A Mixing-Independent Construction of The Unitarity Triangle

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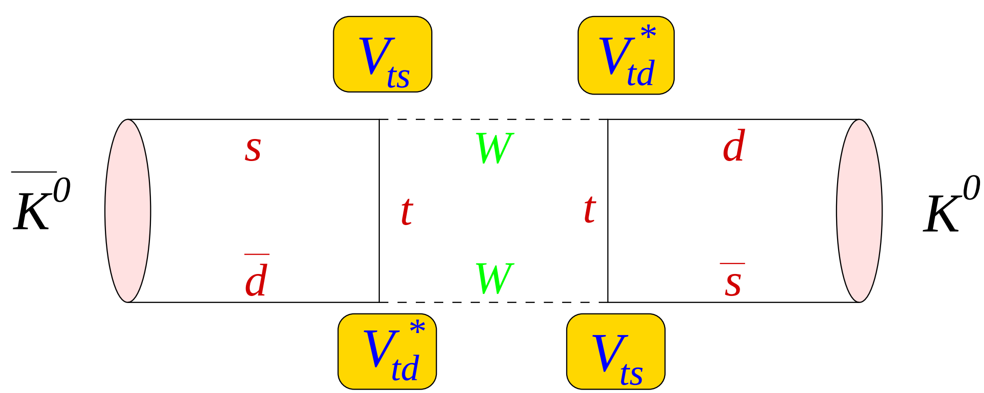
Constraints on the Unitarity Triangle

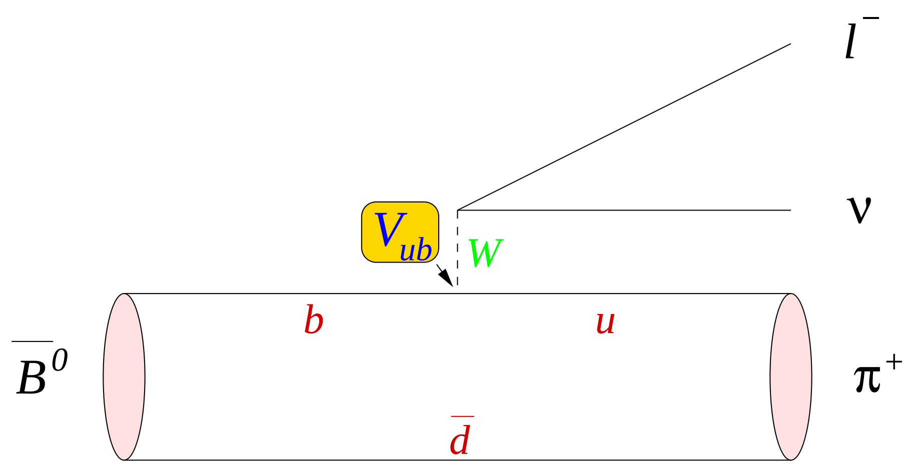
ϵ_K from CP violation in K–$\bar{K}$ mixing:

- due to CP violation, the long-lived strange meson $|K_L\rangle \approx (|K^0\rangle - |\bar{K}^0\rangle)/\sqrt{2}$ is not exactly a CP eigenstate and so can decay into two pions
- ϵ_K is sensitive to Im$[(V_{td}^* V_{ts})^2]$



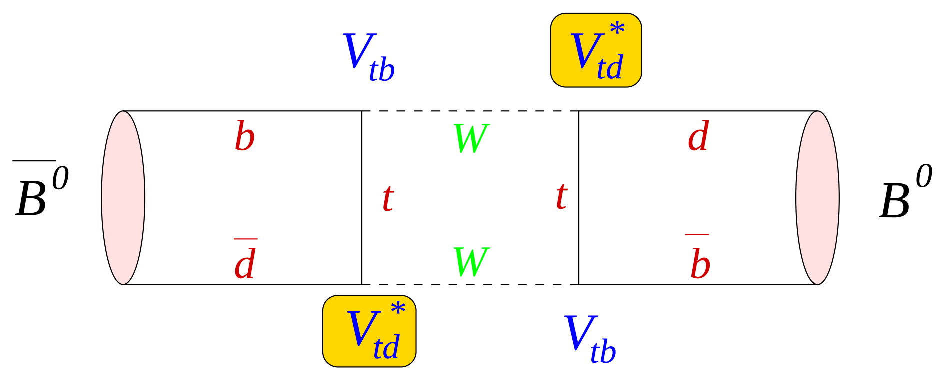
$|V_{ub}/V_{cb}|$ from semileptonic B decays:

- ratio can be measured by comparing semileptonic $b \to ul\nu$ and $b \to cl\nu$ decays



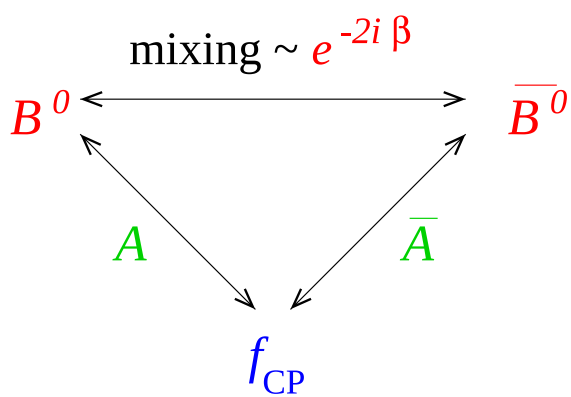
$\Delta m_{d,s}$ from $B_{d,s}$–$\bar{B}_{d,s}$ mixing:

- B–$\bar{B}$ mixing amplitudes are dominated by virtual production of top quarks
- $\Delta m_{d,s}$ is sensitive to $|V_{td,ts}^* V_{tb}|^2$



$\sin 2\beta$ from $B \to J/\psi\, K$ decays:

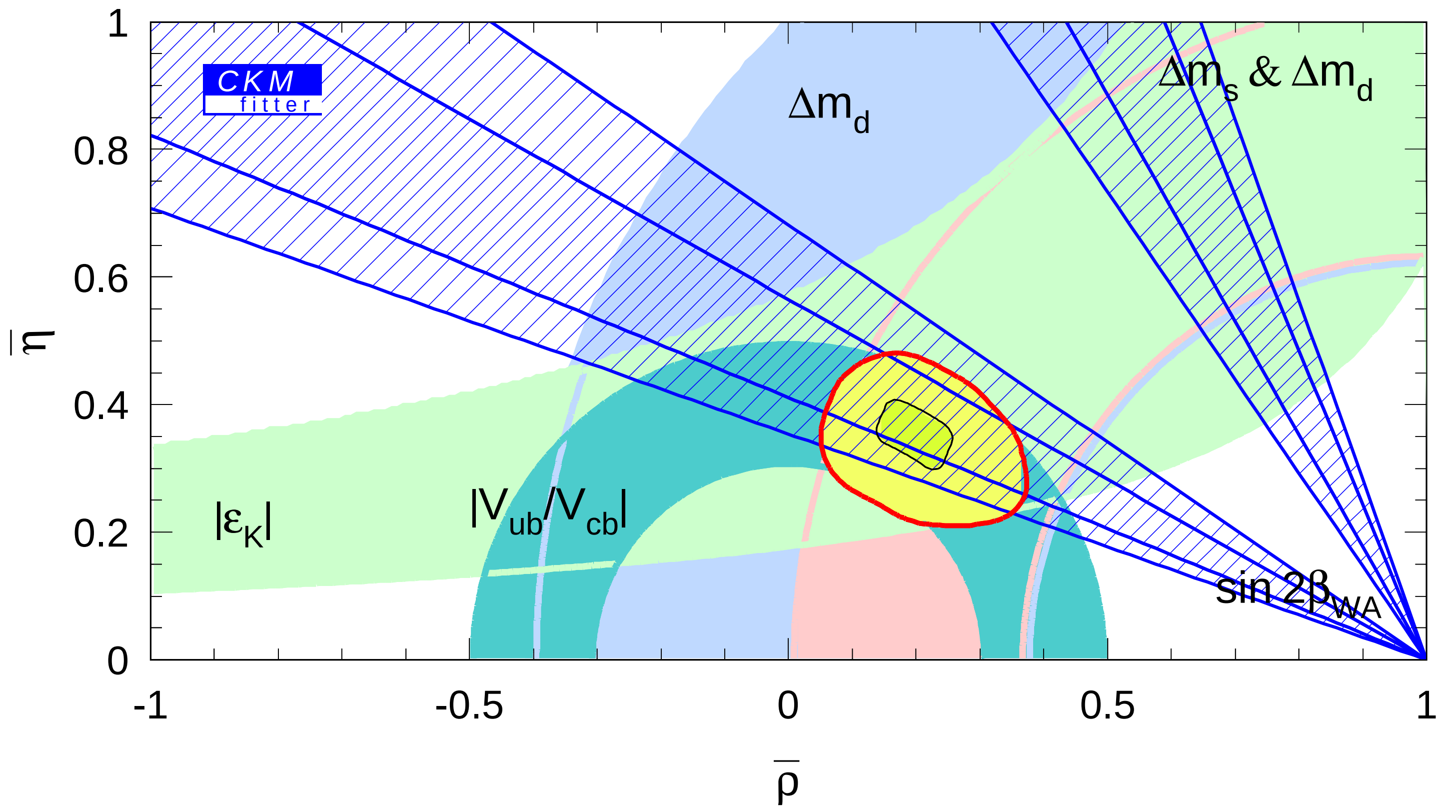
- use amplitude interference in B decays into a CP eigenstate $f_{\rm CP}$:



denote: $\lambda = e^{-2i\beta}\,\frac{\bar{A}}{A}$

- CP asymmetry: $A_{\rm CP}(t) = -\sin 2\beta\,\sin(\Delta m_d t)$

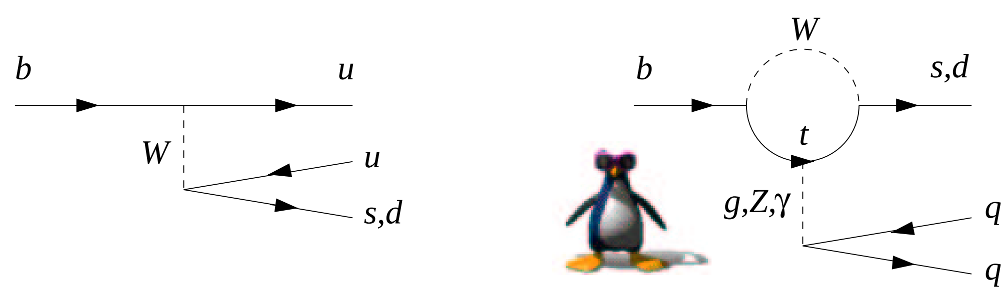
Summary of Constraints (2002)



- has established the existence of a CP-violating phase in the top sector (Im$(V_{td}) \neq 0$)
- with exception of $|V_{ub}|$, all other constraints are sensitive to potential New Physics in B–$\bar{B}$ or K–$\bar{K}$ mixing
- except for $\sin 2\beta$, individual constraints have large theoretical uncertainties

Rare Hadronic B Decays

- after obtaining a consistent picture of CP violation in the top sector, the next step must be to explore the complex phase $\gamma = \arg(V_{ub}^*)$ in the bottom sector
- γ can be probed via the tree–penguin interference in rare hadronic decays $B \to \pi K, \pi\pi, \ldots$



- information from CP asymmetries ($\sim \sin\gamma$) and CP-averaged branching fractions ($\sim \cos\gamma$)

The Challenge

QCD, the marvellous theory of the strong interactions, has a split personality. It explains both "hard" and "soft" phenomena, the softer ones being the hardest.

(Y. Dokshitzer)

high energies $\Leftrightarrow$ weak coupling (asymptotic freedom)

low energies $\Leftrightarrow$ strong coupling (confinement)

Different strategies exist for determining the relevant hadronic matrix elements:

Hadronic Matrix Elements

General Amplitude Parameterizations:
- Isospin and SU(3) Flavor Symmetry
- Amplitude Triangles, Quadrangles, ...
- Maximal Use of Measurements

QCD-Based Calculations:
- QCD Factorization (HQL)
- pQCD, QCD Sum Rules, Lattice
- Maximal Use of Theory (ambitious!)

various combinations

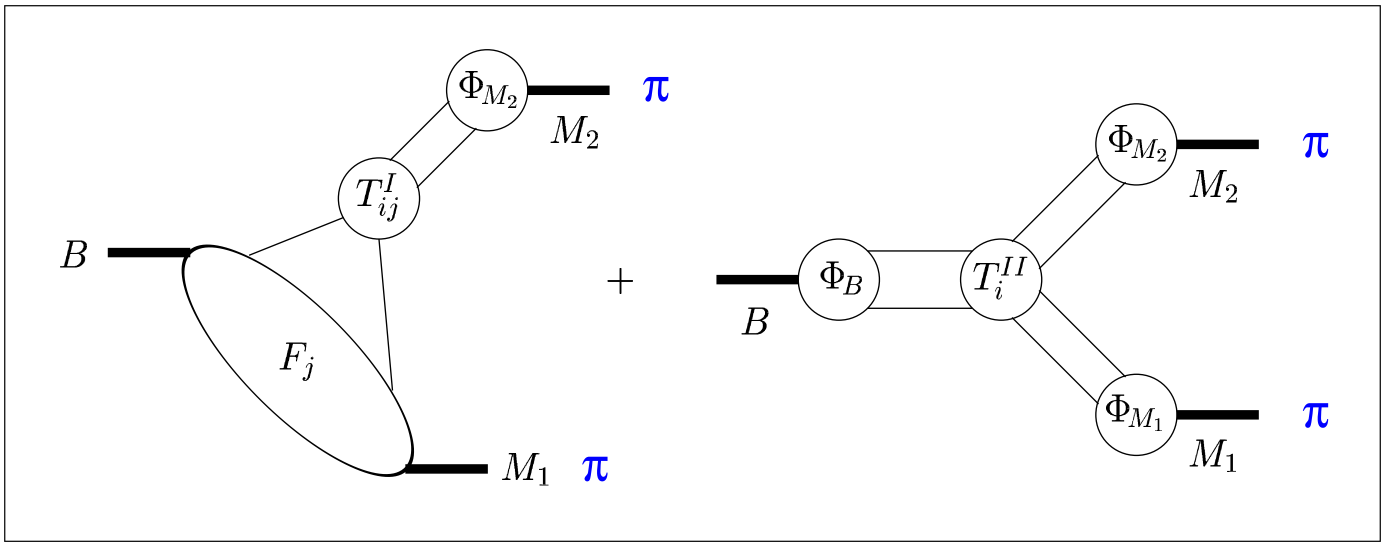
QCD Factorization
+
Fleischer-Mannel Bound
Neubert-Rosner Bound
Bounds -> Determinations

QCD Factorization
+
Phenom. Penguin Amplitude
Charming Penguins, ...

QCD Factorization Approach

Factorization formula for hadronic B-meson decays:

[Beneke, Buchalla, MN, Sachrajda]



$\Rightarrow$ provides a model-independent description of hadronic B-decay amplitudes (including their phases) in the heavy-quark limit

Crucial Tests

- magnitude of tree amplitude:
  Br$(B^\pm \to \pi^\pm\pi^0) = (5.7 \pm 0.9)\cdot 10^{-6}$ compares well with prediction $5.3\,^{+0.8}_{-0.4}\,$(pars.)$\,\pm\, 0.3\,$(power)
- magnitude of tree-to-penguin ratio:

$$\epsilon_{\rm exp} = \tan\theta_C\,\frac{f_K}{f_\pi}\left[\frac{2\text{Br}(B^\pm\to\pi^\pm\pi^0)}{\text{Br}(B^\pm\to\pi^\pm K^0)}\right]^{\frac{1}{2}} = 0.22 \pm 0.02$$

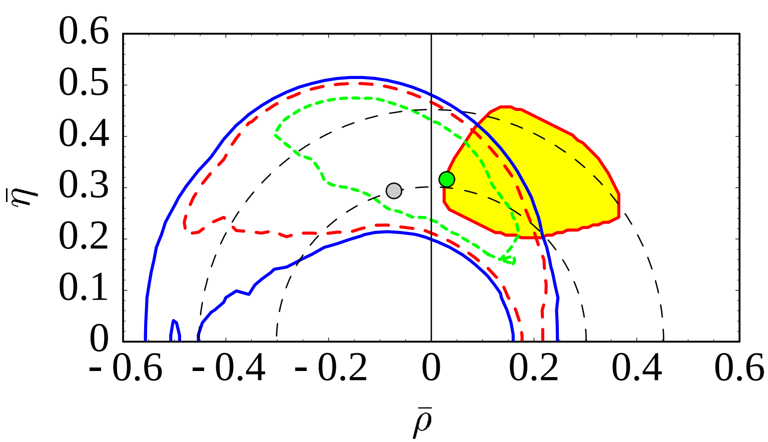
  agrees with prediction

$$0.23 \pm 0.04\,(\text{pars.}) \pm 0.04\,(\text{power}) \pm 0.05\,(V_{ub})$$

- direct CP asymmetries are predicted (and found) to be small

Establishing CPV in the Bottom Sector

- ratios of CP-averaged $B \to \pi K, \pi\pi$ rates exhibit strong dependence on γ and $|V_{ub}|$
- derive constraints on $\bar{\rho}$ and $\bar{\eta}$ from a global analysis of the data in the context of QCD factorization: [BBNS]



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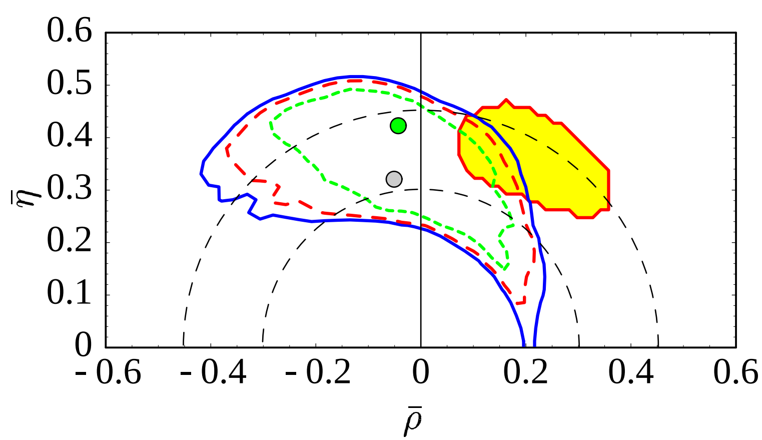


summer 2002

- combination of results from rare hadronic B decays with the $|V_{ub}|$ measurement in semileptonic decays excludes $\bar{\eta} = 0$ and so establishes the existence of a CP phase in the bottom sector of the CKM matrix
- allowed regions obtained from the fit to charmless hadronic decays are compatible with the standard fit, but tend to favor larger γ values
- same trend seen in an analysis that does not rely on QCD factorization but instead employs general amplitude parameterizations and flavor symmetries

  [Fleischer, Matias]

Origins of a Possible Discrepancy?

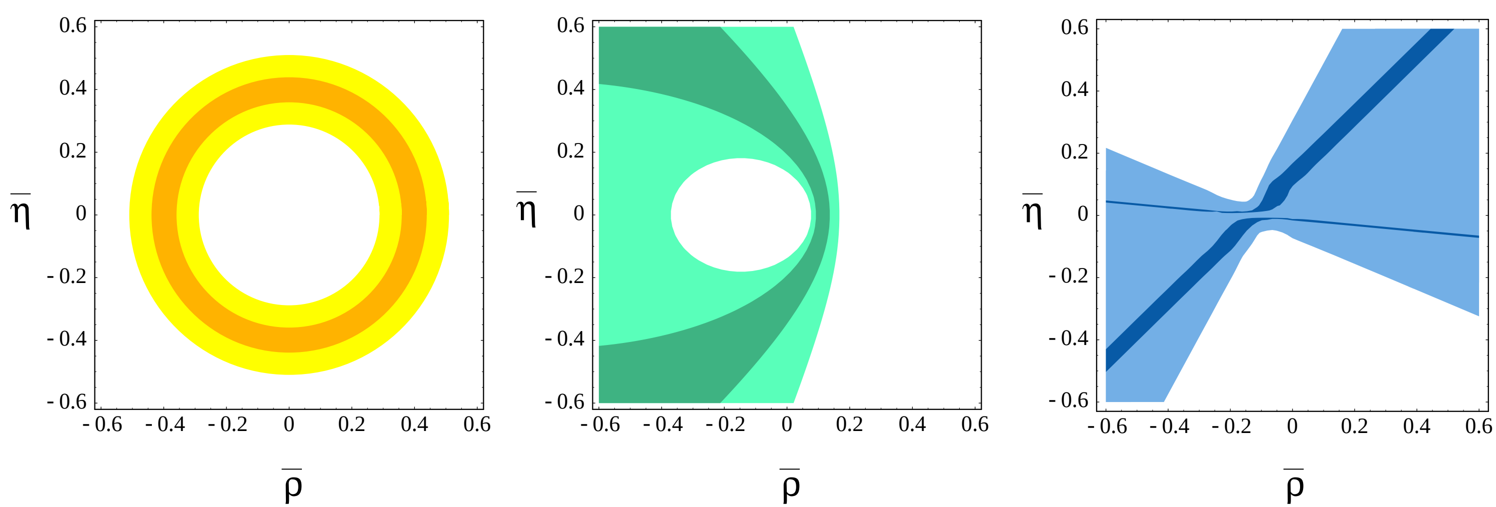
- errors in lattice calculations of matrix elements for B_d–$\bar{B}_d$ and B_s–$\bar{B}_s$ mixing may have been underestimated [Kronfeld, Ryan]
- more exciting: New Physics interpretations!
- New Physics in B_s–$\bar{B}_s$ mixing $\Rightarrow$ check at Tevatron
- New Physics in B_d–$\bar{B}_d$ mixing
- New Physics in $b \to s$ or $b \to d$ FCNC transitions (e.g. from penguin and box graphs with exchange of new heavy particles)
  $\Rightarrow$ clean signal would be a difference in the time-dependent CP asymmetries in $B \to \phi K_S$ and $B \to J/\psi\, K_S$ decays

The Future: “CP-b Triangle”

- if trend toward larger γ values persists, one will want to check compatibility with the standard analysis using measurements whose interpretation is theoretically “clean”
- propose a novel construction of the unitarity triangle which is over-determined, insensitive to potential New Physics effects in B–$\bar{B}$ or K–$\bar{K}$ mixing, and affected by smaller theoretical uncertainties than the standard analysis
- feasible with existing data

Ingredients

- $|V_{ub}/V_{cb}|$ extracted from semileptonic B decays
- ratio of the CP-averaged $B^\pm \to (\pi K)^\pm$ branching fractions (generalized Neubert–Rosner method)
- time-dependent CP asymmetry $S_{\pi\pi} = \sin 2\alpha_{\rm eff}$ in $B \to \pi^+\pi^-$ decays (analysed using QCD factorization and $\sin 2\beta$ measurement)



I. Comments on $|V_{ub}|$

- important recent developments concerning power corrections to the universal shape function connecting Fermi-motion effects in $B \to X_s \gamma$ and $B \to X_u \, l \, \nu$ decays [Bauer, Luke, Mannel; Leibovich, Ligeti, Wise; MN]
- corrections can be included into weight function connecting, e.g., the photon spectrum to the lepton spectrum:

$$F_u(E_0) = \Bigg(1 + \underbrace{\frac{2\Lambda_{\rm SL}(E_0)}{m_b}}_{\text{residual cor.}}\Bigg) \int\limits_{E_0}^{M_B/2} dE_\gamma \, w(E_\gamma, E_0) \, S(E_\gamma)$$

weight function:

$$w(E_\gamma, E_0) = 2\left(1 - \frac{E_0}{E_\gamma}\right)\left\{1 + \frac{\alpha_s(\mu)}{\pi}\, g(E_0/E_\gamma)\right\} - \frac{8\lambda_2}{m_b^2}$$

E_0 [GeV]	NLO pert.	$1/m_b$	total	residual error
2.0	0.313 ± 0.014	-0.040 ± 0.006	0.273 ± 0.015	± 0.003
2.1	0.228 ± 0.010	-0.037 ± 0.006	0.191 ± 0.011	± 0.005
2.2	0.150 ± 0.006	-0.033 ± 0.005	0.117 ± 0.008	± 0.006
2.3	0.083 ± 0.004	-0.026 ± 0.004	0.057 ± 0.006	± 0.008

$\Rightarrow$ method used in a recent CLEO analysis (2002), giving $|V_{ub}| = (4.1 \pm 0.6_{\rm exp} \pm 0.3_{\rm th}) \times 10^{-3}$

Is shape-function sensitivity good or bad?

- often argued that one should avoid sensitivity to Fermi motion using a cut on the lepton invariant mass (“q^2 cut”), and that the region of phase space with low hadronic mass *and* energy is theoretically favored over that with low mass but large energy

  [Bauer, Ligeti, Luke]

- however, this argument ignores the problem of quark–hadron duality violations! [Bigi, Uraltsev]

- usually argue that duality holds, since an inclusive measurement includes a large number of hadronic final states with large mass and/or energy $M_H, E_H \gg \Lambda$ (necessity of having a hard scale!)
- any cut that eliminates the charm background restrict the invariant hadronic mass $M < m_D \sim (\Lambda m_B)^{1/2}$, but in principle still allows large energy $E_H \sim m_B$
- shape function effects result from the region where $\Lambda E_H / M_H^2 \sim 1$, corresponding to large E_H
- $\Rightarrow$ smearing provided by Fermi motion is crucial for restoring quark–hadron duality, and so is a good feature!

II. Comments on generalized NR method

- without recourse to factorization, measurement of

$$R_* = \frac{\text{Br}(B^\pm \to \pi^\pm K^0)}{2\text{Br}(B^\pm \to \pi^0 K^\pm)} = 0.71 \pm 0.10$$

  and of the tree-to-penguin ratio $\epsilon_{\rm exp} = 0.22 \pm 0.02$ provide a bound on $\cos\gamma$, which can be turned into a determination of $\cos\gamma$ when information about the relevant strong phase $\phi_{\pi^0 K^-}$ is available

- QCD predicts that

$$\cos\phi_{\pi^0 K^-} = 1 - O[\alpha_s(m_b)^2, (\Lambda/m_b)^2, \alpha_s(m_b)\,\Lambda/m_b]$$

  equals 1 in the heavy-quark limit up to second-order corrections

- data (!) can be used to place bounds on strong phases:

$$A_{\rm CP}(\pi^+K^-) = -0.05 \pm 0.05 \quad \Rightarrow \quad \phi_{\pi^+K^-} = (8 \pm 10)^\circ$$

$\phi_{\pi^0K^-} \simeq \phi_{\pi^+K^-}$ to good approximation [Gronau, Rosner]
better: use precision measurement of $A_{\rm CP}(\pi^0K^-)$ to constrain $\phi_{\pi^0K^-}$ directly

- $\Rightarrow$ safe to assume that $\cos\phi_{\pi^0K^-} > 0.8$

III. Comments on $S_{\pi\pi}$ theory

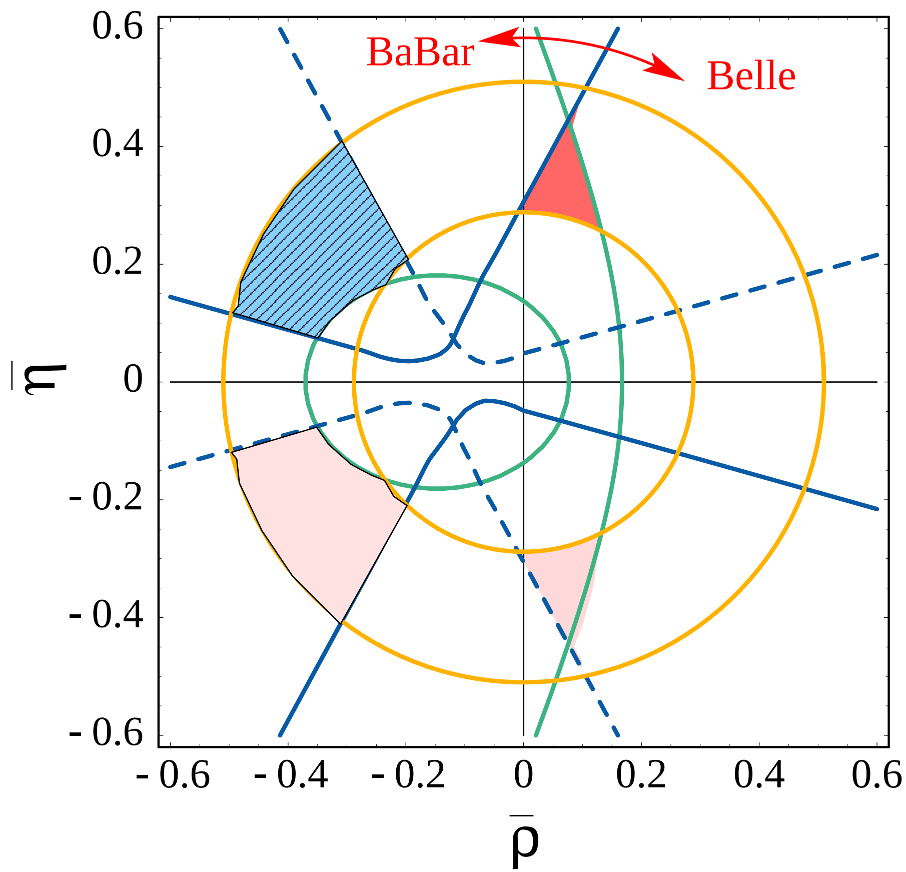
General formula ($\phi_d = 2\beta$ in SM):

$$S_{\pi\pi} = \frac{2\,\text{Im}\lambda_{\pi\pi}}{1 + |\lambda_{\pi\pi}|^2} \quad \text{with} \quad \lambda_{\pi\pi} = e^{-i\phi_d}\,\frac{e^{-i\gamma} + (P/T)_{\pi\pi}}{e^{+i\gamma} + (P/T)_{\pi\pi}}$$

- trick to get insensitive to New Physics in mixing is to use $e^{-i\phi_d} = \pm(1 - s_{\rm exp}^2)^{1/2} - i s_{\rm exp}$ with $s_{\rm exp} = (\sin 2\beta)_{\rm exp}$
- this turns circles in $(\bar\rho, \bar\eta)$ plane into straight lines, which intersect $|V_{ub}|$ circles at (almost) 90° angles
- hadronic uncertainties (from QCD factorization) are large in α, but small when displayed as bands in the $(\bar\rho, \bar\eta)$ plane (and that is what counts!)

Resulting CP-b Triangle

Combine three constraints and construct the resulting allowed regions for the apex of the unitarity triangle:



- if we use that ϵ_K requires positive value of $\bar{\eta}$, only two solutions in the upper half-plane remain
- one of these lies close to the standard fit (though once again somewhat larger γ values are preferred, in particular by the BaBar $S_{\pi\pi}$ result)
- a second allowed region, consistent with the constraints from ϵ_K and charmless hadronic decays, is incompatible with the constraints from $\sin 2\beta$ and $\Delta m_s/\Delta m_d$
  $\Rightarrow$ would require a significant New Physics contribution to B–$\bar{B}$ mixing

Summary

- it is time to move beyond $\sin 2\beta$
- many alternative methods exist that provide powerful constraints on the unitarity triangle
- rare hadronic decays still favor larger γ values than the standard analysis of the unitarity triangle
- construction of the CP-b triangle reinforces this trend, but with smaller theoretical uncertainties than previous methods (large γ favored by R_* and $S_{\pi\pi}^{\rm BaBar}$)
- if this discrepancy is real, it may imply that (after all) New Physics is just around the corner!