Mixing-induced CP Violation in B_d decays

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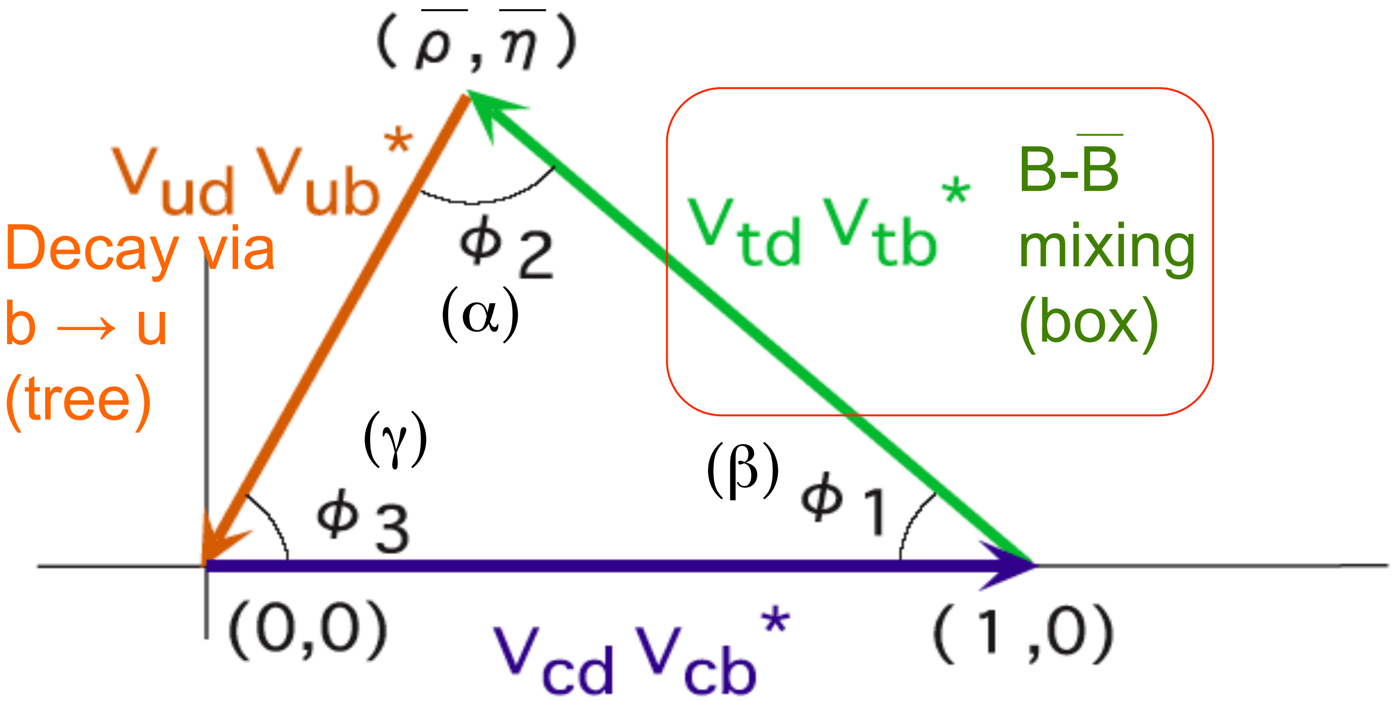
Angle measurements and mixing

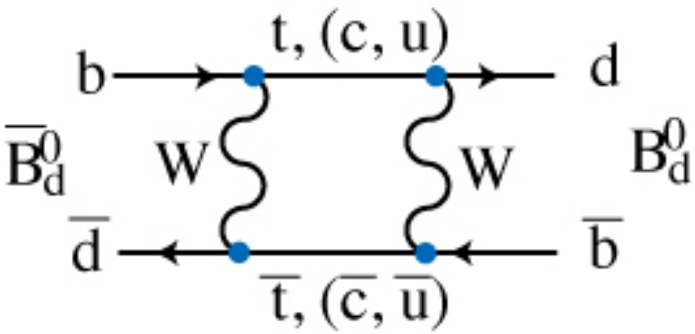


Decay via b → c (tree) to set SM reference.

Decay via about b → s (penguin) to hunt New CPV phase.

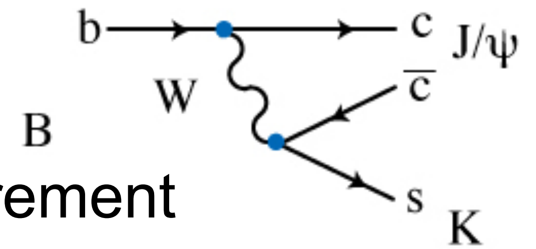
A lot of playground, b→c decays

Mixing

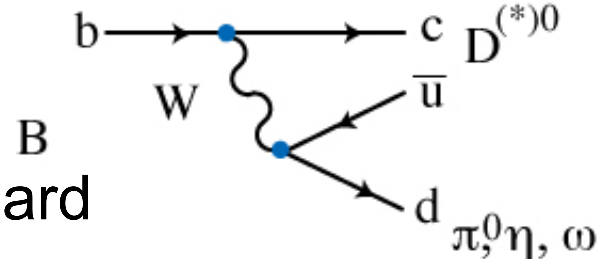


Interferes with

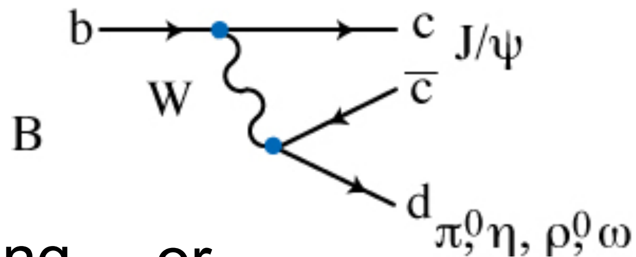
b→c$\overline{c}$s
Flagship measurement



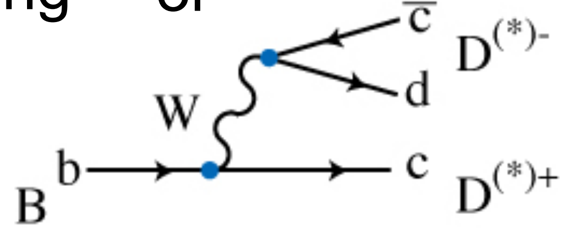
b→c$\overline{u}$d
Gives new standard



b→c$\overline{c}$d
Another interesting approach



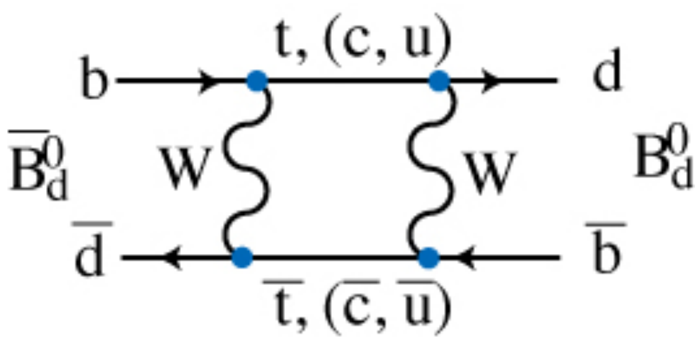
or



All these related to $\phi_1(\beta)$.

In charmless decays

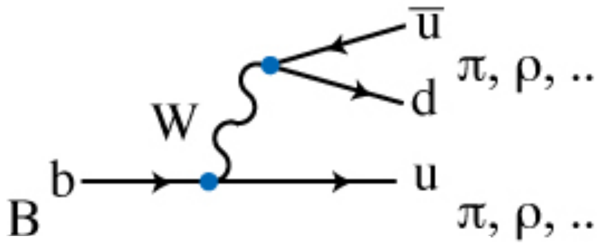
Mixing



Interferes with

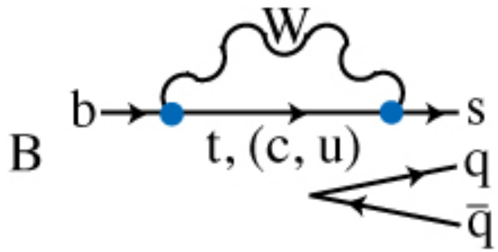
$b \to u\bar{u}d$

Obtain angle ϕ_2



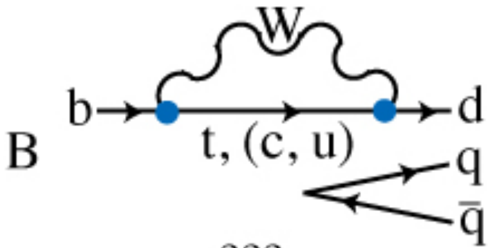
$b \to s\bar{q}q$

effective ϕ_1 to look for NP

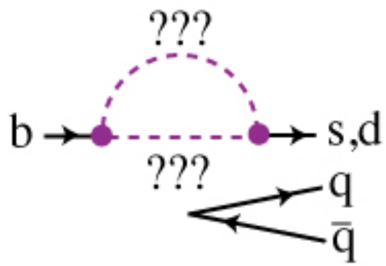


$b \to d\bar{q}q$

Significant CPV = NP signature

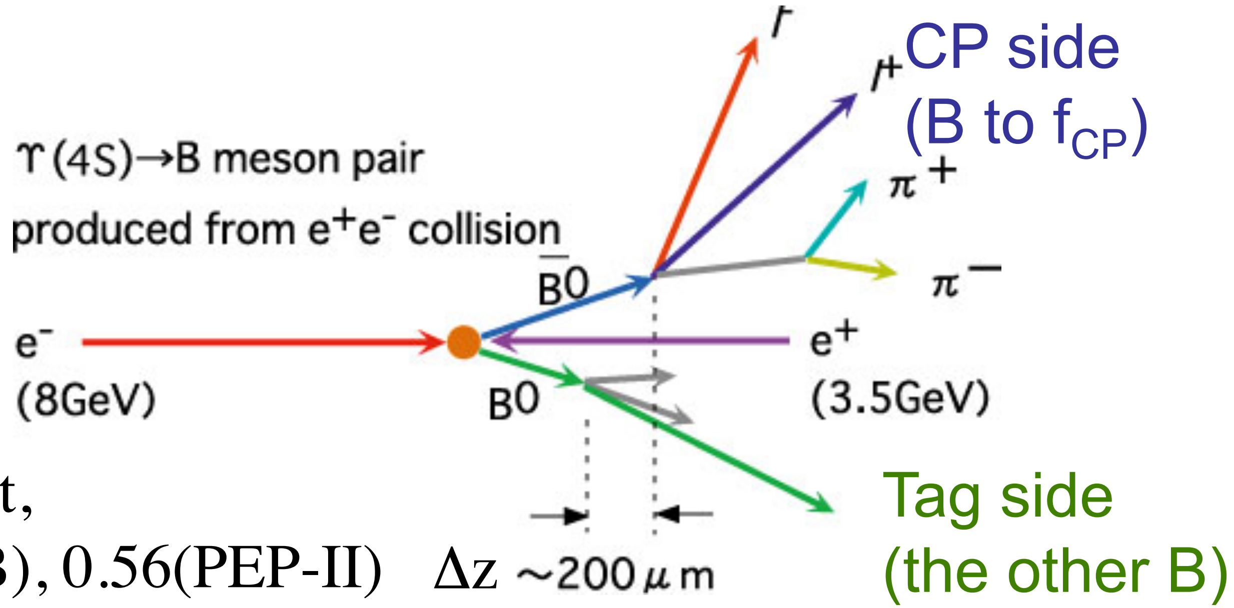


Both penguins may have;



Time-dependent CPV at Υ(4S)

In order to see CPV by interference between decay and mixing.



$\Delta z = \beta\gamma c \Delta t$,

$\beta\gamma = 0.425$(KEKB), 0.56(PEP-II)

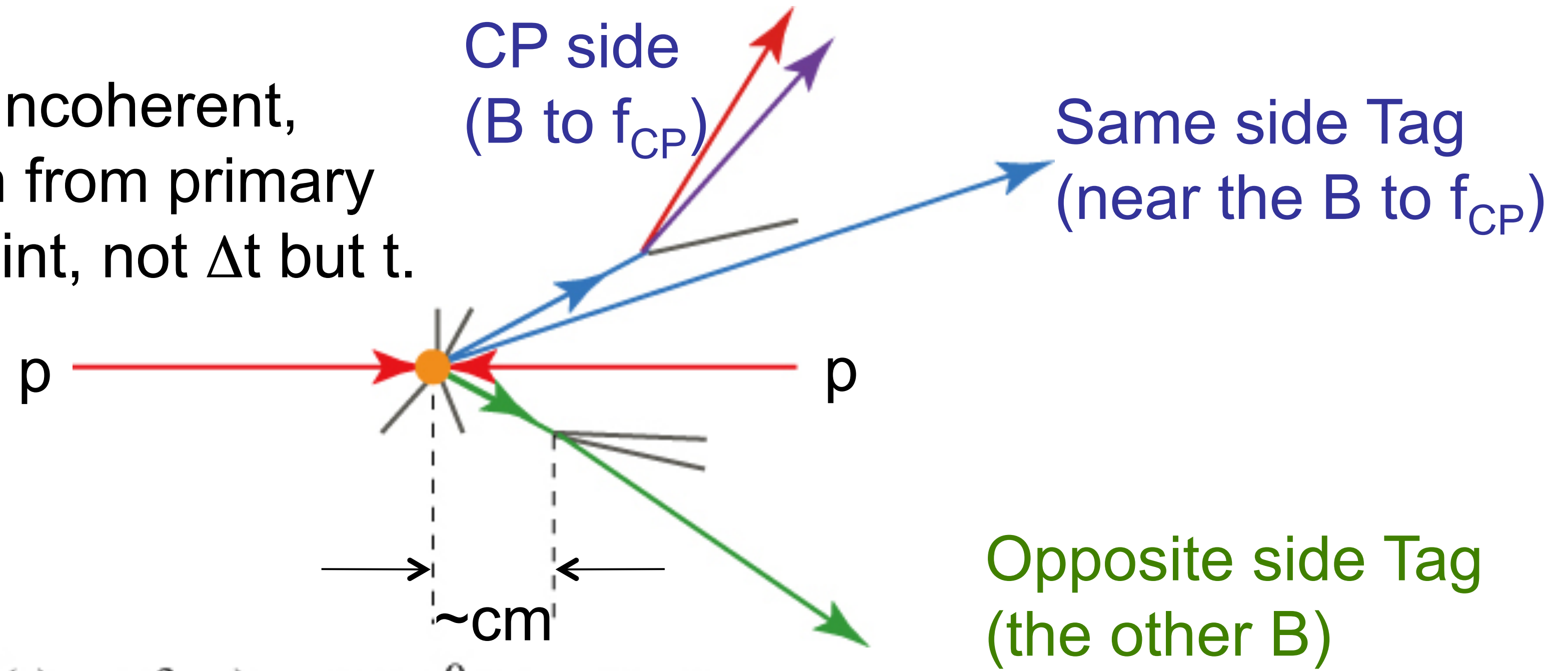
$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})} = S_{f_{CP}} \sin(\Delta m \Delta t) + A_{f_{CP}} \cos(\Delta m \Delta t)$$

$$S_{f_{CP}} = \frac{2\,Im(\lambda)}{|\lambda|^2 + 1} \quad A_{f_{CP}} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \quad \lambda = \frac{q}{p}\frac{\overline{A}(f_{CP})}{A(f_{CP})}$$

$-C_{f_{CP}} = A_{f_{CP}}$ $\quad |\lambda| = 1$ if no DCPV

Time-dependent CPV at LHCb

Oscillation is incoherent, time evolution from primary production point, not Δt but t.



$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})} = S_{f_{CP}} \sin(\Delta m t) + A_{f_{CP}} \cos(\Delta m t)$$

$$S_{f_{CP}} = \frac{2\, Im(\lambda)}{|\lambda|^2 + 1} \qquad A_{f_{CP}} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \qquad \lambda = \frac{q}{p} \frac{\overline{A}(f_{CP})}{A(f_{CP})}$$

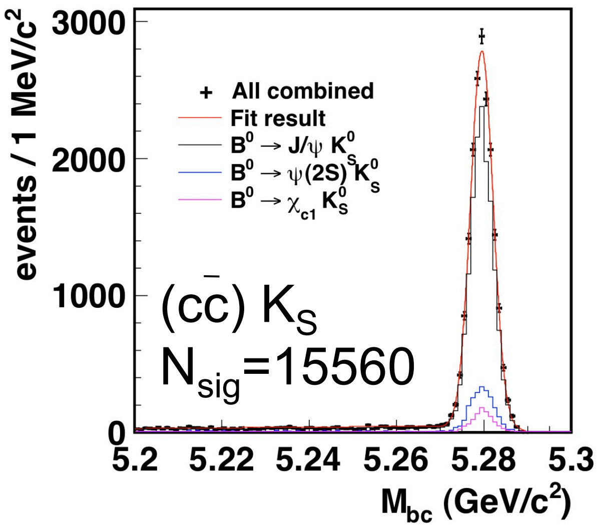
$$-C_{f_{CP}} = A_{f_{CP}} \qquad |\lambda| = 1 \text{ if no DCPV}$$

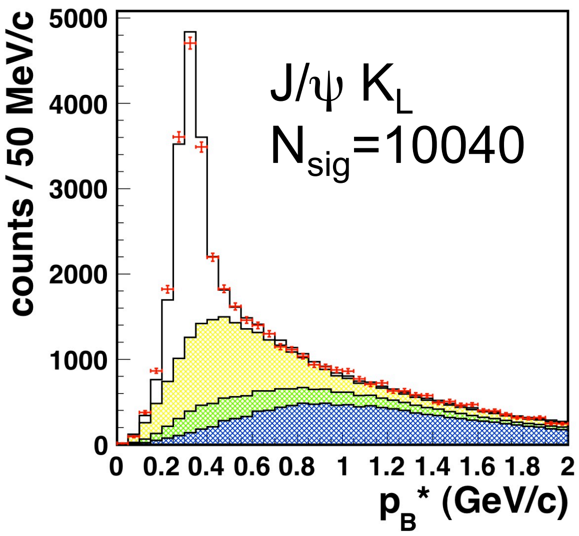
Comparison

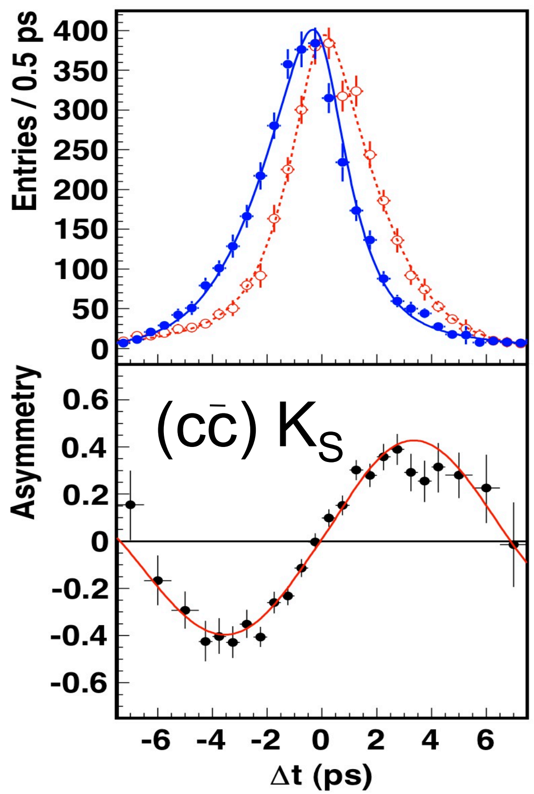
	Number of usable B_d	Flavor tagging	Δt or t resolution	Oscillation	comments
$\Upsilon(4S)$, i.e. BaBar, Belle/Belle II	1 million/fb^{-1}	$\varepsilon(1-2w)^2$ =30%	500~600 fs ($\sim 1/3 \times \tau_B$)	Coherent oscillation	
LHCb	1000~2000 million/fb^{-1}	$\varepsilon(1-2w)^2$ =3%	50~60 fs	Incoherent oscillation	No tag side interference

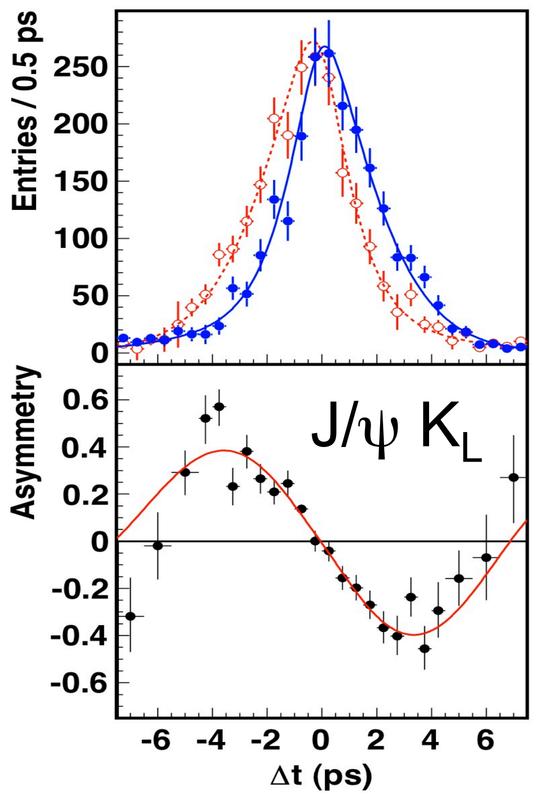
LHCb compensates lower flavor tagging effective efficiency with much larger b-hadron production rate, while better t resolution due to larger boost.
Careful treatment of Δt resolution at $\Upsilon(4S)$ is essential.

$\sin 2\phi_1$ in $(c\bar{c})\,K^0$ at Belle









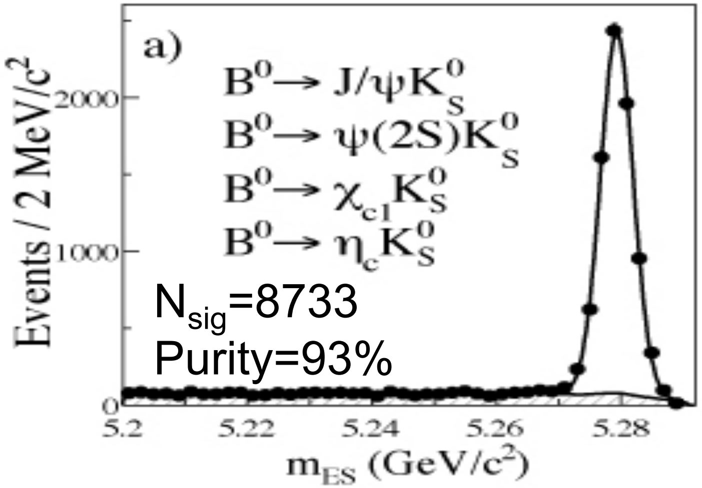
$\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013$

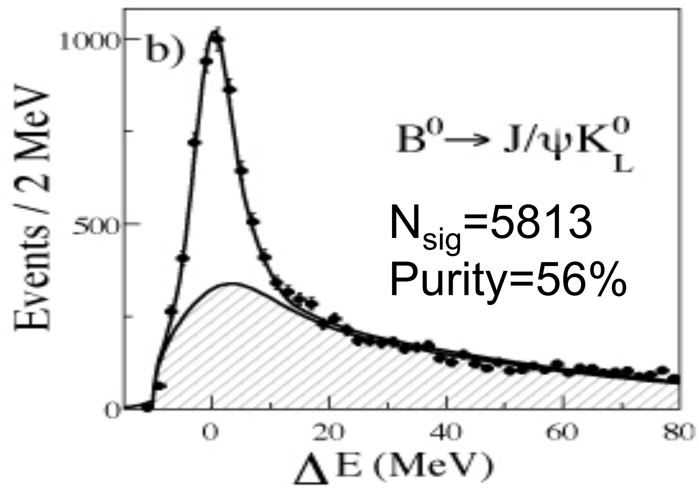
$C_{fcp} = -A_{fCP} = -0.007 \pm 0.016 \pm 0.013$

PRL108,171802(2012)

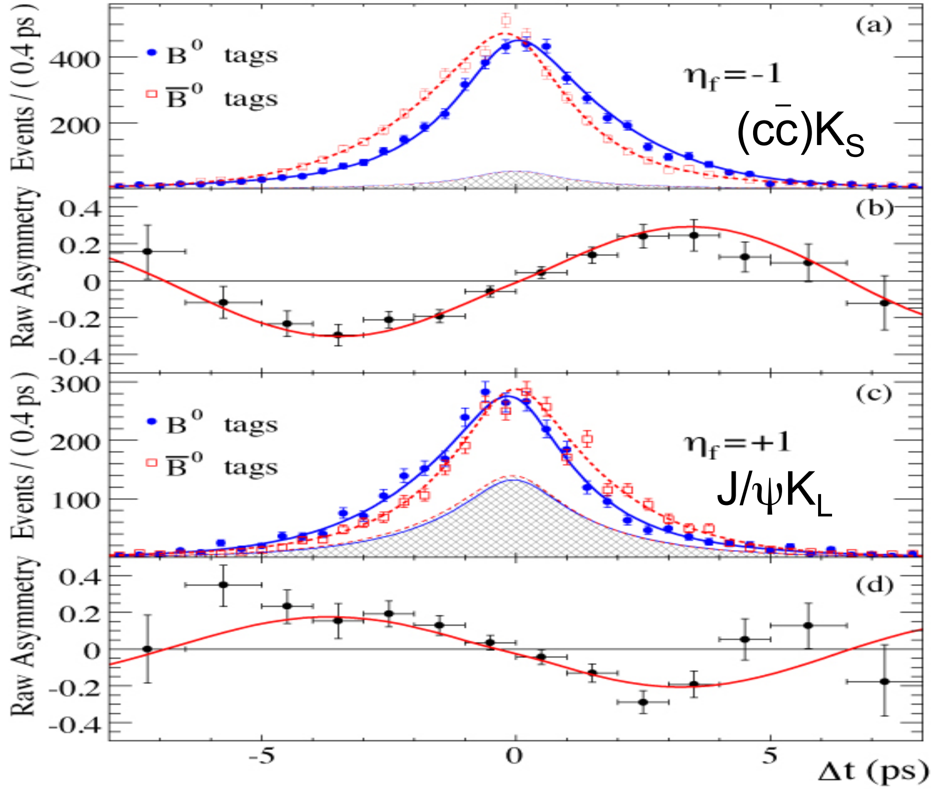
(Full description paper in preparation)

$\sin 2\beta = \sin 2\phi_1$ in $(c\bar{c})\,K^0$ at BaBar





$E_B - E_{CM}/2$

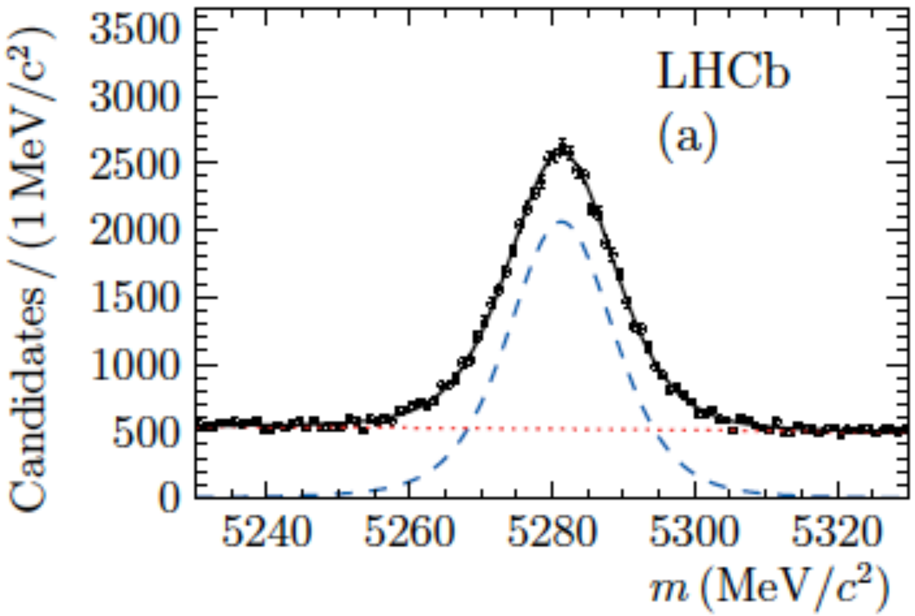


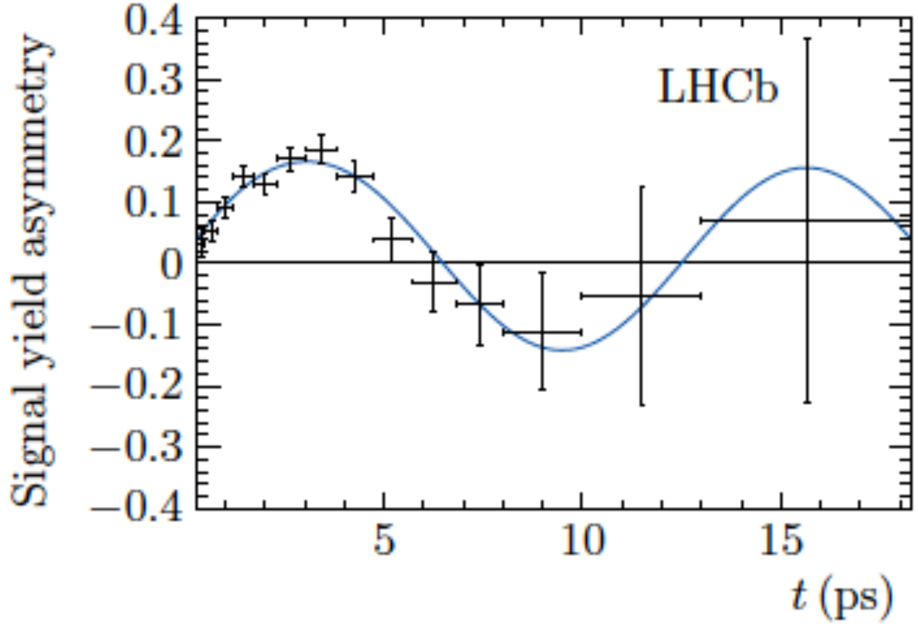
$\sin 2\beta = \sin 2\phi_1 = 0.687 \pm 0.028 \pm 0.012$

$C_{fcp} = -A_{fCP} = 0.024 \pm 0.020 \pm 0.016$

PRD79,072009(2009)

$\sin 2\beta = \sin 2\phi_1$ in $J/\psi\ K_S$ at LHC_b





$\sin 2\beta = \sin 2\phi_1 = 0.731 \pm 0.035 \pm 0.020$

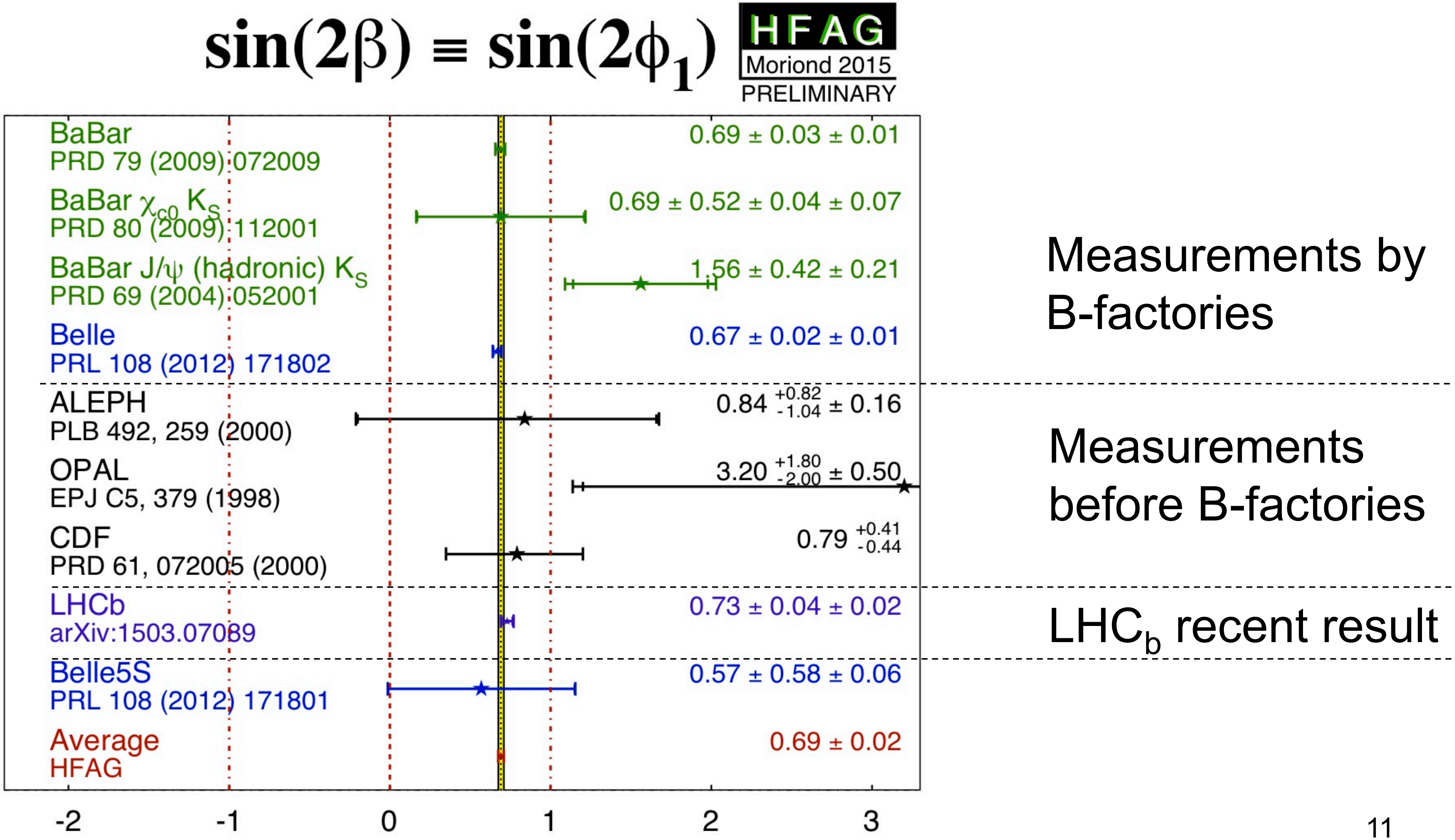
$C_{fCP} = -A_{fCP} = -0.038 \pm 0.032 \pm 0.005$

arXiv:1503.07089, submitted to PRL

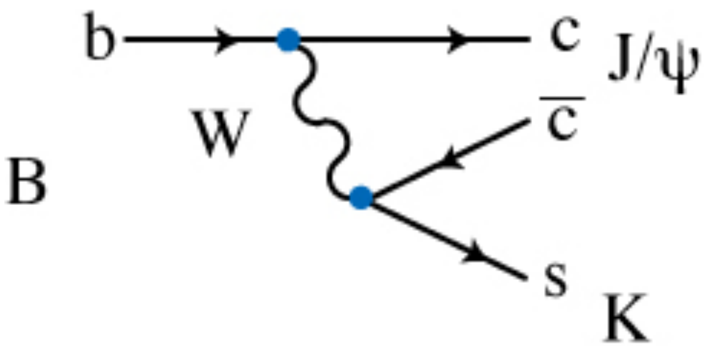
LHC_b's capability has been proven.

Now it is a firm SM reference

$\sin(2\beta) \equiv \sin(2\phi_1)$

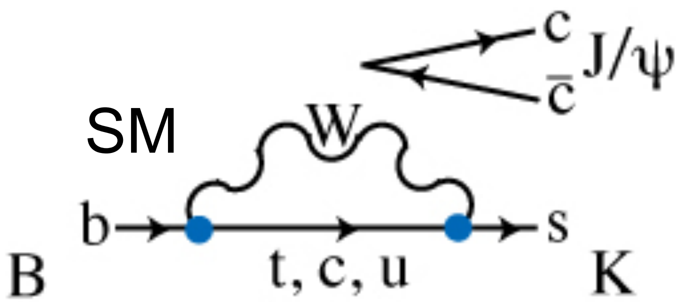


How firm is it?

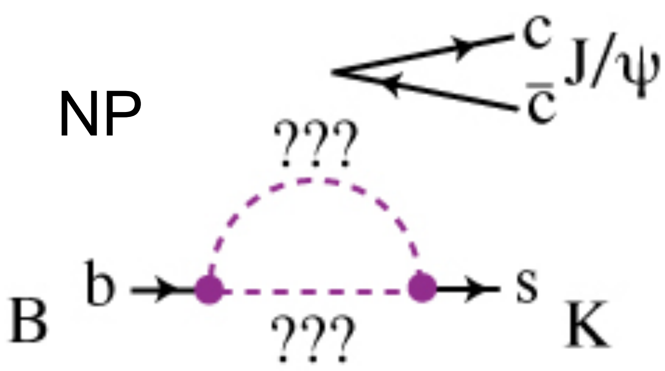


Leading : Tree
No complex phase
in decay amplitude

SM



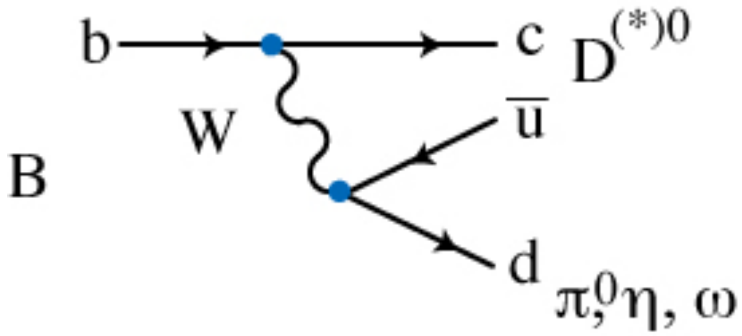
NP

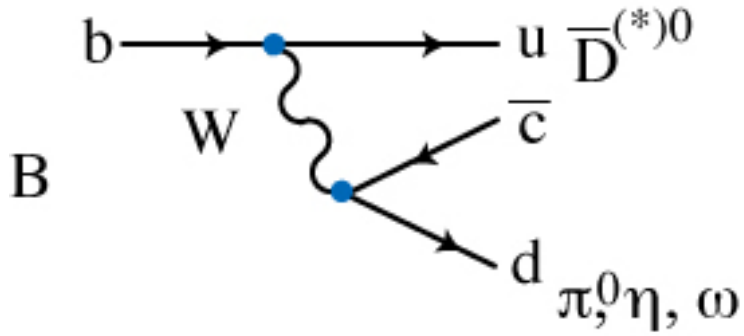


Sub-Leading : Penguin
In principle, New Physics
contribution might not be zero,
how it can be constrained?

One interesting approach, $b \to c\bar{u}d$

$B^0 \to D^{(*)0} h^0$, $h^0 = \pi^0, \eta, \omega$





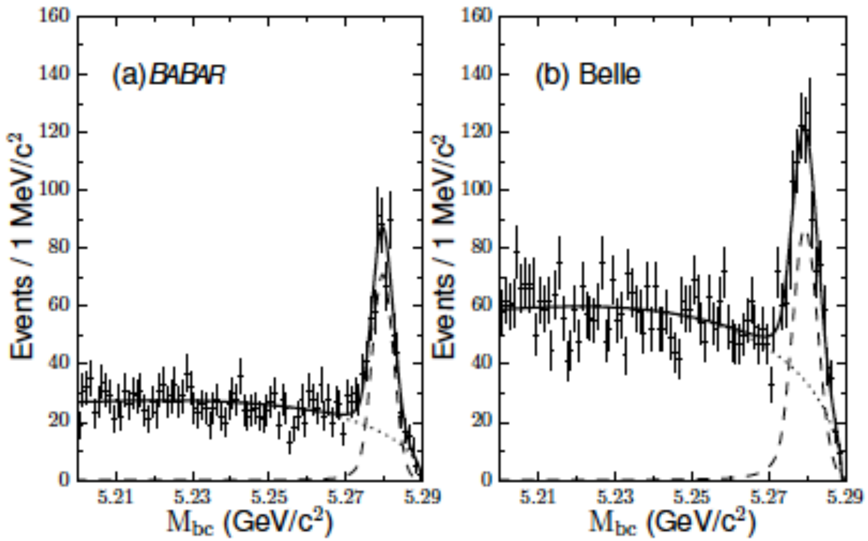
Leading : Tree
No complex phase
in decay amplitude

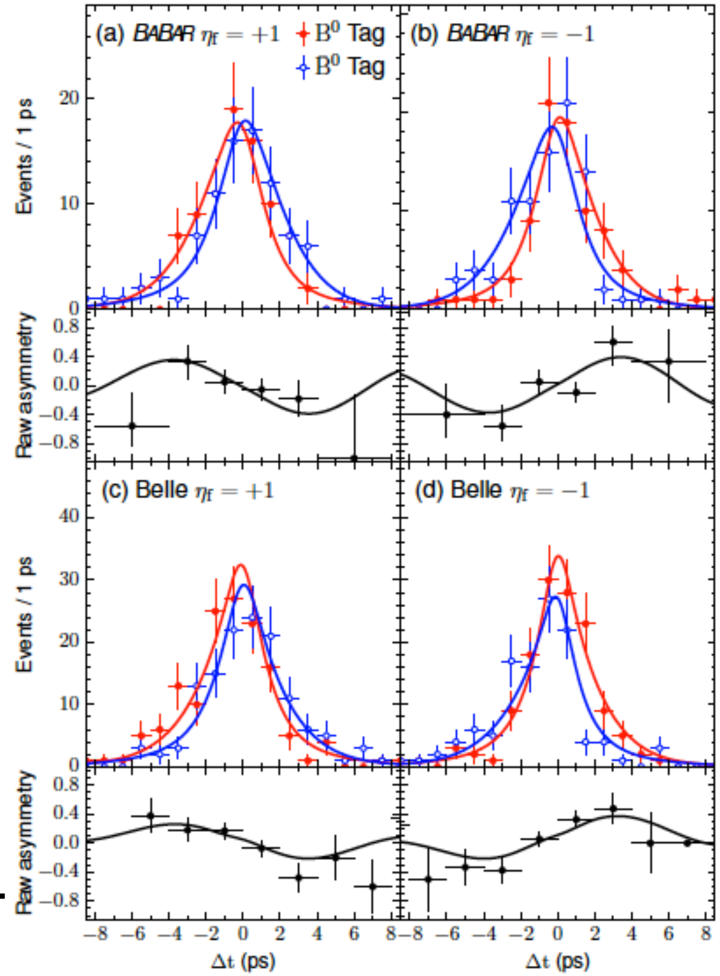
Sub-Leading : also Tree
V_{ub} has complex phase,
but it is within the SM, to be
under control.

When neutral D meson decays to CP eigenstates,
suitable to get ϕ_1, branching fraction is limiting factor.

Thus, BaBar+Belle joint analysis

As for detail, see Markus Roehrken's talk!





$B^0 \to D^{(*)0} h^0$, $h^0=\pi^0, \eta, \omega$

$D^0 \to K^+K^-$, $K_S\pi^0$ and $K_S\omega$

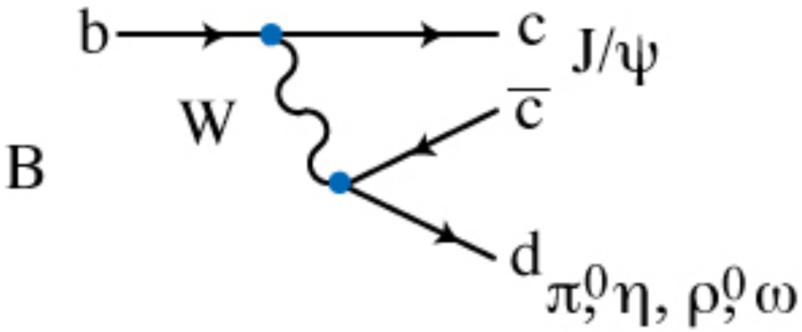
$\sin 2\beta = \sin 2\phi_1 = 0.66 \pm 0.10 \pm 0.06$

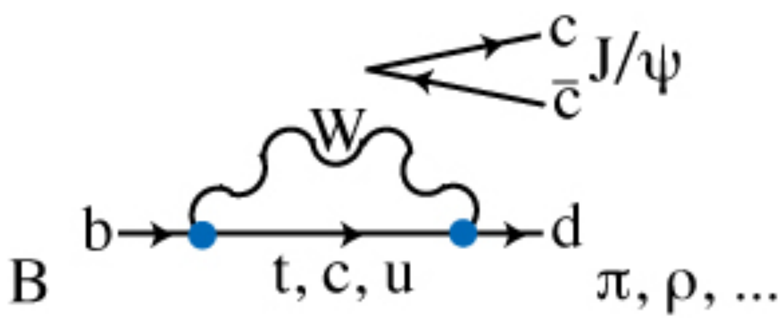
$C_{fCP} = -A_{fCP} = -0.02 \pm 0.07 \pm 0.03$

arXiv:1503.07089, submitted to PRL

First observation of CPV(5.4σ)!

Role of $b \to c\bar{c}d$ transition





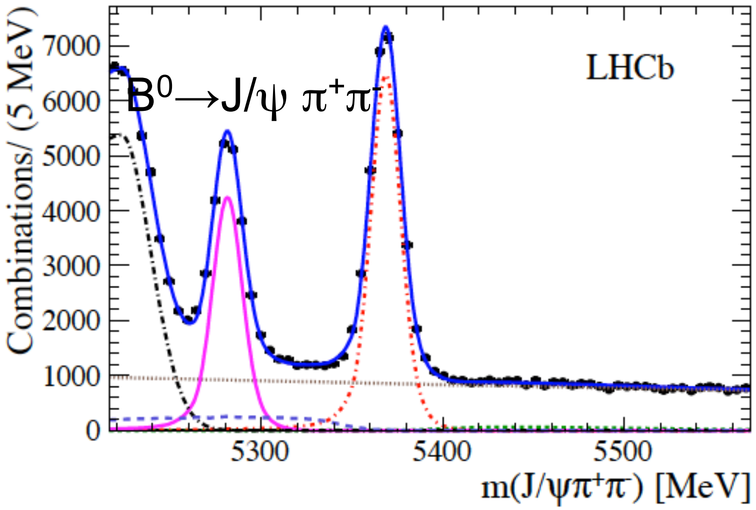
Leading : Tree
No complex phase in decay amplitude

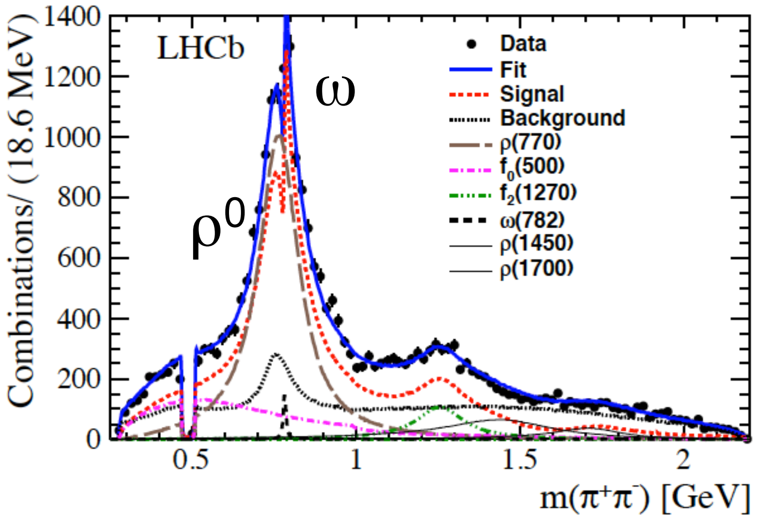
Sub-Leading : Penguin
Even in SM, because of the complex phase in V_{td}, more sensitive to penguin contribution.

Employing plausible assumption based on flavor SU(3) symmetry, penguin in the golden mode is to be constrained.

LHC$_b$ attempt in $B^0 \to J/\psi\ \pi^+\pi^-$

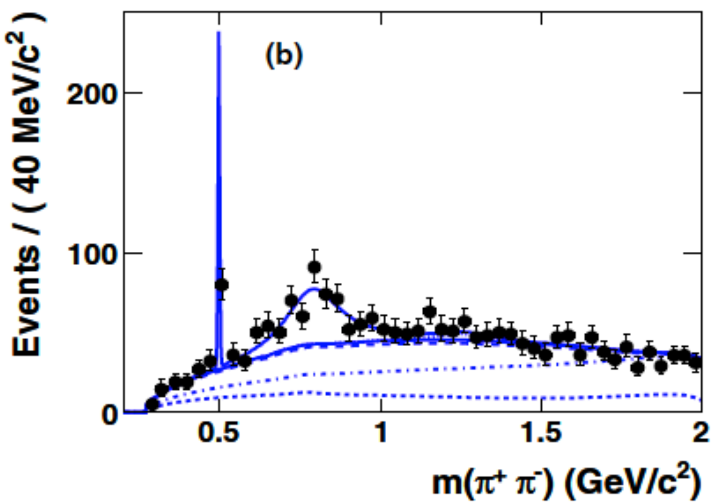
arXiv:1411.1634



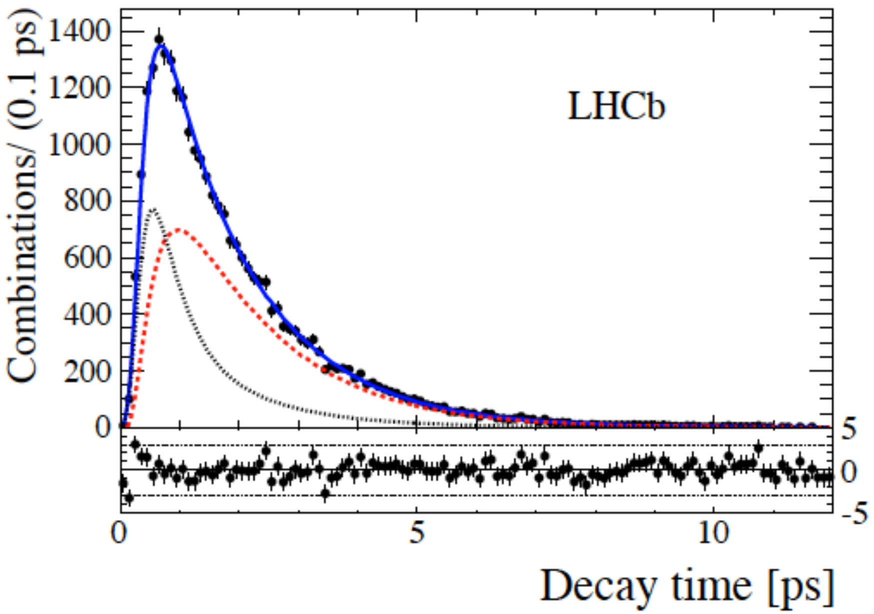


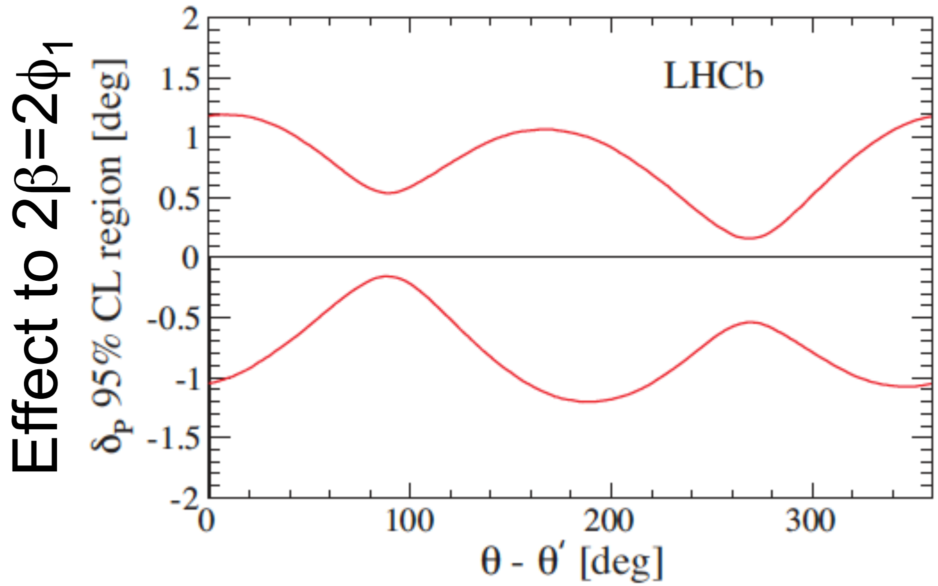
One order of magnitude difference in signal yield.

BaBar (382M B-pairs) PRD76,031101(2007)



Resultant constraint





Strong phase diff.

65% of the $B^0 \to J/\psi\ \pi^+\pi^-$ signal is $J/\psi\ \rho^0$.

Longitudinal polarization has largest fraction, mostly CP-even, CP-odd component is 20%.

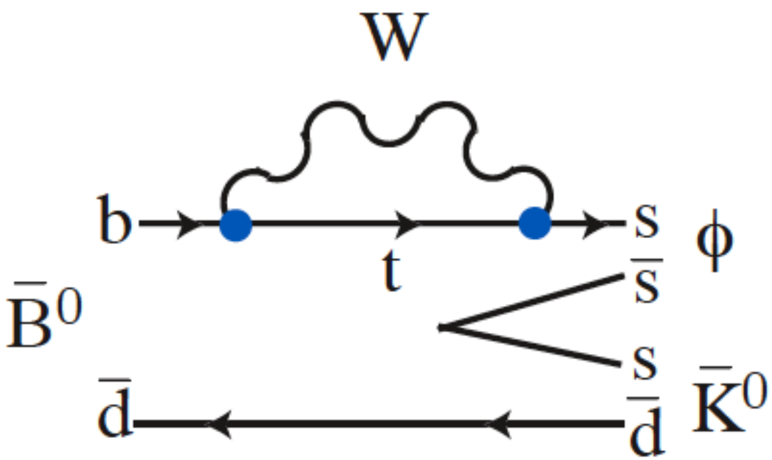
$2\beta_{eff}=2\phi_1^{eff}=41.7\pm9.6+2.8/-6.3°$ →Penguin effect <1° in $J/\psi\ K^0$!

$B^0 \to J/\psi\ \pi^0$ mode also gives such a constraint.

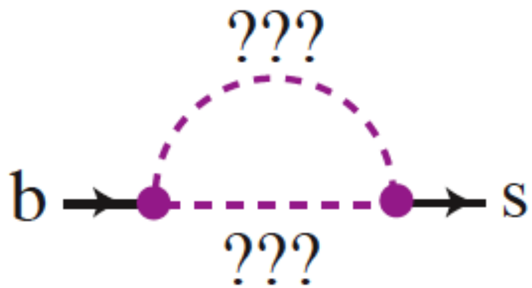
Lesson from this

- Thanks to large b-hadron production rate, LHCb is good at determination of intermediate states' information in multi-body B decays.
- Using it as external information, it may be worth to analyze an e^+e^- B-factory data to get CP violation parameters featuring much higher effective tagging efficiency.

New physics search in loop; penguin decays



as well as

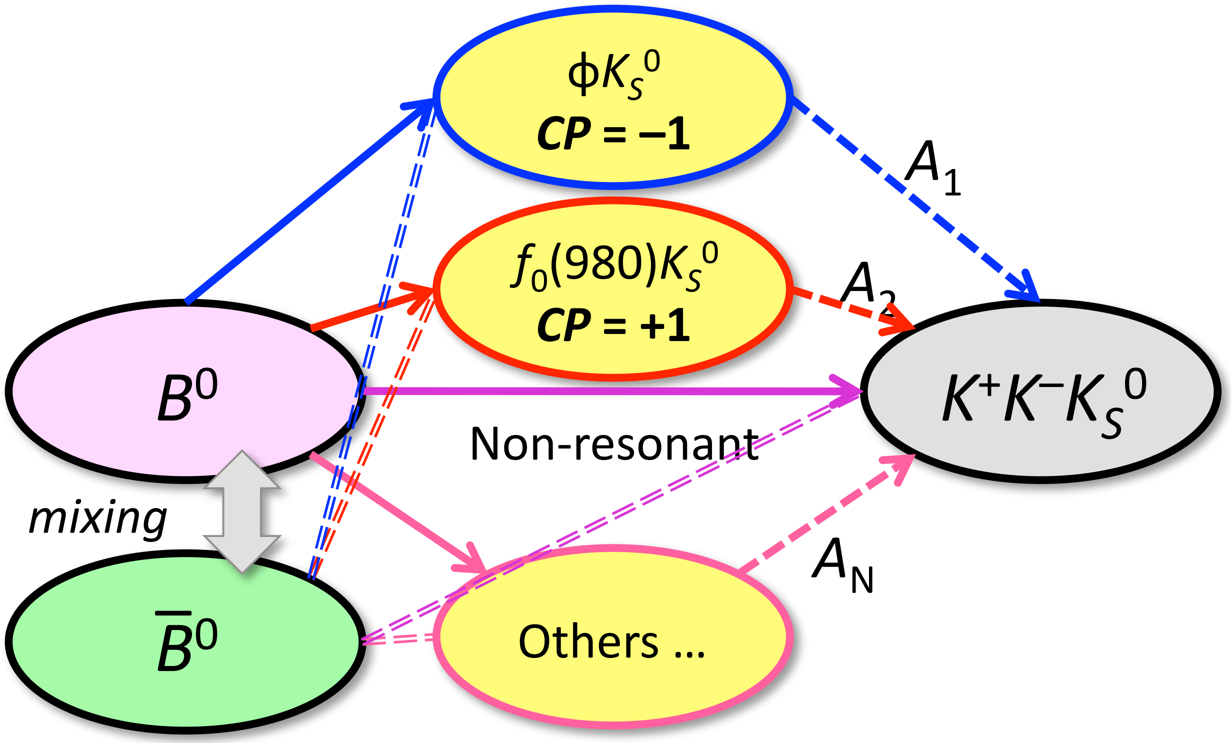


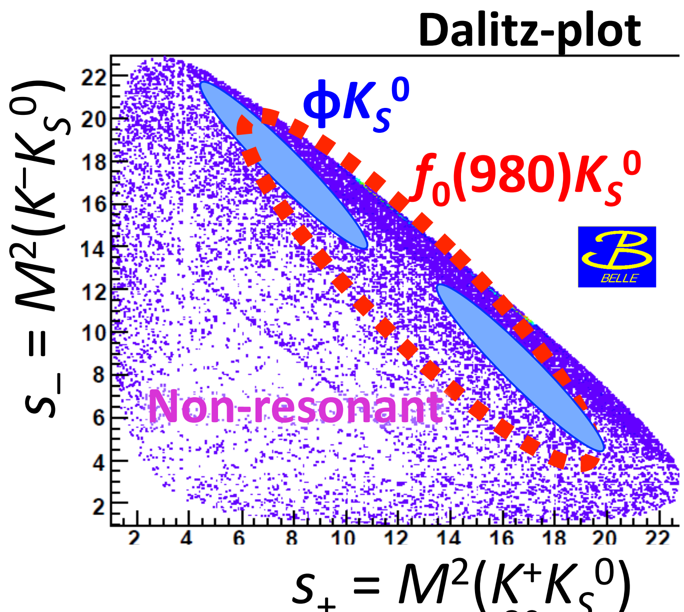
SM penguin;
No complex phase in decay.

New Physics in the loop;
may have a different weak phase.
CPV deviation from J/ψ K^0 is a signature of New Physics.

Several contributions are overlapping

- $B^0 \to K^+K^-K_S$ final state has several different paths.
- Resolve them by fitting the Dalitz distribution. Same approach is required for $B^0 \to \pi^+\pi^-K_S$.
- LHCb better to determine intermediate states composition? (though production rate gain lower in the modes with a K_S)





Summary

- $\sin 2\beta = \sin 2\phi_1$ determination by $b \to c\bar{c}s$ is further investigated by $b \to c\bar{u}d$ and $b \to c\bar{c}d$ mediated B_d decays, $B^0 \to D^0 h^0$ (BaBar+Belle) and $B^0 \to J/\psi \pi^+ \pi^-$ (LHCb), respectively.
- Interplay between hadron end lepton machines are interesting for multi-body B decay modes?
  - Large production at LHCb → determination of intermediate states information
  - Higher effective flavor tagging efficiency at BaBar, Belle/Belle II → CPV improved by external information?
- We should be innovative to realize "state-of-art" approaches to maximize sensitivity to NP.