Beyond the Standard Model with Flavour

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Let us start with the Standard Model

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  SM is not a German machine, robust and working almost indefinitely

Let us start with the Standard Model

- 


  Not even a Chinese machine, cheaper version, can break down any time

Let us start with the Standard Model

- More like an Indian *jugaad*, a contraption that should not work, but works like magic
- But a *jugaad* is funny and incomplete

— 19 free parameters

— Dark matter, dark energy, baryon asymmetry of the universe

— Neutrino mass, stability of EW scale

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We entered the forest expecting a lot of animals $\cdots$

But this is what we found so far.
Not exactly boring, but no animals (except one at 125 GeV)

So, in the forest, if you are still lucky, you may spot a tiger. But even if you are not $\cdots$

Pugmarks will give you a lot of information if you know how to read them

Are there any pugmarks?

Yes!!!
But not very deep as to claim definite evidence of a tiger
Still, worth exploring.

> Circumstantial evidence is occasionally
> very convincing, as when you find
> a trout in the milk.
> — Arthur Conan Doyle

And there we go into the beautiful world of b-hadrons

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Flavour physics has built up the SM

1. First generation of flavour physics (pre-1970)
    - Strange particles, parity violation, eightfold way and Ω^-
    - $K^0 - \overline{K}^0$ oscillation, "tiny" CP violation in K decay
    - Cabibbo hypothesis, GIM mechanism
2. Second generation of flavour physics (1970 - 1995)
    - Kobayashi-Maskawa hypothesis
    - J/ψ and Υ production
    - Observation of $B^0 - \overline{B}^0$ oscillation

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   - Top discovery
   - Observation of $B_s - \overline{B_s}$ and $D^0 - \overline{D}^0$ oscillation
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    - Lepton flavour/universality violation, rare charm and τ decays
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B-factories: past, present, and future

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

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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

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Upgrade I: $\mathcal{L}_{\rm int} > 50$ fb^{-1}, 2×10^{33} $\text{cm}^{-2}\text{s}^{-1}$
Phase II with HL-LHC: $\mathcal{L}_{\rm int} > 300$ fb^{-1}, 2×10^{34} $\text{cm}^{-2}\text{s}^{-1}$
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Why is flavour physics important ?

- Better understanding of SM for $N_{gen} > 1$
  — Window to flavour dynamics (e.g. $B^0 - \overline{B}^0$ mixing, $b \to s\gamma$, $Z \to b\bar{b}$, $B_s \to \mu\mu$)
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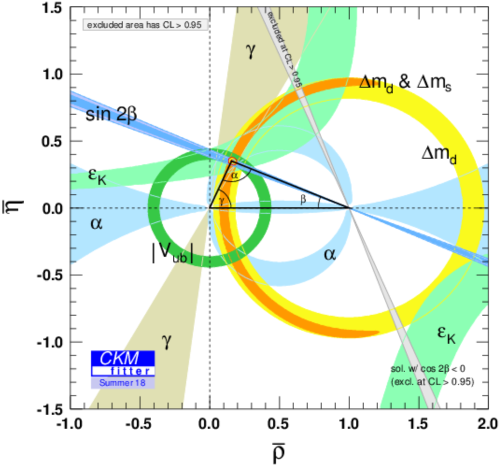
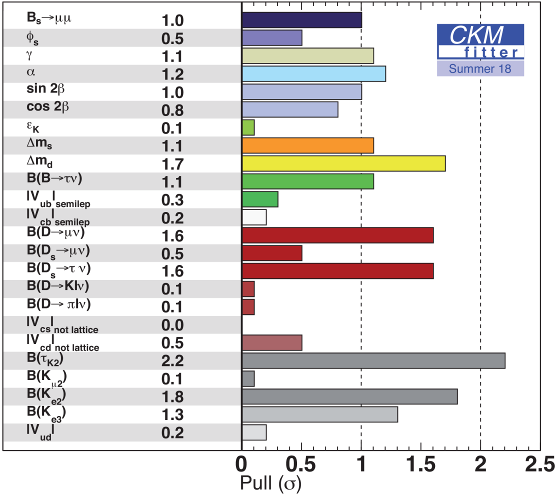


α	$91.6^{+1.7}_{-1.1}$
β direct	$22.14^{+0.69}_{-0.67}$
β indirect	23.9 ± 1.2
β average	$22.51^{+0.55}_{-0.40}$
γ	$65.81^{+0.99}_{-1.66}$


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)

How can B Physics unravel BSM?

If NP is at

- <1 TeV: within direct reach of LHC@8 TeV, ruled out
- a few TeV: within reach of LHC@13 TeV, data analysis coming up
- $>$ a few TeV: beyond LHC. Maybe Belle-II

Indirect detection

Flav. structure	<1 TeV	a few TeV	$>$ a few TeV
Anarchy	huge O(1) **X**	O(1) **X**	small ($<$ O(1))
Small misalignment	Sizable O(1) **X**	small (O(0.1))	tiny (O(0.01-0.1))
Alignment (MFV)	small (O(0.1))	tiny (O(0.01))	out of reach $<$ O(0.01)

If NP is at

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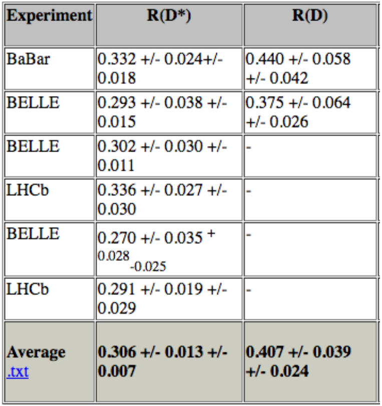
But be careful, theory is not always under control

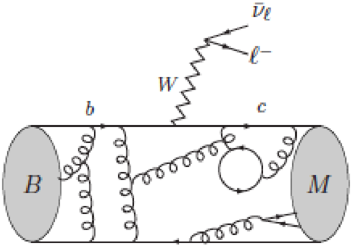
Need a better control over nuisance parameters

- Quark masses and CKM elements
- Form factors, decay constants
  Lattice people doing a commendable job
  uncertainty associated with LCD amplitudes
- Subleading Λ/m corrections
  Also, higher orders in α_s, but they can be summed in most cases
- renormalization scale (μ) dependence

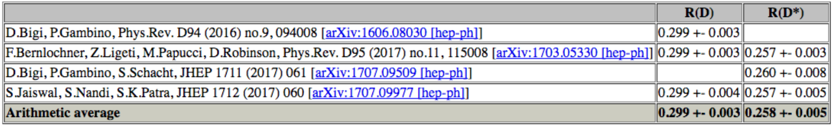
A few interesting anomalies



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 +/- 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**

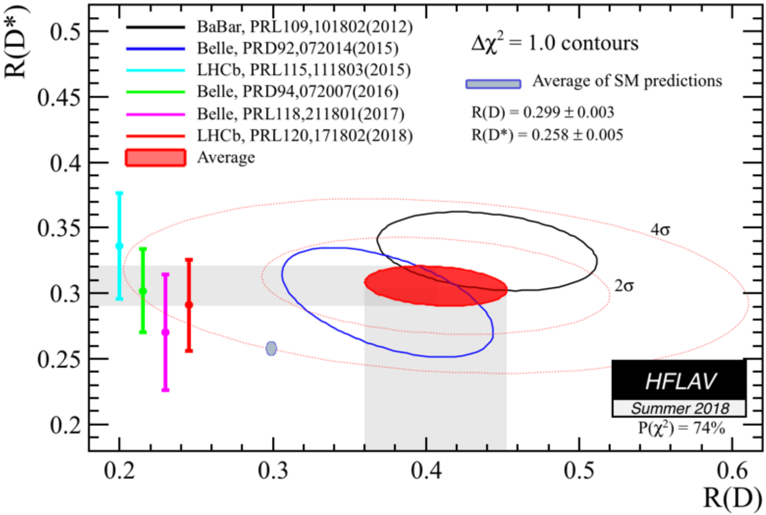


$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$



	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
0.2
0.3
0.4
0.5
0.6
R(D)
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
$P(\chi^2) = 74\%$

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

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

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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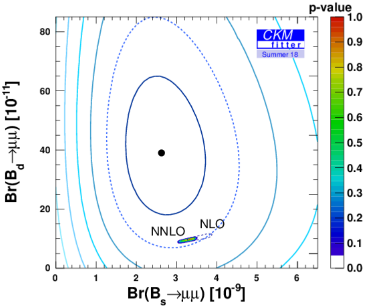
$$
\begin{aligned}
R_K &= 0.745^{+0.090}_{-0.074} \pm 0.036 && q^2 \in [1:6]\ \mathrm{GeV}^2\,,\\
R_{K^*}^{\mathrm{low}} &= 0.66^{+0.11}_{-0.07} \pm 0.03 && q^2 \in [0.045:1.1]\ \mathrm{GeV}^2\,,\\
R_{K^*}^{\mathrm{central}} &= 0.69^{+0.11}_{-0.07} \pm 0.05 && q^2 \in [1.1:6]\ \mathrm{GeV}^2\,.
\end{aligned}
$$

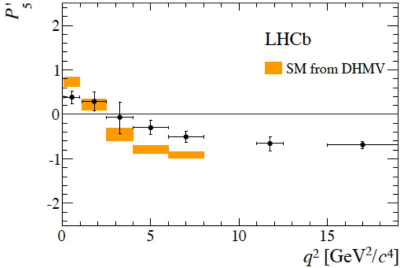
$$
\frac{d}{dq^2}\mathrm{BR}(B_s \to \phi\mu\mu)\Big|_{q^2\in[1:6]\ \mathrm{GeV}^2}
= \begin{cases} \left(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19\right) \times 10^{-8}\ \mathrm{GeV}^{-2} & \text{(exp.)}\\ (4.81 \pm 0.56) \times 10^{-8}\ \mathrm{GeV}^{-2} & \text{(SM)}, \end{cases}
$$

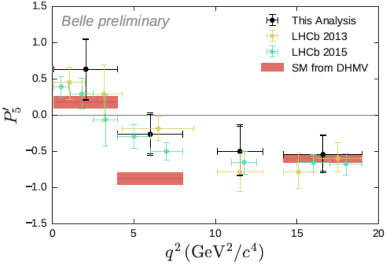
Is there some pattern?

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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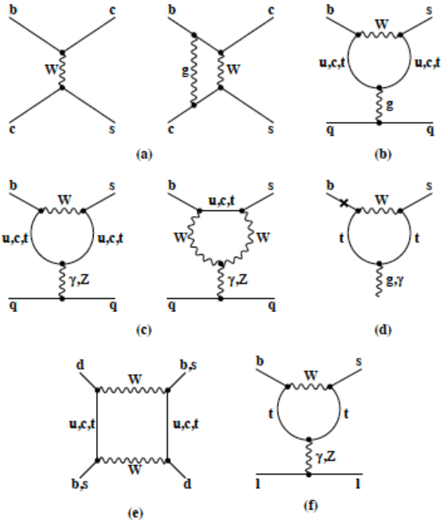
b
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b
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u,c,t
g
q
q
(b)
b
s
W
u,c,t
u,c,t
γ,Z
q
q
b
s
u,c,t
W
W
γ,Z
q
q
(c)
b
s
W
t
t
g,γ
(d)
d
b,s
W
u,c,t
u,c,t
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b,s
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(e)
b
s
W
t
t
γ,Z
l
l
(f)

Top-down:

UV complete theory → Get C_i at high scale with proper matching → Run down to m_b → Check consistency with data

Examples: leptoquarks, extra Z'

Bottom-up:

Fit data with set of chosen operators → 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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- Tension for CC with $\ell = \tau$, comparable with SM tree ($\sim 15\%$ enhancement in amplitude)
- Tension for NC with $\ell = \mu$, comparable with SM loop only. Destructive interference needed

- Tension for CC with $\ell = \tau$, comparable with SM tree ($\sim 15\%$ enhancement in amplitude)
- Tension for NC with $\ell = \mu$, comparable with SM loop only. Destructive interference needed
- Consider a new operator involving τ. Rotate the leptonic (τ, μ) basis to (τ', μ') [Glashow, Guadagnoli, Lane]

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

- If the mixing angle θ is small, $\sin^2\theta$ suppression makes the BSM tree comparable with SM loop

- Tension for CC with $\ell = \tau$, comparable with SM tree ($\sim 15\%$ enhancement in amplitude)
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A simultaneous solution?

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

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

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

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

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

- 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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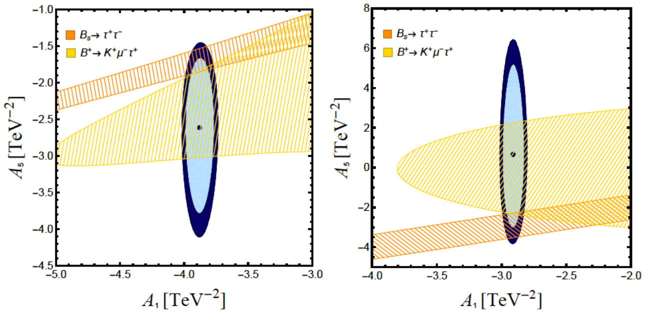
Can also play the same game with

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

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

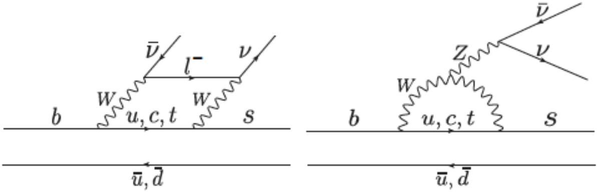


[An ongoing analysis taking all $\sim$ 160 observables into account shows a slightly different fit for these models. Also, Model I seems to be allowed. (Biswas, Calcuttawala, Patra, Priv. Comm.]

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

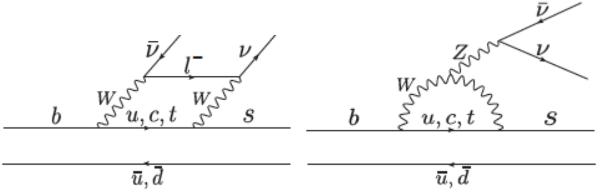
[Calcuttawala, AK, Nandi, Patra 2016]

- 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. $\epsilon_{ab}\bar{L}^a_L\gamma^\mu Q^b_L$: $b \to \nu$, $t \to \ell$
  3. The invisibles can be something different!

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



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- Observables:
  BR, $d\Gamma/dq^2$, $F_T'(q^2)$ (neutrinos), $F_L'(q^2)$ (light scalars)

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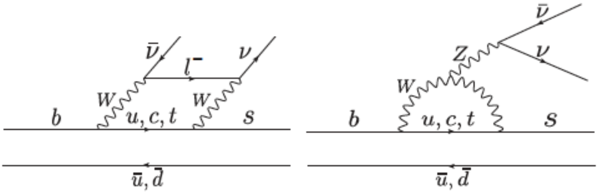

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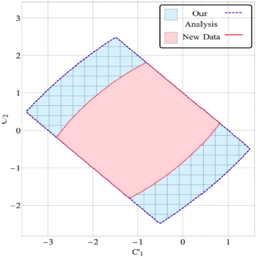
$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_{SM} \left[O_{SM} + C'_1 O_{V_1} + C'_2 O_{V_2} \right] ,$$

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

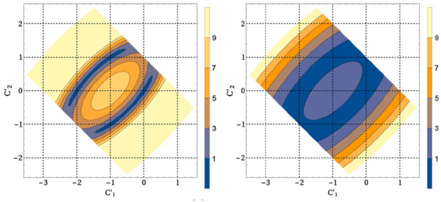
$${\rm Br}(B \to K(K^*)\nu\bar{\nu}) < 1.6(2.7) \times 10^{-5}$$



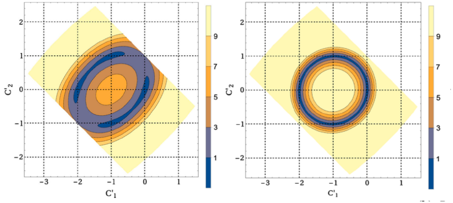
Detection efficiencies are small (Belle, 1303.3719)

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

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



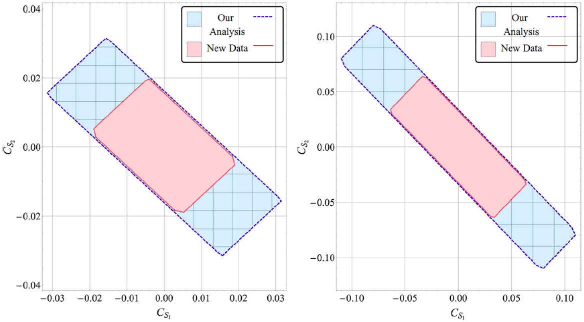
F_T, $B \to X_s \nu \bar{\nu}$ (50 ab^{-1})



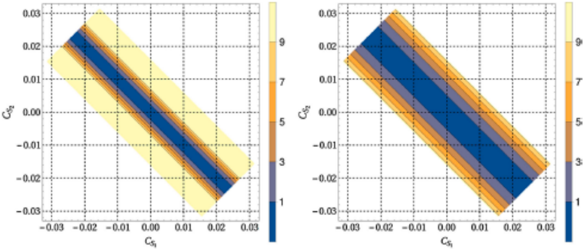
It can also be light invisible scalars (DM?)

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

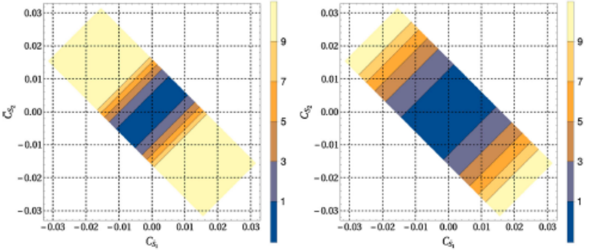
Higgs portal DM – $\langle S\rangle = 0$, hSS coupling small to evade LHC limits



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