Recent constraints on CKM and New Physics by Belle

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on behalf of the Belle Collaboration

Moriond 2014 – Electroweak Session
March 16, 2014

Quark Mixing and CP Violation

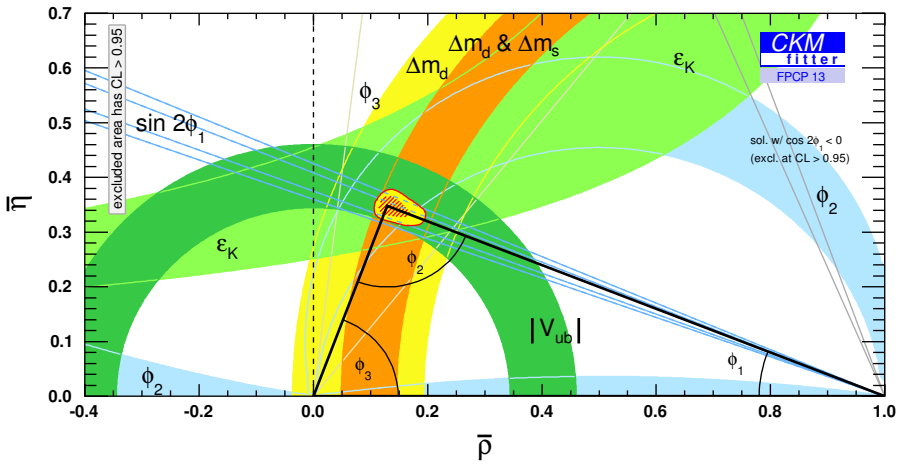
CP Violation (CPV) is established in the Standard Model (SM) in the weak interaction

- Cabibbo-Kobayashi-Maskawa-Matrix: Complex, unitary mixing Matrix between flavor/mass eigenstates

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

$$\lambda = \sin\theta_C \approx 0.2$$

- CPV due to irreducible complex phase
- unitary constraints: $\sum_k V_{ik} V_{jk}^* = 0$; $\underset{\mathcal{O}(\lambda^3)}{V_{ud} V_{ub}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{cd} V_{cb}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{td} V_{tb}^*} = 0$



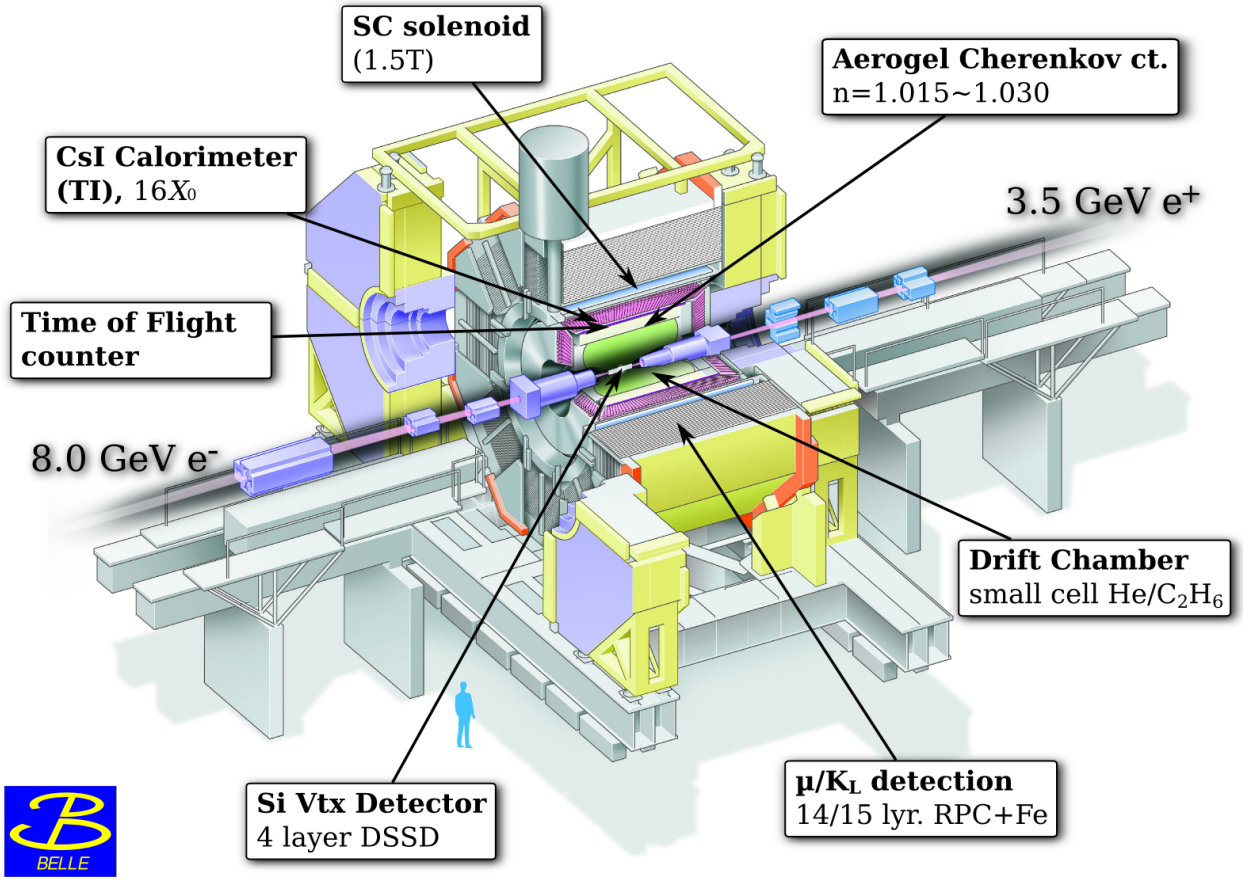
$$\overline{\rho} = \left(1 - \frac{\lambda^2}{2}\right)\rho \qquad \overline{\eta} = \left(1 - \frac{\lambda^2}{2}\right)\eta$$

$$\left.\begin{matrix}\phi_1 \\ \beta\end{matrix}\right\} = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \left.\begin{matrix}\phi_2 \\ \alpha\end{matrix}\right\} = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

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

The Belle Experiment

- multi purpose detector designed for CPV measurement
- was located at the asymmetric e^+e^- collider KEKB in Japan
- was running mainly at the $\Upsilon(4S)$ resonance (10.58 GeV)



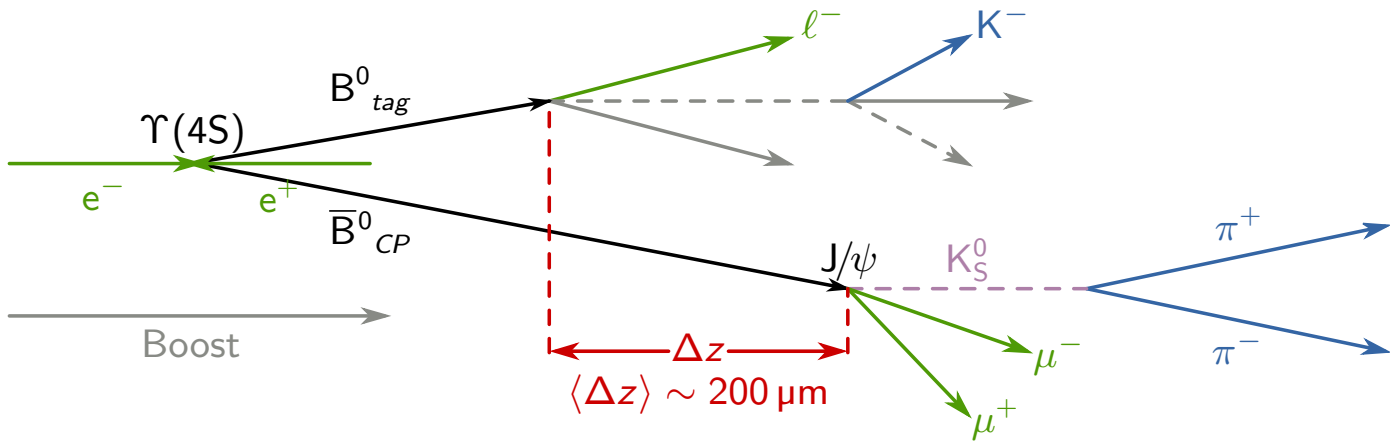
- data taken from 1999–2010
- worlds largest integrated luminosity ($\sim 1\,\mathrm{ab}^{-1}$)
- $\Upsilon(4S)$ dataset with 772 million $B\overline{B}$ pairs
- currently being upgraded to Belle II target $\geq 50\,\mathrm{ab}^{-1}$ (start in 2016)

CPV Measurement at Belle

Time dependent CP Asymmetry $(\Delta m_d = m_H - m_L)$

$$a_{CP}(t) = \frac{\Gamma\left(\overline{B}^0 \to f_{CP}; t\right) - \Gamma\left(B^0 \to f_{CP}; t\right)}{\Gamma\left(\overline{B}^0 \to f_{CP}; t\right) + \Gamma\left(B^0 \to f_{CP}; t\right)} = \mathcal{A}_{CP}\cos(\Delta m_d \Delta t) + \mathcal{S}_{CP}\sin(\Delta m_d \Delta t)$$

- $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ produced in quantum entangled state
- B_{CP} = reconstruct CP eigenstate, B_{tag} = determine flavour
- boost: $t \to \Delta t = \Delta z/\beta\gamma c$



Main Backgrounds:

- Continuum: Events from u, d, s, c production
- $B\overline{B}$: Background from other $B\overline{B}$ decays

Useful variables:

$$M_{BC} = \sqrt{\left(E^{CMS}_{beam}\right)^2 - \left(p^{CMS}_B\right)^2} \qquad \Delta E = E^{CMS}_B - E^{CMS}_{beam}$$

CP Violation in $b \to s\bar{q}q$ transitions

- $b \to c\bar{c}s$ ($B^0 \to J/\psi K^0_S$) is tree dominated
- $b \to s\bar{u}u$ and $b \to s\bar{d}d$ ($B^0 \to \omega K^0_S$) is **penguin dominated**, tree is color and Cabibbo suppressed.
- $b \to s\bar{s}s$ is **penguin only**

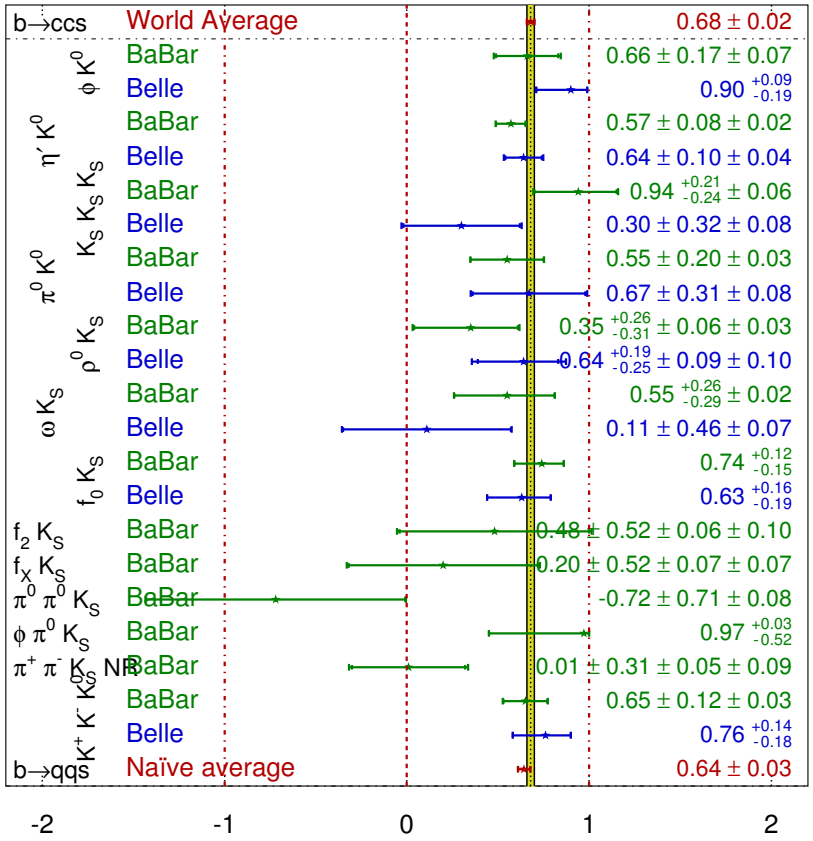
$b \to s\bar{u}u$, $b \to s\bar{d}d$, $b \to s\bar{s}s$ transitions:

- sensitive to New Physics
- same weak phase as $b \to c\bar{c}s$
- SM predictions:

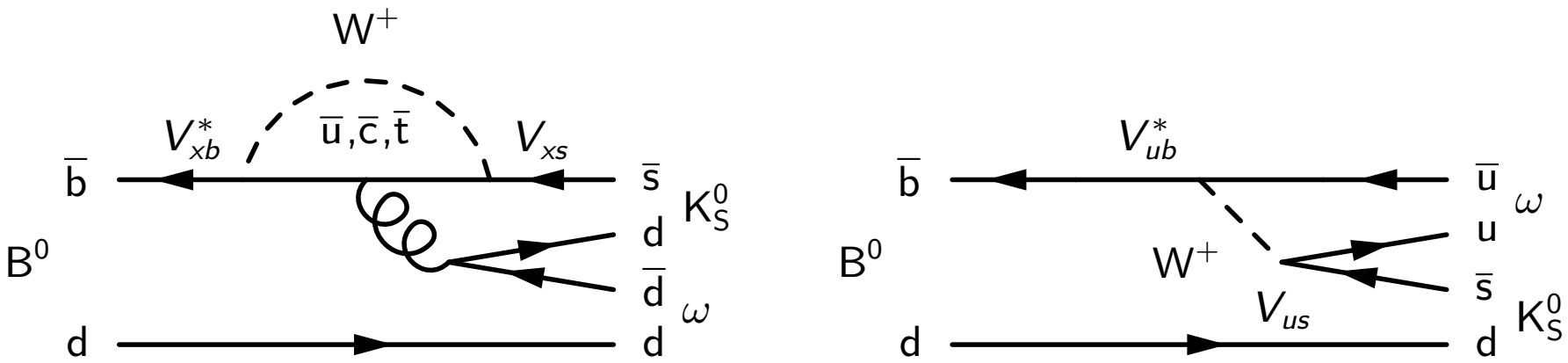
$$\mathcal{A}_{CP} \simeq 0 \qquad \mathcal{S}_{CP} \equiv \sin(2\phi_1^{eff})$$

$$\sin(2\phi_1) \sim \sin(2\phi_1^{eff})$$

$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$ HFAG Moriond 2012 PRELIMINARY



$B^0 \to \omega K^0_S$



- $B^0 \to \omega K^0_S$ penguin dominated
- previous Belle result [Phys.Rev.D 76, 091103(R) (2009)]

$$\mathcal{S}_{CP}(B^0 \to \omega K^0_S) = 0.11 \pm 0.46(\text{stat}) \pm 0.07(\text{syst})$$

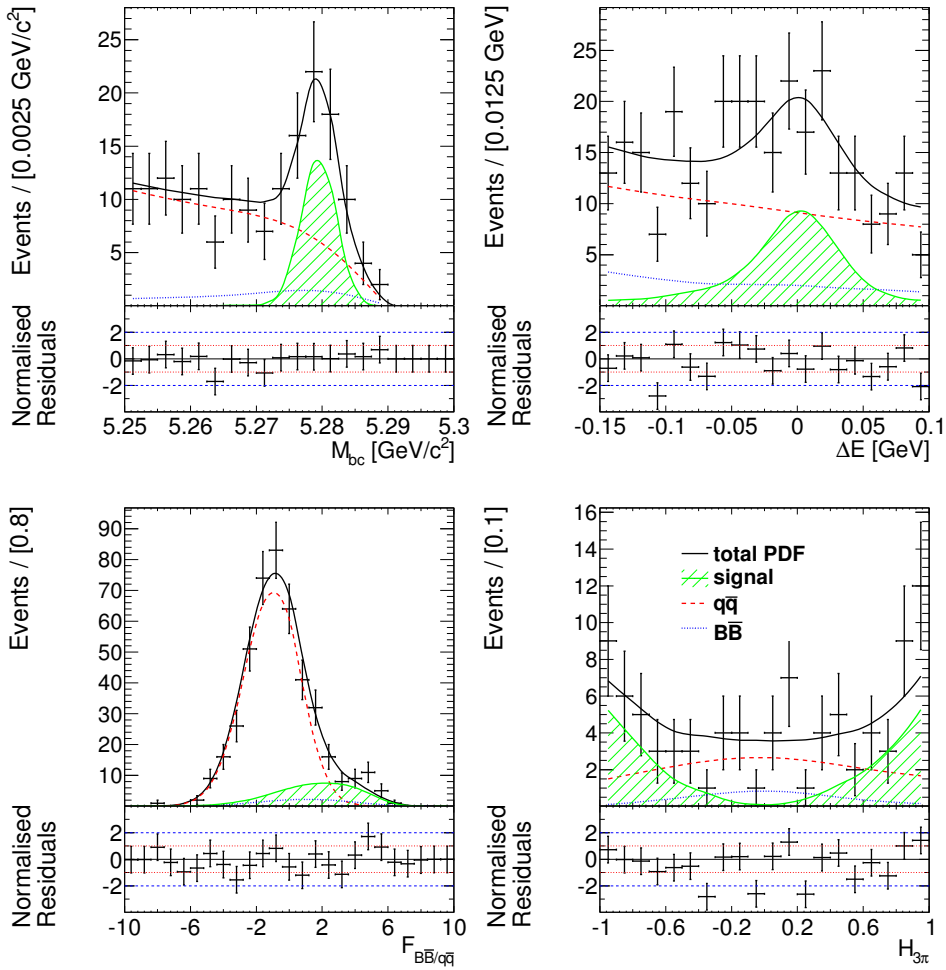
- BaBar result [Phys.Rev.D 79, 052003 (2009)]

$$\mathcal{S}_{CP}(B^0 \to \omega K^0_S) = 0.55^{+0.26}_{-0.29}(\text{stat}) \pm 0.02(\text{syst})$$

- updated result with final data set

$B^0 \to \omega K^0_S$ Analysis

- $B^0 \to \omega K^0_S$ reconstructed from $\omega \to \pi^+\pi^-\pi^0$ and $K^0_S \to \pi^+\pi^-$
- suppress continuum using fisher discriminant
- simultaneous fit of $B^0 \to \omega K^0_S$ and $B^\pm \to \omega K^\pm$ to reduce systematic errors (MC $\leftrightarrow$ data)
- 7D unbinned extended ML fit to M_{BC}, ΔE, $\mathcal{F}_{B\bar{B}/qq}$, $m_{3\pi}$, $\cos\theta^{Hel}_{3\pi}$, Δt, q



$B^0 \to \omega K^0_S$ Results, Preliminary

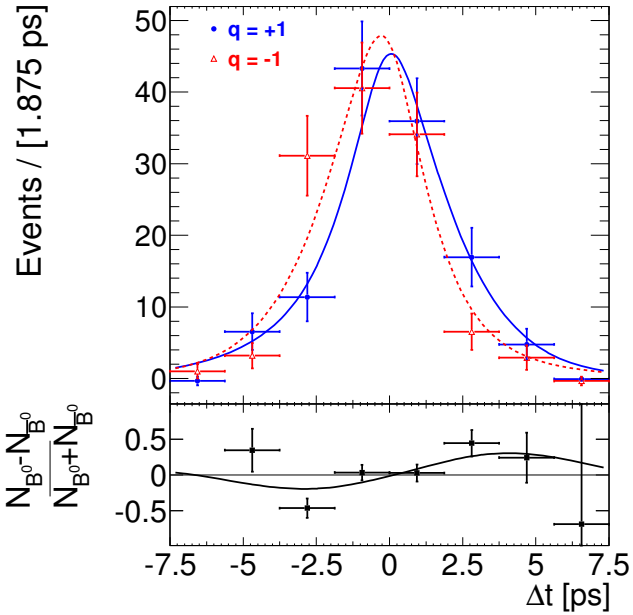
Branching fraction:

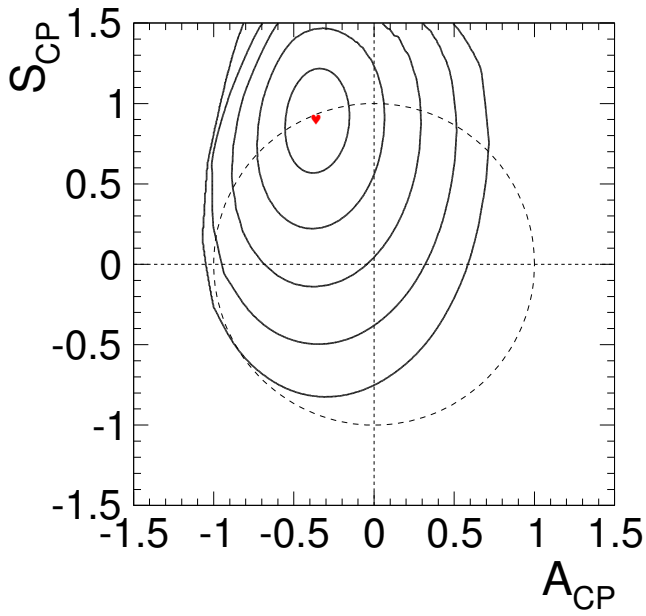
$$\mathcal{B}(B^0 \to \omega K^0_S) = [4.5 \pm 0.4(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-6}$$
$$\mathcal{B}(B^\pm \to \omega K^\pm) = [6.8 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-6}$$

CP Violation:

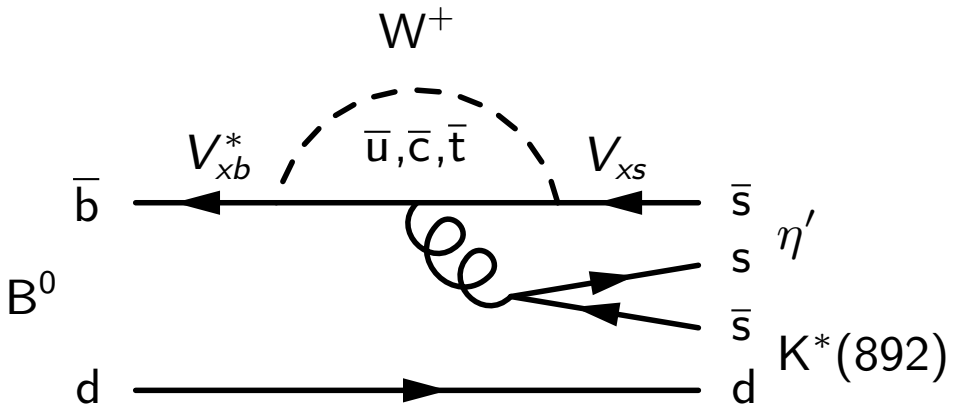
$$\mathcal{A}_{CP}(B^0 \to \omega K^0_S) = -0.36 \pm 0.19(\text{stat}) \pm 0.05(\text{syst})$$
$$\mathcal{S}_{CP}(B^0 \to \omega K^0_S) = +0.91 \pm 0.32(\text{stat}) \pm 0.05(\text{syst})$$
$$\mathcal{A}_{CP}(B^\pm \to \omega K^\pm) = -0.03 \pm 0.04(\text{stat}) \pm 0.01(\text{syst})$$

- first evidence (3.1σ) for CP Violation in $B^0 \to \omega K^0_S$
- no sign of New Physics





$B^0 \to \eta' K^*(892)$



- $B^0 \to \eta' K^*(892)$ is a penguin dominated b $\to$ s transition
- high potential for NP contributions.

- previous Belle analysis with significance of 1.9σ, upper limit with 90 % CL [Phys.Rev.D 75, 092002]

$$\mathcal{B}(B^0 \to \eta' K^*(892)) < 2.6 \times 10^{-6}$$

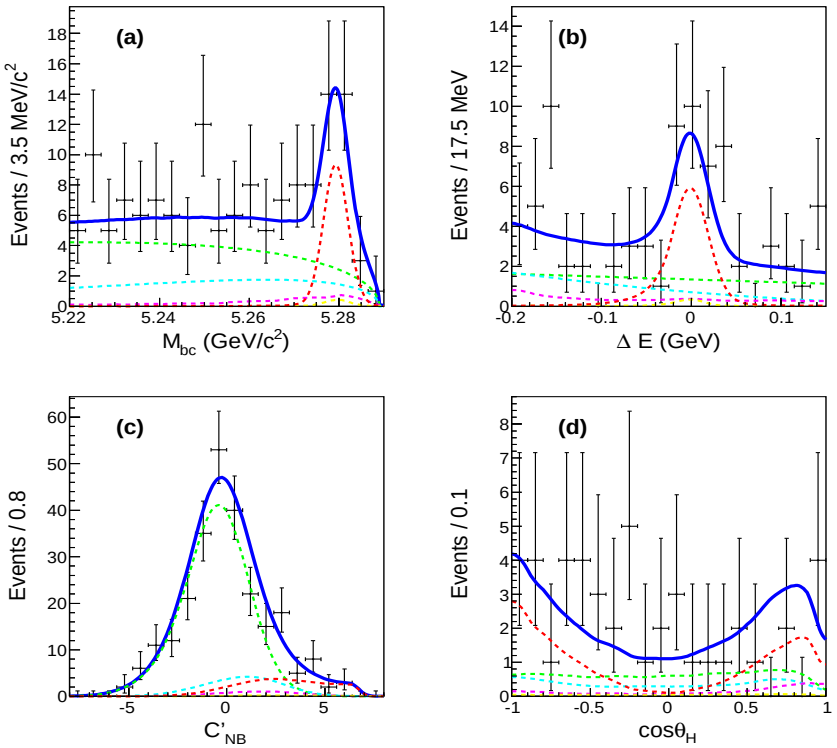
- BaBar found evidence for $B^0 \to \eta' K^*(892)$ with 4σ significance [Phys.Rev.D 82, 011502(R)]

$$\mathcal{B}(B^0 \to \eta' K^*(892)) = [3.1^{+0.9}_{-0.8}(\text{stat}) \pm 0.30(\text{syst})] \times 10^{-6}$$

- pQCD predicts $\mathcal{B} = 3.4 \pm 0.3 \times 10^{-6}$ [Phys.Rev.D 75, 054003]

$B^0 \to \eta' K^*(892)$ Analysis

- $B^0 \to \eta' K^*(892)$ candidates reconstructed from $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$ and $K^*(892) \to K^+\pi^-$
- continuum suppression using Neural Network
- events with good candidates for $B^+ \to \eta' K^+$ and $B^0 \to \eta' K^0$ rejected.



- 4D extended maximum likelihood fit to extract signal yield from M_{BC}, ΔE, $NN' = \ln \frac{NN - NN_{min}}{NN_{max} - NN}$ and the helicity angle $\cos\theta_{\mathcal{H}}$

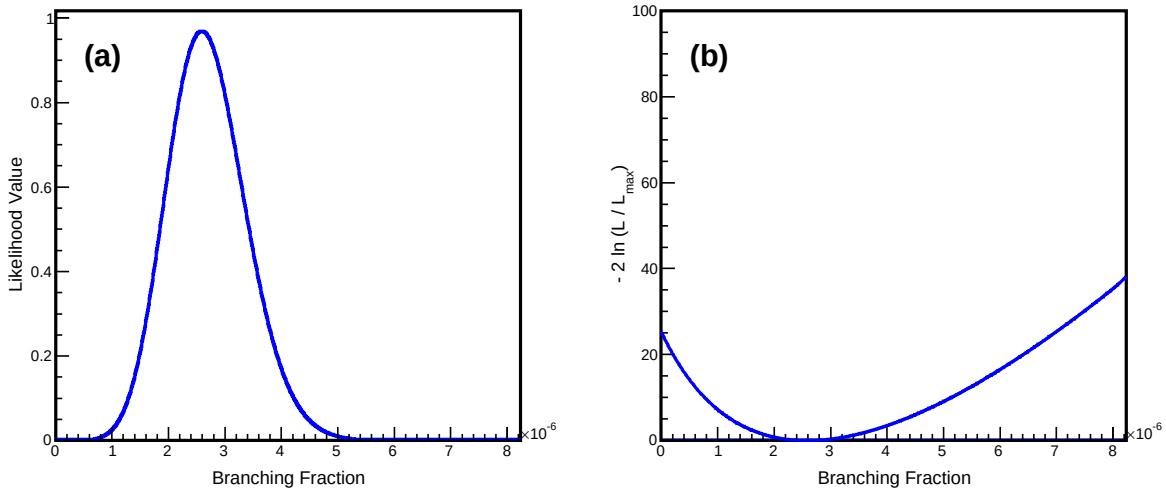
$$\mathcal{B}(B^0 \to \eta' K^*(892)) = \frac{Y_{sig}}{N_{B\overline{B}} \times \epsilon_{rec} \times \epsilon_{PID} \times \epsilon_{Rq\overline{q}}}$$

$B^0 \to \eta' K^*(892)$ Results, Preliminary

Branching fraction:

$$\mathcal{B}(B^0 \to \eta' K^*(892)) = [2.6^{+0.7}_{-0.6}(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-6}$$

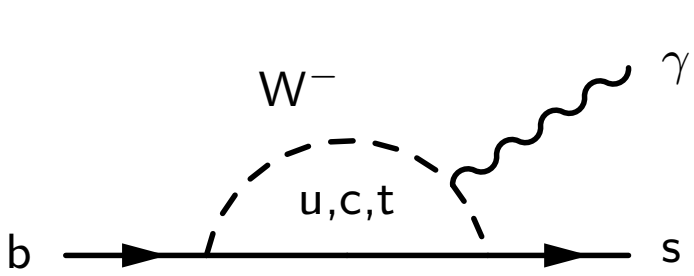
- scan of Likelihood including systematic effects: 5σ significance

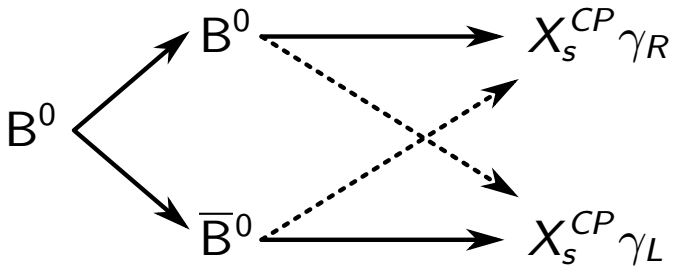


- $B^0 \to \eta' K^*(892)$ is self-tagging (flavour from $K^*(892) \to K^+\pi^-$)
- estimate overall CP asymmetry

$$A_{CP} = -0.22^{+0.18}_{-0.17}(\text{stat})^{+0.02}_{-0.03}(\text{syst})$$

$B^0 \to K^0_S \eta\gamma$





- right handed photon emission in $b \to s\gamma$ is strongly suppressed in SM
- several New Physics models allow right handed emission (LR symmetric, SUSY, 2HDM)
- interference of $B^0 \to X_s^{CP}\gamma_R$ and $\overline{B}^0 \to X_s^{CP}\gamma_L$ is strongly suppressed in SM

$$\mathcal{S}_{CP} = 2\frac{m_s}{m_b}\sin(2\phi_1)$$

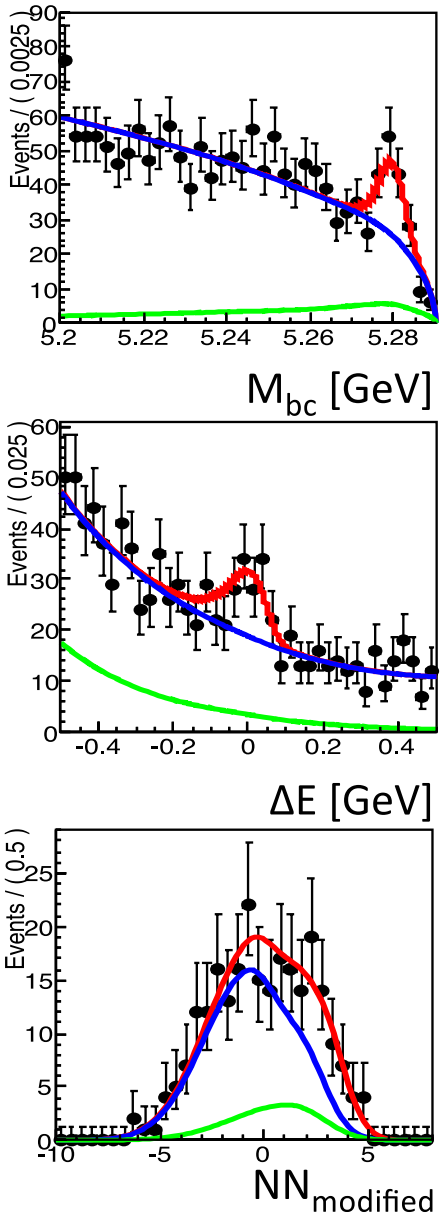
[arXiv:hep-ph/9704272 D.Atwood, M.Gronau, A.Soni]

- large indirect CP asymmetry would be strong evidence for New Physics

$B^0 \to K^0_S \eta\gamma$ Analysis

- $B^0 \to K^0_S \eta\gamma$ candidates reconstructed from $K^0_S \to \pi^+\pi^-$ and $\eta \to \pi^+\pi^-\pi^0$ or $\eta \to \gamma\gamma$
- rejection of continuum using a neural network
- reduce backgrounds by cuts on $m(\gamma K)$, $m(\gamma\eta)$ and $m(K\eta)$. (e.g. $B^0 \to J/\psi K^0_S$: reject $2.9\,\mathrm{GeV}/c^2 < m(\eta\gamma) < 3.2\,\mathrm{GeV}/c$)
- reject events with good $B \to K\pi^0\gamma$ candidate.
- determine event signal probability with 3D extended maximum likelihood fit to M_{BC}, ΔE and $NN' = \ln \frac{NN - NN_{min}}{NN_{max} - NN}$
- signal probability is then used in lifetime fit to Δt

red=signal, green=$B\overline{B}$ bg, blue=$q\overline{q}$ bg

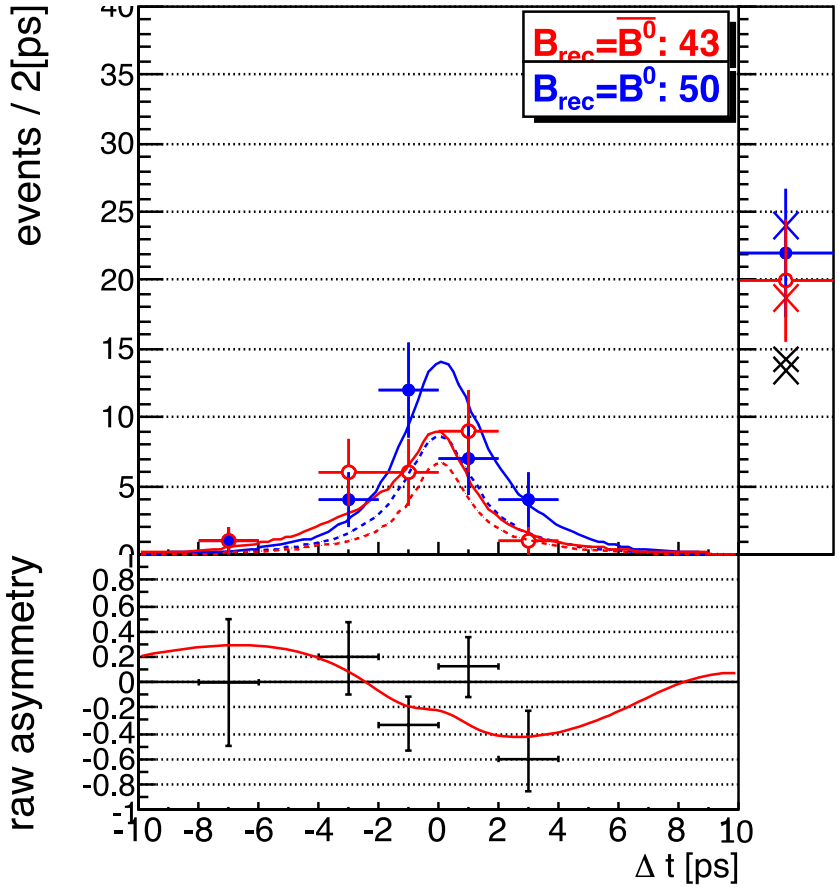


$B^0 \to K^0_S \eta\gamma$ Results, Preliminary

- $B\overline{B}$ background as exponential decay, lifetime determined from MC
- determine continuum shape from sideband

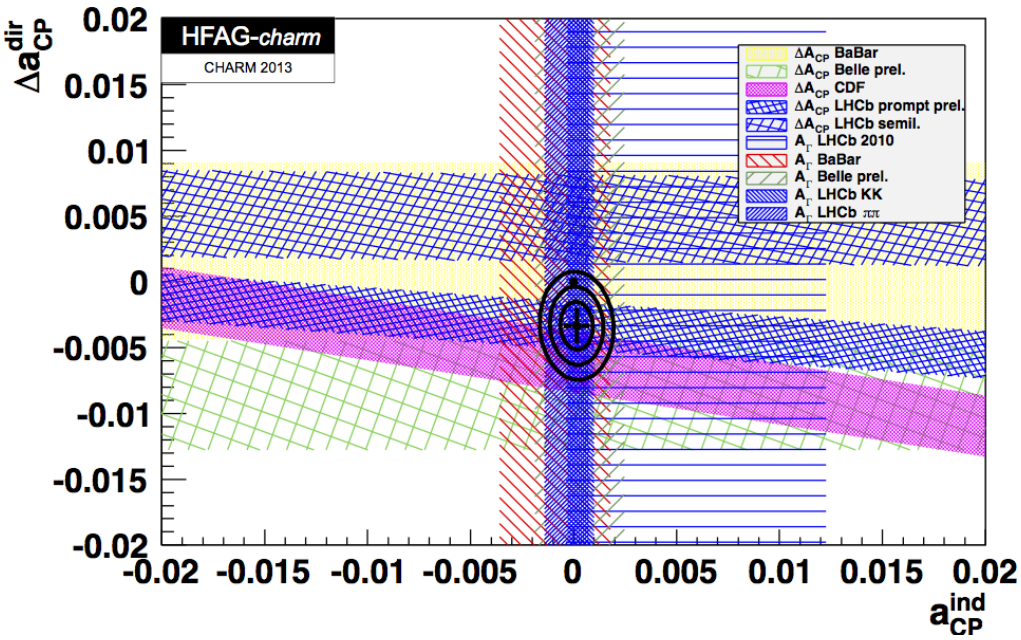
$$\mathcal{A}_{CP} = -0.48 \pm 0.41(\text{stat}) \pm 0.07(\text{syst})$$
$$\mathcal{S}_{CP} = -1.32 \pm 0.77(\text{stat}) \pm 0.36(\text{syst})$$

- No significant deviation from zero



$D^0 \to \pi^0\pi^0$

- Previous results by LHCb and CDF have indicated a possibly large CP asymmetry difference between $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$



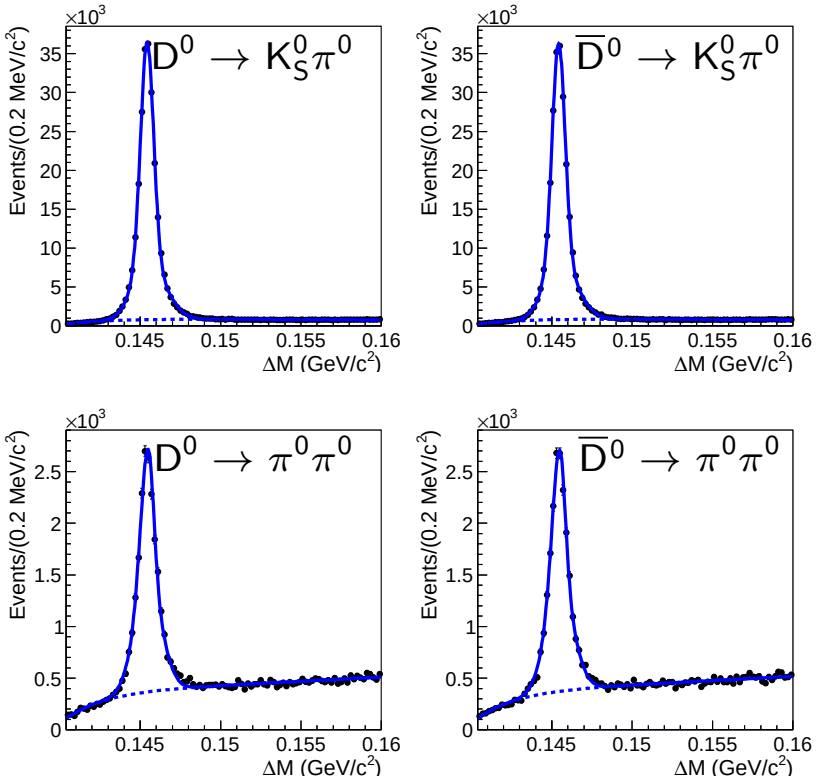
  - isospin considerations can provide constraints and NP predictions on the CP asymmetry for $D^0 \to \pi^0\pi^0$
    [arXiv:1201.2351 B.Bhattacharya, M.Gronau, J.L.Rosner] [arXiv:1206.4369 H.Y.Cheng]
  - so far only one published result $A_{CP}(D^0 \to \pi^0\pi^0) = (+0.1 \pm 4.8)\%$ by CLEO [Phys. Rev. D 63, 071101 (2001)]

$D^0 \to \pi^0\pi^0$ Analysis

- in the decay $D^{*+} \to D^0\pi^+_{slow}$, the charge of the low-momentum pion π^+_{slow} identifies the flavor of the neutral D meson
- Measure the asymmetry

$$A_{rec} = \frac{N_{rec}^{D^{*+}\to D^0\pi^+_{slow}} - N_{rec}^{D^{*-}\to \overline{D}0\pi^-_{slow}}}{N_{rec}^{D^{*+}\to D^0\pi^+_{slow}} + N_{rec}^{D^{*-}\to \overline{D}0\pi^-_{slow}}}$$

for $D^0 \to \pi^0\pi^0$ and $D^0 \to K^0_S\pi^0$ using 966 fb^{-1} of data

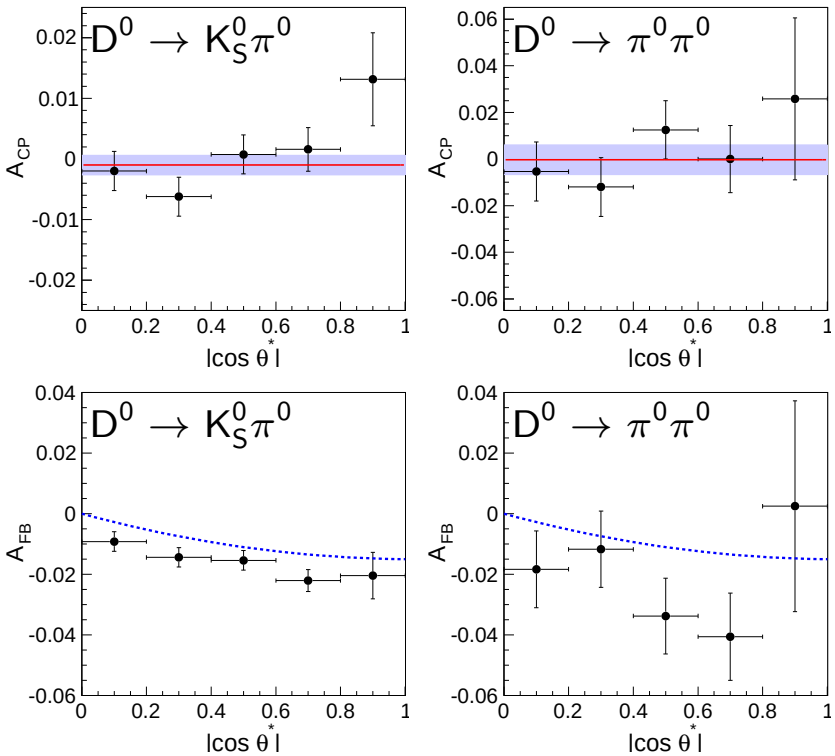


- D mesons from B decays are rejected by requiring $p(D^{*\pm}) > 2.5\,\text{GeV}/c\,(3.1\,\text{GeV}/c)$ for events near the $\Upsilon(4S)$ ($\Upsilon(5S)$) resonance.
- A_{rec} includes A_{CP}, the forward-backward asymmetry A_{FB} and the detection asymmetry $A_e^{\pi_{slow}}$
- $A_e^{\pi_{slow}}$ is determined by subtracting the asymmetries in $D^0 \to K^-\pi^+$ and $D^{*+} \to D^0\pi^+_{slow} \to K^-\pi^+\pi^+_{slow}$ [$\mathcal{O}(0.1\,\%)$]

$D^0 \to \pi^0\pi^0$ Results, Preliminary

- A_{CP} is independent of kinematic variables.
- A_{FB} is odd function of of $\cos\theta^*$, θ^* being the polar angle of the D^{*+} in the center mass system

$$A_{CP} = [A^{cor}_{rec}(\cos\theta^*) + A^{cor}_{rec}(-\cos\theta^*)]/2 \quad A_{FB} = [A^{cor}_{rec}(\cos\theta^*) - A^{cor}_{rec}(-\cos\theta^*)]/2$$



- dashed blue line leading order prediction for $A_{FB}(e^+e^- \to c\bar{c})$ [Z.Phys.C 30, 125 (1986)]

$$A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$$
$$A_{CP}(D^0 \to K^0_S\pi^0) = (-0.21 \pm 0.16 \pm 0.07)\%$$

- improves previous CLEO result by more than an order of magnitude

Conclusions

Branching ratio and CP Violation in $B^0 \to \omega K^0_S$

- first evidence (3.1σ) for CPV

Branching ratio and overall CP Asymmetry in $B^0 \to \eta' K^*(892)$

- first observation of $B^0 \to \eta' K^*(892)$ with 5σ significance

Time dependent CP Violation in $B^0 \to K^0_S \eta\gamma$

- lifetime fit to extract CPV parameters
- no significant CPV observed

Overall CP Asymmetry in $D^0 \to \pi^0\pi^0$

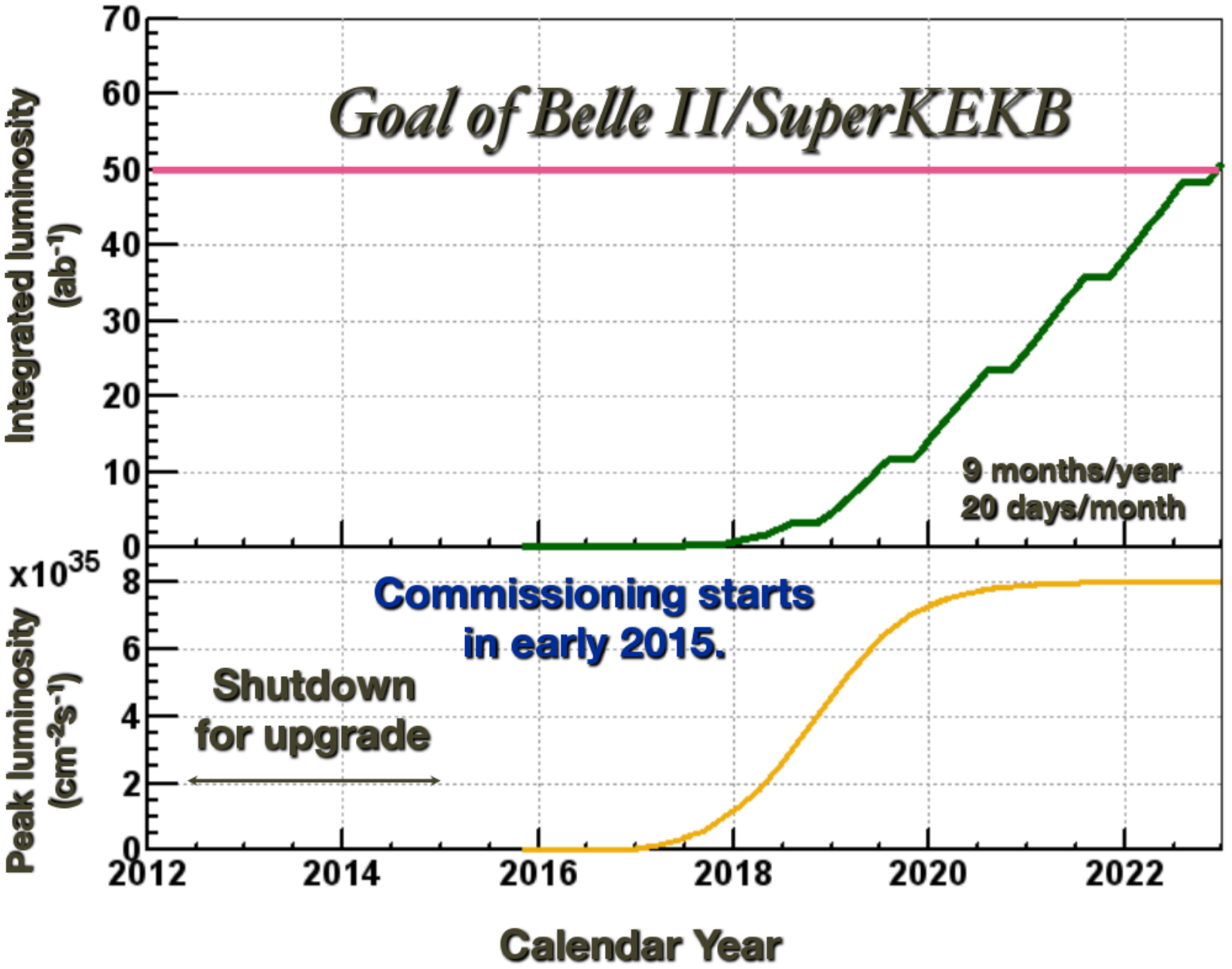
- improvement of precision by more than one order of magnitude
- no direct CP Violation observed

So far, everything is consistent with SM

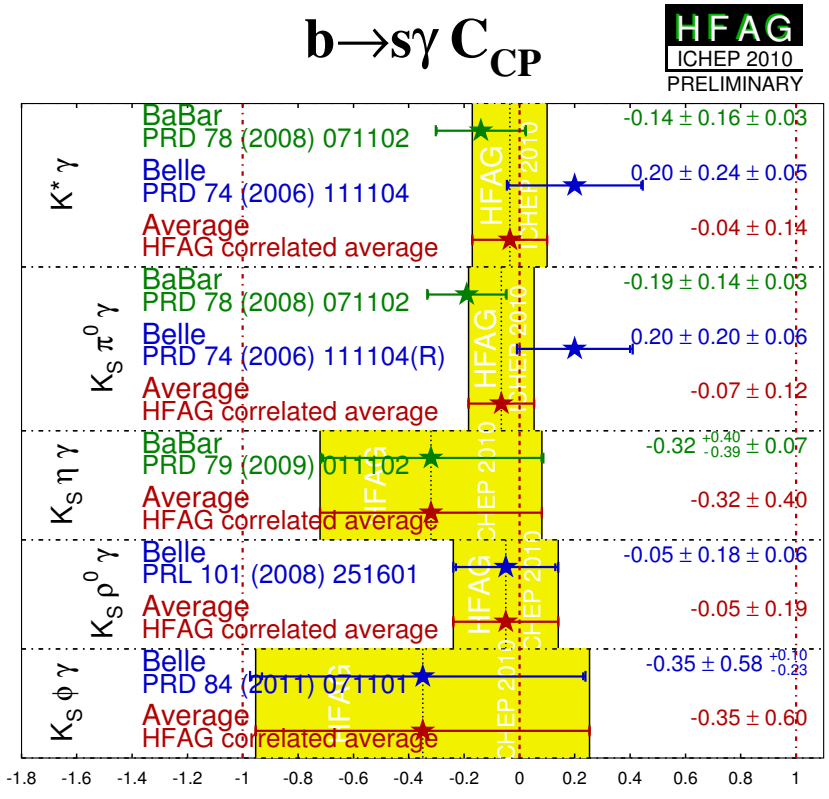
- most analyses are statistically limited

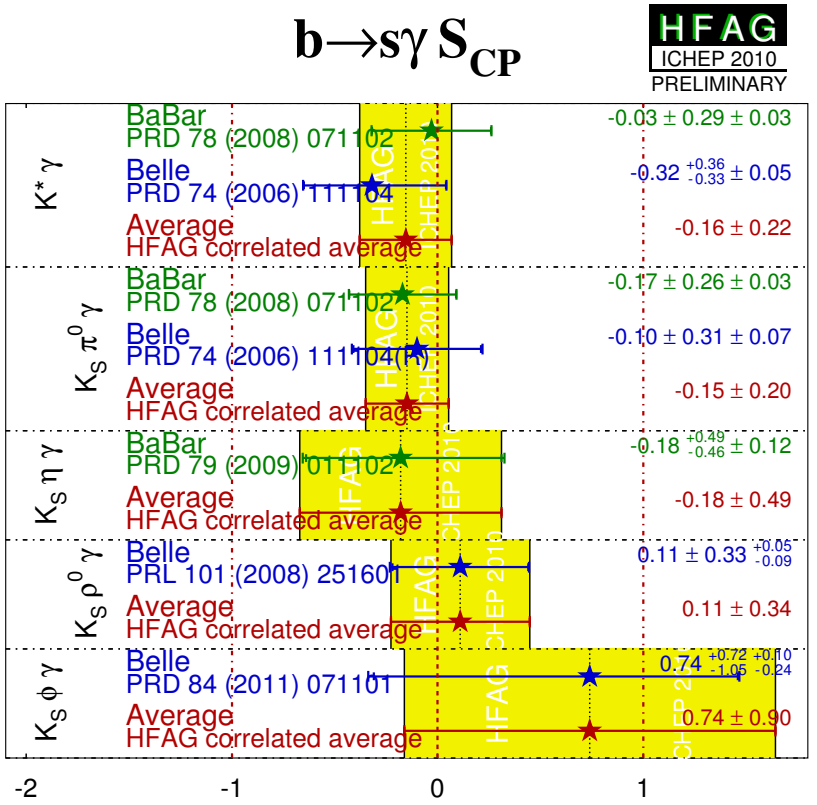
Thank you
for your attention

Belle II Luminosity



$b \to s\gamma$


b→sγ C_CP
HFAG
ICHEP 2010
PRELIMINARY
K* γ
BaBar PRD 78 (2008) 071102 -0.14 ± 0.16 ± 0.03
Belle PRD 74 (2006) 111104 0.20 ± 0.24 ± 0.05
Average -0.04 ± 0.14
HFAG correlated average
K_S π^0 γ
BaBar PRD 78 (2008) 071102 -0.19 ± 0.14 ± 0.03
Belle PRD 74 (2006) 111104(R) 0.20 ± 0.20 ± 0.06
Average -0.07 ± 0.12
HFAG correlated average
K_S η γ
BaBar PRD 79 (2009) 011102 -0.32 +0.40 -0.39 ± 0.07
Average -0.32 ± 0.40
HFAG correlated average
K_S ρ^0 γ
Belle PRL 101 (2008) 251601 -0.05 ± 0.18 ± 0.06
Average -0.05 ± 0.19
HFAG correlated average
K_S φ γ
Belle PRD 84 (2011) 071101 -0.35 ± 0.58 +0.10 -0.23
Average -0.35 ± 0.60
HFAG correlated average
-1.8 -1.6 -1.4 -1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1


b→sγ S_CP
HFAG
ICHEP 2010
PRELIMINARY
K* γ
BaBar PRD 78 (2008) 071102 -0.03 ± 0.29 ± 0.03
Belle PRD 74 (2006) 111104 -0.32 +0.36 -0.33 ± 0.05
Average -0.16 ± 0.22
HFAG correlated average
K_S π^0 γ
BaBar PRD 78 (2008) 071102 -0.17 ± 0.26 ± 0.03
Belle PRD 74 (2006) 111104(R) -0.10 ± 0.31 ± 0.07
Average -0.15 ± 0.20
HFAG correlated average
K_S η γ
BaBar PRD 79 (2009) 011102 -0.18 +0.49 -0.46 ± 0.12
Average -0.18 ± 0.49
HFAG correlated average
K_S ρ^0 γ
Belle PRL 101 (2008) 251601 0.11 ± 0.33 +0.05 -0.09
Average 0.11 ± 0.34
HFAG correlated average
K_S φ γ
Belle PRD 84 (2011) 071101 0.74 +0.72 -1.05 +0.10 -0.24
Average 0.74 ± 0.90
HFAG correlated average
-2 -1 0 1