Flavor physics and *CP* violation

Recent results from combined $B\!A\!B\!A\!R$+Belle measurements, ongoing work at LHCb, and prospects at Belle II

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Outline of the Talk

1) Introduction to flavor physics and *CP* violation

2) Combined $BABAR$+Belle measurements ("small Super-B-Factory"):

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

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

3) Ongoing work at LHCb

   a) Search for new physics in quantum-loops

   b) R&D for the electromagnetic calorimeter upgrade

4) Prospects at Belle II

   a) Time-dependent *CP* violation in quantum-loop transitions, measuring the photon polarization in radiative penguins

   b) Tagged measurements of decays with neutrinos in the final state

   c) Methods developments

5) Summary

Introduction to Flavor Physics

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

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

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

  CKM matrix: 3 real parameters + 1 *CP*-violating phase

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

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

- Discovery of *CP* violation in B mesons

- Exploring and constraining the quark flavor structure of the Standard Model

- Experimental confirmation of the Kobayashi-Maskawa theory
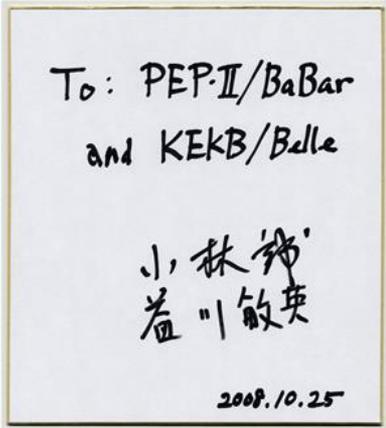
The Nobel Prize in Physics 2008

Introduction to Flavor Physics

- The Standard Model of particle physics is very successful, but has many open problems.
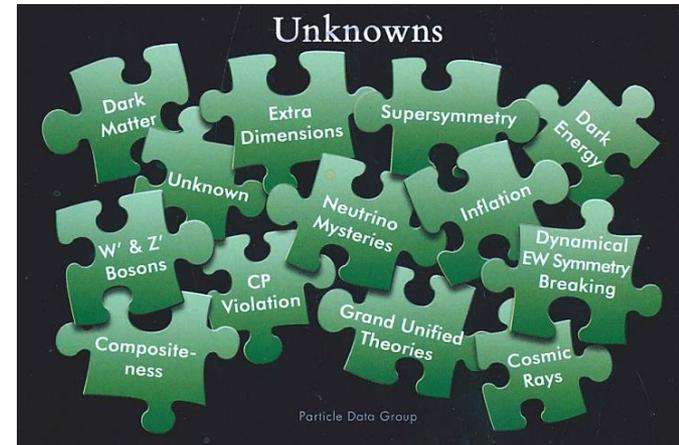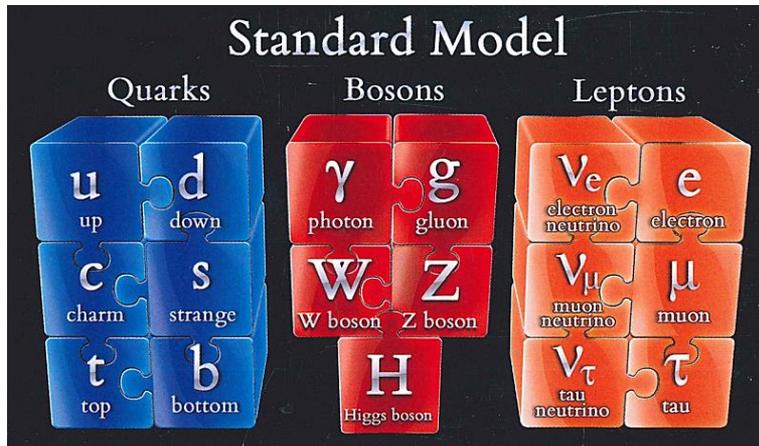
- LHC performs direct searches at the highest energies, no evidence for new effects yet.

- Present (future) collider energies are limited to ~14 (100) TeV at the LHC (FCC).

- Flavor physics searches indirectly by quantum-loop effects. This can probe higher mass scales and different production mechanisms than the direct searches.

> Flavor physics is complementary and important in both cases:
>
>   1) Nothing beyond the Standard Model is found at the LHC
>
>   2) A new effect is found, and its source and consequences need to be studied

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.

$$\frac{\Gamma(K_L^0 \to \pi^- e^+ \nu_e) - \Gamma(K_L^0 \to \pi^+ e^- \bar{\nu}_e)}{\Gamma(K_L^0 \to \pi^- e^+ \nu_e) + \Gamma(K_L^0 \to \pi^+ e^- \bar{\nu}_e)} = \left(+2.24 \pm 0.36 \ (\text{stat.} + \text{syst.})\right) \times 10^{-3}$$
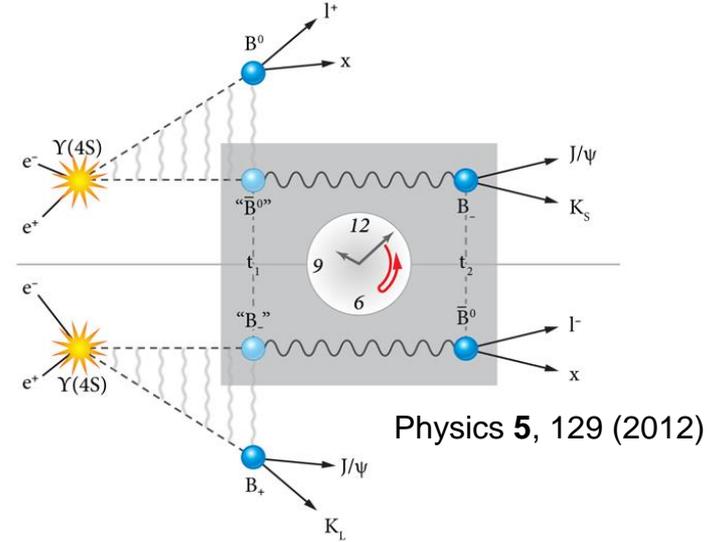
Steinberger *et al.,* PRL **19**, 993 (1967)

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

  $\to$ *CP* violation implies the violation of time-reversal *T*,
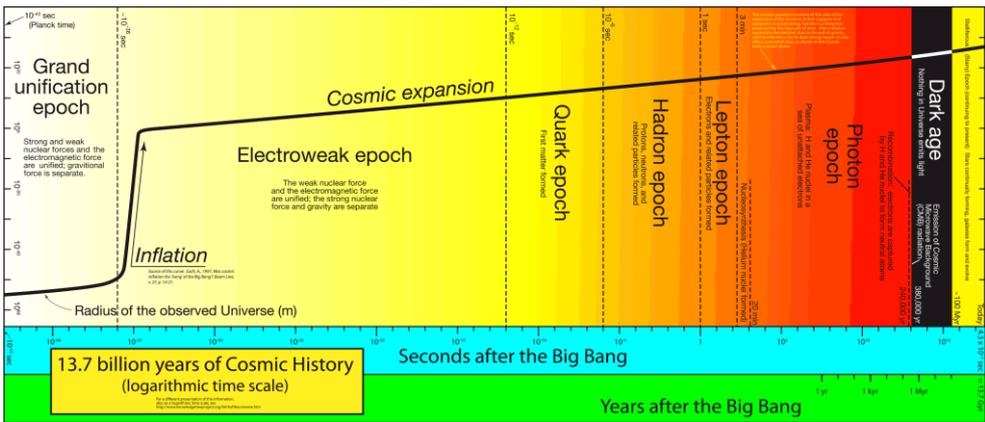 establishing an "arrow of time" on the microscopic level.

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

- $\mathcal{BABAR}$ 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.
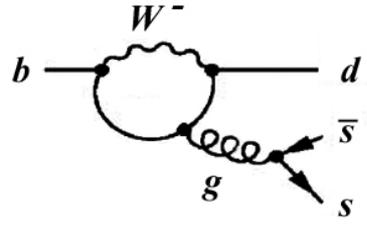
→ Important motivation to search for additional sources of *CP* violation.
(Key field of research in flavor physics experiments)
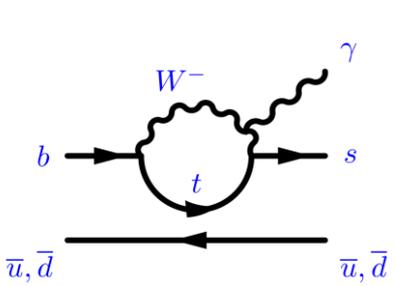
Flavor Physics as Sensitive Probe for New Physics

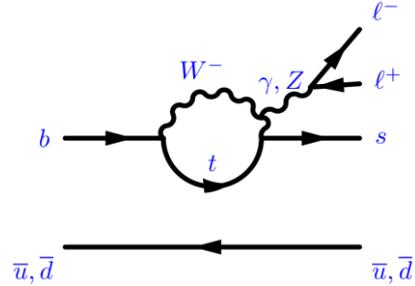The time evolution and decay of *b* hadrons are governed by quantum-loop effects:
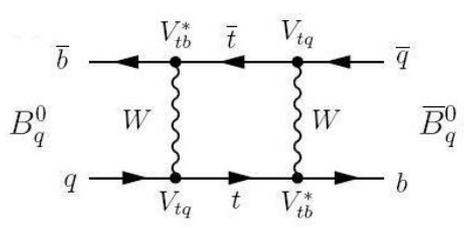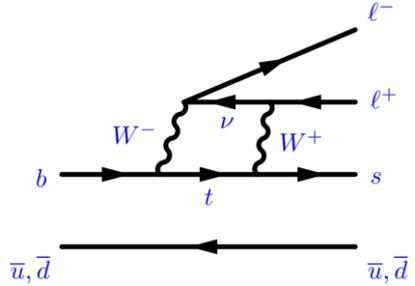

B^0-$\bar{B}^0$ oscillations

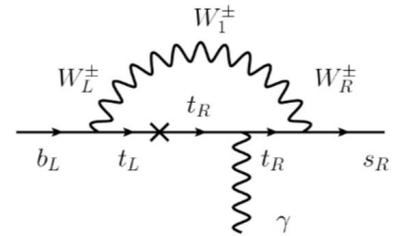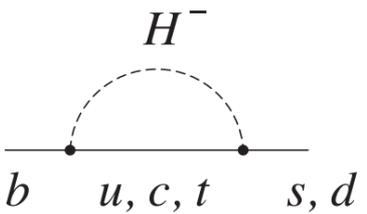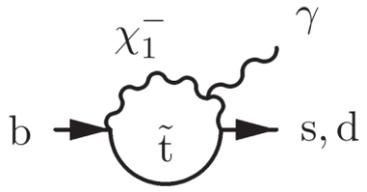Gluonic penguins

Radiative penguins

Electroweak penguins

Electroweak boxes

New physics can enter the loops at same order as the SM processes:

→ B decays provide sensitive probes for new physics effects beyond the SM.

Examples for Indirect Approach

Flavor physics enables to probe for new physics on high mass scales through indirect effects – in history such indirect approaches led to important discoveries:

1970   GIM mechanism predicts the charm quark to explain the absence of $K^0 \to \mu^+ \mu^-$ (suppression of FCNCs)
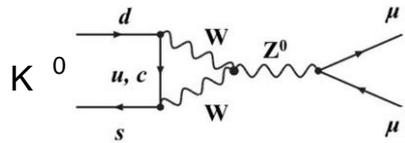
1973   Kobayashi & Maskawa can explain *CP* violation, if three families of quarks exist (only up, down & strange quarks were experimentally known)
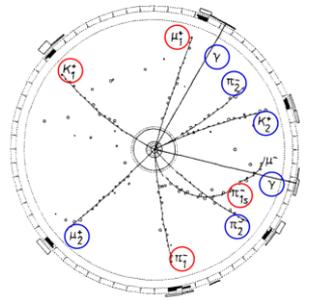
1987   ARGUS at DESY observes B^0-$\bar{B}^0$ oscillations
$\to$ lower bound of $50\,\mathrm{GeV}/c^2$ on the top quark mass

PLB **192**, 245 (1987)

~2000   LEP+SLD precisely predict the Higgs mass through electroweak corrections

$$m_{\mathrm{H}} = 129^{+74}_{-49}\,\mathrm{GeV}/c^2$$

Phys. Rept. **427**, 257 (2006)
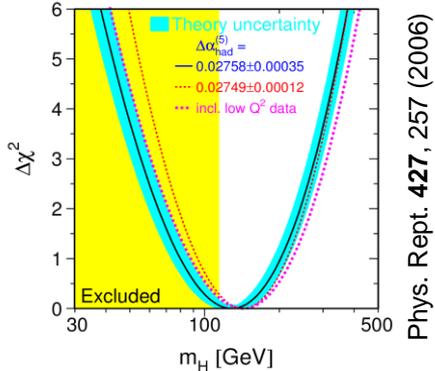
Current Status of Flavor Physics

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

CKM
Unitarity Triangle:

1999

2016
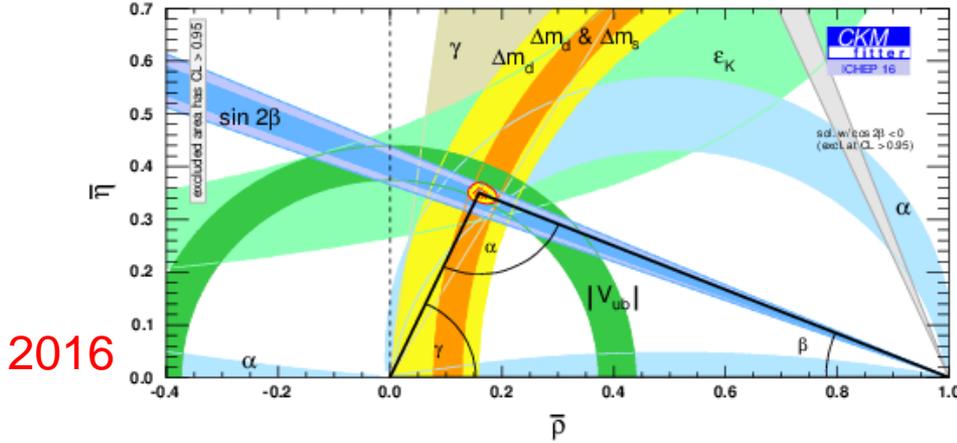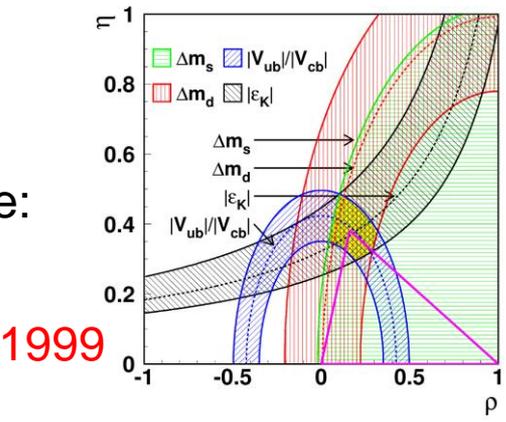
- The CKM picture agrees well in many independent measurements

- 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:

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

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

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

B_d mixing New Physics constraints:

Ratio of New Physics to SM amplitudes
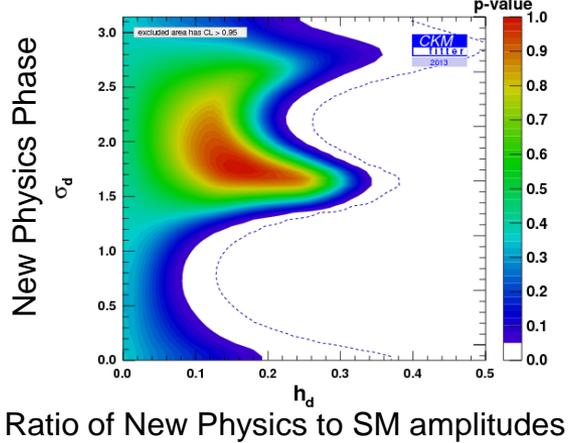
→ High-luminosity flavor experiments (LHCb+Belle II) could pin down potential effects beyond the SM

The $B\!A\!B\!A\!R$ and Belle experiments, and the idea of combined measurements

(The presented work has been carried out in the group
of David Hitlin and Frank Porter at Caltech.)

Cherenkov Detector (DIRC)
Particle identification
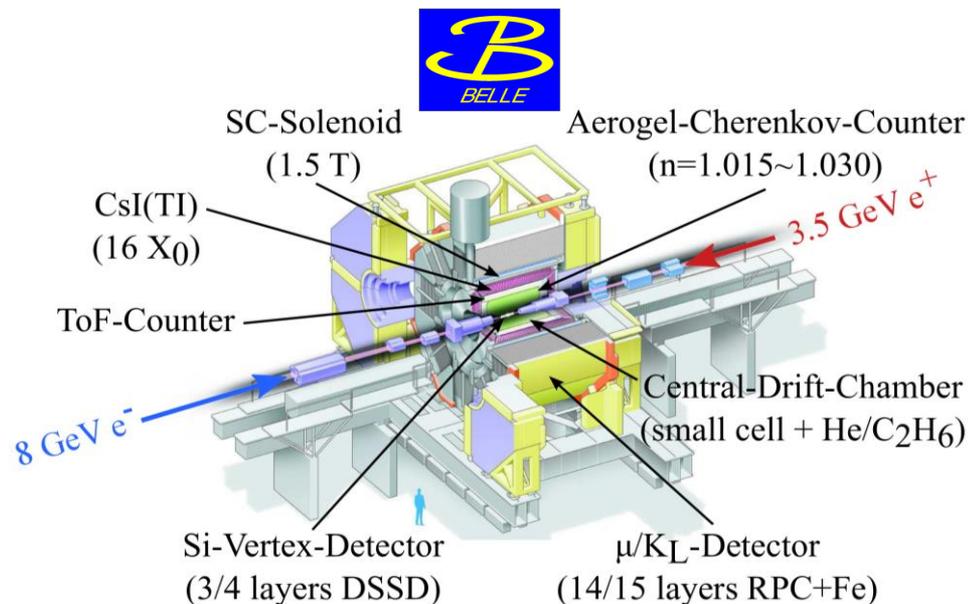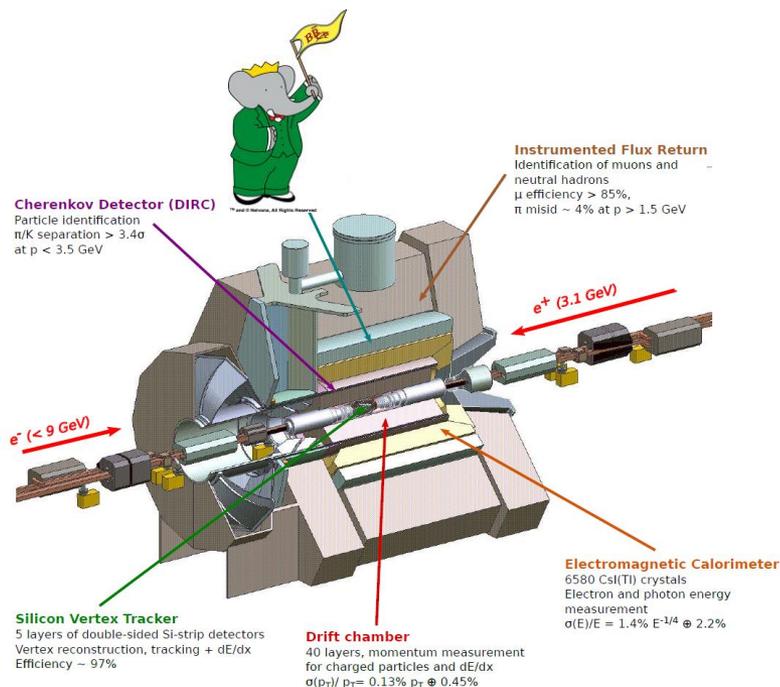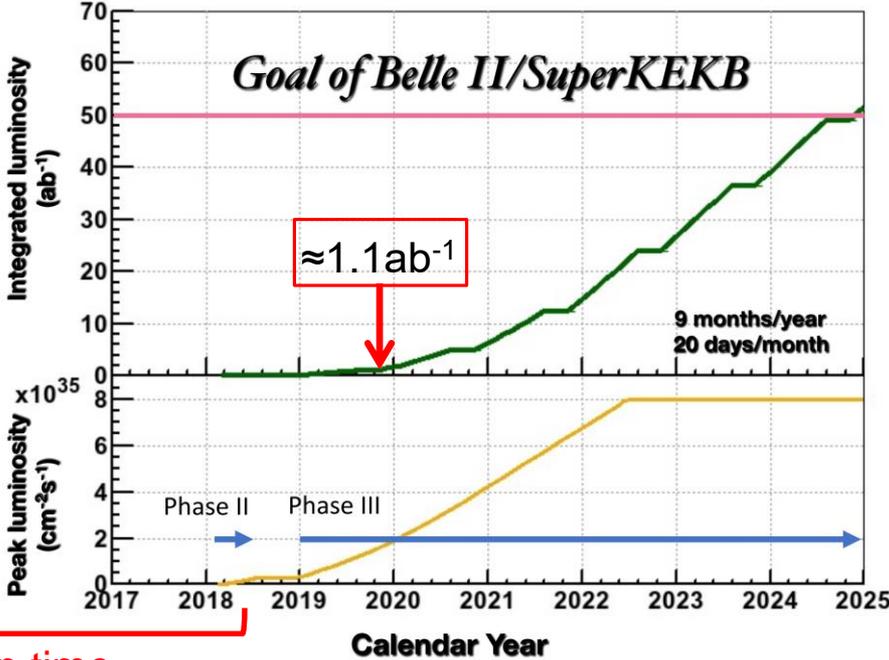π/K separation > 3.4σ
at p < 3.5 GeV

Instrumented Flux Return
Identification of muons and
neutral hadrons
μ efficiency > 85%,
π misid ~ 4% at p > 1.5 GeV

e^+ (3.1 GeV)

e^- (< 9 GeV)

Silicon Vertex Tracker
5 layers of double-sided Si-strip detectors
Vertex reconstruction, tracking + dE/dx
Efficiency ~ 97%

Drift chamber
40 layers, momentum measurement
for charged particles and dE/dx
$\sigma(p_T)/p_T = 0.13\% \, p_T \oplus 0.45\%$

Electromagnetic Calorimeter
6580 CsI(TI) crystals
Electron and photon energy
measurement
$\sigma(E)/E = 1.4\% \, E^{-1/4} \oplus 2.2\%$

SC-Solenoid
(1.5 T)

Aerogel-Cherenkov-Counter
(n=1.015~1.030)

3.5 GeV e^+

CsI(TI)
(16 X_0)

ToF-Counter

8 GeV e^-

Central-Drift-Chamber
(small cell + He/C_2H_6)

Si-Vertex-Detector
(3/4 layers DSSD)

μ/K_L-Detector
(14/15 layers RPC+Fe)

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.

Integrated Luminosity at B-Factories

(fb^{-1})

Total of 1240×10^6 BB pairs

KEKB stopped

≈770M BB

≈470M BB

PEP-II stopped

Gap in time

Goal of Belle II/SuperKEKB

≈1.1ab^{-1}

9 months/year
20 days/month

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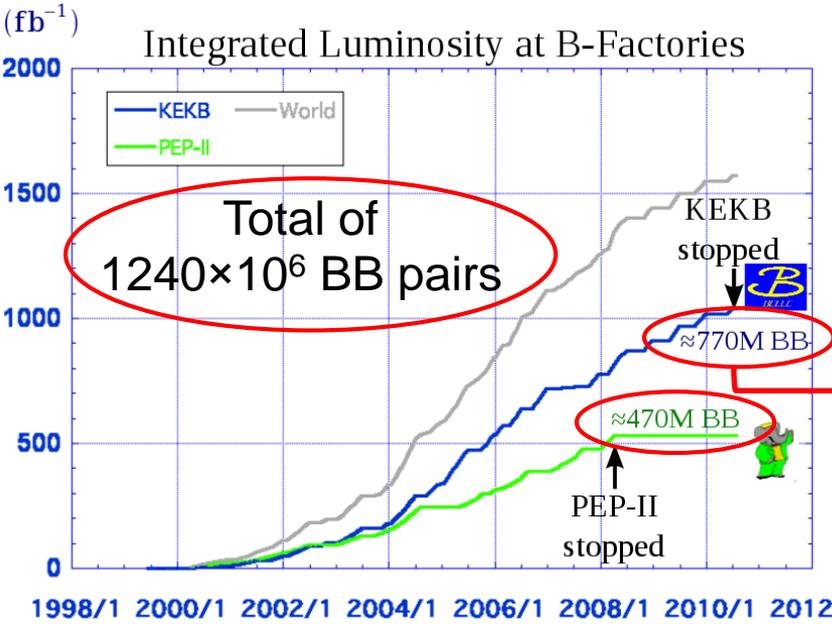
- Combined $BABAR$+Belle analyses allow to use about 1.1 ab^{-1} or ≈1240×10^6 BB pairs.

This corresponds to Belle II in 2019/2020 $\rightarrow$ $BABAR$+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
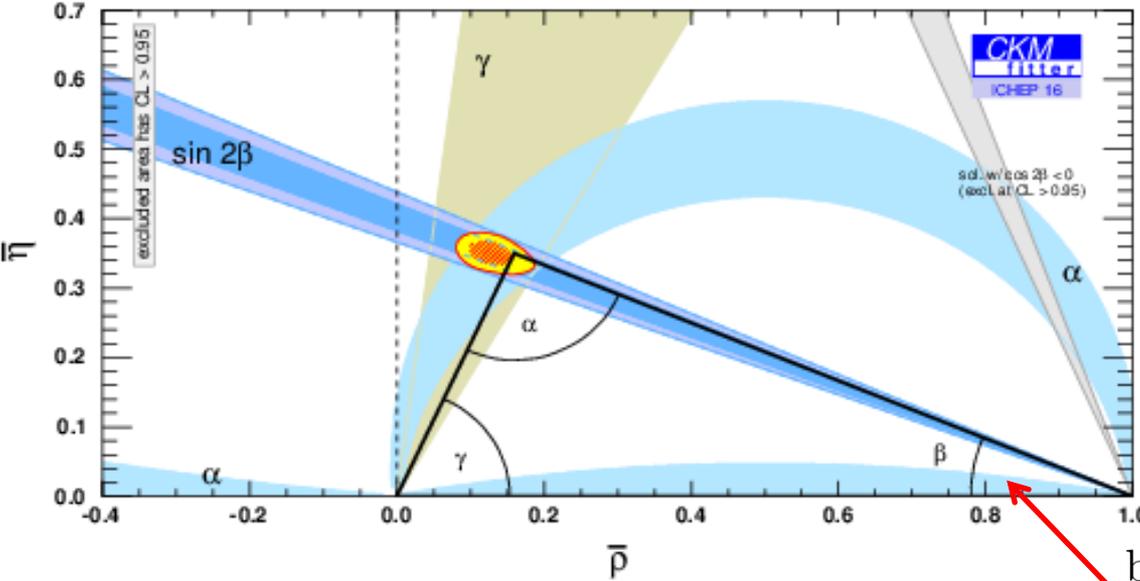   - Joint PRL and PRD publications have been submitted
                         [arXiv:1804.06152, arXiv:1804.06153]

1. Combined $B\!A\!B\!A\!R$ +Belle analysis:

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

The Angles of the CKM Unitarity Triangle

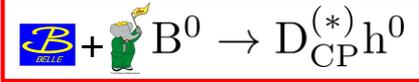- The Unitarity Triangle arises from $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$.

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

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

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

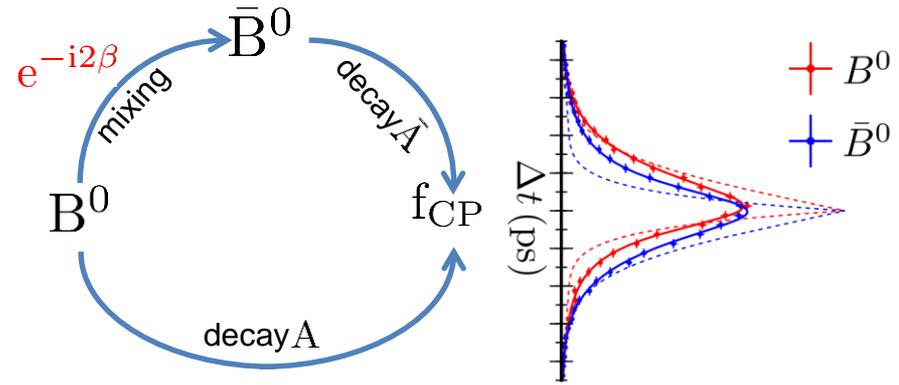$$b \to c\bar{c}s \,(\text{e.g. } B^0 \to J/\psi K_S^0)$$

$$\mathcal{B} + B^0 \to D_{CP}^{(*)}h^0$$

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
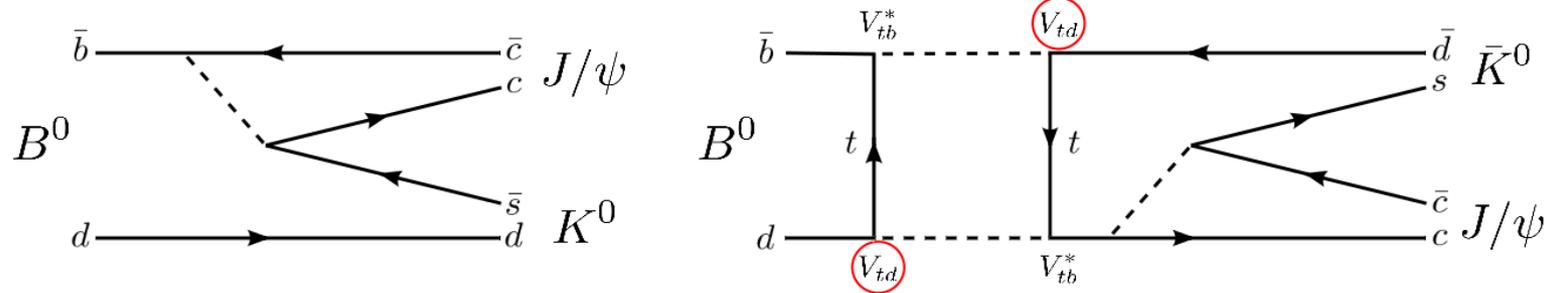
"Young's double slit experiment"

- Time-dependent *CP* asymmetry:

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

Mixing-induced *CPV*   Direct *CPV*

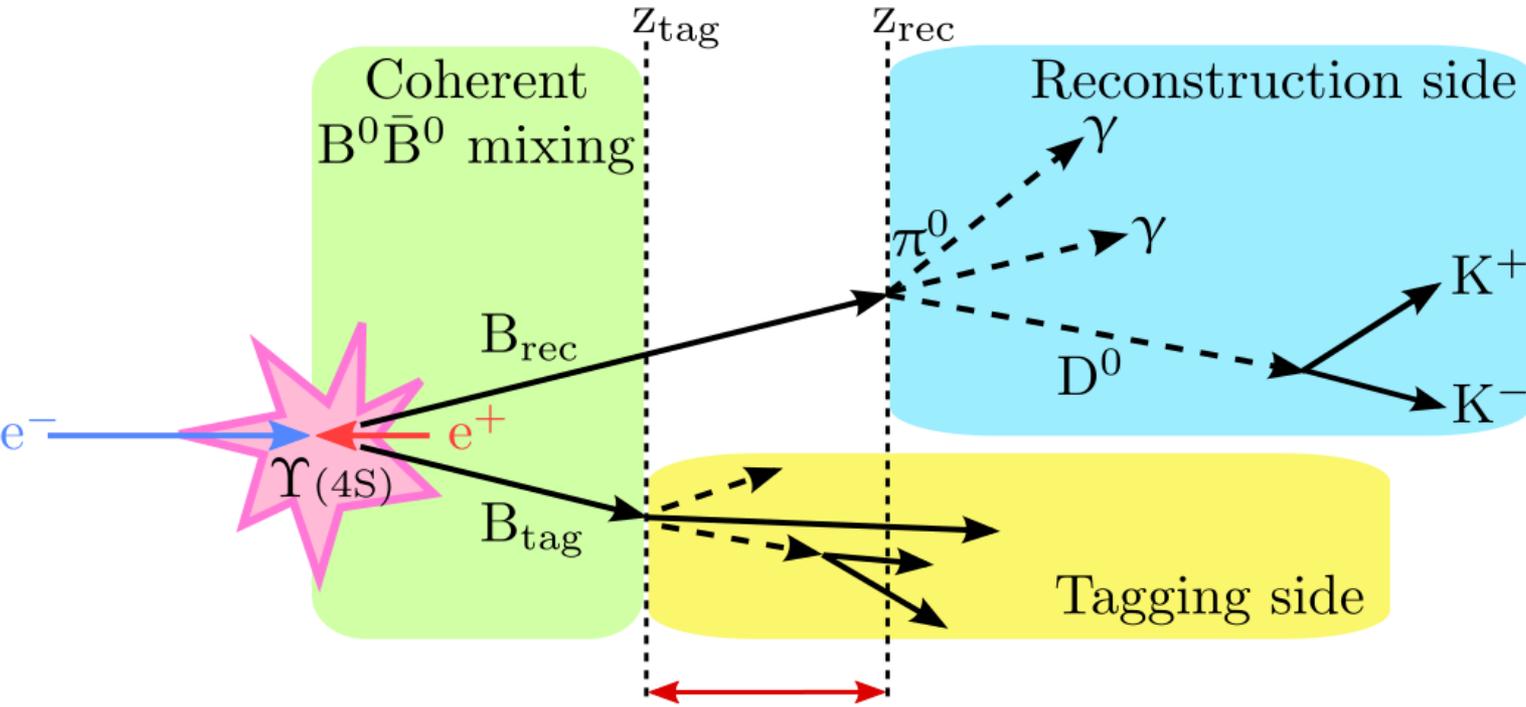- Example $B^0 \to J/\psi K_S^0$ (benchmark for $\sin(2\beta)$):

→ 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 $\Upsilon(4S)$:

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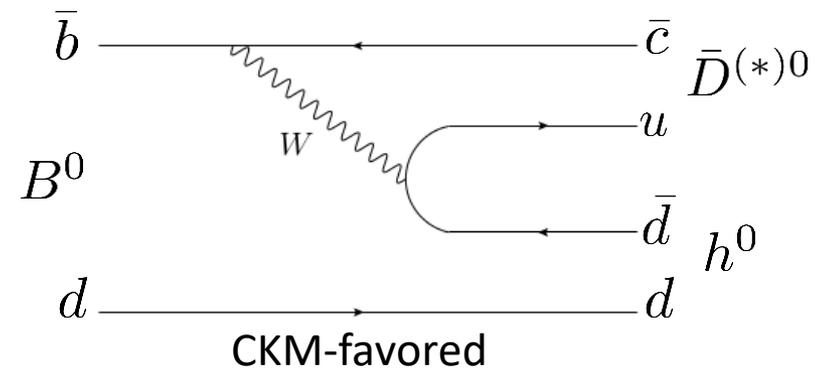$$250\,\mu m\ BABAR$$

Effective 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.

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

CKM-favored

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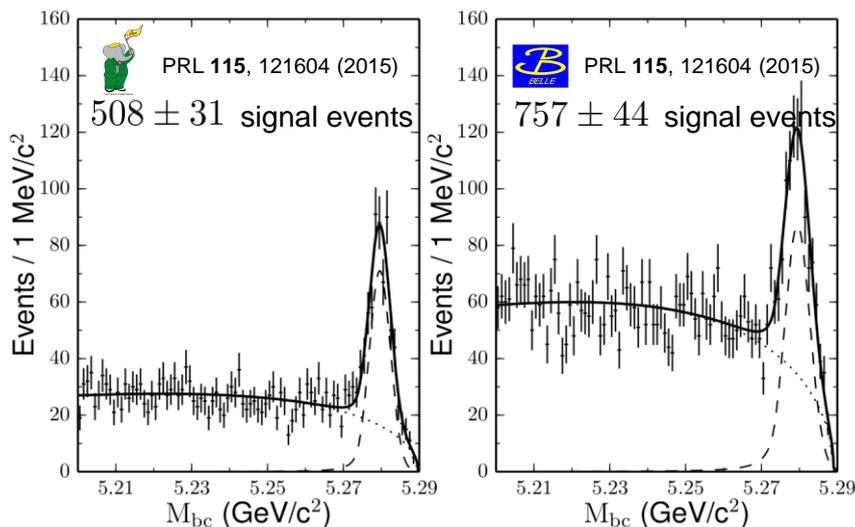
- Theoretically clean [NPB **659**, 321 (2003)]:

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

  $\to$ 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 $\mathcal{O}(\leq 10^{-2})]$

                                 - 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 $\mathrm{B^0 \to D^{(*)}_{CP} h^0}$

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

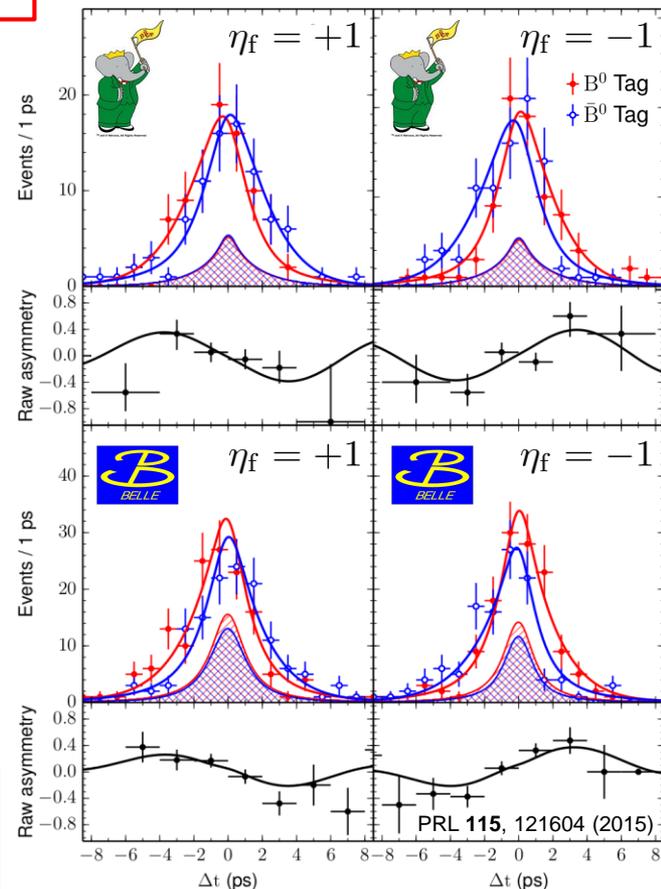$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{\mathit{BABAR}} + \sum_j \ln \mathcal{P}_j^{\mathrm{Belle}}$$

PRL **115**, 121604 (2015)

508 ± 31 signal events

PRL **115**, 121604 (2015)

757 ± 44 signal events

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

- Result:

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

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

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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S. L. Wu,[140,†] H. W. Wulsin,[113,†] H. Yamamoto,[128,‡] J. Yamaoka,[98,‡] S. Yashchenko,[25,‡] C. Z. Yuan,[45,‡] Y. Yusa,[94,‡] A. Zallo,[30,†] C. C. Zhang,[45,‡] Z. P. Zhang,[111,‡] V. Zhilich,[12,13,‡] V. Zhulanov,[12,13,‡] and A. Zupanc[51,‡]

(*BABAR* Collaboration)[†]

(Belle Collaboration)[‡]

[1]*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France*

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

KEK press release

- First observation of *CP*-violation in $B^0 \to D_{CP}^{(*)}h^0$ (5.4σ).

  → This decay 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 inverse attobarn of data.

2. Combined $\mathit{B\!A\!B\!A\!R}$+Belle analysis:

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

Ambiguity of the Unitarity Triangle Angle β

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

$$\beta = \mathbf{21.9°} \quad \text{or} \quad \beta = (\pi/2 - 21.9°) = \mathbf{68.1°}$$
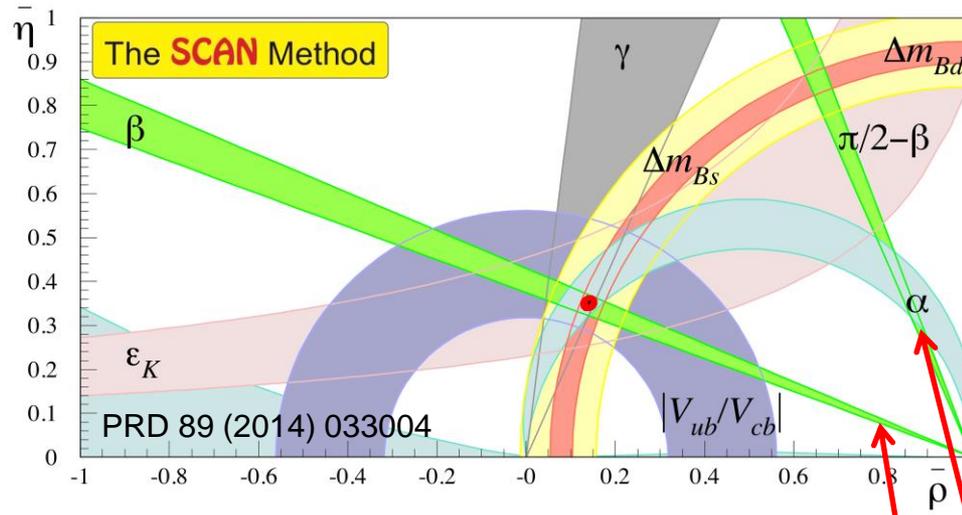
Possible solutions on β from sin(2β)

→ 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 previous best single experimental uncertainty is ≈±0.36. [PRD 94 (2016) 052004]

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

- $B^0 \rightarrow D^{(*)}h^0$ with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays enable to extract both sin(2β) and cos(2β).

- The approach is similar to the GGSZ method to extract γ from multi-body $B^\pm \rightarrow DK^\pm$

- Interference between D^0 and $\bar{D}^0$, 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 $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz plot:

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

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

- If the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ 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 $B^0 \to D^{(*)}h^0$

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

- The $D^0 \to K_S^0 \pi^+ \pi^-$ Dalitz model is directly obtained from flavor-tagged $e^+e^- \to c\bar{c}$ data.

- 924 fb[-1] of Belle yield 1.2×10^6 $D^{*+} \to D^0 \pi_S^+$ with $D^0 \to K_S^0 \pi^+ \pi^-$ decays at high purity.

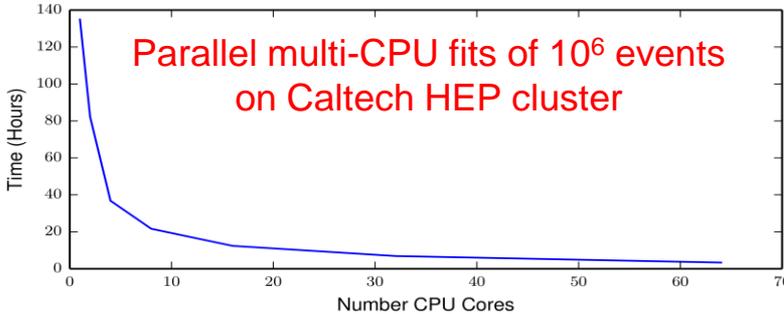- The Dalitz plot amplitude parameters are estimated by a fit to the above distributions.

Establishing the $D^0 \to K_S^0 \pi^+ \pi^-$ Dalitz Plot Model
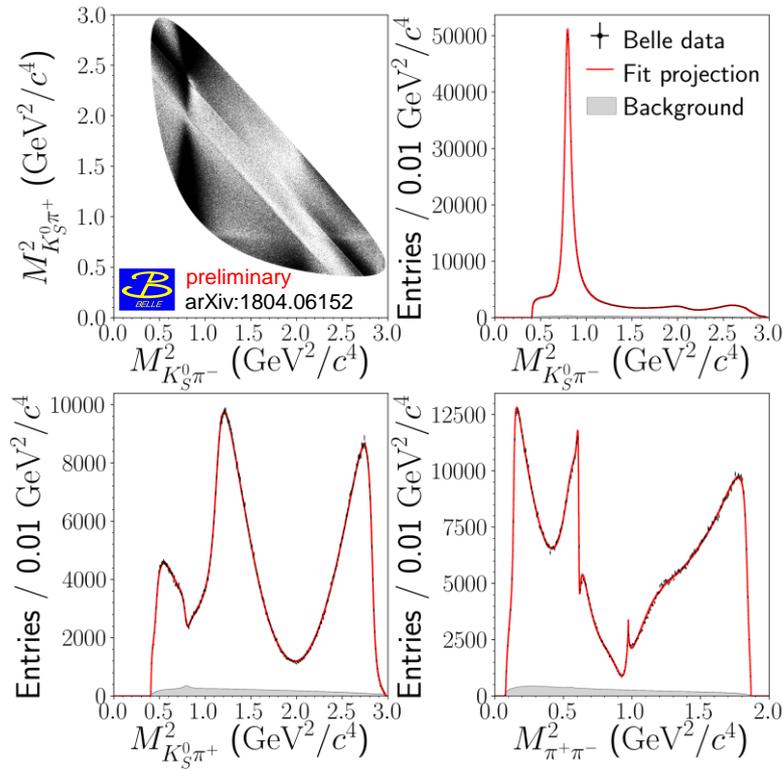
- The Dalitz plot model accounts for 14 intermediate two-body resonances.

- The K-matrix and LASS parameterizations are used to model the ππ and Kπ S-waves.

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

Isobar model for L≠0   LASS   K-matrix

Parallel multi-CPU fits of 10^6 events on Caltech HEP cluster

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

- The framework could have a wide range of applications at Belle II.

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

Linear scale
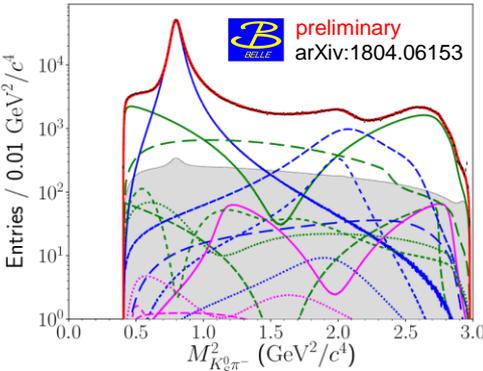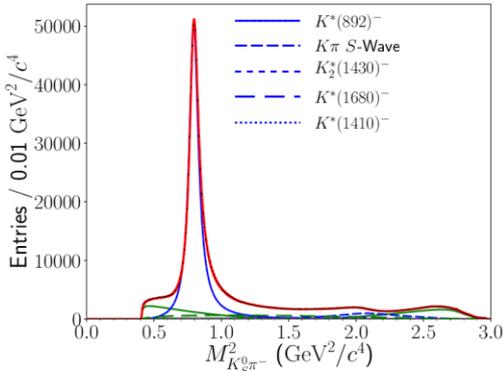
Log scale

Detailed projections of the
Dalitz plot model
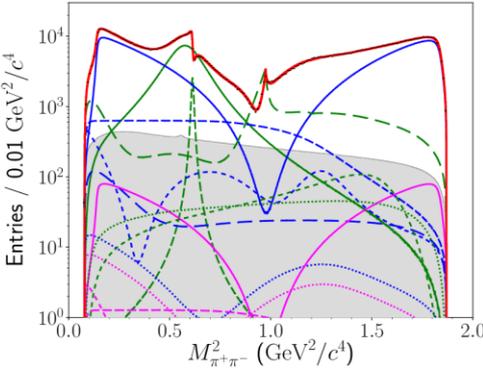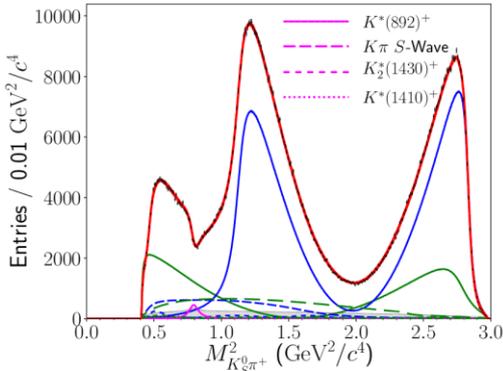
- The $D^0 \to K_S^0 \pi^+ \pi^-$ decay amplitude model extracted from $e^+ e^- \to c\bar{c}$ data is used to extract $\sin(2\beta)$ and $\cos(2\beta)$ from the B^0 decay combining $BABAR$+Belle data.

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

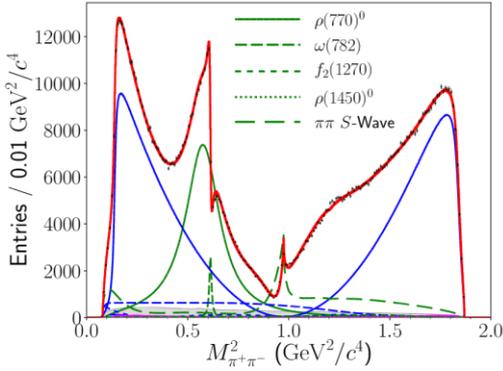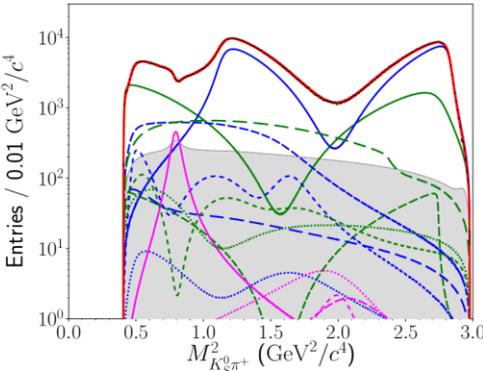- Reconstruct $\mathrm{B^0 \to D^{(*)}h^0}$ with $\mathrm{h^0}$ in $\pi^0 \to \gamma\gamma,\ \eta \to \gamma\gamma, \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$

$$\mathrm{D \to K_S^0\pi^+\pi^-} \text{ and } \mathrm{D^{*0} \to D\pi^0}.$$

- In total, 5 $\mathrm{B^0}$ decay modes are reconstructed.

- $\mathrm{e^+e^- \to q\bar{q}}$ $(\mathrm{q} \in \{\mathrm{u,d,s,c}\})$ continuum background is identified by neural networks.

- Extract signal by 3D fit of beam-constr. mass $\mathrm{M'_{bc}}$, energy-difference $\Delta\mathrm{E}$ and $\mathrm{NN'_{out}}$.
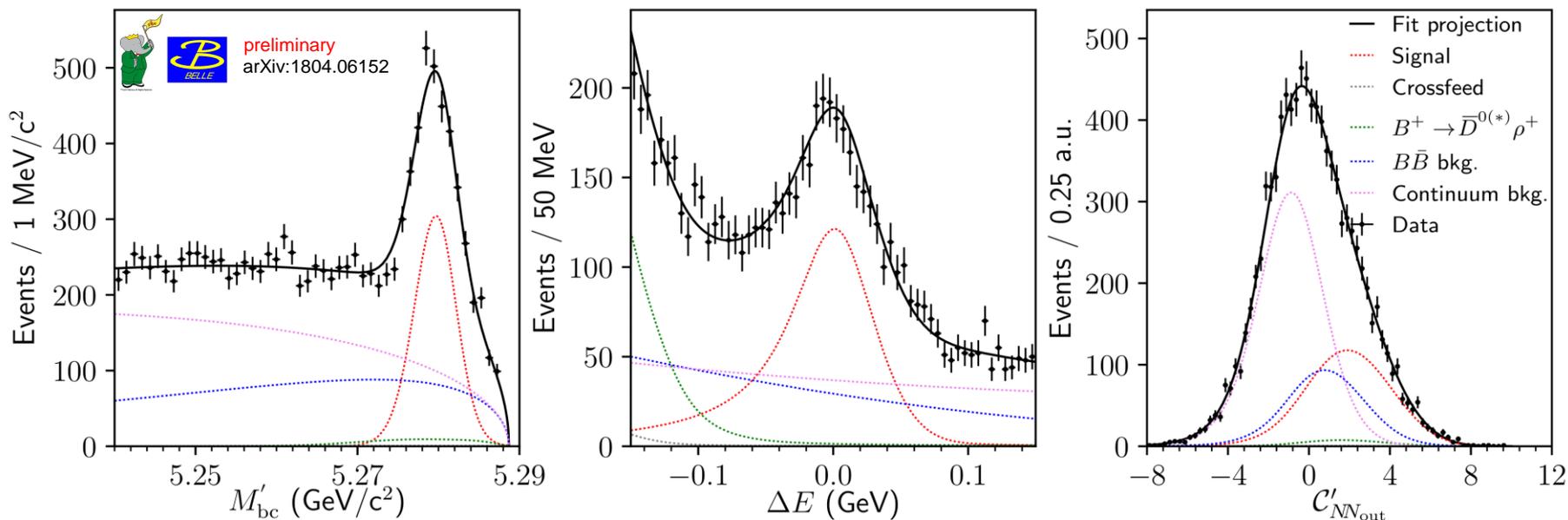
BABAR: 1129 ± 48 signal events
Belle: 1567 ± 56 signal events

2. Combined $\mathcal{B}\!A\!B\!A\!R$+Belle Analysis: cos(2β) from $\mathrm{B^0 \to D^{(*)}h^0}$
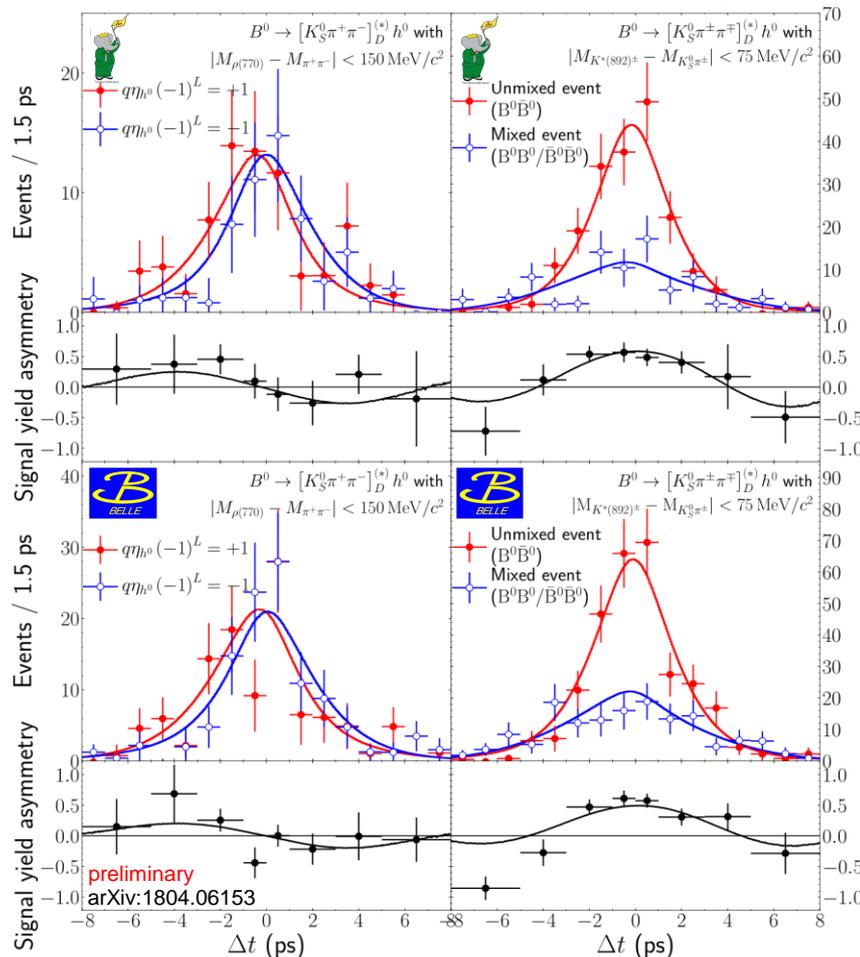
CP eigenstate final states →

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

← Flavor-specific final states

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

$\mathcal{B}\!A\!B\!A\!R$+Belle with 1.1 ab⁻¹:

arXiv:1804.06152   Preliminary
arXiv:1804.06153

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

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

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

2. Combined *BABAR*+Belle Analysis: cos(2β) from $B^0 \to D^{(*)}h^0$
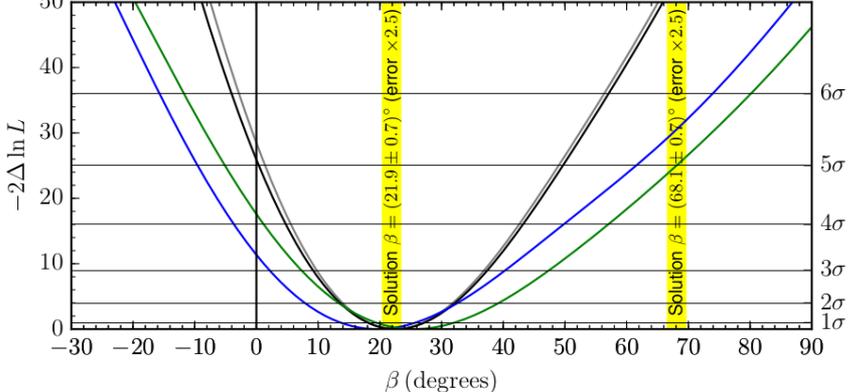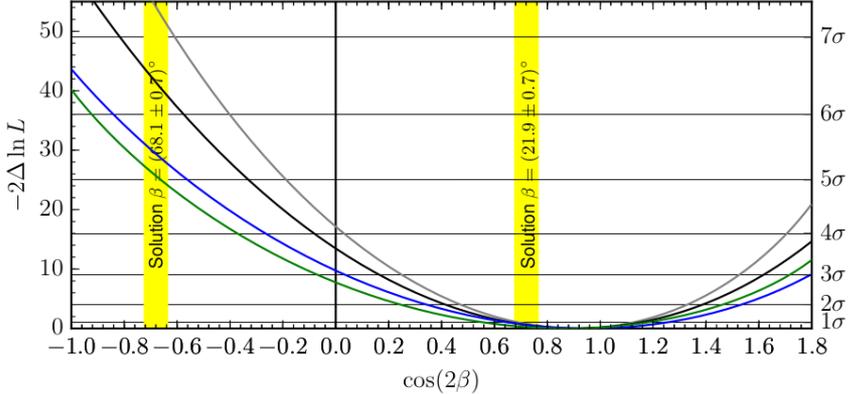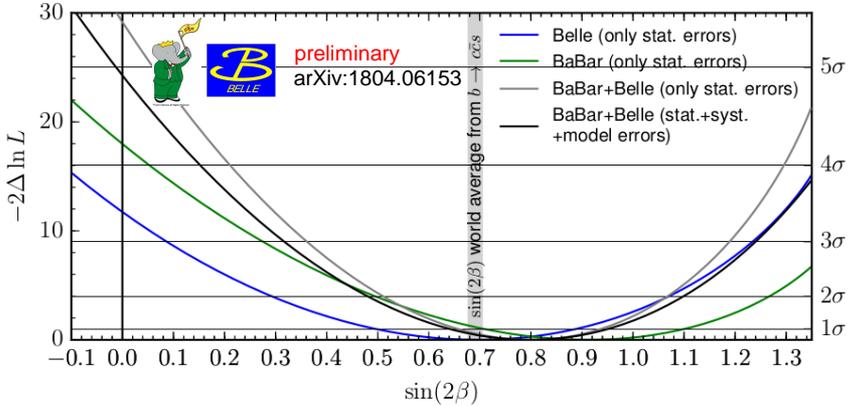
- Single most precise measurement of $\cos(2\beta)$

- 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.

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

Papers for a simultaneous double publication in PRL and PRD:

First evidence for $\cos 2\beta > 0$ and resolution of the CKM Unitarity Triangle

I. Adachi[B,31,28] T. Adye[A,108] H. Ahmed[A,116] J. K. Ahn[B,54] H. Aihara[B,132] S. Akar[A,99] M. S. Alam[A,118] J. Albert[Ab,138] F. Anulli[Aa,106] N. Arnaud[A,56] D. M. Asner[B,10] D. Aston[A,113] H. Atmacan[B,114] T. Aushev[B,82] R. Ayad[B,121] V. Babu[B,122] I. Badhrees[B,121,51] A. M. Bakich[B,120] Sw. Banerjee[A,65] V. Bansal[B,96] R. J. Barlow[A,70,*] G. Batignani[Aab,102] A. Beaulieu[Ab,138] P. Behera[B,39] M. Bellis[A,117] E. Ben-Haim[A,99] D. Bernard[A,60] F. U. Bernlochner[Ab,138] S. Bettarini[Aab,102] D. Bettoni[Aa,24] A. J. Bevan[A,63] V. Bhardwaj[B,35] B. Bhuyan[A,37] F. Bianchi[Aab,135] M. Biasini[Aab,101] J. Biswal[B,46] V. E. Blinov[A,11,12,13] M. Bomben[A,99] A. Bondar[B,11,12] G. R. Bonneaud[A,99] A. Bozek[B,90] C. Bozzi[Aa,24] M. Bračko[B,71,46] T. E. Browder[B,30]

Submitted to PRL
[arXiv:1804.06152]

Measurement of $\cos 2\beta$ in $B^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays by a combined time-dependent Dalitz plot analysis of $BABAR$ and Belle data

I. Adachi[B,31,28] T. Adye[A,106] H. Ahmed[A,114] J. K. Ahn[B,53] H. Aihara[B,130] S. Akar[A,97] M. S. Alam[A,116] J. Albert[Ab,136] F. Anulli[Aa,104] N. Arnaud[A,55] D. M. Asner[B,10] D. Aston[A,111] H. Atmacan[B,112] T. Aushev[B,80] R. Ayad[B,119] I. Badhrees[B,119,50] A. M. Bakich[B,118] Sw. Banerjee[A,64] V. Bansal[B,94] R. J. Barlow[A,68,*] G. Batignani[Aab,100] A. Beaulieu[Ab,136] P. Behera[B,39] M. Bellis[A,115] E. Ben-Haim[A,97] D. Bernard[A,59] F. U. Bernlochner[Ab,136] S. Bettarini[Aab,100] D. Bettoni[Aa,24] A. J. Bevan[A,62] V. Bhardwaj[B,35] B. Bhuyan[A,37] F. Bianchi[Aab,133] M. Biasini[Aab,99] J. Biswal[B,46] V. E. Blinov[A,11,12,13] M. Bomben[A,97] A. Bondar[B,11,12]

Submitted to PRD
[arXiv:1804.06153]

An article for the CERN Courier has been submitted one week ago (to appear in November):

$BABAR$ and Belle join forces on CP Violation

Kenkichi Miyabayashi,[1] Frank C. Porter,[2] and Markus Röhrken[3]

[1] Nara Women's University, Nara 630-8506, Japan
[2] California Institute of Technology, Pasadena, California 91125, USA
[3] European Organization for Nuclear Research (CERN), Geneva, Switzerland

The $BABAR$ and Belle experiments have combined their data to resolve a long-standing ambiguity in CP violation.

Introduction

Understanding nature's fundamental laws has often meant understanding its symmetries, that is, ways that

$\Upsilon(4S)$ resonance in e^+e^- annihilations. To give them a boost so that their decay times can be measured, the $\Upsilon(4S)$ is produced with motion in the laboratory. This is accomplished by arranging the accelerator with two

Ongoing work at LHCb

(Current work as CERN Research Fellow in the LHCb team of Andreas Schopper.)
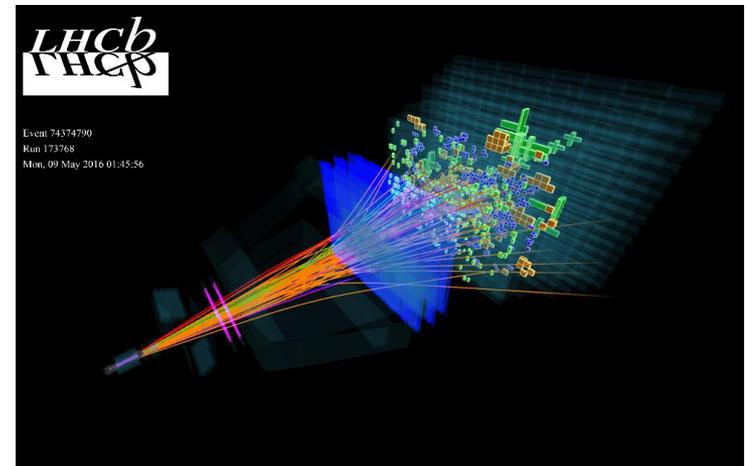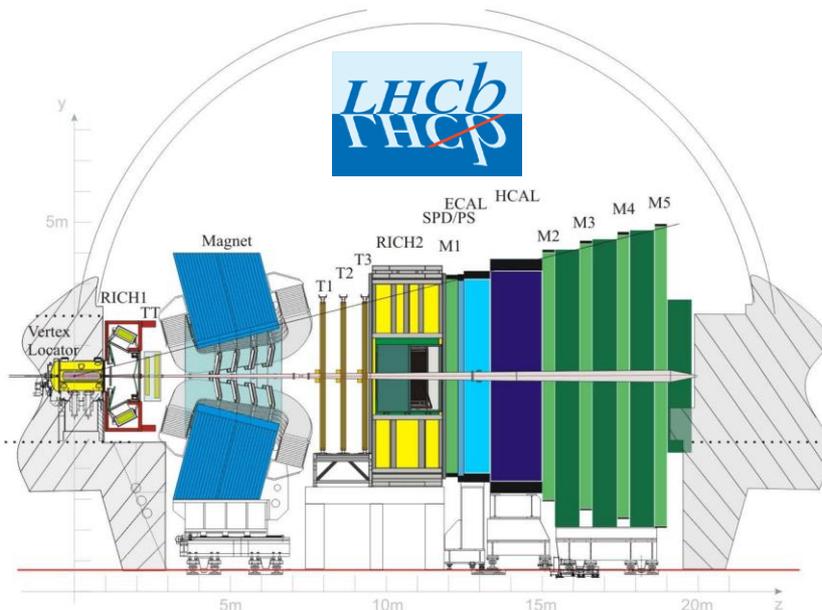
Search for New Physics in Quantum-Loops

- LHCb enables unprecedented sensitivity to rare heavy flavor decays mediated by pure quantum-loop transitions.

- Currently, I'm working on a time-dependent Dalitz plot analysis of $B_s^0 \to \phi\pi^+\pi^-$ decays.

- $B_s^0 \to \phi\pi^+\pi^-$ allows access to various intermediates mediated by $b \to s$ penguins.
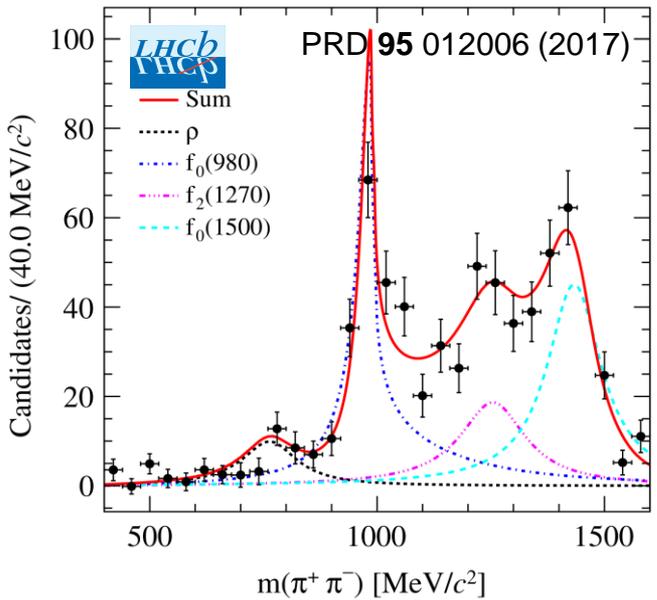
Previous analysis (Run1)
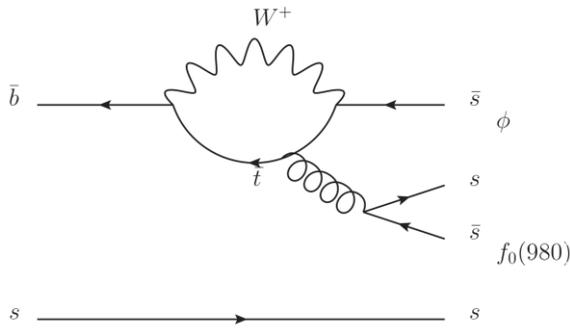
$B_s^0 \to \phi f_0(980)$
Gluonic penguin
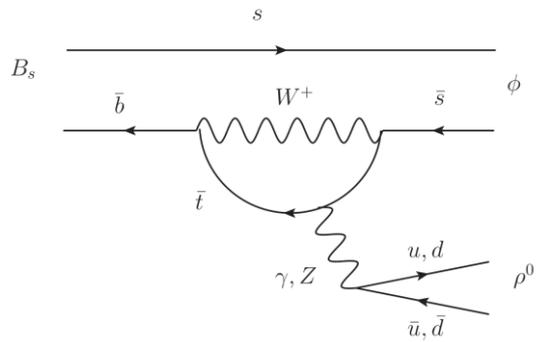
$B_s^0 \to \phi\rho^0$
Electroweak penguin

- Prospects: - Precise amplitude analysis

    - First time-dependent measurement of $\beta_{s,\text{eff.}}$ of various pure quantum-loops
    - First observation of $B_s^0 \to \phi\rho^0$ (very rare electroweak penguin decay)

R&D for the ECAL Upgrade Ib/II

- The HL upgrade of the LHC will require operation of the ECAL of LHCb in extreme conditions.

- An upgrade of the ECAL during LS3 can (ideally) provide:
  - Fast timing (inclusion of silicon planes, fast scintillating crystals, …)
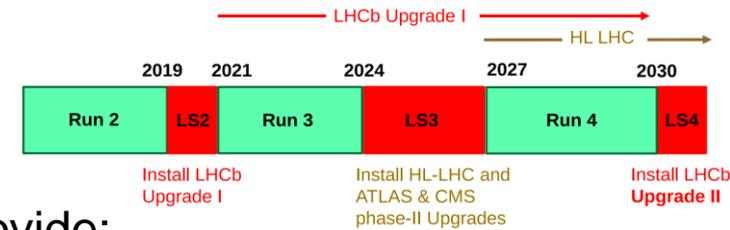 - Better spatial resolution (smaller Moliere radius and cells, silicon, …)
  - High radiation hardness

- Opportunity to improve on ECAL-related physics:
  - Final states with π^0, soft and hard γ, and electrons

- I'm working on the Geant4-based simulations to study possible upgrade options:

  1. "Shashlik"-type sampling calorimeter

  2. Single large scintillating crystals

  3. "SpaCal"-type sampling calorimeter
     (fibers of scintillating crystals in absorber)
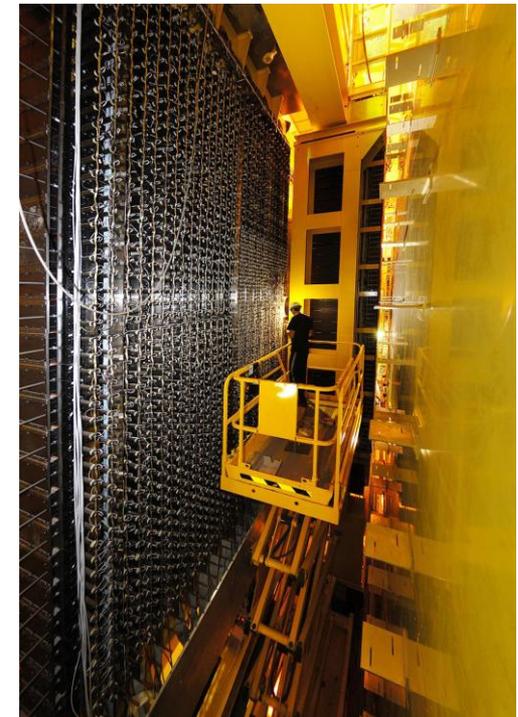
- I'm participating in the R&D of modules (first beam test of a new SpaCal in October).

Prospects at Belle II

The Belle II Experiment

- SuperKEKB: 8×10^{35} cm^{-2} s^{-1} (40× KEKB)

- Belle II-Design: 50 ab^{-1} (100× $BABAR$)

- Sensitive to many potential new physics sources:

  - Flavor changing neutral currents: New flavor couplings and heavy particles

  - Precision CKM measurements: New sources of CP violation

  - Right-handed currents in radiative penguins

  - Charged Higgs in tau-onic B decays

Belle II
50 ab^{-1}
1.1 ab^{-1}
SuperKEKB
preiminary
KEK in Tsukuba, Japan   First collisions: April 26th, 2018

- Clean e$^+$e$^-$ environment

- Many different unique reconstruction and tagging techniques

- Capable to perform precision measurements in final states with one or more neutrinos
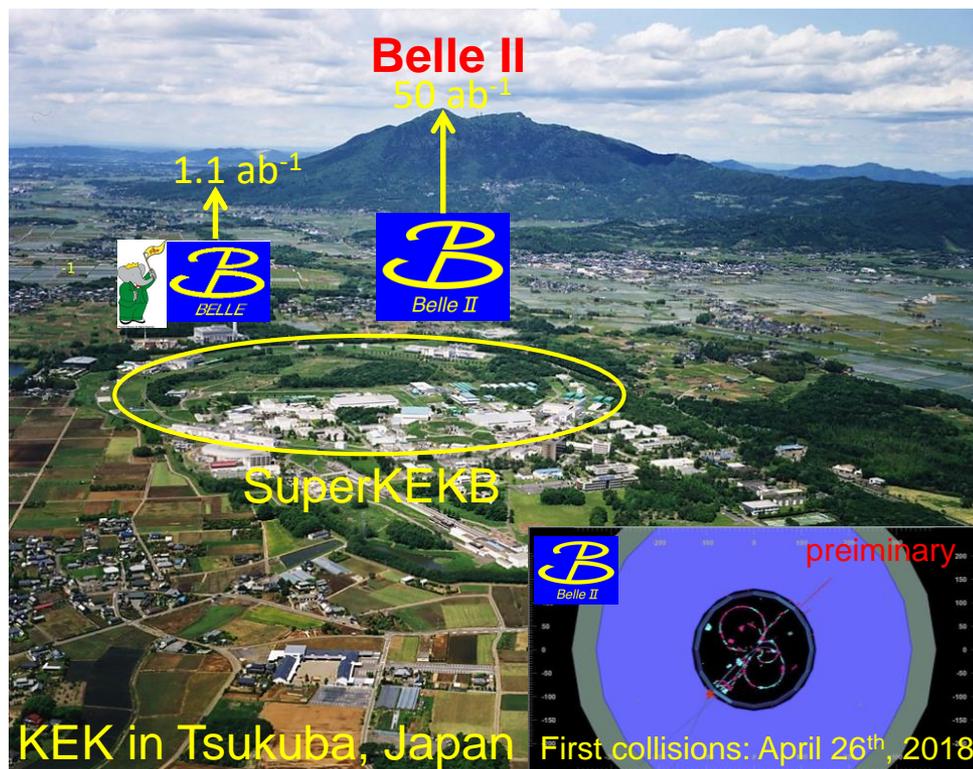
Time-Dependent *CP* Violation

New Physics Searches in the *CP* Violation of b→s Penguins

- Belle II enables for precise *CP* violation measurements of b→s penguin transitions.
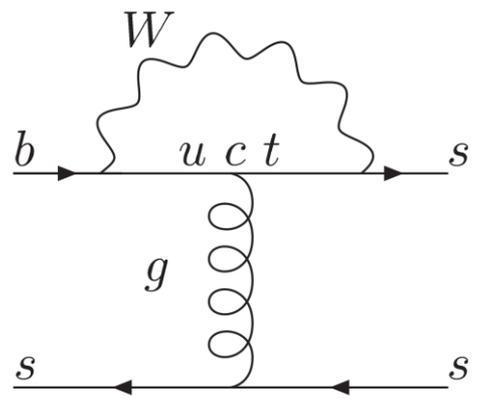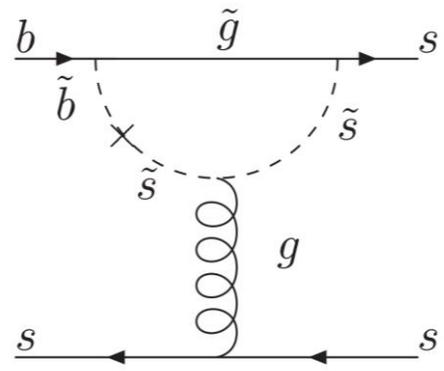
<p style="color:red">Gluonic SM penguin   Example of a SUSY loop</p>

- Examples are of penguin-dominated decays are:

$$B^0 \to \phi K^0, B^0 \to K_S^0 K_S^0 K_S^0 \text{ and } B^0 \to \eta' K^0$$

- Time evolution of $b \to s\bar{s}s$ & co. is effectively governed by the weak phase β.

- Probes for yet unobserved heavy particles and new *CP*-violating phases in the loops.

- New physics contributions would change the time evolution.

New Physics Searches in the *CP* Violation of b→s Penguins

- New physics effects can be probed by comparing the time-dependent *CP* violation of b→s penguins to the SM reference.
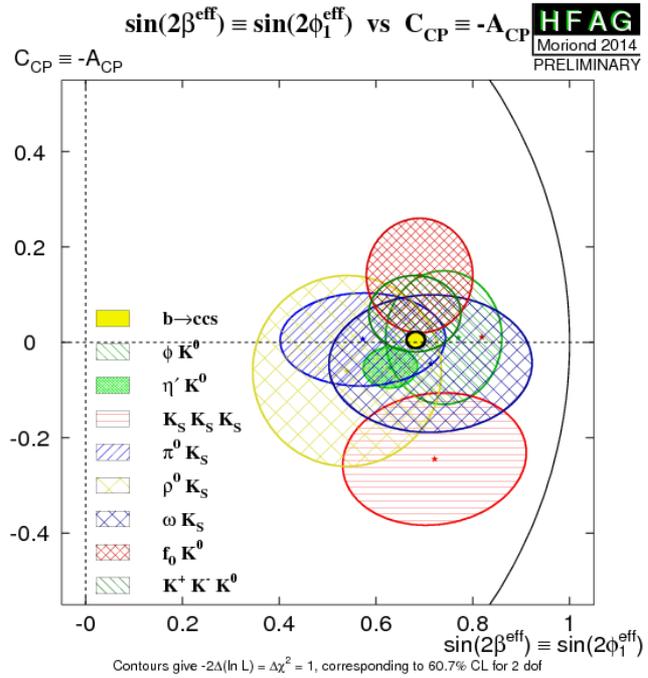
- Important are precise SM reference measurements, such as provided by $B^0 \to D^{(*)}_{CP} h^0$.

  → Probes independently of models or assumptions for beyond the SM physics.

Status after end of BaBar and Belle
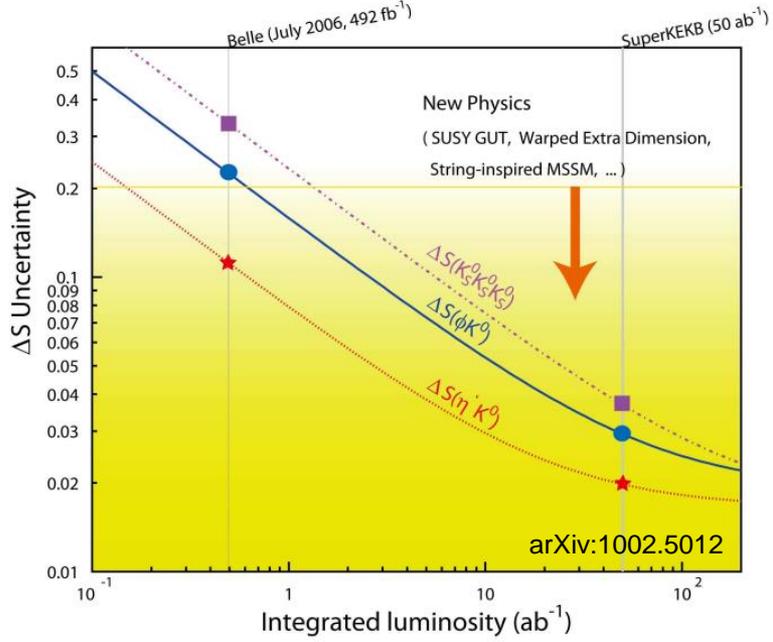
Expected sensitivity at Belle II

Belle II will measure the *CP* violation of penguin transitions at a single percent precision enabling to probe for new effects on the TeV scale and above.

New Physics Searches in Radiative Penguins

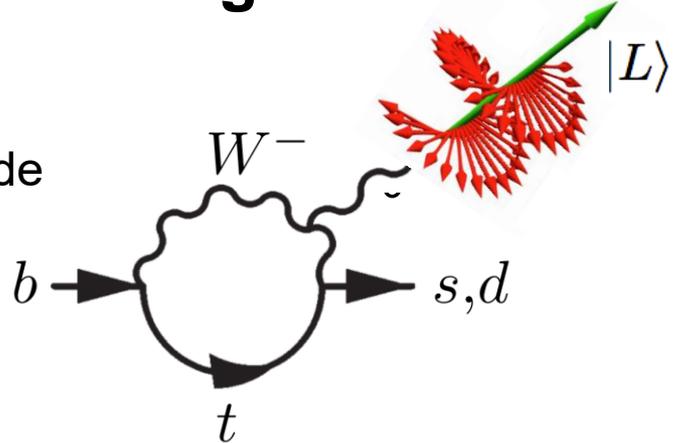- Radiative penguins $b \to s\gamma$ and $b \to d\gamma$ provide unique probes to the photon polarization:

- W's couple only to left-handed quarks, chirality flip suppressed: $b \to \gamma_L + \frac{m_s}{m_b}\gamma_R$

  → Photon is dominantly left-handed (right-handed) in $b\,(\bar{b})$ decays.

- New physics effects can give rise to a right-handed photon polarization:
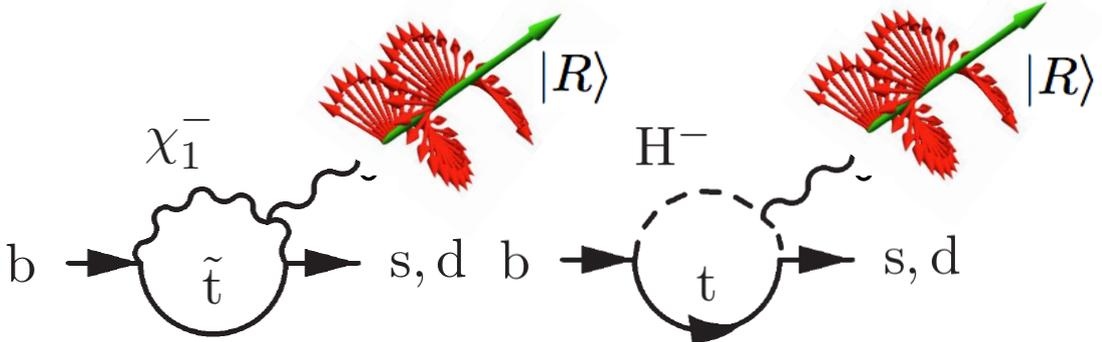
arXiv:0705.4458
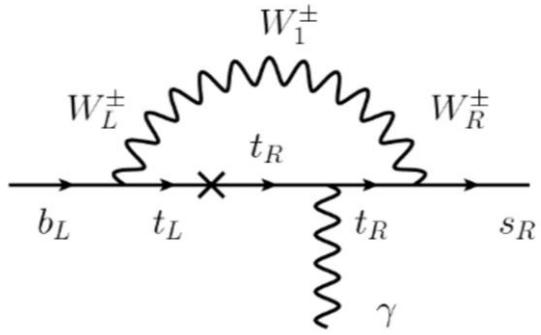
JHEP **12**, 102 (2013)

New heavy particles and flavor couplings (SUSY, extended Higgs sector, …)

Models restoring the Left↔Right symmetry and right-handed interactions $(W_R^\pm, V_{CKM}^R)$

New Physics Searches in Radiative Penguins

- Currently in $b \to s\gamma$ and $b \to d\gamma$ most precise are time-integrated observables (direct *CP* asymmetries, branching fractions), where new effects are predicted small of $\mathcal{O}(< 10\%)$.

- In time-dependent analyses, enhanced effects and more sensitivity to new physics models are possible:

$$B \to f_{CP}\gamma \qquad B \to \bar{B} \to f_{CP}\gamma$$

Interference only, if final states share same photon helicity.

$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}^0(t) \to f_{CP}\gamma\right) - \Gamma\left(B^0(t) \to f_{CP}\gamma\right)}{\Gamma\left(\bar{B}^0(t) \to f_{CP}\gamma\right) + \Gamma\left(B^0(t) \to f_{CP}\gamma\right)}$$
$$= \pm\sin\left(2\psi\right)\sin\left(2\beta - \phi_L - \phi_R\right)\sin\left(\Delta mt\right)$$

$$\mathcal{S}^{\mathrm{SM}}_{K^0_S\pi^0\gamma} \approx 0.04$$

$$\mathcal{S}^{\mathrm{NP,LR}}_{K^0_S\pi^0\gamma} \approx 0.7\sin(2\beta)$$

D. Atwood, M. Gronau, A. Soni PRL **79**, 185 (1997)

→ The time-dependent *CP* violation enables to measure directly the photon polarization.

			Belle 2	
	Observable	Belle and LHCb (present)	$5\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
Radiative penguins	$\mathcal{B}(B \to X_s\gamma)\ [10^{-4}]$	$3.45\,(1 \pm 12\%)$	7%	6%
	$A_{CP}(B \to X_{s,d}\gamma)\ [10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$	1	0.5
	$S(B \to K^0_S\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07

Belle II will significantly reduce the uncertainties, especially the sensitivity to the photon polarization will provide a new unique probe to new physics effects.

Hadronic Tagging
New Physics Searches in Decay Modes with Neutrinos in the Final State

Full Reconstruction and Hadronic Tagging

- The known initial state from e⁺e⁻ collisions enables to measure B decays with one or several neutrinos in the final state.

$$B_{tag}^+ \to \bar{D}^0 \pi^+ \pi^+ \pi^- \qquad B_{sig}^- \to \tau^- \bar{\nu}_\tau$$
$$\hookrightarrow K^+ \pi^- \qquad\qquad \hookrightarrow e^- \bar{\nu}_e \nu_\tau$$
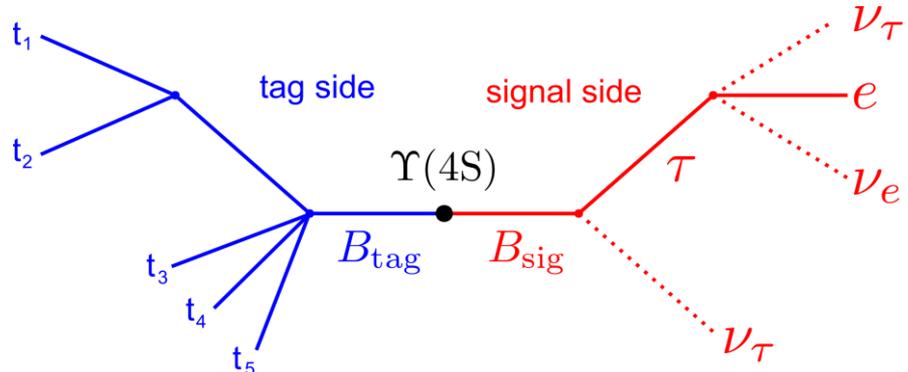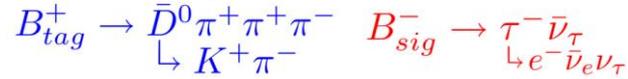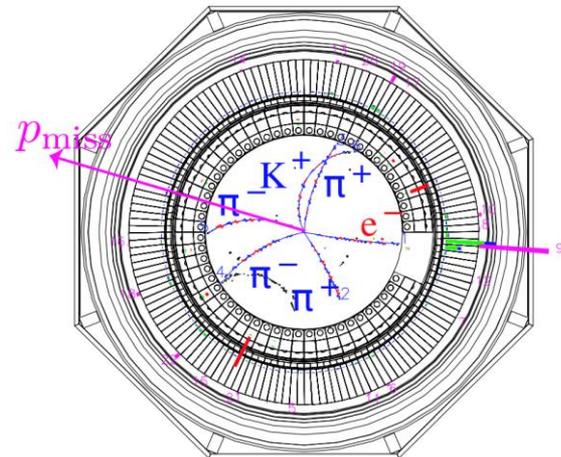
Example of a missing momentum event

Reconstruction of a missing momentum event by full reconstruction of the second B meson

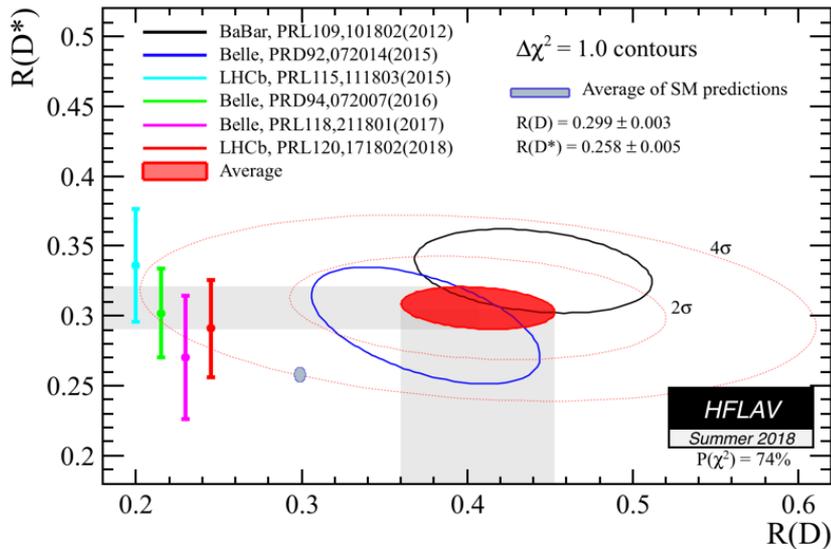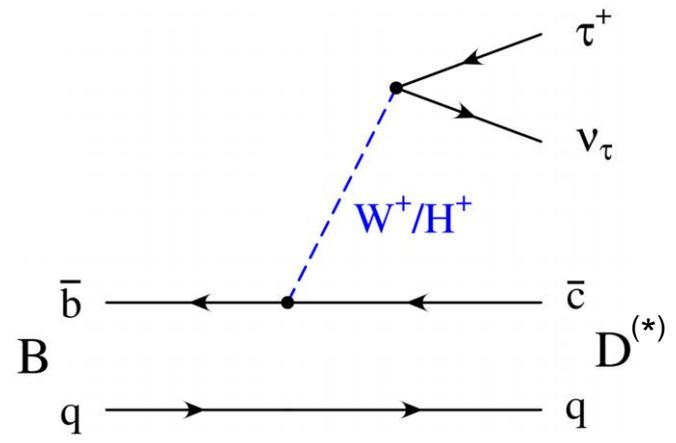- Examples of decays sensitive to new physics signatures accessible by hadronic tag:

$$B \to D^{(*)} \tau \nu \qquad\qquad B \to \nu \nu$$

$$B \to K^{(*)} \nu \nu \qquad\qquad B \to \text{invisible}$$

$$B \to \tau \nu$$

Many more, e.g. semi-leptonic charmless modes

Example for Hadronic Tagging: $B \to D^{(*)} \tau \nu$

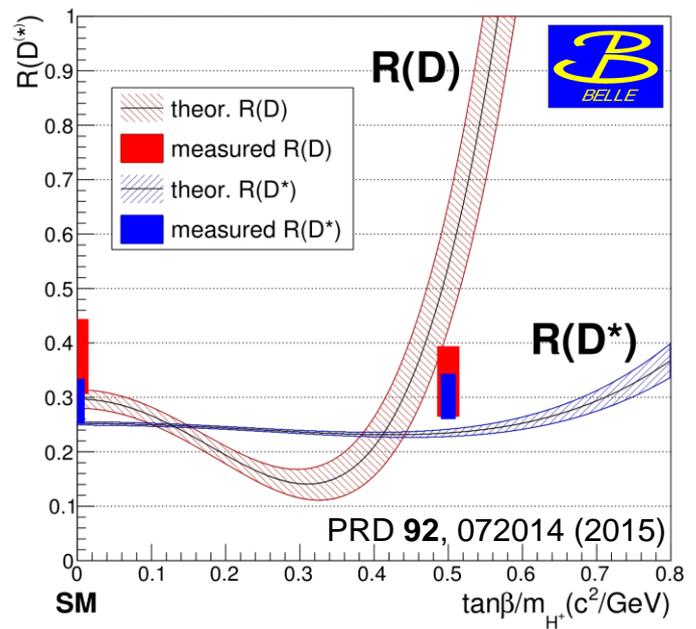- $B \to D^{(*)} \tau \nu$ is a tree-level mediated decay.

- Originally proposed to test models predicting a heavy charged Higgs boson.

- Observable:

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)} l \bar{\nu}_l)} \text{ with } l = e, \mu$$

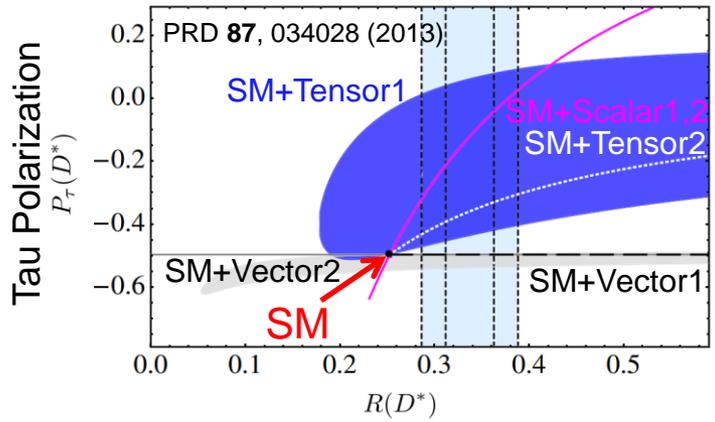*BABAR*, Belle and LHCb combined:

4σ deviation from the SM

Compatibility with 2HDM model type II
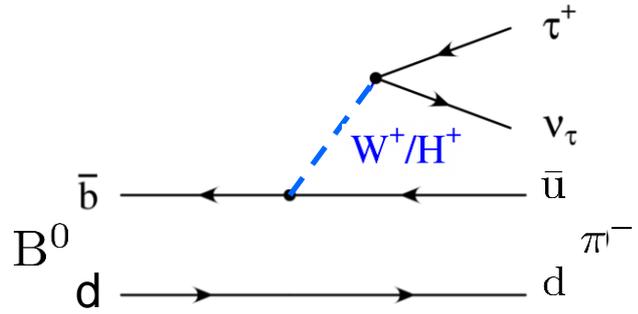
Example for Hadronic Tagging: $B \to D^{(*)} \tau \nu$

- Belle II is expected to resolve the current tension with 5 ab⁻¹. (Though LHCb has several new results in the pipeline.)

- Belle II opens window to completely new observables:

  - Tau polarization probes nature of the interaction.

  - Sensitive to deviations from weak V-A structure, e.g. caused by the scalar Higgs.

PRD **87**, 034028 (2013)
SM+Tensor1
SM+Scalar1,2
SM+Tensor2
SM+Vector2
SM+Vector1
SM

Tau Polarization $P_\tau(D^*)$

$R(D^*)$

  - $B^0 \to \pi^- \tau^+ \nu_\tau$ provides complementary probe:

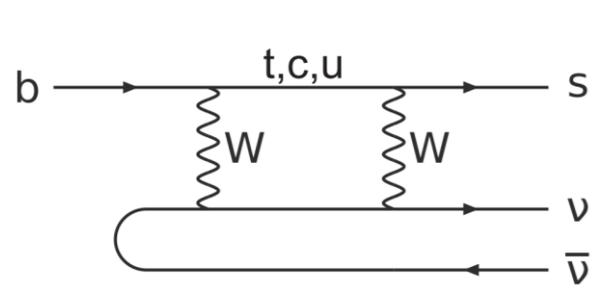$$R(\pi)_{\text{SM}} = \frac{\mathcal{B}(B^0 \to \pi^- \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to \pi^- l^+ \nu_l)} = 0.641(17)$$

- Decay is yet unobserved, only possible at Belle II.

Hadronic Tagging Example: $B \to K^{(*)} \nu\nu$

- LHCb sees 2.9σ deviation in $B \to K^* \mu^+ \mu^-$, Belle II can test this in more final states

- Complementary: $B \to K^{(*)} \nu\nu$

- Pure loop mediated decay

Electroweak boxes
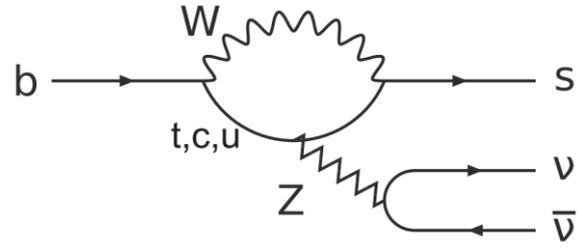
Z penguin

- Reconstruct B meson from one track and two neutrinos → requires tagging
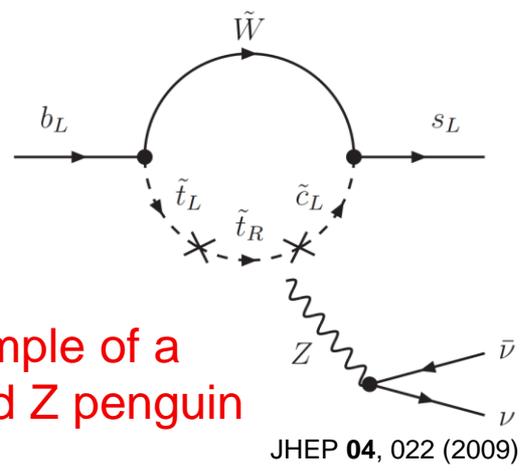
Example of a modified Z penguin

JHEP **04**, 022 (2009)

Theory

$\eta = \dfrac{-\mathrm{Re}(C_L^\nu C_R^{\nu*})}{|C_L^\nu|^2 + |C_R^\nu|^2}$

Present limits

SM

JHEP **04**, 022 (2009)
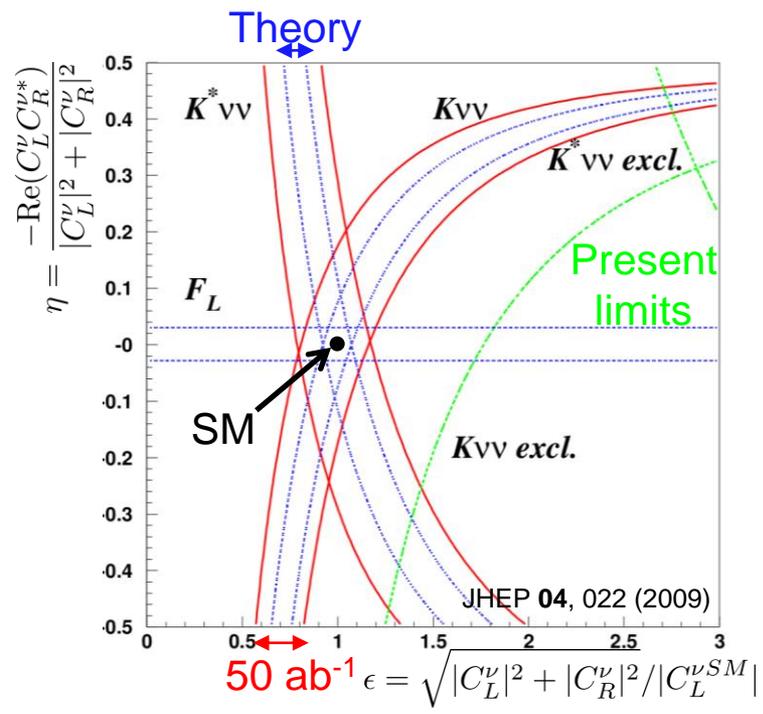
- Clean new physics probe for a variety of models

  (SUSY, right-handed currents, …)

50 ab⁻¹ $\epsilon = \sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}/|C_L^{\nu SM}|$

Method Developments

Framework for Dalitz Plot Amplitude Analyses

- Multi-body heavy flavor decays are governed by complex interference effects which probe the dynamics of the underlying strong and weak interactions.

- Dalitz-plot amplitude analyses played a key role in many discovery since the 50s:

  - Solving the $\tau - \theta$ puzzle [R.H. Dalitz, Phys. Rev. **94**, 1046 (1954)]

  - Discovery and characterization of tetra- and penta-quarks (Belle, BESIII, LHCb)

$M^2(\psi(2S)\pi^+)$

Unusual feature

$B^0 \to K^- \pi^+ \psi(2S)$

$M^2(K^- \pi^+)$

PRL **100**, 142001 (2008)

$Z^+(4430)$
(minimal quark content: $c\bar{c}u\bar{d}$)
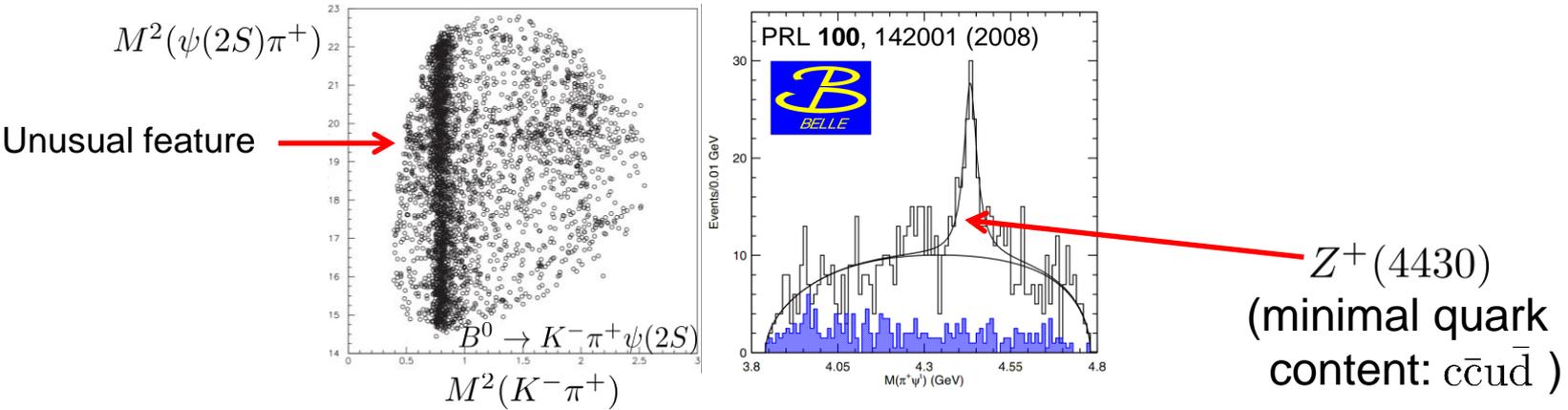
The framework developed for the $BABAR$+Belle analyses is flexible and can be applied to:

- Probing for *CP* violation in multibody D, B and B_s decays.

- Spectroscopy to determine properties of hadronic exotica including tetra-quarks.

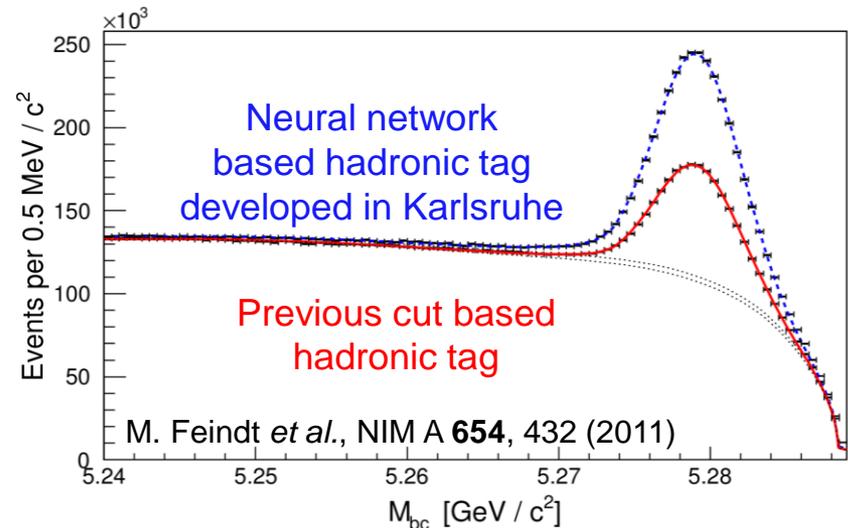- New physics searches by time-dependent Dalitz plot analyses.

The implemented multi-CPU parallelization allows the analysis of very large data sets.

Machine Learning Opportunities at Belle II

- Machine learning techniques such as neural networks enable to exploit complex non-linear correlations between input variables.

  $\rightarrow$ Powerful tool for pattern recognition and classification problems in particle physics.

- Example from Belle:

  The new neural network approach effectively doubled the statistics in hadronic tagging analyses such as such as $B \rightarrow \tau\nu$ and $B \rightarrow D^{(*)}\tau\nu$.

Neural network based hadronic tag developed in Karlsruhe

Previous cut based hadronic tag

M. Feindt *et al.*, NIM A **654**, 432 (2011)

Many machine learning opportunities at Belle II, for example:

- New flavor-tagging algorithms for time-dependent *CP* violation measurements.

- Generic charm suppressor for charmless B decays.

Summary

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

- 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:

  - The end of Run 2 of the LHC is close, and the upgrades of the experiments progress to collect more data after LS2.

  - SuperKEKB+Belle II started full operation and recently produced first collisions in order to collect 50 ab^{-1} until the mid of the 2020s.

- Belle II will play an important and complementary role to the LHC in searching and and studying new physical phenomena beyond the Standard Model.

- The Belle II physics program is very rich and has only been roughly sketched in this talk.