Recent Measurements of the UT Angles

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On behalf of the *BABAR* Collaboration

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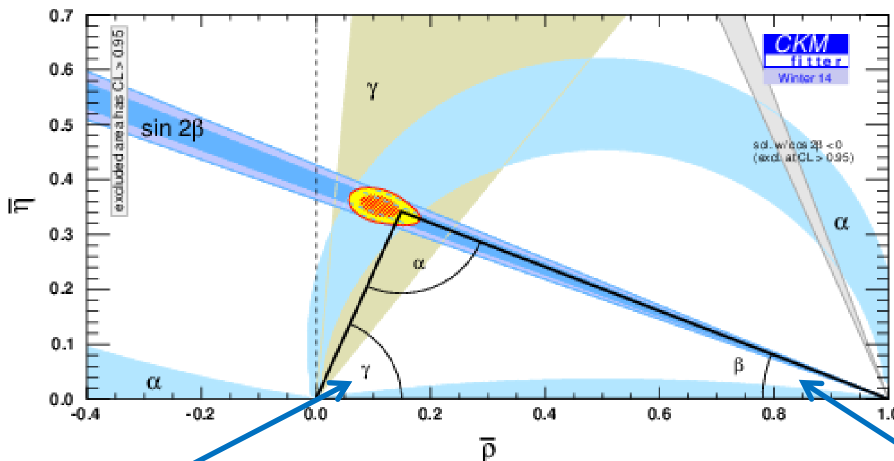
CKM Quark Mixing Matrix and the Unitarity Triangle

- Wolfenstein parameterization of the CKM matrix:

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

3 real parameters (A, λ, ρ) + 1 complex phase (η)
→ only source of CP violation in SM

- Unitarity requires $\mathrm{V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^*} = 0$ → triangle in the complex plane



$$\beta = \phi_1 = \arg\left(-\frac{\mathrm{V_{cd}V_{cb}^*}}{\mathrm{V_{td}V_{tb}^*}}\right)$$

$$\alpha = \phi_2 = \arg\left(-\frac{\mathrm{V_{td}V_{tb}^*}}{\mathrm{V_{ud}V_{ub}^*}}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{\mathrm{V_{ud}V_{ub}^*}}{\mathrm{V_{cd}V_{cb}^*}}\right)$$

LHCb: $\mathrm{B^\pm \to DK^\pm, D \to K_S^0 h^+ h^-}$

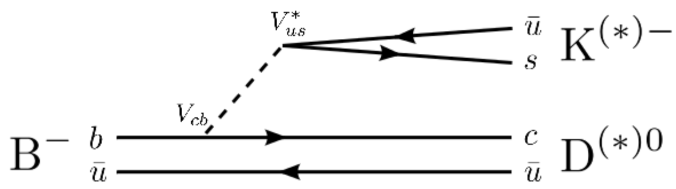
Belle: $\mathrm{B^0 \to DK^{*0}, D \to K_S^0 \pi^+ \pi^-}$ — new result

LHCb: $\mathrm{B^0 \to J/\psi K_S^0}$

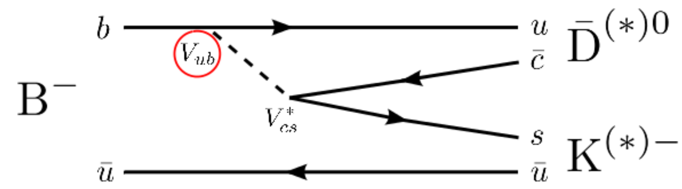
Belle + BaBar: $\mathrm{B^0 \to D_{CP}^{(*)} h^0}$ — new result

Determination of the UT angles is closely related to measurements of CP asymmetries
→ key objective of the Belle, BABAR and LHCb experiments

Accessing γ with $B^{\pm}\to D^{(*)}K^{(*)\pm}$ Decays



$A_1 \sim V_{cb}V_{us}^* \sim A\lambda^3$



$A_2 \sim V_{ub}V_{cs}^* \sim A\lambda^3(\rho - i\eta) \sim e^{-i\gamma}$

- Interference, if D^0 and $\bar{D}^0$ decay into common final state: $|\tilde{D}\rangle = |D^0\rangle + r_B e^{i(\pm\gamma+\delta_B)}|\bar{D}^0\rangle$
- Weak phase γ , strong phase δ_B and amplitude ratio $r_B = \left|\frac{A_2}{A_1}\right| = \left|\frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*}\right| \times [\text{color supp}] \approx 0.1$

GLW PLB **253**, 483 (1991), PLB **265**, 172 (1991)

D decays to CP eigenstates, e.g. $D \to K^+K^-$ — LHCb PLB **712**, 203 (2012), PRD **90**, 112002 (2014)

ADS PRL **78**, 3257 (1997), PRD **63**, 036005 (2001)

Flavored states, e.g. $D \to K\pi$ — LHCb PLB **712**, 203 (2012), PLB **723**, 44 (2013) , PRD **90**, 112002 (2014)

GLS PRD **67**, 71301 (2003)

ADS-like singly Cabibbo-suppressed decays, e.g. $D \to K_S^0 K\pi$ — LHCb PLB **733**, 36 (2014)

GGSZ PRD **68**, 054018 (2003)

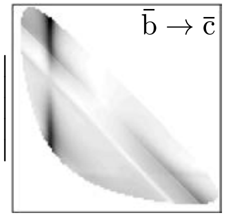
Self-conjugated multi-body D decays, e.g. $D \to K_S^0\pi^+\pi^-$ — LHCb JHEP **10**, 97 (2014), Belle arXiv:1502.07550

Accessing γ with $B^{\pm}\to D^{(*)}K^{(*)\pm}$ Decays

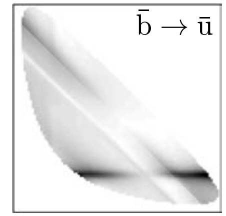
GGSZ method [PRD **68**, 054018 (2003)]:

- Reconstruct D mesons in self-conjugated multi-body states like $D \to K^0_S\pi^+\pi^-$

$$\left|M_{B^+\to DK^+}\left(m^2_{K_S\pi^+}, m^2_{K_S\pi^-}\right)\right|^2 = \Bigg|$$

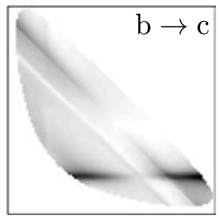


$$+\, r_B e^{i(+\gamma+\delta_B)}$$

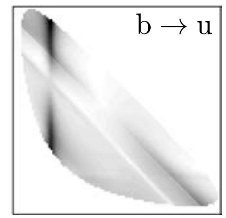


$$\Bigg|^2$$

$$\left|M_{B^-\to DK^-}\left(m^2_{K_S\pi^+}, m^2_{K_S\pi^-}\right)\right|^2 = \Bigg|$$



$$+\, r_B e^{i(-\gamma+\delta_B)}$$



$$\Bigg|^2$$

Advantage: Large interferences can occur in some regions of the Dalitz plot

Problem: Irreducible uncertainty due to D Dalitz model in model-dep. GGSZ analyses

Previous model-dep. GGSZ analyses:

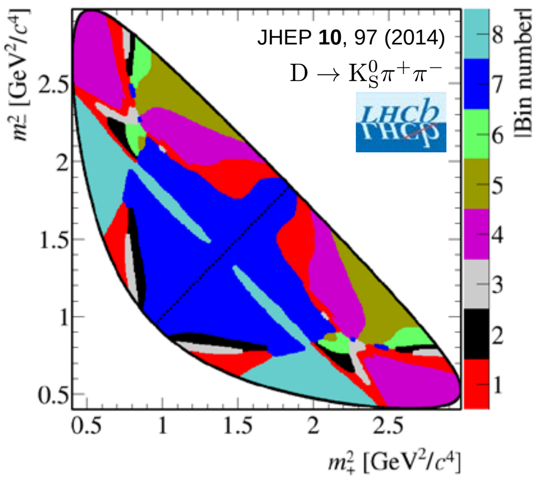
BABAR @ 468×10⁶ BB: $\gamma = \left(68^{+15}_{-14}\,(\text{stat.}) \pm 4\,(\text{syst.}) \pm 3\,(\text{model})\right)^\circ$ PRL **105**, 121801 (2010)
(BW isobar+K-matrix+LASS)

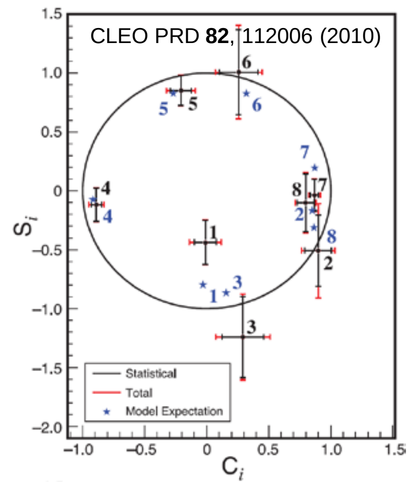
Belle @ 772×10⁶ BB: $\gamma = \left(78^{+11}_{-12}\,(\text{stat.}) \pm 4\,(\text{syst.}) \pm 9\,(\text{model})\right)^\circ$ PRD **81**, 112002 (2010)
(BW isobar)

Model-Independent GGSZ Measurement of γ by LHCb

GGSZ model-independent method pioneered by Belle [EPCJ **55**, 51 (2008), PRD **85**, 112014 (2012)]:

- Bin Dalitz plot and use in each bin strong phases obtained from CLEO measurements on quantum-correlated $\psi(3770) \rightarrow D\bar{D}$ decays



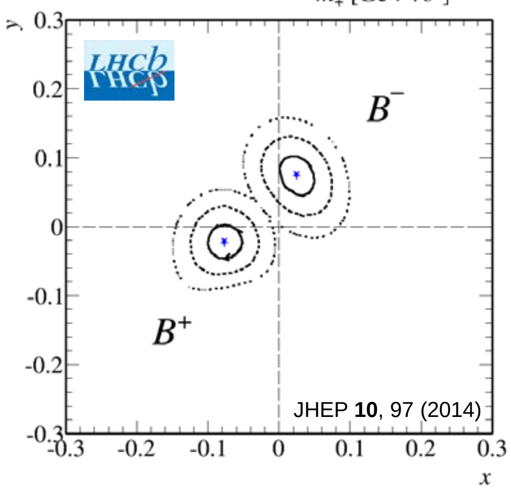


$$N^+_{\pm i} = h_{B^+}[F_{\mp i} + (x^2_+ + y^2_+)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})]$$

$$N^-_{\pm i} = h_{B^-}[F_{\pm i} + (x^2_- + y^2_-)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} - y_- s_{\pm i})]$$

$$x_\pm = r_B \cos(\delta_B \pm \gamma), \quad y_\pm = r_B \cos(\delta_B \pm \gamma)$$

$$c_i = \langle \cos(\delta_B) \rangle, \quad s_i = \langle \sin(\delta_B) \rangle$$



$B^\pm \rightarrow DK^\pm$ with $D \rightarrow K^0_S\pi^+\pi^-$ and $D \rightarrow K^0_S K^+K^-$

LHCb with 3 fb^{-1} model-indep. GGSZ: JHEP **10**, 97 (2014)

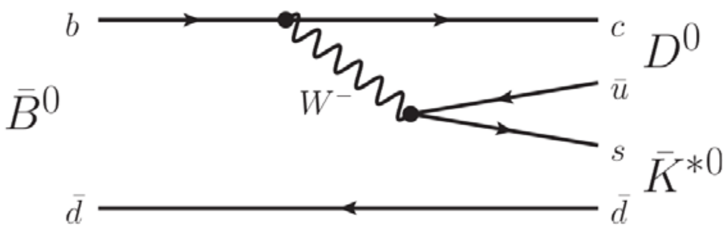
$$\gamma = \left(62^{+15}_{-14}\right)^\circ, \; r_B = 0.080^{+0.019}_{-0.021}, \; \delta_B = \left(134^{+14}_{-15}\right)^\circ$$

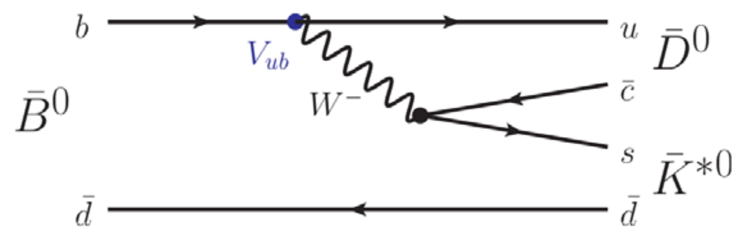
LHCb-CONF-2014-004

LHCb combination GGSZ+GLW+ ADS+GLS+time-dep.: $\gamma = \left(73^{+9}_{-10}\right)^\circ$

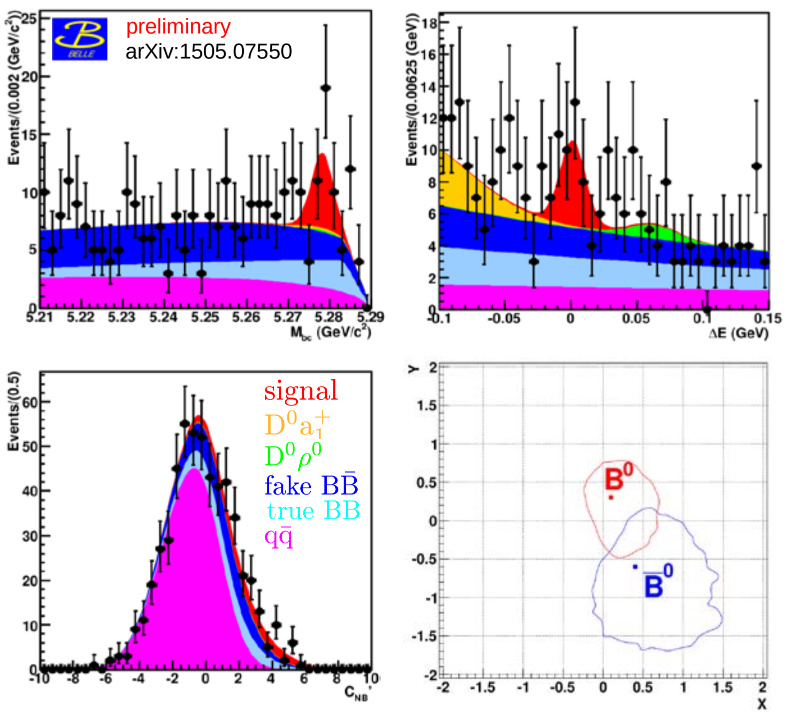
(uncertainties include systematics)

Model-Independent GGSZ Measurement of γ by Belle





- First measurement of the ampl. ratio of $\mathrm{B^0 \to D^0 K^{*0}}$ and $\mathrm{B^0 \to \bar{D}^0 K^{*0}}$ with $\mathrm{D \to K^0_S \pi^+ \pi^-}$
- Flavor of B meson is identified by kaon charge in $\mathrm{K^{*0}(892) \to K^+ \pi^-}$



- Observable $\mathrm{r_S^2 = \dfrac{\int A^2_{b \to u}(p)dp}{\int A^2_{b \to c}(p)dp}}$

Belle with 772×10⁶ BB: arXiv:1505.07550

$$\mathrm{x_- = +0.4^{+1.0}_{-0.6}(stat.)\,^{+0.0}_{-0.1}(syst.) \pm 0.0(c_i,\ s_i\ prec.)}$$

$$\mathrm{y_- = -0.6^{+0.8}_{-1.0}(stat.)\,^{+0.1}_{-0.0}(syst.) \pm 0.1(c_i,\ s_i\ prec.)}$$

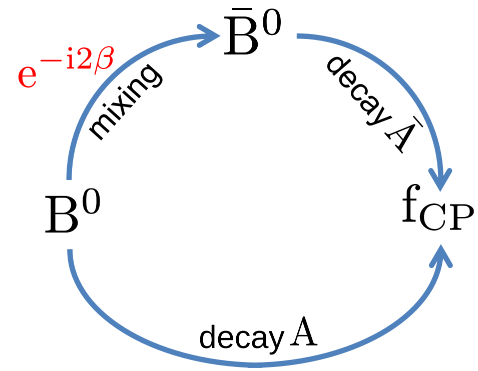
$$\mathrm{x_+ = +0.1^{+0.7}_{-0.4}(stat.)\,^{+0.0}_{-0.1}(syst.) \pm 0.1(c_i,\ s_i\ prec.)}$$

$$\mathrm{y_+ = +0.3^{+0.5}_{-0.8}(stat.)\,^{+0.0}_{-0.1}(syst.) \pm 0.1(c_i,\ s_i\ prec.)}$$

preliminary $\mathrm{r_S < 0.87}$ at 68%C.L.

new result

Measurement of β



- Interference between mixing and decay in neutral B meson decays to a CP eigenstate

- Interference characterized by: $\lambda = \frac{q}{p}\frac{\bar{A}}{A}$

phase factor due to mixing ← → decay amplitude ratio

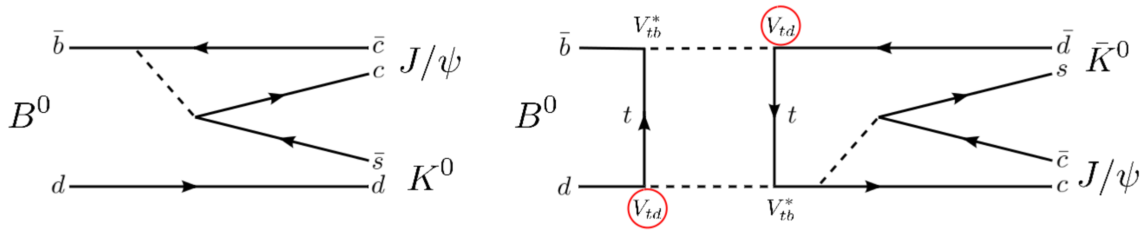
- Time-dependent CP asymmetry:

$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}^0(t) \to f_{CP}\right) - \Gamma\left(B^0(t) \to f_{CP}\right)}{\Gamma\left(\bar{B}^0(t) \to f_{CP}\right) + \Gamma\left(B^0(t) \to f_{CP}\right)} = \mathcal{S}\sin(\Delta m t) - \mathcal{C}\cos(\Delta m t)$$

$\mathcal{S}$ → mixing-induced CPV; $\mathcal{C}$ → direct CPV

$$\mathcal{S} = \frac{2\,\mathrm{Im}(\lambda)}{|\lambda^2| + 1}$$

$$\mathcal{C} = \frac{1 - |\lambda^2|}{1 + |\lambda^2|}$$



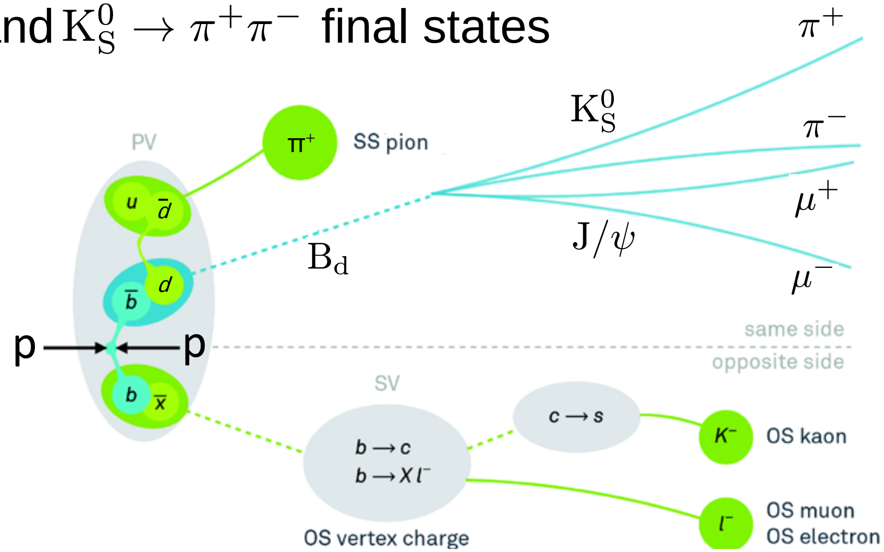
- e.g. $B^0 \to J/\psi K^0_S$, mixing vertices V_{td} introduce phase → $\mathcal{S} = -\eta_{f_{CP}}\sin(2\beta)$ and $\mathcal{C} = 0$

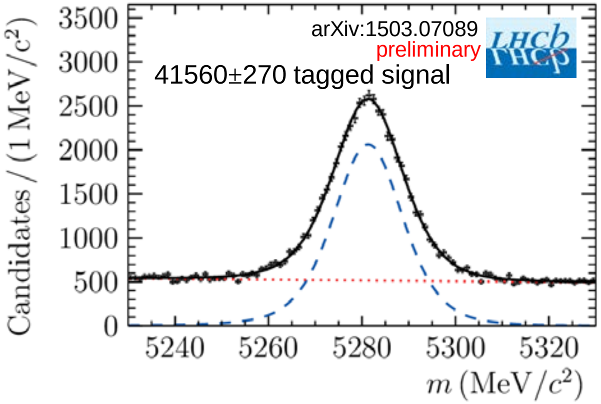
β can be precisely determined from the time-dep. CP asymmetry

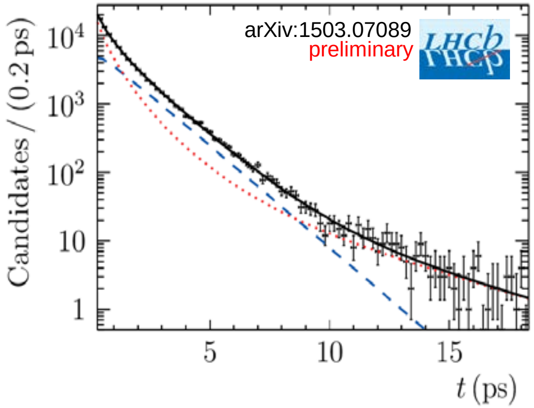
$$A_{CP}(t) = -\eta_{f_{CP}}\sin(2\beta)\sin(\Delta m t)$$

Measurement of sin(2β) in $B^0 \to J/\psi K^0_S$ by LHCb

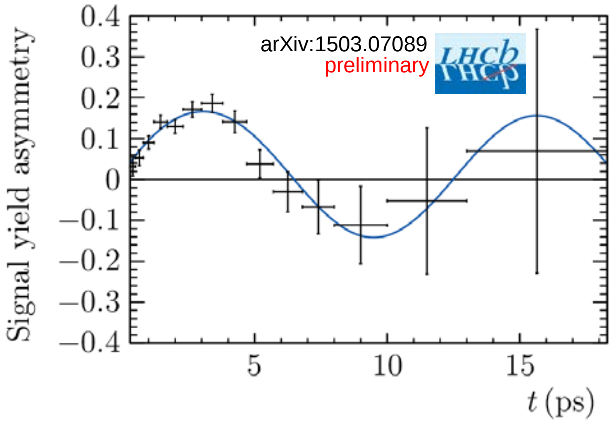
- sin(2β) precisely determined by Belle and BABAR, uncertainty on β<1°
  → Benchmark for time-dependent CP violation measurements
- LHCb measurement of $B^0 \to J/\psi K^0_S$ using Run 1 data set of 3 fb^{-1}
- Reconstruct $B^0 \to J/\psi K^0_S$ with $J/\psi \to \mu^+\mu^-$ and $K^0_S \to \pi^+\pi^-$ final states
- Many B mesons, efficient trigger
- Excellent proper time resolution (55-65 fs)
- Effective tagging efficiency (3.02 ± 0.02)%







Measurement of sin(2β) in $B^0 \to J/\psi K^0_S$ by LHCb

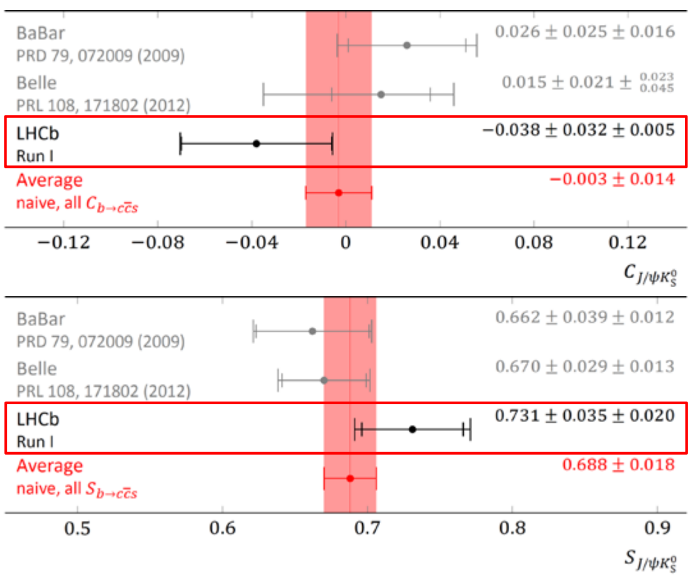


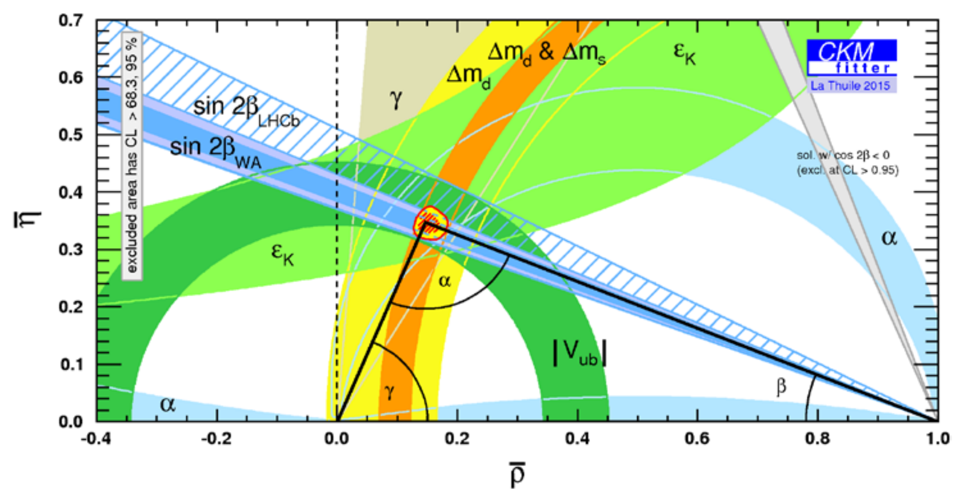
LHCb with 3 fb^{-1}: arXiv:1503.07089

$$\mathcal{S} = 0.731 \pm 0.035\,(\text{stat.}) \pm 0.020\,(\text{syst.})$$

$$\mathcal{C} = -0.038 \pm 0.032\,(\text{stat.}) \pm 0.005\,(\text{syst.})$$

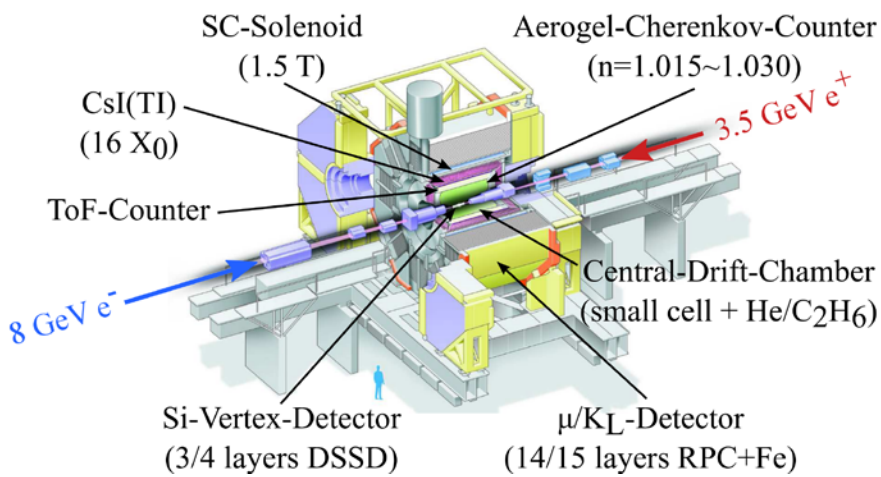
preliminary

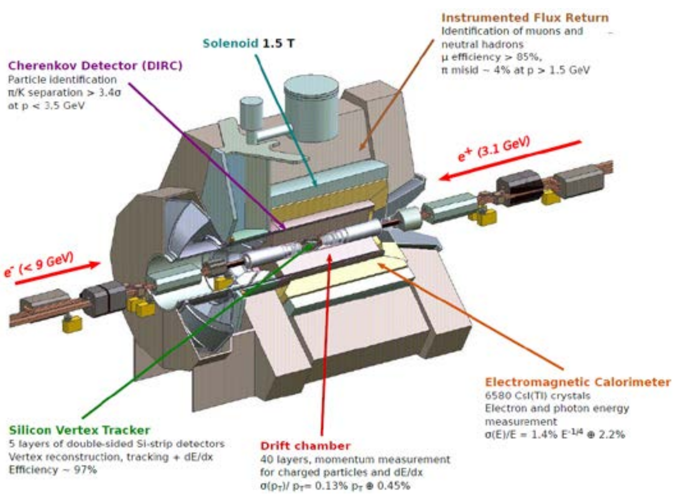


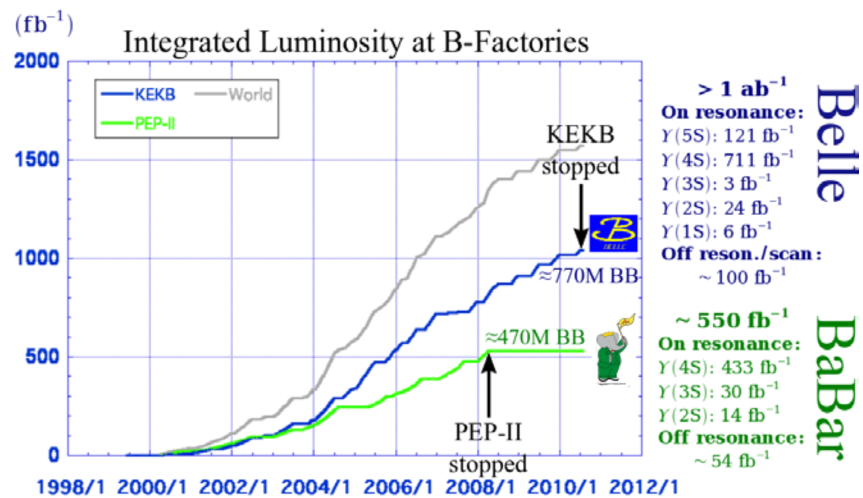


LHCb achieves with Run 1 data similar precision as the B factory experiments in $b \to c\bar{c}s$

Combined Belle and *BaBar* Analysis of $B^0 \to D^{(*)}_{CP} h^0$

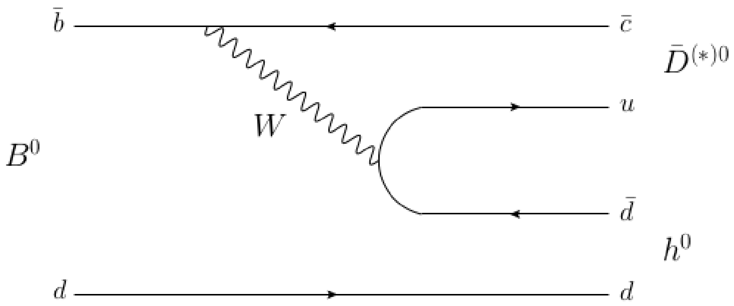


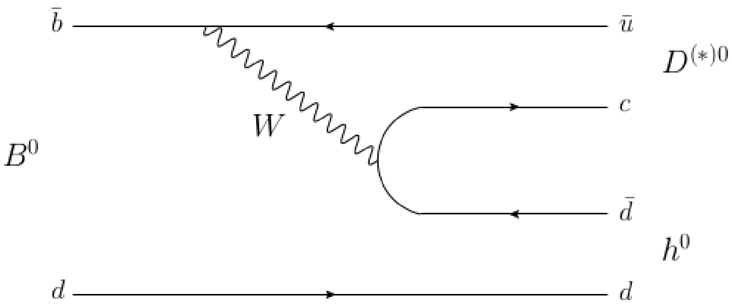




Combined Belle+*BaBar* analysis to make full use of the ≈1240×10^6 BB collected on the $\Upsilon(4S)$

Combined Belle and BaBar Analysis of $\mathbf{B^0 \to D^{(*)}_{CP} h^0}$





- $B^0 \to D^{(*)}_{CP} h^0$ decays with $h^0 \in \{\pi^0, \eta, \omega\}$ mediated only by tree-level amplitudes
- Theoretically clean [NPB **659**, 321 (2003)]:

  → Enables to test the precision measurements of $b \to c\bar{c}s$

  → Can provide a SM reference of $\sin(2\beta)$, e.g. for BSM searches in $b \to s$ penguins

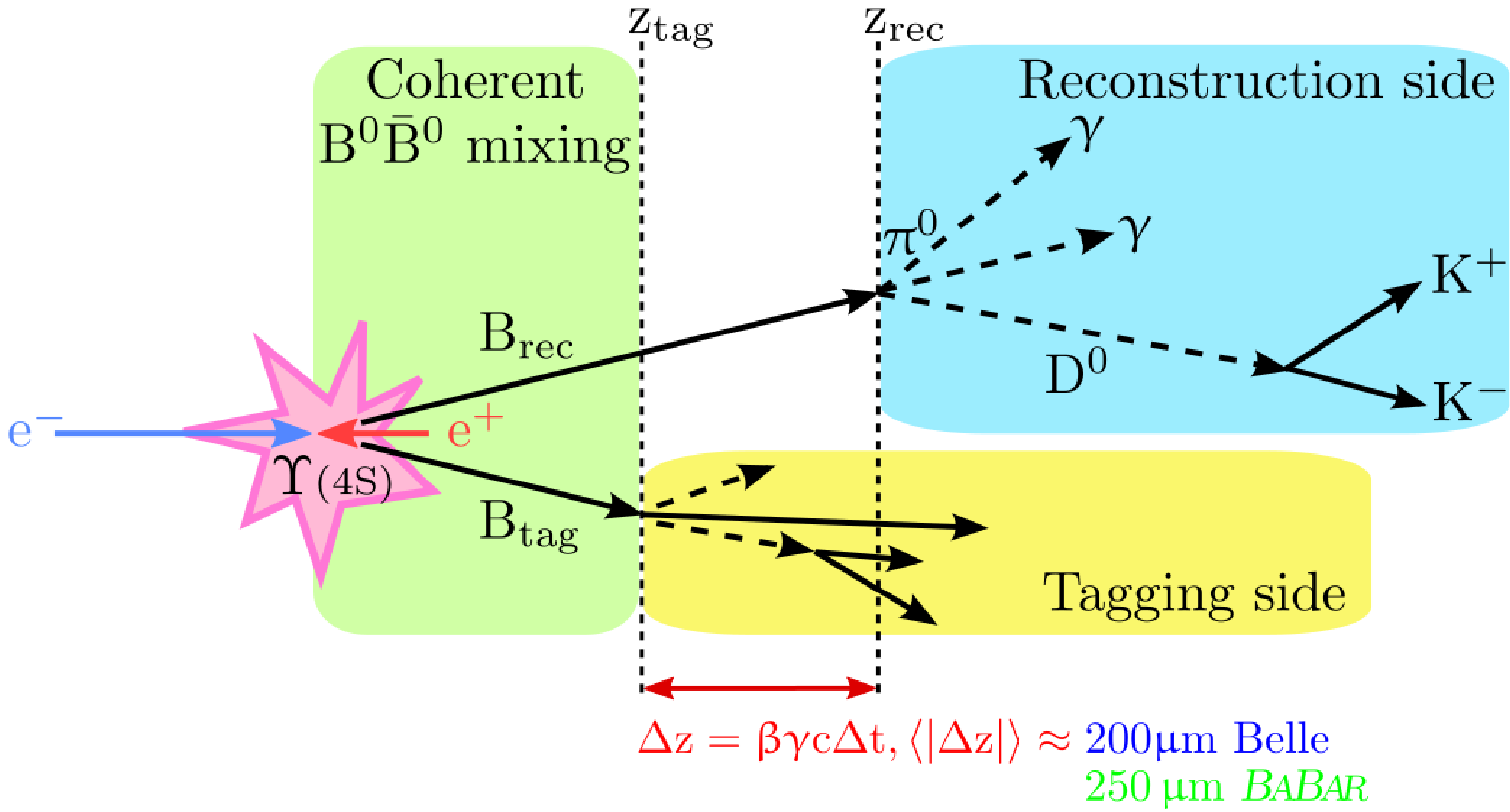
- Experimental difficulties: - Low B and D_{CP} branching fractions [$\mathcal{O}(10^{-4})$ and $\mathcal{O}(\leq 10^{-2})$]

  - Low reconstruction efficiencies
  - Significant background
- Previous measurements by Belle and BaBar could not establish CPV in $B^0 \to D^{(*)} h^0$

Perform time-dep. CP violation measurement combining Belle+BaBar data

Combined Belle and BABAR Analysis of $B^0 \to D^{(*)}_{CP} h^0$

Threshold $B\bar{B}$ production on the $\Upsilon(4S)$:



eff. tagging efficiency >30%

Proper time interval distribution follows:

$$\mathcal{P}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{-\frac{|\Delta t|}{\tau_{B^0}}} \left[1 + q\left(\mathcal{S}\sin(\Delta m \Delta t) - \mathcal{C}\cos(\Delta m \Delta t)\right)\right]$$

Experimental effects due to finite vertex resolution and imperfect tagging are important

Combined Belle and *BaBar* Analysis of $B^0 \to D_{CP}^{(*)} h^0$

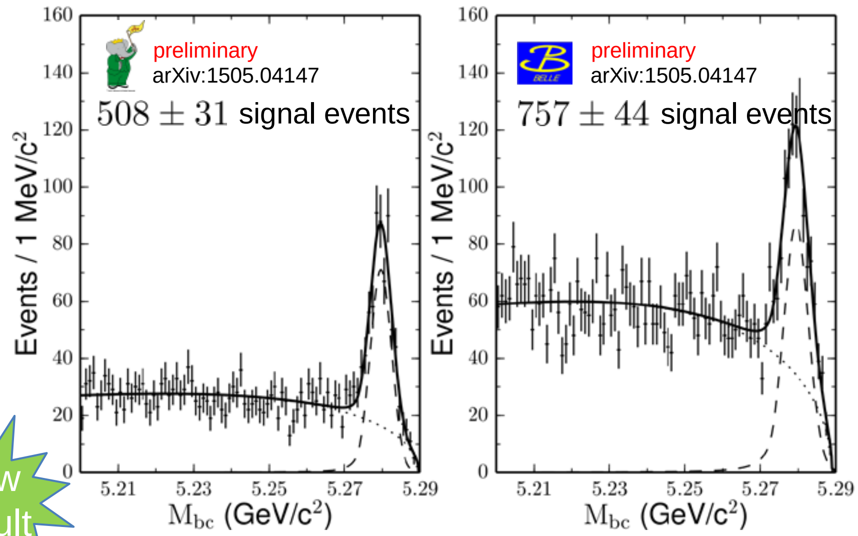
- Reconstruct $B^0 \to D_{CP}^{(*)} h^0$ with h^0 in $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$

$$D_{CP} \to K^+K^-, K_S^0\pi^0, K_S^0\omega$$

$$D^{*0} \to D_{CP}\pi^0$$

- Suppression of $e^+e^- \to q\bar{q}$ $(q \in \{u, d, s, c\})$ continuum background by neural networks
- Coherent analysis strategy, apply almost same selection on Belle and *BaBar* data
- Extract signal from beam-constrained mass $M_{bc} \equiv m_{ES} = \sqrt{(E^*_{beam}/c^2)^2 - (p^*_B/c)^2}$

new result



Combined Belle and *BABAR* Analysis of $\mathbf{B^0 \to D^{(*)}_{CP} h^0}$

- Perform measurement by maximizing the combined log-likelihood function:

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{BABAR} + \sum_j \ln \mathcal{P}_j^{\mathrm{Belle}}$$

- Physics PDFs are convoluted with specific resolution functions

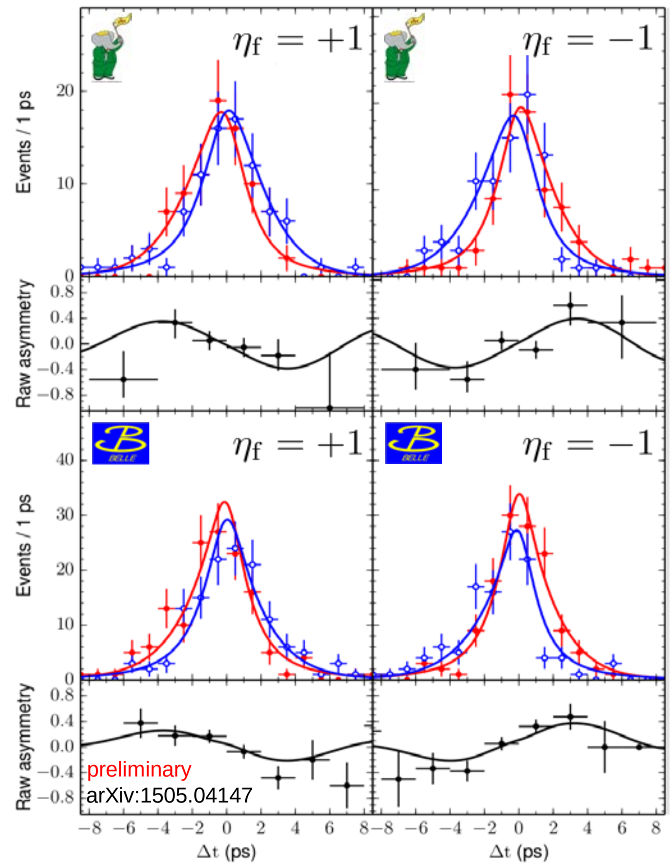
$$\mathcal{P}^{\mathrm{Exp.}} = \sum_{\mathrm{k}} \mathrm{f_k} \int \left[\mathrm{P_k}\left(\Delta \mathrm{t}'\right) \mathrm{R_k}\left(\Delta \mathrm{t} - \Delta \mathrm{t}'\right)\right] \mathrm{d}\left(\Delta \mathrm{t}'\right)$$

- Apply Belle and *BABAR* specific resolution models, and flavor tagging algorithms

- Apply common signal model:

$$\mathrm{P_{sig}}(\Delta \mathrm{t}, \mathrm{q}) = \frac{1}{4\tau_{\mathrm{B^0}}} \mathrm{e}^{-\frac{|\Delta \mathrm{t}|}{\tau_{\mathrm{B^0}}}} \left[1 + \mathrm{q}\left(\mathcal{S}\sin(\Delta \mathrm{m}\Delta \mathrm{t}) - \mathcal{C}\cos(\Delta \mathrm{m}\Delta \mathrm{t})\right)\right]$$

- SM prediction $-\eta_{\mathrm{f}}\mathcal{S} = \sin(2\beta)$ and $\mathcal{C} = 0$



new result

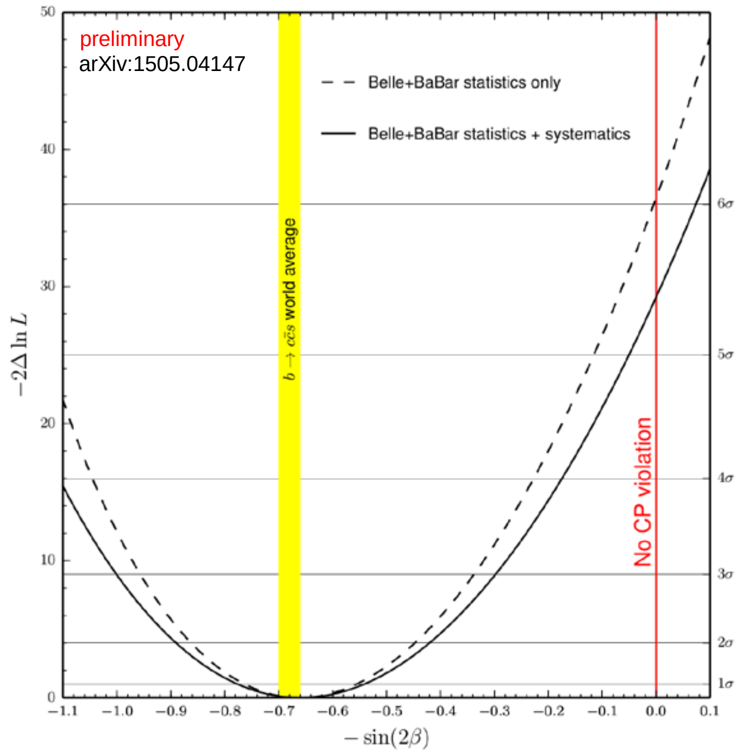
Belle+*BABAR* with 1.1 ab^{-1}: arXiv:1505.04147

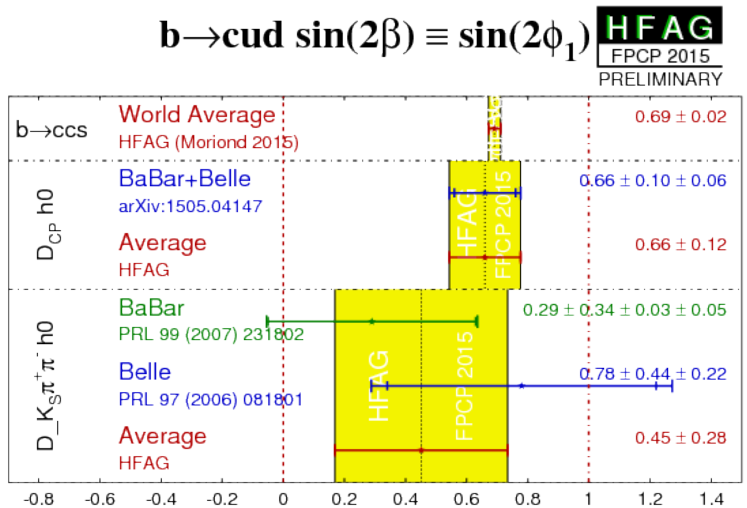
$$-\eta_f \mathcal{S} = +0.66 \pm 0.10\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.})$$

$$\mathcal{C} = -0.02 \pm 0.07\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.})$$

preliminary

Combined Belle and *BaBar* Analysis of $\mathrm{B^0 \to D^{(*)}_{CP} h^0}$





- Very good agreement with the $\sin(2\beta)$ world average from $\mathrm{b \to c\bar{c}s}$
- Exclude the no-mixing induced CP violation hypothesis at 5.4σ
  → First observation of CP violation in $\mathrm{B^0 \to D^{(*)}_{CP} h^0}$ decays
- First measurement performed on more than 1 $\mathrm{ab^{-1}}$ collected on the $\Upsilon(4S)$

Summary

- LHCb achieves a precision of 10° on weak phase γ
- LHCb reaches the precision of the B factory experiments in time-dep. CP violation measurements in the neutral B system and confirms $\sin(2\beta)$ in $B^0 \to J/\psi K^0_S$

  → Promising prospects for Run 2 of the LHC

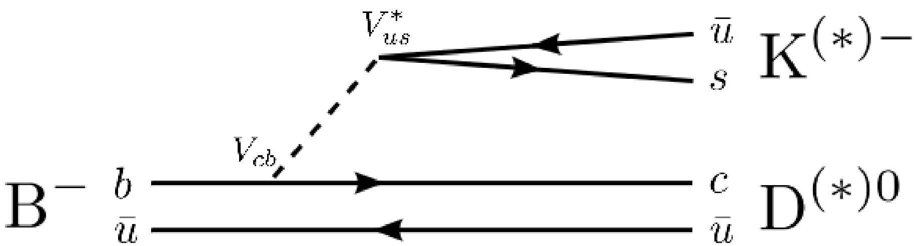
- The B factory experiments Belle and BABAR continue to produce interesting results
  - First measurement of r_S in $B^0 \to D^0 K^{*0}$ with $D \to K^0_S \pi^+ \pi^-$
  - First combined Belle+BABAR measurement
    - Observation of CP violation in $B^0 \to D^{(*)}_{CP} h^0$
    - Usage of more than 1 ab^{-1} collected on the $\Upsilon(4S)$ +

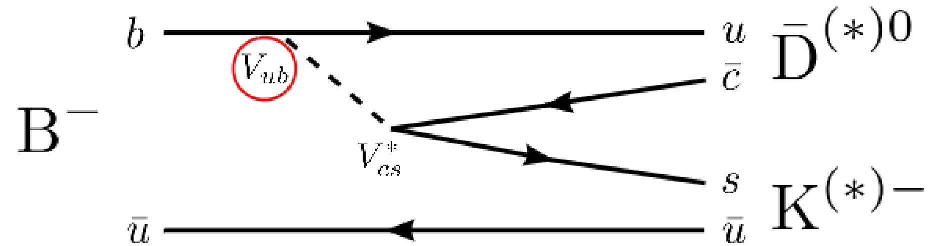
  → Promising prospects for the high-luminosity B factory experiment Belle 2

BACKUP

Accessing γ with $B^{\pm}\to D^{(*)}K^{(*)\pm}$ Decays

- γ is accessible by utilizing the interference of b→c and b→u transitions in $B^{\pm}\to D^{(*)}K^{(*)\pm}$





$$A_1 \sim V_{cb}V_{us}^* \sim A\lambda^3$$

$$A_2 \sim V_{ub}V_{cs}^* \sim A\lambda^3(\rho - i\eta) \sim e^{-i\gamma}$$

- Interference, if D^0 and $\bar{D}^0$ decay into common final state: $|\tilde{D}\rangle = |D^0\rangle + r_B e^{i(\pm\gamma+\delta_B)}|\bar{D}^0\rangle$
- Weak phase difference γ , strong phase difference δ_B and amplitude ratio

$$r_B = \left|\frac{A\left(B^- \to \bar{D}^0K^-\right)}{A\left(B^- \to D^0K^-\right)}\right| = \left|\frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*}\right| \times [\text{color supp}] \approx 0.1$$

Advantage: ▪ only tree amplitudes, no penguins → can provide SM anchor point

Draw back: ▪ small branching fractions due to Cabibbo- and color-suppressions
▪ small amplitude ratio r_B

Accessing γ with $B^\pm \to D^{(*)}K^{(*)\pm}$ Decays

Methods and observables to extract γ from $B^\pm \to D^{(*)}K^{(*)\pm}$

GLW: **G**ronau, **W**yler, **L**ondon

PLB **253**, 483 (1991), PLB **265**, 172 (1991)

Cabibbo-suppressed D decays to CP eigenstates, e.g. $\mathrm{D} \to \mathrm{K}^+\mathrm{K}^-$ (CP-even) and $\mathrm{D} \to \mathrm{K}^0_\mathrm{S}\pi^0$ (CP-odd)

$$A_{CP\pm} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2r_B + \cos\delta_B \cos\gamma}$$

direct CP asymmetry

$$R_{CP\pm} = 1 + r_B^2 + 2r_B + \cos\delta_B \cos\gamma$$

ratio charged averaged decay rates

ADS: **A**twood, **D**unietz, **S**oni

PRL **78**, 3257 (1997), PRD **63**, 036005 (2001)

Doubly Cabibbo-suppressed (e.g. $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$) and Cabibbo-favored ($\bar{\mathrm{D}}^0 \to \mathrm{K}^+\pi^-$) D decays

$$A_{DK} = 2r_B r_D \sin(\delta_B + \delta_D) \frac{\sin\gamma}{R_{DK}}$$

direct CP asymmetry

$$R_{DK} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos\gamma$$

ratio suppressed to favored decay

GGSZ: **G**iri, **G**rossman, **S**offer, **Z**upan

PRD **68**, 054018 (2003)

Dalitz analysis of multi-body D decays to self-conjugated states (e.g. $\mathrm{D} \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-$)

Interference $M_\pm\left(m_\pm^2, m_\mp^2\right) = f_D\left(m_\pm^2, m_\mp^2\right) + r_B e^{i(\pm\gamma+\delta_B)} f_D\left(m_\mp^2, m_\pm^2\right)$ varying over Dalitz plot

The BABAR and Belle Experiments