CP Violation

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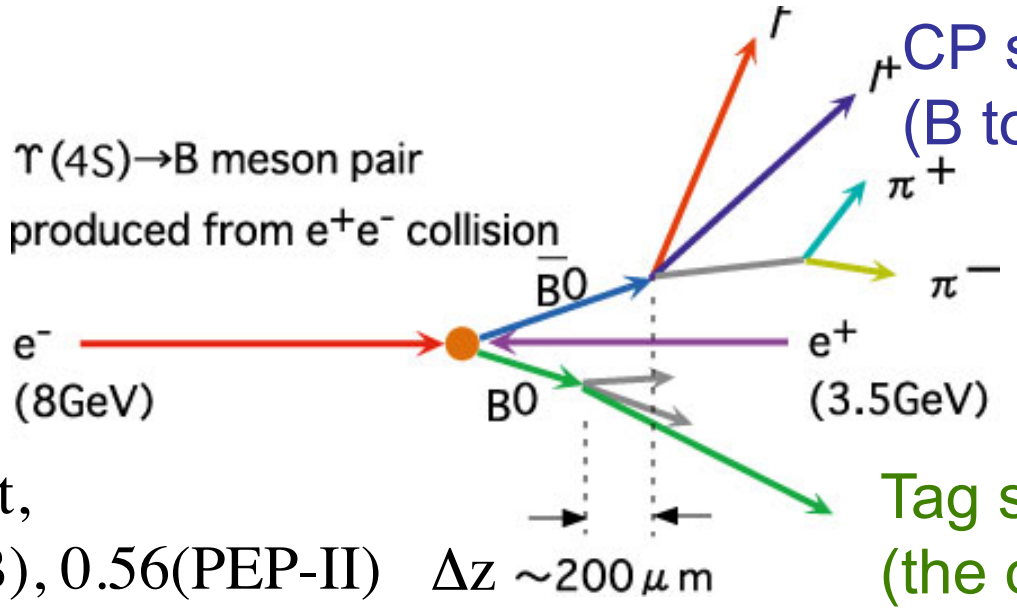
Outline

- Time-dependent CP violation at $\Upsilon(4S)$ and LHCb
- Mixing induced CP violation in B_d decays
  - $\sin 2\phi_1 = \sin 2\beta$ measurement at LHCb
  - $B_d \to D_{CP}\, h^0$ BaBar+Belle joint analysis
  - $B_d \to \rho^+\rho^-$ time-dependent CPV at Belle
  - $\phi_3 = \gamma$
- Mixing induced CP violation in B_s decays
  - ϕ_s determinations in pp colliding beam experiments
  - $B_d \to J/\psi\, \pi^+\pi^-$ study at LHCb to constrain penguin
- Charm CP violation
- Summary

Time-dependent CPV at ϒ(4S)

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



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

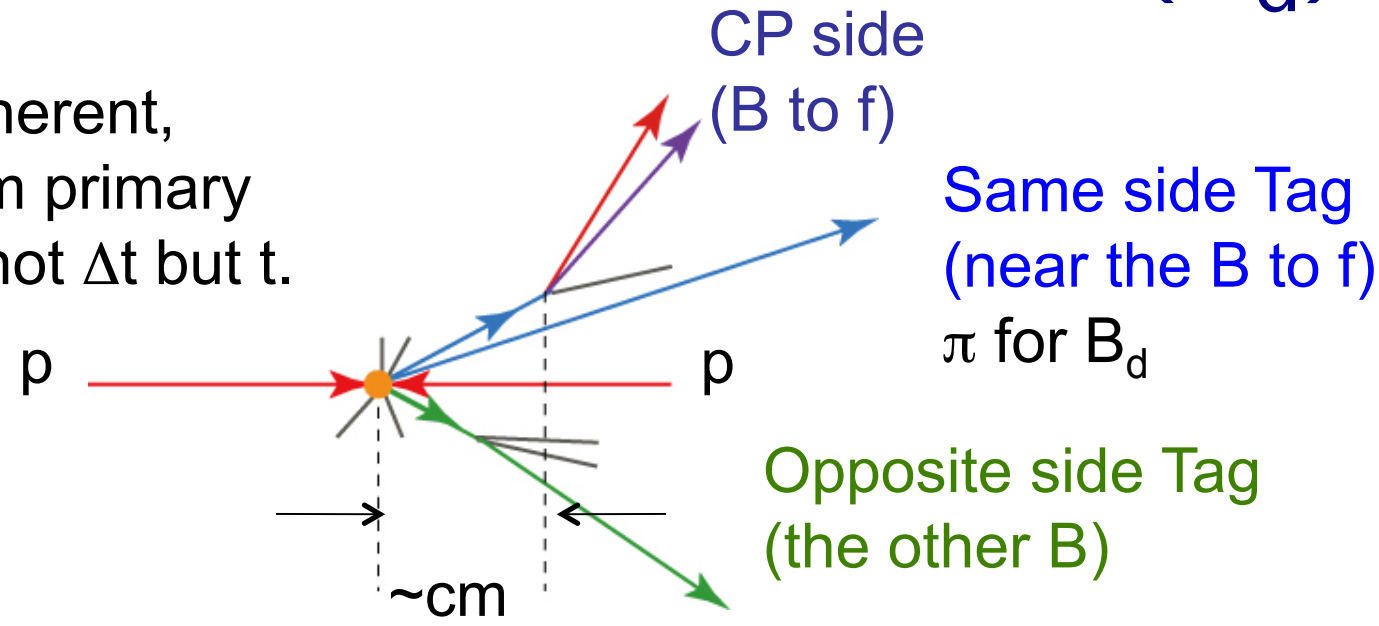
$\beta\gamma = 0.425(\mathrm{KEKB}), 0.56(\mathrm{PEP\text{-}II})$

$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)}{\Gamma(\overline{B}^0(\Delta t) \to f) + \Gamma(B^0(\Delta t) \to f)} = \mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t)$$

$$\mathcal{S}_f = \frac{2\Im(\lambda)}{|\lambda|^2 + 1} \qquad \mathcal{A}_f = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \qquad \lambda = \frac{q}{p}\frac{\bar{A}(f)}{A(f)} \qquad -\mathcal{C}_f = \mathcal{A}_f$$

Time-dependent CPV at LHCb (B_d)

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



B_d case:

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = \mathcal{S}_f \sin(\Delta m_d t) + \mathcal{A}_f \cos(\Delta m_d t)$$

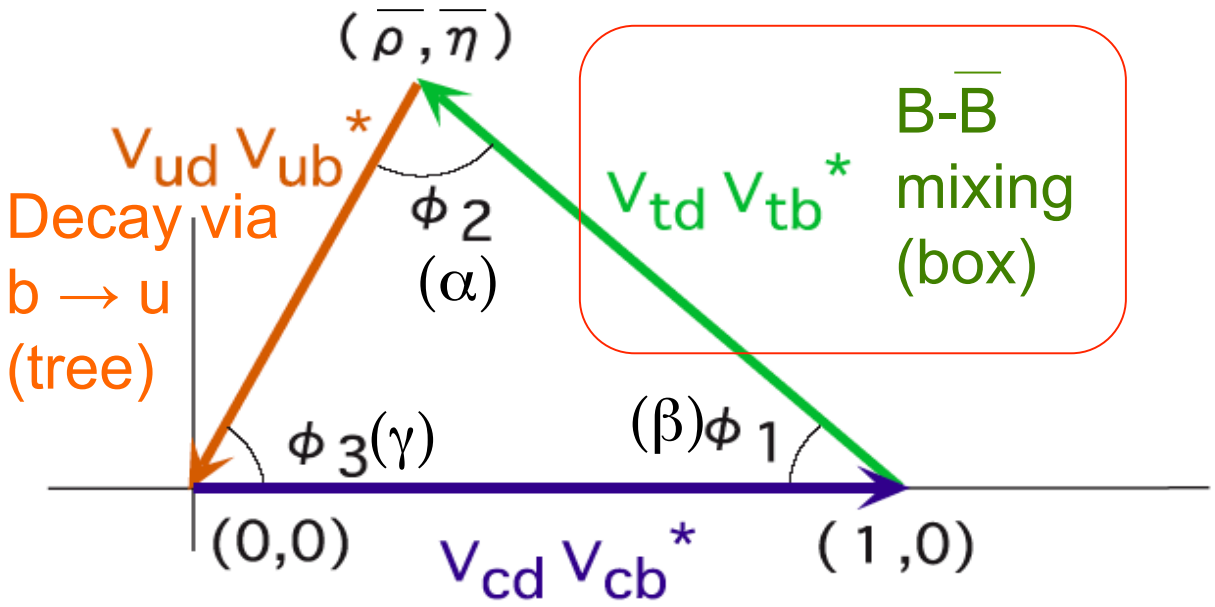
For B_s, will revisit later.

Comparison

	Number of equiv. 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 (~1/3×τ_B)	Coherent oscillation	
LHCb	1000~2000 million/fb^{-1}	$\varepsilon(1-2w)^2$ =3%	50~60 fs	Incoherent oscillation	No tag side interference

ε : tagging efficiency, w : wrong tag fraction.
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.

Unitarity triangle for B_d (and $B^{\pm}$)



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

Decay via b → s (penguin) to hunt NP. If the SM leading term only,

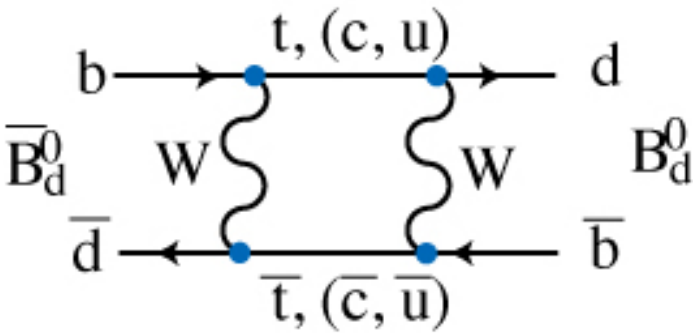
$$\mathcal{S}_f = -\eta_f \sin 2\phi_1 = -\eta_f \sin 2\beta \qquad \mathcal{A}_f = 0$$

where η_f is CP eigenvalue.

In B→VV case, need to solve admixture by angular analysis.

$\beta=\phi_1$ determined by b→c decays

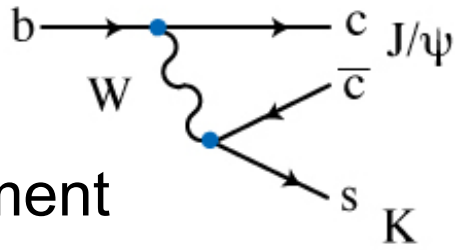
Mixing



Interferes with

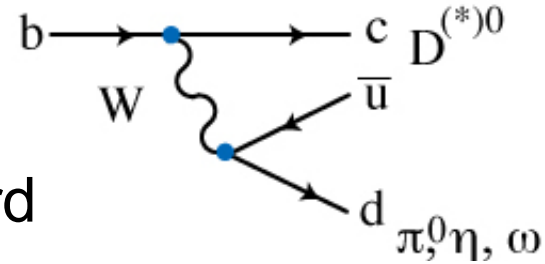
b→c$\bar{c}$s

Flagship measurement



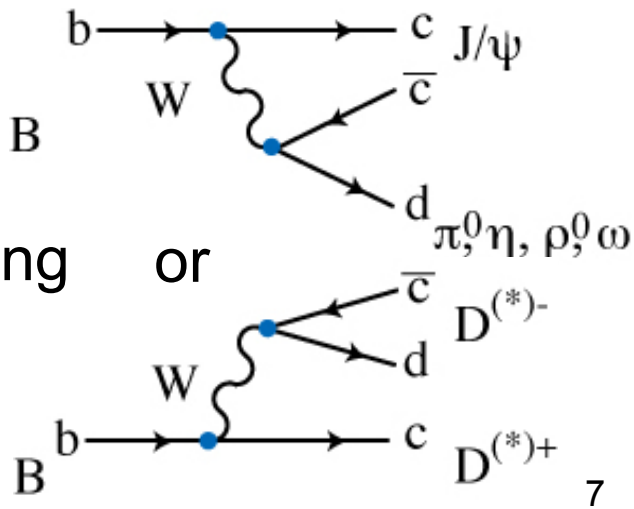
b→c$\bar{u}$d

Gives new standard

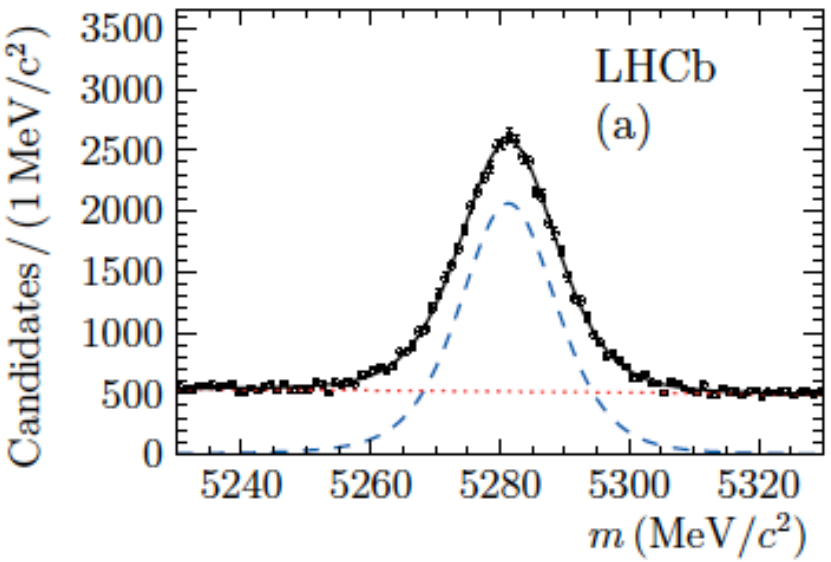


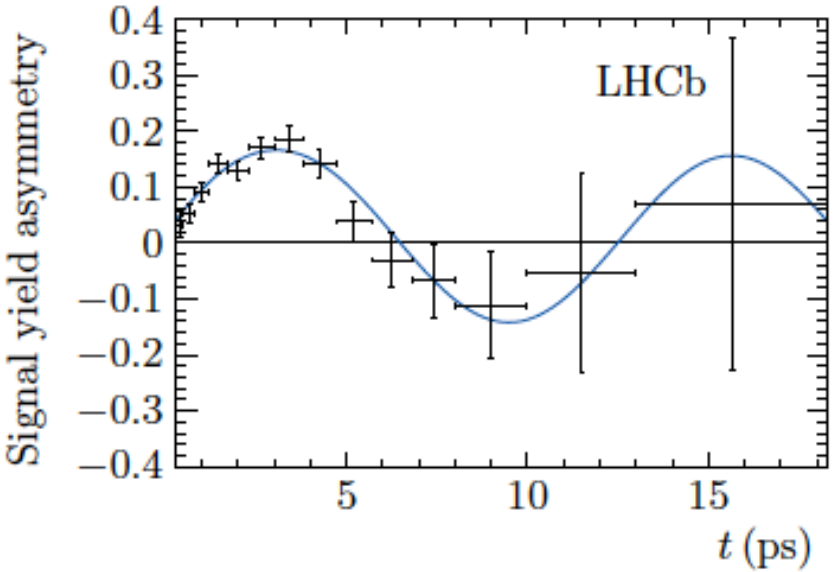
b→c$\bar{c}$d

Another interesting approach



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





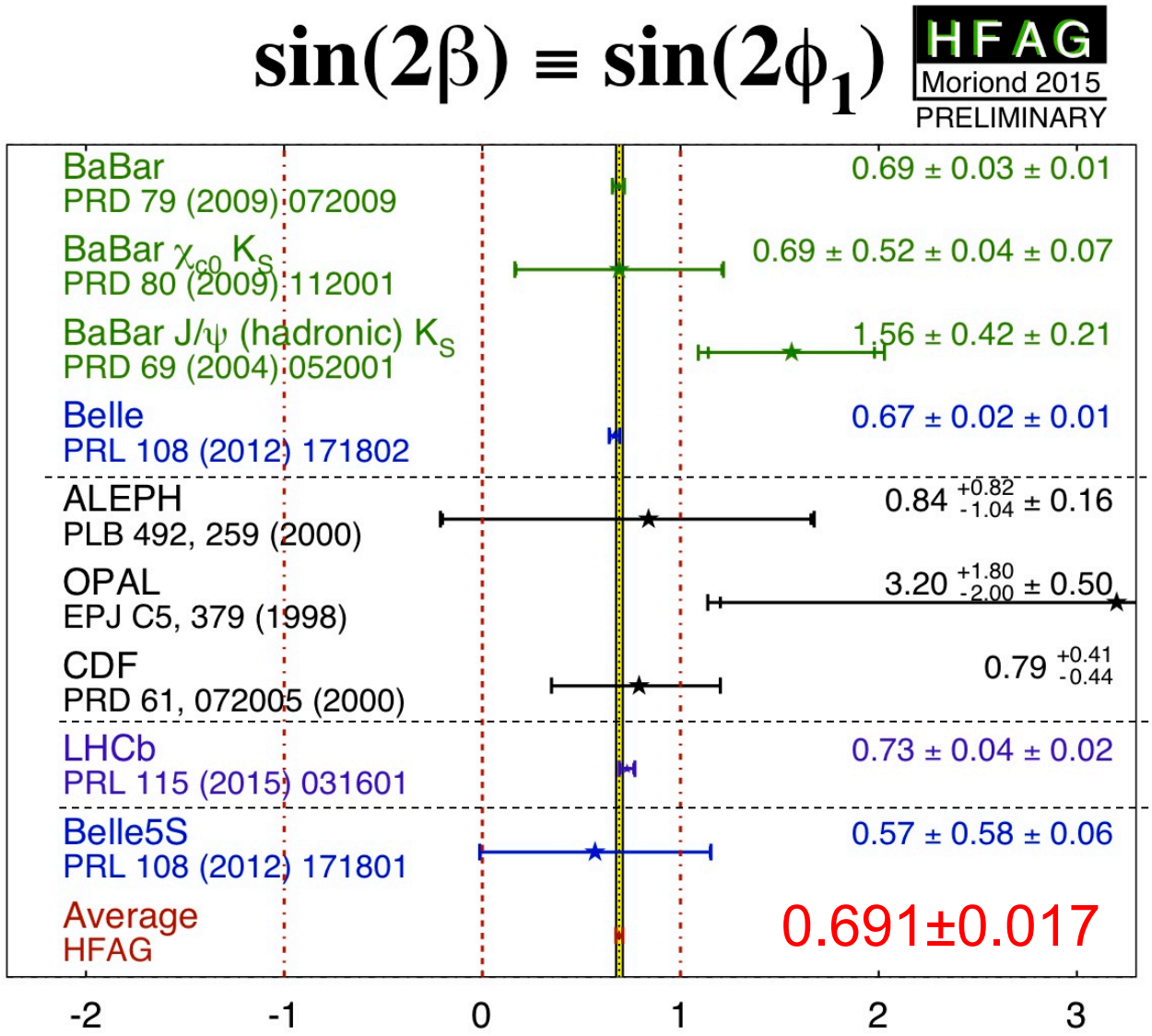
$\sin 2\beta = \sin 2\phi_1 = 0.731 \pm 0.035 \pm 0.020$

$C_f = -A_f = -0.038 \pm 0.032 \pm 0.005$

PRL115(2015)031601

LHCb's capability has been demonstrated.

Now it is a firm SM reference

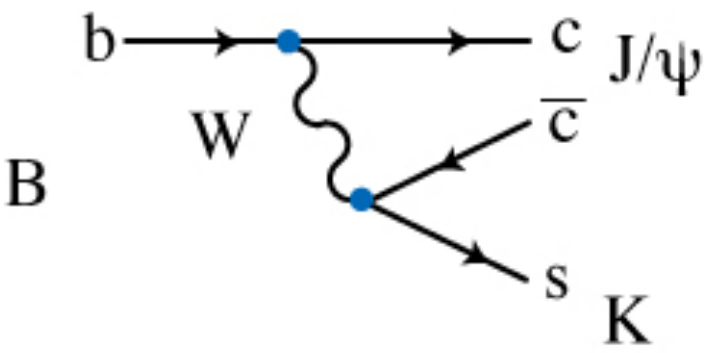


Measurements by B-factories

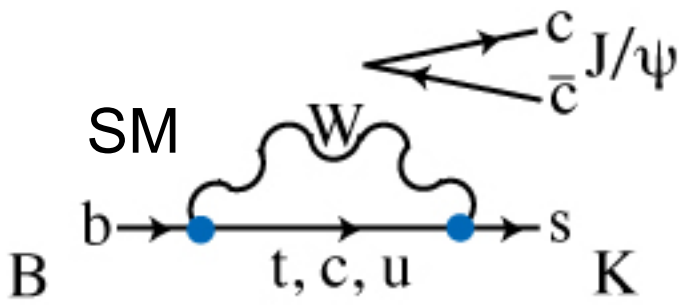
Measurements before B-factories

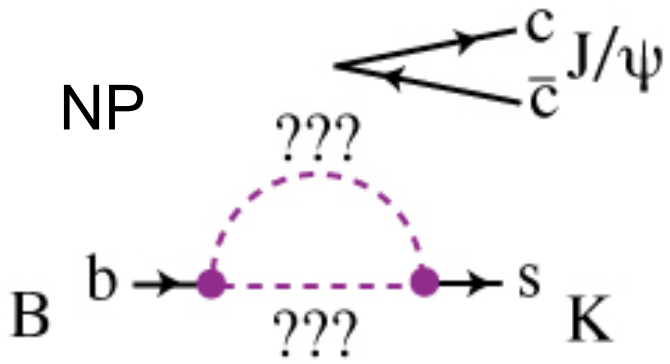
LHCb starts to bring competitive results with B-factories.

How firm is it?



Leading : Tree
No complex phase
in decay amplitude

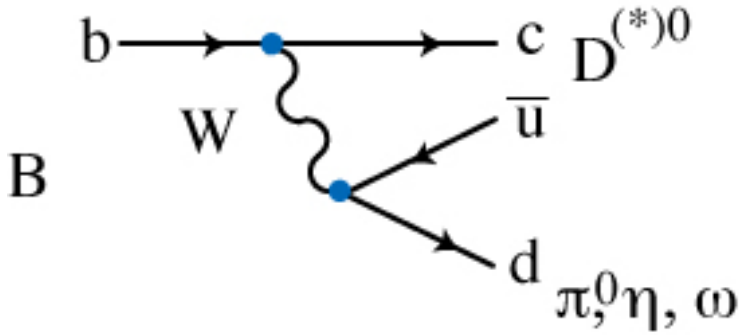


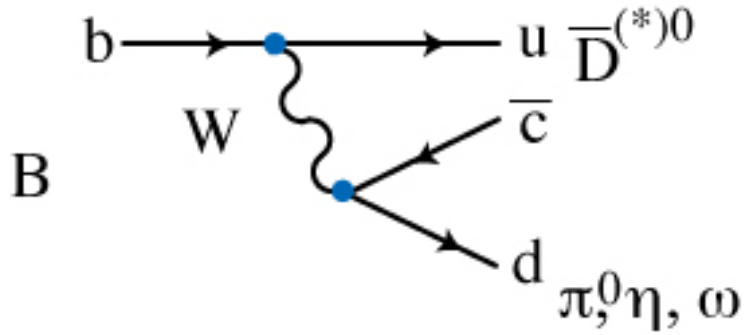


Sub-Leading : Penguin
In principle, New Physics
contribution might not be zero,
how it can be constrained?

Penguin free B decays, $b \to c\bar{u}d$

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





Leading : Tree
No complex phase
in decay amplitude

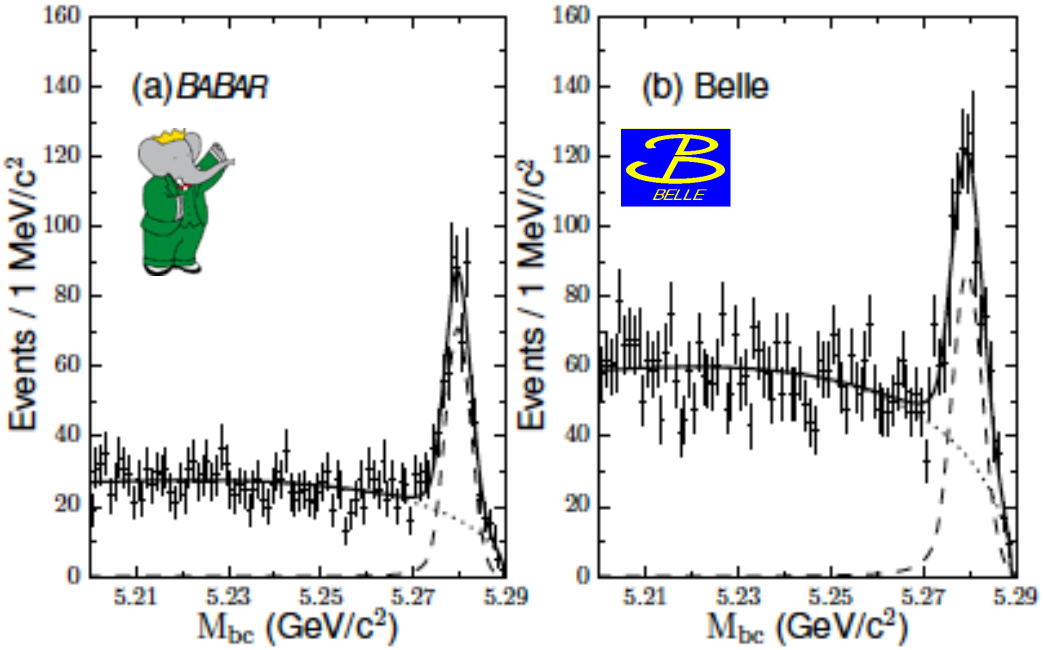
Sub-Leading : also Tree
V_{ub} has complex phase,
but it is within the SM, to be
under control.

When neutral D meson decays to CP eigenstates, suitable to get $\phi_1 = \beta$, branching fraction is limiting factor.

To appear in PRL

$B_d \to D_{CP} h^0$
BaBar+Belle joint analysis

arXiv:1503.07089, to appear PRL



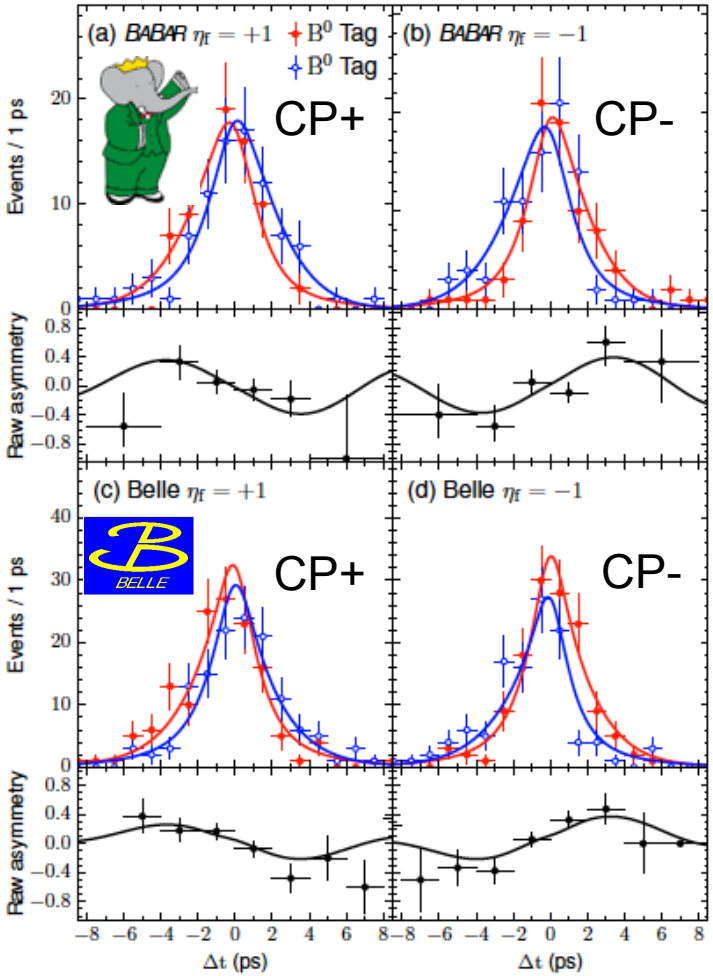
$B^0 \to D^{(*)0} h^0$, $h^0 = \pi^0, \eta, \omega$

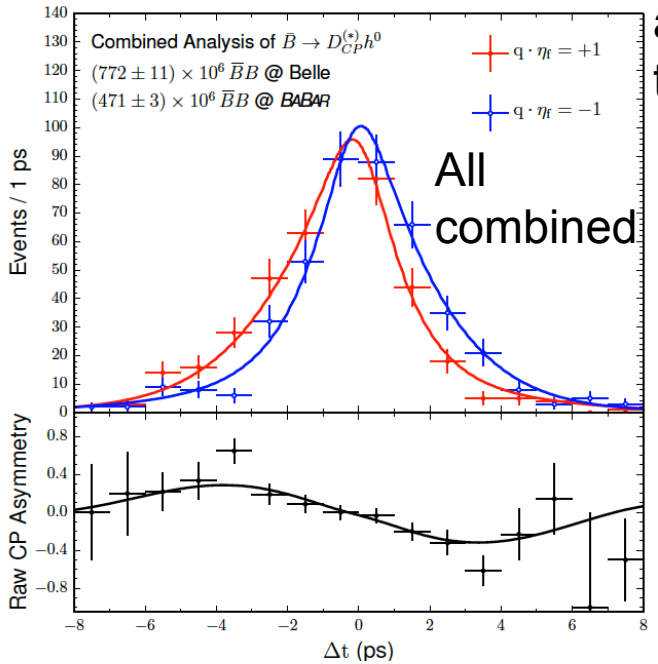
$D^0 \to K^+K^-$, $K_S\pi^0$ and $K_S\omega$

N_{sig} = 508±31events(BaBar) + 757±44events(Belle)

To appear in PRL

$B_d \to D_{CP} h^0$ BaBar+Belle joint analysis





arXiv:1503.07089, to appear PRL

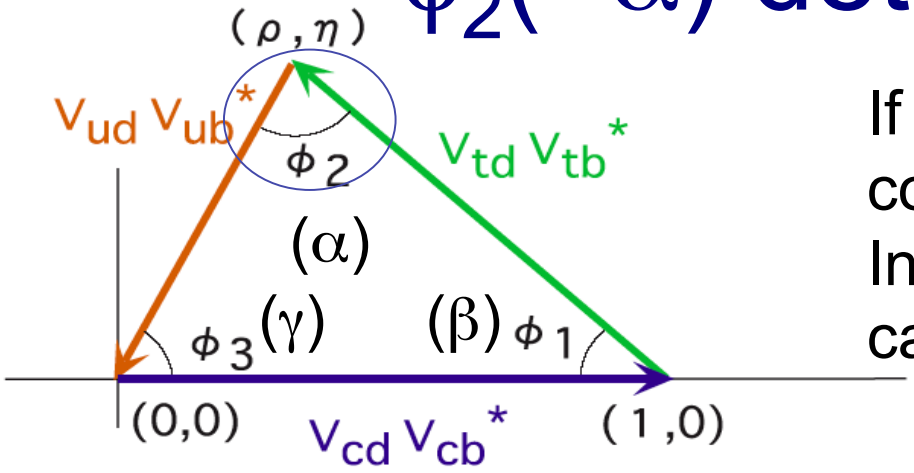
First observation of CPV(5.4σ)!

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

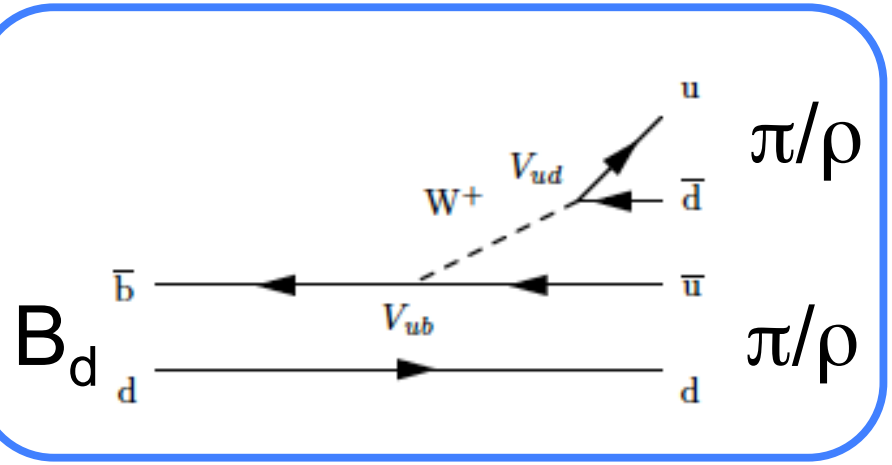
$\to \delta \sin 2\phi_1 \sim 0.015$ @Belle II ($50\,ab^{-1}$)

$C_f = -A_f = -0.02 \pm 0.07 \pm 0.03$

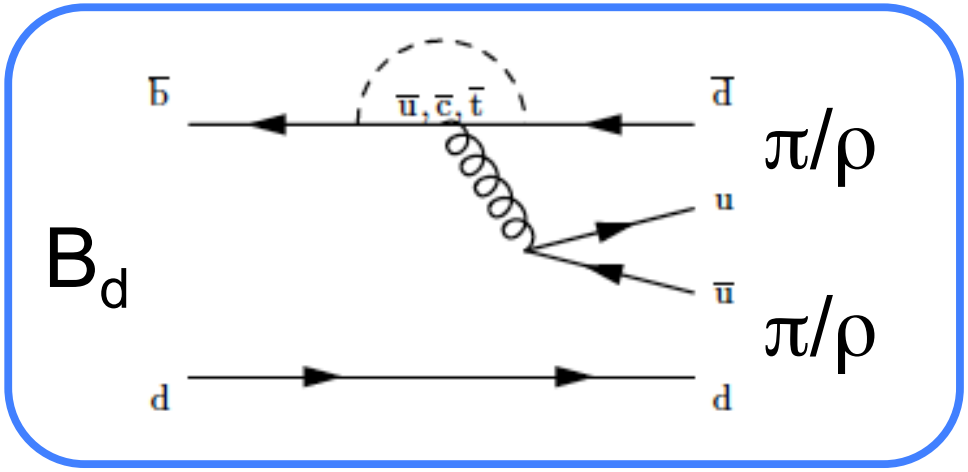
$\phi_2(=\alpha)$ determination



If tree only, S_f is directly connected to $\sin 2\phi_2$ and $A_f=0$. Interference with $b\rightarrow d$ penguin can be solved by isospin analysis.



Decay diagram (tree)

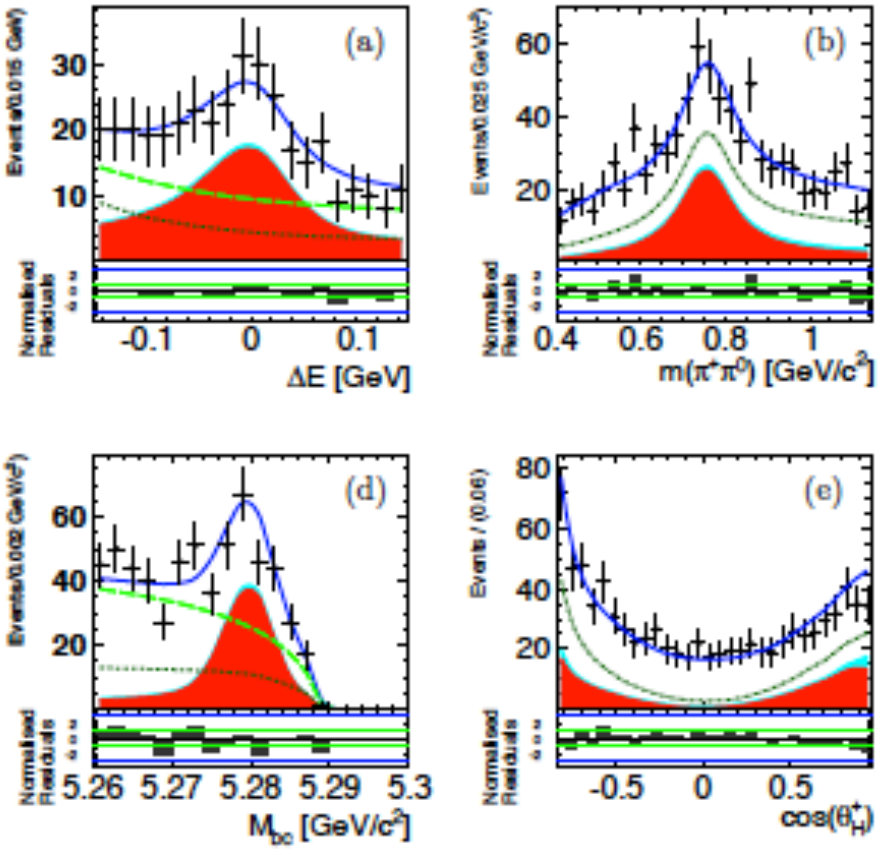


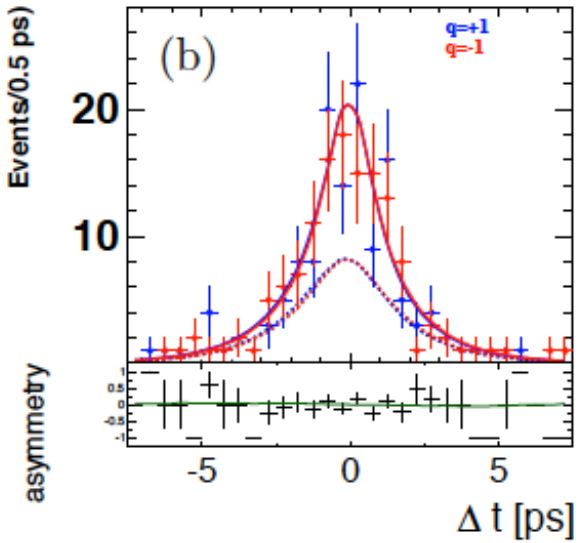
Decay diagram (penguin)

This summer, new Belle $B_d\rightarrow \rho^+\rho^-$ result comes.

New

$B_d \to \rho^+\rho^-$ with Belle full $\Upsilon(4S)$ data





$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (28.3 \pm 1.5\ (\text{stat}) \pm 1.5\ (\text{syst})) \times 10^{-6},$$
$$f_L = 0.988 \pm 0.012\ (\text{stat}) \pm 0.023\ (\text{syst}),$$
$$\mathcal{A}_{CP} = 0.00 \pm 0.10\ (\text{stat}) \pm 0.06\ (\text{syst}),$$
$$\mathcal{S}_{CP} = -0.13 \pm 0.15\ (\text{stat}) \pm 0.05\ (\text{syst}).$$

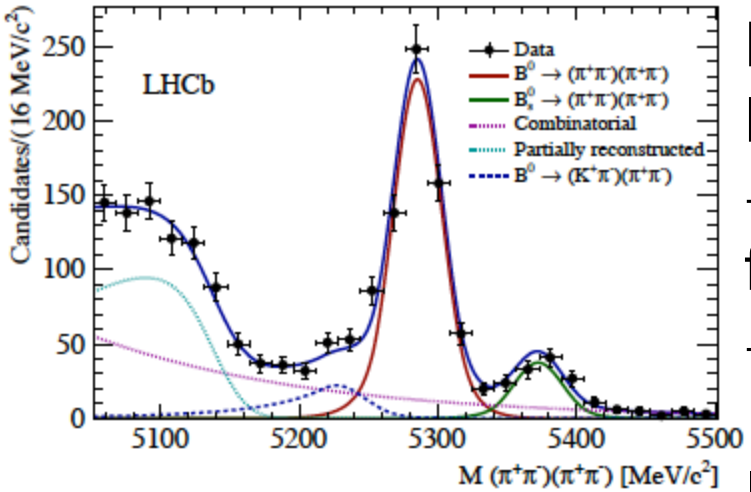
Precision improvement w.r.t. previously published result is factor 2.

Increase of data, simultaneous extraction of observables and analysis optimization for high signal yield.

Just appeared in PLB

LHCb $B_d \to \rho^0\rho^0$

PLB747(2015)468



$N_{sig}(B_d \to (\pi^+\pi^-)(\pi^+\pi^-)) = 634 \pm 28 \pm 8$ events

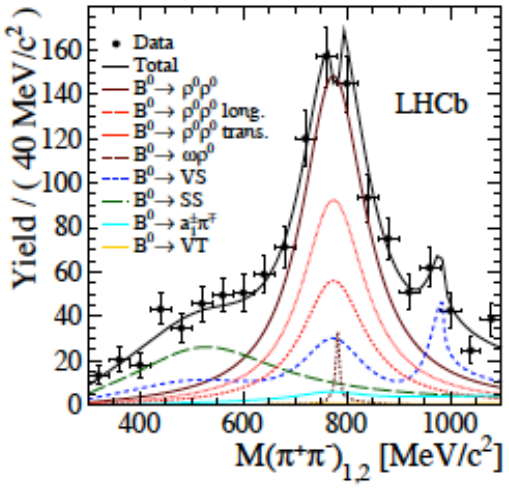
$Br(B_d \to \rho^0\rho^0) = (0.94 \pm 0.17 \pm 0.09 \pm 0.06) \times 10^{-6}$

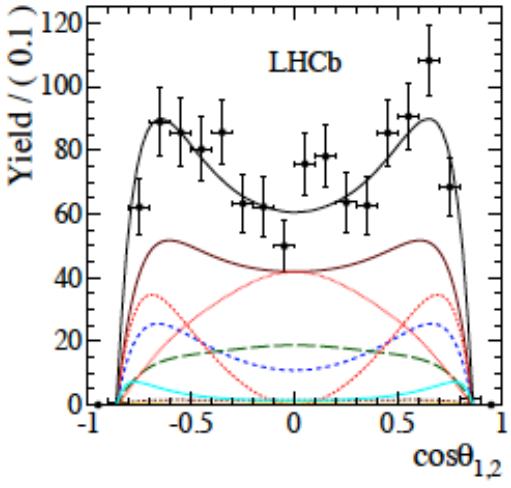
→the most precise to date.

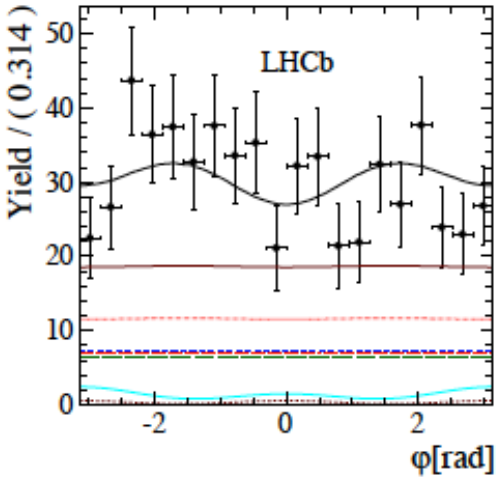
$f_L = 0.745\ ^{+0.048}_{-0.058} \pm 0.034$

→consistent with BaBar, 2.3σ away Belle.

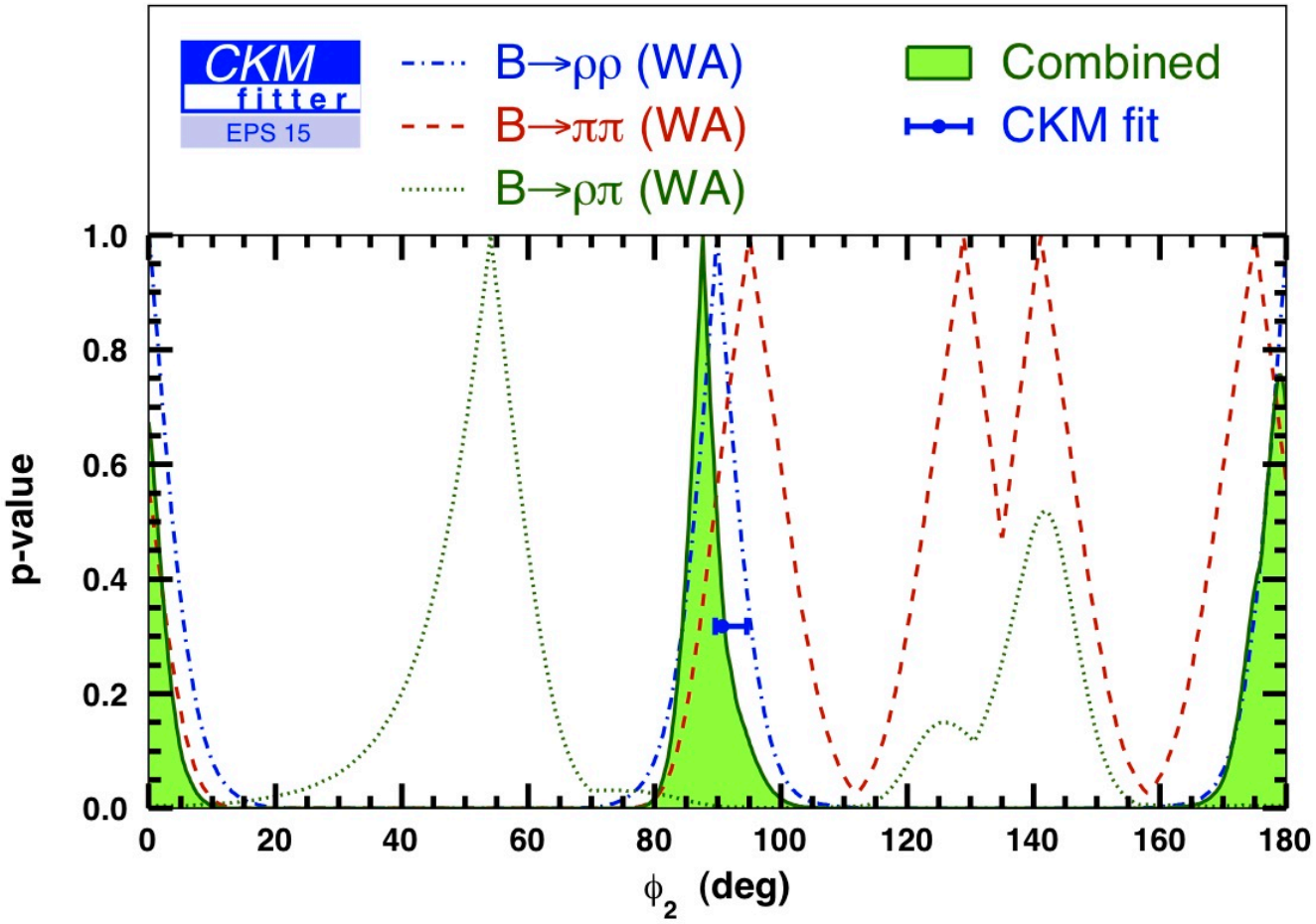
Important input to constrain $\phi_2 = \alpha$.





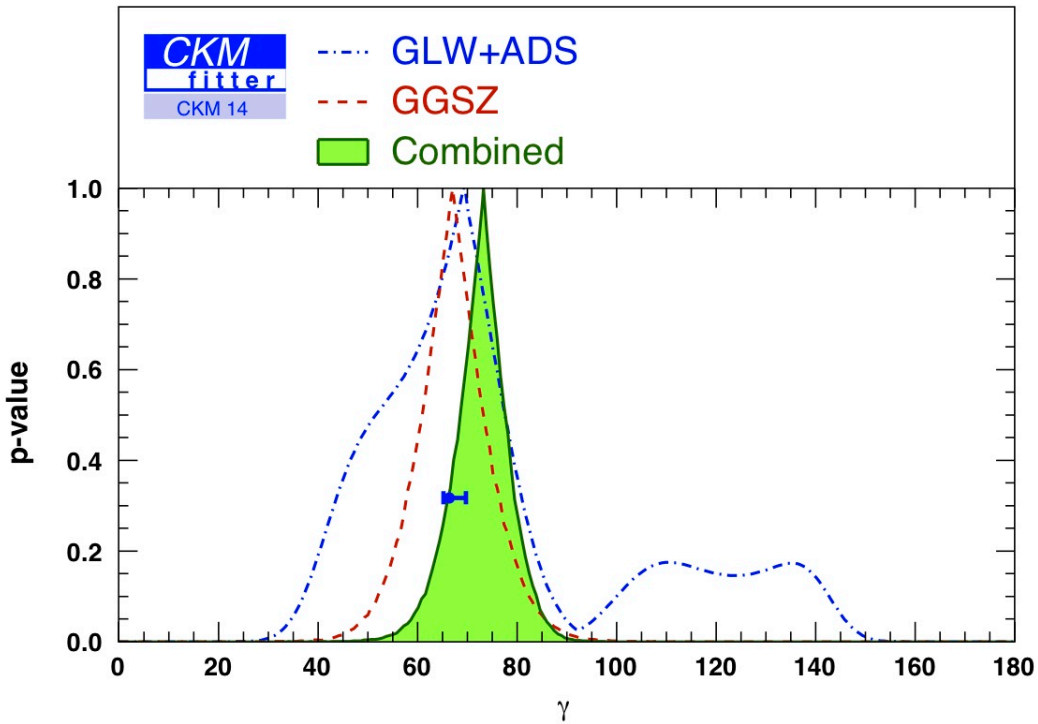


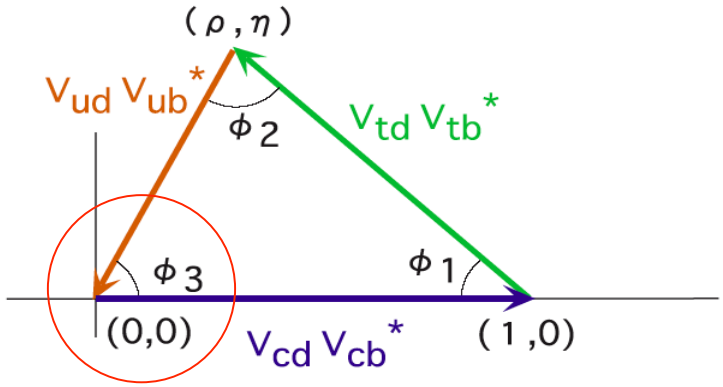
The most updated $\phi_2=\alpha$



$\phi_2=\alpha=90.6\ ^{+3.9}_{-1.1}\ °$

$\phi_3=\gamma$



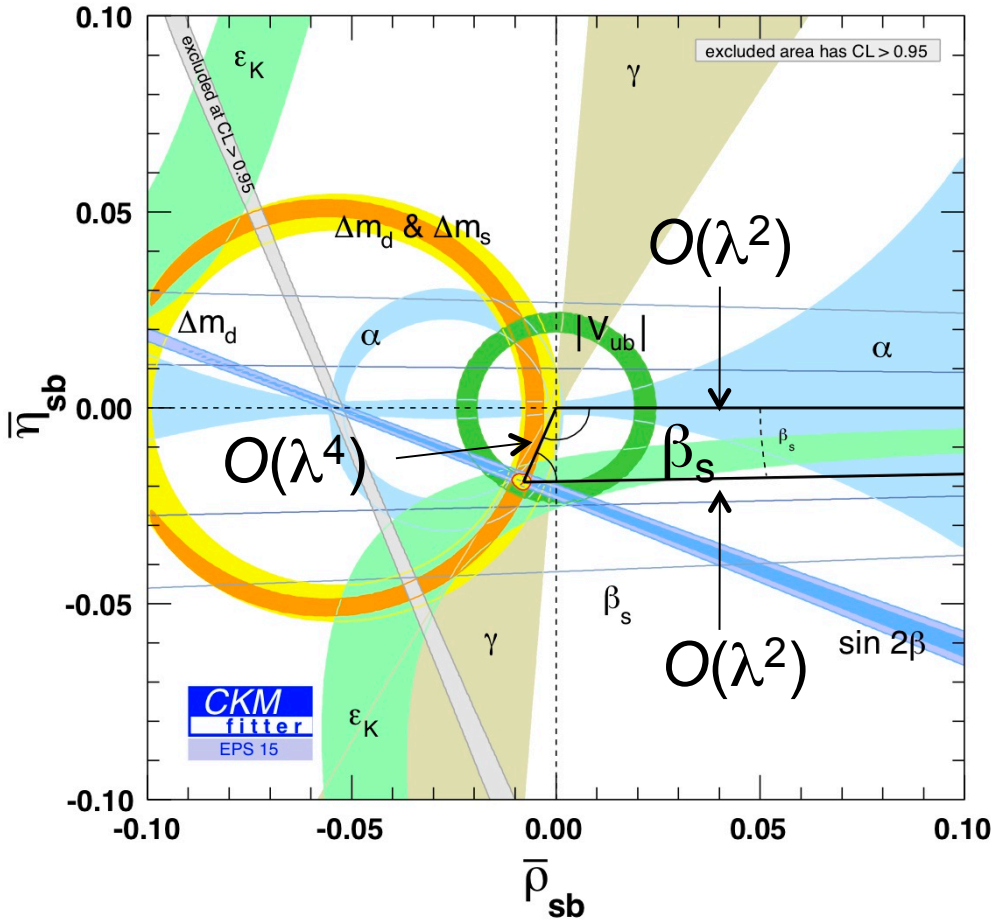


GLW : $B^{\pm}\rightarrow D_{CP} K^{\pm}$
ADS : Asymmetry in suppressed D decay
GGSZ : Dalitz in $D^0\rightarrow K_S h^+h^-$

$\phi_3=\gamma=73.2\ ^{+6.3}_{-7.0}\ °$

New attempts to access $\phi_3=\gamma$ come out, $B^+\rightarrow D(h^+h^-\pi^0)h^+$ (PRD91(2015)112014) and $B^+\rightarrow Dh^+\pi^+\pi^-$ (arXiv:1505.07044), but No major change in $\phi_3=\gamma$ itself from last year.

Mixing induced CP violation in B_s



Another unitarity triangle.

$\lambda=\sin\theta_c$, β_s is $O(\lambda^2)=O(10^{-2})$

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

$\phi_s = -2\beta_s + \Delta\phi_s^P + \delta^{NP}$

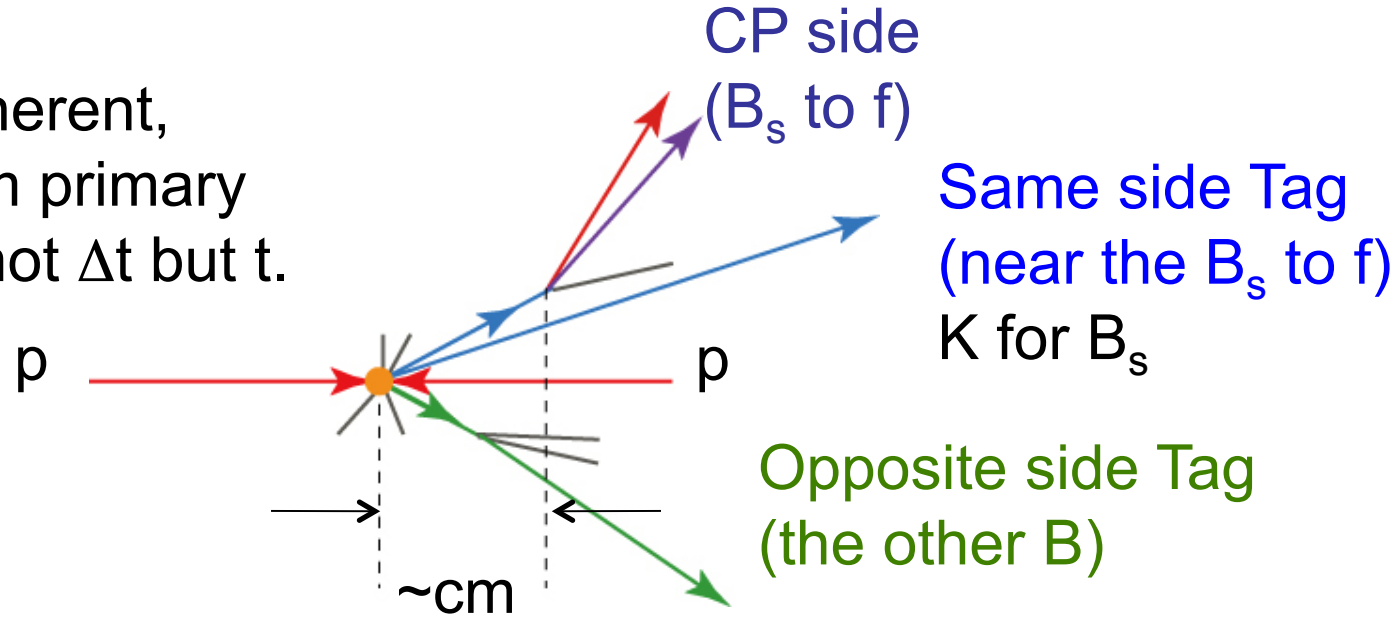
Mixing & decay (Tree) | Penguin | Possible NP

CKMfitter gives ϕ_s(SM, No Penguin) $=-2\beta_s=-0.0365+0.0013/-0.0012$

Possible to extract ϕ_s by $b\to c\bar{c}s$ induced B_s decays to f_{CP}.

Time-dependent CPV at LHCb (B_s)

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



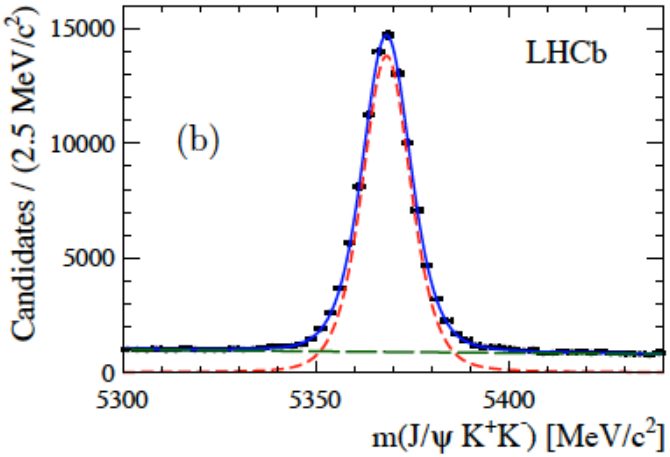
$$A_{CP}(t) = \frac{\Gamma(\overline{B}_s{}^0(t) \to f) - \Gamma(B_s^0(t) \to f)}{\Gamma(\overline{B}_s{}^0(t) \to f) + \Gamma(B_s^0(t) \to f)} = \frac{\mathcal{S}_f \sin(\Delta m_s t) + \mathcal{A}_f \cos(\Delta m_s t)}{\cosh(\Delta\Gamma t/2) + \mathcal{A}_{\Delta\Gamma} \sinh(\Delta\Gamma t/2)}$$

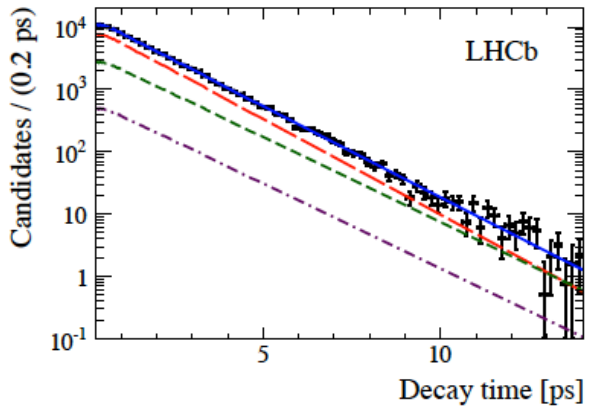
$$\Delta m_s = m_{\mathrm{H}} - m_{\mathrm{L}} \qquad \Delta\Gamma = \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}}$$

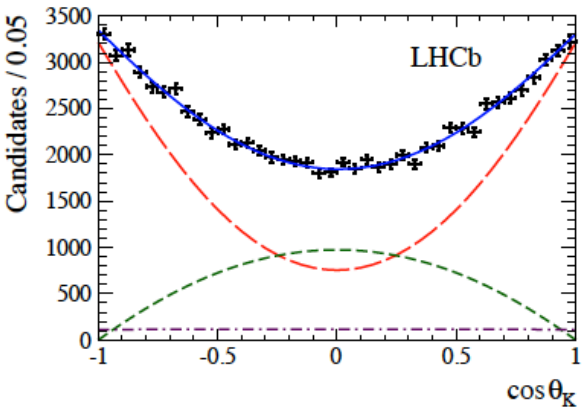
$$\mathcal{S}_f = \frac{2\Im(\lambda)}{|\lambda|^2+1} \qquad \mathcal{A}_f = \frac{|\lambda|^2-1}{|\lambda|^2+1} \qquad \mathcal{A}_{\Delta\Gamma} = -\frac{2\Re(\lambda)}{1+|\lambda|^2} \qquad -\mathcal{C}_f = \mathcal{A}_f$$

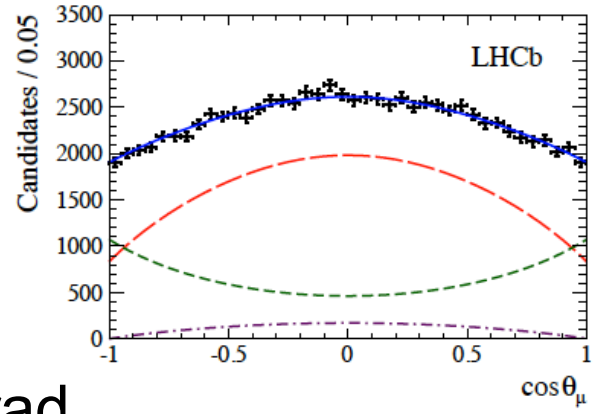
ϕ_s determination by $B_s \to J/\psi\, K^+K^-$

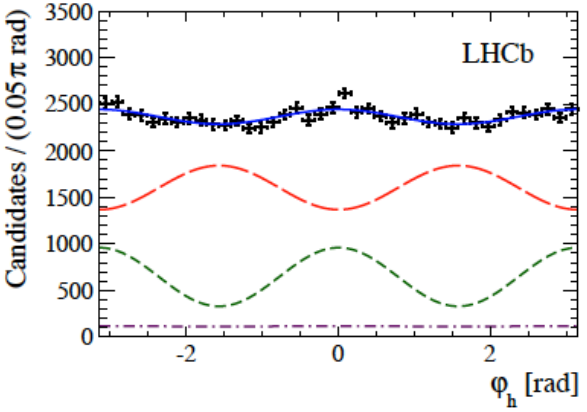
PRL114(2015)041801











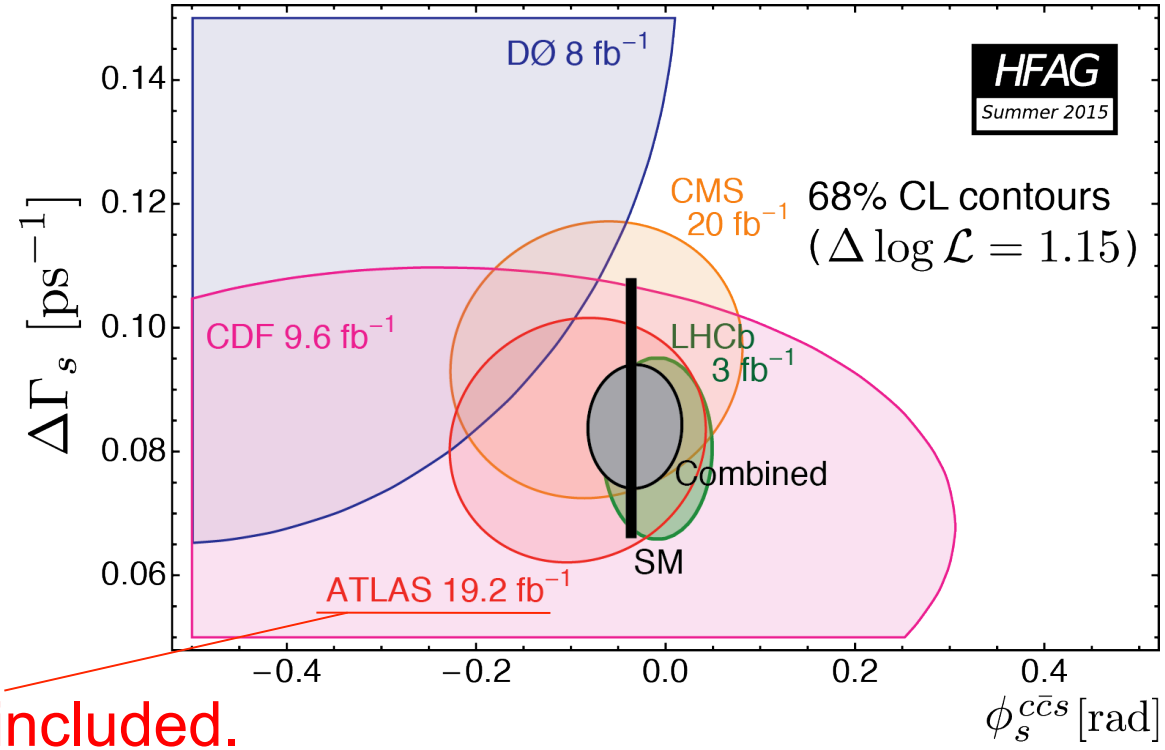
Angular analysis to disentangle polarization states

ϕ_s=-0.058±0.049±0.006 rad

Γ_s=0.6603±0.0027±0.0015 ps^{-1}

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

Recent situation for ϕ_s and $\Delta\Gamma$

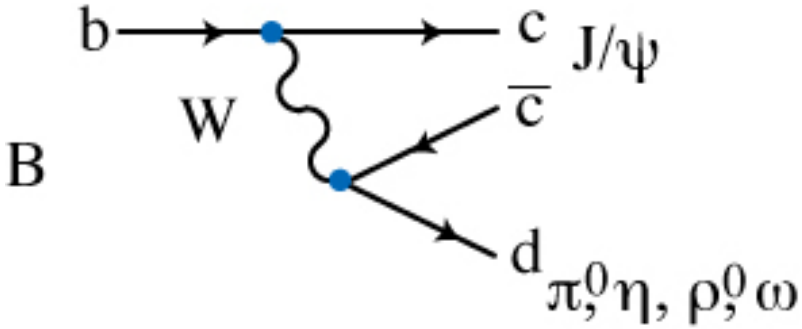


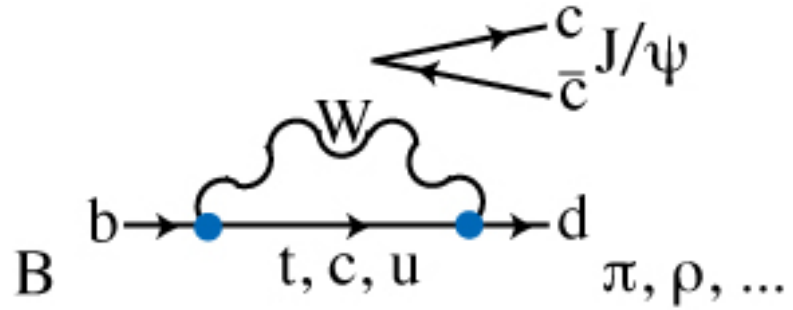
New

2012 data included.

$B_s \to J/\psi\, K^+K^-$(ATLAS, CMS, LHC_b), $B_s \to J/\psi\pi^+\pi^-$(LHCb) and $B_s \to D_s^+D_s^-$(LHC_b) combined: ϕ_s = -0.034±0.033 rad.

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





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 b→ccs modes are constrained.

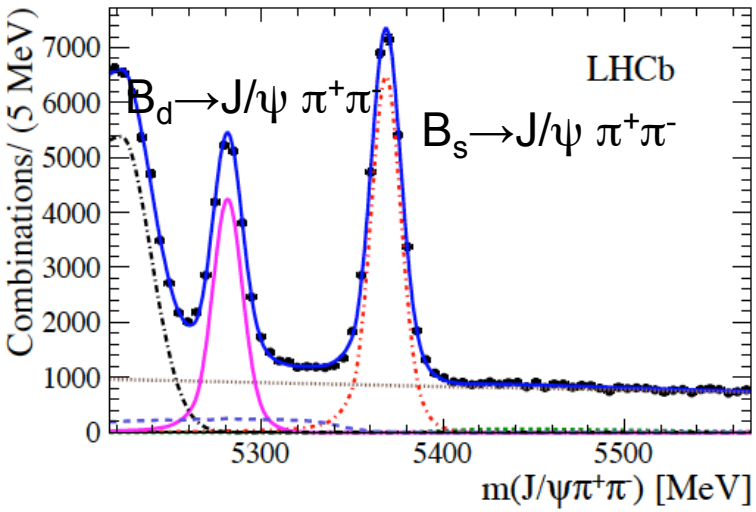
$B_d\to J/\psi\ \pi^0 \to B_d\to J/\psi\ K^0$

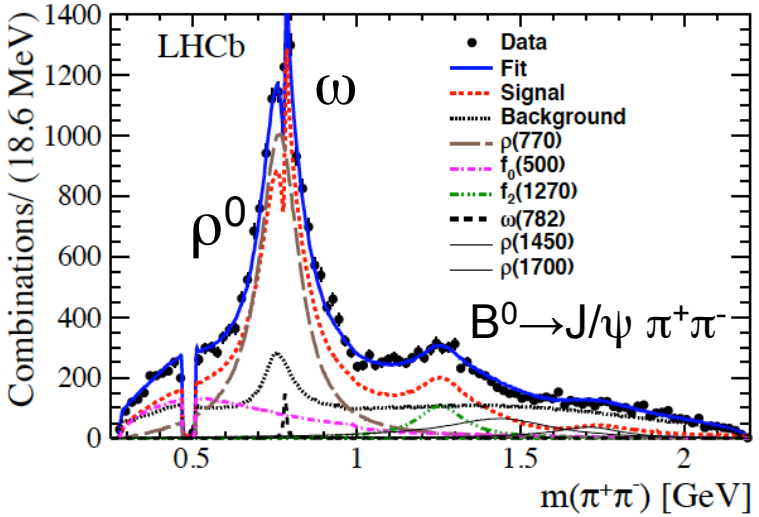
$B_d\to J/\psi\ \rho^0$, $B_s\to J/\psi\ K^* \to B_s\to J/\psi\ \phi$

PRL95(2005)221804
PRD79(2009)014030
PRD79(2009)014005

LHCb study of $B_d \to J/\psi\, \pi^+\pi^-$

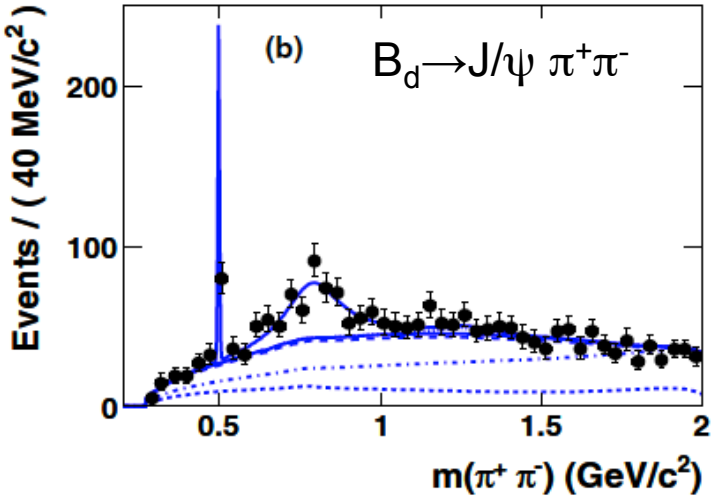
PLB742(2015)38





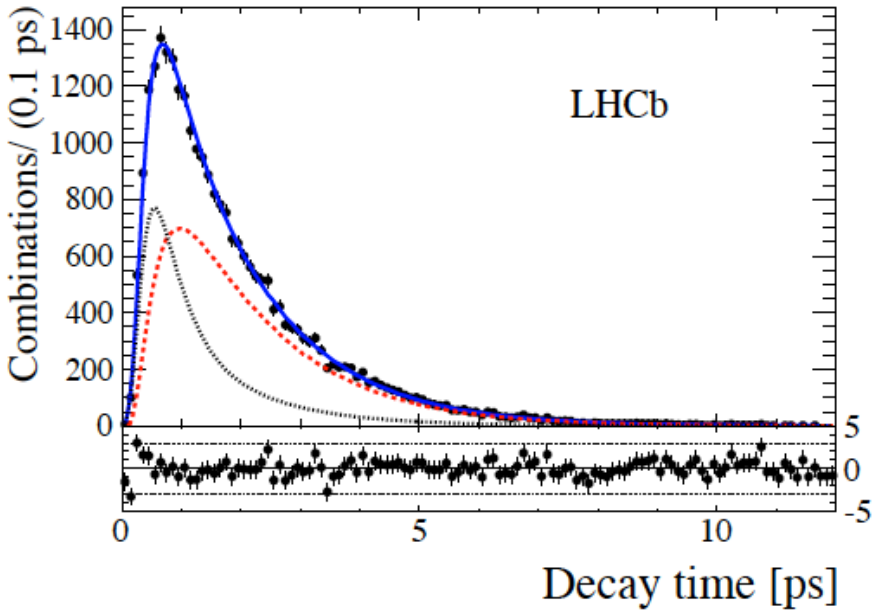
One order of magnitude difference in signal yield.

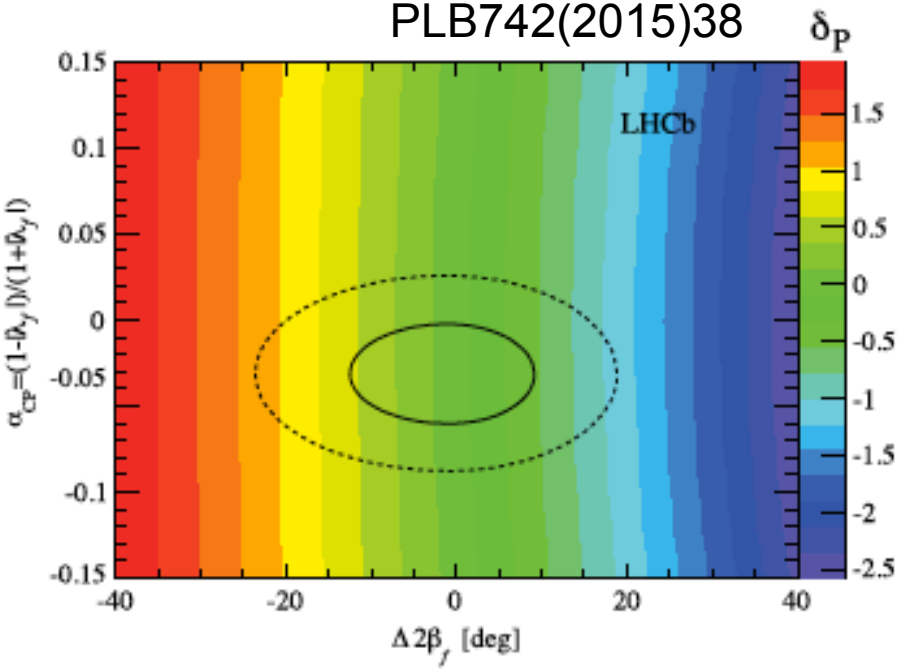
BaBar (382M B-pairs)
PRD76,031101(2007)



Resultant constraint

PLB742(2015)38





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

$B \to VV$: CP-even/odd admixture.

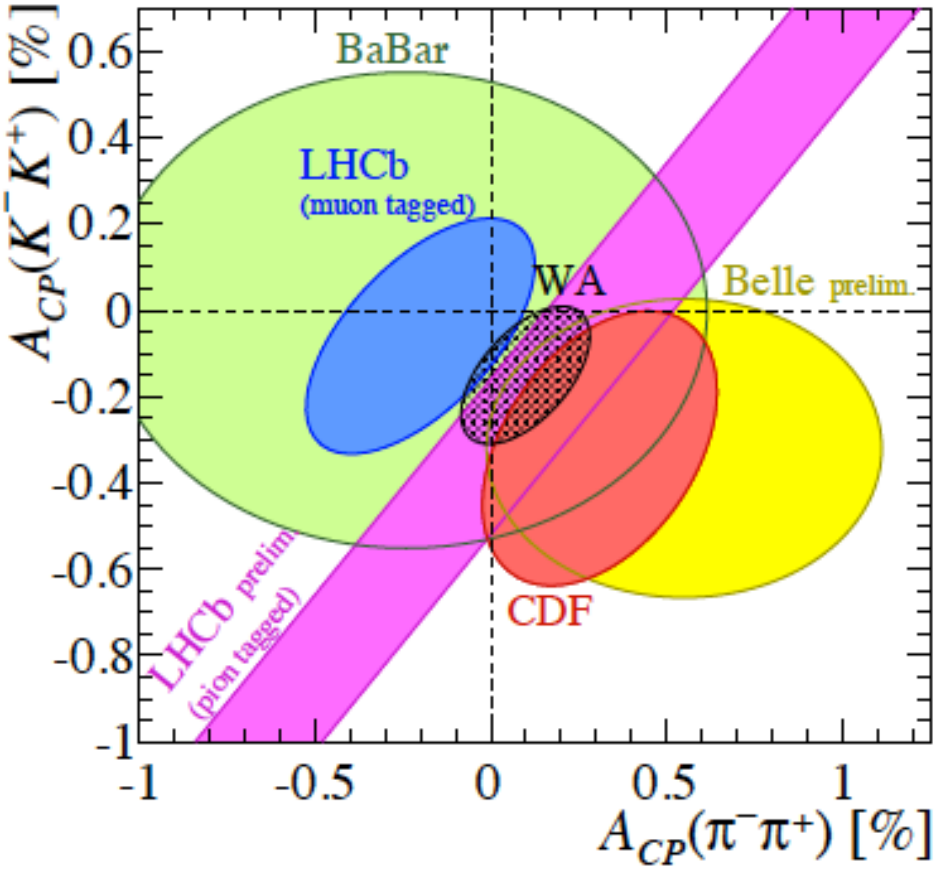
Mostly CP-even, CP-odd component is 20%.

$2\beta_{eff} = 2\phi_1^{eff} = 41.7 \pm 9.6^{+2.8}_{-6.3}° \to -1.05° < \delta_P < 1.18°$ for ϕ_s

$B_s \to J/\psi\, K^{*0}$ result released this summer.

(LHCb-PAPER-2015-034 in preparation)

Charm CP violation



New

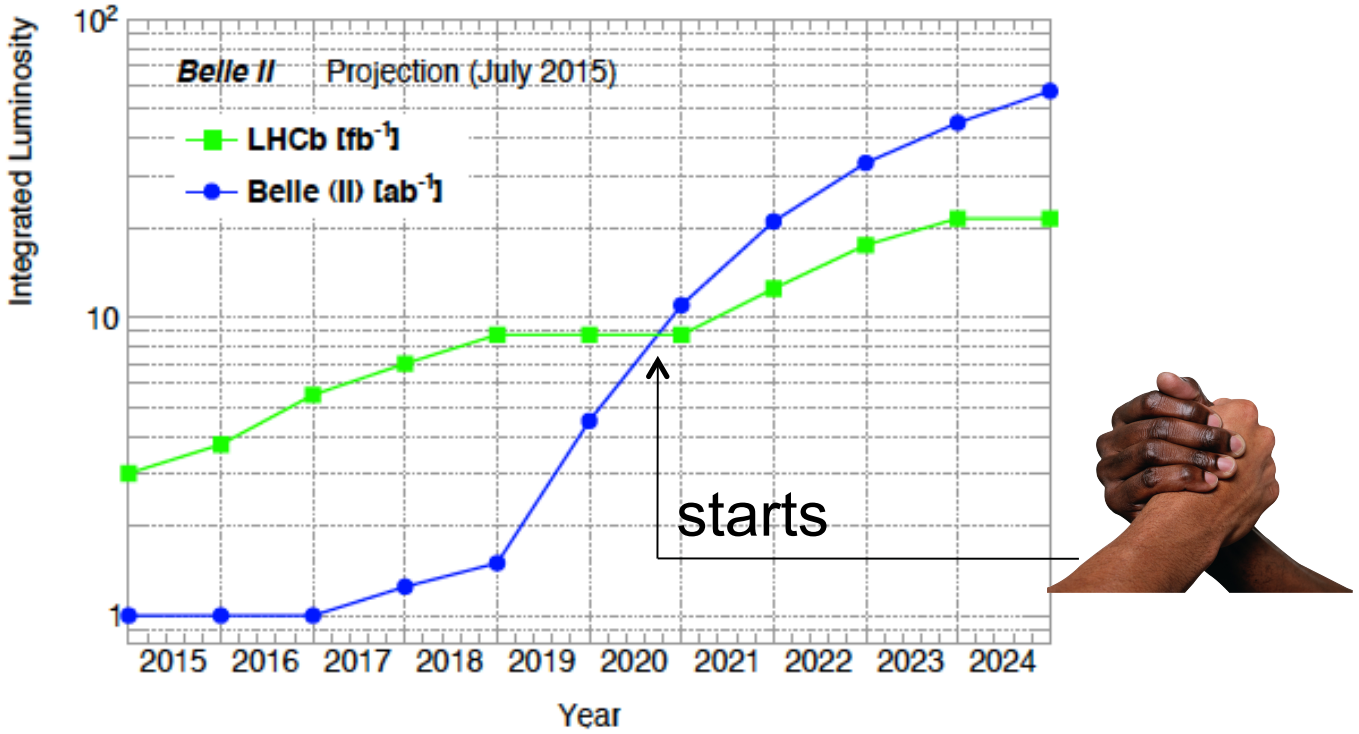
$D^0 \to K_S K_S$ mode at LHC_b

$A_{CP}(K_S K_S) = -(2.9 \pm 5.2 \pm 2.2)\%$ (Prelim.)

(LHCb-PAPER-2015-034 in preparation)

Search for CP violation performed, but no asymmetry appears.

Future



Exciting and friendly competition ahead.
LHCb Run2 has started, Belle II physics run starts at 2018.
Around 2020, well-matched game is anticipated, even before, we try to be innovative to realize novel ideas.

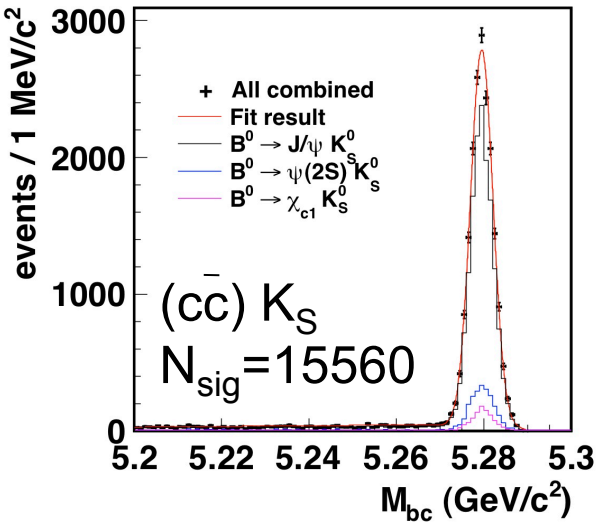
Summary

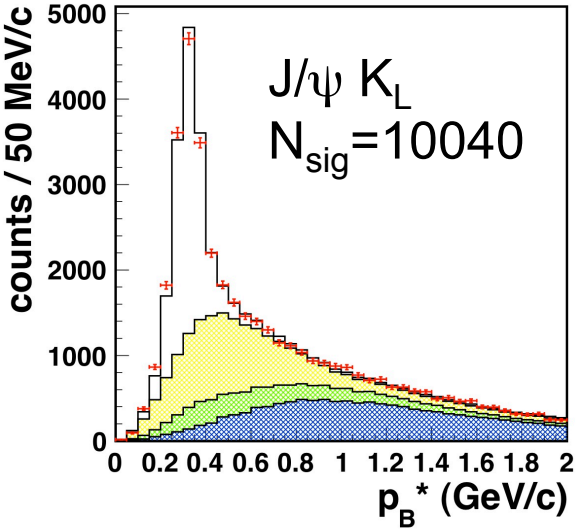
- Mixing induced CP violation in B_d and B_s mesons require very precise discussion to settle firm SM reference.
  - Necessary step to hunt NP in penguin induced B decays.
  - Penguin free mode, $B_d \to D_{CP}\, h^0$ BaBar+Belle joint analysis
  - Exploit SU(3) relation to constrain penguin effects in ϕ_s (and $\phi_1=\beta$) determination(s).
  - Belle $B_d \to \rho^+\rho^-$ br., f_L and CPV, LHC$_b$ $B_d \to \rho^0\rho^0$ br. and f_L come out, $\phi_2=\alpha=90.6$ +3.9/-1.1 °
- LHCb Run2 has started, Belle II physics run starts 2018. Exciting competition ahead.

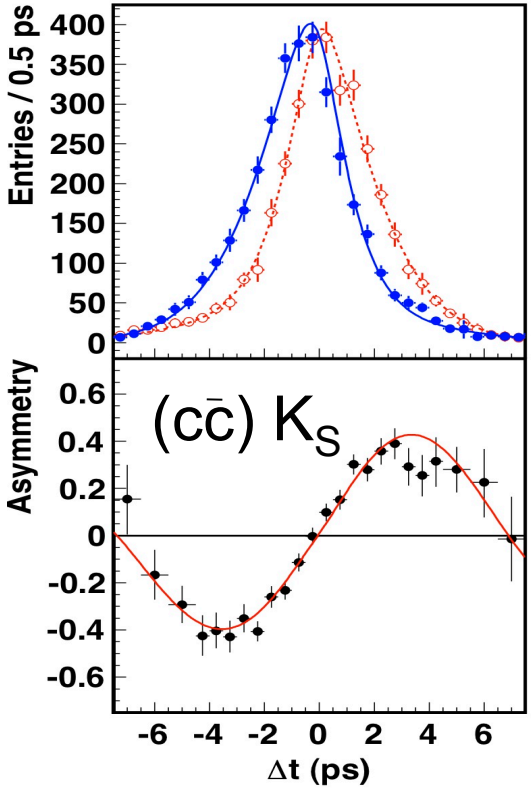
Acknowledgement

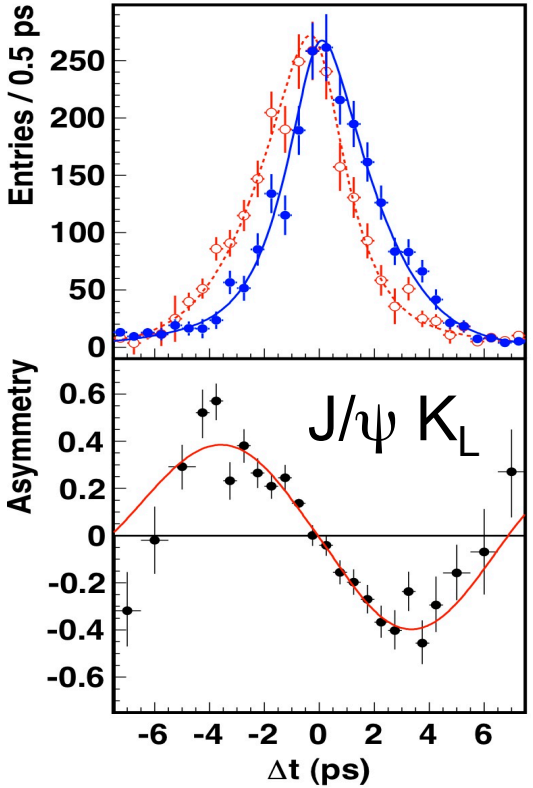
- JSPS grant-in-aid No.26220706 (Prof. Toru Iijima in KMI, Nagoya Univ. as PI) for travel support.
- Profs. Yoshihide Sakai (KEK) and Tim Gershon (Univ. of Warwick) for fruitful discussions.

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









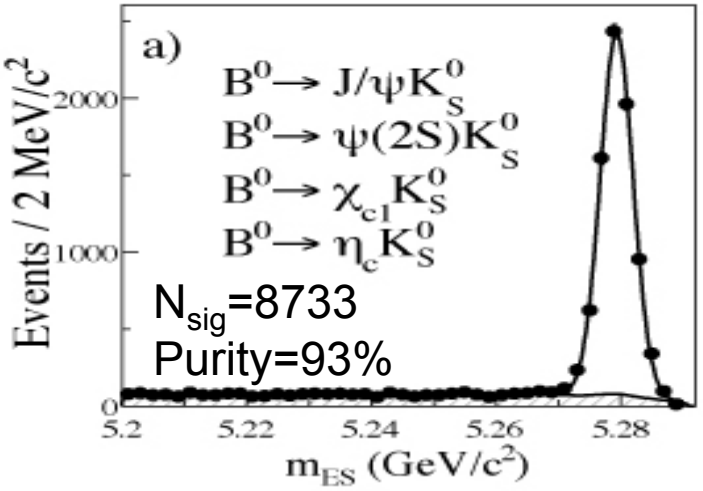
$\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013$

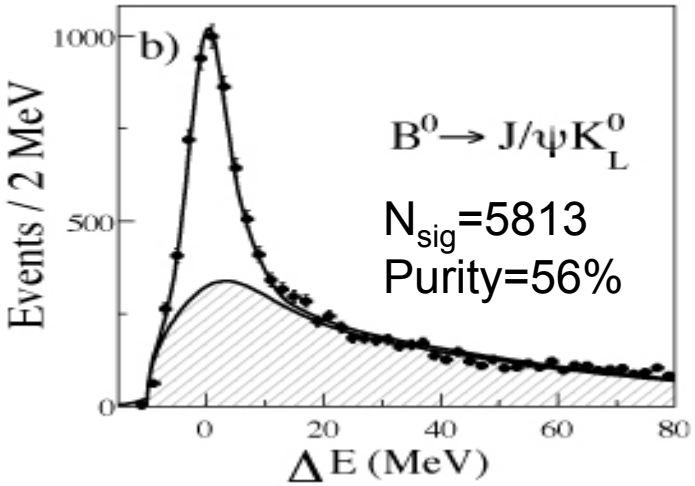
$C_{fcp} = -A_{fCP} = -0.007 \pm 0.016 \pm 0.013$

PRL108,171802(2012)

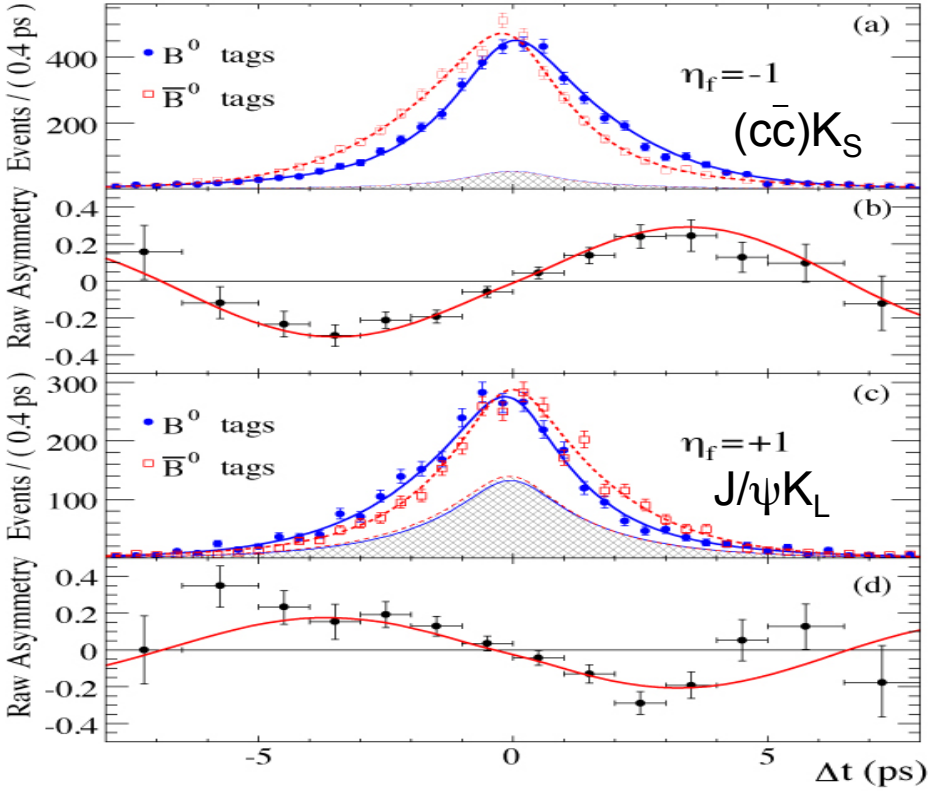
(Full description paper in preparation)

sin2β=sin2ϕ_1 in ($c\bar{c}$) K^0 at BaBar





$E_B - E_{CM}/2$



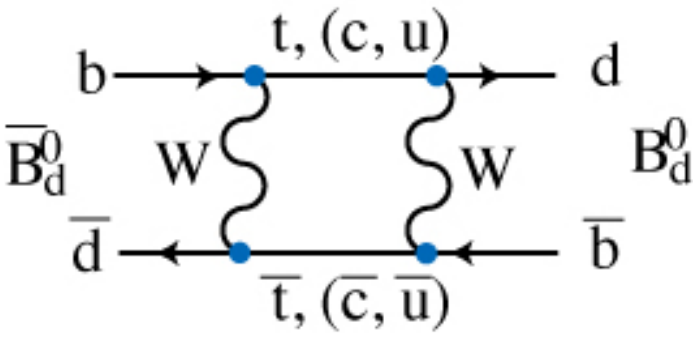
$\sin2\beta=\sin2\phi_1=0.687\pm0.028\pm0.012$

$C_{fcp}=-A_{fCP}=0.024\pm0.020\pm0.016$

PRD79,072009(2009)

In charmless decays

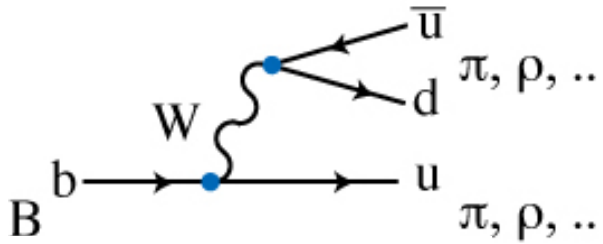
Mixing



Interferes with

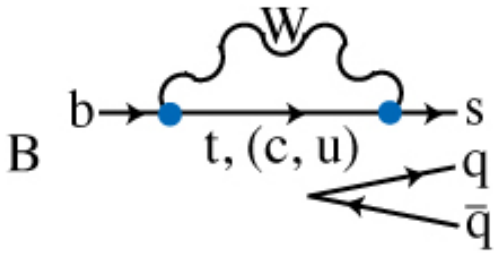
$b \to u\bar{u}d$

obtain angle ϕ_2



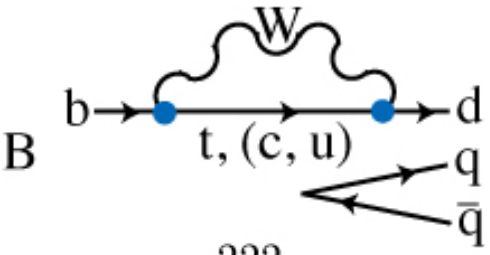
$b \to s\bar{q}q$

effective ϕ_1 to look for NP

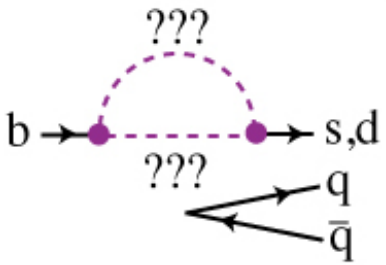


$b \to d\bar{q}q$

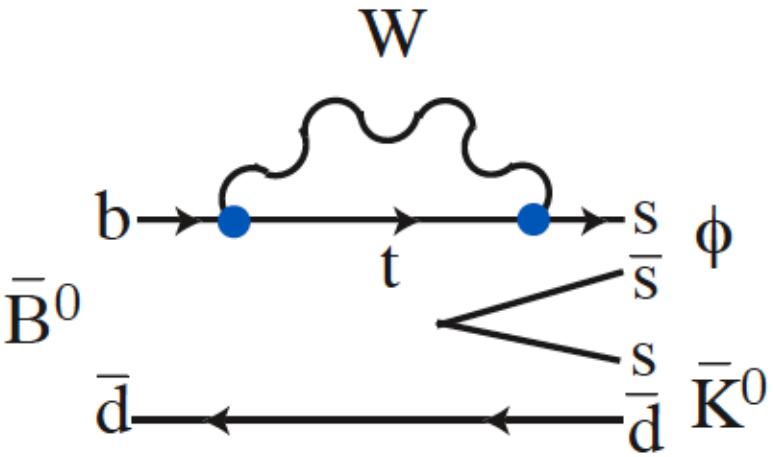
Significant CPV = NP signature



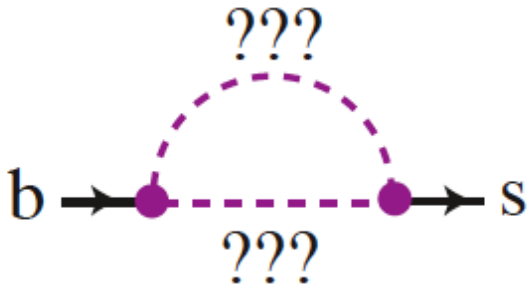
Both penguins may have;



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

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