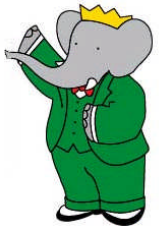
Recent results on CP violation and CKM UT angles from Belle and BABAR



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CP violation in the SM

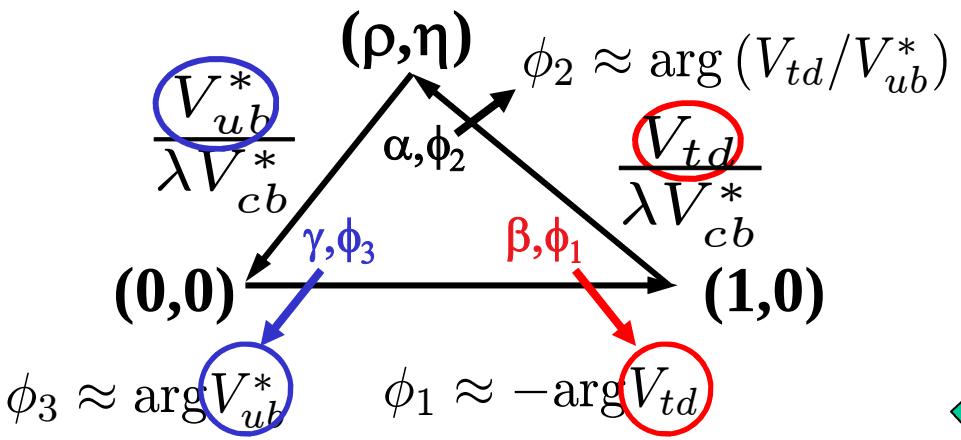
- Single phase in the CKM matrix (flavor → mass) is the key piece

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

Wolfenstein, PRL 51 (1983) 1945

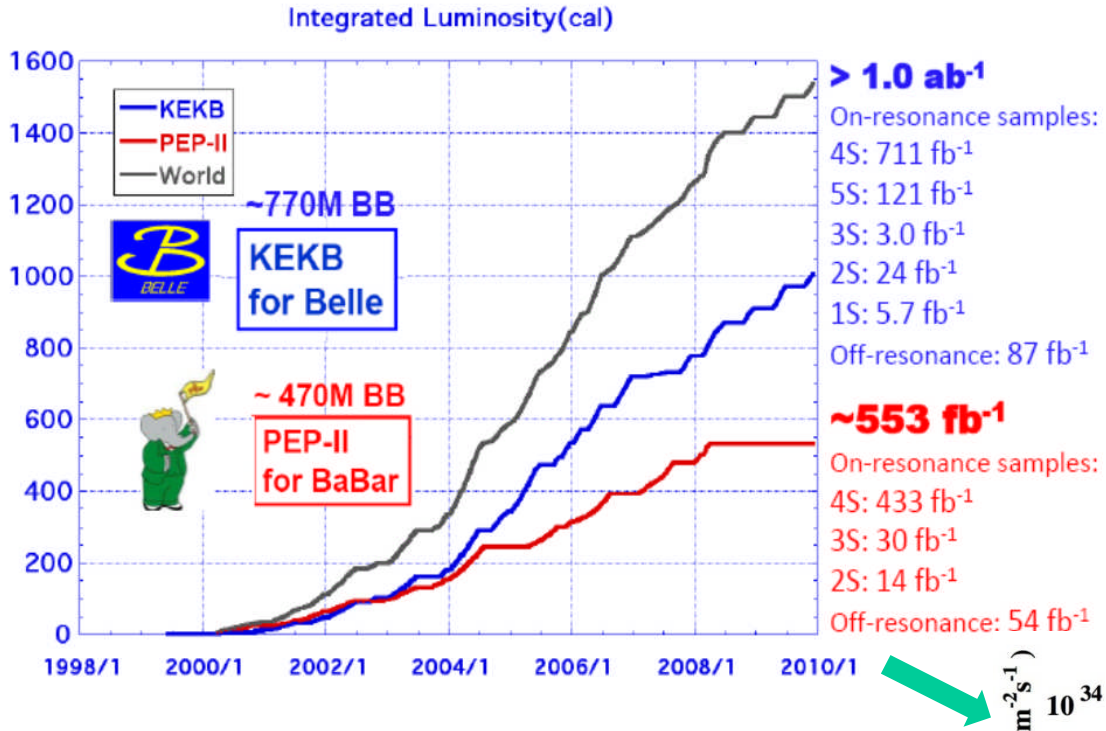
λ~0.22	A~0.80
ρ~0.16	η~0.34

Unitarity: 1st and 3rd columns



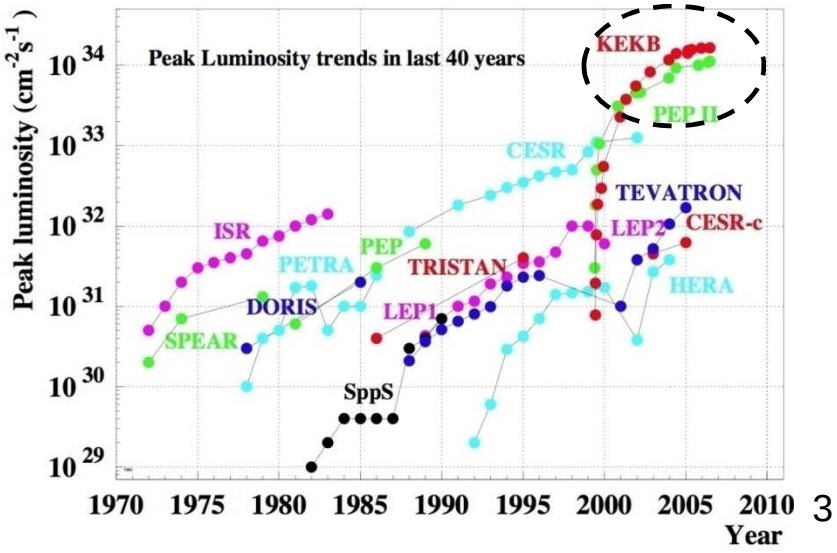
- Check consistency of the CKM framework:
  - measure three angles and two sides of the UT
  - search for potential new physics contributions

A tale of two experiments

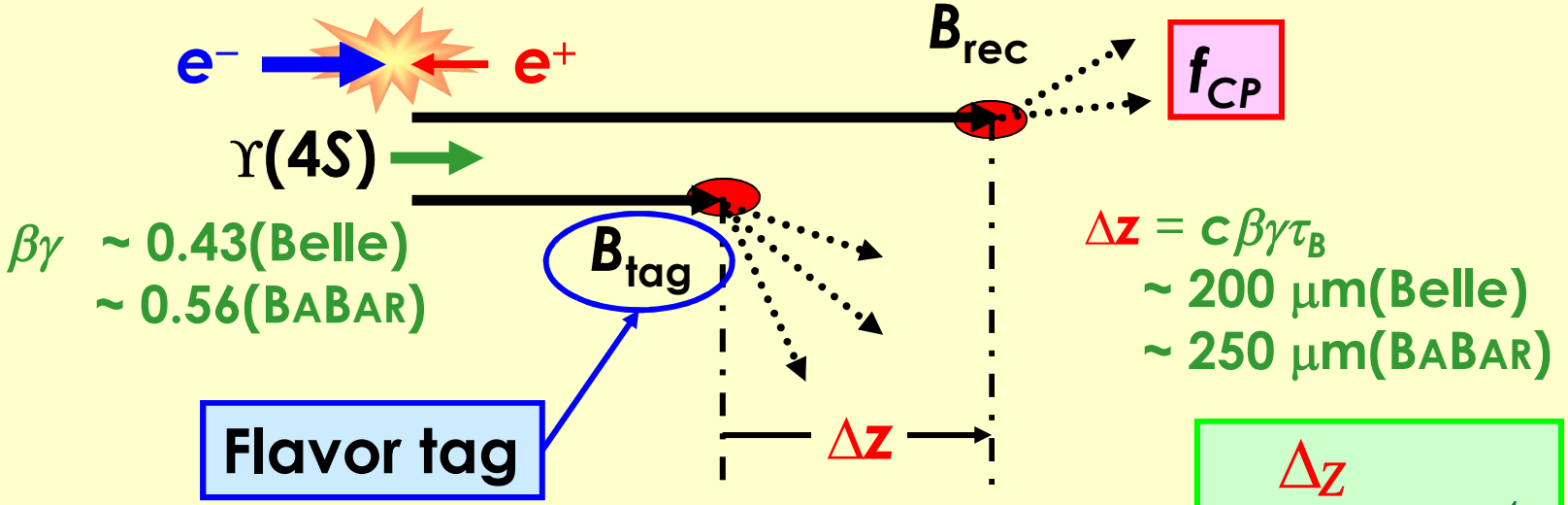


- Belle and BABAR have together collected over 10^9 $B\bar{B}$ pairs:
  - ✓ Test the SM mechanism for CP violation
  - ✓ Explore rare B decays; a window to new physics

- Right plot compares the peak luminosity performance of KEKB and PEP-II with rest



Principle of measurement

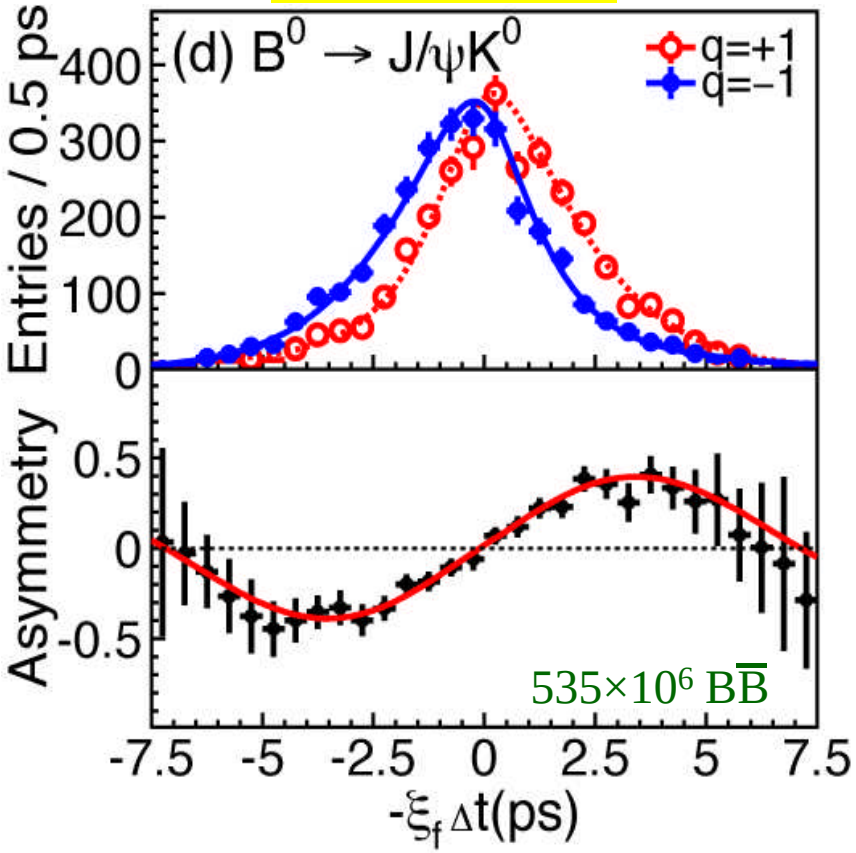


- Reconstruct the $B \rightarrow f_{CP}$ decay
- Measure proper time difference (t) and find the flavor of B_{tag}
- Evaluate $A_{CP}(t) = \frac{N[\overline{B}^0(t) \rightarrow f_{CP}] - N[B^0(t) \rightarrow f_{CP}]}{N[\overline{B}^0(t) \rightarrow f_{CP}] + N[B^0(t) \rightarrow f_{CP}]}$

$$S_f \sin(\Delta m t) + A_f \cos(\Delta m t)$$

sin2ϕ_1 with charmonium+K^0 modes

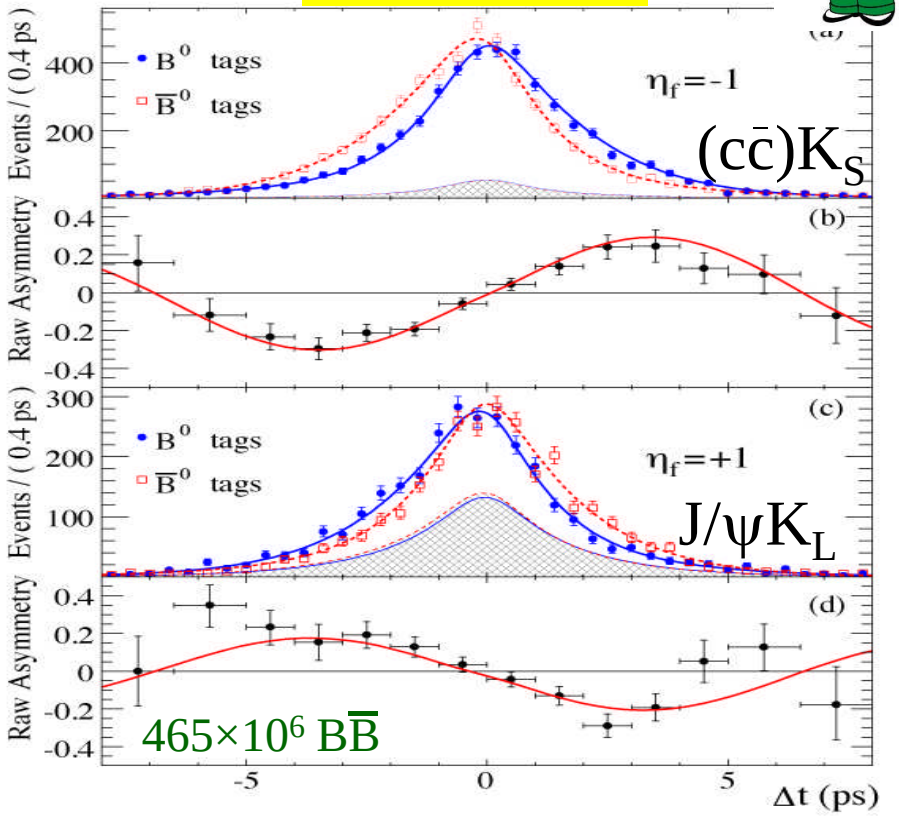
PRL 98 (2007) 031802



$S_f = \sin(2\phi_1) = 0.642 \pm 0.031 \pm 0.017$

$A_f = 0.018 \pm 0.021 \pm 0.014$

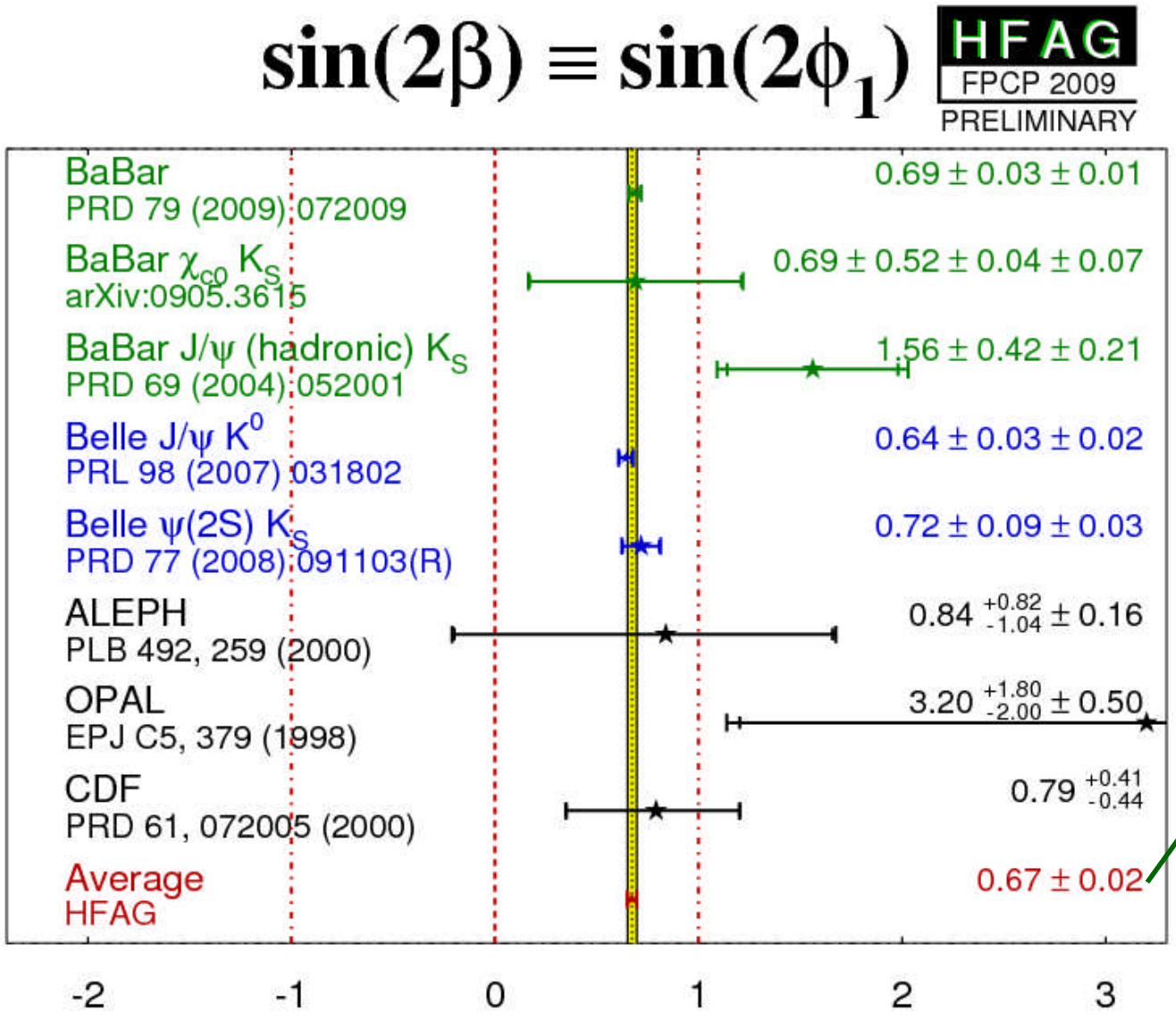
PRD 79 (2009) 072009



$\sin(2\phi_1) = 0.687 \pm 0.028 \pm 0.012$

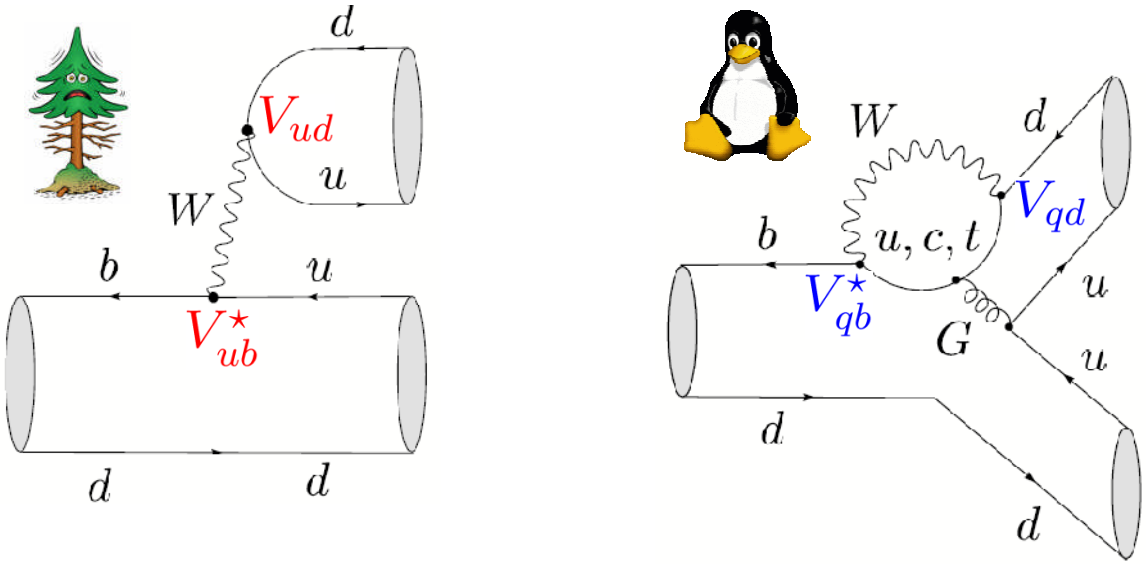
$A_f = -0.024 \pm 0.020 \pm 0.016$

Standard candle



- See the transition: LEP→Tevatron→ B factories
- Entered the precision phase: 3% uncertainty

The second UT angle: φ_2



- Tree-level $b \to u\bar{u}d$ transitions are sensitive to φ_2
  - $B^0 \to \pi^+\pi^-$, $(\rho\pi)^0$, $\rho^+\rho^-$ and so on..
- Possible penguin amplitudes also contribute, leading to

$$A_f \neq 0 \quad \text{and} \quad S_f = \sqrt{1 - A_f^2}\sin\left(2\phi_2^{\text{eff}}\right)$$

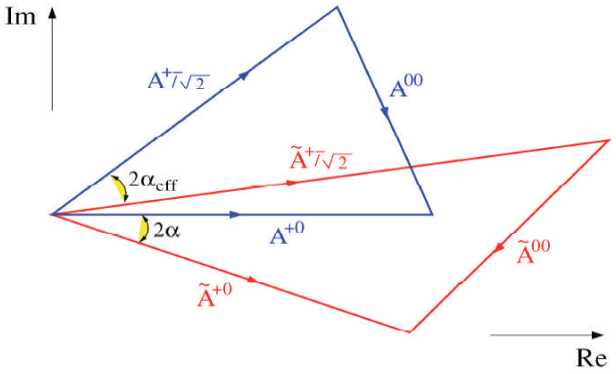
Error shrinks day-by-day

- Almost a precision measurement

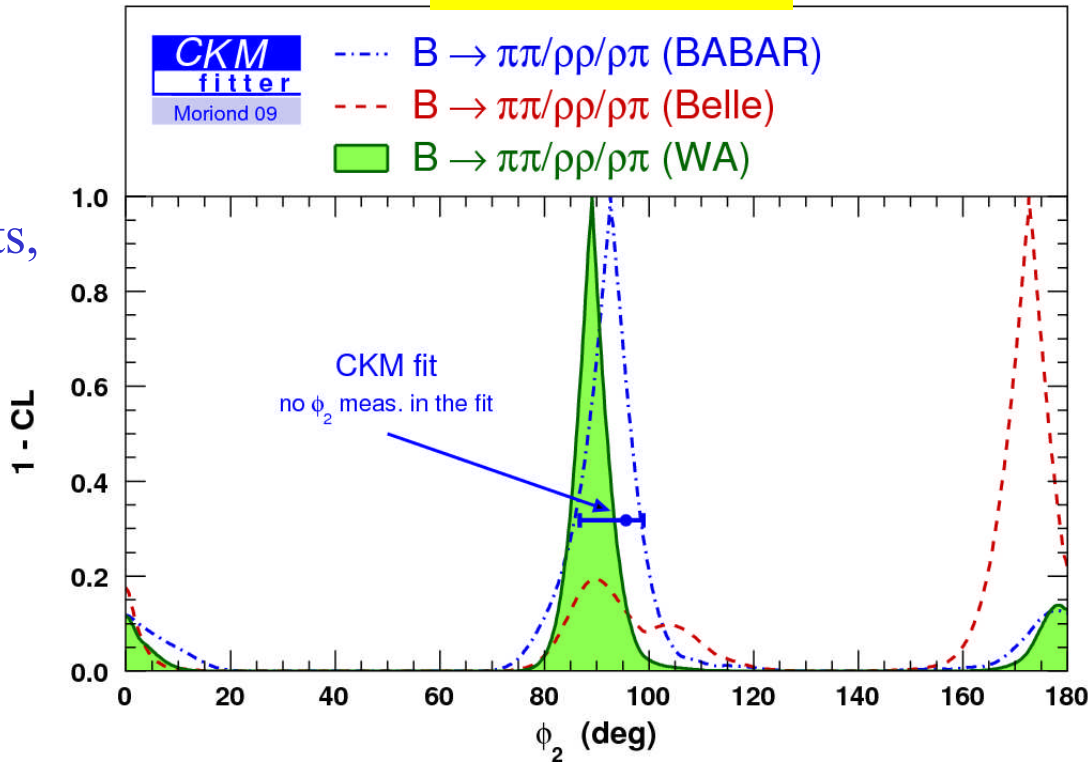
$$\phi_2 = \left(89.0^{+4.4}_{-4.2}\right)^\circ$$

- Dominated by the B→ρρ results, that rely on the isospin relation

Gronau & London, PRL 65 (1990) 3381



Current world-average



- New measured BF of $B^+ \to \rho^+\rho^0$ has stretched the base of the two isospin triangles, making them degenerate **PRL 102 (2009) 141802**

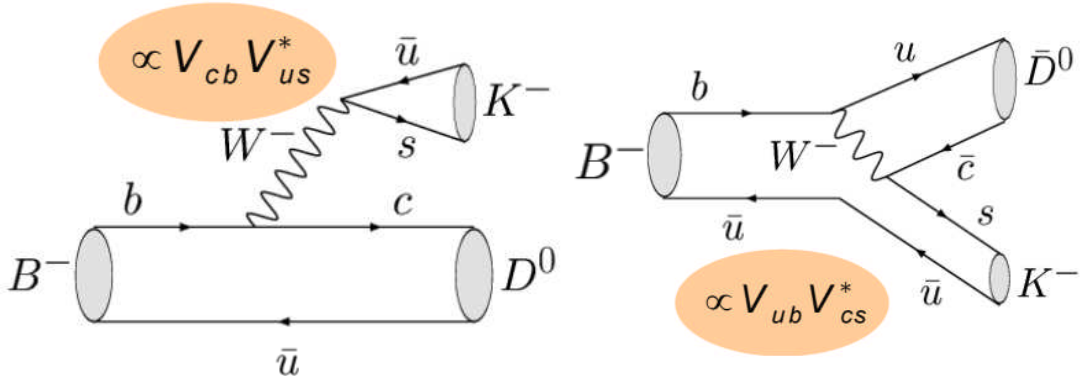
- ❖ Belle's final results on B→ρρ, especially $B^+ \to \rho^+\rho^0$, are eagerly awaited for

What about φ_3?

- Various methods proposed: **Gronau-London-Wyler** **PLB 253 (1991) 483** **PLB 265 (1991) 172**

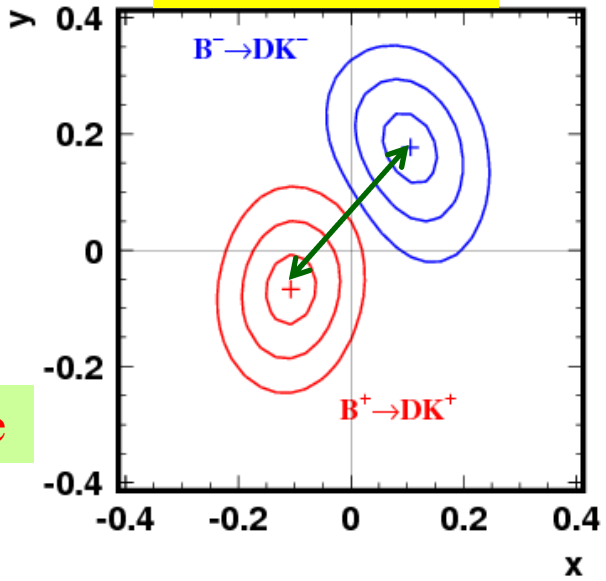
Atwood-Dunietz-Soni **PRL 78 (1997) 3257** **PRD 63 (2001) 036005** **Giri-Grossman-Soffer-Zupan** **PRD 68 (2003) 054018**

- Basic strategy is to exploit the interference between two contributing amplitudes



- Main bottle-neck: small signal
- Now, seems like beginning of an end?

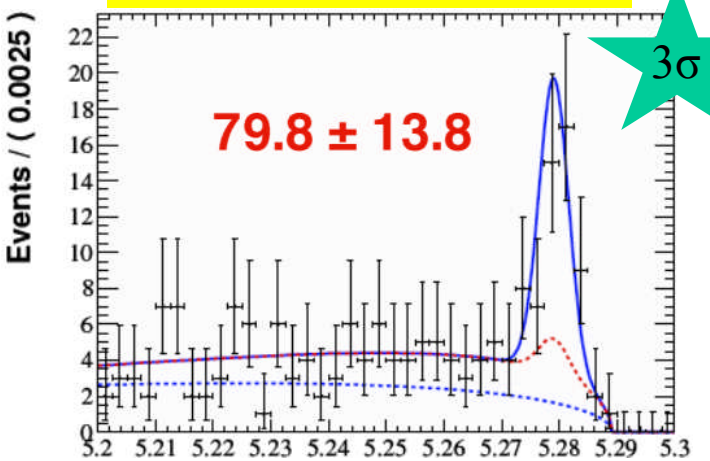
PRD 81 (2010) 112002



$x_\pm = r_\pm \cos(\pm\varphi_3 + \delta)$
$y_\pm = r_\pm \sin(\pm\varphi_3 + \delta)$,
r is the ratio of two amplitudes, δ is the strong phase diff. between them

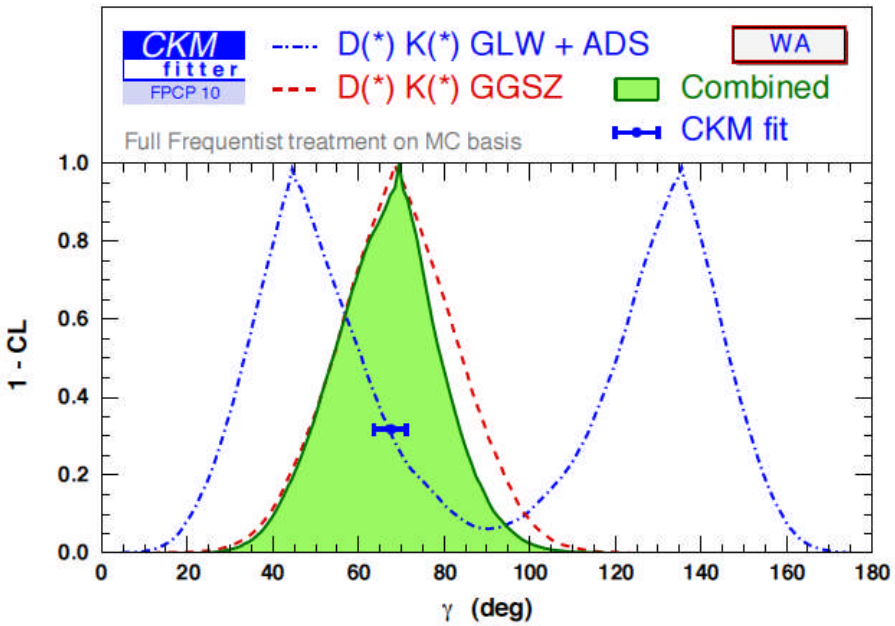
3.5σ evidence

BABAR ADS (D→Kπ) preliminary

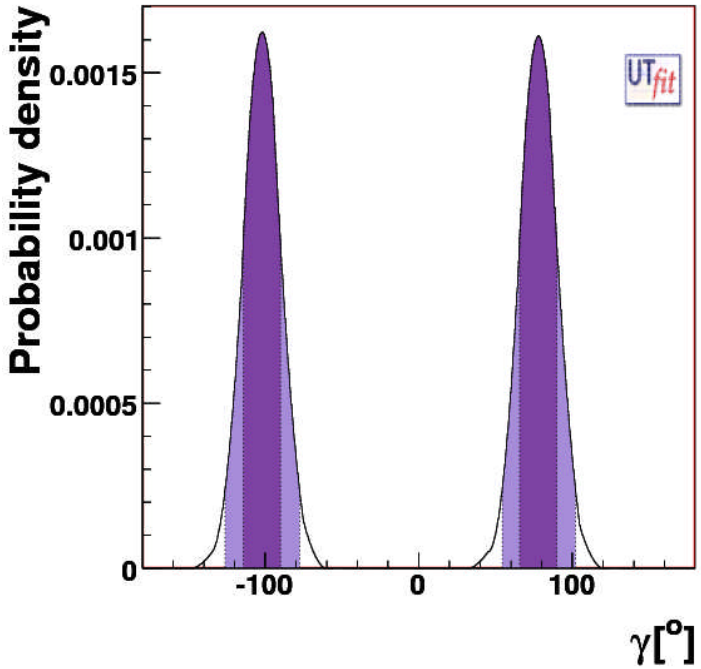


Putting everything together

Frequentist



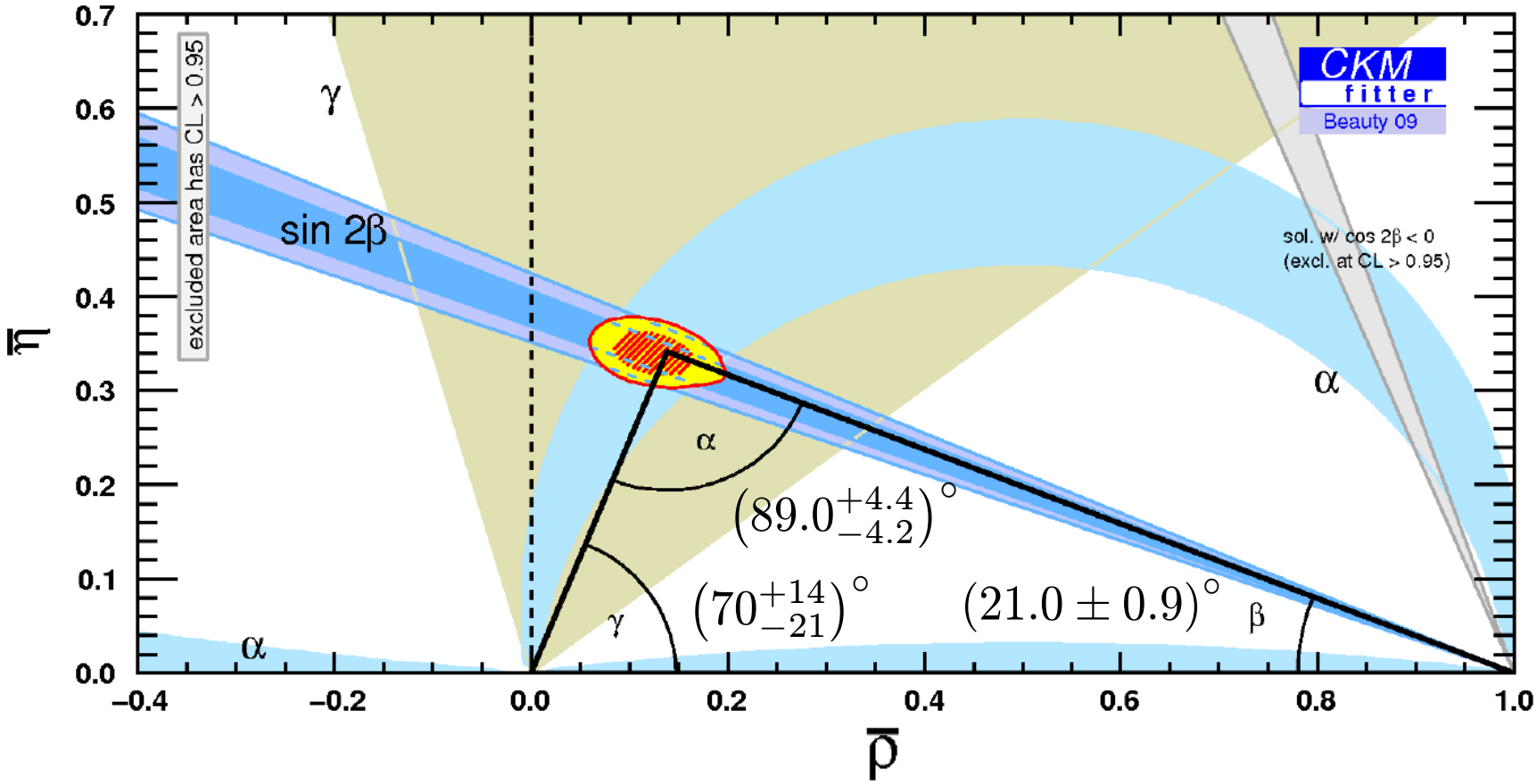
Bayesian



- Measurement: $\phi_3 = \left(70^{+14}_{-21}\right)^\circ$ frequentist vs. $\phi_3 = (74 \pm 11)^\circ$ Bayesian
- Fit prediction: $\phi_3 = \left(67.7^{+3.6}_{-4.1}\right)^\circ$ frequentist vs. $\phi_3 = (69.6 \pm 3.0)^\circ$ Bayesian

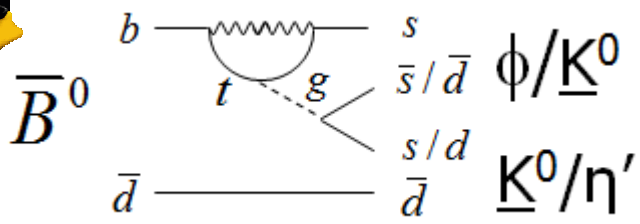
❖ Need a better precision of the measurement

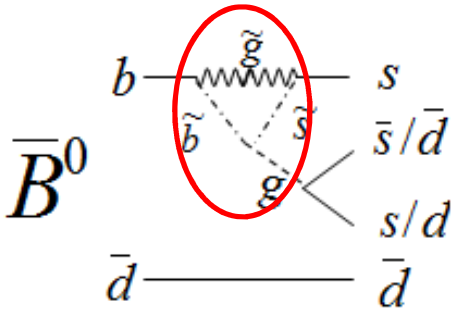
Current world average



- ➢ As far as φ_3 is concerned, it is fair to say that we have made a head-start
- ❑ Final word will come from LHCb and (future) super flavor factories
- ✓ The latter would further improve the measurements of φ_1 and φ_2 too

Probing new physics in CP violation

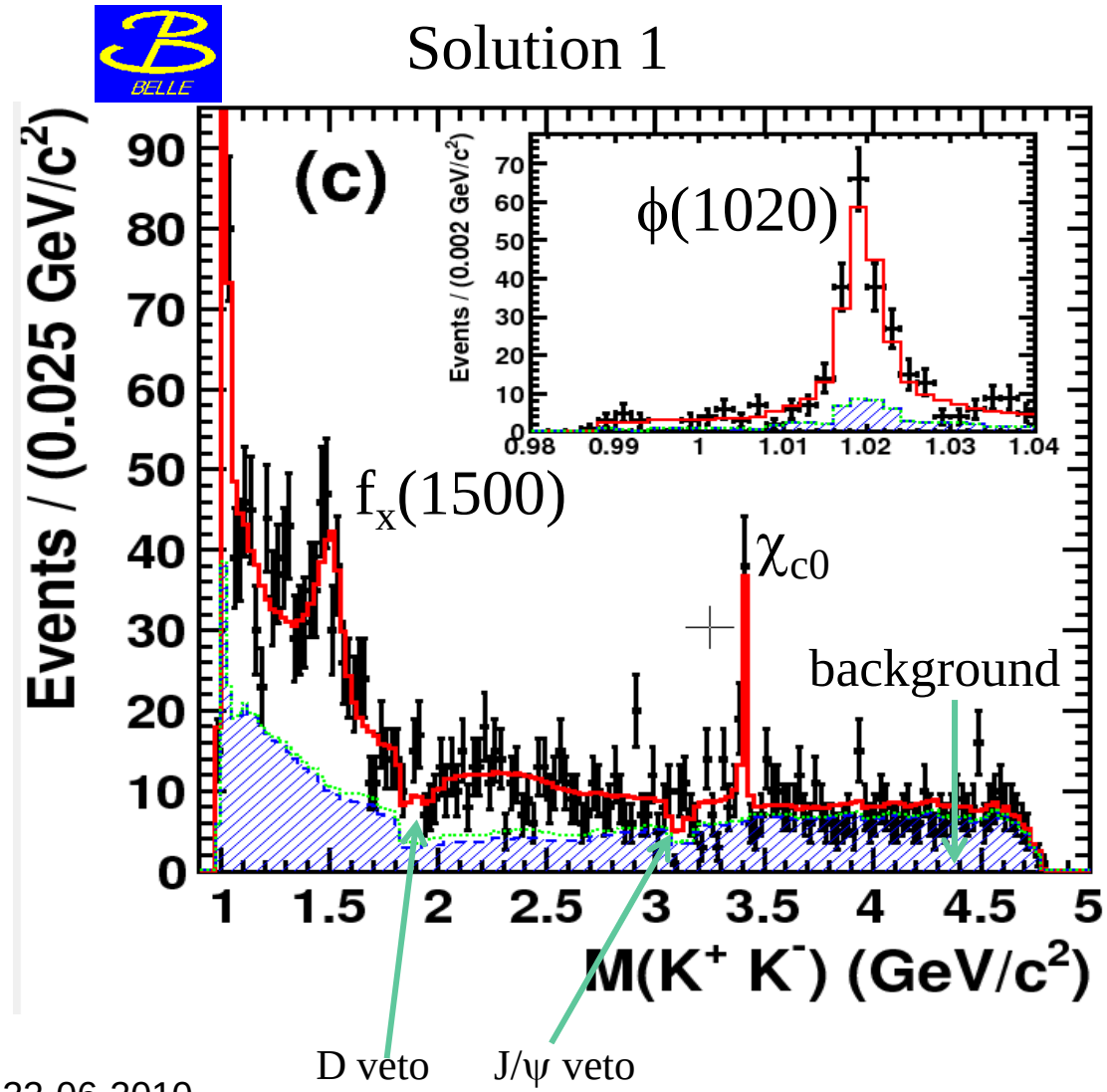




- Study of CP violation in decays dominated by the penguin diagram, e.g., $B^0 \rightarrow \varphi K_S$, constitutes an ideal probe
  - Potential new physics effects, such as SUSY (right plot)

- Compare the measured CP parameters S_f and A_f with that obtained from the charmonium+K^0 modes: standard candle

Dalitz-plot analysis of $B^0 \to K_S K^+ K^-$



- Perform time-dependent CP violation study of the $B^0 \to K_S K^+ K^-$ Dalitz plot
- Measure $(\varphi_1)^{eff}$ without trigonometric ambiguity
- Need to handle the issue of multiple solutions
- We have used results of the $B^+ \to K^+ K^- K^+$ Dalitz plot to determine the best solution

Combined results in $B \to \phi K_S$ and $f_0(980)K_S$

657×10^6 $B\bar{B}$

To be submitted to PRD

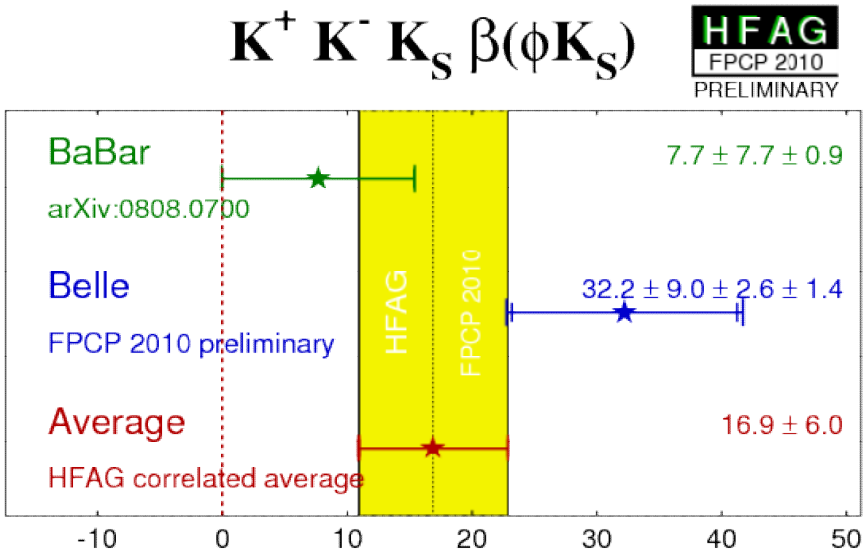
	Solution 1
$\mathcal{A}_{CP}(f_0K_S^0)$	$-0.30 \pm 0.29 \pm 0.11 \pm 0.09$
$\phi_1^{\rm eff}(f_0K_S^0)$	$(31.3 \pm 9.0 \pm 3.4 \pm 4.0)^\circ$
$\mathcal{A}_{CP}(\phi K_S^0)$	$+0.04 \pm 0.20 \pm 0.10 \pm 0.02$
$\phi_1^{\rm eff}(\phi K_S^0)$	$(32.2 \pm 9.0 \pm 2.6 \pm 1.4)^\circ$

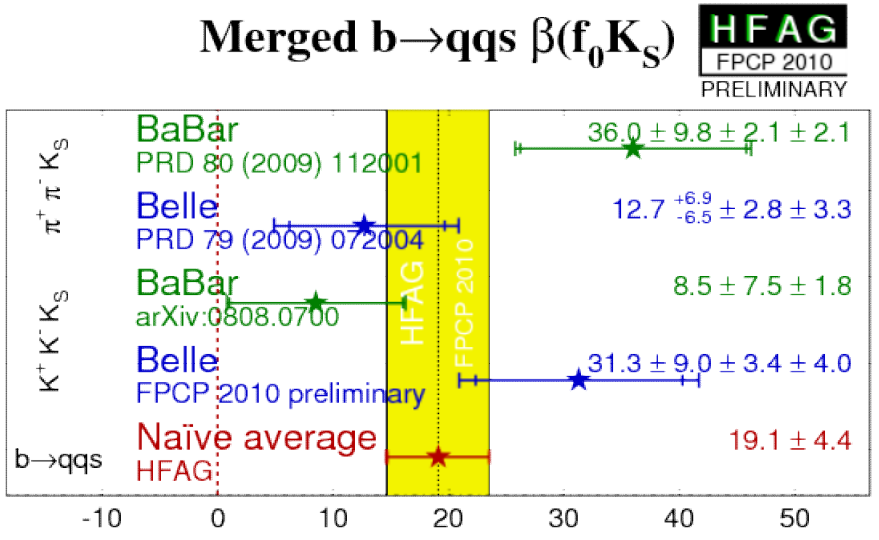
third error: Dalitz-plot model uncertainty

arXiv:0808.0700 [hep-ex]

Name	Solution (1)
1 $A_{CP}(\phi K_S^0)$	$0.14 \pm 0.19 \pm 0.02$
2 $\beta_{\rm eff}(\phi K_S^0)$	$(7.7 \pm 7.7 \pm 0.9)^\circ$
3 $A_{CP}(f_0K_S^0)$	$0.01 \pm 0.26 \pm 0.07$
4 $\beta_{\rm eff}(f_0K_S^0)$	$(8.5 \pm 7.5 \pm 1.8)^\circ$

465×10^6 $B\bar{B}$

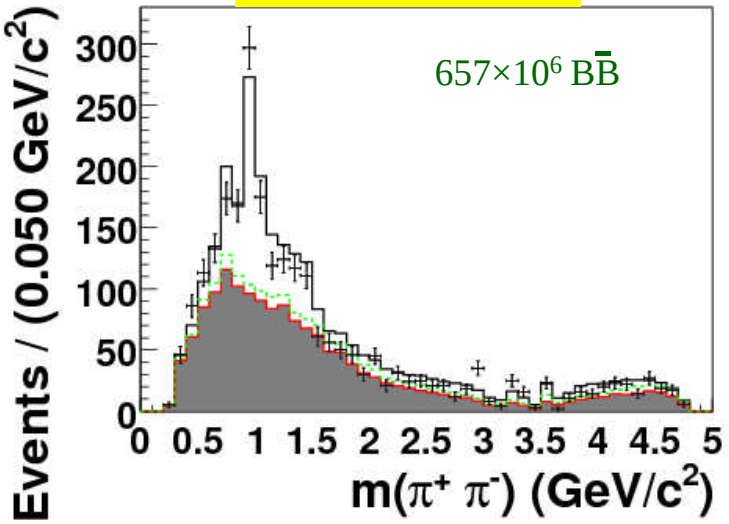




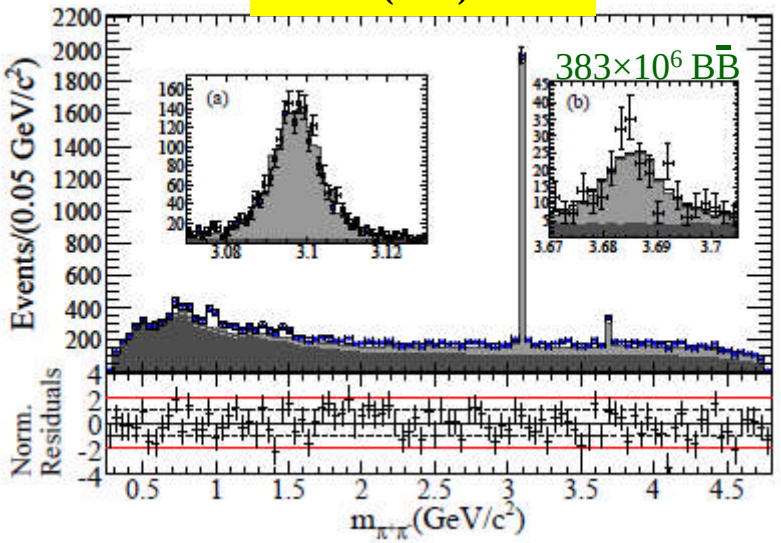
- Consistent with SM predictions at the current sensitivity

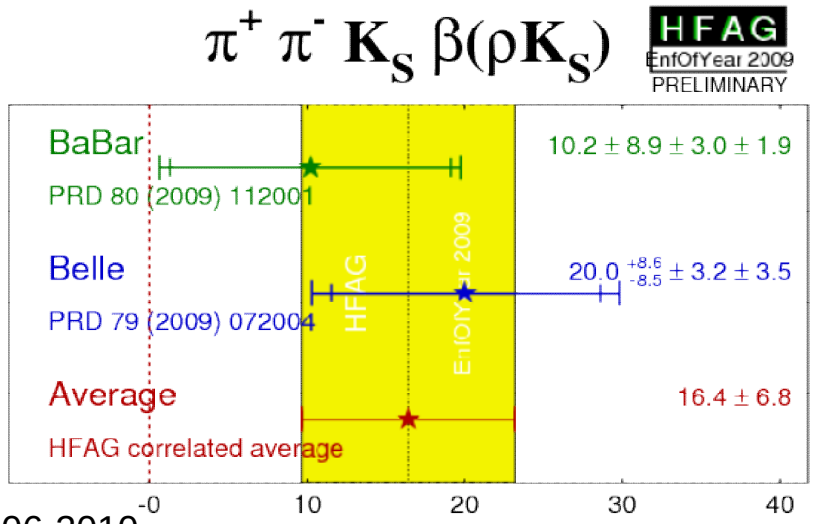
CPV results from $B^0 \to K_S\pi^+\pi^-$

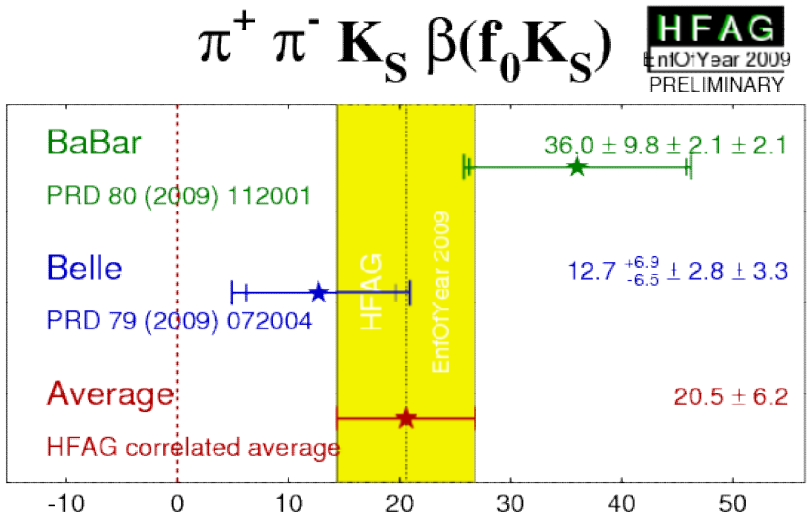
PRD 79 (2009) 072004



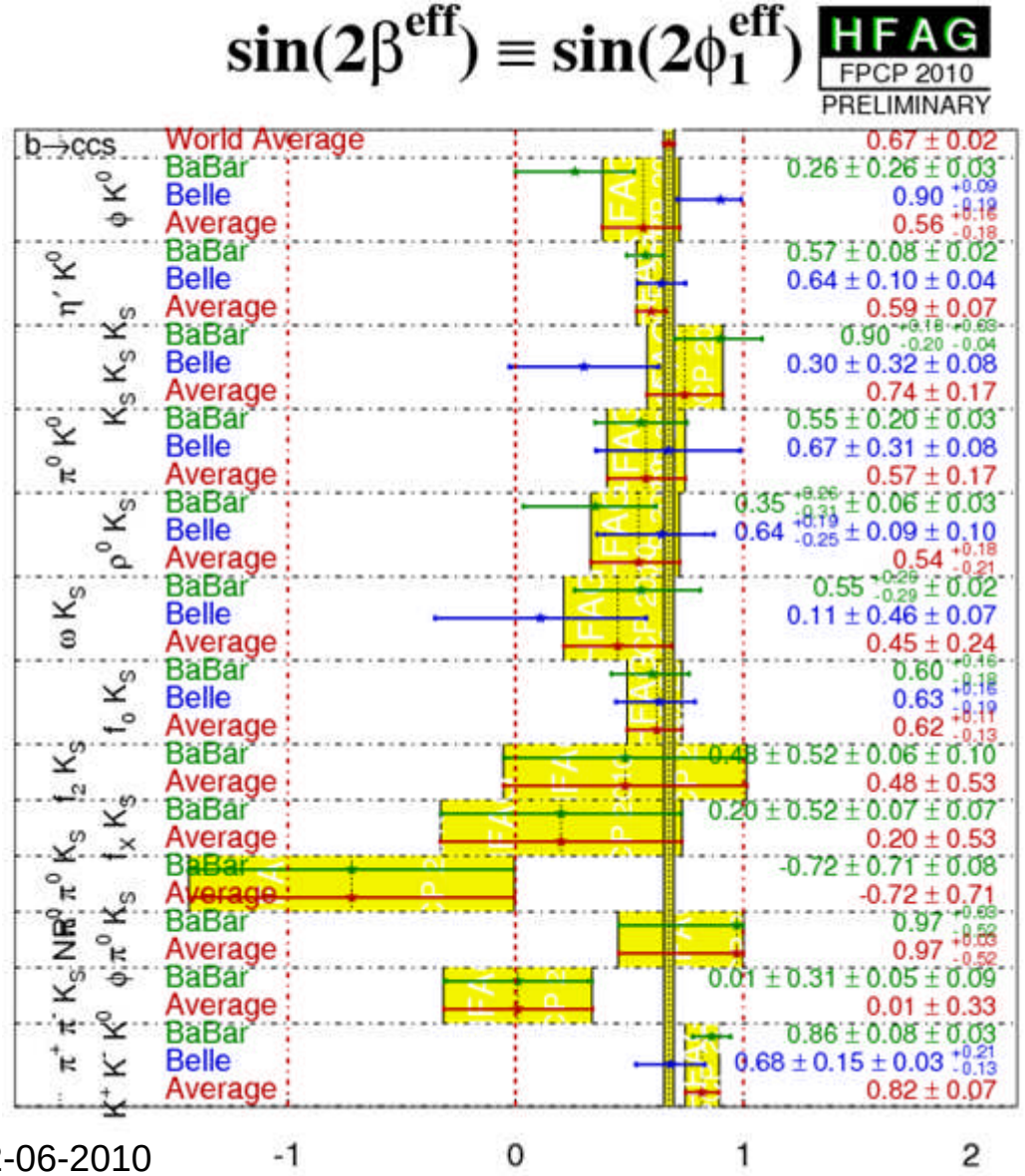
PRD 80 (2009) 112001



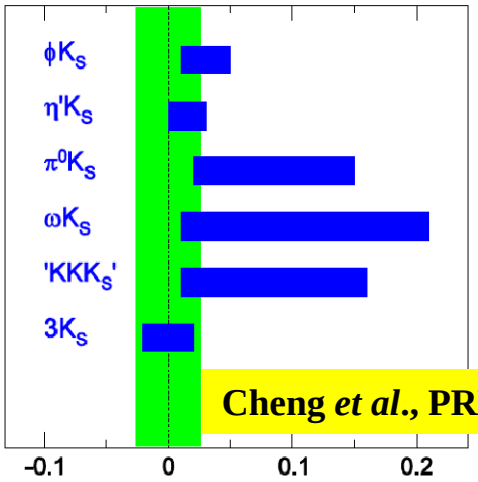




Compilation of effective sin2ϕ_1



- Precision is limited by the statistics
- To obtain sensitivities at 1% level, we need $O(50\ \text{ab}^{-1})$ of integrated luminosity
- One can then compare with **theory uncertainty**



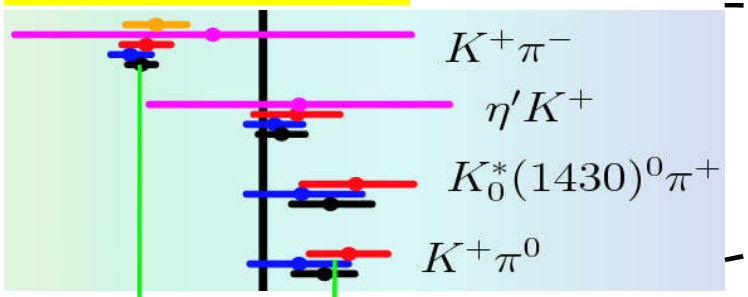
Cheng *et al.*, PRD72 (2005) 094003

Beneke, PLB 620 (2005) 143

Wiliamson & Zupan, PRD 74 (2006) 014003

Direct CP violation

Nature 452 (2008) 332

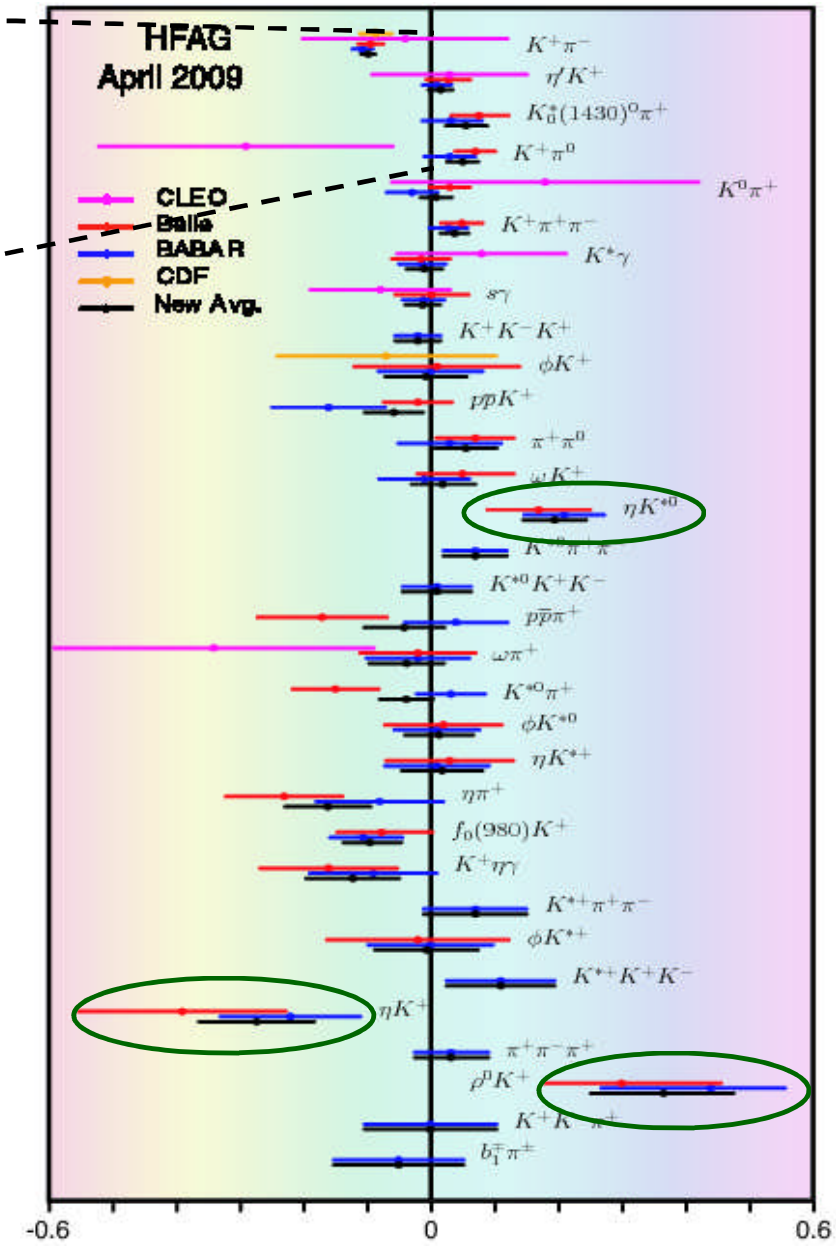


$\Delta A_{K\pi} = A_{CP}(K^+\pi^0) - A_{CP}(K^+\pi^-) = +0.144 \pm 0.029$

- Both decay channels occur via the same diagrams at tree level ➡ $\Delta A_{K\pi}$ should be zero
- ➢ Possible interpretation within the SM and with new physics
- ✓ Precise measurement of the $K^0\pi^0$ mode will be useful to check isospin relation

Gronau, PLB 627 (2005) 82

- Interesting ~3σ evidences found: $B^0 \to \eta K^{*0}$, $B^+ \to \eta K^+$ and $\rho^0 K^+$ (circled) $B^0 \to \rho^+\pi^-$ and $B^+ \to D^{(*)0}K^+$



Closing Remarks

- Both the B factories – Belle and BABAR – have established the CKM paradigm as the only source of CPV in the SM
- CPV content is however too little (by ~10^{10}) to explain the prevailing matter-antimatter asymmetry in our universe
- We know that something is there that we do not know fully
- There are a number of intriguing hints
  - $\sin(2\varphi_1)^{eff}$ in some penguin dominated decays
  - Direct CP asymmetry difference ($\Delta A_{K\pi}$)
  - …
- Look forward to the final updates from Belle (more data and improved tracking software), while warming up to the next generation experiments ➡ LHCb and super flavor factories