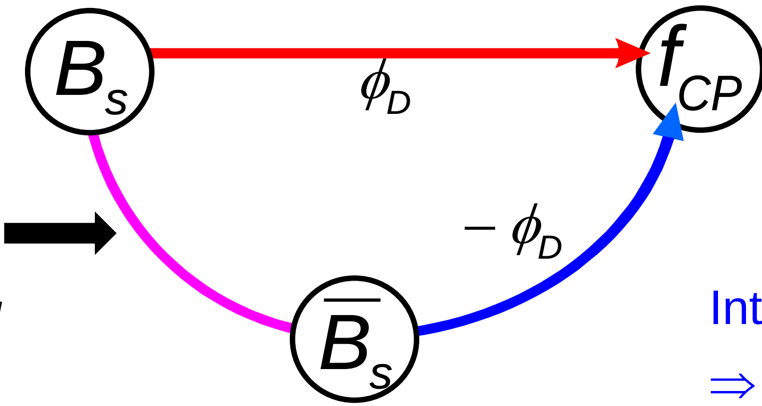
Mixing phase (ignoring CPV in mixing |q/p|=1):

$$\frac{q}{p} = -\exp(-i\phi_M) \qquad \phi_M = \arg(M_{12})$$

New Physics can alter the phase ϕ_M from the Standard Model.
Need an interference experiment to measure phase differences.

Measuring the B_s mixing phase





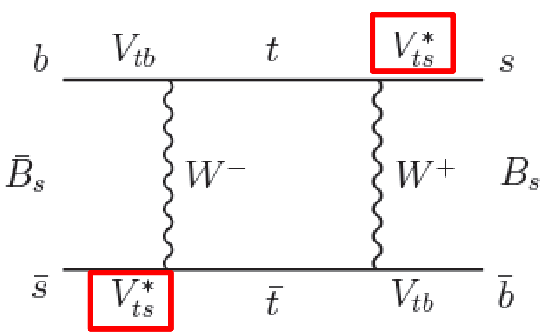
$B_s \to J/\psi\ \phi(KK)$

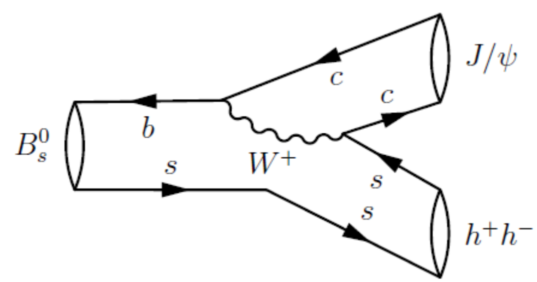
$$A_{mix} = |A_{mix}|\, e^{i\phi_M}$$

Interference of mixing & decay:

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

Standard Model:





+ small penguin pollution

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

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

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

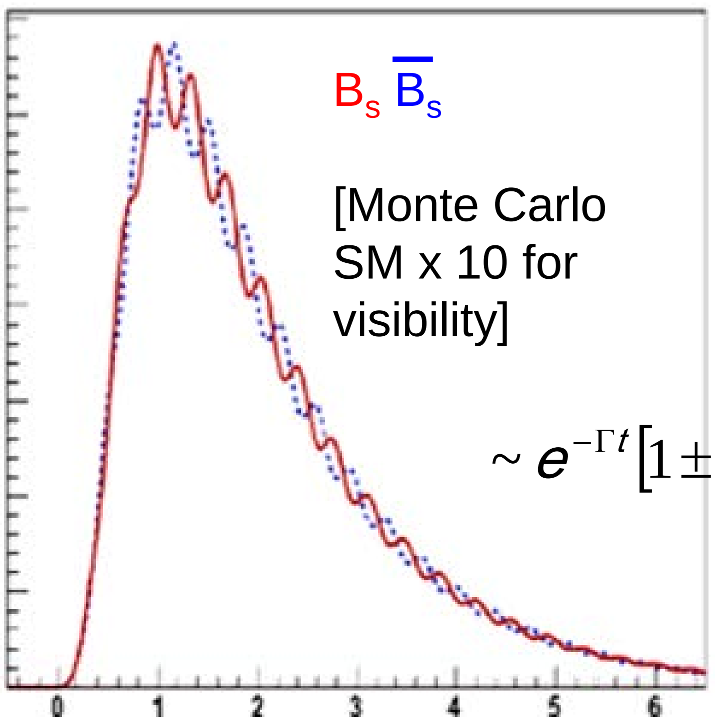
$$\phi_{weak,s}^{SM} = -0.0364 \pm 0.0016\ \text{rad} \quad \textit{(CKMFitter)}$$

$\to$ very small CPV

Standard Model Expectation

Precise Standard Model prediction:

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



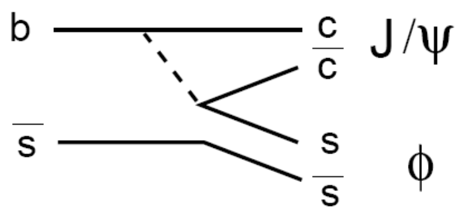
$\Rightarrow$ ϕ_s small:
expect very small CPV

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

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

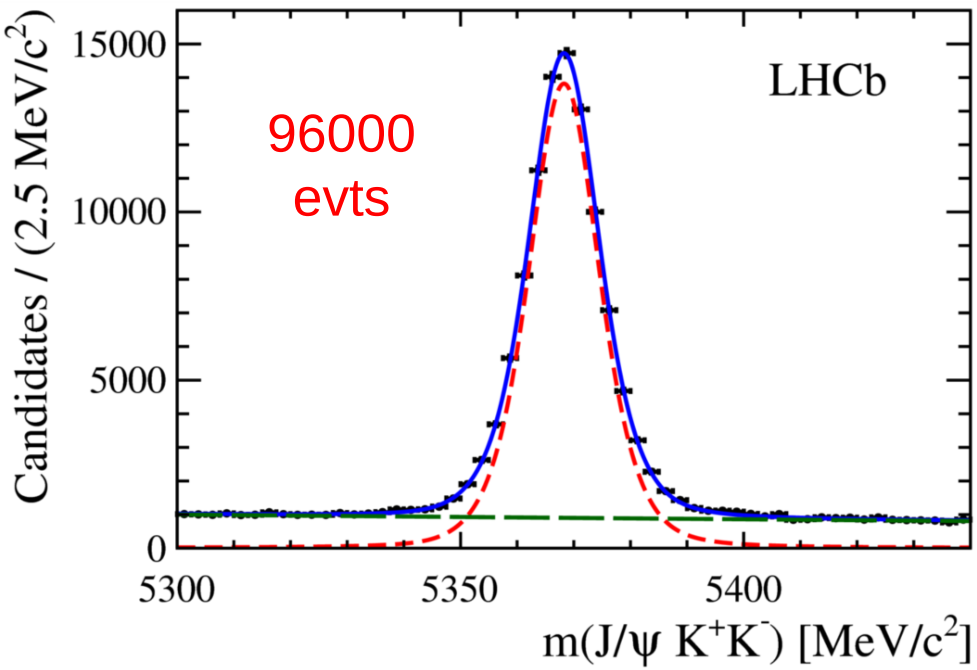
Phys. Rev. Lett. 114, 041801 (2015)

- experimentally clean
- VV final state:



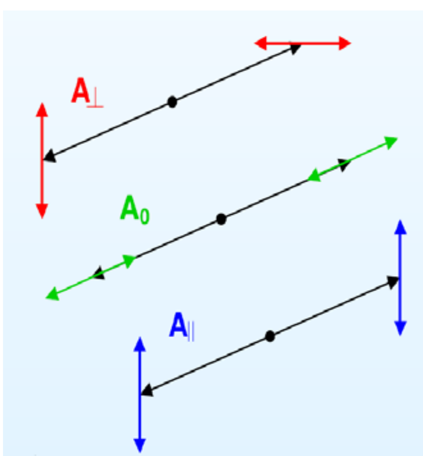
$J^{PC} = 1^{--}$

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



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

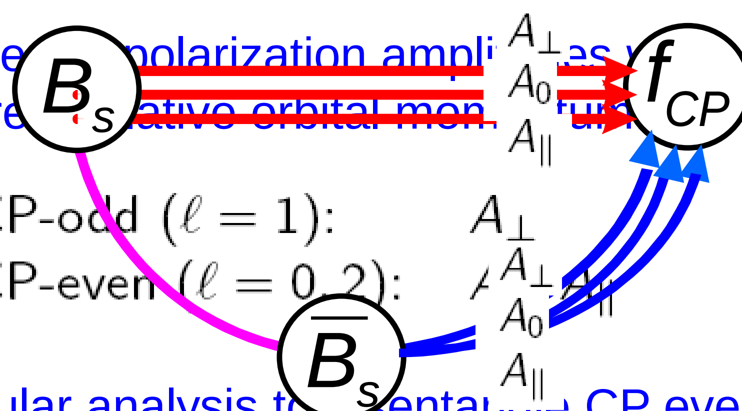
(L = 0, 1,2 = relative orbital momentu



3 diffe… polarization ampli… es w…
differe… lative orbital mom… tu…

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

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

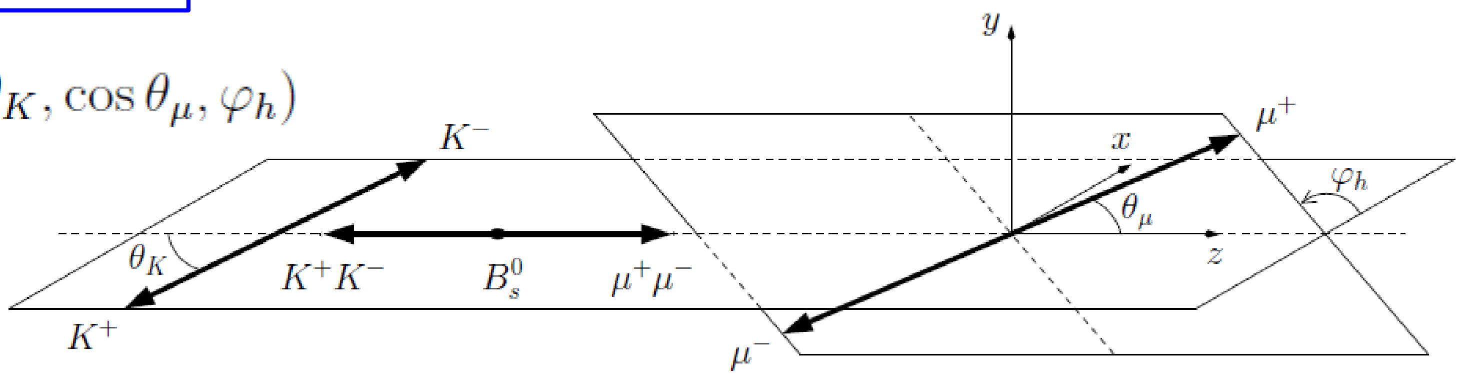


angular analysis to …sentangle CP even/odd state

Angular dependent t distributions

Helicity frame

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



B_s

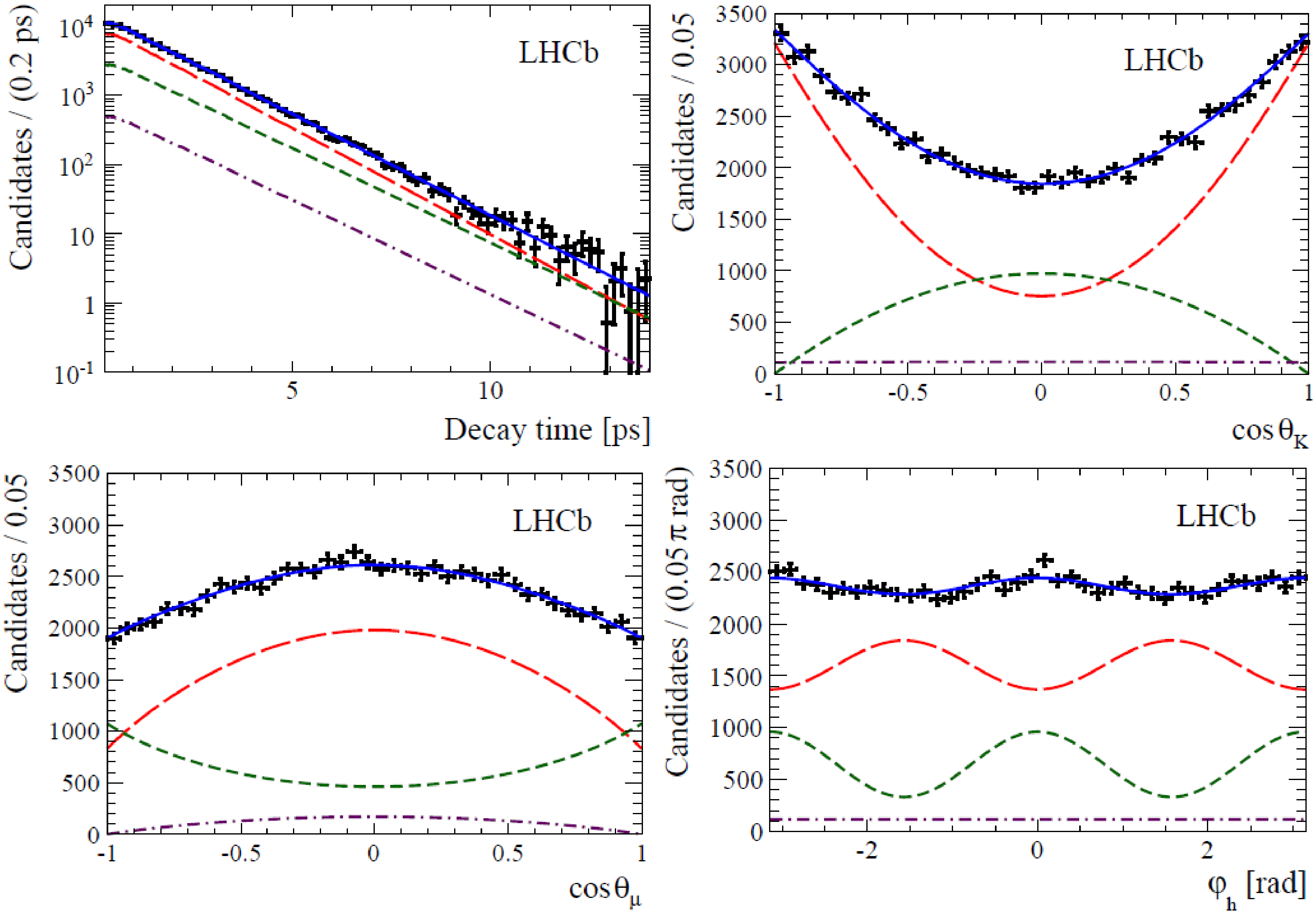
$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

$\overline{B}_s$

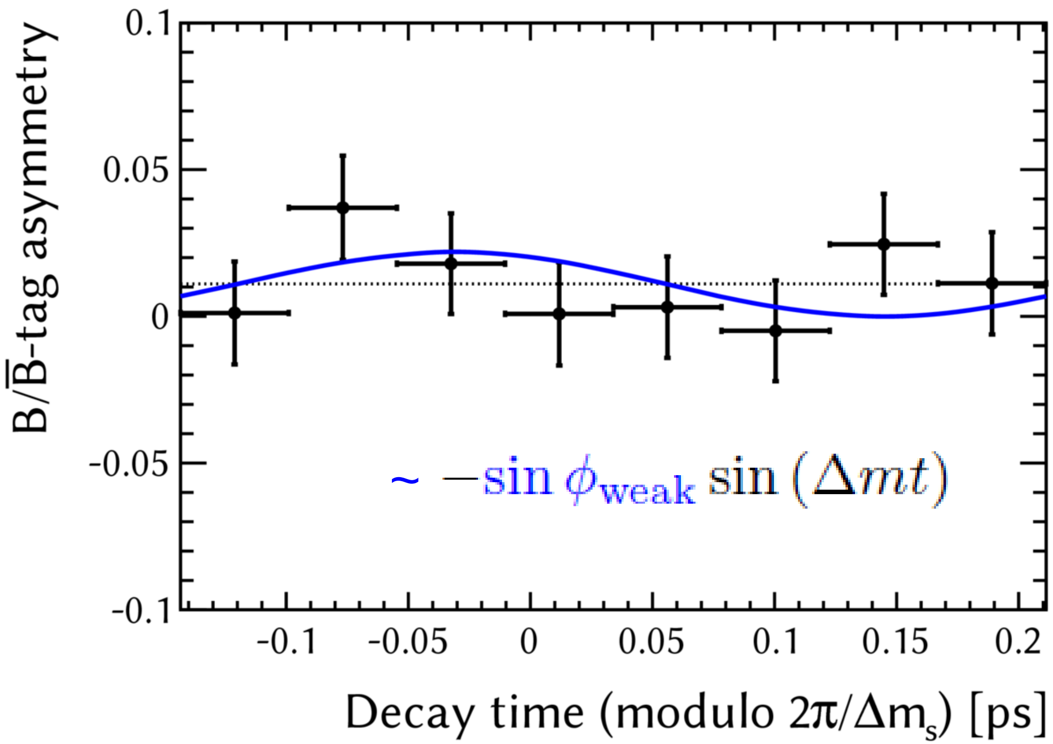
$$\frac{d^4\Gamma(\overline{B}_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} \overline{h}_k(t)\, \overline{f}_k(\Omega)$$

Decay time and decay angles

CP-even CP-odd S-wave



Time-dependent CP Asymmetry for B_s



ϕ_s = -0.058 ± 0.049 ± 0.006

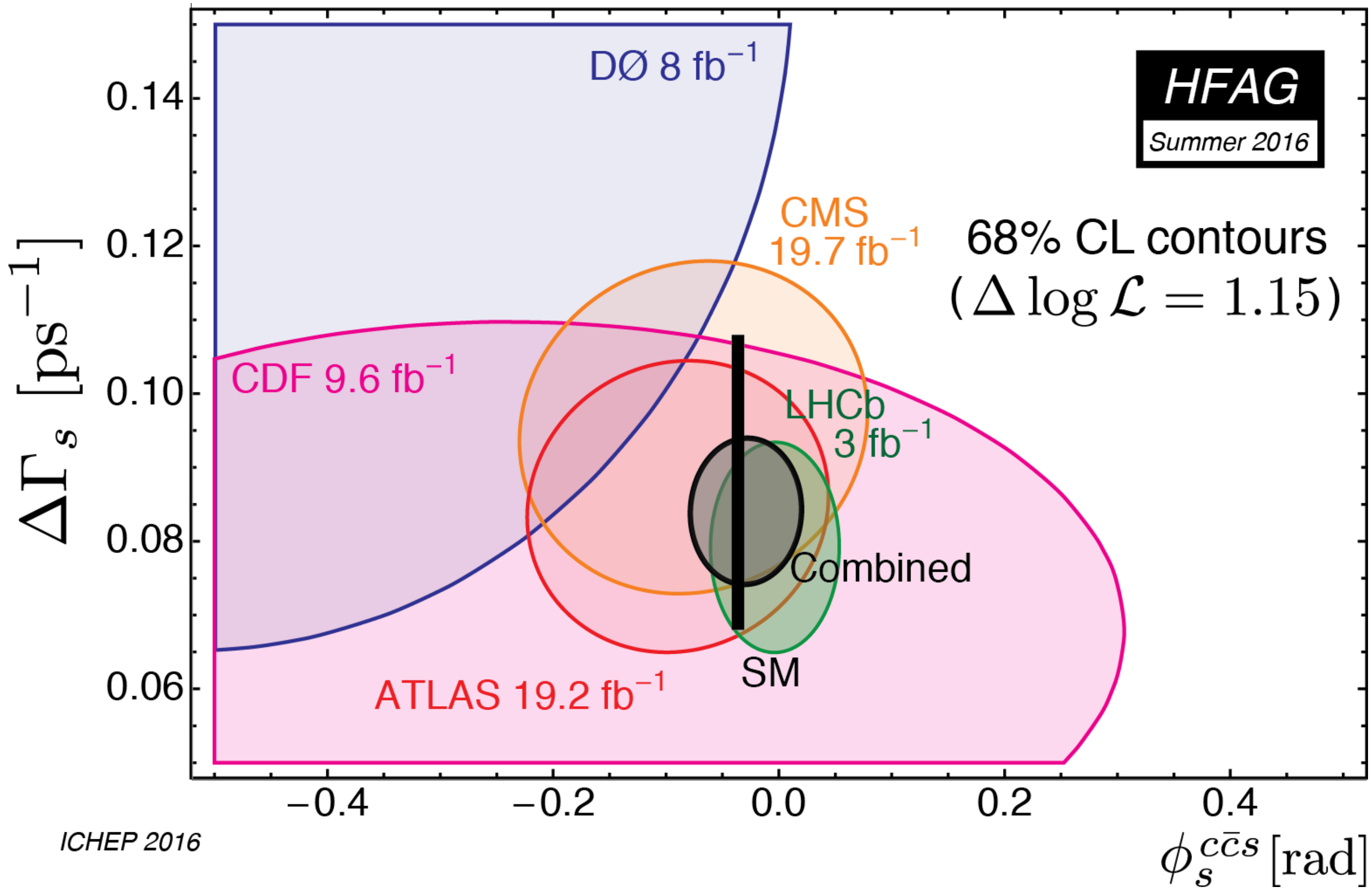
Γ = 0.6603 ± 0.0027 ± 0.0015 ps^{-1}

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

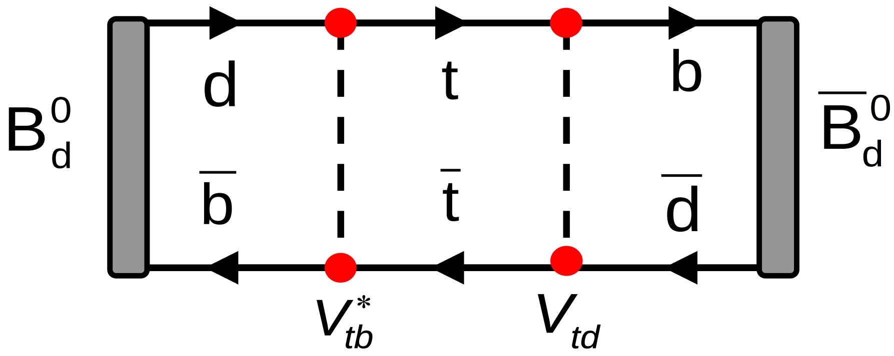
$|\lambda|$ = 0.964 ± 0.019 ± 0.007

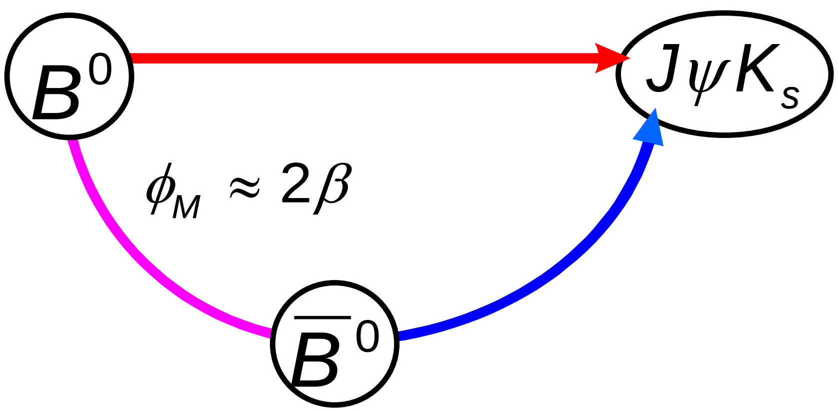
Consistent w/ =1:
no CPV

Experimental Status



B^0 Mixing and CPV in $B^0 \rightarrow J/\psi K_s$



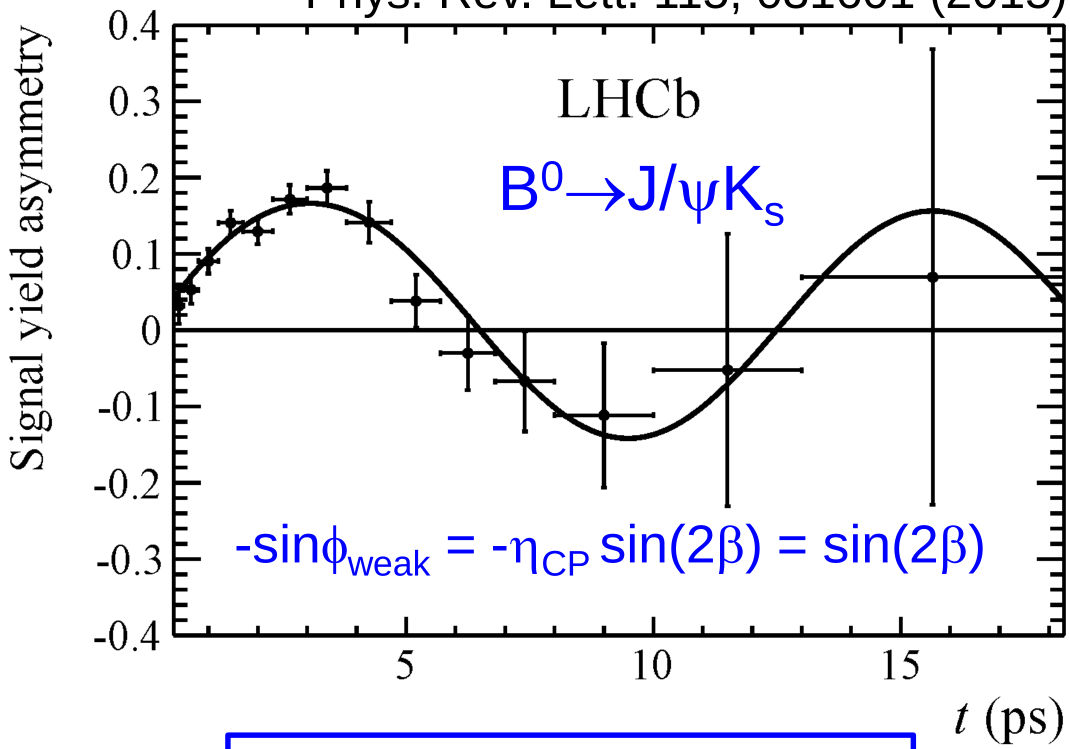


$$\beta \equiv \arg\left[-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right]$$

Time-dependent CPV for B_d^0

$$\mathcal{A}_{CP}(t) \equiv \frac{\Gamma(\overline{B^0} \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B^0} \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$
$$= -\sin\phi_{\text{weak}} \sin(\Delta m t)$$

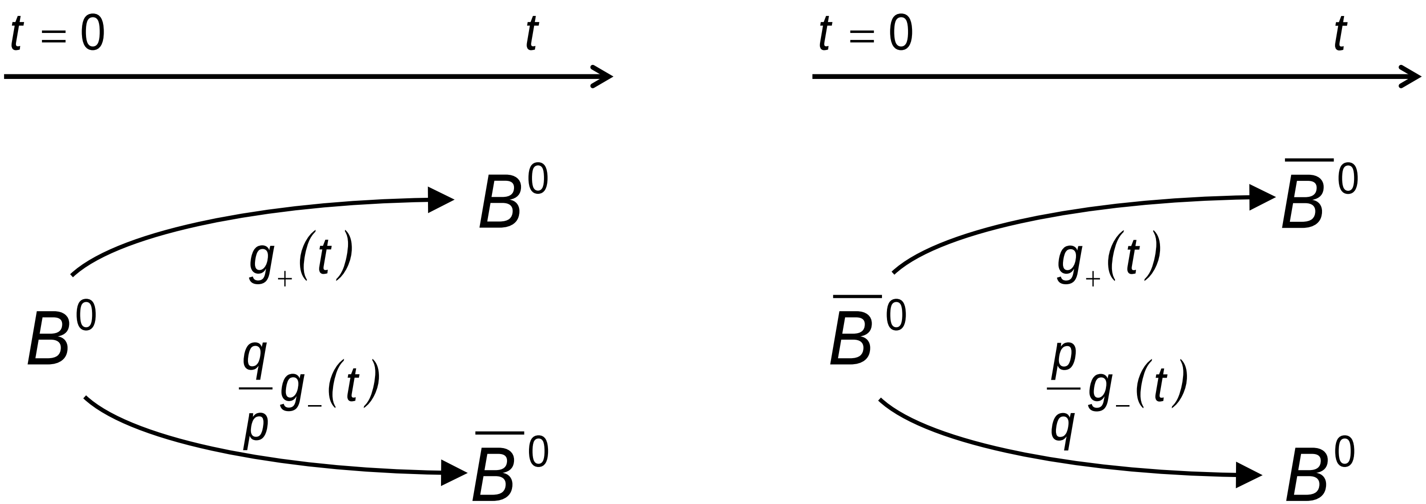
Phys. Rev. Lett. 115, 031601 (2015)



$\boxed{\sin 2\beta = 0.731 \pm 0.035 \pm 0.020}$

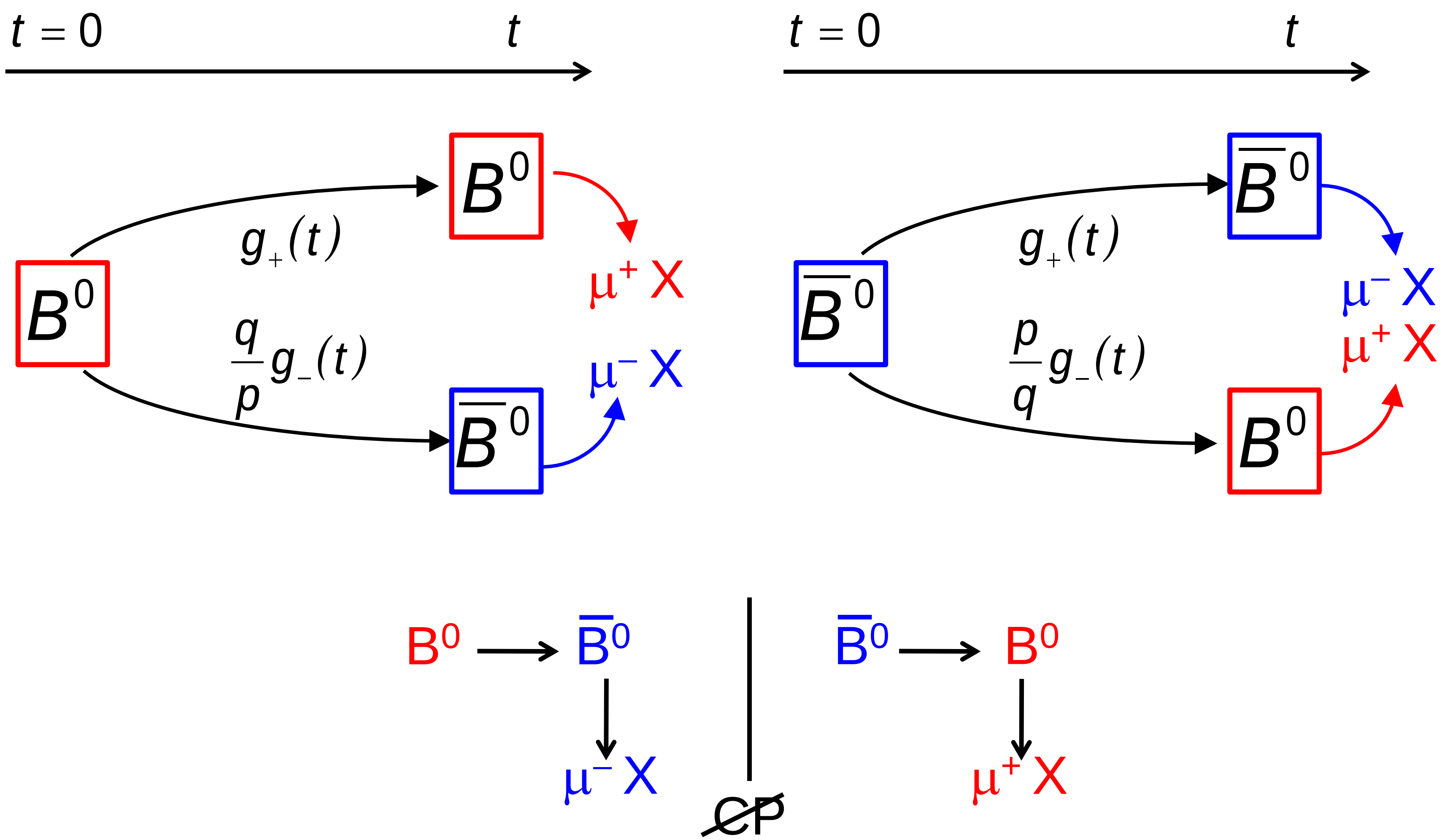
CP Violation in B mixing

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



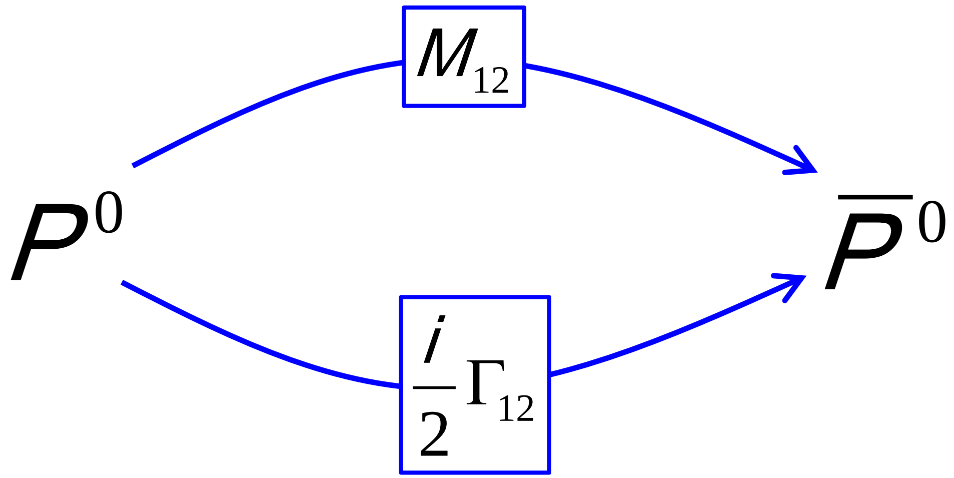
CP violation if $\left|\frac{q}{p}\right| \neq 1$

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: $1 \neq |q/p| = (1-\varepsilon_B)/(1+\varepsilon_B)$ *w/* ε_B *complex*

Physical states ($B_{H,}$ B_L) are not any longer pure CP states.

Time integrated asymmetry

$$
\begin{tikzcd}
\color{red}{B^0} \arrow[r] & \color{blue}{\overline{B}^0} \arrow[d] \\
 & \color{blue}{\mu^- X}
\end{tikzcd}
\qquad
\begin{tikzcd}
\color{blue}{\overline{B}^0} \arrow[r] & \color{red}{B^0} \arrow[d] \\
 & \color{red}{\mu^+ X}
\end{tikzcd}
$$

$\cancel{CP}$

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

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

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

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

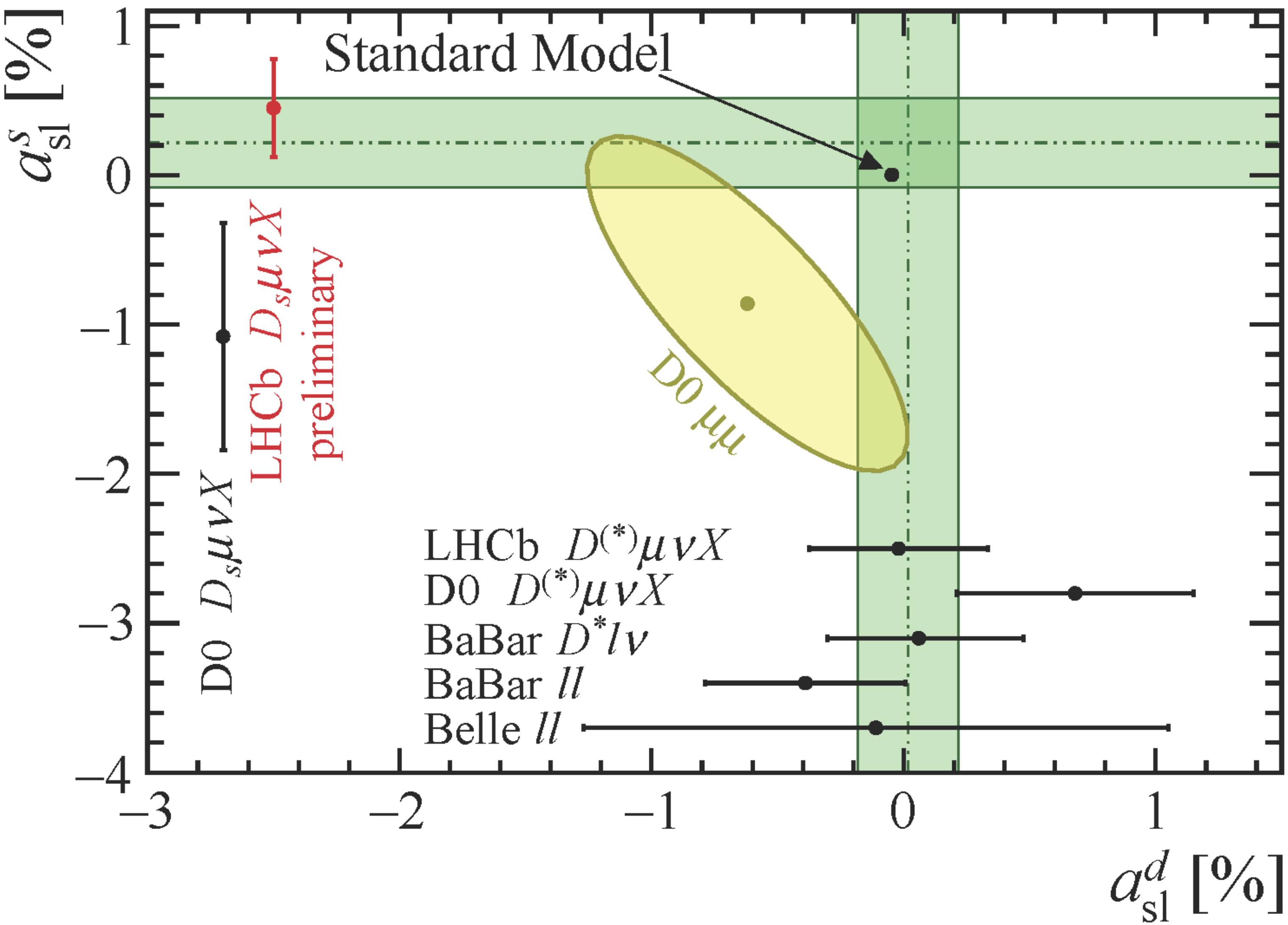
$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$

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

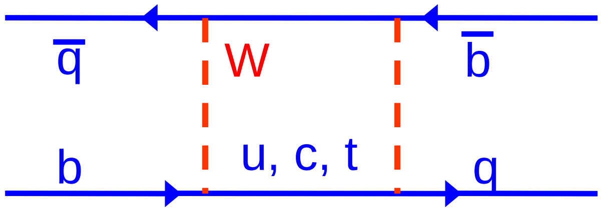
$$A_{\text{meas}}(t) = \frac{N(f,t) - N(\overline{f},t)}{N(f,t) + N(\overline{f},t)} \approx A_D + \frac{a_{sl}^d}{2} + \left(A_P - \frac{a_{sl}^d}{2}\right)\cos(\Delta m_d t)$$

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

Experimental Status



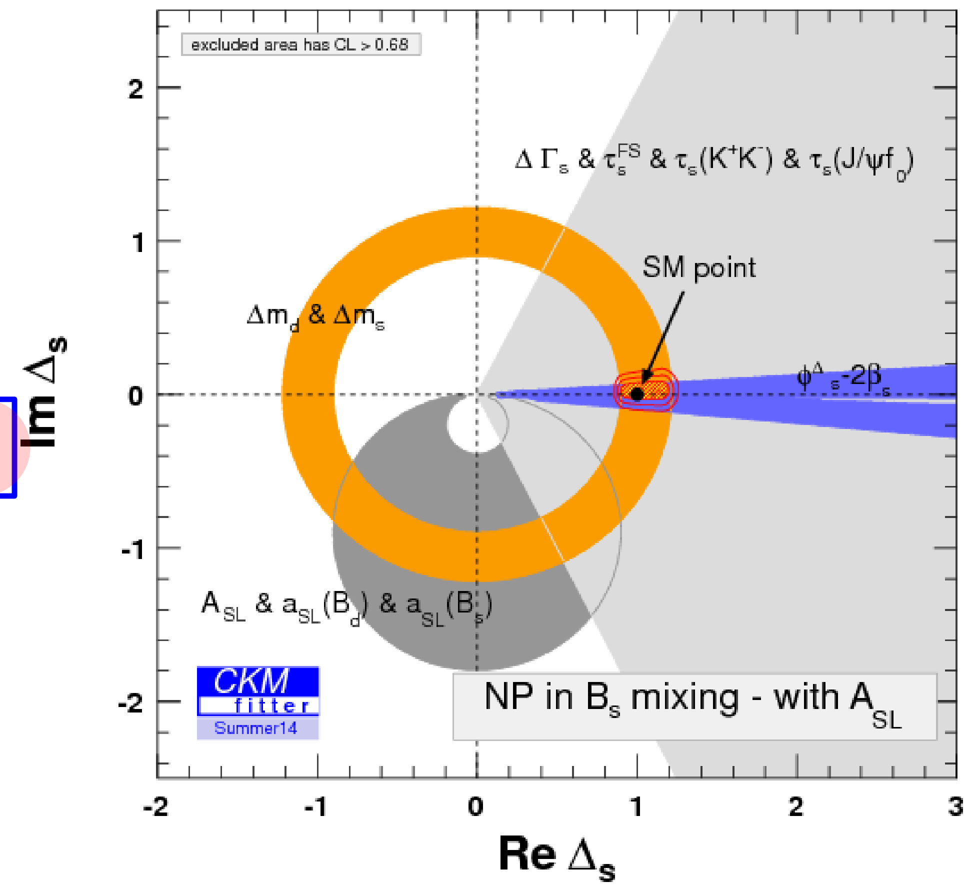
New Physics in B_s Mixing



$$\mathcal{A}_{mix} = \mathcal{A}_{mix}^{SM} + \mathcal{A}_{mix}^{NP} = \mathcal{A}_{mix}^{SM} \times \Delta$$

$$\Delta_s = |\Delta_s| e^{i\phi_s^{NP}}$$

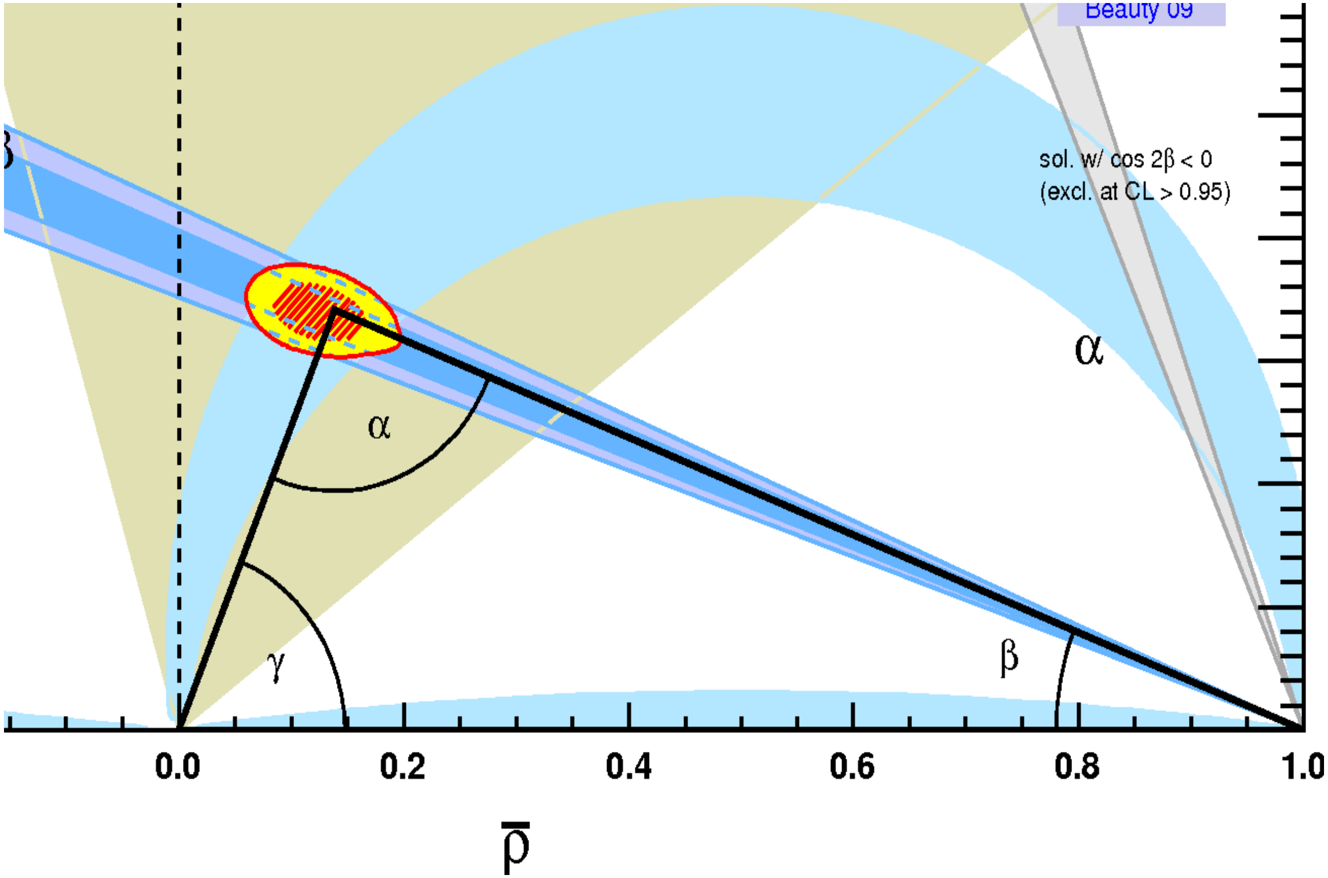
Status CKM 2014



A. Lenz , U. Nierste & CKM Fitter

Agreement with Standard Model, but still room for New Physics (10…20%)

Direct CP Violation & CKM angle γ

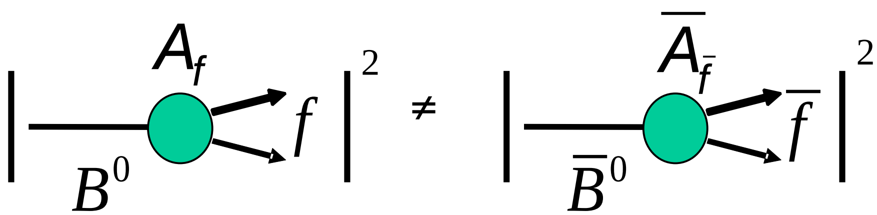


Direct CP Violation & CKM angle γ

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

Indirect CPV

- CP violation in decay



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

(time integrated)

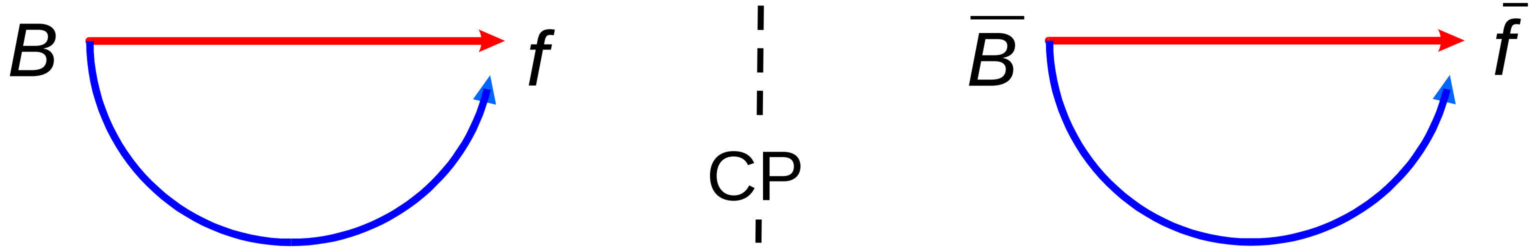
direct CPV

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:

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



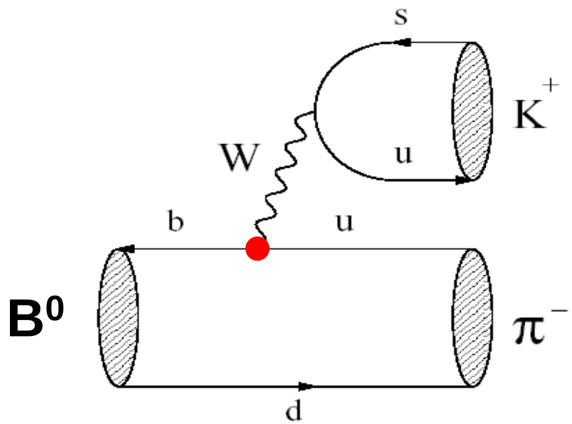
$$\mathcal{A}_2 = A_2 e^{i\phi_2} e^{i\delta_2} \qquad \overline{\mathcal{A}}_2 = A_2 e^{-i\phi_2} e^{i\delta_2}$$

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

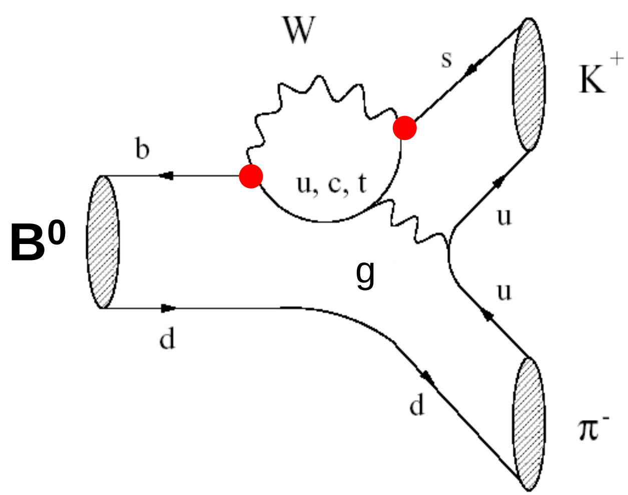
$$\boxed{\left|\overline{\mathcal{A}}\right|^2 - \left|\mathcal{A}\right|^2 = 4\, A_1 A_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)}$$

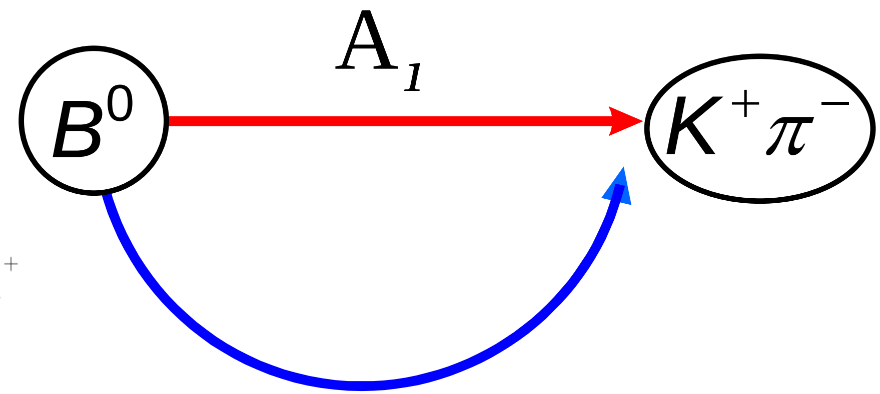
Direct CP Violation in B→Kπ

Tree



Penguin





$$A_2\, e^{i\phi_{CP}} e^{i\delta}$$

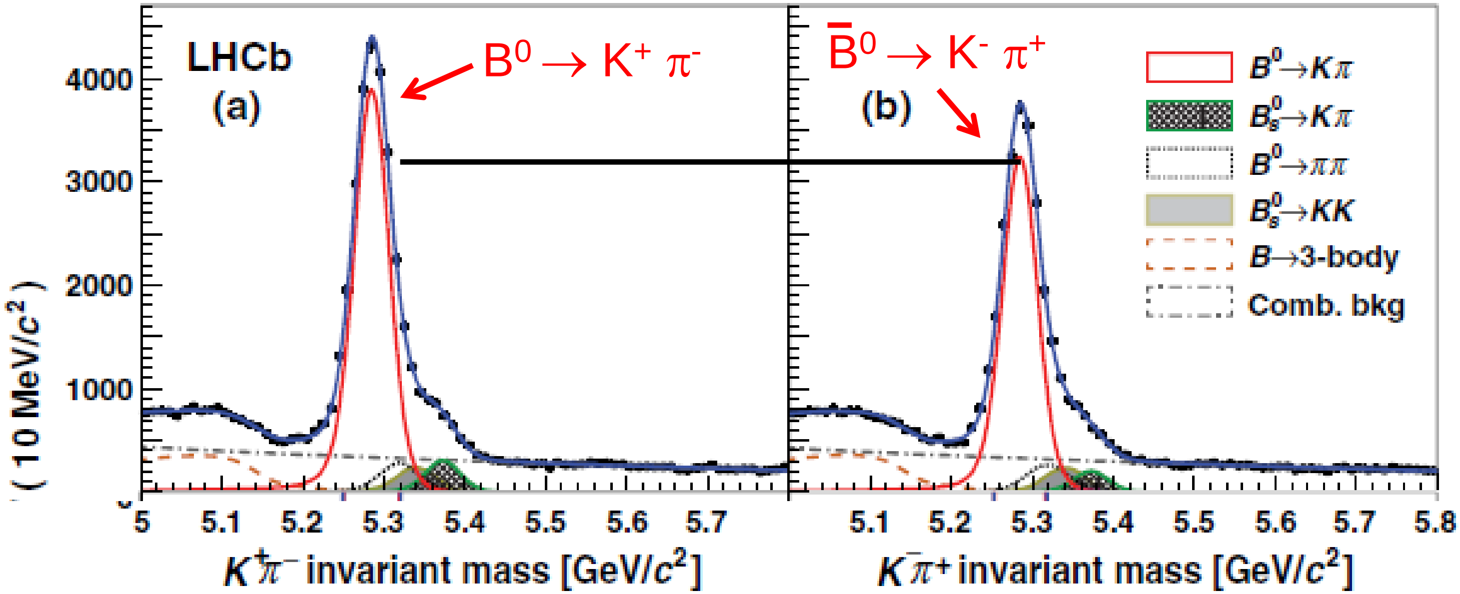
Strong and weak phase difference

CP Asymmetrie $$\left|\overline{A}\right|^2 - \left|A\right|^2 = 4\left|A_1\right|\left|A_2\right|\sin\phi\,\boxed{\sin\delta}$$

Strong phase difficult to predict

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

PRL 110, 221601 (2013)



CP Observables

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

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]

Standard Model relation: *[J.Lipkin Phys. Lett. B621 (2005) 126.] *)*

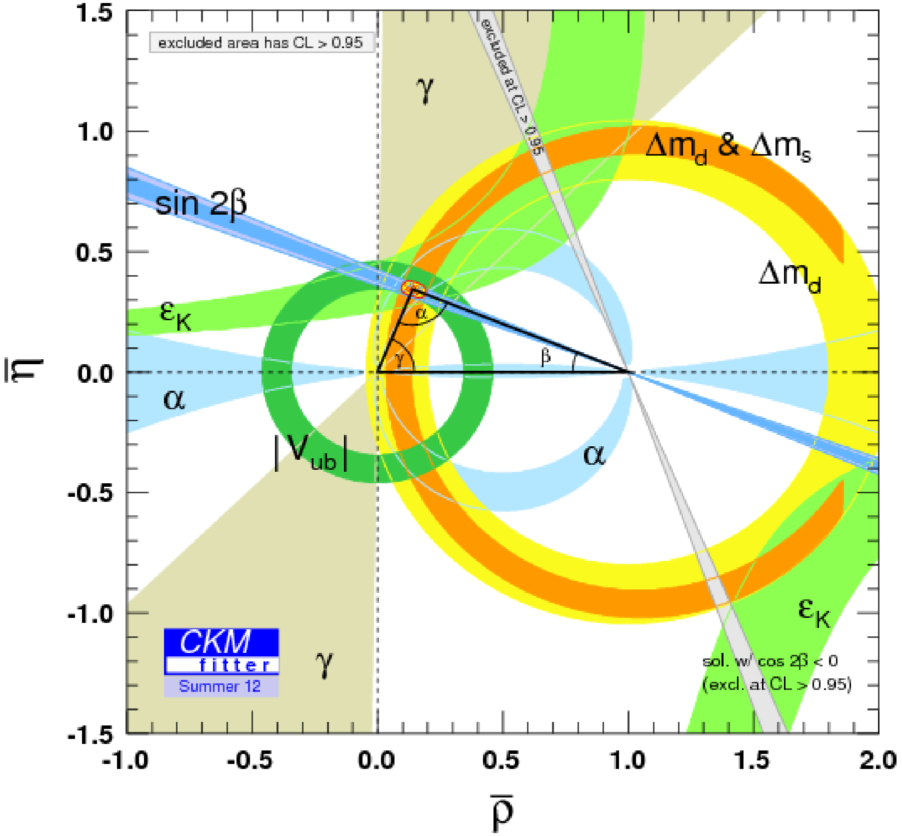
$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0.$$

$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

Direct CPV in B→Kπ fully consistent with SM.

.*) …but in the standard model a miracle occurs …

CKM Angle γ



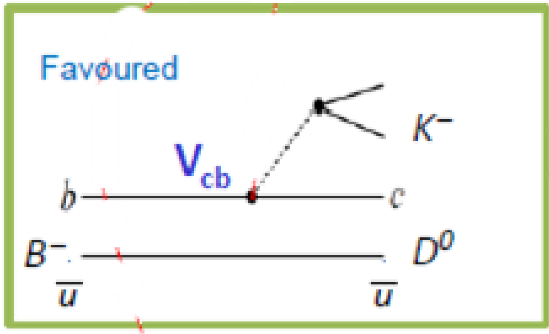
$$\boxed{\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)}$$

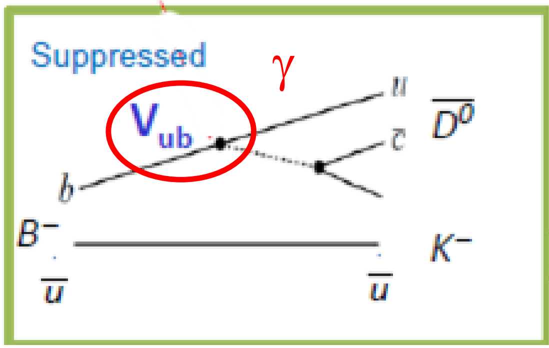
⇩

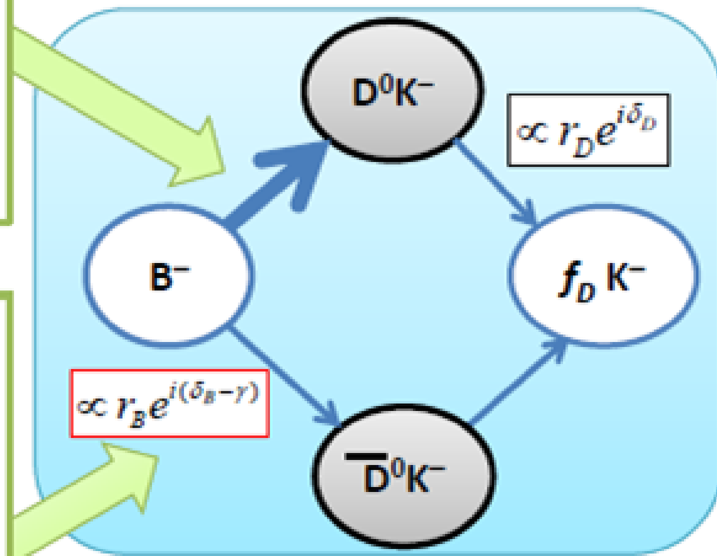
Exploit direct CPV in $B \to DK$ decays

Sensitivity of B→DK decays to γ

Adapted from S. Ricciardi







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

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

All unknowns from data

$\Rightarrow$ No hadronic uncertainties

Gronau, London, Wyler (GLW)

f_D = KK, $\pi\pi$ (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
- $B^\pm \to D(\pi^+K^-)\,K^\pm$
- $B^\pm \to D(\pi^+K^-)\,\pi^\pm$
- $B^\pm \to D(K_s\,K^+\pi^-)\,\pi^\pm$
- $B^\pm \to D(K_s\,K^+\pi^-)\,K^\pm$