Introduction to Heavy Meson Decays and CP Asymmetries

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Thanks to: Adam Falk, Sandrine Laplace, Mike Luke, Yossi Nir

References

An incomplete list:

- Y. Nir, hep-ph/0109090
- A. Falk, hep-ph/0007339
- The Babar Physics Book, SLAC-R-0504
- B Physics at the Tevatron: Run II and Beyond, hep-ph/0201071
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- Bigi and Sanda, CP *Violation,* Cambridge University Press, New York, 2000
- Branco, Lavoura and Silva, CP *Violation,* Clarendon Press, Oxford, 1999

Disclaimers

In these lectures:

... I will not talk about the strong CP problem

see: H. Quinn, hep-ph/0110050
M. Dine, hep-ph/0011376

$$\mathcal{L} = \frac{\theta_{QCD}}{16\pi^2} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

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see: lectures of P. Lepage

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... And most importantly:

If I do not talk about your favorite decay mode [the one you're working on...], it does not mean that I think it's not important!

Dictionary

- SM $=$ standard model
- NP $=$ new physics
- CPV $= CP$ violation/violating
- CPC $= CP$ conserving
- UT $=$ unitarity triangle

Central questions about SM

1. Origin of electroweak symmetry breaking:

   $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$

   spontaneous breaking of a gauge symmetry by $v \sim 250\,$GeV VEV

   $W_L W_L \to W_L W_L$ breaks unitarity $\sim 1\,$TeV ... determines scale of Higgs / NP

2. Origin of flavor symmetry breaking:

   $U(3)_Q \times U(3)_u \times U(3)_d \to U(1)_{\rm Baryon}$ (for leptons don't even know yet!)

   global symmetries (e.g, d_R, s_R, b_R identical if massless) broken by dimensionless Yukawa couplings ... we do not know what scale to look

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It would be nice if flavor and electroweak symmetry breaking were connected

Flavor physics depends on both — Yukawa couplings determine quark masses, mixing, and CP violation

Central questions of flavor physics

1. Does the SM (i.e., only virtual quarks, W, and Z interacting through CKM matrix in tree and loop diagrams) explain all flavor changing interactions?
2. If it does not, then at what level and where can we see deviations?

To answer these questions, we need: Experimental precision
Theoretical precision — cleanliness

corollary:

The point is not simply to measure CKM elements, but to overconstrain the SM description of flavor by many “redundant” measurements

The key processes are those which can teach us about high energy phsyics without hadronic uncertainties

Interplay between weak and strong interactions

- Can we learn about high energy physics from low energy hadronic processes?

QCD coupling is scale dependent:

$$\alpha_s(\mu) = \frac{\alpha_s(M)}{1 + \dfrac{\alpha_s}{2\pi}\,\beta_0 \ln \dfrac{\mu}{M}}$$

High energy (short distance): perturbation theory is useful

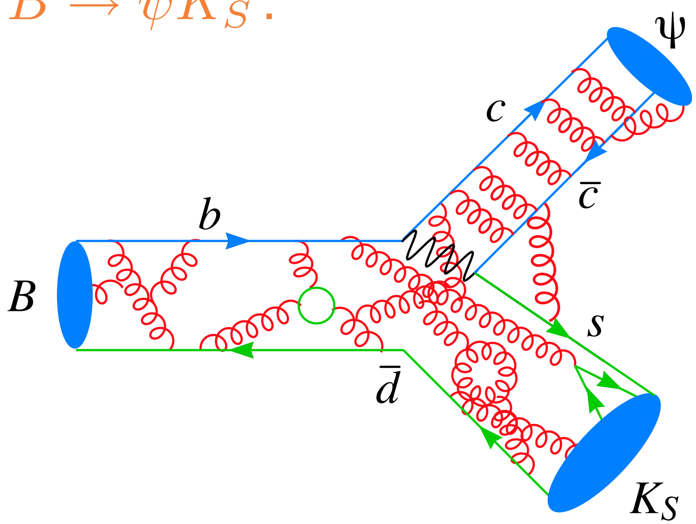
Low energy (long distance): QCD becomes nonperturbative $\Rightarrow$ It is usually very hard, if not impossible, to make precise calculations

- Solutions: – Use symmetries of QCD (exact or approximate)
  – Certain processes are determined by short-distance physics

Sometimes it is possible to use data and symmetries together to eliminate uncalculable hadronic mess

(1) Want to learn about CP violation

- $\sin(2\beta)$ from $B \to \psi K_S$:



energy release:

$m_B - m_\psi - m_K \simeq 1.7$ GeV

Contributions of diagrams with many soft gluons are not suppressed

Theoretically clean measurement of $\sin(2\beta)$ possible (at $< 1\%$ level), because amplitudes with one weak phase dominate

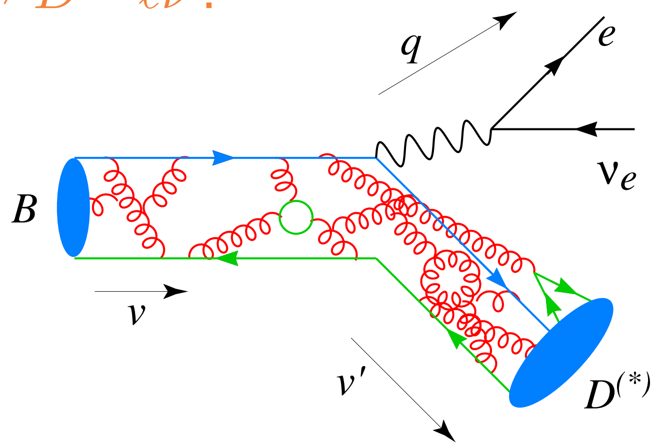
- Solution: CP symmetry of strong interactions (exact symmetry)

The magnitude of the amplitude does not matter, only need the relation:

$$\langle \psi K_S | \mathcal{H} | B^0 \rangle = -\langle \psi K_S | \mathcal{H} | \overline{B}^0 \rangle \times [1 + \mathcal{O}(\alpha_s \lambda^2)]$$

(2) Want to learn about CKM elements

- $|V_{cb}|$ from $B \to D^{(*)} \ell \bar{\nu}$:



Contributions of diagrams with many soft gluons are not suppressed

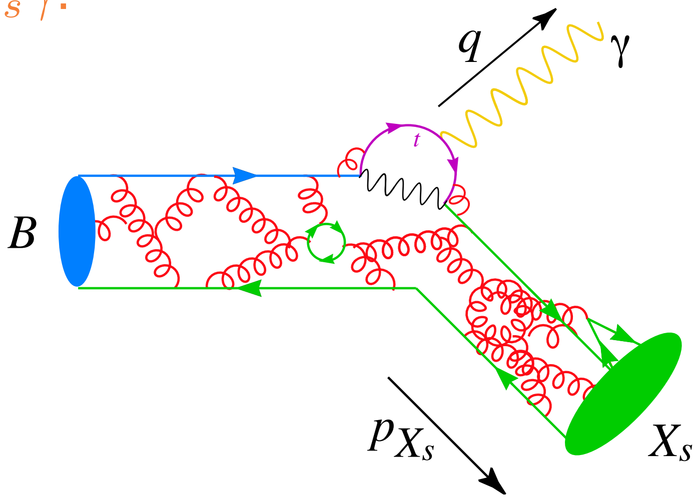
Theoretically clean measurement of $|V_{cb}|$ possible (at 5% level), because hadronic matrix element is known in the $m_{c,b} \to \infty$ limit at “zero recoil” $v \cdot v' = 1$

- Solution: Heavy quark symmetry in heavy mesons (approximate symmetry)

determines rate at zero recoil: $\langle D^*(v)|\, J \,|B(v)\rangle = 1 + \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{(2m_c)^2}\right)$

(3) Want to learn about physics beyond the SM

- E.g.: $B \to X_s \gamma$:



Inclusive decay:
$X_s = K^*,\ K^{(*)}\pi,\ K^{(*)}\pi\pi$, etc.

Diagrams with many gluons are crucial, resumming certain subset of them affects rate at factor-of-two level

Rate calculable at 10% level, using several effective theories, renormalization group, operator product expansion... one of the most involved SM analyses

- Solution: Short distance dominated; unknown corrections suppressed by

$$\Gamma(B \to X_s\gamma) = [\text{known}] \times \left\{1 + \mathcal{O}\left(\alpha_s^3 \ln\frac{m_W}{m_b}, \frac{\Lambda_{\text{QCD}}^2}{m_{b,c}^2}, \frac{\alpha_s \Delta m_c}{m_b}\right)\right\}$$

Outline (1)

1. Introduction to flavor physics and CPV

   ... Brief SM review

   ... How CKM matrix arises from Yukawa couplings

   ... Present status

   Mixing and CPV in neutral meson systems (K, D, B, B_s)

   ... Ways to obtain clean information about short distance physics

   ... Mixing: Δm_{B_d} and Δm_{B_s}

   ... CPV: $B \to \psi K_s$, $B \to \phi K_s$

Outline (2–3)

2. The heavy quark limit

    ... Heavy quark symmetry: spectroscopy, strong decays

    ... Exclusive $B \to D^{(*)}\ell\nu$ decays and $|V_{cb}|$ (HQET)

    ... Inclusive semileptonic decays, $|V_{cb}|$ (OPE)

    ... Inclusive $|V_{ub}|$ measurements and rare decays

3. Some clean CP measurements

    ... $B_s \to D_s K$, $B \to \pi\pi$ isospin analysis, $B \to DK$

    Nonleptonic decays, factorization

    ... Factorization in $B \to D^{(*)}X$ decays; tests of factorization

    ... Factorization in charmless decays

    ... Tests / applications in decays to pseudoscalars (α, γ)

    Final thoughts

Introduction

The Standard Model (SM)

Gauge symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$ — parameters

8 gluons $\quad W^{\pm}$, Z^0, γ — 3

Particle content: 3 generations of quarks and leptons

$Q_L(3,2)_{1/6},\ u_R(3,1)_{2/3},\ d_R(3,1)_{-1/3}$ — 10

$L_L(1,2)_{-1/2},\ \ell_R(1,1)_{-1}$ — $3(+9)$

quarks: $\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$ $\quad$ leptons: $\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix}$

Symmetry breaking: $SU(2)_L \times U(1)_Y \ \to \ U(1)_{\mathrm{EM}}$

$\phi(1,2)_{1/2}$ Higgs scalar, $\quad \langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$ — 2

- The SM agrees (too well...) with all observed particle physics phenomena

Why is CPV interesting?

"CPV is a mystery"

... the SM with 3-generations "predicts" it

"CPV is one of the least understood parts of the SM"

... $\sin 2\beta$, ϵ_K, ϵ' are all in the right ballpark

BUT:

– Almost all extensions of the SM contain new sources of CP and flavor violation

– Major constraint for model building, may distinguish between NP models

– The observed baryon asymmetry of the Universe requires CPV beyond the SM (not necessarily in flavor changing processes)

If $\Lambda_{\rm CPV} \gg \Lambda_{\rm EW}$: no observable effects in B decays $\Rightarrow$ precise SM measurements

If $\Lambda_{\rm CPV} \sim \Lambda_{\rm EW}$: sizable effects possible $\Rightarrow$ could get detailed information on NP

The track record

Bits of history: $K\bar{K}$ mixing $\Rightarrow$ GIM & charm

CP violation $\Rightarrow$ three generations, CKM

$B\bar{B}$ mixing $\Rightarrow$ heavy top

Best sensitivity to some particles predicted in the MSSM comes from (crudely...)

experiment	energy scale	best sensitivity to
Tevatron	~ 2 TeV	squarks, gluinos
LEP	~ 200 GeV	sleptons, charginos
$B \to X_s\gamma$	~ 5 GeV	charged Higgs

SM: where can CP violation occur?

- Kinetic terms: $\mathcal{L}_{\rm kin} = -\frac{1}{4}\sum_{\rm groups} (F^a_{\mu\nu})^2 + \sum_{\rm rep's} \overline{\psi}\, i \not{D}\, \psi$

  always CPC (ignoring $F\widetilde{F}$)

- Higgs terms: $\mathcal{L}_{\rm Higgs} = |D_\mu \phi|^2 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger\phi)^2 \qquad (v^2 = \mu^2/\lambda)$

  CPC if $\exists$ only one Higgs doublet; CPV possible with extended Higgs sector

- Yukawa couplings in interaction basis:

$$\mathcal{L}_Y = -Y^d_{ij}\, \overline{Q^I_{Li}}\, \phi\, d^I_{Rj} - Y^u_{ij}\, \overline{Q^I_{Li}}\, \widetilde{\phi}\, u^I_{Rj} - Y^\ell_{ij}\, \overline{L^I_{Li}}\, \phi\, \ell^I_{Rj} + \text{h.c.}$$

cannot write mass term for ν's!

$i, j \sim$ generations

$$\searrow = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \phi^*$$

CPV is related to unremovable phases of Yukawa couplings:

$$Y_{ij}\, \overline{\psi_{Li}}\, \phi\, \psi_{Rj} + Y^*_{ij}\, \overline{\psi_{Rj}}\, \phi^\dagger\, \psi_{Li}$$

$\Downarrow$ CP exchanges fermion bilinears

$$Y_{ij}\, \overline{\psi_{Rj}}\, \phi^\dagger\, \psi_{Li} + Y^*_{ij}\, \overline{\psi_{Li}}\, \phi\, \psi_{Rj}$$

Quark mixing

- Replacing ϕ with its VEV in Yukawa couplings:

$$\mathcal{L}_{\rm mass} = -(M_d)_{ij}\,\overline{d^I_{Li}}\,d^I_{Rj} - (M_u)_{ij}\,\overline{u^I_{Li}}\,u^I_{Rj} - (M_\ell)_{ij}\,\overline{\ell^I_{Li}}\,\ell^I_{Rj} + \text{h.c.}$$

$M_f = \dfrac{v}{\sqrt{2}} Y^f$ — want to diagonalize these ($f = u, d, \ell$)

$M_f^{\rm diag} \equiv V_{fL}\, M_f\, V_{fR}^\dagger$ — $V_{L,R}$ unitary matrices

Define mass eigenstates:
$$f_{Li} \equiv (V_{fL})_{ij}\, f^I_{Lj}$$
$$f_{Ri} \equiv (V_{fR})_{ij}\, f^I_{Rj}$$

- The quark mass matrices are diagonalized by different transformations for u_{Li} and d_{Li}, which are part of the same $SU(2)_L$ doublet Q_L

$$\begin{pmatrix} u^I_{Li} \\ d^I_{Li} \end{pmatrix} = (V^\dagger_{uL})_{ij} \begin{pmatrix} u_{Lj} \\ (V_{uL}V^\dagger_{dL})_{jk}\, d_{Lk} \end{pmatrix}, \qquad V_{\rm CKM} \equiv V_{uL}V^\dagger_{dL}$$

Which terms in the Lagrangian get modified by this transformation?

SM: where can flavor violation occur?

- In mass basis, charged current ($W^\pm$) weak interactions become complicated:

$$-\frac{g}{2}\,\overline{Q^I_{Li}}\,\gamma^\mu\, W^a_\mu\, \tau^a\, Q^I_{Li} + \text{h.c.} \;\Rightarrow\; -\frac{g}{\sqrt{2}}\,\left(\overline{u_L},\ \overline{c_L},\ \overline{t_L}\right)\gamma^\mu\, W^+_\mu \underbrace{(V_{uL}V^\dagger_{dL})}_{\Uparrow} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

Cabibbo-Kobayashi-Maskawa matrix: $V_{\rm CKM}$

Only source of CPV in flavor changing processes in the SM

- The neutral current (Z^0) interactions remain flavor conserving in the mass basis (True in all models with only left handed doublet and right handed singlet quarks)

$\Rightarrow$ In the SM, only charged current interactions change flavor

How do we know that CP is violated?

- Prior to 1964, the explanation of the large lifetime ratio of the two neutral kaons was CP symmetry (before 1956, it was C alone...)

$$|K^0\rangle = \bar{s}\, d\,, \qquad |\overline{K}^0\rangle = \bar{d}\, s\,, \qquad CP|K^0\rangle = +|\overline{K}^0\rangle$$ (convention dependent)

states of definite CP: $|K_{1,2}\rangle = \frac{1}{\sqrt{2}}\,(|K^0\rangle \pm |\overline{K}^0\rangle)$

$$CP|K_1\rangle = |K_1\rangle\,, \qquad CP|K_2\rangle = -|K_2\rangle$$

If CP were an exact symmetry: $\left.\begin{array}{l}\text{only } K_1 \to \pi\pi \\ \text{both } K_{1,2} \to \pi\pi\pi\end{array}\right\} \Rightarrow \tau(K_1) \ll \tau(K_2)$

- But $K_L \to \pi\pi$ decay was also observed (1964) at the 10^{-3} level!

$$\eta_{00} = \frac{\langle \pi^0\pi^0|\mathcal{H}|K_L\rangle}{\langle \pi^0\pi^0|\mathcal{H}|K_S\rangle} \quad \eta_{+-} = \frac{\langle \pi^+\pi^-|\mathcal{H}|K_L\rangle}{\langle \pi^+\pi^-|\mathcal{H}|K_S\rangle} \quad \epsilon_K \equiv \tfrac{1}{3}\,(\eta_{00} + 2\eta_{+-}) \quad \epsilon'_K \equiv \tfrac{1}{3}\,(\eta_{+-} - \eta_{00})$$

Was <1 yr to propose superweak, but 9 till KM (before 2nd generation complete!)

Baryogenesis

$$\frac{\#\text{ baryons}}{\#\text{ photons}} \sim 10^{-9} \text{ now} \iff \frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim 10^{-9} \text{ at } t < 10^{-6} \text{ sec } (T > 1\,\text{GeV})$$

- To produce such an asymmetry from symmetric initial conditions, need

1. baryon number violating interactions
2. C and CP violation
3. deviation from thermal equilibrium

- SM contains 1–3, but

A. CP violation is too small

B. deviation from thermal equilibrium too small with just one Higgs doublet

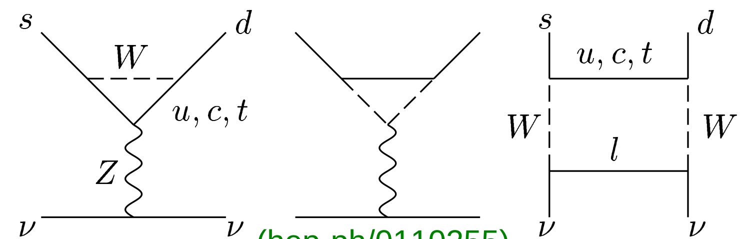
NP models can solve A–B near the weak scale, and may have observable effects (possibly only in flavor diagonal processes, such as electric dipole moments)

Why B physics?

- Observed CPV in K system is at the right level (ϵ_K can be described with $\mathcal{O}(1)$ CKM phase), but hadronic uncertainties preclude precision tests (ϵ'_K is notoriously hard to calculate)

  Plan to measure $K \to \pi\nu\overline{\nu}$ — theoretically clean, but $\mathcal{B} \sim 10^{-10}(K^\pm)$, $10^{-11}(K_L)$

$$\mathcal{A} \propto \begin{cases} (\lambda^5\, m_t^2) + i(\lambda^5\, m_t^2) & t: \text{CKM suppressed} \\ (\lambda\, m_c^2) + i(\lambda^5\, m_c^2) & c: \text{GIM suppressed} \\ (\lambda\, \Lambda_{\text{QCD}}^2) & u: \text{GIM suppressed} \end{cases}$$



(hep-ph/0110255)

- In D decays the SM predicts small CPV, interesting for NP (few words later)

- In the B meson system, large variety of interesting processes:
  - top quark loops neither GIM nor CKM suppressed (large mixing, rare decays)
  - large CP violating effects possible, some of which have clean interpretation
  - some of the hadronic physics understood model independently ($m_b \gg \Lambda_{\text{QCD}}$)

CKM matrix and the unitarity triangle

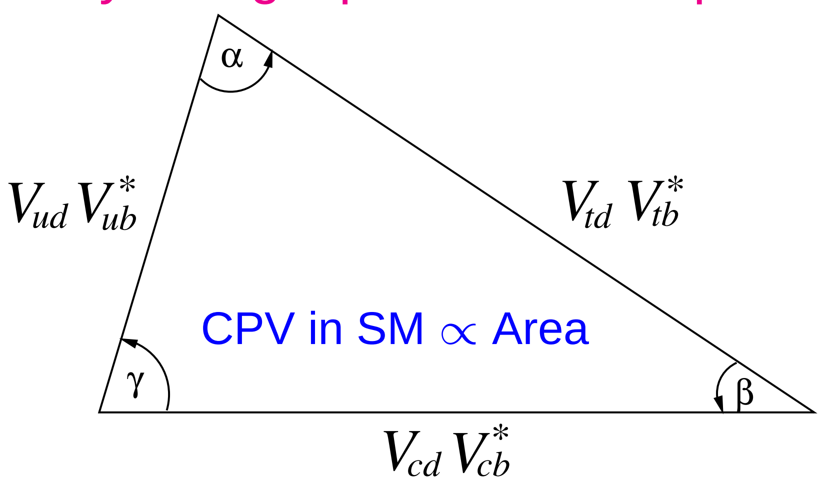
- CKM matrix is hierarchical

$$(u,\, c,\, t) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad \begin{matrix} \sim 1 \\ \sim \lambda \\ \sim \lambda^2 \\ \sim \lambda^3 \end{matrix} \qquad \lambda \sim 0.22$$

Elements depend on 4 real parameters (3 angles $+$ 1 CPV phase)

$\mathbf{V}_{\mathrm{CKM}}$ is the only source of CPV in the SM

- The unitarity triangle provides a simple way to visualize the SM constraints



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

The angles and sides are directly measurable — want to overconstrain this picture

Wolfenstein parameterization

- It is convenient to exhibit the hierarchical structure by expanding in $\lambda = \sin\theta_C$

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

Present uncertainties: $\lambda \sim 1\%$, $A \sim 5\%$, $\eta/\rho \sim 7\%$, $\sqrt{\rho^2+\eta^2} \sim 20\%$,

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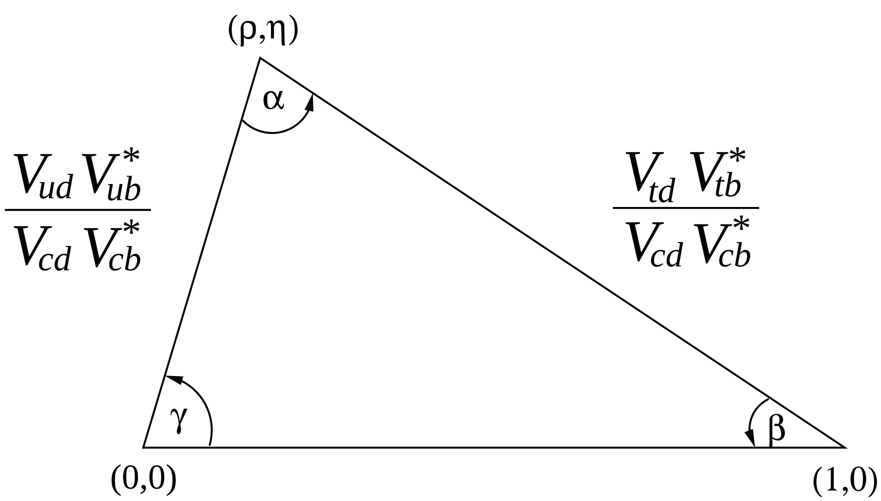
- Constraints on CKM usually plotted on the $(\bar\rho, \bar\eta)$ plane, $\bar\rho + i\bar\eta \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$



$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Experimental program

- Goal: precision tests of the flavor sector via redundant measurements, which in the SM determine CKM elements, but sensitive to different short distance physics

New physics could easily modify:

– SM loop processes: mixing
rare decays

– CP violation

So we want to measure:

– mixing & rare decays

– CPV asymmetries

– compare tree and loop processes

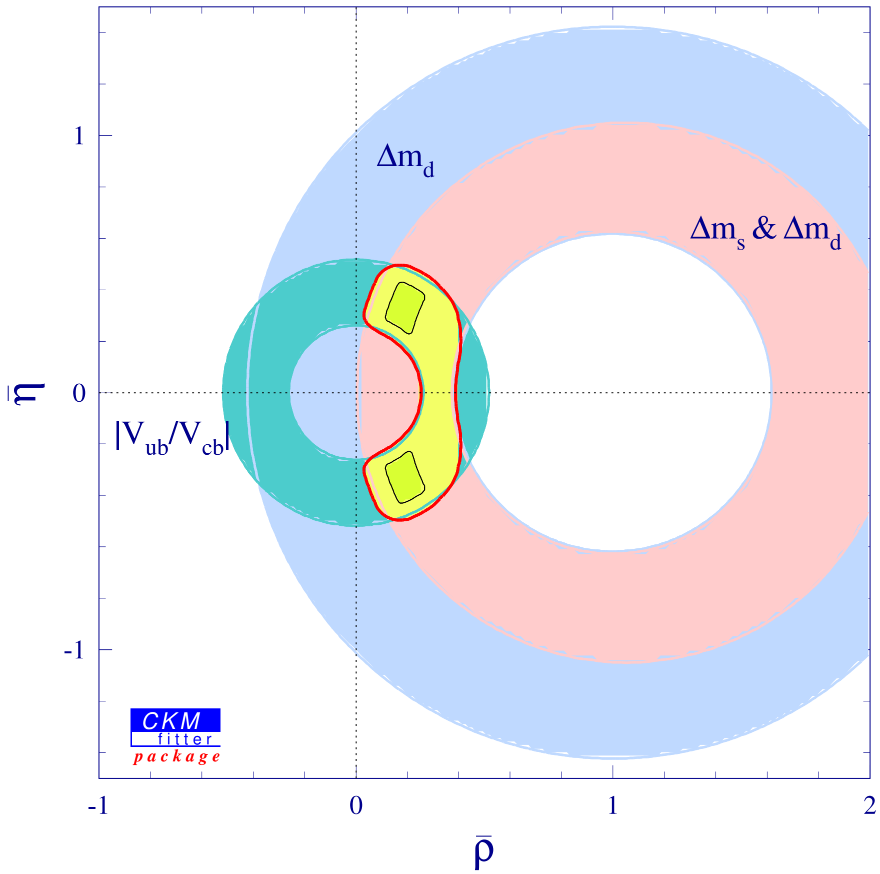
- In the presence of NP, many independent and large CPV phases are possible; Then "α, β, γ" is only a language and two "would-be" γ measurements can be sensitive to different NP contributions (similarly for $|V_{td}|, |V_{ts}|$)

Do all possible measurements which have clean interpretation; correlations may be crucial to narrow down type of NP

$\Rightarrow$ Very broad program — independent measurements are searching for NP!

Present knowledge of $(\bar{\rho}, \bar{\eta})$

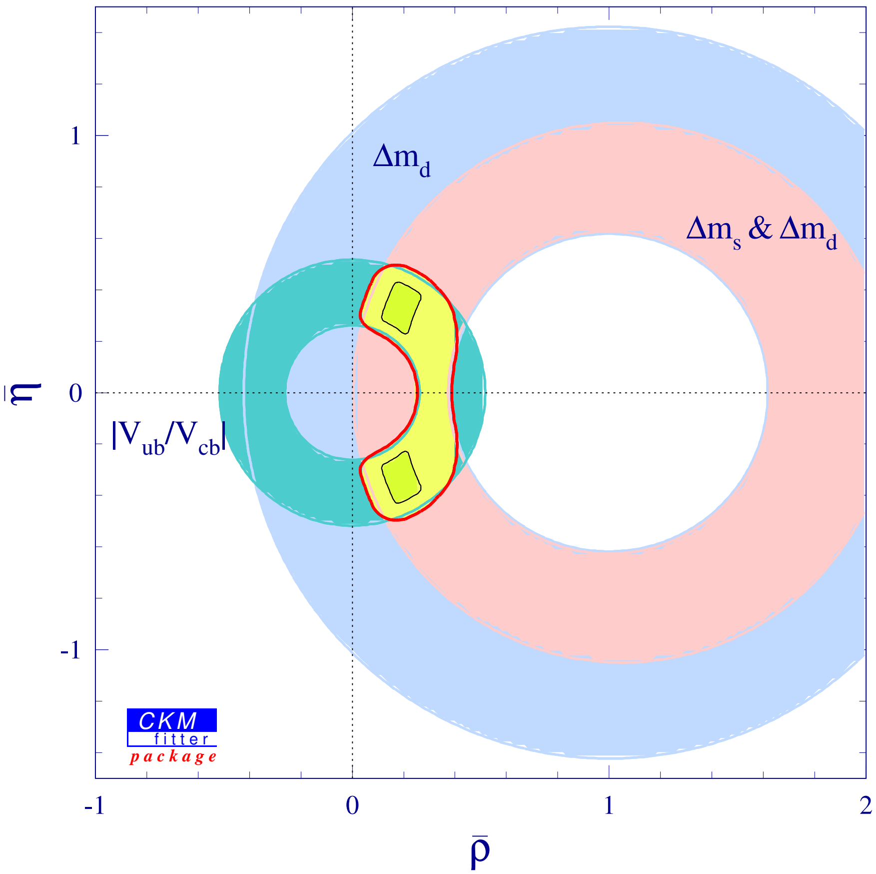
Tree level $+ \, CP$ conserving only

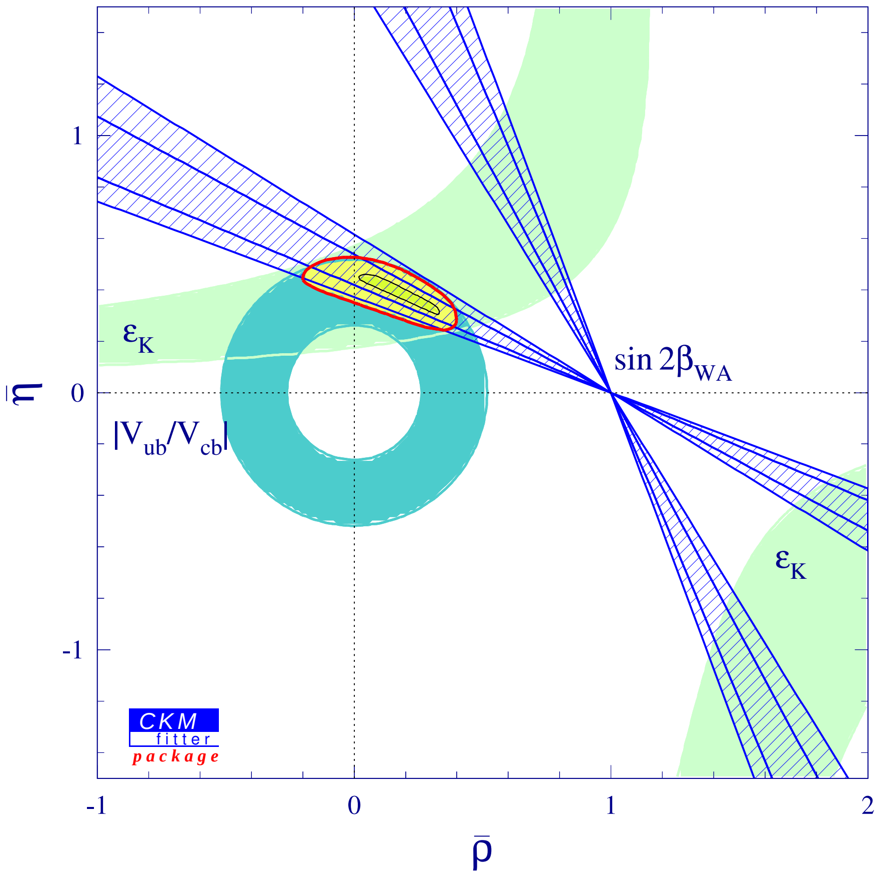


Present knowledge of $(\bar{\rho}, \bar{\eta})$

Tree level $+$ CP conserving

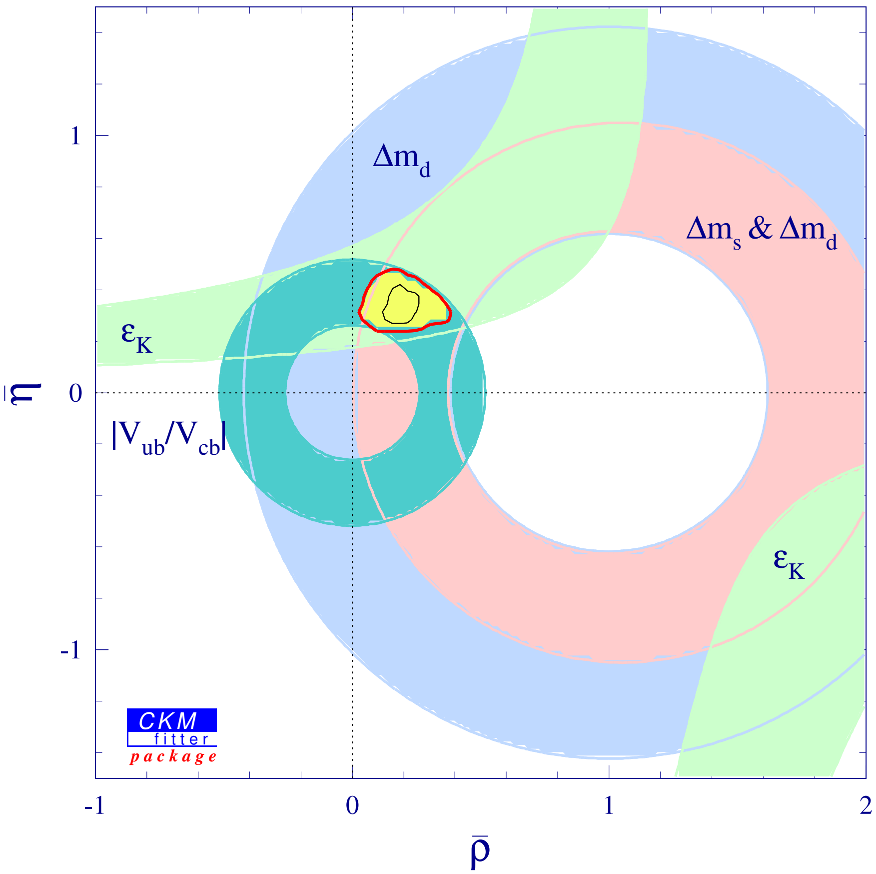
Tree level $+$ CP violating



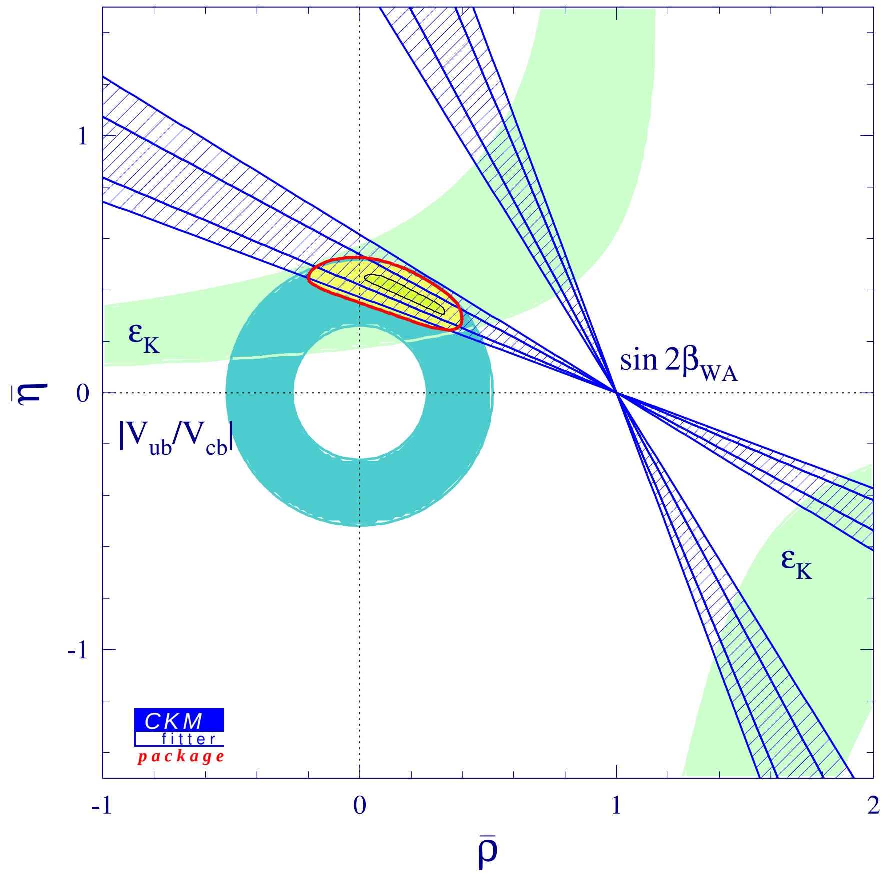


Present knowledge of $(\bar{\rho}, \bar{\eta})$

Tree level $+$ CP conserving $+$ ϵ_K



Tree level $+$ CP violating

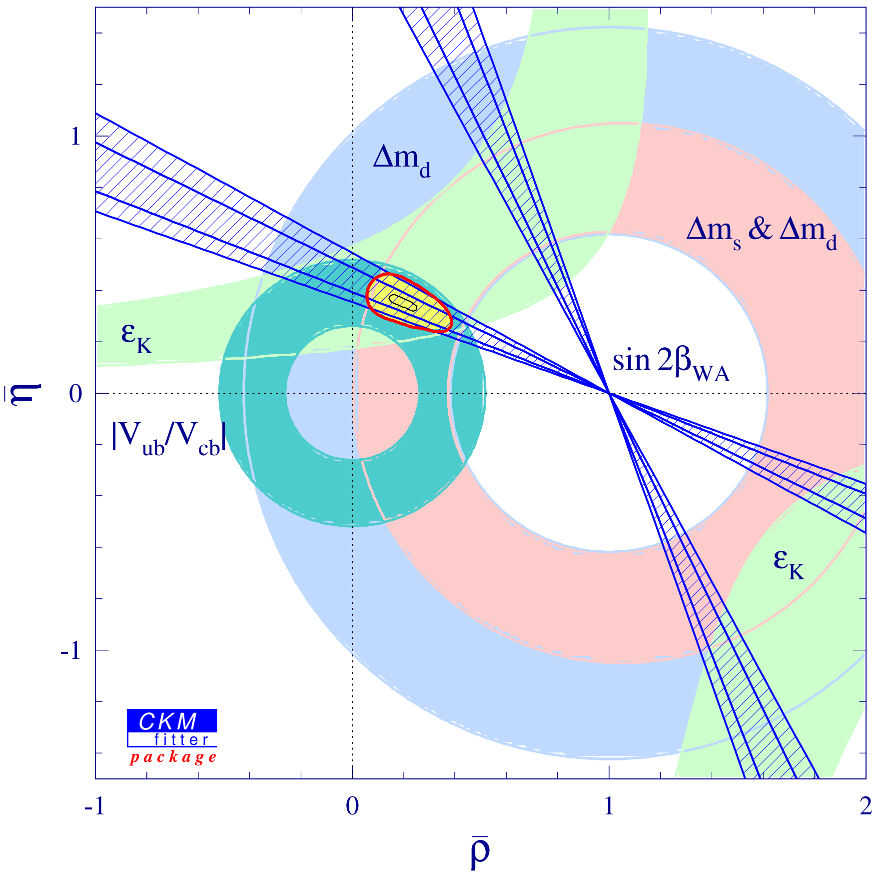


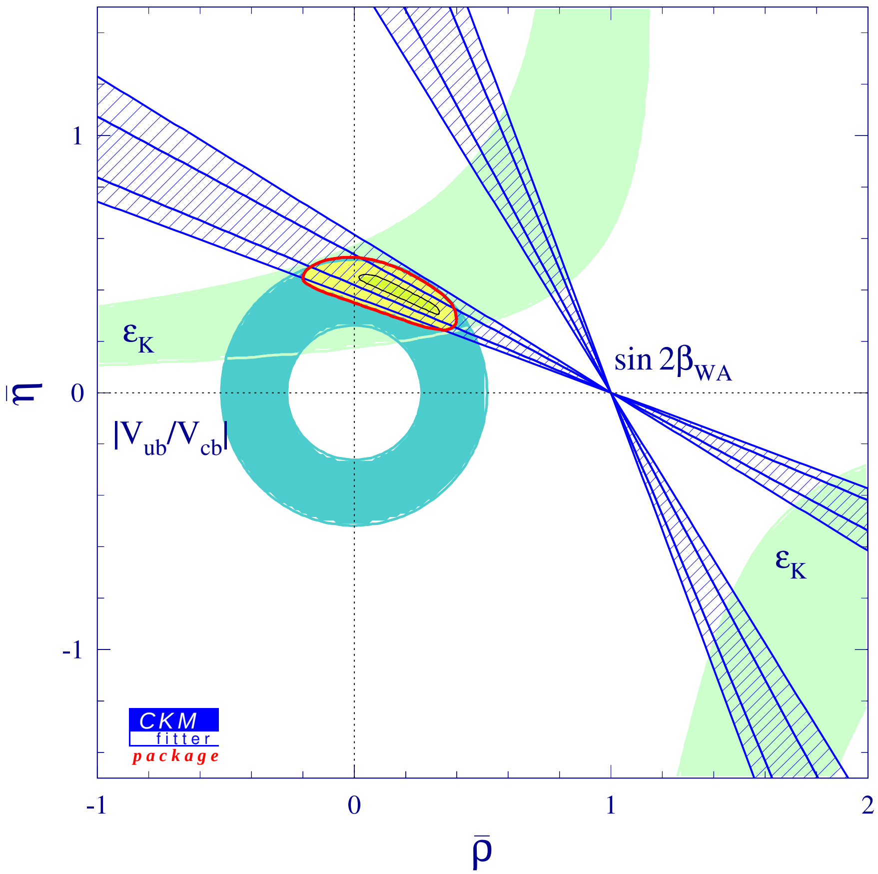
Berkeley Lab

Present knowledge of $(\bar{\rho}, \bar{\eta})$

Full standard model fit

Tree level $+$ CP violating





Summary — so far

- The CKM picture of CPV passed its first non-trivial test; $\sin 2\beta$ has become the best known ingredient of the unitarity triangle

  Paradigm change: look for corrections to – rather than alternatives to CKM picture

  Questions: Is the SM the *only* source of CPV?

  Does the SM *fully* explain flavor physics?

  Key measurements: ones that are theoretically clean and experimentally doable

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- Heading towards $\leq 10\%$ test of CKM: Our ability to test CKM in B decays depends on precision of measurements besides $\sin 2\beta$ and $|V_{td}/V_{ts}|$ (today)

  Central themes: 1) How to determine $|V_{ub}|$ model independently (2nd lecture)

  2) Utility of factorization & $SU(3)$ to determine α / γ from rates or "simple" time dependent asymmetries (3rd lecture)

  3) "Zero prediction" observables: $a_{CP}(B_s \to \psi\phi)$, $a_{dir}(B \to s\gamma)$

Mixing and CPV in neutral mesons

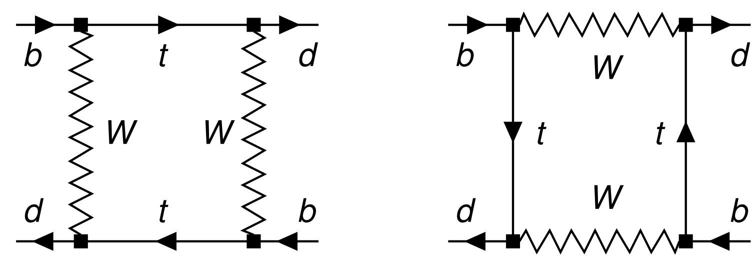
Neutral meson mixing

- Two flavor eigenstates, e.g.: $|B^0\rangle = |\bar{b}\, d\rangle,\ |\overline{B}{}^0\rangle = |b\, \bar{d}\rangle$; time evolution satisfies

$$i\,\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}{}^0(t)\rangle \end{pmatrix} = \Big(M - \frac{i}{2}\,\Gamma\Big)\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}{}^0(t)\rangle \end{pmatrix}$$

  M, Γ are 2×2 Hermitian matrices; CPT implies $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$

  Off-diagonal elements due to box diagrams dominated by top quarks $\Rightarrow$ sensitive to high scales



  Mass eigenstates are eigenvectors of $\mathcal{H}$:

  $|B_L\rangle = p|B^0\rangle + q|\overline{B}{}^0\rangle\,, \qquad |B_H\rangle = p|B^0\rangle - q|\overline{B}{}^0\rangle$

  $|B_{H,L}(t)\rangle = e^{-(iM_{H,L}+\Gamma_{H,L}/2)t}|B_{H,L}\rangle$ time dependence involves mixing and decay

- In the $|\Gamma_{12}| \ll |M_{12}|$ limit, which holds for both $B_{d,s}$ within and beyond the SM

$$\Delta m = 2|M_{12}|\,, \quad \Delta\Gamma = 2|\Gamma_{12}|\cos\phi_{12}\,, \quad \phi_{12} = \arg\Big(-\frac{M_{12}}{\Gamma_{12}}\Big) \quad \Rightarrow$$

  NP cannot enhance B_s width difference

Aside: importance of $|\Gamma_{12}| \ll |M_{12}|$

- New physics in mixing modifies M_{12}; new CPV phases may alter $\phi \equiv \arg(q/p)$[1]
  Observing ϕ different from the SM prediction may be the best hope to find NP

  $$B_{d,s}\!: \;\; \Gamma_{12} \ll M_{12}, \qquad\qquad K\!: \;\; M_{12} \sim \Gamma_{12}, \qquad\qquad D\!: \;\; \Gamma_{12} \sim \text{or} > M_{12}$$

  Solving the eigenvalue equation:

  – If $\Delta m \gg \Delta\Gamma$, the CPV phase can be **LARGE**: $\phi = \arg(M_{12}) + \mathcal{O}(\Gamma_{12}^2/M_{12}^2)$

  – If $\Delta\Gamma \gg \Delta m$, the CPV phase is SMALL: $\phi = \mathcal{O}(M_{12}^2/\Gamma_{12}^2) \times \sin(2\,\phi_{12})$

- If $\Delta\Gamma \gg \Delta m$ then even if new physics dominates M_{12}, the sensitivity of any physical observable to it is suppressed by $\Delta m/\Delta\Gamma$

  In the D system it is possible that long distance contributions and $SU(3)$ breaking enhance $\Delta\Gamma$ compared to Δm, this would make looking for NP hard

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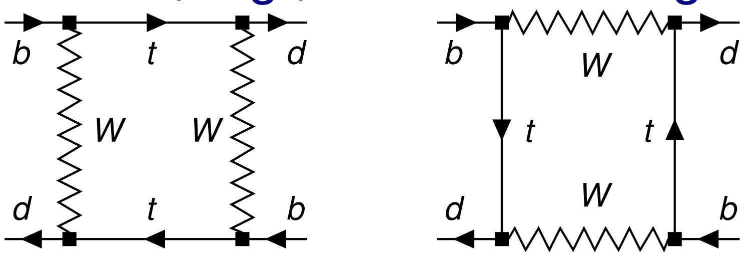
[1]Note: $\arg(q/p)$ is convention dependent; think of it in D decay as the relative phase between q/p and the phase of a tree level decay assumed to be real.

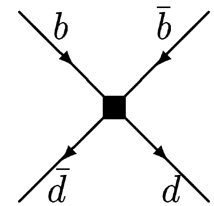
Aside: effective Hamiltonians

- Interactions at high scale (weak or new physics) produce local operators at lower scales (hadron masses)

Consider, e.g., $B^0 - \overline{B}^0$ mixing:



$\Rightarrow$



$$Q(\mu) = (\bar{b}_L\, \gamma_\nu\, d_L)\, (\bar{b}_L\, \gamma^\nu\, d_L)$$

New physics can modify coefficients and/or induce new operators

Going from operators to observables is equally important

In SM:
$$M_{12} = (V_{tb} V_{td}^*)^2\, \frac{G_F^2}{8\pi^2}\, \frac{M_W^2}{m_B}\, S\!\left(\frac{m_t^2}{M_W^2}\right) \eta_B\, b_B(\mu)\, \langle B^0 | Q(\mu) | \overline{B}^0 \rangle$$

what we are after calculable perturbatively nonperturbative

$\eta_B\, b_B(\mu)$: Resumming $\alpha_s^n \ln^n (m_W/\mu)$, where $\mu \sim m_b$, is often very important

$\langle B^0 | Q(\mu) | \overline{B}^0 \rangle = \frac{2}{3}\, m_B^2\, f_B^2 \frac{\widehat{B}_B}{b_B(\mu)}$: Hadronic uncertainties enter here

$B_{d,s}$ mixing: $|V_{td}|$ and $|V_{ts}|$

$$\Delta m_q = 2|M_{12}| = |V_{tb}V_{tq}^*|^2 \, \underbrace{f_{B_q}^2 B_{B_q}} \times [\text{known factors}]$$

Need from lattice QCD — ratio of $q = d, s$ is easier:

$$\xi^2 \equiv \frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}} = 1 \text{ in } SU(3) \text{ limit}$$

Lattice QCD: $\sim [1.15(6)]^2$ "typical lattice average"

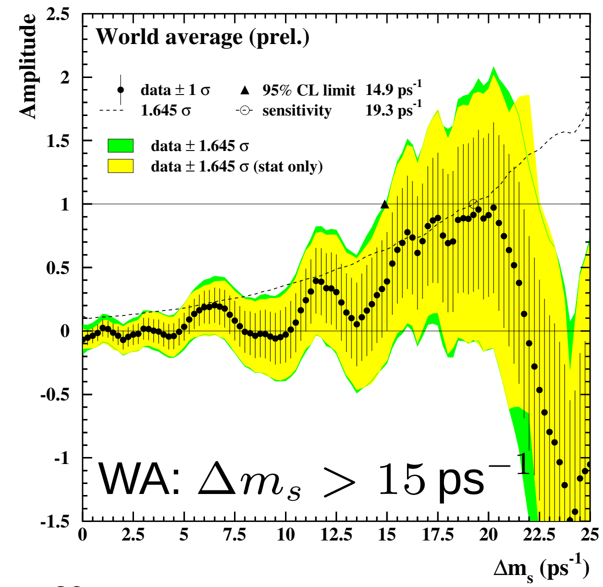
Chiral logs: ~ 1.3 (Grinstein *et al.*, '92)

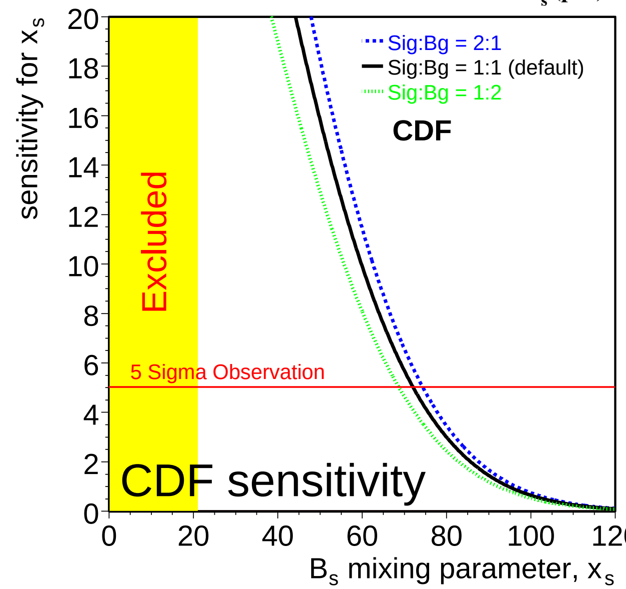
Recent lattice calculation: $\xi = 1.32 \pm 0.1$ (Kronfeld&Ryan)

A conservative error of ξ is probably sizable at present

This will soon be the main limitation to extract $|V_{td}/V_{ts}|$

Effects of light quarks need to be reliably controlled





CPV in mixing

- If CP is conserved then physical states are $\frac{1}{\sqrt{2}}(|B^0\rangle \pm |\overline{B}^0\rangle)$, corresponding to $|q/p| = 1$ and $\arg M_{12} = \arg \Gamma_{12}$

$$\left|\frac{p}{q}\right| \neq 1 \;\Rightarrow \text{CPV in mixing} \qquad \text{occurs iff } \langle B_H | B_L \rangle = |p|^2 - |q|^2 \neq 0$$

- Simplest example is decay to "wrong sign" lepton

$$A_{\rm SL} = \frac{\Gamma[\overline{B}^0(t)\to\ell^+X] - \Gamma[B^0(t)\to\ell^-X]}{\Gamma[\overline{B}^0(t)\to\ell^+X] + \Gamma[B^0(t)\to\ell^-X]} = \frac{1-|q/p|^4}{1+|q/p|^4} = \mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}}$$

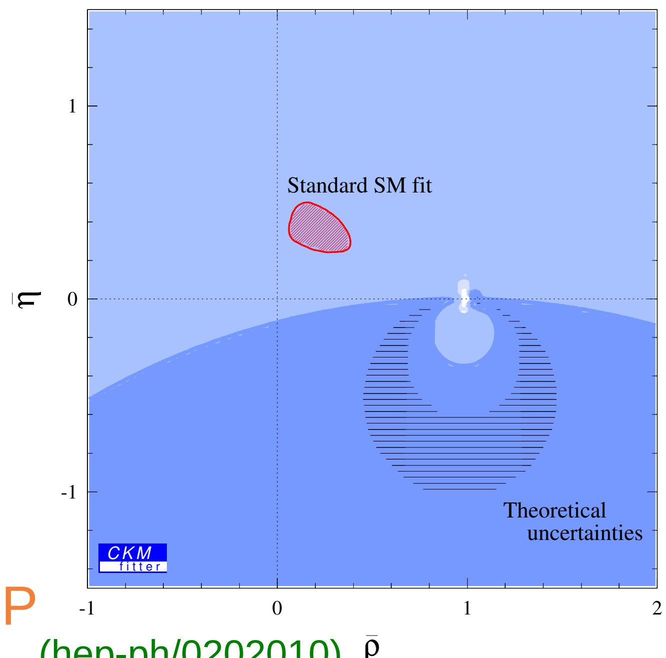
Has been observed in K decay, not yet in B decay

Calculation of Γ_{12} has large hadronic uncertainties

Nevertheless interesting to look for new physics:

$|\Gamma_{12}/M_{12}| = \mathcal{O}(m_b^2/m_W^2)$ model independently

$\arg(\Gamma_{12}/M_{12}) = \mathcal{O}(m_c^2/m_b^2)$ in SM, maybe $\mathcal{O}(1)$ with NP



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CPV in decay

- Decay amplitudes can, in general, receive many contributions:

$$A_f = \langle f|\mathcal{H}|B\rangle = \sum_k A_k\, e^{i\delta_k}\, e^{i\phi_k} \qquad \overline{A}_{\overline{f}} = \langle \overline{f}|\mathcal{H}|\overline{B}\rangle = \sum_k A_k\, e^{i\delta_k}\, e^{-i\phi_k}$$

"weak phases" ϕ_k — complex parameters in Lagrangian (in $V_{\rm CKM}$ in the SM)

"strong phases" δ_k — on-shell intermediate states rescattering, absorptive parts

$$\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1 \;\Rightarrow \text{CPV in decay}$$

Can also occur in charged meson and baryon decays

Requires at least two decay amplitudes with different strong and weak phases:

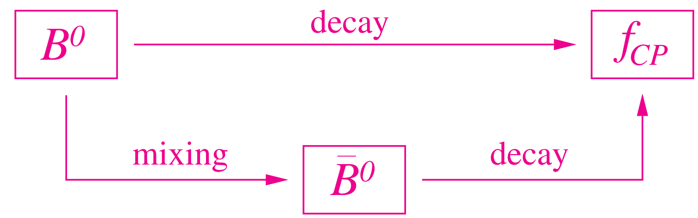
$$|A|^2 - |\overline{A}|^2 = 4 A_1 A_2 \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

Calculations of A_k and δ_k have large model dependence

Can be interesting for looking for NP, when SM prediction is small (e.g., in $b \to s\gamma$)

CPV in interference between decay and mixing

- If both B^0 and $\overline{B}^0$ can decay to same final state, there's another possibility; e.g., if $|f\rangle$ is a CP eigenstate:



$$\lambda_{f_{CP}} = \frac{q}{p}\,\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{f_{CP}}\,\frac{q}{p}\,\frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t)\to f] - \Gamma[B^0(t)\to f]}{\Gamma[\overline{B}^0(t)\to f] + \Gamma[B^0(t)\to f]} = -\frac{(1-|\lambda_f|^2)\cos(\Delta m t) - 2\,\mathrm{Im}\,\lambda_f \sin(\Delta m t)}{1+|\lambda_f|^2}$$

CP is violated either if $|\lambda| \neq 1$ due to CPV in mixing and/or decay, or if

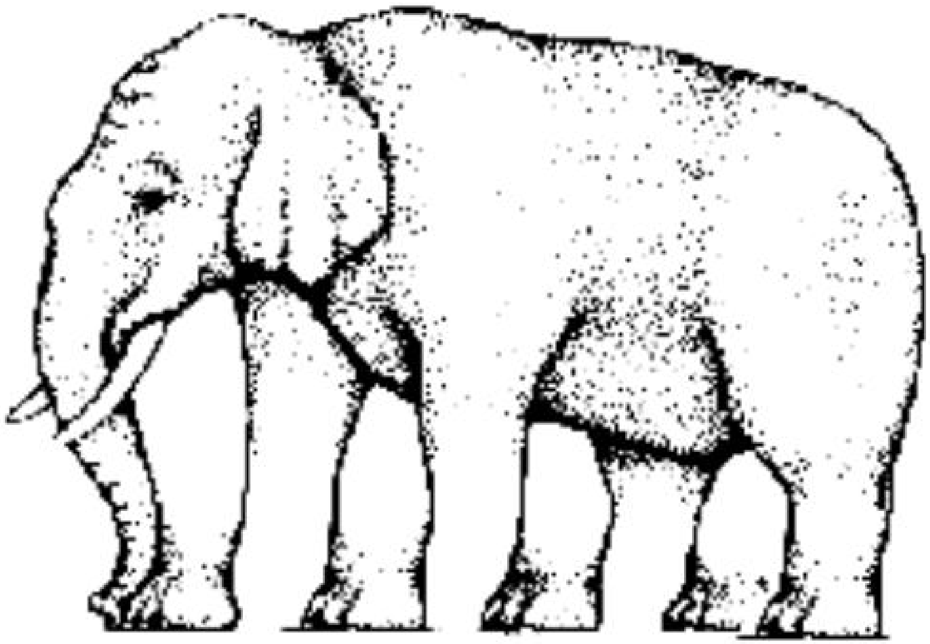
$$|\lambda_f| = 1, \text{ but } \mathrm{Im}\,\lambda_f \neq 0 \;\Rightarrow \text{CPV in interference}$$

- In such cases ($|\lambda_f| = 1$), CP asymmetry measures phase difference in a theoretically clean way

$$a_{f_{CP}} = \mathrm{Im}\,\lambda_f \sin(\Delta m t)$$

In the $B_{d,s}$ systems $|q/p| - 1 < \mathcal{O}(10^{-2})$, so the question is usually $|\overline{A}/A| \stackrel{?}{=} 1$

Even or odd legs?



How many legs does this elephant have?

$B \to \psi K_{S,L}$ — a decay everyone loves

- There are many amplitudes, nevertheless $|\overline{A}/A| - 1 < 10^{-2}$

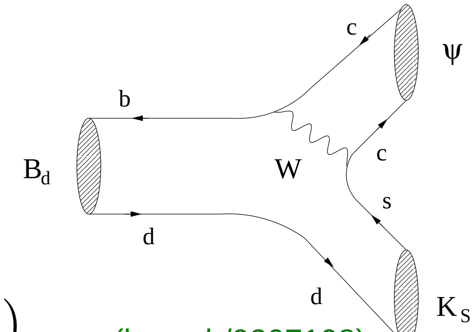
  "Tree" ($b \to c\bar{c}s$): $\overline{A}_T \sim \overbrace{V_{cb}V_{cs}^*}^{[\lambda^2]}$

  "Penguin": $\overline{A}_P \sim \overbrace{V_{tb}V_{ts}^*}^{[\lambda^2]} f(m_t) + \overbrace{V_{cb}V_{cs}^*}^{[\lambda^2]} f(m_c) + \overbrace{V_{ub}V_{us}^*}^{[\lambda^4]} f(m_u)$

  Separation between T and P is scheme and scale dependent!

  Rewrite P using unitarity, $V_{tb}V_{ts}^* + V_{cb}V_{cs}^* + V_{ub}V_{us}^* = 0$

$$\overline{A}_P \sim \underbrace{\overbrace{V_{cb}V_{cs}^*}^{[\lambda^2]}}_{\text{same as Tree phase}} [f(m_c) - f(m_t)] + \underbrace{\overbrace{V_{ub}V_{us}^*}^{[\lambda^4]}}_{\text{suppressed by } \lambda^2} [f(m_u) - f(m_t)]$$



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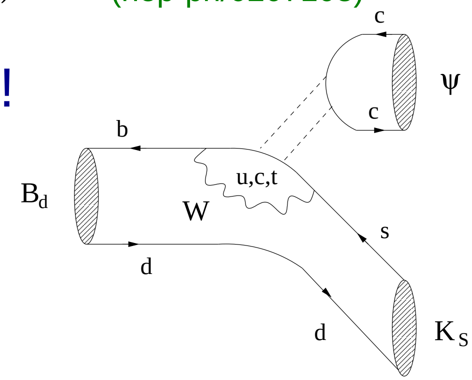


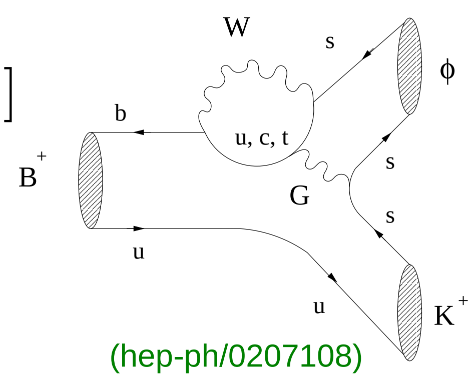
- $|\overline{A}/A| - 1 = \mathcal{O}[\lambda^2 \times (\text{loop})]$ $\Rightarrow$ theoretically very clean

$$\lambda_{\psi K_{S,L}} = \mp \left(\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\right) \left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right) \left(\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right) = \mp e^{-2i\beta} \quad \Rightarrow \quad \mathrm{Im}\lambda_{\psi K_{S,L}} = \pm \sin 2\beta$$

$B \to \phi K_{S,L}$ — window to NP?

- “Naively” no tree contribution to $b \to s\bar{s}s$, use unitarity to write penguins:

Penguin: $\overline{A}_P \sim \underbrace{\overset{[\lambda^2]}{V_{cb}V_{cs}^*}}_{\text{dominant contribution}}[f(m_c)-f(m_t)]+\underbrace{\overset{[\lambda^4]}{V_{ub}V_{us}^*}}_{\text{suppressed by } \lambda^2}[f(m_u)-f(m_t)]$



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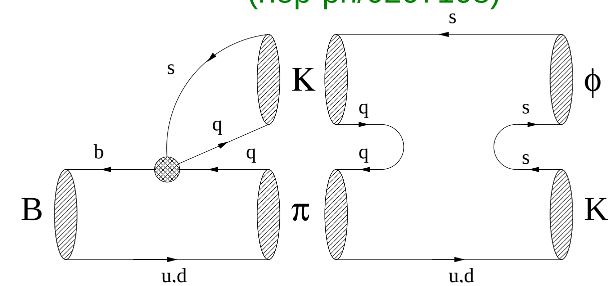
Tree: $b \to u\bar{u}s$ followed by $u\bar{u} \to s\bar{s}$ rescattering

Constrain rescattering by measuring $B^+ \to \phi\pi^+, K^*K^+$

(Grossman, Isidori, Worah)



ψK_S: NP expected to enter $\lambda_{\psi K}$ mainly through q/p

ϕK_S: NP could enter $\lambda_{\phi K}$ through both q/p and $\overline{A}/A$

Expect $\sin 2\beta_{\phi K} = \sin 2\beta_{\psi K}$ to hold in the SM at $\sim 5\%$ level

- Measuring same angle in decays sensitive to different short distance physics is important! [See also the data for $\eta' K_S$ and $K^+K^-K_S$]

Summary

- Seeking experimentally precise and theoretically reliable measurements that in the SM relate to CKM elements but can probe different short distance physics
- The CKM picture passed its first nontrivial test; we can no longer claim to be looking for alternatives of CKM, but to seek corrections due to new physics (Except maybe B_s system, $\mathrm{Im}\lambda_{s\bar{s}s}$, ...)
- Very broad program — a lot more interesting as a whole than any single measurement alone; redundancy / correlations may be the key to new physics
- $B_{d,s}$ mixing ($|V_{td}/V_{ts}|$) and $B \to \psi K$ ($\sin 2\beta$) are "easy" (i.e., both theory and experiment under control)
- Tomorrow we'll start looking at harder things...