Seminar @ CYCU
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Do We Still Have The K π Puzzle?

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National Central Univ. and Academia Sinica

Based on:
(1) S. Baek, CC, and D. London, PLB 675, 59 (2009); and
(2) S. Baek, CC, M. Gronau, D. London, and J. Rosner, PLB 678, 97 (2009).

Outline

- Rudiments and History of the K π puzzles
- Current status of the K π puzzle
- Possible interpretation within SM and in NP
- Summary and outlook

Introduction

KM Mechanism

Cabibbo 1963; Kobayashi, Maskawa 1973

- In the quark sector with 3 generations, there is a mismatch between interaction and mass eigenstates:

2008 Nobel Prize in Physics

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: Universtity of Chicago

Yoichiro Nambu

1/2 of the prize

南部楊一郎

Enrico Fermi Institute, University of Chicago
Chicago, IL, USA

b. 1921
(in Tokyo, Japan)

Photo: KEK

Makoto Kobayashi

1/4 of the prize

Japa 小林誠

High Energy Accelerator Research Organization (KEK)
Tsukuba, Japan

b. 1944

Photo: Kyoto University

Toshihide Maskawa

1/4 of the prize

J 益川敏英

Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP), Kyoto University
Kyoto, Japan

b. 1940

KM Mechanism

Cabibbo 1963; Kobayashi, Maskawa 1973

- In the quark sector with 3 generations, there is a mismatch between interaction and mass eigenstates:

$$\mathcal{L} \ni -\frac{g}{2}\overline{Q^I_{Li}}\gamma^\mu W^a_\mu \tau^a Q^I_{Li} + h.c.$$

$$= -\frac{g}{2}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W^+_\mu \left(V_{uL}V^\dagger_{dL}\right) \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$

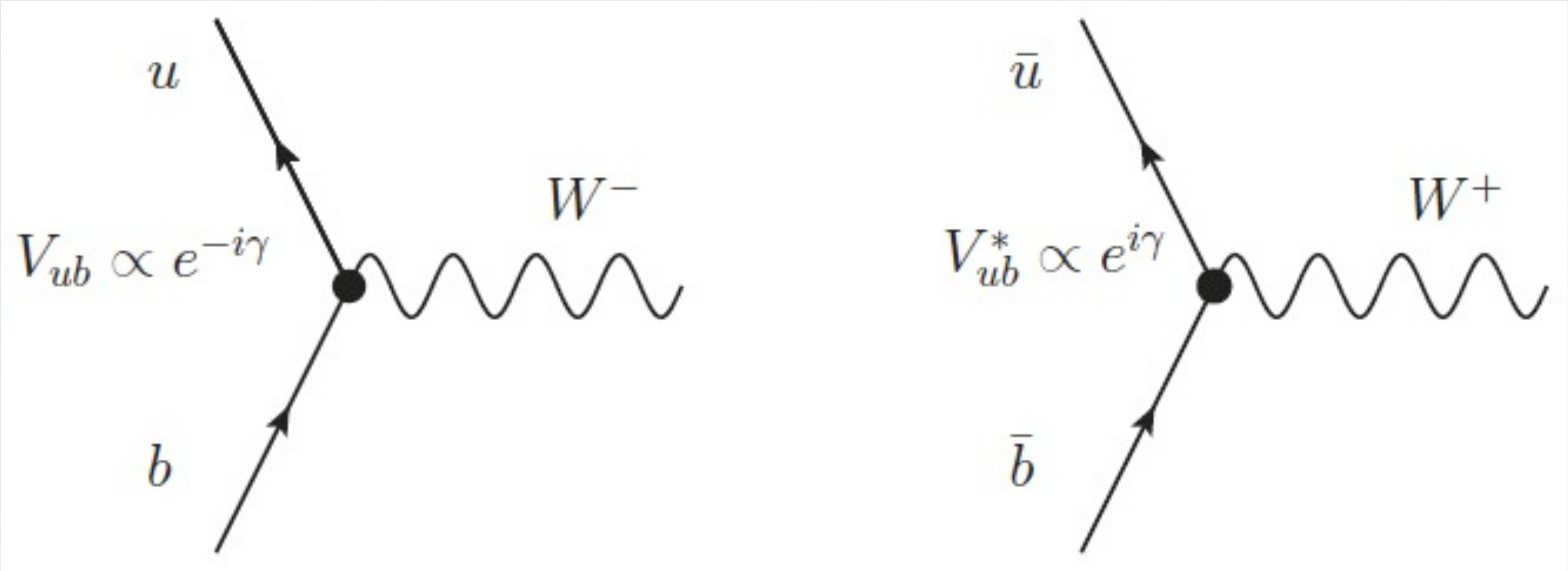
$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CP-violating

$$= \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3[(1-\bar\rho) - i\bar\eta] & -A\lambda^2 & 1 \end{pmatrix}$$

EXAMPLE: $b \to u$ TRANSITION

- Processes such as the following one are CP-conjugate to each other.

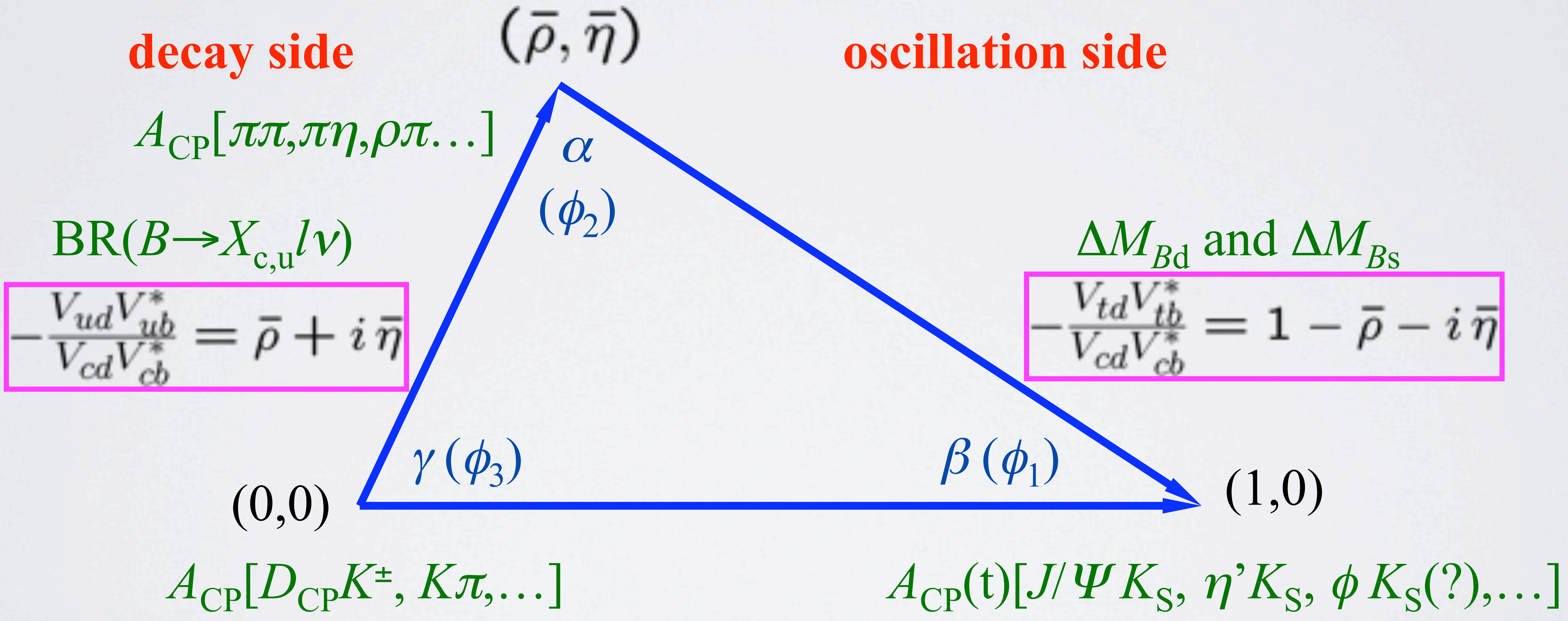


- They involve couplings equal in strength, but opposite in phases. With appropriate interference, one can extract such a CP-violating phase.

Unitarity Triangle

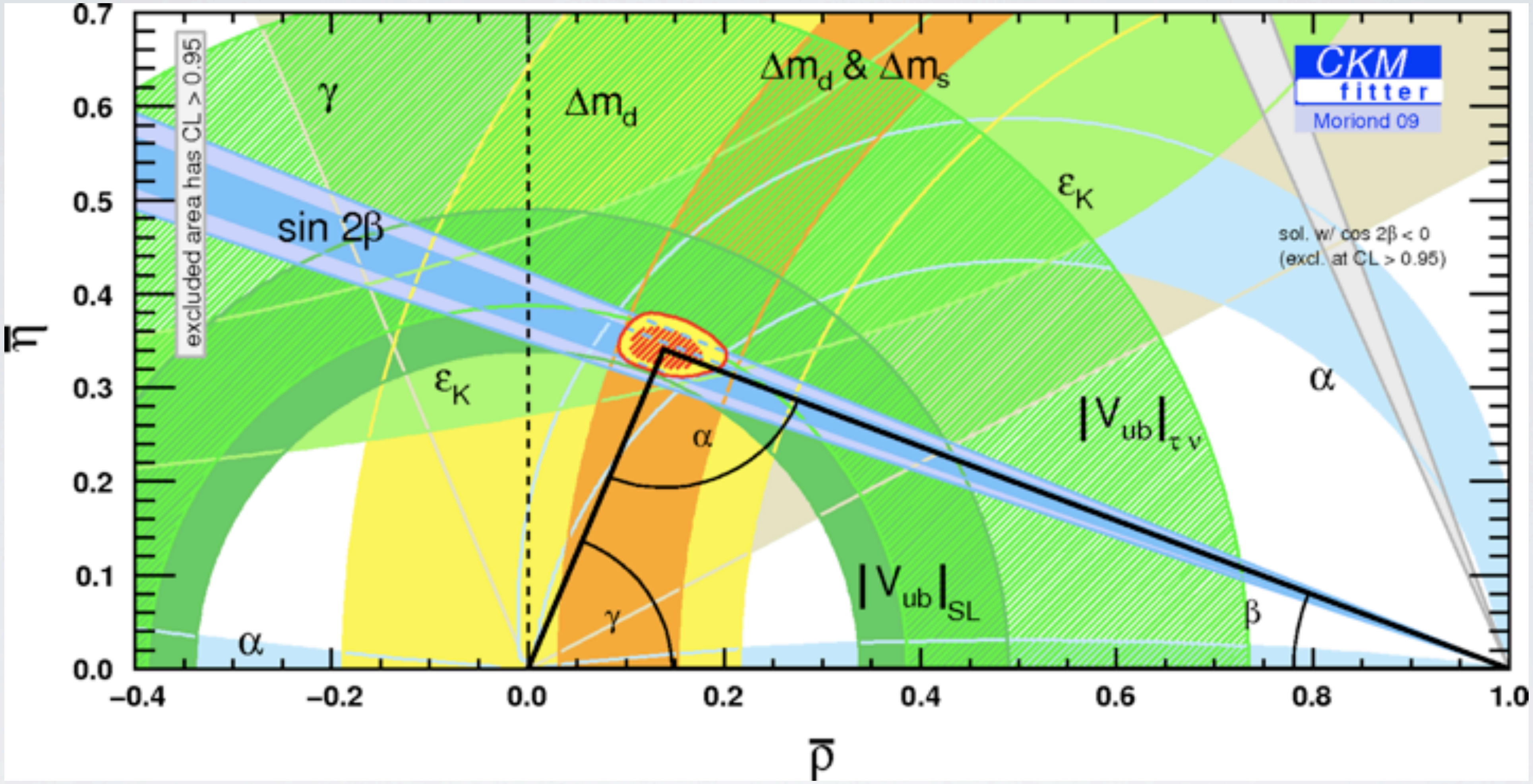
- CP violation can be visualized as a triangle according to one unitarity condition of the CKM matrix:

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



- An important program of the B factories and heavy flavor physics is to fix the UT at high precision.

GLOBAL CONSTRAINTS



- Through decades of careful experimental works, a UT with non-zero area (CP violation) is well-established.
- Almost all the constraints fit nicely with each other, and restrict the (ϱ,η) vertex to a very confined region.

Caveat

- The fact that global fits render good results does not exclude the possibility of new physics effects showing up in certain processes.
- A lot of constraints in the last page come from charmed B decays, instead of charmless ones.
- Though very rare (BR ~ 10^{-6} or a few in every million events), charmless decays directly probe V_{ub} and are sensitive to loop processes.
- We do witness anomalous results here and there in some charmless B decays (e.g., $\sin 2\beta$, $BR(\pi^0\pi^0)$, polarizations of some VP modes, etc).

K π Decays and Puzzles

WHY ARE K π DECAYS INTERESTING?

- First direct CP violation in the B system was observed in the $\pi^- K^+$ mode in 2004.
- These decay modes are dominated by QCD-penguin (loop at work) subprocess.
- They can be sensitive to new dof's mediating in the loop.
- They can provide additional indep. information on the weak phase γ.

$$R \equiv \frac{\bar{\Gamma}^{-+}}{\bar{\Gamma}^{+0}} = 0.948 \pm 0.074 \quad \text{(year 2003)}$$

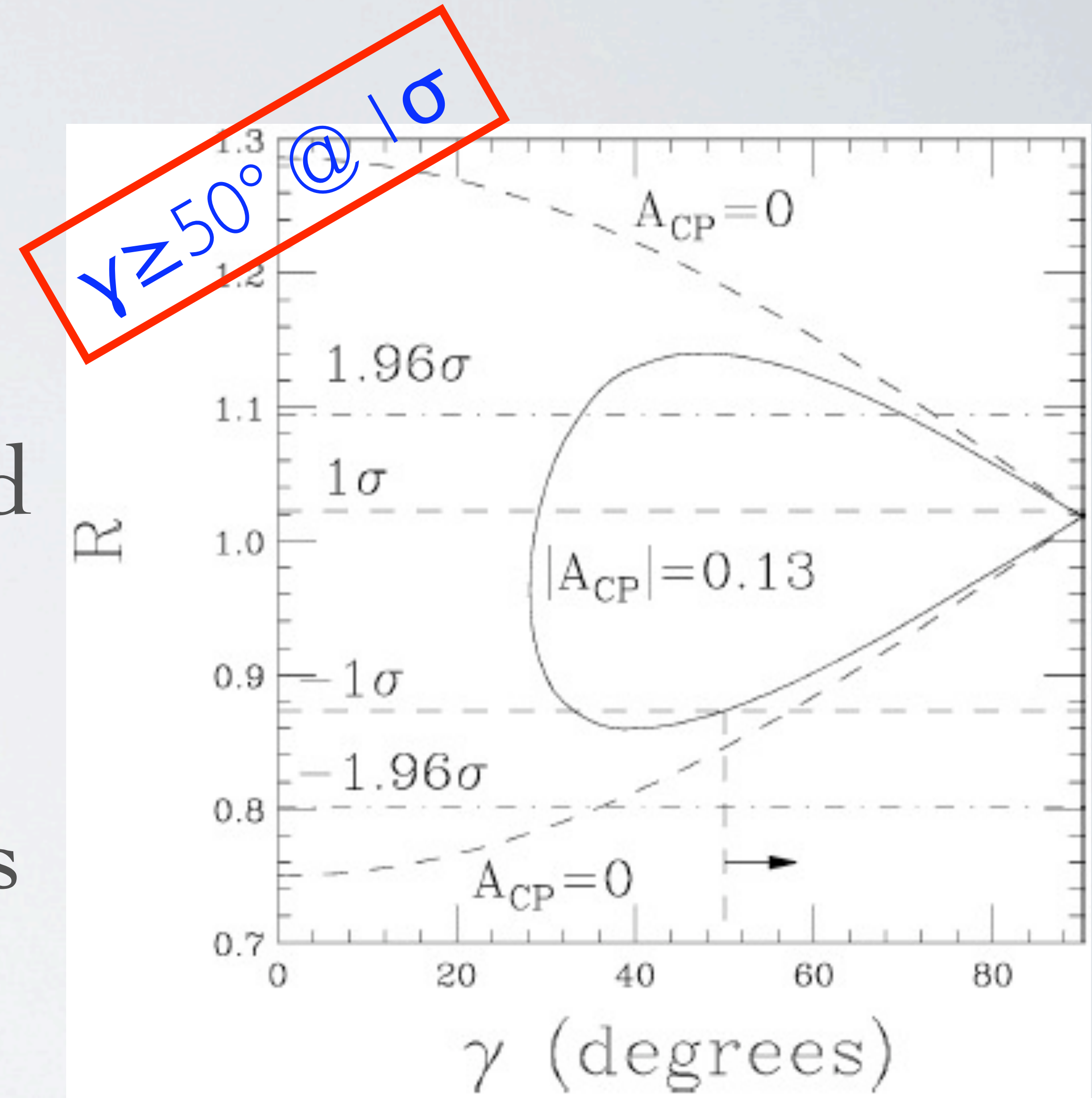


Fig. 1. Behavior of R for $r = 0.13$ and $A_{CP}(B^0 \to K^+\pi^-) = 0$ (dashed curves) or $|A_{CP}(B^0 \to K^+\pi^-)| = 0.13$ (solid curve) as a function of the weak phase γ. Horizontal dashed lines denote $\pm 1\sigma$ experimental limits on R, while dot-dashed lines denote 95% c.l. ($\pm 1.96\sigma$) limits. The upper branches of the curves correspond to the case $\cos\gamma\cos\delta < 0$, while the lower branches correspond to $\cos\gamma\cos\delta > 0$.

Gronau, Rosner 2003

Flavor Diagram Approach

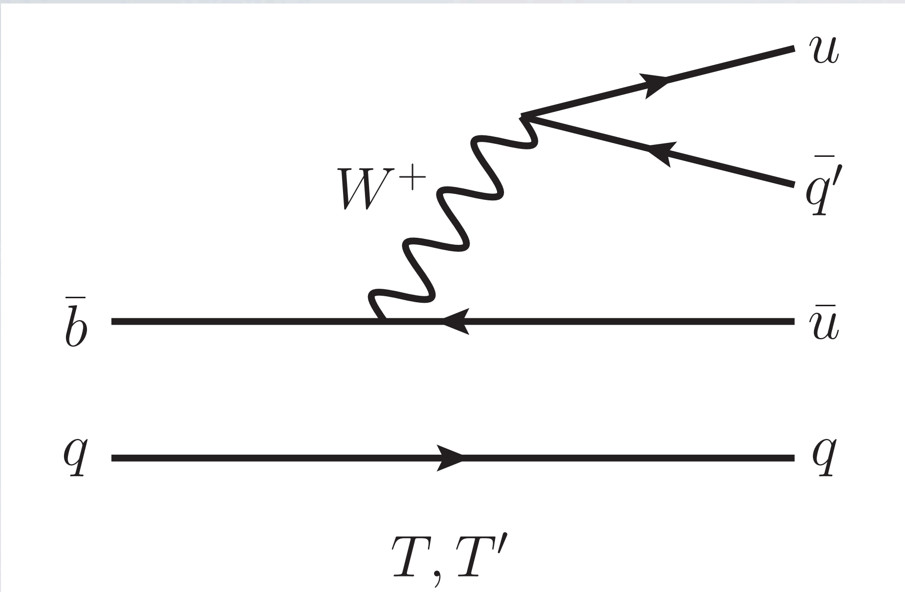
- In contrast to the usual perturbative approaches (pQCD, QCDF, SCET), we adopt a non-perturbative method to tackle the problem, where flavor SU(3) symmetry is used to relate/simplify decay amplitudes and associated strong phases.

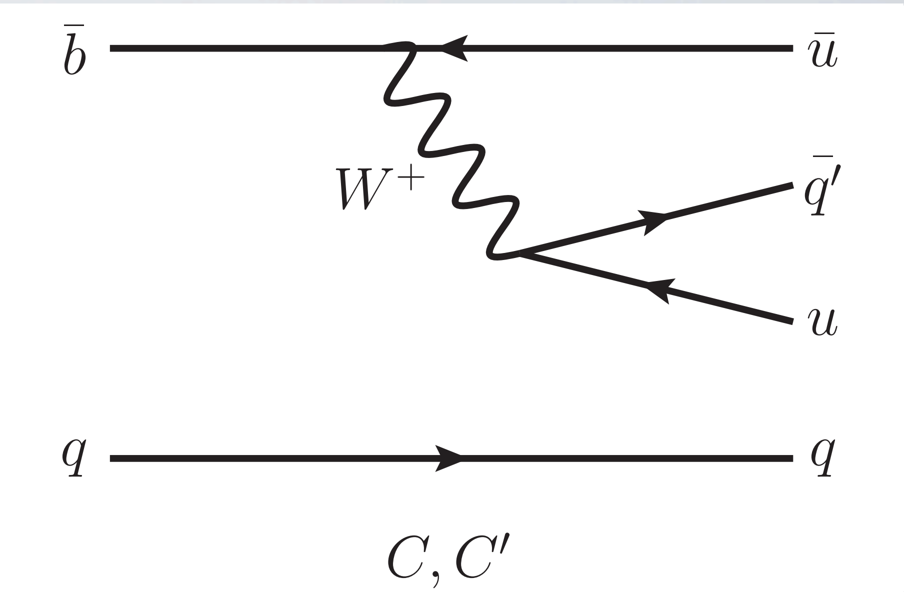
  Zeppenfeld 1981; Chau, Cheng 1986, 1987, 1991; Grinstein, Lebed 1996; Gronau et al 1994; CC, Gronau, Luo, Rosner, Suprun 2003, 2004

- Global analyses have been done to test this approach in the PP and VP decays. We find that, other than some obvious SU(3) breaking factor (e.g., ratio of decay constants), the $SU(3)_F$ symmetry can provide a satisfactory account of the data.

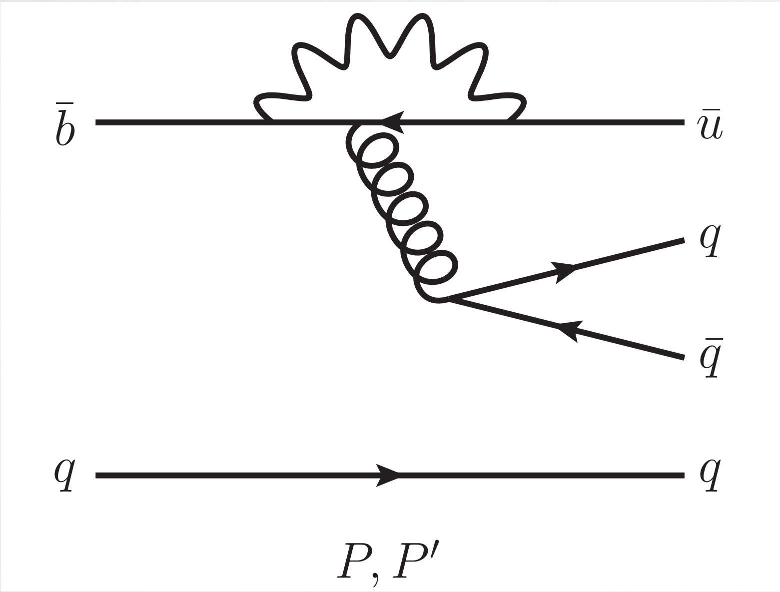
  CC, Zhou 2006, 2009

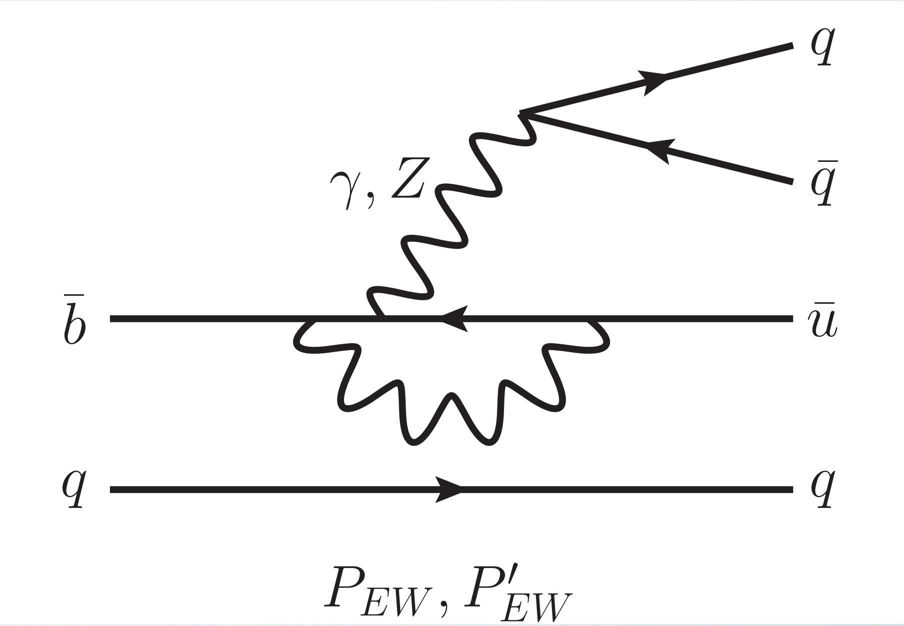
CONTRIBUTING DIAGRAMS



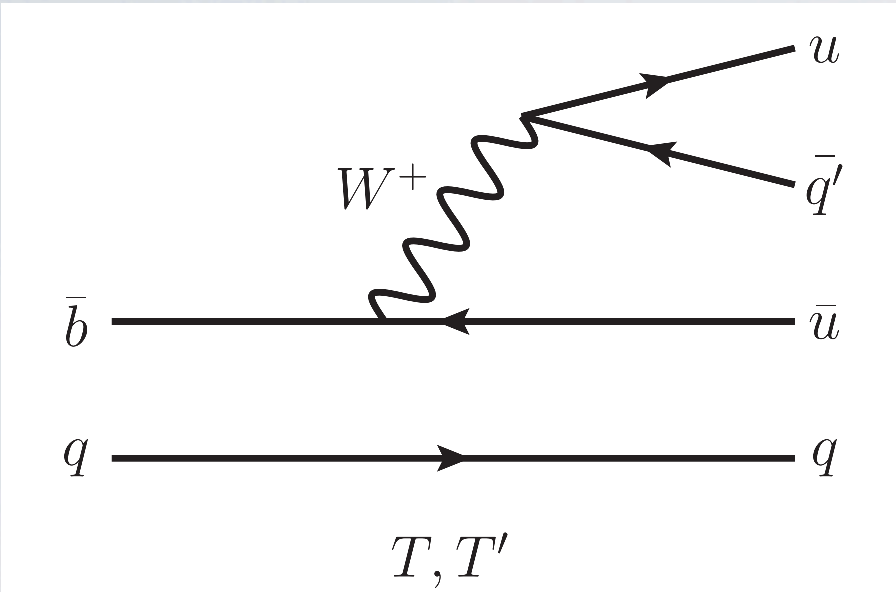


These are flavor diagrams (not Feynman diagrams) in the sense that only flavor flows are concerned.

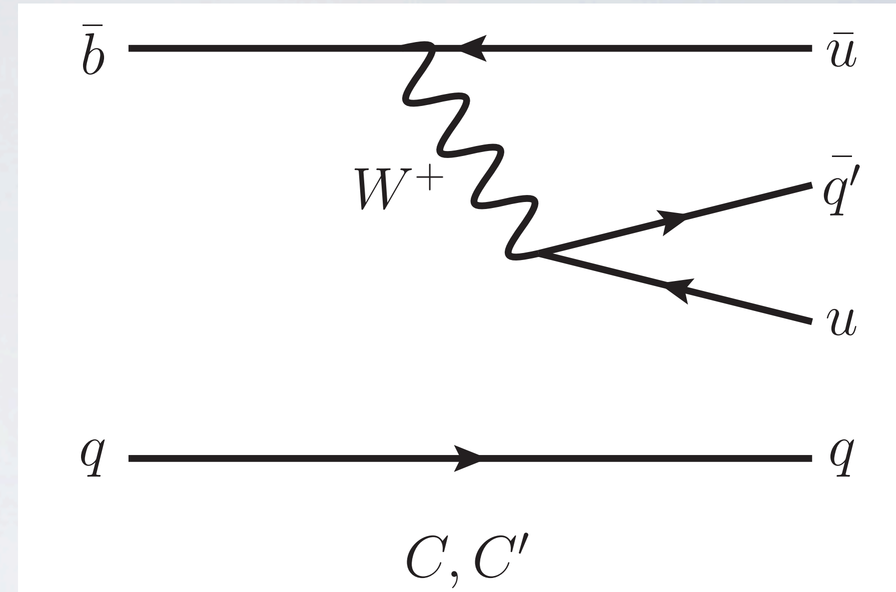




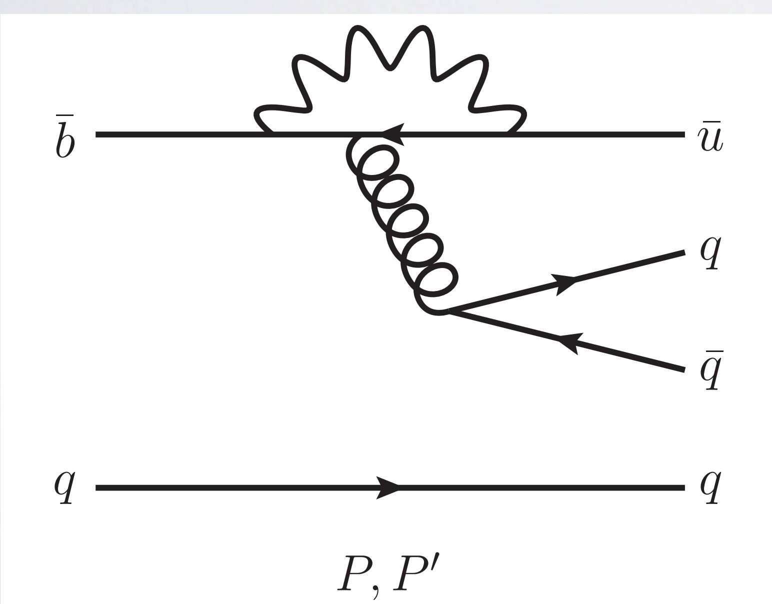
Contributing Diagrams



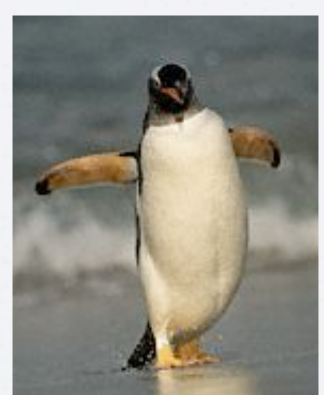
tree-level

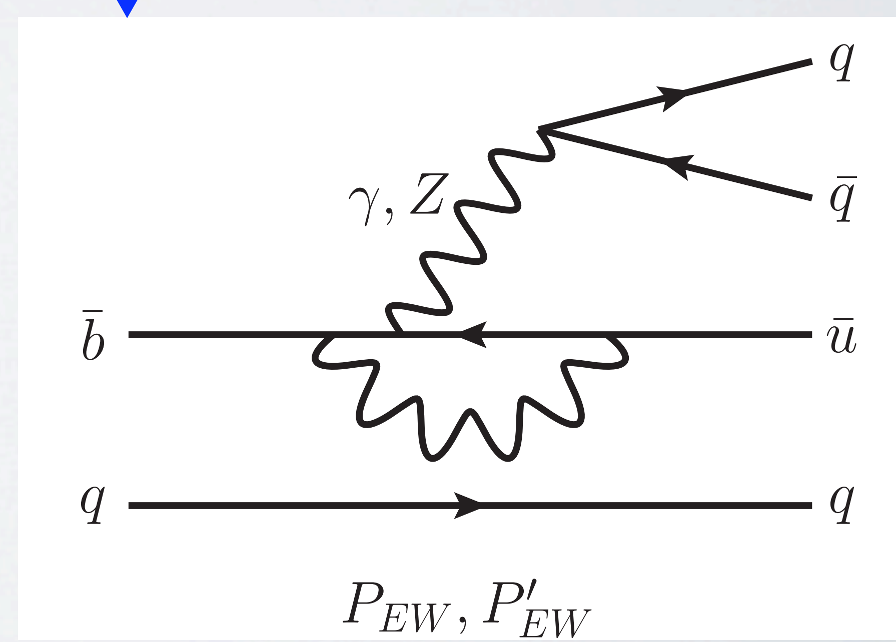


go together

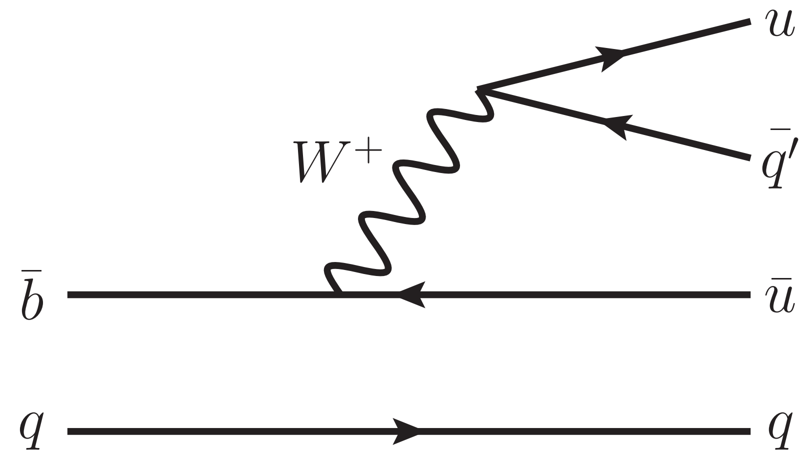


loop-mediated

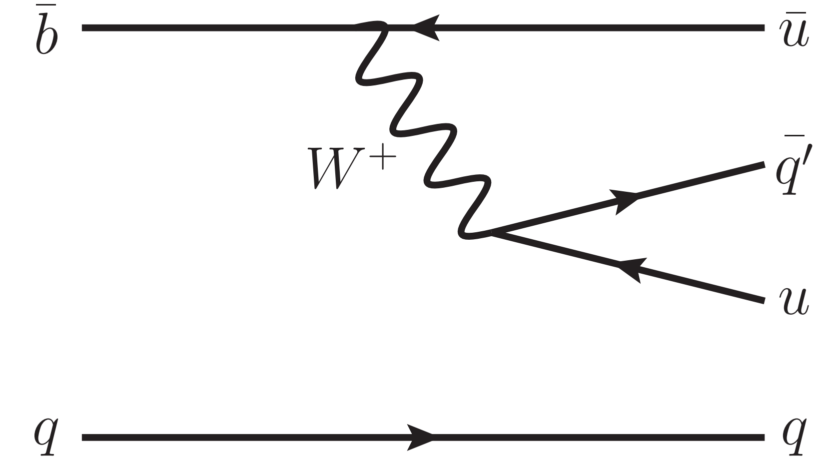




Contributing Diagrams

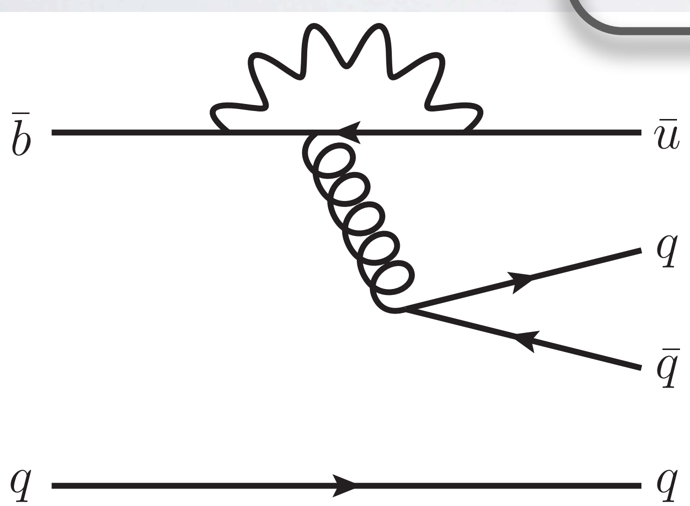


T, T'

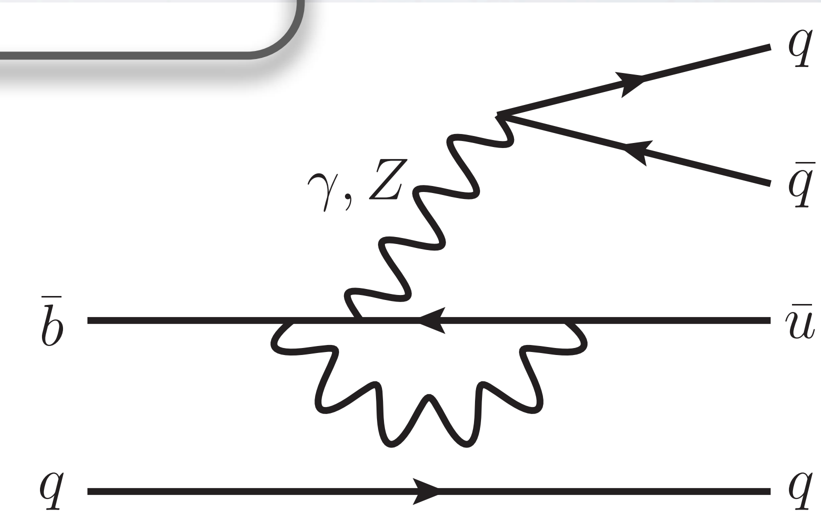


C, C'

Color-allowed tree diagram (external W emission):
~A λ^4 $e^{i\gamma}$ from CKM factors

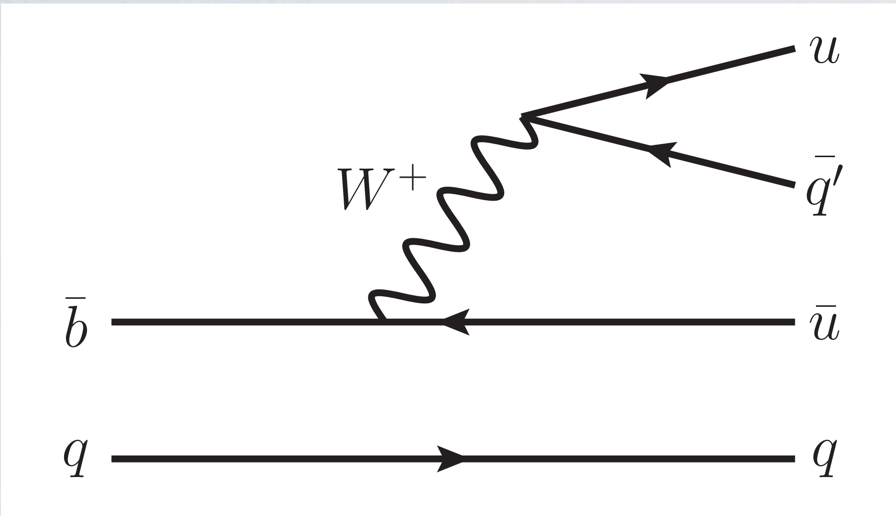


P, P'

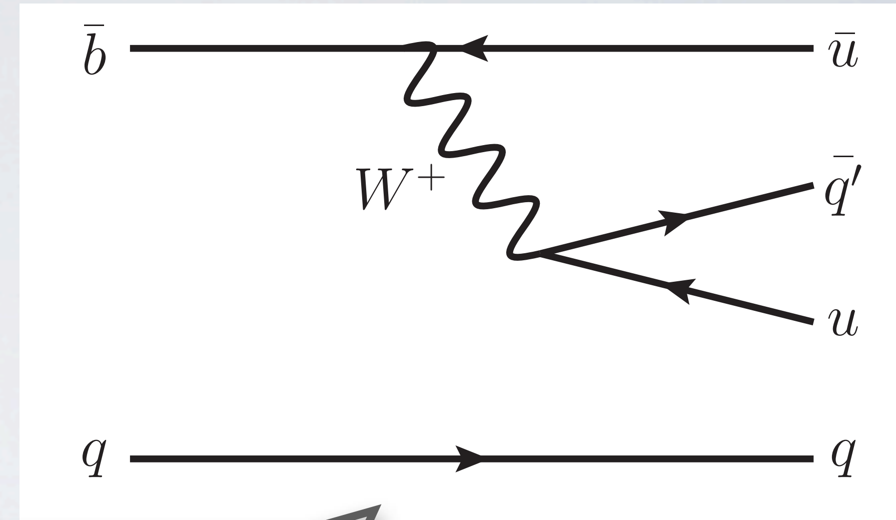


P_{EW}, P'_{EW}

Contributing Diagrams

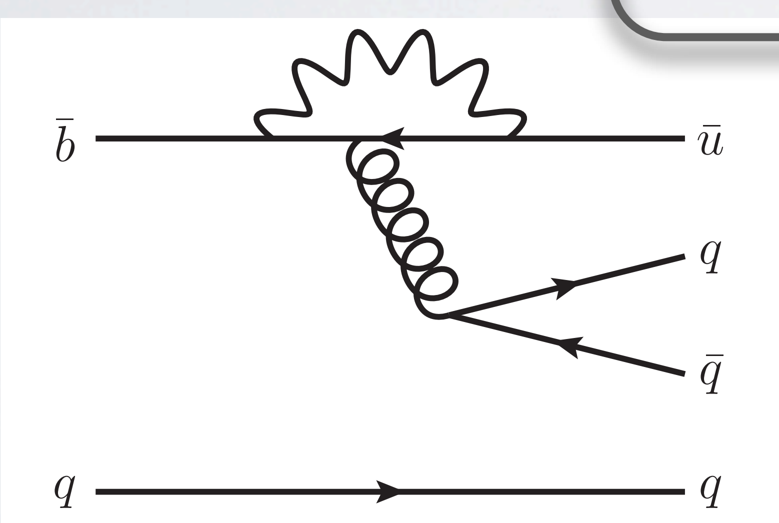


T, T'

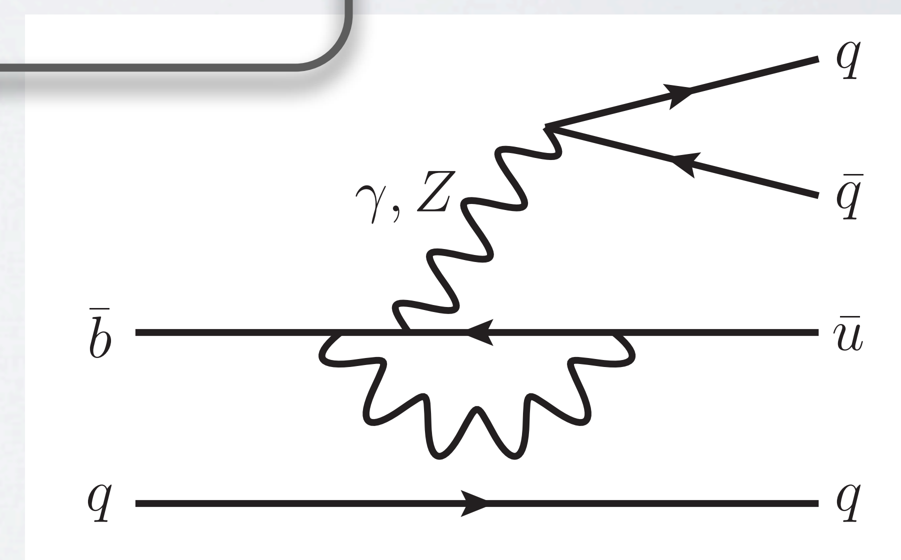


C, C'

Color-suppressed tree diagram (internal W emission): ~A $\lambda^4 e^{i\gamma}$ from CKM factors; down from T by ~1/3 naively

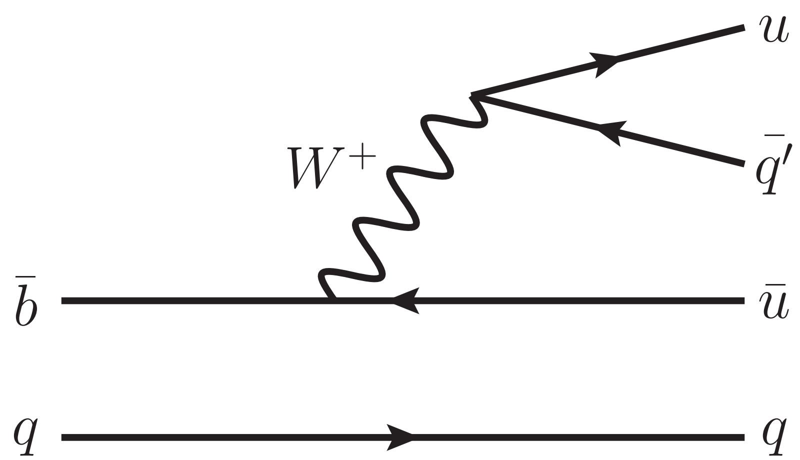


P, P'

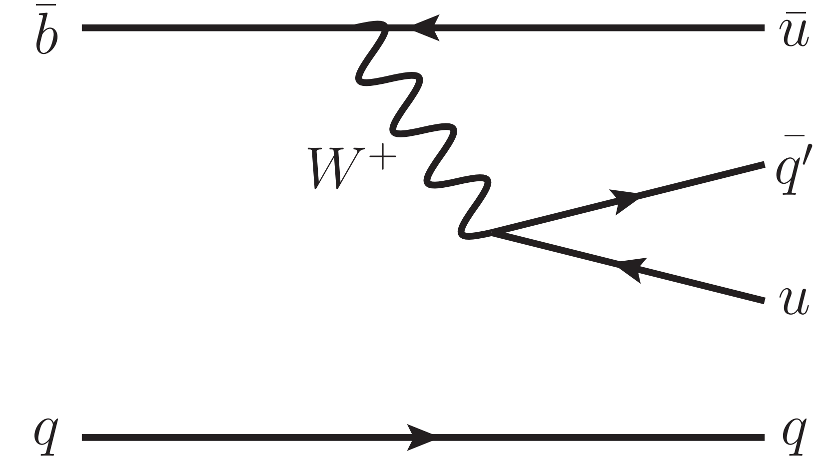


P_{EW}, P'_{EW}

CONTRIBUTING DIAGRAMS

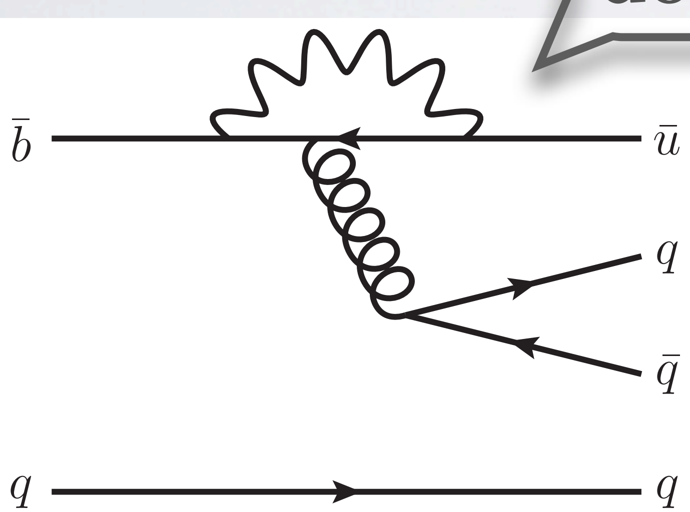


T, T'

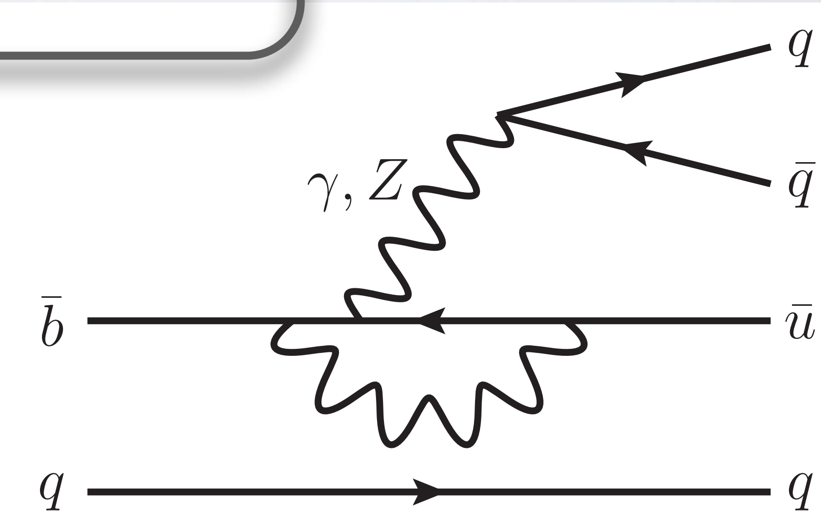


C, C'

QCD-penguin diagram:
~A λ² from CKM factors; u, c, t in the loop; down by one loop; dominant in K π decays

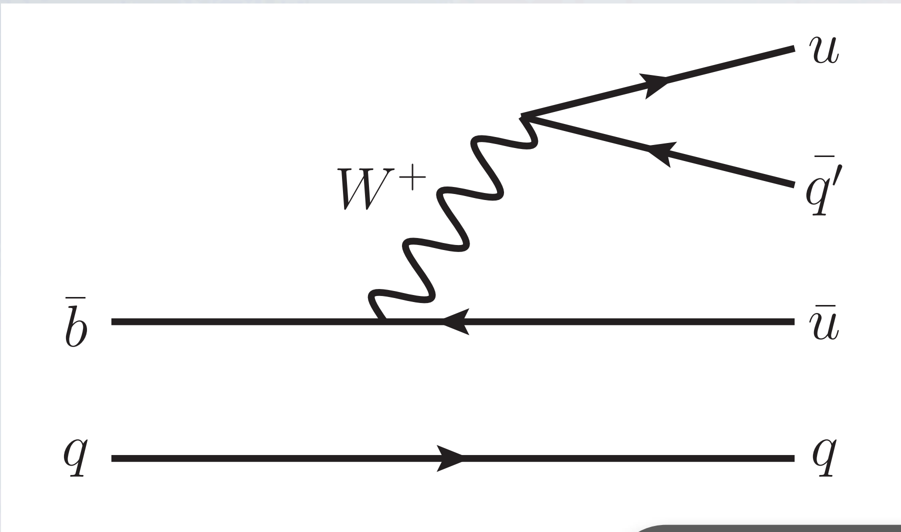


P, P'

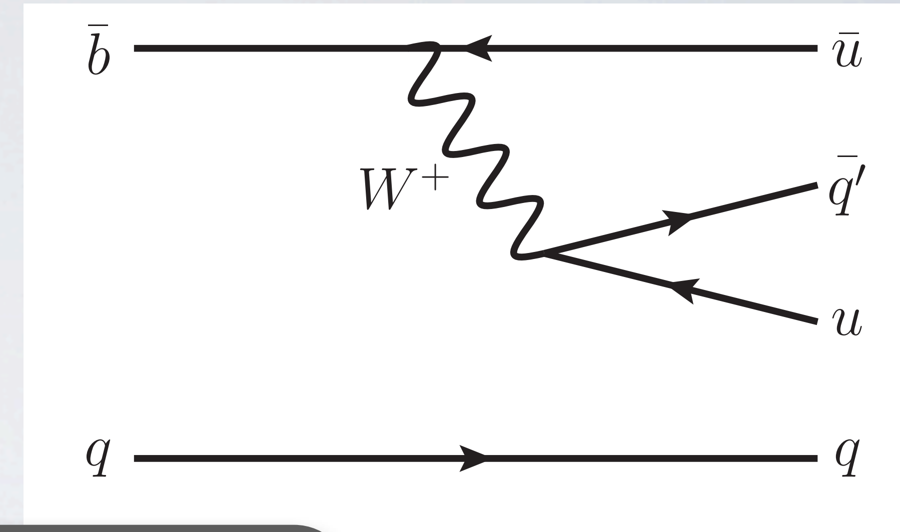


P_{EW}, P'_{EW}

Contributing Diagrams

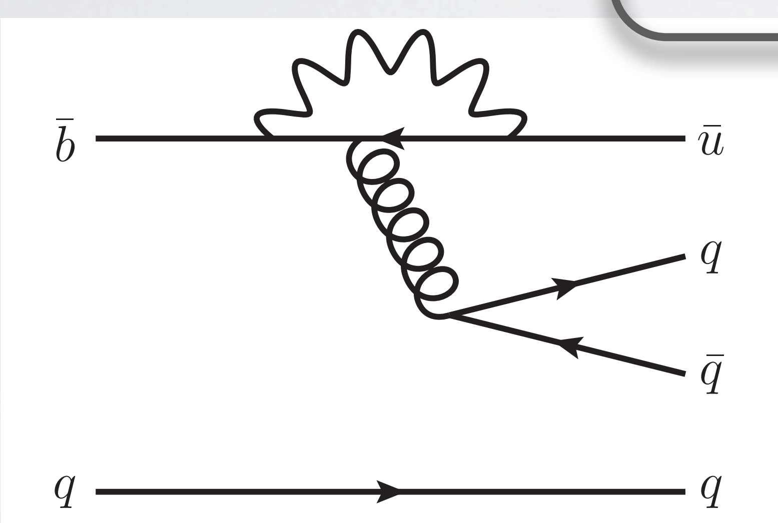


T, T'

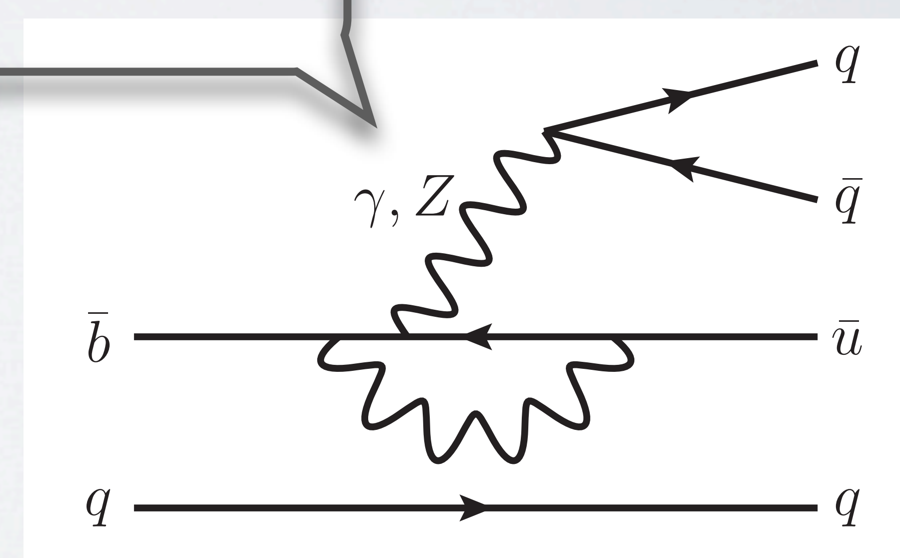


C, C'

EW-penguin diagram:
~A λ^2 from CKM factors; down by one loop and weak couplings

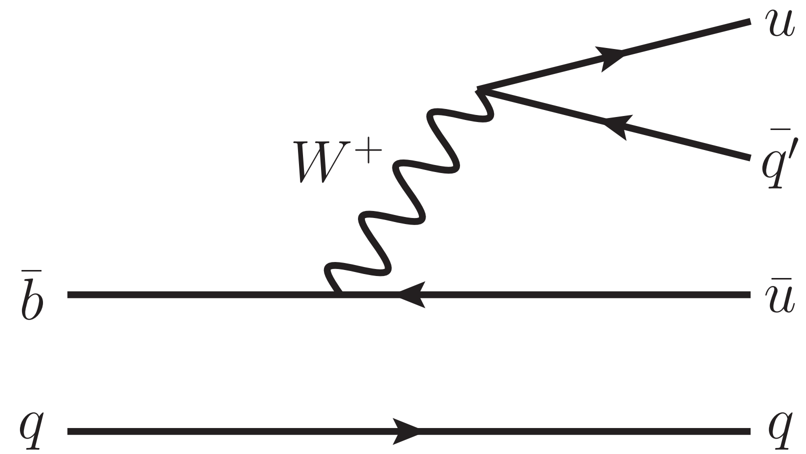


P, P'

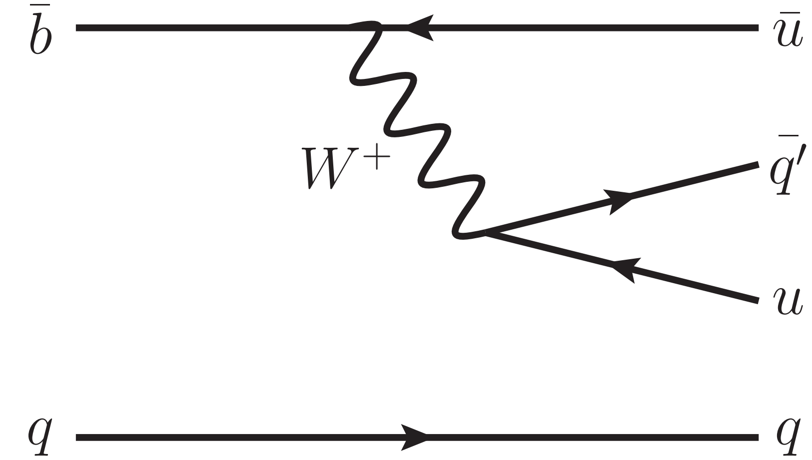


P_{EW}, P'_{EW}

CONTRIBUTING DIAGRAMS

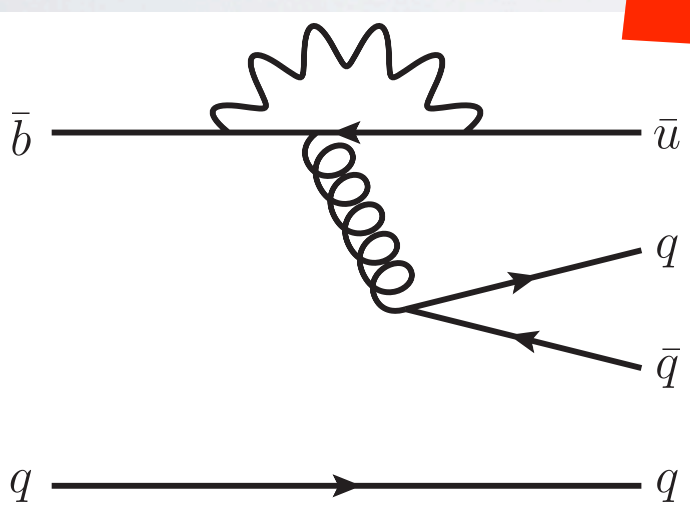


T, T'

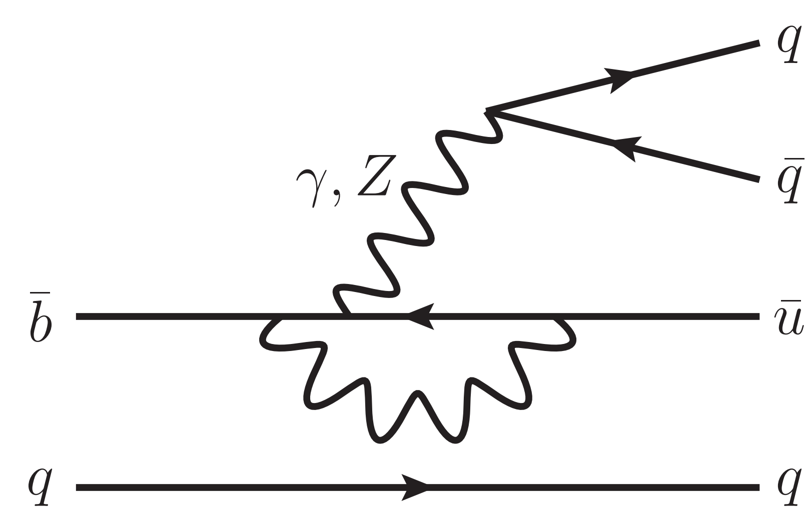


C, C'

$$B^+ \rightarrow \pi^+ K^0 \, (+0)$$

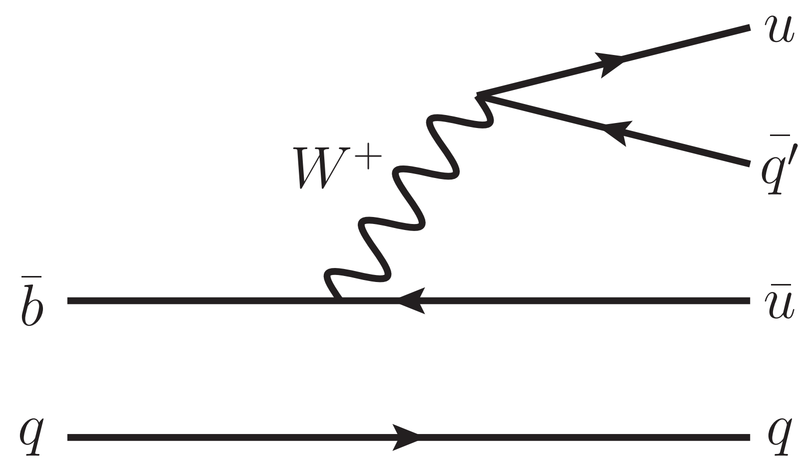


P, P'

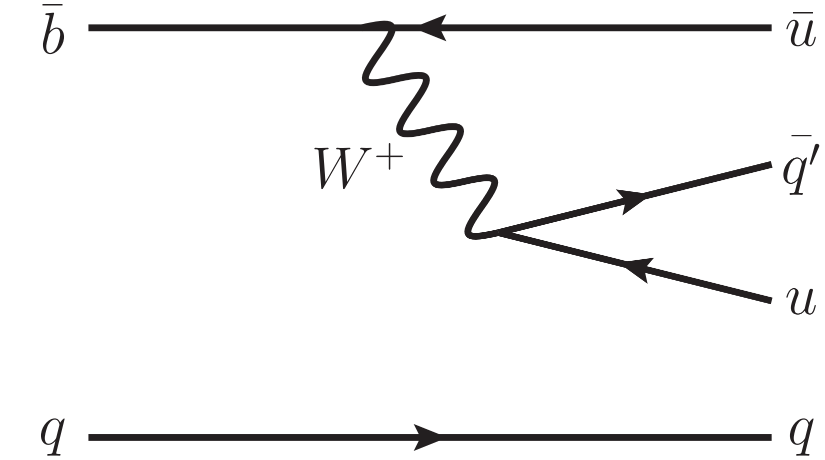


P_{EW}, P'_{EW}

Contributing Diagrams

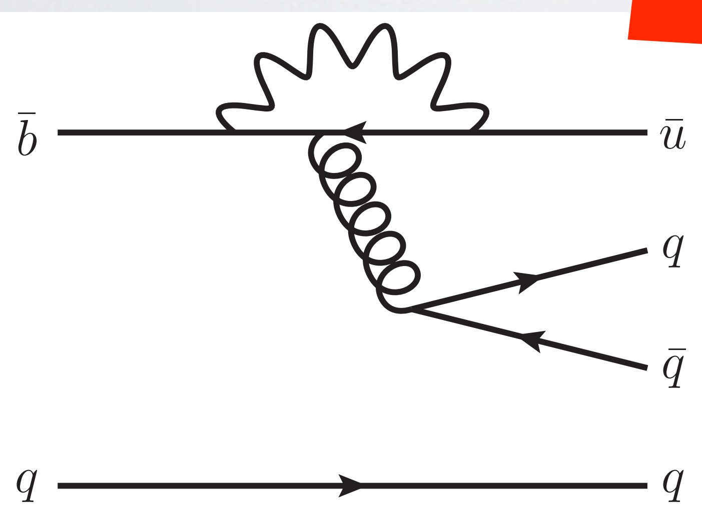


T, T'

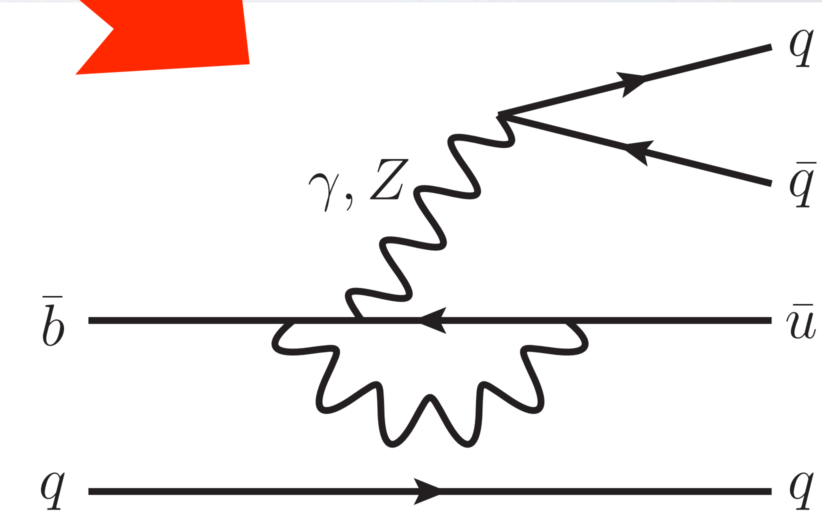


C, C'

$$B^+ \to \pi^0 K^+ \; (0+)$$

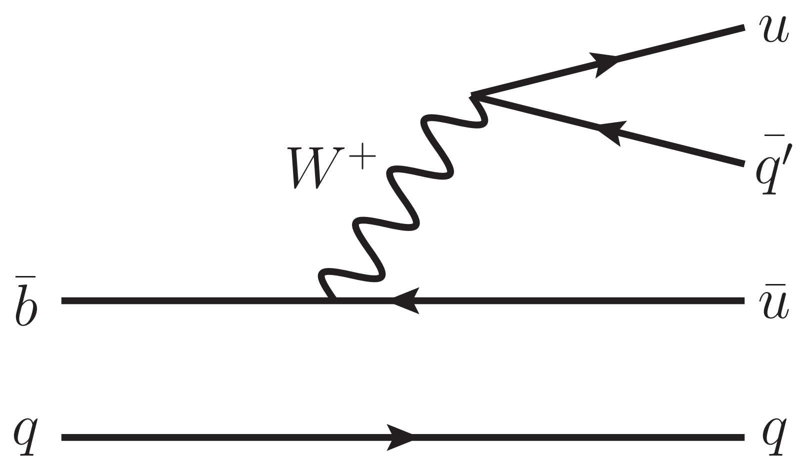


P, P'

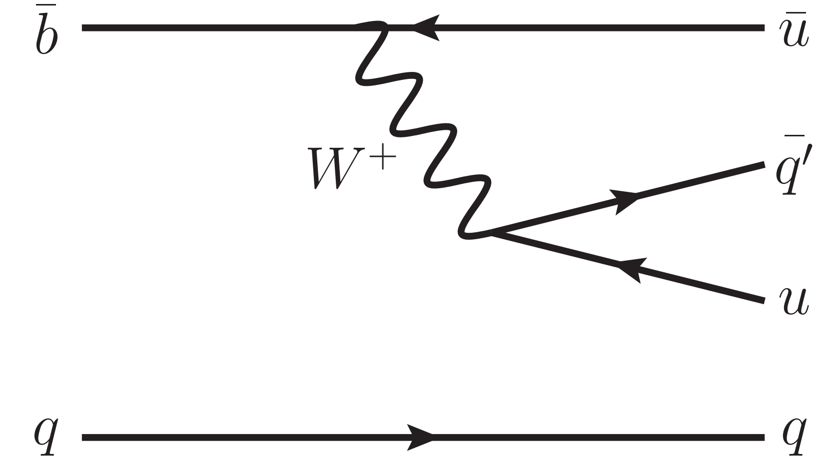


P_{EW}, P'_{EW}

CONTRIBUTING DIAGRAMS

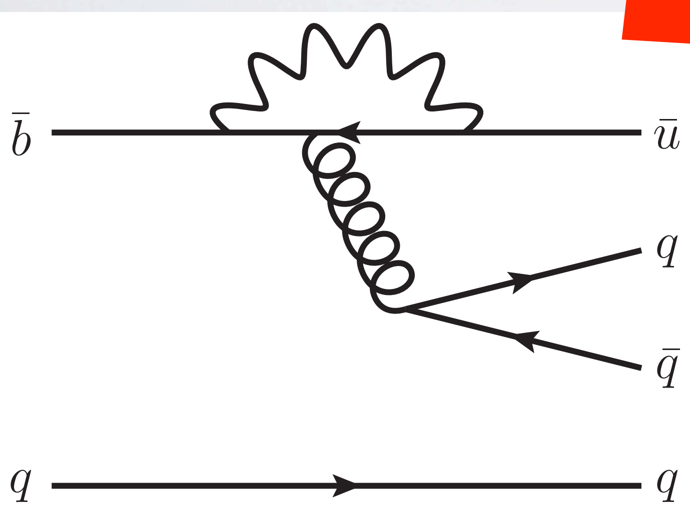


T, T'

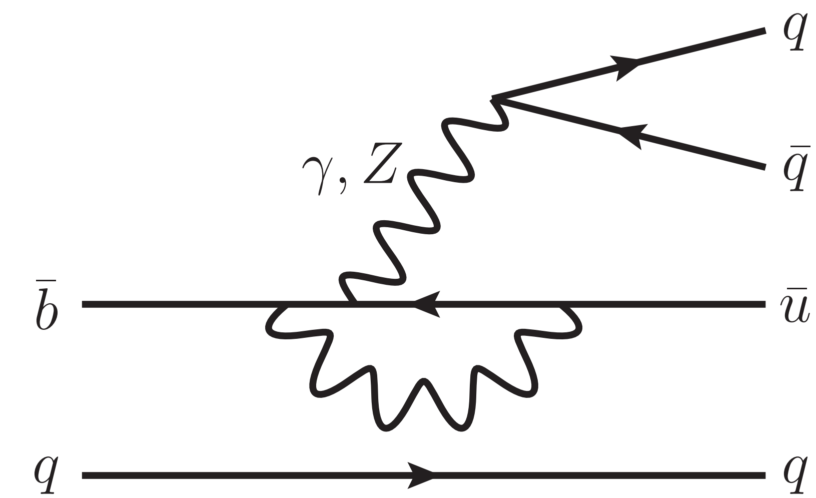


C, C'

$$B^0 \to \pi^- K^+ (-+)$$

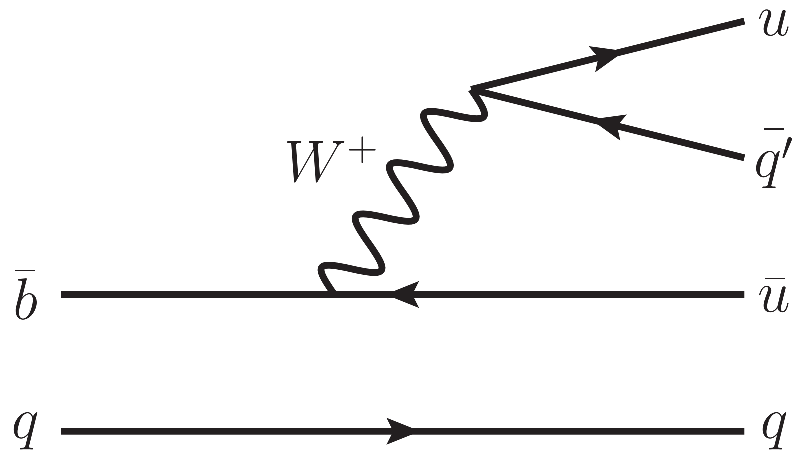


P, P'

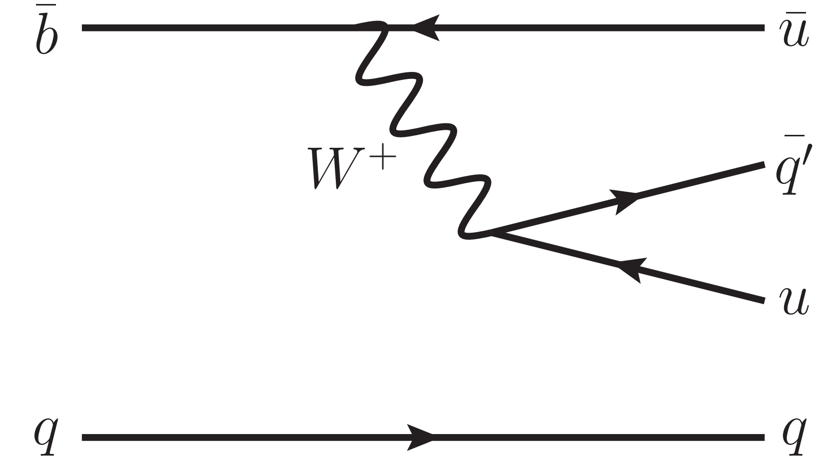


P_{EW}, P'_{EW}

CONTRIBUTING DIAGRAMS

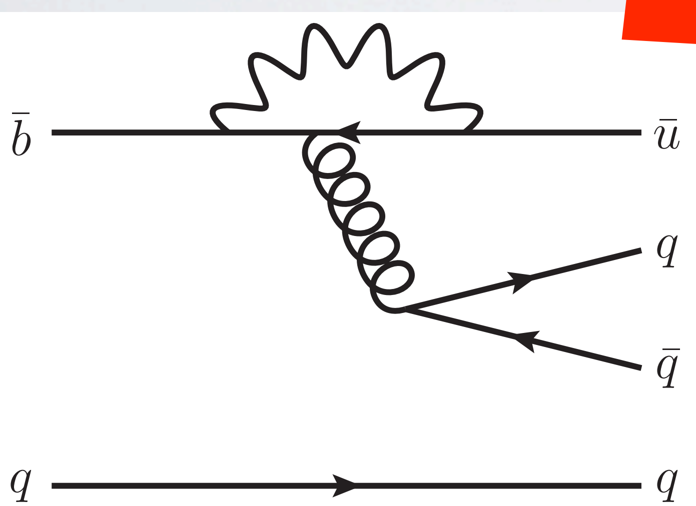


T, T'

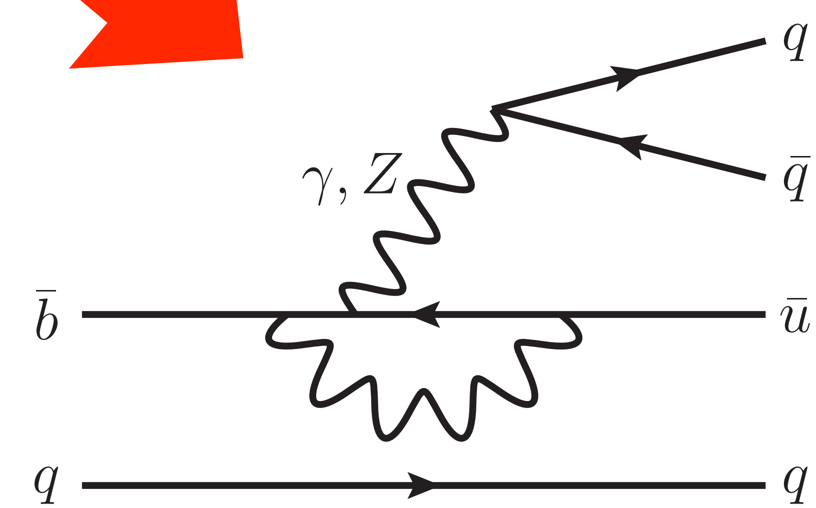


C, C'

$$B^0 \to \pi^0 K^0 \ (00)$$



P, P'



P_{EW}, P'_{EW}

OLD PUZZLE

- Before 2004, the K π puzzle was said to be in the ratios of averaged decay rates:

Year	$R_c \equiv \frac{2\overline{\Gamma}^{0+}}{\overline{\Gamma}^{+0}}$	$R_n \equiv \frac{\overline{\Gamma}^{-+}}{2\overline{\Gamma}^{00}}$	Difference
	$\left\lvert\frac{P'+T'+C'+P'_{EW}}{P'}\right\rvert^2$	$\left\lvert\frac{P'+T'}{P'-C'-P'_{EW}}\right\rvert^2$	$\mathcal{O}(\left[\frac{C'+P'_{EW}}{P'}\right]^2)$
pre-2004	1.15 ± 0.12	0.78 ± 0.10	2.4σ
2004 ICHEP	1.00 ± 0.09	0.79 ± 0.08	1.9σ
2005 LepPho	1.10 ± 0.09	0.82 ± 0.07	1.6σ
2008 ICHEP	1.12 ± 0.07	0.99 ± 0.07	1.3σ

- It is by now clear that this puzzle has been disappearing and the remaining small difference can be explained by the C′ and P'_{EW} amplitudes.

QCDF Predictions of BR's

Du et al 2003

- QCDF predictions with/without chirally enhanced hard spectator contributions and the annihilation penguin.

TABLE III. The best fit values using the global analysis with and without chiral-related contributions for $B \to PP$ and PV decays. "No chiral" means the best fit value neglecting the chirally enhanced hard spectator contributions and the annihilation topology. The branching ratios are in units of 10^{-6}. The experimental data are the uncorrelated average of measurements of BaBar, Belle, and CLEO (see the data in the last column of Table I).

Mode	$B^0 \to \pi^+\pi^-$	$B^+ \to \pi^+\pi^0$	$B^0 \to K^+\pi^-$	$B^+ \to K^+\pi^0$	$B^+ \to K^0\pi^+$
Expt.	4.77±0.54	5.78±0.95	18.5±1.0	12.7±1.2	18.1±1.7
Best fit	4.82	5.35	19.0 19.4±0.6	11.4 12.9±0.6	20.1 23.1±1.0
No chiral	5.68	3.25	18.8	12.6	20.2
Mode	$B^0 \to \pi^0 K^0$	$B^+ \to \eta\pi^+$	$B^0 \to \rho^\pm\pi^\mp$	$B^+ \to \rho^0\pi^+$	$B^+ \to \eta\rho^+$
Expt.	10.2±1.5	<5.2	25.4±4.3	8.6±2.0	<6.2
Best fit	8.2 9.8±0.6	2.8	26.7	8.9	4.6
No chiral	7.3	1.8	29.5	8.5	3.8
Mode	$B^+ \to \phi K^+$	$B^0 \to \phi K^0$	$B^0 \to K^+\rho^-$	$B^0 \to \omega K^0$	
Expt.	8.9±1.0	8.6±1.3	13.1±4.7	5.9±1.9	
Best fit	8.9	8.4	12.1	6.3	
No chiral	7.1	6.7	5.1	1.2	

New Puzzle

- Starting from 2005, a new K π puzzle in two direct CP asymmetries takes over:

Year	A_{CP}^{0+} $\propto P' + T' + C' + P'_{EW}$	A_{CP}^{-+} $\propto P' + T'$	Difference
pre-2004	0.00 ± 0.05	-0.095 ± 0.028	1.7σ
2005 LepPho	0.04 ± 0.04	-0.115 ± 0.018	3.5σ
2006 ICHEP	0.047 ± 0.026	-0.093 ± 0.015	4.7σ
2008 ICHEP	0.050 ± 0.025	-0.098 ± 0.012	5.4σ

- Naively, the two are expected to be the same if both C′ and P'_{EW} are negligibly small.
- People widely believe this as clear evidence of new physics...

Belle Collab. 2008, Peskin 2008

Perturbative Predictions

Group	A_{CP}^{0+}	A_{CP}^{-+}	
2008 ICHEP	0.050 ± 0.025	-0.098 ± 0.012	
QCDF [S4]	-0.036	-0.041	Beneke, Neubert 2003
pQCD	$-0.01^{+0.03}_{-0.05}$	$-0.09^{+0.06}_{-0.08}$	Li, Mishima, Sanda 2005
SCET	-0.11 ± 0.14	-0.06 ± 0.08	Williamson, Zupan 2006

- All the above predictions can roughly agree with observed A_{CP}^{-+}. But all of them have the wrong sign of A_{CP}^{0+}!
- Take QCDF for example, though the inclusion of penguin annihilation amps brings up the K π rates and get the signs of $A_{CP}(\pi^- K^+, \pi^- K^{*+}, \rho^0 K^+, \pi^+\pi^-)$ correct, they mess up with the signs of $A_{CP}(\pi^0 K^+, \eta K^+, \eta K^{*0}, \pi^0\pi^0)$. Subleading $1/m_b$ corrections to C are required.

Cheng, Chua 2009

Possible Explanations

- Within SM: large color-suppressed amplitude (C') with a sizeable strong phase relative to T' [feasible perturbatively from NLO vertex corrections and k_T factorization breakdown].

CC, Gronau, Rosner, Suprun 2004;
Li, Mishima, Sanda 2005, 2009;
CC, Zhou 2006

- Beyond SM: additional EW-penguin type of amplitude from new physics [feasible in, e.g., SUSY, FCNC Z' models, 4G, etc].

Yoshikawa 2004; Buras et al 2004;
Barger, CC, Langacker, Lee 2004;
Baek et al 2005; Hou et al 2005

Is New K π Puzzle Real?

Amplitudes Explicitly

- After using the unitarity relation to remove the $V_{cb}V_{cs}^*$ part of the QCD penguin amplitude, one obtains:

$$
\begin{aligned}
A^{+0} &\equiv A(B^+ \to \pi^+ K^0) = -P'_{tc} + P'_{uc} e^{i\gamma} - \frac{1}{3} P'^{C}_{EW} \\
\sqrt{2} A^{0+} &\equiv \sqrt{2} A(B^+ \to \pi^0 K^+) = -T' e^{i\gamma} - C' e^{i\gamma} + P'_{tc} - P'_{uc} e^{i\gamma} - P'_{EW} - \frac{2}{3} P'^{C}_{EW} \\
A^{-+} &\equiv A(B^0 \to \pi^- K^+) = -T' e^{i\gamma} + P'_{tc} - P'_{uc} e^{i\gamma} - \frac{2}{3} P'^{C}_{EW} \\
\sqrt{2} A^{00} &\equiv \sqrt{2} A(B^0 \to \pi^0 K^0) = -C' e^{i\gamma} - P'_{tc} + P'_{uc} e^{i\gamma} - P'_{EW} - \frac{1}{3} P'^{C}_{EW}
\end{aligned}
$$

  - weak phase explicit; strong phases implicit
  - $P'_{tc} \propto P'_t - P'_c$ and $P'_{uc} \propto P'_u - P'_c$
  - 6 amp sizes, 5 relative strong phases, 2 weak phases (β and γ)
  - rough hierarchy in amplitudes

$\mathcal{O}(1)$	$\mathcal{O}(\tilde{\lambda})$	$\mathcal{O}(\tilde{\lambda}^2)$
$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$, P'_{EW}	$\lvert C'\rvert$, $\lvert P'_{uc}\rvert$, P'^{C}_{EW}

Current and Past Data

- Not much change in BR's and CPA's in most modes, except for A_{CP} and S_{CP} of the $\pi^0 K^0$ mode.
- These changes, however, have significant consequences on overall fits, particularly $A_{CP}(\pi^0 K^0)$.

Table 1
Branching fractions and CP asymmetries for $B \to \pi K$ decays, as of today and for early 2007 (in parentheses) [13].

Mode	$\mathcal{B}(10^{-6})$	A_{CP}	S_{CP}
$B^0 \to \pi^- K^+$	19.4 ± 0.6	$-0.098^{+0.012}_{-0.011}$	
	(19.7 ± 0.6)	(-0.093 ± 0.015)	
$B^+ \to \pi^0 K^+$	12.9 ± 0.6	0.050 ± 0.025	
	(12.8 ± 0.6)	(0.047 ± 0.026)	
$B^0 \to \pi^0 K^0$	9.8 ± 0.6	-0.01 ± 0.10	0.57 ± 0.17
	(10.0 ± 0.6)	(-0.12 ± 0.11)	(0.33 ± 0.21)
$B^+ \to \pi^+ K^0$	23.1 ± 1.0	0.009 ± 0.025	
	(23.1 ± 1.0)	(0.009 ± 0.025)	

depends on β

totally 9 observables

SU(3) Relation

Neubert, Rosner 1998
Gronau, Pirjol, Yan 1999

- Tree-EWP relations

$$P'_{EW} = \frac{3}{4}\frac{c_9+c_{10}}{c_1+c_2}R(T'+C') + \frac{3}{4}\frac{c_9-c_{10}}{c_1-c_2}R(T'-C')$$

$$\simeq \frac{3}{2}\frac{c_9+c_{10}}{c_1+c_2}RT'$$

$$P'^{C}_{EW} = \frac{3}{4}\frac{c_9+c_{10}}{c_1+c_2}R(T'+C') - \frac{3}{4}\frac{c_9-c_{10}}{c_1-c_2}R(T'-C')$$

$$\simeq \frac{3}{2}\frac{c_9+c_{10}}{c_1+c_2}RC'$$

$\frac{3}{2}\frac{c_9+c_{10}}{c_1+c_2}R \to -0.60\pm0.02$

Numerically, $(c_9+c_{10})/(c_1+c_2) \cong (c_9-c_{10})/(c_1-c_2)$ and $R = |(V_{tb}^* V_{ts})/(V_{ub}^* V_{us})| = 48.9\pm1.6$.

- SU(3) breaking introduces theoretical errors about 10% in coefficient magnitude and 5° in strong phase.

Neubert 1999

EXTRACTING PARAMETERS

needed for S_{CP}^{00}

- Totally, we use:
  - 10 data points [BR's and CPA's of K π decays and $\beta = (21.66^{+0.95}_{-0.87})^\circ$ from $B \to (c\bar{c})K_{L,S}$] or
  - 11 data points [further adding $\gamma = (66.8^{+5.4}_{-3.8})^\circ$].

CKMfitter 2008

- Initially, there are 13 parameters.
  ⇒ Tree-EWP relations remove 4 parameters
  ⇒ 9 SM parameters to fit 10 or 11 data points.
- Remark: we only keep the solutions that roughly satisfy the hierarchy mentioned before, where $\tilde{\lambda} \sim 0.2$

$\mathcal{O}(1)$	$\mathcal{O}(\tilde{\lambda})$	$\mathcal{O}(\tilde{\lambda}^2)$
$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$, P'_{EW}	$\lvert C'\rvert$, $\lvert P'_{uc}\rvert$, P'^{C}_{EW}

Otherwise, new physics should have been seen elsewhere.

SM Fit Result

Table 3
Results of the fit to P'_{tc}, T', C', P'_{uc}, β and γ in the SM. The fit includes the constraint $\beta = (21.66^{+0.95}_{-0.87})^\circ$. The amplitude is in units of eV.

χ^2_{min}/d.o.f.	$\lvert P'_{tc} \rvert$	$\lvert T' \rvert$	$\lvert C' \rvert$	$\lvert P'_{uc} \rvert$
0.52/1	67.7 ± 11.8	19.6 ± 6.9	14.9 ± 6.6	20.5 ± 13.3
$\delta_{T'}$	$\delta_{C'}$	$\delta_{P'_{uc}}$	β	γ
$(6.0 \pm 4.0)^\circ$	$(-11.7 \pm 6.8)^\circ$	$(-0.7 \pm 2.3)^\circ$	$(21.66 \pm 0.95)^\circ$	$(35.3 \pm 7.1)^\circ$

47% CL

somewhat large

→ 3.5σ

The SM fit

Table 4
Results of the fit to P'_{tc}, T', C', P'_{uc}, β and γ in the SM. The fit includes the constraints $\beta = (21.66^{+0.95}_{-0.87})^\circ$ and $\gamma = (66.8^{+5.4}_{-3.8})^\circ$. The amplitude is in units of eV.

χ^2_{min}/d.o.f.	$\lvert P'_{tc} \rvert$	$\lvert T' \rvert$	$\lvert C' \rvert$	$\lvert P'_{uc} \rvert$
3.2/2	50.5 ± 1.8	5.9 ± 1.8	3.4 ± 1.0	2.3 ± 4.9
$\delta_{T'}$	$\delta_{C'}$	$\delta_{P'_{uc}}$	β	γ
$(25.5 \pm 11.2)^\circ$	$(252.0 \pm 36.1)^\circ$	$(-9.9 \pm 27.8)^\circ$	$(21.65 \pm 0.95)^\circ$	$(66.5 \pm 5.5)^\circ$

20% CL

a bit too small

Predictions of Best Fits

Table 5

Predictions of the $B \to \pi K$ decay observables based upon the best-fitted results in Table 3 (Fit 1) and Table 4 (Fit 2). Branching ratios are given in units of 10^{-6}. Numbers in parentheses are the corresponding pulls.

Obs.	Fit 1	Fit 2
$\mathrm{BR}(\pi^+ K^0)$	23.1 (+0.02)	23.7 (−0.57)
$A_{\mathrm{CP}}(\pi^+ K^0)$	0.014 (−0.21)	0.016 (−0.29)
$\mathrm{BR}(\pi^0 K^+)$	12.9 (−0.03)	12.5 (+0.72)
$A_{\mathrm{CP}}(\pi^0 K^+)$	0.05 (+0.15)	0.04 (+0.27)
$\mathrm{BR}(\pi^- K^+)$	19.4 (+0.05)	19.7 (−0.46)
$A_{\mathrm{CP}}(\pi^- K^+)$	−0.098 (−0.04)	−0.097 (−0.12)
$\mathrm{BR}(\pi^0 K^0)$	9.8 (−0.07)	9.3 (+0.88)
$A_{\mathrm{CP}}(\pi^0 K^0)$	−0.08 (+0.66)	−0.12 (+1.10)
$S_{\mathrm{CP}}(\pi^0 K^0)$	0.58 (−0.03)	0.58 (−0.08)

- No difficulty in reproducing significantly different CPA's of $\pi^0 K^+$ and $\pi^- K^+$. No problem with S_{CP}^{00} either.
- A_{CP}^{00} has the largest pull in both fits, but not too serious.

Problem With $A_{CP}(\pi^0 K^0)$

- In fact, BaBar and Belle do not agree on this number. Our prediction is closer to BaBar's measurement.

Year	S_{CP}^{00}	A_{CP}^{00}	
2006 ICHEP	0.33 ± 0.26	-0.20 ± 0.16	BaBar
	0.33 ± 0.36	-0.05 ± 0.15	Belle
	0.33 ± 0.21	-0.12 ± 0.11	Average
2008 ICHEP	0.55 ± 0.20	-0.13 ± 0.13	BaBar
	0.67 ± 0.32	0.14 ± 0.14	Belle
	0.57 ± 0.17	-0.01 ± 0.10	Average

Puzzle with $A_{CP}(\pi^0 K^0)$

- In the following fits, we drop the Belle measurement.
- The fit quality improves to 76% and 43%, respectively.

Table 6
Results of the fits to P'_{tc}, T', C', P'_{uc}, β and γ in the SM. The averaged experimental data given in Table 1 is used, except that only the BaBar measurement of $A_{CP}(\pi^0 K^0) = -0.13 \pm 0.13$ is taken. The fits include the constraints $\beta = (21.66^{+0.95}_{-0.87})^\circ$. For γ, we impose no constraint (Fit 1′), or $\gamma = (66.8^{+5.4}_{-3.8})^\circ$ (Fit 2′). The amplitude is in units of eV.

	χ^2_{min}/d.o.f.	$\|P'_{tc}\|$	$\|T'\|$	$\|C'\|$	$\|P'_{uc}\|$	
76% CL	Fit 1′: 0.095/1	66.9 ± 11.9	18.8 ± 7.3	14.1 ± 7.0 (somewhat large)	19.9 ± 13.3 (somewhat large)	
	$\delta_{T'}$	$\delta_{C'}$	$\delta_{P'_{uc}}$	β	γ	
	$(5.4 \pm 4.3)^\circ$	$(-13.6 \pm 8.4)^\circ$	$(0.0 \pm 2.4)^\circ$	$(21.66 \pm 0.95)^\circ$	$(35.9 \pm 7.7)^\circ$	→ 3.5σ
	χ^2_{min}/d.o.f.	$\|P'_{tc}\|$	$\|T'\|$	$\|C'\|$	$\|P'_{uc}\|$	
43% CL	Fit 2′: 1.7/2	41.5 ± 2.4	8.5 ± 2.5 (too small)	13.7 ± 2.6	10.7 ± 3.9	
	$\delta_{T'}$	$\delta_{C'}$	$\delta_{P'_{uc}}$	β	γ	
	$(139.2 \pm 12.8)^\circ$	$(212.2 \pm 7.2)^\circ$	$(184.0 \pm 4.3)^\circ$	$(21.59 \pm 0.95)^\circ$	$(64.6 \pm 4.9)^\circ$	

REMARKS

- Had we picked the Belle measurement for the fits, the fit quality would drop to 18% and 7% for Fit 1' and Fit 2', respectively.
- Moreover, Fit 1' gives $\gamma = (96.4 \pm 12.4)^\circ$ and $|P'_{uc}| = (31.9 \pm 5.4)$ eV; and Fit 2' renders small $|T'/P'_{tc}|$ still.

Isospin Relation

- The P'_{tc} and P'_{uc} amplitudes are isoscalar ($\Delta I = 0$), whereas the rest amplitudes (T', C', and EWP's) are mixtures of isoscalar and isovector ($\Delta I = 1$).

- Quadrangle relation:

Gronau, et al 1994, 1995

$$A^{+0} + \sqrt{2}A^{0+} = A^{-+} + \sqrt{2}A^{00}$$

where isoscalar ($\Delta I = 0$) and isovector ($\Delta I = 1$) parts match on both sides separately.

CP Asymmetry Sum Rule

- Define $\Delta \equiv \Gamma$(anti-B decay)−Γ(B decay), then a very robust sum rule is Gronau, et al 2005

$$\Delta(\pi^- K^+) + \Delta(\pi^+ K^0) \simeq 2\left[\Delta(\pi^0 K^+) + \Delta(\pi^0 K^0)\right]$$

  which is based on the quadrangle relation.
- It can be violated if there is a significantly large isovector new physics amplitude.
- Using all CPA's (except for A_{CP}^{00}) and the above sum rule, we predict $A_{CP}^{00} = -0.149 \pm 0.044$, more consistent with our prediction and BaBar measurement.
- This is more than 3σ away from zero and the largest CPA of the four K π modes!

Summary About SM Fits

- Our SM fit achieves a quality of 20% using all data or 43% when Belle's A_{CP}^{00} is excluded.
- No difficulty in reproducing A_{CP}^{0+}, A_{CP}^{-+}, and S_{CP}^{00}.
- A somewhat large $|C'|$ is required, which is also favored in global fits to all charmless PP decays. CC, Zhou 2006
- A_{CP}^{00} presents the biggest trouble (though not serious).
- Based upon current data, A_{CP}^{00} could be the largest CPA.

New Physics Possibility

Types of New Physics

Datta, London 2004

- All NP operators in B → π K decays take the form

$$\mathcal{O}_{\rm NP}^{ij,q} \sim (\bar{s}\Gamma_i b)(\bar{q}\Gamma_j q) \qquad (q = u, d)$$

  where $\Gamma_{i,j}$ represent Lorentz structures and color indices are suppressed.

- All NP strong phases can be argued to be negligible and equal to that of T′.

- One can thus combine all NP matrix elements into a single NP amplitude, with a single effective weak phase

$$\sum \langle \pi K | \mathcal{O}_{\rm NP}^{ij,q} | B \rangle = A^q e^{i\Phi_q}$$

- We can rearrange to have three types of NP amplitudes:

$$P'_{\rm NP} e^{i\Phi'_P} \ , \quad P'_{\rm EW,NP} e^{i\Phi'_{EW}} \ , \text{ and } P'^{C}_{\rm EW,NP} e^{i\Phi'^{C}_{EW}}$$

isoscalar — isoscalar + isovector

Fits With NP Amplitudes

- We will assume that one single NP amplitude dominates at a time, as we have at most 11 observables.
- To increase the d.o.f. in our fits, we ignore P'_{uc}.
- Among the three types of NP amplitudes, $P'_{\rm NP} e^{i\Phi'_P}$ shows up in all decay modes and is equivalent to redefining the SM QCD-penguin amplitude.

Fit Results

Table 7

Results of the fits to P'_{tc}, T', C', β, γ and a NP amplitude. The fits include the constraints $\beta = (21.66^{+0.95}_{-0.87})^\circ$ and $\gamma = (66.8^{+5.4}_{-3.8})^\circ$, and in all cases, the best-fit values of β and γ are consistent with these. The constraint $\delta_{T'} = \delta_{\rm NP}$ is also added. The amplitude is in units of eV. The entry NA (not applicable) is explained in the text.

$\chi^2_{\rm min}$/d.o.f.	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert C'\rvert$
3.6/2	NA	5.9 ± 2.0	3.6 ± 1.0
$\lvert P'_{\rm NP}\rvert$	$\delta_{C'}$	$\delta_{\rm NP}$	Φ'_P
NA	NA	NA	NA
$\chi^2_{\rm min}$/d.o.f.	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert C'\rvert$
0.4/2	48.2 ± 1.3	2.6 ± 0.4	16.1 ± 28.4
$\lvert P'_{\rm EW,NP}\rvert$	$\delta_{C'}$	$\delta_{\rm NP}$	$\Phi'_{\rm EW}$
20.1 ± 22.3	$(254.8 \pm 21.8)^\circ$	$(95.4 \pm 9.6)^\circ$	$(37.6 \pm 51.8)^\circ$
$\chi^2_{\rm min}$/d.o.f.	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert C'\rvert$
2.5/2	48.2 ± 1.3	1.9 ± 1.4	9.4 ± 2.3
$\lvert P'^{C}_{\rm EW,NP}\rvert$	$\delta_{C'}$	$\delta_{\rm NP}$	$\Phi'^{C}_{\rm EW}$
16.5 ± 15.2	$(192.4 \pm 12.3)^\circ$	$(97.8 \pm 15.3)^\circ$	$(183.9 \pm 7.8)^\circ$

17% CL

Essentially SM fit

NA: unconstrained

82% CL

enormous |C′/T′| and tiny |T′ |

28% CL

NP Fits With Constraint

- Fix $|C'/T'| = 0.5$ (one less parameter):

Table 8

Results of the fits to P'_{tc}, T', C', β, γ and a NP amplitude. The fits include the constraints $\beta = (21.66^{+0.95}_{-0.87})^\circ$ and $\gamma = (66.8^{+5.4}_{-3.8})^\circ$, and in all cases, the best-fit values of β and γ are consistent with these. The constraints $\delta_{T'} = \delta_{NP}$ and $|C'/T'| = 0.5$ are also added. The amplitude is in units of eV. The entry NA (not applicable) is explained in the text.

	χ^2_{min}/d.o.f.	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert P'_{NP}\rvert$
29% CL	3.7/3	NA	6.6 ± 1.1	NA
	$\delta_{C'}$	δ_{NP}	Φ'_P	
	NA	NA	NA	
	χ^2_{min}/d.o.f.	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert P'_{EW,NP}\rvert$
39% CL	3.0/3	48.0 ± 0.6	2.6 ± 0.3	15.7 ± 3.6
	$\delta_{C'}$	δ_{NP}	Φ'_{EW}	
	$(182.5 \pm 53.1)^\circ$	$(98.4 \pm 4.7)^\circ$	$(-11.6 \pm 5.7)^\circ$	
	χ^2_{min}/d.o.f.	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert P'^{C}_{EW,NP}\rvert$
28% CL	3.8/3	49.8 ± 0.7	6.5 ± 1.4	2.1 ± 6.2
	$\delta_{C'}$	δ_{NP}	Φ'^{C}_{EW}	
	$(274.7 \pm 59.2)^\circ$	$(15.6 \pm 10.8)^\circ$	$(69.7 \pm 67.4)^\circ$	

improved quality due to 1 more dof

sizeable $P'_{EW,NP}$

quality decreased markedly!

irrelevant $P'^{C}_{EW,NP}$

essentially SM as NP amp is small

RATE SUM RULE

- The following sum rule of decay rates is sensitive to $\Delta I = 1$ amplitudes:

$$2\left[\mathcal{B}^{0+} + \frac{\tau_+}{\tau_0}\mathcal{B}^{00}\right] = \frac{\tau_+}{\tau_0}\mathcal{B}^{-+} + \mathcal{B}^{+0}$$

- Current data: LHS = 46.8±1.8 and RHS = 43.9±1.2 in units of 10^{-6}, agreeing at 1.4σ level.

Table 2

Comparison of fits of Ref. [12] with and without constraint $|C/T| = 0.5$. Prediction for (a) $A_{CP}(\pi^0 K^0)$, (b) Eq. (19), l.h.s; (c) Eq. (19), r.h.s.

Fit	With $\|C/T\| = 0.5$				Without $\|C/T\| = 0.5$			
	$\chi^2/d.o.f.$	(a)	(b)	(c)	$\chi^2/d.o.f.$	(a)	(b)	(c)
1	3.7/3	−0.11	44.9	44.8	3.6/2	−0.12	44.9	44.8
2	3.0/3	−0.12	47.1	43.2	0.4/2	−0.03	47.0	43.8
3	3.8/3	−0.12	44.9	44.8	2.5/2	−0.03	45.3	44.6

large $P'_{EW,NP}$, thus violating rate sum rule

Summary About NP Fits

- Usable observables do not allow fits with more than one NP amplitude at a time.
- If NP exists, current data point to the color-favored EW-penguin type of amplitude. But even so, the NP fit is not much superior than the SM fit.

- Ockham's razor: When you have two competing theories making exactly the same predictions, the simpler the better. $\Rightarrow$ no urgent need for NP here...

Conclusions

- The very original $K\pi$ puzzle with the ratios of rates has disappeared.
- The $K\pi$ puzzle with the CPA's is not seen to be a serious problem as fits within and beyond SM give similar quality.
- New physics is not strongly called for here.
- A more sensitive observable is A_{CP}^{00}, which BaBar and Belle hopefully can quickly converge to a definite value. Whether it agrees with the isospin sum rule prediction will be conclusive about whether $|C'|$ is large and whether NP is required by the data.

Thank You!