What is the scale of New Physics? Status and prospects (at LHCb)

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21 March 2018, 3rd Workshop on LHCb Upgrade II, Annecy

Outline

- New Physics enters any physics topic relevant for the upgrade…

- Here I will restrict to

  - Standard Model and the Higgs

    $$H \to \bar{c}c$$

  - New Physics

    1) Theoretical Aspects
    2) The Flavour anomalies

  - Extra topics and conclusions

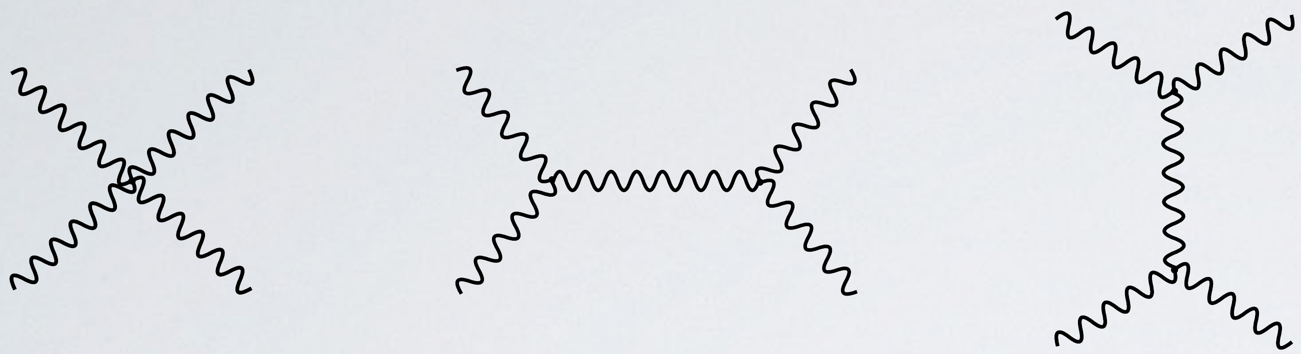
- For a more extensive (and deeper) introduction: LHCb Phase-2 upgrade: a clear case, Z. Ligeti

  https://agenda.infn.it/getFile.py/access?contribId=2&sessionId=0&resId=0&materialId=slides&confId=12253

SM and the Higgs

The Higgs at LHC

- A no-lose theorem for the LHC:



$$a_0(W_L^+ W_L^- \to W_L^+ W_L^-) \simeq \frac{1}{32\pi} \frac{s}{v^2}$$

$$\sqrt{s} \approx \Lambda = 4\pi v \simeq 3\,\mathrm{TeV}$$

Within the reach of LHC energy!

- It seems that Nature prefers the minimal solution: the SM Higgs boson

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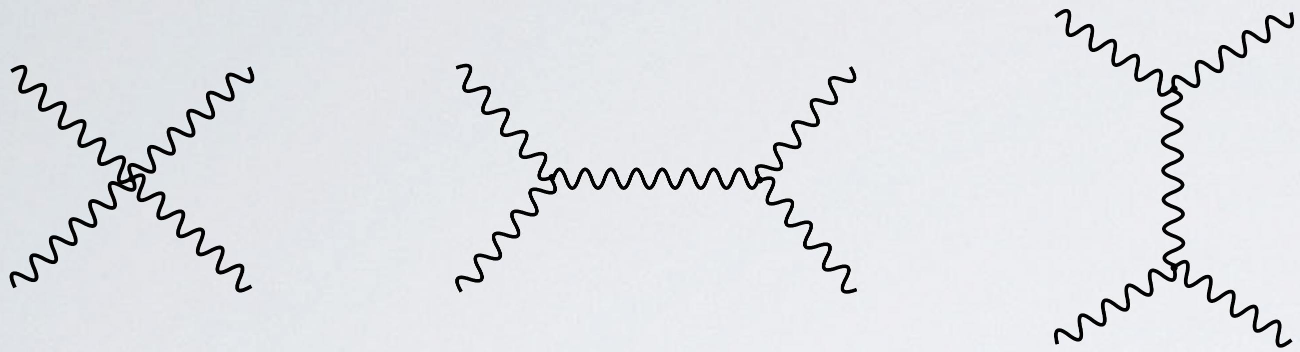

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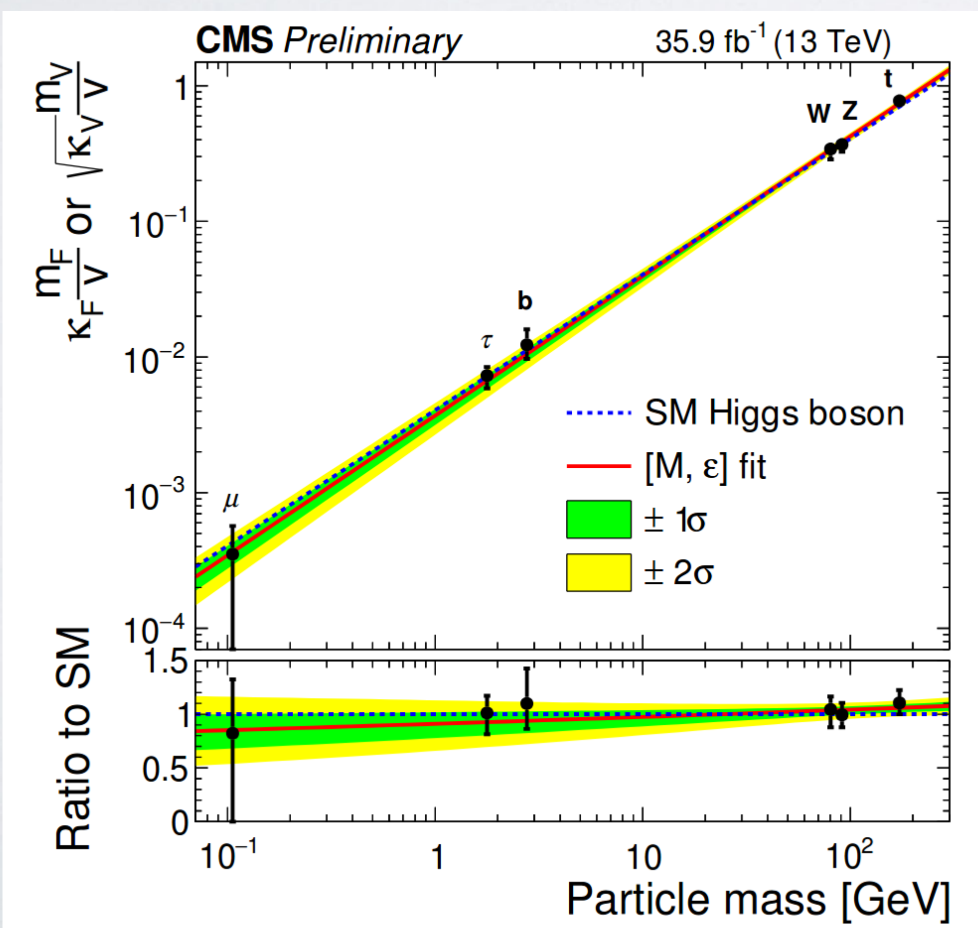
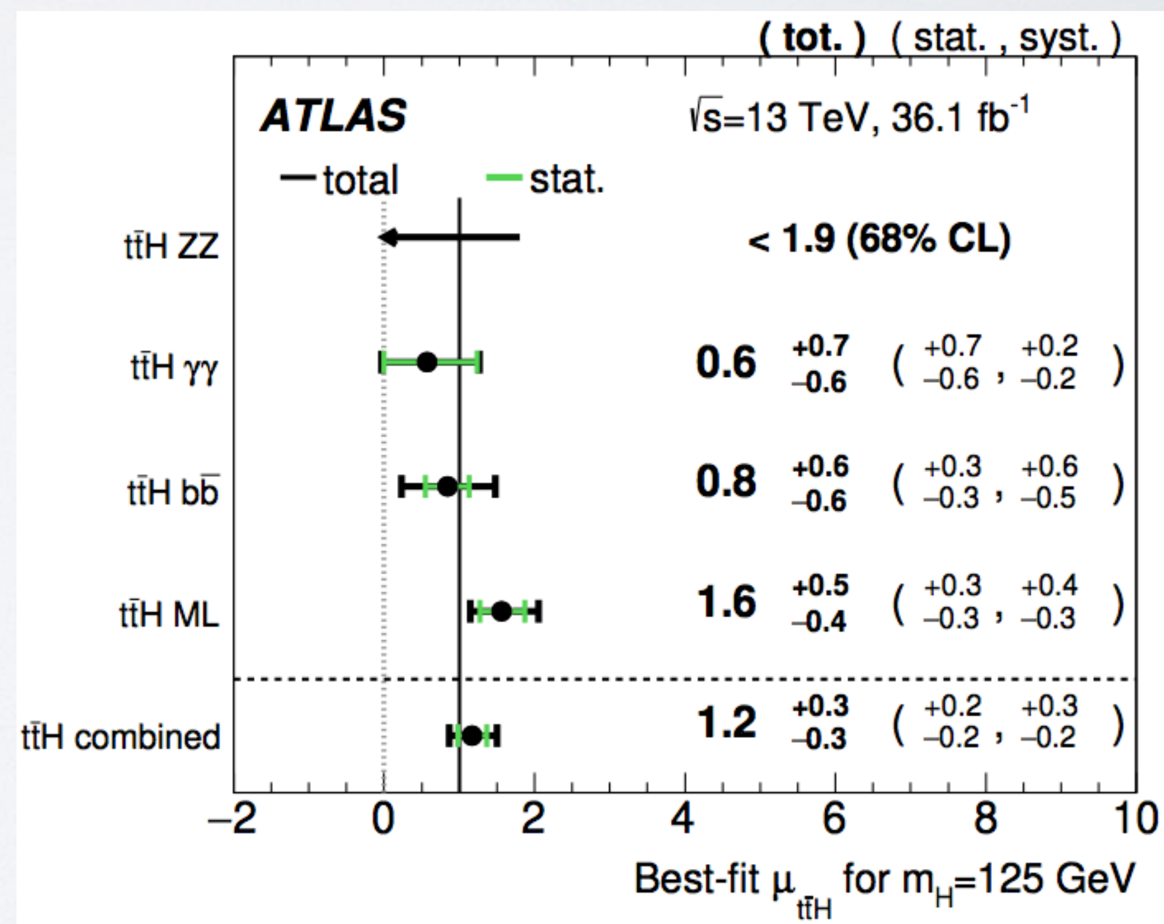
- Growing evidence of SM-like couplings of the Higgs with the third family of fermions

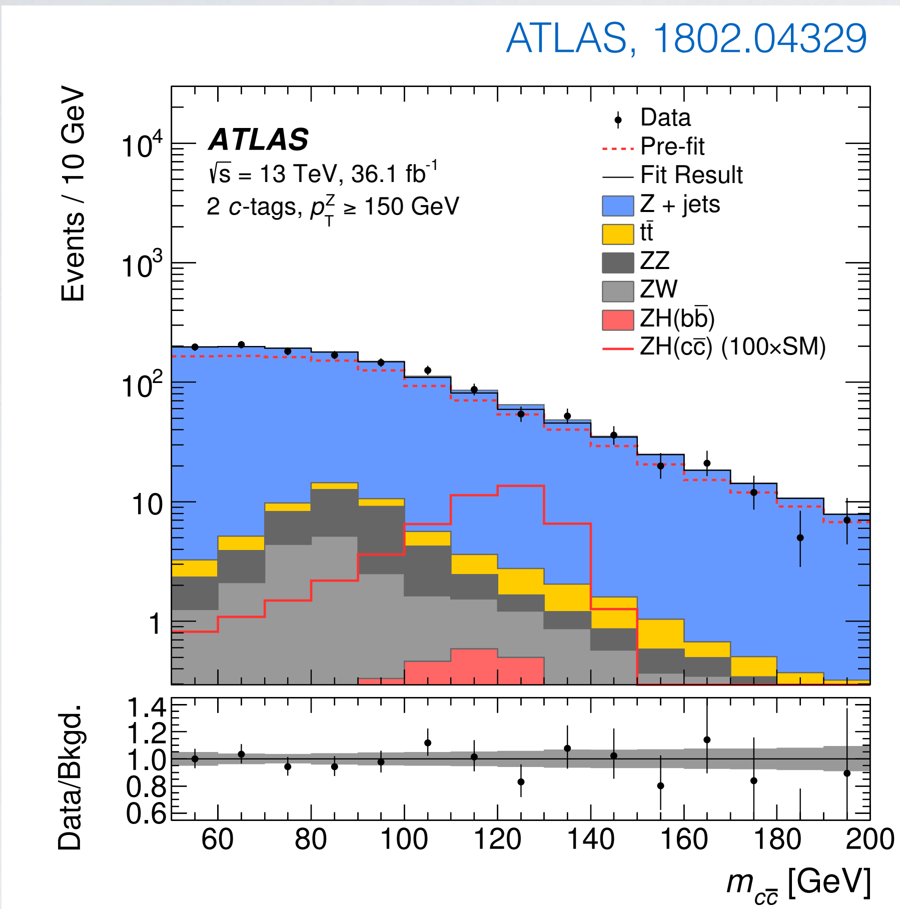
[Moriond EW 2018]

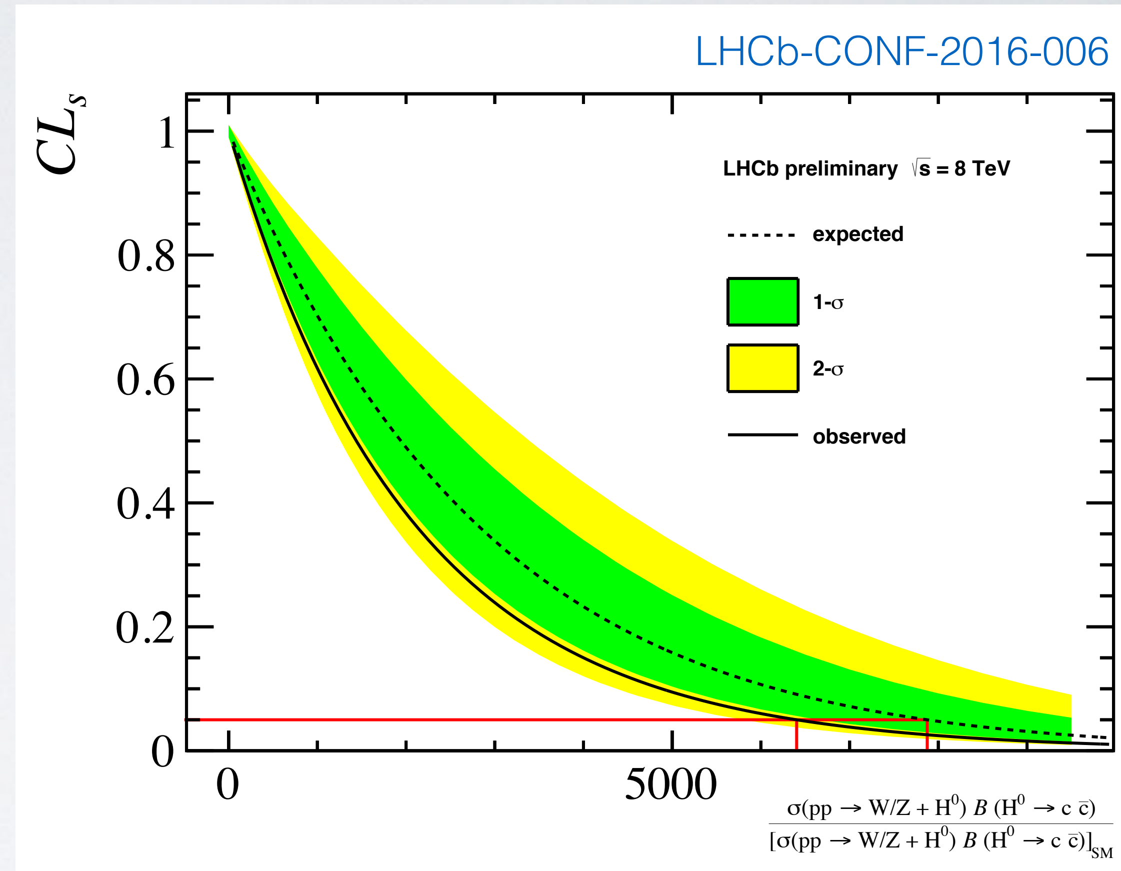




The Higgs at LHCb

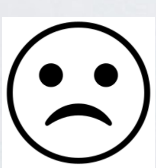
- LHCb might play an important role for the study of the Higgs with the second generation





$$\mu_{cc} < 110 \qquad |k_c| < 10$$

$$\mu_{cc} < 6400 \qquad |k_c| < 80$$

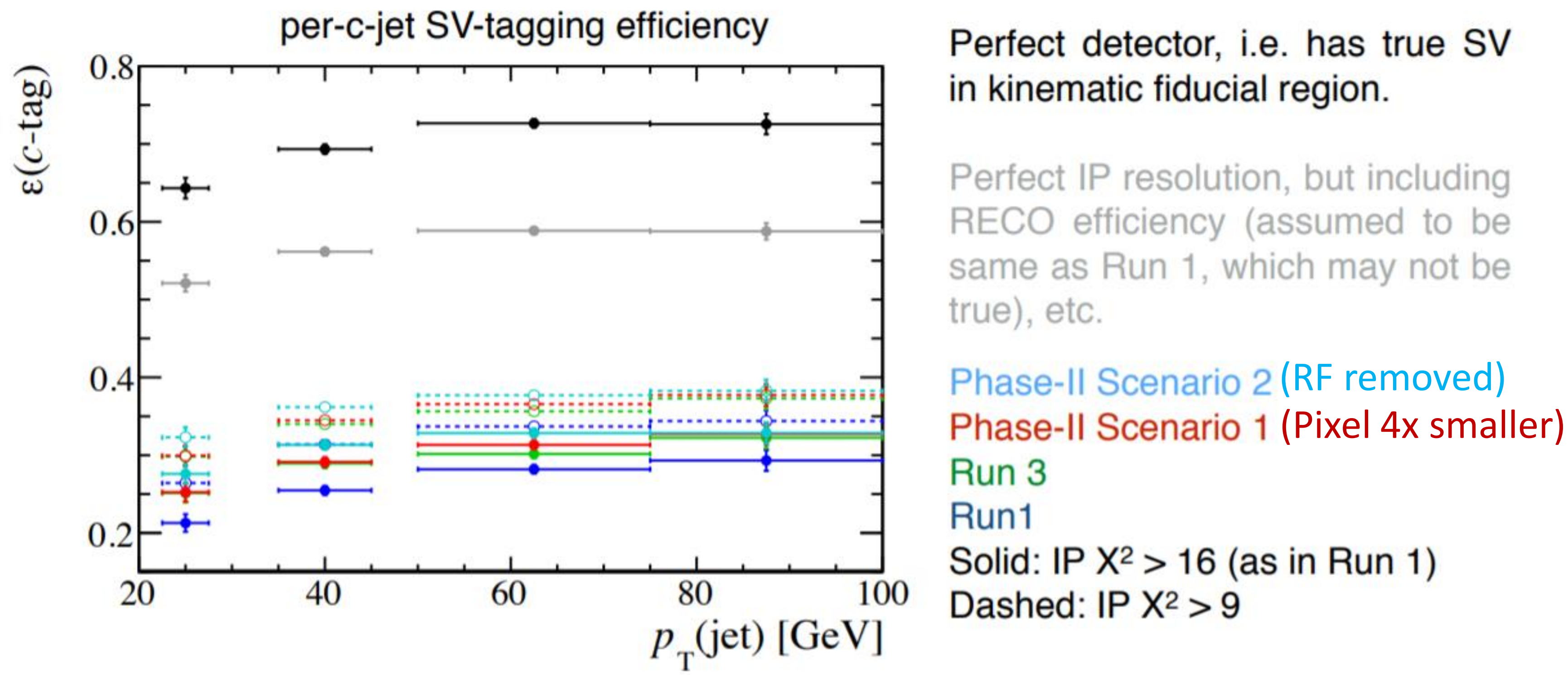


- Lower luminosity and reduced acceptance

- Unique c-tagging capability

Prospects: H→ $c\bar{c}$ @ LHCb

The c-tagging efficiency will be better in the Phase II due to improvements in the secondary vertex resolution



More information in the Flavour WG: session 4 - LHCb material reduction impact (G. M. Ciezarek)

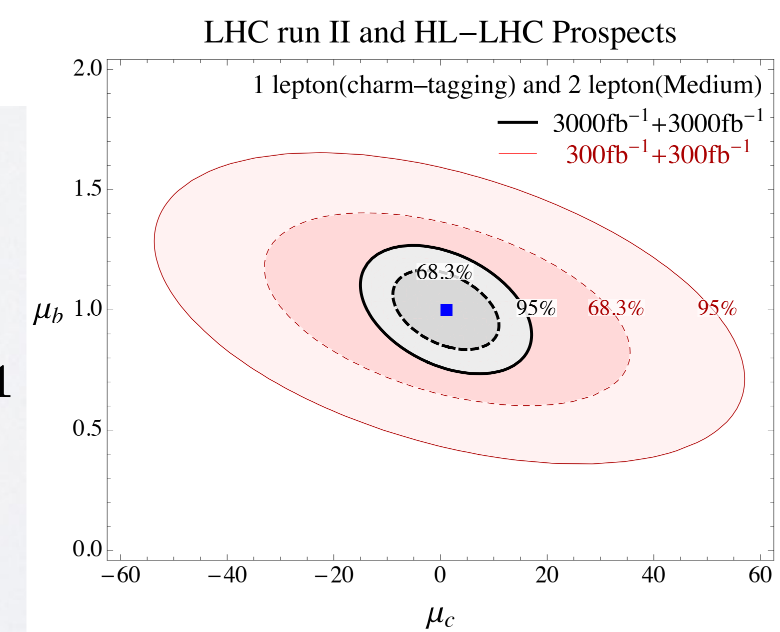
- Considering the improvements in the c-jet tagging and the detector Phase-II, the limit in the branching ratio can be pushed down to 5-10 × BR(SM)

- Prospects: ATLAS+CMS

[From Perez, et al. arXiv:1503.00290]

$$\Delta\mu_c = \begin{cases} 23\,(45) & \text{with } 2\times 300\ \text{fb}^{-1} \\ 6.5\,(13) & \text{with } 2\times 3000\ \text{fb}^{-1} \end{cases}$$

$$68\,(95)\%\ \text{CL}$$



Strong and EW interactions at LHCb

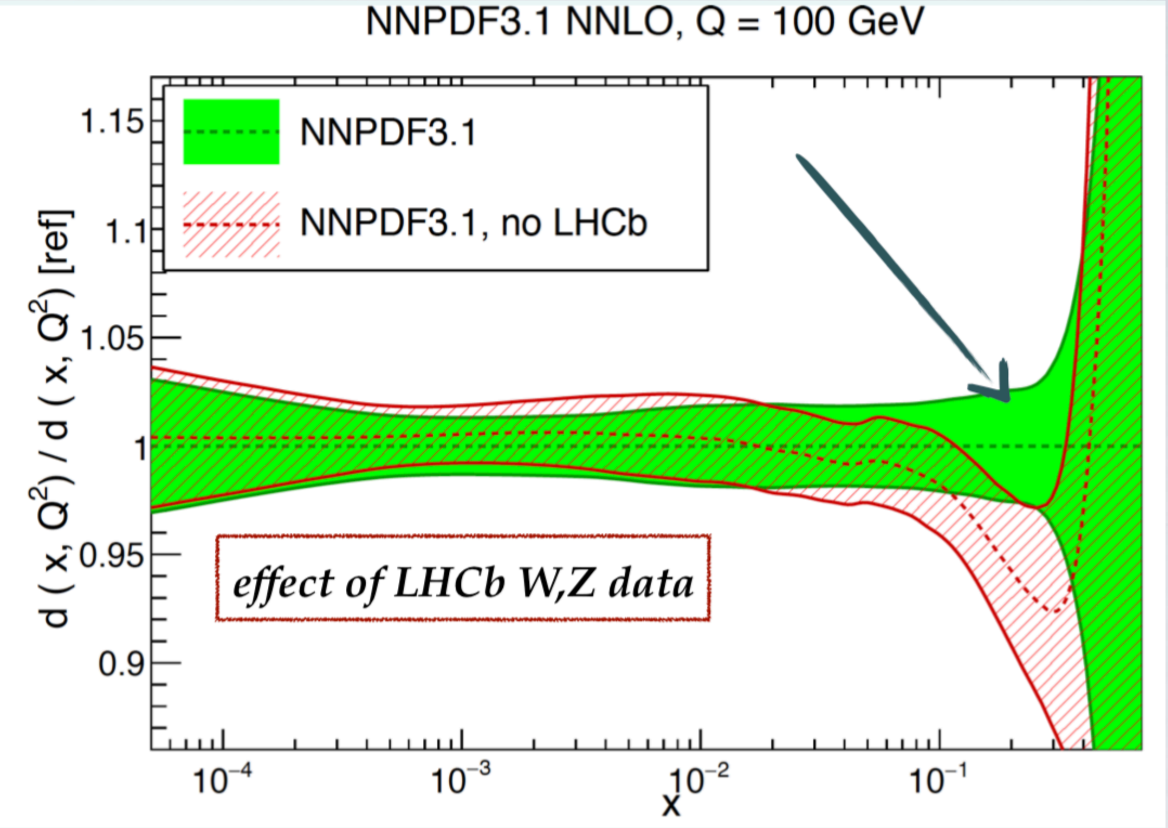
• PDF are an important input for almost any BSM search, unique kinematical region at LHCb

- gluon @ small x from charm, bottom, top production

- light quarks @ large x from W and Z production

• A clear case for high precision at LHCb

[See next talk by S. Farry]



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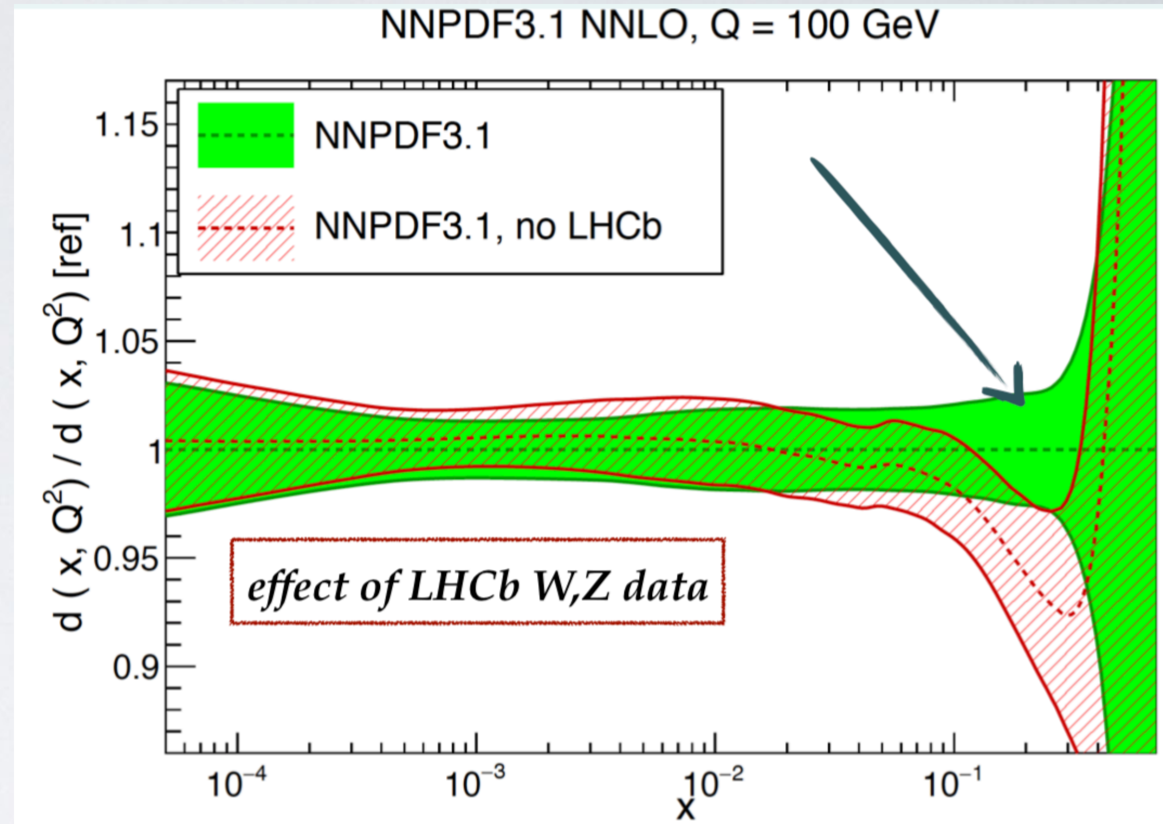


- gluon @ small x from charm, bottom, top production

- light quarks @ large x from W and Z production

- A clear case for high precision at LHCb

[See next talk by S. Farry]

- Understanding the strong interactions remains a crucial aspect (regardless of the possible NP)

1. **Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays**
(535) 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**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Interactions.org article; Link to BBC News article; Link to SYMMETRY;
Record dettagliato - Citato da 535 record 500+

2. **Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays**
(530) 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**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Record dettagliato - Citato da 530 record 500+

12. **Determination of the X(3872) meson quantum numbers**
(289) LHCb Collaboration (R Aaij (NIKHEF, Amsterdam) *et al.*). Feb 25, 2013. 8 pp.
Published in **Phys.Rev.Lett. 110 (2013) 222001**
LHCB-PAPER-2013-001, CERN-PH-EP-2013-017
DOI: 10.1103/PhysRevLett.110.222001
e-Print: **arXiv:1302.6269 [hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI.gov Server
Record dettagliato - Citato da 289 record 250+

15. **Observation of the resonant character of the $Z(4430)^-$ state**
(267) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Apr 7, 2014. 9 pp.
Published in **Phys.Rev.Lett. 112 (2014) no.22, 222002**
LHCB-PAPER-2014-014, CERN-PH-EP-2014-061
DOI: 10.1103/PhysRevLett.112.222002
e-Print: **arXiv:1404.1903 [hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Interactions.org article; Link to SYMMETRY
Record dettagliato - Citato da 267 record 250+

[See talk on spectroscopy by A. Polosa]

New Physics

What is the scale of NP?

- SM is very successful in describing physics up to the EW scale
- SM is not a complete theory (neutrino masses, dark matter, baryon asymmetry)

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

- Big question is Λ?

- Unfortunately, no unique indication from observed BSM physics

1. Neutrino masses, from Dirac neutrino to GUT see-saw

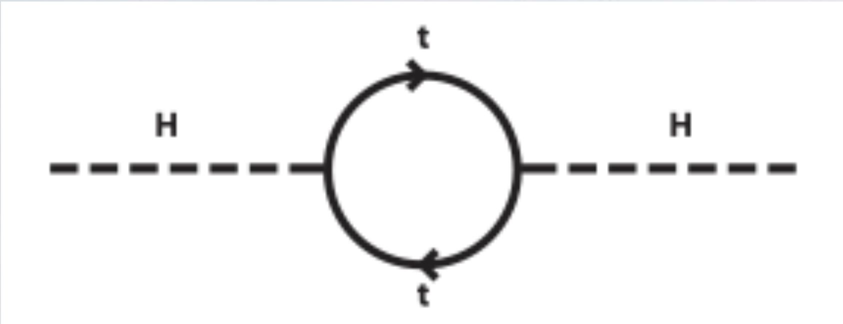
2. Dark Matter, from axions to Wimpzillas

3. Baryon asymmetry, from EW baryogenesis to GUT baryogenesis

- However we have some indications….

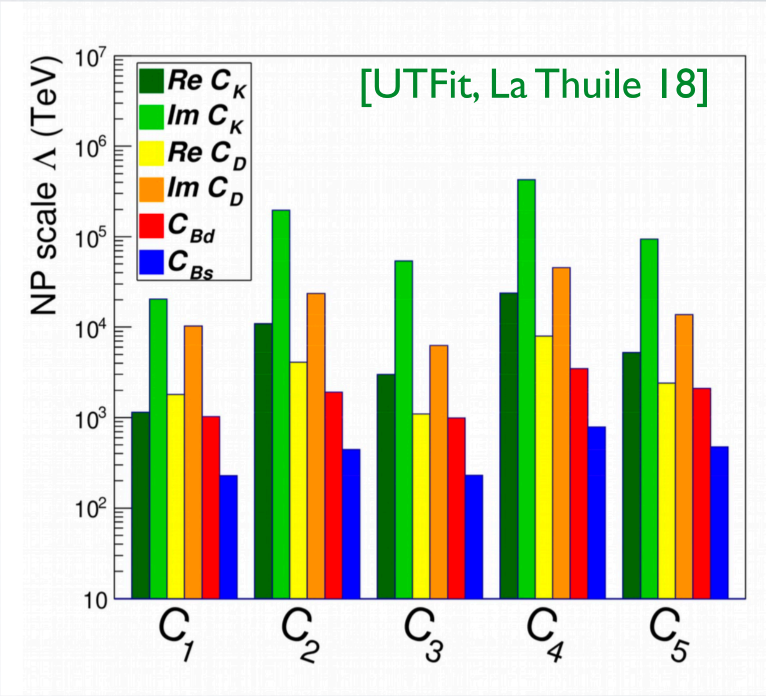
Pre-LHC prejudice VS data

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



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

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



- Lower bounds from FCNC

$$\Lambda > \begin{cases} 1.3 \times 10^4\ \mathrm{TeV} \times |c_{sd}|^{1/2} \\ 5.1 \times 10^2\ \mathrm{TeV} \times |c_{bd}|^{1/2} \\ 1.1 \times 10^2\ \mathrm{TeV} \times |c_{bs}|^{1/2} \end{cases}$$

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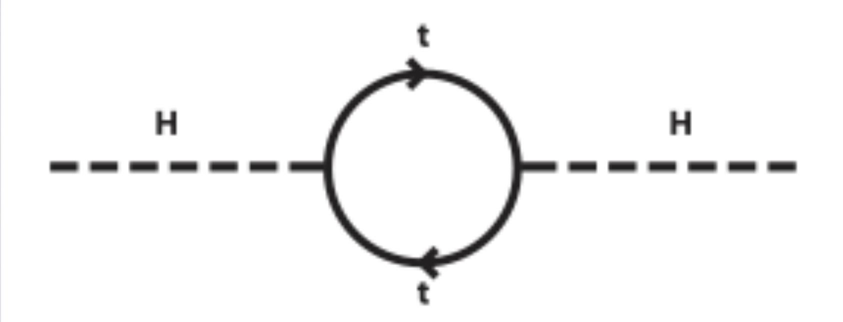

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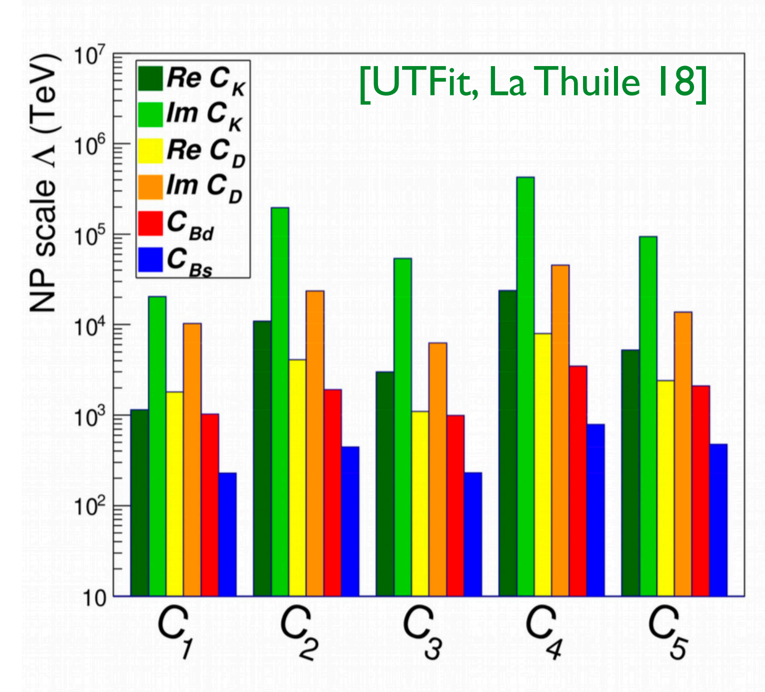

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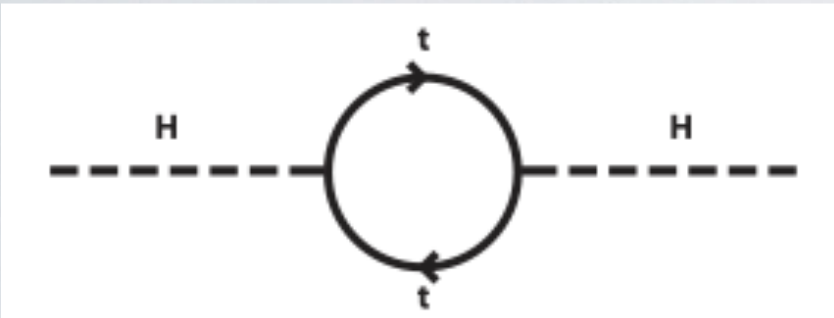
• Two (problematic) possibilities:

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

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

Pre-LHC prejudice VS data

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



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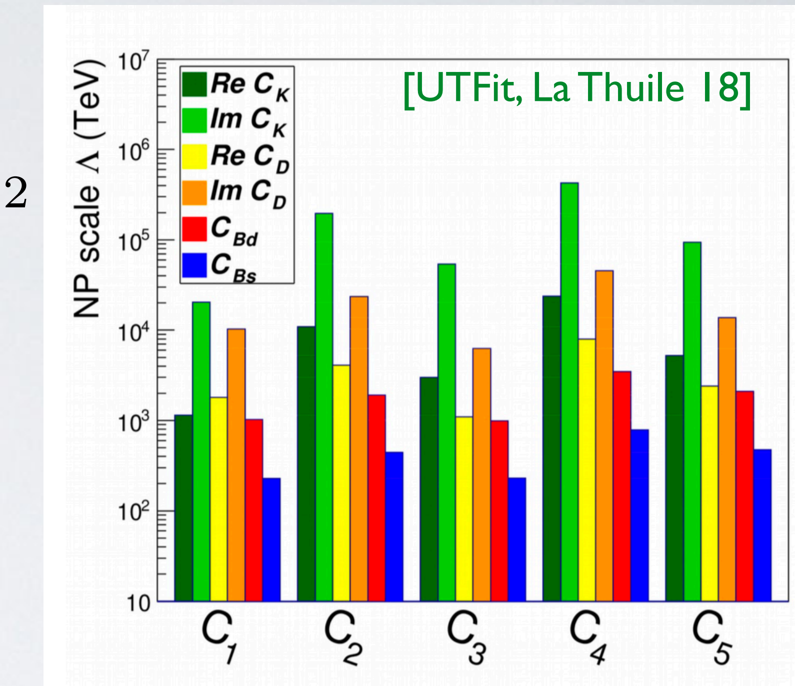

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- "Standard" solution to (ii): exciting NP at ATLAS-CMS, boring flavour physics at LHCb protected by MFV

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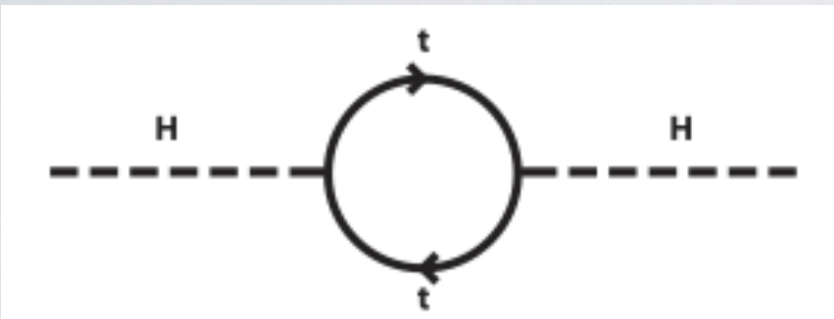

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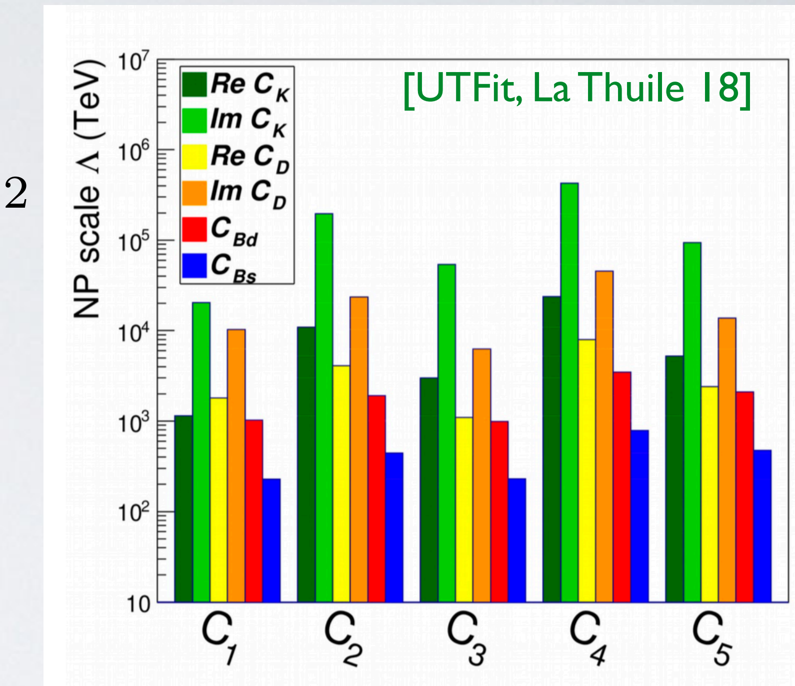

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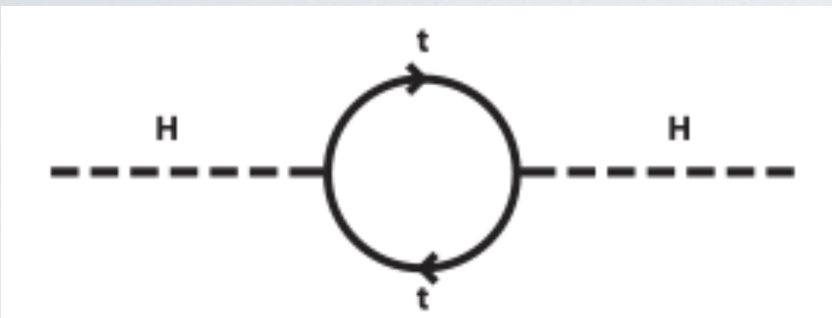
• "Standard" solution to (ii): exciting NP at ATLAS-CMS, boring flavour physics at LHCb protected by MFV

• However data are suggesting the opposite…. no on-shell effects but very interesting series of flavour anomalies….

Is Nature ‘natural’?

- A theoretical argument for New Physics the LHC:
- Upper bound from naturalness of the Higgs mass $\Lambda < 1\ \mathrm{TeV}$



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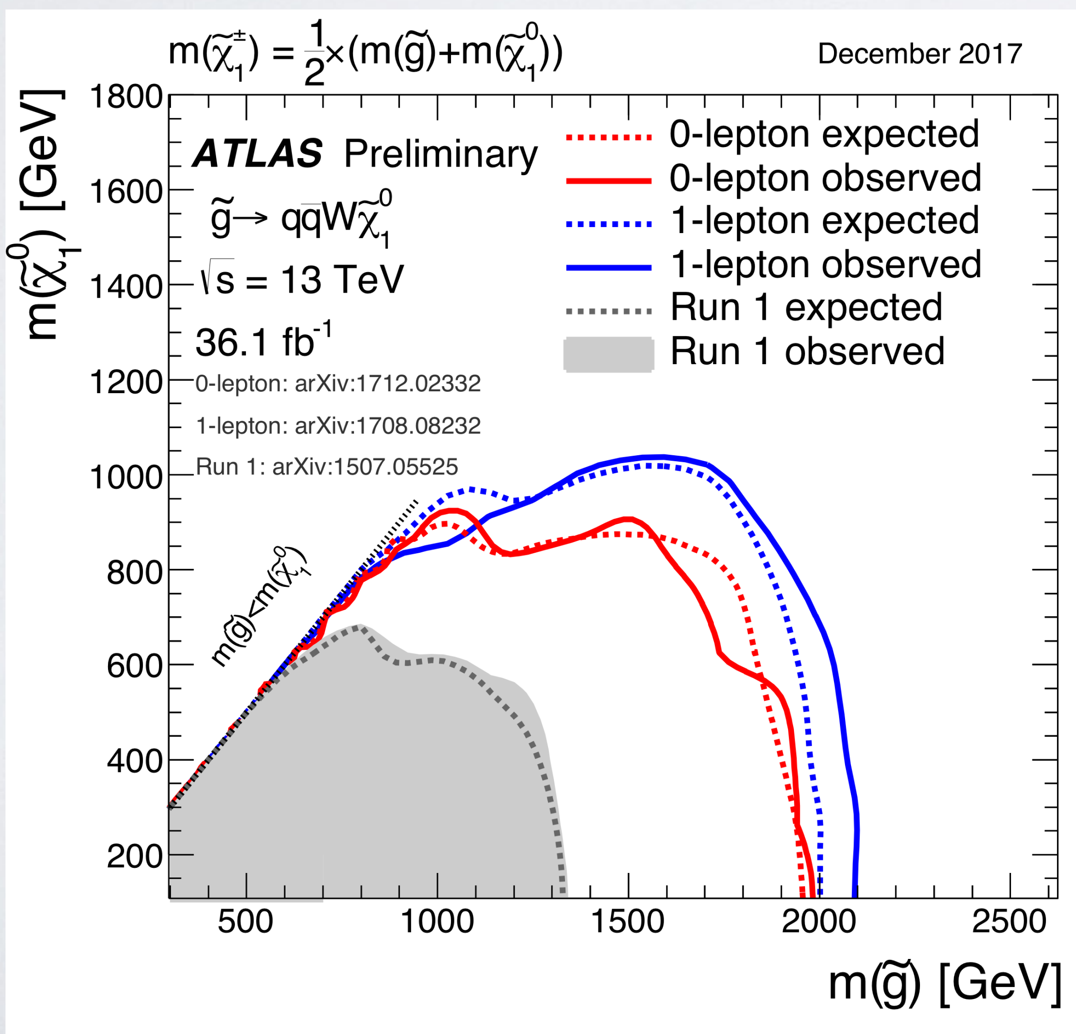
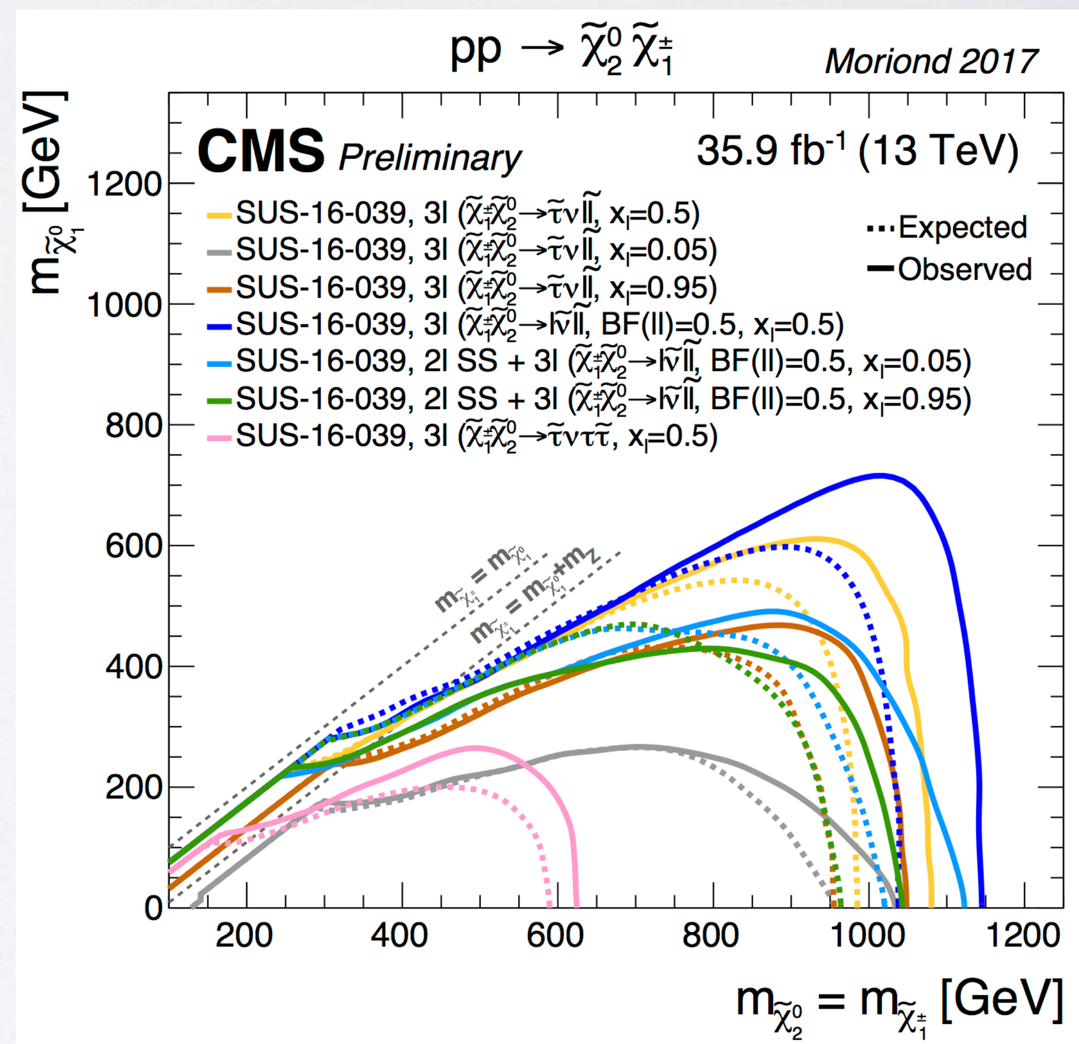
Main Solutions:

1) Supersymmetry
2) Composite Higgs

- But..





Flavour Anomalies

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

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

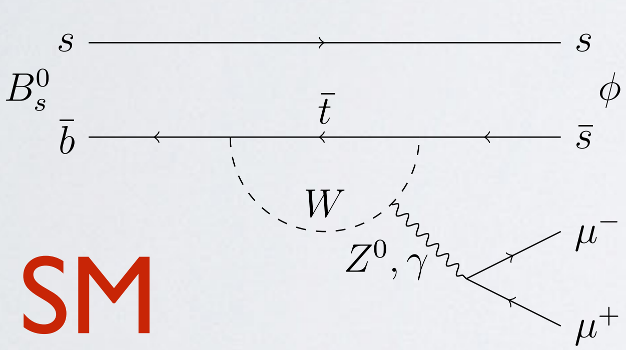
2) Branching ratios $\gtrsim 3.5\sigma$ (?!)

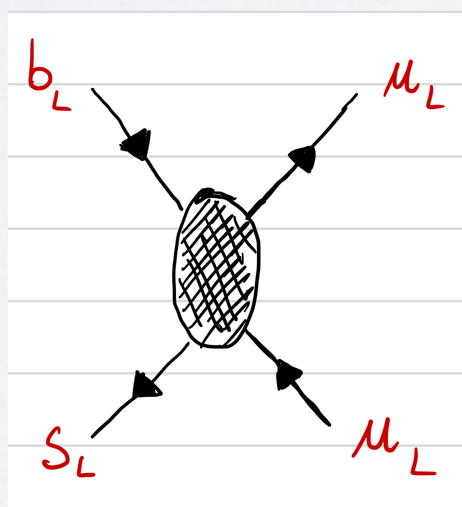
3) LFU violation in R_K 2.6σ

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

"clean" only $\approx 4\sigma$

SM

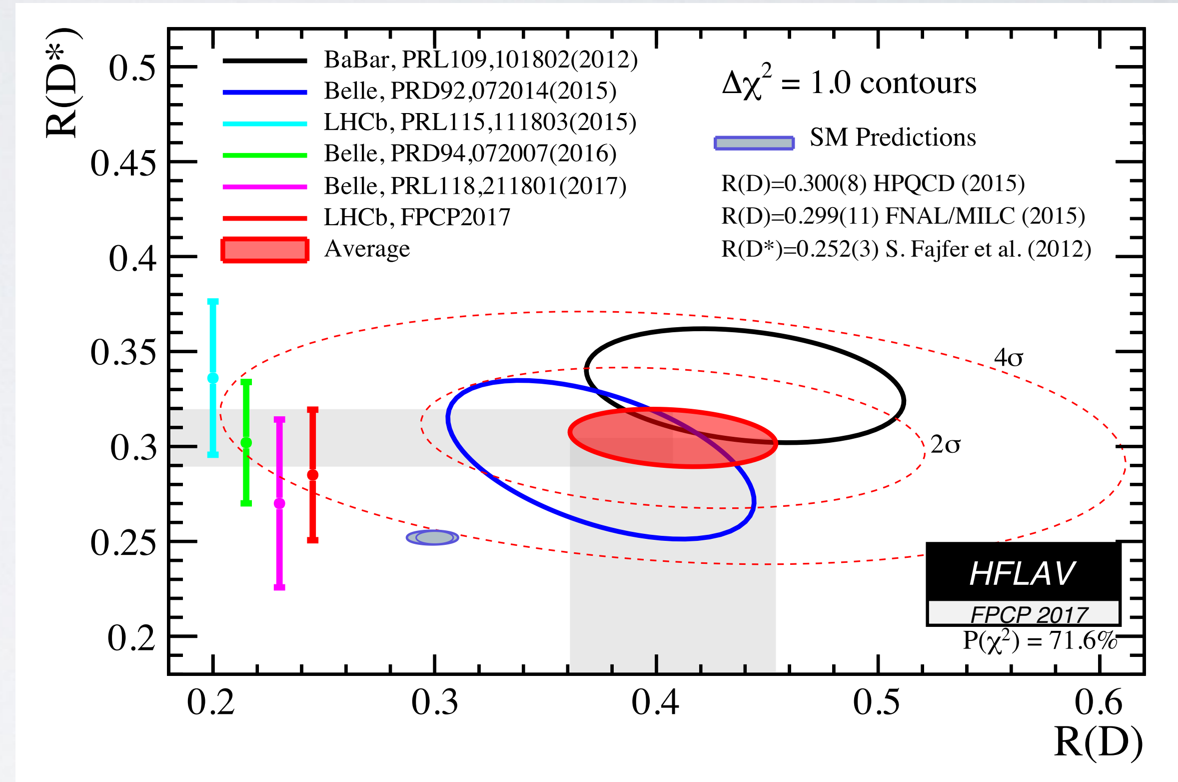


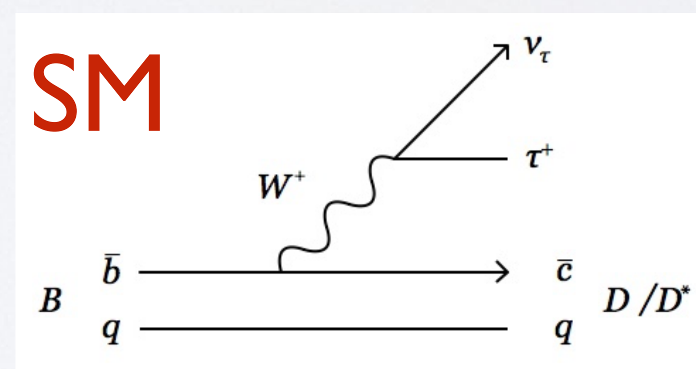


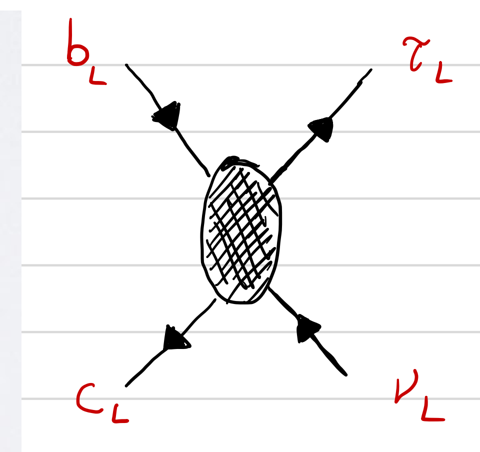
$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2_{R_K}} \bar{s}_L \gamma^\mu b_L \, \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

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

- *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

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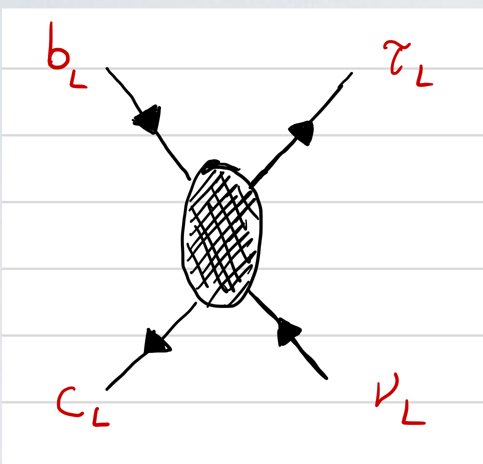
- *What do we expect?* (Worst case scenario)



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

Tree-Level Pertubative
Unitarity criterium

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

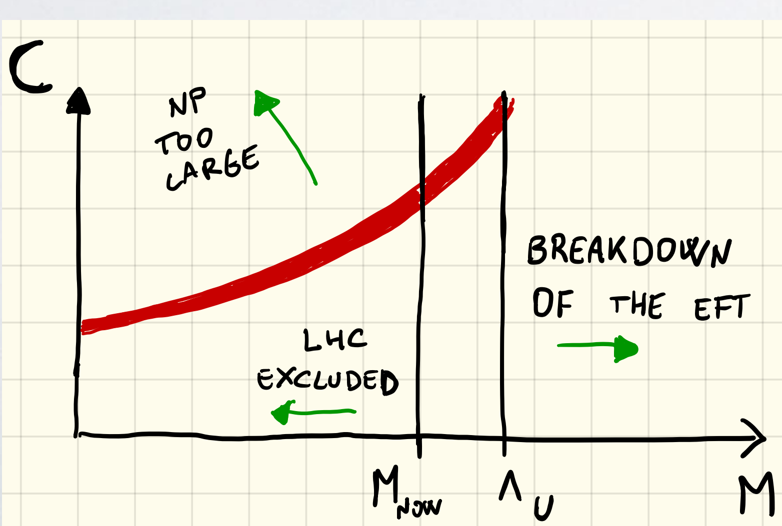
[Di Luzio, MN, 1706.01868]

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

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

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

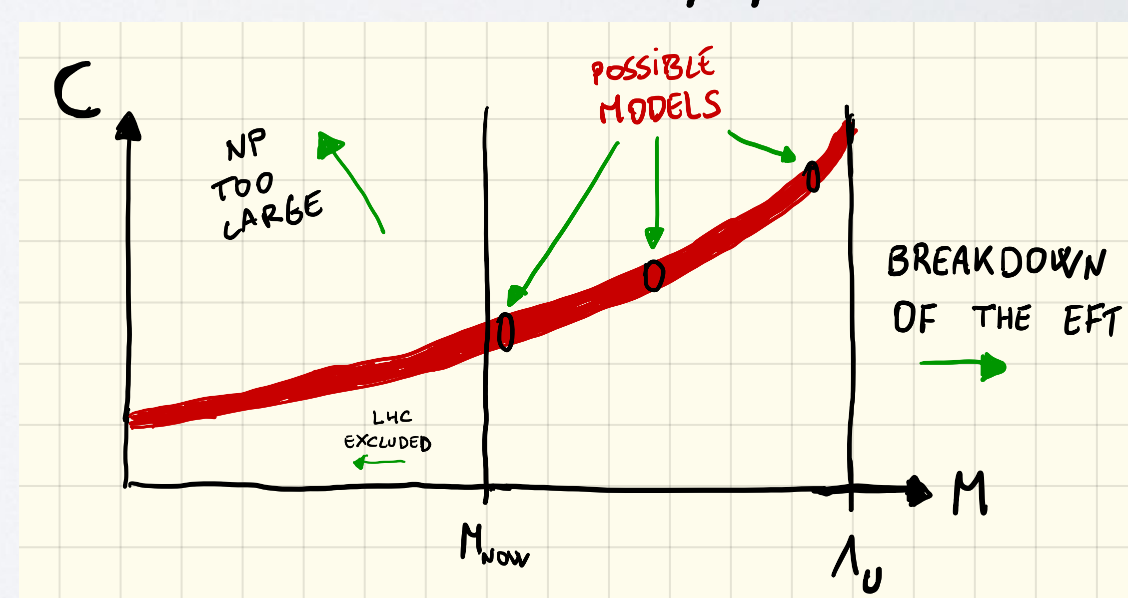
$$b \to c\tau\nu$$



Absence of New Physics
at high energy

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

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



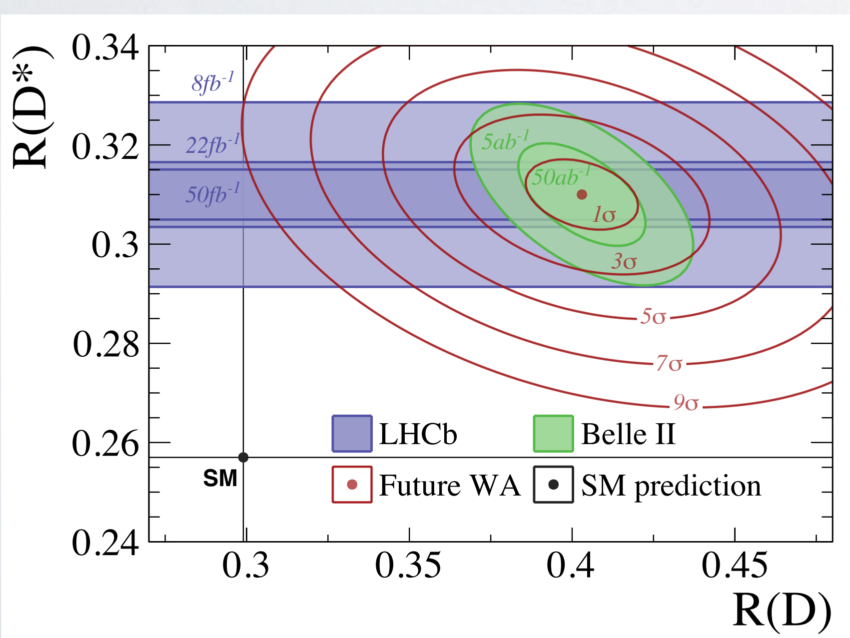
Prospects

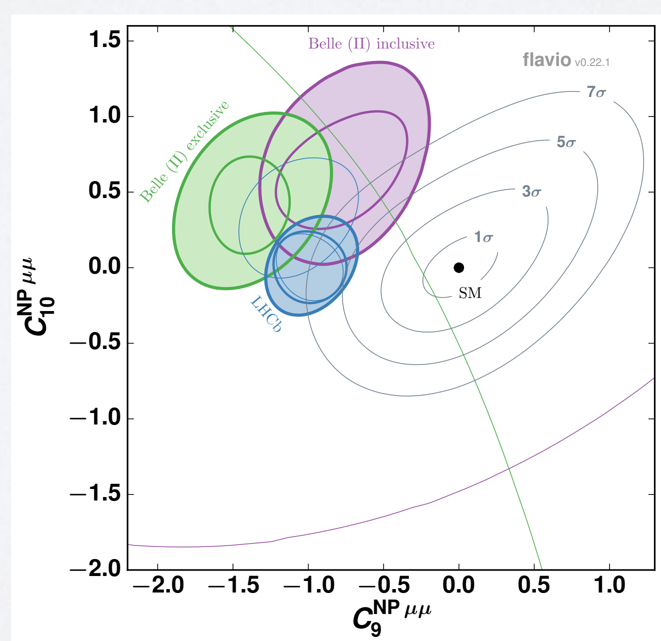
[Albrecht, Bernlochner, Kenzie, Reichert, Straub, Tully, arXiV:1709.10308]

		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	-

- 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%





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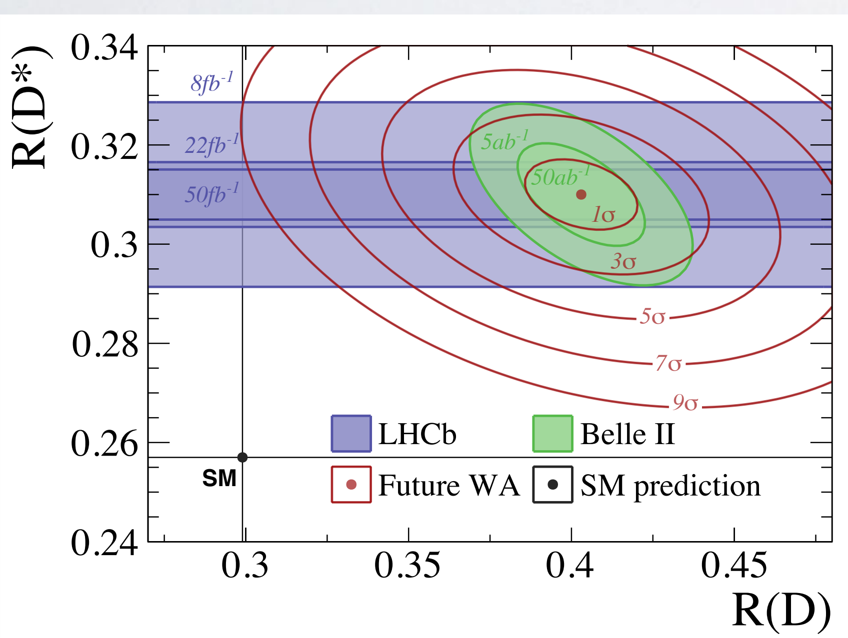
	$n(B\bar{B})$	0.1×10^{10}	0.54×10^{10}	5.4×10^{10}	-
	$\sqrt{s}$	10.58 GeV	10.58 GeV	10.58 GeV	-

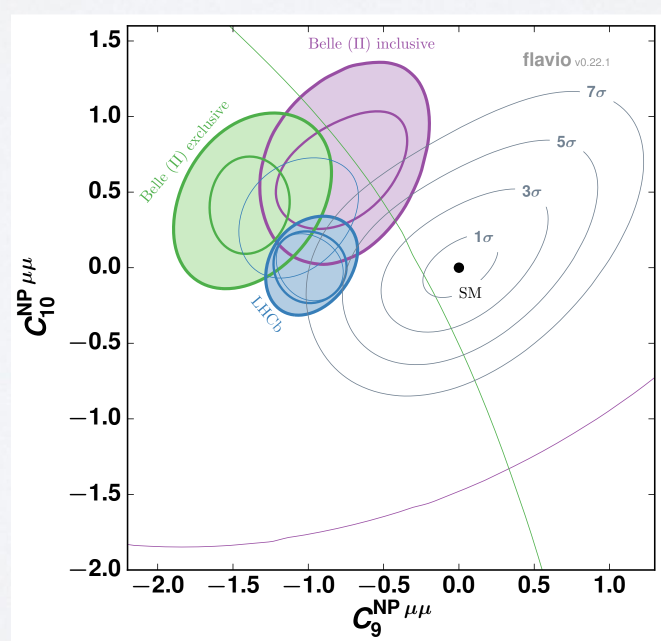
[Albrecht, Bernlochner, Kenzie, Reichert, Straub, Tully, arXiV:1709.10308]

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%

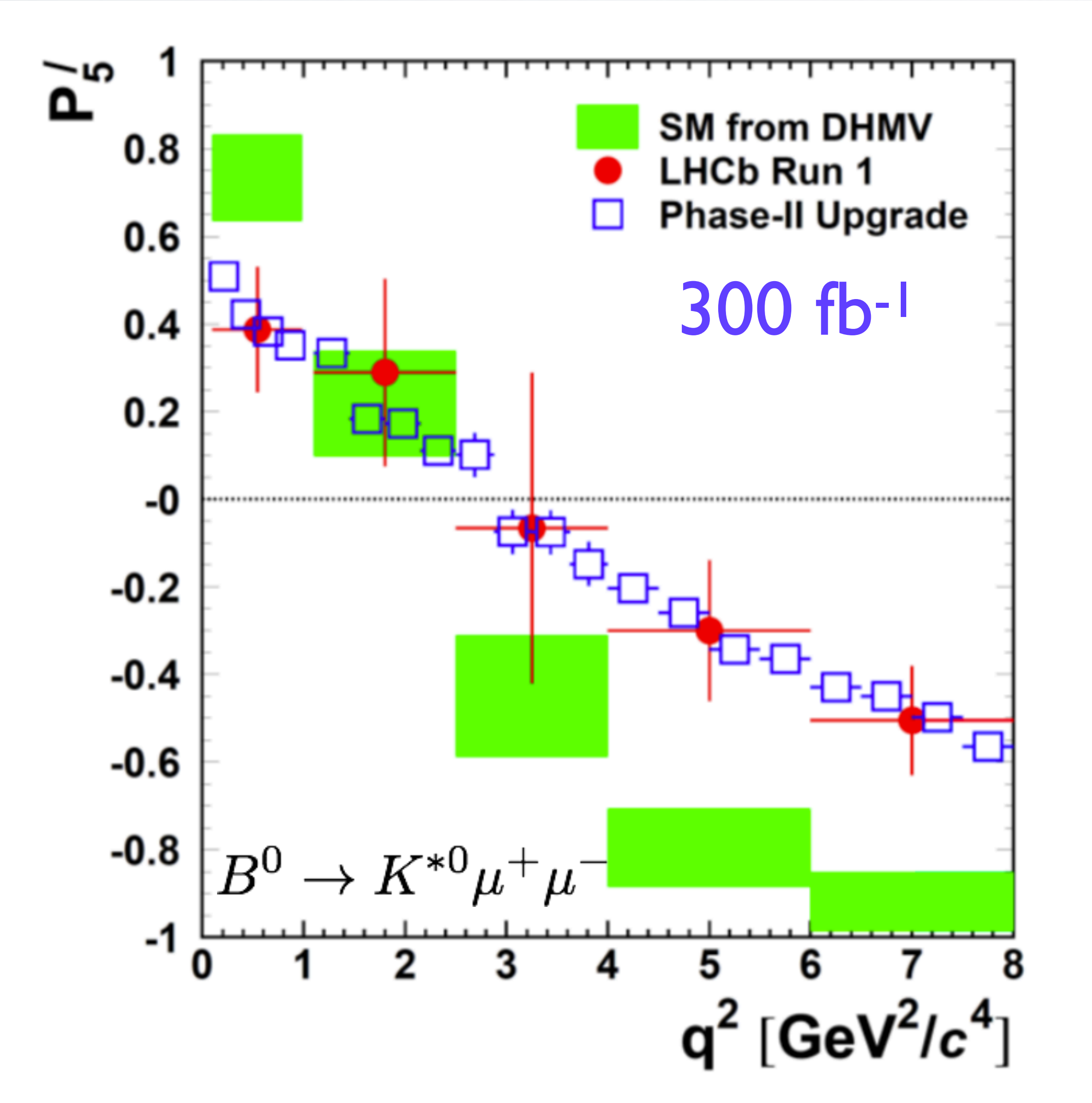




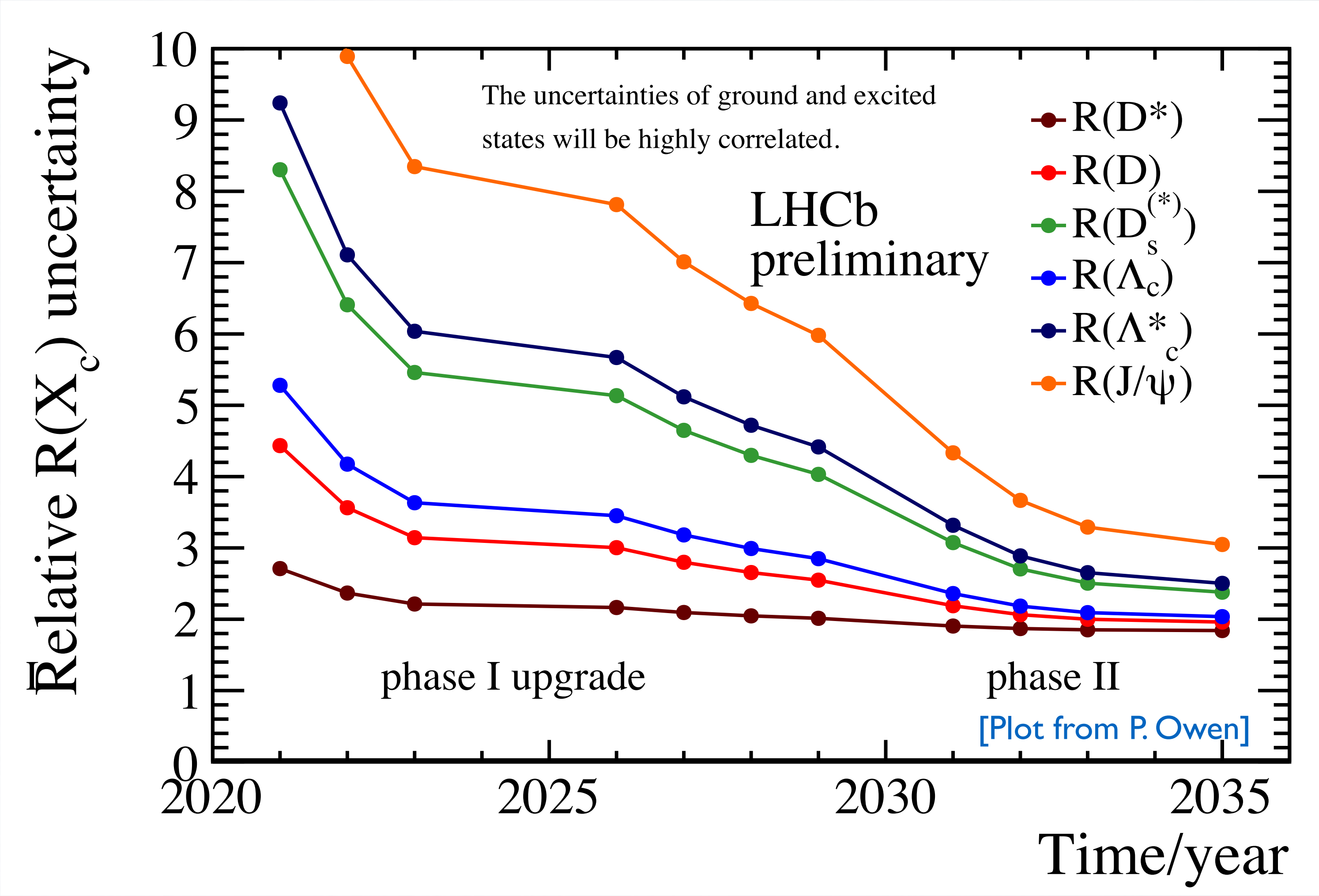
- Confirming/disproving the anomalies is not physics for Phase-II Upgrade!!

- (An answer from Run 2? We are really looking forward to…)

Prospects



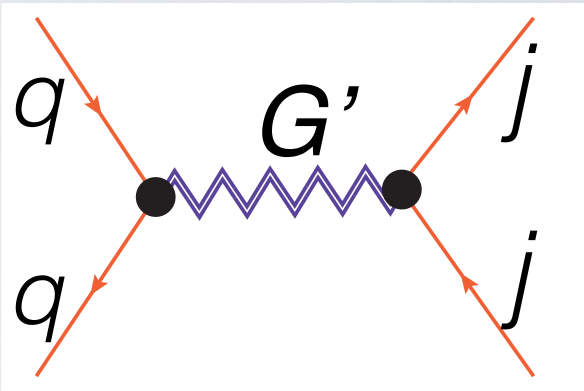
P_5'
SM from DHMV
LHCb Run 1
Phase-II Upgrade
300 fb^{-1}
$B^0 \to K^{*0}\mu^+\mu^-$
q^2 [GeV^2/c^4]



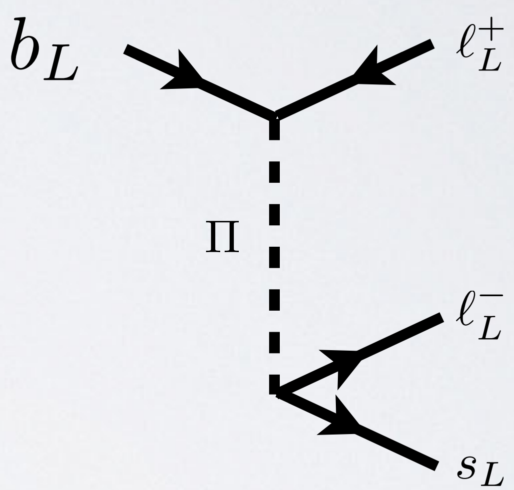
Relative R(X_c) uncertainty
The uncertainties of ground and excited states will be highly correlated.
LHCb preliminary
R(D*)
R(D)
R($D_s^{(*)}$)
R(Λ_c)
R(Λ^*_c)
R(J/ψ)
phase I upgrade
phase II
[Plot from P. Owen]
Time/year

Bottom-up path

Theoretical input / bias

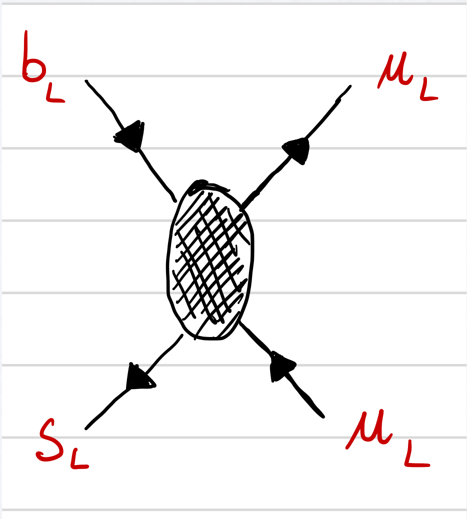


"Complete" Models — Address more questions/open problems: naturalness, origin of flavour,…



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

EFT — New Physics in a model independent way



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

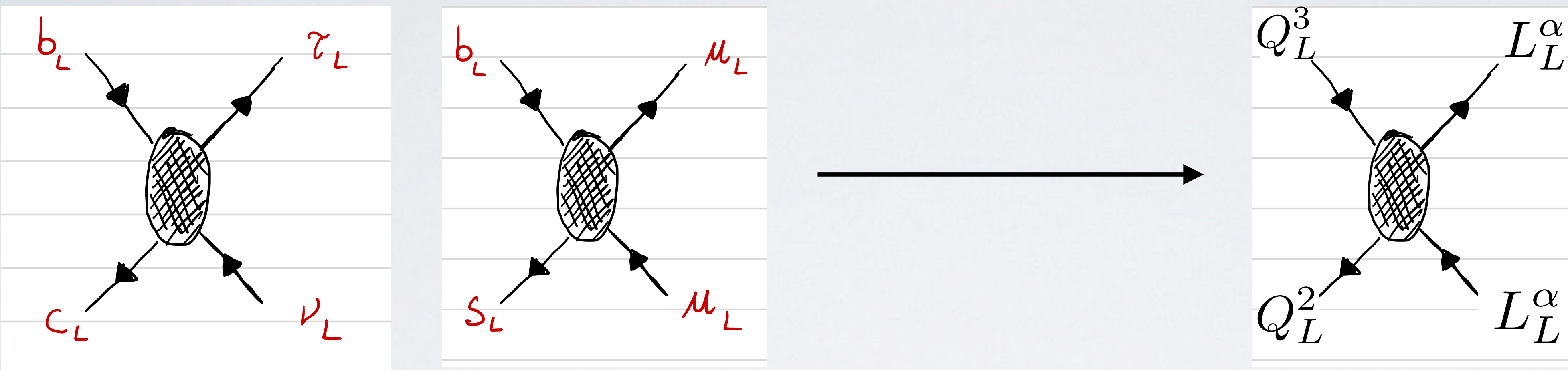
$$\Lambda_{R_K} = 31 \text{ TeV}$$

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

EFT considerations

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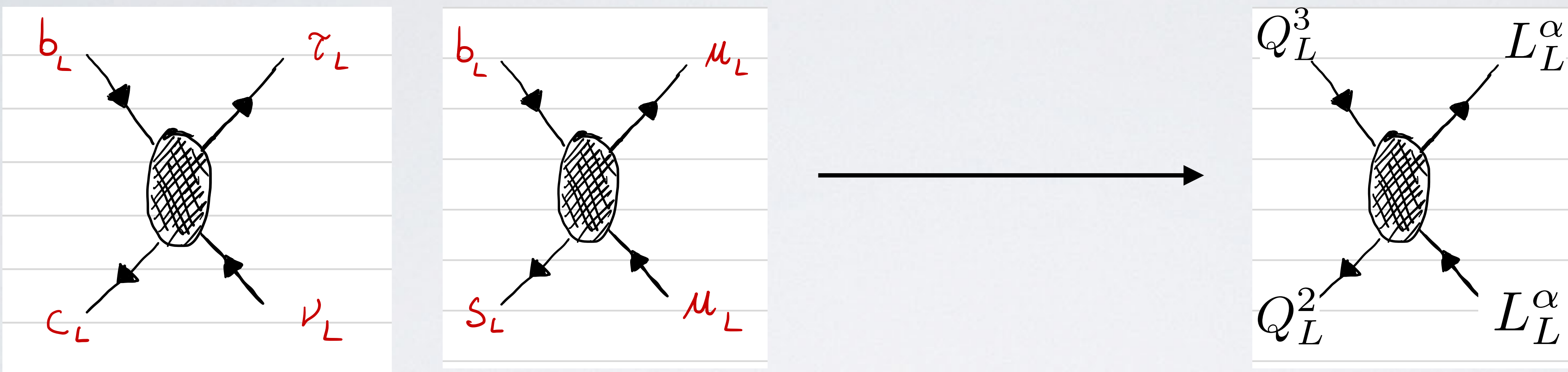


SU(2) structure induce correlations

- 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?

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

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

- Motivated flavour ansatz in the quark sector (NMFV, U(2),Partial Compositeness, Froggat-Nielsen,…) 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

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%) [$R_K = R_\pi$]	$B \to \pi \tau\tau$ $\to$ 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*	$K \to \mu e$???

Simplified model considerations

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

Colourless mediators (Z', V')

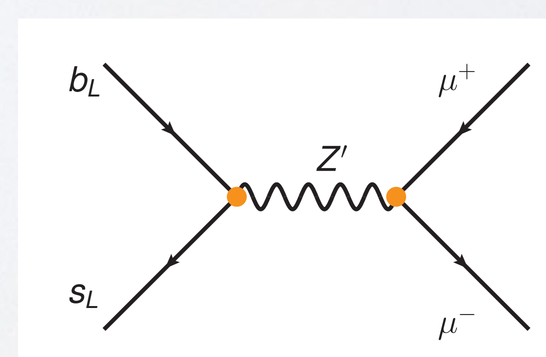
Leptoquarks (S_1, S_3, U_1, U_3)

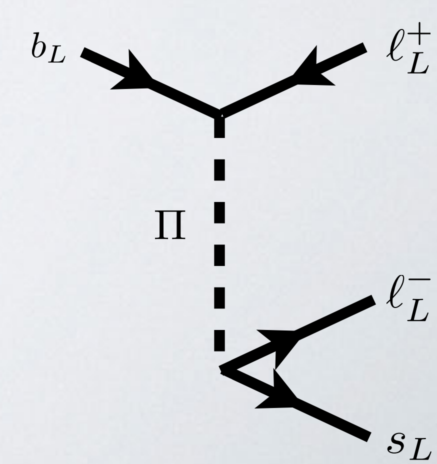
1) Resonance searches for charged current anomalies

- Colourless mediator Z'+V' not viable (excluded already $Z' \to \tau\tau$)
- Vector Leptoquark, U1, decaying into SM fermions of the third family
- Scalar Leptoquarks, S1+ S3, decaying into SM fermions of the third family
- More complicated linear combinations can be thought

2) Resonance searches for neutral current anomalies only (and no flavour bias)

- Z' to muons
- Leptoquark in final states with muons

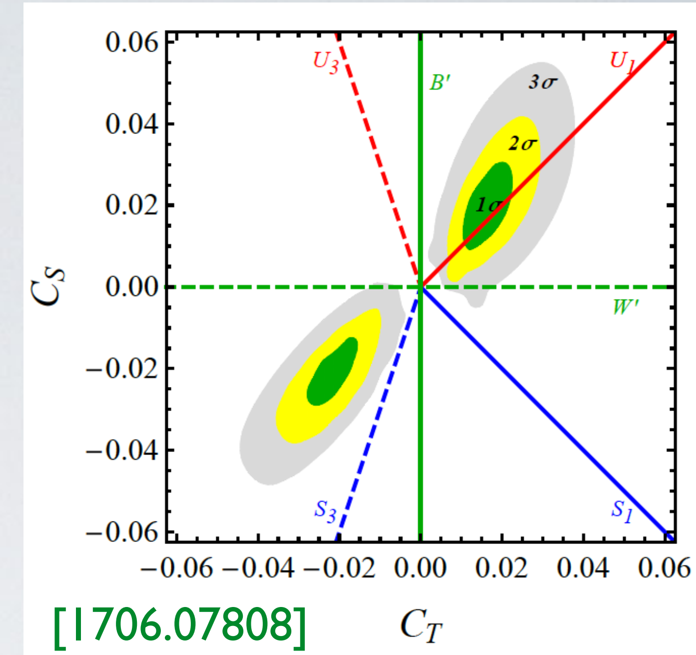




3) Non-resonant searches

- High-pT dilepton tails $pp \to \tau\tau, pp \to \mu\mu$

Explicit models



- Addressing the charged current anomalies is quite challenging
- Completing the picture of the simplified models is not an academic question, correlations are model dependent
- The '4321' model [L. Di Luzio, A. Greljo, MN, 1708.08450]

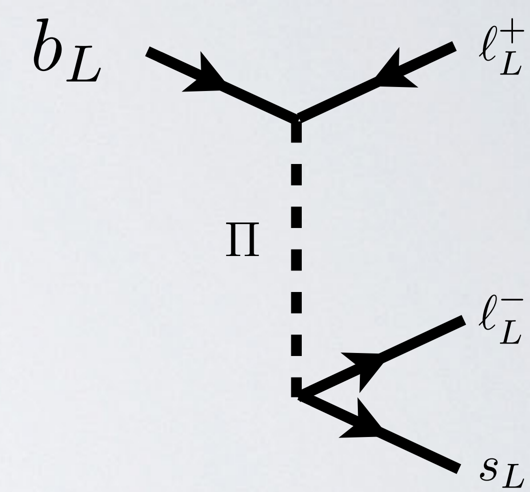
$$G = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

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

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

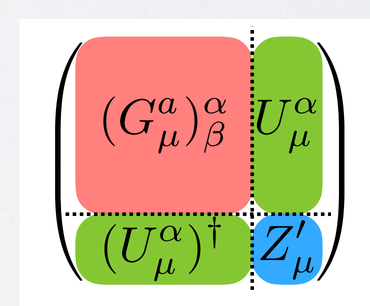
New states from the breaking:

1) A leptoquark
2) A color octet
3) A SM singlet



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

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



- At low energy, possible large effects in

$\tau \to 3\mu$ Z'-exchange

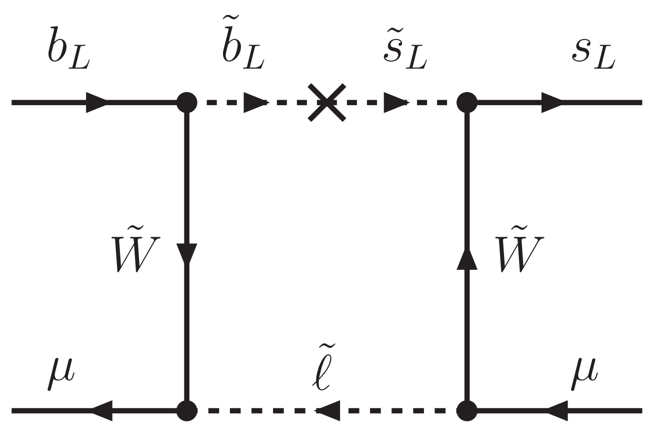
CPV in D-mixing g'-exchange

- Other interesting models with vector leptoquark [PS3-1712.01368, Composite 1712.06844]

MSSM

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

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

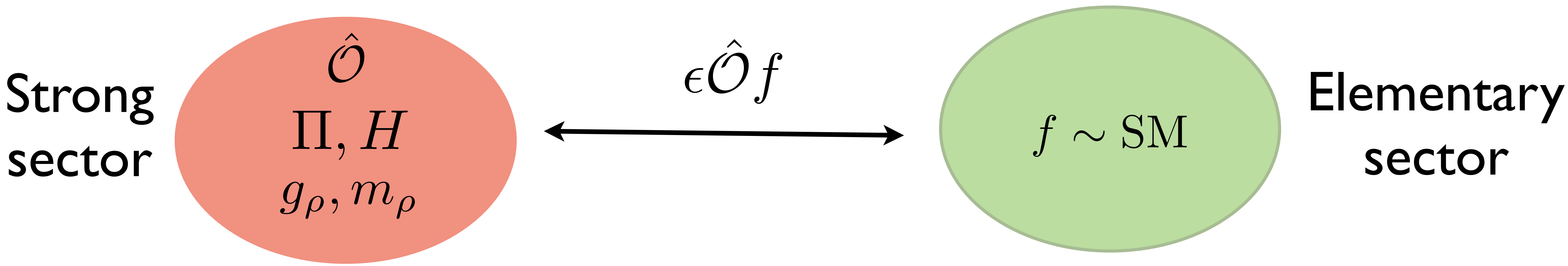


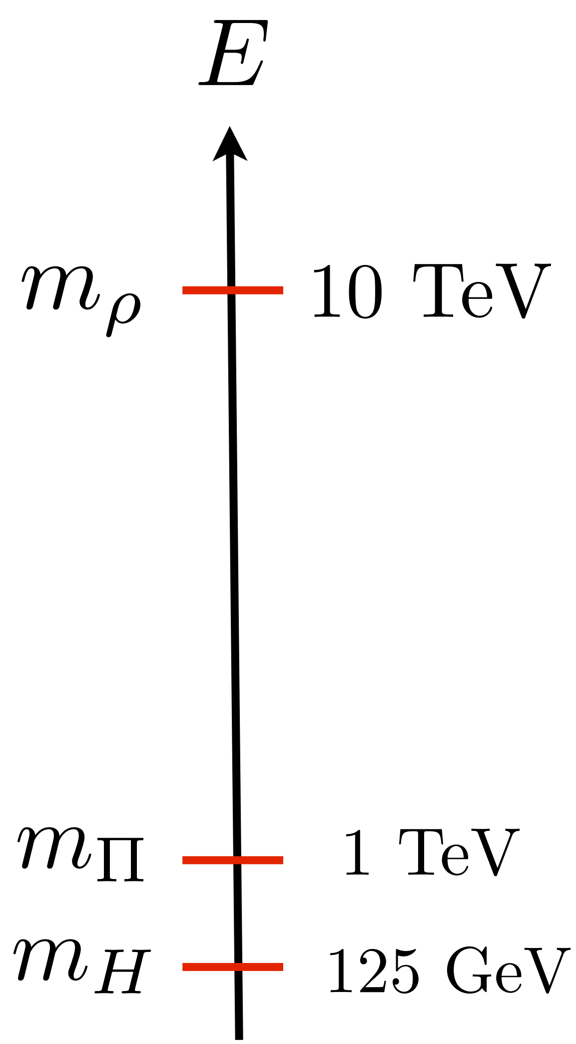
- Lepton universality is broken by slepton masses $m_{\tilde{e}} \gg m_{\tilde{\mu}}$
- Box diagrams are numerically small, very light particles in the loop
- No free parameter on the Feynman vertices: EW couplings
- Direct searches (LHC+LEP) give strong constraints, (probably) no hope left (but a careful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

- MSSM wit R-Parity Violation: basically SM + some specific leptoquark

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

Composite Higgs Framework





- Being PGB, Higgs and Leptoquarks are lighter than the other resonances coming from the strong sector

- SM fermion masses are generated by the mechanism of partial compositeness

$$|SM\rangle = \cos\epsilon |f\rangle + \sin\epsilon |\mathcal{O}\rangle$$

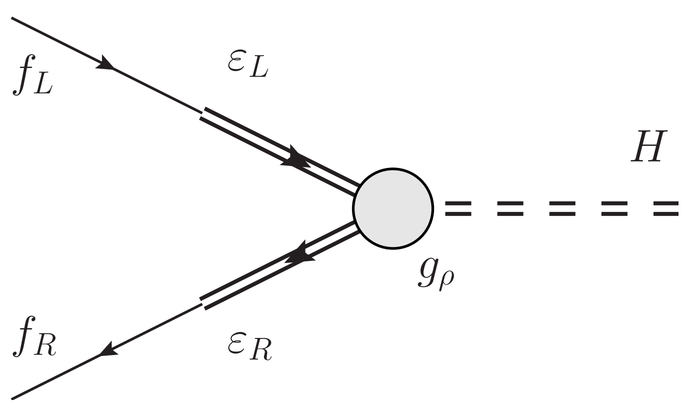
- BSM Flavour violation regulated by the same mechanism

- Naturalness (…)

Based on 1412.5942, JHEP,
Ben Gripaios and Sophie Renner

Partial Compositeness in CH models

- Yukawa sector:



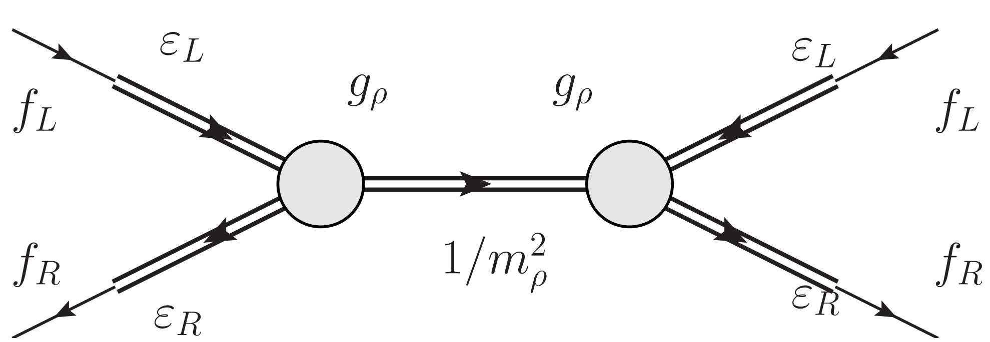
$$\mathcal{L}_{\rm elem} = i\overline{f}\gamma^\mu D_\mu f$$

$$\mathcal{L}_{\rm comp} = \mathcal{L}_{\rm comp}(g_\rho, m_\rho, H)$$

$$\mathcal{L}_{\rm mix} = \epsilon_L\, f_L \mathcal{O}_L + \epsilon_L\, f_R \mathcal{O}_R + h.c.$$

$$Y^{ij} = c_{ij}\,\epsilon_L^i \epsilon_R^j\, g_\rho \longrightarrow Y^{ij} \sim \epsilon_L^i \epsilon_R^j g_\rho$$

- Flavor violation beyond the CKM one is generated:



$$\sim \frac{g_\rho^2}{m_\rho^2}\epsilon_L^i \epsilon_R^i \epsilon_L^j \epsilon_R^j$$

FV related to the SM one but not in a Minimal FV way

A couple of extra topics

Charm mixing

• CPV violation in SM suppressed by small CKM matrix element. $\mathcal{O}(10^{-4})$

• Not small enough for LHCb 300/fb

• No competitor for LHCb

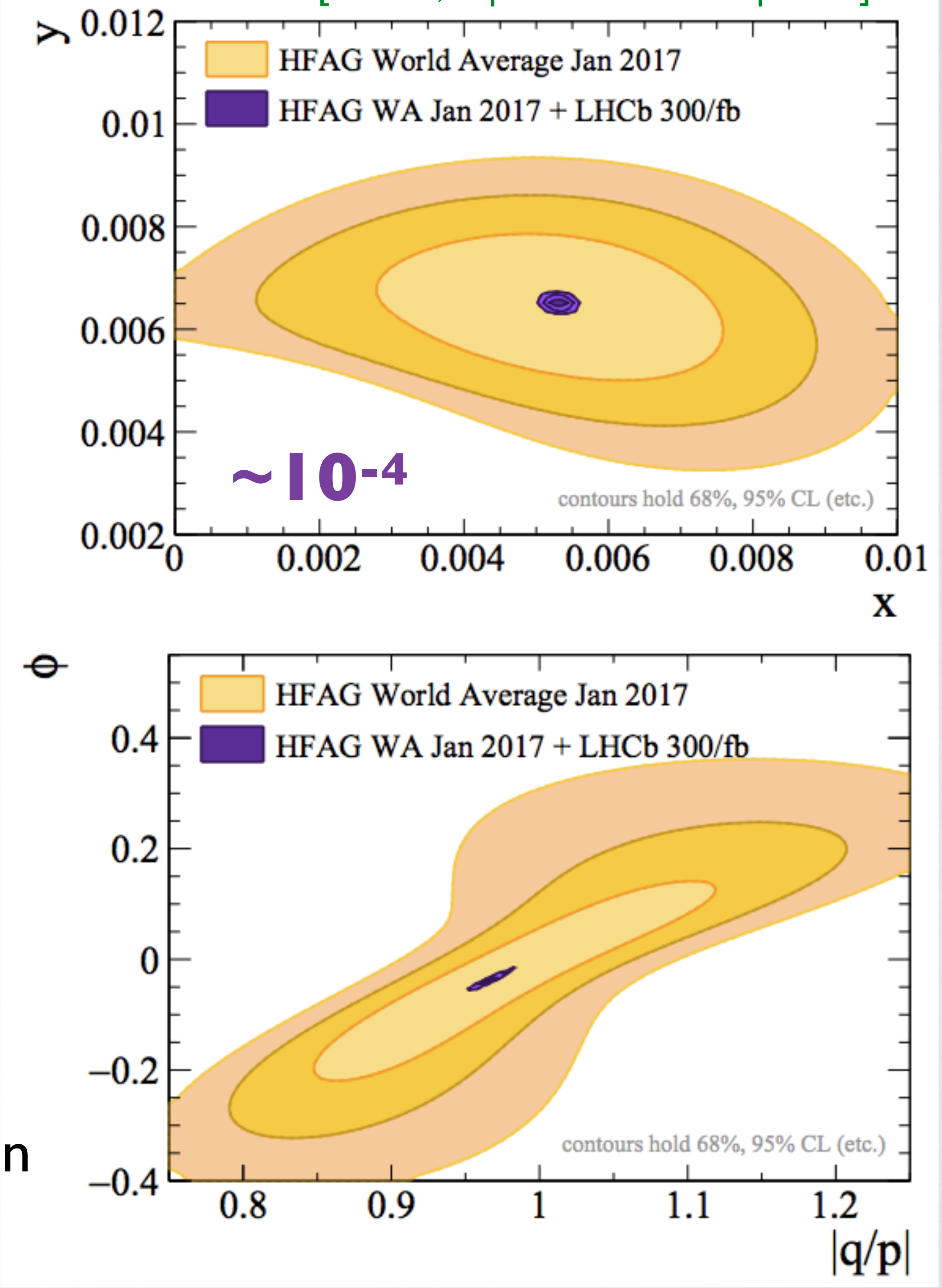
• Strong constraints for the NP

• Crucial for NP models involving quark doublets

$$(X_{ij}\overline{Q}^i\gamma^\mu Q^j)^2$$

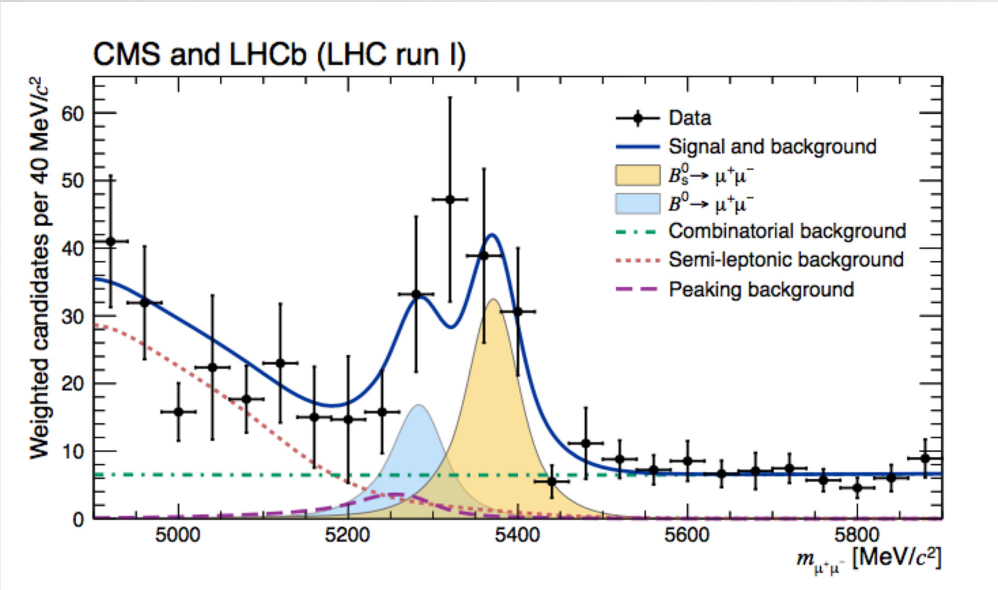
Cannot align simultaneously to up and and down quarks, K-mixing forces down alignment, so this is one of the main constraints

[Cowan, Implication workshop 2017]



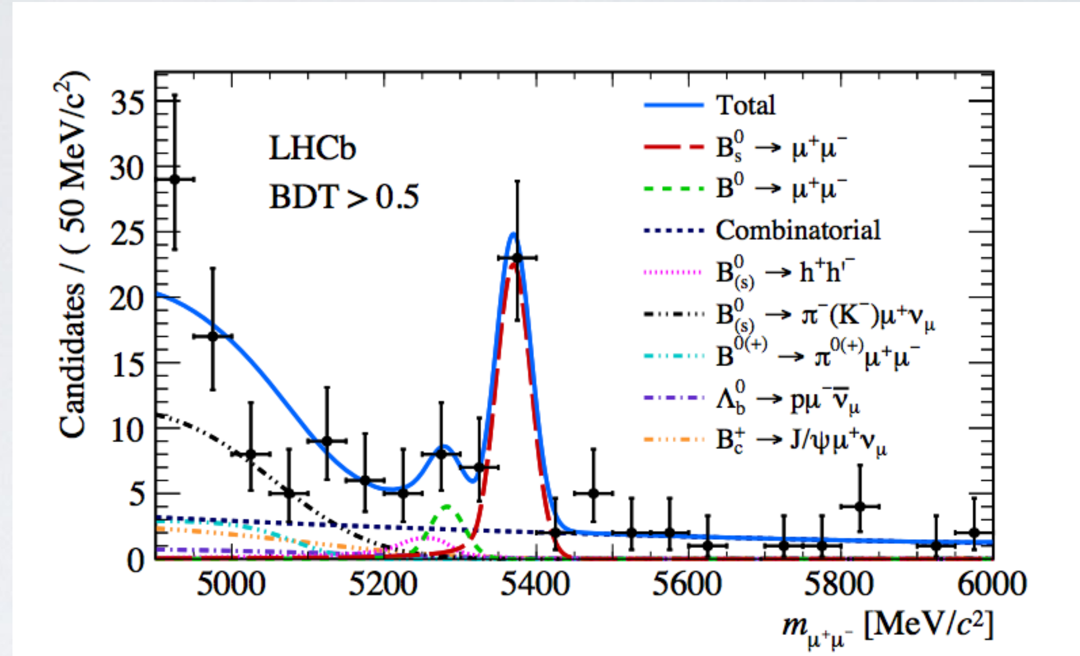
[See also talk by A. Lenz]

$B_s, B_d \to \mu\mu$



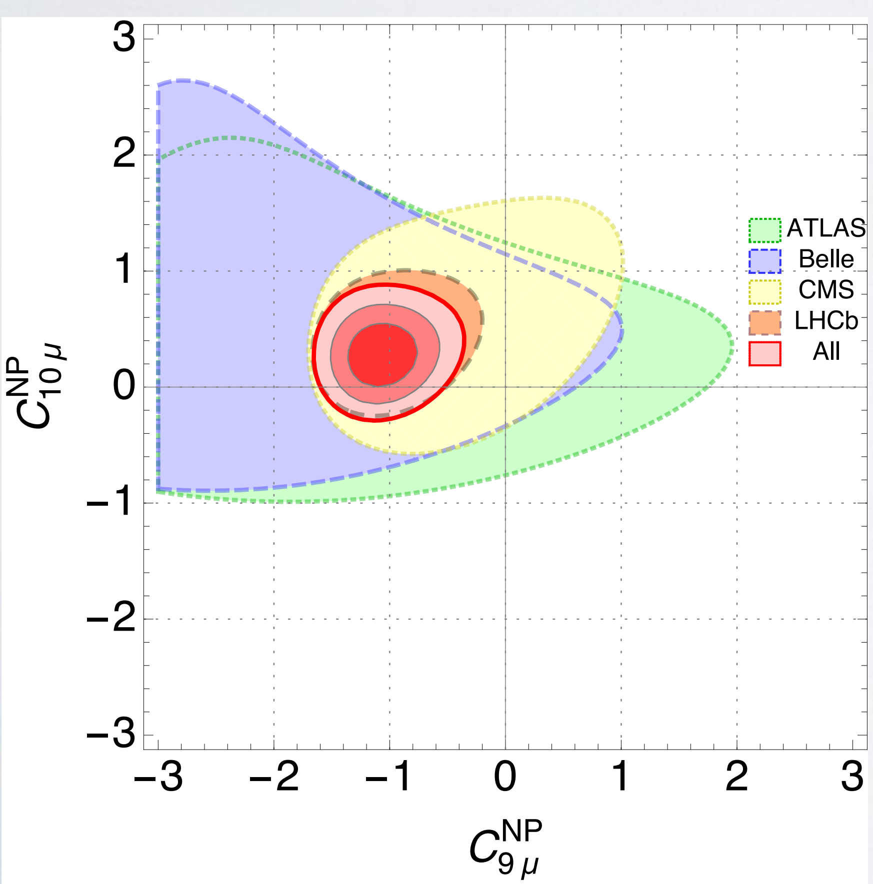
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

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



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

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



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

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

Conclusions

- My apologies, I didn't discuss a lot of topics: CPV in B-mixing, LFV, dark sectors, γ ,…

- The LHCb Phase-2 upgrade is a win-win case:
  - if flavor anomalies will be confirmed, the importance to continue with the physics program at LHCb cannot be underestimated. It will be crucial not only for the flavor community but for the whole HEP
  - If flavor anomalies will disappear and no evidence of NP on-shell at LHC, flavor 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

- 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

- 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.

- We are really looking forward for new data and for the LHCb upgrade!

Backup

New Physics (Model Independent)

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

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

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

$$\begin{aligned}
C_7^{SM} &= -0.319, \\
C_9^{SM} &= 4.23, \\
C_{10}^{SM} &= -4.41.
\end{aligned}$$

SM gives lepton flavour universal contribution

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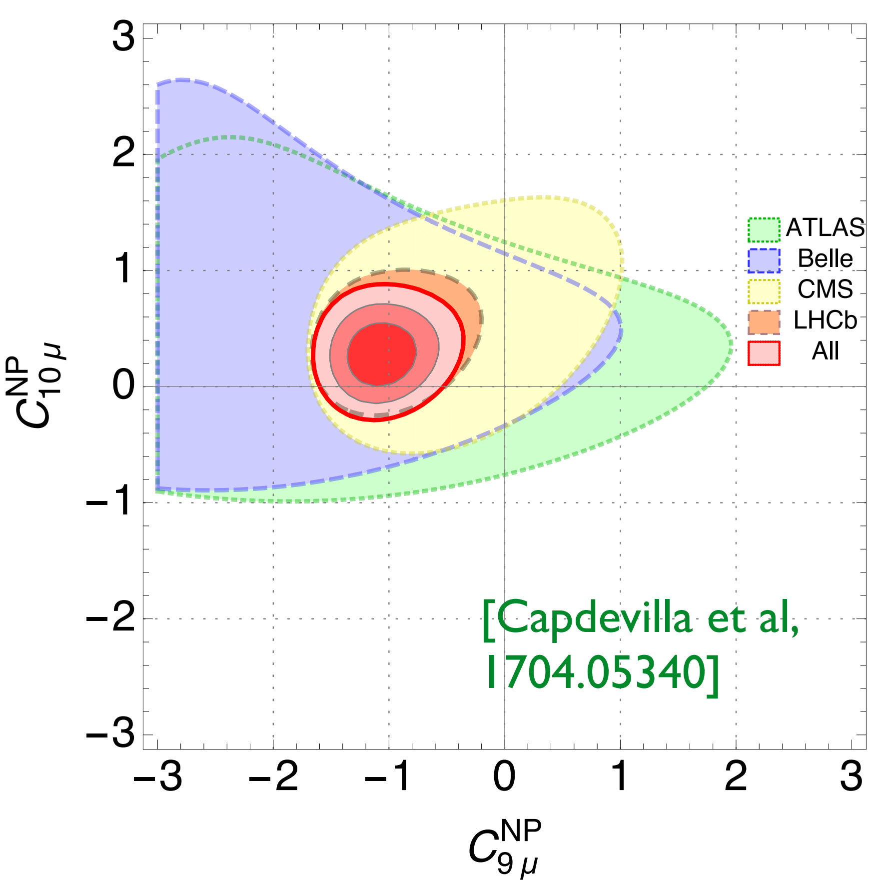
$$\mathcal{O}_7^{(\prime)} = \frac{e}{16\pi^2}\, m_b\,(\bar{s}\sigma_{\alpha\beta}P_{R(L)}b)\,F^{\alpha\beta}\,, \qquad C_7^{SM} = -0.319,$$
$$\mathcal{O}_9^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi}\,(\bar{s}\gamma_\alpha P_{L(R)}b)\,(\bar{\ell}\gamma^\alpha\ell)\,, \qquad C_9^{SM} = 4.23,$$
$$\mathcal{O}_{10}^{\ell(\prime)}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

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

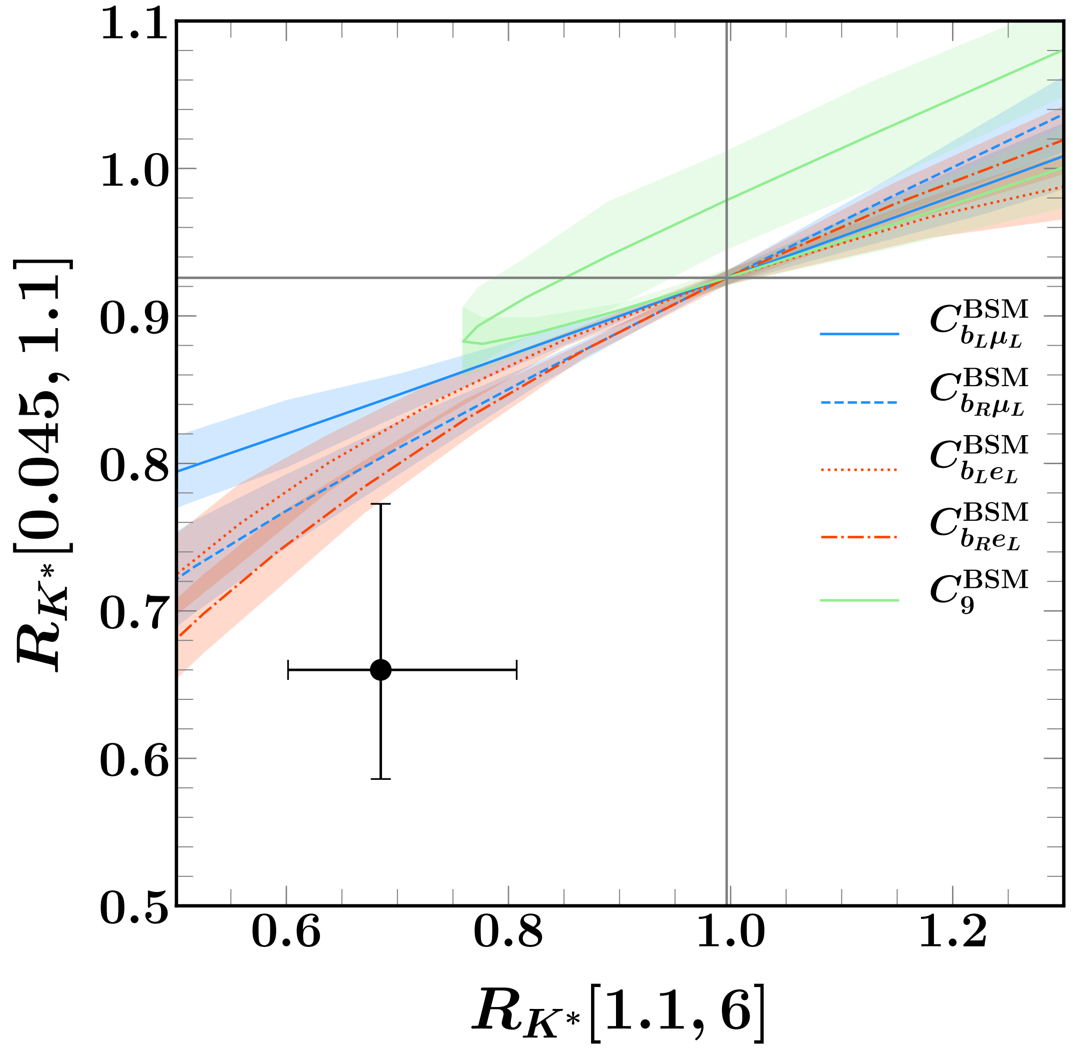
$$\bar{\ell}\gamma^\alpha\ell,\ \bar{\ell}\gamma^\alpha\gamma_5\ell \longrightarrow \bar{\ell}_L\gamma^\alpha\ell_L,\ \bar{\ell}_R\gamma^\alpha\ell_R$$

Best Fit with Left-Left currents

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

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

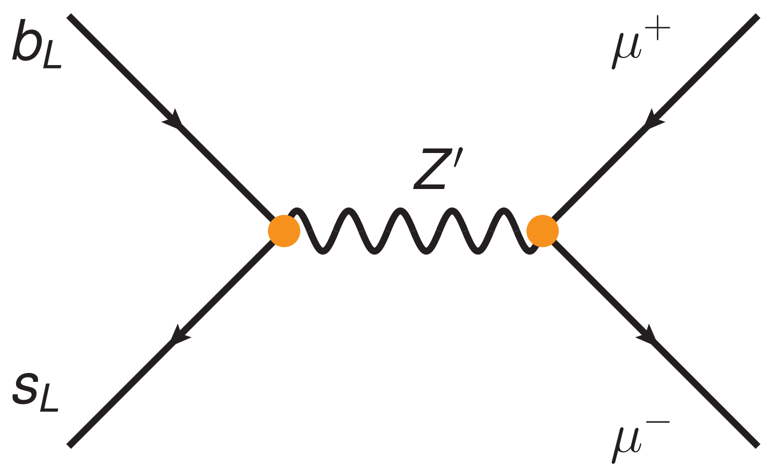


[D'Amico, et al. JHEP, 1704.05438]

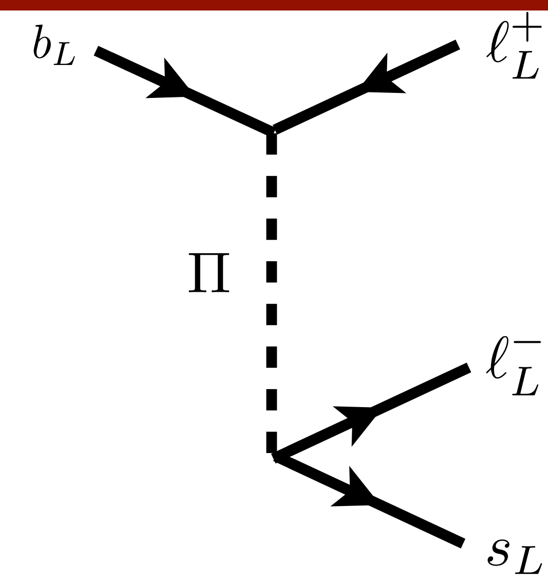
- Can be a sanity check of the measurement
- Having a large effect here requires light long range New Physics

[see for example 1711.07494]

Simplified Models



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



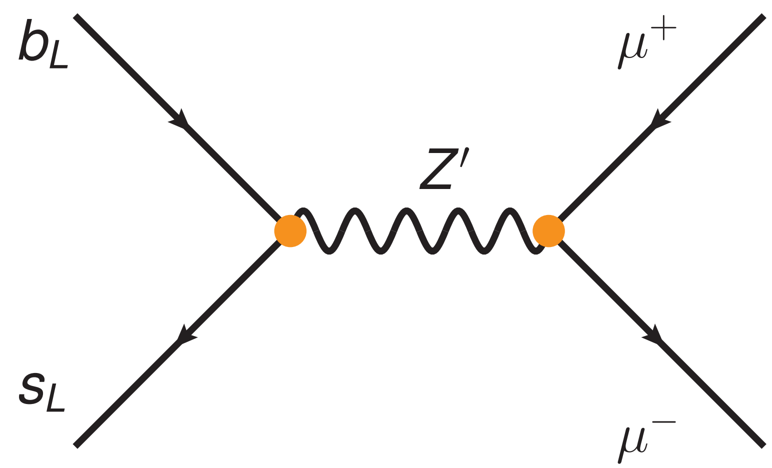
[more than 100 papers]

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

- 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

Simplified Models



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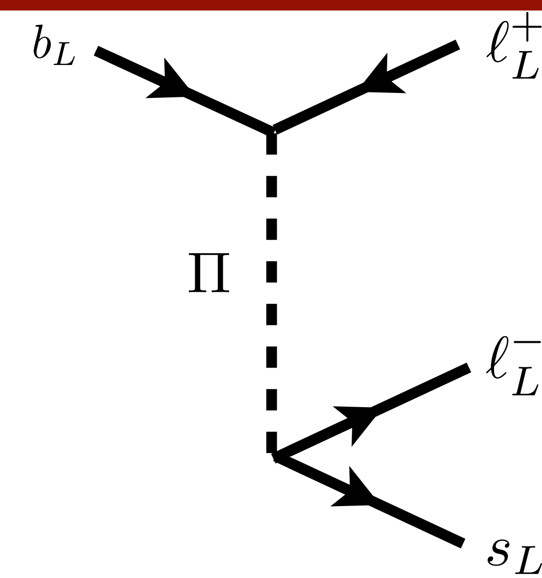

[more than 100 papers]

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- Main constraint to face is Bs mixing:
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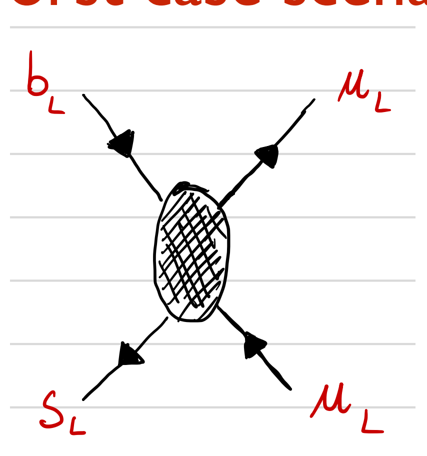
  - Leptoquark way out: tree VS loop

- Direct searches: need more theoretical input

- (Worst case scenario)

[Di Luzio, MN, 1706.01868]



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

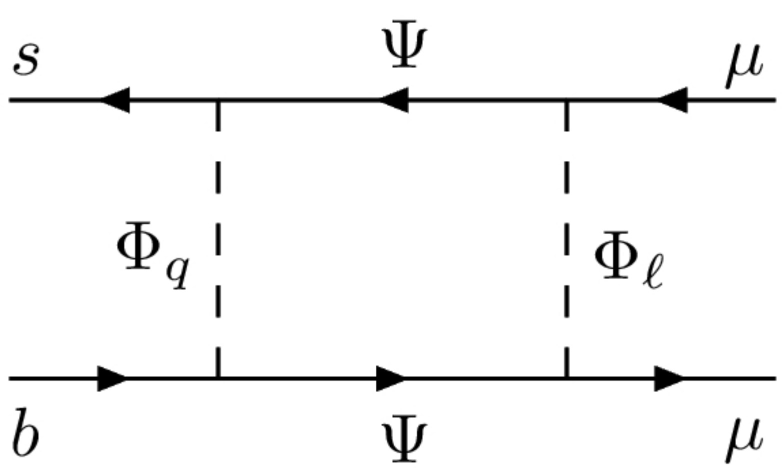
Tree-Level Pertubative Unitarity criterium

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

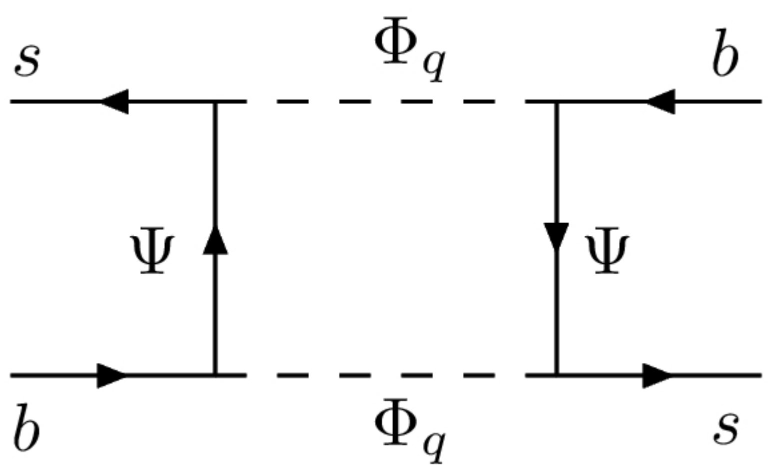
$$\begin{cases} \sqrt{s}_{max} \equiv \Lambda_U = 9\ \text{TeV} & b \to c\tau\nu \\ \sqrt{s}_{max} \equiv \Lambda_U = 80\ \text{TeV} & b \to s\mu\mu \end{cases}$$

Loop induced

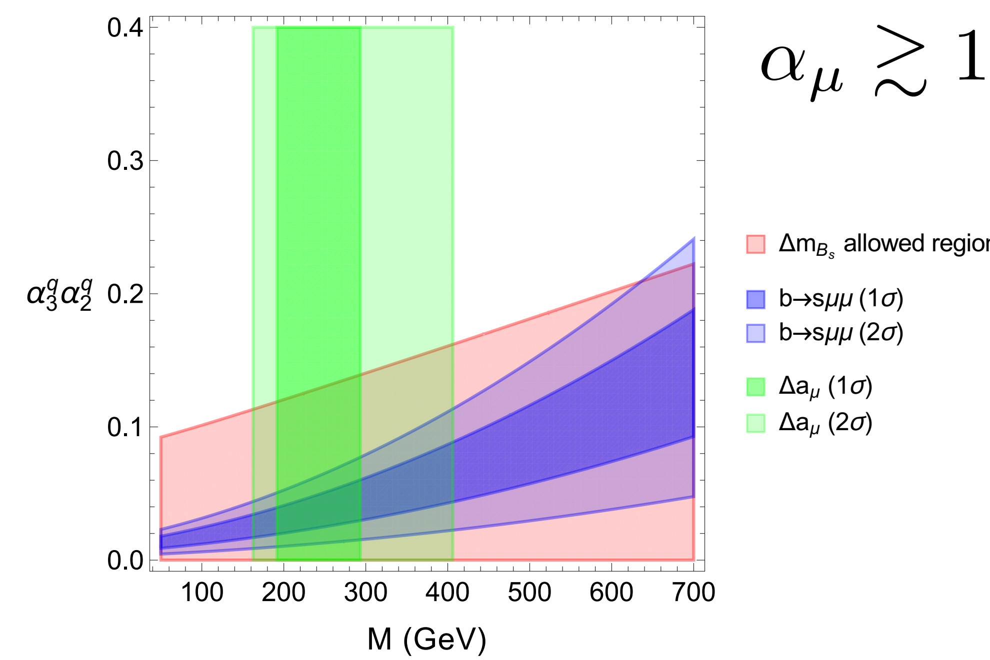
[Gripaios, MN, Renner 1509.05020
see also 1608.07832]



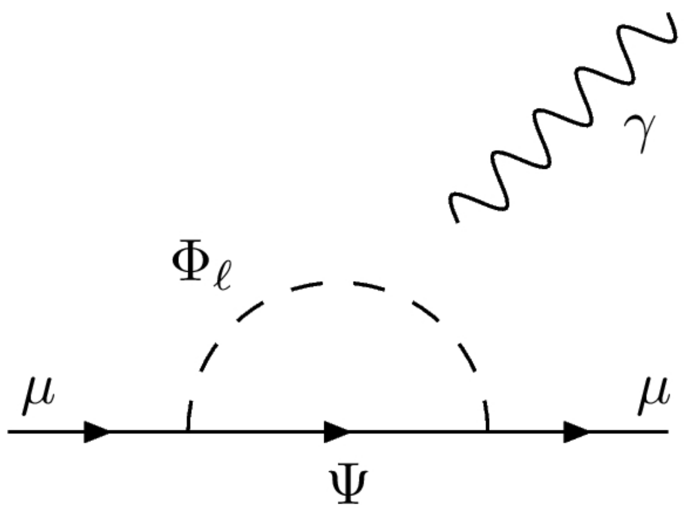
$$\alpha_i^q\, \overline{\Psi} Q_L^i \Phi_q + \alpha_i^\ell\, \overline{\Psi} L_L^i \Phi_\ell + \mathrm{h.c.}$$



- Main constraint



$\alpha_\mu \gtrsim 1$



- muon g-2, large leptonic coupling

- Direct searches are important

Low energy constraints

- The Yukawa sector

$$\mathcal{L}_Y \supset -\overline{q}'_L\, Y_d\, H d'_R - \overline{q}'_L\, Y_u\, \tilde{H} u'_R - \overline{\ell}'_L\, Y_e\, H e'_R \qquad (9)$$
$$- \overline{q}'_L\, \lambda_q\, \Omega_3^T \Psi_R - \overline{\ell}'_L\, \lambda_\ell\, \Omega_1^T \Psi_R - \overline{\Psi}_L\, M\, \Psi_R + \mathrm{h.c.}\ ,$$

B and L number are conserved accidentally!

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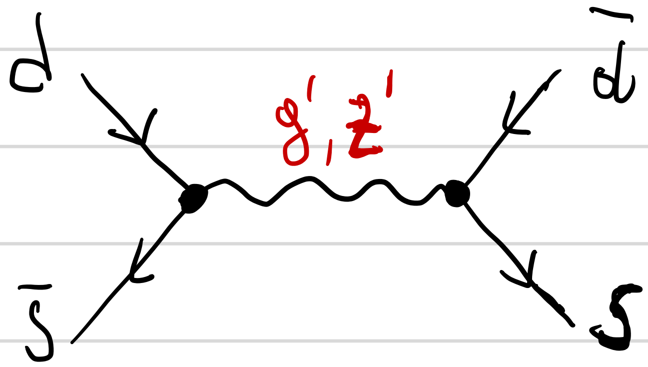
- The extra gauge bosons contributes to FCNC and CPV in the quark sector



Contrary to the leptoquark contribution, all quarks contribute. We need a protection mechanism in particular for FCNC in the down sector, 2 possibilities:

1) *Full flavour alignment*: No FCNC in the up and down sector! However unsuppressed couplings with first family implying large coupling to valence quark

$$M^{ij} \propto \lambda_q^{ij}$$

$$M, \lambda_q, Y_d = \text{diagonal}$$

2) *Down alignment*: No FCNC in the down sector, misalignment with the up sector leads to contribution to D mixing.

- Both cases can be motivated by flavour symmetry (see later)

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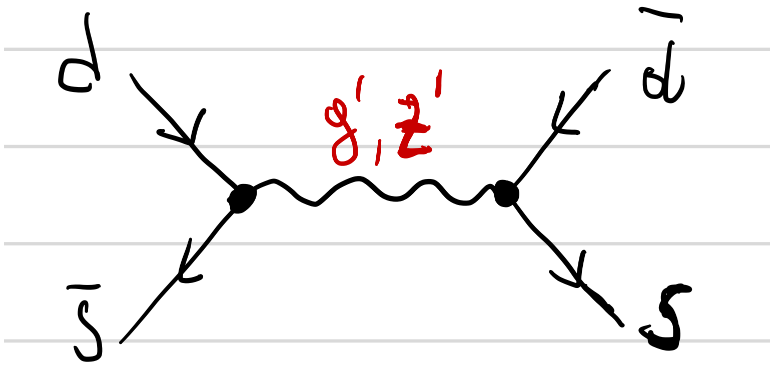

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- Both cases can be motivated by flavour symmetry (see later)
- EWPT, Z and W constraints under control for the leptoquark, less important for the other gauge bosons (because EW singlets). [1706.07808]
- Purely leptonic processes induced by the Z' at the tree level are under control $(\tau \to 3\mu, \tau \to \mu\nu\nu)$
- Constraints due vector-like mixing are protected by mass suppression [1304.4219]

Mass scale of New Physics (*new colored & flavored particles*)

Simplifying a complicated multi-dim. problem...

c_{ij} \ Λ	< 1 TeV	few TeV	> few TeV
Direct New Physics searches @ high pT:	NP within direct reach @ 8 TeV	NP within reach @ 14 TeV	NP beyond direct searches @ LHC
NP effects in Quark Flavor Physics:			
Anarchic	huge [> O(1)]	sizable [O(1)]	sizable/small [< O(1)]
Small misalignment (*e.g. partial compositeness*)	sizable [O(1)]	small [O(10%)]	small/tiny [O(1-10%)]
Aligned to SM (*MFV*)	small [O(10%)]	tiny [O(1%)]	not visible [< 1%]

Flavor Structure