

Hints of New Physics in flavor anomalies

Enrico Maria Sessolo

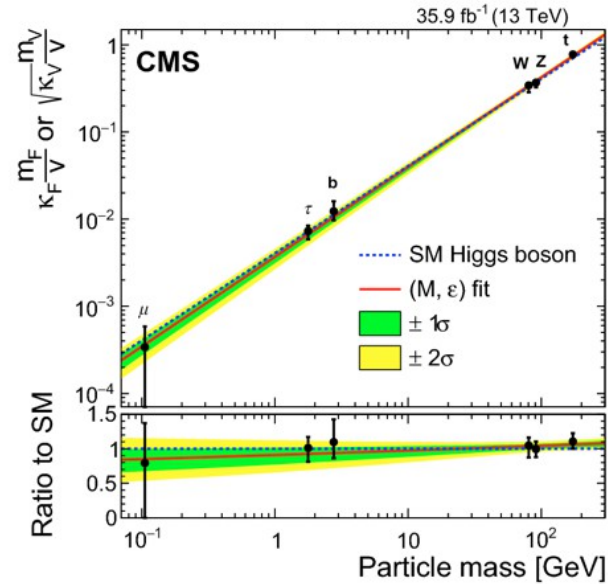
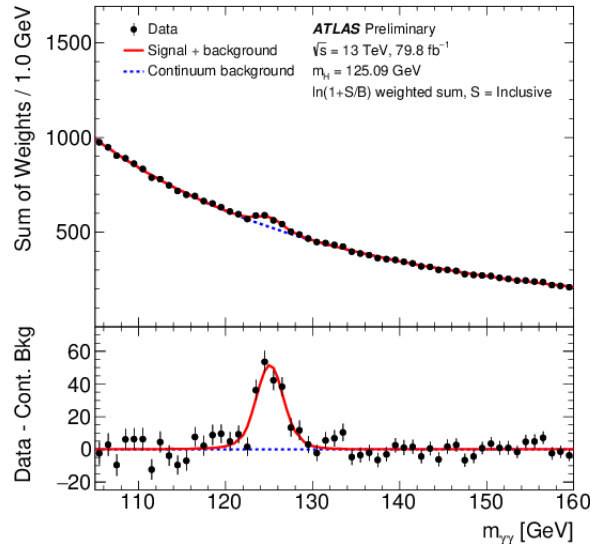
BP-2

NCBJ Symposium

10.12.2019 Warsaw

Direct searches at the LHC

A very SM-like Higgs boson at 125 GeV...



... but no new physics below 1-2 TeV!

ATLAS SUSY Searches* - 95% CL Lower Limits
July 2019

ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}$

Model	Signature	$\mathcal{L} \cdot \text{Br} (\text{fb}^{-1})$	Mass limit	Reference	
Inclusive Searches	$gg \rightarrow \mu\mu$	2.4 jets	35.1	1712.0330	
	$gg \rightarrow \mu\mu$	monojet	1.9 jets	35.1	1718.0331
	$gg \rightarrow \mu\mu$	2 jets	35.1	1712.0332	
	$gg \rightarrow \mu\mu$	3 jets	35.1	1708.0731	
	$gg \rightarrow \mu\mu$	4 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	5 jets	35.1	1708.0734	
	$gg \rightarrow \mu\mu$	6 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	7 jets	35.1	1708.0734	
	$gg \rightarrow \mu\mu$	8 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	9 jets	35.1	1708.0734	
1 γ gen. quark event production	$gg \rightarrow \mu\mu$	3 jets	35.1	1712.0330	
	$gg \rightarrow \mu\mu$	4 jets	35.1	1718.0331	
	$gg \rightarrow \mu\mu$	5 jets	35.1	1712.0332	
	$gg \rightarrow \mu\mu$	6 jets	35.1	1708.0731	
	$gg \rightarrow \mu\mu$	7 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	8 jets	35.1	1708.0734	
	$gg \rightarrow \mu\mu$	9 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	10 jets	35.1	1708.0734	
	$gg \rightarrow \mu\mu$	11 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	12 jets	35.1	1708.0734	
EW direct	$gg \rightarrow \mu\mu$	3 jets	35.1	1712.0330	
	$gg \rightarrow \mu\mu$	4 jets	35.1	1718.0331	
	$gg \rightarrow \mu\mu$	5 jets	35.1	1712.0332	
	$gg \rightarrow \mu\mu$	6 jets	35.1	1708.0731	
	$gg \rightarrow \mu\mu$	7 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	8 jets	35.1	1708.0734	
	$gg \rightarrow \mu\mu$	9 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	10 jets	35.1	1708.0734	
	$gg \rightarrow \mu\mu$	11 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	12 jets	35.1	1708.0734	
Long-lived particles	$gg \rightarrow \mu\mu$	3 jets	35.1	1712.0330	
	$gg \rightarrow \mu\mu$	4 jets	35.1	1718.0331	
	$gg \rightarrow \mu\mu$	5 jets	35.1	1712.0332	
	$gg \rightarrow \mu\mu$	6 jets	35.1	1708.0731	
	$gg \rightarrow \mu\mu$	7 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	8 jets	35.1	1708.0734	
	$gg \rightarrow \mu\mu$	9 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	10 jets	35.1	1708.0734	
	$gg \rightarrow \mu\mu$	11 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	12 jets	35.1	1708.0734	
RPV	$gg \rightarrow \mu\mu$	3 jets	35.1	1712.0330	
	$gg \rightarrow \mu\mu$	4 jets	35.1	1718.0331	
	$gg \rightarrow \mu\mu$	5 jets	35.1	1712.0332	
	$gg \rightarrow \mu\mu$	6 jets	35.1	1708.0731	
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	$gg \rightarrow \mu\mu$	11 jets	35.1	1805.1131	
	$gg \rightarrow \mu\mu$	12 jets	35.1	1708.0734	

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018

ATLAS Preliminary
 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets	E_{miss}	$\mathcal{L} \cdot \text{Br} (\text{fb}^{-1})$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/\ell$	0 μ, μ	1-4	Yes	36.1	1711.0330
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	1707.0417
	ADD GBH	-	2j	-	37.0	1703.0937
	ADD BH High Σp_T	2 μ, μ	2j	-	3.2	1606.0205
	ADD BH multijet	-	2-3j	-	3.6	1512.0298
	RSt $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	1707.0417
	BRA RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	1606.0205
	BRA RS $G_{KK} \rightarrow tt$	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1804.10823
	ZUED/RSF	1 μ, μ	$\geq 2b, \geq 3j$	Yes	36.1	1803.0678
	SM $Z' \rightarrow \ell\ell$	2 ℓ	-	-	36.1	1707.0204
Leptophobic $Z' \rightarrow b\bar{b}$	-	2b	-	36.1	1803.0699	
Leptophobic $Z' \rightarrow t\bar{t}$	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1804.10823	
SM $W' \rightarrow \ell\nu$	1 ℓ	-	Yes	36.1	1606.0205	
HVT $W' \rightarrow W\nu$ - eepg Model B	0 μ, μ	2j	-	79.8	1803.0699	
HVT $W' \rightarrow W\nu$ /Z model B	0 μ, μ	2j	-	79.8	1803.0699	
LRSM $W'_2 \rightarrow b\bar{b}$	multi-channel	-	-	36.1	1707.0204	
Gauge bosons	SM $Z' \rightarrow \ell\ell$	2 ℓ	-	-	36.1	1707.0204
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2b	-	36.1	1803.0699
	Leptophobic $Z' \rightarrow t\bar{t}$	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1804.10823
	SM $W' \rightarrow \ell\nu$	1 ℓ	-	Yes	36.1	1606.0205
	HVT $W' \rightarrow W\nu$ - eepg Model B	0 μ, μ	2j	-	79.8	1803.0699
	HVT $W' \rightarrow W\nu$ /Z model B	0 μ, μ	2j	-	79.8	1803.0699
	LRSM $W'_2 \rightarrow b\bar{b}$	multi-channel	-	-	36.1	1707.0204
	CI $\ell\ell$ eepg	-	2j	-	37.0	1703.0937
	CI $\ell\ell$ eepg	2 μ, μ	-	-	36.1	1707.0204
	CI eepg	2 ℓ, ℓ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1707.0204
DM	Axial-vector mediator (Dirac DM)	0 μ, μ	1-4j	Yes	36.1	1711.0330
	Colored scalar mediator (Dirac DM)	0 μ, μ	1-4j	Yes	36.1	1711.0330
	VV $\gamma\gamma$ EFT (Dirac DM)	0 μ, μ	1, 4, 5, j	Yes	3.2	1606.0272
	Scalar LO 1 γ gen	2 ℓ	2-2j	-	3.0	1606.0205
	Scalar LO 2 γ gen	2 μ, μ	2-2j	-	3.2	1606.0205
	Scalar LO 3 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 4 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 5 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 6 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 7 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
LO	Scalar LO 1 γ gen	2 ℓ	2-2j	-	3.0	1606.0205
	Scalar LO 2 γ gen	2 μ, μ	2-2j	-	3.2	1606.0205
	Scalar LO 3 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 4 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 5 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 6 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 7 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 8 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 9 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
	Scalar LO 10 γ gen	1 μ, μ	$\geq 1b, \geq 1b\bar{c}$	Yes	36.1	1606.0205
Excited fermions/heavy quarks	Excited quark $q^* \rightarrow q\gamma$	-	2j	-	37.0	1703.0937
	Excited quark $q^* \rightarrow q\ell$	1 $\gamma, 1 \ell$	-	-	36.7	1708.1040
	Excited quark $q^* \rightarrow q\tau$	1 $\tau, 1 b, 1 j$	-	-	36.1	1803.0699
	Excited lepton $\ell^* \rightarrow \ell\gamma$	2 ℓ, μ	-	-	20.3	1606.0205
	Excited lepton $\ell^* \rightarrow \ell\tau$	3 ℓ, μ, τ	-	-	20.3	1606.0205
	Excited lepton $\ell^* \rightarrow \ell\mu$	3 ℓ, μ, τ	-	-	20.3	1606.0205
	Excited lepton $\ell^* \rightarrow \ell\tau$	3 ℓ, μ, τ	-	-	20.3	1606.0205
	Excited lepton $\ell^* \rightarrow \ell\mu$	3 ℓ, μ, τ	-	-	20.3	1606.0205
	Excited lepton $\ell^* \rightarrow \ell\tau$	3 ℓ, μ, τ	-	-	20.3	1606.0205
	Excited lepton $\ell^* \rightarrow \ell\mu$	3 ℓ, μ, τ	-	-	20.3	1606.0205
Other	Type III Seesaw	1 μ, μ	2-2j	Yes	79.8	1803.0699
	LRSM Majorana ν	2 μ, μ	2-2j	-	20.3	1606.0205
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2, 3, 4 μ, μ (SS)	-	-	36.1	1707.0204
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 μ, μ, τ	-	-	36.1	1707.0204
	Monopole (non-res. prod.)	1 μ, μ	1b	Yes	20.3	1606.0205
	Multi-charged particles	1 μ, μ	-	-	20.3	1606.0205
	Magnetic monopoles	1 μ, μ	-	-	7.0	1606.0205
	Excited quark $q^* \rightarrow q\gamma$	-	2j	-	37.0	1703.0937
	Excited quark $q^* \rightarrow q\ell$	1 $\gamma, 1 \ell$	-	-	36.7	1708.1040
	Excited quark $q^* \rightarrow q\tau$	1 $\tau, 1 b, 1 j$	-	-	36.1	1803.0699

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

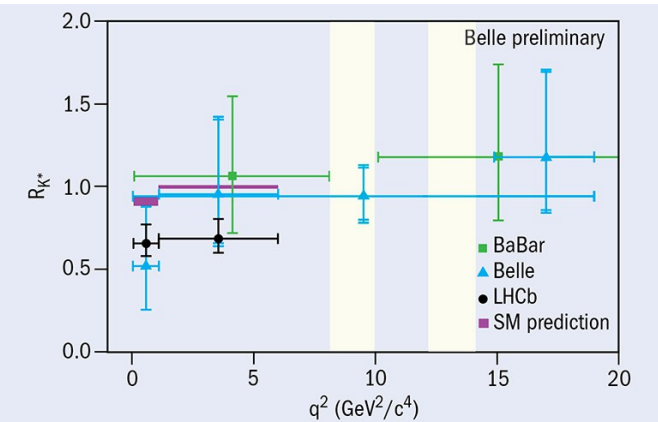
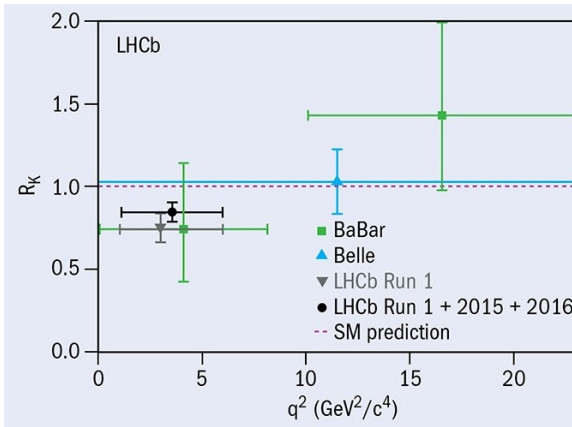
Indirect hints for BSM physics from LHCb

- Violation of lepton-flavor universality (LHCb, $\sim 2.5 \sigma$)

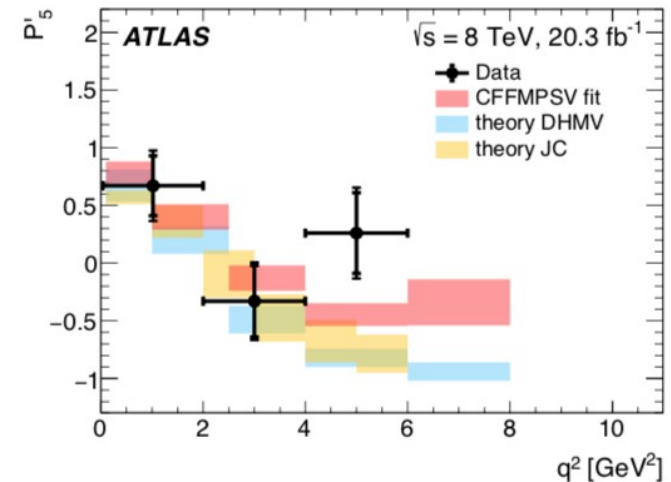
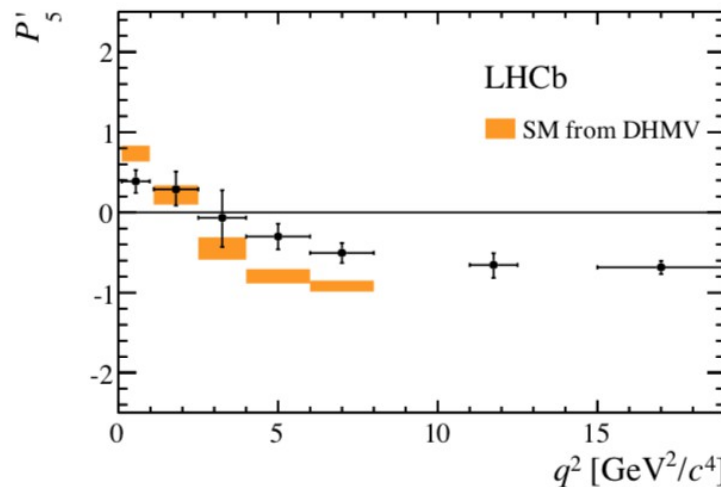
$$R_K = \frac{\text{BR}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{BR}(B^+ \rightarrow K^+ e^+ e^-)}$$

$$R_{K^*} = \frac{\text{BR}(B^0 \rightarrow K^{0*} \mu^+ \mu^-)}{\text{BR}(B^0 \rightarrow K^{0*} e^+ e^-)}$$

Data was updated in March 2019!



- Deviations in angular observables of $B^0 \rightarrow K^{0*} \mu^+ \mu^-$ (LHCb and ATLAS, $\sim 3 \sigma$)



Indirect hints for BSM physics from LHCb

- Deviations in differential branching ratios $\frac{dB\Gamma}{dq^2}$ (LHCb, **2 σ – 3.5 σ**)

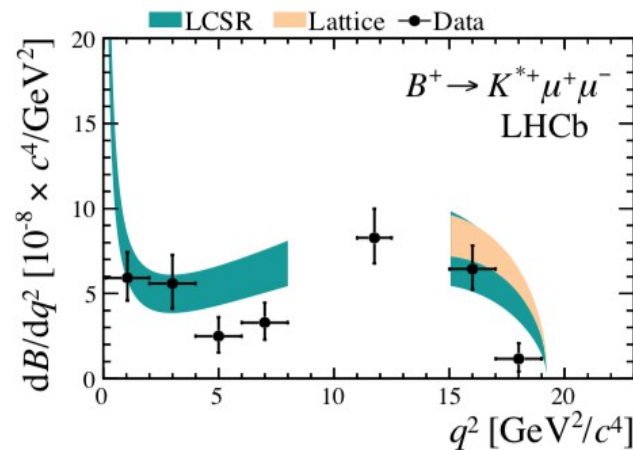
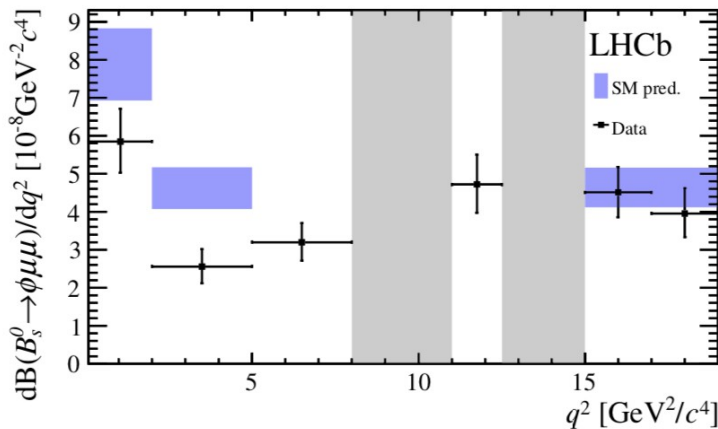
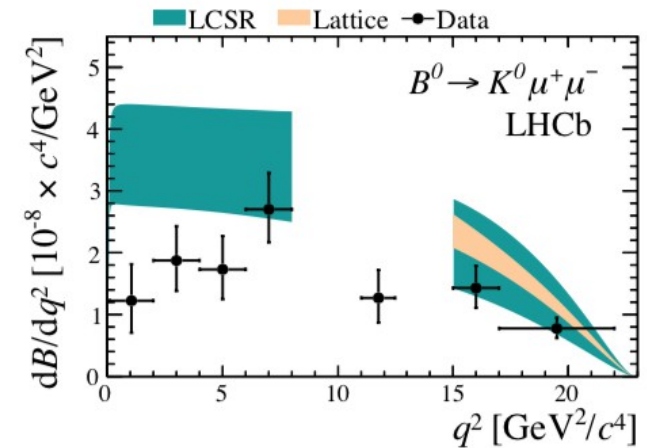
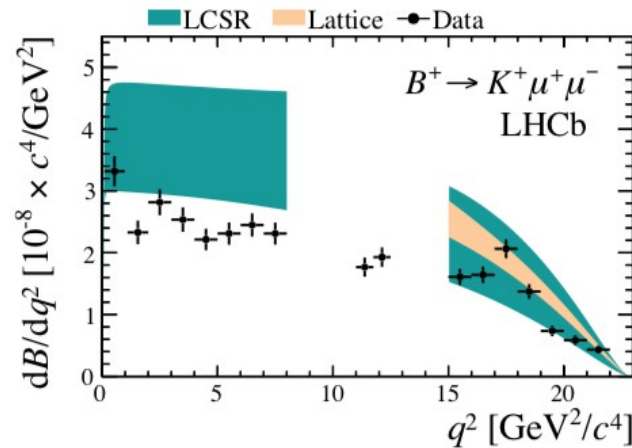
$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

$$B^0 \rightarrow K^0 \mu^+ \mu^-$$

$$B^+ \rightarrow K^{*+} \mu^+ \mu^-$$

$$B_s^0 \rightarrow \phi \mu^+ \mu^-$$

$$\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$$

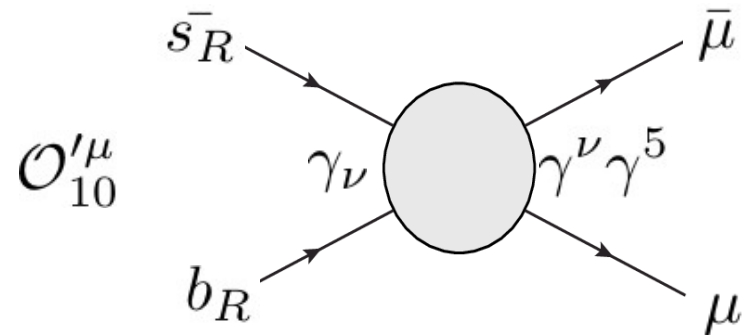
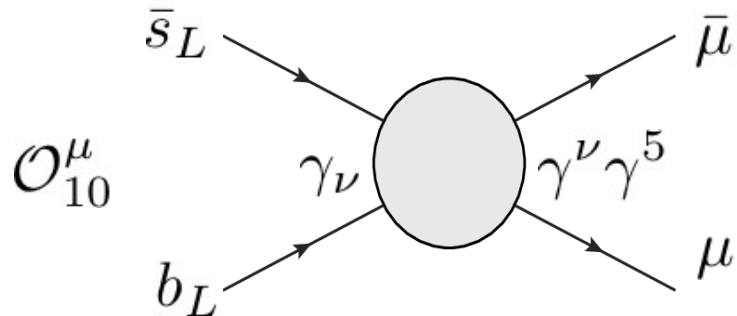
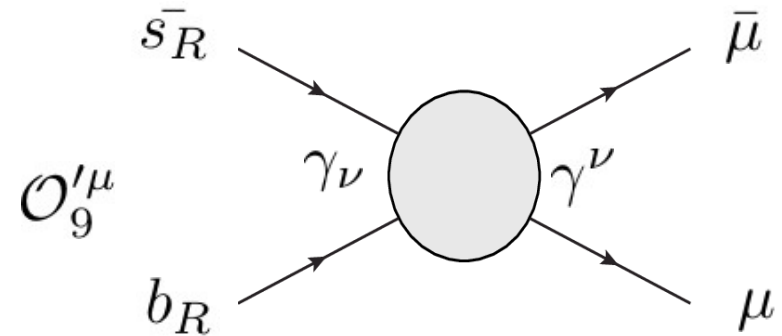
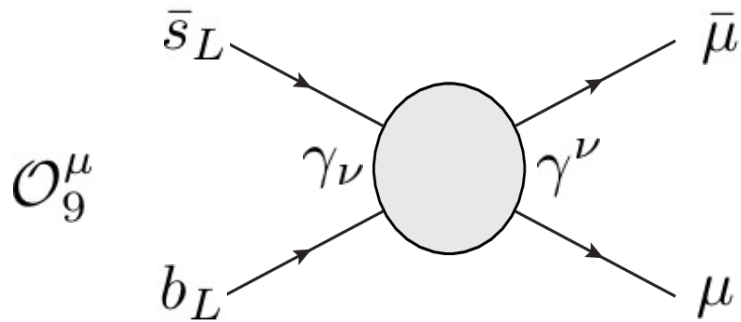


Statistical evidence of New Physics

In the last 4-5 years the flavor anomalies have generated speculations about New Physics (NP)

- > 300 papers in the literature
- ~ 15 global fits
- **Emerging dominant NP operators in the effective Hamiltonian approach:**

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i,l} (C_i^l O_i^l + C_i'^l O_i'^l) + \text{H.c.}$$



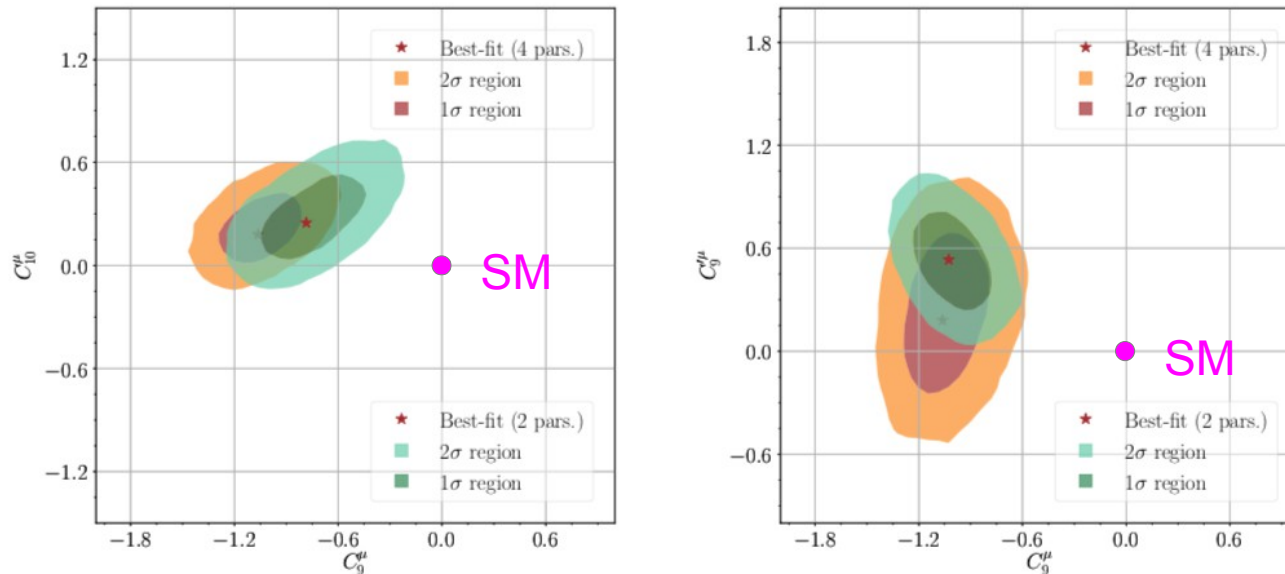
Statistical evidence of New Physics

After the March '19 update we published the only **fully Bayesian** fit on the market

K.Kowalska, D.Kumar, E.M.Sessolo,
Eur.Phys.J. C79 (2019) no.10, 840

- 140 observables with experimental + theoretical correlations
- Up to 9 parameters scanned simultaneously
- Employed both the effective field theory and NP models approach

Posterior PDF:

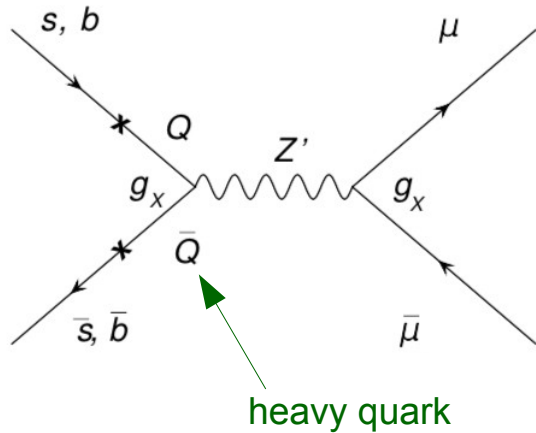


- Pull of the best-fit point: **5.1 σ**
- Bayes factor NP vs Standard Model: **10^5 to 1** (“decisive”)*

* unless underestimating hadronic uncertainties, unknown systematics, etc.

Models of New Physics for the flavor anomalies

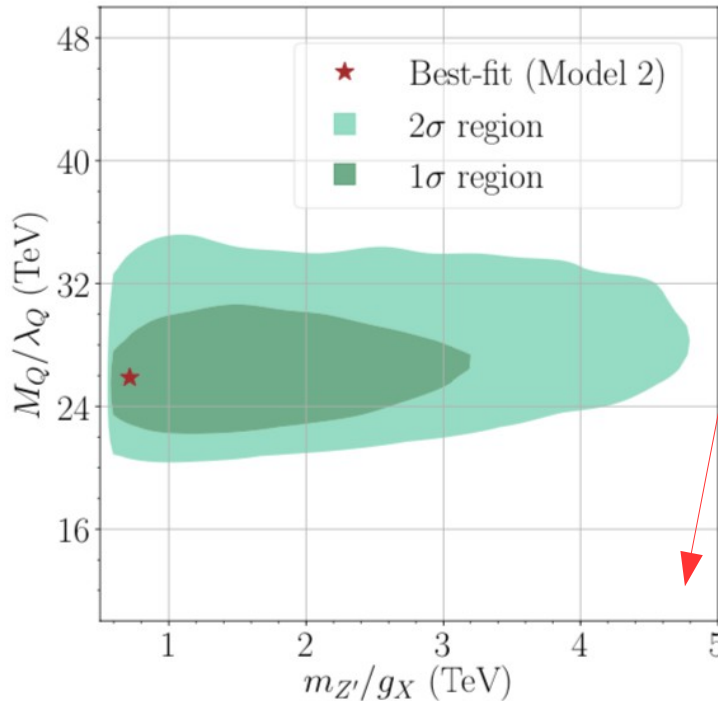
- Option 1 New heavy gauge boson Z'



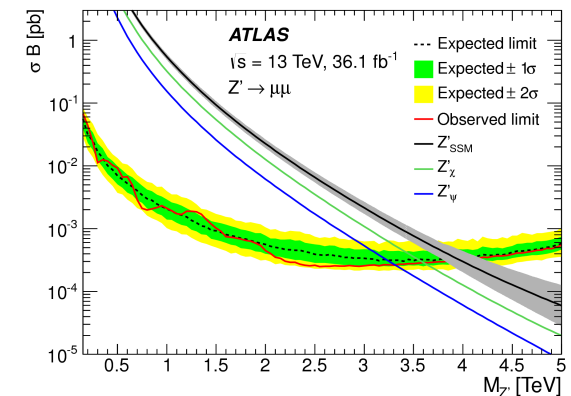
Requires a heavy quark mixing with b and s :

$$\mathcal{M}_d = \begin{pmatrix} & \lambda_{Q,1} v_1 / \sqrt{2} \\ Y_{d,ij} v_d & \lambda_{Q,2} v_1 / \sqrt{2} \\ & \lambda_{Q,3} v_1 / \sqrt{2} \\ 0 & 0 & 0 & -M_Q \end{pmatrix}$$

Kowalska, Kumar, Sessolo '19



Z' in LHC reach?



Models of New Physics for the flavor anomalies

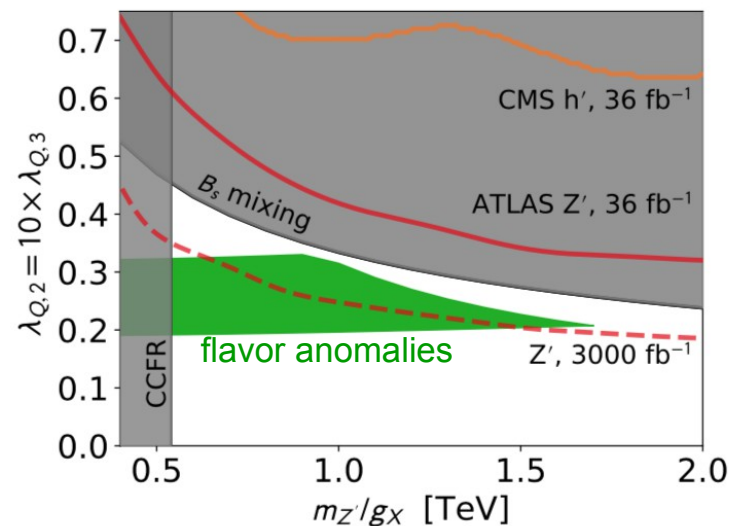
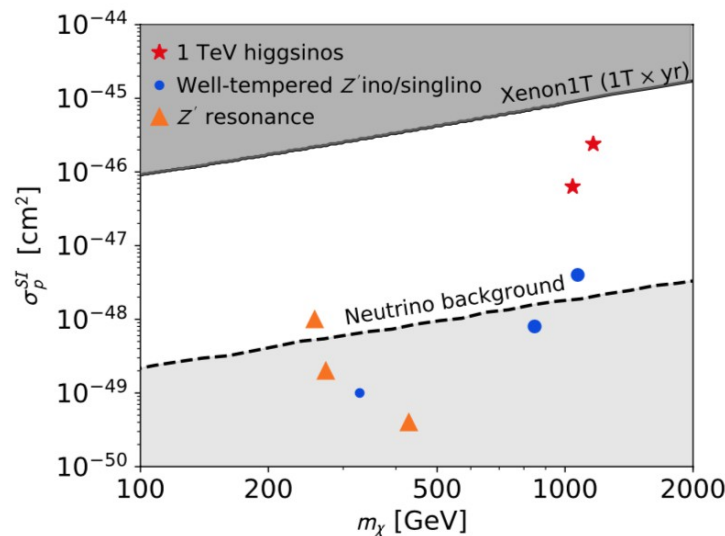
- There is *at least* one extra scale in the picture... What is its origin?

One option is supersymmetry-breaking...

- It protects all scalar mass parameters
- It agrees with expectations from the Higgs boson mass (SUSY ~ 10 s TeV)

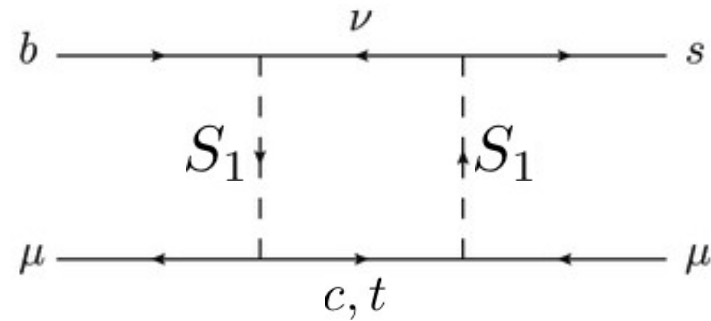
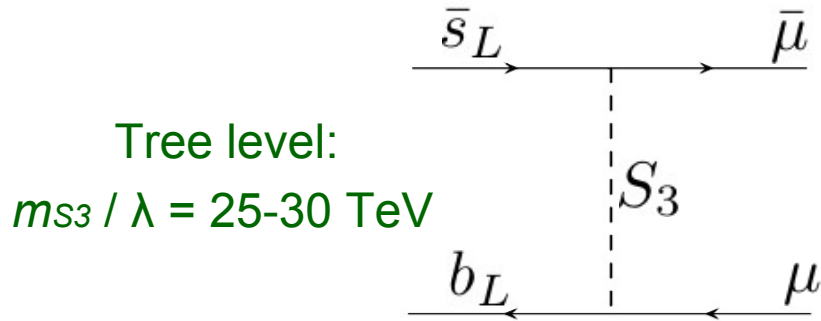
- Enticing connections with dark matter
- Complementary signatures (LHC, muon $g-2$)

L.Darmé, K.Kowalska, L.Roszkowski, E.M.Sessolo,
JHEP 1810 (2018) 052



Models of New Physics for the flavor anomalies

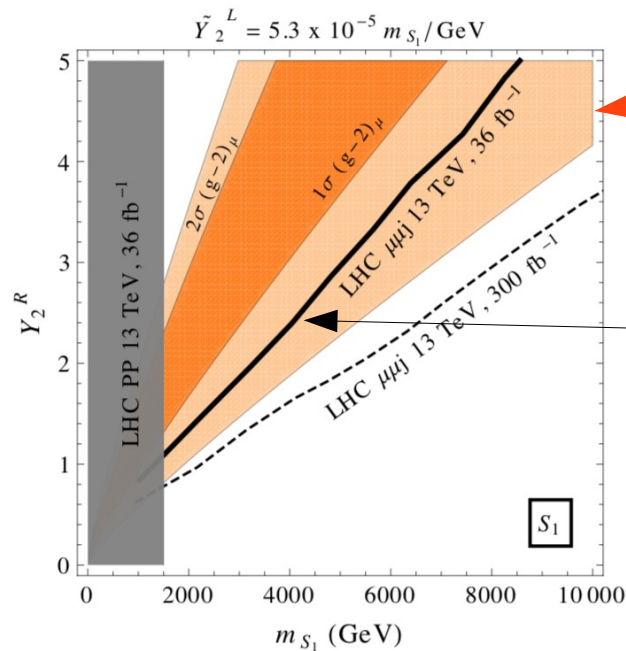
- Option 2 **Leptoquarks**



Loop level: $m_{S1} / \lambda \sim 2 \text{ TeV}$

Rich phenomenology intersecting flavor decays, muon $g-2$, and collider bounds:

K.Kowalska, E.M.Sessolo, Y.Yamamoto,
Phys.Rev. D99 (2019) no.5, 055007



Muon $g-2$ (2 σ region)

LHC direct bound
(numerical recast)

To take home

- The statistical evidence for NP in flavor anomalies at LHCb and others remains very strong
- Possibilities include heavy states (new gauge bosons, leptoquarks, vector-like heavy fermions) and light feebly interacting particles (not discussed here)
- NCBJ has been able to enter this competitive subfield with a number of relevant contributions
- Exciting times ahead?