Lecture 2

New Physics in Rare B Decays

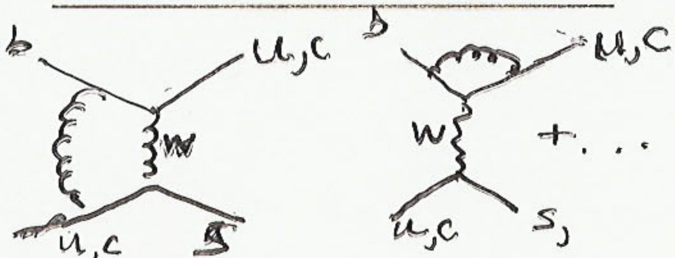
I. The Effective Hamiltonian
- examples of NP

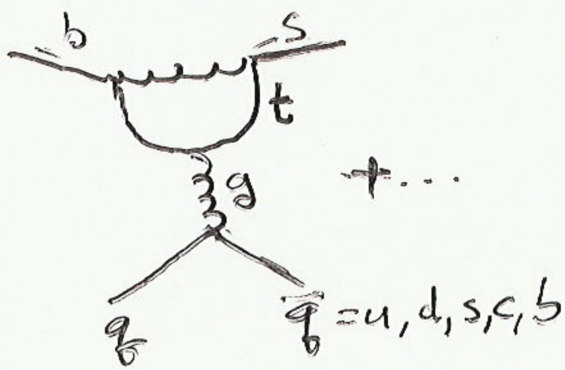
II. Radiative B decays

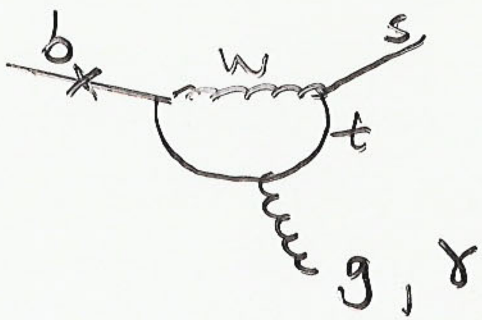
III. $B \to PP / VP / VV$ decays
- QCD factorization for $B \to VP$
- case study: Parity Inv NP
- Time-Dep CP asymmetries

SM Effective Hamiltonian for Rare Decays

Full Theory Diagrams







Current – Current Operators :

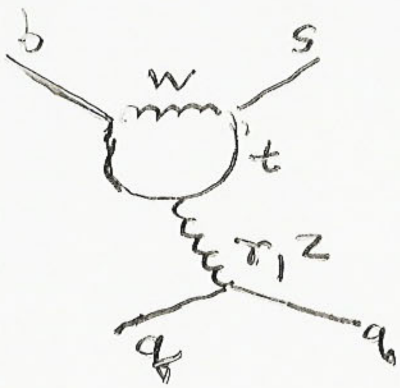
$$Q_1^p = (\bar{s}_i p_j)_{V-A}\,(\bar{p}_j b_i)_{V-A}\ ,\ p = u, c$$
$$Q_2^p = (\bar{s}_i p_i)_{V-A}\,(\bar{p}_j b_j)_{V-A}$$

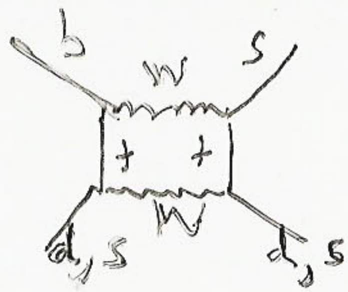
QCD Penguin Operators :

$$Q_3 = (\bar{s}_i b_i)_{V-A} \sum\nolimits_{q=u,..,b} (\bar{q}_j q_j)_{V-A}$$
$$Q_4 = (\bar{s}_i b_j)_{V-A} \sum\nolimits_{q} (\bar{q}_j q_i)_{V-A}$$
$$Q_5 = (\bar{s}_i b_i)_{V-A} \sum\nolimits_{q} (\bar{q}_j q_j)_{V+A}$$
$$Q_6 = (\bar{s}_i b_j)_{V-A} \sum\nolimits_{q} (\bar{q}_j q_i)_{V+A}$$

Chromo/Elecro – magnetic Penguin Ops

$$Q_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) b_i F_{\mu\nu}$$
$$Q_{8g} = \frac{g_s}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) T^a_{ij} b_j G^a_{\mu\nu}$$





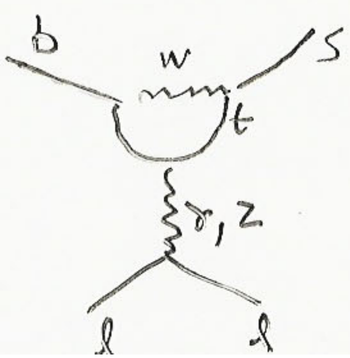
Electroweak Penguin Operators :

$$Q_7 = \frac{3}{2}(\bar{s}_i b_i)_{\mathrm{V-A}} \sum_q e_q (\bar{q}_j q_j)_{\mathrm{V+A}}$$

$$Q_8 = \frac{3}{2}(\bar{s}_i b_j)_{\mathrm{V-A}} \sum_q e_q (\bar{q}_j q_i)_{\mathrm{V+A}}$$

$$Q_9 = \frac{3}{2}(\bar{s}_i b_i)_{\mathrm{V-A}} \sum_q e_q (\bar{q}_j q_j)_{\mathrm{V-A}}$$

$$Q_{10} = \frac{3}{2}(\bar{s}_i b_j)_{\mathrm{V-A}} \sum_q e_q (\bar{q}_j q_i)_{\mathrm{V-A}}$$



SemileptonicOperators :

$$Q_{9\mathrm{V}} = (\bar{s}b)_{\mathrm{V-A}}(\bar{\ell}\ell)_{\mathrm{V}}$$

$$Q_{10\mathrm{A}} = (\bar{s}b)_{\mathrm{V-A}}(\bar{\ell}\ell)_{A}$$

$$Q_{11} = (\bar{s}b)_{\mathrm{V-A}}(\bar{\nu}\nu)_{\mathrm{V-A}}$$

New Physics Effective Hamiltonian for Rare Decays

Extensions of SM often require enlarged operator basis

- Opposite chirality operators ($V-A \leftrightarrow V+A$), e.g.,

$$Q_{3,5} = (\bar{s}b)_{V-A}\,(\bar{q}q)_{V\mp A} \quad \to \tilde{Q}_{3,5} = (\bar{s}b)_{V+A}\,(\bar{q}q)_{V\pm A}$$

$$Q_{4,6} = (\bar{s}_i b_j)_{V-A}\,(\bar{q}_j q_i)_{V\mp A} \quad \to \tilde{Q}_{4,6} = (\bar{s}_i b_j)_{V+A}\,(\bar{q}_j q_i)_{V\pm A}$$

$$Q_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) b_i F_{\mu\nu} \quad \to \tilde{Q}_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1-\gamma_5) b_i F_{\mu\nu}$$

$$Q_{8g} = \frac{g_s}{8\pi^2} m_b \bar{s} \sigma^{\mu\nu}(1+\gamma_5) T^a b G^a_{\mu\nu} \quad \to \tilde{Q}_{8g} = \bar{s}\sigma^{\mu\nu}(1-\gamma_5) T^a b G^a_{\mu\nu}$$

- Other Dirac structures, e.g.,

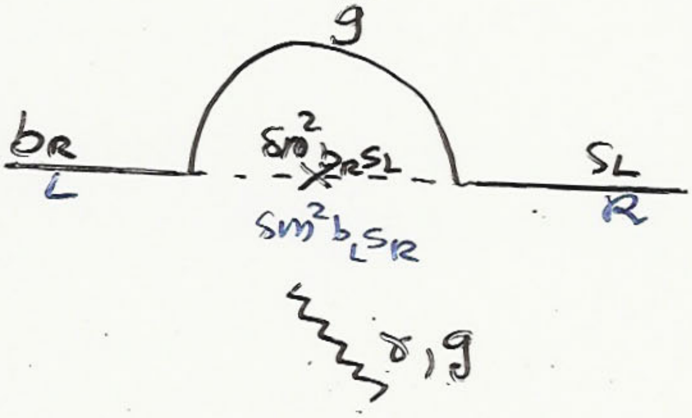
$(\bar{q}b)_{V-A}\,(\bar{q}s)_{V+A}$ fierz equivalent to $(\bar{s}b)_{S-P}\,(\bar{q}q)_{S+P}$

or tensor-tensor: $\sigma^{\mu\nu} \times \sigma_{\mu\nu}$

- U-spin violation: flavor structure $\bar{s}b\,(\bar{d}d - \bar{s}s)$

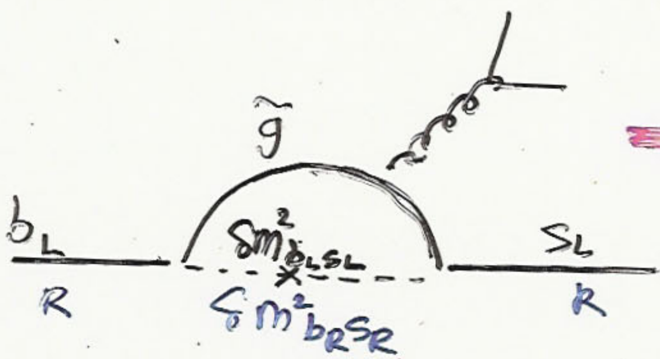
Examples of NP

a) SUSY: squark-gluino loops Mascero, Bertolini, Borzumati
+ many others

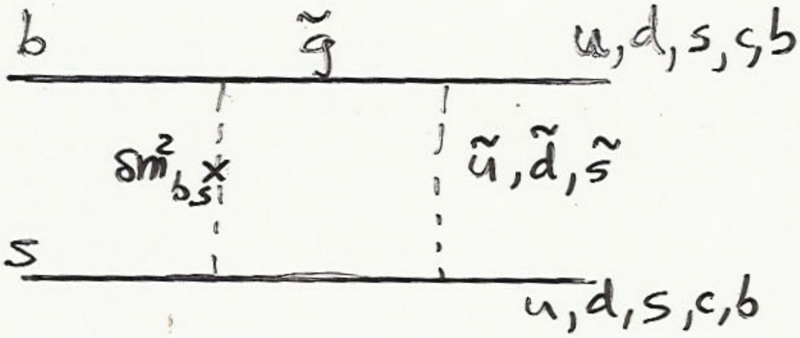


$\Rightarrow$ $Q_{7\gamma}$; $\tilde{Q}_{7\gamma}$

Q_{8g} ; $\tilde{Q}_{8g}$



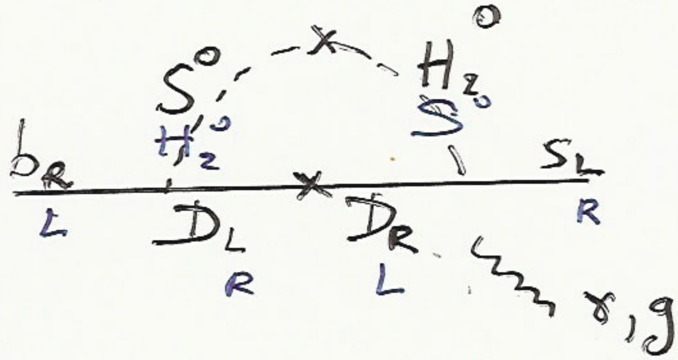
$\Rightarrow$ $Q_{3,..,6}$; $\tilde{Q}_{3,..,6}$



$\Rightarrow$ $Q_{3,..10}$ or $\tilde{Q}_{3,\dots,10}$

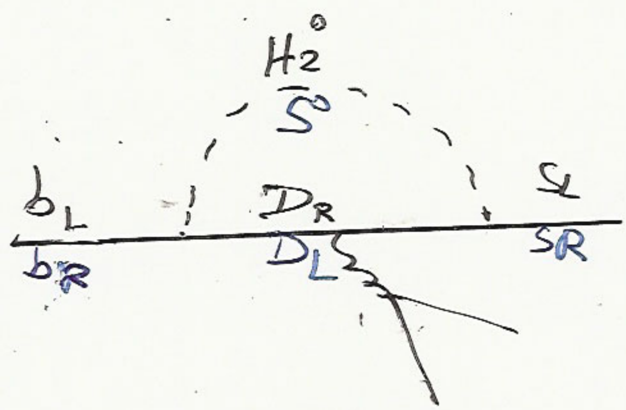
U spin violation also possible, i.e.
$b \to s d\bar{d} \neq b \to s s\bar{s}$
if $m^2_{\tilde{d}} \neq m^2_{\tilde{s}}$

b) loops containing new vectorlike quarks, scalars:



$\Rightarrow Q_{7\gamma}, Q_{8g}$

similarly, can obtain $\tilde{Q}_{7\gamma}, \tilde{Q}_{8g}$



$\Rightarrow Q_3, \ldots, Q_6$

$\Rightarrow \tilde{Q}_3, \ldots, \tilde{Q}_6$

+ box graphs $\Rightarrow$ possible U spin violation

c) Flavor changing Z couplings

eg) admixture of d quarks with vectorlike SU(2) singlet quarks $\chi_L, \bar{\chi}_R$

eg
$$|b_L\rangle = |d_L^3\rangle + \epsilon_L |\chi_L\rangle$$
$$|b_R\rangle \simeq |d_R^3\rangle + \epsilon_R |\chi_R\rangle$$

$$\Rightarrow \quad Z s_L b_L \propto \langle s_L | \sum_{i=1}^{3} |d_i^L\rangle\langle d_i^L| b_L\rangle$$
$$\propto -\langle s_L|\chi_L\rangle\langle\chi_L|b_L\rangle$$
$$\sim \epsilon_L^2 V_{cb} \text{ if } V_{cb} \text{ generated in down sector}$$

- Can easily saturated bound from $b \to s l^+ l^-$

- Large contributions to hadronic penguins $b \to s q\bar{q}$

$B \to X_s \gamma$ in the SM

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[\sum_{i=1}^{6} C_i(\mu_b) Q_i(\mu_b) + C_{7\gamma}(\mu_b) Q_{7\gamma}(\mu_b) + C_{8g}(\mu_b) Q_{8g} \right.$$

- To very good approximation in the SM can just keep $Q_2, Q_{7\gamma}, Q_{8g}$

- Branching Ratio Structure in Parton Model:

Traditional approach - normalize wrt semileptonic BR

For $E_\gamma > (1-\delta) E_\gamma^{max}$ (in parton model $E_\gamma^{max} = m_b/2$) defi

$$R_{th}(\delta) = \frac{\Gamma(B \to X_s \gamma)\big|_{E_\gamma > (1-\delta) E_\gamma^{max}}}{\Gamma(B \to X_c e \bar{\nu})} = \frac{6\alpha}{\pi f(z)} \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 K_{NLO}(\delta$$

- $f(z)$ is semileptonic phase space factor, $z = (m_c/m_b)$

- normalization wrt semileptonic rate removes strong m_b dependence

$$Br(B \to X_s \gamma)\big|_{E_\gamma > (1-\delta) E_\gamma^{max}} = .105 N_{SL} R_{th}(\delta)$$

where $N_{SL} = Br(B \to X_c e \bar{\nu}) / 10.5\%$

- take $\delta = .9$ for definition of fully inclusive branching ratio (avoids singularity in soft photon limit from certain bremsstrahlung contributions)
- For realistic choice of photon low-energy cutoff, e.g., $\delta \approx .25$ ($E_\gamma \gtrsim 2$ GeV) have to understand photon spectum to obtain theoretical branching ratio
- $K_{\rm NLO}(\delta) = |C_7|^2 + ...$ contains corrections to LO result, to first order in α_s, $1/m_b^2$, $1/m_c^2$, and α/α_s :

$$K_{\rm NLO}(\delta) = \sum_{\substack{i,j=2,7,8 \\ i\leq j}} k_{ij}(\delta,\mu_b)\, \mathrm{Re}\left[C_i^{(0)}(\mu_b)\, C_j^{(0)*}(\mu_b)\right] + S(\delta)\,\frac{\alpha_s(\mu_b)}{2\pi}\, \mathrm{Re}\left[C_7^{(1)}(\mu_b)\, C_7^{(0)*}(\mu_b)\right] + S(\delta)\,\frac{\alpha}{\alpha_s(\mu_b)}\left(2\,\mathrm{Re}\left[C_7^{(\rm em)}(\mu_b)\, C_7^{(0)*}(\mu_b)\right] - k_{\rm SL}^{(\rm em)}(\mu_b)\,|C_7^{(0)}(\mu_b)|^2\right)$$

Re[ ] since CP averaging

- Large theoretical uncertainty from definitions of m_c, m_b in $z = m_c^2/m_b^2$. z appears in two places:
  - phase space factor $f(z)$ in $\Gamma(B \to X_c\, e\, \bar{\nu})$. here sensible to use pole masses, $z = .29 \pm .02$,
  - two-loop matrix element $\langle Q_2 \rangle$. Recently suggested that since charm quark in loop far off-shell over large region of loop integration, here more appropriate to use running $\overline{MS}$ charm mass $m_c(\mu)$, $z = .22 \pm .04 \Rightarrow$ $+10\%$ shift in rate

Gambino +Misiak

$$\mathrm{Br}^{\mathrm{SM}}(B \to X_s \gamma)_{\delta=.9} = (3.64 \pm .33) \times 10^{-4}$$

- Ambiguity in mass definition can only be resolved with a NNLO calculation

Modified treatment of $b \to s\gamma$

Bruis, Becher, Neubert, AK

- In the $b \to s\gamma$ decay rate, replace m_b^{pole} with the 'Upsilon mass' m_b^{1S}

Hoang, Ligeti, Manohar

up to a small non-pert correction $m_b^{1S} = m_\Upsilon/2$.

m_b^{1S} is very well determined, $m_b^{1S} = 4.72 \pm .06$ GeV

Hoang; Neubert + Becher

$$m_b^{pole} = m_b^{1S} + \underbrace{\frac{2 m_b^{1S} \alpha_s(\mu)^2}{9}}_{\text{absorbed in NLO}} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} (\quad) + \ldots \right\}$$

absorbed in NLO correction to the rate in K_{NLO}

- Since m_b^{1S} so well known we do not normalize wrt semileptonic rate:

$$BR(B \to X_s\gamma)\Big|_{E_\gamma > E_{\gamma min}} = \frac{\tau_B G^2}{32\pi^4} \alpha (m_b^{1S})^3 m_b^2(m_b) |V_{ts}^* V_{tb}|^2 K_{NLO}(\delta)$$

now charm quark mass only appears in $b \to c\bar{c}s$ charm loop

- Like Gambino + Misiak, use running charm mass $m_c(\mu)$ – but also use the running b mass $m_b(\mu)$ in the $b \to c\bar{c}s$ matrix element

$\Rightarrow$ work with scale invariant mass ratio $\sqrt{z} = m_c(\mu)/m_b(\mu)$

$m_c(m_c) = 1.25 \pm .10$, $m_b(m_b) = 4.2 \pm .05$ GeV

- In SM obtain for $E_\gamma > 2$ GeV

$$10^4 \, BR(B \to X_s \gamma)^{\text{THEORY}}_{E_\gamma > 2 \text{ GeV}} = 3.36 \,{}^{+.26}_{-.29} \times \left(\frac{V_{tb}V_{ts}^*}{.04}\right)$$

PRELIMINARY $= 3.36 \,{}^{+.42}_{-.45}$ for $\delta V_{tb}V_{ts}^* = .0$

Compare to experiment

$$\text{CLEO} \quad BR_{E_\gamma > 2 \text{ GeV}} = (3.06 \pm .41 \pm .26) \times 10^{-4}$$

$$\text{BABAR} \quad BR_{E_\gamma > 2.1 \text{ GeV}} = (3.55 \pm .32 \pm .32) \times 10^{-4}$$

- Used shape function to implement E_γ cut. $\bar{\Lambda}$ is fixed in Υ^{1S} scheme, $\bar{\Lambda} = .51 \pm .06$. Took $\lambda_1 = .32 \pm .10$

Constraints on New Physics

Criterion for determining which models are or are not tightly constrained:

note $C_7(\mu_b) \approx -.31 + .67\, C_7^{NP}(M_W) + .09\, C_8^{NP}(M_W)$

Define $\chi = \dfrac{C_7^{NP}(M_W)}{Q_d\, C_8(M_W)^{NP}}$ $\qquad (Q_d = -\frac{1}{3})$

Then $C_7(\mu_b) \approx -.31 + C_8^{NP}(M_W)\left[.67\, Q_d \chi + .09\right]$

- so small +ve χ allows large C_8^{NP} and to a lesser extent, small −ve χ

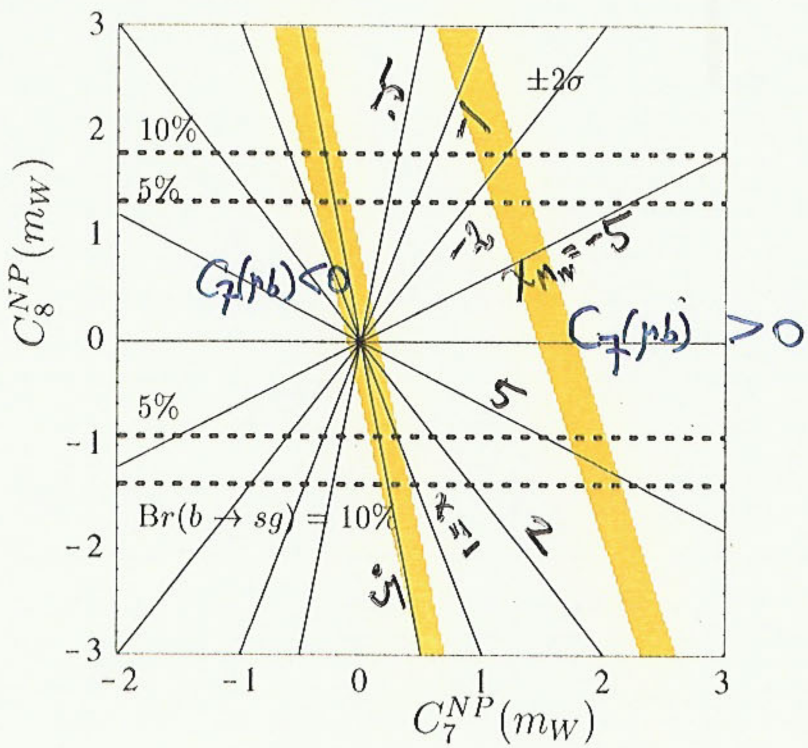
Since largest contributions to Br involve $C_7(\mu_b)$

- So for smaller $|\chi|$ can probe larger region of C_7^{NP} - C_8^{NP} plane

- χ is real for individual graphs which contribute to both C_7, C_8

A) C_7^{NP}, C_8^{NP} Real - No CP Violation

$\tilde{C}_7 = \tilde{C}_8 = 0$



For $E_\gamma \geq 2$ geV

- $Br(b \to sg) < 6.8\%$ CLEO (90% CL)

Low χ	$\chi(M_{NP})$	High χ	$\chi(M_{NP})$
neutral scalar–vector quark	1	Scalar diquark/top	$5-8$
gluino/squark, $m_{\tilde g} < 1.37\, m_{\tilde q}$	$-(.15-1)$	gluino/squark, $m_{\tilde g} > 1.37\, m_{\tilde q}$	$-(1-3)$
techniscalar	$\approx -.5$	charged Higgs/top	$-(2.4-21)$
		left-right W/top	≈ -6.7
		Higgsino/stop	$\approx -(2.$ [illegible] $-21)$

1) Have allowed masses of particles in loop in range ~ 200 GeV – 2.5 TeV

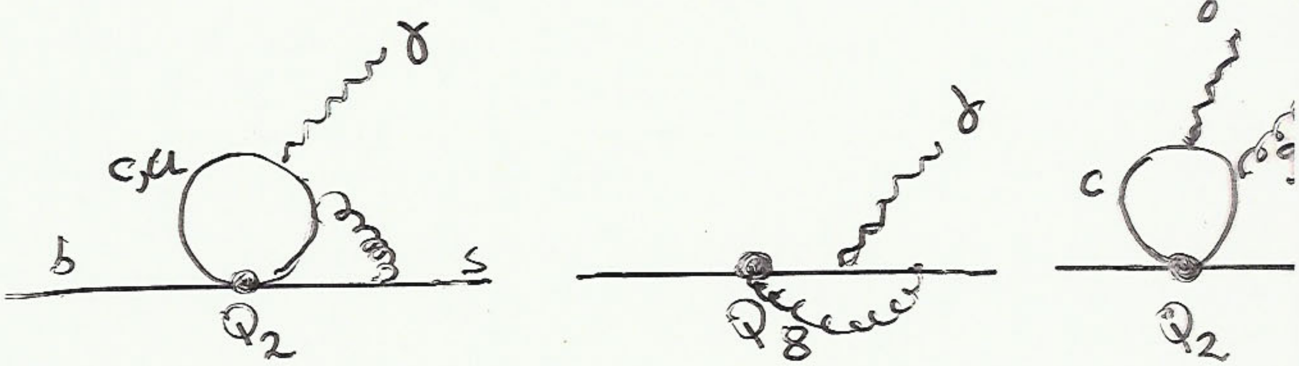
2) Kept the contributions due to internal chirality flip – generally dominate

Direct CP Violation in $B \to X_s \gamma$:

weak phases: CKM in $V_{ub} V_{us}^*$,

possible NP phases in $C_7, C_8 \ldots$

strong phases: are calculable perturbatively



$\Longrightarrow A_{CP} \propto \alpha_s(\mu_b)$

$$A_{CP}(\delta) = \left. \frac{\Gamma(\bar{B} \to X_{\bar{s}} \gamma) - \Gamma(B \to X_s \gamma)}{\Gamma(\bar{B} \to X_s \gamma) + \Gamma(B \to X_s \gamma)} \right|_{E_\gamma > (1-\delta) E_\gamma^{max}}$$

In SM have 3-fold suppression:

CKM, $\underset{(m_c^2/m_b^2)}{GIM}$, $\alpha_s \Longrightarrow A_{CP} \lesssim 1\%$

- so will neglect up loop CKM suppressed contributions in NP discussion

$X(M_W) = -.6$, g, $m_{\tilde g} = 300$, $m_{\tilde q} = 1\,\text{TeV}$ for LR insertion loop

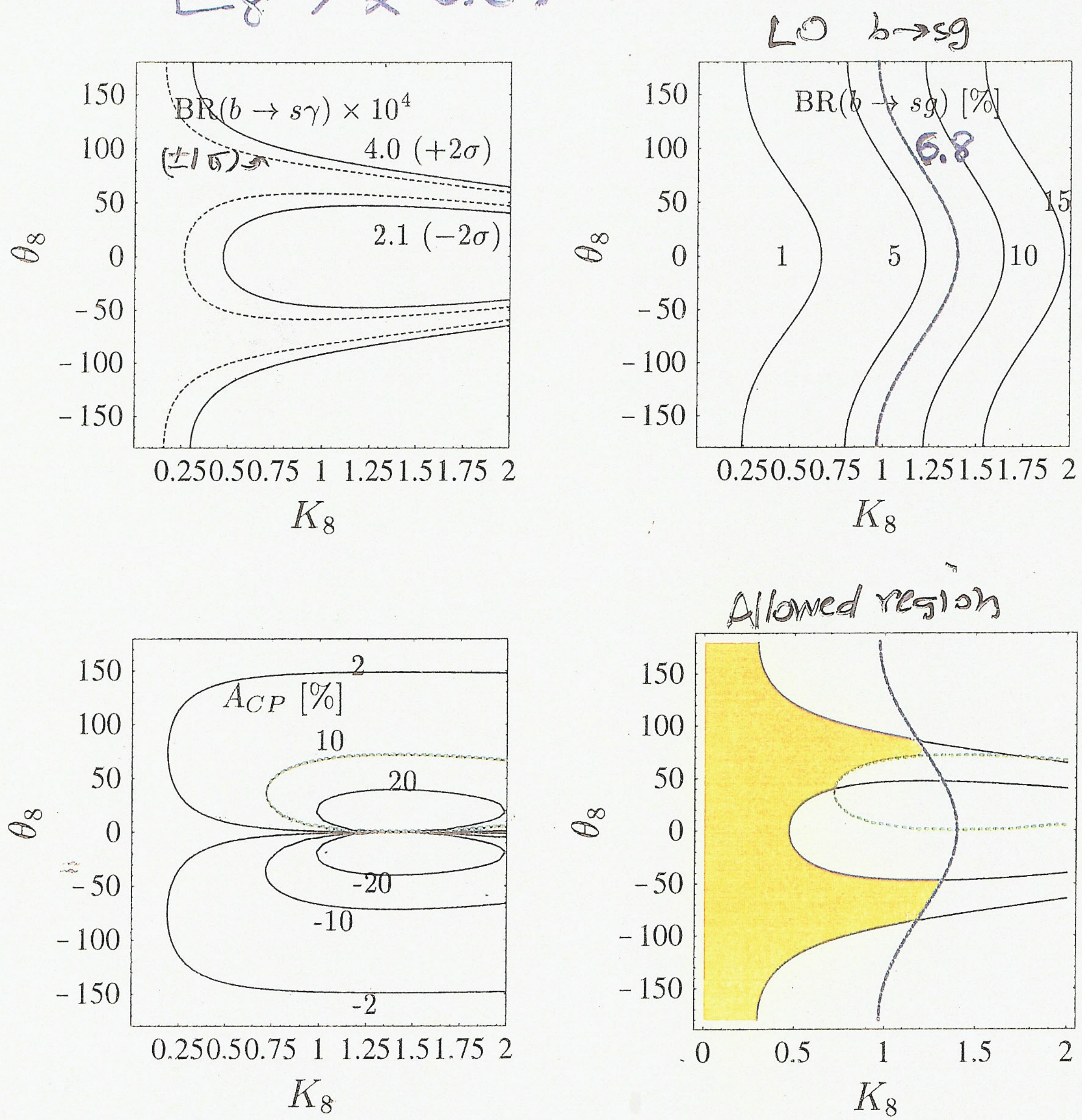
(in old approach – normalize wrt B_{SL})

$E_\gamma > 2$ GeV

$BR(b \to sg)^{CLEO} < 6.8\ \%$ [90% cl]

$$C_8(M_W) = K_8 e^{i\theta_8}$$

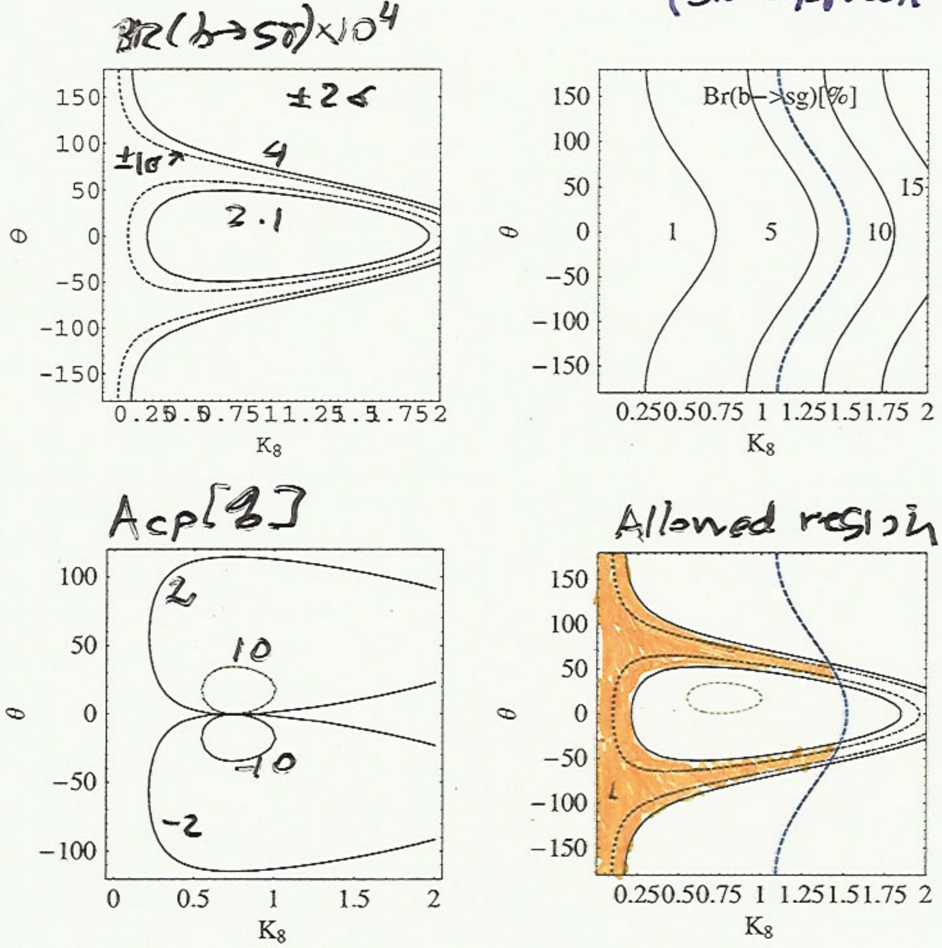
- - - - CLEO ACP bound



CLEO [90% cl] $-27\% < A_{CP} < 10\%$

$\chi(M_W) = -1.5$, eg $m_{\tilde{g}} = 1$ TeV, $m_{\tilde{q}} = 500$ GeV
for LR insertion loop

(old approach – normalize wrt Br_s



Isospin Violation in $B \to K^*\gamma$

$$10^5\,\mathrm{Br}(\bar{B}^0 \to \bar{K}^{*0}\gamma) = \begin{cases} 4.55\,^{+0.72}_{-0.68} \pm 0.34 & \text{CLEO} \\ \cancel{4.96 \pm 0.67 \pm 0.45} & \text{Belle}\quad 4.08\,^{+3.5}_{-3.3} \pm 2.6 \\ 4.23 \pm 0.40 \pm 0.22 & \text{BaBar} \\ \cancel{4.44 \pm 0.35} & \text{Average}\quad 4.21 \pm .29 \end{cases}$$

$$10^5\,\mathrm{Br}(B^- \to \bar{K}^{*-}\gamma) = \begin{cases} 3.76\,^{+0.89}_{-0.83} \pm 0.28 & \text{CLEO} \\ \cancel{3.89 \pm 0.93 \pm 0.41} & \text{Belle}\quad 4.92\,^{+5.9}_{-5.4}\,^{+3.8}_{-3.7} \\ 3.83 \pm 0.62 \pm 0.22 & \text{BaBar} \\ \cancel{3.82 \pm 0.47} & \text{Average}\quad 4.21 \pm .42 \end{cases}$$

Isospin Violation

$$\Delta_{0-} \equiv \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to \bar{K}^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to \bar{K}^{*-}\gamma)} = \cancel{0.11 \pm 0.07}\,.$$

$.03 \pm .05$

- Small effect from $\Gamma(B^0) \neq \Gamma(B^-)$ included.
  ($\Rightarrow$ Br$(\bar{B}^0 \to \bar{K}^{*0}\gamma) \approx .94\,Br(B^- \to \bar{K}^{*-}\gamma)$)
- No significant variation from zero
- However, the data raises the question: Can the Standard Model account for isospin breaking effects of order 10%?

Will adress this question in the framework of QCD factorization

$B \to K^*\gamma$ in QCD Factorization

Buchalla, Bosch; Beneke, Feldmann, Seidel

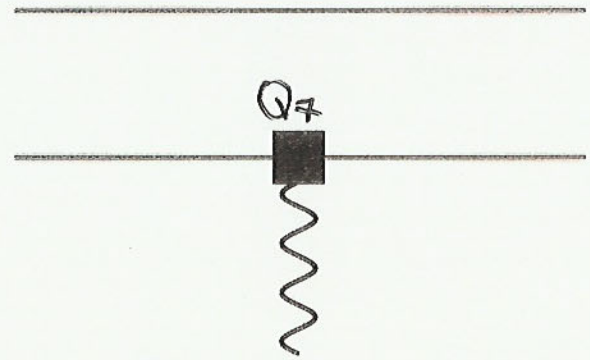
- Systematic analysis possible in heavy quark limit $m_b >> \Lambda_{QCD}$. Can factorize long-distance / short-distance physics.
- QCD factorization formula for $B \to V\gamma$, Leading Order in expansion in Λ_{QCD}/m_b

$$\langle V\gamma(\epsilon)|Q_i|\bar{B}\rangle = \left[F^{B\to V}(0)\, T_i^I + \int_0^1 d\xi\, dv\, \underbrace{T_i^{II}(\xi, v)\, \Phi_B(\xi)\, \Phi_V(v)}_{\text{hard spectator interactions}}\right] \cdot$$

  - $F^{B\to V}$ is a $B \to V$ transition form factor
  - $\Phi_B(\xi), \Phi_V(v)$ are light-cone distribution amplitudes
  - T_i^I, T_i^{II} are perturbative hard scattering kernels

Contributions of T_i^I - no hard spectator interactions

At leading order (LO) in α_s:

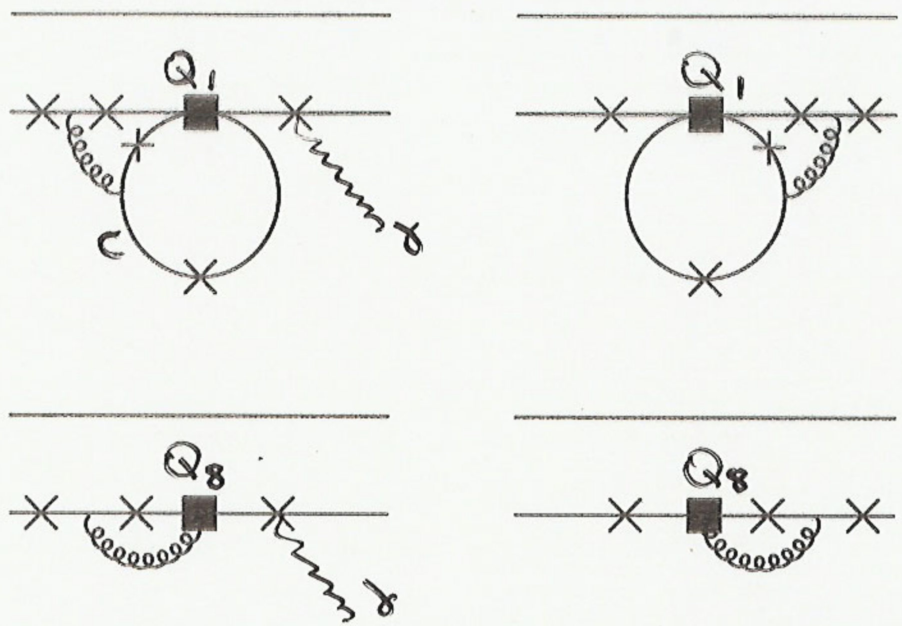


k, q : momenta
η, ε : polarizn vectors

$$\langle K^*(k,\eta)\gamma(q,\epsilon)|Q_7|\bar{B}\rangle = -\frac{e}{2\pi^2} m_b F_{K^*}\left[\varepsilon^{\mu\nu\lambda\rho}\epsilon_\mu\eta_\nu k_\lambda q_\rho + i(\epsilon\cdot\eta\, k\cdot q - \epsilon\cdot k\eta\cdot q)\right]$$

- F_{K^*} is the tensor form factor evaluated at $q^2 = 0$. (Includes effect of gluon exchanges between the quark lines)

Next-to leading order (NLO) in α_s

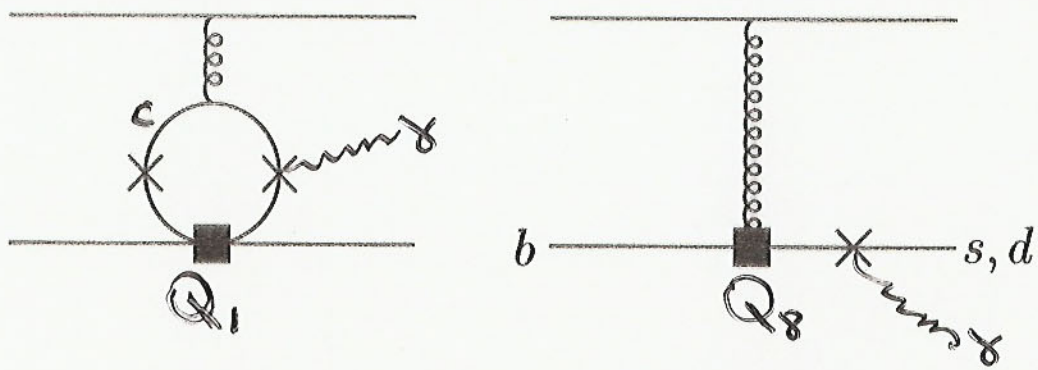


$$\langle Q_{1,8} \rangle^{I} = \langle Q_7 \rangle \frac{\alpha_s}{4\pi} G_{1,8}$$

- $G_{1,8}$ originate from one-loop short distance physics
- Dominated by hard scales $\sim m_b \Rightarrow$ IR finite
- Already calculated in the context of $B \to X_s \gamma$ decays

Greub, Hurth, Wyler; Buras, Czarnecki, Misiak, Urban

NLO Contributions of T_i^{II} - Hard Spectator Interactions



$$\langle Q_{1,8}\rangle^{II} = \langle Q_7\rangle \frac{\alpha_s(\mu_h)}{4\pi} H_{1,8}$$

- $\mu_h \sim \sqrt{\Lambda_{QCD} m_b}$ is scale of gluon momentum transfer
- $H_{1,8}$ are convolutions of the hard scattering kernels with the B, K^* light cone distribution amplitudes $\Phi_{B1}(\xi)$, $\Phi_\perp(v)$

e.g., $H_8 = \frac{4\pi^2}{3N} \frac{f_B f_{K^*}^\perp}{F_{K^*} m_B^2} \int_0^1 d\xi \frac{\Phi_{B1}(\xi)}{\xi} \int_0^1 dv \frac{\Phi_\perp(v)}{v}$

f_B, $f_{K^*}^\perp$ are meson decay constants

The Sum of Leading Power Contributions - Standard Model

$$A(\bar{B} \to K^*\gamma)_{\text{lead}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \, a_7 \, \langle K^*\gamma | Q_7 | \bar{B} \rangle$$

- At NLO in α_s

$$\begin{aligned} a_7 = C_7 \quad & + \frac{\alpha_s(\mu) C_F}{4\pi} \left(C_1(\mu) G_1(s_p) + C_8(\mu) G_8 \right) \\ & + \frac{\alpha_s(\mu_h) C_F}{4\pi} \left(C_1(\mu_h) H_1(s_p) + C_8(\mu_h) H_8 \right) \end{aligned}$$

- For central values of parameters, and $\mu \approx m_b$

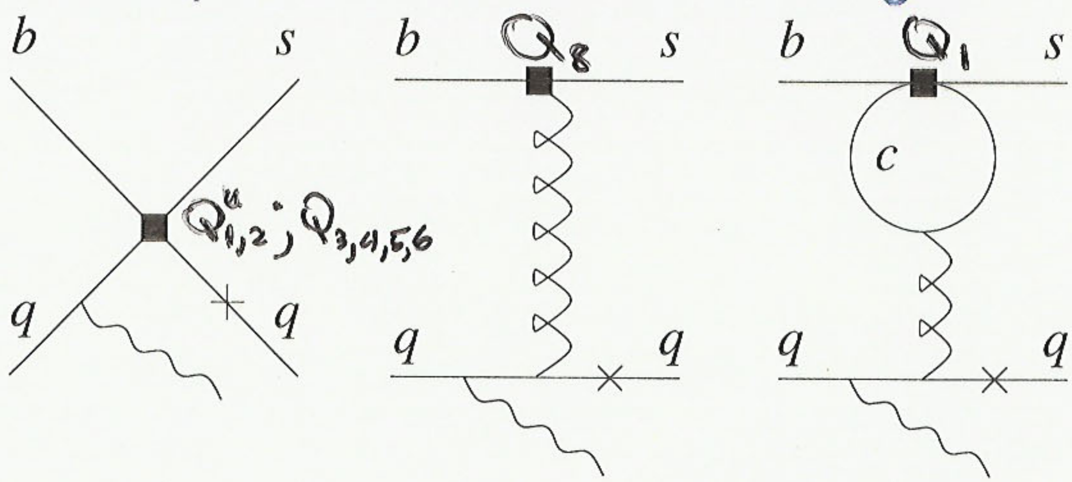
$$\begin{aligned} a_7 \quad & = -.31 - .082 - .015i - .02 - .015i \\ & = -.41 - .03i \end{aligned}$$

- NLO corrections are important, as in $B \to X_s \gamma$ decays
- Br$(\bar{B} \to K^*\gamma)^{Exp}$ reproduced if $F_{K^*} \approx .27 \pm .04$ -Beneke et al
- QCD sum rules give $F_{K^*} \approx .38 \pm .06$ -Ball, Braun
- Rate uncertainty from other inputs $\sim 10 - 15\%$

Isospin Violation in QCD Factorization - Standard Model

A.K. and M. Neubert

- Due to annihilation, exchange graphs with photon radiated off of spectators of different charge



- Subleading $\mathcal{O}(\Lambda_{QCD}/m_b)$ effects, but the dominant contributions are calculable, factorizable
- Parametrize isospin breaking contributions as $A_q = b_q A_{\text{lead}}$, $q = u$ for B^-, $q = d$ for $\bar{B}^0$.

$$\Rightarrow \quad \Delta_{0-} = \text{Re}(b_d - b_u)$$

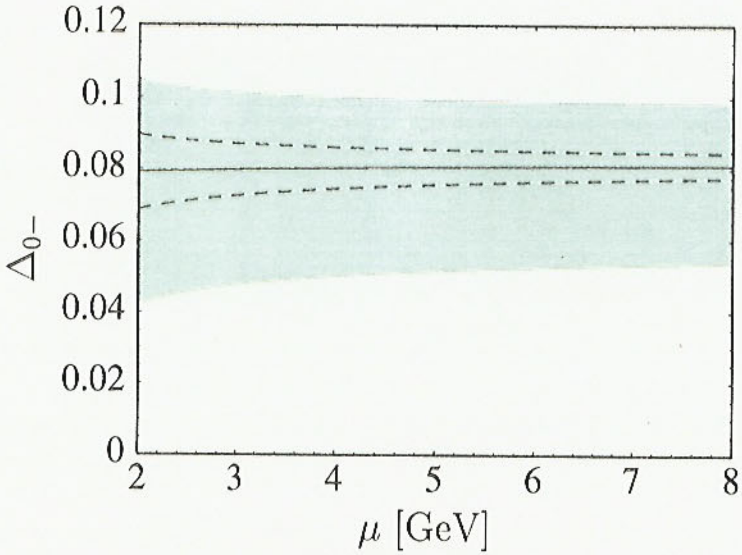
- The most important source of isospin breaking is due to the penguin operator Q_6. Its contribution is $\approx +9\%$ to Δ_{0-}
- Remaining terms much smaller. Contribution of Q_8, for which factorization does not hold, is $\lesssim 1\%$
- Therefore, isospin breaking mainly tests the magnitude and sign of the ratio $\mathrm{Re}\frac{C_6}{C_7}$

$$\mathrm{sign}\,[\Delta_{0-}] = \mathrm{sign}\left[\mathrm{Re}\frac{C_6}{C_7}\right]$$

- Complementary to forward-backward asymmetry in $B \to K^* \ell^+ \ell^-$, probes relative signs, magnitudes of C_7 and electroweak penguin coefficient C_9

Isospin Breaking: Numerical Results

Predictions for Δ_{0-} as a function of renormalization scale μ, assuming $F_{K^*} = .3$. Dark lines refer to variation in estimate of residual NLO contributions. The band shows the theoretical uncertainty



- Combining uncertainties $\Rightarrow \Delta_{01} = (8.0^{+2.1}_{-3.2})\% \times \frac{.3}{F_{K^*}}$
- The largest uncertainties: λ_B ($^{+1.0}_{-2.5}\%$), the divergent integral $X_\perp$ ($\pm 1.2\%$), the decay constant f_B ($\pm 0.8\%$) $\left(\int d\xi \frac{\phi_{B1}(\xi)}{\xi} = \frac{m_B}{\lambda_B} \right)$
- The sign of Δ_{0-} predicted unambiguously

Isospin Breaking: New Physics

- With more precise data, models in which $\mathrm{sign}\Delta_{0-}$ is flipped could be ruled out
- tightly constrain models in which Δ_{0-} can be greatly enhanced, e.g., the operators $\bar{s}\sigma_{\mu\nu}(1 \pm \gamma_5)q\bar{q}\sigma^{\mu\nu}(1 \pm \gamma_5)b$ contribute to Δ_{0-} at leading power
- For simplicity, consider models in which SM operator basis not enlarged and penguin coefficients $C_{3,..,6}$ do not receive large contributions.

$\Rightarrow$ Isospin breaking probes the sign of $\mathrm{Re}C_7(m_b)$.

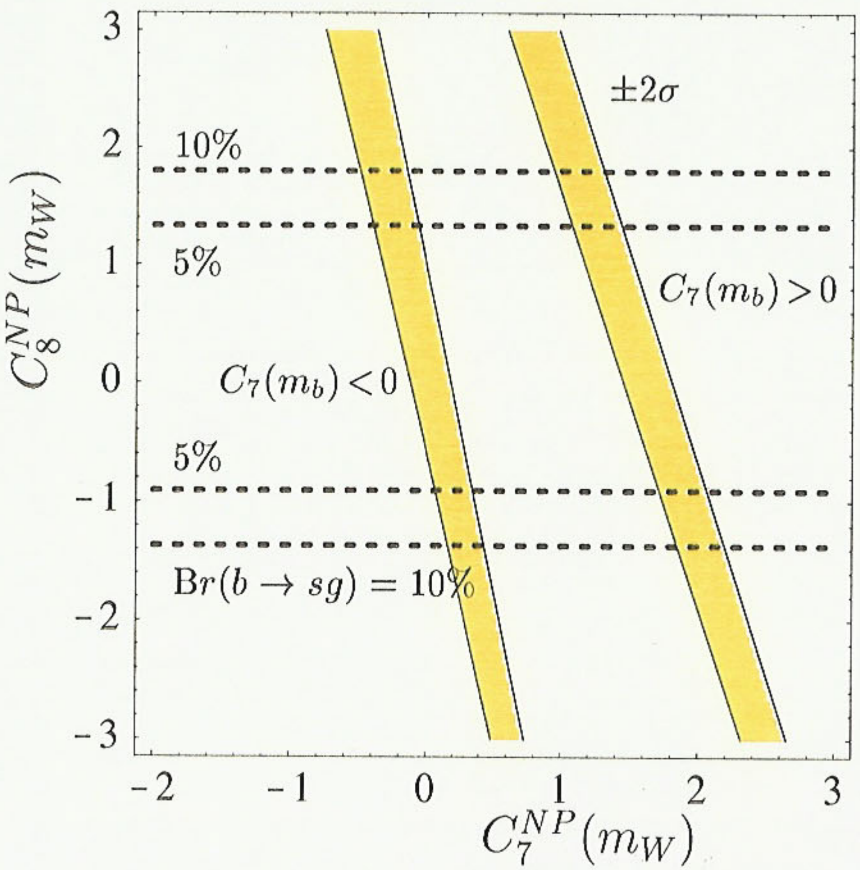
Update on $B \to X_s\gamma$ Constraints

$$A(b \to s\gamma) = -\frac{4G_F\lambda_t}{\sqrt{2}}\,\hat{D}\,\langle s\gamma|O_7(\mu)|b\rangle_{tree} + \text{gluon bremsstrahlung}$$

$$\hat{D} = C_7^{eff}(\mu) + \frac{\alpha_s(\mu)}{4\pi}\sum_{i=2,7,8} C_i^{(0)eff}(\mu)G_i(\mu) \approx a_7\,(K^*\gamma)$$

NLO constraints on $C_7^{NP}(m_W)$, $C_8^{NP}(m_W)$ from $\text{Br}(B \to X_s\gamma)$

(for simplicity, consider Real C_7, C_8)



$\Delta_{0-} > 0 \Rightarrow$
rule out $\hat{D}$, a_7, $C_7 > 0$ band

except if C_6 flips sign,
or at very large C_8 (due to increased theoretical uncertainty)

Example: MSSM with Minimal Flavor Violation

- Enhanced contributions to $C_7(m_b)$, Br($B \to X_s\gamma$) in large $\tan\beta$ limit due to chargino-stop loops. Degrassi, Gambino, Giudice; Carena, Garcia, Nierste, Wagner

- New contributions to $Q_{3,..,6}$ and Q_8 are too small to have a significant effect

- At large $\tan\beta$, both $\mathrm{Re}C_7 < 0$ (same as in SM) and $\mathrm{Re}C_7 > 0$ (opposite to SM) possible, with positive values increasingly probable as $\tan\beta$ increases recent discussions by Boz and Pak, Lungi

  $\Rightarrow$ significant regions of MSSM parameter space could be ruled out at large $\tan\beta$

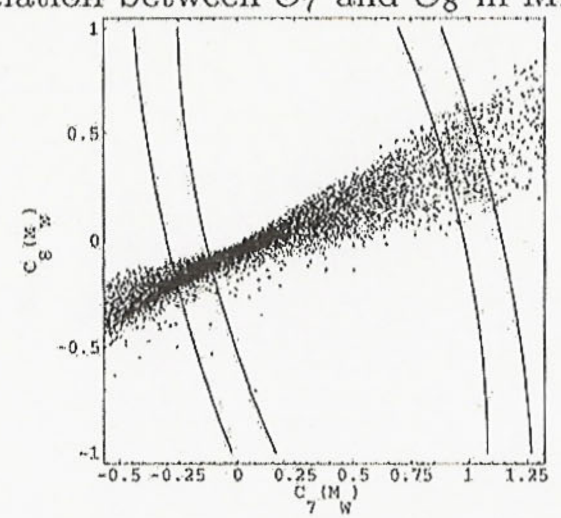
From Lunghi-Moriond
(Ali, Hiller, Lunghi)

Minimal Flavour Violating MSSM

- The MFV parameter space is:

$M_{\tilde{t}} = 90$ GeV $\div$ 1 TeV
$\theta_{\tilde{t}} = -\pi \div \pi$
$\mu = -1$ TeV $\div$ 1 TeV
$M_2 = 0 \div 1$ TeV
$M_{H^\pm} = 78.6$ GeV $\div$ 1 TeV
$M_{\tilde{q}} \simeq 1$ TeV, $M_{\tilde{\nu}} \geq 50$ GeV

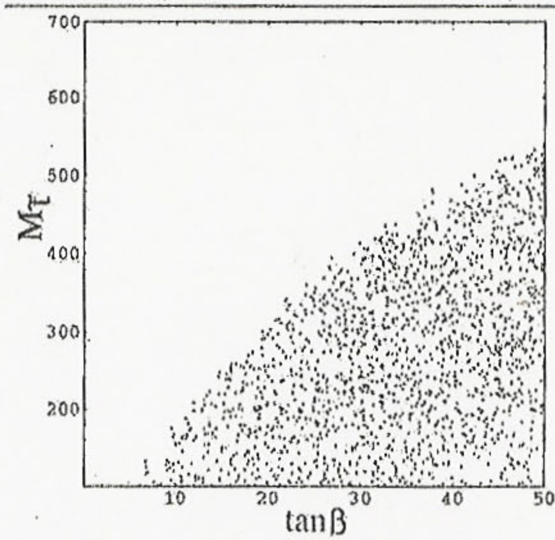
- Correlation between C_7 and C_8 in MFV:



- Allowed ranges for C_9 and C_{10} compatible with the $B \to X_s\gamma$ constraint:

  - $C_7 > 0 \Rightarrow \begin{cases} C_9 = -0.17 \div 0.29 \\ C_{10} = -0.85 \div 0.46 \end{cases}$
  - $C_7 < 0 \Rightarrow \begin{cases} C_9 = -0.18 \div 0.35 \\ C_{10} = -0.84 \div 0.62 \end{cases}$

- Points that satisfy the $B \to X_s\gamma$ constraint with a positive (opposite to the SM) C_7:

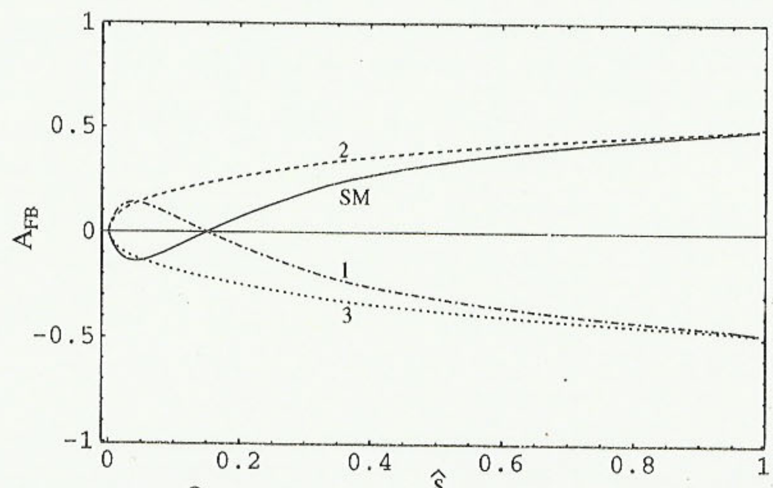


From Hiller

forward backward asymmetry in $b \to s\ell^+\ell^-$

asymmetry between N(forward) and N(backward) scattered ℓ^- in dilepton CMS w.r.t. B-meson $\quad A_{FB}(\hat{s}) \sim C_{10A}[C_7 + \beta(\hat{s}) Re(C_{9V})]$

- SM or $C_7 < 0$:A_{FB} has zero in low inv mass
- $C_7 > 0$ NO zero (curve 2) e.g. MFV MSSM
- C_{10} non-SM curve 3 or 1 or flat $A_{FB}(\hat{s}) \sim 0$ possible !!



$A_{FB}(\hat{s})$ in exclusive $B \to K^{*0}\mu^+\mu^-$ opportunity for hadron colliders

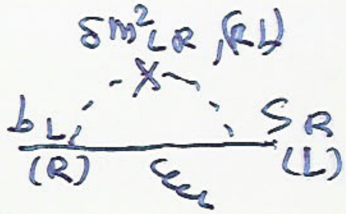
yield for $2fb^{-1}$ CDF,BTeV,ATLAS, CMS, LHCb 59, 2240, 665,4200, 4500

Rare $B \to PP, VP, VV$ decays

Speculations about Parity Invariant (Left-Right Sym.) New Physics

- a case study on the discriminating power of the B-factories with regards to New Physics

- limitations of QCD factorization

In our SUSY example: 

if underlying theory is P invariant, i.e. $SU(2)_L \times SU(2)_R$ symmetric or $SO(10)$ symmetric at scale Λ at which SUSY breaking masses are generated, eg $\Lambda \sim M_{GUT}$

$$\Rightarrow \quad \delta m^2_{\tilde{b}_L \tilde{s}_R} = \delta m^2_{\tilde{b}_R \tilde{s}_L}, \text{ or}$$

$$\delta m^2_{\tilde{b}_L \tilde{s}_L} = \delta m^2_{\tilde{b}_R \tilde{s}_R}$$

$\therefore$ at $\mu \sim M_W$
up to small RGE effects

$$\boxed{C_i^{NP}(\mu) = \tilde{C}_i^{NP}(\mu)}$$

Several other P inv examples

Parity Invariant New Physics

applying $\mathcal{P}$ transformation $\Rightarrow$

a) $$\langle PP | Q_{i=3,\ldots,6,8g} | B \rangle = -\langle PP | \tilde{Q}_i | B \rangle$$

$$\therefore \; A_i^{NP}(B \to PP) \propto C_i^{NP}(m_b) - \tilde{C}_i^{NP}(m_b)$$

b) $$\langle VP | Q_i | B \rangle = \langle VP | \tilde{Q}_i | B \rangle$$

$$\therefore \; A_i^{NP}(B \to VP) \propto C_i^{NP}(m_b) + \tilde{C}_i^{NP}(m_b)$$

$\mathcal{P}$ invariance $\Rightarrow$ $C_i^{NP}(m_b) = \tilde{C}_i^{NP}(m_b) \Longrightarrow$

$\therefore$ negligible impact on $B \to PP$,

$\;\;$ substantial effect on $B \to VP$

c) $\langle VV|Q_i|B\rangle_{S,D} = -\langle VV|\tilde{Q}_i|B\rangle_{S,D}$

for S, D wave amplitudes

(P even final states)

or $\vec{\epsilon}_0$, $\vec{\epsilon}_{\parallel}$ in transversity basis

$\therefore A_i^{NP}(B \to VV)_{\epsilon_0, \epsilon_{\parallel}} \propto C_i^{NP} - \tilde{C}_i^{NP}$

- $\langle VV|Q_i|B\rangle_P = \langle VV|\tilde{Q}_i|B\rangle_P$

for P wave amplitude, $\vec{\epsilon}_{\perp}$ in transversity basis

(parity odd final state)

$\therefore A_i^{NP}(B \to VV)_{\epsilon_{\perp}} \propto C_i^{NP} + \tilde{C}_i^{NP}$

$\mathcal{P}$ invariance $\Rightarrow$

little or no effect on ϵ_0, $\epsilon_{\parallel}$ amplitudes substantial effect on $\epsilon_{\perp}$ amplitude

$B \to PP\ /\ VP$ in QCD Factorization

Beneke, Buchalla, Neubert, Sachrajda

- neglecting $1/m_b$ power suppressed effects can write in SM

$$\langle M_1 M_2 | H_{SM} | \bar{B} \rangle = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \langle M_1 M_2 | T_p | \bar{B} \rangle$$

Current-current "tree" amp

$$T_p = a_1(M_1 M_2)\, \delta_{pu} (\bar{u} b)_{V-A} \otimes (\bar{s} u)_{V-A}$$

$$+ \; a_2(M_1, M_2)\, \delta_{pu} (\bar{s} b)_{V-A} \otimes (\bar{u} u)_{V-A}$$

QCD "penguin" amp

$$+ \; a_3(M_1, M_2) \sum_q (\bar{s} b)_{V-A} \otimes (\bar{q} q)_{V-A}$$

$$+ \; a_4^p(M_1, M_2) \sum_q (\bar{q} b)_{V-A} \otimes (\bar{s} q)_{V-A}$$

$$+ \; a_5(M_1, M_2) \sum_q (\bar{s} b)_{V-A} \otimes (\bar{q} q)_{V+A}$$

$$-2\, a_6^p(M_1, M_2) \sum_q (\bar{q} b)_{S-P} (\bar{s} q)_{S+P} + \ldots$$

Important difference between

$B \to PP$, $B \to VP$:

eg $B^\pm \to K^{*0}\pi^\pm$ vs $B^\pm \to K^0\pi^\pm$

At leading order in α_s both receive contributions from Q_4 (or a_4).

$$\langle \pi^\pm | (\bar{d} b)_{V-A} | B^\pm \rangle \langle K^0 \text{ or } K^{*0} | (\bar{s} d)_{V-A} | 0 \rangle \, C_4$$

But only $B^\pm \to K^0\pi^\pm$ gets (chirally-enhanc contribution from Q_6

$$\sim \langle \pi^\pm | \bar{d} b | B \rangle \langle K^0 | (\bar{s} d)_{S+P} | 0 \rangle \, C_6$$

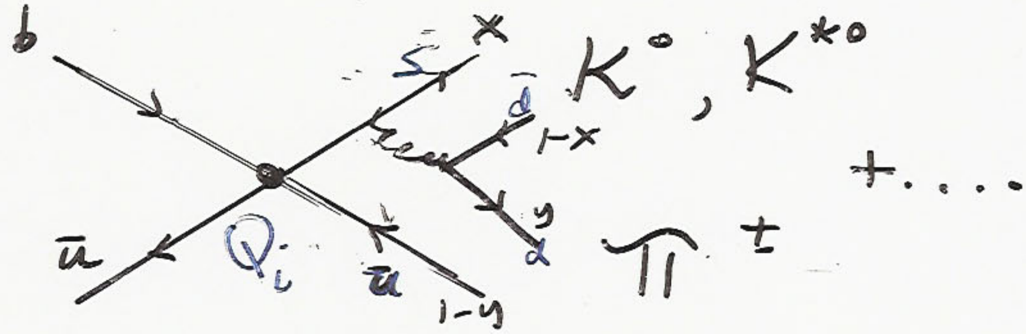
$\Rightarrow$ At leading power in $1/m$

$BR(B \to K\pi) \gg BR(B \to K^*\pi)$

Since Q_4, Q_6 are the dominant penguin operators

Trouble at $\mathcal{O}(1/m)$: annihilation graphs

eg



$$\propto \; C_i \, \alpha_s f_B f_{K^{(*)}} f_\pi \int \phi_{K^{(*)}}^{(x)} \phi_\pi^{(y)} f(x,y)\, dx$$

The convolutions contain Logarithmic divergences in end point regions of light meson wave functions

- eg Q_6: divergences in $x \to 1$, $y \to 0$ limit

  ie, in limit of soft gluon ($q^2 \to 0$)

  ($k_{\bar d} \to 0$, $k_d \to 0$)

Convolution Integral $\propto \int_0^1 \frac{dy}{y} \int_0^1 \frac{dx}{1-x}$

$\Rightarrow$ Can't factorize short, long distance physics in annihilation graphs

Factorization breaks down at $\mathcal{O}(\frac{1}{m})$

- To estimate such effects will follow BBNS

Let $X = \int \frac{dy}{y} = \ln \frac{m_B}{\Lambda_h}(1 + \underline{\underline{\rho_A e^{i\phi}}})$, $\rho_A \leq 1$

- $\Lambda_h \sim .5$ GeV is hadronic scale which "regulates" the divergence
- allow for strong phase ϕ
- Although power suppressed ($\mathcal{O}(1/m)$) could be important due to phase space enhancement relative to standard decay topology

Numerical Results - SM

- use analytical results of BBNS for $B \to K\pi$
- use analytical results of Du et al, Cheng+Yang for $B \to \phi K, K^* \pi$
+ additional contributions due to Beneke + Neubert (in preparation)

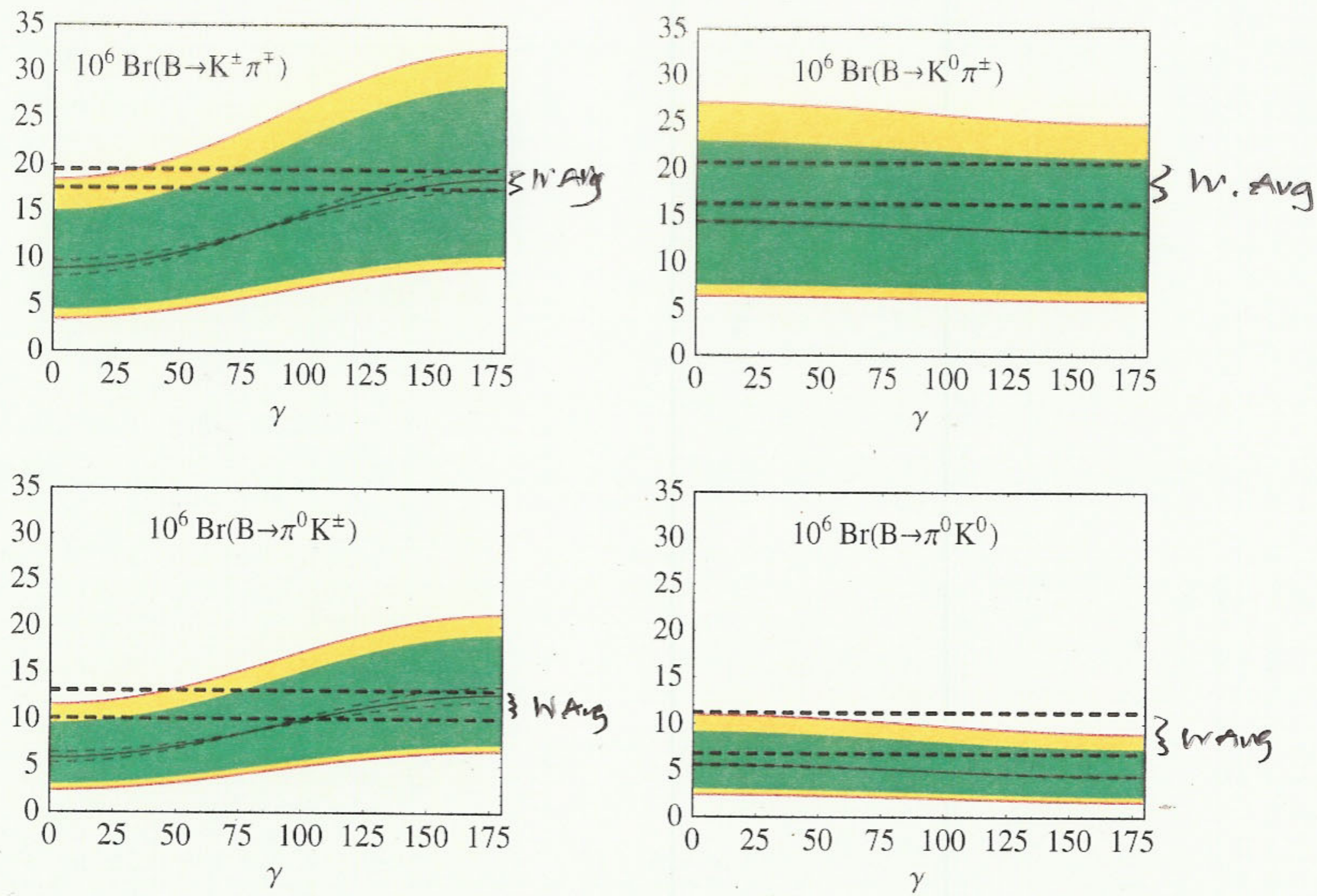
- **Uncertainties**

a) input parameters: f_B, f_{K^*}, form fact.
meson wave functions, quark masses, scale dependence, V_{ub}, ...

b) treatment of IR divergences in annihilation graphs (Largest uncertainties),
hard scattering graphs

- take $\rho_A \leq 1$. (Default is $\rho_A = 0$)

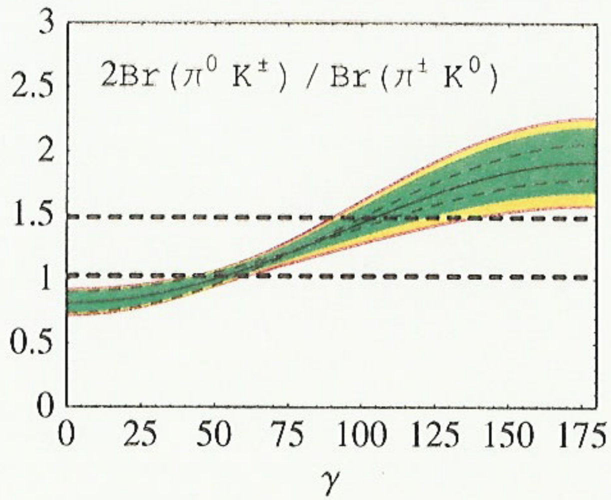
BR's for $B \to K\pi$ SM

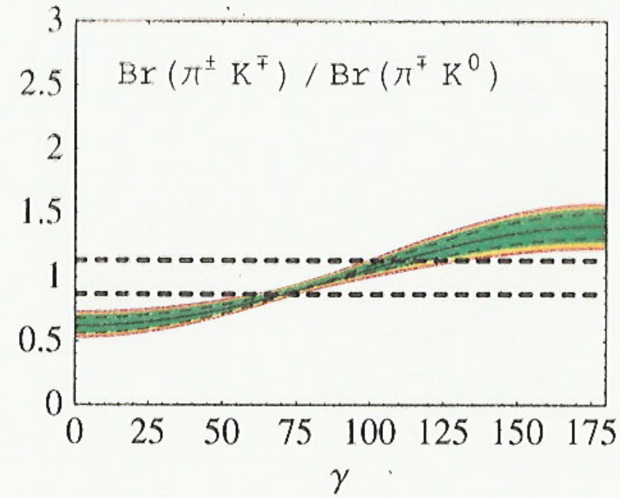


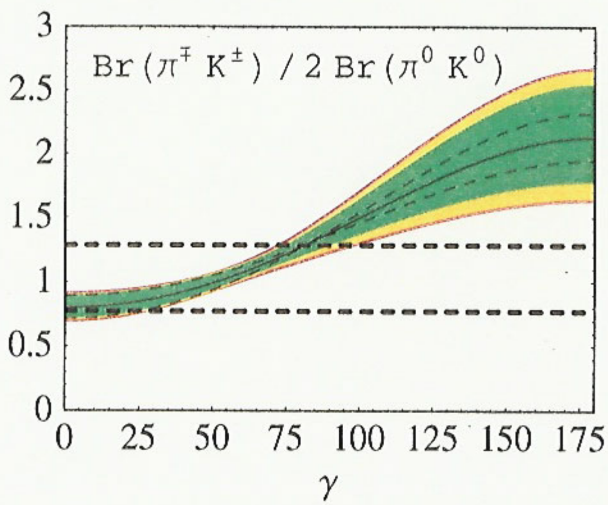
Green band – input parameter uncertainty, "default" annihilation contribution

Yellow band – annihilation uncertainty added in quadrature

Ratios of B → Kπ BR's SM

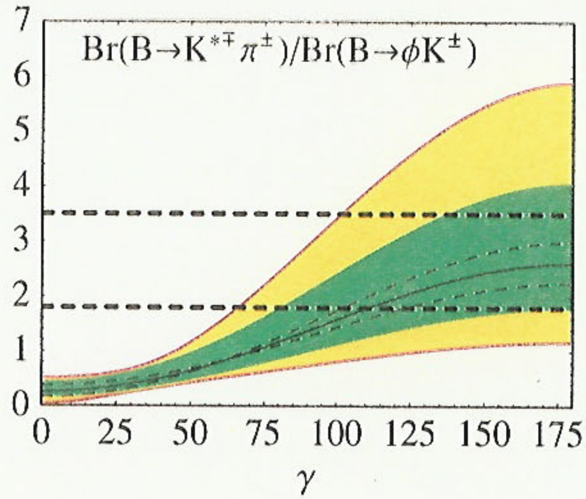


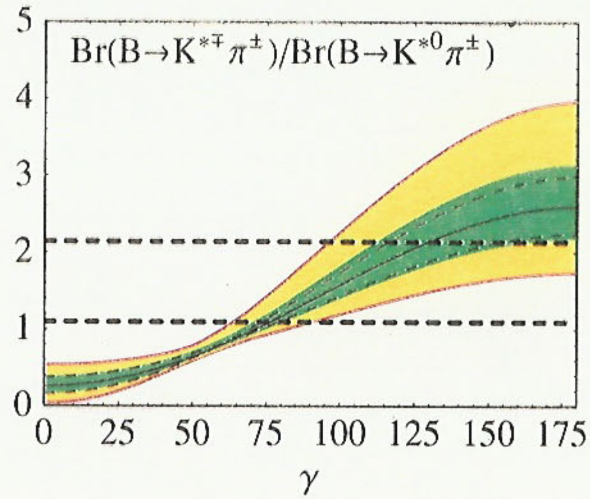


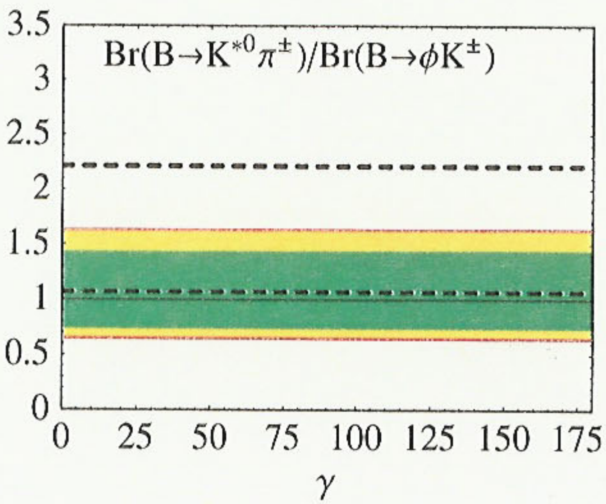


- uncertainty substantially reduced in ratios of BR's
- good agreement with data
  ⇒ can't have large isospin breaking contributions from New Physics

Ratios of BR's

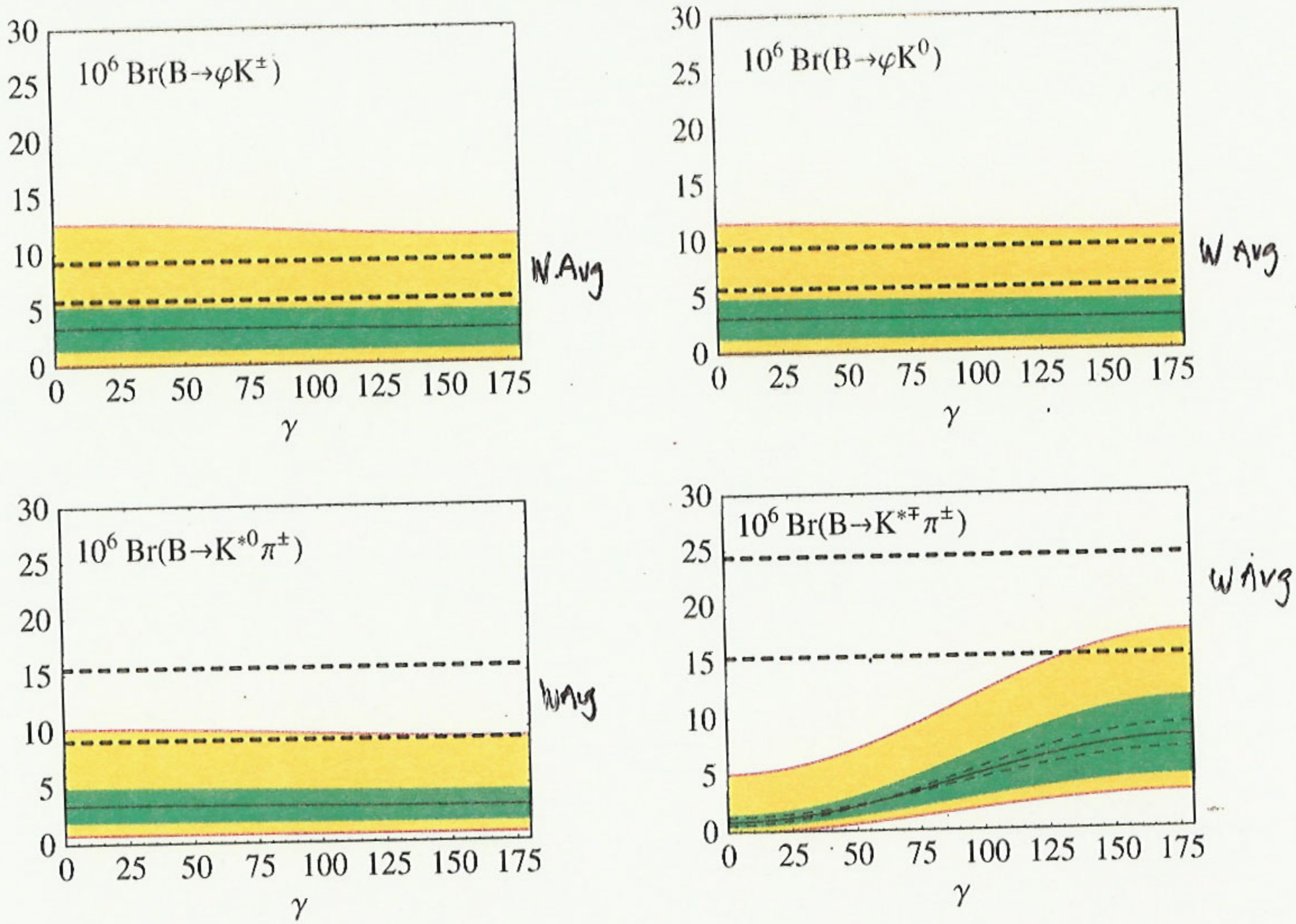






- data may favor large γ as in $B \to PP$
- Annihilation amplitudes in ϕK, $K^*\pi$ related by $SU(3) \Rightarrow$ reduced annihilation uncertainty

$B \to K\pi$ / φK DKS   SM



- Predictions for $K^*\pi$ on the small side, but <u>huge</u> theoretical uncertainty due to annihilation, large experimental uncertainties

IV. A Possible role for New Physics:

- To reproduce the $B \to K^* \pi$ data need large annihilation contribution from Q_6, ie need $A_{ann}(B \to K^* \pi) \approx A_{std}(B \to K^* \pi)$
  std penguin contbns

Default: $A_{ann} \sim .15\, A_{std,penguin}$ $(\rho_A = 0)$

- Perhaps the excess relative to default range of predictions due to New Physics

- But New Physics should not ruin consistency between theory/expt in $K\pi$ system.

- Have argued that P-inv New Phy
is an attractive possibility

$\Rightarrow$ new contributions conserve isospi

∴ Two alternatives in this framework

a) the chromomagnetic dipole operators

$$Q_{8g} = \bar{s}\,\sigma^{\mu\nu}(1+\gamma_5)T^a b\, G^a_{\mu\nu}$$

$$\tilde{Q}_{8g} = \bar{s}\,\sigma^{\mu\nu}(1-\gamma_5)T^a b\, G^a_{\mu\nu}$$

Take $C_{8g}^{NP} = \tilde{C}_{8g}^{NP}$ at $\mu \sim m_b$

parametrize $C_{8g}^{NP}(m_b) = \tilde{C}_{8g}^{NP}(m_b) = K_8 e^{i\theta_8}$

- need to be consistent with
$b \to s\gamma$ constraints !

) QCD penguin ops

$Q_{3,\dots,6}$, $\tilde{Q}_{3,\dots,6}$ with $C_i \approx \tilde{C}_i$

ll consider a) here

• In general for $m_{\tilde g} \ll m_{\tilde q}$ $b \to s\gamma$ constraints on LR insertion graphs considerably weakened!

(in $\overline{MS}$ scheme)

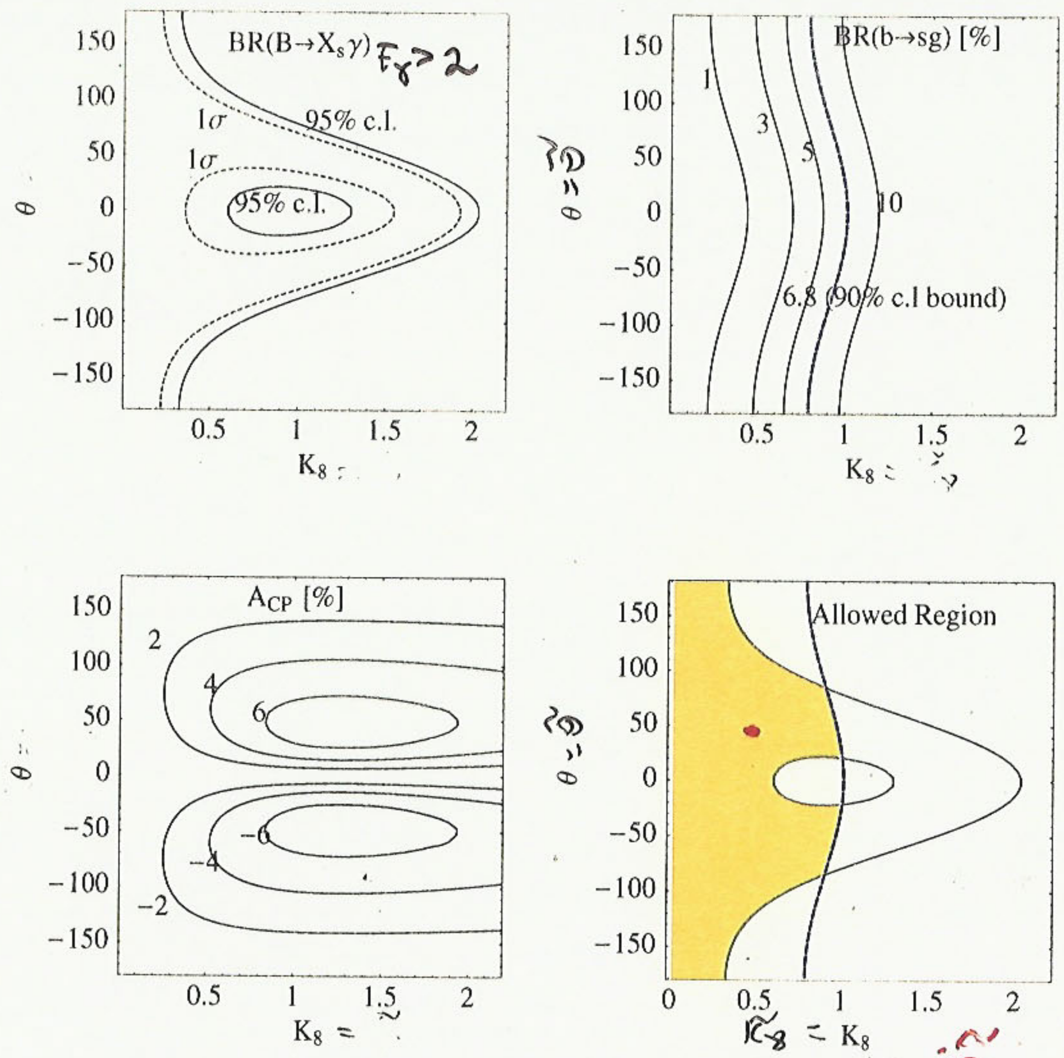
Example

$C^{NP}_{8,7} = \tilde{C}^{NP}_{8,7}$

$x = -.6$, eg

$m_{\tilde g} = 300$ geV,

$m_{\tilde q} = 1$ TeV for LR squar insertion loop



CLEO bound

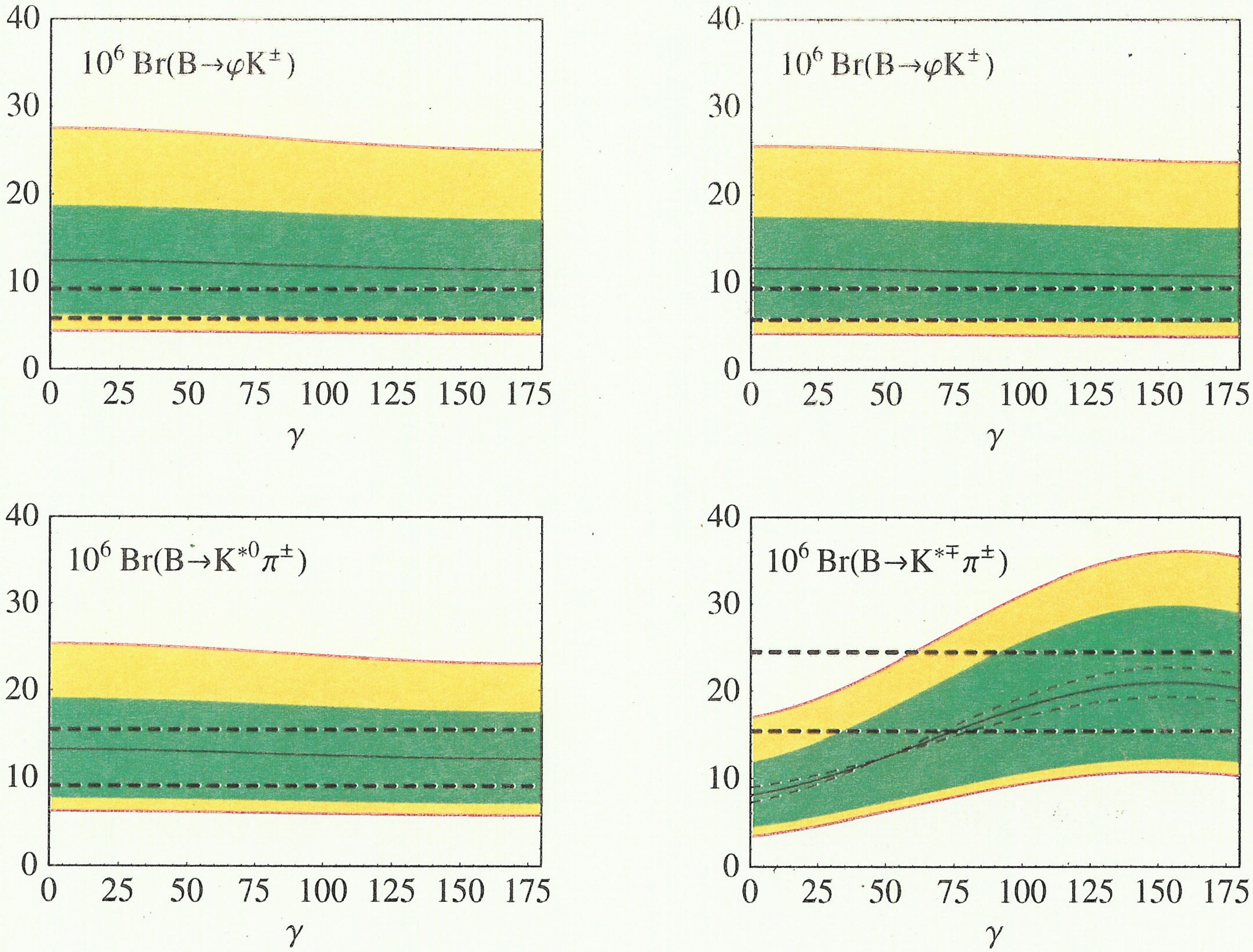
$-27\% < A_{cp} < 10\%$ [90% c.l.]

Example $\tilde{K}_8 e^{i\tilde{\theta}_8} = K_8 e^{i\theta_8} = .5 e^{i45°}$

$\approx 3 \times C^{SM}_{8g}$ in magnitude

→ $BR(b \to sg) \sim 2\%$

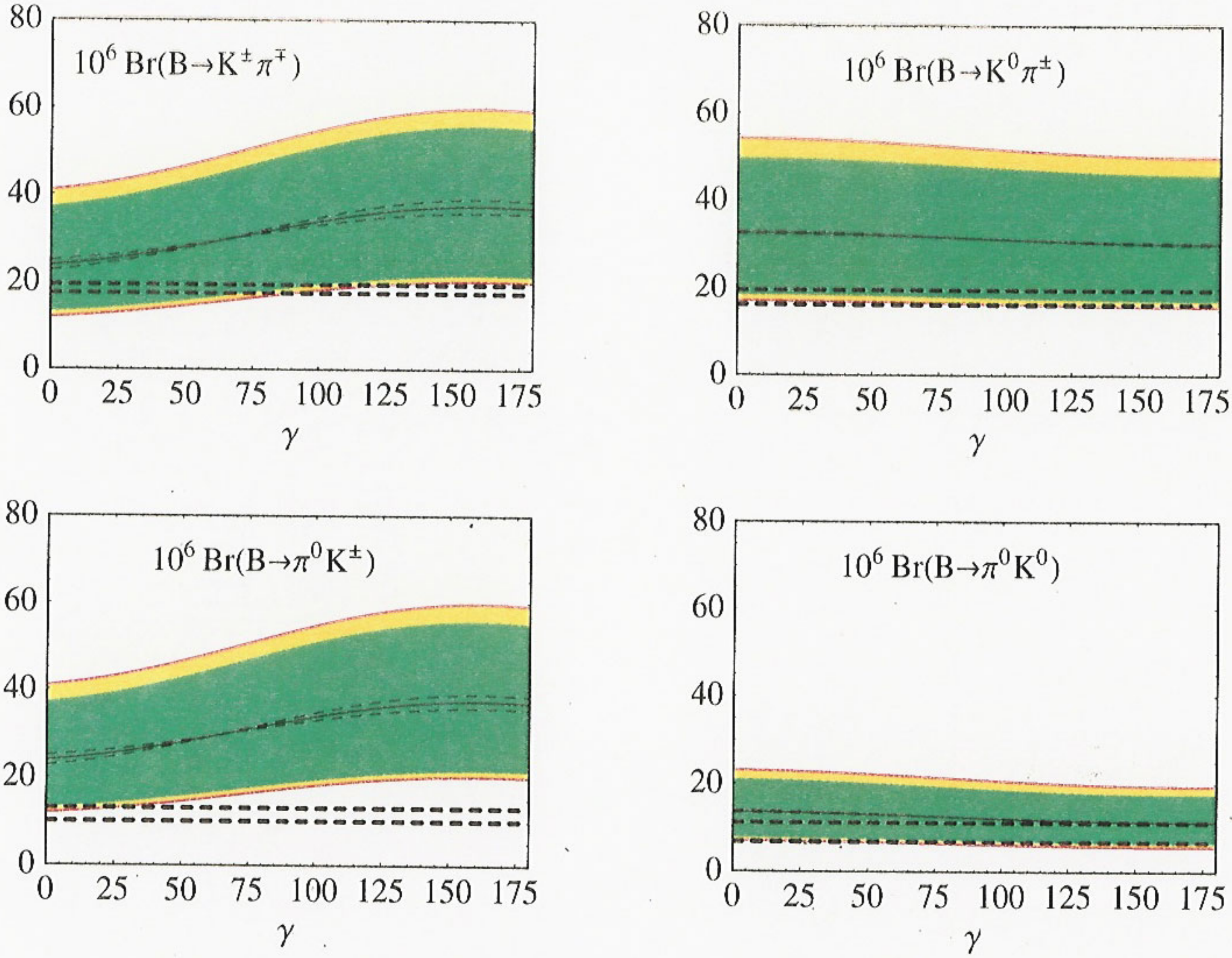
B → Kπ / φK BRs for $K_8 e = .5 e$ $= C_8(M_W) = C_8(M_W)$



no effect on B → Kπ rates

What if instead took $\tilde{C}_{8g}^{NP} = 0$, doubled C_{8g}^{NP}

Impact on $B \to K\pi$ BR's



no longer good consistency

For our example, effect of NP on amplitude

$$\frac{|A(K^{*0}\pi^{\pm})_{\text{opposite } \chi\text{'lity}}|}{|A(K^{*0}\pi^{\pm})_{SM\ \chi\text{'lity}}|} \sim .4$$ (Default BBNS parameter)

$$\frac{|A^{NP}(K^{*0}\pi^{\pm})|}{|A^{SM}(K^{*0}\pi^{\pm})|} \sim 1.3$$

so $|A^{tot}| \sim 2.3\,|A^{SM}|$

b) for New Physics contributions to QCD penguin operators, comparable enhancement of $B \to K^*\pi$, ϕK obtained for

$$C_6(M_W) = \tilde{C}_6(M_W) = C_4(M_W) = \tilde{C}_4(M_W) = -3\,\tilde{C}_{5,3}(M_W) = 3($$

$$\simeq -.025$$

so new contributions $C_i^{NP}(m_b) = \tilde{C}_i^{NP}(m_b) \sim C_i^{SM}(m$

Other Implications

a) Time-dependent CP asymmetries
in $B \to \phi K_s$, $\eta' K_s$, $K^+K^-K_s$ vs. ψK_s

$\sin 2\beta(\psi K_s) = .734 \pm .054$ WAvg
CP odd

$\sin 2\beta(\phi K_s) = \begin{cases} -.19 {}^{+.52}_{-.50} \pm .09 & \text{BaBar} \\ -.73 \pm .64 \pm .18 & \text{Belle} \\ \text{WAvg} = -.39 \pm .41 & \end{cases}$
CP odd

$\sin 2\beta(\eta' K_s) = .76 \pm .36 \pm {}^{.05}_{.06}$ Belle
CP even

$\sin 2\beta(K^+K^-K_s) = -.52 \pm .46 \pm .11 {}^{+.27}_{-.03}$ Belle

$\boxed{\begin{array}{l}\text{CP odd fraction } 3\% \\ \text{CP even fraction } 97\%\end{array}}$ after subtracting ϕK_s

In SM: Penguin dominated decays ⇒

$\sin 2\beta(\phi K_s) \approx \sin 2\beta(\psi K_s)$

$\sin 2\beta(\eta' K_s) \approx -\sin 2\beta(\psi K_s)$

$\sin 2\beta(K^+K^-K_s) \approx -\sin 2\beta(\psi K_s)$

But $\mathcal{O}(1)$ NP Penguin Amp w/ Large weak phase can have sizable discrepancies w.r.t $\sin 2\beta(\phi K_S)$

see Z. Ligeti's Lectures

- in our example have such a situation.

But P-invariance would imply that a discrepancy could only show up in $\sin 2\beta(\phi K_S)$ since P odd final state !

– both $\eta' K_S$ / $K^+K^-K_S$ are P even final state

- other examples of NP which could lead to $\mathcal{O}(1)$ amplitudes in ϕK_S and $\mathcal{O}(1)$ discrepancy in $\sin 2\beta(\phi K_S)$:

Flavor Changing Z penguins – G. Hiller

R-parity violating $b \to s\bar{s}s$ Datta

⋮

b) $B \to VV$, eg, $B \to \phi K^*$, ρK^*

In transversity basis (in terms of linear polarization vec.

$$A(B \to V_1 V_2) \sim \underbrace{A_0 \epsilon_1^{*L} \epsilon_2^{*L}}_{\text{Longitudinal}} - \underbrace{A_{\parallel} \frac{\epsilon_1^{*T} \cdot \epsilon_2^{*T}}{\sqrt{2}}}_{\text{Transverse + parallel}} - \underbrace{i A_\perp \epsilon_1^* \times \epsilon_2^* \cdot \hat{p}}_{\text{Transverse + perpendic}}$$

$\hat{p}$ is unit vector in V_1 rest frame in V_2 dirn of motion

$\epsilon^L \equiv \hat{p} \cdot \epsilon$

- A_0, $A_{\parallel}$ unaffected by Parity Inv New Physics
- $A_\perp$ receives new contributions, $A_\perp^{NP} \propto C_i + \tilde{C}_i$

- In SM, in generalized factorization framework

  A_0 is dominant

  For example: $\left|\frac{A_\perp}{A_0}\right| \sim \left|\frac{A_{\parallel}}{A_0}\right| \sim .2$ (ϕK^*, ρK^*)

  - similar result in QCD Factorization framework - Cheng + Yang

- $BR \propto |A_0|^2 + |A_\parallel|^2 + |A_\perp|^2$

$$\simeq |A_0|^2$$

and $\dfrac{|A_\perp|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} \sim 4\,\%$

- Parity Inv New Physics implemented in $B \to VP$ decays will typically increase $|A_\perp|^2$ by factor ~ 5

$\Rightarrow$ only modest increase in overall BR's for $K^*\rho$, ϕK^* ...

$\therefore$ measured rates should be consistent w/ QCD factorizn predictions

- But a transversity angular analysis may reveal a factor of 5 increase in $|A_\perp|^2$?

Taking $BR_{total} \sim 10^{-5} \Rightarrow BR_\perp \sim 2\times10^{-6}$ vs 4×10^{-7} in S

c) relative increases in

ηK^* vs $\eta' K$,

$\eta' X_s$ vs. $\eta' K$

d) Expect similar excesses in ρK, ωK modes vs SM predictions, which can be accounted for via New Physic as in case of $K^* \pi$

e) at a Giga-Z facility or at LHC-B / BTEV should be possible to directly measure presence of significant opposite χ'lity contributions via angular distributions in, eg,

$\Lambda_b \to \Lambda \phi$ decays

G. Hiller, AK - see G. Hiller Snowmass

Conclusion

Still Lots of Room for NP in B decays.