A Beautiful Way of Going Beyond the Standard Model

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Yes!!!

Not yet at the 5σ level to claim definite evidence of BSM

Still, worth exploring.

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$\boxed{\text{And there we go into the beautiful world of } b\text{-hadrons}}$

B-factories: past, present, and future

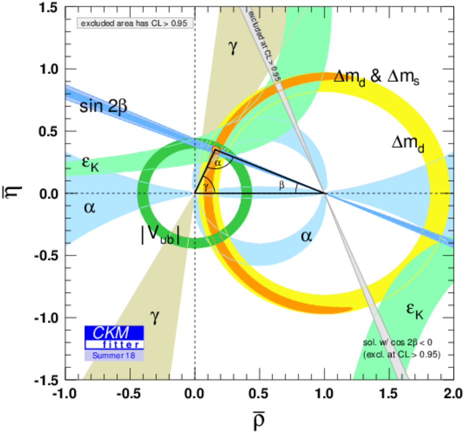
$\boxed{\text{BaBar@SLAC}}$: e^+e^-, 429 fb^{-1}, 4.7×10^8 $B\bar{B}$ pairs

$\boxed{\text{Belle@KEK}}$: e^+e^-, over 1 ab^{-1}, 7.72×10^8 $B\bar{B}$ pairs

LHCb : 6.8 fb^{-1} till 2017 (3.6 fb^{-1} at 13 TeV)
7 TeV: $\sigma(pp \to b\bar{b}X) = (89.6 \pm 6.4 \pm 15.5)$ μb, scales linearly with $\sqrt{s}$

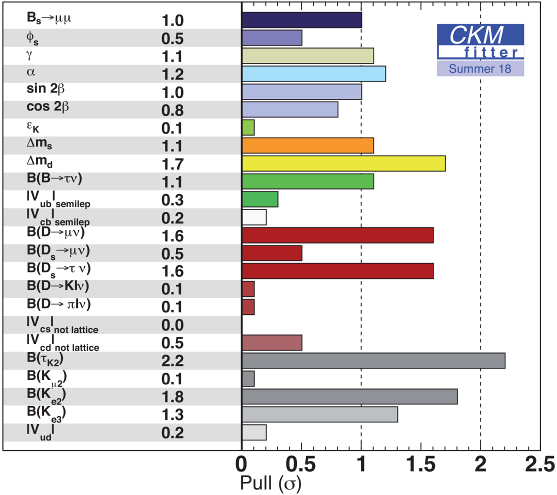
ATLAS and CMS also have dedicated flavour physics programme

LHCb:
Upgrade I: $\mathcal{L}_{\rm int} > 50$ fb^{-1}, 2×10^{33} cm^{-2}s^{-1}
Phase II with HL-LHC: $\mathcal{L}_{\rm int} > 300$ fb^{-1}, 2×10^{34} cm^{-2}s^{-1}
Belle-II:
$\mathcal{L}_{\rm int} = 50$ ab^{-1} in 5 years, can go up even higher



α	$91.6^{+1.7}_{-1.1}$
β direct	$22.14^{+0.69}_{-0.67}$
β indirect	23.9 ± 1.2
β average	$22.51^{+0.55}_{-0.40}$
γ	$65.81^{+0.99}_{-1.66}$

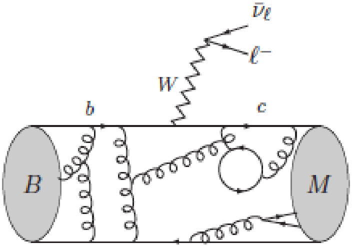
CKM paradigm rules !!!
NP has to be subdominant



Bs→μμ 1.0
φs 0.5
γ 1.1
α 1.2
sin 2β 1.0
cos 2β 0.8
εK 0.1
Δms 1.1
Δmd 1.7
B(B→τν) 1.1
|Vub|semilep 0.3
|Vcb|semilep 0.2
B(D→μν) 1.6
B(Ds→μν) 0.5
B(Ds→τ ν) 1.6
B(D→Klν) 0.1
B(D→ πlν) 0.1
|Vcs|not lattice 0.0
|Vcd|not lattice 0.5
B(τK2) 2.2
B(Kμ2) 0.1
B(Ke2) 1.8
B(Ke3) 1.3
|Vud| 0.2
CKM fitter
Summer 18
0 0.5 1 1.5 2 2.5
Pull (σ)

A few interesting anomalies

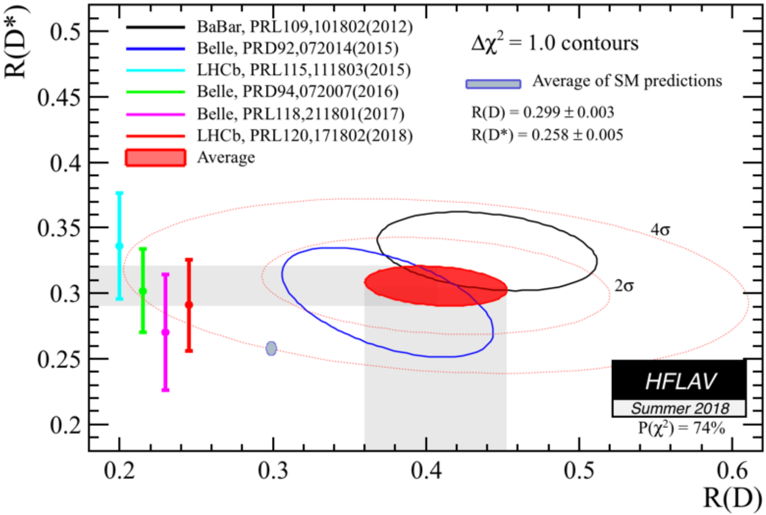
Experiment	R(D*)	R(D)
BaBar	0.332 +/- 0.024+/- 0.018	0.440 +/- 0.058 +/- 0.042
BELLE	0.293 +/- 0.038 +/- 0.015	0.375 +/- 0.064 +/- 0.026
BELLE	0.302 +/- 0.030 +/- 0.011	-
LHCb	0.336 +/- 0.027 +/- 0.030	-
BELLE	$0.270 \pm 0.035\ ^{+0.028}_{-0.025}$	-
LHCb	0.291 +/- 0.019 +/- 0.029	-
Average .txt	**0.306 +/- 0.013 +/- 0.007**	**0.407 +/- 0.039 +/- 0.024**



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

	R(D)	R(D*)
D.Bigi, P.Gambino, Phys.Rev. D94 (2016) no.9, 094008 [arXiv:1606.08030 [hep-ph]]	0.299 +- 0.003	
F.Bernlochner, Z.Ligeti, M.Papucci, D.Robinson, Phys.Rev. D95 (2017) no.11, 115008 [arXiv:1703.05330 [hep-ph]]	0.299 +- 0.003	0.257 +- 0.003
D.Bigi, P.Gambino, S.Schacht, JHEP 1711 (2017) 061 [arXiv:1707.09509 [hep-ph]]		0.260 +- 0.008
S.Jaiswal, S.Nandi, S.K.Patra, JHEP 1712 (2017) 060 [arXiv:1707.09977 [hep-ph]]	0.299 +- 0.004	0.257 +- 0.005
Arithmetic average	**0.299 +- 0.003**	**0.258 +- 0.005**

2.3σ for $R(D)$, 3.0σ for $R(D^*)$, 3.78σ combined with corr.


R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, PRL120,171802(2018)
Average
$\Delta\chi^2 = 1.0$ contours
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
4σ
2σ
HFLAV
Summer 2018
$P(\chi^2) = 74\%$
0.2
0.3
0.4
0.5
0.6
R(D)

Longitudinal polarization fraction for $B \to D^*\tau\nu$

$$F_L = 0.457 \pm 0.010\ (\mathrm{SM})\,, \quad 0.60 \pm 0.09\ (\mathrm{Belle}\ 1903.03102)$$

While we are talking about $b \to c\tau\nu$

$$R_{J/\psi} = \frac{\mathrm{BR}(B_c \to J/\psi\,\tau\nu)}{\mathrm{BR}(B_c \to J/\psi\,\ell\nu)} = 0.71 \pm 0.17 \pm 0.18\ (\mathrm{exp})\,, \quad 0.283 \pm 0.048\ (\mathrm{SM})$$

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And the neutral current $b \to s\ell^+\ell^-$

$$R_{K(K^*)} = \frac{\mathrm{BR}(B \to K(K^*)\mu^+\mu^-)}{\mathrm{BR}(B \to K(K^*)e^+e^-)}$$

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e or μ? $B_s \to \phi\mu^+\mu^-$ is also interesting $\cdots$

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$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036 \qquad q^2 \in [1:6]\ \mathrm{GeV}^2\,,$$

$$R_{K^*}^{\mathrm{low}} = 0.66^{+0.11}_{-0.07} \pm 0.03 \qquad q^2 \in [0.045:1.1]\ \mathrm{GeV}^2\,,$$

$$R_{K^*}^{\mathrm{central}} = 0.69^{+0.11}_{-0.07} \pm 0.05 \qquad q^2 \in [1.1:6]\ \mathrm{GeV}^2\,.$$

$$\frac{d}{dq^2}\mathrm{BR}(B_s \to \phi\mu\mu)\Big|_{q^2\in[1:6]\ \mathrm{GeV}^2} = \begin{cases} \left(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19\right) \times 10^{-8}\ \mathrm{GeV}^{-2} & (\mathrm{exp.}) \\ (4.81 \pm 0.56) \times 10^{-8}\ \mathrm{GeV}^{-2} & (\mathrm{SM}), \end{cases}$$

Is there some pattern?

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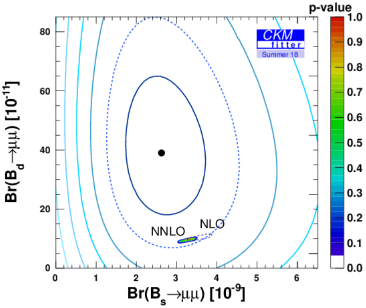
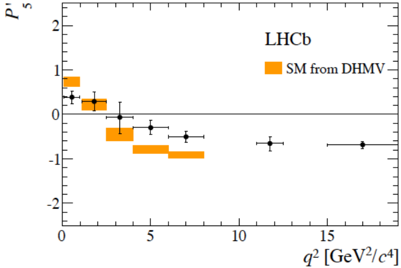
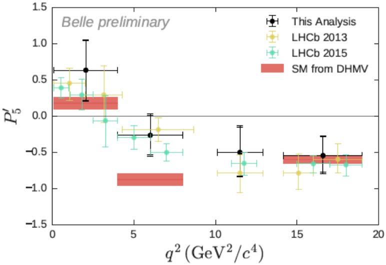
But $B_s/B_d \to \mu\mu$ is consistent with the SM
(Only theory errors are from f_{B/B_s} and CKM. NLO EW, NNLO QCD, soft photon, large $\Delta\Gamma_s$ effects taken into account)



while $B \to K^* \mu\mu$ observable P_5' shows a deviation





LHCb: two bins deviating by 2.8σ and 3.0σ
Belle confirms with larger uncertainty
CMS and ATLAS: Consistent with both LHCb/Belle and SM, large uncertainties

Effective theory approach

$$\mathcal{H}_{\rm eff} = (CKM) \sum_i C_i O_i$$

Main source of uncertainty: FF in $\langle M | \mathcal{H}_{\rm eff} | B \rangle$
Ratios are relatively insensitive

Example: $b \to s\mu^+\mu^-$

$$\mathcal{H}_{\rm eff}^{\rm SM} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu)$$

with the relevant operators

$$\begin{aligned}
O_7 &= \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\mu\nu} P_R b\right) F^{\mu\nu}, \quad C_7 = -0.304 \\
O_9 &= \frac{e^2}{16\pi^2} \left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\mu}\gamma_\mu \mu\right), \quad C_9 = 4.211 \\
O_{10} &= \frac{e^2}{16\pi^2} \left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\mu}\gamma_\mu \gamma_5 \mu\right), \quad C_{10} = -4.103
\end{aligned}$$

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Top-down:
UV complete theory $\longrightarrow$ Get C_i at high scale with proper matching $\longrightarrow$ Run down to m_b $\longrightarrow$ Check consistency with data

Examples: leptoquarks, extra Z'

Bottom-up:
Fit data with set of chosen operators $\longrightarrow$ Get the corresponding C_i

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How reliable are the form factors?

- $B \to K, D$: Only two FF, f_0 and f_1, determined over the entire q^2-range from lattice
- $B \to K^*, D^*$: Four FF, V, A_0, A_1, A_2, lattice not yet complete, HQET is helpful, higher-order corrections can be estimated
- There can be more FF with BSM operators (like tensor)

Are there other pitfalls?

D^* is detected as $D\pi$, take finite decay width into consideration

Reduces tension to 2.2σ [Chavez-Saab and Toledo, 1806.06997]

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- Consider a new operator involving τ. Rotate the leptonic (τ, μ) basis to (τ', μ') [Glashow, Guadagnoli, Lane]

$$\tau = \tau' \cos\theta + \mu' \sin\theta \,, \quad \nu'_\tau = \nu_\tau \cos\theta + \nu_\mu \sin\theta$$

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A simultaneous solution?

[Choudhury, AK, Mandal, SInha, PRL 2017, NPB 2018]

$$\begin{aligned}\mathcal{O}_{\rm I} \quad &= \quad \sqrt{3}\, A_1\, (\bar{Q}_{2L}\gamma^\mu L_{3L})_3\, (\bar{L}_{3L}\gamma_\mu Q_{3L})_3 \\ & \quad\;\; -2\, A_2\, (\bar{Q}_{2L}\gamma^\mu L_{3L})_1\, (\bar{L}_{3L}\gamma_\mu Q_{3L})_1\end{aligned}$$

- Only 3rd gen leptons, but can rotate to get muons
- Can give a good fit to $R(D)$, $R(D^*)$, R_K, R_{K^*}, $R_{J/\psi}$, ${\rm BR}(B_s \to \phi\mu\mu)$, ${\rm BR}(B_s \to \mu\mu)$ and within limits for $b \to s+$ invisible and $B \to K^{(*)}\mu\tau$
- Much improved χ^2 compared to the SM

$$\chi^2 = \sum_{i=1}^{8} \frac{\left(\mathcal{O}_i^{\rm exp} - \mathcal{O}_i^{\rm th}\right)^2}{\left(\Delta\mathcal{O}_i^{\rm exp}\right)^2 + \left(\Delta\mathcal{O}_i^{\rm th}\right)^2}$$

- $\chi^2/d.o.f. = 1.5$ (this model), 6.1 (SM), with $A_1 = 0.028/{\rm TeV}^2$, $A_2 = -2.90/{\rm TeV}^2$, $|\sin\theta| = 0.018$, $C_9^{\rm NP} = -C_{10}^{\rm NP} = -0.61$

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- For these models $C_9^{\rm NP} = -C_{10}^{\rm NP}$: only LH currents
- $B_s \to \tau^+\tau^-$ gets sizable contribution from C_{10}, not C_9
- R_K and R_{K^*} need at least one of C_9 and C_{10} to be significant
- This is ruled out by $B_s \to \tau^+\tau^-$ (as well as by ΔM_s)
- We need to break $C_0 = -C_{10}$ — introduce RH currents

$$
\begin{aligned}
\mathcal{O}_{\rm II} &= \sqrt{3}\,A_1\left[-(Q_{2L},Q_{3L})_3\,(L_{3L},L_{3L})_3+\frac{1}{2}\,(Q_{2L},L_{3L})_3\,(L_{3L},Q_{3L})_3\right] \\
&+ \sqrt{2}\,A_5\,(Q_{2L},Q_{3L})_1\,\{\tau_R,\tau_R\} \\
&= \frac{3\,A_1}{4}\,(c,b)\,(\tau,\nu_\tau)+\frac{3\,A_1}{4}(s,b)(\tau,\tau)+A_5\,(s,b)\,\{\tau,\tau\} \\
&+ \frac{3\,A_1}{4}\,(s,t)\,(\nu_\tau,\tau)+A_5(c,t)\{\tau,\tau\}+\frac{3\,A_1}{4}(c,t)\,(\nu_\tau,\nu_\tau)
\end{aligned}
$$

with $\{x,y\} \equiv \bar{x}_R\gamma^\mu y_R\,, \quad (x,y) \equiv \bar{x}_L\gamma^\mu y_L \quad \forall\ \ x,y$

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&+ \sqrt{2}\,A_5\,(Q_{2L}, Q_{3L})_1\,\{\tau_R, \tau_R\} \\
&= \frac{3\,A_1}{4}\,(c, b)\,(\tau, \nu_\tau) + \frac{3\,A_1}{4}(s, b)(\tau, \tau) + A_5\,(s, b)\,\{\tau, \tau\} \\
&+ \frac{3\,A_1}{4}\,(s, t)\,(\nu_\tau, \tau) + A_5(c, t)\{\tau, \tau\} + \frac{3\,A_1}{4}(c, t)\,(\nu_\tau, \nu_\tau)
\end{aligned}
$$

with $\{x, y\} \equiv \bar{x}_R \gamma^\mu y_R\,, \quad (x, y) \equiv \bar{x}_L \gamma^\mu y_L \quad \forall \;\; x, y$

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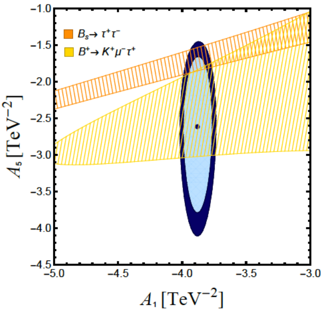
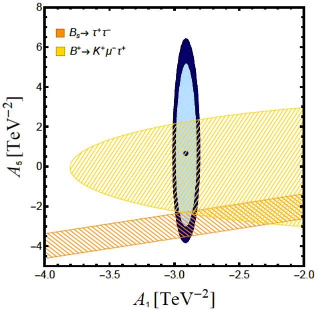
Can also play the same game with

$$
\begin{aligned}
\mathcal{O}_{\rm III} &= -\sqrt{3}\, A_1\, (Q_{2L}, Q_{3L})_3\, (L_{3L}, L_{3L})_3 + A_1\, (Q_{2L}, Q_{3L})_1\, (L_{3L}, L_{3L})_1 \\
&+ \sqrt{2}\, A_5\, (Q_{2L}, Q_{3L})_1\, \{\tau_R, \tau_R\} \\
&= A_1\, (c, b)\, (\tau, \nu_\tau) + A_1\, (s, b)\, (\tau, \tau) + A_5\, (s, b)\, \{\tau, \tau\} \\
&+ A_1\, (s, t)\, (\nu_\tau, \tau) + A_1\, (c, t)(\nu_\tau, \nu_\tau) + A_5\, (c, t)\, \{\tau, \tau\}
\end{aligned}
$$

Best fit points	Model II	Model III
$\lvert\sin\theta\rvert$	0.016	0.016
A_1 in TeV^{-2}	-3.88	-2.91
A_5 in TeV^{-2}	-2.61	0.66





[Slightly different fit taking all $\sim$ 160 observables into account. Also, Model I seems to be allowed. (Bhattacharya, Biswas, Calcuttawala, Patra, 1902.02796)]

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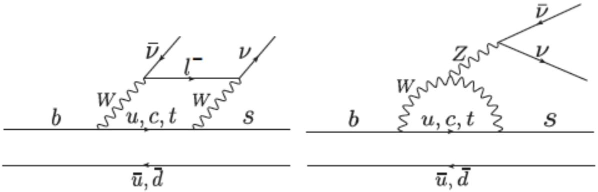
Something futuristic: $b \to s$ + invisibles at Belle-II

[Calcuttawala, AK, Nandi, Patra 2016]

- SM: $b \to s\nu\bar{\nu}$, only penguin and box



- Not always related to $b \to s\ell^+\ell^-$:
  1. Leptons can be R with no neutrino counterpart
  2. $\epsilon_{ab}\overline{L}_L^a\gamma^\mu Q_L^b$: $b \to \nu$, $t \to \ell$
  3. The invisibles can be something different!

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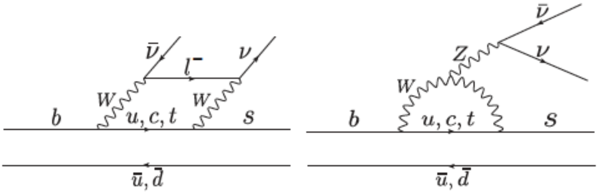

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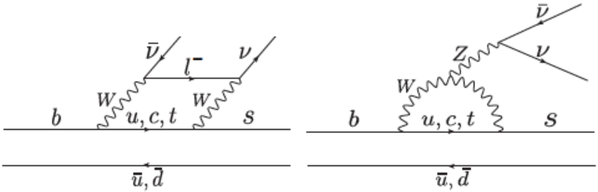
  2. $\epsilon_{ab}\bar{L}_L^a\gamma^\mu Q_L^b$: $b \to \nu$, $t \to \ell$
  3. The invisibles can be something different!
- Observables:
  BR, $d\Gamma/dq^2$, $F_T'(q^2)$ (neutrinos), $F_L'(q^2)$ (light scalars)

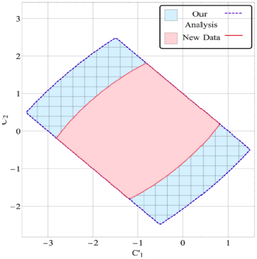
- SM: $b \to s\nu\bar{\nu}$, only penguin and box



- Not always related to $b \to s\ell^+\ell^-$:
  1. Leptons can be R with no neutrino counterpart
  2. $\epsilon_{ab}\bar{L}_L^a \gamma^\mu Q_L^b$: $b \to \nu$, $t \to \ell$
  3. The invisibles can be something different!
- Observables:
  BR, $d\Gamma/dq^2$, $F_T'(q^2)$ (neutrinos), $F_L'(q^2)$ (light scalars)

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_{SM} \left[O_{SM} + C_1' O_{V_1} + C_2' O_{V_2} \right] ,$$

$$\begin{aligned} O_{SM} = O_{V_1} &= (\bar{s}_L \gamma^\mu b_L)(\bar{\nu}_{iL} \gamma_\mu \nu_{iL}) , \\ O_{V_2} &= (\bar{s}_R \gamma^\mu b_R)(\bar{\nu}_{iL} \gamma_\mu \nu_{iL}) . \end{aligned}$$



$$\mathrm{Br}(B \to K(K^*)\nu\bar{\nu}) < 1.6(2.7) \times 10^{-5}$$

Detection efficiencies are small (Belle, 1303.3719)

Mode	$N_{\rm tot}$	$N_{\rm sig}$	Significance	$\epsilon, 10^{-4}$	Upper limit
$B^+ \to K^+\nu\bar{\nu}$	43	$13.3^{+7.4}_{-6.6}(\text{stat}) \pm 2.3(\text{syst})$	2.0σ	5.68	$< 5.5 \times 10^{-5}$
$B^0 \to K^0_s\nu\bar{\nu}$	4	$1.8^{+3.3}_{-2.4}(\text{stat}) \pm 1.0(\text{syst})$	0.7σ	0.84	$< 9.7 \times 10^{-5}$
$B^+ \to K^{*+}\nu\bar{\nu}$	21	$-1.7^{+1.7}_{-1.1}(\text{stat}) \pm 1.5(\text{syst})$	–	1.47	$< 4.0 \times 10^{-5}$
$B^0 \to K^{*0}\nu\bar{\nu}$	10	$-2.3^{+10.2}_{-3.5}(\text{stat}) \pm 0.9(\text{syst})$	–	1.44	$< 5.5 \times 10^{-5}$

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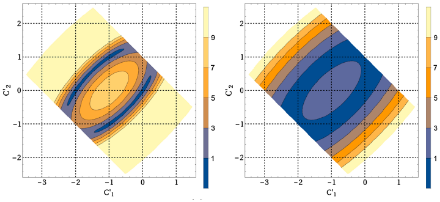
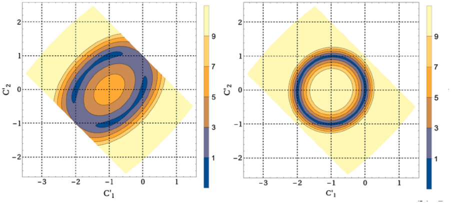
$B \to K^* \nu \bar{\nu}$ (50 and 2 ab^{-1})



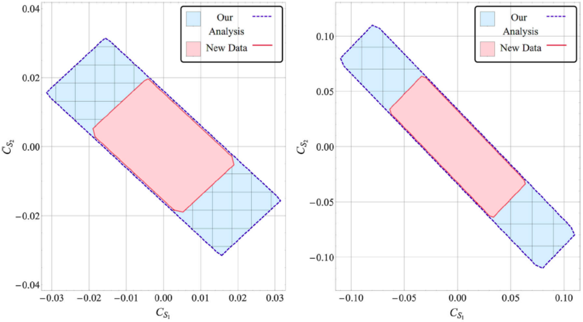
F_T, $B \to X_s \nu \bar{\nu}$ (50 ab^{-1})



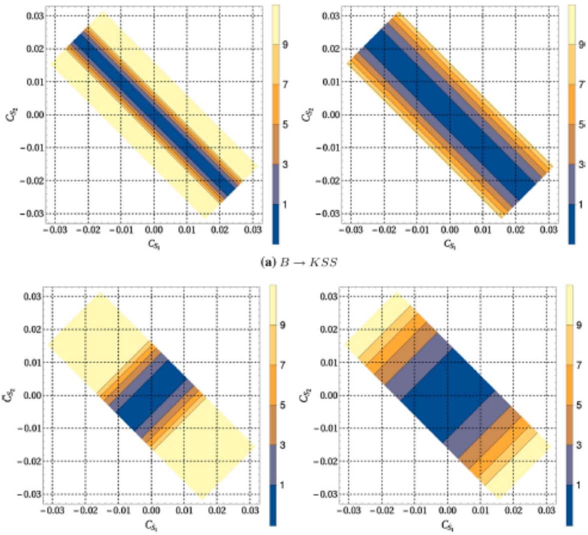
It can also be light invisible scalars (DM?)

$$\mathcal{L}_{b\to sSS} = C_{S_1} m_b \bar{s}_L b_R S^2 + C_{S_2} m_b \bar{b}_L s_R S^2 + \mathrm{H.c.} \tag{1}$$

Higgs portal DM – $\langle S \rangle = 0$, hSS coupling small to evade LHC limits



$B \to K$ and $B \to K^*$ for $m_S = 0.5\ (1.8)$ GeV, $\mathcal{L}_{\rm int} = 50\ {\rm ab}^{-1}$



(a) $B \to KSS$

(b) $B \to K^*SS$

To conclude:

- The CKM paradigm works quite well. BSM CPV needed to explain the baryon asymmetry, but it has to be subleading at least in the B sector (also in K and probably D)
- Flavour physics is the only tool to probe BSM if the scale is beyond the direct reach of LHC
- There are some intriguing anomalies. The pattern is not yet clear but LFU violation is indicated
- The third generation may be the window to BSM.
- Watch out for LHCb and Belle-II for new results, confirmatory tests, and possible surprises!

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Thank you!

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Thank you!