Flavor Physics

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base on talks of
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Highlights from GRC, July 13th, Kavli IPMU

Belle(II), LHCb side by side

(in the context of B anomalies)

Belle (II)

$e^+e^- \to \Upsilon(4S) \to b\bar{b}$

at $\Upsilon(4S)$: 2 B's (B^0 or B^+) and nothing else ⇒ clean events

$\sigma_{b\bar{b}} \sim 1\,\mathrm{nb} \Rightarrow 1\ \mathrm{fb}^{-1}$ produces $10^6\ B\bar{B}$

$\sigma_{b\bar{b}}/\sigma_{total} \sim 1/4$

LHCb

$pp \to b\bar{b}X$

production of B^+, B^0, B_s, B_c, Λ_b...
but also a lot of other particles in the event

⇒ lower reconstruction efficiencies

$\sigma_{b\bar{b}}$ much higher than at the $\Upsilon(4S)$

	$\sqrt{s}$ [GeV]	$\sigma_{b\bar{b}}$ [nb]	$\sigma_{b\bar{b}}/\sigma_{tot}$
HERA pA	42 GeV	~30	~10^{-6}
Tevatron	2 TeV	5000	~10^{-3}
LHC	8 TeV	~3×10^5	~ 5×10^{-3}
	14 TeV	~6×10^5	~10^{-2}

$b\bar{b}$ production cross-section ~ 5× Tevatron, ~ 500,000 × BaBar/Belle !!

$\sigma_{b\bar{b}}/\sigma_{total}$ much lower than at the $\Upsilon(4S)$

⇒ lower trigger efficiencies

B mesons live relativey long

Belle (II): mean decay length $\beta\gamma c\tau \sim 200\ \mu\mathrm{m}$

LHCb: **mean decay length $\beta\gamma c\tau \sim 7$ mm**

data taking period(s)

Belle (II): [1999-2010] = 1 ab^{-1}

LHCb: [run I: 2010-2012] = 3 fb^{-1},
[run II: 2015-2018] = 2 fb^{-1} → 8 fb^{-1} ?

(near) future

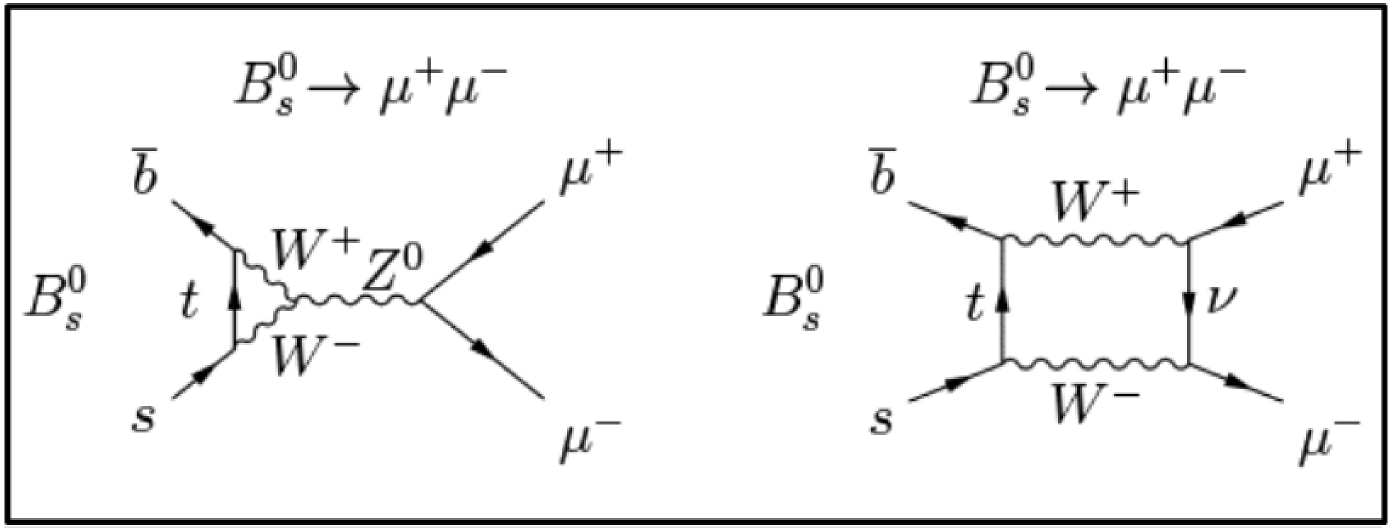
Belle (II): [Belle II from 2018] → 50 ab^{-1}

LHCb: [LHCb upgrade from 2020]

$B_{(s)} \to \mu\mu$: ultra rare processes…

loop diagram + suppressed in SM + theoretically clean =

an excellent place to look for new physics

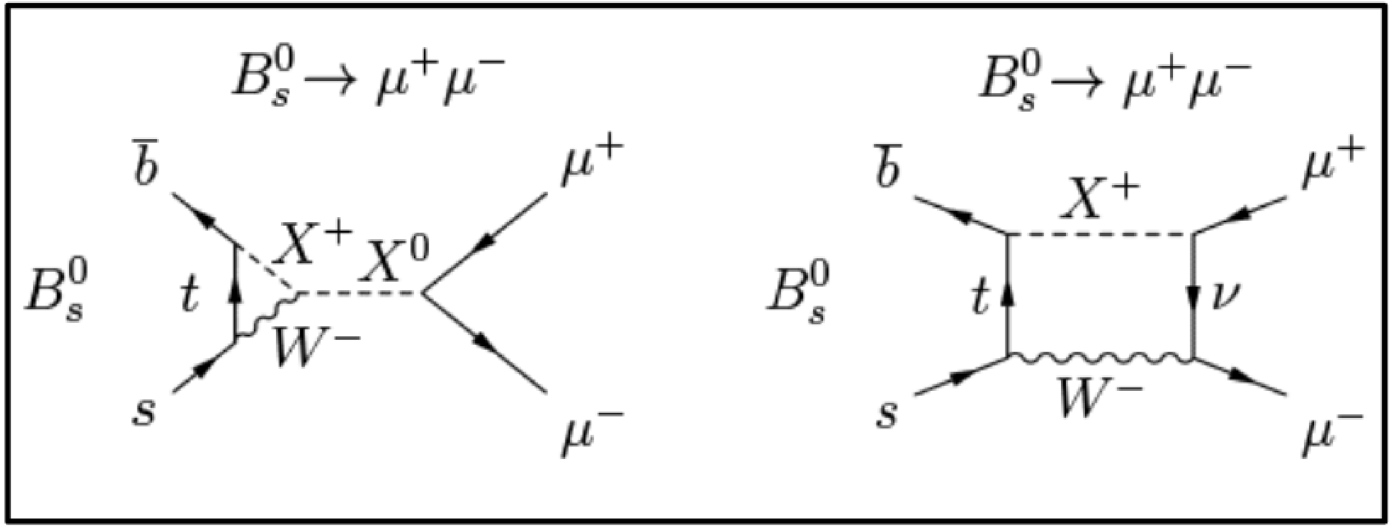


higher-order FCNC allowed in SM

$B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

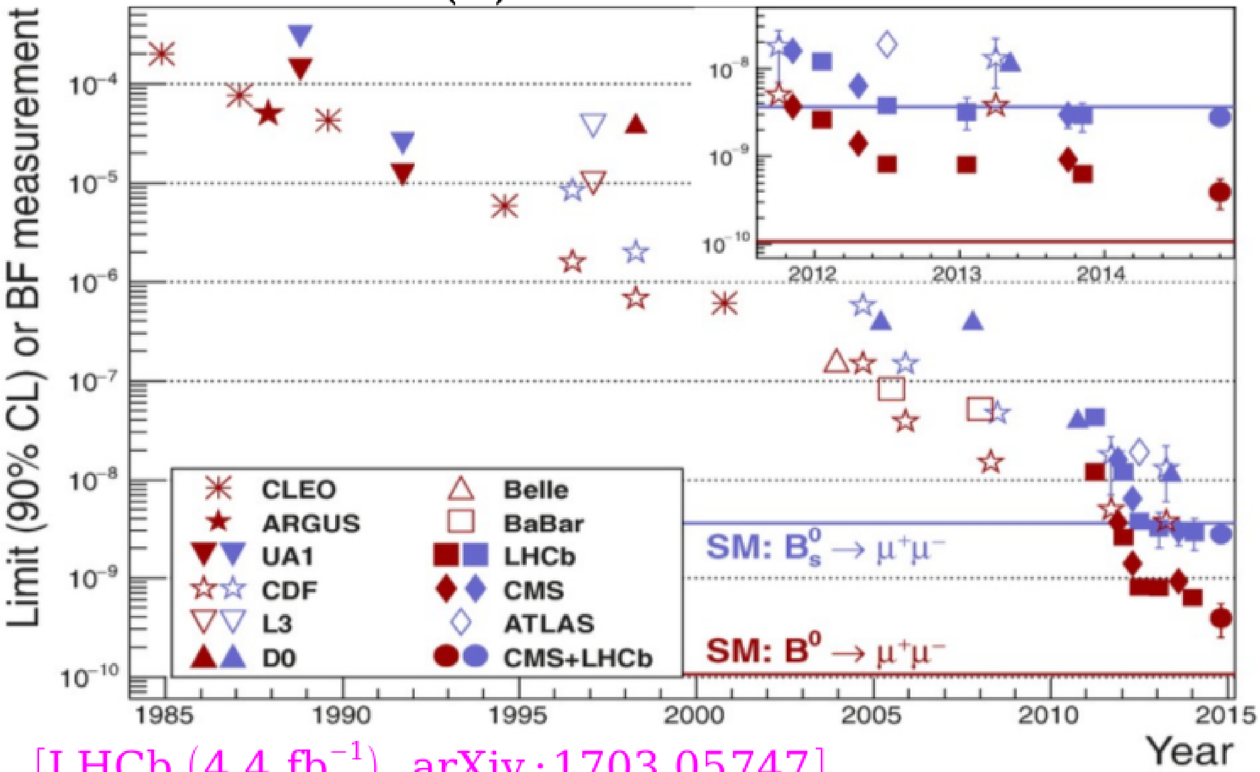
$B(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

[Bobeth et al, PRL 112 (2014) 101801]



same decay in theories extending the SM (some of NP scenarios may boost the $B \to \mu\mu$ decay rates)

$B_{(s)} \to \mu\mu$: ultra rare processes...

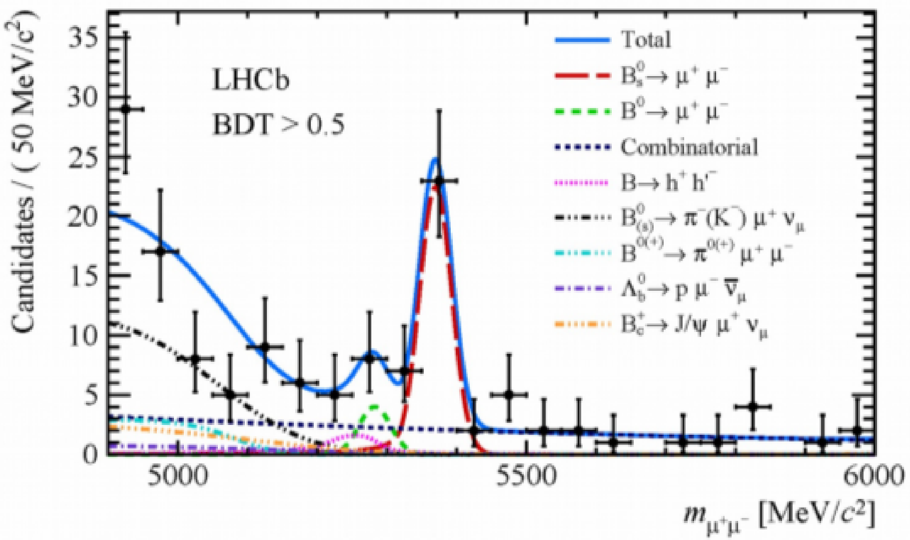


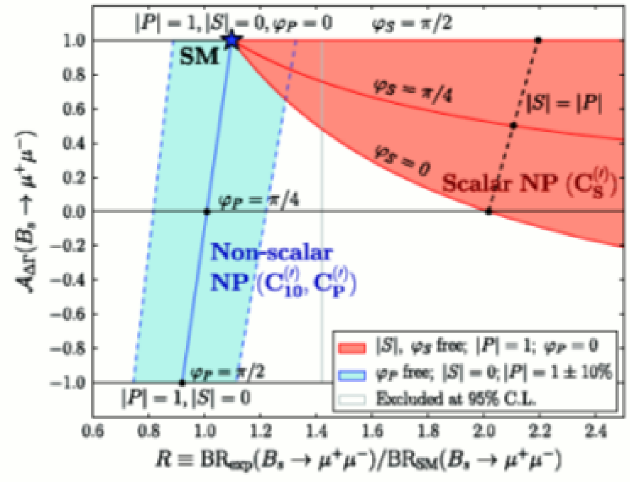
''I'm too old for limits,
I want to see signals''
(Francis Halzen, EPS15)

[LHCb (4.4 fb^{-1}), arXiv:1703.05747]

$B(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\ ^{+0.3}_{-0.2}) \times 10^{-9}$ (8σ significance)
$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 90%CL

SM: heavy state decays to $\mu^+\mu^-$
first lifetime measurement:
$\tau(B_s \to \mu^+\mu^\pm) = 2.04 \pm 0.44 \pm 0.05$ ps

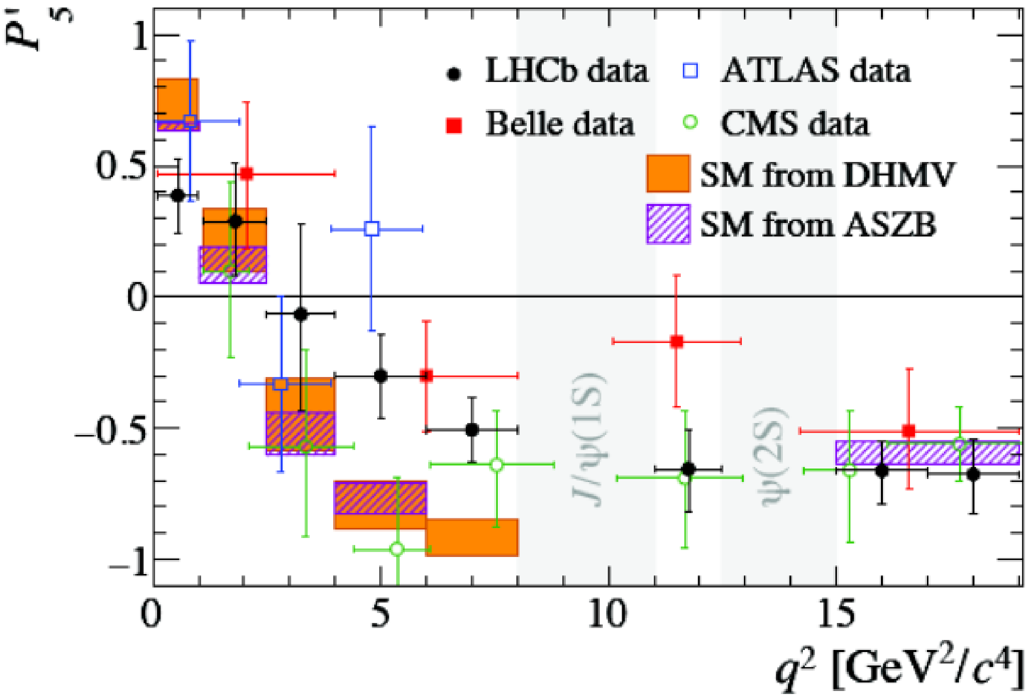




[De Bruyn et al., PRL 109, 041801 (2012)]

Angular analysis of $B_d^0 \to K^* l^+ l^-$ decays

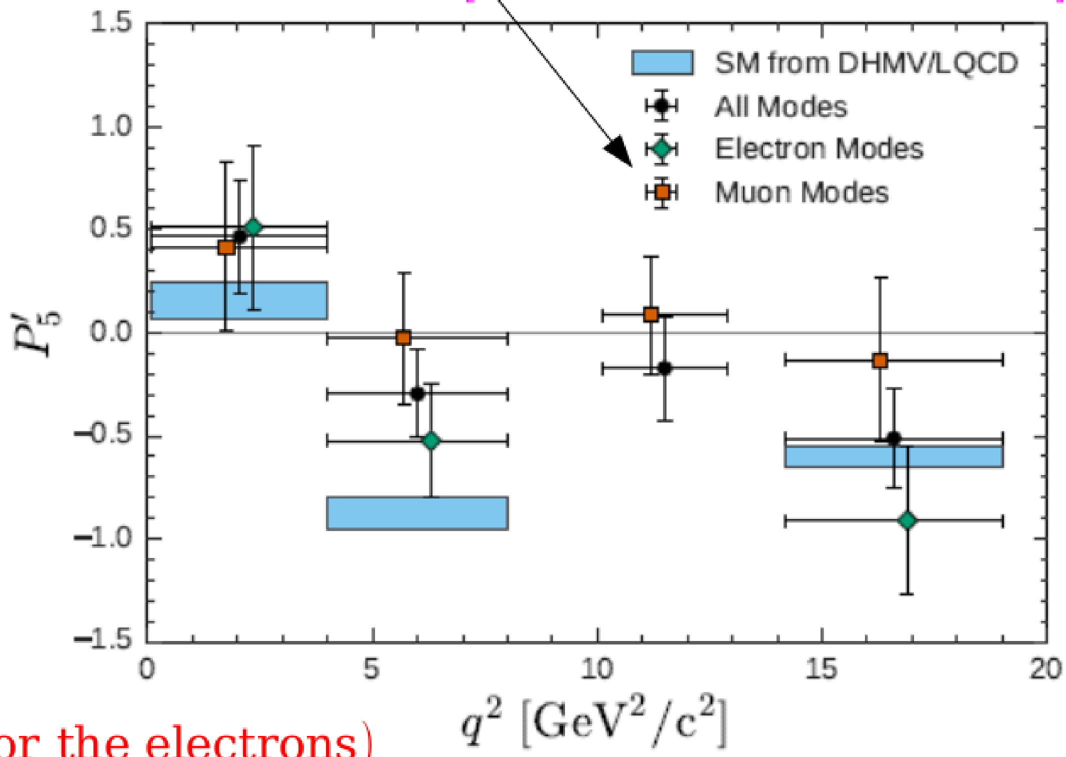
- Form-factor less dependent observables $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$



- LHCb, Belle and ATLAS show deviations in $4 < q^2 < 8\ \mathrm{GeV}^2/c^4$
- CMS shows better agreement

not only use K^{*0}, also K^{*+} ($\to K_S \pi^+$, $K^+ \pi^0$

[Belle, arXiv:1612.05014]



- LFU test, measurement of $Q^i = P^i_\mu - P^i_e$
- 2.6σ in P'_5 for the muons channels (1.3σ for the electrons)

Results

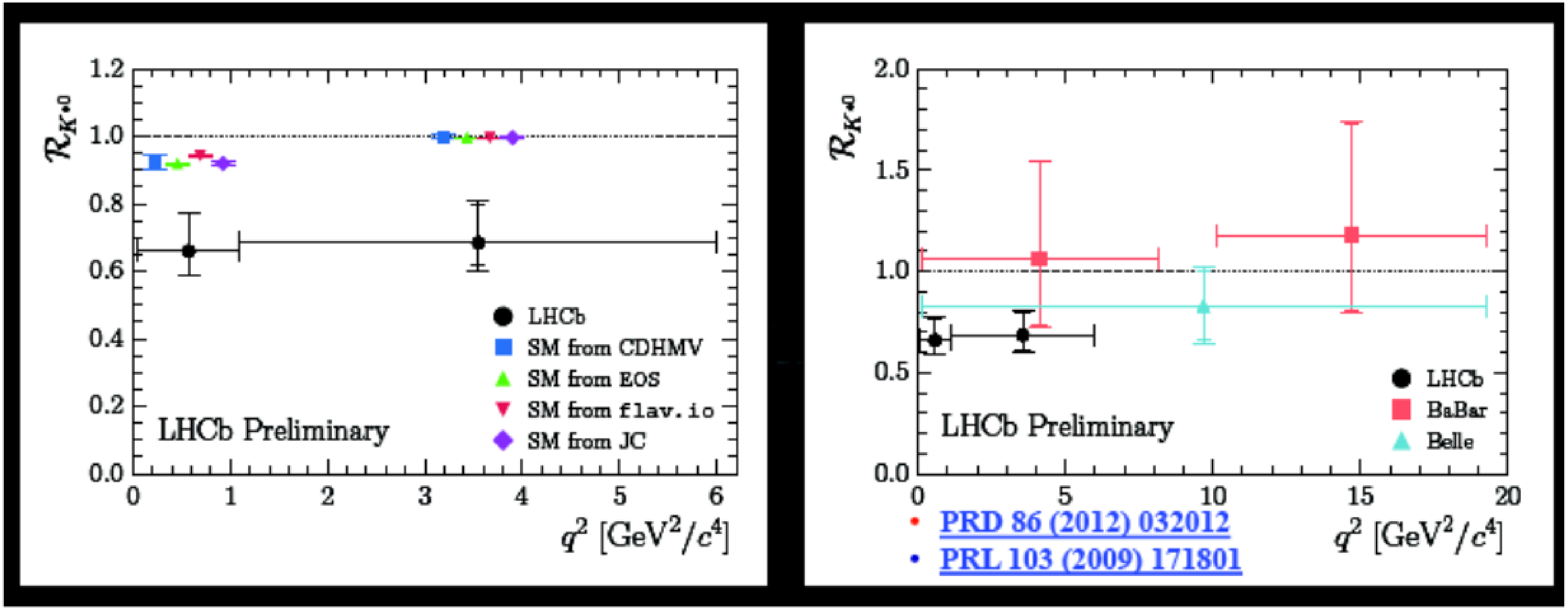
[LHCb, arXiv:1705.05802]

Precision of the measurement driven by the statistics of the electron samples

	$B^0 \to K^{*0}\ell^+\ell^-$ low-q^2	$B^0 \to K^{*0}\ell^+\ell^-$ central-q^2	$B^0 \to K^{*0}J/\psi(\to \ell^+\ell^-)$
$\mu^+\mu^-$	$285\,^{+18}_{-18}$	$353\,^{+21}_{-21}$	$274416\,^{+602}_{-654}$
e^+e^- (L0E)	$55\,^{+9}_{-8}$	$67\,^{+10}_{-10}$	$43468\,^{+222}_{-221}$
e^+e^- (L0H)	$13\,^{+5}_{-5}$	$19\,^{+6}_{-5}$	$3388\,^{+62}_{-61}$
e^+e^- (L0I)	$21\,^{+5}_{-4}$	$25\,^{+7}_{-6}$	$11505\,^{+115}_{-114}$

for $0.045 < q^2 < 1.1$ GeV^2/c^4,
$R_{K^{*0}} = 0.66\,^{+0.11}_{-0.07}\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$
for $1.1 < q^2 < 6.0$ GeV^2/c^4,
$R_{K^{*0}} = 0.69\,^{+0.11}_{-0.07}\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$

In total, about 90 and 110 $B^0 \to ee$ candidates at low- and central-q^2



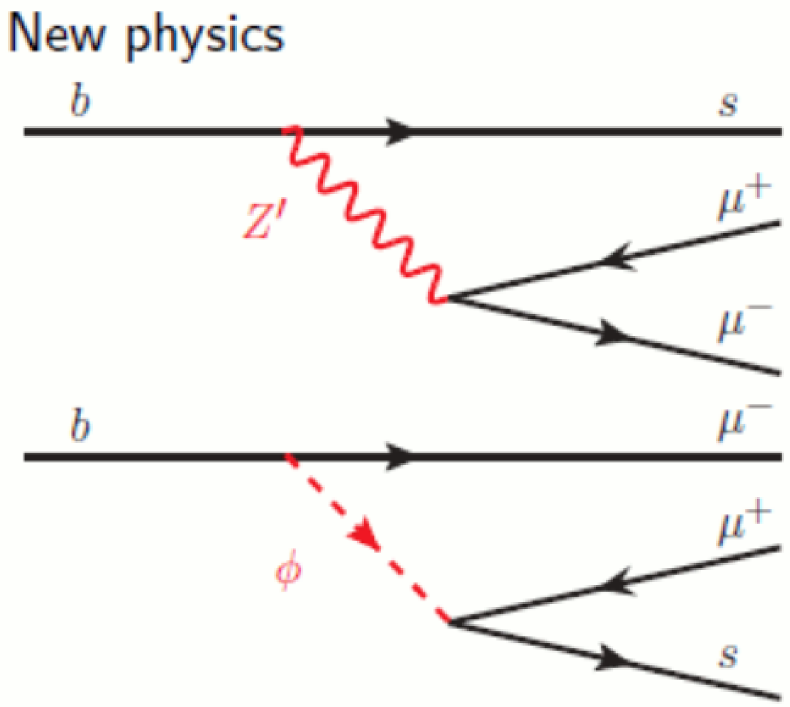
- compatibility of result in the **low-q^2** with respect to SM is of **2.2-2.4** standard dev.
- compatibility of result in the **central-q^2** with respect to SM is of **2.4-2.5** standard dev.

NP or hadronic effect ?

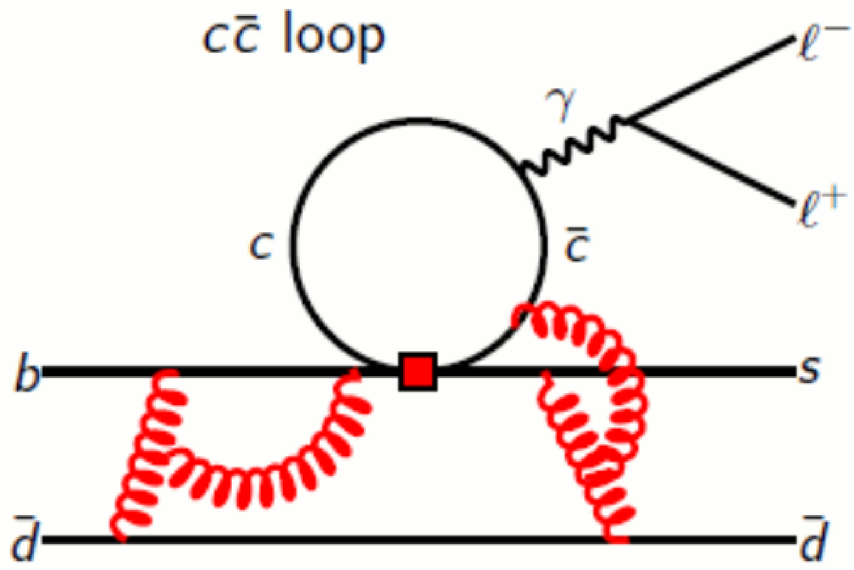
Possible explanations for shift in C_9:

a potential new physics contribution C_9^{NP} enters amplitudes always with
a charm-loop contribution $C_9^{c\bar{c}\,i}(q^2)$

⇒ **spoiling an unambiguous interpretation of the fit result in terms of NP**



NP e.g. Z', leptoquarks

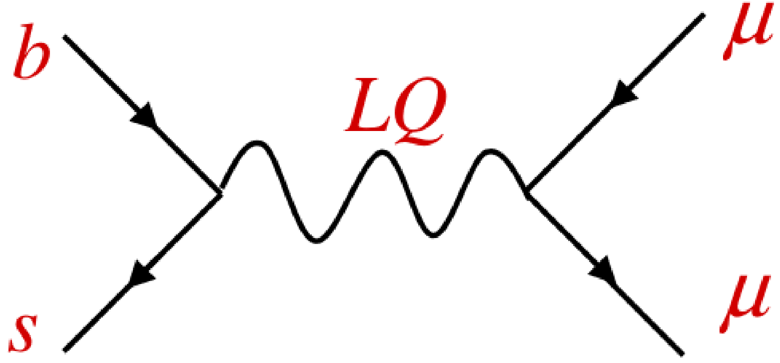


hadronic charm loop contributions

b→sμμ explenation

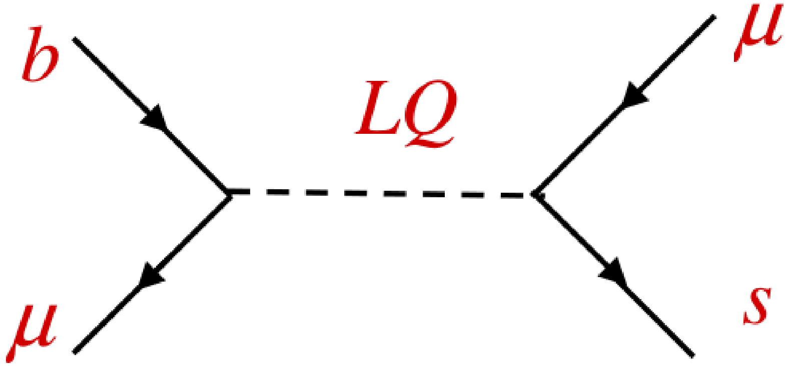
- Z' see also talk of Peter Cox

  U. Haisch et al. 1308.1959, Buras et al. 1311.6729
  W. Altmannshofer et al. 1403.1269,
  AC. et al. 1501.00993, …..



- Leptoquarks Talk of Svjetlana

  Gudrun Hiller, Martin Schmaltz.
  arXiv:1411.4773
  B. Gripaios, M. Nardecchia, S.A. Renner.
  arXiv:1412.1791
  D. Bečirević, N. Košnik, O. Sumensari,
  …



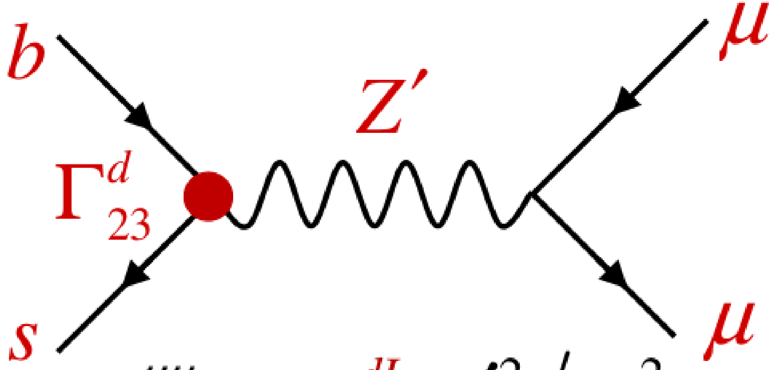
- Loop effects (more soon)

  B. Gripaios, M. Nardecchia, S. Renner, arXiv:1509.05020

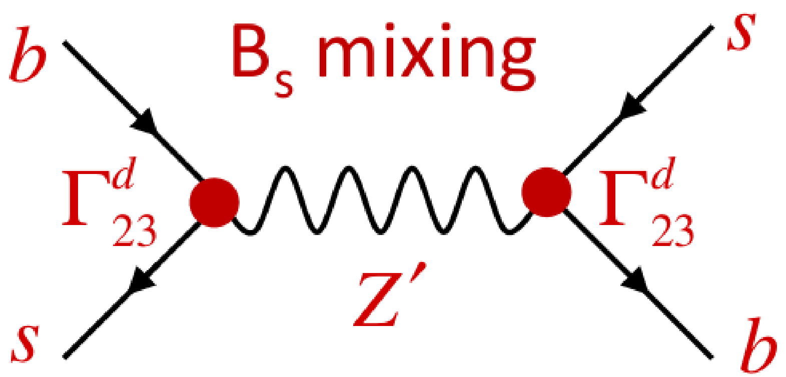
Even high scale NP explanations possible

Z' solution for b→sμμ with VLQ

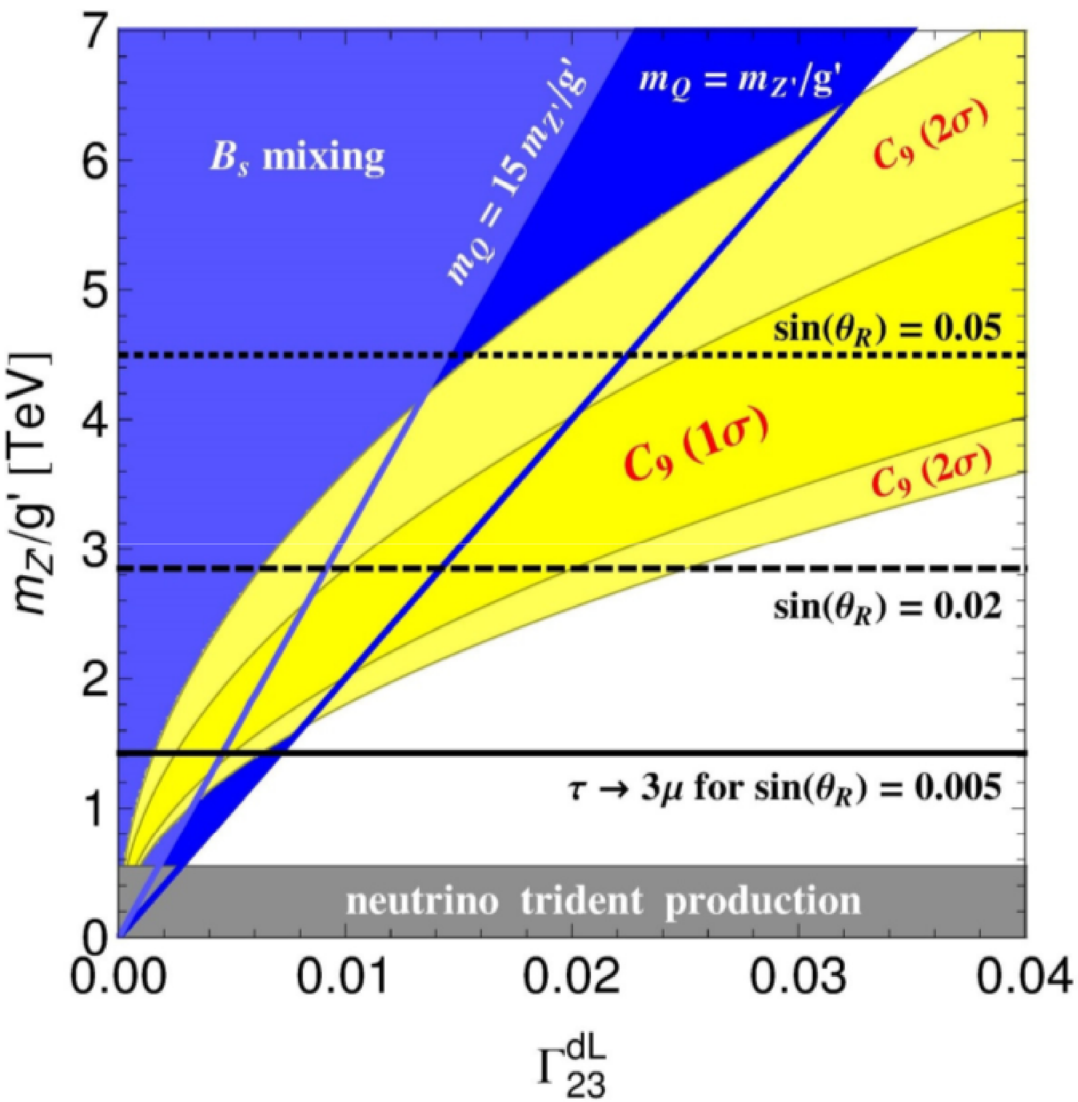
b→sμμ



$$C_9^{\mu\mu} \propto \Gamma_{23}^{dL}\, g'^2 / m_{Z'}^2$$



$$\frac{\Delta M_{12}}{M_{12}^{\mathrm{SM}}} \propto \left(\Gamma_{23}^{dL}\right)^2 g'^2 / m_{Z'}^2$$



allowed regions

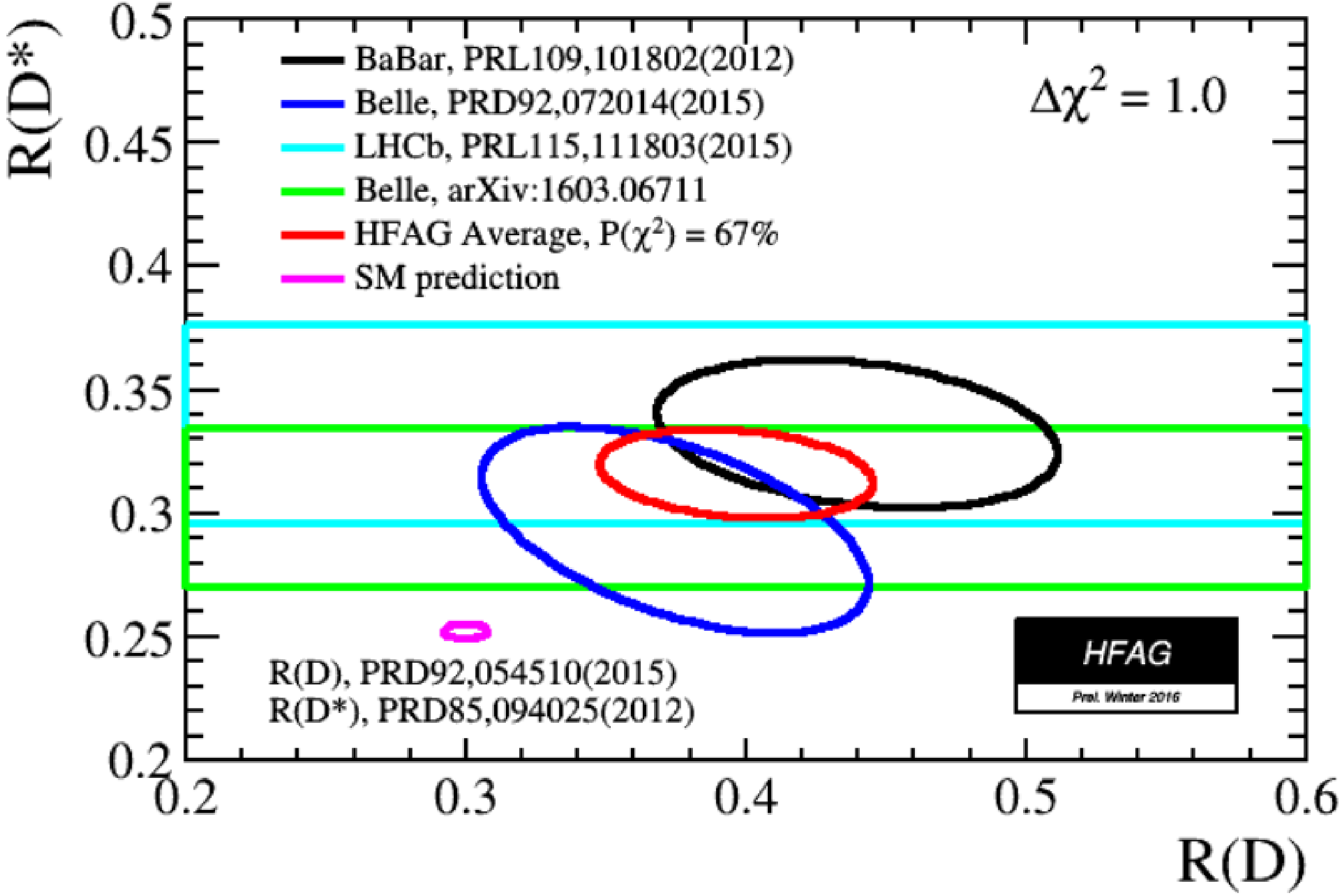
Solution with horizontal U(1) charges

- Avoid vector-like quarks by assigning charges to baryons as well
  - Same mechanism in the quark and lepton sector
- L_μ-L_τ in lepton sector
  - Good symmetry for the PMNS matrix
  - Effect in $C_9^{\mu\mu}$ but not C_9^{ee}
- First two quark generations must have the same charges because the large Cabibbo angle would lead to huge effect in Kaon mixing
- Anomaly freedom

Q(L)=(0,1,-1)   Q(B)=(a,a,-2a)

Summary for $B \to D^{(*)} \tau \nu$ in 2016

$$\Rightarrow \; R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$



BaBar

$R(D) = 0.440 \pm 0.058 \pm 0.042$
$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Belle

$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

$R(D^*) = 0.302 \pm 0.030 \pm 0.011$

LHCb

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

average

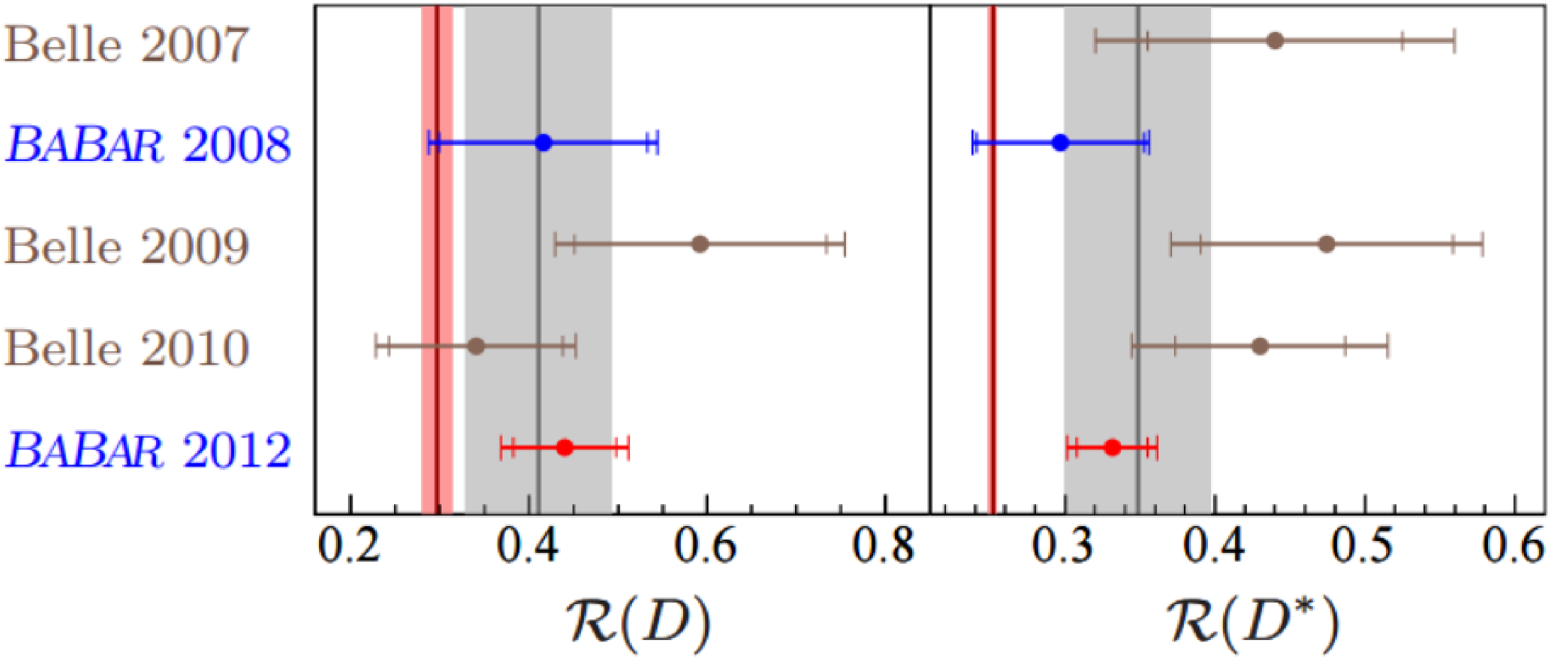
$R(D) = 0.397 \pm 0.040 \pm 0.028$
$R(D^*) = 0.316 \pm 0.016 \pm 0.010$

difference with SM predictions is at **4.0** σ level

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

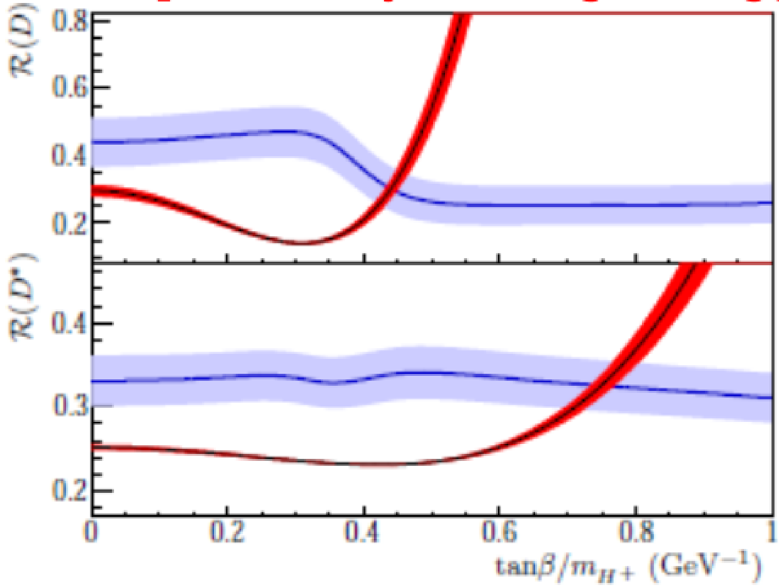
$$R(D^{(*)}) = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)}$$

Babar and Belle measurements hint to deviation from SM



BaBar (arXiv:1303.0571) observes a 3.4 σ excess over SM expectation

''This excess cannot be explained by a charged Higgs boson in the 2HDM type II''



$B \to D^{*} \tau \nu$ at Belle

$D^{(*)}$ leptonic with hadronic tagging, arXiv:1507.03233
D^{*} with leptonic tagging, arXiv:1607.07923

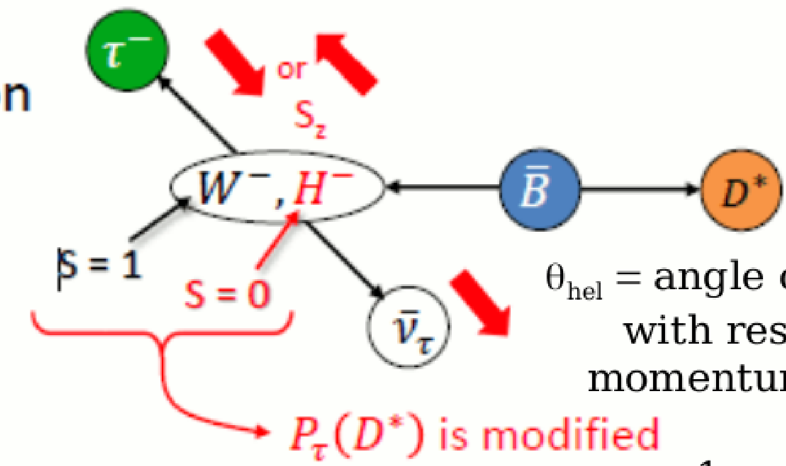
New result using:
- hadronic decays of $\tau^{-} \to \pi^{-} \nu_{\tau}, \rho^{-} \nu_{\tau}$
- hadronic tagging

$\tau^{-} \to \pi^{-}\nu_{\tau}, \rho^{-}\nu_{\tau}$ are good polarimeter for τ polarization

$$P_{\tau}(D^{*}) = \frac{\Gamma^{+} - \Gamma^{-}}{\Gamma^{+} + \Gamma^{-}}$$

$\Gamma^{+(-)}$ for right-(left-)handed τ

$P_{\tau}(D^{*})_{SM} = -0.497 \pm 0.013$
M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)



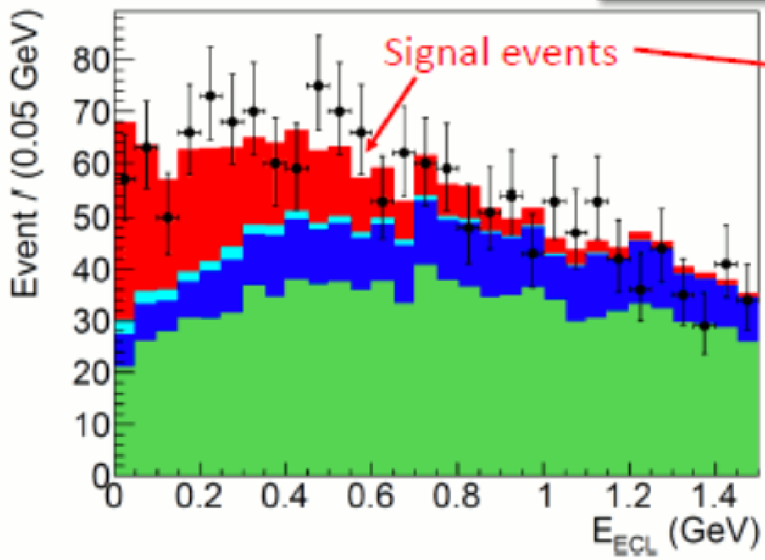
θ_{hel} = angle of τ daughter meson momentu with respect to direction opposite to momentum of $\tau\nu$ system in τ rest frame

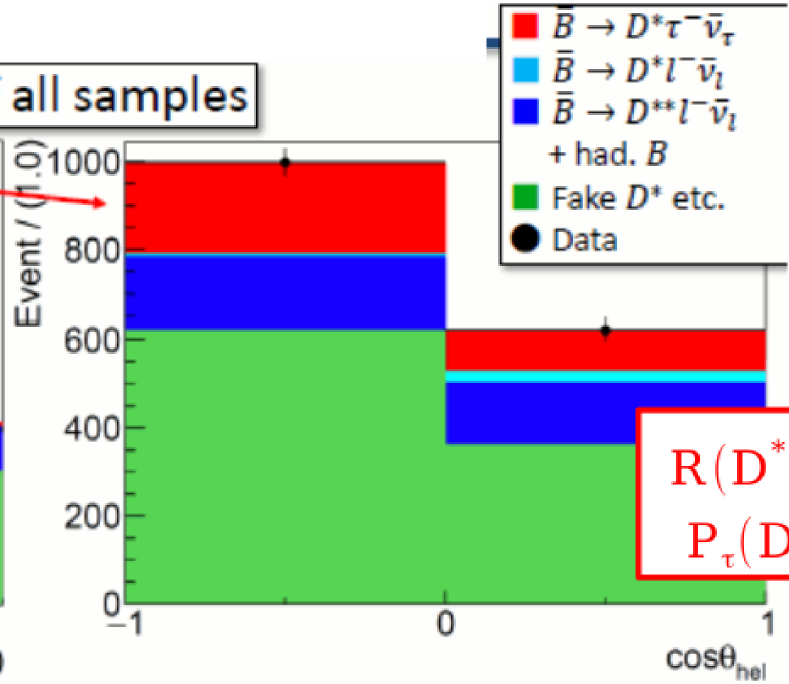
$$\frac{1}{\Gamma(D^{*})}\frac{d\Gamma(D^{*})}{d\cos\theta_{hel}} = \frac{1}{2}[1 \alpha P_{\tau}(D^{*})\cos\theta_{hel}]$$

τ polarization is a variable sensitive to NP

[Belle, arXiv:1612.00529]

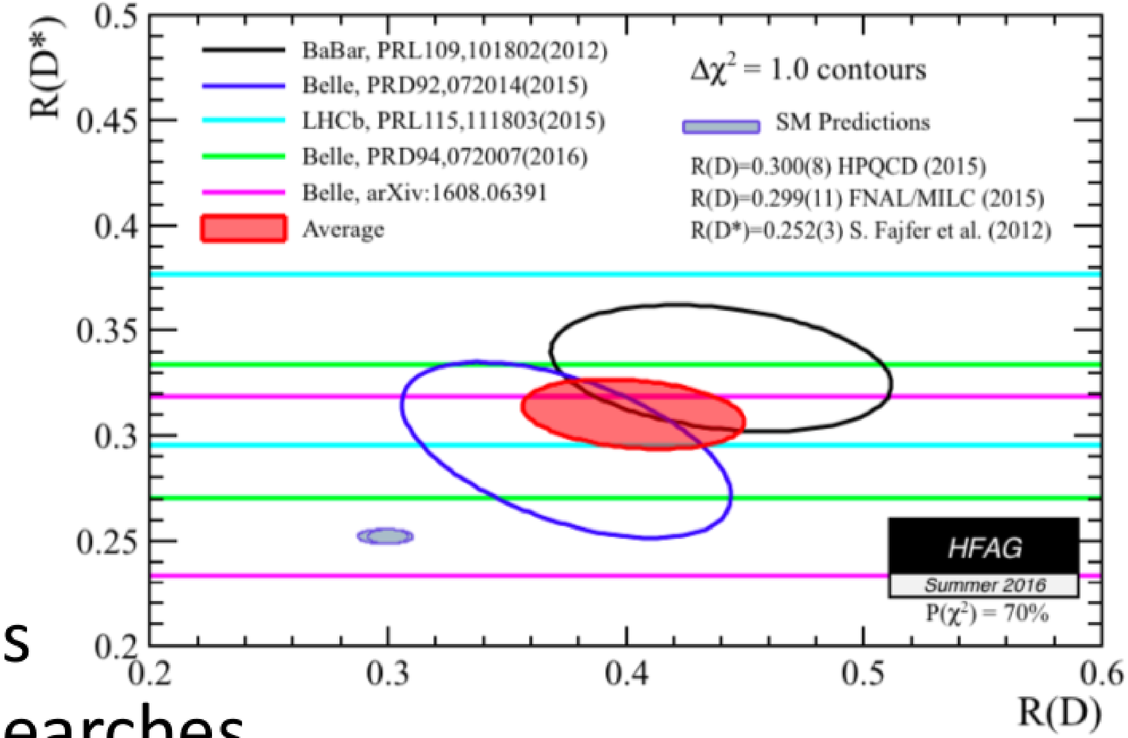
Sum of all samples





$$R(D^{*}) = 0.270 \pm 0.035 \,^{+0.028}_{-0.025}$$
$$P_{\tau}(D^{*}) = -0.38 \pm 0.51 \,^{+0.21}_{-0.16}$$

R(D) & R(D*)



- Charged scalars
  - Problems with q^2 distributions and B_c lifetime
- W'
  - Strong constraints from direct LHC searches
- Leptoquark see talk of Svjetlana
  - Strong signals in $qq \rightarrow \tau\tau$ searches

Faroughy et al. arXiv:1609.07138

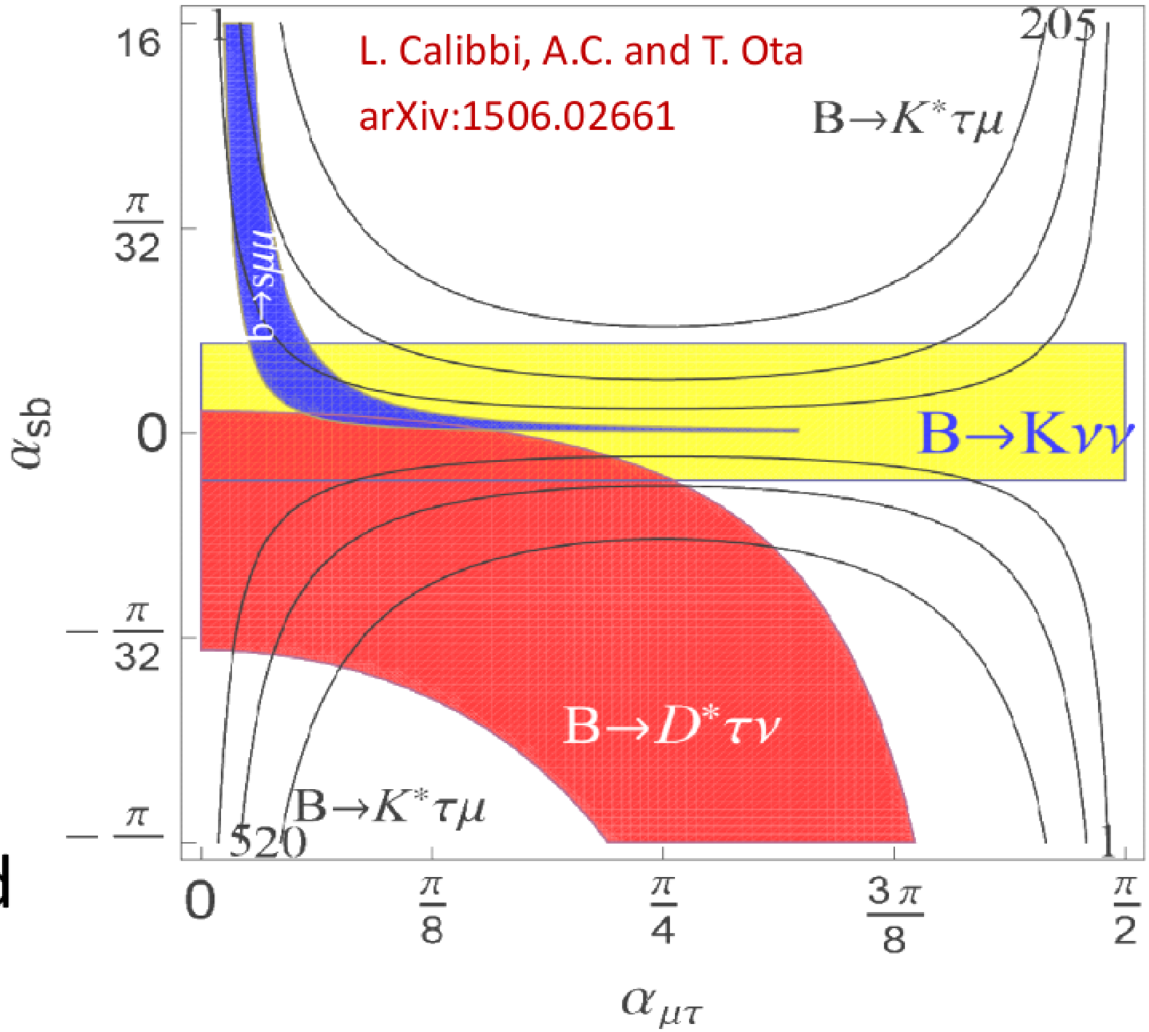
Explanation difficult

Leptoquarks in b→sμμ and b→cτν

Third generation couplings

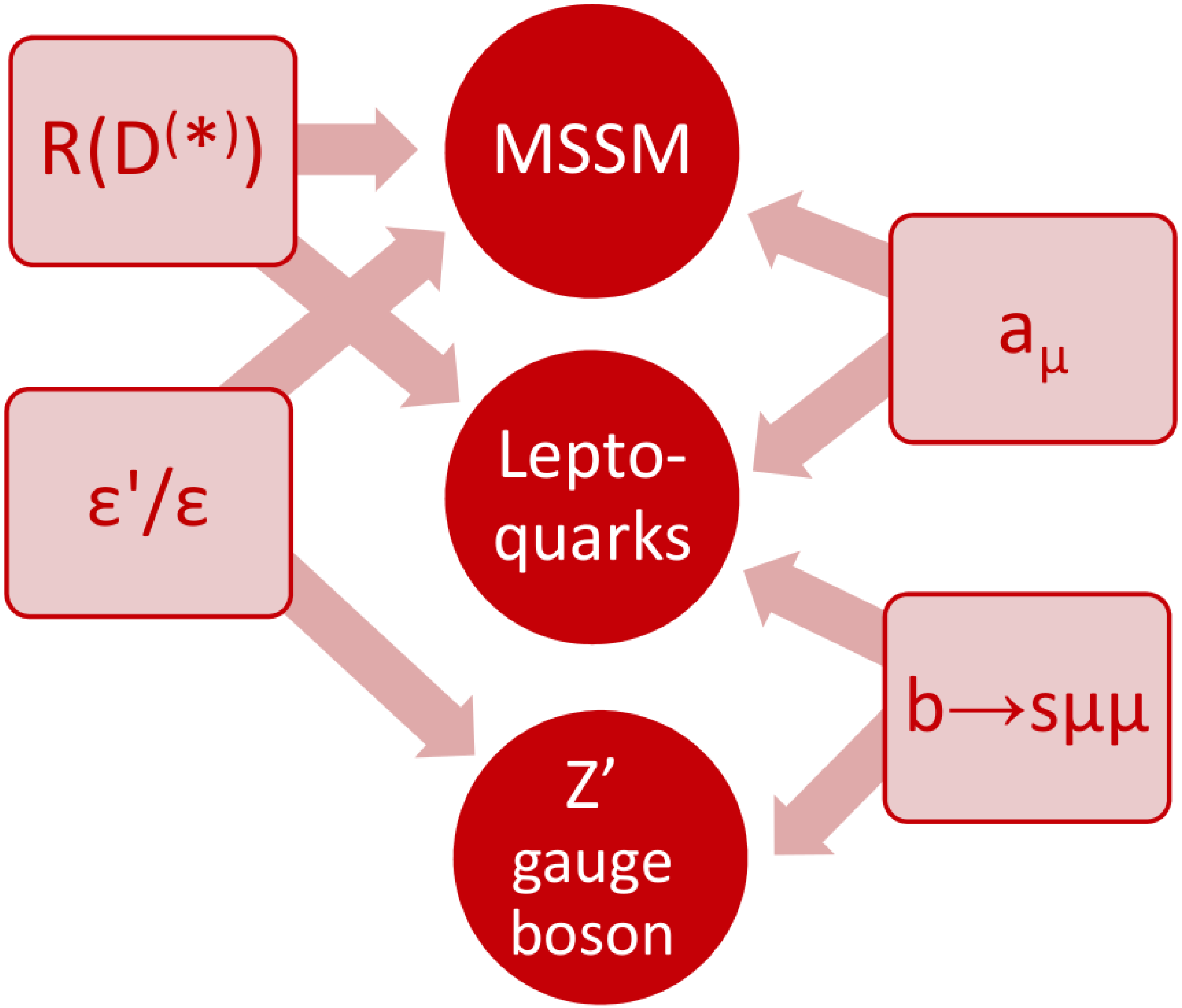
$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

α Misalignment between interaction and mass basis



Simultaneous explanation possible

Implications for New Particles



cLFV : beyond the Standard Model

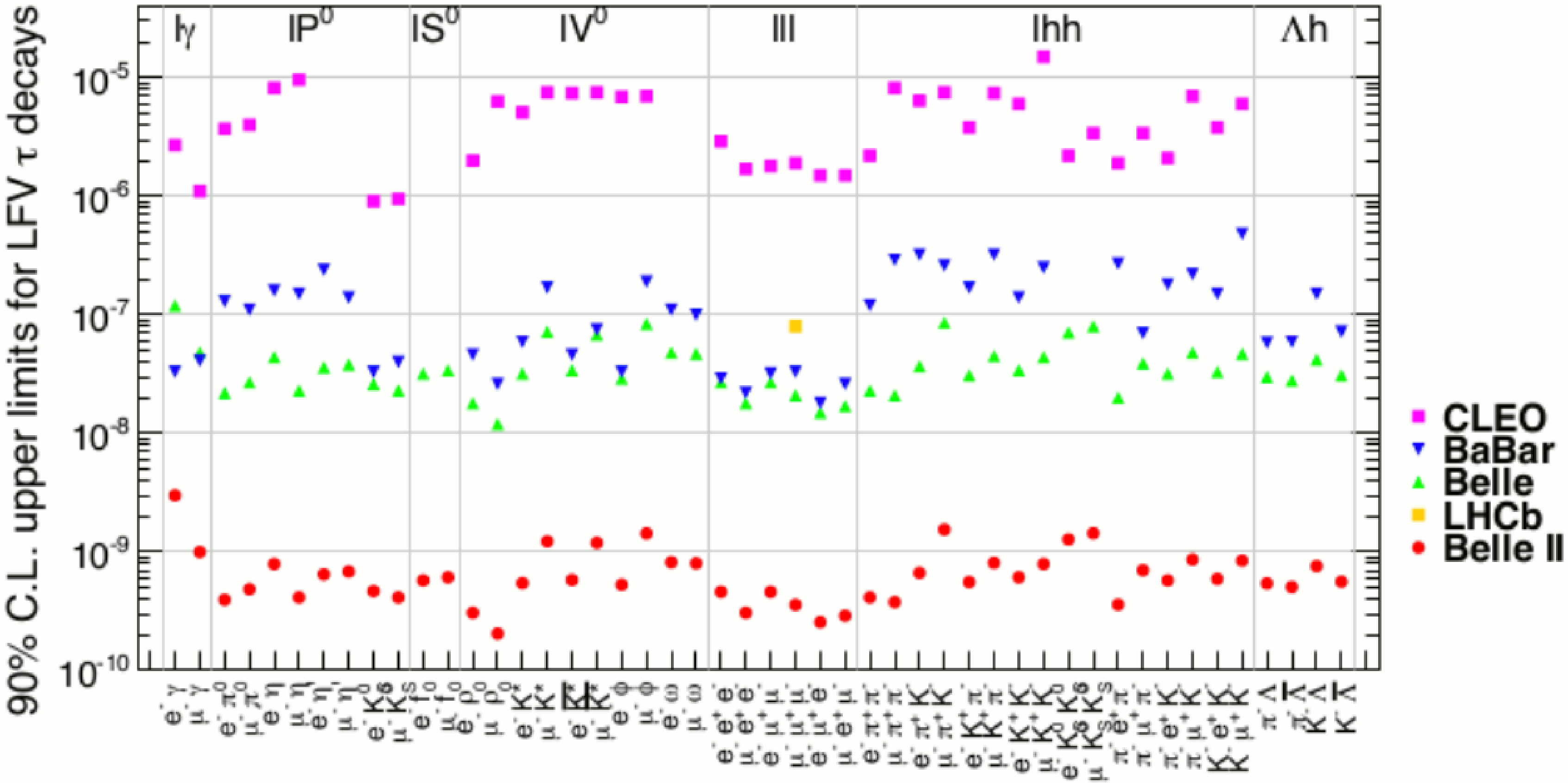
$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left|U^*_{\tau i}U_{\mu i}\frac{\Delta m^2_{3i}}{m^2_W}\right|^2 < 10^{-40}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda}O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}O_i^{(6)} + \ldots$$

Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

		$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
4-lepton	$O^{4\ell}_{S,V}$	✓	–	–	–	–	–
dipole	O_D	✓	✓	✓	✓	–	–
lepton-quark	O^q_V	–	–	✓ (I=1)	✓(I=0,1)	–	–
lepton-quark	O^q_S	–	–	✓ (I=0)	✓(I=0,1)	–	–
lepton-gluon	O_{GG}	–	–	✓	✓	–	–
lepton-quark	O^q_A	–	–	–	–	✓ (I=1)	✓ (I=0)
lepton-quark	O^q_P	–	–	–	–	✓ (I=1)	✓ (I=0)
lepton-gluon	$O_{G\tilde{G}}$	–	–	–	–	–	✓

Celis, Cirigliano, Passemar (2014)



Summary

- There are anomalies among the B-meson. They can be checked by Belle-II in near future.

- Bs-->dimuon and b-->s+dimuon are relevant.

- NP simultaneously explains some anomalies and gives predictions. These can be used as model selection.