CP Violation and Hints for New Physics at the B factories

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Before I Start...

Disclaimers

- The talk pretends to be a poor man's review
  - An overview of CP violation and rare B decays
  - Cover results mostly from the B factories
  - Skip all the gory analysis details
  - Religiously provide relevant references for the interested

Credits

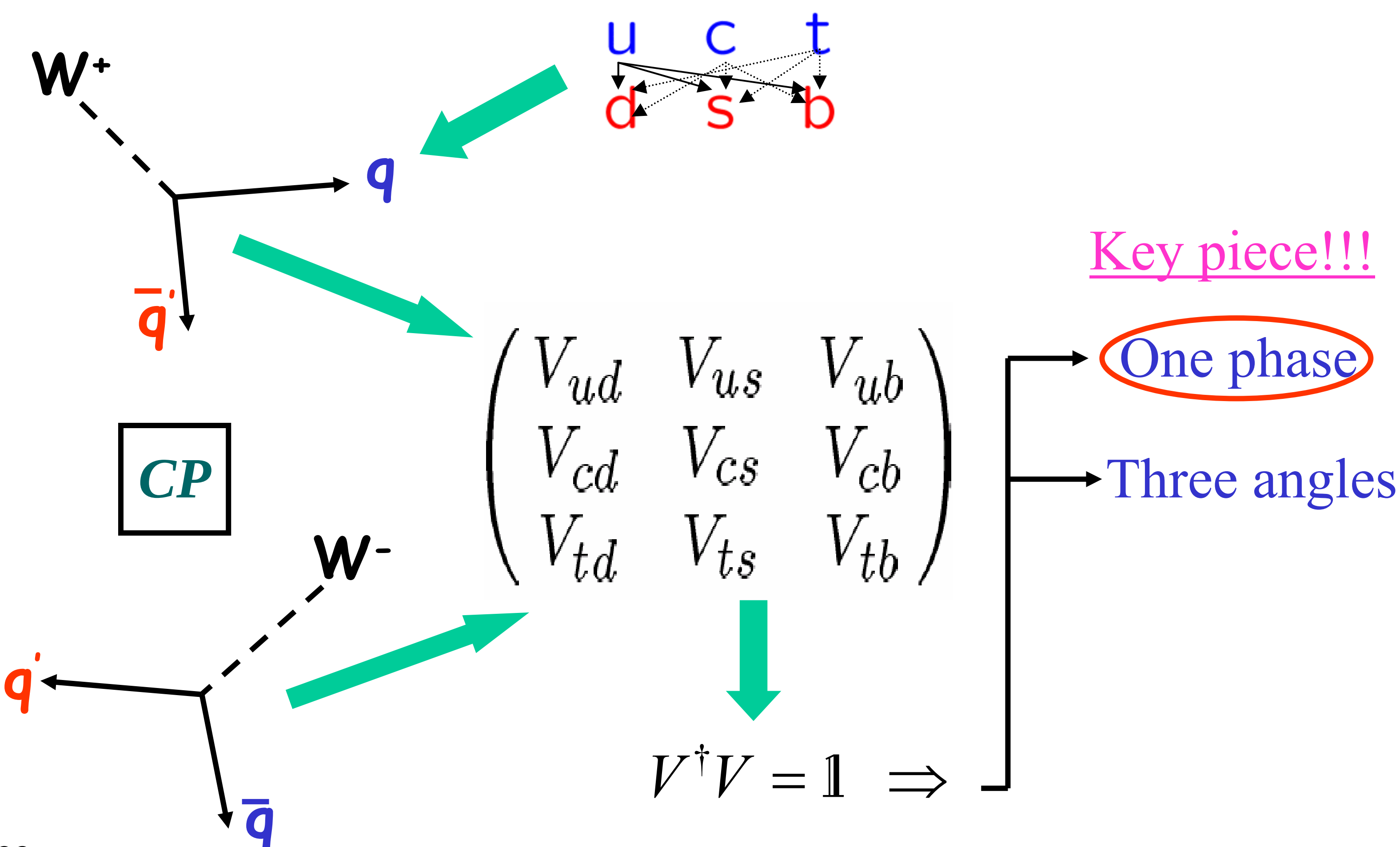
- Most materials inherited from Iijima (LP09) and Nakao (Beauty09)
- Heavy Flavor Averaging Group (HFAG):

  http://www.slac.stanford.edu/xorg/hfag/

- CKMfitter: http://ckmfitter.in2p3.fr/

CPV in Standard Model

- The CKM paradigm in charged vector-boson decays provides the framework for CP violation in the SM

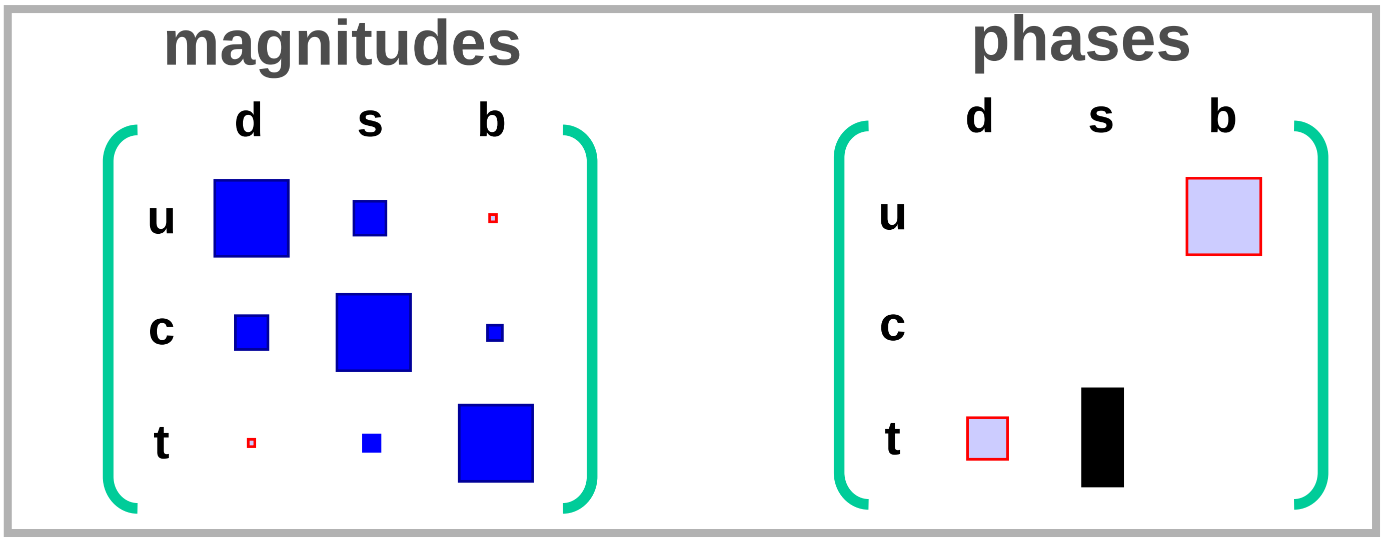


Hierarchical expansion of CKM

Wolfenstein parameterization of the CKM matrix V: (1983)

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

$$\lambda \quad \simeq \quad \sin\theta_c \simeq 0.22$$

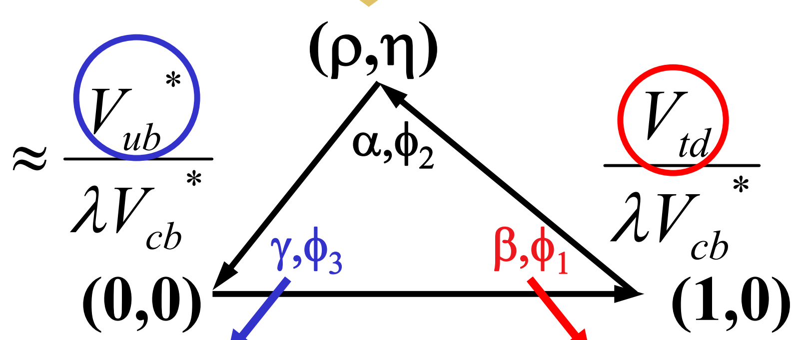


A triangle at the heart

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

d•b* = 0 **B Mesons**

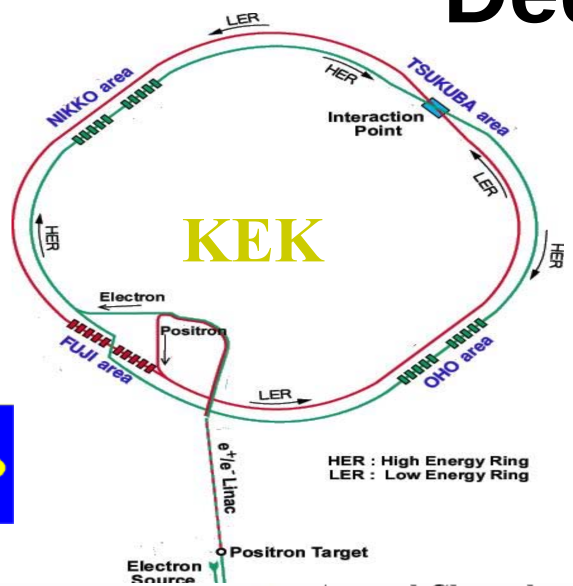
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

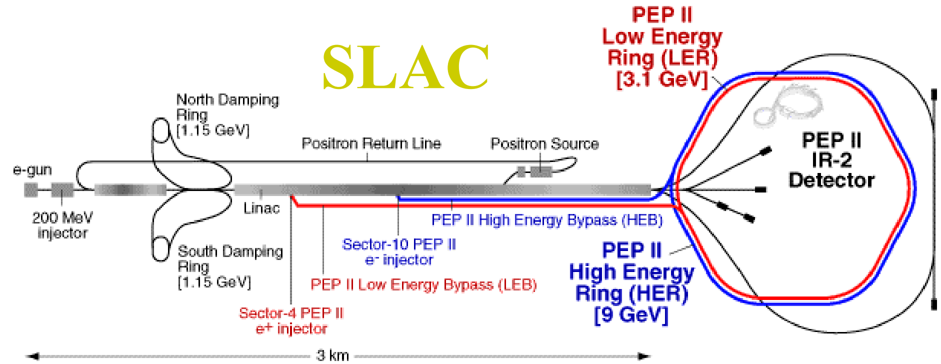


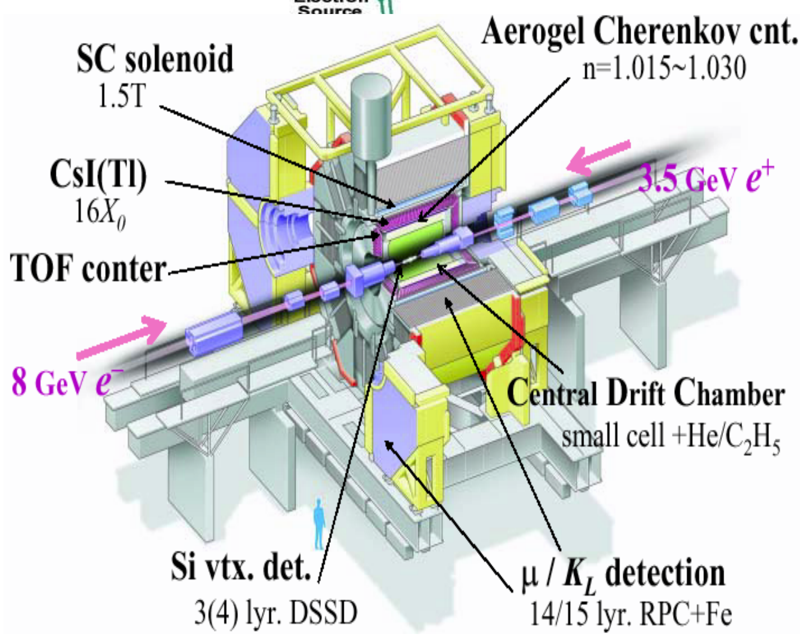
$$\varphi_3 \approx \arg V_{ub}^* \qquad \varphi_1 \approx -\arg V_{td} \qquad \varphi_2 = \pi - \varphi_1 - \varphi_3$$

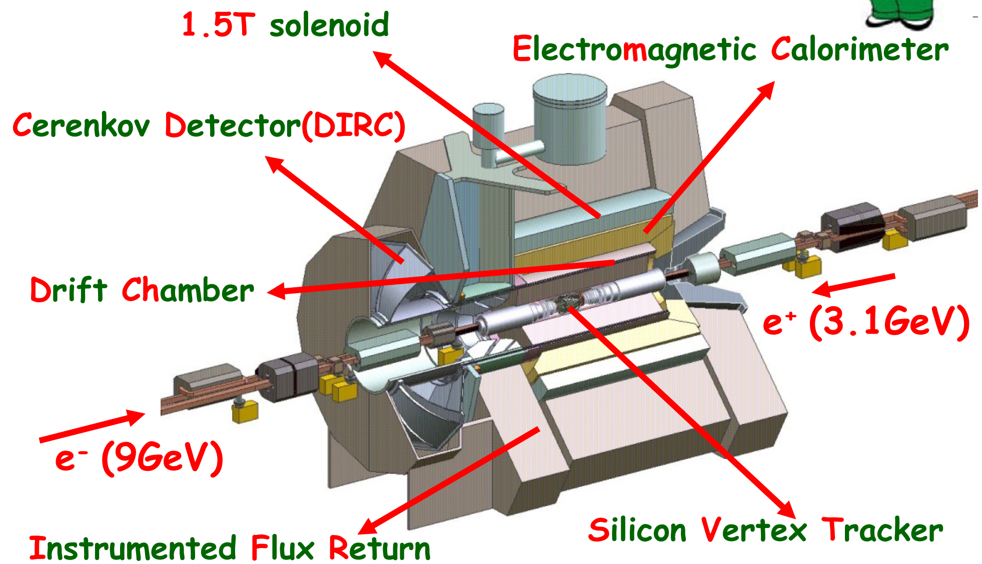
- Check consistency of the CKM paradigm:
  - ✓ measure three angles and two side lengths
  - ✓ look for possible new physics contributions

Dedicated B Factories

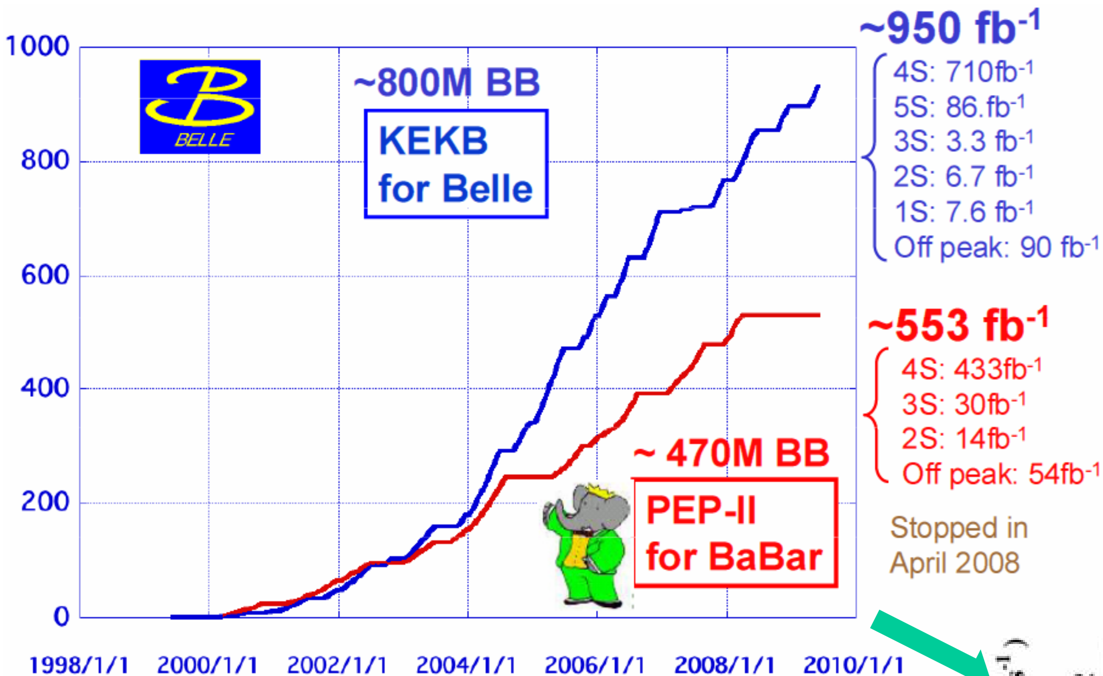






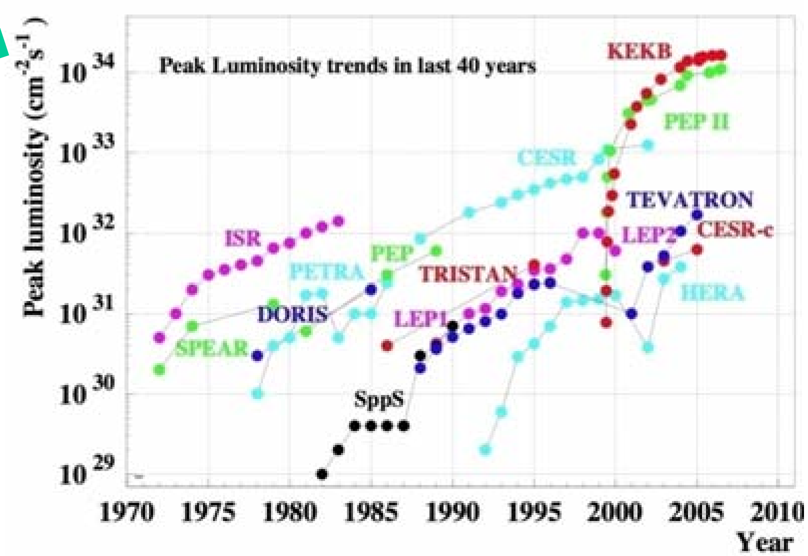


Breaking own records times and again



- Together collected over 10^9 (Gillion) $B\bar{B}$ pairs:
  - ✓ Test the KM paradigm of CP violation
  - ✓ Explore rare B decays – window to new physics

- Data at other Υ(nS) peaks as well as a large number of $c\bar{c}$ and $\tau^+\tau^-$ events



Most Visible Recognition

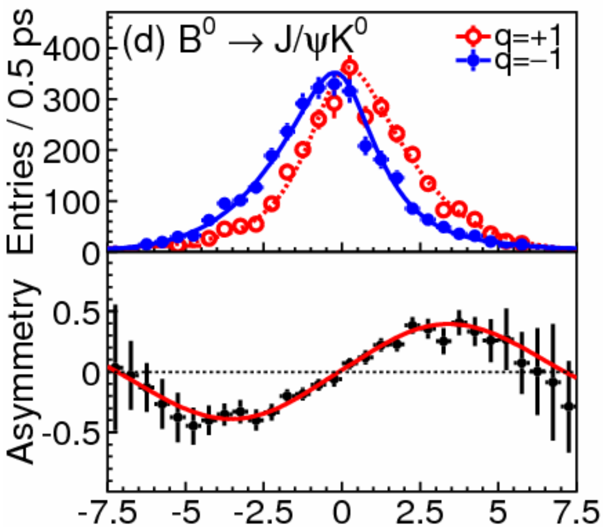
Half of the 2008 Nobel prize in physics to

Makoto Kobayashi, KEK, Tsukuba, Japan
and
Toshihide Maskawa, YITP, Kyoto University, Japan

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

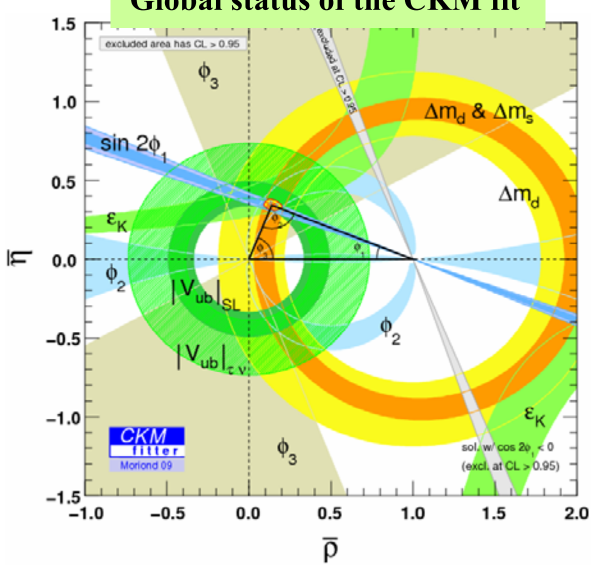
…As late as 2001, the two particle detectors **BaBar** at Stanford, USA and **Belle** at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as **Kobayashi** and **Maskawa** had predicted almost three decades earlier…

PRL 98 (2007) 031802



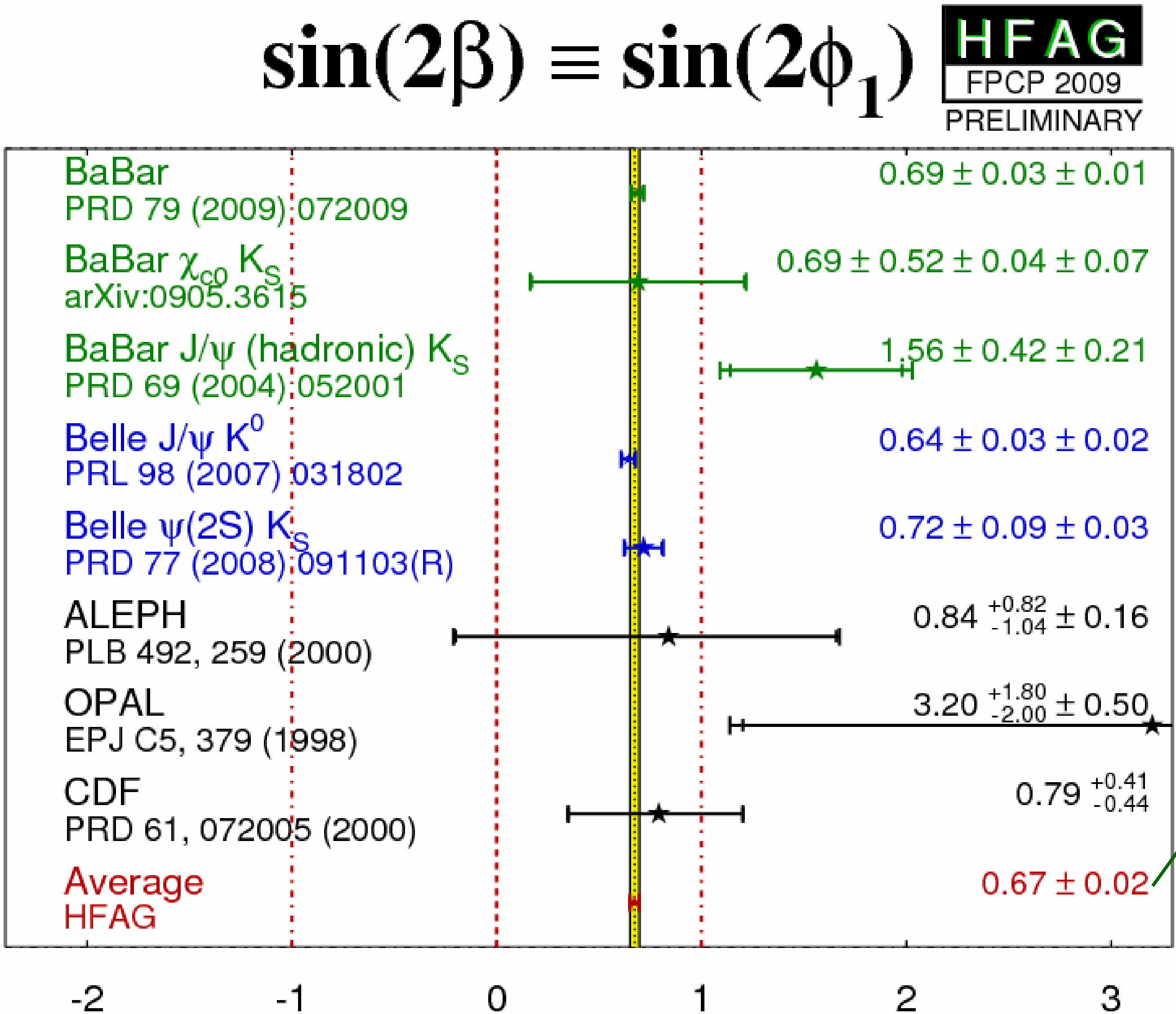
Proper time difference between two B mesons (ps)

Global status of the CKM fit



Standard Candle

$\sin(2\beta) \equiv \sin(2\phi_1)$



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

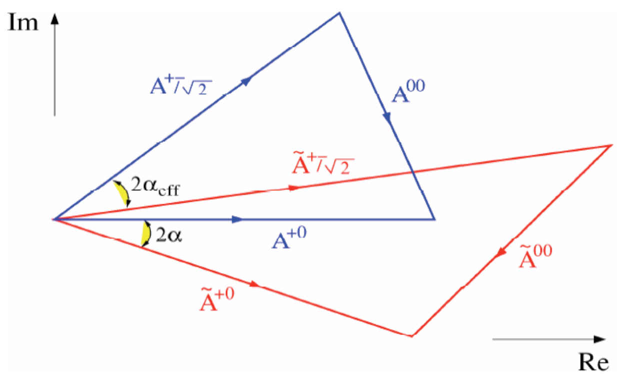
$\varphi_2(\alpha)$: Error shrinks day-by-day

- Almost a precision measurement

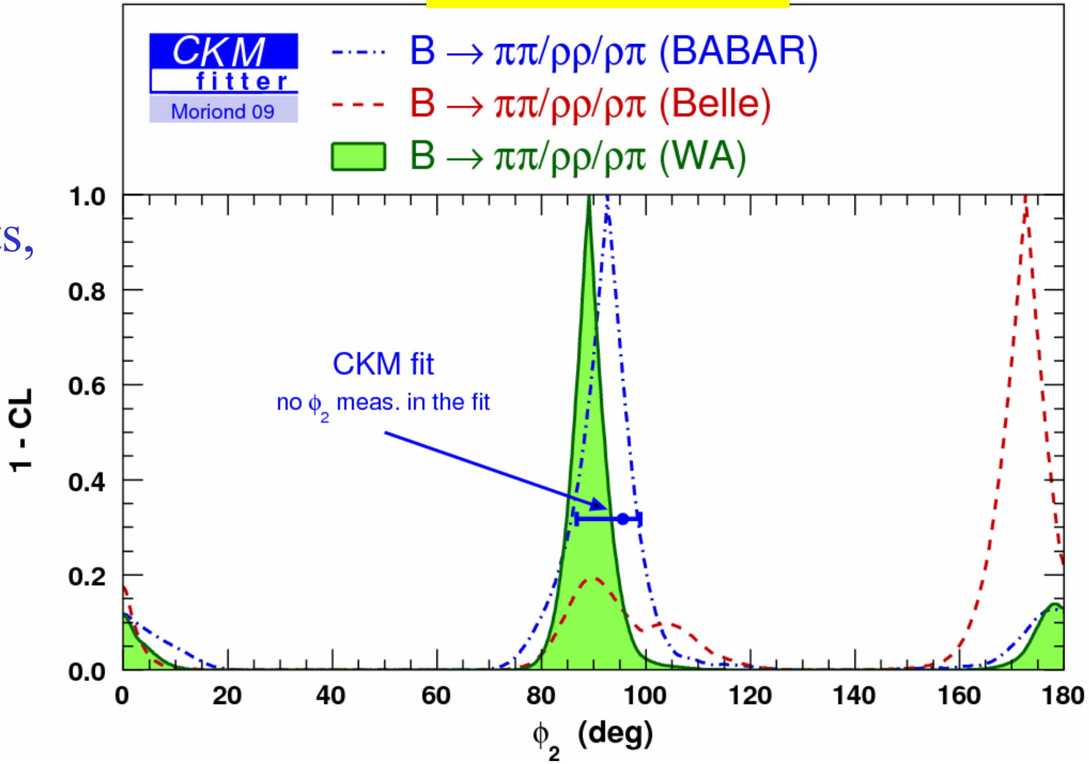
direct measurement
$\alpha = (89.0^{+4.4}_{-4.2})^\circ$

- Dominated by the $B\to\rho\rho$ results, that rely on the isospin relation

Gronau, London, PRL 65 (1990) 3381



Current world-average



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

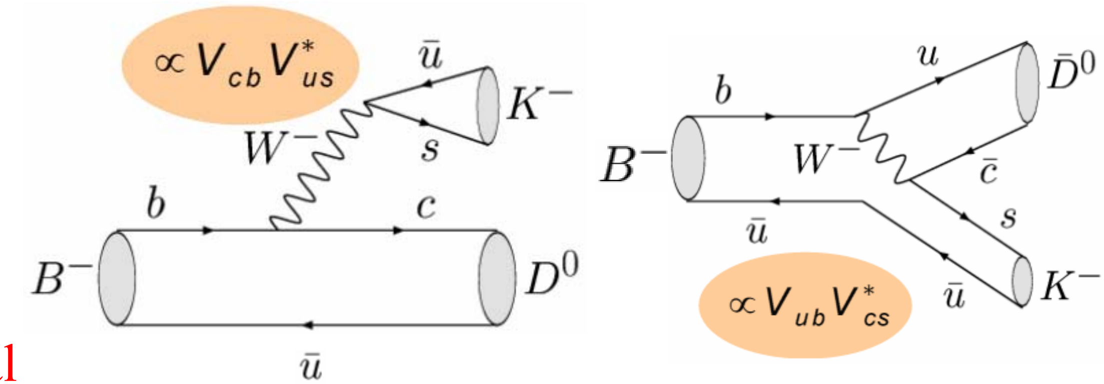
❖ Belle's final results on $B\to\rho\rho$, especially $\rho^+\rho^0$, are eagerly awaited for

Now, what about $\varphi_3(\gamma)$?

- 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

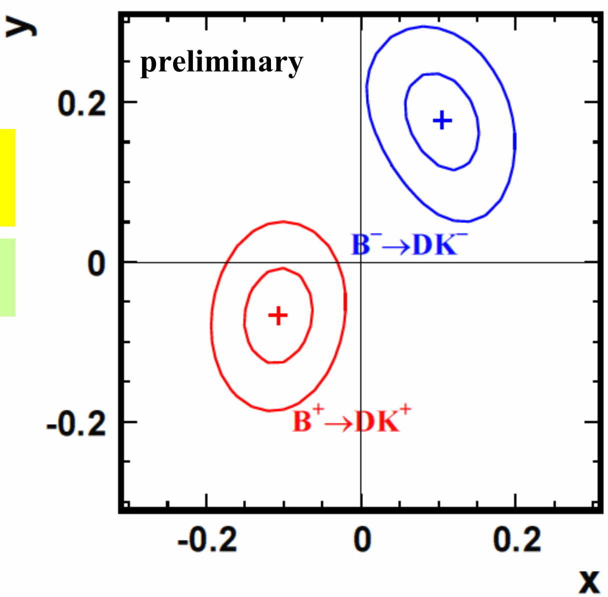
- Basic strategy is to exploit interference between two diagrams



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

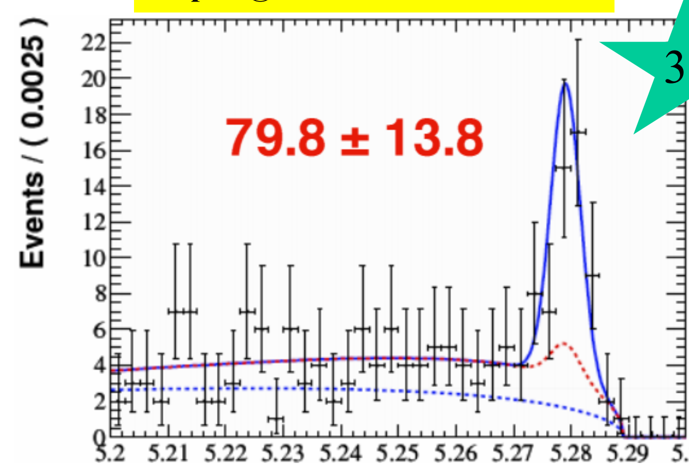
Poluektov @ EPS09: Belle $D \to K_S\pi\pi$

3.5σ evidence

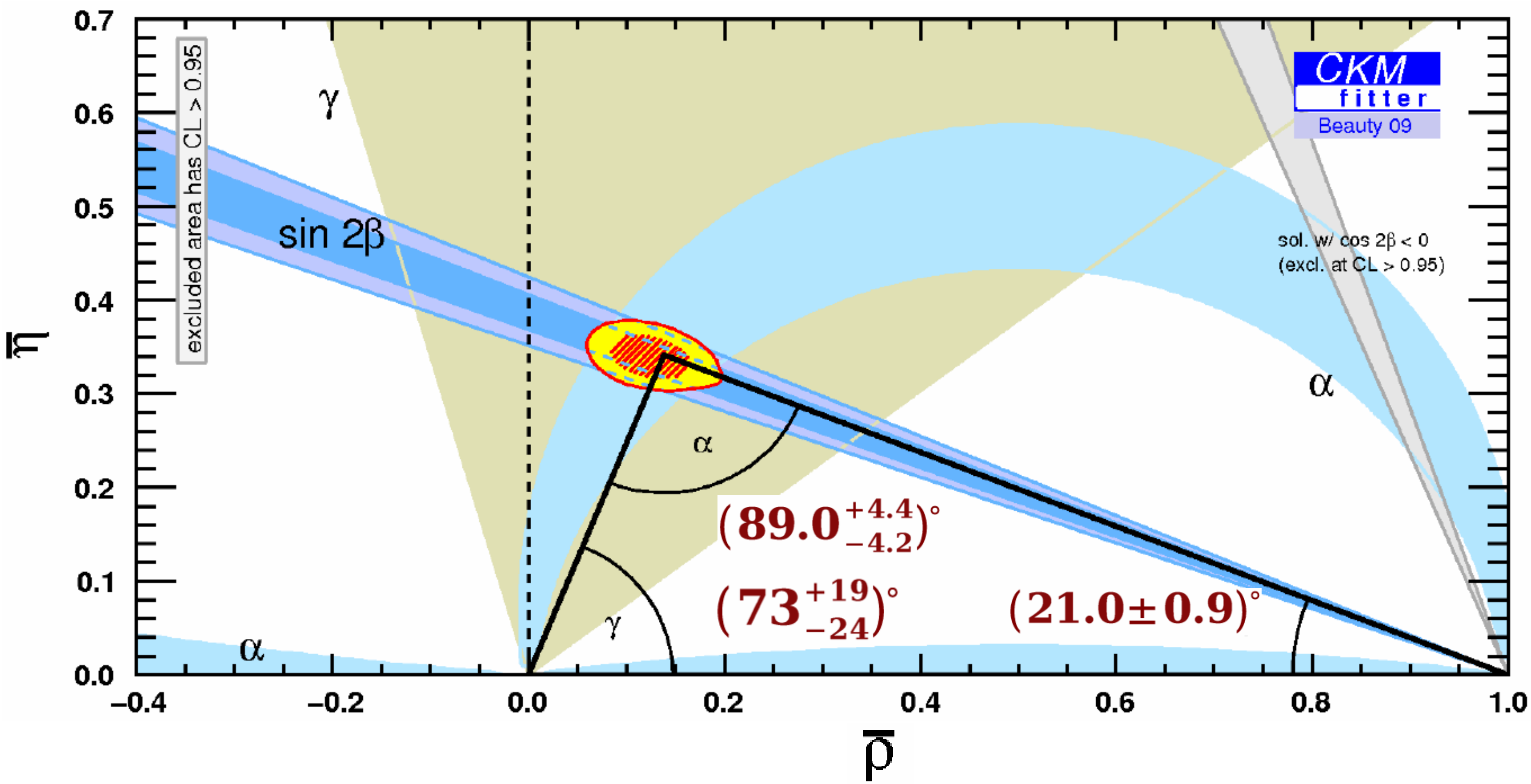


Lopez @ EPS09: BaBar $D \to K\pi$

3σ



Current World Average

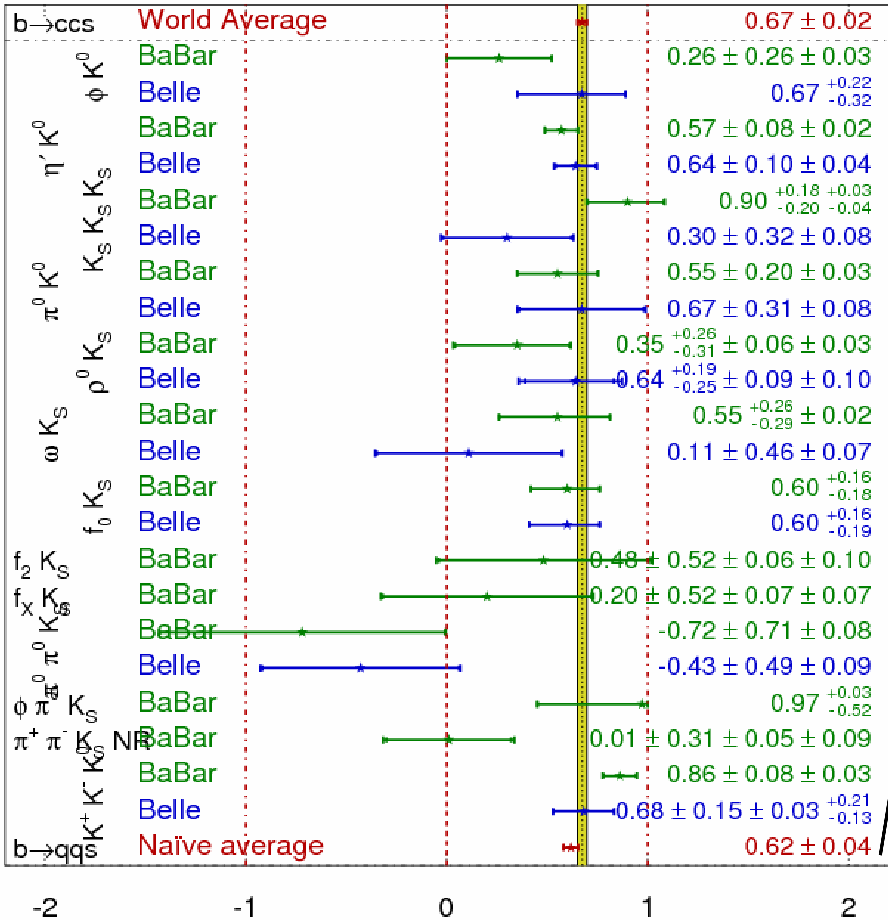


- ➢ As far as $\varphi_3(\gamma)$ is concerned, it is fair to say that we have made a head-start
- ❑ Final word will come from LHCb and (future) super flavor factories
- ✓ The latter would also improve the measurements of $\varphi_1(\beta)$ and $\varphi_2(\alpha)$

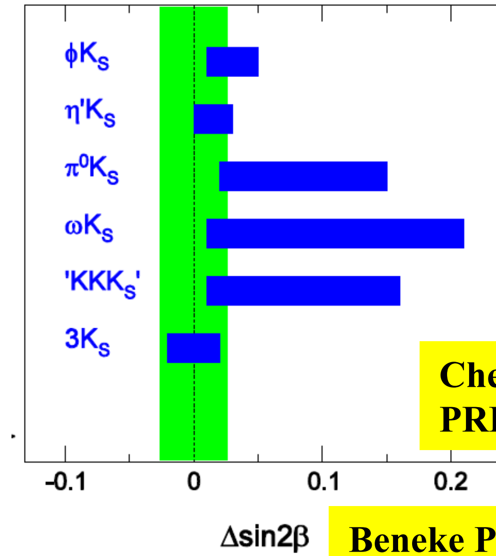
Turn to the second part

HFAG
FPCP 2009
PRELIMINARY

$\sin(2\varphi_1)$ with the Penguins



- Measured $\sin(2\varphi_1^{eff})$ in loop diagrams disagree with the charmonium world average
  - While considering the naive average, we need to be extra careful because of the **theory uncertainty**



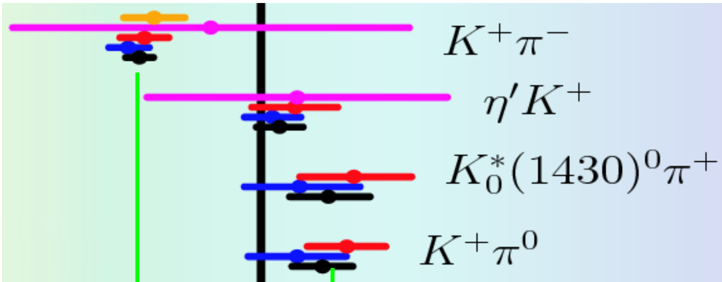
Cheng *et al.*, PRD72, 094003

Beneke PLB 620, 143

Wiliamson, Zupan, PRD 74, 014003

- Need to pin down on the expt. uncertainty in each of these measurements (call for the super flavour factory)

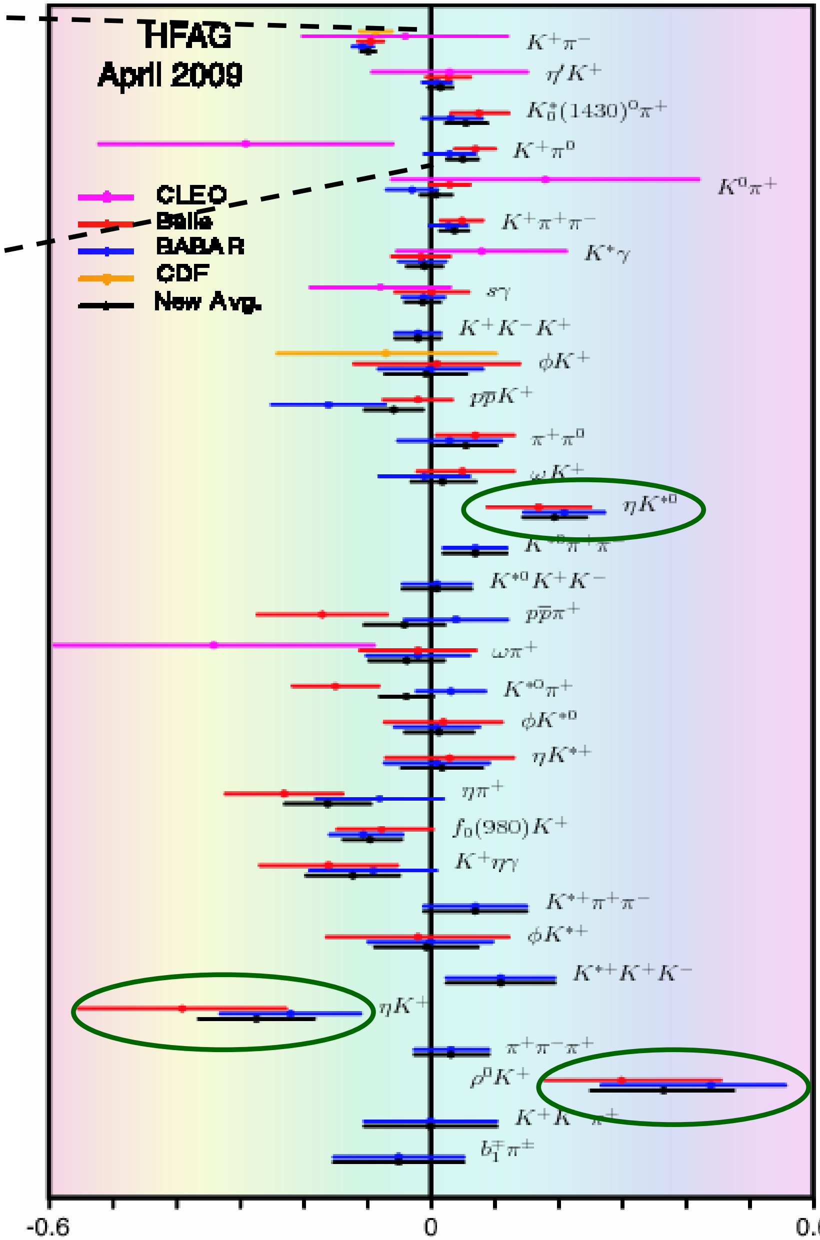
Direct CP Violation



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

- ❑ Both decay channels occur via the same diagrams at tree level ➡ $\Delta A_{K\pi}$ should be zero
- ➢ Interpretation with SM and non-SM
- ✓ $K^0\pi^0$ data would be useful to check the isospin relation

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



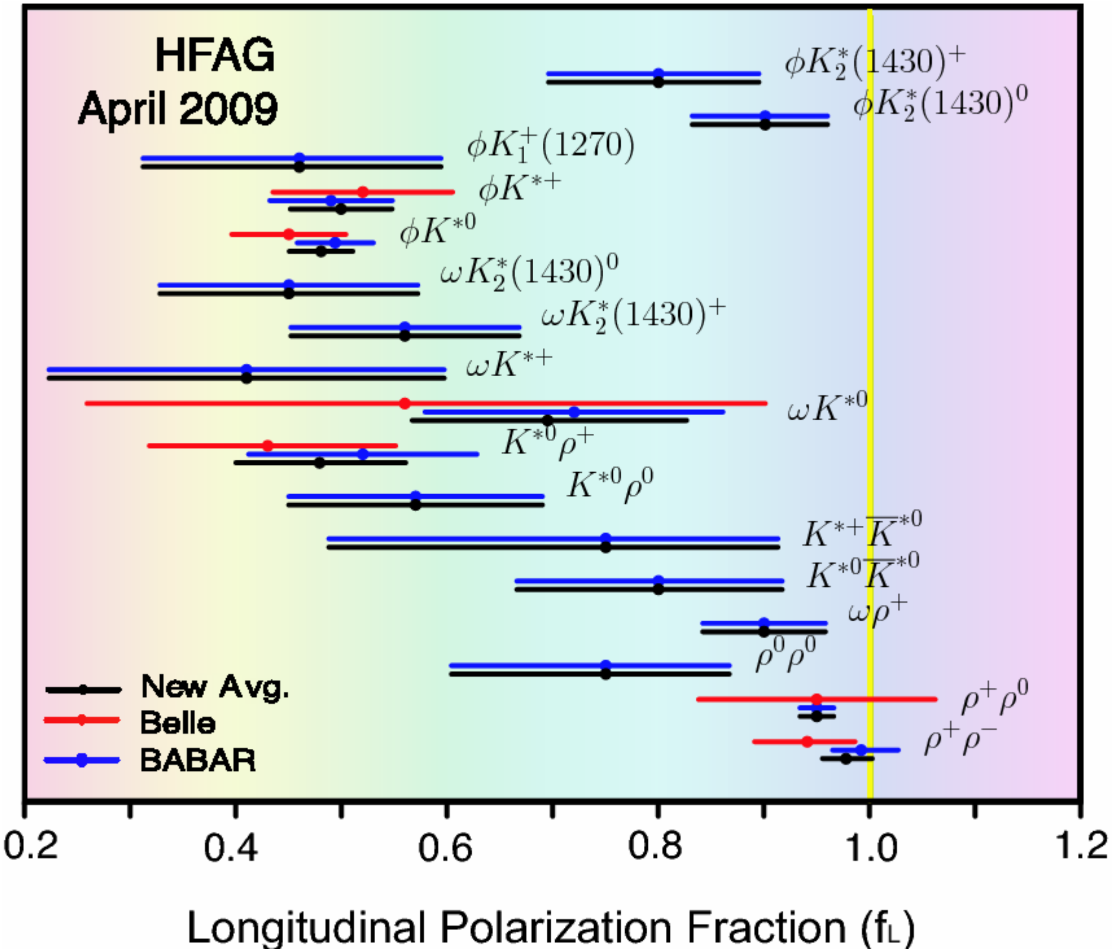
Polarization Puzzle

- $B \to \rho\rho$ decays fit to the expected pattern:

$$f_L = 1 - \frac{m_V^2}{m_B^2}$$

- One could say, within errors f_L for $K^* \overline{K}^{*0}$, $\omega\rho^+$, φK_2^* and ρK^{*+} follow the trend

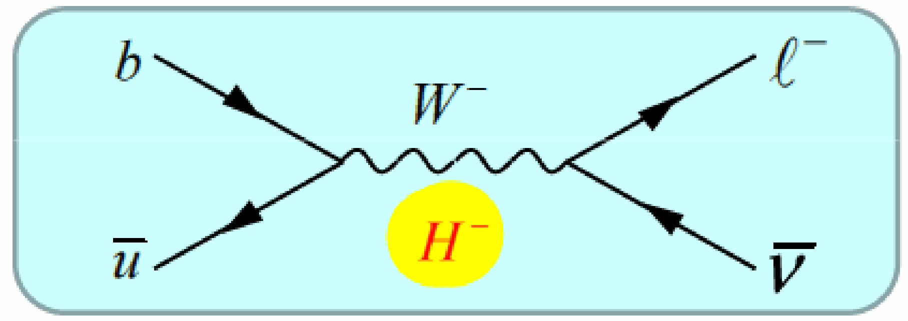
- But what is going on for some of loop-dominated modes, e.g., φK^* or $\rho^+ K^{*0}$?



Nice review talks by Bevan and Nagashima at HINTS09:

http://belle.kek.jp/hints09/program.html

Enter $B^+ \to \tau^+ \nu_\tau$



$$\mathcal{B}(B^- \to \tau^- \overline{\nu})_{SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

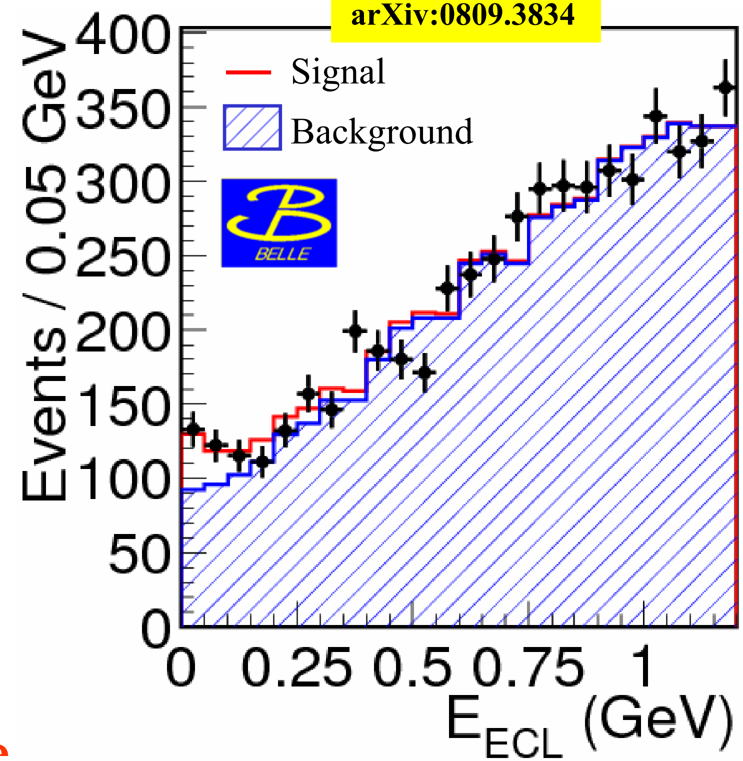
- Within standard model, proceeds through W annihilation
  - Helicity suppression similar to π^- decay
- B-meson decay constant f_B: 190±13 MeV

HPQCD Collab., arXiv:0902.1815

- Sensitive to new physics, *e.g.*, charged Higgs

- Presented result corresponds to the case, where one B meson is decaying semileptonically

arXiv:0809.3834



3.8σ significance

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = (1.65^{+0.38}_{-0.37}(\text{stat})^{+0.35}_{-0.37}(\text{syst})) \times 10^{-4}$$

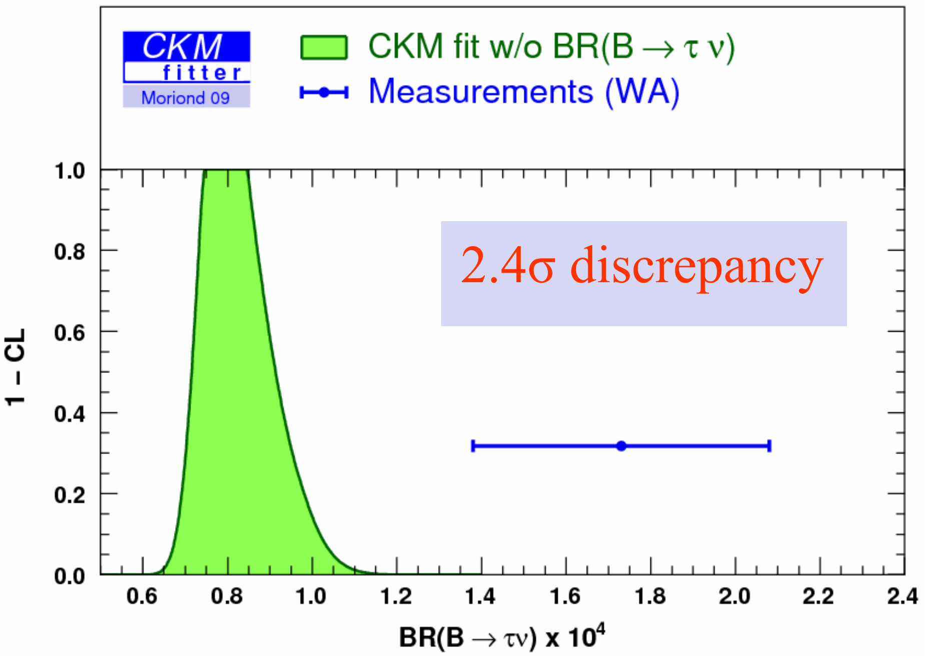
Obvious Tension

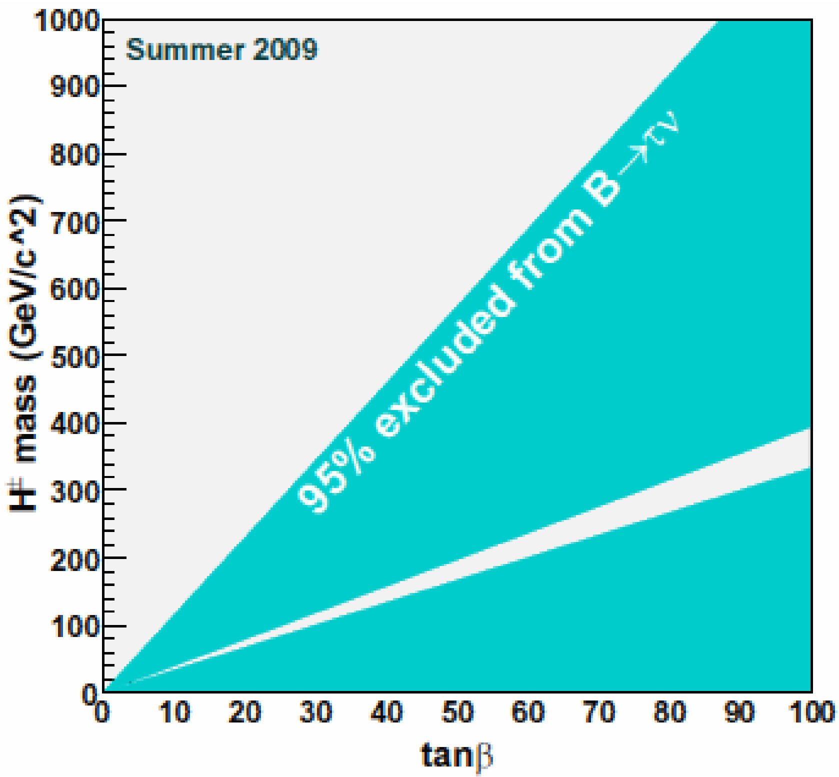
- From the global analysis:

$$\mathrm{Br}(\tau\nu) = (0.79^{+0.16}_{-0.10}) \times 10^{-4}$$

- Belle+BaBar measured value:

$$\mathrm{Br}(\tau\nu) = (1.73 \pm 0.35) \times 10^{-4}$$





Constraint on charged Higgs:

$$\mathcal{B}(B^- \to \tau^- \overline{\nu}_\tau) = \mathcal{B}_{\mathrm{SM}}(B^- \to \tau^- \overline{\nu}_\tau) \times \left(1 - \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2$$

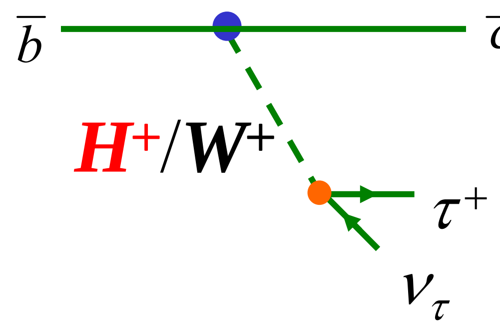
- Use the world-average (WA) value with

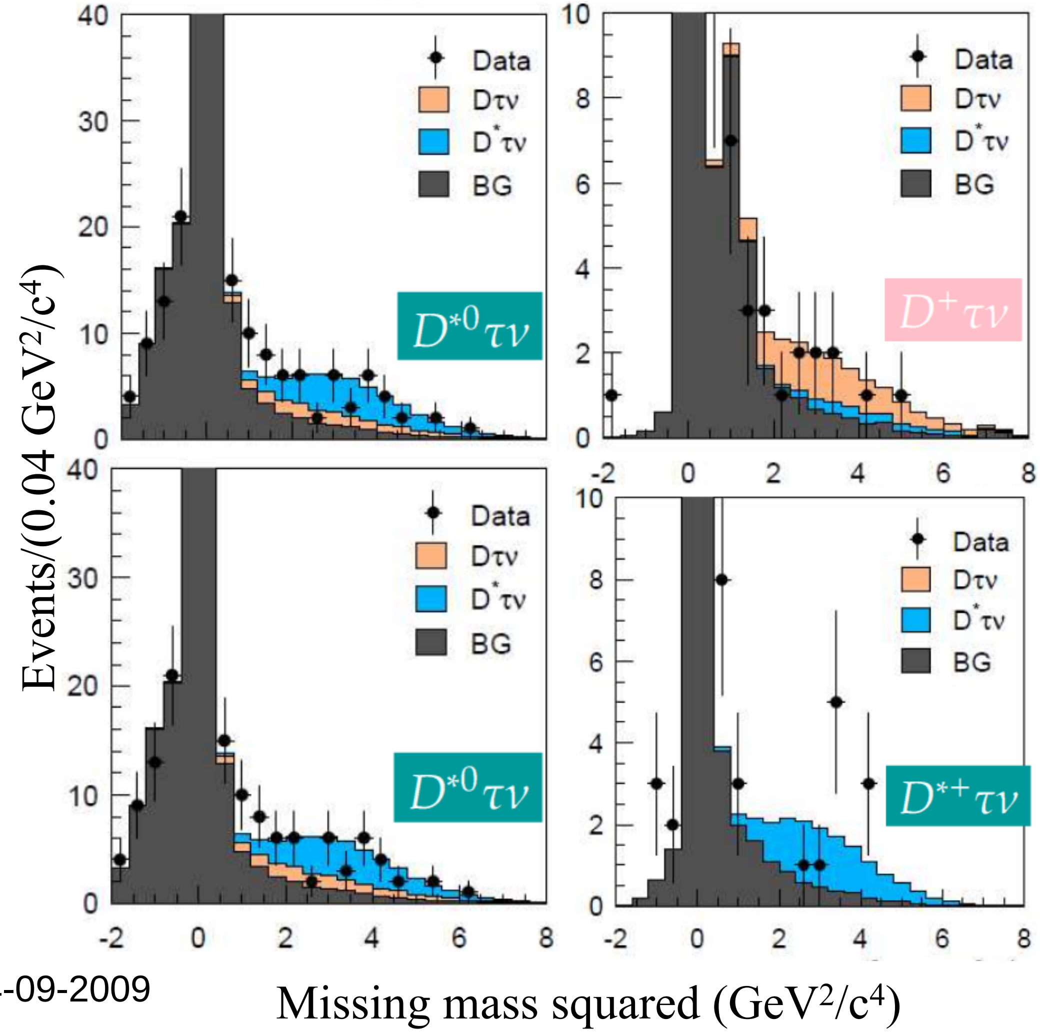
$$\mathcal{B}_{\mathrm{SM}}(B^+ \to \tau^+ \nu) = (1.20 \pm 0.25) \times 10^{-4}$$

to get bounds on m(H±) and tanβ

Results on $B \to D^{(*)}\tau\nu_\tau$

- Similar Feynman's diagram as $B \to \tau\nu_\tau$: replace the up with a charm quark



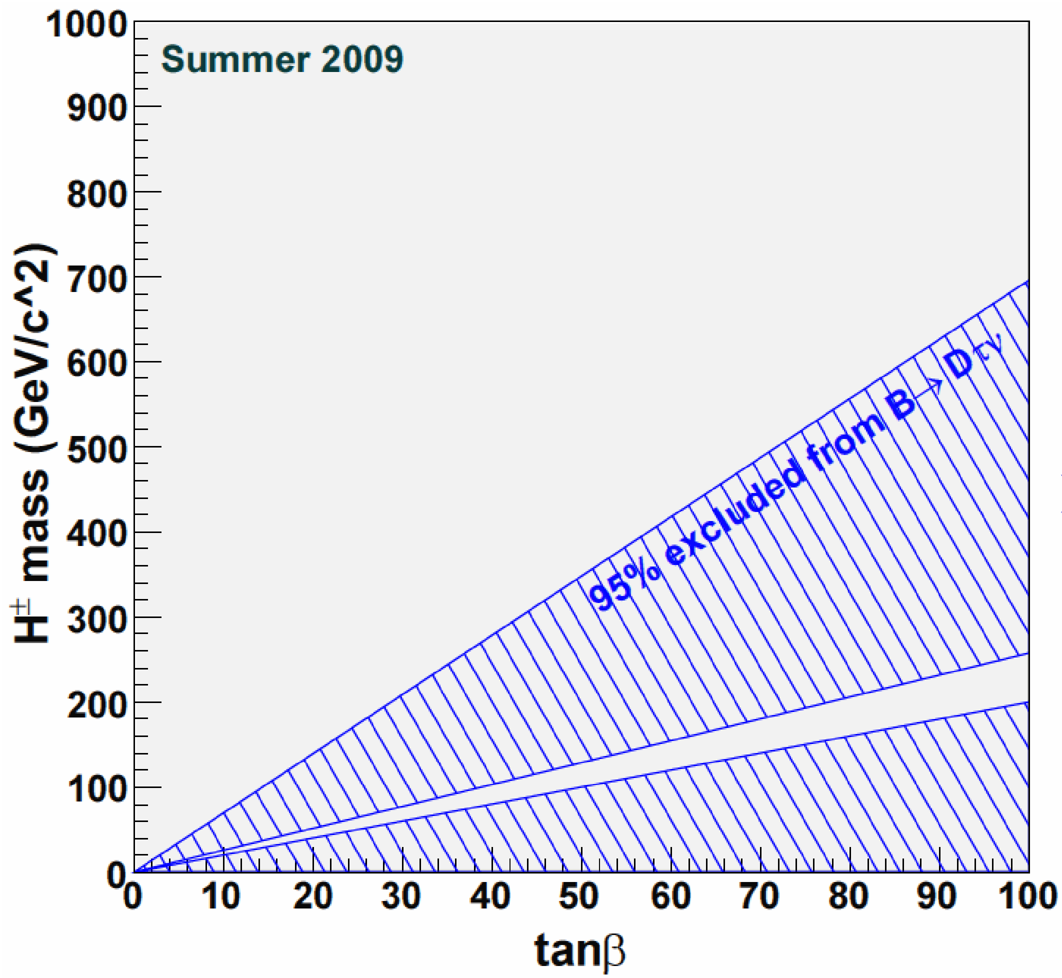


- Dominant background is from $B \to D^{(*)} l \nu_l$ (l=e or μ)
- Feed-across from D^*(D) to $B \to D\tau\nu_\tau$($D^*\tau\nu_\tau$) with a missed π^0/γ ($\pi^\pm$ exchanged with recoil B)
- 2D fit of missing mass squared and E_{ECL}

preliminary

$R(B^+ \to \overline{D}^0\tau^+\nu)$	$(70.2\ ^{+18.9}_{-18.0}\ ^{+11.0}_{-9.1})\%$
$R(B^+ \to \overline{D}^{*0}\tau^+\nu)$	$(46.8\ ^{+10.6}_{-10.2}\ ^{+6.2}_{-7.2})\%$
$R(B^0 \to D^-\tau^+\nu)$	$(47.6\ ^{+21.6}_{-19.3}\ ^{+6.3}_{-5.4})\%$
$R(B^0 \to D^{*-}\tau^+\nu)$	$(48.1\ ^{+14.0}_{-12.3}\ ^{+5.8}_{-4.1})\%$

Constraint on New Physics



WA (LP09): R(B→Dτν)= 49±10%

vs.

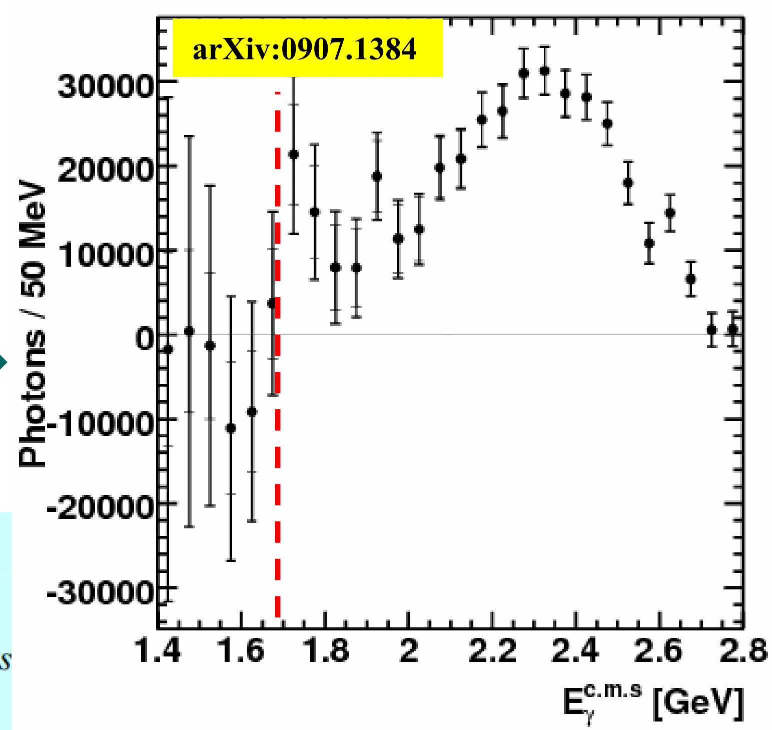
SM value: R(B→Dτν)= 31±2%

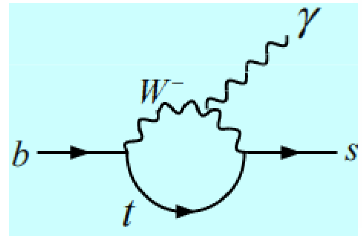
- Charged Higgs exclusion region is complementary to B→τν

Itoh *et al.*, Prog.Theor.Phys. 114 (2005) 179

Inclusive $b \to s\gamma$ Measurement

- No kinematic constraint
- Only requirement is to measure a high energy photon in the $\Upsilon(4S)$ rest frame
  - Sometimes we ask for a lepton in the recoil side (lepton tag)
  - Otherwise, fully inclusive sample
- ✓ Low E_γ threshold (1.7 GeV)

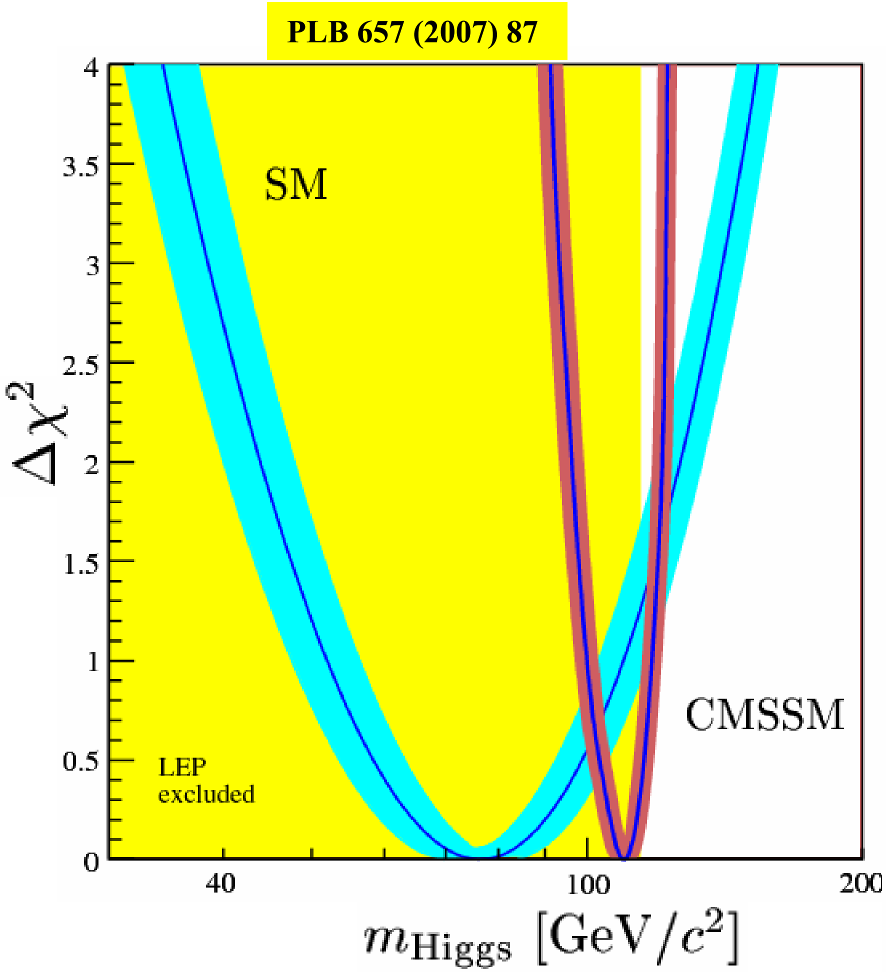


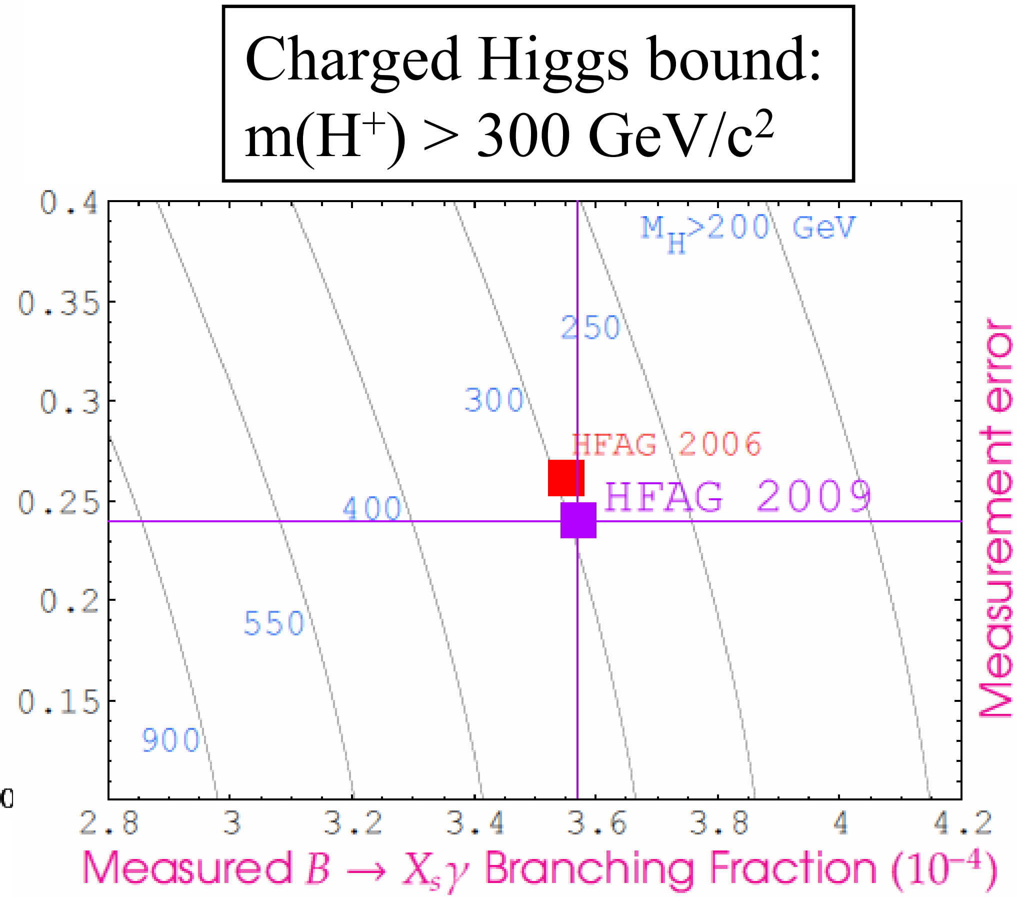


$\mathcal{B}(B \to X_S\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$

- The most precise measurement of $B \to X_s\gamma$ to date
- BFs are also given for other E_γ thresholds: 1.8, 1.9 and 2.0 GeV
- Tighter constraint on the SM as well as on the new physics model

Constraints from b→sγ

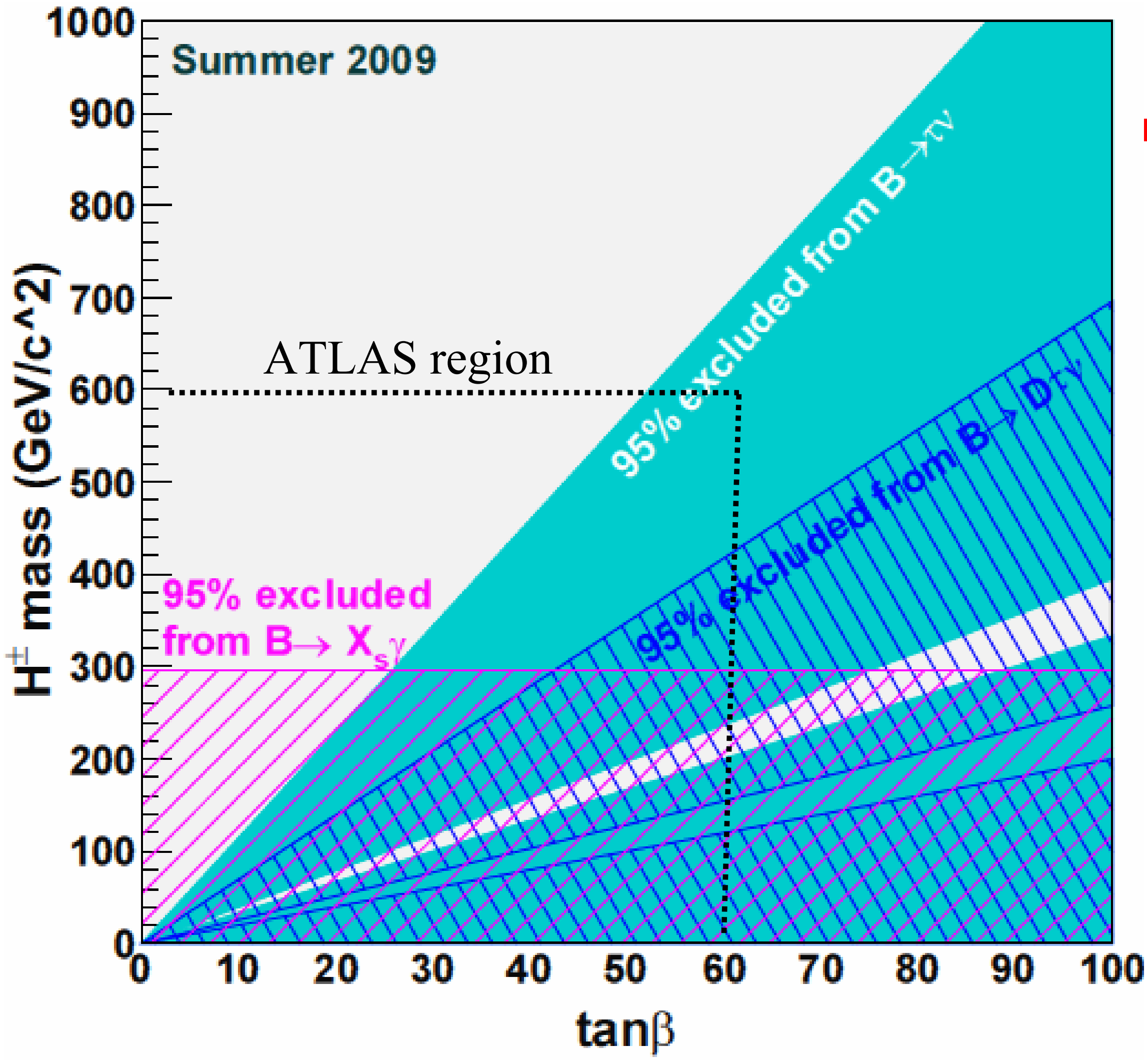




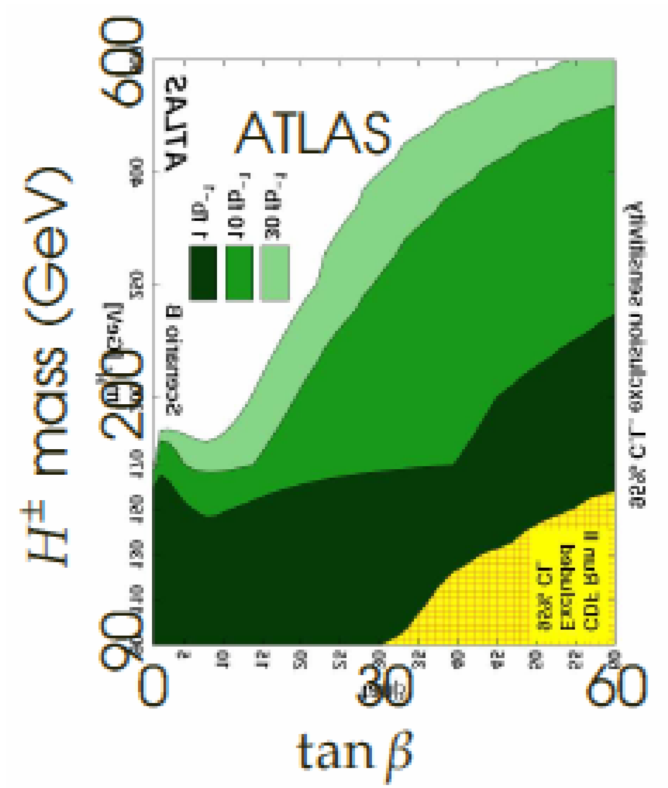
(Left) b→sγ BF is a part of CMSSM ➡ improvement on the indirect m_H limit

(Right) Constraint on the charged Higgs mass

Combined $H^{\pm}$ bounds from B factories

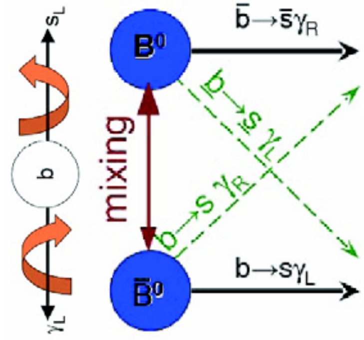


➡ Covers almost whole of the exclusion region envisioned by ATLAS



Observation of $B \rightarrow K\phi\gamma$

- Time-dependent CP violation study
  - In the SM, photon polarization is b-flavor specific
  - Sensitive to non-SM right-handed currents ➡ the decay channel acts as if a polarimeter

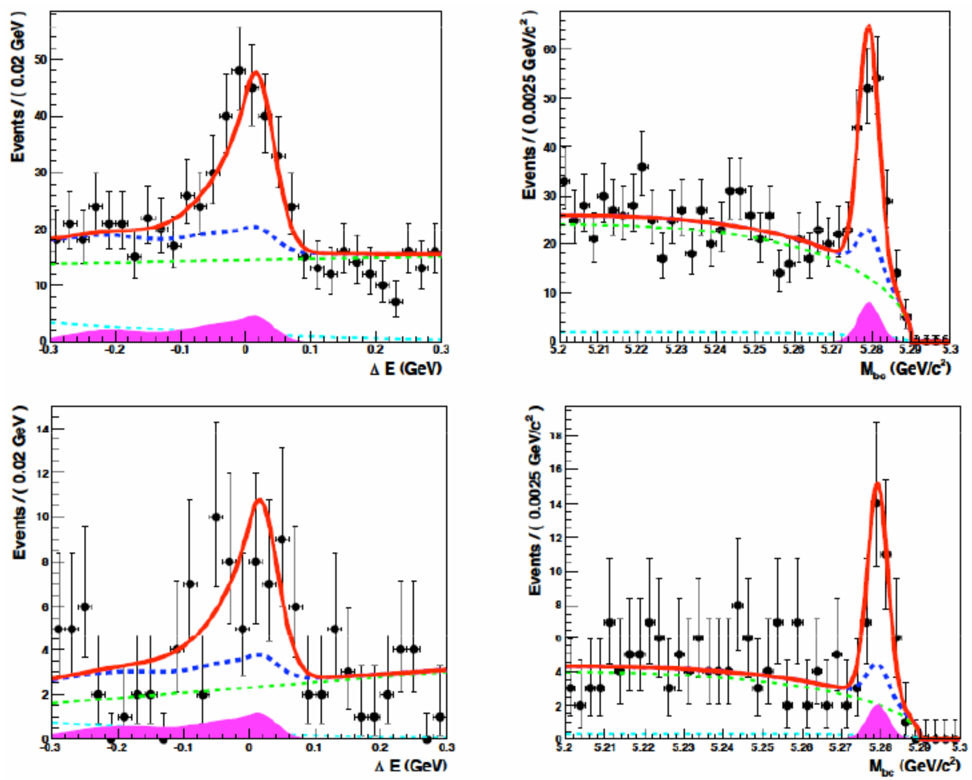


Atwood *et al.*, PRL 79 (1997) 185
PRD 71 (2005) 076003

$$\mathcal{B}(B^+ \rightarrow K^+\phi\gamma) = (2.34 \pm 0.29 \pm 0.23) \times 10^{-6}$$

$N_S = 136 \pm 17$ (10.5σ stat. significance)

preliminary



$$\mathcal{B}(B^0 \rightarrow K^0\phi\gamma) = (2.66 \pm 0.60 \pm 0.32) \times 10^{-6}$$

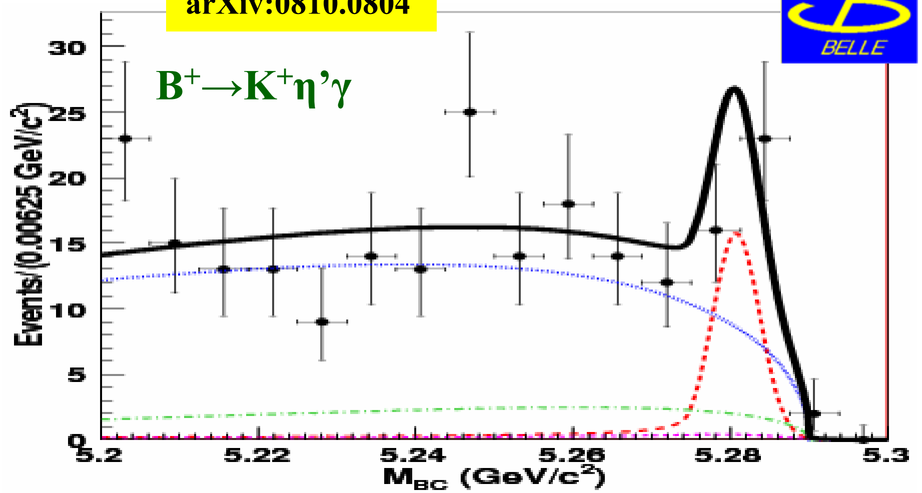
$N_S = 35 \pm 8$ (5.8σ stat. significance)

Evidence for B→Kη'γ

- Test the possible suppression of B→Kη'γ with respect to Kηγ due to destructive interference between two penguin diagrams **Lipkin, PLB 254 (1991) 247**
- Neutral mode could be used for time-dependent CPV study, similar to Kφγ

arXiv:0810.0804

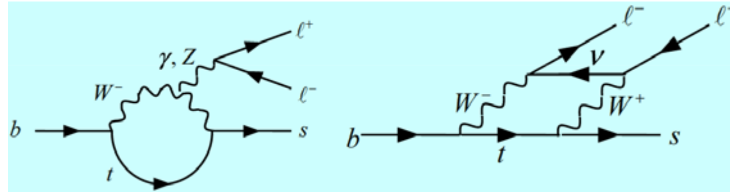
- Analysis restricted to m(Kη')<3.4 GeV
- η' meson is reconstructed through its decay to $\eta\pi^+\pi^-$ or $\rho^0\gamma$, where $\eta\to\gamma\gamma$ or $\pi^+\pi^-\pi^0$ and $\rho^0\to\pi^+\pi^-$
- 2D fit to M_{bc} and ΔE for all sub-modes



Mode	Yield(events)	$\mathcal{B}(10^{-6})$	$\mathcal{S}(\sigma)$	UL(10^{-6})
$B^+\to K^+\eta'\gamma$	$32.6^{+11.8}_{-10.8}$	$3.6\pm1.2\pm0.4$	3.3	5.6
$B^0\to K^0\eta'\gamma$	$5.1^{+5.0}_{-4.0}$	$2.5^{+2.4+0.4}_{-1.9-0.5}$	1.3	6.4

✓ Our measurements and $\mathcal{B}$(B→Kηγ) ~8.0×10^{-6} (PDG) agree with Lipkin's prediction

Study of $B \to K^{(*)}\lambda^+\lambda^-$



- Multitude of measurements: $\mathcal{B}$, CP asymmetry, lepton flavor ratio, F_L (for K^* mode), lepton forward-backward asymmetry (A_{FB}) and isospin asymmetry (A_I)
- Lepton flavor ratio: ratio of muon to electron contribution for a given channel

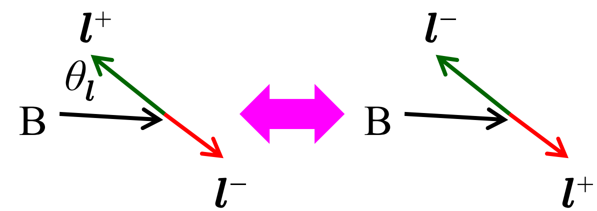
Angular distributions used to extract F_L and A_{FB}:

K^* longitudinal polarization F_L from kaon angle θ_K

$$\frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

Forward-backward asymmetry A_{FB} from lepton angle θ_ℓ

$$\frac{3}{4}F_L(1-\cos^2\theta_\ell) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell$$



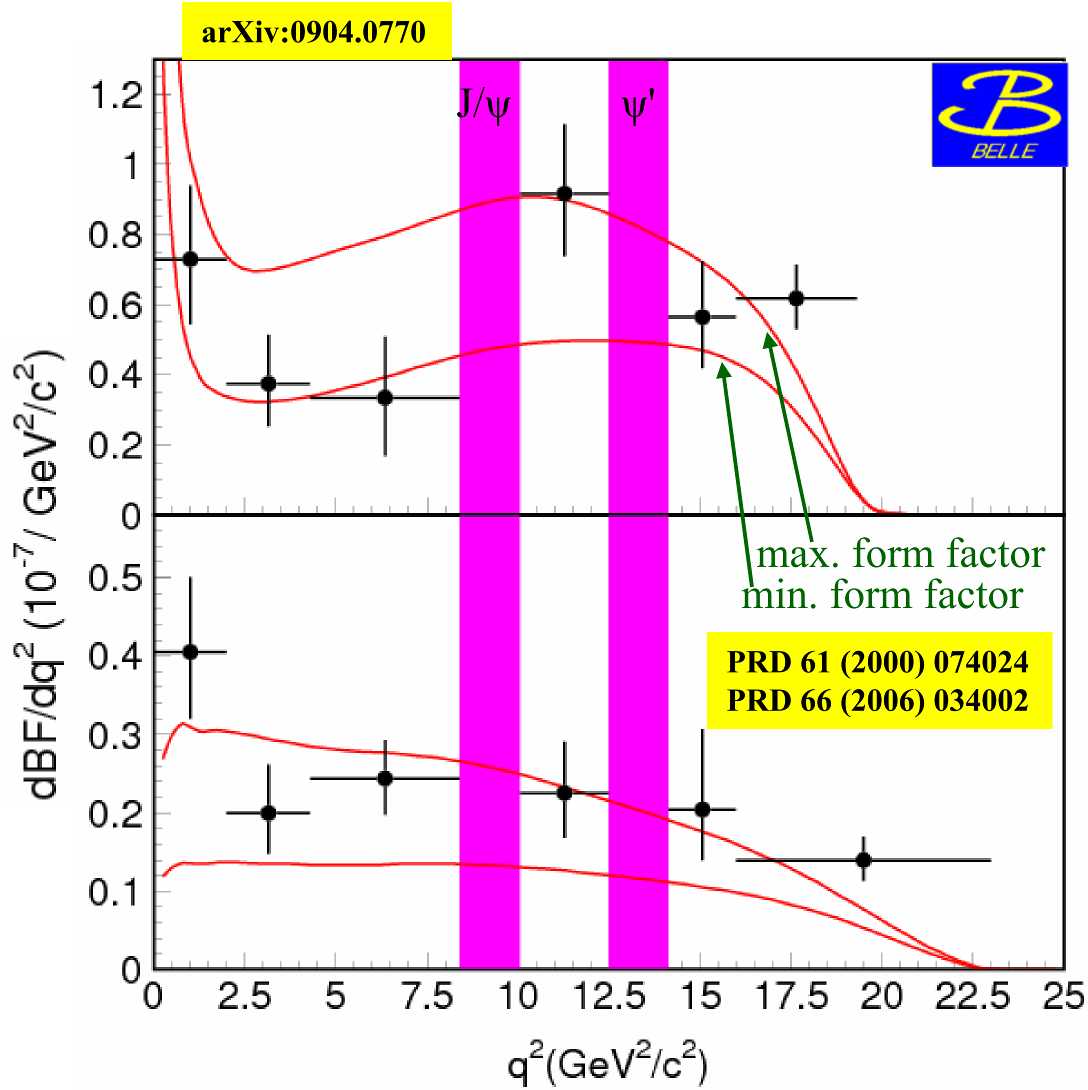
θ_K is the angle between K and opposite of B in the K^* frame

$$A_I \equiv \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(K^{(*)0}\ell^+\ell^-) - \mathcal{B}(K^{(*)\pm}\ell^+\ell^-)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(K^{(*)0}\ell^+\ell^-) + \mathcal{B}(K^{(*)\pm}\ell^+\ell^-)}$$

$$\tau_{B^+}/\tau_{B^0} = 1.071$$

- Three-body decay: observables as functions of q^2 [$= m^2(l^+l^-)$]

Study of B→K$^{(*)}\lambda^+\lambda^-$



- Total branching fraction:

$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (10.7^{+1.1}_{-1.0} \pm 0.9) \times 10^{-7}$$
$$\mathcal{B}(B \to K\ell^+\ell^-) = (4.8^{+0.5}_{-0.4} \pm 0.3) \times 10^{-7}$$

- No evidence for CP violation

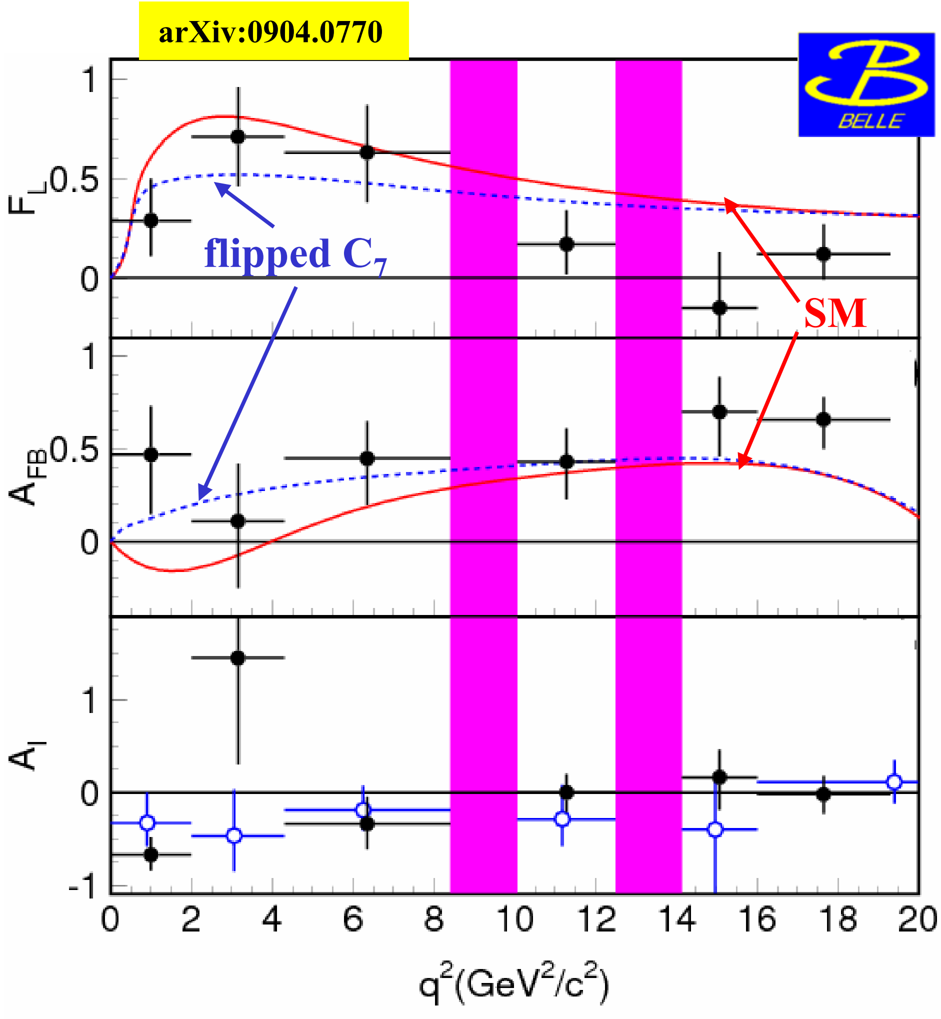
$$A_{CP}(K^*\ell^+\ell^-) = -0.10 \pm 0.10 \pm 0.01$$
$$A_{CP}(K^+\ell^+\ell^-) = 0.04 \pm 0.10 \pm 0.02$$

- Lepton flavor ratio

$$R_{K^*} = 0.83 \pm 0.17 \pm 0.08$$
$$R_K = 1.03 \pm 0.19 \pm 0.06$$

consistent with expectation (0.65 for K* and 1.0 for K)

Any Smoking Gun?



- For F_L(top) and A_{FB} (middle), the SM prediction and flipped C_7 case (new physics) are plotted
- Both are consistent with the SM
  - For A_{FB} the flipped C_7 case looks little more favoured (integrated significance is 2.7σ)
- ✓ Need more data to settle the dust

- Isospin asymmetry for $K\ell^+\ell^-$ (open circles) and $K^*\ell^+\ell^-$ (closed circles) shown in the bottom plot

$$A_I(B \to K^*\ell^+\ell^-) = -0.29^{+0.16}_{-0.16} \pm 0.09 \quad \sigma = 1.37$$
$$A_I(B \to K\ell^+\ell^-) = -0.31^{+0.17}_{-0.14} \pm 0.08 \quad \sigma = 1.75$$
$$A_I(B \to K^{(*)}\ell^+\ell^-) = -0.30^{+0.12}_{-0.11} \pm 0.08 \quad \sigma = 2.22$$

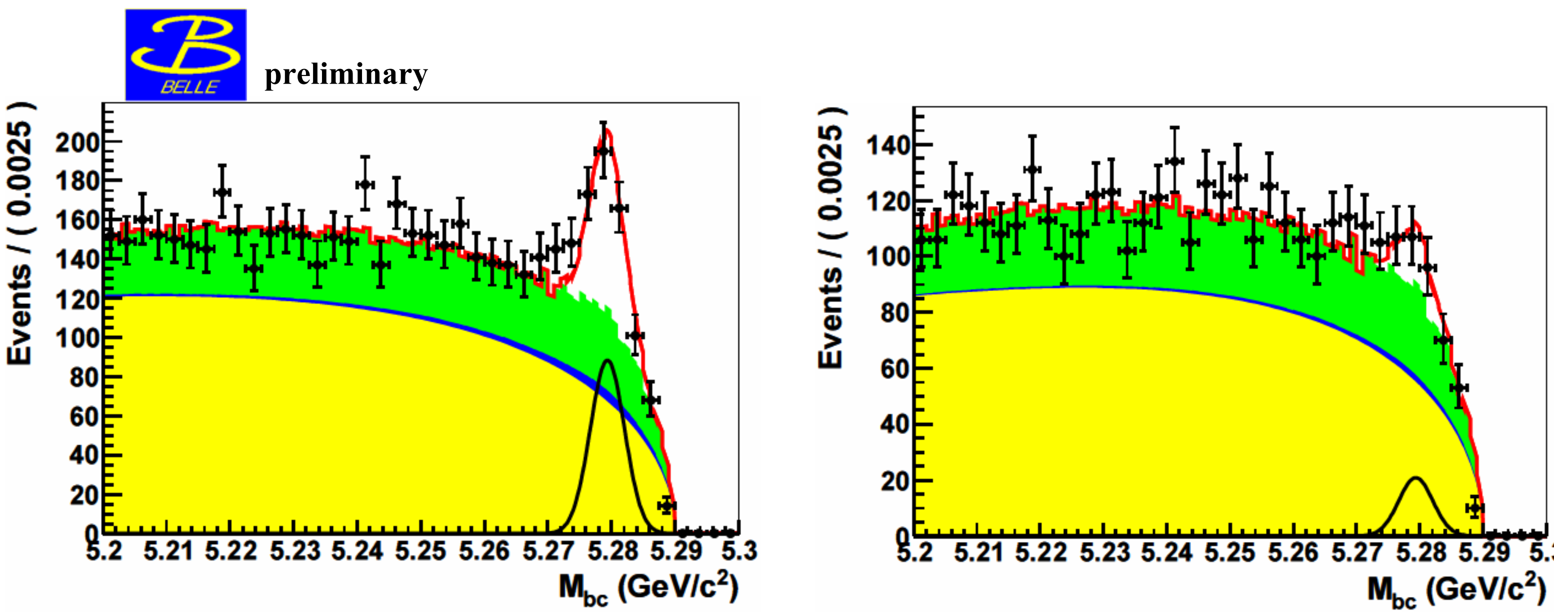
σ denotes the deviation from null asymmetry

Inclusive $b \to s\lambda^+\lambda^-$

- Not fully inclusive, rather the sum of a number of exclusive final states: $X_S = K + n\pi$, where n=0..4, for $m(X_S) < 2$ GeV/c^2
- Backgrounds from semi-leptonic B decays, continuum, leakage from J/ψ and ψ' veto, and $B \to X_S\pi^+\pi^-$ (double $\pi \to \mu$ misidentification)

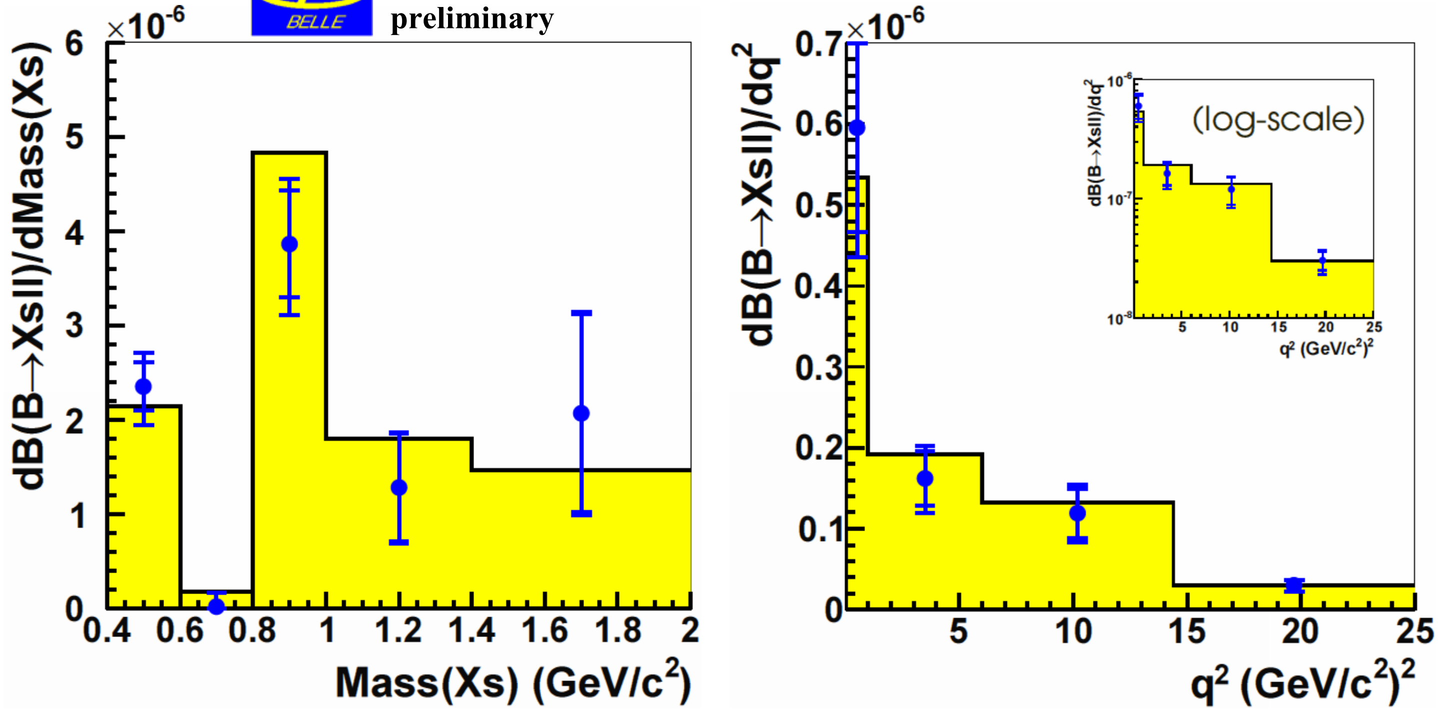
Left: About 10σ signal for the whole considered $m(X_S)$ spectrum

Right: 3σ signal for the high mass signal selection with $m(X_S) > 1$ GeV/c^2



Inclusive $b \to s\lambda^+\lambda^-$

preliminary



$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (3.33 \pm 0.80\,^{+0.19}_{-0.24}) \times 10^{-6}$$

- HFAG average: $\mathcal{B} = (3.66\,^{+0.76}_{-0.77}) \times 10^{-6}$

vs.

- SM prediction: $\mathcal{B} = (4.2 \pm 0.7) \times 10^{-6}$

The flipped C_7 case is not favored

Closing Remarks

- Both the B factories – Belle and BaBar – have established the KM paradigm as the only source of CP violation in SM
- The CPV content is however too little (by $\sim 10^{10}$) to explain the matter-antimatter asymmetry in our universe
- We know that something is there that we do not know
- There are also a number of hints and puzzles

Large Br($B \to \tau\nu$) ?	$\leftrightarrow$	tension between $|V_{ub}|$ - $\sin 2\phi_1$?
Large $A_{FB}(K^*ll)$?		Deviation of $A_l(K^*ll)$ in low q^2 ?
A_{CP} ($K\pi$) puzzle ?		Polarization puzzle in $B \to VV$?

- Eagerly look forward to the final updates from B factories, while warming up to the next-generation experiments ➡ LHCb and (future) super flavor factories