Measurements of the Sides of the Unitarity Triangle @ BaBar

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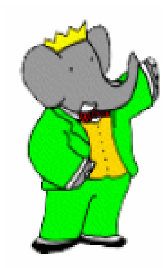
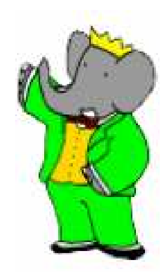

On behalf of the **BaBar** Collaboration


PHENO 06
May 15-17 2006

Overview

- Introduction to CKM Matrix & Unitarity Triangle (UT)
- Measuring the sides of the UT @ BaBar
- Interesting and recent measurements @ BaBar *(& Belle… & CDF…)*

Due to limited time: I will highlight the most recent analyses… And give you the general status…

Introduction to CKM Matrix & UT

Cabbibo-Kobayashi-Maskawa (**CKM**) quark mixing matrix

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

Relates the quark mass eigenstates and the weak eigenstates.

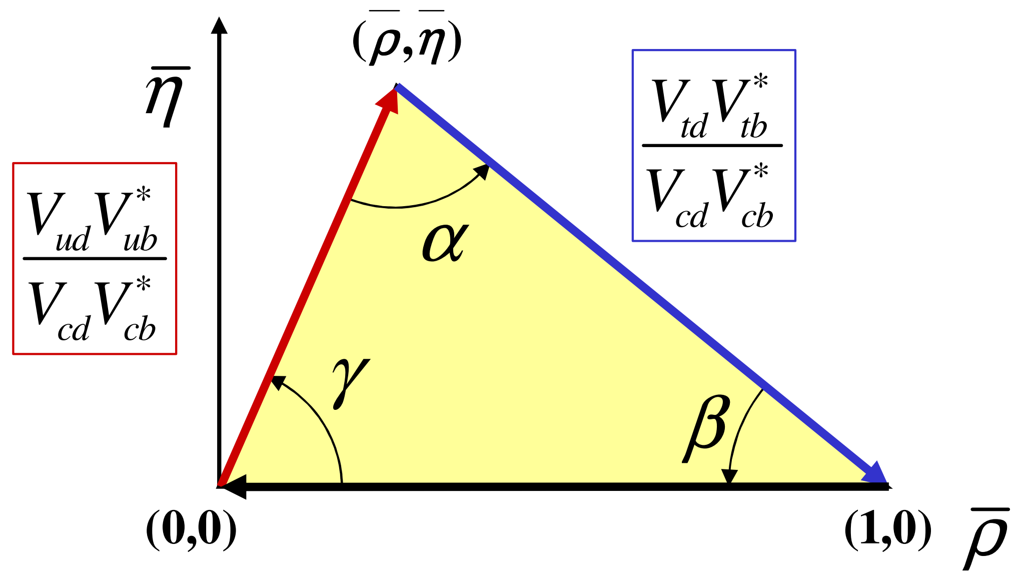
<u>In other words:</u>

CKM matrix element $|V_{xy}|$~ probability of a quark of flavor "x" to become a quark of flavor "y"

One of the unitarity conditions:

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

Representation: Unitarity Triangle



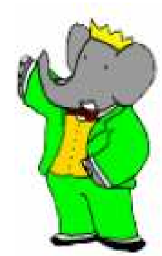
ULTIMATE GOAL:
we want to measure the sides & angles of the unitarity triangle to constrain & test the Standard Model

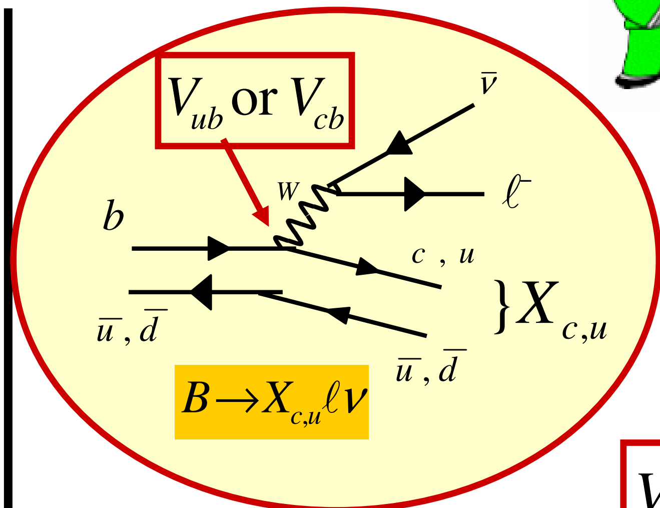
<u>In this talk:</u> measurements of the **sides** of the UT

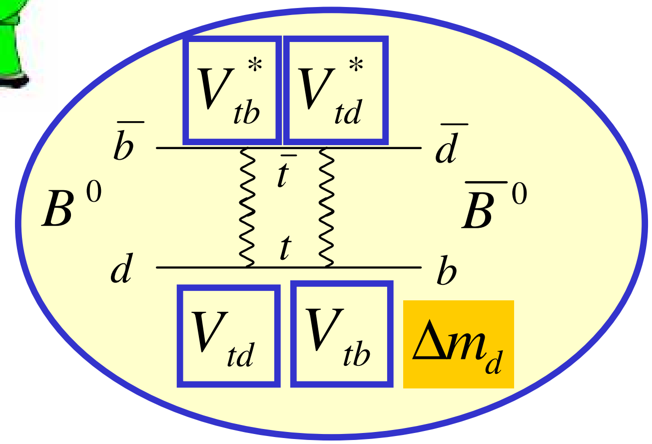
Info on the **angles**: see <u>Francesco Polci's talk</u>

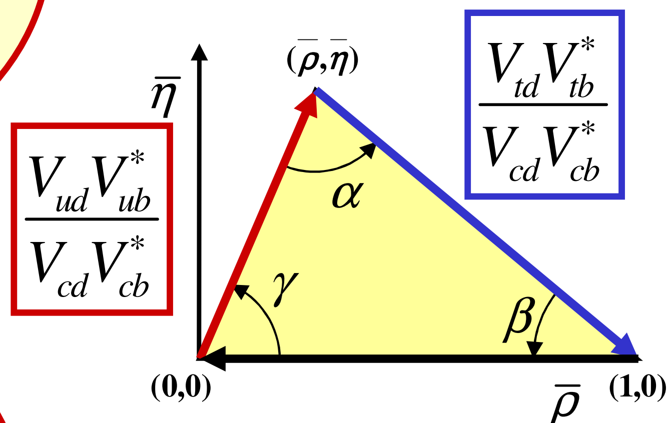
Measuring the sides of the unitarity triangle @ BaBar

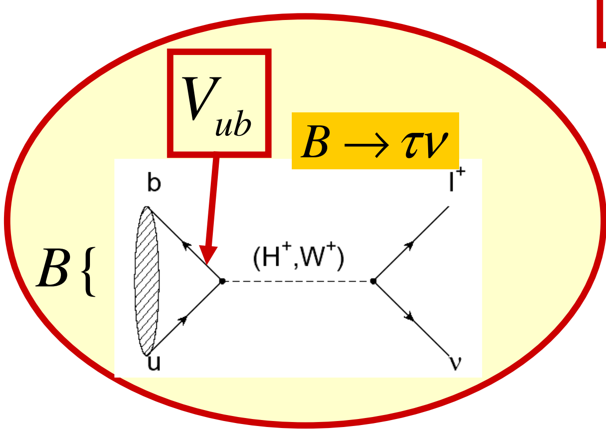
BaBar:
Let's use our
B mesons!!!!

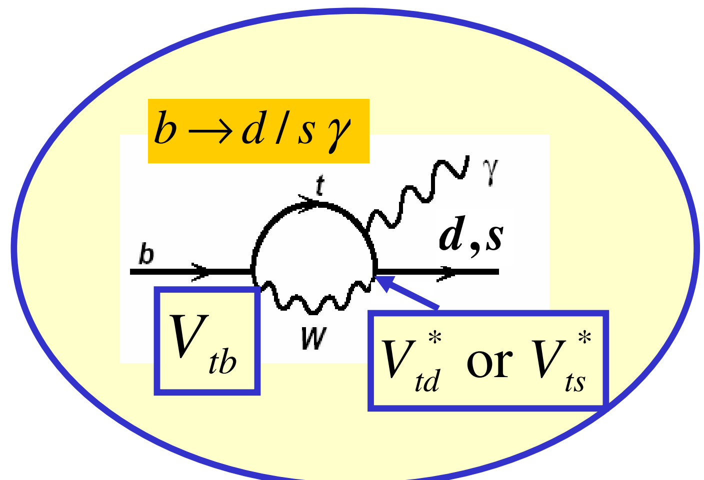












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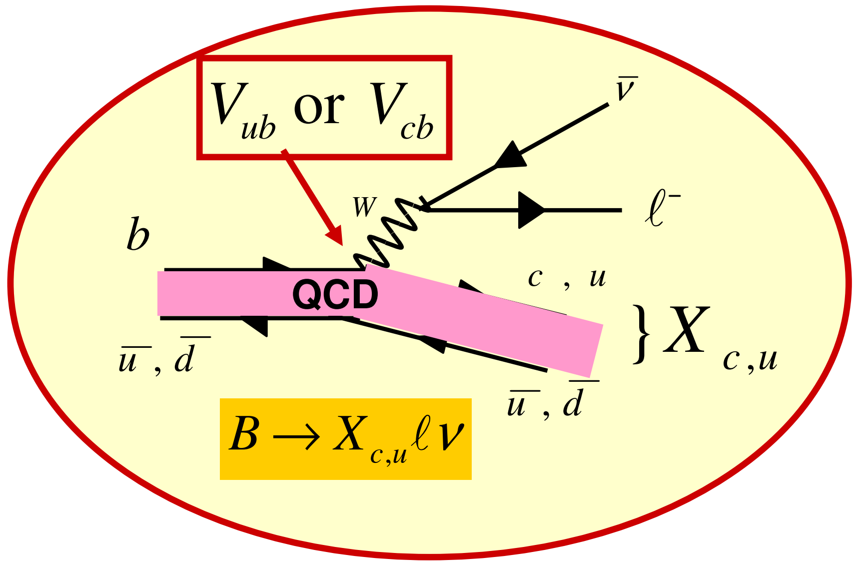
$|V_{ub}|$ and $|V_{cb}|$ from $b \to u\ell\nu$ and $b \to c\ell\nu$ decays



Common feature: Need help from theory to describe the QCD part

3 new BaBar measurements:

- $|V_{ub}|$ from lepton endpoint PRD73, 012006 (2006)
- $|V_{ub}|$ with reduced model dependence hep-ex/0601046
- $B \to D^{*}\ell\nu$ Form Factors hep-ex/0602023

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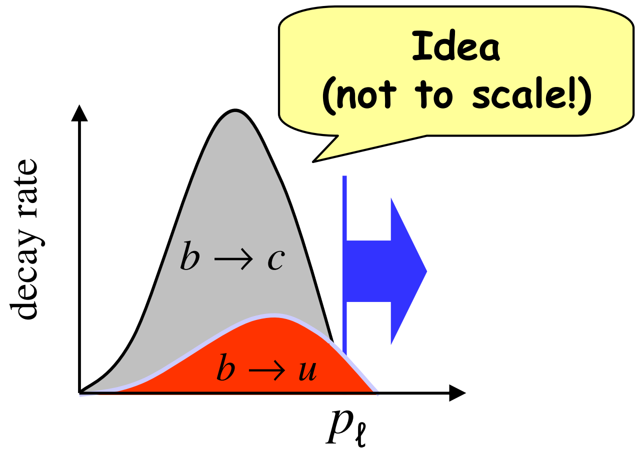
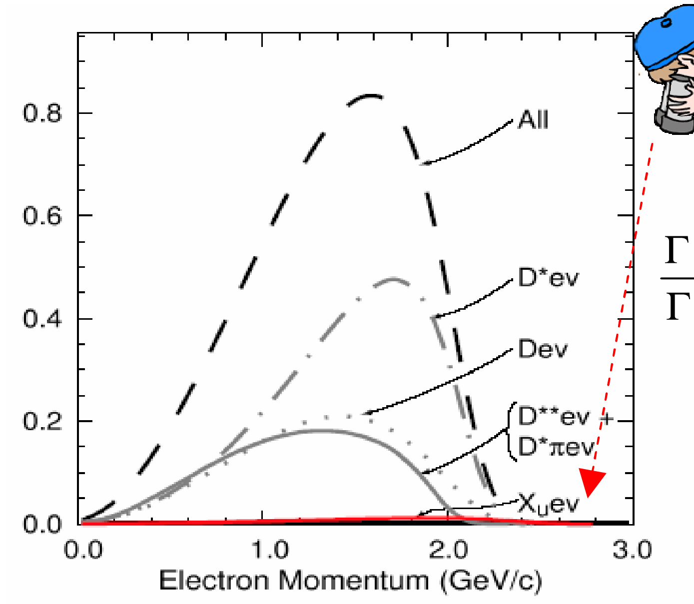
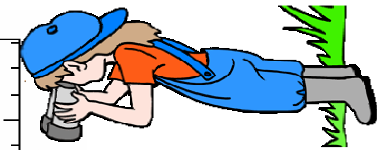
PRD73, 012006 (2006)

$|V_{ub}|$ From Lepton Endpoint (1)

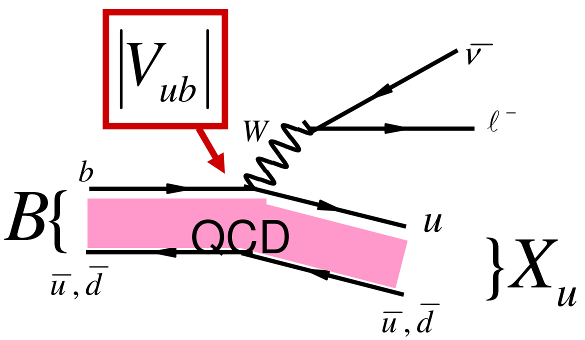






$$\frac{\Gamma(b \to u \ell \bar{\nu})}{\Gamma(b \to c \ell \bar{\nu})} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50}$$

reality



- measure partial branching fraction ΔB
- get predicted partial rate Δζ from theory

$$|V_{ub}| = \sqrt{\frac{\Delta B(B \to X_u \ell \nu)}{\Delta\zeta \cdot \tau_B}}$$

theoretical input

PRD73, 012006 (2006)

$|V_{ub}|$ From Lepton Endpoint (2)

Best result: electrons with 2.0< p_l < 2.6 GeV

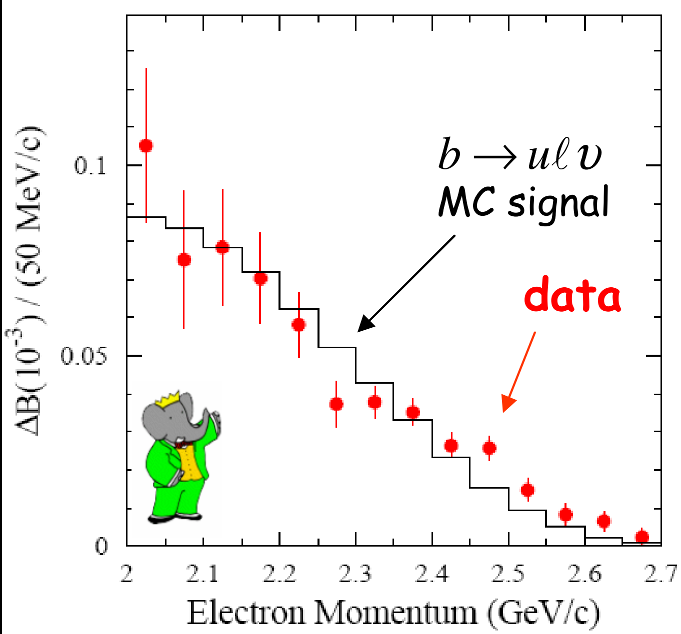
Compared to previous measurement:

Use larger part of the electron spectrum: 10% → 25%

→ smaller theoretical error

→ Accurate subtraction of background is needed!

Measured electron spectrum



88×10^{6} BB pairs

Measure BF:

Uses inputs from other b → q analyses to describe the motion of the b-quark in the B meson ("shape function (SF)")

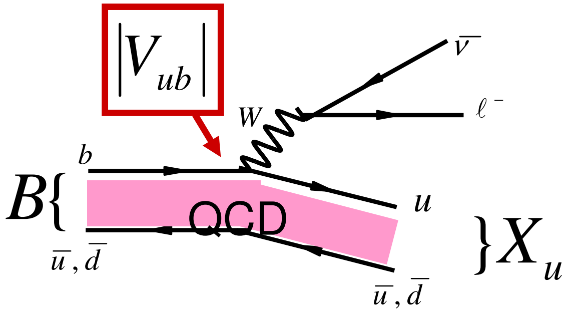
$$BR(B \to X_u e \nu) = \left(2.27 \pm 0.26_{\exp} \pm {}^{0.33}_{0.26\,SF} \pm 0.17_{theo}\right)\times 10^{-3}$$

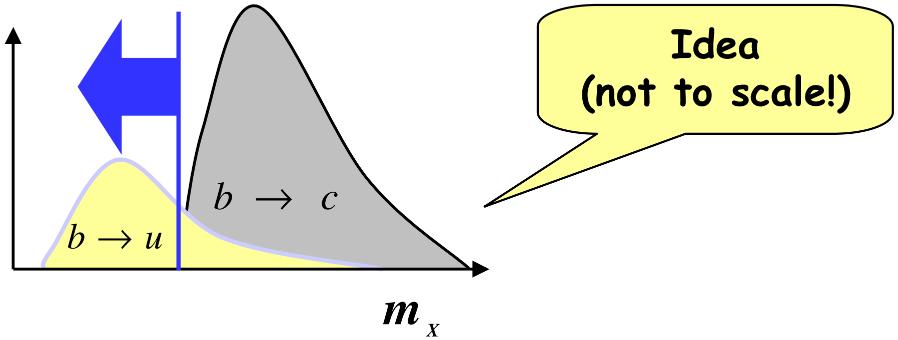
Extract $|V_{ub}|$ from BNLP calculations: new!

(Bosch-Lange-Neubert-Paz Nucl. Phys. B 699, 335, 2004)

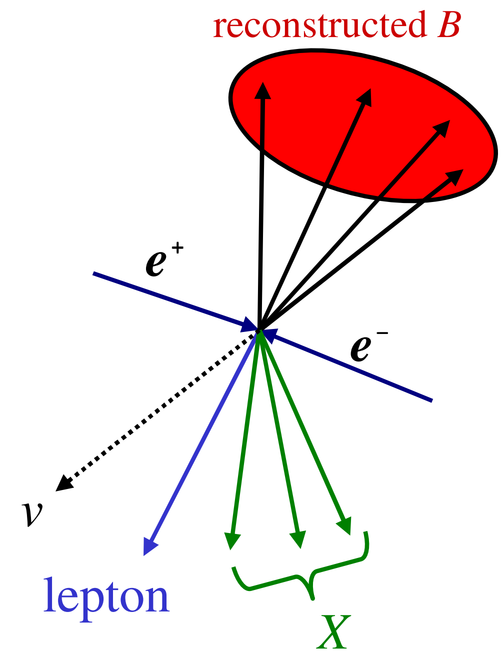
$$|V_{ub}| = \left(4.44 \pm 0.25_{\exp} \pm {}^{0.42}_{0.38\,SF} \pm 0.22_{theo}\right)\times 10^{-3}$$

$|V_{ub}|$ From m_x, reduced model dependence (1)

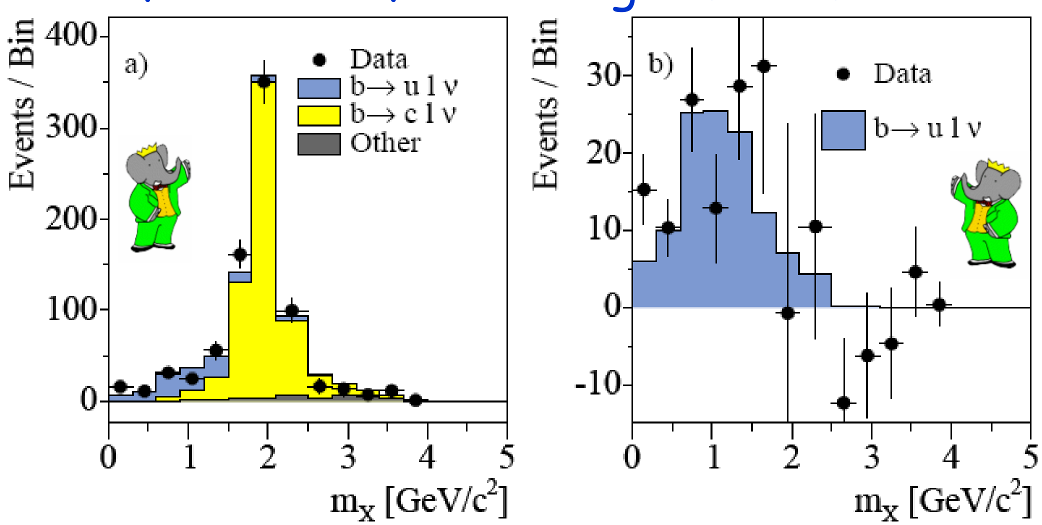




- m_x = mass of the hadronic system
- Fully reconstruct one B in hadronic decay mode (clean sample)
- Seach for $X\ell\nu$ in the other B
- Subtract $X_c\ell\nu$ background



Before and after background subtraction



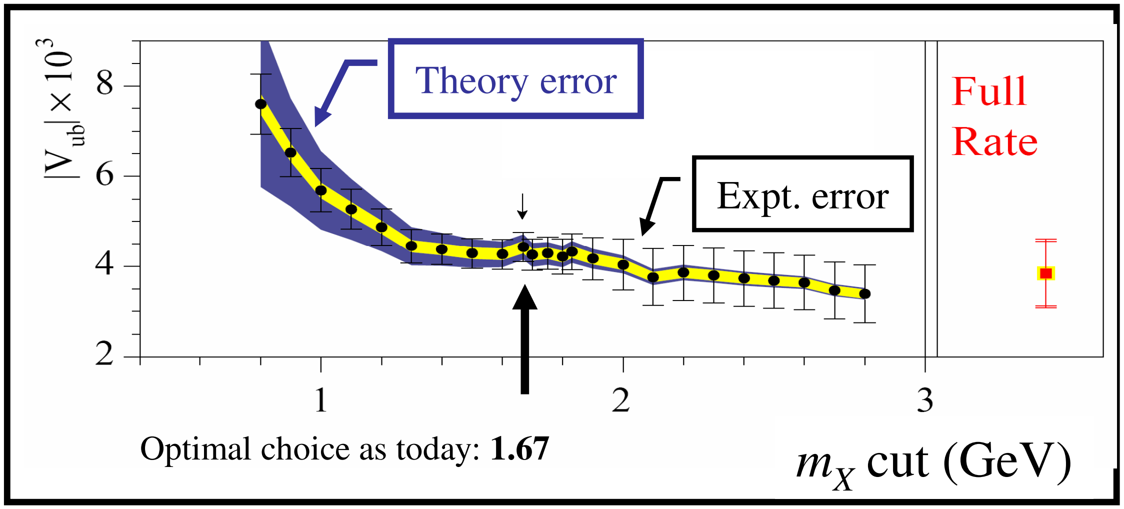
$|V_{ub}|$ From m_X, reduced model dependence (2)

- Possible to combine $b \to u\ell\nu$ and $b \to s\gamma$ so that the SF cancels

$$\Gamma(B \to X_u \ell \nu) = \frac{|V_{ub}|^2}{|V_{ts}|^2} \int W(E_\gamma) \frac{d\Gamma(B \to X_s \gamma)}{dE_\gamma} dE_\gamma$$

Weight function

(Following LLR : Leibovich, Low, Rothstein - **hep-ph/0005124,0105066**)



Loose m_X cut:
Trade SF error → Stat. error
(you don't have to extrapolate to full decay rate; however, you have more background)

89×10^6 $B\bar{B}$ pairs

Acceptance:

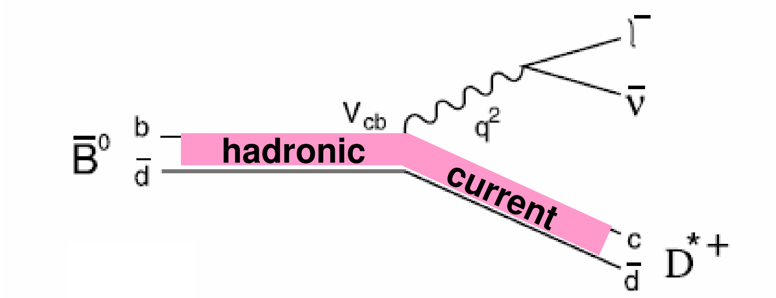
$M_X < 1.67$ GeV: $|V_{ub}| = (4.43 \pm 0.38_{stat} \pm 0.25_{syst} \pm 0.29_{theo})\ 10^{-3}$ — **72%**

$M_X < 2.50$ GeV: $|V_{ub}| = (3.84 \pm 0.70_{stat} \pm 0.30_{syst} \pm 0.10_{theo})\ 10^{-3}$ — **98%**

new!

hep-ex/0602023

$B \to D^* \ell \nu$ Form Factors (1)

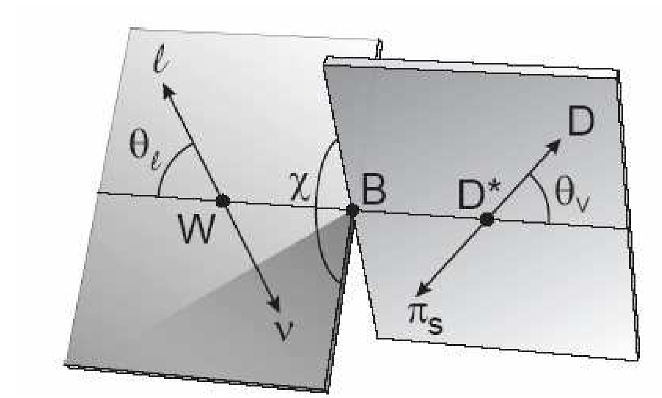


- Hadronic current described by 3 FF.
- Can be parameterized by R_1 R_2 ρ^2
- Uses constraints from theory (Caprini-Lellouch-Neubert Nucl. Phys. B 530, 153, 1998)

Interests of the measurement:

1) FF themselves (previous measurement 10 years ago!)
2) Reduce $|V_{cb}|$ error
3) Reduce $|V_{ub}|$ error (important background)

•Decay can be experimentally characterized by 4 kinematic variables: θ_ℓ θ_V χ W
where W = D* boost in B rest frame



$$\frac{d\Gamma\left(B \to D^* \ell \nu\right)}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} = \left|V_{cb}\right|^2 f\left(w, \theta_\ell, \theta_V, \chi, \rho^2, R_1, R_2\right)$$

Extract R_1, R_2 and ρ^2 from multi-dimensional fit to differential decay rate hep-ex/0602023

$B \to D^{*} \ell \nu$ Form Factors (2)

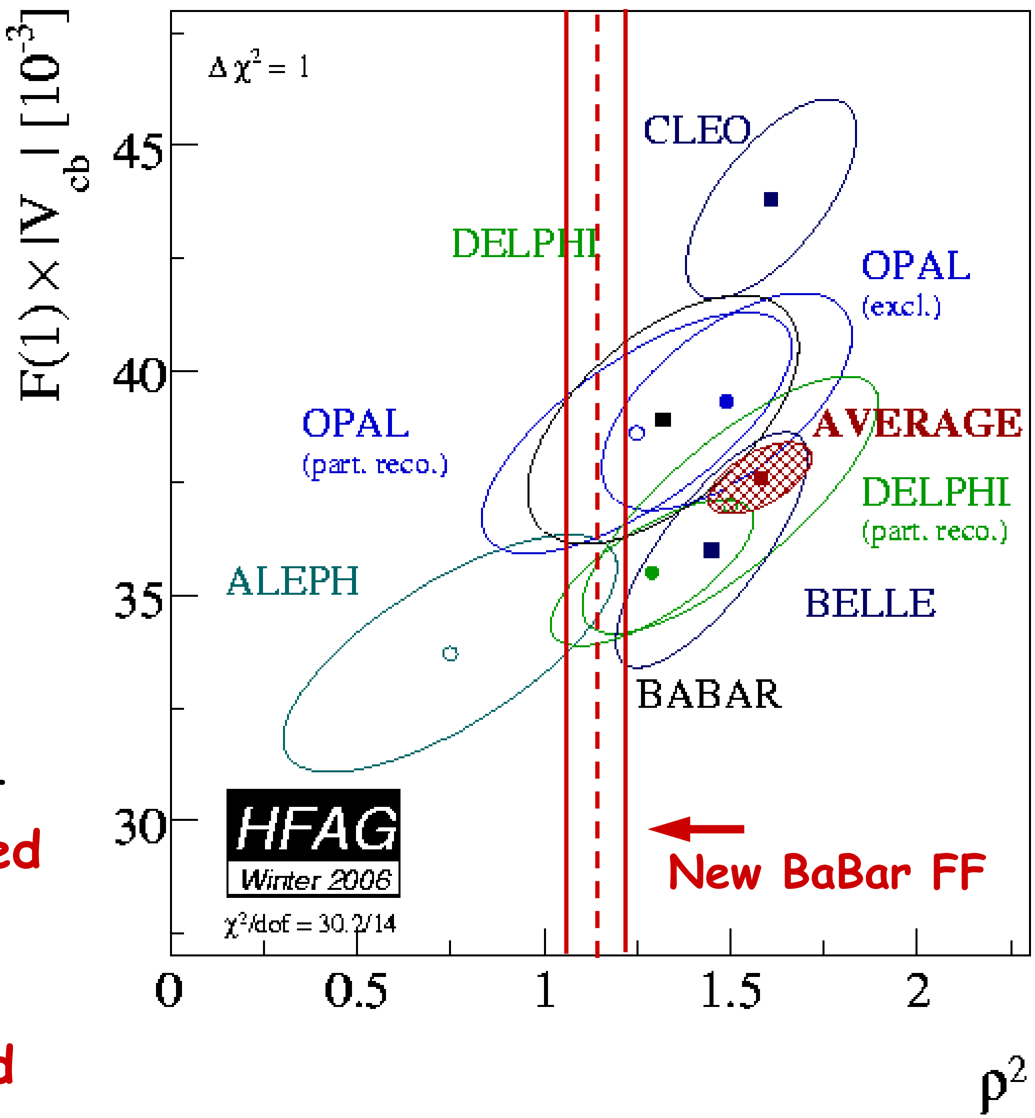
Results: new! $86\times10^{6}\ B\overline{B}$ pairs

	stat data	stat MC	theo
$R_1 = 1.396$	$\pm$ 0.060	$\pm$ 0.035	$\pm$ 0.027
$R_2 = 0.885$	$\pm$ 0.040	$\pm$ 0.022	$\pm$ 0.013
$\rho^2 = 1.145$	$\pm$ 0.059	$\pm$ 0.030	$\pm$ 0.035

- **Factor 5 improvement** on FF uncertainties wrt. previous CLEO measurement (PRL 76 (1996) 3898)!

-Updated a BaBar $|V_{cb}|$ measurement (PRD-RC 051502 (2005)) : syst. error **is reduced by 25%** !

-BaBar lepton endpoint measurement (PRD73, 012006 (2006)) :syst. error **is reduced by 20% on the partial BF!**



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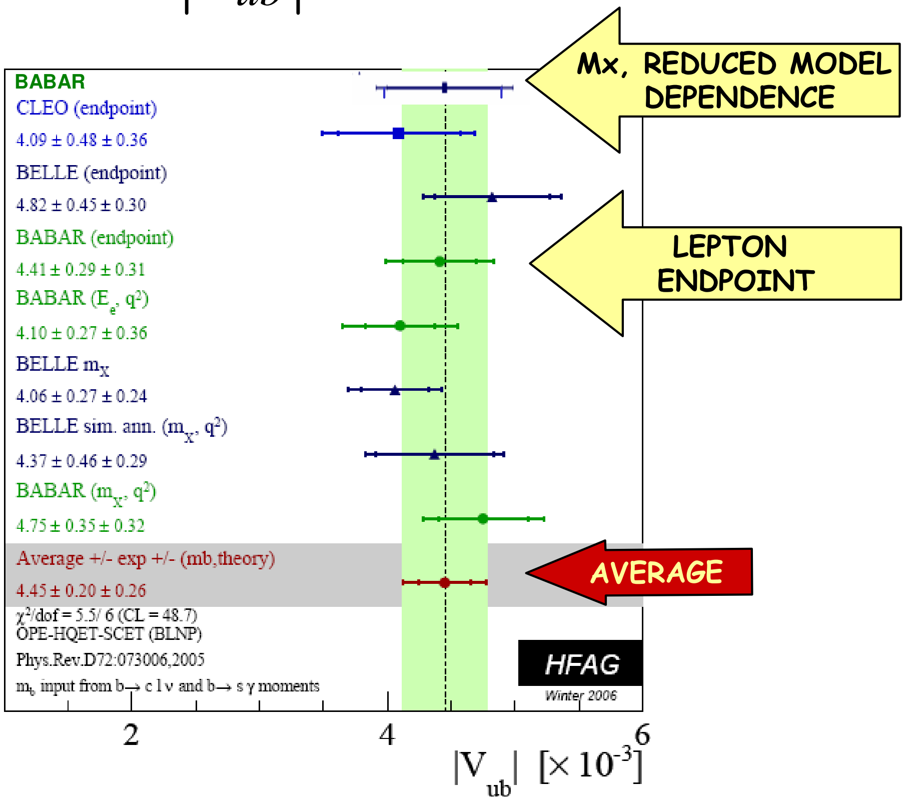
$|V_{ub}|$ & $|V_{cb}|$ Status (HFAG Winter 2006)

$|V_{ub}| \quad \sigma \approx 7\%$



BLNP: Shape Function, PRD72:073006(2005)

$(4.45 \pm 0.20_{exp} \pm 0.18_{SF} \pm 0.19_{theo})\times 10^{-3}$

Andersen-Gardi: DGE, JHEP0601:097(2006)

$(4.41 \pm 0.20_{exp} \pm 0.20_{theo})\times 10^{-3}$

→NEW THEORETICAL SCHEME!

$|V_{cb}| \quad \sigma \approx 2\%$

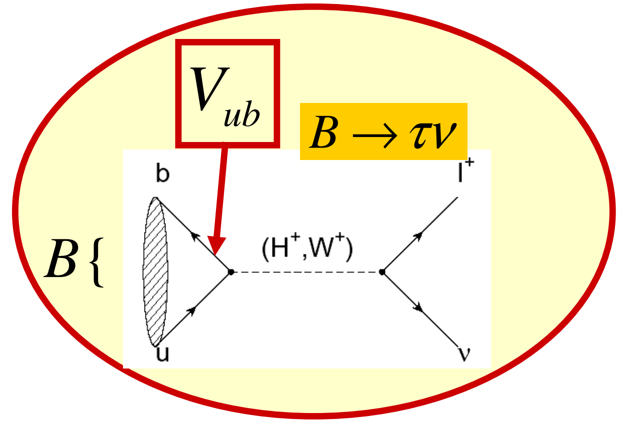
Best result: Global fit on many inclusive measurements.

Buchmüller, Flächer: hep-ph/0507253

Uses inputs from BaBar, Belle, CLEO, CDF & DELPHI.

$B \to \tau\nu$

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



Interests:

- f_B , $|V_{ub}|$, Physics Beyond the SM,

  $BR(B \to \tau\nu) / \Delta m_{B_d}$ constrains $|V_{ub}|^2 / |V_{td}|^2$

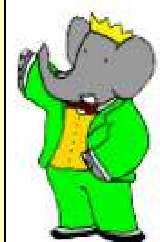
new!

No evidence of signal seen @ **BaBar** Phys.Rev.D73:057101 (2006)

Reconstruct one B in semileptonic or hadronic modes

$$\mathrm{BF}(B^+ \to \tau^+\nu_\tau) = \left(1.28^{+0.95}_{-0.90}\right)\times 10^{-4} \left(< 2.6\times 10^{-4}, 90\%\mathrm{CL}\right)$$

$f_B < 0.34$ GeV, 90% CL $\quad$ $(232/88)\times 10^6$ $B\bar{B}$ pairs



new!

Belle @ FPCP06 : First evidence ! hep-ex/0604024

Reconstruct one B in hadronic modes

$$\mathrm{BF}(B^+ \to \tau^+\nu_\tau) = 1.06\ {}^{+0.34}_{-0.28}\ {}^{+0.18}_{-0.16} \times 10^{-4} \quad (4.2\sigma \text{ significance})$$

$$f_B = 0.176\ {}^{+0.028}_{-0.023}\ {}^{+0.020}_{-0.018}\ \mathrm{GeV}$$

447×10^6 $B\bar{B}$ pairs

BELLE

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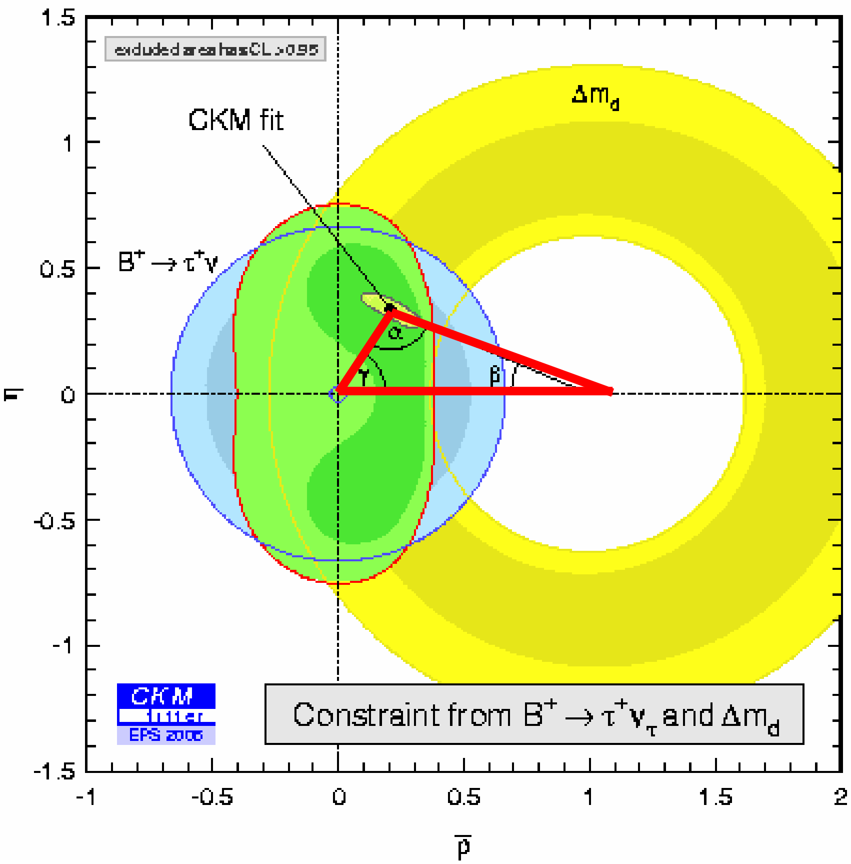
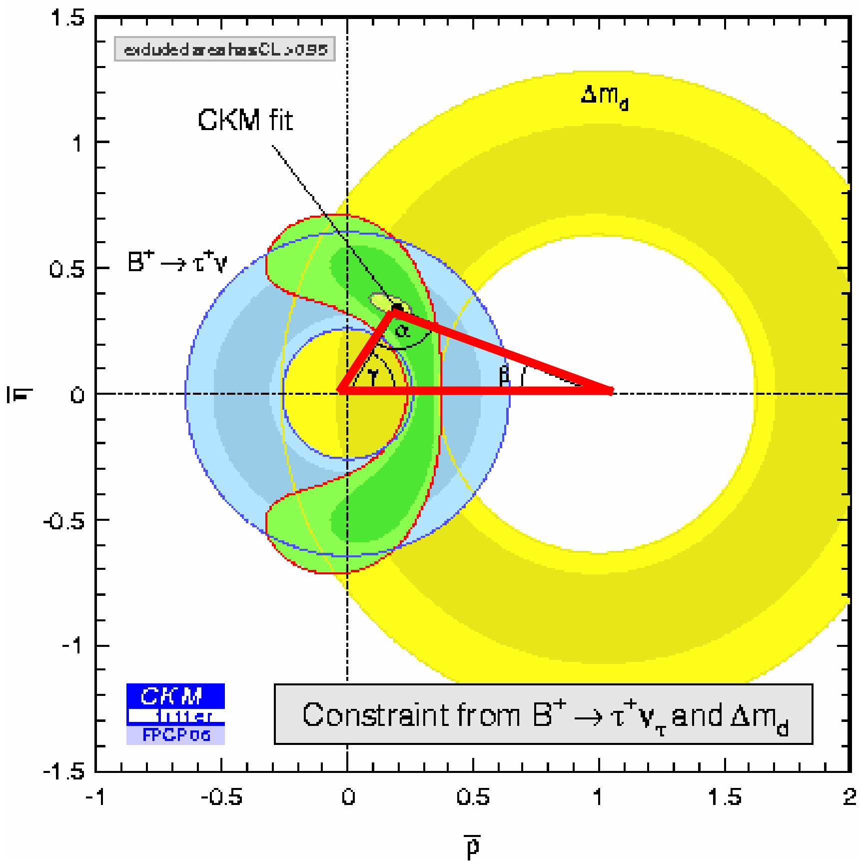
$B \to \tau\nu$ & Δm_d :Constraints on the UT

EPS 2005

new $B \to \tau\nu$

FPCP 2006



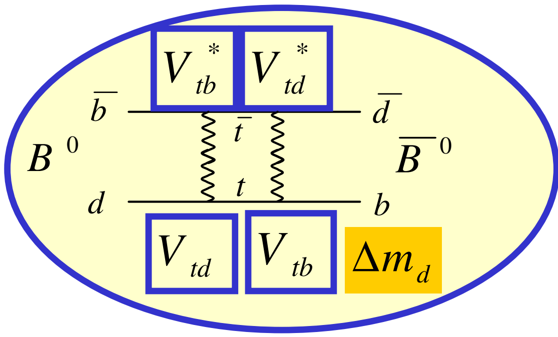


B factories: B_d only

Phys. Rev. D 73, 012004 (2006)

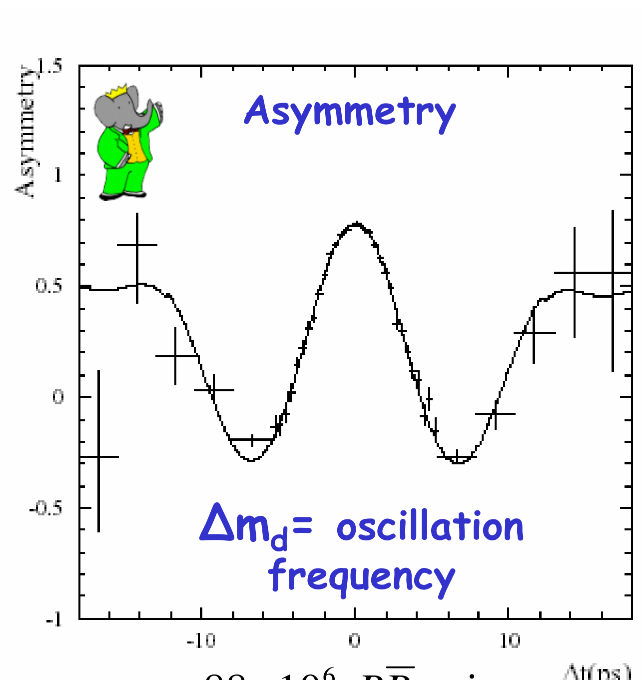
Δm_d and $B^0\overline{B}^0$ oscillations

$$\text{Prob}(B^0\overline{B}^0 \rightarrow B^0B^0 \text{ or } \overline{B}^0\overline{B}^0, B^0\overline{B}^0) = \frac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left(1 \mp \cos(\Delta m_d \Delta t)\right)$$



$$\Delta m_d = \frac{G_F}{6\pi^2} m_{Bd} \hat{B}_{Bd} F_{Bd}^2 \eta_B m_w^2 S_0(x_t) |V_{td}|^2$$

dominant theoretical uncertainties (σ~20%)



88×10^6 $B\overline{B}$ pairs

-Fit the number of mixed/unmixed events in many Δt bins

$$\mathcal{A}(\Delta t) = \frac{\mathcal{N}_{\text{unmix}}(\Delta t) - \mathcal{N}_{\text{mix}}(\Delta t)}{\mathcal{N}_{\text{unmix}}(\Delta t) + \mathcal{N}_{\text{mix}}(\Delta t)}$$

$$\Delta m_d = \left(0.511 \pm 0.007(stat)^{+0.007}_{-0.006}(syst)\right) ps^{-1} \rightarrow \sigma \approx 1.9\%$$

Can compare to HFAG Average Winter 2006

$$\Delta m_d = 0.507 \pm 0.004\, ps^{-1} \quad \rightarrow \sigma \approx 0.8\%$$

Adding the Δm_s ingredient

Δm_d ~ (lots of QCD) x $|V_{td}|^2$

Δm_s ~ (lots of QCD) x $|V_{ts}|^2$

$\Delta m_s / \Delta m_d$ ~ (much less QCD) x $|V_{ts}|^2 / |V_{td}|^2$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

new! from CDF

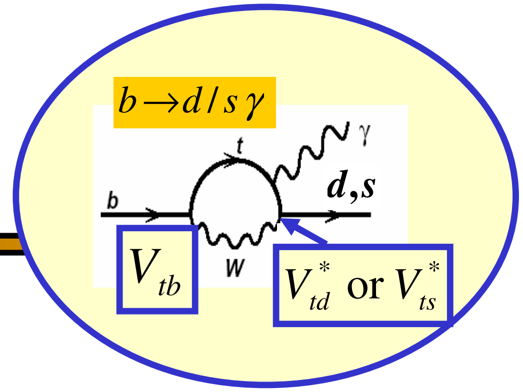
Input	Value	Source	
$m(B_d)/m(B_s)$	0.98320	PDG	
ξ^2	$1.21\ ^{+0.047}_{-0.035}$	Okamoto, Lattice 2005	$\rightarrow \sigma \approx 4\%$
Δm_d	0.505 ± 0.005	PDG	$\rightarrow \sigma \approx 1\%$
Δm_s	$17.330\ ^{+0.426}_{-0.221}$	This analysis	$\rightarrow \sigma \approx 3\%$

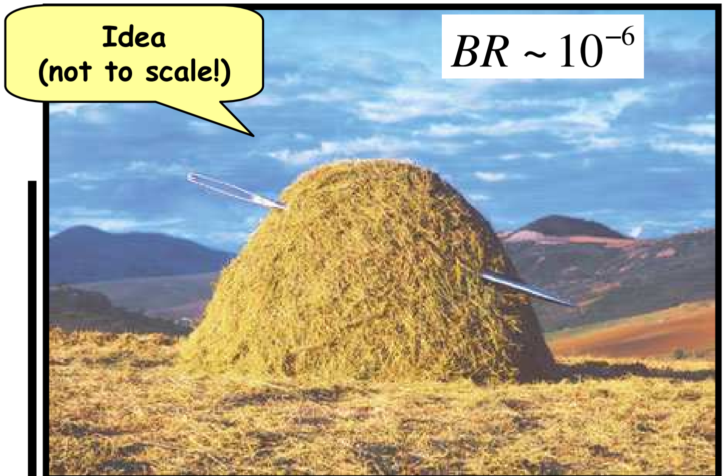
Copied from Guillelmo Gomez-Ceballos's talk, FPCP 2006

$$|V_{td}|/|V_{ts}| = 0.208\ ^{+0.008}_{-0.007} \rightarrow \sigma \approx 4\%$$

PRL 94 011801 (2005)

Search for $B \to \rho / \omega \gamma$





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

Theoretical inputs

No evidence of signal seen @ **BaBar** PRL 94 011801 (2005) 211×10^6 $B\bar{B}$ pairs

$$B(B \to (\rho,\omega)\gamma) = (0.6 \pm 0.3 \pm 0.1) \times 10^{-6}\ (2.1\sigma)$$

$$|V_{td}/V_{ts}| < 0.19 \quad (90\% CL)$$

Belle @ LP 2005: hep-ex/0506079 : First observation! 386×10^6 $B\bar{B}$ pairs

$$B(B \to (\rho,\omega)\gamma) = \left(1.32\ {}^{+0.34}_{-0.31}\ {}^{+0.10}_{-0.09}\right) \times 10^{-6} \quad (5.1\sigma)$$

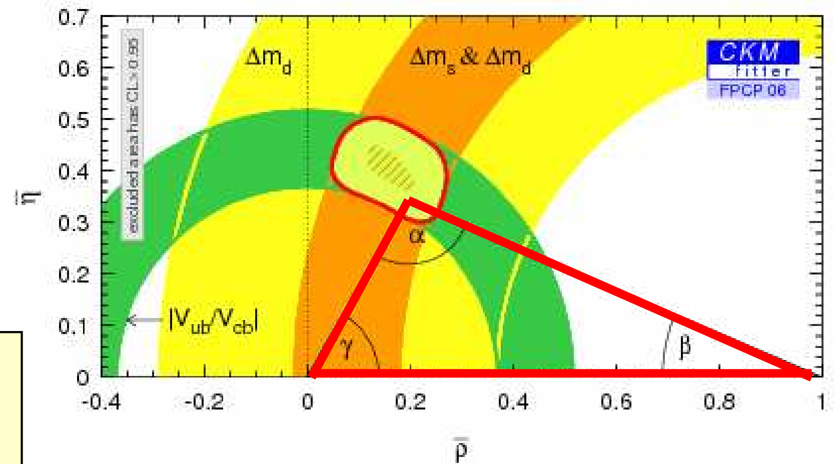
$$|V_{td}/V_{ts}| = 0.199\ \underbrace{{}^{+0.026}_{-0.025}}_{\text{exp.}}\ \underbrace{{}^{+0.018}_{-0.015}}_{\text{theo.}}$$

UT fit to all modes $|V_{td}/V_{ts}| = 0.16 \pm 0.02 \quad \to \sigma \approx 13\%$

Independent of Δm_s CDF: B_s- Mixing (FPCP06): $|V_{td}|/|V_{ts}| = 0.208\ {}^{+0.008}_{-0.007}$ $\to \sigma \approx 4\%$

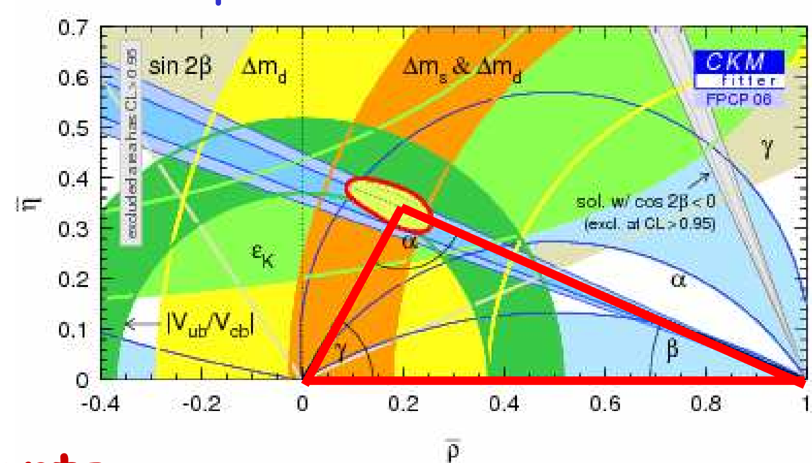
Summary

Apex fit with the “sides” constraints only



•B factories: Can use B mesons to measure the sides of the UT $|V_{ub}|$, $|V_{cb}|$, $|V_{td}|$, $|V_{tb}|$…

Apex fit with all constraints

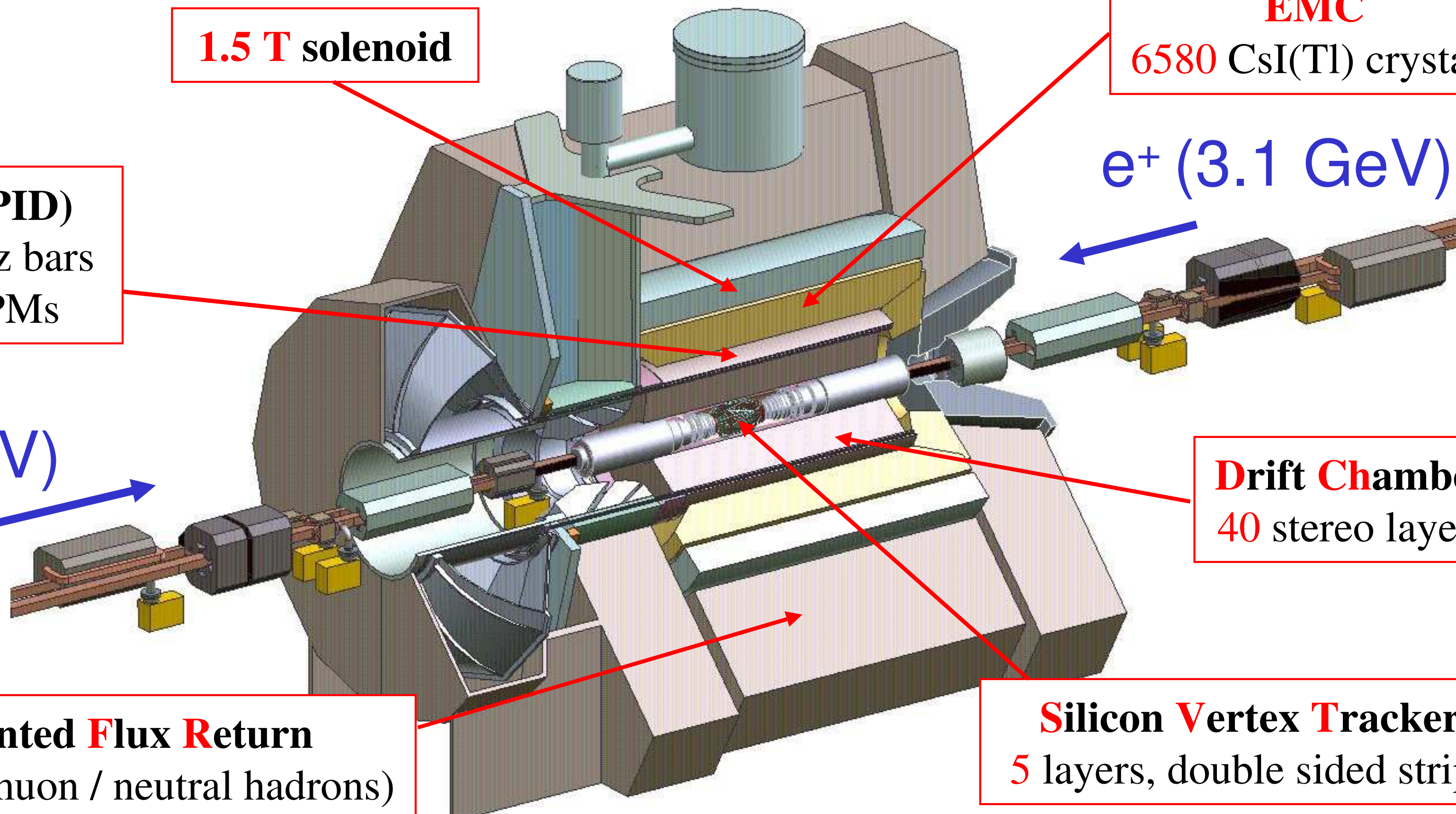


- **$|V_{ub}|$:** $\sigma \sim 7\%$, 2 new BaBar results
- **$|V_{cb}|$:** $\sigma \sim 2\%$, new BaBar $B \rightarrow D^*$lnu FF result
- **$B \rightarrow \tau\nu$**: ($|V_{ub}|$, $|V_{ub}|/|V_{td}|$) new BaBar result, Belle’s first observation, UT constraints improved!
- **Δmd**: $\sigma \sim 0.8\%$, combined with Δms ($\sigma \sim 3\%$) new results from CDF and D0: $|V_{td}|/|V_{ts}|$, $\sigma \sim 4\%$
- **$B \rightarrow \rho/\omega\gamma$**: BaBar & Belle “state of the art”.Combined with $B \rightarrow K^*\gamma$: $|V_{td}|/|V_{ts}|$, $\sigma \sim 12\%$

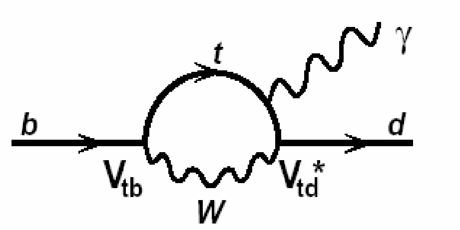
Great improvements since last few years, let’s continue the good work!

Backup Slides

The BABAR Detector



Theoretical inputs… more details (I)



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

Theoretical inputs

$$b \to d\gamma \,/\, b \to s\gamma$$

ζ Flavor-SU(3) breaking between ρ and K^*

$\Delta\zeta/\zeta \approx 10\%$

ΔR Annihilation correction ~ 0, small impact

$$\Delta m_d = \frac{G_F}{6\pi^2} m_{Bd} \hat{B}_{Bd} F_{Bd}^2 \eta_B m_w^2 S_0(x_t) |V_{td}|^2$$

$$\Delta m_d \,\&\, \Delta m_s$$

Theoretical inputs

Bag Factor & meson decay constant taken from LQCD, dominates theoretical error (~20%)

Using Δm_s, many uncertainties cancel… theoretical error on $\left|\frac{V_{ts}}{V_{td}}\right|$ (~5%) $\quad \frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \left|\frac{V_{ts}}{V_{td}}\right|^2$

Theoretical inputs… more details (II)

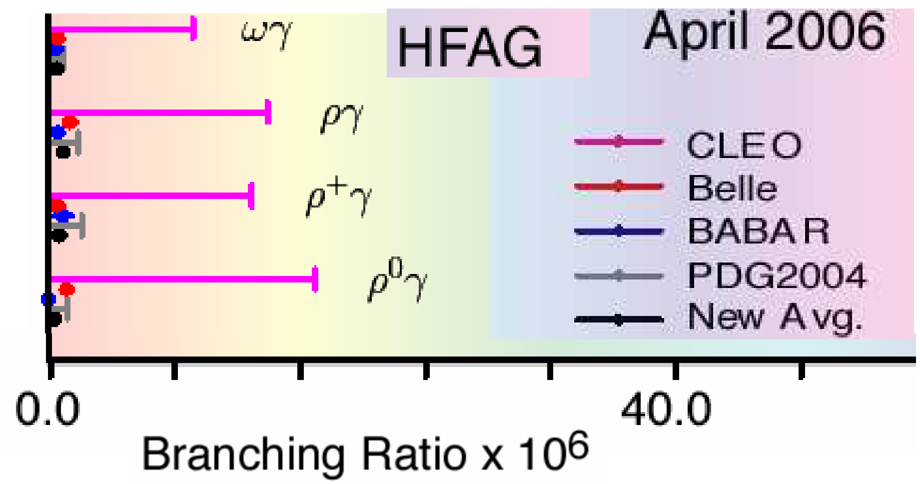
$B \to D^* \ell \nu$ FF

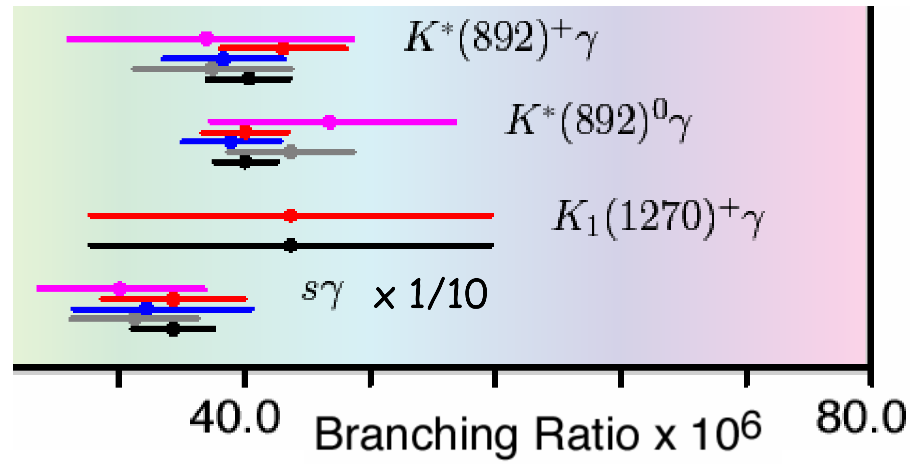
$$\frac{d\Gamma}{dw} \propto \mathcal{G}(w)\mathcal{F}(w)^2 |V_{cb}|^2$$

G(w) known phase space factor
F(w) Form Factor (FF)
w = D* boost in B rest frame

- F(1)=1 in heavy quark limit; lattice QCD says: F(1) = 0.919 Hashimoto et al, PRD 66 (2002) 014503
- Shape of F(w) unknown
- Parametrized with ρ^2 (slope at w = 1) and form factor ratios
  R_1, R_2 ~ independent on w
  h_{A1} expansion a-la Caprini-Lellouch-Neubert Nucl. Phys. B 530, 153 (1998)

$b \to d\gamma$ / $b \to s\gamma$ Status (HFAG Winter 2006)





$\sigma \approx 30\%$

$\sigma \approx 10\%$

$$|V_{td}/V_{ts}| = 0.16 \pm 0.02$$

$\sigma \approx 13\%$

Δm_s (CDF)

Copied from Guillelmo Gomez-Ceballos's talk, FPCP 2006

Frequency domain: amplitude scan

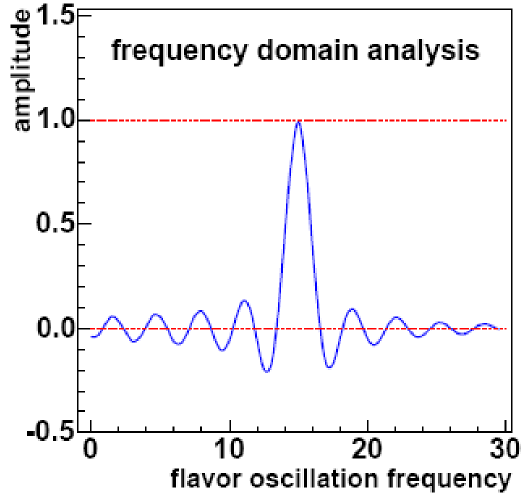
+ introduce amplitude:

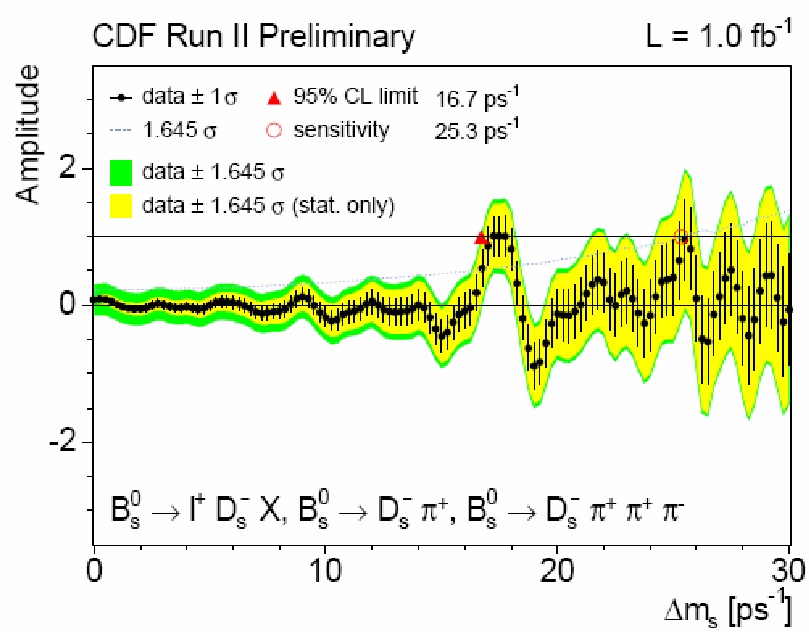
  $P(t) \sim (1 \pm \mathcal{A} D \cos \Delta m_s t)$

+ fit for $\mathcal{A}$ at different Δm_s

$\Rightarrow$ obtain frequency spectrum

+ true $\Delta m_s \Rightarrow \mathcal{A} = 1$, else $\mathcal{A} = 0$



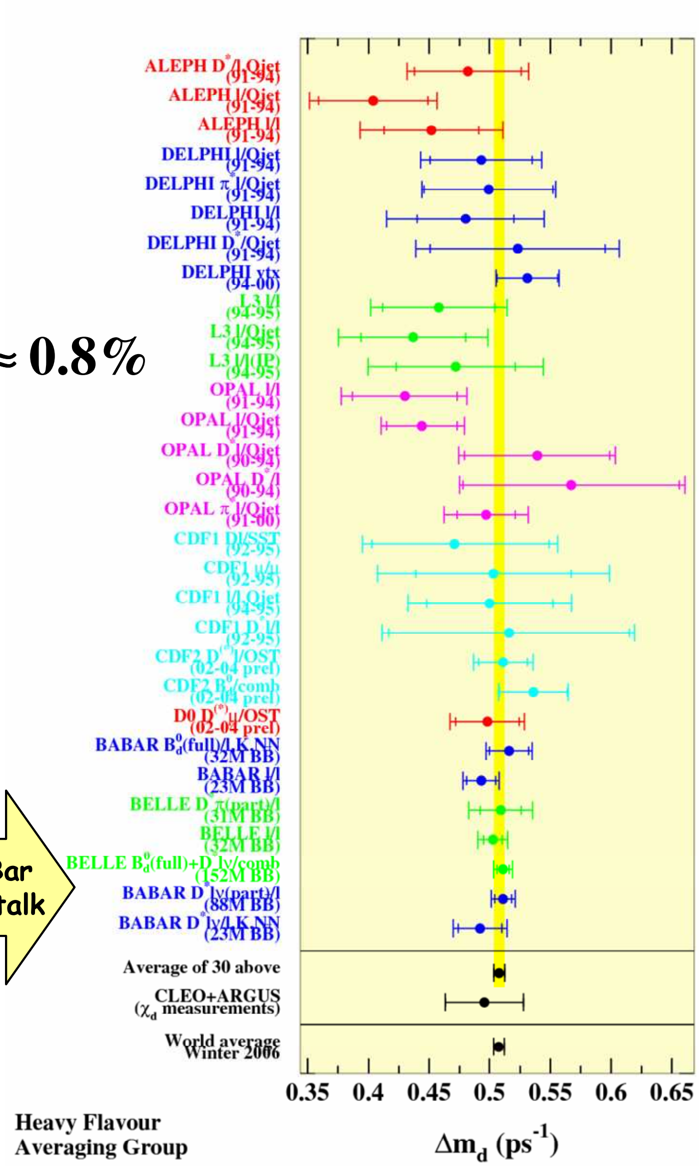


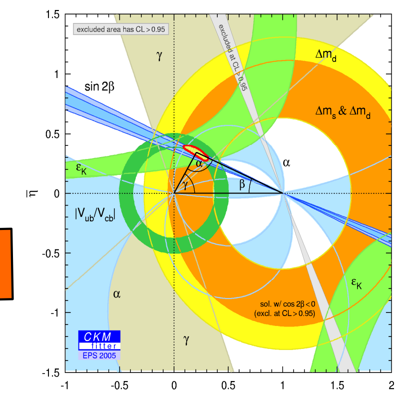
$\mathcal{A}$ compatible with 1 for $\Delta m_s \sim 17.25$ ps^{-1}!

Δm_d and Δm_s Status

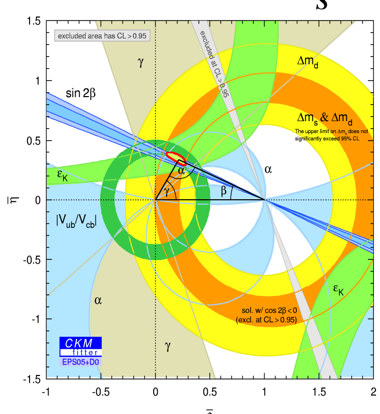
$\Delta m_d : \sigma \approx 0.8\%$

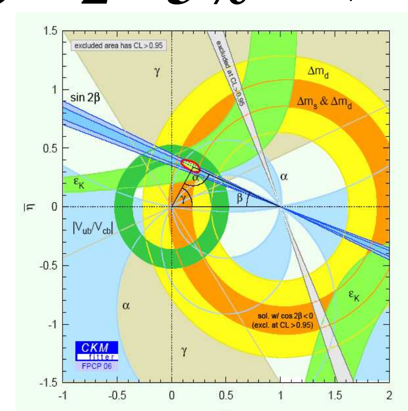
Δmd from BaBar shown in this talk





$\Delta m_s : \sigma \approx 2-3\%$





$$\left|V_{td}/V_{ts}\right| = 0.208^{+0.008}_{-0.007}$$

$\sigma \approx 4\%$

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