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

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DPF 2015

August 4-8, 2015

Ann Arbor, MI

On behalf of the BABAR and Belle collaborations

CP violation in the Standard Model

- *Yukawa couplings of fermions to Higgs field generate quark masses and mixing*

$$\mathcal{L}_Y = -Y^d_{ij}\bar{Q}^I_{Li}\phi d^I_{Rj} - Y^u_{ij}\bar{Q}^I_{Li}\epsilon\phi^* u^I_{Rj} + h.c.$$

- *Quarks couple in charged-current $W^\pm$ interactions as*

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

Cabbibo-Kobayashi-Maskawa matrix

- *CKM matrix*
  - *Complex, unitary 3 × 3 matrix*
  - *Describes the coupling between up- and down-type quarks*
  - *Only 4 free parameters: 3 mixing angles + **1 complex CPV phase***

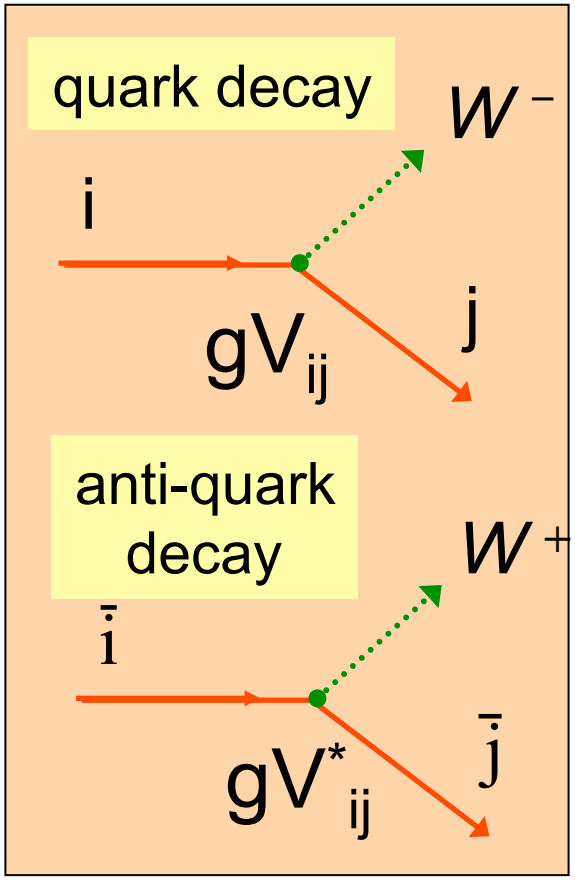
Charged current transitions of quarks

"Complex CKM matrix elements" lead to different b → u and t → d amplitudes for quarks and anti-quarks

$$\mathbf{V}_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & e^{-i\gamma}|V_{ub}| \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ e^{-i\beta}|V_{td}| & -|V_{ts}| & |V_{tb}| \end{pmatrix}$$

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

(Wolfenstein's convention and parameterization)



convention independent:

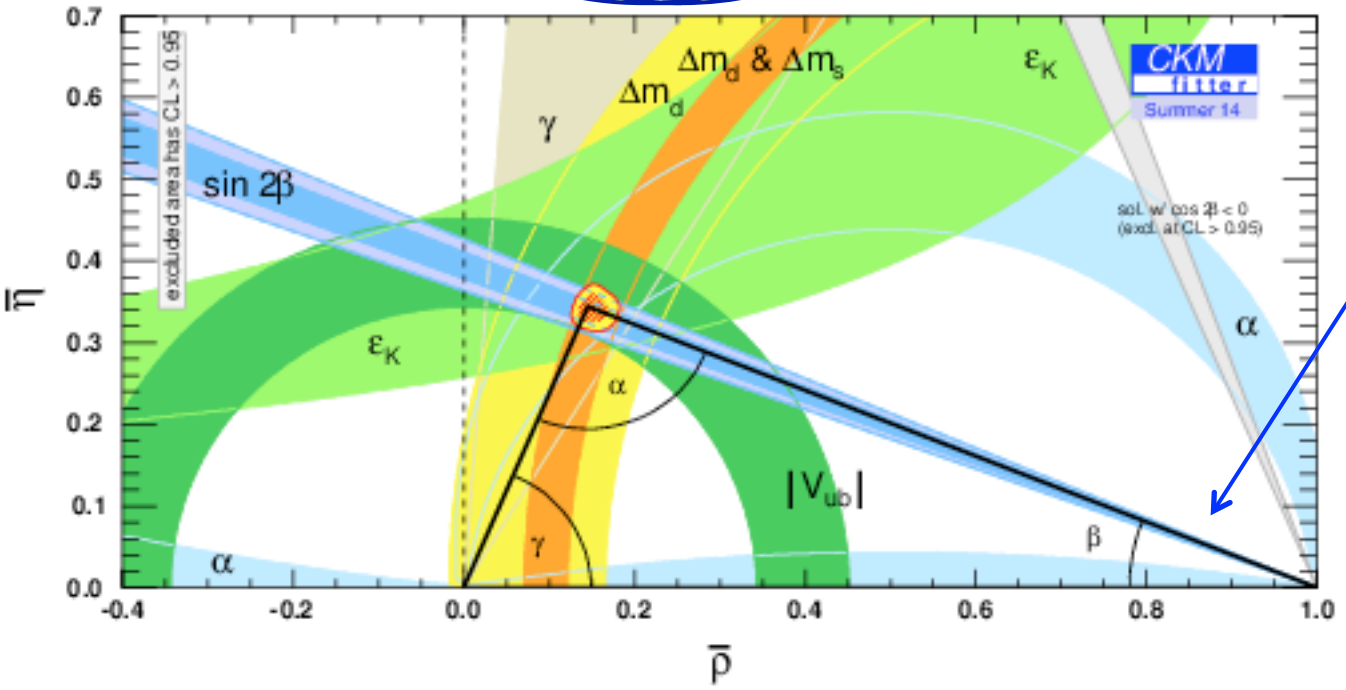
e.g. $\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$

The (B) Unitarity Triangle

$$\mathbf{V}_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & e^{-i\gamma}|V_{ub}| \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ e^{-i\beta}|V_{td}| & -|V_{ts}| & |V_{tb}| \end{pmatrix}$$

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

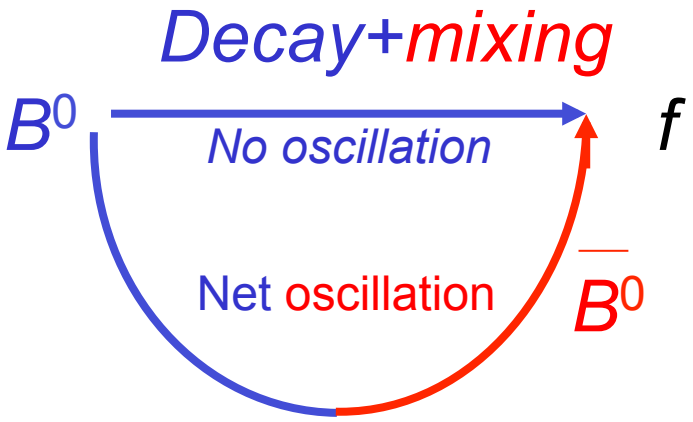
- ***Sides*** *are measured with decay rates*
- ***Angles*** *are measured with CP asymmetries*
  - *CP asymmetry in $B^0 \to D_{CP}^{(*)} h^0$ decays is related to β*

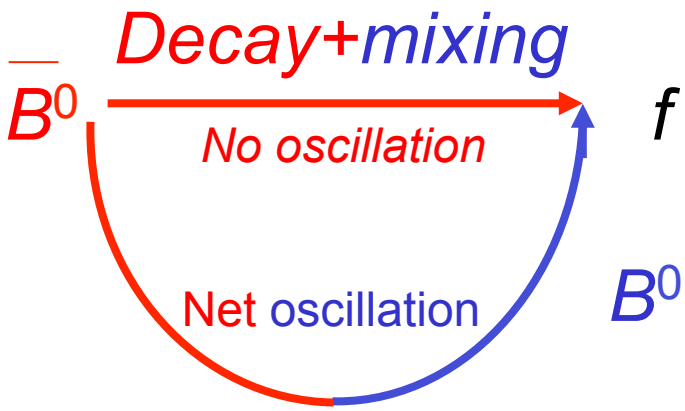


Inconsistent measurements could indicate new physics.

$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2} + \ldots\right), etc.$$

Mixing-induced CP Violation in B decays





$$\Gamma\left(B^0_{phys}(t)\to f\right) \neq \Gamma\left(\overline{B}^0_{phys}(t)\to f\right)$$

Define CP Asymmetry as:

$$A_{CP}(t)=\frac{\Gamma\left(\overline{B}^0_{phys}(t)\to f\right)-\Gamma\left(B^0_{phys}(t)\to f\right)}{\Gamma\left(B^0_{phys}(t)\to f\right)+\Gamma\left(\overline{B}^0_{phys}(t)\to f\right)}$$

$$A_{CP}=-C\cos(\Delta m\ t)+S\sin(\Delta m\ t)$$

$$\lambda=\frac{q}{p}\cdot\frac{\overline{A}}{A}$$

Amplitude ratio

$$\approx e^{-2i\beta}$$

Mixing phase

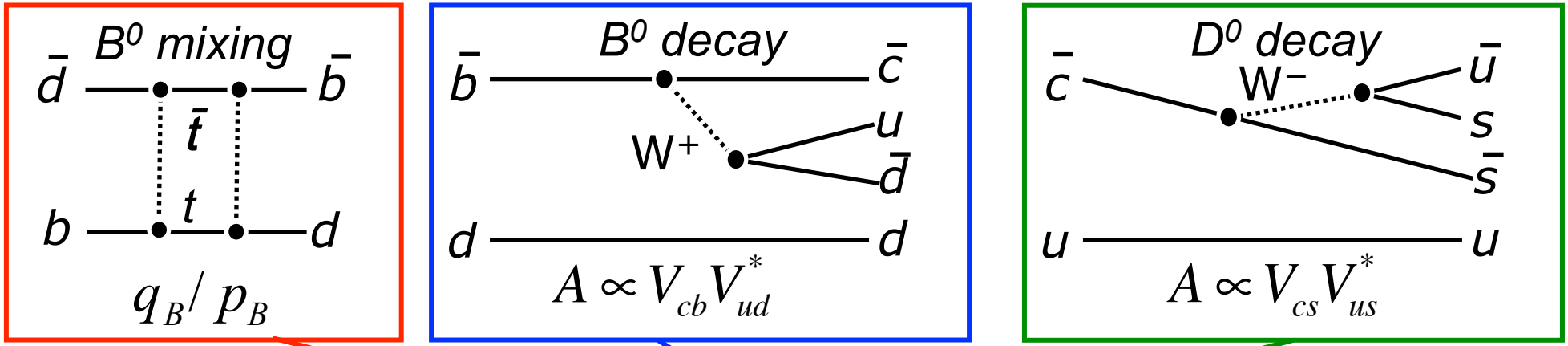
single weak decay amplitude

$$C=\frac{1-|\lambda|^2}{1+|\lambda|^2} \quad =0$$

$$S=\frac{-2\,\mathrm{Im}\,\lambda}{1+|\lambda|^2} \quad =-\mathrm{Im}\,\lambda$$

$C\neq 0$ implies Direct CP violation

CP violation in $B^0 \to D_{CP}^{(*)} h^0$ decays



$$\lambda = \frac{q}{p}\frac{\bar{A}}{A} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{ud} V_{cb}^*}{V_{ud}^* V_{cb}}\frac{V_{us} V_{cs}^*}{V_{us}^* V_{cs}}$$

$$\Rightarrow \mathrm{Im}(\lambda) = \sin(2\beta)$$

$$\Rightarrow |\lambda| = 1$$

$$\Gamma(B^0 \to f) \propto e^{-t/\tau}[1 + \eta_f \sin 2\beta \sin \Delta m\ t]$$

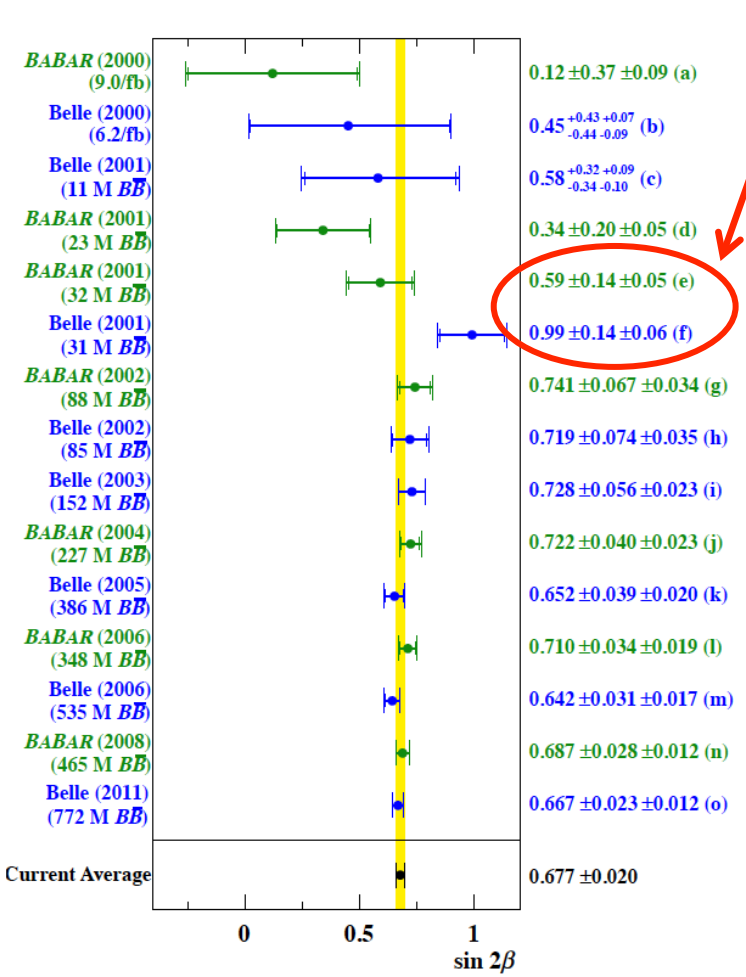
$$\Gamma(\bar{B}^0 \to f) \propto e^{-t/\tau}[1 - \eta_f \sin 2\beta \sin \Delta m\ t]$$

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

$\eta_f = +1\ (-1)$ *CP-even (odd) final states*

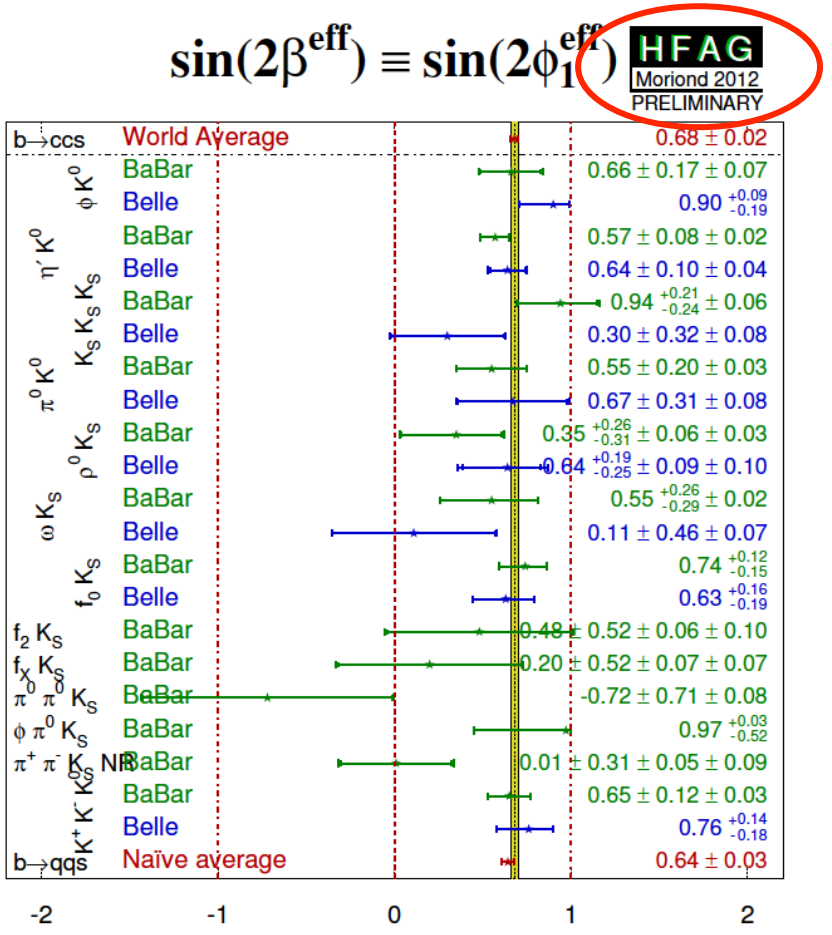
Previous BaBar + Belle measurements of sin2β

First observation of CP violation in the B meson system



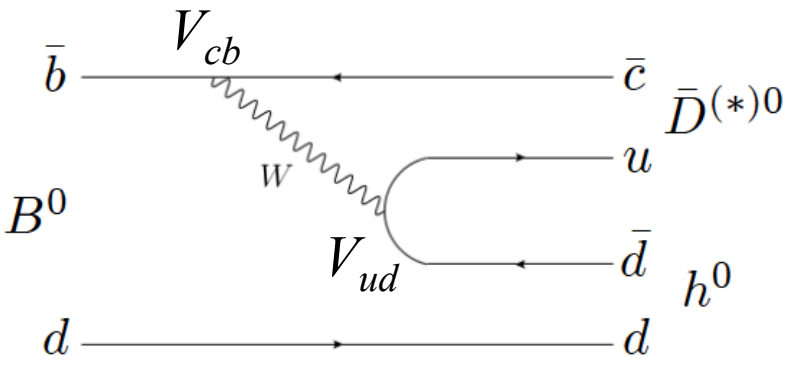
History of BaBar + Belle sin2β measurements with b → (cc̄) s decays (e.g. B → J/ψ K_S)

BaBar and Belle members have collaborated on HFAG to average their results (and others) since 2002

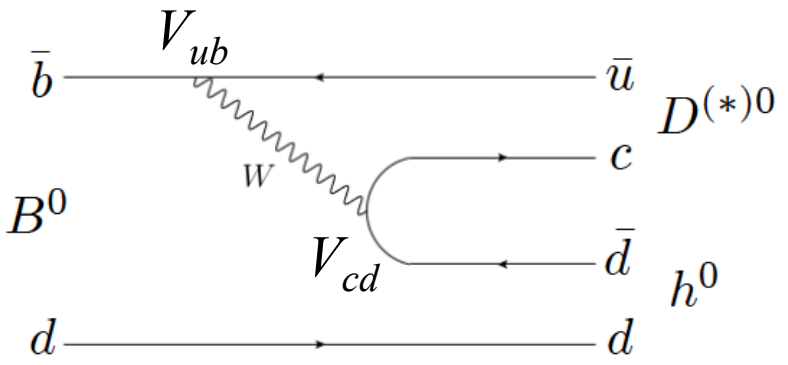


Summary of BaBar + Belle sin2β_{eff} measurements from charmless B decays. (New Physics could lead to large difference between sin2β_{eff} and sin2β.)

BABAR and Belle analysis of $B^0 \to D_{CP}^{(*)} h^0$



CKM-favored

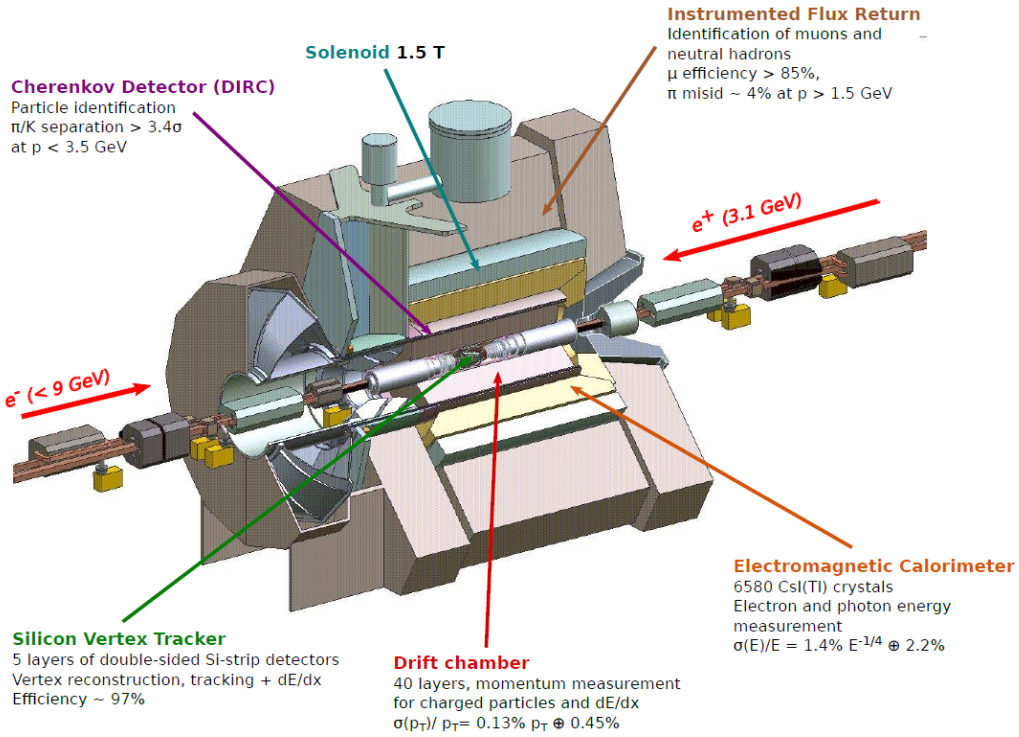


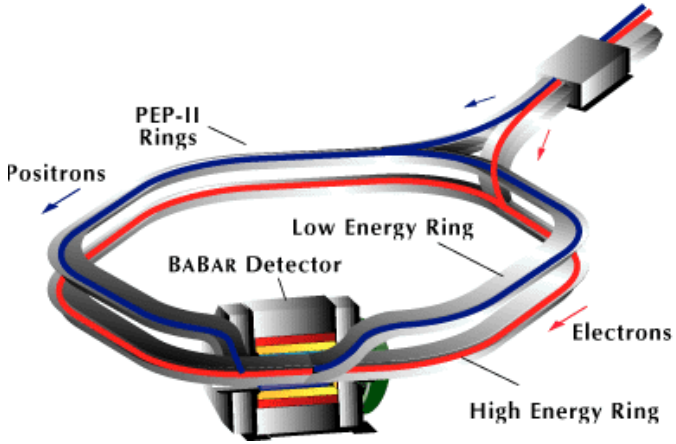
CKM-suppressed ($|V_{ub}V_{cd}^*/V_{cb}V_{ud}^*| \approx 0.02$)

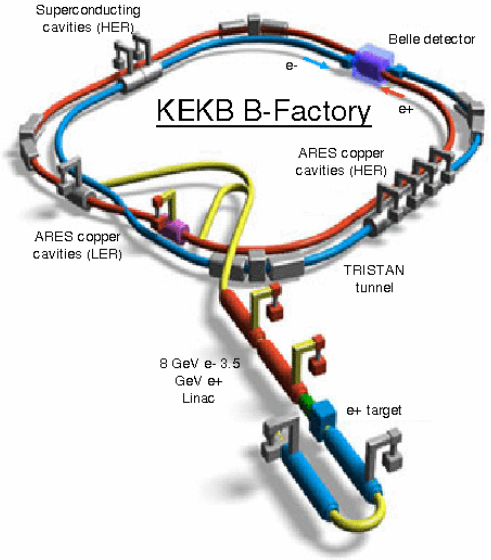
- $B^0 \to D_{CP}^{(*)} h^0$ *decays with* $h^0 \in \{\pi^0, \eta, \omega\}$ *are dominated by tree-level amplitudes*
- *Provide theoretically clean measurement of sin2β [Fleischer, NPB 659, 321 (2003)]*
  - *Strongly suppressed b → u amplitude can be safely neglected at the expected precision*
  - *Test precision measurements with b → cc̄s decays and provide reference for BSM searches in charmless B decays*
- *Experimental challenges*
  - *Low B and D_{CP} branching fractions [$\mathcal{O}(10^{-4})$ and $\mathcal{O}(10^{-2})$]*
  - *Low reconstruction efficiencies*
  - *"Large" background from B and non-B decays*
- *Previous BABAR measurement with 383M $B\bar{B}$ could not establish CPV (2.3σ) in $B^0 \to D_{CP}^{(*)} h^0$ decays [BABAR, PRL 99, 081801 (2007)].*

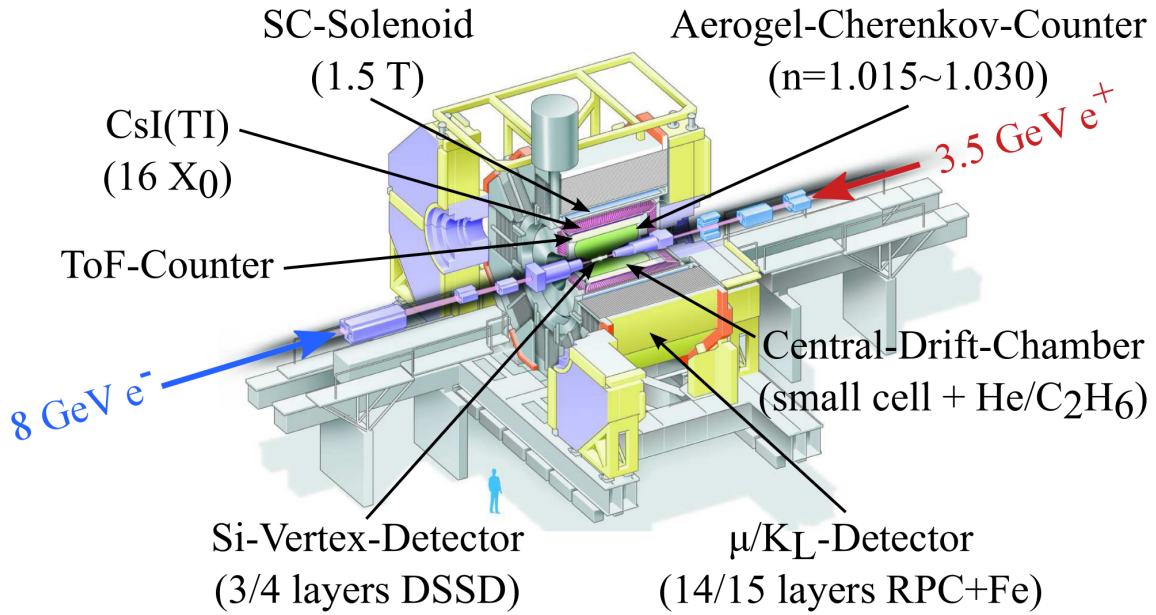
Use full BABAR + Belle data set for measurement of time-dependent CP violation

The BABAR and Belle Experiments

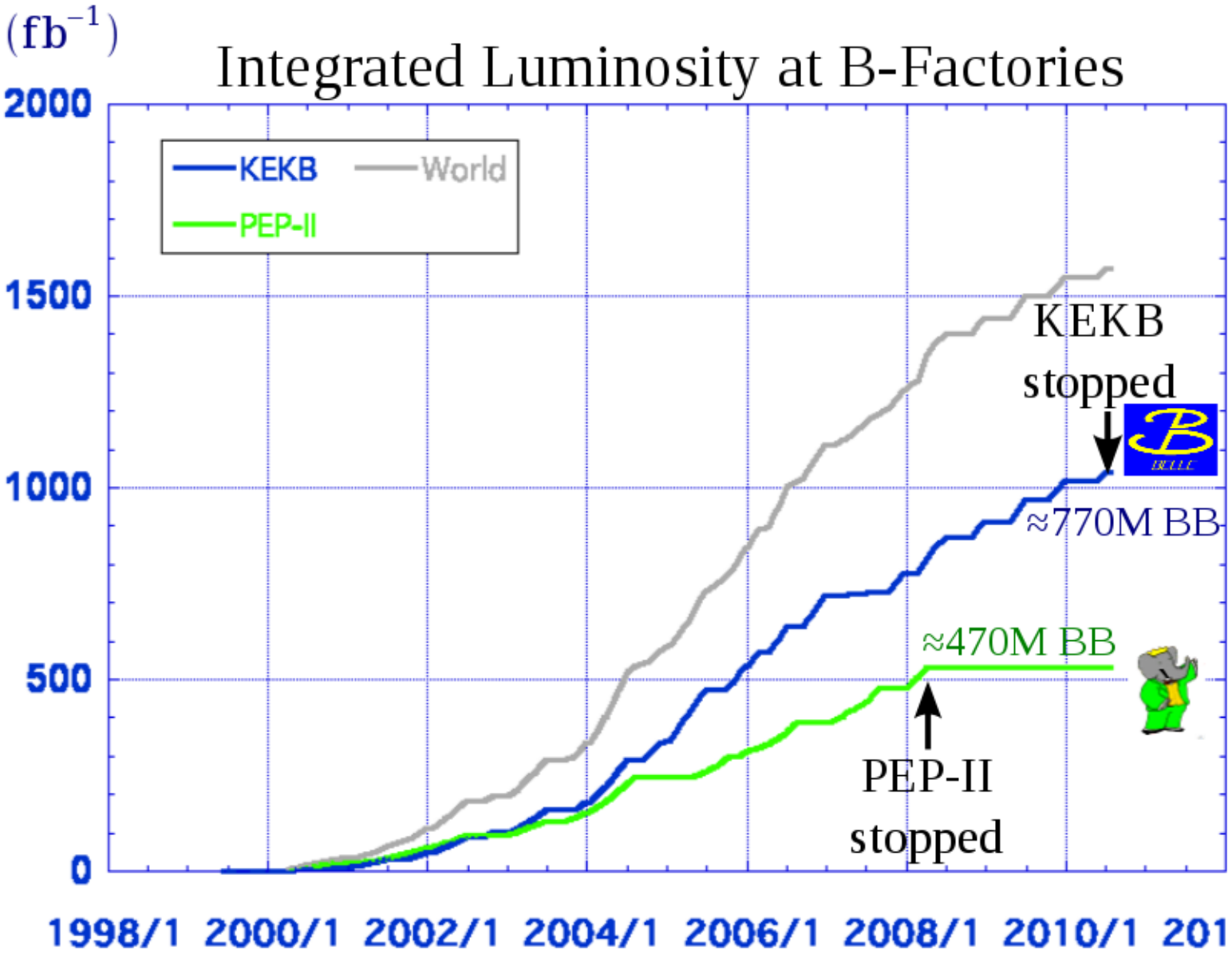








BABAR and Belle combined data set



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}

BABAR and Belle combined analysis uses ≈ 1240 × 10^6 $B\bar{B}$ collected at the $\Upsilon(4S)$

B Meson Production at PEP-II and KEKB

B production

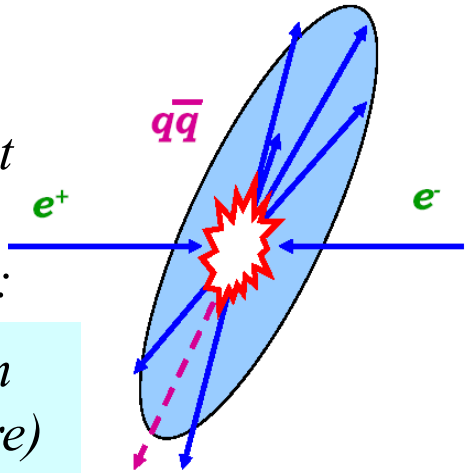
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$

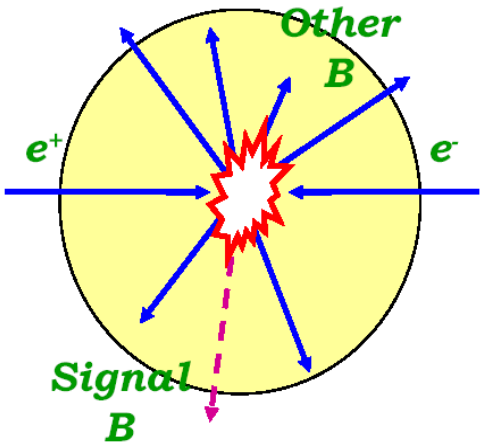
Dominant background for charmless B decays:

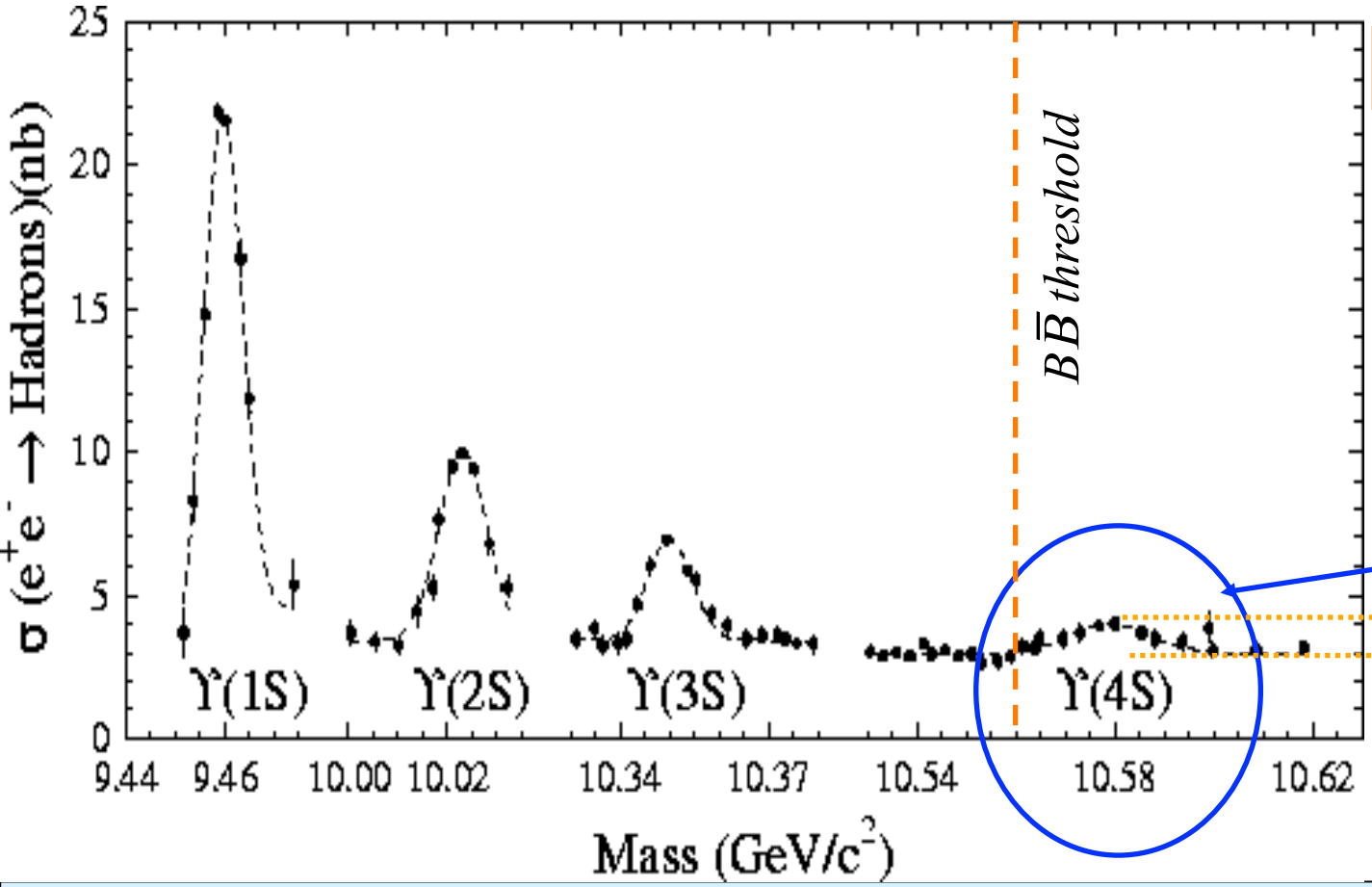
$e^+e^- \rightarrow q\bar{q}$ *(continuum)*

Suppress with event shape variables:

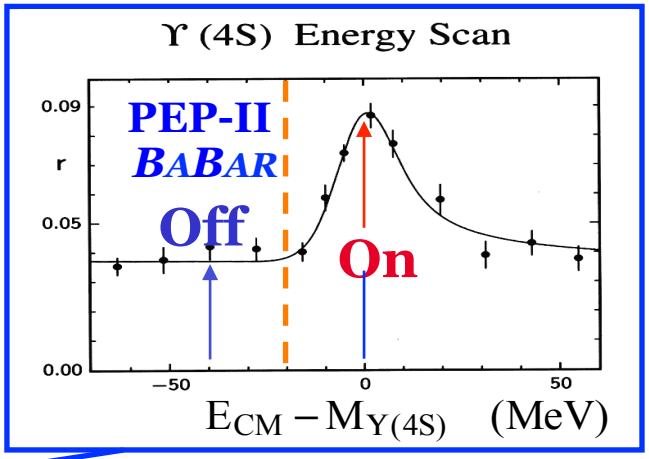
Continuum (jet-structure)







BB̄ (spherical)



$$\frac{\sigma(b\bar{b})}{\sigma(\text{hadr})} = 0.28$$

Selection of $B^0 \to D_{CP}^{(*)} h^0$ events

- Reconstruct $B^0 \to D_{CP}^{(*)} h^0$ in **7 CP-even** ($\eta_f = +1$, $D_{CP}(K_S\pi^0/\omega)\pi^0/\eta$, $D_{CP}(K_S\pi^0)\,\omega$, $D^*_{CP}((K^+K^-)\,\pi^0)\pi^0/\eta$) and **5 CP-odd final states** ($\eta_f = -1$, $D_{CP}(K^+K^-)\pi^0/\eta/\omega$, $D^*_{CP}((K_S\pi^0)\,\pi^0)\pi^0$)

- Similar selection criteria applied to *BABAR* and Belle data

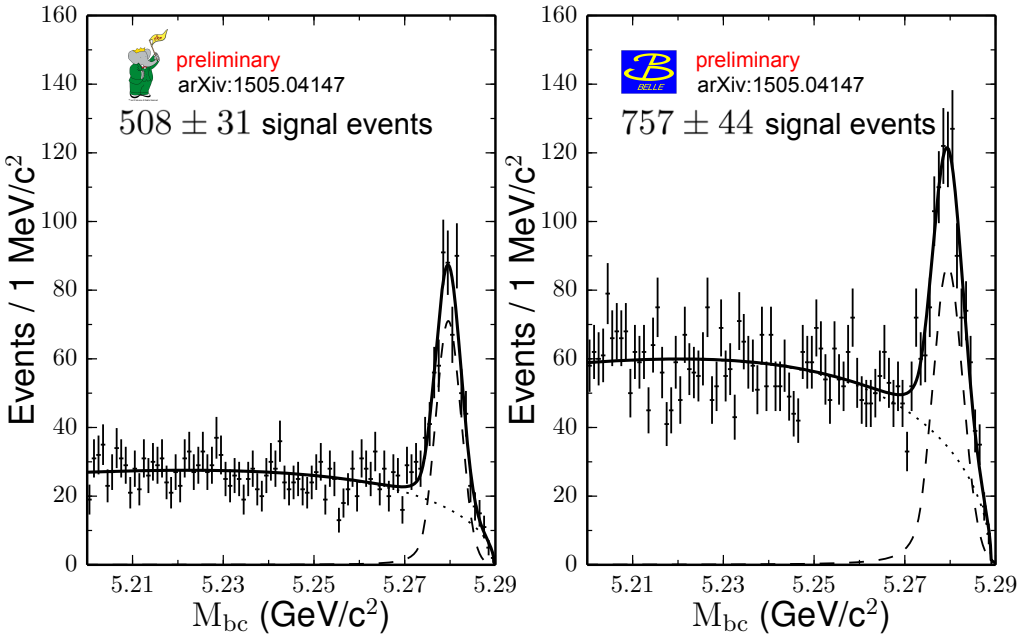
- Neural networks based on event-shape variables suppress $e^+e^- \to q\bar{q}$ ($q = u,d,s,c$) continuum background

- Signal extracted from beam-constrained mass distribution

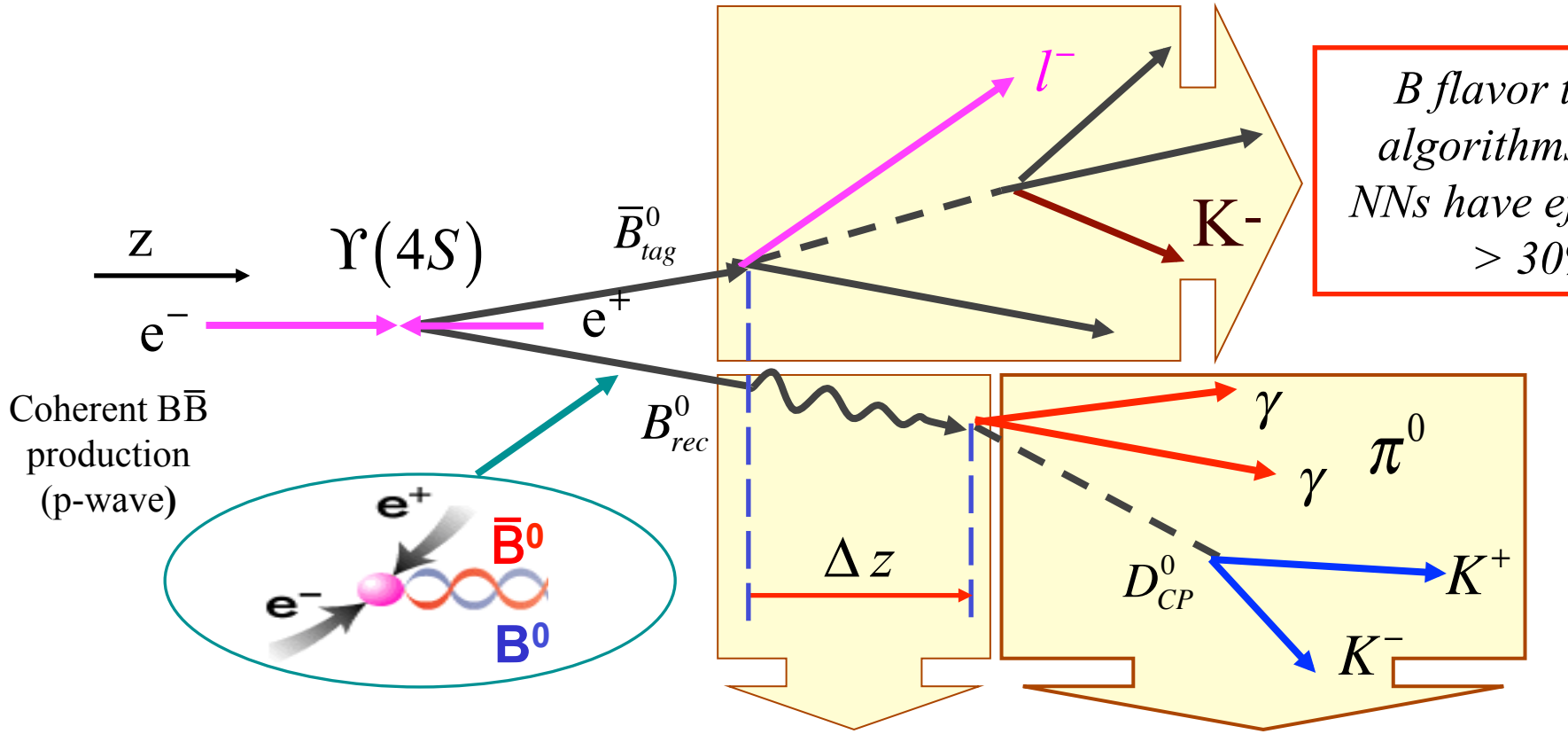
$$M_{bc} = \sqrt{\left(E^*_{beam}\right)^2 - \left(p^*_B\right)^2}$$

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

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



Time-dependent CP violation analyses at BABAR and Belle



B flavor tagging algorithms using NNs have efficiency > 30%

$\Delta t = t_{rec} - t_{tag} \approx \Delta z / \beta\gamma c$

($\langle|\Delta z|\rangle = 200\mu$m Belle, 250μm BABAR)

Reconstruction of B decays to exclusive final state

- *Proper time-difference distribution given by*

$$P_{Sig}(\Delta t, q) = \frac{1}{4\tau_B} e^{-\frac{|\Delta t|}{\tau_B}} \left[1 + q\left(S\sin(\Delta m \Delta t) - C\cos(\Delta m \Delta t)\right)\right]$$

$\left[q = +1(-1) \text{ if } B_{tag} = B^0\left(\bar{B}^0\right)\right]$

- *Need to account for effects of vertex position resolution and B flavor mis-tagging*

$B^0 \to D_{CP}^{(*)} h^0$ CP fit and results

- *Perform CP measurement by maximizing the combined log-likelihood function*

$$\ln L = \sum_i \ln P_i^{BABAR} + \sum_j \ln P_j^{Belle}$$

- *The experimental P^{Exp} are the background PDF and the physics signal PDF P_{Sig} convolved with specific Δt resolution functions and accounting for flavor mis-tag rates*

$$P_{Sig}(\Delta t, q) = \frac{1}{4\tau_B} e^{-\frac{|\Delta t|}{\tau_B}} \left[1 + q\left(S\sin(\Delta m \Delta t) - C\cos(\Delta m \Delta t)\right)\right]$$

new result

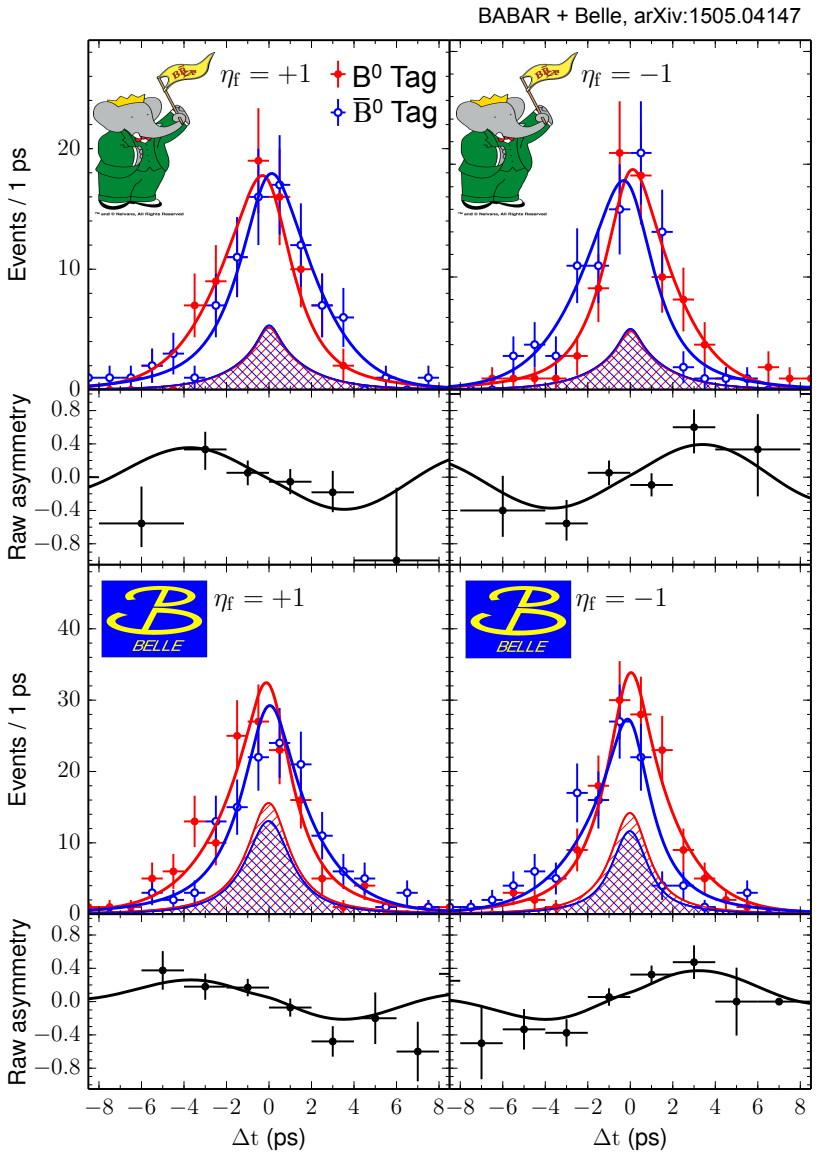
Belle+*BABAR* with 1.1 ab^{-1}: arXiv:1505.04147

$$-\eta_f \mathcal{S} = +0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.})$$
$$\mathcal{C} = -0.02 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.})$$

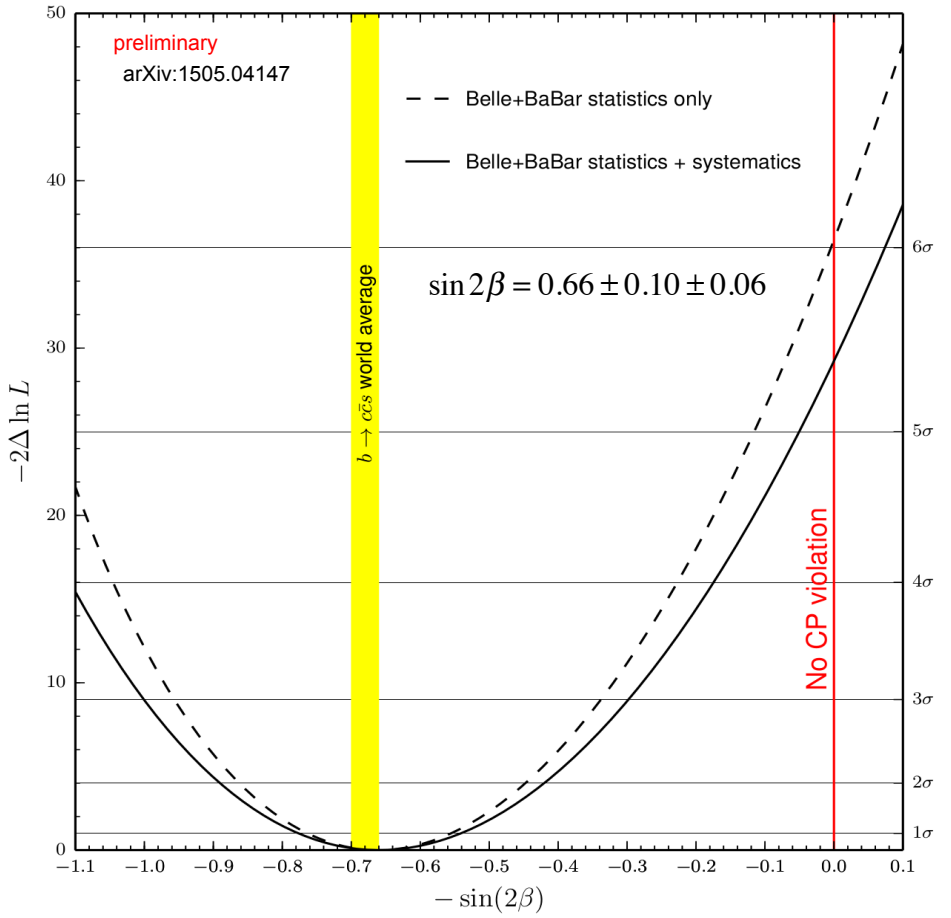
preliminary

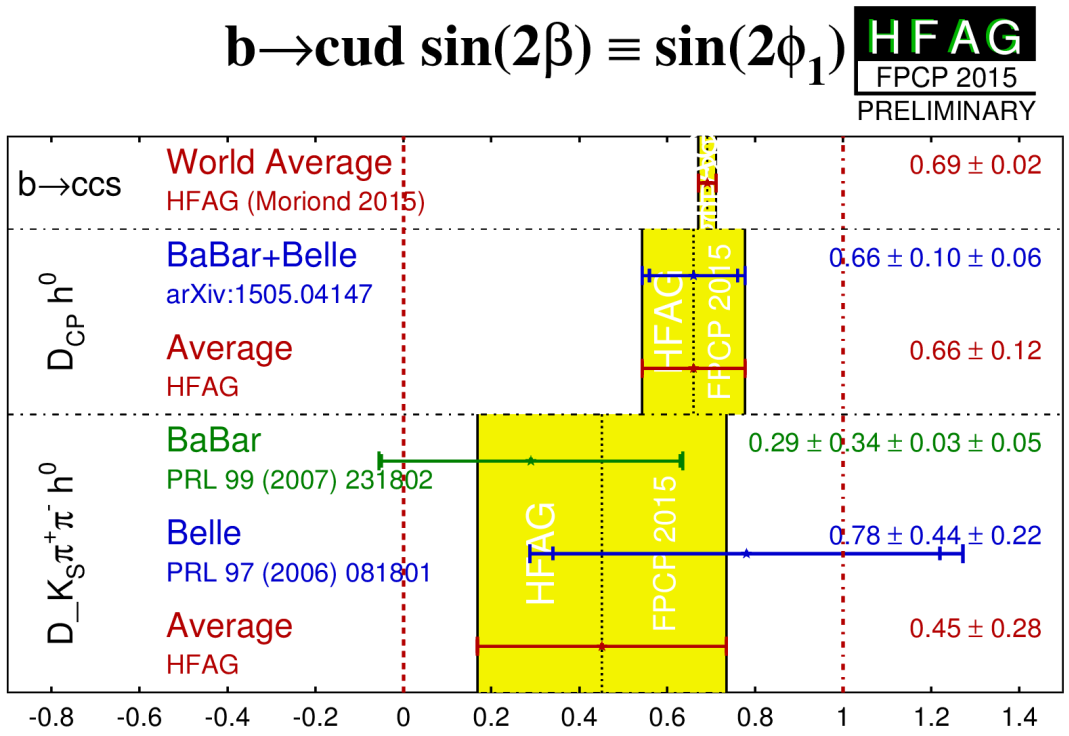
- *sin2β result by experiment and η_f*

$$\sin 2\beta(BABAR) = 0.52 \pm 0.15(stat)$$
$$\sin 2\beta(Belle) = 0.83 \pm 0.15(stat)$$
$$\sin 2\beta(\text{CP-even}) = 0.52 \pm 0.15(stat)$$
$$\sin 2\beta(\text{CP-odd}) = 0.80 \pm 0.15(stat)$$



Significance of CP Violation in $B^0 \to D_{CP}^{(*)} h^0$

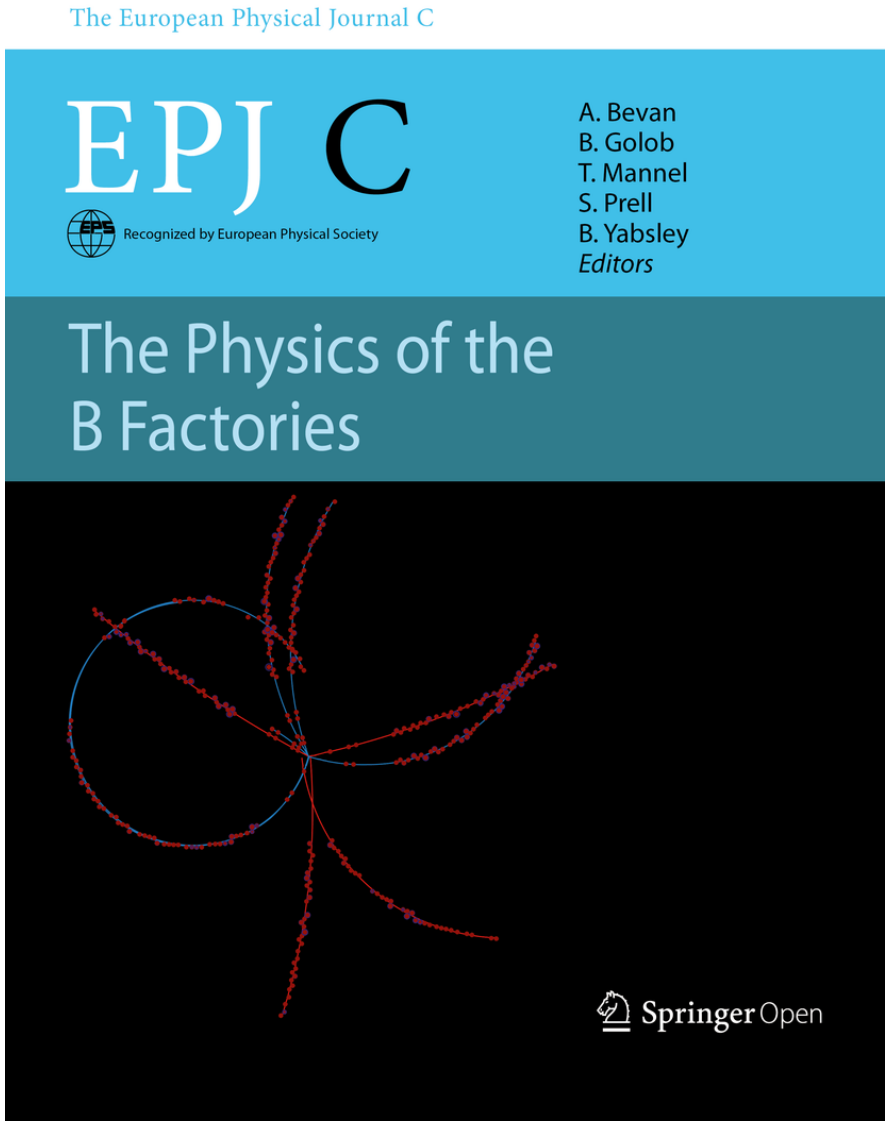




- *No mixing-induced CP violation in $B^0 \to D_{CP}^{(*)} h^0$ hypothesis excluded at 5.4σ*
  - *First observation of CP violation in $B^0 \to D_{CP}^{(*)} h^0$ decays !*
- *sin2β measurement agrees with world-average from $b \to (c\bar{c})s$ decays*
- *First measurement performed on more than 1 ab^{-1} collected at the Y(4S)*

Another collaboration between BaBar and Belle

- *At the beginning (in the early 2000's) there was tough competition between BaBar and Belle…*
- *… a decade and over 700 papers later the two collaborations decided to write together the "Physics of the B Factories"*
  - *Detailed reviews of the detectors, analysis methods and measurements written from a pedagogical perspective to be interesting to the student and expert alike*
- *Available under open access policy at Eur. Phys. J. C74 (2014) 3026 or http://arxiv.org/abs/1406.6311*



Conclusions

- *BABAR and Belle performed a measurement of CP violation in $B^0 \to D_{CP}^{(*)} h^0$ decays on their combined final data sets*
  - *First analysis using more than 1 ab^{-1} collected at the Y(4S)*
  - *sin2β measurement excludes no mixing-induced CP violation in $B^0 \to D_{CP}^{(*)} h^0$ decays hypothesis at 5.4σ ($\sin 2\beta = 0.66 \pm 0.10 \pm 0.06$)*
    - *First observation of CP violation in $B^0 \to D_{CP}^{(*)} h^0$ decays*
  - *Good agreement with sin2β from $b \to (c\bar{c})\, s$ decays*
  - *No evidence for direct CP violation ($C = -0.02 + 0.07 + 0.03$)*
- *The paper has been submitted to Physical Review Letters (arXiv: 1505.04147)*
- *For the interested, reviews on all BaBar and Belle measurements (except the most recent ones) on B decays and CP violation (and much more) can be found in the "Physics of the B Factories" (arXiv:1406.6311)*