Heavy-Quark Physics

Lecture 3: QCD Factorization and "α"

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QCD Factorization

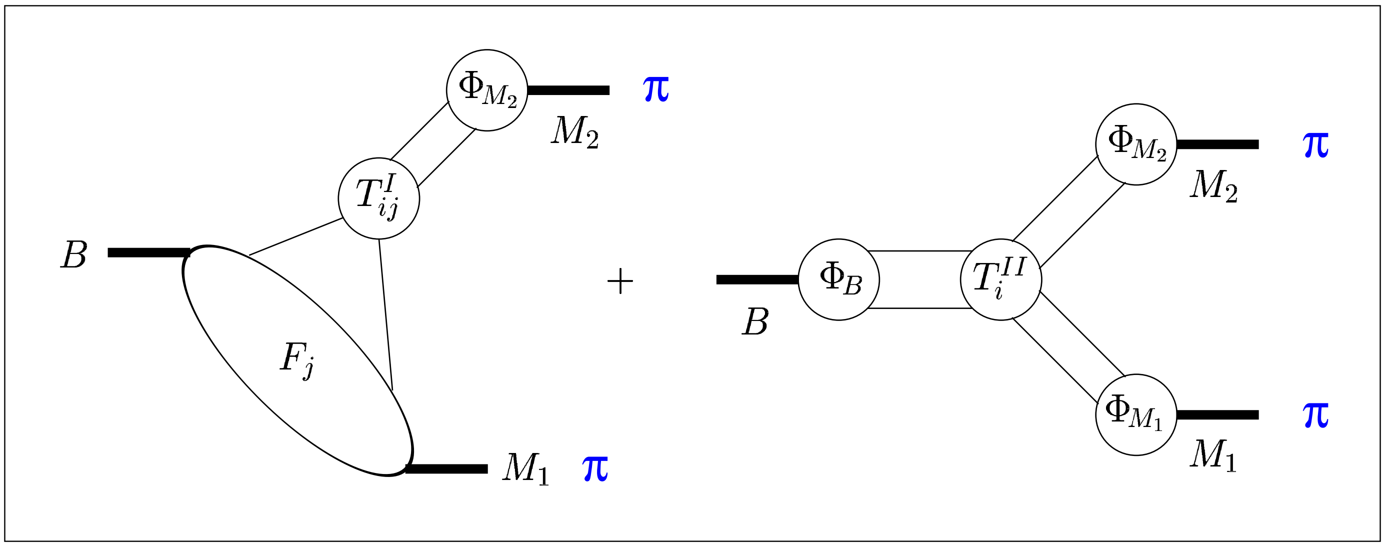
Hadronic weak decays simplify greatly in the heavy-quark limit $m_b \gg \Lambda_{\rm QCD}$

- fast-moving light meson produced by a point-like source decouples from soft QCD interactions (color transparency)
- systematic QCD treatment $\Rightarrow$ QCD factorization
- rigorous results in the heavy-quark limit, valid to all orders of perturbation theory
- dominant power corrections are included in phenomenological analyses

QCD Factorization Approach

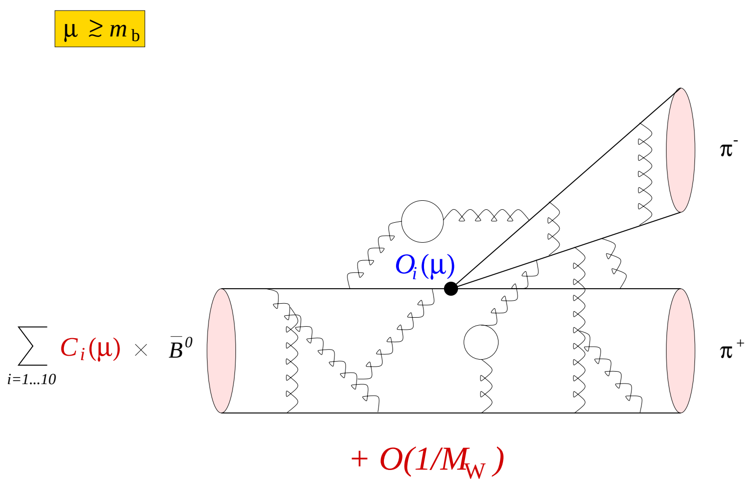
Factorization formula for hadronic B-meson decays:

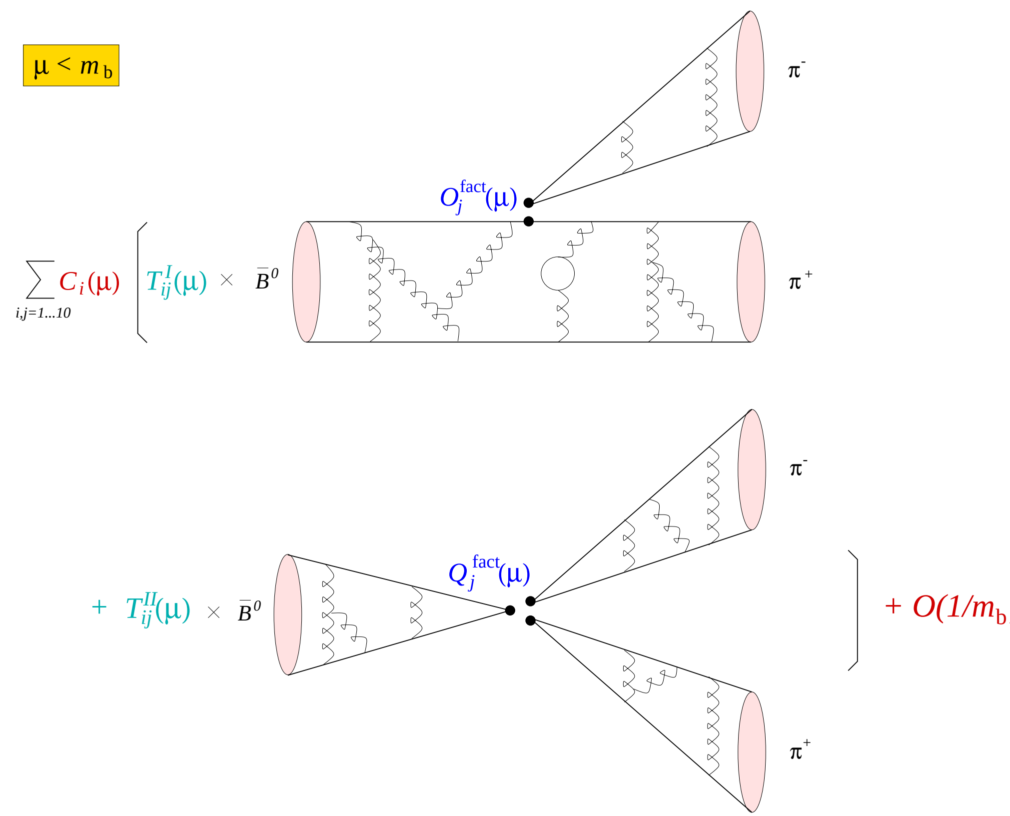
[Beneke, Buchalla, MN, Sachrajda]



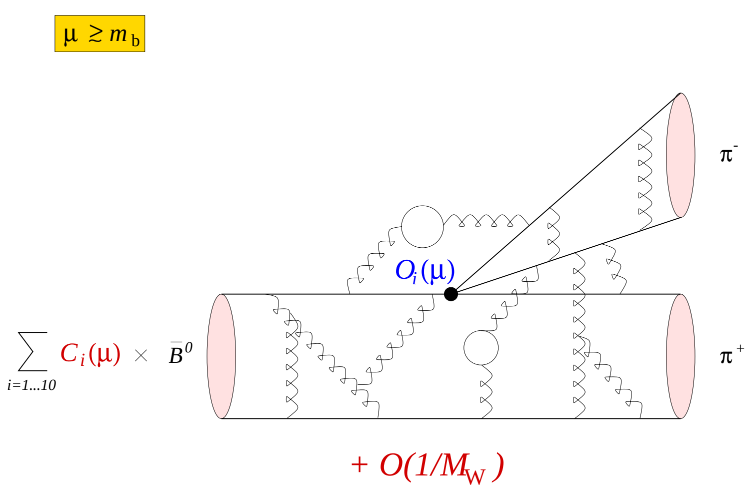
$\Rightarrow$ provides a model-independent description of hadronic B-decay amplitudes (including their phases) in the heavy-quark limit

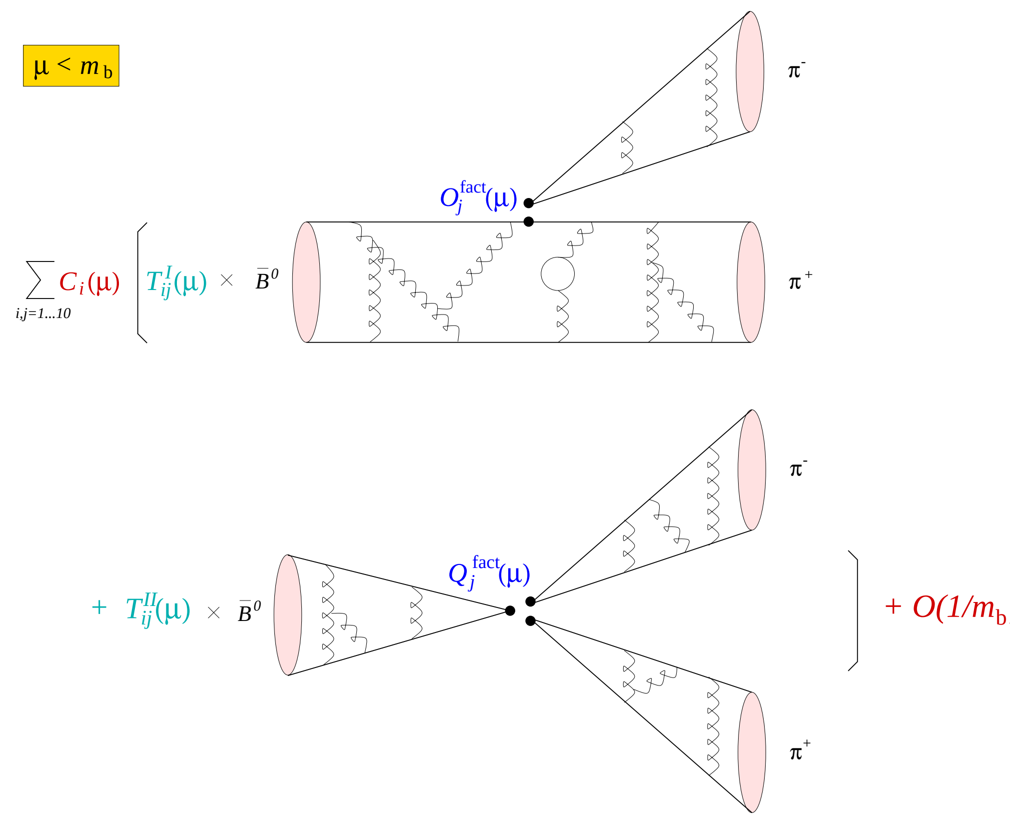
Hard gluon effects with $\mu \gg m_b$ can be calculated and factorized into the Wilson coefficients $C_i(\mu)$ of an effective weak Hamiltonian





Hard gluon effects with $\mu \sim m_b$ can be calculated and factorized into the hard-scattering kernels $T_{ij}(\mu)$ of the factorization formula





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- QCD factorization makes testable predictions
- data will teach us about importance of power-suppressed effects

Factorization in $\bar{B}^0 \to D^{(*)+} L^-$

Simplest application of the factorization formula leads to the quasi-universal prediction:

$$|a_1^{D^{(*)}L}| = 1.05 \pm 0.02 + O(\Lambda_{\rm QCD}/m_b)$$

Experimental determination (Bjorken ratio):

$$\frac{\Gamma(\bar{B}^0 \to D^{*+} L^-)}{d\Gamma(\bar{B}^0 \to D^{*+} l^- \nu)/dq^2 \big|_{m_L^2}} = 6\pi^2 |V_{ud}|^2 f_L^2\, |a_1^{D^* L}|^2$$

Results (CLEO):

$$|a_1^{D^*\pi}| = 1.08 \pm 0.07, \quad |a_1^{D^*\rho}| = 1.09 \pm 0.10, \quad |a_1^{D^* a_1}| = 1.08 \pm 0.11$$

- good agreement within errors, indicating that power corrections are under control

Factorization in $B \to \pi K, \pi\pi$

- factorization in decays $B \to$ two light mesons can be probed using $B^\pm \to \pi^\pm \pi^0$ ($\simeq$ pure tree) and $B^\pm \to \pi^\pm K^0$ ($\simeq$ pure penguin), which have negligible amplitude interference
- crucial properties:
  - magnitude of tree amplitude
  - magnitude of T/P ratio
  - strong phase of T/P ratio
- once these tests are conclusive, factorization can be used to constrain the unitarity triangle

Magnitude of the Tree Amplitude

Absolute prediction for $B^\pm \to \pi^\pm \pi^0$ branching ratio:

$$\text{Br}(B^\pm \to \pi^\pm \pi^0) = \left[5.6\,^{+0.8}_{-0.4}\,(\text{pars.}) \pm 0.3\,(\text{power})\right] \cdot 10^{-6} \times \left[\frac{|V_{ub}|}{0.0037}\,\frac{F_0^{B\to\pi}(0)}{0.28}\right]^2$$

$$\text{Exp.:}\quad (5.54 \pm 0.89) \times 10^{-6}$$

Sensitivity to semileptonic form factor and $|V_{ub}|$ can be eliminated in the ratio:

$$\frac{\Gamma(B^\pm \to \pi^\pm \pi^0)}{d\Gamma(\bar{B}^0 \to \pi^+ l^- \bar{\nu})/dq^2|_{q^2=0}} = 3\pi^2 f_\pi^2 \underbrace{|a_1^{(\pi\pi)} + a_2^{(\pi\pi)}|^2}_{1.33\,^{+0.20}_{-0.11}\,(\text{pars.}) \pm 0.07\,(\text{power})}$$

Magnitude and Phase of the T/P Ratio

Tree-to-penguin ratio can be measured via:

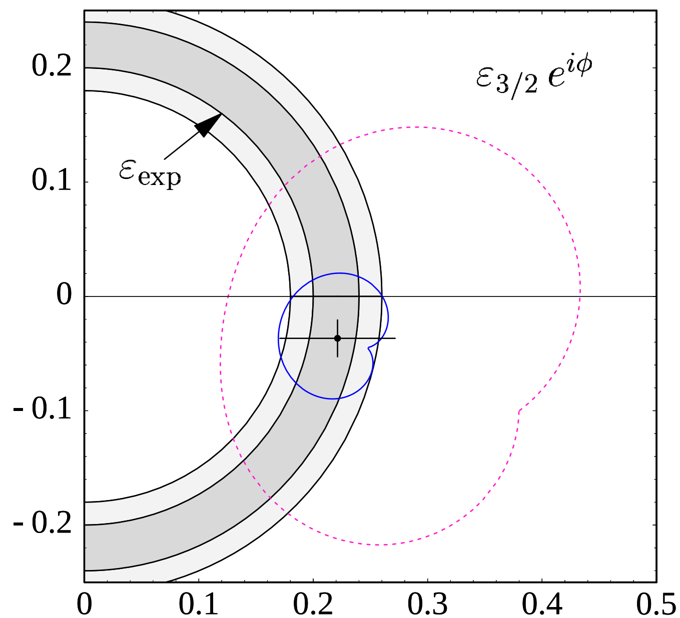
$$\varepsilon_{\rm exp} = \left|\frac{T}{P}\right| = \tan\theta_C \, \frac{f_K}{f_\pi} \left[\frac{2\text{Br}(B^\pm \to \pi^\pm \pi^0)}{\text{Br}(B^\pm \to \pi^\pm K^0)}\right]^{\frac{1}{2}} = 0.215 \pm 0.020$$

- independent of form factors, but $\propto |V_{ub}/V_{cb}|$
- agrees well with theoretical prediction:

$$\varepsilon_{\rm th} = 0.22 \pm 0.04 \,(\text{pars.}) \pm 0.04 \,(\text{power}) \pm 0.05 \,(V_{ub})$$

- strong indication that weak annihilation contributions are reasonably estimated!

Direct comparison with data:



- excellent agreement (solid: $\rho_A = 1$, dashed: $\rho_A = 2$)
- larger values of ρ_A would require extreme fine-tuning!

QCD factorization predicts that (most) strong phases are parametrically suppressed:

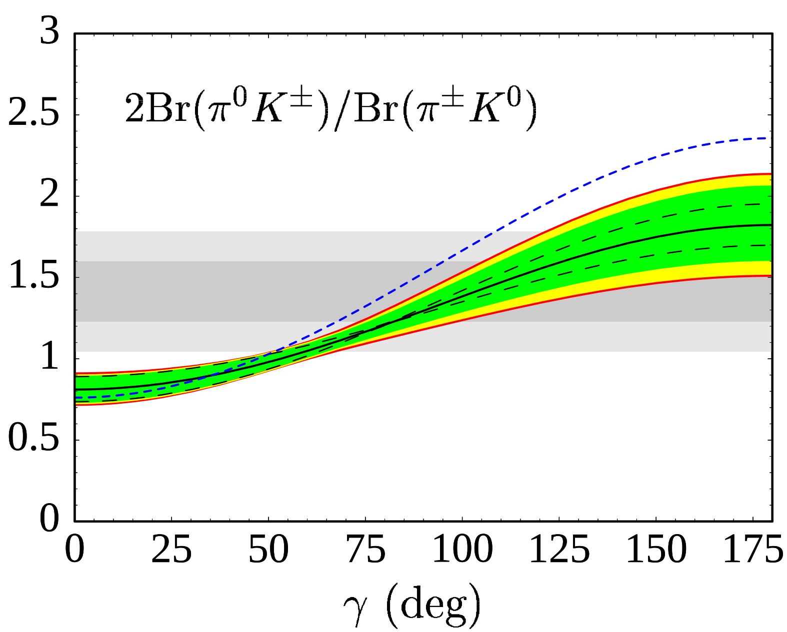
$$\sin\phi_{\rm st} = O\left[\alpha_s(m_b);\,\frac{\Lambda_{\rm QCD}}{m_b}\right] \Rightarrow$$ small direct CP asymmetries

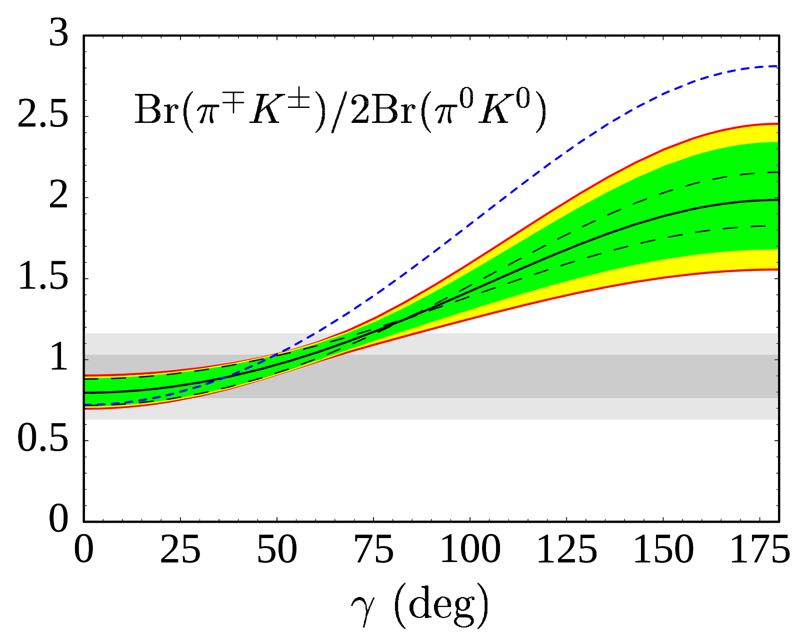
	Experiment (CLEO, BaBar, Belle)	Theory BBNS	Keum, Li, Sanda	Ciuchini et al.
$A_{\rm CP}(\pi^+K^-)$	-8.8 ± 4.4	5 ± 9	-18	$\pm(17\pm6)$
$A_{\rm CP}(\pi^0K^-)$	-10.1 ± 7.7	7 ± 9	-15	$\pm(18\pm6)$
$A_{\rm CP}(\pi^-\bar K^0)$	4.4 ± 8.0	1 ± 1	-2	$\pm(3\pm3)$

- supported by data

Ratios of $B \to \pi K, \pi\pi$ Rates

Various ratios of CP-averaged $B \to \pi K, \pi\pi$ branching fractions have a strong dependence on γ and $|V_{ub}|$, e.g.:





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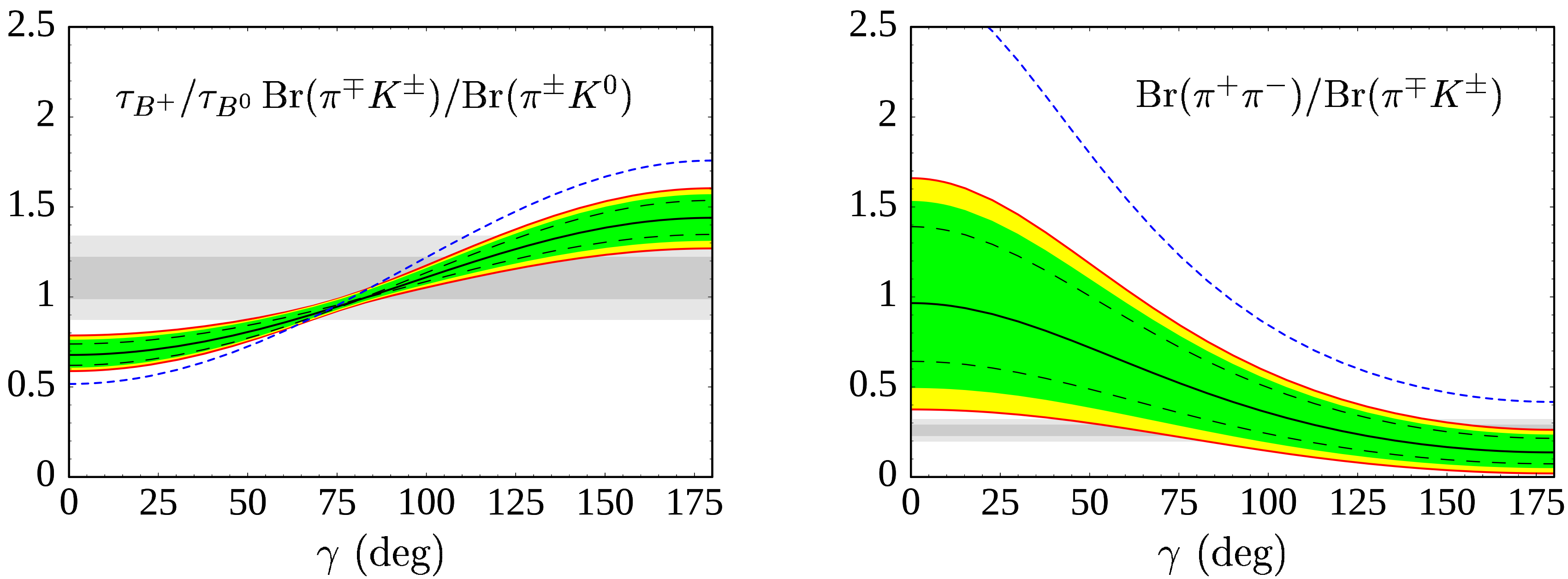

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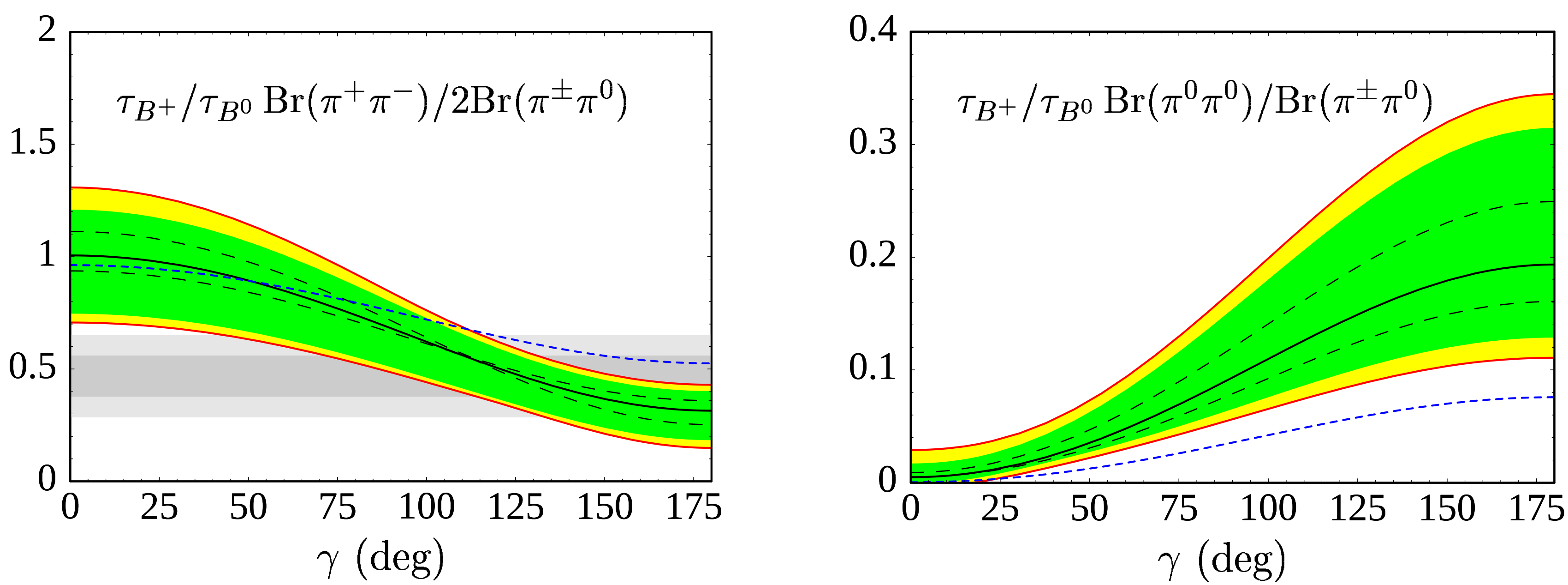
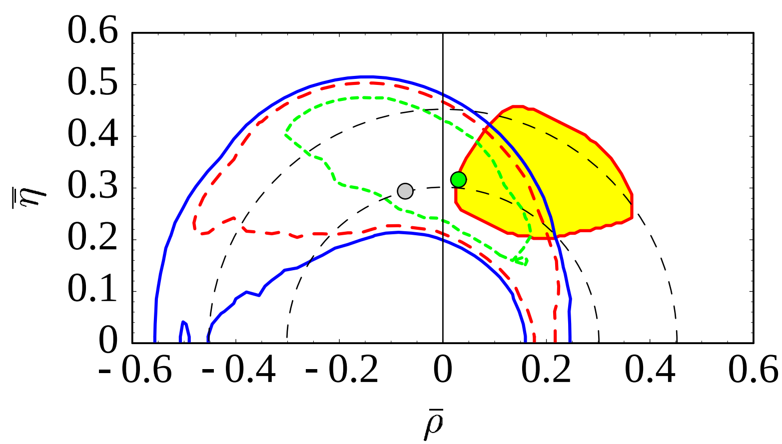


- tends to favor large γ

Global Fit

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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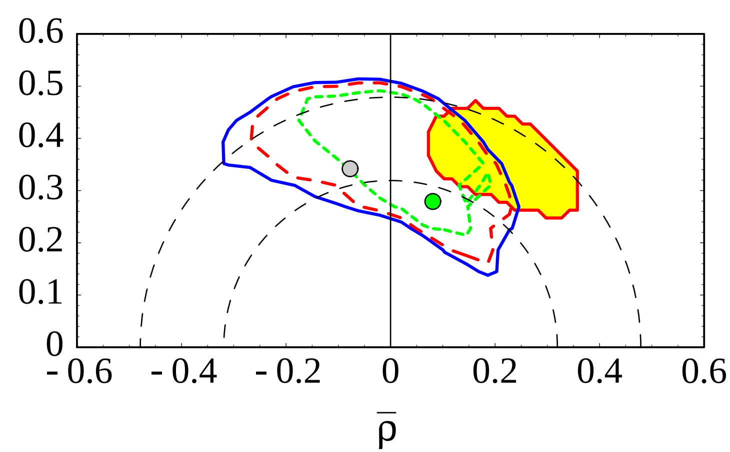

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- fit is excellent, with $\chi^2/\text{dof} = 4.4/3$
- allowed region has shrunk as data got more precise

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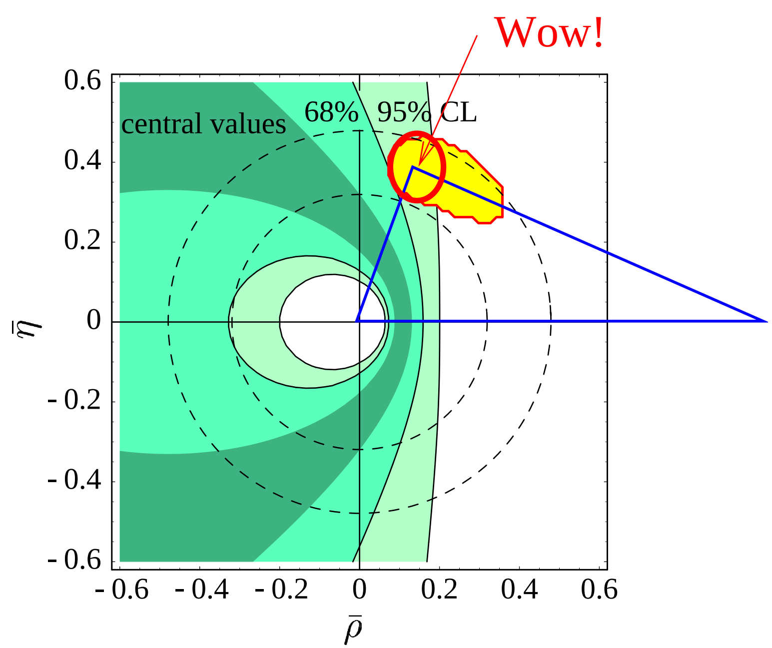
- allowed regions obtained from the fit to charmless hadronic decays are compatible with the standard fit, but once again tend to favor larger γ values

Lesson

- QCD factorization has successfully passed several crucial tests, including the magnitudes of the tree and penguin amplitudes, their relative strong-interaction phase, and the size of weak annihilation effects
- results of the global fit are consistent with the constraint obtained from the analysis of the R_* ratio



Lesson

- QCD factorization has successfully passed several crucial tests, including the magnitudes of the tree and penguin amplitudes, their relative strong-interaction phase, and the size of weak annihilation effects
- results of the global fit are consistent with the constraint obtained from the analysis of the R_* ratio
- will now use QCD factorization to estimate (with generous errors) the penguin-to-tree ratio in the decay $B \to \pi^+\pi^-$ to get the last constraint in the construction of the CP-b triangle

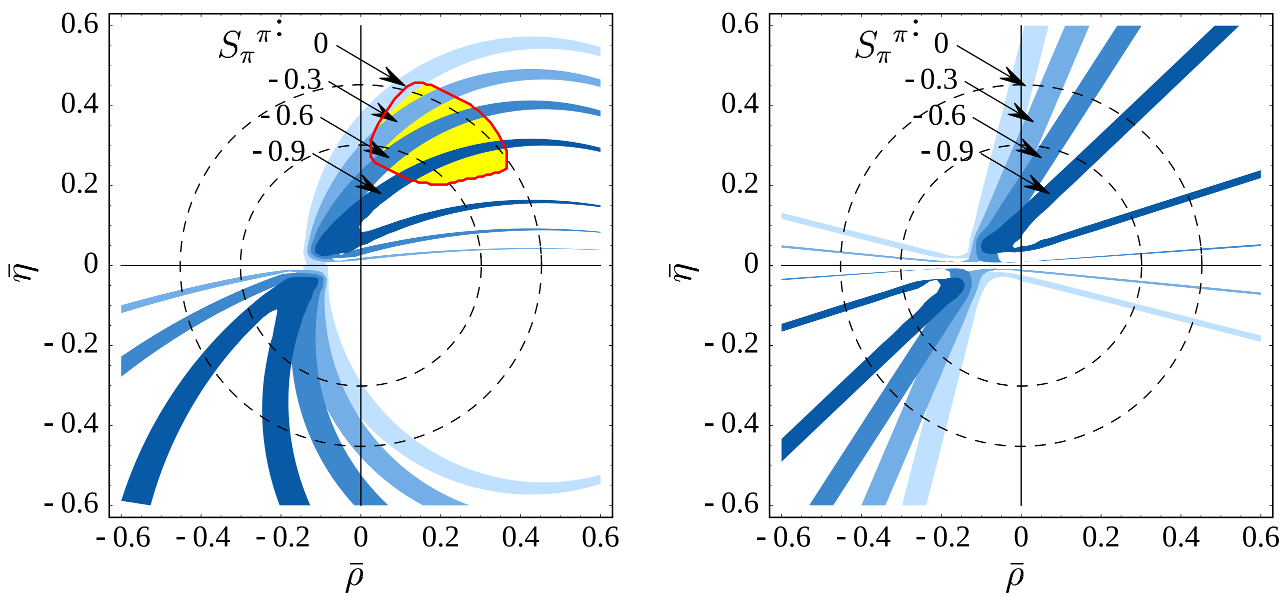
Mixing-Independent Analysis of $S_{\pi\pi}$

If we define $A_{\rm CP}^{B\to\pi\pi}(t) = S_{\pi\pi}\sin(\Delta m_d\,t) + C_{\pi\pi}\cos(\Delta m_d\,t)$, then the coefficient $S_{\pi\pi}$ is given by the 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 measured value $s_{\rm exp} = (\sin 2\beta)_{\rm exp} = 0.73 \pm 0.05$
- this turns circles in $(\bar\rho,\bar\eta)$ plane into straight lines, which intersect $|V_{ub}|$ circles at (almost) 90° angles

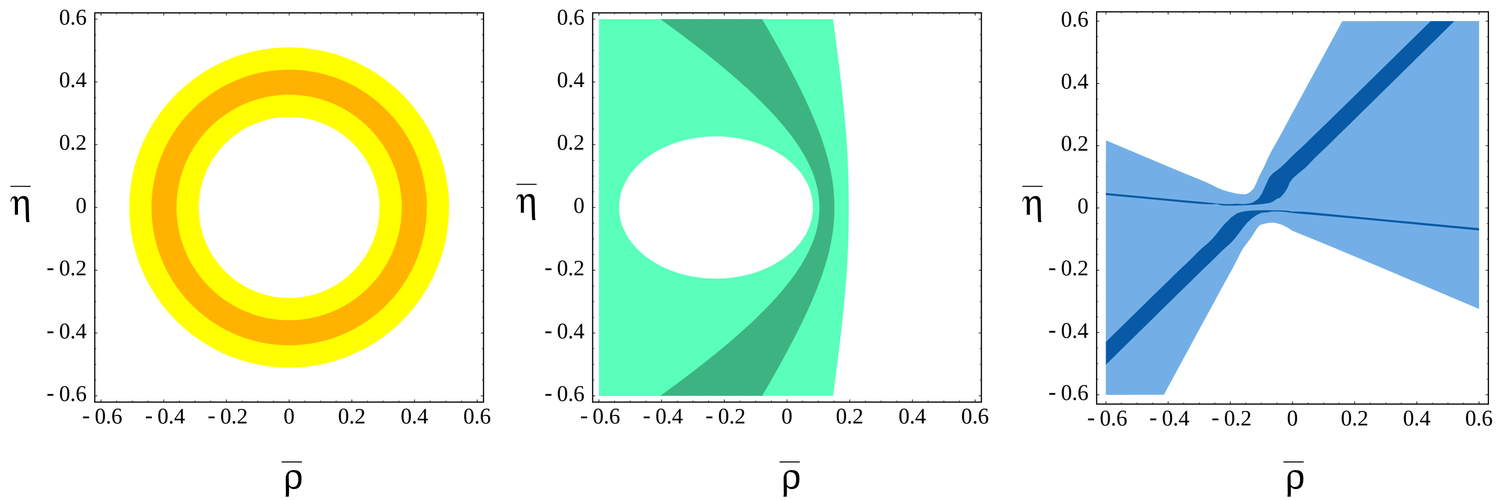
Hadronic uncertainties (QCD factorization) are large in α, but small when displayed as bands in the $(\bar{\rho}, \bar{\eta})$ plane:



exp. results: $S_{\pi\pi} = 0.02 \pm 0.34 \pm 0.05$ (BaBar)

versus $S_{\pi\pi} = -1.23 \pm 0.41 \,^{+0.08}_{-0.07}$ (Belle)

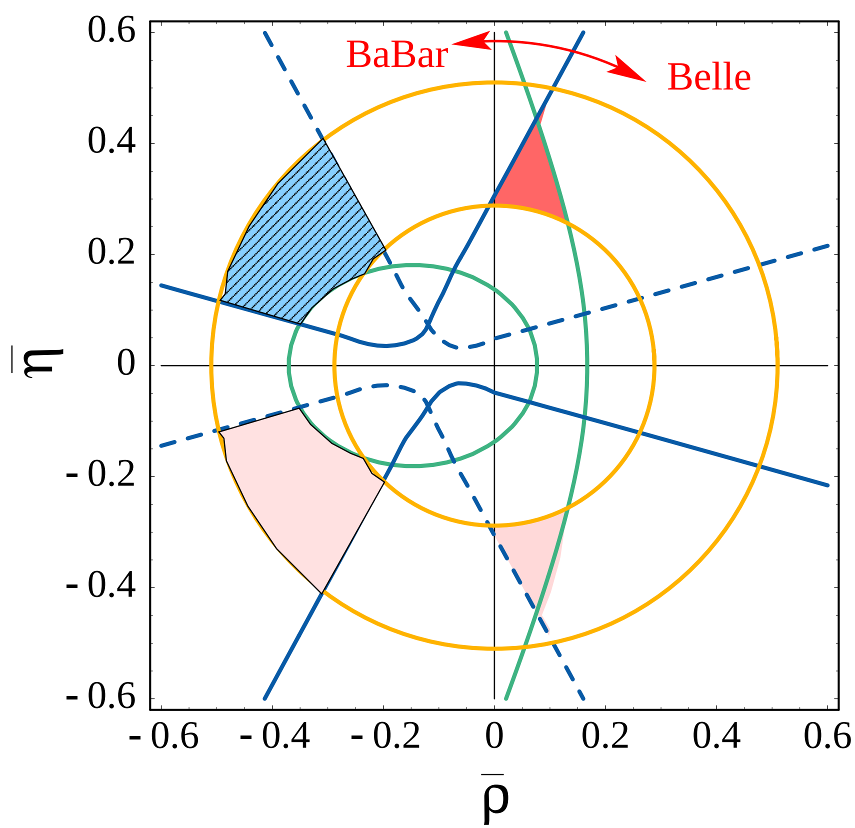
This provides the third constraint in the construction:



- based on above discussion we have good reasons to trust the error analysis within QCD factorization
- but even doubling the theoretical error on $(P/T)_{\pi\pi}$ would at present not change the analysis at all!

Resulting CP-b Triangle

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



- combination of the three constraints establishes CP violation in the bottom sector!
- 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
- 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 $\Delta m_s/\Delta m_d$

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]

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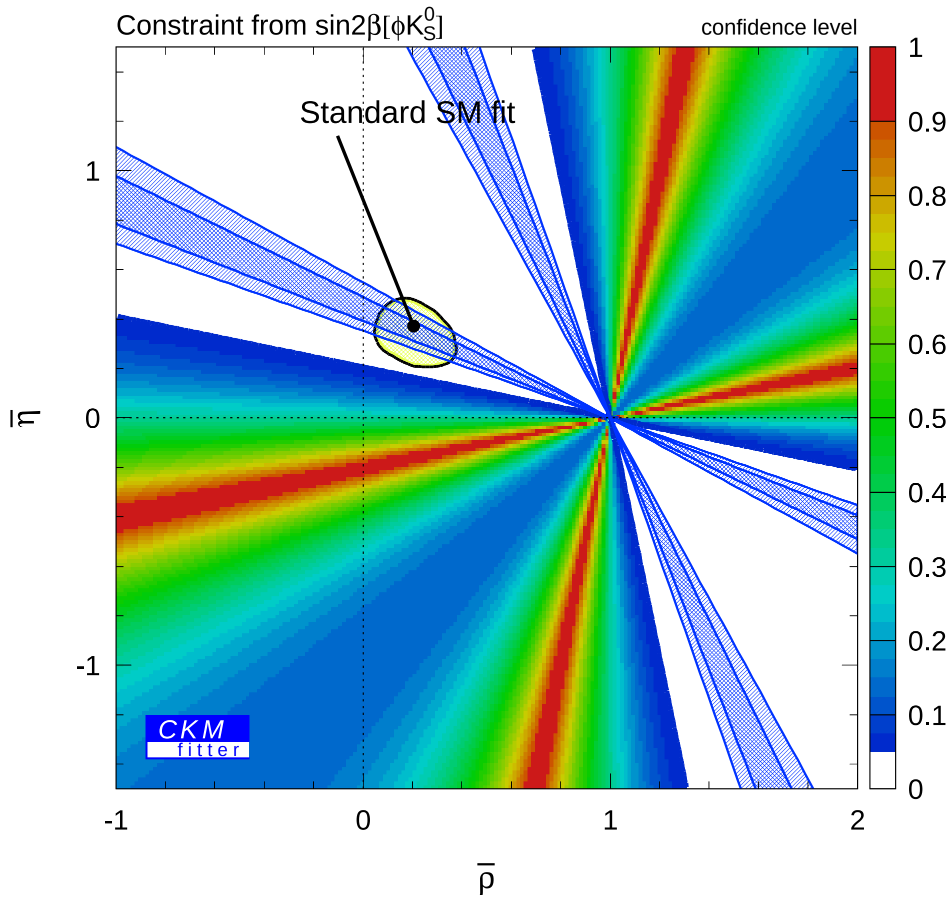
- New Physics in B_d–$\bar{B}_d$ mixing
- New Physics in $b \to s$ or $b \to d$ FCNC transitions (e.g. from penguin and box graphs with exchange of new heavy particles)
  $\Rightarrow$ clean signal would be a difference in the time-dependent CP asymmetries in $B \to \phi K_S$ and $B \to J/\psi\, K_S$ decays
  (tentative evidence seen in recent data!)

The ϕK_S Story



$\Rightarrow$ future will tell . . .

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  - origin of families and hierarchies ?
  - origin of CP violation ?
- current and future B-physics program, combined with continuing progress in heavy-flavor theory, is vital to answering these questions
- after all, New (B) Physics may be just around the corner . . .