Flavour Physics Theory
(A BSM point of view)

M. Nardecchia

INFN & Sapienza University of Rome

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Outline

• Not able to cover all the aspects. This presentation is a personal and biased (BSM-hep/ph) point of view.

• In recent years (let's say from 2012) the two most import experimental sets of experimental data that are impacting the field of Flavour Physics (BSM) are

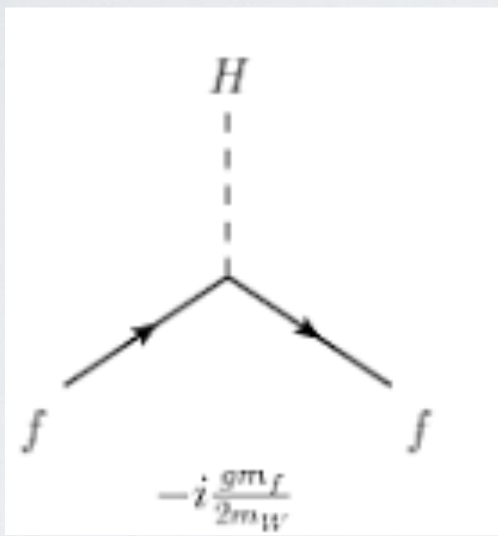
1) Higgs discovery, no evidence of New Physics in direct searches as well as in purely hadronic or purely leptonic processes

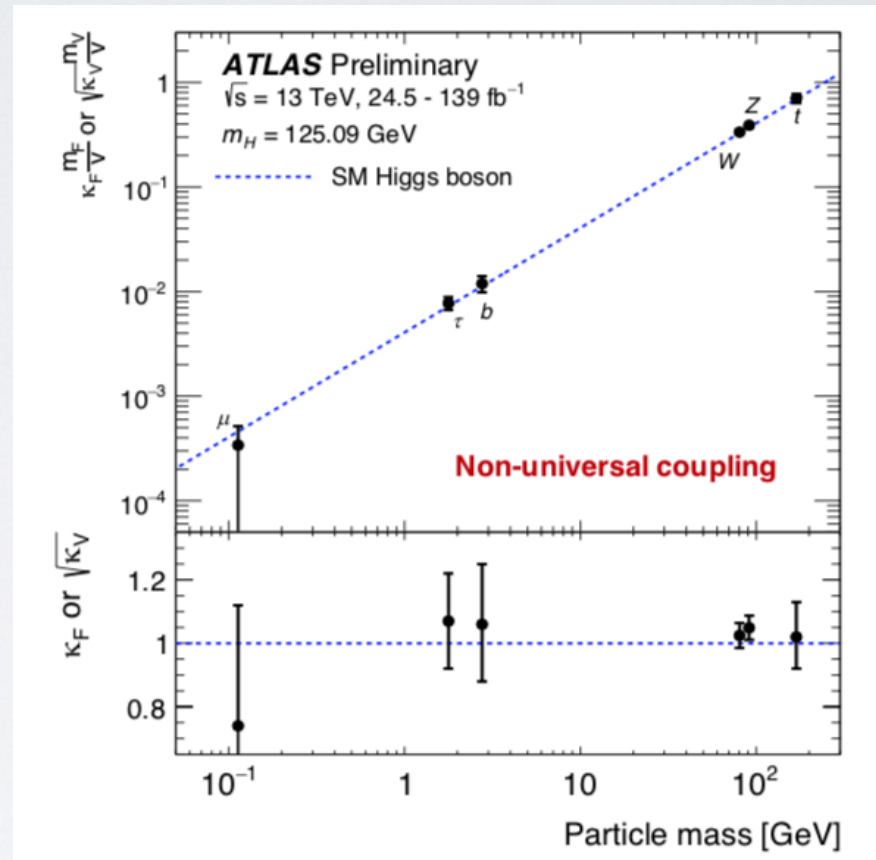
2) Slow but steady growing case for possible New Physics effects in semileptonic B-meson decays both in neutral and charged currents

• I will try to talk about theoretical implications of these two sets of measurements

The (SM) Higgs at the LHC

• Higgs looks very SM-like. Flavour highlight: Higgs direct measurement of its couplings to third generations of fermions





Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 ± 0.35	1.01 ± 0.20	1.34 ± 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 ± 0.27 *	1.04 ± 0.20	1.26 ± 0.26 **

* 13 TeV only derived from cross section measurements

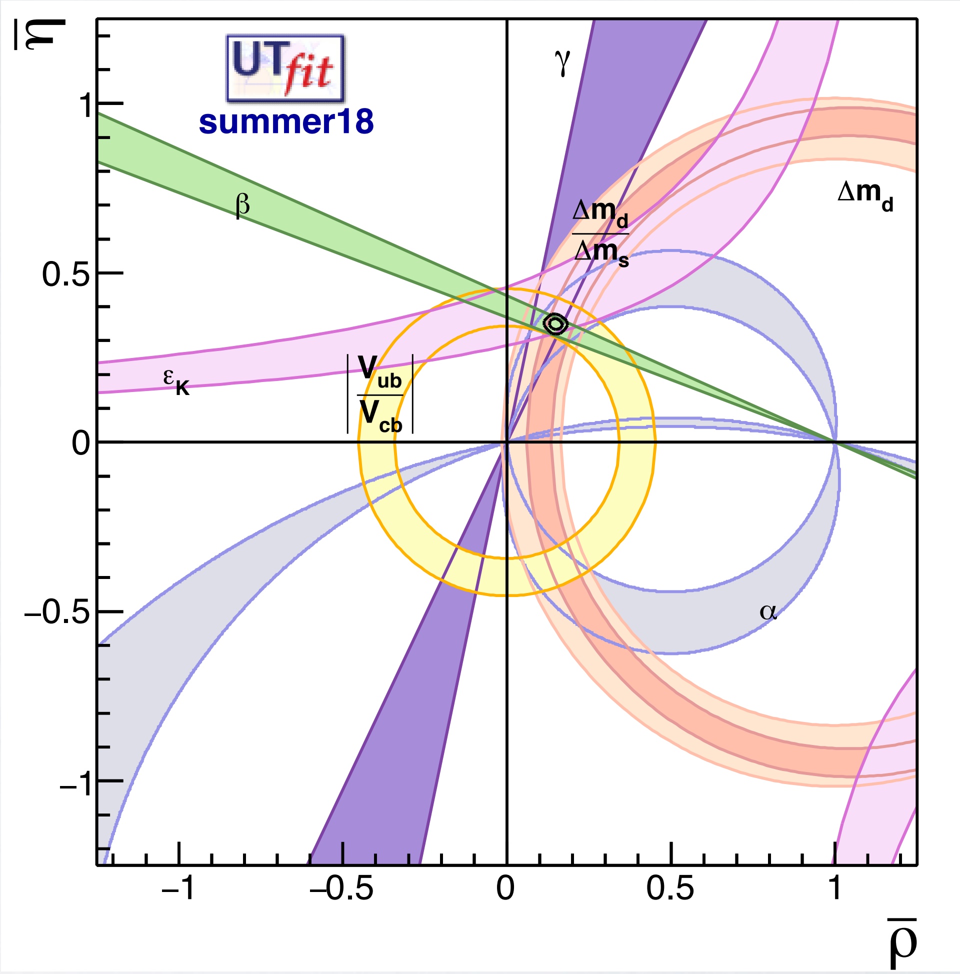
** Lower uncertainty (upper uncertainty 31)

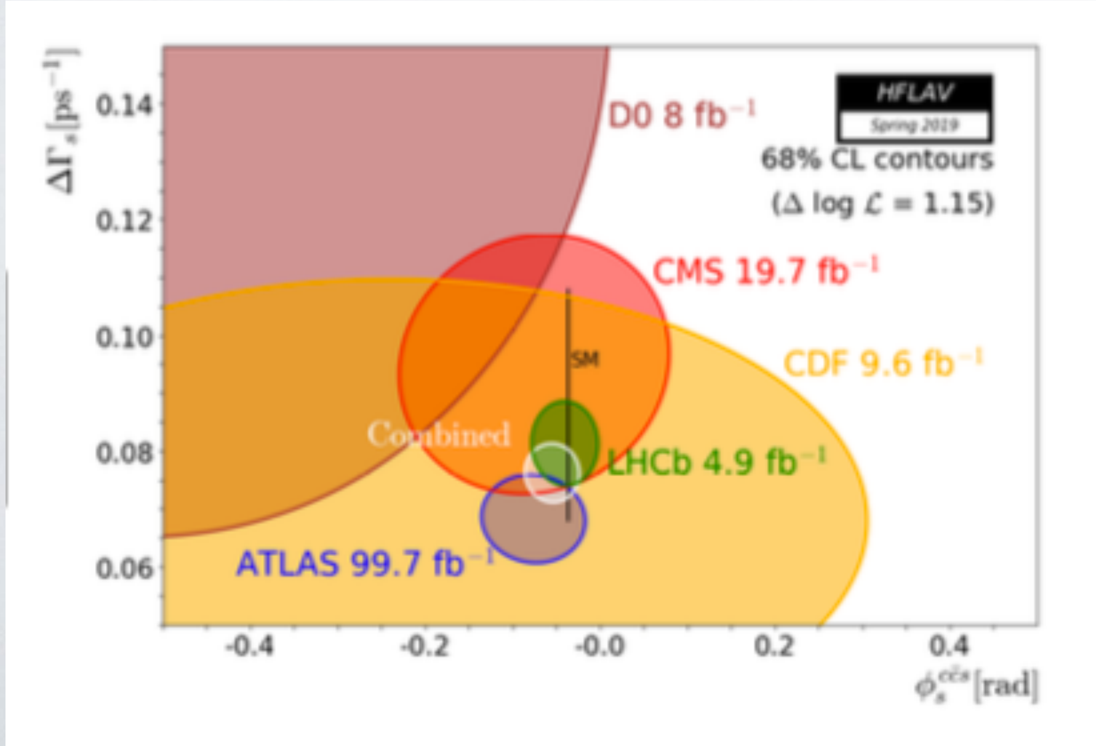
[M. Kado @ IFAE 2019]

Testing the (SM) Flavour

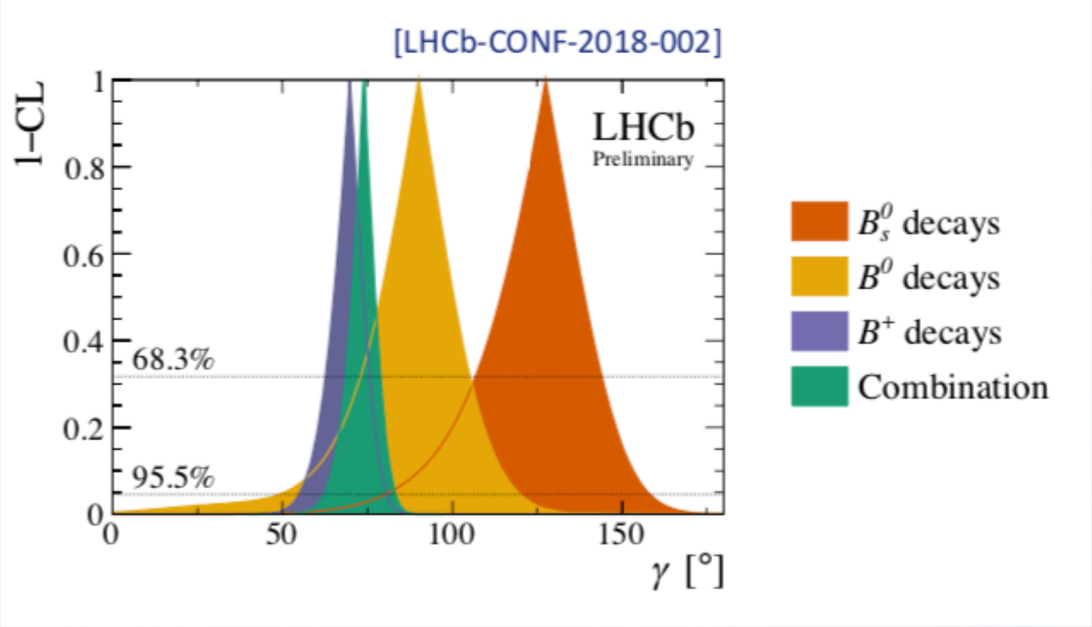
- Flavour violation looks CKM-like:

$$\mathcal{L}_{\rm Yuk} = \mathbf{y_u}\tilde{h}qu^c + \mathbf{y_d}hqd^c + \mathbf{y_e}hle^c + \text{ h.c.}$$





Talks by C. Chobanova, A. Barton



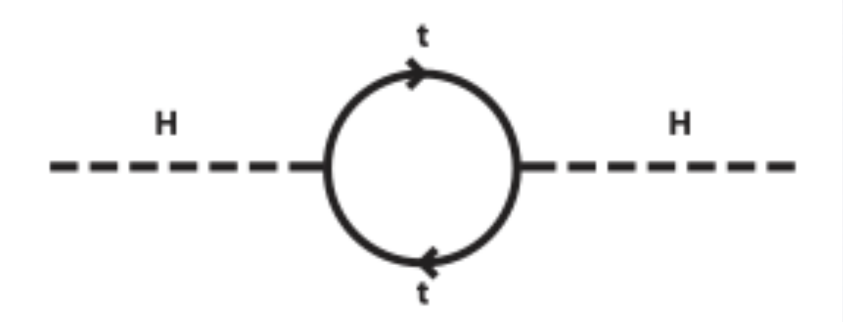
Talks by A. Rollings, Resmi P K

Direct searches

- A theoretical argument for New Physics the LHC:

[See talk by G. Panico]

- Upper bound from naturalness of the Higgs mass $\Lambda < 1\ \mathrm{TeV}$



$$m_H^2 = m_{\mathrm{tree}}^2 + \delta m_H^2$$

$$\delta m_H^2 = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \approx (0.3\,\Lambda)^2$$

Main Solutions:

1) Supersymmetry
2) Composite Higgs

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[See talk by G. Panico]

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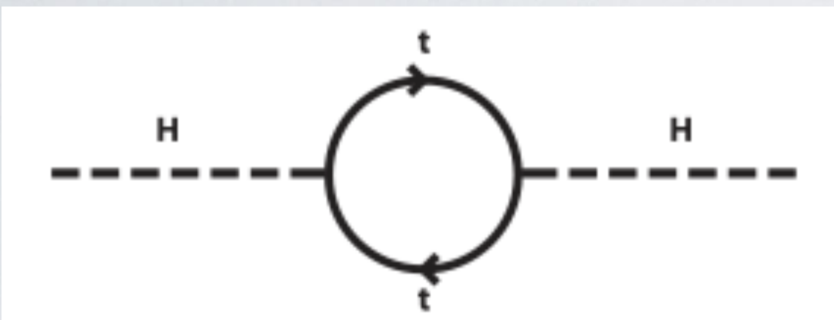

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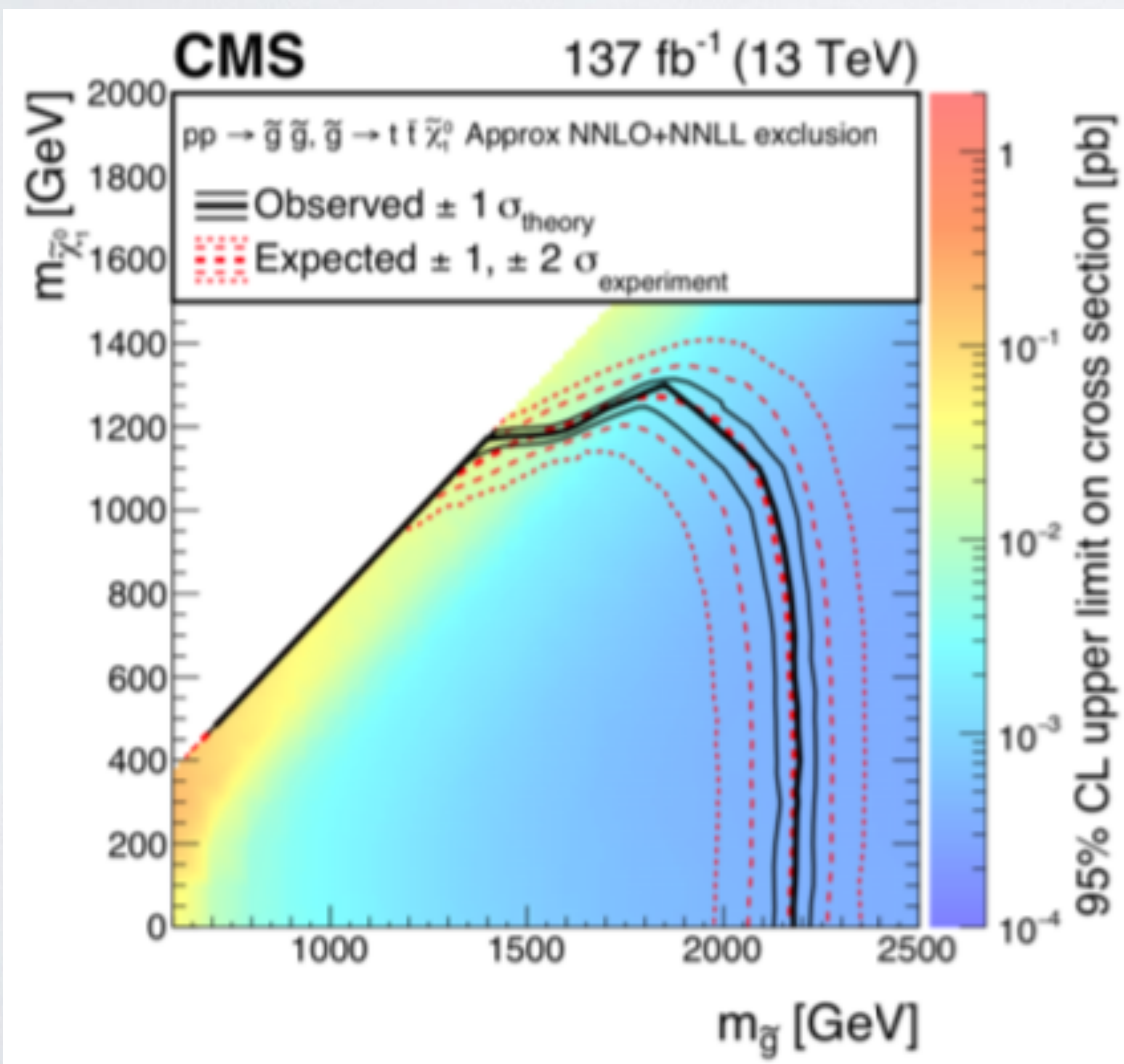
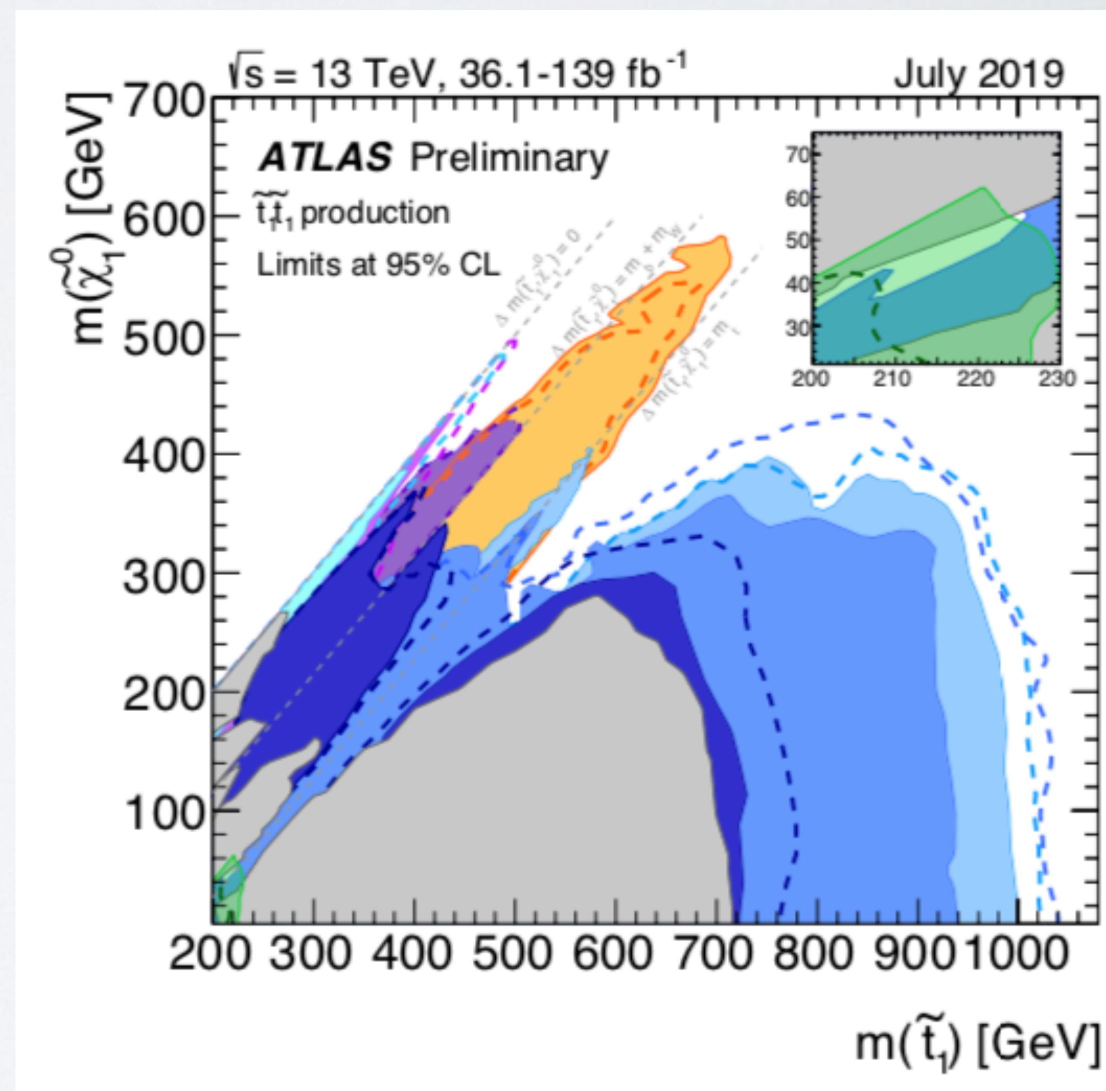
- But..





Flavour physics as NP probe

- Standard Model is very successful in describing physics up to the electroweak scale
- Standard Model is not a complete theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$

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- Strategy: measure with precision processes containing SM particles at lower energies

$$\mathcal{A}_{i\to j} = \mathcal{A}_{ij}^{\rm SM} + \frac{c_{ij}}{\Lambda^2}$$

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- We can learn about the combination $\dfrac{c_{ij}}{\Lambda^2}$

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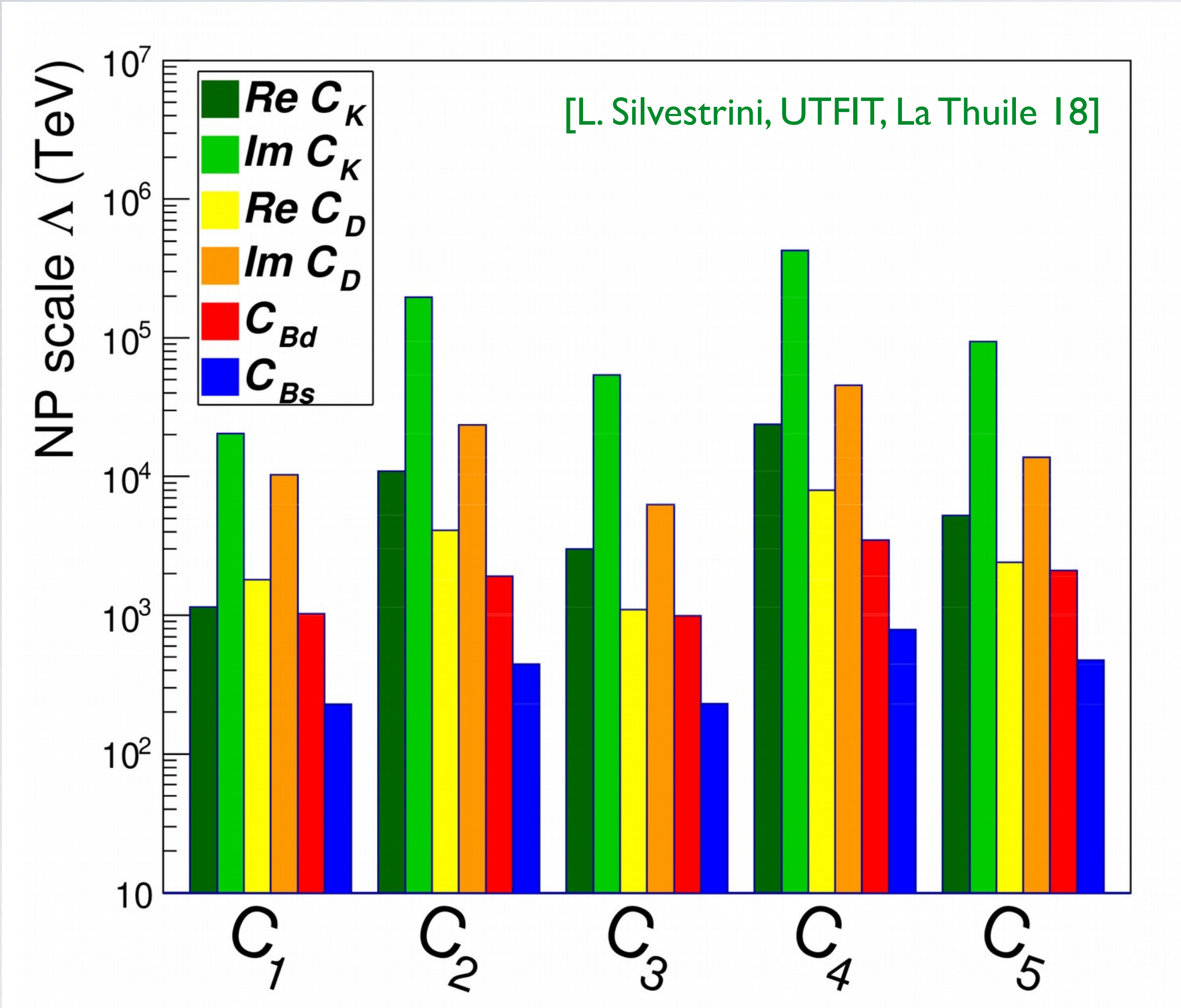
- Which are good observables? Any, but in particular those ones suppressed/forbidden in the SM

$$p \to \pi^0 e^+ \qquad\qquad d_i \to d_j \ell^+ \ell^-$$

$$\mathcal{A}^{\text{SM}} = 0 \qquad\qquad \mathcal{A}^{\text{SM}} = \frac{1}{16\pi^2} V_{ik} V_{kj}^* f\left(\frac{m_k}{m_W}\right)$$

Flavour physics as NP probe



$$\mathcal{A}_{i\to j} = \mathcal{A}_{ij}^{\rm SM} + \frac{c_{ij}}{\Lambda^2}$$

- What can we probe indirectly?

$$\frac{c_{ij}}{\Lambda^2}$$

c_{ij} → Model dependent part

C= (loops) x (couplings) x (flavour)

Λ^2 → On-shell effects @ colliders

- No evidence of NP in ΔF=2 processes

$$\Lambda > \begin{cases} 4.3\cdot 10^5\ \text{TeV} \times |c_{sd}|^{1/2} & \epsilon_K \\ 4.5\times 10^4\ \text{TeV}\times |c_{cu}|^{1/2} & D \text{ mixing} \\ 3.5\times 10^3\ \text{TeV}\times |c_{bd}|^{1/2} & B_d \text{ mixing} \\ 7.9\times 10^2\ \text{TeV}\times |c_{bs}|^{1/2} & B_s \text{ mixing}\end{cases}$$

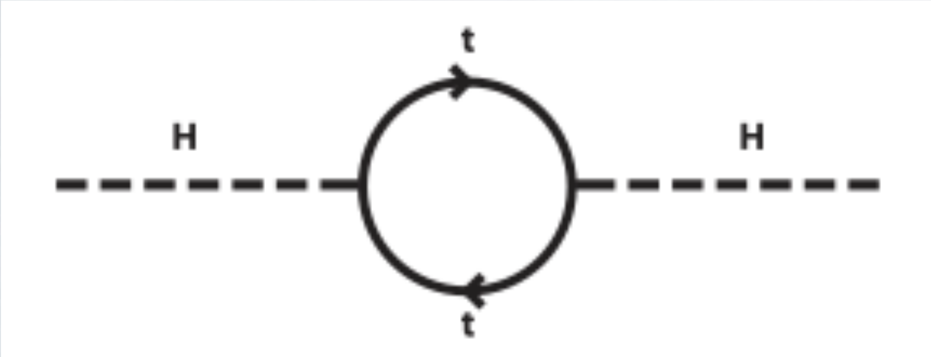
$$\begin{aligned} Q_1^{q_iq_j} &= \bar q^\alpha_{jL}\gamma_\mu q^\alpha_{iL}\bar q^\beta_{jL}\gamma^\mu q^\beta_{iL}\,, \\ Q_2^{q_iq_j} &= \bar q^\alpha_{jR} q^\alpha_{iL}\bar q^\beta_{jR} q^\beta_{iL}\,, \\ Q_3^{q_iq_j} &= \bar q^\alpha_{jR} q^\beta_{iL}\bar q^\beta_{jR} q^\alpha_{iL}\,, \\ Q_4^{q_iq_j} &= \bar q^\alpha_{jR} q^\alpha_{iL}\bar q^\beta_{jL} q^\beta_{iR}\,, \\ Q_5^{q_iq_j} &= \bar q^\alpha_{jR} q^\beta_{iL}\bar q^\beta_{jL} q^\alpha_{iR}\,. \end{aligned}$$

Λ?

- “Large” effects still possible $\left|\frac{\mathcal{A}_{NP}}{\mathcal{A}_{SM}}\right| \lesssim 20\%$
- To progress we need extra theoretical input

Naturalness (Pre-LHC)

- Upper bound from naturalness of the Higgs mass $\Lambda \lesssim 500\ \mathrm{GeV}$



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- Lower bounds from FCNC

$$\Lambda > \begin{cases} 4.3 \cdot 10^5\ \mathrm{TeV} \times |c_{sd}|^{1/2} & \epsilon_K \\ 4.5 \times 10^4\ \mathrm{TeV} \times |c_{cu}|^{1/2} & D \text{ mixing} \\ 3.5 \times 10^3\ \mathrm{TeV} \times |c_{bd}|^{1/2} & B_d \text{ mixing} \\ 7.9 \times 10^2\ \mathrm{TeV} \times |c_{bs}|^{1/2} & B_s \text{ mixing} \end{cases}$$

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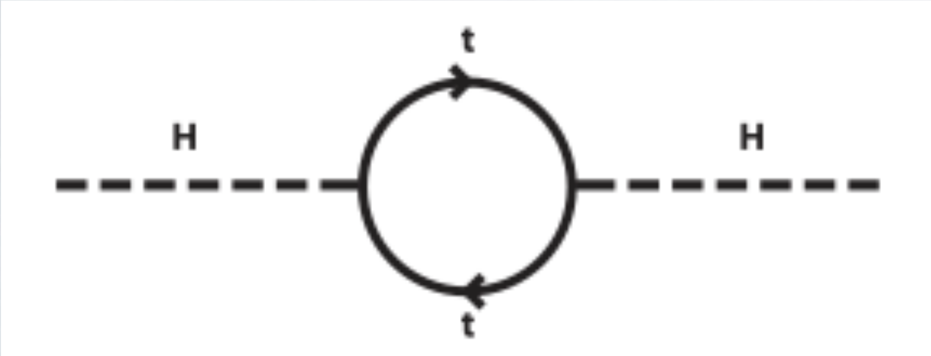

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- Two (problematic) possibilities:

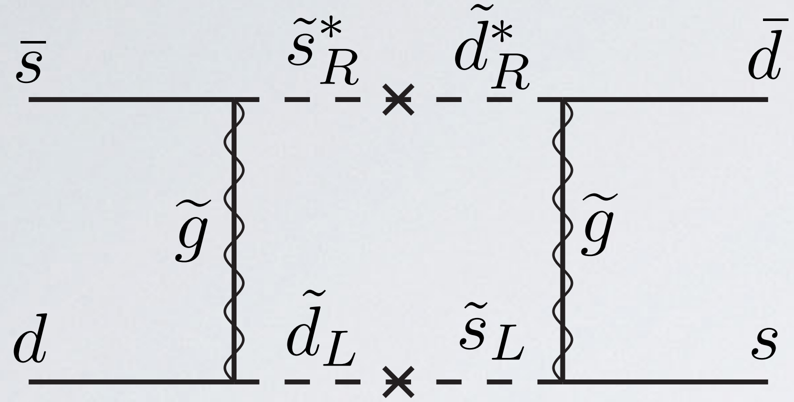
(i) Non canonical, $\Lambda \gg 1 \text{ TeV and } c_{ij} = \mathcal{O}(1)$ Hierarchy Problem

(ii) Canonical, $\Lambda < 1 \text{ TeV and } c_{ij} \ll 1$ BSM Flavour Problem

- "Canonical" solution: spectacular New Physics in direct searches, boring flavour structure highly constrained, typically invoking Minimal Flavour Violation (MFV)

$$\text{MFV} = \begin{cases} SU(3)^3 & \text{symmetry} \\ y_u, y_d & \text{spurions} \end{cases} \qquad c_{ij} = c_{ij}(y_u, y_d) \qquad \Lambda > 500 \text{ GeV}$$

MFV-SUSY: direct VS indirect



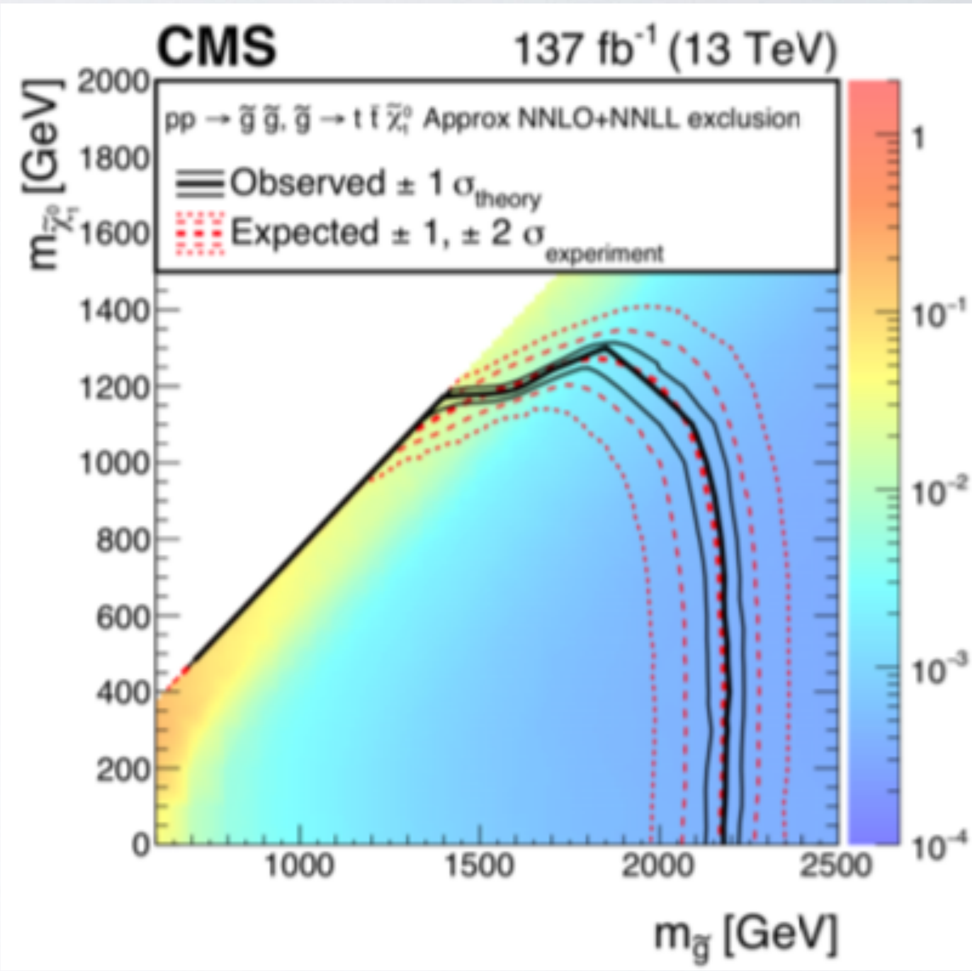
$$\frac{c_{ij}\mathcal{O}_{ij}}{\Lambda^2}$$

$$c_{ij} = \frac{\alpha_s}{4\pi}\left(y_u y_u^\dagger\right)_{ij}$$

$$\Lambda = m_{susy}$$

Flavour $m_{susy} > 500\ \mathrm{GeV}$

Direct searches $m_{susy} > 2000\ \mathrm{GeV}$



Small (non-observable) NP effects
in the flavour sector!

Time to shift point of view and consider richer flavour structures
(giving up (some of) the naturalness)

Two possible approaches

- Motivated structures connect FV in the SM and beyond the SM
- Partial misalignment with the SM (departure from the MFV)

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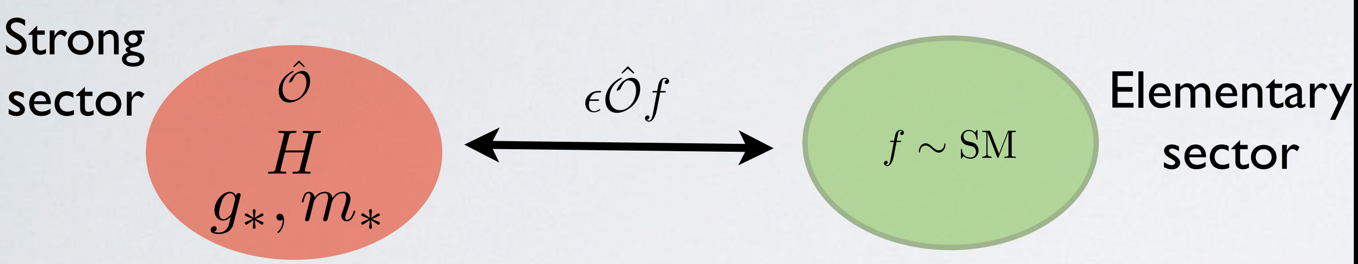
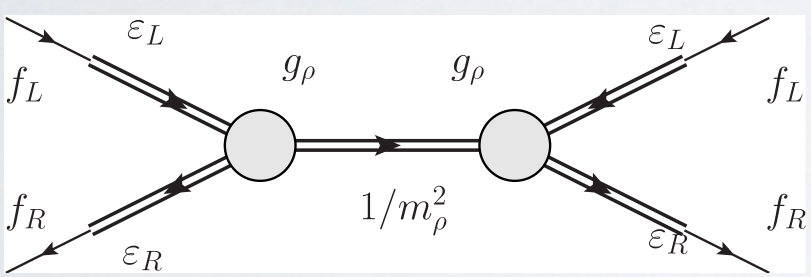
Dynamics



$$|SM\rangle = \cos\epsilon |f\rangle + \sin\epsilon|\mathcal{O}\rangle \qquad y_{ij}^{SM} \sim \epsilon_i^L \epsilon_j^R$$



$$\sim \frac{g_*^2}{m_*^2} \epsilon_i^L \epsilon_j^L \epsilon_i^R \epsilon_j^R$$

$$m_* \gtrsim \begin{cases} 15 \text{ TeV} & \epsilon_K, b \to s, \dots \\ 40 \text{ TeV} & \text{nEDM} \end{cases}$$

Symmetry

[Froggatt-Nielsen, see F. Tellander]

- Choose a subgroup of

$$G_f = U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$$

- Choose a set of spurions and apply selection rules imposed by symmetry
  - An example $U(2)^3$ [arXiv1108.5125]

$$Y_u = y_t \left(\begin{array}{c|c} \Delta Y_u & x_t V \\ \hline 0 & 1 \end{array} \right) \qquad Y_d = y_b \left(\begin{array}{c|c} \Delta Y_d & x_b V \\ \hline 0 & 1 \end{array} \right)$$

$$\Delta Y_u \sim (2, \bar{2}, 1) \quad \Delta Y_d \sim (2, 1, \bar{2}) \quad V \sim (2, 1, 1)$$

- Largest effects in b physics

- In both cases lepton sector is more model dependent, we have direct access only to charged lepton Yukawa coupling. Generically we expect $|C_\tau^{NP}| \gg |C_\mu^{NP}| \gg |C_e^{NP}|$

Messages

- After Run 1 & 2 of LHC, “Naturalness crisis” allows for richer and motivated flavour structures with associated potential signatures.

- Absence BSM effects at high pT makes flavour and intensity frontier physics extremely important.

1. **Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays**
(820) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Jun 25, 2014. 10 pp.
Published in **Phys.Rev.Lett. 113 (2014) 151601**
CERN-PH-EP-2014-140, LHCB-PAPER-2014-024
DOI: 10.1103/PhysRevLett.113.151601
e-Print: **arXiv:1406.6482 [hep-ex] | PDF**
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CERN Document Server; ADS Abstract Service
Detailed record - Cited by 820 records 500+

2. **Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ De**
(741) LHCb Collaboration (Roel Aaij (CERN) *et al.*). Jul 13, 2015. 15 pp.
Published in **Phys.Rev.Lett. 115 (2015) 072001**
CERN-PH-EP-2015-153, LHCB-PAPER-2015-029
DOI: 10.1103/PhysRevLett.115.072001
e-Print: **arXiv:1507.03414 [hep-ex] | PDF**
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CERN Document Server; ADS Abstract Service; Interactions.org article; Link to BBC News article; Link to Symmetry M
Detailed record - Cited by 741 records 500+

3. **Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$**
(595) LHCb Collaboration (Roel Aaij (CERN) *et al.*). Jun 29, 2015. 10 pp.
Published in **Phys.Rev.Lett. 115 (2015) no.11, 111803**, Erratum: **Phys.Rev.Lett. 115 (2015) no.15, 159901**
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DOI: 10.1103/PhysRevLett.115.159901, 10.1103/PhysRevLett.115.111803
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4. **Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$**
(519) LHCb Collaboration (R Aaij (NIKHEF, Amsterdam) *et al.*). Aug 7, 2013. 8 pp.
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DOI: 10.1103/PhysRevLett.111.191801
e-Print: **arXiv:1308.1707 [hep-ex] | PDF**
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5. **First Evidence for the Decay $B_s^0 \to \mu^+\mu^-$**
(476) LHCb Collaboration (R Aaij (NIKHEF, Amsterdam) *et al.*). Nov 2012. 9 pp.
Published in **Phys.Rev.Lett. 110 (2013) no.2, 021801**
CERN-PH-EP-2012-335, LHCB-PAPER-2012-043
DOI: 10.1103/PhysRevLett.110.021801
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6. **Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity**
(466) LHCb Collaboration (Roel Aaij (CERN) *et al.*). Dec 14, 2015.
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CERN Document Server; ADS Abstract Service; Link to Article from SCOAP3; Link to Figures, tables and other inform
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7. **Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis**
(455) CMS and LHCb Collaborations (Vardan Khachatryan (Yerevan Phys. Inst.) *et al.*). Nov 17, 2014. 4
Published in **Nature 522 (2015) 68-72**
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8. **Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays**
(422) LHCb Collaboration (R. Aaij (CERN) *et al.*). May 16, 2017.
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DOI: 10.1007/JHEP08(2017)055
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Data: INSPIRE | HepData
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9. **Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and search for B^0**
(396) LHCb Collaboration (R. Aaij (NIKHEF, Amsterdam) *et al.*). Jul 18, 2013. 9 pp.
Published in **Phys.Rev.Lett. 111 (2013) 101805**
CERN-PH-EP-2013-128, LHCB-PAPER-2013-046
DOI: 10.1103/PhysRevLett.111.101805
e-Print: **arXiv:1307.5024 [hep-ex] | PDF**
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10. **Measurement of J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV**
(393) LHCb Collaboration (R. Aaij (NIKHEF, Amsterdam) *et al.*). Mar 2011. 24 pp.
Published in **Eur.Phys.J. C71 (2011) 1645**
LHCb-PAPER-2011-003, CERN-PH-EP-2011-018
DOI: 10.1140/epjc/s10052-011-1645-y
e-Print: **arXiv:1103.0423 [hep-ex] | PDF**
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CERN Document Server; ADS Abstract Service
Data: INSPIRE | HepData
Detailed record - Cited by 393 records 250+

11. **Evidence for CP violation in time-integrated $D^0 \to h^-h^+$ decay rates**
(361) LHCb Collaboration (R. Aaij (NIKHEF, Amsterdam) *et al.*). Dec 2011. 8 pp.
Published in **Phys.Rev.Lett. 108 (2012) 111602**
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DOI: 10.1103/PhysRevLett.108.111602, 10.1103/PhysRevLett.108.129903
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Detailed record - Cited by 361 records 250+

12. **Determination of the X(3872) meson quantum numbers**
(334) LHCb Collaboration (R Aaij (NIKHEF, Amsterdam) *et al.*). Feb 25, 2013. 8 pp.
Published in **Phys.Rev.Lett. 110 (2013) 222001**
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References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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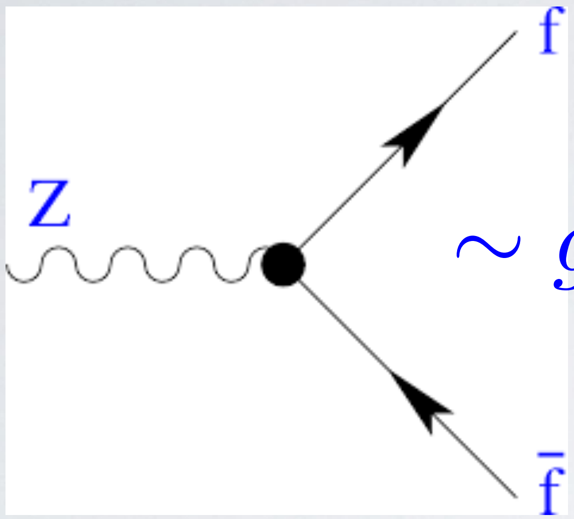
Lepton Flavour Universality in the SM

- Leptons appear in the Standard Model in the gauge and Yukawa sector:



$\sim g\,\delta_{ij}$

$$\mathcal{L}_{\rm SM} \supset i\left(\overline{L}^i_L \gamma^\mu D_\mu L^A_L + \overline{E}^i_R \gamma^\mu D_\mu E^i_R\right)$$

- Global symmetry $U(3)_{L_L} \times U(3)_{E_R}$
- Gauge interactions are Lepton Flavour Universal (LFU)

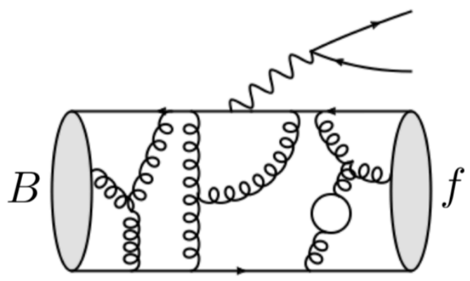
- Yukawa sector breaks the universality in two ways $\mathcal{L}_{\rm SM} \supset Y^E_{ij}\,\overline{L}^i_L E^j_R\, H + {\rm h.c}$

1) In the mass terms $m_e \neq m_\mu \neq m_\tau$
2) Higgs interactions (negligible)

- The Standard Model is Lepton Flavour Non Universal (LFNU)

- Testing the LFU in the Standard Model means testing the universality of the gauge interaction

LFU in $B^+ \to K^+\ell^+\ell^-$



e.g. semileptonic decay

$$R_K = \frac{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

Measurement performed in $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ on

- Reanalysed **2011 & 2012 data (3 fb^{-1})**,
  - $\rightarrow$ Improved reconstruction and re-optimised analysis strategy
- Added **2015 and 2016 datasets (~2 fb^{-1})**,
  - $\rightarrow$ Larger $b\bar{b}$ cross-section due to higher $\sqrt{s}$

In total, this update uses **~twice as many B's as previous analysis**.

Result

[PRL 122 (2019) 191801]

- R_K is extracted through simultaneous fit to 8 datasets: muons/electrons (3 trigger categories) Run1/Run2

$$\boldsymbol{R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}}\ \text{(stat., syst.)}$$

  - Consistent with the SM at 2.5 standard deviations
  - Dominated by statistics of the rare electron mode
  - Dominant systematics: corrections to the simulation (trigger), fit model

- Updated measurement of dielectron differential branching fraction

$$\frac{d\mathcal{B}(B^+ \to K^+ e^+ e^-)}{dq^2}(1.1 < q^2 < 6.0\,\text{GeV}^2/c^4) = (28.6\,^{+2.0}_{-1.7} \pm 1.4) \times 10^{-9}\,c^4/\text{GeV}^2\,.$$

  - Consistent with the SM predictions

[Talk by V. Lisovskyi]

Flavour Anomalies

[About 20 talks related @EPS2019]

$b \to s\mu\mu$

(LHCb from 2013)

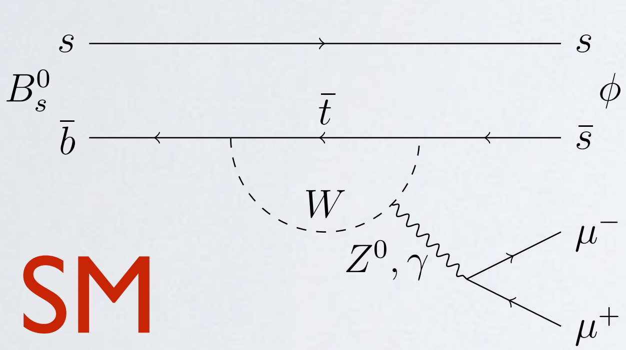
1) Angular observables in $B \to K^*\mu^+\mu^-$ $\sim 4\sigma$ (?!)

2) Branching ratios $\gtrsim 3.5\sigma$ (?!) [Various talks@EPS]

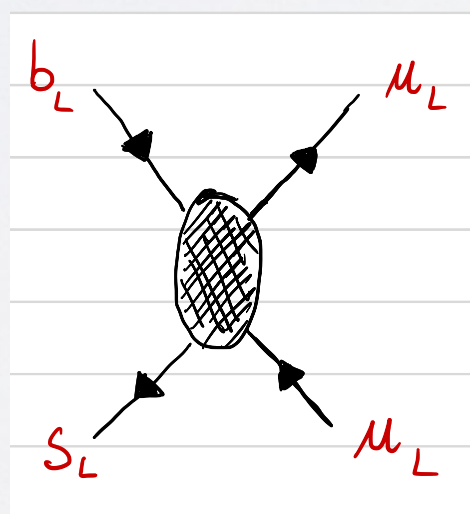
3) LFU violation in R_K 2.6σ

4) LFU violation in R_{K^*} (2 bins) $2.3\sigma,\ 2.6\sigma$

"clean" only $\approx 4\sigma$



SM



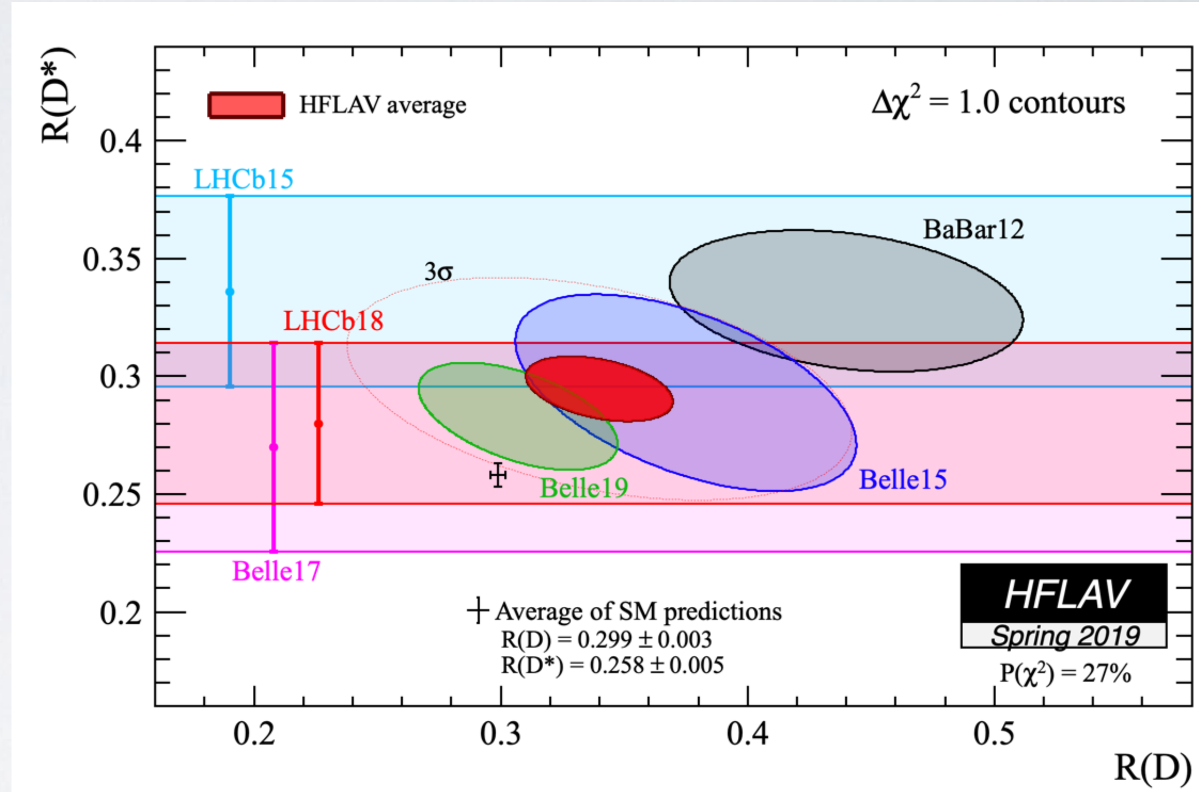
[Talk by D. Kumar]

$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2_{R_K}} \bar{s}_L \gamma^\mu b_L\ \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

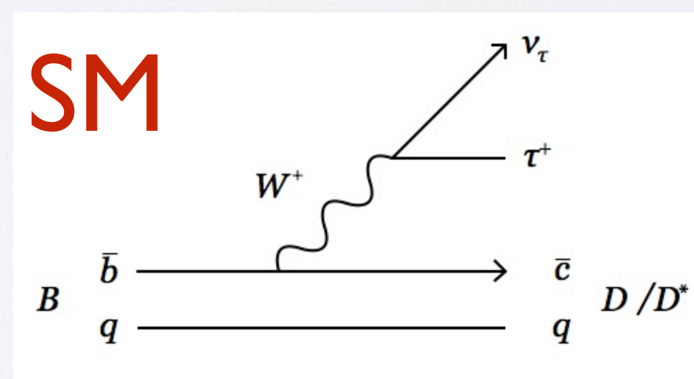
$$|C_\mu^{\rm NP}| \gg |C_e^{\rm NP}| \qquad \Lambda_{R_K} = 37\ \text{TeV}$$

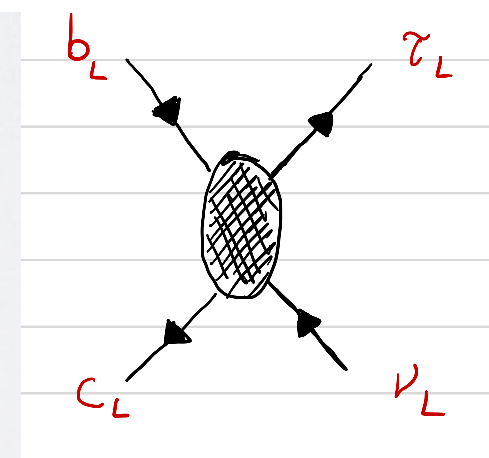
$b \to c\tau\nu$

Babar+Belle+LHCb from 2012



SM





[Talk by A. Penuelas]

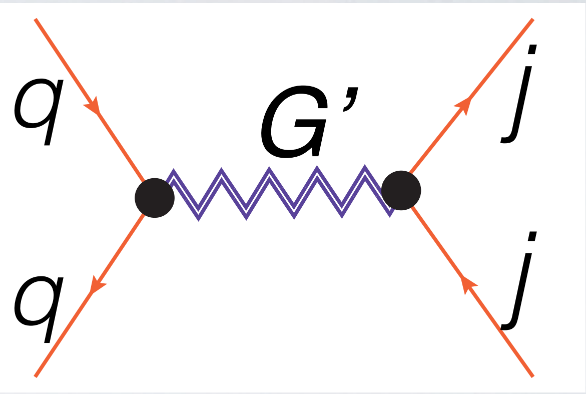
$$\mathcal{L}_{eff} = -\frac{2}{\Lambda^2_{R_D}} \bar{c}_L \gamma^\mu b_L\ \bar{\tau}_L \gamma_\mu \nu_L + h.c.$$

$$|C_\tau^{\rm NP}| \gg |C_\mu^{\rm NP}|, |C_e^{\rm NP}| \qquad \Lambda_{R_D} = 3.7\ \text{TeV}$$

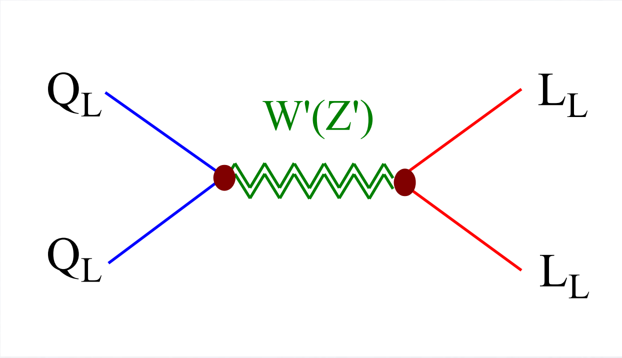
Bottom-up path

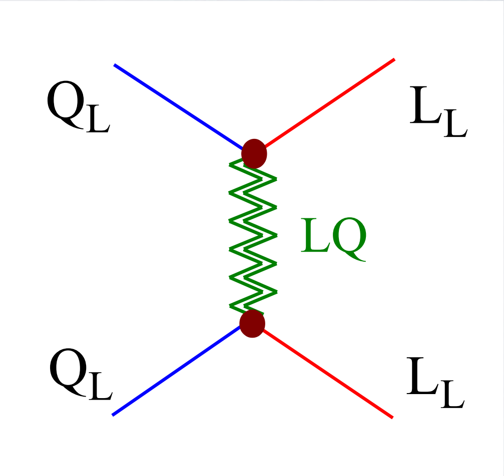
Theoretical input / bias

"Motivated" Models — Address more questions/open problems: naturalness, origin of flavour, renormalizability/accidental symmetries.….

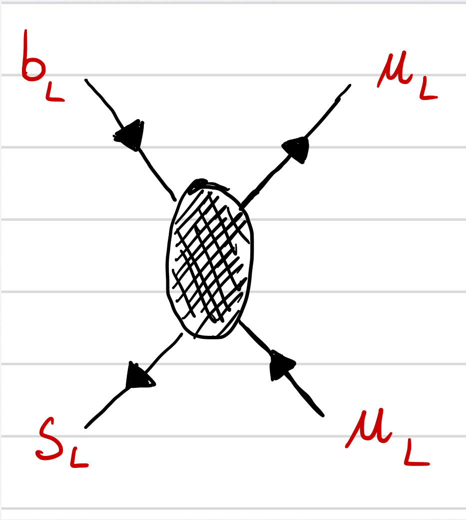


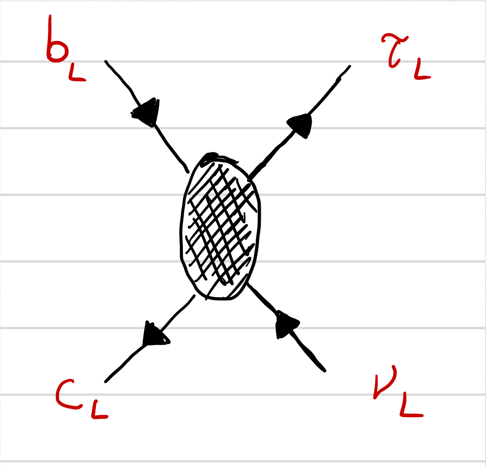
Simplified Models — Introducing explicitly New Physics, in the simplest way as possible





EFT — New Physics in a model independent way





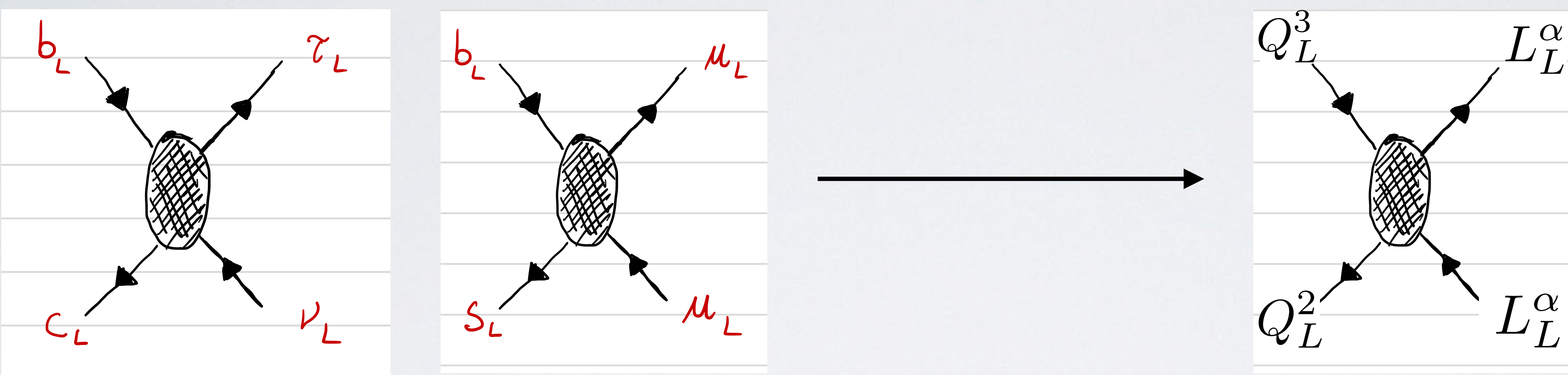
$\Lambda_{R_K} = 37\ \text{TeV}$ $\quad \Lambda_{R_D} = 3.7\ \text{TeV}$

Experimental input

EFT considerations

• Fits to data suggest a sizeable (most likely dominant) contribution of the New Physics to left currents for both quarks and leptons

$$C_S(\overline{Q}^i_L\gamma^\mu Q^j_L)(\overline{L}^\alpha_L\gamma^\mu L^\beta_L) + C_T(\overline{Q}^i_L\gamma^\mu\sigma^a Q^j_L)(\overline{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)$$



SU(2) structure induce correlations

• Considering the whole set of data (neutral and charged currents), a possible link with the SM flavour structure is emerging

$$b \to c\tau\nu \qquad 3_q \to 2_q 3_\ell 3_\ell$$

$$b \to s\mu\mu \qquad 3_q \to 2_q 2_\ell 2_\ell$$

SM VS NP
A link?

$$|C^{\rm NP}_\tau| \gg |C^{\rm NP}_\mu| \gg |C^{\rm NP}_e|$$

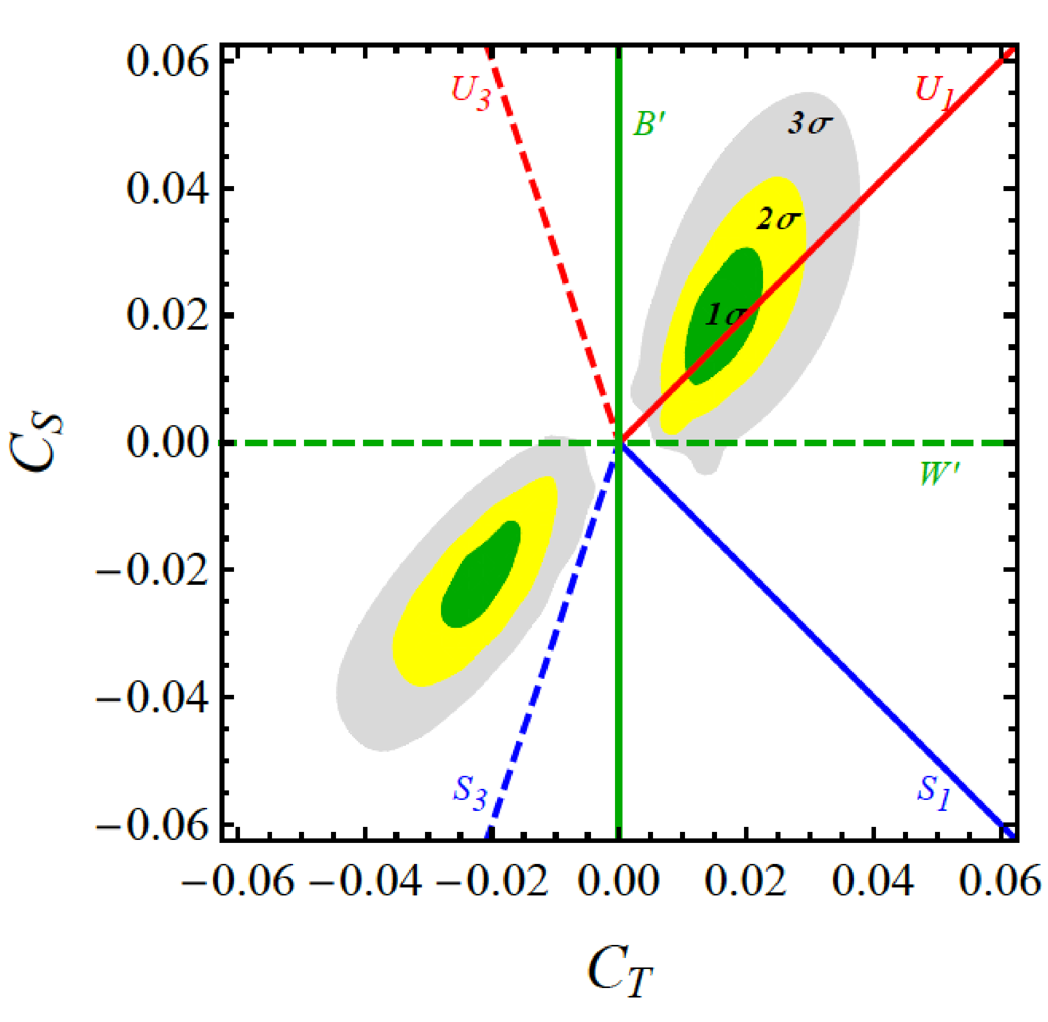
$$|Y^{SM}_\tau| \gg |Y^{SM}_\mu| \gg |Y^{SM}_e|$$

• Motivated flavour ansatz in the quark sector (U(2),Partial Compositeness…) predicts dominant coupling of the New Physics with the third family (with suppressed transitions between the first two).

• A good starting point even if flavor anomalies will disappear

Simplified models

Simplified Model	Spin	SM irrep	c_1/c_3	$R_{D^{(*)}}$	$R_{K^{(*)}}$	No $d_i \to d_j \nu\overline{\nu}$
Z'	1	$(1,1,0)$	∞	$\times$	$\checkmark$	$\times$
V'	1	$(1,3,0)$	0	$\checkmark$	$\checkmark$	$\times$
S_1	0	$(\overline{3},1,1/3)$	-1	$\checkmark$	$\times$	$\times$
S_3	0	$(\overline{3},3,1/3)$	3	$\checkmark$	$\checkmark$	$\times$
U_1	1	$(3,1,2/3)$	1	$\checkmark$	$\checkmark$	$\checkmark$
U_3	1	$(3,3,2/3)$	-3	$\checkmark$	$\checkmark$	$\times$



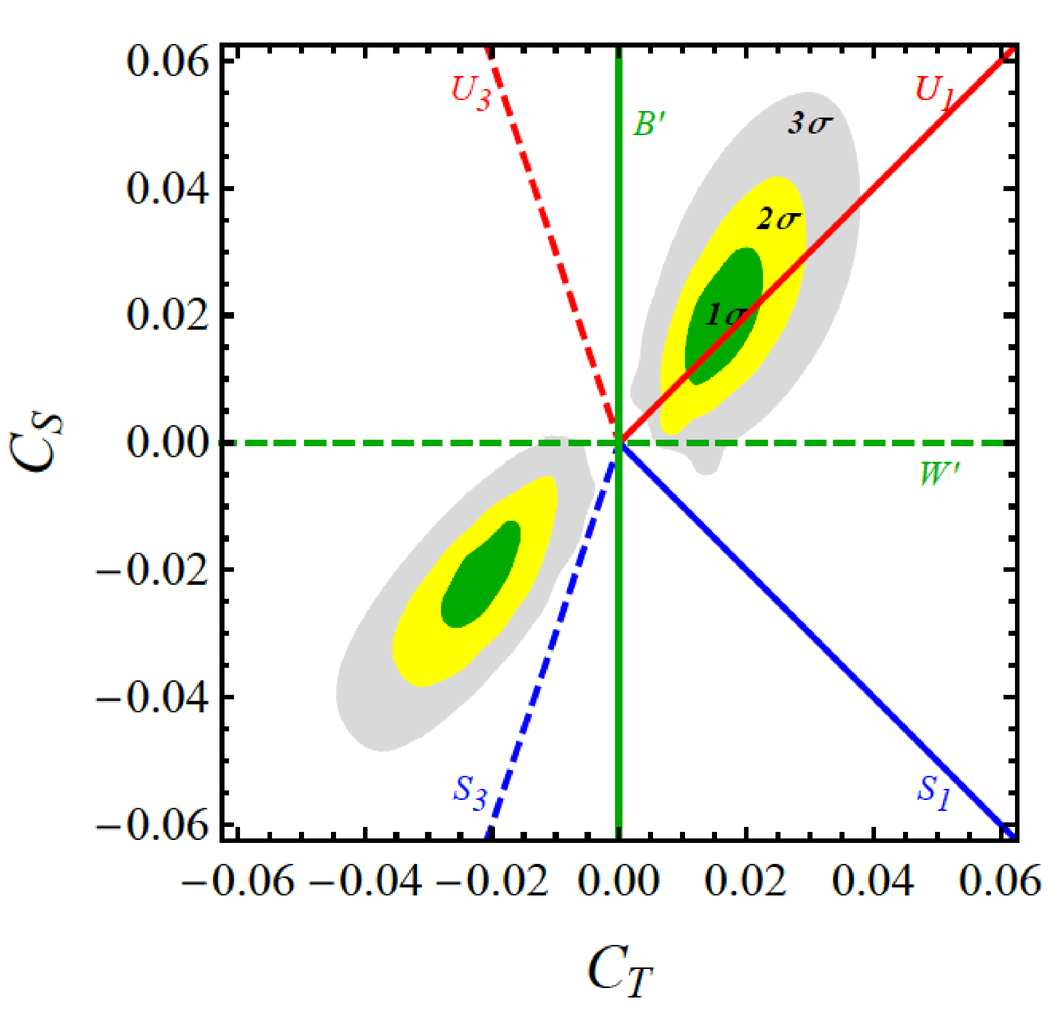
[Buttazzo, Greljo, Isidori Marzocca 1706.07808]

- Remarkably there is a unique solution, if we consider a single mediator

A clear winner! $U_\mu = (3,1,2/3)$

Simplified models

Simplified Model	Spin	SM irrep	c_1/c_3	$R_{D^{(*)}}$	$R_{K^{(*)}}$	No $d_i \to d_j \nu\bar{\nu}$
Z'	1	$(1,1,0)$	∞	×	✓	×
V'	1	$(1,3,0)$	0	✓	✓	×
S_1	0	$(\bar{3},1,1/3)$	-1	✓	×	×
S_3	0	$(\bar{3},3,1/3)$	3	✓	✓	×
U_1	1	$(3,1,2/3)$	1	✓	✓	✓
U_3	1	$(3,3,2/3)$	-3	✓	✓	×



[Buttazzo, Greljo, Isidori Marzocca 1706.07808]

- Remarkably there is a unique solution, if we consider a single mediator

A clear winner! $U_\mu = (3,1,2/3)$

- A spin 1 state calls for a UV completion. This is not an academic question, collider searches and indirect probes are dominated by the phenomenology of the extra states that emerge with the leptoquark.

Spin one particle → Composite dynamics [see for example Barbieri, Tesi, 1712.06844]

Spin one particle → Gauge bosons [see for example
- L. Di Luzio, A. Greljo, MN, 1708.08450
-Bordone et al., 1712.01368]

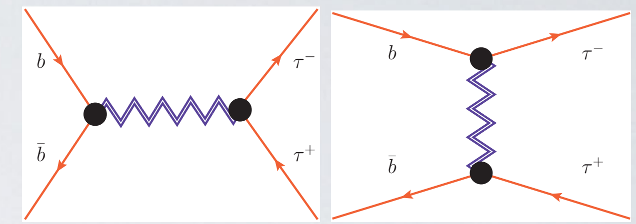
[See talk by J. Fuentes Martin]

Phenomenological constraints

1) Direct searches.

$$\mathcal{L}_{eff} = -\frac{2}{\Lambda_{R_D}} \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_L + h.c. \rightarrow \left(\frac{1}{1\ \text{TeV}}\right)^2 \bar{b}_L \gamma^\mu b_L \bar{\tau}_L \gamma^\mu \tau_L$$

$$\Lambda_{R_D} = 3.4\ \text{TeV}$$

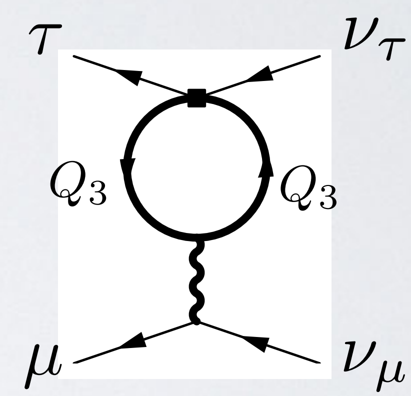


[Faroughy,Greljo,Kamenik, 1609.07138]

2) Radiative contraints from lepton sector

$$(\overline{Q}_L \gamma^\mu Q_L)(\overline{L}_L \gamma_\mu L_L) \rightarrow (\overline{L}_L \gamma^\mu L_L)(\overline{L}_L \gamma_\mu L_L)$$

$$\delta g^Z_{\tau_L}, \delta g^Z_{\nu_\tau}, \delta g^W_\tau, \mathcal{B}(\tau \rightarrow 3\mu)$$



[Feruglio, Paradisi, Pattori, 1606.00524,1705.00929]

3) Flavour observables, for example FCNC with neutrinos, Bs mixing

$$\mathcal{B}(B \rightarrow K^{(*)}\nu\nu) \approx \mathcal{B}(B \rightarrow K^{(*)}\nu_\tau\nu_\tau) \gg \mathcal{B}(B \rightarrow K^{(*)}\nu\nu)_{SM}$$

$$\frac{\mathcal{B}(B \rightarrow K^{(*)}\nu\nu)}{\mathcal{B}(B \rightarrow K^{(*)}\nu\nu)_{SM}} \lesssim 4$$

The 4321 model

[L. Di Luzio, A. Greljo, MN 1708.08450]

- We need two ingredients: an enlarged gauge structure and extra matter fields

$$G = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

$$\downarrow \langle \Omega_3 \rangle, \langle \Omega_1 \rangle$$

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

New states from the breaking:

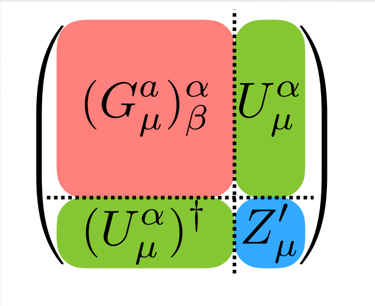
1) A leptoquark $\quad M_U = \frac{1}{2} g_4 \sqrt{v_1^2 + v_3^2}\,,$

2) A color octet $\quad M_{g'} = \frac{1}{\sqrt{2}} \sqrt{g_4^2 + g_3^2} v_3\,,$

3) A SM singlet $\quad M_{Z'} = \frac{1}{2} \sqrt{\frac{3}{2}} \sqrt{g_4^2 + \frac{2}{3} g_1^2} \sqrt{v_1^2 + \frac{1}{3} v_3^2}\,.$

- Extra gauge bosons don't decouple, for example in some limit:

$$3M_U^2 = M_{g'}^2 + 2M_{Z'}^2$$



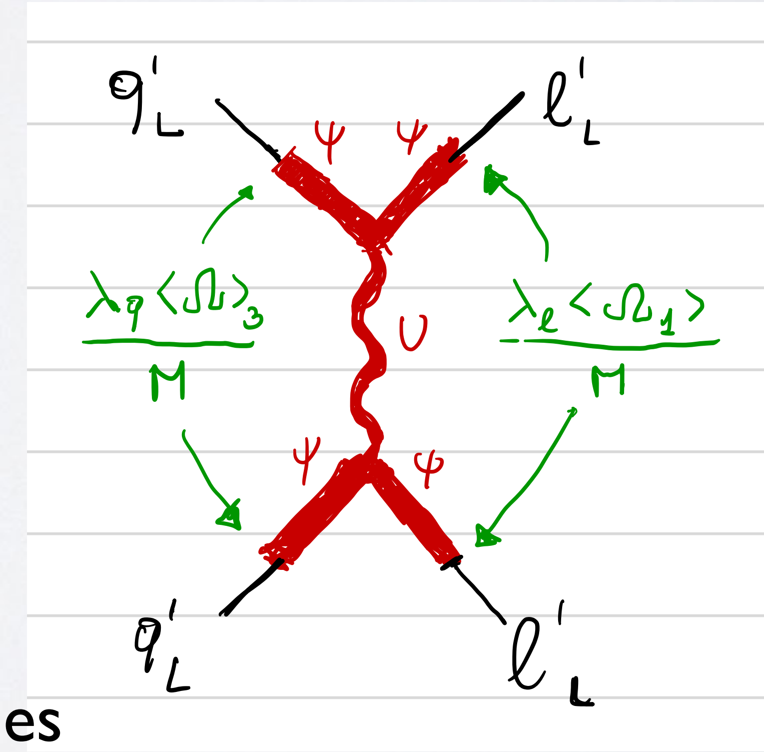
- Field content

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L^{\prime i}$	1	3	2	1/6
$u_R^{\prime i}$	1	3	1	2/3
$d_R^{\prime i}$	1	3	1	−1/3
$\ell_L^{\prime i}$	1	1	2	−1/2
$e_R^{\prime i}$	1	1	1	−1
Ψ_L^i	4	1	2	0
Ψ_R^i	4	1	2	0
H	1	1	2	1/2
Ω_3	$\bar{4}$	3	1	1/6
Ω_1	$\bar{4}$	1	1	−1/2

q_L' … e_R': would-be SM states

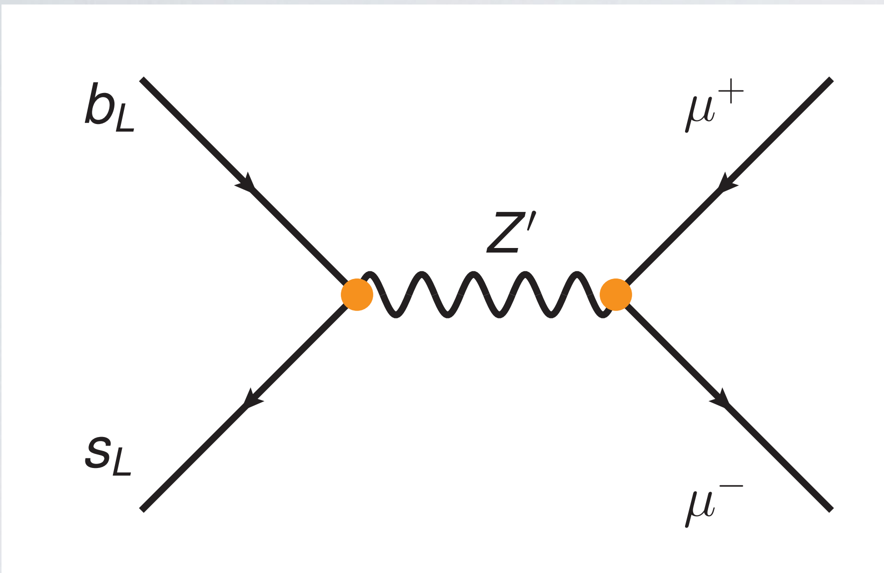
Ψ_L, Ψ_R: vector-like states (Q+L)

H, Ω_3, Ω_1: symmetry breaking

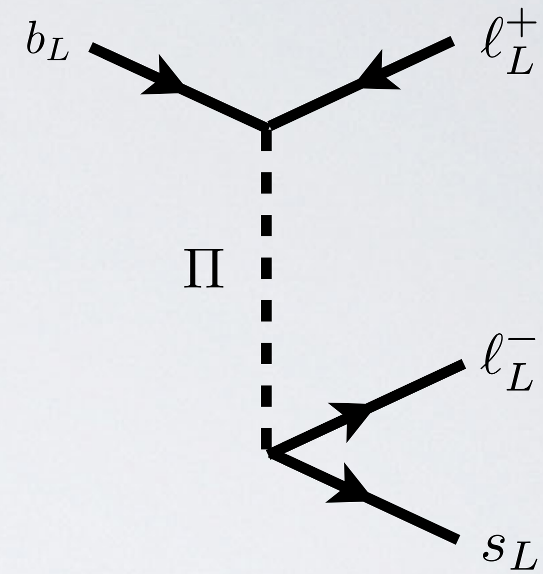


- Baryon and Lepton numbers are global accidental symmetries

Models for NC anomalies $b \to s\mu\mu$

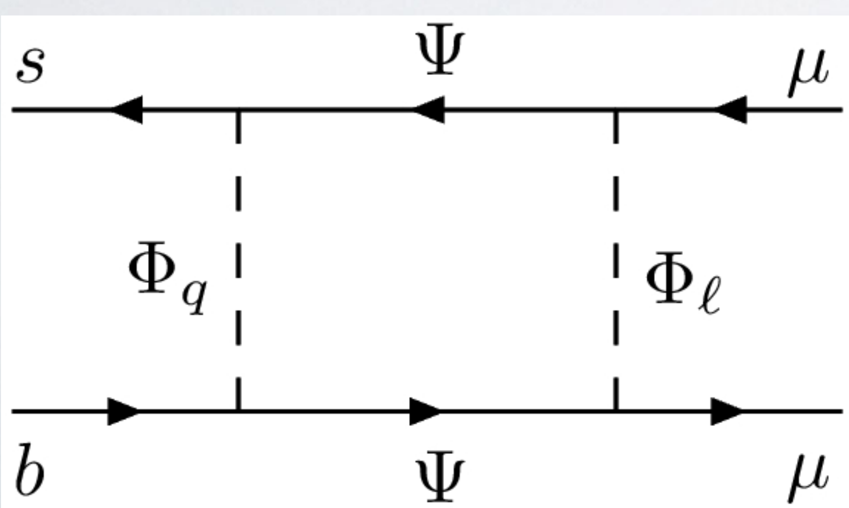


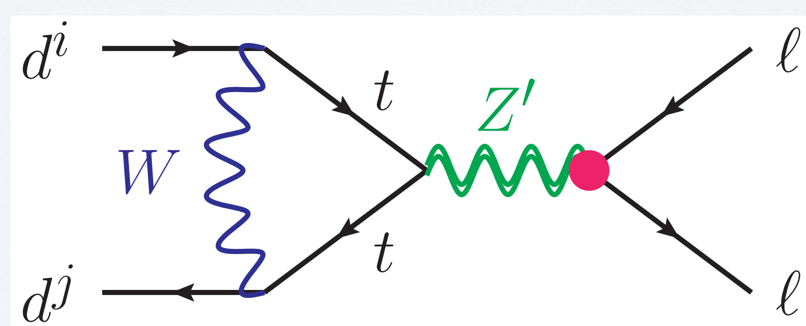
$$\frac{\Delta_{bs}\Delta_{\mu\mu}}{m_{Z'}^2} \approx \frac{1}{(30\mathrm{TeV})^2}$$



$$\frac{\lambda_{b\mu}\lambda_{s\mu}}{m_\Pi^2} \approx \frac{1}{(30\,\mathrm{TeV})^2}$$

[See talk by I. Dorsner]





$$\frac{y^4}{16\pi^2}\frac{1}{m_{NP}^2} \approx \frac{1}{(30\ \mathrm{TeV})^2}$$

[See talk by P.Arnan]

[See also talk by D. Marzocca]

Implications for low-energy measurements

If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables

E.g.: correlations among down-type FCNCs [*using the results of* U(2)-*based EFT*]:

	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ $\to$ 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ $\to \sim 10^{-6}$	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [R_K=R_π]	$B \to \pi \tau\tau$ $\to$ 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ $\to \sim 10^{-7}$	$B \to \pi \mu e$???
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi \nu\nu$ O(1)	*NA*	$K \to \mu e$???

Prospects

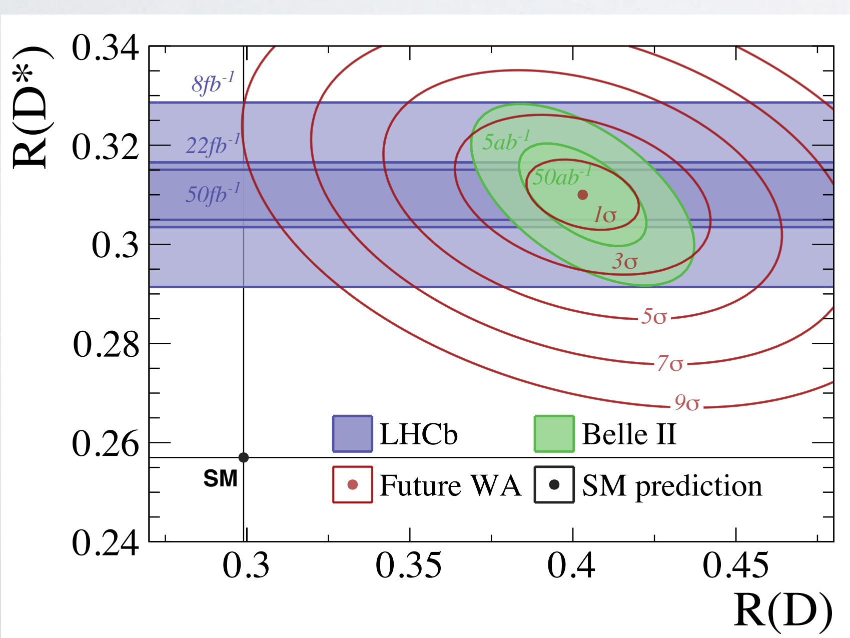
		Run 1 (2010-2012)	Run 2 (2015-2018)	Run 3 (2021-2023)	Run 4 (2026-2029)
			'Milestone I'	'Milestone II'	'Milestone III'
year		2012	2020	2024	2030
LHCb	$\mathcal{L}$ [fb^{-1}]	3	8	22	50
	$n(b\bar{b})$	0.3×10^{12}	1.1×10^{12}	37×10^{12}	87×10^{12}
	$\sqrt{s}$	7/8 TeV	13 TeV	14 TeV	14 TeV
Belle (II)	$\mathcal{L}$ [ab^{-1}]	0.7	5	50	-
	$n(B\bar{B})$	0.1×10^{10}	0.54×10^{10}	5.4×10^{10}	-
	$\sqrt{s}$	10.58 GeV	10.58 GeV	10.58 GeV	-

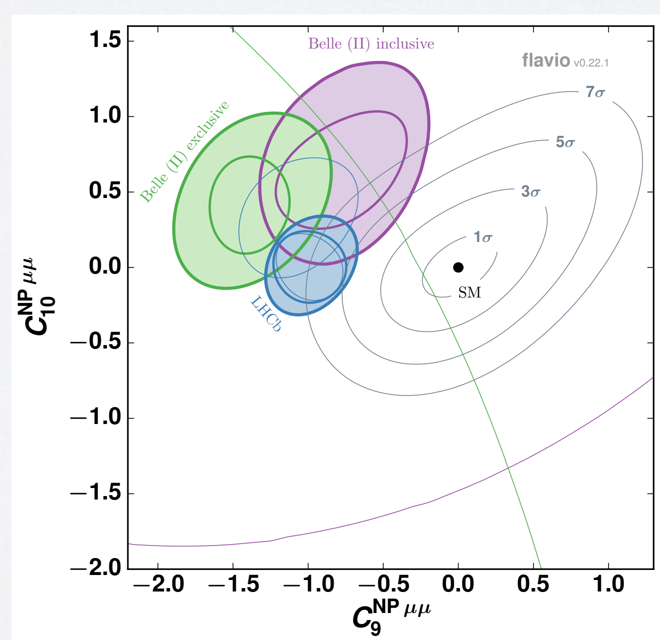
[Albrecht, Bernlochner, Kenzie, Reichert, Straub, Tully, arXiV:1709.10308]

tematic uncertainties can be neglected. If the anomalies in $R(K)$ and $R(K^*)$ persist at the current central values, LHCb will measure $R(K)$ with a significance of $> 5\sigma$ with respect to the SM prediction at milestone I, increasing to 15σ with the milestone III dataset. Concerning $R(K^*)$ at low q^2, the tension would increase to $3.4 - 3.8\sigma$ $(6.2 - 6.9\sigma)$, depending on the SM prediction, at milestone I (II); a tension of around 10σ would be reached by milestone III. For $R(K^*)$ at high

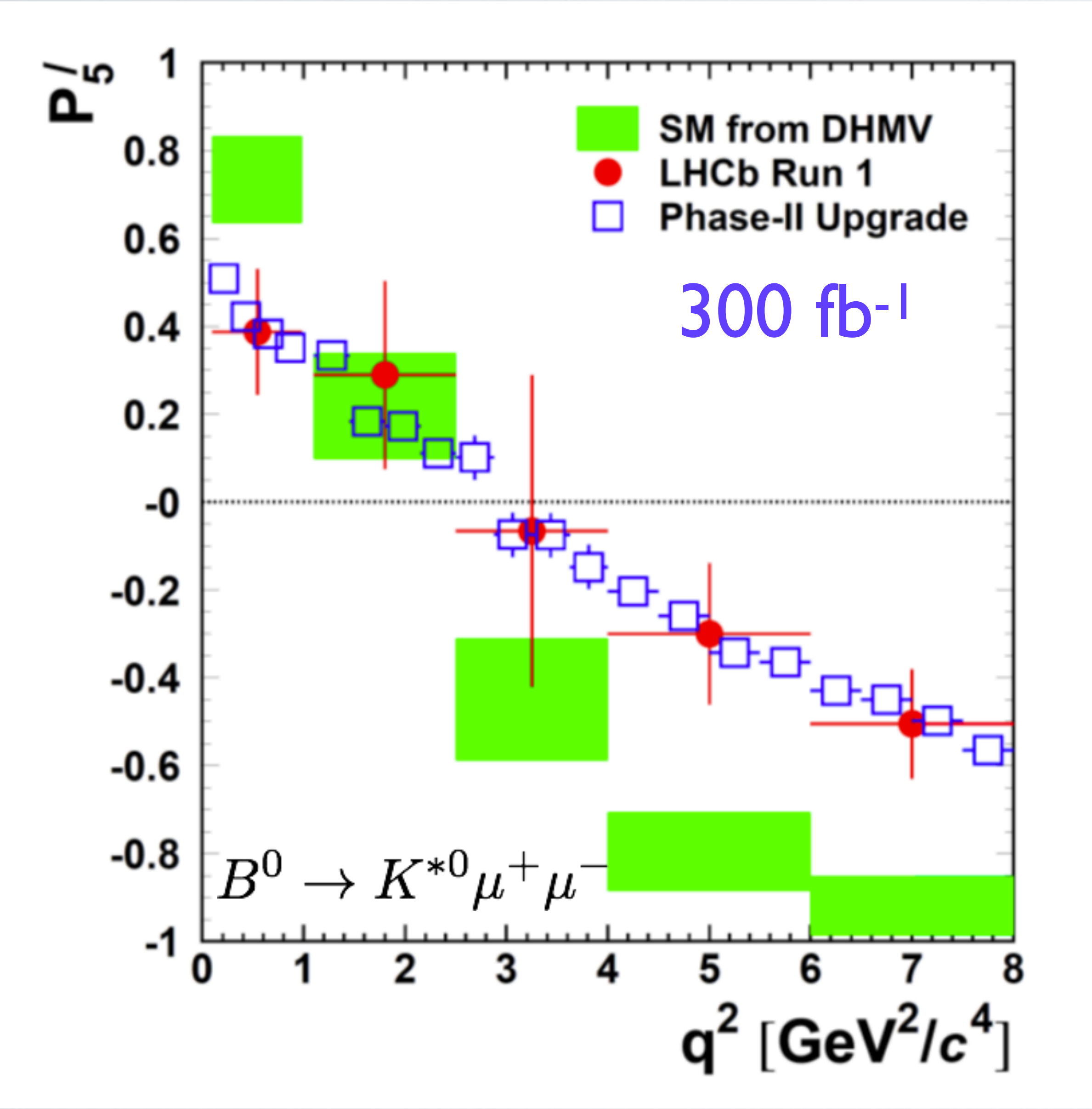
- The fate of the anomalies

Measurement	SM prediction (Ref. [43])	Current World Average (Ref. [35])	Current Uncertainty (Ref. [35])	Projected Uncertainty Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 8 fb^{-1}	LHCb 22 fb^{-1}	LHCb 50 fb^{-1}
$R(D)$	(0.299 ± 0.003)	$(0.403 \pm 0.040 \pm 0.024)$	11.6%	5.6%	3.2%	-	-	-
$R(D^*)$	(0.257 ± 0.003)	$(0.310 \pm 0.015 \pm 0.008)$	5.5%	3.2%	2.2%	3.6%	2.1%	1.6%

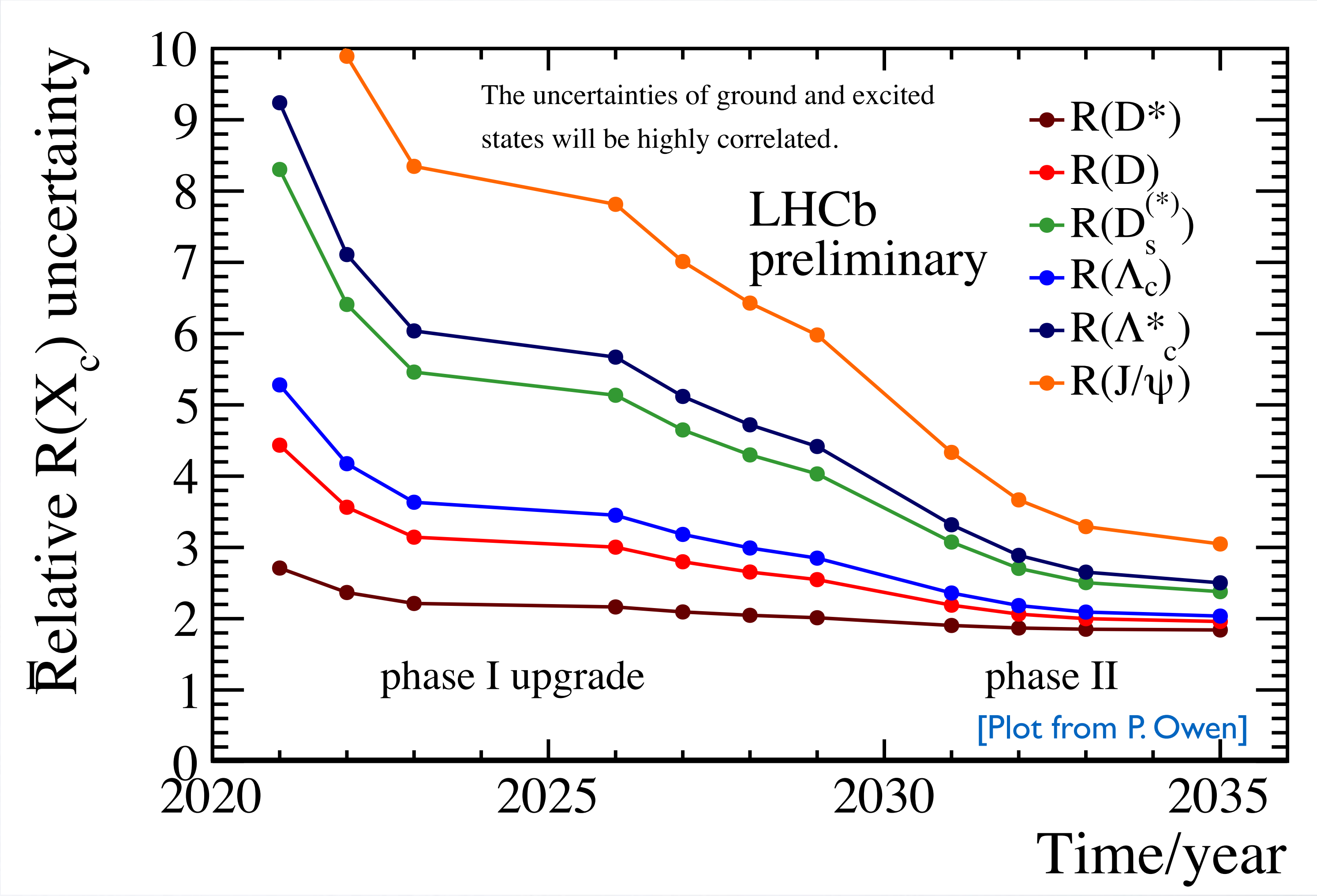




Prospects



P_5'
SM from DHMV
LHCb Run 1
Phase-II Upgrade
300 fb^{-1}
$B^0 \to K^{*0}\mu^+\mu^-$
q^2 [GeV^2/c^4]



Relative R(X_c) uncertainty
The uncertainties of ground and excited states will be highly correlated.
LHCb preliminary
R(D*)
R(D)
R($D_s^{(*)}$)
R(Λ_c)
R(Λ^*_c)
R(J/ψ)
phase I upgrade
phase II
[Plot from P. Owen]
Time/year

Conclusions

- Flavour physics is and it will remain strategically important for the HEP community:
    - if flavour anomalies will be confirmed, the interest towards the physics results of LHCb, BelleII (and other experiments!) cannot be underestimated.
    - If flavour anomalies will disappear and no evidence of NP on-shell at LHC, flavour physics will remain a unique probe to test higher energy scales in a indirect way

- Theoretical guidelines based on the naturalness of the EW scale are not providing the expected answers, this make us rethinking about various aspects including the flavor problem

- Flavour anomalies are surviving in a coherent way in both charged current (2012) and neutral current (2013).

- Current anomalies in B decays have a simple and consistent interpretation at the effective field theory level (model independent). There are hints of dominant couplings of the NP with the third family of SM fermions

- The NP scale inferred from the charged current anomalies is within the reach of present or near future colliders. Explicit constructions provide correlations with other observables. Fair to say that models are subject to a series of stringent constraints.

- We are really looking forward for new data!

BACKUP

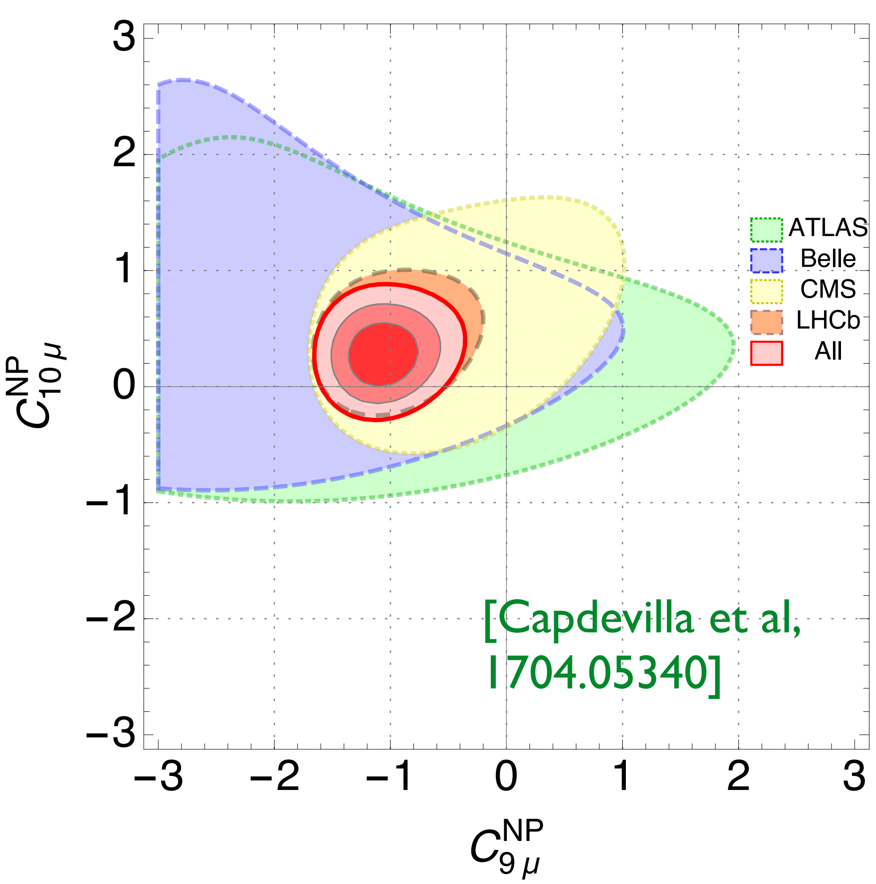
New Physics (Model Independent)

- Model independent analysis via a low-energy effective hamiltonian, assuming short-distance New Physics in the following operators

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

$$\begin{aligned}
\mathcal{O}_7^{(\prime)} &= \frac{e}{16\pi^2}\, m_b\, \left(\bar{s}\sigma_{\alpha\beta}P_{R(L)}b\right) F^{\alpha\beta}\,, \\
\mathcal{O}_9^{\ell(\prime)} &= \frac{\alpha_{\rm em}}{4\pi}\,\left(\bar{s}\gamma_\alpha P_{L(R)}b\right)\left(\bar{\ell}\gamma^\alpha\ell\right)\,, \\
\mathcal{O}_{10}^{\ell(\prime)} &= \frac{\alpha_{\rm em}}{4\pi}\,\left(\bar{s}\gamma_\alpha P_{L(R)}b\right)\left(\bar{\ell}\gamma^\alpha\gamma_5\ell\right).
\end{aligned}
\qquad
\begin{aligned}
C_7^{SM} &= -0.319, \\
C_9^{SM} &= 4.23, \\
C_{10}^{SM} &= -4.41.
\end{aligned}$$

SM gives lepton flavour universal contribution



- Preference for lepton vector current $C_9^{\mu,NP} \approx -1$

- Short distance effects from New Physics are expected to have a chiral structure

$$\begin{matrix}\bar{\ell}\gamma^\alpha\ell \\ \bar{\ell}\gamma^\alpha\gamma_5\ell\end{matrix} \longrightarrow \begin{matrix}\bar{\ell}_L\gamma^\alpha\ell_L \\ \bar{\ell}_R\gamma^\alpha\ell_R\end{matrix}$$

Best Fit with Left-Left currents

$$C_9^{\mu,NP} = -C_{10}^{\mu,NP}$$

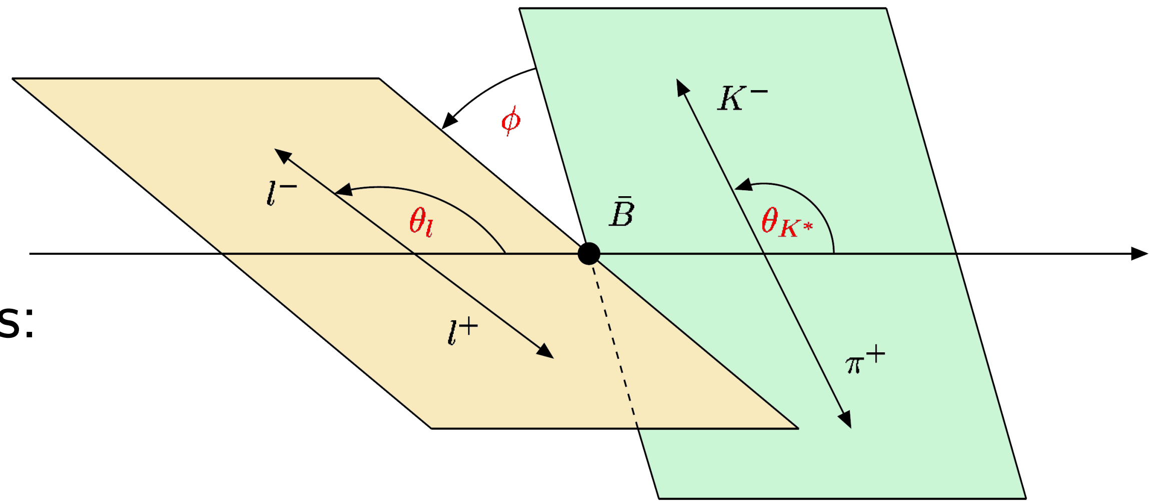
[After Moriond 2019, hep-ph 1903.10434]

Coeff.	best fit	1σ	2σ	pull
$C_9^{bs\mu\mu}$	-0.95	$[-1.10, -0.79]$	$[-1.26, -0.63]$	5.8σ
$C_9'^{bs\mu\mu}$	$+0.09$	$[-0.07, +0.24]$	$[-0.23, +0.39]$	0.5σ
$C_{10}^{bs\mu\mu}$	$+0.73$	$[+0.59, +0.87]$	$[+0.46, +1.01]$	5.6σ
$C_{10}'^{bs\mu\mu}$	-0.19	$[-0.30, -0.07]$	$[-0.41, +0.04]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.05, +0.35]$	$[-0.09, +0.51]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.62, -0.45]$	$[-0.70, -0.36]$	6.5σ
C_9^{bsee}	$+0.88$	$[+0.62, +1.15]$	$[+0.36, +1.44]$	3.4σ
$C_9'^{bsee}$	$+0.32$	$[+0.09, +0.61]$	$[-0.16, +0.91]$	1.3σ
C_{10}^{bsee}	-0.82	$[-1.06, -0.59]$	$[-1.31, -0.37]$	3.7σ
$C_{10}'^{bsee}$	-0.27	$[-0.52, -0.05]$	$[-0.78, +0.17]$	1.2σ
$C_9^{bsee} = C_{10}^{bsee}$	-1.65	$[-1.93, -1.36]$	$[-2.19, -1.02]$	4.0σ
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.45$	$[+0.31, +0.59]$	$[+0.19, +0.74]$	3.6σ
$(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}) \times \text{GeV}$	-0.005	$[-0.008, -0.003]$	$[-0.013, -0.001]$	2.6σ
$(C_S'^{bs\mu\mu} = C_P'^{bs\mu\mu}) \times \text{GeV}$	-0.005	$[-0.008, -0.003]$	$[-0.013, -0.001]$	2.6σ

$B \to K^* \mu^+ \mu^-$

Angular distributions

$\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ $(\bar{K}^{*0} \to K^-\pi^+)$ full angular distribution described by four kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ



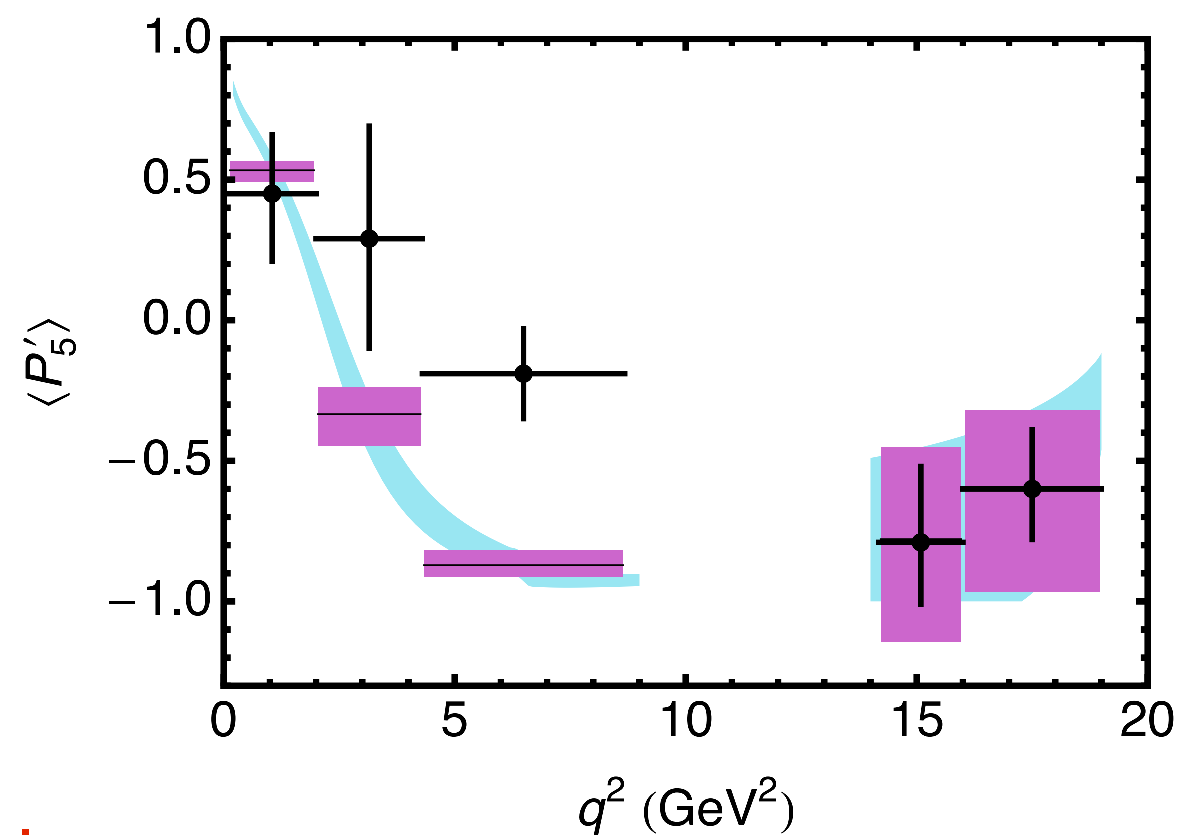
$$\frac{d^4\Gamma[B \to K^*(\to K\pi)\ell\ell]}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi}$$

3.7σ discrepancy in one of q² bins

Explanations:

1. Statistical fluctuation?
2. Hadronic uncertainties
3. New Physics

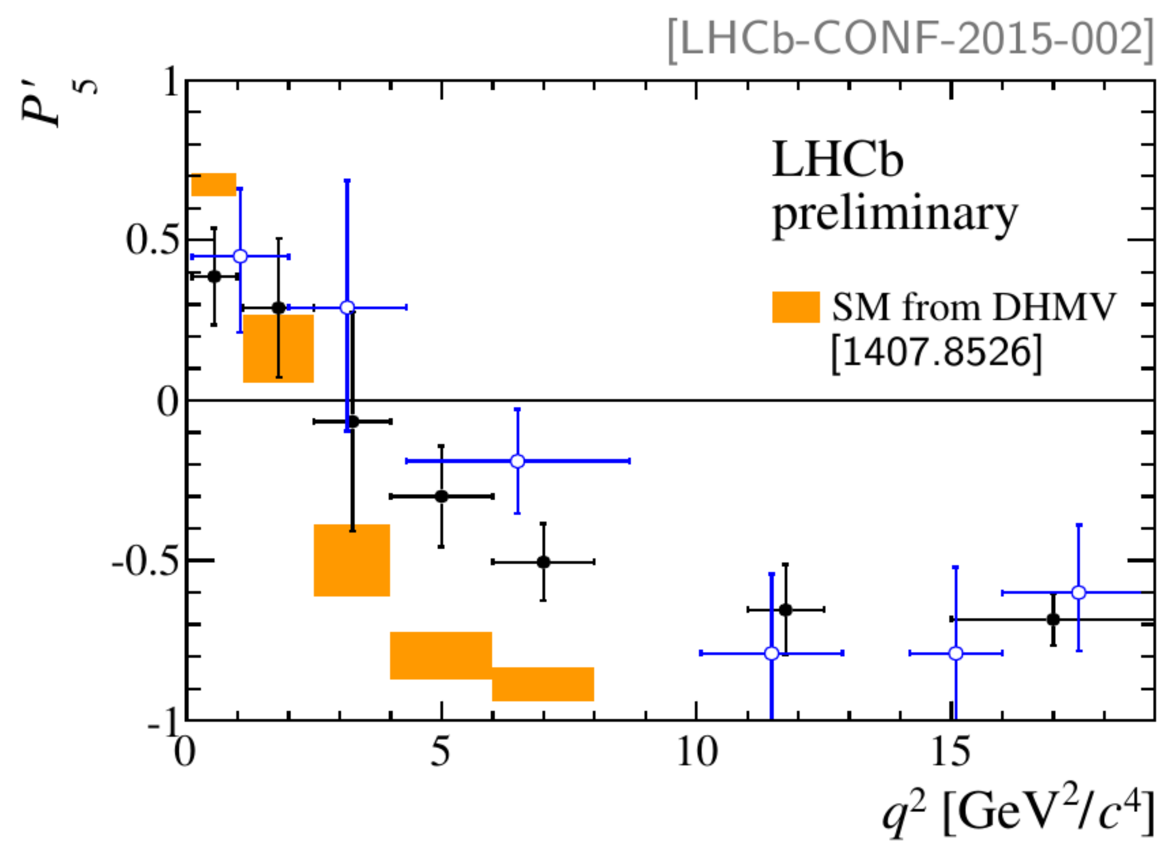
LHCb, 1308.1707, PRL



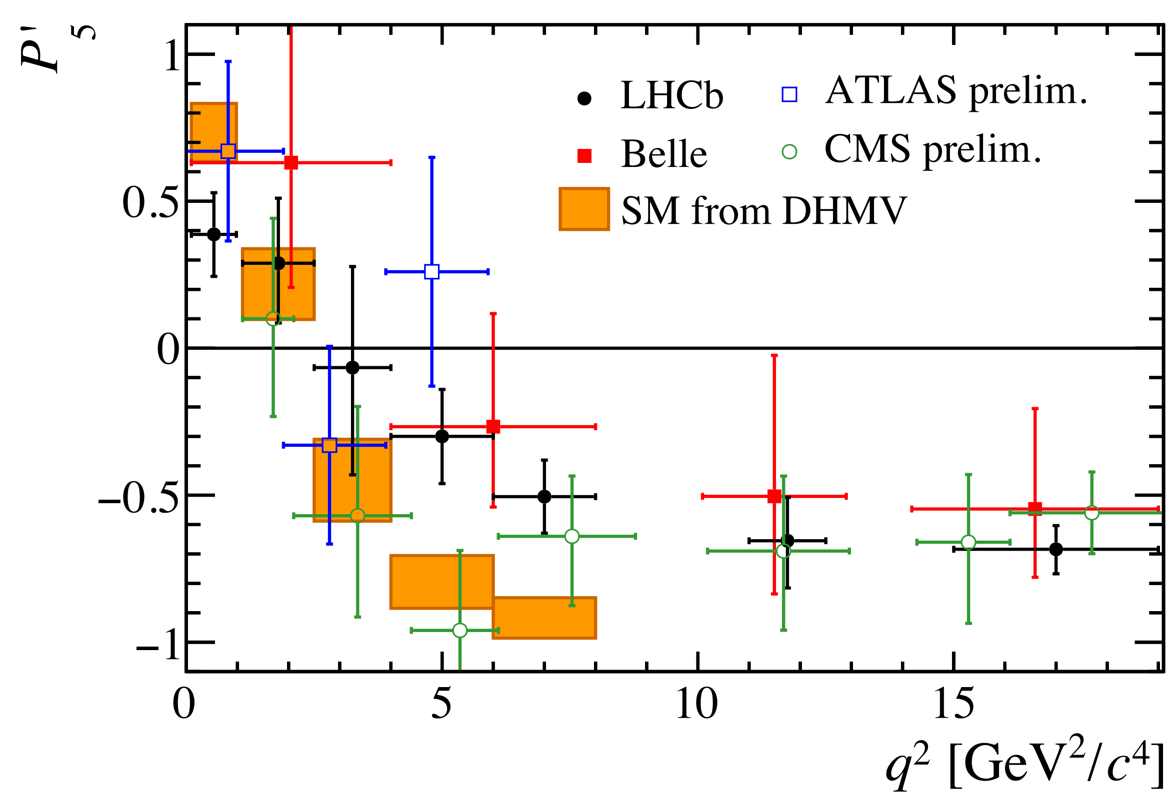
SM=JHEP, 1303.5794

2. From Ciuchini, et al., JHEP, 1512.07157
"No deviation is present once all the theoretical uncertainties are take into account"

$B \to K^* \mu^+ \mu^-$



Moriond EW 2015



Moriond EW 2017

Branching ratios

Various measurements of branching ratios are low compared to the SM prediction

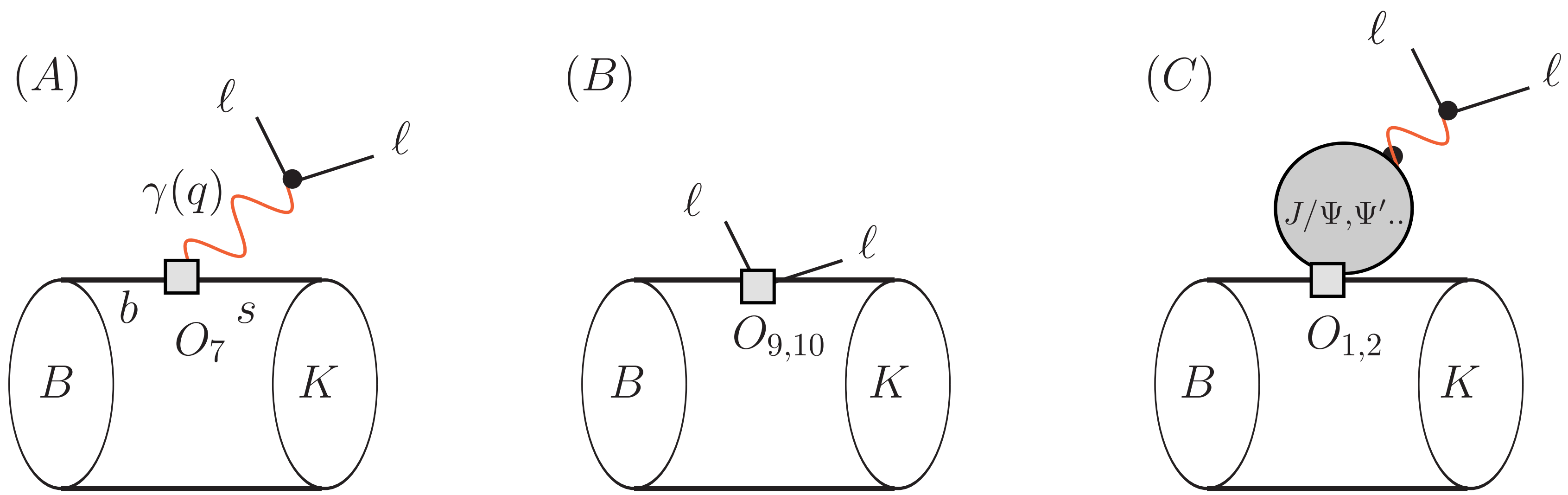
Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

[Altmannshofer, Straub 1503.06199]

[updated, LHCB 1506.08777] 0.26 ± 0.04 $+3.5$

1. Statistical fluctuation (now in different channels)
2. Hadronic uncertainties
3. New Physics

(Theoretical uncertainties)



1. Form factors, however at low q^2 can use Light-Cone Sum Rules (LCSR) and at high q^2 lattice result

$$\langle M(\lambda)|\bar{s}\not\epsilon^*(\lambda)P_{L(R)}b|\bar{B}\rangle$$

2. Contributions from hadronic weak hamiltonian (non local effects)

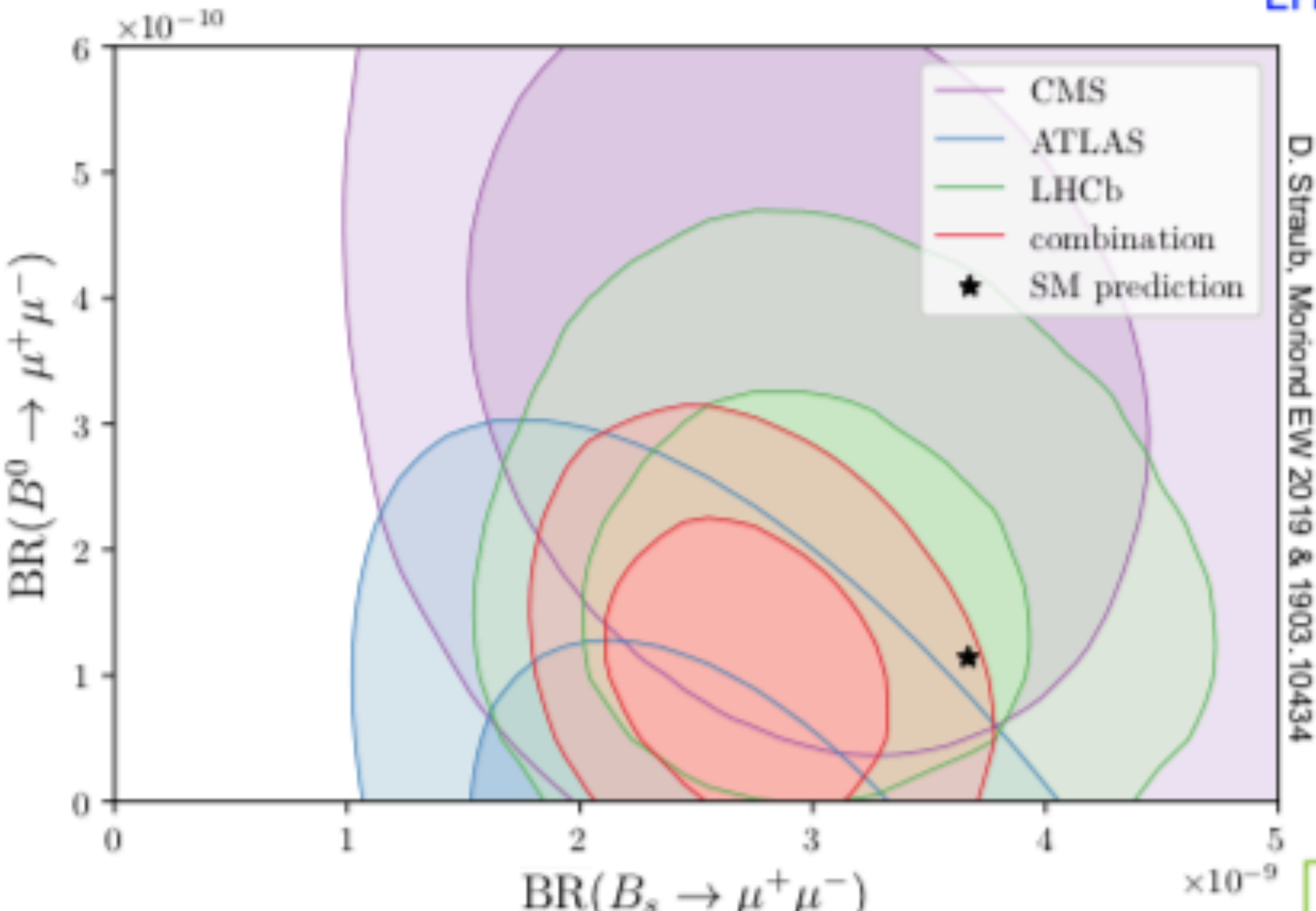
$$-i\frac{e^2}{q^2}\int d^4x e^{-iq\cdot x}\langle\ell^+\ell^-|j_\mu^{\text{em,lept}}(x)|0\rangle\int d^4y\, e^{iq\cdot y}\langle M|j^{\text{em,had},\mu}(y)\mathcal{H}_{\text{eff}}^{\text{had}}(0)|\bar{B}\rangle$$

Main effect is encoded in
$$\begin{aligned} h_\lambda(q^2) &= \frac{\epsilon_\mu^*(\lambda)}{m_B^2}\int d^4x e^{iqx}\langle\bar{K}^*|T\{j_{\text{em}}^\mu(x)\mathcal{H}_{\text{eff}}^{\text{had}}(0)\}|\bar{B}\rangle \\ &= h_\lambda^{(0)} + \frac{q^2}{1\,\text{GeV}^2}h_\lambda^{(1)} + \frac{q^4}{1\,\text{GeV}^4}h_\lambda^{(2)}\,, \end{aligned}$$

[Barcelona 1701.08672
Rome 1512.07157]

- Combination of ATLAS, CMS & LHCb

ATLAS: JHEP 04 (2019) 098
CMS: PRL111(2013)101804
LHCb: PRL118(2017)191801



Combining all three LHC experiments

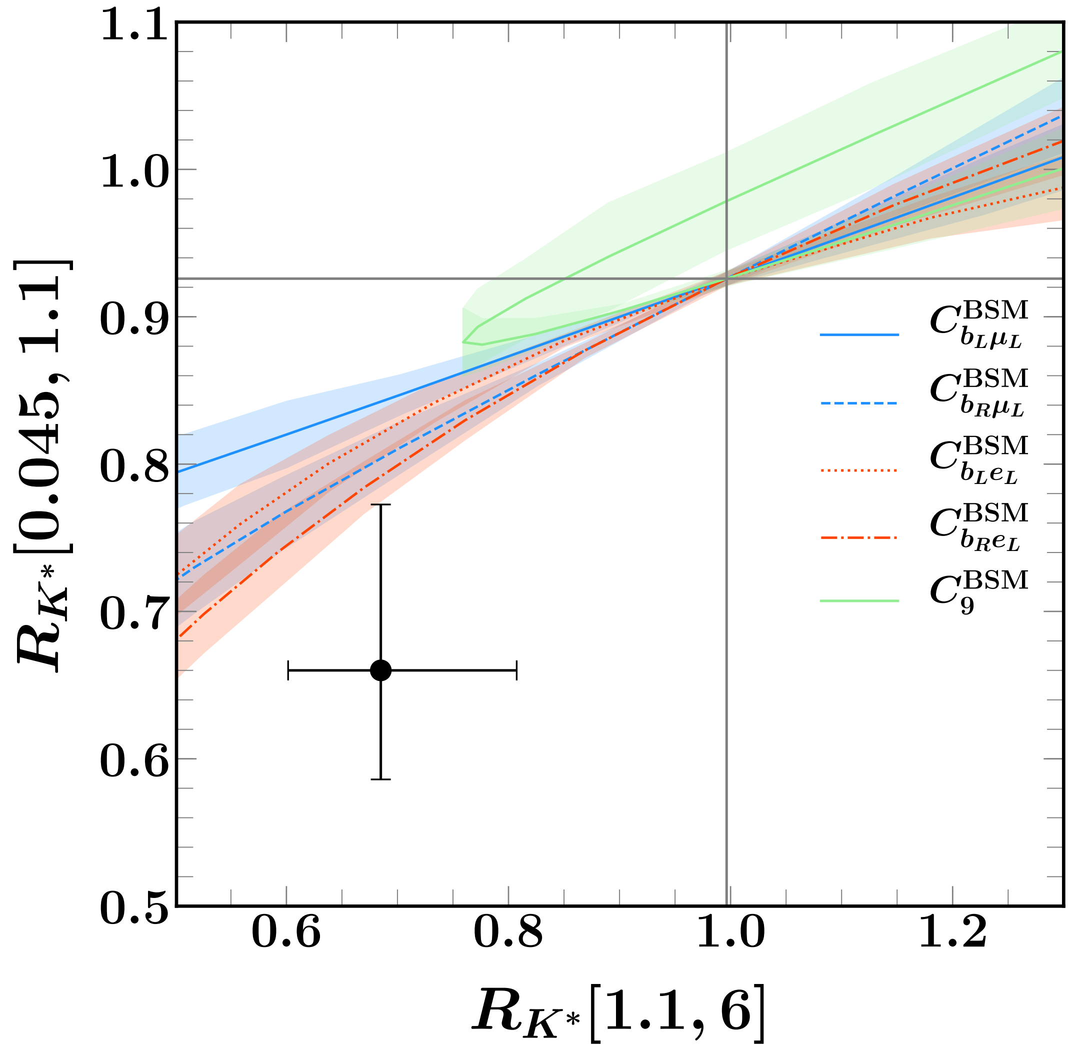
$$BR(B_S \to \mu^+\mu^-) = (2.71 \pm 0.4) \times 10^{-9}$$

SM: Buras, Isidori et al
EPJC72(2012) 2172
$BR(B_s \to \mu^+\mu^-) = 3.5 \pm 0.3 \times 10^{-9}$

→ agrees within 2σ

The low q^2 bin

- At low q^2, Standard Model contribution is dominate by dipole operator (due the photon pole)
- NP effects are reduced in this bin



[D'Amico, et al. JHEP, 1704.05438]

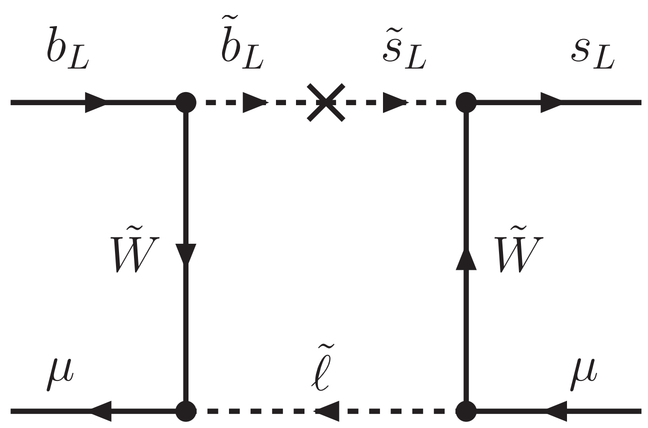
- Can be a sanity check of the measurement
- Having a large effect here requires light long range New Physics

[see for example 1711.07494]

MSSM

- LFU in the MSSM without R-Parity Violation: loop level

Altmannshofer, Straub, 1411.3161
D'Amico et al, 1704.05438



- Lepton universality is broken by slepton masses $m_{\tilde{e}} \gg m_{\tilde{\mu}}$
- Box diagrams are numerically small, very light particles in the loop
- No free parameter on the Feynman vertices: EW couplings
- Direct searches (LHC+LEP) give strong constraints, (probably) no hope left (but a careful analysis is required)

- MSSM wit R-Parity Violation: basically SM + some specific leptoquark + …
- An attempt to address charged current anomalies with RPV, however have to tune neutrino masses…

Altmannshofer,Dev, Soni 1704.06659

The LHCb results with large effect in muons suggest an extensions of the MSSM

- *What is the scale of New Physics?*

$$\Lambda_{R_{D^{(*)}}} = 3.4 \pm 0.4 \text{ TeV}\,,$$
$$\Lambda_{R_{K^{(*)}}} = 31 \pm 4 \text{ TeV}\,,$$

"Measured" Fermi constant

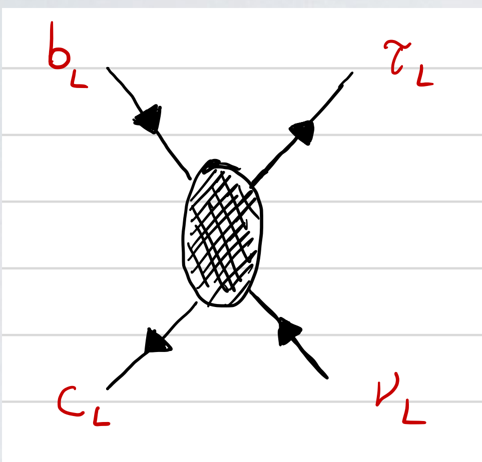
$$\frac{1}{\Lambda^2} = \frac{C}{M^2}$$

Model dependent part

C= (loops) x (couplings) x (flavour)

On-shell effects @ colliders

- *What do we expect?* (Worst case scenario)



$$\mathcal{A}(\psi\psi \to \psi\psi) \propto s$$

Tree-Level Pertubative Unitarity criterium

$$|\mathcal{A}_{J=0}| < 1/2$$

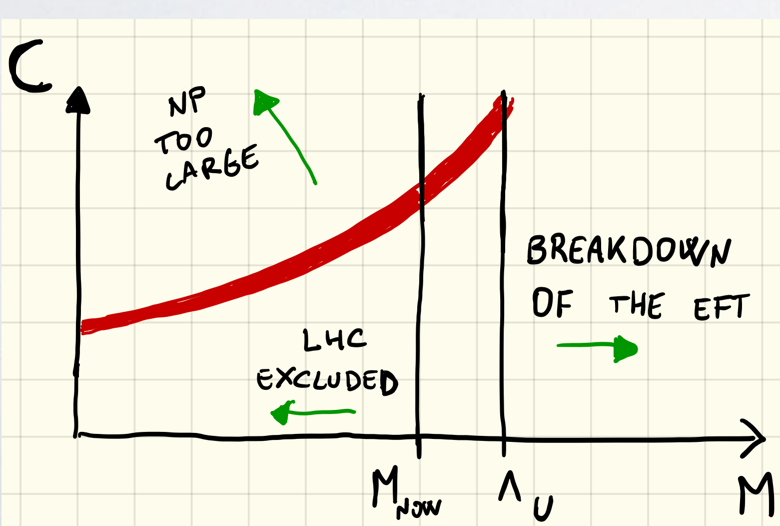
[Di Luzio, MN, 1706.01868]

$$\begin{cases} \sqrt{s}_{max} \equiv \Lambda_U = 9 \text{ TeV} & b \to c\tau\nu \\ \sqrt{s}_{max} \equiv \Lambda_U = 80 \text{ TeV} & b \to s\mu\mu \end{cases}$$

An old lesson: VV scattering…
$\Lambda_U = 2 \text{ TeV}, m_h = 125 \text{ GeV}$

- *What do we expect?* (Warning: a simplified cartoon!)

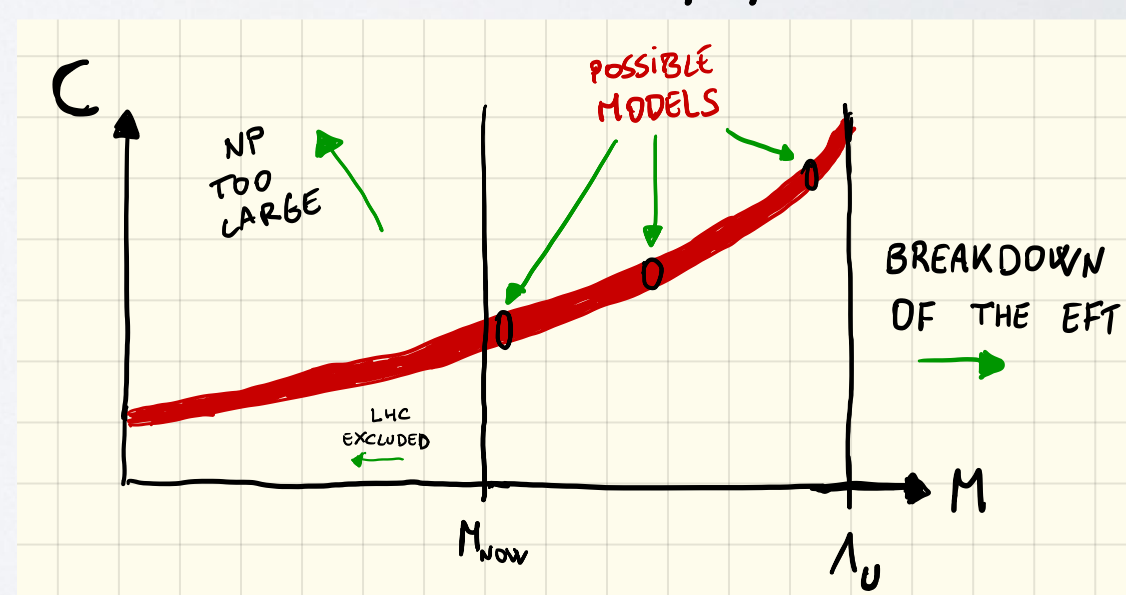
$$b \to c\tau\nu$$



Absence of New Physics at high energy

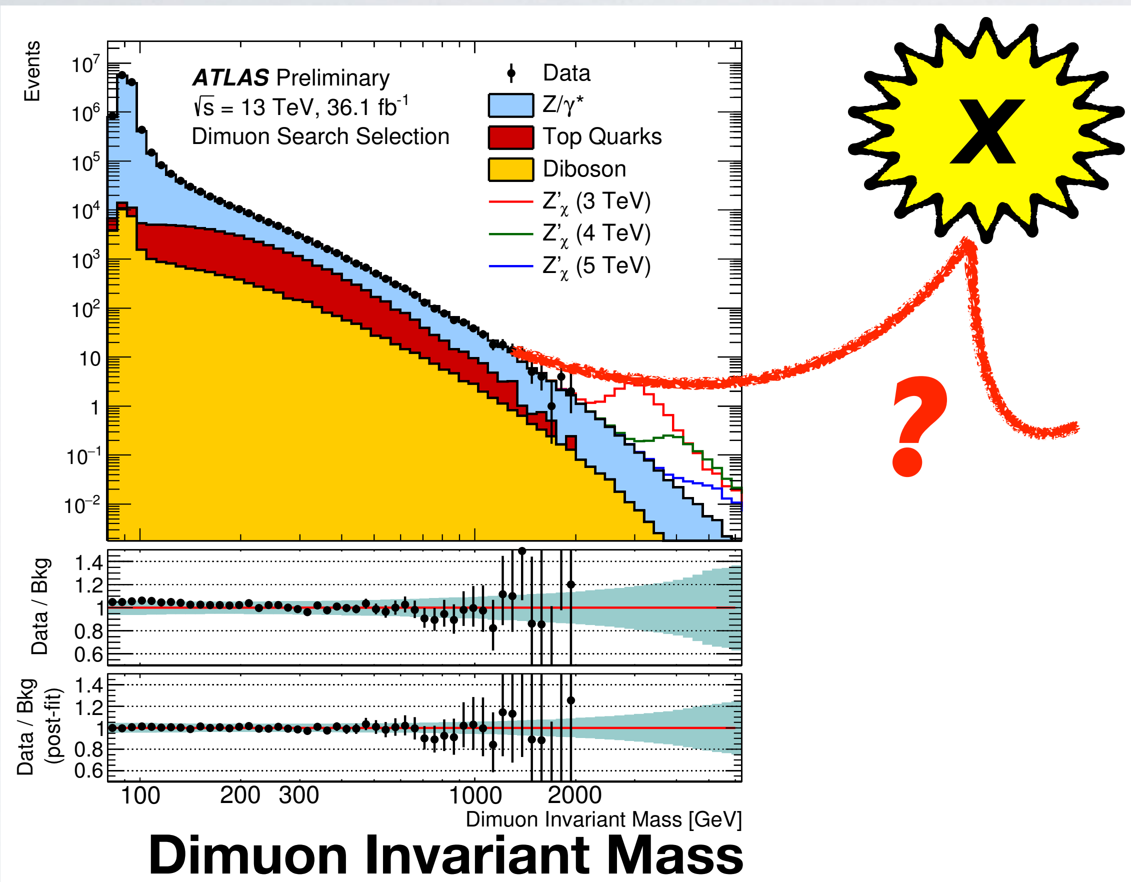
$$M_{now} \gtrsim 1 \text{ TeV}$$

$$b \to s\mu\mu$$



SM-EFT regime: tails

- If the New Physics is very heavy the strategy is to look for di-lepton pair at high-pT

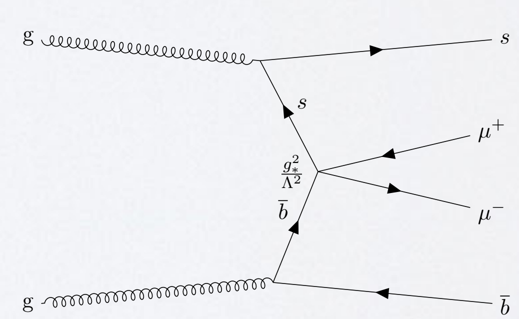


$$\mathcal{L}^{\rm SMEFT} \supset \frac{C}{M^2}\overline{Q}\gamma^\mu Q\overline{L}\gamma_\mu L$$

$$\mathcal{A} \propto \frac{E^2}{M^2} \qquad \text{valid when } E \lesssim M$$

- NC anomalies [1704.09015,180511402]

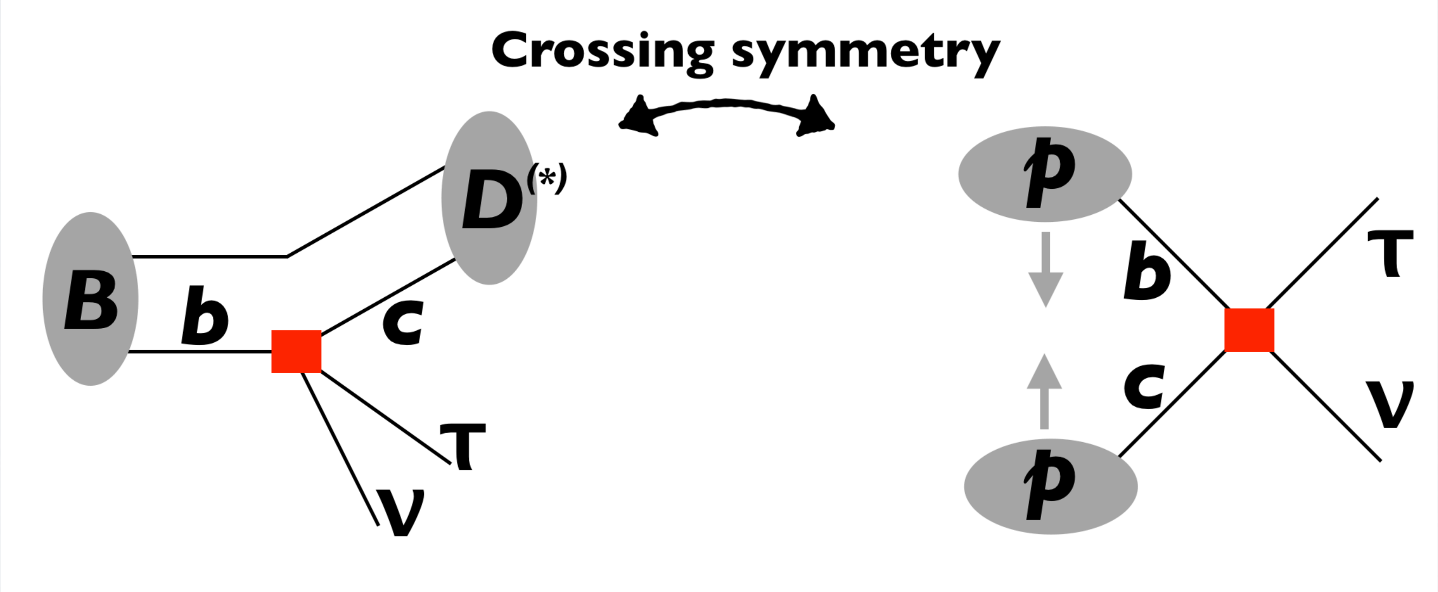
$$pp \to \mu^+\mu^-$$



No sensitivity at HL-LHC if it is present ONLY

$$\frac{1}{(30\ \text{TeV})^2}(\bar{b}\Gamma s)(\bar{\mu}\Gamma\mu)$$

$pp \to \tau\nu$



[Greljo, Martin Camalich, Ruiz-Alvarez 1811.07920]

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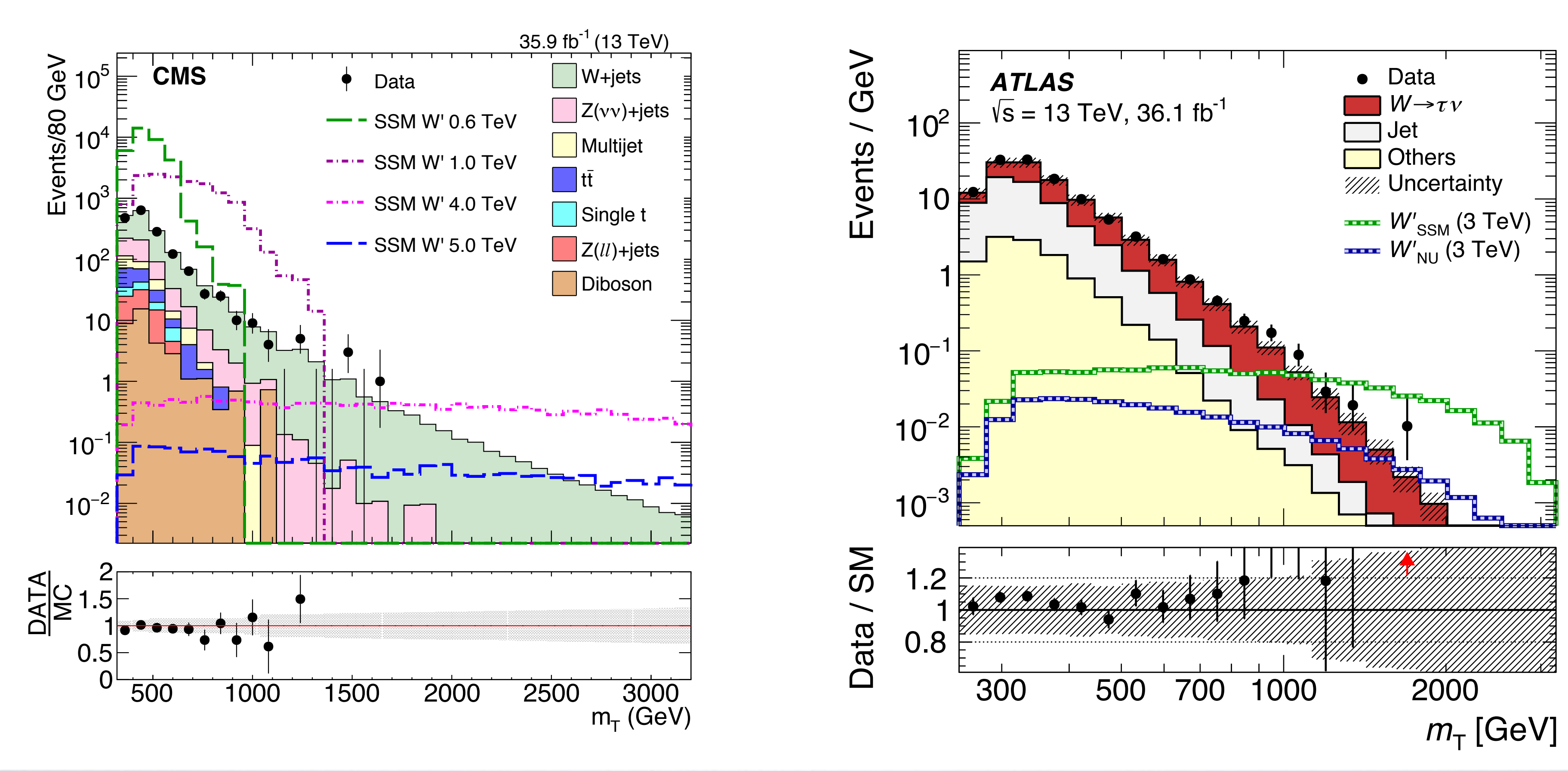
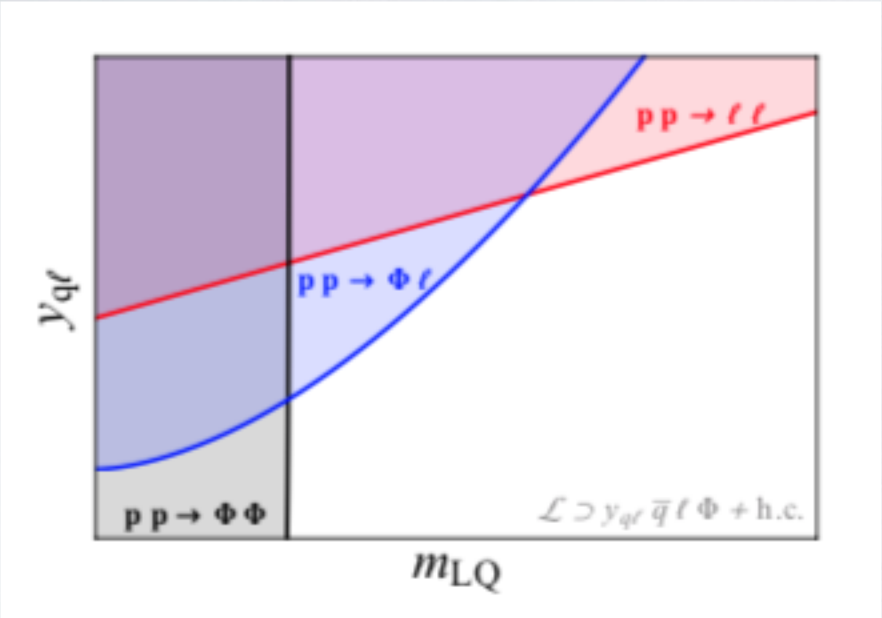
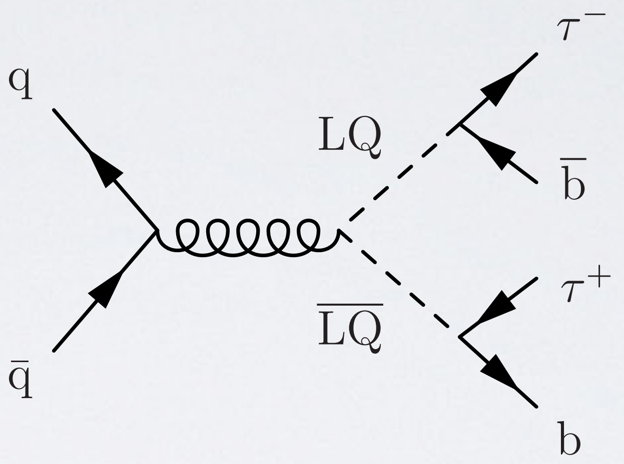
- Making use of the ATLAS and CMS mono-tau serches

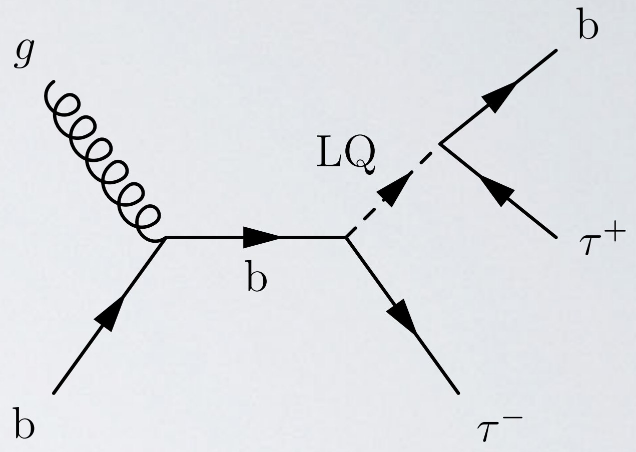


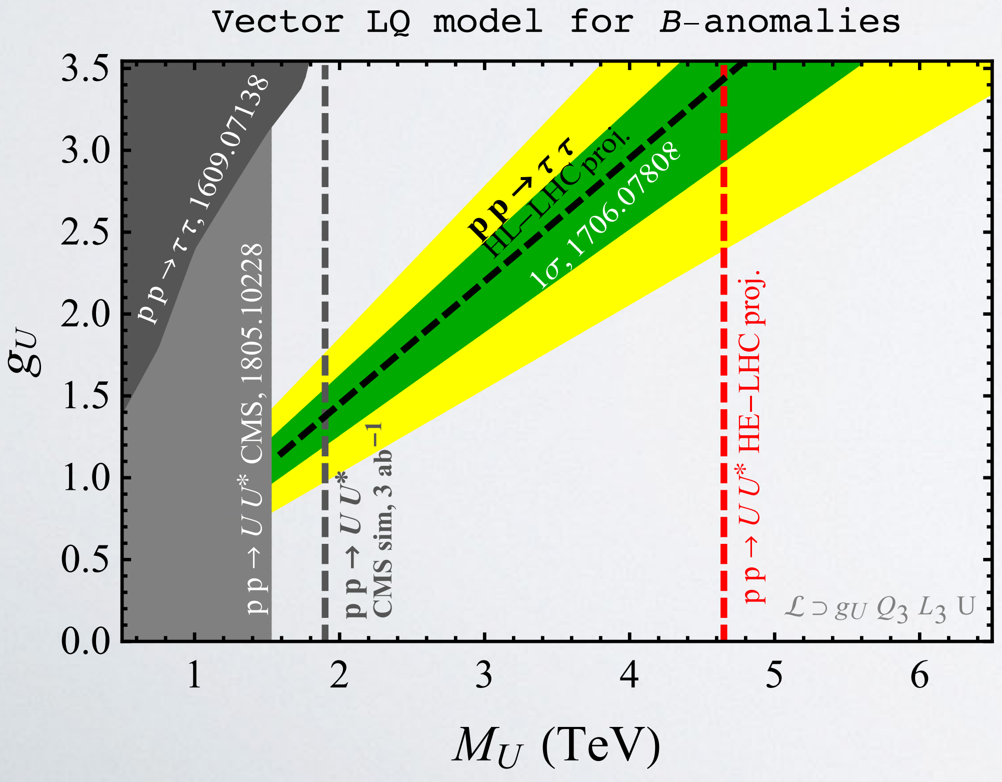
Leptoquarks

- Working assumption: decays into third family. Relevant parameters: LQ coupling and mass:









- HL-LHC and HE-LHC report [1812.07638]
- Two decay channels: bottom-tau, top-neutrino. SU(2) fix the BR to be equal
- Top-neutrino: see N.Vignaroli 1808.10309
- Message: LQ survives at the LHC and HL-LHC in large part of the parameter space…