Recent results from the B factories

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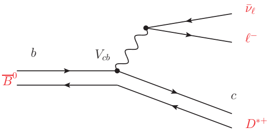
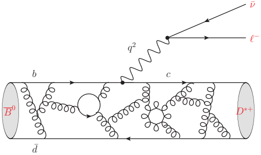
DESY seminar
Hamburg, 26th May 2009

Flavour physics

- Understand flavour structure of Standard Model
- Measure properties of weak interaction, i.e. flavour-changing interactions of quarks
  - *CP* violation
  - Over-constrain CKM matrix
- Test Standard Model predictions
- Search for New Physics

- Want to access quark-level quantities, but only can measure hadron decays:





- Need handle on QCD dynamics to understand flavour physics

This talk

Flavour physics

- Experiments: *BABAR* and Belle
- *CP* violation

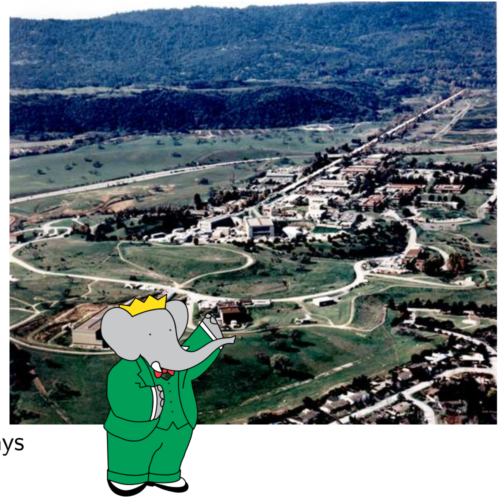
Angles of Unitarity Triangle (UT)

- $\sin 2\beta$
- α
- γ

Sides of Unitarity Triangle

- $|V_{cb}|$ from semileptonic B decays
- Purely leptonic decay $B \to \tau\nu$
- B mixing

Summary and conclusions



Physics programme of B factories

includes:

- B physics: CKM, CPV, BF, ...
- Charm physics: discovery of charm mixing, ...
- τ physics
- $e^+e^- \rightarrow hadrons$: form factors, input to SM prediction of $(g-2)_\mu$
- Spectroscopy: discovery of X, Y, Z
- Discovery of η_b
- ...

Theoreticians' toolbox

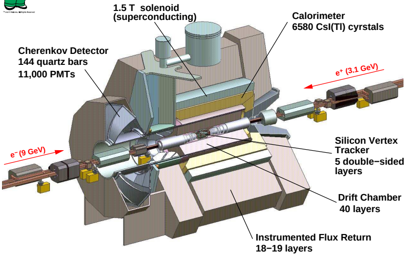
Need theoretical tools to

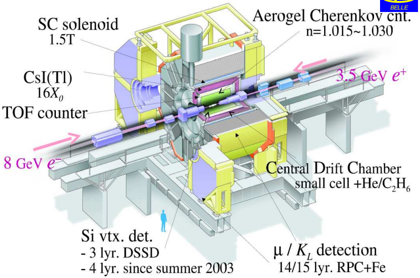
- make predictions for
  branching fractions, *CP* asymmetries ...
- compute hadronic corrections

- Effective Hamiltonian: integrate out W and t
- $m_b \gg \Lambda_{\mathrm{QCD}}$
  - factorisation: form factors, distribution amplitudes, ...
  - heavy quark expansion (powers of $\Lambda_{\mathrm{QCD}}/m_b$)
  - perturbation theory: expansion in $\alpha_s(m_b)$
- $\Lambda_{\mathrm{QCD}} \gg m_u, m_d, m_s$: $SU(2)$ or $SU(3)$ global symmetries
- Lattice gauge theory (LQCD)
  difficult to deal with light energetic particles

The B-factories *BABAR* at SLAC and Belle at KEK

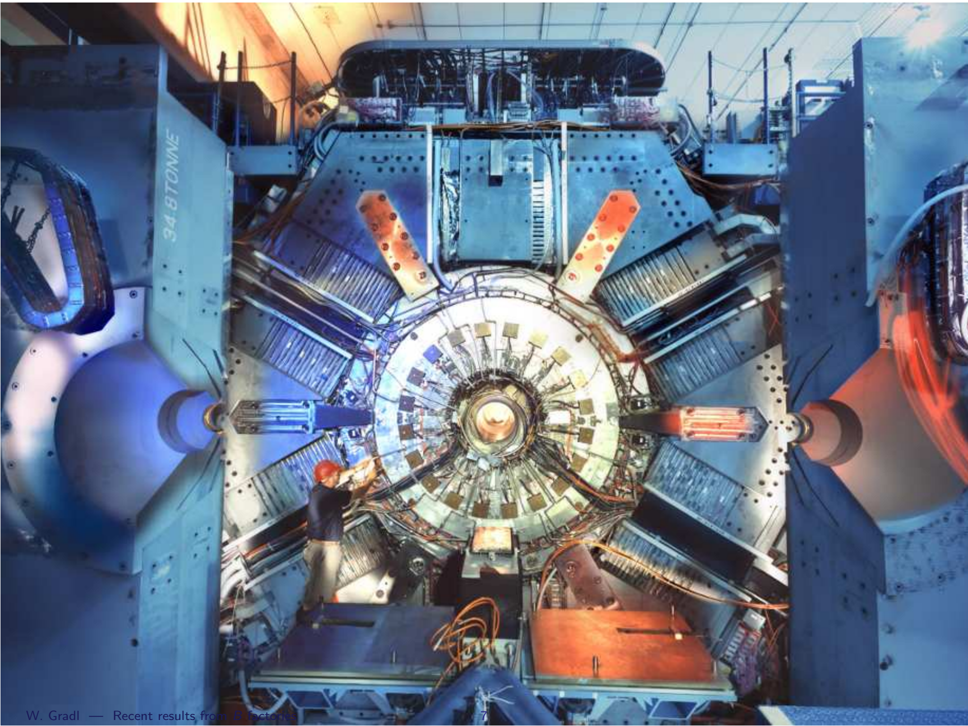
- e^+e^--colliders running at $\sqrt{s} = m(\Upsilon(4S)) = 10.58\,\mathrm{GeV}$
- Asymmetric beam energies
- High luminosity ($\mathcal{O}(10^{34})\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) ➠ data samples of $\mathcal{O}(10^{10})$ B decays





- Data taking stopped a year ago
- $\mathcal{L}_{\mathrm{int}} = 531\,\mathrm{fb}^{-1}$
  465 million $B\overline{B}$ pairs on-$\Upsilon(4S)$

- Record luminosity:
  $1.96 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Current data sample $> 900\,\mathrm{fb}^{-1}$
- Approved to collect $1\,000\,\mathrm{fb}^{-1}$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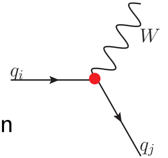
Quark-mixing matrix V_{CKM}

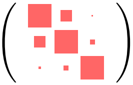


$\sim gV_{ij}$

- Mass eigenstates $\neq$ eigenstates of weak interaction
- Mixing of mass- to flavour-eigenstates described by **C**abbibo-**K**obayashi-**M**askawa matrix
- For 3 quark families: 3 mixing angles, 1 irreducible phase

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Practical: Wolfenstein-parametrisation: λ, A, ρ, η, all of $\mathcal{O}(1)$
- $V_{us} \equiv \lambda \approx \sin\theta_C \simeq 0.2257$ (Cabbibo angle)

$\Rightarrow$ hierarchy 

Unitarity Triangle and CP violation

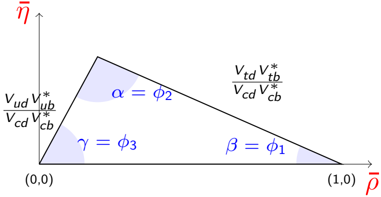
$$V_{\mathrm{CKM}} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Assuming unitarity of V_{CKM} (universality of weak interaction):

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

➡ triangle in complex $(\overline{\rho}, \overline{\eta})$ plane
$\overline{\rho} \equiv (1-\lambda^2/2)\rho$

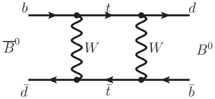
➡ apex at
$\overline{\rho} + i\overline{\eta} \equiv (V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$



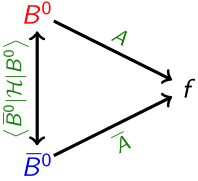
- Kobayashi & Maskawa 1973:
  Non-zero phase in CKM matrix generates CP violation:
  $\eta \neq 0 \Leftrightarrow$ Unitarity triangle is not flat
  (Nobel Price 2008)

Time-dependent CP asymmetries

- Neutral B mesons oscillate between B^0 and $\overline{B}^0$.

$\langle \overline{B}^0 | \mathcal{H} | B^0 \rangle =$  $+$ long distance

- Mass eigenstates $|B_{\mathrm{H,L}}\rangle = p\,|B^0\rangle \pm q\,|\overline{B}^0\rangle$; $q/p \simeq e^{-2i\beta}$
- Decay into common final state f:



  - If f is CP eigenstate:
    interference between two decay paths
  - V_{CKM} complex
    ➠ B^0 and $\overline{B}^0$ decays have different weak phase
  - Leads to lifetime dependent differences
    $\Gamma(\,B^0\big|_{t=0} \rightarrow f\big|_t) \neq \Gamma(\,\overline{B}^0\big|_{t=0} \rightarrow f\big|_t)$

Time-dependent CP asymmetries

Time evolution of $B_{\text{tag}} = B^0(\overline{B}^0)$ is

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 \pm [-\eta_f S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\}$$

$\Delta m_d = m_H - m_L = 0.507 \pm 0.005 \hbar/\text{ps}$
τ_B: B^0 lifetime $(1.530 \pm 0.009\,\text{ps})$
η_f: CP eigenvalue of final state f

- Construct asymmetry as a function of Δt:

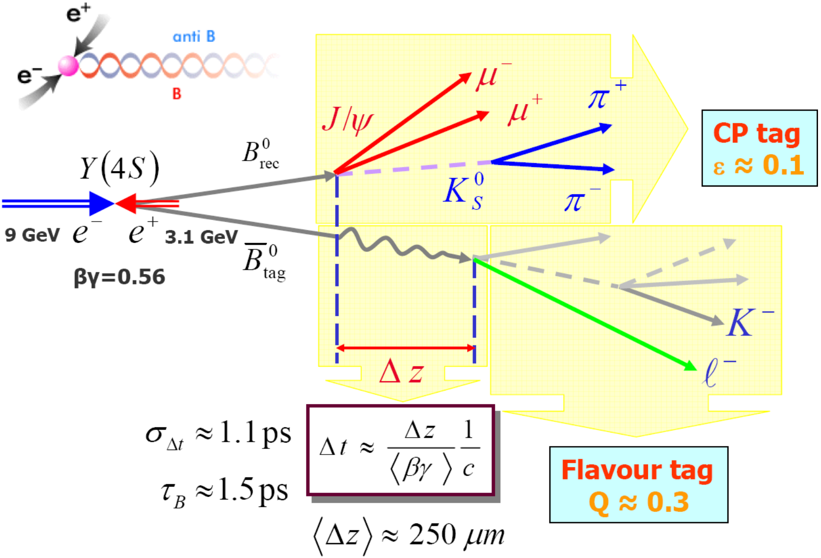
$$\begin{aligned} \mathcal{A}_{cp}(\Delta t) &= \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)} \\ &= -\eta_f S_f \sin \Delta m_d \Delta t - C_f \cos \Delta m_d \Delta t \end{aligned}$$

Time-dependent CP asymmetries

$$\mathcal{A}_{cp}(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)}$$
$$= -\eta_f S_f \sin \Delta m_d \Delta t - C_f \cos \Delta m_d \Delta t$$

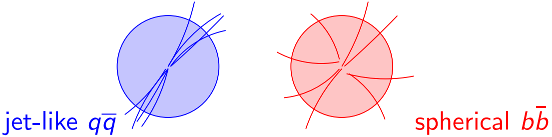
- S_f, C_f encode information about CP violation:
  $\lambda_f = \frac{q}{p} \frac{\overline{A}_f}{A_f}$
  $S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}, C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$
- $|\lambda_f| \neq 1 \Rightarrow C_f \neq 0$: "direct CPV" ($CP$ violation in decay)
  needs two contributing amplitudes with different weak and strong phases
- $S_f \neq 0$: "indirect CPV"
  (CP violation in interference between decays with and without mixing)

Measuring Δt



Detecting a signal

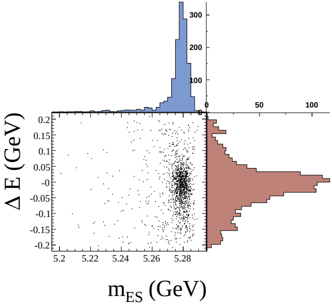
- Largest backgrounds from $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$)
- Use event shape for background suppression:



- Kinematic variables identify B:

$$\Delta E = E_B^* - E_{\mathrm{beam}}^* \sim 0$$

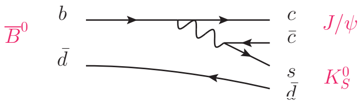
$$m_{\mathrm{ES}} = \sqrt{{E_{\mathrm{beam}}^*}^2 - {p_B^*}^2} \sim m_B$$



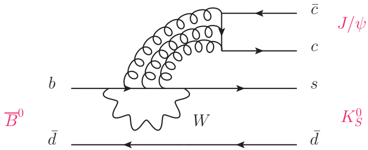
- Multi-dimensional likelihood fits

CP violating asymmetry in $B^0 \to (c\bar{c})K^0$

- Measure S and C in several $b \to c\bar{c}s$ decays
  $$S = -\eta_f \sqrt{1 - C^2} \sin 2\beta$$
- Theoretically clean: dominated by single (tree) amplitude:



- Gluonic loop (penguin) is small:

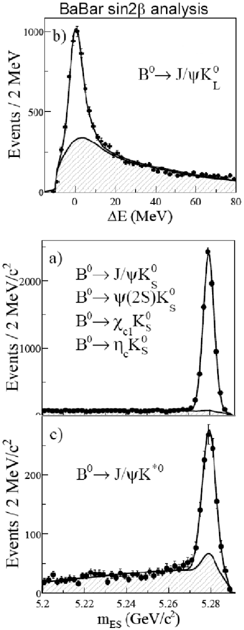


- Calculations suggest $C < 10^{-3}$

$\eta_f = +1$

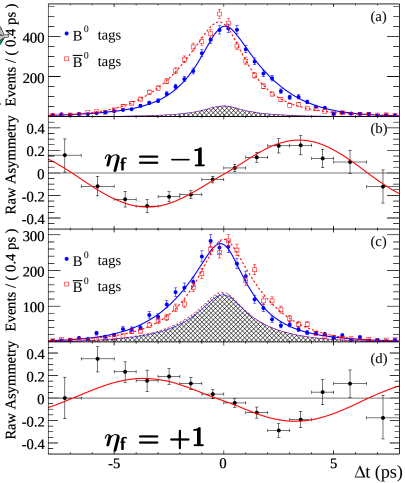
$\eta_f = -1$

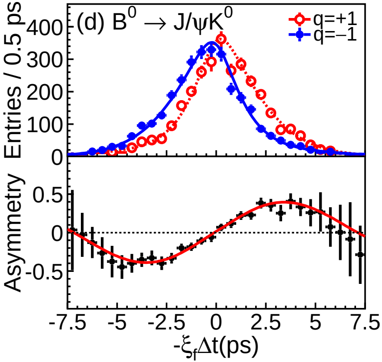
$\eta_f^{\text{eff}} \approx 0.5$



$\sin 2\beta$

$\beta \equiv \arg[-V_{cd} V_{cb}^{*} / V_{td} V_{tb}^{*}]$





$\sin 2\beta = 0.687 \pm 0.028(stat) \pm 0.012(syst)$

BaBar, 465M $B\overline{B}$ events

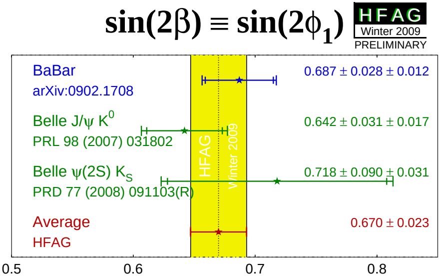
Phys. Rev. D **79**, 072009 (2009)

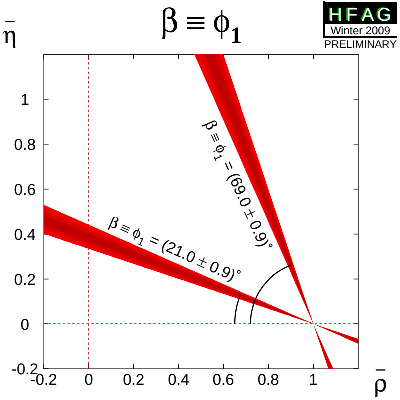
$\sin 2\beta = 0.642 \pm 0.031(stat) \pm 0.017(syst)$

Belle, 535M $B\overline{B}$ events

Phys. Rev. Lett. **98**, 031802 (2007)

Precise measurement of β



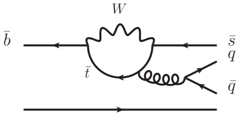


$$\boxed{\beta = (21.0 \pm 0.9)^\circ}$$

Exploit this precision to search for New Physics

Searching for new physics in *CP* violation

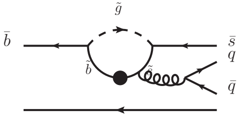
- Measure CPV in $b \to s$ loop ('penguin') dominated decays: S_f



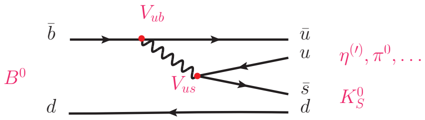
- 'Golden mode' $B^0 \to \phi K_s^0$
- Standard model & penguin only

$$\boxed{S_f = -\eta_f \sin 2\beta}$$

- New Physics (NP) can show up in loops and modify S_f



- Sensitive to masses $\sim \mathcal{O}(10\,\text{TeV})$
- But: sub-leading SM amplitudes not negligible, and have different weak phases

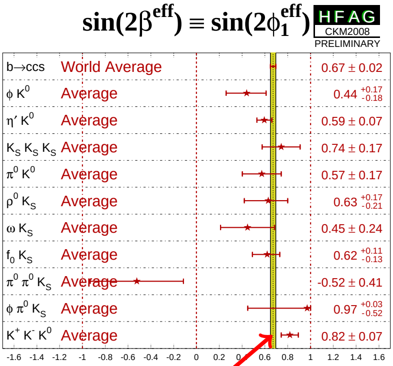


➠ In order to see NP in

$$0 \neq \Delta S_{\text{NP}} \equiv S_f - S_{c\bar{c}s} - \Delta S_{\text{SM}}$$

need to control 'SM pollution'

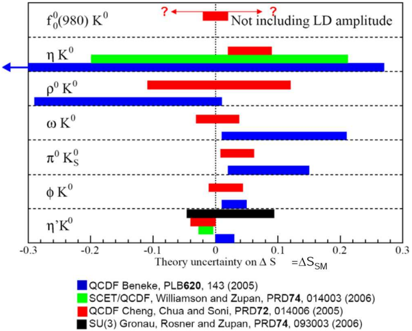
$\sin 2\beta$ from $b \to q\bar{q}s$ penguins



$\sin 2\beta$ from $b \to c\bar{c}s$

- Experiments seem to favour $\Delta S < 0$
- Was more exciting 2 years ago

SM expectation for ΔS_{SM}



- $\Delta S_{\rm SM}$ tend to be small and positive
- Neither experimental nor theoretical precision high enough to confirm or rule out New Physics

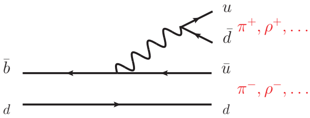
$\alpha \equiv \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$

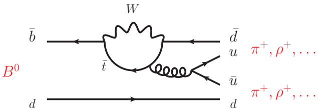
Measuring α

- Process involving both B-mixing (β) and $b \to u$ transition (γ):

$$\alpha = \pi - \beta - \gamma.$$

- Complication: penguin amplitudes not negligible, different weak phase and (unknown) strong phase





$\delta = \delta_P - \delta_T$, P/T different for each final state

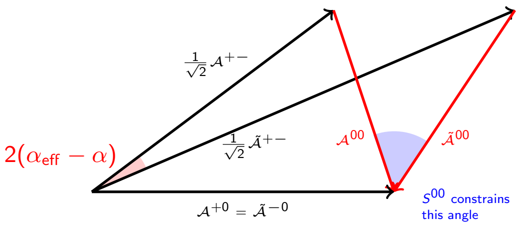
➠ Can only measure α_{eff}, and

$$C_{hh} \propto \sin\delta; \qquad S_{hh} = \sqrt{1 - C_{hh}^2}\,\sin 2\alpha_{\text{eff}}$$

Isospin analysis to constrain $\alpha_{\text{eff}} - \alpha$

- Time dependent $\pi^+\pi^-$ or $\rho^+\rho^-$ CP asymmetry ➠ measure α_{eff}
- Use SU(2) isospin to relate amplitudes of all $\pi\pi$ ($\rho\rho$) modes and constrain $\alpha_{\text{eff}} - \alpha$ Gronau & London, Phys. Rev. Lett. **65**, 3381

$$\frac{\mathcal{A}^{+-}}{\sqrt{2}} + \mathcal{A}^{00} = \mathcal{A}^{+0} = e^{2i\gamma}\overline{\mathcal{A}}^{-0}$$



$$\begin{aligned} \mathcal{A}^{+-} &= \mathcal{A}(B^0 \to h^+h^-) \\ \mathcal{A}^{+0} &= \mathcal{A}(B^+ \to h^+h^0) \\ \mathcal{A}^{00} &= \mathcal{A}(B^0 \to h^0h^0) \end{aligned}$$

$$\tilde{\mathcal{A}} \equiv e^{2i\gamma}\overline{\mathcal{A}}$$

If only $\mathcal{B}$ are measured: 4-fold ambiguity for $\kappa = 2(\alpha_{\text{eff}} - \alpha)$

Angular analysis: $B \to VV$

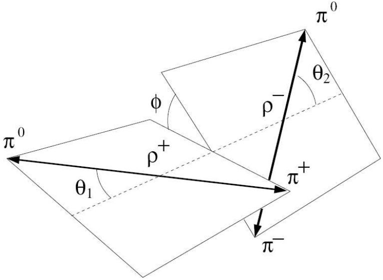
- J^P: $0^- \to 1^- 1^-$
- With enough statistics, full angular analysis possible:

$$\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_1 \mathrm{d}\cos\theta_2 \mathrm{d}\phi} \propto \left| \sum_{m=-1,0,1} H_m Y_{1,m}(\theta_1,\phi) Y_{1,-m}(\theta_2,\phi) \right|^2$$

- Fraction of longitudinally polarised events

$$f_L \equiv \frac{|H_0|^2}{|H_0|^2 + |H_{+1}|^2 + |H_{-1}|^2}$$

- In transversity basis:



$$\begin{aligned} \color{red}{A_0} &= H_0 \\ \color{red}{A_\parallel} &= \frac{1}{\sqrt{2}}(H_{+1} + H_{-1}) \\ \color{blue}{A_\perp} &= \frac{1}{\sqrt{2}}(H_{+1} - H_{-1}) \end{aligned}$$

CP even

CP odd

α from $B \to \rho\rho$

BABAR Phys. Rev. D **78** 071104 (2008)

$\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$

$f_L = 0.75^{+0.11}_{-0.14} \pm 0.14$
$S_L^{00} = 0.3 \pm 0.7 \pm 0.2,\ C_L^{00} = 0.2 \pm 0.8 \pm 0.3$

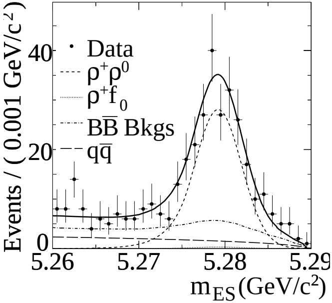
Belle Phys. Rev. D **78** 111102 (2008)

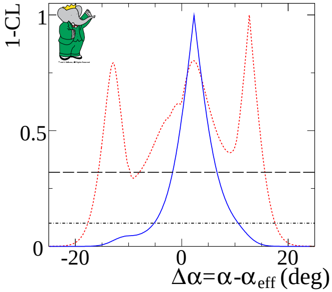
$\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.4 \pm 0.4^{+0.2}_{-0.3}) \times 10^{-6}$
$< 1.0 \times 10^{-6}$ @90%$C.L.$

BABAR arXiv:0901.3522, sub. to PRL

$\mathcal{B}(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$

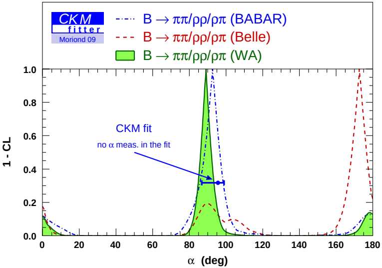
$B^0 \to \rho^0\rho^0$ small
➠ isospin triangle flattened,
decreases ambiguity due to $\alpha_{\rm eff} - \alpha$

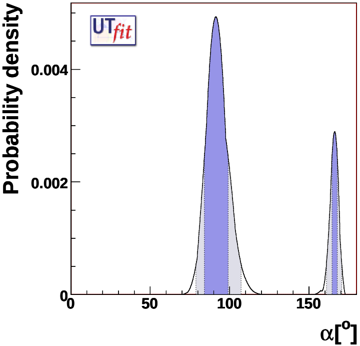




Summary on α

Combine measurements from *CP* violation in $B^0 \to \pi\pi, \rho\rho, (\rho\pi)^0$





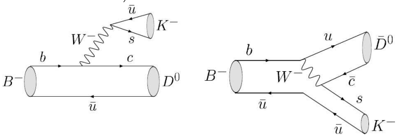
$\alpha = (89.0^{+4.4}_{-4.2})^\circ$ (68% C.L.)

SM solution: $\alpha = (90 \pm 9)^\circ$

Measuring γ

- Study direct CP violation in $b \to c\bar{u}s, u\bar{c}s$

$B^- \to K^{(*)-} D^{(*)0}$



- Three approaches in use:

GLW

- $D^{(*)0} \to f_{CP}$
- (Small) interference between amplitudes
- Hadronic uncertainties from $D^{(*)0}$ decay cancel

Gronau, London (1991); Gronau, Wyler (1990)

ADS

- D^0 decays to $K^-\pi^+$ (favoured) and $K^+\pi^-$ (suppressed)
- Larger interference
- Hadronic uncertainties from D decays

Atwood, Danietz, Soni (1997)

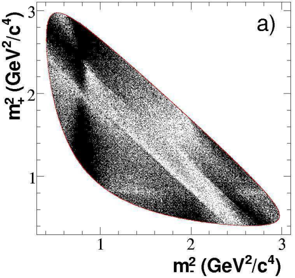
GGSZ

- D^0 decays to $K_s^0\pi^+\pi^-$
- Interference in Dalitz plot
- Currently most sensitive

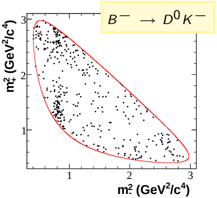
Giri, Grossman, Sofer, Zupan (2003)

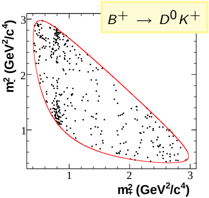
BABAR GGSZ measurement

Model DP with $D^{*+} \to D^0 \pi_s^+$



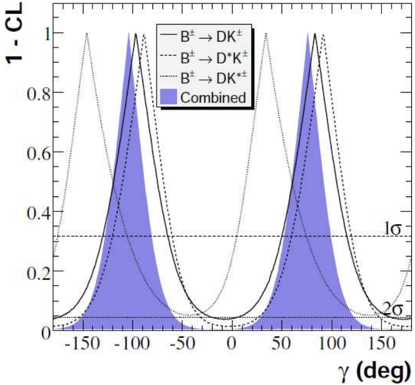
Use DP model on B decays to fit for CP parameters





BABAR, 383 M $B\bar{B}$

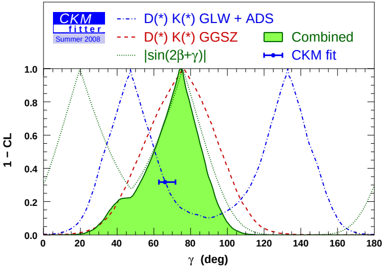
Phys. Rev. D **78**, 034023 (2008)



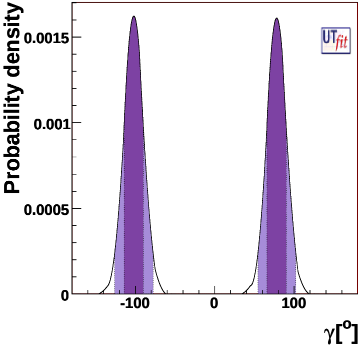
$$\gamma = (76 \pm 22 \pm 5 \pm 5)^\circ$$

Results on γ

- Many new results from *BABAR* and Belle in summer 2008
- Latest *BABAR* $B^+ \to DK^+$ ADS and GLW analyses not included
- Use also $\sin(2\beta + \gamma)$ from $B^0 \to D^+\pi^-(\rho^-)$



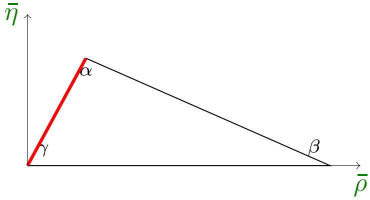
$\gamma = (76^{+16}_{-23})^\circ$

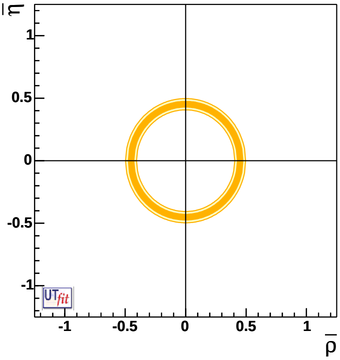


$\gamma = (78 \pm 12)^\circ$

Unitarity triangle side from semileptonic B decays

$$\frac{|V_{ub}|}{|V_{cb}|} = \frac{\lambda}{1-\lambda^2/2}\sqrt{\overline{\rho}^2+\overline{\eta}^2}$$

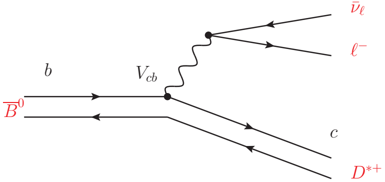




Semileptonic $b \to c$ decays

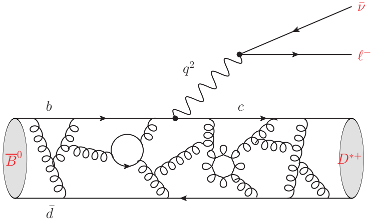
- $|V_{cb}|$ (and $|V_{ub}|$) determined from semileptonic B decays
- Tree-level process: free from new physics!
- Everything nice and clean at quark-level:

$$\Gamma \propto |V_{cb}|^2$$



Need to include QCD corrections

- Inclusive measurements ($\bar{B} \to X_c \ell \overline{\nu}$) Operator Product Expansion
- Exclusive measurements: Form factors from Lattice QCD
- Complementarity between incl. and excl.



Inclusive semileptonic decay width

$\boxed{\mathcal{B}(B \to X_c e\nu) = (10.08 \pm 0.30 \pm 0.22)\,\%}$ Belle, Phys. Rev. D **75**, 032001 (2007)

$$\Gamma(\overline{B} \to X_c \ell \overline{\nu}) = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3} \left[f(\rho) + k(\rho)\frac{\mu_\pi^2}{2m_b^2} + g(\rho)\frac{\mu_G^2}{2m_b^2} + d(\rho)\frac{\rho_D^3}{m_b^3} + l(\rho)\frac{\rho_{LS}^3}{m_b^3} + \mathcal{O}(m_b^{-4}) \right] \qquad \rho = \frac{m_c^2}{m_b^2}$$

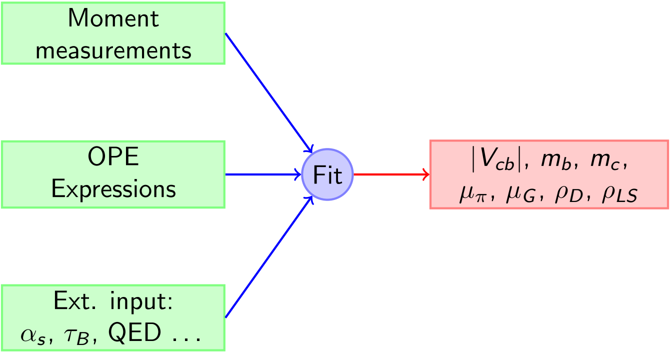
Wilson coefficients f, k, g, d, l calculable in perturbation theory

Non-perturbative parameters μ_π, μ_G, ρ_D, ρ_{LS} matrix elements of local operators in HQET

Same matrix elements (but different Wilson coefficients) appear in OPE for moments of

- lepton energy spectrum E_ℓ in $B \to X_c \ell \overline{\nu}$
- hadronic mass spectrum M_X in $B \to X_c \ell \overline{\nu}$
- photon energy spectrum E_γ in $B \to X_s \gamma$

Inclusive $|V_{cb}|$ — moment analysis



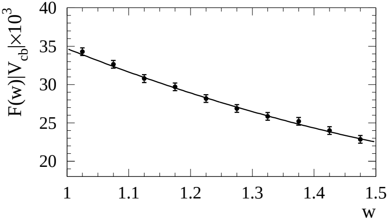
World average (HFAG; kinetic scheme)

$$
\begin{aligned}
|V_{cb}| &= (41.67 \pm 0.43_{\text{fit}} \pm 0.08_{\tau_B} \pm 0.58_{\text{th}}) \times 10^{-3} \\
m_b &= (4.601 \pm 0.034)\,\text{GeV} \\
\mu_\pi^2 &= (0.440 \pm 0.040)\,\text{GeV}^2
\end{aligned}
$$

Exclusive $|V_{cb}|$ measurements

$$\frac{d\Gamma(B \to D^* \ell \nu)}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} \mathcal{K}(w) \mathcal{F}(w)^2$$

- w : four-velocity transfer from b to $\ell\nu$
- $\mathcal{K}$: known phase-space factor, vanishes as $w \to 1$
- $\mathcal{F}$: form factor; in limit of infinite quark mass: $\mathcal{F}(w = 1) = 1$
  LQCD: $\mathcal{F}(1)^{B \to D^* \ell \nu} = 0.924 \pm 0.022$ FNAL, arXiv:0710.1111
- Typically, experiments measure $d\Gamma/dw$ and extrapolate to $w \to 1$ to determine $|\mathcal{F}(1) V_{cb}|$

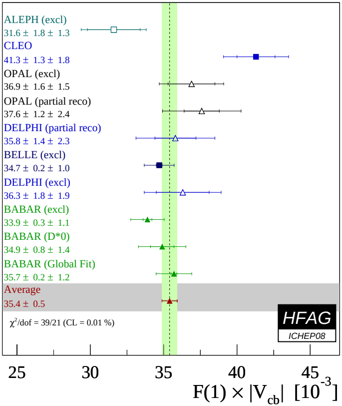


$\mathcal{F}(1)|V_{cb}| = (34.4 \pm 0.3 \pm 1.1) \times 10^{-3}$

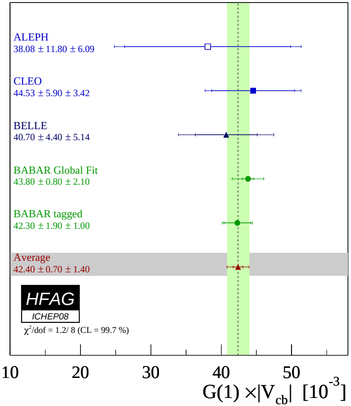
BABAR, Phys. Rev. D **77** 032002 (2008)

Exclusive $|V_{cb}|$ results

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



$B \to D \ell \nu$



$$\mathcal{F}(1) = 0.921(13)(20)$$

C. Bernard et al., arXiv:0808.2519[hep.lat]

$$|V_{cb}| = (38.2 \pm 0.6 \pm 0.9) \times 10^{-3}$$

$$\mathcal{G}(1) = 1.074 \pm 0.018 \pm 0.016$$

M. Okamoto et al., arXiv:hep-lat/0409116

$$|V_{cb}| = (39.2 \pm 1.5 \pm 0.9) \times 10^{-3}$$

Consistent, but $\approx 2\sigma$ lower than $|V_{cb}|$ from inclusive

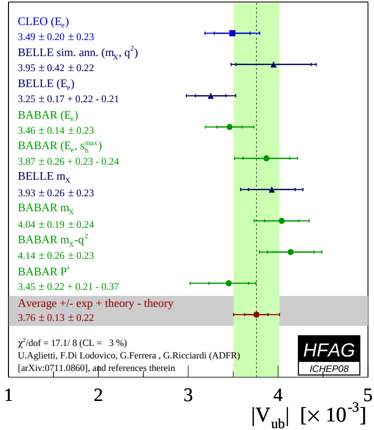
$(|V_{cb}|_{\text{incl}} = (41.67 \pm 0.43_{\text{fit}} \pm 0.08_{\tau_B} \pm 0.58_{\text{th}}) \times 10^{-3})$

Measurements of $|V_{ub}|$

- Proceed along the lines of $|V_{ub}|$: inclusive and exclusive, similar formalism
- Inclusive measurement complicated by charm background:
  - ➡ $\approx 50\times$ larger than signal
  - ➡ Use kinematics to distinguish X_u from X_c
  - ➡ Additional had. uncertainties from kinematic cuts
- Exclusive:
  - ➡ low statistics
    $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.36 \pm 0.09) \times 10^{-4}$
  - ➡ Form factors more difficult to compute

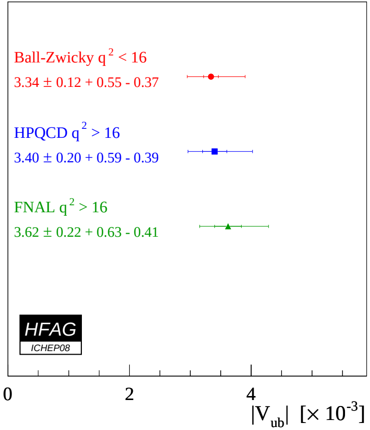
$|V_{ub}|$ summary

Inclusive



$\sim$ 5 theoretical approaches to extract $|V_{ub}|$ from partial decay rates ...

Exclusive, from $B \to \pi \ell \nu$



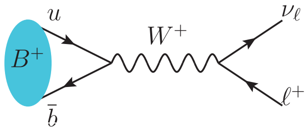
Open issues

- Inclusive $|V_{cb}|$ precision at 2% level
- Many new results on exclusive $|V_{cb}|$ ($B \to D^{(*)}\ell\nu$)
  Precision limited by form factor knowledge
  $|V_{cb}|$ 2σ lower than from inclusive ??

- Inclusive $|V_{ub}|$ precision at 8%
  limited by calculation of theoretical phase space acceptances
  (more than one model on the market)
- Exclusive $|V_{ub}|$ measurements limited by form factor knowledge
  Need more data and progress on theoretical calculations
  Exclusive vs. inclusive $|V_{ub}|$?

$|V_{ub}|$ from purely leptonic decay $B \to \tau\nu$

- $B \to \tau\nu$ first leptonic B decay seen (light leptons strongly suppressed by helicity conservation: $\tau : \mu : e \sim 1 : 0.004 : 10^{-7}$)



- Standard model:

$$\mathcal{B}(B \to \ell\nu)_{\mathrm{SM}} = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$
$$= (1.39 \pm 0.44) \times 10^{-4}$$

using $|V_{ub}| = (44.9 \pm 3.3) \times 10^{-4}$ (incl. $B \to u\ell\nu$)
and $f_B = 0.189 \pm 0.027\,\mathrm{GeV}$ (LQCD)

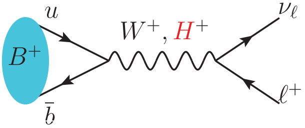
- Charged Higgs $H^\pm$ may contribute to BF:

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} \times (1 - \frac{m_B^2}{m_H^2}\tan^2\beta)^2$$

[W-S Hou, Phys. Rev. D **48**, 2342 (1993)]

$|V_{ub}|$ from purely leptonic decay $B \to \tau\nu$

- $B \to \tau\nu$ first leptonic B decay seen (light leptons strongly suppressed by helicity conservation: $\tau : \mu : e \sim 1 : 0.004 : 10^{-7}$)



- Standard model:

$$\mathcal{B}(B \to \ell\nu)_{\rm SM} = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$
$$= (1.39 \pm 0.44) \times 10^{-4}$$

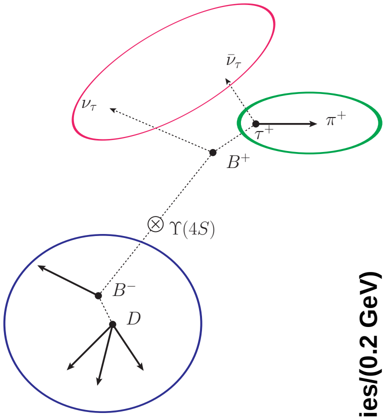
using $|V_{ub}| = (44.9 \pm 3.3) \times 10^{-4}$ (incl. $B \to u\ell\nu$)
and $f_B = 0.189 \pm 0.027\,\mathrm{GeV}$ (LQCD)

- Charged Higgs $H^\pm$ may contribute to BF:

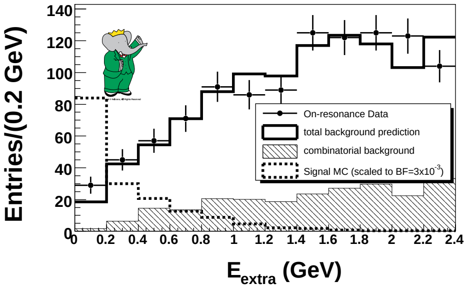
$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\rm SM} \times \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

[W-S Hou, Phys. Rev. D **48**, 2342 (1993)]

Leptonic decay $B^+ \to \tau^+\nu_\tau$



- $B^+ \to \tau^+\nu_\tau$ very challenging due to invisible particles: ≥ 2 neutrinos
- Reconstruct companion B partially (semi-leptonic) or fully (hadronic tag) efficiency typically $\lesssim 1\%$
- Reconstruct observable τ daughters in a few decay modes $(e, \mu, \pi, \ldots)$
- Require nothing else in the detector



$\mathcal{B}(B \to \tau\nu) =$

$$(1.65^{+0.38+0.35}_{-0.37-0.37}) \times 10^{-4}$$

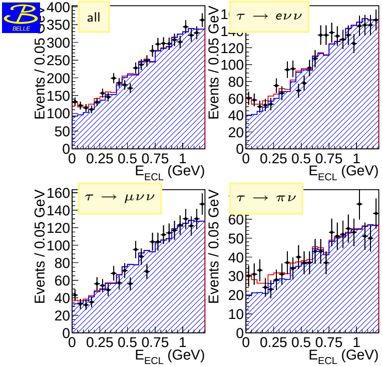
Belle 657M $B\overline{B}$, semileptonic tags

arXiv:0809.3834 [hep-ex]

$$(1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2) \times 10^{-4}$$

BABAR 459M $B\overline{B}$, hadronic tags

Phys. Rev. D **77** 011107 (2008)



combine with *BABAR* semileptonic

$(0.9 \pm 0.6 \pm 0.1) \times 10^{-4}$

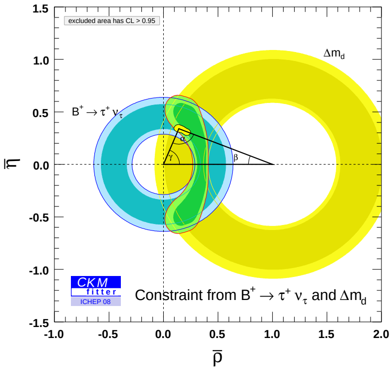
Phys. Rev. D **76**, 0520 (2007)

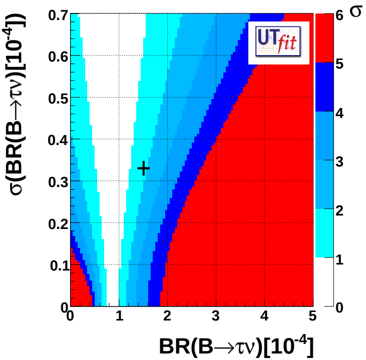
HFAG average, April 2009

$$\boxed{(1.43 \pm 0.37) \times 10^{-4}}$$

$B \to \tau\nu$: UT constraints

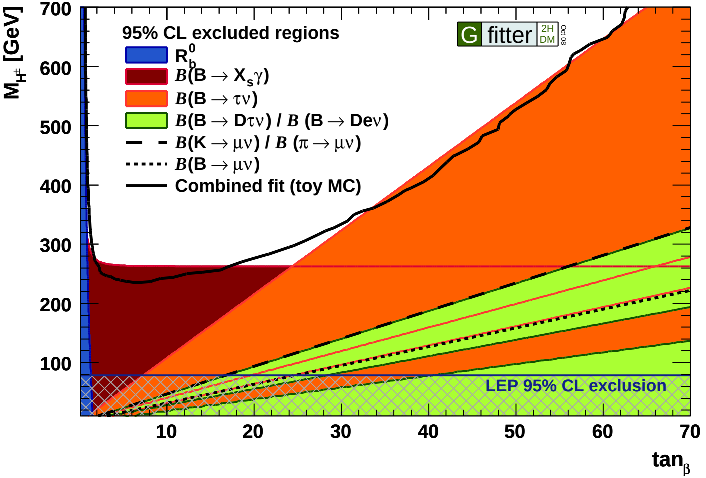
- Use $\mathcal{B}(B \to \tau\nu)$ to constrain $\bar{\rho}^2 + \bar{\eta}^2$ independent of semileptonic V_{ub} assuming f_B is known (10% uncertainty)
- Slight tension ($< 2\sigma$) with UT fit





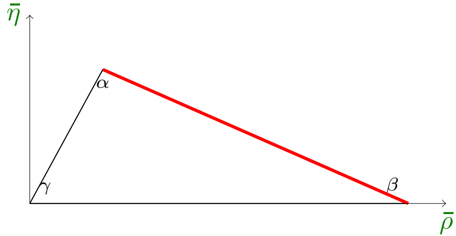
- No $|V_{ub}|$ or lattice input in global UT fit:
  $\mathcal{B}(B \to \tau\nu) = (0.73 \pm 0.12) \times 10^{-4}$ (UT$_{fit}$)

$B \to \tau\nu$: constraints for New Physics



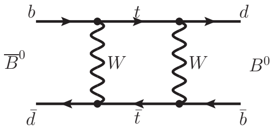
http://gfitter.desy.de

Unitarity triangle side from B mixing (Δm_d, Δm_s)



Constrain side with Δm_d

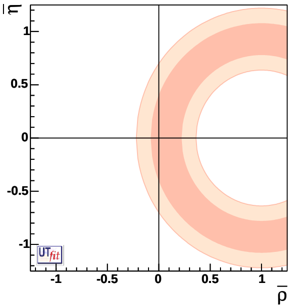
- Δm_d related to B^0–$\overline{B}^0$ oscillations
- In Standard Model:



t box dominates

- Experiment:

$\boxed{\Delta m_d = 0.507 \pm 0.005\, \hbar\text{ps}^{-1}}$



$$\Delta m_d \quad = \quad \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 B_{B_d} |V_{cb}|^2 \lambda^2 ((1-\overline{\rho})^2 + \overline{\eta}^2)$$

$f_{B_d}^2 B_{B_d}$: non-perturbative contribution, uncertainty $\approx 10\%$

$\Delta m_d / \Delta m_s$

- B_s also oscillates ➠ Δm_s
- Precisely measured at Tevatron — CDF, Phys. Rev. Lett. **97** 062003 (2006)

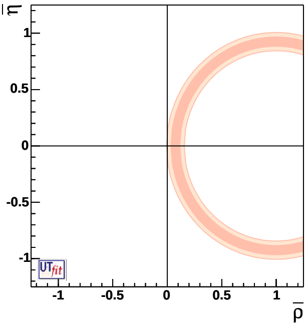
$$\boxed{\Delta m_s = 17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{sys})\,\hbar\mathrm{ps}^{-1}}$$

- $f_{B_s}^2 B_{B_s}$ easier to calculate in LQCD: larger mass of s quark
  ➠ smaller uncertainties than $f_{B_d}^2 B_{B_d}$

- Ratio $\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$ can be calculated even better

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

$$\propto \frac{1}{\xi^2}((1-\overline{\rho})^2 + \overline{\eta}^2)$$



Turning the tables

- Use overconstrained UT to fit for B_K, $f_{B_s}\sqrt{B_{B_s}}$, ξ
- Include angles and $|V_{ub}|/|V_{cb}|$ information in fit, exclude Δm_d, Δm_s, ε_K
- Compare to Lattice QCD Lubitz & Tarantino, arXiv:0807.4605v1 [hep-lat]

	UT	LQCD
B_K	0.75 ± 0.07	0.75 ± 0.07
$f_{B_s}\sqrt{B_{B_s}}$(MeV)	264.7 ± 3.6	270 ± 30
ξ	1.26 ± 0.05	1.21 ± 0.04
f_{B_d}(MeV)	191 ± 13	200 ± 20

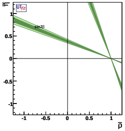
UT*fit*

➠ Remarkable agreement

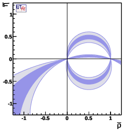
➠ Precision from UT fit comparable to current LQCD

Constraints as of Winter 2009

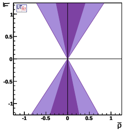
$\sin 2\beta$



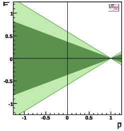
α



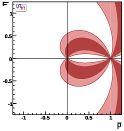
γ



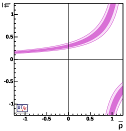
$\cos\beta$



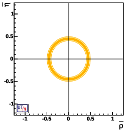
$\sin(2\beta+\gamma)$



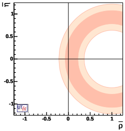
ϵ_K



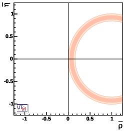
V_{ub}/V_{cb}



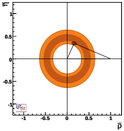
Δm_d



$\Delta m_d/\Delta m_s$

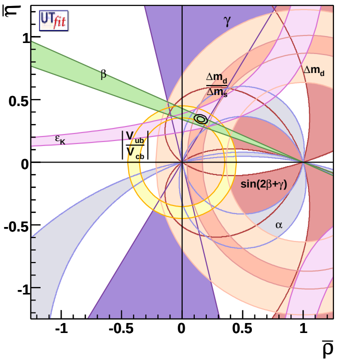


$\mathcal{B}(B\to\tau\nu)$



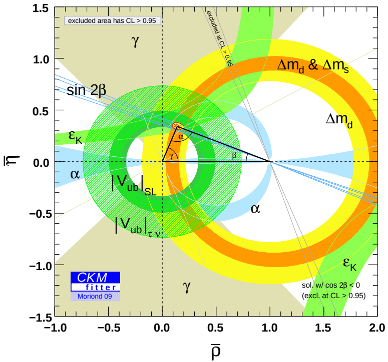
UTfit collaboration (M. Bona *et al.*), http://www.utfit.org

The Unitarity Triangle as of Winter 2009



$$\bar{\rho} = 0.154 \pm 0.022$$
$$\bar{\eta} = 0.342 \pm 0.014$$
$$\sin 2\beta = 0.695 \pm 0.020$$

http://www.utfit.org

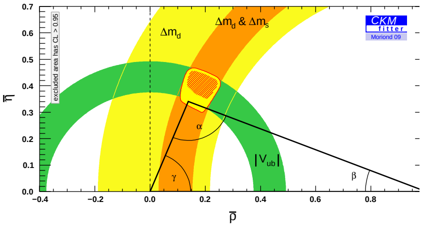


$$\bar{\rho} = 0.139^{+0.025}_{-0.027}$$
$$\bar{\eta} = 0.341^{+0.016}_{-0.015}$$
$$\sin 2\beta = 0.684^{+0.023}_{-0.021}$$

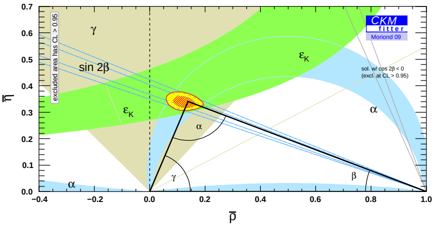
http://ckmfitter.in2p3.fr

CP conserving vs *CP* violating constraints

CP conserving
(sides)



CP violating
(UT angles, *CP*V in K^0)



- Non-degenerate UT from *CP* conserving quantities!
- Some tension between global and sides-only fits but below 3σ

Summary

- *B* Factory programme very successful in establishing CKM theory
- CKM dynamics provides at least lion's share of observed *CP* violation [I. Bigi]
- Works beautifully at current precision
- Some (hints of) tensions exist, but effects of New Physics likely to be subtle
- Good control of QCD essential for precision flavour physics

➠ Need to acquire high precision data and
interpret it with high precision:
Progress in experiment and theory needed

➠ Next generation Flavour factories:
LHCb starting soon
Super Flavour Factory under consideration