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Recent status on $b \to s$ process

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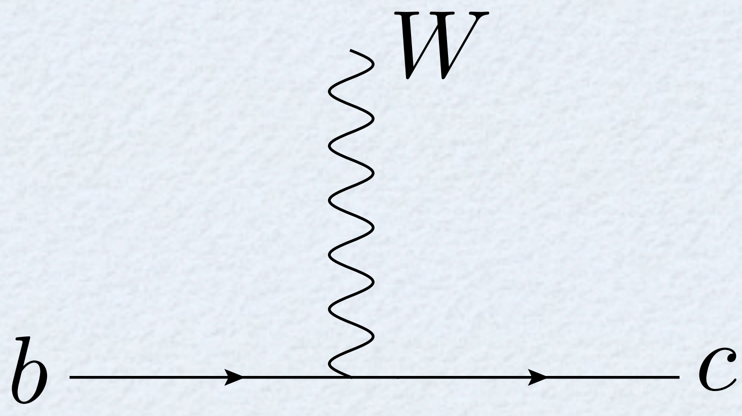
References:
(PH) arXiv:1308.1501, 1405.5182
(EXP) arXiv:1304.6325, 1308.1707, 1403.8044

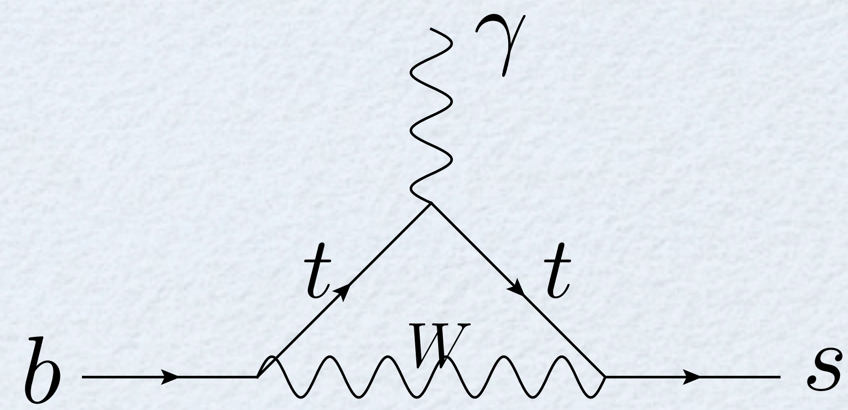
Content

- Overview
- Effective operators of new physics
- Processes
- Constraints of new physics

Overview

In the Standard Model, “b→s” transition only occurs at a loop level, which then, is sensitive to new physics.





Many b→s processes were measured by several experiments.
In particular, LHCb collaboration has improved their results.
Today, I will show you summary of experimental results.

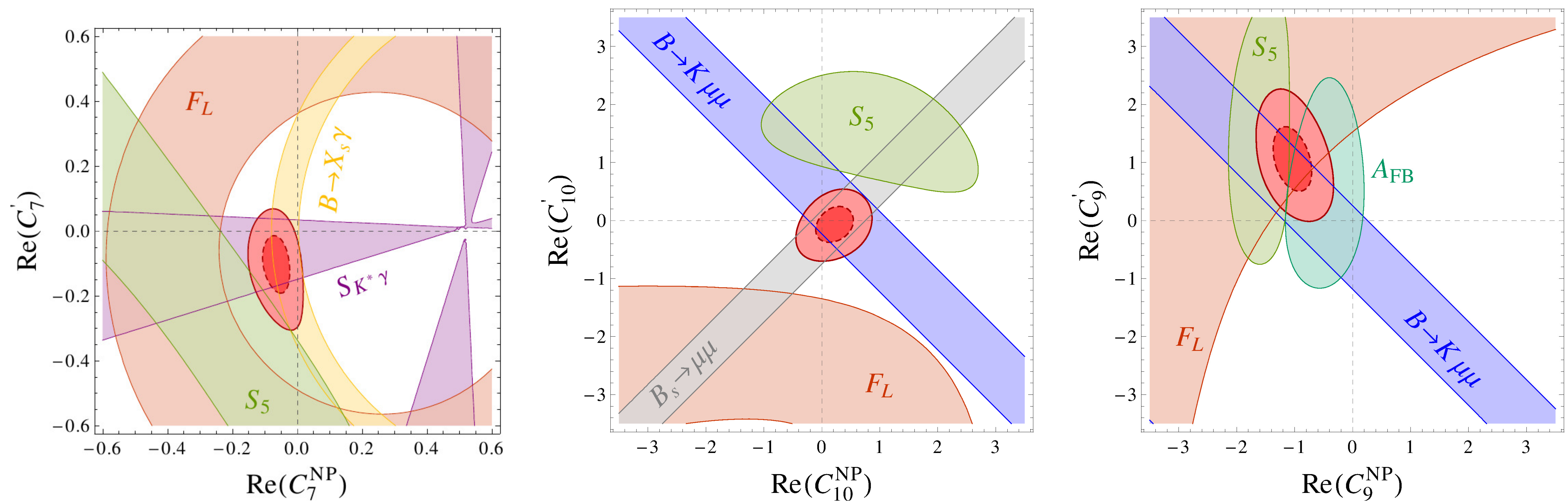
Overview

For more details, I summarize the following processes:

$$b \to s\gamma : \quad B \to X_s\gamma \quad B \to K^*\gamma$$

$$b \to s\ell\ell : \quad B \to X_s\mu^+\mu^- \quad B \to K^{(*)}\mu^+\mu^- \quad B_s \to \mu^+\mu^-$$

From the above observables, new physics is constrained in terms of Wilson coefficients, which are so called as C_7, C_9, C_{10}



Effective operators

Effective Lagrangian relevant for $b \to s\gamma$ and $b \to s\ell^+\ell^-$ is given by

$$\mathcal{L}_{\rm eff} \equiv 2\sqrt{2}G_F V_{tb}V_{ts}^* \frac{e^2}{16\pi^2}\sum_i \left(C_i\mathcal{O}_i + C_i'\mathcal{O}_i'\right) + \text{h.c.}$$

* $C_i^{(\prime)}$: Wilson coefficient ("effective vertex")
* $\mathcal{O}_i^{(\prime)}$: effective operator

Traditionally, these operators are defined as follows $(\mathcal{O}_i' : P_R \leftrightarrow P_L)$

$b \to s + \text{others}: \quad \mathcal{O}_{1\sim 6,8}$

*Today, we don't consider scalar & tensor type operators

$b \to s\gamma: \quad \mathcal{O}_7 = \dfrac{m_b}{e}\left(\bar{s}\sigma_{\mu\nu}P_R b\right)F^{\mu\nu}$

$b \to s\ell\ell: \quad \mathcal{O}_9 = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\ell}\gamma^\mu\ell\right) \quad \mathcal{O}_{10} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\ell}\gamma^\mu\gamma^5\ell\right)$

SM contributions are calculated and obtained as follows:

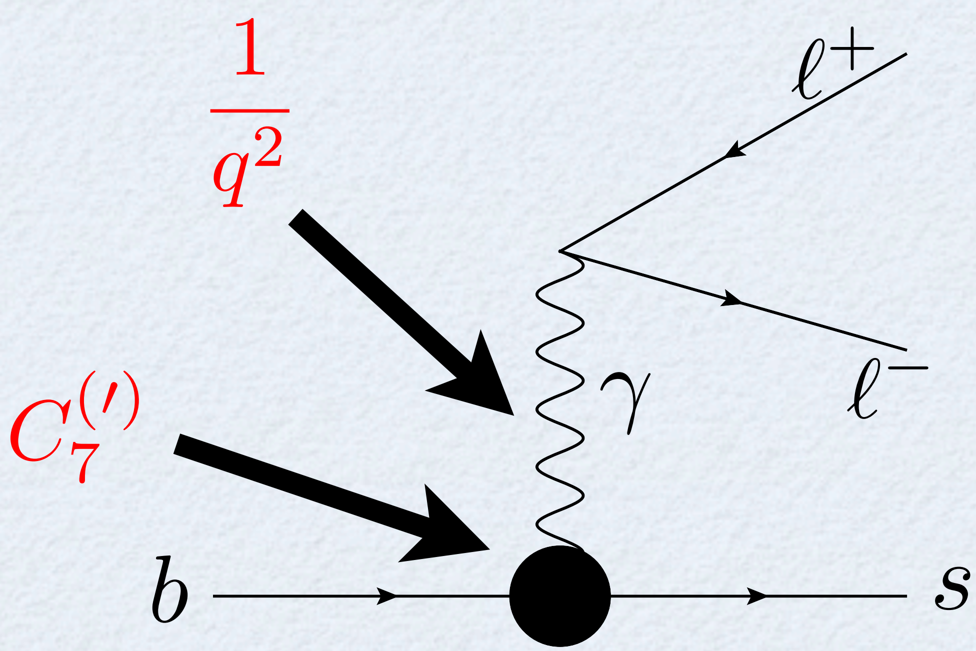
$$\boxed{C_i \equiv C_i^{\mathrm{SM}} + C_i^{\mathrm{NP}} \quad (i = 7, 9, 10)}$$

SM prediction with NNLL accuracy:

$$C_7^{\mathrm{SM}}(\mu) = -0.304, \quad C_9^{\mathrm{SM}}(\mu) = 4.211, \quad C_{10}^{\mathrm{SM}}(\mu) = -4.103$$

$$C_7'^{\,\mathrm{SM}}(\mu) = C_9'^{\,\mathrm{SM}}(\mu) = C_{10}'^{\,\mathrm{SM}}(\mu) \simeq 0$$ at scale $\mu = m_b = 4.6\,\mathrm{GeV}$

Note that $\mathcal{O}_7^{(\prime)}$ can contribute to $b \to s\ell^+\ell^-$ process:



O7 is sensitive in low q^2 region

$$q^2 = (p_{\ell^+} + p_{\ell^-})^2$$

Processes

$B \to X_s \gamma$

B : meson which contain b together with u or d

X_s : sum of all meson which contain s (inclusive mode)

Observable: Branching ratio

$$\mathcal{BR}\left(B \to X_s \gamma\right)_{\text{exp.}} = (3.55 \pm 0.26) \times 10^{-4}$$ Belle +BABAR +CLEO

$$\mathcal{BR}\left(B \to X_s \gamma\right)_{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4}$$ NNLO

Status: SM prediction is consistent with exp. within 2σ region

NP sensitivity: C_7, C_7'

$$\mathcal{BR}\left(B \to X_s \gamma\right) \propto |C_7 + C_7'|^2$$

$B \to K^* \gamma$

A collective term for $B^0 \to K^{*0}\gamma$ **and** $\bar{B}^0 \to \bar{K}^{*0}\gamma$

$B^0\,(d\bar{b}),\ \ \bar{B}^0\,(\bar{d}b),\ \ K^{*0}\,(d\bar{s}),\ \ \bar{K}^{*0}\,(\bar{d}s)$ **K* = vector meson**

Observable: **Time-dependent CP asymmetry**

$$\frac{\Gamma(\bar{B}^0(t)\to\bar{K}^{*0}\gamma)-\Gamma(B^0(t)\to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t)\to\bar{K}^{*0}\gamma)+\Gamma(B^0(t)\to K^{*0}\gamma)} \equiv S_{K^*\gamma}\sin(\Delta M_d t) - C_{K^*\gamma}\cos(\Delta M_d t)$$

$$S_{K^*\gamma}^{\mathrm{exp.}} = -0.16 \pm 0.22$$ **Belle + BABAR**

$$S_{K^*\gamma}^{\mathrm{SM}} \simeq -2\frac{m_s}{m_b}\sin(2\beta) = -0.023 \pm 0.016$$ **LCSR**

Status: **both are consistent with 0 and have large exp. error**

NP sensitivity: $C_7,\ C_7'$

$$S_{K^*\gamma} \simeq \frac{2\mathrm{Im}\left(e^{-2i\beta}C_7C_7'\right)}{|C_7|^2+|C_7'|^2}$$

$B \to X_s \ell^+ \ell^-$

Note:

$q^2 = (p_{\ell^+} + p_{\ell^-})^2$ **distribution can be measured, but charmonium ($c\bar{c}$) resonance exists around** $6(\mathrm{GeV})^2 < q^2 < 14.4(\mathrm{GeV})^2$.

Observable: Partial BR

$$\mathcal{BR}\left(B \to X_s \ell^+ \ell^-\right)_{\mathrm{exp.}}\Big|_{\mathrm{low}q^2} = (1.63 \pm 0.50) \times 10^{-6}$$

$$\mathcal{BR}\left(B \to X_s \ell^+ \ell^-\right)_{\mathrm{SM}}\Big|_{\mathrm{low}q^2} = (1.59 \pm 0.11) \times 10^{-6}$$

$q^2 < 6(\mathrm{GeV})^2$

$$\mathcal{BR}\left(B \to X_s \ell^+ \ell^-\right)_{\mathrm{exp.}}\Big|_{\mathrm{high}q^2} = (4.3 \pm 1.2) \times 10^{-7}$$

$$\mathcal{BR}\left(B \to X_s \ell^+ \ell^-\right)_{\mathrm{SM}}\Big|_{\mathrm{high}q^2} = (2.3 \pm 0.7) \times 10^{-7}$$

$14.4(\mathrm{GeV})^2 < q^2$

Status: SM prediction is consistent with exp. within 2σ region

NP sensitivity: $C_9^{(\prime)}, C_{10}^{(\prime)}$ **and** $C_7^{(\prime)}$ **for low** q^2 **region**

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

K* = vector meson

Note:

- Charmonium resonance also exists in q^2 distribution
- K* is identified using $K^* \to K\pi$, so final particles are $(K\pi\ell^+\ell^-)$ which are all directly measured.

↓

All the angular distributions are available ! (9 observables)

- Charge conjugated mode is also available

↓

of the observables get twice ! (18 observables)

Rough definition:

$$\frac{d^4\Gamma(\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\ell^+\ell^-)}{dq^2\, d\theta_1\, d\theta_2\, d\theta_3} \equiv F(q^2, \theta_1, \theta_2, \theta_3) \equiv \sum_{i=1}^{9} I_i(q^2) f_i(\theta_1, \theta_2, \theta_3)$$

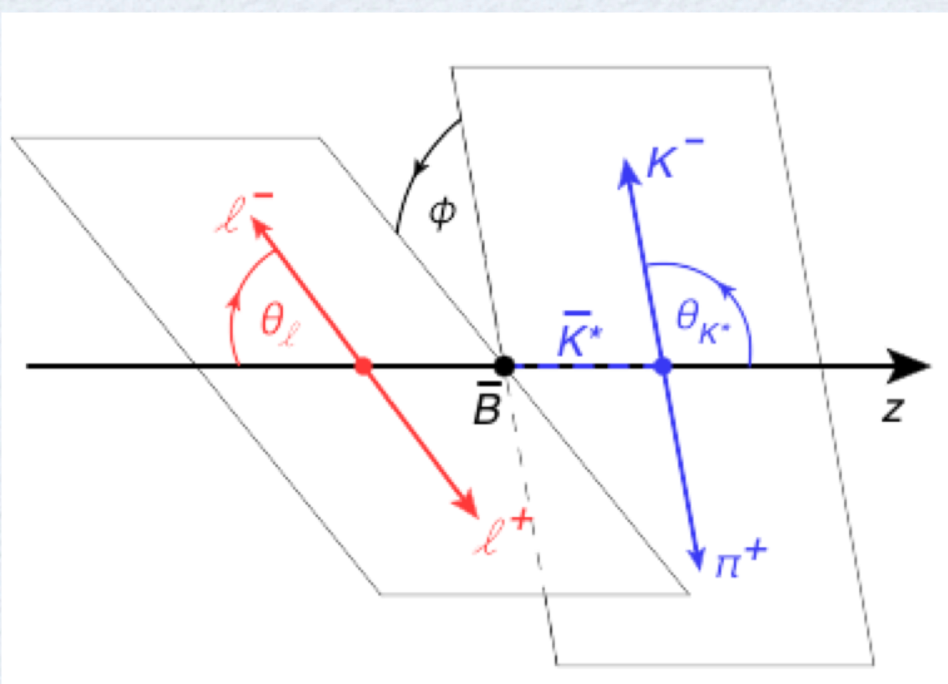
$B \to K^* \mu^+ \mu^-$

Precise definition:

$$\frac{d^4\Gamma(\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\ell^+\ell^-)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} \equiv F(q^2, \theta_\ell, \theta_{K^*}, \phi) \equiv \sum_{i=1}^{9} I_i(q^2) f_i(\theta_\ell, \theta_{K^*}, \phi)$$

$$\frac{d^4\Gamma(B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} \equiv \bar{F}(q^2, \theta_\ell, \theta_{K^*}, \phi) \equiv \sum_{i=1}^{9} \bar{I}_i(q^2) f_i(\theta_\ell, \theta_{K^*}, \phi)$$

$$\begin{aligned} F(q^2, \theta_\ell, \theta_{K^*}, \phi) = {} & I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*}) \cos 2\theta_l \\ & + I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi \\ & + I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi \\ & + (I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*}) \cos\theta_l + I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\ & + I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi\,. \end{aligned}$$



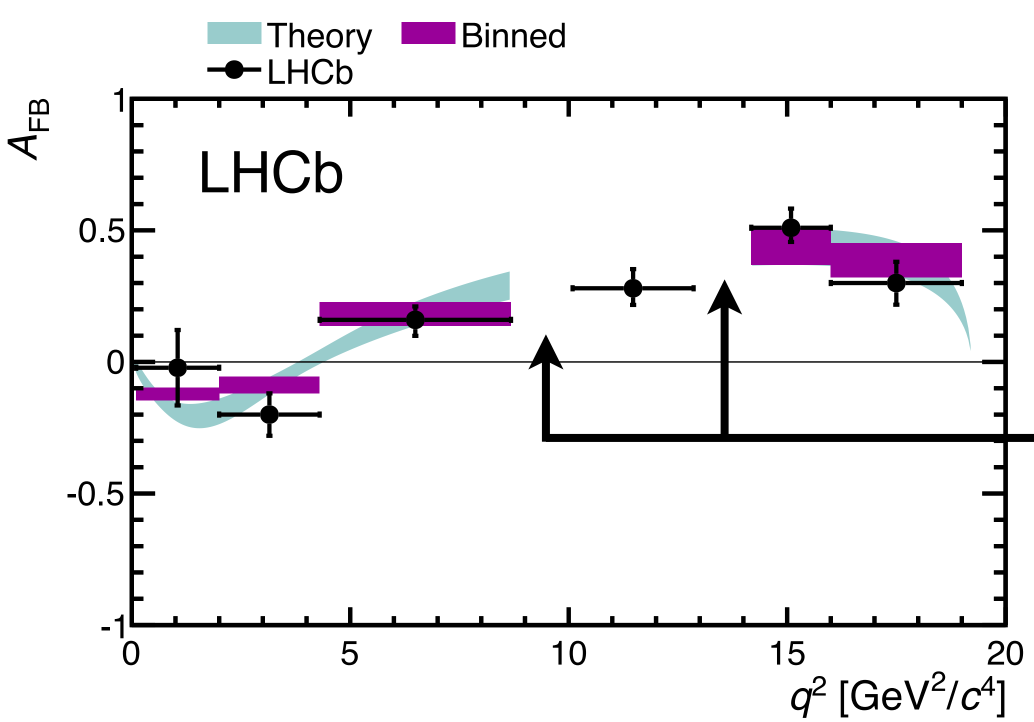
Complicated !

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

Observable(1): FB asymmetry

LHCb, arXiv:1304.6235

$$A_{\mathrm{FB}}(q^2) = \int d\cos\theta_{K^*}\, d\phi \left(\int_0^1 - \int_{-1}^0 \right) d\cos\theta_\ell \, (F - \bar{F}) \Bigg/ \frac{d\Gamma + d\bar{\Gamma}}{dq^2}$$



: SM prediction (distribution)

: SM prediction (bin)

No data due to charmonium resonances

Status: SM and data are consistent with each other

NP sensitivity: C_7, C_9

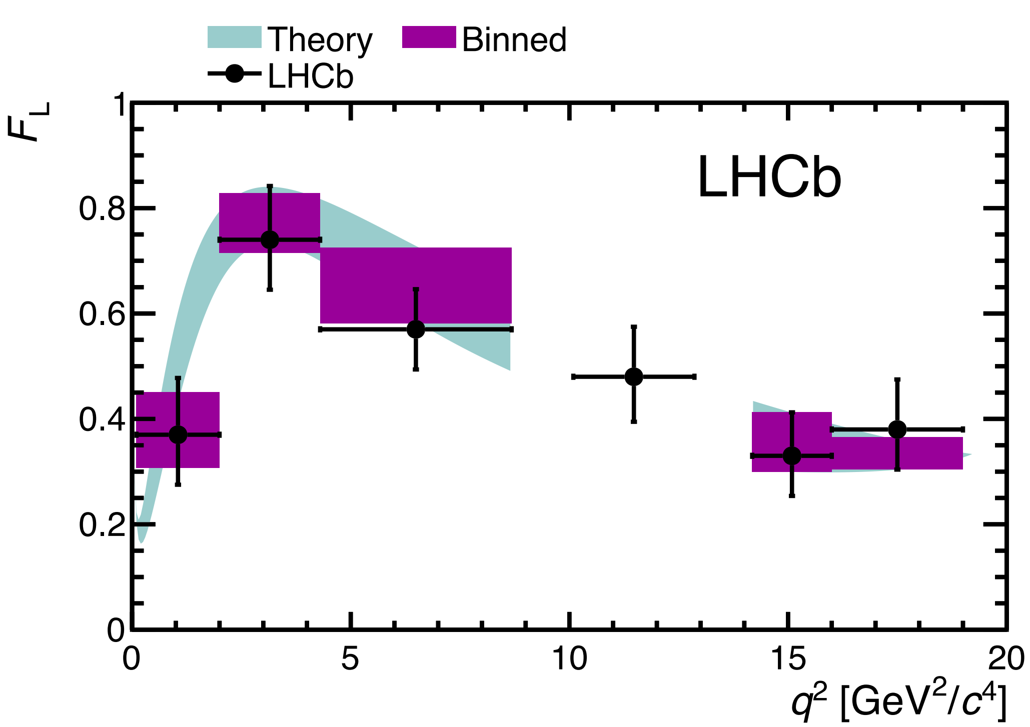
$$B \to K^* \mu^+ \mu^-$$

Observable(2): K* polarization

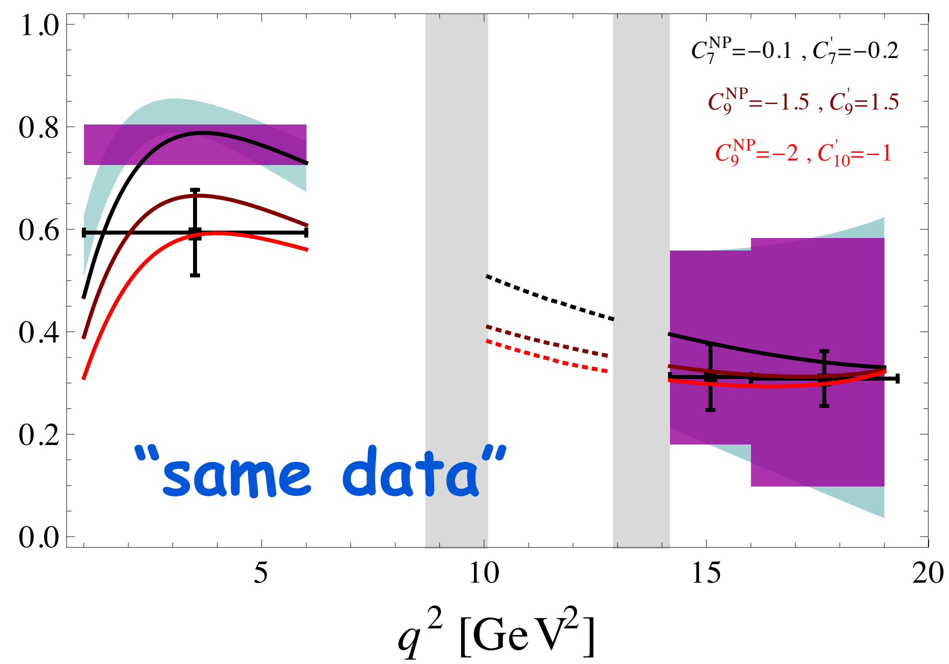
LHCb, arXiv:1304.6235

$$F_L(q^2) = \left(I_2^c(q^2) - \bar{I}_2^c(q^2)\right) \Big/ \frac{d\Gamma + d\bar{\Gamma}}{dq^2}$$

(The paper chose this)



"Other SM prediction"



"same data"

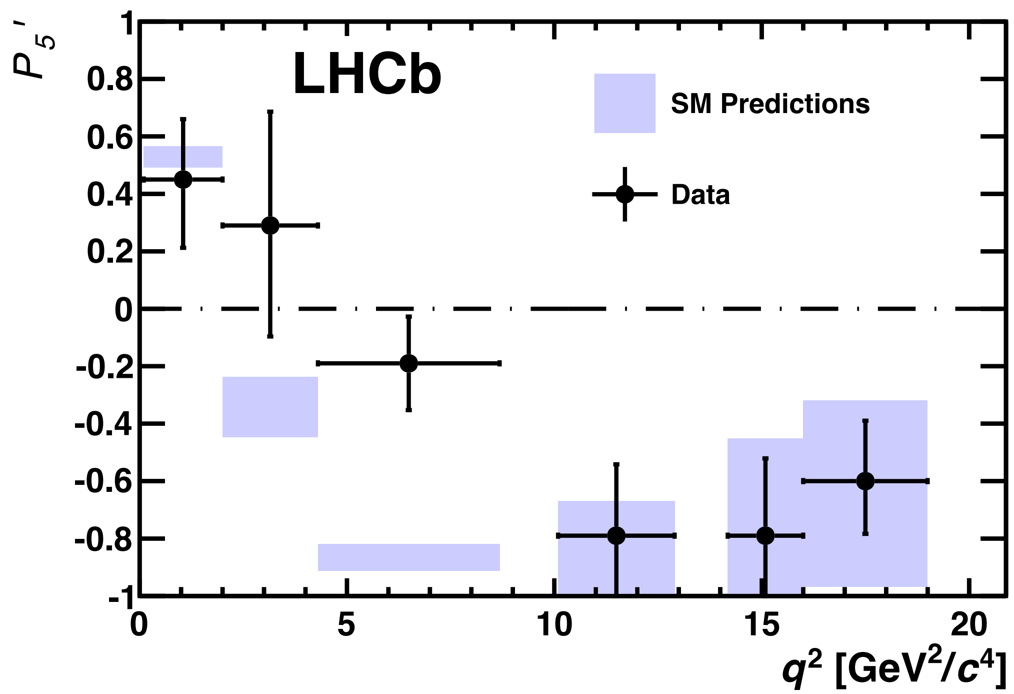
Status: Two SM predictions which result in different status

NP sensitivity: $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

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

Observable(3): "optimized" quantity LHCb, arXiv:1308.1707

$$S_5(q^2) = -\frac{4}{3} \int d\cos\theta_\ell \left(\int_0^1 - \int_{-1}^0 \right) d\cos\theta_{K^*} \left(\int_{\pi/2}^{3\pi/2} - \int_0^{\pi/2} - \int_{2\pi}^{3\pi/2} \right) d\phi \, (F - \bar{F}) \Big/ \frac{d\Gamma + d\bar{\Gamma}}{dq^2}$$



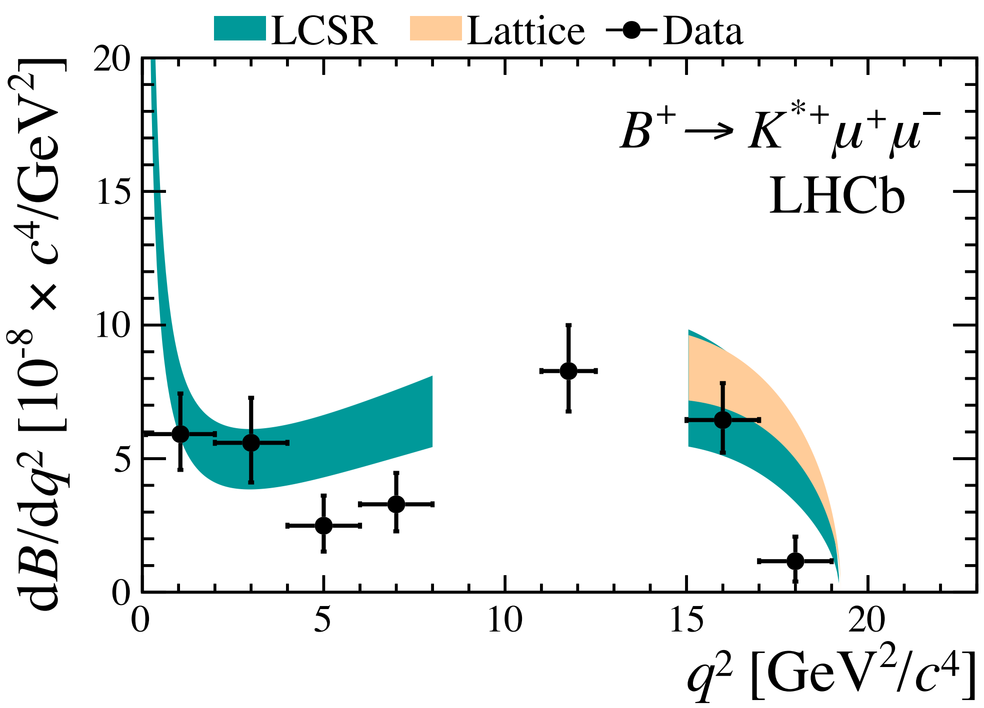
: SM prediction (bin)

Status: Large deviation in low q^2 region?

NP sensitivity: $C_7^{(\prime)}, C_9, C_{10}'$

$B \to K^* \mu^+ \mu^-$ **Recent update**

Observable(4): q^2 distribution of BR **LHCb, arXiv:1403.8044**



: SM from QCD sum rule

: SM from Lattice study

Status: Small deviation from SM ?

Note:

"Recent update" is not included in the analysis which I will show

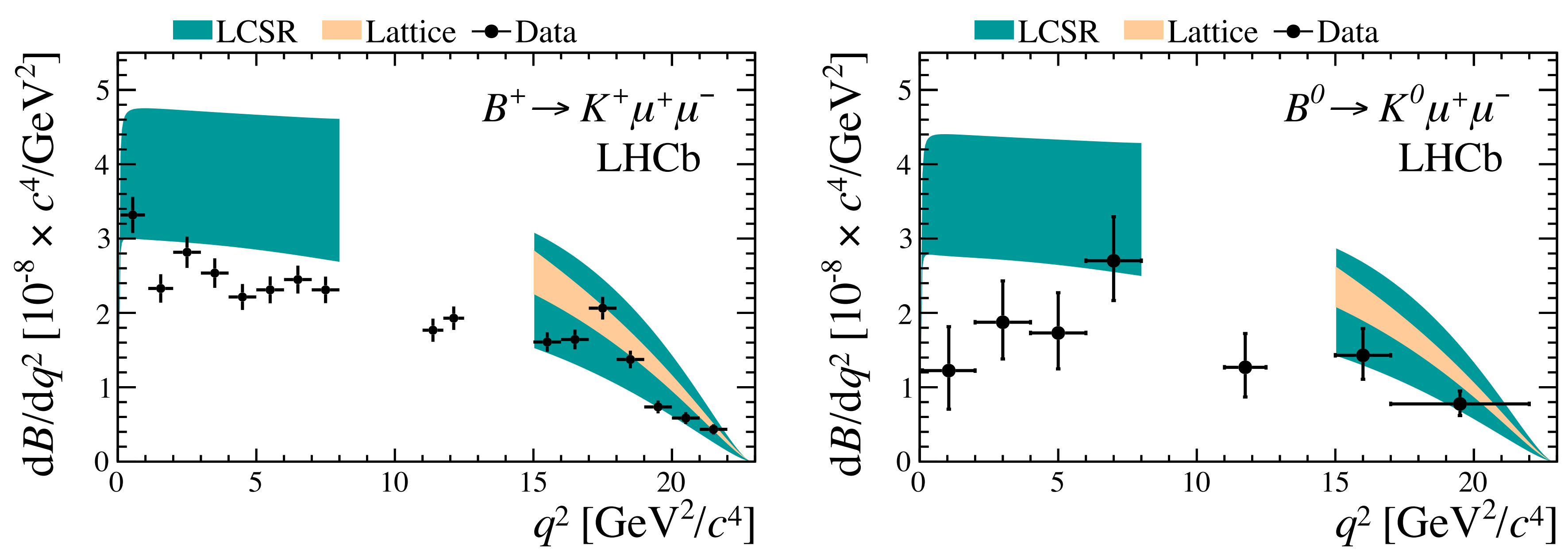
$B \to K\mu^+\mu^-$ **Recent update**

Note: K = pseudo-scalar meson

- **Full angular analysis can be done,**
  but for now, only q^2 distribution has been measured

- **In the B→K transition, γ cannot intermediate**
  due to their spin property, thus, $O_7^{(\prime)}$ never contributes

Observable: q^2 distribution of BR **LHCb, arXiv:1403.8044**



Status: Data all have lower values than SM predictions

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

Note:

- This mode was finally observed in 2013
- $O_7^{(\prime)}$ cannot contribute as well as B→K transition
- Because of "pseudo-scalar → vacuum" transition,
  only axial vector current ($O_{10}^{(\prime)}$) can contribute to this mode

Observable: Branching Ratio

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm exp} = (2.9 \pm 0.7) \times 10^{-9}$$ LHCb + CMS

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.23 \pm 0.27) \times 10^{-9}$$ NLO by Buras et.al.

Status: SM prediction is consistent with exp. within 1σ region

NP sensitivity: $C_{10}^{(\prime)}$

Summary of status: (* = The most recent update)

Process	Observable	SM vs DATA
$B \to X_s \gamma$	Branching Ratio (BR)	consistent (<2σ)
$B \to K^* \gamma$	CP asymmetry	consistent with 0
$B \to X_s \ell^+ \ell^-$	Partial BR	consistent (<2σ)
$B \to K^* \mu^+ \mu^-$	FB asymmetry	consistent
	K* polarization	deviation ←
	S5	large deviation ←
	BR	small deviation*
$B \to K \mu^+ \mu^-$	BR	small deviation*
$B_s \to \mu^+ \mu^-$	BR	consistent (<1σ)

Constraints

Analysis in arXiv:1308.1501

In this paper, several constraints on the Wilson coefficients are evaluated.
To visualize the bound, they consider three cases as follows:

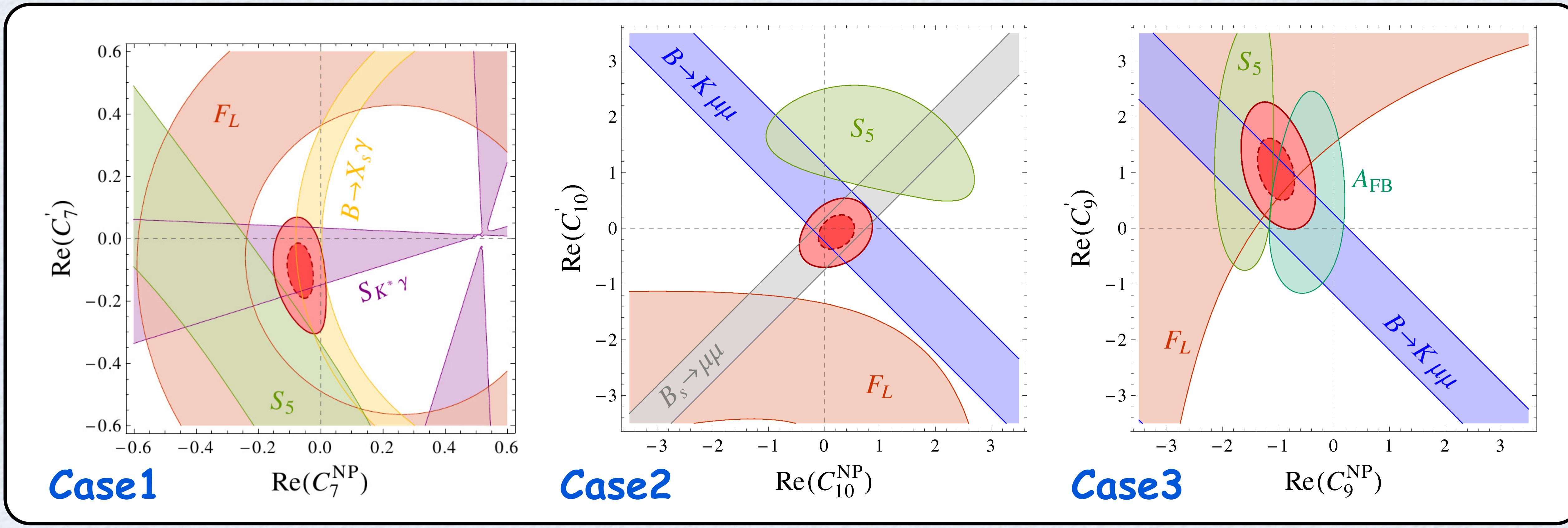
1. NP only in $\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}\left(\bar{s}\sigma_{\mu\nu}P_{R(L)}b\right)F^{\mu\nu}$ **: constraint on** $C_7^{(\prime)}$
2. NP only in $\mathcal{O}_{10}^{(\prime)} = \left(\bar{s}\gamma_\mu P_{L(R)}b\right)\left(\bar{\ell}\gamma^\mu\gamma^5\ell\right)$ **: constraint on** $C_{10}^{(\prime)}$
3. NP only in $\mathcal{O}_9^{(\prime)} = \left(\bar{s}\gamma_\mu P_{L(R)}b\right)\left(\bar{\ell}\gamma^\mu\ell\right)$ **: constraint on** $C_9^{(\prime)}$

Considered processes:

$$b \to s\gamma : \quad B \to X_s\gamma \quad B \to K^*\gamma$$

$$b \to s\ell\ell : \quad B \to X_s\mu^+\mu^- \quad B \to K^{(*)}\mu^+\mu^- \quad B_s \to \mu^+\mu^-$$

Results of χ^2 fit to data:



Comment:

1. Case1 is strongly constrained by data on $B\to X_s\gamma$, $K^*\gamma$ and the tension in S_5 can only be improved, but not in F_L

2. Case2 is strongly constrained by the combination of data on $B\to K\mu\mu$ and $B_s\to\mu\mu$, and cannot reduce the tension in S_5 & F_L

3. Case3 gives a consistent explanation of the discrepancy

→ Let's see for more detail

Detailed comment on “case3”:

- $C_9^{\rm NP} \sim -1.5$ can account for the observed value of S5, which correspond to **-35% of the SM contribution:** $C_9^{\rm SM} = 4.2$

- The bound from B→Kμμ can be completely avoided

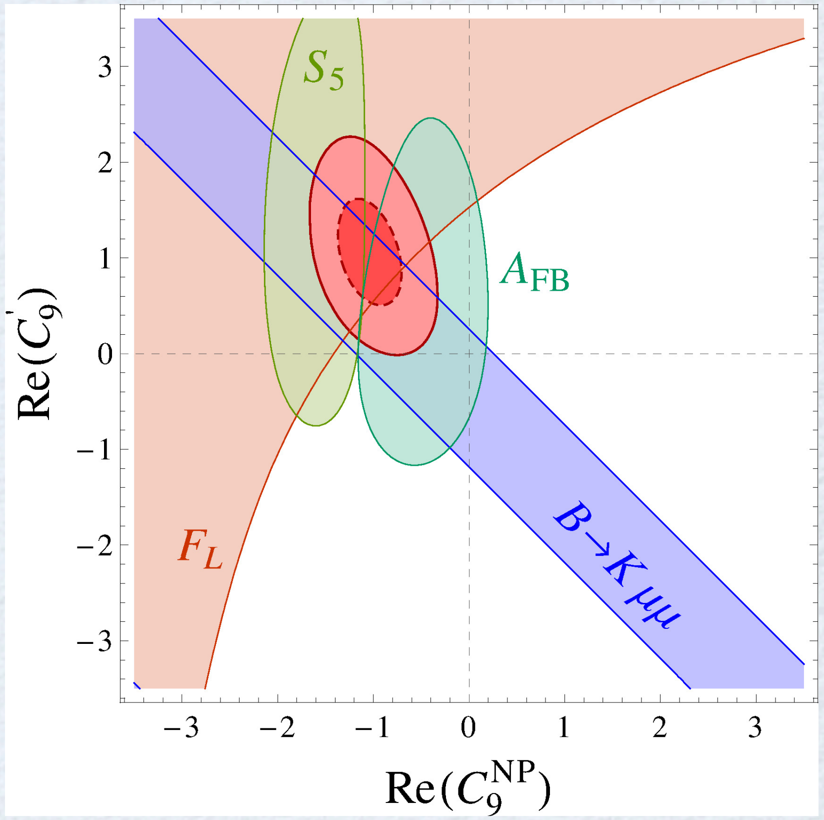
- The best fit values are $C_9^{\rm NP} = -1.0 \pm 0.3, \quad C_9' = 1.0 \pm 0.5,$

- The best fit values correspond to **a NP scale** as follows:

$$\Lambda_9^{(\prime)} \simeq 35\,\mathrm{TeV} \quad \text{as for a tree level contribution}$$

$$\Lambda_9^{(\prime)} \simeq 3\,\mathrm{TeV} \quad \text{as for 1-loop level contribution}$$

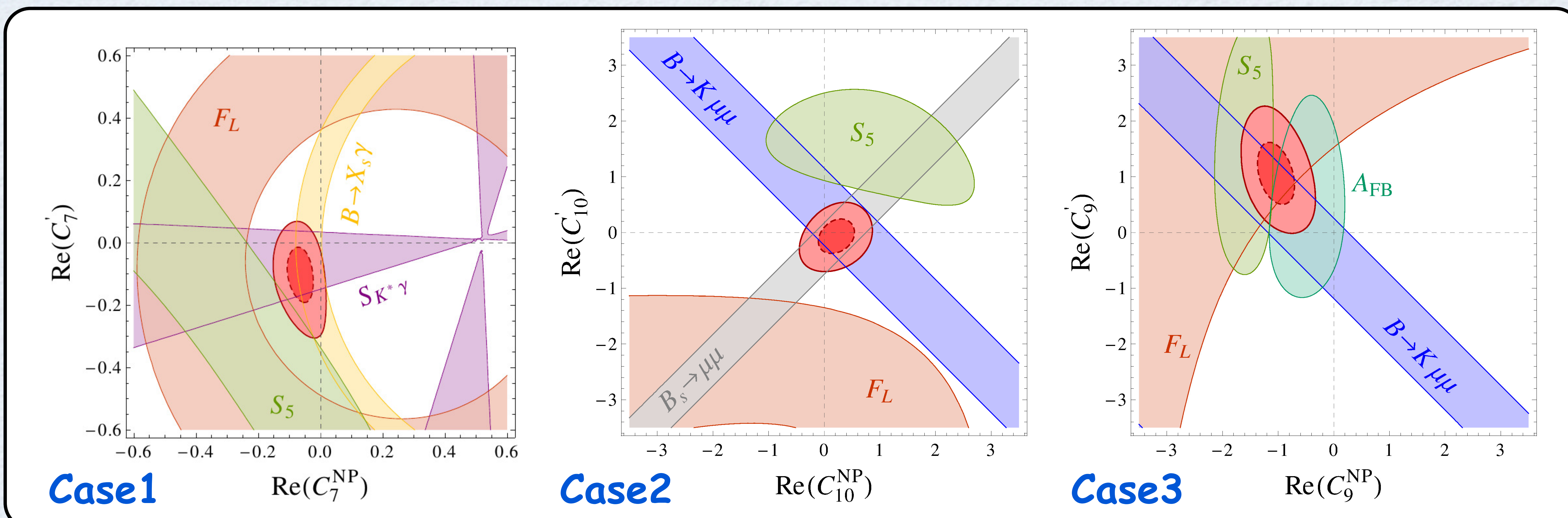
where we define $\mathcal{H}_{\rm eff} = -\sum_i \mathcal{O}_9/\Lambda_9^2$



Conclusion of this analysis:

Recent LHCb results on the B→K*μμ decay show a discrepancy with SM predictions. A consistent explanation of this discrepancy in terms of new physics is possible if NP of O₉ operator with an appropriate value of the coupling is involved, as is confirmed by various model independent analyses (which I did not show).

If the observed discrepancy in the B→K*μμ decay will be confirmed by an experimental analysis of the full LHCb data set, future precision measurement related to b→sγ and sll will be invaluable in identifying a possible underlying new physics.

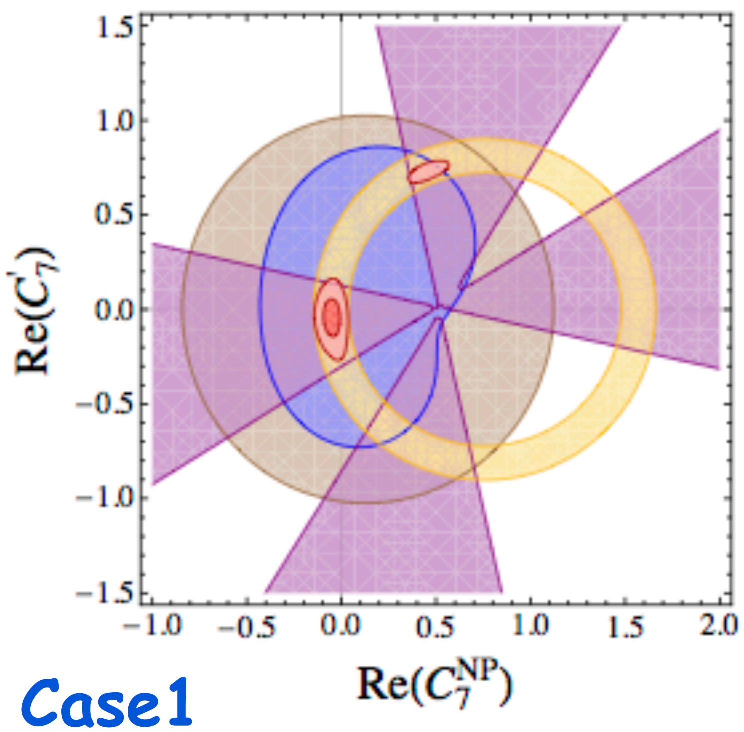


Back up

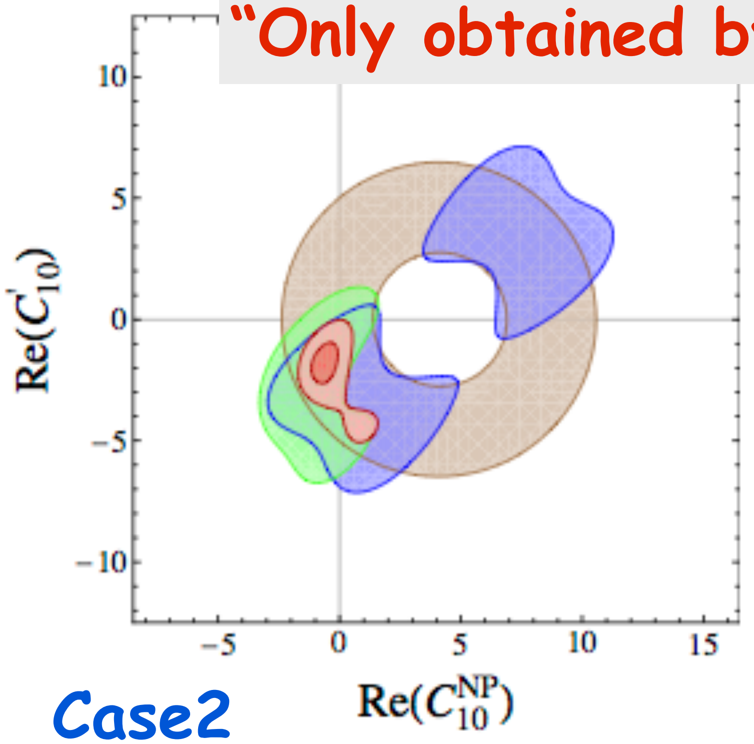
Update history:

Analysis in 2011

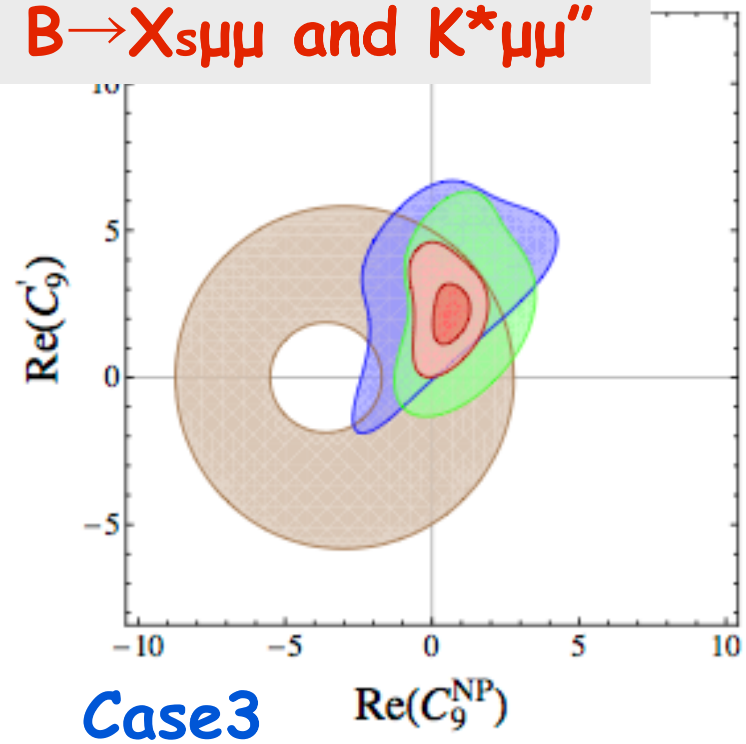
"Only obtained by B→Xsμμ and K*μμ"



Case1

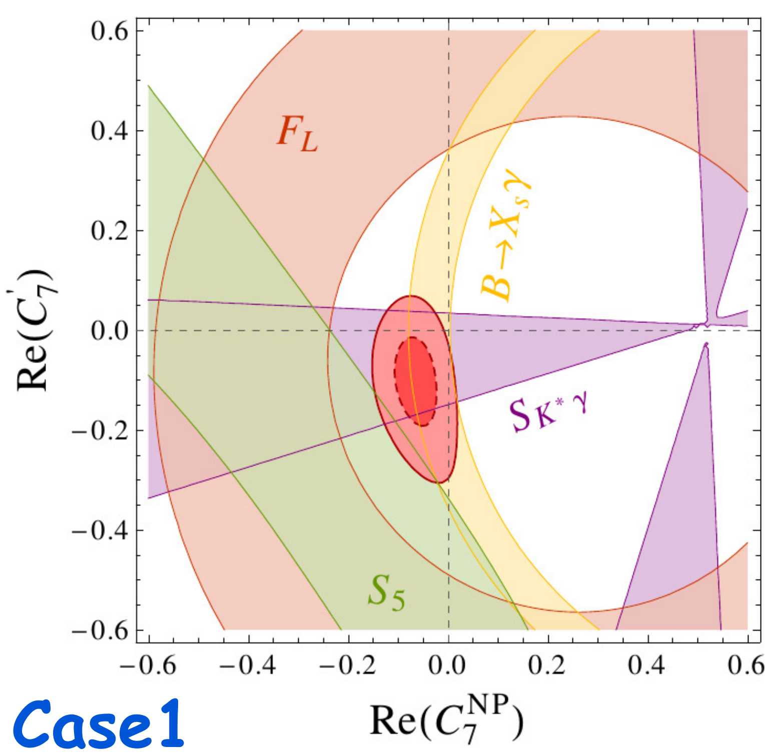


Case2

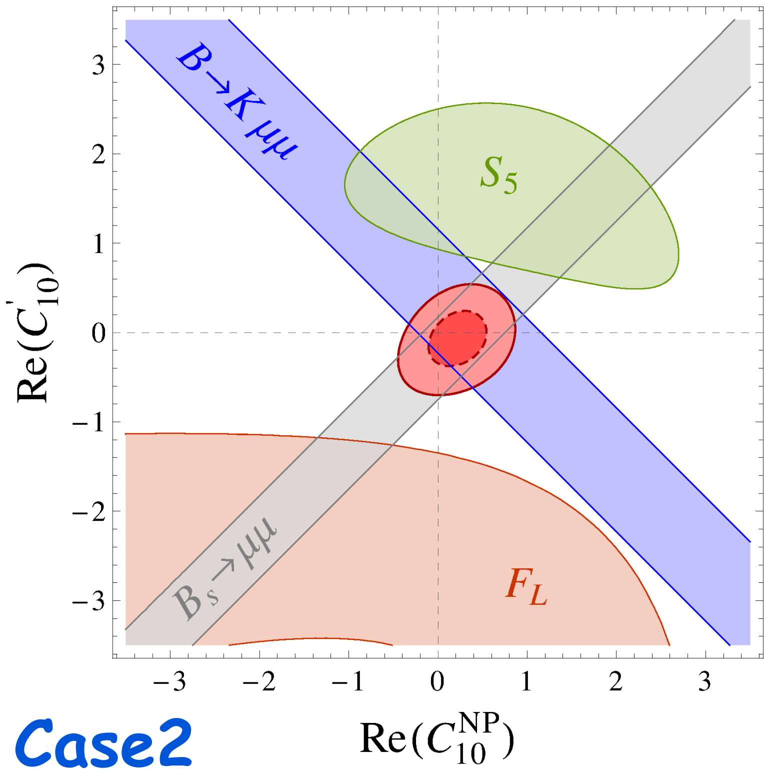


Case3

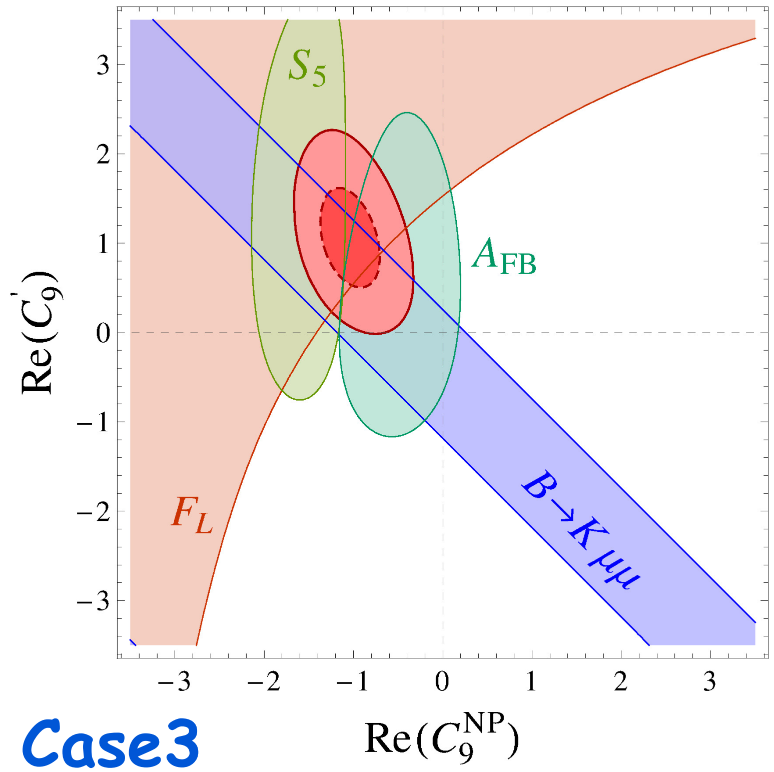
Analysis in 2014



Case1



Case2



Case3

Candidate for NP model:

The presence of the operator O_9 together with the absence of O_{10} can be realized by the model with Z' gauge bosons.

(ex.) U(1)' gauge with vector like quarks

$$C_9 = \frac{Y_{Qb} Y_{Qs}^*}{2 m_Q^2} \,, \quad C_9' = - \frac{Y_{Db} Y_{Ds}^*}{2 m_D^2} \qquad\qquad m_{Z'} = g' v_\Phi$$