B Physics and CP Violation

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Part I:
Introduction

The Role of Flavor Physics

$*$ flavor sector contains most of the undetermined parameters of the SM: Yukawa couplings

$\rightarrow$ determine quark masses and mixings, lepton and neutrino masses and mixings, CP violation

$*$ not as well tested as the gauge sector of the SM

- quark mixings correctly described by CKM model?
- CKM phase only source of CP violation?
- hierarchical patterns caused by new symmetries?

$*$ CP violation in SM is not sufficient to explain baryon asymmetry in Universe

$*$ need New Physics, but many possibilities:

- TeV scale physics? GUT scale physics? Physics at an intermediate scale?
- CP violation in lepton sector?

$*$ complementarity between new particle searches and measurements of flavor parameters

Lessons from Kaons

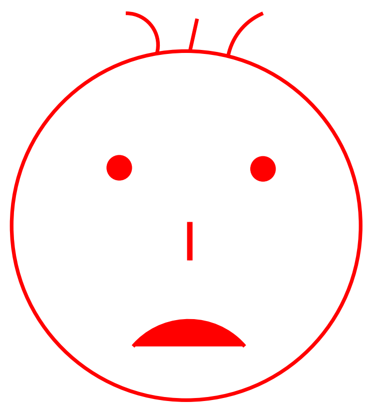
* observation of CP violation in K–$\bar{K}$ mixing (parameter ϵ_K) in 1964 showed that CP is not a symmetry of Nature, but left open the question whether the pattern of CP violation predicted by the Standard Model is correct (e.g., "superweak" interactions?)
* confirmation of CP violation in $K \to \pi\pi$ decays ("direct CP violation", parameter ϵ') in 1999 proved that CP is violated in flavor-changing charged-current interactions, as predicted by the Standard Model:

  complex phase $\delta_{\rm CKM} = \gamma$ in CKM matrix
  $\Rightarrow$ CP violation in mixing and weak decays

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) \approx 13 \underbrace{\left[(1-\Omega_{\eta\eta'})B_6^{(1/2)} - 0.4 B_8^{(3/2)} + \dots\right]}_{\text{hadronic matrix elements}}$$

$$\times \underbrace{\mathrm{Im}(V_{td}V_{ts}^*)}_{|V_{ub}||V_{cb}|\sin\gamma}$$

* ideally, would determine $\sin\gamma$...



... if we only knew how to compute the hadronic matrix elements!

* but: order of magnitude is as predicted by the Standard Model!

* CKM mechanism relates all CP-violating observables to a single parameter $\delta_{\rm CKM}$
  - very predictive!
  - in particular, expect large CP asymmetries in some B decays
* important: B system is more accessible to a solid theoretical analysis, since $m_b \gg \Lambda_{\rm QCD}$
  - strong-interaction effects can be dealt with using heavy-quark expansions, i.e., expansions in powers of $\alpha_s(m_b) \ll 1$ and $\Lambda_{\rm QCD}/m_b \ll 1$
  - systematic, model-independent framework with controlled theoretical uncertainties

The CKM Paradigm

Cabibbo–Kobayashi–Maskawa matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

3×3 unitary matrix connecting mass eigenstates of down-type quarks with interaction eigenstates

$\rightarrow$ described by 4 real parameters

Wolfenstein parameterization:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- accurately known: $|V_{us}|$ and $|V_{cb}|$ (λ and A)
- more uncertain: $|V_{ub}|$ and $|V_{td}|$ (ρ and η)

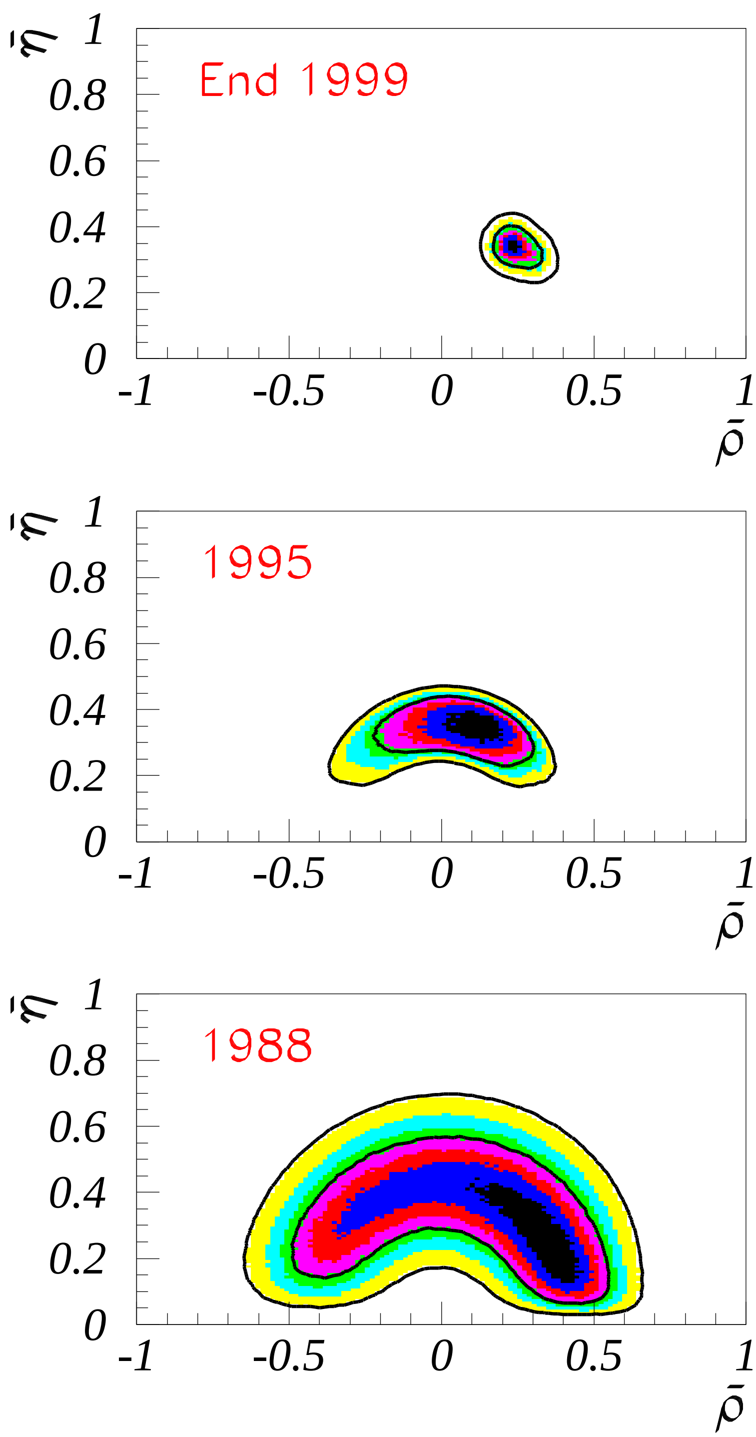
* in past 15 years, strong combined efforts of several complementary experiments (e^+e^- at $\Upsilon(4S)$, e^+e^- at Z^0, hadron colliders), accompanied by significant progress in theory, has led to tremendous advances in our knowledge of the CKM matrix

  Example 1: $|V_{cb}|(1990) = 0.043 \pm 0.010$, whereas $|V_{cb}|(1999) = 0.040 \pm 0.002$ has a precision not much worse than that in the Cabibbo angle

  Example 2: $|V_{ub}|(1990) \stackrel{?}{=} 0$ still possible since $b \to u$ decays were not yet observed, whereas $|V_{ub}|(1999) = (3.4 \pm 0.7) \cdot 10^{-3}$ is known with 20% accuracy despite its smallness

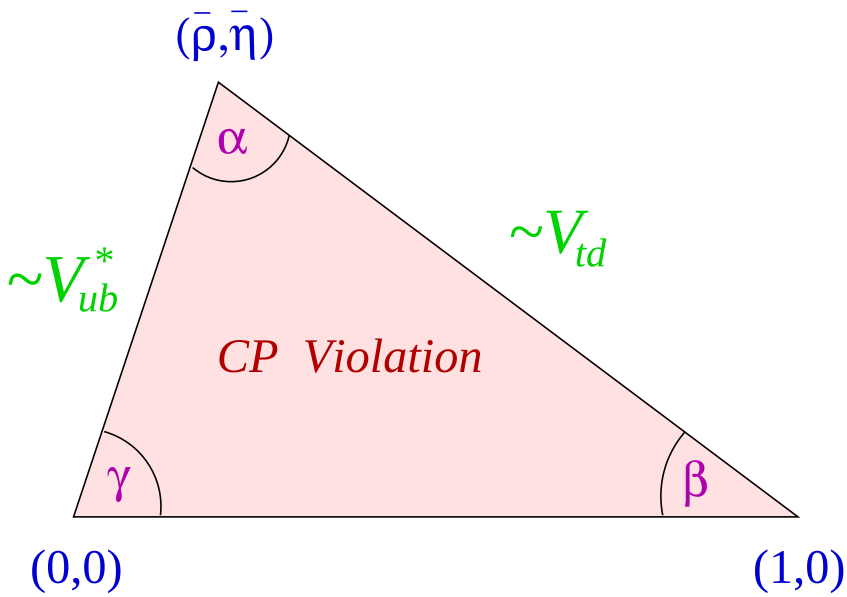
Example 3: exploring the (ρ, η)-plane

(F. Caravaglios et al., 2000)



Unitarity triangle:

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



* combining the measurements of $|V_{ub}|$ in semi-leptonic decays, $|V_{td}|$ in $B_{d,s}$–$\bar{B}_{d,s}$ mixing, and ϵ_K in K–$\bar{K}$ mixing, the parameters of the unitarity triangle are determined already with great accuracy:

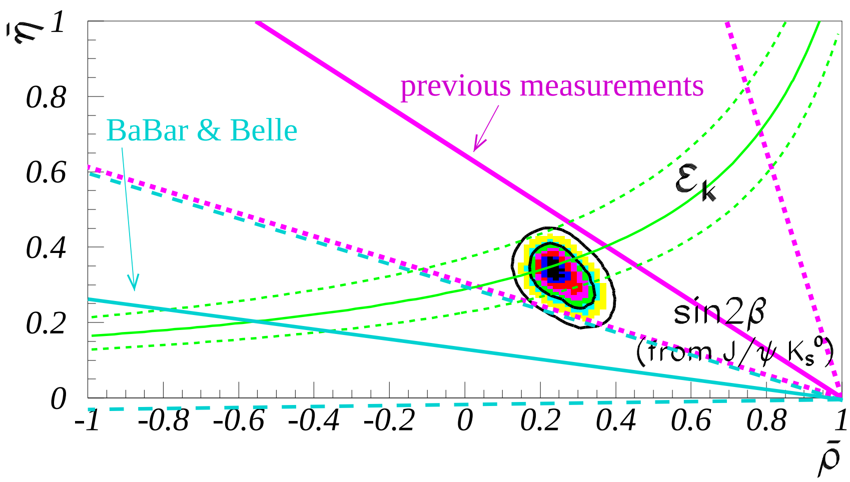
  (F. Caravaglios et al., 2000)

  - $\bar{\rho} = 0.240^{+0.057}_{-0.047}$ and $\bar{\eta} = 0.335 \pm 0.042$
  - $\sin 2\beta = 0.750^{+0.058}_{-0.064}$, $\sin 2\alpha = -0.38^{+0.24}_{-0.28}$, and $\gamma = (55.5^{+6.0}_{-8.5})^\circ$

Key feature:

- in SM, all CP violation results from a single complex phase $\delta_{\rm CKM} = \gamma = \arg(V_{ub}^*)$ in the CKM matrix

  $\to$ beginning to be tested by confronting measurements of ϵ_K (from K–$\bar K$ mixing) and $\sin 2\beta$ (from $B \to J/\psi\, K_S$ decays) with information obtained from measurements of CP-conserving quantities ($|V_{ub}|$, Δm_d, Δm_s)



Where Do We Go from Here?

* precise determination of ρ and η in itself is only one of many goals

* focus has now shifted towards testing the consistency of the entire CKM picture

  $\rightarrow$ 4 parameters, unitarity relations, 1 phase (not just checking "whether the triangle closes")

* in addition, B factories are now in focus for having a realistic chance of finding deviations from the SM

* to this end:

  • need many different, independent measurements of the unitarity triangle using B_d, B_s and K decays, and based on CP-conserving and CP-violating processes

  • need many manifestations of CP violation, in mixing ("indirect"), decay ("direct"), and their interference

  • need to test for New Physics in rare processes (penguins and boxes)

The Tools

* several existing and approved facilities, as well as proposed new experiments, will help us to explore the quark sector with unprecedented precision

B factories:

* Existing e^+e^- colliders at $\Upsilon(4S)$:
  - BaBar (SLAC), Belle (KEK), CLEO-3 (Cornell), HERA-B (DESY)

  → BaBar and Belle plan luminosity upgrades in several stages

  → PEP-II as an example (similar for KEK-B):

Year	$\mathcal{L}$ (cm^{-2} s^{-1})	$B\bar{B}$ (yr^{-1})	Cumulative
Phase 1:			
2000–2002	3×10^{33}	20×10^6	60×10^6
Phase 2:			
2003–2005	1×10^{34}	67×10^6	260×10^6
Phase 3:			
2006–2008	3×10^{34}	200×10^6	860×10^6

→ will have about 2.5×10^8 $B\bar{B}$ pairs per experiment at end of phase 2, and about 10^9 $B\bar{B}$ pairs per experiment at end of phase 3

* Existing hadron collider:
  - CDF and D0 (Fermilab) at Tevatron Run-II

* Approved hadron colliders:
  - BTeV (Fermilab), LHC-b (CERN)

  → will produce about 4×10^{11} $B\bar{B}$ pairs per year at luminosity $\mathcal{L} = 2 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$

  → trigger and particle reconstruction are big issues!

* Future possibilities:
  - High-luminosity e^+e^- collider ($\mathcal{L} \sim 10^{35-36}\,\text{cm}^{-2}\,\text{s}^{-1}$) at $\Upsilon(4S)$
  - High-luminosity e^+e^- collider ($\mathcal{L} \sim 10^{33-34}\,\text{cm}^{-2}\,\text{s}^{-1}$) at Z^0 ("Giga-Z")

Rare kaon experiments:

$*$ measurements of $K \to \pi\nu\bar{\nu}$ provide direct information on the Wolfenstein parameters ρ and η, and are theoretically very clean:

$$K^+ \to \pi^+\nu\bar{\nu} \quad \Rightarrow \quad |V_{td}V_{ts}^*| \sim |1-\rho-i\eta|$$

$$K_L^0 \to \pi^0\nu\bar{\nu} \quad \Rightarrow \quad \mathrm{Im}(V_{td}V_{ts}^*) \sim \eta$$

Existing and approved experiments:

• E787 (BNL) has reported 1 $K^+ \to \pi^+\nu\bar{\nu}$ event, corresponding to a branching ratio of $(1.5^{+3.5}_{-1.3}) \times 10^{-10}$ — about twice the SM prediction

• modestly upgraded experiment E949 (BNL) expects about 10 $K^+ \to \pi^+\nu\bar{\nu}$ events in SM

Proposed experiments:

• CKM (Fermilab) expects about 100 $K^+ \to \pi^+\nu\bar{\nu}$ events in SM

"Contemplated" experiments:

• K0PI0 (BNL) and KAMI (Fermilab) expect about 65 $K_L^0 \to \pi^0\nu\bar{\nu}$ events in SM

Part II:

Charmless Hadronic B Decays

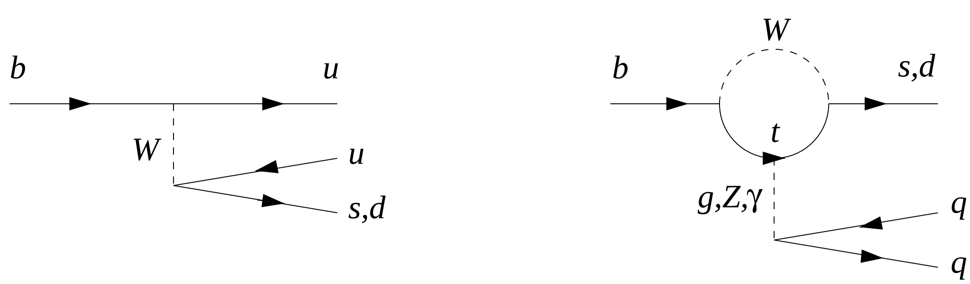
Reason for Excitement

* recent experimental data on charmless hadronic B decays from CLEO, BaBar and Belle have caused a lot of excitement in the theory community

  → here focus on $B \to \pi K$ and $B \to \pi\pi$ decays, which at present are best understood theoretically

* in general, sensitivity to CP-violating "weak" phases requires sizable interference of decay topologies which differ in their CKM parameters

* in charmless hadronic B decays, there is significant interference of tree and penguin topologies!



Tree	Penguin	Ratio
$V_{ub}V_{us}^* \sim \lambda^4\, e^{-i\gamma}$	$V_{tb}V_{ts}^* \sim \lambda^2$	$\lvert T/P\rvert \sim 0.3$
$V_{ub}V_{ud}^* \sim \lambda^3\, e^{-i\gamma}$	$V_{tb}V_{td}^* \sim \lambda^3\, e^{i\beta}$	$\lvert P/T\rvert \sim 0.3$

* implies potentially large CP asymmetries, e.g.:

$$A_{\rm CP}(B^\pm \to \pi^0 K^\pm) \approx \underbrace{2\left|\frac{T}{P}\right| \sin\gamma}_{\approx 0.5} \quad \underbrace{\sin\delta_{\rm st}}_{\text{strong phase}}$$

* sensitivity to γ also in CP-averaged rates, e.g.:

$$\frac{\Gamma(B \to \pi^\mp K^\pm)}{\Gamma(B \to \pi^\pm K_S)} \approx 1 + 2\left|\frac{T}{P}\right| \cos\gamma \cos\delta_{\rm st}$$

* varying $-1 \le \cos\delta_{\rm st} \le 1$ yields bounds on $\cos\gamma$:

  → Fleischer–Mannel bound, Neubert–Rosner bound

  → see lectures by Helen Quinn at last year's SSI

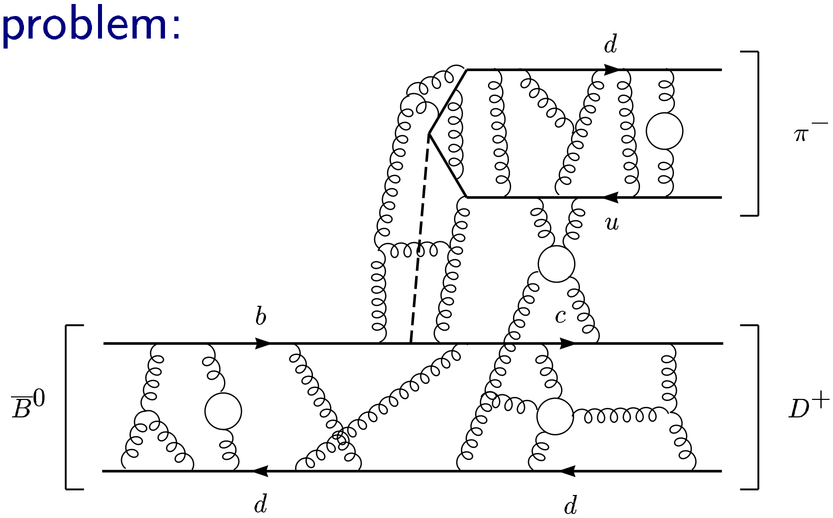
* in some cases, one can use symmetries (isospin, Fierz relations, SU(3)) to eliminate hadronic uncertainties

* to do better, need a theory of hadronic B decays

  → recent progress using the heavy-quark expansion

The Challenge

* theoretical description of hadronic weak decays is difficult due to non-perturbative hadronic dynamics
* this affects interpretation of B factory data, studies of CP violation, and searches for New Physics
* the problem:



* hard gluon effects can be calculated and lead to an effective weak Hamiltonian:

$$\boxed{\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i^{\text{CKM}}\, C_i(\mu)\, O_i(\mu)}$$

* difficulty is to calculate hadronic matrix elements of local operators $O_i(\mu)$

"Naive" factorization:

* consider $\bar{B}^0 \to D^+\pi^-$ as an example:

$$\begin{aligned}\mathcal{A}_{\bar{B}^0\to D^+\pi^-} &\sim \left(C_1 + \frac{C_2}{N_c}\right)\langle D^+\pi^-|(\bar{d}u)(\bar{c}b)|\bar{B}^0\rangle \\ &\quad + 2C_2\,\langle D^+\pi^-|(\bar{d}t_a u)(\bar{c}t_a b)|\bar{B}^0\rangle \\ &\stackrel{\text{fact.}}{\to} \left(C_1 + \frac{C_2}{N_c}\right)\underbrace{\langle \pi^-|(\bar{d}u)|0\rangle}_{\sim f_\pi}\underbrace{\langle D^+|(\bar{c}b)|\bar{B}^0\rangle}_{\sim F_0^{B\to D}}\end{aligned}$$

hence:

$$\mathcal{A}_{\bar{B}^0\to D^+\pi^-} \sim G_F V_{cb} V_{ud}^*\, f_\pi\, F_0^{B\to D}(m_\pi^2)\, a_1$$

with

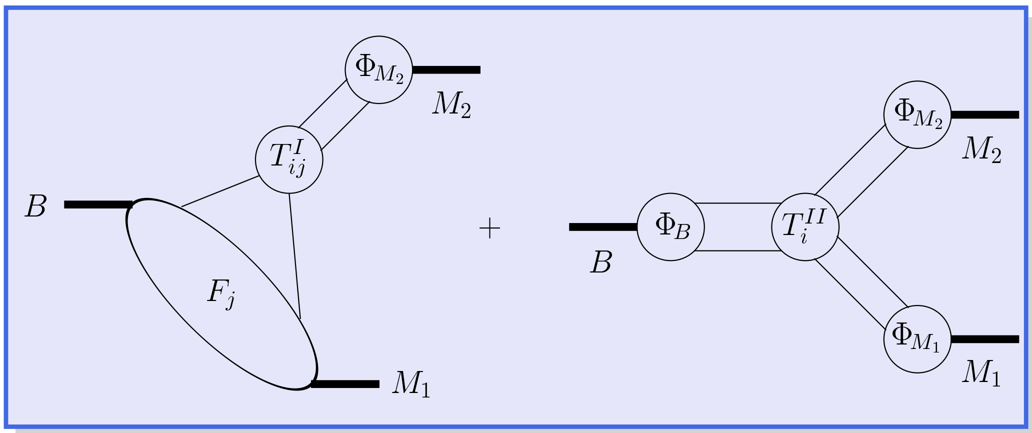
$$\boxed{a_1 = C_1(\mu) + \frac{C_2(\mu)}{N_c}}$$

* similarly, define parameter $a_2 = C_2 + C_1/N_c$, and further parameters $a_3, \ldots, a_{10}$ for more complicated decays

Problem: a_i are renormalization-scale and -scheme dependent in "naive" factorization!

QCD Factorization Formula

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = F_j^{B\to M_1} f_{M_2} T_{ij}^{\rm I} \otimes \Phi_{M_2} + T_i^{\rm II} \otimes \Phi_B \otimes \Phi_{M_1} \otimes \Phi_{M_2} + \text{power suppressed contributions}$$



(M. Beneke et al., 1999–2000)

* if M_1 is heavy, the second term is power suppressed and should be dropped
* factorization does not hold if M_2 is a heavy-light meson, but it works for an onium state such as J/ψ
* validity of factorization formula demonstrated by explicit 1-loop (and 2-loop) calculation; general arguments support factorization to all orders in perturbation theory

Implications:

* obtain approach that allows for a systematic, model-independent calculation of corrections to "naive" factorization, which emerges as leading term in heavy-quark limit

* possibility to compute systematically logarithmic corrections to "naive" factorization solves problem of scale and scheme dependences (scale and scheme dependences of hard scattering kernels compensate those of Wilson coefficients)

* non-factorizable corrections are process dependent and hence non-universal, in contrast with basic assumption of "generalized" factorization models

* strong FSI and rescattering phases are calculable and are perturbative or power suppressed (soft rescattering vanishes in the heavy-quark limit)

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

* useful to define "transition operator":

$$\mathcal{T} = \frac{G_F}{\sqrt{2}}\, V_{ud}^* V_{cb} \Big[a_1^{DL}\, \bar{c}\gamma_\mu b \otimes \bar{d}\gamma^\mu (1-\gamma_5) u - a_1^{D^* L}\, \bar{c}\gamma_\mu\gamma_5 b \otimes \bar{d}\gamma^\mu (1-\gamma_5) u \Big]$$

* obtain explicit, renormalization-scheme invariant expression for parameters a_1 at next-to-leading order in α_s and leading power in $\Lambda_{\rm QCD}/m_b$:

$$a_1 = C_1(\mu) + \frac{C_2(\mu)}{N_c} + \frac{C_2(\mu)}{N_c}\,\frac{C_F\alpha_s}{4\pi}\left[\underbrace{12\ln\frac{m_b}{\mu} - B}_{\text{cancels scale and scheme dep.}} + \Delta_{D^{(*)}L}\!\left(\frac{m_c}{m_b}\right)\right]$$

with

$$\Delta_{D^{(*)}L}(z) = \int_0^1 \mathrm{d}x\, \Phi_L(x)\, T_{D^{(*)}}(x,z)$$

process-dependent, non-universal correction

* however, for these decays $|a_1^{D^{(*)}L}| = 1.05 \pm 0.02$

Predictions for class-I decay amplitudes:

Model-independent predictions for the branching ratios (in units of 10^{-3}) of $\bar{B}_d \to D^{(*)+} L^-$ decays in the heavy-quark limit. Theory numbers are $\times(|V_{cb}|/0.04)^2 \times (|a_1|/1.05)^2 \times (\tau_{B_d}/1.56\,\text{ps})$.

Decay mode	Theory (HQL)	PDG98
$\bar{B}_d \to D^+\pi^-$	$3.27 \times [F_+(0)/0.6]^2$	3.0 ± 0.4
$\bar{B}_d \to D^+K^-$	$0.25 \times [F_+(0)/0.6]^2$	—
$\bar{B}_d \to D^+\rho^-$	$7.64 \times [F_+(0)/0.6]^2$	7.9 ± 1.4
$\bar{B}_d \to D^+K^{*-}$	$0.39 \times [F_+(0)/0.6]^2$	—
$\bar{B}_d \to D^+a_1^-$	$7.76 \times [F_+(0)/0.6]^2$	6.0 ± 3.3
$\bar{B}_d \to D^{*+}\pi^-$	$3.05 \times [A_0(0)/0.6]^2$	2.8 ± 0.2
$\bar{B}_d \to D^{*+}K^-$	$0.22 \times [A_0(0)/0.6]^2$	—
$\bar{B}_d \to D^{*+}\rho^-$	$7.59 \times [A_0(0)/0.6]^2$	6.7 ± 3.3
$\bar{B}_d \to D^{*+}K^{*-}$	$0.40 \times [A_0(0)/0.6]^2$	—
$\bar{B}_d \to D^{*+}a_1^-$	$8.53 \times [A_0(0)/0.6]^2$	13.0 ± 2.7

* good agreement may be taken as indication that in these decays there are no unexpectedly large power corrections

  → confirmed by explicit estimates!

Extraction of $\cos\gamma$ *in* $B \to \pi K, \pi\pi$

* applying the QCD factorization formula to the present case gives

$$\langle \pi K | \mathcal{H}_{\text{eff}} | B \rangle = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb}^* V_{ps} \, \langle \pi K | \mathcal{T}_p | B \rangle$$

with the "transition "operator":

$$\begin{aligned}
\mathcal{T}_p = {} & a_1^{\pi K} \, \delta_{pu} \, (\bar{b}u)_{V-A} \otimes (\bar{u}s)_{V-A} \\
& + a_2^{\pi K} \, \delta_{pu} \, (\bar{b}s)_{V-A} \otimes (\bar{u}u)_{V-A} \\
& + a_3^{\pi K} \sum\nolimits_q (\bar{b}s)_{V-A} \otimes (\bar{q}q)_{V-A} \\
& + a_{4p}^{\pi K} \sum\nolimits_q (\bar{b}q)_{V-A} \otimes (\bar{q}s)_{V-A} \\
& + a_5^{\pi K} \sum\nolimits_q (\bar{b}s)_{V-A} \otimes (\bar{q}q)_{V+A} \\
& + a_{6p}^{\pi K}(\mu) \sum\nolimits_q (-2)(\bar{b}q)_{S-P} \otimes (\bar{q}s)_{S+P} \\
& + a_7^{\pi K} \sum\nolimits_q (\bar{b}s)_{V-A} \otimes \tfrac{3}{2} e_q (\bar{q}q)_{V+A} \\
& + a_{8p}^{\pi K}(\mu) \sum\nolimits_q (-2)(\bar{b}q)_{S-P} \otimes \tfrac{3}{2} e_q (\bar{q}s)_{S+P} \\
& + a_9^{\pi K} \sum\nolimits_q (\bar{b}s)_{V-A} \otimes \tfrac{3}{2} e_q (\bar{q}q)_{V-A} \\
& + a_{10p}^{\pi K} \sum\nolimits_q (\bar{b}q)_{V-A} \otimes \tfrac{3}{2} e_q (\bar{q}s)_{V-A}
\end{aligned}$$

* contributions of $(S-P)\otimes(S+P)$ penguin operators are multiplied by a factor:

$$\frac{2\mu_K}{m_b} = \frac{2m_K^2}{(m_s+m_d)m_b} \sim \frac{\Lambda_{\rm QCD}}{m_b} \quad [\approx 0.8]$$

$\rightarrow$ include all such "chirally enhanced" power corrections, since they are numerically important

* terms proportional to the same factor also appear at twist-3 order in the collinear expansion

* these terms involve the logarithmically IR-divergent integral:

$$\boxed{X = \int_0^1 \frac{du}{1-u}}$$

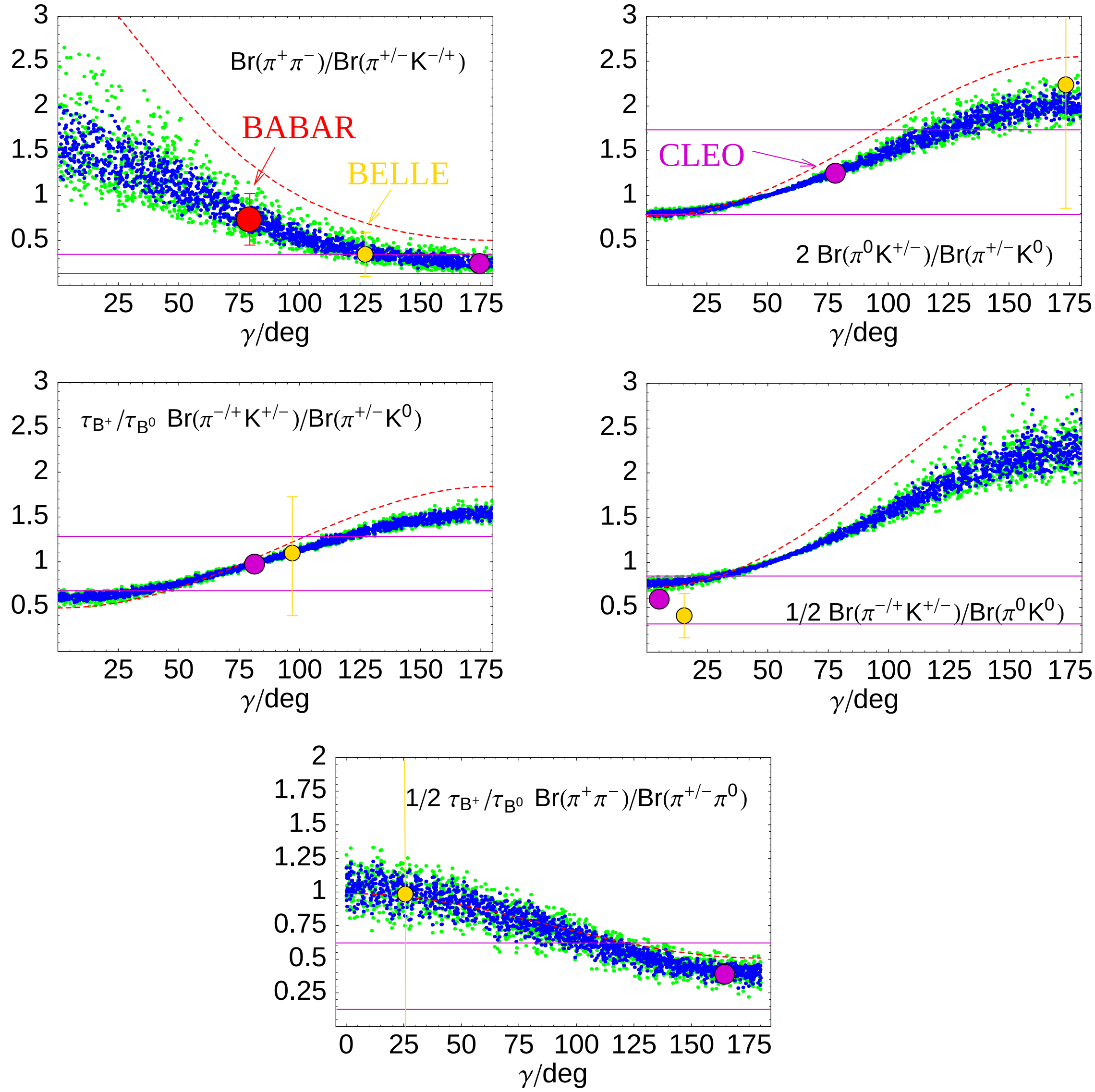
indicating the dominance of soft gluon exchange (violation of factorization at next-to-leading power)

* set $X = \ln(m_B/\Lambda) + r$ with r a complex random number such that $|r| < 3$ ("realistic" $\rightarrow$ blue dots) or $|r| < 6$ ("conservative" $\rightarrow$ green dots)

* vary all theory parameters over conservative ranges:

renormalization scale, quark masses, wave function parameters, X parameters, etc.

* focus on ratios of decay rates, which are independent of semi-leptonic form factors:

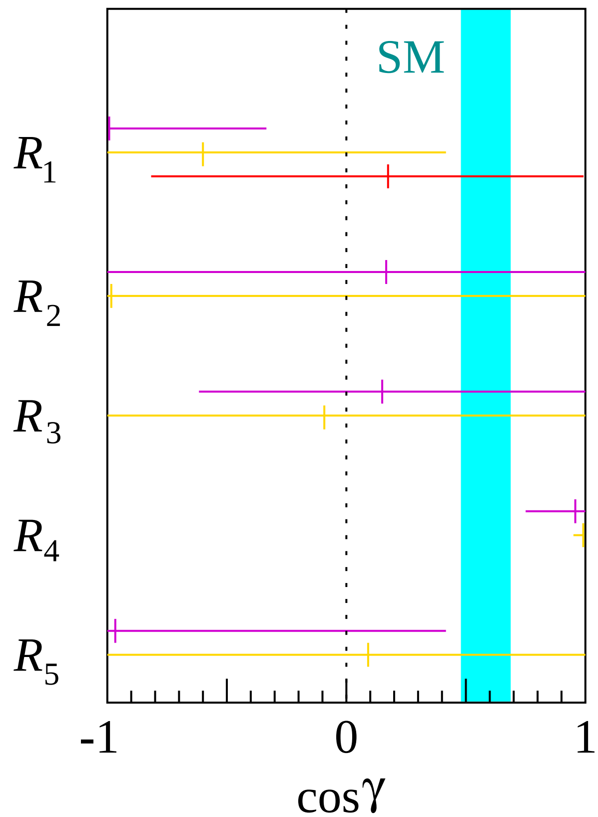


(M. Beneke et al., hep-ph/0007256)

* with more data, comparison with these predictions will provide a crucial test of the approach

* this will determine γ up to a sign ambiguity

* at present, experimental errors are too large to obtain a meaningful determination:



* in future, this will be a powerful analysis

* sign of γ can be determined by comparing direct CP asymmetries with theoretical predictions

  $\rightarrow$ ultimately, will obtain γ without any discrete ambiguities!

Some modes to keep an eye on:

* branching ratios with $\gamma = (60 \pm 20)^\circ$ and $|V_{ub}/V_{cb}| = 0.085$:

  $\text{Br}(B \to \pi^+\pi^-) = (9 \pm 2) \cdot 10^{-6} \times (F_+^{B\to\pi}/0.3)^2$

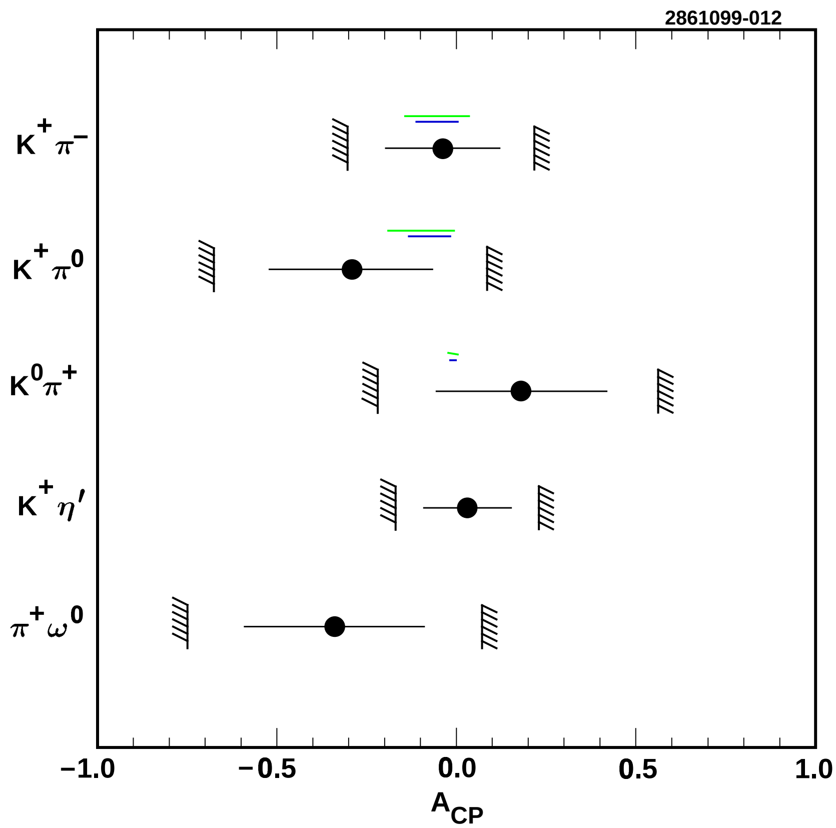
  $\text{Br}(B \to \pi^0 K^0) = (4.5 \pm 2.5) \cdot 10^{-6} \times (F_+^{B\to\pi}/0.3)^2$

* first result is larger than CLEO (4.3 ± 1.6), but in good agreement with BaBar (9.3 ± 2.8) and Belle (6.3 ± 4.0)

* second result is smaller than CLEO (14.6 ± 6.2) and Belle (21.0 ± 8.9)

Direct CP Asymmetries

- generic theoretical prediction:
  strong phases are suppressed (subleading in the heavy-quark expansion), except for very rare decays such as $B \to \pi^0\pi^0$
- implies that direct CP asymmetries will be much below the present CLEO bounds:

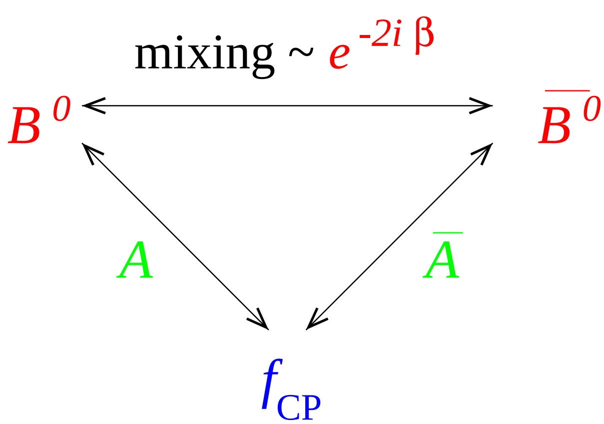


- observing these asymmetries is an important long-term goal!

Part III: Mixing-Induced CP Violation

Strong Phases from Quantum Mechanics

* in B decays into a CP eigenstate $f_{\rm CP}$, observable CP asymmetries can arise from interference of weak phases in the amplitudes for B–$\bar{B}$ mixing and decay:



* resulting time-dependent CP asymmetry:

$$A_{\rm CP}(t) = \frac{\Gamma(B^0 \to f_{\rm CP}) - \Gamma(\bar{B}^0 \to f_{\rm CP})}{\Gamma(B^0 \to f_{\rm CP}) + \Gamma(\bar{B}^0 \to f_{\rm CP})}$$
$$= -\frac{2\,{\rm Im}\lambda}{1+|\lambda|^2}\,\sin(\Delta m_B\,t) + \frac{1-|\lambda|^2}{1+|\lambda|^2}\,\cos(\Delta m_B t)$$

where:

$$\lambda = e^{-2i\beta}\,\frac{\bar{A}}{A} = \eta_{f_{\rm CP}}\,e^{-2i\beta}\,\frac{\sum_i A_i\,e^{i\delta_i}\,e^{-i\phi_i}}{\sum_i A_i\,e^{i\delta_i}\,e^{i\phi_i}}$$

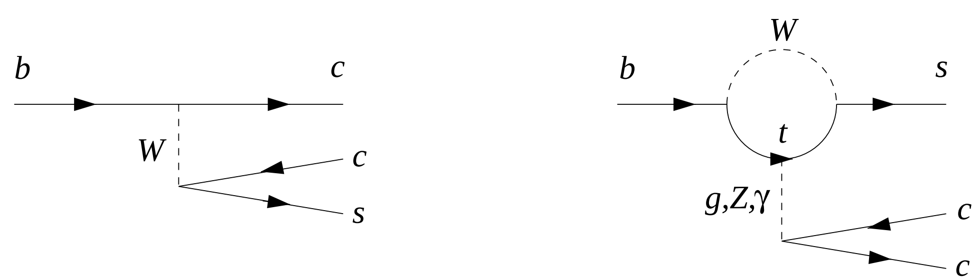
* if the decay amplitude is dominated by a single weak phase ϕ_A, then $|\lambda| \simeq 1$ and

$$\boxed{\mathrm{Im}(\lambda) \simeq -\eta_{f_{\mathrm{CP}}} \sin 2(\beta + \phi_A)}$$

Example 1:

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

($b \to c\bar{c}s$ transitions, $\eta_{J/\psi\, K_S} = -1$)



Tree	Penguin
$V_{cb}V_{cs}^* \sim \lambda^2$	$V_{tb}V_{ts}^* \sim \lambda^2, \lambda^4\, e^{-i\gamma}$

hence: $\phi_A \simeq 0 \Rightarrow \mathrm{Im}(\lambda) \simeq \sin 2\beta$

* above discussion relies on Standard Model

* it could be upset if there existed a New Physics contribution to $b \to c\bar{c}s$ transitions with $\phi_{\mathrm{NP}} \neq 0$

* but such a contribution would also yield

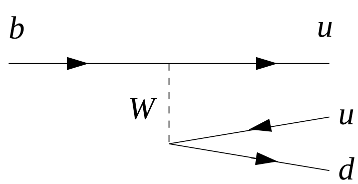
$$A_{\mathrm{CP}}(B^{\pm} \to J/\psi\, K^{\pm}) \sim \sin\delta_{\mathrm{st}}\,\sin\phi_{\mathrm{NP}} \neq 0$$

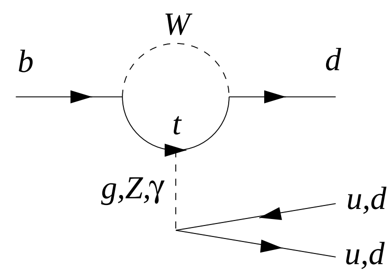
* unless strong phase δ_{st} vanishes accidentally, there is not much room given the CLEO result:

$$A_{\mathrm{CP}}(B^{\pm} \to J/\psi\, K^{\pm}) = (1.8 \pm 4.3 \pm 0.4)\%$$

Example 2:

$\sin 2\alpha$ from $B \to \pi^+\pi^-$ decays
($b \to u\bar{u}d$ transitions, $\eta_{\pi^+\pi^-} = 1$)





Tree	Penguin
$V_{ub}V_{ud}^* \sim \lambda^3\, e^{-i\gamma}$	$V_{tb}V_{td}^* \sim \lambda^3\, e^{i\beta}$

hence: $\phi_A \simeq \gamma +$ "penguin pollution"
$\Rightarrow$ Im$(\lambda) \simeq \sin 2\alpha \times [1 + O(P/T)]$

* conventional way to circumvent this problem is to perform an isospin analysis, using measurements of $B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$ and their CP conjugates (nearly impractical)

Extraction of $\sin 2\alpha$ *in* $B \to \pi^+\pi^-$

* QCD factorization approach can be used to calculate the "penguin pollution" in $B \to \pi^+\pi^-$, thereby allowing a determination of α without isospin analysis

* time-dependent, mixing-induced CP asymmetry in $B_d \to \pi^+\pi^-$ decays:

$$A_{\rm CP}(t) = \frac{\Gamma(B^0(t) \to \pi^+\pi^-) - \Gamma(\bar{B}^0(t) \to \pi^+\pi^-)}{\Gamma(B^0(t) \to \pi^+\pi^-) + \Gamma(\bar{B}^0(t) \to \pi^+\pi^-)}$$

$$= -S \cdot \sin(\Delta m_B\, t) + C \cdot \cos(\Delta m_B\, t)$$

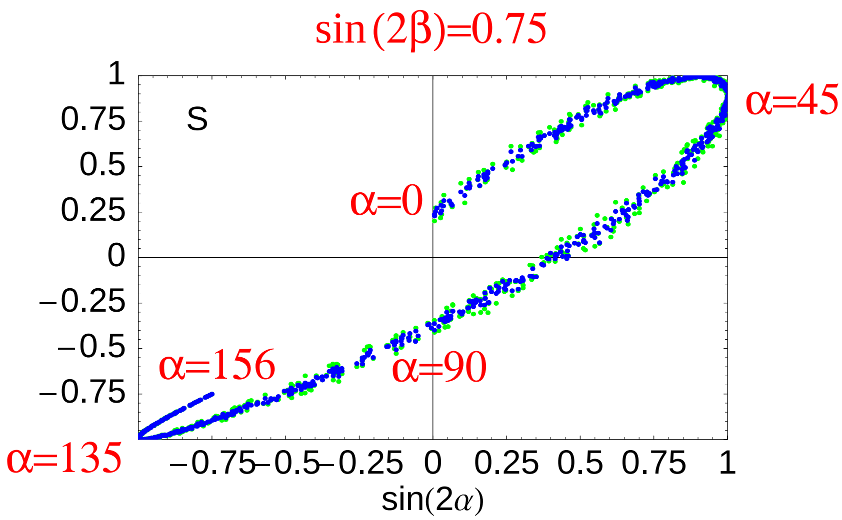
* without "penguin pollution":

$$S = \sin 2\alpha \,, \qquad C = 0$$

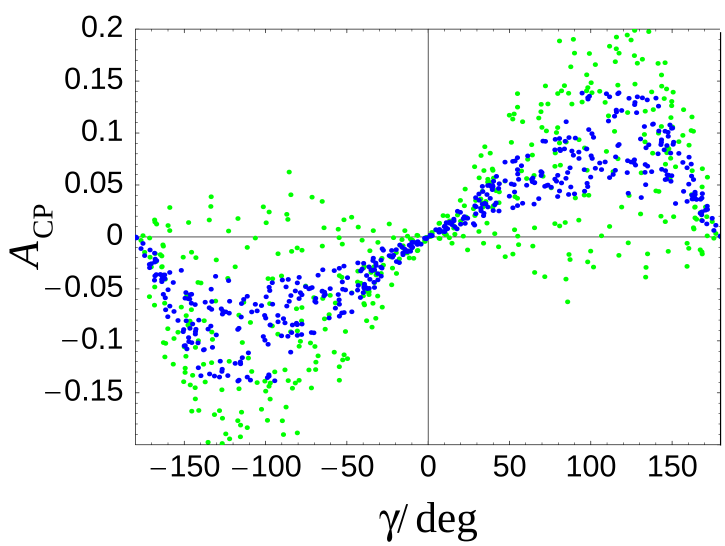
  free of hadronic uncertainties

* interference of tree and (subdominant) penguin topologies introduces hadronic uncertainties, which can be controlled by applying the QCD factorization theorem to the $B \to \pi\pi$ decay amplitudes

- we can calculate this effect with small theoretical uncertainty: (M. Beneke et al., hep-ph/0007256)



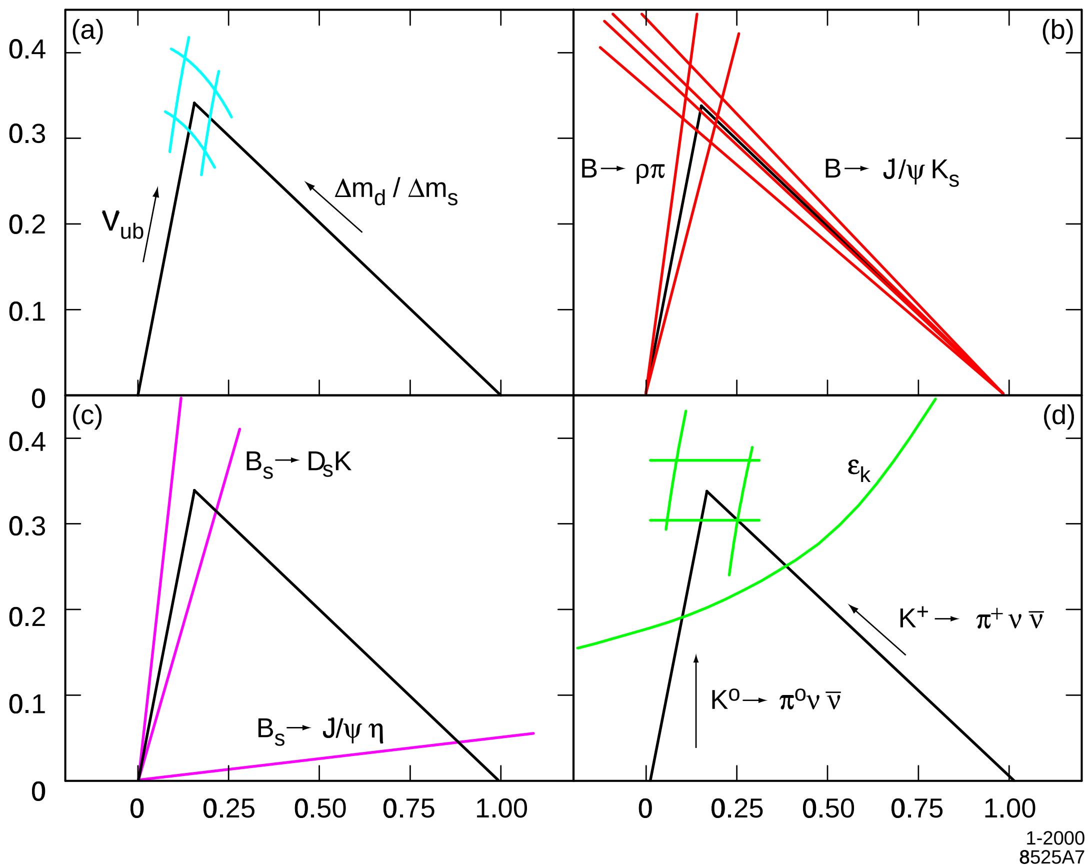
- consistency check is provided by the calculation of the direct CP asymmetry ($= C$):



Part IV: Looking Ahead... Beyond the Standard Model

Many Determinations of the UT

* generalize discussion presented by Peskin at LP99, indicating precision that could be achieved 10 years from now:



* pursue different strategies, the most important ones being as follows...

(a) Non-CP triangle:

determine the triangle by measuring the length of the two sides in semi-leptonic B decays ($|V_{ub}|$ from exclusive and inclusive $B \to X_u \, \ell \, \nu$ decays) and $B_{d,s}$–$\bar{B}_{d,s}$ mixing ($|V_{td}|$ from Δm_d and Δm_s)

$\to$ no CP violation involved

$\to$ main sensitivity to New Physics via magnitude of B–$\bar{B}$ mixing amplitude

(b) B triangle:

determine the angles β, $2\beta+\gamma$, and $\beta+\gamma$ by measuring time-dependent CP violation in $B\to J/\psi\,K_S$, $B\to D^{(*)\pm}\pi^\mp$, and $B\to\pi\rho$

$\to$ CP violation in interference of mixing and decay

$\to$ main sensitivity to New Physics via mixing

Decay mode	Tree	Mix + Tree	e^+e^-	hadron
$B\to J/\psi\,K_S$ ($b\to c\bar{c}s$, $\bar{b}\to\bar{c}c\bar{s}$)	1	$e^{2i\beta}$	P1,P2	$\surd$
$B\to D^{(*)\pm}\pi^\mp$ ($b\to c\bar{u}d$, $\bar{b}\to\bar{u}c\bar{d}$)	1	$\lambda^2 e^{i(2\beta+\gamma)}$	P2,P3	$\surd$
$B\to\pi\rho$ ($b\to u\bar{u}d$, $\bar{b}\to\bar{u}u\bar{d}$)	$e^{-i\gamma}$	$e^{i(2\beta+\gamma)}$	P2,P3	$\surd$

(b') B triangle:

determine the angle γ using isospin analysis in $B^{\pm} \to DK^{\pm}$ decays

$\to$ only tree amplitudes involved

$\to$ lowest sensitivity to New Physics of all weak phase determinations!

Decay mode	Tree	Tree	e^+e^-	hadron
$B^{\pm} \to DK^{\pm}$ $(b \to c\bar{u}s,\ b \to u\bar{c}s)$	1	$e^{i\gamma}$	P2?,P3	?

(c) B_s triangle:

determine the angle $\gamma - 2\chi$ and the B_s mixing phase $-\chi$ (SM predicts $\chi = O(\lambda^2\eta)$ of order 1%) by measuring CP asymmetries in B_s decays, such as $B_s \to D_s^\pm K^\mp$, and $B_s \to J/\psi\,\phi$ or $B_s \to J/\psi\,\eta^{(\prime)}$

→ CP violation in interference of mixing and decay

→ main sensitivity to New Physics via mixing

Decay mode	Tree	Mix + Tree	e^+e^-	hadron
$B_s \to J/\psi\,\phi$ or $\eta^{(\prime)}$ ($b \to c\bar{c}s$, $\bar{b} \to \bar{c}c\bar{s}$)	1	$e^{-2i\chi}$	–	$\surd$
$B_s \to D_s^\pm K^\mp$ ($b \to c\bar{u}s$, $\bar{b} \to \bar{u}c\bar{s}$)	1	$e^{i(-2\chi+\gamma)}$	–	$\surd$

(d) K triangle:

determine the coordinates (ρ,η) from measurements of rare K decays ($K^+ \to \pi^+\nu\bar{\nu}$ and $K_L^0 \to \pi^0\nu\bar{\nu}$) and K–$\bar{K}$ mixing (ϵ_K)

$\rightarrow$ CP violation in mixing and decay

$\rightarrow$ sensitivity to New Physics in mixing and decay

$*$ performing these measurements is of comparable importance as the B_s physics program at hadron B factories!

Strategy for Exploring New Flavor Physics

Q: What if $\sin 2\beta_{\psi K}$ is low?

Q: More generally, what if there is New Physics affecting the particle–antiparticle mixing amplitudes of B_d, B_s and K mesons?

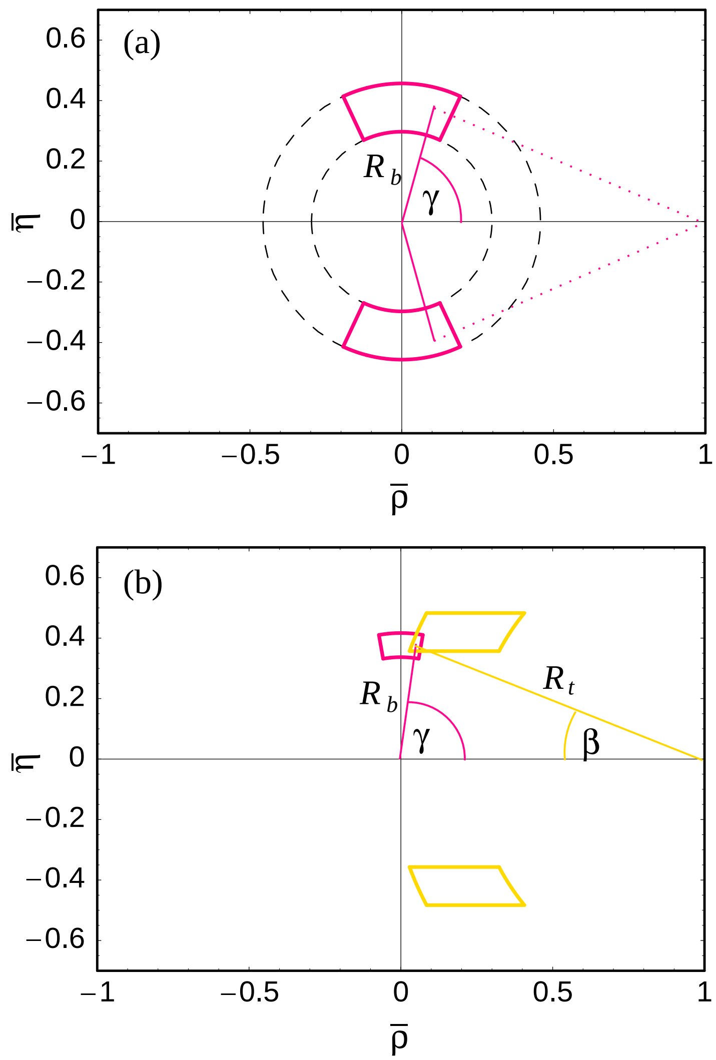
(see: A. Kagan and M. Neubert, hep-ph/0007360;
J.P. Silva and L. Wolfenstein, hep-ph/0008004;
G. Eyal, Y. Nir and G. Perez, hep-ph/0008009)

* then none of the triangle constructions discussed above should really close!

* need a reference triangle constructed independently of any information from mixing

  - B system: extract $|V_{ub}|$ from semi-leptonic B decays, and $\gamma = \arg(V_{ub}^*)$ using a variety of methods (e.g., charmless hadronic decays, $B \to DK$ decays, B_s decays)

  - K system: extract $|V_{td}|$ and $\mathrm{Im}(V_{td})$ from $K \to \pi\nu\bar{\nu}$ decays



Reference triangle in the near and long-term future:

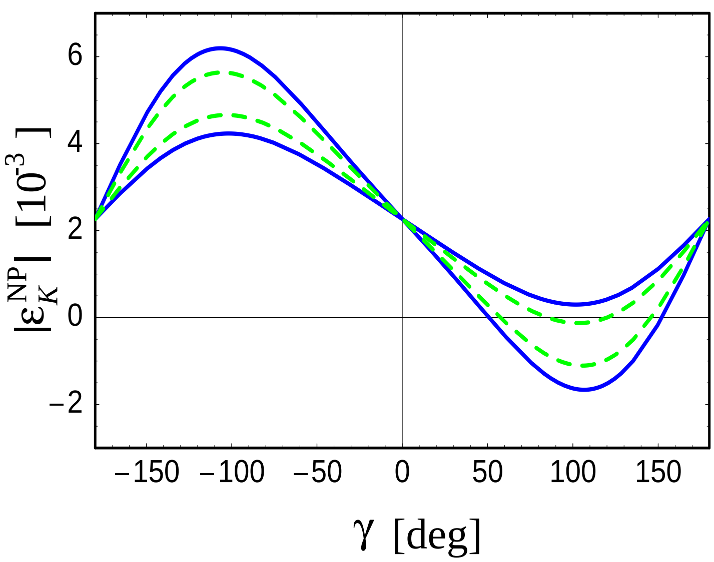
(a) B-decay triangle with two-fold ambiguity, assuming uncertainties of 20% in $|V_{ub}/V_{cb}|$ and $\pm 25^\circ$ in γ (near-term).

(b) B-decay triangle (pink) with no ambiguity, assuming uncertainties of 10% in $|V_{ub}/V_{cb}|$ and $\pm 10^\circ$ in γ, and K-decay triangle (gold) with four-fold ambiguity, assuming 15% uncertainties in R_t and $|\eta|$ (long-term).

* once the reference triangle is known, one can explore separately potential New Physics contributions to mixing in the B_d, B_s and K systems

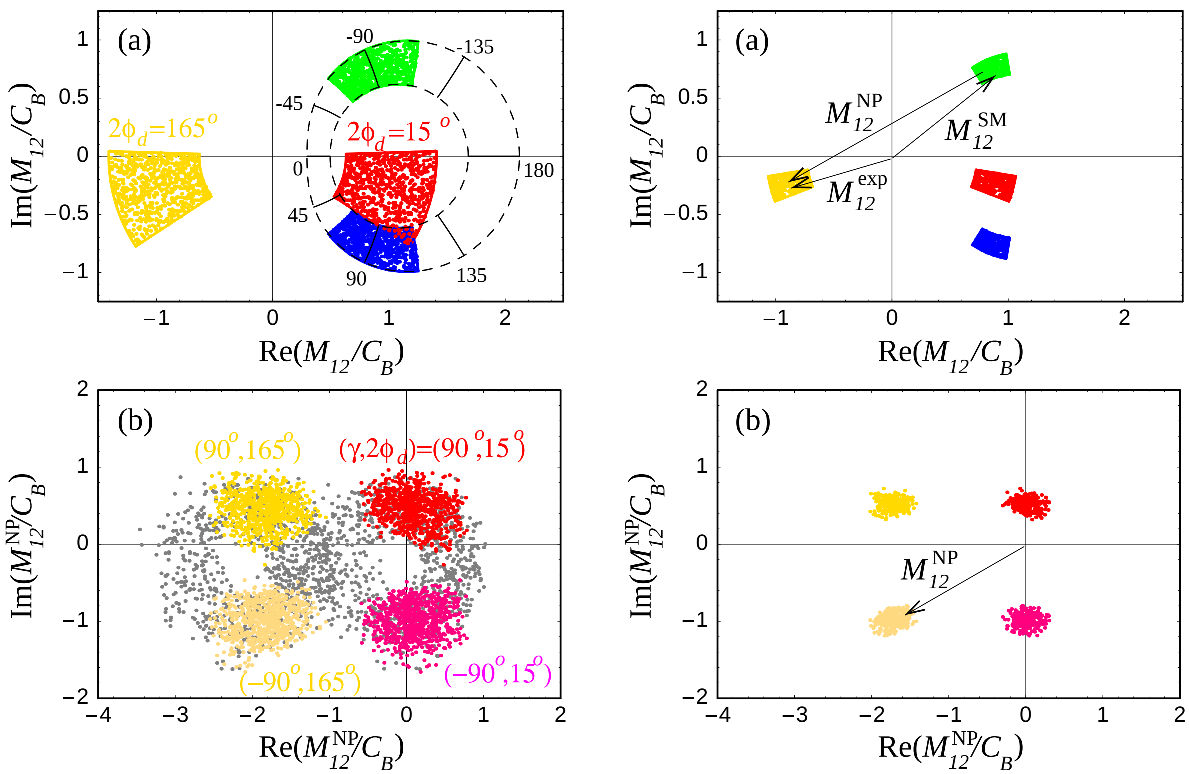
* knowledge of γ is the key ingredient that makes this strategy feasible and powerful!

New Physics in K–$\bar{K}$ mixing:



New Physics contribution to $|\epsilon_K|$ in units of 10^{-3}, assuming present day uncertainties (region bounded by blue curves, using $B_K = 0.86 \pm 0.10$ and $|V_{ub}/V_{cb}| = 0.085 \pm 0.018$) and future smaller errors (region bounded by green curves, using $B_K = 0.86 \pm 0.05$ and $|V_{ub}/V_{cb}| = 0.085 \pm 0.009$).

New Physics in B_d–$\bar{B}_d$ mixing:



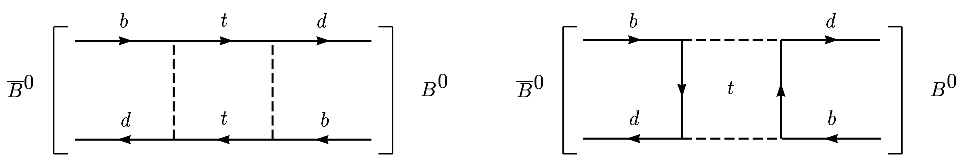
Determination of the B_d–$\bar{B}_d$ mixing amplitude M_{12} with present day (left) and future (right) uncertainties on the input parameters.

(a) Standard Model contribution $M_{12}^{\rm SM}$ (region bounded by dashed circles) with marks indicating fixed values of γ. The experimentally determined regions for M_{12} are shown for $\sin 2\phi_d = 0.26 \pm 0.29$.

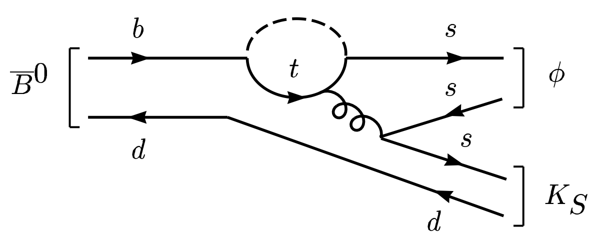
(b) New Physics contribution $M_{12}^{\rm NP}$ corresponding to the four different solutions for γ and $2\phi_d$.

New Physics in Penguins

* above strategies are sensitive to New Physics mainly via the B_d–$\bar{B}_d$ and B_s–$\bar{B}_s$ mixing amplitudes (box diagrams)



* there is, in addition, a large class of loop-dominated processes sensitive to New Physics in the decay amplitude (penguins)



* consider some examples of how to explore this type of New Physics...

1. determine β from interference of mixing and decay in the penguin-mediated mode $B \to \phi K_S$, and compare with β from $B \to J/\psi\, K_S$

Decay mode	Peng.	Mix + Peng.	e^+e^-	hadron
$B \to \phi K$ ($b \to s\bar{s}s$, $\bar{b} \to \bar{s}s\bar{s}$)	1	$e^{2i\beta}$	P2,P3	$\surd$

2. certain observables are particularly sensitive to New Physics contributions to chromo-magnetic or chromo-electric dipole operators

   $\to$ direct CP asymmetry in inclusive radiative decays $B^\pm \to X_s\gamma$ is a clean probe of such effects, with basically no SM background

   (A. Kagan and M. Neubert, 1998)

3. certain observables are particularly sensitive to isospin-violating New Physics contributions in $b \to s(d) + \bar{q}q$ transitions (with $q = u$ or d)

$\to$ potentially large effect on γ determined from $B \to \pi K$ decays, which would show up if $\gamma_{\pi K}$ is compared with $\gamma_{\rm tree} = \gamma_{DK}$ or $\gamma_{\pi\rho}$:

(Y. Grossman et al., 1999)

New Physics Model	$\lvert\gamma_{\pi K} - \gamma_{\rm tree}\rvert$ isospin-cons.	$\lvert\gamma_{\pi K} - \gamma_{\rm tree}\rvert$ isospin-viol.
FCNC Z exchange	3°	180°
Extra Z' boson	180°	180°
SUSY without R-parity	180°	180°
SUSY with R-parity:		
max. $\tilde{s}_R$–$\tilde{b}_R$ mixing	7°	25°
max. $\tilde{s}_L$–$\tilde{b}_L$ mixing	7°	180°
2-Higgs-doublet model	0°	10°
($m_{H^+} > 100$ GeV, $\tan\beta > 1$)		
anom. gauge-boson couplings	0°	20°

Instead of a Summary...

Four Reasons Why B Physics is Cooler than String Theory

1. B theorists look forward to confronting experiment.

   String theorists look forward to not confronting experiment.

2. B theorists make effective theories:
   heavy-quark effective theory, large-energy effective theory, non-relativistic effective theory...

   String theorists make:
   A theory (of the Universe) ... K theory ... M theory ...
   1-branes ... 5-branes ... d-branes ... p-branes ...

3. String theorists dream of a Theory of Everything.

   B theorists have a Theory of Something.

4. We know what we are talking about...