UK Flavour 2013

CP Violation in Hadronic Decay Modes

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Outline

1. $\beta\ (\phi_1)$

   $B^0 \to K^+K^-K^0_S,\ \ \pi^+\pi^-K^0_S$

2. $\alpha\ (\phi_2)$

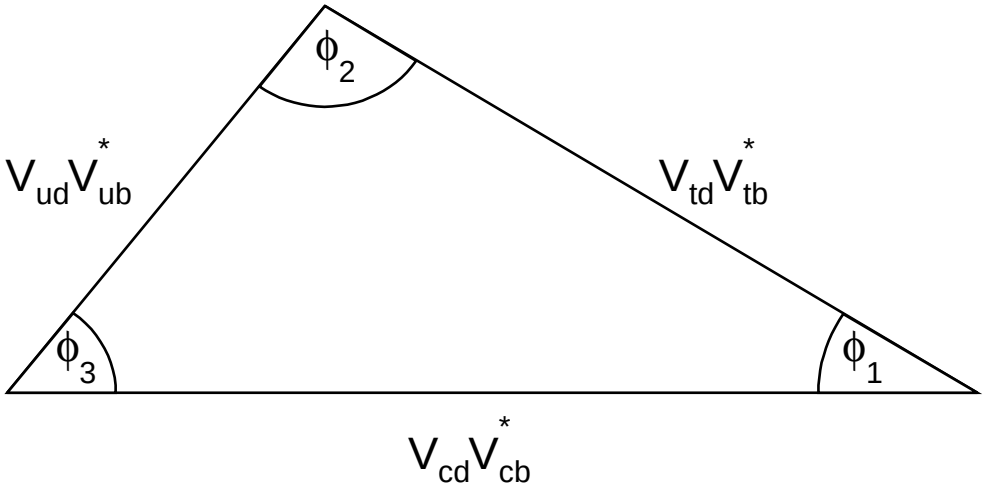
   $B^0 \to \pi^+\pi^-$

3. $\gamma\ (\phi_3)$

   $B^+ \to K^+\pi^-\pi^+,\ \ B^0 \to K^0_S\pi^+\pi^-$

4. ϕ_s

   $B_s \to K^+K^-$



5. Isospin Symmetry

   $B \to \pi\pi,\ \ B \to K\pi$

6. U-spin Symmetry

   $(B^0 \to K^+\pi^-,\ \ B_s \to K^-\pi^+)$ and $(B^0 \to \pi^+\pi^-,\ \ B_s \to K^+K^-)$

   $(B^+ \to \pi^+K^+K^-,\ \ K^+\pi^+\pi^-)$ and $(B^+ \to \pi^+\pi^+\pi^-,\ \ K^+K^+K^-)$

β

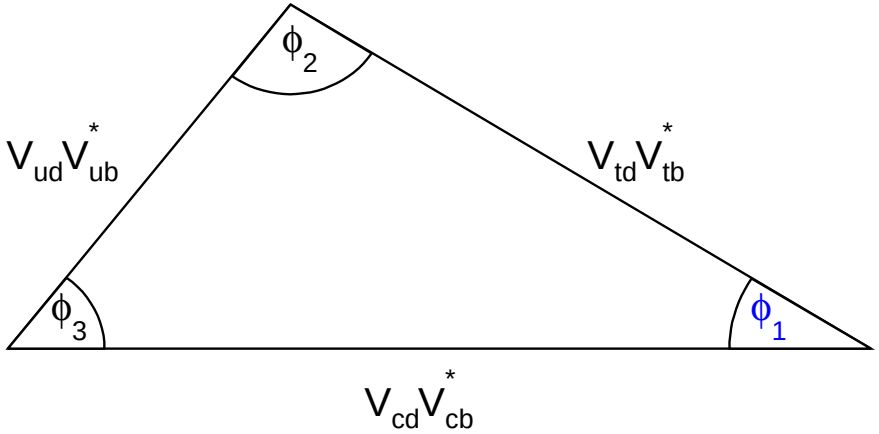
$\beta = \phi_1 \equiv \arg(\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*})$

Best measured internal angle by B factories

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

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

Confirmed CKM mechanism

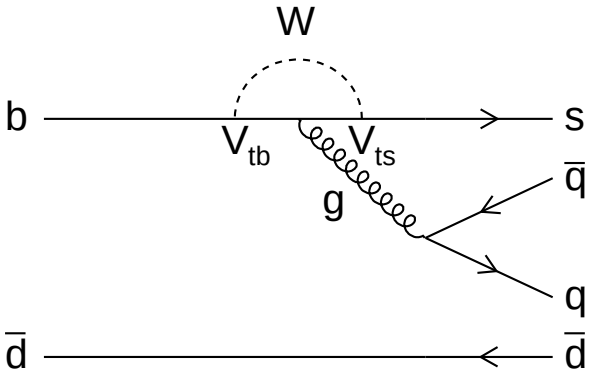


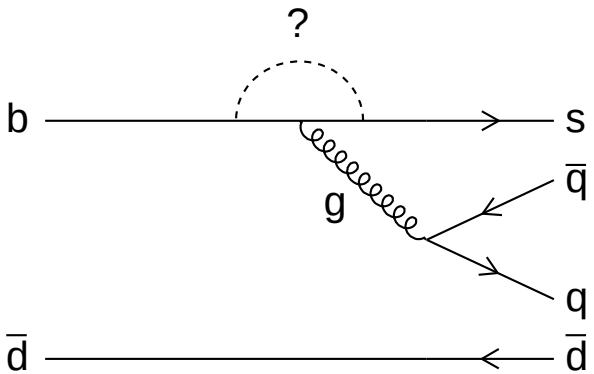
$b \to sq\bar{q}$ transitions are also sensitive to β

Forbidden at tree level

Loop-mediated decays have high potential for NP

eg. Heavy unknown particle in the loop



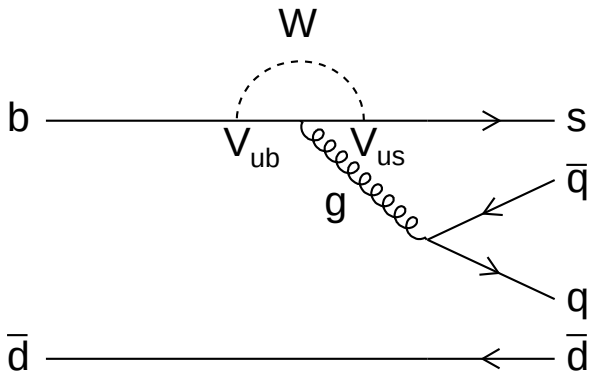


β

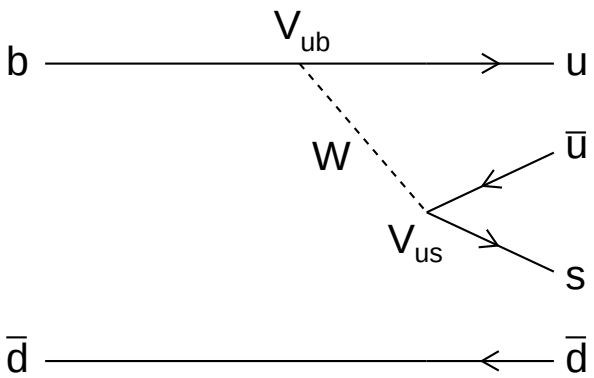
$B^0 \to K^+K^-K^0_S,\ \ \pi^+\pi^-K^0_S$

Experimental measurement of β may contain 2 sources of SM contamination

No t-quark in the loop



CKM suppressed $b \to u$ tree



Experimentally, we speak of a measured $\beta_{\rm eff}$ instead

Of all possible intermediate decays, $B^0 \to \phi K^0_S$ theoretically cleanest

Test for NP: $\Delta A_{\rm mix} \equiv \sin 2\beta_{\rm Peng} - \sin 2\beta_{\rm Tree}$

β

Time-dependent Dalitz Plot approach

Exploiting interference effects in the DP allows direct access to $\beta_{\rm eff}$

In principle, no ambiguities in $\beta_{\rm eff}$ unlike those inherent to quasi-two-body analyses

Time-dependent decay rate at a B factory given by

$$|A(\Delta t, q)|^2 = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big[(|A|^2+|\bar{A}|^2) - q(|A|^2-|\bar{A}|^2)\cos\Delta m_d\Delta t + 2q\Im(\bar{A}A^*)\sin\Delta m_d\Delta t\Big]$$

Δt is the time difference between the $B^0\bar{B}^0$ pair, q is the flavour of the accompanying tagging B

$A(\bar{A})$ is the Lorentz-invariant amplitude of $B^0(\bar{B}^0)$

In the isobar approximation, the total amplitude is written as sum of decay channels,

$$A(s_+,s_-) = \sum_i a_i' F_i(s_+,s_-), \quad \bar{A}(s_-,s_+) = \sum_i \bar{a}_i' \bar{F}_i(s_-,s_+)$$

$s_\pm \equiv (p_\pm + p_0)^2$ are the Dalitz plot variables, F are the line shapes describing strong dynamics

β

$$A(s_+, s_-) = \sum_i a'_i F_i(s_+, s_-), \quad \bar{A}(s_-, s_+) = \sum_i \bar{a}'_i \bar{F}_i(s_-, s_+)$$

a'_i are complex coefficients describing relative magnitude and phase between intermediate states

Free parameters of the model

Convenient construction

$a'_i \equiv a_i(1 + c_i)e^{i(b_i+d_i)}$ for A, $\bar{a}'_i \equiv a_i(1 - c_i)e^{i(b_i-d_i)}$ for $\bar{A}$

If the decay via the intermediate resonance i, is a CP eigenstate

$$A^i_{\rm dir} = \frac{|\bar{a}'_i|^2 - |a'_i|^2}{|\bar{a}'_i|^2 + |a'_i|^2}$$

$$\beta^i_{\rm eff} = d_i$$

$$A^i_{\rm mix} = \frac{2\eta_{CP}\Im(\bar{a}'_i a'^*_i)}{|a'_i|^2 + |\bar{a}'_i|^2}$$

η_{CP} is the CP eigenvalue of the decay, i

β

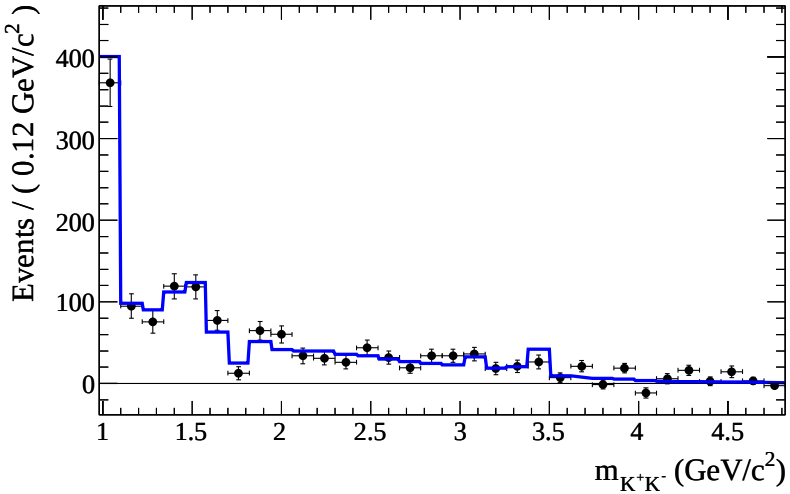
BaBar and Belle have performed time-dependent DP analyses in

$B^0 \to K^+K^-K^0_S$

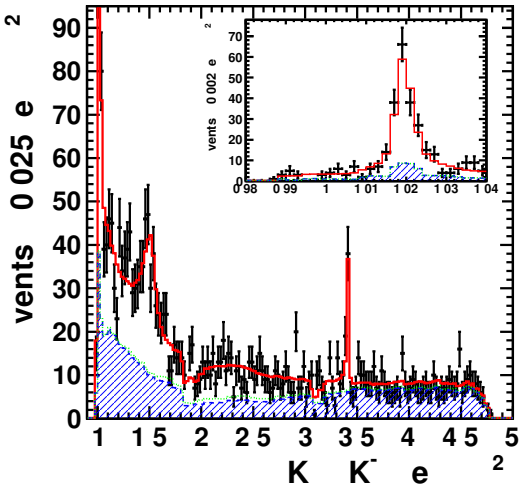
PRD **85** 112010

PRD **82** 073011

BaBar: 470M $B\bar{B}$ pairs



Belle: 657M $B\bar{B}$ pairs

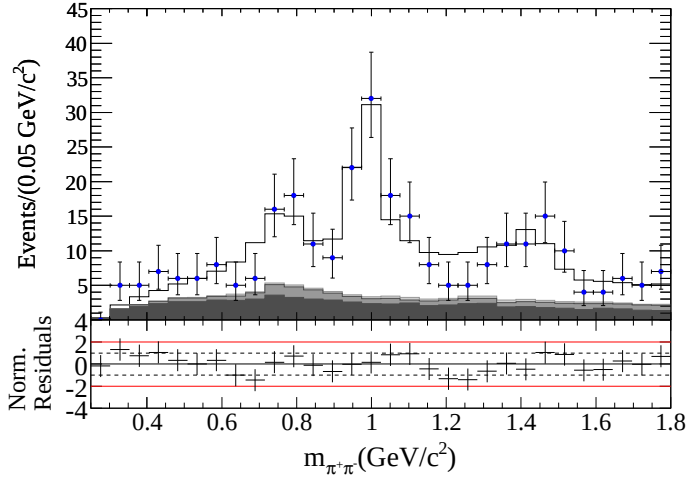


$B^0 \to \pi^+\pi^-K^0_S$

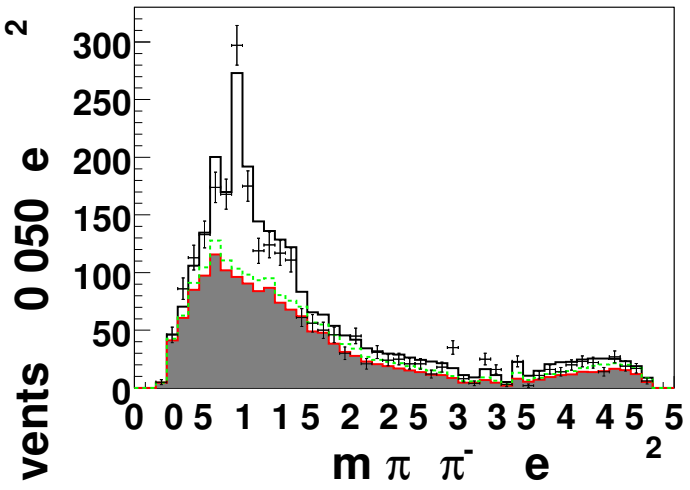
PRD **80** 112001

PRD **79** 072004

BaBar: 383M $B\bar{B}$ pairs



Belle: 657M $B\bar{B}$ pairs

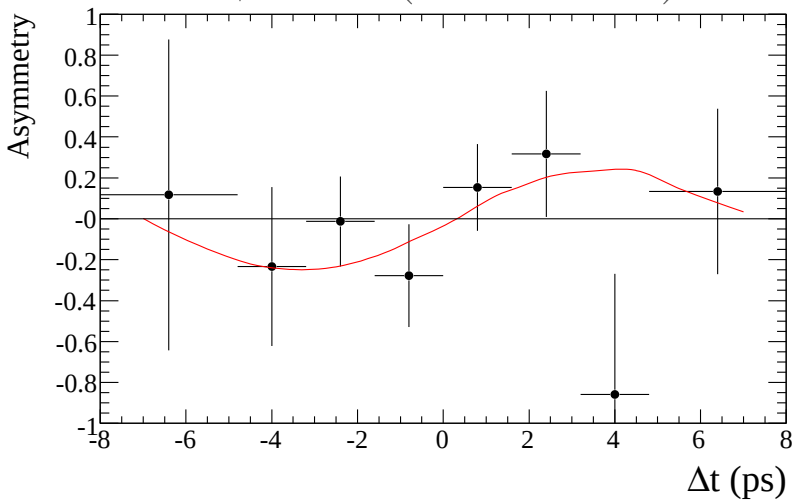


β

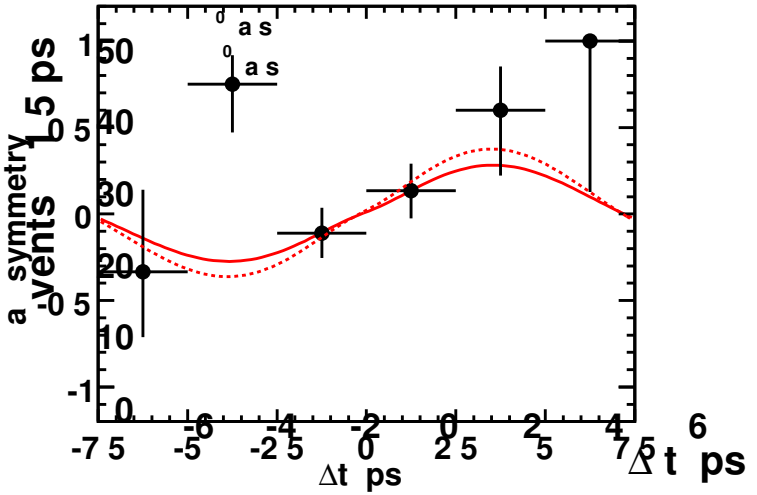
Clear asymmetries can be seen in the time distributions

$B^0 \to \phi K^0_S$

BaBar: $\beta_{\rm eff} = (21 \pm 6 \pm 2)^\circ$



Belle: $\beta_{\rm eff} = (32 \pm 9 \pm 3)^\circ$

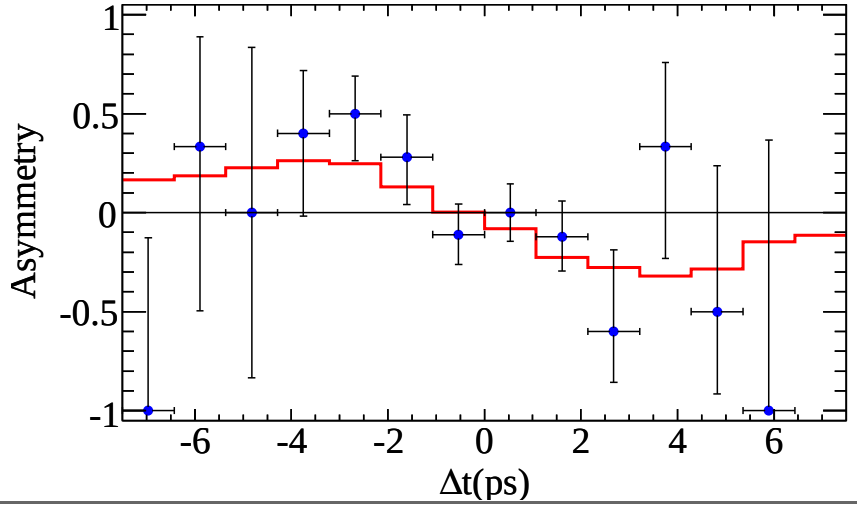


$B^0 \to f_0(980) K^0_S$

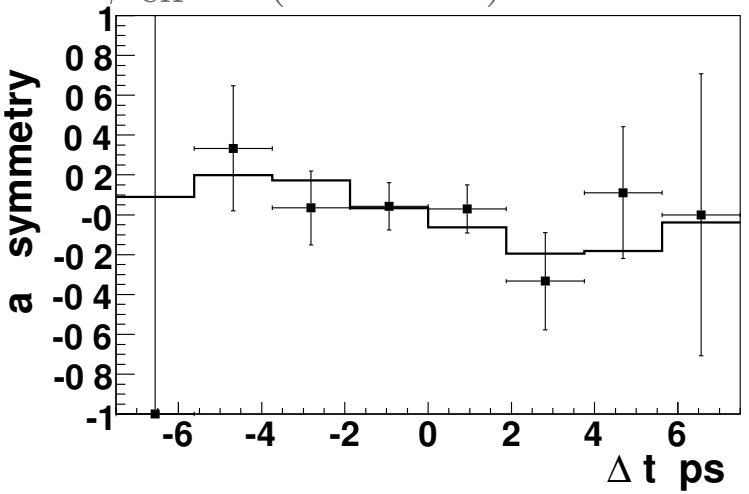
where

$f_0(980) \to \pi^+\pi^-$

BaBar: $\beta_{\rm eff} = (36 \pm 10 \pm 3)^\circ$



Belle: $\beta_{\rm eff} = (13 \pm 7 \pm 4)^\circ$



β

World averages of $\sin 2\beta_{\rm eff}$ from $b \to sq\bar{q}$ transitions

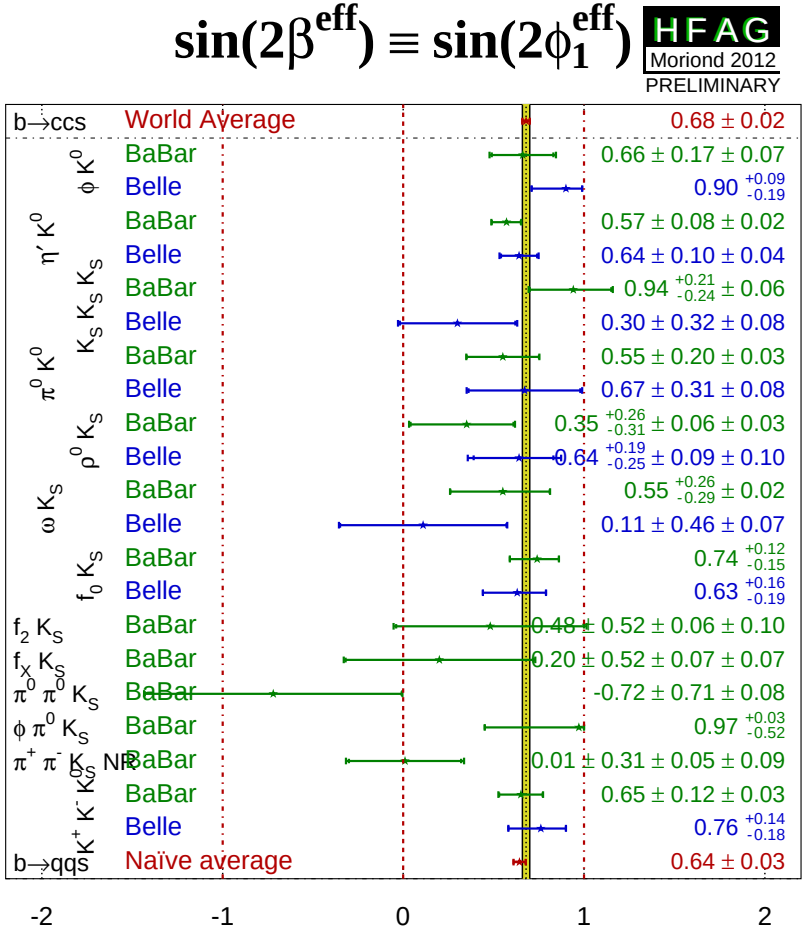
Theory predicts $\sin 2\beta_{\rm eff} > \sin 2\beta_{\rm Tree}$

But central values of most measurements tend to be lower

Not significant at this time

Could this be a hint of New Physics?

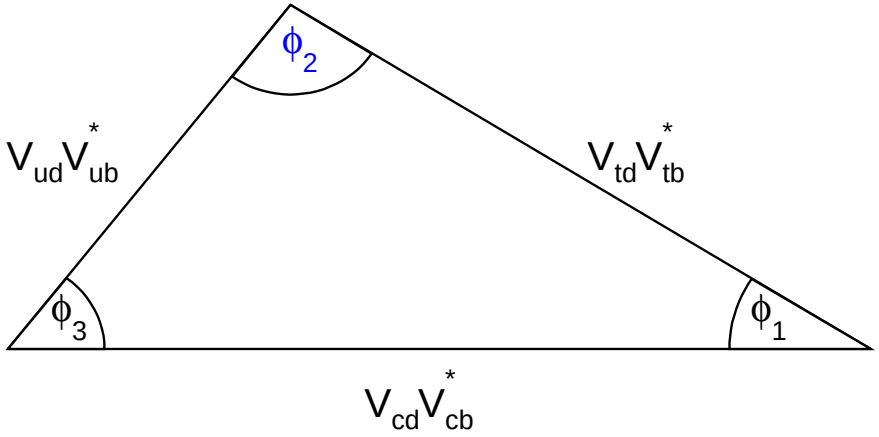
Great potential for LHCb to clear this up



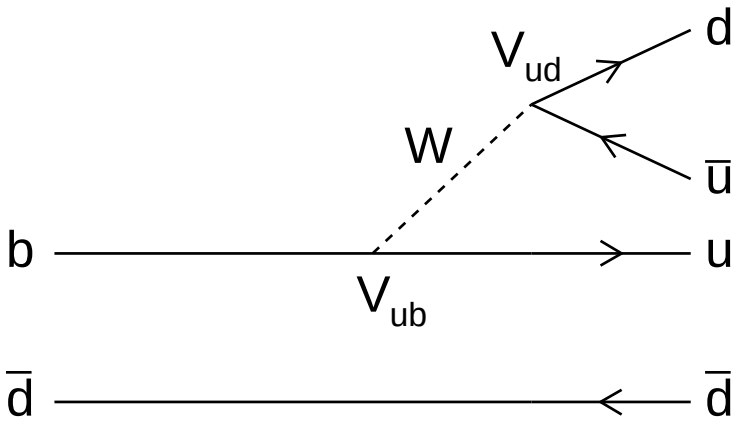
α

$\alpha = \phi_2 \equiv \arg(\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*})$

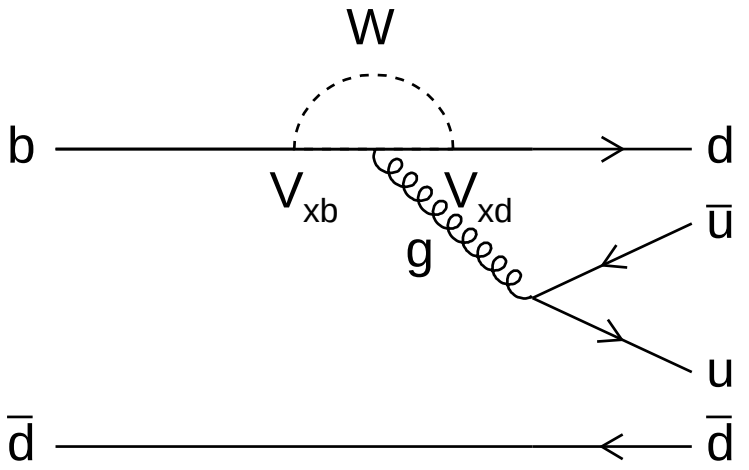
Second best measured internal angle



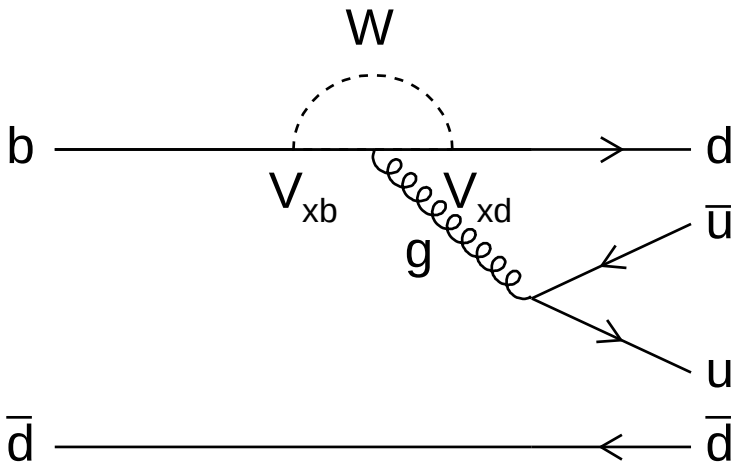
Sensitivity through tree-level $b \to u\bar{u}d$ transitions

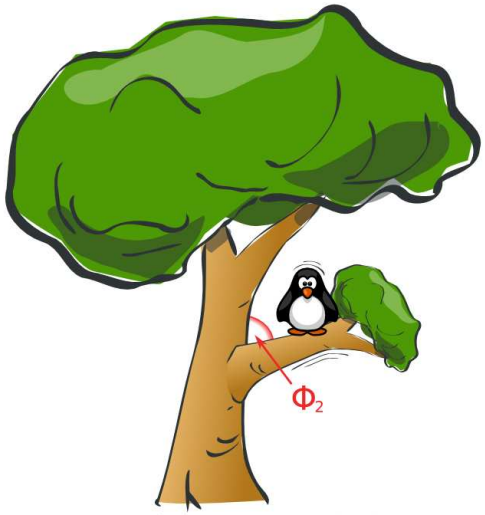


Penguins may contribute significantly



α





How the penguin distorts the tree level measurement

Both tree and penguin amplitudes may contribute to the final state

Penguin amplitudes would carry different weak phase

Distorts measurement of CP violating parameter

$$A_{\rm mix} = \sqrt{1 - A^2_{\rm dir}}\sin(2\alpha - 2\Delta\alpha)$$

Penguin contribution can be accounted for

See talk by D. Derkach

α

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

Time-dependent asymmetry given by

$$A_{CP}(t) = A_{\rm dir} \cos \Delta m_d t + A_{\rm mix} \sin \Delta m_d t$$

BaBar: 467M $B\bar{B}$ pairs

PRD **87** 052009

$A_{\rm dir} = +0.25 \pm 0.08 \pm 0.02$

$A_{\rm mix} = -0.68 \pm 0.10 \pm 0.03$

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

arXiv:1302.0551

$A_{\rm dir} = +0.33 \pm 0.06 \pm 0.03$

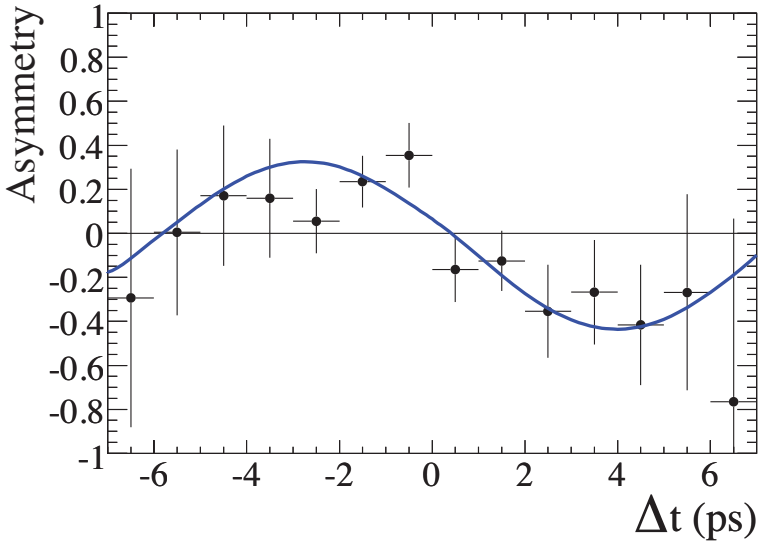
$A_{\rm mix} = -0.64 \pm 0.08 \pm 0.03$

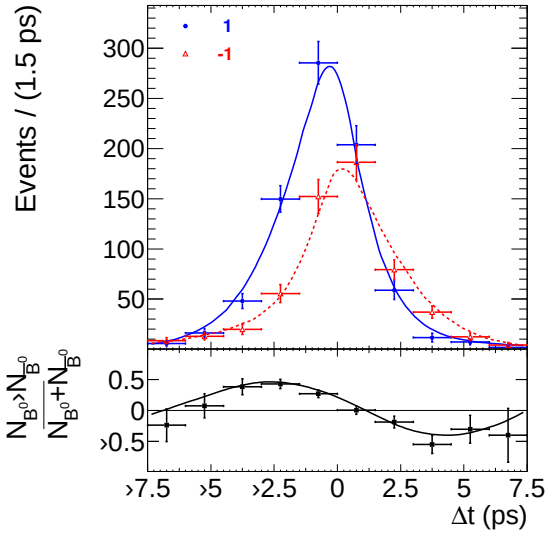
LHCb: $1.0\ \text{fb}^{-1}$

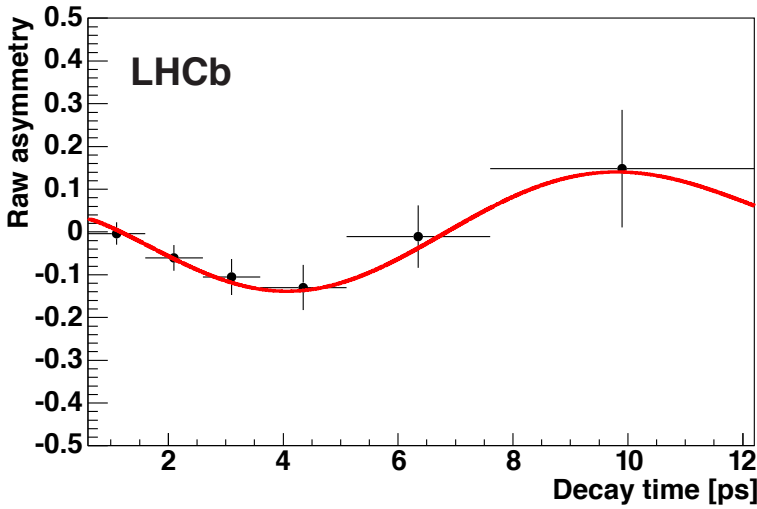
arXiv:1308.1428

$A_{\rm dir} = +0.38 \pm 0.15 \pm 0.02$

$A_{\rm mix} = -0.71 \pm 0.13 \pm 0.02$







α

Precision measurements of $A_{\rm dir}$ and $A_{\rm mix}$ from LHCb will provide important constraints on α

However, LHCb can't constrain it alone in the $B \to \pi\pi$ system

Will need input from BelleII eg. $\mathcal{B}(B^0 \to \pi^0\pi^0)$, $A_{\rm dir}(B^0 \to \pi^0\pi^0)$

Difficult to constrain α in $B \to \pi\pi$ system due to significant penguin contribution

If BelleII can measure $A_{\rm mix}(B^0 \to \pi^0\pi^0)$, reduce to 2 solutions for α

Can LHCb perform the time-dependent DP analysis of $B^0 \to \pi^+\pi^-\pi^0$?

- Best chance for LHCb only α constraint

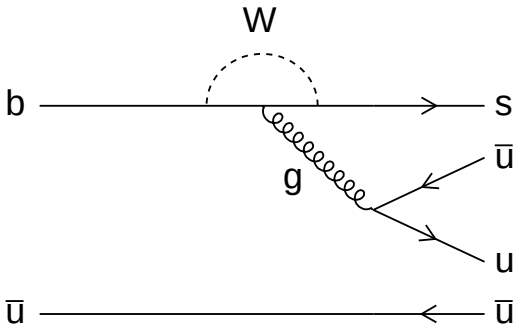
$B \to \rho\rho$ currently the best system to constrain α

- LHCb can contribute significantly to $B^0 \to \rho^0\rho^0$
- However, measurements in quasi-two-body approximation fairly useless
- Better to perform $B^0 \to \pi^+\pi^-\pi^+\pi^-$ DP analysis
- In which case, may as well make it a time-dependent DP analysis

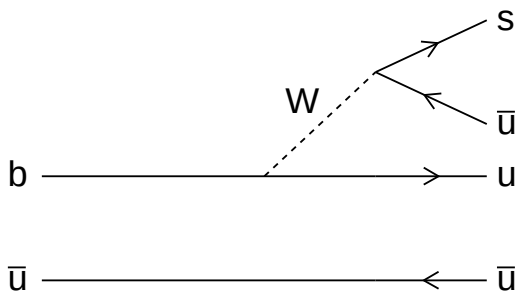
Isospin Symmetry

$B^0 \to K^+\pi^-$	$B^+ \to K^+\pi^0$	$B^+ \to K^0\pi^+$	$B^0 \to K^0\pi^0$
$P + T$	$P + T + C + P_{\rm EW}$	P	$P + C + P_{\rm EW}$

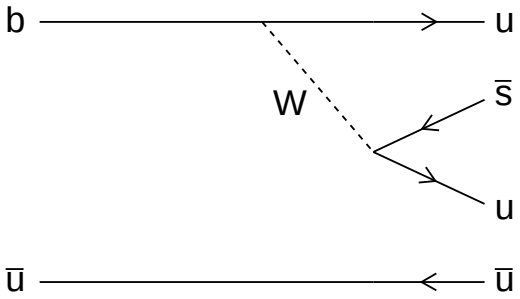
Penguin (P)



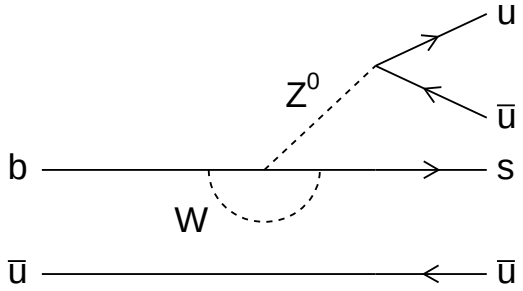
Tree (T)



Colour-suppressed tree (C)

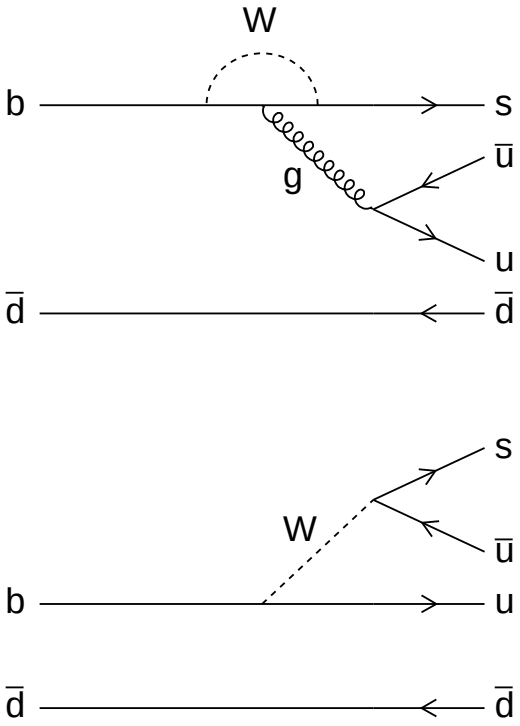


Electroweak penguin ($P_{\rm EW}$)

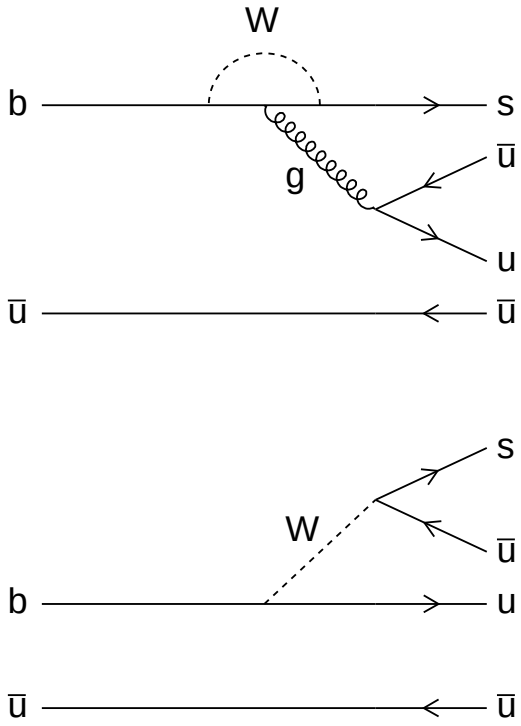


Isospin Symmetry

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



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



Two dominant amplitudes, penguin (P) and tree (T)

Direct CP violation is possible through interference of P and T

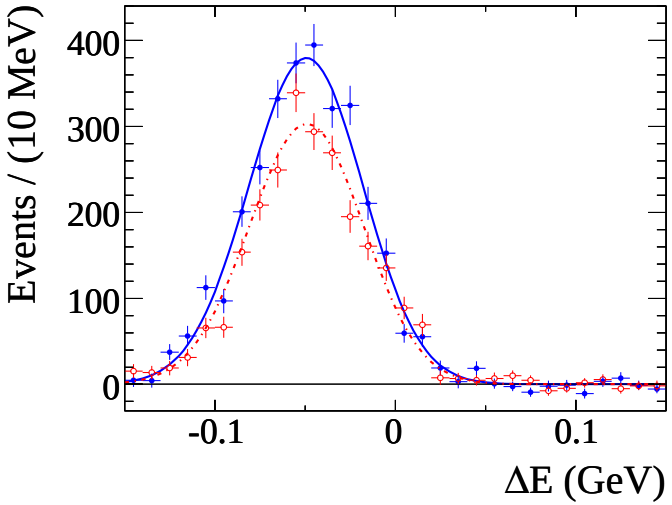
Naive expectation is that $A_{\rm dir}(K^+\pi^-) \sim A_{\rm dir}(K^+\pi^0)$

Isospin Symmetry

BaBar: 467M $B\bar{B}$ pairs

PRD **87** 052009

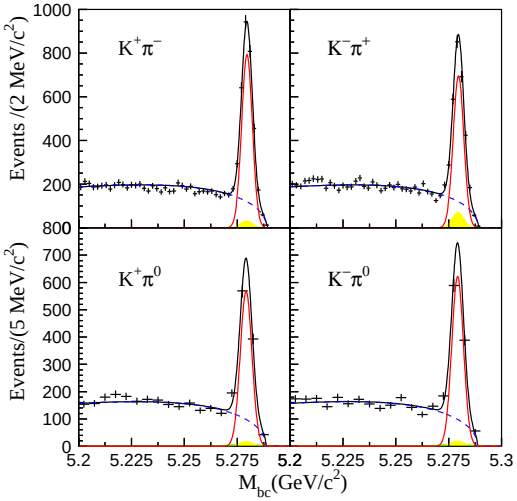
$A_{\rm dir} = -0.107 \pm 0.016\ ^{+0.006}_{-0.004}$



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

PRD **87** 031103

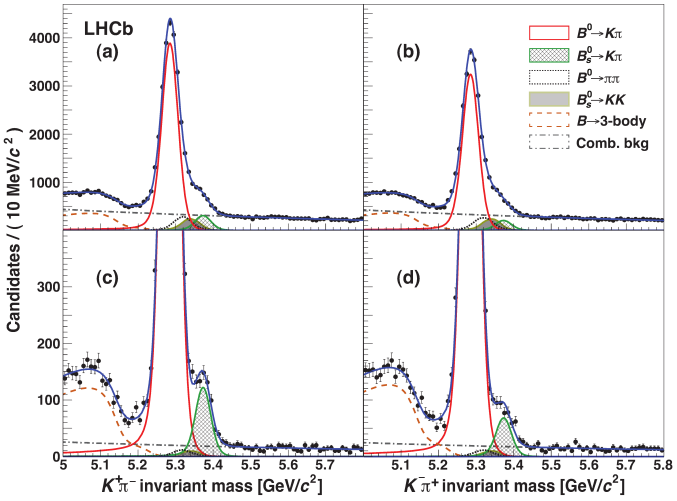
$A_{\rm dir} = -0.069 \pm 0.014 \pm 0.007$



LHCb: $1.0\ \mathrm{fb}^{-1}$

PRL **110** 221601

$A_{\rm dir} = -0.080 \pm 0.007 \pm 0.003$



Direct CP violation observed in $B^0 \to K^+\pi^-$

Significant difference in CP violation is also clearly seen (naive average from HFAG input)

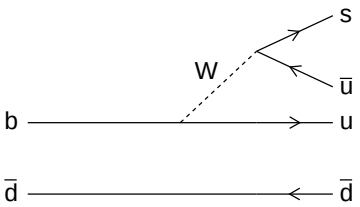
$$\Delta A_{\rm dir} \equiv A_{\rm dir}(K^+\pi^0) - A_{\rm dir}(K^+\pi^-) = +0.122 \pm 0.022$$

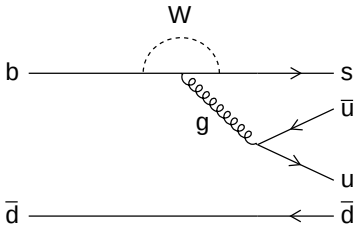
This is known as the "$K\pi$ puzzle"

Isospin Symmetry

$\Delta A_{\rm dir} \sim 0$ if colour-suppressed tree (C) and electroweak penguins are ignored ($P_{\rm EW}$)

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





C.-W. Chiang, *et al.* PRD **70**, 034020

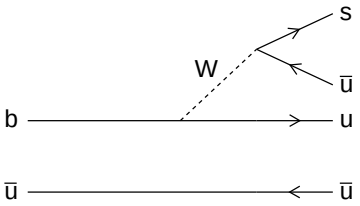
Y.-Y. Chang, *et al.* PRD **71**, 014036

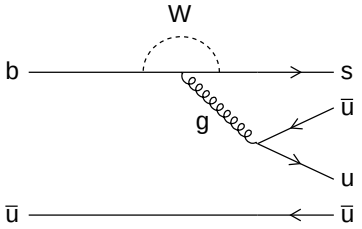
W.-S. Hou, *et al.* PRL **95**, 141601

S. Baek, *et al.* PRD **71**, 057502, PLB **653**, 249

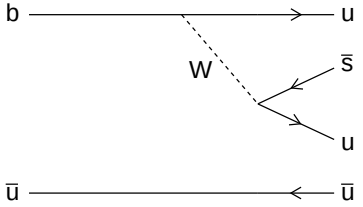
H.-N. Li, *et al.* PRD **72**, 114005 etc...

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

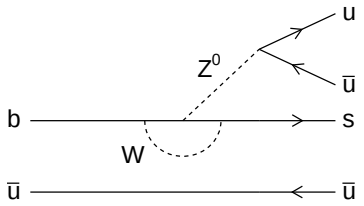




C



$P_{\rm EW}$



Enhancement of C? Then $C > T$ required $\rightsquigarrow$ breakdown of theoretical understanding

Enhancement of $P_{\rm EW}$? New Physics is present

Poor understanding of strong interactions effects in B decays?

Isospin Symmetry

Model independent test of New Physics, M. Gronau, PLB **672**, 82-88 (2005)

Relates branching fractions and CP asymmetries of $K\pi$ modes using isospin

$$A_{\rm dir}(K^+\pi^-) + A_{\rm dir}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} - A_{\rm dir}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} - A_{\rm dir}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

Difference from zero would indicate New Physics

Current experimental value (naive average from HFAG input)

Experiment: $\mathrm{Sum\ Rule} = -0.14 \pm 0.11$

Need to improve precision

LHCb can make meaningful contributions to many parameters here

Certain systematics cancel in asymmetry and ratios of branching fraction measurements

Limited by $A_{\rm dir}(K^0\pi^0)$ as the least known experimental quantity

May be difficult at LHCb due to K^0_S, π^0 and flavour tagging penalty

U-spin Symmetry

SU(2) subgroup of SU(3) under which d and s can be interchanged

$\Delta S = 0$ ($b \to d$) effective Hamiltonian same as corresponding $\Delta S = 1$ ($b \to s$) with $d \leftrightarrow s$

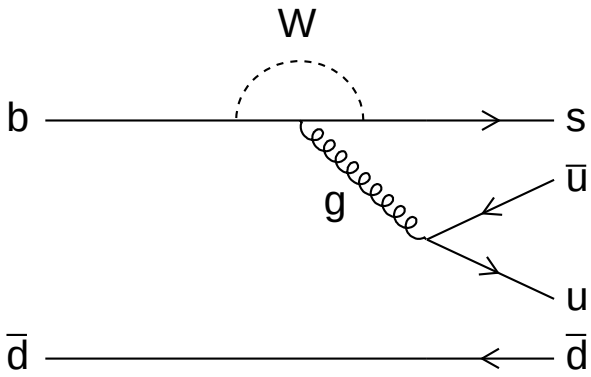
Using CKM unitarity relation $\Im(V_{ub}^* V_{us} V_{cb} V_{cs}^*) = -\Im(V_{ub}^* V_{ud} V_{cb} V_{cd}^*)$

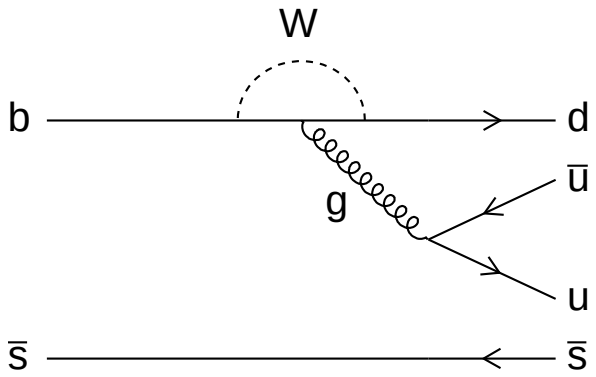
U-spin Theorem relating $\Delta S = 0$ and $\Delta S = 1$ decays

$$\Delta\Gamma(B \to f) = -\Delta\Gamma(\hat{U}B \to \hat{U}f)$$

Up to U-spin breaking corrections (20% - 30%)

Another precision test of the Standard Model





U-spin Symmetry

$(B^0 \to K^+\pi^-,\ \ B_s \to K^-\pi^+)$

LHCb: $1.0\ \mathrm{fb}^{-1}$

$$A_{\mathrm{dir}}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007 \pm 0.003$$

$$\frac{A_{\mathrm{dir}}(B_s \to \pi^+K^-)}{A_{\mathrm{dir}}(B^0 \to K^+\pi^-)} = -\frac{\tau_{B_s}}{\tau_{B^0}} \frac{\mathcal{B}(B^0 \to K^+\pi^-}{\mathcal{B}(B_s \to \pi^+K^-}$$

Using world averages, U-spin predicts

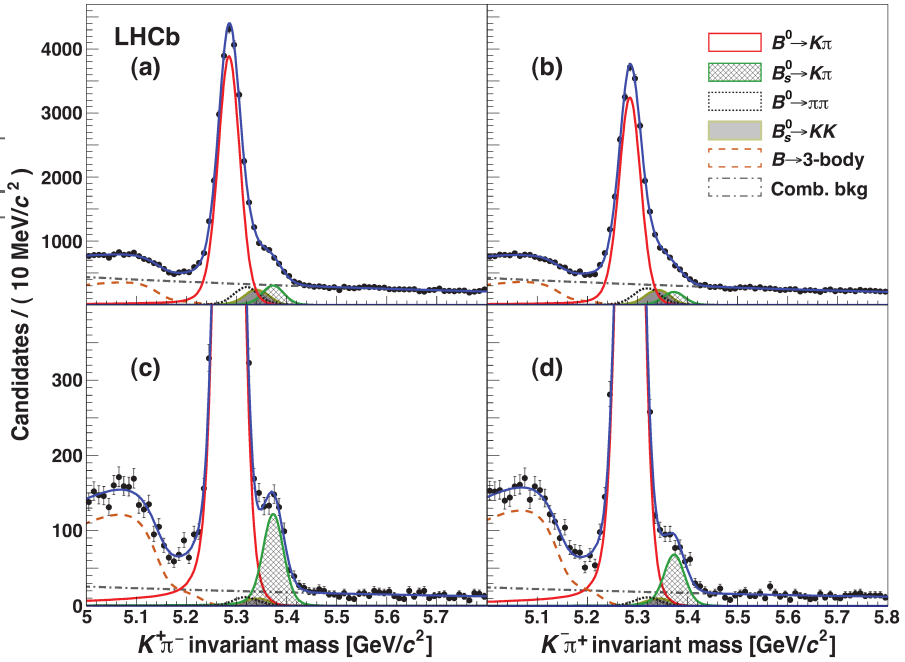
M. Gronau, arXiv:1308.3448

$$A_{\mathrm{dir}}(B_s \to \pi^+K^-) = +0.30 \pm 0.04$$

$$A_{\mathrm{dir}}(B_s \to \pi^+K^-) = +0.27 \pm 0.04 \pm 0.01$$

First observation of CP violation in B_s system

PRL **110** 221601



U-spin asymmetry obeyed quite well, violation of 20% - 30% still allowed

U-spin Symmetry

$(B^0 \to \pi^+\pi^-,\ \ B_s \to K^+K^-)$

LHCb: $1.0\ \mathrm{fb}^{-1}$

arXiv:1308.1428

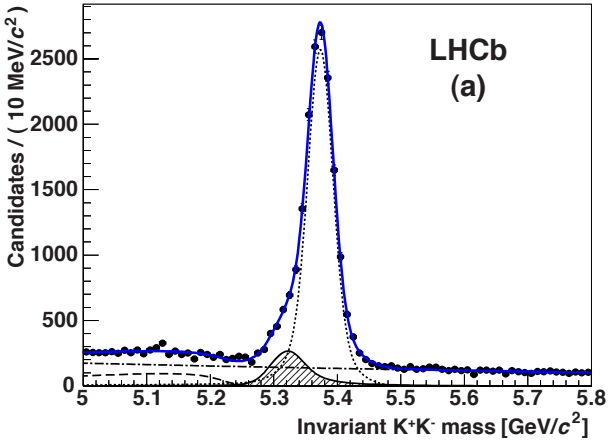
$$A_{\mathrm{dir}}(B^0 \to \pi^+\pi^-) = +0.38 \pm 0.015 \pm 0.02$$

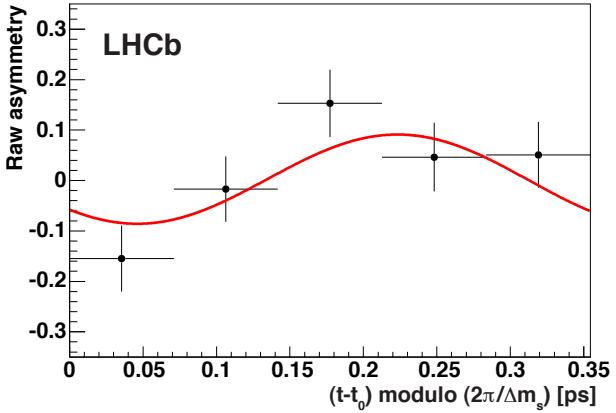
$$\frac{A_{\mathrm{dir}}(B_s \to K^+K^-)}{A_{\mathrm{dir}}(B^0 \to \pi^+\pi^-)} = -\frac{\tau_{B_s}}{\tau_{B^0}} \frac{\mathcal{B}(B^0 \to \pi^+\pi^-)}{\mathcal{B}(B_s \to K^+K^-)}$$

Using world averages, U-spin predicts tight

$$A_{\mathrm{dir}}(B_s \to K^+K^-) = -0.064 \pm 0.012$$

$$A_{\mathrm{dir}}(B_s \to K^+K^-) = -0.14 \pm 0.11 \pm 0.03$$





First measurent of time-dependent CP violation in $B_s \to K^+K^-$

Sign is correct, let's see what happens

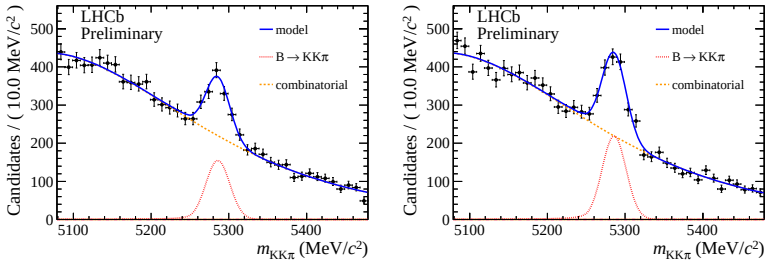
U-spin Symmetry

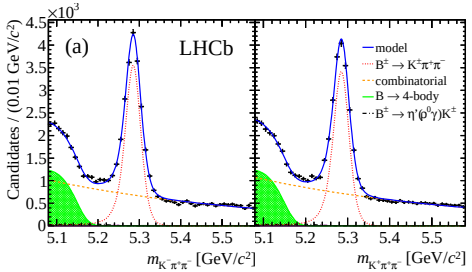
$(B^+ \to \pi^+K^+K^-,\ \ K^+\pi^+\pi^-)$

$$\frac{A_{\rm dir}(B^+ \to \pi^+K^+K^-)}{A_{\rm dir}(B^+ \to K^+\pi^+\pi^-)} = -\frac{\mathcal{B}(B^+ \to K^+\pi^+\pi^-)}{\mathcal{B}(B^+ \to \pi^+K^+K^-)}$$

U-spin symmetry predicts

$$\frac{A_{\rm dir}(B^+ \to \pi^+K^+K^-)}{A_{\rm dir}(B^+ \to K^+\pi^+\pi^-)} = -10.0 \pm 1.5$$





LHCb:

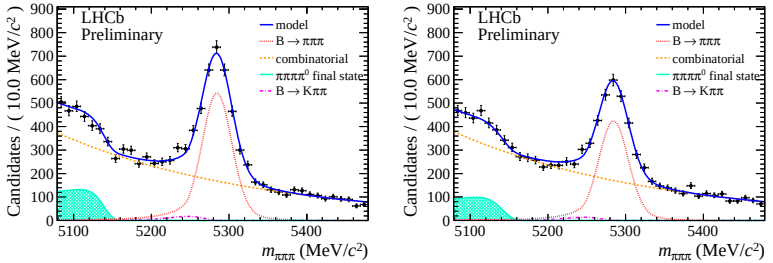
$$\frac{A_{\rm dir}(B^+ \to \pi^+K^+K^-)}{A_{\rm dir}(B^+ \to K^+\pi^+\pi^-)} = -4.8 \pm 2.3$$

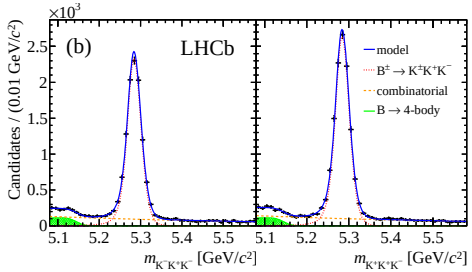
$(B^+ \to \pi^+\pi^+\pi^-,\ \ K^+K^+K^-)$

$$\frac{A_{\rm dir}(B^+ \to \pi^+\pi^+\pi^-)}{A_{\rm dir}(B^+ \to K^+K^+K^-)} = -\frac{\mathcal{B}(B^+ \to K^+K^+K^-)}{\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)}$$

U-spin symmetry predicts

$$\frac{A_{\rm dir}(B^+ \to \pi^+\pi^+\pi^-)}{A_{\rm dir}(B^+ \to K^+K^+K^-)} = -2.2 \pm 0.2$$





LHCb:

$$\frac{A_{\rm dir}(B^+ \to \pi^+\pi^+\pi^-)}{A_{\rm dir}(B^+ \to K^+K^+K^-)} = -2.8 \pm 1.0$$

U-spin Symmetry

U-spin violation in ($B^+ \to \pi^+ K^+ K^-$, $K^+ \pi^+ \pi^-$) at 2.0σ

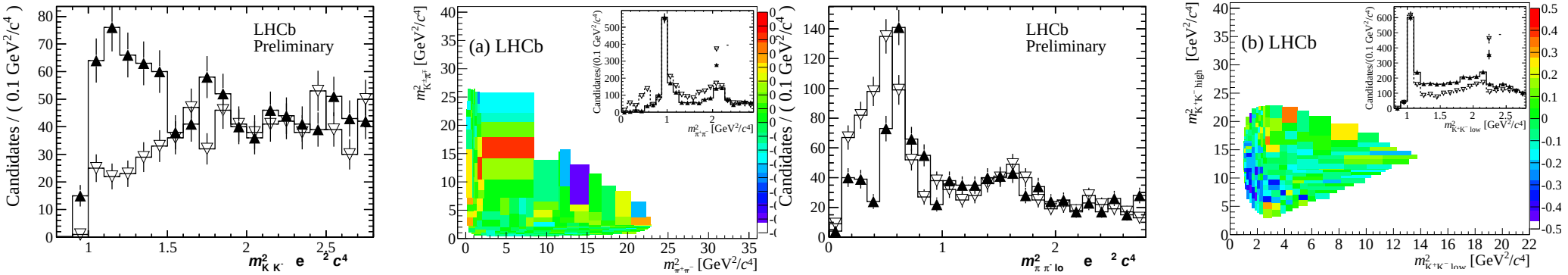
But not surprising given different resonant structure in DP is source of U-spin breaking

LHCb has seen first evidence of CP violation of these 3-body charmless B^+ decay

Even more significant amounts of CP violation particularly in low mass regions of the DP

LHCb: $1.0\ \mathrm{fb}^-1$, arXiv:1306.1246, LHCb-CONF-2012-028

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



Ultimately need amplitude analyses to test U-spin

Other promising tests of U-spin in DD' sector, PRD **87** 092007

γ

$\gamma = \phi_3 \equiv \arg(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$

Least known SM parameter

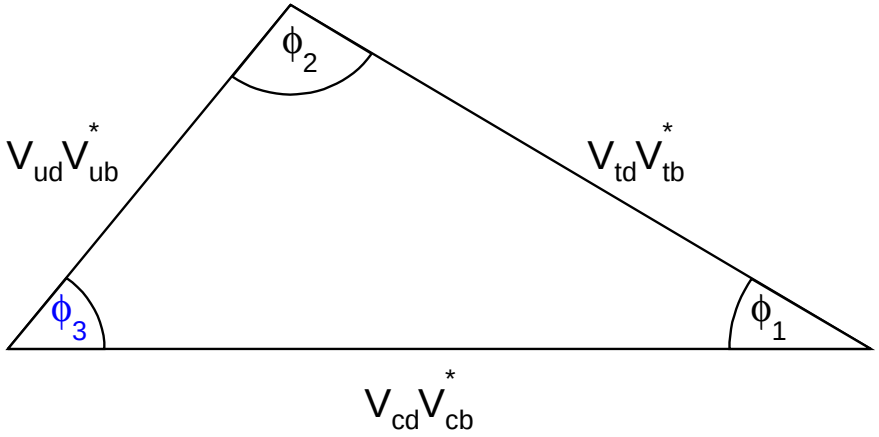
Interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions

eg. $B^{\pm} \to D[K^+K^-\pi^+\pi^-]K^{\pm}$

See talk by D. Derkach

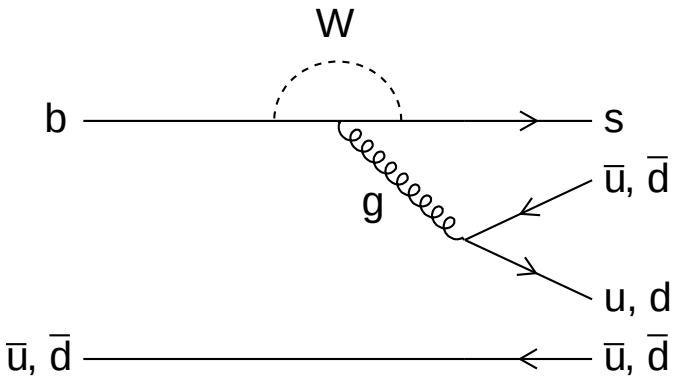
Other promising methods

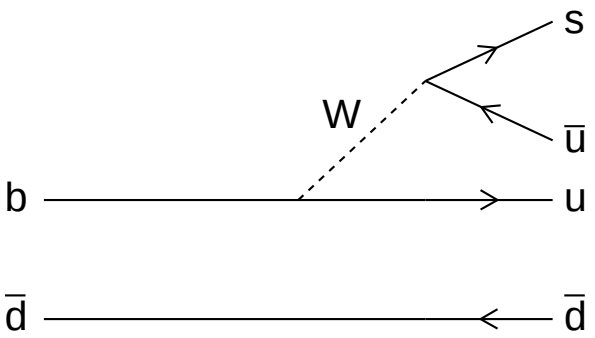
Involving $b \to s$ penguin dominated decays



Interfering with $b \to u$ tree gives γ

Focus on method for LHCb





γ

$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{0}(\bar{B}^{0}) \to K^{0}_{S}\pi^{+}\pi^{-}$

Method involving only charged tracks and no flavour tagging penalty for neutral B channel

I. Bediaga, G. Guerrer and J.M. de Miranda, PRD **76** 073011 (2007)

Perform standard DP analysis of $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ decays

Need to check penguin amplitude is dominant ie. $A(B^{+} \to K^{*0}\pi^{+}) \approx \bar{A}(B^{-} \to \bar{K}^{*0}\pi^{-})$

$B^{\pm} \to K^{*0}(\bar{K}^{*0})\pi^{\pm}$: $a_P e^{i\delta_P}$

From SU(2) flavour symmetry, assume same penguin amplitudes for all 4 $B \to K^{*}\pi$ processes

Then perform joint $B^{0}(\bar{B}^{0}) \to K^{0}_{S}\pi^{+}\pi^{-}$ analysis

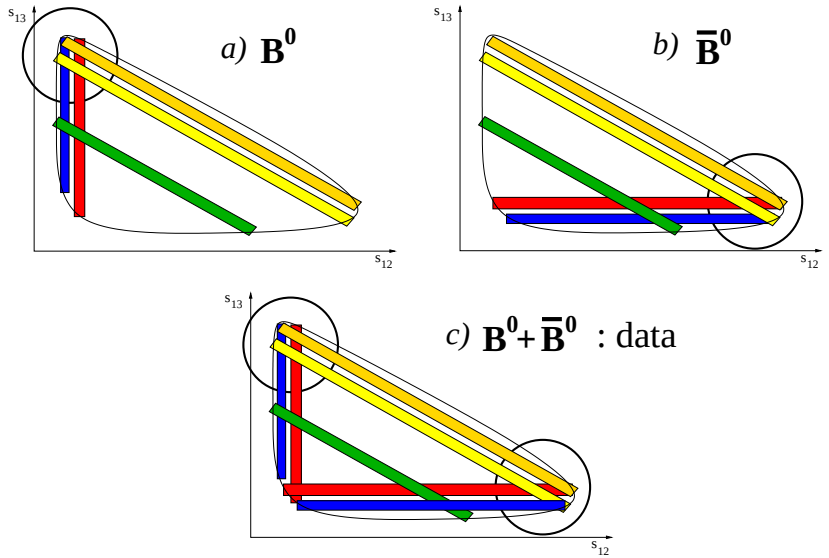
$B^{0} \to K^{*+}\pi^{-}$: $a_P e^{i\delta_P} + a_T e^{i(\delta_T+\gamma)}$

$\bar{B}^{0} \to K^{*-}\pi^{-}$: $a_P e^{i\delta_P} + a_T e^{i(\delta_T-\gamma)}$

If you can fix $a_P e^{i\delta_P}$ contribution with an anchor channel eg. $B \to K\chi_{c0}$, fit for γ

γ

Distinct regions of interference between B^0 and $\bar{B}^0$ "tag" the decay



$$\mathcal{P}(K^0_S\pi^+\pi^-) \propto |a_\chi e^{i\delta_\chi} + \sum_i a_i e^{i\delta_i} A|^2 + |\bar{a}_\chi e^{i\bar{\delta}_\chi} + \sum_i \bar{a}_i e^{i\bar{\delta}_i} \bar{A}|^2$$

Fix penguin contribution from $B^\pm \to K^\pm\pi^+\pi^-$

Free scale factor $\bar{a}_\chi$ and remaining tree amplitudes

Pure signal MC studies with input from BaBar and 100K neutral B events

Precision could be as good as $\delta\gamma \sim 5^\circ$

γ

There are many many other ways to measure γ from charmless 3-body $B_{u,d,s}$ decays

$B^+ \to \pi^+\pi^+\pi^-$ (and $B^+ \to K^+\pi^+\pi^-$): PRL **81** 4067, PRL **86** 2720

$B^0 \to K^+\pi^-\pi^0$ and $B^0 \to K^0_S\pi^+\pi^-$: PRD **74** 051301, PRD **75** 014002, PRD **77** 057504, PRD **78** 017505

$B^0 \to K^+\pi^-\pi^0$, $K^0_S\pi^+\pi^-$ and $B^+ \to K^0_S\pi^+\pi^0$: PRD **74** 051301

$B_s \to K^-\pi^+\pi^0$ and $B_s \to K^0_S\pi^+\pi^-$: PLB **645** 201

They either require flavour tagging and/or π^0 reconstruction

Always beneficial to work with other collaborations eg. Minimise DP model uncertainties

Would be good to attempt these solely at LHCb eventually as well

γ measurements from penguin-dominated decays very important

Compare with tree-level measurements, another avenue to find NP

ϕ_s

ϕ_s is a CP violating phase related to $B_s\bar{B}_s$ mixing

$\phi_s \equiv \arg(-M_{12}/\Gamma_{12}) \approx -\arg(\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}) = -2\beta_s$

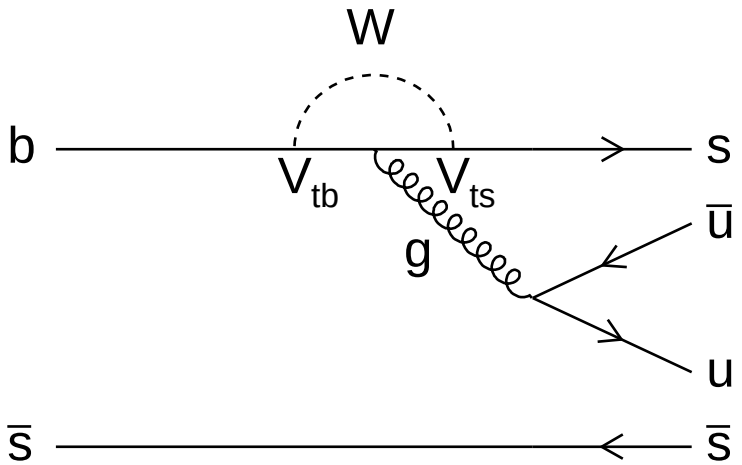
Analogous to 2β from $B^0\bar{B}^0$ mixing, however expected to be small in SM, $\mathcal{O}(1^\circ)$

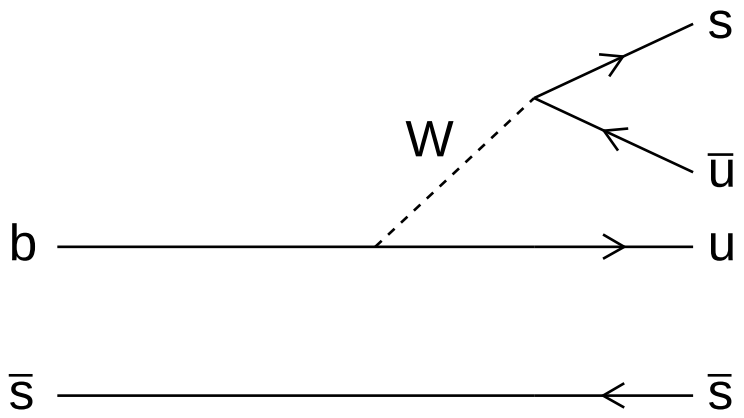
ϕ_s precisely predicted in SM $\delta\phi_s = \mathcal{O}(0.1^\circ)$, so sensitive to NP contributions in $B_s\bar{B}_s$ mixing

Measure from $b \to c\bar{c}s$ transitions eg. $B_s \to J/\psi\phi$

Can also measure from $b \to s\bar{q}q$

$b \to u\bar{u}s$ gives sensitivity to γ





ϕ_s

$\Delta\Gamma_s \neq 0$ in B_s system

Time-dependent asymmetry given by

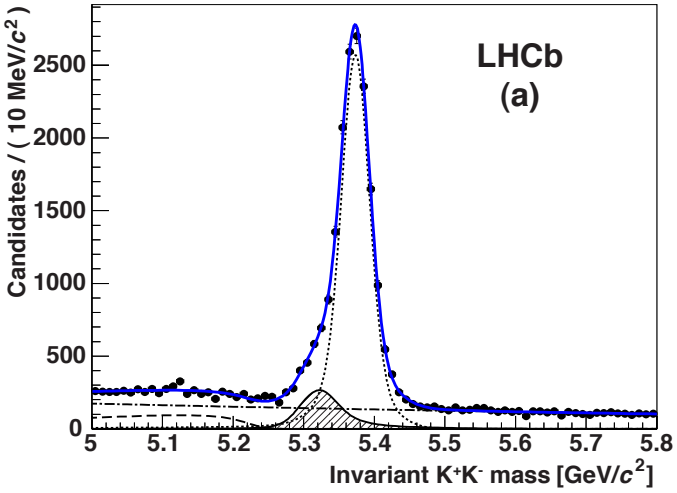
$$A(t) = \frac{A_{\rm dir} \cos \Delta m_s t + A_{\rm mix} \sin \Delta m_s t}{\cosh \Delta\Gamma_s t/2 - A_{\Delta\Gamma} \sinh \Delta\Gamma_s t/2}$$

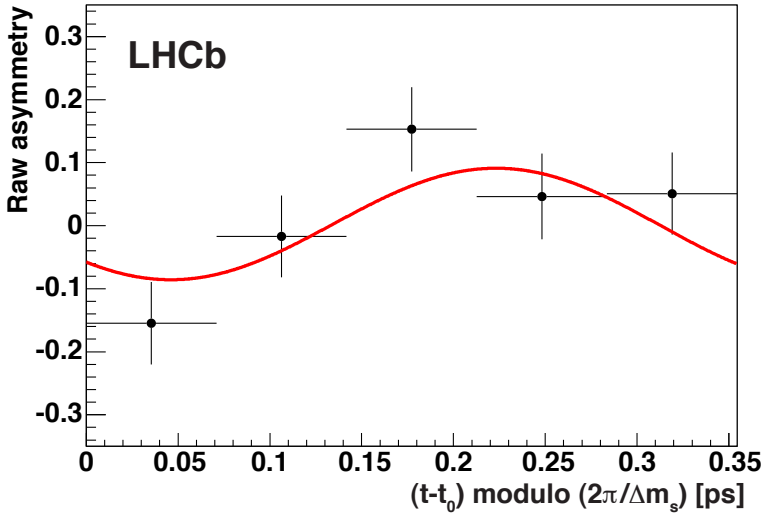
$A_{\Delta\Gamma}$ grants access to $\Re(\lambda_{CP})$, so ϕ_s can be determined without ambiguity

LHCb: $1.0\ {\rm fb}^-1$, arXiv:1308.1428

$\Delta\Gamma_s$ free but constrained positive

$A_{\Delta\Gamma} = +\sqrt{1 - A_{\rm dir}^2 - A_{\rm mix}^2}$ fixed





$A_{\rm dir} = -0.14 \pm 0.11 \pm 0.03$

$A_{\rm mix} = +0.30 \pm 0.12 \pm 0.04$

ϕ_s

U-spin relations with $B^0 \to \pi^+\pi^-$ allow extraction of γ, R. Fleischer, PLB **459** 306

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

$$A_{\rm dir} = \frac{-2d\sin\theta\sin\gamma}{1-2d\cos\theta\cos\gamma+d^2}$$

$$A_{\rm mix} = \frac{\sin(2\beta+2\gamma)-2d\cos\theta\sin(2\beta+\gamma)+d^2\sin 2\beta}{1-2d\cos\theta\cos\gamma+d^2}$$

$$A_{\Delta\Gamma} = 0$$

$B_s \to K^+K^-$

$$A_{\rm dir} = \frac{2\tilde{d}'\sin\theta'\sin\gamma}{1+2\tilde{d}'\cos\theta'\cos\gamma+\tilde{d}'^2}$$

$$A_{\rm mix} = \frac{\sin(\phi_s+2\gamma)+2\tilde{d}'\cos\theta'\sin(\phi_s+\gamma)+\tilde{d}'^2\sin\phi_s}{1+2\tilde{d}'\cos\theta'\cos\gamma+\tilde{d}'^2}$$

$$A_{\Delta\Gamma} = -\frac{\cos(\phi_s+2\gamma)+2\tilde{d}'\cos\theta'\cos(\phi_s+\gamma)+\tilde{d}'^2\cos\phi_s}{1+2\tilde{d}'\cos\theta'\cos\gamma+\tilde{d}'^2}$$

d, θ ($\tilde{d}'$, θ') relative amplitude between tree and penguin in B^0 (B_s) decay

U-spin relates d, θ with $\tilde{d}'$, θ'

$\tilde{d}' = d(1-\lambda^2)/\lambda^2$, where $\lambda = |V_{us}|$, $\theta' = \theta$

5 unknowns: d, θ, ϕ_s, γ, β

System constrained, but need more statistics

Summary

High potential for NP in CP violation measurements in charmless hadronic B decays

Many avenues for investigation: β, α, γ, ϕ_s, isospin and U-spin symmetries

Many new exciting results coming out of LHCb

CP violation in B_s system and 3-body charmless B^+ decays

NP discovery potential tends to increase with more measurements

Single channel $<$ Group of related channels $<$ Fit of SM parameters

Continue to increase precision in multiple measurements to challenge the SM