Current Status and Future Prospect of Flavor Physics

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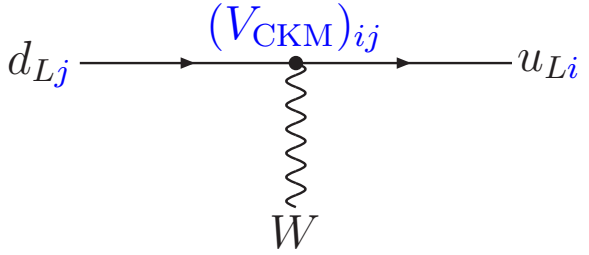
Introduction

Great progress in flavor (b) physics

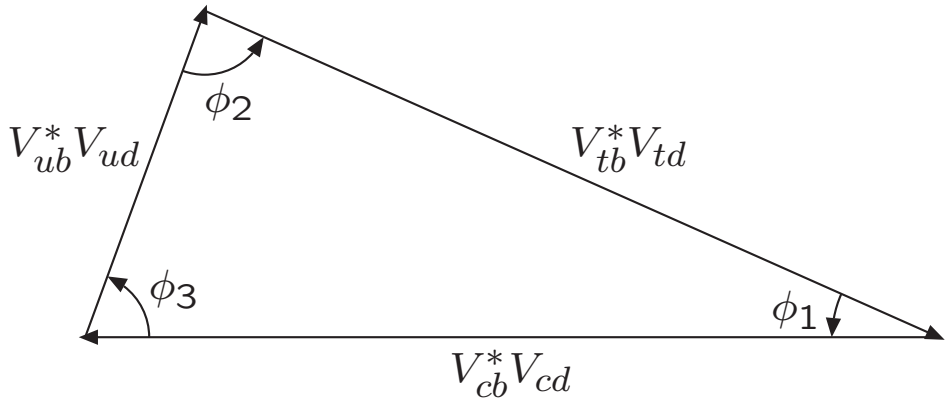
- $e^+ e^-$ B-factory experiments: $B^{\pm,0}$
  - ▷ Belle @KEKB (KEK) ~ 711 fb^{-1} @$\Upsilon(4S)$
  - $\Rightarrow$ Bell-II @SuperKEKB under construction.
    - $*$ $\mathcal{L} = 8 \times 10^{35}$ cm^{-2}s^{-1} $\rightarrow$ 8 ab^{-1}/100days.
  - ▷ BaBar @PEP-II (SLAC) ~ 433 fb^{-1} @$\Upsilon(4S)$
- Hadron collider experiments: $B^{\pm,0}$, B_s
  - ▷ CDF & D0@TeVatron (FNAL) ~ 12 fb^{-1} @1.96TeV $p\bar{p}$ per exp.
  - ▷ LHCb @LHC (CERN) ~ 1.2 fb^{-1} @7TeV + 1.5 fb^{-1} @8TeV pp

Flavor mixing in SM: Cabibbo-Kobayashi-Maskawa matrix.

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



- Three mixing angles, one complex phase.
  - ▷ $|V_{us}| \Leftarrow$ strange particle decays ($s \to u$)
  - ▷ $|V_{cb}| \Leftarrow b$ decays ($b \to c$)

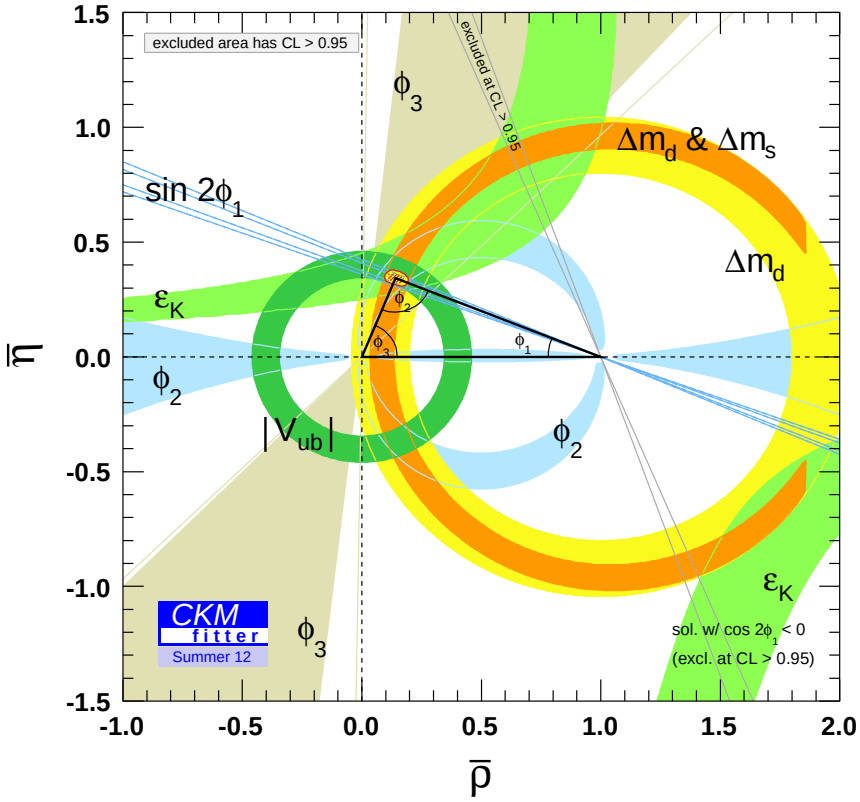


$$\overline{\rho} + i\overline{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

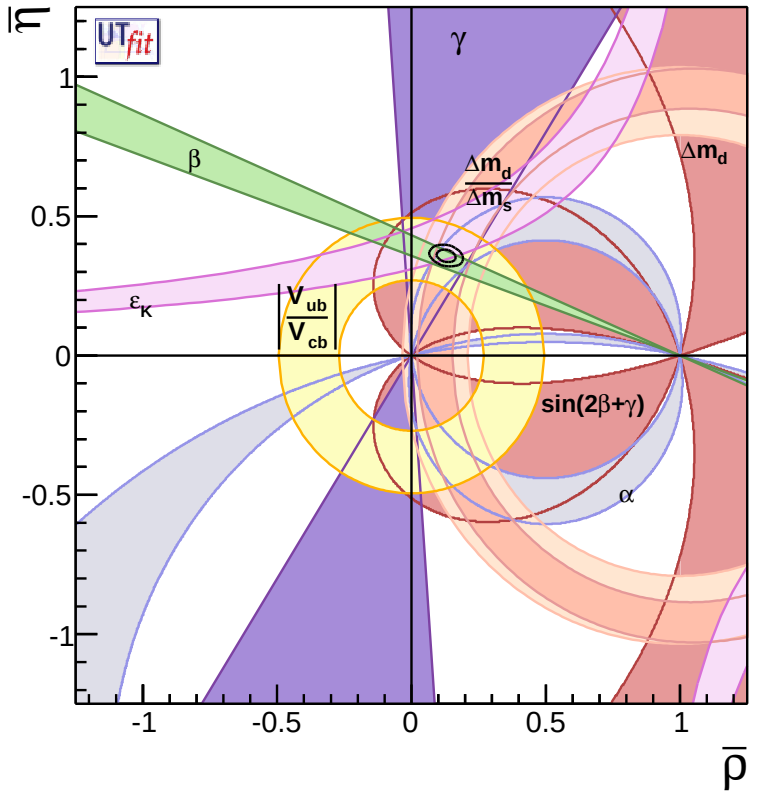
$b \leftrightarrow d$ unitarity: $V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$ depicted by a triangle.

Plenty of measurements $\Rightarrow$ overconstraining V_{CKM} possible.

- Mismatch $\Rightarrow$ indication of New Physics.



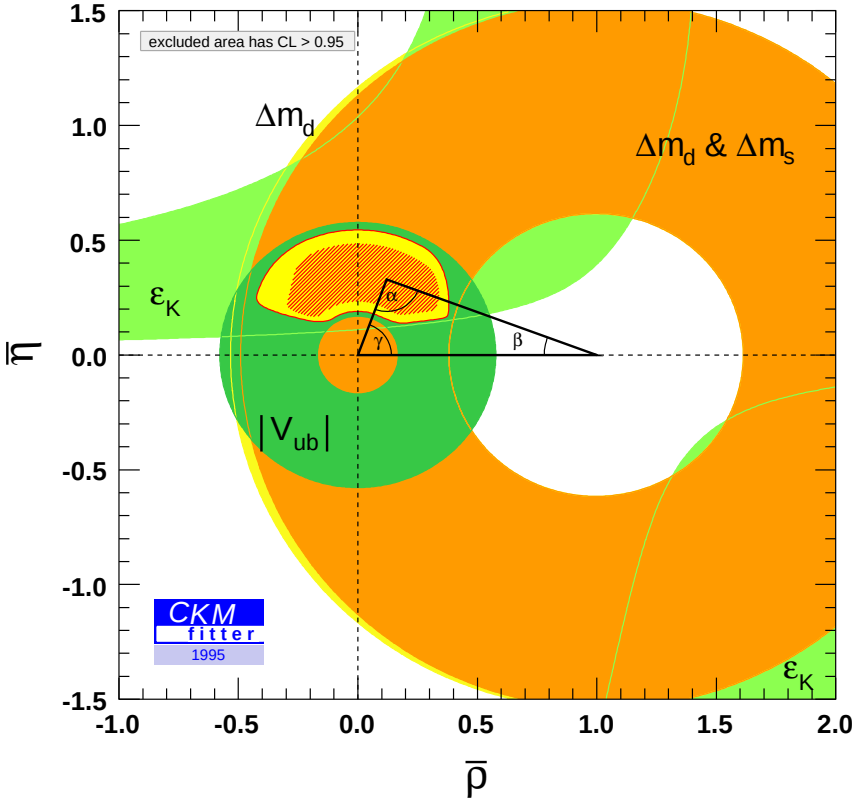
[CKM fitter http://ckmfitter.in2p3.fr/]



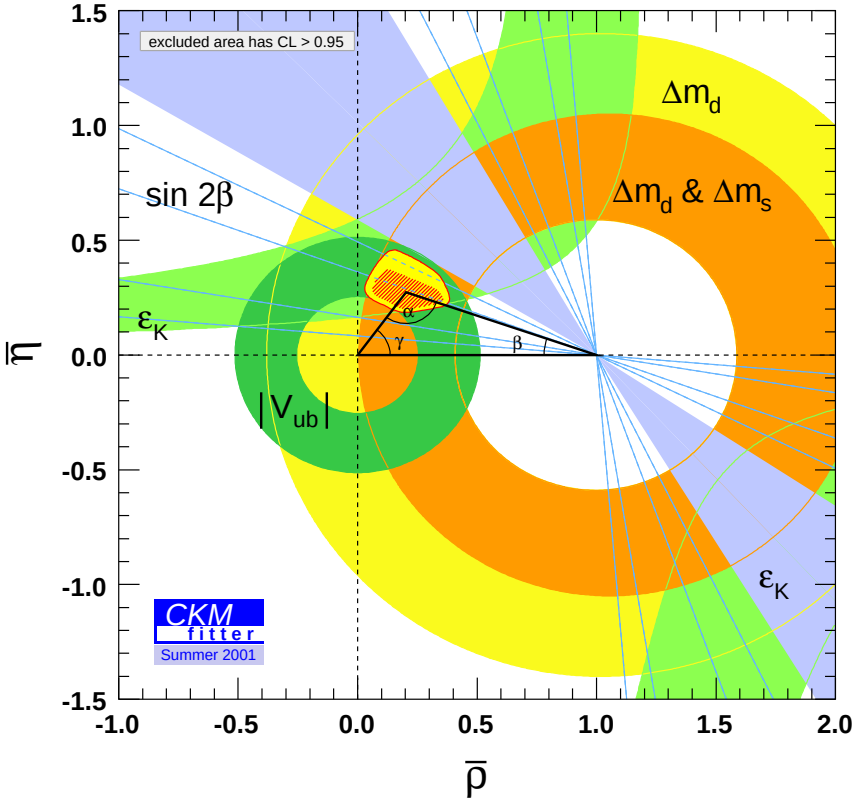
[UTfit http://www.utfit.org/]

Unitarity triangle: history

1995

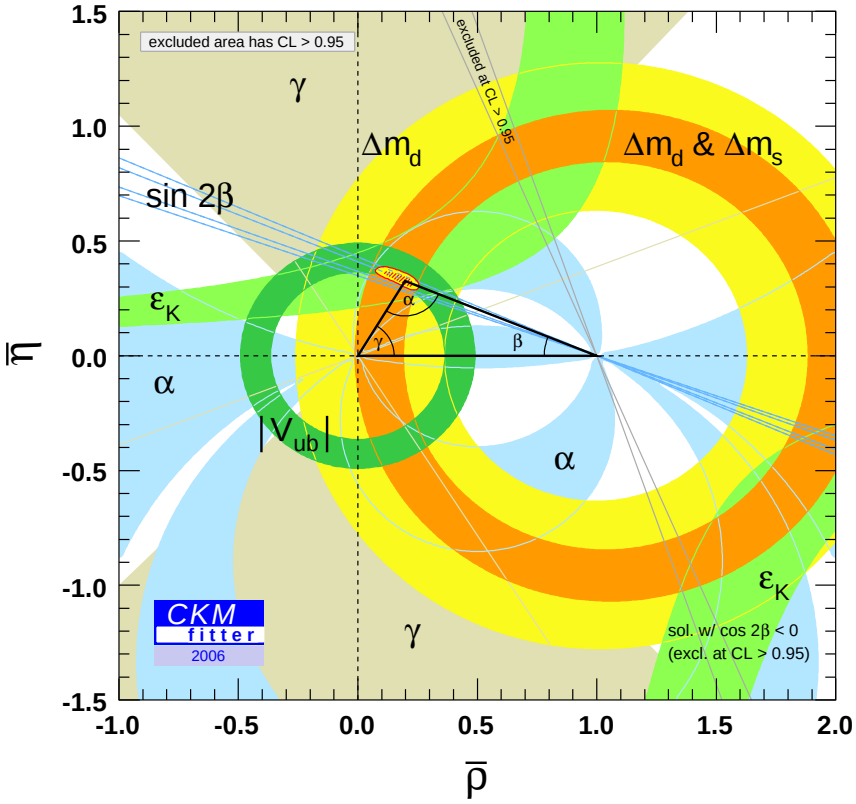


2001

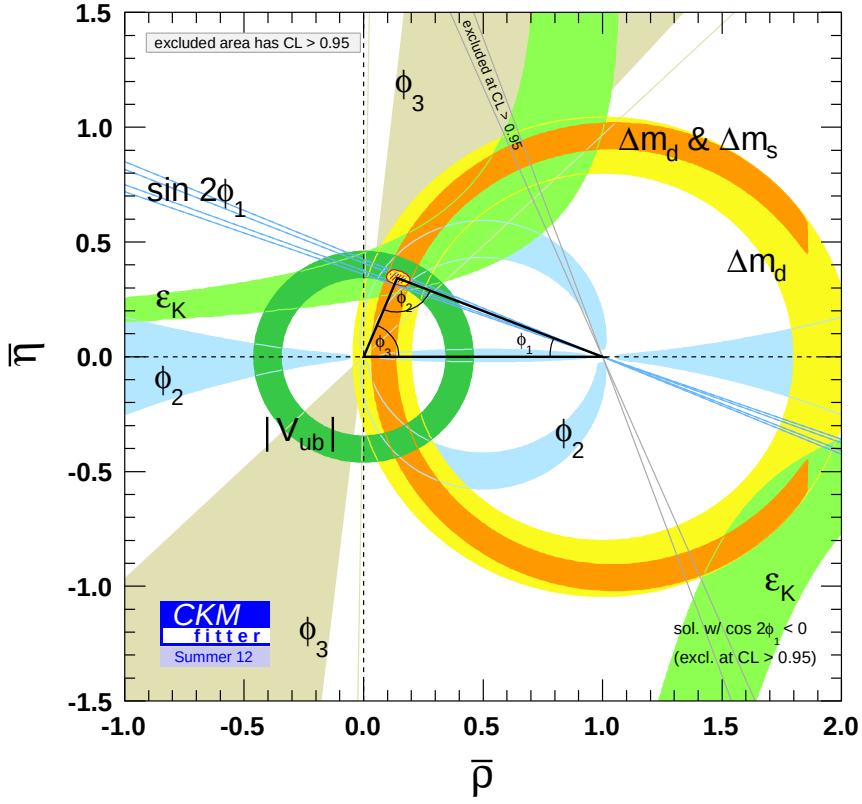


Unitarity triangle: history

2006



2012



Good news for SM, bad news for NP search.

Contents

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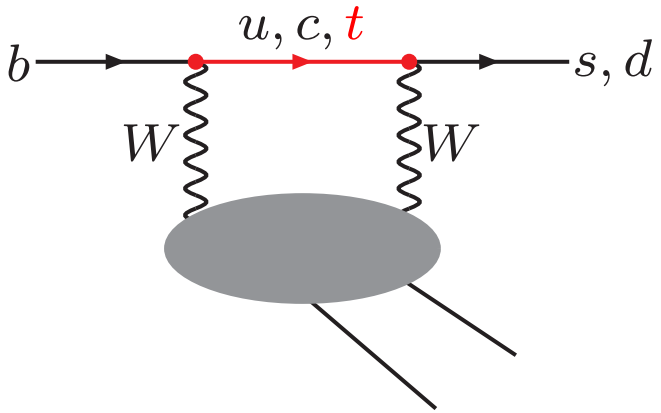
$b \to s$ transitions

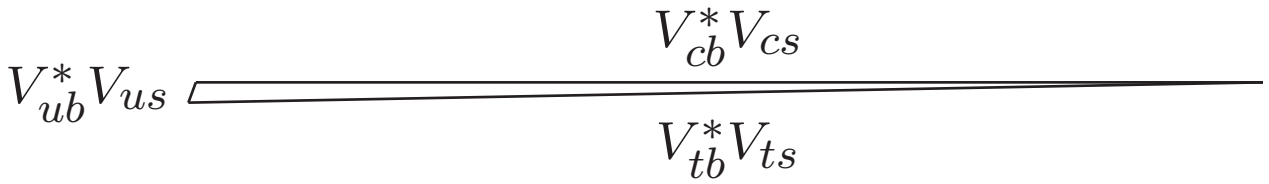


$$= V_{ts}^* V_{tb} \left[f(\frac{m_t^2}{m_W^2}) - f(\frac{m_u^2}{m_W^2}) \right]$$
$$+ V_{cs}^* V_{cb} \left[f(\frac{m_c^2}{m_W^2}) - f(\frac{m_u^2}{m_W^2}) \right] .$$

$$\frac{m_t^2}{m_W^2} \gtrsim 1 \gg \frac{m_{u,c}^2}{m_W^2}, \qquad V_{ts}^* V_{tb} \approx -V_{cs}^* V_{cb} \qquad \Rightarrow \qquad \text{Amp} \approx V_{ts}^* V_{tb} F(\frac{m_t^2}{m_W^2}).$$

Uncertainties in SM predictions relatively small.

$b \leftrightarrow s$ UT:



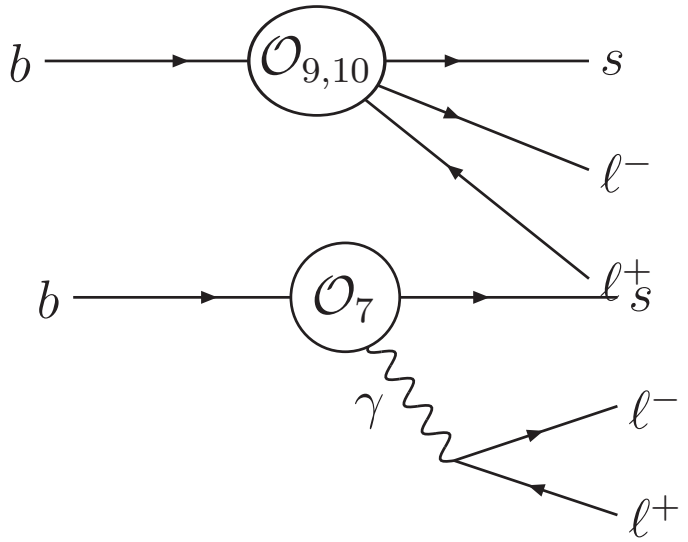
$b \to s\,\ell^+\,\ell^-$

Effective Hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{e^2}{(4\pi)^2} \sum_i C_i(\mu) \mathcal{O}_i(\mu),$$

Relevant effective operators in SM

$$\begin{aligned} \mathcal{O}_9 &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \\ \mathcal{O}_{10} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), \\ \mathcal{O}_7 &= m_b(\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}, \end{aligned}$$



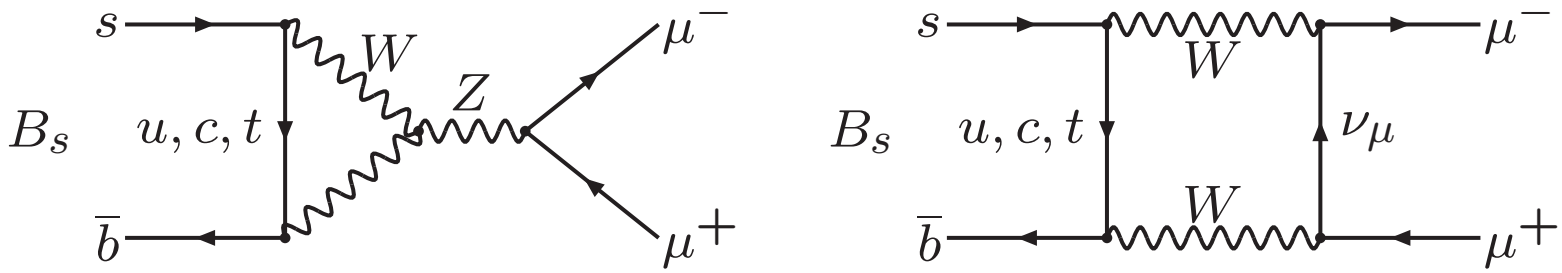
- NP: $(\bar{s}P_L b)(\bar{\ell}\ell)$, $(\bar{s}P_L b)(\bar{\ell}\gamma_5\ell)$, ...
- $\mathcal{O}_7 \Rightarrow b \to s\,\gamma$.
- $\mathcal{O}_{10} \Rightarrow B_s \to \ell^+\,\ell^-$.

LHCb is strong for $\ell = \mu$.

$B_s \to \mu^+ \mu^-$

- "First evidence": $\mathrm{B} = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$. [LHCb, arXiv:1211.2674]
- "Strong constraint": $\mathrm{B} < 4.5 \times 10^{-9}$ (95% C.L.) [LHCb, arXiv:1203.4493]

SM [Buras *et al.*, arXiv:1208.0934]:



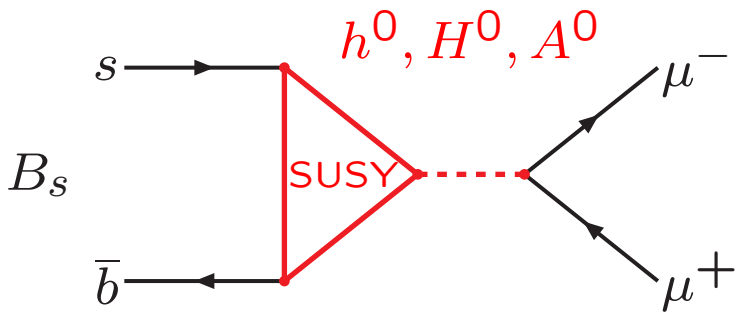
$$\begin{aligned}\mathrm{B_{SM}} &= \frac{G_F^2}{\pi}\left[\frac{\alpha_{\mathrm{em}}(m_Z)}{4\pi \sin^2\theta_W}\right]^2 \tau_{B_s} f_{B_s}^2 m_{B_s} m_\mu^2 \sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}\,|V_{tb}^* V_{ts}|^2\, Y^2(x_{tW}, x_{ht}; \alpha_s) \\ &= (3.23 \pm 0.27) \times 10^{-9}\,.\end{aligned}$$

- Main source of theoretical uncertainty: decay constant f_{B_s}.

$B_s \to \mu^+ \mu^-$ in SUSY

Large $\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$ CMSSM strongly constrained.

- MSSM Higgs = Type-II 2HDM at tree level (NFC).
- SUSY breaking $\Rightarrow$ FCNC in neutral Higgs (h^0, H^0, A^0) interactions at loop level.

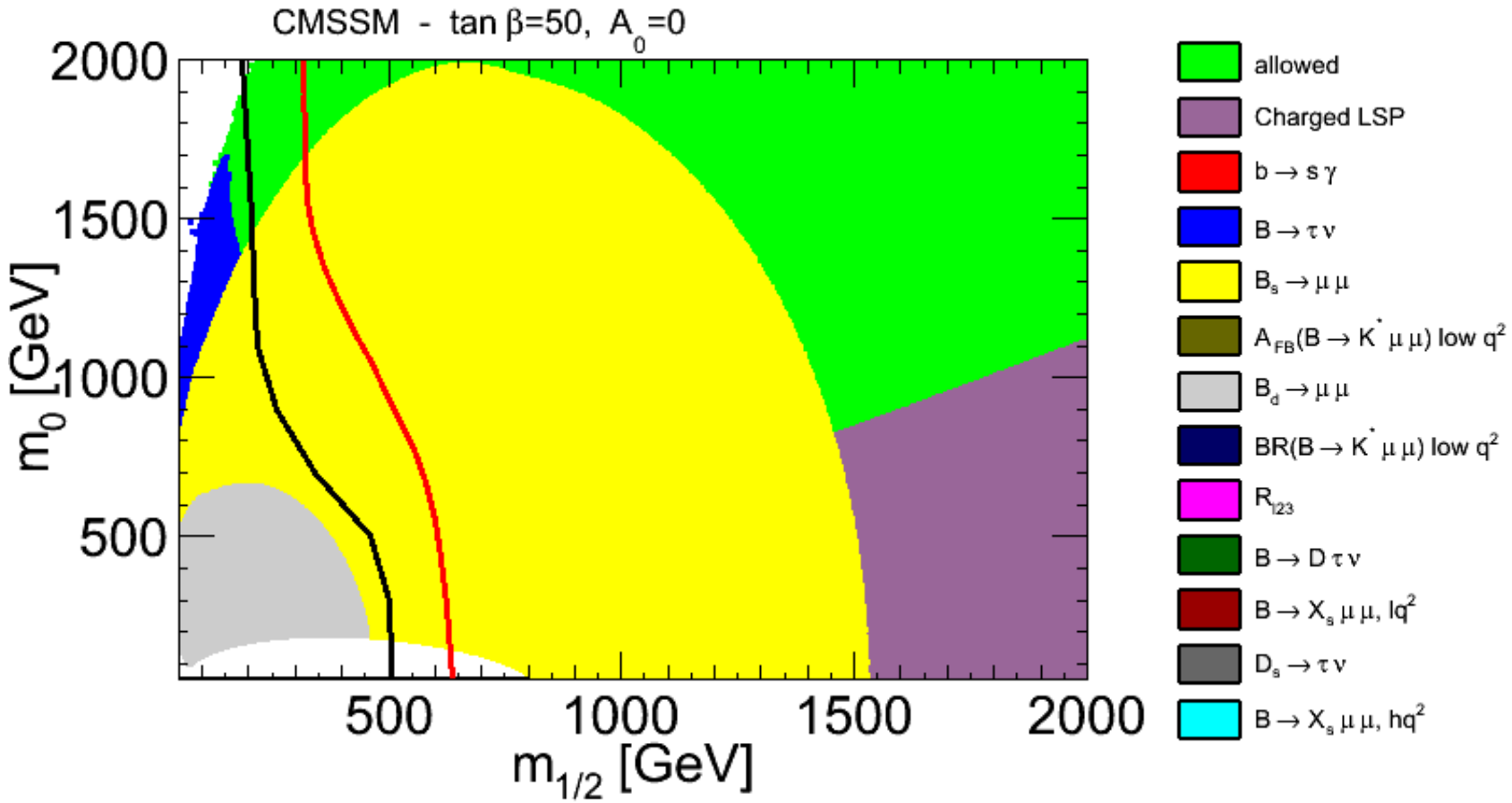


$$\propto \quad \frac{\tan^3\beta}{m^2_{A^0}} \,.$$

[Choudhury & Gaur, hep-ph/9810307]

$B_s \to \mu^+ \mu^-$ in CMSSM

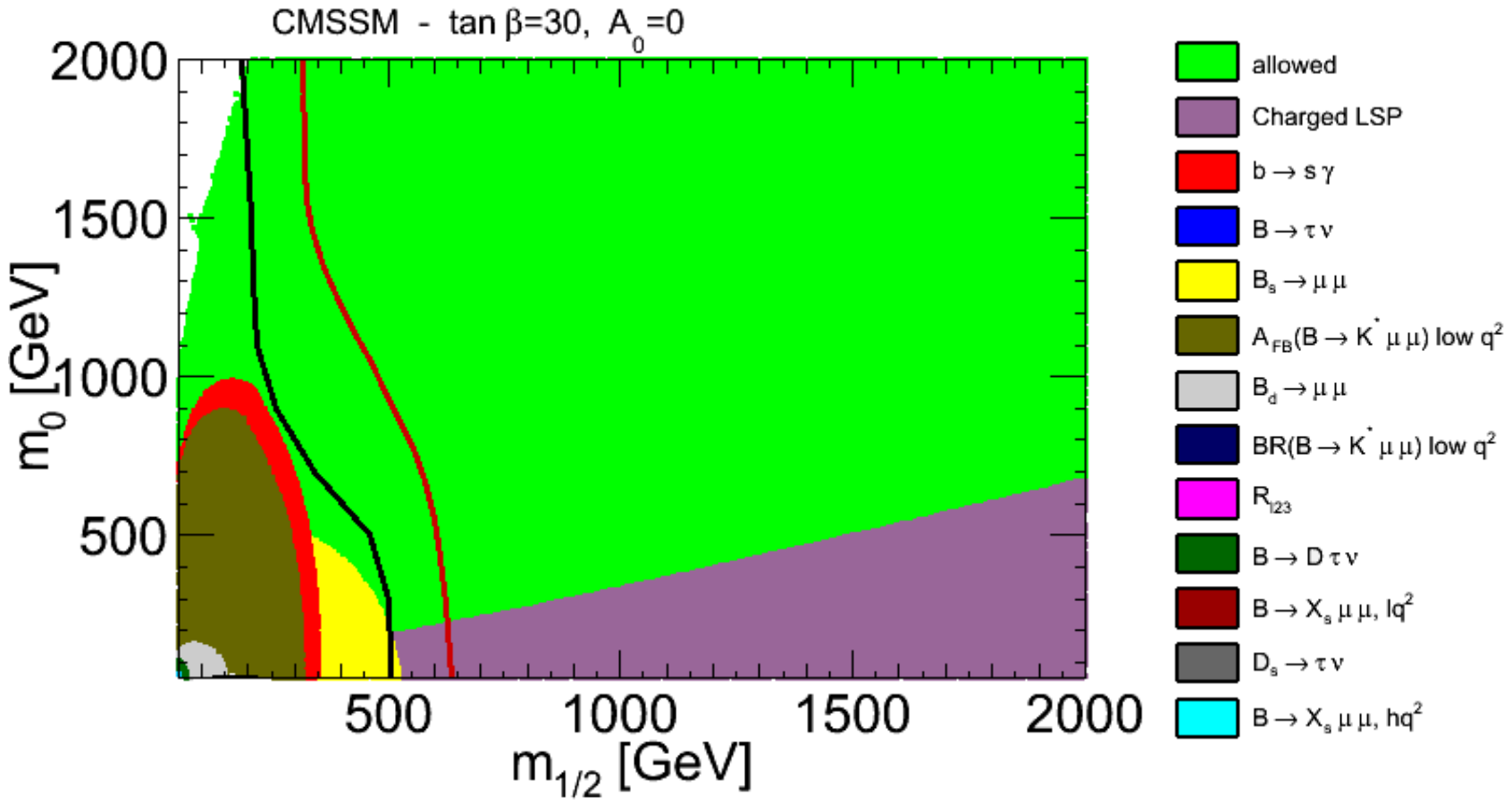
$\tan\beta = 50$ [Mahmoudi, arXiv:1205.3099]



Lines: CMS exclusion limit with 4.4 (1.1) fb^{-1} data.

$B_s \to \mu^+ \mu^-$ in CMSSM

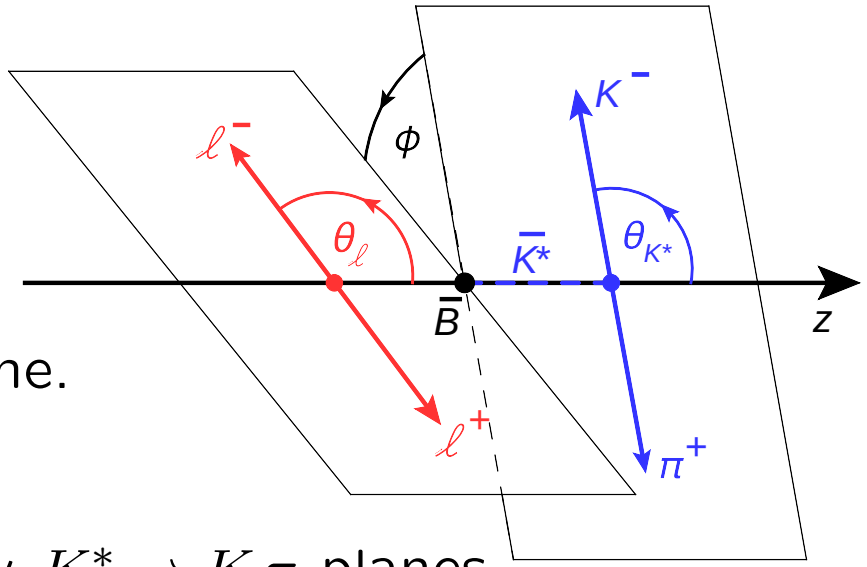
$\tan\beta = 30$ [Mahmoudi, arXiv:1205.3099]



Lines: CMS exclusion limit with 4.4 (1.1) fb^{-1} data.

$B \to K^*(\to K\,\pi)\,\mu^+\,\mu^-$

Kinematical variables:



- q^2: $(\ell^+\ell^-)$ invariant mass^2.
- θ_ℓ: lepton angle in $\ell^+\,\ell^-$ CM frame.
- θ_K: K angle in K^* rest frame.
- ϕ: angle between $B \to K^*\,\ell^+\,\ell^-$ & $K^* \to K\,\pi$ planes.

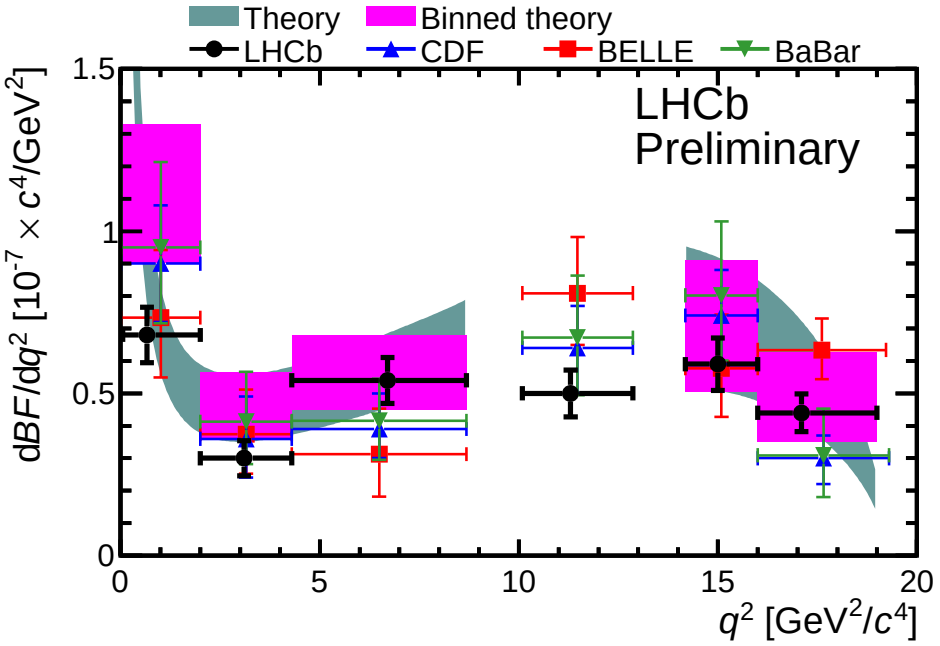
Angular distributions

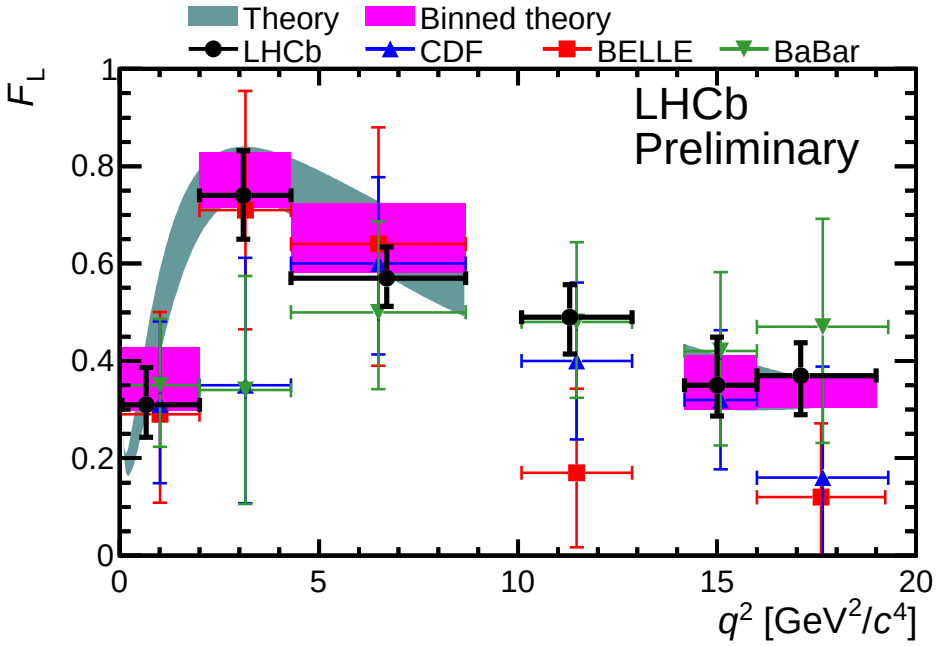
$$\frac{1}{(d\Gamma/dq^2)}\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = \frac{3}{4}F_L\sin^2\theta_\ell + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{\rm FB}\cos\theta_\ell\,,$$

$$\frac{1}{(d\Gamma/dq^2)}\frac{d^2\Gamma}{dq^2 d\cos\theta_K} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)\sin^2\theta_K\,.$$

- $A_{\rm FB}$: forward-backward asymmetry.
- F_L: longitudinal fraction of K^*.

$B \to K^*(\to K\,\pi)\,\mu^+\,\mu^-$: $d\,\mathrm{B}\,/dq^2$ and F_L



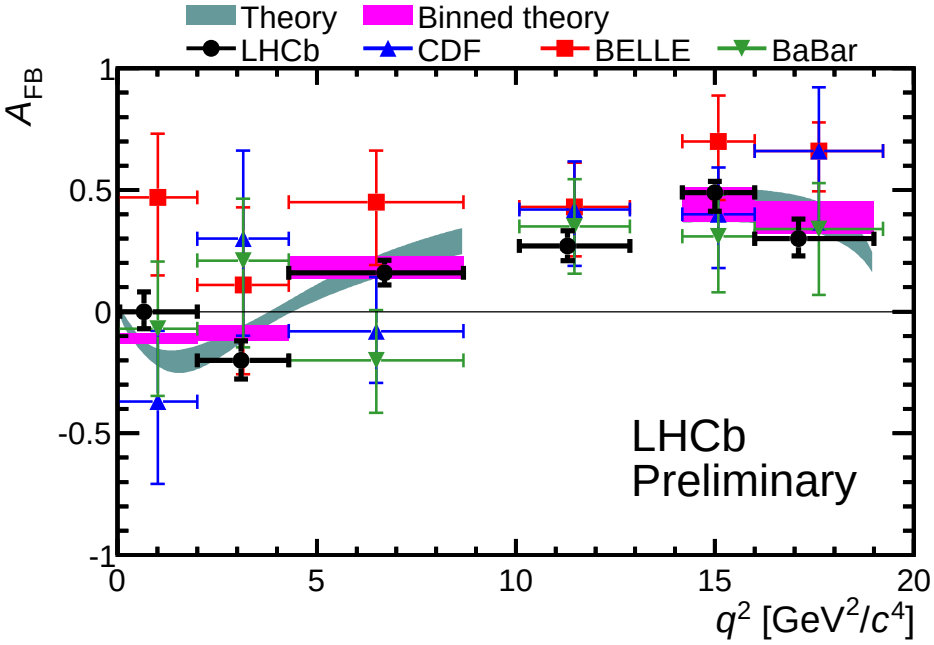


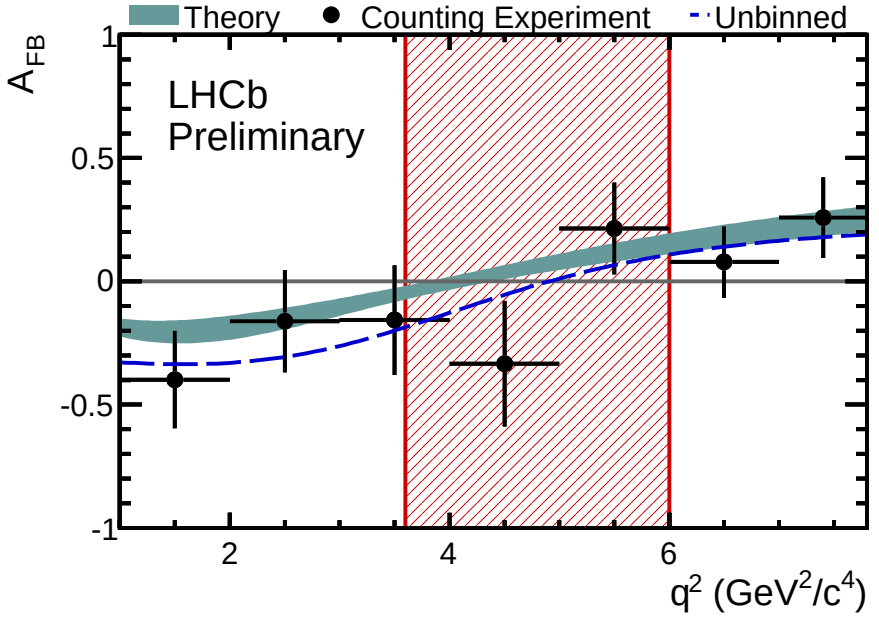
[LHCb-CONF-2012-008] [Belle, arXiv:0904.0770] [BaBar, arXiv:1204.3933]
[CDF, arXiv:1108.0695] [Bobeth *et al.*, arXiv:1105.0379]

- Main theoretical uncertainty: $B \to K^*$ form factors.
- $q^2 \approx m^2_{J/\psi,\psi'}$: $B \to K^*\{J/\psi,\,\psi'\}(\to \mu^+\,\mu^-)$ dominate.

$B \to K^*(\to K\,\pi)\,\mu^+\,\mu^-$: $A_{\rm FB}$

- $A_{\rm FB} \sim C_{10}(q^2 C_9 + 2 m_b^2 C_7)$
  - ▷ "C_9" and "C_7": opposite sign in SM $\Rightarrow$ $A_{\rm FB}$ crosses zero.
  - ▷ Hadronic uncertainty of zero-crossing point q_0^2 small.
  - ▷ LHCb observed the zero-crossing: $q_0^2 = 4.9^{+1.1}_{-1.3}$ GeV^2.

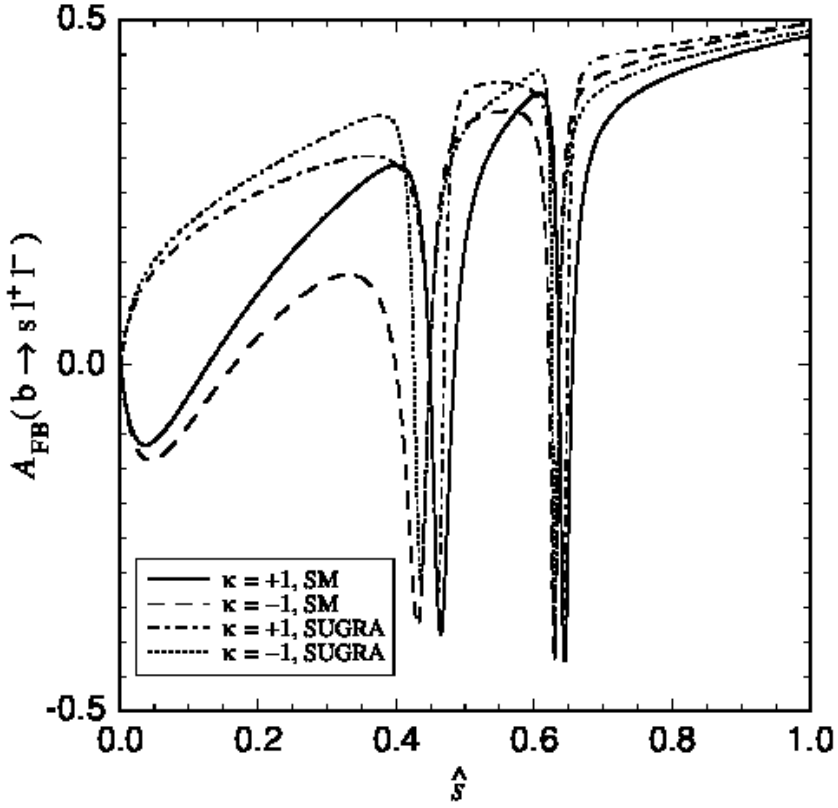




[LHCb-CONF-2012-008]

$B \to K^*(\to K\,\pi)\,\mu^+\,\mu^-$: $A_{\rm FB}$

Zero-crossing of $A_{\rm FB}$ kills the possibility $C_7 = C_7^{\rm SM} + C_7^{\rm NP} = -C_7^{\rm SM}$ (occurs in certain parameter region in mSUGRA).

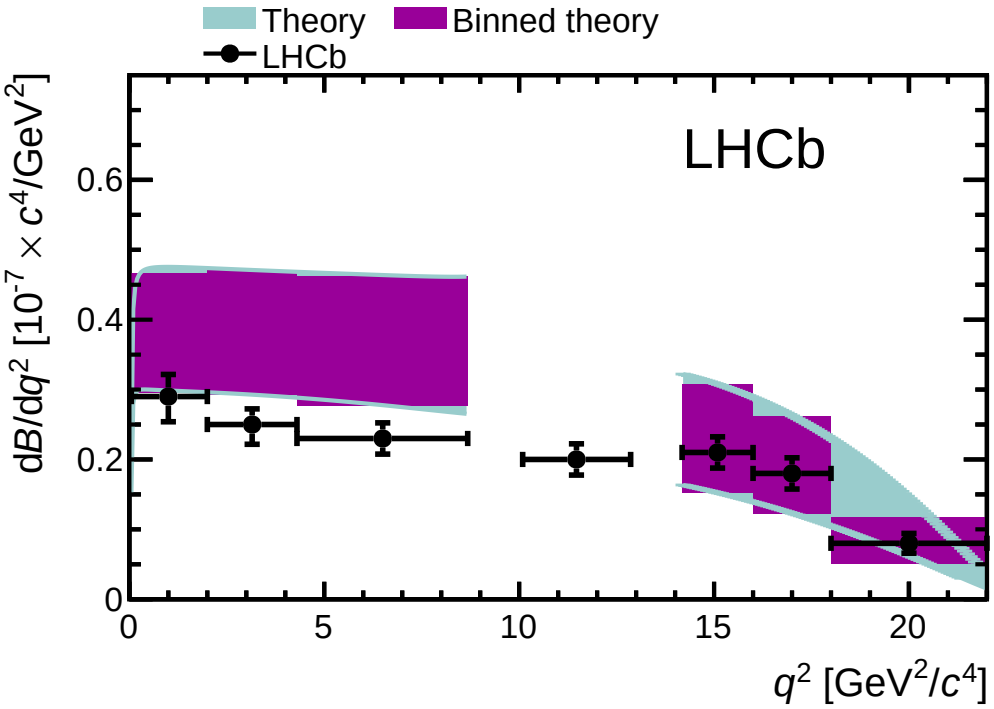


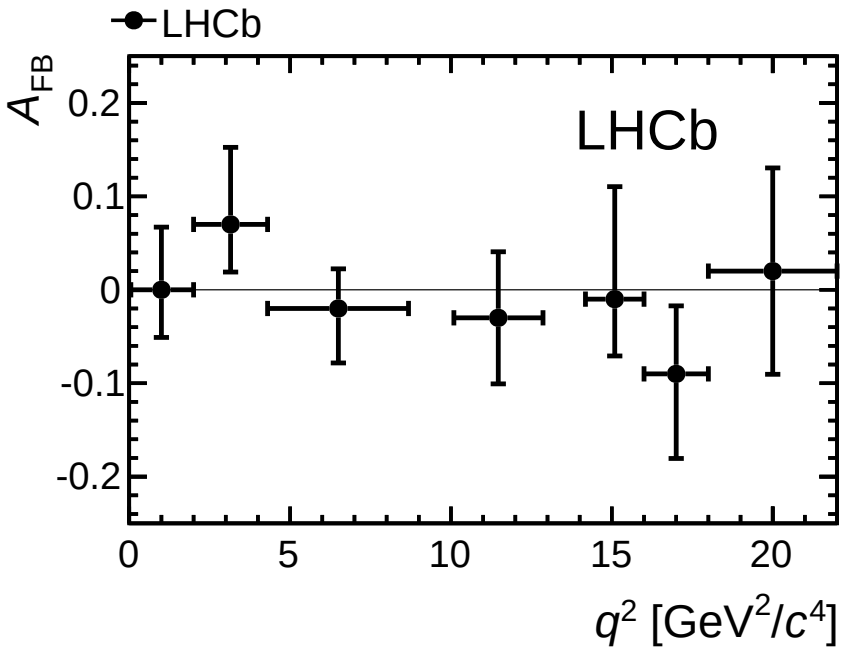
[Goto *et al.*, hep-ph/9609512]

$B \to K \mu^+ \mu^-$

$$\frac{1}{(d\Gamma/dq^2)}\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = \frac{3}{4}(1 - F_H)\sin^2\theta_\ell + \frac{1}{2}F_H + A_{\rm FB}\cos\theta_\ell\,.$$

- $A_{\rm FB} = 0$ in SM.

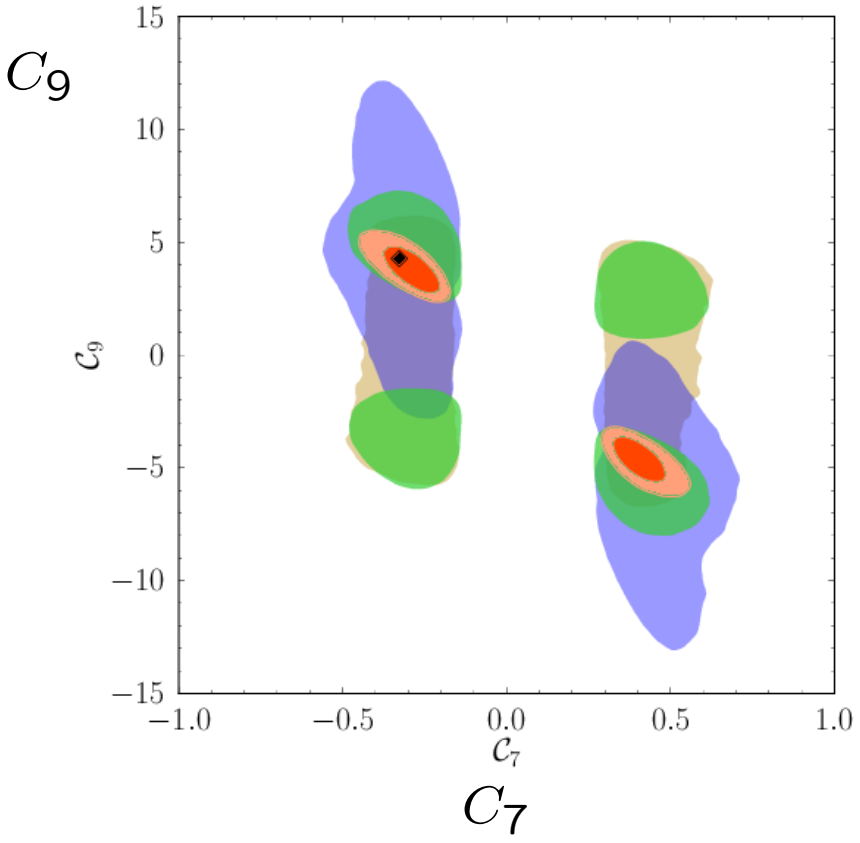




[LHCb, arXiv:1209.4284] [Bobeth *et al.*, arXiv:1111.2558]

Fit with $C_{7,9,10}$

Combined fit with $B_s \to \mu^+ \mu^-$, $B \to K^* \ell^+ \ell^-$, $B \to K \ell^+ \ell^-$, $B \to K^* \gamma$:

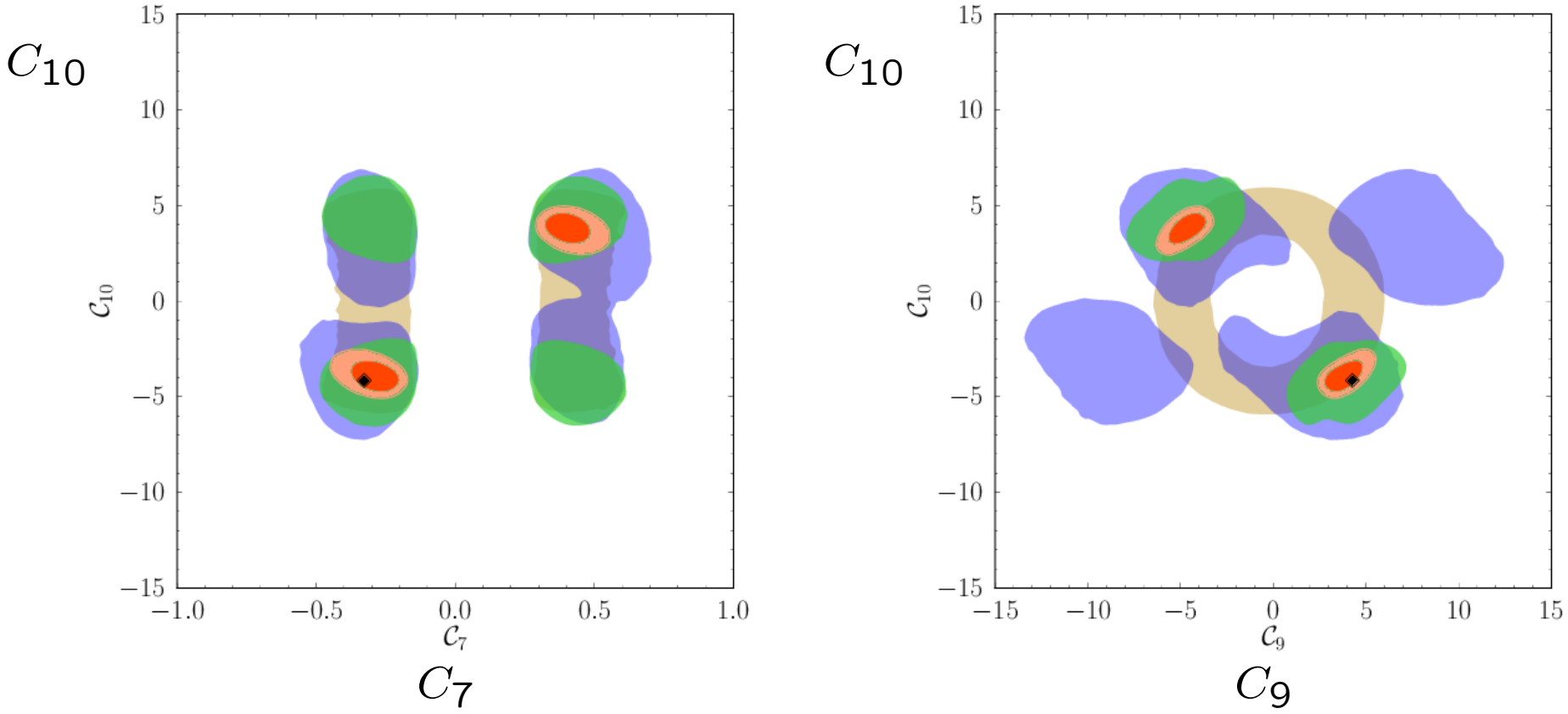


- $B \to K^* \gamma$ & $B \to K \ell^+ \ell^-$
- $B \to K^* \gamma$ & $B \to K^* \ell^+ \ell^-$(low-q^2)
- $B \to K^* \gamma$ & $B \to K^* \ell^+ \ell^-$(high-q^2)
- All (68%), (95%)

[Beaujean *et al.*, arXiv:1205.1838]

Fit with $C_{7,9,10}$

Combined fit with $B \to K^* \gamma$, $B \to K \ell^+ \ell^-$, $B \to K^* \ell^+ \ell^-$, $B_s \to \mu^+ \mu^-$:

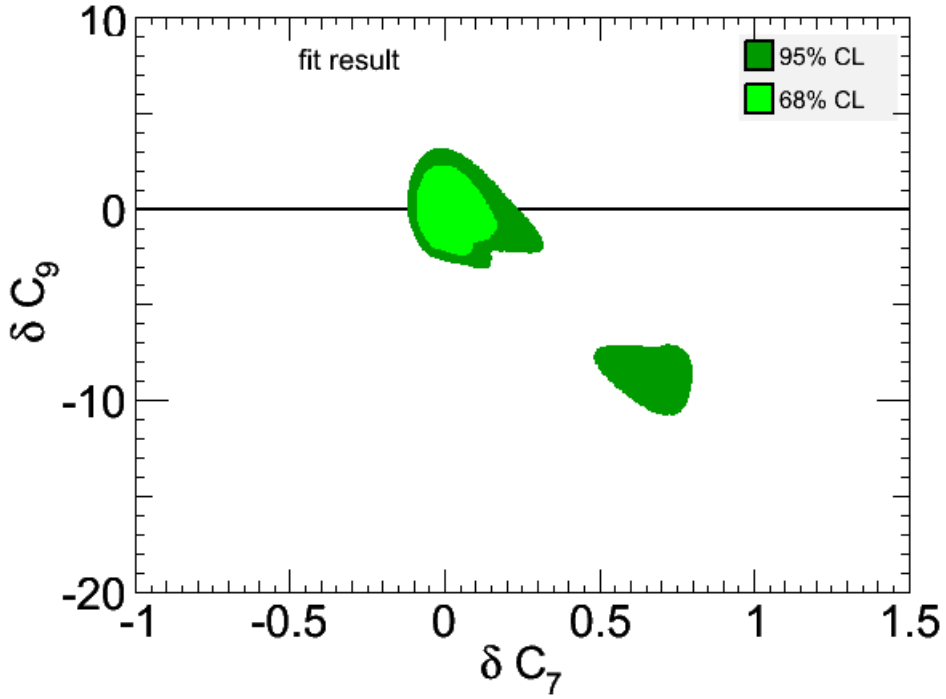


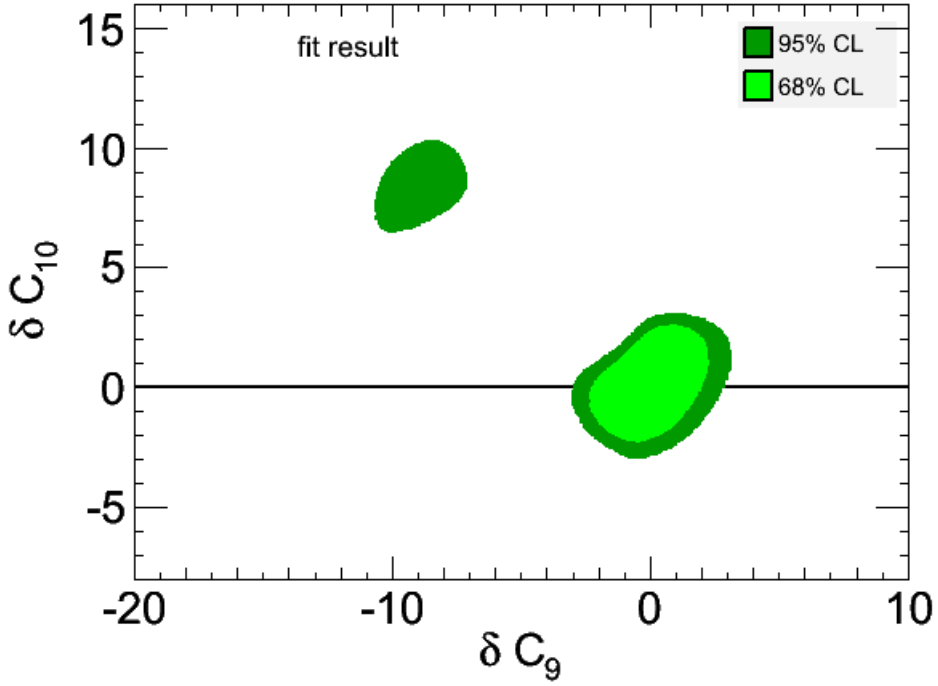
[Beaujean *et al.*, arXiv:1205.1838]

$$C_7^{\rm SM} \approx -0.3, \qquad C_9^{\rm SM} \approx 4.2, \qquad C_{10}^{\rm SM} \approx -4.2.$$

Two-fold: $(C_7^{\rm SM}, C_9^{\rm SM}\, C_{10}^{\rm SM}\ )$ or $(-C_7^{\rm SM}, -C_9^{\rm SM} - C_{10}^{\rm SM}\ )$ favored.

Fit with $C_{7,9,10}$





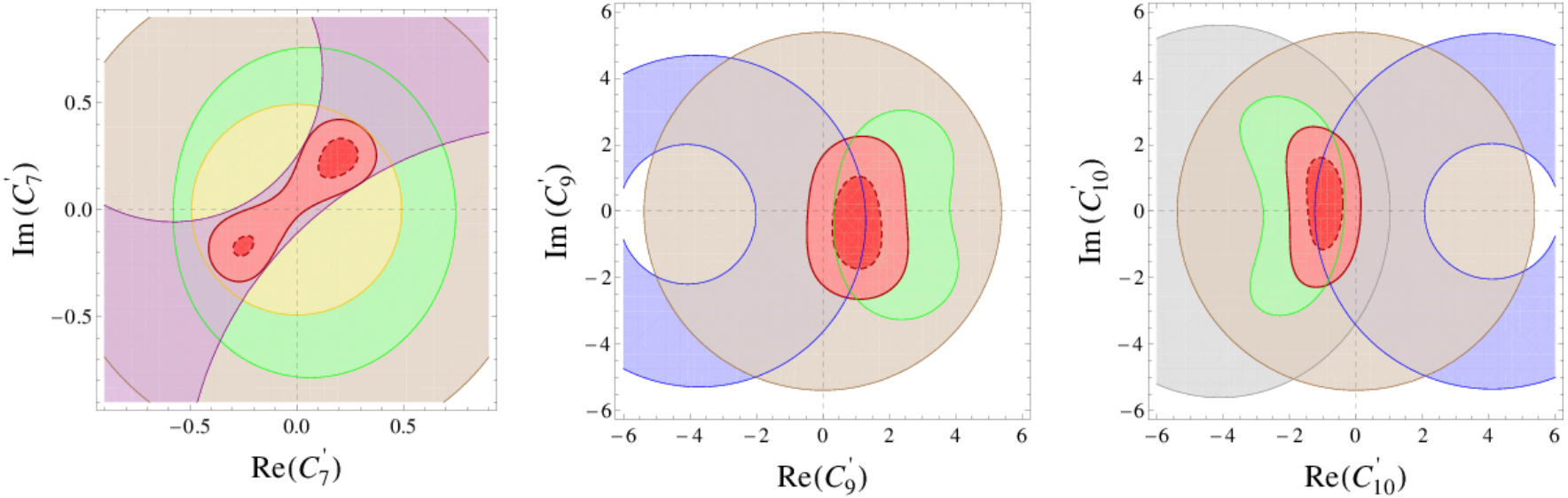
[Hurth & Mahmoudi, arXiv:1211.6453]

$$\delta C_i = C_i - C_i^{\rm SM}, \qquad C_7^{\rm SM} \approx -0.3, \qquad C_9^{\rm SM} \approx 4.2, \qquad C_{10}^{\rm SM} \approx -4.2.$$

Constraints on NP contributions

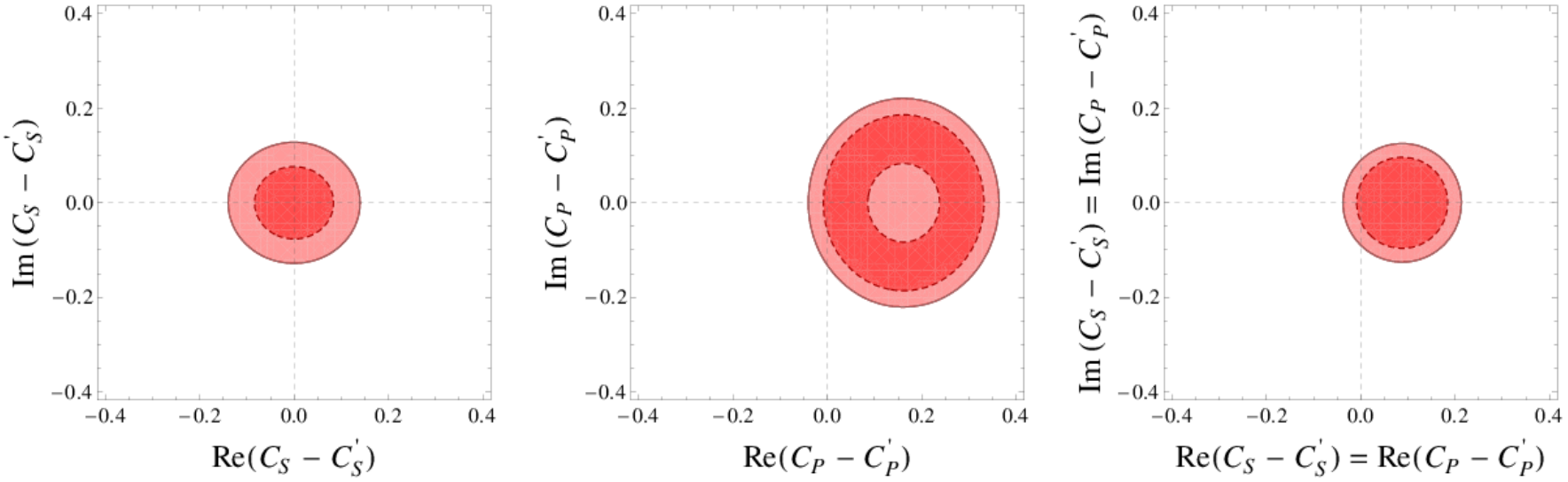
NP operators: chirality flipped & (pseudo-)scalars

$$\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$
$$\mathcal{O}_7' = m_b(\bar{s}\sigma^{\mu\nu} P_L b)F_{\mu\nu}\,,$$
$$\mathcal{O}_S^{(\prime)} = \frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\ell)\,, \qquad \mathcal{O}_P^{(\prime)} = \frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)\,.$$



[Altmannshofer & Straub, arXiv:1206.0273]

Constraints on NP contributions

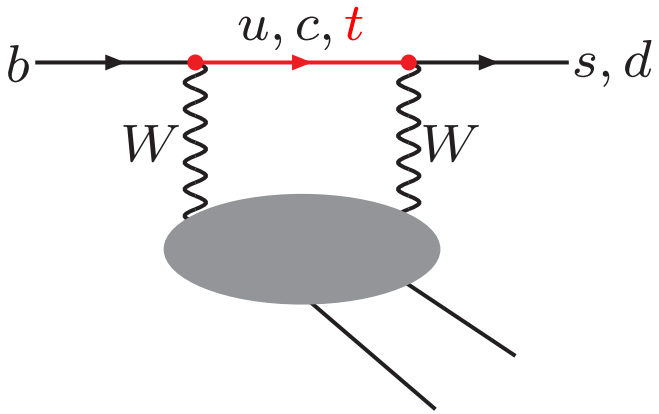


$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\sum_i \left(\frac{c_i}{\Lambda^2}\mathcal{O}_i + \frac{c_i'}{\Lambda^2}\mathcal{O}_i' \right) + \text{H. c.} \quad \Rightarrow \quad \left| \frac{c_i^{(\prime)}}{\Lambda^2} \right| \lesssim \left(\frac{1}{20 - 200\,\text{TeV}} \right)^2 .$$

[Altmannshofer & Straub, arXiv:1206.0273]

SM: $\dfrac{4G_F}{\sqrt{2}} \dfrac{\alpha_{\text{em}}}{4\pi} V_{ts}^* V_{tb} C_i \approx \left(\dfrac{1}{35\,\text{TeV}} \right)^2 O(1) \Leftarrow$ (weak)$\otimes$(EWloop)$\otimes$(CKM).

$b \to d$ vs. $b \to s$



$$= V_{tq}^* V_{tb} \left[f(\frac{m_t^2}{m_W^2}) - f(\frac{m_u^2}{m_W^2}) \right]$$
$$+ V_{cq}^* V_{cb} \left[f(\frac{m_c^2}{m_W^2}) - f(\frac{m_u^2}{m_W^2}) \right] .$$
$$(q = s,\, d)$$

$\frac{m_t^2}{m_W^2} \gtrsim 1 \gg \frac{m_{u,c}^2}{m_W^2}$, $\left|V_{tq}^* V_{tb}\right| \sim \left|V_{cq}^* V_{cb}\right| \quad \Rightarrow \quad V_{tq}^* V_{tb}$ term dominates.

$$\frac{\text{Amp}(b \to d)}{\text{Amp}(b \to s)} = \frac{V_{td}}{V_{ts}} \otimes (\text{SU(3) (U-spin) breaking}) .$$

$$\left|\frac{V_{td}}{V_{ts}}\right| \approx 0.213 \ (\sim 5\% \text{ unc.}) \quad [\text{CKMfitter, 2012}] .$$

$b \to d$ vs. $b \to s$

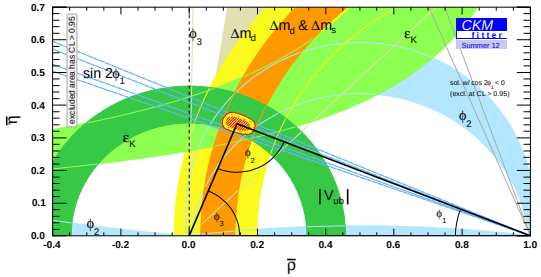
- $B^0 - \overline{B}^0$ mixings

$$\Delta m_d = 0.507 \pm 0.004\,\text{ps}^{-1}$$

[HFAG: ALEPH,DELPHI,L3,OPAL,CDF,D0,BaBar,Belle,LHCb]

$$\Delta m_s = 17.719 \pm 0.043\,\text{ps}^{-1}$$ [HFAG: CDF,LHCb]

$$\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}} = 1.237 \pm 0.032\,,$$



[http://latticeaverages.org/]

- $b \to d\,\gamma$ ($B \to \{\rho, \omega\}\,\gamma$) vs. $b \to s\,\gamma$ ($B \to K^*\,\gamma$)

$$\left|\frac{V_{td}}{V_{ts}}\right| = \begin{cases} 0.195^{+0.020}_{-0.019}(\text{exp.}) \pm 0.015(\text{th.}) & \text{excl.} \\ 0.199 \pm 0.022(\text{stat.}) \pm 0.024(\text{syst.}) \pm 0.002(\text{th.}) & \text{incl.} \end{cases}$$

[excl.: Belle, arXiv:0804.4770] [incl.: BaBar, arXiv:1005.4087]

$b \to d$ vs. $b \to s$

Newcomer: $b \to d\,\ell^+\,\ell^-$

First observation of $B^+ \to \pi^+\,\mu^+\,\mu^-$ [LHCb, arXiv:1210.2645]:

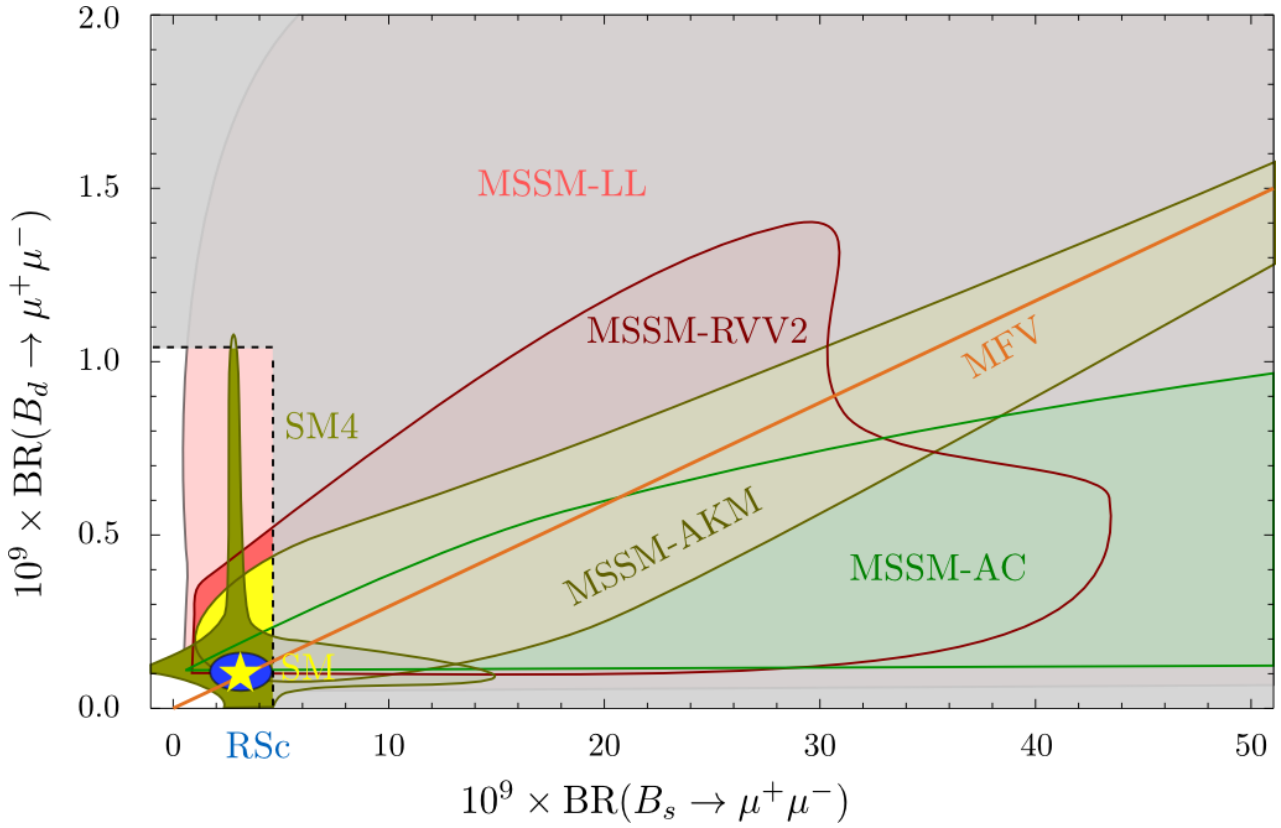
$$\mathrm{B}(B^+ \to \pi^+\,\mu^+\,\mu^-) \;=\; (2.3 \pm 0.6 \pm 0.1) \times 10^{-8}\,.$$

Combined with $B \to K\,\mu^+\,\mu^-$ measurement,

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.266 \pm 0.035(\text{stat.}) \pm 0.003(\text{syst.})\,.$$

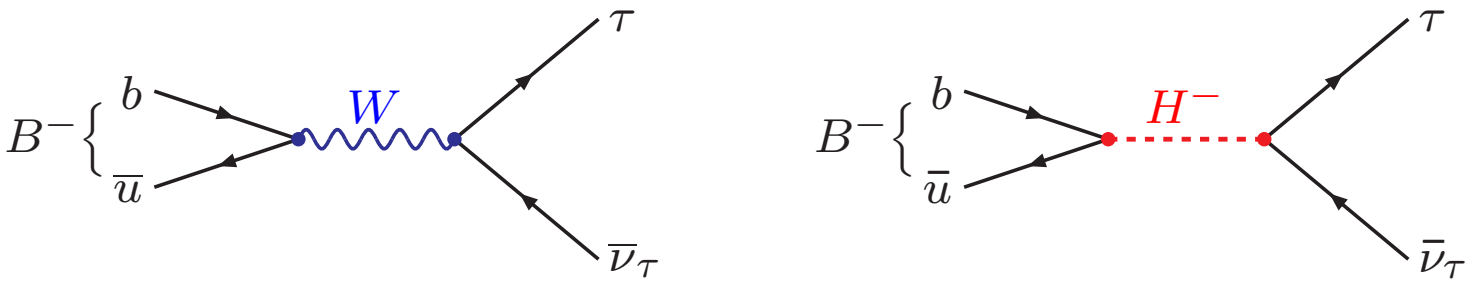
$B_s \to \mu^+ \mu^-$ vs. $B_d \to \mu^+ \mu^-$

$\mathrm{B}(B_d \to \mu^+ \mu^-) < 9.4 \times 10^{-10}$ (95%CL) [LHCb, arXiv:1211.2674]
$\mathrm{B}^{\mathrm{SM}} = (1.07 \pm 0.10) \times 10^{-10}$ [Buras *et al.*, 1208.0934]



[Straub, arXiv:1205.6094]

$B^- \to \tau^- \bar{\nu}$



$$\mathrm{B}(B^- \to \tau^- \bar{\nu})_{\mathrm{SM}} = \frac{G_F^2 m_B^3 \tau_B}{8\pi} f_B^2 |V_{ub}|^2 \frac{m_\tau^2}{m_B^2} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 ,$$

- $|V_{ub}|$: semileptonic $b \to u\,\ell^-\,\nu$, global CKM fit
- $f_B = (190.6 \pm 4.7)$ MeV [http://latticeaverages.org/]

$$\mathrm{B}(B^- \to \tau^- \bar{\nu})_{\mathrm{2HDM-II}} = \mathrm{B}(B^- \to \tau^- \bar{\nu})_{\mathrm{SM}} \left(1 - \frac{m_B^2}{m_{H^-}^2} \tan^2\beta\right)^2 .$$

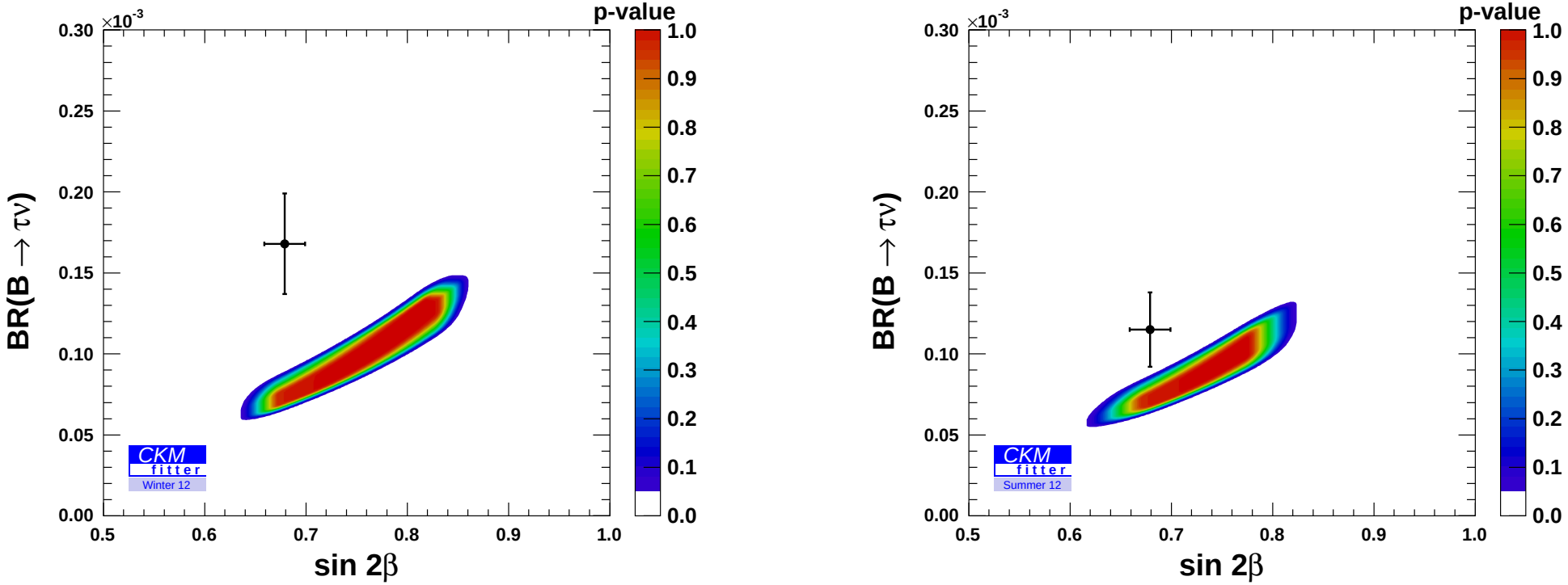
$\mathrm{B}_{\mathrm{exp}} = \mathrm{B}_{\mathrm{SM}} \quad \Rightarrow \quad \frac{m_B^2}{m_{H^-}^2} \tan^2\beta = 0$ or 2.

$B^- \to \tau^- \bar{\nu}$

New result: $\mathrm{B}(B^- \to \tau^- \bar{\nu}) = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$ [Belle, arXiv:1208.4678].

- WA: $(1.14 \pm 0.23) \times 10^{-4}$ [Nakao, ICHEP2012] $\Rightarrow$ "tension" reduced.

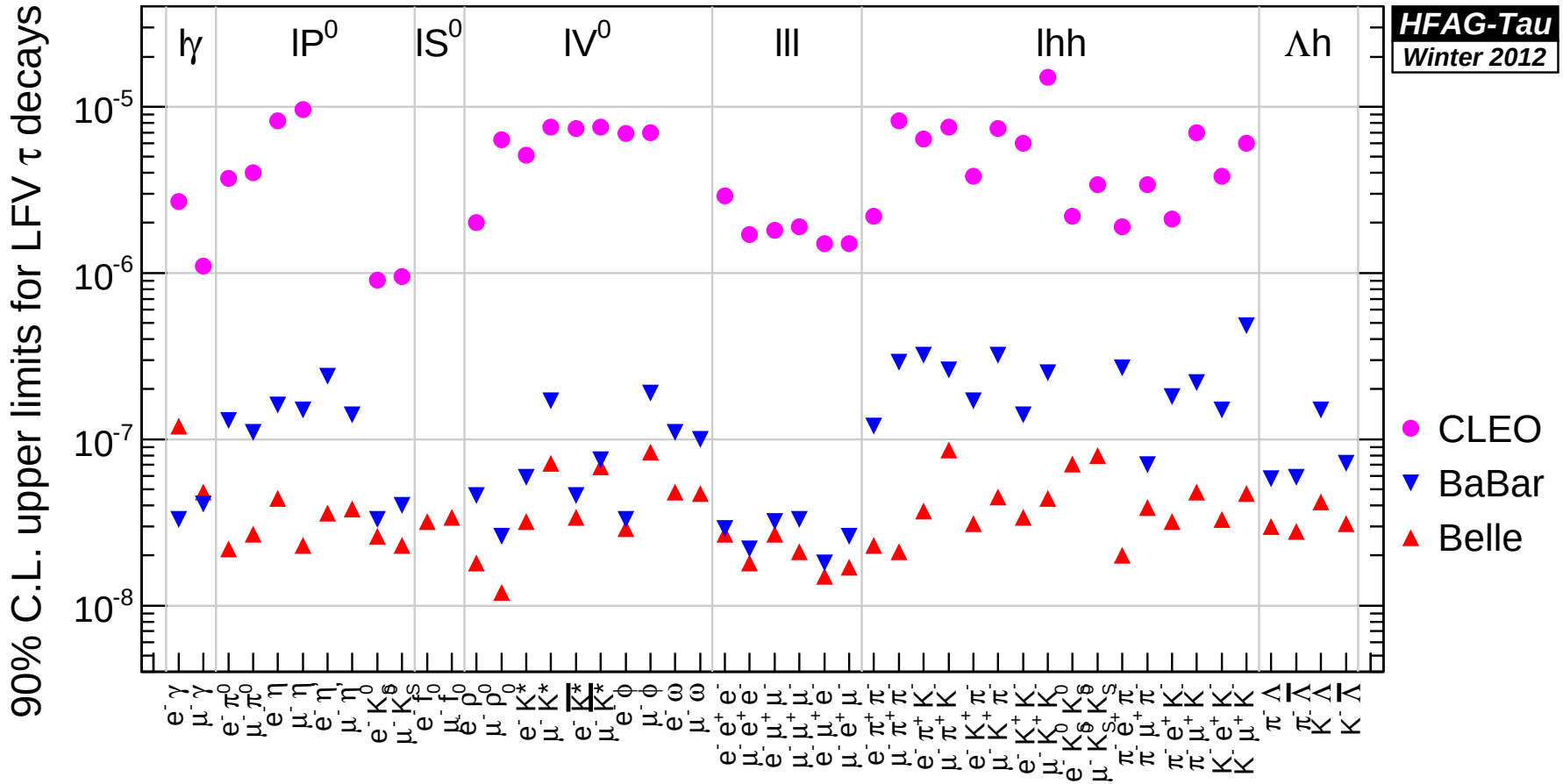
Winter 2012 $\Rightarrow$ Summer 2012



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

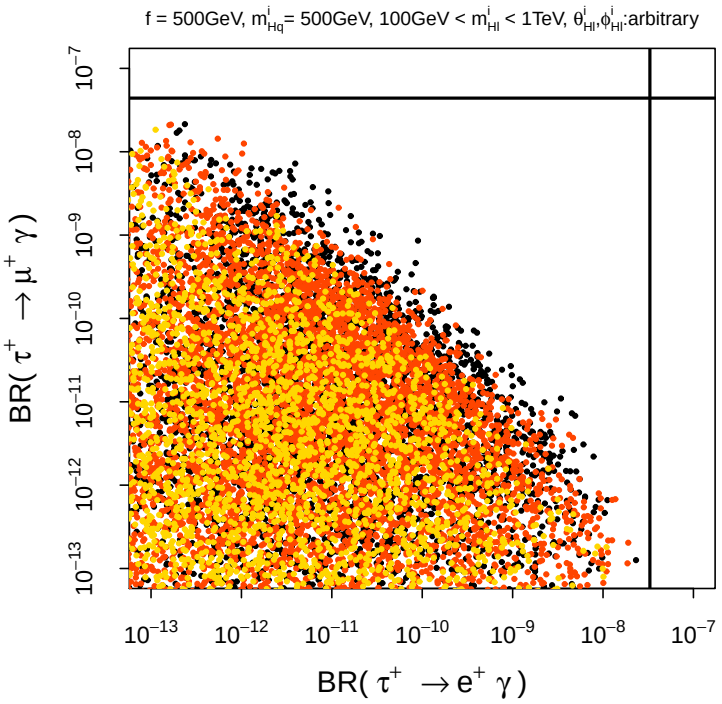
Ask R. Watanabe!

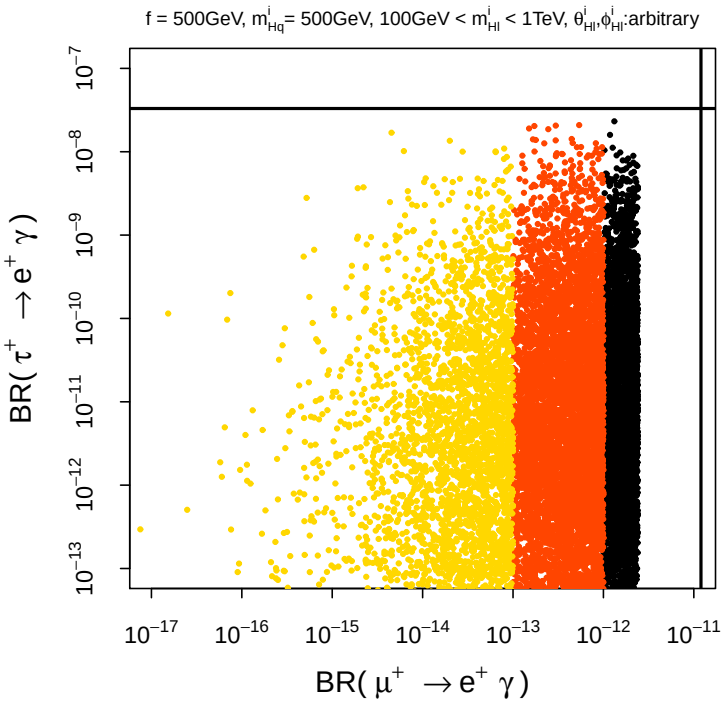
τ LFV



[HFAG, arXiv:1207.1158]

τ LFV in LHT





[Goto *et al.*, arXiv:1012.4385]

$$\mathrm{B}(\mu \to e\,\gamma) < \begin{cases} 2.4 \times 10^{-12} & \text{[MEG, arXiv:1107.5547]} \\ 10^{-12} & \\ 10^{-13} & \end{cases}$$

Summary

Recent measurements (on b physics) are consistent with SM in general.

- Large ($> O(1)$) deviations are unlikely.
- $O(10\%)$ NP contributions are still allowed.

There are some deviations of 3σ level.

- $B \to D^{(*)} \tau \nu$,
- a_{sl},
  $\cdots$

Wait for more precise measurements by the next flavor factory experiments (Belle-II, LHCb, $\cdots$).

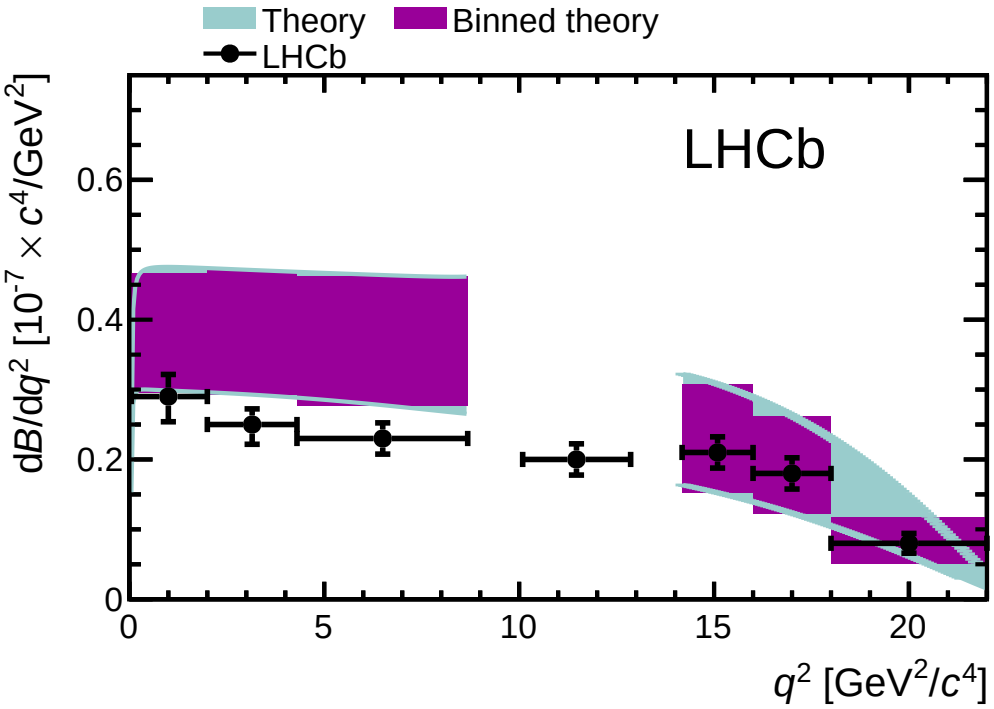

2nd KEK Flavor Factory Workshop
(KEK-FF 2013)
B
D
τ
K
Sharing the understanding and exchanging ideas among theorists and experimentalists on quark-flavor physics of K, D and B mesons and the physics of lepton-flavor violation of muons and tau leptons
Invited speakers:
A. Bevan (Queen Mary, U. of London),
A. Bozek (IFJ Krakow), G. Buchalla (LMU Munich),
M. Ciuchini (INFN Rome), J. Flynn (Southampton U.),
Z. Ligeti (LBL), T. Mannel (U. of Siegen), S. Mihara (KEK),
T. Moroi (U. of Tokyo), C. Parkes (U. of Manchester),
G. Paz (Wayne State U.), C.P. Shen (Nagoya U.),
J. Zupan (U. of Cincinnati), A. Zupanc (KIT)
Organizing Committee: B. Golob (Ljubljana U.),
T. Goto (KEK), S. Hashimoto (KEK),
K. Hayasaka (Nagoya U.), T. Mannel (U. of Siegen),
Y. Sakai (KEK), K. Trabelsi (KEK), Y. Ushiroda (KEK)
March 12th - 14th 2013, KEK, Tsukuba, Japan
http://kds.kek.jp/conferenceDisplay.py?confId=10415
email: kekff@bpost.kek.jp

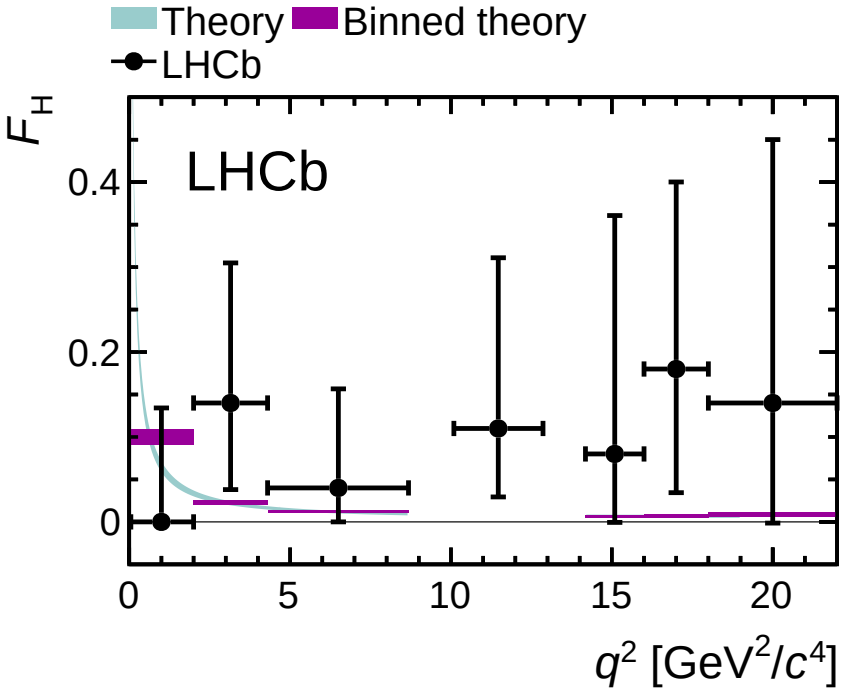
Backup Slides

$B \to K \mu^+ \mu^-$

$$\frac{1}{(d\Gamma/dq^2)}\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = \frac{3}{4}(1 - F_H)\sin^2\theta_\ell + \frac{1}{2}F_H + A_{\rm FB}\cos\theta_\ell\,.$$

- $A_{\rm FB} = 0$ in SM.





[LHCb, arXiv:1209.4284] [Bobeth *et al.*, arXiv:1111.2558]

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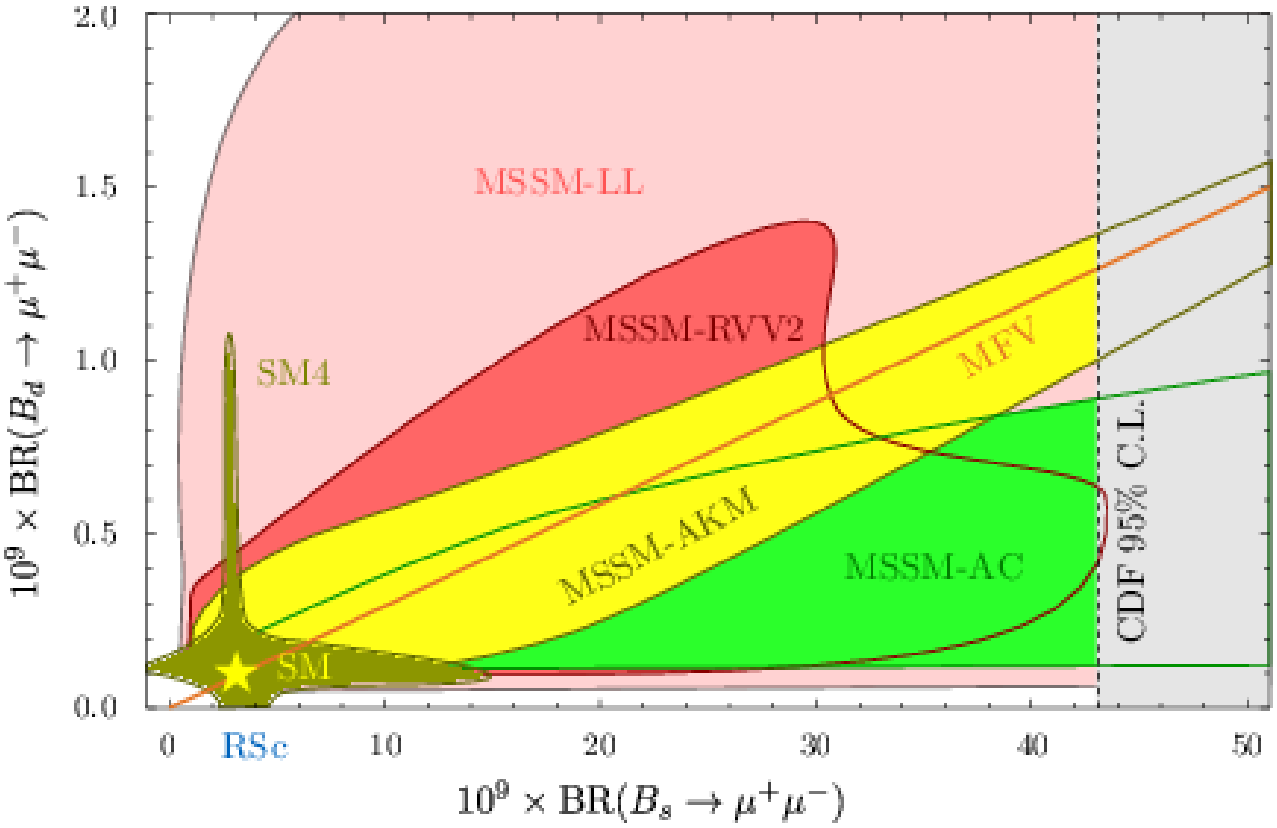

[Straub, arXiv:1205.6094]

τ LFV in LHT