CP Violation in $B \to V_L V_L$

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References

This talk is based on the paper [M.B., G. Buchalla, C. Kraus, 2008].

Papers on $B \to VV$, that are also based on QCD factorization, are e.g. [M. Beneke, J. Rohrer, D. Yang, 2007] and [H. Y. Cheng, K. C. Yang, 2008].

Outline

CKM triangle – status of $|V_{ub}|$ and γ

Structure of calculation

Phenomenological analysis

- $|V_{ub}|$ determination and NP constraint
- Controlling power corrections for indirect γ determination
- Standardmodel limit to $B_s \to \phi_L \phi_L$

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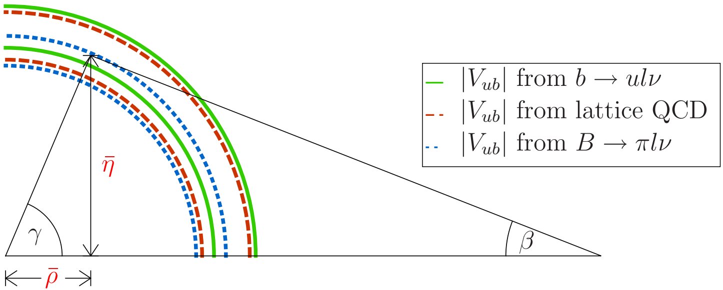
Current status of $|V_{ub}|$ and γ

Inclusive, lattice QCD and exclusive determination of $|V_{ub}|$:



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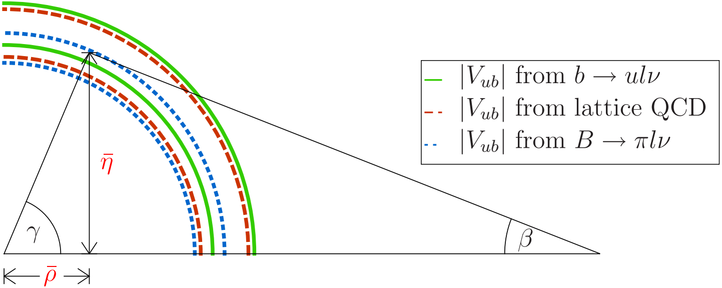
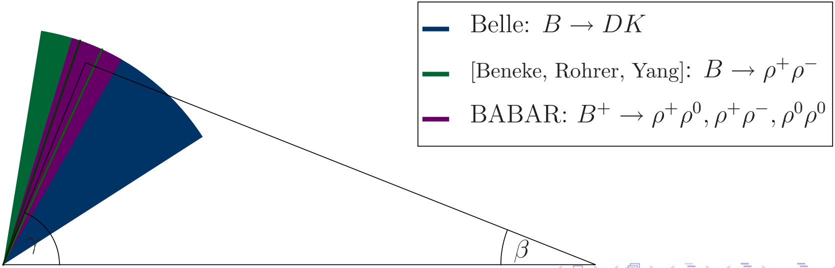


Direct and indirect determination methods of γ:



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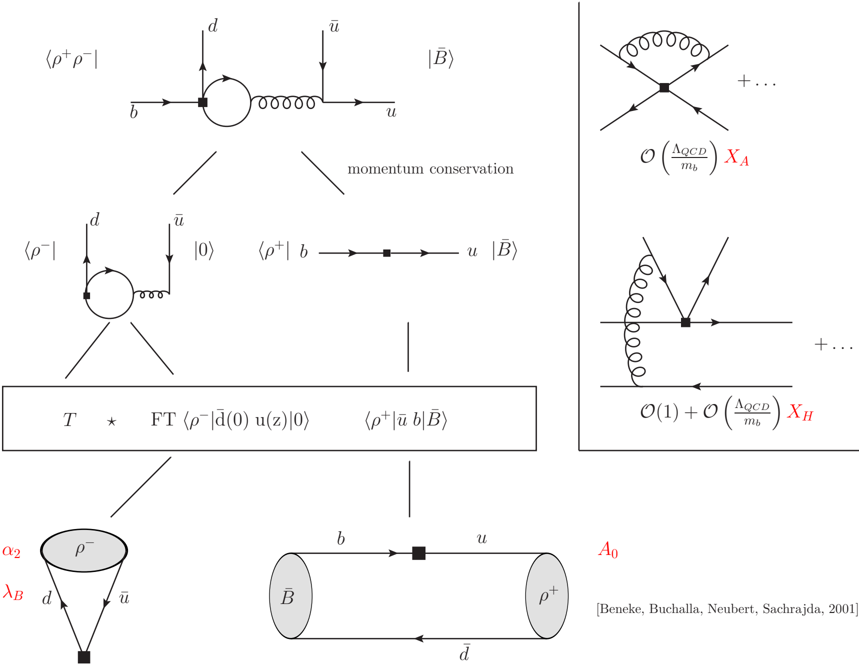
Structure of calculation and sources of uncertainties



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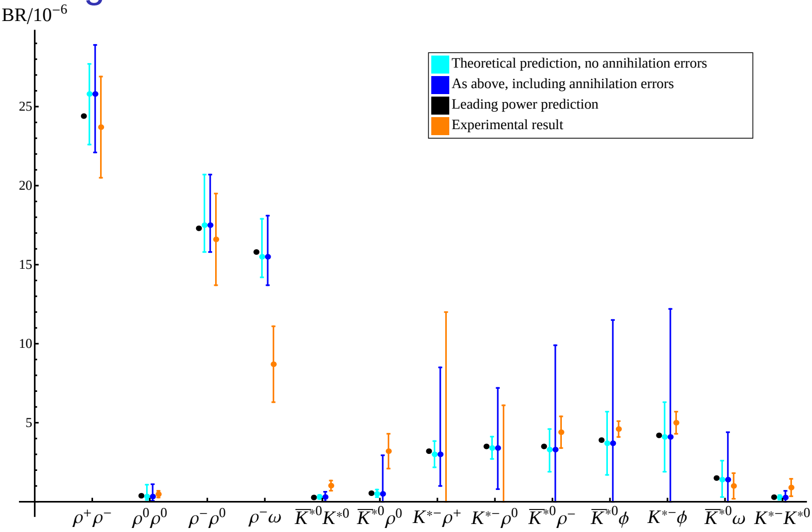
Branching Ratios



Higher twist contributions more effectively suppressed $\mathcal{O}(0.1)$ than for pseudoscalar final states $\mathcal{O}(1)$.

$\rightarrow$ Smaller numerical impact of model dependent terms.

Influence of ω-ϕ mixing

- Mixing of ω and ϕ can be parametrized by:

$$\phi = s\bar{s}\cos\theta + \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}\sin\theta$$

$$\omega = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}\cos\theta - s\bar{s}\sin\theta,$$

  where the mixing angle is $\theta \approx 3.4^\circ$.
- Branching ratios can differ by several orders of magnitude $\rightarrow$ large effects.
  E.g.: $BR(B^- \rightarrow \rho^-\omega) = 15.5 \cdot 10^{-6}$ and $BR(B^- \rightarrow \rho^-\phi) = 6.0 \cdot 10^{-9}$. Variation for $\rho^-\phi$ relative to BR at $\theta = 0$: $\theta = 3.4^\circ$: +49.8 $\theta = 6.8^\circ$: +207.5
- ω-ϕ-error $\mathcal{O}(10)$ bigger than other uncertainties of otherwise clean mode $\bar{B}_d \rightarrow \omega\phi$.
- Modes $B^- \rightarrow \rho^-\omega$, $B^- \rightarrow K^{*-}\phi$ and $\bar{B}_s \rightarrow \phi\phi$ have small effects on BR.

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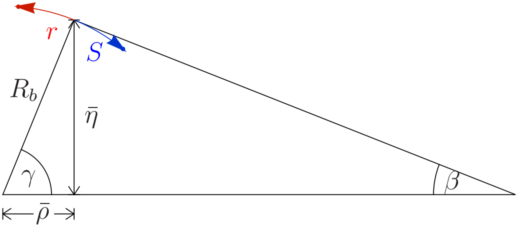
Determination of $|V_{ub}|$ from $\sin 2\beta$ and S_ρ in $B \to \rho_L^+ \rho_L^-$



- The leading order term in r_ρ and S_ρ marks the minimum value for R_b, since $\alpha = 90°$ in that order.
  $\Rightarrow$ First order corrections in r_ρ and S_ρ vanish.

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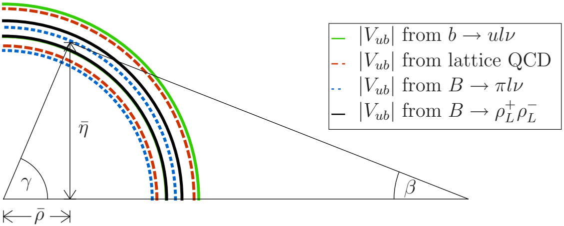


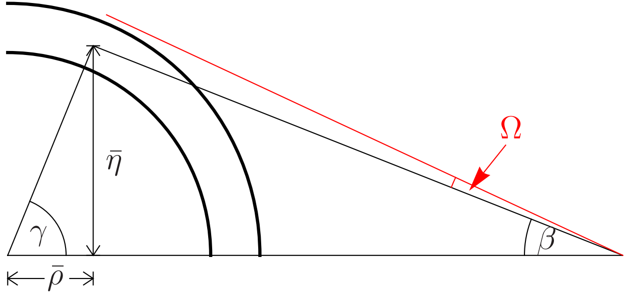
- The leading order term in r_ρ and S_ρ marks the minimum value for R_b, since $\alpha = 90°$ in that order.
  $\Rightarrow$ First order corrections in r_ρ and S_ρ vanish.
- Using $|V_{ub}| = \left|\frac{V_{cb}V_{cd}}{V_{ud}}\right| R_b$ one obtains

$$|V_{ub}| = (3.54^{+0.15}_{-0.15}(\sin 2\beta)^{+0.04}_{-0.01}(r_\rho, S_\rho) \pm 0.06(V_{cb}, V_{us}))\cdot 10^{-3}$$

inclusive: $|V_{ub}| = (3.70 \pm 0.32) \cdot 10^{-3}$ [Neubert]
QCD SR $B \to \pi l \nu$: $|V_{ub}| = (3.36 \pm 0.23) \cdot 10^{-3}$ [Bourrely, Caprini, Lellouch]
and lattice (average): $|V_{ub}| = (3.54 \pm 0.40) \cdot 10^{-3}$ [Lubicz, Tarantino]

Constraint on New Physics phase in $B_d - \bar{B}_d$ mixing

New physics phase Ω in $B_d - \bar{B}_d$ mixing enters $B_d \to J/\psi K_s$ and $B_d \to \rho^+\rho^-$. Measured phase changes to $\sin(2(\beta + \Omega))$.
Change in CKM triangle:



Independent measurement of $|V_{ub}|$ constrains Ω:

$$R_b = \frac{|1 - \tau \tan\Omega|}{\sqrt{1+\tau^2}} \left[1 - \tan\Omega \left(\frac{\tau r_\rho \cos\phi_\rho}{1 - \tau\tan\Omega} + \frac{S_\rho}{2}\right)\right] + \mathcal{O}(r_\rho^2, r_\rho S_\rho, S_\rho^2),$$

where $\tau \equiv \cot\beta \approx 2.5$. Valid for $\Omega < 20^\circ$.

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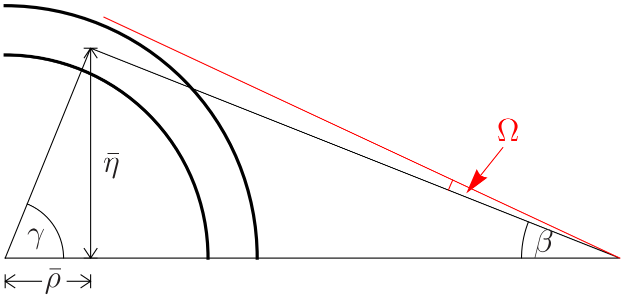

Independent measurement of $|V_{ub}|$ constrains Ω:

$$\Omega = \left(0.0^{-0.9}_{+1.0}(\tau)\,^{+0.2}_{-0.1}(S_\rho)\,^{+0.2}_{-0.1}(r_\rho)\,^{+0.3}_{-0.3}(V_{cb})\,^{-2.5}_{+2.5}(|V_{ub}|)\right)^\circ,$$

using $|V_{ub}|$ from lattice QCD. Valid for $\Omega < 20^\circ$.

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$SU(3)$ relation to all orders in $\frac{\Lambda_{QCD}}{m_b}$ (1)

- $SU(3)$-symmetric final states $\bar{K}_L^{*0} K_L^{*0}$ and $\rho_L^+ \rho_L^-$. Branching fractions of B_d decaying into these final states exhibit V-spin symmetry.

$$b \equiv \frac{B(\bar{B}_d \to \bar{K}_L^{*0} K_L^{*0})}{B(\bar{B} \to \rho_L^+ \rho_L^-)} = \frac{((1-\bar{\rho})^2 + \bar{\eta}^2)\,|\xi|^2\, r_\rho^2}{\bar{\rho}^2 + \bar{\eta}^2 + r_\rho^2 + 2\bar{\rho}\, r_\rho \cos\phi_\rho}$$

plus CKM-suppressed corrections.

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- $SU(3)$-breaking parameter: $\xi \approx 1.28$ (QCD factorization). Used range: $\xi = 1.28 \pm 0.14$.

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  plus CKM-suppressed corrections.
- $SU(3)$-breaking parameter: $\xi \approx 1.28$ (QCD factorization). Used range: $\xi = 1.28 \pm 0.14$.
- Use 4 measured observables: $\cot\beta = 2.54 \pm 0.13$, $S_\rho = -0.05 \pm 0.17$, $C_\rho = -0.06 \pm 0.13$, $b = 0.043 \pm 0.015$ and one predicted parameter ξ to extract: 2 hadronic parameters r_ρ and ϕ_ρ and 2 CKM parameters: $\bar{\eta}$ and $\bar{\rho}$.

Discussion of Corrections to b

Corrections come from the branching ratio for $B_d \to \bar{K}_L^{*0} K_L^{*0}$:

$$B(\bar{B}_d \to \bar{K}_L^{*0} K_L^{*0}) =$$
$$\frac{\tau_{B_d} G_F^2 \, |\lambda_c|^2}{32\pi m_B} \left[f_0 |a_c(K^*)|^2 + 2 f_1 \, \mathrm{Re}\, a_c^*(K^*) \, \Delta(K^*) + f_2 |\Delta(K^*)|^2 \right]$$

f_0, f_1 and f_2 are CKM-factors. f_1 and f_2 are much smaller:

$$f_0 = 0.835^{+0.162}_{-0.125}, \qquad f_1/f_0 = 0.018 \pm 0.086, \qquad f_2/f_0 = 0.161^{+0.042}_{-0.026}$$

In addition suppression of hadronic factors:

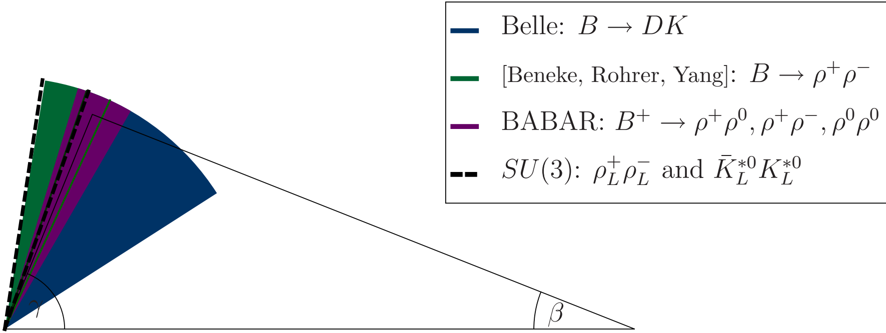
$$\frac{|\Delta(K^*)|}{|a_c(K^*)|} = 0.25^{+0.12}_{-0.10}$$

$\Rightarrow$ Neglect terms multiplying f_1 and f_2.
Relative importance to leading term: 3%.

Result from $SU(3)$ analysis (2)

$$r_\rho = 0.064 \pm 0.012^{-0.006}_{+0.008}(|\xi|)$$

$$\gamma = \left(76.2^{+1.0}_{-1.0}(\cot\beta)^{+4.7}_{-4.9}(S_\rho)^{+0.0}_{-1.6}(C_\rho)^{+1.5}_{-1.8}(b)^{-0.9}_{+1.1}(|\xi|)\right)^\circ$$



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- Error on γ dominated by S_ρ.
- Error from $SU(3)$-factor ξ smaller than from experimental quantities $\cot\beta$, S_ρ, b $\rightarrow$ improvement possible.
- Comparing penguin parameter to value from $B \rightarrow \rho_L^+ \rho_L^-$:

$$r_\rho = 0.038 \pm 0.005^{+0.019}_{-0.026}(X_A)$$

  - Larger, but within errors consistent.
  - Still small, which is basis of analysis.

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CP Violation in $B_s \to \phi_L \phi_L$

$$A_{CP,\phi}(t) = \frac{\Gamma[\bar{B}^0(t) \to \phi_L \phi_L] - \Gamma[B^0(t) \to \phi_L \phi_L]}{\Gamma[\bar{B}^0(t) \to \phi_L \phi_L] + \Gamma[B^0(t) \to \phi_L \phi_L]} = $$
$$= S_\phi \sin(\Delta m t) - C_\phi \cos(\Delta m t)$$

Theoretical prediction of S_ϕ and C_ϕ from QCD-factorization:

$$S_\phi = 2\lambda^2 \eta \,\mathrm{Re} \frac{a_c(\phi) - a_u(\phi)}{a_c(\phi)}, \qquad C_\phi = 2\lambda^2 \eta \,\mathrm{Im} \frac{a_c(\phi) - a_u(\phi)}{a_c(\phi)}$$

$$|a_c(\phi) - a_u(\phi)|/\mathrm{GeV}^3 =$$
$$= 0.057^{+0.007}_{-0.007}(A_0)\,^{-0.008}_{+0.010}(\alpha_2^V)\,^{+0.016}_{-0.015}(m_c)\,^{-0.012}_{+0.021}(\mu)$$

$\lambda = 0.226$ small $\to S_\phi$ and C_ϕ small.

Determination of $|a_c(\phi)|$ from Experiment

$$B(\bar{B}_s \to \phi_L \phi_L) = \frac{\tau_{B_s} G_F^2 \, |\lambda_c'|^2}{64\pi m_{B_s}} \, |a_c(\phi)|^2$$

From that one obtains

$$|a_c(\phi)| = 0.177\,\mathrm{GeV}^3 \left[\frac{B(\bar{B}_s \to \phi_L \phi_L)}{15 \cdot 10^{-6}}\right]^{1/2} \left[\frac{1.53\,\mathrm{ps}}{\tau_{B_s}}\right]^{1/2}$$

Upper limit for S_ϕ and $|C_\phi|$:

$$S_\phi \lesssim 0.02 \qquad |C_\phi| \lesssim 0.02$$

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- Branching ratios will be measured at LHCb: $10fb^{-1} \to \Delta S_{\phi\phi} \approx 0.05$, upgraded LHCb: $100fb^{-1} \to \Delta S_{\phi\phi} \approx 0.01$ to 0.02
- Measurement in excess of these limits constitutes evidence for new physics.

Conclusions

- Precise determination of $|V_{ub}|$ from $B_d \to \rho_L^+ \rho_L^-$ and $\sin 2\beta$.
- Constraint on New Physics phase by independent measurements of $|V_{ub}|$.
- Determination of γ from $B_d \to \rho_L^+ \rho_L^-$ and $SU(3)$-related decay. Provides additional constraint on power corrections. Potential for improvements up to $1^\circ - 2^\circ$ on precision extraction of γ.
- Upper Standard model limit for S_ϕ and $|C_\phi|$ provided.

Thank you very much for your attention!

Backup slides

Future prospects of the determination of $|V_{ub}|$

The uncertainty of $|V_{ub}|$ is dominated by the statistical uncertainty of $\sin 2\beta = 0.681 \pm 0.025$:
$\Delta|V_{ub}| = \pm 0.15 \cdot 10^{-3}$.

- Hadronic uncertainties (S_ρ, r_ρ) are much smaller: $\binom{+0.05}{-0.02} \cdot 10^{-3}$
- LHCb upgrade with $100 fb^{-1}$ promises to measure $\sin 2\beta$ at ± 0.003 to ± 0.01. Potential for $|V_{ub}|$ at value of $\Delta \sin 2\beta = 0.006$:
  $\Delta|V_{ub}| = \pm 0.08 \cdot 10^{-3}$.

Constraint on New Physics phase in $B_d - \bar{B}_d$ mixing (1)

- Assuming a (small) contribution of New Physics in $B_d - \bar{B}_d$ mixing, we measure in $\bar{B}_d \to J/\psi K_s$ the CP violation $S = \sin(2(\beta + \Omega))$.
- Disentangling standard model part:

$$\bar{\rho} = \frac{(1 - \tau\bar{\eta}) - (\tau + \bar{\eta}) \tan\Omega}{1 - \tau \tan\Omega}$$

- Measurement of S_ρ used to eliminate $\bar{\rho}$:

$$\bar{\eta} = \frac{\tau(1 - \tau \tan\Omega)}{1 + \tau^2} + \mathcal{O}(r_\rho, S_\rho)$$

- $\tau = 2.54$ enhances the sensitivity to Ω.

Constraint on New Physics phase in $B_d - \bar{B}_d$ mixing (2)

- We get an expression for $|V_{ub}|$ depending on $(\tau, S_\rho, r_\rho, \phi_\rho, \Omega)$:

$$|V_{ub}| = \frac{|V_{cd} V_{cb}|}{|V_{ud}|} \frac{|1-\tau\tan\Omega|}{\sqrt{1+\tau^2}} \left[1 - \tan\Omega \left(\frac{\tau r_\rho \cos\phi_\rho}{1-\tau\tan\Omega} + \frac{S_\rho}{2} \right)\right] + \mathcal{O}(r_\rho^2, r_\rho S_\rho, S_\rho^2)$$

- $\tan\Omega$ appears already in leading order and is enhanced by τ.
- Using the lattice measurement of $|V_{ub}|$, Ω can be constrained to

$$\Omega = \left(0.0^{-0.9}_{+1.0}(\tau)\,^{+0.2}_{-0.1}(S_\rho)\,^{+0.2}_{-0.1}(r_\rho)\,^{+0.3}_{-0.3}(V_{cb})\,^{-2.5}_{+2.5}(|V_{ub}|)\right)^\circ$$

- The constraint is valid for $|\Omega| \leq 20^\circ$.