Recent Highlights in CKM and CP Physics from BaBar

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Representing the BaBar Collaboration

At the Brookhaven Forum

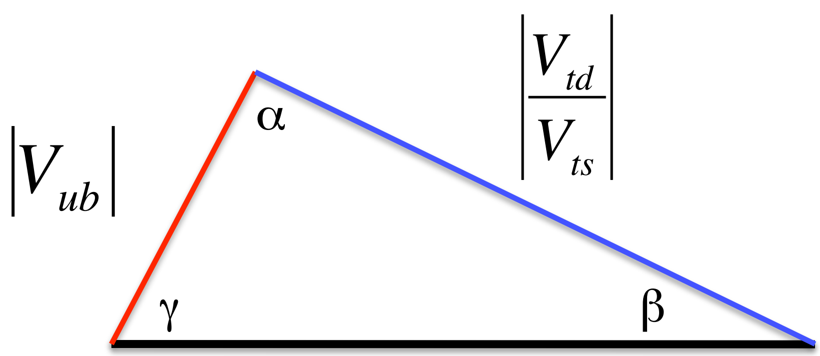
CKM Mechanism for CP Violation

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

CP violation from single phase in CKM matrix

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

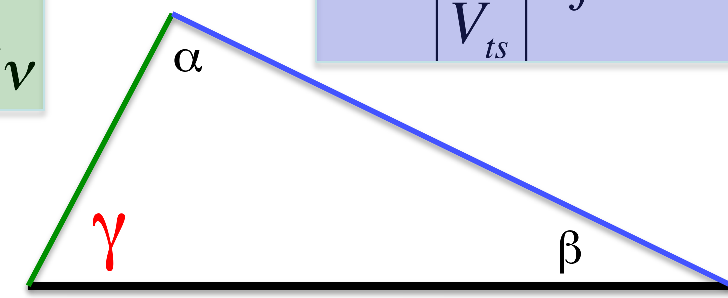
Search for new physics by measuring the unitarity triangle or directly looking for effects of new phases in quark couplings



New Measurements from BaBar

2. $|V_{ub}|$ *from* $B \rightarrow \pi l \nu, B \rightarrow \rho l \nu$

3. $\left|\frac{V_{td}}{V_{ts}}\right|$ *from* $\frac{\Gamma(B \rightarrow X_d \gamma)}{\Gamma(B \rightarrow X_s \gamma)}$

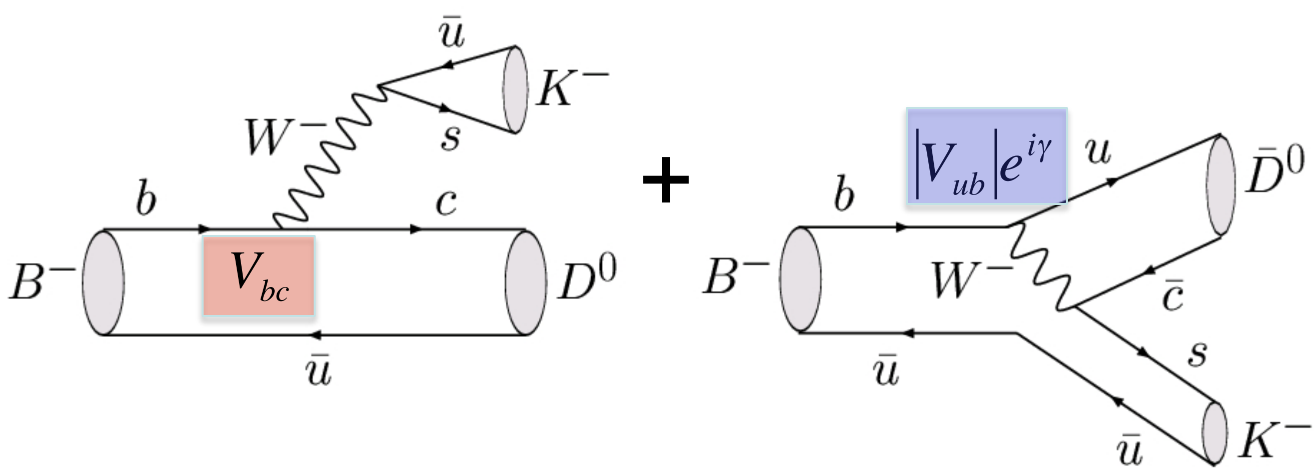


1. γ *from* $B^{\mp} \rightarrow D^{0(*)} K^{\mp(*)}$

4. *Search for CP violation in* $D^{+}_{(s)} \rightarrow K^{0}_{s} K^{+} \pi^{+} \pi^{-}$

1. $\gamma\ from\ B^{\mp} \rightarrow D^{0(*)}K^{\mp(*)}$

γ is measured in Direct CP violation from interference of two tree level amplitudes



If D^0 and D^0 decay to the same final state f_D then there is interference:

$$Amp.\left(B^- \rightarrow f_D K^-\right) = Amp.\left(b \rightarrow c\right)\left(1 + r_b e^{i(\gamma+\delta)}\right)$$

r_b is the ratio of the modulus of the two amplitudes

δ is the strong phase which can be extracted from data

Challenges and History of γ at BaBar

Most difficult angle to measure because rates and interference (r_b) are small

GLW

Gronau & London, PLB 253, 483 (1991); Gronau & Wyler, PLB 265, 172 (1991)

$D^0 \,\&\, \overline{D}^0 \rightarrow CP\ eigenstates$

$CP+ \quad \pi^+\pi^-, K^+K$

$CP- \quad K_S^0\pi^0, K_S^0\omega, K_S^0\phi, K_S^0\eta$

$$A_{CP+} = 0.27 \pm 0.09(stat.) \pm 0.04(sys.)$$

$$A_{CP-} = -0.09 \pm 0.09(stat.) \pm 0.02(sys.)$$

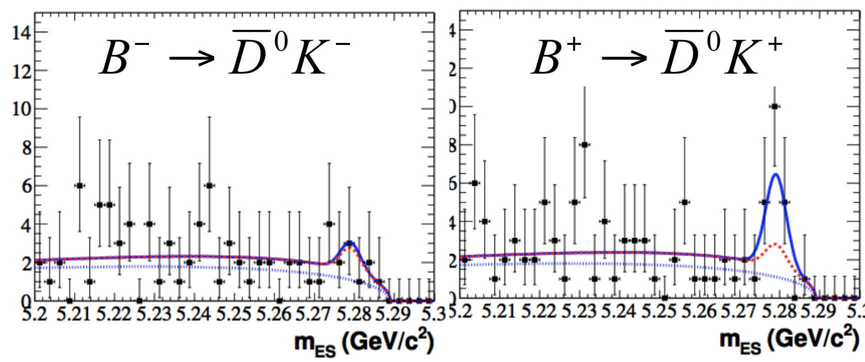
$$A_{CP\pm} = \frac{\Gamma(B^- \rightarrow D^0_{CP\pm}K^-) - \Gamma(B^+ \rightarrow D^0_{CP\pm}K^+)}{\Gamma(B^- \rightarrow D^0_{CP\pm}K^-) + \Gamma(B^+ \rightarrow D^0_{CP\pm}K^+)}$$

PRD 77 111102

ADS

Atwood, Dunietz, & Soni, PRL 78, 3257 (1997), Atwood, Dunietz, & Soni, PRD 63, 036005 (2001)

$D^0 \,\&\, \overline{D}^0 \rightarrow K^+\pi^-$ *(Double Cabbibo Suppressed)*



$$A_{CP}(K^+\pi^-) = -0.86 \pm 0.47(stat.)^{+0.11}_{-0.15}$$

See talk by Neus-Lopez at EPS 09 for full preliminary results

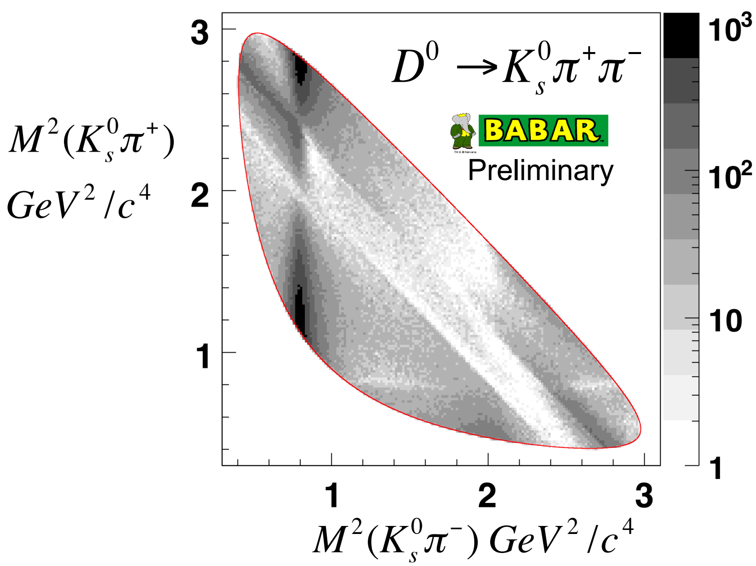
GLW gives small asymmetry. ADS gives large asymmetry but statistically challenged. The 3 body Dalitz plot technique described next gives best sensitivity

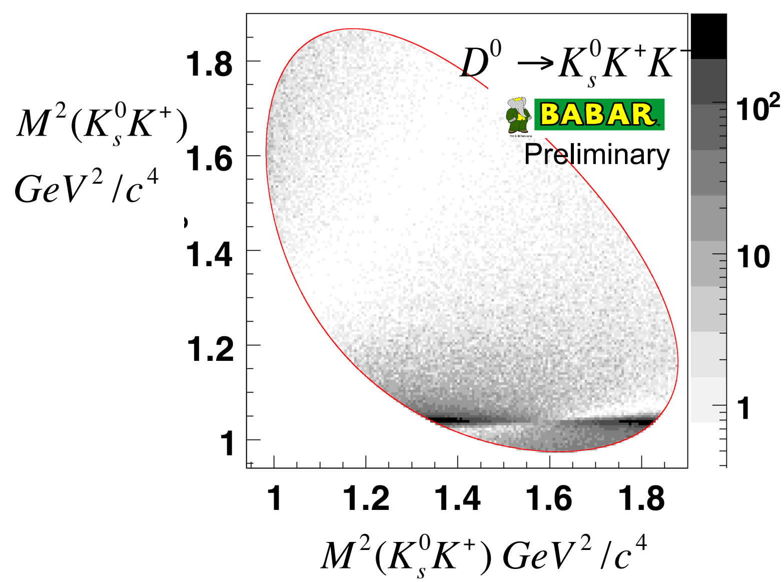
Dalitz Plot Technique for extracting γ

GGSZ:

Giri, Grossman, Soffer, & Zupan, PRD 68, 054018 (2003)
Bondar, PRD 70, 072003 (2004)

Use 3 body decays D^0 & $\overline{D}^0 \to K_s^0\pi^+\pi^-, K_s^0K^+K^-$



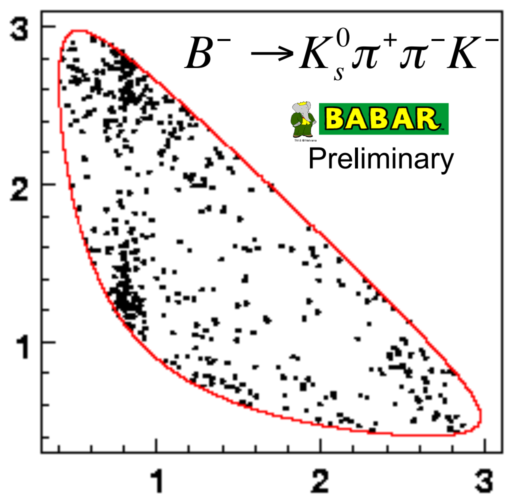


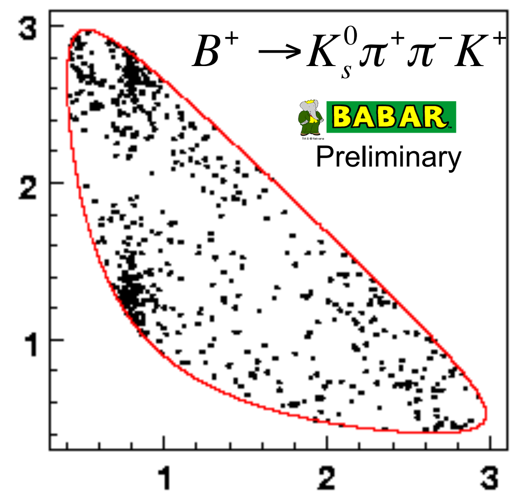
Dalitz Amplitudes from fits to resonance structure from $e^+e^- \to c\overline{c}$ Data (*arXiv: 1004:5053)*

Dalitz Amplitudes provide the information about strong phase δ to extract γ

Measurement of γ with Dalitz Technique

$$B^- \to D^0K^-, D^{*0}\left(D^0\pi^0\right)K^-, D^{*0}\left(D^0\gamma\right)K^-, D^0K^{*-}\left(K_s^0\pi^-\right) \text{ with } D^0 \ \& \ \overline{D}^0 \to K_s^0\pi^+\pi^-, K_s^0K^+K^-$$





Extract CP information from multidimensional fits including signal & background

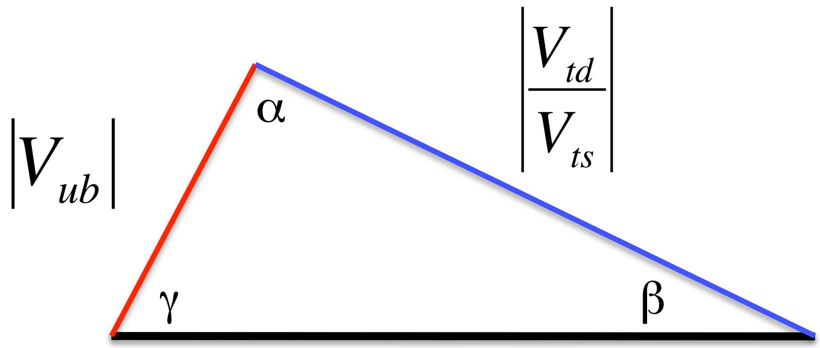
Mode	$r_B = \frac{A(b \to u)}{A(b \to c)}$	δ_{strong}
$B^\pm \to D^0K^\pm$	$9.6 \pm 2.9 \pm 0.5 \pm 0.4\,\%$	$119^{+19}_{-20} \pm 3 \pm 3^0$
$B^\pm \to D^{*0}K^\pm$	$13.3^{+4.2}_{-3.9} \pm 1.3 \pm 0.3\,\%$	$-82 \pm 21 \pm 5 \pm 3^0$
$B^\pm \to D^0K^{*\pm}$	$14.9^{+6.6}_{-6.2} \pm 2.6 \pm 0.6\,\%$	$111 \pm 32 \pm 11 \pm 3^0$

$486M\ B\overline{B}$ $\quad arXiv:1005.1096v$

$$\gamma = 68 \pm 14(stat) \pm 4(sys.) \pm 3(\text{mod.})\ ^0$$

(*model errors are from Dalitz Amplitude model used*)

Angles of Unitarity Triangle



BaBaR Only

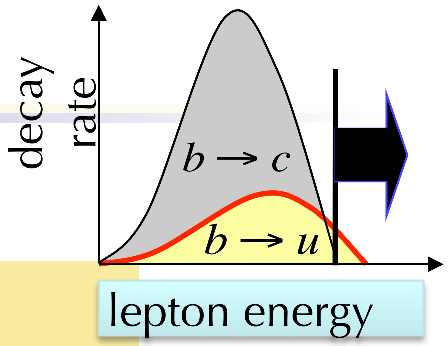
α	$92.4^0 \pm 6.0^0$	*PRD* 78 071104,76 052007
β	$21.7^0 \pm 1.2^0$	*PRD* 72 072009
γ	$68^0 \pm 16^0$	*This analysis*
$\alpha+\beta+\gamma$	$182^0 \pm 17^0$	*Sum (No correlations)*

CKM Fitter (Beauty 09)

α	$89.4^0 \pm 4.0^0$
β	$21.7^0 \pm 0.9^0$
γ	$67.9^0 \pm 4.1^0$
$\alpha+\beta+\gamma$	$179.0^0 \pm 5.8^0$

No evidence of additional phases in the CKM triangle from angles. Next the sides..

Measuring $|V_{ub}|$



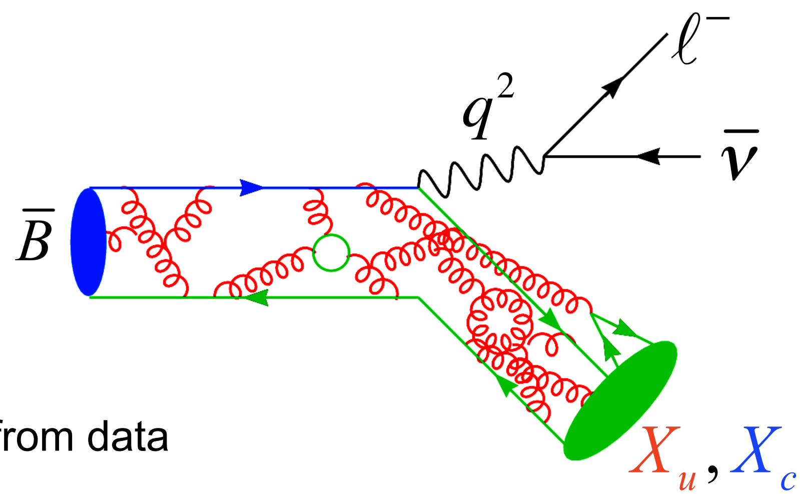
V_{ub} is measured in semileptonic decays in two ways

1. Inclusively: Experiment: High rate, Large X_c background Theory: HQE
2. Exclusively: Experiment: Low rates (10^{-4}) but cleaner signal. Theory: Form Factors

Two approaches are complementary with different experimental and theoretical systematics

New measurement from BaBar in exclusive modes: $B \to \pi l \upsilon$ and $B \to \rho l \upsilon$

$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2$$



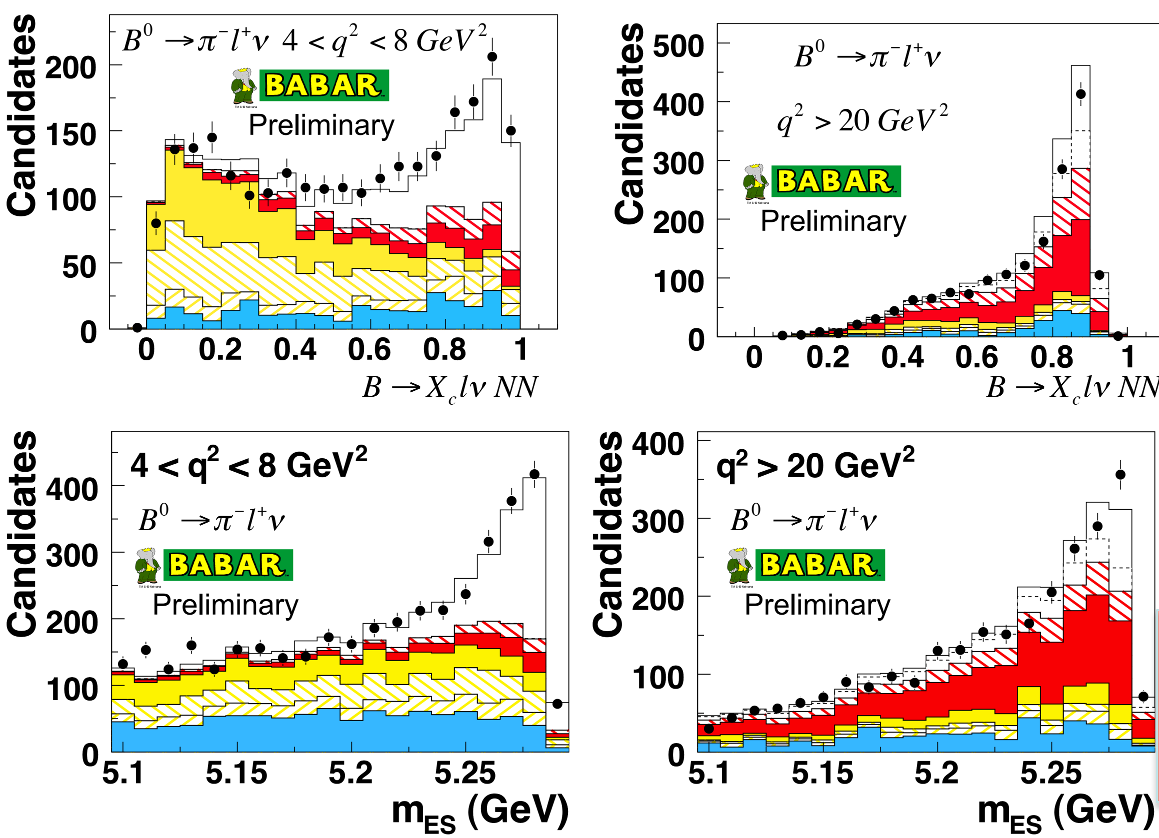
$|f_+(q^2)|^2$ dependence on q^2 can be extracted from data

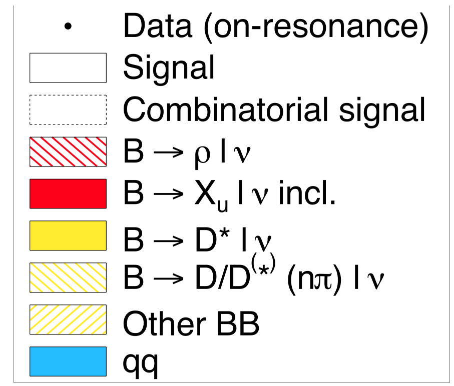
Selection of B->πlν B-> ρlν candidates

$$Select \quad B \to \pi l \nu, B \to \rho l \nu \quad with\ l = e, \mu$$

$$Backgrounds: \quad q\bar{q}, B \to X_c l \nu, B \to X_u l \nu$$

NN selectors for three different backgrounds for each of 6(3) q^2 bins for π(ρ)



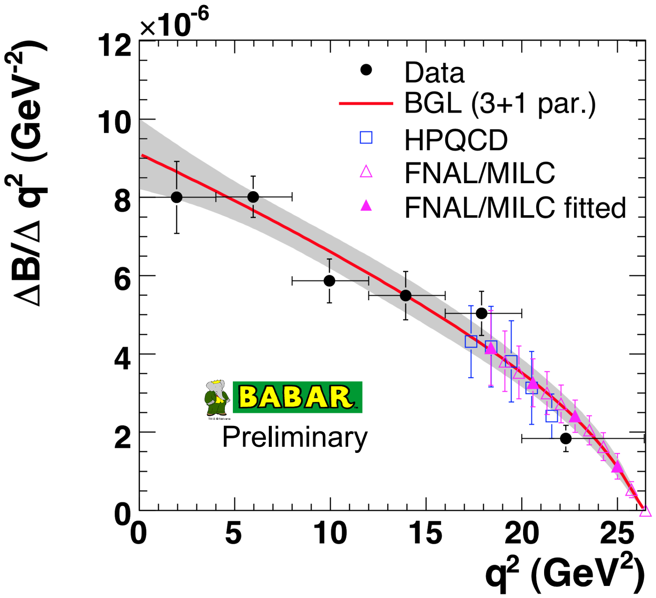


Four mode ($\pi^0,\pi^-,\rho^0,\rho^-$) fit in $M_{ES}, \Delta E, q^2$ imposing Isospin to extract yield

$$B(B^0 \to \pi^- l^+ \gamma) = (1.41 \pm 0.05 \pm 0.07) \times 10^{-4}$$
$$B(B^0 \to \rho^- l^+ \gamma) = (1.15 \pm 0.15 \pm 0.27) \times 10^{-4}$$
$$(\pm stat. \pm sys.)$$

Extracting V_{ub} from B(B->$\pi l\nu$,B->$\rho l\nu$)

BGL:PRL 74 4603 (1995)
PRD 56 303 (1997)
PLB 478 417 (2000)
FNAL/MILC: PRD 05407 (2009)



Combined fit of BGL parameterization to data and FNAL/MILC lattice calculation

$$|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$$

(arXiv:1005.3288v1)

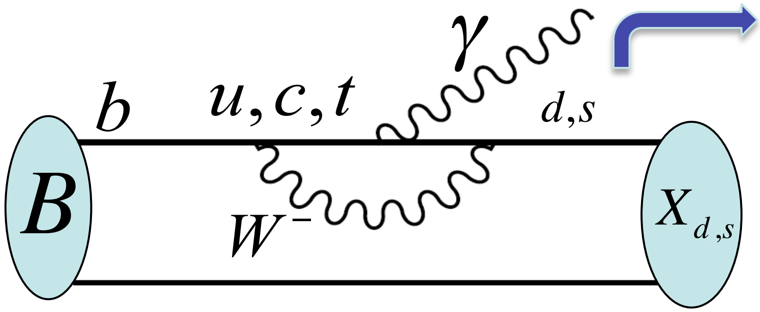
Most precise exclusive measurement to date

Compared to inclusive $|V_{ub}| = (4.27 \pm 0.39) \times 10^{-3}$ *PDG*2010 Is 2.6σ different

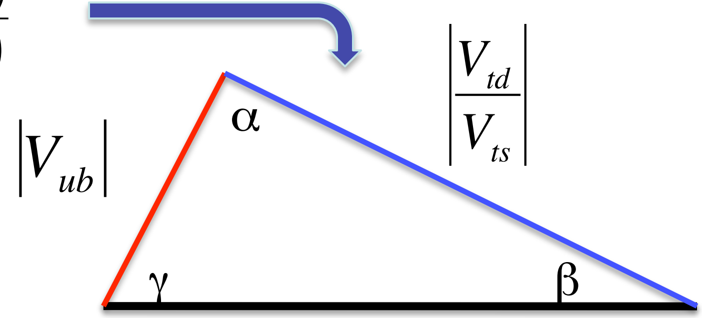
CKM Fitter Prediction: $|V_{ub}| = (3.48 \pm 0.16) \times 10^{-3}$ *ICHEP*2010

UT Fitter Prediction: $|V_{ub}| = (3.51 \pm 0.16) \times 10^{-3}$ *Beauty*09

Measurement of $B \to X_d\gamma$ and Extraction of $|V_{td}/V_{ts}|$



$$\frac{\Gamma(B \to X_d\gamma)}{\Gamma(B \to X_s\gamma)}$$



$\left|\frac{V_{td}}{V_{ts}}\right|$ is most precisely measured with B_d/B_s mixing

Measurement with penguins to search for New Physics

Previously used ratio of exclusives (ρ,ωγ/K*γ) but limited by form factor uncertainty

Inclusive method is theoretically cleaner

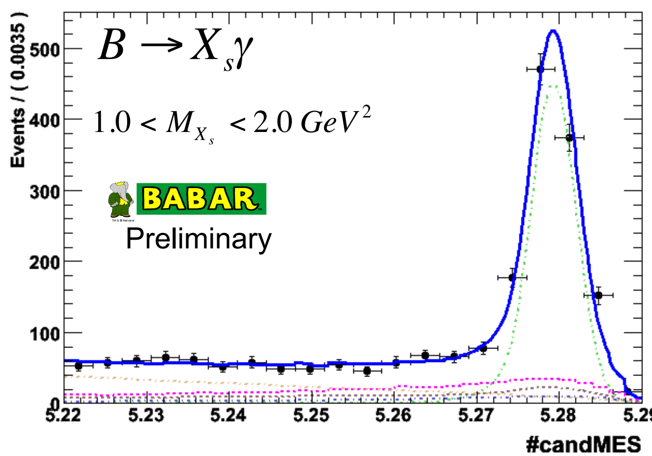
Use the sum-of-exclusives technique

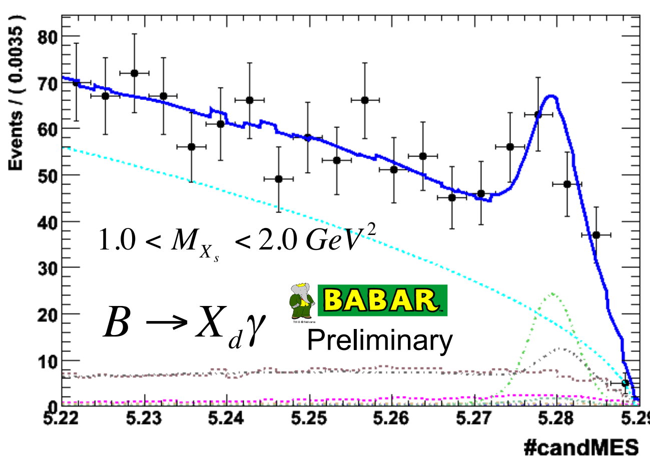
(~50% of modes covered. Largest systematic from missing modes)

$B \to X_d\gamma$	$B \to X_s\gamma$
$B^0 \to \pi^+\pi^-\gamma$	$B^0 \to K^+\pi^-\gamma$
$B^+ \to \pi^+\pi^0\gamma$	$B^+ \to K^+\pi^0\gamma$
$B^+ \to \pi^+\pi^-\pi^+\gamma$	$B^+ \to K^+\pi^-\pi^+\gamma$
$B^0 \to \pi^+\pi^-\pi^0\gamma$	$B^0 \to K^+\pi^-\pi^0\gamma$
$B^0 \to \pi^+\pi^-\pi^+\pi^-\gamma$	$B^0 \to K^+\pi^-\pi^+\pi^-\gamma$
$B^+ \to \pi^+\pi^-\pi^+\pi^0\gamma$	$B^+ \to K^+\pi^-\pi^+\pi^0\gamma$
$B^+ \to \pi^+\eta\gamma$	$B^+ \to K^+\eta\gamma$

Measurement of $B \to X_d\gamma$ and Extraction of $|V_{td}/V_{ts}|$

$471M\ B\overline{B}$





BABAR

Measure for $M_{X_{d,s}} < 2.0\ GeV^2$

$$\frac{\Gamma(B \to X_d\gamma)}{\Gamma(B \to X_s\gamma)} = 0.040 \pm 0.009(stat.) \pm 0.010(sys.)$$

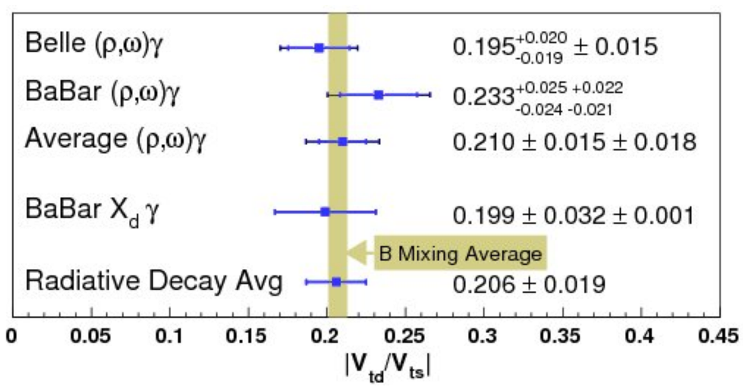
Correct for unmeasured $M_{X_{d,s}} > 2.0\ GeV^2$ using Kagan & Neubert (PRD 58 094012) spectrum with

$m_b = 4.65 \pm 0.05\ \mu_\pi^2 = -0.52 \pm 0.08\ (HFAG)$

Extract $\left|\frac{V_{td}}{V_{ts}}\right|$ using the calculations of Ali, Asatrian & Greub using β as input rather than (ρ,η) (Phy. Lett. B 429 87 (1998))

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199 \pm 0.022(\text{stat.}) \pm 0.024(\text{sys.}) \pm 0.002(\text{th.})$$

C



arXiv 1005.4087v1

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Search for CP Violation in D mesons

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

CP violation is suppressed in SM ~O(10^{-3})

New Physics could produce CPV:

Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D75, 036008 (2007)
I. I. Bigi, hep-ph/0104008 (2001)

Previous Searches at ~ 1% sensitivity for Direct CPV in Decay,Dalitz plots and in mixing have yielded null result: (Phys. Rev. Lett. 100, 061803 (2008), Phys. Rev. D78, 051102(R) (2008), Phys. Rev. D78, 051102(R) (2008), Phys. Rev. D78.011105 (2008))

New BaBar analysis uses T-odd observables (Vector Triple Products)

CPT implies CP violation = T reversal violation

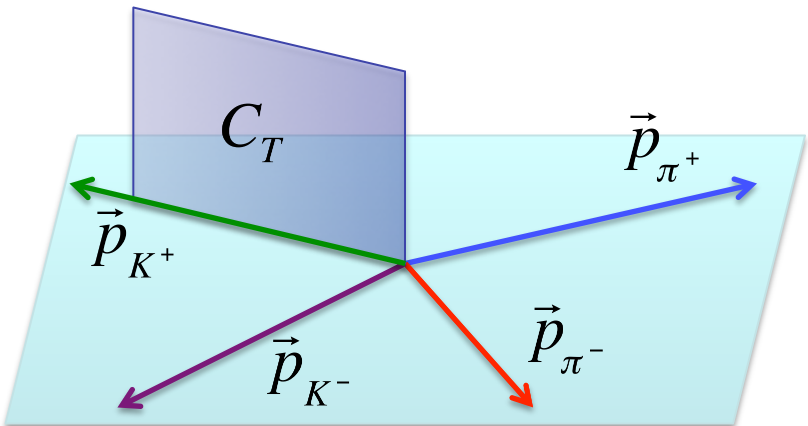
Proposed by I. Bigi: http://arxiv.org/abs/hep-ph/0107102v1

W. Bensalem, A. Datta and D. London, Phys. Rev. D66, 094004 (2002)
W. Bensalem and D. London, Phys. Rev. D64, 116003 (2001)
W. Bensalem, A. Datta and D. London, Phys. Lett. B538, 309 (2002)

T-odd Observable in $D^0 \to K^+K^-\pi^+\pi^-$

Need at least 4 final state particles in decay so have three independent vectors

$$C_T = \vec{p}_{K^+} \cdot \left(\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}\right)$$



In D^0 rest frame

$$\alpha_T = \frac{\Gamma(D^0, C_T > 0) - \Gamma(D^0, C_T < 0)}{\Gamma(D^0, C_T > 0) + \Gamma(D^0, C_T < 0)}$$

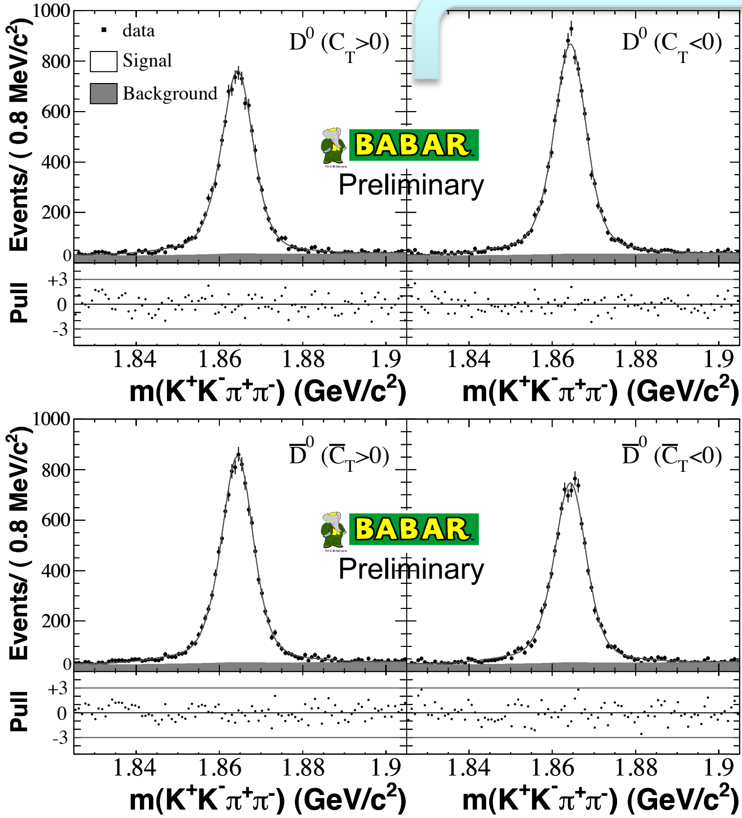
$$\bar{\alpha}_T = \frac{\Gamma(\bar{D}^0, -C_T > 0) - \Gamma(\bar{D}^0, -C_T < 0)}{\Gamma(\bar{D}^0, -C_T > 0) + \Gamma(\bar{D}^0, -C_T < 0)}$$

$$CP\ observable: \quad A_T = \frac{1}{2}\left(\alpha_T - \bar{\alpha}_T\right)$$

Search for CP Violation in D mesons

470fb^{-1} *arXiv:1003.3397*

$$e^+e^- \rightarrow XD^{*+}; D^{*+} \rightarrow \pi^+_{slow} D^0; D^0 \rightarrow K^+K^-\pi^+\pi^-$$



Signal Yields (events)

10974 ± 117	12587 ± 125
10749 ± 116	12380 ± 124

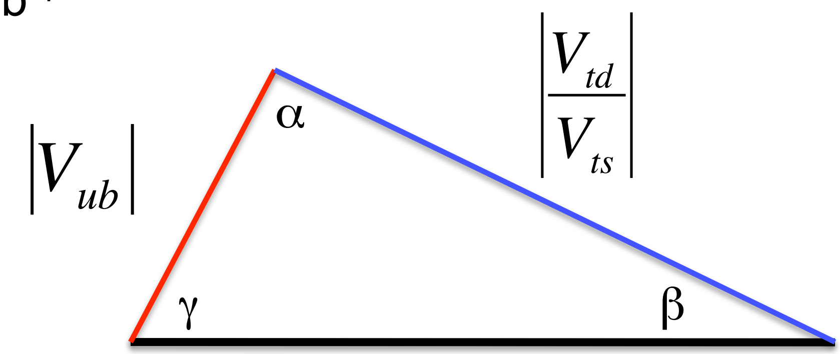
$$A_T = \left(1.0 \pm 5.1(stat.) \pm 4.4(sys.)\right) \times 10^{-3}$$

(arXiv:1003.3397v1)

No CPV observed

Conclusions

BaBar continues to mine a dataset of 470 fb^{-1}



New measurement of γ
New Measurement of V_{ub}
New Measurement of V_{td}/V_{ts} in penguins
Search for CPV in D meson Decay

The CKM mechanism of CP violation beautifully explains all observed CP violation but we continue to search for small CP violating effects in the flavour sector