Results from the B-Factories

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(BaBar Collaboration)

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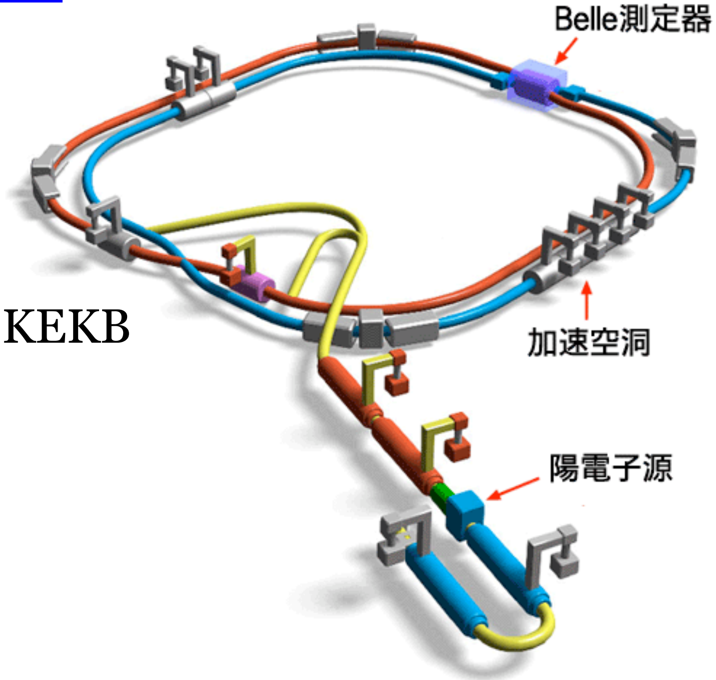
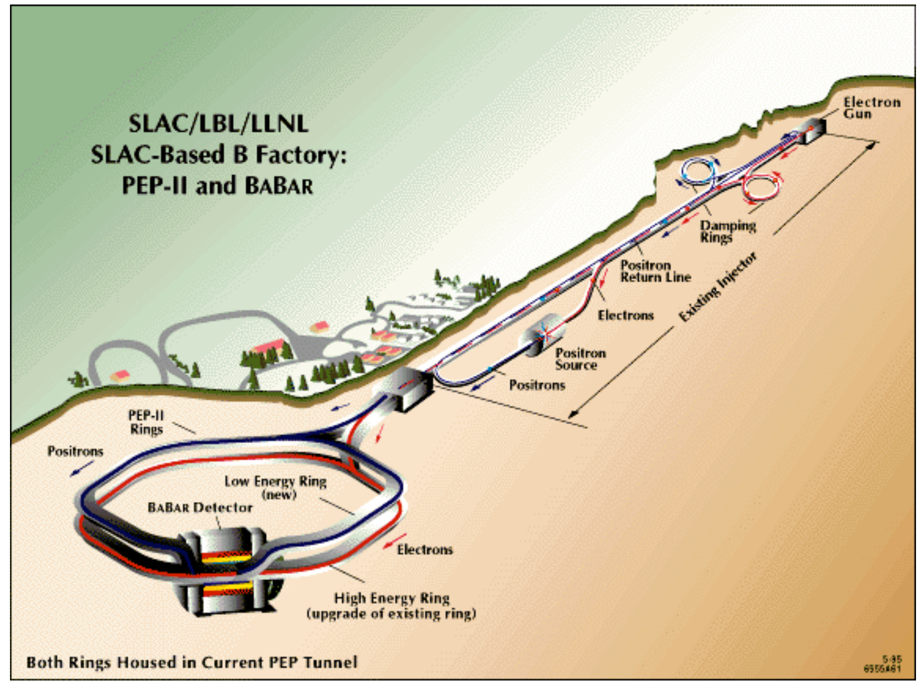
e+e- B-factories have a very broad scientific program

- CP & T-violation
- Precision CKM measurements
- Rare decays
- Searches for Processes beyond the SM
- Hadron production in Initial State Radiation
- Spectroscopy (see e.g. Yuan Changzheng presentation Tues. pm)
- ...

….. can only scratch the surface in this sampling of results

asymmetric B factories





$\sqrt{s}=10.58$ GeV

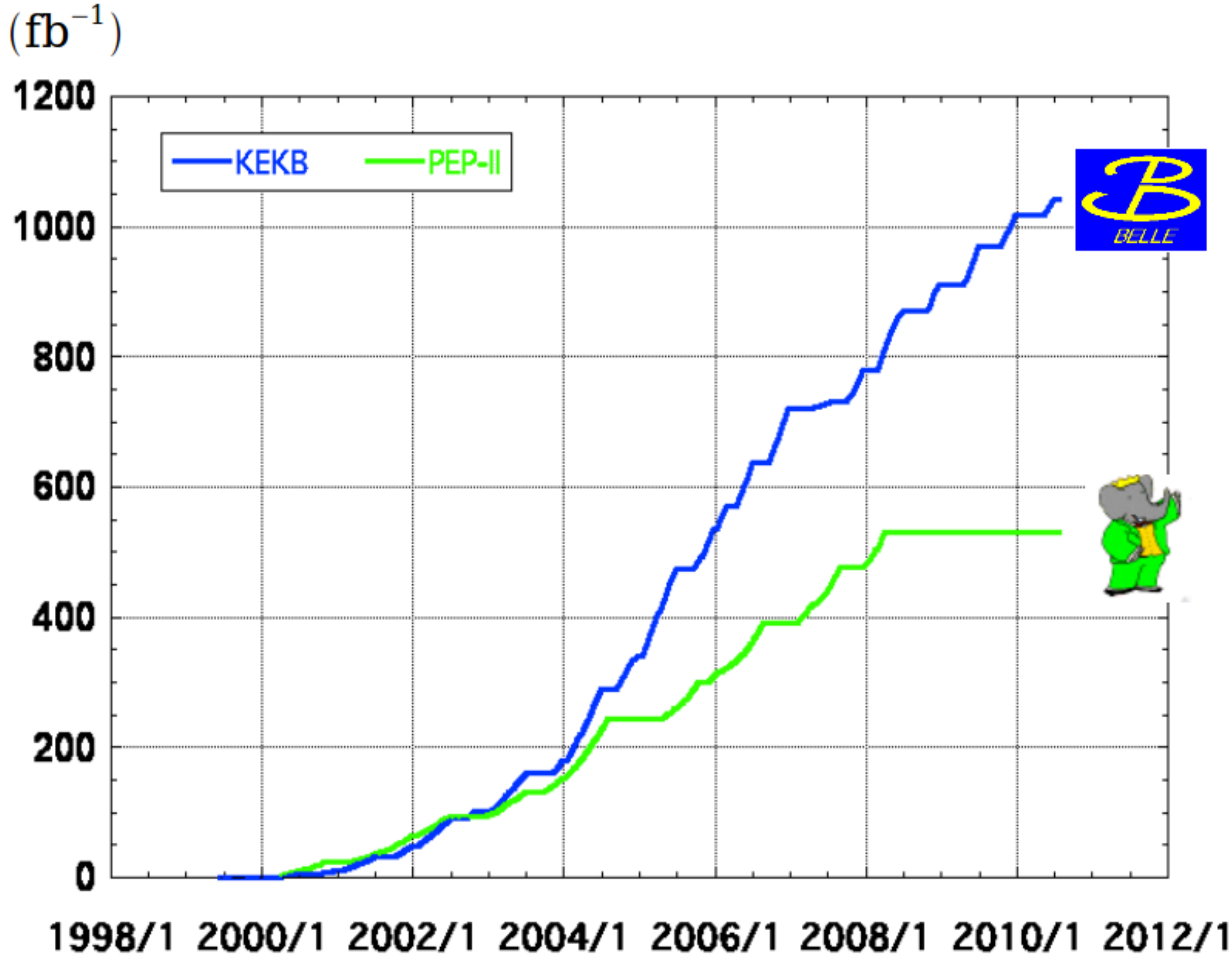
$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$

$\Upsilon(4s) \rightarrow B \bar{B}$

$\Delta_z \sim c\beta\gamma t_B \sim 200\mu m$

BaBar	$p(e^-)=9$ GeV	$p(e^+)=3.1$ GeV	$\beta\gamma=0.56$
Belle	$p(e^-)=8$ GeV	$p(e^+)=3.5$ GeV	$\beta\gamma=0.42$

Integrated luminosity of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

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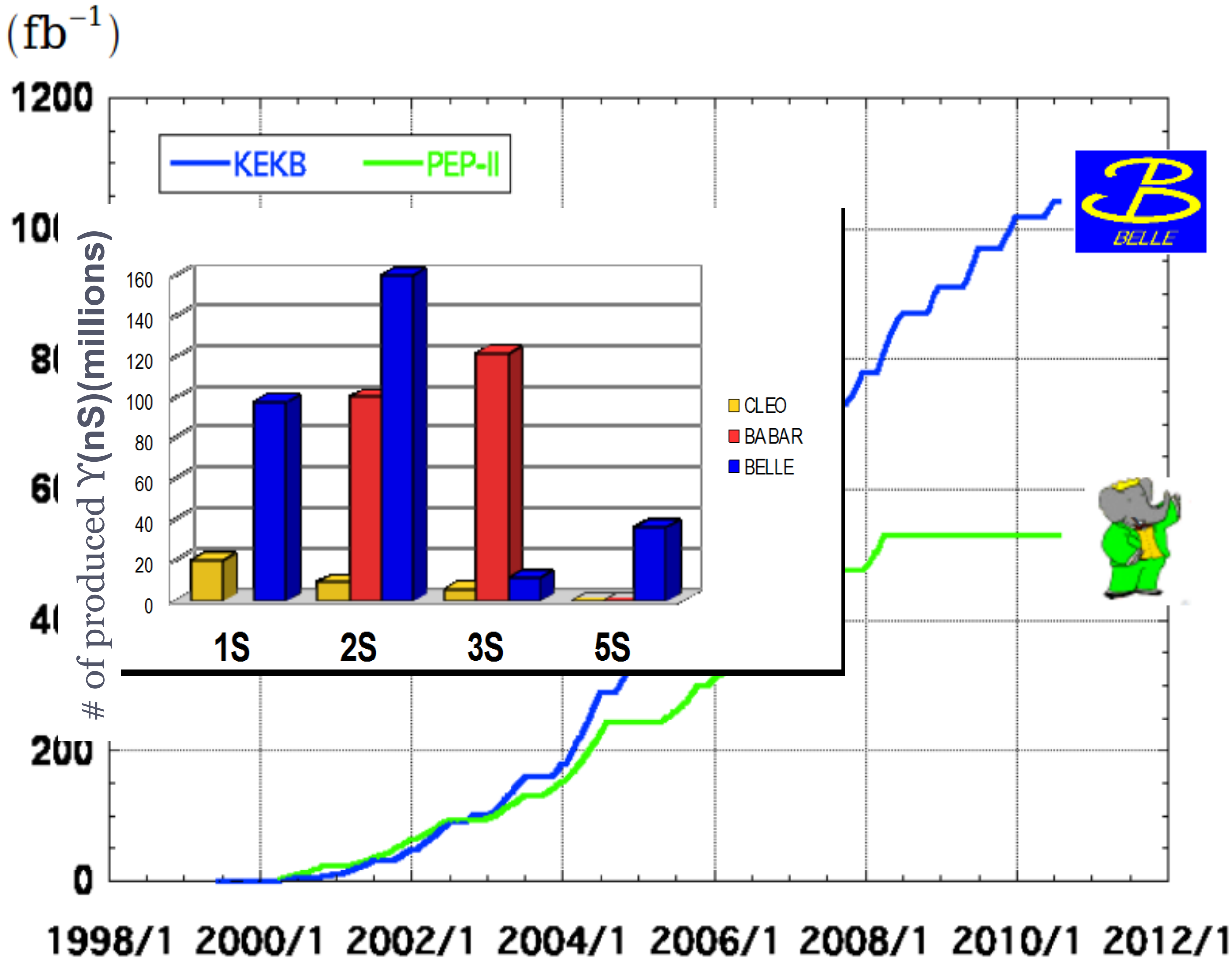
Integrated luminosity of B factories



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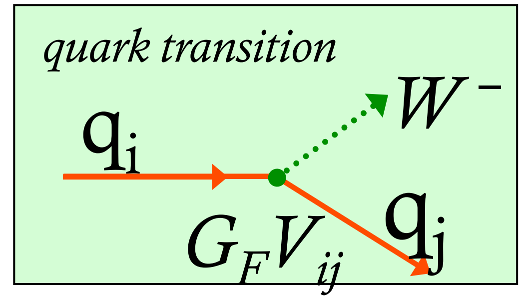
Off resonance:

~ 54 fb^{-1}

In SM weak charged transitions mix quarks of different generations - encoded in unitary CKM matrix:

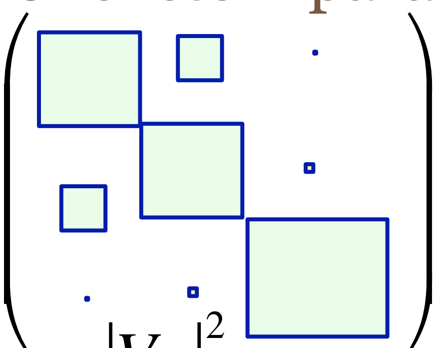
$$
\begin{pmatrix} d' & s' & b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}
$$



Unitarity → 4 independent parameters
one is the complex phase and sole source of CP violation in SM

In the Wolfenstein parameterisation:

$$
\mathbf{V}_{CKM} =
$$



$$
= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)
$$

$$
\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}; \quad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}; \quad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}
$$

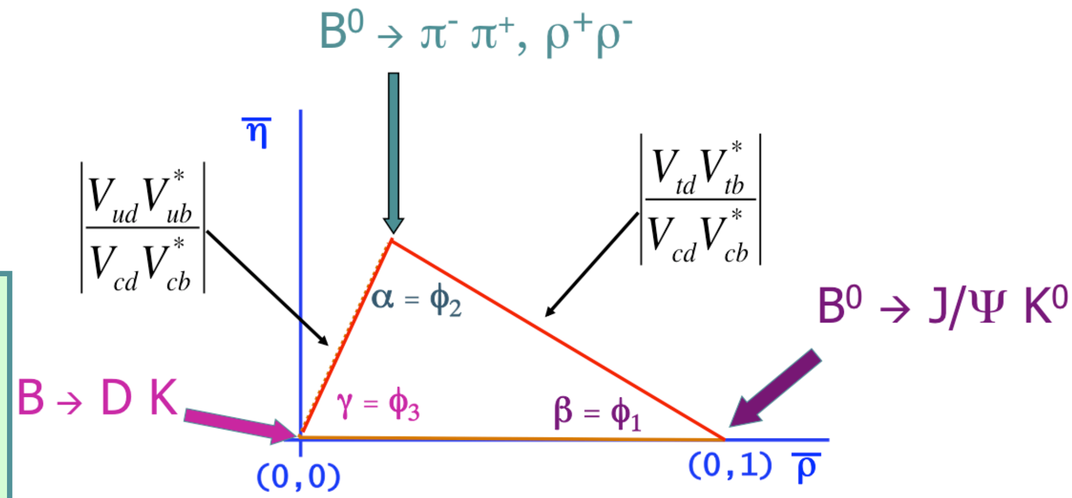
CKM Matrix

Physics beyond the SM signaled by breakdown of unitarity of CKM matrix: non-closure of the 'unitarity triangle'

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

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

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \quad \beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$



Area of triangle
in complex plane ~ CP violation

•Make as many precision measurements as possible that overconstrain the four CKM parameters (A, λ, ρ, η)

•New Physics would be revealed in discrepancies between measurements

•Generally requires non-perturbative QCD input to convert measurements to a SM CKM interpretation (but exceptions where single weak phase dominate as in J/φ Ks)

Belle and *BABAR* designed to measure and test CKM framework

- Sum of angles: $\alpha+\beta+\gamma = (177 \pm 9)^o$

  $\alpha = (88.5 \pm 4.5)^o$ $\beta = (21.4 \pm 0.8)^o$ $\gamma = (67 \pm 8)^o$

- Sides of triangle from semileptonic B decays:

$|V_{cb}|$ (Lattice QCD for FF)

$$|V_{cb}|^{LQCD}_{\rm excl} = (39.04 \pm 0.55_{\rm exp} \pm 0.74_{\rm th}) \times 10^{-3}$$
$$|V_{cb}|_{\rm incl} = (42.01 \pm 0.46_{\rm exp} \pm 0.59_{\rm th}) \times 10^{-3}$$
$$|V_{cb}|_{\rm average} = (40.81 \pm 0.90_{\rm exp} \pm 1.14_{\rm th}) \times 10^{-3}$$

NB: errors scaled by 2.4

$$|V_{ub}|^{LQCD}_{\rm excl} = (3.26 \pm 0.16_{\rm exp} \pm 0.24_{\rm th}) \times 10^{-3}$$
$$|V_{ub}|_{\rm incl} = (4.42 \pm 0.19_{\rm exp} \pm 0.15_{\rm th}) \times 10^{-3}$$
$$|V_{ub}|_{\rm average} = (3.95 \pm 0.38_{\rm exp} \pm 0.39_{\rm th}) \times 10^{-3}$$

NB: errors scaled by 3.0

$|V_{cb}|$ (HF Sum Rules for FF)

$$|V_{cb}|^{HFSR}_{\rm excl} = (40.93 \pm 0.57_{\rm exp} \pm 0.94_{\rm th}) \times 10^{-3}$$
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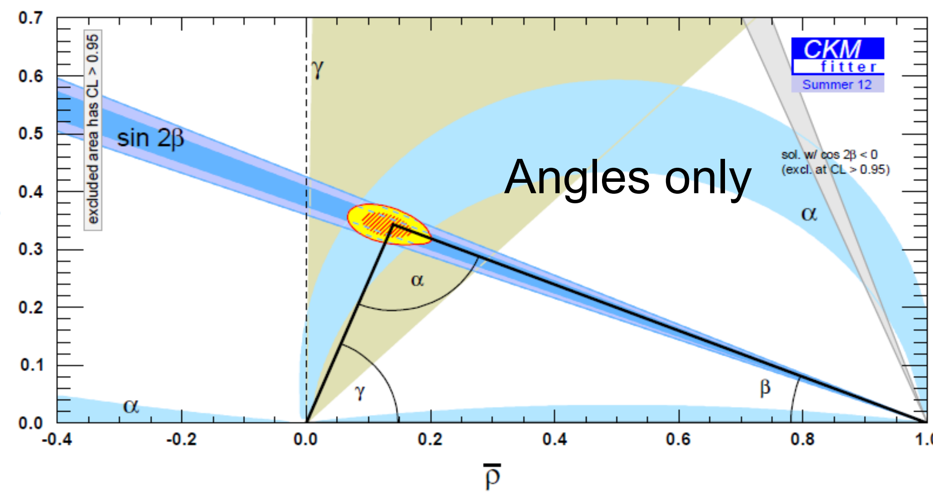

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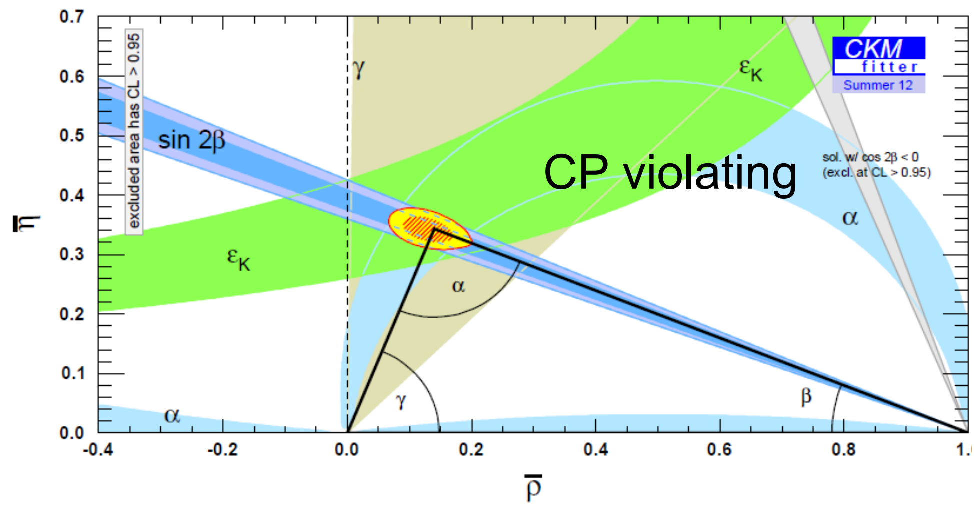

Unitarity Triangle and B System CP violation

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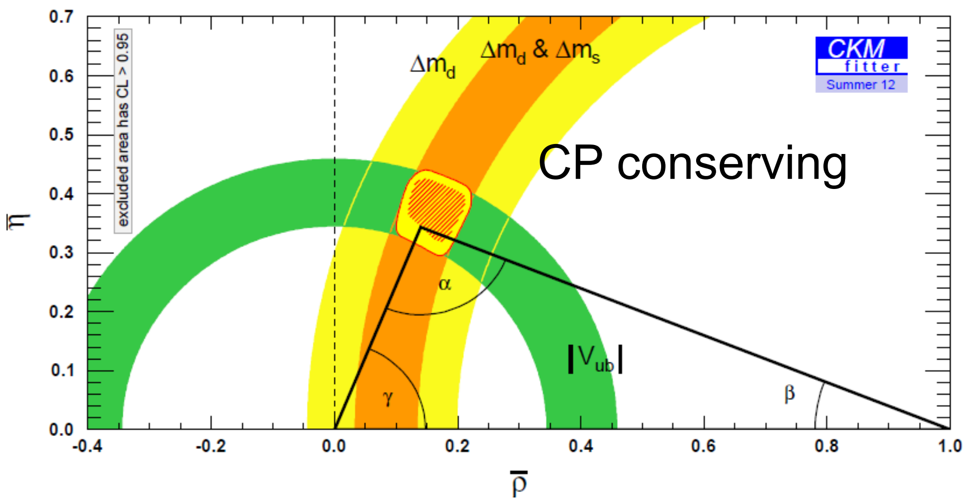

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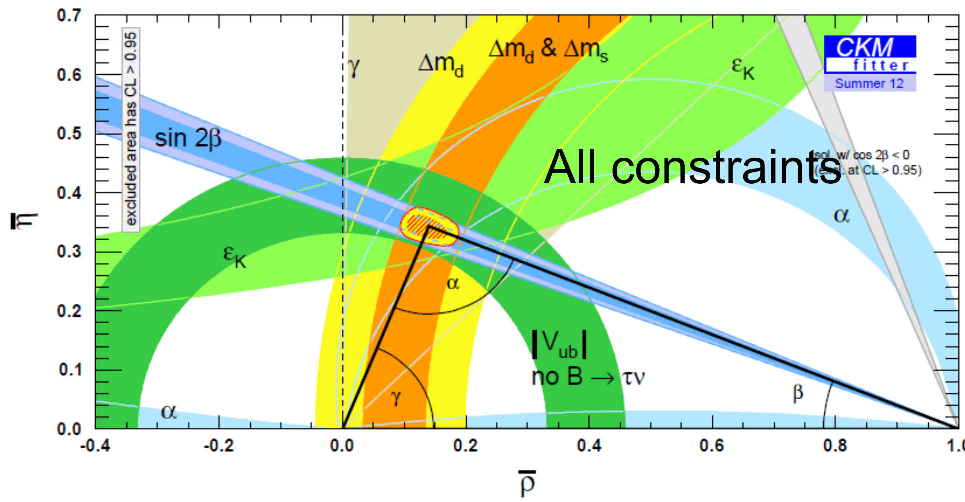
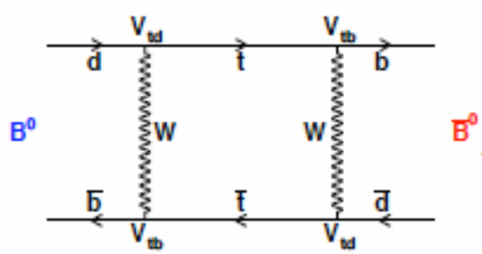


Data generally well described by CKM framework

Angle $\alpha=\phi_2$

$\alpha=\phi_2$ accessible via $b \to u$ transitions in $B \to \pi\pi, B \to \rho\rho$, or $B \to \rho\pi$

e.g. $B \to \pi^+\pi^-$ and $B \to \bar{B} \to \pi^+\pi^-$ interference



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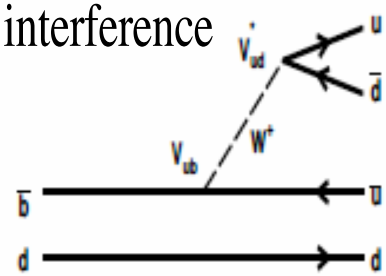
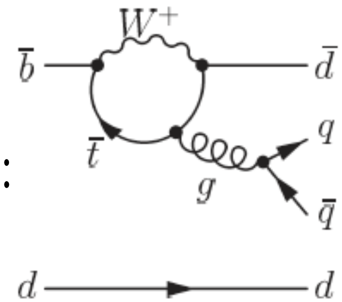


Complicated by penguins:



Time-dependent decay rate of a B or a $\bar{B}$ meson decaying into common CP eigenstate

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q \left[\mathcal{S}_{CP} \sin(\Delta m_d \Delta t) + \mathcal{A}_{CP} \cos(\Delta m_d \Delta t) \right] \right\}$$

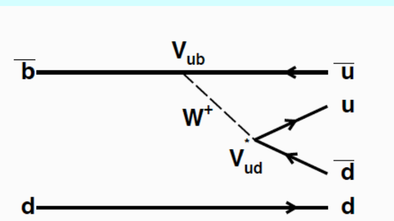
$S_{CP}=\sin 2\alpha$; $A_{CP}=0$ at tree level

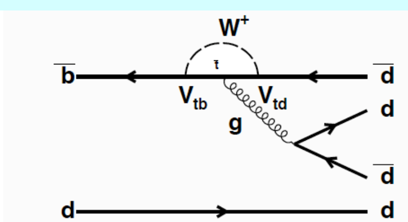
With additional penguin diagrams ('pollution')

$S_{CP}=\sqrt{1-A_{CP}^2}\sin 2\alpha_{eff}$; $A_{CP} \neq 0$ allowed

Isospin analysis using, e.g. $B \to \pi^0\pi^0$, recovers $\sin 2\alpha$

(penguin dominates over colour suppressed internal tree)





$\mathcal{A}_{CP}$: direct CP violation ($= -\mathcal{C}_{CP}$)

$\mathcal{S}_{CP}$: mixing induced CP violation

q: flavor of B_{tag}, $q=+1$ for $B_{tag}=B^0$

τ_{B^0}: B life time

Δm_d: mass difference of B_H and B_L

Δt: decay time difference of B_{CP} and B_{tag}

Angle $\alpha=\phi_2$

- New published result on $B \to \pi^+\pi^-$ from BaBar and Belle (BaBar also has $B \to \pi^0\pi^0$ on full dataset)

- $B \to \rho\rho$: VV final state, helicity analysis to measure CP
  - $B \to \rho^+\rho^-$ older from BaBar and Belle
  - $B \to \rho^0\rho^0$ full dataset from BaBar and Belle (new 2012)

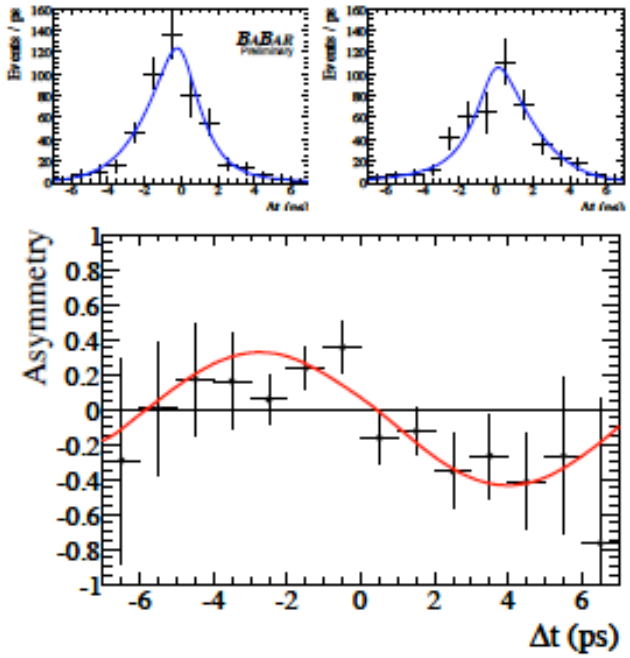
- $B \to (\rho\pi)^0$ new result from BaBar: warning about lack of robustness in extracting $\alpha = \phi_2$ with current statistics

Angle $\alpha=\phi_2$

$B \to \pi^+\pi^-$

BaBar PRD **87** 052009(2013)

$467 \times 10^6 B\bar{B}$ pairs

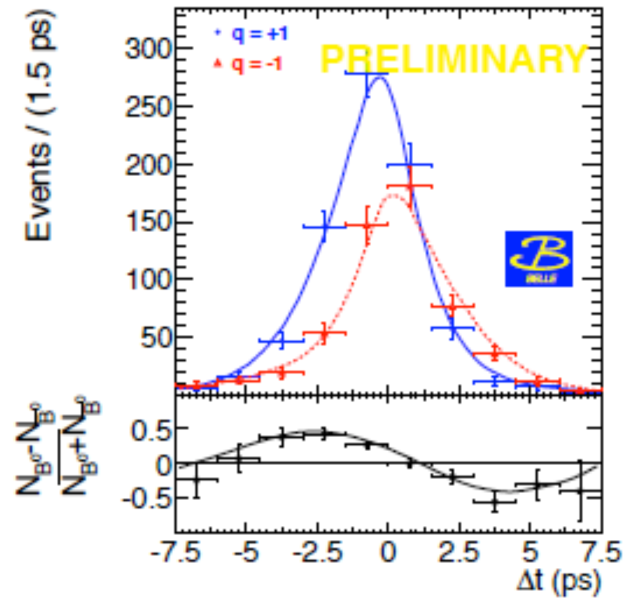


$$\mathcal{S}_{CP}^{\pi^+\pi^-} = -0.68 \pm 0.10 \pm 0.03$$

$$\mathcal{A}_{CP}^{\pi^+\pi^-} = +0.25 \pm 0.08 \pm 0.02$$

Belle arXiv:1302.0551

$772 \times 10^6 B\bar{B}$ pairs



$$\mathcal{S}_{CP}^{\pi^+\pi^-} = -0.636 \pm 0.082 \pm 0.027$$

$$\mathcal{A}_{CP}^{\pi^+\pi^-} = +0.328 \pm 0.061 \pm 0.027$$

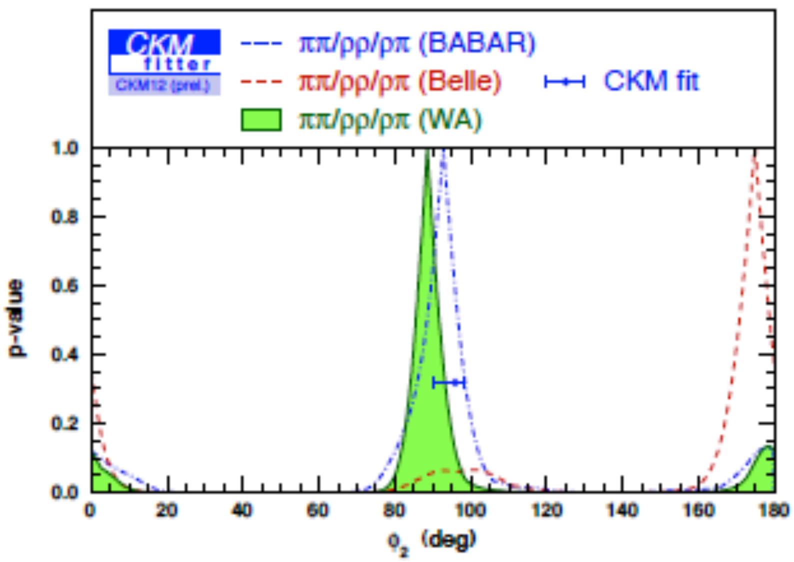
$\Rightarrow$ clear mixing induced $\not{CP}$ and presence of penguins

Angle $\alpha = \phi_2$

Overall fits for $\alpha = \phi_2$ using

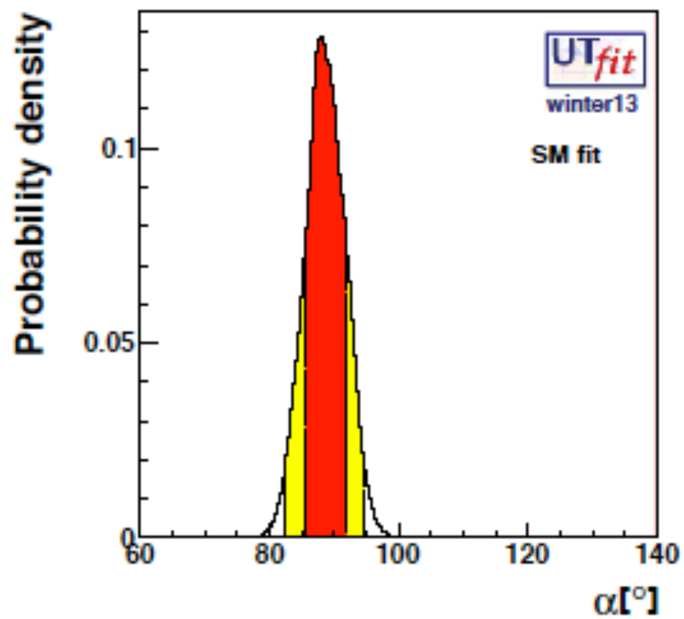
$B \to \pi\pi$, $B \to \rho\rho$, or $B \to \rho\pi$

(frequentist)



$$\phi_2/\alpha = (88.5^{+4.7}_{-4.4})^\circ$$

(bayesian)

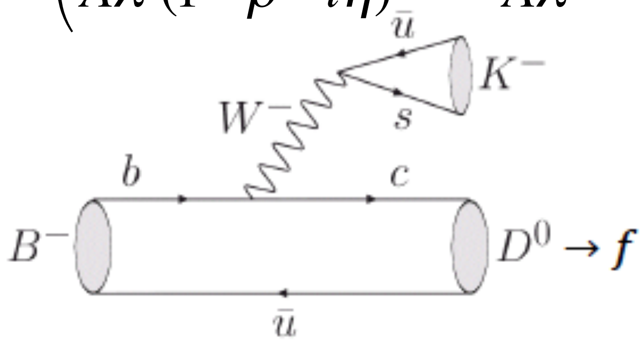


$$\phi_2/\alpha = (88.7 \pm 3.1)^\circ$$

$B^{\pm} \to D^{(*)0} K^{(*)\pm}$ decays dominate $\gamma = \phi_3$ measurements

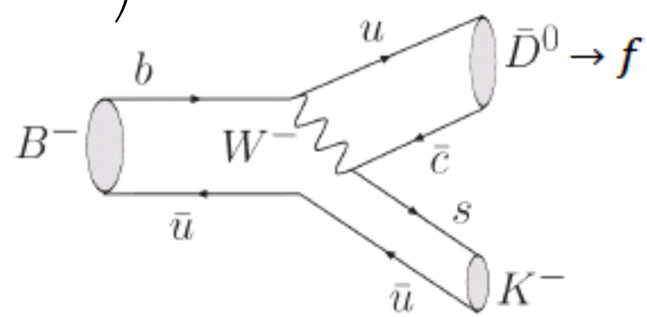
$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$|V_{ub}| e^{-i\gamma}$



color allowed

$A_1 \propto V_{cb} V_{us}^* \sim A\lambda^3$



color suppressed

$A_2 \propto V_{ub} V_{cs}^* \sim A\lambda^3(\rho + i\eta)$

$$|A_{total}|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(-\gamma + \delta)$$

Theoretically clean: no penguin pollution

$$r_b = \left| \frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \overline{D}^0 K^+)} \right|$$

strong phase from B and D decay

Unknowns: $\gamma,\ r_b,\ \delta_b + \delta_D$

r_b & δ_b B hadronic parameters extracted with γ

δ_D measured at charm factories

Angle $\gamma=\phi_3$

$B^{\pm} \to D^{(*)0}K^{(*)\pm}$ decays dominate $\gamma = \phi_3$ measurements

Different methods for extracting $\gamma = \phi_3$ depending on the D decay mode final state

GLW [M. Gronau, D. London, D. Wyler, PLB253,483 (1991); PLB 265, 172 (1991)]

- D^0 to two-body CP eigenstates K^+K^-, $\pi^+\pi^-$ (even), $K_s\pi^0$, $K_s\omega$ (odd)

ADS [D. Atwood, I. Dunietz, A. Soni, PRL 78, 3357 (1997)]

- D^0 to doubly Cabibbo suppressed decays $K^+\pi^-$, $K^+\pi^-\pi^0$, ...

GGSZ (Dalitz) [D. Atwood et al., PRL78, 3257 (1997); A. Giri et al., PRD68, 054018 (2003)]

- D^0 to 3-body decays $K_s\pi^+\pi^-$, $K_sK^+K^-$, $\pi^+\pi^-\pi^0$, etc.
  - Dalitz plot fitted to determine how the strong phase of D^0 decay amplitude varies over the Dalitz plane
  - model independent analysis

BABAR and Belle have reconstructed the most sensitive decay modes using all or nearly all of their full datasets

GLW+ADS+GGSZ Combinations

BABAR PRD87 052015 (2013)	*BABAR* and Belle	Belle CKM2012 arXiv:1301.2033
$\gamma = \left(69^{+17}_{-16}\right)^{\circ}$ (mod 180°)	Physics of the B Factories to be submitted EPJC	
exp+DP model systematic= $\pm 4^{\circ}$	$\gamma = (67 \pm 11)^{o}$ (mod 180^{o})	$\gamma = \left(68^{+15}_{-14}\right)^{o}$ (mod 180^{o})

Angle $\gamma=\phi_3$

$B^\pm \to D^{(*)0}K^{(*)\pm}$ decays dominate $\gamma = \phi_3$ measurements

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BABAR and Bell[...]ve decay modes
us[...]ts

LHCb with 3fb^{-1}

$$\gamma = (67 \pm 12)^o \quad (\text{mod } 180^o)$$

BABAR PRD87 052015 (2013)

$$\gamma = \left(69^{+17}_{-16}\right)^\circ \quad (\text{mod } 180^\circ)$$

exp+DP model systematic=$\pm 4^\circ$

BABAR and Belle

Physics of the B Factories to be submitted EPJC

$$\gamma = (67 \pm 11)^o \quad (\text{mod } 180^o)$$

Belle CKM2012 arXiv:1301.2033

$$\gamma = \left(68^{+15}_{-14}\right)^o \quad (\text{mod } 180^o)$$

T Violation: BABAR, PRL 102, 211801 (2013)

- Well established canon of SM that weak interactions maximally violate parity (P) and charge conjugation (C) – neutrinos are LH, antineutrinos are RH.
- CP also measured to be violated in neutral kaon and B-meson systems – phenomena well described within CKM framework
- The CPT Theorem (Locally Lorentz-invariant QFT conserves CPT) $\longrightarrow$ if there is CP violation, there is also violation of time reversal invariance (T)
- Difficult to establish experimentally T violation independent of CPT: need a system where we experimentally know what QM state is in before it decays.

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B(\alpha)\, B(\overline{\alpha})$ is an entangled P-wave state: EPR tells us the state of a B-meson prior to its decay if its EPR-entangled partner decays and is identified – it's how BaBar and Belle measure CP violation …
can also use this to search for direct T violation and test CPT using this approach

Bernabeau, Martinez-Vidal, Villanueva-Perez, arXiv: JHEP08,064 (2012)

T Violation: BABAR, PRL 102, 211801 (2013)

- *BABAR* uses this approach to measure a non-zero T violation - strength predicted by CPT and the CP violation measured by *BABAR* and Belle

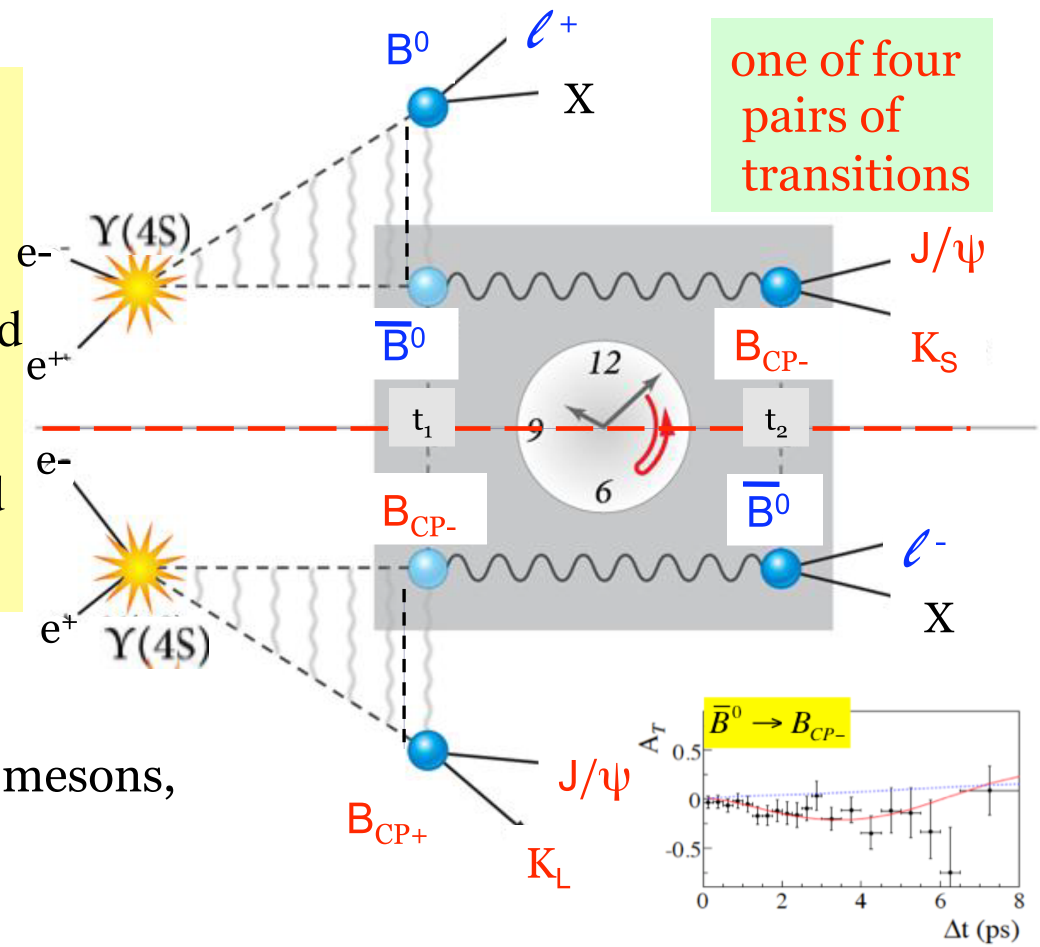
$$|i\rangle = \frac{1}{\sqrt{2}}\left[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)\right] = \frac{1}{\sqrt{2}}\left[B_{CP+}(t_1)B_{CP-}(t_2) - B_{CP-}(t_1)B_{CP+}(t_2)\right]$$

Define ratio

$$A_T = \frac{P(a \to b) - P(b \to a)}{P(a \to b) + P(b \to a)}$$

a : Flavour eigenstate B^0 or $\bar{B}^0$ identified by semileptonic decay : ℓ^+ or ℓ^-

b : *CP* eigenstate B_{CP+} or B_{CP-} identified by decay to : $J/\psi K_S$ or $J/\psi K_L$



one of four pairs of transitions

Measure time-ordered decays of both B-mesons, time difference defined as:

$\Delta t = t_{CP} - t_{flavour}$ > 0 for $B^0 \rightarrow B_{CP-}$
< 0 for $B_{CP-} \rightarrow B^0$

T Violation: BABAR, PRL 102, 211801 (2013)

- Time dependent rate 8 decays

$$g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma\Delta\tau}\{1 + S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \Delta\tau) + C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \Delta\tau)\}$$

four pairs of transitions

S and C probe interference in decay-mixing and decay

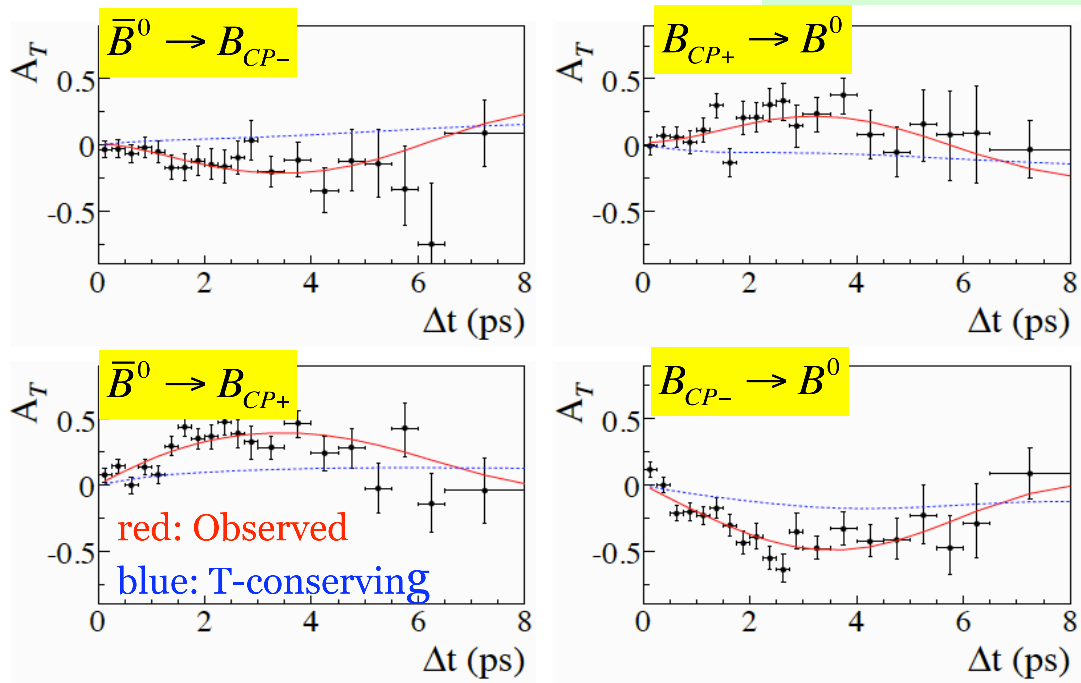
ML fit to determine 8 pairs of $S^{\pm}_{\alpha,\beta}$ and $C^{\pm}_{\alpha,\beta}$ parameters

$\pm$ {Δt>0, Δt <0}

α flavour tag {ℓ^+, ℓ^-}

β CP tag {K_L,K_S}

$$A_T(\Delta t) \approx \frac{\Delta C_T^+}{2}\cos\Delta m\Delta t + \frac{\Delta S_T^+}{2}\sin\Delta m\Delta t$$



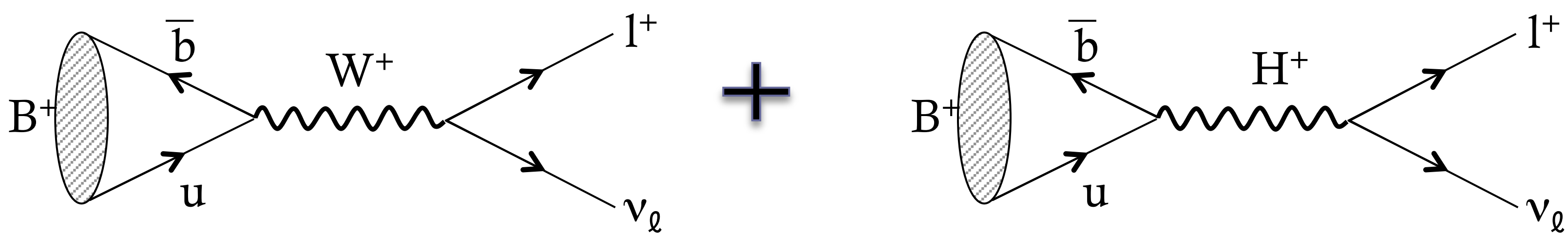
Combined Fit results:	Expected:
ΔS^+_T = -1.37 ± 0.14 ± 0.06	-2 sin2β
ΔC^+_T = +0.10 ± 0.14 ± 0.08	0.0
ΔS^-_T = +1.17 ± 0.18 ± 0.11	+2 sin2β
ΔC^-_T = +0.04 ± 0.14 ± 0.08	0.0

14σ signal
Consistent with sin2β results on CP Violation and with CPT invariance

$B^- \to \ell^- \nu_\ell$ simple purely leptonic pseudo-scalar decays carry information about product of CKM element and strong interaction 'decay constant'

$$BF(B \to \ell\nu)_{SM} = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 |V_{ub}|^2 f_B^2 \tau_M \left(1 + \delta_{EM}^{B\ell 2}\right)$$

- Interesting because some New Physics theories have charged Higgs contributing to observed decay rate



- Additional tree level contribution from a charged Higgs
  - It does not suffer from helicity suppression, but gets the same m_l dependence from Yukawa coupling
  - Branching fraction theoretical expression depends on the NP model

$$\mathcal{B}(B \to l\nu)_{2HDM} = \mathcal{B}(B \to l\nu)_{SM} \times \left(1 - tan^2\beta \frac{m_B^2}{m_H^2}\right)^2$$

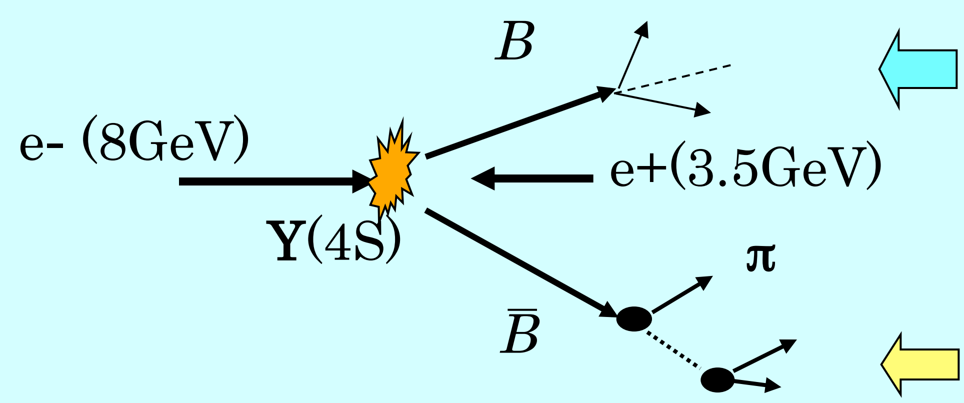
W. S. Hou, Phys. Rev. D 48 (1993) 2342.

$$\mathcal{B}(B \to l\nu)_{SUSY} = \mathcal{B}(B \to l\nu)_{SM} \times \left(1 - \frac{tan^2\beta}{1 + \epsilon_0 tan\beta} \frac{m_B^2}{m_H^2}\right)^2$$

A.G. Akeroyd and S.Recksiegel J.Phys.G29:2311-2317,2003

Uses full reconstruction tagging

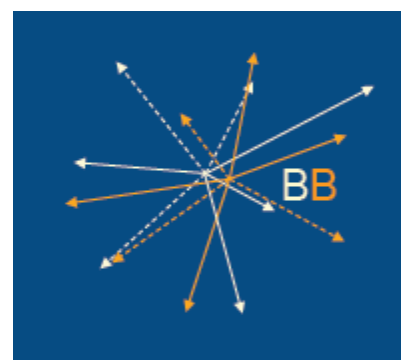
- fully reconstruct one of the B's to tag B flavour/charge, determine its momentum, and exclude decay products of this B from further analysis



Signal Decays:
- $B \to \tau\nu$
- $B \to D(*)\, \tau\nu$,
- $B \to K\, \nu\, \nu$
- $B \to X_u\, l\, \nu$,

full reconstruction
$B \to D\pi$ etc. (0.1-0.3%)

Powerful tool for B decays with neutrino
→unique feature at e+e- B factories



At the Υ(4S) the B^+ and B^- decay products overlap, this associates parent B with each particle

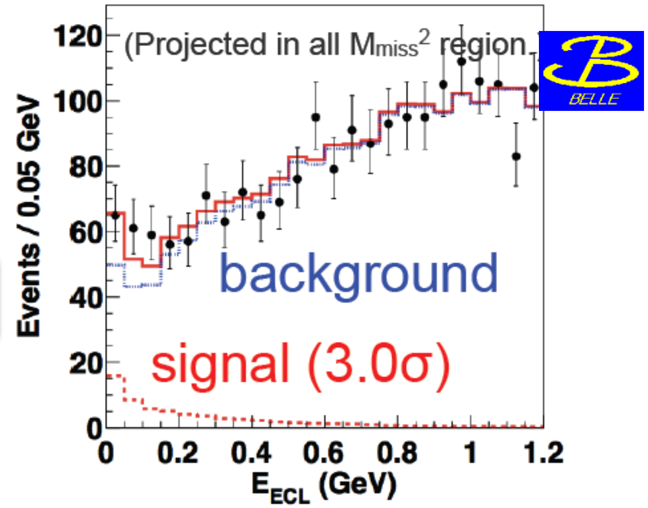
$B^- \to \tau^- \nu_\tau$ Results

Main discriminating variable on the signal side: remaining energy in the calorimeter, not associated with any charged track or photon

→ Signal at $E_{ECL} = 0$

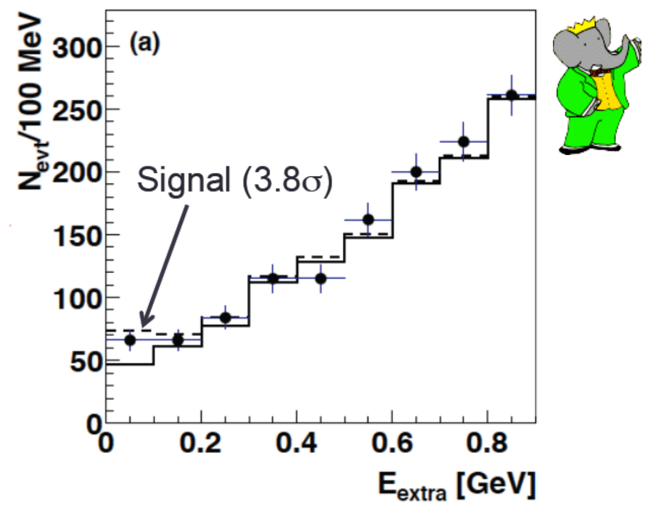
Belle $$Br(B \to \tau\nu) = [0.72\ ^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$$

PRL 110 (2013) 131801



BABAR $$Br(B \to \tau\nu) = [1.83\ ^{+0.53}_{-0.49} \pm 0.24] \times 10^{-4}$$

arXiv:1207.0698[hep-ex] submitted to PRD



All measurements combined:

$$BF(B \to \tau\nu) = (1.15 \pm 0.23) \cdot 10^{-4}$$

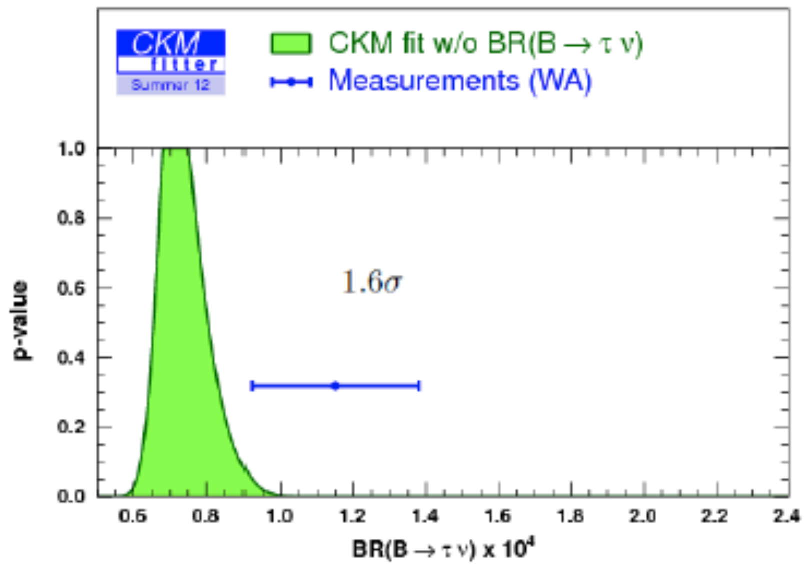
cf Standard Model:

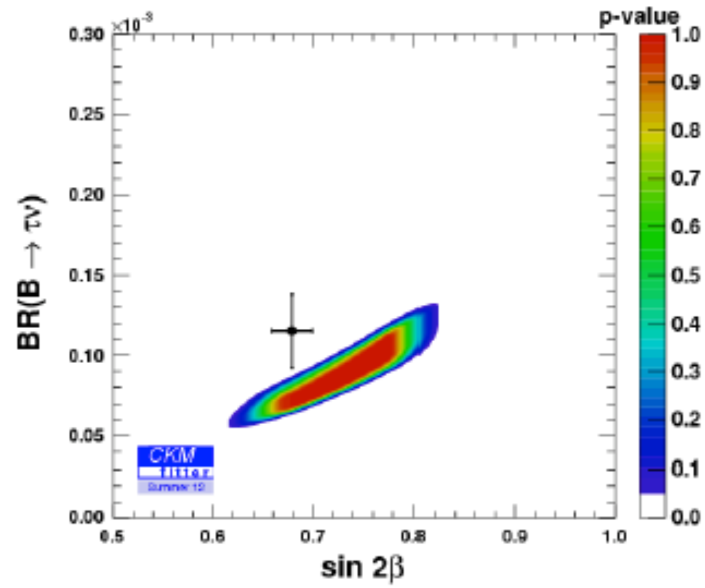
$$BF(B \to \tau\nu)_{SM} = (1.01 \pm 0.29) \times 10^{-4}$$

$$\text{(using } |V_{ub}| = (3.95 \pm 0.38 \pm 0.39) \times 10^{-4}\text{)}$$

Results after ICHEP 2012

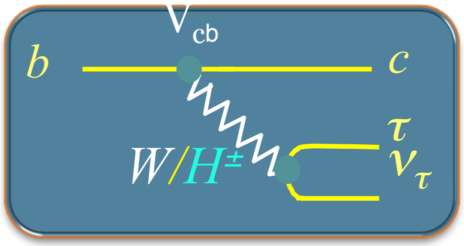
$$BF(B \to \tau\nu) = (1.15 \pm 0.23) \cdot 10^{-4}$$





B → D(*)τν Decays

Semileptonic decay sensitive to charged Higgs



Ratio of τ to μ,e could be reduced/enhanced significantly

$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

- A well understood process, form factors measured for B → D(*)ℓν, decays involving τ have additional helicity amplitude
- Several experimental and theoretical uncertainties cancel in the ratio!
- non-SM contribution from H± expected to change rates for B → D(*)τν

Scalar Helicity Amplitude: (good to 1% for $m_{H^\pm} > 15\text{GeV}$)

$$H_S^{2HDM} \approx H_S^{SM} \times \left(1 - \frac{\tan^2\beta}{m_{H^\pm}^2} \frac{q^2}{1 \mp m_c/m_b}\right) \quad \begin{matrix} - & \text{for } B \to D\tau\upsilon \\ + & \text{for } B \to D^*\tau\upsilon \end{matrix}$$

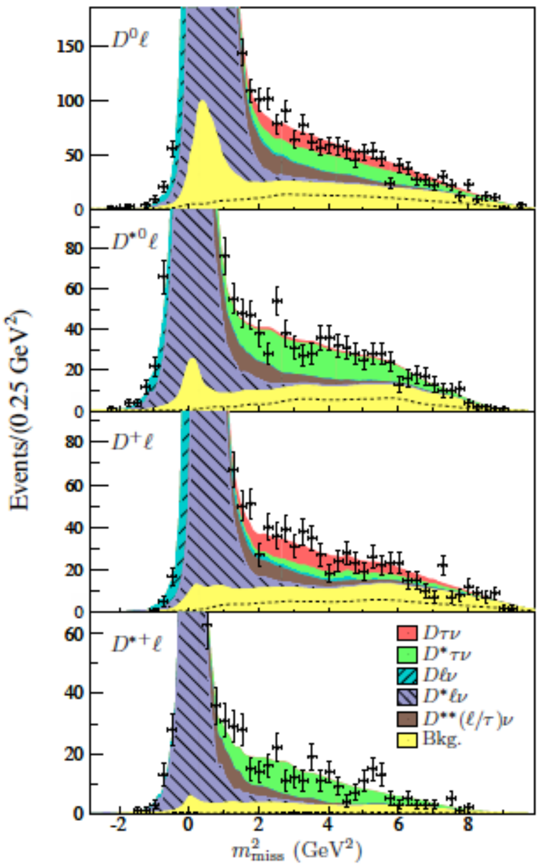
BABAR, PRL101802 (2012)

$$\mathcal{R}(D)_{\rm exp} = 0.440 \pm 0.072 \quad \mathcal{R}(D^*)_{\rm exp} = 0.332 \pm 0.030$$

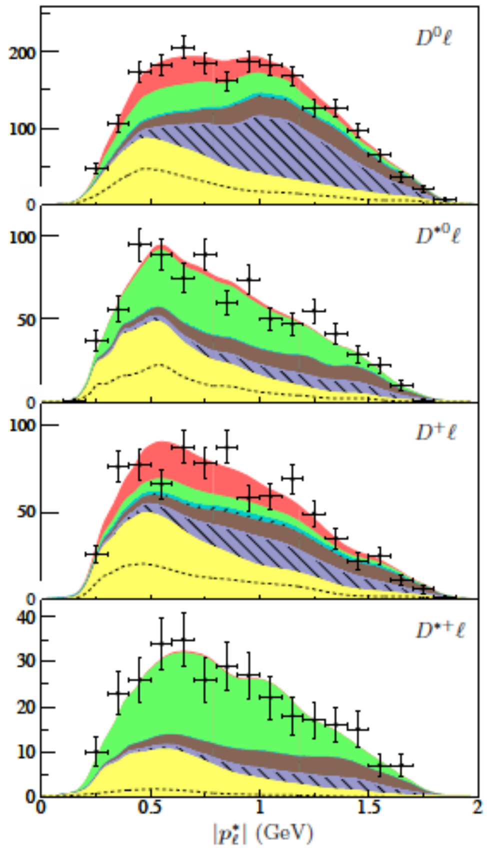
2.0σ 2.7σ

$$\mathcal{R}(D)_{\rm SM} = 0.297 \pm 0.017 \quad \mathcal{R}(D^*)_{\rm SM} = 0.252 \pm 0.003$$

SM expectations in S. Fajfer, J. Kamenik, I. Nisandzic, PRD 85, 094025 (2012).

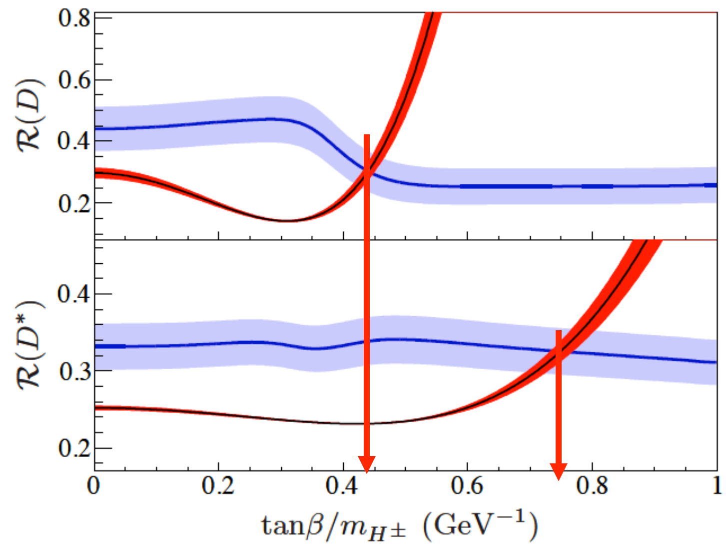


Missing Mass Squared



Lepton momentum in B frame

Combined BaBar result: 3.4σ above SM



$$\frac{BF(B \to D^{(*)}\tau\upsilon)}{BF(B \to D^{(*)}\ell\upsilon)} \quad vs \ \tan\beta/m_{H^\pm}$$

BABAR, PRL101802 (2012)

$$\mathcal{R}(D)_{\rm exp} = 0.440 \pm 0.072 \quad \mathcal{R}(D^*)_{\rm exp} = 0.332 \pm 0.030$$

2.0σ   2.7σ

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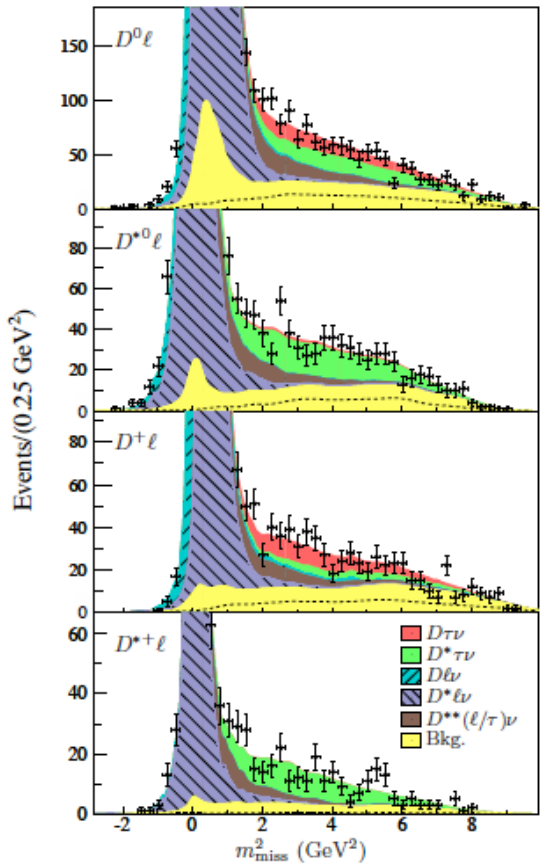
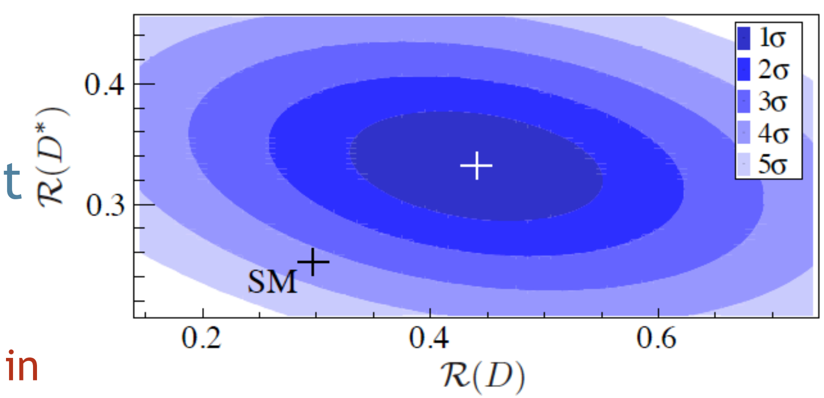


Missing Mass Squared

If discrepancy with SM holds, result cannot be explained by Type II 2HDM; excluded over full parameter space at 99.8%CL

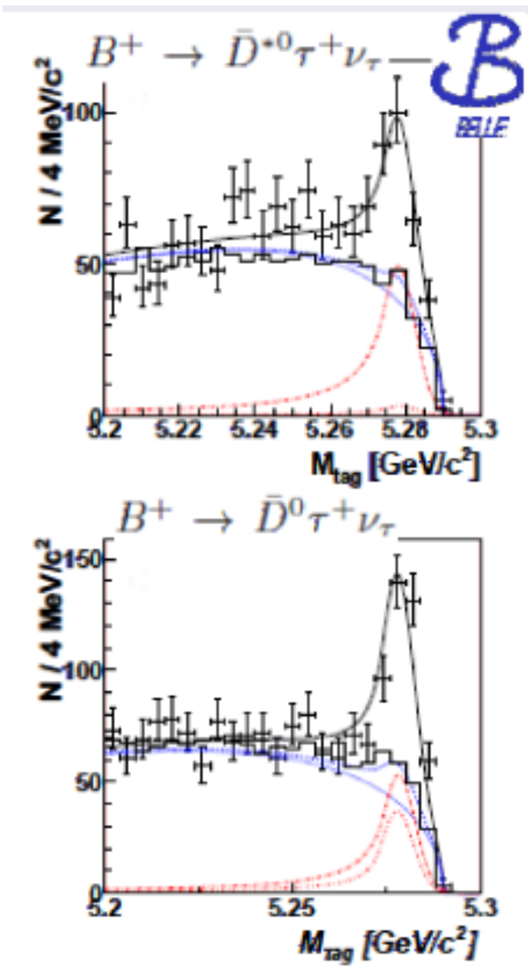
Can be accommodated in more general extensions of Type III 2HDM

Combined BaBar result: 3.4σ above SM



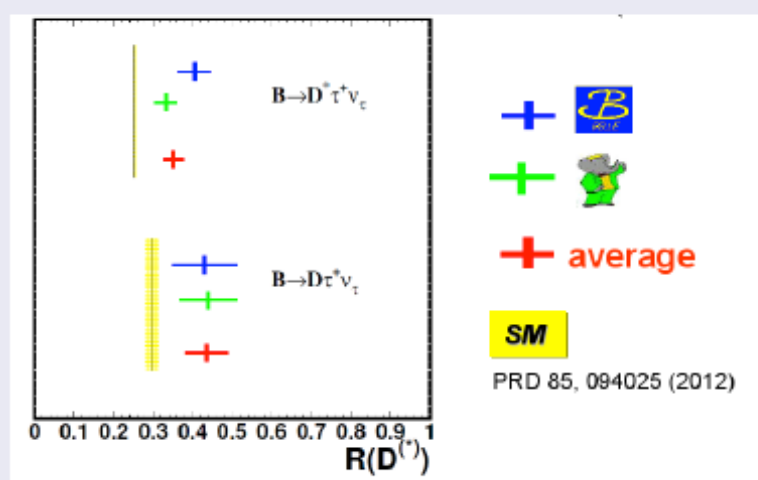
Belle, PRL99, 191807(2007)
Belle, PRD 82 (2010)

First observation of B → $D^{*-}\tau\nu$ by Belle (2007)



Belle did not publish a measurement of the ratio directly for all modes and so did not quote average R values. Publications based on fraction of Belle data

At May 2013 FPCP meeting Andrej Bozek (Belle) presented a 'private average' of the published Belle results



private average of Belle results

Belle Deviations from SM based on A. Bozek average of Belle results (FPCP 2013)
$R(D^*) = 3.0\sigma$
$R(D) = 1.4\sigma$
$R(D^{(*)}) = 3.3\sigma$

Bozek reports a combined BaBar and Belle deviation from the SM of 4.8σ

Searches for Light CP-odd Higgs

- $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \text{hadrons}$
- $\Upsilon(1S) \to \gamma A^0, A^0 \to \tau^+\tau^-,\ \mu^+\mu^-$

Dark Higgs Searches

- $e^+e^- \to A'h',\ \ h' \to A'A',\ \ A' \to h_1h_2\ \ (h_i = e, \mu, \pi)$

New BABAR result – shown first here at Lepton Photon 2013:

Search for light Higgs decaying to two gluons or $s\bar{s}$ in radiative decays of the $\Upsilon(1S)$

BaBar Searches for Light CP-odd Higgs

Search for light Higgs decaying to two gluons or $s\bar{s}$ in radiative decays of the $\Upsilon(1S)$

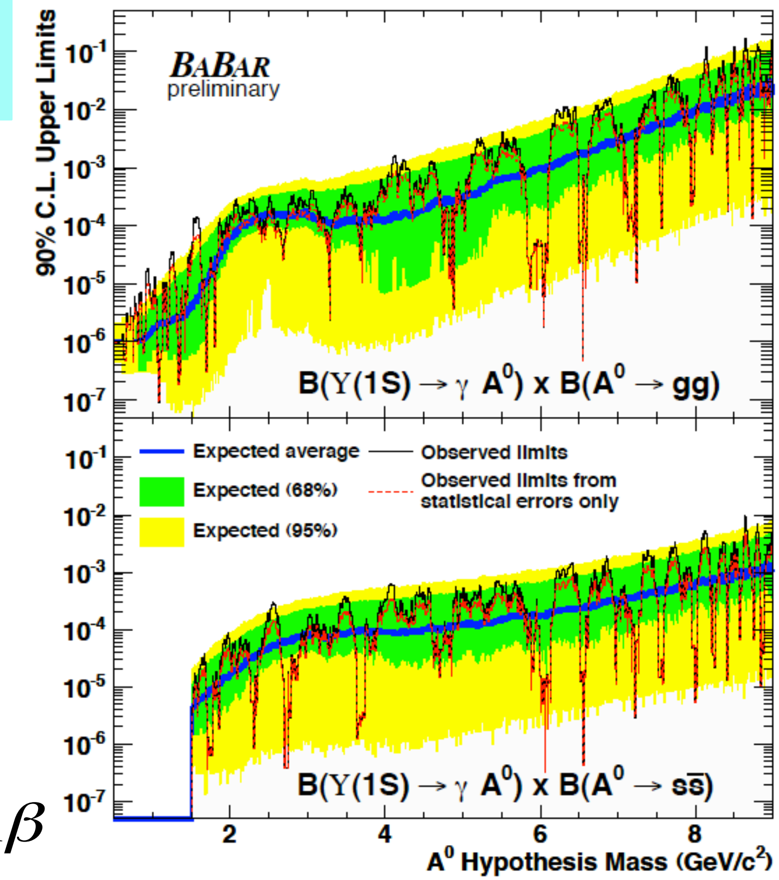
$$e^+e^- \to \Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$$

$$\Upsilon(1S) \to \gamma A^0;\, A^0 \to gg \text{ or } s\bar{s}$$

Sample: 17.6×10^6 $\Upsilon(1S)$ decays

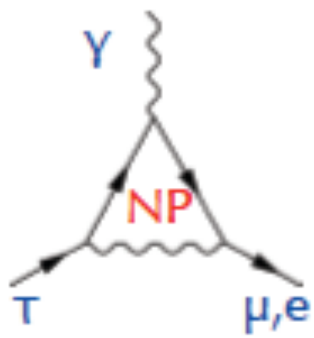
At low Higgs mass, $m_A < 2m_\tau$:

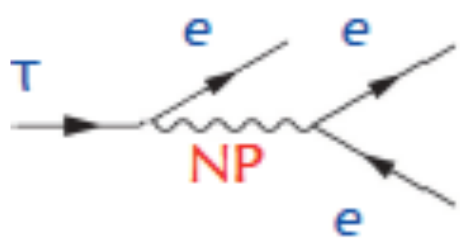
- expect $s\bar{s}$ to dominate rate at high $\tan\beta$
- expect gg to dominate rate at low $\tan\beta$



Lepton Flavour Violation in Tau Decays

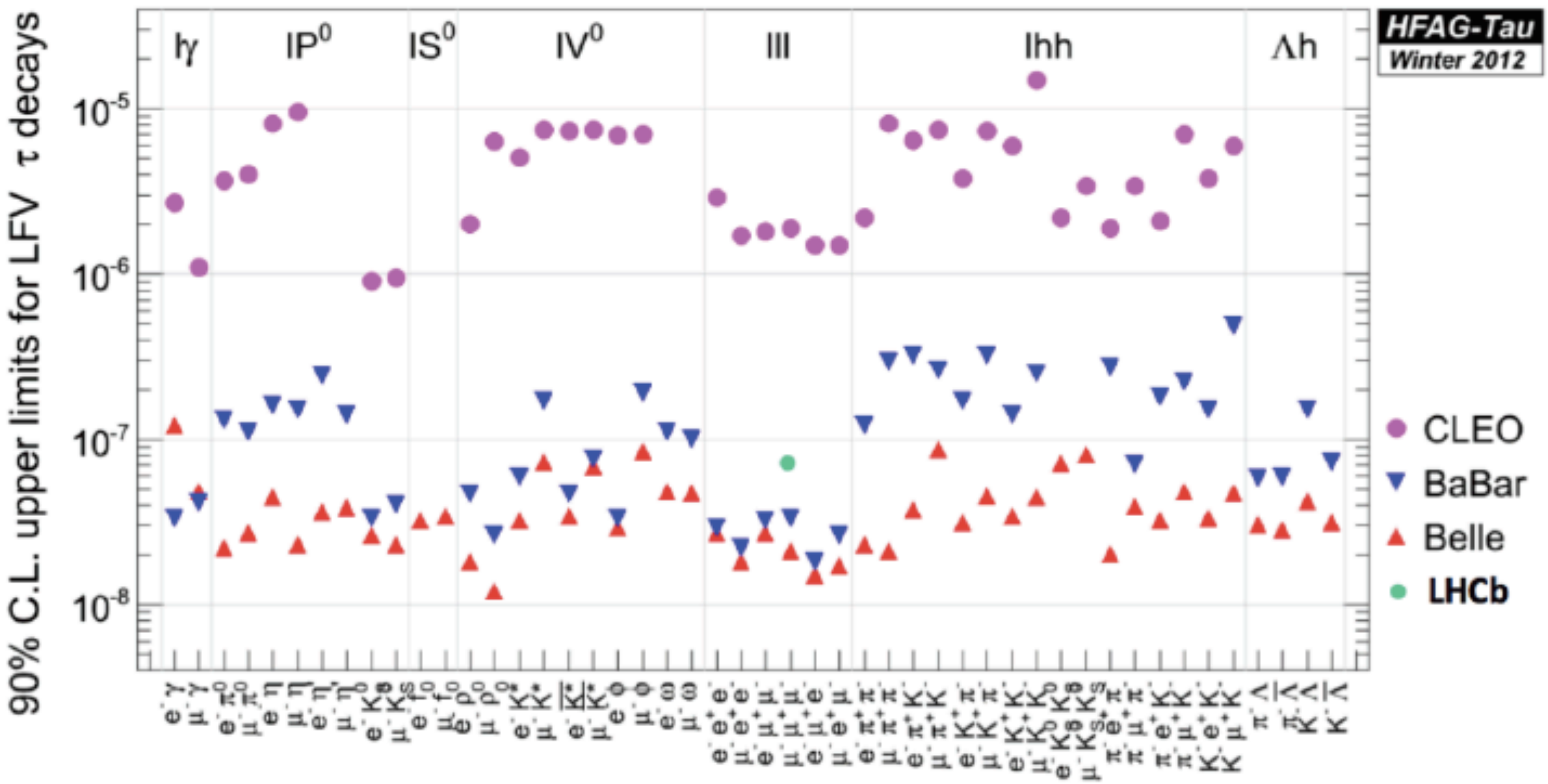
LFV is long established way of seeking evidence of New Physics





J. Michael Roney
UVic

- 48 channels probed by Belle and BABAR
- LHCb has recently entered the game



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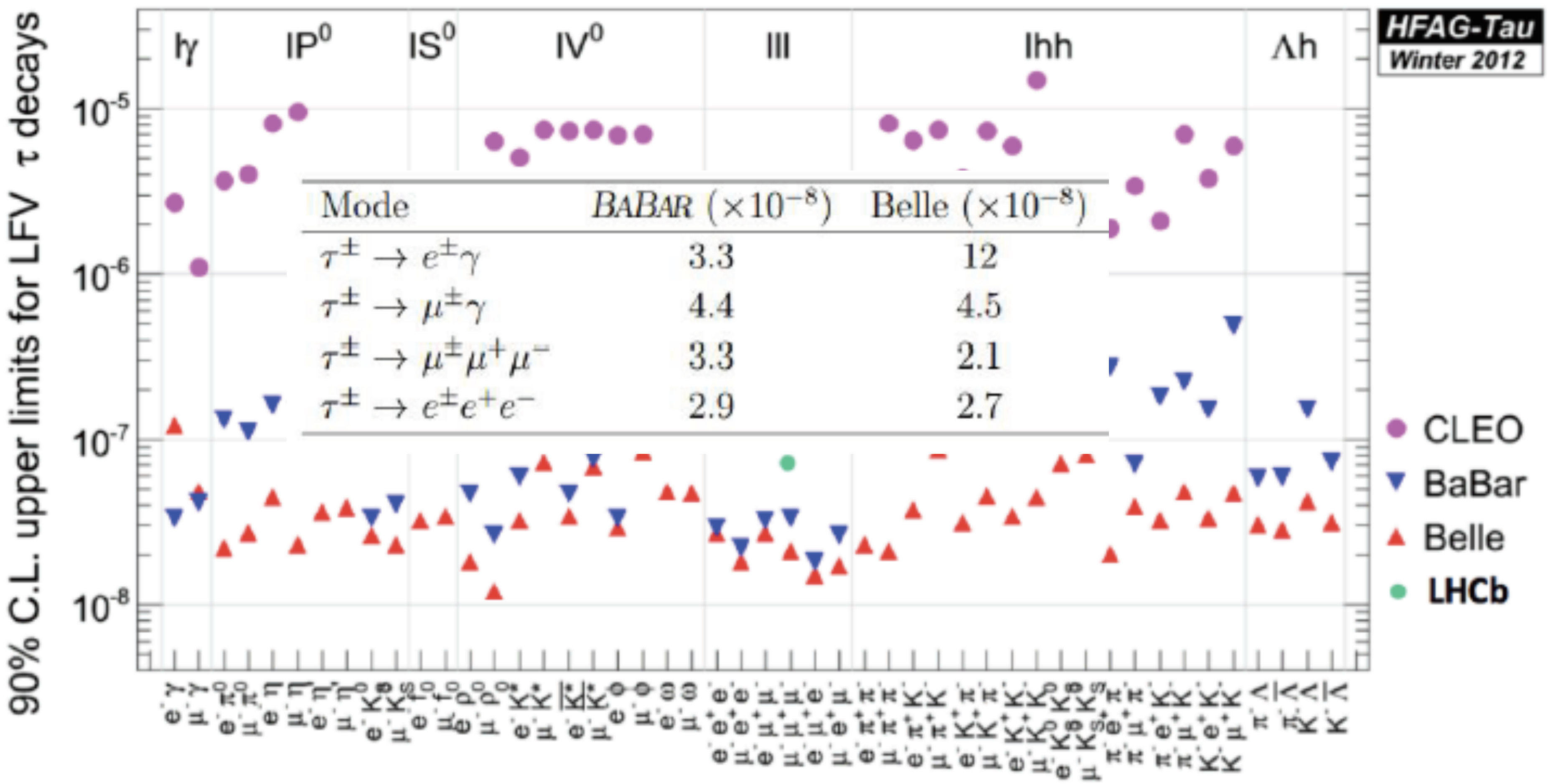


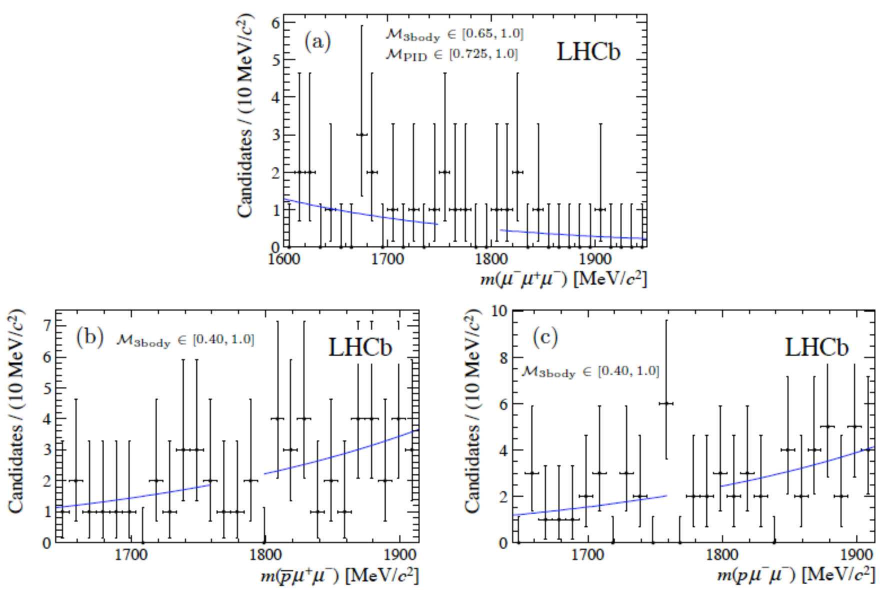
Mode	BABAR ($\times 10^{-8}$)	Belle ($\times 10^{-8}$)
$\tau^\pm \to e^\pm \gamma$	3.3	12
$\tau^\pm \to \mu^\pm \gamma$	4.4	4.5
$\tau^\pm \to \mu^\pm \mu^+ \mu^-$	3.3	2.1
$\tau^\pm \to e^\pm e^+ e^-$	2.9	2.7

LHCb uses $D_s \rightarrow \tau\, \nu$ as source of taus

PhysLett B 7224(2013)

Published on fb^{-1} of data looking for LFV and Baryon number and Lepton number non-conserving decays

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$$
$$= \mathcal{B}(D_s^- \to \phi(\mu^+\mu^-)\pi^-) \times \frac{f_\tau^{D_s}}{\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)} \times \frac{\epsilon_{\rm cal}^{\rm REC\&SEL}}{\epsilon_{\rm sig}^{\rm REC\&SEL}} \times \frac{\epsilon_{\rm cal}^{\rm TRIG}}{\epsilon_{\rm sig}^{\rm TRIG}} \times \frac{N_{\rm sig}}{N_{\rm cal}}$$

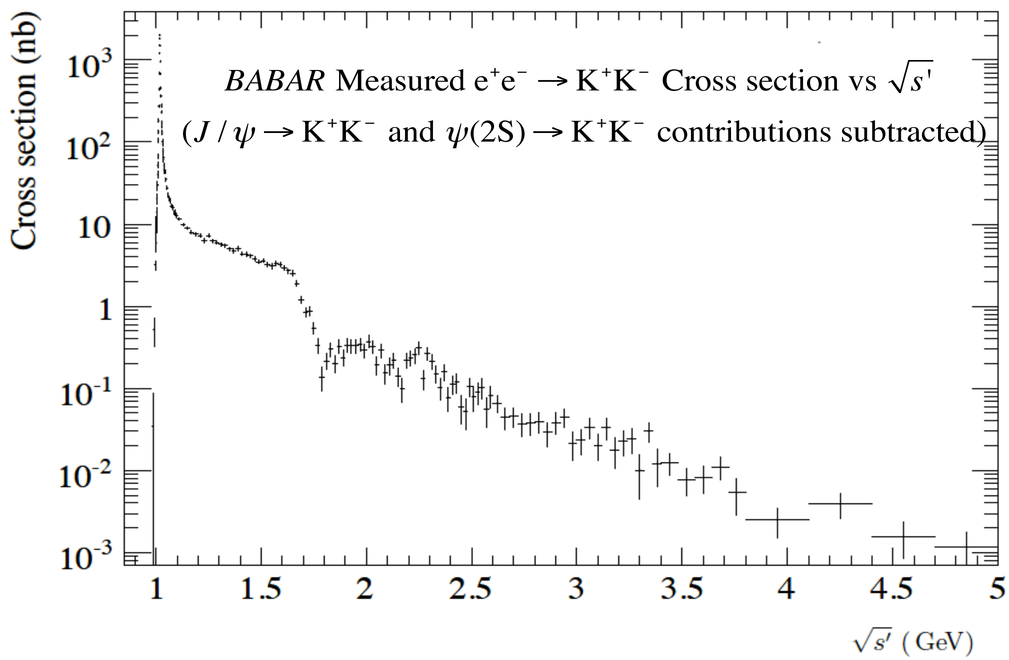


LHCb 90(95)%CL Limits

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 8.0\ (9.8) \times 10^{-8}$$
$$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3\ (4.3) \times 10^{-7}$$
$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4\ (5.7) \times 10^{-7}$$

J. Michael Roney
UVic

Precision Cross Section of $e^+e^- \to K^+K^-(\gamma)$ *BaBar*, submitted to PRD arXiv 1306.3600



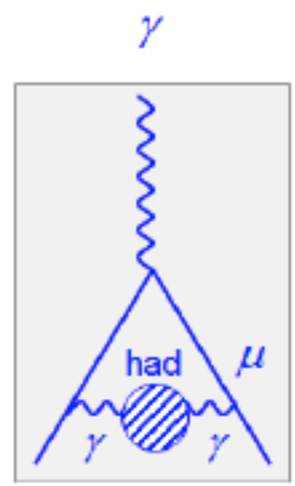
$e^+e^- \to$ hadrons cross section related to $a_\mu = \frac{(g-2)_\mu}{2}$ through dispersion relation:

$$a_\mu^{\text{had,LO}} = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} ds K(s)\sigma_{e^+e^-\to\text{hadrons}}(s)$$

Davier *et al* Eur.Phys.J. C71 (2011) 1515

$a_\mu^{had,LO} = (692.3 \pm 4.2)\times 10^{-10}$ - without *BABAR* K^+K^-

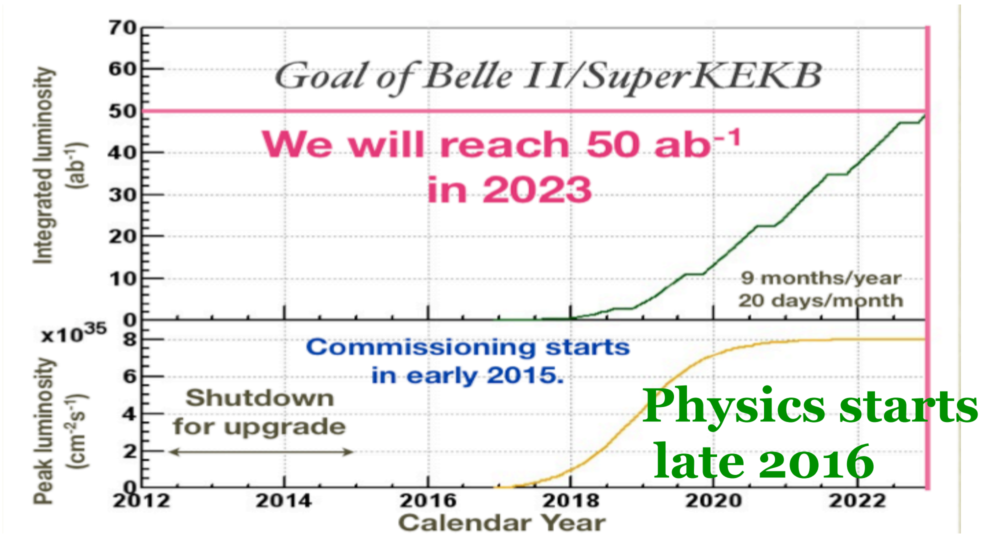
$a_\mu^{SM} - a_\mu^{Exp} = (-28.7 \pm 8.0)\times 10^{-10}$



$a_\mu^{KK,LO} = (22.93 \pm 0.18_{STAT} \pm 0.22_{SYST} \pm 0.03_{VP})\times 10^{-10}$
contribution from threshold to 1.8GeV

$a_\mu^{KK,LO} = (21.63 \pm 0.27_{STAT} \pm 0.68_{SYST})\times 10^{-10}$ - non-*BABAR*
contribution from threshold to 1.8GeV

Belle II at SuperKEKB



Machine design parameters

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	φ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	5.0	nm
Emittance ratio	κ	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.31	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0886	0.0830	
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

- **Small beam size & high current** to increase luminosity
- **Large crossing angle**
- **Change beam energies** to solve the problem of LER short lifetime

Physics Programme

- Test CKM at 1% level
  - CPV in B decays from new physics (non-CKM)
- B-recoil technique for $B \to K^{(*)}\ell^+\ell^-$, $B \to \tau\nu$, $B \to D^{(*)}\tau\nu$
- τ physics: lepton flavour violation, g-2, EDM, CPV, $|V_{us}|$...
- Charm: mixing, CPV,...
- Many other topics:
  - ϒ(5S) physics, , ISR radiative return, spectroscopy, Dark Sector probe, low mass Higgs...
- Physics motivation is independent of LHC
  - If LHC finds NP, precision flavour input essential
  - If LHC finds no NP, high statistics B and τ decays are unique way of probing >TeV scale physics

Belle II and LHCb (and ATLAS & CMS) are Complementary

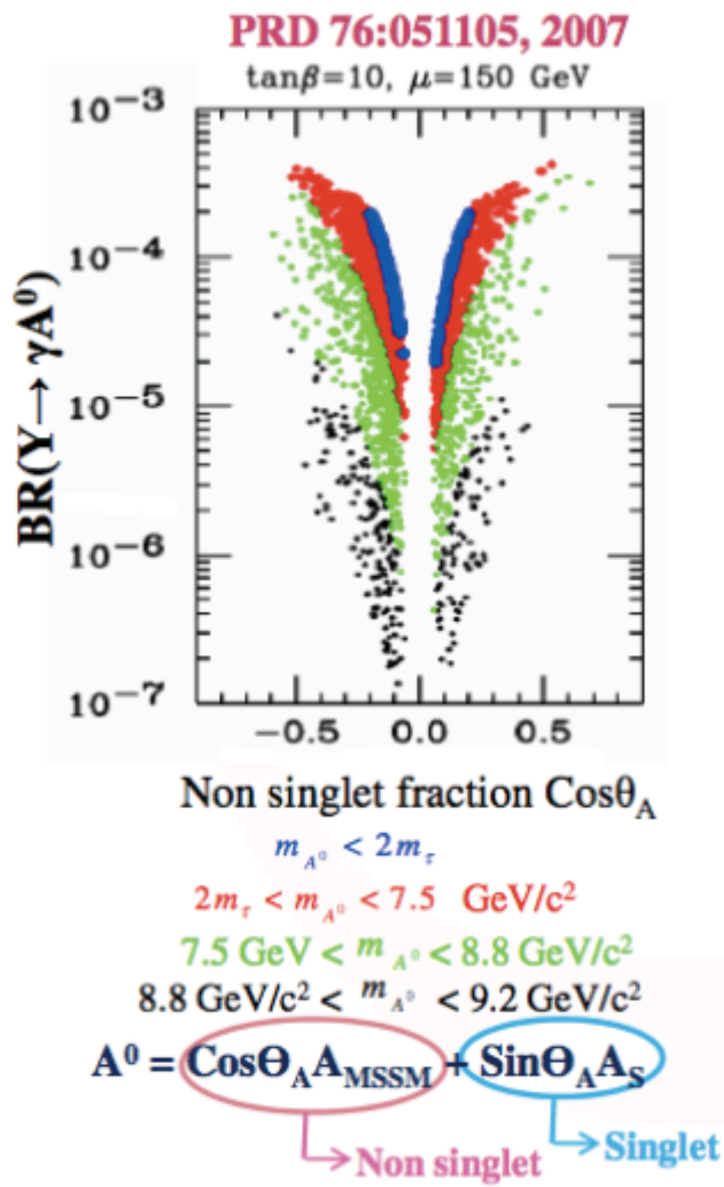
Summary

- Belle and *BABAR* are continuing to publish
  - Completing Physics of the B-Factories Book summarizing the papers currently published by both collaborations
  - Completing the CKM program but also going into new areas – e.g. T-violation; light Higgs searches, Dark Sector searches
  - CKM is generally describing the data well
- 3.4σ tension with SM in *BABAR* $B \rightarrow D^{(*)}\tau\nu$ decays, earlier published Belle results see similar hints
  - eagerly awaiting new analysis on Belle full data set
- Looking forward to future data from Belle II at SuperKEKB and LHCb

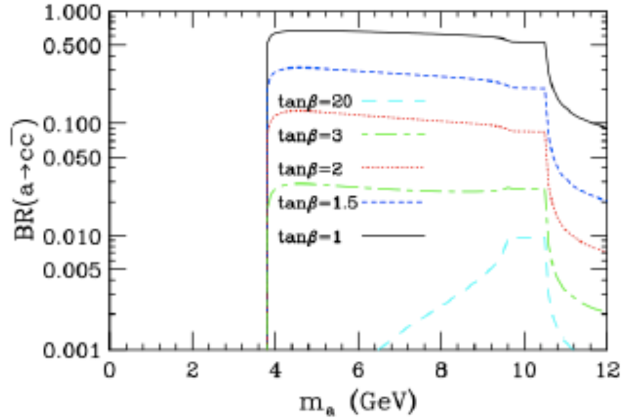
Additional Slides

NMSSM Parameter Space

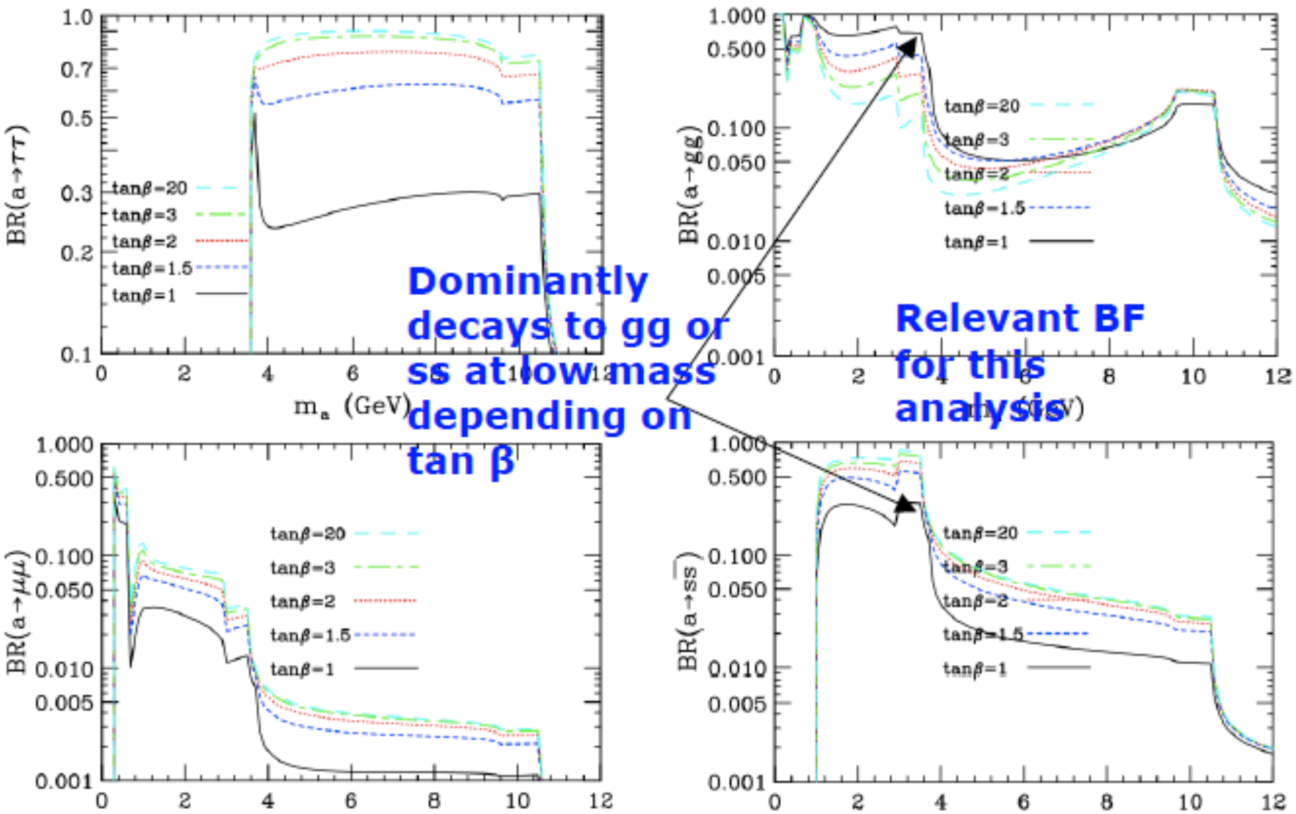
- BF($\Upsilon(1S) \rightarrow \gamma A^0$) depends on non-singlet fraction
- High mass Higgs very difficult to exclude



Higgs Branching Fractions



$$B\left(A^0 \to f\bar{f}\right) \propto m_f^2/\tan^2\beta \quad \text{up-type fermions}$$
$$B\left(A^0 \to f\bar{f}\right) \propto m_f^2\tan^2\beta \quad \text{down-type fermions}$$



Channel	$a_\mu^{\rm had,LO}$ $[10^{-10}]$	$\Delta\alpha_{\rm had}(M_Z^2)$ $[10^{-4}]$
$\pi^0\gamma$	$4.42 \pm 0.08 \pm 0.13 \pm 0.12$	$0.36 \pm 0.01 \pm 0.01 \pm 0.01$
$\eta\gamma$	$0.64 \pm 0.02 \pm 0.01 \pm 0.01$	$0.08 \pm 0.00 \pm 0.00 \pm 0.00$
$\pi^+\pi^-$	$507.80 \pm 1.22 \pm 2.50 \pm 0.56$	$34.43 \pm 0.07 \pm 0.17 \pm 0.04$
$\pi^+\pi^-\pi^0$	$46.00 \pm 0.42 \pm 1.03 \pm 0.98$	$4.58 \pm 0.04 \pm 0.11 \pm 0.09$
$2\pi^+2\pi^-$	$13.35 \pm 0.10 \pm 0.43 \pm 0.29$	$3.49 \pm 0.03 \pm 0.12 \pm 0.08$
$\pi^+\pi^-2\pi^0$	$18.01 \pm 0.14 \pm 1.17 \pm 0.40$	$4.43 \pm 0.03 \pm 0.29 \pm 0.10$
$2\pi^+2\pi^-\pi^0$ (η excl.)	$0.72 \pm 0.04 \pm 0.07 \pm 0.03$	$0.22 \pm 0.01 \pm 0.02 \pm 0.01$
$\pi^+\pi^-3\pi^0$ (η excl., from isospin)	$0.36 \pm 0.02 \pm 0.03 \pm 0.01$	$0.11 \pm 0.01 \pm 0.01 \pm 0.00$
$3\pi^+3\pi^-$	$0.12 \pm 0.01 \pm 0.01 \pm 0.00$	$0.04 \pm 0.00 \pm 0.00 \pm 0.00$
$2\pi^+2\pi^-2\pi^0$ (η excl.)	$0.70 \pm 0.05 \pm 0.04 \pm 0.09$	$0.25 \pm 0.02 \pm 0.02 \pm 0.03$
$\pi^+\pi^-4\pi^0$ (η excl., from isospin)	$0.11 \pm 0.01 \pm 0.11 \pm 0.00$	$0.04 \pm 0.00 \pm 0.04 \pm 0.00$
$\eta\pi^+\pi^-$	$1.15 \pm 0.06 \pm 0.08 \pm 0.03$	$0.33 \pm 0.02 \pm 0.02 \pm 0.01$
$\eta\omega$	$0.47 \pm 0.04 \pm 0.00 \pm 0.05$	$0.15 \pm 0.01 \pm 0.00 \pm 0.02$
$\eta 2\pi^+2\pi^-$	$0.02 \pm 0.01 \pm 0.00 \pm 0.00$	$0.01 \pm 0.00 \pm 0.00 \pm 0.00$
$\eta\pi^+\pi^-2\pi^0$ (estimated)	$0.02 \pm 0.01 \pm 0.01 \pm 0.00$	$0.01 \pm 0.00 \pm 0.00 \pm 0.00$
$\omega\pi^0$ ($\omega \to \pi^0\gamma$)	$0.89 \pm 0.02 \pm 0.06 \pm 0.02$	$0.18 \pm 0.00 \pm 0.02 \pm 0.00$
$\omega\pi^+\pi^-, \omega 2\pi^0$ ($\omega \to \pi^0\gamma$)	$0.08 \pm 0.00 \pm 0.01 \pm 0.00$	$0.03 \pm 0.00 \pm 0.00 \pm 0.00$
ω (non-$3\pi, \pi\gamma, \eta\gamma$)	$0.36 \pm 0.00 \pm 0.01 \pm 0.00$	$0.03 \pm 0.00 \pm 0.00 \pm 0.00$
K^+K^-	$21.63 \pm 0.27 \pm 0.58 \pm 0.36$	$3.13 \pm 0.04 \pm 0.08 \pm 0.05$
$K_S^0K_L^0$	$12.96 \pm 0.18 \pm 0.25 \pm 0.24$	$1.75 \pm 0.02 \pm 0.03 \pm 0.03$
ϕ (non-$K\overline{K}, 3\pi, \pi\gamma, \eta\gamma$)	$0.05 \pm 0.00 \pm 0.00 \pm 0.00$	$0.01 \pm 0.00 \pm 0.00 \pm 0.00$
$K\overline{K}\pi$ (partly from isospin)	$2.39 \pm 0.07 \pm 0.12 \pm 0.08$	$0.76 \pm 0.02 \pm 0.04 \pm 0.02$
$K\overline{K}2\pi$ (partly from isospin)	$1.35 \pm 0.09 \pm 0.38 \pm 0.03$	$0.48 \pm 0.03 \pm 0.14 \pm 0.01$
$K\overline{K}3\pi$ (partly from isospin)	$-0.03 \pm 0.01 \pm 0.02 \pm 0.00$	$-0.01 \pm 0.00 \pm 0.01 \pm 0.00$
$\phi\eta$	$0.36 \pm 0.02 \pm 0.02 \pm 0.01$	$0.13 \pm 0.01 \pm 0.01 \pm 0.00$
$\omega K\overline{K}$ ($\omega \to \pi^0\gamma$)	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$
J/ψ (Breit-Wigner integral)	6.22 ± 0.16	7.03 ± 0.18
$\psi(2S)$ (Breit-Wigner integral)	1.57 ± 0.03	2.50 ± 0.04
$R_{\rm data}$ [3.7 – 5.0 GeV]	$7.29 \pm 0.05 \pm 0.30 \pm 0.00$	$15.79 \pm 0.12 \pm 0.66 \pm 0.00$
$R_{\rm QCD}$ $[1.8 - 3.7\ {\rm GeV}]_{uds}$	33.45 ± 0.28	24.27 ± 0.19
$R_{\rm QCD}$ $[5.0 - 9.3\ {\rm GeV}]_{udsc}$	6.86 ± 0.04	34.89 ± 0.18
$R_{\rm QCD}$ $[9.3 - 12.0\ {\rm GeV}]_{udscb}$	1.21 ± 0.01	15.56 ± 0.04
$R_{\rm QCD}$ $[12.0 - 40.0\ {\rm GeV}]_{udscb}$	1.64 ± 0.01	77.94 ± 0.12
$R_{\rm QCD}$ $[> 40.0\ {\rm GeV}]_{udscb}$	0.16 ± 0.00	42.70 ± 0.06
$R_{\rm QCD}$ $[> 40.0\ {\rm GeV}]_{t}$	0.00 ± 0.00	-0.72 ± 0.01
Sum	$692.3 \pm 1.4 \pm 3.1 \pm 2.4 \pm 0.2_\psi \pm 0.3_{\rm QCD}$	$274.97 \pm 0.17 \pm 0.78 \pm 0.37 \pm 0.18_\psi \pm 0.52_{\rm QCD}$

Contributions to $a_\mu^{had,LO}$ and $\Delta\alpha_{had}(M_Z^2)$

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For most of these channels, BaBar provides the most precise measurements from ISR studies