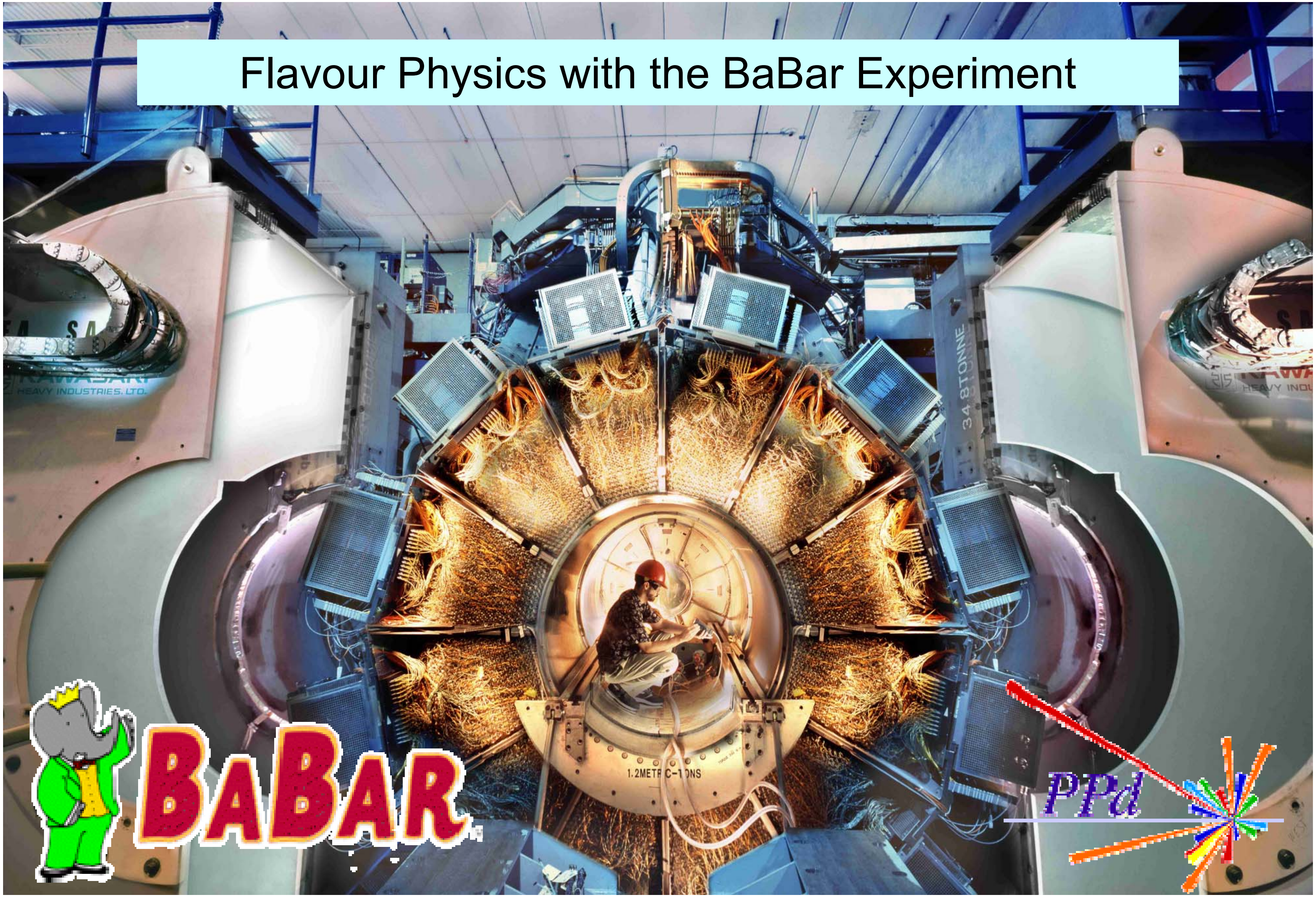
Flavour Physics with the BaBar Experiment



Introduction

Introduction

- Covered today:
  - Unitarity Triangle
    - Angles
      - α,β,γ
    - Sides
      - V_{qq}
  - Rare Decays
  - New Physics Searches
  - Upsilon $\Upsilon(3S)$

- Not covered today:
  - Charmonium
  - Exotic States
    - Pentaquarks
    - Glueballs
    - baryonium
  - ISR Physics
  - $e^+e^- \rightarrow$ Quasi-2-body states
  - Lepton Flavour Violation (at least, not in detail).

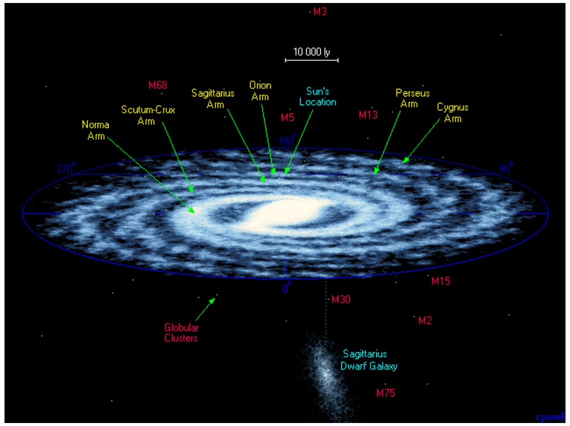
The expected? The unexpected?

In the beginning…and now.

What we see in the Universe:

- Matter Galaxies: 10^{11}
- Anti-Matter Galaxies: 0

If Electro-weak CP Violation (CPV) was the answer:

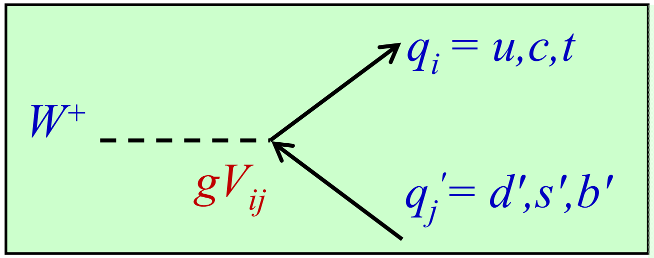


- Matter Galaxies: 10^{11}
- Anti-Matter Galaxies: 10^{11}-1

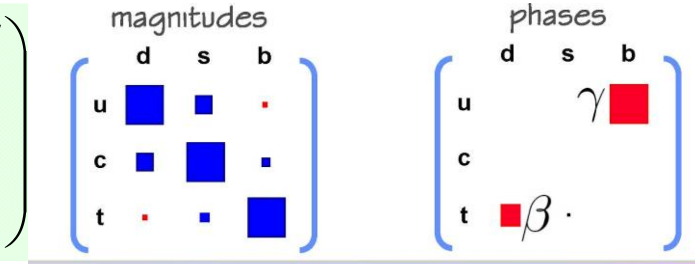
If CPV explains the asymmetry, there must be another source of CP Violation. ➡ New Physics

CP Violation

CKM Matrix and Unitarity Triangle



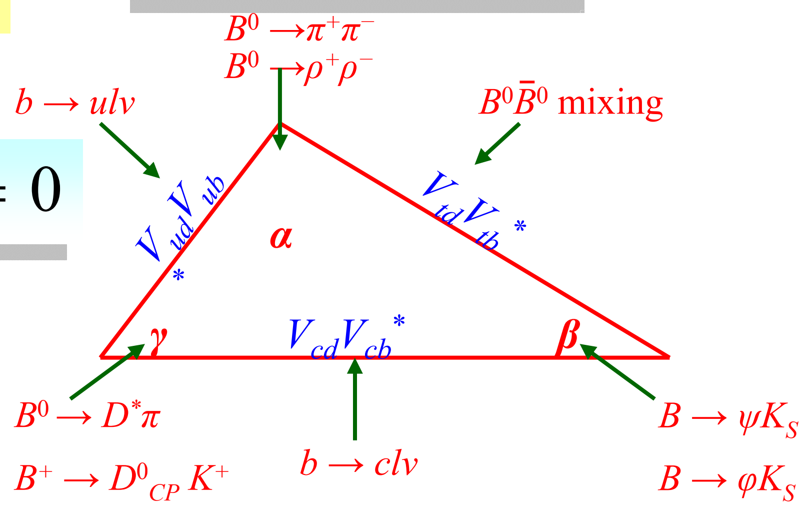
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$V_{\text{CKM}} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

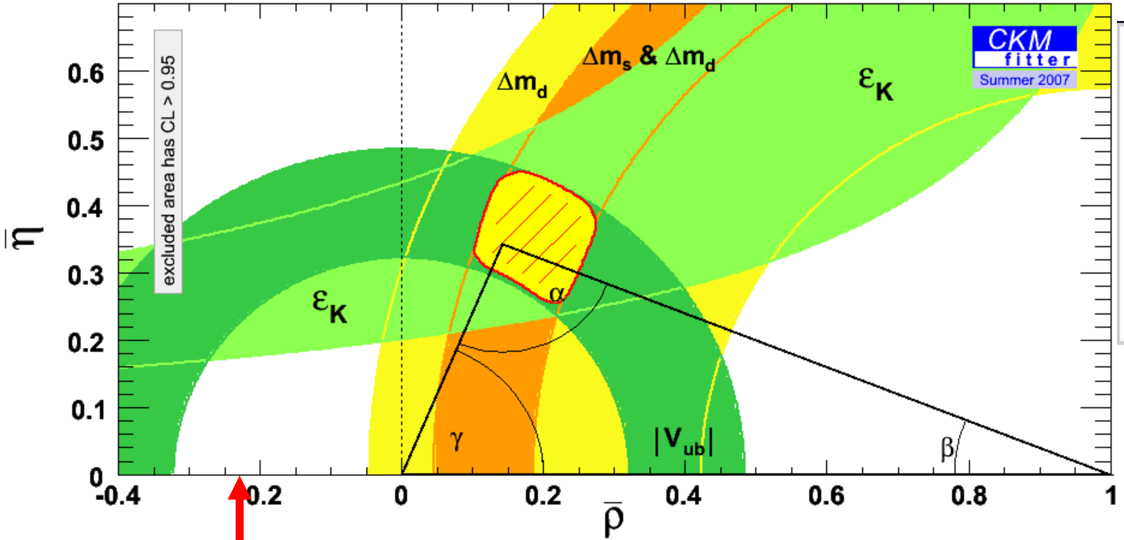
$$A \approx 0.8, \quad \lambda \approx 0.23,$$
$$\rho \approx 0.2, \quad \eta \approx 0.4$$

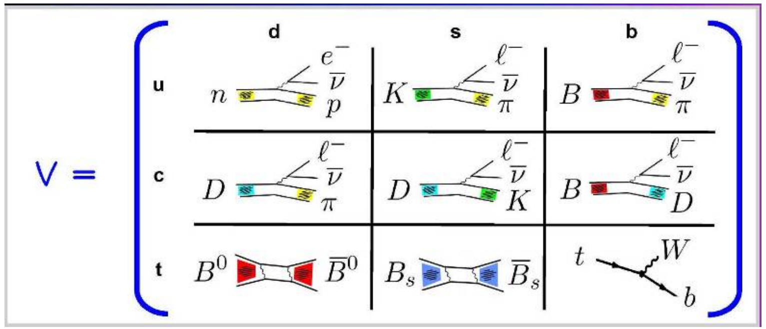
$$V^\dagger V = 1 \Rightarrow V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \quad \alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \quad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

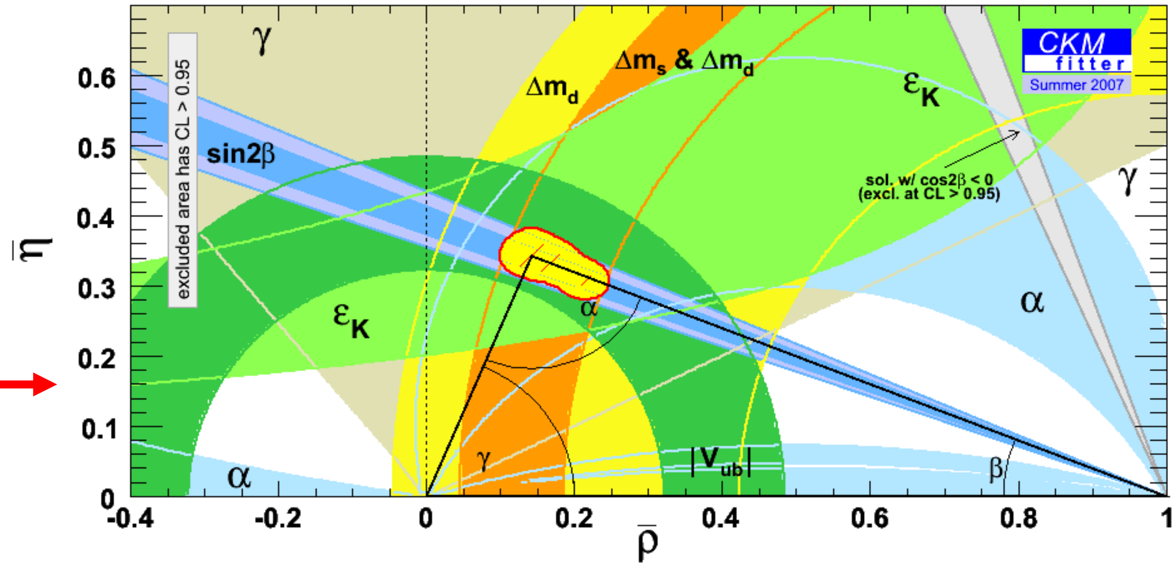
Some Constraints





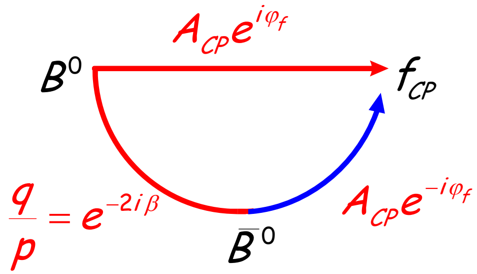
Constraints without angle measurements

Constraints with angle measurements



Time Dependent CP Violation

Time evolution of $B^0 / \overline{B}^0$ asymmetry:



$$A_{f_{CP}}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$

$$= -\eta_{CP}[S_{f_{CP}} \sin(\Delta m_d \Delta t) + C_{f_{CP}} \cos(\Delta m_d \Delta t)]$$

$$\Delta m_d = 0.508 \pm 0.004 \, \mathrm{ps}^{-1}$$

S : CPV in interference between mixing and decay.

$$S_{f_{CP}} = \frac{2 \, \mathrm{Im}(\lambda_{f_{CP}})}{1 + |\lambda_{f_{CP}}|^2}$$

C : direct CPV from decays.

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

Decay Amplitudes

$$\lambda_{f_{CP}} = \frac{q}{p} \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

If only 1 decay amplitude:

$C_{f_{CP}} = 0, \quad \lambda = \eta_f e^{-2\beta}$

$S_{f_{CP}} = \mathrm{Im}(\lambda_{f_{CP}})$

$e.g.$ $\sin(2\beta)$

If more than 1 decay amplitude :

$C_{f_{CP}} \neq 0$

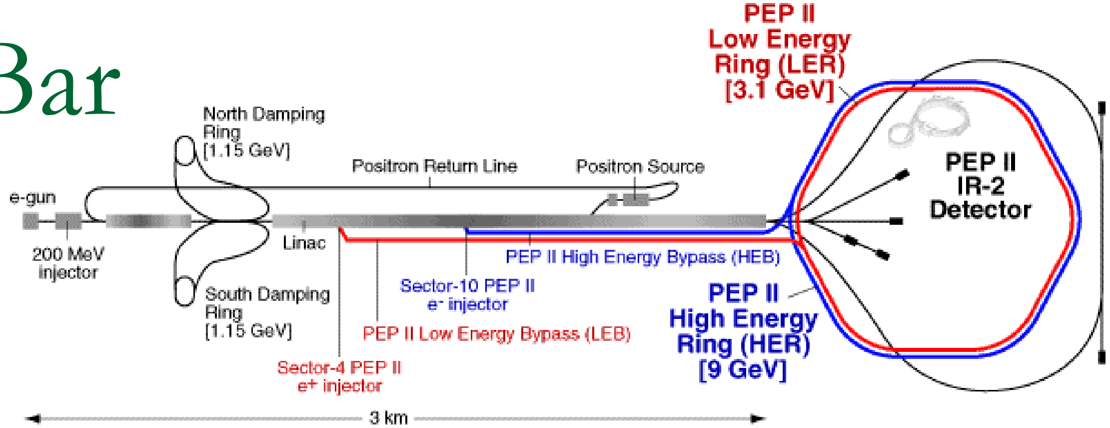
$S_{f_{CP}}$ = not trivially related to CKM angles

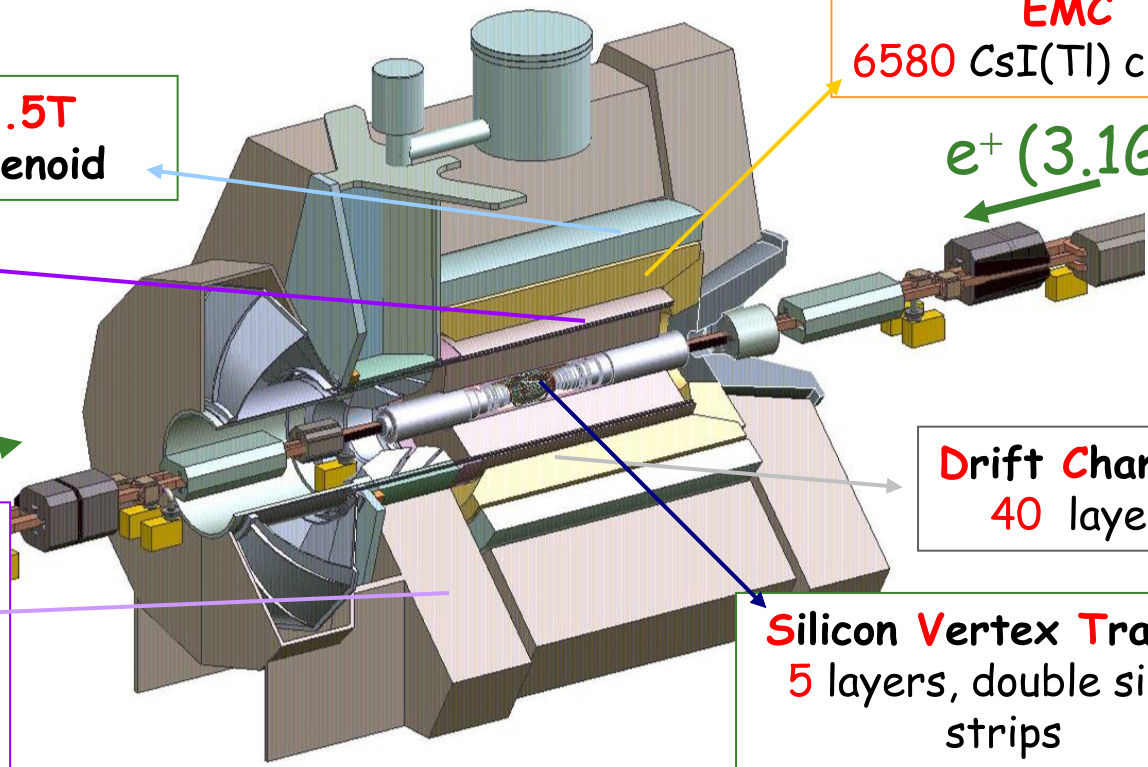
$e.g.$ $\sin(2\alpha_{eff})$

BaBar Analysis methods

PEP II and BaBar

10 countries
77 institutions
623 collaborators





EMC
6580 CsI(Tl) crystals

e^+ (3.1GeV)

1.5T solenoid

DIRC (PID)
144 quartz bars
11000 PMs

e^- (9GeV)

Drift Chamber
40 layers

Instrumented Flux Return
Iron / Resistive Plate Chambers or Limited Streamer Tubes (muon / neutral hadrons)

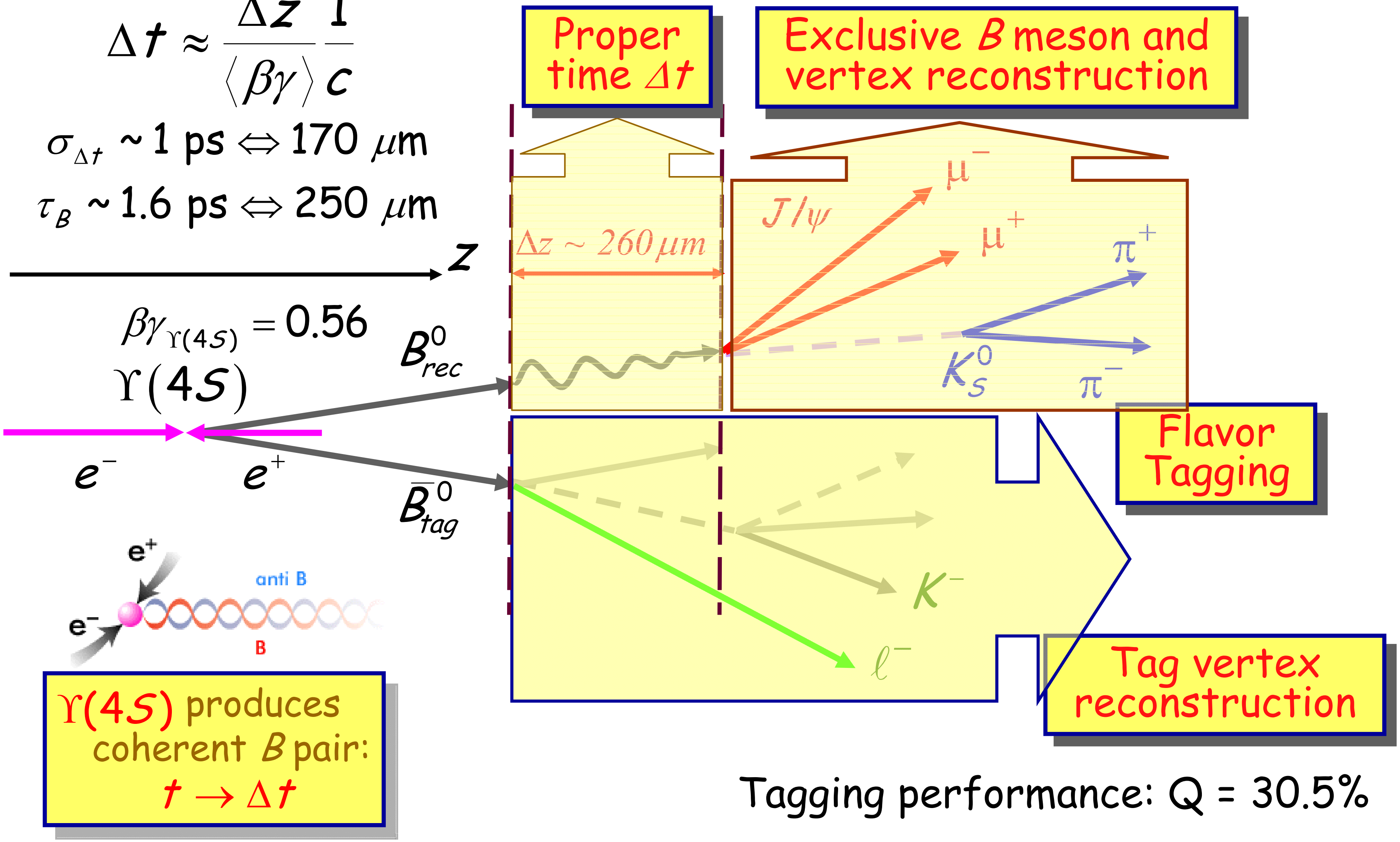
Silicon Vertex Tracker
5 layers, double sided strips

Measuring time-dependent CP asymmetries

$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle} \frac{1}{c}$$

$\sigma_{\Delta t} \sim 1$ ps $\Leftrightarrow$ 170 μm

$\tau_B \sim 1.6$ ps $\Leftrightarrow$ 250 μm

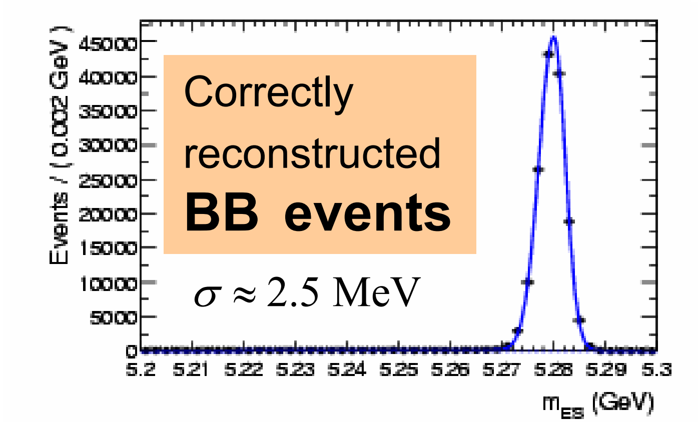


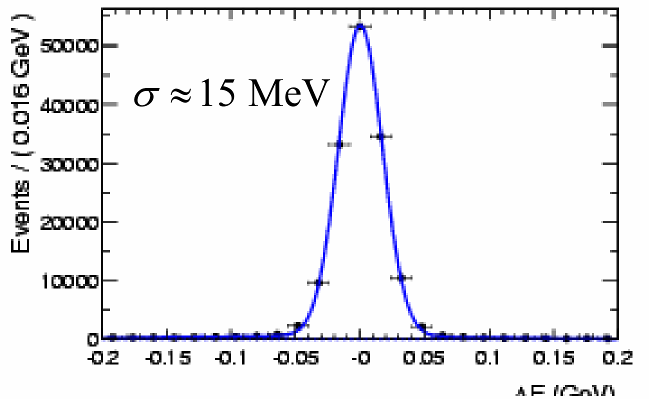
Tagging performance: Q = 30.5%

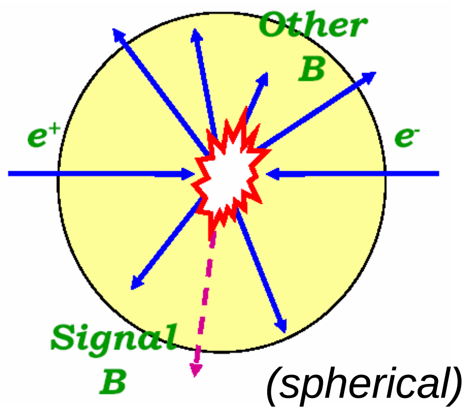
B Meson Reconstruction

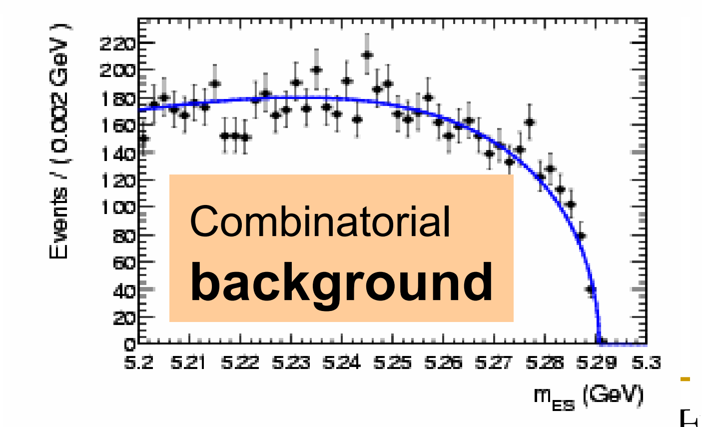
Exploit kinematics of $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B^0}$ for signal selection

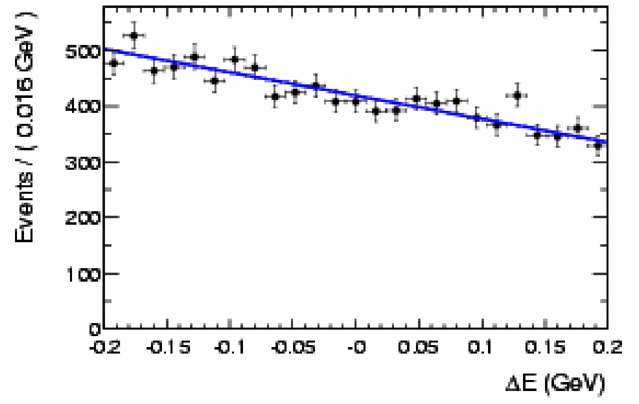
Beam-energy substituted mass	*Energy difference*	*Event topology*
$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$	$\Delta E = E^*_B - E^*_{beam}$	*(multivariate methods)*

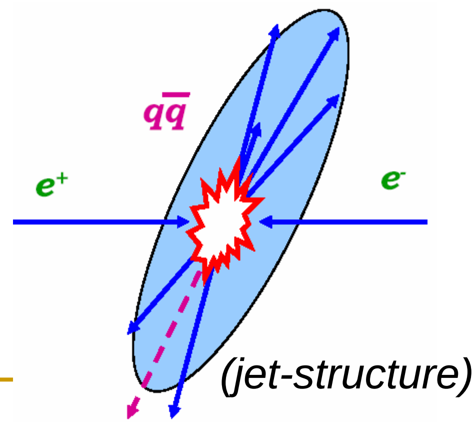








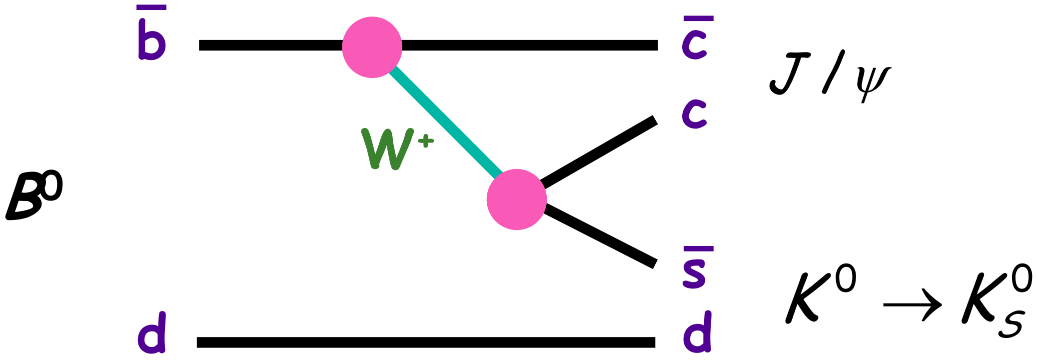




β

CP asymmetry in B°–> Ks J/ψ

CP Eigenstate: h_{CP} = -1



Golden Channel

Dominant (tree) amplitude has no weak phase

- Diagrams with different weak phase are strongly suppressed

SM: expect ηS = sin2β and C = 0

$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})} = S_{J/\psi K_S^0} \sin \Delta m_d t$$

Amplitude of CP asymmetry

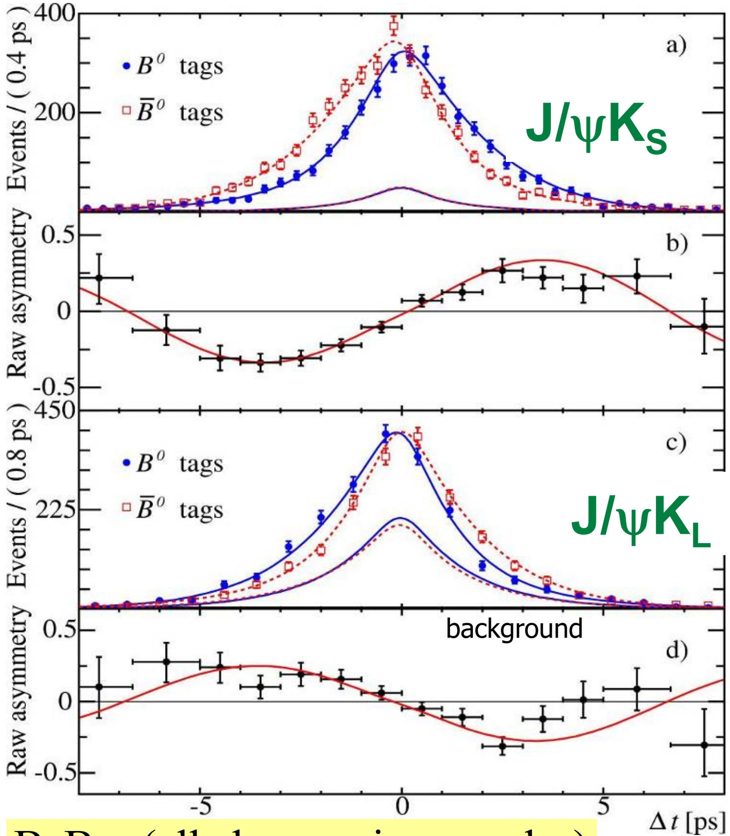
$$\mathrm{Im}\,\lambda_{J/\psi K_S^0} = -\eta_{f_{CP}}\,\mathrm{Im}\left\{\frac{V_{cs}V_{cb}^*}{V_{cs}^*V_{cb}} \times \frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}} \times \frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right\} = \mathrm{Im}\frac{V_{td}^*}{V_{td}} = \sin 2\beta$$

Quark subprocess | **B^0 mixing** | **K^0 mixing**

hep-ex/0703021 – 383Mevts

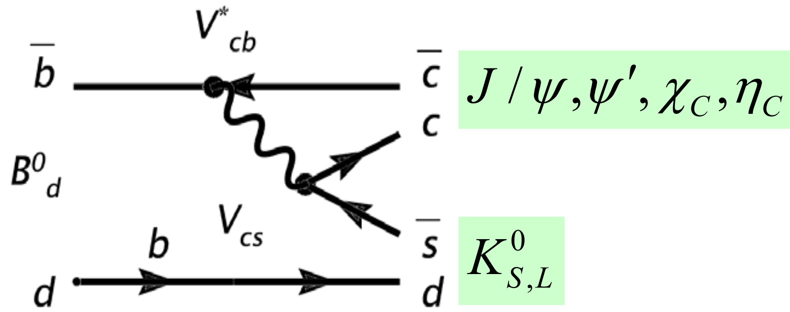
$B^0 \rightarrow$charmonium $\bar{K}^0$ ($b \rightarrow c\bar{c}s$)

Dominated by single tree diagram with no weak phase. In SM expect
$S = -\eta_{CP}\sin 2\beta$ and $C \approx 0$

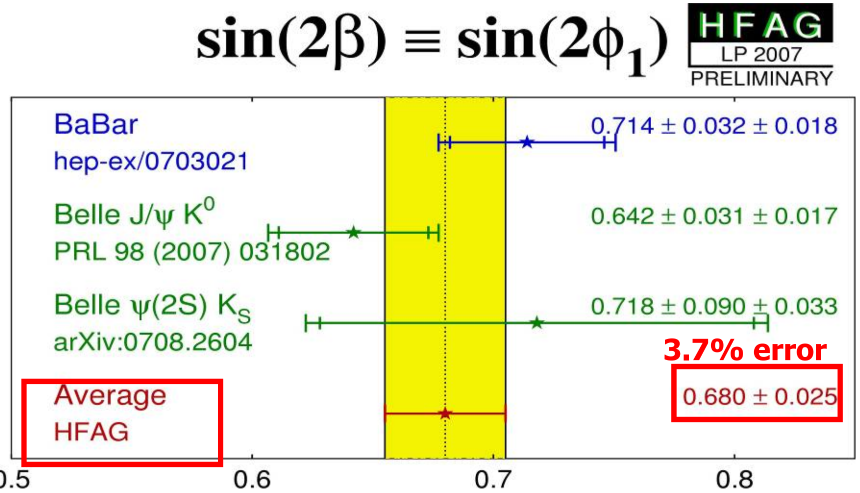


BaBar (all charmonium modes)

$$\eta_{CP} S = 0.714 \pm 0.032 \pm 0.018$$
$$C = 0.049 \pm 0.022 \pm 0.017$$

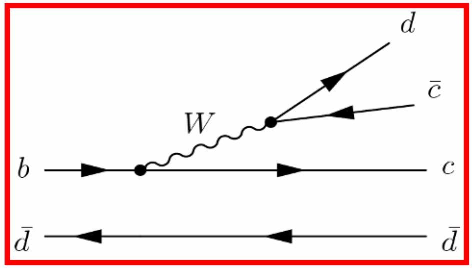


Sample	N_{tag}	$P(\%)$	$\sin 2\beta$	$\lvert\lambda\rvert$
Full CP sample	12677	75	0.714 ± 0.032	0.952 ± 0.022
$J/\psi K^0_S(\pi^+\pi^-)$	4459	96	0.702 ± 0.042	0.976 ± 0.030
$J/\psi K^0_S(\pi^0\pi^0)$	1086	88	0.617 ± 0.103	0.812 ± 0.058
$\psi(2S)K^0_S$	687	83	0.947 ± 0.112	0.867 ± 0.079
$\chi_{c1}K^0_S$	313	89	0.759 ± 0.170	0.804 ± 0.102
$\eta_c K^0_S$	328	69	0.778 ± 0.195	0.948 ± 0.141
$J/\psi K^0_L$	4748	55	0.734 ± 0.074	1.061 ± 0.063
$J/\psi K^{*0}$	1056	66	0.477 ± 0.271	0.954 ± 0.083
$J/\psi K^0$	10275	76	0.697 ± 0.035	0.966 ± 0.025
$J/\psi K^0_S$	5547	94	0.686 ± 0.039	0.950 ± 0.027
$\eta_f = -1$	6873	92	0.711 ± 0.036	0.935 ± 0.024

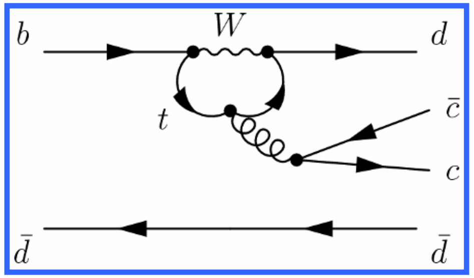


$B^0 \to D^+D^-$, $D^{*+}D^{*-}$ ($b \to ccd$)

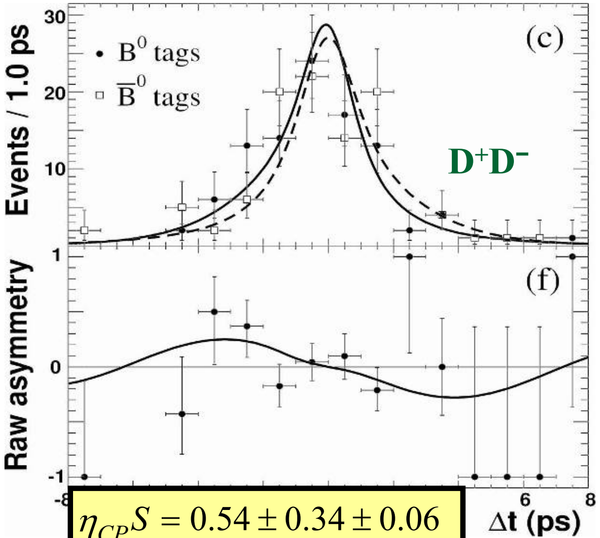
arXiv:0708.1549 – 383Mevts



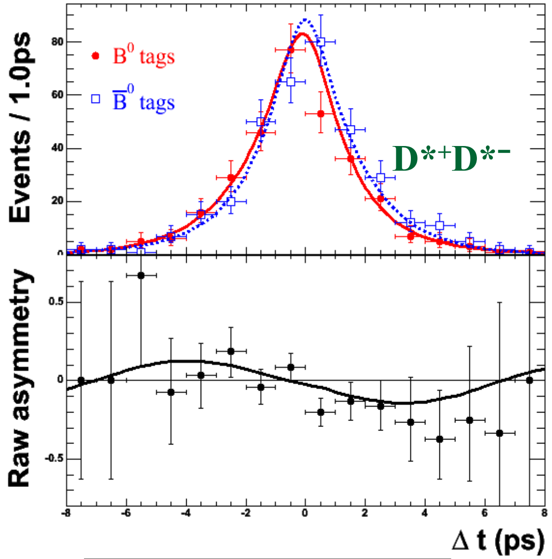
SM penguin-induced Direct CP <2%.



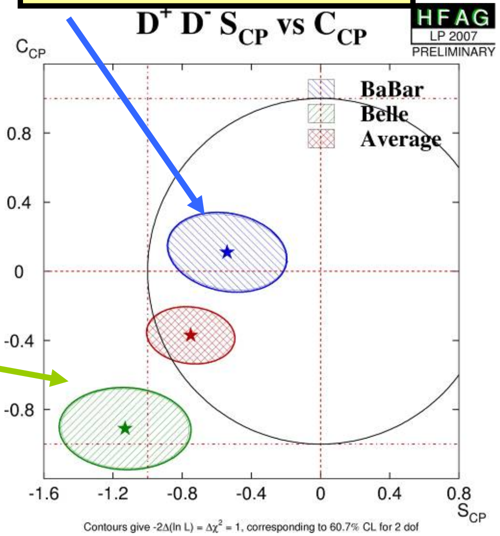
New physics particle can enter in loop.

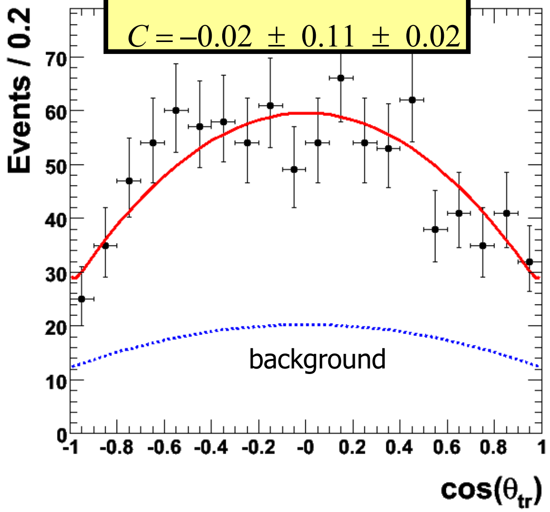


$$\eta_{CP} S = 0.54 \pm 0.34 \pm 0.06$$
$$C = 0.11 \pm 0.22 \pm 0.07$$



$$R_{\perp} = 0.143 \pm 0.034 \pm 0.008$$
$$S = -0.66 \pm 0.19 \pm 0.04$$
$$C = -0.02 \pm 0.11 \pm 0.02$$





Belle result (Direct CP?):

$$\eta_{CP} S = 1.13 \pm 0.37 \pm 0.09$$
$$C = -0.91 \pm 0.23 \pm 0.06 \; (3.2\sigma)$$

- **ηS consistent with $\sin 2\beta$ from $b \to ccs$**
- **no evidence for direct CP violation**

cos(2β) from $B^0 \to D^{(*)0}h^0$ ($h^0 \to \pi^0,\eta,\eta',\omega$)

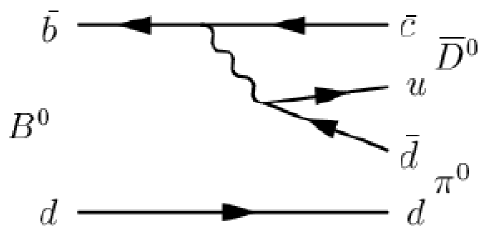
arXiv:0708.1544 – 383Mevts

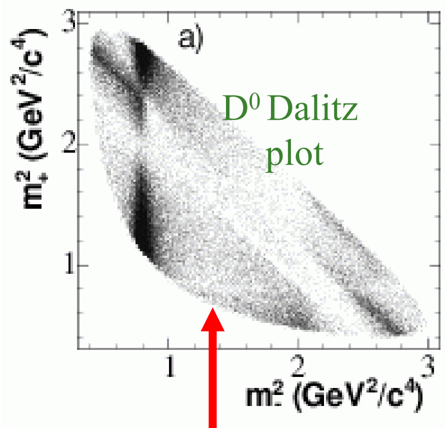
b→cud **color-suppressed** tree diagram

Time-dependent Dalitz analysis of $D^0\left(\overline{D}^0\right) \to K_s\pi^+\pi^-$

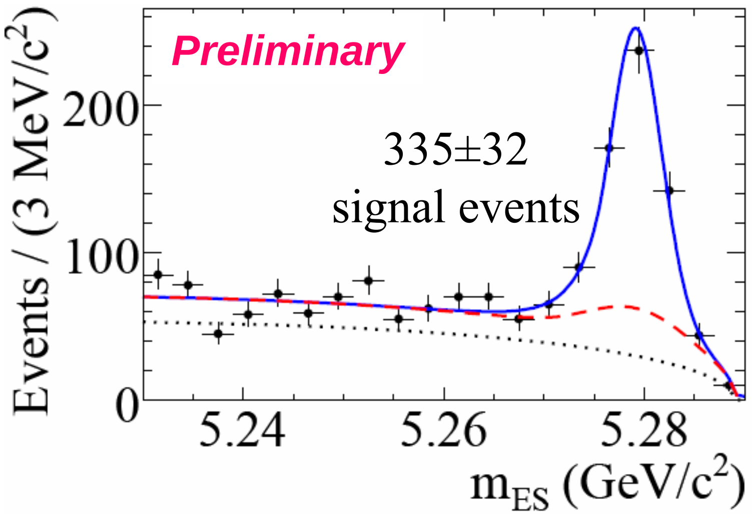
Interference of D^0 and $\overline{D}^0$.

Sensitive to $\sin 2\beta$ and $\sin 2\alpha$

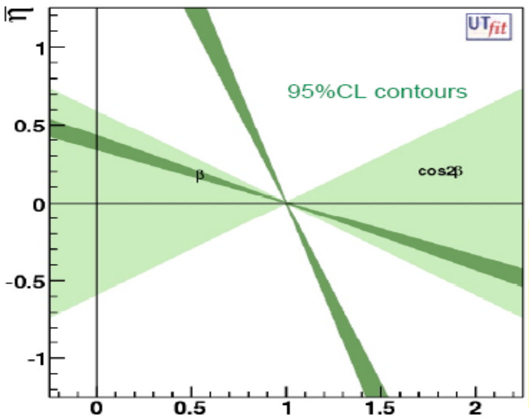




About 13 resonances + background have to be fitted

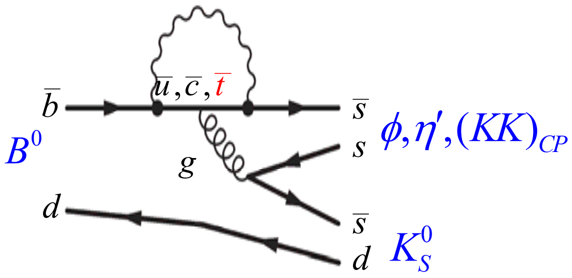


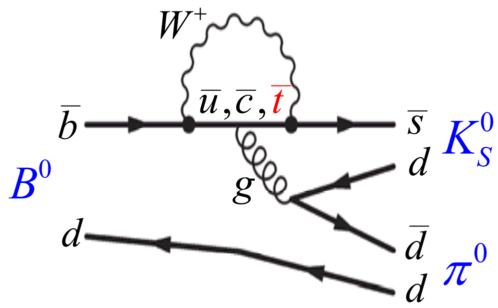
$$\sin 2\beta = 0.29 \pm 0.34 \pm 0.03 \pm 0.04$$
$$\cos 2\beta = 0.42 \pm 0.49 \pm 0.09 \pm 0.13$$
$$\Rightarrow \cos 2\beta > 0 \text{ @ } 86\% \text{ C.L.}$$



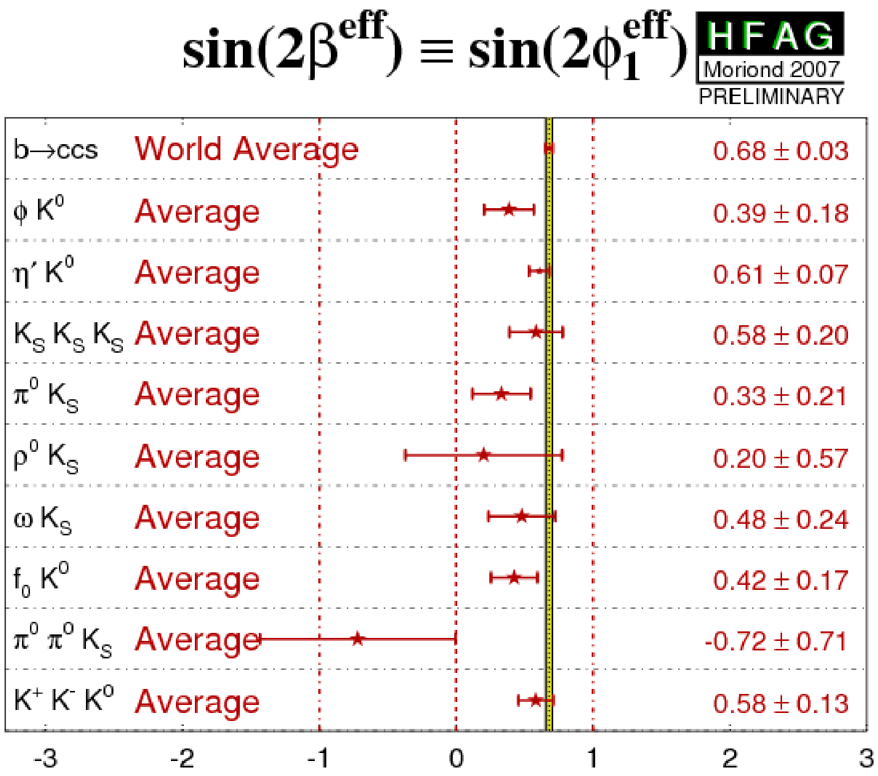
$\cos 2\beta > 0$ @ 89% C.L. from $B^0 \to J/\psi K^{*0}$ [BABAR, PRD 71, 032005 (2005)]
$\cos 2\beta > 0$ @ 94% C.L. from $B^0 \to D^{*+}D^{*-}K_S^0$ [BABAR, PRD 74, 091101 (2006)]
$\cos 2\beta > 0$ @ 4.6σ from $B^0 \to K^+K^-K_S^0$ [BABAR, hep-ex/0607112]

$\sin 2\beta_{eff}$ from $b \to qqs$ (q=s,d,u)





Approximately the same phase as $b \to ccs$ but sensitive to New Physics in loops



PRL 99 (2007) 161802

PRL 98 (2007) 031801

hep-ex/0702046

arXiv:0707.2980

arXiv:0708.2097

hep-ex/0607101

arXiv:0706.3885

hep-ex/0702010

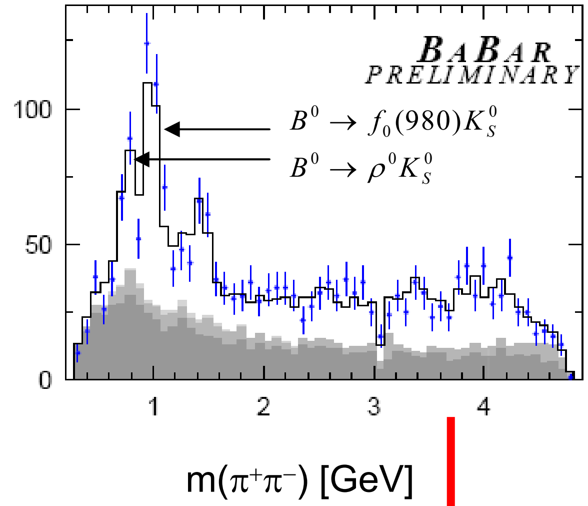
arXiv:0706.3885

Charmless Penguins !

Dalitz Analysis of $B^0 \rightarrow K^0_s \pi^+ \pi^-$

arXiv:0708.2097 – 383Mevts

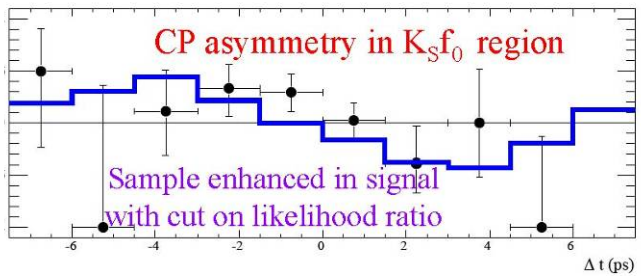
Resonance Name	$\|c_\sigma\|$	ϕ[degrees]	$\|\bar{c}_\sigma\|$ $(\|\bar{c}_{\bar{\sigma}}\|)$	$\bar{\phi}$[degrees]
$f_0(980)K^0_S$	4.0	0.0	2.8 ± 0.7	-88.6 ± 21.3
$\rho^0(770)K^0_S$	0.10 ± 0.02	58.6 ± 16.4	0.09 ± 0.02	21.3 ± 21.2
$f_0(1300)K^0_S$	1.9 ± 0.4	117.6 ± 22.6	1.1 ± 0.3	-15.2 ± 23.8
Nonresonant	3.0 ± 0.6	13.8 ± 14.3	3.7 ± 0.5	-16.2 ± 17.3
$K^{*+}(892)\pi^-$	0.136 ± 0.021	-60.7 ± 18.5	0.113 ± 0.018	102.6 ± 22.9
$K^{*+}(1430)\pi^-$	4.9 ± 0.7	-82.4 ± 16.8	7.1 ± 0.9	79.2 ± 20.5
$f_2(1270)K^0_S$	0.011 ± 0.004	62.9 ± 23.3	0.010 ± 0.003	-73.9 ± 27.8
$\chi_{c0}(1P)K^0_S$	0.34 ± 0.15	68.7 ± 31.1	0.40 ± 0.11	154.5 ± 28.6



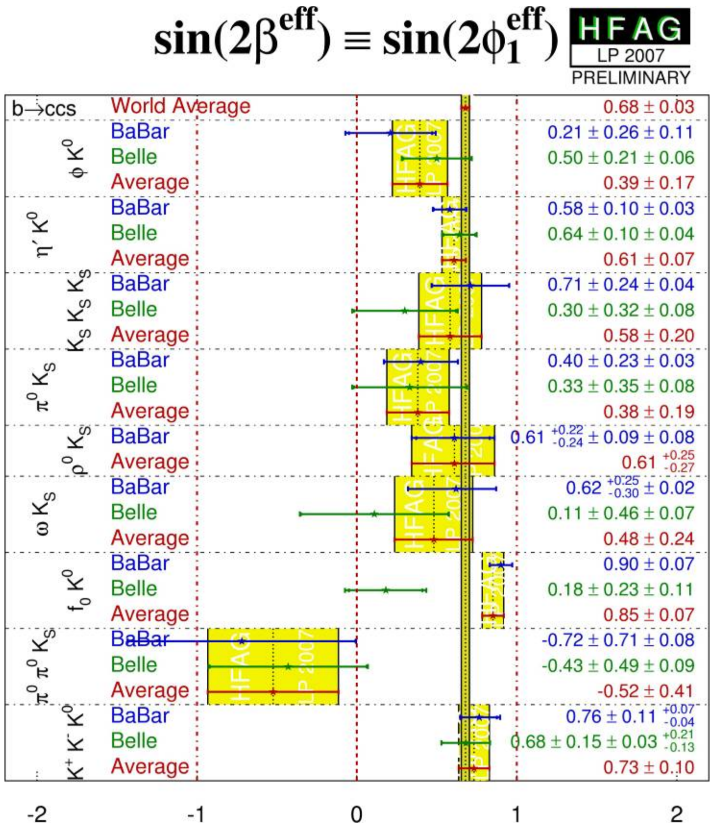
Parameter	Value	Parameter	Value
$C(f_0(980)K^0_S)$	$0.35 \pm 0.27 \pm 0.07 \pm 0.04$	$C(\rho^0(770)K^0_S)$	$0.02 \pm 0.27 \pm 0.08 \pm 0.06$
$^\dagger 2\beta_{\rm eff}(f_0(980)K^0_S)$	$(89^{+22}_{-20} \pm 5 \pm 8)^\circ$	$^\dagger 2\beta_{\rm eff}(\rho^0(770)K^0_S)$	$(37^{+19}_{-17} \pm 5 \pm 6)^\circ$
$^\dagger S(f_0(980)K^0_S)$	$-0.94^{+0.07+0.05}_{-0.02-0.03} \pm 0.02$	$^\dagger S(\rho^0(770)K^0_S)$	$0.61^{+0.22}_{-0.24} \pm 0.09 \pm 0.08$
$f(f_0(980)K^0_S)$	$14.3^{+2.8}_{-1.8} \pm 1.5 \pm 0.6$	$f(\rho^0(770)K^0_S)$	$9.0 \pm 1.4 \pm 1.1 \pm 1.1$
$A_{CP}(K^{*+}(892)\pi^-)$	$-0.18 \pm 0.10 \pm 0.03 \pm 0.03$	$^\dagger \Delta\phi(f_0 K^0_S, \rho^0 K^0_S)$	$(-59^{+16}_{-17} \pm 6 \pm 6)^\circ$
$^\dagger \Delta\phi(K^*(892)\pi)$ [a]	$(-164 \pm 24 \pm 12 \pm 15)^\circ$		
$f(K^*(892)\pi)$	$11.7 \pm 1.3 \pm 1.3 \pm 0.6$		
$f(K^*(1430)\pi)$	$38.9 \pm 2.5 \pm 0.7 \pm 1.3$	$f(NR)$	$25.6 \pm 2.5 \pm 1.9 \pm 0.5$
$f(f_0(1300)K^0_S)$	$6.3 \pm 1.3 \pm 0.6 \pm 0.3$	$f(f_2(1270)K^0_S)$	$2.1 \pm 0.8 \pm 0.0 \pm 0.2$
$f(\chi_{c0}(1P)K^0_S)$	$1.2 \pm 0.5 \pm 0.0 \pm 0.1$		

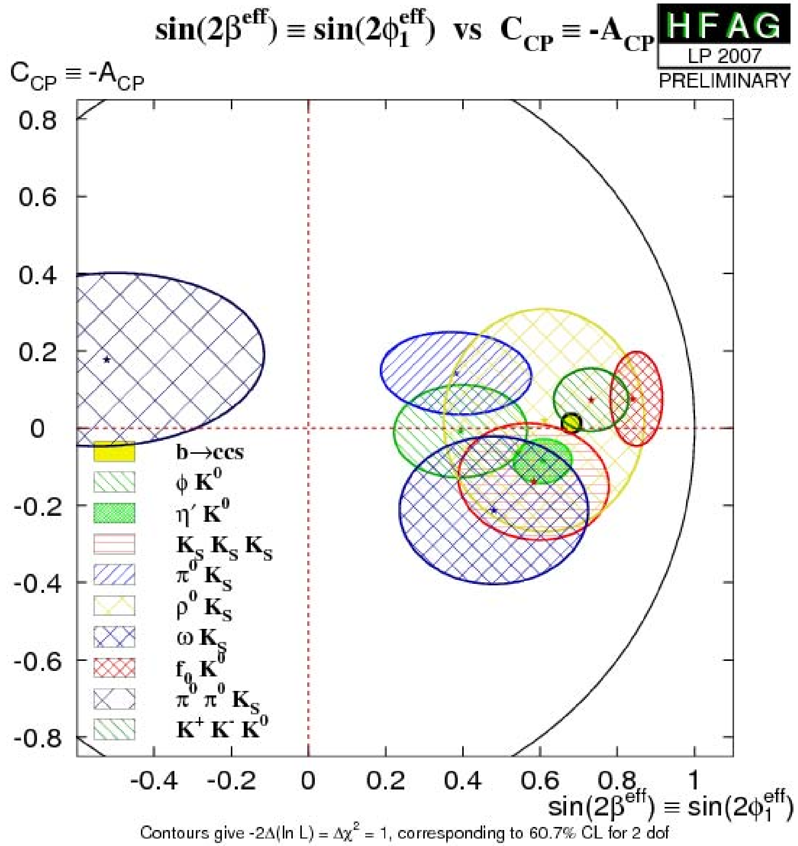
$B^0 \rightarrow K_S f_0(980): 2\beta_{\rm eff} = 89^{+22}_{-20} \pm 5 \pm 8^\circ$

$B^0 \rightarrow K_S \rho^0(770): 2\beta_{\rm eff} = 37^{+19}_{-17} \pm 5 \pm 6^\circ$



Summary of β measurements





$$\langle \sin 2\beta_{eff} \rangle = 0.68 \pm 0.04$$

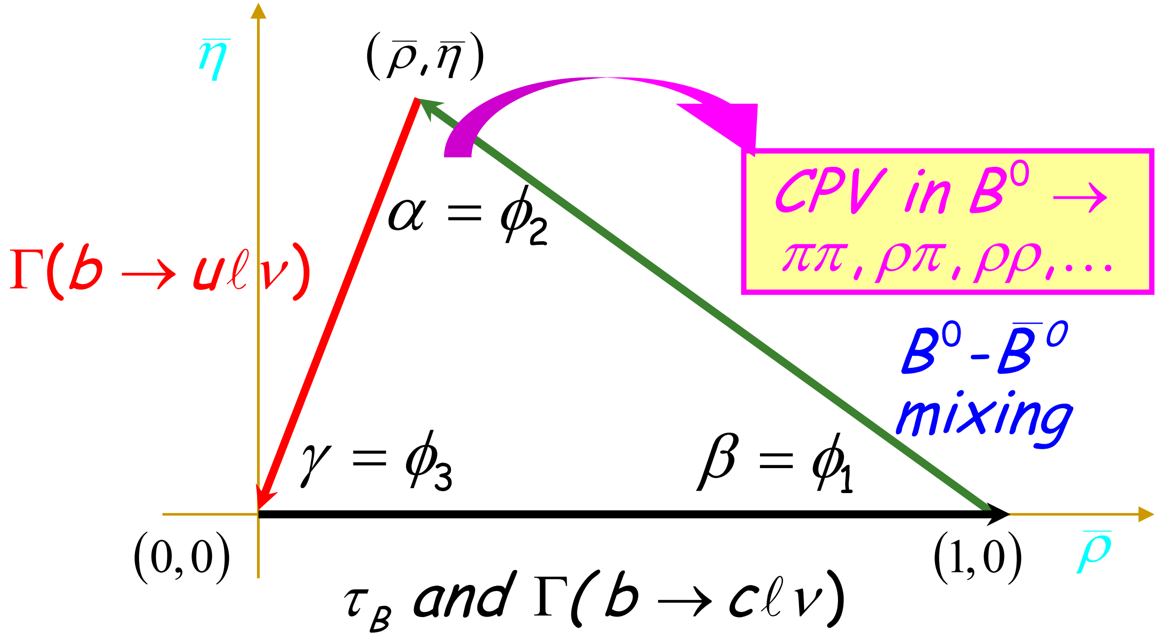
but the fit is poor

$K_s f_0$ from Dalitz analysis is 2.1σ above average. If excluded, sin2β=0.56±0.05

The discrepancy between charm and charmless sin2β seems to have gone away.

α

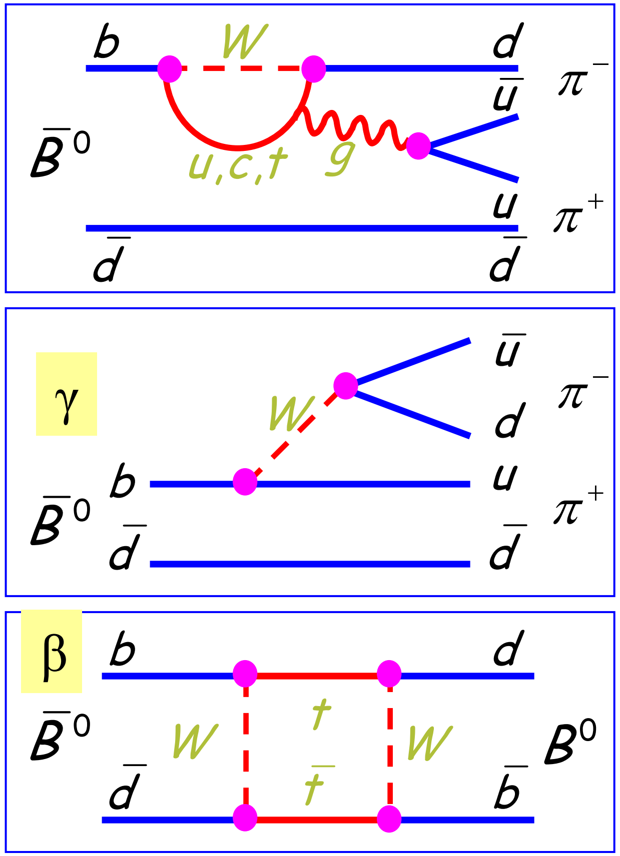
CPV in charmless modes



Interference of suppressed $b \to u$ tree decay with mixing

$\alpha = \pi - \beta - \gamma \Rightarrow$ process involving both B^0 mixing and $b \to u$ transition

3rd component: sizable Penguin diagram



SU(2) Symmetry: Isospin Analysis

- Two Isospin relations (one for (B^0,B+) and (B^0,B-)).

$$\Rightarrow A^{+-} + A^{00} = A^{+0} + \tilde{A}^{-0} e^{2i\gamma} = \tilde{A}^{+-} \big/ \sqrt{2} + \tilde{A}^{00}$$

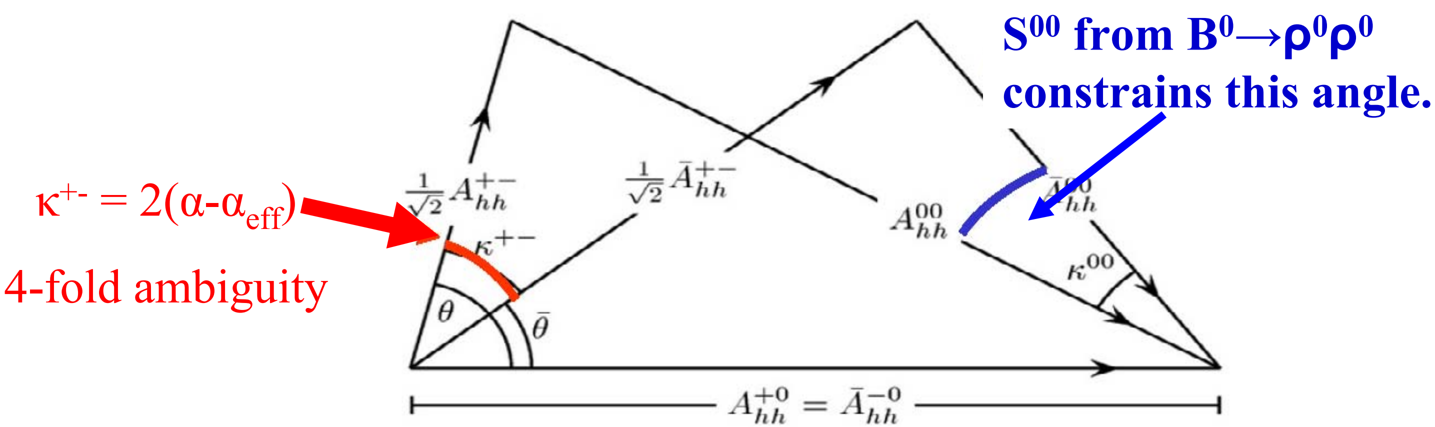
- Neglecting EW penguins, $B^+ \rightarrow h^+ h^0$ (I=2) is pure tree diagram:

$$\Rightarrow A(B^+ \rightarrow h^+ h^0) = \overline{A}(B^- \rightarrow h^- h^0)$$

$$\mathbf{A}^{+-} = \mathrm{A}(B^0 \rightarrow h^+ h^-)$$

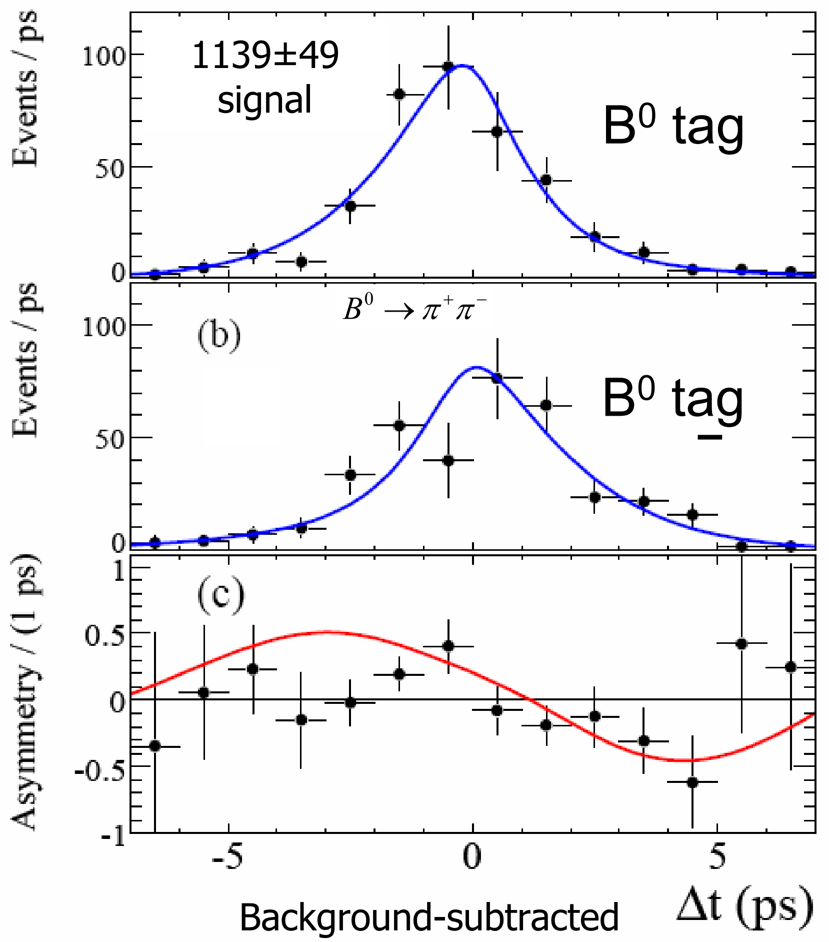
$$\mathbf{A}^{+0} = \mathrm{A}(B^+ \rightarrow h^+ h^0)$$

$$\mathbf{A}^{00} = \mathrm{A}(B^0 \rightarrow h^0 h^0)$$

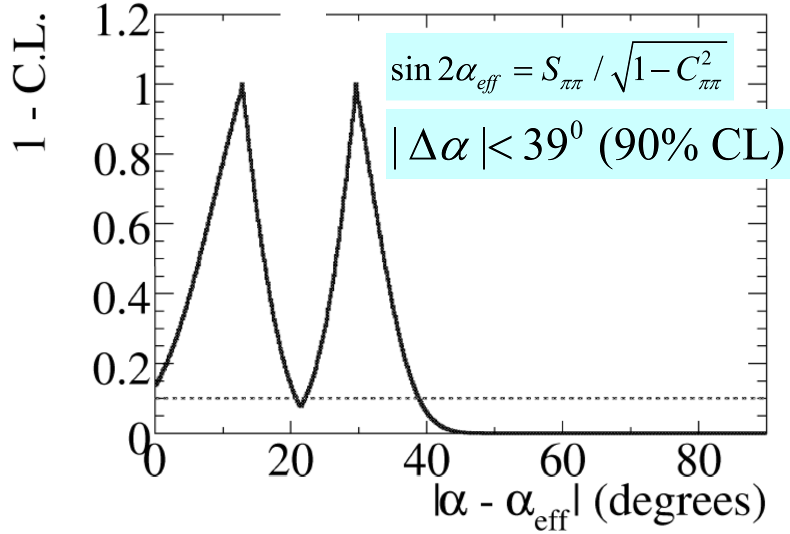


CP Violation in $B^0 \to \pi^+\pi^-$, $K^+\pi^-$

PRL 99, 021603 (2007) –383Mevts



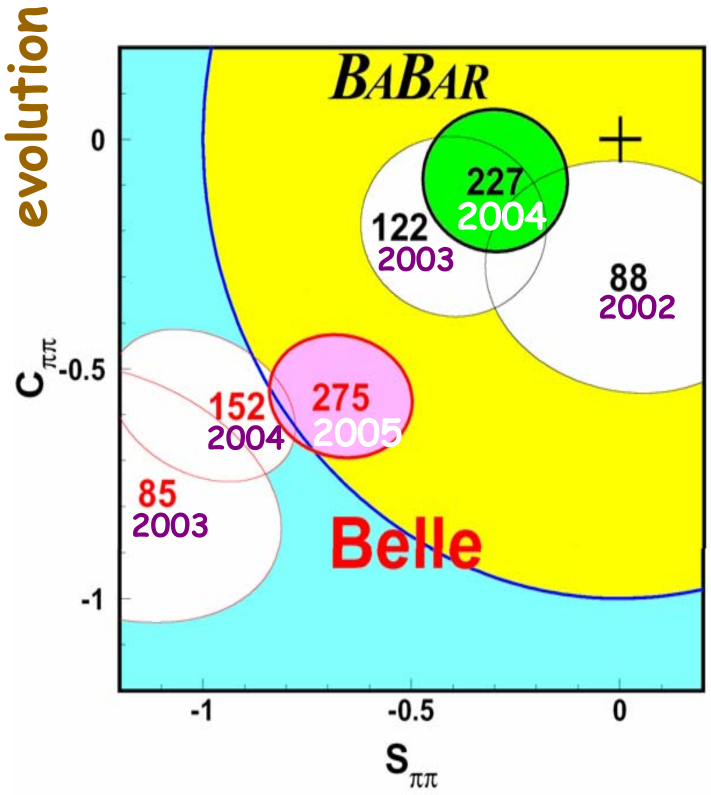
Combined with new prelim. BaBar measurements of $B^0 \to \pi^0\pi^0$ and $B^\pm \to \pi^\pm\pi^0$ (arXiv:0707.2798 [hep-ex]) gives constraints on $|\alpha - \alpha_{eff}|$



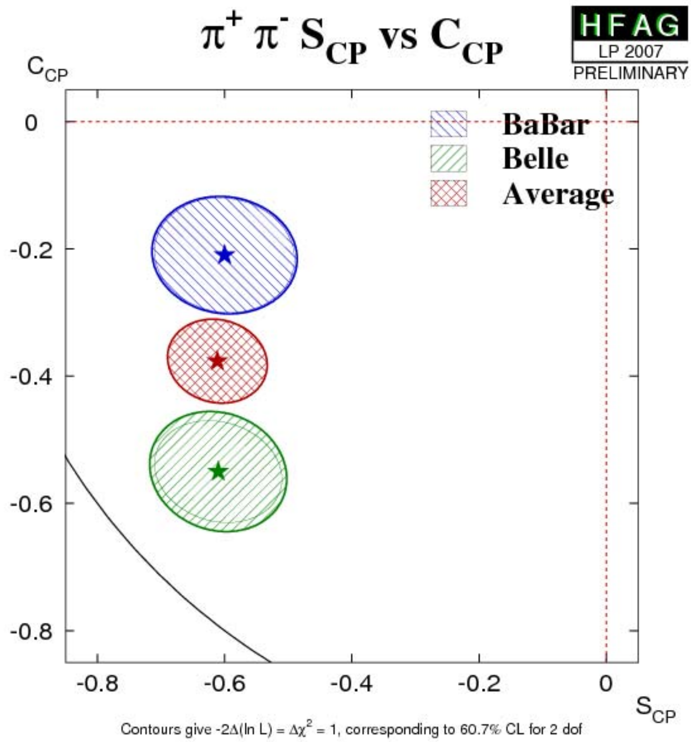
Direct CP !

$$S_{\pi\pi} = -0.60 \pm 0.11 \pm 0.03 \; (5.2\sigma)$$
$$C_{\pi\pi} = -0.21 \pm 0.09 \pm 0.02 \; (2.2\sigma)$$
$$A_{K\pi} = -0.107 \pm 0.018 \,^{+0.007}_{-0.004} \; (5.5\sigma)$$

Consistency of CP results for $B \to \pi\pi$



size of samples indicated in million BB pairs



Belle and BABAR in marginal agreement (2.1σ)

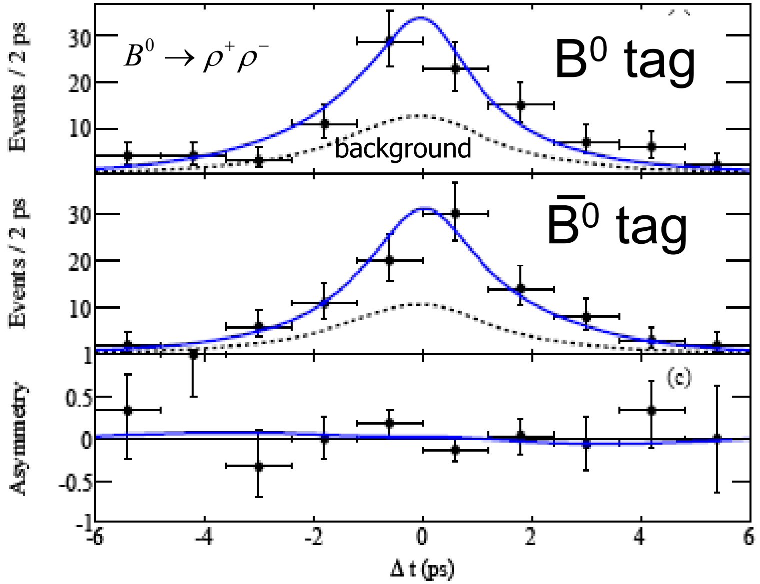
Belle observes significant direct *CP*, BaBar does not.

Constraints on α from $B \rightarrow \rho\rho$

PRD 76, 052007 (2007) –383Mevts

arXiv:0708.1630v2 – 427Mevts

PRL 97, 261801 (2006) - 232Mevts



- Vector-vector final state requires helicity analysis.
- Isospin analysis of $B^0 \rightarrow \rho^+\rho^-$, $B^\pm \rightarrow \rho^\pm\rho^0$, $B^0 \rightarrow \rho^0\rho^0$ constrains $|\alpha - \alpha_{eff}|$
- Smaller penguin contribution than $B \rightarrow \pi\pi$ leads to tighter constraint

$B^0 \rightarrow \rho^+\rho^-$:

$BF = (25.5 \pm 2.1^{+3.6}_{-3.9}) \times 10^{-6}$

$f_L = 0.992 \pm 0.024^{+0.026}_{-0.013}$

$C_L = 0.01 \pm 0.11 \pm 0.06$

$S_L = -0.17 \pm 0.20^{+0.05}_{-0.06}$

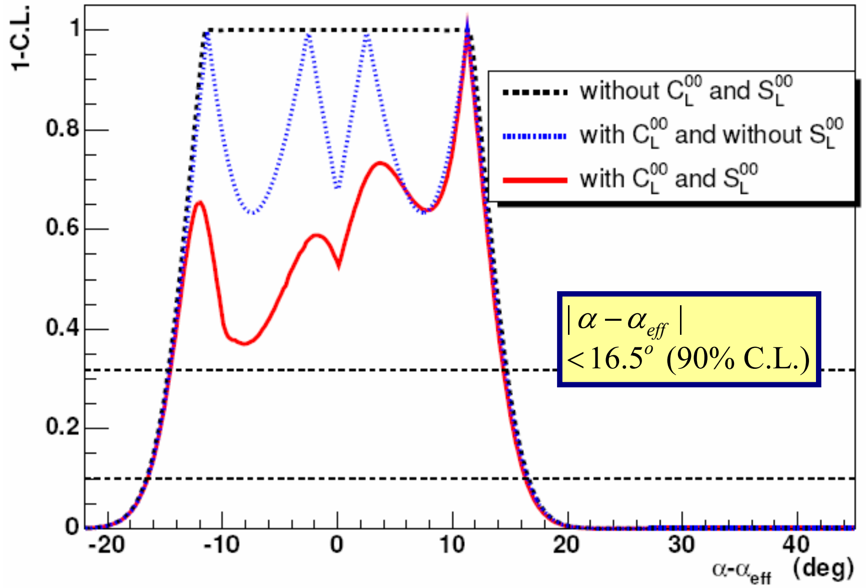
$B^0 \rightarrow \rho^0\rho^0$:

$BF = (0.84 \pm 0.29 \pm 0.17) \times 10^{-6}$

$f_L = 0.70 \pm 0.14 \pm 0.05$

$C_{CP} = 0.4 \pm 0.9 \pm 0.2$

$S_{CP} = 0.5 \pm 0.9 \pm 0.2$



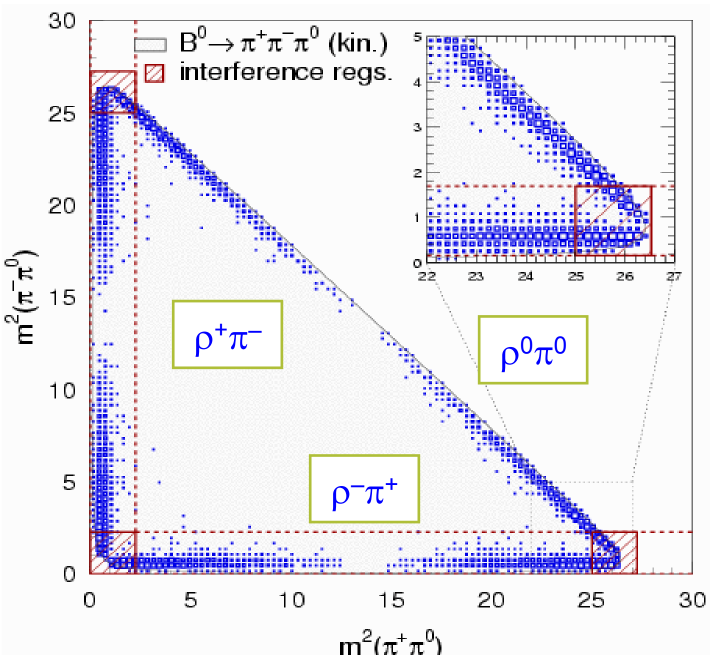
Constraints on α from $B^0 \to (\rho\pi)^0$

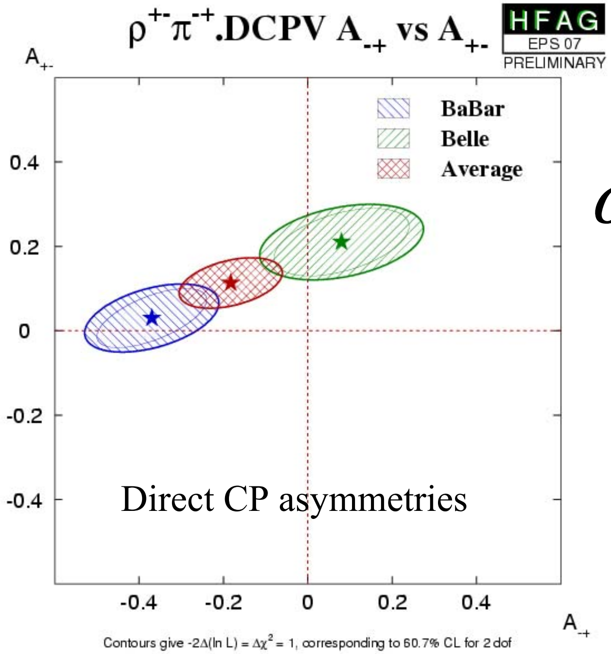
PRD 76, 012004 (2007) – 375Mevts

- Dominant decay $B^0 \to \rho^+\pi^-$: not a CP eigenstate
- Isospin analysis not viable, too many amplitudes

$B^0 \to \rho^+\pi^-$, $B^0 \to \rho^-\pi^+$, $B^0 \to \rho^0\pi^0$, $B^+ \to \rho^+\pi^0$, $B^+ \to \rho^0\pi^+$ and charge conjugates

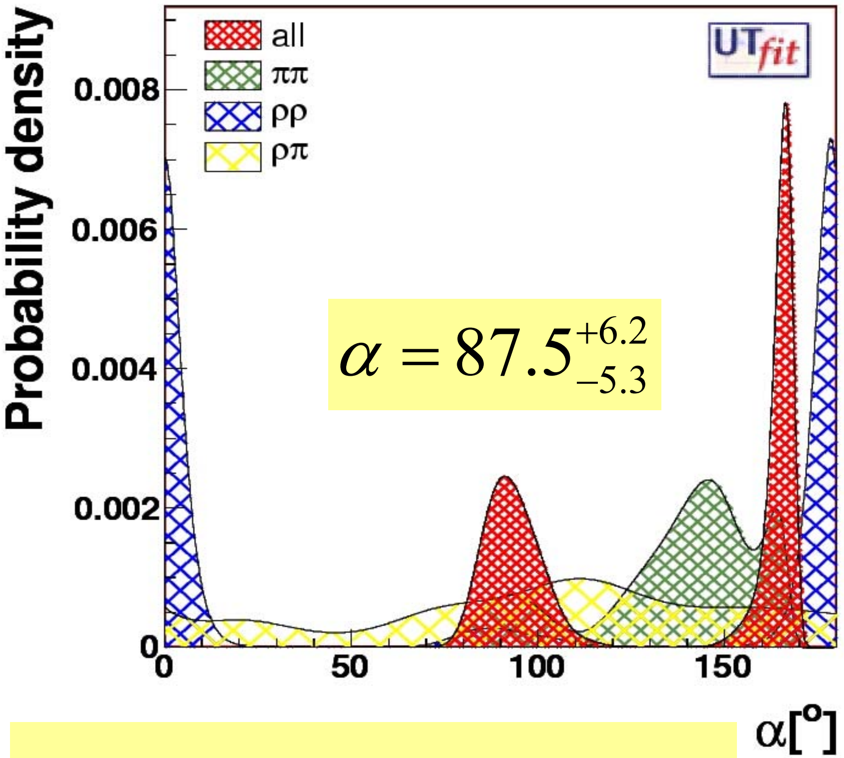
- Better approach: Time-dependent Dalitz analysis
  - Simultaneous fit of α and Tree, Penguin amplitudes
  - α constrained with no ambiguity (unlike $\sin(2\alpha)$ measurement)

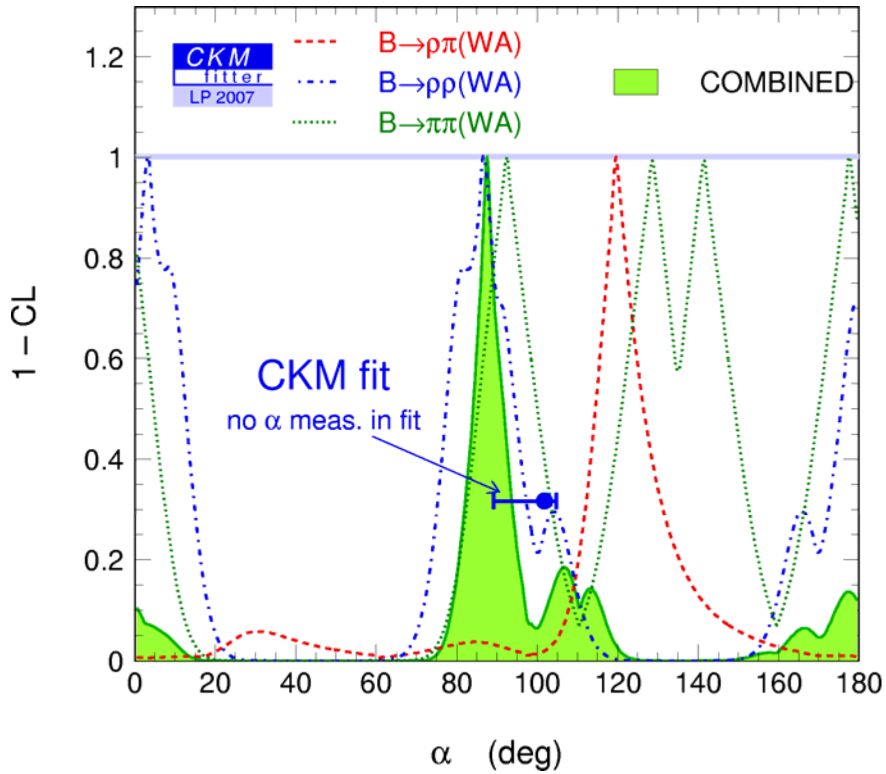




$$\alpha = \left(87^{+45}_{-13}\right)^0$$

Summary of constraints on α





α = [80,107]° and [156,171]°
@ 95% Probability

New modes coming on line: B→a_1π/K and B→K_1π/K

Use SU(3) symmetry to constrain α-α_{eff}

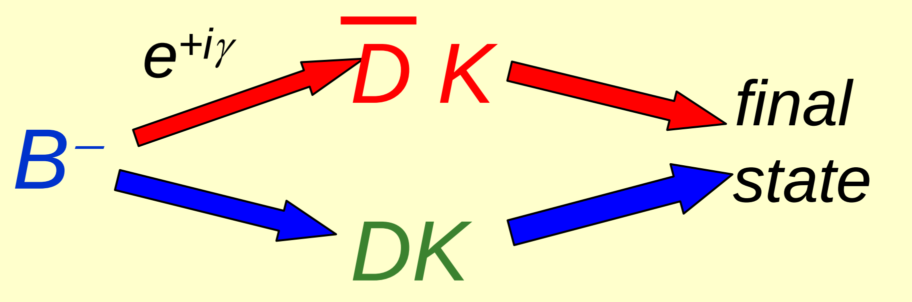
$\alpha_{eff}^{a_1\pi} = 78.6^0 \pm 7.3^0$

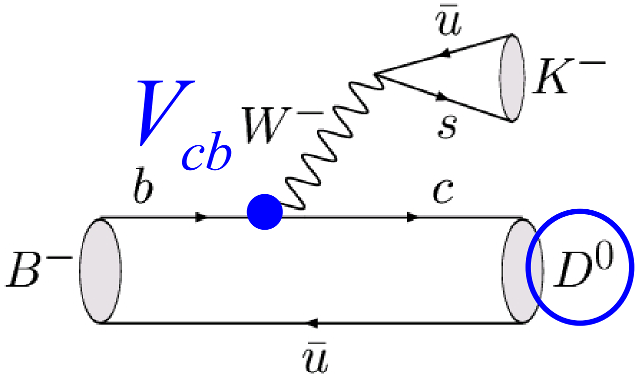
PRL 98, 181803 (2007)

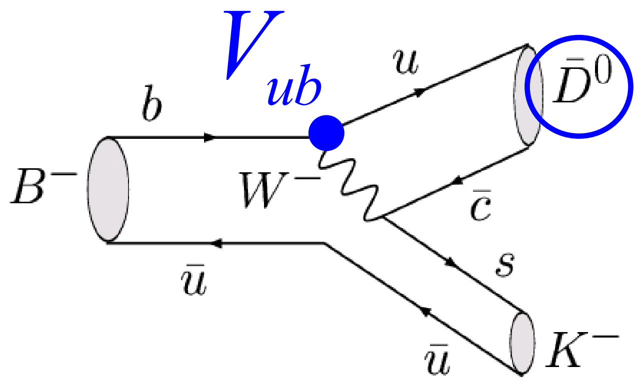
γ

Determination of γ

Use interference between tree decays of:
Cabibbo-suppressed (b→c) $B^- \to$ anti-D^0K^- and
CKM- and colour-suppressed (b→ u) $B^- \to D^0K^-$
where D^0 and anti-D^0 decay to same final state.







Interference depends on amplitude ratio

$$r = |A(B^- \to \bar{D}^0 K^-)| / |A(B^- \to D^0 K^-)| \sim 0.1$$

	Method	Modes	Final State	Advantage	Disadvantage
1	GLW	$D^0(CP_\pm)$	CP Eigenstate	Constraints	Low stats, small interf.
2	ADS	$D^0(K\pi)$	Flavour Eigenstate	Large interf.	Low stats
3	GGSW	$D^0(K_s hh)$ Dalitz	Three-body	Large stats, Dalitz info	Dalitz model

GLW: CP Violation in $B^\pm \to D^0_{CP} K^\pm$

arXiv:0708.1534 – 382Mevts

Final States: KK and ππ (CP=+1) and

$K^0_s\pi^0$ and $K^0_s\omega$ (CP=-1)

$$R_{CP\pm} \equiv \frac{BR(B^- \to D^0_{CP\pm}K^-) + BR(B^+ \to D^0_{CP\pm}K^+)}{[BR(B^- \to D^0K^-) + BR(B^+ \to D^0K^+)]/2}$$

$$= 1 + r_B^2 \pm 2r_B \cos\delta \cos\gamma$$

$$A_{CP\pm} \equiv \frac{BR(B^- \to D^0_{CP\pm}K^-) - BR(B^+ \to D^0_{CP\pm}K^+)}{BR(B^- \to D^0_{CP\pm}K^-) + BR(B^+ \to D^0_{CP\pm}K^+)}$$

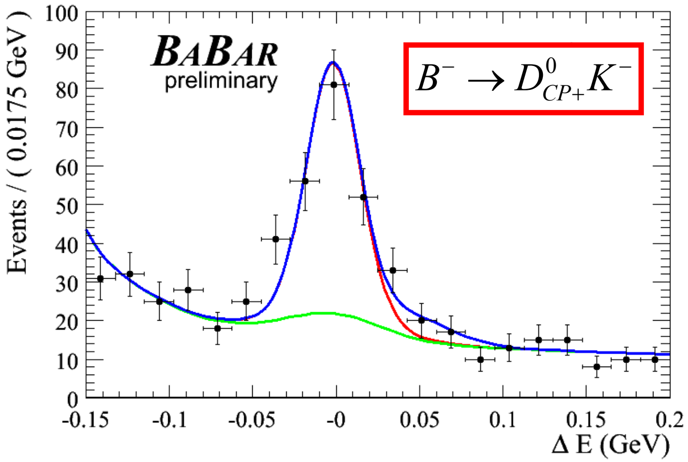
$$= \frac{\pm 2r_B \sin\delta \sin\gamma}{R_{CP\pm}}$$

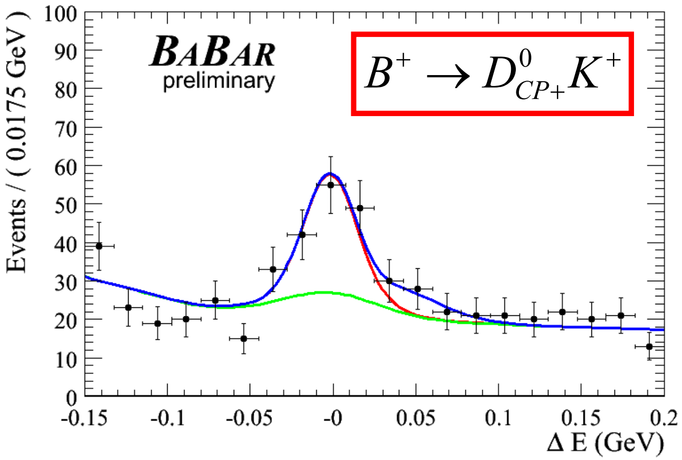
$$r_B = \left|\frac{A(b \to u)}{A(b \to c)}\right|$$

$$\delta = \arg\left|\frac{A(b \to u)}{A(b \to c)}\right|$$

$$R_{CP-} = 0.81 \pm 0.10 \pm 0.05$$
$$R_{CP+} = 1.07 \pm 0.10 \pm 0.04$$
$$A_{CP-} = -0.19 \pm 0.12 \pm 0.02$$
$$A_{CP+} = 0.35 \pm 0.09 \pm 0.05$$

First evidence (3.4σ) for direct CP violation in B → DK decays





PRD 72, 032004 (2005) –232Mevts
PRD 72, 071104 (2005) –232Mevts
arXiv:0708.182 – 226Mevts

ADS: B-→D$^{(*)}$K$^{(*)-}$ and D$^{(*)}\pi^-$

Final States: $K^+\pi^-, K^+\pi^-\pi^0$

$$R_{ADS} \equiv \frac{BR(B^- \to D_{K^+\pi^-}K^-) - BR(B^+ \to D_{K^-\pi^+}K^+)}{BR(B^- \to D_{K^-\pi^+}K^-) + BR(B^+ \to D_{K^+\pi^-}K^+)}$$

$$= r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

$$A_{ADS} \equiv \frac{BR(B^- \to D_{K^+\pi^-}K^-) + BR(B^+ \to D_{K^-\pi^+}K^+)}{BR(B^- \to D_{K^-\pi^+}K^-) + BR(B^+ \to D_{K^+\pi^-}K^+)}$$

$$= \frac{2r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{R_{ADS}}$$

$$r_D \equiv \left|\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)}\right| = 0.0613 \pm 0.001$$

$r_B \sim 0.01$ (expected)

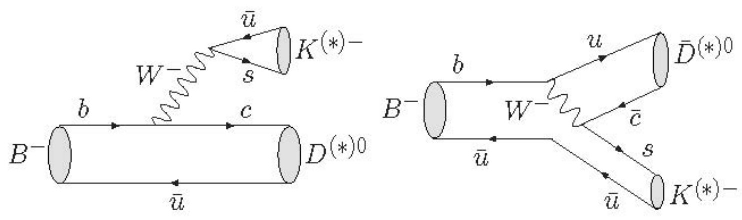
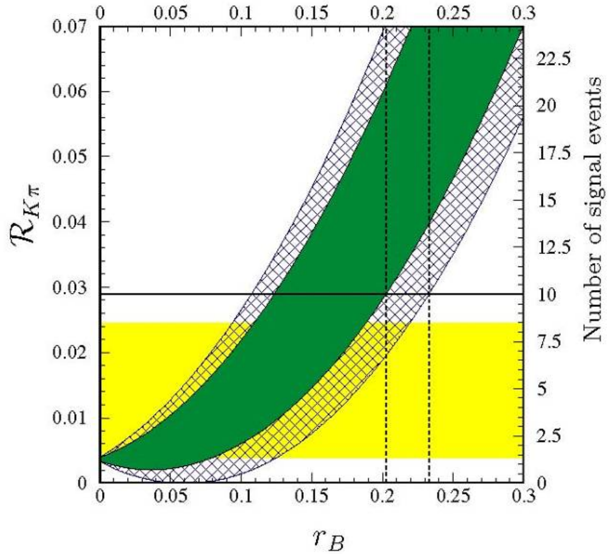
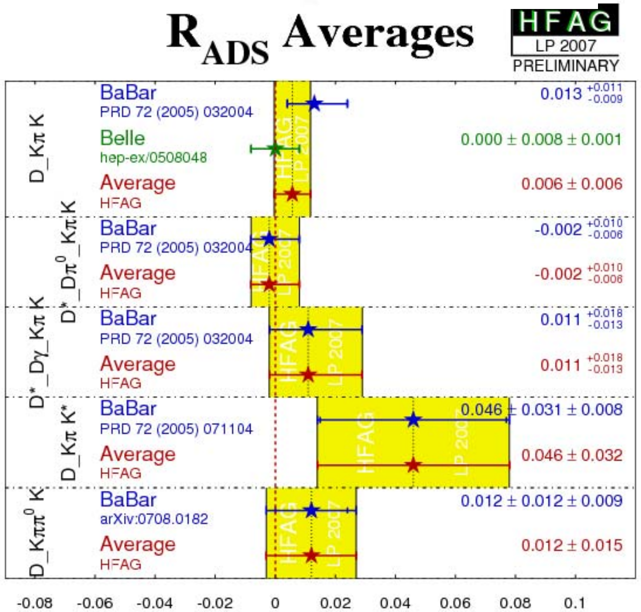


FIG. 1: Feynman diagrams for $B^- \to D^{(*)0}K^{(*)-}$ and $\overline{D}^{(*)0}K^{(*)-}$. The latter is CKM and color suppressed with respect to the former. The CKM-suppression factor is $|V_{ub}V_{cs}^*/V_{cb}V_{us}^*| \approx 0.4$. The naive color-suppression factor is $\frac{1}{3}$.



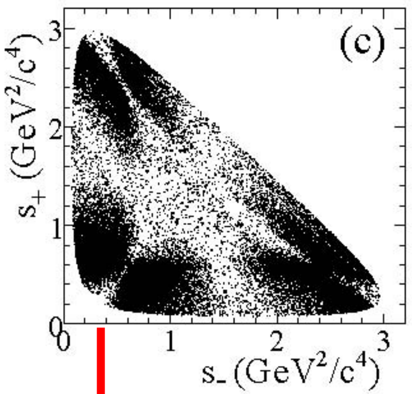


GGSZ: $B^{\pm} \to D^{(*)0}K^{\pm}$, $D^{(*)0} \to (K^0_S/\pi^0)\pi^+\pi^-$

hep-ex/0703037 – 324 Mevts

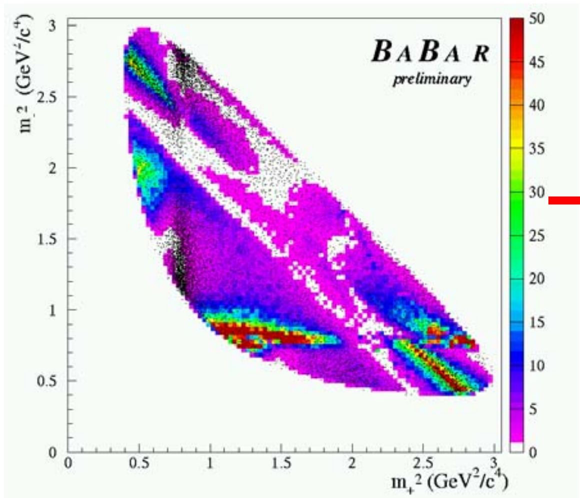
hep-ex/0607104 – 347 Mevts

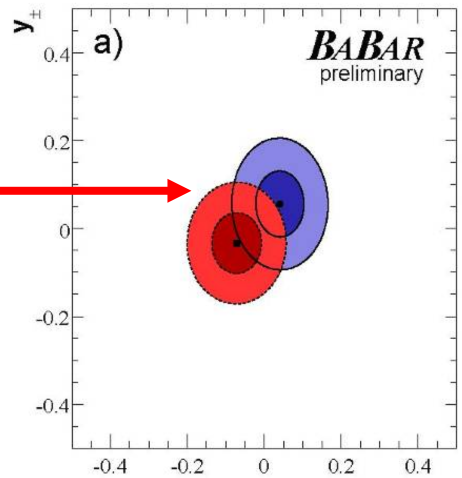
$$B^+ \to D^0\left[\to \pi^0\pi^+\pi^-\right]K^+$$



State	R_r (%)	$\Delta\phi_r$ (°)	f_r(%)
$\rho^+(770)$	100	0	67.8±0.0±0.6
$\rho^0(770)$	58.8±0.6±0.2	16.2±0.6±0.4	26.2±0.5±1.1
$\rho^-(770)$	71.4±0.8±0.3	−2.0±0.6±0.6	34.6±0.8±0.3
$\rho^+(1450)$	21±6±13	−146±18±24	0.11±0.07±0.12
$\rho^0(1450)$	33±6±4	10±8±13	0.30±0.11±0.07
$\rho^-(1450)$	82±5±4	16±3±3	1.79±0.22±0.12
$\rho^+(1700)$	225±18±14	−17±2±3	4.1±0.7±0.7
$\rho^0(1700)$	251±15±13	−17±2±2	5.0±0.6±1.0
$\rho^-(1700)$	200±11±7	−50±3±3	3.2±0.4±0.6
$f_0(980)$	1.50±0.12±0.17	−59±5±4	0.25±0.04±0.04
$f_0(1370)$	6.3±0.9±0.9	156±9±6	0.37±0.11±0.09
$f_0(1500)$	5.8±0.6±0.6	12±9±4	0.39±0.08±0.07
$f_0(1710)$	11.2±1.4±1.7	51±8±7	0.31±0.07±0.08
$f_2(1270)$	104±3±21	−171±3±4	1.32±0.08±0.10
$\sigma(400)$	6.9±0.6±1.2	8±4±8	0.82±0.10±0.10
Non-Res	57±7±8	−11±4±2	0.84±0.21±0.12

$$B^+ \to D^{(*)0}\left[\to K^0_S\pi^+\pi^-\right]K^+$$





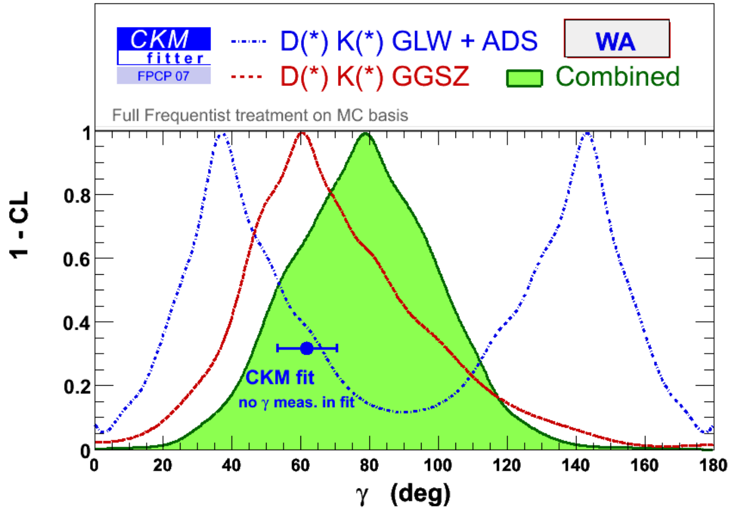
Dalitz allows measurement of γ, δ and r_B

$$x_+ = r_B\cos(\delta_B+\gamma) \quad y_+ = r_B\sin(\delta_B+\gamma)$$
$$x_- = r_B\cos(\delta_B-\gamma) \quad y_- = r_B\sin(\delta_B-\gamma)$$

Extract from fit:

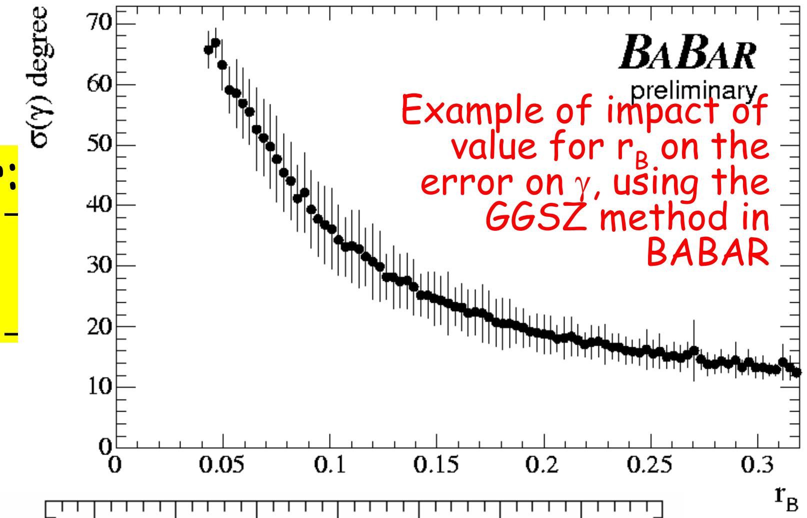
$$\gamma = (92 \pm 41 \pm 11 \pm 12)^o$$
$$\delta_B^* = (-62 \pm 59 \pm 18 \pm 10)^o$$

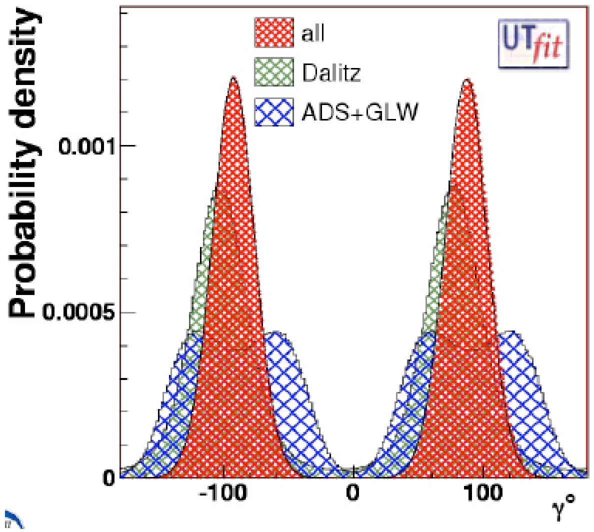
Status of γ



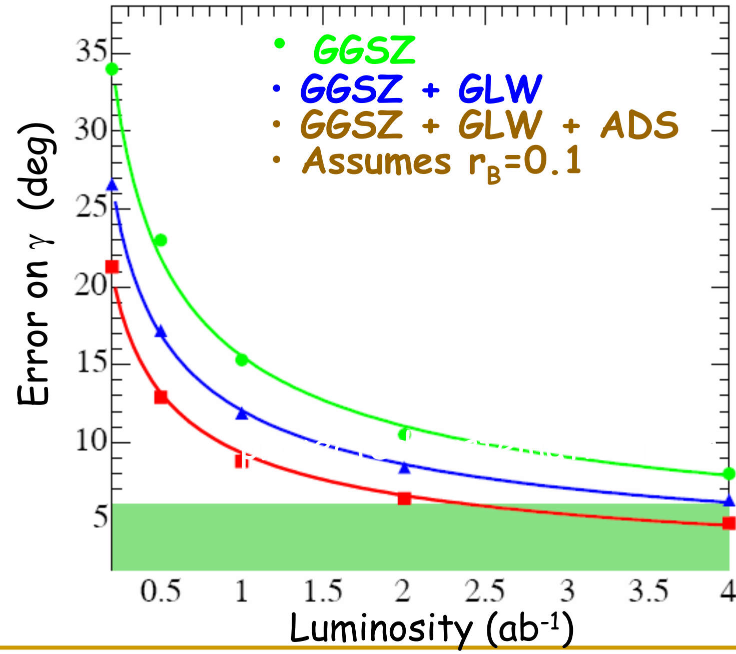
CKM Fitter:

$$\gamma = \left[77\,^{+30}_{-32}\right]$$





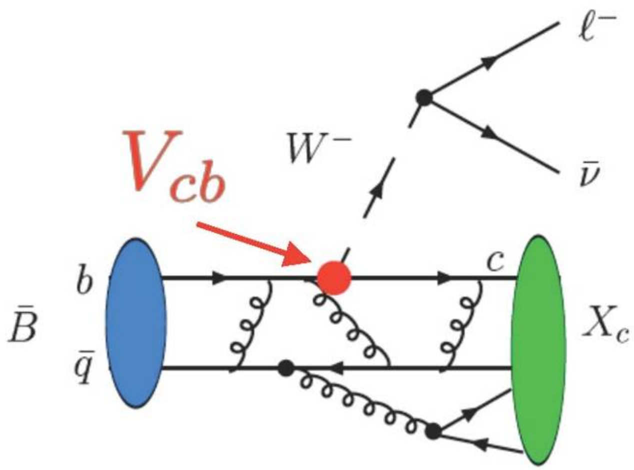
Still large uncertainty on γ



UT Sides

V_{cb} from $b \rightarrow X_c l\nu$

arXiv:0707.2670 – 232Mevts



$$\Gamma_{sl}(B \to X_c \ell \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 (1 + A_{EW}) A_{pert} A_{nonpert}$$

$$\frac{\mathcal{B}(B \to X_c \ell \nu)}{\tau_B} = f_{HQE}^{(0)} |V_{cb}|^2$$

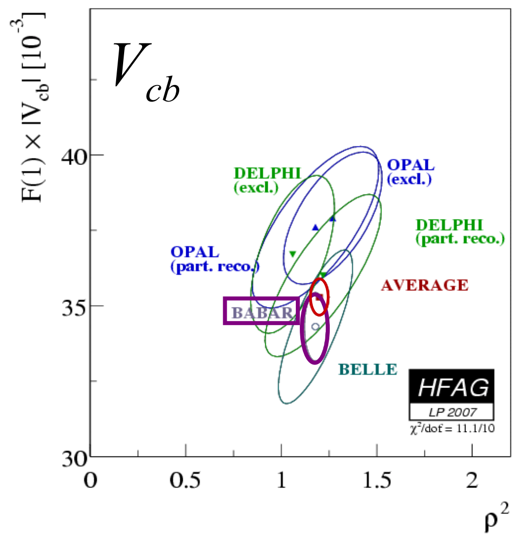
depends on m_b, m_c and HQE parameters

$$\langle m_X^n \rangle = f_{HQE}^{(n)}(p_\ell^* > p_{\ell,\min}^*; m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3)$$

- Measurement of
  - hadronic mass, lepton energy moments in $b \to c l \nu$
    - mixed hadronic moments $n_X^2 = m_X^2 - 2\tilde{\Lambda} E_X + \tilde{\Lambda}^2$
  - Photon energy moments in $b \to s\gamma$

preliminary

	$\lvert V_{cb} \rvert$ $\times 10^3$	m_b [GeV/c^2]	m_c [GeV/c^2]	$\mathcal{B}$ [%]
Results	41.88	4.552	1.070	10.597
Δ_{exp}	0.44	0.038	0.055	0.171
Δ_{theo}	0.35	0.040	0.065	0.053
$\Delta_{\Gamma_{sl}}$	0.59			
Δ_{tot}	0.81	0.055	0.085	0.179
Δ_{tot} [%]	1.9	1.2	7.9	1.7



arXiv:0708.3702 – 383Mevts

V_{ub} from $b \rightarrow X_u l \nu$

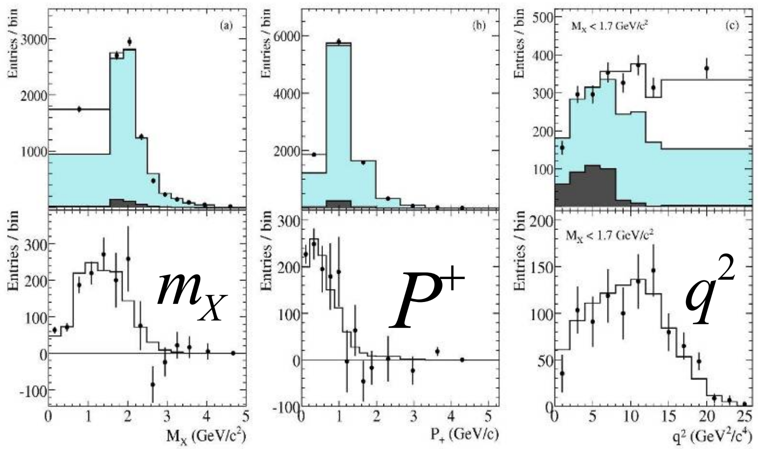
- Hadronic B tagged measurement

E_l = lepton energy

q^2 = lepton-neutrino mass quared

m_X = mass of hadronic system X

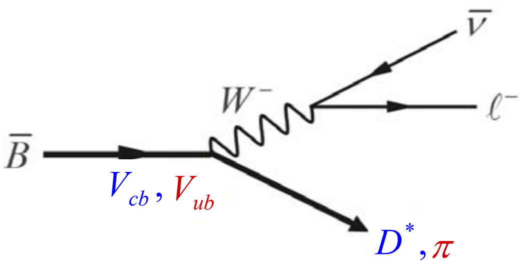
$P^+ = E_X - |p_X|$

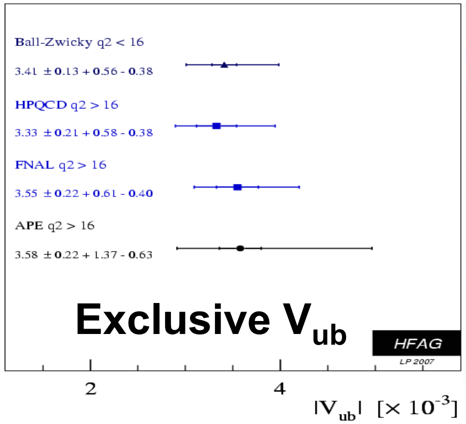


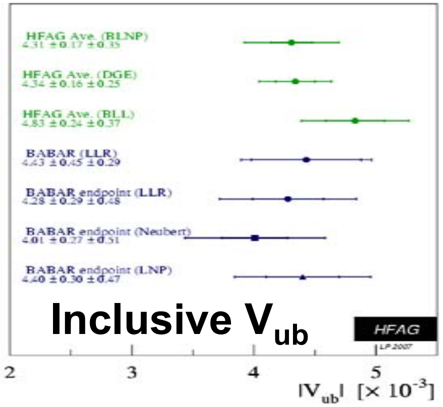
Relate Branching Fractions to V_{ub} via QCD calculations

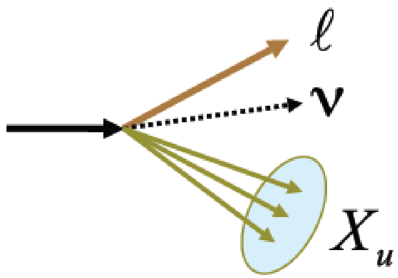
Kinematic Region	$B(B \rightarrow X_u l\nu)$ Δ(stat. sys. th.)	$\|V_{ub}\|$ (10^{-3}) Δ(stat. sys. th.)	Theory
M_X<1.55 GeV/c²	1.18 ± 0.09 ± 0.07 ± 0.01	4.27 ± 0.16 ± 0.13 ± 0.30	BLNP
		4.56 ± 0.17 ±0.14 ± 0.32	DGE
P_+<0.66 GeV/c²	0.95 ± 0.10 ± 0.08 ± 0.01	3.88 ± 0.19 ± 0.16 ± 0.28	BLNP
		3.99 ± 0.20 ± 0.16 ± 0.24	DGE
M_X<1.7 GeV/c² & q^2>8.0 GeV²/c²	0.76 ± 0.08 ± 0.07 ± 0.02	4.48 ± 0.22 ± 0.19 ± 0.30	BLNP
		4.53 ± 0.22 ± 0.19 ± 0.25	DGE
		4.81 ± 0.23 ± 0.20 ± 0.36	BLL

- **Summary – Inclusive and exclusive modes**



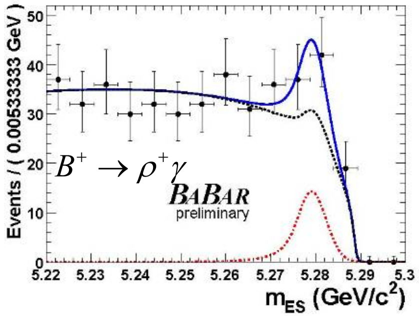


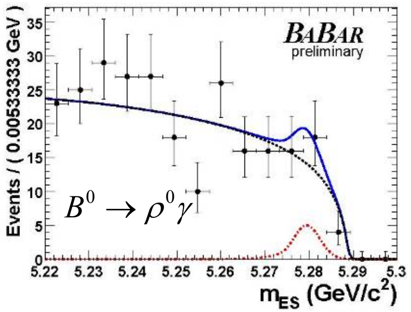


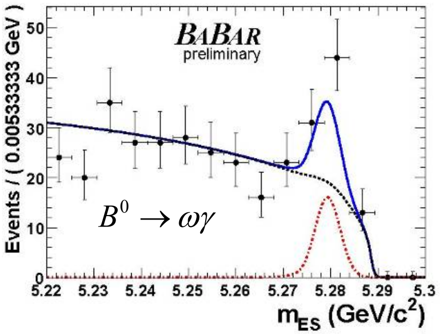


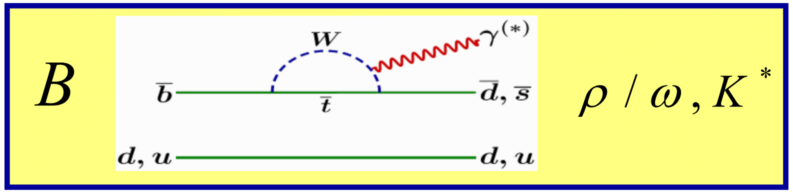
V_{td} / V_{ts} from $B \to (\rho/\omega)\gamma$

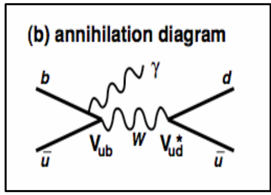
hep-ex/0607099 – 347Mevts





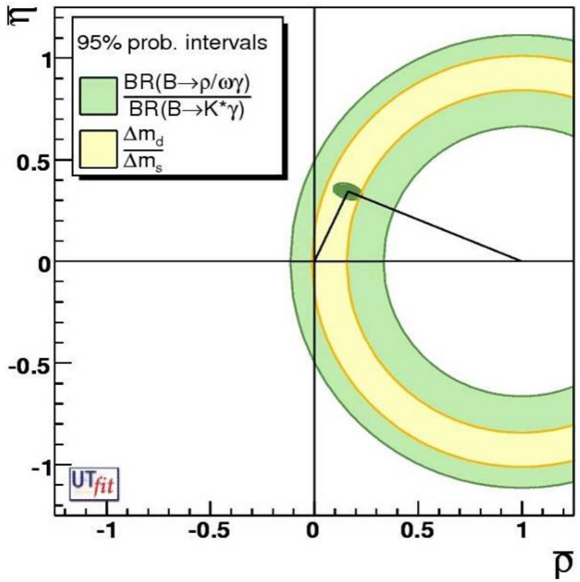






$$\frac{BF(B \to (\rho/\omega)\gamma)}{BF(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{m_B^2 - m_\rho^2}{m_B^2 - m_{K^*}^2}\right)^3 \zeta^2 (1 + \Delta R)$$

Light Cone Sum Rules



$\rho\gamma/K^*\gamma \to |V_{td}/V_{ts}| = 0.200 \pm 0.021(\text{exp}) \pm 0.015(\text{thy})$

mixing $\to |V_{td}/V_{ts}| = 0.2060 \pm 0.0007(\text{exp}) \pm 0.0081(\text{thy})$

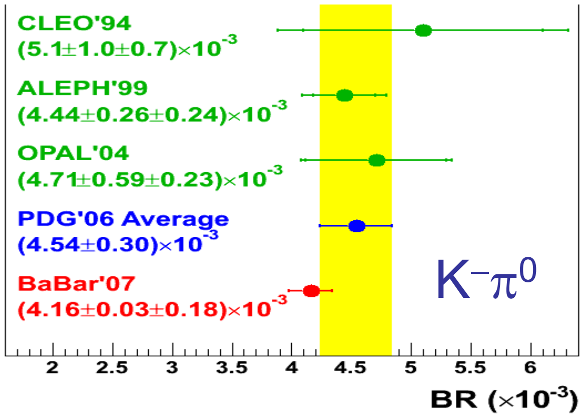
V_{us} from $\tau^- \to K^-\pi^+\pi^-\nu$, $K^-\pi^0\nu$ decays

arXiv:0707.2922 – 316Mevts
arXiv:0707.2981 – 316Mevts
arXiv:0707.3058 – Summary

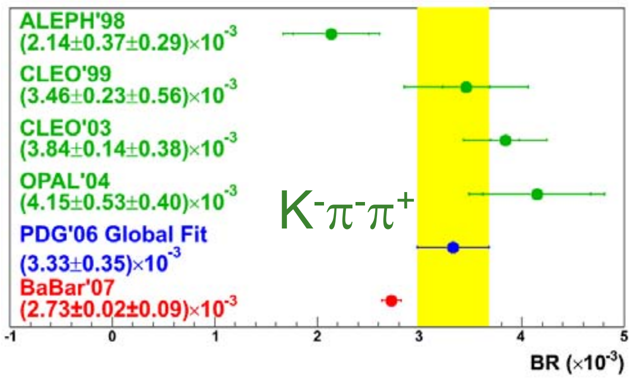
$$R_\tau^{kl} = \int_0^1 dz(1-z)^k z^l \frac{dR_\tau}{dz} \qquad z = \frac{q^2}{m_\tau^2}$$

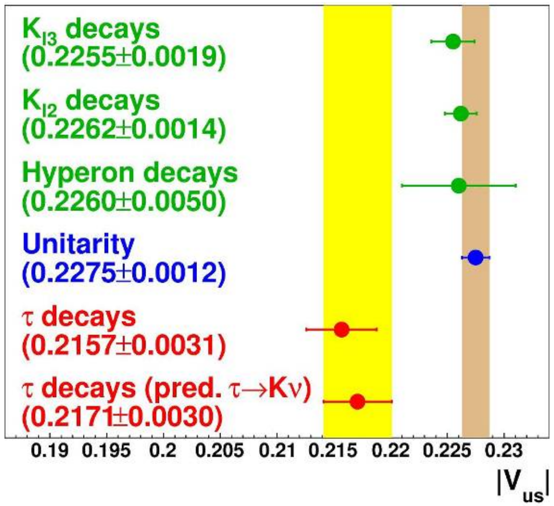
$$R_\tau = \frac{\Gamma[\tau^- \to had^- \nu_\tau(\gamma)]}{\Gamma[\tau^- \to e^- \overline{\upsilon}_e \nu_\tau(\gamma)]}$$

Spectral functions of τ decays to strange final states determines V_{us}



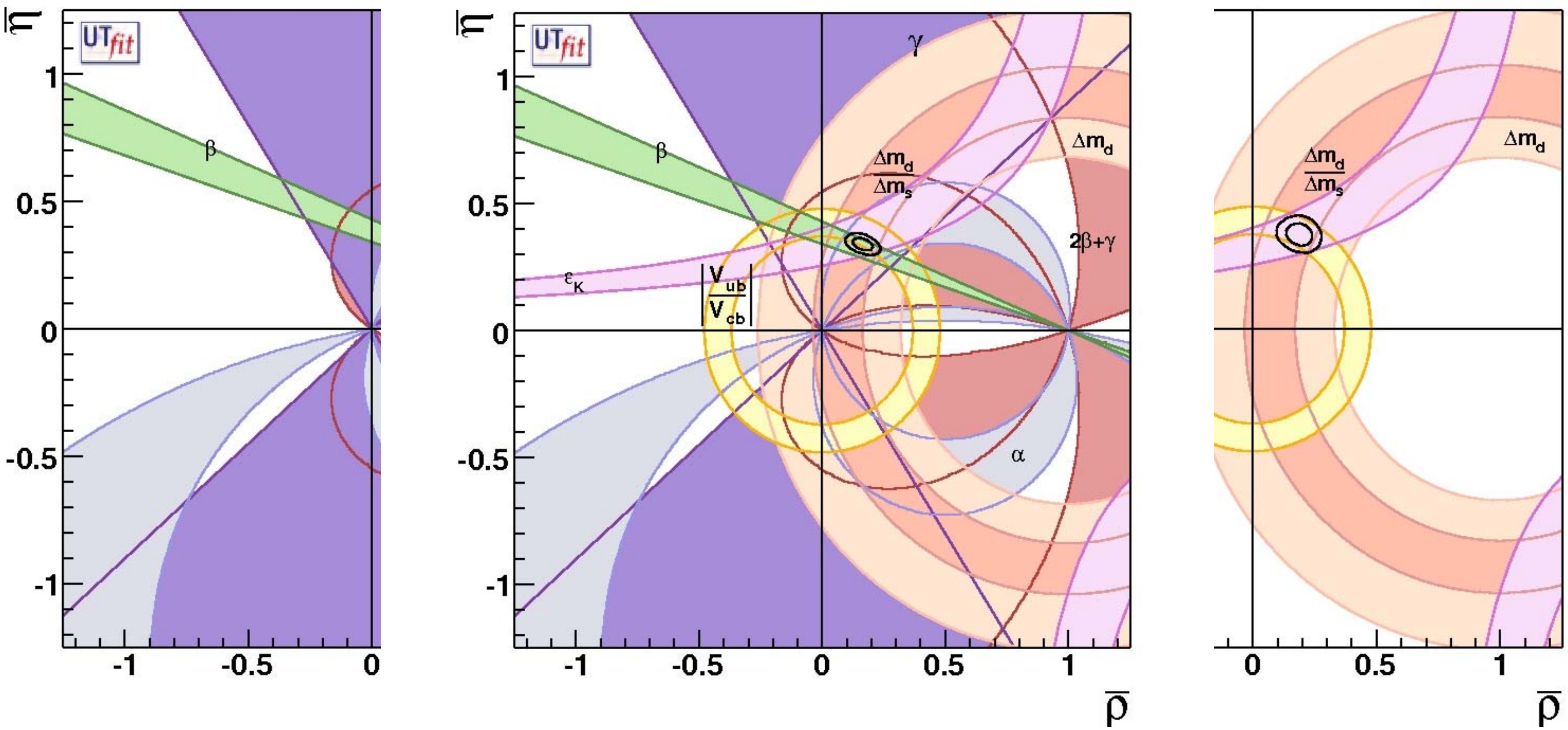
$$BF(\tau^- \to K^-\pi^-\pi^+\nu) = (0.273 \pm 0.002 \pm 0.009)\%$$
$$BF(\tau^- \to K^-\pi^-K^+\nu) = (0.1346 \pm 0.0010 \pm 0.0036)\%$$
$$BF(\tau^- \to \pi^-\pi^-\pi^+\nu) = (8.83 \pm 0.01 \pm 0.13)\%$$
$$BF(\tau^- \to \phi\pi^-\nu) = (3.42 \pm 0.55 \pm 0.25)\%$$
$$BF(\tau^- \to \phi K^-\nu) = (3.39 \pm 0.20 \pm 0.28)\%$$





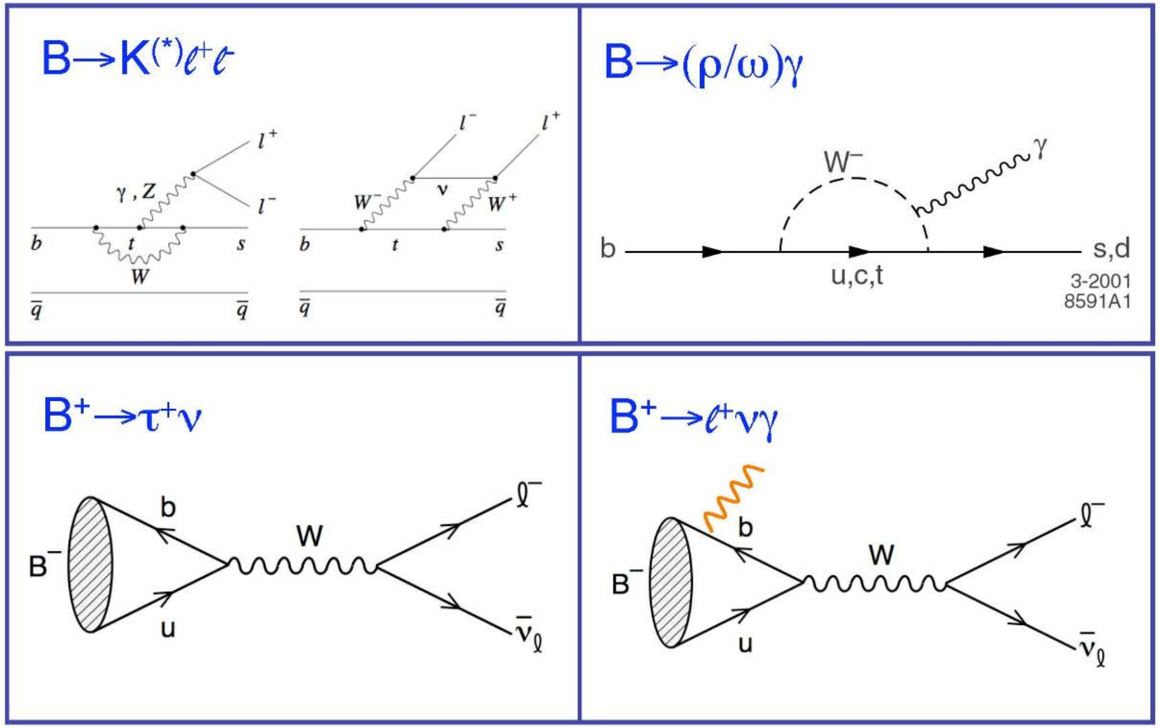
3σ difference between τ and K decays

CKM Unitarity: Angles and Sides



Consistent apex of Unitarity Triangle from Angles and Sides !

New Physics?



$B \to K^{(*)} \ell^+ \ell^-$
$B \to (\rho/\omega)\gamma$
W−
γ
b
s,d
u,c,t
3-2001
8591A1
$B^+ \to \tau^+ \nu$
$B^+ \to \ell^+ \nu \gamma$
b
W
u
B^-
ℓ^-
$\bar{\nu}_\ell$

$B \rightarrow \tau\nu$

arXiv:0708.2260 – 383Mevts
arXiv:0705.1820 – 383Mevts

$$\mathrm{B}(B^+ \rightarrow \tau^+ \upsilon) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left[1 - \frac{m_\tau^2}{m_B^2}\right] \tau_B f_B^2 \left|V_{ub}\right|^2$$

Semileptonic Tag: $B_{tag} \rightarrow D^0 l^- \bar{\upsilon} X$

$$BF(B \rightarrow \tau\upsilon) = (0.9 \pm 0.6 \pm 0.1) \times 10^{-4}$$

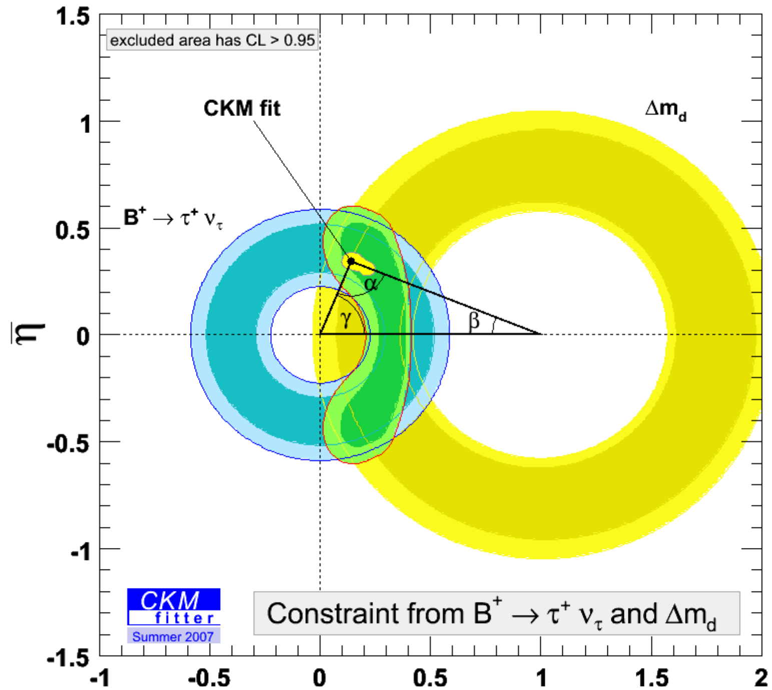
$$f_B \left|V_{ub}\right| = (7.2^{+2.0}_{-2.8} \pm 0.2) \times 10^{-4} \text{ GeV}$$

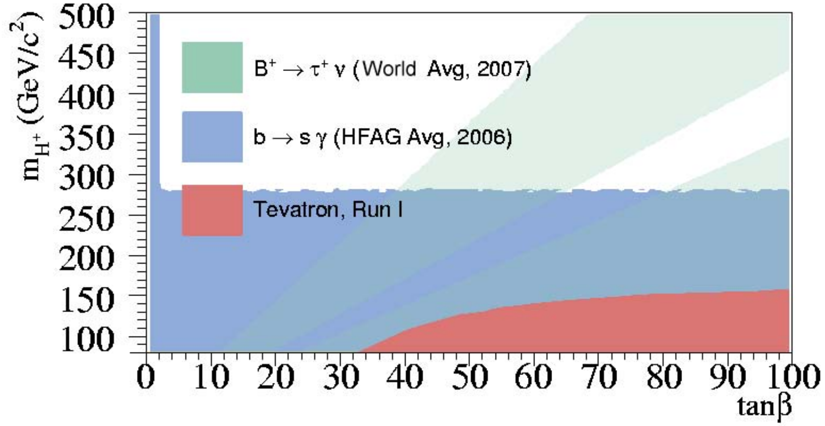
Hadronic Tag: $B_{tag} \rightarrow D^0 X$

$$BF(B \rightarrow \tau\upsilon) = (1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2) \times 10^{-4}$$

$$f_B \left|V_{ub}\right| = (10.1^{+2.3+1.2}_{-2.5-1.5}) \times 10^{-4} \text{ GeV}$$

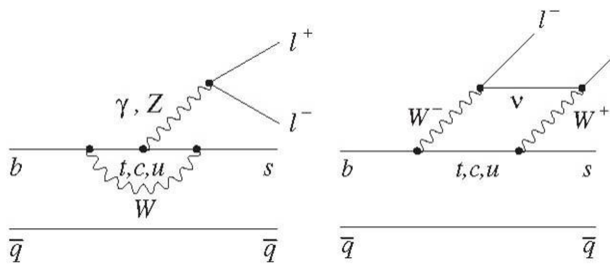
$$R_{B\rightarrow\tau\upsilon} \equiv \frac{SUSY}{SM} \approx \left(1 - \frac{\tan^2\beta}{m_{H^\pm}^2} m_B^2\right)^2$$





$B \to K^{(*)} l^+ l^-$

PRD 73 (2006) 092001 – 229Mevts



$$\frac{1}{\Gamma}\frac{d\Gamma(B\to K^* l^+ l^-)}{d\cos\theta_K} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

$$\frac{1}{\Gamma}\frac{d\Gamma(B\to K^* l^+ l^-)}{d\cos\theta_l} = \frac{3}{4}F_L(1-\cos^2\theta_l) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l) + A_{FB}cos\theta_l$$

$$\frac{1}{\Gamma}\frac{d\Gamma(B\to K l^+ l^-)}{d\cos\theta_l} = \frac{3}{4}(1-F_S)(1-\cos^2\theta_l) + \frac{1}{2}F_S + A_{FB}cos\theta_l$$

Branching Fraction:

$BF(B\to K l^+ l^-) = (0.34\pm0.07\pm0.02)\times10^{-6}$ (SM~0.4×10^{-6})

$BF(B\to K^* l^+ l^-) = (0.78^{+0.19}_{-0.17}\pm0.11)\times10^{-6}$ (SM~1.2×10^{-6})

$BF(B\to K^* l^+ l^-)_{q^2>0.1} = (0.73^{+0.19}_{-0.17}\pm0.11)\times10^{-6}$

CP Asymmetry:

$A_{CP}(K) = -0.07\pm0.22\pm0.02$ (SM~0)

$A_{CP}(K^*) = 0.03\pm0.23\pm0.03$ (SM~0)

Ratio of BF($K^{(*)}\mu\mu$) to BF($K^{(*)}ee$):

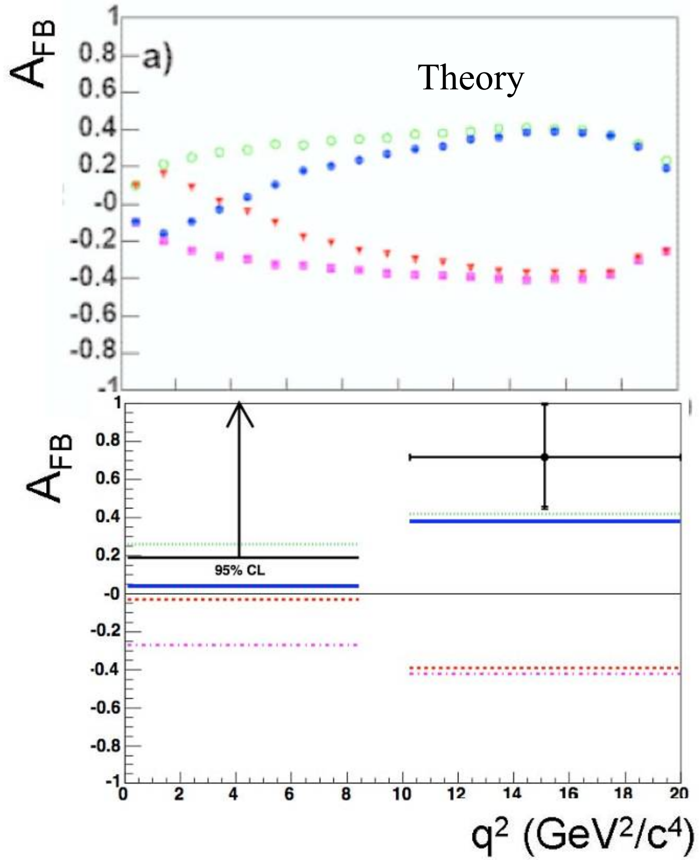
$R_K = 1.06\pm0.48\pm0.08$ (SM~1)

$R_{K^*} = 0.91\pm0.45\pm0.06$ (SM~0.75)

$R_{K^*}(q^2>0.1) = 1.40\pm0.78\pm0.10$ (SM~1)

$$A_{FB}(B\to K^* l^+ l^-)_{q^2>0.1} > 0.55$$

$$A_{FB}(B\to K l^+ l^-)_{q^2>0.1} = 0.15^{+0.21}_{-0.23}\pm0.08$$



$B \rightarrow (\rho/\omega)\gamma$

PRL 98 (2007) 151802 – 347 Mevts

$BF(B^+ \rightarrow \rho^+\gamma) = (1.1 \pm 0.37 \pm 0.09) \times 10^{-6}$

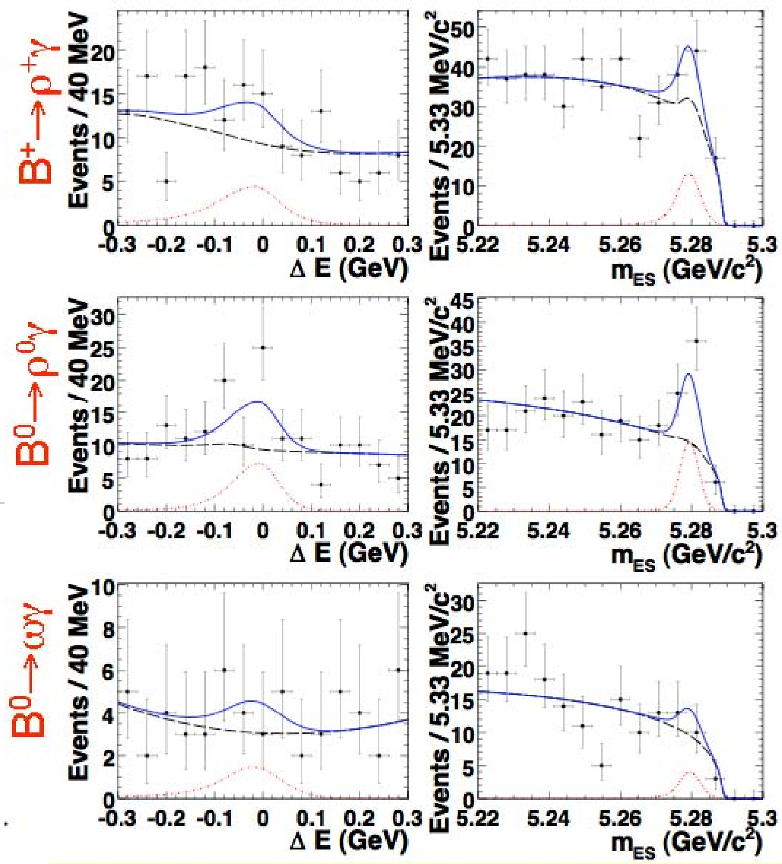
$BF(B^0 \rightarrow \rho^0\gamma) = (0.79 \pm 0.22 \pm 0.06) \times 10^{-6}$

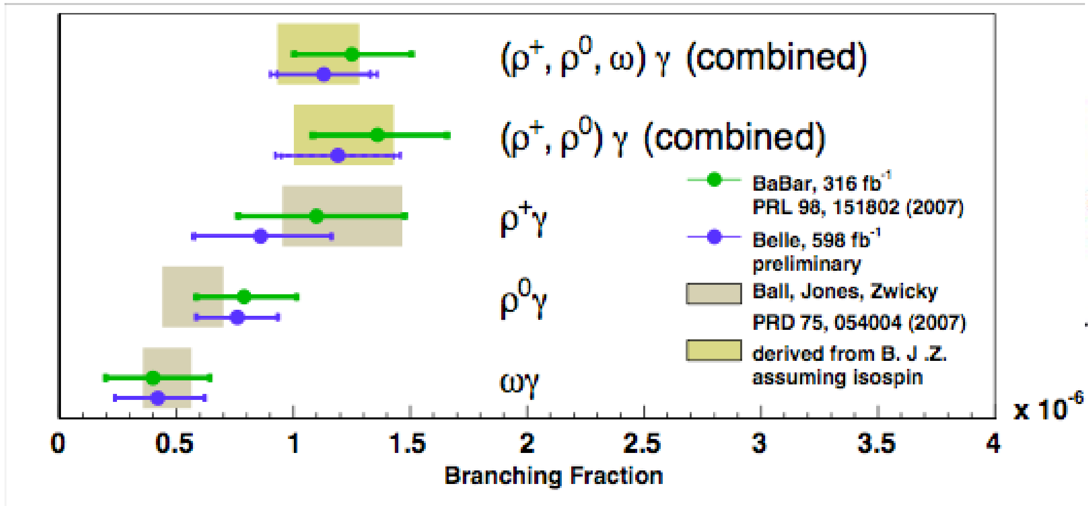
$BF(B^0 \rightarrow \omega\gamma) < 0.78 \times 10^{-6}$ @ 90% CL

$BF(B \rightarrow (\rho/\omega)\gamma) = (1.25 \pm 0.25 \pm 0.09) \times 10^{-6}$

Compare with SM prediction:

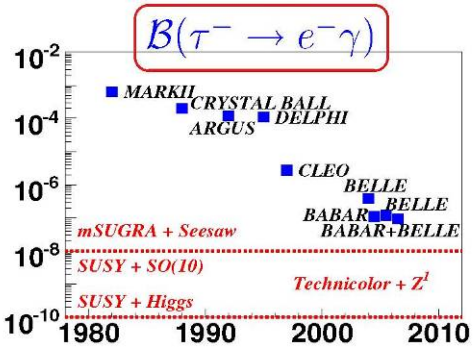
$BF(B \rightarrow (\rho/\omega)\gamma) = (1.38 \pm 0.42) \times 10^{-6}$

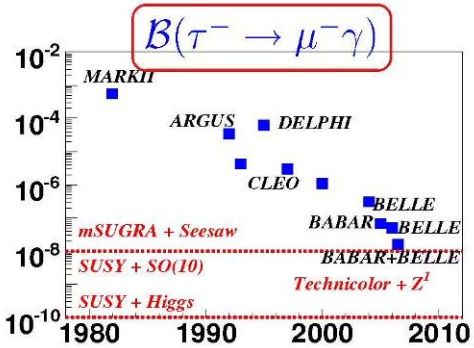


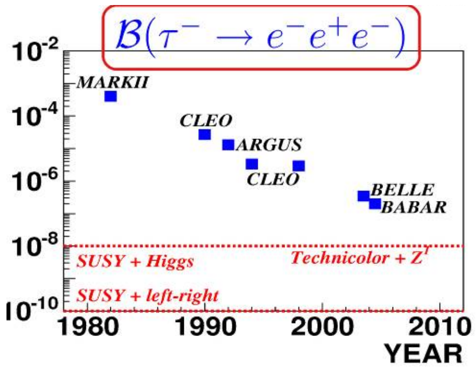


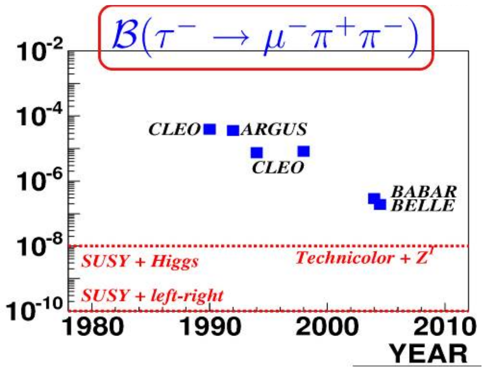
Lepton Flavour Violation

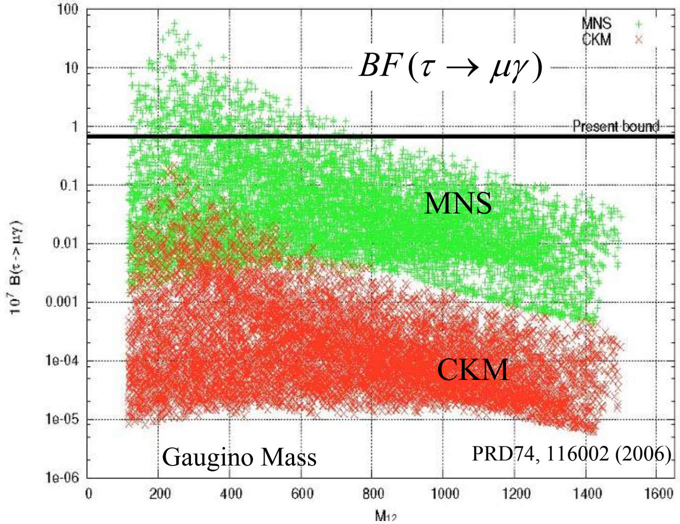
$\tau \to \mu\gamma$	BR < 0.68 x 10^{-7} (PRL 95 (2005) 041802)
$\tau \to e\gamma$	BR < 1.10 x 10^{-7} (PRL 96 (2006) 041801)
$\tau \to lll$	BR < (0.4-0.8) x 10^{-7} (PRL 99 (2007) 251803)
$\tau \to l\pi/\eta/\eta'$	BR < (1.1-1.6) x 10^{-7} (PRL 98 (2007) 061803)
$\tau \to lhh'$	BR < (0.7-4.8) x 10^{-7} (PRL 95 (2005) 191801)

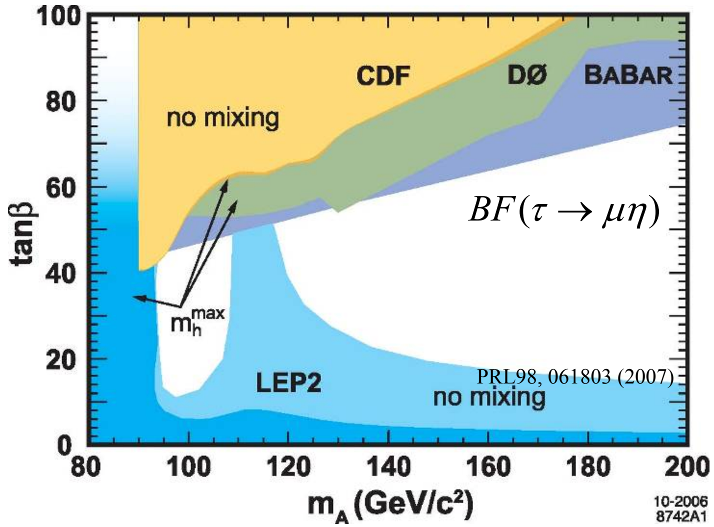




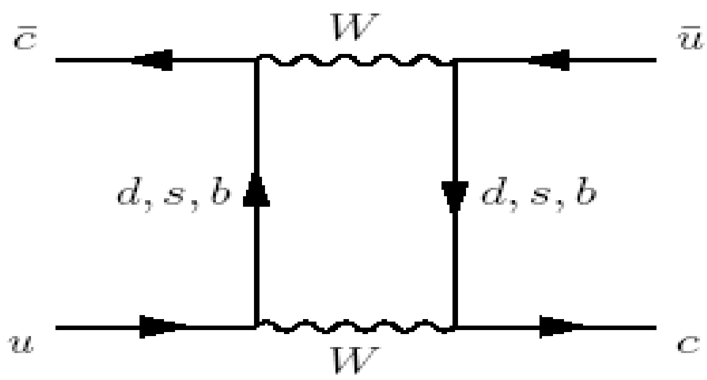








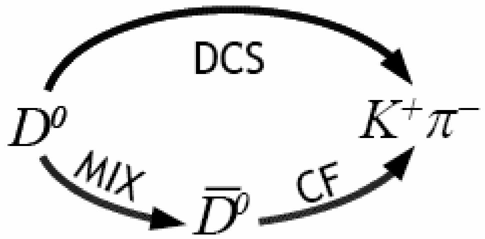
D Mixing



Wrong Sign $D^0 \rightarrow K^+\pi^-$

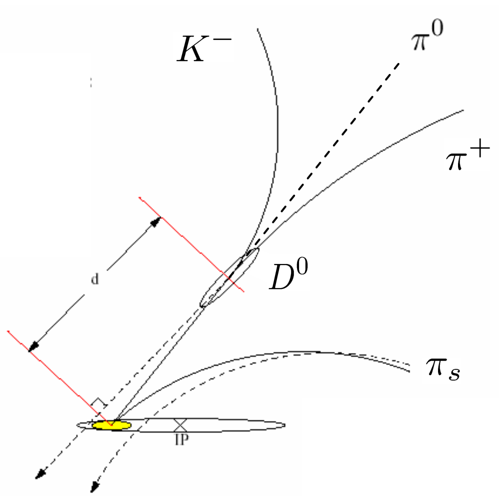
PRL 98 (2007) 211802 – 383Mevts

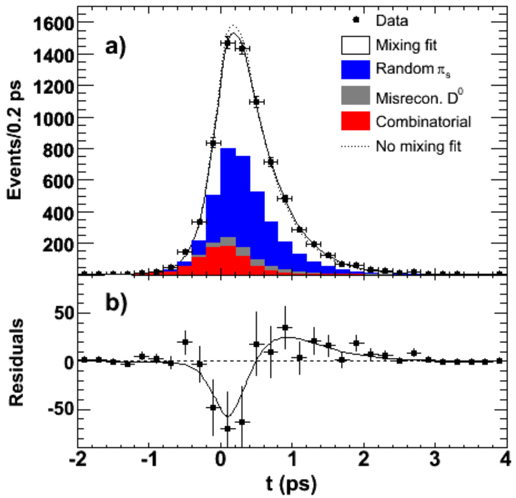
$$\frac{dN}{dt} \propto e^{-\Gamma t}\left[\underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}\, y'(\Gamma t)}_{\text{interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{mixing}}\right]$$

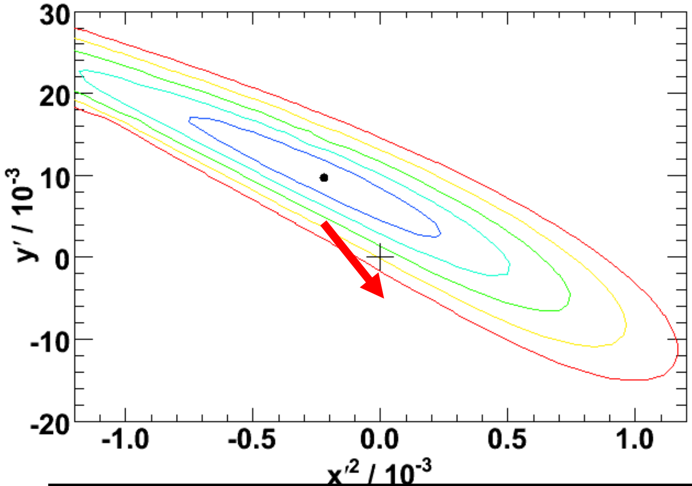


$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$

δ = strong phase between CF and DCS decay (zero in SU(3) limit)





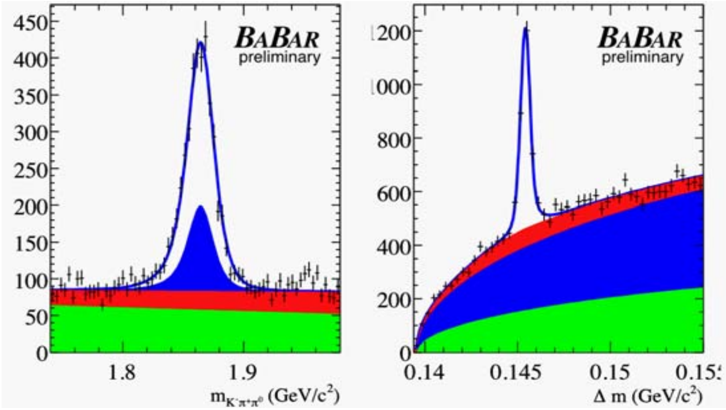


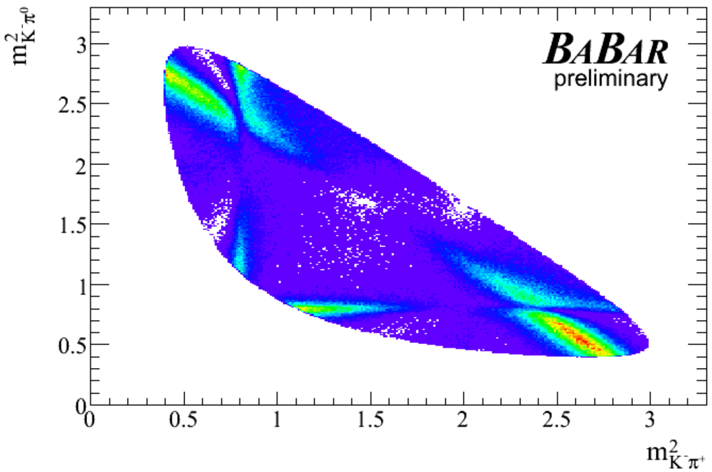
R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$
x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

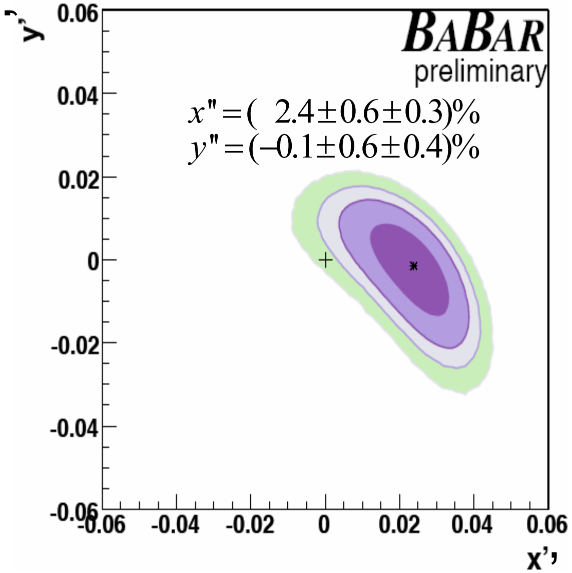
Wrong Sign $D^0 \to K^+\pi^-\pi^0$

1483 ± 56 wrong-sign $D^0 \to K^+\pi^-\pi^0$ events

Resonance	Amplitude	Phase (degrees)	Fit Fraction (%)
$\rho(770)$	1 (fixed)	0 (fixed)	39.8 ± 6.5
$K_2^{*0}(1430)$	0.088 ± 0.017	-17.2 ± 12.9	2.0 ± 0.7
$K_0^{*+}(1430)$	6.78 ± 1.00	69.1 ± 10.9	13.1 ± 3.3
$K^{*+}(892)$	0.899 ± 0.005	-171.0 ± 5.9	35.6 ± 5.5
$K_0^{*0}(1430)$	1.65 ± 0.59	-44.4 ± 18.5	2.8 ± 1.5
$K^{*0}(892)$	0.398 ± 0.038	24.1 ± 9.8	6.5 ± 1.4
$\rho(1700)$	5.4 ± 1.6	157.4 ± 20.3	2.0 ± 1.1







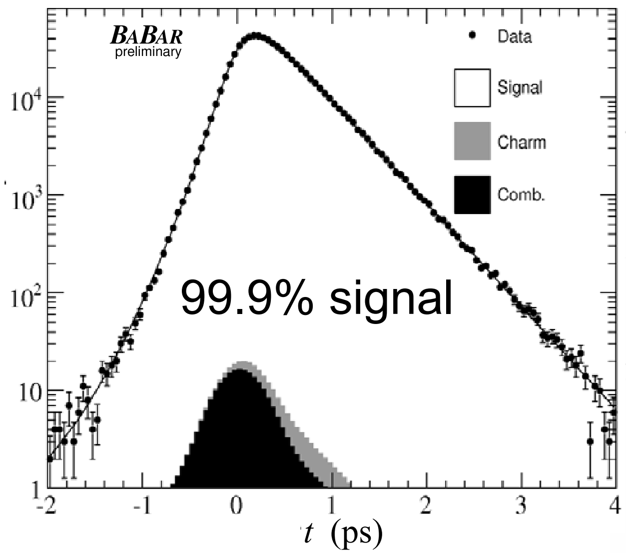
Results consistent with no mixing at 0.8% (incl. systematics)

y_{CP} lifetime fits

$$y_{CP} = \frac{\tau_D}{\langle \tau_{hh} \rangle} - 1$$

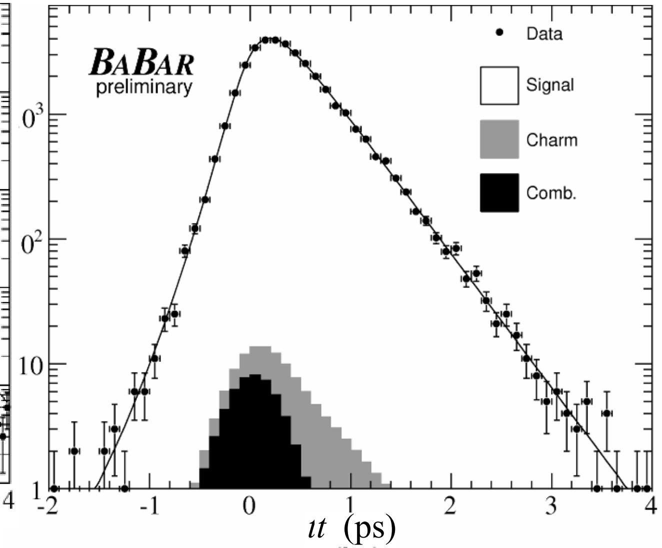
arXiv:0712.2249 – 412Mevts

$D^0 \to K^- \pi^+ + \text{c.c.}$



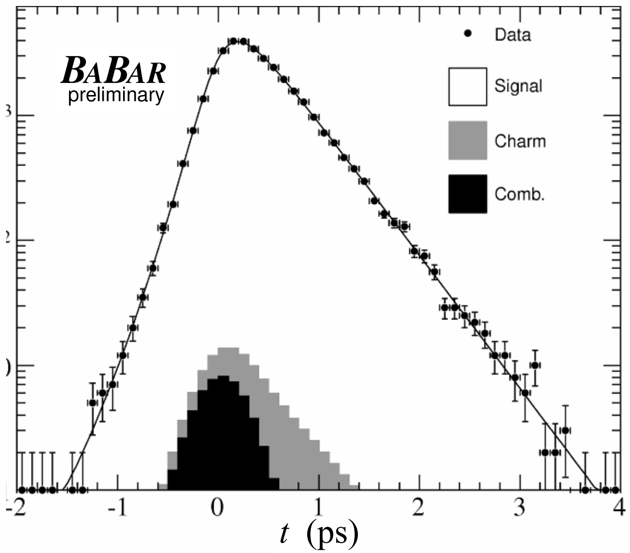
$\tau = 409.3 \pm 0.7$ fs

$D^0 \to K^+ K^-$



$\tau = 401.3 \pm 2.5$ fs

$\bar{D}^0 \to K^+ K^-$



$\tau = 404.5 \pm 2.5$ fs

D⁰ *lifetimes*

70,000 KK events
99.6% purity

31,000 ππ events
98.0% purity

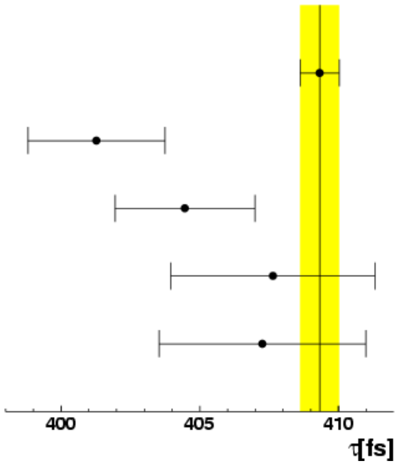
$D^0, \bar{D}^0 \to K\pi$

$D^0 \to KK$

$\bar{D}^0 \to KK$

$D^0 \to \pi\pi$

$\bar{D}^0 \to \pi\pi$



Tagged D^0 sample:

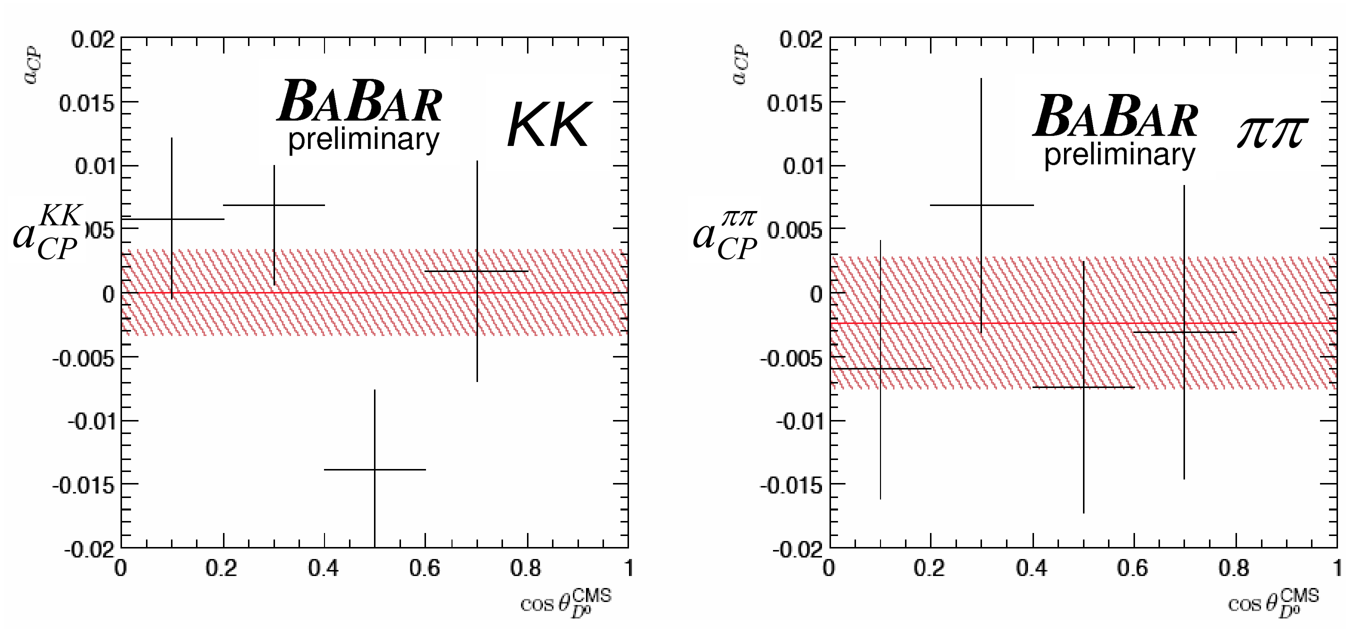
$y_{CP} = 1.24 \pm 0.39 \pm 0.13\%$ (3σ)

Combined with untagged D^0 sample:

$y_{CP} = 1.03 \pm 0.33 \pm 0.19\%$ (3.0σ)

Search for CPV in $D^0 \to K^+K^-, \pi^+\pi^-$

arXiv:0712.2249 – 412Mevts

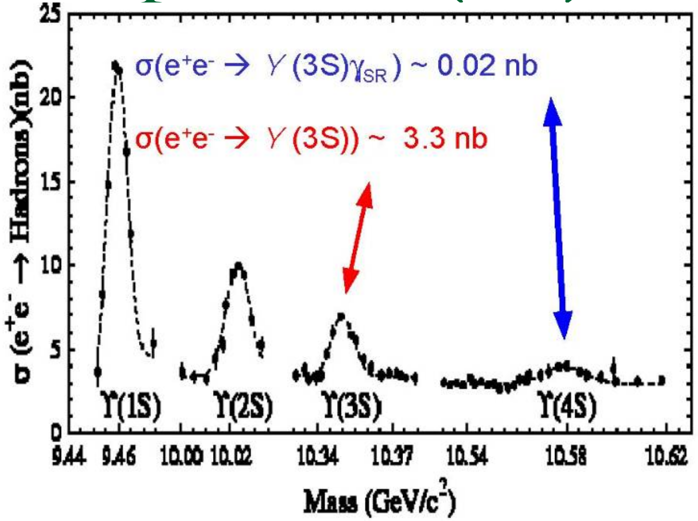


$$a_{CP}^{KK} = (\ \ 0.00 \pm 0.34\ (\text{stat.}) \pm 0.13\ (\text{syst.}))\%$$
$$a_{CP}^{\pi\pi} = (-0.24 \pm 0.52\ (\text{stat.}) \pm 0.22\ (\text{syst.}))\%$$

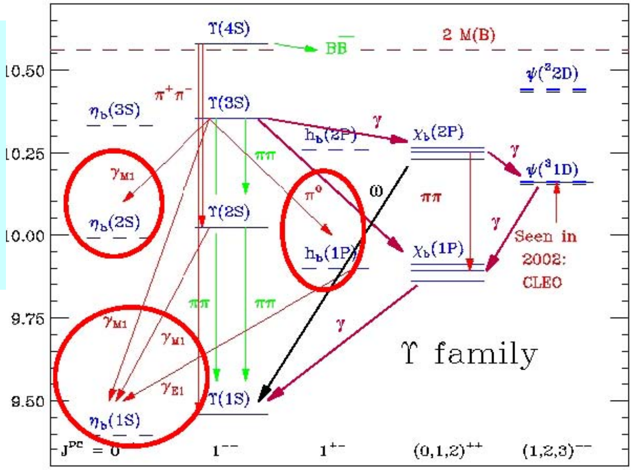
No evidence for CPV in either mode

The Future?

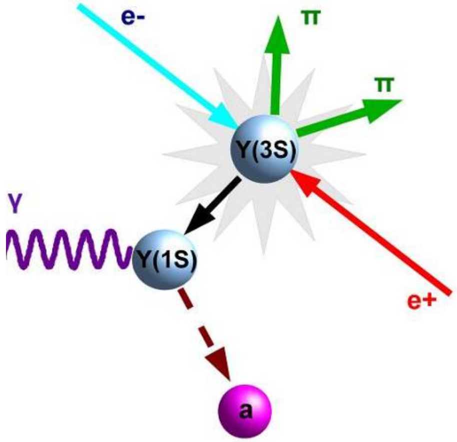
Upsilon (3S)



Singlet modes predicted but not yet seen.

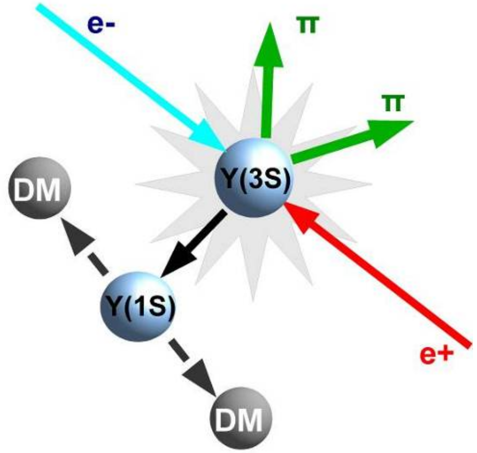


Spectroscopy



Little Higgs

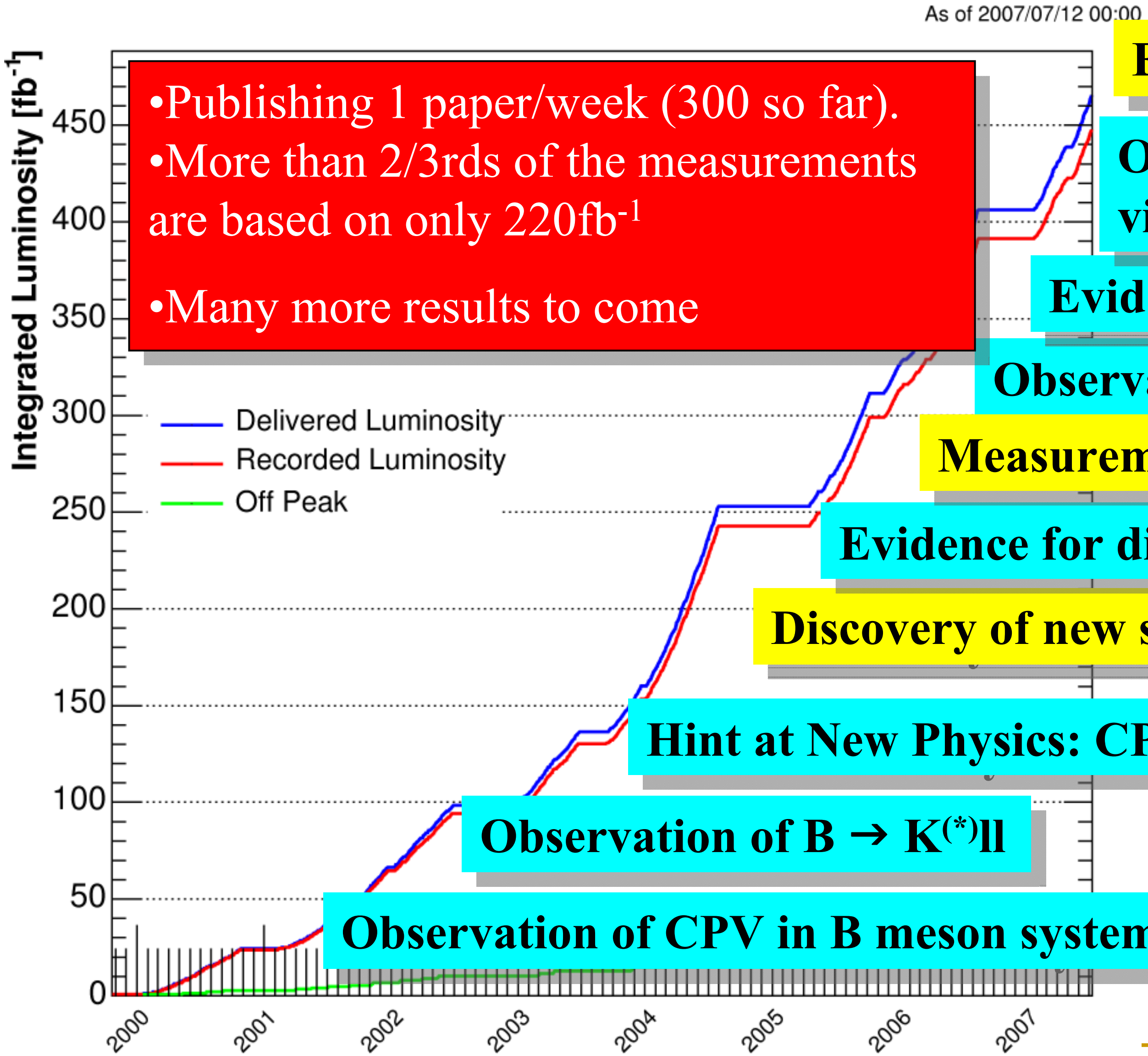
Aim to collect 30 fb^{-1} by 1st March 2008 (10x previous world sample).



Dark Matter

Conclusion

- Publishing 1 paper/week (300 so far).
- More than 2/3rds of the measurements are based on only 220fb^{-1}
- Many more results to come



Higgs ?! Dark Matter ?!

Evidence for D^0 mixing

Observation of direct CP violation in $B \to K^+\pi^-$

Evidence for $B \to \tau\nu$

Observation of $b \to d\gamma$

Measurement of angle γ

Evidence for direct CPV in $B \to K^+\pi^-$

Discovery of new states Ds and X

Hint at New Physics: CPV in $B \to \phi Ks$

Observation of $B \to K^{(*)}ll$

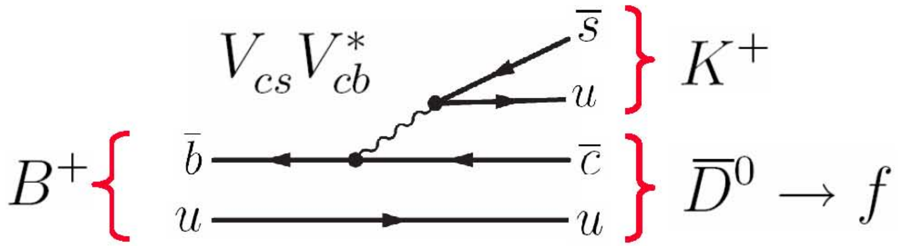
Observation of CPV in B meson system (angle β)

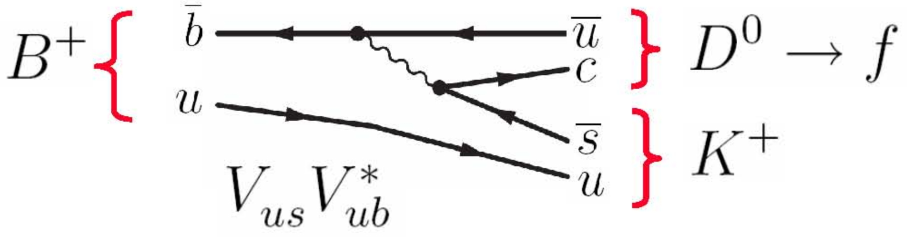
Backup

The three ways to γ

Basic Idea

use *interference* between tree decays
Cabibbo-suppressed ($b \to c$) $B^+ \to$ anti-$D^0 K^+$ and
CKM- and color-suppressed ($b \to u$) $B^+ \to D^0 K^+$,
where the D^0 and the anti-D^0 decay to a common final state





only tree diagrams:
no issue with
New Physics in loops

$$r_B \equiv A(b \to u)/A(b \to c)$$
$$\approx 0.39 f_c \sim 0.1 - 0.3$$

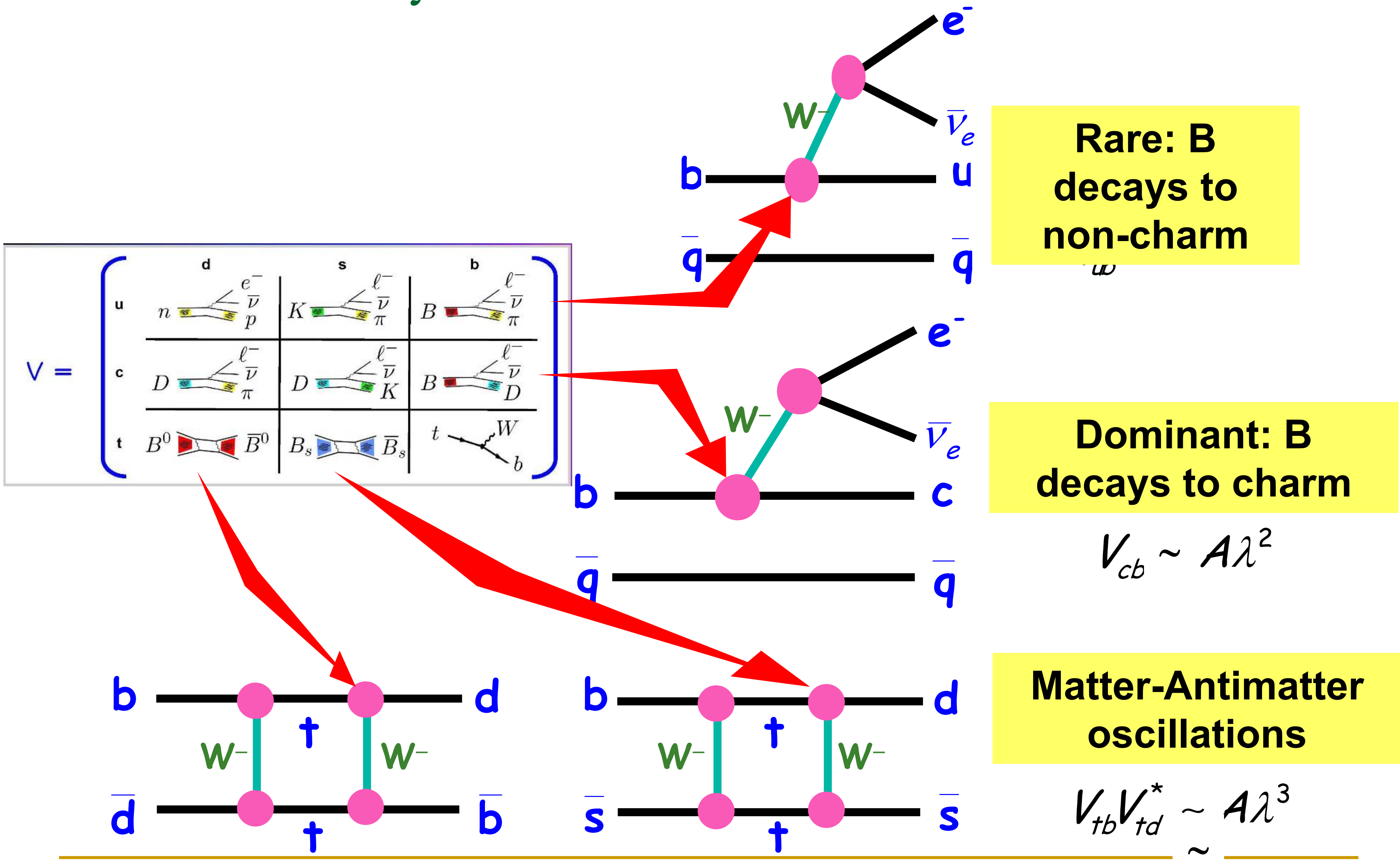
color factor

interference parameter

$$R = r_B \frac{A(D^0 \to f)}{A(\overline{D}^0 \to f)}$$

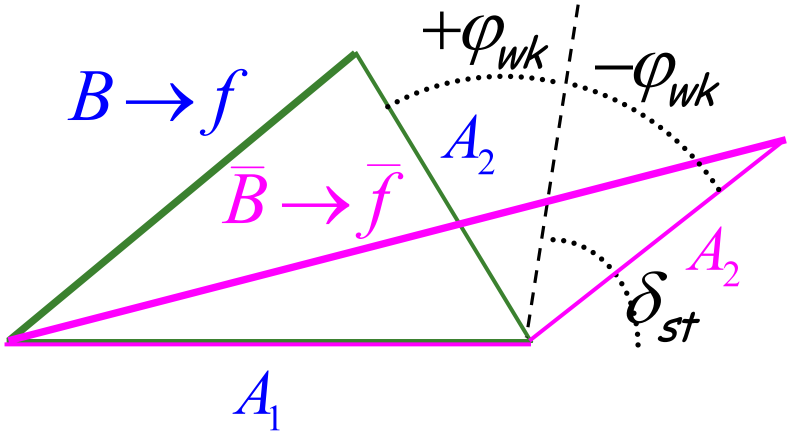
- GWL (Gronau-Wyler-London) f is a *CP* eigensate
- ADS (Atwood-Dunietz-Soni) $\overline{D}^0 \to f$ is doubly-Cabibbo suppressed
- GGSZ (Giri-Grossman-Soffer-Zupan) $D^0(\overline{D}^0) \to K_S^0 \pi^+ \pi^-$

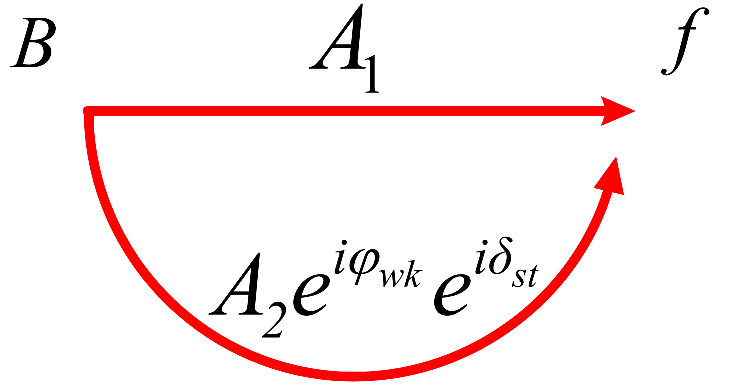
Weak decays of B mesons



2) Time Integrated CP Violation

CP violation through interference of decay amplitudes





$$\Gamma(B \to f) = \left| A_1 + A_2 e^{i\varphi_{wk}} e^{i\delta_{st}} \right|^2$$

$$\Gamma(\bar{B} \to \bar{f}) = \left| A_1 + A_2 e^{-i\varphi_{wk}} e^{i\delta_{st}} \right|^2$$

$$A_{f^\pm} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{-2|A_1||A_2|\sin(\varphi_{wk})\sin(\delta_{st})}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\varphi_{wk})\cos(\delta_{st})}$$

$\Gamma(\mathrm{B} \to \mathrm{f}) \neq \Gamma(\bar{\mathrm{B}} \to \bar{\mathrm{f}})$ for $\varphi_{\mathrm{wk}} \neq 0$ and $\delta_{\mathrm{st}} \neq 0$