The CKM matrix and CP Violation
(in the continuum approximation)

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Plan of the talk

- Introduction

  Why you might care

- CP violation — present status

  β: from $b \to c$ and $b \to s$ modes

  α & γ: interesting results last year

  Implications for NP in $B - \overline{B}$ mixing

- Theory developments: semileptonic and nonleptonic decays in SCET

  Semileptonic form factors

  Nonleptonic decays

- Future / Conclusions

Plan of the talk

- Introduction

  Why you might care

- CP violation — present status

β: from $b \to c$ and $b \to s$ modes	Precision test of CKM; search for NP
α & γ: interesting results last year	Best present α, γ methods are new
Implications for NP in $B - \overline{B}$ mixing	First significant constraints

- Theory developments: semileptonic and nonleptonic decays in SCET

Semileptonic form factors	Few applications, connections between
Nonleptonic decays	semileptonic and nonleptonic

- Future / Conclusions

Why is flavor physics and CPV interesting?

- Sensitive to very high scales

$$\epsilon_K\text{:}\ \frac{(s\bar{d})^2}{\Lambda_{\rm NP}^2} \Rightarrow \Lambda_{\rm NP} \gtrsim 10^4\,\text{TeV}, \qquad B_d \text{ mixing: } \frac{(b\bar{d})^2}{\Lambda_{\rm NP}^2} \Rightarrow \Lambda_{\rm NP} \gtrsim 10^3\,\text{TeV}$$

- Almost all extensions of the SM contain new sources of CP and flavor violation
  (e.g., 43 new CPV phases in SUSY [must see superpartners to discover it])

- A major constraint for model building
  (flavor structure: universality, heavy squarks, squark-quark alignment, ...)

- May help to distinguish between different models
  (mechanism of SUSY breaking: gauge-, gravity-, anomaly-mediation, ...)

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

How to test the flavor sector?

- Only Yukawa couplings distinguish between generations; pattern of masses and mixings inherited from interaction with something unknown (couplings to Higgs)
- Flavor changing processes mediated by $\mathcal{O}(100)$ nonrenormalizable operators $\Rightarrow$ intricate correlations between different decays of s, c, b, t quarks

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Deviations from CKM paradigm may result in:

- Subtle (or not so subtle) changes in correlations, e.g., B and K constraints inconsistent or $S_{\psi K_S} \neq S_{\phi K_S}$
- Enhanced or suppressed CP violation, e.g., sizable $S_{B_s \to \psi\phi}$ or $A_{s\gamma}$
- FCNC's at unexpected level, e.g., $B \to \ell^+\ell^-$ or B_s mixing incompatible w/ SM

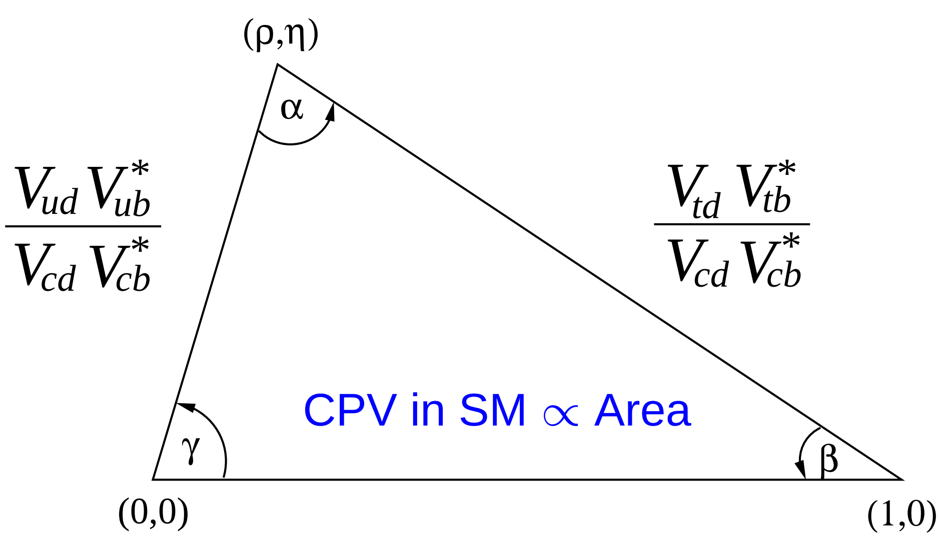
- Question: does the SM (i.e., virtual W, Z, and quarks interacting through CKM matrix in tree and loop diagrams) explain all flavor changing interactions?

CKM matrix and unitarity triangle

- Convenient to exhibit hierarchical structure $(\lambda = \sin\theta_C \simeq 0.22)$

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

- A “language” to compare overconstraining measurements



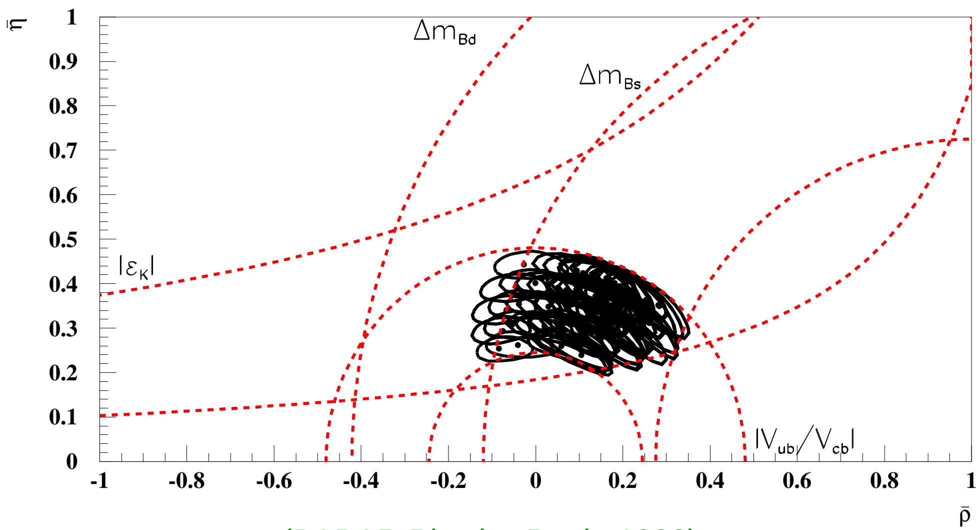
$$V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$$

Goal: “redundant” measurements sensitive to different short distance physics

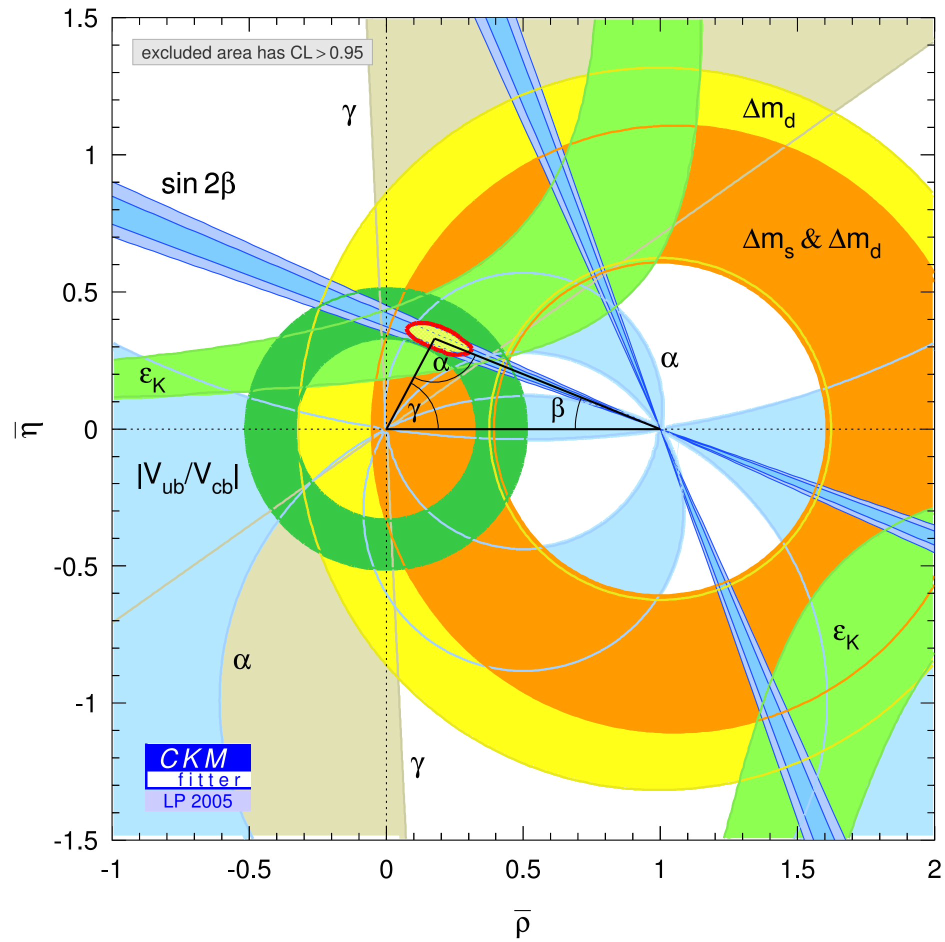
E.g.: B_d mixing and $b \to d\gamma$ given by different op’s in $\mathcal{H}$, but both $\propto V_{tb}V_{td}^*$ in SM

Tests of the flavor sector

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



(BABAR Physics Book, 1998)



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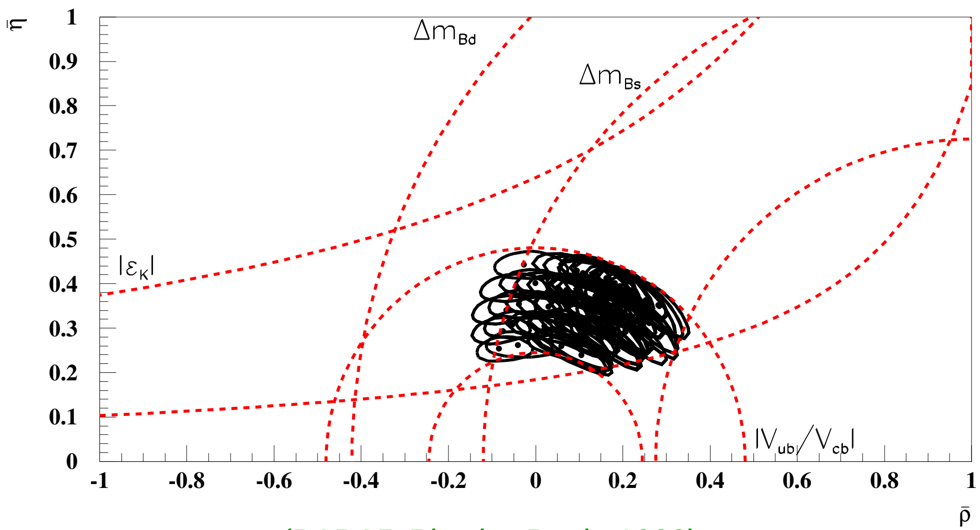

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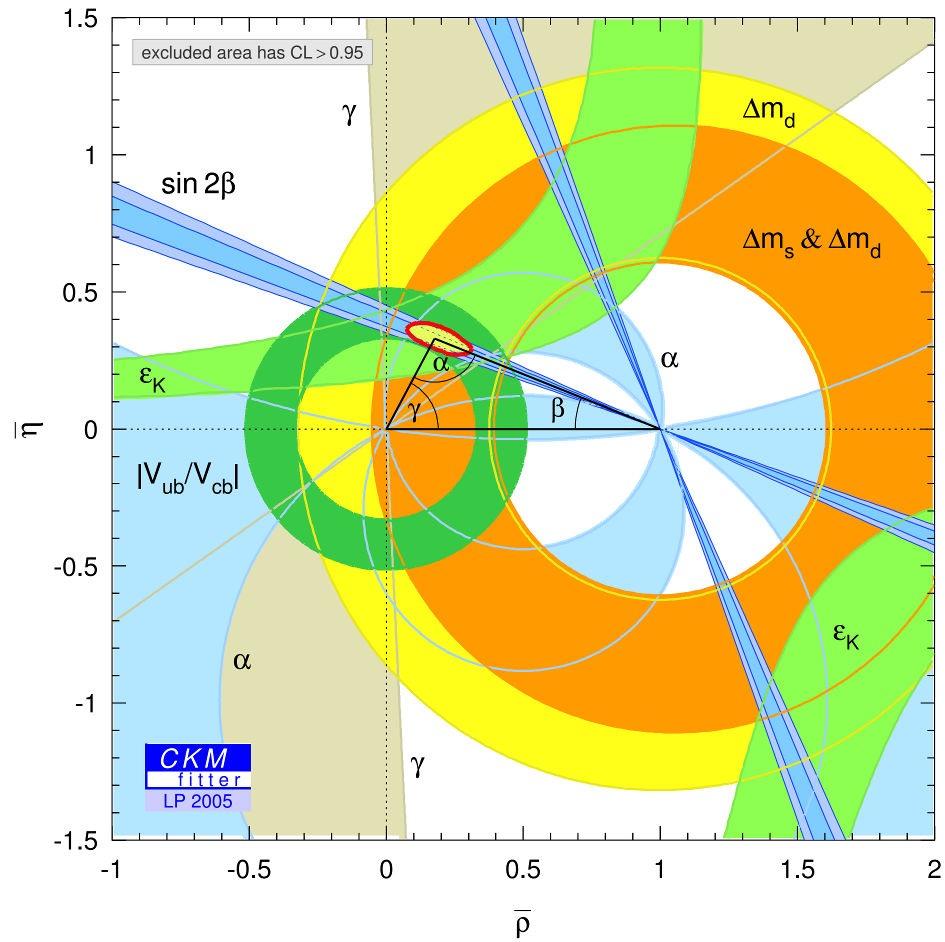

- $\sin 2\beta = 0.687 \pm 0.032$, order of magnitude smaller error than first measurements

What are we after?

- Flavor and CP violation are excellent probes of New Physics
  - 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?

SM tests with K and D mesons

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

  Observation (3 events): $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.5^{+1.3}_{-0.9}) \times 10^{-10}$ — need more data

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- D system complementary to K, B:

  Only meson where mixing is generated by down type quarks (SUSY: up squarks)

  CPV & FCNC both GIM and CKM suppressed $\Rightarrow$ tiny in SM and not yet observed

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

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

  Can lattice help to understand SM prediction for $\Delta m_D, \Delta\Gamma_D$? (SD part for sure)

CP Violation

CPV in decay

- Simplest, count events; amplitudes with different weak (ϕ_k) & strong (δ_k) phases

$|\overline{A}_{\overline{f}}/A_f| \neq 1$: $A_f = \langle f|\mathcal{H}|B\rangle = \sum A_k\, e^{i\delta_k}\, e^{i\phi_k}, \qquad \overline{A}_{\overline{f}} = \langle \overline{f}|\mathcal{H}|\overline{B}\rangle = \sum A_k\, e^{i\delta_k}\, e^{-i\phi_k}$

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

$$A_{K^-\pi^+} \equiv \frac{\Gamma(\overline{B} \to K^-\pi^+) - \Gamma(B \to K^+\pi^-)}{\Gamma(\overline{B} \to K^-\pi^+) + \Gamma(B \to K^+\pi^-)} = -0.115 \pm 0.018$$

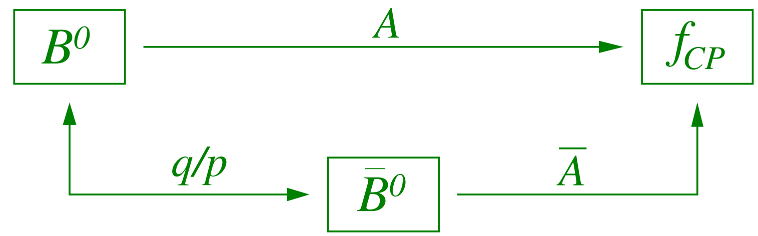
  - After "K-superweak", also "B-superweak" excluded: CPV is not only in mixing
  - There are large strong phases (also in $B \to \psi K^*$); challenge to some models

- Current theoretical understanding insufficient for both ϵ'_K and $A_{K^-\pi^+}$ to either prove or to rule out that NP contributes

Sensitive to NP when SM prediction is model independently small (e.g., $A_{b\to s\gamma}$)

CPV in interference between decay and mixing

- Can get theoretically clean information in some cases 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, hadronic physics drops out from λ_f, and $a_{f_{CP}}$ measures a phase in the Lagrangian theoretically cleanly:

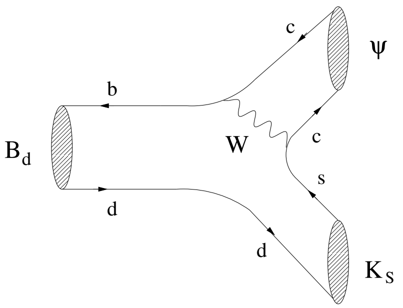
$$a_{f_{CP}} = \mathrm{Im}\,\lambda_f\,\sin(\Delta m\,t) \qquad \arg\lambda_f = \text{phase difference between decay paths}$$

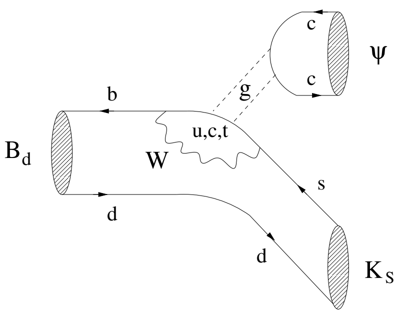
The cleanest case: $B \to J/\psi\, K_S$

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

  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

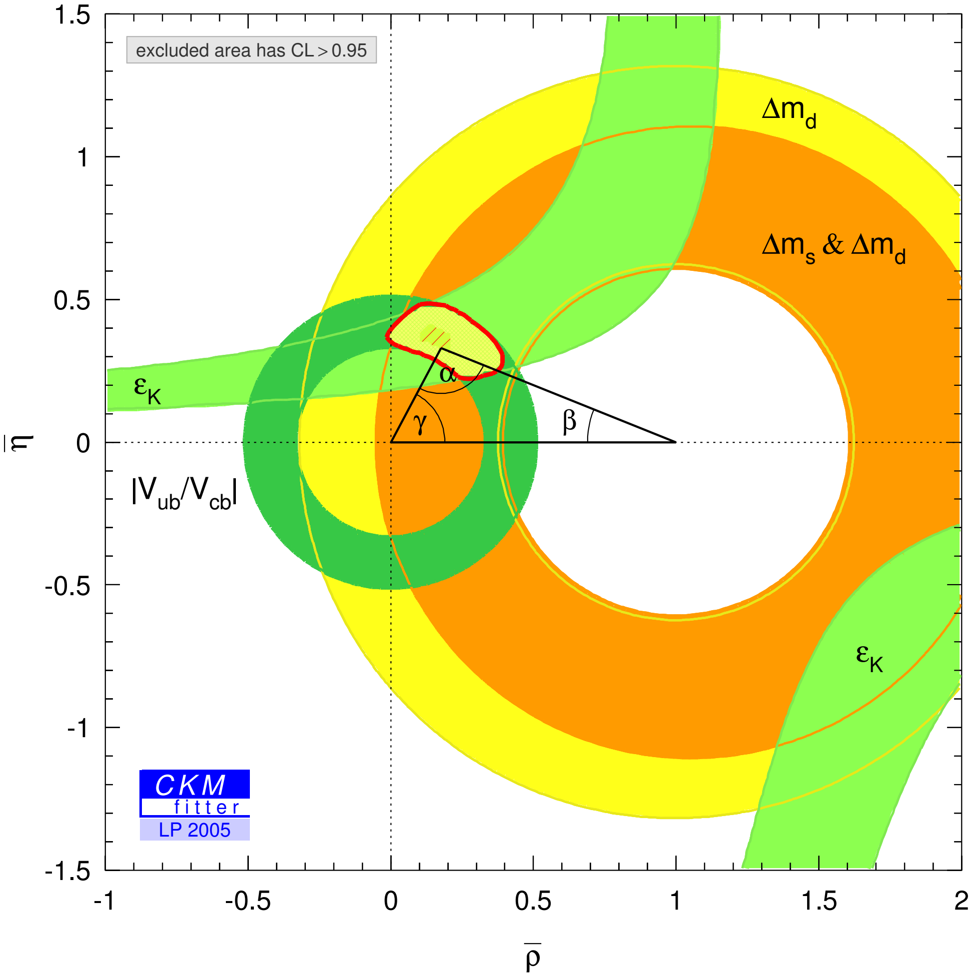
  $\arg \lambda_{\psi K_S} = (B\text{-mix} = 2\beta) + (\text{decay} = 0) + (K\text{-mix} = 0)$

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

- World average: $\sin 2\beta = 0.687 \pm 0.032$ — a 5% measurement!

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

Standard model fit without $S_{\psi K}$



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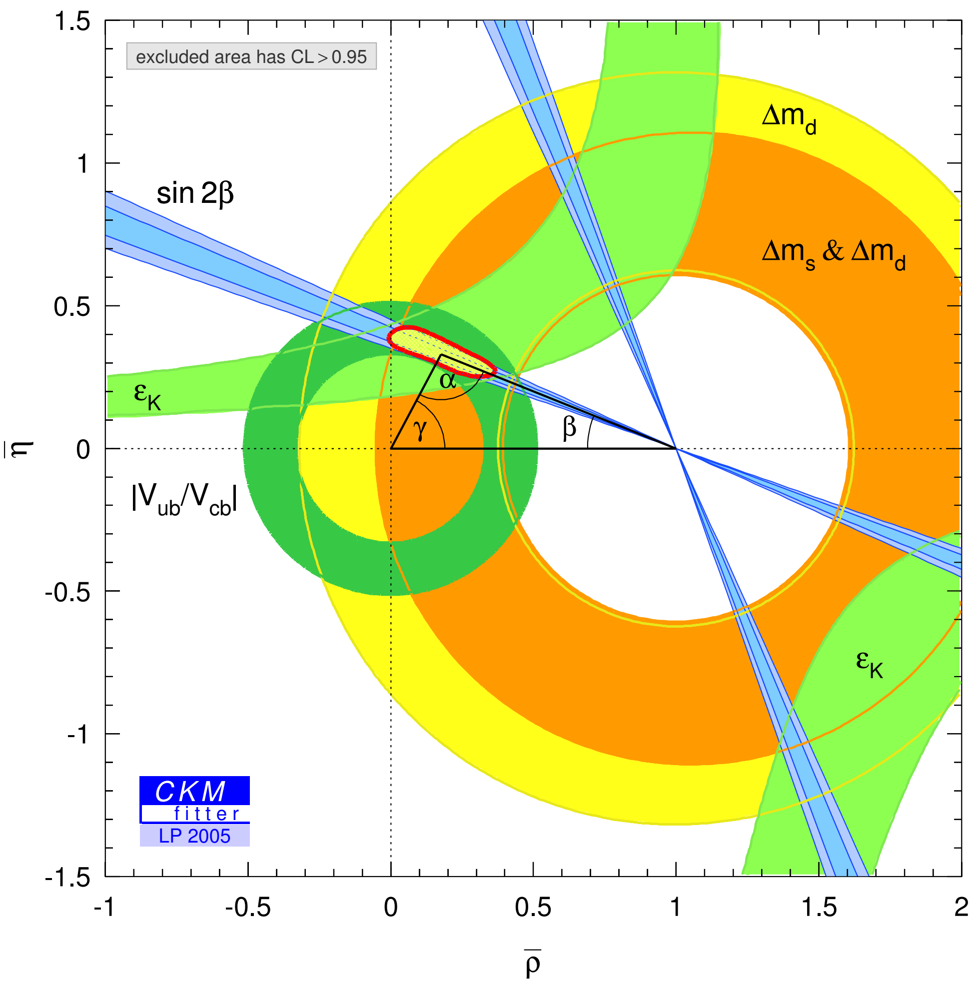

First precise test of the CKM picture

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

Without V_{ub} 4 sol's; ψK^* and $D^0 K^0$ data show $\cos 2\beta > 0$, removing non-SM ray

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

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$\sin 2\beta$ is only the beginning

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

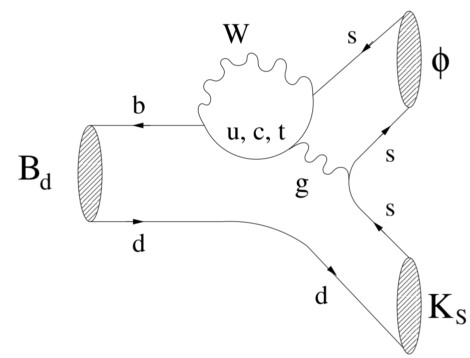
$\Rightarrow$ Need detailed tests

Theoretical cleanliness essential

CPV in $b \to s$ mediated decays

- Measuring same angle in decays sensitive to different short distance physics may give best sensitivity to NP ($\phi K_S, \eta' K_S$, etc.)

  Amplitudes with one weak phase expected to dominate:



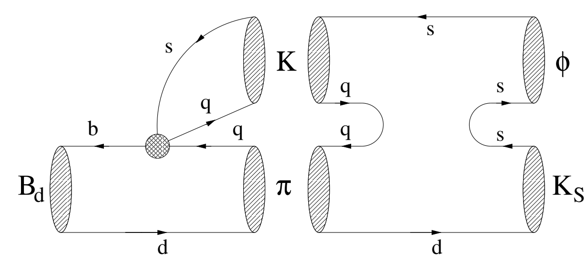
$$\overline{A} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)}[P_c - P_t + T_c] + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)}[P_u - P_t + T_u]$$

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

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

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

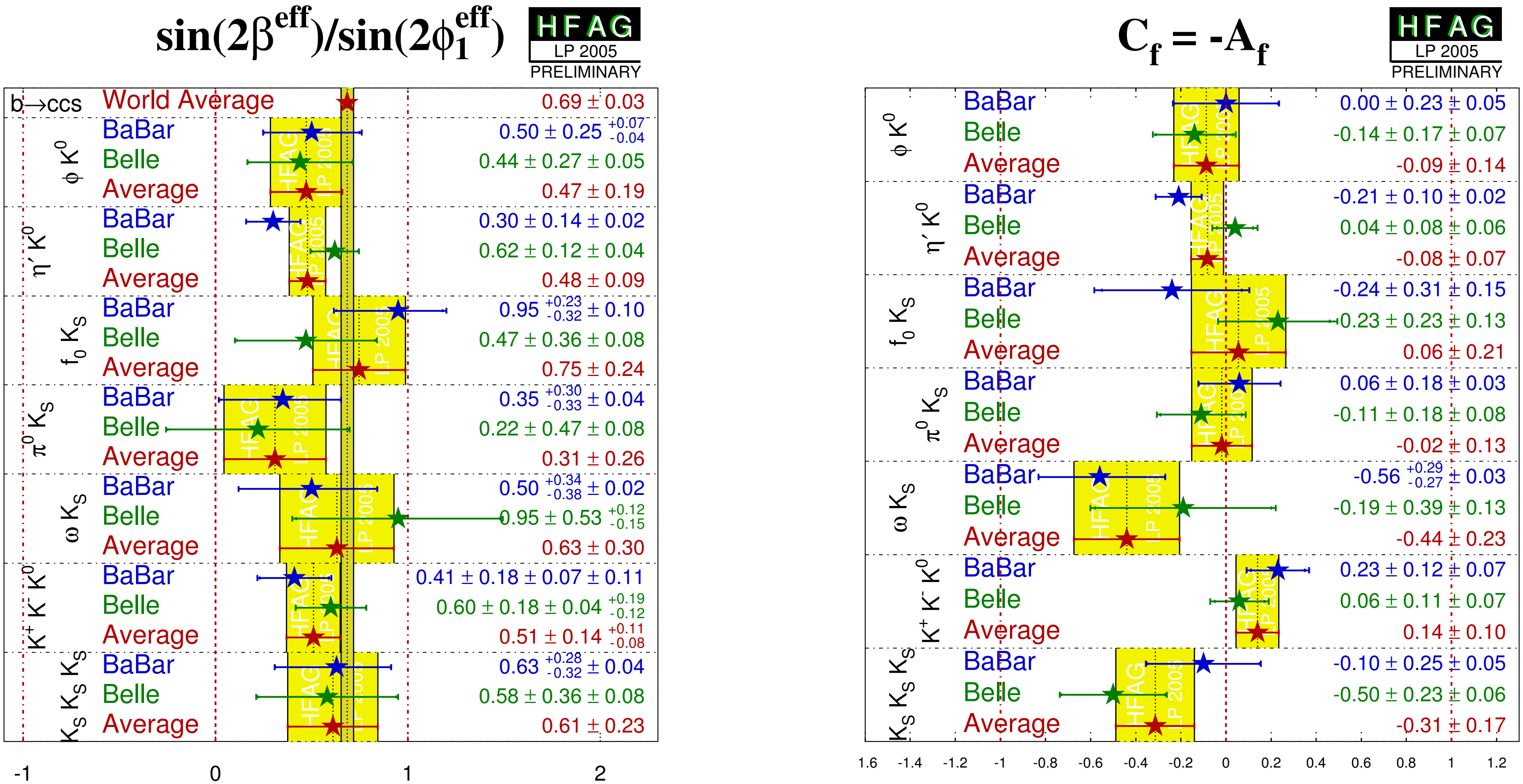
  Depend on size & phase of SM and NP amplitude



  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 — there is room left for NP

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



- Largest hint of deviations from SM: $S_{\eta' K_S}\ (2\sigma)$ and $S_{\psi K} - \langle S_{b\to s}\rangle = 0.18 \pm 0.06\ (3\sigma)$

  (Averaging somewhat questionable; although in QCDF the mode-dependent shifts are mostly up)

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

Dominant process	f_{CP}	SM allowed range 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	$+0.687 \pm 0.032$	$+0.016 \pm 0.046$
$b \to c\bar{c}d$	$\psi\pi^0$	~ 0.2	$+0.69 \pm 0.25$	-0.11 ± 0.20
	$D^{*+}D^{*-}$	~ 0.2	$+0.67 \pm 0.25$	$+0.09 \pm 0.12$
	D^+D^-	~ 0.2	$+0.29 \pm 0.63$	$+0.11 \pm 0.36$
$b \to s\bar{q}q$	ϕK^0	< 0.05	$+0.47 \pm 0.19$	-0.09 ± 0.14
	$\eta' K^0$	< 0.05	$+0.48 \pm 0.09$	-0.08 ± 0.07
	$K^+K^-K_S$	~ 0.15	$+0.51 \pm 0.17$	$+0.15 \pm 0.09$
	$K_SK_SK_S$	~ 0.15	$+0.61 \pm 0.23$	-0.31 ± 0.17
	$\pi^0 K_S$	~ 0.15	$+0.31 \pm 0.26$	-0.02 ± 0.13
	$f^0 K_S$	~ 0.25	$+0.75 \pm 0.24$	$+0.06 \pm 0.21$
	ωK_S	~ 0.25	$+0.63 \pm 0.30$	-0.44 ± 0.23

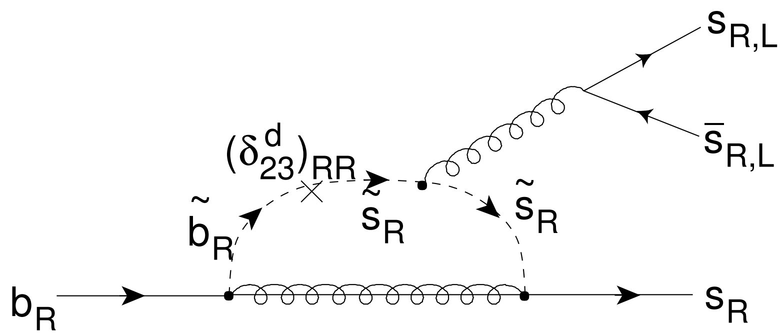
* My estimates of reasonable limits (strict bounds worse, model calculations better [Buchalla, Hiller, Nir, Raz; Beneke])

- No significant deviation from SM, still there is a lot to learn from more precise data

In SM, both $|S_{\psi K} - S_{\eta' K_S}|$ and $|S_{\psi K} - S_{\phi K_S}| < 0.05$ [model estimates $\mathcal{O}(0.02)$]

Model building more interesting

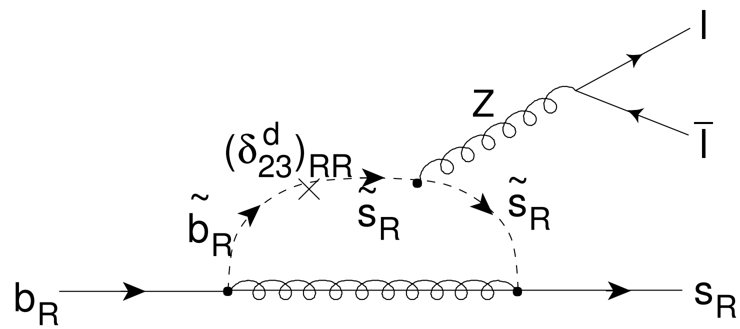
- The present $S_{\eta' K_S}$ and $S_{\phi K_S}$ central values can be reasonably accommodated with NP (unlike an $\mathcal{O}(1)$ deviation from $S_{\psi K_S}$ two years ago)



- Other constraints: $\mathcal{B}(B \to X_s\gamma) = (3.5 \pm 0.3) \times 10^{-6}$ 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



- Models must satisfy growing number of constraints simultaneously

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 from:

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

$\arg \lambda_{\pi^+\pi^-} = (B\text{-mix} = 2\beta) + (\overline{A}/A = 2\gamma + \ldots) \Rightarrow$ gives $\sin 2\alpha$ if P/T were small [expectation was $P/T \sim \mathcal{O}(\alpha_s/4\pi)$]

$K\pi$ and $\pi\pi$ rates $\Rightarrow$ comparable amplitudes in $B \to \pi\pi$ with different weak phases

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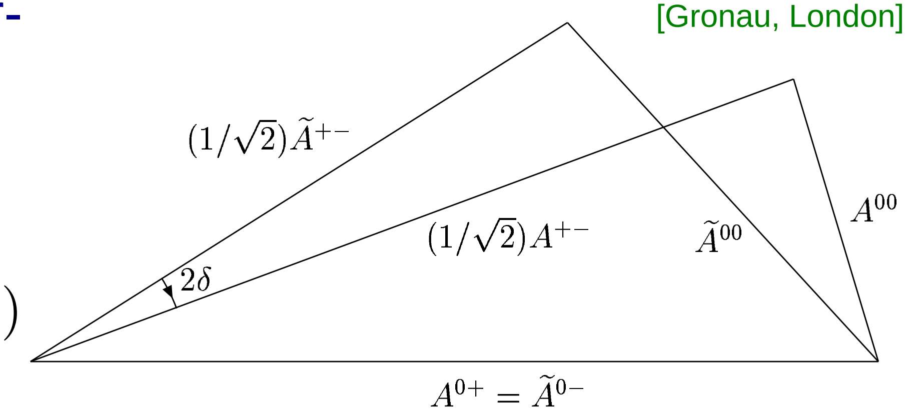
- Isospin analysis: 6 measurements determine 5 hadronic parameters $+$ weak phase

[Gronau, London]



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

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

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

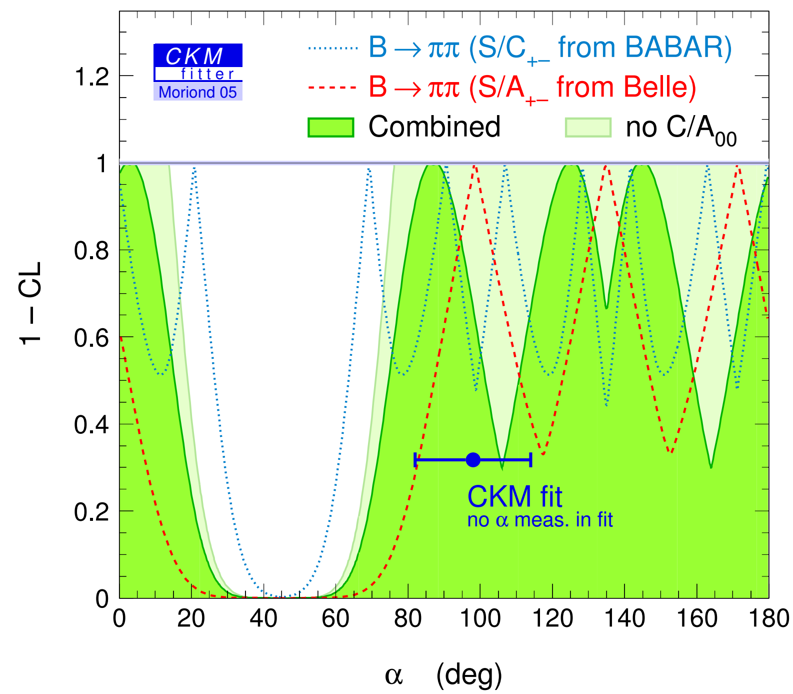
- Tagged $B \to \pi^0\pi^0$ rates are the hardest input

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

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

Need lot more data to pin down $\Delta\alpha$ from isospin analysis... current bound:

$$|\Delta\alpha| < 39^\circ \text{ (90\% CL)}$$



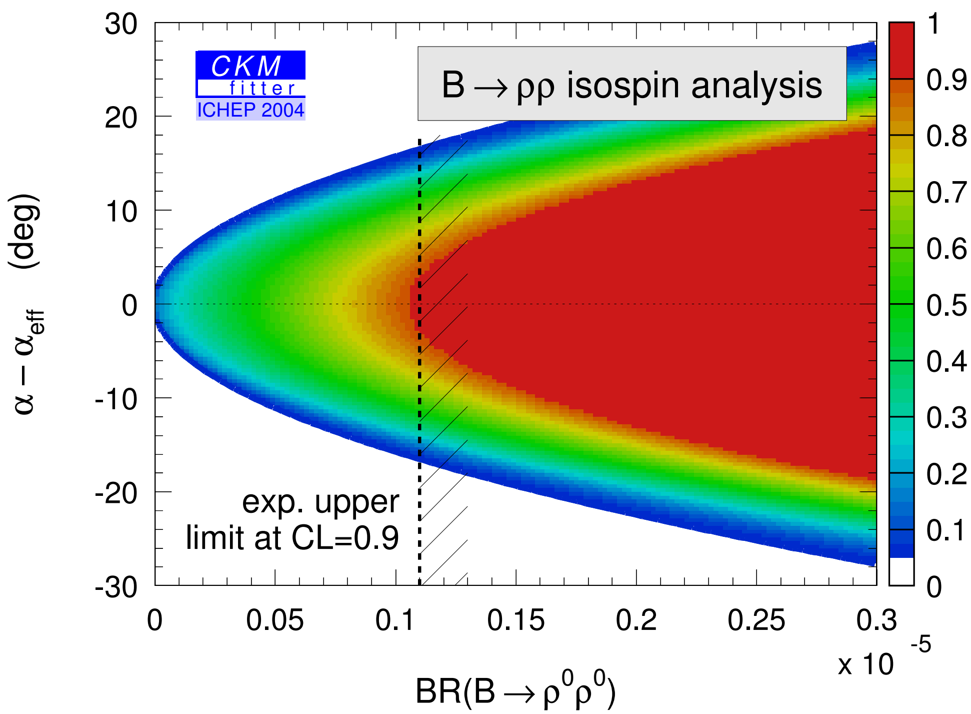
- Constraint on α weak (measurements 2.3σ apart):

$B \to \pi^+\pi^-$	$S_{\pi^+\pi^-}$	$C_{\pi^+\pi^-}$
BABAR (227m)	-0.30 ± 0.17	-0.09 ± 0.15
BELLE (275m)	-0.67 ± 0.17	-0.56 ± 0.13
average	-0.50 ± 0.12	-0.37 ± 0.11

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

- Lucky^2: longitudinal polarization dominates (CP-even; could be even/odd mixed)
  Isospin analysis applies for each L, or in transversity basis for each σ $(= 0, \|, \perp)$
- Small rate: $\mathcal{B}(B \to \rho^0\rho^0) < 1.1 \times 10^{-6}$ $(90\%\ \mathrm{CL}) \Rightarrow$ small penguin pollution

$$\frac{\mathcal{B}(B\to\pi^0\pi^0)}{\mathcal{B}(B\to\pi^+\pi^0)} = 0.26 \pm 0.06 \quad \text{vs.} \quad \frac{\mathcal{B}(B\to\rho^0\rho^0)}{\mathcal{B}(B\to\rho^+\rho^0)} < 0.04 \ \ (90\%\ \mathrm{CL})$$



Isospin bound: $|\Delta\alpha| < 11^\circ$

$S_{\rho^+\rho^-}$ yields: $\alpha = (96 \pm 13)^\circ$

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]

[Falk, ZL, Nir, Quinn]

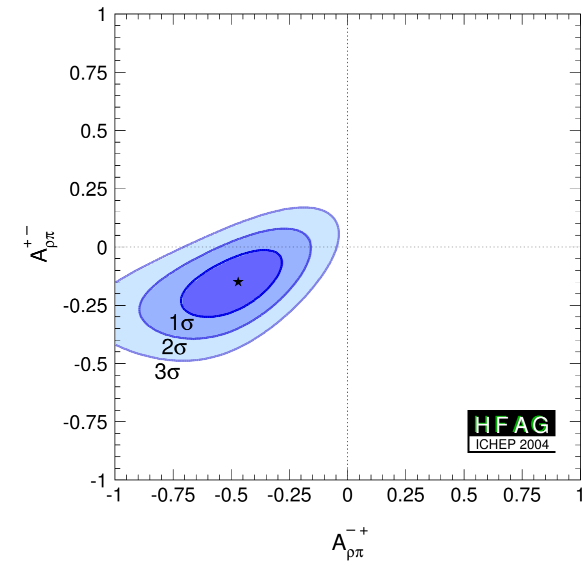
$B \to \rho\pi$: Dalitz plot analysis

- 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: $\begin{cases} A_{\pi^-\rho^+} = -0.47^{+0.13}_{-0.14} \\ A_{\pi^+\rho^-} = -0.15 \pm 0.09 \end{cases}$

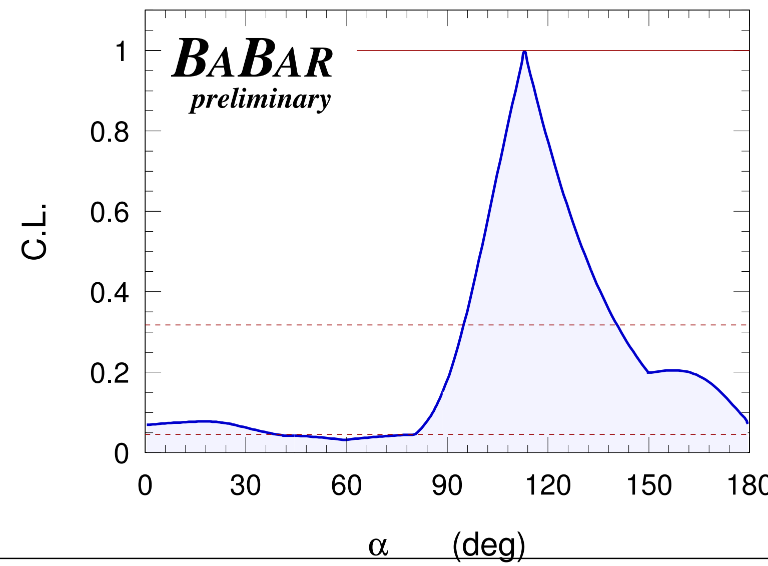
  3.4σ from 0, challenges some models

  Interpretation for α model dependent



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

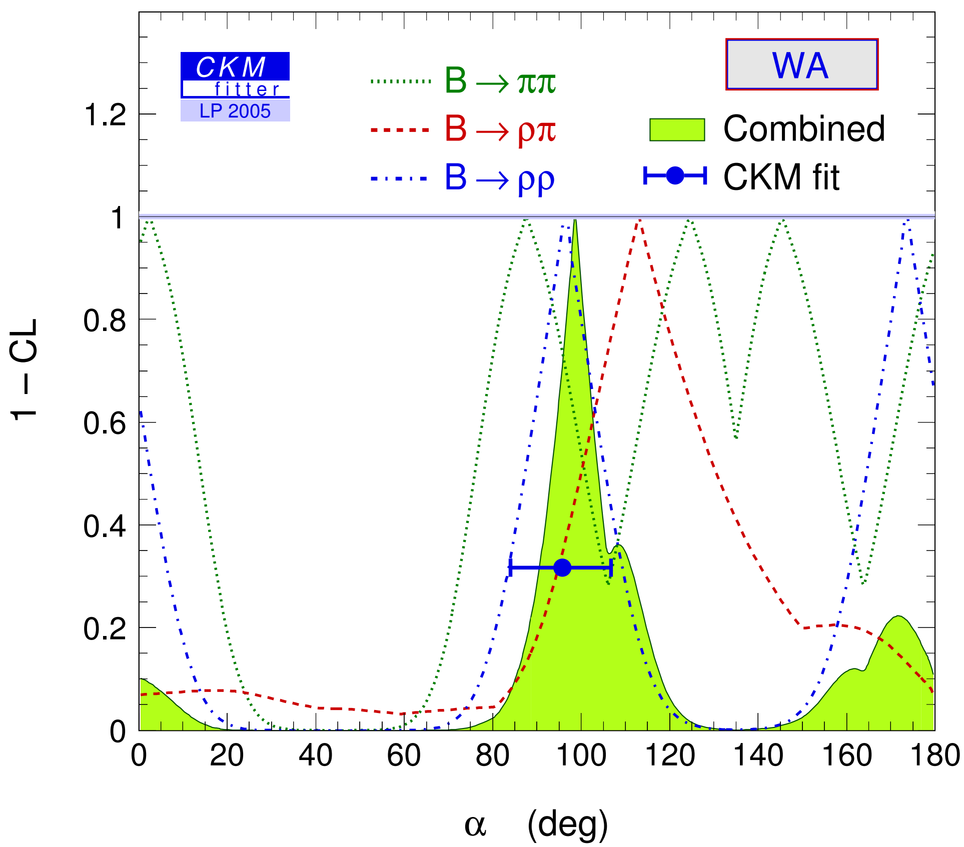
  Result: $\alpha = (113^{+27}_{-17} \pm 6)^\circ$

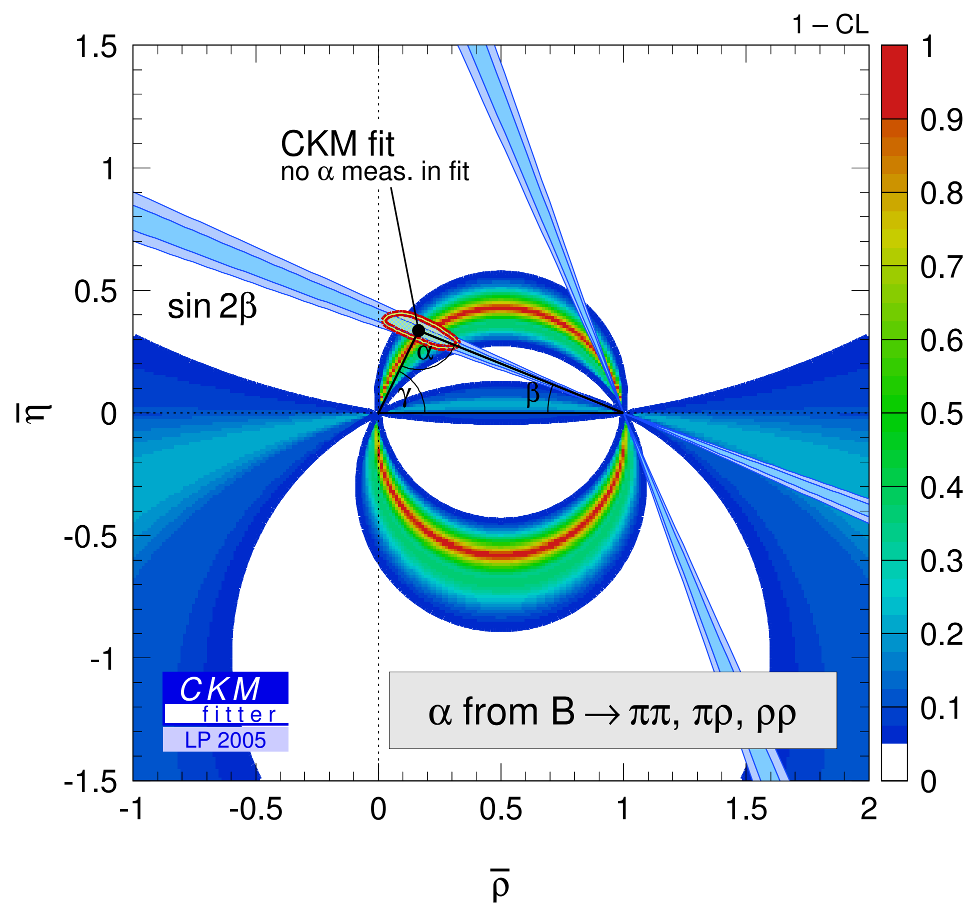


Combined α measurements

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

Combined result: $\alpha = (99^{+12}_{-9})^\circ$ — better than indirect fit $92 \pm 15^\circ$ (w/o α and γ)





γ from $B^\pm \to DK^\pm$

- Tree level: interfere $b \to c$ $(B^- \to D^0 K^-)$ and $b \to u$ $(B^- \to \overline{D}{}^0 K^-)$
  Need $D^0, \overline{D}{}^0 \to$ same final state; determine B and D decay amplitudes from data

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

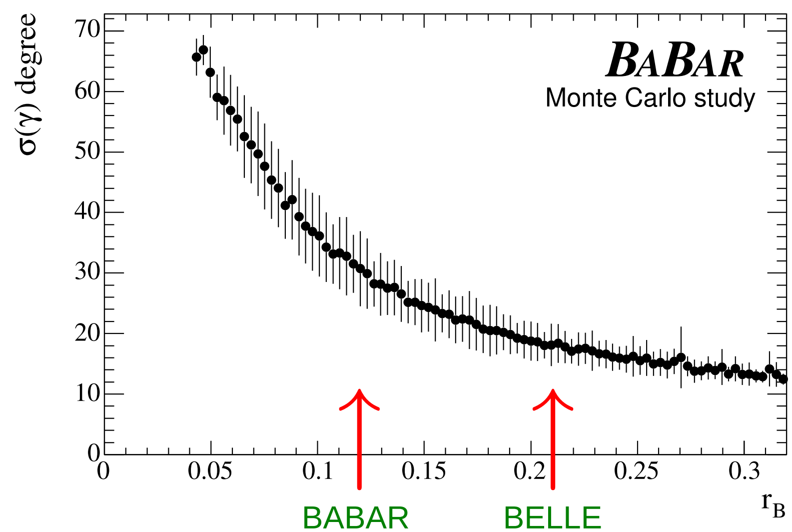
  Sensitivity crucially depends on: $r_B = |A(B^- \to \overline{D}{}^0 K^-)/A(B^- \to D^0 K^-)|$

- Best measurement now: $D^0, \overline{D}{}^0 \to K_S \pi^+ \pi^-$

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

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

  $$\gamma = (67 \pm 28 \pm 13 \pm 11)^\circ$$ [BABAR, 227 m]



- Need more data to determine γ more precisely (and settle value of r_B)

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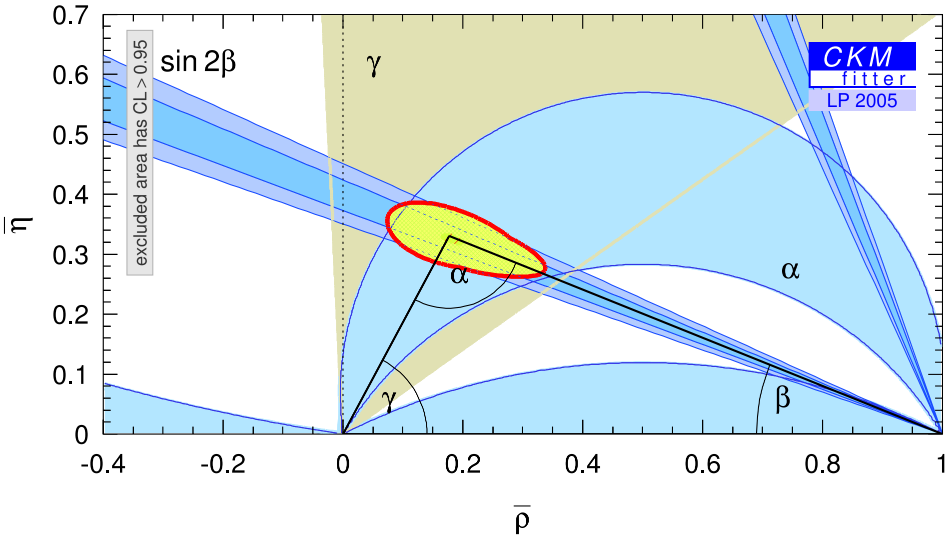
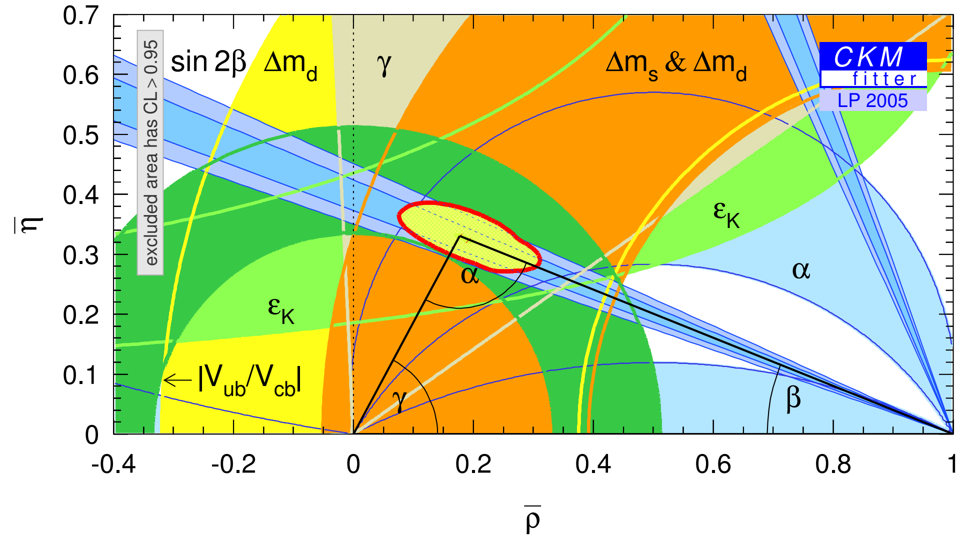
Overconstraining the CKM matrix

- SM fit: α, β determine ρ, η nearly as precisely as all data combined





- New era: constraints from angles surpass the rest; will scale with statistics

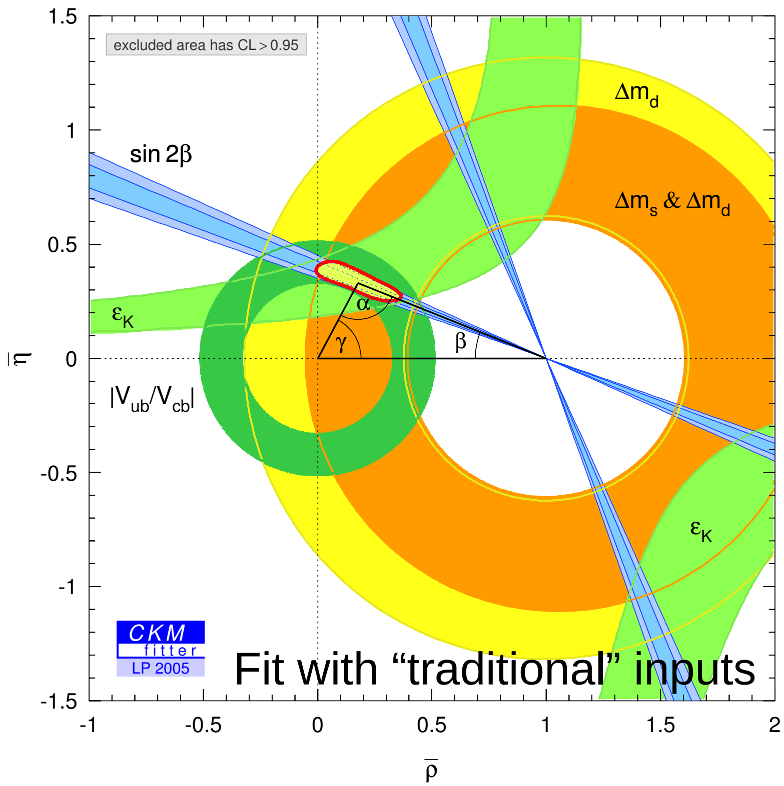
  (By the time Δm_s is measured, α may be competitive for $|V_{td}|$ side)

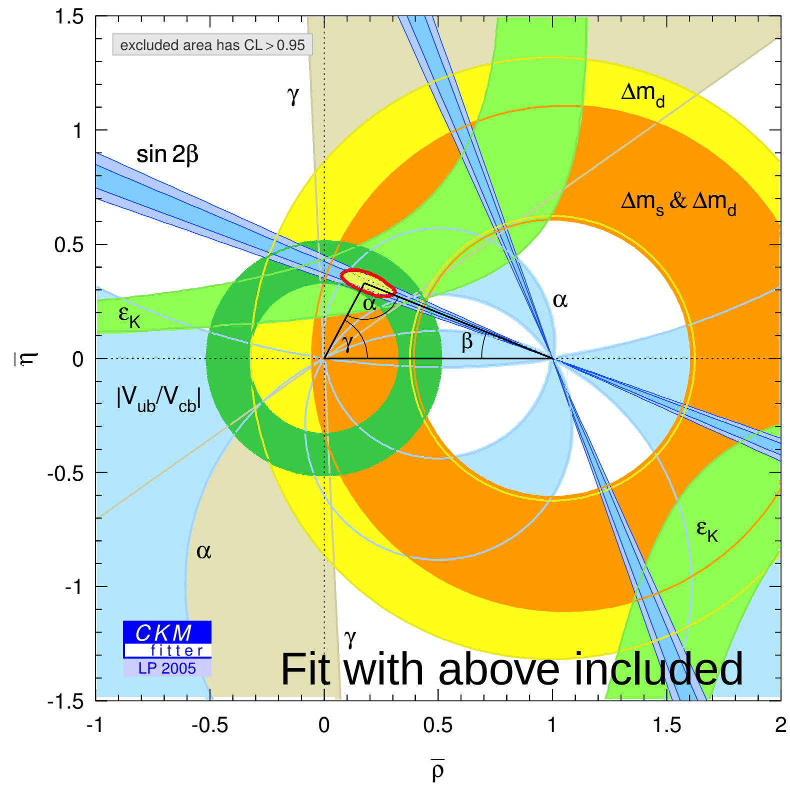
- ϵ_K, Δm_d, Δm_s, $|V_{ub}|$, etc., can be used to overconstrain the SM and test NP

  Let's see how it works...

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)





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

$\Delta m_s = (17.9^{+3.6\,[+8.6]}_{-1.4\,[-2.4]})\ {\rm ps}^{-1}$

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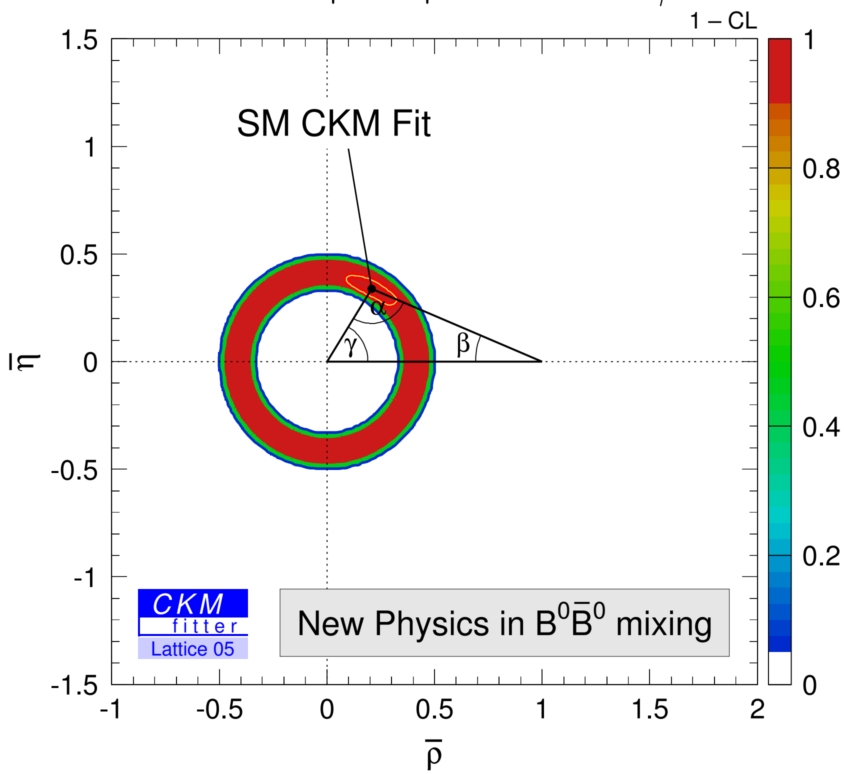
Constraining NP in mixing: $\rho - \eta$ view

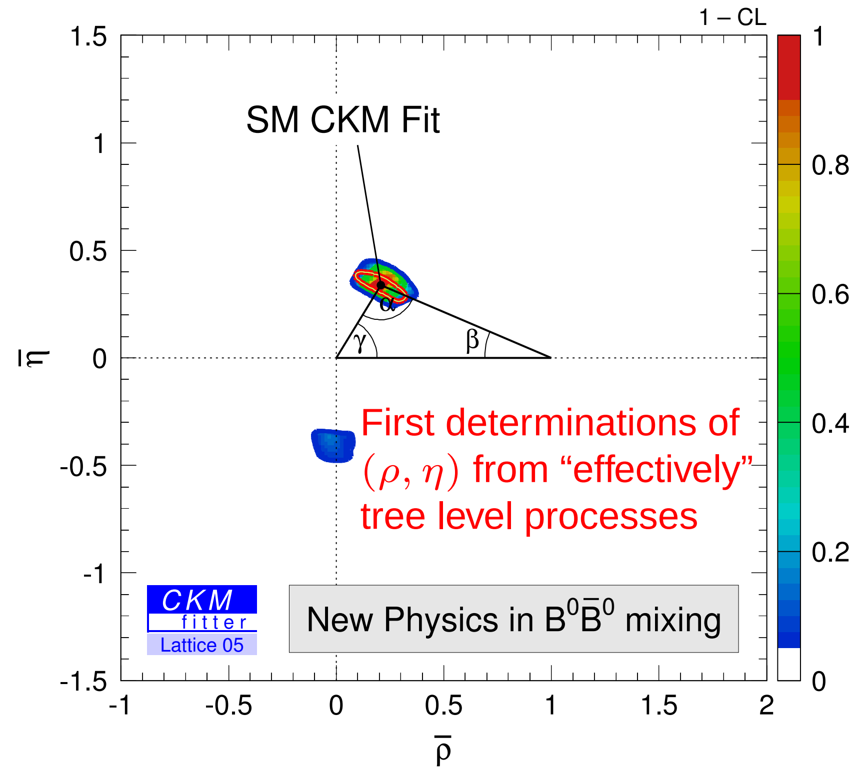
- NP in mixing amplitude only, 3×3 unitarity preserved: $M_{12} = M_{12}^{(\mathrm{SM})}\, r_d^2\, e^{2i\theta_d}$

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

Constraints with $|V_{ub}|$, Δm_d, $S_{\psi K}$



Add: α, γ, $2\beta + \gamma$, $\cos 2\beta$



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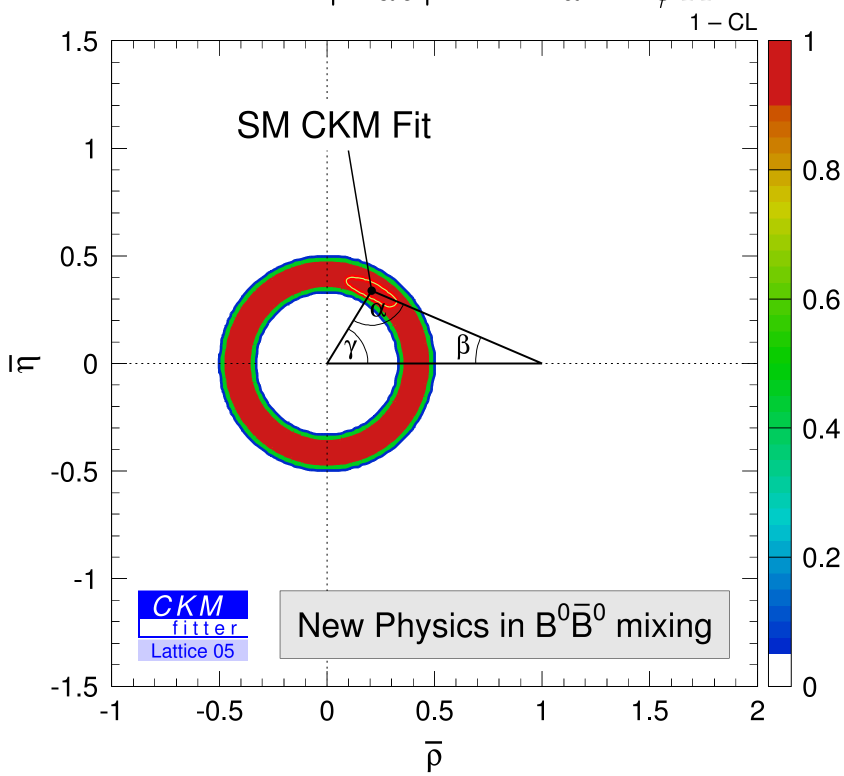
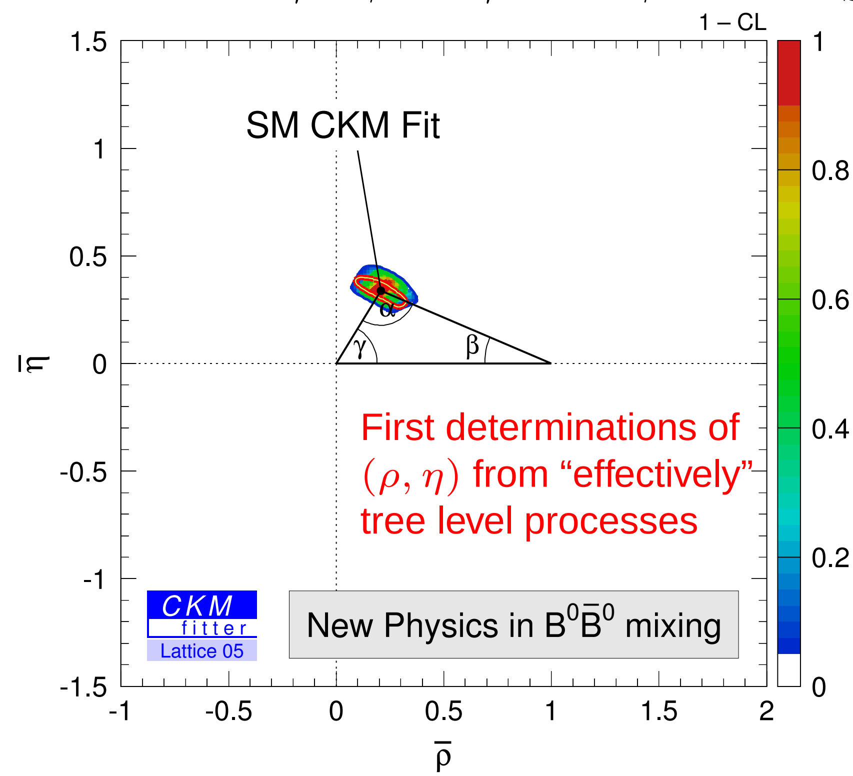


Add: α, γ, $2\beta + \gamma$, $\cos 2\beta$ and $A_{\rm SL}$



- Only the SM region left even in the presence of NP in mixing

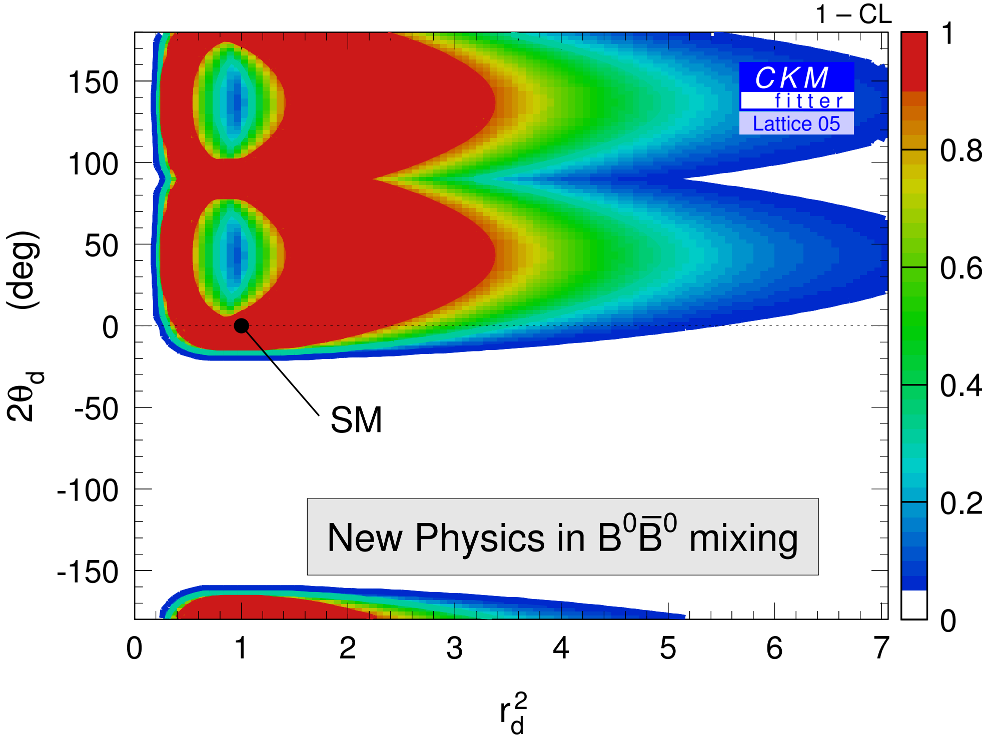
[Similar fits also by UTfit]

Constraining NP in mixing: $r_d^2 - \theta_d$ view

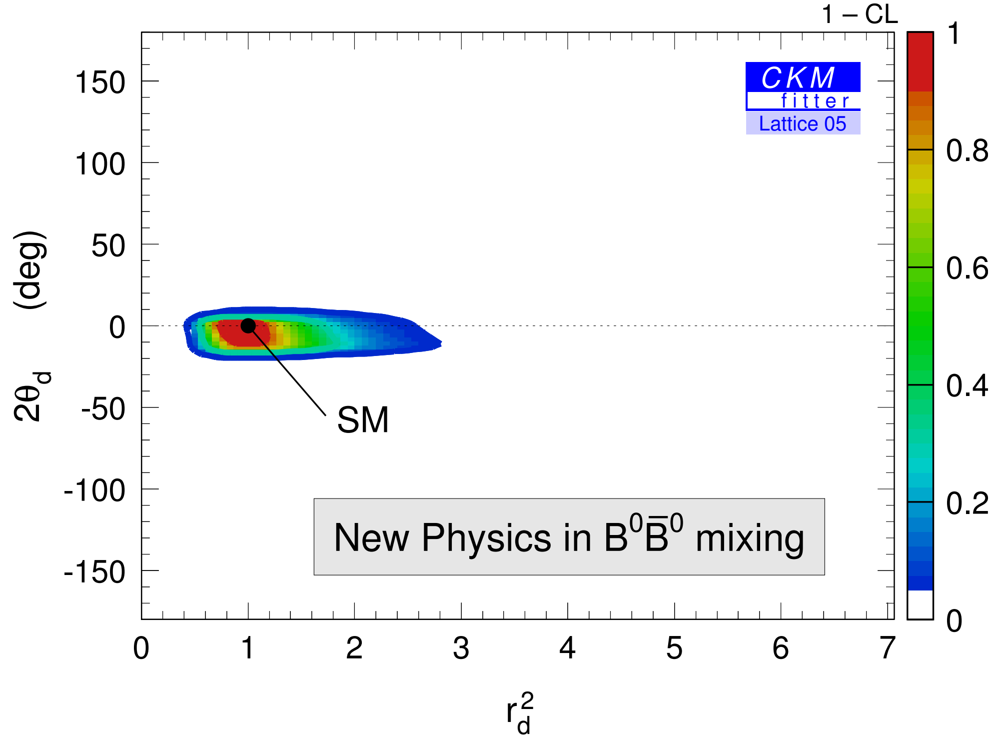
- NP in mixing amplitude only, 3×3 unitarity preserved: $M_{12} = M_{12}^{(\mathrm{SM})}\, r_d^2\, e^{2i\theta_d}$

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

Constraints with $|V_{ub}|$, Δm_d, $S_{\psi K}$



Add: α, γ, $2\beta+\gamma$, $\cos 2\beta$ and A_{SL}



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

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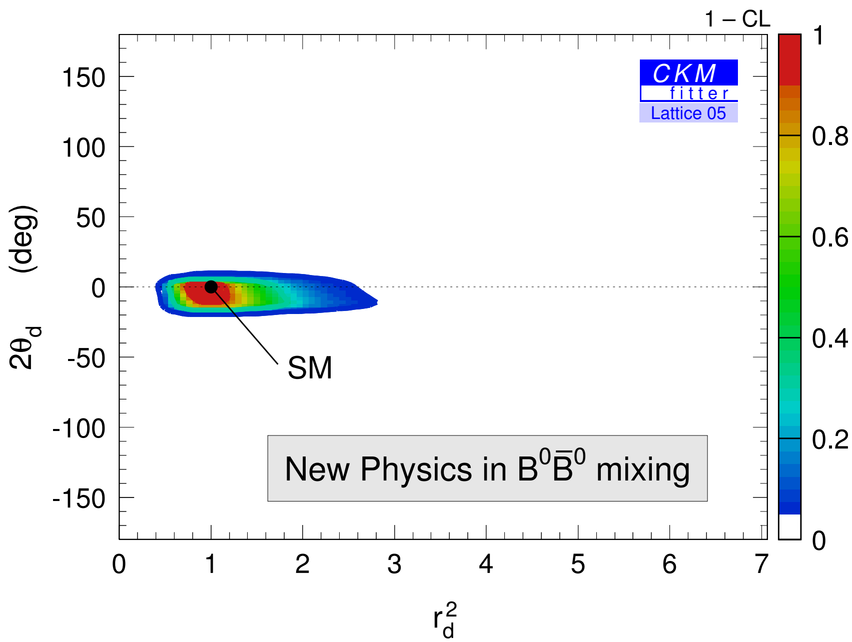
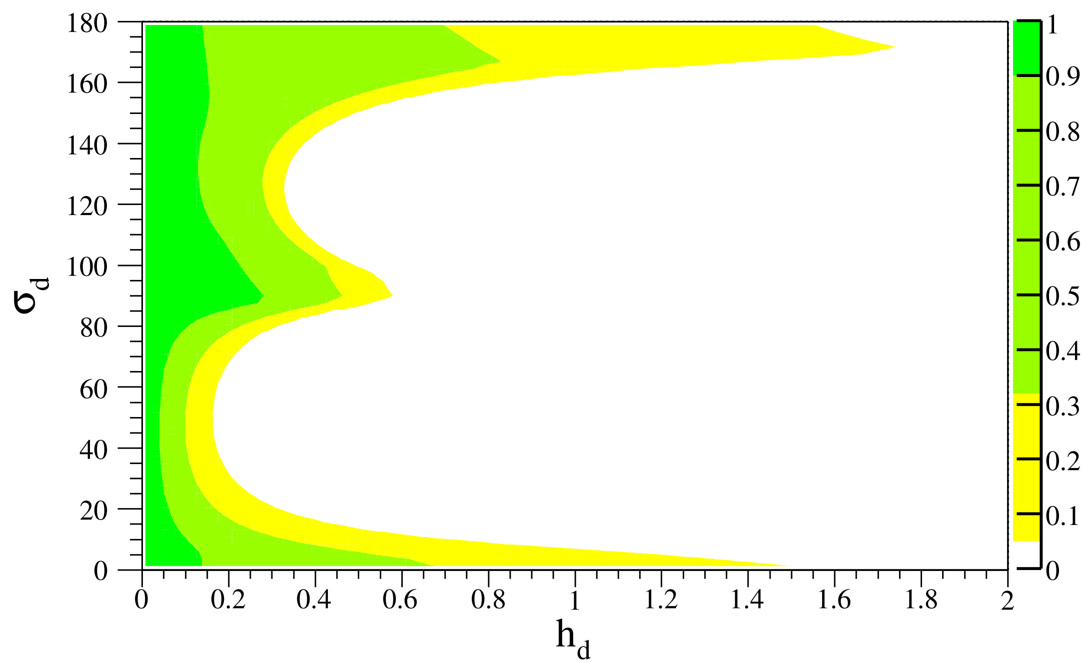
NP in mixing: $h_d - \sigma_d$ view

- Previous fits: $|M_{12}/M_{12}^{\rm SM}|$ can only differ significantly from 1 if $\arg(M_{12}/M_{12}^{\rm SM}) \sim 0$

  More transparent parameterization: $M_{12} = M_{12}^{\rm (SM)}\, r_d^2\, e^{2i\theta_d} \equiv M_{12}^{\rm (SM)} (1 + h_d\, e^{2i\sigma_d})$

  Modest NP contribution can still have arbitrary phase [Agashe, Papucci, Perez, Pirjol, to appear]





- For $|h_d| < 0.2$, the phase σ_d is unconstrained; if $|h_d| < 0.4$, σ_d can take half of $(0, \pi)$

Intermediate summary

- $\sin 2\beta = 0.687 \pm 0.032$

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

- $S_{\psi K} - S_{\eta' K_S} = 0.21 \pm 0.10$ and $S_{\psi K} - \langle S_{b\to s}\rangle = 0.18 \pm 0.06$

  $\Rightarrow$ Decreasing deviations from SM (same values with 5σ would still signal NP)

- $A_{K^-\pi^+} = -0.12 \pm 0.02$

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

- Measurements of $\alpha = \left(99^{+12}_{-9}\right)^\circ$ and $\gamma = \left(64^{+16}_{-13}\right)^\circ$

  $\Rightarrow$ Angles start to give tightest constraints

  $\Rightarrow$ First serious bounds on NP in B–$\overline{B}$ mixing; $\sim 30\%$ contributions still allowed

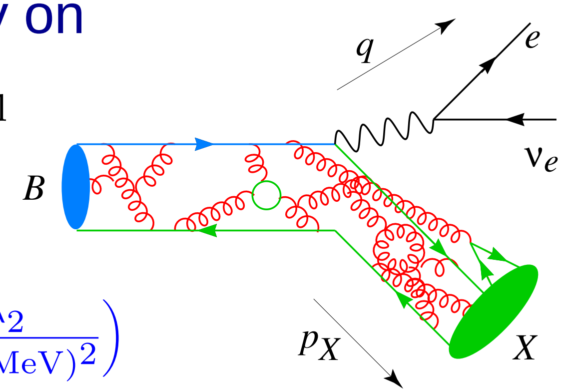
Theoretical developments

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

Factorization for $B \to M$ form factors for $q^2 \ll m_B^2$ and certain $B \to M_1 M_2$ nonleptonic decays

Determinations of $|V_{cb}|$ and $|V_{ub}|$

- Inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ determinations rely on heavy quark expansions; theoretically cleanest is $|V_{cb}|_{\rm incl}$



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

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

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

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

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

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 determined from fits to many shape variables

- Error of $|V_{cb}|_{\rm incl} \sim 2\%$! New small parameters complicate expansions for $|V_{ub}|_{\rm incl}$

Exclusive $b \to u$ decays

- In the hands of LQCD, less constraints from heavy quark symmetry than in $b \to c$
  - $B \to \ell\bar\nu$: measures $f_B \times |V_{ub}|$ — need f_B from lattice
  - $B \to \pi\ell\bar\nu$: useful dispersive bounds on form factors
  - Ratios $= 1$ in heavy quark or chiral symmetry limit ($+$ study corrections)

- Deviations of "Grinstein-type double ratios" from unity are more suppressed:

$\Rightarrow \dfrac{f_B}{f_{B_s}} \times \dfrac{f_{D_s}}{f_D}$ — lattice: double ratio $= 1$ within few $\%$ [Grinstein]

$\Rightarrow \dfrac{\mathcal{B}(B \to \ell\bar\nu)}{\mathcal{B}(B_s \to \ell^+\ell^-)} \times \dfrac{\mathcal{B}(D_s \to \ell\bar\nu)}{\mathcal{B}(D \to \ell\bar\nu)}$ — very clean... after 2010?

$\Rightarrow \dfrac{f^{(B\to\rho\ell\bar\nu)}}{f^{(B\to K^*\ell^+\ell^-)}} \times \dfrac{f^{(D\to K^*\ell\bar\nu)}}{f^{(D\to\rho\ell\bar\nu)}}$ or q^2 spectra — accessible soon? [ZL, Wise; Grinstein, Pirjol]

New CLEO-C $D \to \rho\ell\bar\nu$ data still consistent w/ no $SU(3)$ breaking in form factors [ZL, Stewart, Wise]
Could lattice do more to pin down the corrections?

One-page introduction to SCET

- Effective theory for processes involving energetic hadrons, $E \gg \Lambda$

[Bauer, Fleming, Luke, Pirjol, Stewart, + ...]

Introduce distinct fields for relevant degrees of freedom, power counting in λ

modes	fields	$p = (+, -, \perp)$	p^2
collinear	$\xi_{n,p},\ A^\mu_{n,q}$	$E(\lambda^2, 1, \lambda)$	$E^2\lambda^2$
soft	$q_q,\ A^\mu_s$	$E(\lambda, \lambda, \lambda)$	$E^2\lambda^2$
usoft	$q_{us},\ A^\mu_{us}$	$E(\lambda^2, \lambda^2, \lambda^2)$	$E^2\lambda^4$

SCET$_{\rm I}$: $\lambda = \sqrt{\Lambda/E}$ — jets $(m{\sim}\Lambda E)$

SCET$_{\rm II}$: $\lambda = \Lambda/E$ — hadrons $(m{\sim}\Lambda)$

Match QCD $\to$ SCET$_{\rm I}$ $\to$ SCET$_{\rm II}$

- Can decouple ultrasoft gluons from collinear Lagrangian at leading order in λ

$$\xi_{n,p} = Y_n\, \xi^{(0)}_{n,p} \qquad A_{n,q} = Y_n\, A^{(0)}_{n,q}\, Y_n^\dagger \qquad Y_n = {\rm P}\exp\Big[ig \int_{-\infty}^x {\rm d}s\, n\cdot A_{us}(ns)\Big]$$

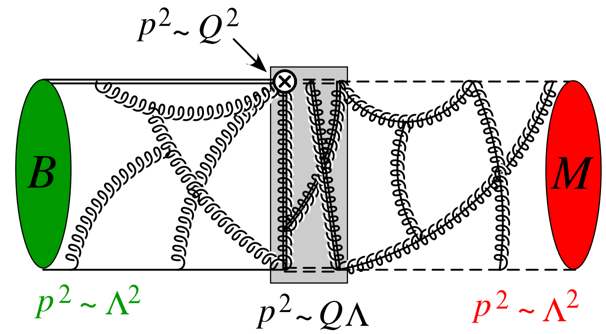
Nonperturbative usoft effects made explicit through factors of Y_n in operators

New symmetries: collinear / soft gauge invariance

- Simplified / new $(B \to D\pi, \pi\ell\bar\nu)$ proofs of factorization theorems [Bauer, Pirjol, Stewart]

Semileptonic $B \to \pi, \rho$ form factors

- Issues: endpoint singularities, Sudakov effects, etc.



At leading order in Λ/Q, to all orders in α_s, form factors for $q^2 \ll m_B^2$ written as ($Q = E, m_b$; omit μ-dep's)

[Beneke & Feldmann; Bauer, Pirjol, Stewart; Becher, Hill, Lange, Neubert]

$$F(Q) = C_k(Q)\, \zeta_k(Q) + \frac{m_B f_B f_M}{4E^2} \int \mathrm{d}z \mathrm{d}x \mathrm{d}r_+\, T(z,Q)\, J(z,x,r_+,Q)\, \phi_M(x) \phi_B(r_+)$$

Matrix elements of distinct $\int \mathrm{d}^4x\, T\big[J^{(n)}(0)\, \mathcal{L}_{\xi q}^{(m)}(x)\big]$ terms (turn spectator $q_{us} \to \xi$)

- Symmetries $\Rightarrow$ nonfactorizable (1st) term obey form factor relations [Charles *et al.*]

  3 $B \to P$ and 7 $B \to V$ form factors related to 3 universal functions

- Relative size? SCET: 1st $\sim$ 2nd QCDF: 2nd $\sim \alpha_s \times$(1st) PQCD: 1st ~ 0

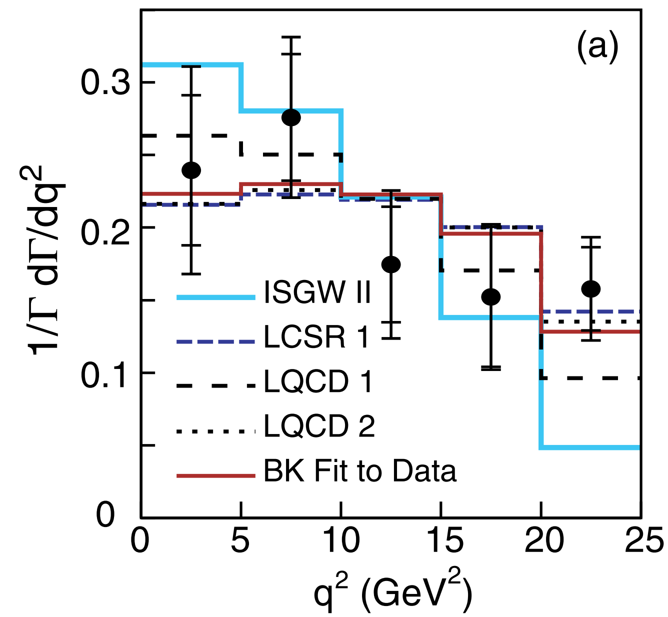
  Some relations between semileptonic and nonleptonic decays can be insensitive to this, while other predictions may be sensitive (e.g., $A_{\rm FB} = 0$ in $B \to K^* \ell^+ \ell^-$?)

$|V_{ub}|$ from $B \to \pi\ell\bar{\nu}$

- Lattice is under control for large q^2 (small $|\vec{p}_\pi|$), experiment loses a lot of statistics

$$\frac{d\Gamma(\overline{B}^0 \to \pi^+\ell\bar{\nu})}{dq^2} = \frac{G_F^2|\vec{p}_\pi|^3}{24\pi^3}\,|V_{ub}|^2\,|f_+(q^2)|^2$$

Best would be to use the q^2-dependent data and its correlation (both lattice and experiment) to get $|V_{ub}|$, reducing role of model-dependent fits

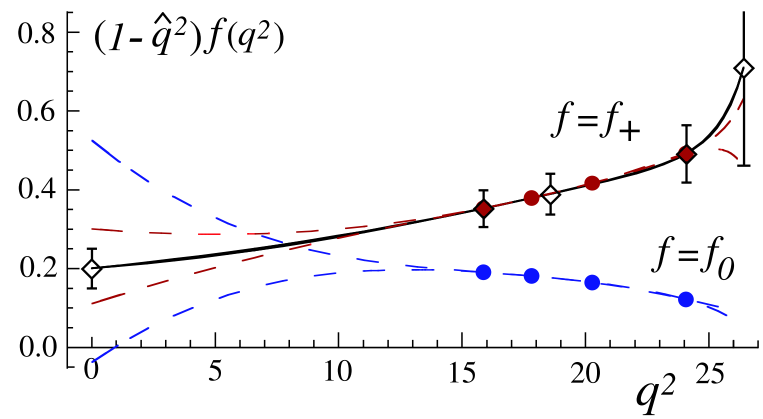


- Dispersion relation and a few points for $f_+(q^2)$ give strong constraints on shape [Boyd, Grinstein, Lebed]

$B \to \pi\pi$ using factorization constrains $|V_{ub}|\,f_+(0)$

[Bauer *et al.*]

- Can combine dispersive bounds with lattice and possibly $B \to \pi\pi$ [Fukunaga, Onogi; Arnesen *et al.*]



Tension between $\sin 2\beta$ and $|V_{ub}|$?

- SM fit favors slightly smaller $|V_{ub}|$ than inclusive determination, or larger $\sin 2\beta$

Inclusive average (error underestimated?)

$$|V_{ub}|_{\rm incl}^{\rm (HFAG)} = (4.38 \pm 0.19 \pm 0.27) \times 10^{-3}$$

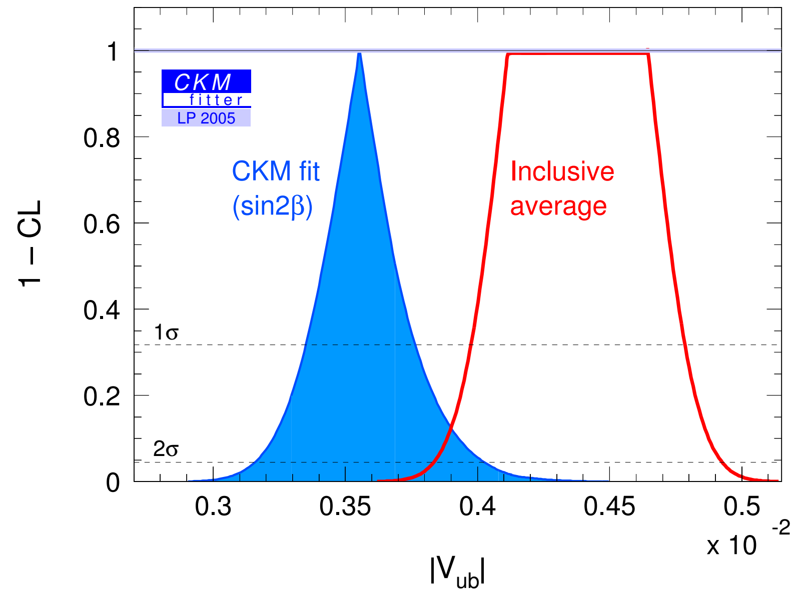
Lattice $\pi\ell\nu$ average [HPQCD & FNAL from Stewart @ LP'05]

$$|V_{ub}| = (4.1 \pm 0.3^{+0.7}_{-0.4}) \times 10^{-3}$$

Depends on whether only $q^2 > 16\,\mathrm{GeV}^2$ is used

Light-cone SR [Ball, Zwicky; Braun *et al.*, Colangelo, Khodjamirian]

$$|V_{ub}| = (3.3 \pm 0.3^{+0.5}_{-0.4}) \times 10^{-3}$$



Statistical fluctuations? Problem with inclusive? New physics?

Precise $|V_{ub}|$ crucial to be sensitive to small NP entering $\sin 2\beta$ via mixing

- To sort this out, need precise and model independent f_B and $B \to \pi$ form factor

Chasing $|V_{td}/V_{ts}|$: $B \to \rho\gamma$ vs. $B \to K^*\gamma$

- Factorization formula: $\langle V\gamma|\mathcal{H}|B\rangle = T_i^{\rm I} F_V + \int {\rm d}x\, {\rm d}k\, T_i^{\rm II}(x,k)\, \phi_B(k)\, \phi_V(x) + \ldots$

  [Bosch, Buchalla; Beneke, Feldman, Seidel; Ali, Lunghi, Parkhomenko]

  $$\frac{\mathcal{B}(B^0 \to \rho^0\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} = \frac{1}{2}\left|\frac{V_{td}}{V_{ts}}\right|^2 \xi^{-2}(1 + \text{tiny})$$

  No weak annihilation in B^0, cleaner than $B^\pm$

  $SU(3)$ breaking: $\xi = 1.2 \pm 0.1$ (CKM '05)

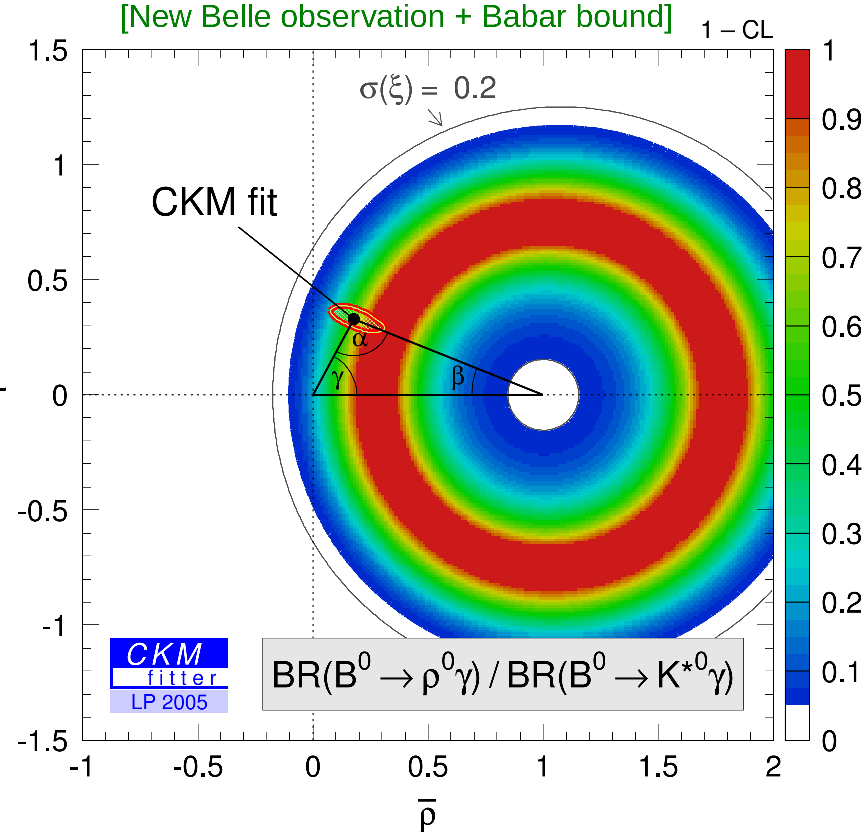
  [Ball, Zwicky; Becirevic; Mescia]

  Conservative? $\xi - 1$ is model dependent

  $\sigma(\xi) = 0.2$ doubles error estimate

  Could LQCD help more?

[New Belle observation + Babar bound]



- Mild indication that Δm_s might not be right at the current lower limit?

$B \to \tau\nu$ might also precede Δm_s

- Δm_s is not the only way to eliminate the f_B error in Δm_d; f_B cancels in $\Gamma(B \to \tau\nu)/\Delta m_d$

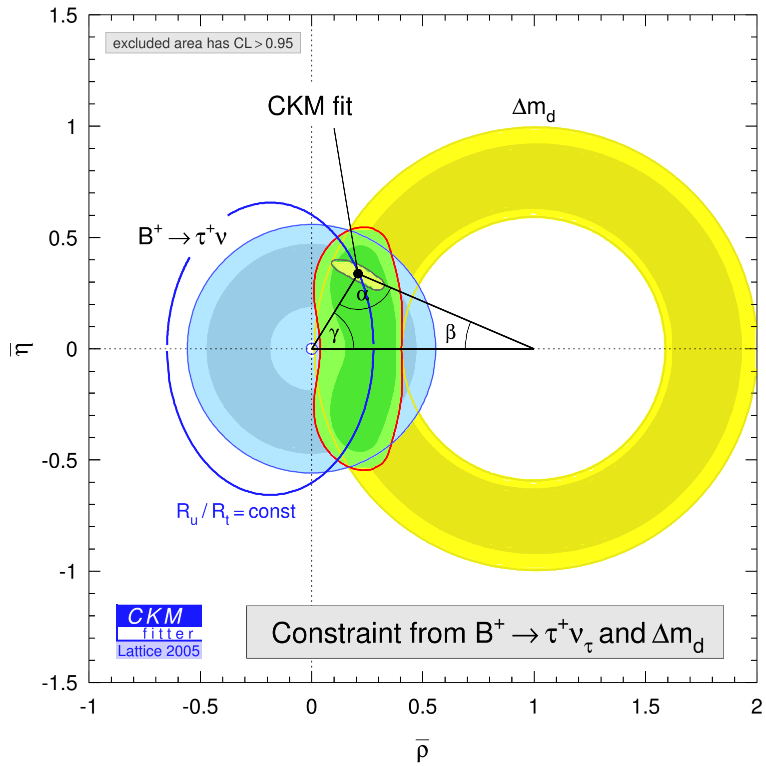
  If no exp. errors: determine $|V_{ub}/V_{td}|$ independent of f_B (left with B_d; ellipse for fixed V_{cb}, V_{ts})

  If f_B is known: get two circles that intersect at $\alpha \sim 100^\circ \Rightarrow$ powerful constraints

- Nailing down f_B will remain essential

  Recall: Δm_s remains important to constrain NP entering B_s and B_d mixing differently (not just to determine $|V_{td}/V_{ts}|$)

Shown are 1 and 2σ contours with $f_B = 216 \pm 9 \pm 21$ MeV [HPQCD]



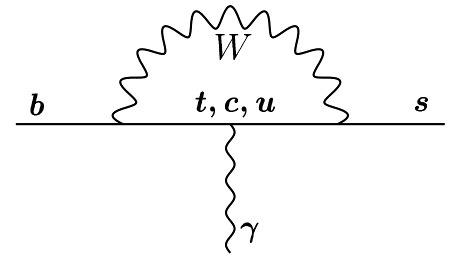
($B \to \tau\nu$ usually quoted as upper bounds)

- Error of $\Gamma(B \to \tau\nu)$ will improve incrementally (precise only at a super B factory) Δm_s will be instantly accurate when measured

Photon polarization in $B \to K^*\gamma$

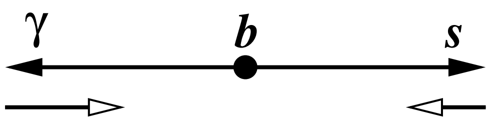
- SM predicts $\mathcal{B}(B \to X_s\gamma)$ correctly to $\sim 10\%$; rate does not distinguish $b \to s\gamma_{L,R}$

SM: $O_7 \sim \bar{s}\,\sigma^{\mu\nu} F_{\mu\nu}(m_b P_R + m_s P_L) b$, therefore mainly $b \to s_L$



Photon must be left-handed to conserve J_z along decay axis

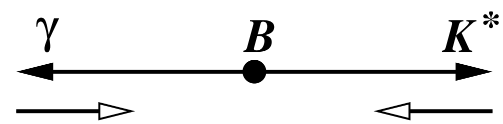
Inclusive $B \to X_s\gamma$



Assumption: 2-body decay

Does not apply for $b \to s\gamma g$

Exclusive $B \to K^*\gamma$



... quark model (s_L implies $J_z^{K^*} = -1$)

... higher K^* Fock states

- Only measurement so far; had been expected to give $S_{K^*\gamma} = -2\,(m_s/m_b)\sin 2\beta$

[Atwood, Gronau, Soni]

$$\frac{\Gamma[\overline{B}^0(t) \to K^*\gamma] - \Gamma[B^0(t) \to K^*\gamma]}{\Gamma[\overline{B}^0(t) \to K^*\gamma] + \Gamma[B^0(t) \to K^*\gamma]} = S_{K^*\gamma}\sin(\Delta m\, t) - C_{K^*\gamma}\cos(\Delta m\, t)$$

- What is the SM prediction? What limits the sensitivity to new physics?

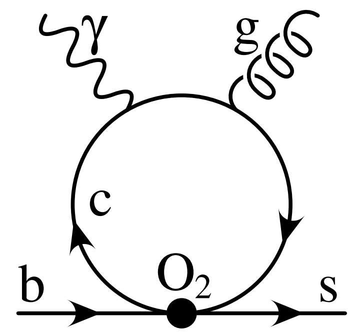
Right-handed photons in the SM

- Dominant source of "wrong-helicity" photons in the SM is O_2 [Grinstein, Grossman, ZL, Pirjol]

  Equal $b \to s\gamma_L,\ s\gamma_R$ rates at $\mathcal{O}(\alpha_s)$; calculated to $\mathcal{O}(\alpha_s^2\beta_0)$

  Inclusively only rates are calculable: $\Gamma_{22}^{(\rm brem)}/\Gamma_0 \simeq 0.025$

  Suggests: $A(b \to s\gamma_R)/A(b \to s\gamma_L) \sim \sqrt{0.025/2} = 0.11$



- Exclusive $B \to K^*\gamma$: factorizable part contains an operator that could contribute at leading order in $\Lambda_{\rm QCD}/m_b$, but its $B \to K^*\gamma$ matrix element vanishes

  Subleading order: several contributions to $\overline{B}{}^0 \to \overline{K}{}^{0*}\gamma_R$, no complete study yet

  We estimate: $$\frac{A(\overline{B}{}^0 \to \overline{K}{}^{0*}\gamma_R)}{A(\overline{B}{}^0 \to \overline{K}{}^{0*}\gamma_L)} = \mathcal{O}\bigg(\frac{C_2}{3C_7}\,\frac{\Lambda_{\rm QCD}}{m_b}\bigg) \sim 0.1$$

- Data: $S_{K^*\gamma} = -0.13 \pm 0.32$ — both the measurement and the theory can progress

Nonleptonic decays

Some motivations

- Two hadrons in the final state are also a headache for us, just like for you

  Lot at stake, even if precision is worse

  Many observables sensitive to NP — can we disentangle from hadronic physics?

  – $B \to \pi\pi, K\pi$ branching ratios and CP asymmetries (related to α, γ in SM)

  – Polarization in charmless $B \to VV$ decays

- First derive correct expansion in $m_b \gg \Lambda_{\rm QCD}$ limit, then worry about predictions

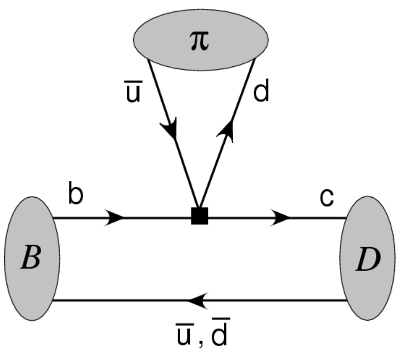
  – Need to test accuracy of expansion (even in $B \to \pi\pi$, $|\vec{p}_q| \sim 1\,{\rm GeV}$)

  – Sometimes model dependent additional inputs needed

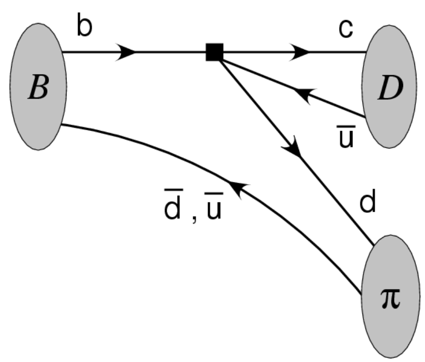
$B \to D^{(*)}\pi$ decays in SCET

- Decays to $\pi^\pm$: proven that $A \propto \mathcal{F}^{B\to D} f_\pi$ is the leading order prediction
  Also holds in large N_c, works at 5–10% level, need precise data to test mechanism

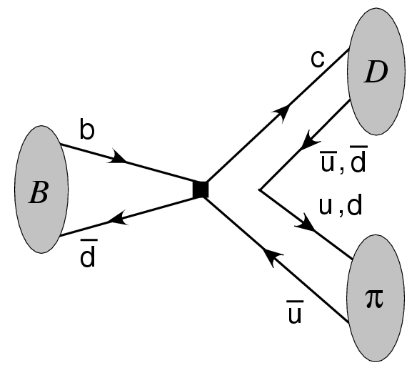
$\overline{B}^0 \to D^+\pi^-$
$B^- \to D^0\pi^-$



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



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



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

- 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)
$\Rightarrow\ \mathcal{O}(30\%)$ power corrections
[Beneke, Buchalla, Neubert, Sachrajda; Bauer, Pirjol, Stewart]

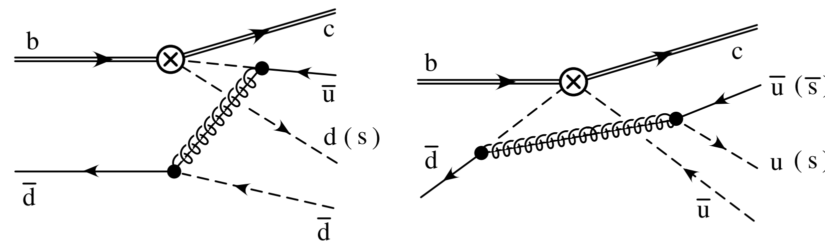
$$\frac{\mathcal{B}(\overline{B}^0 \to D^0\pi^0)}{\mathcal{B}(\overline{B}^0 \to D^{*0}\pi^0)} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\,,$$

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

Color suppressed $B \to D^{(*)0}\pi^0$ decays

- Single class of power suppressed SCET_I operators: $T\{\mathcal{O}^{(0)}, \mathcal{L}_{\xi q}^{(1)}, \mathcal{L}_{\xi q}^{(1)}\}$

  [Mantry, Pirjol, Stewart]



$$A(D^{(*)0}M^0) = N_0^M \int \mathrm{d}z\, \mathrm{d}x\, \mathrm{d}k_1^+ \mathrm{d}k_2^+\, T^{(i)}(z)\, J^{(i)}(z, x, k_1^+, k_2^+)\, \underbrace{S^{(i)}(k_1^+, k_2^+)}_{\text{complex} - \text{nonpert. strong phase}}\, \phi_M(x) + \dots$$

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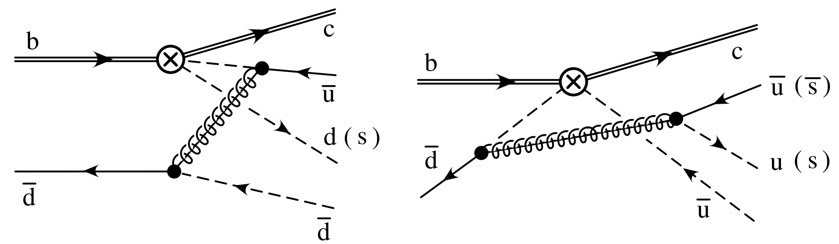
[Mantry, Pirjol, Stewart]



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- Not your garden variety factorization formula... $S^{(i)}(k_1^+, k_2^+)$ know about n

$$S^{(0)}(k_1^+, k_2^+) = \frac{\langle D^0(v')|(\bar h_{v'}^{(c)} S)\, \not{n} P_L (S^\dagger h_v^{(b)})(\bar d S)_{k_1^+}\, \not{n} P_L (S^\dagger u)_{k_2^+} |\bar B^0(v)\rangle}{\sqrt{m_B m_D}}$$

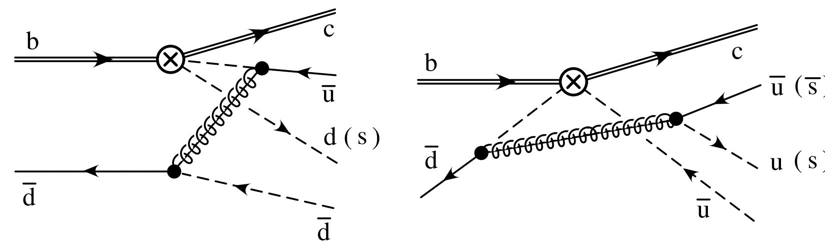
Separates scales, allows to use HQS without $E_\pi/m_c = \mathcal{O}(1)$ corrections

($i = 0, 8$ above)

Color suppressed $B \to D^{(*)0}\pi^0$ decays

- Single class of power suppressed SCET_I operators: $T\{\mathcal{O}^{(0)}, \mathcal{L}_{\xi q}^{(1)}, \mathcal{L}_{\xi q}^{(1)}\}$

[Mantry, Pirjol, Stewart]



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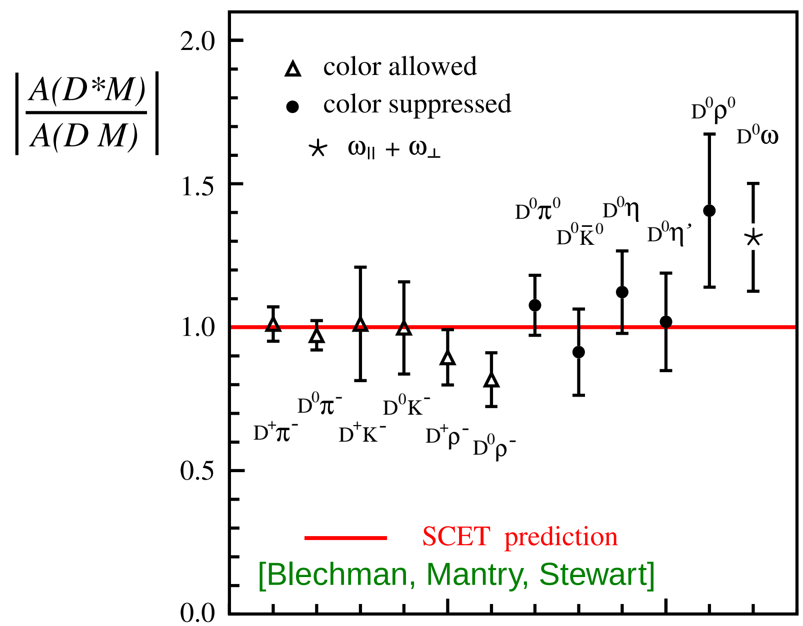
- Ratios: the $\triangle = 1$ relations follow from naive factorization and heavy quark symmetry

The $\bullet = 1$ relations do not — a prediction of SCET not foreseen by model calculations

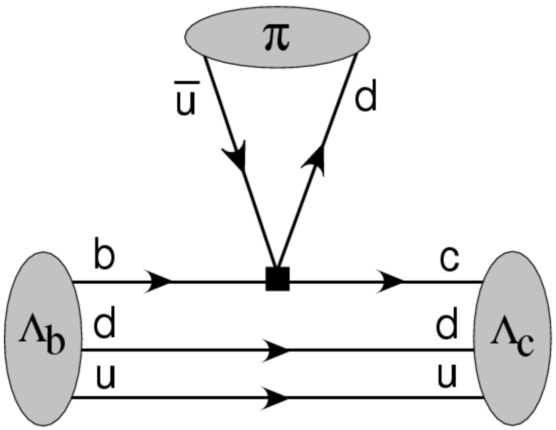
Also predict equal strong phases between amplitudes to $D^{(*)}\pi$ in $I = 1/2$ and $3/2$

Data: $\delta(D\pi) = (30 \pm 5)^\circ$, $\delta(D^*\pi) = (31 \pm 5)^\circ$



Λ_b and B_s decays

- CDF measured in 2003: $\Gamma(\Lambda_b \to \Lambda_c^+ \pi^-)/\Gamma(\overline{B}^0 \to D^+\pi^-) \approx 2$



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

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

[Leibovich, ZL, Stewart, Wise]

Isgur-Wise functions may be expected to be comparable

Lattice could nail this

- $B_s \to D_s \pi$ is pure tree, can help to determine relative size of E vs. C

[CDF '03: $\mathcal{B}(B_s \to D_s^- \pi^+)/\mathcal{B}(B^0 \to D^-\pi^+) \simeq 1.35 \pm 0.43$ (using $f_s/f_d = 0.26 \pm 0.03$)]

Lattice could help: Factorization relates tree amplitudes, need $SU(3)$ breaking in $B_s \to D_s \ell\bar\nu$ vs. $B \to D\ell\bar\nu$ form factors from exp. or lattice

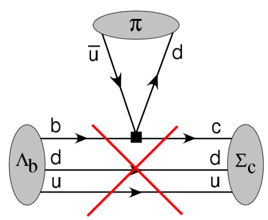
More complicated: $\Lambda_b \to \Sigma_c \pi$

- Recall quantum numbers:

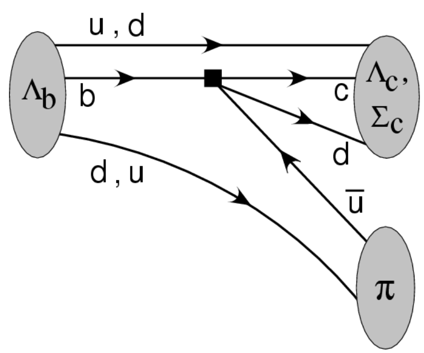
multiplets	s_l	$I(J^P)$
Λ_c	0	$0(\frac{1}{2}^+)$
$\Sigma_c,\ \Sigma_c^*$	1	$1(\frac{1}{2}^+),\ 1(\frac{3}{2}^+)$

$$\Sigma_c = \Sigma_c(2455),\ \Sigma_c^* = \Sigma_c(2520)$$

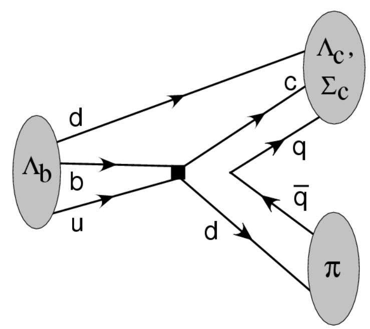
- Can't address in naive factorization, since $\Lambda_b \to \Sigma_c$ form factor vanishes by isospin



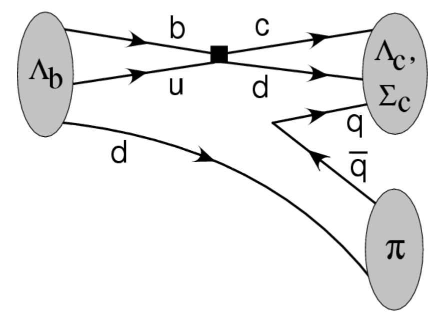
[Leibovich, ZL, Stewart, Wise]



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



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



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

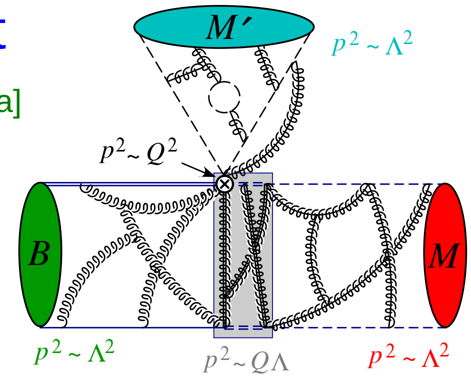
- Prediction: $$\frac{\Gamma(\Lambda_b \to \Sigma_c^* \pi)}{\Gamma(\Lambda_b \to \Sigma_c \pi)} = 2 + \mathcal{O}\big[\Lambda_{\rm QCD}/Q\,,\ \alpha_s(Q)\big] = \frac{\Gamma(\Lambda_b \to \Sigma_c^{*0} \rho^0)}{\Gamma(\Lambda_b \to \Sigma_c^0 \rho^0)}$$

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

Charmless $B \to M_1 M_2$ decays

- Limited consensus about implications of the heavy quark limit

[Bauer, Pirjol, Rothstein, Stewart; Chay, Kim; Beneke, Buchalla, Neubert, Sachrajda]



$$A = A_{c\bar{c}} + N \Big[f_{M_2}\, \zeta^{BM_1} \int \mathrm{d}u\, T_{2\zeta}(u)\, \phi_{M_2}(u) + f_{M_2} \int \mathrm{d}z \mathrm{d}u\, T_{2J}(u,z)\, \zeta_J^{BM_1}(z)\, \phi_{M_2}(u) + (1 \leftrightarrow 2) \Big]$$

- $\zeta_J^{BM_1} = \int \mathrm{d}x \mathrm{d}k_+\, J(z,x,k_+)\, \phi_{M_1}(x)\, \phi_B(k_+)$ also appears in $B \to M_1$ form factors

$\Rightarrow$ Relations to semileptonic decays do not require expansion in $\alpha_s(\sqrt{\Lambda Q})$

- Charm penguins: suppression of long distance part argued, not proven

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

- SCET: fit both ζ's and ζ_J's, calculate T's; QCDF: fit ζ's, calculate factorizable (1st) terms perturbatively; PQCD: 1st line dominates and depends on $k_\perp$

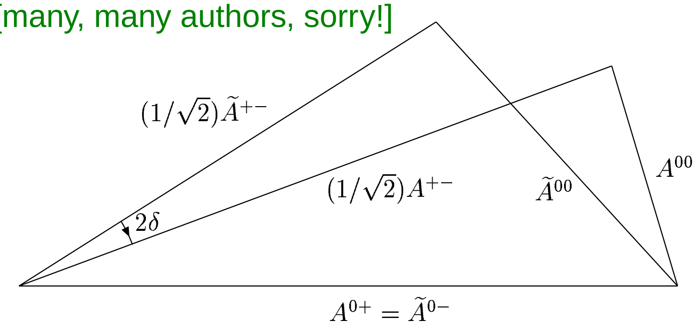
$B \to \pi\pi$ amplitudes

$$A_{+-} = -\lambda_u(T + P_u) - \lambda_c P_c - \lambda_t P_t = e^{-i\gamma}\, T_{\pi\pi} - P_{\pi\pi}$$

$$\sqrt{2} A_{00} = \lambda_u(-C + P_u) + \lambda_c P_c + \lambda_t P_t = e^{-i\gamma}\, C_{\pi\pi} + P_{\pi\pi}$$

$$\sqrt{2} A_{-0} = -\lambda_u(T + C) = e^{-i\gamma}(T_{\pi\pi} + C_{\pi\pi})$$

[many, many authors, sorry!]



Alternatively, eliminate λ_t terms, then $e^{i\beta} P'_{\pi\pi}$

Diagrammatic language can be justified in SCET at leading order

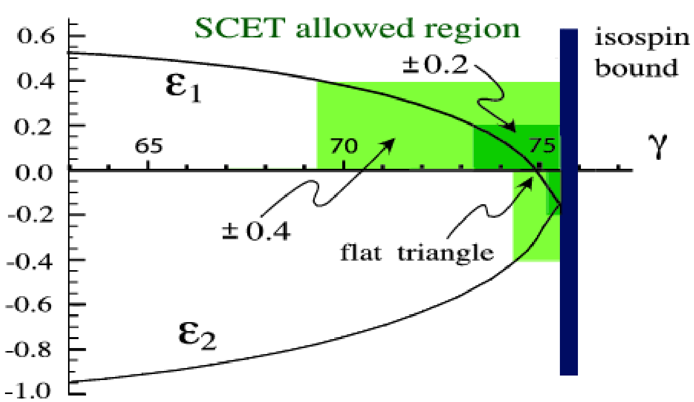
- We know: $\arg(T/C) = \mathcal{O}(\alpha_s, \Lambda/m_b)$, P_u is calculable (small),
  - P_t: "chirally enhanced" power correction in QCDF (treated like others by BPRS)
  - P_c: treated as $\mathcal{O}(1)$ in SCET (argued to be small by BBNS)
- Isospin analysis: 6 observables determine weak phase $+\ 5$ hadronic parameters

  $\mathcal{B}(B \to \pi^0\pi^0)$ is large, so $\Delta\alpha$ can be large, but $C_{\pi^0\pi^0}$ is hard to measure
- Can we use the theory constraint to determine α without $C_{\pi^0\pi^0}$?

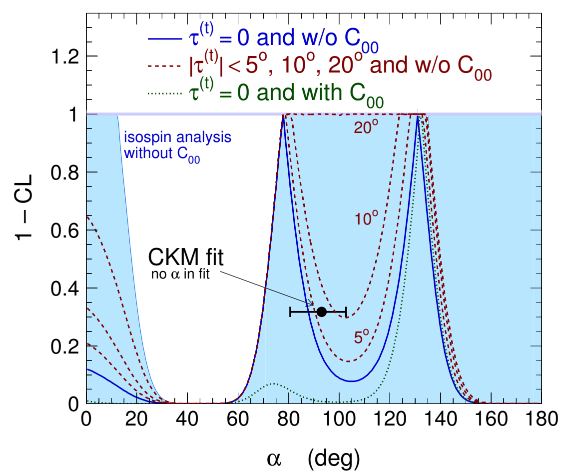
Phenomenology of $B \to \pi\pi$

- Imposing a constraint on either $\epsilon \equiv \mathrm{Im}(C_{\pi\pi}/T_{\pi\pi})$ or $\tau \equiv \arg[T_{\pi\pi}/(C_{\pi\pi} + T_{\pi\pi})]$ mixes "tree" and "penguin" amplitudes [expect $\epsilon, \tau = \mathcal{O}(\alpha_s, \Lambda/m_b)$]

[Bauer, Rothstein, Stewart]



[Höcker, Grossman, ZL, Pirjol]

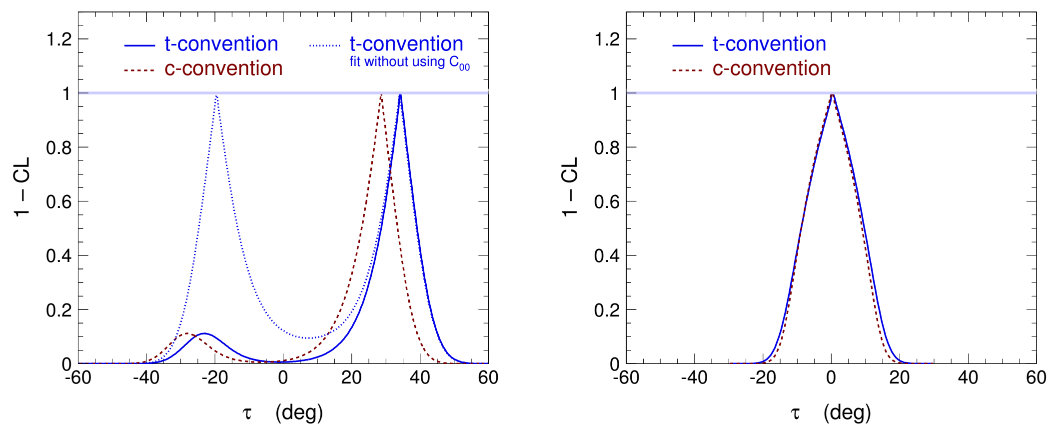


For $\alpha \sim 90°$,
$\epsilon \sim 0.2 \leftrightarrow \tau \sim 5°$
$\epsilon \sim 0.4 \leftrightarrow \tau \sim 10°$

For a given τ, theo and exp errors highly correlated

- CKM fit $\Rightarrow$ unexpectedly large τ (2σ)
  - large power corrections to T, C?
  - large up penguins?
  - large weak annihilation?

May be more applicable to $B \to \rho\rho$



Few comments

- More work & data needed to understand the expansions

  Why some predictions work at $\lesssim 10\%$ level, while others receive $\sim 30\%$ corrections

  Clarify role of charming penguins, chirally enhanced terms, annihilation, etc.

  We have the tools to try to address the questions

- Where can lattice help?

  – Semileptonic form factors (precision, include ρ and K^*, larger recoil)

  – Light cone distribution functions of heavy and light mesons

  – $SU(3)$ breaking in form factors and distribution functions

  – Probably more remote: nonleptonic decays, nonlocal matrix elements
  e.g., large $B \to \pi^0\pi^0$ rate in SCET accommodated by $\langle k_+^{-1}\rangle_B = \int \mathrm{d}k_+\, \phi_B(k_+)/k_+$

The future

Theoretical limitations (continuum methods)

- 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°
$B \to \phi K_S,\ \eta^{(\prime)} K_S$, ... ($\beta$)	$\sim 2^\circ$	$\sim 10^\circ$
$B \to \pi\pi,\ \rho\rho,\ \rho\pi$ (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

  Belle & Babar data sets continue to double every ~ 2 years, will reach $\sim 1000\,\text{fb}^{-1}$ 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, powerful constraints on model building in the LHC era

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

Conclusions

- Much more is known about the flavor sector and CPV than few years ago
  CKM phase is probably the dominant source of CPV in flavor changing processes

- Deviations from SM in B_d mixing, $b \to s$ and even in $b \to d$ decays are constrained

- New era: new set of measurements are becoming more precise than old ones; existing data could have shown NP, lot more is needed to achieve theoretical limits

- The point is not just to measure magnitudes and phases of CKM elements (or ρ, η and α, β, γ), but to probe the flavor sector 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 model independently understanding more observables

  Lattice QCD is important; in some cases the only way to make progress

Thanks

- To the organizers for the invitation, and for looking after our needs

⇒

- To A. Höcker, H. Lacker, Y. Nir, G. Perez, and I. Stewart for helpful discussions

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

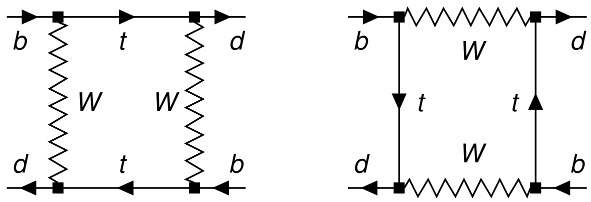
  Can ultimately constrain these using data

CPV in neutral meson mixing

- CPV in mixing and decay: typically sizable hadronic uncertainties

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

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



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.*]

$$A_{\mathrm{SL}} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = (-0.0026 \pm 0.0067)$$

$\Rightarrow |q/p| = 1.0013 \pm 0.0034$ [dominated by BELLE]

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

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

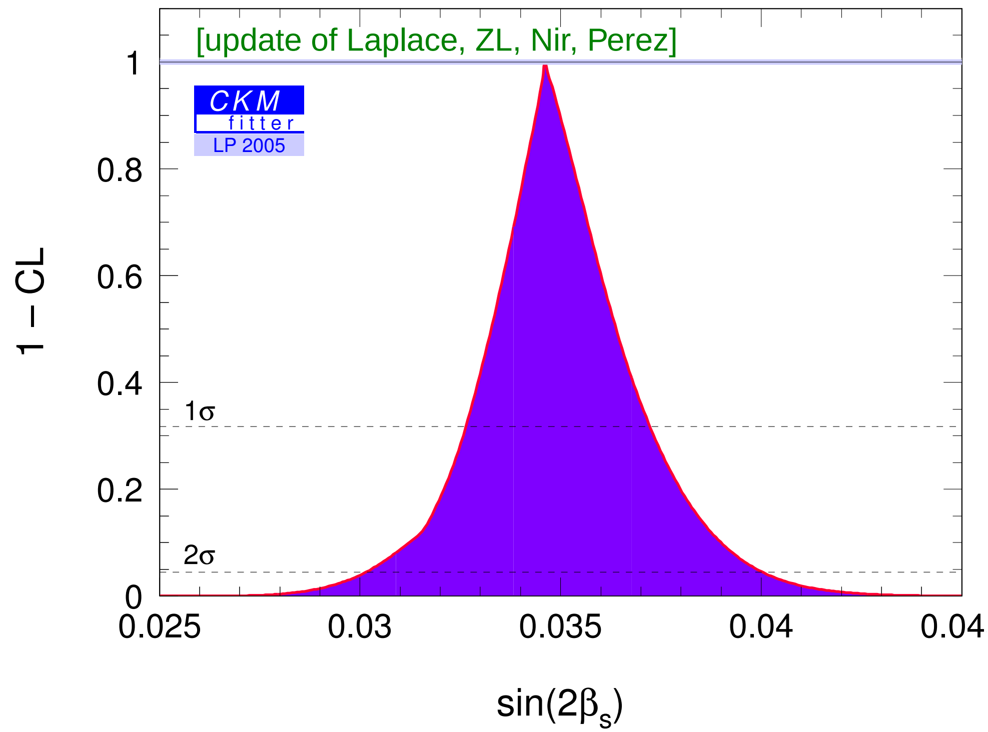
- Analog of $B \to \psi K_S$ in B_s decay — determines the phase between B_s mixing and $b \to c\bar{c}s$ decay, β_s, as cleanly as $\sin 2\beta$ from ψK_S

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

$$\sin 2\beta_s = 0.0346^{+0.0026}_{-0.0020}$$

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

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

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

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)

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?

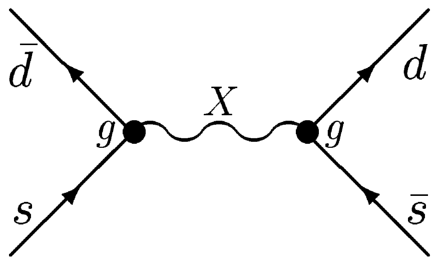
- $|V_{td}/V_{ts}|$: B_s mixing (Tevatron may still have a chance)
- Rare decays: $B \to X_s\gamma$ near theory limited; $B \to X_s\ell^+\ell^-$ is becoming comparably precise
- $|V_{ub}|$: reaching $\lesssim 10\%$ will be very significant (a Babar/Belle measurement that may survive LHCB)
- Pursue $B \to \ell\nu$, 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!)

More slides removed

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



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

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

- 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

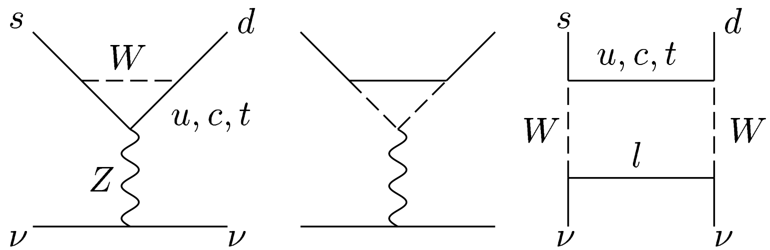
Precision tests with Kaons

- 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)

- $K \to \pi\nu\bar{\nu}$: 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 $> 10^{-3}$ 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

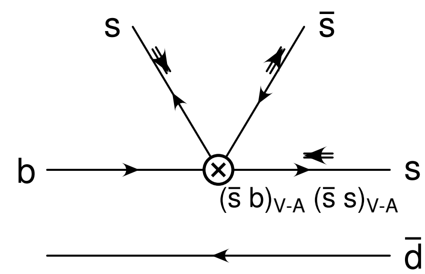
Can lattice help to understand the SM prediction for $D - \overline{D}$ mixing?

Polarization in charmless $B \to VV$

B decay	Longitudinal polarization fraction BELLE	BABAR
$\rho^- \rho^+$	0.95 ± 0.11	$0.98^{+0.02}_{-0.03}$
$\rho^0 \rho^+$		$0.97^{+0.05}_{-0.08}$
$\omega \rho^+$		$8^{+0.12}_{-0.15}$
$\rho^0 K^{*+}$		$0.96^{+0.06}_{-0.16}$
$\rho^- K^{*0}$	$0.43^{+0.12}_{-0.11}$	0.79 ± 0.09
ϕK^{*0}	0.45 ± 0.05	0.52 ± 0.05
ϕK^{*+}	0.52 ± 0.09	0.46 ± 0.12

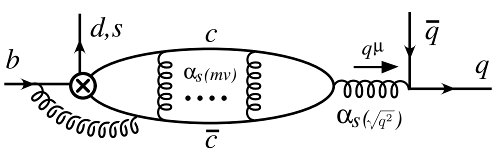
Chiral structure of SM and HQ limit claimed to imply

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

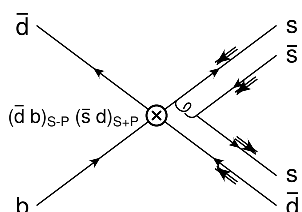


ϕK^*: penguin dominated — NP reduces f_L?

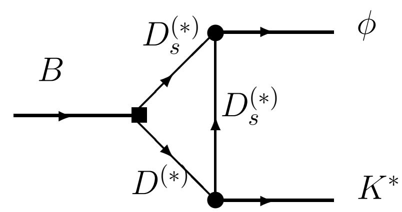
Proposed explanations:



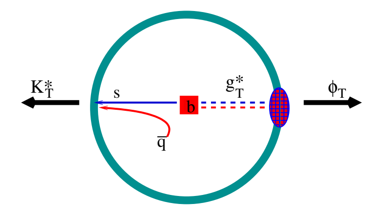
$\mathcal{O}(1)$



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



(model)



(model)

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

- Can it 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	$+0.00 \pm 0.16$

[Fleischer & Mannel, Neubert & Rosner; Lipkin; Buras & Fleischer; Yoshikawa; Gronau & Rosner; Buras *et al.*; ...]

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

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

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

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

- Pattern quite different than until 2004: R_c closer to 1, while R further from 1
  No strong motivation for NP contribution to EW penguin, will be exciting to sort out