

B の物理の現状と展望

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Introduction

近年の B 物理の実験 \Rightarrow 豊富なデータ

- e^+e^- B ファクトリー実験: $B^{\pm,0}$

- ▷ Belle @KEKB (KEK, 1999-2010) $\sim 711 \text{ fb}^{-1}$ @ $\Upsilon(4S)$

- * $\sim 772\text{M } B\bar{B}$ pairs.

- ▷ BaBar @PEP-II (SLAC, 1999-2008) $\sim 433 \text{ fb}^{-1}$ @ $\Upsilon(4S)$

\Rightarrow Belle II @SuperKEKB (KEK, 2017?-)

- * $\mathcal{L} = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (KEKBの40倍) $\rightarrow 7 \text{ ab}^{-1}/100\text{days}$.

- ハドロンコライダー実験: $B^{\pm,0}$, B_s , 他の b ハドロン

- ▷ CDF & D0@TeVatron (FNAL, RUN2: 2001-2011) $\sim 12 \text{ fb}^{-1}$
@1.96TeV $p\bar{p}$ per exp.

- ▷ LHCb @LHC (CERN, 2010-2012) $\sim 1.2 \text{ fb}^{-1}$ @7TeV + 1.5 fb^{-1}
@8TeV pp

\Rightarrow 2015: 13TeVで再開

Introduction

目的・動機 = 標準模型を超える新物理の探索。

- 測定結果は標準模型とどれくらい合うか？

以下、

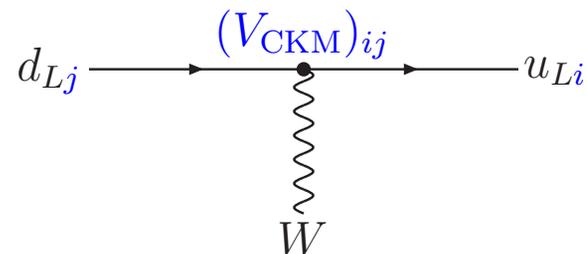
- Unitarity Triangle
- $b \rightarrow s l^+ l^-$, $b \rightarrow s \gamma$
- $b \rightarrow c$ & $b \rightarrow u$ semileptonic decays

を紹介。

Unitarity Triangle

標準模型では、(クォーク) フレイバー混合と CP の破れは Cabibbo-Kobayashi-Maskawa 行列で記述される。

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



- 4パラメータのユニタリ行列: 混合角3個、複素位相1個。

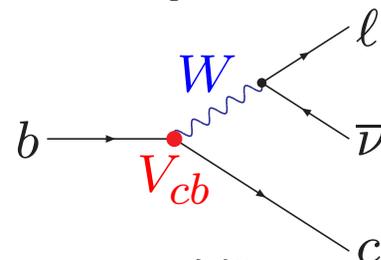
▷ $|V_{us}|$: $K \rightarrow \pi \ell \nu$ 等 $s \rightarrow u$

$$|V_{us}| = 0.2253 \pm 0.0008 \quad [\text{PDG2014}]$$

▷ $|V_{cb}|$: $b \rightarrow c \ell \nu$

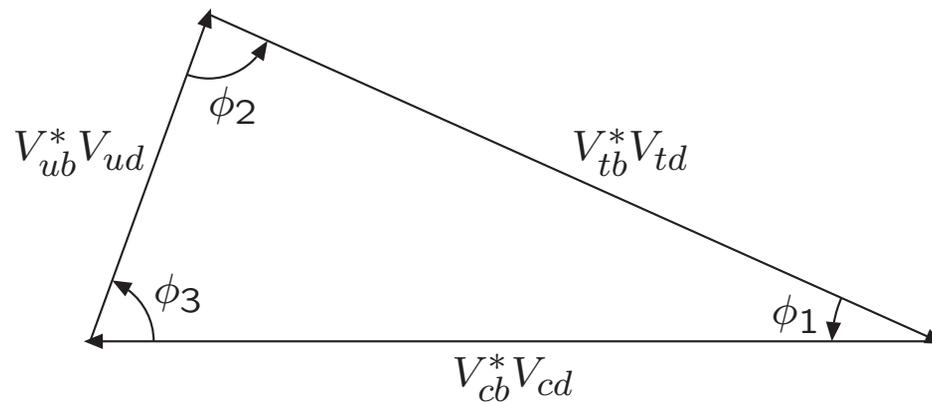
$$|V_{cb}| = (41.1 \pm 1.3) \times 10^{-3} \quad [\text{PDG2014}]$$

2個は精度がよい (ただし $|V_{cb}|$ は後で再考)。



Unitarity Triangle

ユニタリ性: $V_{ud}^*V_{ub} + V_{cd}^*V_{cb} + V_{td}^*V_{tb} = 0$ を複素平面上の三角形で表す ($b \leftrightarrow d$ unitarity triangle)。



Rephasing invariant な量 $\bar{\rho}$ 、 $\bar{\eta}$ を定義。

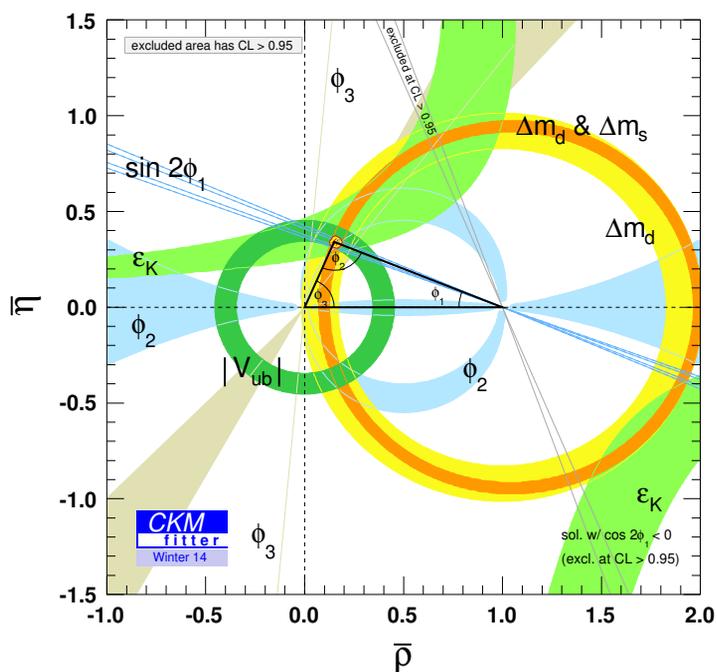
$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

(Wolfenstein parametrization の精密化)

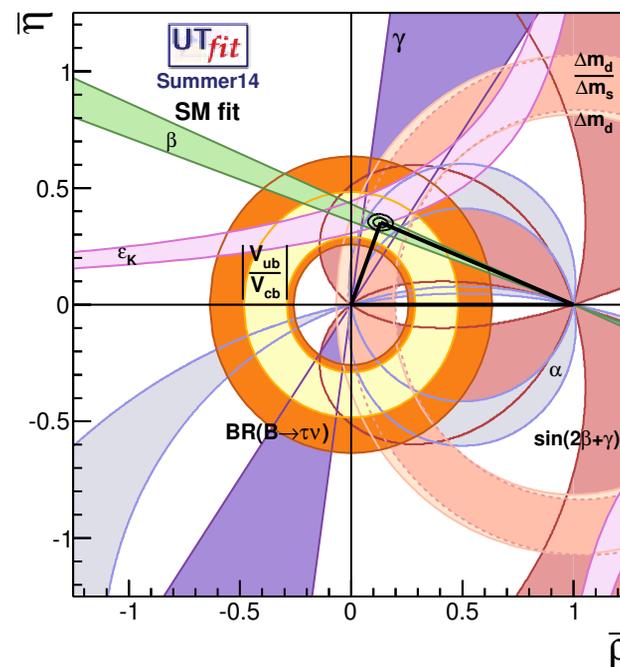
Unitarity Triangle

標準模型の検証: すべての観測量が同一の $(\bar{\rho}, \bar{\eta})$ で説明できるか?

- 不整合 \Rightarrow 新物理の寄与



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



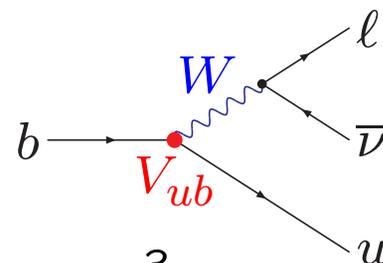
[UTfit <http://www.utfit.org/>]

Unitarity triangle: 辺

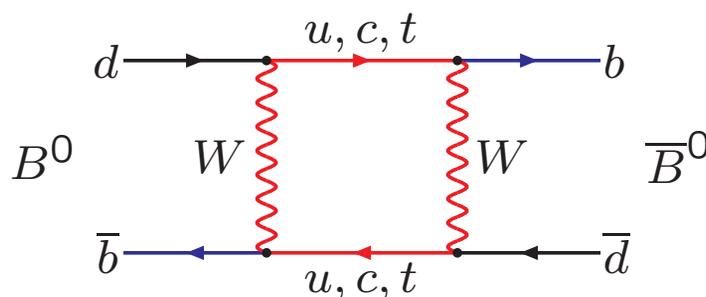
- $|V_{ub}|$: $b \rightarrow u \ell \bar{\nu}$, $B^-(b\bar{u}) \rightarrow \tau \bar{\nu}$

$$|V_{ub}| = (4.13 \pm 0.49) \times 10^{-3} \quad [\text{PDG2014}]$$

(後で再考)



- $|V_{td}|$: $B - \bar{B}$ 混合



$$\Delta m_B \propto |(V_{td}^* V_{tb})^2| \times F\left(\frac{m_t^2}{m_W^2}\right) \times \eta_{\text{QCD}} \times (\text{ハドロン行列要素})$$

$$\triangleright m_{u,c} \ll m_W \lesssim m_t$$

$$\triangleright \frac{\Delta m_B}{\Delta m_{B_s}} = \left| \frac{V_{td}}{V_{ts}} \right|^2 \times (\text{SU(3) breaking}) \text{ で更に高精度}$$

Unitarity triangle: ϕ_1, ϕ_2

Time-dependent CP asymmetries で測る。



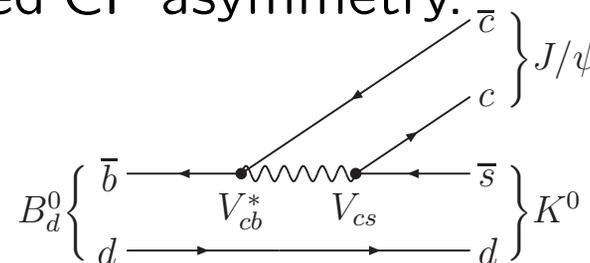
$$\frac{\Gamma(\bar{B}^0(t) \rightarrow f_{CP}) - \Gamma(B^0(t) \rightarrow f_{CP})}{\Gamma(\bar{B}^0(t) \rightarrow f_{CP}) + \Gamma(B^0(t) \rightarrow f_{CP})} \quad (f_{CP}: \text{CP固有状態})$$

$$= A_{CP}(f) \cos |\Delta M_B| t + S_{CP}(f) \sin |\Delta M_B| t.$$

$A_{CP}(f)$: direct CP asymmetry; $S_{CP}(f)$: mixing-induced CP asymmetry.

- 終状態の選び方でCKM行列要素の組み合わせが決まる。

$$\triangleright f_{CP} = J/\psi K_S (b \rightarrow c \bar{c} s) \Rightarrow \phi_1$$

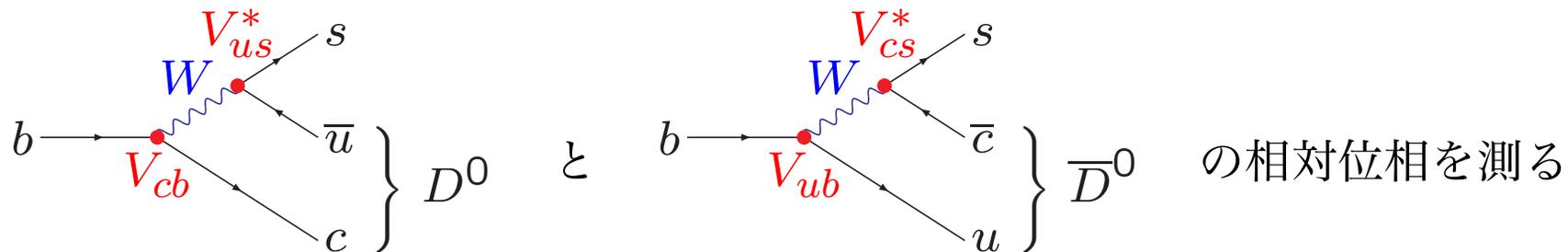
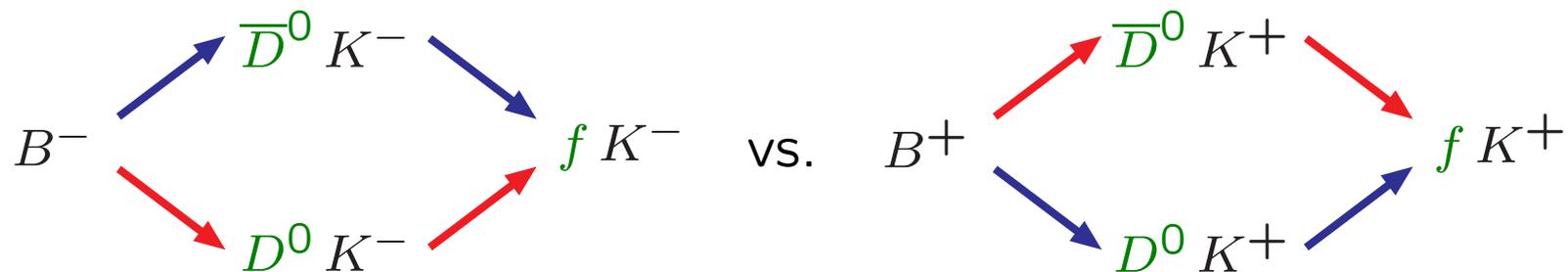


$$S_{CP}(J/\psi K_S) = -\text{Im} \left(\frac{V_{td} V_{tb}^* V_{cd}^* V_{cb}}{V_{td}^* V_{tb} V_{cd} V_{cb}^*} \right) = \sin 2\phi_1.$$

$$\triangleright f_{CP} = \pi \pi, \rho \rho \Rightarrow \phi_2$$

Unitarity triangle: ϕ_3

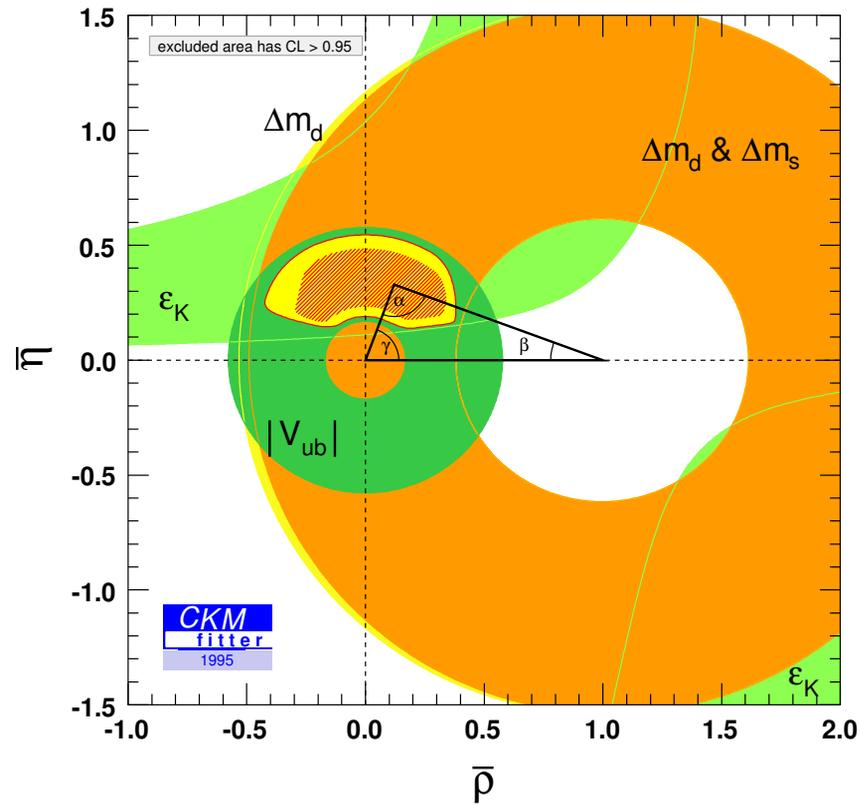
$B \rightarrow DK$ direct CP asymmetry 等



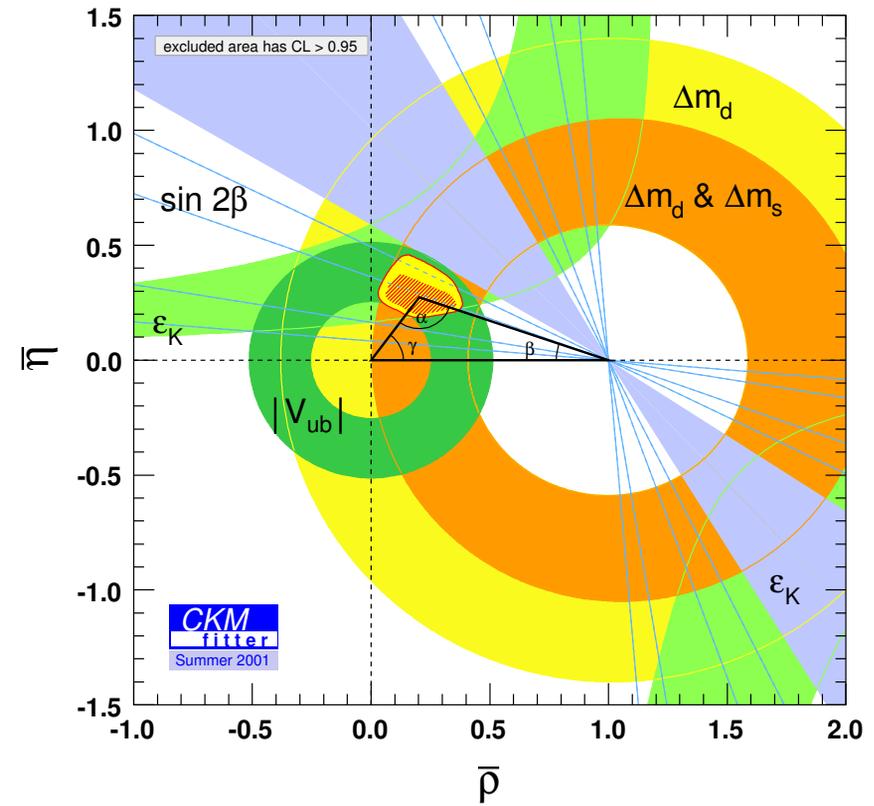
他の崩壊モードを使う方法もいろいろある。

Unitarity triangle: history

1995



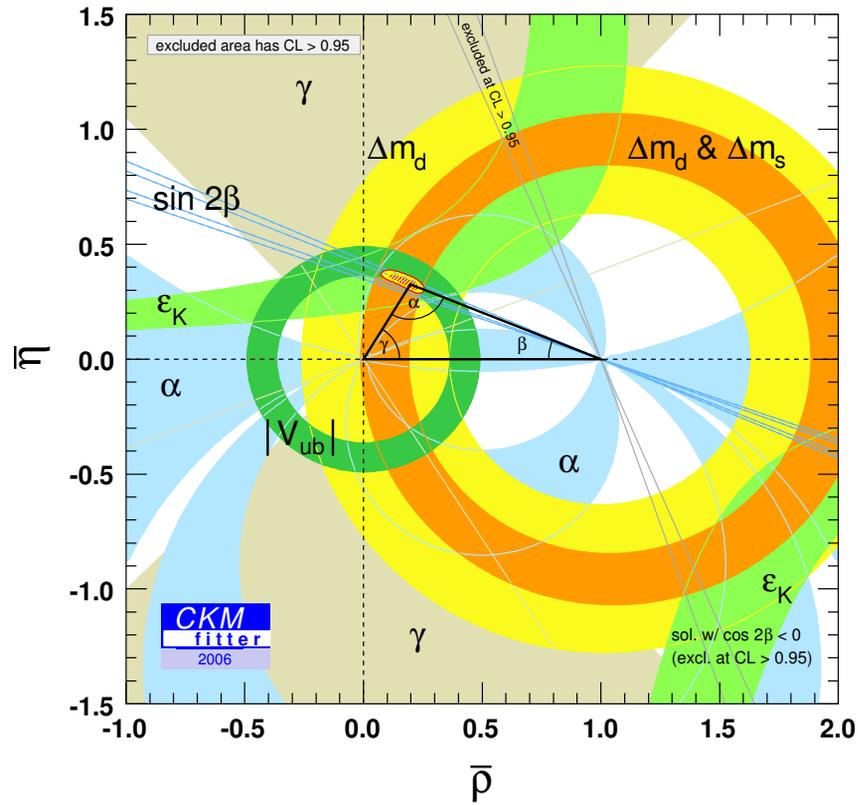
2001



$\sin 2\phi_1$ (Belle, BaBar)

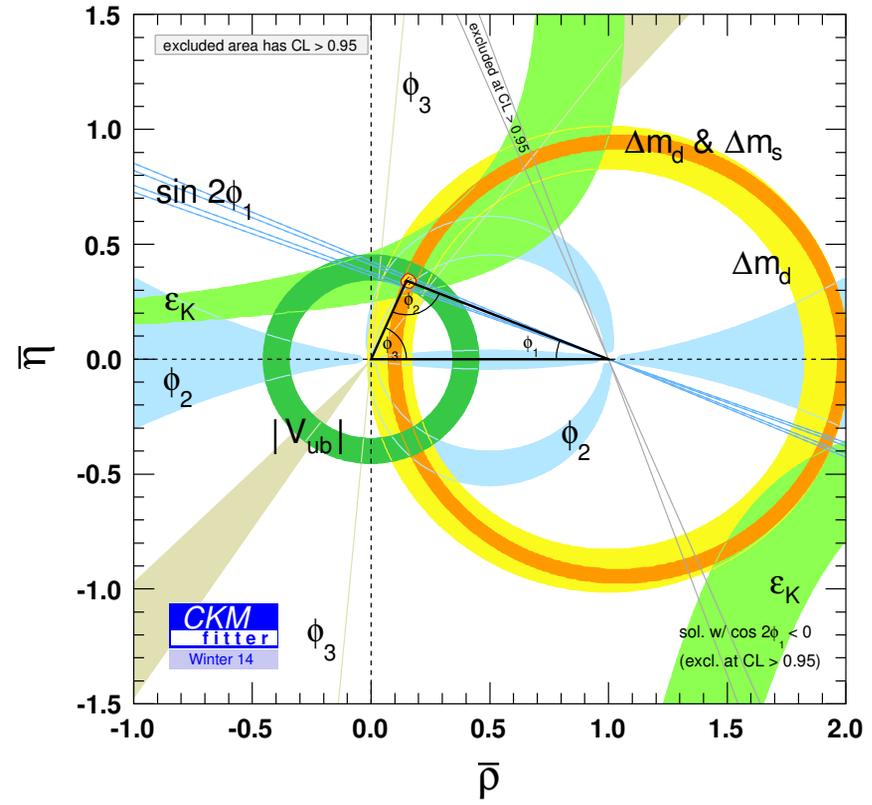
Unitarity triangle: history

2006

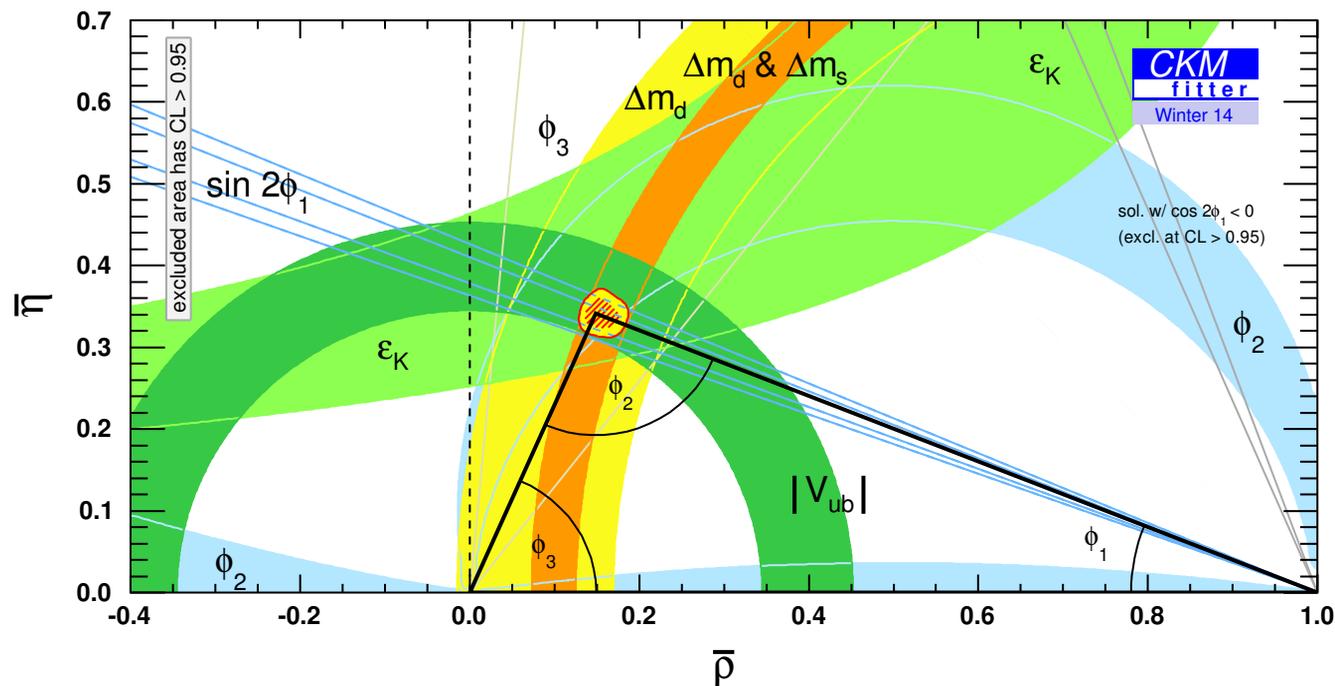


Δm_{B_s} (CDF, D0)

2014



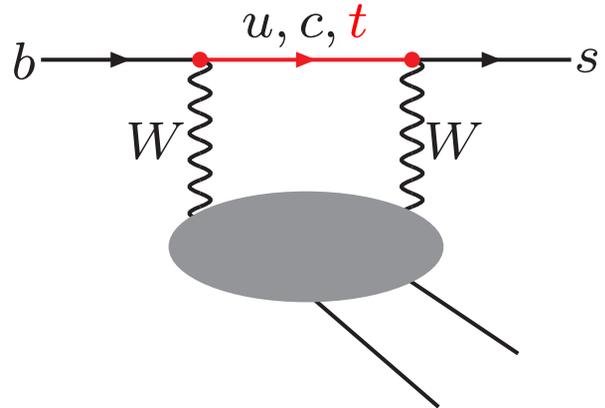
Unitarity triangle



$$\bar{\rho} = 0.1489^{+0.0158}_{-0.0084}, \quad \bar{\eta} = 0.342^{+0.013}_{-0.011}$$

- 標準模型でよく合っている (good news & bad news)。
 - ▷ 新物理の余地は $\sim 10\%$ 程度。
- $\epsilon_K, \Delta m_B, \Delta m_{B_s}$: ハドロン行列要素の理論誤差が主 (\Rightarrow 格子QCD)。

$b \rightarrow s$ transitions



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

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

標準模型の予言値の不定性は比較的小さい。

$b \leftrightarrow s$ UT:

$$V_{ub}^* V_{us} \frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}}$$

$b \rightarrow s \ell^+ \ell^-$

有効ハミルトニアン

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i(\mu) \mathcal{O}_i(\mu), \quad C_i : \text{Wilson 係数}$$

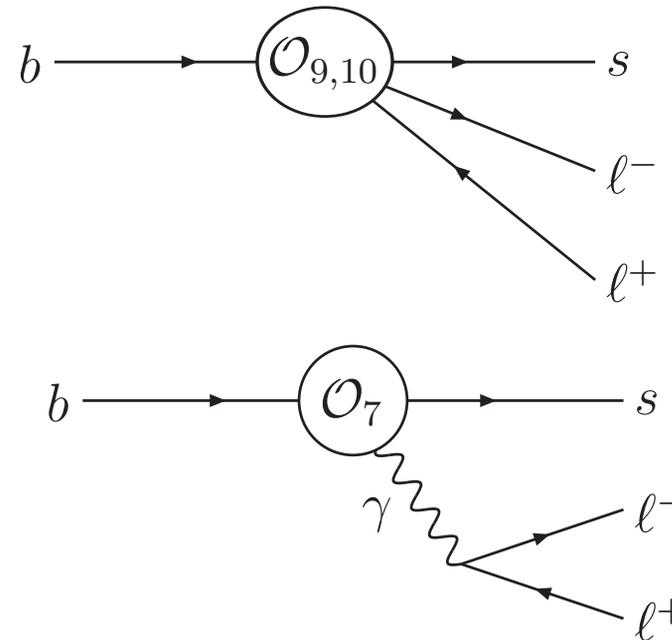
標準模型での主要項:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2} (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \ell),$$

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \gamma_5 \ell),$$

$$\mathcal{O}_7 = \frac{e}{(4\pi)^2} m_b (\bar{s} \sigma^{\mu\nu} P_R b) F_{\mu\nu},$$

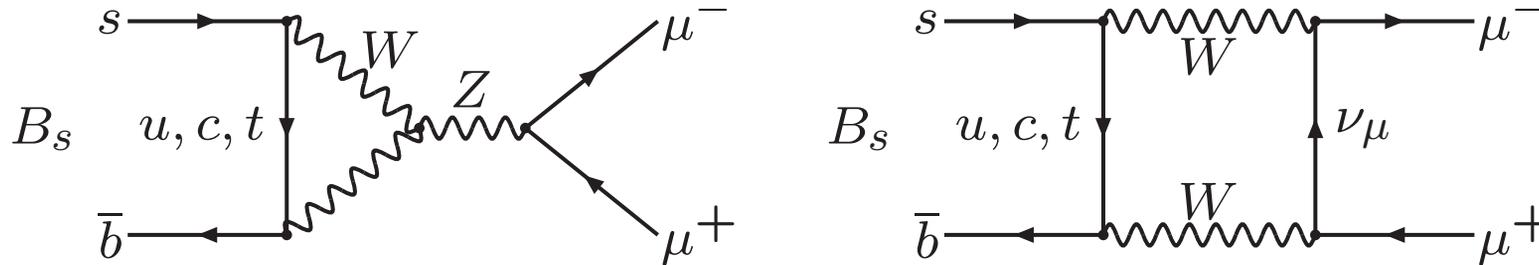
- 新物理: $(\bar{s} P_L b) (\bar{\ell} \ell)$, $(\bar{s} P_L b) (\bar{\ell} \gamma_5 \ell)$, ...
- $\mathcal{O}_7 \Rightarrow b \rightarrow s \gamma$.
- $\mathcal{O}_{10} \Rightarrow B_s \rightarrow \ell^+ \ell^-$.



$$B_s \rightarrow \mu^+ \mu^-$$

- $B = (3.1 \pm 0.7) \times 10^{-9}$ [PDG2014 = LHCb + CMS + CDF]
 - ▷ “First evidence”: [LHCb, arXiv:1211.2674]

標準模型 [Bobeth, arXiv:1405.4907, Buras *et al.*, arXiv:1208.0934]:



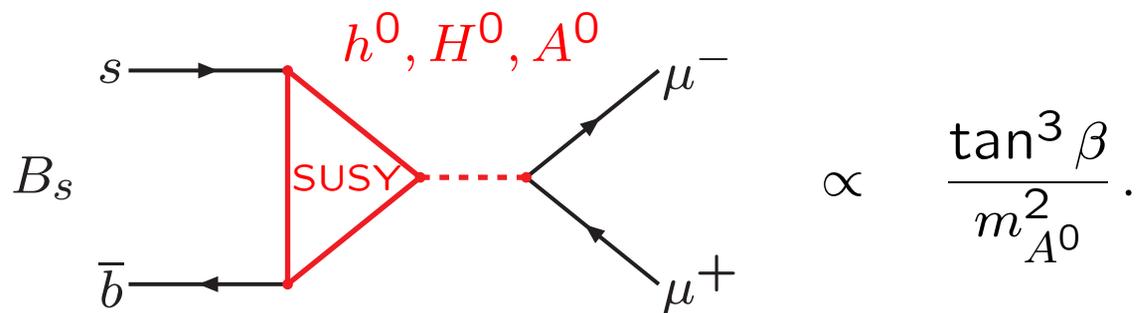
$$\begin{aligned}
 B_{\text{SM}} &= \frac{G_F^2}{\pi} \left[\frac{\alpha_{\text{em}}(m_Z)}{4\pi \sin^2 \theta_W} \right]^2 \tau_{B_s} f_{B_s}^2 m_{B_s} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} |V_{tb}^* V_{ts}|^2 Y^2(x_{tW}, x_{ht}; \alpha_s) \\
 &= (3.53 \pm 0.20) \times 10^{-9}.
 \end{aligned}$$

- 崩壊定数 f_{B_s} の不定性が主要な理論誤差 (4% in B)

$B_s \rightarrow \mu^+ \mu^-$ 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.

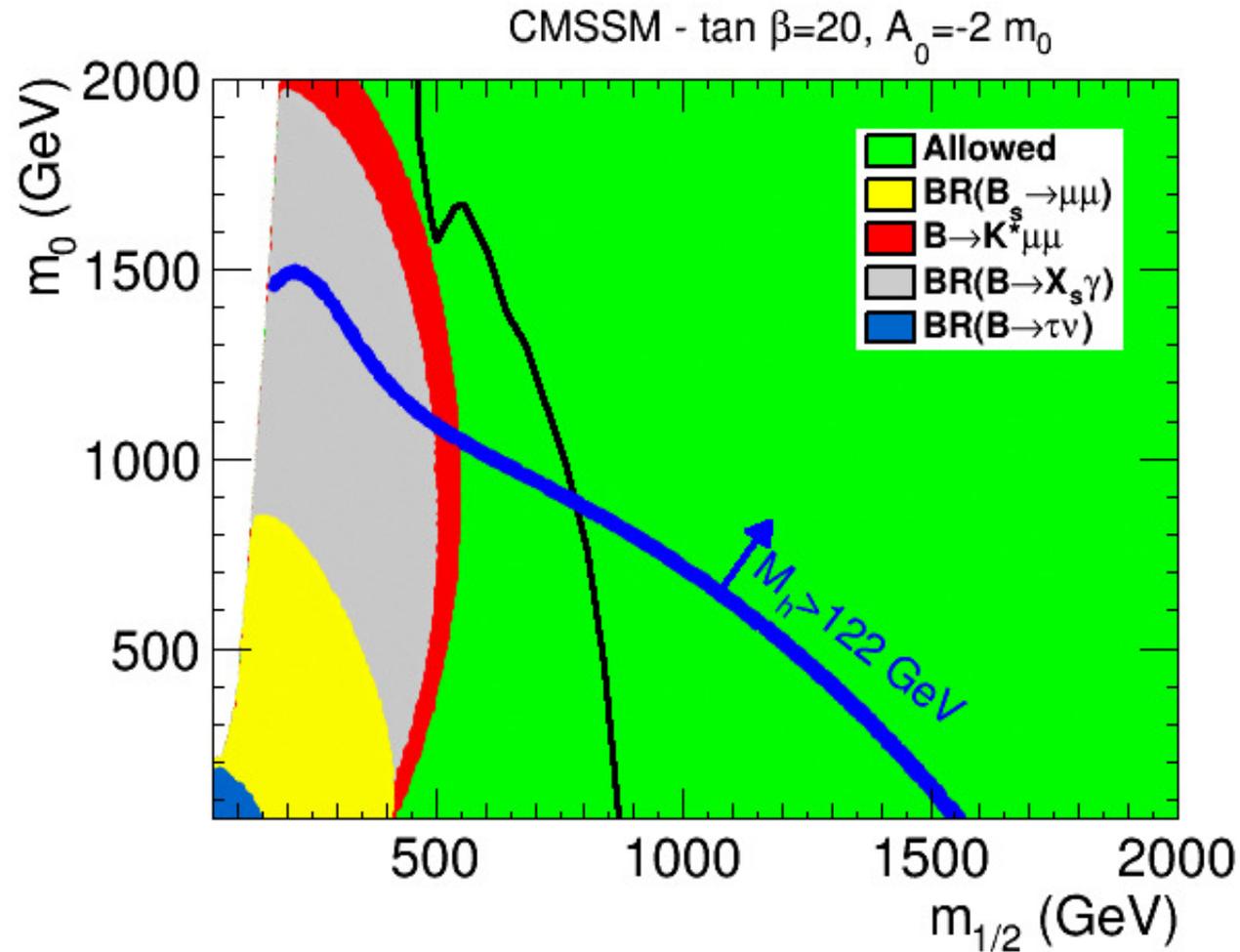


[Choudhury & Gaur, hep-ph/9810307]

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

$\tan \beta = 20$

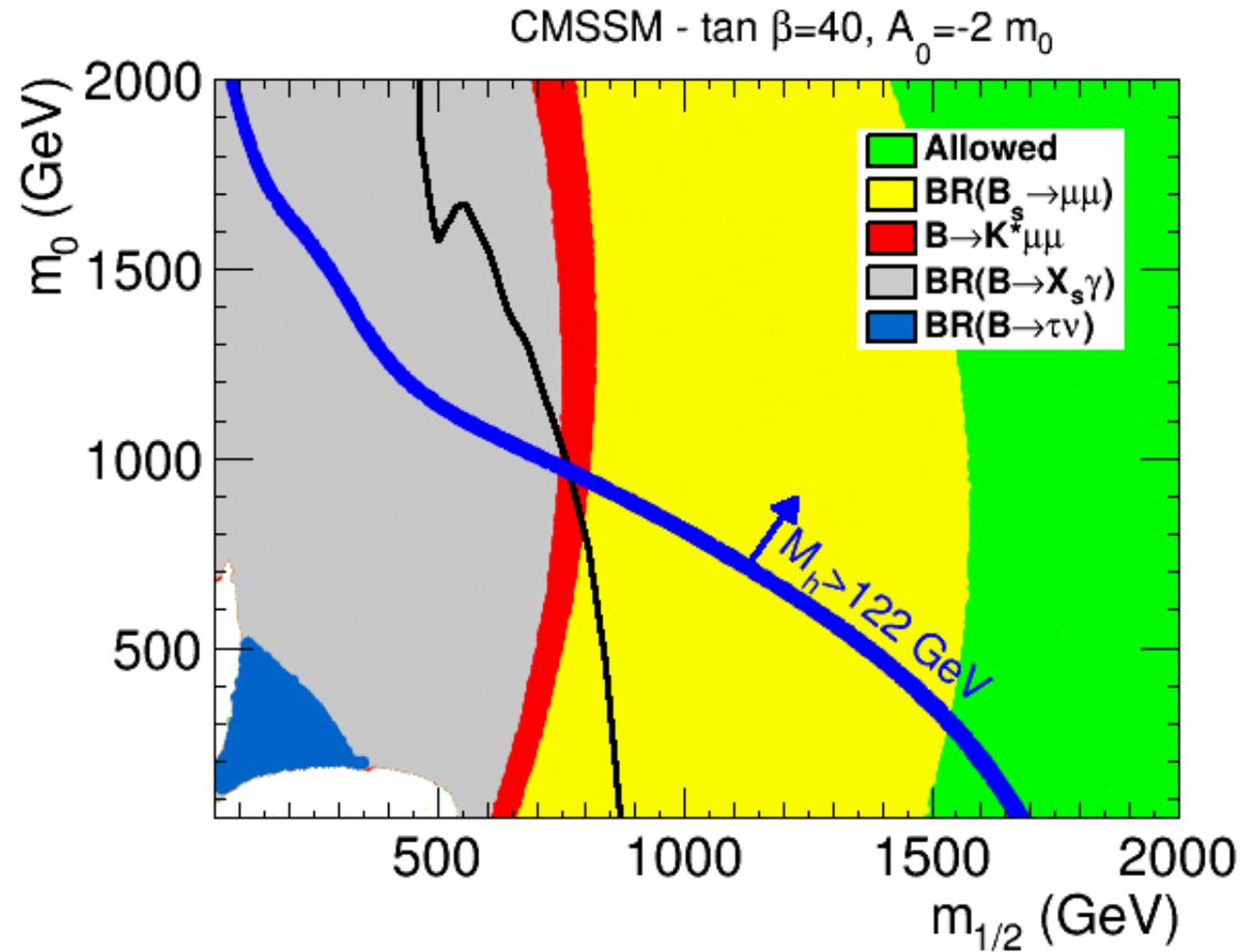
[Mahmoudi *et al.*, arXiv:1401.2145]

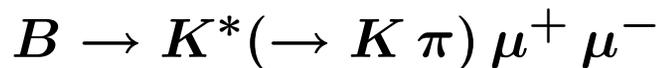


$B_s \rightarrow \mu^+ \mu^-$ in CMSSM

$\tan \beta = 40$

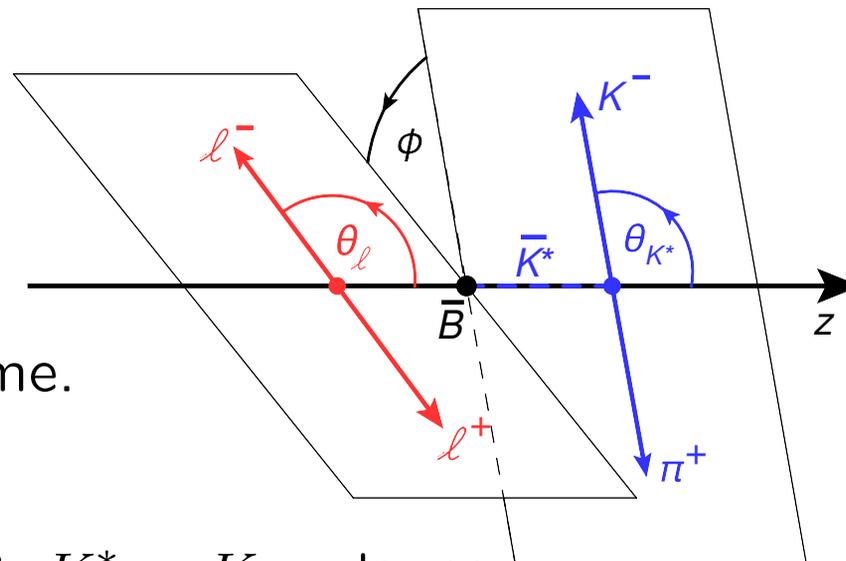
[Mahmoudi *et al.*, arXiv:1401.2145]





Kinematical variables:

- q^2 : $(\ell^+ \ell^-)$ invariant mass².
- θ_ℓ : lepton angle in $\ell^+ \ell^-$ CM frame.
- θ_K : K angle in K^* rest frame.
- ϕ : angle between $B \rightarrow K^* \ell^+ \ell^-$ & $K^* \rightarrow K \pi$ planes.



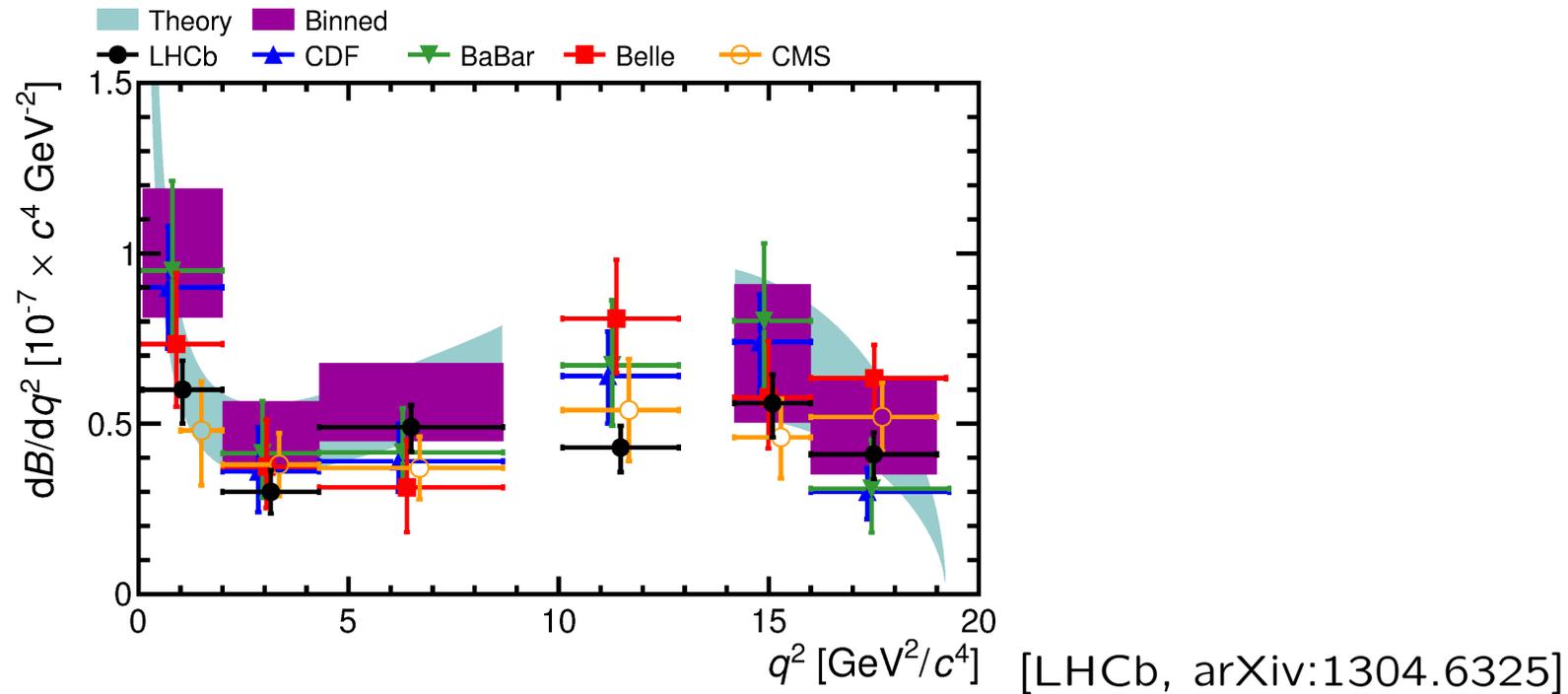
Differential decay rate [Descotes-Genon et al., arXiv:1303.5794]:

$$\begin{aligned} \frac{d^4\Gamma}{dq^2 d\cos\theta_K d\cos\theta_\ell d\phi} = & \frac{9}{32\pi} \left[J_{1s} \sin^2\theta_K + J_{1c} \cos^2\theta_K \right. \\ & + (J_{2s} \sin^2\theta_K + J_{2c} \cos^2\theta_K) \cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi \\ & + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\ & + (J_{6s} \sin^2\theta_K + J_{6c} \cos^2\theta_K) \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\ & \left. + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 2\theta_K \sin^2 2\theta_\ell \sin 2\phi \right]. \end{aligned}$$

各 J_i は q^2 に依存。

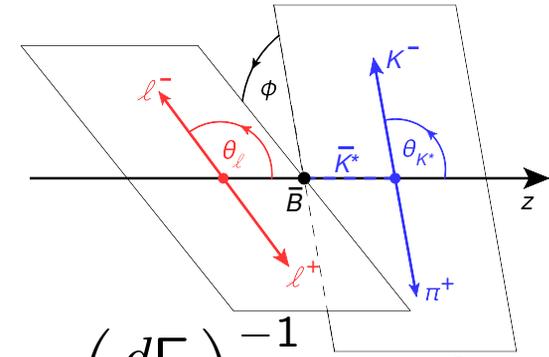
$$B \rightarrow K^*(\rightarrow K \pi) \mu^+ \mu^-$$

$$\frac{d\Gamma}{dq^2} \propto 3J_{1c}(q^2) + 6J_{1s}(q^2) - J_{2c}(q^2) - 2J_{2s}(q^2).$$

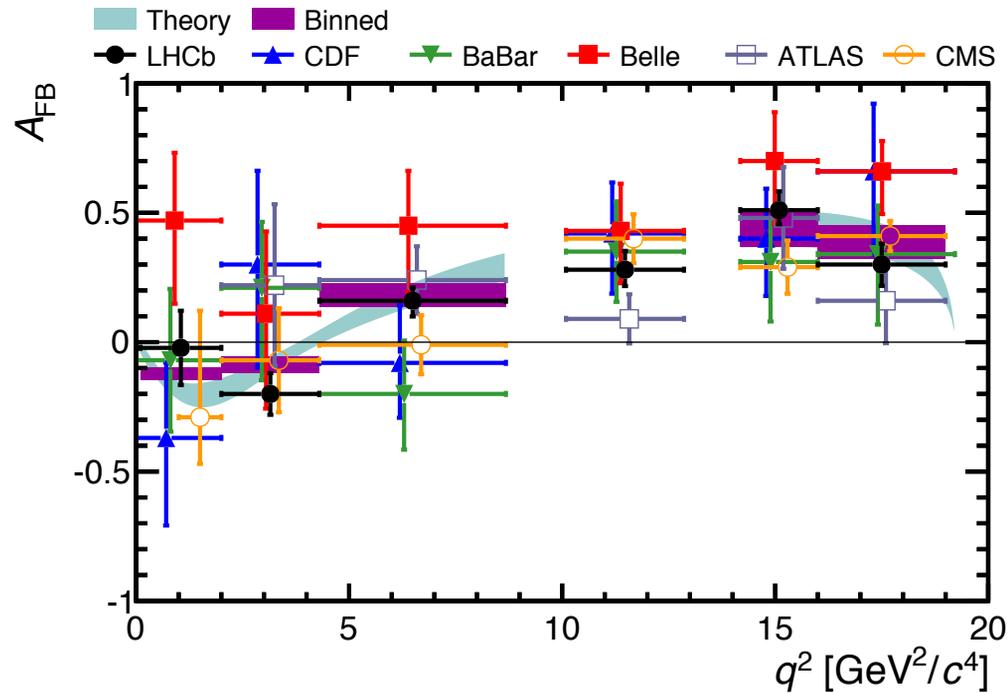


- $q^2 \approx m_{J/\psi}^2$ は $B \rightarrow K^* J/\psi(\rightarrow \mu^+ \mu^-)$ が大きいので除く。 $q^2 \approx m_{\psi'}^2$ も同様。

$B \rightarrow K^*(\rightarrow K \pi) \mu^+ \mu^-: A_{\text{FB}}$



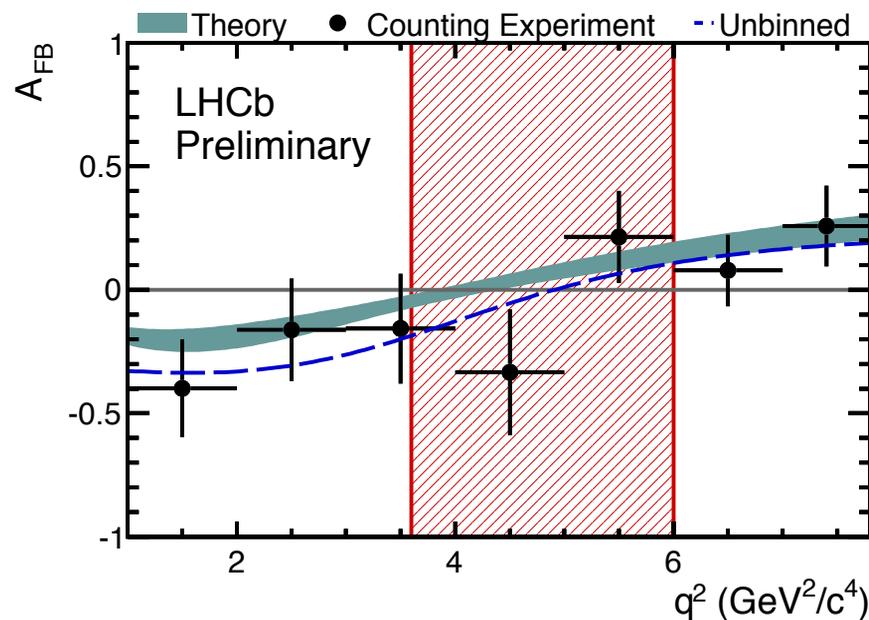
$$A_{\text{FB}} = \left(\frac{d\Gamma}{dq^2} \right)^{-1} \left(\int_0^1 - \int_{-1}^0 \right) d \cos \theta_\ell \frac{d^2\Gamma}{dq^2 d \cos \theta_\ell} \propto \left(\frac{d\Gamma}{dq^2} \right)^{-1} J_{6s}(q^2).$$



[LHCb, arXiv:1304.6325]

$B \rightarrow K^*(\rightarrow K \pi) \mu^+ \mu^-: A_{\text{FB}}$

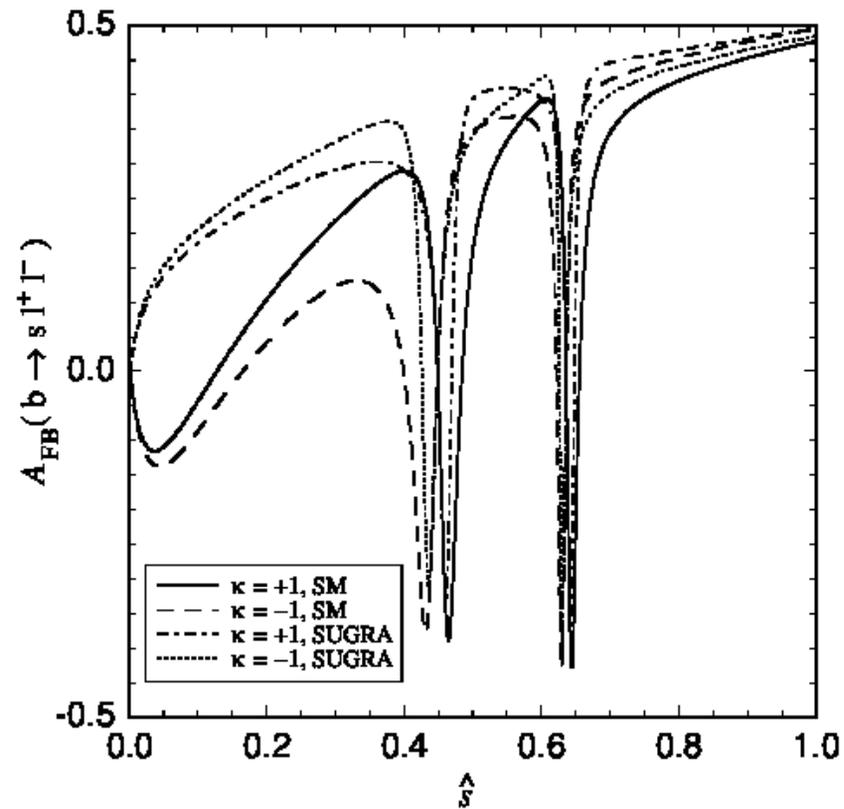
- $A_{\text{FB}} \sim C_{10}(q^2 C_9 + 2m_b^2 C_7)$
 - ▷ “ C_9 ” and “ C_7 ”: opposite sign in SM $\Rightarrow A_{\text{FB}}$ crosses zero.
 - ▷ Hadronic uncertainty of zero-crossing point q_0^2 small.
 - ▷ LHCb observed the zero-crossing: $q_0^2 = 4.9 \pm 0.9 \text{ GeV}^2$.



[LHCb-CONF-2012-008]

$B \rightarrow K^*(\rightarrow K \pi) \mu^+ \mu^-: A_{\text{FB}}$

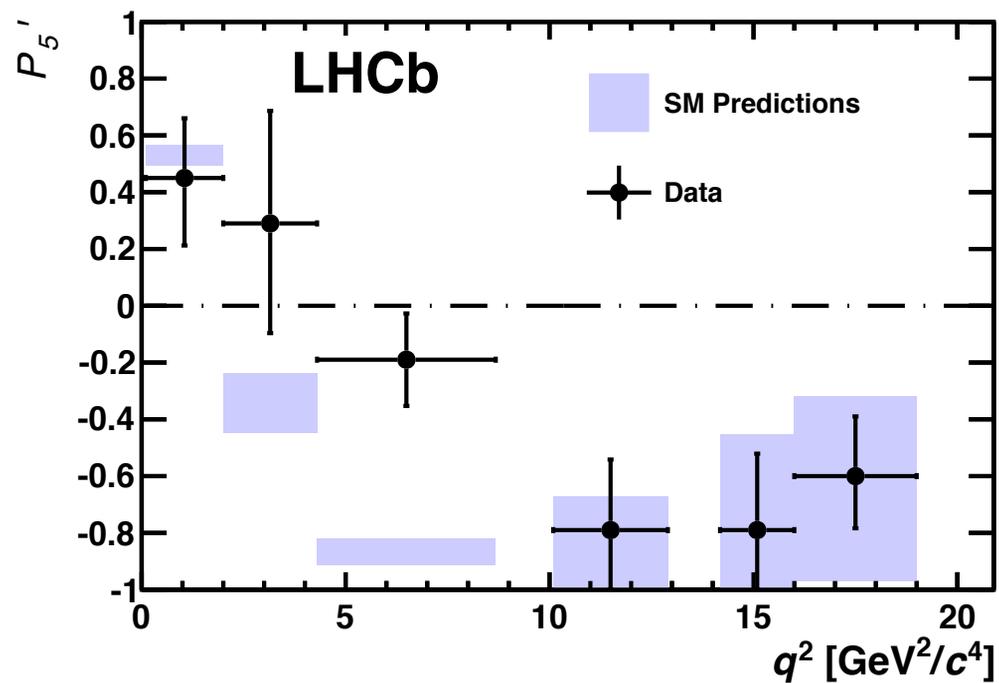
Zero-crossing of A_{FB} kills the possibility $C_7 = C_7^{\text{SM}} + C_7^{\text{NP}} = -C_7^{\text{SM}}$ (occurs in certain parameter region in mSUGRA).



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

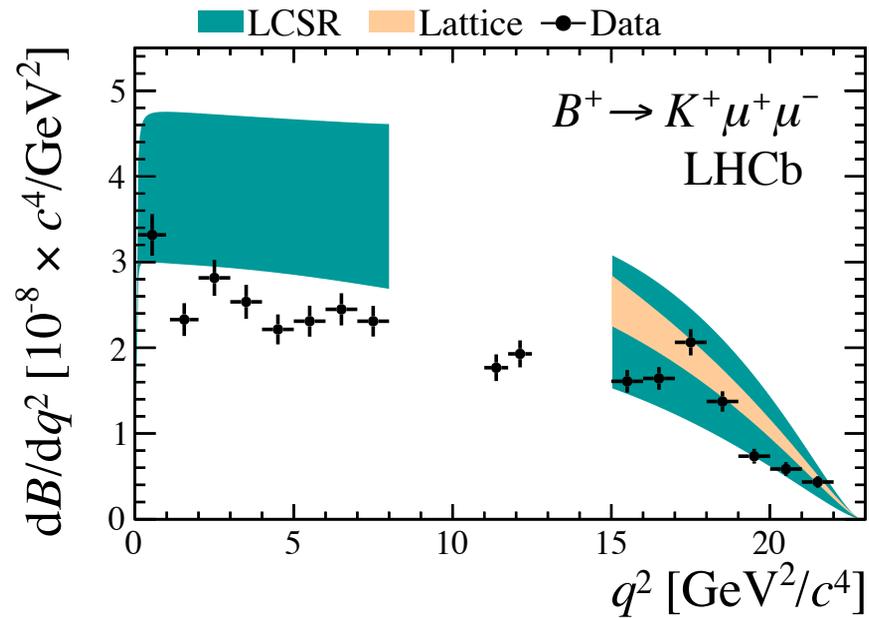
$$B \rightarrow K^*(\rightarrow K \pi) \mu^+ \mu^-$$

- 3.7σ “anomaly” in $P'_5 \propto J_5(q^2)$.

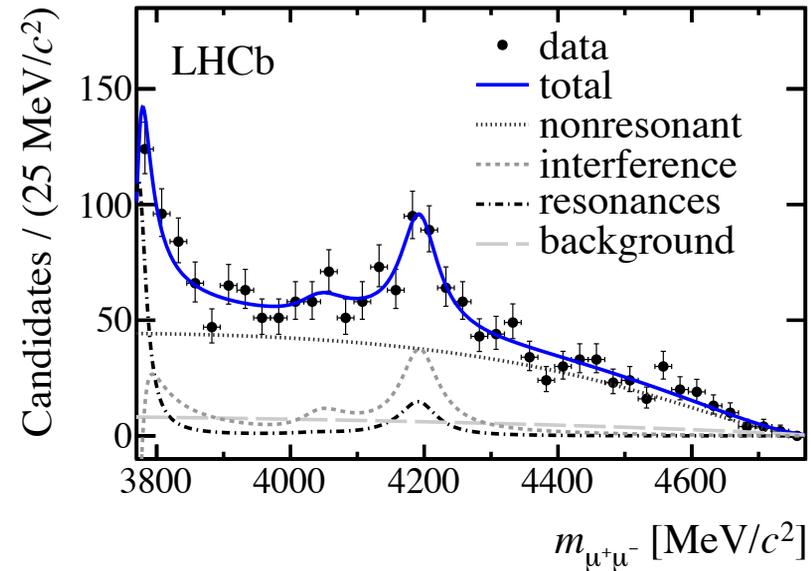


[LHCb, arXiv:1308.1707]

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



[LHCb, arXiv:1403.8044]

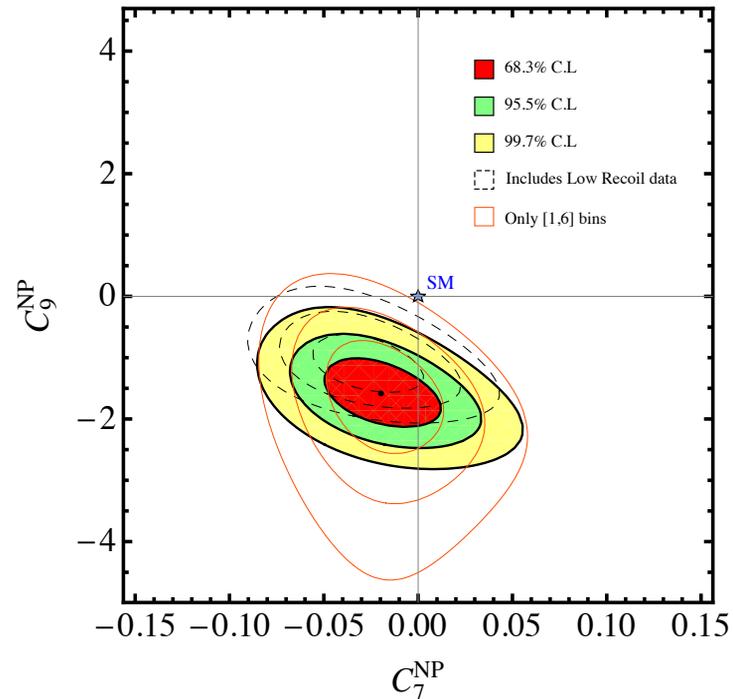


[LHCb, arXiv:1307.7595]

- Discrepancy in low q^2 ?
- $c\bar{c}$ resonances observed in high q^2 region.
 - ▷ $\psi(3770)$, $\psi(4040)$ $\psi(4140)$

Wilson coefficients fit with $b \rightarrow s \mu^+ \mu^-$ and $b \rightarrow s \gamma$ observables

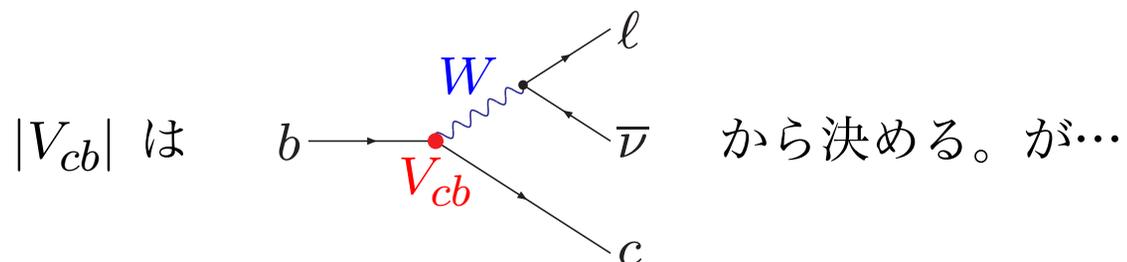
$$C_7 = C_7^{\text{SM}} + C_7^{\text{NP}}, \quad C_9 = C_9^{\text{SM}} + C_9^{\text{NP}}$$



[Descotes-Genon *et al.*, arXiv:1307.5683]

- New Physics or SM higher order corrections?

Semileptonic decays



- Exclusive: $B \rightarrow D \ell \bar{\nu}$, $B \rightarrow D^* \ell \bar{\nu}$

$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$$

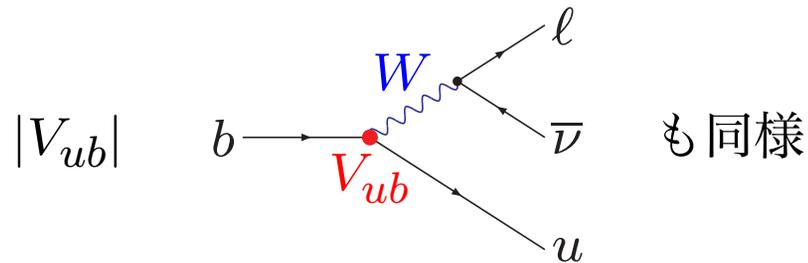
- Inclusive: $B \rightarrow X_c \ell \bar{\nu}$

$$|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3}$$

▷ ずれている？

▷ Unitarity triangle fit では平均を取ったが？

Semileptonic decays



- Exclusive: $B \rightarrow \pi \ell \bar{\nu}$, $B \rightarrow \rho \ell \bar{\nu}$

$$|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3}$$

- Inclusive: $B \rightarrow X_u \ell \bar{\nu}$

$$|V_{ub}| = (4.41 \pm 0.15_{-0.17}^{+0.15}) \times 10^{-3}$$

Semileptonic decays

$$|V_{cb}|_{\text{exclusive}} \stackrel{?}{\neq} |V_{cb}|_{\text{inclusive}}, \quad |V_{ub}|_{\text{exclusive}} \stackrel{?}{\neq} |V_{ub}|_{\text{inclusive}}$$

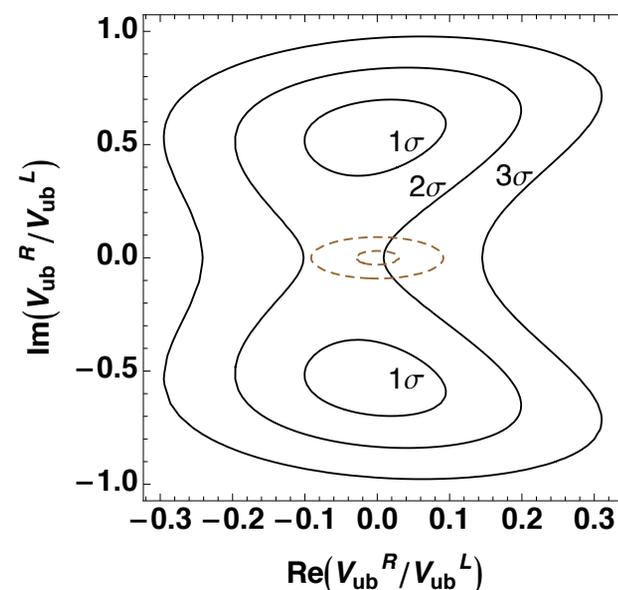
- QCD/ハドロン物理由来？
- 新物理？

$|V_{ub}|$ 新物理解釈の例 [Enomoto & Tanaka, arXiv:1411.1177]

- $b \rightarrow u$ right-handed current を追加

$$|V_{ub}|_{\pi l \nu} = |V_{ub}^L + V_{ub}^R|,$$

$$|V_{ub}|_{\text{incl}} = \sqrt{|V_{ub}^L|^2 + |V_{ub}^R|^2}.$$



Semileptonic decays: $R(D^{(*)})$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)} \quad \ell = e, \mu$$

- V_{cb} に依存しない。
- Form factor 由来の不定性は小さい。

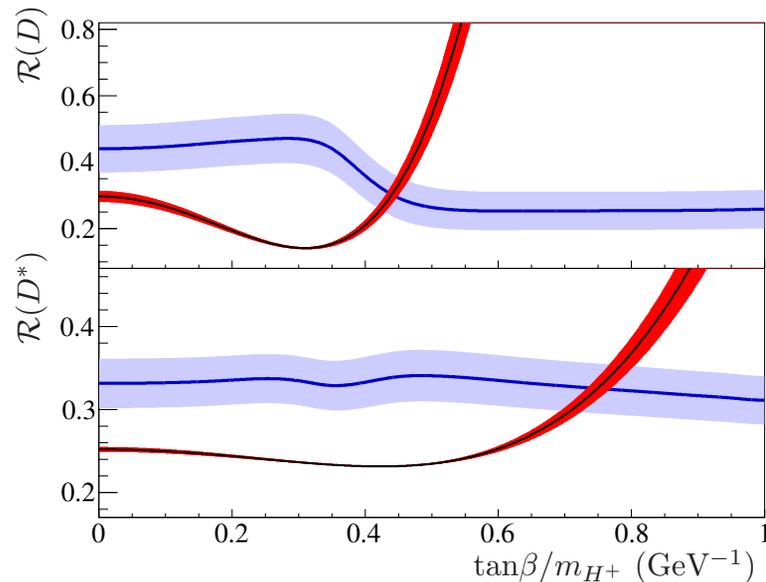
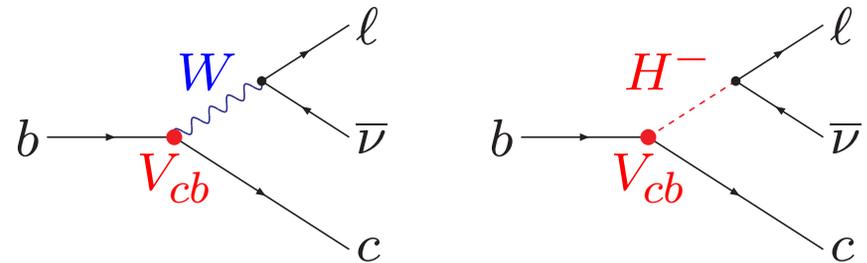
$$R(D)_{\text{SM}} = 0.297 \pm 0.017, \quad R(D^*)_{\text{SM}} = 0.252 \pm 0.003.$$

$$R(D)_{\text{exp}} = 0.440 \pm 0.058 \pm 0.042, \quad R(D^*)_{\text{exp}} = 0.332 \pm 0.024 \pm 0.018.$$

[BaBar, arXiv:1205.5442] 合わせて 3.4σ の不一致。

Semileptonic decays: $R(D^{(*)})$

Type-II two Higgs double model:



赤 理論値 (type-II 2HDM)
 青 実験値

[BaBar, arXiv:1205.5442]

- 両方同時には合わない。
- Belle の解析はまだ (“will appear soon”).
- 新物理解釈 (レプトクォーク模型) [Sakaki *et al.*, arXiv:1309.0301]

Summary

- B (フレーバー) の物理は新物理の間接探索。
 - B ファクトリー / LHC 実験で多くの測定結果が得られた。
 - 実験結果は標準模型 (CKM) とよく合っている。
 - ▷ 概ね $\sim 10\%$ 程度の精度。
 - 3σ レベルの “anomalies” も見つかっている。
 - ▷ より高精度の測定 (Belle II, LHC) に期待。
 - ▷ 標準模型の高精度計算も重要 (QCD / ハドロンの不定性を減らす)。
- ⇒ $\sim 1\%$ レベルの高精度検証へ。