Bファクトリーの物理

田中 実

大阪大学

@信州大学, 2011/06/20

INTRODUCTION

標準模型

Gauge sector

gauge symmetry

$\alpha\,,\ \sin\theta_W\,,\ \alpha_s$

LEP, ...

Spontaneous
Symmetry
Breaking

Yukawa sector

Higgs sector

quark, lepton
masses

$m_u\,,\ m_d\,,\cdots$

V_{CKM} quark mixing

CP violation

B factories

$G_F\,,\ m_H$

LHC

Neutrino sector

$m_\nu\,,\ V_{\mathrm{PNMS}}$

Why Yukawa sector?

Lots of parameters: 9 masses, 3 angles, and a phase.

Determined with some precision.

Hierarchy, but .....

No principle at present.

History

CPV in K decays ——KM——→ 3rd gen.

Future

B (Flavor) physics - - - - - → New physics

SUSY, Extra Dim., ...

目次

CKM and B PHYSICS

CKM行列の構造

$$\mathcal{L}_{CC} = \frac{g_2}{\sqrt{2}} W_\mu^+ \, \bar{u}_L \gamma^\mu \, V_{\rm CKM} \, d_L + {\rm h.c.}$$

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

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \, , \; s_{ij} = \sin\theta_{ij}$$

PDG parameterization

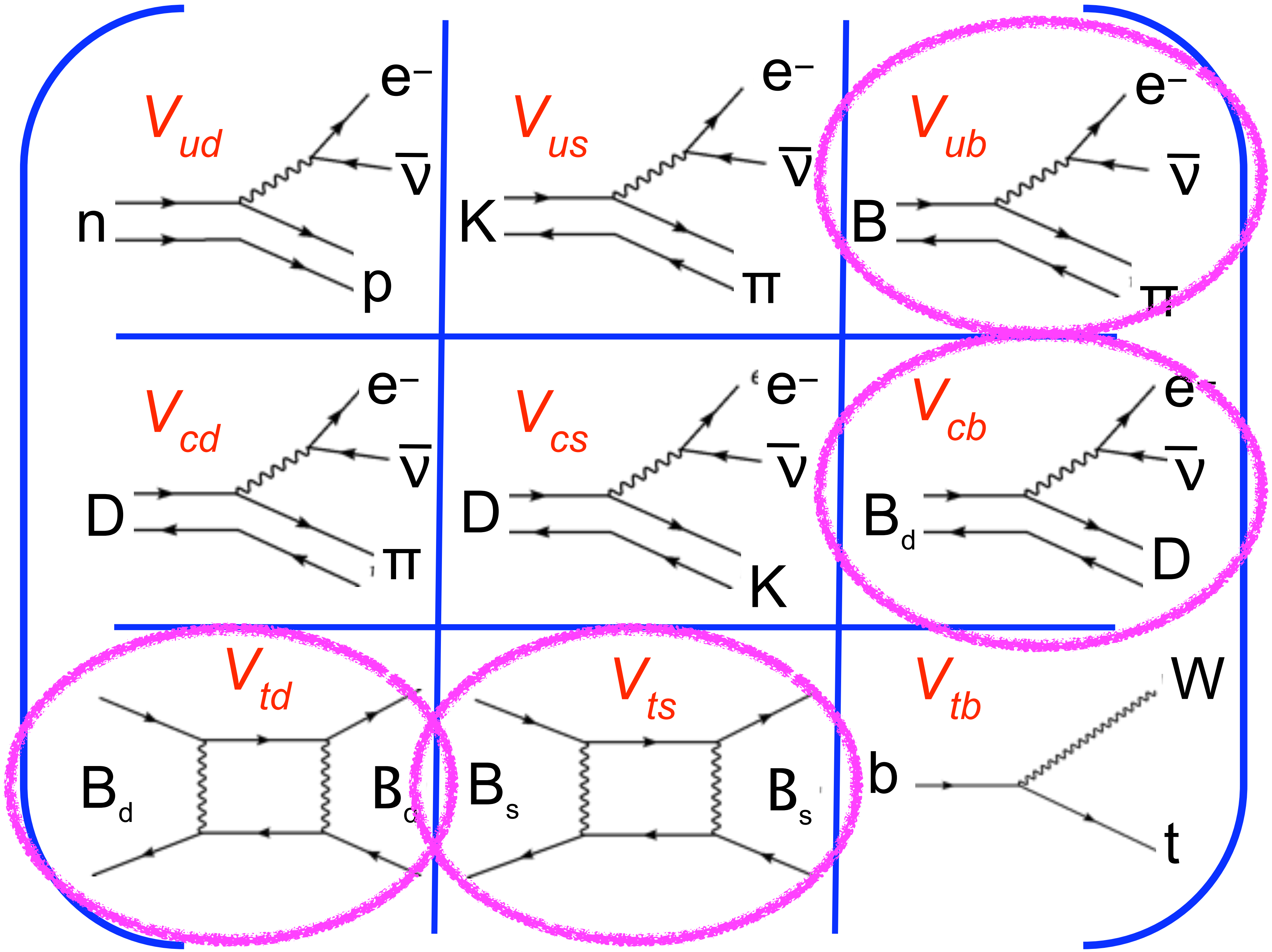
Wolfenstein parametrization

実験: $1 \gg |V_{us}| \gg |V_{cb}| \gg |V_{ub}|$

$$s_{12} = \lambda \simeq 0.22,\ s_{23} = \lambda^2 A,\ s_{13} e^{-i\delta_{13}} = \lambda^3 A(\rho - i\eta)$$

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

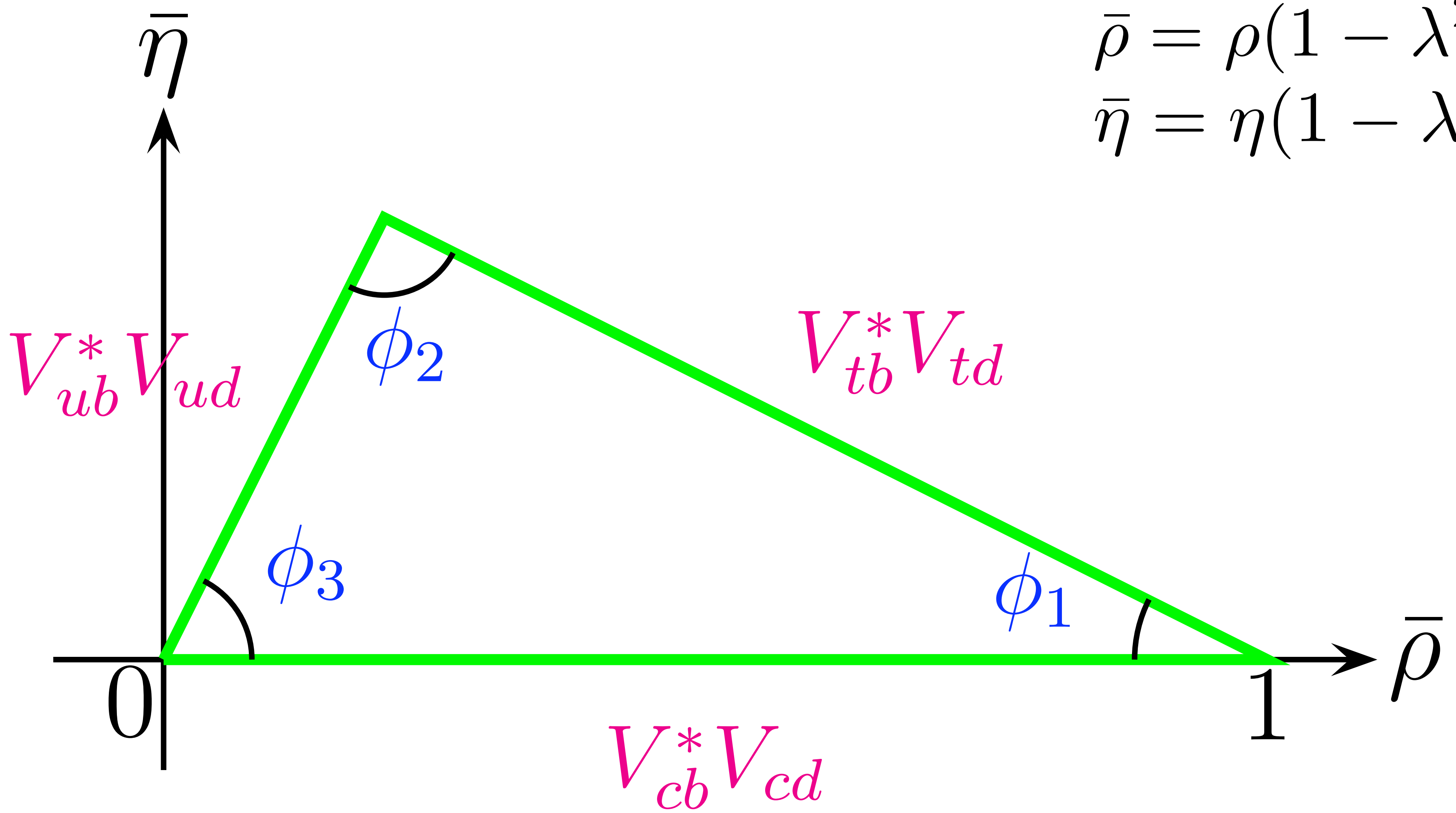
CKM Matrix Element Magnitudes

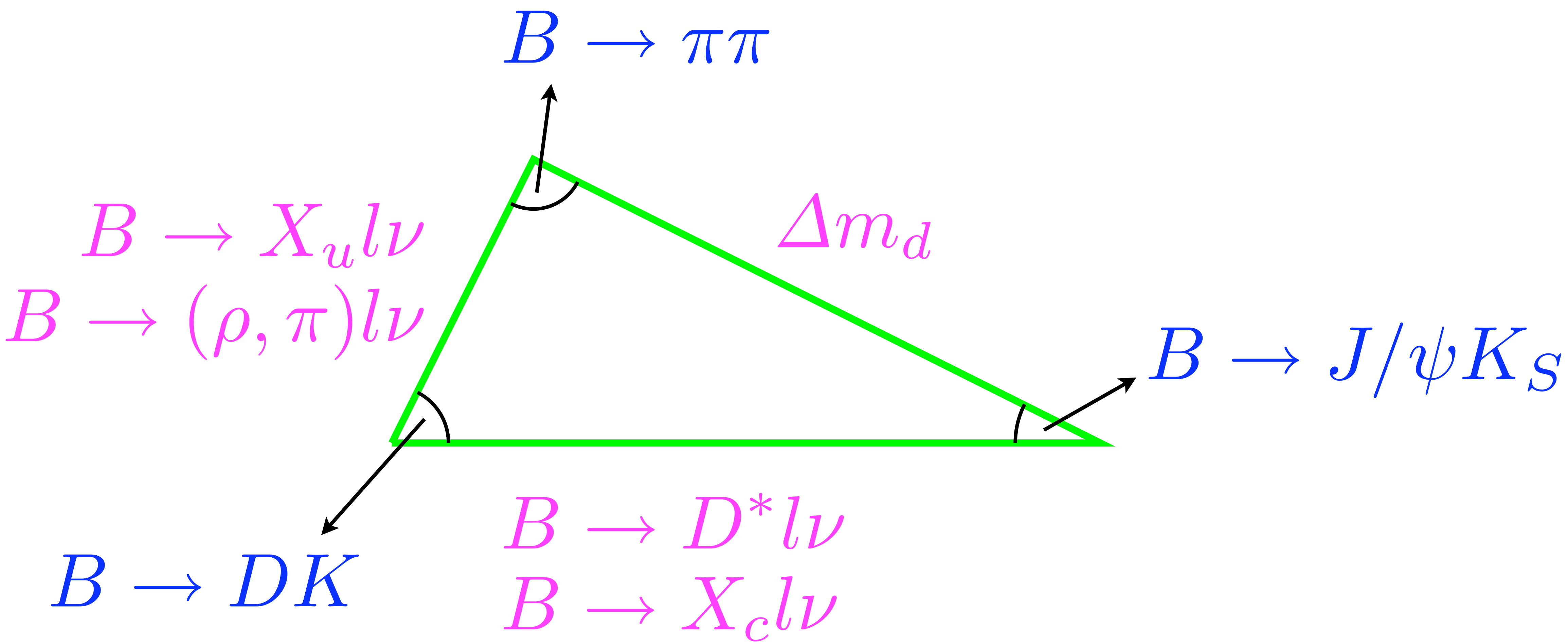


B中間子とUnitarity Triangle

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

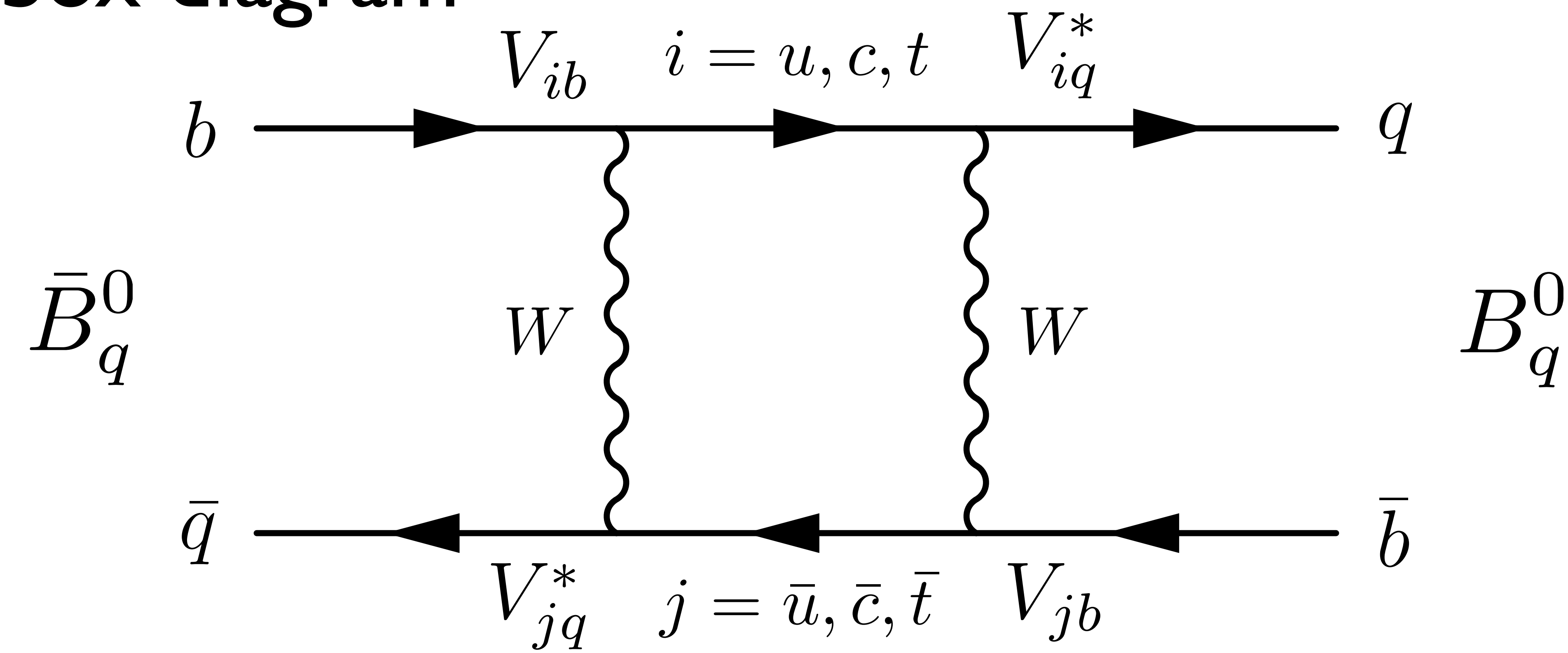
$$\bar{\rho} = \rho(1 - \lambda^2/2 + \cdots)$$
$$\bar{\eta} = \eta(1 - \lambda^2/2 + \cdots)$$




$B \to \pi\pi$
$B \to X_u l\nu$
$B \to (\rho, \pi) l\nu$
Δm_d
$B \to J/\psi K_S$
$B \to DK$
$B \to D^* l\nu$
$B \to X_c l\nu$

B^0–$\bar{B}^0$ 混合

box diagram



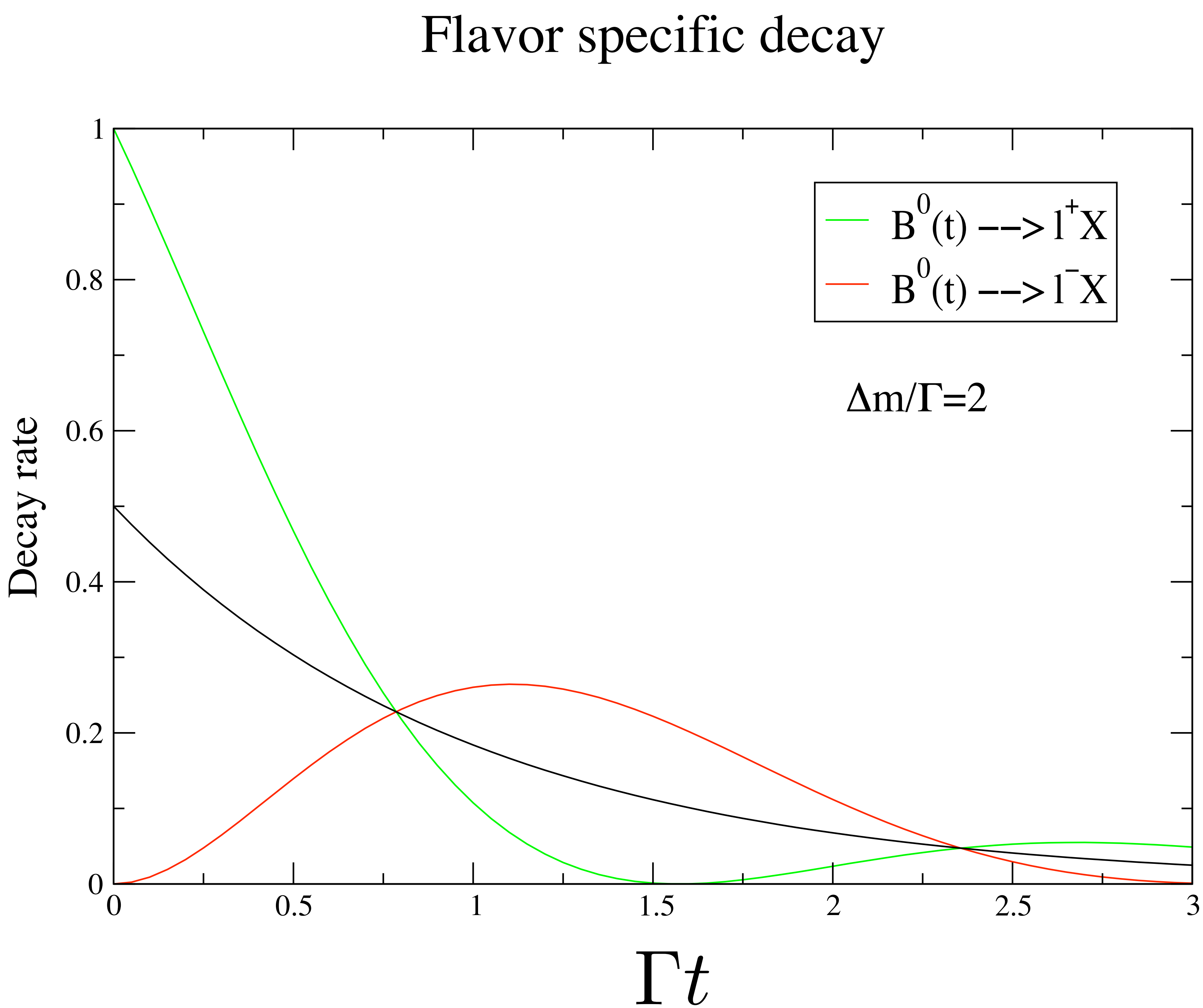
topの寄与が支配的

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

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

質量差

$$\Delta m_q \simeq 2|M_{12}(B_q)| \quad (q = d, s)$$



実験値: $\Delta m_d = 0.507 \pm 0.004\,\mathrm{ps}^{-1}$

$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\,\mathrm{ps}^{-1}$

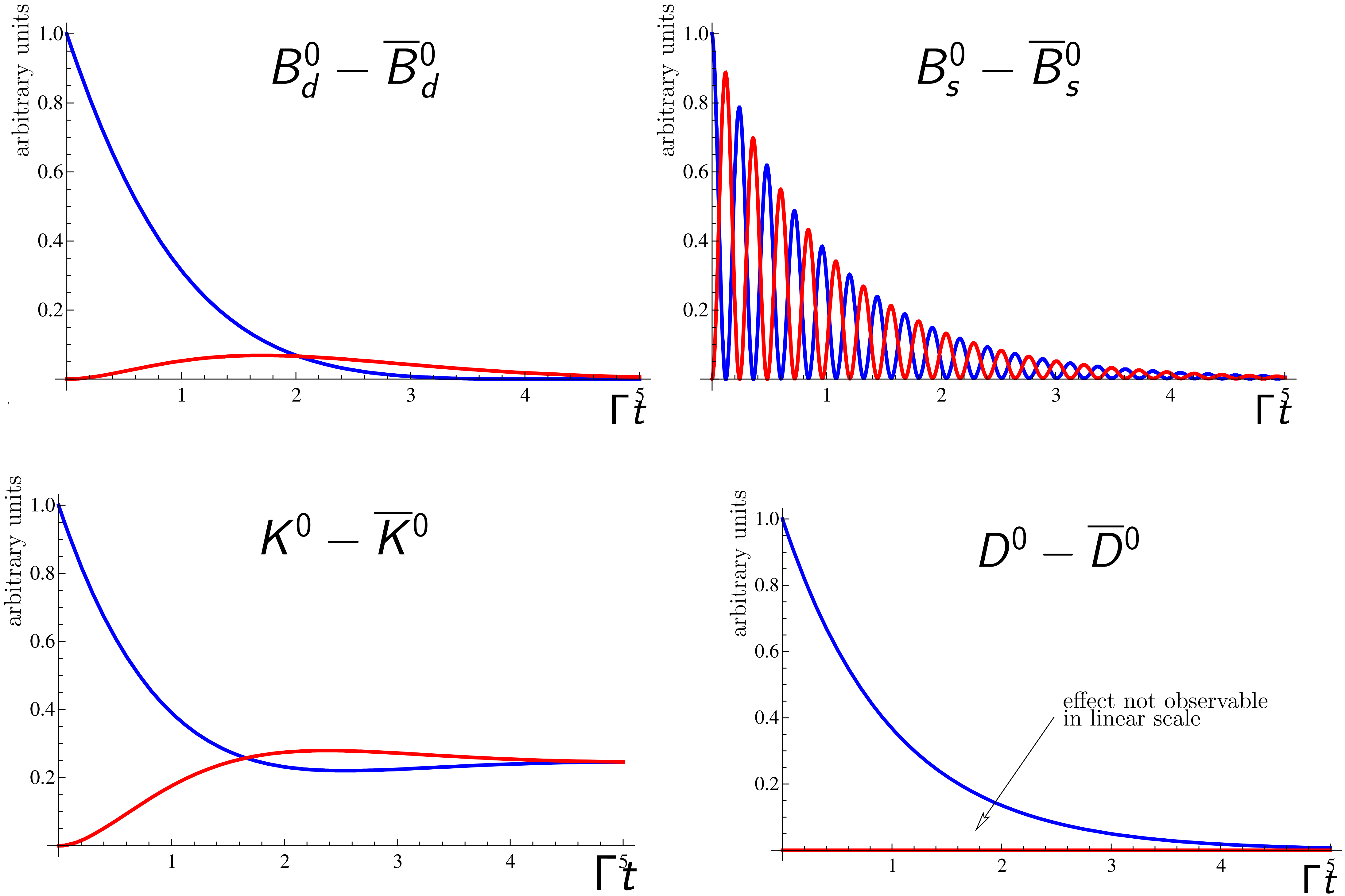
$$\frac{\Delta m_d}{\Delta m_s} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \xi^2$$

ξ : SU(3)の破れ

$$\xi = 1.23 \pm 0.02 \pm 0.03$$

lattice QCD

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.209 \pm 0.001 \pm 0.006$$



Zupanc, FPCP2011

CP非対称性

$$\Gamma(B^0(t) \to f) \propto 1 + |\lambda_f|^2 \; + \; (1 - |\lambda_f|^2) \cos \Delta m\, t \; + \; 2\,\mathrm{Im}\lambda_f \, \sin \Delta m\, t$$

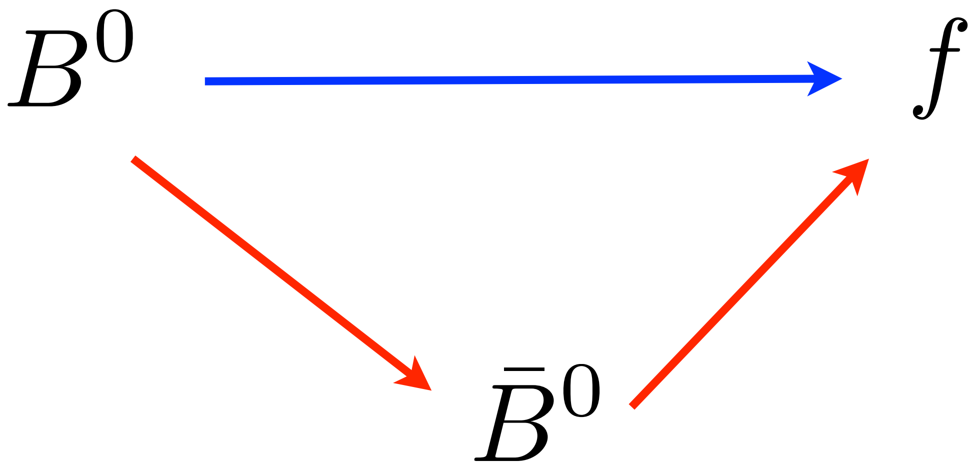
$$\Gamma(\bar{B}^0(t) \to f) \propto 1 + |\lambda_f|^2 \; - \; (1 - |\lambda_f|^2) \cos \Delta m\, t \; - \; 2\,\mathrm{Im}\lambda_f \, \sin \Delta m\, t$$

$$\lambda_f = \frac{q}{p} \frac{\langle f | \bar{B}^0 \rangle}{\langle f | B^0 \rangle} \simeq \frac{M_{12}^*}{|M_{12}|} \frac{\langle f | \bar{B}^0 \rangle}{\langle f | B^0 \rangle}$$

$$\begin{aligned} \mathcal{A}_f &= \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} \\ &= S_f \sin \Delta m\, t - C_f \cos \Delta m\, t \end{aligned}$$

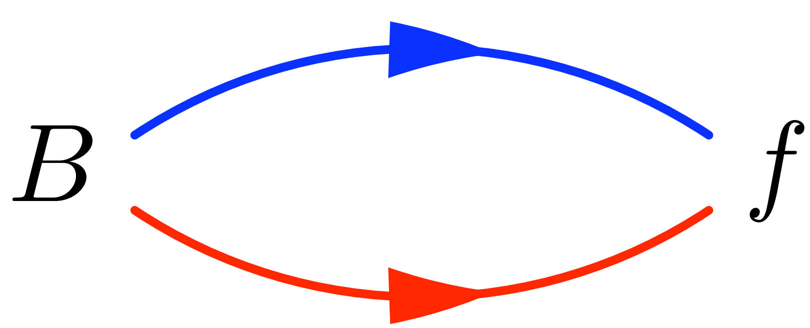
$$S_f = -\frac{2\,\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}$$

Mixing-induced CPV



$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

Direct CPV



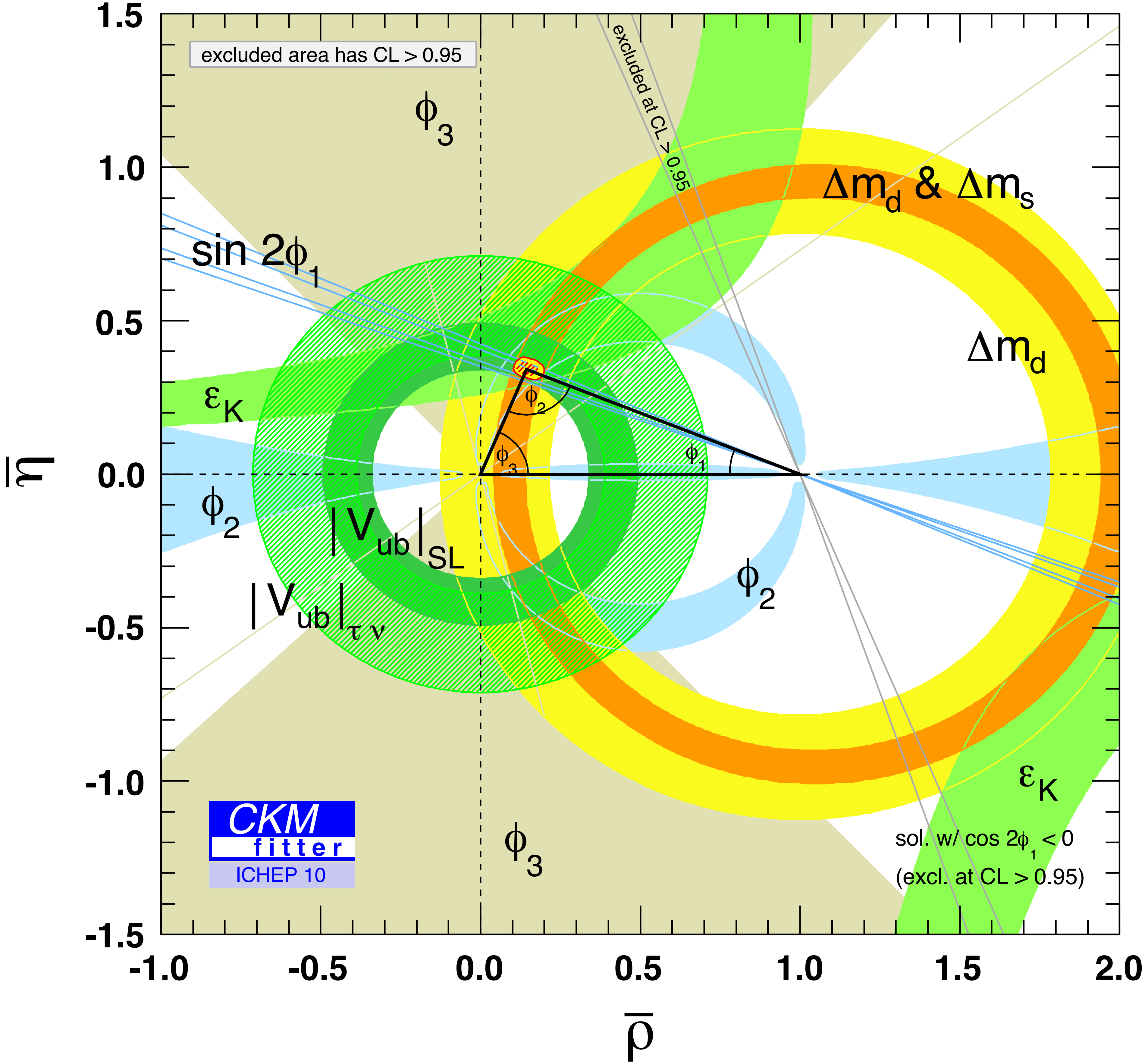
$f = J/\psi\, K_S$ (CP odd)

$$\lambda_{J/\psi K_S} = \frac{M_{12}^*}{|M_{12}|} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = e^{-2i\phi_1}$$

$$S_{J/\psi K_S} = \sin 2\phi_1 \qquad C_{J/\psi K_S} = 0$$

実験値

$$\sin 2\phi_1 = 0.676 \pm 0.020$$

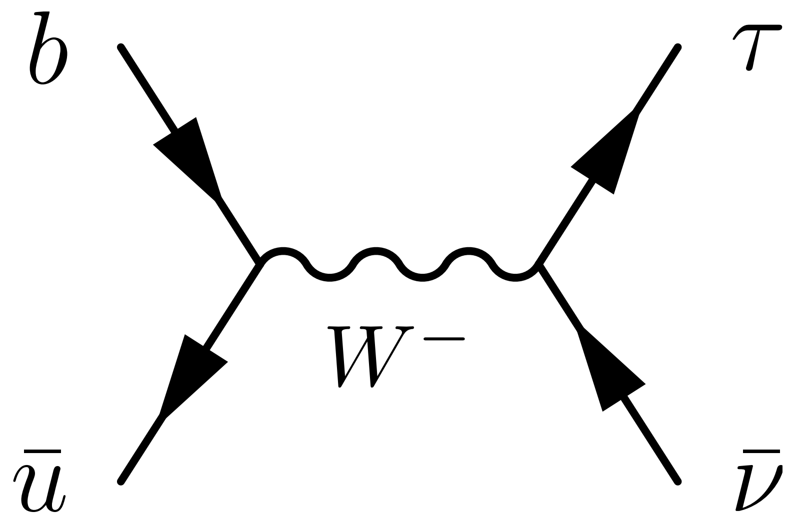


Good in ~10% accuracy

~1% at Belle II, SuperB, LHCb

NEW PHYSICS?

B → τν



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

Exp.

$$\mathcal{B} = (1.64 \pm 0.34) \times 10^{-4}$$

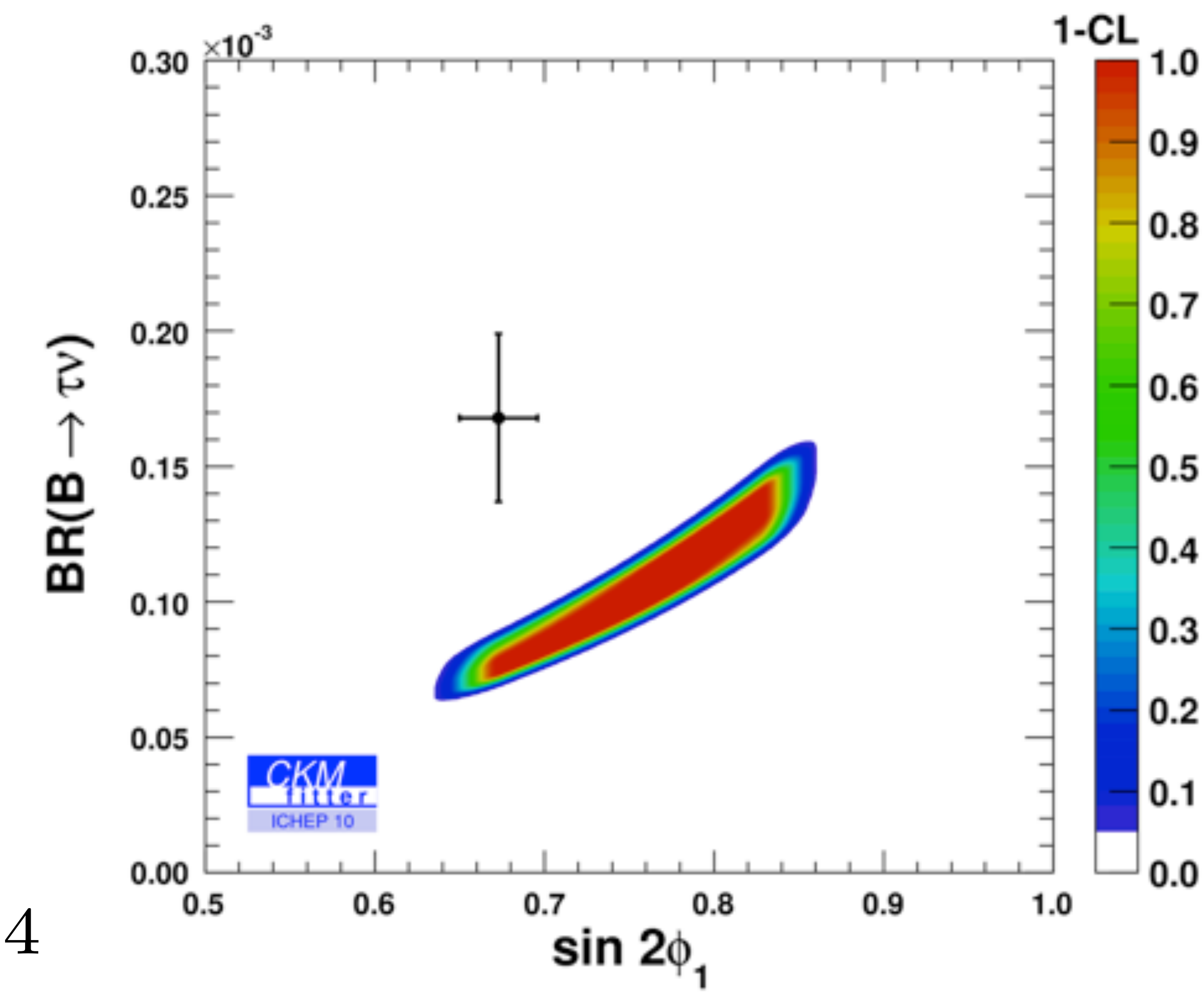
Theory

$f_B = 190 \pm 13\,\mathrm{MeV}$ (HPQCD)

$|V_{ub}| = (3.4 \pm 0.4) \times 10^{-3}$

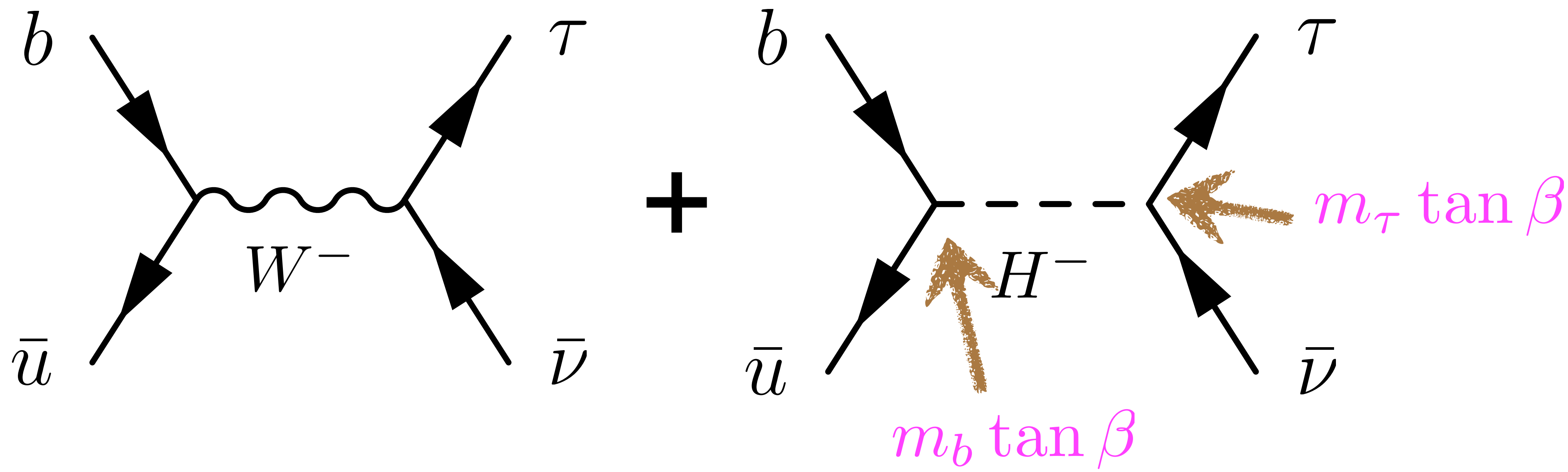
↓

$$\mathcal{B} = (0.80 \pm 0.20) \times 10^{-4}$$



Charged Higgs in B → τν

Type-II 2HDM (SUSY)



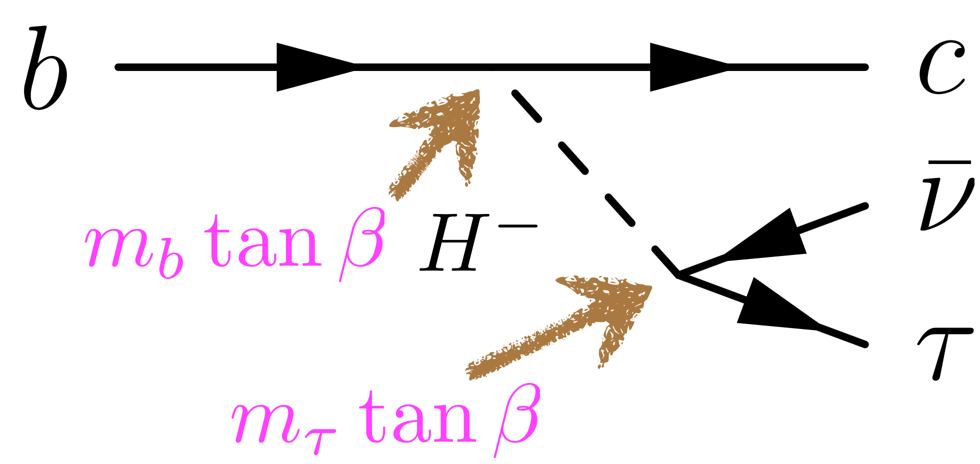
$$\mathcal{B}_{\rm 2HDM} = \mathcal{B}_{\rm SM}\left(1 - \tan^2\beta\,\frac{m_B^2}{m_H^2}\right)^2$$

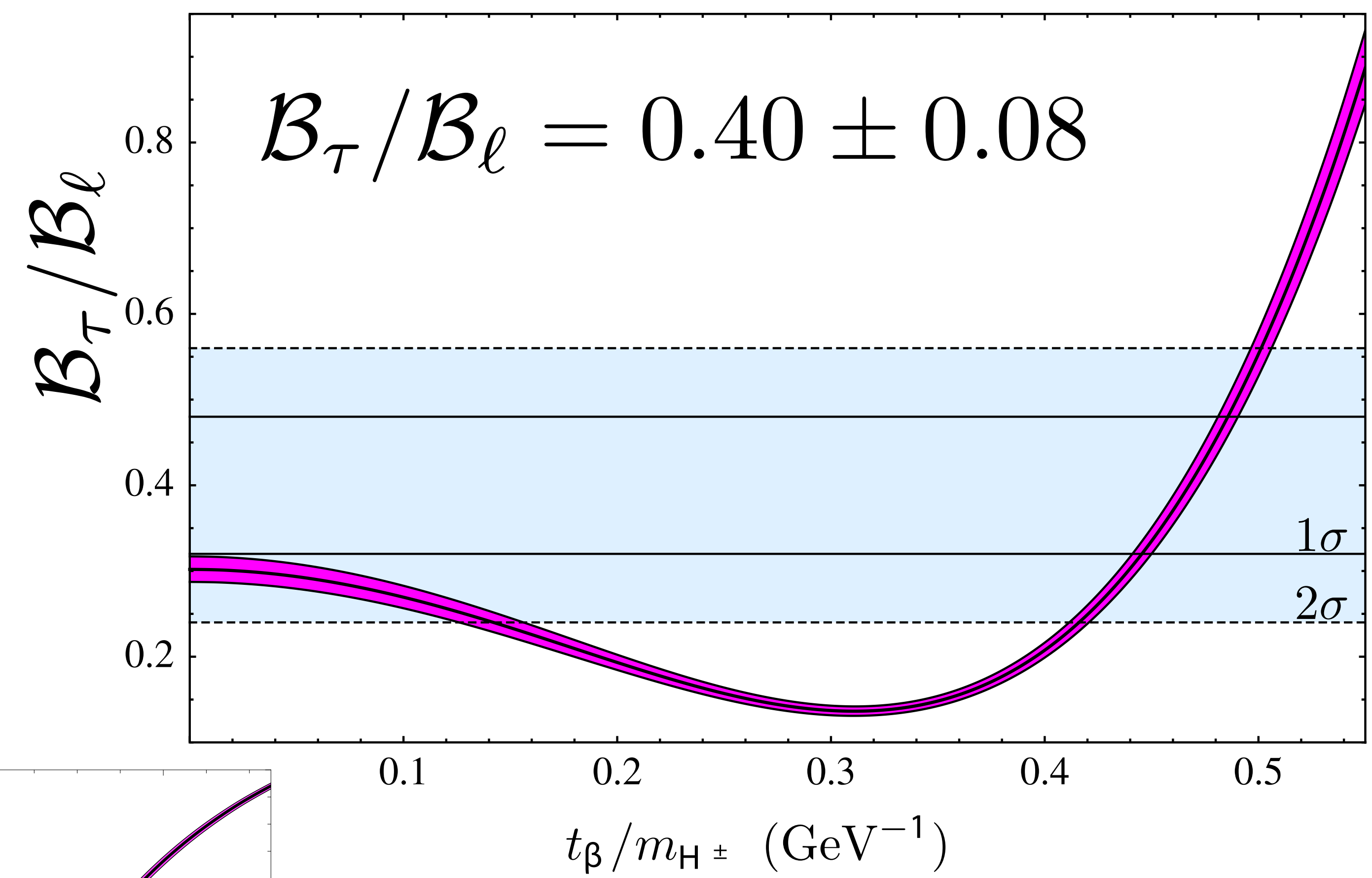
Negative interference!

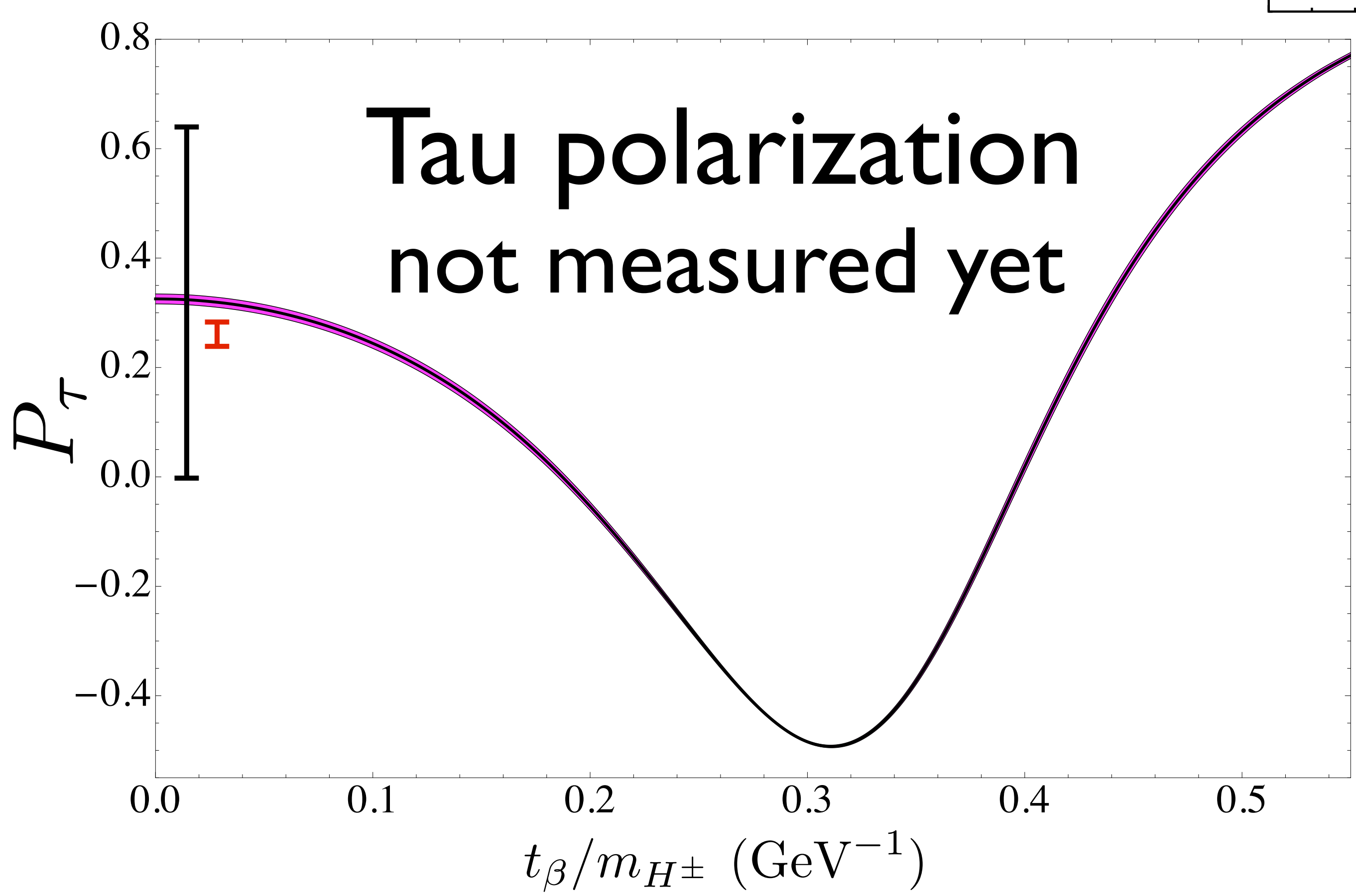
$$\frac{\tan\beta}{m_{H^\pm}} < 0.11\,{\rm GeV}^{-1},\; 0.24\,{\rm GeV}^{-1} < \frac{\tan\beta}{m_{H^\pm}} < 0.31{\rm GeV}^{-1}$$

Charged Higgs in B → Dτν

MT, R. Watanabe (2010)



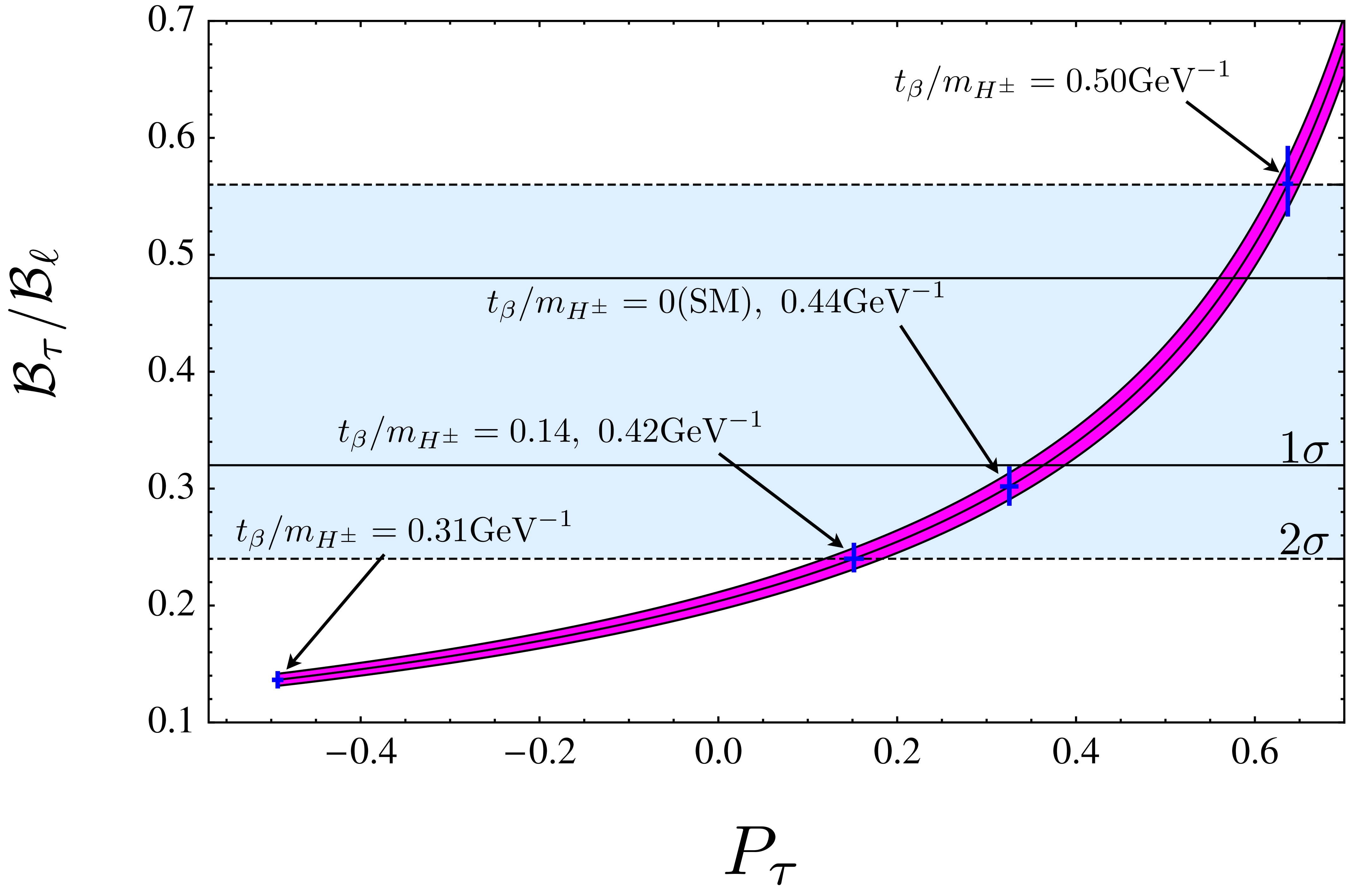




Belle $\delta P_\tau \sim 0.3$

Belle II $\delta P_\tau \sim 0.04$

BR and tau pol.



Like-Sign Dimuon Charge Asymmetry

$$p\bar{p} \longrightarrow b\bar{b}X \longrightarrow \mu^{\pm}\mu^{\pm}X'$$

Charge asymmetry

$$A^b_{\rm sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = \frac{f_d Z_d a^d_{\rm sl} + f_s Z_s a^s_{\rm sl}}{f_d Z_d + f_s Z_s}$$

$$A^b_{\rm sl} = (0.506 \pm 0.043) a^d_{\rm sl} + (0.494 \pm 0.043) a^s_{\rm sl}$$

Charge asymmetry in wrong-sign decays

$$a^q_{\rm sl} \equiv \frac{\Gamma(\bar{B}_q(t) \to \ell^+ X) - \Gamma(B_q(t) \to \ell^- X)}{\Gamma(\bar{B}_q(t) \to \ell^+ X) + \Gamma(B_q(t) \to \ell^- X)}$$

$$= \frac{\Delta\Gamma_q}{\Delta m_q} \tan\phi_q$$

$$\phi_s = 0.0042 \pm 0.0014$$

in the SM

The SM prediction

$$a_{\rm sl}^d({\rm SM}) = (-4.8^{+1.0}_{-1.2}) \times 10^{-4}$$
$$a_{\rm sl}^s({\rm SM}) = (2.1 \pm 0.6) \times 10^{-5}$$

$\longrightarrow$ $A_{\rm sl}^b({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$

Experiments

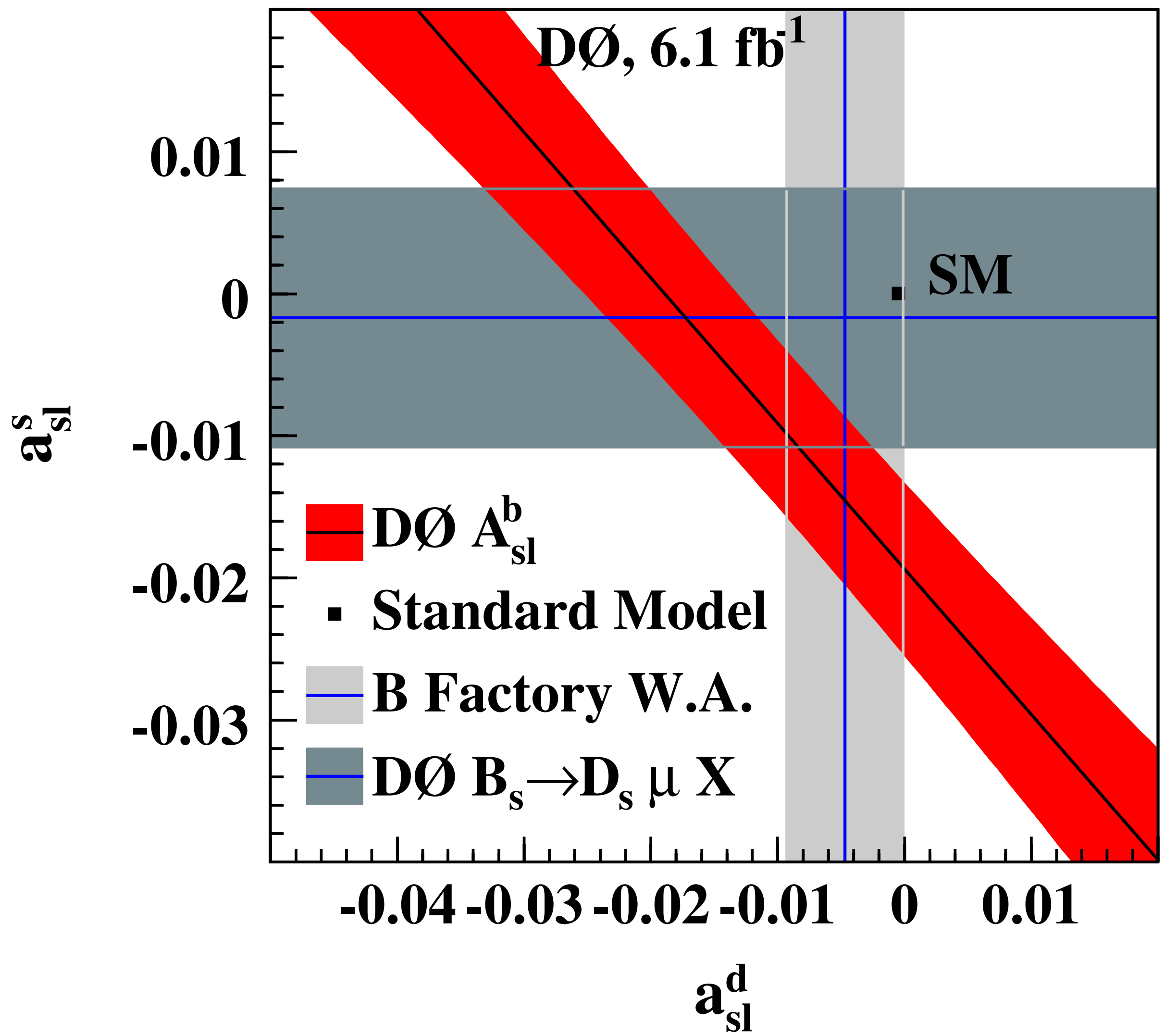
$a_{\rm sl}^d = -0.0047 \pm 0.0046$ Belle, BaBar

$a_{\rm sl}^s = -0.0017 \pm 0.0091$ D0

$A_{\rm sl}^b = -0.009\,57 \pm 0.002\,51\ ({\rm stat}) \pm 0.001\,46\ ({\rm syst}).$ D0

Implication

$$A^b_{\rm sl} = (0.506 \pm 0.043)a^d_{\rm sl} + (0.494 \pm 0.043)a^s_{\rm sl}.$$



$$a^d_{\rm sl} = -0.0047 \pm 0.0046$$

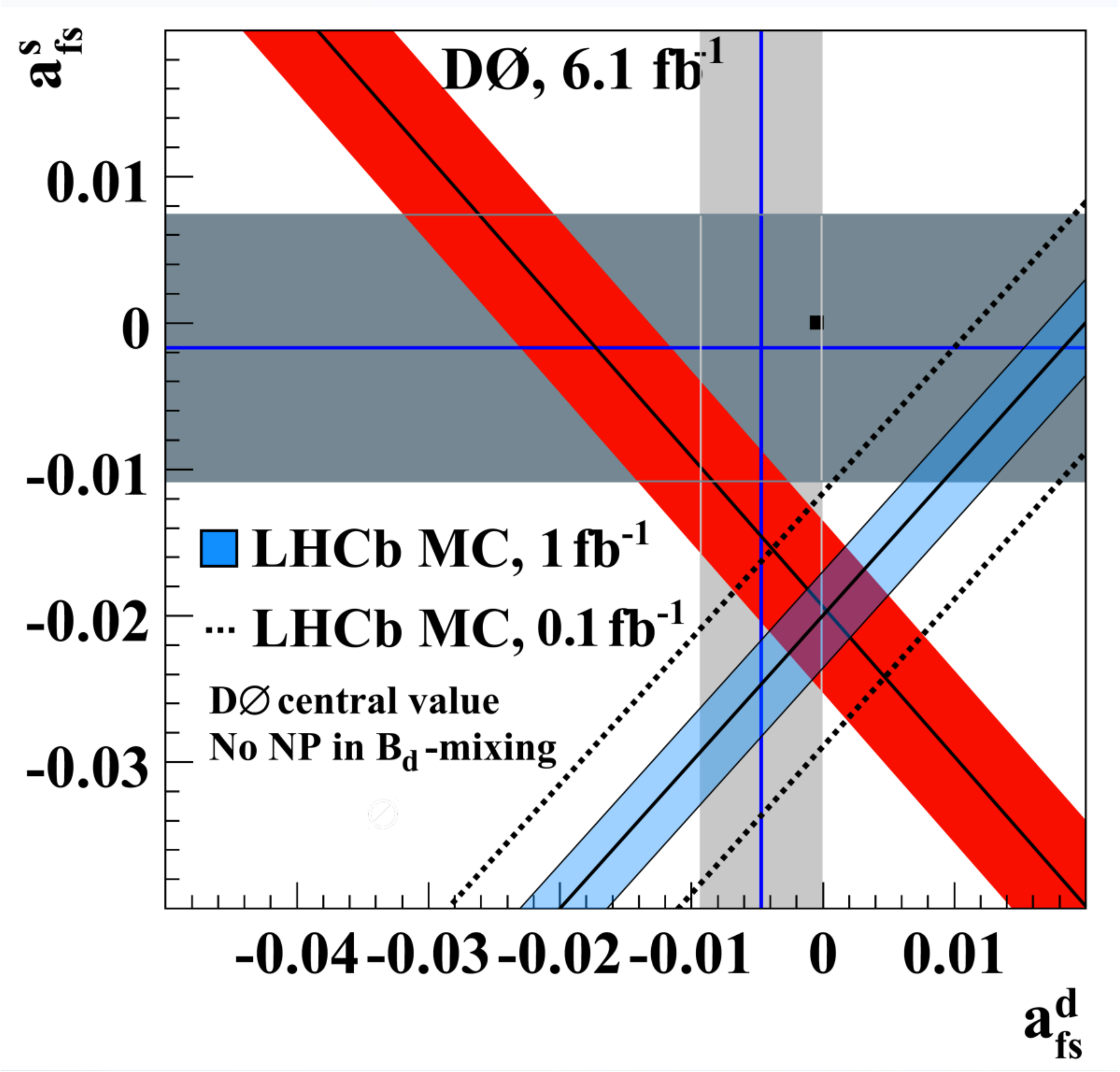
$$a^s_{\rm sl} = -0.0146 \pm 0.0075.$$

$$a^q_{\rm sl} = \frac{\Delta\Gamma_q}{\Delta m_q} \tan\phi_q$$

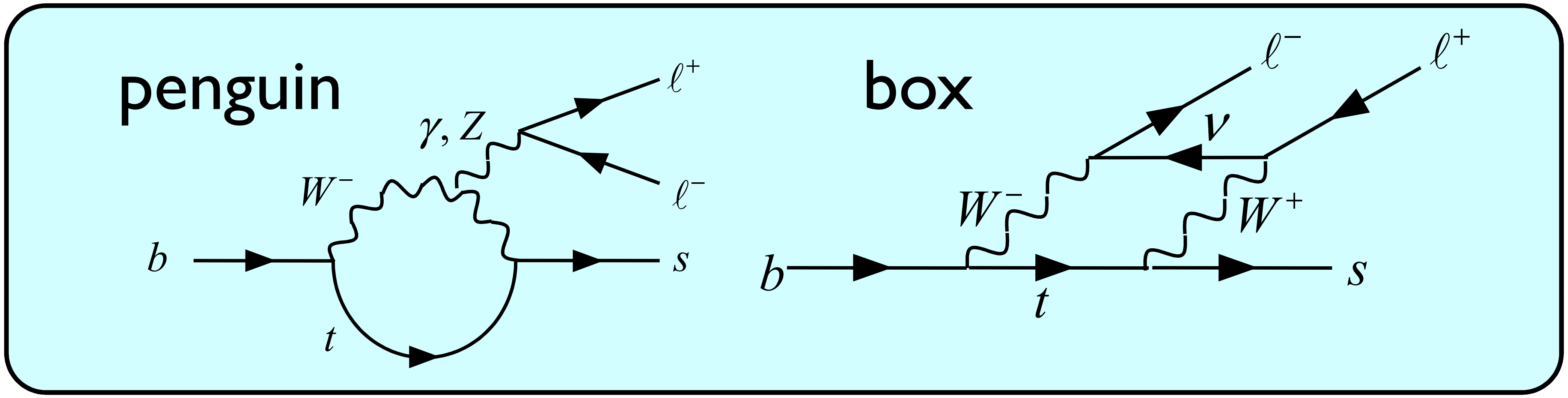
3.2σ

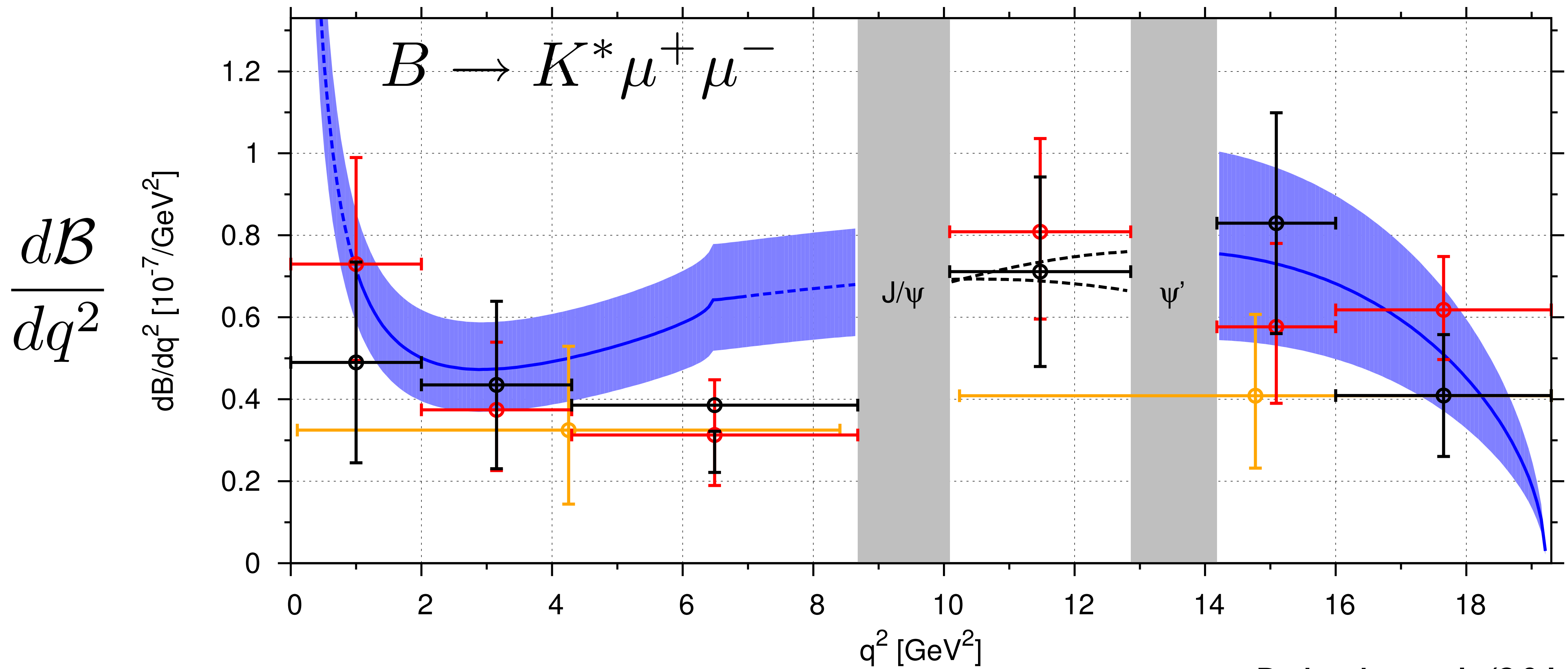
CPV in Bs mixing

LHCb expectation



$b \to s\ell\bar{\ell}$





Bobeth et al. (2010)

Forward-Backward asymmetry in $B \to K^* \ell \bar{\ell}$

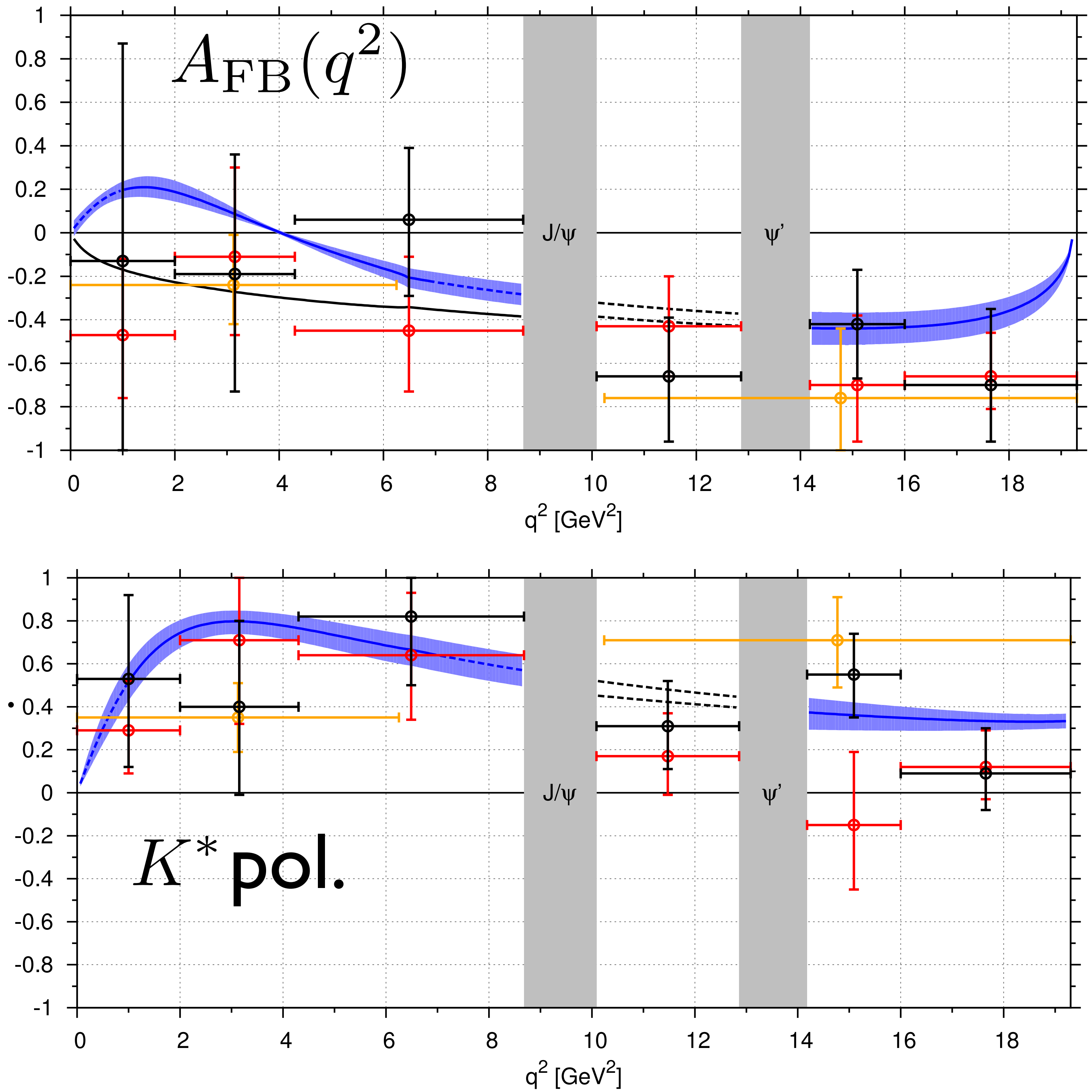
$$H_{\rm eff} = \frac{4G_F}{\sqrt{2}} \sum_{i=1}^{10} C_i(Q) O_i(Q)$$

$$O_7 = \frac{e}{16\pi^2} m_b (\bar{s}_{L\alpha} \sigma_{\mu\nu} b_{R\alpha}) F^{\mu\nu},$$

$$O_9 = \frac{e^2}{16\pi^2} (\bar{s}_{L\alpha} \gamma_\mu b_{L\alpha})(\bar{l} \gamma^\mu l),$$

$$O_{10} = \frac{e^2}{16\pi^2} (\bar{s}_{L\alpha} \gamma_\mu b_{L\alpha})(\bar{l} \gamma^\mu \gamma_5 l).$$

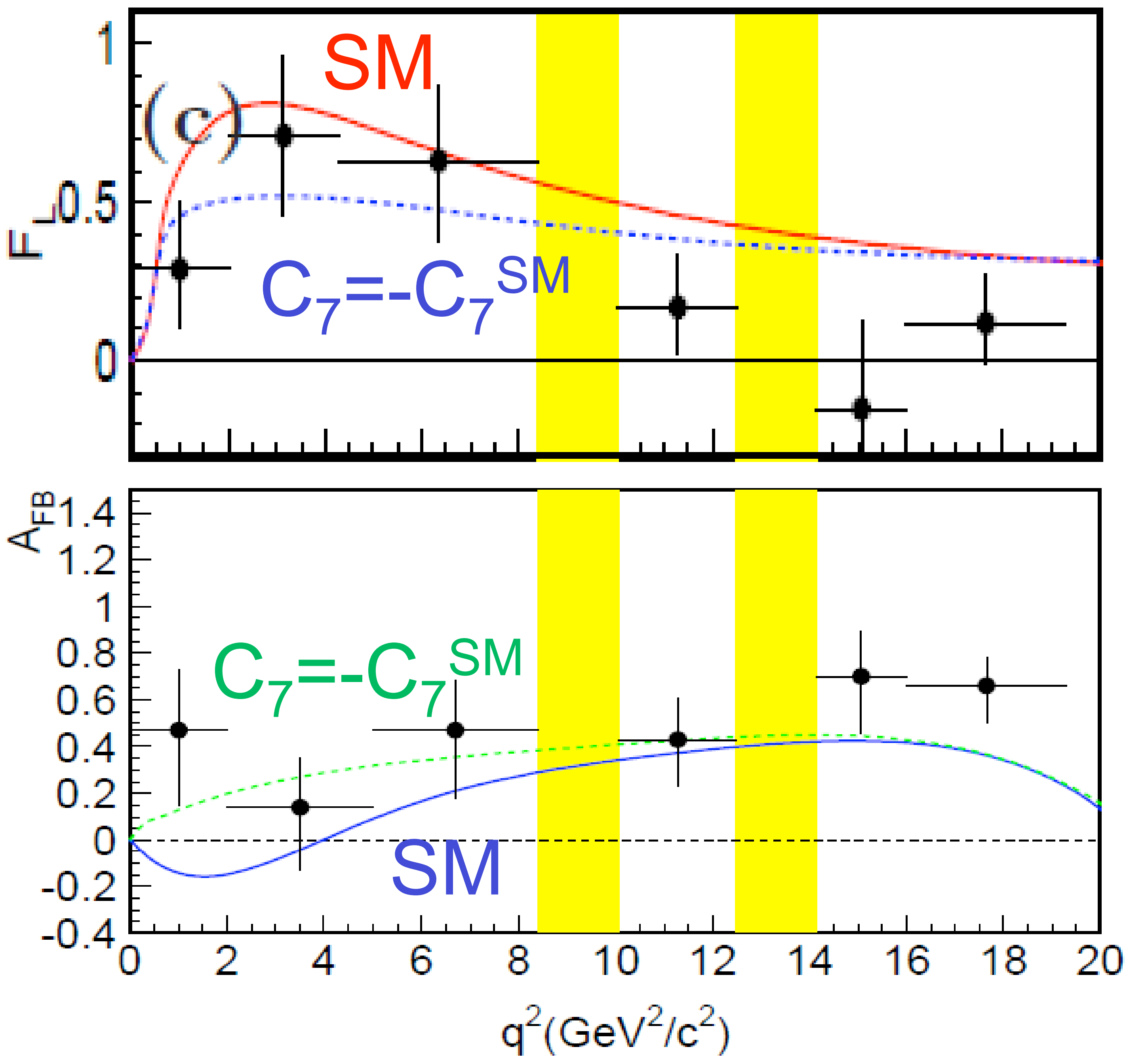
$$\mathrm{BR}(b \to s\gamma) \propto |C_7|^2$$

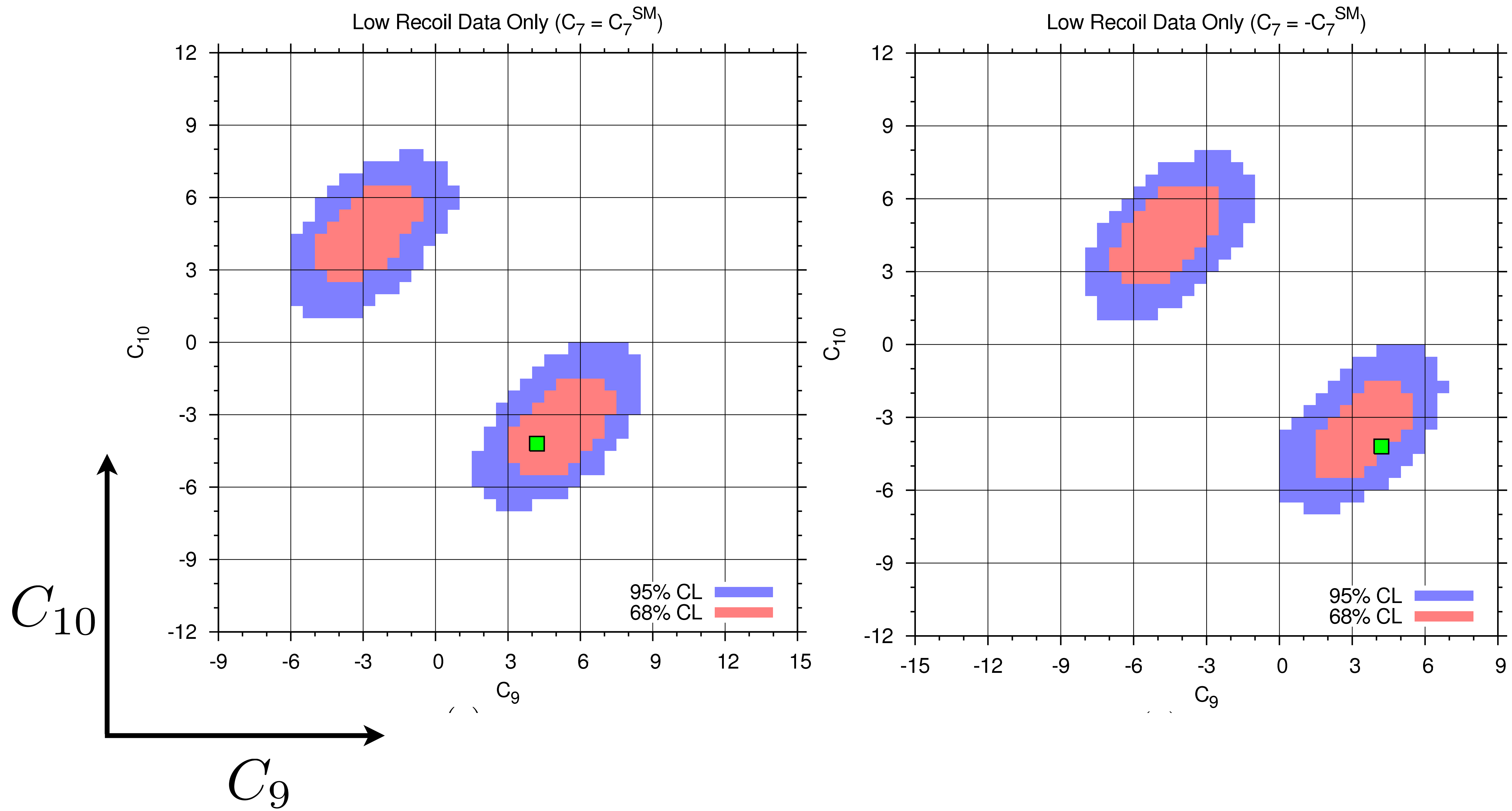


Bobeth et al. (2010)

657 M BB,

submitted to PRL, arXiv: 0904.0770





Low Recoil Data Only ($C_7 = C_7^{SM}$)
C_{10}
C_9
95% CL
68% CL
Low Recoil Data Only ($C_7 = -C_7^{SM}$)
C_{10}
C_9
95% CL
68% CL
C_{10}
C_9

Flavor Structure of the Standard Model

Flavor symmetry of the SM gauge sector
(i.e. turning off the Yukawa couplings)

$$l_{Li},\ e_{Ri},\ q_{Li},\ u_{Ri},\ d_{Ri} \quad (i=1,2,3)$$

$$\begin{aligned}\mathcal{G}_F &= U(3)^5 \\ &= SU(3)^5 \times U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{\rm PQ} \times U(1)_{e_R}\end{aligned}$$

Turning on the Yukawa couplings,

$$\mathcal{G}_F \xrightarrow[\mathcal{L}_Y]{} U(1)_B \times U(1)_L \times U(1)_Y$$

What about new physics at the TeV scale?

Minimal Flavor Violation

$\mathcal{G}_F$ and CP are broken solely by Yukawa as in the SM.

All flavor and CP violations are controlled by Y.

Ex. MSSM with real and universal soft breakings (minimal supergravity model)

Rather small deviations from the SM.

→ More precise measurements at super B factory.

Non-Minimal Flavor Violation

New sources of flavor and CP violation

Ex. SU(5) SUSY GUT with ν_R

Neutrino Yukawa breaks $\mathcal{G}_F$.

U(2) flavor symmetry model

U(2) breakings in soft SUSY breakings

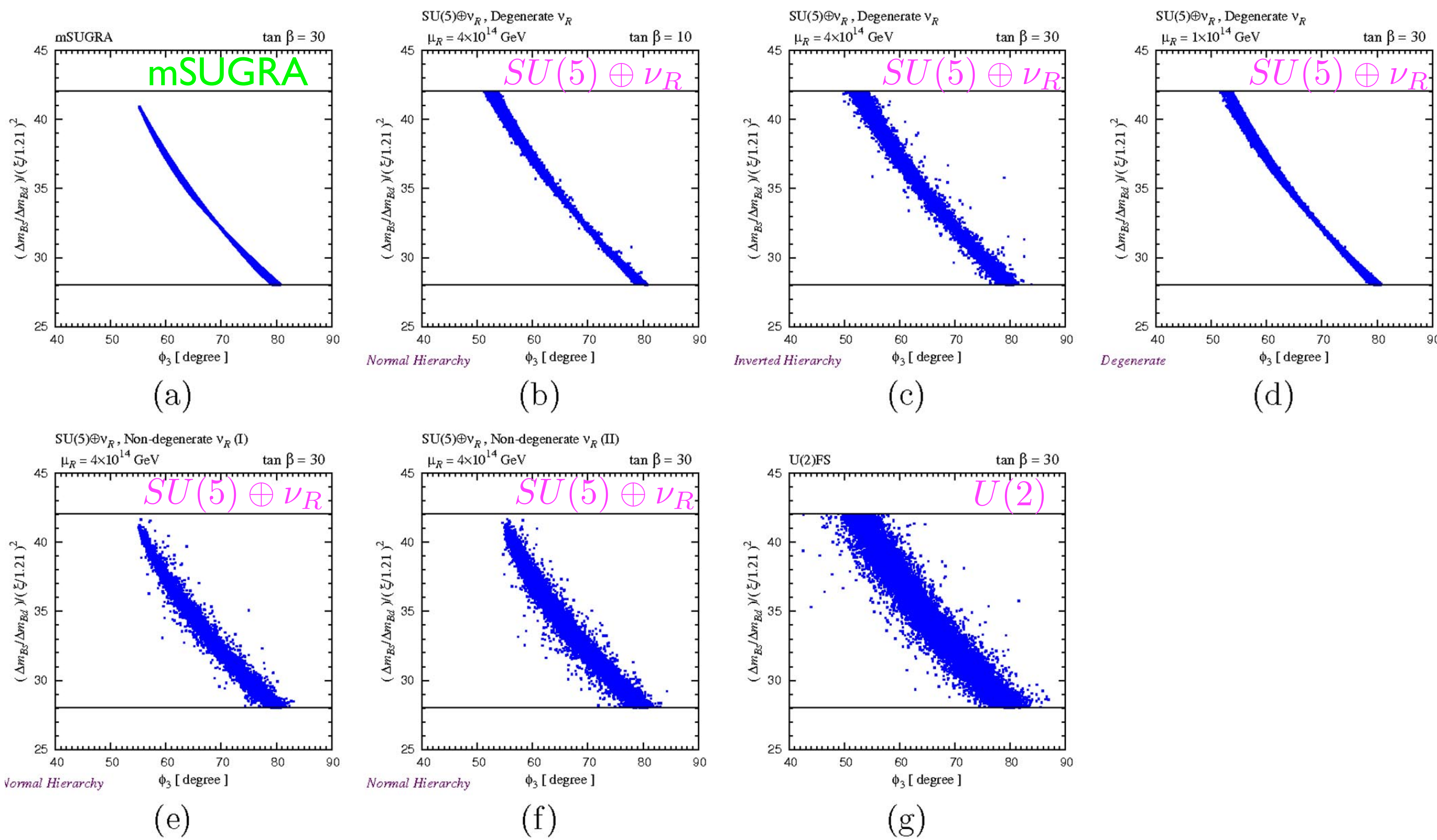
$$(U(2) \subset \mathcal{G}_F)$$

Larger deviations from the SM.

⟶ Rather restricted.

ϕ_3 vs $\Delta m_{B_s}/\Delta m_{B_d}$

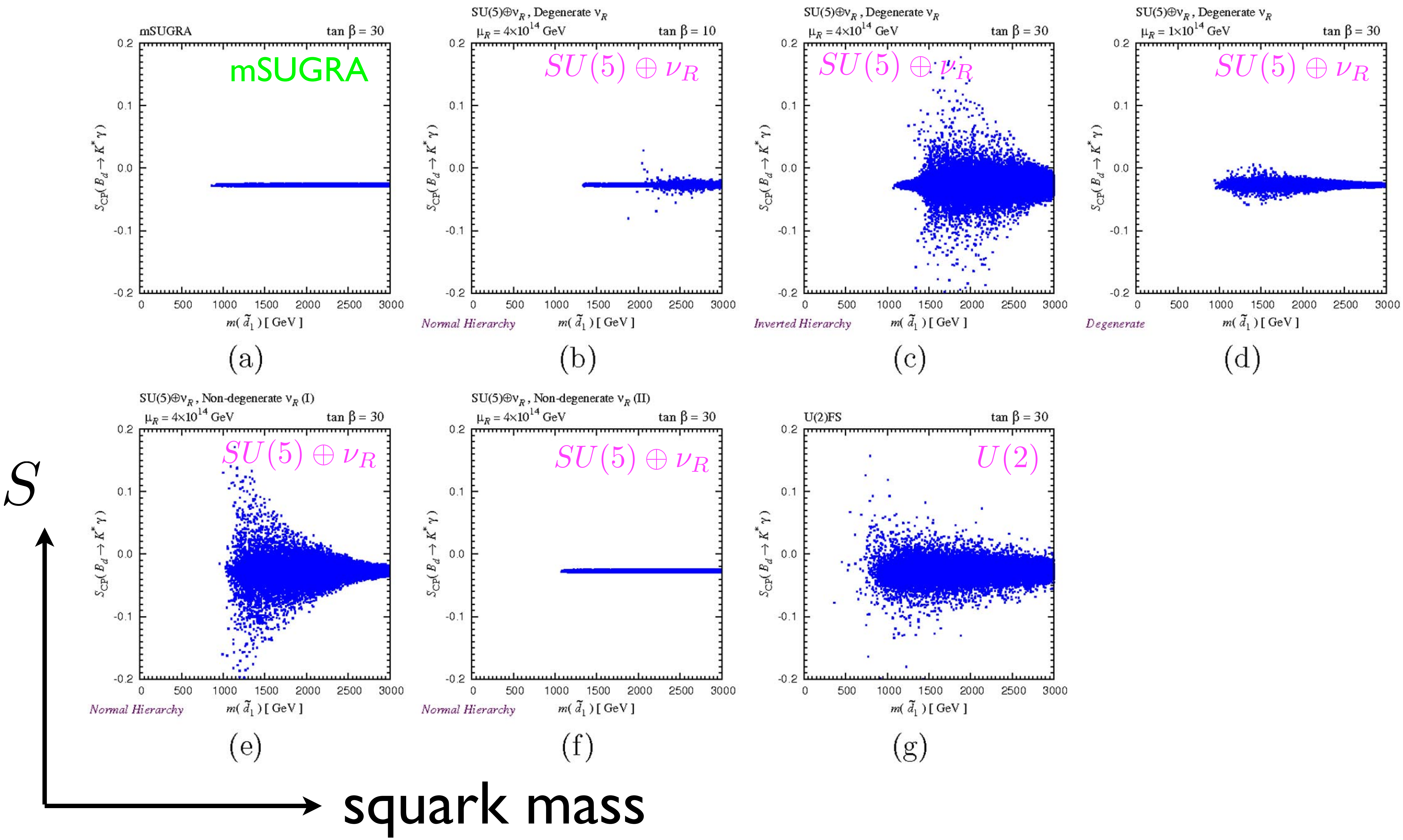
GOTO, OKADA, SHINDOU, AND TANAKA PHYSICAL REVIEW D **77,** 095010 (2008)



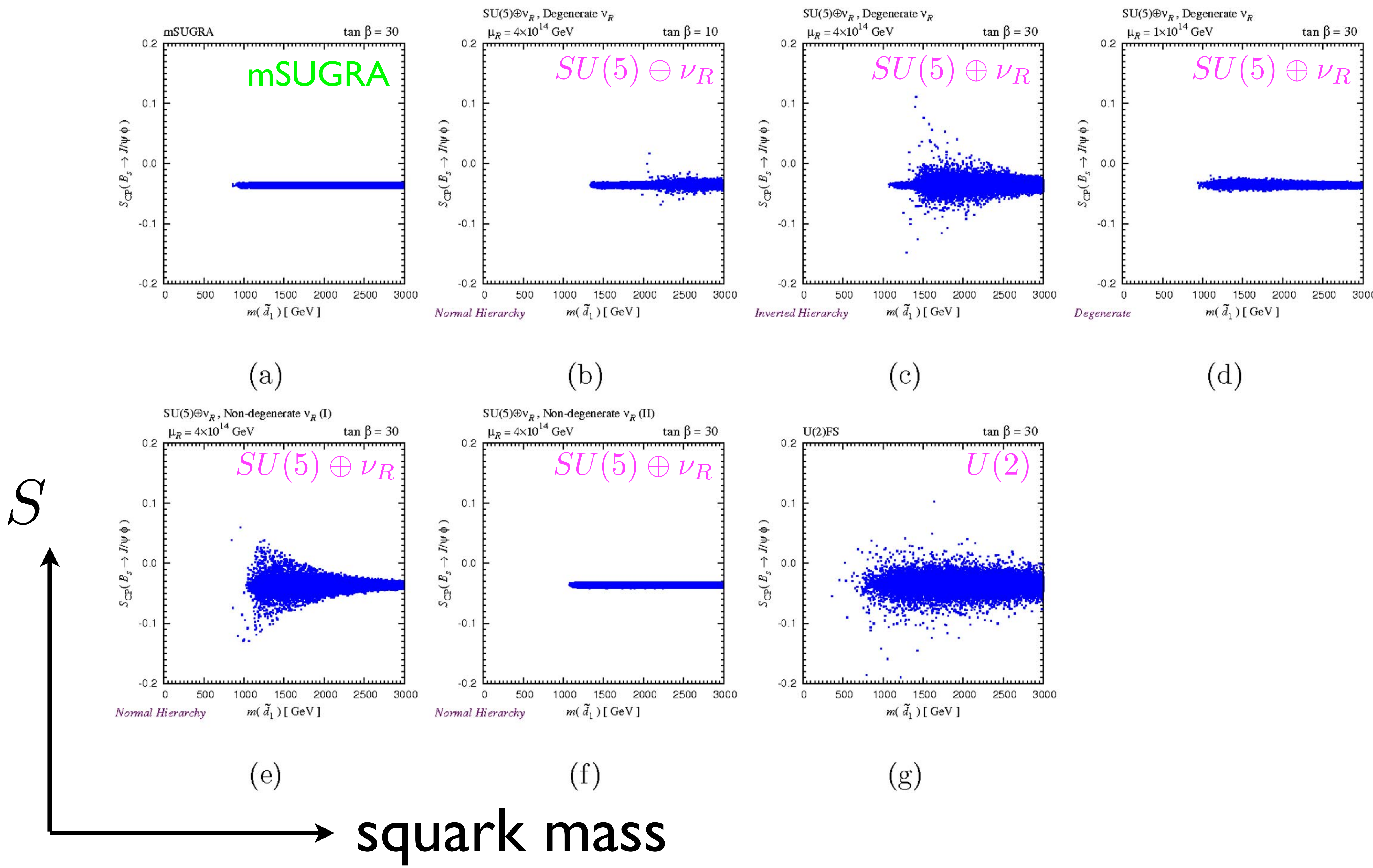
$$\frac{\Delta m_{B_s}}{\Delta m_{B_d}}$$

$$\phi_3$$

Mixing-induced CPV in $B_d \to K^* \gamma$



CP Violation in $B_s \to J/\psi\,\phi$



CP Violation in $B_s \to J/\psi\,\phi$

$$J/\psi \to \mu^+\mu^-\,,\ \phi \to K^+K^-$$

$$\frac{d^4\Gamma}{dt\,d\cos\theta\,d\varphi\,d\cos\psi} \propto 2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)|A_0(t)|^2 + \sin^2\psi(1-\sin^2\theta\sin^2\varphi)|A_\|(t)|^2 + \sin^2\psi\sin^2\theta|A_\perp(t)|^2$$
$$+ (1/\sqrt{2})\sin 2\psi\sin^2\theta\sin 2\varphi\,\mathrm{Re}(A_0^*(t)A_\|(t)) + (1/\sqrt{2})\sin 2\psi\,\sin 2\theta\cos\varphi\,\mathrm{Im}(A_0^*(t)A_\perp(t))$$
$$- \sin^2\psi\,\sin 2\theta\,\sin\varphi\,\mathrm{Im}(A_\|^*(t)A_\perp(t)).$$

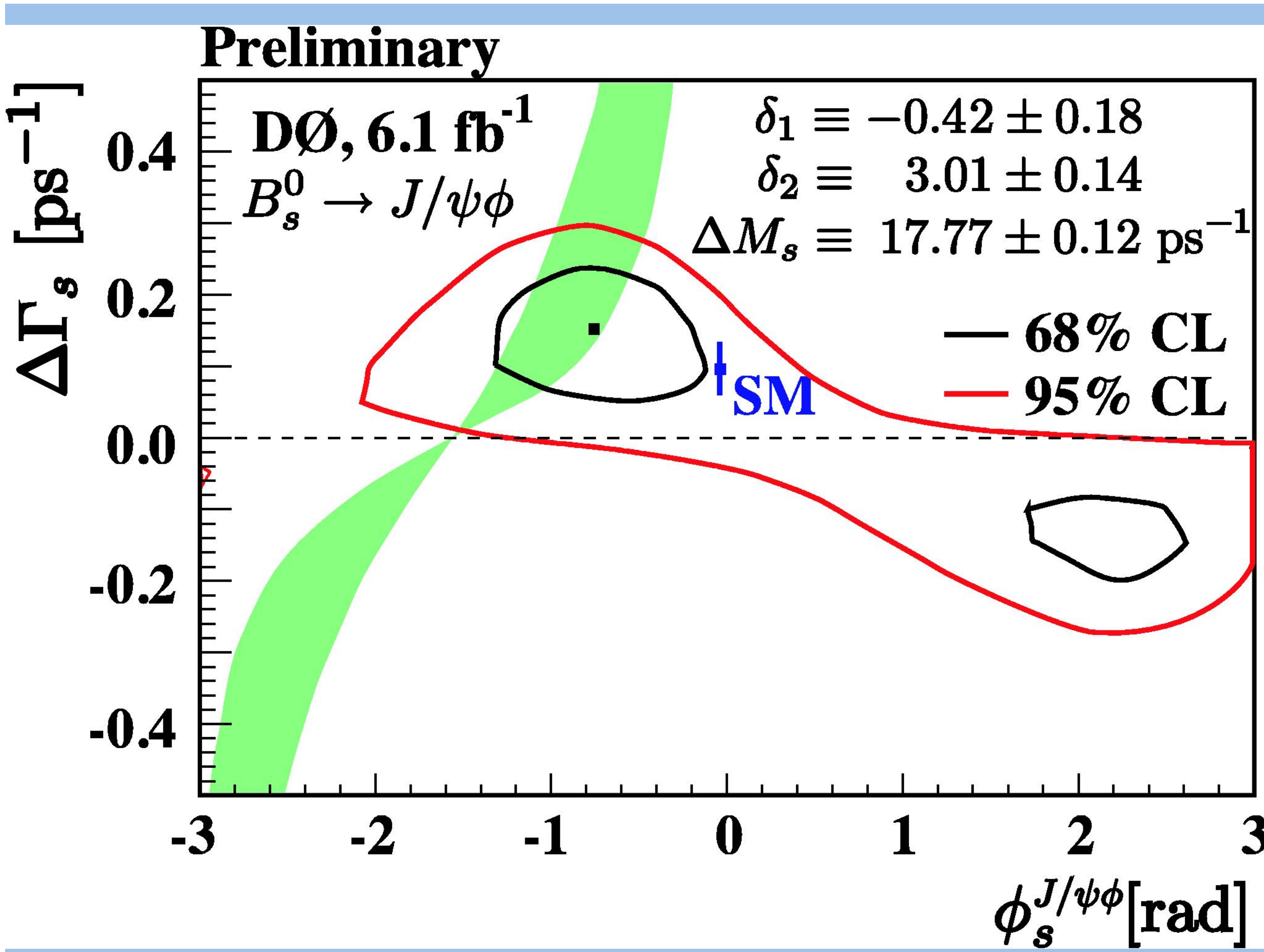
$$|A_{0,\|}(t)|^2 = |A_{0,\|}(0)|^2[\mathcal{T}_+ \pm e^{-\bar{\Gamma}' t}\sin\phi_s\sin(\Delta M_s t)], \qquad |A_\perp(t)|^2 = |A_\perp(0)|^2[\mathcal{T}_- \mp e^{-\bar{\Gamma}' t}\sin\phi_s\sin(\Delta M_s t)],$$

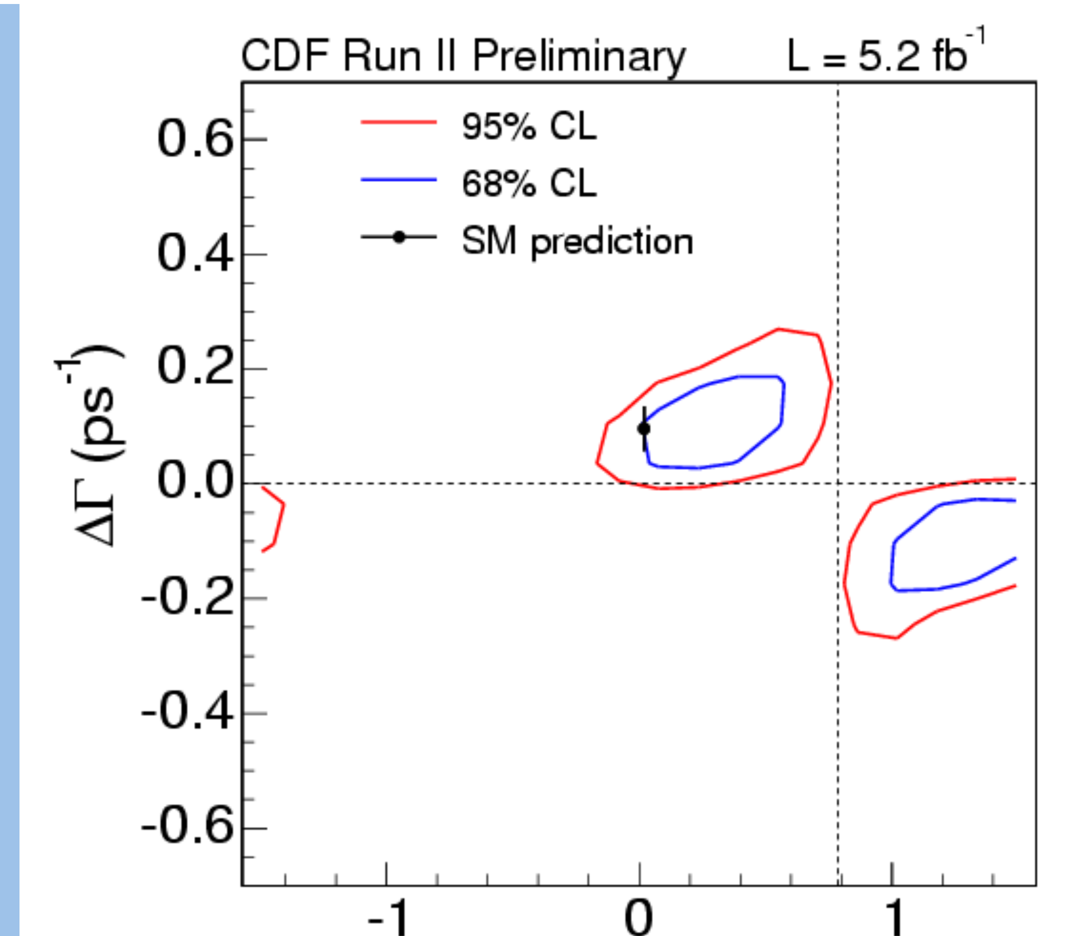
$$\mathrm{Re}\,(A_0^*(t)A_\|(t)) = |A_0(0)||A_\|(0)|\cos(\delta_2-\delta_1)\times[\mathcal{T}_+ \pm e^{-\bar{\Gamma}' t}\sin\phi_s\sin(\Delta M_s t)],$$

$$\mathrm{Im}(A_0^*(t)A_\perp(t)) = |A_0(0)||A_\perp(0)|| \times [e^{-\bar{\Gamma} t}(\pm\sin\delta_2\cos(\Delta M_s t) \mp \cos\delta_2\sin(\Delta M_s t)\cos\phi_s)$$
$$- (1/2)(e^{-\Gamma_H t} - e^{-\Gamma_L t})\sin\phi_s\cos\delta_2],$$

$$\mathrm{Im}(A_\|^*(t)A_\perp(t)) = |A_\|(0)||A_\perp(0)| \times [e^{-\bar{\Gamma} t}(\pm\sin\delta_1\cos(\Delta M_s t) \mp \cos\delta_1\sin(\Delta M_s t)\cos\phi_s)$$
$$- (1/2)(e^{-\Gamma_H t} - e^{-\Gamma_L t})\sin\phi_s\cos\delta_1],$$

$$\mathcal{T}_\pm = (1/2)[(1\pm\cos\phi_s)e^{-\Gamma_L t} + (1\mp\cos\phi_s)e^{-\Gamma_H t}]$$





Φ_s=-2β_s 2 -2

Abbott, FPCP2011

SUMMARY

★ CKM scheme seems OK at ~10% accuracy.

★ A few % new physics might be there.

★ Yukawa sector, flavor structure

→ Key issue for new physics

MFV or Non-MFV

★ Interplay between LHC and flavor factories.

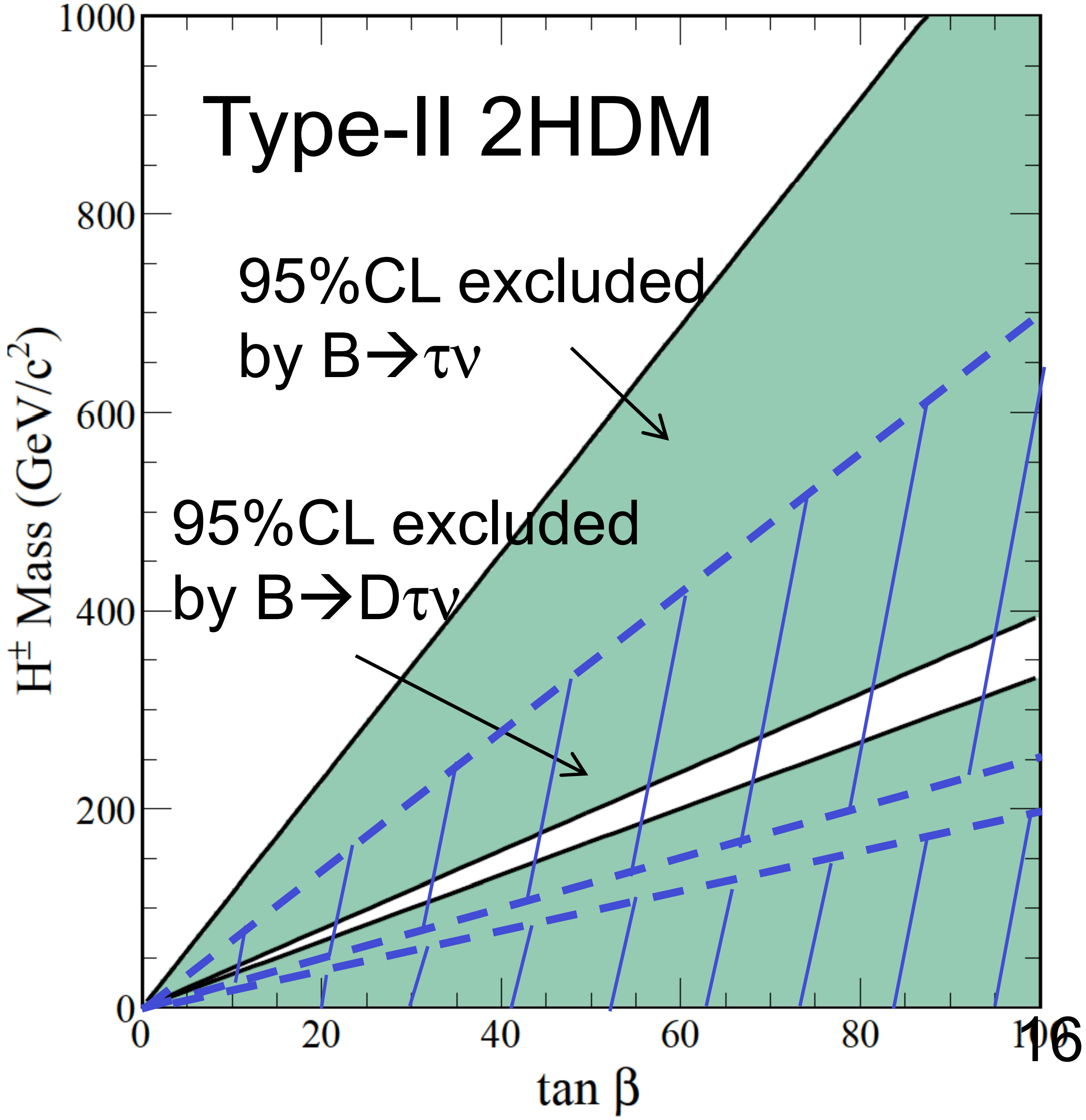
Super KEKB, JPARC K experiments,
LFV searches, EDM, neutrinos, β decays, etc.

Several other issues

$K\pi$ puzzle, D mixing, tau LFV decays, ...

Thank you.

Backup Slides


Type-II 2HDM
95%CL excluded
by B→τν
95%CL excluded
by B→Dτν
1000
800
600
400
200
0
$H^{\pm}$ Mass (GeV/c^2)
0
20
40
60
80
100
tan β
16