CP Violation in B Physics

Chuan-Hung Chen

陳泉宏

Department of Physics

National Cheng-Kung U.

Cross Strait Meeting on PP and Cosmology 2011, Taiwan

Outline

- Preamble
- CP and charge asymmetries
- Anomalous events at Tevatron in B_q physics
- New Physics for the anomalies
- Summary

Preamble: Data and New Physics

B→ππ (tree dominated)				
		$B \to \pi^+ \pi^-$	$B^- \to \pi^0 \pi^-$	$B \to \pi^0 \pi^0$
BR (10^{-6})	Data	5.16+/- 0.22	$5.59^{+0.41}_{-0.40}$	1.55+/-0.19
	PQCD	$6.5^{+6.5}_{-3.8}$	$4.0^{+3.4}_{-1.9 1.1}$	$0.29^{+0.50}_{-0.20}$
	QCDF	$7.0^{+0.4+0.7}_{-0.7-0.7}$	$5.9^{+2.2+1.4}_{-1.1-1.1}$	$1.1^{+1.0+0.7}_{-0.4-0.3}$
CPA (%)	Data	**38+/-6**		43^{+25}_{-24}
	PQCD	$\mathbf{18^{+20}_{-12}}$		63^{+35}_{-34}
	QCDF	$\mathbf{17^{+4.5}_{-8.8}}$		$57.2^{+33.7}_{-40.4}$

PQCD: Li, Mishima, Sanda, PRD72(05)
QCDF : Cheng & Tsai, PRD80(09)

Preamble:

B→ π K (gluonic penguin dominated)					
		$B^- \to \pi^- K^0$	$B \to \pi^+ K^-$	$B^- \to \pi^0 K^-$	$B \to \pi^0 K^0$
$BR(10^{-6})$	Data	23.1+/-1.	19.4+/-0.6	12.9+/-0.6	9.8+/-0.6
	PQCD	$23.6^{+14.5}_{-8.4}$	$20.4^{+16.1}_{-8.4}$	$13.6^{+10.3}_{-5.7}$	$8.7^{+6.0}_{-3.4}$
	QCDF	$21.7^{+9.2+9.0}_{-6.0-6.9}$	$19.3^{+7.9+8.2}_{-4.8-6.2}$	$12.5^{+4.7+4.9}_{-3.0-3.8}$	$8.6^{+3.8+3.8}_{-2.2-2.9}$
CP(%)	Data		$-9.8^{+1.2}_{-1.1}$	**5.0+/-2.5**	-1+/-10
	PQCD		-10^{+7}_{-8}	$\mathbf{-1^{+3}_{-6}}$	-7^{+3}_{-4}
	QCDF		$-7.4^{+4.6}_{-5.0}$	$\mathbf{4.9^{+5.9}_{-5.8}}$	$-10.6^{+2.7+5.6}_{-1.2-8.7}$

Preamble

$B_s \to \pi K$			
		$B_s \to \pi^- K^+$	$B \to \pi^+ K^-$
BR(10^{-6})	Data	5.0+/- 1.1	5.16+/- 0.22
	PQCD	$6.3^{+2.6}_{-1.9}$	$6.5^{+6.5}_{-3.8}$
	QCDF	$5.3^{+0.4+0.4}_{-0.8-0.5}$	$7.0^{+0.4+0.7}_{-0.7-0.7}$
CP(%)	Data	**39+/- 17**	**38+/-6**
	PQCD	$\mathbf{25.8^{+5.6}_{-6.3}}$	$\mathbf{18^{+20}_{-12}}$
	QCDF	$\mathbf{20.7^{+5.0+3.9}_{-3.0-8.8}}$	$\mathbf{17^{+4.5}_{-8.8}}$

PQCD : Liu, Zhou, Xiao, arXiv:0812.2312
QCDF: Phys.Rev.D80 (09)

"Puzzle(s)"

- π K puzzle

Native estimation: $A_{CP}(B^- \to \pi^0 K^-) \approx A_{CP}(B \to \pi^+ K^-)$

Data : $A_{CP}(B^- \to \pi^0 K^-) - A_{CP}(B \to \pi^+ K^-) = -(14.8^{+1.3}_{-1.4})\%$

- Problem in $B \to \pi \pi$ and $B_s \to \pi K$

$A_{CP}(B \to \pi^- \pi^+) = (38 +/- 6)\%$

$A_{CP}(B_s \to \pi^+ K^-) = (39 +/- 17)\%$

U-spin

- **What can we learn from the U-spin relation ?**

"A theorem" : " pairs of U-spin related processes involve CP rate differences which are equal in magnitude and are opposite in sign.", **by M. Gronau, PLB492(00)**

$$B_d \to \pi^- K^+ \;\; vs. \; B_s \to K^- \pi^+$$

$$B_d \to \pi^- \pi^+ \;\; vs. \; B_s \to K^- K^+$$

U-spin

- with the U-spin concept,

$$A_{CP}\left(B_s \to K^-\pi^+\right) = -\frac{\tau_{B_s}}{\tau_{B_d}} \frac{BR\left(B_d \to \pi^- K^+\right)}{BR\left(B_s \to K^-\pi^+\right)} A_{CP}\left(B_d \to \pi^- K^+\right)$$

$$A_{CP}\left(B_s \to \pi^+ K^-\right) = -\frac{1.47}{1.53} \frac{19.4\times 10^{-6}}{5.0\times 10^{-6}} \left(-0.097\right) = 0.36$$

- Interestingly, the result with U-spin is consistent with CDF's result

$$A_{CP}\left(B_s \to K^-\pi^+\right) = 0.39 \pm 0.17$$

Kobayashi-Maskawa (KM) phase

- In the SM, the ~~CP~~ is arisen from the charged weak current,

$$-L_{int} = \bar{U}\gamma_\mu V_L^U V_L^{D\dagger} P_L D\, W^\mu$$

$$V_{CKM} \equiv V_L^U V_L^{D\dagger}$$

- One CP violating phase remains in three generations

- Neutron EDM, lepton EDM, matter-antimatter asymmetry are highly suppressed

With Wolfenstein's parametrization (83)

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\,\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$A \approx 0.808, \lambda \approx 0.2253, \rho \sim 0.13, \eta \sim 0.34$$

Unitarity ↔ Triangle

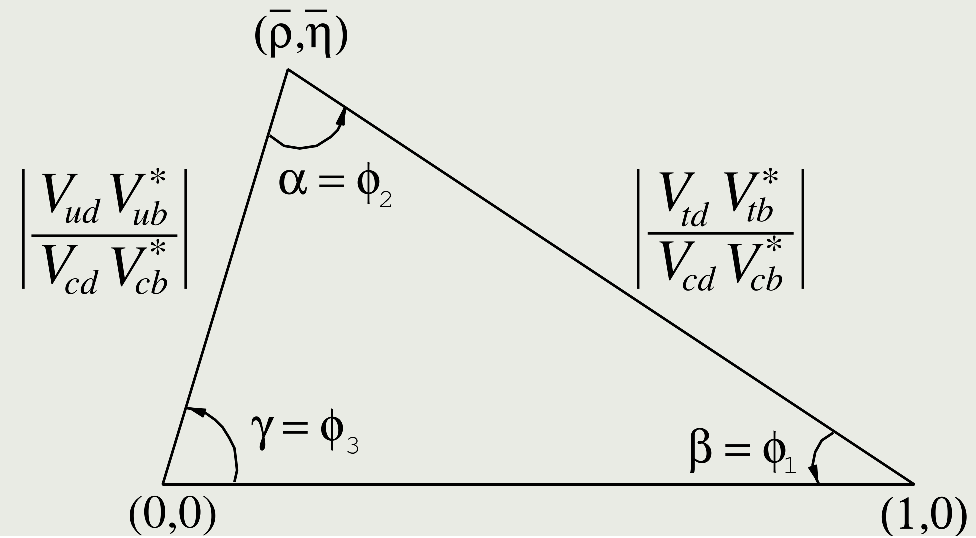
$$V_{CKM}V_{CKM}^{\dagger} = 1$$

$$\beta = \phi_1 = arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

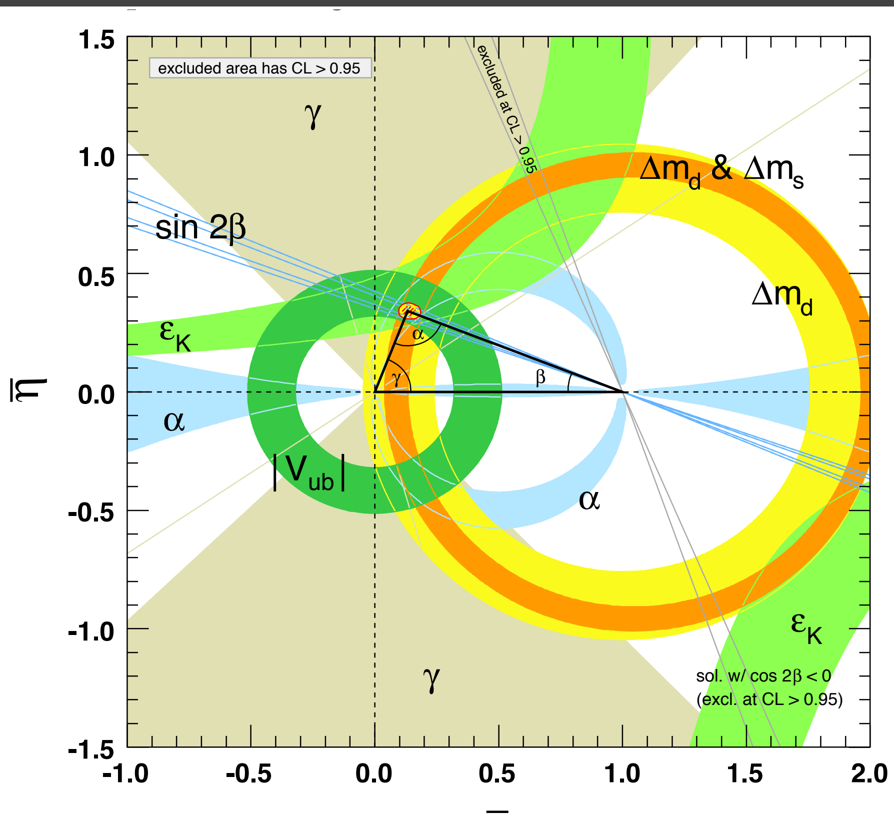
$$\alpha = \phi_2 = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\alpha + \beta + \gamma = \pi$$

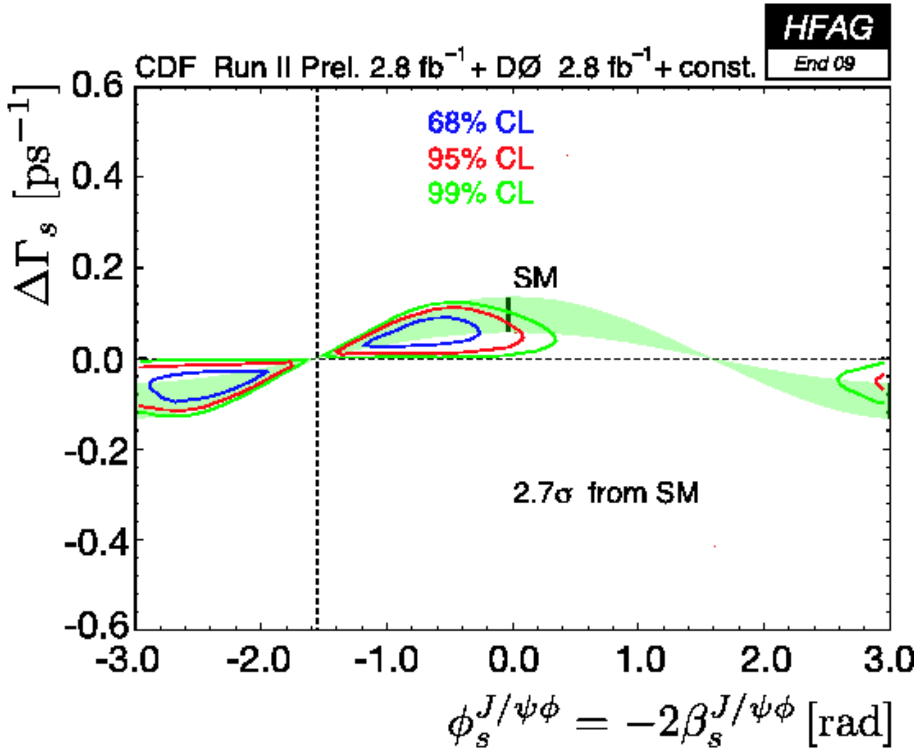


Data



$$\alpha + \beta + \gamma = (183^{+32}_{-25})^{\circ}$$

Data in B_s system



$$V_{ts} \approx -0.041\, e^{i\beta_s}$$
$$\Delta\Gamma^s = 2|\Gamma_{12}^s| cos\phi_s, \phi_s \approx -2\beta_s$$

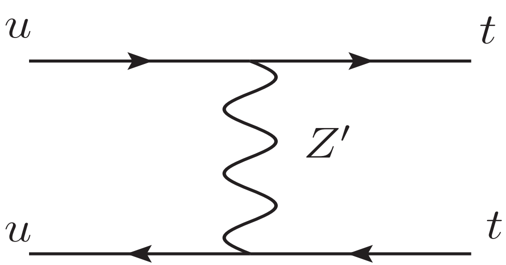
Indication: a large deviation from the SM result

Rare B decays and top quark FBA

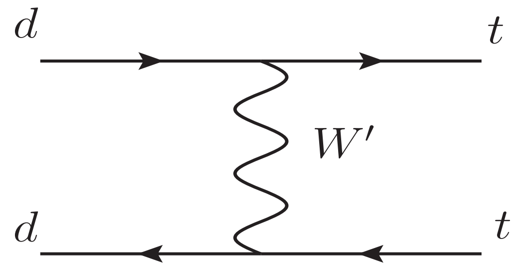
$$A^{t\bar{t}}(|\Delta y| < 1.0) = 0.026 \pm 0.118\,[0.039 \pm 0.006]\,,$$
$$A^{t\bar{t}}(|\Delta y| \geq 1.0) = 0.611 \pm 0.256\,[0.123 \pm 0.008]\,,$$
$$A^{t\bar{t}}(M_{t\bar{t}} < 450\ \mathrm{GeV}) = -0.116 \pm 0.153\,[0.040 \pm 0.006]\,,$$
$$A^{t\bar{t}}(M_{t\bar{t}} \geq 450\ \mathrm{GeV}) = 0.475 \pm 0.114\,[0.088 \pm 0.013]\,.$$

T.~Aaltonen etal [CDF Collaboration], arXiv:1101.0034 [hep-ex].

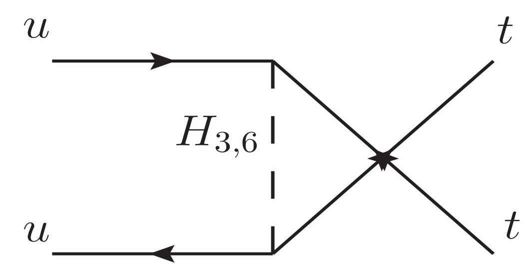
t or u channel, C-H Chen, Sandy Law, Run-Hui Li



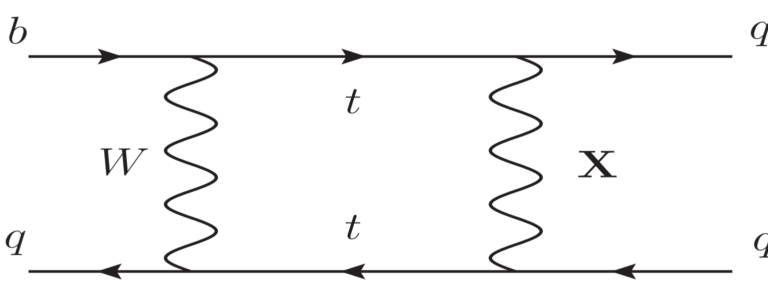
S. Jung etal, PRD81(10)

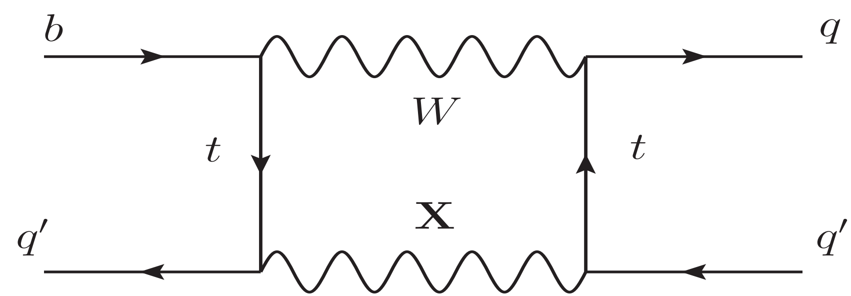


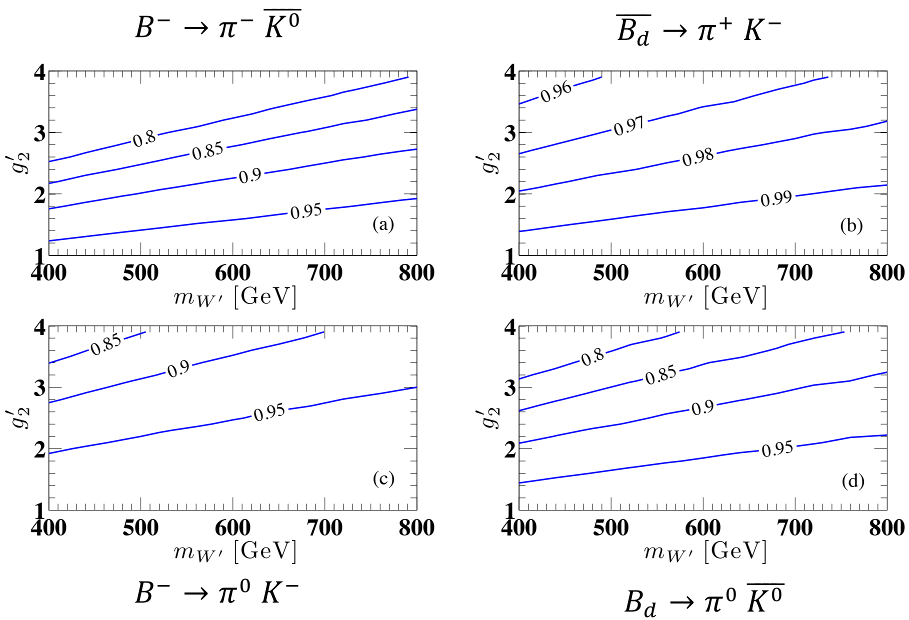
K. Cheung etal, PLB682

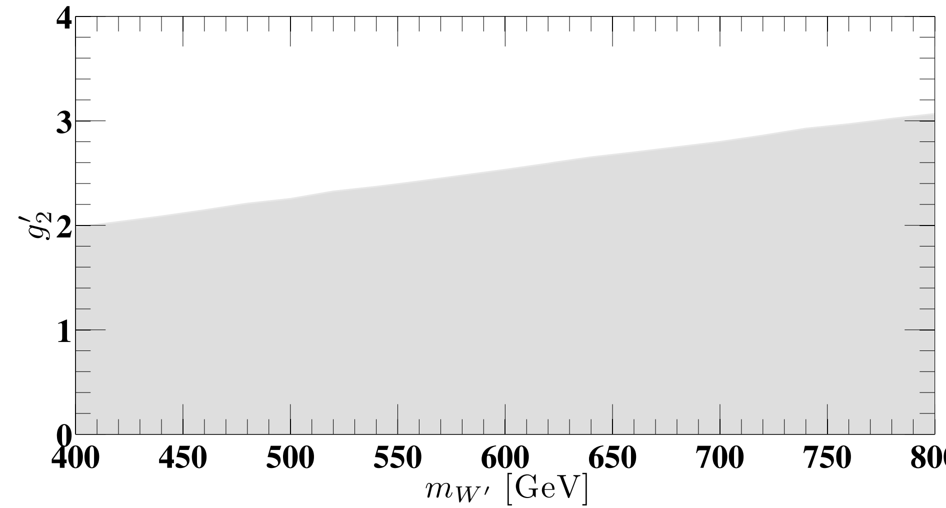


Arhrib etal, PRD82(10)









g_2'	$M_{W'}$ [GeV]	$\sigma(t\bar{t})$ [pb]	A_{FB}	A_{FB} $M_{t\bar{t}} < 450$ GeV	A_{FB} $450 < M_{t\bar{t}} < 800$ GeV	A_{FB} $\lvert\Delta y\rvert < 1$	A_{FB} $\lvert\Delta y\rvert > 1$
3.0	700	8.45	0.06	-0.01	0.136	0.03	0.14
3.5	700	9.05	0.11	0.01	0.22	0.06	0.26
3.5	650	9.8	0.16	0.03	0.26	0.06	0.36
3.0	550	10.4	0.22	0.04	0.33	0.09	0.42
2.5	500	10.5	0.19	0.003	0.32	0.07	0.40
Data [4][19]		7.70 ± 0.52	0.158 ± 0.074	-0.116 ± 0.153	0.475 ± 0.122	0.026 ± 0.118	0.611 ± 0.256
SM		$7.45^{+0.72}_{-0.63}$	0.058 ± 0.009	0.04 ± 0.006	0.088 ± 0.0013	0.039 ± 0.006	0.123 ± 0.018
NP		–	0.100 ± 0.074	-0.156 ± 0.147	0.387 ± 0.121	0.387 ± 0.112	0.488 ± 0.257

Barger etal, Phys.Lett.B698:243-250,2011

Time-dependent CPA I

CP final state

- Two neutral strong eigenstates B_q, B_q-bar (q=d, s), with weak interactions the corresponding Hamiltonian is given by

$$H = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

- The mass eigenstates:

$$|B_L\rangle = p|B\rangle + q|\bar{B}\rangle$$
$$|B_H\rangle = p|B\rangle - q|\bar{B}\rangle$$

- The time evolution of flavor states:

$$|B(t)\rangle = g_+(t)|B\rangle - \frac{q}{p} g_-(t)|\bar{B}\rangle$$
$$|\bar{B}(t)\rangle = g_+(t)|B\rangle - \frac{p}{q} g_-(t)|\bar{B}\rangle$$

- The relationship among p, q, M, Γ in B-meson:

$$\frac{q}{p} = \left(\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}\right)^{1/2}, \Gamma_{12} \ll M_{12}$$

- TDCPA is defined by

$$A_{CP}(t) = \frac{\Gamma(\bar{B}(t) \to f_{CP}) - \Gamma(B(t) \to f_{CP})}{\Gamma(\bar{B}(t) \to f_{CP}) + \Gamma(B(t) \to f_{CP})}$$
$$= S_{f_{CP}} sin\Delta m_B t - C_{f_{CP}} cos\Delta m_B t$$

$$S_{f_{CP}} = \frac{2Im\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2}, C_{f_{CP}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}$$

- f_{CP}:CP eigenstate

$$\lambda_{f_{CP}} = -\left(\frac{M_{12}^*}{M_{12}}\right)^{\frac{1}{2}} \frac{A(\bar{B} \to f_{CP})}{A(B \to f_{CP})}$$
$$= -e^{-i(2\beta+\phi^{NP})} \frac{A(\bar{B} \to f_{CP})}{A(B \to f_{CP})}$$

- Not only mixing-induced effects, but also decay amplitudes lead to CPA

- Tree level : b→c c-bar s, A(B-bar→f_{CP})/A(B-bar→f_{CP}) ~1

❖ B_d→J/Ψ K_S

$$V_{td} = |V_{td}|e^{-i\beta_d}, \beta_d \sim 22°$$
$$S_{J\Psi K_S} = \sin(2\beta_d + \phi_d^{NP})$$
$$S_{J\Psi K_S}^{Exp} = 0.671 \pm 0.023$$

precision measurement

❖ B_s→J/Ψ ϕ

$$V_{ts} = -|V_{ts}|e^{i\beta_s}, \beta_s \sim 0.019$$

$$2\beta_s^{J/\Psi\phi} = 2\beta_s + \phi_s^{NP}$$
$$= -0.75^{+0.32}_{-0.21}$$
$$\text{or} = -2.38^{+0.25}_{-0.34}$$

Time-dependent CPA II

semi-leptonic decay

- Wrong sign charge asymmetry (WSCA): indication of ~~CP~~

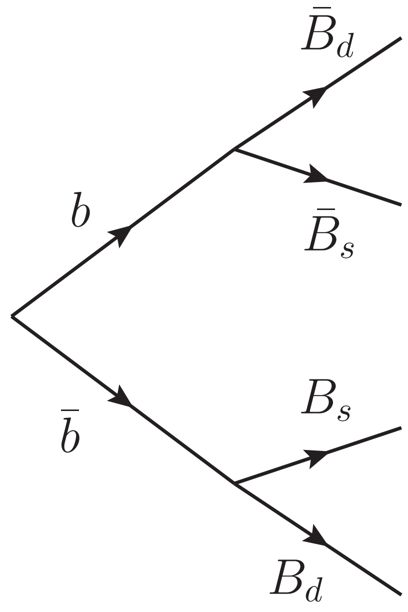
$$a_{s\ell}^{q} = \frac{d\Gamma\left(\bar{B}_q(t) \to \ell^+ X\right) - d\Gamma(B_q \to \ell^- X)}{d\Gamma\left(\bar{B}_q(t) \to \ell^+ X\right) + d\Gamma(B_q \to \ell^- X)}$$

$$= \frac{\left|\frac{p}{q} A(B_q \to \ell^+ X)\right|^2 - \left|\frac{q}{p} A(\bar{B}_q \to \ell^- X)\right|^2}{\left|\frac{p}{q} A(B_q \to \ell^+ X)\right|^2 + \left|\frac{q}{p} A(\bar{B}_q \to \ell^- X)\right|^2}$$

With

$$A_{s\ell}^{mix} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx Im \frac{\Gamma_{12}}{M_{12}}$$

$$A_{s\ell}^{DCP} = \frac{|A(\bar{B}_q \to \ell^- X)|^2 - \left|A\left(B_q \to \ell^+ X\right)\right|^2}{|A(\bar{B}_q \to \ell^- X)|^2 + \left|A\left(B_q \to \ell^+ X\right)\right|^2}$$



$b \longrightarrow q\ell^-\bar{\nu}$

$b \longrightarrow \bar{q} \longrightarrow \bar{q}\ell^+\nu$

$\bar{b} \longrightarrow \bar{q}\ell^+\nu$

$\bar{b} \longrightarrow b \longrightarrow q\ell^-\bar{\nu}$

- The WSCA could be expressed as

$$a_{s\ell}^{q} = \frac{A_{s\ell}^{mix} - A_{s\ell}^{DCP}}{1 - A_{s\ell}^{mix} A_{s\ell}^{DCP}}$$
$$\approx A_{s\ell}^{mix} - A_{s\ell}^{DCP}$$

- Unlike the multiplication in the case for CP final state, DCPA from the semi-leptonic B decay is a addition

- Model-independent analysis, **Rosner etal PLB694(11)**

$$A_{s\ell}^{DCP} < 10^{-6}$$

- Compare with the mixing-induced WSCA in the SM,

$$A_{s\ell}^{mix}(B_d, SM) = (-4.8^{+1.0}_{-1.2})\times 10^{-4}$$
$$A_{s\ell}^{mix}(B_s, SM) = (2.06 \pm 0.57)\times 10^{-5}$$

Lenz & Nierste, JHEP0706(07)

DCPA could be neglected

$$a_{s\ell}^{q} \approx A_{s\ell}^{mix}$$

- Current data

$$a_{s\ell}^{d}(Exp) = (-4.7 \pm 4.6)\times 10^{-3}$$
$$a_{s\ell}^{s}(Exp) = (-1.7 \pm 9.1)\times 10^{-3}$$

Like-sign charge asymmetry

- Like-sign charge asymmetry (LSCA) at Tevatron

$$A^b_{s\ell} = \frac{\Gamma(b\bar{b} \to \ell^+\ell^+X) - \Gamma(\bar{b}b \to \ell^-\ell^-X)}{\Gamma(b\bar{b} \to \ell^+\ell^+X) + \Gamma(\bar{b}b \to \ell^-\ell^-X)}$$
$$= \frac{f_d Z_d a^d_{s\ell} + f_s Z_s a^s_{s\ell}}{f_d Z_d + f_s Z_s}$$

Grossman etal. PRL97(06)

- f_q : fraction to produce B_q

$$Z_q = \frac{1}{1-y_q^2} - \frac{1}{1-x_q^2}$$
$$y_q = \frac{\Delta\Gamma_{B_q}}{2\Gamma_{B_q}}, x_q = \frac{\Delta m_{B_q}}{\Gamma_{B_q}}$$

- With data

$$f_d = 0.323(37), f_s = 0.118(15)$$
$$x_d = 0.774(8), y_d \sim 0,$$
$$x_s = 26.2 \pm 0.5, y_s = 0.046(27)$$

one can obtain

$$A^b_{s\ell} = 0.506(43)\boldsymbol{a^d_{s\ell}} + 0.494(43)\boldsymbol{a^s_{s\ell}}$$

- Clearly, LSCA depends on b→d and/or b→s transition(s)

D0 anomalous events

- D0 observed the like-sign charge asymmetry in dimuon events, defined by

$$A^b_{s\ell} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

D0 Co, PRD82(10)

$N^{++(--)}$: The number of events that b and $\bar{b}$-hadron semi-leptonically decay into two positive(negative) muons

- Data & SM prediction

$$A^b_{s\ell} = (-9.57 \pm 2.51 \pm 1.46)\times 10^{-3}$$

$$A^b_{s\ell}(SM) = (-2.3^{+0.5}_{-0.6})\times 10^{-4}$$

Lenz & Nierste, JHEP0706(07)

- The experimental measurements on $\mathbf{A^b_{sl}}$ and $\mathbf{S_{J/\psi\,\phi}}$ sound inconsistent with the SM predictions. If we take the "anomalies" seriously, what effect could solve them ?

Solutions to the Do anomaly

- Summary:

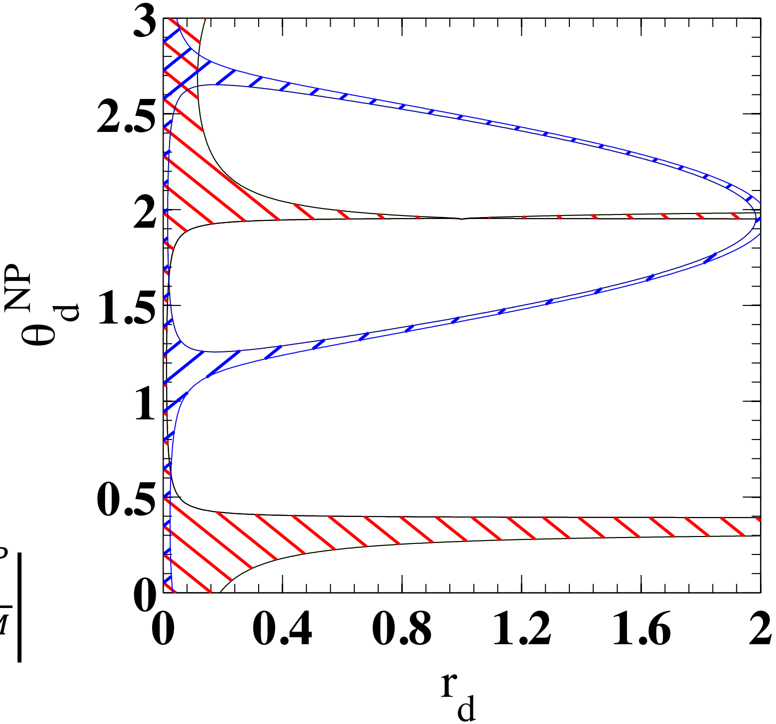
- LSCA is directly related to WSCA

$$a_{s\ell}^{q} \approx Im \frac{\Gamma_{12}^{q}}{M_{12}^{q}} \qquad \phi_q = \arg\left(-\frac{M_{12}^{q}}{\Gamma_{12}^{q}}\right)$$

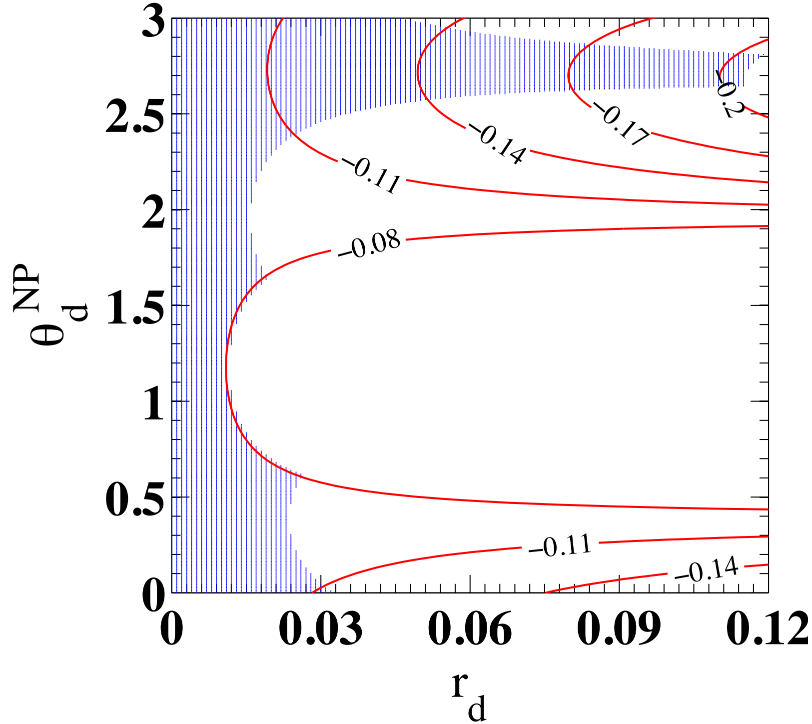
- Both dispersive and absorptive parts could affect the WSCA

- Due to the strict limits of Δm_{Bd} and $\sin 2\beta_d$, plausibly one can assume large WSCA is arisen from b→s transition

Constraints on b→d transition



(a)



(b)

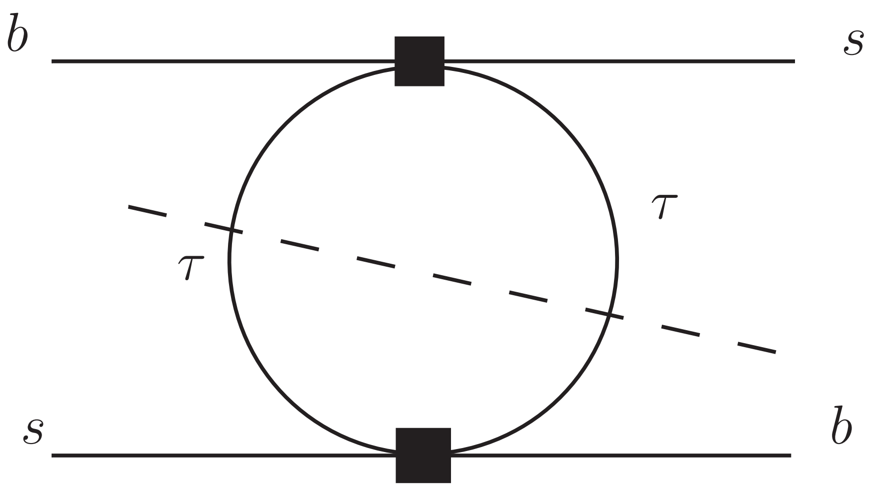
$$r_d = \left| \frac{M_{12}^{d,NP}}{M_{12}^{d,SM}} \right|$$

I. New Physics on Γ^s_{12}

- $\Gamma^s_{12} = \Gamma^{s,SM}_{12} + \Gamma^{s,NP}_{12}$
- No limit on the coupling for $b \to s\ \tau^+ \tau^-$

$$BR^{Exp}(B_s \to \tau^+\tau^-) < 5\%$$
$$BR^{Exp}(B_s \to X_s\tau^+\tau^-) < 5\%$$

A. Dighe et al. arXiv:1005.4051; Bauer&Dunn arXiv: 1006.1629; Bai&Nelson arXiv:1007.0596; Alok etal.arXiv: 1010.133



II. New Physics on M^s_{12} Chen&Faisel PLB(11)

- Chiral color model: $SU(3)_C$ SM QCD is the relic of the large gauge group $SU(3)_A \times SU(3)_B$

  $SU(3)_A \times SU(3)_B \rightarrow SU(3)_C$

  Pati&Salam PLB58(75); Hall&Nelson PLB153(85); Frampton*Glashow PLB190(87), PRL58(87)

- Axigluon: colored massive gauge boson and axial vector current coupling to quarks

- Non-universal axigluon provides a rich phenomena for FCNC processes (tree level)

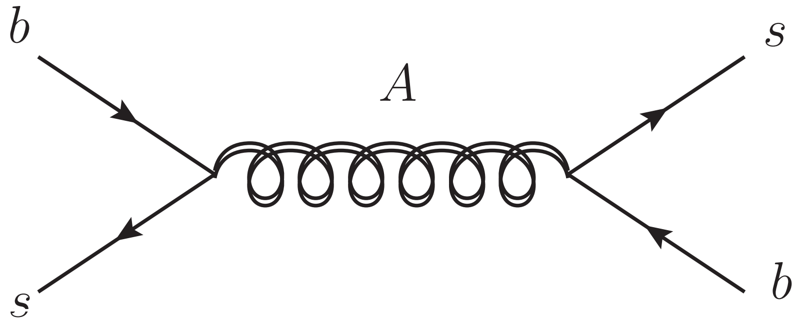
- Phenomenological approach : Following the scheme proposed by Frompton etal PLB 683(10), the coupling of axigluon to the first two generation is different from that to the 3rd generation

$$\mathcal{L}_A = g_V \bar{q}' \gamma_\mu T^b q' G_A^{b\mu} + g_A \bar{q}' \gamma_\mu \gamma_5 \mathbf{Z} T^b q' G_A^{b\mu} ,$$

Non-universal axigluon

$$Z = \begin{pmatrix} 1 & & \\ & 1 & \\ & & a \end{pmatrix}$$

$$\mathcal{L}_{b\to q} \;=\; g_A \bar{q}\gamma_\mu (F^{QR}_{qb} P_R - F^{QL}_{qb} P_L) T^b b G^{b\mu}_A$$



- The interesting result: the factorizable parts of B→J/ ψ (K, ϕ) are suppressed naturally

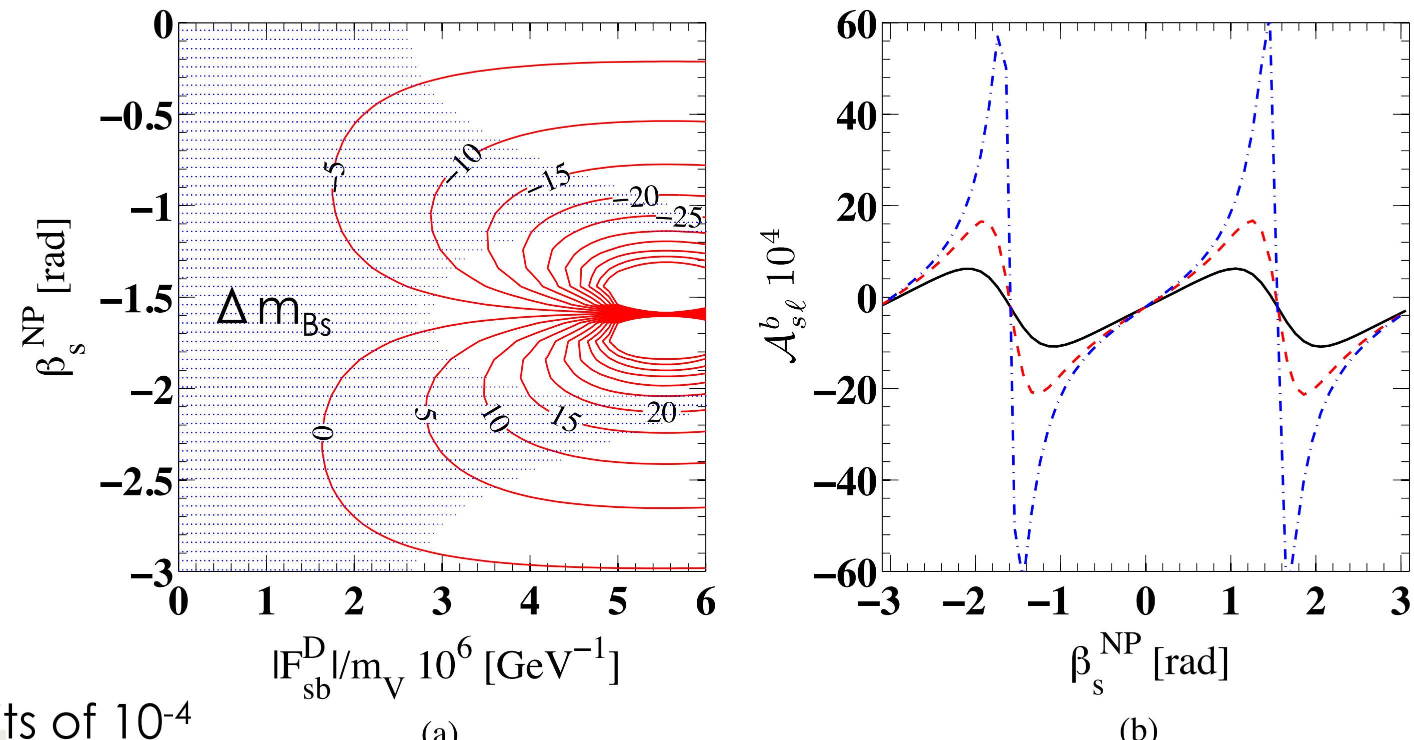
$$C_i' + \frac{C_j'}{N_C} \to 0, C_j' = -N_C C_i'$$

$$T^b_{ij} T^b_{k\ell} = -\frac{1}{2N_C}\delta_{ij}\delta_{k\ell} + \frac{1}{2}\delta_{i\ell}\delta_{jk}$$

$A^{b}_{s\ell}(Exp) = (-9.57 \pm 2.51 \pm 1.46)\times 10^{-3}$

Axigluon on A^b_{sl}

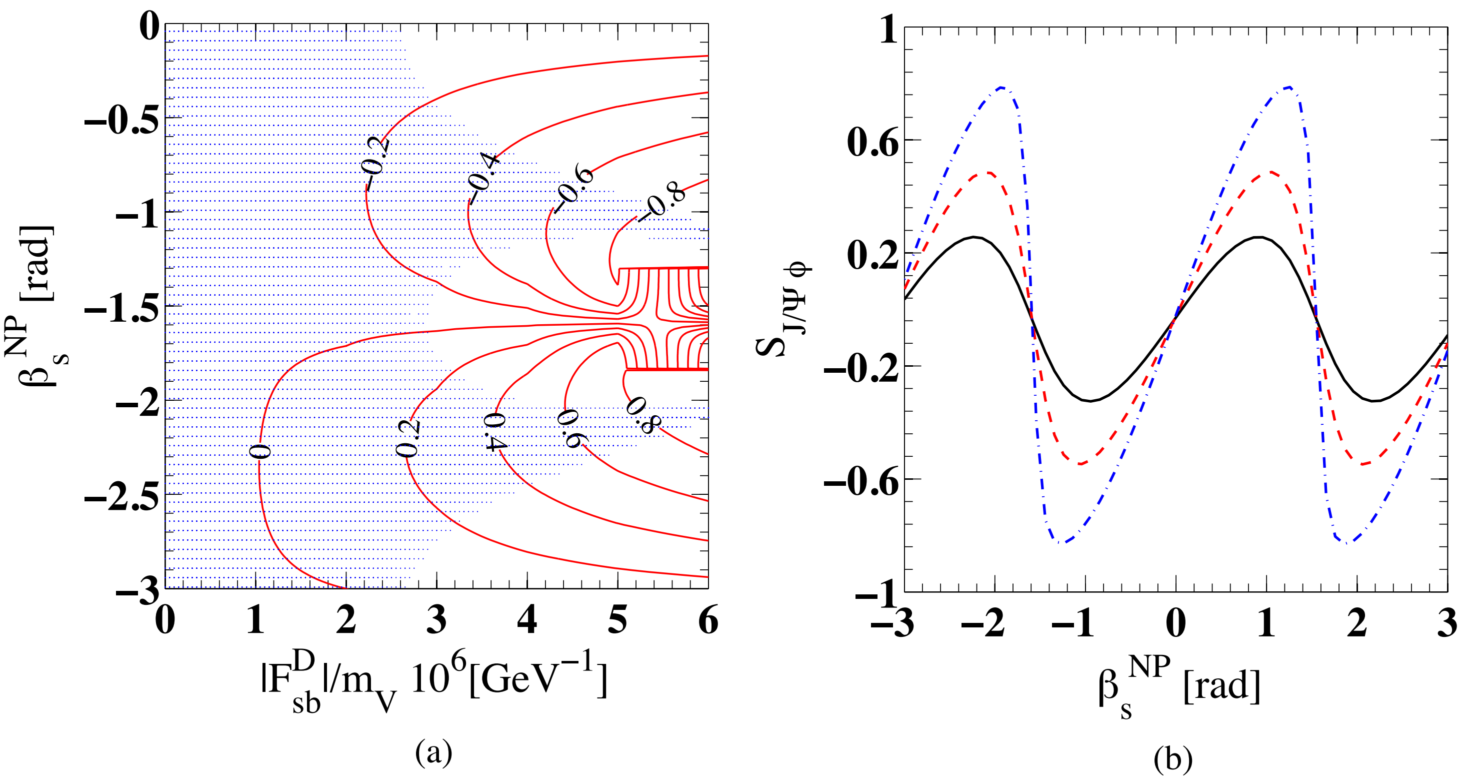
One order of magnitude larger than the SM result



In units of 10^{-4}

$$S_{f_{CP}} = \frac{2Im\lambda_{f_{J/\Psi\phi}}}{1+\left|\lambda_{f_{J/\Psi\phi}}\right|^2} \approx \sin(2\beta_s + \phi_s^{NP})\,;\, S_{J/\Psi\phi}^{Exp} \in (-1,-0.4)$$

Axigluon on $S_{J/\psi Ks}$



Summary

- LHC could observe the new particle(s) directly, however, low energy physics such as B-physics, could test the SM in indirect way
- Time-dependent CPA in B_s and charge asymmetry in $B_{d,s}$ are predicted to be around -4% and -2×10^{-4} in the SM, respectively, where the results are inconsistent with the current data
- If the anomalies are confirmed with more accurate data, then we have solid evidence for the existence of New Physics (NP). The NP, such as unparticle, axigluon etc could be the candidates. Collider physics could further make the NP clearly.

[redacted]

Preambole

Polarization (f_L)					
		$B^- \rightarrow \phi K^{*-}$	$B \rightarrow \phi K^{*0}$	$B^- \rightarrow \rho^- K^{*0}$	$B^- \rightarrow \rho^0 K^{*-}$
f_L	Data	0.50+/-0.05	0.48+/-0.03	0.48+/-0.08	$0.96^{0.06}_{-0.16}$
	PQCD	0.6-0.8	0.6-0.8	0.82	0.85
	QCDF	$0.49^{+0.04+0.51}_{-0.07-0.42}$	$0.5^{+0.004+0.51}_{-0.06-0.43}$	$0.48^{+0.03+0.52}_{-0.04-0.40}$	$0.67^{+0.02+0.31}_{-0.03-0.48}$