Heavy Flavor Physics

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Matter–antimatter asymmetry

- Gravity, electromagnetism, strong interaction are same for matter and antimatter

$$\frac{N(\text{baryon})}{N(\text{photon})} \sim 10^{-9} \quad \Rightarrow \quad \frac{N_q - N_{\bar q}}{N_q + N_{\bar q}} \sim 10^{-9}$$

at $t < 10^{-6}\,$s ($T > 1\,$GeV)

- Sakharov conditions:

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

SM contains 1–3, but:

i. CP violation is too small

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

- New physics can solve i–ii near the weak scale, and may have observable effects

Why is CPV interesting?

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

  Major constraint for model building, may distinguish between new physics models

  The observed baryon asymmetry of the Universe requires CPV beyond the SM (not necessarily in flavor changing processes, not necessarily near weak scale)

- 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

What are we after?

- Flavor and CP violation are excellent probes of New Physics (worked in the past)
  - Absence of $K_L \to \mu\mu$ predicted charm
  - ϵ_K predicted 3rd generation
  - Δm_K predicted charm mass
  - Δm_B predicted heavy top

  If there is NP at the TEV scale, it must have a very special flavor / CP structure

- What does the new B factory data tell us?

Outline

- Flavor in the Standard Model

  ... What is flavor and why you might care?

  ... How to test the flavor sector?

- Cleanest measurements

  ... CP violation in $B \to \psi K_S$ — $\sin 2\beta$

  ... Independent measurements of β

- Recent developments

  ... α and γ getting interesting

  ... Implications for new physics

- Theory: understanding hadronic physics

  ... Inclusive B decays

  ... Progress with factorization, SCET

- Outlook & Conclusions

Outline

- Flavor in the Standard Model
  ... What is flavor and why you might care?
  ... How to test the flavor sector?

- Cleanest measurements
  ... CP violation in $B \to \psi K_S$ — $\sin 2\beta$ Establish CPV in B decay $\Rightarrow$ precision
  ... Independent measurements of β Start to look at penguins, hints of NP?

- Recent developments Why so many measurements?
  ... α and γ getting interesting Best present α, γ methods are new
  ... Implications for new physics First constraints on NP in $B-\overline{B}$ mixing

- Theory: understanding hadronic physics
  ... Inclusive B decays
  ... Progress with factorization, SCET

- Outlook & Conclusions

Preliminaries

Disclaimers: Concentrate on CPV in B decays — most new developments

I will not talk about: lattice QCD, the strong CP problem, detailed new physics scenarios

Dictionary: CPV $=$ CP violation

SM $=$ standard model

NP $=$ new physics

Couple of references: hep-ph/0302031, hep-ph/0408267

Identity in quantum mechanics

- Hamiltonian $\Rightarrow$ eigenstates, eigenenergies

  Degeneracy $=$ unresolved ambiguity in naming things

  - degeneracy broken by perturbations — “good” states
  - degeneracy unbroken — symmetry?

- Examples:

  1. e_L and e_R are “degenerate”, but e_L and μ_L are “different”
  2. $u_L^{\rm red}$ and $u_L^{\rm green}$ are the “same”, but $u_L^{\rm red}$ and $c_L^{\rm red}$ are “different”

  Fundamentally, e_L, e_R, μ_L, $u_L^{\rm red}$, $u_L^{\rm green}$, $c_L^{\rm red}$, $\ldots$, are all on the same footing

- Some perturbations break degeneracies and assign identities

The Standard Model

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

  internal symmetry made local, e.g., $\psi(x) \to e^{i\alpha(x)}\psi(x)$

  8 gluons $W^{\pm}$, Z^0, γ — 3

- Particle content: 5 types of chiral fermions $\times\, 3$ generations

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

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

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

  Generations indistinguishable at this point

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

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

Fermion masses

- Three copies of each fermion fields: $Q^i,\ u^i,\ d^i,\ L^i,\ \ell^i \qquad (i = 1, 2, 3)$

  Degeneracy under choosing "good" combinations, e.g.:

  $$\widetilde{Q}^i = \sum_j h^{ij} Q^j, \quad \widetilde{u}^i = \sum_j k^{ij} u^j, \ \text{etc.}$$

  Ambiguity in assigning identities to particles: are Q^i or $\widetilde{Q}^i$ fundamental?

  Global flavor symmetry: $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_\ell$

- Massive particles $\Rightarrow$ there is a rest frame, "handedness" is not well-defined

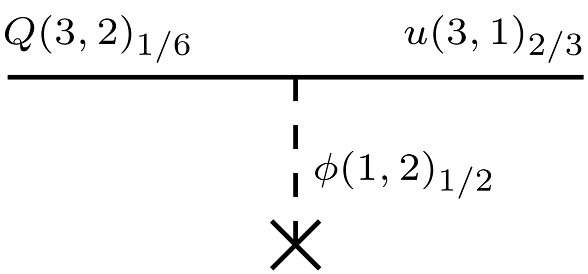
  Fermion masses are forbidden by gauge symmetries of SM

  (Cannot write down a gauge invariant mass term $\bar{\psi}_i \psi_j$)

- If this was the whole story, all fermions would be massless

Masses: interaction with Higgs

- Loophole: the vacuum can also be charged



Vacuum has $SU(2)$, $U(1)$ charge — "Higgs condensate"
(also gives mass to $W^{\pm}$, Z^0, but not to photon)
Mass is an interaction with something unknown

Interactions of fermions with condensate break flavor symmetries

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- What is the physics of Higgs condensate? What generates it? What else is there?

The LHC will address this, directly exciting the new physics (make Higgs bosons)

"Electroweak symmetry breaking"

- How do the fermions see the condensate and the new physics associated with it?

How do these interactions break the global flavor symmetries?

How do the fermions get their identities? "Flavor physics"

Yukawa couplings and CPV

- SM is the simplest possible scenario: Higgs background $=$ single scalar field ϕ

  Yukawa couplings in interaction basis:

  $$\mathcal{L}_Y = -Y_{ij}^d\, \overline{Q_{Li}^I}\, \phi\, d_{Rj}^I - Y_{ij}^u\, \overline{Q_{Li}^I}\, \widetilde{\phi}\, u_{Rj}^I \qquad \widetilde{\phi} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \phi^*$$

  $Y_{ij} = 3 \times 3$ complex matrices

  36 arbitrary couplings in $Y_{ij}^{u,d}$ break quark flavor symmetries and lift degeneracies

- Mass terms after ϕ acquires VEV

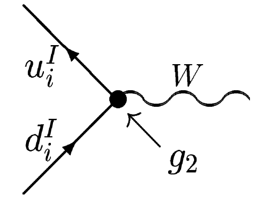
  $$\mathcal{L}_{\rm mass} = -(M_d)_{ij}\, \overline{d_{Li}^I}\, d_{Rj}^I - (M_u)_{ij}\, \overline{u_{Li}^I}\, u_{Rj}^I \,, \qquad M_{u,d} \propto Y^{u,d}$$

  Diagonalize mass matrices: $M_f^{\rm diag} \equiv V_{fL}\, M_f\, V_{fR}^\dagger \qquad (f = u, d)$

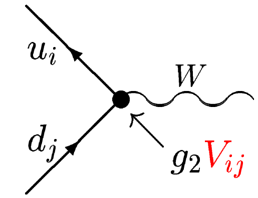
  Eigenstates with names: $u,\ d,\ s,\ c,\ b,\ t$ — The pattern of masses and mixings are inherited from the interactions of fermions with the Higgs background

Charged and neutral currents

- Weak interactions started out simple: $d^I_{Li} \to u^I_{Li} + W$ (same i only)



  Mass matrices for u_{Li} and d_{Li} diagonalized by different transformations $\Rightarrow$ couplings to W change quark flavor



- $V_{\rm CKM} \equiv V_{uL} V^\dagger_{dL}$: unitary matrix that rotates between the bases

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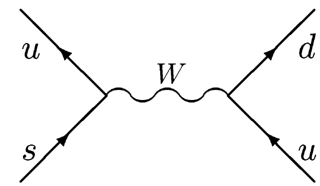
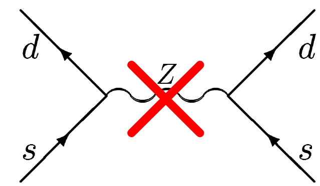
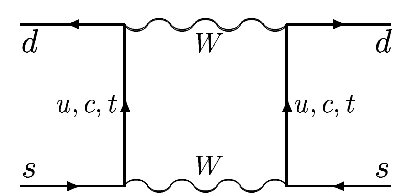
- Flavor changing charged currents at tree level
  e.g.: $K \to \pi\pi$ or $K \to \pi\ell\bar\nu$



  No flavor changing neutral currents at tree level (GIM)
  e.g.: No $K^0 - \overline{K}^0$ mixing, no $K \to \mu^+\mu^-$



- Neutral flavor change requires loop processes in SM
  e.g.: $K^0\overline{K}^0$ mixing (predicted m_c before its discovery)



Discrete symmetries: C, P and T

- $C =$ charge conjugation (particle $\leftrightarrow$ antiparticle), e.g.: $u_L^- \to u_L^+$

  $P =$ parity ($\vec{x} \leftrightarrow -\vec{x}$), e.g.: $u_L^- \to u_R^-$

  $T =$ time reversal

  CPT cannot be broken in a relativistically covariant local quantum field theory

  Weak interactions maximally violate C and P, but would conserve CP if there were only two generations or if Y_{ij}'s were real

- In SM, CP violation is related to unremovable phases of Yukawa couplings

  Beyond SM, there could be new CPV in Higgs sector, lepton sector, flavor conserving, flavor changing processes

- Complex Lagrangian couplings $\Rightarrow$ purely quantum effect $\Rightarrow$ study in interference

Quark masses and mixing

- Mass eigenstates: ($1\,\mathrm{GeV} \simeq$ proton mass)

$Q = \frac{2}{3}\,\lvert e\rvert$		$Q = -\frac{1}{3}\,\lvert e\rvert$	
$u =$ up	$0.005\,\mathrm{GeV}$	$d =$ down	$0.01\,\mathrm{GeV}$
$c =$ charm	$1.4\,\mathrm{GeV}$	$s =$ strange	$0.11\,\mathrm{GeV}$
$t =$ top	$175\,\mathrm{GeV}$	$b =$ bottom	$4.8\,\mathrm{GeV}$

- Weak interactions:

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

- Global symmetries: $U(3)^3 \to U(1)$ quark number

$$[36 \text{ couplings}] - [26 \text{ broken symmetries}] = 10 \text{ parameters with physical meaning}$$

$$= [6 \text{ masses}] + \overbrace{[3 \text{ angles}] + \underbrace{[1 \text{ phase}]}_{\text{source of } CP \text{ violation in SM}}}^{\text{parameters in } V_{\mathrm{CKM}}}$$

Questions about the SM

- Origin of electroweak symmetry breaking? $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$
  spontaneous breaking of a gauge symmetry
  $W_L W_L \to W_L W_L$ breaks unitarity ~ 1 TeV ... determines scale of Higgs / NP

- Origin of flavor symmetry breaking? $U(3)_Q \times U(3)_u \times U(3)_d \to U(1)_{\rm Baryon}$
  dimensionless Yukawas break global sym's (e.g., d_R, s_R, b_R identical if massless)
  ... we do not know the associated scale

Are they related? Flavor physics depends on both — Yukawa couplings determine quark masses, mixing, and CP violation; flavor is a problem for EWSB scenarios

Know from baryon asymmetry that CPV in the SM cannot be the full story

How precisely can we test the SM? Can we see deviations? At what level?

Testing the flavor sector

How to test the flavor sector?

- In SM, all flavor-changing processes are determined by only 4 parameters

  $\Rightarrow$ Intricate correlations between dozens of different decays of s, c, b, t quarks

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Deviations from CKM paradigm may upset some predictions:

- Flavor-changing neutral currents at unexpected level, e.g., B_s mixing incompatible with SM
- Subtle (or not so subtle) changes in correlations, e.g., CP asymmetries not equal in $B \to \psi K_S$ and $B \to \phi K_S$
- Enhanced or suppressed CP violation, e.g., $B_s \to \psi\phi$
- Enhanced decay rates, e.g., $B \to \ell^+\ell^-$

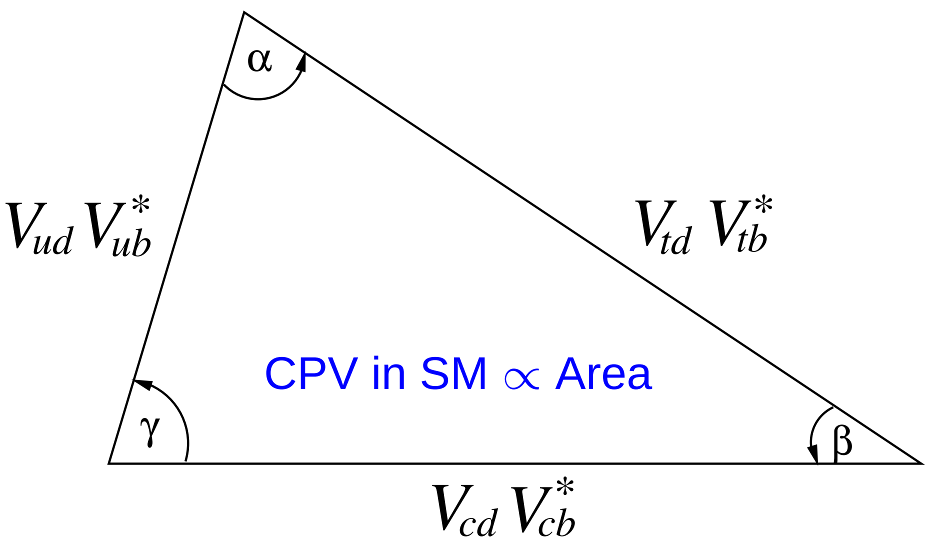
- Main question: does the SM (i.e., virtual quarks, W, and Z interacting through CKM matrix in tree and loop diagrams) explain all flavor changing interactions?

A convenient parametrization of CKM matrix

- Exhibit hierarchical structure by expanding in $\lambda = \sin\theta_C \simeq 0.22$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Unitarity triangle: a simple way to visualize the SM constraints



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

Goal: overconstrain by many measurements sensitive to different short distance physics

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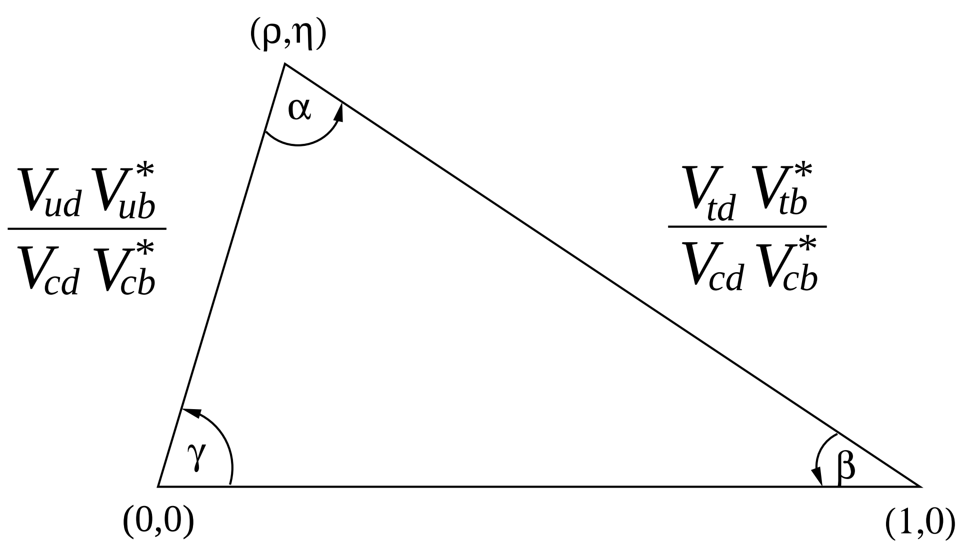
- Measurements often shown in the (ρ, η) plane (a "language" to compare data)



Angles & sides directly measurable

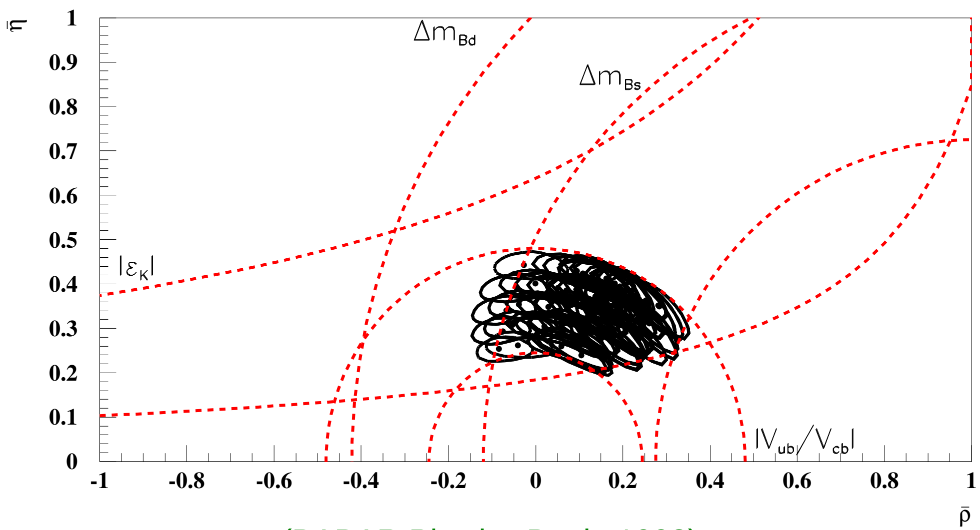
Main uncertainties of two sides:

V_{ub}/V_{cb}: $B \to X_u \ell\bar{\nu}$ and $B \to X_c \ell\bar{\nu}$

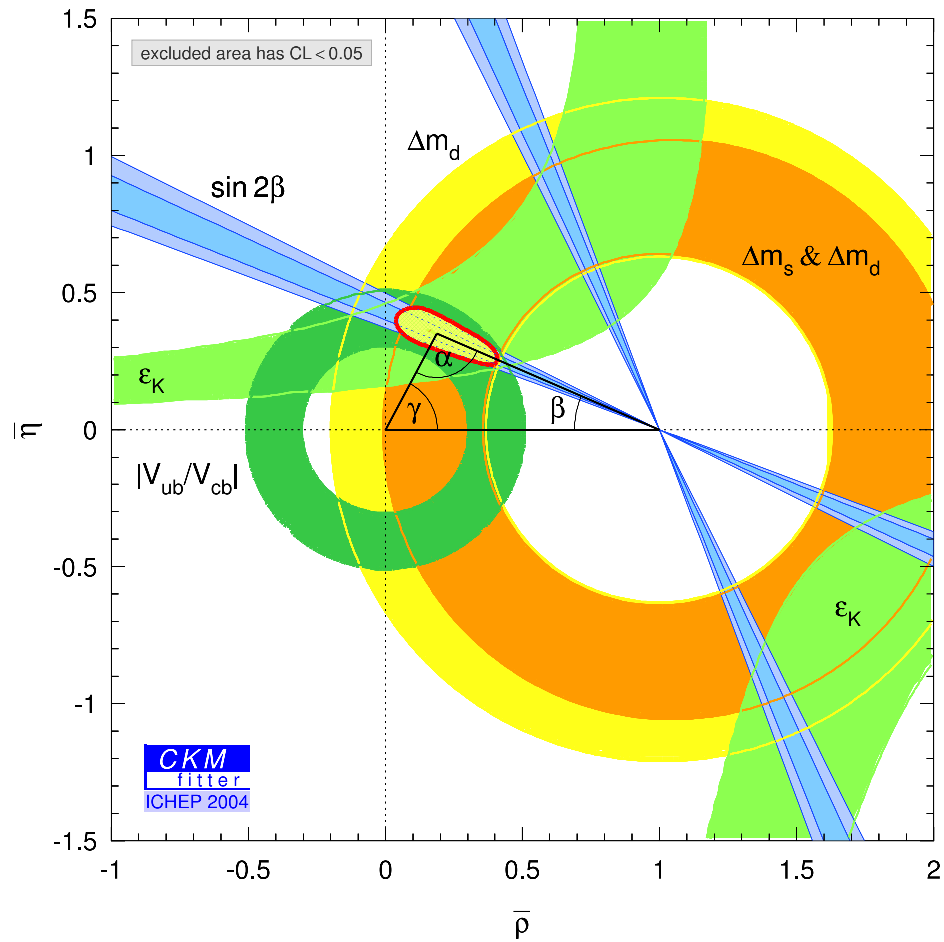
V_{td}: B_d and B_s mixing

Constraints on CKM matrix

- For 35 years, untill 1999, the only unambiguous measurement of CPV was ϵ_K



(BABAR Physics Book, 1998)



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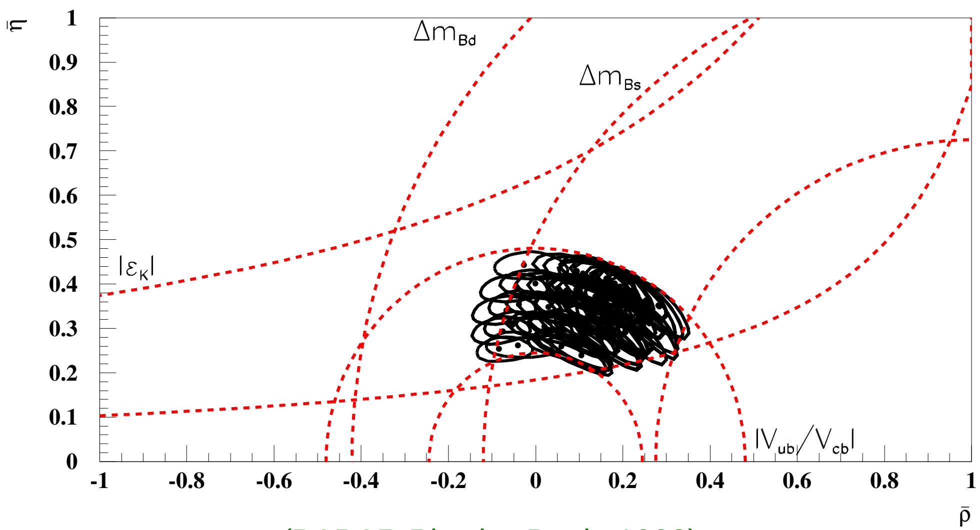

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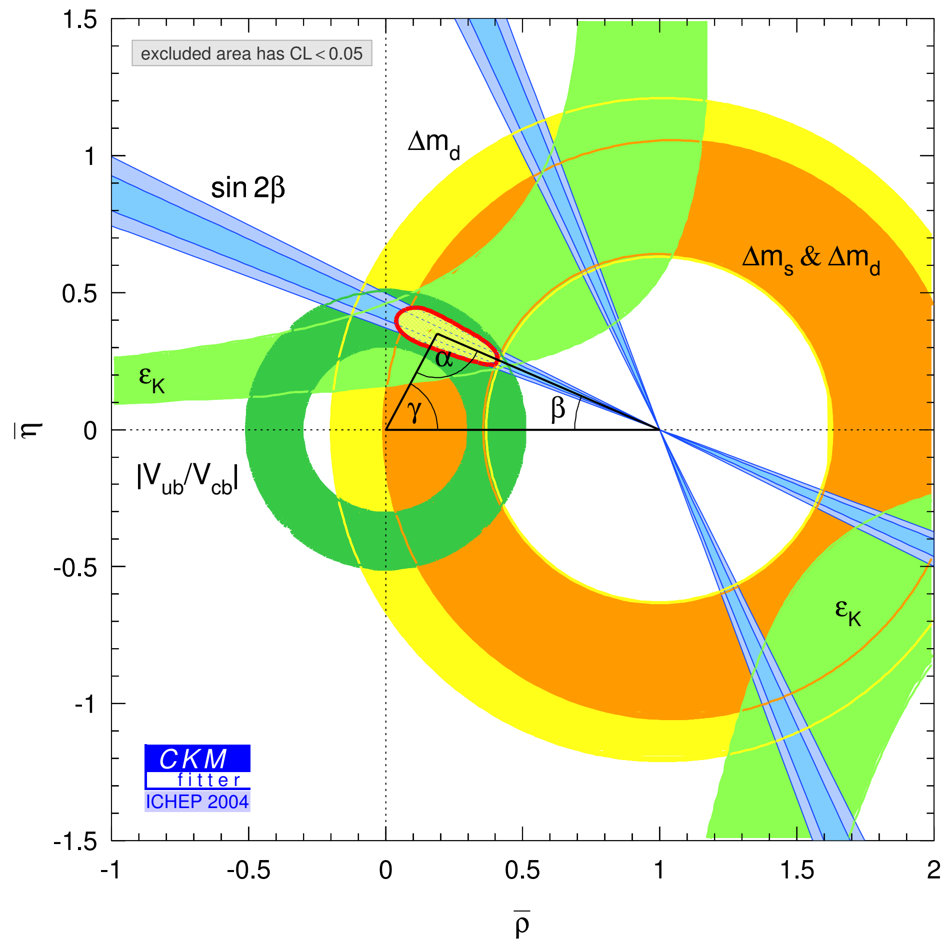
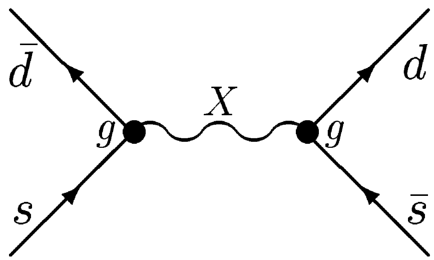


- $\sin 2\beta = 0.726 \pm 0.037$, order of magnitude smaller error than first measurements

Δm_K, ϵ_K are built in NP models since 70's

- If tree-level exchange of a heavy gauge boson was responsible for a significant fraction of the measured value of ϵ_K



$$|\epsilon_K| \sim \left|\frac{\mathrm{Im}\, M_{12}}{\Delta m_K}\right| \sim \left|\frac{g^2\, \Lambda^3_{\rm QCD}}{M_X^2\, \Delta m_K}\right| \Rightarrow M_X \sim g \times 6 \cdot 10^4\ \mathrm{TeV}$$

Similarly, from $B^0 - \overline{B}{}^0$ mixing: $M_X \sim g \times 3 \cdot 10^2\ \mathrm{TeV}$

- Or new particles at TeV scale can have large contributions in loops $[g \sim \mathcal{O}(10^{-2})]$

  Pattern of deviations/agreements with SM may distinguish between models

$K^0 - \overline{K}^0$ mixing and supersymmetry

- $$\frac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm EXP}} \sim 10^4 \left(\frac{1\,{\rm TeV}}{\tilde m}\right)^2 \left(\frac{\Delta\tilde m^2_{12}}{\tilde m^2}\right)^2 {\rm Re}\Big[(K_L^d)_{12}(K_R^d)_{12}\Big]$$

  $K^d_{L(R)}$: mixing in gluino couplings to left-(right-)handed down quarks and squarks

- Constraint from ϵ_K: replace $10^4\,{\rm Re}\Big[(K_L^d)_{12}(K_R^d)_{12}\Big]$ with $\sim 10^6\,{\rm Im}\Big[(K_L^d)_{12}(K_R^d)_{12}\Big]$

- Solutions to supersymmetric flavor problems:

  (i) Heavy squarks: $\tilde m \gg 1\,{\rm TeV}$

  (ii) Universality: $\Delta m^2_{\tilde Q,\tilde D} \ll \tilde m^2$ (GMSB)

  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (Horizontal symmetry)

  The CP problems ($\epsilon_K^{(\prime)}$, EDM's) are alleviated if relevant CPV phases $\ll 1$

- With many measurements, we can try to distinguish between models

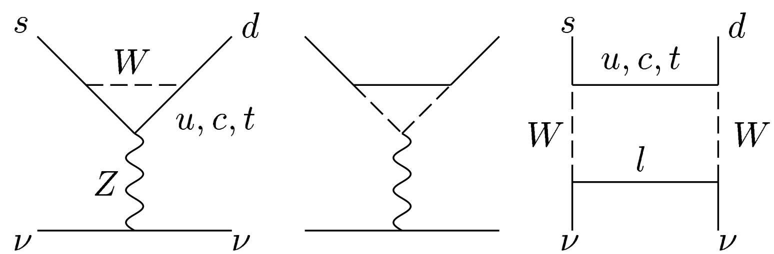
Precision tests with Kaons

- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ CKM phase)

  Hadronic uncertainties preclude precision tests (ϵ'_K notoriously hard to calculate)

- $K \to \pi\nu\overline{\nu}$: Theoretically clean, but rates small $\mathcal{B} \sim 10^{-10}(K^{\pm}),\ 10^{-11}(K_L)$

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



So far three events observed: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$

Need much higher statistics to make definitive tests

The D meson system

- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM
  - Only meson where mixing is generated by down type quarks (SUSY: up squarks)
  - D mixing expected to be small in the SM, since it is DCS and vanishes in the flavor $SU(3)$ symmetry limit
  - Involves only the first two generations: CPV $\gg 10^{-3}$ would be unambiguously new physics
  - Only neutral meson where mixing has not been observed; possible hint:

$$y_{CP} = \frac{\Gamma(CP\text{ even}) - \Gamma(CP\text{ odd})}{\Gamma(CP\text{ even}) + \Gamma(CP\text{ odd})} = (0.9 \pm 0.4)\%$$

[Babar, Belle, Cleo, Focus, E791]

- At the present level of sensitivity, CPV would be the only clean signal of NP

Why B physics?

- In the B meson system, large variety of interesting processes:
  - top quark loops neither GIM nor CKM suppressed
  - large CP violating effects possible, some with clean interpretation
  - some of the hadronic physics understood model independently ($m_b \gg \Lambda_{\rm QCD}$)
- Experimentally feasible to study:
  - $\Upsilon(4S)$ resonance is clean source of B mesons
  - Long B meson lifetime
  - Timescale of oscillation and decay comparable $\Delta m/\Gamma \simeq 0.77\, [= \mathcal{O}(1)]$ (and $\Delta\Gamma \ll \Gamma$)

CP Violation

CPV in decay

- CPV in decay: simplest form of CPV — count events

  $|\overline{A}_{\overline{f}}/A_f| \neq 1$: need amplitudes with different weak (ϕ_k) & strong (δ_k) phases

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

- Unambiguously established by $\epsilon'_K \neq 0$, and last year also in B decays:

$$A_{K^-\pi^+} \equiv \frac{\Gamma(\overline{B} \to K^-\pi^+) - \Gamma(B \to K^+\pi^-)}{\Gamma(\overline{B} \to K^-\pi^+) + \Gamma(B \to K^+\pi^-)} = -0.109 \pm 0.019 \quad (5.7\sigma)$$

  – After "K-superweak", also "B-superweak" excluded: CPV is not only in mixing

  – There are large strong phases (also in $B \to \psi K^*$); challenge to some models

- Theoretical understanding for both ϵ'_K and $A_{K^-\pi^+}$ insufficient to either prove or to rule out that NP enters (3.6σ signal also in $B \to \rho\pi$)

  Sensitive to NP in cases when SM prediction is model independently small

B – $\overline{B}$ mixing: matter – antimatter oscillation

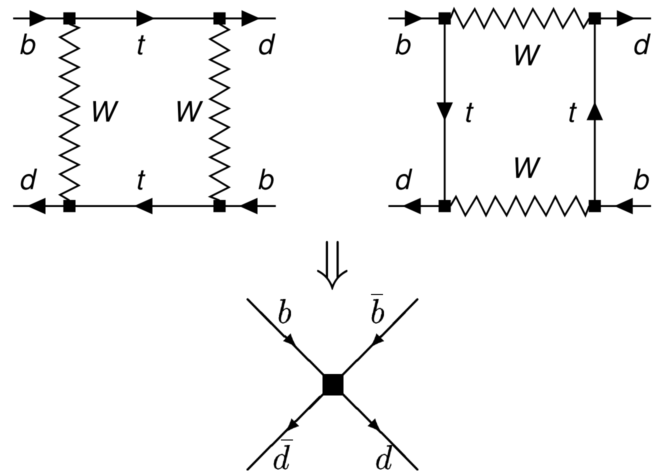
- Mixing dominated by box diagrams with top quarks $\Rightarrow$ sensitive to high scales

  Quantum mechanical two-level system

  Flavor eigenstates: $|B^0\rangle = |\bar b\, d\rangle,\ |\overline{B}^0\rangle = |b\, \bar d\rangle$

  Mass eigenstates: $|B_{H,L}\rangle = p\,|B^0\rangle \mp q\,|\overline{B}^0\rangle$

  $$|B_{H,L}(t)\rangle = e^{-(iM_{H,L}+\Gamma_{H,L}/2)t}|B_{H,L}\rangle$$



$$(\bar b_L \gamma_\nu d_L)(\bar b_L \gamma^\nu d_L)$$

- CPV: mass eigenstates $\neq CP$ eigenstates

  (Iff $|q/p| \neq 1$, then $\langle B_H|B_L\rangle \neq 0$)

  In the SM: $q/p = e^{-2i\beta} + \mathcal{O}(10^{-3})$

$$\Delta m = |V_{tb}V_{td}^*|^2\, \underbrace{f_B^2 B_B} \times [\text{known}]$$

Nonperturbative matrix element

- Interpreting CPV in mixing also has sizable hadronic uncertainties

  Sensitive to NP, there are still cleaner ways to study CPV...

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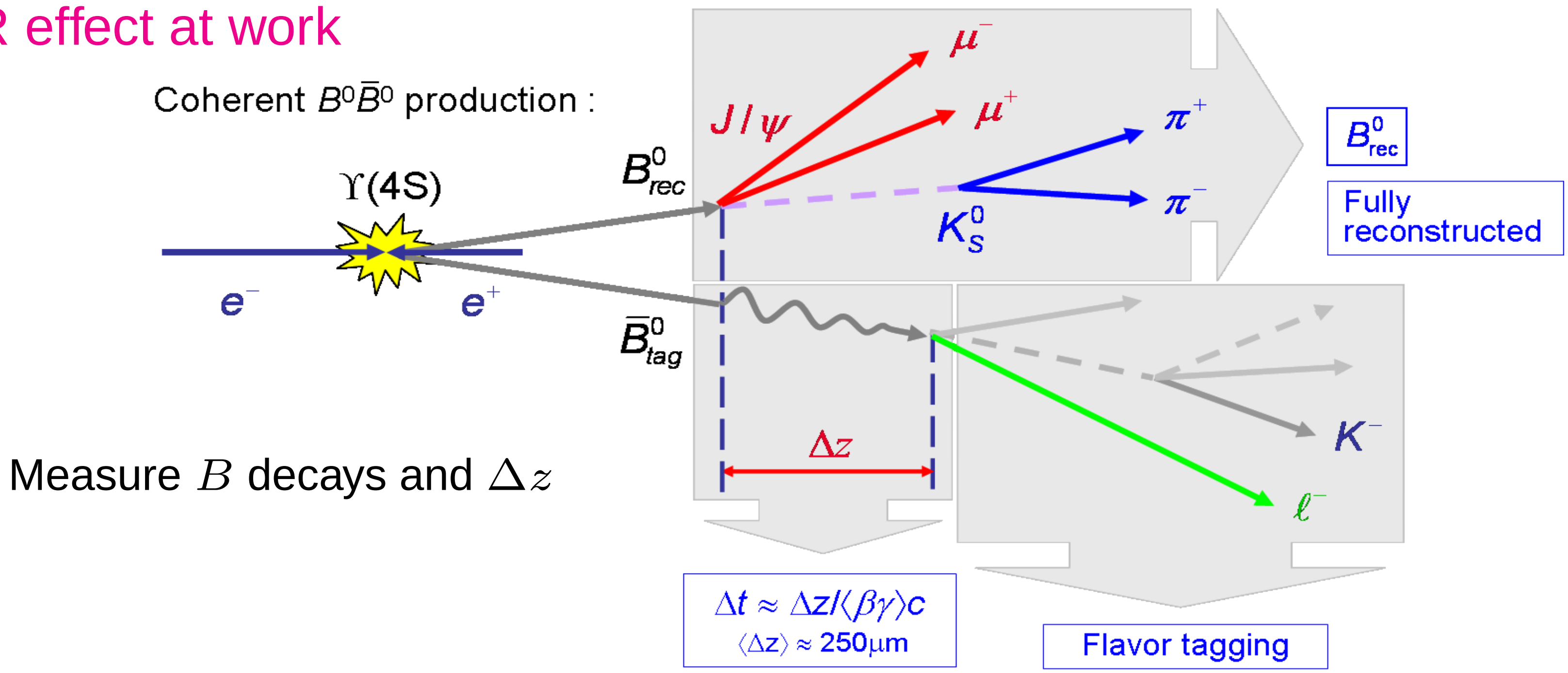
Quantum entanglement in $\Upsilon(4S) \to B^0\overline{B}^0$

- $B^0\overline{B}^0$ pair created in a p-wave ($L = 1$) evolve coherently and undergo oscillations

  Two identical bosons cannot be in an antisymmetric state — if the first B mesons decays as a B^0 ($\overline{B}^0$), then at the same time the other B must be $\overline{B}^0$ (B^0)

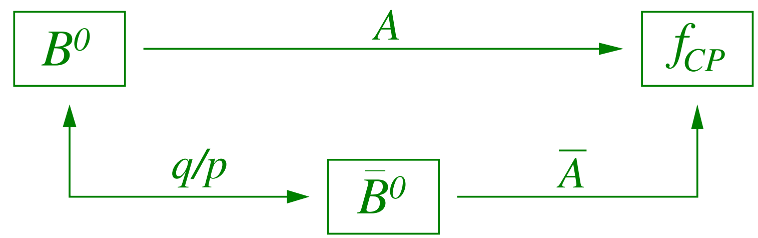
- EPR effect at work



- First decay ends quantum correlation and "tags" the flavor of the other B at $t = t_1$

CPV in interference between decay and mixing

- Possible to get theoretically clean information when B^0 and $\overline{B}^0$ decay to same final state



$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle \qquad \lambda_{f_{CP}} = \frac{q}{p}\,\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

Time dependent CP asymmetry:

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

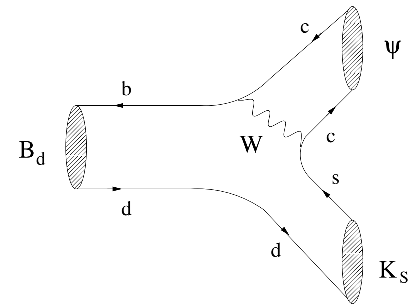
- If amplitudes with one weak phase dominate a decay, $a_{f_{CP}}$ measures a phase in the Lagrangian theoretically cleanly:

$$a_{f_{CP}} = \mathrm{Im}\,\lambda_f\ \sin(\Delta m\, t) \qquad \arg\lambda_f = \text{phase difference between decay paths}$$

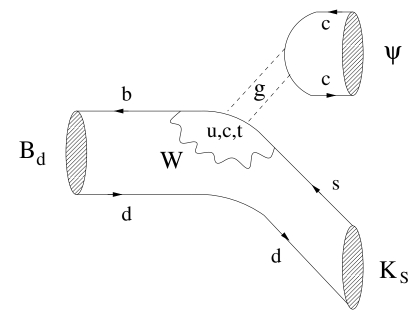
The cleanest case: $B \to J/\psi\, K_S$

- Interference between $\overline{B}^0 \to \psi \overline{K}^0$ ($b \to c\bar{c}s$) and $\overline{B}^0 \to B^0 \to \psi K^0$ ($\bar{b} \to c\bar{c}\bar{s}$)

  Penguins with different than tree weak phase are suppressed
  [CKM unitarity: $V_{tb}V_{ts}^* + V_{cb}V_{cs}^* + V_{ub}V_{us}^* = 0$]



$$\overline{A}_{\psi K_S} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)}\, T + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)}\, P$$



  First term $\gg$ second term $\Rightarrow$ theoretically very clean

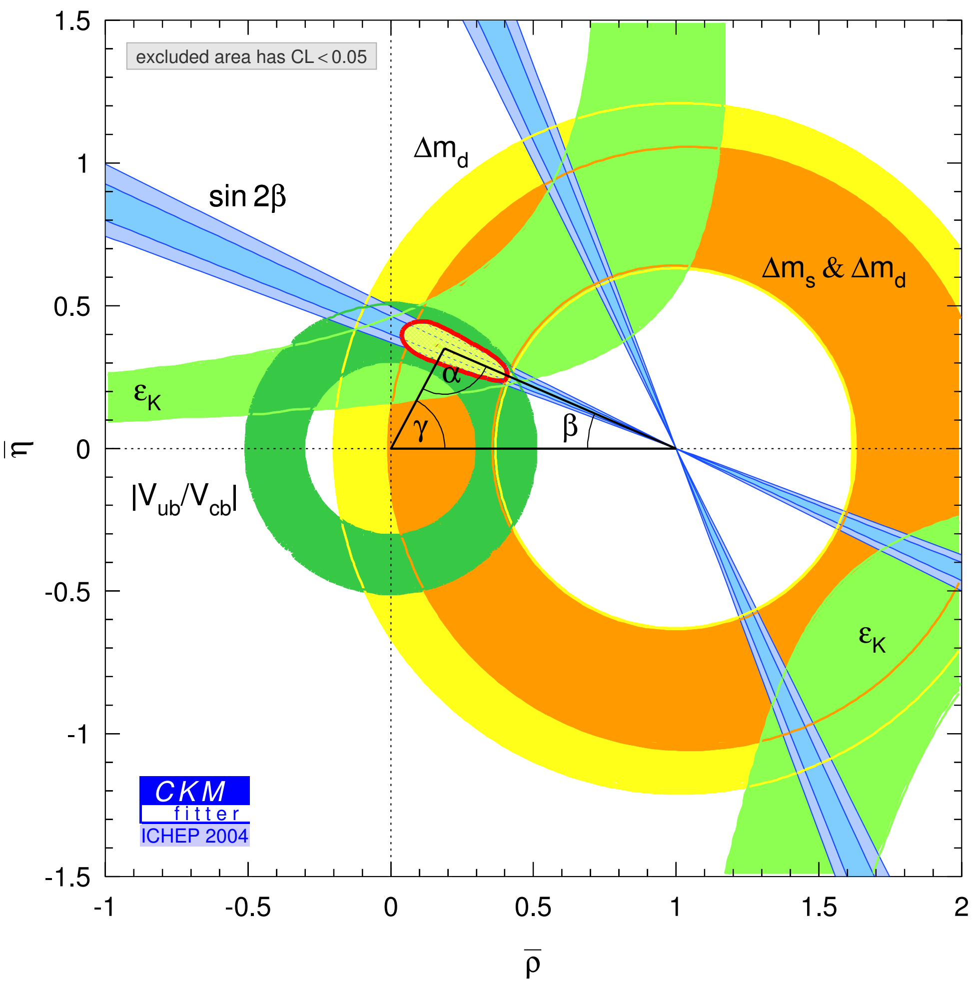
  $\arg \lambda_{\psi K_S} = (B\text{-mix} = 2\beta) + (\text{decay} = 0) + (K\text{-mix} = 0)$

  $\Rightarrow a_{\psi K_S}(t) = \sin 2\beta\, \sin(\Delta m\, t)$ to better than 1% accuracy

- World average: $\sin 2\beta = 0.726 \pm 0.037$ — a 5% measurement!

$S_{\psi K}$: a precision game now

Standard model fit including $S_{\psi K}$



First precise test of the CKM picture

Error of $S_{\psi K}$ near $|V_{cb}|$ (only $|V_{us}|$ better)

Without $|V_{ub}|$ 4 solutions; study of $\cos 2\beta$ in $B \to \psi K^*$ disfavors 2

Approximate CP (in the sense that all CPV phases are small) excluded

$S_{\psi K}$ is only the beginning

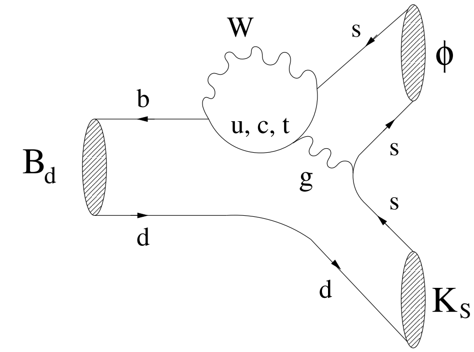
Paradigm change: look for corrections, rather than alternatives to CKM

$\Rightarrow$ Need detailed tests ($S_{\phi K_S}$, Δm_{B_s}, ...)

Theoretical cleanliness essential

CPV in $b \to s$ decays and NP

- Amplitudes with one weak phase expected to dominate:



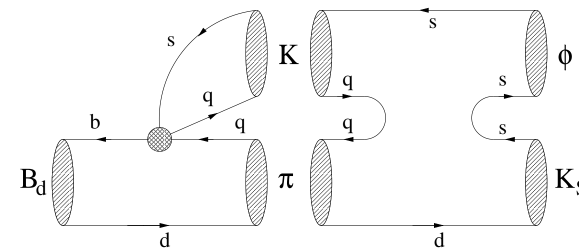
$$\overline{A} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} [P_c - P_t + T_c] + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} [P_u - P_t + T_u]$$

SM: expect: $S_{\phi K_S} - S_{\psi K}$ and $C_{\phi K_S} \lesssim \mathcal{O}(0.05)$

NP: $S_{\phi K_S} \neq S_{\psi K}$ possible

Expect different S_f for each $b \to s$ mode

Depend on size & phase of SM and NP amplitude



NP could enter $S_{\psi K}$ mainly in mixing, while $S_{\phi K_S}$ through both mixing and decay

Interesting to pursue independent of present results — lots of room left for NP

- Measuring same angle in decays sensitive to different short distance physics may be the key to finding deviations from the SM

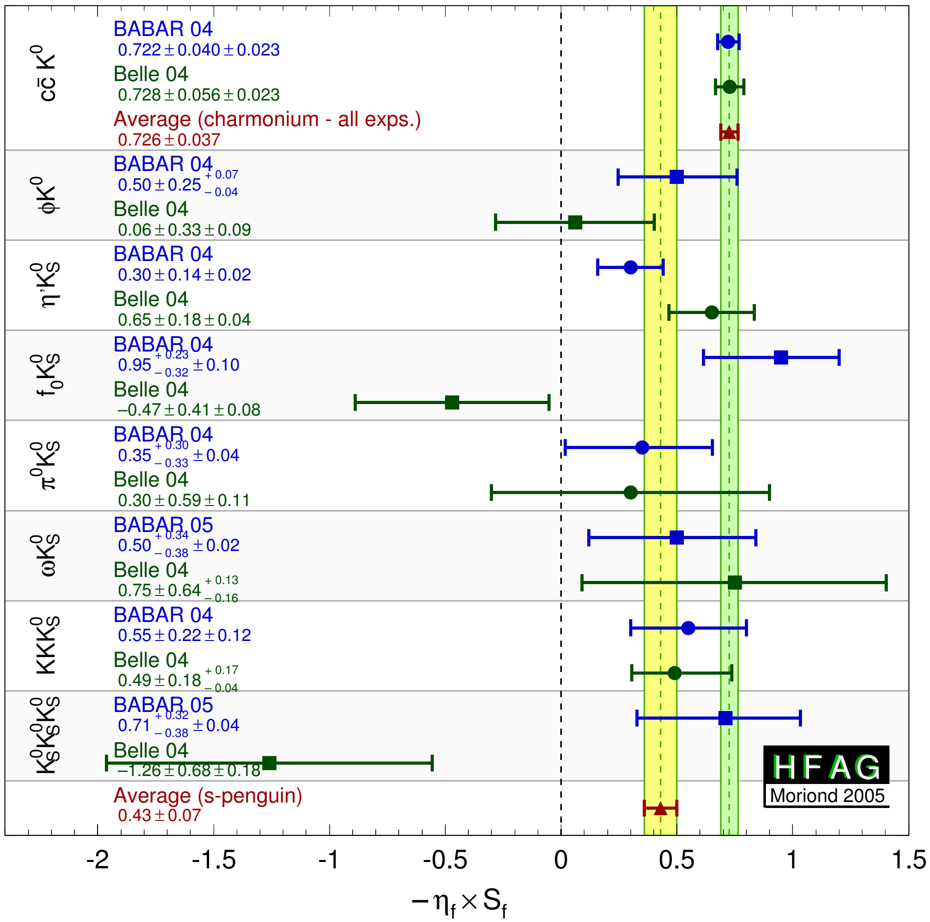
Status of $\sin 2\beta_{\rm eff}$ measurements

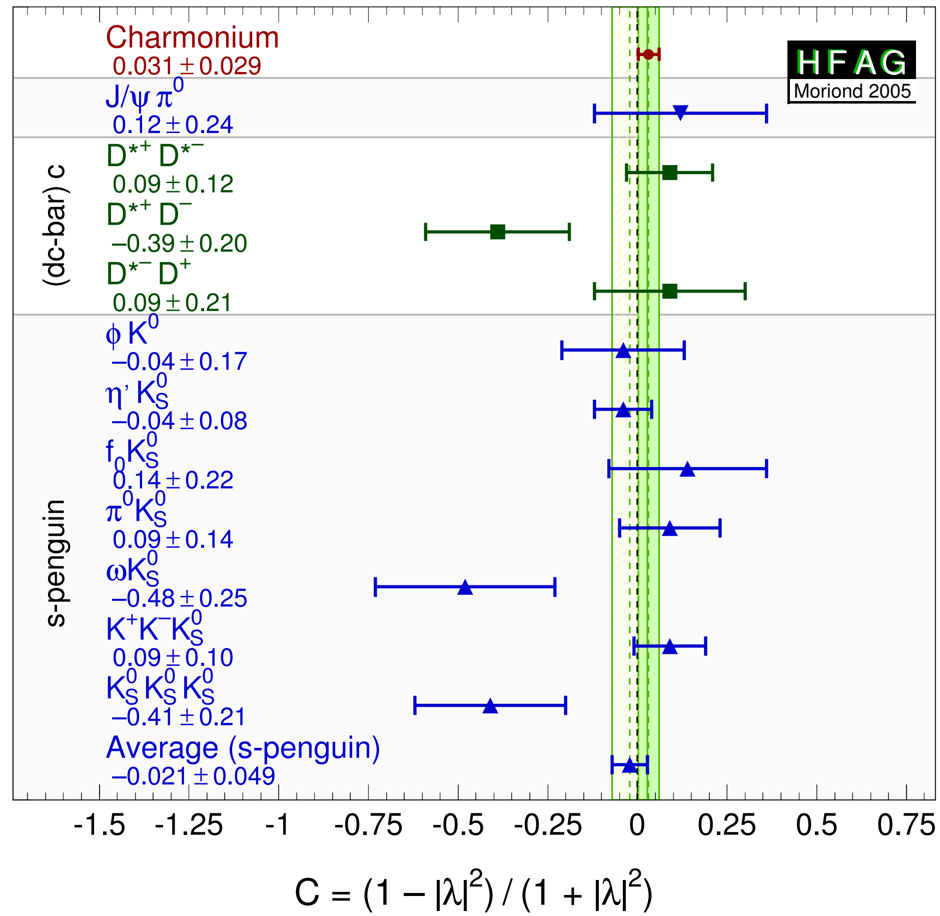
Dominant process	f_{CP}	SM estimates of* $\lvert -\eta_{f_{CP}} S_{f_{CP}} - \sin 2\beta \rvert$	$\sin 2\beta_{\rm eff}$	C_f
$b \to c\bar{c}s$	ψK_S	< 0.01	$+0.726 \pm 0.037$	$+0.031 \pm 0.029$
$b \to c\bar{c}d$	$\psi\pi^0$	~ 0.2	$+0.40 \pm 0.33$	$+0.12 \pm 0.24$
	$D^{*+}D^{*-}$	~ 0.2	$+0.67 \pm 0.25$	$+0.09 \pm 0.12$
$b \to s\bar{q}q$	ϕK^0	< 0.05	$+0.34 \pm 0.20$	-0.04 ± 0.17
	$\eta' K_S$	< 0.05	$+0.43 \pm 0.11$	-0.04 ± 0.08
	$K^+K^-K_S$	~ 0.15	$+0.53 \pm 0.17$	$+0.09 \pm 0.10$
	$K_SK_SK_S$	~ 0.15	$+0.26 \pm 0.34$	-0.41 ± 0.21
	$\pi^0 K_S$	~ 0.15	$+0.34 \pm 0.28$	$+0.09 \pm 0.14$
	$f^0 K_S$	~ 0.15	$+0.39 \pm 0.26$	$+0.14 \pm 0.22$
	ωK_S	~ 0.15	$+0.55 \pm 0.31$	-0.48 ± 0.25

* My estimates of reasonable limits (strict bounds worse)

- Largest deviations from SM: $S_{\eta' K_S}$ (2.6σ) and $S_{\psi K} - \langle S_{b\to s}\rangle = 0.30 \pm 0.08$ (3.5σ)

Babar vs. Belle and direct CPV





- Average of $S_{\eta' K_S}$ and $S_{\phi K_S}$ already 3σ from $S_{\psi K_S}$ — these are the cleanest

Implications of $S_{\eta' K_S}$ and $S_{\phi K}$

- $S_{\psi K} - S_{\eta' K_S} = 0.31 \pm 0.12 \;\; (2.6\sigma)$ Largest single deviation from SM at present

  $S_{\phi K}$: significant effect still possible, need to further decrease errors

  In SM, both $|S_{\psi K} - S_{\eta' K_S}|$ and $|S_{\psi K} - S_{\eta' K_S}| < 0.05$ [model estimates $\mathcal{O}(0.01)$]

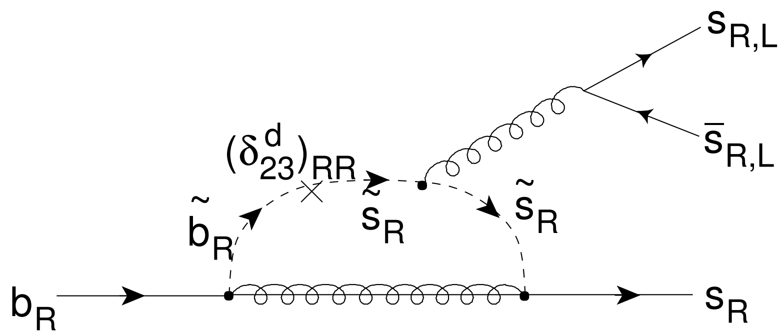
- $S_{\eta' K_S}$ or $S_{\phi K_S}$ at their present central values would be signs of NP

  $\Rightarrow$ There is a lot to learn from more precise measurements

- Current central values with greater significance would not only exclude SM, but MFV and universal SUSY models such as GMSB

Model building more interesting

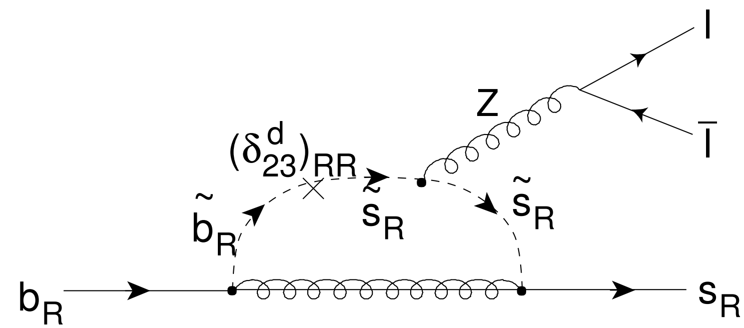
- The present $S_{\eta' K_S}$ and $S_{\phi K_S}$ central values can be reasonably accommodated with NP (unlike an $\mathcal{O}(1)$ deviation from $S_{\psi K_S}$)



- $\mathcal{B}(B \to X_s\gamma) = (3.5 \pm 0.3) \times 10^{-6}$ mainly constrains LR mass insertions

Now also $\mathcal{B}(B \to X_s\ell^+\ell^-) = (4.5 \pm 1.0) \times 10^{-6}$ agrees with the SM at 20% level

$\Rightarrow$ new constraints on RR & LL mass insertions



Summary — Part 1

- 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
- Broad program — a lot more interesting as a whole than any single measurement alone; redundancy / correlations may be the key to finding new physics
- Vibrant theoretical and experimental program — we shall soon know if hints of deviations from the SM in CPV in $b \to s$ modes are fluctuations or due to NP

Second part

- Recent developments

  ... α and γ getting interesting

  ... Implications for new physics

- Theory: understanding hadronic physics

  ... Inclusive B decays

  ... Progress with factorization, SCET

- Outlook & Conclusions

New last year: α and γ

$$[\gamma = \arg(V_{ub}^*)\,,\ \ \alpha \equiv \pi - \beta - \gamma]$$

α measurements in $B \to \pi\pi$, $\rho\rho$, and $\rho\pi$

γ in $B \to DK$: tree level, independent of NP

[The presently best α and γ measurements were not talked about before 2003]

α from $B \to \pi\pi$

- Until $\sim$'97 the hope was to determine α simply from:

$$\frac{\Gamma(\overline{B}^0(t) \to \pi^+\pi^-) - \Gamma(B^0(t) \to \pi^+\pi^-)}{\Gamma(\overline{B}^0(t) \to \pi^+\pi^-) + \Gamma(B^0(t) \to \pi^+\pi^-)} = S\sin(\Delta m\, t) - C\cos(\Delta m\, t)$$

$\arg\lambda_{\pi^+\pi^-} = (B\text{-mix} = 2\beta) + (\overline{A}/A = 2\gamma + \ldots) \Rightarrow$ measures $\sin 2\alpha$ if amplitudes with one weak phase dominated — relied on expectation that $P/T = \mathcal{O}(\alpha_s/4\pi)$

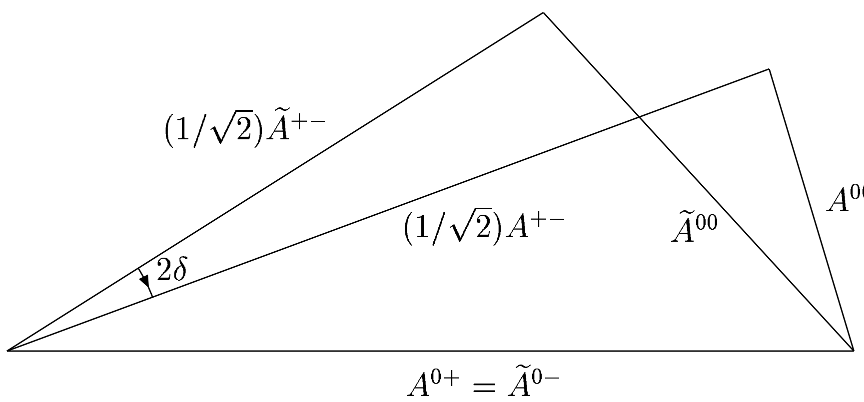
$K\pi$ and $\pi\pi$ rates $\Rightarrow$ comparable amplitudes with different weak & strong phases

---

- Isospin analysis: Determine $\delta \equiv \alpha - \alpha_{\text{eff}}$ $(\sin 2\alpha_{\text{eff}} = S_{\pi^+\pi^-}/\sqrt{1 - C^2_{\pi^+\pi^-}})$

Bose statistics $\Rightarrow \pi\pi$ in $I = 0, 2$

Triangle relations between B^+, B^0 $(B^-$, $\overline{B}^0)$ decay amplitudes



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α from $B \to \pi\pi$: Isospin analysis

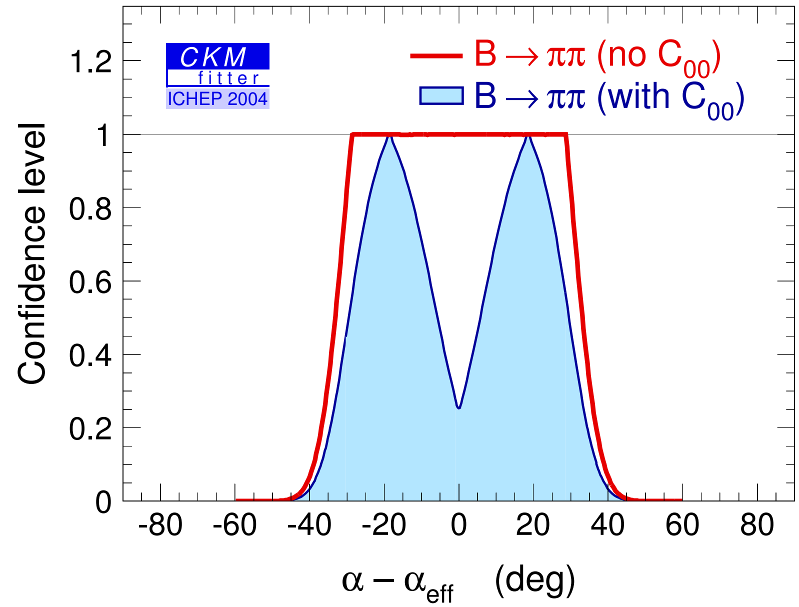
- First measurements of tagged $B \to \pi^0\pi^0$ rates, hardest input to isospin analysis:

$$\frac{\Gamma(\overline{B} \to \pi^0\pi^0) - \Gamma(B \to \pi^0\pi^0)}{\Gamma(\overline{B} \to \pi^0\pi^0) + \Gamma(B \to \pi^0\pi^0)} = 0.28 \pm 0.39$$

$$\mathcal{B}(B \to \pi^0\pi^0) = (1.45 \pm 0.29) \times 10^{-6}$$

Need a lot more data to pin down $\alpha - \alpha_{\text{eff}}$ from isospin analysis... current bound:

$$\alpha - \alpha_{\text{eff}} < 39^\circ \ (90\% \ \text{CL})$$



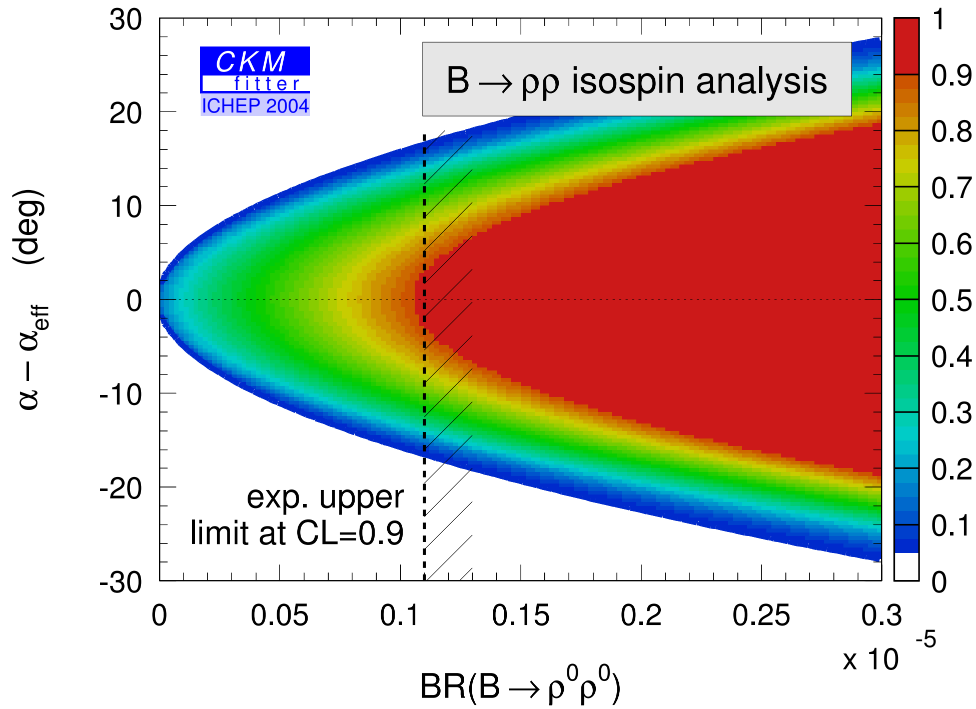
- Interpretation unclear until $S_{\pi^+\pi^-}$ measurements become more consistent

$B \to \pi^+\pi^-$	$S_{\pi^+\pi^-}$	$C_{\pi^+\pi^-}$
BABAR	-0.30 ± 0.17	-0.09 ± 0.16
BELLE	-0.67 ± 0.17	-0.58 ± 0.13
average	-0.50 ± 0.12	-0.37 ± 0.11

$B \to \rho\rho$: the best α at present

- $\rho\rho$ is mixture of CP even/odd (as all VV modes); data: $CP =$ even dominates
  Isospin analysis applies for each L, or in transversity basis for each σ $(= 0, \|, \perp)$

- Small rate $\mathcal{B}(B \to \rho^0\rho^0) < 1.1 \times 10^{-6}$ (90% CL) $\Rightarrow$ small penguin pollution
  $\frac{\mathcal{B}(B\to\pi^0\pi^0)}{\mathcal{B}(B\to\pi^+\pi^0)} = 0.26 \pm 0.06$ vs. $\frac{\mathcal{B}(B\to\rho^0\rho^0)}{\mathcal{B}(B\to\rho^+\rho^0)} < 0.04$ (90% CL)



Ultimately, more complicated than $\pi\pi$, $I = 1$ possible due to finite Γ_ρ, giving $\mathcal{O}(\Gamma_\rho^2/m_\rho^2)$ effects [can be constrained]

$S_{\rho^+\rho^-}$ and isospin bound yields:

$\alpha = [96 \pm 10 \pm 4 \pm 11(\alpha - \alpha_{\rm eff})]^\circ$

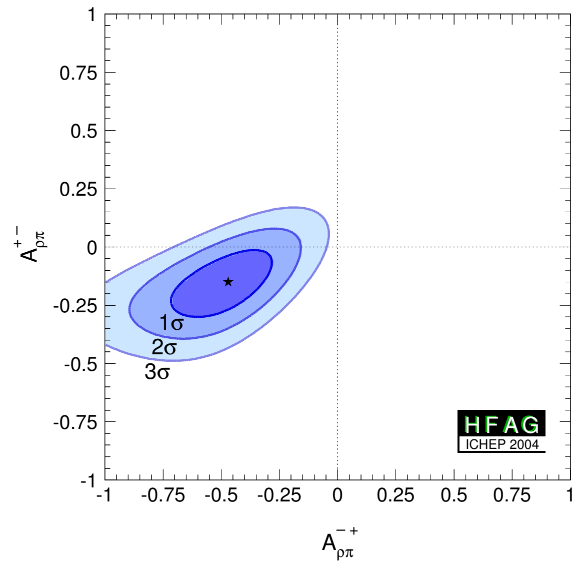
$B \to \rho\pi$: Dalitz plot analysis

- Two-body $B \to \rho^\pm \pi^\mp$: two pentagon relations from isospin; would need rates and CPV in all $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ modes to get α — hard!

  Direct CPV: $\begin{cases} A_{\pi^-\rho^+} = -0.48^{+0.14}_{-0.15} \\ A_{\pi^+\rho^-} = -0.15 \pm 0.09 \end{cases}$

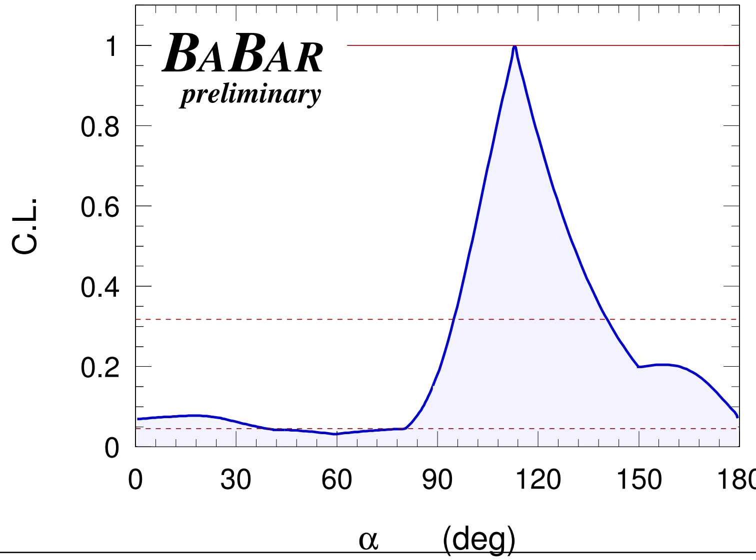
  3.6σ from 0, challenges some models

  Interpretation for α model dependent



- New: Dalitz plot analysis of the interference regions in $B \to \pi^+\pi^-\pi^0$

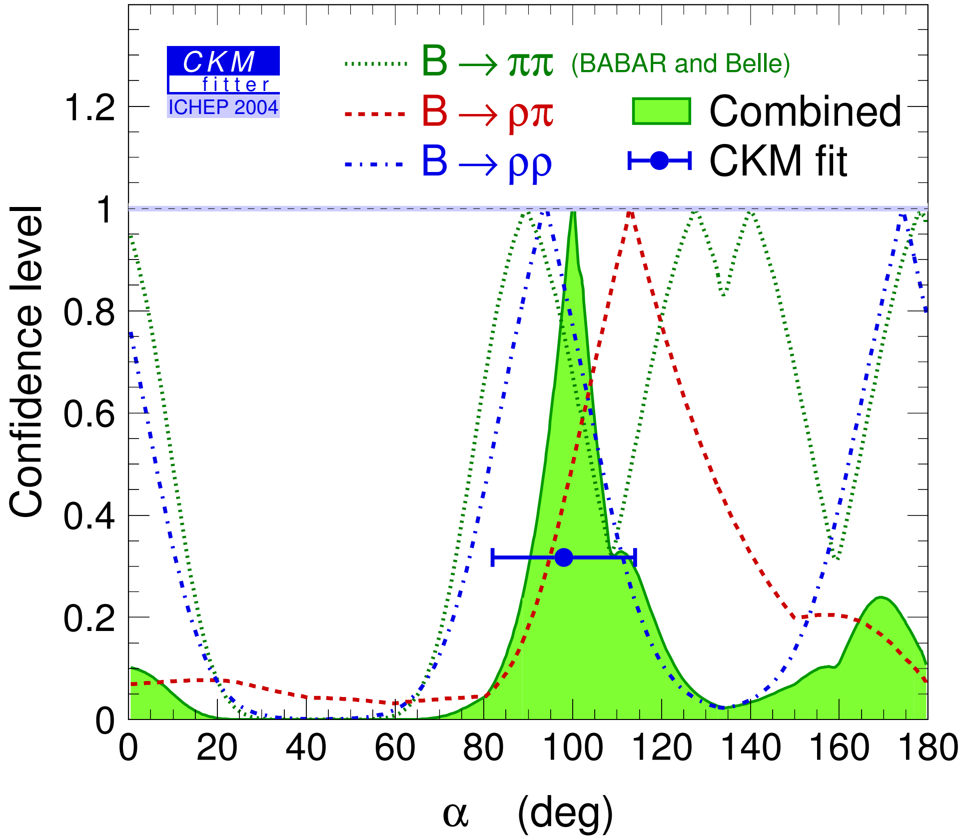
  Result: $\alpha = (113^{+27}_{-17} \pm 6)^\circ$

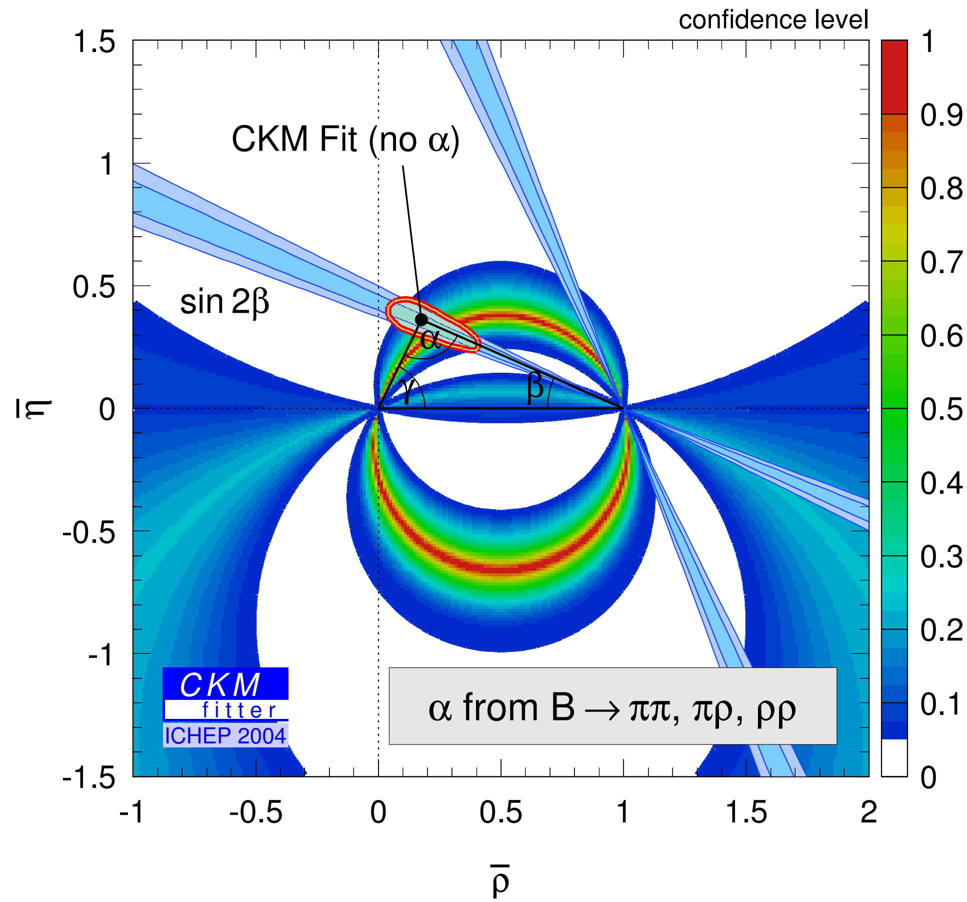


Measurements of α combined

- Sensitivity mainly from $S_{\rho^+\rho^-}$ and $\rho\pi$ Dalitz, $\pi\pi$ has small effect at present

Combined result: $\alpha = (100^{+12}_{-10})^\circ$ ($103 \pm 11^\circ$ w/o $\pi\pi$); better than indirect fit $98 \pm 16^\circ$





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γ: measurements and constraints

- $B^- \to D^0 K^- \; (b \to c)$ and $\overline{D}^0 K^- \; (b \to u)$ interfere if $D^0, \overline{D}^0 \to$ same final state

  B and D decay amplitudes and strong phases determined from analysis

  Many variants according to D decay: D_{CP} [GLW], DCS/CA [ADS], CS/CS [GLS]

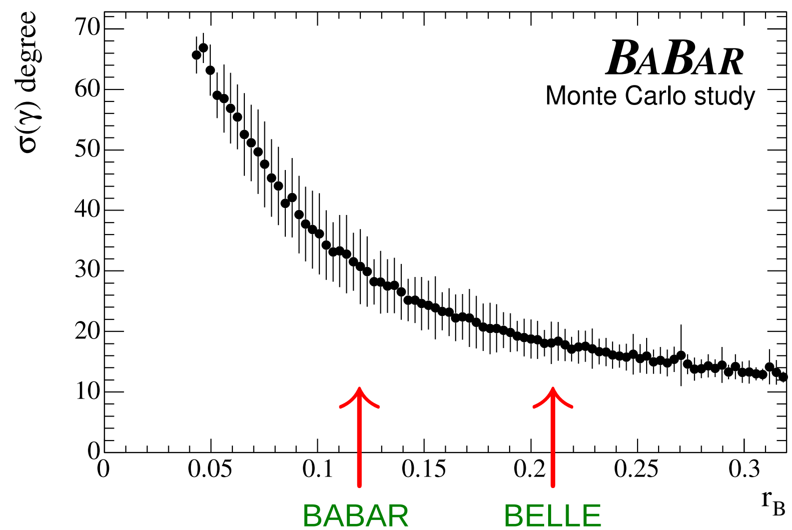
  Sensitivity crucially depends on: $r_B = |A(B^- \to \overline{D}^0 K^-)/A(B^- \to D^0 K^-)|$

- New analyses considering: $D^0, \overline{D}^0 \to K_S \pi^+ \pi^-$

  Both amplitudes Cabibbo allowed; can integrate over regions in $m_{K\pi^+} - m_{K\pi^-}$ Dalitz plot

  $$\gamma = \left(68^{+14}_{-15} \pm 13 \pm 11\right)^\circ \qquad \text{[BELLE, 275 m]}$$

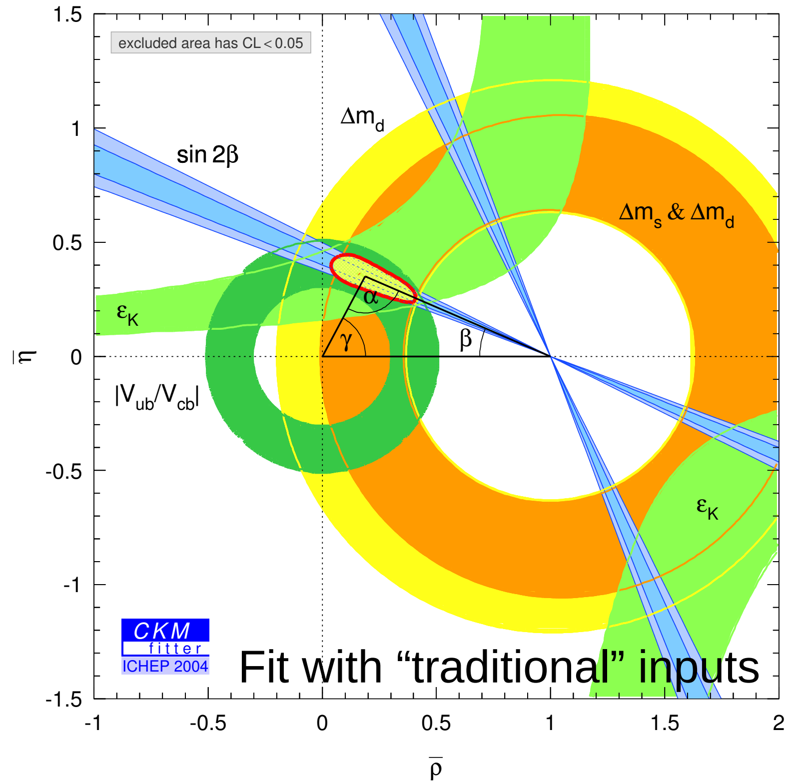
  $$\gamma = \left(70 \pm 31^{+12+14}_{-10-11}\right)^\circ \qquad \text{[BABAR, 227 m]}$$



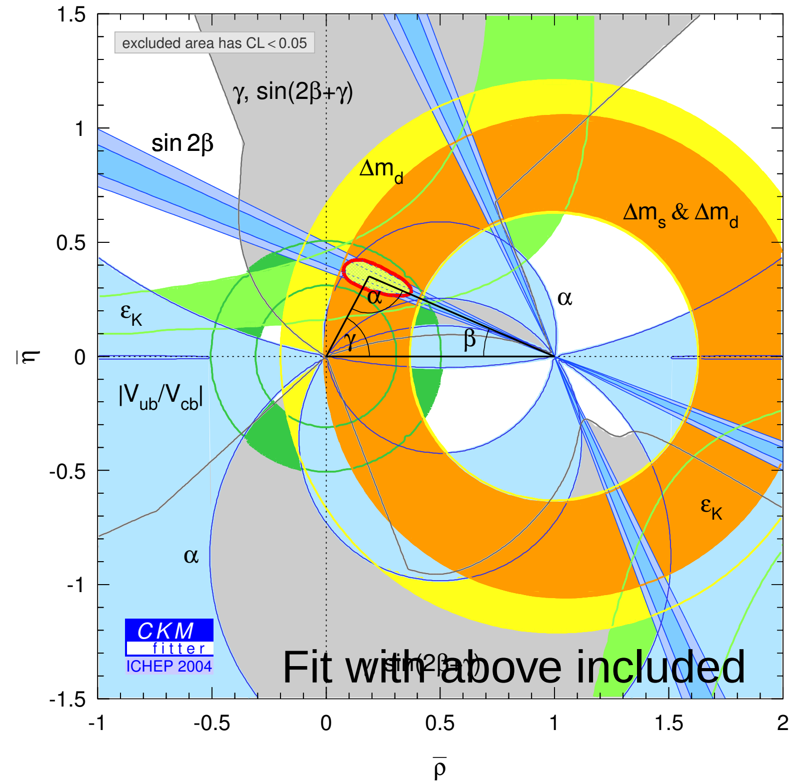
- Need more data to firm up value of r_B and determine γ more precisely

The “new” CKM fit

- Include measurements that give meaningful constraints and NOT theory limited
  - α from $B \to \rho\rho$ and $\rho\pi$ Dalitz
  - $2\beta + \gamma$ from $B \to D^{(*)\pm}\pi^{\mp}$
  - γ from $B \to DK$ (with D Dalitz)
  - $\cos 2\beta$ from ψK^* and $A_{\rm SL}$ (for NP)



$$\Delta m_s = (17.9^{+10.5\ [+20.0]}_{-1.7\ \ [-2.8]})\ {\rm ps}^{-1} \text{ at } 1\sigma\ [2\sigma]$$



$$\Delta m_s = (17.9^{+7.4\ [+13.3]}_{-1.4\ [-2.7]})\ {\rm ps}^{-1}$$

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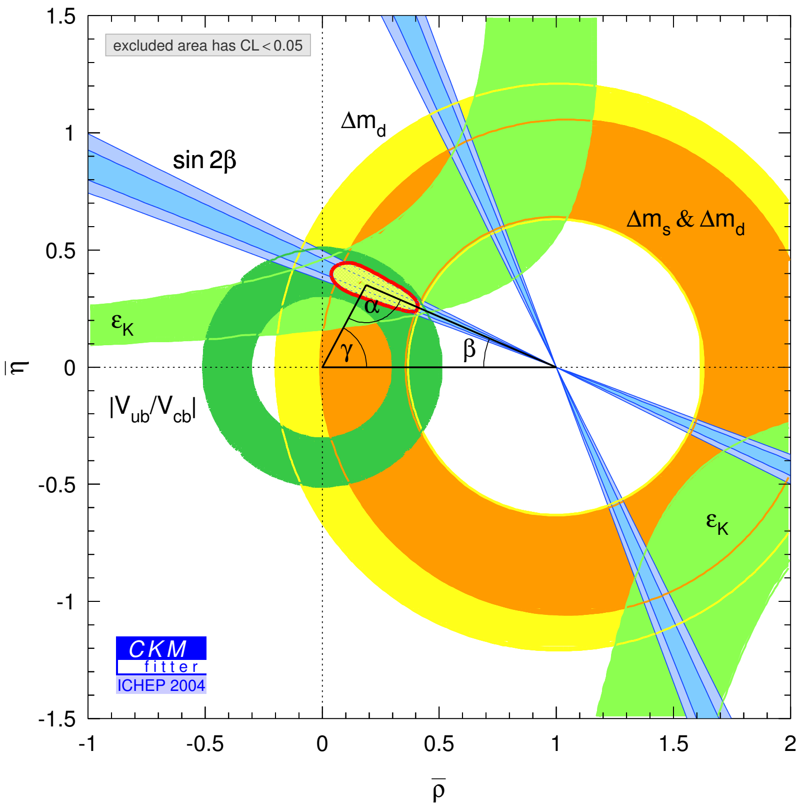
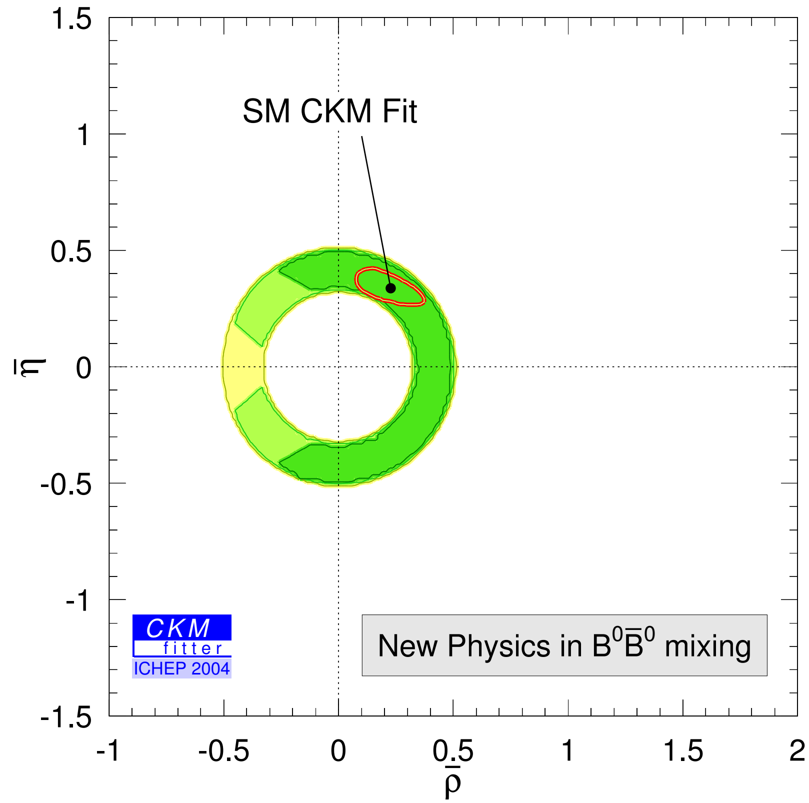
CKM fits with and without assuming SM

- Consistency of SM fit often said to imply tight constraints on NP — this is wrong

SM fit: impressive agreement



NP in loops: constraints relaxed



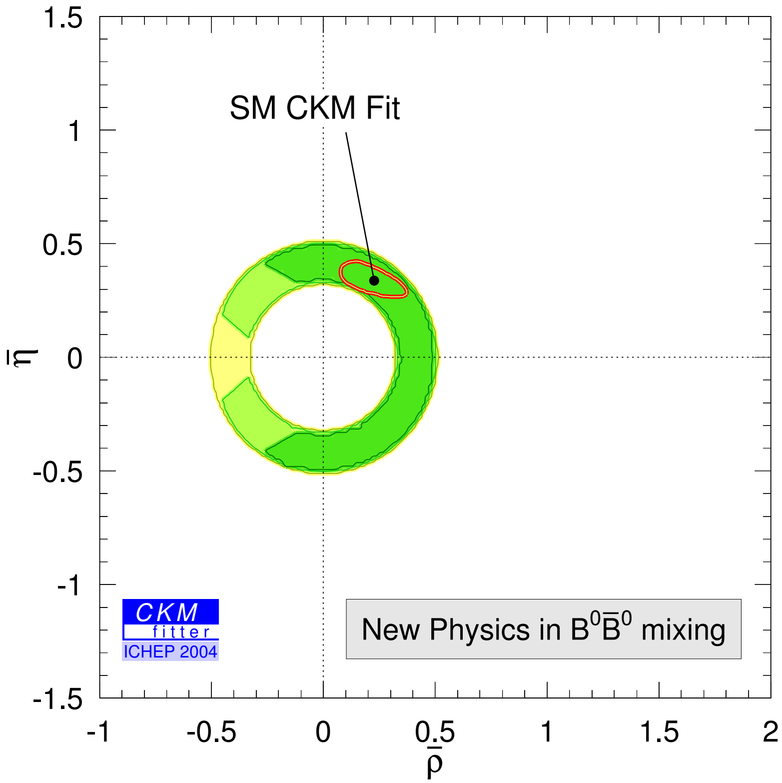
- These measurements alone cannot exclude NP in loop processes (coincidence)

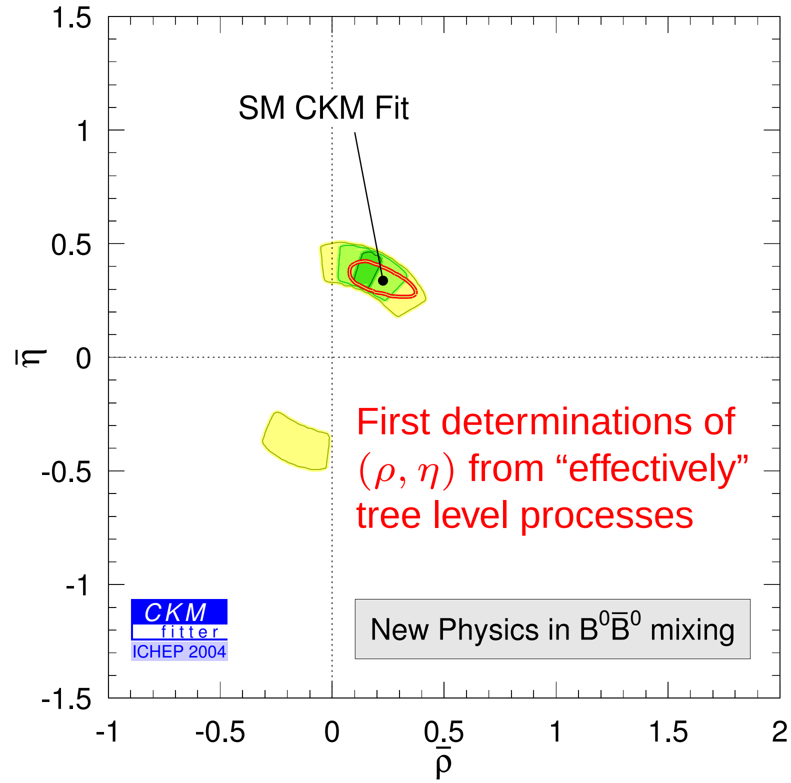
Constraining NP in mixing: the '04 news

- NP in mixing amplitude only, 3×3 unitarity preserved: $M_{12} = M_{12}^{(\mathrm{SM})}\, r_d^2\, e^{2i\theta_d}$

$\Rightarrow \Delta m_B = r_d^2 \Delta m_B^{(\mathrm{SM})}$, $S_{\psi K} = \sin(2\beta + 2\theta_d)$, $S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$, $\gamma(DK)$ unaffected

Constraints with $|V_{ub}|$, Δm_d, $S_{\psi K}$, A_{SL} — New in '04: α, γ, $2\beta + \gamma$, $\cos 2\beta$





- Similar to EW fit: $m_H <$ few $\times 100\,\mathrm{GeV}$ in SM; model independently only $\lesssim 1\,\mathrm{TeV}$

Constraining NP in mixing: the '04 news

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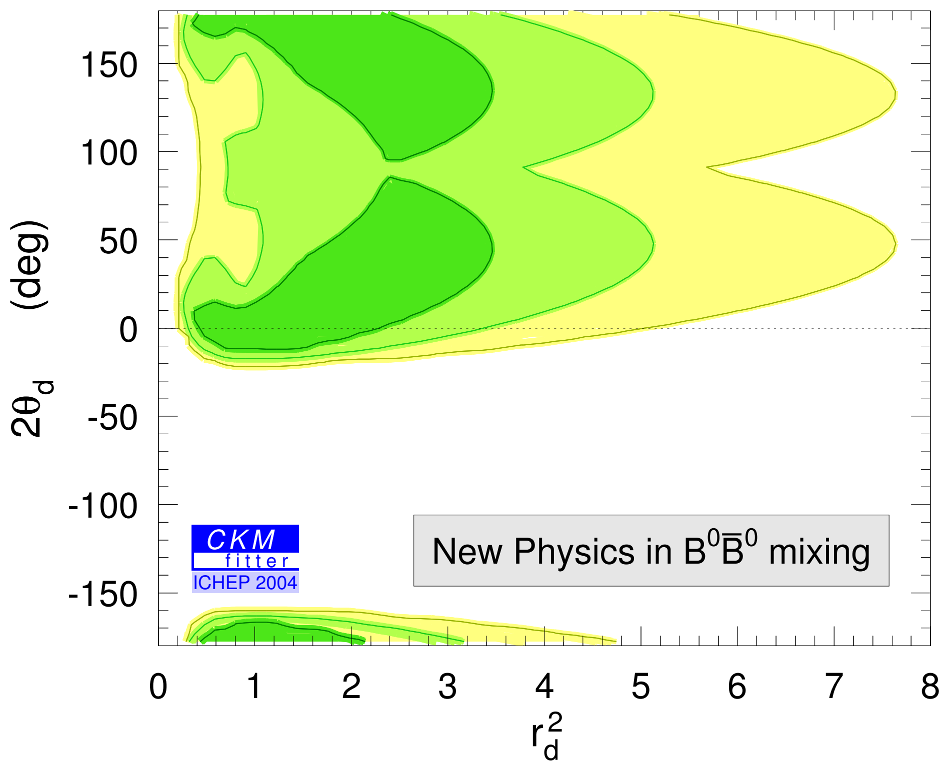
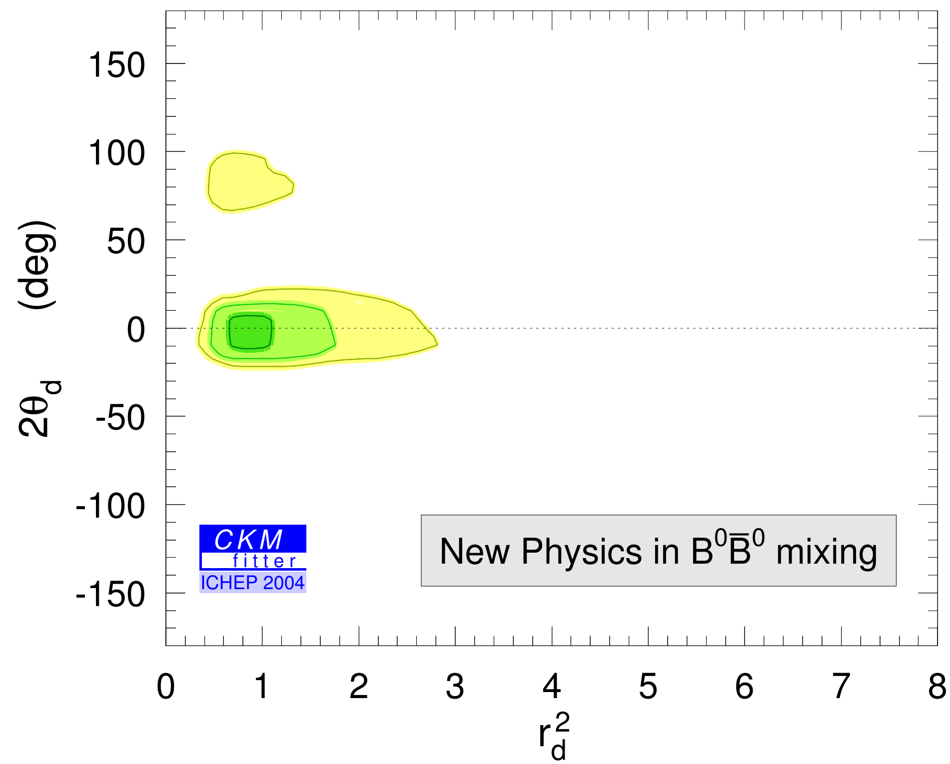


New in '04: α, γ, $2\beta + \gamma$, $\cos 2\beta$



- New data restrict θ_d, r_d^2 significantly for the first time — still plenty of room left

Understanding (some) hadronic physics

Disentangling weak and strong interactions

- Want to learn about electroweak physics, but hadronic physics is nonperturbative

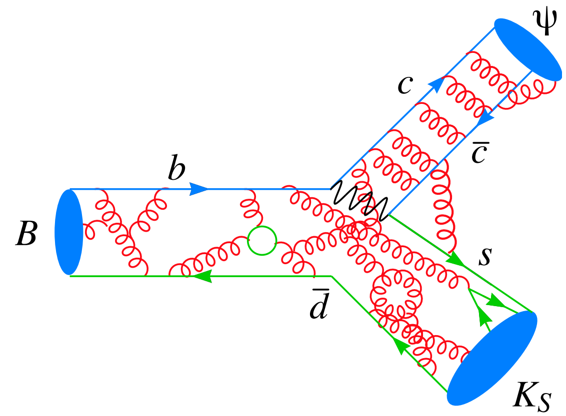
  Model independent ways:

- Symmetries of QCD (exact or approximate)

  E.g.: $\sin 2\beta$ from $B \to J/\psi K_S$: amplitude not calculable

  Solution: CP symmetry of QCD ($\theta_{\rm QCD}$ can be neglected)

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

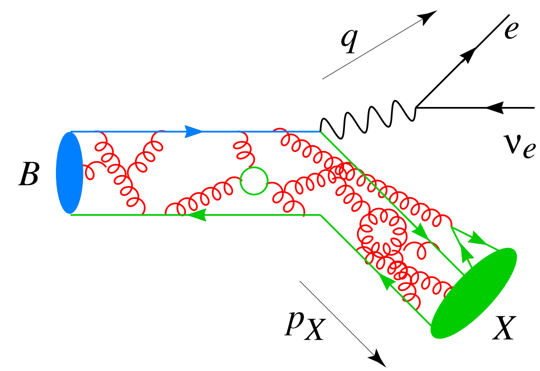


- Effective field theories (separation of scales)

  E.g.: $|V_{cb}|$ and $|V_{ub}|$ from semileptonic B decays

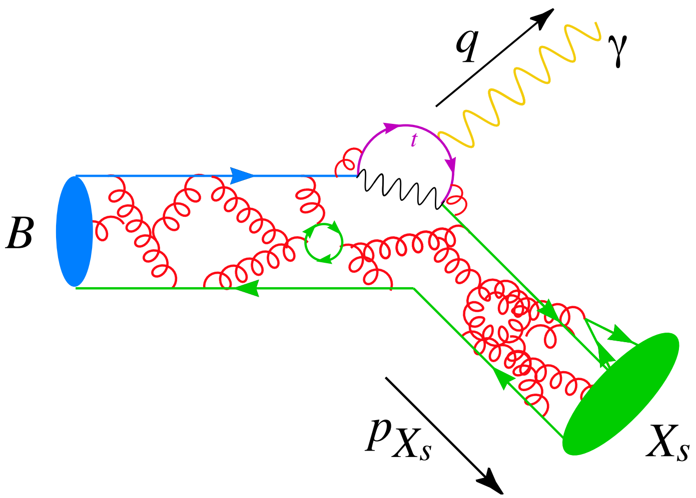
  Solution: Heavy quark expansions

$$\Gamma = |V_{cb}|^2 \times (\text{known factors}) \times [1 + \mathcal{O}(\Lambda^2_{\rm QCD}/m_b^2)]$$



Many relevant scales: $B \to X_s\gamma$

- Disentangle physics at: $(m_W, m_t \sim 100\,\mathrm{GeV}) \gg (m_b \sim 5\,\mathrm{GeV}) \gg (\Lambda \sim 0.5\,\mathrm{GeV})$



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

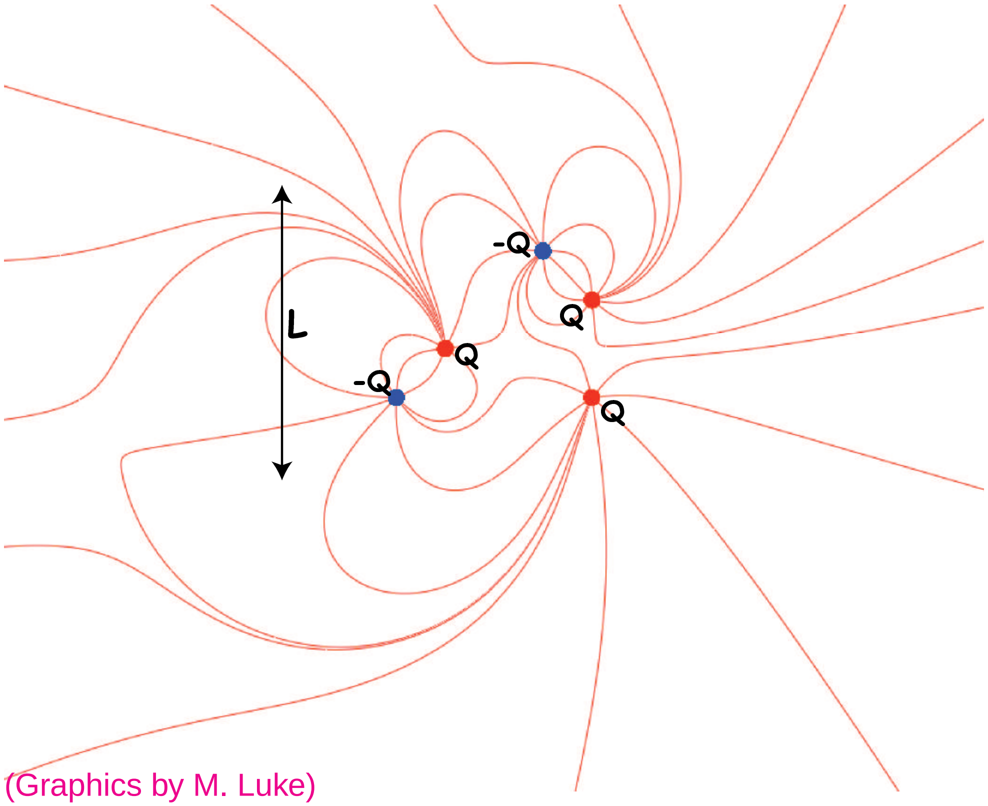
Diagrams with many gluons are crucial, resumming certain subset of them affects rate at factor-of-two level

Rate calculated 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

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

The multipole expansion

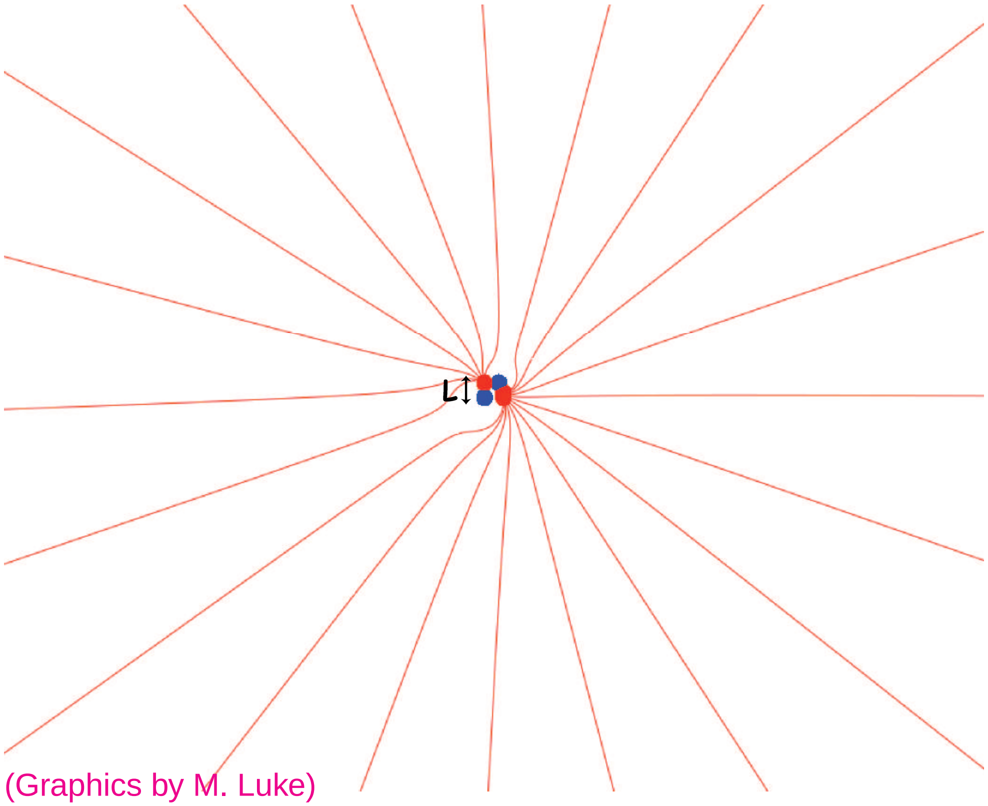


(Graphics by M. Luke)

Physics at $r \sim L$ is complicated

Depends on the details of the charge distribution

The multipole expansion



(Graphics by M. Luke)

Physics at $r \gg L$ is much simpler

Charge distribution characterized by total charge, q

Details suppressed by powers of L/r, and can be parameterized in terms of $p_i,\ Q_{ij},\ \ldots$

Simplifications occur due to separating physics at different distance scales

- Complicated charge distribution can be replaced by a point source with additional interactions (multipoles) — underlying idea of effective theories

The multipole expansion (cont.)

- Potential: $$V(x) = q\,\frac{1}{r} + p_i\,\frac{x_i}{r^3} + \frac{1}{2}\,Q_{ij}\,\frac{x_i x_j}{r^5} + \ldots$$

  Short distance quantities:

  $$q = \int \rho(x)\,\mathrm{d}^3x, \qquad p_i = \int x_i\,\rho(x)\,\mathrm{d}^3x, \qquad Q_{ij} = \int (3x_i x_j - r^2\delta_{ij})\,\rho(x)\,\mathrm{d}^3x$$

  Long distance quantities:

  $\left\langle \frac{1}{r} \right\rangle, \left\langle \frac{x_i}{r^3} \right\rangle, \left\langle \frac{x_i x_j}{r^5} \right\rangle$ — calculable in E&M, but nonperturbative in QCD

- Higher moments: new interactions from “integrating out” short distance physics

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- Any theory at momentum $p \ll M$ can be described by an effective Hamiltonian

$$H_{\text{eff}} = H_0 + \sum_i \frac{C_i}{M^{n_i}}\,O_i$$

$M \to \infty$ limit $+$ corrections with well-defined power counting
H_0 may have more symmetries than full theory at nonzero p/M
Can work to higher orders in p/M; can sum logs of p/M

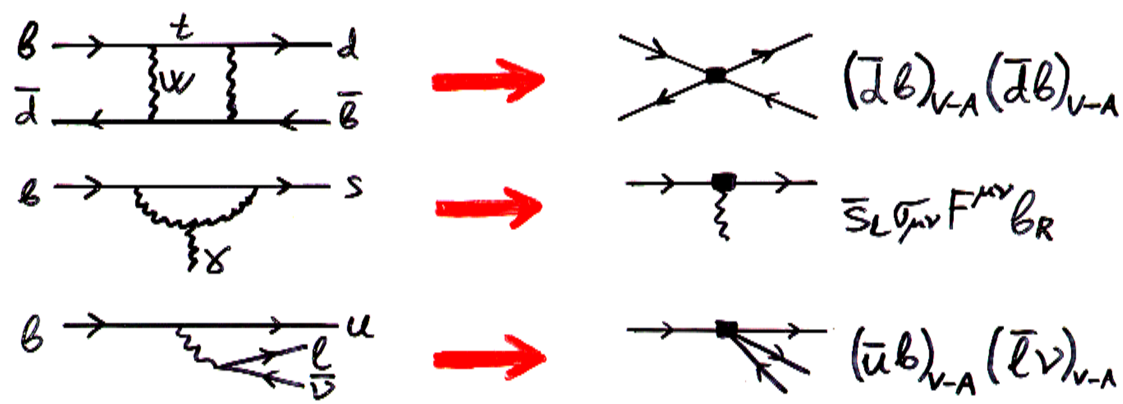
NP can modify C_i or give rise to new O_i's — right coefficients? right operators?

Goal of B physics in EFT language

- At scale m_b, flavor changing processes are mediated by “non-renormalizable” operators

  Several dozens, with a priori independent Wilson coefficients

$\sim$ weak scale $\qquad\qquad$ $\sim 5\,$GeV



  Determine cleanly as many as possible — the key is “redundancy”

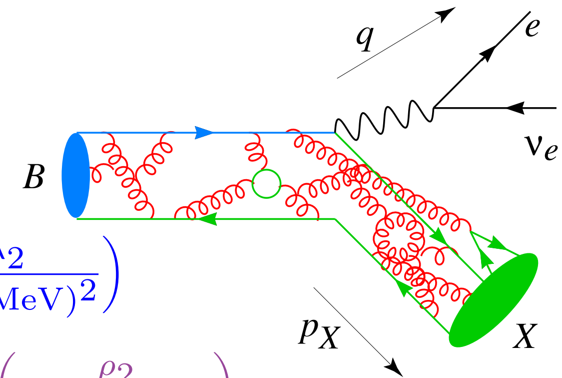
  E.g.: B_d mixing and $b \to d\gamma$ given by different op’s in $\mathcal{H}$, but both $\propto V_{tb}V_{td}^*$ in SM

- Are all the higher dimension flavor changing operators which occur at $\sim 5\,$GeV consistent with integrating out virtual quarks, W, Z? At what level can we check?

- New physics most likely to modify SM loop amplitudes, so study: mixing & rare decays, comparison of tree and loop processes, CPV asymmetries

Classic application: inclusive $|V_{cb}|$

- Want to determine $b \to c$ weak coupling



$$\Gamma(B \to X_c \ell \bar\nu) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3} \left(\frac{m_\Upsilon}{2}\right)^5 (0.534) \times$$

$$\bigg[1 - 0.22\left(\frac{\Lambda_{1S}}{500\,\text{MeV}}\right) - 0.011\left(\frac{\Lambda_{1S}}{500\,\text{MeV}}\right)^2 - 0.052\left(\frac{\lambda_1}{(500\,\text{MeV})^2}\right) - 0.071\left(\frac{\lambda_2}{(500\,\text{MeV})^2}\right)$$

$$- 0.006\left(\frac{\lambda_1 \Lambda_{1S}}{(500\,\text{MeV})^3}\right) + 0.011\left(\frac{\lambda_2 \Lambda_{1S}}{(500\,\text{MeV})^3}\right) - 0.006\left(\frac{\rho_1}{(500\,\text{MeV})^3}\right) + 0.008\left(\frac{\rho_2}{(500\,\text{MeV})^3}\right)$$

$$+ 0.011\left(\frac{T_1}{(500\,\text{MeV})^3}\right) + 0.002\left(\frac{T_2}{(500\,\text{MeV})^3}\right) - 0.017\left(\frac{T_3}{(500\,\text{MeV})^3}\right) - 0.008\left(\frac{T_4}{(500\,\text{MeV})^3}\right)$$

$$+ 0.096\epsilon - 0.030\epsilon^2_{\text{BLM}} + 0.015\epsilon\left(\frac{\Lambda_{1S}}{500\,\text{MeV}}\right) + \ldots \bigg]$$

Corrections: $\mathcal{O}(\Lambda/m)$: $\sim 20\%$, $\mathcal{O}(\Lambda^2/m^2)$: $\sim 5\%$, $\mathcal{O}(\Lambda^3/m^3)$: $\sim 1-2\%$, $\mathcal{O}(\alpha_s)$: $\sim 10\%$, Unknown terms: $<$ few $\%$

Matrix elements extracted from shape variables — good fit to lots of data

- Error of $|V_{cb}| \sim 2\%$ — a precision field

Other processes

- $|V_{ub}|$ and $B \to X_s\gamma$
  - Similar, just a lot more complicated...
  - Experimentally required phase-space cuts introduce new small parameters

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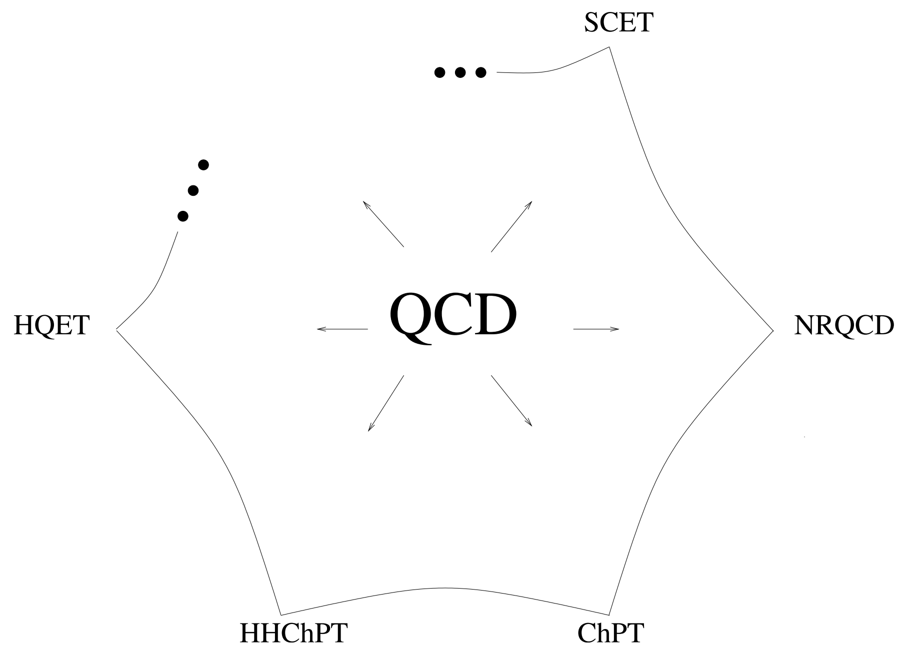
- Nonleptonic decays
  - When there are more than one hadrons in the final state, things become more complicated yet again...



(Graphics by S. Mantry)

Some recent developments

Not only a great place to look for NP, but also to study the SM

Significant steps toward a model independent theory of certain exclusive nonleptonic decays in the $m_B \gg \Lambda_{\rm QCD}$ limit

Fascinating (field) theory developments, work in progress

Theoretical developments

- Observables very sensitive to NP — can we disentangle from hadronic physics?
  - Polarization in charmless $B \to VV$ decays
  - $B \to K\pi$ branching ratios and direct CP asymmetries (closely related to $\pi\pi$)

  First derive correct expansion in $m_b \gg \Lambda_{\rm QCD}$ limit, then worry about predictions
  Different assumptions in QCDF and PQCD $\Rightarrow$ SCET (consistent power counting)

- Charm penguins: No suppression of long distance part has been proven (without that, a model dependent term that can give rise to "unexpected" things)

  Lore: "long distance charm loops", "charming penguins", "$D\overline{D}$ rescattering" are the same (unknown) term; may yield strong phases, transverse polarization, etc.

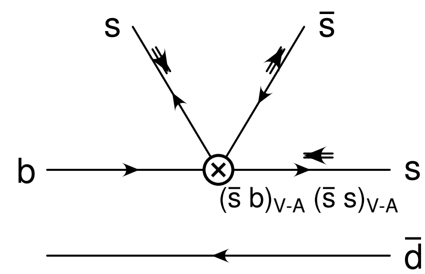
  Many implications: strong phases $\mathcal{O}(1)$ or suppressed? [$A_{K^-\pi^+} \Rightarrow$ some $\mathcal{O}(1)$]

Polarization in charmless $B \to VV$

B decay	Longitudinal polarization fraction BELLE	BABAR
$\rho^-\rho^+$		$0.98^{+0.02}_{-0.03}$
$\rho^0\rho^+$	0.95 ± 0.11	$0.97^{+0.05}_{-0.08}$
$\omega\rho^+$		$0.88^{+0.12}_{-0.15}$
$\rho^0 K^{*+}$		$0.96^{+0.06}_{-0.16}$
$\rho^- K^{*0}$	$0.43^{+0.12}_{-0.11}$	0.79 ± 0.09
ϕK^{*0}	0.45 ± 0.05	0.52 ± 0.05
ϕK^{*+}	0.52 ± 0.09	0.46 ± 0.12

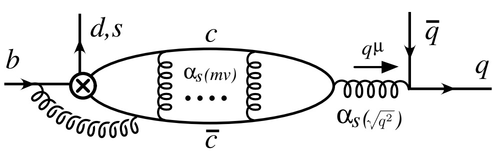
Chiral structure of SM and HQ limit claimed to imply

$$f_L = 1 - \mathcal{O}(1/m_b^2)$$ [Kagan]

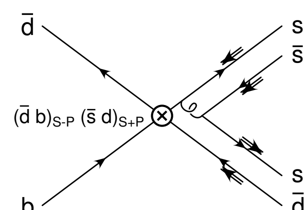


ϕK^*: penguin dominated — NP reduces f_L?

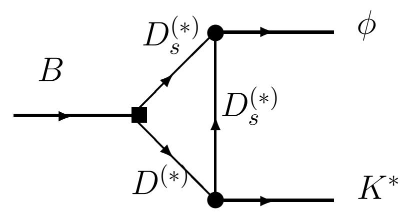
Proposed explanations:



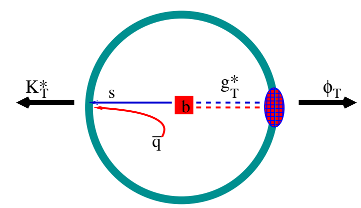
$\mathcal{O}(1)$



$\mathcal{O}(1/m_b^2) \times$ large



(model)



(model)

c penguin [Bauer *et al.*]; penguin annihilation [Kagan]; rescattering [Colangelo *et al.*]; g fragment. [Hou, Nagashima]

Not clear if it can be made a clean signal of NP

$B \to \pi K$ rates and CP asymmetries

Sensitive to interference between $b \to s$ penguin and $b \to u$ tree (and possible NP)

Decay mode	CP averaged $\mathcal{B}$ $[\times 10^{-6}]$	A_{CP}
$\overline{B}^0 \to \pi^+ K^-$	18.2 ± 0.8	-0.11 ± 0.02
$B^- \to \pi^0 K^-$	12.1 ± 0.8	$+0.04 \pm 0.04$
$B^- \to \pi^- \overline{K}^0$	24.1 ± 1.3	-0.02 ± 0.03
$\overline{B}^0 \to \pi^0 \overline{K}^0$	11.5 ± 1.0	$+0.00 \pm 0.16$

$$R_c \equiv 2\, \frac{\mathcal{B}(B^+ \to \pi^0 K^+) + \mathcal{B}(B^- \to \pi^0 K^-)}{\mathcal{B}(B^+ \to \pi^+ K^0) + \mathcal{B}(B^- \to \pi^- \overline{K}^0)} = 1.00 \pm 0.08$$

$$R_n \equiv \frac{1}{2}\, \frac{\mathcal{B}(B^0 \to \pi^- K^+) + \mathcal{B}(\overline{B}^0 \to \pi^+ K^-)}{\mathcal{B}(B^0 \to \pi^0 K^0) + \mathcal{B}(\overline{B}^0 \to \pi^0 \overline{K}^0)} = 0.79 \pm 0.08$$

$$R \equiv \frac{\mathcal{B}(B^0 \to \pi^- K^+) + \mathcal{B}(\overline{B}^0 \to \pi^+ K^-)}{\mathcal{B}(B^+ \to \pi^+ K^0) + \mathcal{B}(B^- \to \pi^- \overline{K}^0)}\, \frac{\tau_{B^\pm}}{\tau_{B^0}} = 0.82 \pm 0.06 \qquad \Rightarrow \text{FM bound} : \gamma < 75^\circ \; (95\%\,\text{CL})$$

$$R_L \equiv 2\, \frac{\bar\Gamma(B^- \to \pi^0 K^-) + \bar\Gamma(\overline{B}^0 \to \pi^0 \overline{K}^0)}{\bar\Gamma(B^- \to \pi^- \overline{K}^0) + \bar\Gamma(\overline{B}^0 \to \pi^+ K^-)} = 1.12 \pm 0.07$$

- Pattern quite different than before 2004: R_c closer to 1 while R further from 1
  Seems to disfavor NP explanation in EW penguin only $\Rightarrow$will be exciting to sort out

Future

Theoretical limitations

- Many interesting decay modes will not be theory limited for a long time

Measurement (in SM)	Theoretical limit	Present error
$B \to \psi K_S$ (β)	$\sim 0.2^\circ$	1.6°
$B \to \phi K_S$, $\eta^{(\prime)} K_S$, ... (β)	$\sim 2^\circ$	$\sim 10^\circ$
$B \to \pi\pi,\ \rho\rho,\ \rho\pi$ (α)	$\sim 1^\circ$	$\sim 15^\circ$
$B \to DK$ (γ)	$\ll 1^\circ$	$\sim 25^\circ$
$B_s \to \psi\phi$ (β_s)	$\sim 0.2^\circ$	—
$B_s \to D_s K$ ($\gamma - 2\beta_s$)	$\ll 1^\circ$	—
$\lvert V_{cb}\rvert$	$\sim 1\%$	$\sim 3\%$
$\lvert V_{ub}\rvert$	$\sim 5\%$	$\sim 15\%$
$B \to X\ell^+\ell^-$	$\sim 5\%$	$\sim 20\%$
$B \to K^{(*)}\nu\bar\nu$	$\sim 5\%$	—
$K^+ \to \pi^+\nu\bar\nu$	$\sim 5\%$	$\sim 70\%$
$K_L \to \pi^0\nu\bar\nu$	$< 1\%$	—

It would require breakthroughs to go significantly below these theory limits

Outlook

- If there are new particles at TeV scale, new flavor physics could show up "any time" (are $S_{\eta' K_S}$ and $S_{\phi K_S}$ hints or fluctuations?)

  Babar & Belle data have roughly doubled each year, will reach $500–1000\,\mathrm{fb}^{-1}$ each in a few years; $B \to J/\psi K_S$ was a well-defined target

- Goal for further flavor physics experiments:

  If NP is seen in flavor physics: study it in as many different operators as possible

  If NP is not seen in flavor physics: achieve what's theoretically possible

  Even in latter case, flavor physics will give powerful constraints on model building in the LHC era

  LHCB: new frontiers in the B_s sector, and complements e^+e^- studies for B_d

- The program as a whole is a lot more interesting than any single measurement

Recap of recent highlights

- $\sin 2\beta = 0.726 \pm 0.037$

  $\Rightarrow$ good overall consistency of SM ($\delta_{\rm CKM}$ is probably the dominant source of CPV in flavor changing processes)

- $S_{\psi K} - \langle S_{b\to s}\rangle = 0.30 \pm 0.08\ (3.5\sigma)$ and $S_{\psi K} - S_{\eta' K_S} = 0.31 \pm 0.12\ (2.6\sigma)$

  $\Rightarrow$ possible hints of NP (same central values with 5σ would be convincing)

- $A_{K^-\pi^+} = -0.11 \pm 0.02\ (5.7\sigma)$

  $\Rightarrow$ "B-superweak" excluded, sizable strong phases

- First α and γ measurements

  $\Rightarrow$ First serious constraints on NP in B–$\overline{B}$ mixing — still lots of room left

Conclusions

- We know a lot more about the flavor sector and CPV than we did 4–5 years ago: CKM phase is probably the dominant source of CPV in flavor changing processes
- Existing measurements could have shown deviations from the SM, and we may be seeing hints already
- The point is not only to measure the sides and angles of the unitarity triangle, (ρ, η) and (α, β, γ), but to probe CKM by overconstraining it in as many ways as possible (rare decays, correlations)
- Many processes give clean information on short distance physics, and there is progress toward being able to model independently interpret more observables

Additional Topics

Further interesting CPV modes

$B \to \rho\rho$ vs. $\pi\pi$ isospin analysis

- Due to $\Gamma_\rho \neq 0$, $\rho\rho$ in $I = 1$ possible, even for $\sigma = 0$ [Falk, ZL, Nir, Quinn]

  Can have antisymmetric dependence on both the two ρ mesons' masses and on their isospin indices $\Rightarrow I = 1$ ($m_i =$ mass of a pion pair; $B =$ Breit-Wigner)

$$A \sim B(m_1)B(m_2)\,\frac{1}{2}\big[f(m_1,m_2)\,\rho^+(m_1)\rho^-(m_2) + f(m_2,m_1)\,\rho^+(m_2)\rho^-(m_1)\big]$$

$$= B(m_1)B(m_2)\,\frac{1}{4}\Big\{\big[f(m_1,m_2) + f(m_2,m_1)\big]\underbrace{\big[\rho^+(m_1)\rho^-(m_2) + \rho^+(m_2)\rho^-(m_1)\big]}_{I=0,2}$$

$$+\big[f(m_1,m_2) - f(m_2,m_1)\big]\underbrace{\big[\rho^+(m_1)\rho^-(m_2) - \rho^+(m_2)\rho^-(m_1)\big]}_{I=1}\Big\}$$

  If Γ_ρ vanished, then $m_1 = m_2$ and $I = 1$ part is absent

  E.g., no symmetry in factorization: $f(m_{\rho^-}, m_{\rho^+}) \sim f_\rho(m_{\rho^+})\, F^{B\to\rho}(m_{\rho^-})$

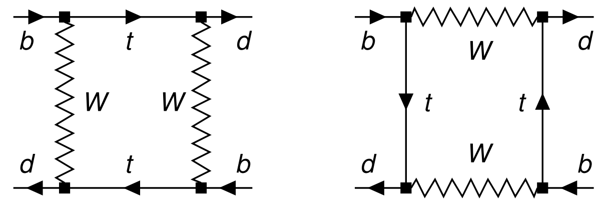
- Cannot rule out $\mathcal{O}(\Gamma_\rho/m_\rho)$ contributions; no interference $\Rightarrow$ $\mathcal{O}(\Gamma_\rho^2/m_\rho^2)$ effects

  Can ultimately constrain these using data

CPV in neutral meson mixing

- CPV in mixing and decay: typically sizable hadronic uncertainties

Flavor eigenstates: $|B^0\rangle = |\overline{b}\, d\rangle, \;\; |\overline{B}^0\rangle = |b\, \overline{d}\rangle$



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

Mass eigenstates: $|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$

- CPV in mixing: Mass eigenstates $\neq CP$ eigenstates $(|q/p| \neq 1$ and $\langle B_H|B_L\rangle \neq 0)$

Best limit from semileptonic asymmetry $(4\mathrm{Re}\,\epsilon)$ [NLO: Beneke *et al.*; Ciuchini *et al.*]

$$A_{\rm SL} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = (-0.05 \pm 0.71)\% \text{ (WA)}$$

$\Rightarrow |q/p| = 1.0003 \pm 0.0035$ [dominated by new BELLE result]

Allowed range $\gg$ than SM region, but already sensitive to NP [Laplace, ZL, Nir, Perez]

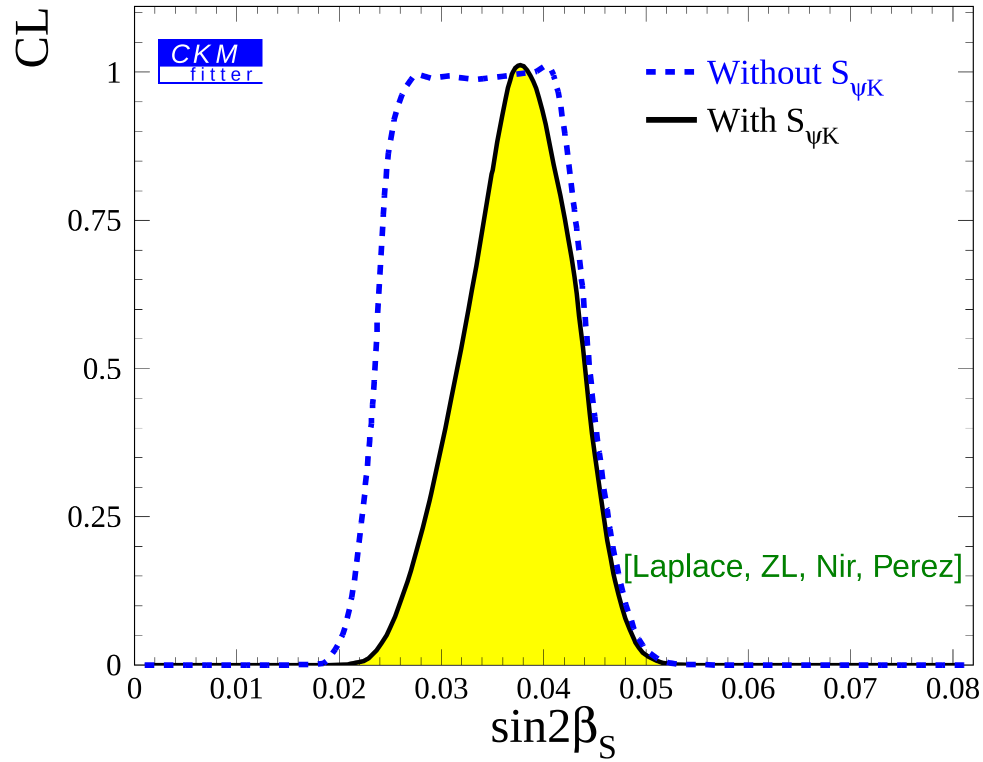
$B_s \to \psi\phi$ and $B_s \to \psi\eta^{(\prime)}$

- Analog of $B \to \psi K_S$ in B_s decay — determines the phase between B_s mixing and $b \to c\bar{c}s$ decay, β_s, as cleanly as $\sin 2\beta$ from ψK_S

β_s is a small $\mathcal{O}(\lambda^2)$ angle in one of the "squashed" unitarity triangles

$\psi\phi$ is a VV state, so the asymmetry is diluted by the CP-odd component

$\psi\eta^{(\prime)}$, however, is pure CP-even



- Large asymmetry $(\sin 2\beta_s > 0.05)$ would be clear sign of new physics

$B_s \to D_s^\pm K^\mp$ and $B^0 \to D^{(*)\pm}\pi^\mp$

- Single weak phase in each $B_s, \overline{B}_s \to D_s^\pm K^\mp$ decay $\Rightarrow$ the 4 time dependent rates determine 2 amplitudes, strong, and weak phase (clean, although $|f\rangle \neq |f_{CP}\rangle$)

Four amplitudes: $\overline{B}_s \overset{A_1}{\to} D_s^+ K^- \quad (b \to c\bar{u}s)\,, \qquad \overline{B}_s \overset{A_2}{\to} K^+ D_s^- \quad (b \to u\bar{c}s)$

$$B_s \overset{A_1}{\to} D_s^- K^+ \quad (\bar{b} \to \bar{c}u\bar{s})\,, \qquad B_s \overset{A_2}{\to} K^- D_s^+ \quad (\bar{b} \to \bar{u}c\bar{s})$$

$$\frac{\overline{A}_{D_s^+K^-}}{A_{D_s^+K^-}} = \frac{A_1}{A_2}\left(\frac{V_{cb}V_{us}^*}{V_{ub}^*V_{cs}}\right), \qquad \frac{\overline{A}_{D_s^-K^+}}{A_{D_s^-K^+}} = \frac{A_2}{A_1}\left(\frac{V_{ub}V_{cs}^*}{V_{cb}^*V_{us}}\right)$$

Magnitudes and relative strong phase of A_1 and A_2 drop out if four time dependent rates are measured $\Rightarrow$ no hadronic uncertainty:

$$\lambda_{D_s^+K^-}\,\lambda_{D_s^-K^+} = \left(\frac{V_{tb}^*V_{ts}}{V_{tb}V_{ts}^*}\right)^2 \left(\frac{V_{cb}V_{us}^*}{V_{ub}^*V_{cs}}\right)\left(\frac{V_{ub}V_{cs}^*}{V_{cb}^*V_{us}}\right) = e^{-2i(\gamma-2\beta_s-\beta_K)}$$

- Similarly, $B_d \to D^{(*)\pm}\pi^\mp$ determines $\gamma + 2\beta$, since $\lambda_{D^+\pi^-}\,\lambda_{D^-\pi^+} = e^{-2i(\gamma+2\beta)}$
... ratio of amplitudes $\mathcal{O}(\lambda^2)$ $\Rightarrow$ small asymmetries (and tag side interference)

Photon polarization in $B^0 \to K^{*0}\gamma$

- The SM predicts $\mathcal{B}(B \to X_s\gamma)$ correctly at $\sim$$10\%$ level, but the rate alone does not tell us which operator causes the transition: $\bar{s}\,\sigma^{\mu\nu}F_{\mu\nu}P_R\,b$ or $\bar{s}\,\sigma^{\mu\nu}F_{\mu\nu}P_L\,b$

  SM: $O_7 \sim \bar{s}\,\sigma^{\mu\nu}F_{\mu\nu}\,(m_b P_R + m_s P_L)\,b$ — predominantly $b \to \gamma_L$ and $\bar{b} \to \gamma_R$

  O_7 contribution to interference and CPV suppressed by m_s/m_b, but four-quark operators may give a $\sim 10\%$ "wrong helicity" amplitude

  NP can easily modify SM prediction; motivated, e.g., by trying to explain the $S_{\eta' K_S}$ and $S_{\eta' K_S}$ data

  Time dependent measurement required new vertexing with K_S and π^0 only

  $$S_{K^*\gamma} = -0.38 \pm 0.34\,, \qquad C_{K^*\gamma} = -0.30 \pm 0.20$$ [Babar & Belle]

- Will be very interesting with (much) higher luminosity

A (near future & personal) best buy list

- β: reduce error in $B \to \phi K_S$, $\eta' K_S$, $K^+K^-K_S$ (and $D^{(*)}D^{(*)}$) modes
- α: refine $\rho\rho$ (search for $\rho^0\rho^0$); $\pi\pi$ (improve C_{00}); $\rho\pi$ Dalitz
- γ: pursue all approaches, impressive start
- β_s: is CPV in $B_s \to \psi\phi$ small?

- $|V_{td}/V_{ts}|$: B_s mixing (Tevatron may still have a chance)
- Rare decays: $B \to X_s\gamma$ near theory limited; $B \to X_s\ell^+\ell^-$ is becoming comparably precise
- $|V_{ub}|$: reaching $\lesssim 10\%$ will be very significant (a Babar/Belle measurement that may survive LHCB)
- try $B \to \ell\nu$, search for "null observables", $a_{CP}(b \to s\gamma)$, etc., for enhancement of $B_{(s)} \to \ell^+\ell^-$, etc.

(apologies if your favorite decay omitted!)

Nonleptonic decays

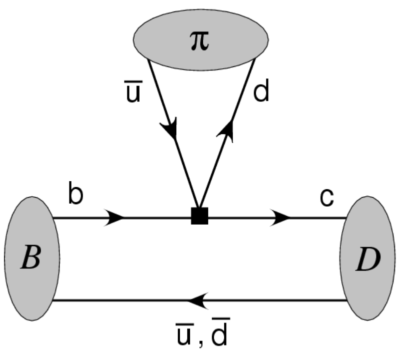
Predictions of SCET not foreseen in any model:

Color suppressed B- and isospin violating Λ_b decays

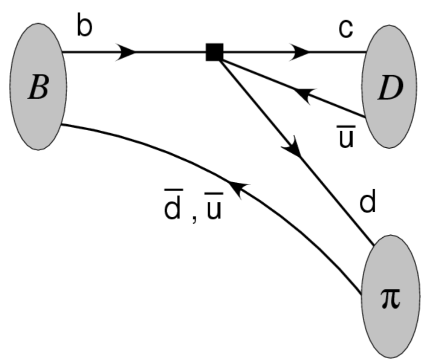
$B \to D^{(*)}\pi$ decay and SCET

- "Naive" factorization: $A(\overline{B}^0 \to D^+\pi^-) \propto \mathcal{F}^{B\to D} f_\pi$, works at $\mathcal{O}(5\text{–}10\%)$ level
  Factorization also in large N_c limit ($1/N_c^2$) — need precise data to test mechanism

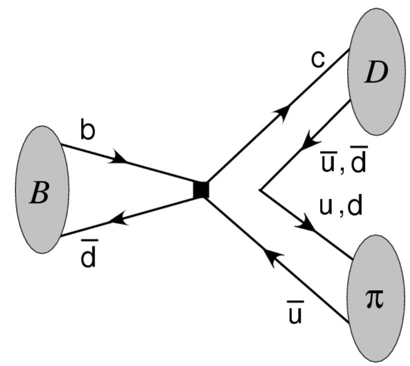
$\overline{B}^0 \to D^+\pi^-$
$B^- \to D^0\pi^-$



$B^- \to D^0\pi^-$
$\overline{B}^0 \to D^0\pi^0$



$\overline{B}^0 \to D^+\pi^-$
$\overline{B}^0 \to D^0\pi^0$



SCET: $\mathcal{O}(1)$ $\quad\mathcal{O}(\Lambda_{\rm QCD}/Q)$ $\quad\mathcal{O}(\Lambda_{\rm QCD}/Q)$ $\quad Q = \{E_\pi, m_{b,c}\}$

- Predictions: $$\frac{\mathcal{B}(B^- \to D^{(*)0}\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\pi^-)} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\,,$$

  data: $\sim 1.8 \pm 0.2$ (also for ρ)
  $\Rightarrow\ \mathcal{O}(35\%)$ power corrections

$$\frac{\mathcal{B}(\overline{B}^0 \to D^0\pi^0)}{\mathcal{B}(\overline{B}^0 \to D^{*0}\pi^0)} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\,,$$

data: $\sim 1.1 \pm 0.25$
Totally unexpected before SCET
[Mantry, Pirjol, Stewart]

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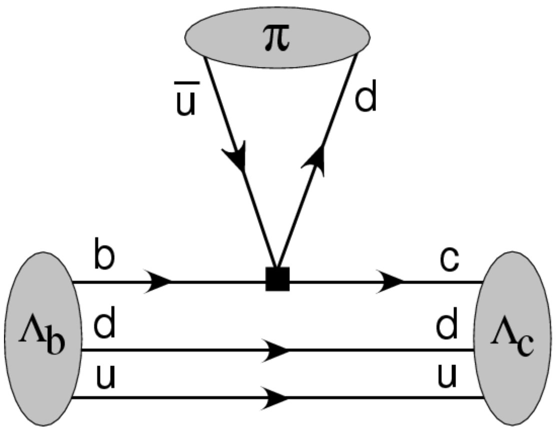
Λ_b baryon decays

- CDF recently measured: $\Gamma(\Lambda_b \to \Lambda_c^+ \pi^-)/\Gamma(\overline{B}^0 \to D^+\pi^-) = 2.7 \pm 0.9$



Factorization holds again at leading order in $\Lambda_{\rm QCD}/Q$, but it does not follow from large N_C

Obtain: [Leibovich, Z.L., Stewart, Wise]

$$\frac{\Gamma(\Lambda_b \to \Lambda_c \pi^-)}{\Gamma(\overline{B}^0 \to D^{(*)+}\pi^-)} \simeq 1.8 \left(\frac{\zeta(w_{\rm max}^{\Lambda})}{\xi(w_{\rm max}^{D^{(*)}})}\right)^2$$

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(Explain "≈ 2": one baryon vs. two meson ground states)

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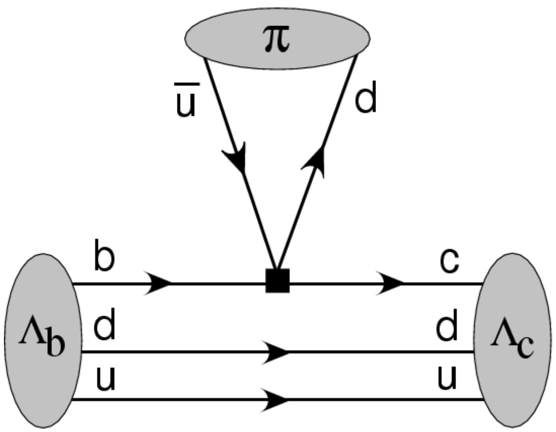

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- If weakly decaying heavy pentaquarks exist ($\Theta_Q = \bar{Q}udud$), their decays may be a goldmine to study pattern of corrections to factorization

$$\Theta_b^+ \to \Theta_c^0 \pi^+\,, \qquad \Theta_c^0 \to \Theta^+\pi^- \to K_S\, p\, \pi^- \to \pi^+\pi^- p\, \pi^-$$

More complicated: $\Lambda_b \to \Sigma_c \pi$

- Recall quantum numbers:

multiplets	s_l	$I(J^P)$
Λ_c	0	$0(\frac{1}{2}^+)$
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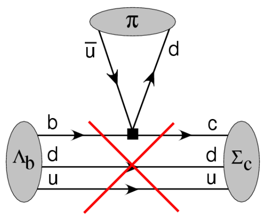
$$\Sigma_c = \Sigma_c(2455),\ \Sigma_c^* = \Sigma_c(2520)$$

Can't address in naive factorization, since $\Lambda_b \to \Sigma_c$ form factor vanishes by isospin



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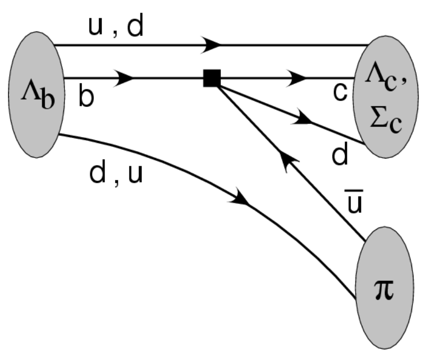
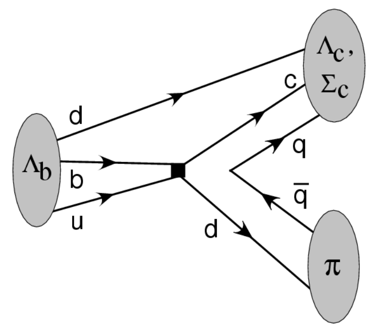


$\mathcal{O}(\Lambda_{\rm QCD}/Q)$



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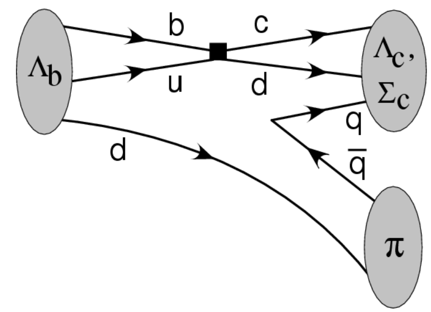

$\mathcal{O}(\Lambda_{\rm QCD}^2/Q^2)$

Prediction: $$\frac{\Gamma(\Lambda_b \to \Sigma_c^* \pi)}{\Gamma(\Lambda_b \to \Sigma_c \pi)} = 2 + \mathcal{O}\big[\Lambda_{\rm QCD}/Q\,,\ \alpha_s(Q)\big]$$

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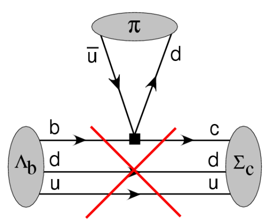

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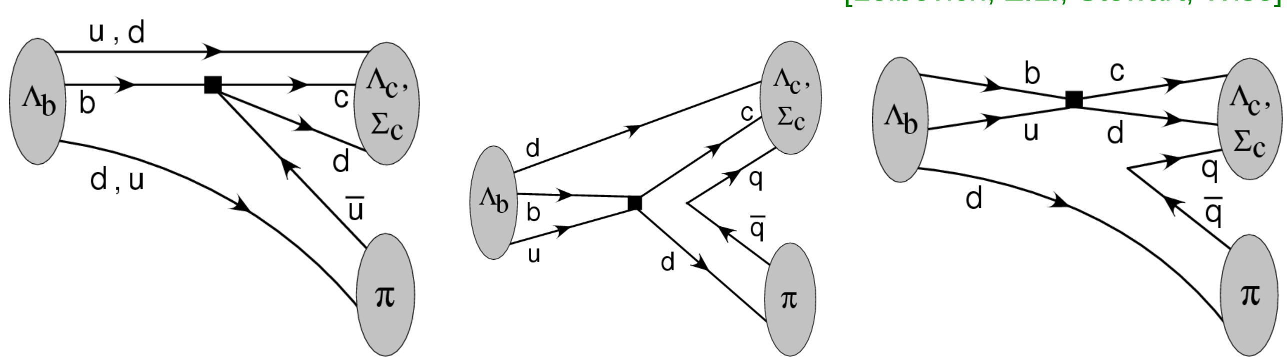

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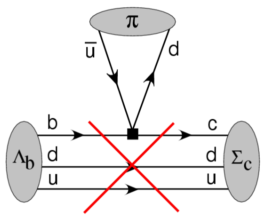

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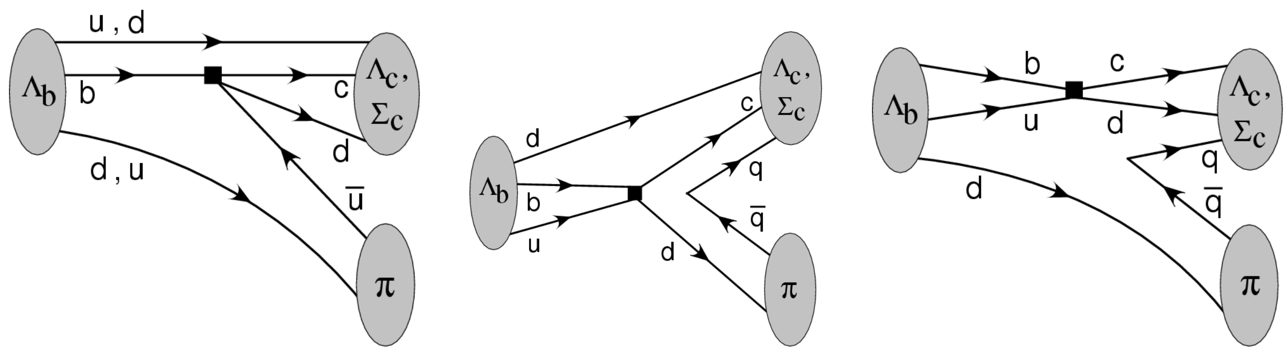

$\mathcal{O}(\Lambda_{\rm QCD}/Q)$ $\quad$ $\mathcal{O}(\Lambda_{\rm QCD}/Q)$ $\quad$ $\mathcal{O}(\Lambda_{\rm QCD}^2/Q^2)$

Prediction: $$\frac{\Gamma(\Lambda_b \to \Sigma_c^* \pi)}{\Gamma(\Lambda_b \to \Sigma_c \pi)} = 2 + \mathcal{O}\big[\Lambda_{\rm QCD}/Q\,,\ \alpha_s(Q)\big] = \frac{\Gamma(\Lambda_b \to \Sigma_c^{*0}\rho^0)}{\Gamma(\Lambda_b \to \Sigma_c^0 \rho^0)}$$

Can avoid π^0's from $\Lambda_b \to \Sigma_c^{(*)0}\pi^0 \to \Lambda_c \pi^- \pi^0$ or $\Lambda_b \to \Sigma_c^{(*)+}\pi^- \to \Lambda_c \pi^0 \pi^-$