Combined Time-Dependent *CP* Violation Measurements by the *B* factory experiments BABAR and Belle

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(The presented work has been carried out at Caltech.)

CERN Seminar, 8th of May 2018

Outline of the Talk

1) Introduction to flavor physics and *CP* violation

2) The $B\kern-0.1em{\scriptstyle A}\kern-0.1em B\kern-0.1em{\scriptstyle A\kern-0.1em R}$ and Belle experiments, and the idea of combined measurements

3) Combined $B\kern-0.1em{\scriptstyle A}\kern-0.1em B\kern-0.1em{\scriptstyle A\kern-0.1em R}$+Belle Measurements:

   a) Measuring sin(2β) by a time-dependent *CP* violation analysis of $\mathrm{B}^0 \to \mathrm{D}_{\mathrm{CP}}^{(*)}\mathrm{h}^0$

   b) Measuring cos(2β) by a time-dependent Dalitz plot analysis of $\mathrm{B}^0 \to \mathrm{D}^{(*)}\mathrm{h}^0$ with $\mathrm{D} \to \mathrm{K}_\mathrm{S}^0\pi^+\pi^-$

4) Summary & Outlook

Introduction to Flavor Physics

- The quark masses and mixing arise from Yukawa couplings of the fermion fields to the Higgs condensate:

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

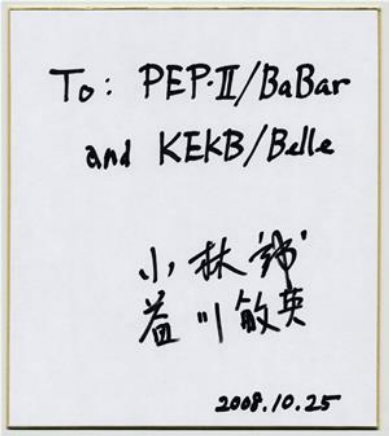
- Kobayashi + Maskawa: cannot simultaneously align up- and down-type quarks,

CKM matrix: 3 real parameters + 1 CP violating phase

$$\mathbf{V}_{\mathrm{CKM}} = \mathbf{V}^u_L \mathbf{V}^{d\dagger}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx$$

B factories BABAR (US) and Belle (Japan):

- Discovery of *CP* violation in B meson system
- Exploring and constraining the quark flavor structure of the Standard Model
- Experimental confirmation of the Kobayashi-Maskawa theory



The Nobel Prize in Physics 2008

CP Violation

- *CP* violation is of fundamental importance and related to basic properties of the SM:

  Number of fermion families, quark flavor structure, and mass hierarchy

- *CP* violation enables unambiguous assignment of matter and antimatter.

$$\frac{\Gamma(K_L^0 \to \pi^- e^+ \nu_e) - \Gamma(K_L^0 \to \pi^+ e^- \bar{\nu}_e)}{\Gamma(K_L^0 \to \pi^- e^+ \nu_e) + \Gamma(K_L^0 \to \pi^+ e^- \bar{\nu}_e)} = \left(+2.24 \pm 0.36\ (\text{stat.} + \text{syst.})\right) \times 10^{-3}$$

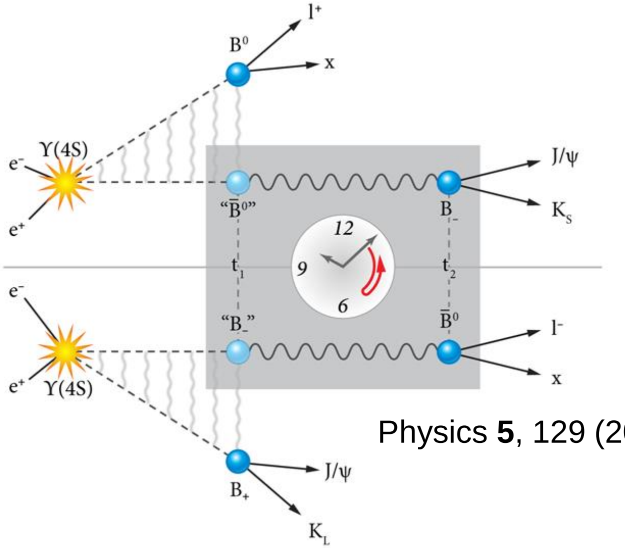
Steinberger *et al.*, PRL **19**, 993 (1967)

- *CPT* theorem: all local Lorentz invariant QFTs respect combination of *C*, *P* and *T*.

→ *CP* violation implies the violation of time-reversal *T*, establishing an “arrow of time” on the microscopic level.

- *B* factories can test *CP*, *T* and *CPT* by exploiting the coherent $B^0\bar{B}^0$ mixing on the $\Upsilon(4S)$.

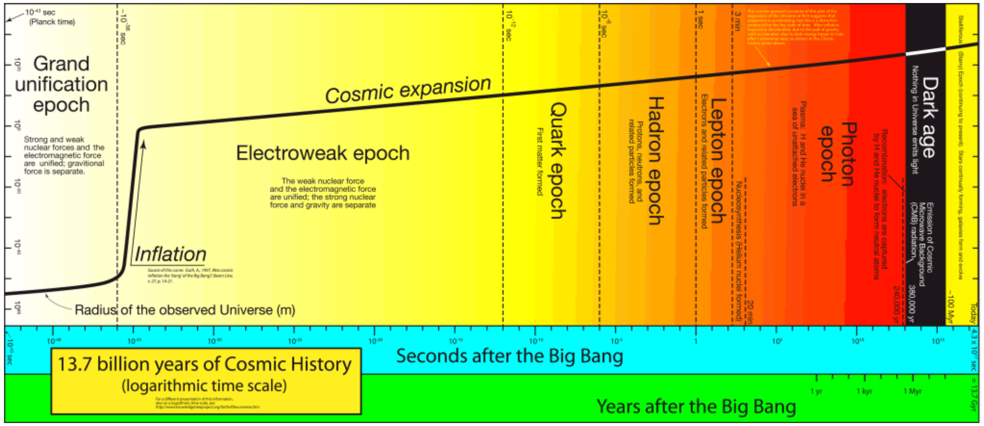
- BABAR has demonstrated *T* violation in 2012.



Physics **5**, 129 (2012)

CP Violation in the Cosmological Context

The Big Bang created equal amounts of matter and antimatter, but today we see a matter dominated universe.



Conditions for baryogenesis by Sakharov (1967):

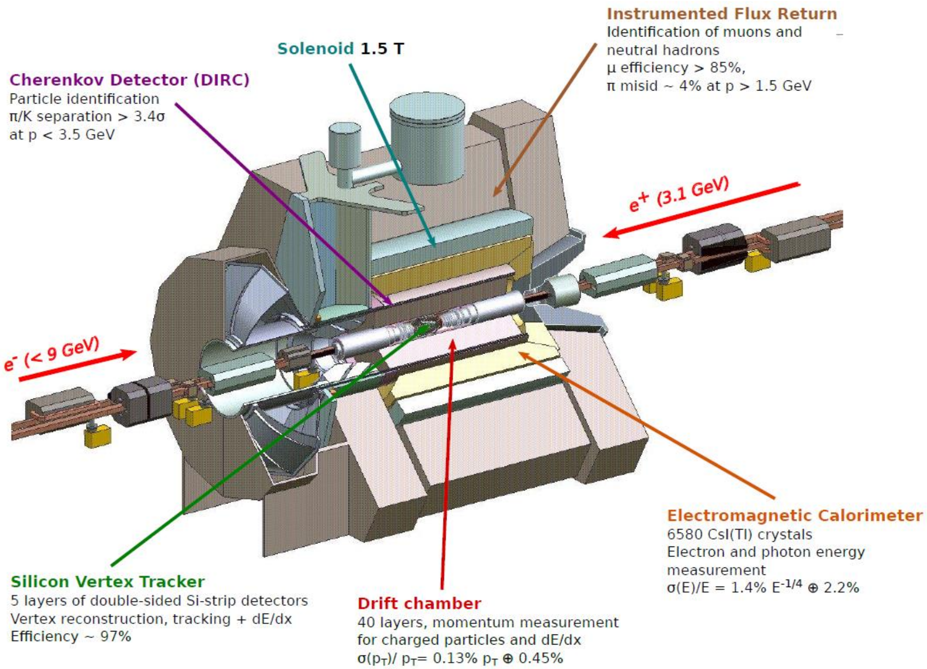
1. Baryon number violation
2. Departure from thermal equilibrium
3. *C* and *CP* violation

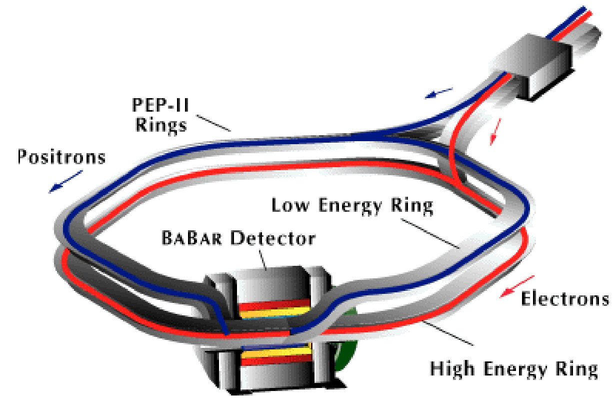
CP violation in the SM generated by the Kobayashi-Maskawa mechanism is insufficient to generate the observed matter-antimatter asymmetry.

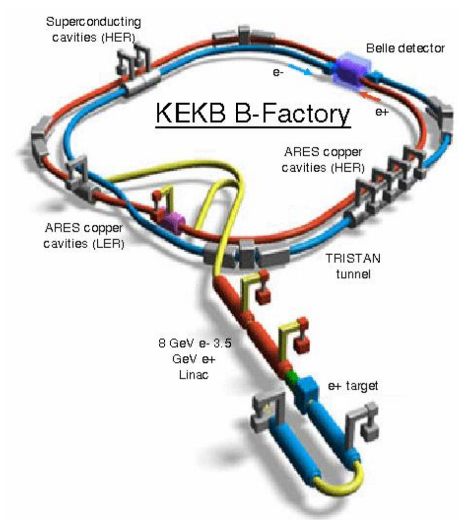
→ Important motivation to search for additional sources of *CP* violation.
(Key field of research in flavor physics experiments)

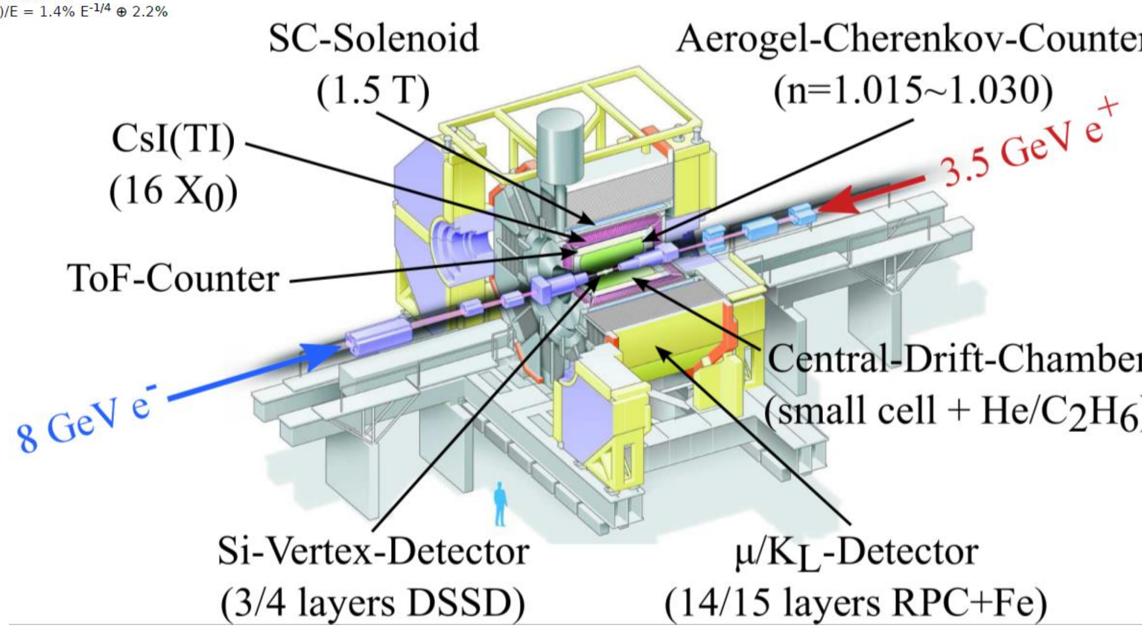
The BaBar and Belle experiments, and the idea of combined measurements

The BABAR and Belle Experiments



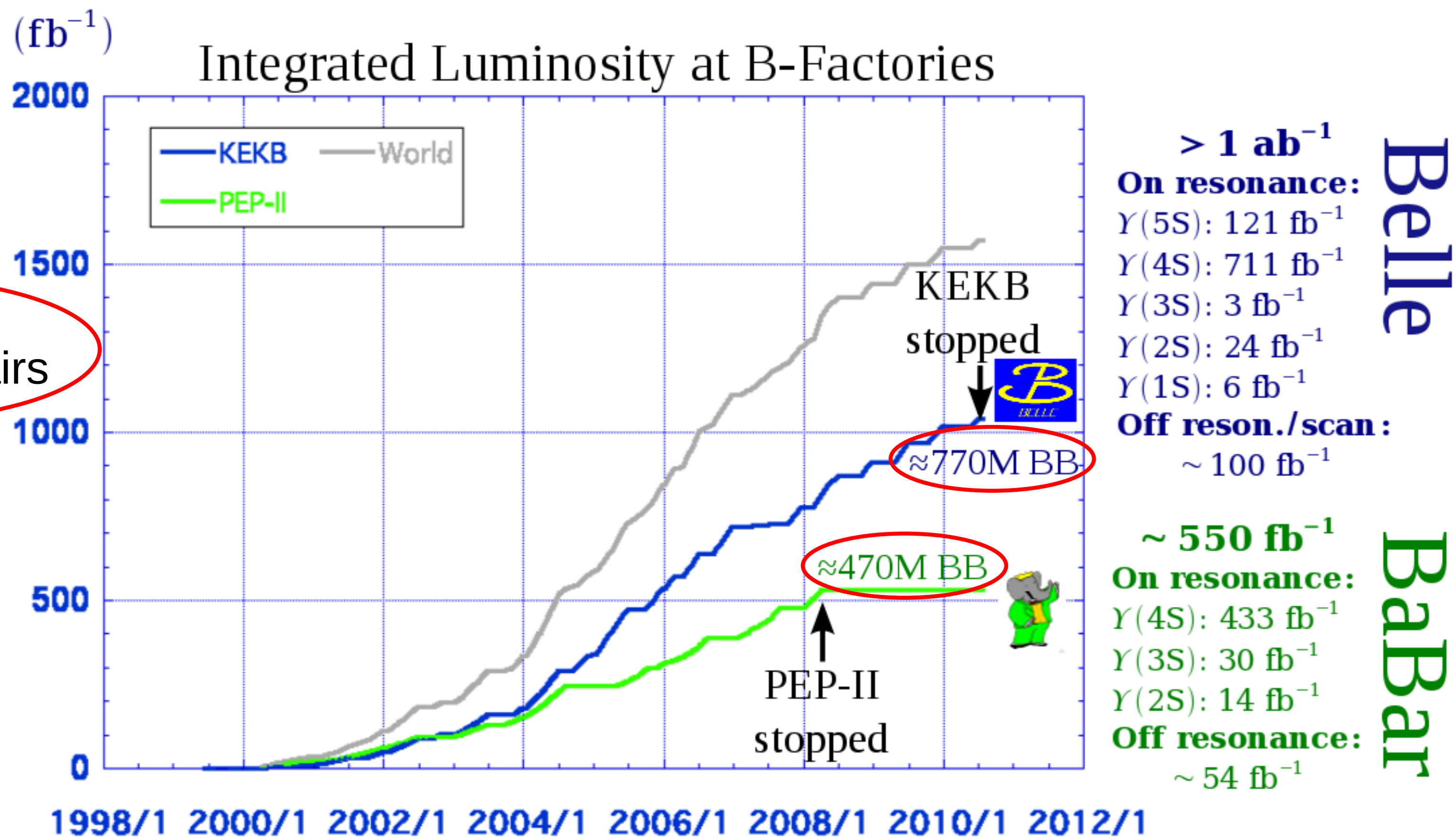






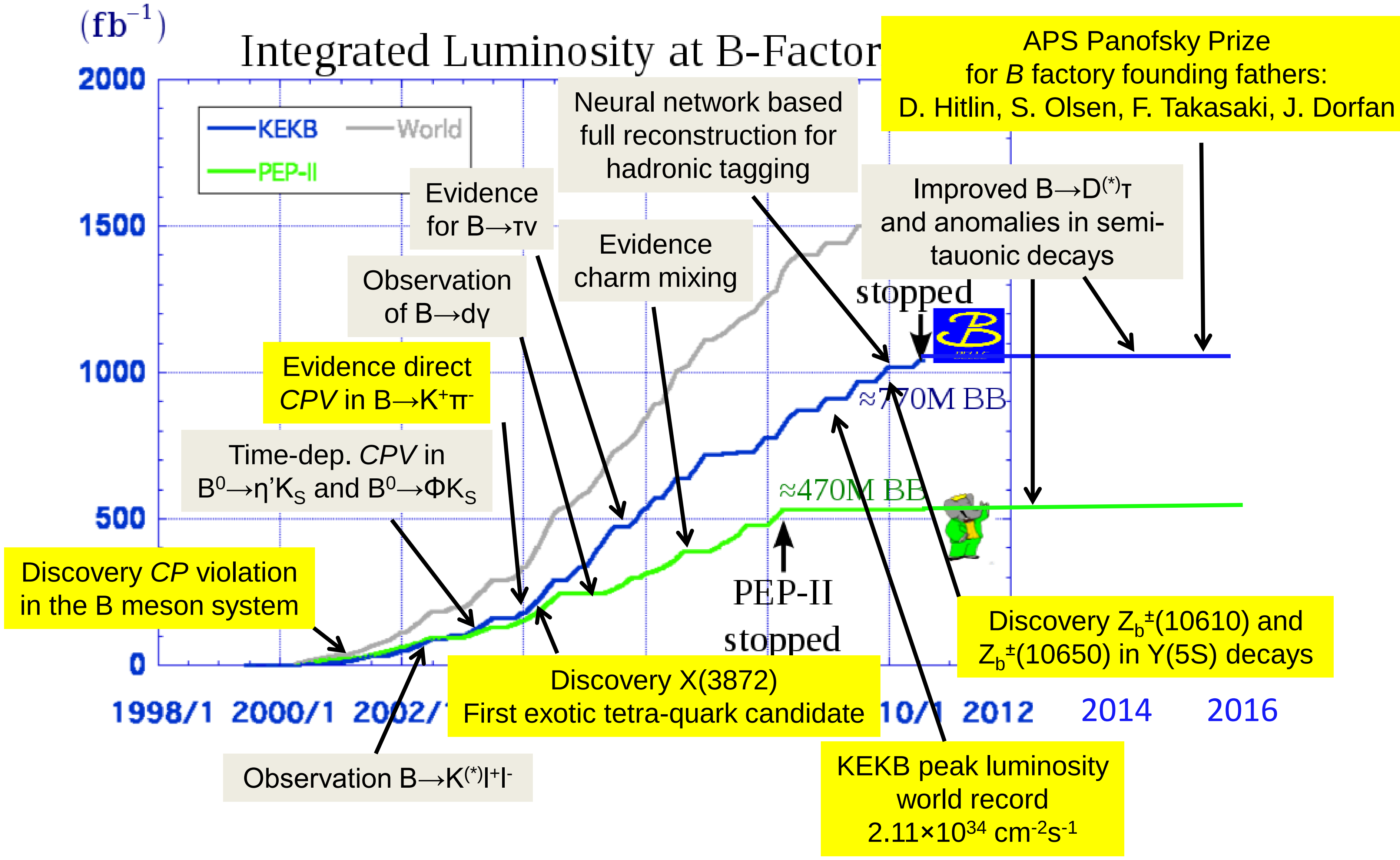
The *BaBar* and Belle Experiments

Total of 1240×10^{6} BB pairs



During the last decade, *BaBar* and Belle performed a very successful flavor physics program leading to many major discoveries.

The BABAR and Belle Experiments

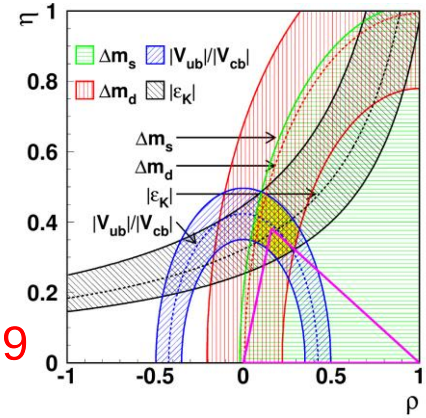


The BABAR and Belle Experiments

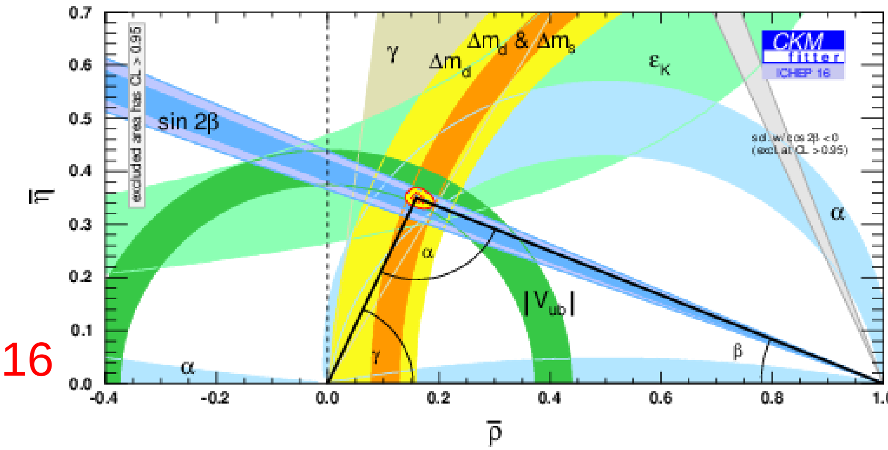
- BABAR and Belle greatly advanced our understanding of the quark flavor sector:

CKM Unitarity Triangle:

1999



2016



- The CKM picture agrees well in many independent measurements

- Still, a 10-20% new physics amplitude in B_d mixing would be perfectly in agreement with current data

- A couple of anomalies (~2.5-4σ) exist in flavor physics:

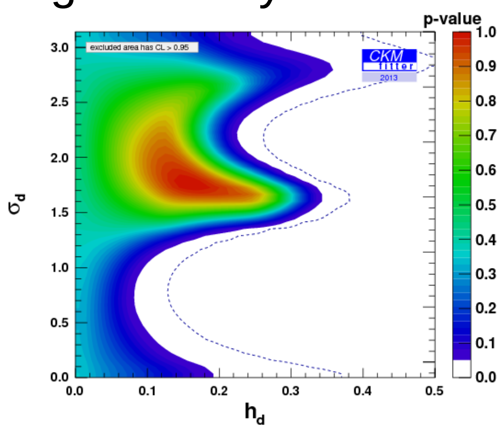
$$R_K = \frac{\Gamma(B\to K^*\mu^+\mu^-)}{\Gamma(B\to K^* e^+ e^-)}$$ (LHCb)

$$B \to K^*\mu^+\mu^-$$ (LHCb)

$$B \to D^{(*)}\tau\nu$$ (BABAR, Belle, LHCb)

B_d mixing New Physics constraints:

New Physics Phase

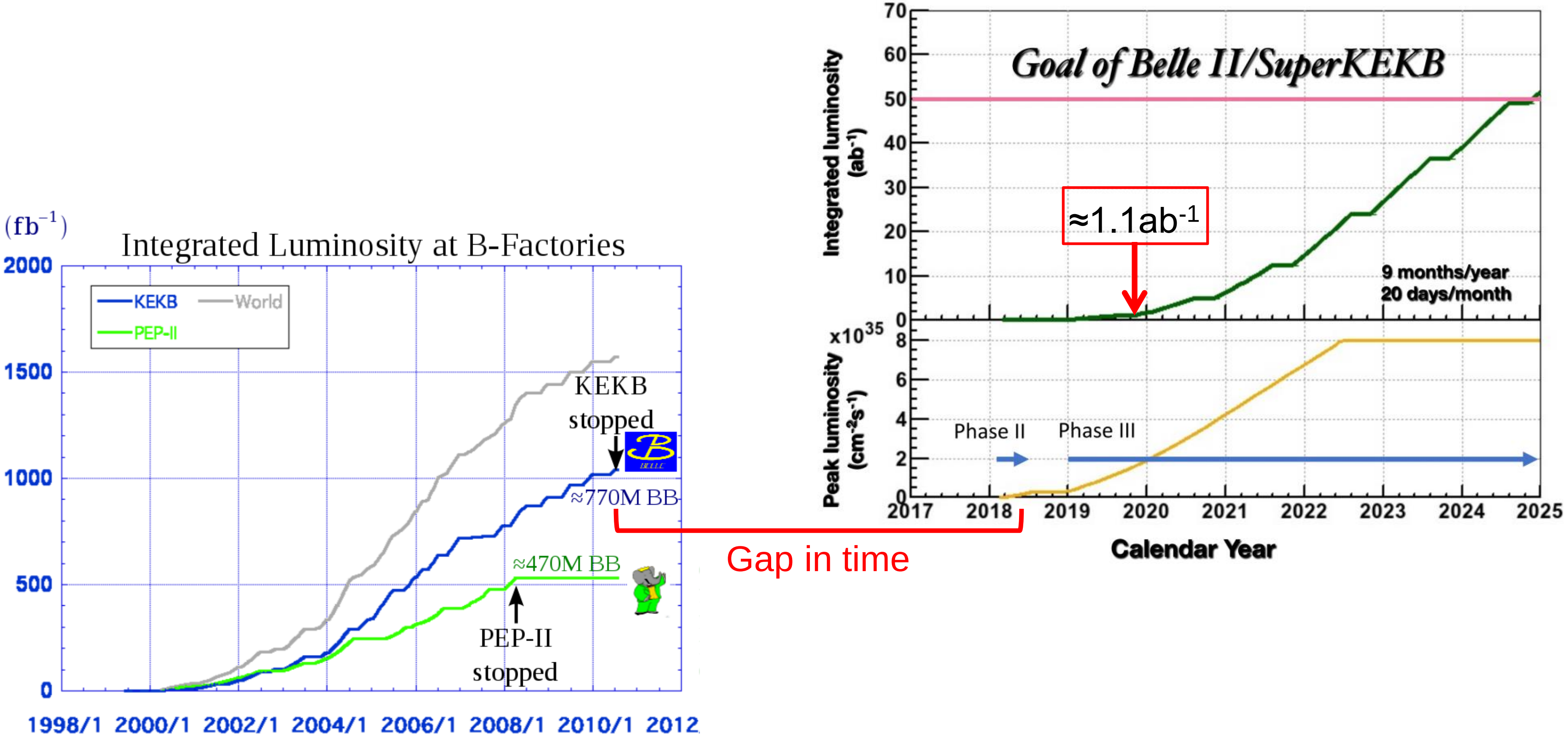


Ratio of New Physics to SM amplitudes

→ High-luminosity flavor experiments (LHCb+Belle II) could pin down potential effects beyond the SM

Combined BABAR+Belle Measurements

- In my last years at Caltech, my attempt was to do early Belle II-like measurements with the existing BABAR and Belle data.



- Combined BABAR+Belle analyses allow to use about 1.1 ab^{-1} or ≈1240×10^{6} BB pairs.

This corresponds to Belle II in 2019/2020 → BABAR+Belle = "small Super *B* Factory"

Overview of Combined BABAR+Belle Measurements

1. $B^0 \to D^{(*)}_{CP} h^0$ with two-body D meson decays to *CP* eigenstates:

   - Time-dependent *CP* violation measurement of $\sin(2\beta)$
   - Theoretically clean mode, could provide new $\sin(2\beta)$ SM reference

   Result: - First observation of *CP* violation in this mode
   - Published in PRL [PRL **115**, 121604 (2015)]

2. $B^0 \to D^{(*)} h^0$ with the three-body D meson $D \to K^0_S \pi^+ \pi^-$ decay:

   - Time-dependent Dalitz plot analysis to measure $\cos(2\beta)$
   - Make full use of the joint approach by applying common assumptions and the same model simultaneously to the BABAR and Belle data sets

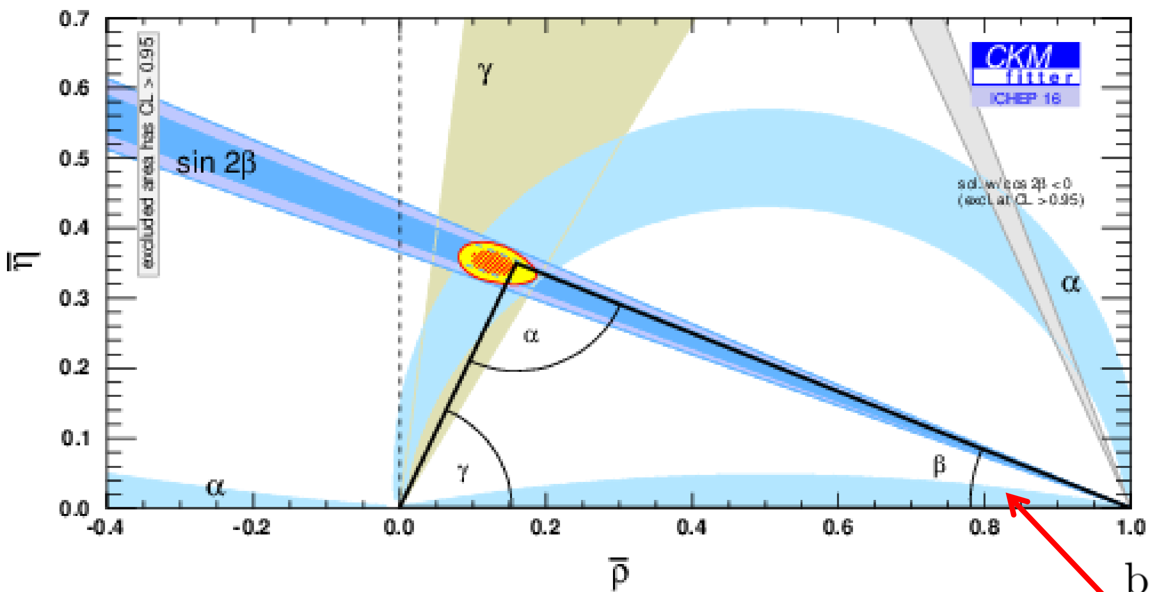
   Result: - Most precise measurement of $\cos(2\beta)$
   - First evidence for $\cos(2\beta) > 0$
   - Exclusion of multifold solutions of the Unitarity Triangle
   - Joint PRL and PRD publications have been submitted [arXiv:1804.06152, arXiv:1804.06153]

1. Combined *BaBar*+Belle analysis:

Measurement of sin(2β) by a time-dependent *CP* violation analysis of $\mathbf{B^0} \to \mathbf{D^{(*)}_{CP} h^0}$ decays

The Angles of the Unitarity Triangle

- Unitarity Triangle arises from $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



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

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

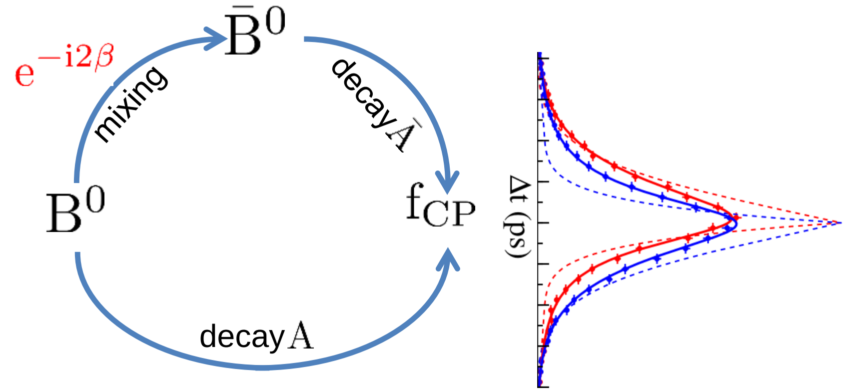
$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$b \to c\bar{c}s$ (e.g. $B^0 \to J/\psi K_S^0$)

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

Determination of the angles $\Longleftrightarrow$ Measurements of *CP* asymmetries

Time-Dependent *CP* Violation



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

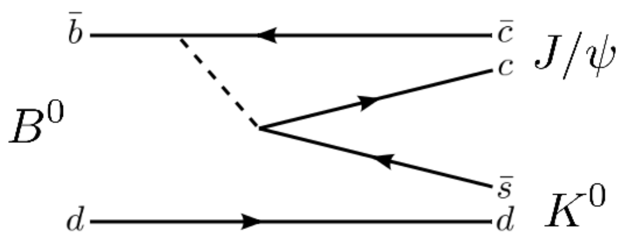
“Young’s double slit experiment”

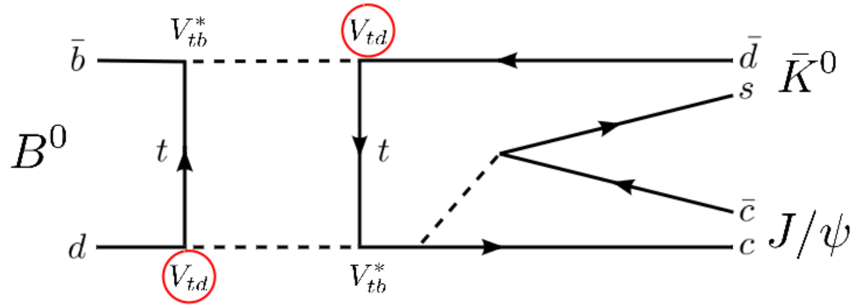
- Time-dependent *CP* asymmetry:

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

Mixing-induced *CPV* | Direct *CPV*

- Example $B^0 \to J/\psi K^0_S$ (benchmark for $\sin(2\beta)$):



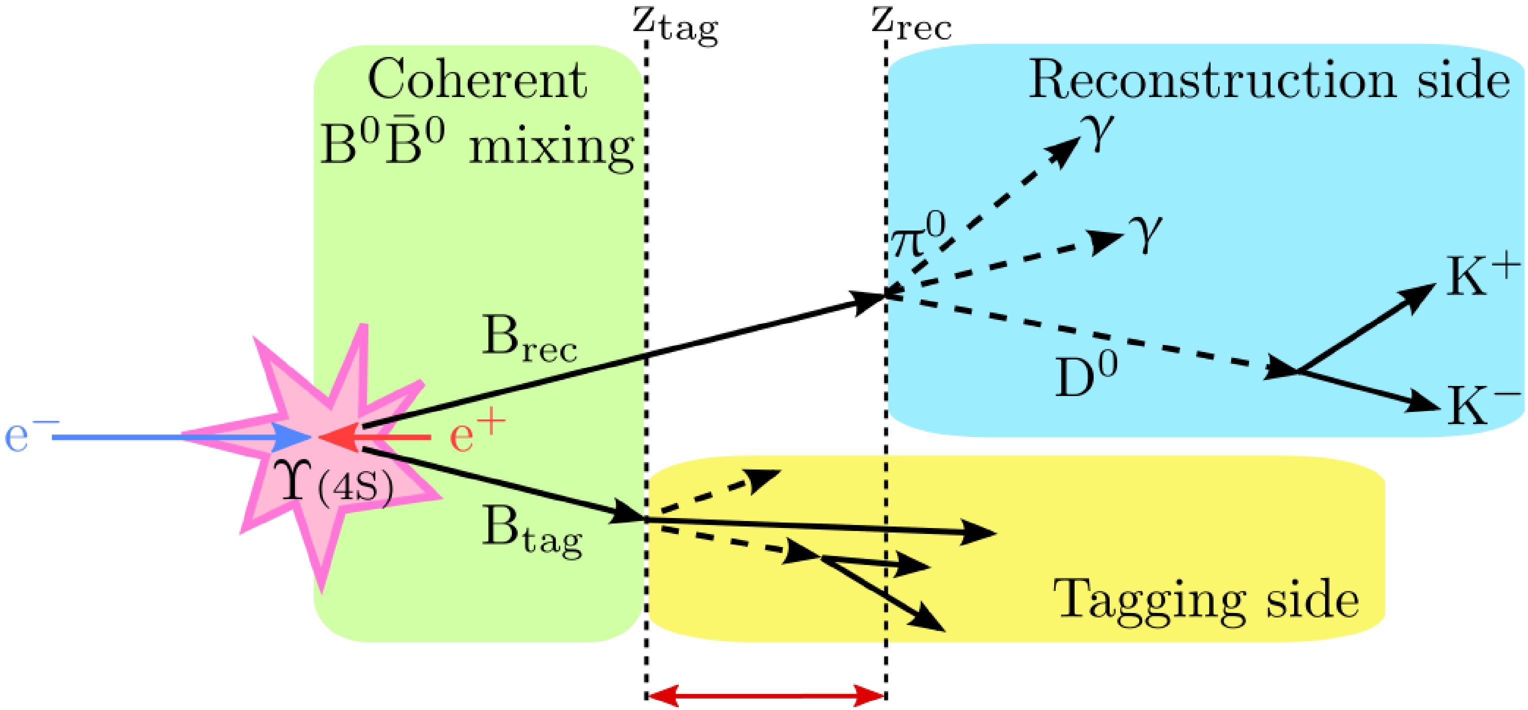


→ Mixing vertices V_{td} introduce phase → $\mathcal{S} = -\eta_{f_{CP}}\sin(2\beta)$ and $\mathcal{C} = 0$

The mixing-induced and direct *CP* violation can be precisely determined from the flavor-tagged time evolution of the B decay

Principle of Time-dependent Measurements at BABAR and Belle

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



$\Delta z = \beta\gamma c\Delta t$, $\langle|\Delta z|\rangle \approx$ 200µm Belle

250 µm BABAR

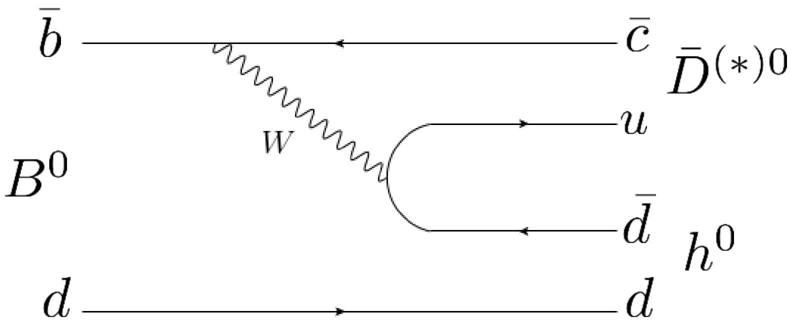
effective tag efficiency >30%

Proper time interval distribution follows:

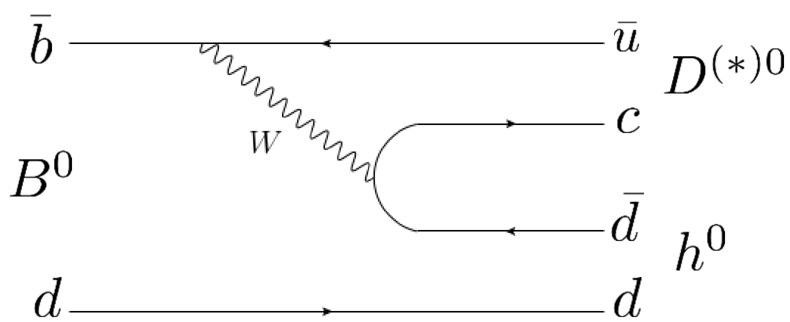
$$\mathcal{P}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{-\frac{|\Delta t|}{\tau_{B^0}}} \left[1 + q\left(\mathcal{S}\sin(\Delta m \Delta t) - \mathcal{C}\cos(\Delta m \Delta t)\right)\right]$$

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

1. Combined $BABAR$+Belle Analysis: sin(2β) from $B^0 \to D^{(*)}_{CP} h^0$



CKM-favored



CKM-disfavored

- $B^0 \to D^{(*)}_{CP} h^0$ 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 clean SM reference for $\sin(2\beta)$ for BSM searches in $b \to s$ penguins.

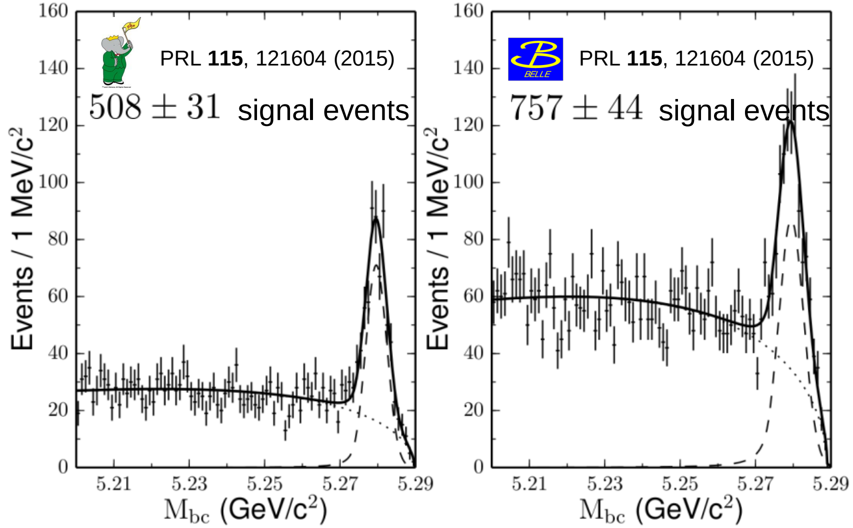
- Experimental difficulties: - Low B and D_{CP} branching fractions [$\mathcal{O}(10^{-4})$ and $\mathcal{O}(\lesssim 10^{-2})$]
  - Low reconstruction efficiencies
  - Significant background
- Previous measurements by $BABAR$ and Belle and could not establish CPV in $B^0 \to D^{(*)} h^0$.

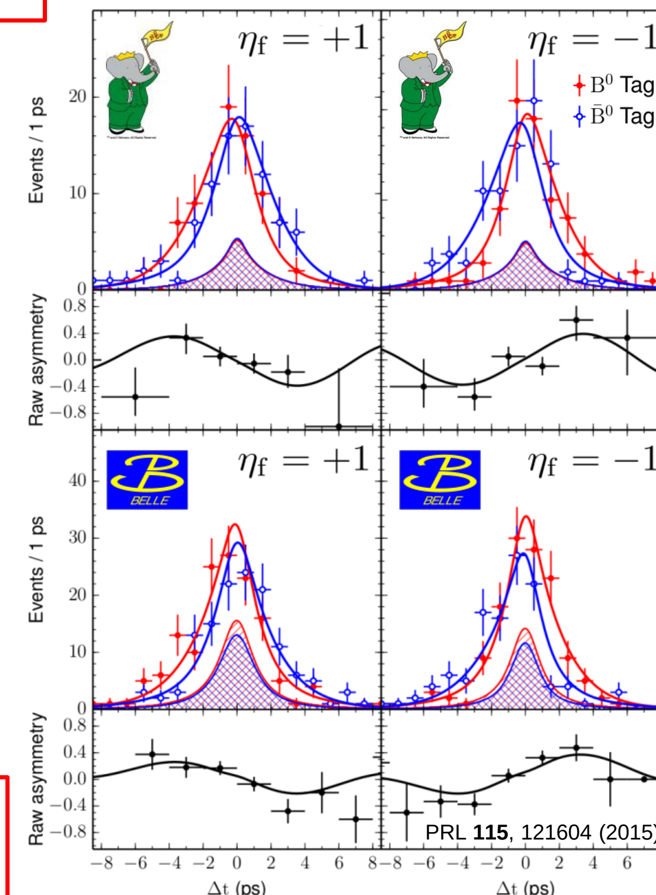
Perform time-dependent CP violation measurement combining $BABAR$+Belle data

1. Combined BABAR+Belle Analysis: sin(2β) from $B^0 \to D^{(*)}_{CP} h^0$

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

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





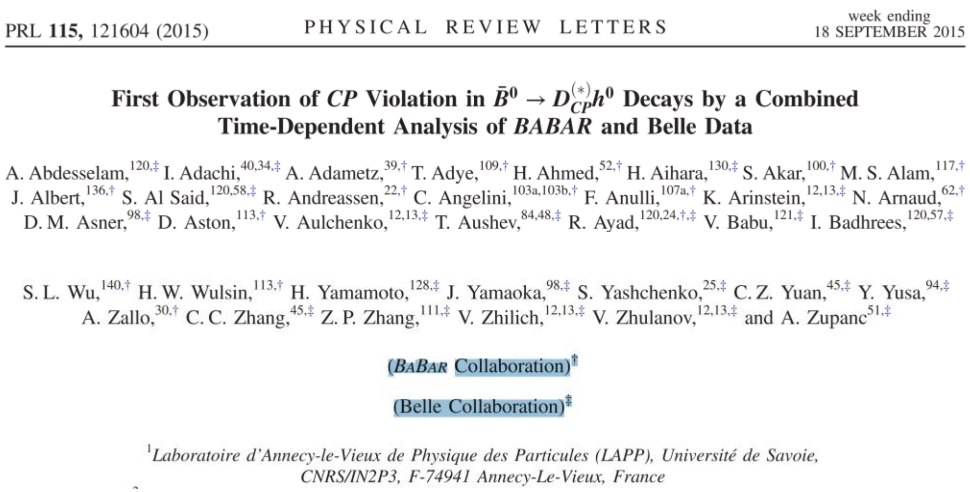
- SM prediction $-\eta_f \mathcal{S} = \sin(2\beta)$ and $\mathcal{C} = 0$

- Result:

Belle+BABAR with 1.1 ab^{-1}: PRL **115**, 121604 (2015)

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

1. Combined BABAR+Belle Analysis: sin(2β) from $B^0 \to D^{(*)}_{CP}h^0$



PRL **115**, 121604 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

First Observation of *CP* Violation in $\bar{B}^0 \to D^{(*)}_{CP}h^0$ Decays by a Combined Time-Dependent Analysis of *BABAR* and Belle Data

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(Belle Collaboration)[‡]

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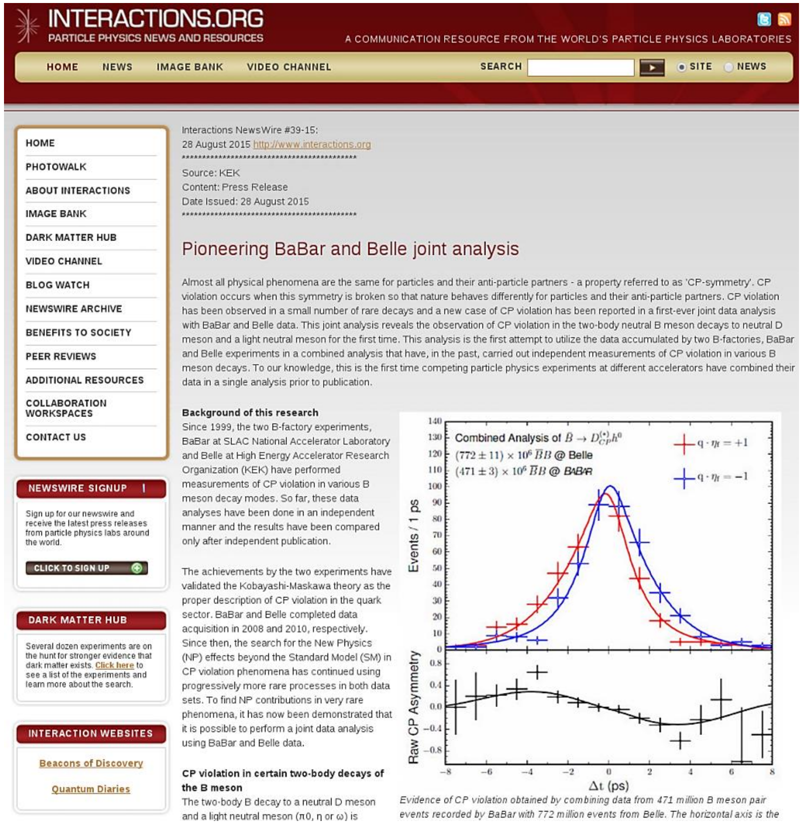
First joint BABAR+Belle paper
[PRL **115**, 121604 (2015)]



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28 August 2015 http://www.interactions.org
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Source: KEK
Content: Press Release
Date Issued: 28 August 2015
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Pioneering BaBar and Belle joint analysis

Almost all physical phenomena are the same for particles and their anti-particle partners - a property referred to as 'CP-symmetry'. CP violation occurs when this symmetry is broken so that nature behaves differently for particles and their anti-particle partners. CP violation has been observed in a small number of rare decays and a new case of CP violation has been reported in a first-ever joint data analysis with BaBar and Belle data. This joint analysis reveals the observation of CP violation in the two-body neutral B meson decays to neutral D meson and a light neutral meson for the first time. This analysis is the first attempt to utilize the data accumulated by two B-factories, BaBar and Belle experiments in a combined analysis that have, in the past, carried out independent measurements of CP violation in various B meson decays. To our knowledge, this is the first time competing particle physics experiments at different accelerators have combined their data in a single analysis prior to publication.

Background of this research
Since 1999, the two B-factory experiments, BaBar at SLAC National Accelerator Laboratory and Belle at High Energy Accelerator Research Organization (KEK) have performed measurements of CP violation in various B meson decay modes. So far, these data analyses have been done in an independent manner and the results have been compared only after independent publication.

The achievements by the two experiments have validated the Kobayashi-Maskawa theory as the proper description of CP violation in the quark sector. BaBar and Belle completed data acquisition in 2008 and 2010, respectively. Since then, the search for the New Physics (NP) effects beyond the Standard Model (SM) in CP violation phenomena has continued using progressively more rare processes in both data sets. To find NP contributions in very rare phenomena, it has now been demonstrated that it is possible to perform a joint data analysis using BaBar and Belle data.

CP violation in certain two-body decays of the B meson
The two-body B decay to a neutral D meson and a light neutral meson (π0, η or ω) is

Evidence of CP violation obtained by combining data from 471 million B meson pair events recorded by BaBar with 772 million events from Belle. The horizontal axis is the

KEK press release

- First observation of *CP*-violation in $B^0 \to D^{(*)}_{CP}h^0$ (5.4σ).
  → Can provide new $\sin(2\beta)$ SM reference at Belle II and could be used to search for new physics in b→s quantum-loop transitions.
- First measurement performed using more than 1 ab^{-1} data collected on the Y(4S).

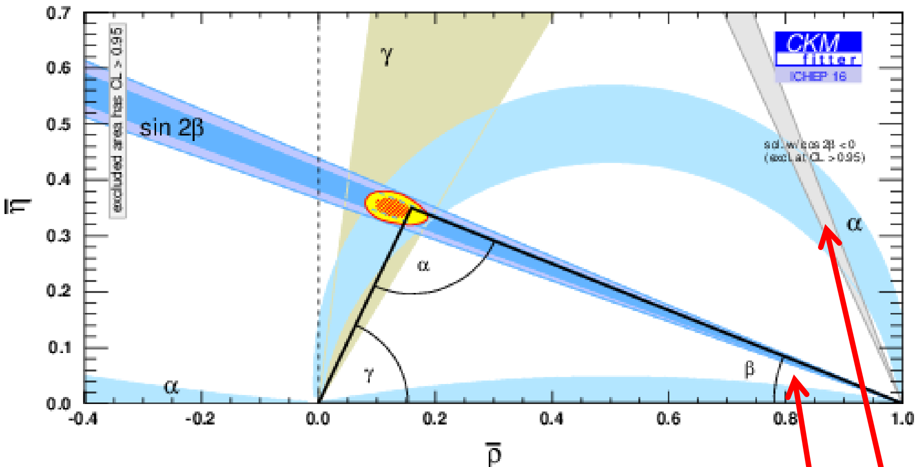
2. Combined BABAR+Belle analysis:

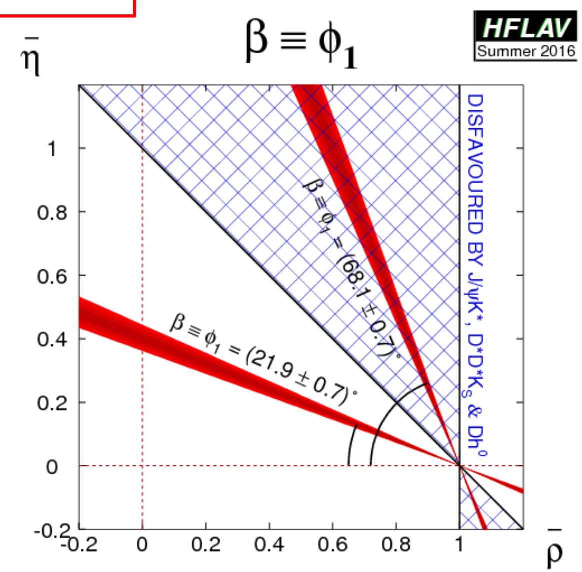
Measurement of cos(2β) by a time-dependent Dalitz plot analysis of $\mathbf{B^0} \to \mathbf{D^{(*)}h^0}$ with $\mathbf{D} \to \mathbf{K^0_S}\pi^+\pi^-$

Ambiguity of the Unitarity Triangle Angle β

- The determination of the angle β of the Unitarity Triangle from sin(2β) measurements, for example, using $B^0 \to J/\psi K^0_S$, leads to a trigonometric ambiguity:

β=21.9° or **β=(π/2-21.9°)=68.1°**





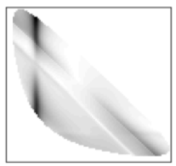
Possible solutions on β from sin(2β)

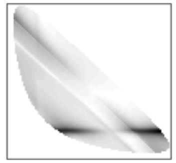
→ The ambiguity can be resolved by measuring also cos(2β) in addition to sin(2β).

- cos(2β) is not well measured. The uncertainties of previous measurements are large, and some results are outside of the physical parameter space.
- The current best single experimental uncertainty is ≈±0.36 [PRD 94 (2016) 052004]

2. Combined BaBar+Belle Analysis: cos(2β) from $\mathbf{B^0 \to D^{(*)}h^0}$

- $\mathrm{B}^0 \to \mathrm{D}^{(*)}\mathrm{h}^0$ with $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-$decays enable to extract both sin(2β) and cos(2β).
- The approach is similar to the GGSZ method to extract γ from multi-body $\mathrm{B}^\pm \to \mathrm{DK}^\pm$.
- Interference between D^0 and $\bar{\mathrm{D}}^0$, and the strong phase variations over the Dalitz plot provide access to the *CP*-violating weak phase 2β.
- Illustration of the B meson decay rate as function of the $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-$ Dalitz plot:

$|M_{B^0}(\Delta t)|^2 = \Big|$  $\times \cos(\Delta m \Delta t/2) - ie^{+2i\beta} \times$  $\times \sin(\Delta m \Delta t/2)\Big|^2$

$|M_{\bar{B}^0}(\Delta t)|^2 = \Big|$  $\times \cos(\Delta m \Delta t/2) - ie^{-2i\beta} \times$  $\times \sin(\Delta m \Delta t/2)\Big|^2$

- If the $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-$ Dalitz plot amplitude model is known, then both sin(2β) and cos(2β) can be extracted from the time evolution of the B decay.

[A. Bondar, P. Krokovny, T. Gershon PLB **624** 1 (2005)]

→ Perform time-dependent Dalitz analysis combining BaBar+Belle data to improve the sensitivity on cos(2β).

2. Combined BaBar+Belle Analysis: cos(2β) from $\mathbf{B^0 \to D^{(*)}h^0}$

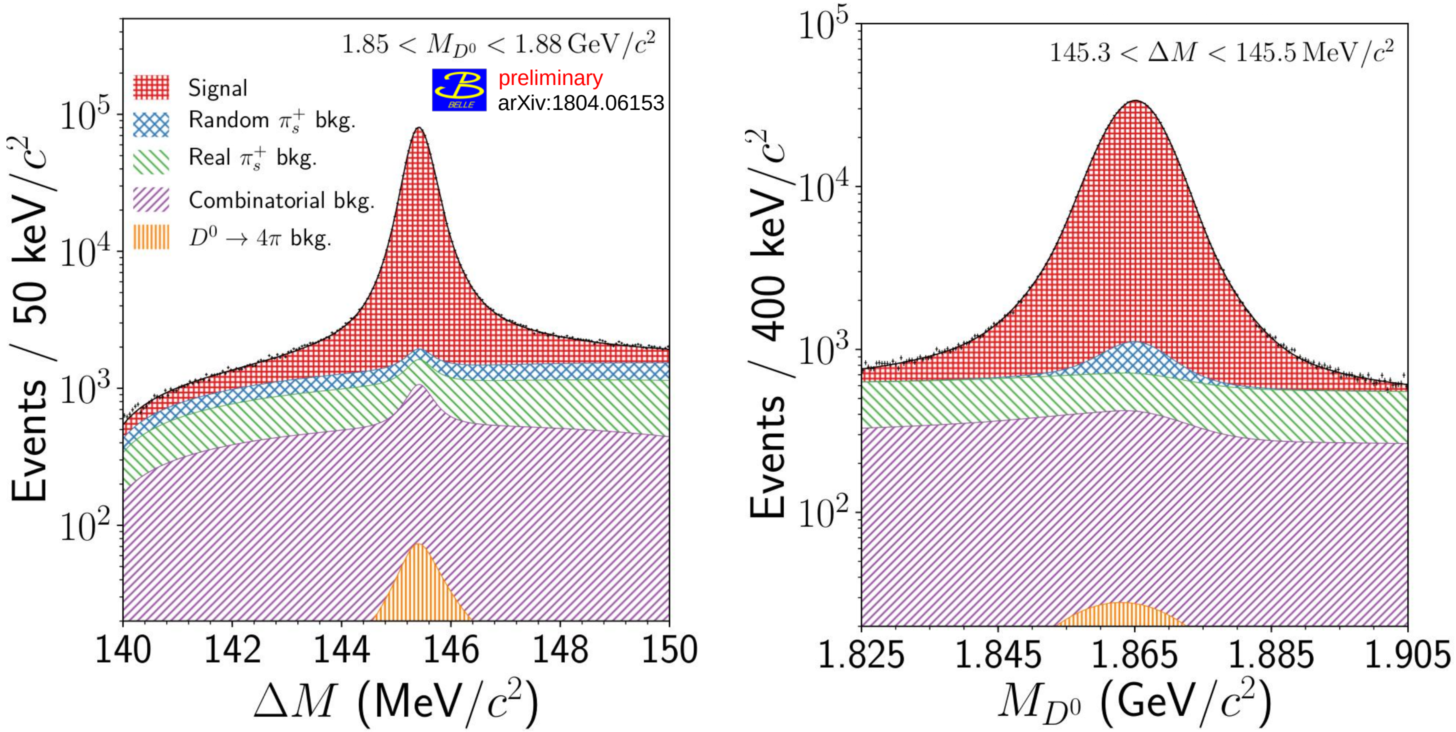
The time-dependent Dalitz plot analysis of cos(2β) is performed in two separate steps:

1. Perform a **full Dalitz plot amplitude analysis** of $D^0 \to K_S^0\pi^+\pi^-$ decays using a high-statistics flavor-tagged $e^+e^- \to c\bar{c}$ data sample to establish the $D^0 \to K_S^0\pi^+\pi^-$ **decay amplitude model** directly from data.

2. Apply the $D^0 \to K_S^0\pi^+\pi^-$ decay amplitude model, and perform the combined BaBar+Belle time-dependent Dalitz plot measurement to **extract cos(2β)** from $B^0 \to D^{(*)}h^0$ decays.

Establishing the $\mathbf{D^0 \to K^0_S \pi^+ \pi^-}$ Dalitz Plot Model

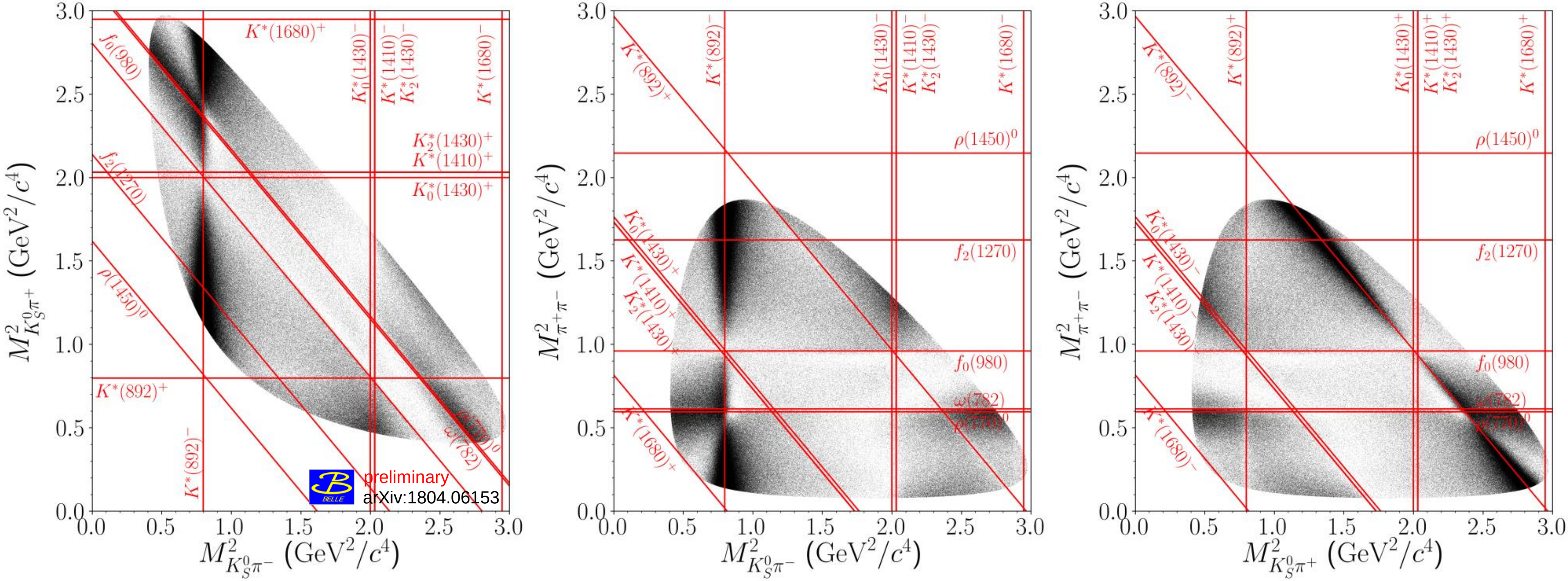
- The $\mathrm{D^0 \to K^0_S \pi^+ \pi^-}$ Dalitz model is directly obtained from flavor-tagged $\mathrm{e^+e^- \to c\bar{c}}$ data.
- Reconstruct $\mathrm{D^{*+} \to D^0 \pi_S^+}$ with $\mathrm{D^0 \to K^0_S \pi^+ \pi^-}$ decays using 924 $\mathrm{fb^{-1}}$ from Belle.
- The charge of the low-momentum pion π_S^+ tags the neutral D meson flavor.



- The yield is (1,217,300 ± 2,000) $\mathrm{D^0 \to K^0_S \pi^+ \pi^-}$ decays.
- The purity is 94% in the signal region.

Establishing the $D^0 \to K_S^0 \pi^+ \pi^-$ Dalitz Plot Model

- The $D^0 \to K_S^0 \pi^+ \pi^-$ Dalitz plot data distributions from the flavor-tagged $e^+e^- \to c\bar{c}$ data:



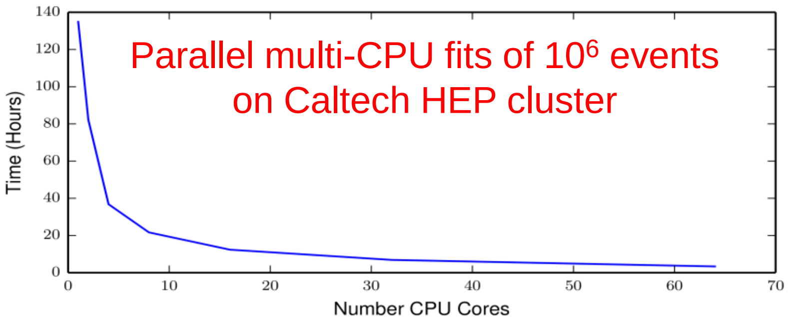
- The $D^0 \to K_S^0 \pi^+ \pi^-$ Dalitz plot is parameterized by the following model:

$$\mathcal{A}_{D^0}(m_+^2, m_-^2) = \sum_{r \neq (K\pi/\pi\pi)_{L=0}} a_r e^{i\phi_r} \mathcal{A}_r(m_+^2, m_-^2) + \mathcal{A}_{K\pi_{L=0}}(s) + F_1(s)$$

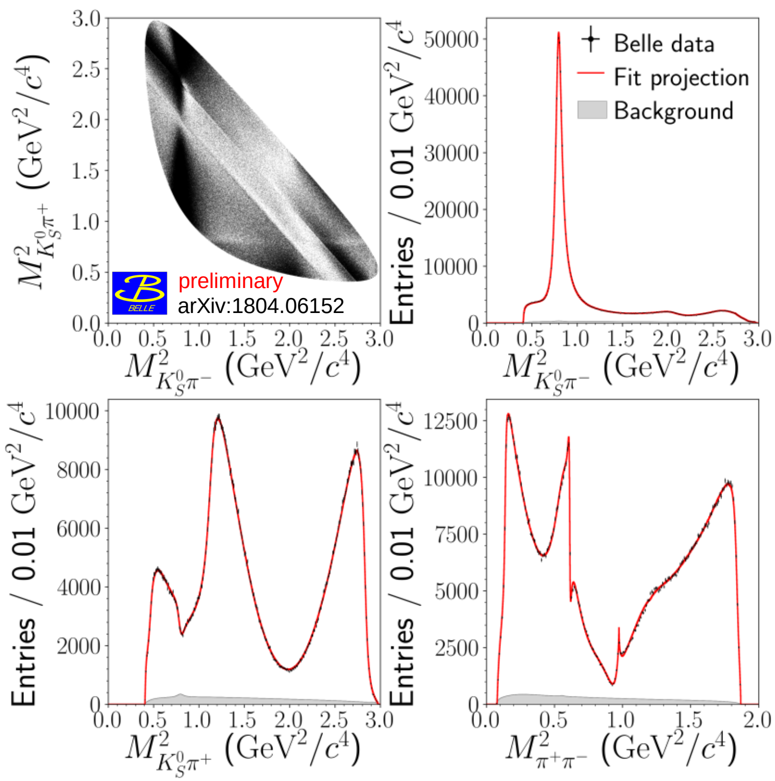
Isobar model for L≠0 — LASS — K-matrix

- The model parameters are estimated by a fit to the above Dalitz plot distributions.

Establishing the $\mathrm{D^0} \to \mathrm{K^0_S}\pi^+\pi^-$ Dalitz Plot Model



- To perform the Dalitz plot fit, the development of a new parallelized framework was required. (40x speed up of fits, if run on 64 CPU cores)



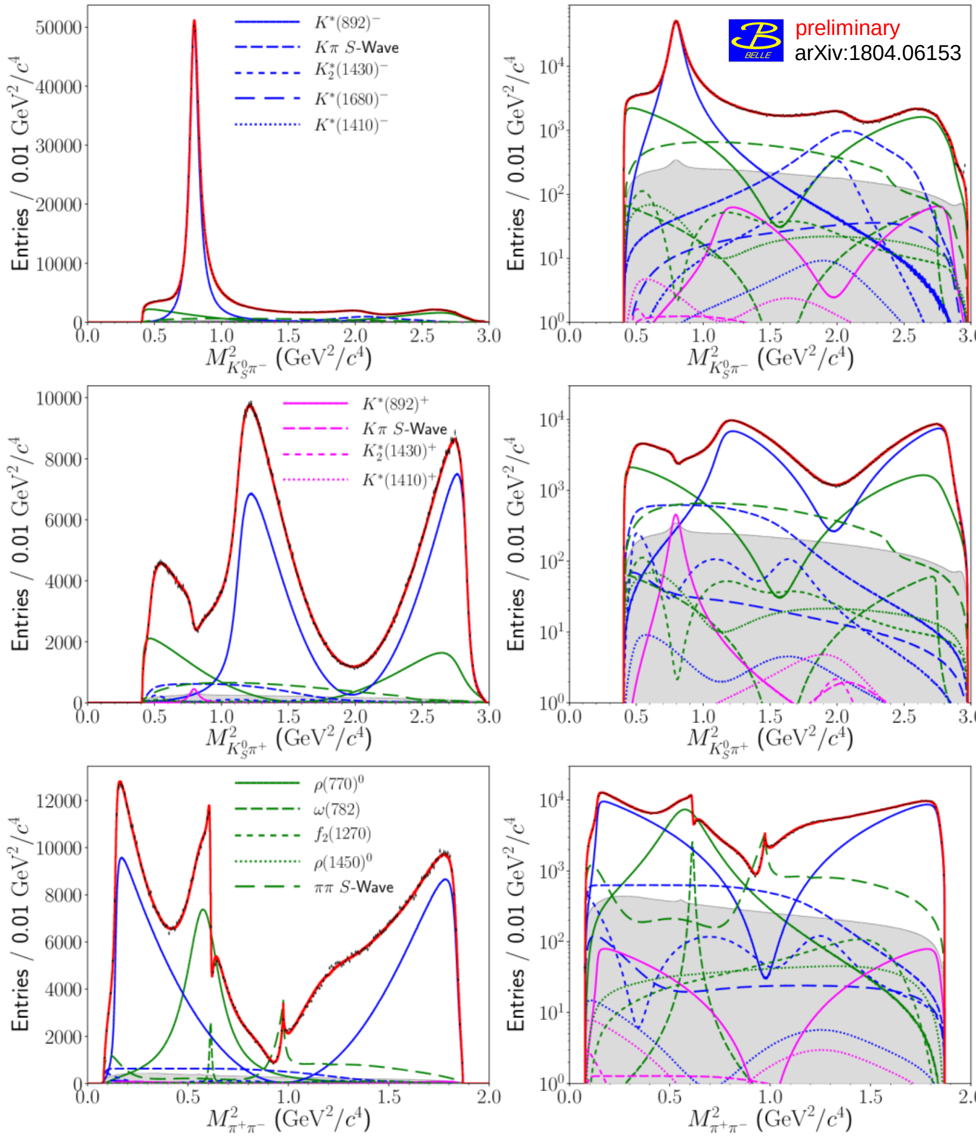
- The Dalitz plot model accounts for 14 intermediate two-body resonances.
- The K-matrix and LASS parameterizations are used to model the ππ and Kπ S-waves.

Establishing the $\mathrm{D^0 \to K^0_S \pi^+ \pi^-}$ Dalitz Plot Model

Linear scale

Log scale

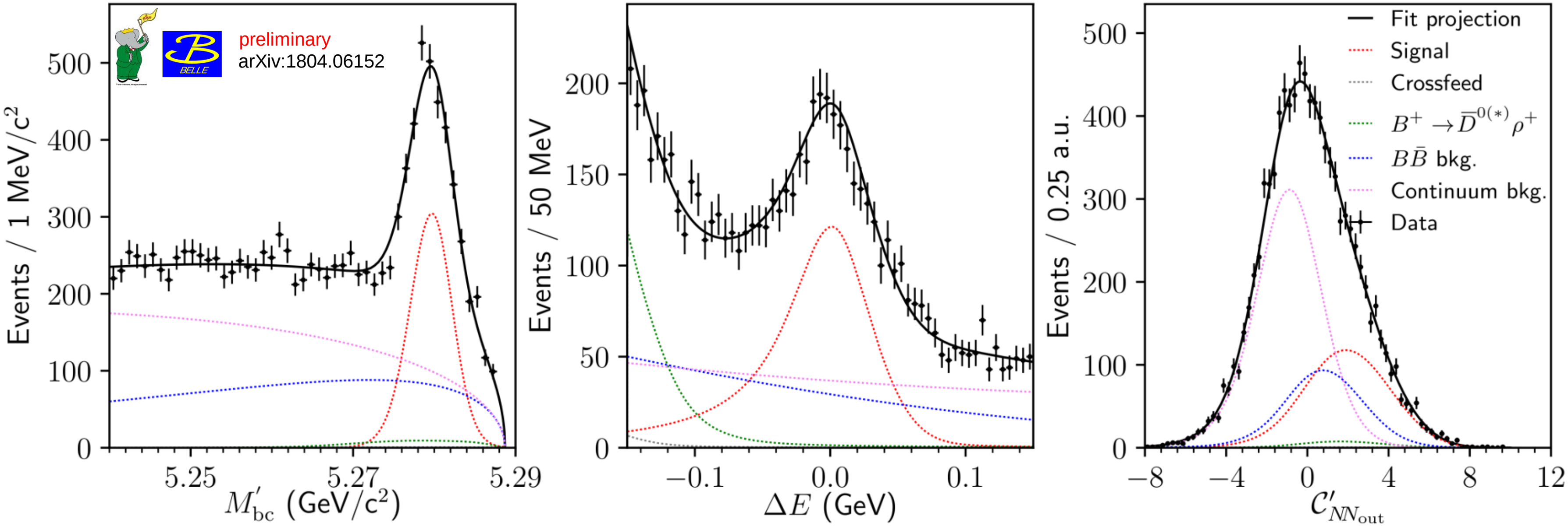
Detailed projections of the Dalitz plot model



- The $\mathrm{D^0 \to K^0_S \pi^+ \pi^-}$ decay amplitude model extracted from $\mathrm{e^+e^- \to c\bar{c}}$ data is used to extract sin(2β) and cos(2β) from the $\mathrm{B^0}$ decay combining *BABAR*+Belle data.

2. Combined BABAR+Belle Analysis: cos(2β) from $B^0 \to D^{(*)}h^0$

- Reconstruct $B^0 \to D^{(*)}h^0$ with h^0 in $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$
  $D \to K^0_S\pi^+\pi^-$ and $D^{*0} \to D\pi^0$.
- In total, 5 B^0 decay modes are reconstructed.
- $e^+e^- \to q\bar{q}$ $(q \in \{u, d, s, c\})$ continuum background is identified by neural networks.
- Extract signal by 3D fit of beam-constr. mass M'_{bc}, energy-difference ΔE and NN'_{out}.



BABAR: 1129 ± 48 signal events
Belle: 1567 ± 56 signal events

2. Combined BaBar+Belle Analysis: cos(2β) from $\mathbf{B^0 \to D^{(*)} h^0}$

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

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

- Apply common signal model:

$$\begin{aligned}\mathrm{P_{sig}}(\Delta\mathrm{t}) \propto \Big[& |\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2 \\ & \mp \left(|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2\right) \cos(\Delta m \Delta t) \\ & \pm 2\eta_{h^0} \left(-1\right)^L \left[\mathrm{Im}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right) \cos(2\beta) - \mathrm{Re}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right) \sin(2\beta)\right] \sin(\Delta m \Delta t)\Big]\end{aligned}$$

- Result:

BaBar+Belle with 1.1 ab^{-1}:

arXiv:1804.06152 Preliminary
arXiv:1804.06153

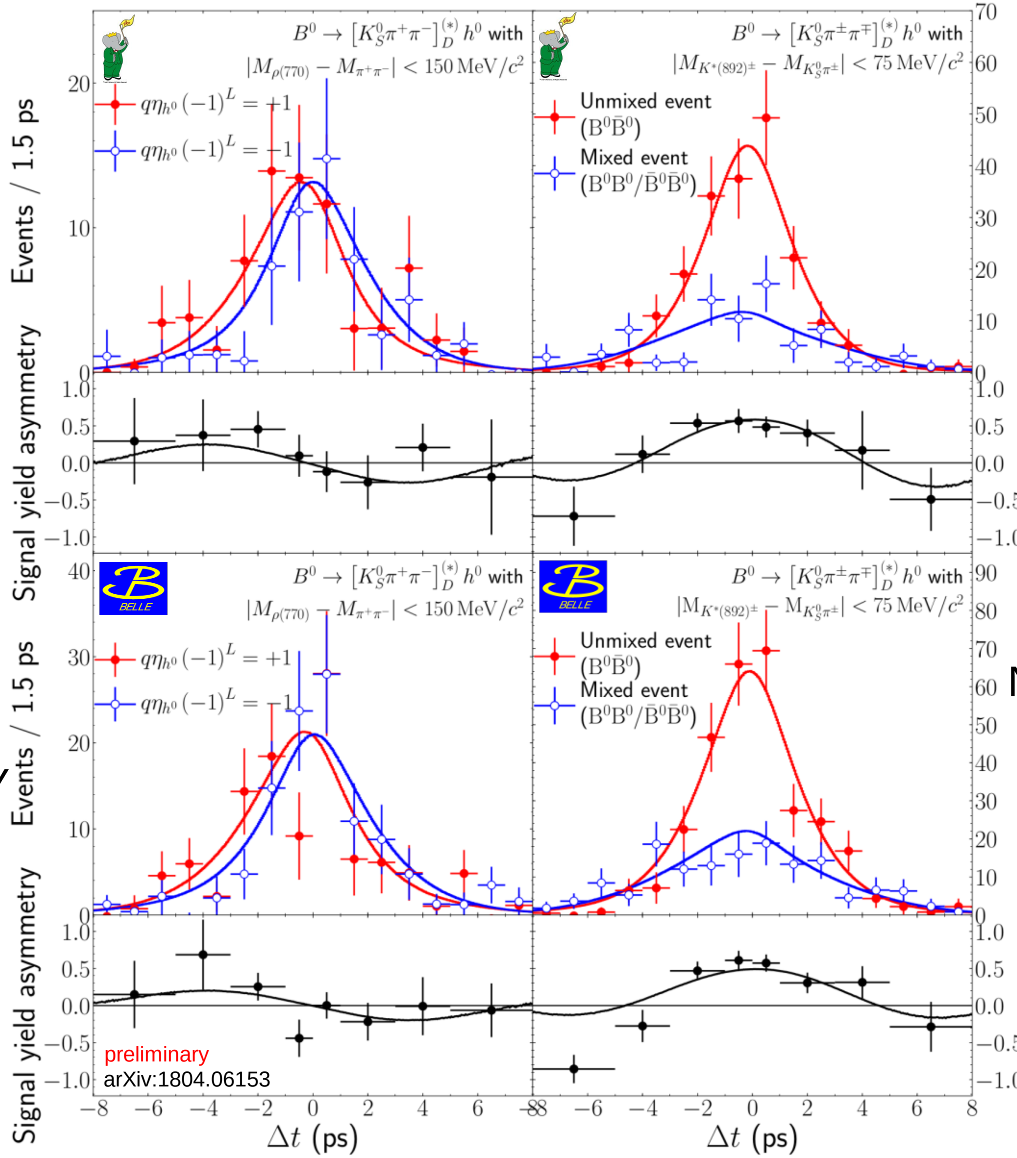
$$\sin(2\beta) = 0.80 \pm 0.14\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.}) \pm 0.03\,(\mathrm{model})$$

$$\cos(2\beta) = 0.91 \pm 0.22\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.07\,(\mathrm{model})$$

$$\beta = (22.5 \pm 4.4\,(\mathrm{stat.}) \pm 1.2\,(\mathrm{syst.}) \pm 0.6\,(\mathrm{model}))^\circ$$

2. Combined BABAR+Belle Analysis: cos(2β) from $B^0 \to D^{(*)}h^0$

CP eigenstate final states →

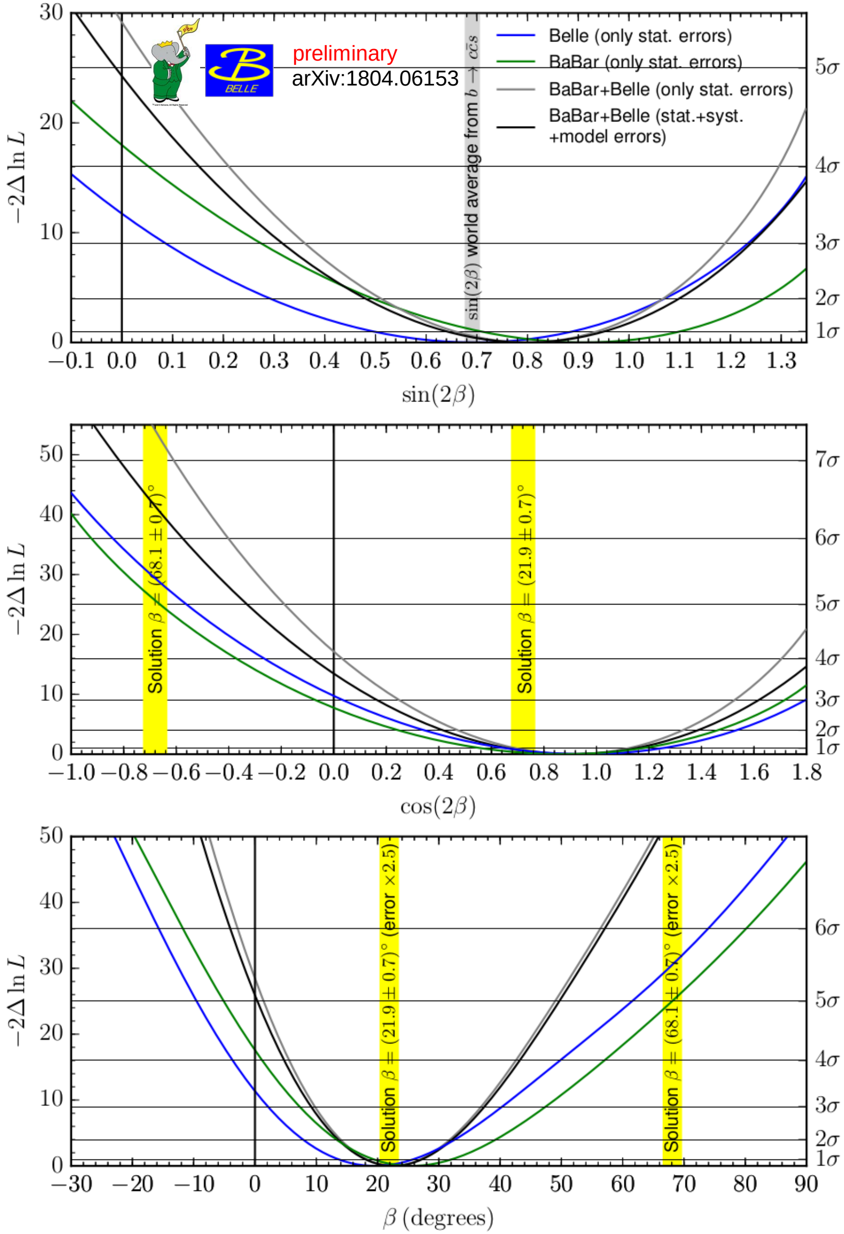


← Flavor-specific final states

Interference between B^0 and $\bar{B}^0$ → time-dependent *CPV* with characteristic pattern as in sin(2β) measurements

No interference between B^0 and $\bar{B}^0$ → characteristic B^0-$\bar{B}^0$ oscillation pattern for quantum-entangled B meson pairs

2. Combined BABAR+Belle Analysis: cos(2β) from $B^0 \to D^{(*)}h^0$



- Single most precise measurement of $\cos(2\beta)$
- First evidence for $\cos(2\beta) > 0$ (3.7σ)
- Direct exclusion of the 2nd solution

$$\pi/2 - \beta = (68.1 \pm 0.7)°$$

  of the CKM Unitarity Triangle (7.3σ)

  → Reduction of the trigonometric ambiguity of the CKM Unitarity Triangle

- Exclusion of $\beta = 0°$ (5.1σ)

  → Observation of CP violation in $B^0 \to D^{(*)}h^0$ decays

- Joint PRL (arXiv:1804.06152) and PRD (arXiv:1804.06153) papers have been submitted.

Summary

- Two combined *BABAR*+Belle measurements using 1.1 ab^{-1} have been presented.

- Effectively doubling the statistics and the joint approach enables unique sensitivity in time-dependent *CP* violation measurements in the B_d system.

- The first observation of *CP* violation in $\mathrm{B}^0 \to \mathrm{D}^{(*)}_{\mathrm{CP}}\mathrm{h}^0$ decays has been reported.

  PRL **115**, 121604 (2015)

- The first evidence for $\cos(2\beta) > 0$ and the exclusion of multifold solutions on the Unitarity Triangle have been obtained by a time-dependent Dalitz plot analysis of $\mathrm{B}^0 \to \mathrm{D}^{(*)}\mathrm{h}^0$ with $\mathrm{D}^0 \to \mathrm{K}^0_{\mathrm{S}}\pi^+\pi^-$.

  arXiv:1804.06152 submitted to PRL
  arXiv:1804.06153 submitted to PRD

- The $\cos(2\beta)$ measurement also has a small symbolic character:

  While *BABAR* and Belle competed to establish and precisely determine $\sin(2\beta)$ during their lifespan, it required the combination of both to establish $\cos(2\beta) > 0$.

Outlook

- The BABAR+Belle approach was as a small attempt to peek into the attobarn regime.
- The near future is very exciting due to order(s) of magnitudes of more data:
  - SuperKEKB+Belle II started full operation and just produced first collisions.
  - The realization of the LHCb upgrade progresses well, and further future upgrades are already being considered.