# New CP Phase in $B_q$ system

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# Outline

- Preamble
- Time-dependent CP asymmetries
- D0 anomalous events
- Solutions to the “anomaly”
- Summary

# Preamble: historical review

- Historical review
  - First event : 1964, indirect ~~CP~~ observed in K-meson, $\varepsilon \sim 2.2*10^{-3}$, Nobel Prize in Physics 1980 awarded to Cronin & Fitch

*"for the discovery of violations of fundamental symmetry Principles in the decay of neutral K-mesons"*

# Preamble: historical review

- 2nd event : 1999, confirmed nonzero D~~CP~~ in K-meson, $\varepsilon'/\varepsilon \sim 1.7*10^{-3}$

- 3rd event : 2000, indirect ~~CP~~ observed in $B \rightarrow J/\psi K_S$, $\sin 2\beta = 0.671 +/- 0.023$, led to Nobel Prize 2008

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

- 4th event: 2007, D~~CP~~ in $B \rightarrow K\pi$, led to "$K\pi$ puzzle"

# Selected Models:

- 1964, L. Wolfenstein proposed a superweak model, excluded by nonzero $\varepsilon'/\varepsilon$
- In 1973, Kobayashi and Maskawa proposed **3** generation quarks in $SU(2)_L \times U(1)_Y$ gauge theory
- In 1973, T.D. Lee proposed spontaneous CP Violation: Two-Higgs-doublet, led to FCNC at tree level

$$\langle H_2 \rangle = \langle v_2\, e^{i\theta} \rangle, \theta \xrightarrow{CP} -\theta$$

- In 1976, S. Weinberg proposed three-Higgs-doublet to avoid FCNC at tree level

# Kobayashi-Maskawa (KM) phase

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

$$-L_{int} = \overline{U}\gamma_\mu V_L^U V_L^{D\dagger} P_L D\, W^\mu$$
$$V_{CKM} \equiv V_L^U V_L^{D\dagger}$$

- One CP violating phase remains in three generation quarks

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

With Wolfenstein's parametrization (83)

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\,\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

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

# Unitarity ↔ Triangle

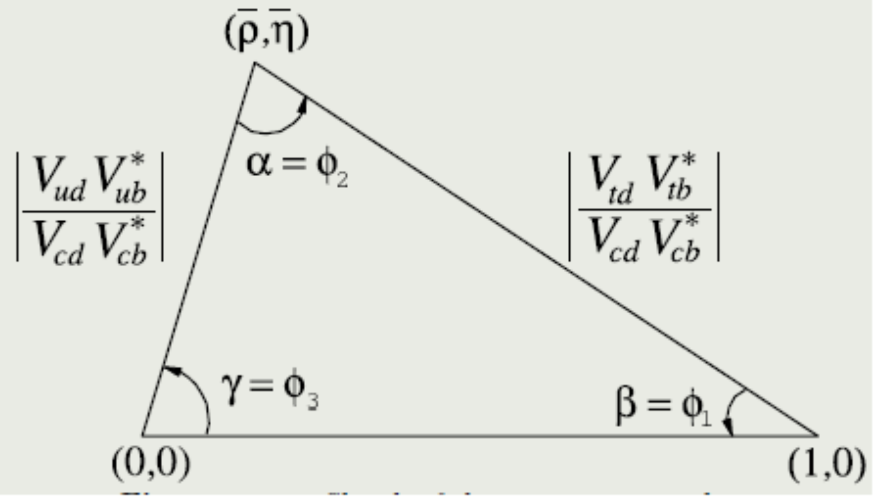
$$V_{CKM}V_{CKM}^{\dagger} = 1$$

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

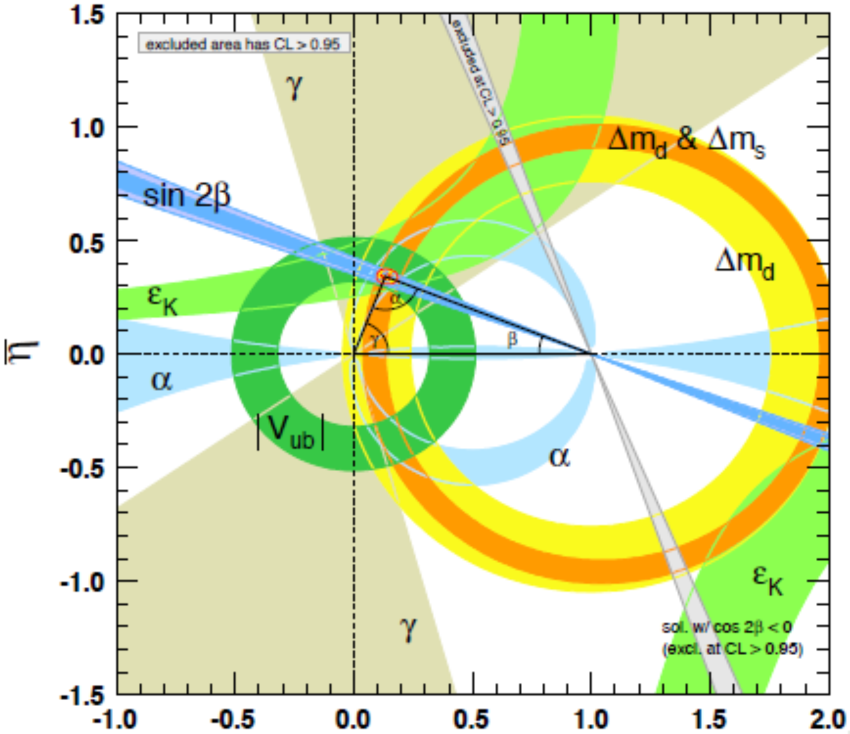
$$\alpha = \phi_2 = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

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

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



# Triangle




$$\alpha + \beta + \gamma = (183^{+22}_{-25})^{\circ}$$

# Time-dependent CPA I

*CP final state*

- Two neutral strong eigenstates $B_{q,}$ $B_q$-bar ( q= d, s), with weak interaction the corresponding Hamiltonian is given by

$$H = M - \frac{i}{2}\Gamma$$

- The mass eigenstates:

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

- The time evolution of flavor states:

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

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

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

- TDCPA is defined by

$$A_{CP}(t) = \frac{\Gamma(\bar{B}(t) \to f_{CP}) - \Gamma(B(t) \to f_{CP})}{\Gamma(\bar{B}(t) \to f_{CP}) + \Gamma(B(t) \to f_{CP})}$$

$$= S_{f_{CP}} sin\Delta m_B t - C_{f_{CP}} cos\Delta m_B t$$

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

- $f_{CP}$ : 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

  - $B_d \to J/\Psi K_S$

$$S_{J/\Psi K_S} = \sin(2\beta_d + \phi_d^{NP})$$
$$S_{J/\Psi K_S}^{Exp} = 0.671 \pm 0.023$$

  - $B_s \to J/\Psi\ \phi$

$$2\beta_s \sim -0.038$$
$$2\beta_s^{J/\Psi\phi} = 2\beta_s + \phi_s^{NP}$$
$$= -0.75^{+0.32}_{-0.21}$$
$$or = -2.38^{+0.25}_{-0.34}$$

# Time-dependent CPA II

*semi-leptonic decays*

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

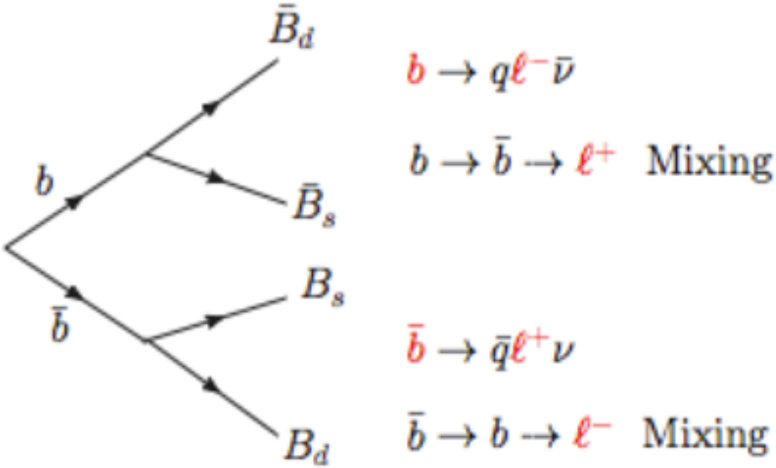
$$a_{s\ell}^{q} = \frac{d\Gamma(\bar{B}_q(t) \to \ell^+ X)dt - d\Gamma(B_q(t) \to \ell^- X)/dt}{d\Gamma(\bar{B}_q(t) \to \ell^+ X)/dt + d\Gamma(B_q(t) \to \ell^- X)/ft}$$

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

With

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

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



- The WSCA could be expressed as

$$a^q_{s\ell} = \frac{A^{ind}_{s\ell} - A^{DCP}_{s\ell}}{1 - A^{ind}_{s\ell} A^{DCP}_{s\ell}} \approx A^{ind}_{s\ell} - A^{DCP}_{s\ell}$$

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

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

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

- Comparing with mixing-induced WSCA in the SM,

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

Lenz &Nierste, JHEP, 0706, 072 (07)

DCPA could be neglected

$$a^q_{s\ell} \approx A^{ind}_{s\ell}$$

- Current Data of WSCA:

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

# Motivation for new source of $\not{CP}$

- KM phase cannot solve the matter-antimatter asymmetry

$$\frac{n_B}{n_\gamma} \sim 10^{-10}$$

- $K\pi$ puzzle

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

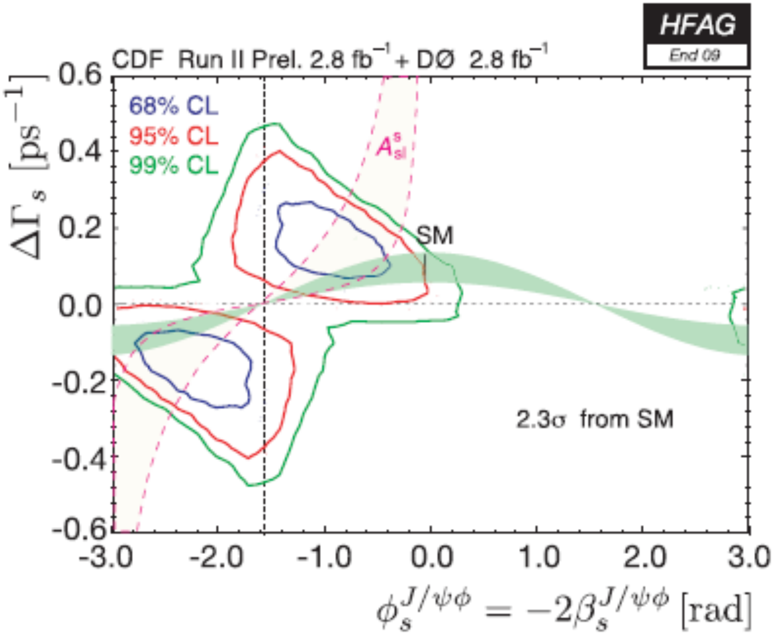
Uncertain QCD effects? Or new physics (NP)?

- Large TDCPA in $B_s \to J/\psi\, \phi$ : the related CKM matrix element is

$$V_{ts} = \bar{V}_{ts} e^{-i\beta_s}$$
$$\beta_s \approx -0.019$$

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\,\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

# Motivation for New CP phase(s)




- Large like-sign charge asymmetry observed by D0

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

D0 Co. PRD82(10)

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

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

# D0 anomalous events

- Like-sign charge asymmetry (LSCA) at Tevatron

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

Grossman etal, PRL97, 151801(06)

- $f_q$ : the fraction to produce $B_q$

$$Z_q = \frac{1}{1-y_q^2} - \frac{1}{1-x_q^2}\,,$$

$$y_q = \frac{\Delta\Gamma_{B_q}}{2\Gamma_{B_q}}\,, \quad x_q = \frac{\Delta m_{B_q}}{\Gamma_{B_q}}\,.$$

- With data, one can have

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

- Clearly, LSCA could be from b→d or/and b→s transition

- SM prediction

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

Lenz &Nierste, JHEP, 0706, 072 (07)

- D0 shows in di-muon events

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

PRD82, arXiv:1005.2757

# Solutions to the "anomaly"

- LSCA is directly related to WSCA

$$a_{s\ell}^{q} \approx A_{s\ell}^{ind}(B_q) \approx Im\frac{\Gamma_{12}^{q}}{M_{12}^{q}}$$

$$\phi_q = \arg\left(-\frac{M_{12}^{q}}{\Gamma_{12}^{q}}\right)$$

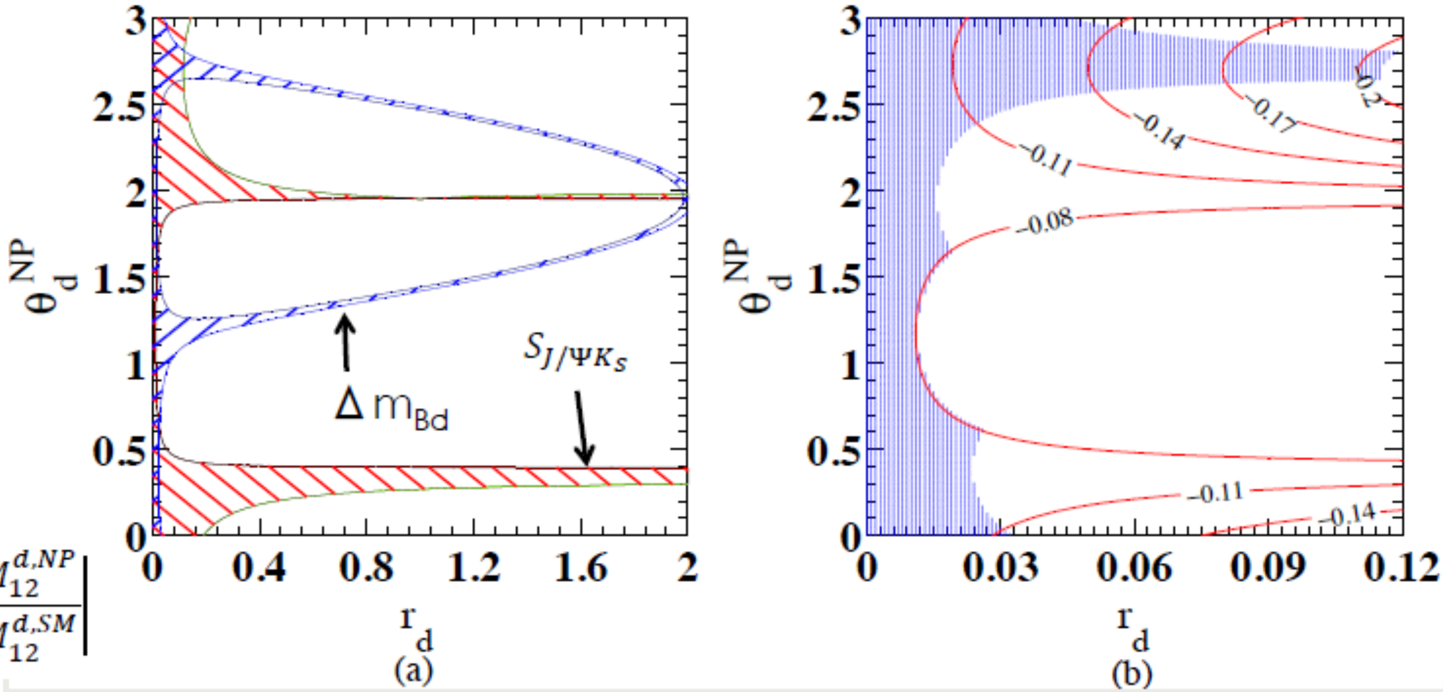
$$\Delta\Gamma^{q} = 2\left|\Gamma_{12}^{q}\right| cos\ \phi_q$$

$$\Delta\Gamma^{s}(SM) \approx 0.096\ ps^{-1}$$

$$\Delta\Gamma^{s}(Exp) = [-0.163, 0.163]$$

- Lifetime difference contains the dispersive and absorptive parts
- New Physics on $\Gamma_{12}$ and $M_{12}$
- Since the strict limits of $\Delta m_d$ and $\sin 2\beta_d$, plausibly one can assume large LSCA is arisen from b→s transition

# Constraint on b→d transition



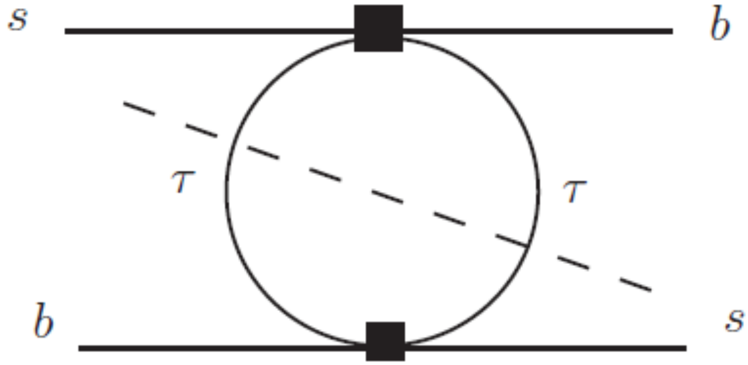

$$r_d = \left|\frac{M_{12}^{d,NP}}{M_{12}^{d,SM}}\right|$$

# New Physics on $\Gamma^s_{12}$

- $\Gamma_{12} = \Gamma^{SM}_{12} + \Gamma^{NP}_{12}$

- 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: 1010.1333

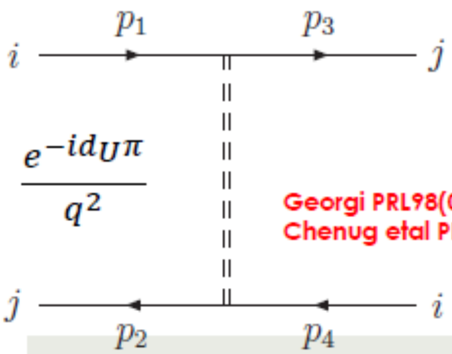
# New Physics on $\Gamma^s_{12}$

- Unparticle phase

$$H^U_{12} = M^{q,U}_{12} - i\frac{\Gamma^{q,U}_{12}}{2},$$

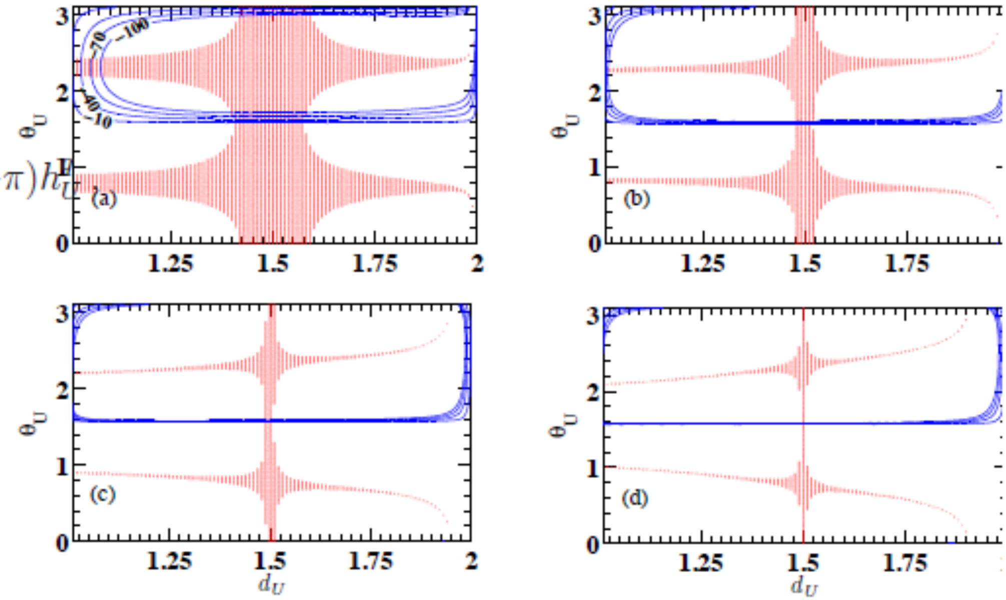
$$M^{q,U}_{12} = \cos(d_U\pi)h^q_U, \quad \Gamma^{q,U}_{12} = 2\sin(d_U\pi)h^q_U,$$

$$h^q_U = \frac{C_S}{18}\left(f^R_{qb} + f^L_{qb}\right)^2 \left(\frac{m^2_{B_q}}{\Lambda^2_U}\right)^{d_U} \frac{f^2_{B_q}}{m_{B_q}}$$




$$\frac{e^{-id_U\pi}}{q^2}$$

Georgi PRL98(07)
Chenug etal PRL99(07)



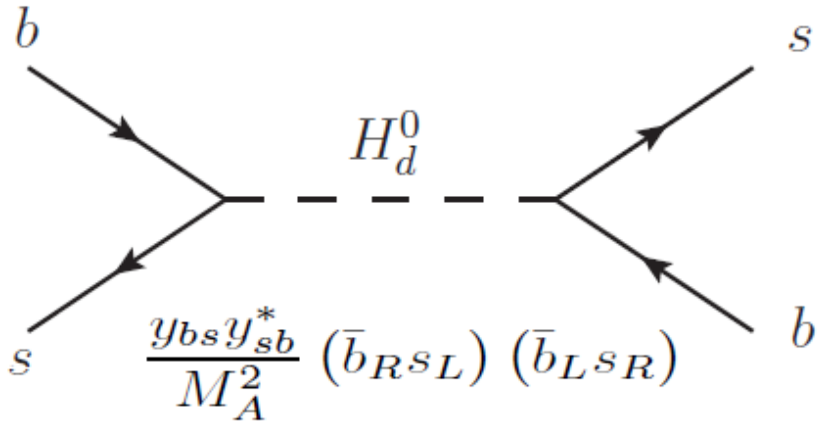

Ren, He, Xie, arXiv:1009.3398;
Chen, Kim, Li, arXiv:1012.0095

# New Physics on $M^s_{12}$

- General 2Higgs-Doublet,
  **Dobrescu etal PRL105(10)**

$$-H_d^0\left(y_{bs}\bar{b}_R s_L + y_{sb}\bar{s}_R b_L\right) + H.c.$$

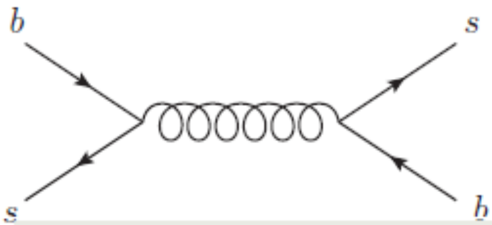
- Realized in the framework of Uplifted Supersymmetry



# New Physics on $M^s_{12}$ Chen & Gaber PLB(11)

- Axigluon: massive colored gauge boson, which is from the breaking of $SU(3)_A \times SU(3)_B$
  Frampton etal, PLB 683(10)
- Non-universal axigluon → FCNC at tree level

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




- Interesting result: no contributions to factorizable parts of B→J/$\psi$(K, $\phi$), fit the data that indicate small DCP

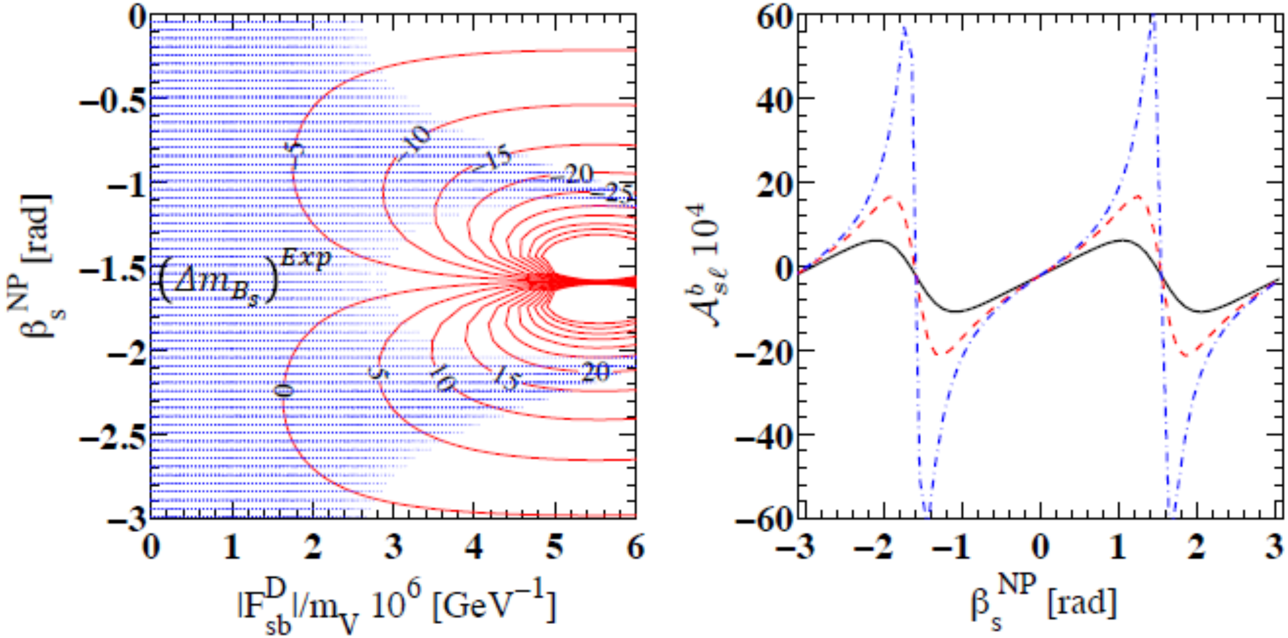
$$C_i' + \frac{C_j'}{N_C} \to 0, C_j' = -N_C C_i'$$

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

# Non-universal Axigluon contributions

One order of magnitude larger than the SM

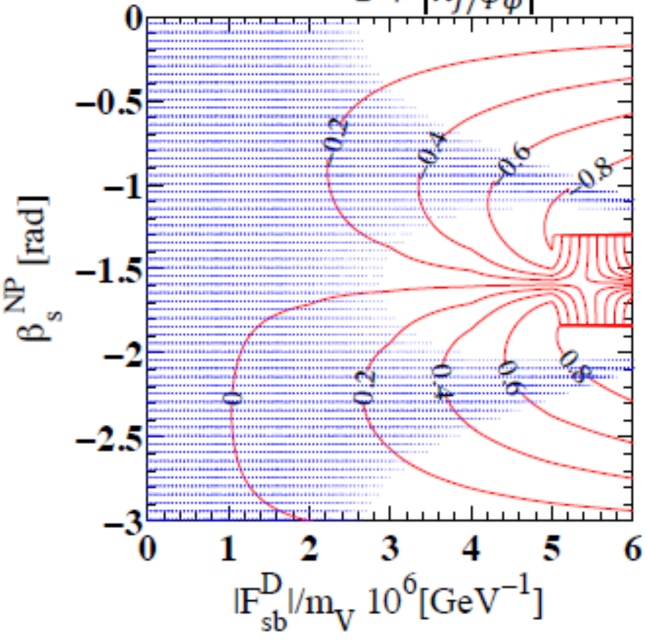
LSCA

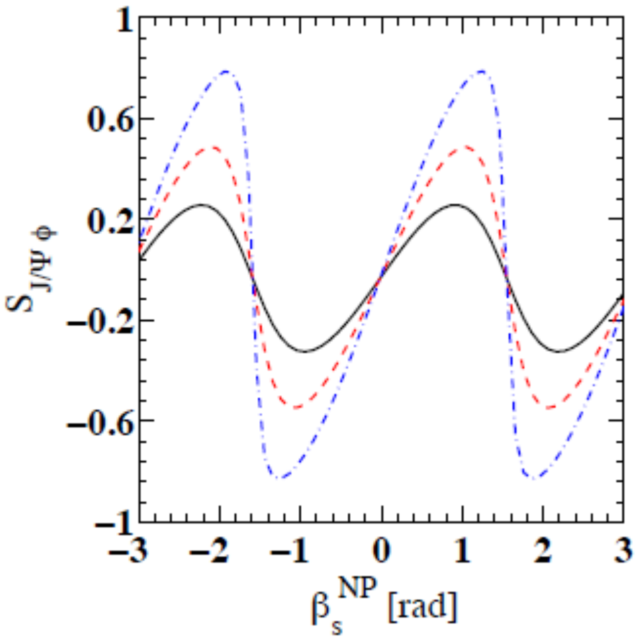


# TDCPA of $B_s \to J/\Psi\ \phi$ by axigluon

$$S_{J/\Psi\phi} = \frac{2Im\lambda_{J/\Psi\phi}}{1+\left|\lambda_{J/\Psi\phi}\right|^2} = sin(\phi_s^{NP}+2\beta_s);\ S_{J/\Psi\phi}^{Exp} \in (-1.,-0.40)$$

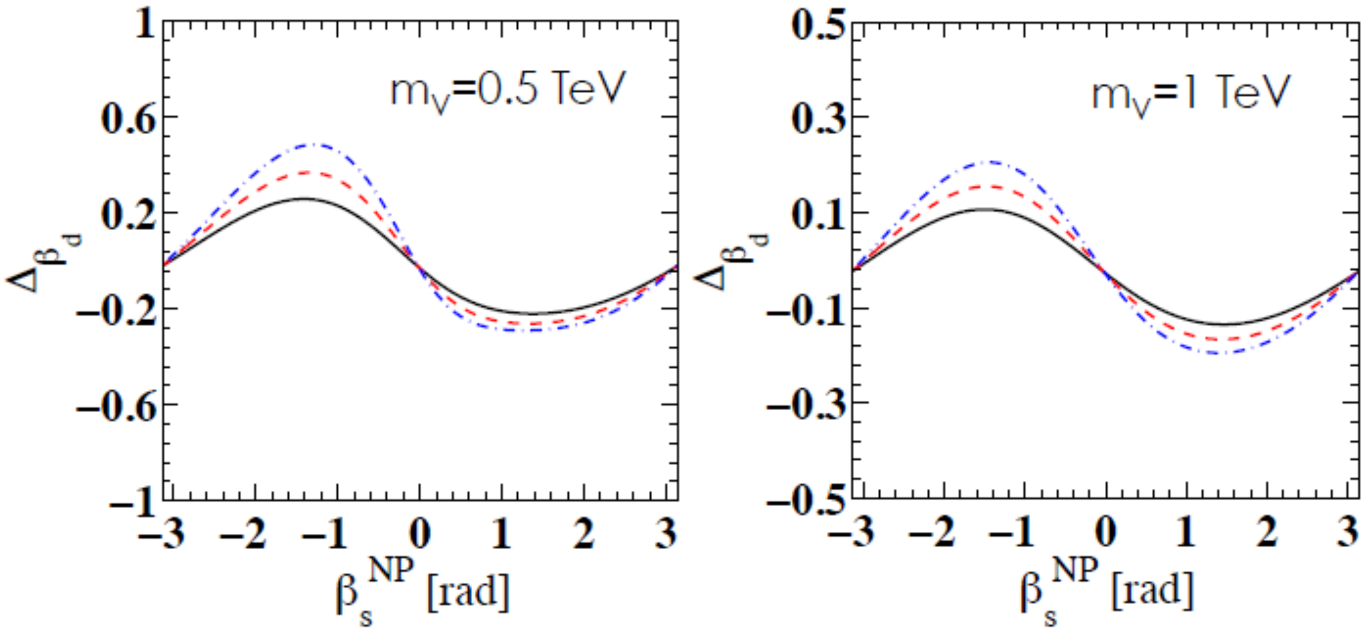
TDCPA



# CPA diff. between $J/\psi\,\phi$ and $K_S\,\phi$ by axialuon

$\Delta_{\beta_d} = S_{J/\psi K^0}(SM) - S_{\phi K^0}(SM) < 5\%$ Grossman & Worah PLB395(97)



# Summary

- Although the SM fits most precision measurements, it is necessary to extend the SM for explaining

  massive neutrinos, matter-antimatter asymmetry, dark matter etc

- Collider such as LHC could observe the new particle(s) at high energy directly, however, low energy system such as B decays may show the NP effects indirectly

- The potential candidates with less QCD effects to probe new CP phase(s) are

  TDCPA of $B_s \to J/\Psi\ \phi \sim -4\%$

  WSCA: $a^d_{sl}$ (SM) ~ $10^{-4}$, $a^s_{sl}$ (SM) ~ $10^{-5}$ ; $A^b_{sl}$(SM) ~ $10^{-4}$

- More accurate data from Tevatron, LHCb, SuperB factories will show the potential