Observation of CP violation in $B^0 \to D_{CP}^{(*)} h^0$ with a combined analysis of BABAR and Belle data

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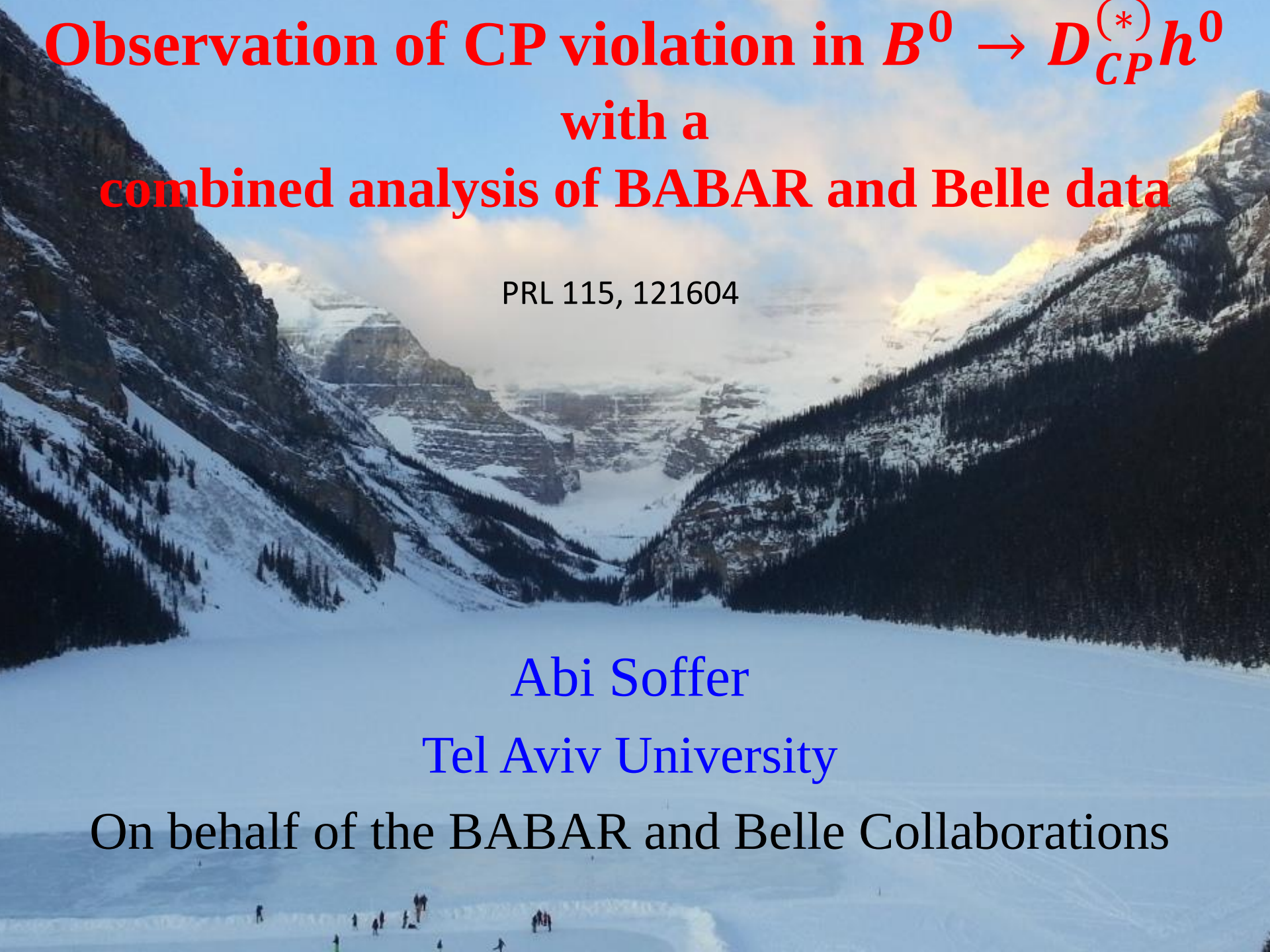

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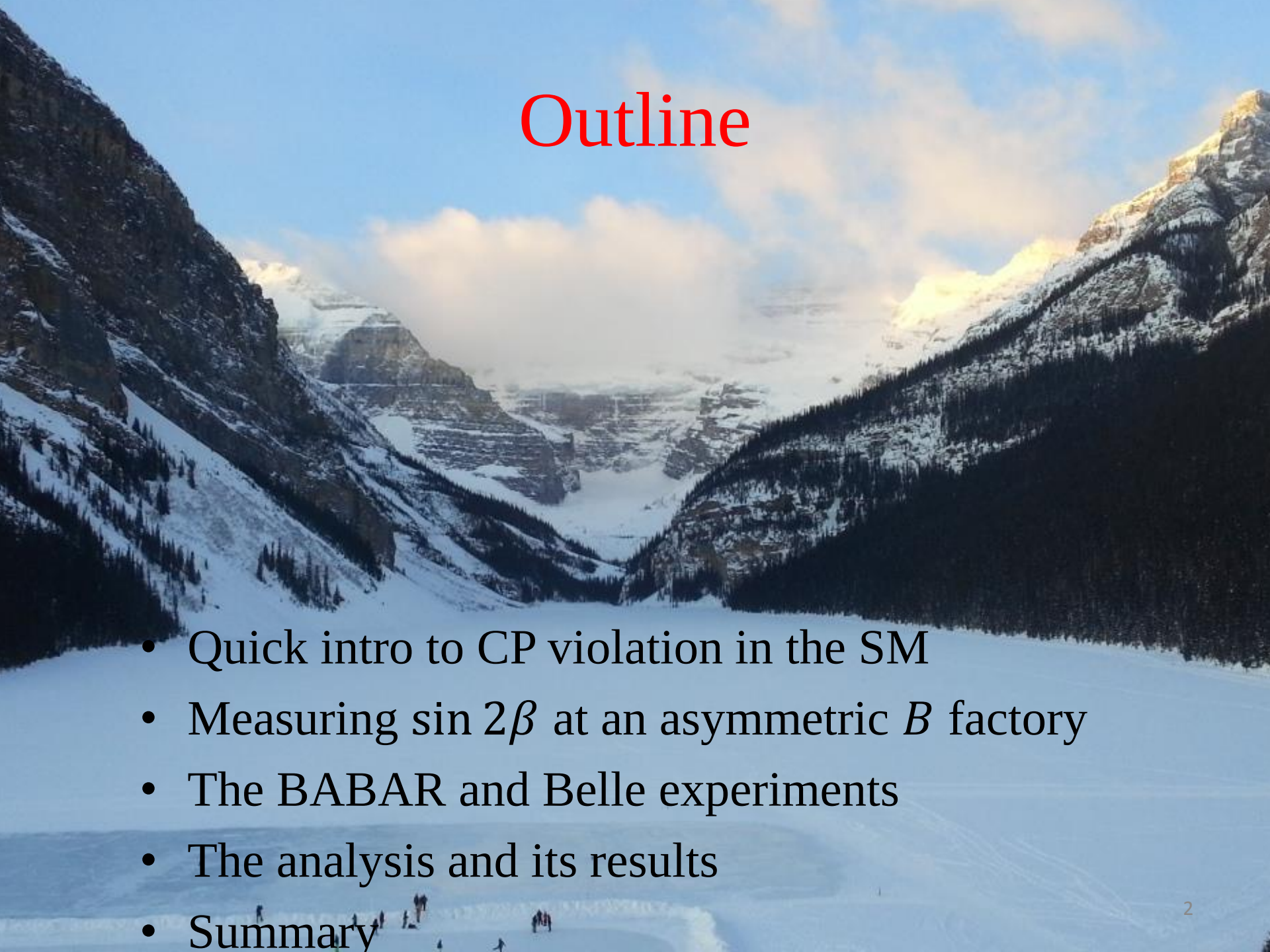


Outline

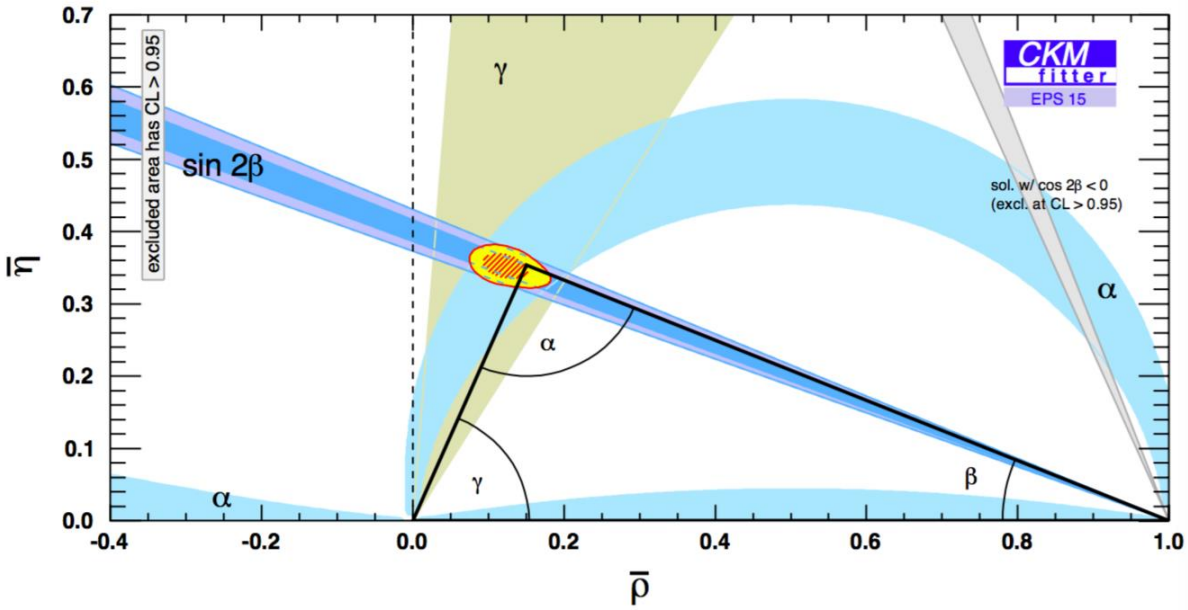
- Quick intro to CP violation in the SM
- Measuring sin 2β at an asymmetric B factory
- The BABAR and Belle experiments
- The analysis and its results
- Summary

Quick intro to CP Violation in the SM

- Yukawa couplings of Higgs to fermion fields → quark mixing and masses
- Charged-current Lagrangian in the quark-mass basis:

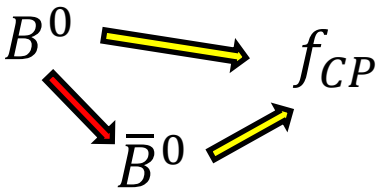
$$-\frac{g}{\sqrt{2}}\left(\bar{u}_L, \bar{c}_L, \bar{t}_L\right)\gamma^\mu W_\mu^{\pm}\underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{CKM}}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$

- V_{CKM} has 3 angles and 1 complex phase δ_{CP} → CPV
- δ_{CP} related to angles α, β, γ of the unitarity triangle $\sum_{i=u,c,t} V_{ib}V_{id}^* = 0$
- α, β, γ measured from CP asymmetries: comparison of process rates in B and $\bar{B}$ decays

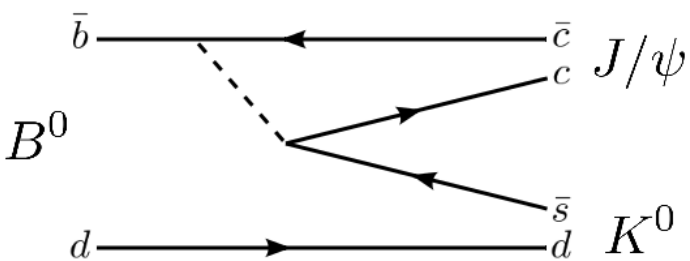


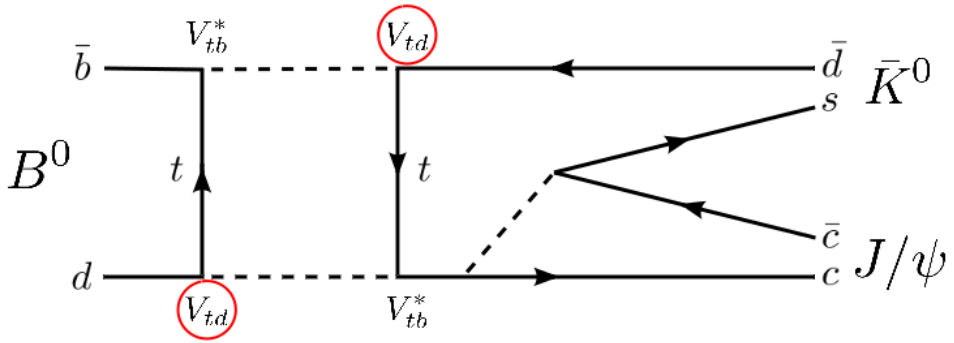
Measuring $\beta = \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$

- Measure in processes with interference between
  - Direct decay of a B^0 to a CP-eigenstate f_{CP}
  - $B^0 \to \bar{B}^0$ mixing followed by decay to the same final state

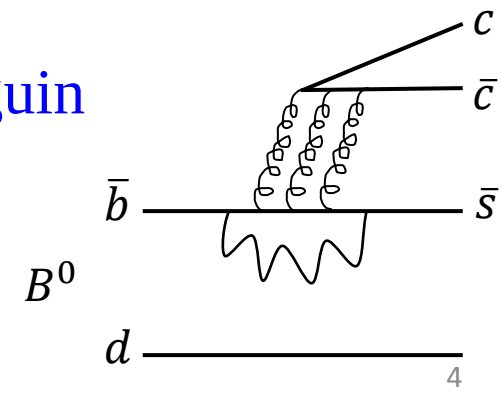


- E.g., in $B^0 \to J/\psi K_S$ ("golden mode"):



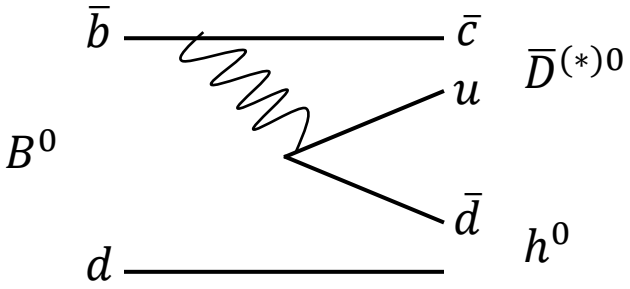


- $b \to c\bar{c}s$ decays may be affected by small penguin contribution, sensitive to new physics
- → motivates cross checks with other modes
  - particularly in the LHCb-upgrade / Belle-II era

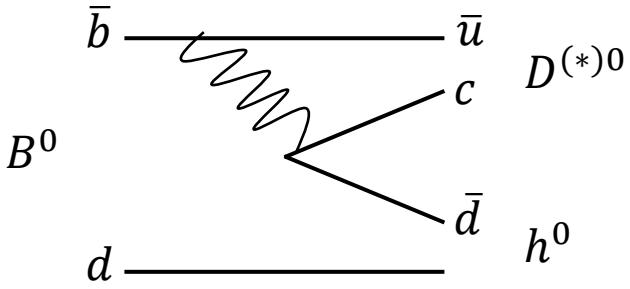


$\sin 2\beta$ from $B^0 \to D_{CP}^{(*)} h^0$

- One such cross check uses $B^0 \to D_{CP}^{(*)} h^0$, where
  - $D_{CP} \equiv D \to K^+K^-, K_S\pi^0, K_S\omega$
  - $D_{CP}^* \equiv D^* \to D_{CP}\pi^0$
  - $h^0 \equiv \pi^0, \eta, \omega$
- Only tree-level diagrams (less new-physics sensitivities):



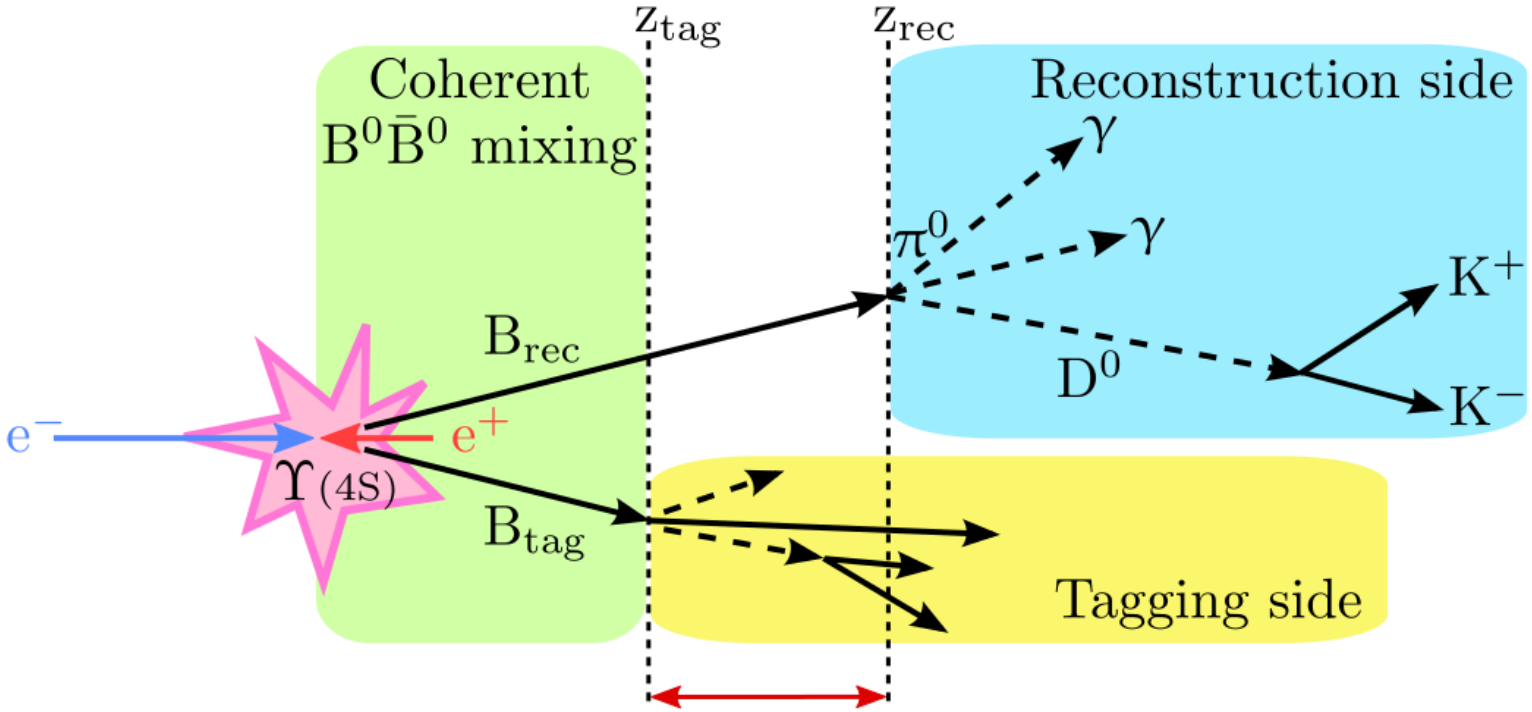
Dominant



Suppressed by $\frac{V_{ub}}{V_{cb}}\frac{V_{cd}^*}{V_{ud}^*} \approx 0.02$

- Experimental difficulties:
  - Small branching fraction, $O(10^{-6})$
  - Low reconstruction efficiencies
  - High background

$\sin 2\beta$ at an asymmetric B factory



$\Delta z = \beta\gamma c\Delta t$, $\langle|\Delta z|\rangle \approx 200\mu m$ Belle
$250\ \mu m$ *BABAR*

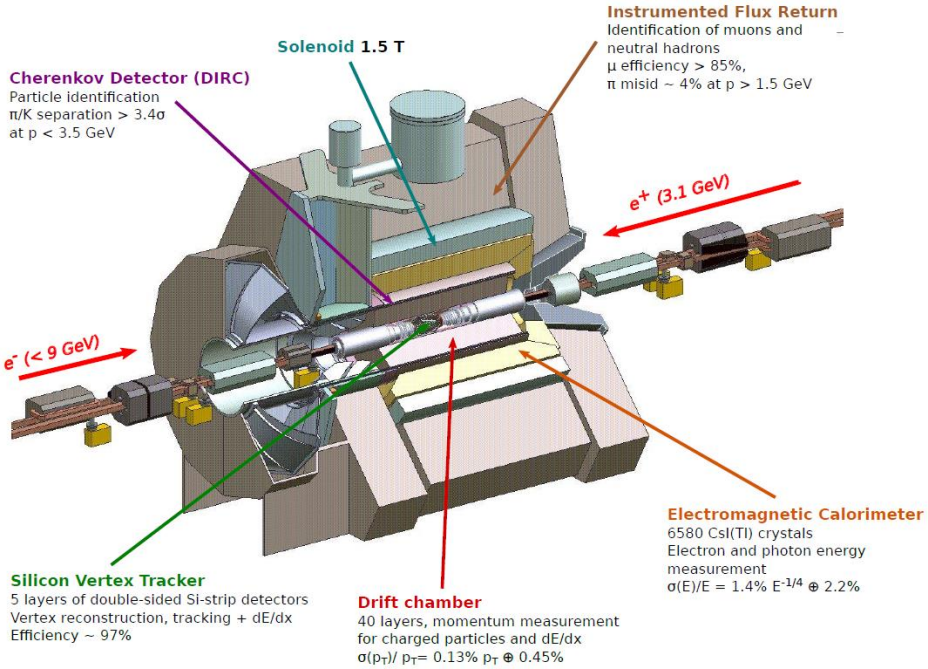
Mass-eigenstate mass difference

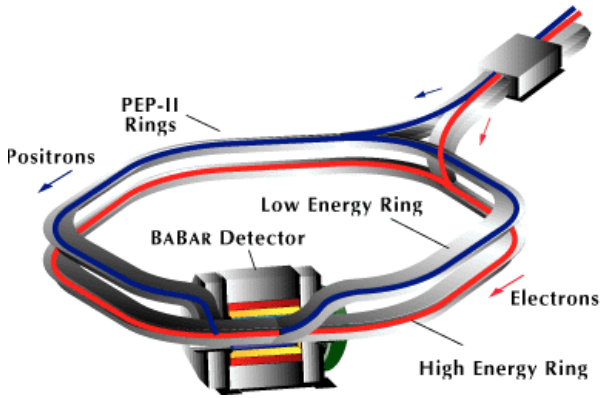
$$\mathcal{P}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{-\frac{|\Delta t|}{\tau_{B^0}}} \left[1 + q\left(\mathcal{S}\sin(\Delta m \Delta t) - \mathcal{C}\cos(\Delta m \Delta t)\right)\right]$$

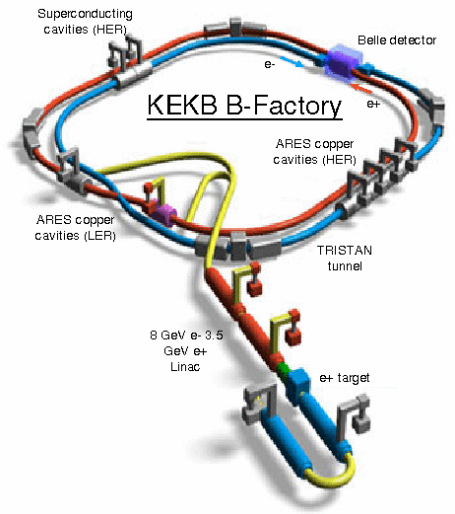
$q = +1(-1)$ when B_{tag} is B^0 ($\bar{B}^0$)

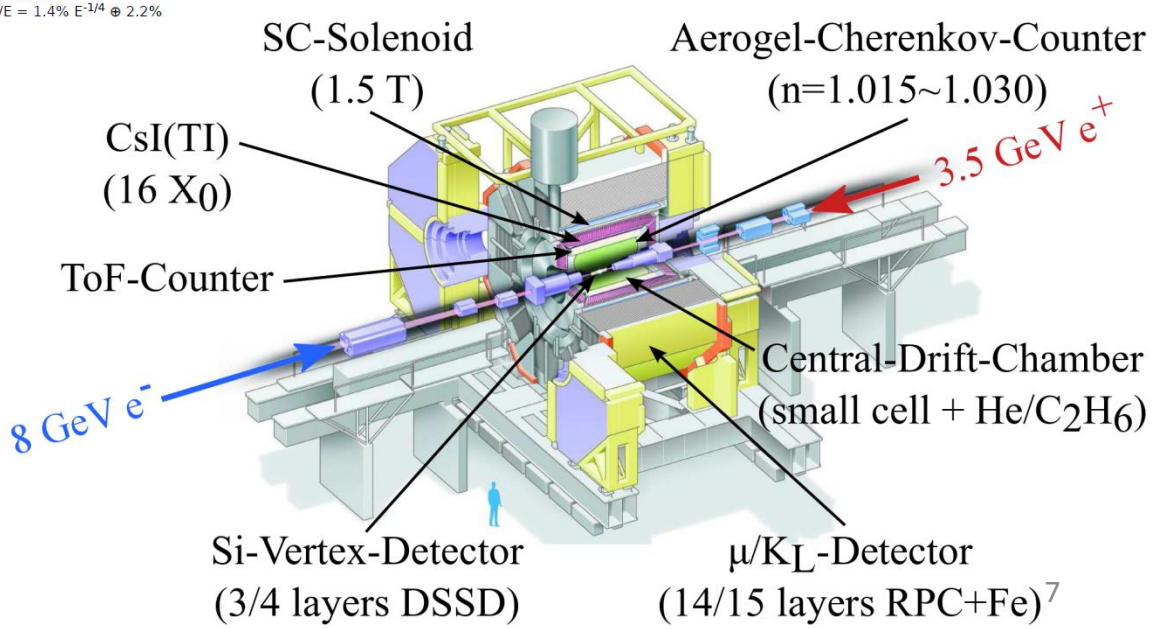
Neglecting the CKM-suppressed diagram
$S = -\eta_{f_{CP}} \sin 2\beta$, $C = 0$

BABAR and Belle experiments

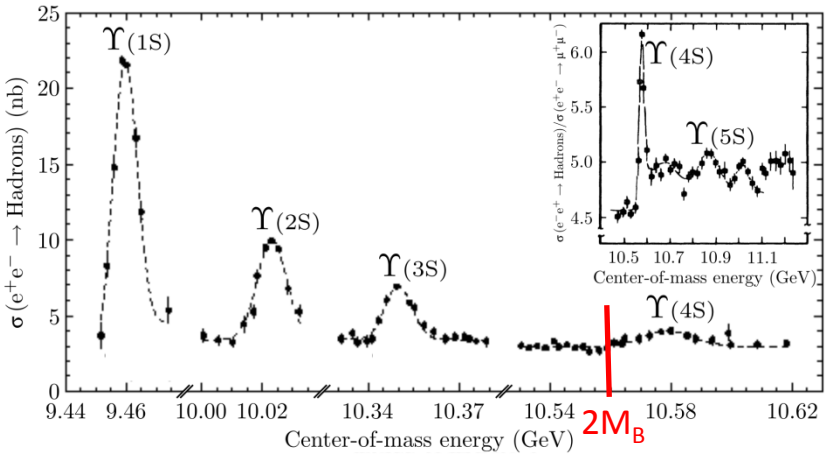


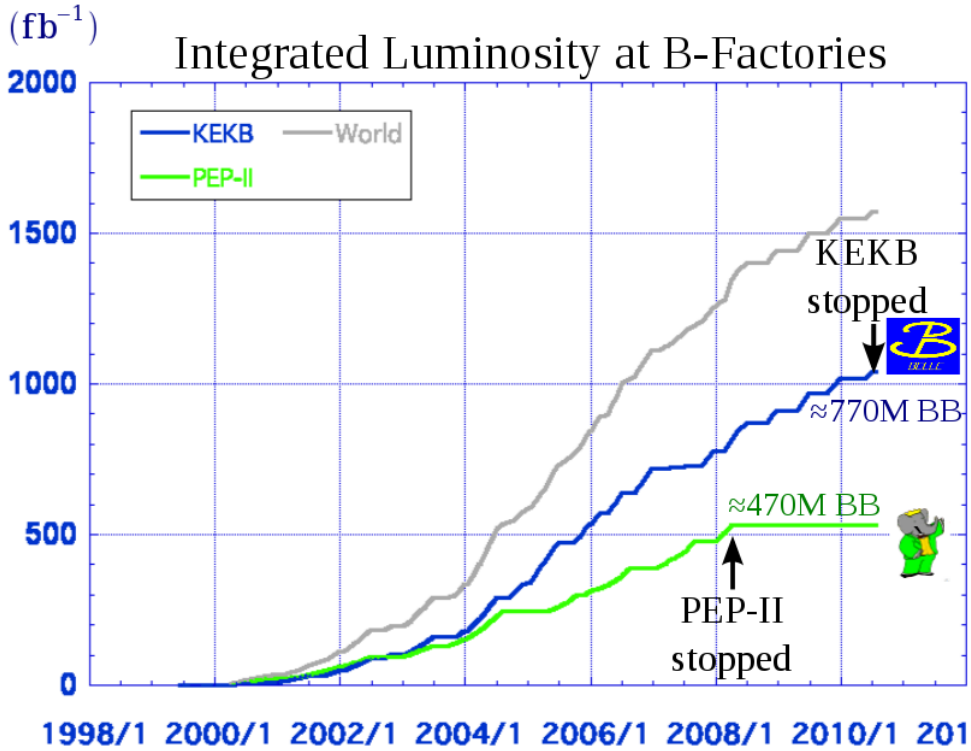






Data sets





Belle

> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 24 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

BaBar

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Combined dataset needed for significant measurement

Using 1.24×10^9 $B\bar{B}$ pairs and > 1.1 ab^{-1}

Analysis

- Joint analysis when clear benefit over combining separate results
  - Neither experiment has enough statistics for significant result
- Apply coherent analysis strategy to both data sets:
  - Almost same selections and other procedures
  - But often employing different state-of-the-art for each detector
- Dominant background from "continuum" $e^+e^- \to q\bar{q}$
  - Suppressed with neural networks of event-shape variables
- Signal yield from distributions of $M_{bc} \equiv \sqrt{E_{beam}^2 - p_B^2}$:

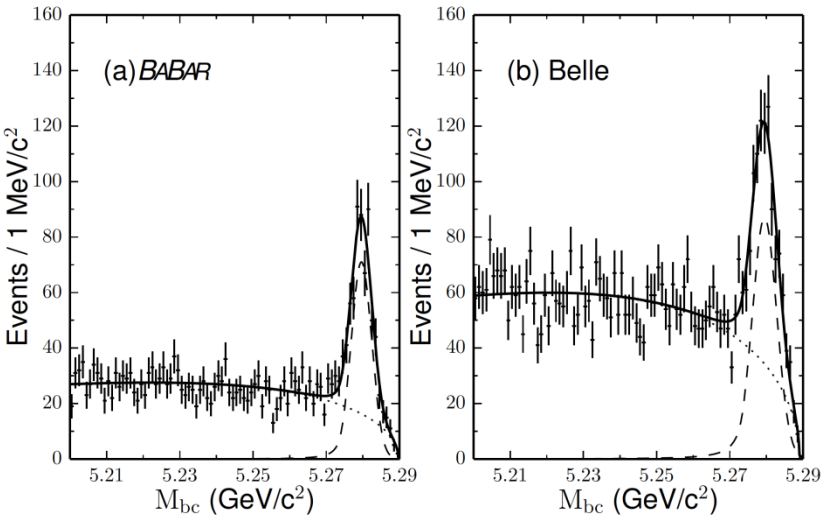


TABLE I. Summary of $\overline{B}^0 \to D_{CP}^{(*)} h^0$ signal yields.

Decay mode	*BABAR*	Belle
$\overline{B}^0 \to D_{CP}\pi^0$	241 ± 22	345 ± 25
$\overline{B}^0 \to D_{CP}\eta$	106 ± 14	148 ± 18
$\overline{B}^0 \to D_{CP}\omega$	66 ± 10	151 ± 17
$\overline{B}^0 \to D_{CP}^*\pi^0$	72 ± 12	80 ± 14
$\overline{B}^0 \to D_{CP}^*\eta$	39 ± 8	39 ± 10
$\overline{B}^0 \to D_{CP}^{(*)} h^0$ total	508 ± 31	757 ± 44

Obtaining sin 2β

- Unbinned maximum-likelihood fit of the Δt distributions to the model

$$(P_s + P_b) \otimes R$$

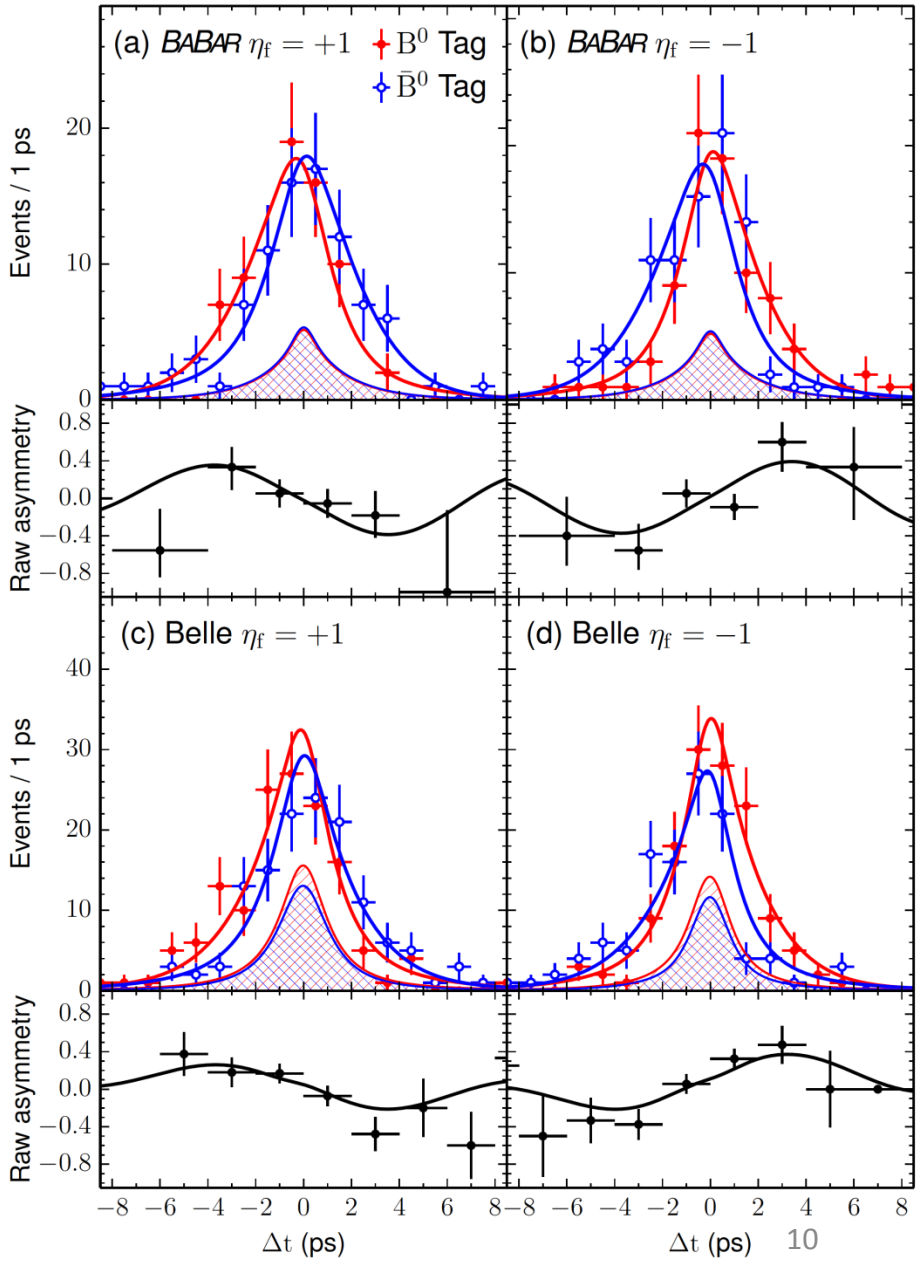
Background, from M_{bc} SB

Resolution, from data

Signal:

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

- Each event's signal weight comes from its M_{bc} value
- Floating in the fit: $\mathcal{S}$ and $\mathcal{C}$

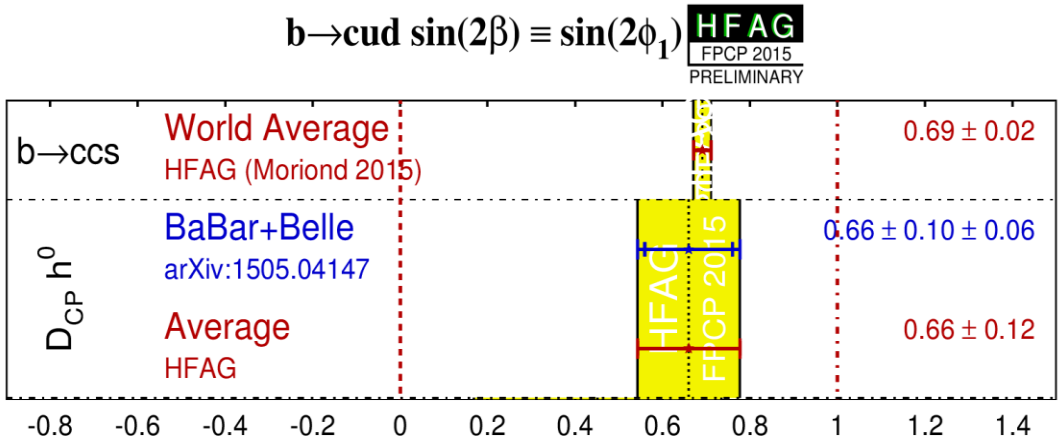


Results

$$-\eta_{f_{CP}} S = 0.66 \pm 0.10\,(stat) \pm 0.06\,(syst)$$

$$C = -0.02 \pm 0.07\,(stat) \pm 0.03\,(syst)$$

$S = 0$ excluded at $5.4\,\sigma$



$\sim 0.2\sigma$ agreement with $b \to c\bar{c}s$

Source	$\mathcal{S}$	$\mathcal{C}$
Vertex reconstruction	1.5	1.4
Δt resolution functions	2.0	0.4
Background Δt PDFs	0.4	0.1
Signal purity	0.6	0.3
Flavor-tagging	0.3	0.3
Physics parameters	0.2	< 0.1
Possible fit bias	0.6	0.8
Peaking background	4.9	0.9
Tag-side interference	0.1	1.4
Total	5.6	2.5

Systematic uncertainties (%)

Summary

- First observation of significant CP violation in $B^0 \to D_{CP}^{(*)} h^0$
- Excludes the no-CPV hypothesis at 5.4σ
- Result consistent with SM expectation, i.e.,
  - $\sin 2\beta$ from $b \to c\bar{c}s$
  - C consistent with 0
- First analysis using combined BABAR+Belle data
- First collider analysis performed with $1.1\ \text{ab}^{-1}$ of data