Introduction to Flavour Physics

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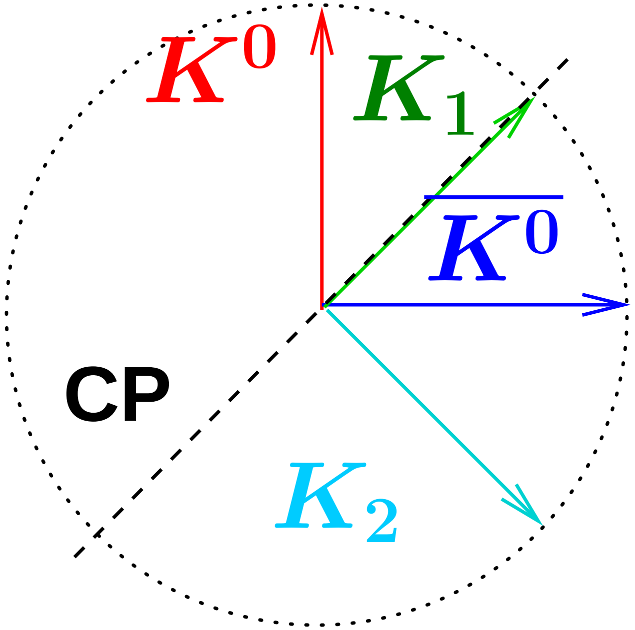
Birthday of Heavy Flavour

- 1947, G. D. Rochester and C. C. Butler, discovered kaons in cloud chamber studying cosmic rays

- 1953: new quantum number “strangeness” (Gellmann & Pais): conserved in strong IA, not conserved in weak IA

$$+\ p\ !\qquad {}^{0} + \overline{K}^{0} + X$$



$$CP(K^0) = \overline{K^0}$$
$$CP(\overline{K^0}) = K^0$$

$$K_1 = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0})$$
$$CP(K_1) = +K_1$$

$$K_2 = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0})$$
$$CP(K_2) = -K_2$$

K^0, $\overline{K^0}$: flavour eigenstates; clear defined quark content ($K^0 = |d\bar{s}>$, $\overline{K^0} = |\bar{d}s>$)

K_1, K_2: CP eigenstates

K_S, K_L: mass eigenstates

(with clear defined mass and lifetime, $\psi_{S/L}(t) = e^{-im_{S/L}t}e^{-\Gamma_{S/L}t/2}$)

in absence of CPV: $K_S = K_1, K_L = K_2$

Kaon Mixing

$$jK_S >= pjK^0 > +qj\overline{K}^0 >, \quad jK_S(t) >= jK_S > e^{\frac{S}{2}t} e^{im_S t}$$

$$jK_L >= pjK^0 > \quad qj\overline{K}^0 >, \quad jK_L(t) >= jK_L > e^{\frac{L}{2}t} e^{im_L t}$$

$jpj^2 + jqj^2 = 1$ complex coef cients; $q = p = \frac{p1}{2}$, $K_S = K_1, K_L = K_2$

Flavour eigenstates:

$$jK^0 >= \frac{1}{2p}(jK_S > +jK_L >)$$

$$j\overline{K}^0 >= \frac{1}{2q}(jK_L > \quad jK_S >)$$

time development of originally (at t=0) pure K^0 and $\overline{K}^0$ states:

$$jK^0(t) >= \frac{1}{2p}(jK_S(t) > +jK_L(t) >)$$

$$j\overline{K}^0(t) >= \frac{1}{2q}(jK_L(t) > \quad j \; K_S(t) >)$$

Kaon Mixing

$$P(K^0 \rightarrow \overline{K^0}) = |\langle K^0(t)|\overline{K^0}\rangle|^2 =$$
$$\frac{1}{4}\left|\frac{q}{p}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right]$$

$$P(\overline{K^0} \rightarrow K^0) = |\langle \overline{K^0}(t)|K^0\rangle|^2 =$$
$$\frac{1}{4}\left|\frac{p}{q}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right]$$

CP conserved: $P(K^0 \rightarrow \overline{K^0}) = P(\overline{K^0} \rightarrow K^0)$

$$\Leftrightarrow$$

$$\left|\frac{q}{p}\right| = 1$$

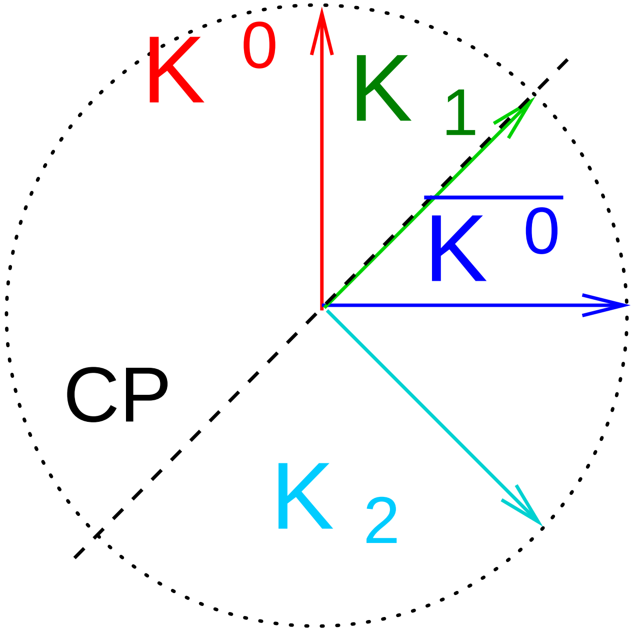
(+ normalisation $q^2 + p^2 = 1$)

$$\Leftrightarrow$$

$$q = p = \frac{1}{\sqrt{2}}$$

$$\Leftrightarrow$$

$$K_S = K_1, K_L = K_2$$



$CP(K^0) = \overline{K}^0$

$CP(\overline{K}^0) = K^0$

$K_1 = \frac{1}{\sqrt{2}}(K^0 + \overline{K}^0)$

$CP(K_1) = + K_1$

$K_2 = \frac{1}{\sqrt{2}}(K^0 \quad \overline{K}^0)$

$CP(K_2) = \quad K_2$

P ((   )) = P ((q)) P (($\bar{q}$)) (1)$^{L=0}$ = 1   1 1 (   ) =   (   )

C ((   )) = C ((q$\bar{q}$)) = (1)$^{L+S}$ (q$\bar{q}$) = + (   )

CP (($^{+}$)) = CP (($^{+}$)) CP ((   )) (1)$^{L=0}$ = + ($^{+}$)

L = 0 in K^0 ! $^{+}$

CP (($^{+}$ ^{0})) = CP ((   ))^{3} (1)^{L} = ($^{+}$ ^{0})

L = 0 in K^0 ! $^{+}$ ^{0}

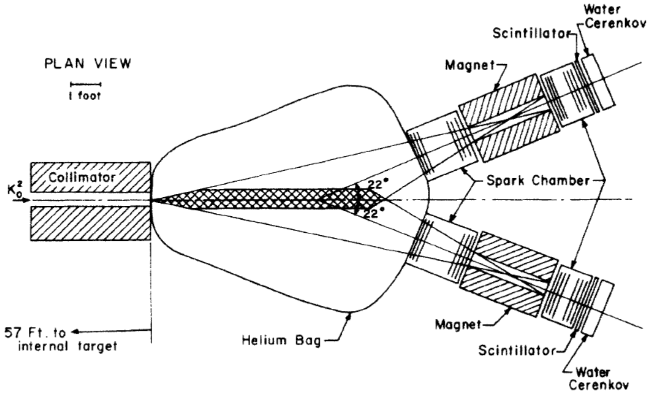
If there is no CPV in decay, then: K_1 ! $^{+}$; K_2 ! $^{+}$ ^{0}

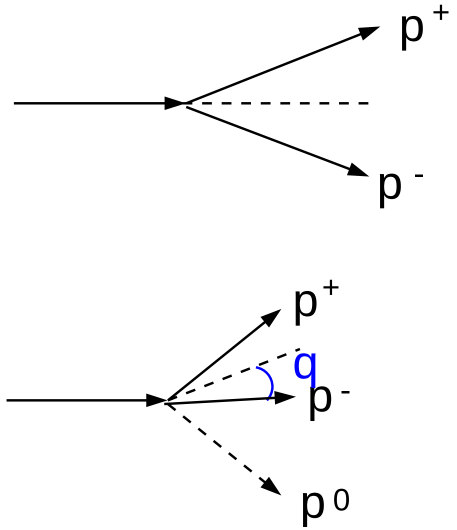
1964: Discovery of CPV

produce K^0, wait long enough for K_S component to decay away $\to$ pure K_L beam

search for CP violation: $K_L \to \pi^+\pi^-$

$\to$ excess of 56 events: BR($K_L \to \pi^+\pi^-$) 2 10^{-3}





mass eigenstates ≠ CP eigenstates: $|\mathbf{K_L}> = \sqrt{\frac{1}{1+|\epsilon^2|}}(|\mathbf{K_2}> + \epsilon|\mathbf{K_1}>)$

CP=-1 CP=+1

Nobel prize for Cronin and Fitch in 1980

Good guessing ..... ?

three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$ where τ_1 and τ_2 are the K_1^0 and K_2^0 mean lives

R_T is the branching ratio including decay to and

in this paper they call K_2 what we call nowadays K_L ....

In my opinion one could not conclude from this experiment if the observed CPV is CPV in mixing or in decay.

CPV in mixing:

$$|K_L\rangle = \frac{1}{\sqrt{1+|\;|^2}}(|K_2\rangle + \;|K_1\rangle)$$

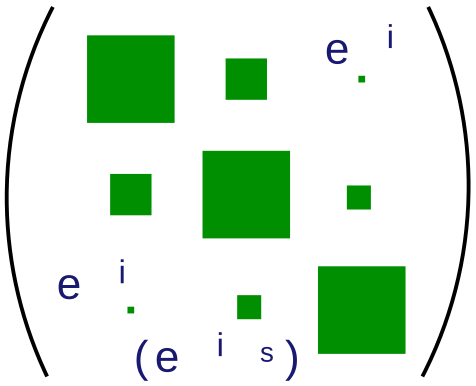
CPV in decay:

$K_1 \rightarrow$ and $K_2 \rightarrow$

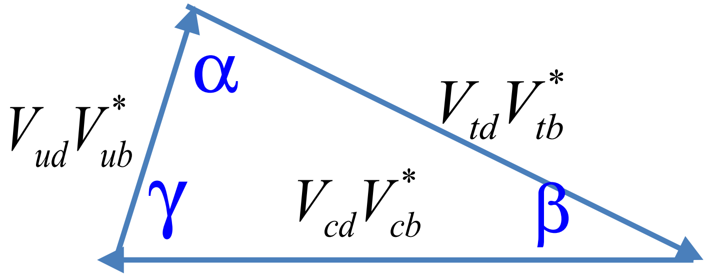
CKM Matrix and Angles

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

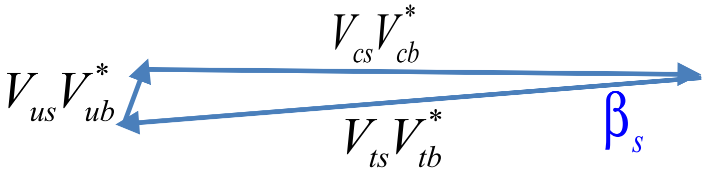
size of box, illustrates absolute value



B_d triangle:



B_s triangle:



CPV in Kaon System

Interfering amplitudes which cause CPV in mixing:

long range contribution

short range contribution m

Interfering amplitudes which cause CPV in decay:

1974: Discovery of J=

$p + Be\ !\ ? + X\ !\ e^{+} + e\ X$

$e^{+} + e\ !\ e^{+} + e = {}^{+} + \ = h^{+} + h$

Phenomenology of Mixing II

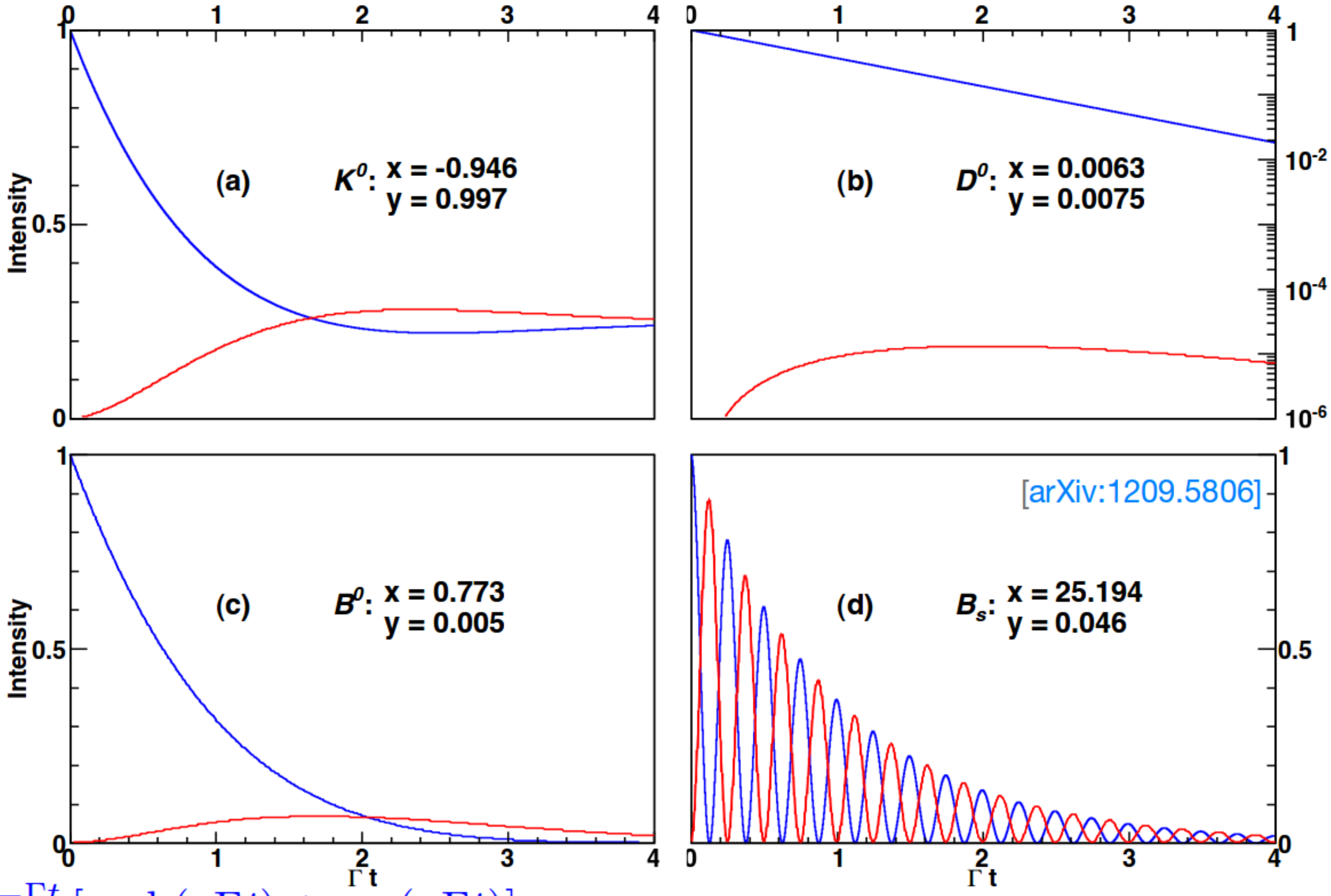
!

$$H = \begin{matrix} m_{11} & \frac{i}{2} & 11 & \frac{m}{2} & \frac{i}{2} \\ \frac{m}{2} & \frac{i}{2} & & m_{22} & \frac{i}{2} & 22 \end{matrix}$$

	$K^0/\overline{K^0}$	$D^0/\overline{D^0}$	$B^0/\overline{B^0}$	$B_s^0/\overline{B_s^0}$
τ [ps]	89.3 51700	0.415	1.564	1.47
Γ [ps^{-1}]	5.61 10^{-3}	2.4	0.643	0.62
y=$\frac{\Delta\Gamma}{2\Gamma}$	0.9966	0.008	0.0075	0.059
Δm [ps^{-1}]	5.301 10^{-3}	0.16	0.506	17.8
x=$\frac{\Delta m}{\Gamma}$	0.945	0.010	0.768	26.1

Blue line:
given a P^0, at t=0, the probability of finding a P^0 at t

Red Line:
given a P^0, at t=0, the probability of finding a $\bar{P}^0$ at t



$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}\,[\cosh(y\Gamma t) + \cos(x\Gamma t)]$$

$$|\langle P^0(0)|\overline{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}\,[\cosh(y\Gamma t) - \cos(x\Gamma t)]$$

New physics in B_s mixing?

- $P(B \to \overline{B}) \neq P(\overline{B} \to B)$

semileptonic asymmetry

$(B^0 + B_s)$

B ⟶ B̄ ⟶ μ̄
B̄ ⟶ μ̄

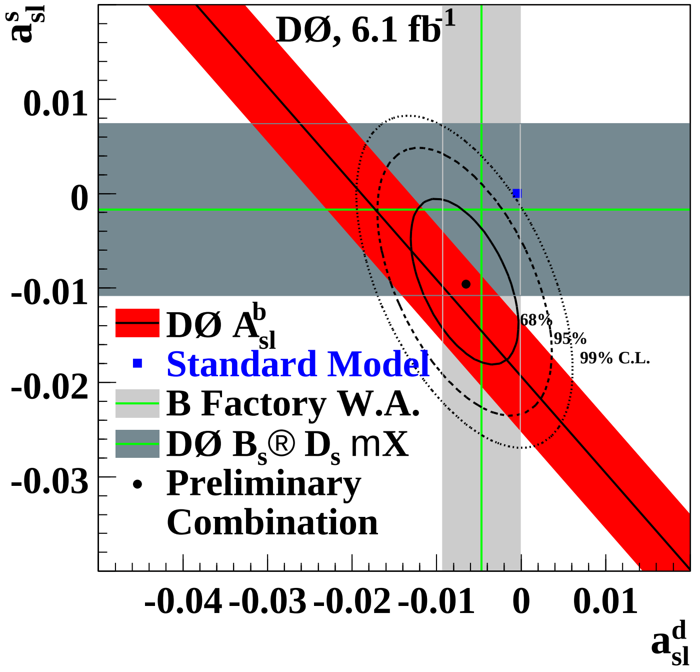
B̄ ⟶ B ⟶ μ⁺
B ⟶ μ⁺

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

$$a = \frac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)}$$

SM: A^b_{sl} = (-0.20 0.03) 10^{-3}

A. Lenz, U. Nierste, (2006/2011)



A^b_{sl} = -0.957 0.251 (stat) 0.14 (syst) %

(Phys. Rev. Lett 105, 081802 (2010))

! 3.2σ deviation from SM

a_{sl} at LHCb

$$a_{sl} = \frac{\Gamma(\overline{B}\to B\to f)-\Gamma(B\to\overline{B}\to\overline{f})}{\Gamma(\overline{B}\to B\to f)+\Gamma(B\to\overline{B}\to\overline{f})}$$

If there is no CPV in decay $\Gamma(B \to f) = \Gamma(\overline{B} \to \overline{f})$:

$$a_{sl} \neq 0\ , \quad \Gamma(\overline{B} \to B) \neq \Gamma(B \to \overline{B})$$

However tagging the initial flavour is difficult at hadron colliders ...

(tagging power 4% $\to$ $\sigma^{tag}_{stat} = \frac{1}{\sqrt{0.04}}\ \sigma^{no\,tag}_{stat} = 5\ \sigma^{no\,tag}_{stat}$)

Untagged method:

Assuming there is no production asymmetry ($N(B, t=0) = N(\overline{B}, t=0)$)

and no CPV in decay:

$$\frac{N(f)(t)-N(\overline{f})(t)}{N(f)(t)+N(\overline{f})(t)} = \frac{a_{sl}}{2}\left[1 \quad \frac{\cos\Delta M t}{\cosh\frac{\Delta\Gamma t}{2}}\right]$$

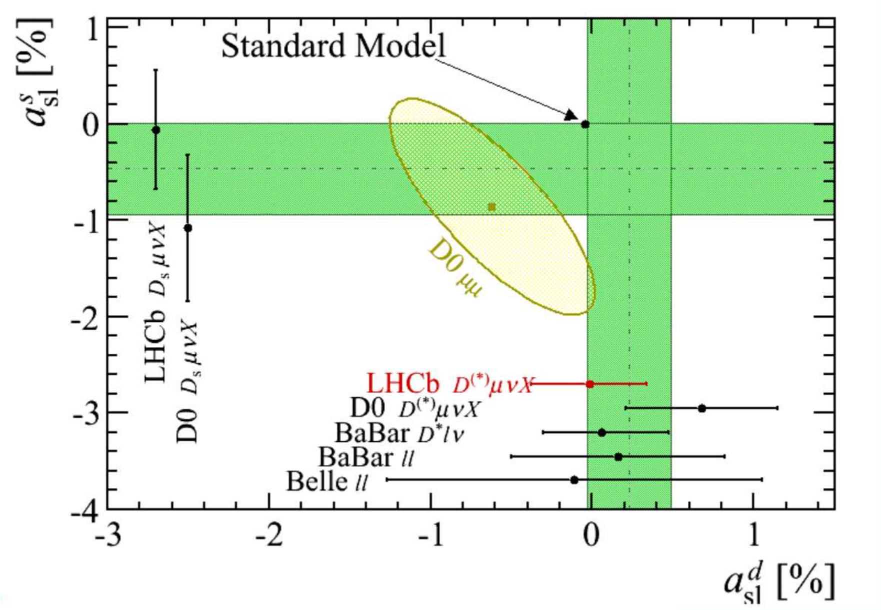
index sl: semileptonic decays ... simply due to large statistics

a_{sl} at LHCb

For B_s^0 system, can perform time integrated analysis (fast oscillation)

$$\frac{N(f)-N(\bar{f})}{N(f)+N(\bar{f})} = \frac{a_{sl}^s}{2} + [a_P \quad \frac{a_{sl}^s}{2}]\frac{\int e^{-\Gamma_s t}\cdot\cos\Delta M t\, dt}{\int e^{-\Gamma_s t}\, dt\cdot\cosh\frac{\Delta\Gamma_s t}{2}}] \quad \frac{a_{sl}^s}{2}$$

For B_d^0 time dependent analysis is required. Due to missing neutrino in $B_d^0\ !\ \ D^-\mu^+X$ decays need to correct for missing momentum to reconstruct B_d^0 momentum and thus the B_d^0 decay time.



More tomorrow in Concezzio's talk

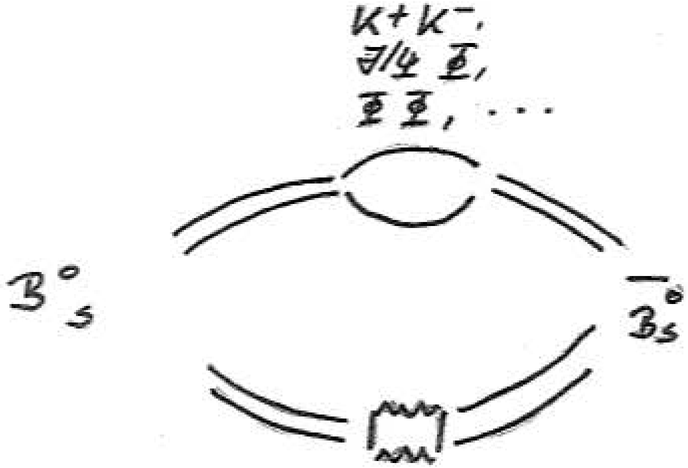
What are the interfering amplitudes?

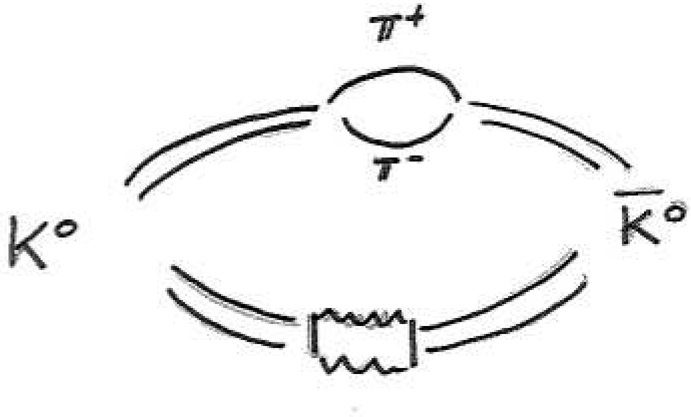
Why is CPV in B mixing so much smaller than CPV in K^0 mixing?

CPV in B Mixing

branching ratio into non-flavour specific decays

10^{4} > 0.95%





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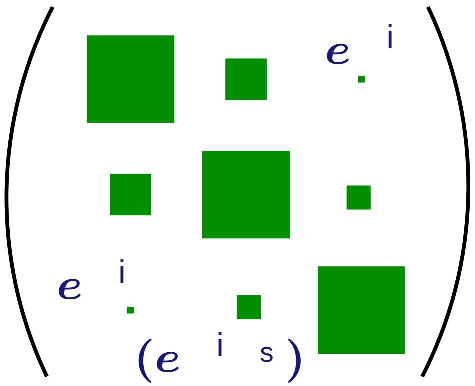
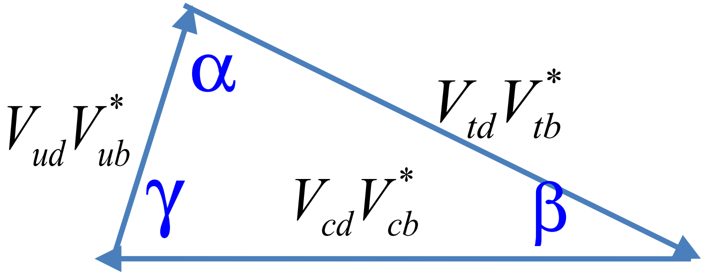
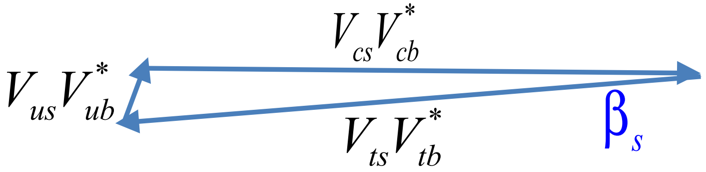


B_d triangle:



B_s triangle:



CP violation is caused by phases of CKM matrix

! how can we use CP violation to extract CKM angles?

CP Violation in one Page

Mass eigenstates:

$$B_L = p|B^0\rangle + q|\overline{B^0}\rangle \quad \text{w. } m_L, \Gamma_L$$

$$B_H = p|B^0\rangle - q|\overline{B^0}\rangle \quad \text{w. } m_H, \Gamma_H$$

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

Flavour eigenstates:

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

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

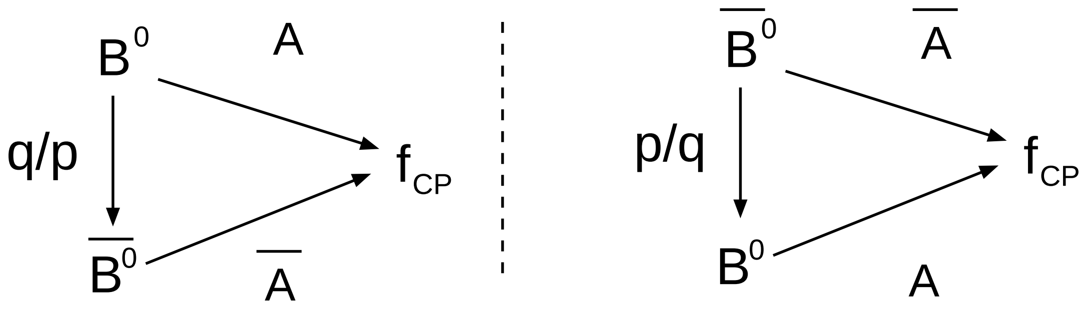
- CP Violation in mixing

  If $|\frac{q}{p}| \neq 1$; mass eigenstates are no CP eigenstates;

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

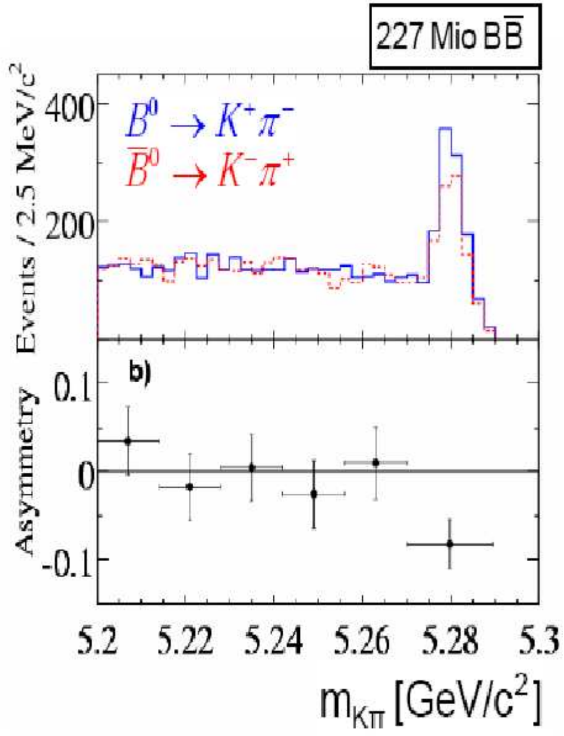
- CP violation in decay $|A(B \rightarrow f)| \neq |\overline{A}(\overline{B} \rightarrow \overline{f})|$

- CP violation in interference of mixing and decay: $Im(\frac{q}{p}\frac{\overline{A}}{A}) \neq 0$

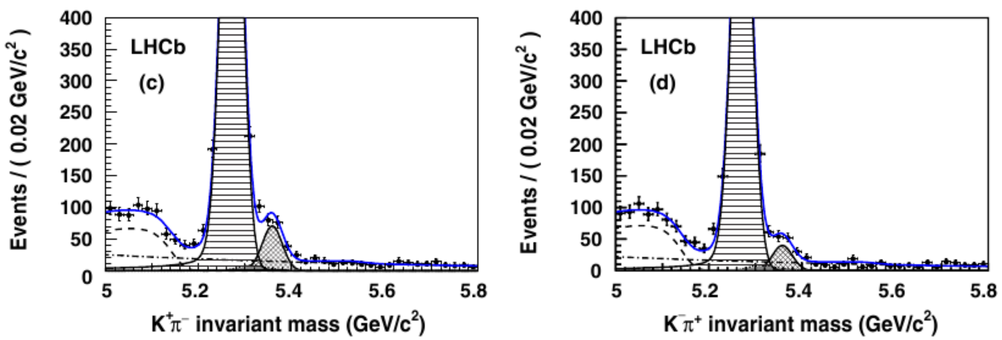


First direct CPV in ...

B^0 ! $K^+\pi^-$/$\overline{B^0}$! $K^-\pi^+$



$\overline{B^0}_s$! $K^+\pi^-$ B^0_s ! $K^-\pi^+$



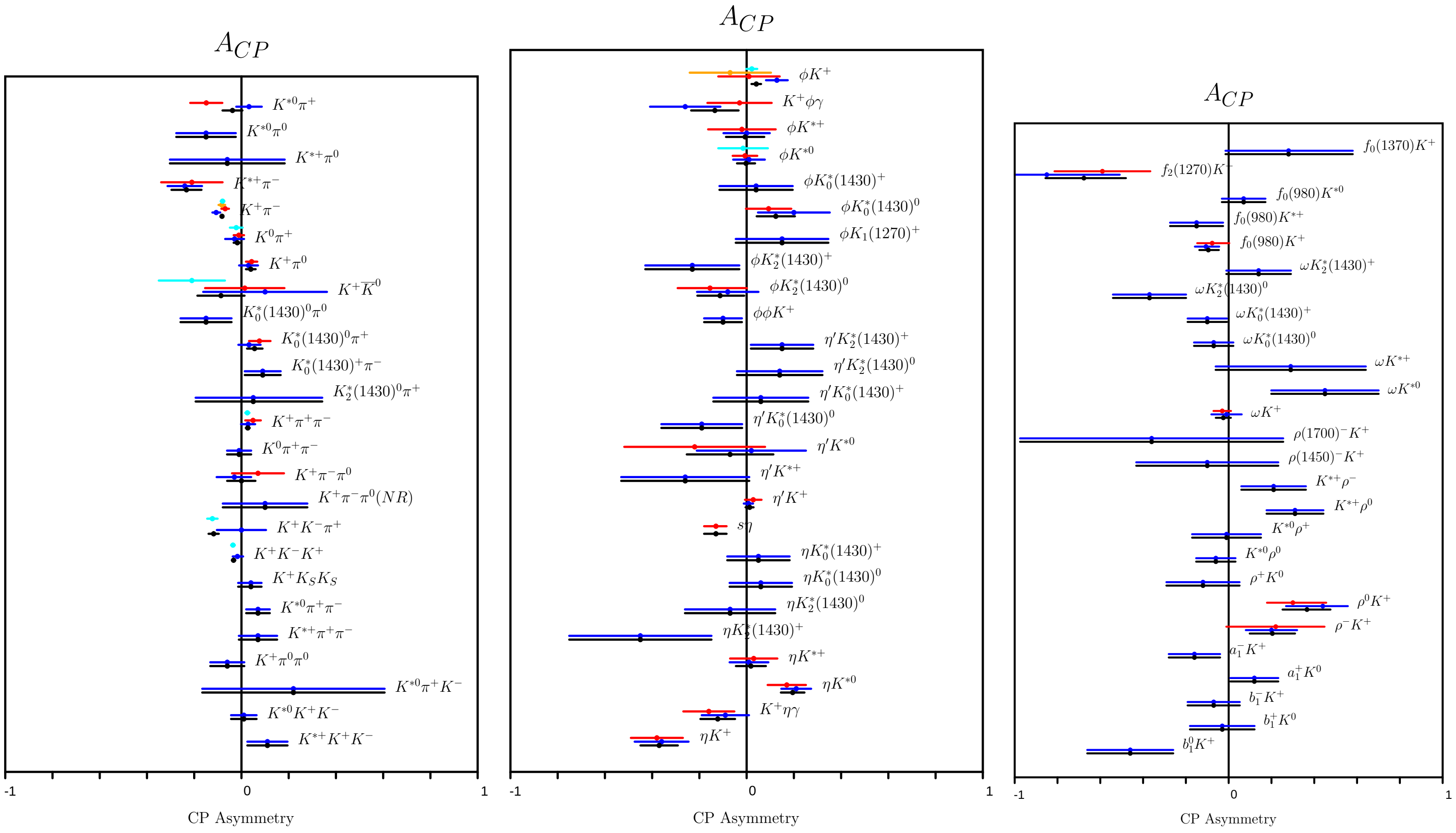
WA: $A_{CP} = 0.26 \quad 0.04$

WA: $A_{CP} = \quad 0.082 \quad 0.006$

First direct CPV in charged B decays:

WA: $A_{CP}(B^+$! $D^0($! $KK/\pi\pi)K^+) = 0.19 \quad 0.03$

Lot’s of direct CPV ...



Due to unknown strong phases, hard to relate CPV directly to CKM parameters :-(.

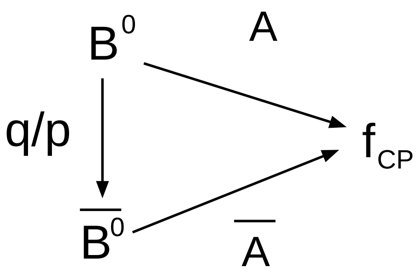
"The strong interaction can be seen either as the unsung hero or the villain in the story of quark avour physics” ; I. Bigi.

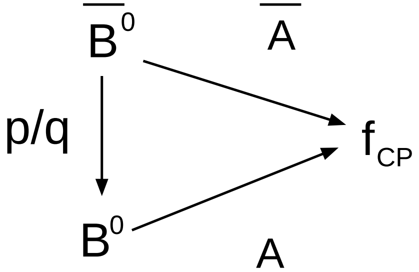
same true for CPV in mixing ...

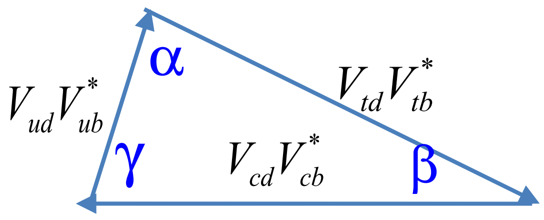
CPV in interference of mixing and decay

Measurement of $\sin(2\beta)$: golden channel B_d ! $J/\psi K_s$

"Golden": large statistics, easy to detect, (almost) no CPV in decay







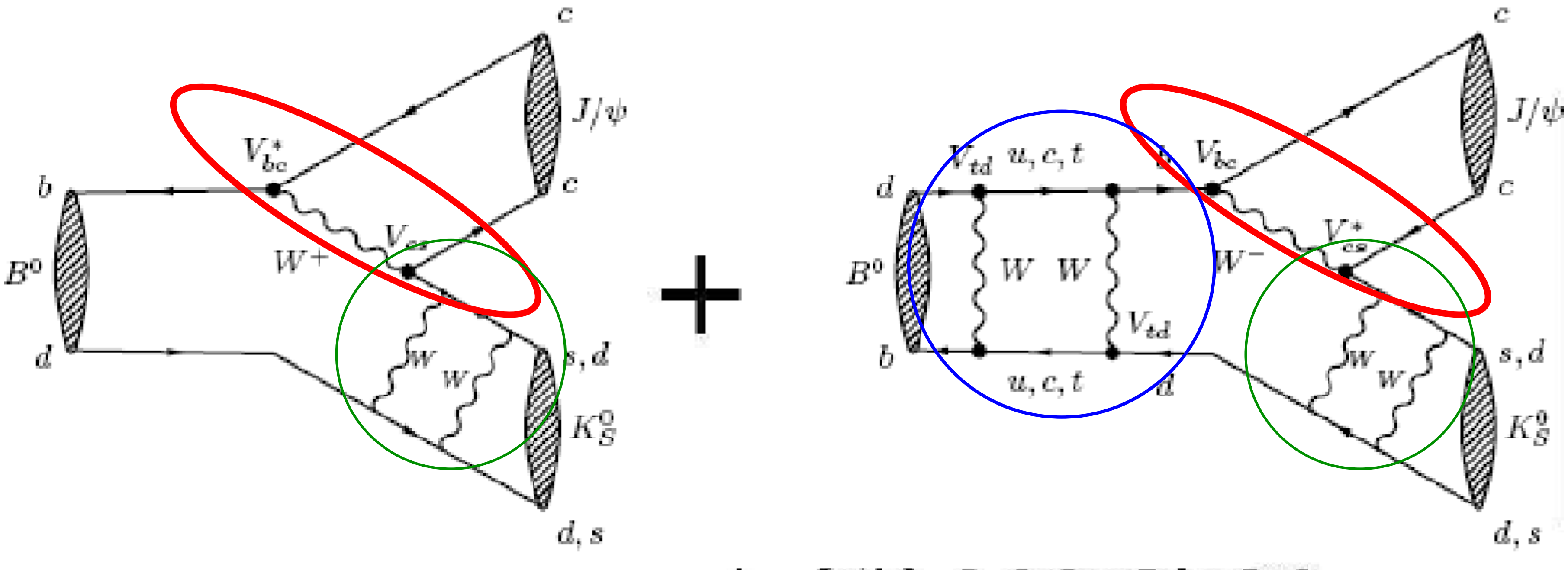
Weak phase: $Im(\frac{q}{p}\frac{\overline{A}}{A})$

$$\beta = \arg \frac{V_{cb}V_{cd}}{V_{tb}V_{td}} \qquad \arg V_{td}$$

$B_d \rightarrow J/\Psi K^0$

Reach same final state through decay & mixing + decay

(assume no CPV in mixing and no CPV in decay)



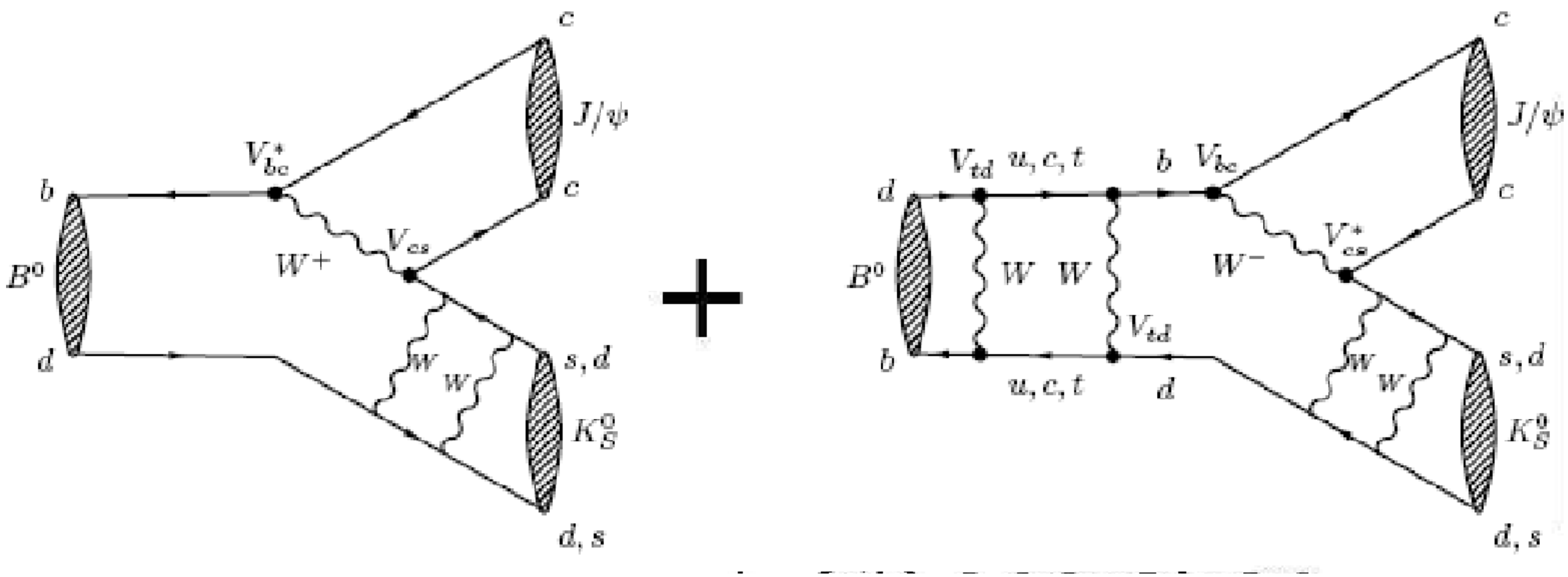
$$\mathcal{A}_1 = \mathcal{A}_{mix}(B^0 \rightarrow B^0) * \mathcal{A}_{decay}(B^0 \rightarrow J/\Psi K^0) = \cos(\frac{\Delta m t}{2}) * A * e^{i\omega} * A_K$$

$$\mathcal{A}_2 = \mathcal{A}_{mix}(B^0 \rightarrow \overline{B^0}) * \mathcal{A}_{decay}(\overline{B^0} \rightarrow J/\Psi K^0) = i \sin(\frac{\Delta m t}{2}) * e^{+i\phi} * A * e^{-i\omega} A_K * e^{+i\xi}$$

weak phase difference A $_2$ A $_1$: $\Delta\phi = \phi$ $2\omega + \xi = 2\beta$

strong phase difference $\Delta\delta = \pi/2$ (mixing introduces second phase difference

$B_d \to J/\Psi K^0$



$$\Delta\phi = \phi \quad 2\omega + \xi = arg[\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}]$$

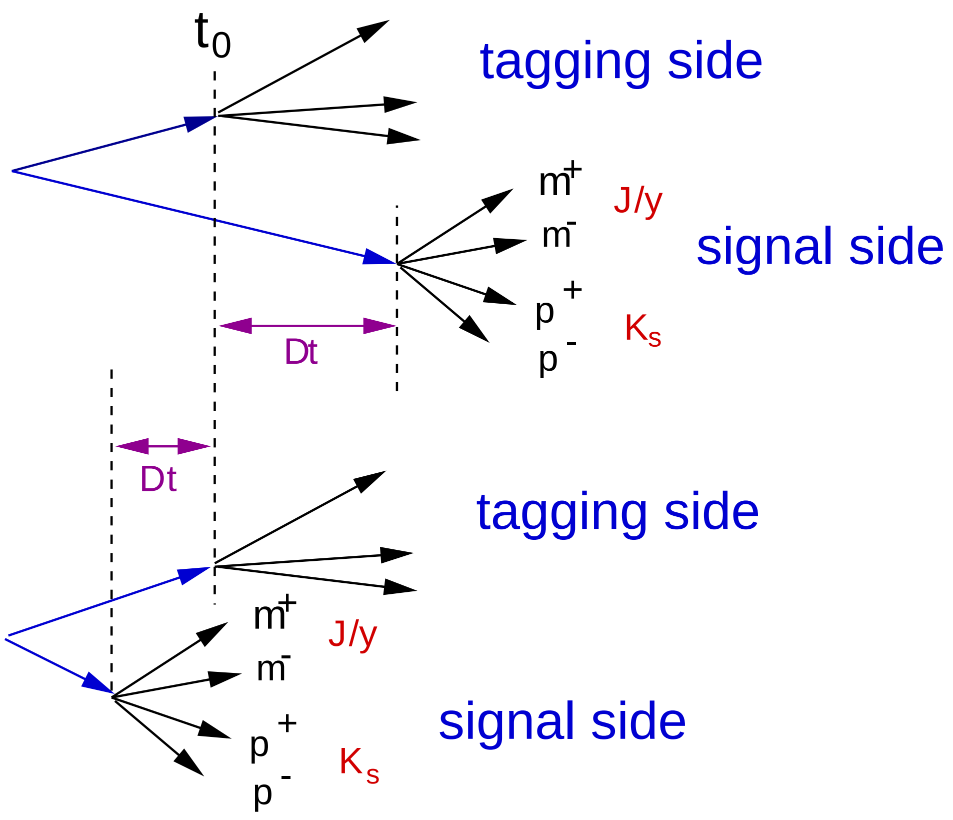
$$= arg[\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cd}^*}{V_{cb}^*V_{cd}}] = 2arg[\frac{V_{cb}V_{cd}^*}{V_{tb}V_{td}^*}] = 2\beta$$

c quark dominates mixing box diagram

Correlated B Production

$$A(t) = \frac{N(\overline{B}\to J/\psi K_s)(t) - N(B\to J/\psi K_s)(t)}{N(\overline{B}\to J/\psi K_s)(t) + N(B\to J/\psi K_s)(t)} = \eta_{CP}\sin(2\beta)\sin\Delta m_d t$$

(for K_s η_{CP} = -1, for K_L η_{CP} = +1 ... neglecting CP in kaon mixing)

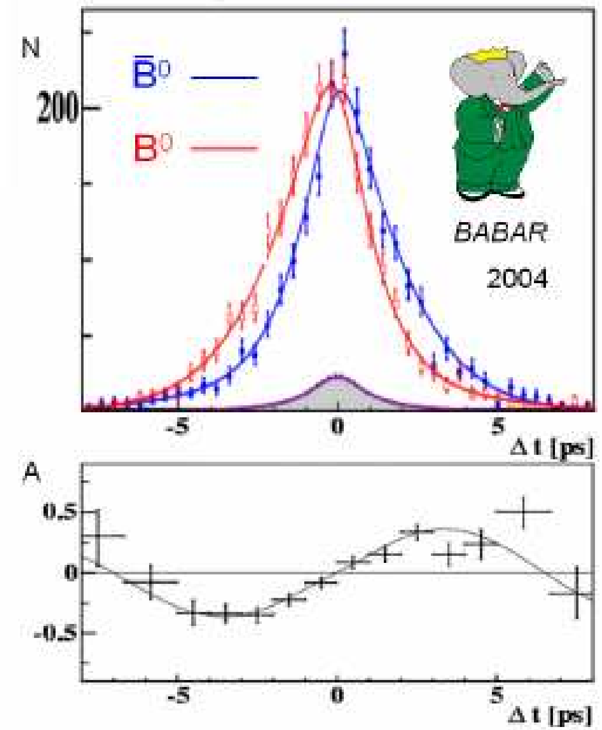


This is how it works at e^+e^- B factories

B $\overline{B}$ pair produced on Y(4S) resonance with well defined quantum numbers.

! Correlated B $\overline{B}$ state till the time of the decay of the first B.

$B_d \to J/\psi K_s$



$$A(t) \;=\; \frac{N(B^0)(t) \quad N(\overline{B^0})(t)}{N(B^0)(t) \quad N(\overline{B^0})(t)}$$

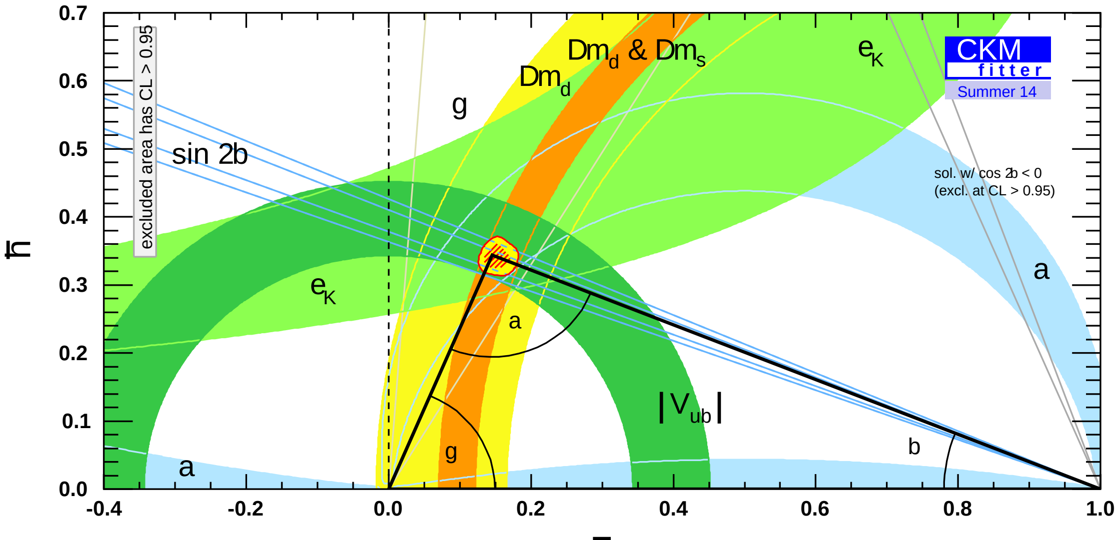
$$= \quad \sin(2\ )\,\sin(\ \ m_d t)$$

Babar:

$\sin(2\ ) = 0.722 \quad 0.040 \quad 0.023$

Belle:

$\sin(2\ ) = 0.652 \quad 0.039 \quad 0.020$



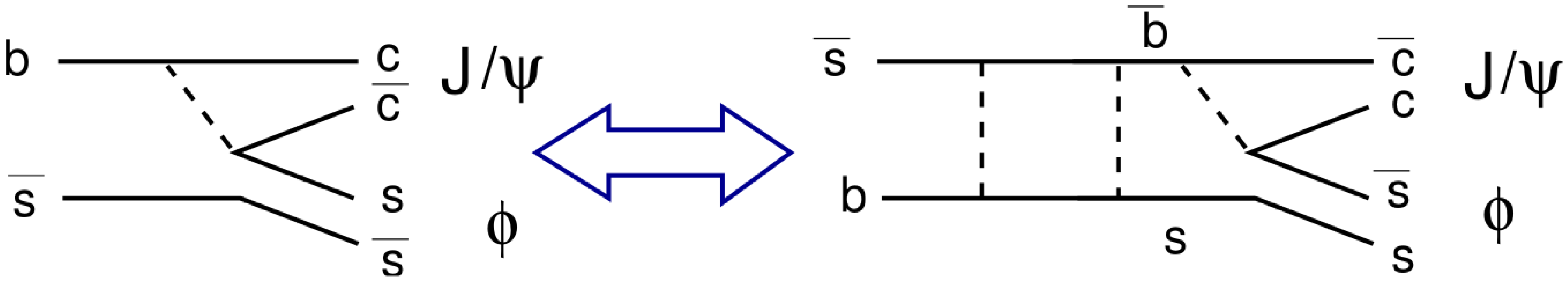
Nobel Prize 2008

Kobayashi & Maskawa:

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

$B_s \to J/\psi\phi$

Basic idea similar to measurement of $\sin(2\beta)$:



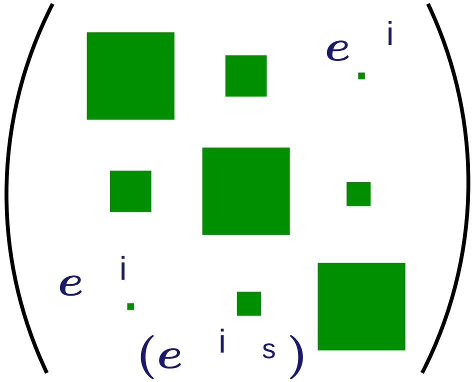
No CP violation in mixing

No CP violation in decay (watch out penguin pollution ..)

$\phi_{mix} = arg((V_{ts}V_{tb}^*)^2) = \quad 2\beta_s \quad 0.04(SM)$, (top quark dominates the box)

$\omega = arg((V_{cb}V_{cs}^*)^2) = 0$

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



$B_s \to J/\psi\phi$

B_s : J^P = 0^{-1} (pseudo scalar)

J/ψ: : J^{CP} = 1^{-1-1} (vector)

ϕ: : J^{CP} = 1^{-1-1} (vector)

Angular momentum conservation:

0 = J ($J/\psi\phi$) = j$\vec{S} + \vec{L}$j; ! L = 0,1,2

P($J/\psi\phi$) = P(J/ψ)*P(ϕ)*(-1)^L

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

L = 0,2 ! CP even final state

L = 1 ! CP odd final state

Final state no CP eigenstate but linear combination!

Angular analysis, to separate CP even/odd contributions.

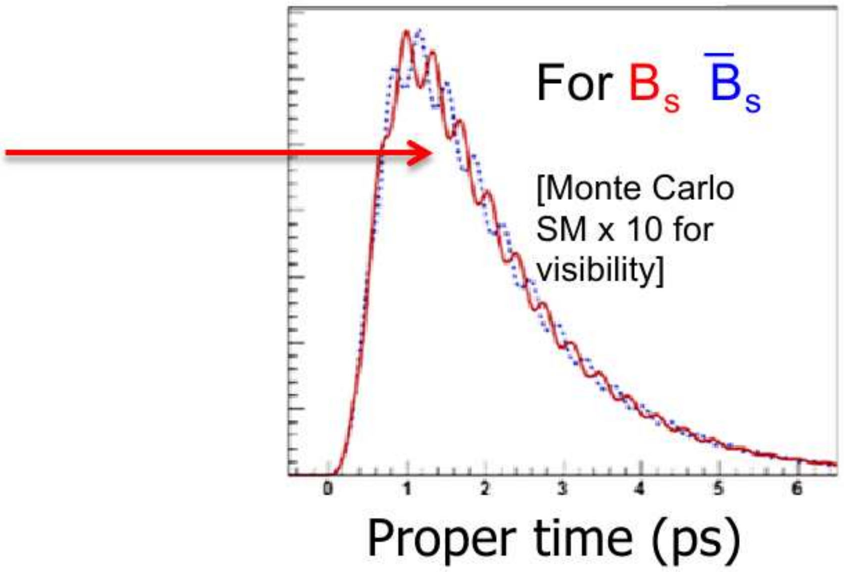
Three decay amplitudes: j$A_\perp$j (L=1), j$A_{||}$j, jA_0j (L=0,2),

+ two rel. strong phases: $\delta_1 = \arg(A_{||}(0)A_\perp)$, $\delta_2 = \arg(A_0(0)A_\perp(0))$

Messung von ϕ_s

Measurement of modulation

in decay time distribution



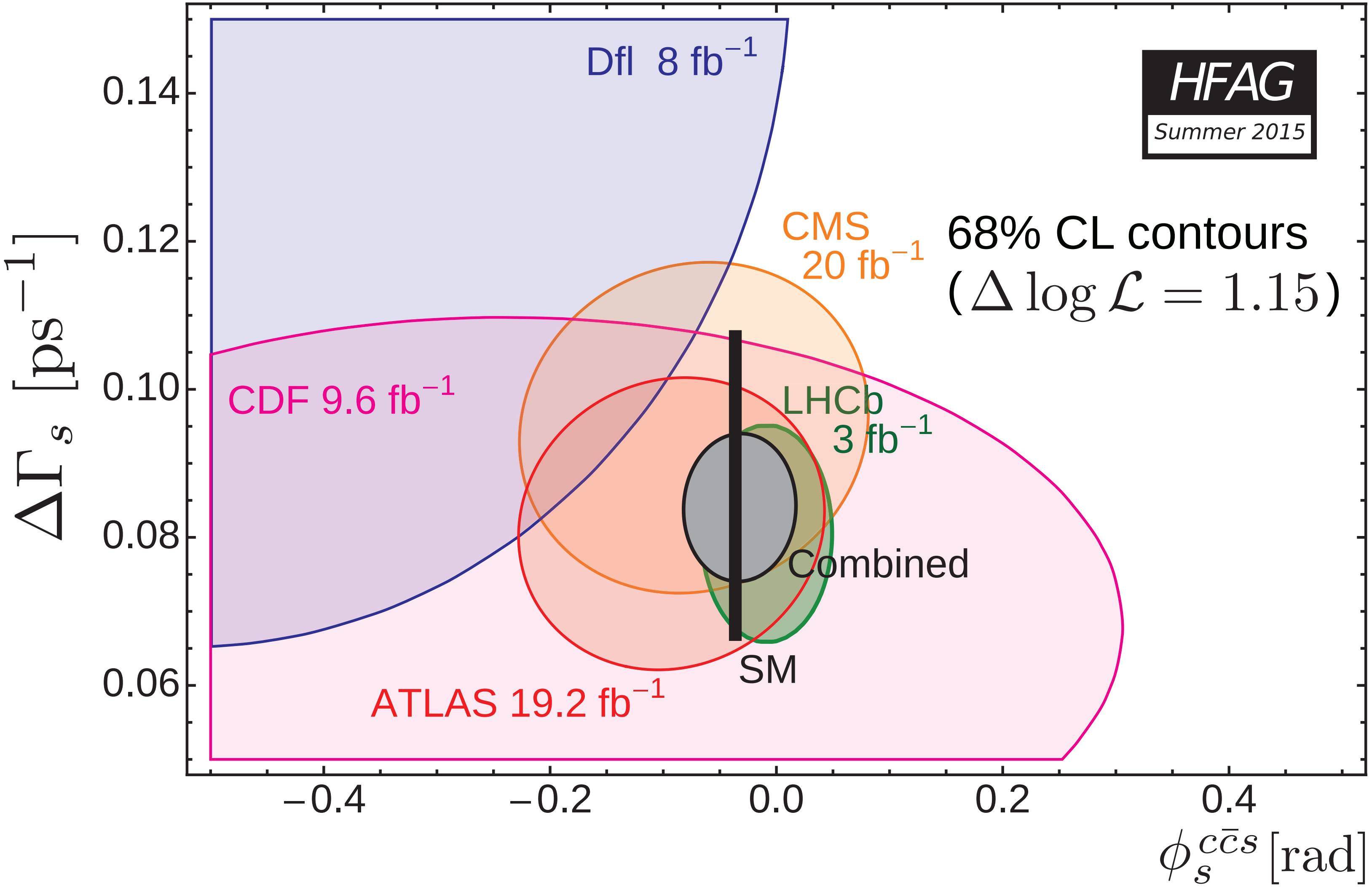
- amplitude of modulation: $D \sin \phi_s$
- sign of modulation depend on production flavour (B_s or $\overline{B_s}$) and from CP value of final state η_{CP}

Most important tools: Flavour-Tagging and decay time resolution

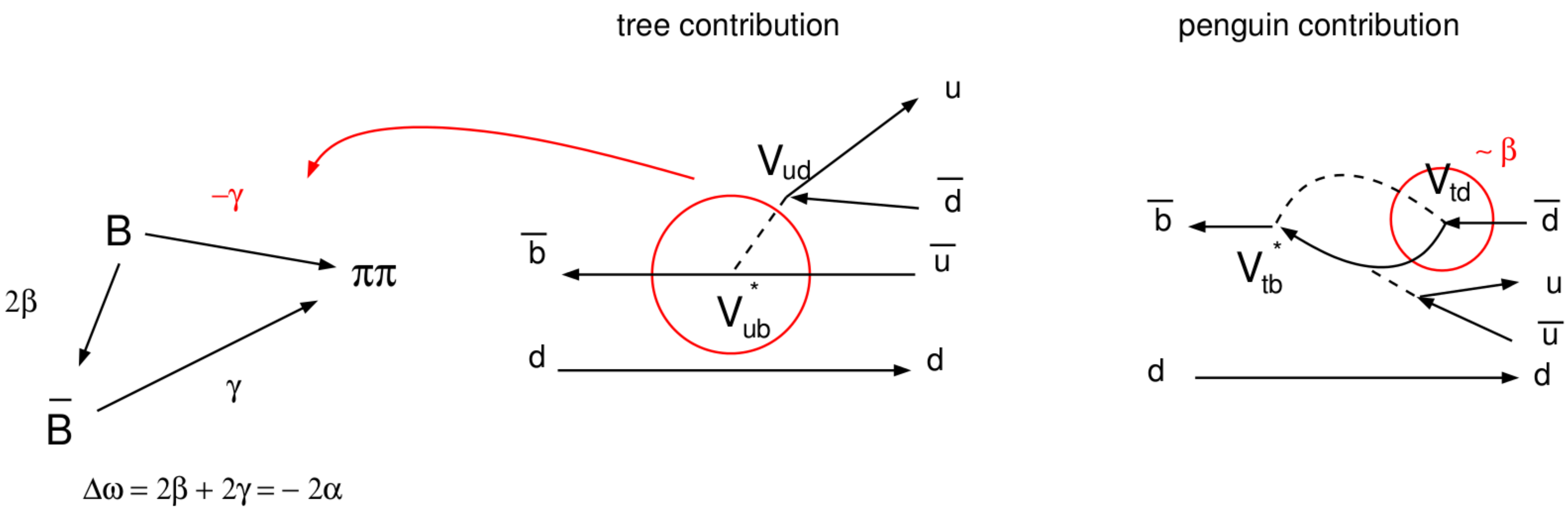
$J/\Psi\phi$ is combination of different CP eigenstates

! combined measurement of Γ, $\Delta\Gamma$, Δm_s and ϕ_s possible

$B_s^0 \to J/\Psi\phi$



CKM angle α

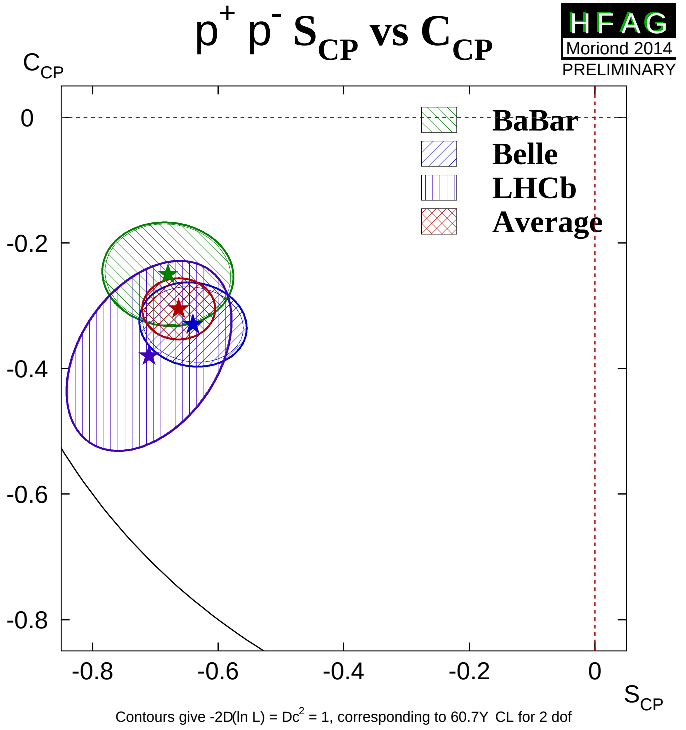


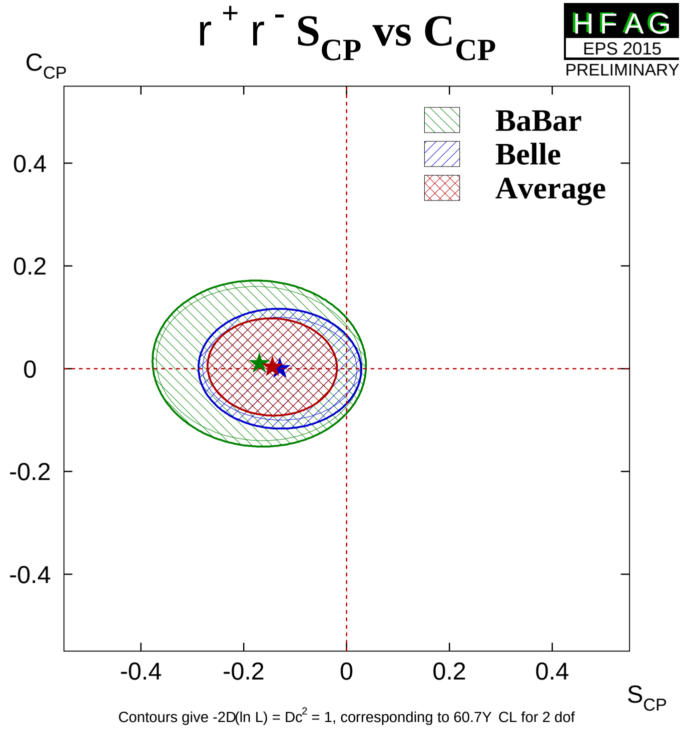
- Very same analysis idea, then B_d ! $J/\psi K^0$
- In absence of penguins, weak phase difference: $2\beta + 2\gamma = \quad 2\alpha$
- However sizable contributions from penguin decays (come in with phase β)
- Two approaches:

  1) use isospin relations w. other B ! $\pi\pi$ modes to determine T vs. P rate

  2) use alternative mode with little P contribution (e.g. B^0 ! $\rho^0\rho^0$)

$B_d \to \pi^+\pi^- / \rho\rho$





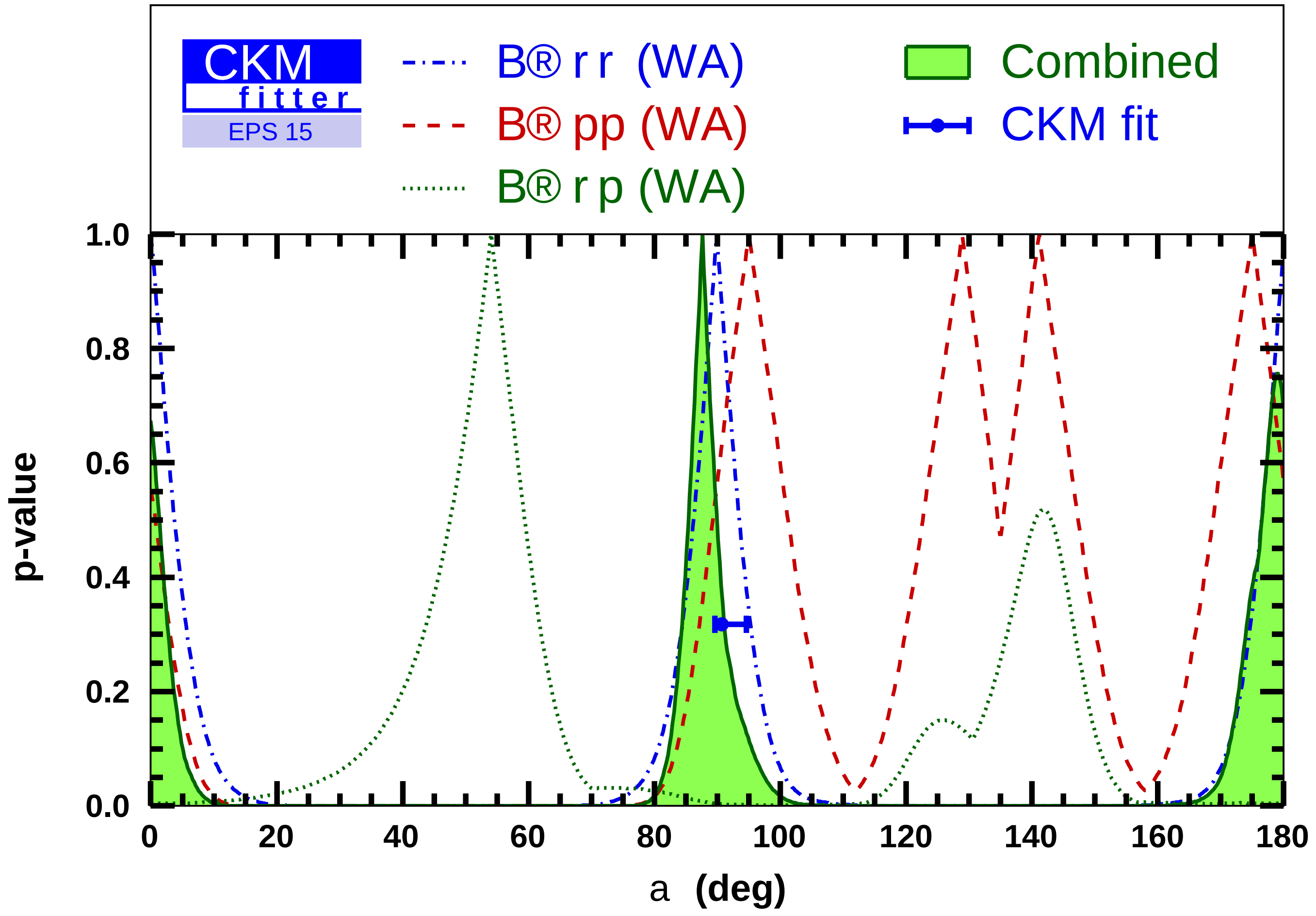
$$\Gamma(B^0 \; ! \quad f_{CP}(t)) \quad e^{-\Gamma t}(1 \quad (S\sin(\Delta m t) \quad C\cos(\Delta m t)))$$

$$\Gamma(\overline{B^0} \; ! \quad f_{CP}(t)) \quad e^{-\Gamma t}(1 + (S\sin(\Delta m t) \quad C\cos(\Delta m t)))$$

$$S = \frac{2Im(\lambda_{CP})}{1+|\lambda^2_{CP}|}, \quad C = \frac{1-|\lambda^2_{CP}|}{1+|\lambda^2_{CP}|}, \quad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

no CPV in mixing and decay: jλj $= 1$! $\quad C = 0$ (e.g. in B_d ! $\quad J/\psi K^0$)

Constraints on α

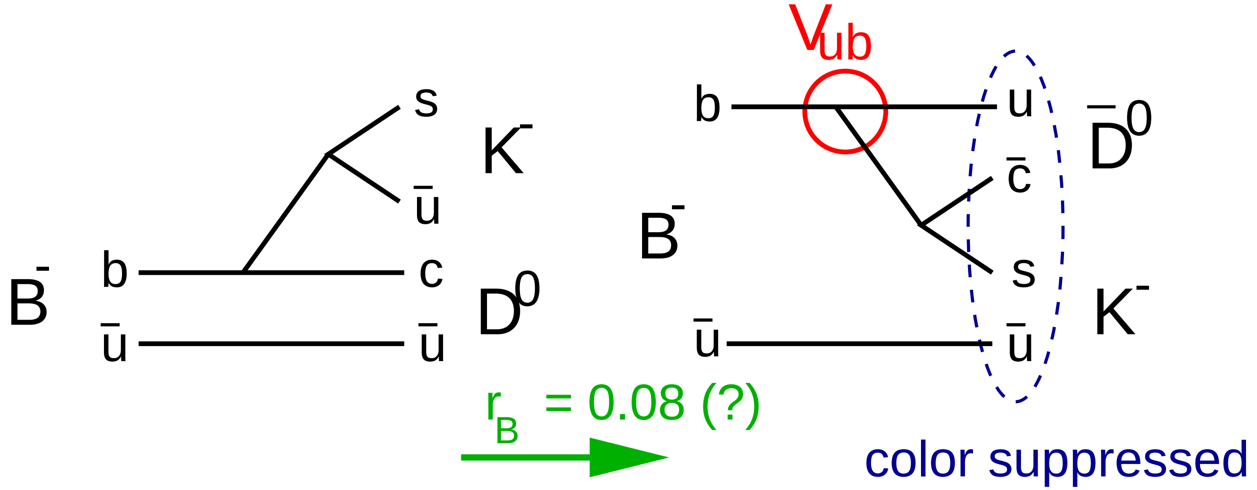


= 0 and = excluded by branching ratio measurements

world average: $= 87{:}6^{+3:5}_{3:3}$

measurement or how to attack strong phases

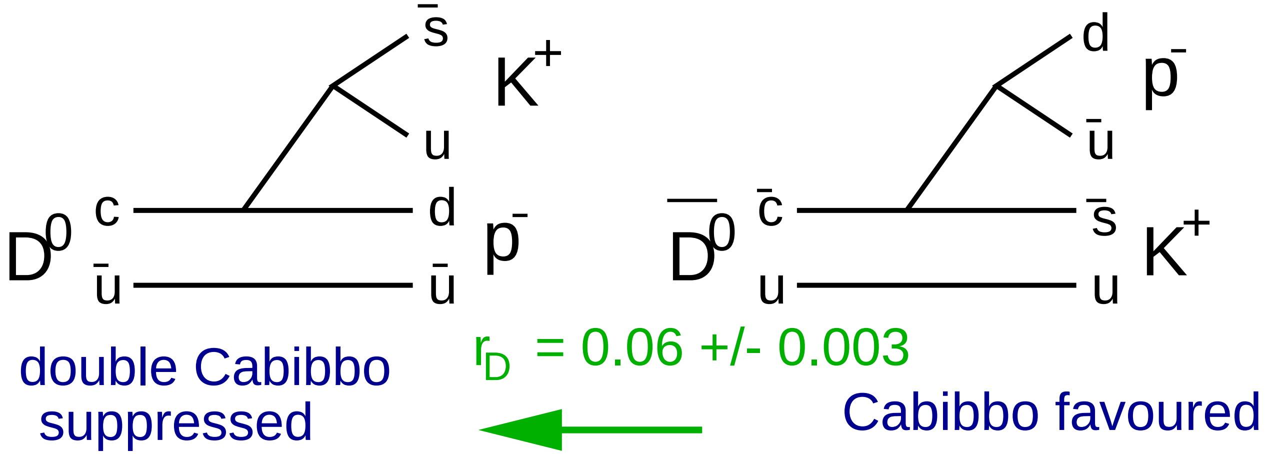
γ from Trees: $B \to DK$



- $D^0/\overline{D^0}$ decay in common flavour state ($K^+\pi^-$, $K^+3\pi$ ...)

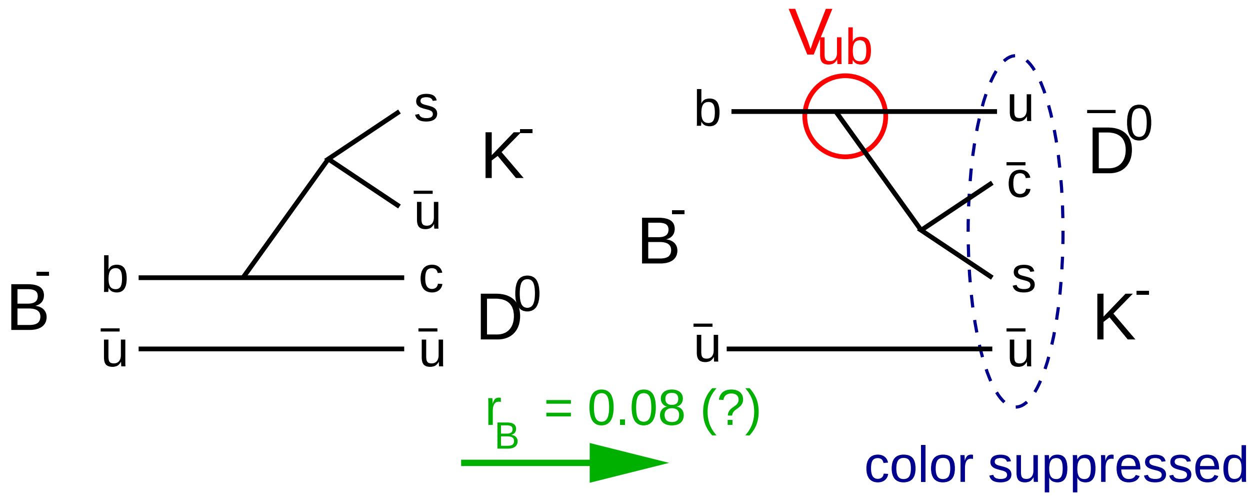
  5 param.: $r_B = |\frac{A(B^- \to D^0 K^-)}{A(B^- \to \overline{D^0} K^-)}|$, δ_B, γ, δ_D^{π}, $\delta_D^{3\pi}$ (r_D from CLEO-c)

  Low event rate; large interference



Atwood-Dunietz-Soni Method

γ from Trees: $B \to DK$



Gronau-London-Wyler Method

- D^0/$\overline{D^0}$ decay in common CP eigenstate (K^+K^-, $\pi^+\pi^-$, ...)

  3 parameters: r_B, δ_B, γ ($r_D = 1,\ \delta_D = 0$)

  Large event rate; small interference (r_B small)

Both analyses are decay time independent,

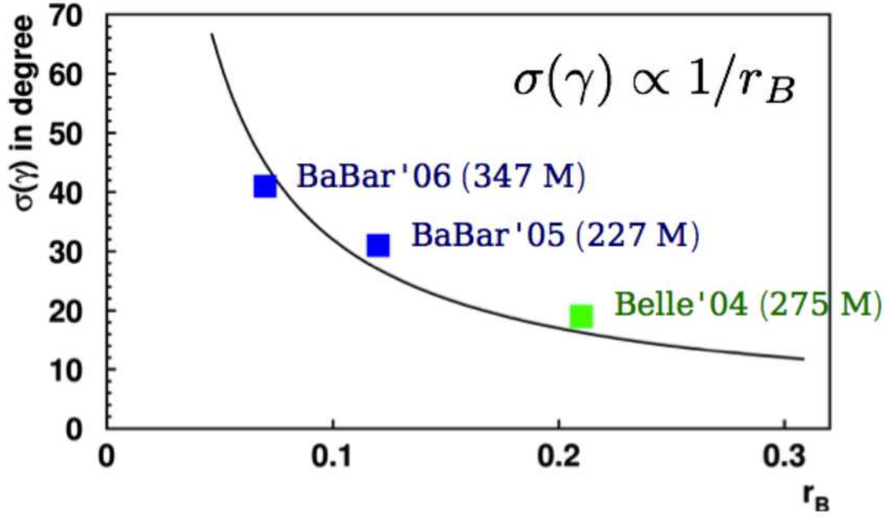
no flavour tagging needed!

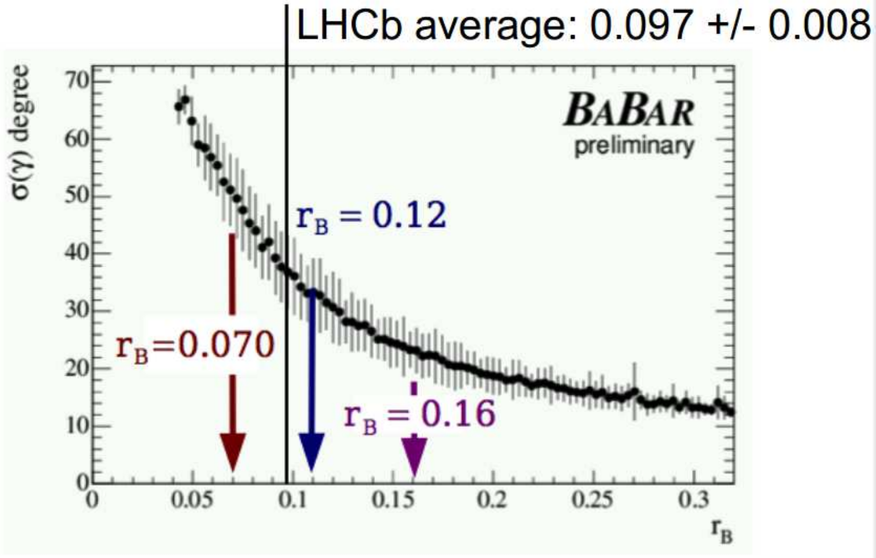
Strategy: Perform analysis in as many as possible channels, measure ratios of decay rates and perform a combined analysis.

Side-remark

The amplitude ratio r_B drives the sensitivity:

$$r_B \equiv |A(b \to u)/A(b \to c)| \qquad r_B = \frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \overline{D^0} K^+)}$$



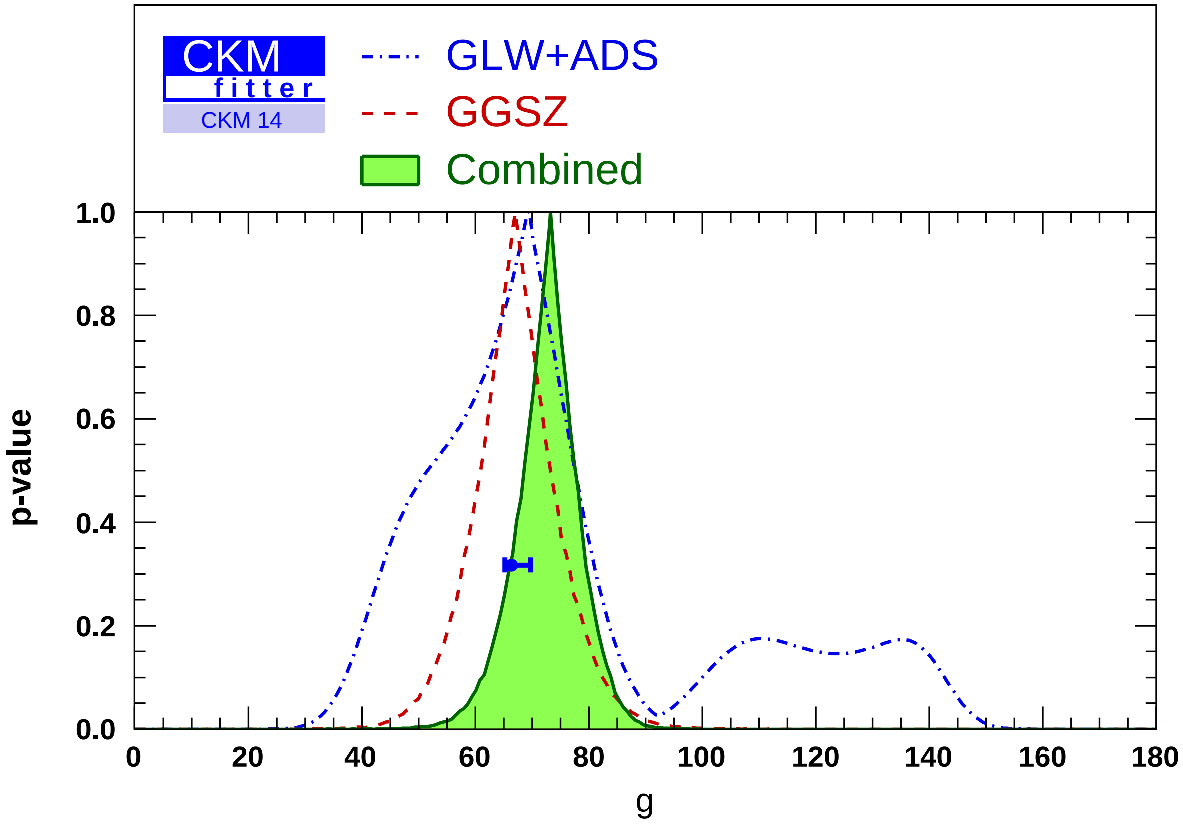


(was a big discussion in 2009 ...)

Results

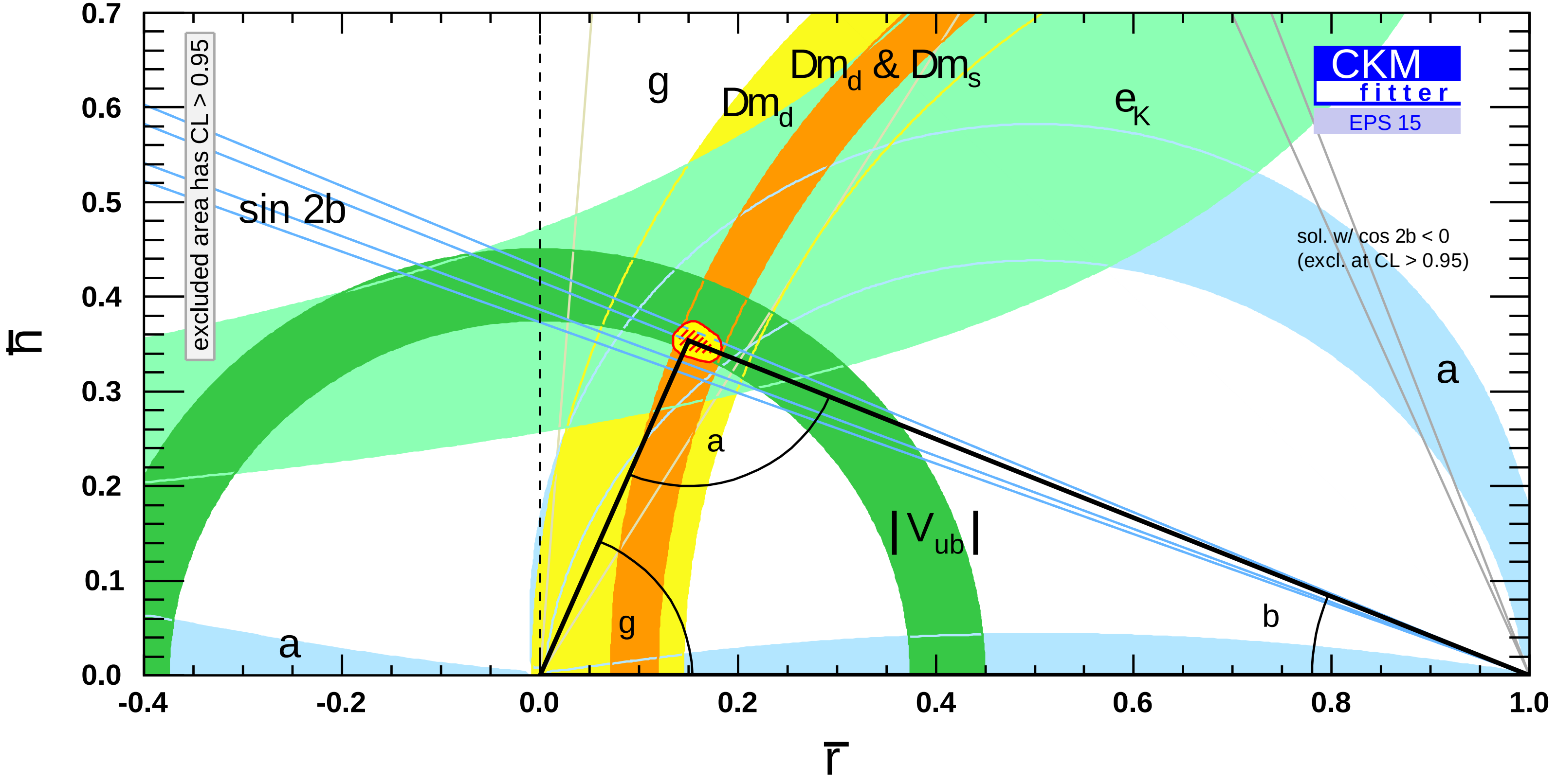
GGSZ (Giri, Grossman, Soffer, Zupan): GLW/ADS method combined with

Dalitz-Plot analysis of D^0 ! $K_S^0\pi^+\pi^-$ decay.



In this combination enters the GLW, ADS & GGSZ method.

world average: γ = 73.2$^{+\ .3}_{-7.0}$



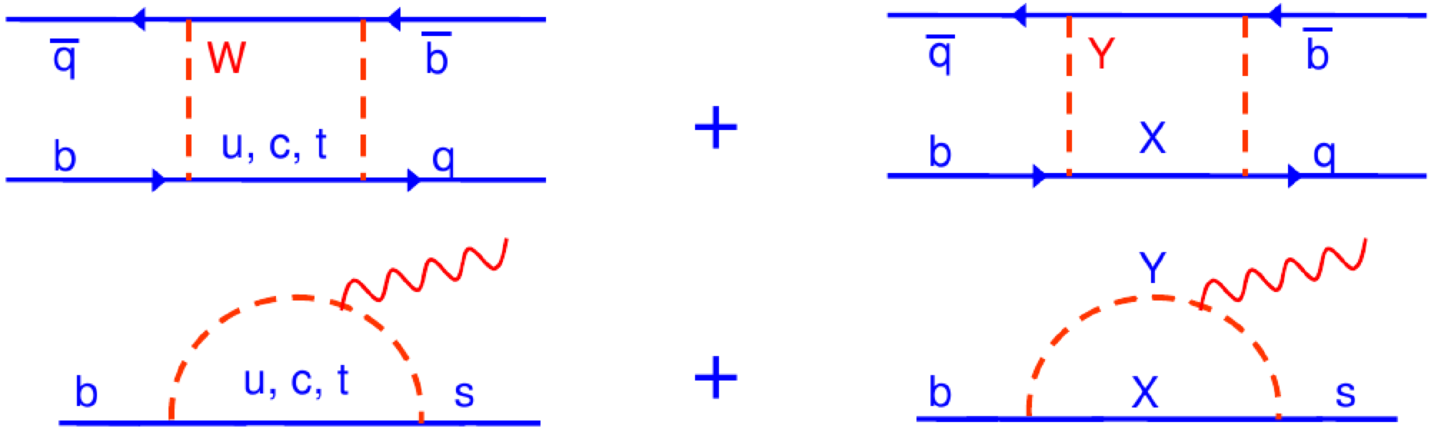
excluded area has CL > 0.95
sin 2b
g
Dm_d & Dm_s
Dm_d
e_K
CKM
fitter
EPS 15
sol. w/ cos 2b < 0
(excl. at CL > 0.95)
a
|V_ub|
b

What next?

New Physics in B decays

New Physics effects only appear as correction to leading SM terms.

Standard Model | New Physics



$$\text{A}_{BSM} = \text{A}_0 \left(\frac{C_{SM}}{m_W^2} + \frac{C_{NP}}{\lambda_{NP}^2} \right) \quad ; \quad (C_{SM} = \frac{g_W^2}{4\pi} \sim \frac{1}{30}, \lambda_{NP} \sim 1 \text{ TeV (?)})$$

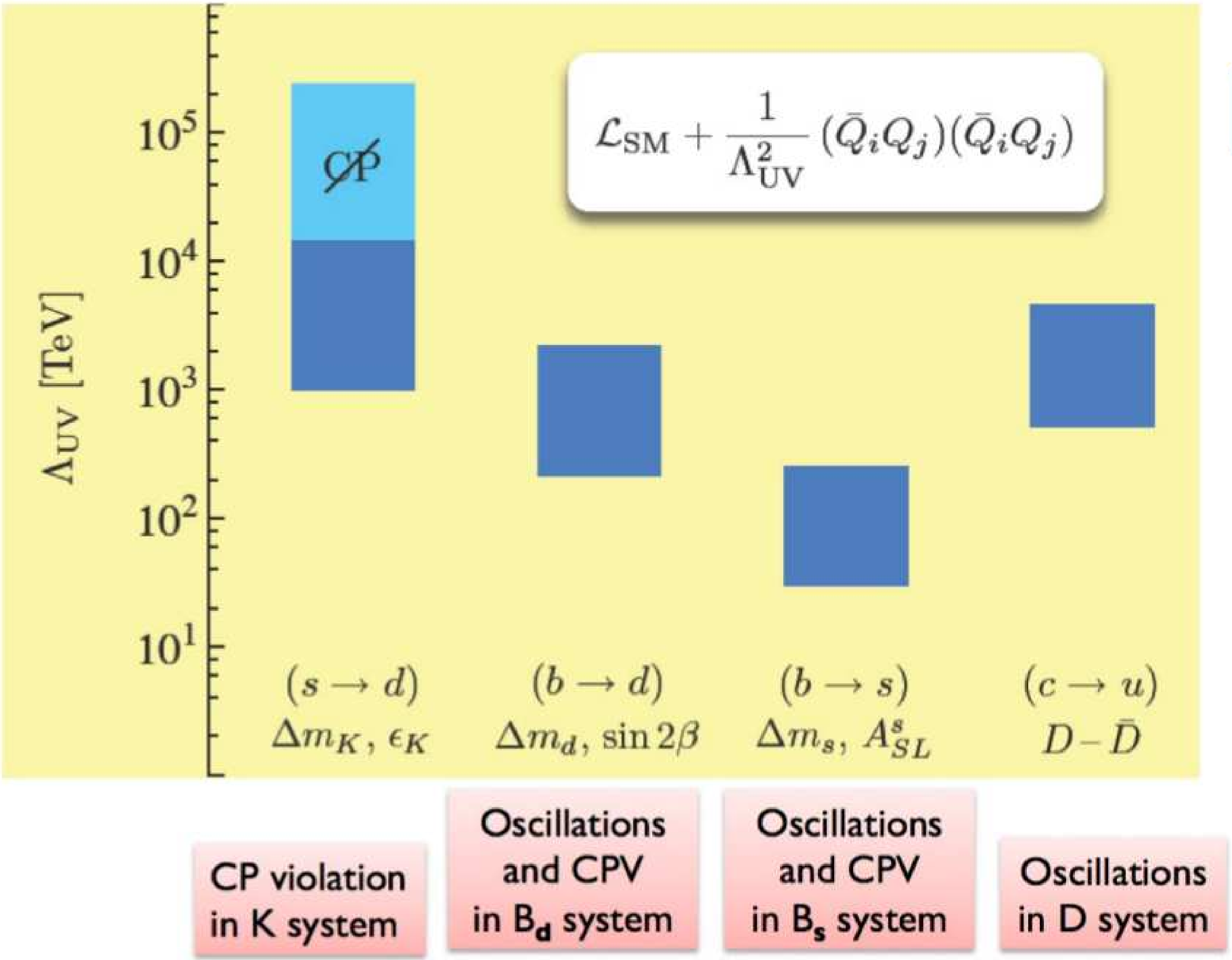
Flavour physics approach to new physics:

- study processes which are sensitive to quantum corrections:

  e.g. very rare (SM suppressed) decays, CPV

New Physics in the Flavour Sector?

If couplings are of order O(1) ...



arXiv:1302.0661