Probing New Physics in CP violation of B mesons

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Collaborated with Yusuke Shimizu and Kei Yamamoto

Plan of My talk

1Brief Review of CP Violation

2Experimental Status

3 Sbottom-Quark Mixing

1 Probing New Physics in B mesons

SM explains successfully CP violation of K (B^0) and Bd mesons.

Triumph of Kobayashi-Maskawa model

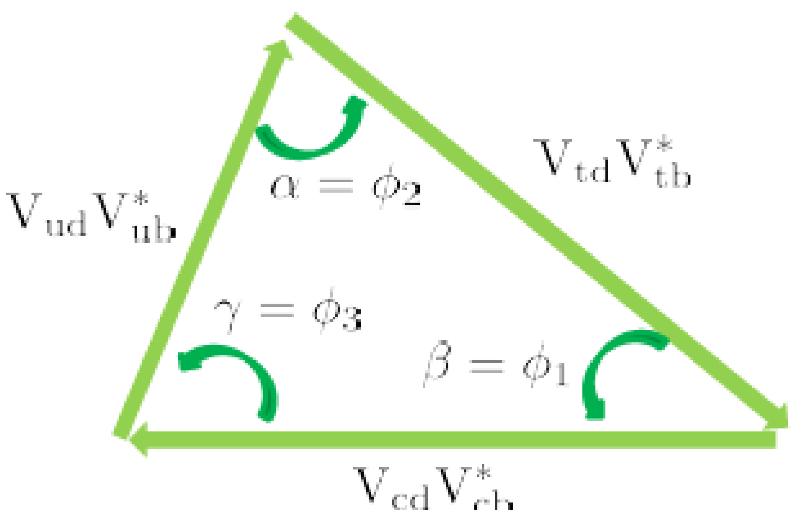
Cabibbo Angle $(\lambda_c = 0.2257)$

CKM matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda_c^2}{2} & \lambda_c & A\lambda_c^3(\rho - i\eta) \\ -\lambda_c & 1-\frac{\lambda_c^2}{2} & A\lambda_c^2 \\ A\lambda_c^3(1-\rho-i\eta) & -A\lambda_c^2 & 1 \end{pmatrix}$$

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

The unitarity triangle on Complex Plane



$$\phi_1 = \pi - \arg\left(\frac{-V_{tb}^* V_{td}}{-V_{cb}^* V_{cd}}\right) \quad \leftarrow \quad B_d \to J/\psi K_s$$

$$\phi_2 = \arg\left(\frac{V_{tb}^* V_{td}}{-V_{ub}^* V_{ud}}\right) \quad \leftarrow \quad B_d \to \pi^+\pi^-$$

$$\phi_3 = \arg\left(\frac{V_{ub}^* V_{ud}}{-V_{cb}^* V_{cd}}\right) \quad \leftarrow \quad B \to D\,K$$

CP violation for beginner

$$\mathrm{CP}|K^o\rangle = +|\bar{K}^o\rangle \quad \mathrm{CP}|\bar{K}^o\rangle = +|K^o\rangle$$

Neutral Meson Mixing

Neutral Meson P at t

$$|\psi(t)\rangle = a(t)|P^0\rangle + b(t)|\bar{P}^0\rangle$$

Schrödinger equation

$$K^0(d\bar{s}) \quad \bar{K}^0(\bar{d}s)$$

$$B_d^0(\bar{b}d) \quad \bar{B}_d^0(b\bar{d})$$

$$B_s^0(\bar{b}s) \quad \bar{B}_d^0(b\bar{s})$$

$$i\frac{d}{dt}\psi(t) = H\psi(t)$$

Hamiltonian

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

Mass term (→ M)

Decay term (→ Γ)

$$i\frac{d}{dt}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = H \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$i\frac{d}{dt}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix} \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

Eigenstate

$$|P_1\rangle = p|P^0\rangle - q|\bar{P}^0\rangle$$

$$|P_2\rangle = p|P^0\rangle + q|\bar{P}^0\rangle$$

$$\frac{q}{p} = \pm\sqrt{\frac{{M_{12}}^* - \frac{i}{2}{\Gamma_{12}}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

$$\left|\frac{q}{p}\right| \neq 1$$ → **CP violation**

Eigenvalues

$$M_1 - \frac{i}{2}\Gamma_1 = M_{11} - \frac{i}{2}\Gamma_{11} + \frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)$$

$$M_2 - \frac{i}{2}\Gamma_2 = M_{11} - \frac{i}{2}\Gamma_{11} - \frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)$$

$$\left[\begin{array}{l} \Delta M = M_2 - M_1 \\ \Delta\Gamma = \Gamma_1 - \Gamma_2 \end{array}\right.$$

The decay amplitude

$$A(f) = \langle f|H|P^0\rangle, \bar{A}(\bar{f}) = \langle \bar{f}|H|\bar{P}^0\rangle$$

Under the CP invariance

$$A(f) = \langle f|H|P^0\rangle$$
$$= \langle f|(CP)^{-1}(CP)H(CP)^{-1}(CP)|P^0\rangle$$
$$= \langle \bar{f}|H|\bar{P}^0\rangle = \bar{A}(\bar{f})$$

$$\frac{\bar{A}(\bar{f})}{A(f)} \neq 1$$ ➡ **CP violation**

CP violations originate from decay amplitudes or neutral meson mixing

$$\bar{\rho}(f) = \frac{\bar{A}(f)}{A(f)}$$ **Direct CP violation** (amplitude)

$$\frac{q}{p}$$ **Indirect CP violation** (mixing)

$$\bar{\lambda} = \frac{q}{p}\bar{\rho}(f)$$ (mixing & amplitude)

The three type of CP violation in Meson Decays

1. CP violation in decay without mixing

$$\left|\frac{\bar{A}(\bar{f})}{A(f)}\right| \neq 1$$

Asymmetry

$$a = \frac{\Gamma\left(P^0(t) \to f\right) - \Gamma\left(\bar{P}^0(t) \to \bar{f}\right)}{\Gamma\left(P^0(t) \to f\right) + \Gamma\left(\bar{P}^0(t) \to \bar{f}\right)} = \frac{1 - \left|\frac{\bar{A}}{A}\right|^2}{1 + \left|\frac{\bar{A}}{A}\right|^2}$$

2. CP violation in mixing

$$\left|\frac{q}{p}\right| \neq 1$$

The time dependent decay rate

$$\Gamma(P^0(t) \to l^- + X) \propto e^{-\Gamma_1 t} K_-(t) \left|\frac{q}{p}\right|^2 |A_{SL}|^2$$

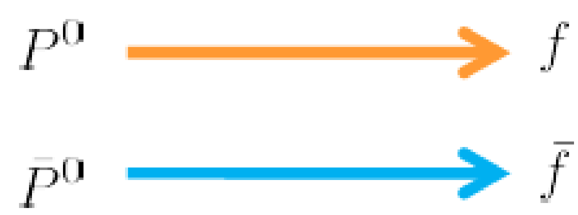
$$\Gamma(\bar{P}^0(t) \to l^+ + X) \propto e^{-\Gamma_1 t} K_-(t) \left|\frac{p}{q}\right|^2 |A_{SL}|^2$$

Asymmetry

$$a = \frac{\Gamma\left(P^0(t) \to \ell^- X\right) - \Gamma\left(\bar{P}^0(t) \to \ell^+ X\right)}{\Gamma\left(P^0(t) \to \ell^- X\right) + \Gamma\left(\bar{P}^0(t) \to \ell^+ X\right)} = \frac{1 - \left|\frac{p}{q}\right|^4}{1 + \left|\frac{p}{q}\right|^4}$$

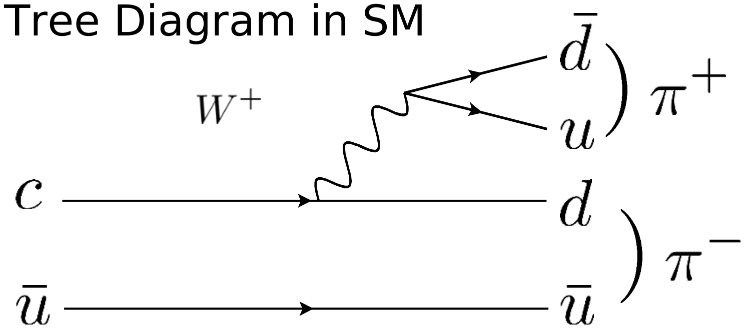
Flavor specific decay (semileptonic decay)

$$P^0 \to f \not\leftarrow \bar{P}^0$$

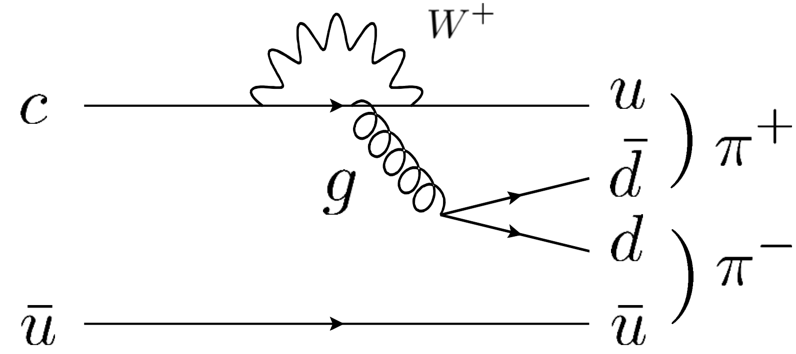


Direct CP Violation

Tree Diagram in SM



Penguin Diagram in SM



Decay Amplitudes

$$A_f(D^0 \to f) = T_f e^{i(\delta_T - \gamma_T)} + P_f e^{i(\delta_P - \gamma_P)}$$

$$= T_f \left[1 + r_f e^{i(\delta_f - \gamma)}\right]$$

$$\bar{A}_{\bar{f}}(\bar{D}^0 \to \bar{f}) = T_f \left[1 + r_f e^{i(\delta_f + \gamma)}\right]$$

T_f - Tree , P_f -Penguin

r_f-Ratio of Penguin and Tree

δ_f strong phase shift , γ -weak CP phase

CP asymmetry

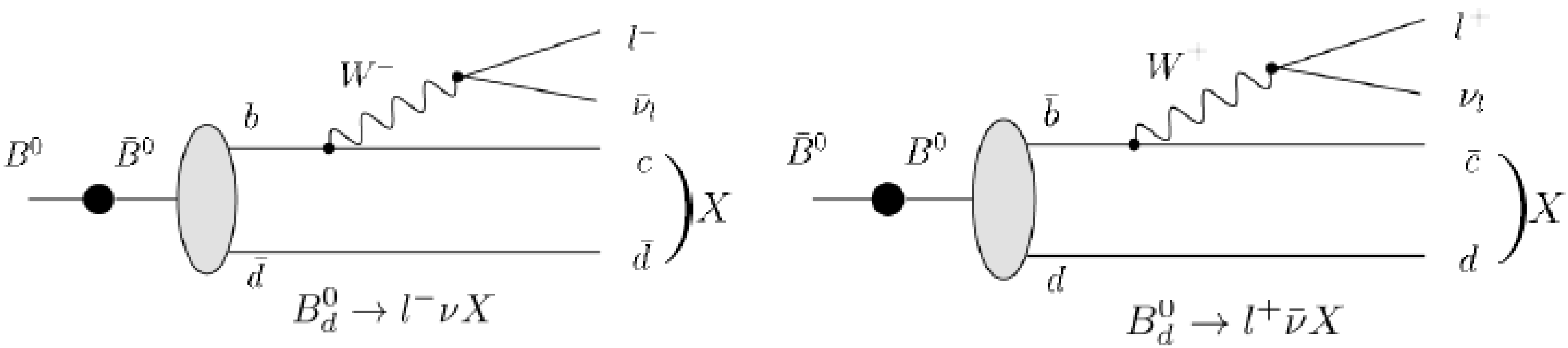
$$A_f^{dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

$$= 2 r_f \underline{\sin\gamma \sin\delta_f}$$

CP Violation in Mixing

CP violation in Bd

$B_d^0 \to l^- \nu X$ **Flavor specific decay (semileptonic decay)** $(P^0 \to f \nleftarrow \bar{P}^0)$



Asymmetry

$$a = \frac{1 - \left|\frac{p}{q}\right|^4}{1 + \left|\frac{p}{q}\right|^4} \sim -\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)$$

3. CP violation in mixing and decay

$$\arg\left(\frac{q}{p}\right) + \arg\left(\bar{\rho}\right) \neq 0$$

decay amplitude ratio

$$\bar{\rho}(f) = \frac{\bar{A}(f)}{A(f)}$$

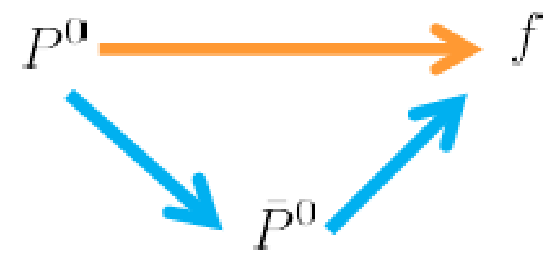
Asymmetry

$$a = \frac{\Gamma\left(P^0(t)\to f\right) - \Gamma\left(\bar{P}^0(t)\to f\right)}{\Gamma\left(P^0(t)\to f\right) + \Gamma\left(\bar{P}^0(t)\to f\right)}$$

$$= \frac{-2\sin\left(\arg\left(\frac{q}{p}\right) + \arg\left(\bar{\rho}\right)\right) e^{\frac{1}{2}\Delta\Gamma t}\sin\left(\Delta M t\right)}{1 + e^{\Delta\Gamma t} + \cos\left(\arg\left(\frac{q}{p}\right) + \arg\left(\bar{\rho}\right)\right)\left(1 - e^{\Delta\Gamma t}\right)}$$

Flavor non-specific decay

$$P^0 \to f \leftarrow \bar{P}^0$$

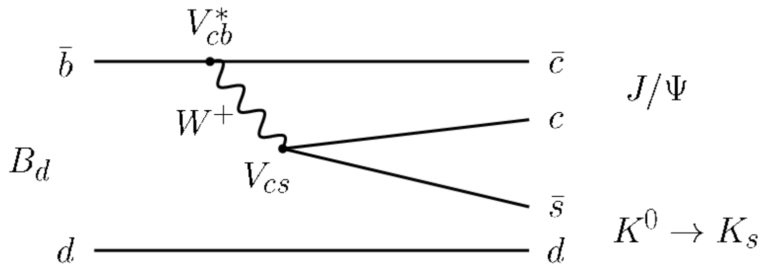


Bd and Bs non-leptonic decays

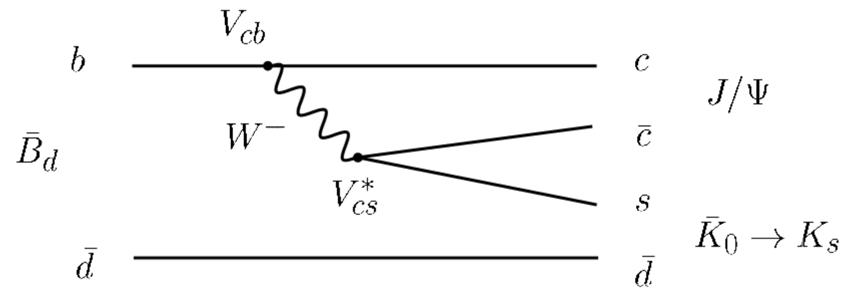
$$B_d^0 \to J/\psi K_s$$

Golden Mode in CP violation of B meson

$$B_d^0 \to J/\psi K_s \qquad (P^0 \to f \leftarrow \bar{P}^0)$$



$B_d^0 \to J/\psi K_s$



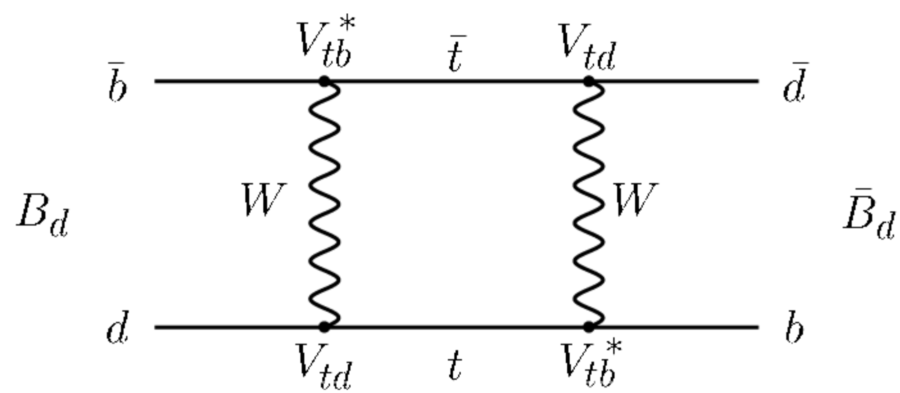
$\bar{B}_d^0 \to J/\psi K_s$

Standard Model

$$\left.\frac{q}{p}\right|_{B_d} \simeq \sqrt{\frac{M_{12}^*}{M_{12}}}$$

$$M_{12} \propto (V_{tb} V_{td}^*)^2$$

$$\simeq \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$



New Physics ?

$$M_{12} = \frac{G_F^2 M_B}{12\pi^2} M_W^2 \left(V_{tb} V_{td}^*\right)^2 \hat{\eta}_B S_0 f_{B_d}^2 B_d$$

$$\bar{\rho}(\psi K_s) \simeq \frac{\langle \psi K_s | H | \bar{B}_d^0 \rangle}{\langle \psi K_s | H | B_d^0 \rangle} = \frac{\langle \psi K_s | \psi \bar{K}^0 \rangle \langle \psi \bar{K}^0 | H | \bar{B}_d^0 \rangle}{\langle \psi K_s | \psi K^0 \rangle \langle \psi K^0 | H | B_d^0 \rangle}$$

$$\langle \psi K^0 | H | B_d^0 \rangle \propto V_{cb}^* V_{cs}$$

$$\langle \psi K_s | \psi K^0 \rangle \propto V_{cs}^* V_{cd}$$

$$\simeq -\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} = -\frac{V_{cd}^* V_{cb}}{V_{cd} V_{cb}^*}$$

$$\lambda = \frac{q}{p} \bar{\rho}(\psi K_s) = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cd}^* V_{cb}}{V_{cd} V_{cb}^*} = -\mathrm{e}^{-2i\phi_1}$$

Time-dependent Asymmetry

$$a = \frac{\Gamma\left(P^0(t) \to f\right) - \Gamma\left(\bar{P}^0(t) \to \bar{f}\right)}{\Gamma\left(P^0(t) \to f\right) + \Gamma\left(\bar{P}^0(t) \to \bar{f}\right)}$$

$$= \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \cos\left(\Delta m_B t\right) + \frac{2\mathrm{Im}\lambda}{|\lambda|^2 + 1} \sin\left(\Delta m_B t\right)$$

$$= \sin\left(\Delta m_B t\right) \mathrm{Im}\lambda$$

$$= \sin\left(\Delta m_B t\right) \sin\left(2\phi_1\right)$$

Experiment

$$a \neq 0$$

$$\sin(2\phi_1) = 0.673 \pm 0.023$$

CP Violation !

However,

there is still **possibility to find**
New Physics in the CP violation
phenomena (especially in **Bs system**) !

TeV Scale Physics in LHC Era!

Precise measurement of CP violation in B mesons !

Parameterization of New Physics(NP)

- The dispersive part of the $B_q^0 - \overline{B}_q^0$ mixing

$$M_{12}^q = (M_{12}^q)^{SM} + (M_{12}^q)^{NP}$$

$$= (M_{12}^q)^{SM} \left(1 + \frac{(M_{12}^q)^{NP}}{(M_{12}^q)^{SM}}\right)$$

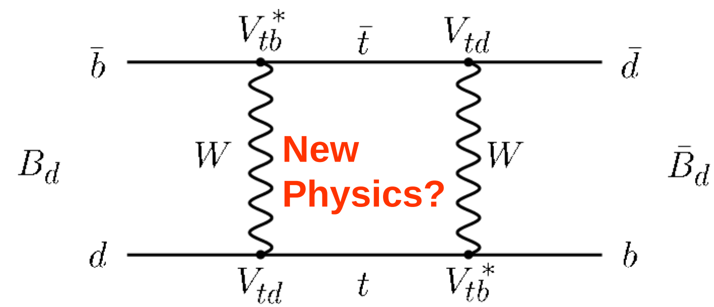
$$= (M_{12}^q)^{SM} \left(1 + h_q e^{2i\sigma_q}\right)$$

$$(q = d, s)$$

Hamiltonian inducing mixing

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

dispersive part (M) — absorptive part (Γ)



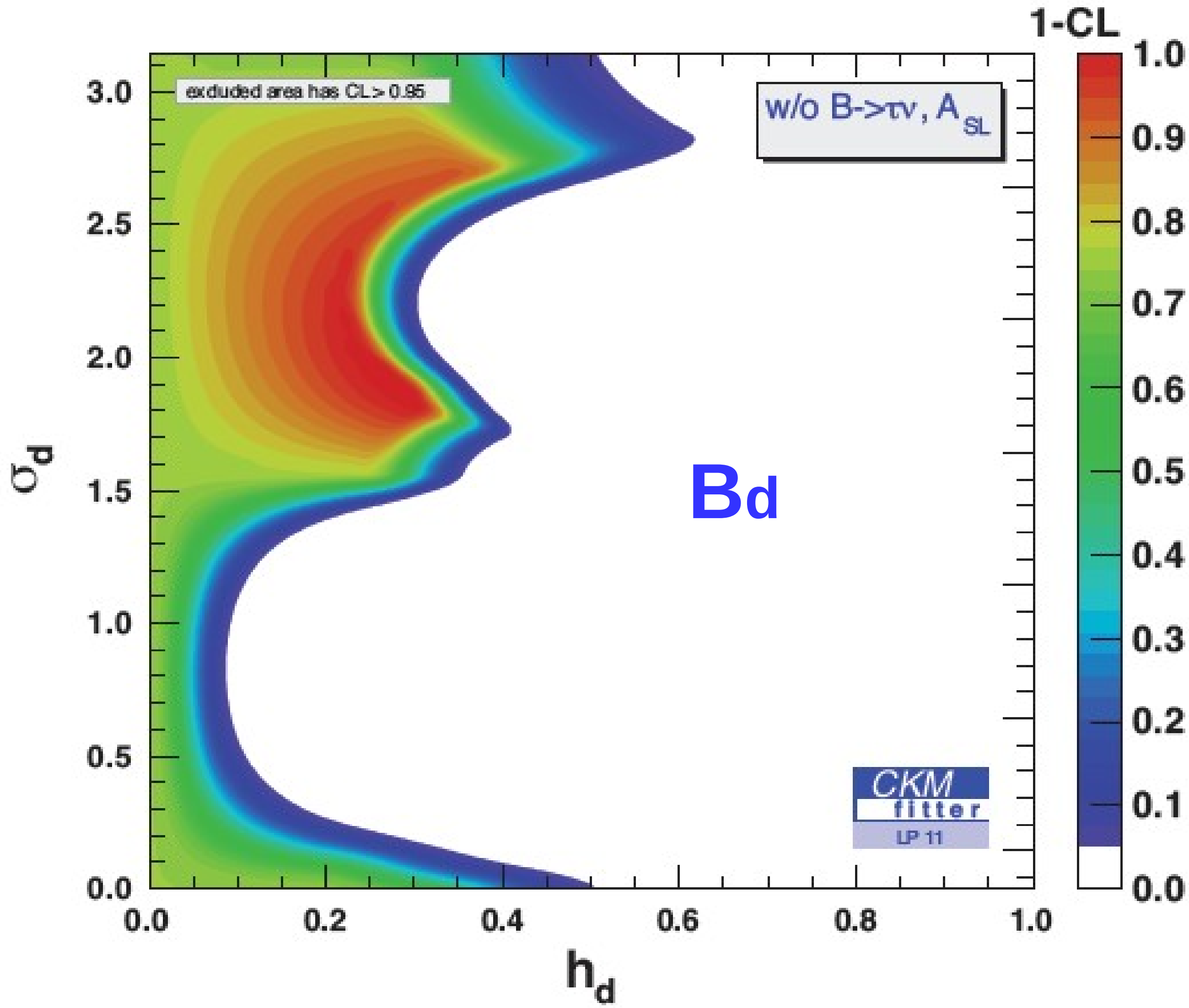
h_q : Magnitude of NP normalized to SM

σ_q : NP relative phase

- The absorptive part of the $B_q^0 - \overline{B}_q^0$ mixing

$$\Gamma_{12}^q = (\Gamma_{12}^q)^{SM}$$

(We neglect NP at tree level decay in our work)



1-CL
excluded area has CL > 0.95
w/o B->τν, A_SL
Bd
CKM
fitter
LP 11
σd
hd
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.2
0.4
0.6
0.8
0.1
0.3
0.7
0.9

2 Expeimental Staus of B mesons

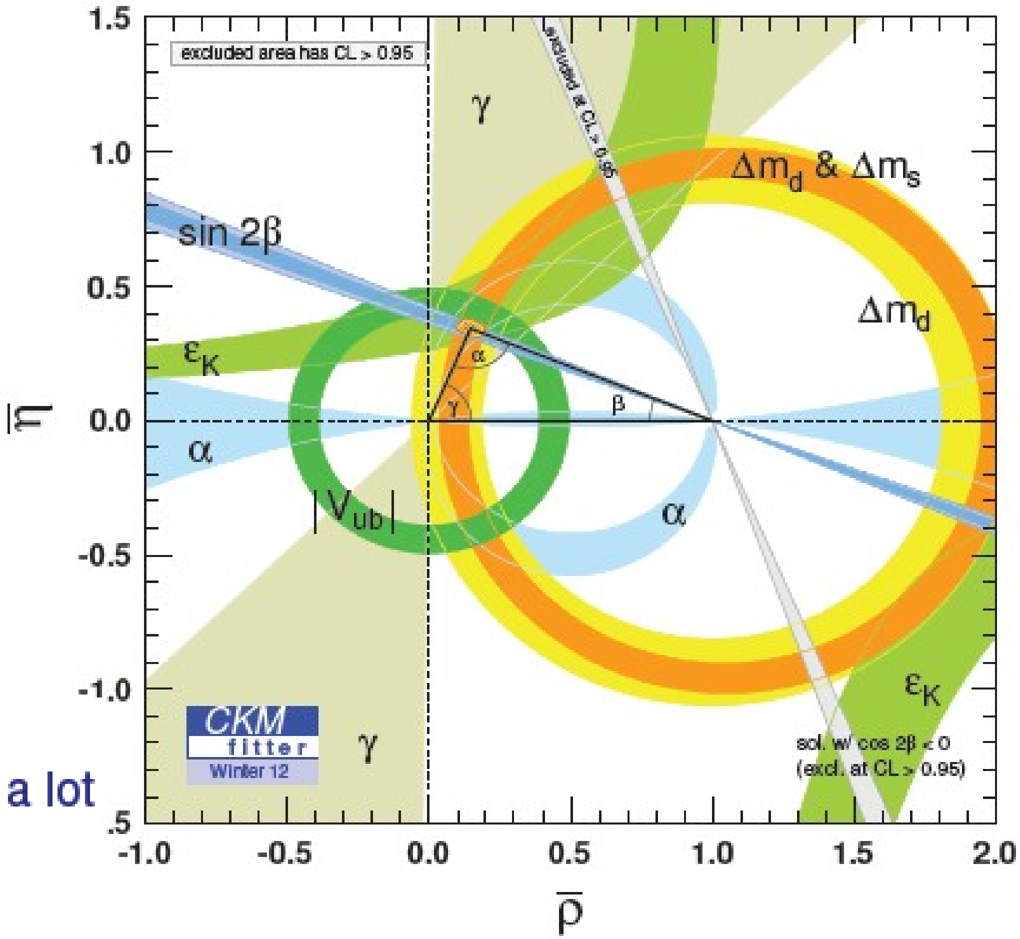
Some recent news:

– Discovery of SM-like Higgs, lack of deviations from SM

– Not even $B_s \to \mu^+\mu^-$ deviates from the SM by $\mathcal{O}(1)$

CKM fit

No significant deviation !
but,



– a number of tensions
– many measurements can improve a lot

Allowed region is much larger using only tree-level information: γ and $|V_{ub}|$

$\mathcal{O}(20\%)$ **New Physics Contributions to most loop processes still possible !**

Measurement of $B^- \to \tau\bar{\nu}_\tau$

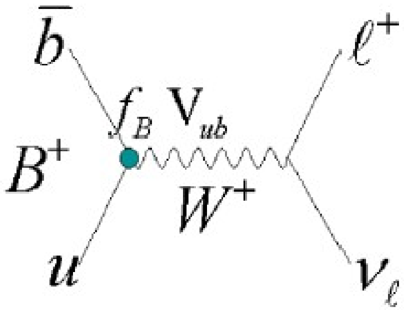
New Results from Belle

Rencontres de Moriond EW 2013

Matthias Huschle | 03.03.2013

$$\Gamma(B^+ \to \ell^+\nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

- helicity-suppressed:
  $\Gamma(B^+ \to e^+\nu_e) \ll \Gamma(B^+ \to \mu^+\nu_\mu) \ll \Gamma(B^+ \to \tau^+\nu_\tau)$
- very clean place to measure f_B (or V_{ub}?) and/or search for new physics (e.g. H^+, LQ)
- charged boson may take the role of the W



(a)

Charged Higgs Contributions

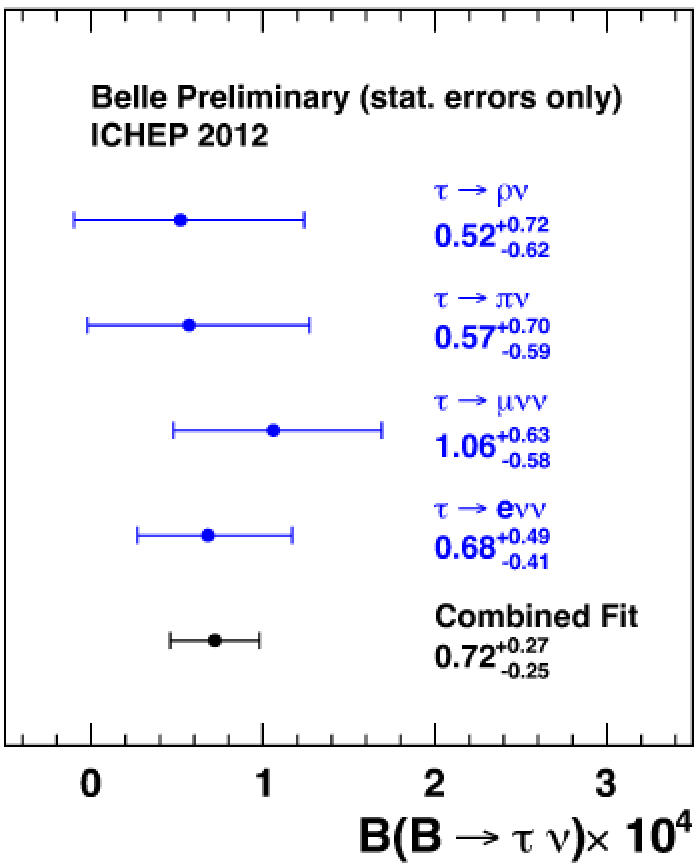
- e.g. H^+ of 2-Higgs doublet model (type II)[3]:

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu_\tau) \times r_H$$

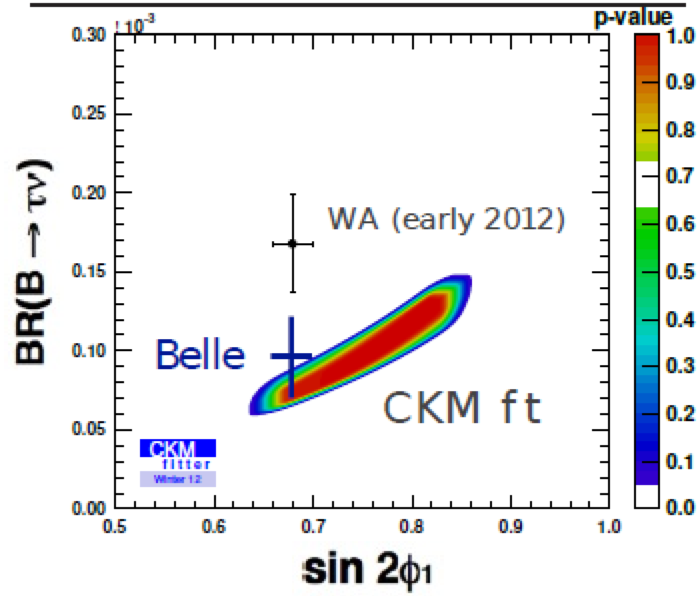
$$r_H = \left[1 - (m_B^2/m_H^2)\tan^2\beta\right]^2$$

Results

- consistency over all τ decay modes



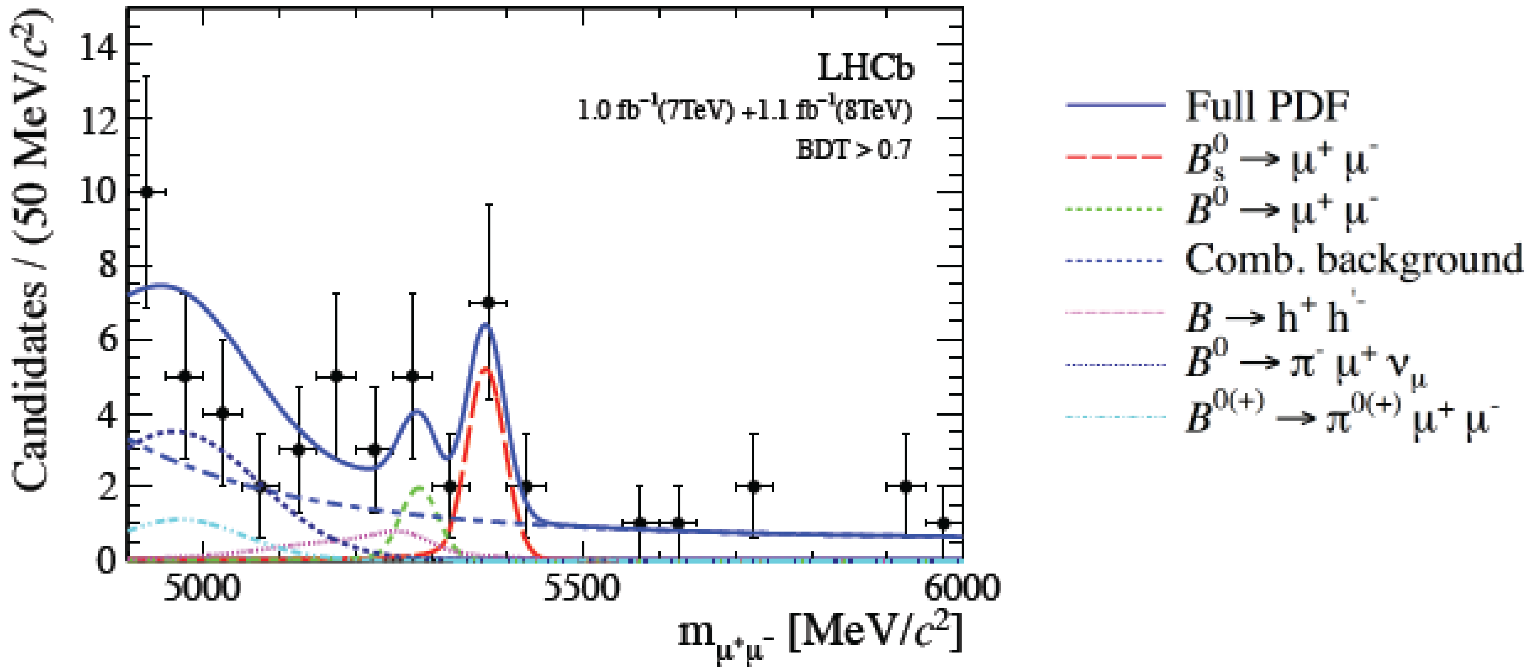
Sub-mode	N_{sig}	(10^{-4})	$B\ (10^{-4})$
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	16^{+11}_{-9}	3.0	$0.68^{+0.49}_{-0.41}$
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	26^{+15}_{-14}	3.1	$1.06^{+0.63}_{-0.58}$
$\tau^- \to \pi^- \nu_\tau$	8^{+10}_{-8}	1.8	$0.57^{+0.70}_{-0.59}$
$\tau^- \to \pi^- \pi^0 \nu_\tau$	14^{+19}_{-16}	3.4	$0.52^{+0.72}_{-0.62}$
Combined	62^{+23}_{-22}	11.2	$0.72^{+0.27}_{-0.25}$



Latest results on $B_{(s)}^0 \to \mu\mu$

Combined dataset result

R. Aaij et al. (LHCb Collaboration)
Phys. Rev. Lett. 110, 021801 (2013)

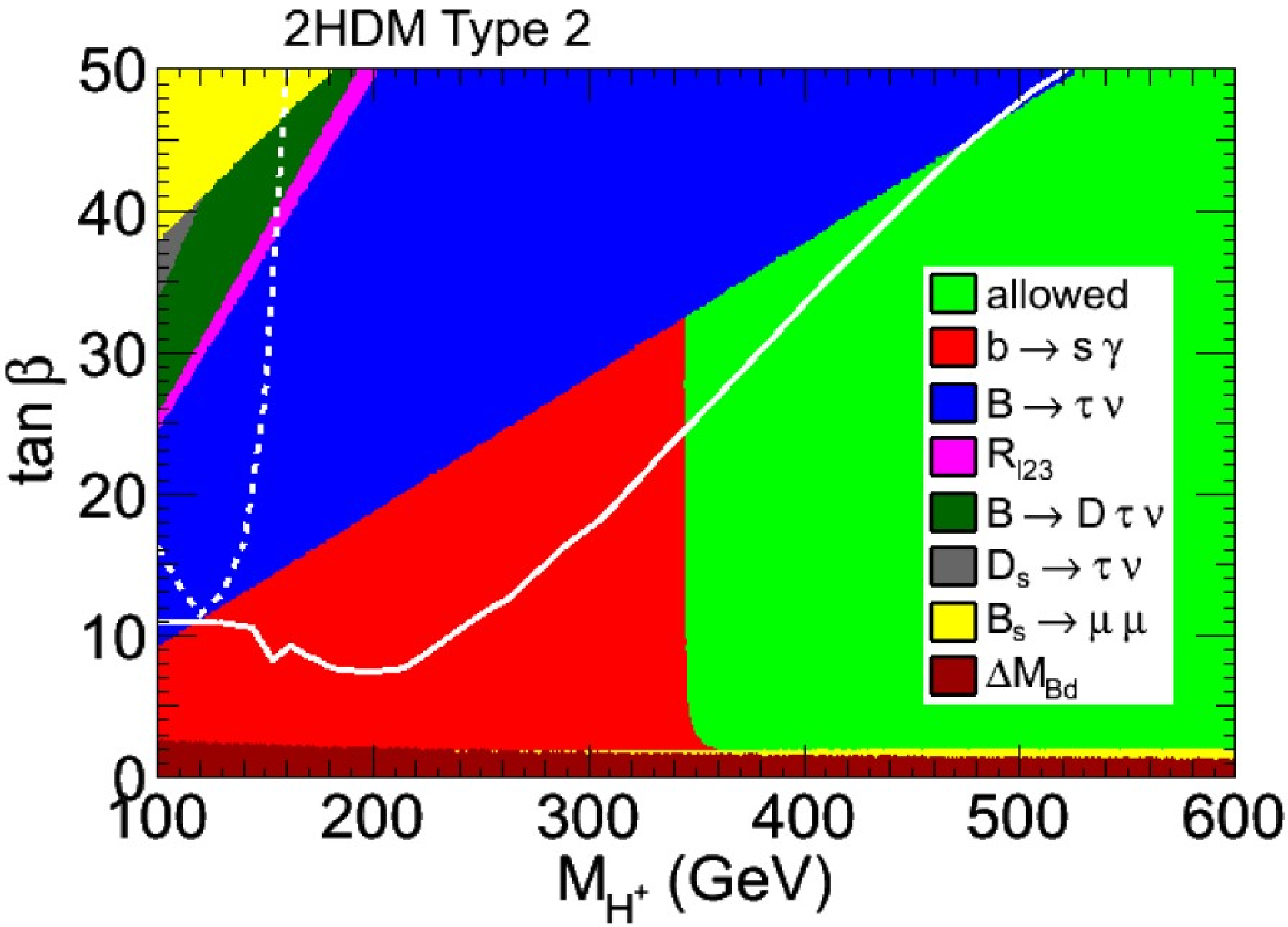


syst from nuisance parameters and background models:

BR = $(3.2^{+1.4}_{-1.2}\,(stat)\ ^{+0.5}_{-0.3}\,(syst))\times 10^{-9}$ fully dominated by stat error

BR($B^0_s \to \mu^+\mu^-$) = $(3.2^{+1.5}_{-1.2})\times 10^{-9}$

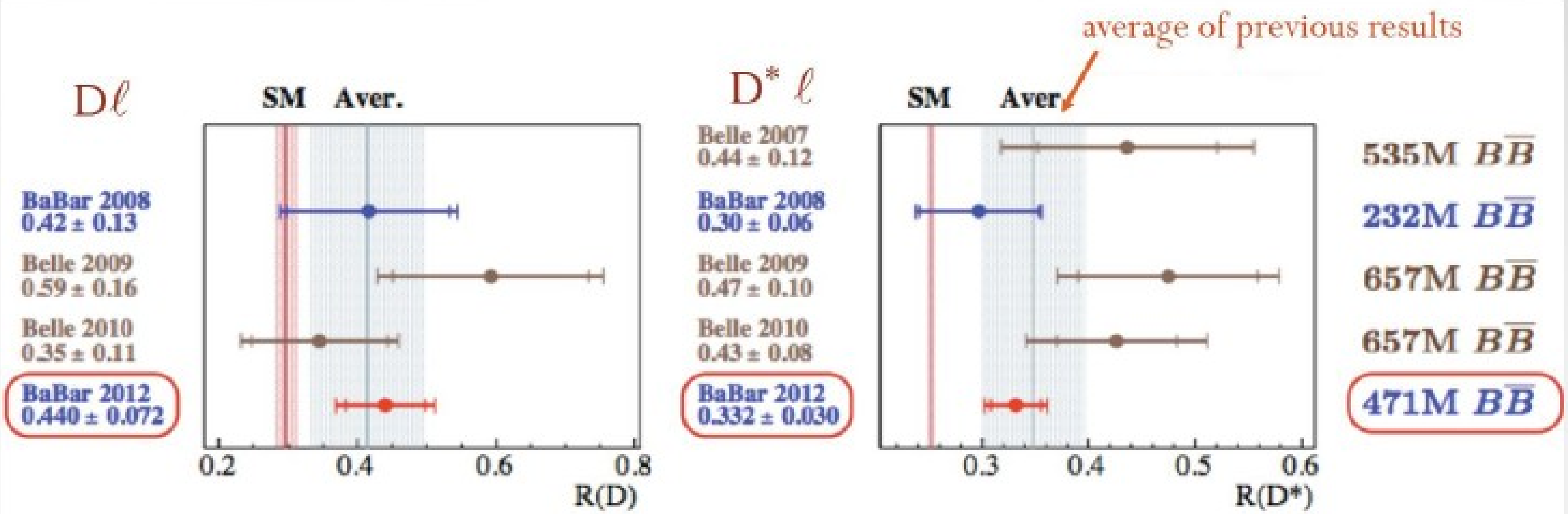
SM expectation
$(3.54 \pm 0.30)\times 10^{-9}$



T. Hurth, Mahmound, FarXiv:1211.6453v2

K. Hara KEK-ph 2013 March 6

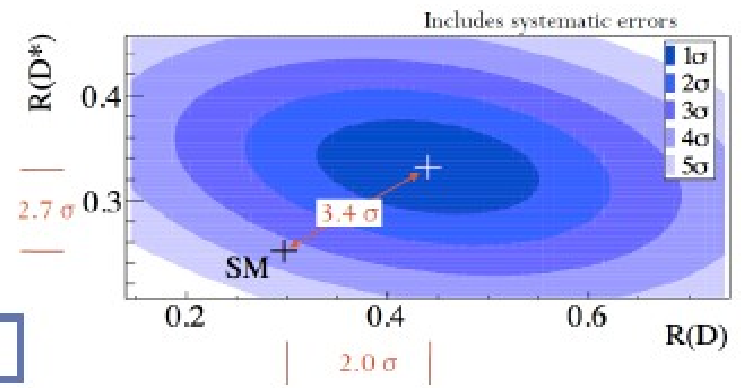
$B \to D^{(*)} \tau \nu$ Results



- Belle and BaBar results are consistent
- All R measurements are higher than the SM expectation
- BaBar result is inconsistent with SM by 3.4 σ

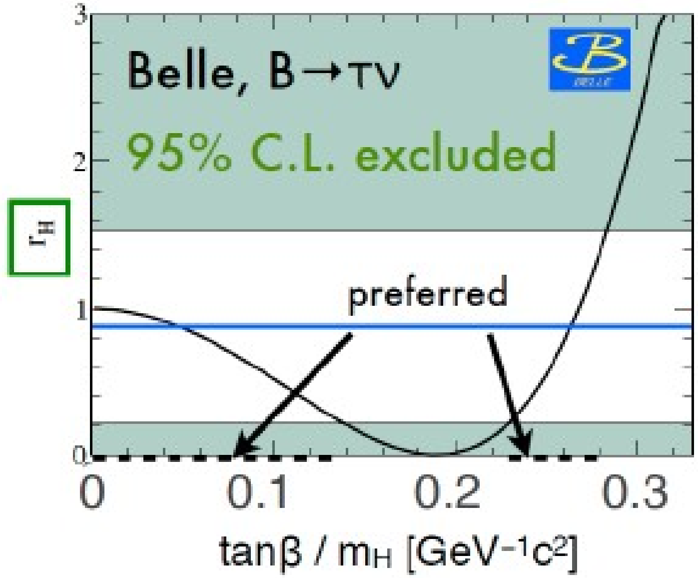
Belle's new hadronic tag result will come soon!

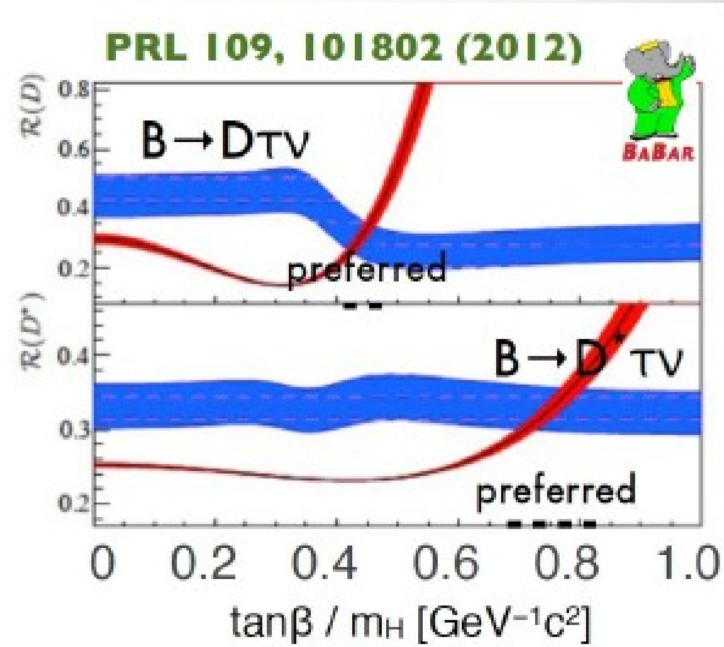
Comparison to SM [BaBar]

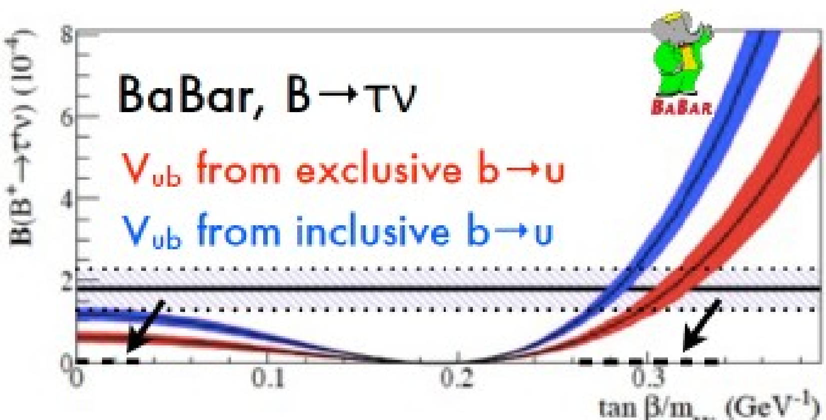


LHCb first result in autumn 2013 ?

Constraint on Charged Higgs







- B→τν, BaBar's B→Dτν and B→D(*)τν prefer different regions of tanβ/m_H
- Type-II 2HDM is disfavored?

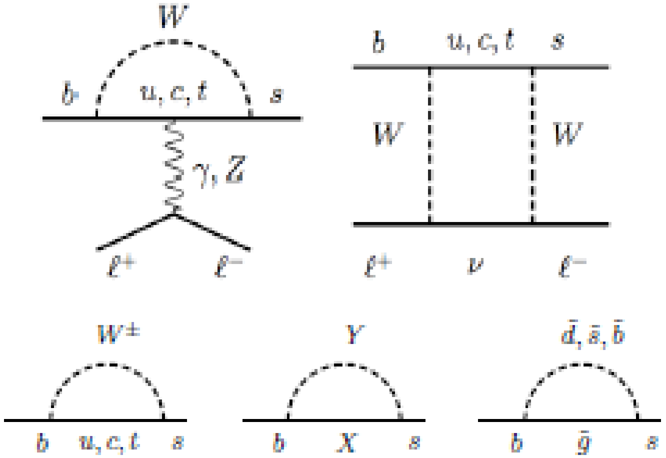
→ Belle result with full data and future measurement at Belle II is important.

Note: Belle regions correspond to 2σ, while BaBar regions are for 1σ

Exclusive semileptonic FCNC $b \to s\mu^+\mu^-$ decays

$\Delta F = 1$ FCNC; sensitive to flavor in and beyond the SM.

$Br_{\rm SM} \sim 10^{-6} - 10^{-7}$



observed (at SM level):

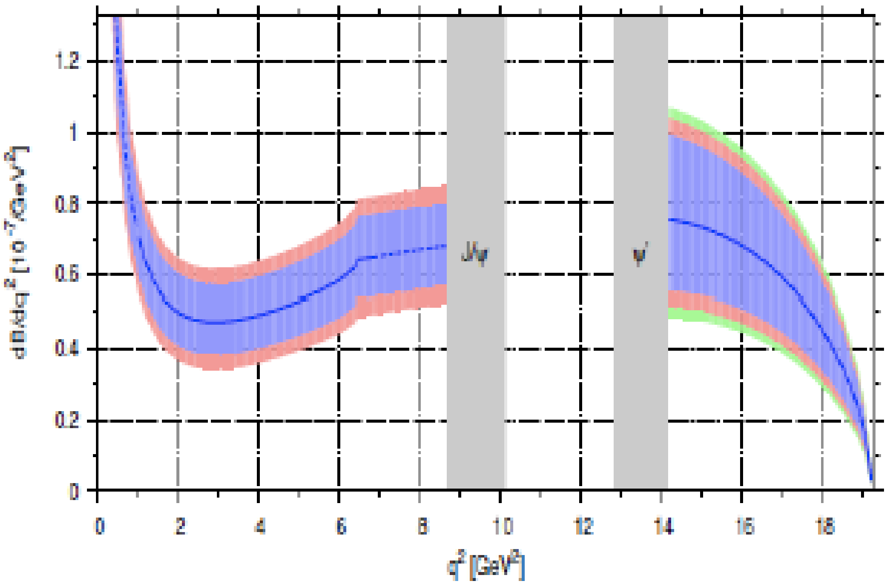
$B \to K^{(*)}\mu^+\mu^-$ BaBar, Belle, CDF 6.8 fb^{-1} and LHCb 1 fb^{-1} LHCb-CONF-2012-008

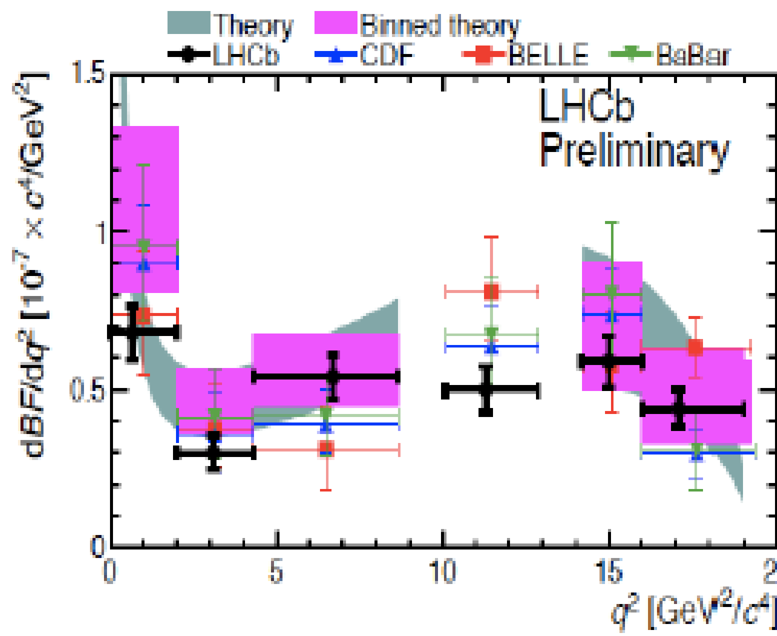
$B_s \to \Phi\mu^+\mu^-$ CDF 2011 1101.1028 [hep-ex] LHCb 2012 LHCb-CONF-2012-008

$\Lambda_b \to \Lambda\mu^+\mu^-$ CDF 2011 1107.3753 [hep-ex]

distributions measured. precision physics started.

Situation: Dilepton Mass Spectrum in $B \to K^* \mu^+ \mu^-$





left-hand Fig. from 1006.5013 [hep-ph] Blue band: form factor uncertainties, red: $1/m_b$ right-hand Fig. from LHCb-CONF-2012-008

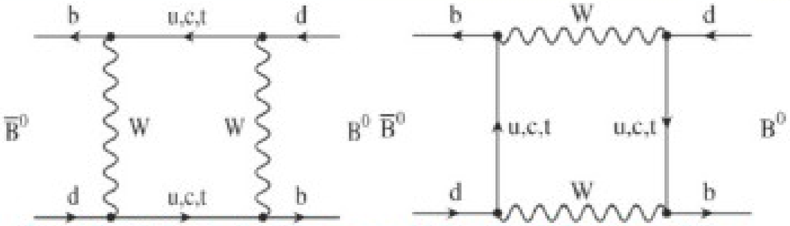
Biggest source of theory uncertainty: the $B \to K^*$ form factors.

Gudrun Hiller, Dortmund

CPV in $B^0\overline{B}^0$ mixing
Introduction

- **CPV in B^0 mixing if:**

$$P(\overline{B}_d \rightarrow B_d) \neq P(B_d \rightarrow \overline{B}_d)$$



New Particles in the boxes could modify SM expectations

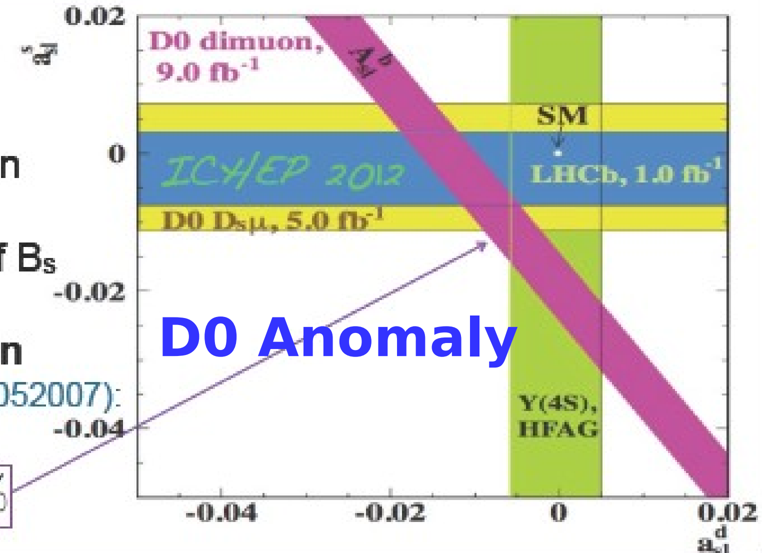
- **CP Asymmetry** (time-independent):

$$A_{CP} = \frac{N(B^0,B^0) - N(\overline{B}^0,\overline{B}^0)}{N(B^0,B^0) + N(\overline{B}^0,\overline{B}^0)} = \frac{1-|q/p|^4}{1+|q/p|^4} \approx 2(1-|q/p|)$$

  - SM expectation: $\mathcal{O}(10^{-4})$

- **Status of CPV in mixing:**
  - **HFAG average from $\Upsilon(4S)$ measurement in agreement with SM**
  - Hadronic colliders measure combination of B_s and B_d CP: A^{b}_{SL}
  - **D0** result on charge asymmetry of **like-sign dimuons differs by 3.9 σ** (Phys. Rev. D 84, 052007):

$$A^{b}_{SL} = (-0.787 \pm 0.172 \pm 0.093)\%$$

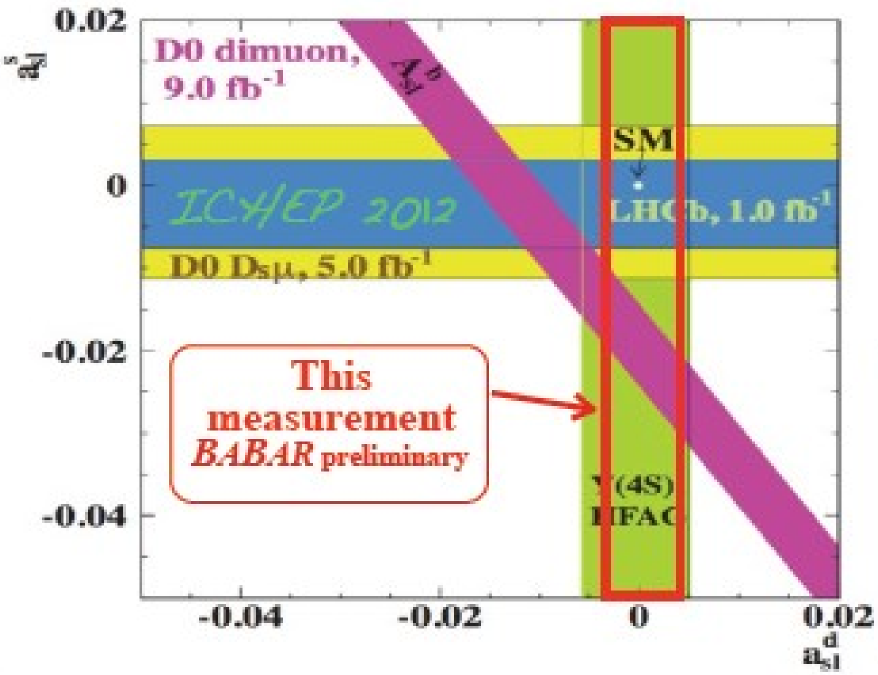


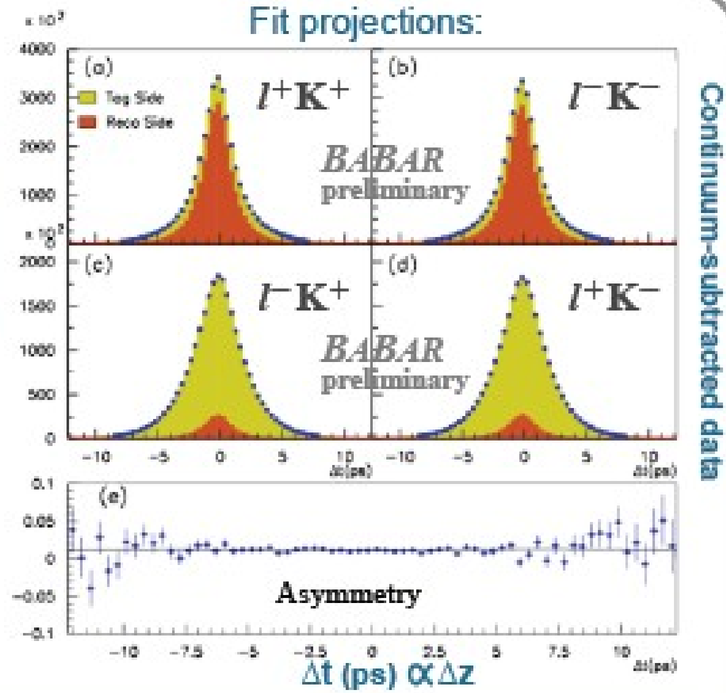
CPV in $B^0\bar{B}^0$ mixing
Results

- **Asymmetry parameters:**

BABAR preliminary

$$\mathcal{A}_{CP} = (0.06 \pm 0.17^{+0.36}_{-0.32})\%$$
$$1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$$





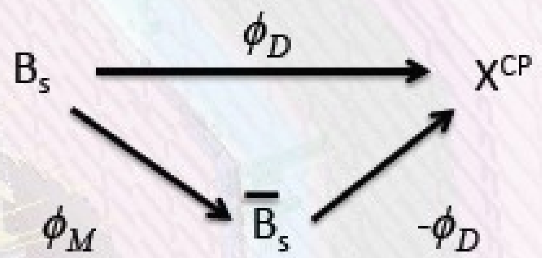
- Consistent with HFAG average
- Consistent with SM expectations
- Single most precise measurement
- Expect more results from Belle & LHCb

CP Violation in Bs

ϕ_s notation

In this presentation, ϕ_s is used to denote the CP violation interference between mixing and decay:

I.e. $\phi_s = \phi_M - 2\phi_D$



Same symbol (ϕ_s) is used regardless of the final state of the B_s decay.

$$\lambda_f = \frac{q}{p}\bar{\rho}\,, \qquad \frac{q}{p} = \sqrt{\frac{M_{12}^{q*} - \frac{i}{2}\Gamma_{12}^*}{M_{12}^q - \frac{i}{2}\Gamma_{12}}}, \qquad \bar{\rho} \equiv \frac{\bar{A}(\bar{B}_q^0 \to f)}{A(B_q^0 \to f)}.$$

$$B_d \to J/\psi K_s$$

SM

New Physics

$$\lambda_{J/\psi K_S} = -e^{-i\phi_d}, \qquad \phi_d = 2\beta_d + \arg(1 + h_d e^{2i\sigma_d})$$

Observation $S_{J/\psi K_S} = 0.658 \pm 0.024$

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

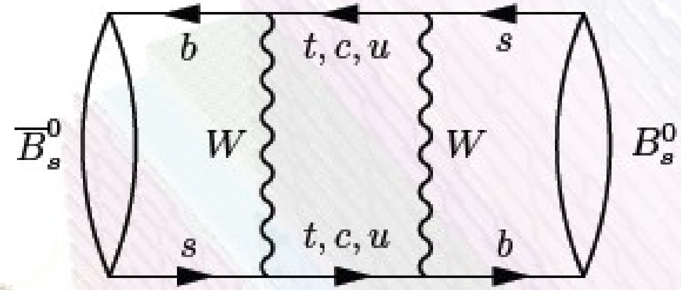
$$\lambda_{J/\psi\phi} = e^{-i\phi_s}, \qquad \phi_s = -2\beta_s + \arg(1 + h_s e^{2i\sigma_s})$$

$$\phi_s^{J/\psi\phi,SM} = -2\beta_s = -0.0363 \pm 0.0017 \text{ rad}$$

ϕ_s New Physics prospects

Mixing

There could be new physics contributions, that would manifest as new contributions in B_s mixing diagrams (arXiv:1008.1593)



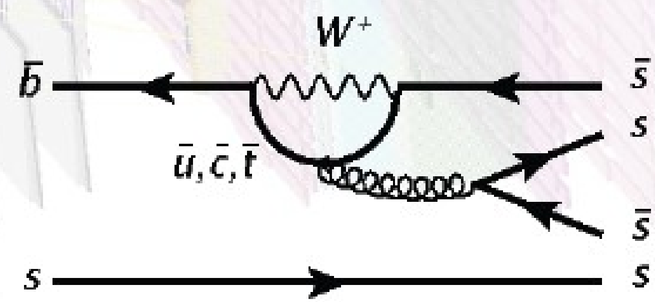
Large effects are ruled out through existing measurements of B_s->J/ψϕ

Decay

New contributions could also appear in penguin diagrams (hep-ph/0007328, arXiv:1212.6486v1).

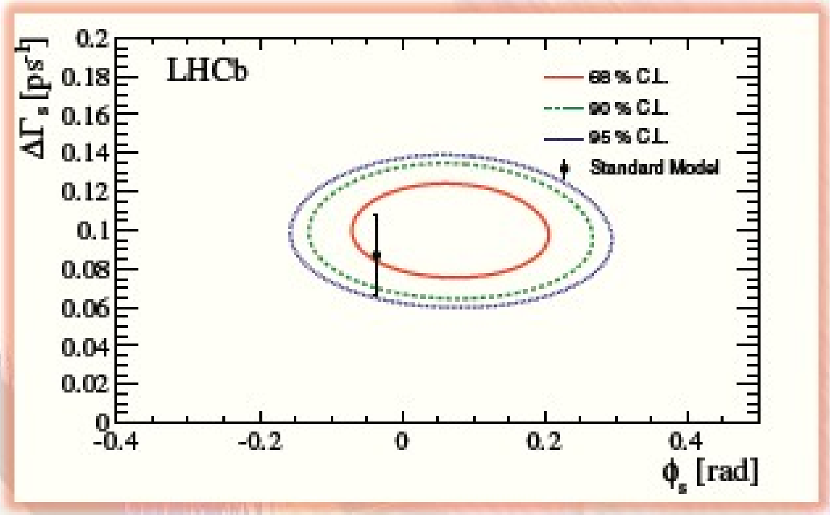
Loop suppressed ➔ need large datasets to measure

Now becoming accessible.



$B_s \to J/\psi\phi$: Results

Result consistent with SM expectation



Measurement of $\Delta\Gamma_s$ over 6σ from zero

$$\begin{aligned}
\phi_s &= 0.07 \pm 0.09\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{rad},\\
\Gamma_s \equiv (\Gamma_L + \Gamma_H)/2 &= 0.663 \pm 0.005\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1},\\
\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H &= 0.100 \pm 0.016\ (\text{stat}) \pm 0.003\ (\text{syst})\ \text{ps}^{-1}
\end{aligned}$$

First measurement of the CP-violating phase in hadronic $B_s \to \phi\phi$ decays
LHCb-PAPER-2013-007

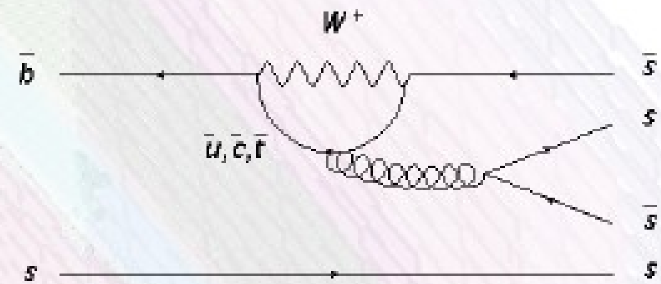
$B_s \to \phi\phi$ a pure penguin P->VV decay

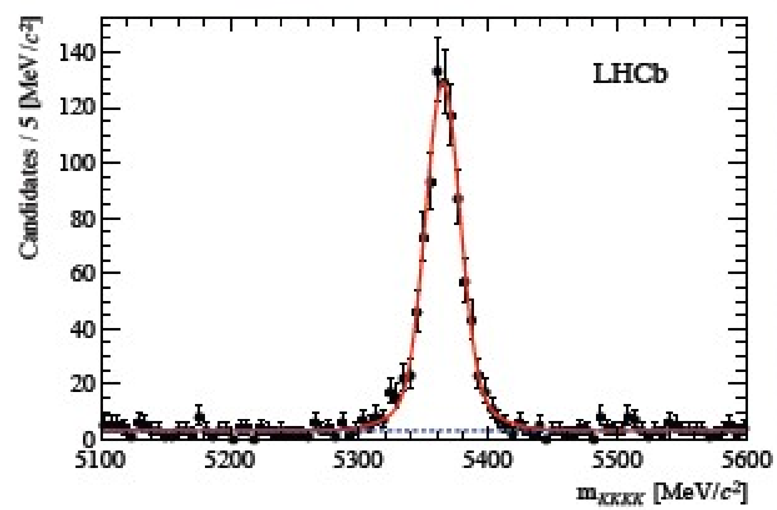
Sensitive to new physics in mixing and decay

880±31 events observed in KKKK final state using 1.0 fb^{-1} LHCb data.

Results presented based on time-dependent tagged angular analysis

$B_s \to \phi\phi$ decay originates from a $b \to s\bar{s}\bar{s}$ transition ➔ SM expectation of ϕ_s is zero as cancellation between mixing and decay weak phases





- A first time-dependent tagged analysis of CP violation in the interference between mixing and decay for the $B_s \to \phi\phi$ decay yields a 68% C.L of:

[-2.46,-0.76] rad

- The p-value of the Standard Model hypothesis is 16%.

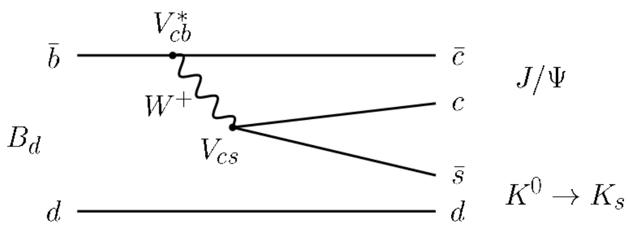
SM prediction is same as in $B_s \to J/\psi\phi$

$$-0.0363^{+0.0016}_{-0.0015}$$

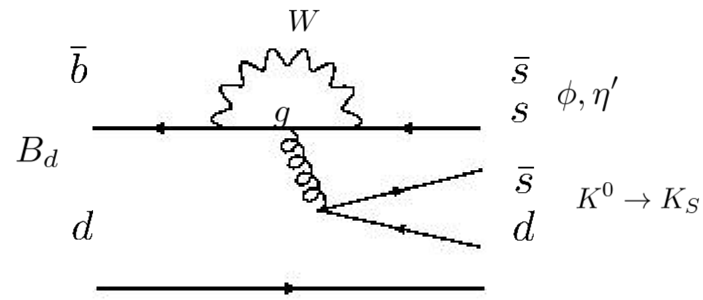
Non-leptonic CP asymmetry in Bd and Bs

Let's discussion about CP asymmetries of B_d meson .

$B_d \to J/\psi K_S$



$B_d \to \phi K_S, \eta' K^0$



SM

SM prediction

If there is only the KM phase,

Time dependent CP asymmetries

$$S_{J/\psi K_S} = S_{\phi K_S, \eta' K_S}$$

there may be deviation between SM prediction and experimental result

The time dependent CP asymmetry in B^0 decays

- CP asymmetry:

$$A = \frac{\Gamma(B^0(t) \to f) - \Gamma(\bar{B}^0(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\bar{B}^0(t) \to f)}$$
$$= C_f \cos(\Delta m_{B^0} t) + S_f \sin(\Delta m_{B^0} t),$$

where

$$S_f = \frac{2\mathrm{Im}\lambda_f}{|\lambda_f|^2 + 1}, \quad \lambda_f = \frac{q}{p}\bar{\rho}, \quad \bar{\rho} \equiv \frac{\bar{A}(\bar{B}^0 \to f)}{A(B^0 \to f)}$$

- $S_{J/\psi K_S}(\mathrm{exp}) = 0.658 \pm 0.024$
- $S_{\phi K_S}(\mathrm{exp}) = 0.74^{+0.11}_{-0.13}$, $S_{\eta' K^0}(\mathrm{exp}) = 0.59 \pm 0.07$

Y. Amhis *et al.* [Heavy Flavor Averaging Group Collaboration], arXiv:1207.1158 [hep-ex].

In SM, $S_{\phi K_S}(\mathrm{SM}) = S_{\eta' K^0}(\mathrm{SM}) = S_{J/\psi K_S} = \sin(2\beta_{\mathrm{SM}})$.

$|\epsilon_K|$-$\sin 2\beta$ tension (CP violation in K meson)

- $|\epsilon_K^{\rm SM}|$ is related to $\sin(2\beta_{\rm SM})$ since SM has only one CP phase.

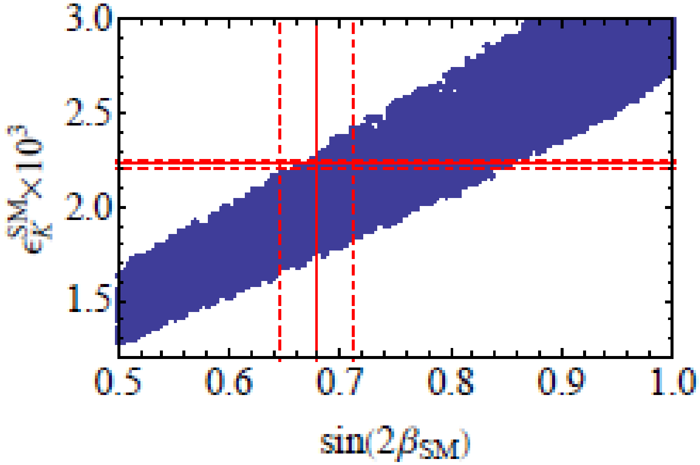
  A. J. Buras and D. Guadagnoli, Phys. Rev. D **78** (2008) 033005

$$|\epsilon_K^{\rm SM}| \propto F_K^2 \hat{B}_K |V_{cb}|^4 \sin(2\beta_{\rm SM})$$

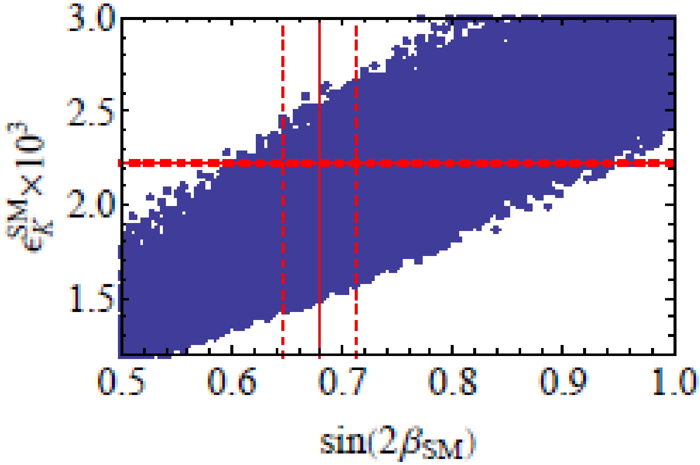
F_K: decay constant, $\hat{B}_K$: lattice calc. (0.7643 ± 0.0097)

F. Mescia and J. Virto, Phys. Rev. D **86** (2012) 095004.

- $|V_{cb}|$: best fit



- $|V_{cb}|$: 90% C.L.



$$|\epsilon_K^{\rm exp}| = (2.228 \pm 0.011) \times 10^{-3}, \quad \sin(2\beta_{\rm exp}) = 0.679 \pm 0.02$$

- The constraint from $|\epsilon_K|$ is severe in SUSY.

Direct CP Violation in Charm Decays

In the case of Final state being a CP eigenstate

$$A_{CP}(f_{CP}) \equiv \frac{\Gamma\left(D^0 \to f_{CP}\right) - \Gamma\left(\bar{D}^0 \to f_{CP}\right)}{\Gamma\left(D^0 \to f_{CP}\right) + \Gamma\left(\bar{D}^0 \to f_{CP}\right)}$$

$$\approx A_{CP}^{\rm dir}(f) + \frac{\langle t(f)\rangle}{\tau_D} A_{CP}^{\rm ind}(f) \qquad f_{CP} = K^+K^-,\ \pi^+\pi^-$$

$$D^0 \to K^+K^-,\ \pi^+\pi^-$$

$$D^0 \to \bar{D}^0 \to K^+K^-,\ \pi^+\pi^-$$

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx \Delta A_{CP}^{\rm dir} + \frac{\Delta\langle t\rangle}{\tau_D} A_{CP}^{\rm ind}$$

$$\Delta A_{CP}^{\rm dir} = (-0.67 \pm 0.16)\% \qquad A_{CP}^{\rm ind} = (-0.02 \pm 0.22)\%$$

$$A_f^{dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

$$= 2r_f \sin\gamma \sin\delta_f$$

Naive Estimation in SM

$$\Delta A_{CP}^{\rm dir} = \mathcal{O}(10^{-5})$$

Conclusion

- The LHCb experiment performed two independent analyses on the 2011 data set.

Semileptonic: $\Delta A_{CP} = (+0.49 \pm 0.30(stat.) \pm 0.14(syst.))\ \%$

LHCb-PAPER-2013-003, arXiv:1303.2614

Prompt: (preliminary) $\Delta A_{CP} = (-0.34 \pm 0.15(stat.) \pm 0.10(syst.))\ \%$

LHCb-CONF-2013-003, available on CDS soon

- Both results compatible at 3 % level.
- LHCb does not confirm evidence of CP violation in Charm decays. $\Delta A_{CP,LHCb} = (-0.15 \pm 0.16)\ \%$ (naive average)

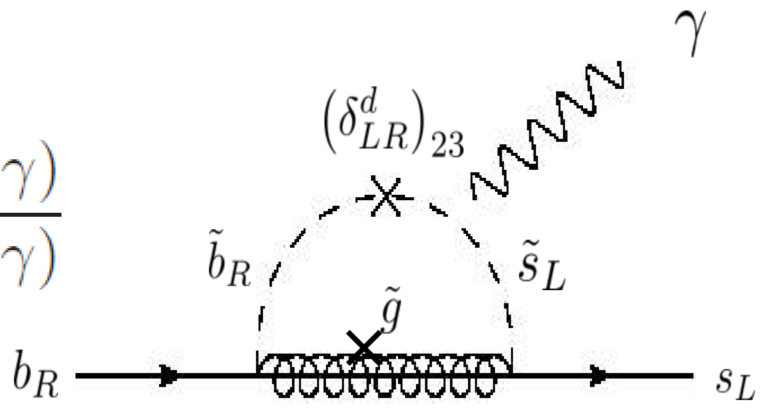
~3 fb^{-1} on tape.

Looking forward to analyses of 2012 data.

Another Direct CP Violation

CP Violation of $b \to s\gamma$?

$$A_{\rm CP}^{b\to s\gamma} \equiv \frac{\Gamma(\bar{B}\to X_s\gamma)-\Gamma(B\to X_{\bar{s}}\gamma)}{\Gamma(\bar{B}\to X_s\gamma)+\Gamma(B\to X_{\bar{s}}\gamma)}$$



$$\text{SM prediction } A_{\rm CP}^{b\to s\gamma} \simeq 0.005$$

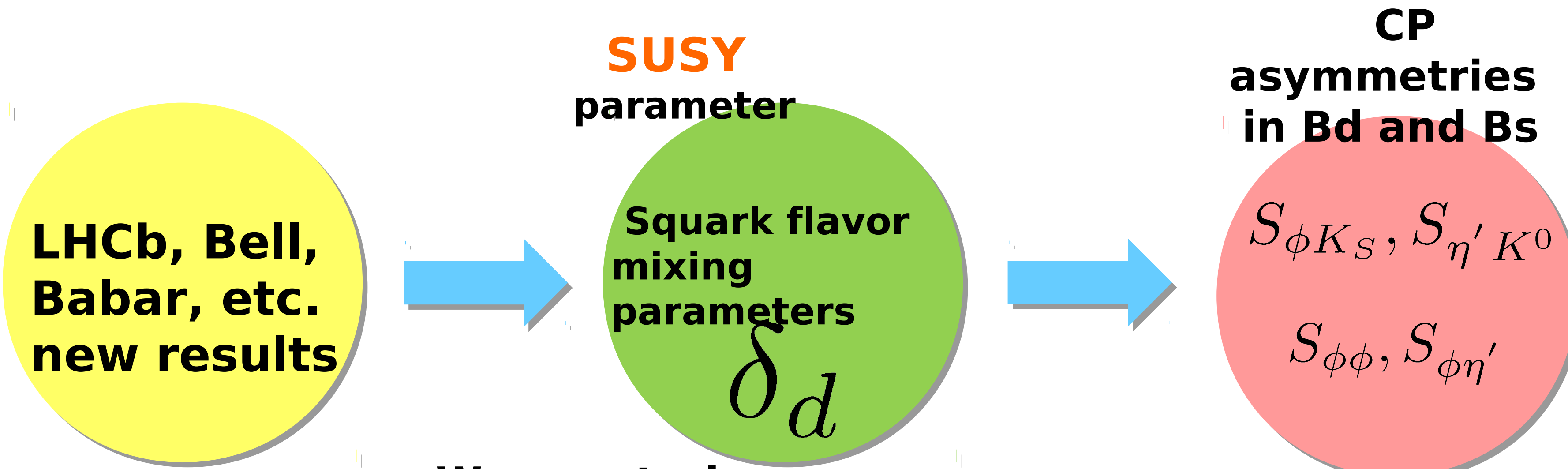
$$\text{The present data } A_{\rm CP}^{b\to s\gamma} = -0.008 \pm 0.029$$

Still large error , New Physics ?

3 Can we find SUSY in B decays ?

- **How large** contributions of Squark flavor mixing in CP asymmetries of B mesons ?

- **Our strategy:**



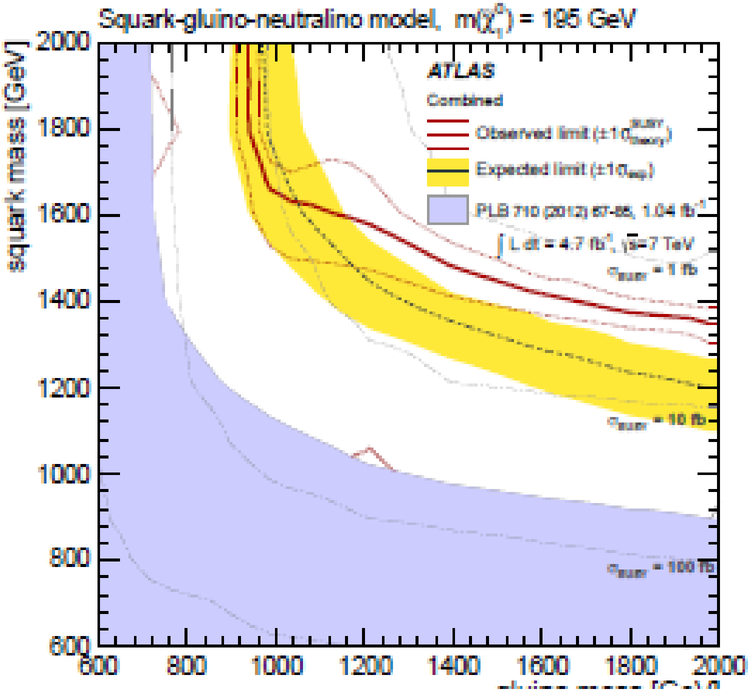
We constrain squark flavor mixing parameters by LHCb etc. results + CEDM of strange quark

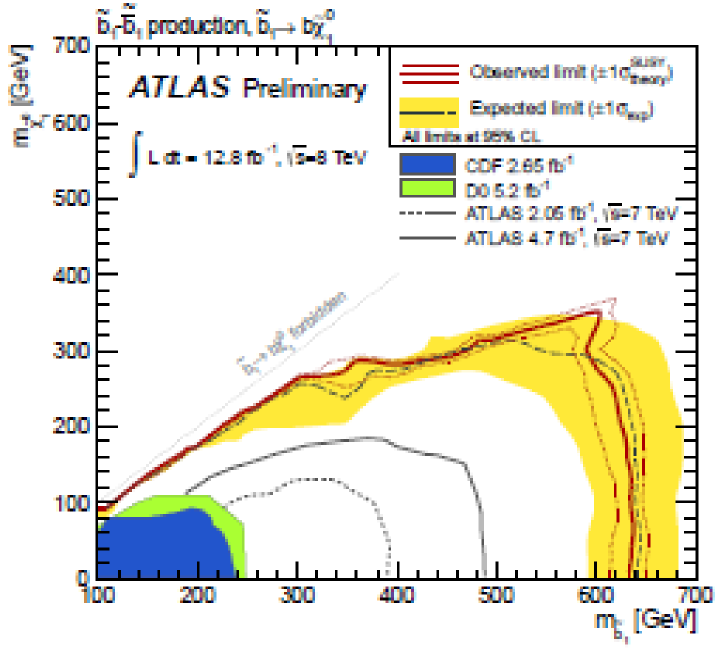
We predict CP asymmetries.

Search for SUSY particles

- Searching for SUSY particles at LHC (ATLAS, CMS).
  But SUSY particle has not been discovered.

$$m_{\tilde{g}} \gtrsim 1.4 \text{ TeV}, \quad m_{\tilde{q}} \gtrsim 1.5 \text{ TeV}, \quad m_{\tilde{t}} \gtrsim 600 \text{ GeV}, \quad m_{\tilde{b}} \gtrsim 650 \text{ GeV}.$$





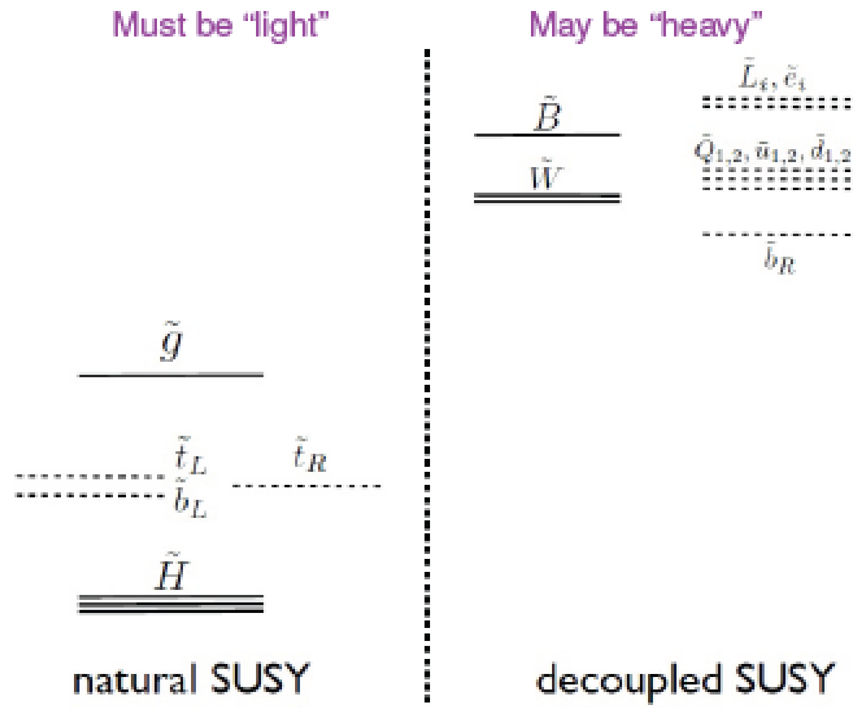
So indirect search is also significant.
For example, CP asymmetries of B mesons.

Natural SUSY and flavor

- Simplest bottom-up approach to keep SUSY as natural as possible, in light of ATLAS & CMS constraints

  [Papucci, Ruderman, Weiler, 1110.6926; Brust, Katz, Lawrence, Sundrum, 1110.6670; Kats, Meade, Reece, Shih, 1110.6444; Essig, Izaguirre, Kaplan, Wacker, 1110.6443]

  Can have approximate MFV, GIM, etc., but as the first two generations are pushed heavier, expect larger flavor non-universality, and increasing signals



Squark flavor mixing

Split-family

- In these experimental situations, we consider split-family.

F. Mescia and J. Virto, Phys. Rev. D **86** (2012) 095004.

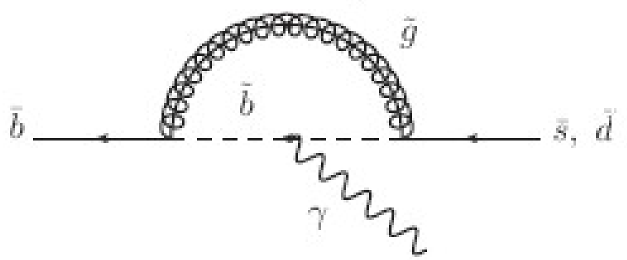
$$m_{\tilde{g}} = 1.5 \text{ TeV}, \quad m_{\tilde{b}} = 750 \text{ GeV}, \quad m_{\tilde{q}_{1,2}} \simeq \mathcal{O}(10) \text{ TeV}$$

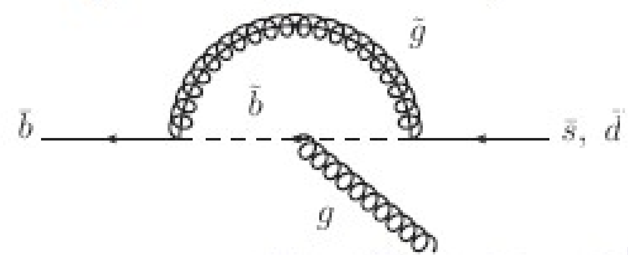
- The Lagrangian of the gluino-quark-sbottom interaction:

$$\mathcal{L}_{\text{int}}(\tilde{g}q\tilde{b}) = -i\sqrt{2}g_3 \sum \widetilde{b}_i^*(T^a)\overline{\widetilde{G}^a}\left[(\Gamma_{GL}^{(d)})_{ij}P_L + \Gamma_{GR}^{(d)})_{ij}P_R\right] q_j + \text{h.c.} \,,$$

$$\Gamma_{GL}^{(d)} = \begin{pmatrix} 1 & 0 & \delta_{13}^{dL}c_\theta & 0 & 0 & -\delta_{13}^{dL}s_\theta e^{i\phi} \\ 0 & 1 & \delta_{23}^{dL}c_\theta & 0 & 0 & -\delta_{23}^{dL}s_\theta e^{i\phi} \\ -\delta_{13}^{dL*} & -\delta_{23}^{dL*} & c_\theta & 0 & 0 & -s_\theta e^{i\phi} \end{pmatrix} \begin{matrix} d \\ s \\ b \end{matrix} \quad q_L$$

$$\Gamma_{GR}^{(d)} = \begin{pmatrix} 0 & 0 & \delta_{13}^{dR}s_\theta e^{-i\phi} & 1 & 0 & \delta_{13}^{dR}c_\theta \\ 0 & 0 & \delta_{23}^{dR}s_\theta e^{-i\phi} & 0 & 1 & \delta_{23}^{dR}c_\theta \\ 0 & 0 & s_\theta e^{-i\phi} & -\delta_{13}^{dR*} & -\delta_{23}^{dR*} & c_\theta \end{pmatrix} \quad q_R$$





$$B_d \;\Rightarrow\; \delta_{13}^{dL(R)}$$

$$B_s \;\Rightarrow\; \delta_{23}^{dL(R)}$$

$$K \;\Rightarrow\; \delta_{13}^{dL(R)} \times \delta_{23}^{dL(R)}$$

Assume

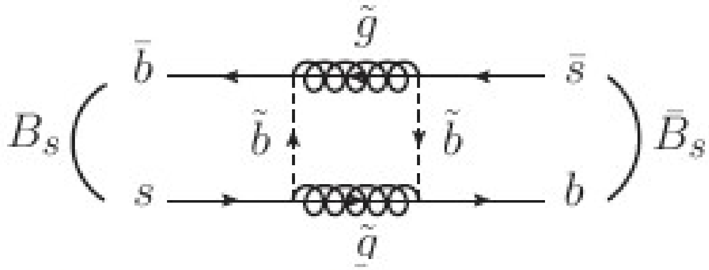
$$|\delta_{ij}^{dL}| = |\delta_{ij}^{dR}|$$

$m_{\tilde{b}_1} = 750\mathrm{GeV}$ $m_{\tilde{b}_2} = 900\mathrm{GeV}$

LR mixing : $\sin\theta\cos\theta = 0.45$

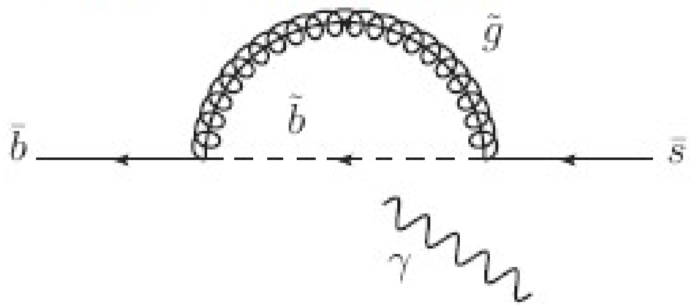
The relevant constraints

- $\Delta F = 2$ process:



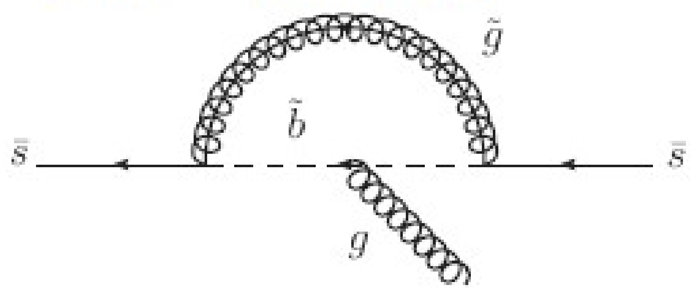
$\rightarrow \quad \Delta M_{B_s},\ \Delta M_{B^0},\ |\epsilon_K|$

- $\Delta F = 1$ Process:



$\rightarrow \quad \mathrm{BR}(b \rightarrow s\gamma)$

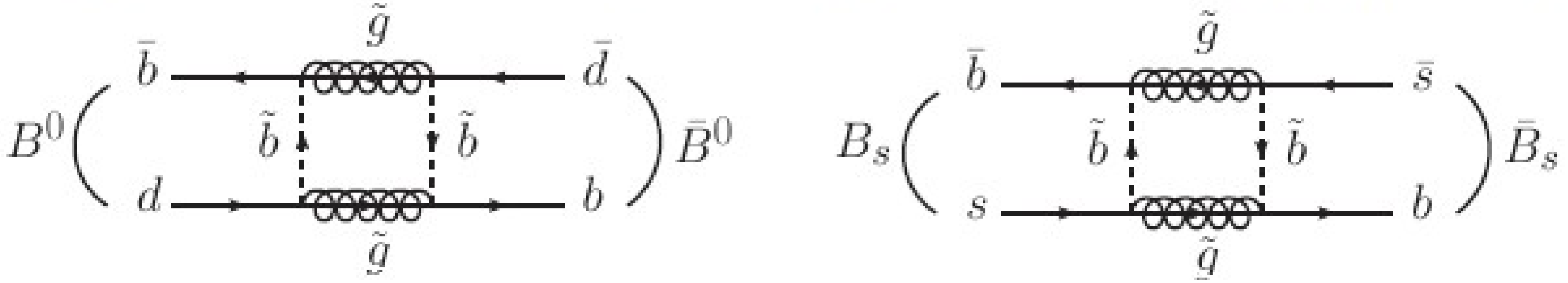
- $\Delta F = 0$ Process:



$\rightarrow \quad |d_s^C|$ (CEDM)

$\Delta F = 2$ process

The gluino-squark box diagram: dispersive part in B_q-$\bar{B}_q$ mixing



$$\begin{aligned} M_{12}^{q} &= M_{12}^{q,\mathrm{SM}} + M_{12}^{q,\mathrm{SUSY}} \\ &= M_{12}^{q,\mathrm{SM}} \left(1 + \frac{M_{12}^{q,\mathrm{SUSY}}}{M_{12}^{q,\mathrm{SM}}}\right) \\ &= M_{12}^{q,\mathrm{SM}} (1 + h_q e^{2i\sigma_q}) \end{aligned}$$

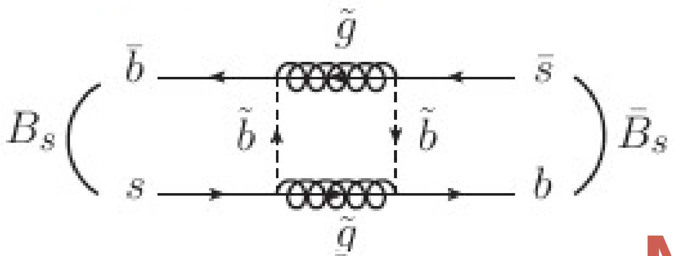
$$M_{12}^{q,\mathrm{SM}} = \frac{G_F^2 M_{B_q}}{12\pi^2} M_W^2 (V_{tb} V_{tq}^*)^2 \hat{\eta}_B S_0(x_t) f_{B_q}^2 B_q$$

$$\Delta M_{B_q} = 2 |M_{12}^{q,\mathrm{SM}} + M_{12}^{q,\mathrm{SUSY}}|$$

Experimental Constraints

$\Delta F = 2$ process

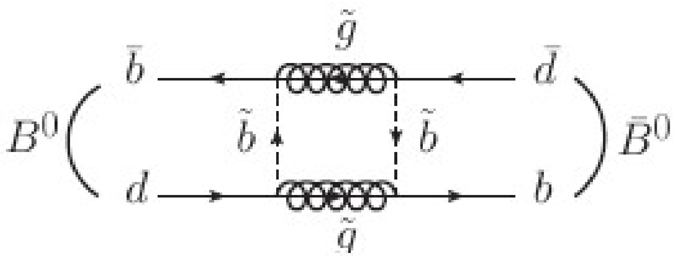
- B_s-$\bar{B}_s$ mixing:



constrains to δ^d_{23}.
$\Delta M_{B_s}(\text{exp}) = (17.7 \pm 0.1)/\text{ps}$

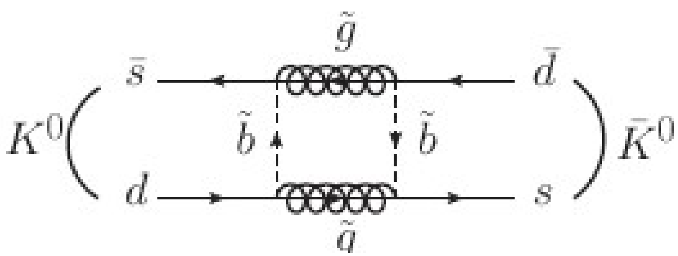
Moriond201 17.768 ± 0.024

- B^0-$\bar{B}^0$ mixing:



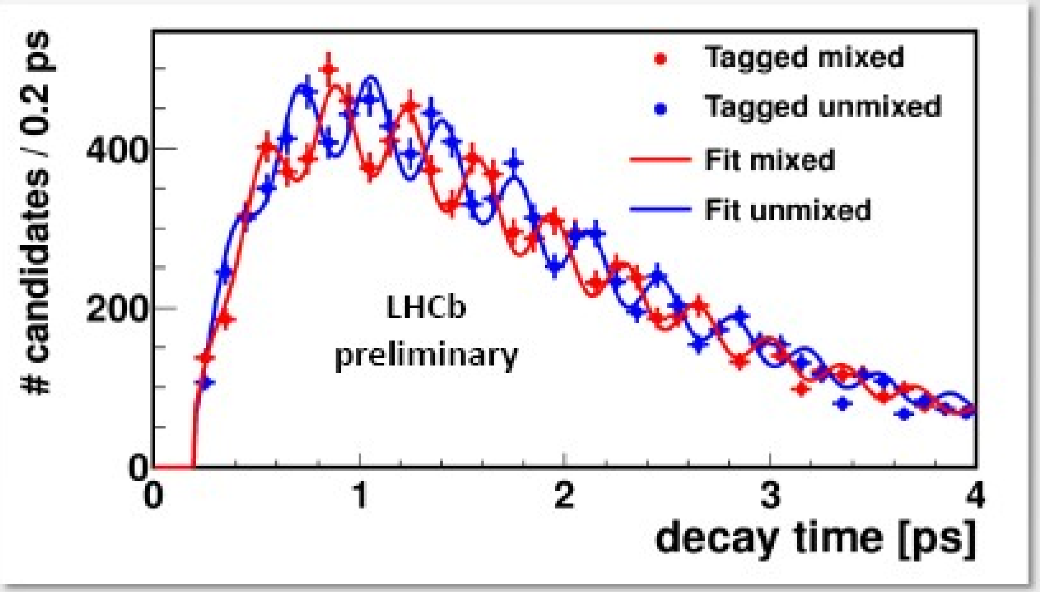
constrains to δ^d_{13}.
$\Delta M_{B^0}(\text{exp}) = (0.507 \pm 0.004)/\text{ps}$

- K^0-$\bar{K}^0$ mixing:



constrains to δ^d_{13} and δ^d_{23}.
$|\epsilon_K^{\text{exp}}| = (2.228 \pm 0.011) \times 10^{-3}$

Result



New result (preliminary)

$$\Delta m_s = 17.768 \pm 0.023(stat) \pm 0.006(syst)\, ps^{-1}$$

Dominant systematics from decay length scale and momentum scale

$\Delta F = 1$ process

- Effective Hamiltonian

$$H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \left[\sum_{q'=u,c} V_{q'b} V^*_{q's} \sum_{i=1,2} C_i O_i^{(q')} - V_{tb} V^*_{ts} \sum_{i=7\gamma,8G} \left(C_i O_i + \widetilde{C}_i \widetilde{O}_i \right) \right.$$

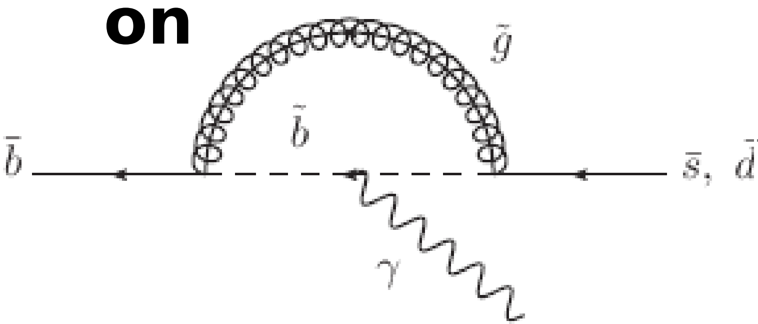
- The dim. 6 local operators:

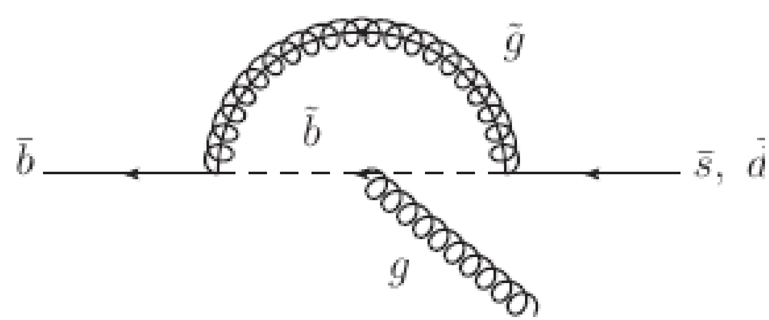
$$O_1^{(q')} = (\bar{s}_\alpha \gamma_\mu P_L q'_\beta)(\bar{q}'_\beta \gamma^\mu P_L b_\alpha), \qquad O_2^{(q')} = (\bar{s}_\alpha \gamma_\mu P_L q'_\alpha)(\bar{q}'_\beta \gamma^\mu P_L b_\beta),$$

$$O_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} P_R b_\alpha F_{\mu\nu}, \qquad O_{8G} = \frac{g_s}{16\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} P_R T^a_{\alpha\beta} b_\beta G^a_{\mu\nu}$$

$$P_R = (1+\gamma_5)/2, \quad P_L = (1-\gamma_5)/2$$

- photon Penguin ($C^{\tilde{g}}_{7\gamma}$) and gluon Penguin ($C^{\tilde{g}}_{8G}$) diagrams:





Wilson coefficients

$$C_{7\gamma}^{\tilde g}(m_{\tilde g}) = \frac{8}{3}\frac{\sqrt{2}\alpha_s\pi}{2G_F V_{tb}V_{tq}^*}$$
$$\times\left[\frac{(\Gamma_{GL}^{(d)})_{k3}}{m_{\tilde b_1}}\left\{(\Gamma_{GL}^{(d)})_{33}\left(-\frac{1}{3}F_2(x_1,x_1)\right)+\frac{m_{\tilde g}}{m_b}(\Gamma_{GR}^{(d)})_{33}\left(-\frac{1}{3}F_4(x_1,x_1)\right)\right\}\right.$$
$$\left.+\frac{(\Gamma_{GL}^{(d)})_{k6}}{m_{\tilde b_2}}\left\{(\Gamma_{GL}^{(d)})_{36}\left(-\frac{1}{3}F_2(x_2,x_2)\right)+\frac{m_{\tilde g}}{m_b}(\Gamma_{GR}^{(d)})_{36}\left(-\frac{1}{3}F_4(x_2,x_2)\right)\right\}\right],$$

$$C_{8G}^{\tilde g}(m_{\tilde g}) = \frac{8}{3}\frac{\sqrt{2}\alpha_s\pi}{2G_F V_{tb}V_{tq}^*}\left[\frac{(\Gamma_{GL}^{(d)})_{k3}}{m_{\tilde b_1}}\left\{(\Gamma_{GL}^{(d)})_{33}\left(-\frac{9}{8}F_1(x_1,x_1)-\frac{1}{8}F_2(x_1,x_1)\right)\right.\right.$$
$$\left.+\frac{m_{\tilde g}}{m_b}(\Gamma_{GR}^{(d)})_{33}\left(-\frac{9}{8}F_3(x_1,x_1)-\frac{1}{8}F_4(x_1,x_1)\right)\right\}$$
$$+\frac{(\Gamma_{GL}^{(d)})_{k6}}{m_{\tilde b_2}}\left\{(\Gamma_{GL}^{(d)})_{36}\left(-\frac{9}{8}F_1(x_2,x_2)-\frac{1}{8}F_2(x_2,x_2)\right)\right.$$
$$\left.\left.+\frac{m_{\tilde g}}{m_b}(\Gamma_{GR}^{(d)})_{36}\left(-\frac{9}{8}F_3(x_2,x_2)-\frac{1}{8}F_4(x_2,x_2)\right)\right\}\right]$$

Experimental Constraints

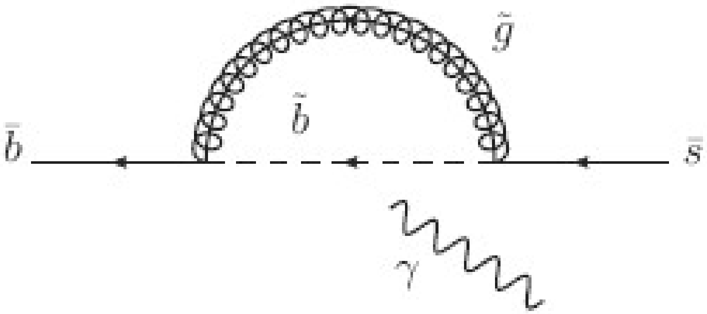
$\Delta F = 1$ process

- The dim. 6 local operator (Penguin operator):

$$O_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} P_R b_\alpha F_{\mu\nu}$$

$$P_R = (1+\gamma_5)/2, \quad P_L = (1-\gamma_5)/2$$

- $b \to s\gamma$ decay ($C^{\tilde{g}}_{7\gamma}$):



constrains to δ^d_{23}.

- $\mathrm{BR}(b \to s\gamma)(\exp) = (3.53 \pm 0.24) \times 10^{-4}$

J. Beringer *et al.* [Particle Data Group Collaboration], Phys. Rev. D **86** (2012) 010001.

Experimental Constraints

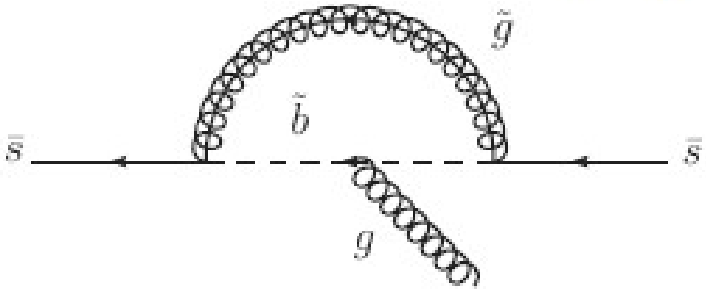
$\Delta F = 0$ process

- The dim. 6 local operator (Penguin operator):

$$O_{8G} = \frac{g_s}{16\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} P_R T^a_{\alpha\beta} b_\beta G^a_{\mu\nu}$$

$$P_R = (1+\gamma_5)/2, \quad P_L = (1-\gamma_5)/2$$

- CEDM of the strange quark ($C^{\tilde{g}}_{8G}$):



also constrains to δ^d_{23}.

- $e|d^C_s| < 1 \times 10^{-25}$ ecm **from Neutron EDM**

J. Hisano and Y. Shimizu, Phys. Rev. D **70** (2004) 093001.

Improved 0.5×10^{-25} ecm **arXiv:1211.5228 Hisano et al.**

h_s and h_d

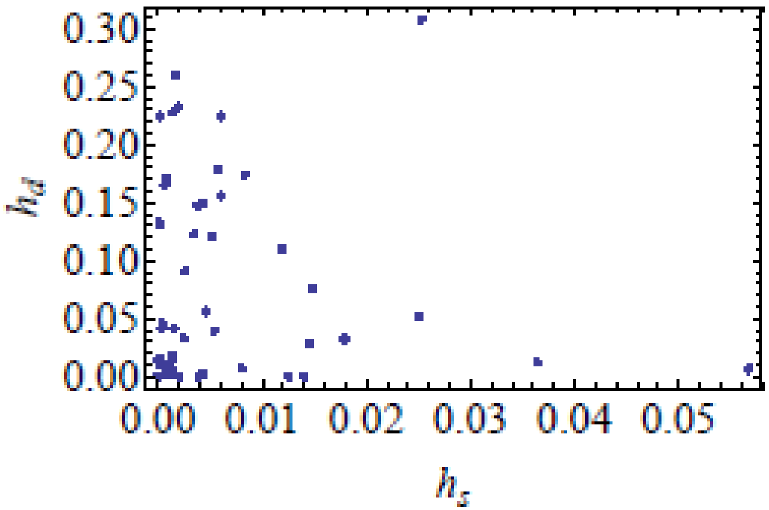


Figure: new

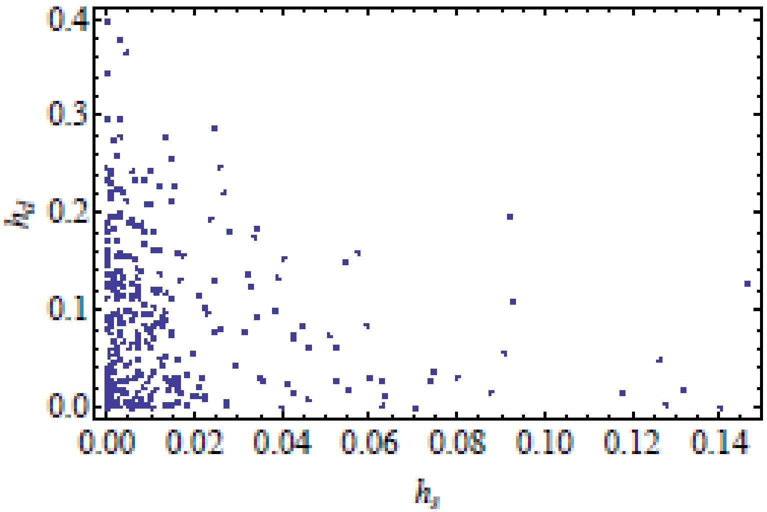
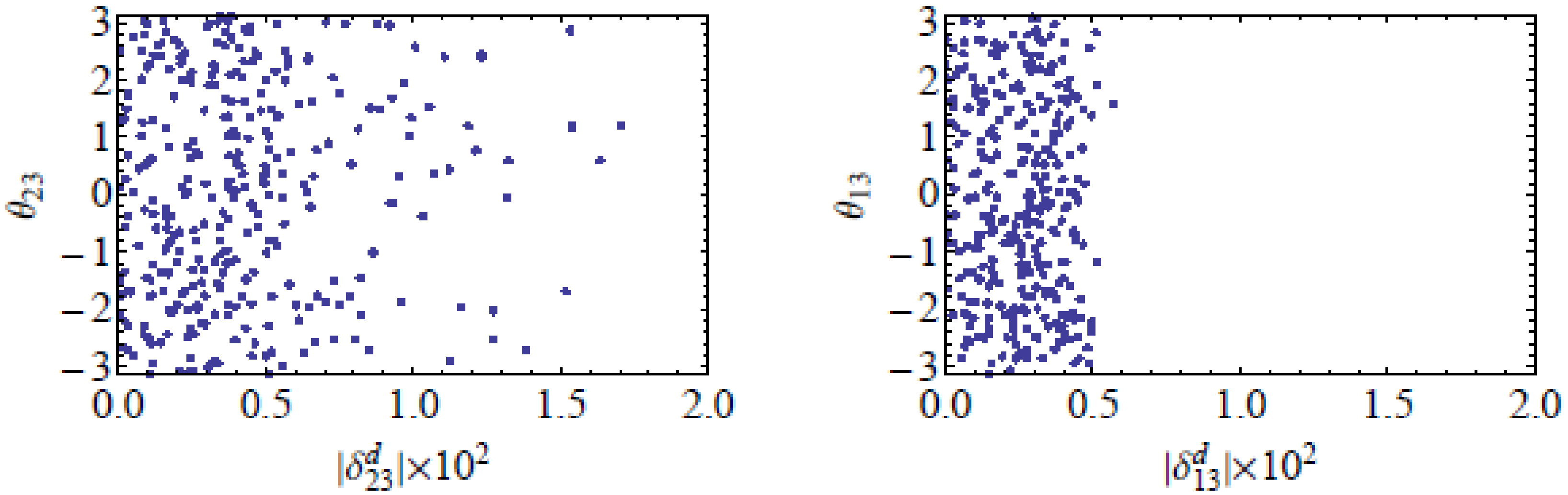


Figure: old

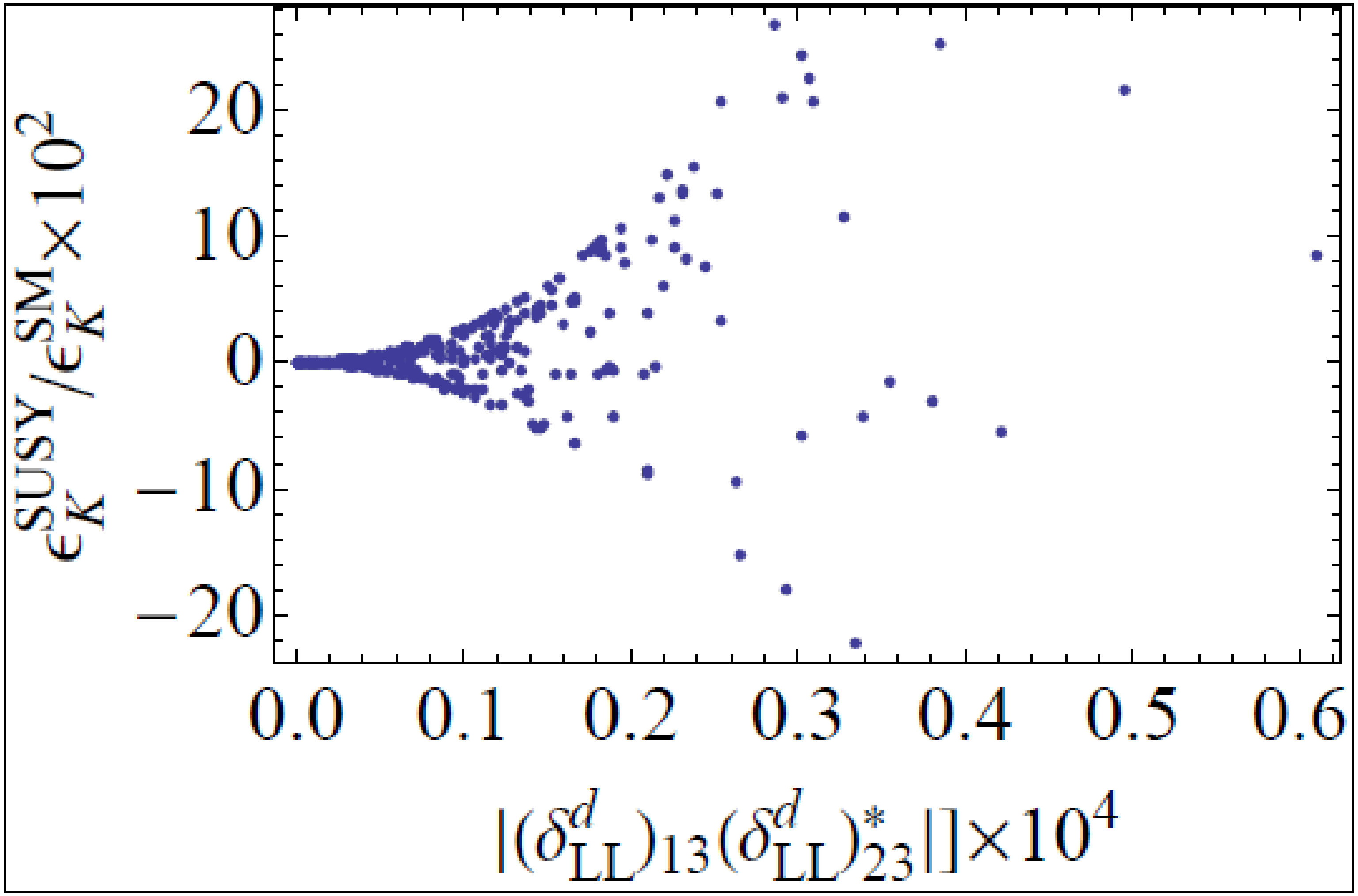
Mixing Parameters δ_{23}^d and δ_{13}^d

- Constraints: ΔM_{B_s}, ΔM_{B^0}, $|\epsilon_K|$, $\mathrm{BR}(b \to s\gamma)$, $|d_s^C|$



- $|\delta_{23}^d| \lesssim 1.8 \times 10^{-2}$, $|\delta_{13}^d| \lesssim 0.5 \times 10^{-2}$

By using these mixing parameters,
we calculate the time dependent CP asymmetries.



$\epsilon_K^{SUSY}/\epsilon_K^{SM} \times 10^2$
20
10
0
−10
−20
0.0
0.1
0.2
0.3
0.4
0.5
0.6
$|(\delta^d_{LL})_{13}(\delta^d_{LL})^*_{23}|] \times 10^4$

$b \to s\gamma$

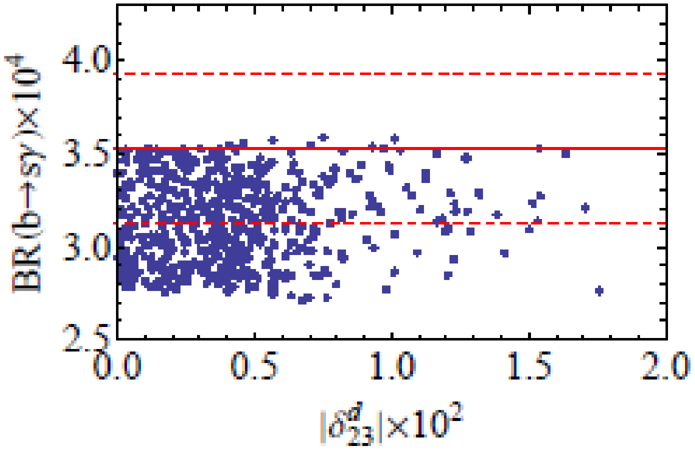
- Constraint of $b \to s\gamma$ decay: A. J. Buras, hep-ph/9806471.

$$\frac{BR(b \to X_s\gamma)}{BR(b \to X_c e\bar{\nu}_e)} = \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2} \frac{6\alpha}{\pi f(z)} C_{7\gamma}^{\mathrm{eff}\,2},$$

$$\alpha = \frac{e^2}{4\pi}, \quad f(z) = 1 - 8z + 8z^3 - z^4 - 12z^2 \ln z, \quad z = \frac{m_c^2}{m_b^2}.$$

- $C_{7\gamma}^{\mathrm{eff}}$: Wilson coefficient

$$C_{7\gamma}^{\mathrm{eff}\,2} = |C_{7\gamma}(\mathrm{SM}) + C_{7\gamma}^{\tilde{g}}(\mathrm{SUSY})|^2 + |\tilde{C}_{7\gamma}^{\tilde{g}}(\mathrm{SUSY})|^2.$$



$$\mathrm{BR}(b \to s\gamma)(\mathrm{SM}) = (3.15 \pm 0.23) \times 10^{-4},$$

$$\mathrm{BR}(b \to s\gamma)(\mathrm{exp}) = (3.53 \pm 0.24) \times 10^{-4}$$

The time dependent CP asymmetry in B meson decays

$$A = \frac{\Gamma(B_q(t) \to f) - \Gamma(\bar{B}_q(t) \to f)}{\Gamma(B_q(t) \to f) + \Gamma(\bar{B}_q(t) \to f)}$$
$$= C_f \cos(\Delta m_{B_q} t) + S_f \sin(\Delta m_{B_q} t).$$

where

$$C_f = \frac{|\lambda_f|^2 - 1}{|\lambda_f|^2 + 1}, \quad S_f = \frac{2\mathrm{Im}\lambda_f}{|\lambda_f|^2 + 1}, \quad \lambda_f = \frac{q}{p}\bar{\rho}, \quad \bar{\rho} \equiv \frac{\bar{A}(\bar{B}_q^0 \to f)}{A(B_q^0 \to f)}.$$

SUSY contributions come from both:

- Mixing part: $q/p = \sqrt{M_{12}^{q*}/M_{12}^q}$
- Amplitude part

Non-leptonic decays $B^0 \to \phi K_S, \eta' K^0$

HFAG

$$S_{J/\psi K_S} = 0.658 \pm 0.024,$$
$$S_{\phi K_S} = 0.74^{+0.11}_{-0.13},$$
$$S_{\eta' K^0} = 0.59 \pm 0.07$$

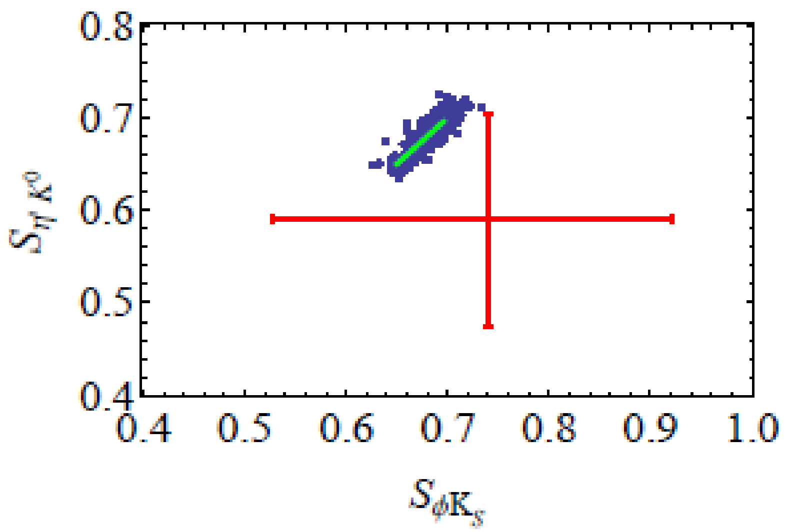
PDG

$$S_{J/\psi K_S} = 0.658 \pm 0.024,$$
$$S_{\phi K_S} = 0.39 \pm 0.17,$$
$$S_{\eta' K^0} = 0.60 \pm 0.07$$

- In SM, $S_{J/\psi K_S} = S_{\phi K_S, \eta' K^0}$
- SUSY contributions:

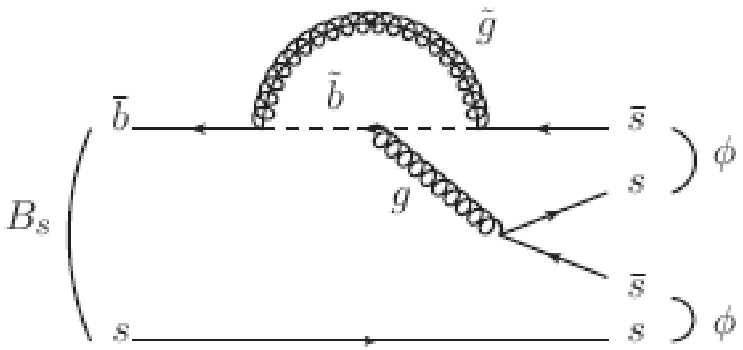
$$A^{\mathrm{SUSY}}(B^0 \to \phi K_S) \propto C_{8G}^{\tilde{g}}(m_b) + \tilde{C}_{8G}^{\tilde{g}}(m_b),$$
$$A^{\mathrm{SUSY}}(B^0 \to \eta' K^0) \propto C_{8G}^{\tilde{g}}(m_b) - \tilde{C}_{8G}^{\tilde{g}}(m_b)$$

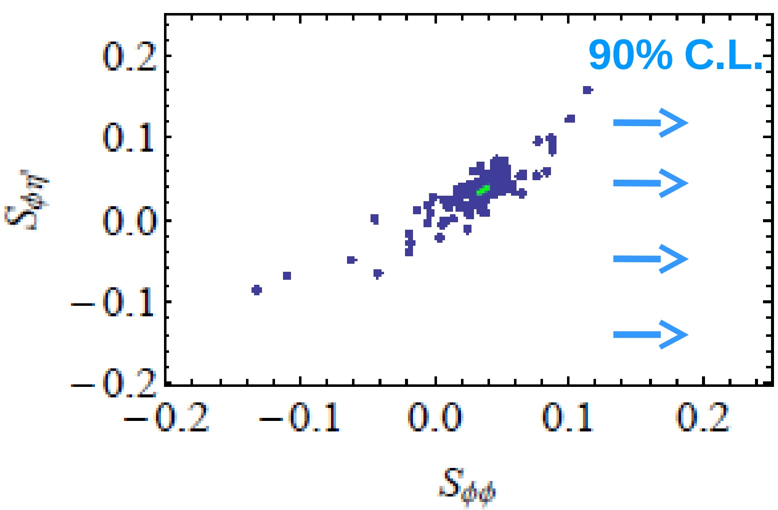
M. Endo, S. Mishima and M. Yamaguchi,
Phys. Lett. B **609** (2005) 95.



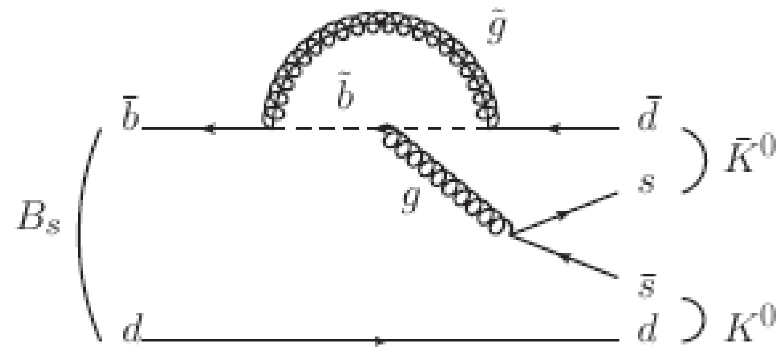
Our predictions

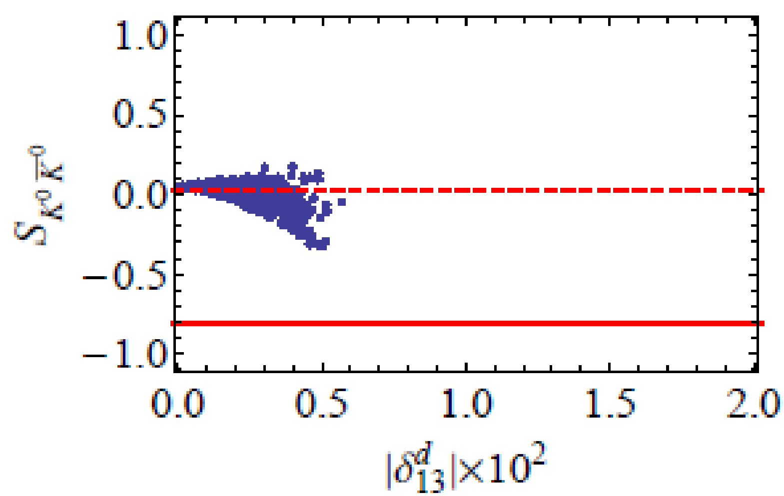
- $S_{\phi\phi}$ depends on δ^d_{23}.





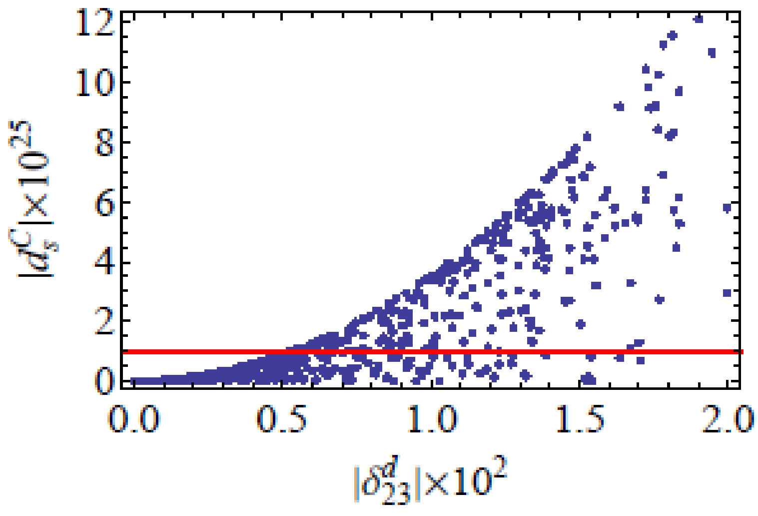
- $S_{K^0\bar{K}^0}$ depends on δ^d_{13}.





$\Delta F = 0$ process

- CEDM of the strange quark $|d_s^C|$:



4 Summary

- We study SUSY contribution in the CP violation.
- SUSY particle has not been discovered.
  $\rightarrow$ We consider split-family.
- The relevant constraints:
  ΔM_{B_s}, ΔM_{B^0}, $|\epsilon_K|$, BR($b \rightarrow s\gamma$), and $|d_s^C|$
  $\rightarrow$ $|\delta_{23}^d| \lesssim 1.8 \times 10^{-2}$ and $|\delta_{13}^d| \lesssim 0.5 \times 10^{-2}$.
- We predict $-0.14 \lesssim S_{\phi\phi} \lesssim 0.12$ and $-0.4 \lesssim S_{KK} \lesssim 0.2$.
  $\rightarrow$ It is testable in near future experiments.
- The measurement of ϕ_s use only 1 fb^{-1} of data (2011).
  Additional 2 fb^{-1} from 2012 is being analyzed now.
  $\rightarrow$ Our predicted region will be restricted.

Flavor Physics progress in LHC Era !

FLASY13

Third Workshop on Flavor Symmetries

1-5 July 2013

TOKIMATE, Niigata, Japan

The topics include:

- Discrete & continuous flavor symmetries
- Flavor dynamics & local flavor symmetries
- SUSY & flavor
- Extra dimensions & flavor
- GUTs & flavor
- CP violation & flavor
- Cosmology & flavor: dark matter, baryon asymmetry
- Hot observables (B/Bs, neutrino, dark matter, g-2, LFV, ...)
- NEW IDEAS!!

萬代橋 (Bandai Bridge)

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CONTACT: flasy13@muse.sc.niigata-u.ac.jp

ΔB=1 Effective Hamiltonian

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \left[\sum_{q'=u,c} V_{q'b} V_{q's}^* \sum_{i=1,2} C_i O_i^{(q')} - V_{tb} V_{ts}^* \sum_{i=3-6,7\gamma,8G} \left(C_i O_i + \widetilde{C}_i \widetilde{O}_i \right) \right]$$

$$O_1^{(q')} = (\bar{s}_\alpha \gamma_\mu P_L q'_\beta)(\bar{q}'_\beta \gamma^\mu P_L b_\alpha), \qquad O_2^{(q')} = (\bar{s}_\alpha \gamma_\mu P_L q'_\alpha)(\bar{q}'_\beta \gamma^\mu P_L b_\beta),$$

$$O_3 = (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_q (\bar{q}_\beta \gamma^\mu P_L q_\beta), \quad O_4 = (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_q (\bar{q}_\beta \gamma^\mu P_L q_\alpha),$$

$$O_5 = (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_q (\bar{q}_\beta \gamma^\mu P_R q_\beta), \quad O_6 = (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_q (\bar{q}_\beta \gamma^\mu P_R q_\alpha),$$

$$O_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} P_R b_\alpha F_{\mu\nu}, \qquad O_{8G} = \frac{g_s}{16\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} P_R T^a_{\alpha\beta} b_\beta G^a_{\mu\nu},$$

$$P_R = (1+\gamma_5)/2, \; P_L = (1-\gamma_5)/2$$

New CP Violating phases in $C_i^{\tilde{g}}$

$$\lambda_{\phi K_S,\, \eta' K^0} = -e^{-i\phi_d} \frac{\sum\limits_{i=3-6,7\gamma,8G} \left(C_i^{\rm SM}\langle O_i\rangle + C_i^{\tilde{g}}\langle O_i\rangle + \widetilde{C}_i^{\tilde{g}}\langle \widetilde{O}_i\rangle \right)}{\sum\limits_{i=3-6,7\gamma,8G} \left(C_i^{\rm SM*}\langle O_i\rangle + C_i^{\tilde{g}*}\langle O_i\rangle + \widetilde{C}_i^{\tilde{g}*}\langle \widetilde{O}_i\rangle \right)}$$

$$\langle \phi K_S | O_i | B_d^0 \rangle = \langle \phi K_S | \widetilde{O}_i | B_d^0 \rangle \qquad \langle \eta' K^0 | O_i | B_d^0 \rangle = -\langle \eta' K^0 | \widetilde{O}_i | B_d^0 \rangle$$

$$\lambda_{\phi\phi} = e^{-i\phi_s} \frac{\sum\limits_{i=3-6,7\gamma,8G} C_i^{\rm SM}\langle O_i\rangle + C_i^{\tilde{g}}\langle O_i\rangle + \widetilde{C}_i^{\tilde{g}}\langle \widetilde{O}_i\rangle}{\sum\limits_{i=3-6,7\gamma,8G} C_i^{\rm SM*}\langle O_i\rangle + C_i^{\tilde{g}*}\langle O_i\rangle + \widetilde{C}_i^{\tilde{g}*}\langle \widetilde{O}_i\rangle}$$

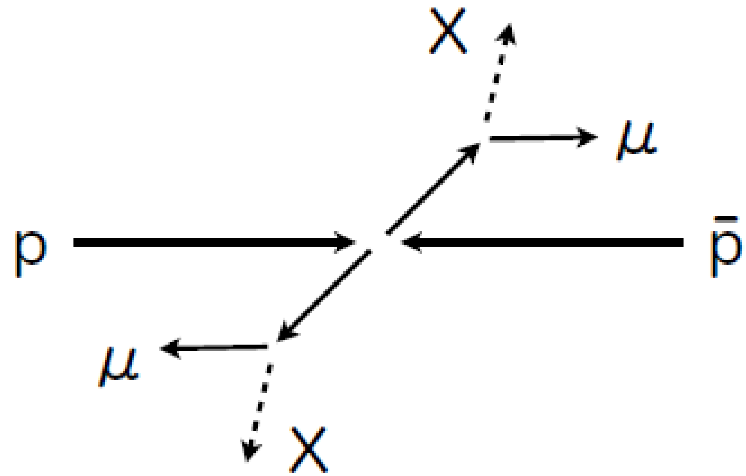
$$\langle \phi\phi | O_i | B_s^0 \rangle = -\langle \phi\phi | \widetilde{O}_i | B_s^0 \rangle$$

D0 Anomaly (Tevatron)

like-sign dimuon charge asymmetry

- $p\bar{p} \rightarrow \mu\mu XX$ event
- $\mu^+\mu^+$と$\mu^-\mu^-$のAsym

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



- SMではB_q-$\bar{B}_q$ mixingによりsame-sign dimuon
- AsymmetryはCPの破れ

$B_q \rightarrow \mu^+X$, $\bar{B}_q \rightarrow B_q \rightarrow \mu^+X$

$$A^b_{sl} \simeq 0.5a^d_{sl} + 0.5a^s_{sl}$$

$$a^q_{sl} = \frac{\Gamma(\bar{B}^0_q(t) \rightarrow \mu^+X) - \Gamma(\bar{B}^0_q(t) \rightarrow \mu^-X)}{\Gamma(\bar{B}^0_q(t) \rightarrow \mu^+X) + \Gamma(\bar{B}^0_q(t) \rightarrow \mu^-X)}$$

D0 Anomaly

like-sign dimuon charge asymmetry

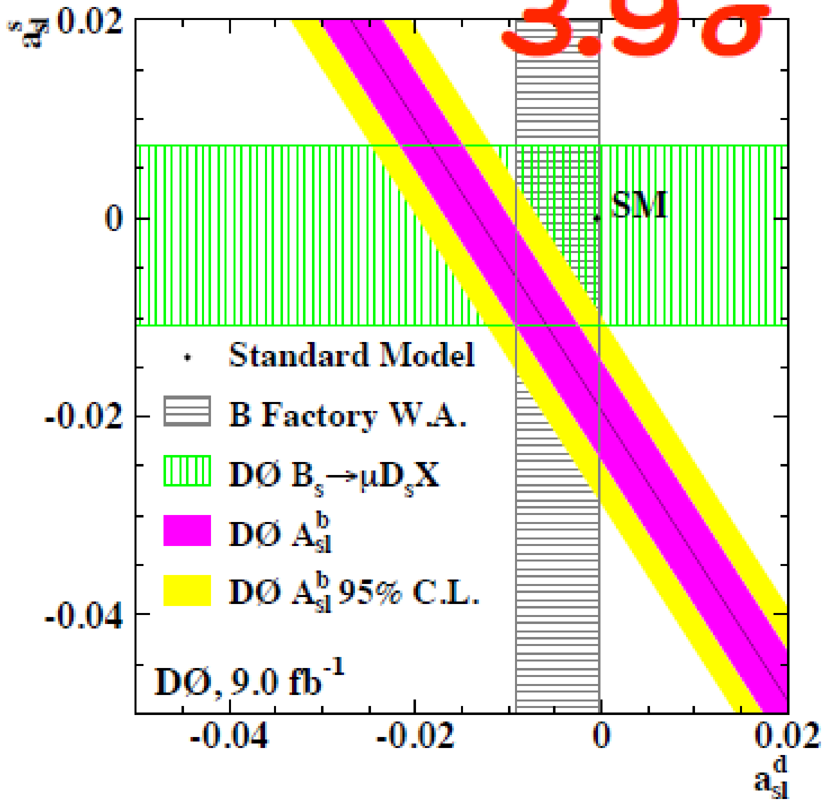
- $p\bar{p} \to \mu\mu XX$ event
- $\mu^+\mu^+$と$\mu^-\mu^-$のAsym

$$A_{sl}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

- SMではB_q-$\bar{B}_q$ mixingによりsame-sign dimuon
- AsymmetryはCPの破れ

$$A_{sl}^b \simeq 0.5 a_{sl}^d + 0.5 a_{sl}^s$$

3.9σ



Constraints from

Direct CP violation of $b \to s\gamma$ decay

Dominant term in SM

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

$$= \frac{\alpha_s(m_b)}{|C_{7\gamma}|^2}\left[\frac{40}{81}{\rm Im}[C_2C_{7\gamma}^*] - \frac{8z}{9}[v(z)+b(z,\delta)]{\rm Im}\left[\left(1+\frac{V_{us}^*V_{ub}}{V_{ts}^*V_{tb}}\right)C_2C_{7\gamma}^*\right]\right.$$

$$\left. - \frac{4}{9}{\rm Im}[C_{8G}C_{7\gamma}^*] + \frac{8z}{27}b(z,\delta){\rm Im}\left[\left(1+\frac{V_{us}^*V_{ub}}{V_{ts}^*V_{tb}}\right)C_2C_{8G}^*\right]\right],$$

Experimental results : $A_{\rm CP}^{b\to s\gamma} = -0.008 = \pm 0.029$

SM prediction : $A_{\rm CP}^{b\to s\gamma} \simeq 0.005$

NP scale

$$\frac{NP}{SM}: \quad h_{K,d,s} \sim \left(\frac{4\pi v}{m_x \lambda_c^{5,3,2}} \right)^2$$

- m_x : New particle mass
- λ_c : Walfenstein parameter
- v : VEV of Higgs

Experiments indicate at most

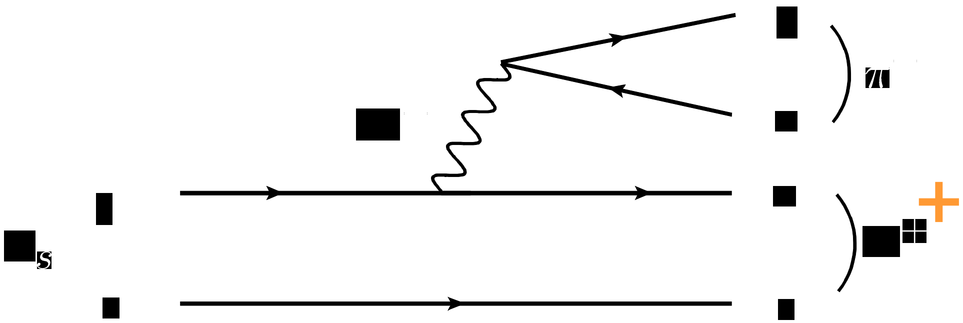
$$h \sim \mathcal{O}(1)$$

Bs can probe TeV scale

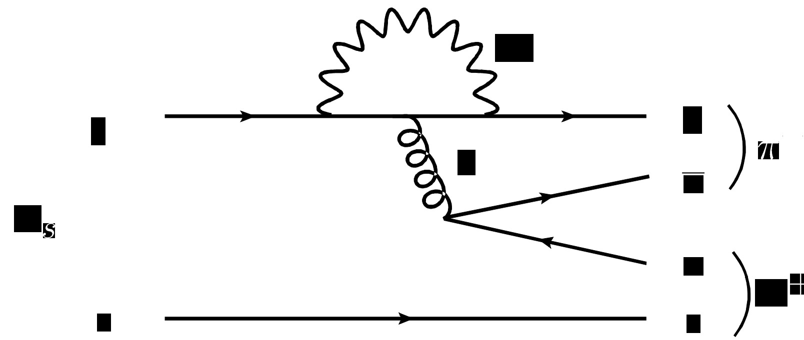
10-100 TeV, but depends on models

Direct CP asymmetry

$B_s \to K^- \pi^+$ $B_s \to K^+ \pi^-$



Tree



Penguin

$$A_f(B \to f) = A_f^T(1 + r_f e^{i(\delta_f - \gamma)})$$

$$\bar{A}_{\bar{f}}(\bar{B} \to \bar{f}) = A_f^T(1 + r_f e^{i(\delta_f + \gamma)})$$

- A_f^T : **Tree level amplitude**
- r_f : **relative magnitude of Penguin**
- δ_f : **strong phase**
- γ : **weak phase**

$$\mathcal{A}_f^{dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} = 2 r_f \sin\gamma \sin\delta_f$$

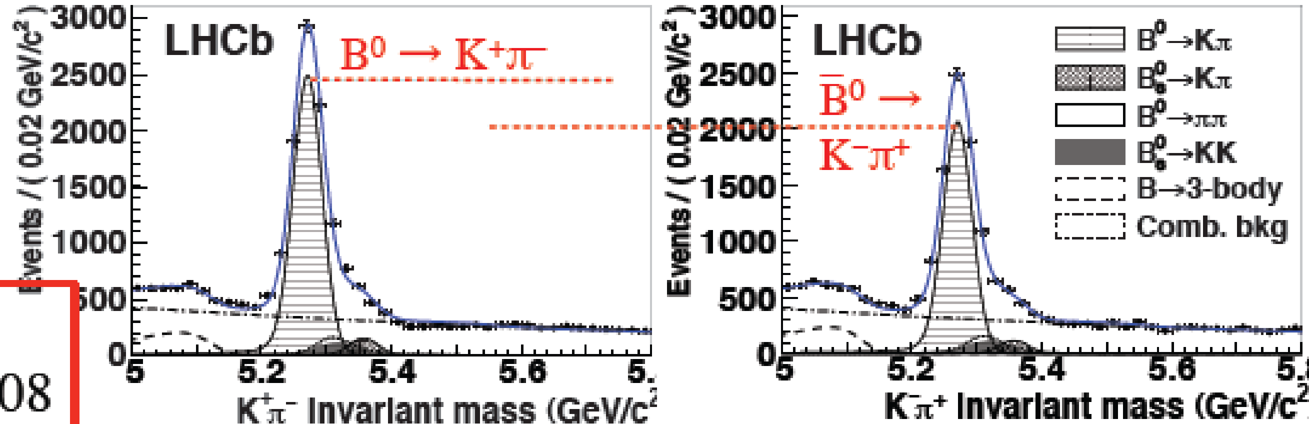
Direct CPV in $B_{(s)} \to K\pi$

LHCb, arXiv:1202.6251
subm. to PRL

- With 0.35 fb^{-1}
  — most precise results

$A_{CP}(B^0 \to K\pi) =$
$-0.088 \pm 0.011 \pm 0.008$

$> 6\sigma$

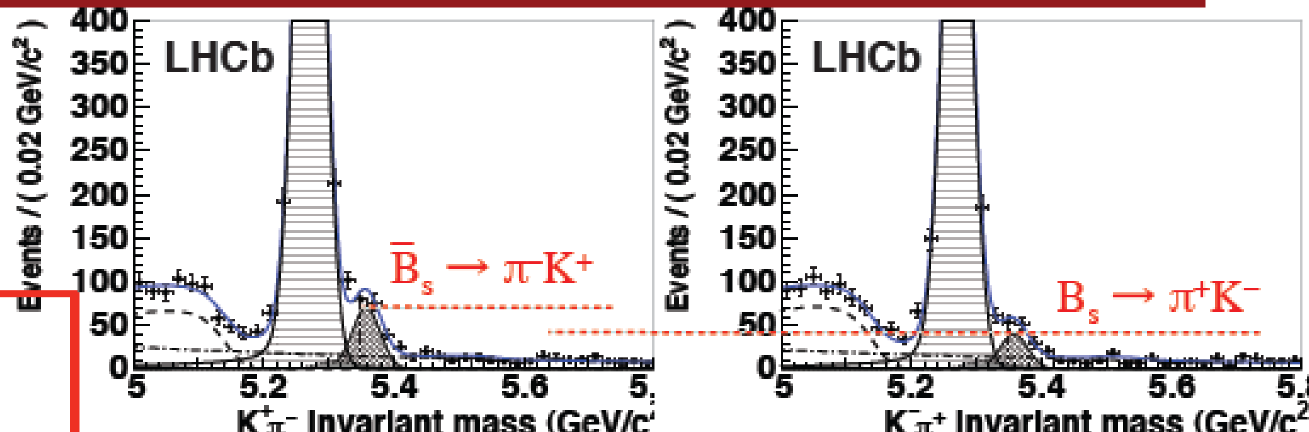


First observation of direct CPV in B decays at a hadron collider

opposite sign, as expected in SM

$A_{CP}(B_s \to \pi K) =$
$+0.27 \pm 0.08 \pm 0.02$

3.3σ



First evidence of direct CPV in B_s decays !

A_{CP} of $B \to K\pi$

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(B_d^0 \to K^+\pi^-) - A_{\mathrm{CP}}(B^+ \to K^+\pi^0)$$
$$= 0.121 \pm 0.022 \quad (5.5\sigma)$$

[P.Chang,EPS2011]

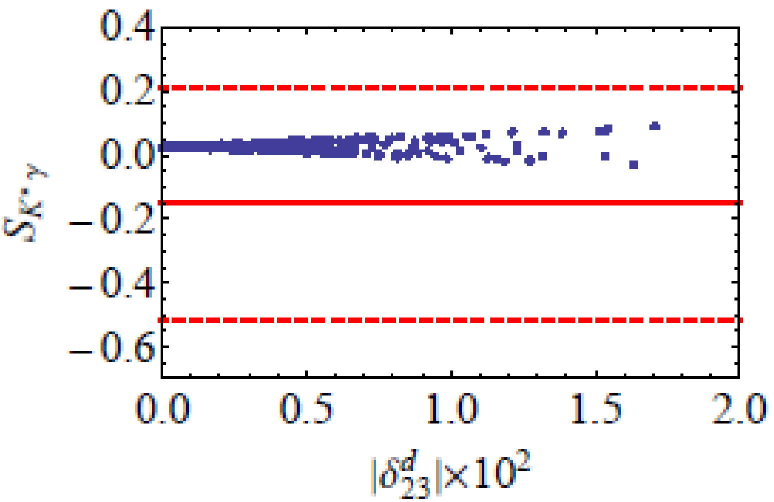
SM : A few %

$K\pi$ puzzle

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

$$S_{K^*\gamma} = \frac{2\mathrm{Im}\left[e^{-i\phi_d}\widetilde{C}_{7\gamma}(m_b)/C_{7\gamma}(m_b)\right]}{\left|\widetilde{C}_{7\gamma}(m_b)/C_{7\gamma}(m_b)\right|^2 + 1}$$

$$S_{K^*\gamma}(\mathrm{SM}) = -\frac{2m_s}{m_b}\sin\phi_d$$
$$\simeq -0.019$$
$$S_{K^*\gamma}(\mathrm{exp}) = -0.15 \pm 0.22$$



CP violation of $B^0 \to K^*\gamma$ is almost consistent with results of the inclusive decay.