Flavour e intensità: Status e visione teorica

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About myself and INFN-ROMA1

- I was a bachelor and master student in Rome (2001-2006). I re-joined the University of Rome and our INFN section since March 2019

- My research is about theoretical and phenomenological aspects of Physics Beyond the Standard model (naturalness problem, signatures at colliders, astro-particles, ecc.) and Flavour Physics

- I am happy to talk about physics, my office is in Marconi, second floor, room 250 (former office of Riccardo Faccini)

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Outline

- Not able to cover all the aspects, personal and biased (BSM) 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

- For more experimental aspects and activities @ Rome1 see next two talks

Testing the Standard Model

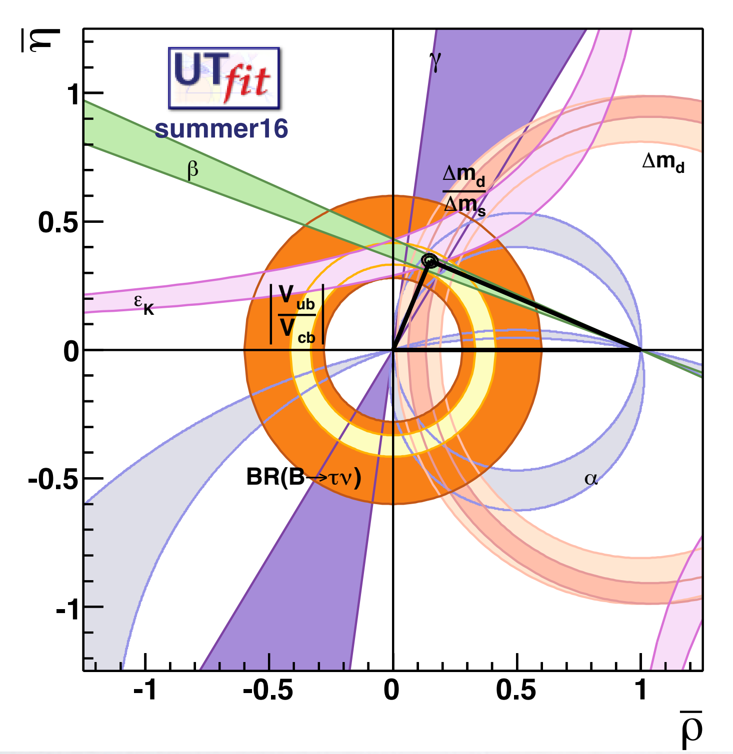
- Higgs looks very SM-like. We have a direct measurement of its coupling to third generations

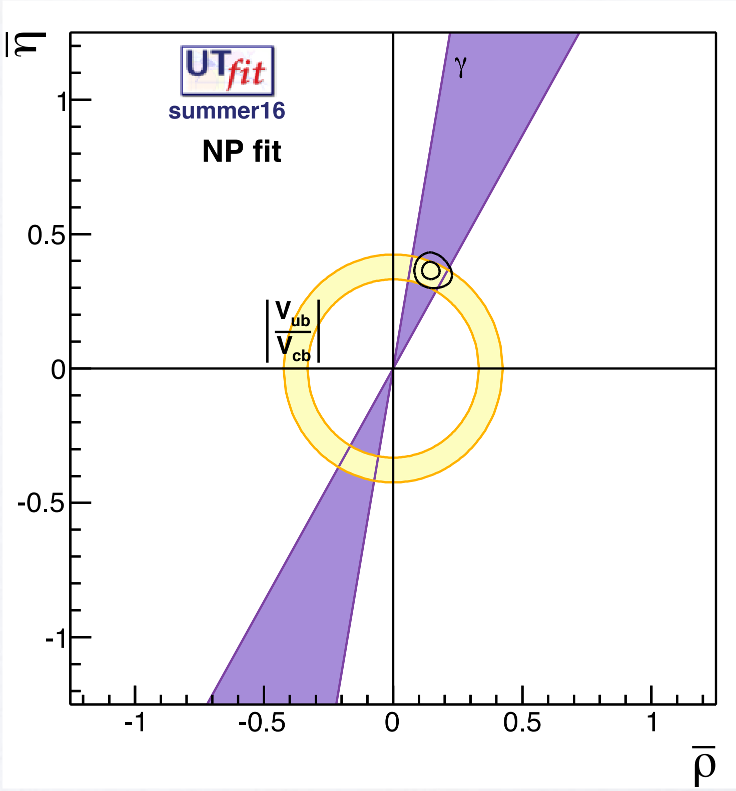
Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 ± 0.35	1.01 ± 0.20	1.34 ± 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 ± 0.27 *	1.04 ± 0.20	1.26 ± 0.26 **

* 13 TeV only derived from cross section measurements
** Lower uncertainty (upper uncertainty 31)

[M. Kado @ IFAE 2019]

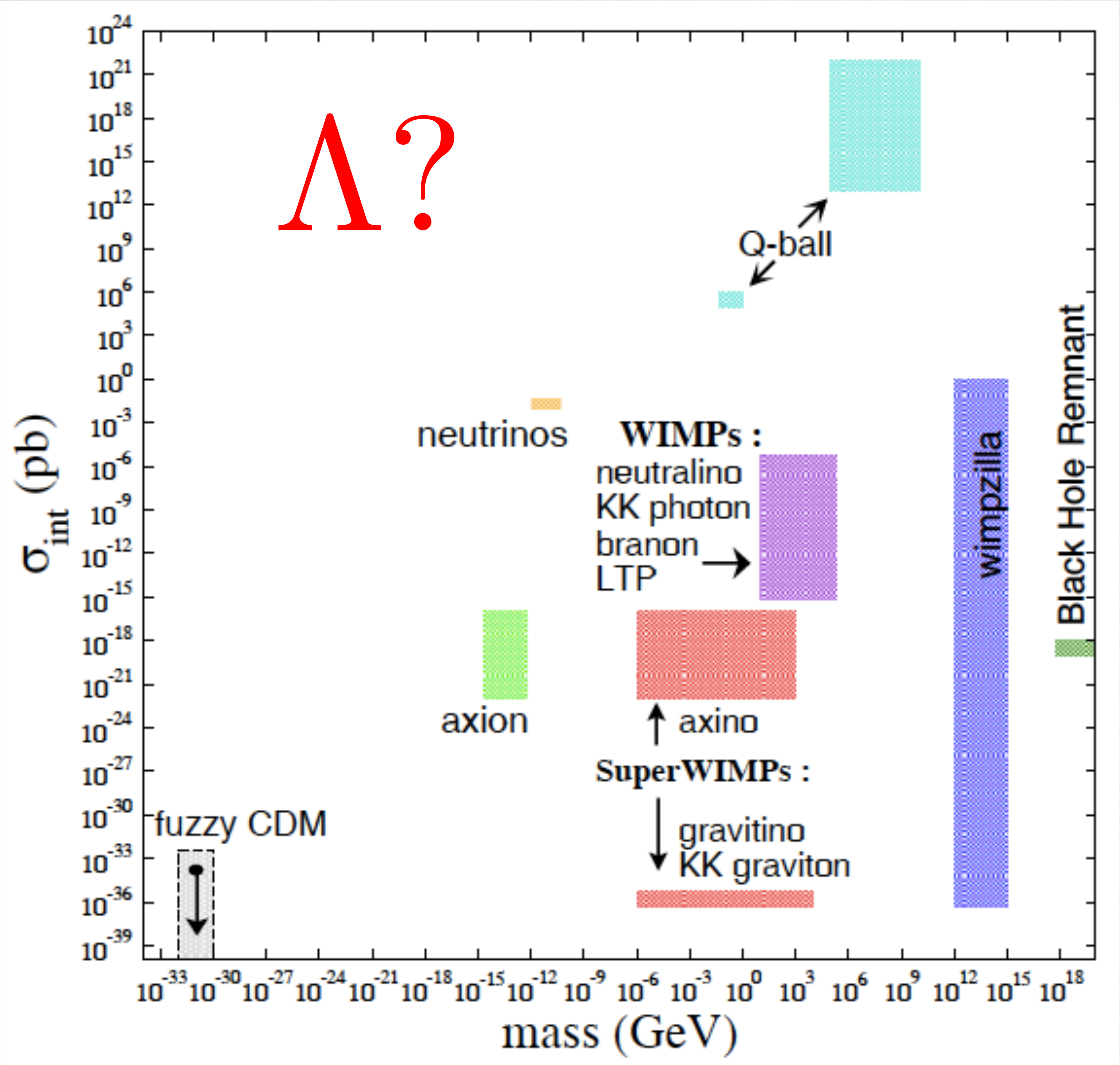
- Flavour violation looks CKM-like





What is the scale of New Physics?

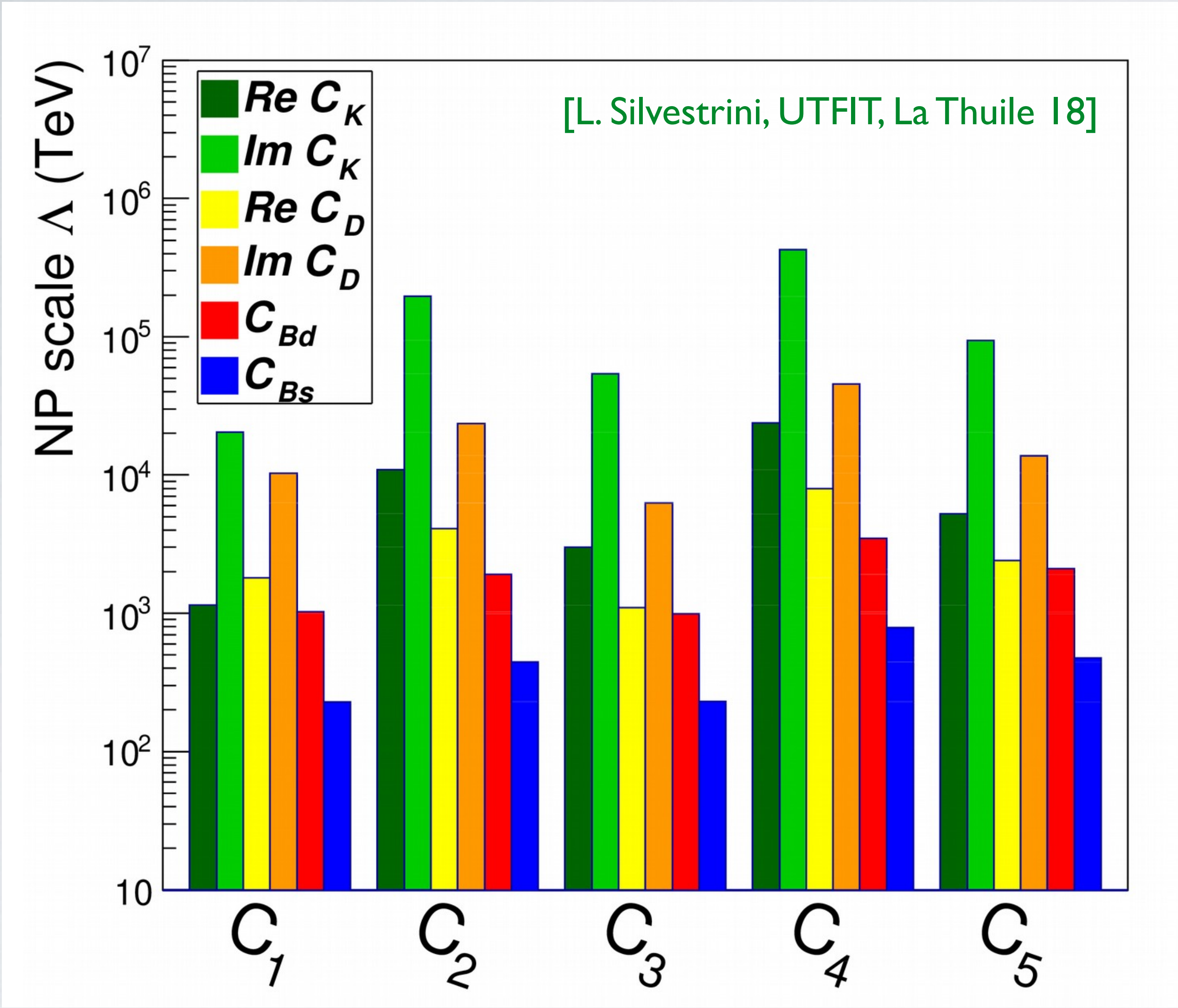
- The Neutrino Masses, the Dark Matter, the Baryon Asymmetry of the Universe,…
- New Physics exists but we have a Log-Log problem



- Indirect searches give us some indications….

- A theoretical argument gives us an “orthogonal” indication….

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

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

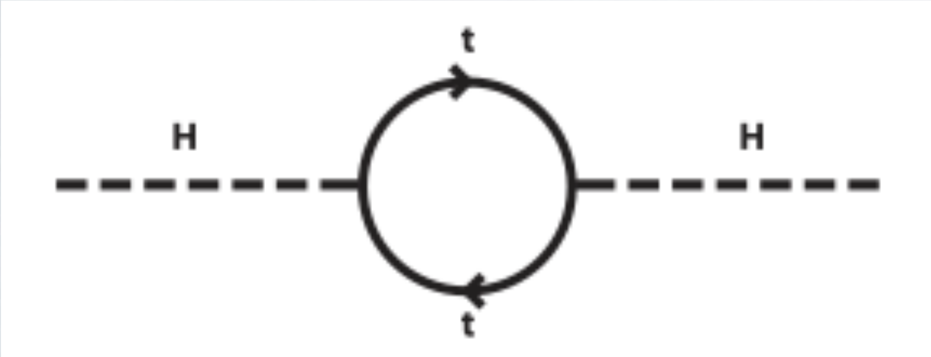
$$\begin{aligned} Q_1^{q_iq_j} &= \bar q^\alpha_{jL}\gamma_\mu q^\alpha_{iL}\bar q^\beta_{jL}\gamma^\mu q^\beta_{iL}\,,\\ Q_2^{q_iq_j} &= \bar q^\alpha_{jR}q^\alpha_{iL}\bar q^\beta_{jR}q^\beta_{iL}\,,\\ Q_3^{q_iq_j} &= \bar q^\alpha_{jR}q^\beta_{iL}\bar q^\beta_{jR}q^\alpha_{iL}\,,\\ Q_4^{q_iq_j} &=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

$\Lambda?$

- "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 $\Lambda \lesssim 500\ \mathrm{GeV}$



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

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

- 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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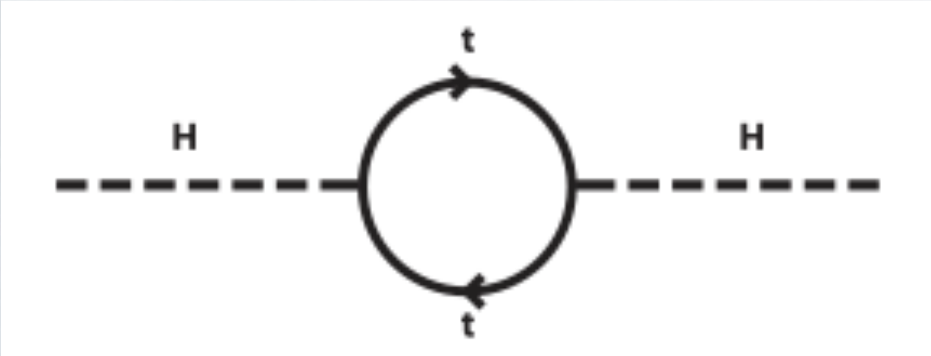

$$m_H^2 = m_{\text{tree}}^2 + \delta m_H^2$$

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

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- Two (problematic) possibilities:

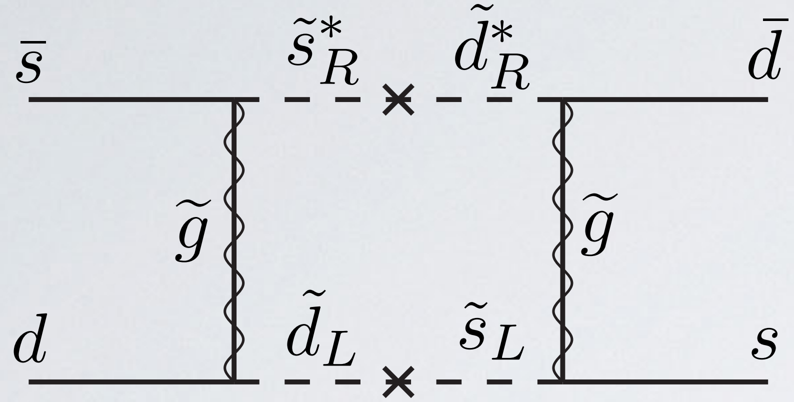
(i) Non canonical, $\Lambda \gg 1 \text{ TeV and } c_{ij} = \mathcal{O}(1)$ Hierarchy Problem

(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



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

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

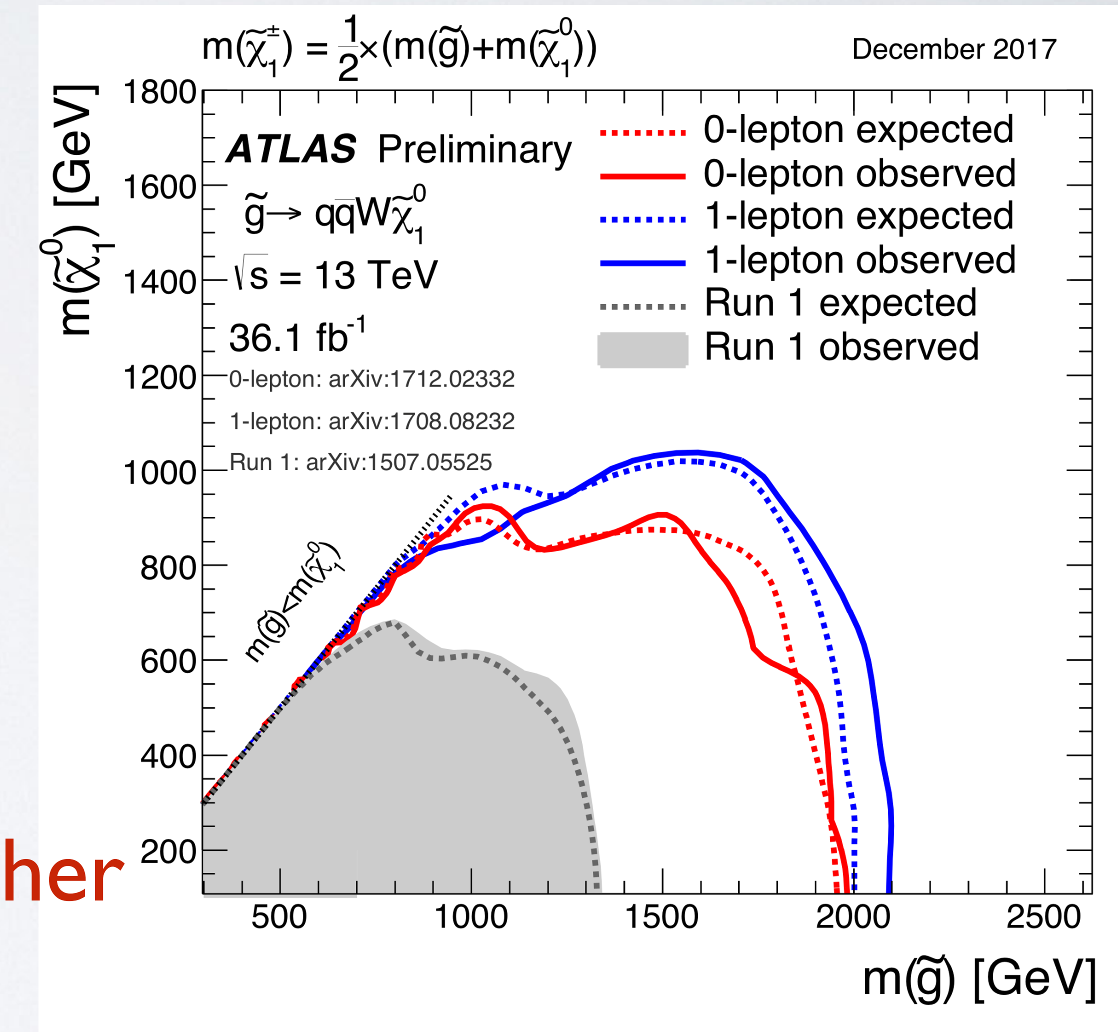
$$\Lambda = m_{susy}$$

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

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

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

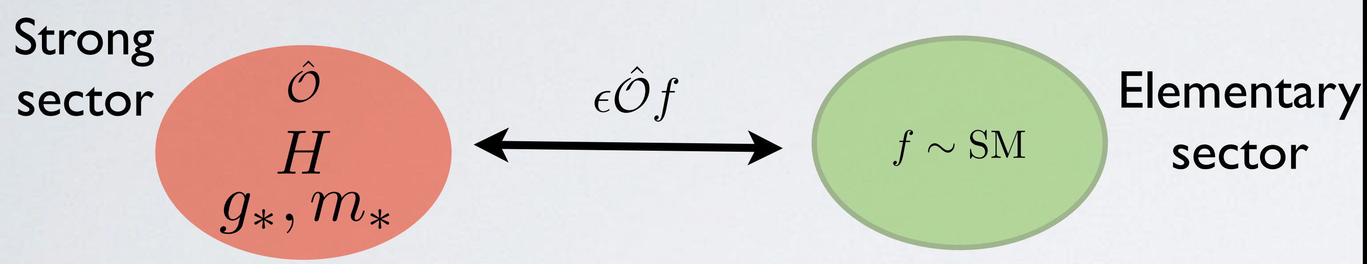
Time to shift point of view and consider richer flavour structures
(giving up (some of) the naturalness and giving more centrality to other aspects)



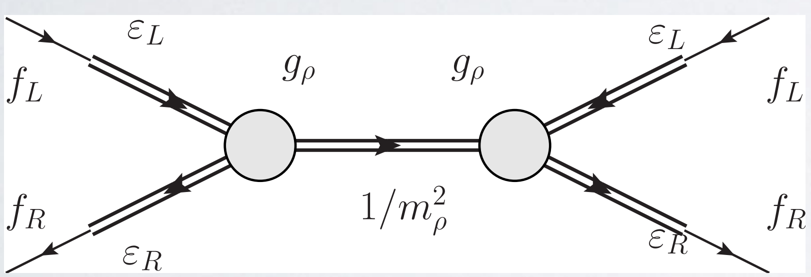
Two possible approaches

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

Dynamics



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



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

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

Symmetry

- 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.
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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
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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
e-Print: **arXiv:1211.2674 [hep-ex] | PDF**
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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.
Published in **JHEP 1602 (2016) 104**
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DOI: 10.1007/JHEP02(2016)104
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CERN Document Server; ADS Abstract Service; Link to Article from SCOAP3; Link to Figures, tables and other inform
Data: INSPIRE | HepData
Detailed record - Cited by 466 records 250+

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**
CERN-PH-EP-2014-220, CMS-BPH-13-007, LHCB-PAPER-2014-049
DOI: 10.1038/nature14474
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Detailed record - Cited by 455 records 250+

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.
Published in **JHEP 1708 (2017) 055**
LHCB-PAPER-2017-013, CERN-EP-2017-100
DOI: 10.1007/JHEP08(2017)055
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CERN Document Server; ADS Abstract Service; Link to Article from SCOAP3; Link to Figu
Data: INSPIRE | HepData
Detailed record - Cited by 422 records 250+

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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Detailed record - Cited by 396 records 250+

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**
LHCB-PAPER-2011-023, CERN-PH-EP-2011-208
DOI: 10.1103/PhysRevLett.108.111602, 10.1103/PhysRevLett.108.129903
e-Print: **arXiv:1112.0938 [hep-ex] | PDF**
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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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DOI: 10.1103/PhysRevLett.110.222001
e-Print: **arXiv:1302.6269 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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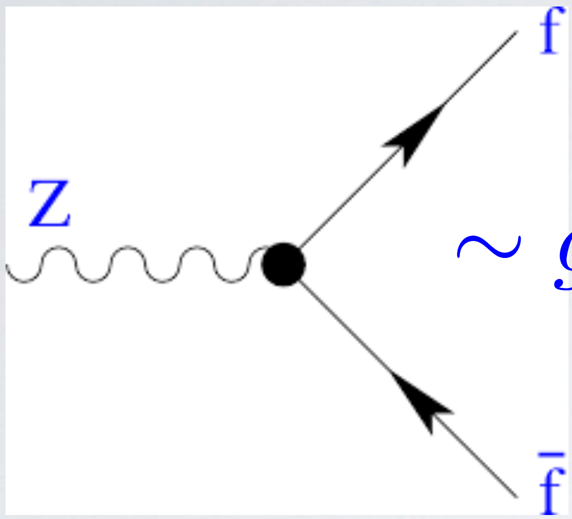
Detailed record - Cited by 334 records 250+

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)

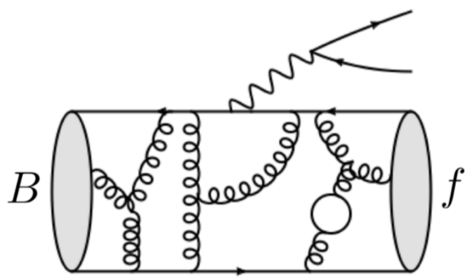
- Yukawa sector breaks the universality in two ways $\mathcal{L}_{\rm SM} \supset Y^E_{ij}\,\overline{L}^i_L E^j_R\,H + \text{h.c}$

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

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

Strategy

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

$$= \frac{N(B^+ \to K^+\mu^+\mu^-)}{N(B^+ \to K^+J/\psi(\mu^+\mu^-))} \times \frac{\varepsilon_{B^+\to K^+J/\psi(\mu^+\mu^-)}}{\varepsilon_{B^+\to K^+\mu^+\mu^-}}$$

$$\times \frac{N(B^+ \to K^+J/\psi(e^+e^-))}{N(B^+ \to K^+e^+e^-)} \times \frac{\varepsilon_{B^+\to K^+e^+e^-}}{\varepsilon_{B^+\to K^+J/\psi(e^+e^-)}}$$

- R_K is measured as a **double ratio** to cancel out most systematics
  $\rightarrow$ $B^+ \to K^+J/\psi(\ell^+\ell^-)$ measured to be LF-universal within 0.4%
- Yields determined from a fit to the invariant mass of the final state particles
- Efficiencies computed using simulation that is calibrated with control channels in data

Final results

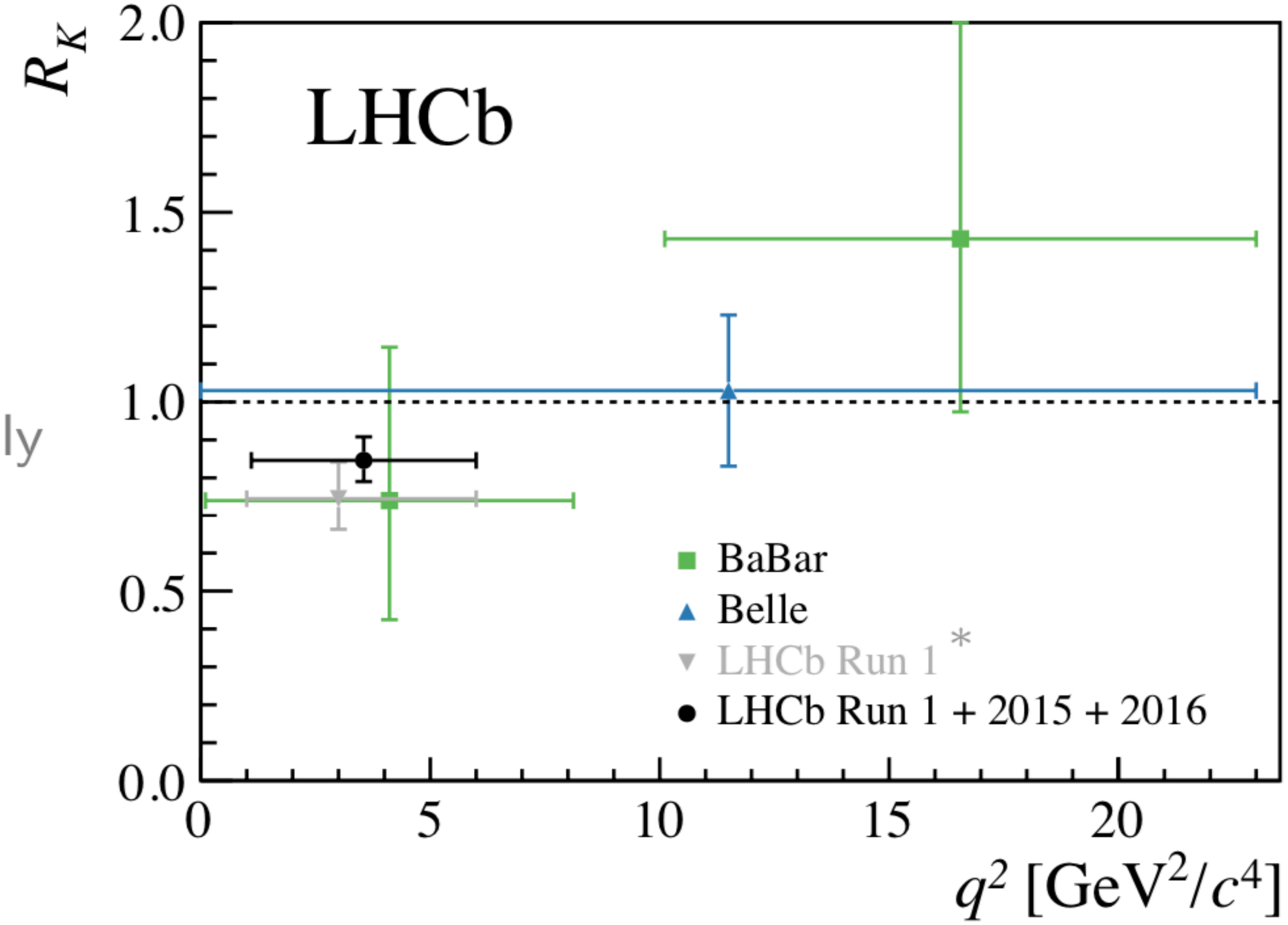
[LHCb-PAPER-2019-009]

[LHCb, PRL 113 (2014) 151601]

[BaBar, PRD 86 (2012) 032012]

[Belle, PRL 103 (2009) 171801]

* LHCb Run1 bin centre horizontally displaced for illustration.



Using 2011 and 2012 LHCb data:

$$R_K = 0.745\ ^{+0.090}_{-0.074}\ (\text{stat})\ \pm 0.036\ (\text{syst}),$$

compatible with the SM expectation at 2.6σ.

Reanalysing 2011-2012 and adding 2015 and 2016 data, R_K becomes

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

which is compatible with the SM expectation at 2.5σ.

Flavour Anomalies

$b \to s\mu\mu$ (LHCb from 2013)

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

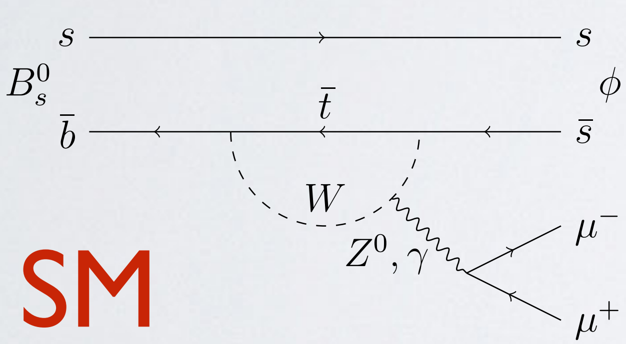
2) Branching ratios $\gtrsim 3.5\sigma$ (?!)

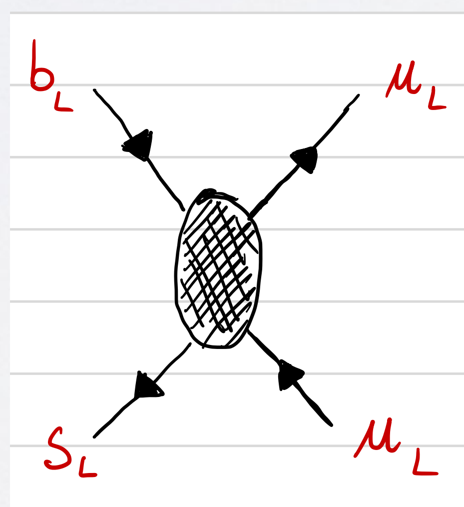
3) LFU violation in R_K 2.6σ

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

"clean" only $\approx 4\sigma$

SM

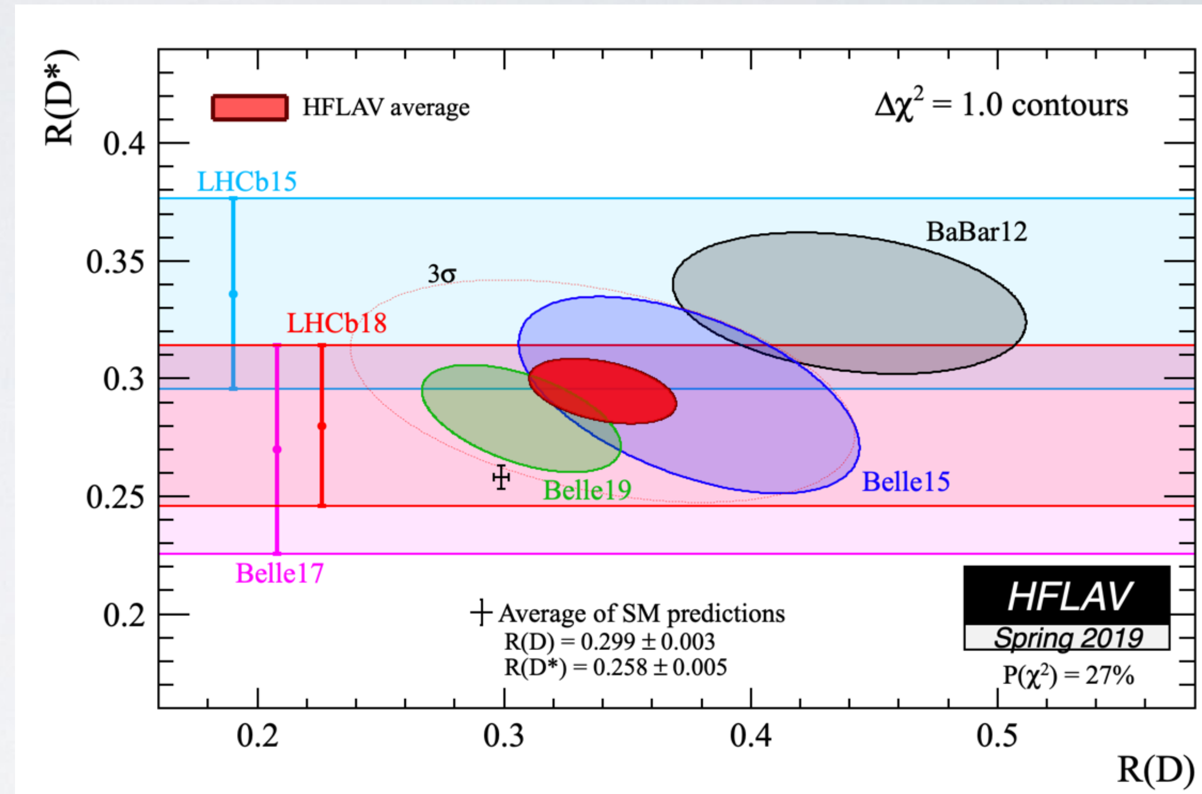


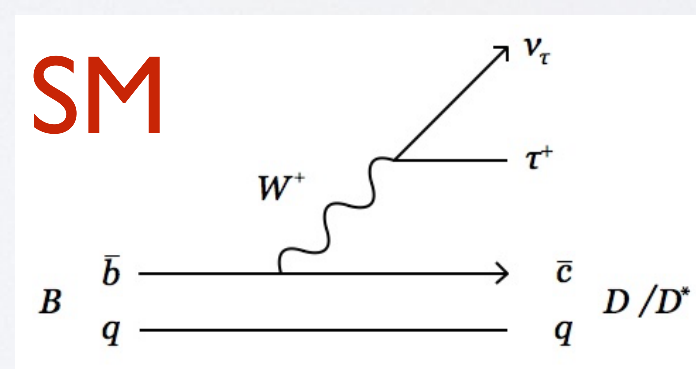


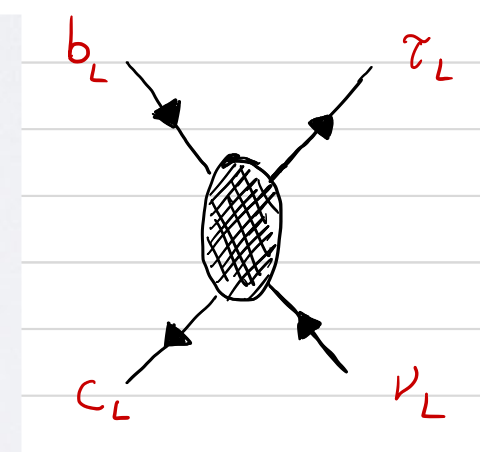
$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2_{R_K}} \bar{s}_L \gamma^\mu b_L \, \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

$|C_\mu^{NP}| \gg |C_e^{NP}|$ $\Lambda_{R_K} = 31$ TeV

$b \to c\tau\nu$ Babar+Belle+LHCb from 2012







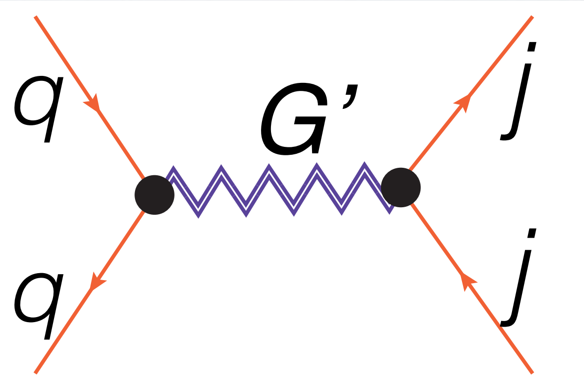
$$\mathcal{L}_{eff} = -\frac{2}{\Lambda^2_{R_D}} \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_L + h.c.$$

$|C_\tau^{NP}| \gg |C_\mu^{NP}|, |C_e^{NP}|$ $\Lambda_{R_D} = 3.4$ TeV

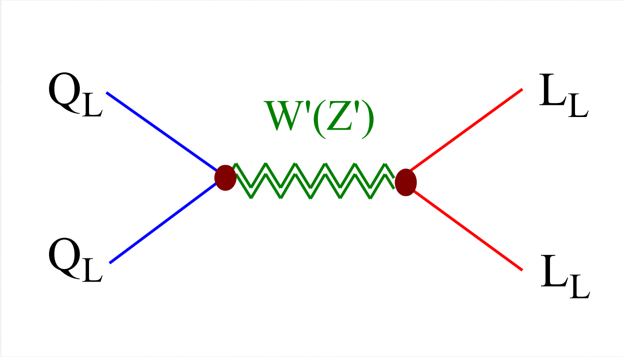
Bottom-up path

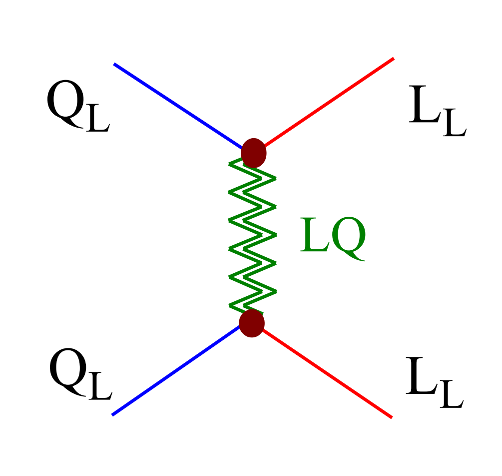
Theoretical input / bias

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

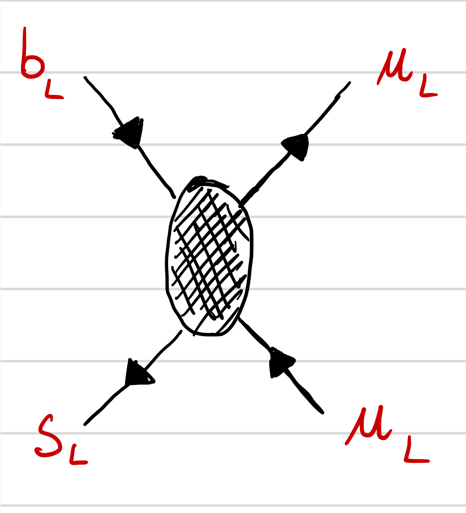


Simplified Models — Introducing explicitly New Physics, in the simplest way as possible

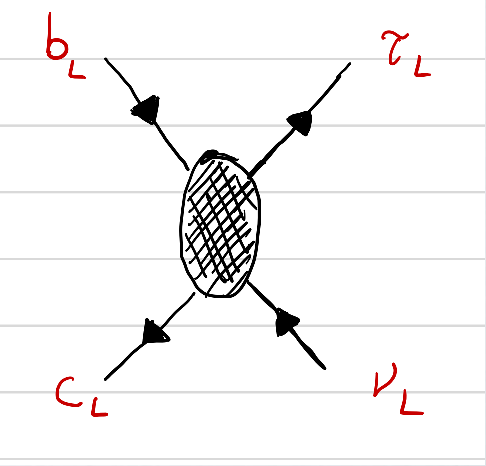




EFT — New Physics in a model independent way



$\Lambda_{R_K} = 31\ \mathrm{TeV}$



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

Experimental input

- *What is the scale of New Physics?*

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

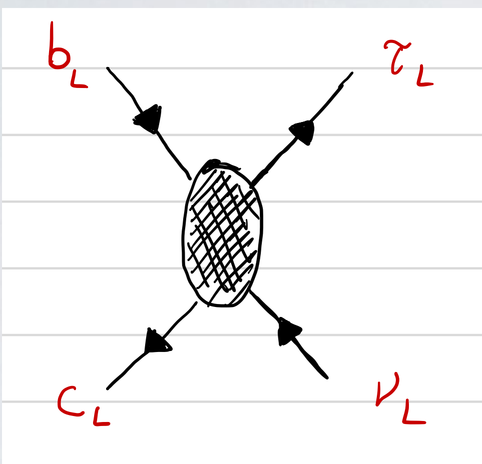
"Measured" Fermi constant ← $\frac{1}{\Lambda^2} = \frac{C}{M^2}$

C → Model dependent part

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

M^2 → 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

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

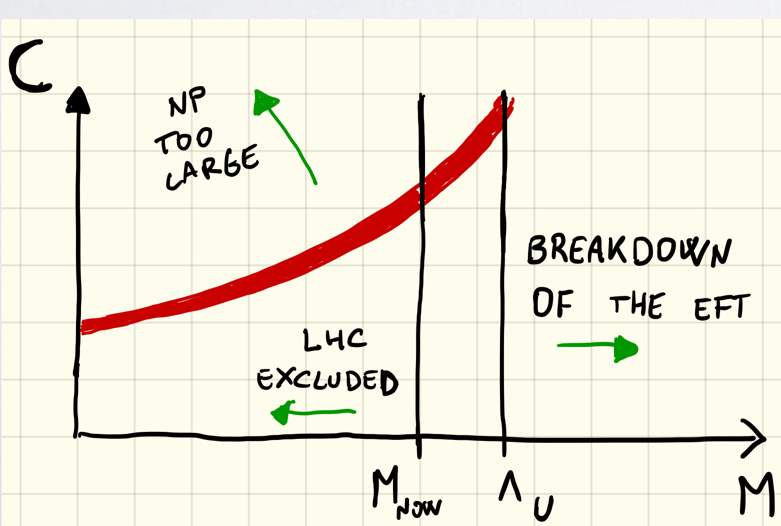
[Di Luzio, MN, 1706.01868]

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

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

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

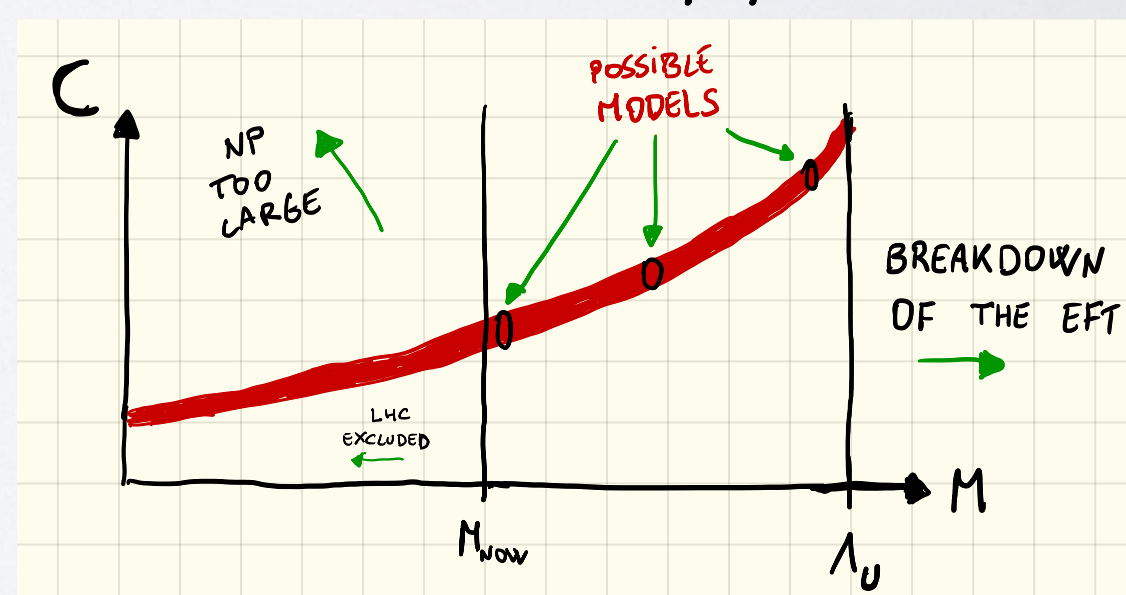
$$b \to c\tau\nu$$



Absence of New Physics at high energy

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

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



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*]:

	μμ (ee)	ττ	νν	τμ	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%) [$R_K = R_\pi$]	$B \to \pi\tau\tau$ $\to$ 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

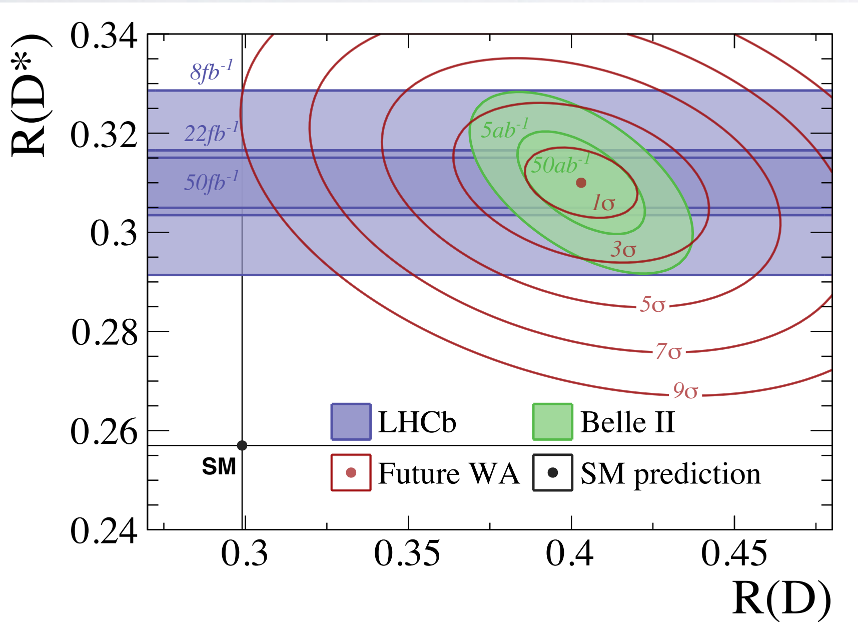
		Run 1 (2010-2012)	Run 2 (2015-2018)	Run 3 (2021-2023)	Run 4 (2026-2029)
			'Milestone I'	'Milestone II'	'Milestone III'
year		2012	2020	2024	2030
LHCb	$\mathcal{L}$ [fb^{-1}]	3	8	22	50
	$n(b\bar{b})$	0.3×10^{12}	1.1×10^{12}	37×10^{12}	87×10^{12}
	$\sqrt{s}$	7/8 TeV	13 TeV	14 TeV	14 TeV
Belle (II)	$\mathcal{L}$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

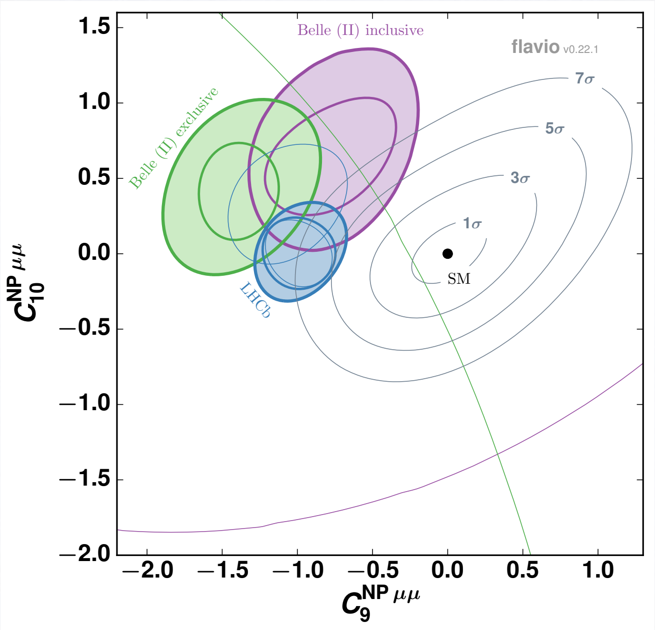
[Albrecht, Bernlochner, Kenzie, Reichert, Straub, Tully, arXiV:1709.10308]

- The fate of the anomalies

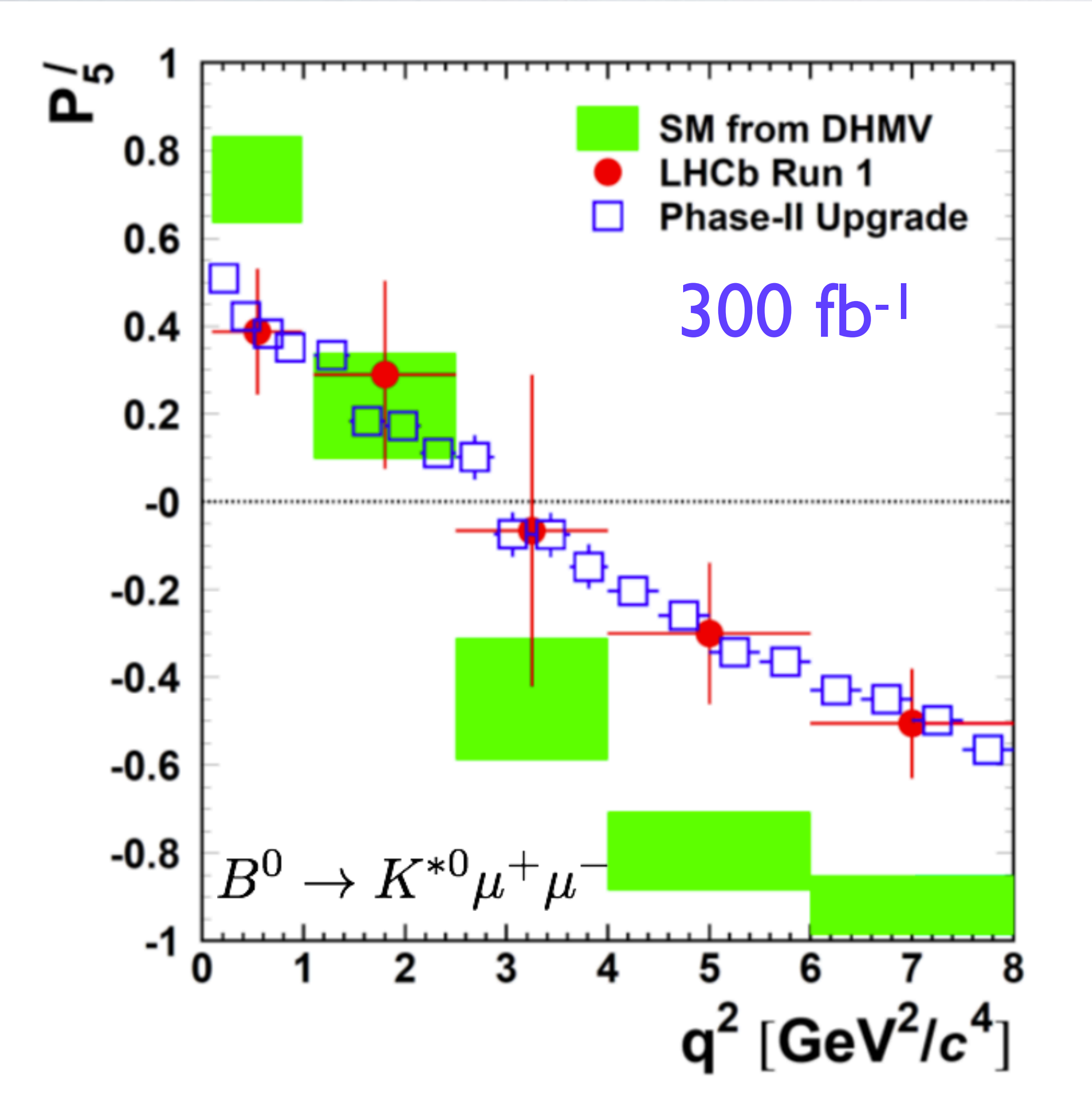
Measurement	SM prediction (Ref. [43])	Current World Average (Ref. [35])	Current Uncertainty (Ref. [35])	Projected Uncertainty Belle II		LHCb		
				5 ab^{-1}	50 ab^{-1}	8 fb^{-1}	22 fb^{-1}	50 fb^{-1}
$R(D)$	(0.299 ± 0.003)	$(0.403 \pm 0.040 \pm 0.024)$	11.6%	5.6%	3.2%	-	-	-
$R(D^*)$	(0.257 ± 0.003)	$(0.310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

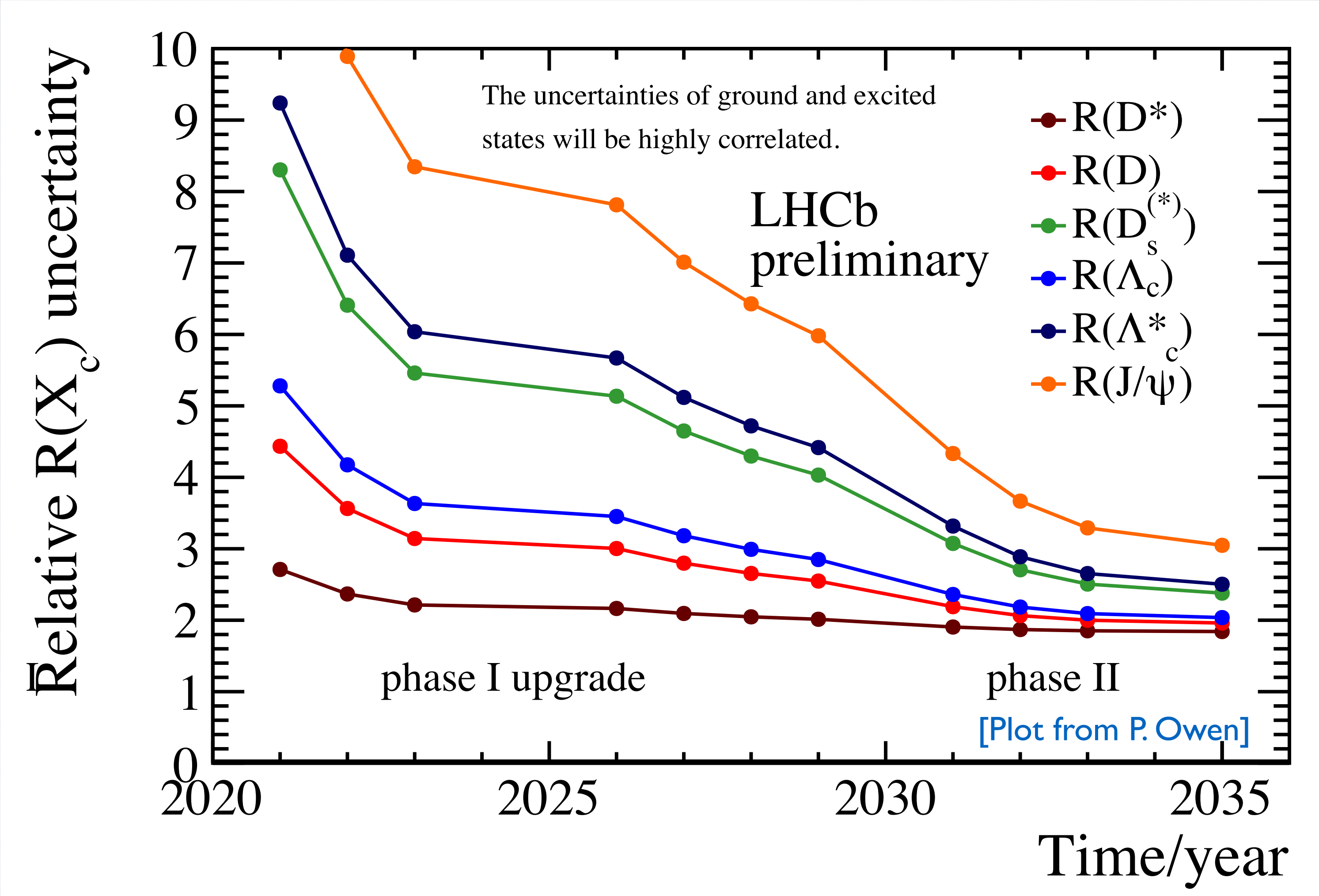
tematic uncertainties can be neglected. If the anomalies in $R(K)$ and $R(K^*)$ persist at the current central values, LHCb will measure $R(K)$ with a significance of $> 5\sigma$ with respect to the SM prediction at milestone I, increasing to 15σ with the milestone III dataset. Concerning $R(K^*)$ at 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





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
$R(D^*)$
$R(D)$
$R(D_s^{(*)})$
$R(\Lambda_c)$
$R(\Lambda^*_c)$
$R(J/\psi)$
phase I upgrade
phase II
[Plot from P. Owen]
Time/year

Messages

• More observables can be correlated to the “anomalous” ones.

• Situation will be clarified soon (few years). LHCb analysis are based mostly on data from Run1 and Belle II will enter soon the game

• For discussion, what about B-Physics @ Rome I? Belle II? LHCb? CMS?

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

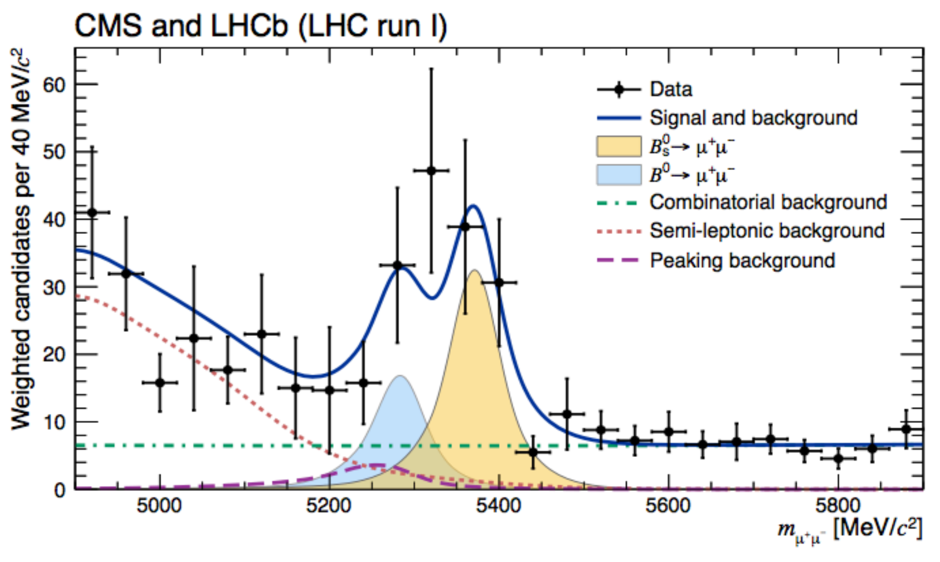
- Flavour anomalies are surviving in a coherent way in both charged current (2012) and neutral current (2013).

- Current anomalies in B decays have a simple and consistent interpretation at the effective field theory level (model independent). Hint of dominant coupling 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.

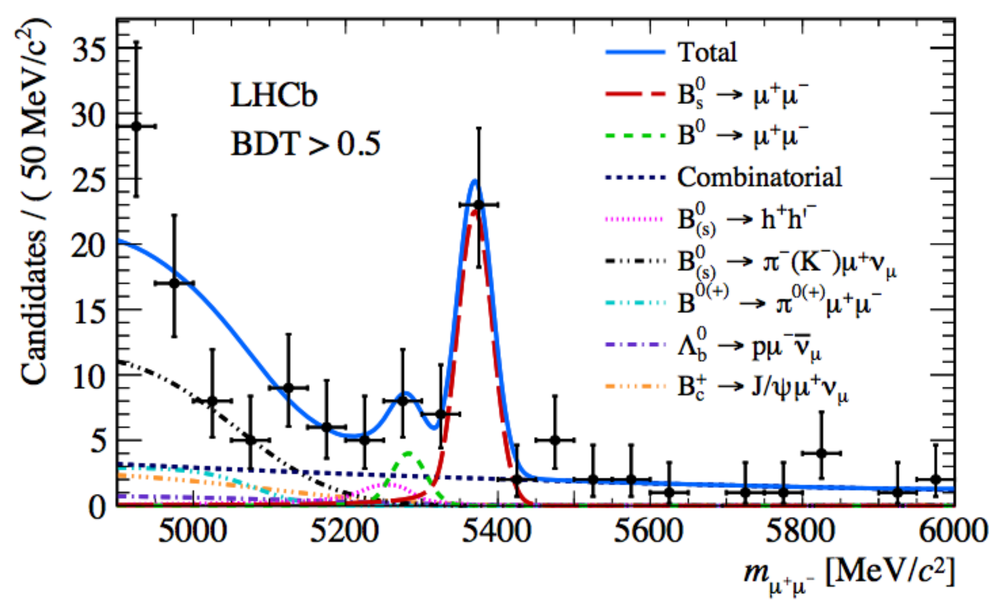
- We are really looking forward for new data!

$B_s, B_d \to \mu\mu$



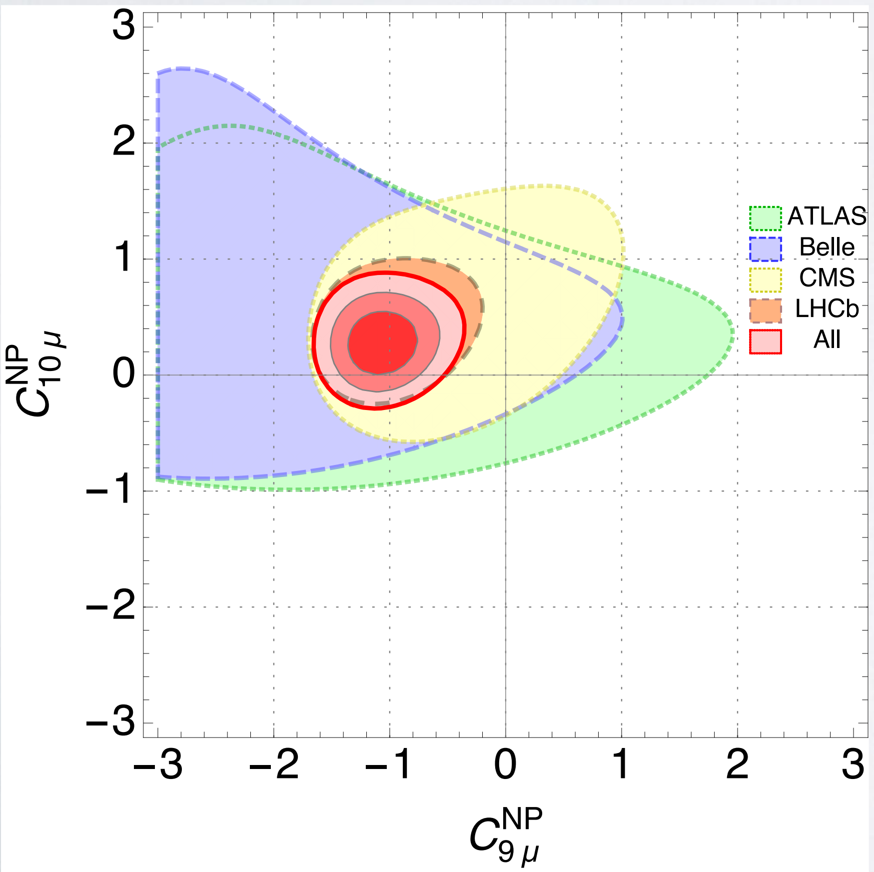
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

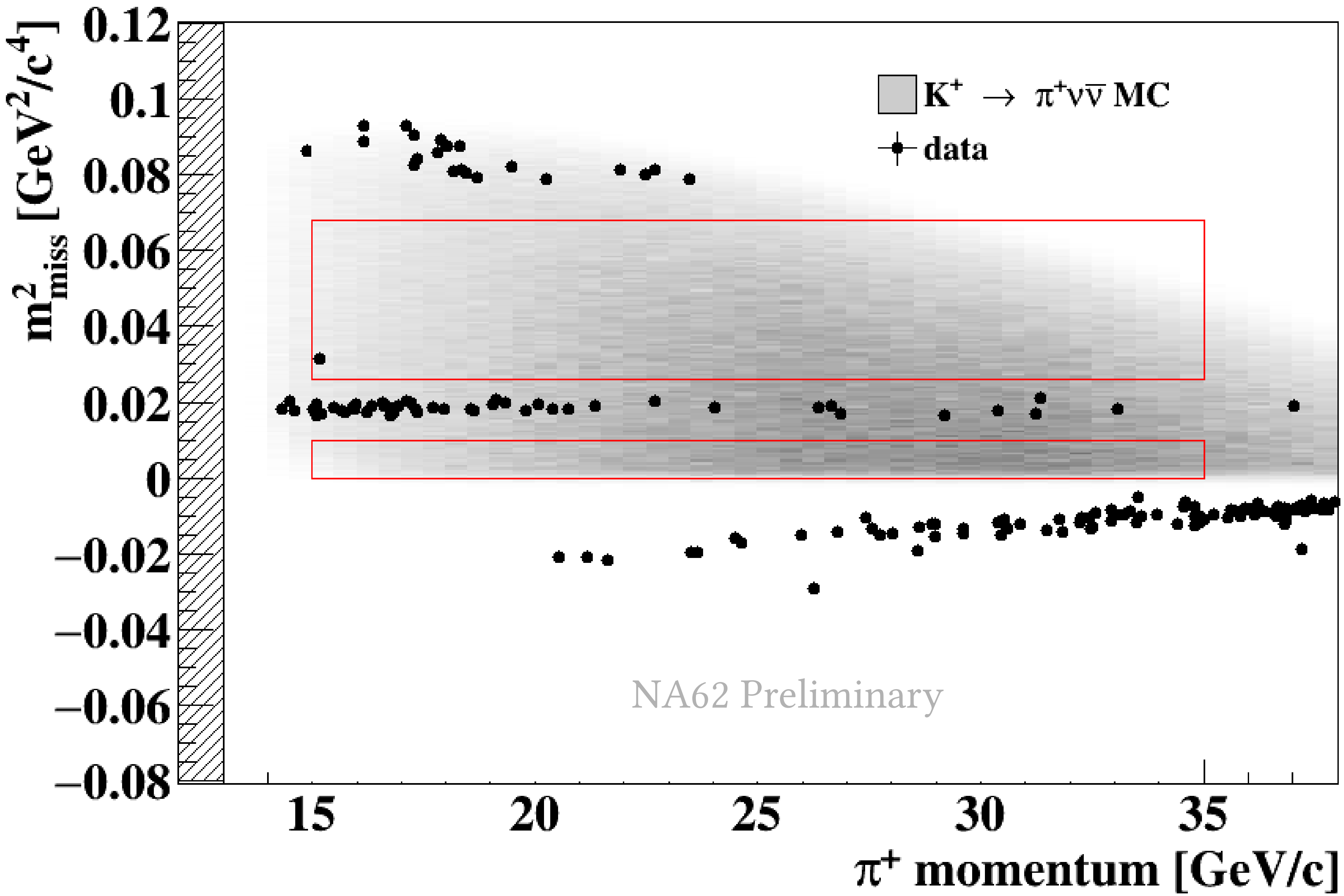
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ [95\% CL]}$$



- Helicity suppressed in the SM
- Ratio of the decay rates very clean, can test NP
- Sensitive to scalar currents
- Sensitive to the axial structure of the lepton current, can discriminate NP option for FCNC anomalies

$$\bar{s}_L \gamma^\mu b_L\, \bar{\mu}\gamma_\mu \mu \quad \text{vs} \quad \bar{s}_L \gamma^\mu b_L\, \bar{\mu}_L \gamma_\mu \mu_L$$

Results — Updates from NA62, Moriond EW



One event observed

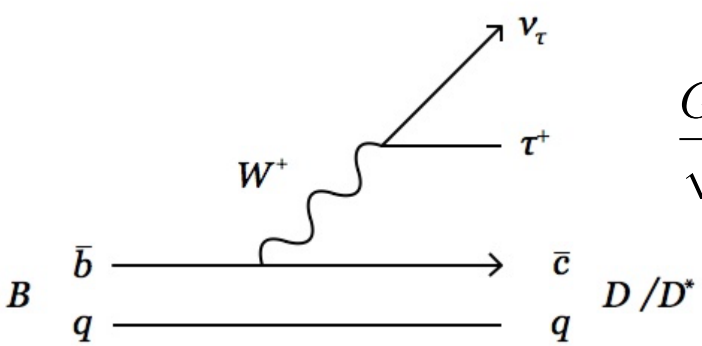
$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 11 \times 10^{-10}$ @ 90% CL

$BR(K^+ \rightarrow \pi^+\nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$

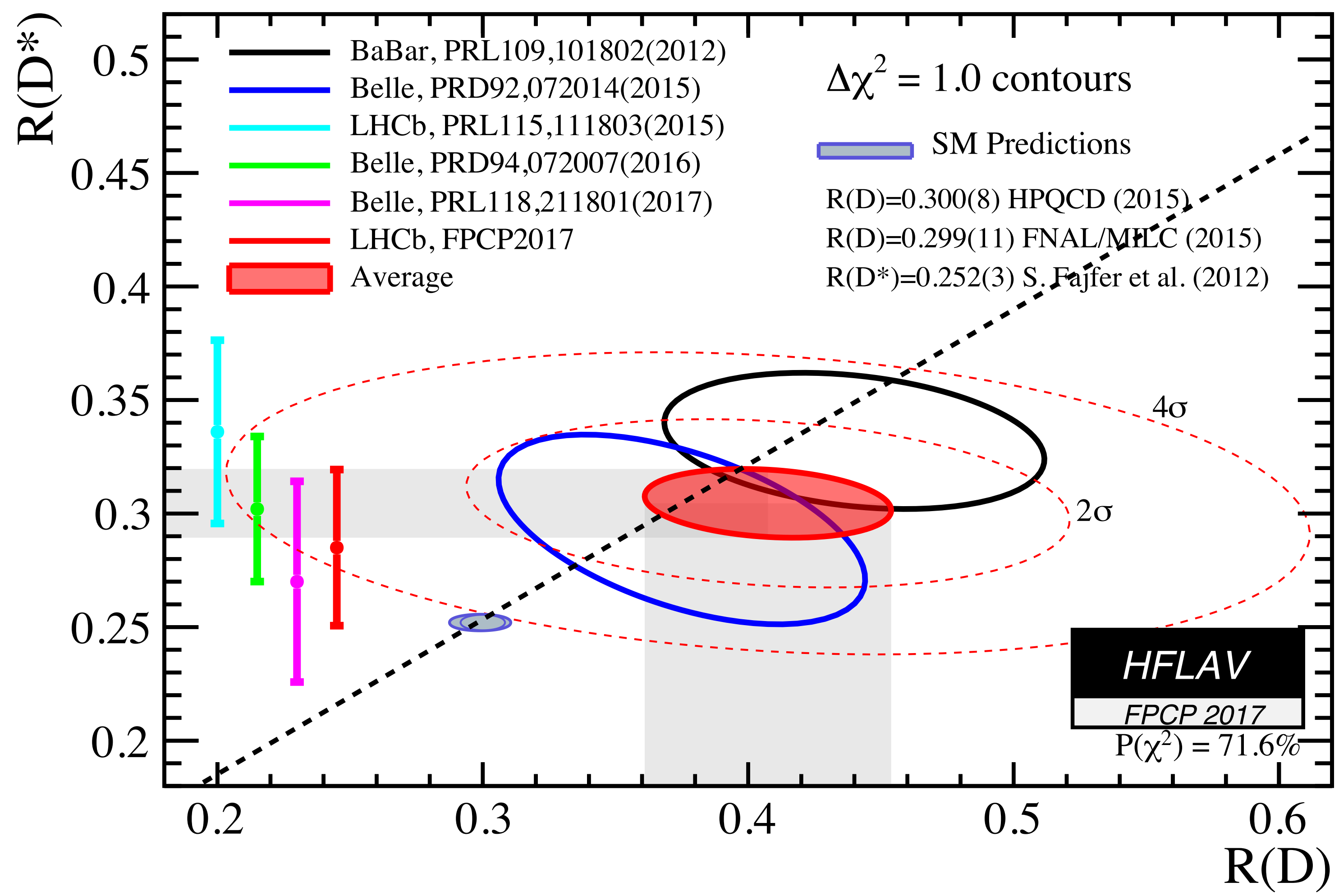
$b \to c\tau\nu$

$$R(X) = \frac{\mathcal{B}(\bar{B} \to X\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to Xl\bar{\nu})} \qquad X = D, D^* \quad l = \mu, e$$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{bc}^* (\bar{b}_L \gamma^\alpha c_L)(\bar{\tau}_L \gamma_\alpha \nu_\tau)$$



$$\frac{G_F}{\sqrt{2}} V_{bc}^* = \frac{1}{(1.7\ \text{TeV})^2}$$



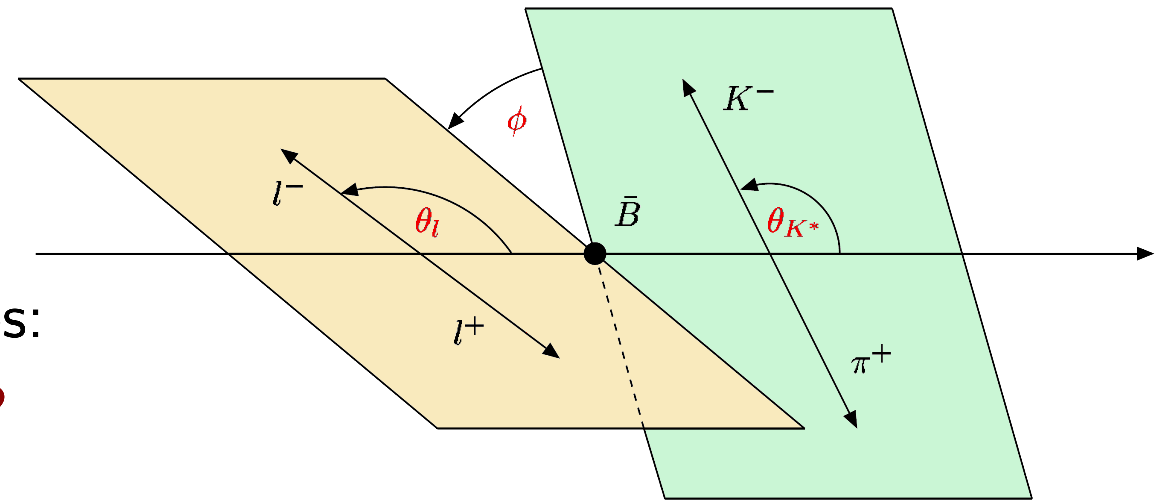
- SM predictions are quite robust
- Seen in 3 different experiments in a consistent way, combined significance 4.1σ
- Measurements are consistent with e/mu universality
- In the SM the flavour transition is unsurpassed by loop factor (tree-level charged current)
- Assuming central values, NP has to be large, fits prefer SM structure (left current)
- Data could be fitted by new interactions with mediator at the EW scale
- Various constraints on model building, EWPT, other flavour observables, direct searches

- Best fit: purely left operator SM(1+30%)

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

Angular distributions

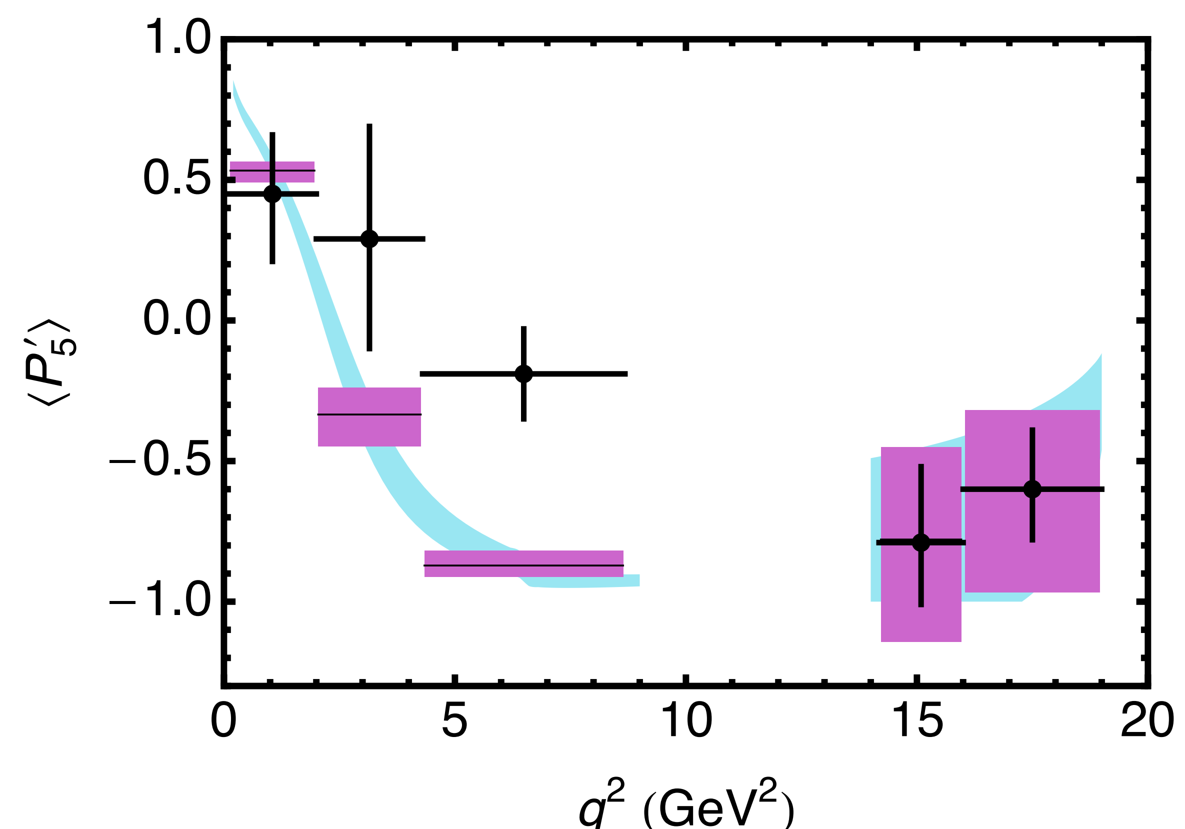
$\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ ($\bar{K}^{*0} \to K^-\pi^+$) full angular distribution described by four kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ



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

3.7σ discrepancy in one of q² bins

LHCb,1308.1707, PRL



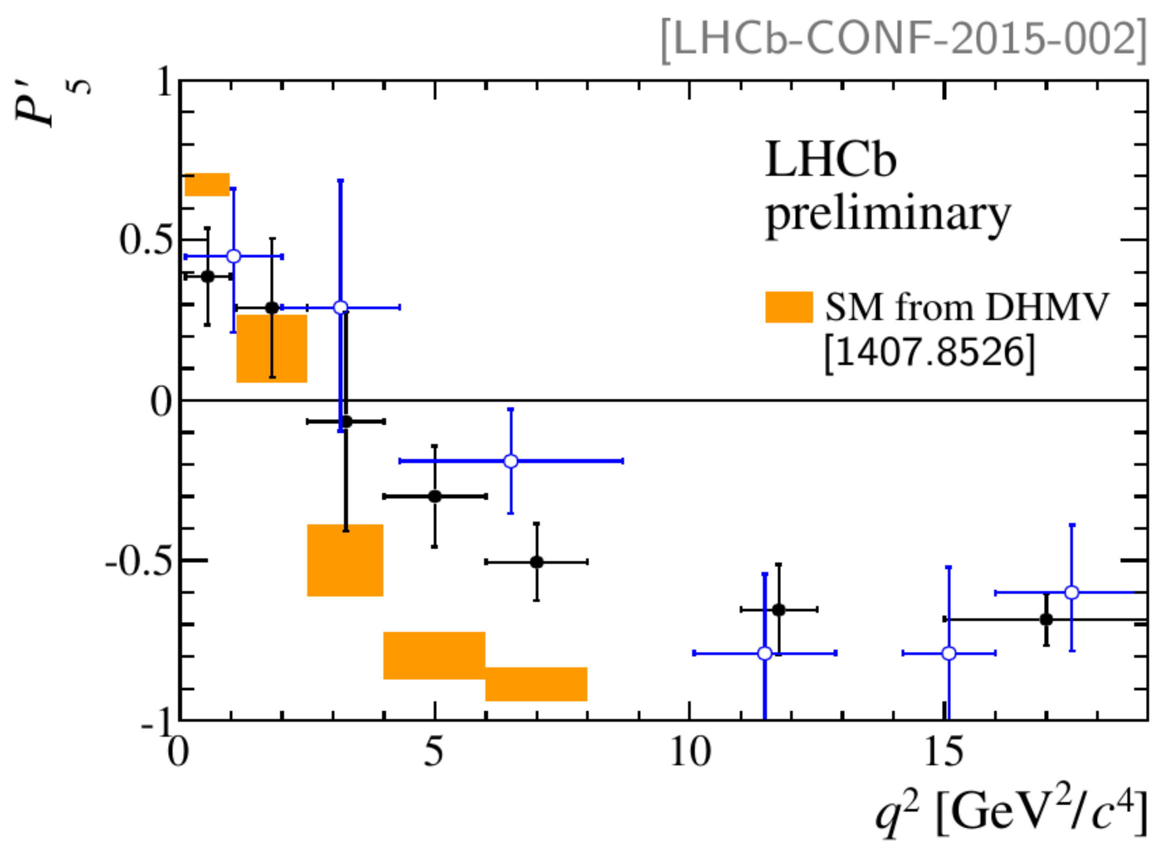
SM=JHEP,1303.5794

Explanations:

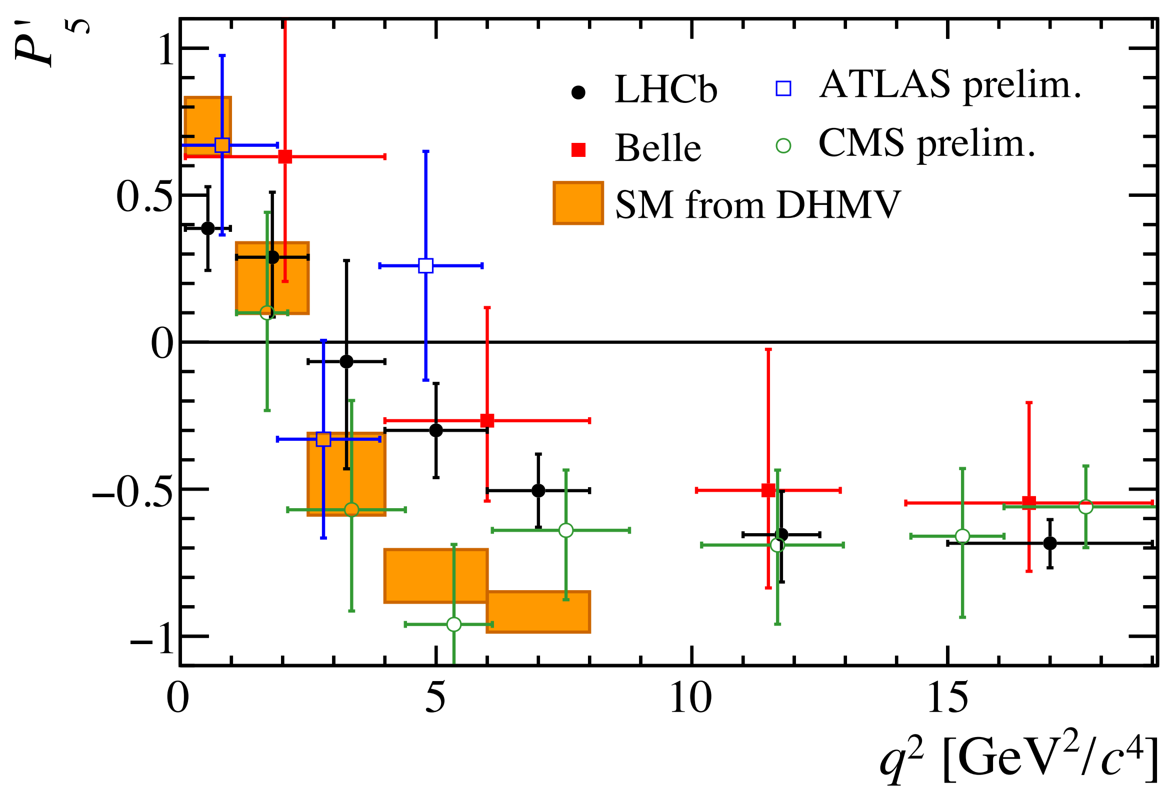
1. Statistical fluctuation?
2. Hadronic uncertainties
3. New Physics

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

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

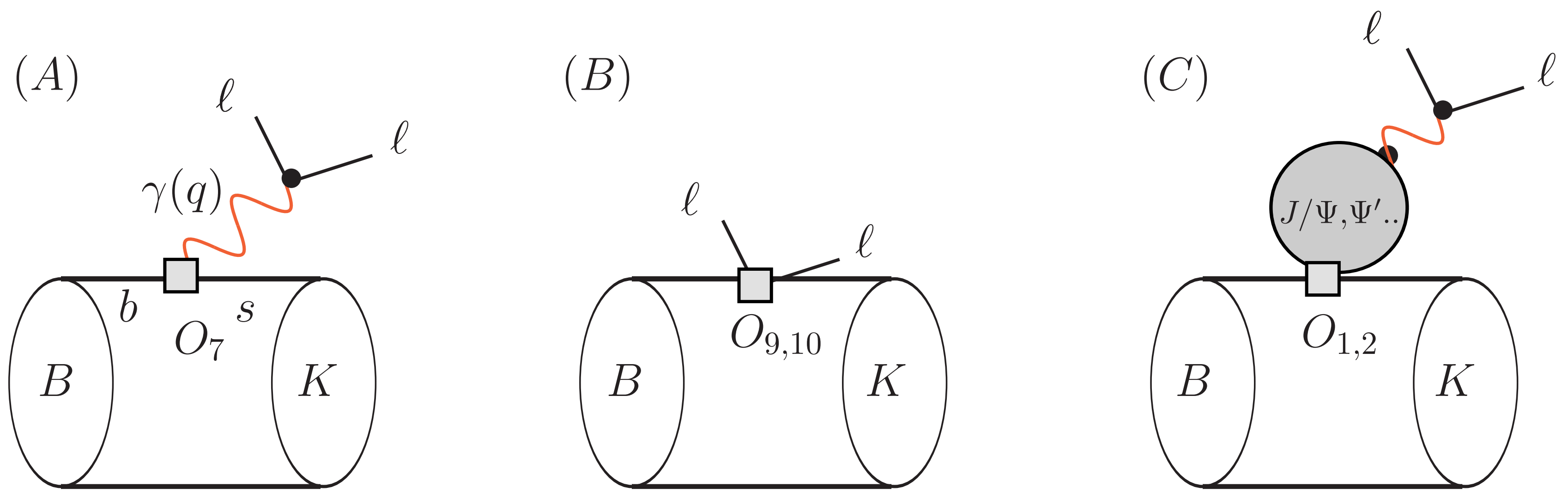


Moriond EW
2015



Moriond EW
2017

(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)

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

Main effect is encoded in

$$h_\lambda(q^2) = \frac{\epsilon_\mu^*(\lambda)}{m_B^2}\int d^4x e^{iqx}\langle \bar{K}^*|T\{j_{\rm em}^\mu(x)\mathcal{H}_{\rm eff}^{\rm had}(0)\}|\bar{B}\rangle$$
$$= h_\lambda^{(0)} + \frac{q^2}{1\,{\rm GeV}^2}h_\lambda^{(1)} + \frac{q^4}{1\,{\rm GeV}^4}h_\lambda^{(2)}\,,$$

[Aggressive 1701.08672
Conservative 1512.07157]

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	$+3.1$

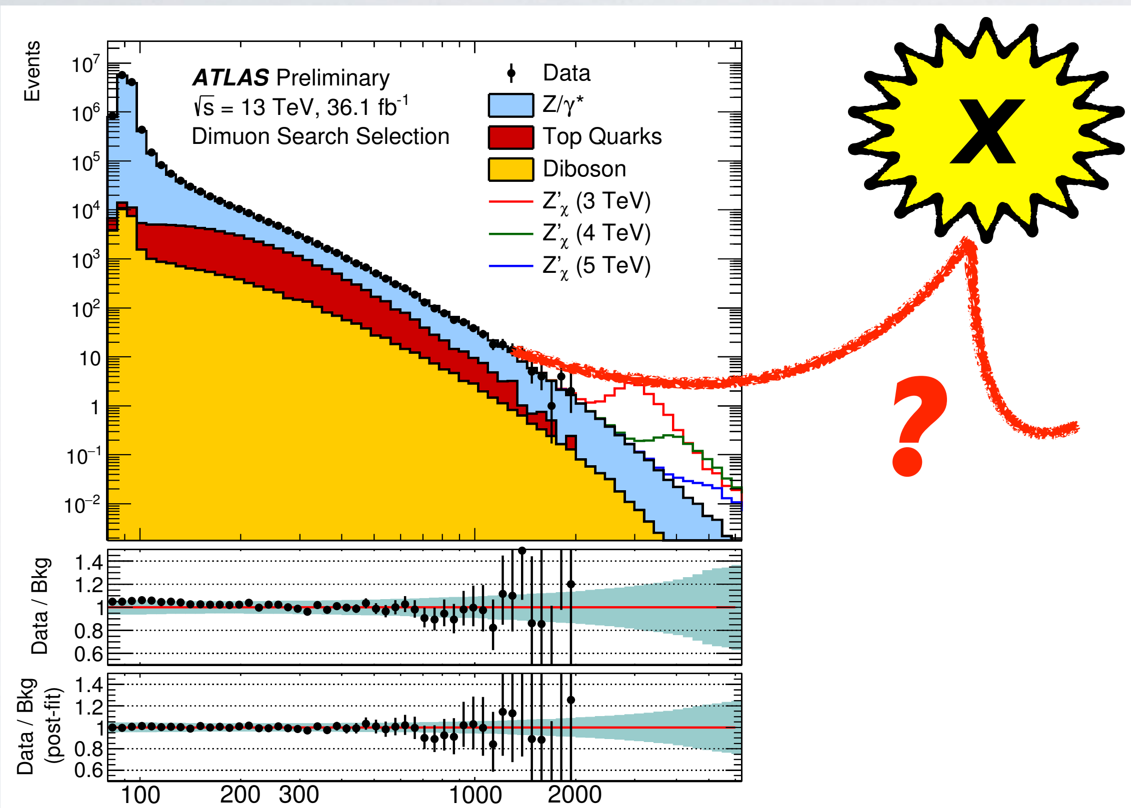
[Altmannshofer, Straub 1503.06199]

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

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

SM-EFT regime: tails

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



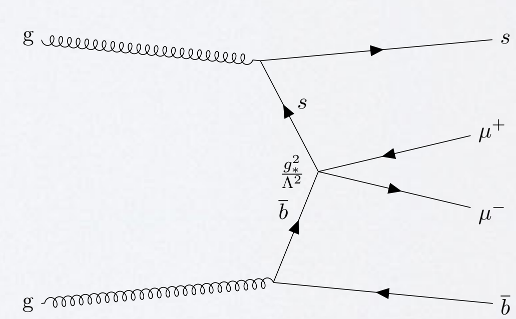
Dimuon Invariant Mass

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

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

- NC anomalies [1704.09015,180511402]

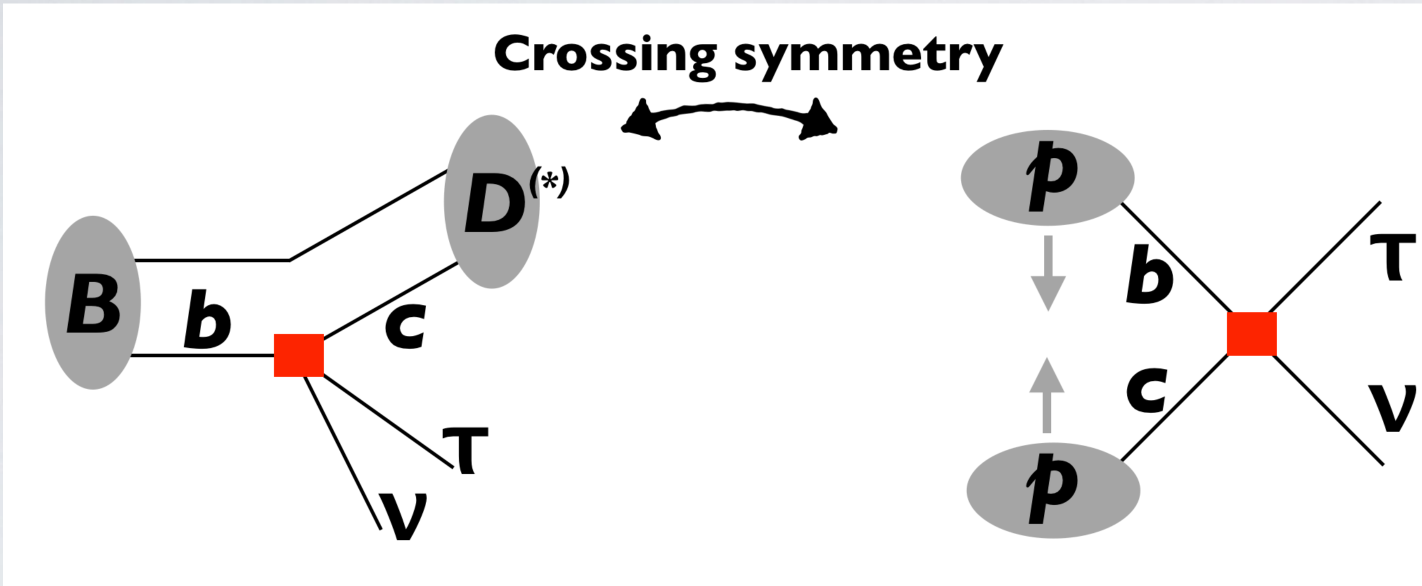
$$pp \to \mu^+\mu^-$$



No sensitivity at HL-LHC if it is present ONLY

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

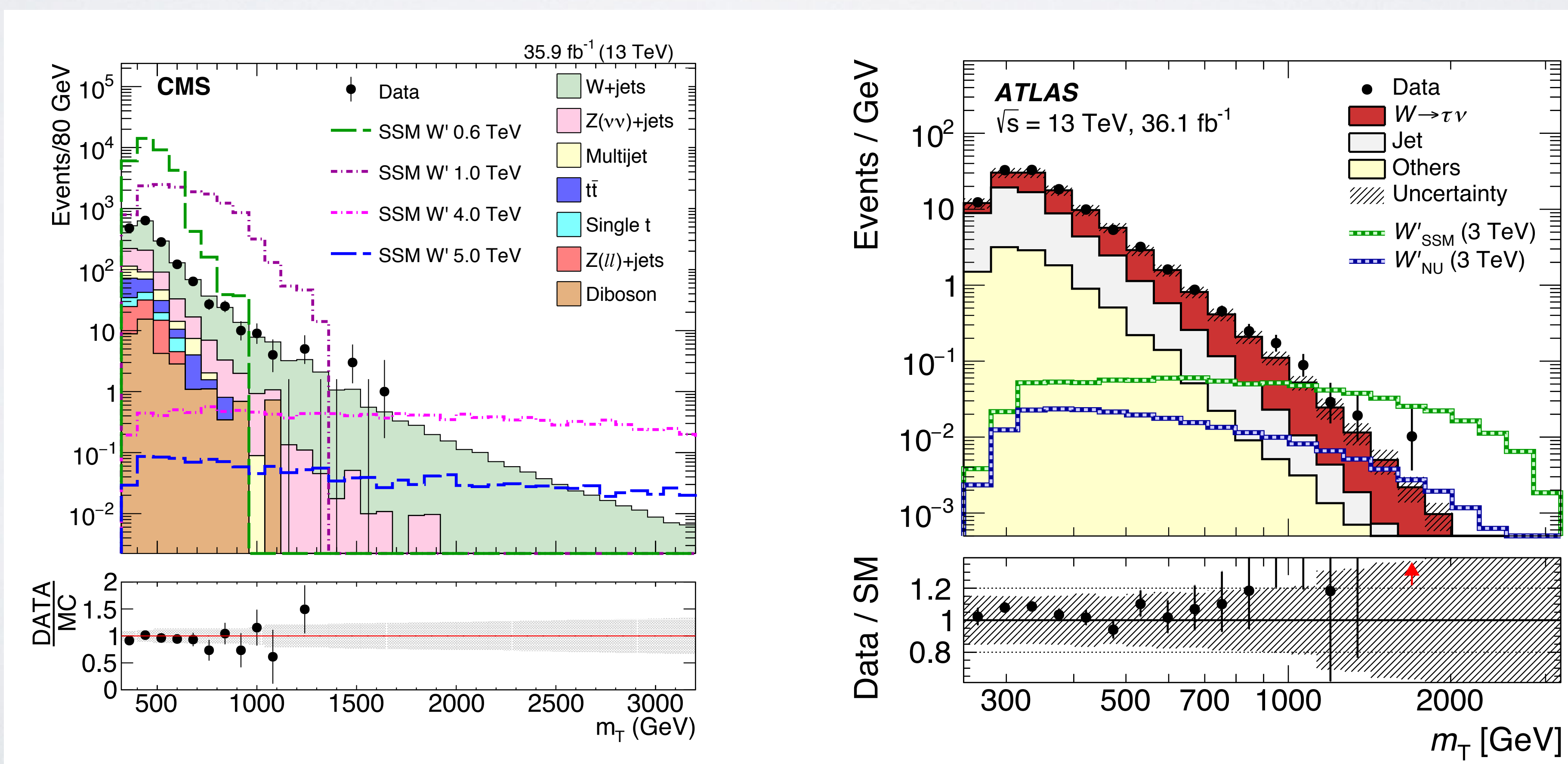
$pp \to \tau\nu$



[Greljo, Martin Camalich, Ruiz-Alvarez 1811.07920]

Phys.Rev.Lett. 122 (2019)

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

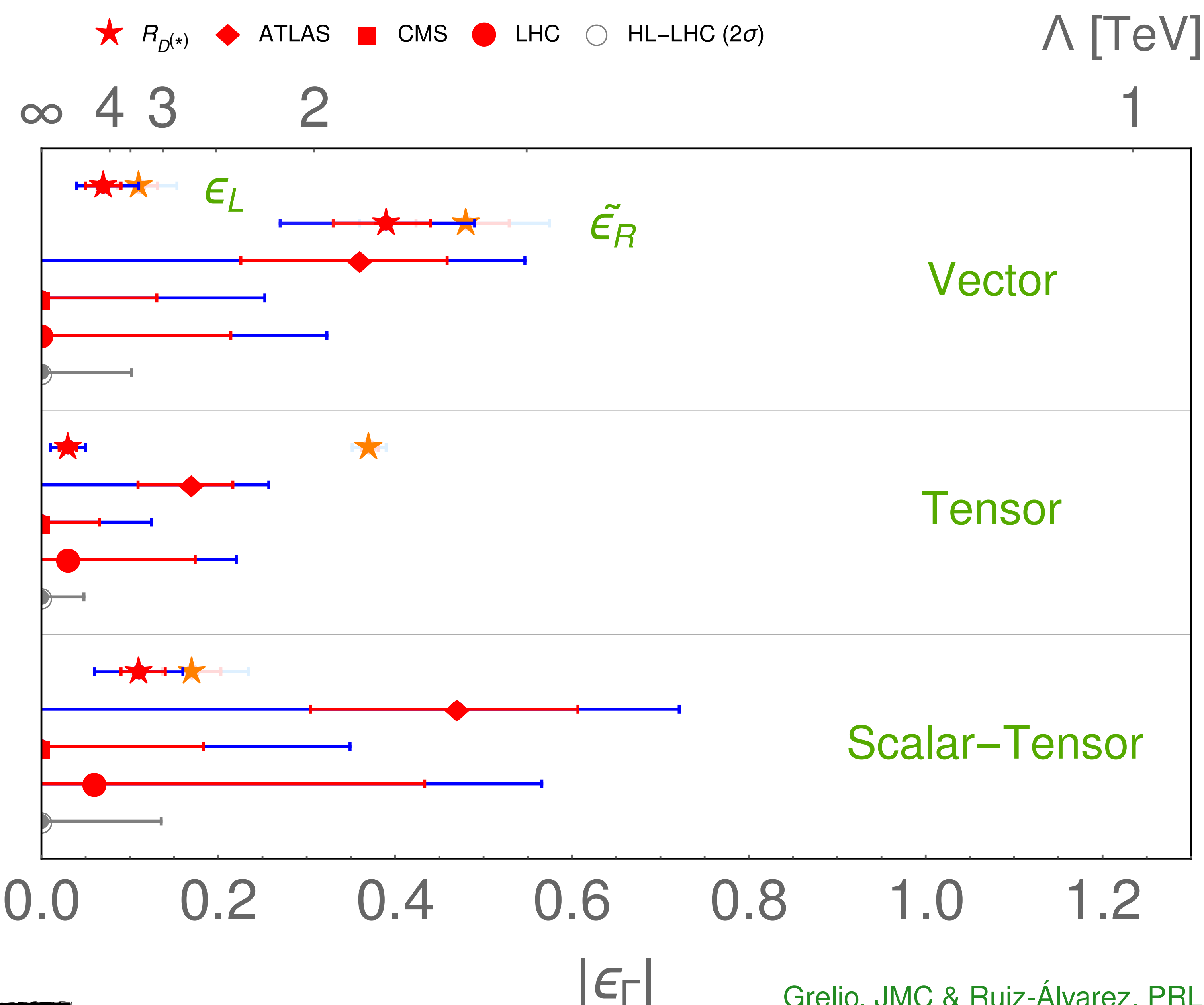


$$\mathcal{L}_{\mathrm{LEEFT}} \supset -\frac{2V_{kl}}{v^2}\Big[\Big(1+\epsilon_L^{kl\tau}\Big)\bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{u}_k \gamma^\mu P_L d_l + \epsilon_R^{kl\tau}\bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{u}_k \gamma^\mu P_R d_l$$

$$+\epsilon_T^{kl\tau}\,\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau \cdot \bar{u}_k \sigma^{\mu\nu} P_L d + \epsilon_{S_L}^{kl\tau}\bar{\tau}P_L\nu_\tau \cdot \bar{u}_k P_L d_l + \epsilon_{S_R}^{kl\tau}\bar{\tau}P_L\nu_\tau \cdot \bar{u}_k P_R d_l\Big] + \text{h.c.},$$

$$\Lambda = v/\sqrt{|V_{cb}||\epsilon_\Gamma|}$$

* 1σ (red) and 2σ (blue) ranges on the absolute value of the WCs of semi-tauonic cb transitions at μ = mb



Greljo, JMC & Ruiz-Álvarez, PRL122, 131803 (updated)

A lot of room for improvements:

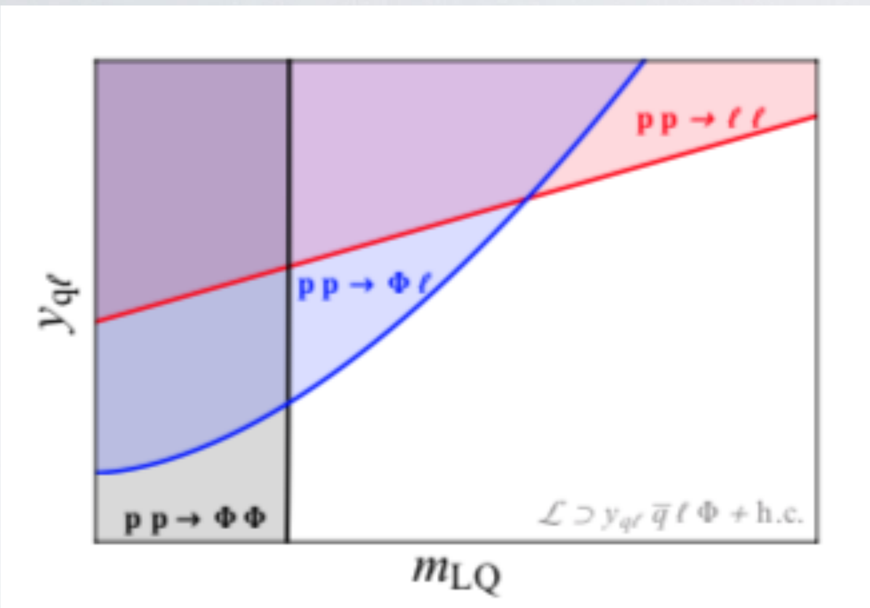
- b-tag,
- tau charge-asymetries,
- rapidity distribution,
- polarization.

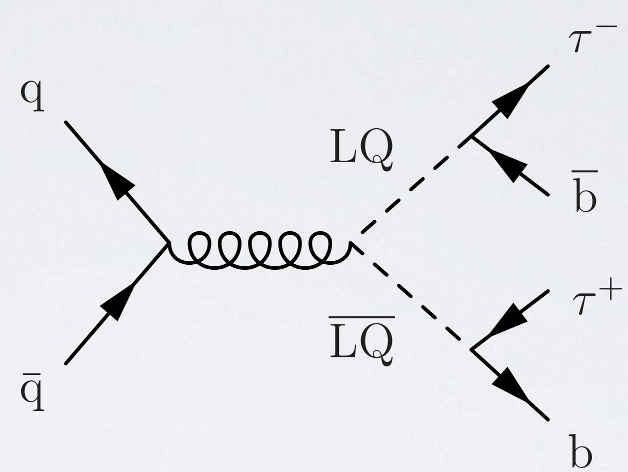
$$pp \to \tau\nu$$

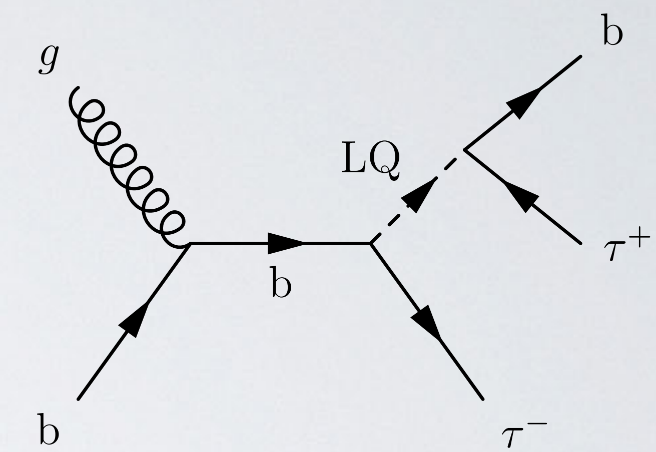
[Thanks to A. Greljo]

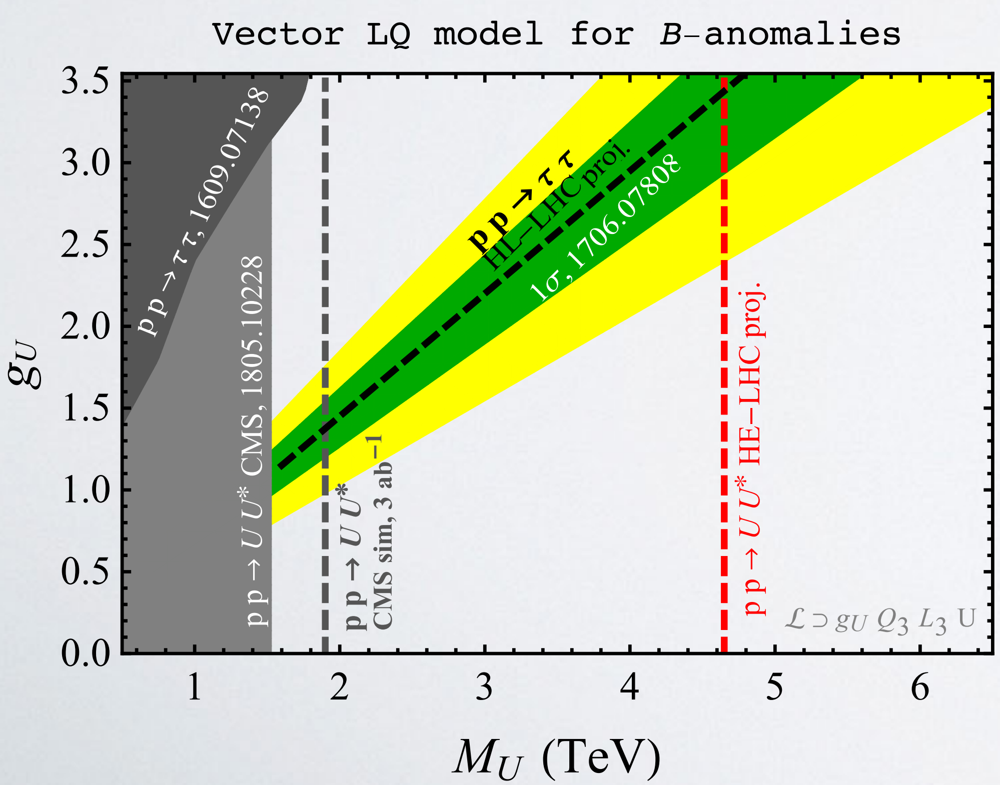
Leptoquarks

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







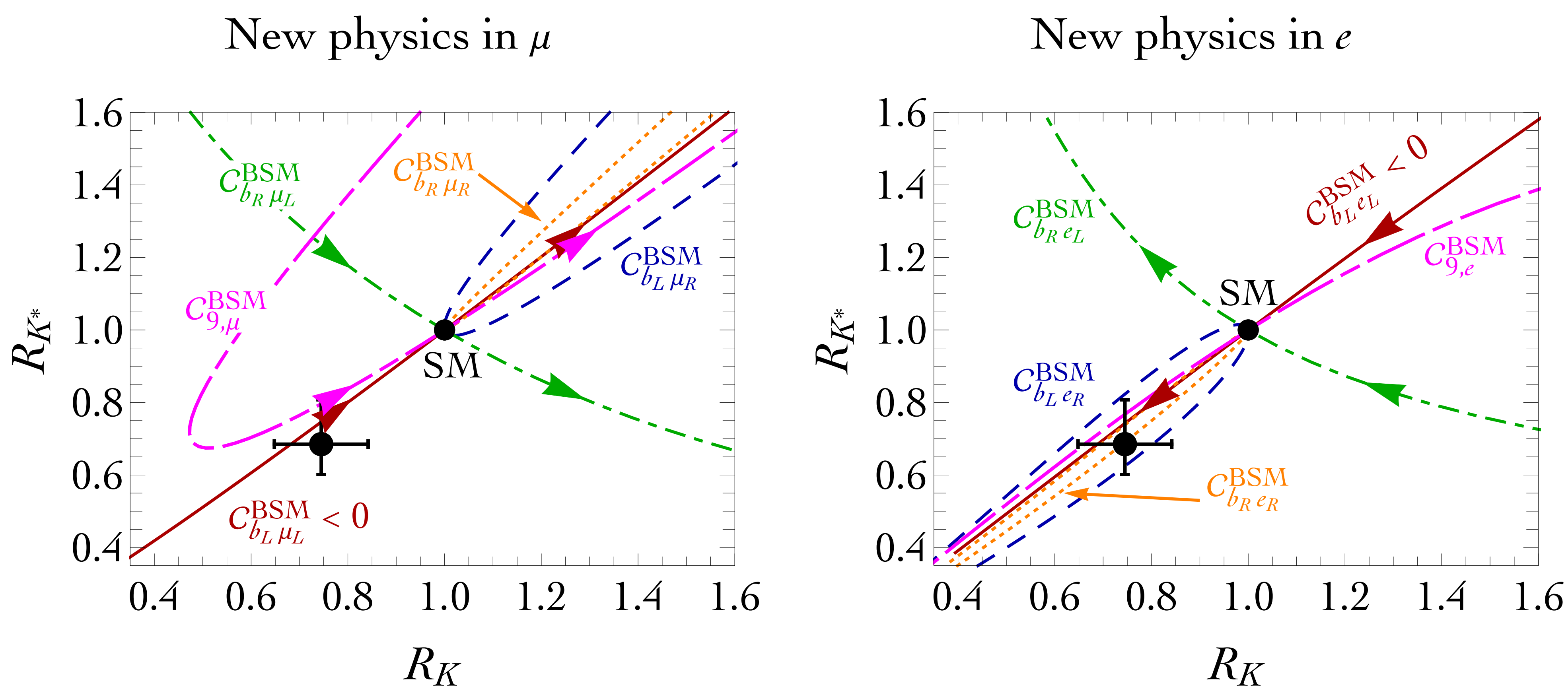


- HL-LHC and HE-LHC report [1812.07638]
- Two decay channels: bottom-tau, top-neutrino. SU(2) fix the BR to be equal
- Top-neutrino: see N.Vignaroli 1808.10309
- Message: LQ survives at the LHC and HL-LHC in large part of the parameter space…

After R_{K^*}

- RK and RK* observables alone are now sufficient to draw various conclusions (without doing fits!)

[1704.05340, 1704.05435
1704.05438, 1705444,
17054446, 1705447]



$$R_{K^*} \simeq R_K - 4p\frac{\mathrm{Re}\, C^{\rm BSM}_{b_R(\mu-e)_L}}{C^{\rm SM}_{b_L\mu_L}}$$

$$4p/C^{\rm SM}_{b_L\mu_L} \approx 0.40$$

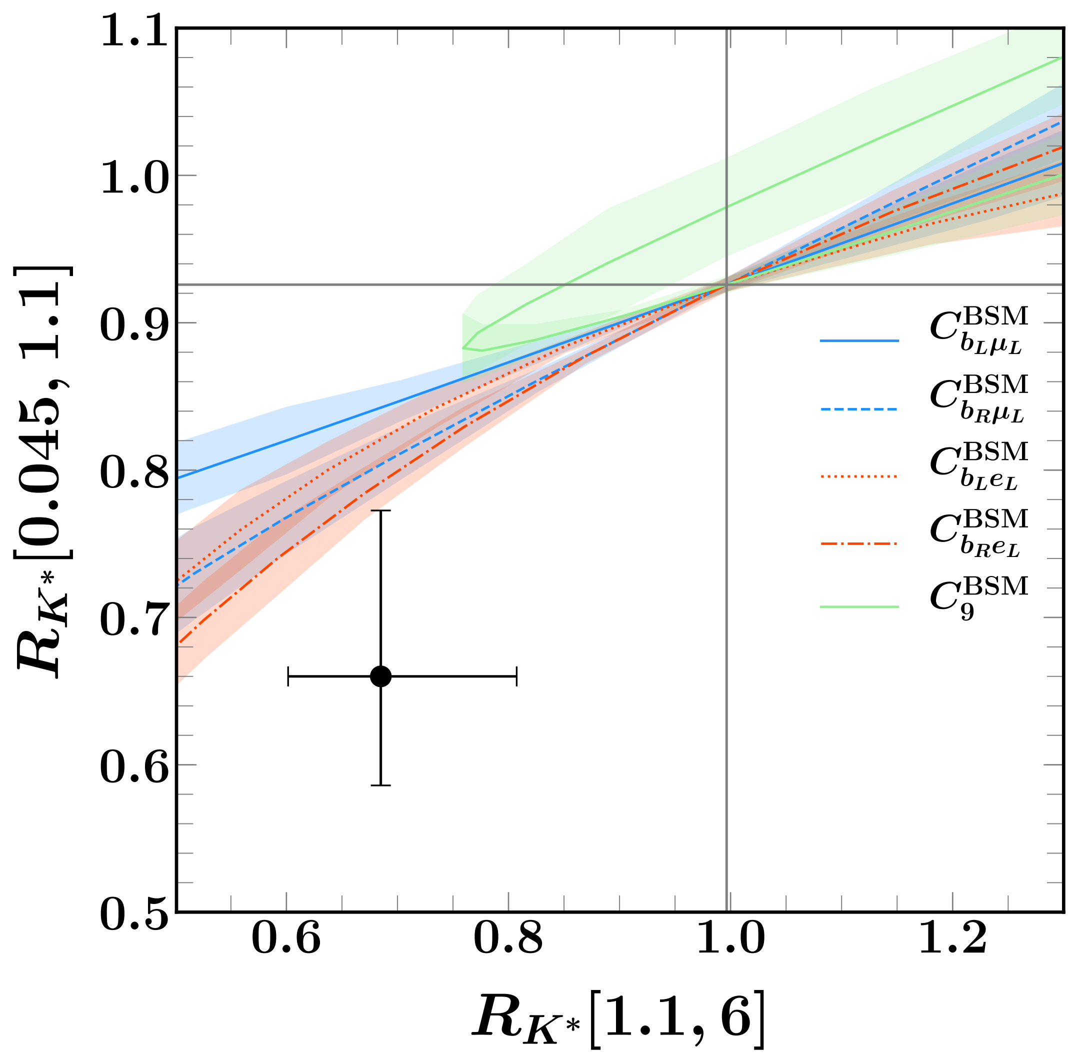
$$R_K \simeq 1 + 2\frac{\mathrm{Re}\, C^{\rm BSM}_{b_{L+R}(\mu-e)_L}}{C^{\rm SM}_{b_L\mu_L}}$$

- Deviation from the Standard Model, using only the most cleaner observable gives $\sim 4\sigma$
- New Physics in muons wants destructive interference with the SM
- New Physics in electrons is possible, but cannot explain angular observables and low branching ratios….

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

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]

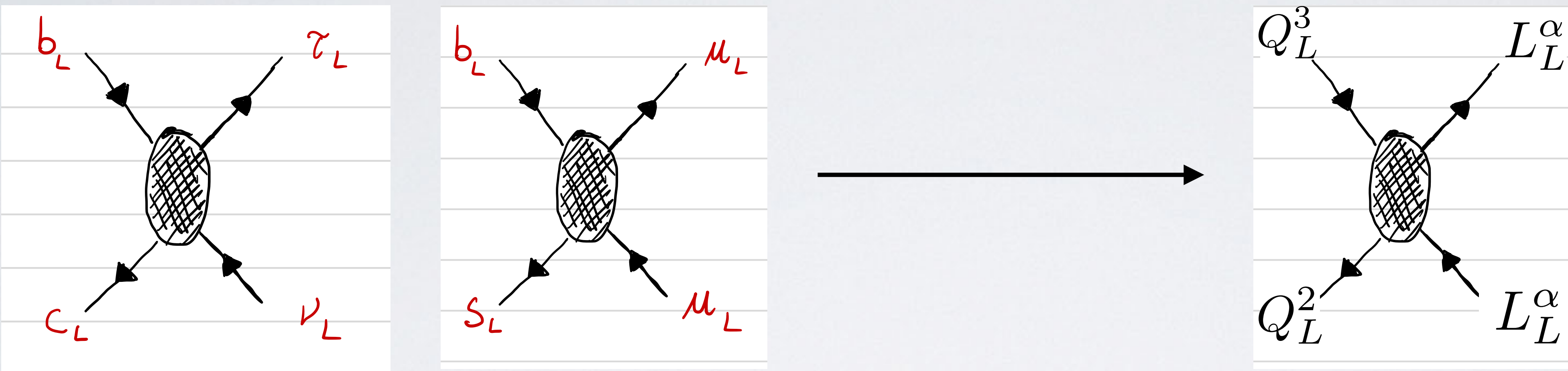
- Can be a sanity check of the measurement
- Having a large effect here requires light long range New Physics

[see for example 1711.07494]

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?

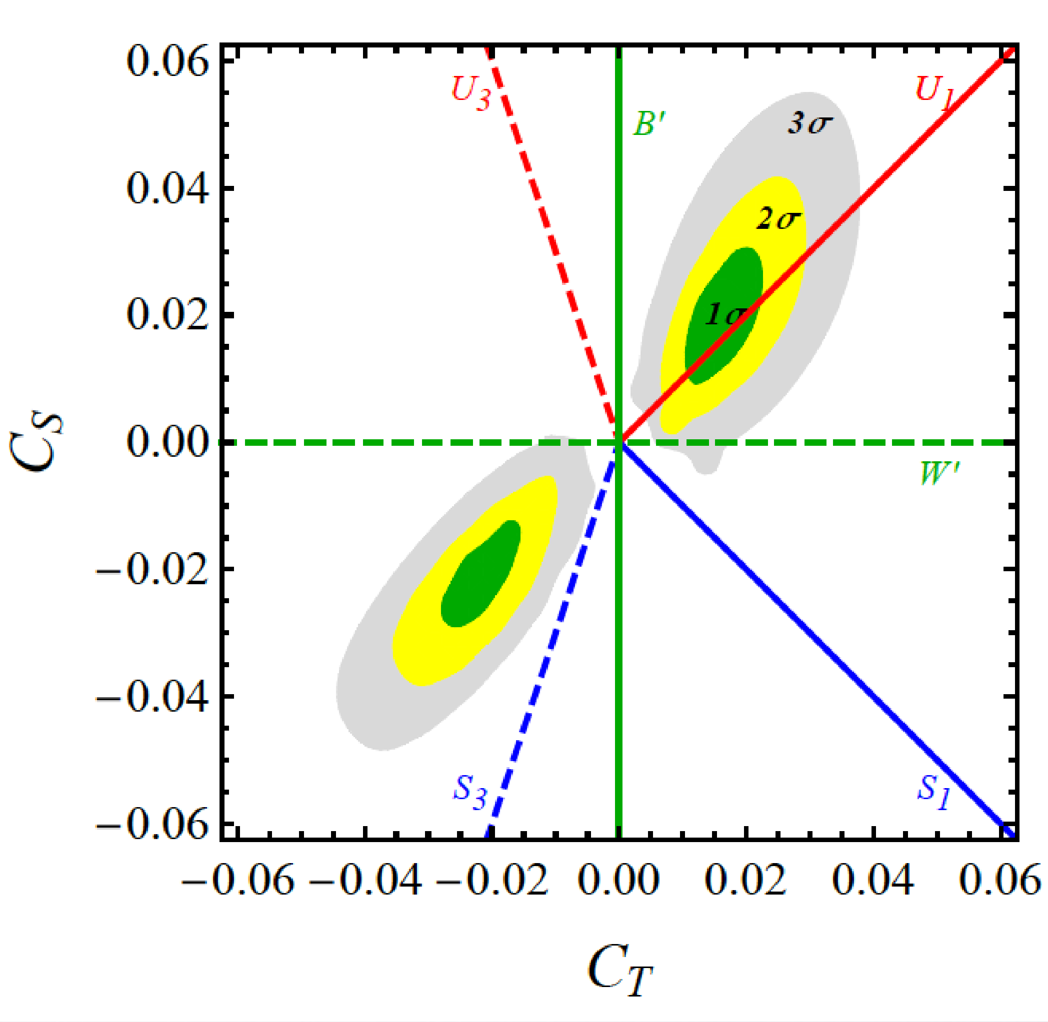
$$|C^{\rm NP}_\tau| \gg |C^{\rm NP}_\mu| \gg |C^{\rm NP}_e|$$

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

- 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

The Vector Leptoquark

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 are dominated by the phenomenology of the extra states that emerge with the leptoquark.

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

Spin one particle → Gauge bosons [L. Di Luzio, A. Greljo, MN, 1708.08450 Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368]

[Since August:
1708.06350
1709.00692
1801.07256
1802.04274
+ in progress..]

New Physics (Model Independent)

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

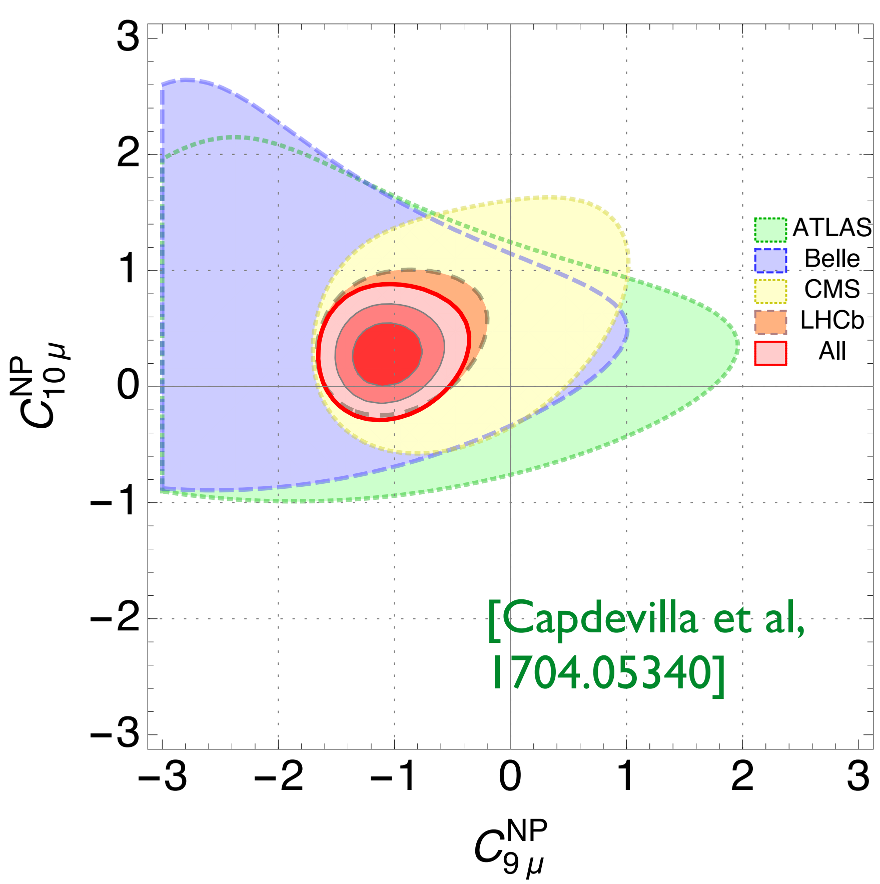
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\,(V_{ts}^* V_{tb})\,\sum_i C_i^\ell(\mu)\,\mathcal{O}_i^\ell(\mu)$$

$$\mathcal{O}_7^{(\prime)} = \frac{e}{16\pi^2}\, m_b\,\left(\bar{s}\sigma_{\alpha\beta}P_{R(L)}b\right)F^{\alpha\beta}\,,\qquad C_7^{SM} = -0.319,$$

$$\mathcal{O}_9^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi}\,\left(\bar{s}\gamma_\alpha P_{L(R)}b\right)\left(\bar{\ell}\gamma^\alpha\ell\right)\,,\qquad C_9^{SM} = 4.23,$$

$$\mathcal{O}_{10}^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi}\,\left(\bar{s}\gamma_\alpha P_{L(R)}b\right)\left(\bar{\ell}\gamma^\alpha\gamma_5\ell\right).\qquad C_{10}^{SM} = -4.41.$$

SM gives lepton flavour universal contribution



[Capdevilla et al, 1704.05340]

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

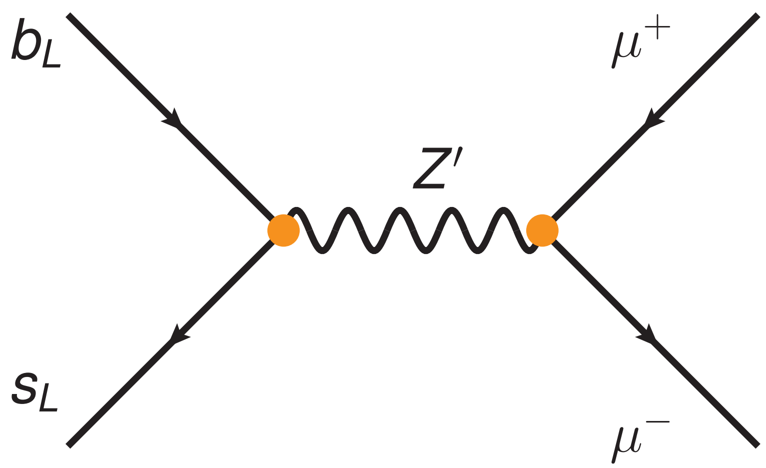
• Short distance effects from New Physics are expected to have a chiral structure

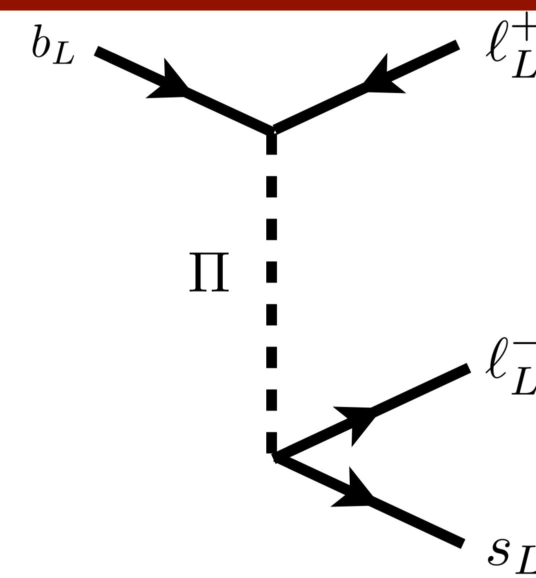
$$\begin{matrix}\bar{\ell}\gamma^\alpha\ell \\ \bar{\ell}\gamma^\alpha\gamma_5\ell\end{matrix} \longrightarrow \begin{matrix}\bar{\ell}_L\gamma^\alpha\ell_L \\ \bar{\ell}_R\gamma^\alpha\ell_R\end{matrix}$$

Best Fit with Left-Left currents

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

Simplified Models





[more than 100 papers]

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

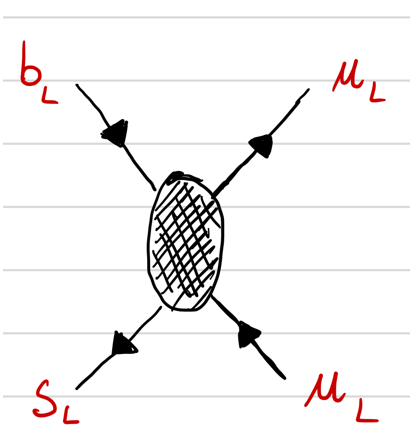
$$\frac{\lambda_{b\mu}\lambda_{s\mu}}{m_{\Pi}^2} \approx \frac{1}{(30\ \mathrm{TeV})^2}$$

- Main constraint to face is Bs mixing:
  - Z' way out: $\Delta_{bs} \ll \Delta_{\mu\mu}$
  - Leptoquark way out: tree VS loop

- Direct searches: need more theoretical input

- (Worst case scenario)

[Di Luzio, MN, 1706.01868]



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

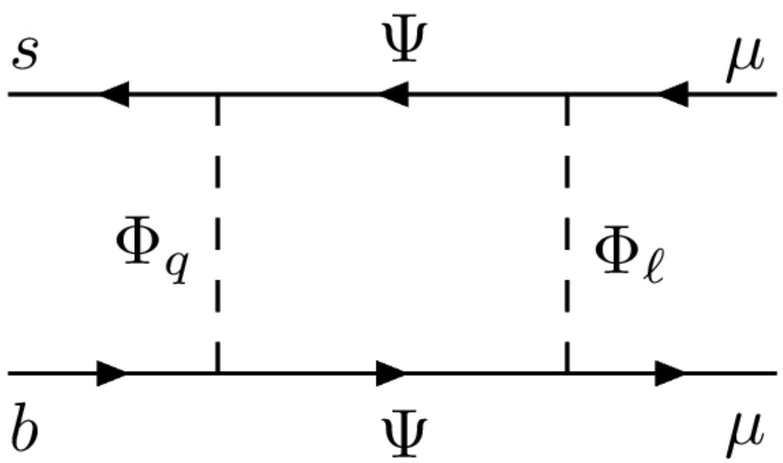
Tree-Level Pertubative Unitarity criterium

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

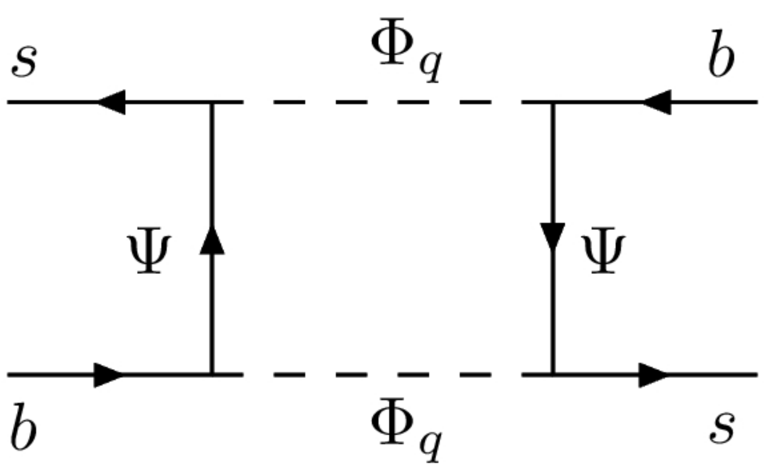
$$\begin{cases} \sqrt{s}_{max} \equiv \Lambda_U = 9\ \mathrm{TeV} & b \to c\tau\nu \\ \sqrt{s}_{max} \equiv \Lambda_U = 80\ \mathrm{TeV} & b \to s\mu\mu \end{cases}$$

Loop induced

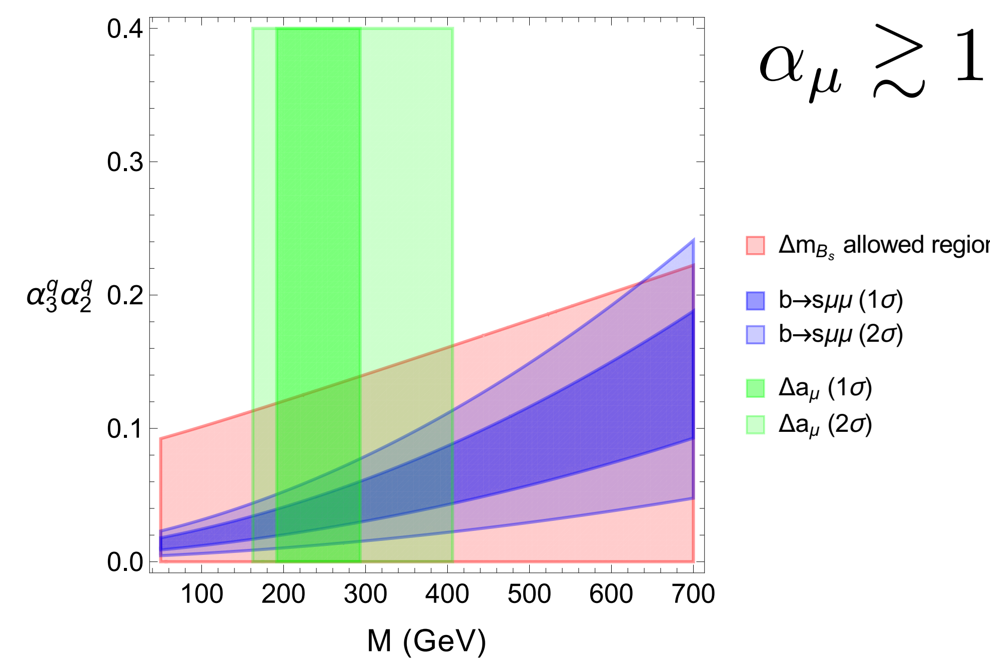
[Gripaios, MN, Renner 1509.05020
see also 1608.07832]



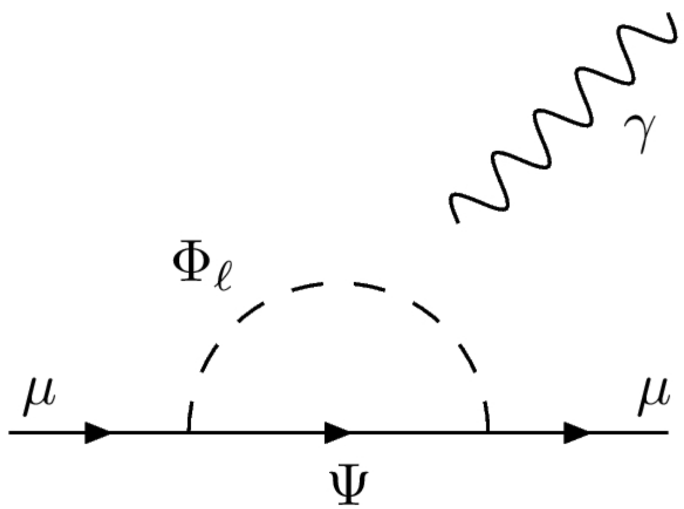
$$\alpha_i^q\,\overline{\Psi}Q_L^i\Phi_q + \alpha_i^\ell\,\overline{\Psi}L_L^i\Phi_\ell + \text{h.c.}$$



- Main constraint



$$\alpha_\mu \gtrsim 1$$



- muon g-2, large leptonic coupling

- Direct searches are important