Going beyond the Standard Model with Flavour

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Introduction to flavour physics

Although you have heard / will hear a lot about BSM,

Standard Model is doing extremely well

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm fermion}$$

and all sectors checked (not at same precision level though)

No wonder. It has 19 free parameters

With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.

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Isidor Isaac Rabi
(1898-1988)

The first question in flavour physics:

Who ordered that?

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
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    - e^+e^- B factories, "large" CP violation in B system
    - Top discovery
    - Observation of $B_s - \overline{B_s}$ and $D^0 - \overline{D}^0$ oscillation
    - Rare B decays, Start of precision flavour physics

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B-factories: past, present, and future

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

ATLAS and CMS also have dedicated flavour physics programme

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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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- Need a basis transformation for quarks
- Mass and Yukawa matrices are diagonalised by same transformation
- GIM to ban tree-level FCNC

$$\begin{aligned}\mathcal{L}_{wk}^{CC} &= -\frac{g}{\sqrt{2}}\bar{u'}_j(\mathcal{U}^\dagger_{ji}\mathcal{D}_{ik})\gamma^\mu P_L d'_k W^+_\mu + \mathrm{h.c.}\\ &= -\frac{g}{\sqrt{2}}V_{jk}\bar{u'}_j\gamma^\mu P_L d'_k W^+_\mu + \mathrm{h.c.}\end{aligned}$$

$V \equiv \mathcal{U}^\dagger\mathcal{D}$ is the CKM matrix. Three real angles and one CP-violating phase.

$\mathcal{U}^\dagger\mathcal{U} = \mathcal{D}^\dagger\mathcal{D} = \mathbf{1} \Rightarrow$ **GIM**

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

$$= \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$V_{td} = |V_{td}|\exp(-i\beta)$, $V_{ub} = |V_{ub}|\exp(-i\gamma)$ Wolfenstein

$\lambda = 0.224747^{+0.000254}_{-0.000059}$, $A = 0.8403^{+0.0056}_{-0.0201}$,

$\underbrace{\rho(1-\frac{1}{2}\lambda^2)}_{\equiv \bar{\rho}} = 0.1577^{+0.0096}_{-0.0074}$, $\underbrace{\eta(1-\frac{1}{2}\lambda^2)}_{\equiv \bar{\eta}} = 0.3493^{+0.0095}_{-0.0071}$

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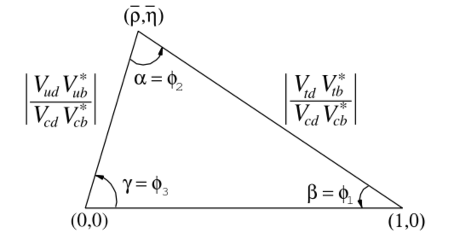
$$\boxed{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 1}$$



- Nonzero area indicates CP violation
- All UTs must have same area
- Falls short by about a billion

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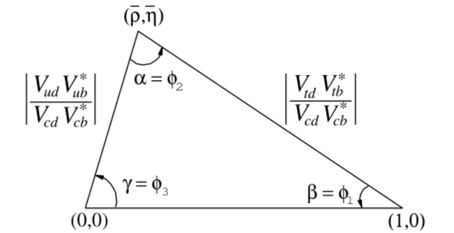

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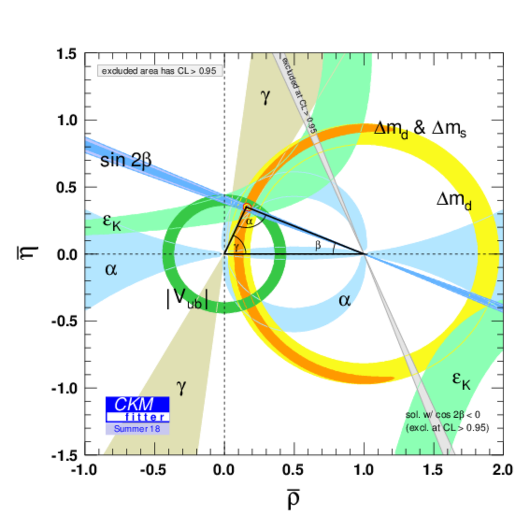

α	$91.6^{+1.7}_{-1.1}$
β direct	$22.14^{+0.69}_{-0.67}$
β indirect	23.9 ± 1.2
β average	$22.51^{+0.55}_{-0.40}$
γ	$65.81^{+0.99}_{-1.66}$

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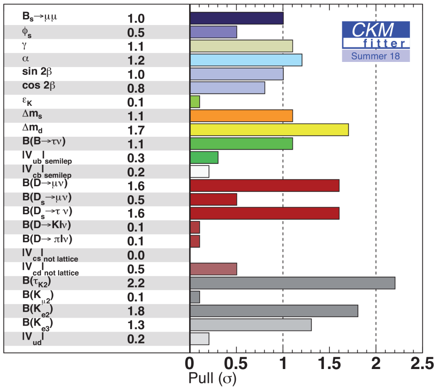
B_s→μμ 1.0
φ_s 0.5
γ 1.1
α 1.2
sin 2β 1.0
cos 2β 0.8
ε_K 0.1
Δm_s 1.1
Δm_d 1.7
B(B→τν) 1.1
|V_ub|_semilep 0.3
|V_cb|_semilep 0.2
B(D→μν) 1.6
B(D_s→μν) 0.5
B(D_s→τν) 1.6
B(D→Klν) 0.1
B(D→πlν) 0.1
|V_cs|_not lattice 0.0
|V_cd|_not lattice 0.5
B(τ_K2) 2.2
B(K_μ2) 0.1
B(K_e2) 1.8
B(K_e3) 1.3
|V_ud| 0.2
CKM 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 ($O(0.01\text{-}0.1)$)
Alignment (MFV)	small ($O(0.1)$)	tiny ($O(0.01)$)	out of reach $< O(0.01)$

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Alignment (MFV)	small (O(0.1))	tiny (O(0.01))	out of reach $<$ O(0.01)

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$B^0 - \overline{B}^0$ and $B_s - \overline{B_s}$ mixing have been measured very precisely

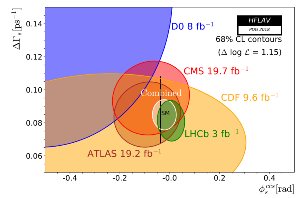
$$\Delta M_d = 0.5065 \pm 0.0019 \ \mathrm{ps}^{-1} \qquad \Delta M_s = 17.757 \pm 0.021 \ \mathrm{ps}^{-1}$$

$$\Delta\Gamma_s/\Gamma_s = 0.132 \pm 0.008 \qquad \tau_s/\tau_d = 0.993 \pm 0.004$$

- Major uncertainties in ΔM come from decay constants and bag factors

$$\Delta M \approx \frac{G_F^2}{16\pi^2} |V_{tq}^* V_{tb}|^2 M_W^2 S_0(x_t) \eta_B B_B f_B^2 M_B$$

- $\Delta\Gamma_s$ has $\sim 15\%$, mostly from $1/m_b$ and scale



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$$H = \begin{pmatrix} M_q - \frac{i}{2}\Gamma_q & M_q^{12} - \frac{i}{2}\Gamma_q^{12} \\ M_q^{12*} - \frac{i}{2}\Gamma_q^{12*} & M_q - \frac{i}{2}\Gamma_q \end{pmatrix}$$

$$\frac{M_q^{12}}{M_{q,SM}^{12}} \equiv \mathrm{Re}\Delta_q + i\mathrm{Im}\Delta_q = |\Delta_q| \exp(2i\Phi_{q,NP})$$

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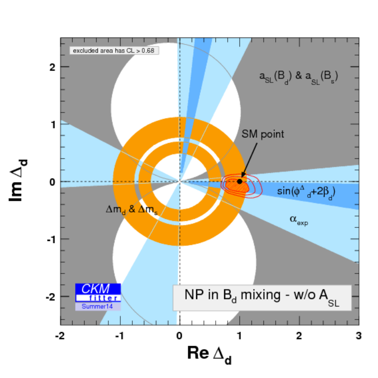

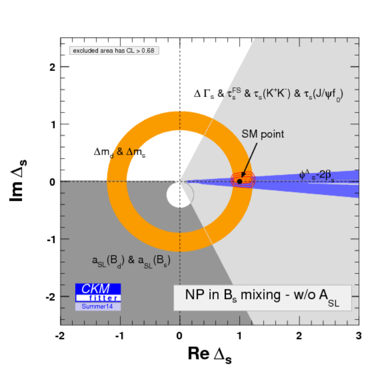

B_s plot does not include DØ dimuon

Caution !!!

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

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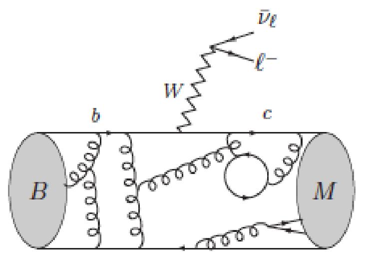
A few interesting anomalies

[Also, talk by G. Mohanty]

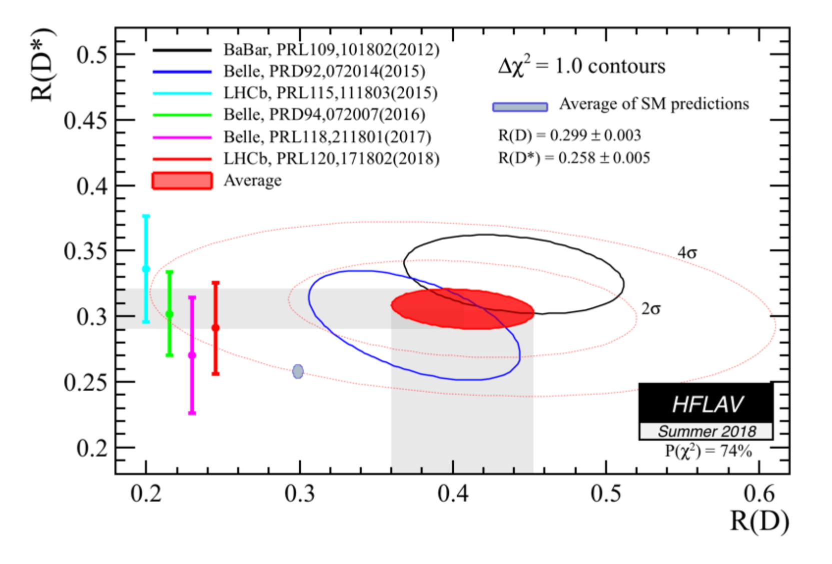
Experiment	R(D*)	R(D)
BaBar	0.332 +/- 0.024+/- 0.018	0.440 +/- 0.058 +/- 0.042
BELLE	0.293 +/- 0.038 +/- 0.015	0.375 +/- 0.064 +/- 0.026
BELLE	0.302 +/- 0.030 +/- 0.011	-
LHCb	0.336 +/- 0.027 +/- 0.030	-
BELLE	0.270 +/- 0.035 $^{+0.028}_{-0.025}$	-
LHCb	0.291 +/- 0.019 +/- 0.029	-
Average .txt	**0.306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



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

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

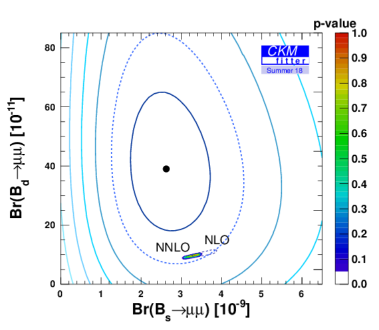
$$R_{K^*}^{\mathrm{low}} = 0.66^{+0.11}_{-0.07} \pm 0.03 \qquad q^2 \in [0.045:1.1]\ \mathrm{GeV}^2\,,$$

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

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

Is there some pattern?

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

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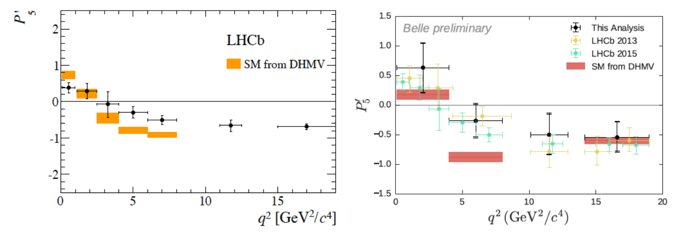

LHCb: two bins deviating by 2.8σ and 3.0σ

Belle confirms with larger uncertainty

CMS and ATLAS: Consistent with both LHCb/Belle and SM, large uncertainties

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

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

with the relevant operators

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

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

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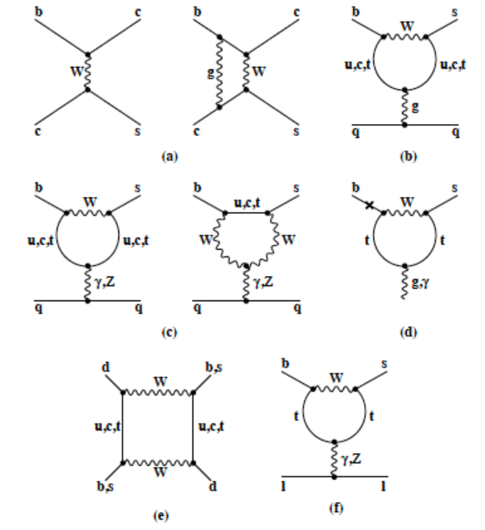
b
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(f)

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

Bottom-up:

Fit data with set of chosen operators $\longrightarrow$ Get the corresponding C_i

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]

For $B \to K^{(*)}$, no estimate for charmonium-dominated bins, have to be removed

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

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A simultaneous solution?

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

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

- 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

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

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

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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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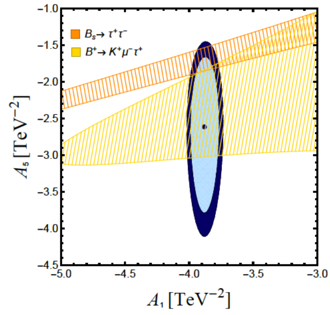
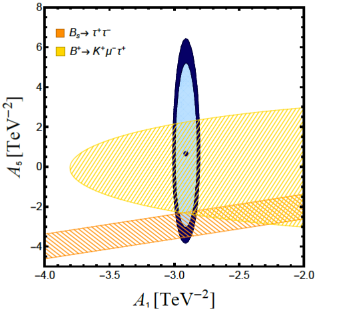
Can also play the same game with

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

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



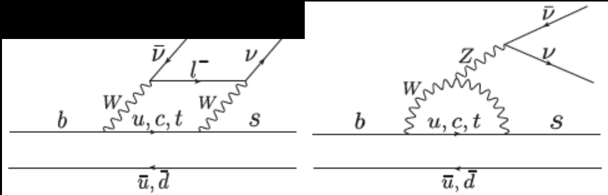


[An ongoing analysis taking all $\sim$ 160 observables into account shows a slightly different fit for these models. Also, Model I seems to be allowed. (Biswas, Calcuttawala, Patra, Priv. Comm.]

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!

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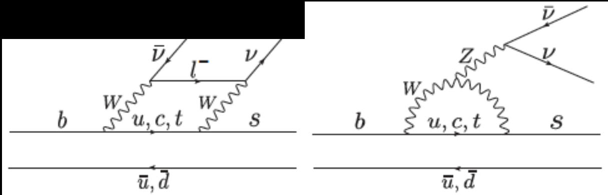

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- Observables:
  BR, $d\Gamma/dq^2$, $F'_T(q^2)$ (neutrinos), $F'_L(q^2)$ (light scalars)

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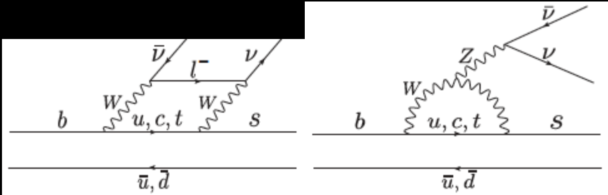

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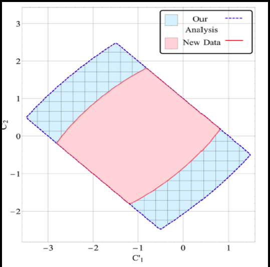
$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_{SM} \left[O_{SM} + C_1' O_{V_1} + C_2' O_{V_2} \right] ,$$

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



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

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

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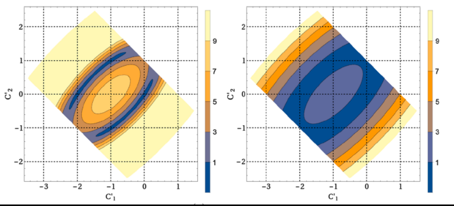
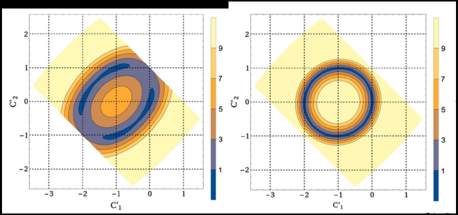
$B \to K^* \nu\bar{\nu}$ (50 and 2 ab^{-1})



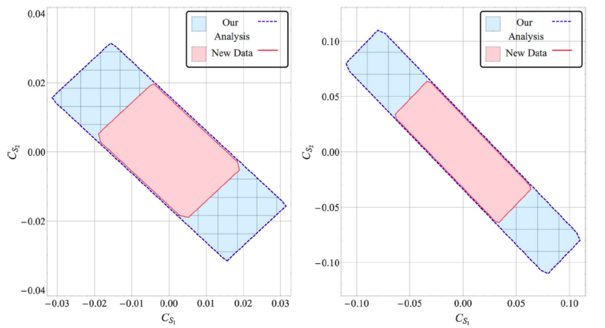
F_T, $B \to X_s \nu\bar{\nu}$ (50 ab^{-1})



It can also be light invisible scalars (DM?)

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

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



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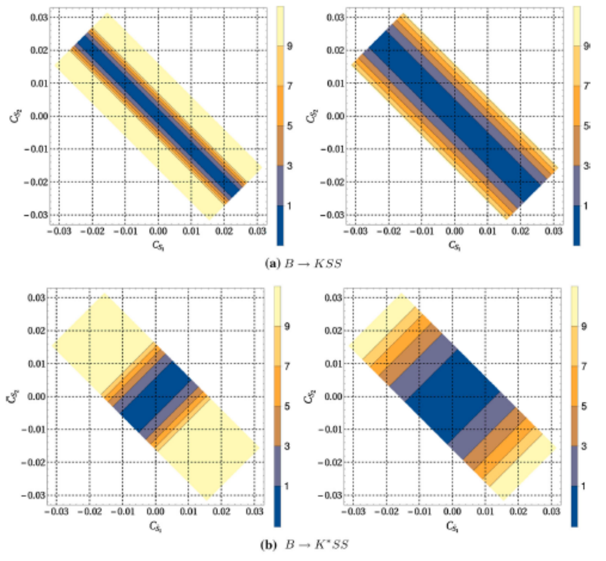
$B \to K$ and $B \to K^*$ for $m_S = 0.5$ (1.8) GeV, $\mathcal{L}_{\text{int}} = 50$ ab^{-1}



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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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