The CKM matrix and CP Violation

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Thanks to: Tom Browder, Andreas Höcker, Heiko Lacker, Yossi Nir, Gilad Perez, Jeff Richman

August 20, 2004

Plan of the talk

- Introduction

  Tests with K and D mesons

- CP violation — why/when it's clean

  β: $b \to c$ measurements

  β: $b \to s$ measurements, implications

- New: α and γ getting interesting

  α: $B \to \pi\pi,\ \rho\rho,\ \rho\pi$

  γ: various $B \to DK$ methods

  Implications

- Theoretical developments: progress with nonleptonic decays

- Future / Conclusions

Plan of the talk

- Introduction

  Tests with K and D mesons

- CP violation — why/when it's clean

  β: $b \to c$ measurements

  β: $b \to s$ measurements, implications

  Establish CPV in B sector $\Rightarrow$ precision

  Start look at penguins, hints of NP?

- New: α and γ getting interesting

  α: $B \to \pi\pi,\ \rho\rho,\ \rho\pi$

  γ: various $B \to DK$ methods

  Implications

  Why need so many measurements?

  Overconstraining / redundancy crucial

  Best present α, γ methods are new

  NP in $B - \overline{B}$ mixing well-constrained

- Theoretical developments: progress with nonleptonic decays

- Future / Conclusions

Notations

Dictionary: CPV $= CP$ violation

SM $=$ standard model

NP $=$ new physics

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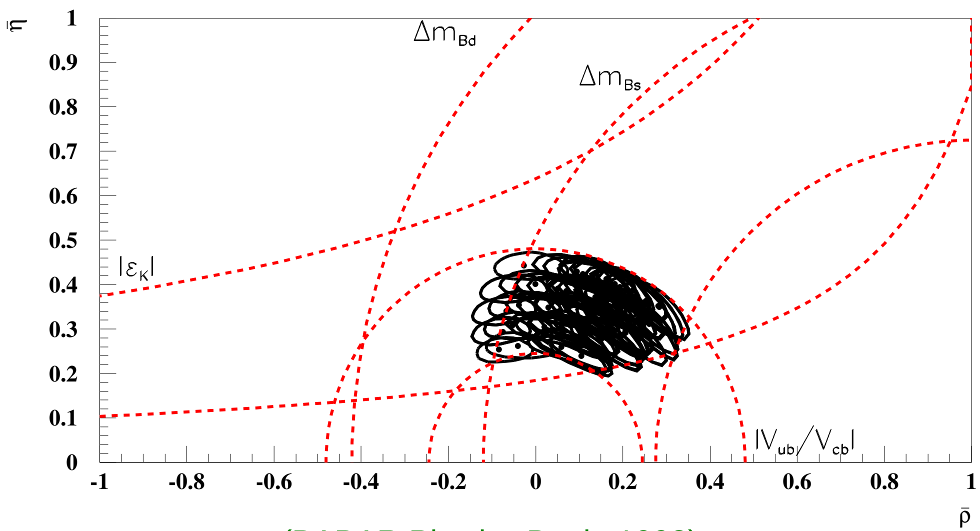
SM $=$ standard model

NP $=$ new physics

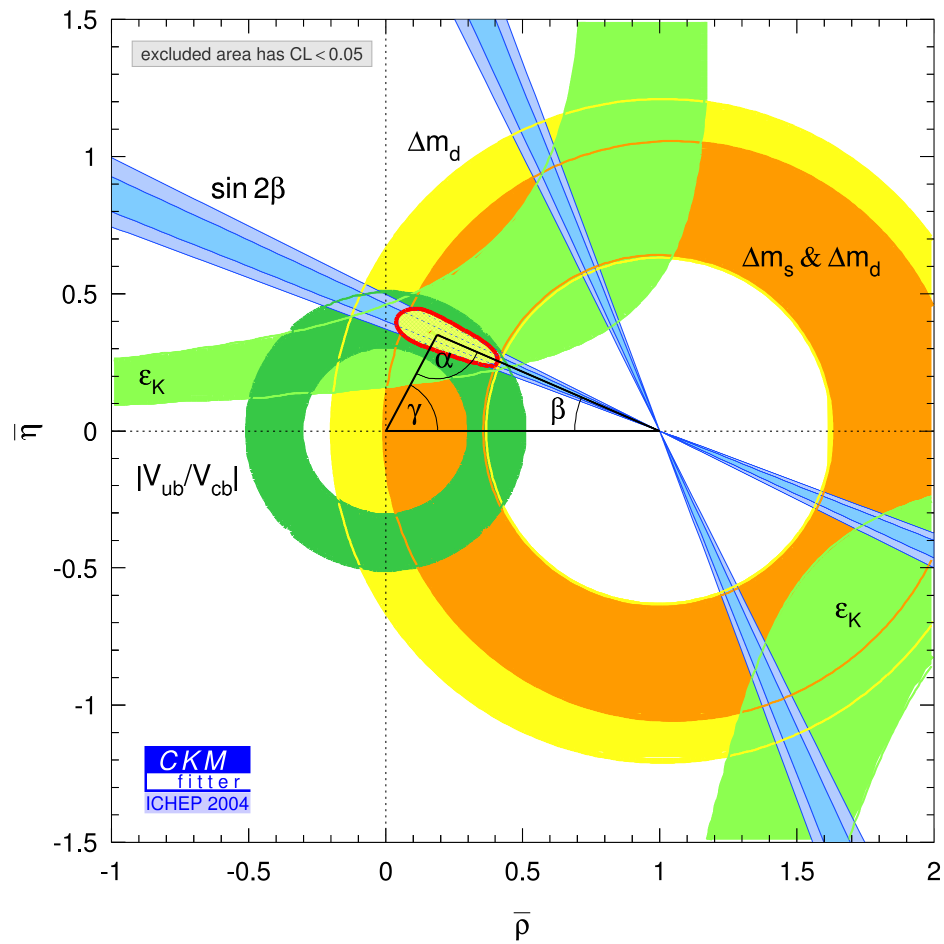
Unitarity triangle angles			
BABAR:	β	α	γ
BELLE:	ϕ_1	ϕ_2	ϕ_3
This talk:	易	難	魔

Testing the flavor sector

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



(BABAR Physics Book, 1998)



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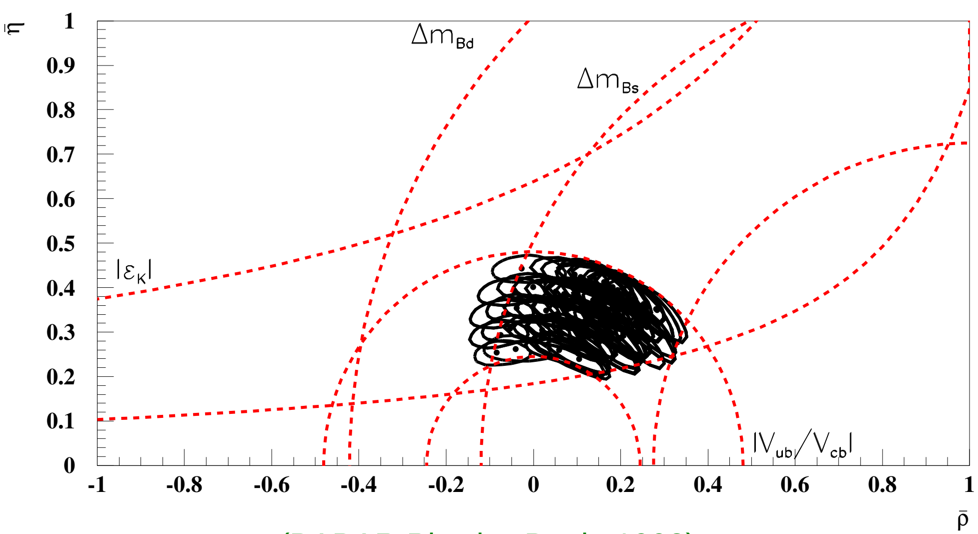

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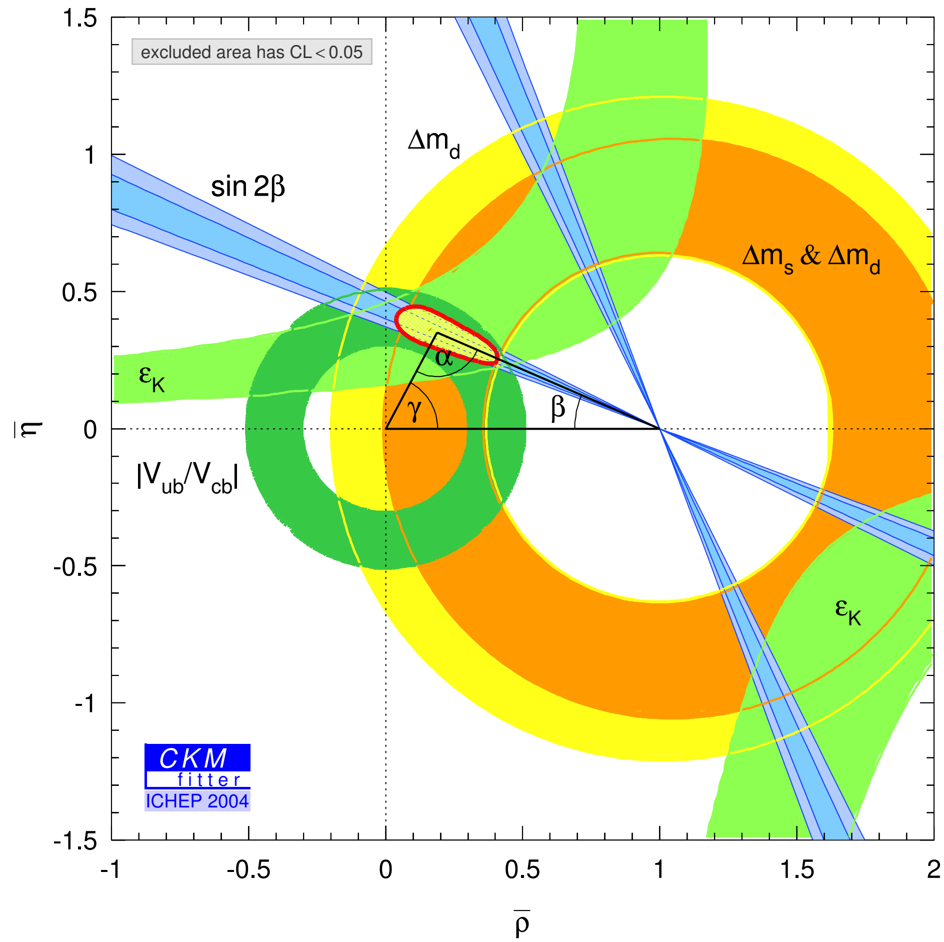


$\sin 2\beta = 0.726 \pm 0.037$, order of magnitude smaller error than first measurements

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 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 $\mathcal{B} \sim 10^{-10}(K^\pm)$, $10^{-11}(K_L)$

  By now 3 events observed: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ [BNL E949]

  Need higher statistics to make definitive tests

- D system complementary to K, B: CPV, FCNC both GIM and CKM suppressed
  $\Rightarrow$ tiny in SM and not yet observed

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

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

[See Shipsey's talk this afternoon]

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

CPV in decay

- CPV in decay: Amplitudes w/ different weak (ϕ_k) & strong (δ_k) phase, $|\overline{A}_{\overline{f}}/A_f| \neq 1$

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

- Unambiguously established by $\epsilon'_K \neq 0$, now also in B decay:

$$A_{K^-\pi^+} \equiv \frac{\Gamma(\overline{B} \to K^-\pi^+) - \Gamma(B \to K^+\pi^-)}{\Gamma(\overline{B} \to K^-\pi^+) + \Gamma(B \to K^+\pi^-)} = -0.11 \pm 0.02 \quad (5.7\sigma)$$

[BABAR 4.2σ, BELLE 4.0σ, CDF, CLEO]

  – After "K-superweak", also "B-superweak" excluded: CPV phase not only in M_{12}

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

- Theoretical understanding insufficient to either prove or to rule out that NP enters

$A_{K^-\pi^+}$ is 3.3σ from $A_{K^-\pi^0} = 0.04 \pm 0.04$ [BABAR, BELLE, CLEO] — another challenge

CPV in interference between decay and mixing

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

$$
\begin{tikzcd}
\boxed{B^0} \arrow[rr, "A"] \arrow[d, "q/p"'] & & \boxed{f_{CP}} \\
\boxed{\bar{B}^0} \arrow[urr, "\bar{A}"'] & &
\end{tikzcd}
$$

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

Time dependent CP asymmetry:

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

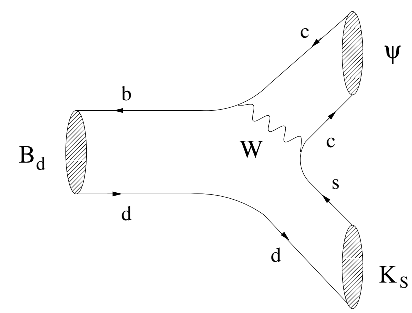
- If amplitudes with one weak phase dominate a decay, $a_{f_{CP}}$ measures a phase in the Lagrangian theoretically cleanly:

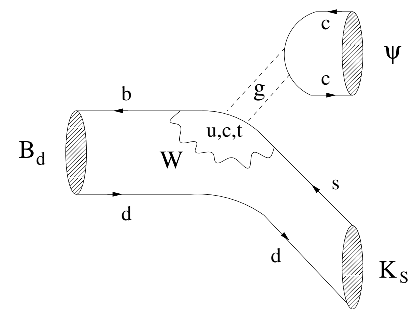
$$a_{f_{CP}} = \mathrm{Im}\,\lambda_f\ \sin(\Delta m\, t) \qquad \arg\lambda_f = \text{phase difference between decay paths}$$

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

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

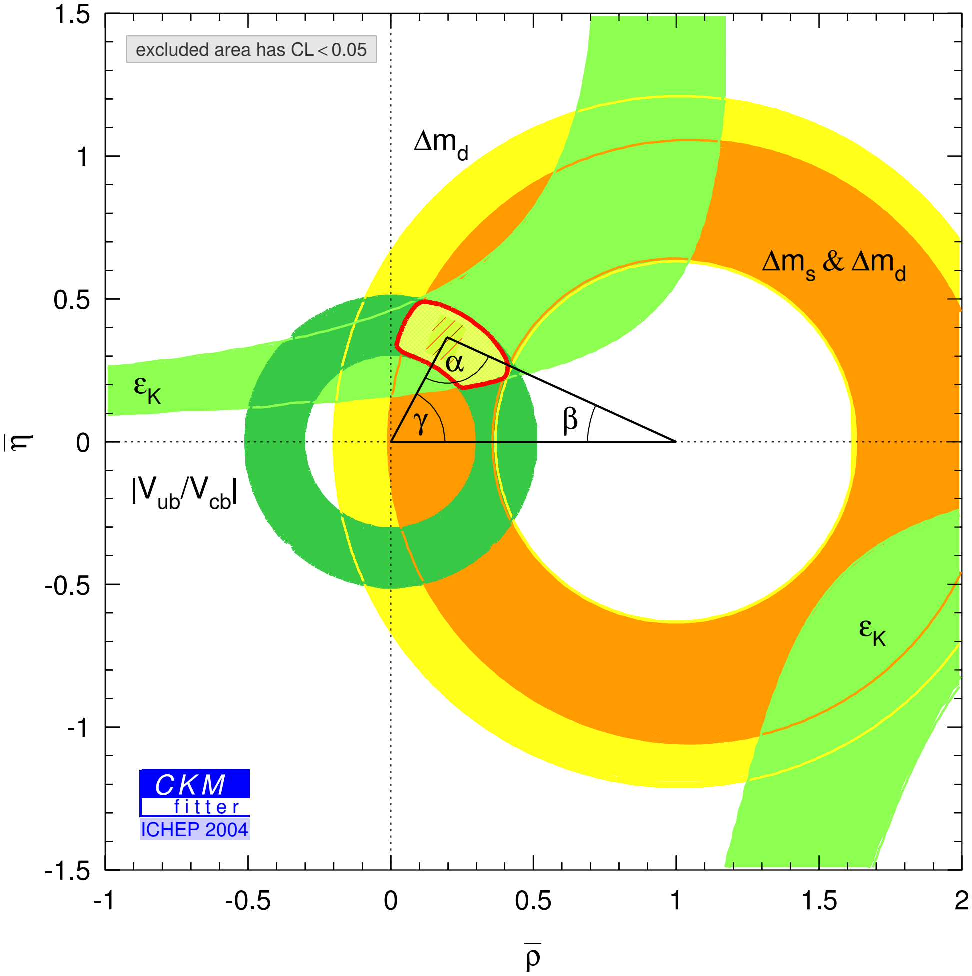
  $\arg\lambda_{\psi K_S} = (B\text{-mix} = 2\beta) + (\text{decay} = 0) + (K\text{-mix} = 0)$

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

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

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

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



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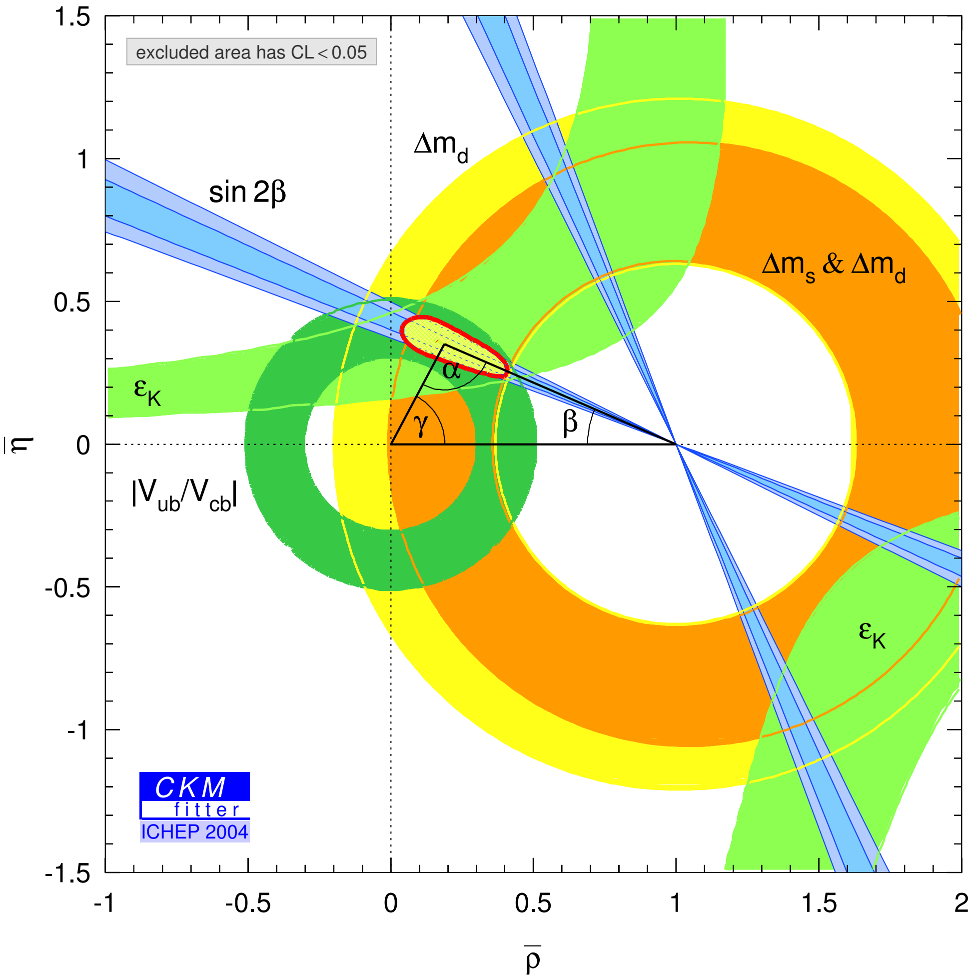

First precise test of the CKM picture

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

Without $|V_{ub}|$, 4 solutions; remove 2 this year: $\cos 2\beta = +2.72^{+0.50}_{-0.79} \pm 0.27$ [BABAR]

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

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$\sin 2\beta$ is only the beginning

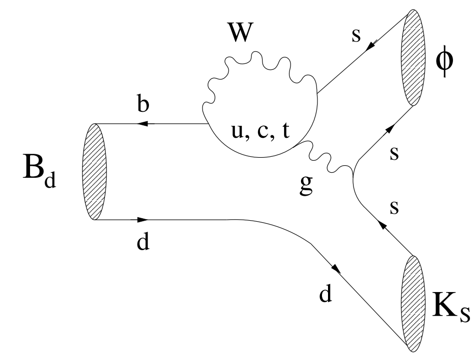
Paradigm change: look for corrections, rather than alternatives to CKM

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

Theoretical cleanliness essential

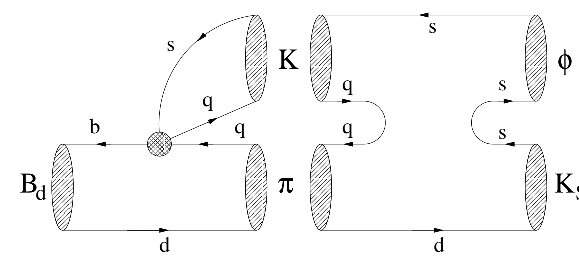
CPV in $b \to s$ decays and NP

- 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 $C_{\phi K_S} \lesssim \mathcal{O}(\lambda^2) = 0.05$



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

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These CPV measurements are interesting independent of present numbers

- 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 expectation for * $\lvert -\eta_{CP}\, S_f - \sin 2\beta\rvert$	$-\eta_{CP}\, S_f$	C_f
$b \to c\bar{c}s$	ψK_S	< 0.01	$+0.726 \pm 0.037$	$+0.034 \pm 0.030$
$b \to c\bar{c}d$	$\psi\pi^0$	~ 0.2	$+0.40 \pm 0.33$	$+0.13 \pm 0.24$
	$D^{*+}D^{*-}$	~ 0.2	$+0.19 \pm 0.32$	$+0.27 \pm 0.17$
$b \to s\bar{q}q$	ϕK^0	~ 0.05	$+0.34 \pm 0.21$	-0.05 ± 0.20
	$\eta' K_S$	~ 0.1	$+0.41 \pm 0.11$	-0.04 ± 0.08
	$K^+K^-K_S$	~ 0.15	$+0.52 \pm 0.16$	$+0.09 \pm 0.10$
	$\pi^0 K_S$	~ 0.15	$+0.34 \pm 0.29$	$+0.09 \pm 0.14$
	$f^0 K_S$	~ 0.15	$+0.40 \pm 0.26$	$+0.14 \pm 0.22$
	ωK_S	~ 0.15	$+0.75 \pm 0.67$	$+0.26 \pm 0.50$

* My estimates of reasonable limits (strict bounds worse)

Results more consistent than before, only BA-BE difference above 2σ is in $f^0 K_S$

- 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)

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

  Conservative SM bound (estimates smaller): $|S_{\psi K} - S_{\eta' K_S}| < 0.2$ [Grossman, ZL, Nir, Quinn]

  $\Rightarrow S_{\eta' K_S} = 0.4$ would be a sign of NP

  Would not only exclude SM, but MFV and universal SUSY models such as GMSB

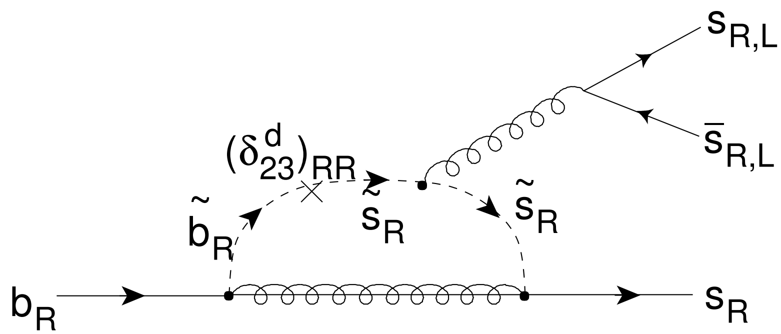
- $S_{\phi K}$: significant effect still possible, need to further decrease errors

  $\Rightarrow S_{\phi K_S}$ at its present central value would be a sign of NP

- There is a lot to learn from more precise measurements

Model building more interesting

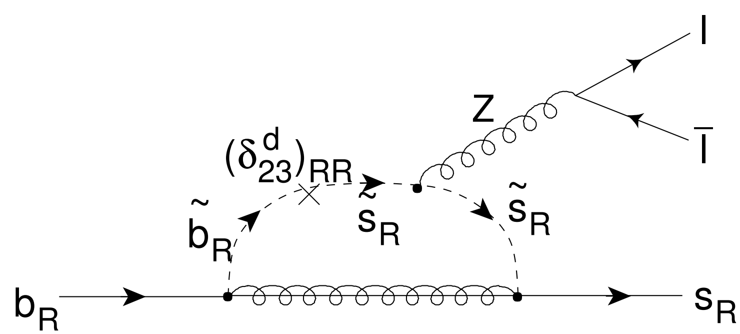
- The present $S_{\eta' K_S}$ and $S_{\phi K_S}$ central values can be reasonably accommodated with NP (unlike an $\mathcal{O}(1)$ deviation from $S_{\psi K_S}$)



- $B \to X_s \gamma$ mainly constrains LR mass insertions

Now also $B \to X_s \ell^+ \ell^-$ agrees with the SM at the $\mathcal{O}(25\%)$ level [new BELLE results]

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



New this 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 $B \to \pi\pi$: Isospin analysis

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

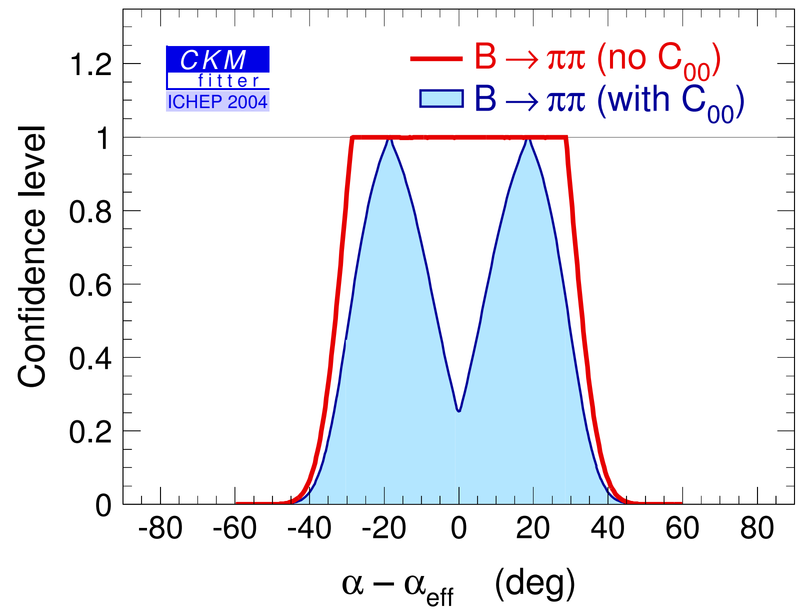
$$\frac{\Gamma(\overline{B} \to \pi^0\pi^0) - \Gamma(B \to \pi^0\pi^0)}{\Gamma(\overline{B} \to \pi^0\pi^0) + \Gamma(B \to \pi^0\pi^0)} = 0.28 \pm 0.39$$

[BABAR, BELLE]

$$\mathcal{B}(B \to \pi^0\pi^0) = (1.51 \pm 0.28) \times 10^{-6}$$

Need a lot more data to pin down $\alpha - \alpha_{\rm eff}$ from isospin analysis... Bound now:

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



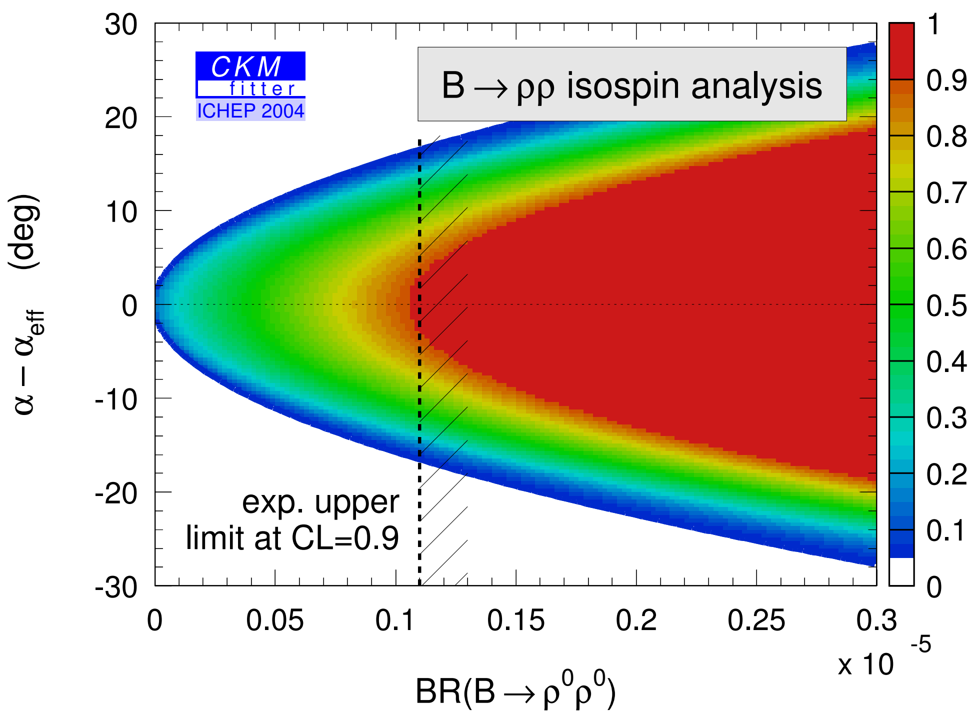
- Interpretation unclear because of marginal consistency of $S_{\pi^+\pi^-}$ measurements

$B \to \pi^+\pi^-$	$-\eta_{CP}\, S_f$	C_f
BABAR	0.30 ± 0.17	-0.09 ± 0.15
BELLE	1.00 ± 0.22	-0.58 ± 0.17
average	$0.56 \pm 0.13(0.34)$	$-0.31 \pm 0.11(0.24)$

(PDG-scaled-errors)

$B \to \rho\rho$: 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 $\sigma\ (= 0, \|, \perp)$
- Small rate $\mathcal{B}(B \to \rho^0\rho^0) < 1.1 \times 10^{-6}$ (90% CL) $\Rightarrow$ small penguin pollution
  $\frac{\mathcal{B}(B\to\pi^0\pi^0)}{\mathcal{B}(B\to\pi^-\pi^+)} = 0.33 \pm 0.07$ vs. $\frac{\mathcal{B}(B\to\rho^0\rho^0)}{\mathcal{B}(B\to\rho^-\rho^+)} < 0.04$ (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 [Falk, ZL, Nir, Quinn]

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

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

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

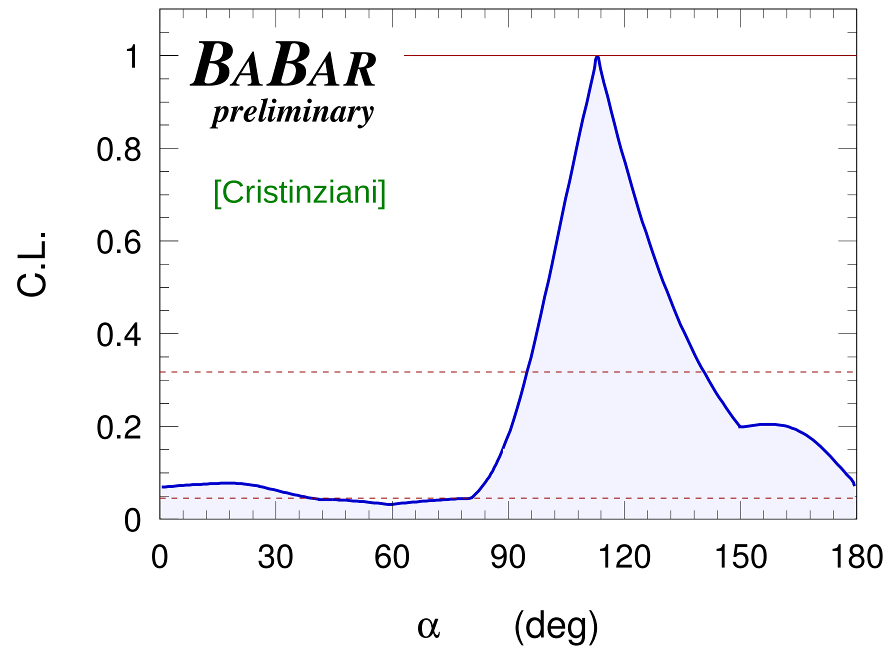
- Two-body $B \to \rho^\pm \pi^\mp$: two pentagon relations from isospin; would need rates and CPV in all $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ modes to get α [Lipkin, Nir, Quinn, Snyder]

  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

  With assumptions about factorization, $SU(3)$: $\alpha = 95^\circ \pm 6^\circ_{(\mathrm{exp})} \pm 15^\circ_{(\mathrm{th})}$ [Gronau, Zupan]

- New: Dalitz plot analysis of the interference regions in $B \to \pi^+\pi^-\pi^0$ [Snyder, Quinn]

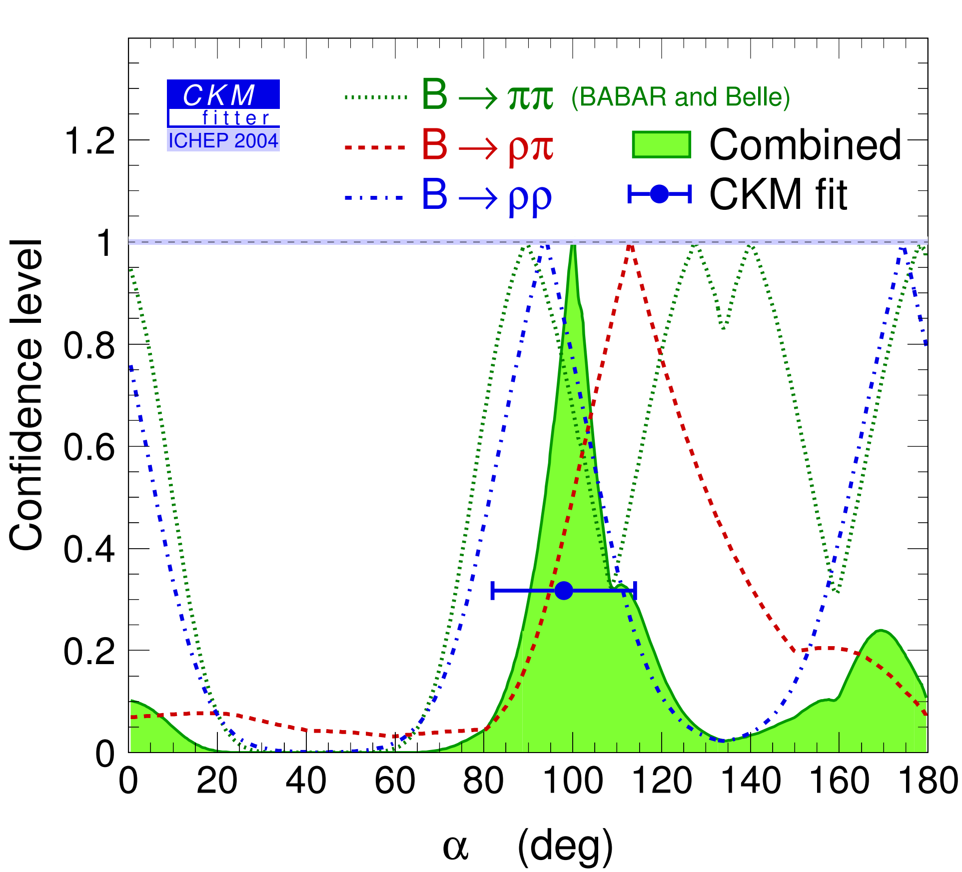
  Result: $\alpha = (113^{+27}_{-17} \pm 6)^\circ$

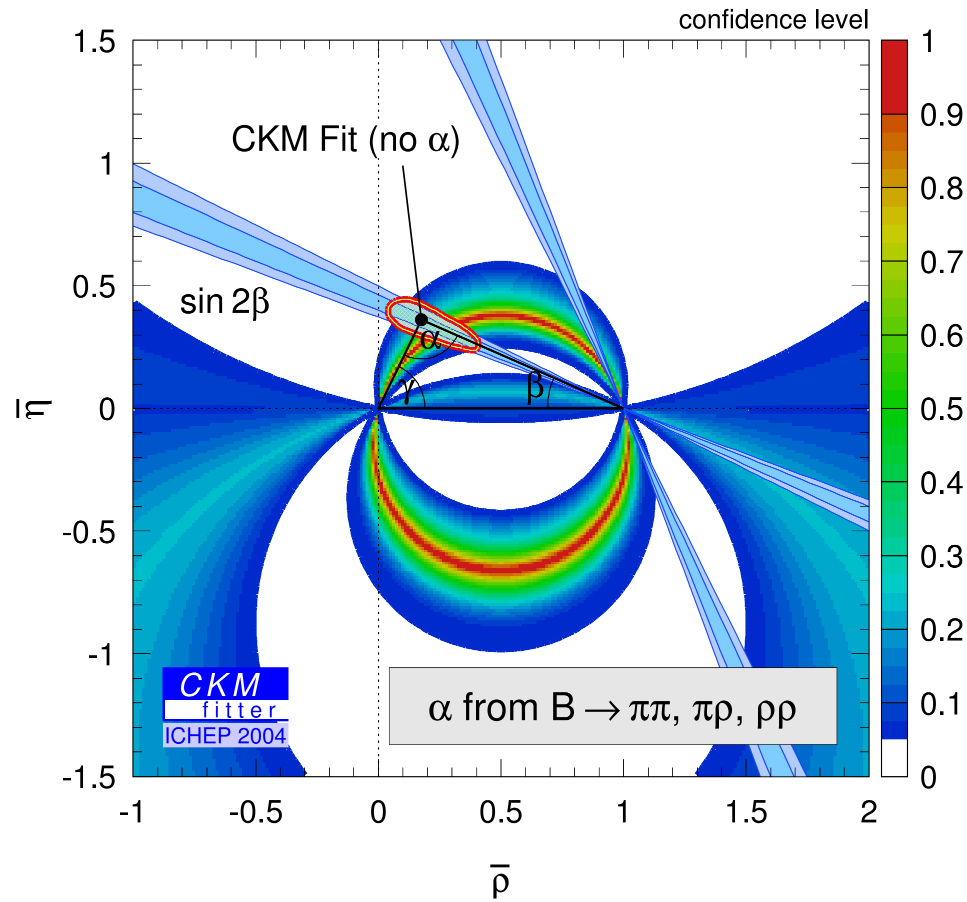


Measurements of α combined

- 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 $98 \pm 16^\circ$





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

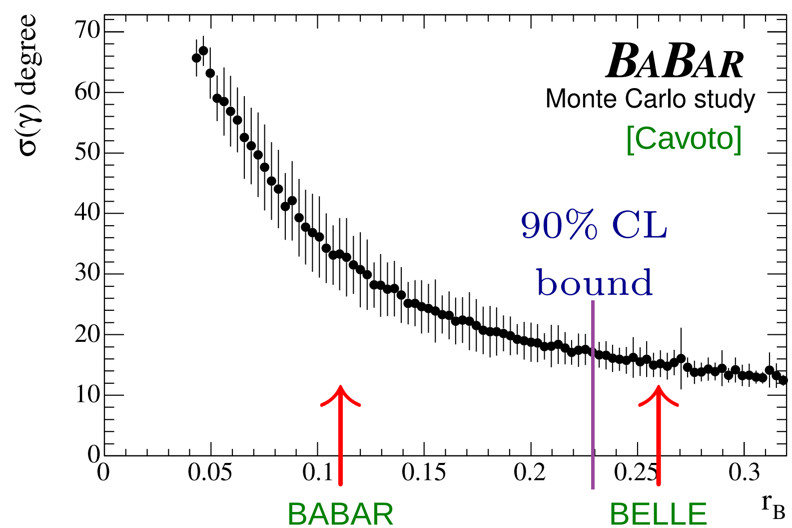
  [Giri, Grossman, Soffer, Zupan; Bondar @ BELLE workshop]

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

  $$\gamma = 77^{+17}_{-19} \pm 13 \pm 11^\circ \qquad \text{[BELLE, } 140\,\text{fb}^{-1}\text{]}$$

  $$\gamma = 88 \pm 41 \pm 19 \pm 10^\circ \qquad \text{[BABAR, } 191\,\text{fb}^{-1}\text{]}$$

  Difference in r_B only 1σ, but rather important

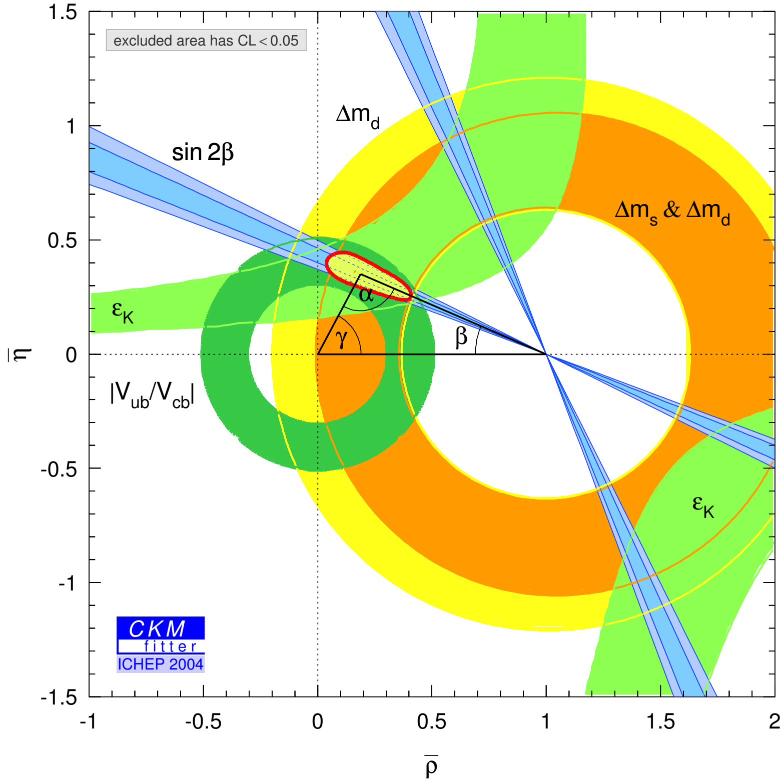


- Need more data to firm up value of r_B and determine γ more precisely

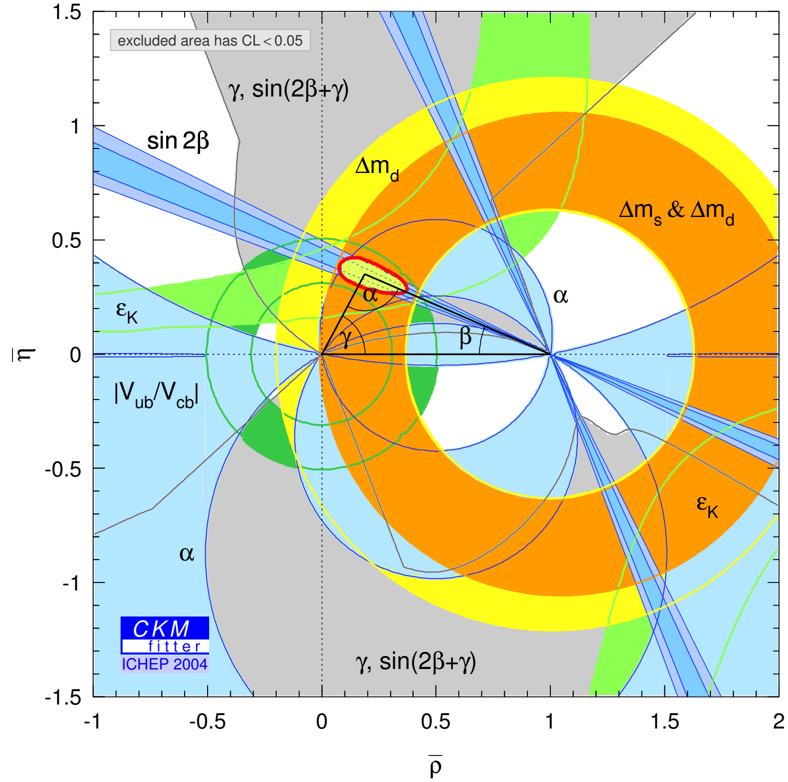
A (slightly) new CKM fit

- 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)

Fit with “traditional” inputs



Fit with above included

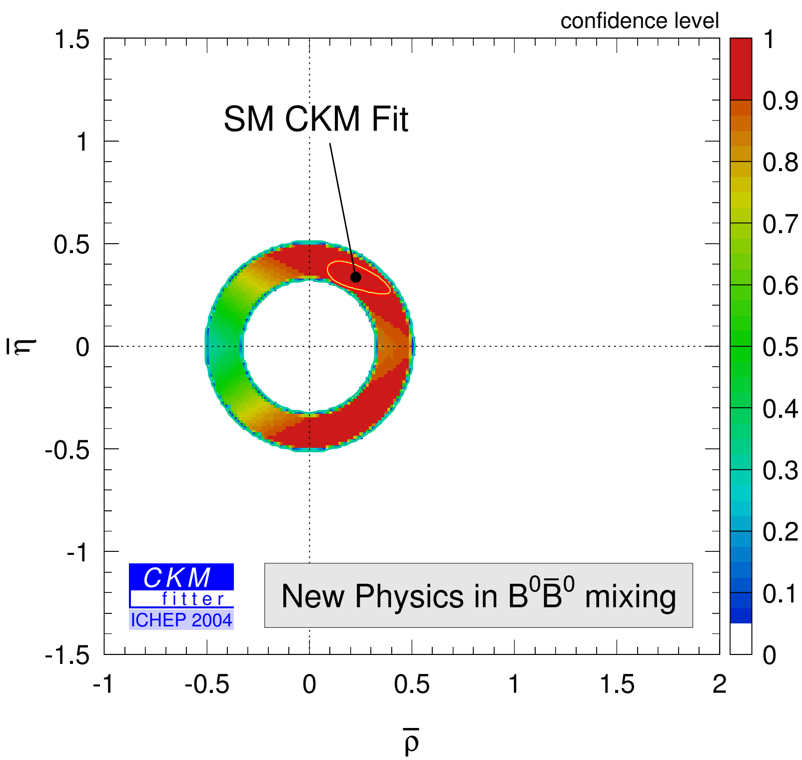


NP in mixing, model independently

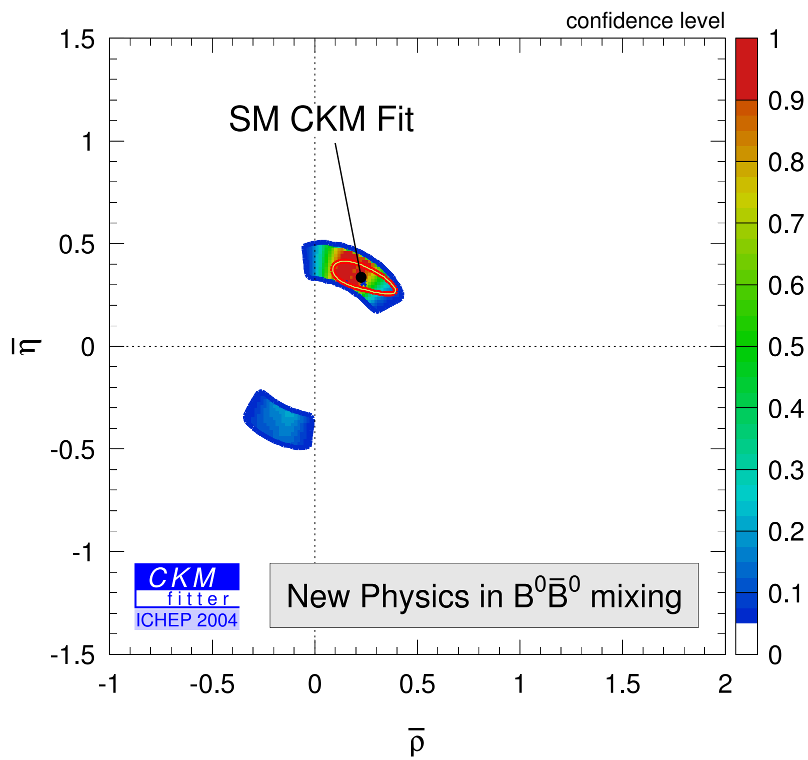
- NP in mixing amplitude only, 3×3 unitarity preserved: $M_{12} = M_{12}^{(\mathrm{SM})}\, r_d^2\, e^{2i\theta_d}$

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

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



Plus α, γ, $2\beta + \gamma$, $\cos 2\beta$



New measurements restrict ρ, η almost completely to the SM region

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

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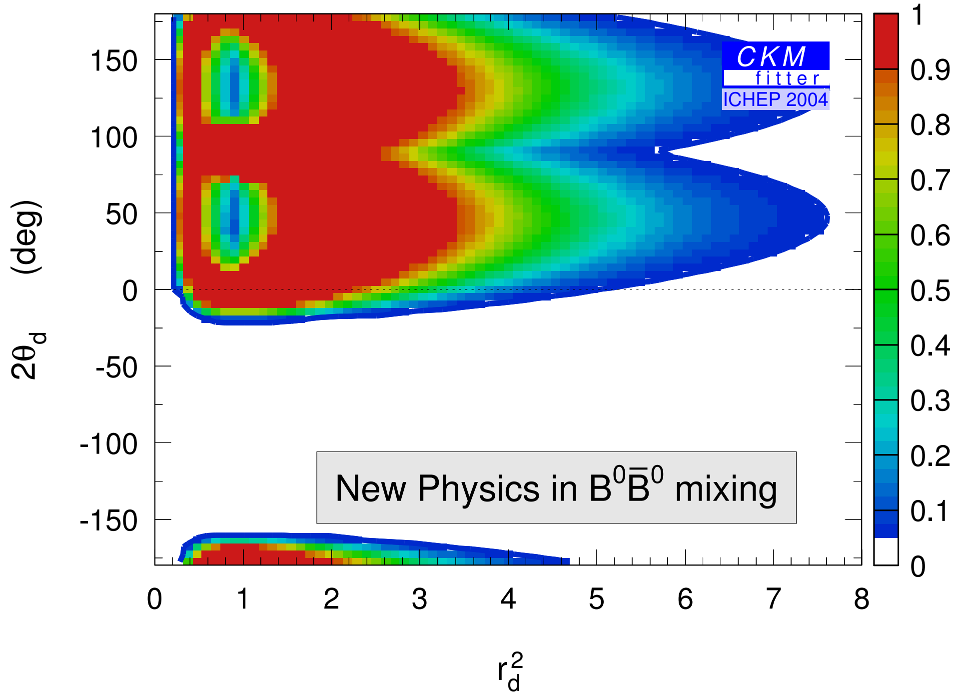
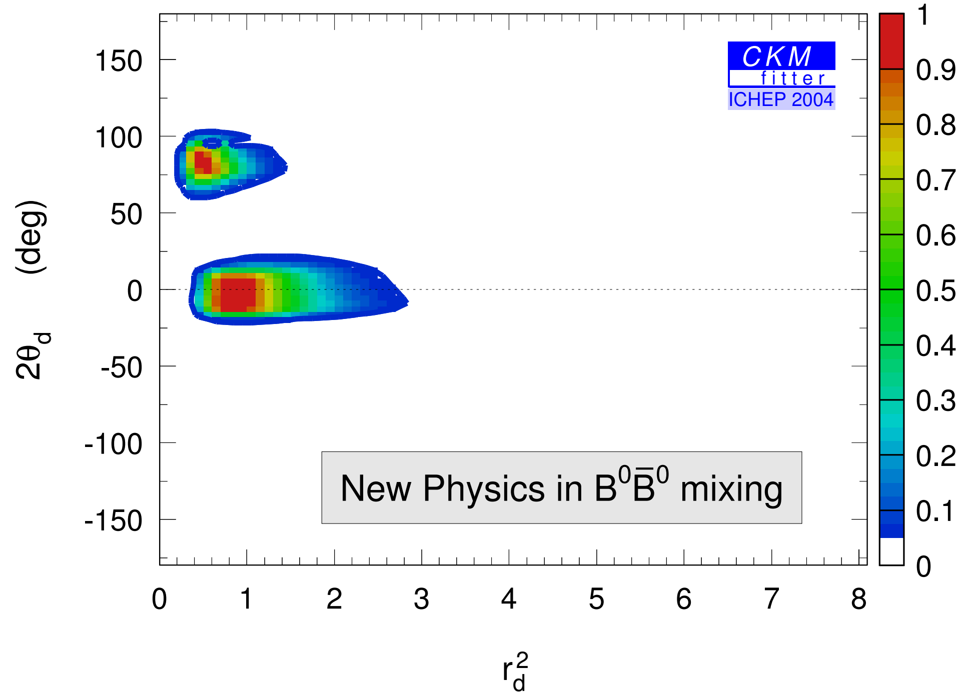


Plus α, γ, $2\beta + \gamma$, $\cos 2\beta$



New measurements restrict θ_d, r_d^2 very significantly for the first time

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 phsyics?
  - 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.

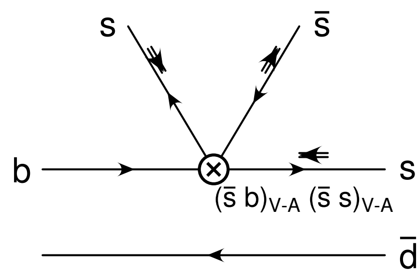
  Many implications: strong phases $\mathcal{O}(1)$ or suppressed? [$A_{K^-\pi^+} \Rightarrow$ some $\mathcal{O}(1)$]

Polarization in charmless $B \to VV$

B decay	Longitudinal polarization fraction BELLE	BABAR
$\rho^-\rho^+$		$0.99^{+0.05}_{-0.04}$
$\rho^0\rho^+$	0.95 ± 0.11	$0.97^{+0.06}_{-0.08}$
$\omega\rho^+$		$0.88^{+0.12}_{-0.15}$
$\rho^0 K^{*+}$		$0.96^{+0.06}_{-0.16}$
$\rho^- K^{*0}$	0.50 ± 0.20	0.79 ± 0.09
ϕK^{*0}	0.52 ± 0.08	0.52 ± 0.05
ϕK^{*+}	0.49 ± 0.14	0.46 ± 0.12

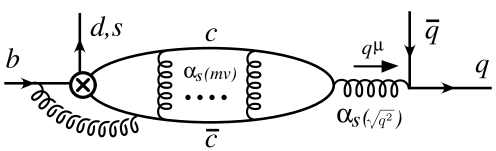
Chiral structure of SM and HQ limit claimed to imply

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

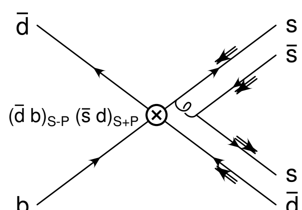


ϕK^*: penguin dominated — NP reduces f_L?

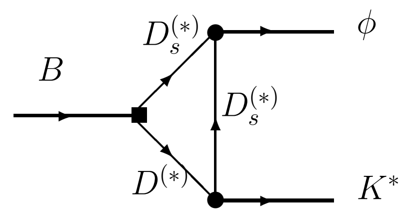
Proposed explanations:



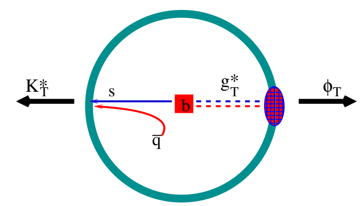
$\mathcal{O}(1)$



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



(model)



(model)

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

No longer viewed as a clear 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	$+0.01 \pm 0.16$

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

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

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

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

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

- Pattern quite different than before ICHEP: 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

Conclusions

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

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

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

Summary

- $\sin 2\beta = 0.726 \pm 0.037$
  $\Rightarrow$ 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, large strong phases

- First α and γ measurements
  $\Rightarrow$ Finally strong constraints on NP in B–$\overline{B}$ mixing

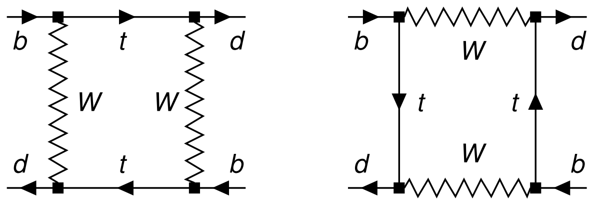
Additional Topics

Further interesting CPV modes

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.*]

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

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

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

$B^0 \to K^{*0}\gamma$

- 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 $\bar{b} \to \gamma_R$

  $\Rightarrow$ interference and CPV suppressed by m_s/m_b, while NP could enhance it

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

  $$S = +0.25 \pm 0.63 \pm 0.14\,, \qquad C = -0.57 \pm 0.32 \pm 0.09$$ [BABAR]

  $$S = -0.79^{+0.63}_{-0.50} \pm 0.10$$ [BELLE]

  Average: $S = -0.30 \pm 0.44$

- Will be very interesting with (much) higher luminosity [SM: $S \sim 2(m_s/m_b)\sin 2\beta$]

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

- Due to $\Gamma_\rho \neq 0$, $\rho\rho$ in $I=1$ possible, even for $\sigma = 0$ [Falk, Z.L., 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

$B_s \to D_s^\pm K^\mp$ 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)

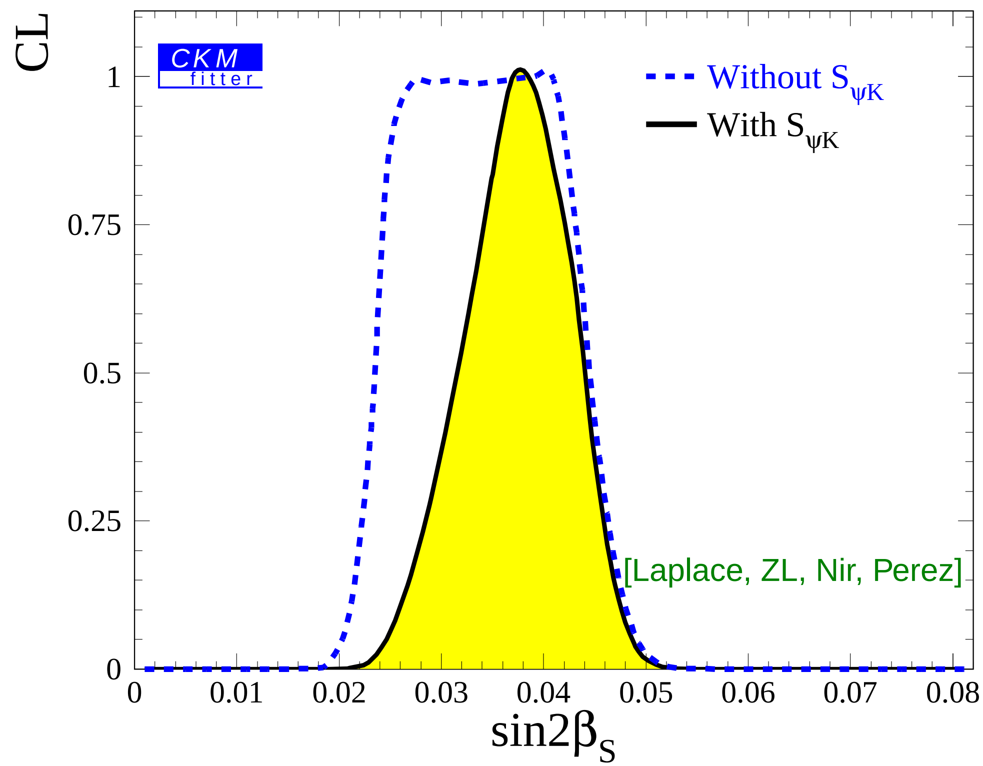
$B_s \to \psi\phi$ and $B_s \to \psi\eta^{(\prime)}$

- 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

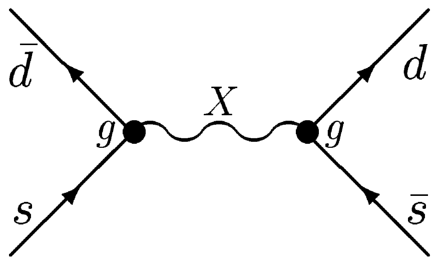


- Large asymmetry $(\sin 2\beta_s > 0.05)$ would be clear sign of new physics

Kaons and New Physics

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



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

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

- 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

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

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

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

  $K_{L(R)}^d$: 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: $|(K_{L,R}^d)_{12}| \ll 1$ (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

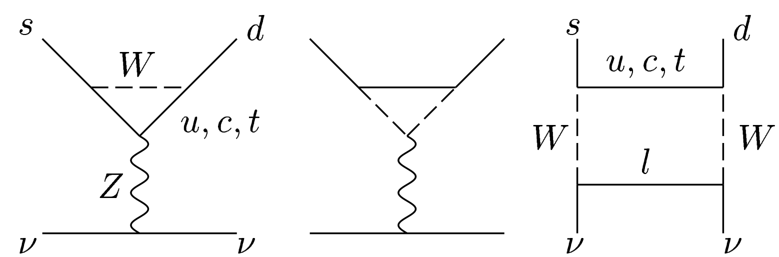
Precision tests with Kaons

- 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 $\mathcal{B} \sim 10^{-10}(K^\pm),\ 10^{-11}(K_L)$

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



By now 3 events observed: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ [BNL E949]

Need higher statistics to make definitive tests

Unitarity in the 1st row

- PDG: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1-(3.3 \pm 1.5) \times 10^{-3}$ $[(4.2 \pm 1.9)$ with PDG'02]

  Unitarity + $|V_{ud}| \Rightarrow |V_{us}^{(\mathrm{SM})}| = 0.2274 \pm 0.0021$; problem with $|V_{ud}|$, $|V_{us}|$, or the SM?

Experiments measure $|V_{us}|\, f_+(0)$

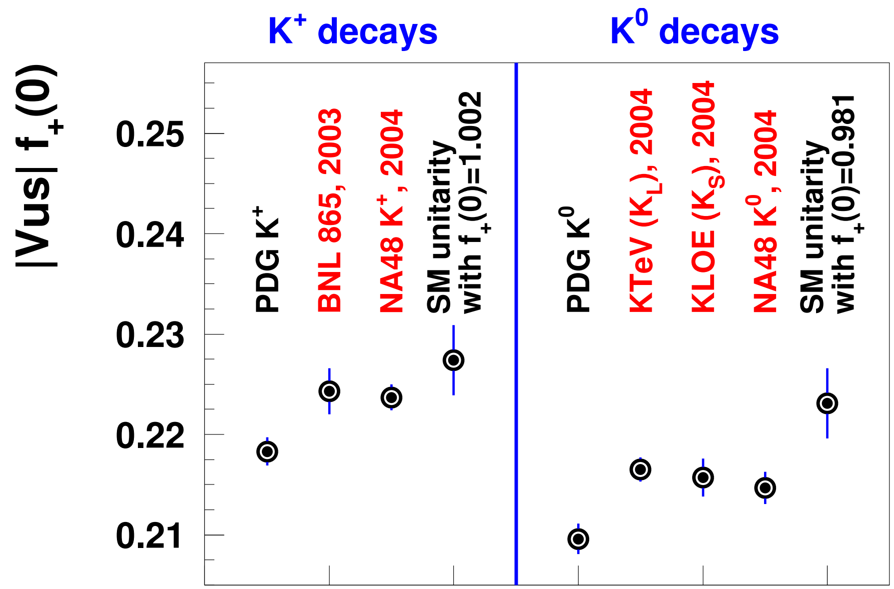
Need $f_+(0)$ from theory

$f_+(0,K^+) - f_+(0,K^0) =$ 1st order in $SU(2)$ breaking; $1 - f_+(0) =$ (almost) 2nd order in $SU(3)$

$$f_+(0,K^0) = \begin{cases} 0.961 \pm 0.008 & \text{Leutwyler \& Roos ('84)} \\ 0.981 \pm 0.010 & \text{Cirigliano, Neufeld, Pichl ('04)} \end{cases}$$

Understand hadronic physics well enough to reduce $(m_K/1\,\mathrm{GeV})^4 \sim 5\%$ to $\mathcal{O}(1\%)$?

New data: BNL, KTeV, KLOE, NA48



Unitarity in the first row of the CKM matrix may be on its way to be resolved

The D meson system

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

New search results reported at this conference [See Shipsey's talk this afternoon]

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

Nonleptonic decays

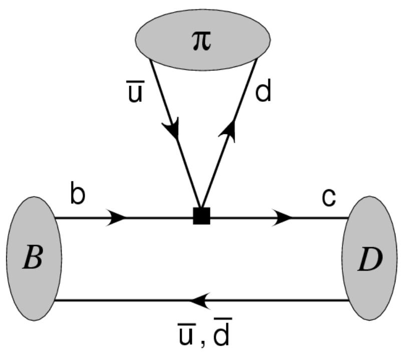
Predictions of SCET not foreseen in any model:

Color suppressed B- and isospin violating Λ_b decays

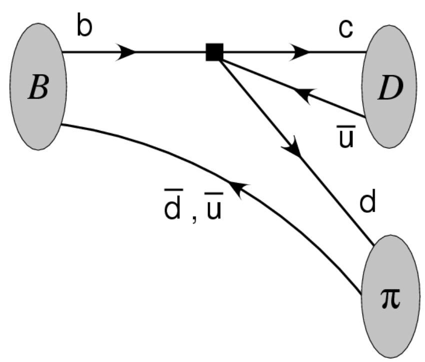
$B \to D^{(*)}\pi$ decay and SCET

- "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

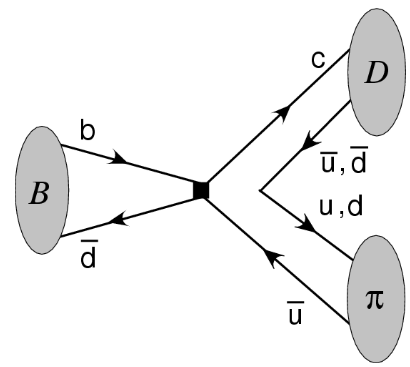
$\overline{B}^0 \to D^+\pi^-$
$B^- \to D^0\pi^-$



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



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



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

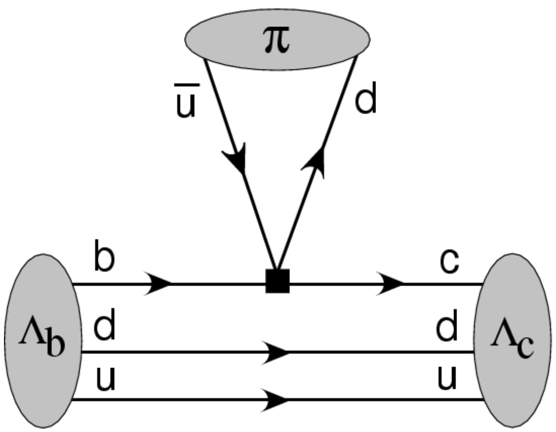
$$\frac{\mathcal{B}(\overline{B}^0 \to D^0\pi^0)}{\mathcal{B}(\overline{B}^0 \to D^{*0}\pi^0)} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\,,$$

data: $\sim 1.1 \pm 0.25$
Totally unexpected before SCET

[Mantry, Pirjol, Stewart]

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]

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

Isgur-Wise functions may be expected to be comparable

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

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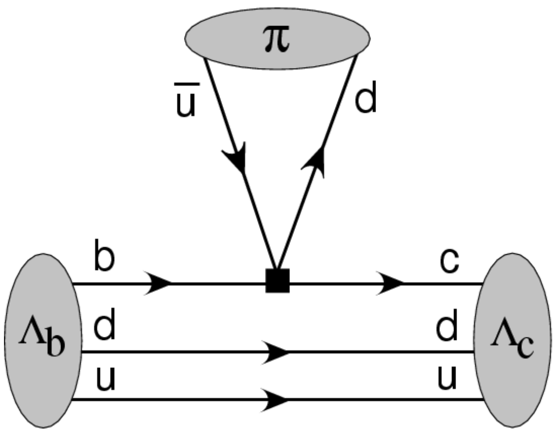

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Isgur-Wise functions may be expected to be comparable (Explain "≈ 2": one baryon vs. two meson ground states)

- 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: $\Lambda_b \to \Sigma_c \pi$

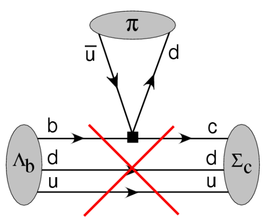
- Recall quantum numbers:

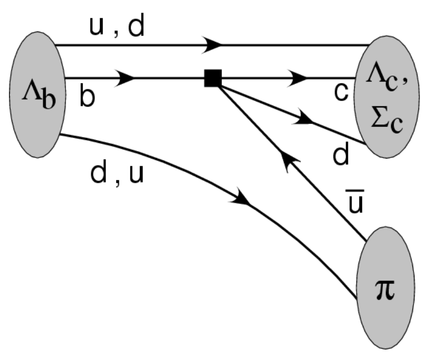
multiplets	s_l	$I(J^P)$
Λ_c	0	$0(\frac{1}{2}^+)$
$\Sigma_c,\ \Sigma_c^*$	1	$1(\frac{1}{2}^+),\ 1(\frac{3}{2}^+)$

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

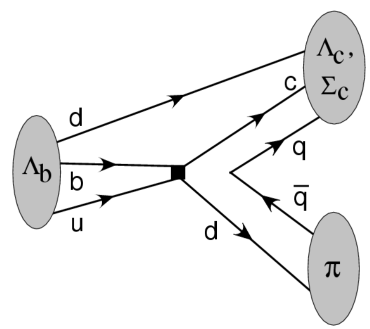
[Leibovich, Z.L., Stewart, Wise]

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





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



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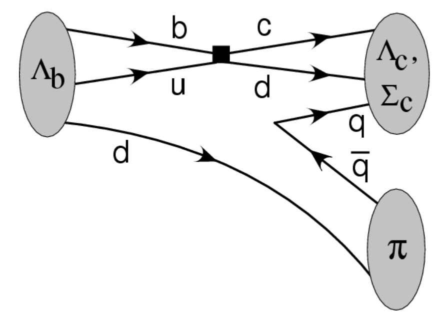

$\mathcal{O}(\Lambda_{\rm QCD}^2/Q^2)$

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

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

- Recall quantum numbers:

multiplets	s_l	$I(J^P)$
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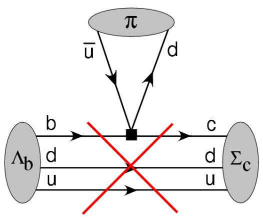
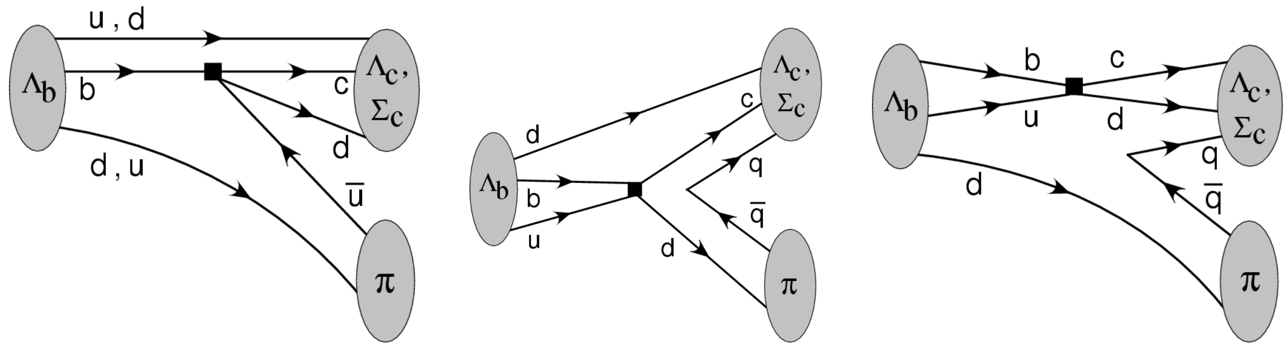


[Leibovich, Z.L., Stewart, Wise]



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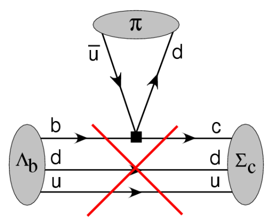
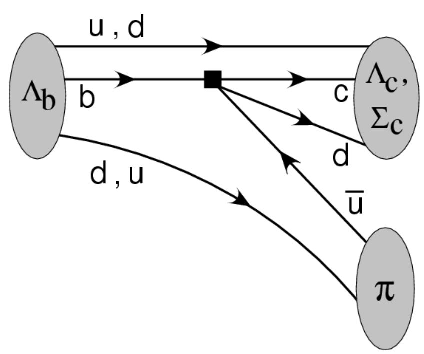


[Leibovich, Z.L., Stewart, Wise]



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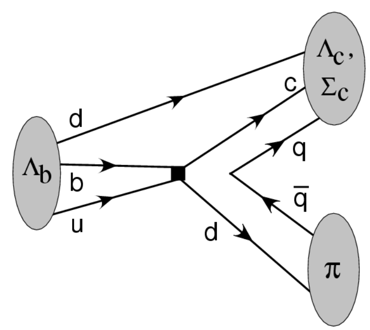

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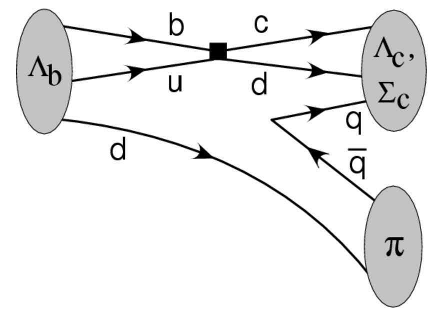

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Prediction: $$\frac{\Gamma(\Lambda_b \to \Sigma_c^* \pi)}{\Gamma(\Lambda_b \to \Sigma_c \pi)} = 2 + \mathcal{O}\big[\Lambda_{\rm QCD}/Q\,,\ \alpha_s(Q)\big] = \frac{\Gamma(\Lambda_b \to \Sigma_c^{*0} \rho^0)}{\Gamma(\Lambda_b \to \Sigma_c^0 \rho^0)}$$

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

More slides removed from talk

The big questions

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

  spontaneous breaking of gauge sym. — Higgs/NP at $1\,\text{TeV}$ (W scattering)

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

  The LHC will address this, directly exciting the new physics

- 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 — we don't know the scale

  How fermions see the condensate and NP associated with it? How do these interactions break the flavor symmetries? How fermions get their identities?

Related? Flavor depends on both: Yukawas determine masses, mixing, CPV

Baryon asymmetry $\Rightarrow$ CPV in SM not the full story; how precisely can we test it?

- Most new physics scenarios involve new flavor physics, but this is not guaranteed

What are we after?

- Only Yukawa couplings distinguish between generations; pattern of masses and mixings inherited from interaction with something unknown (couplings to Higgs)

- SM: all flavor-changing processes determined by only 4 parameters (1 CPV)

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

  NP: dozens of $\Delta F = 1,\, 2$ operators have a priori independent Wilson coefficients

  Does the SM explain all flavor changing interactions? Can we see deviations?

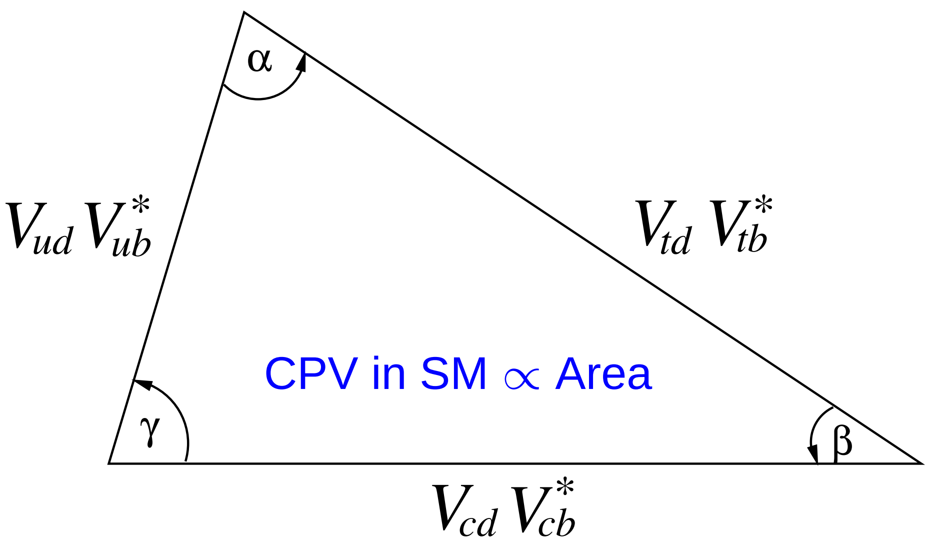
- Many NP scenarios involve new flavor physics, and may upset some predictions:
  - FCNC's at unexpected level; e.g.: enhanced B_s mixing or $B_{(s)} \to \ell^+\ell^-$
  - Subtle (or not so subtle) changes in correlations; e.g.: CP asymmetries not equal in $B \to \psi K_S$ and $B \to \phi K_S$
  - Enhanced or suppressed CP violation; e.g.: $B_s \to \psi\phi$

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



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

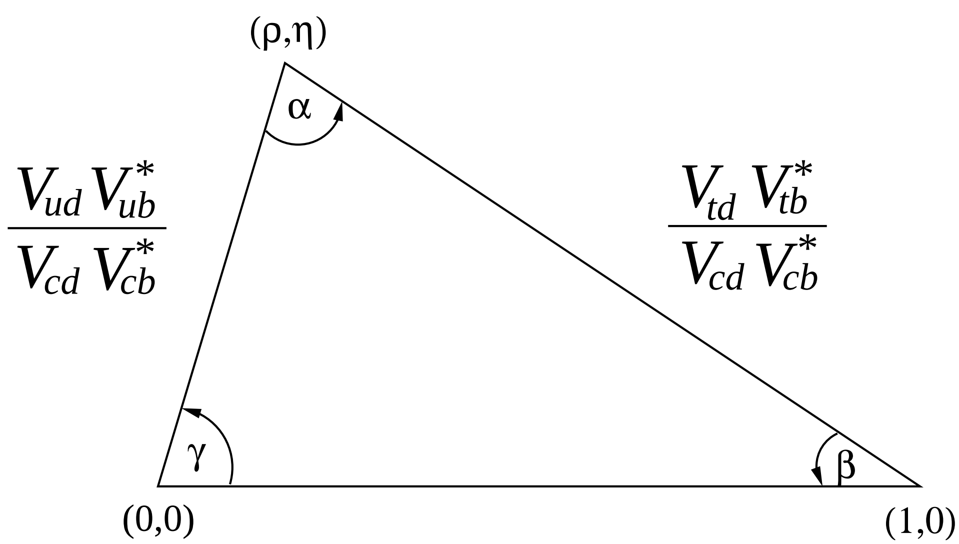
Angles & sides directly measurable

A convenient parametrization of CKM matrix

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

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

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



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

Goal of B physics: overconstrain CKM

- Dozens of “nonrenormalizable” operators, with a priori independent Wilson coeff’s

  Determine as many as possible; in the SM this is huge “redundancy” (the key!)

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

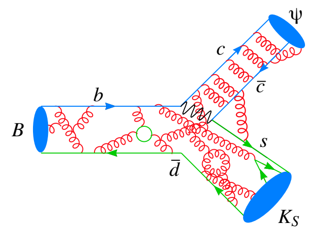
  Many measurements have clean theoretical interpretation:

  – top quark loops neither GIM nor CKM suppressed

  – large CP violating effects, some with small hadronic uncertainty

    Symmetries of QCD (exact or approximate)

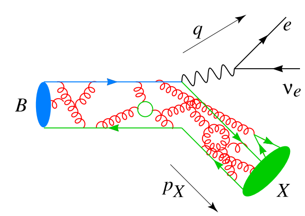
    E.g.: $\sin 2\beta$ because of CP



  – hadronic physics sometimes understood model independently ($m_b \gg \Lambda_{\rm QCD}$)

    Some processes short distance dominated

    E.g.: $|V_{cb}|$ and $|V_{ub}|$ from $B \to X\ell\bar\nu$



- Key processes: teach us about high energy physics w/o hadronic uncertainties

α from $B \to \pi\pi$

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

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

$S = \sin 2\alpha$ if amplitudes with one weak phase dominated (def: $\sin 2\alpha_{\rm eff} \equiv S_{\pi^+\pi^-}$)

Relied on naive expectation: penguin matrix element $\mathcal{O}(\alpha_s/4\pi)$ smaller than tree

$K\pi$ and $\pi\pi$ BR's imply two comparable amplitudes with different weak phases

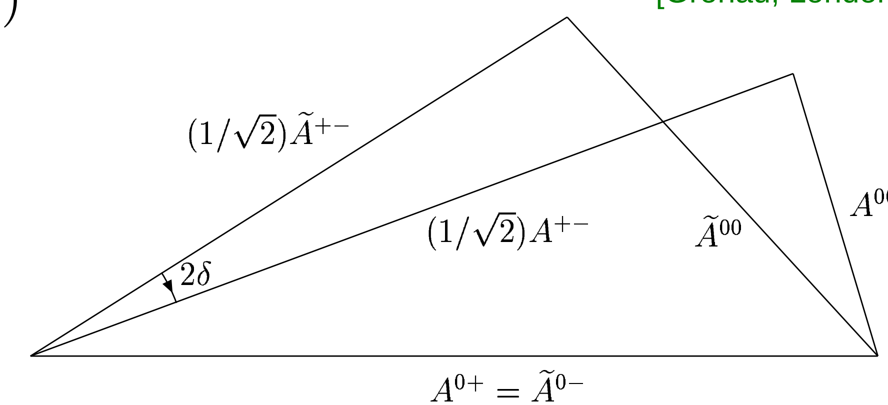
- Isospin analysis: Determine $2\delta \equiv 2(\alpha - \alpha_{\rm eff})$

[Gronau, London]

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

$$A_{ij} = T_{ij}e^{+i\gamma} + P_{ij}e^{-i\beta}$$
$$\widetilde{A}^{ij} \equiv e^{2i\gamma}\overline{A}^{ij} = T_{ij}e^{+i\gamma} + P_{ij}e^{+i(\beta+2\gamma)}$$

A_{ij} [$\overline{A}_{ij}$] denote B^+, B^0 [B^-, $\overline{B}^0$] decays



A (near future & personal) best buy list

- β: reduce error in $B \to \phi K_S$, $K^+K^-K_S$, $\eta' K_S$ (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 measure it by next ICHEP)
- Rare decays: $B \to X_s\gamma$ near theory limited; q^2 distribution in $B \to X_s\ell^+\ell^-$ will be very interesting
- $|V_{ub}|$: reaching $\lesssim 10\%$ will be very significant (a Babar/Belle measurement that may well survive LHCB/BTeV)
- 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!)