New Physics and Experimental Anomalies in B-meson Decays

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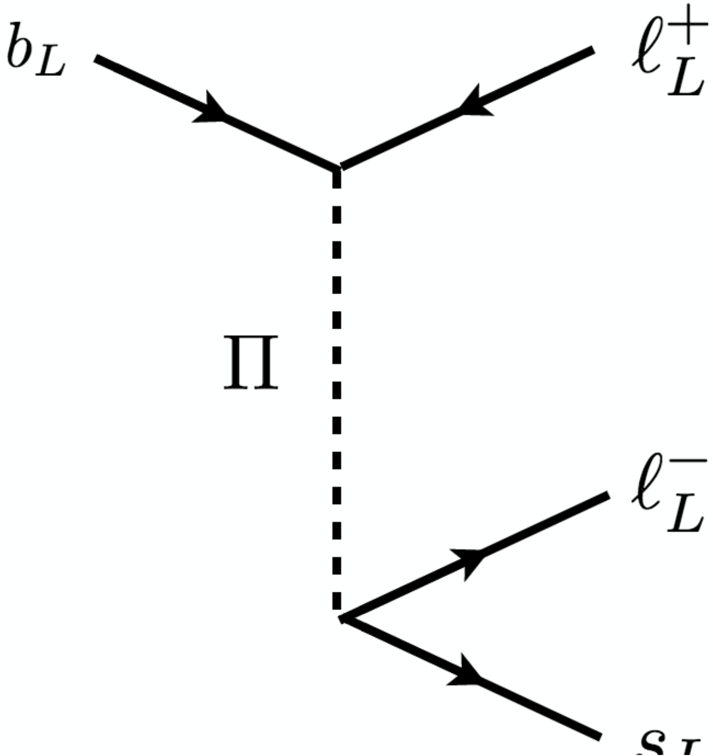
14 April 2015, Florence

Outline 1/2

- Standard Model
- Flavour problem
- Impact of the first run of the LHC
- Anomalies in semileptonic B-meson decays

Outline 2/2

Based on 1412.5942 in collaboration with
Ben Gripaios and Sophie Renner



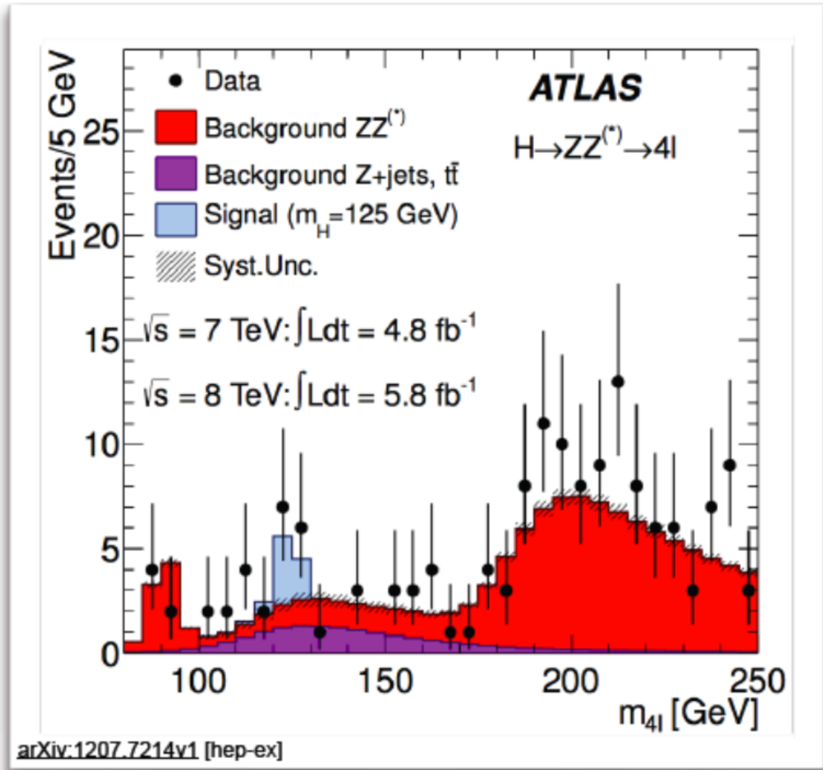
- Explaining the anomalies in semileptonic B-meson decays, in the context of a Composite Higgs model with an extra PNGB

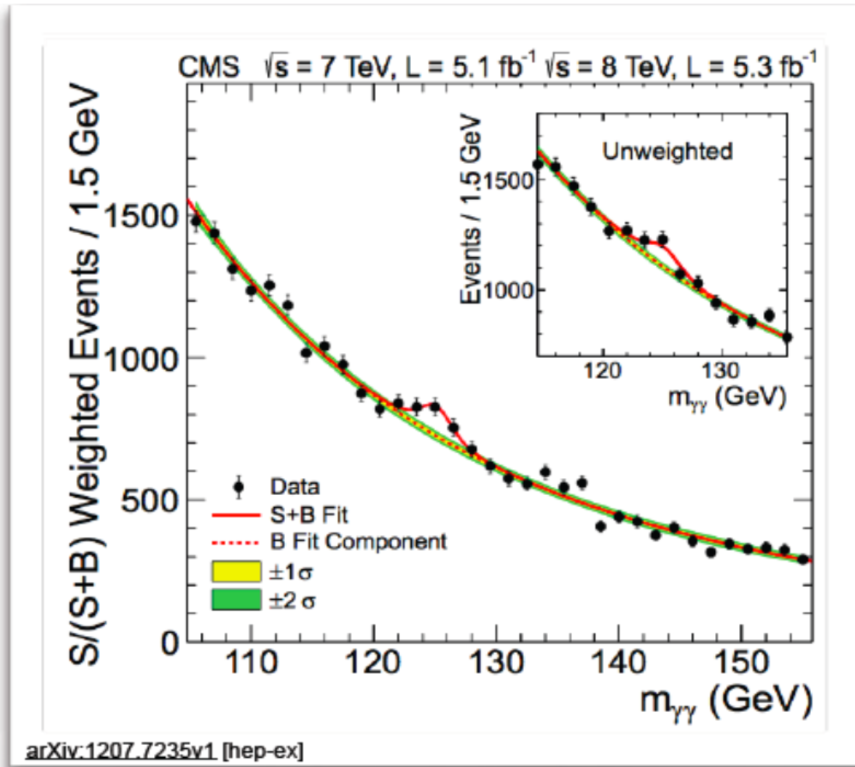
$$\Pi \sim (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

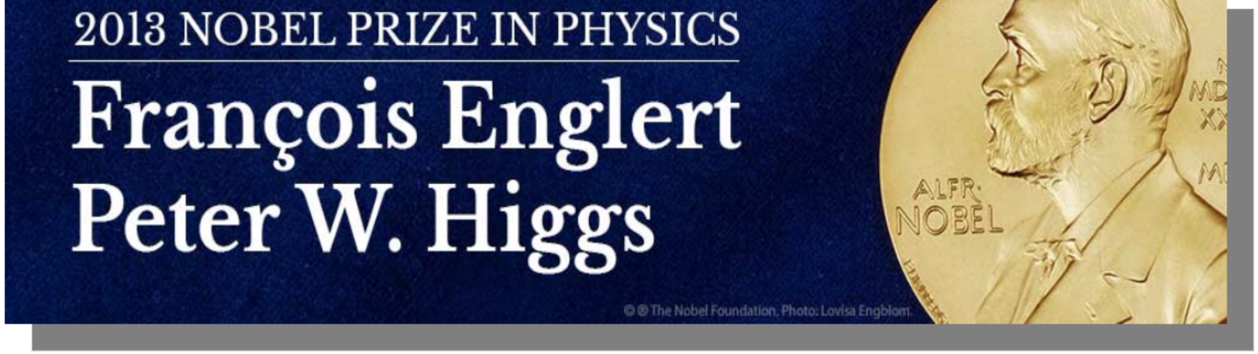
- Flavour Violation regulated by the mechanism of partial compositeness

After LHC-1

1) Discovery of a SM Higgs-like scalar

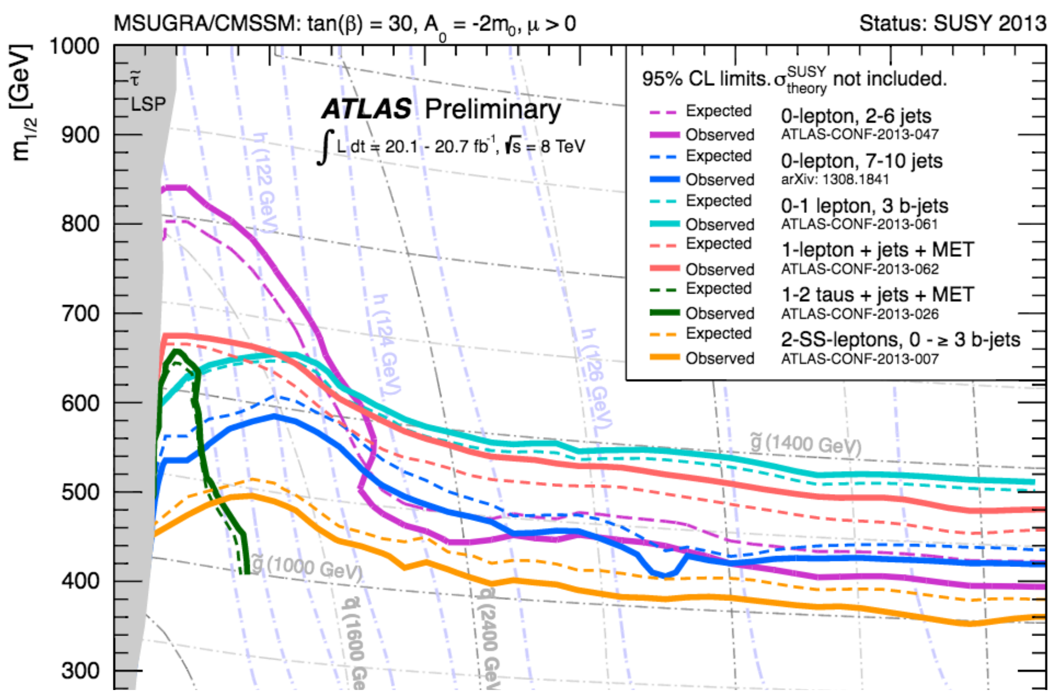


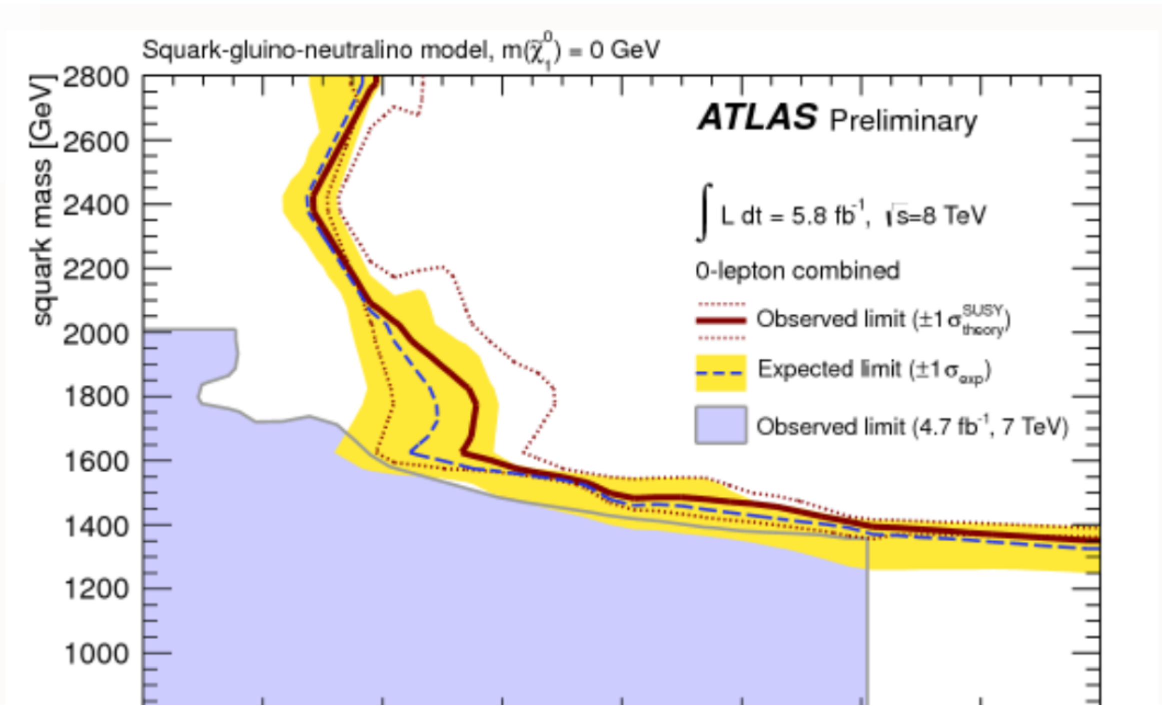


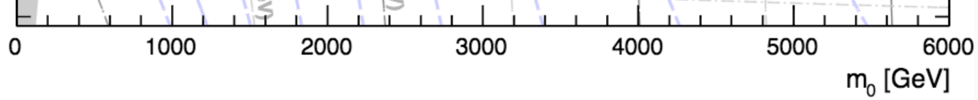


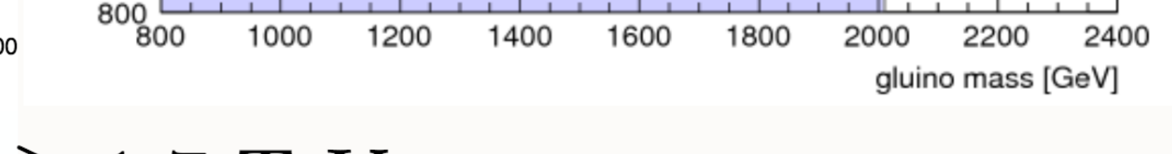
After LHC-1

2) No evidence of New Physics from direct searches*







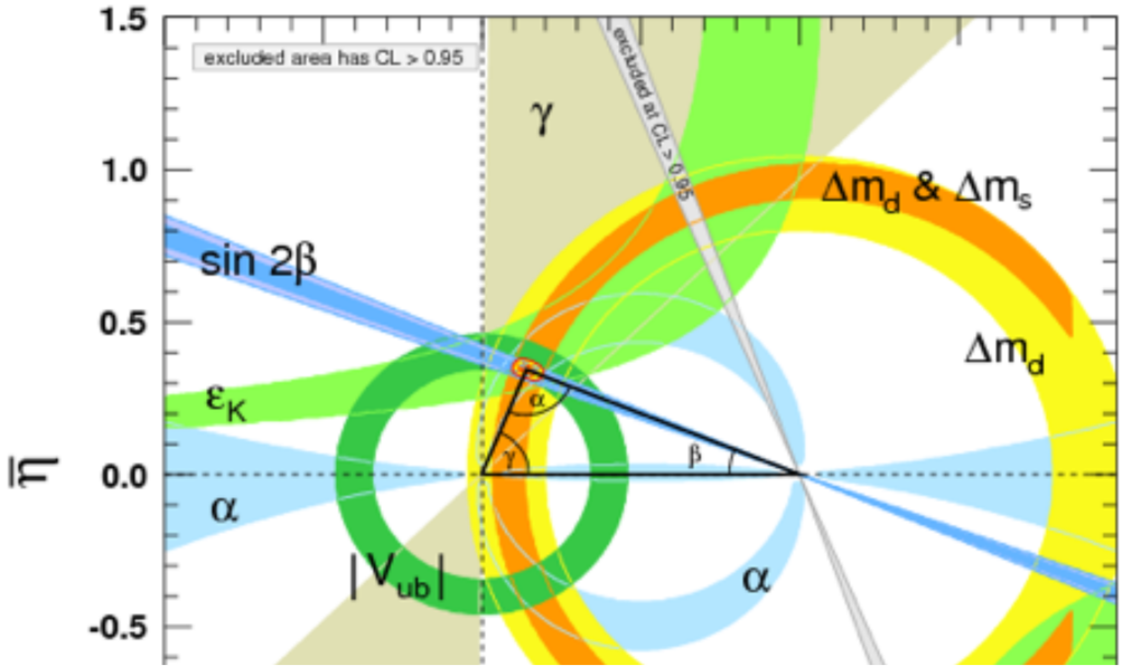


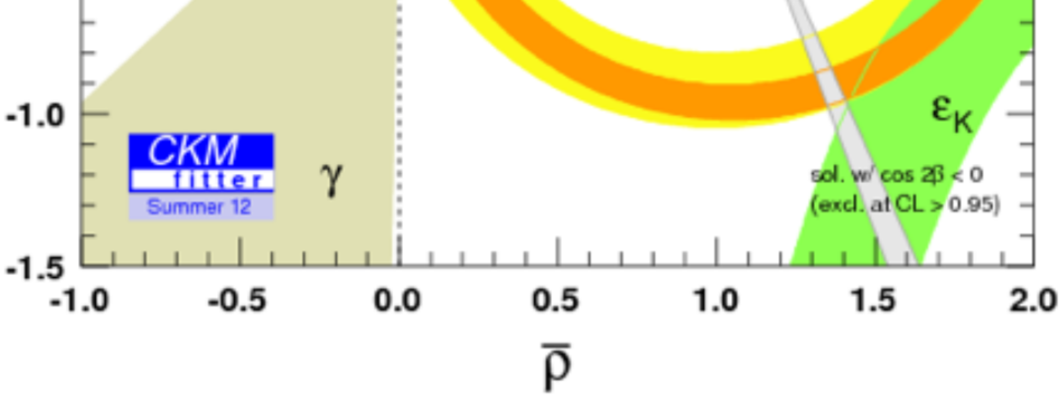
$$m_{\tilde{q}}, m_{\tilde{g}} \gtrsim 1.7 \text{ TeV}$$

* 2 sigma effects recently seen by CMS

After LHC-I

3) No (clear)* evidence of New Physics from indirect searches





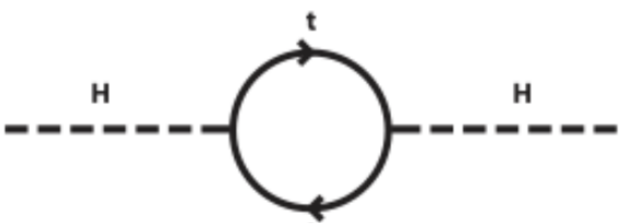
*more details in a few slides

The Flavour Problem

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

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

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



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

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

•Lower bounds from FCNC

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

Isidori, Nir, Perez
1002.0900

•Two (problematic) possibilities:

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

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

Minimal Flavor Violation

D'Ambrosio, et al.
hep-ph/0207036

•MFV hypothesis consists in the assumptions that

(i) the full EFT is formally invariant with respect to the flavor symmetry

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

(ii) the SM Yukawa couplings are the only irreducible source of flavor breaking

$$c_i^{(d)} = c_i^{(d)}(y_u, y_d, y_e)$$

MFV consequences

- Let us work in a basis where $y_u = V_{\rm CKM}^\dagger \frac{\hat{m}_u}{v},\ y_d = \frac{\hat{m}_d}{v},\ y_e = \frac{\hat{m}_e}{v}$ $\qquad \frac{c_{ij}\mathcal{O}_{ij}}{\Lambda^2}$
- Consequences

  (i) flavor violating contribution from combination of the type $(y_u y_u^\dagger)^{ij} \approx \lambda_t^2 (V_{\rm CKM}^{3i})^* V_{\rm CKM}^{3j}$

  (ii) predictive hypothesis with correlations among observables

  (iii) flavor problem is practically solved (see table)

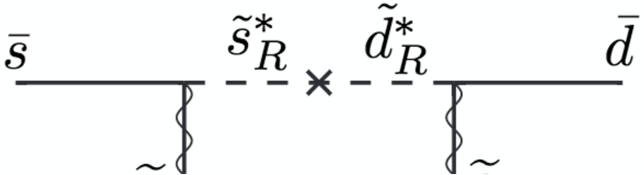
(iv) there is no flavor violation in the lepton sector

Operator	Bound on Λ	Observables
$H^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)(eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma,\ B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L)^2$	5.9 TeV	$\epsilon_K,\ \Delta m_{B_d},\ \Delta m_{B_s}$
$H_D^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma,\ B \to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)\left(\overline{E}_R \gamma_\mu E_R\right)$	2.7 TeV	$B \to X_s\ell^+\ell^-,\ B_s \to \mu^+\mu^-$
$i\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \to X_s\ell^+\ell^-,\ B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)\left(\overline{L}_L \gamma_\mu L_L\right)$	1.7 TeV	$B \to X_s\ell^+\ell^-,\ B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)(eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s\ell^+\ell^-$

Isidori, Nir, Perez 1002.0900
UTfit 0707.0636
Hurth el al. 0807.5039

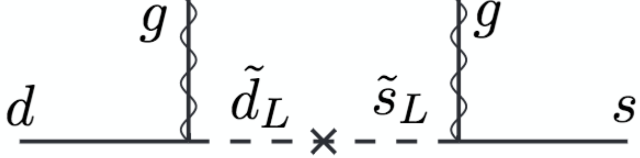
MFV after LHC I

- Let me assume that (coloured) New Physics enters at the one-loop level (like in the MSSM)



$$c_{ij}\mathcal{O}_{ij}$$

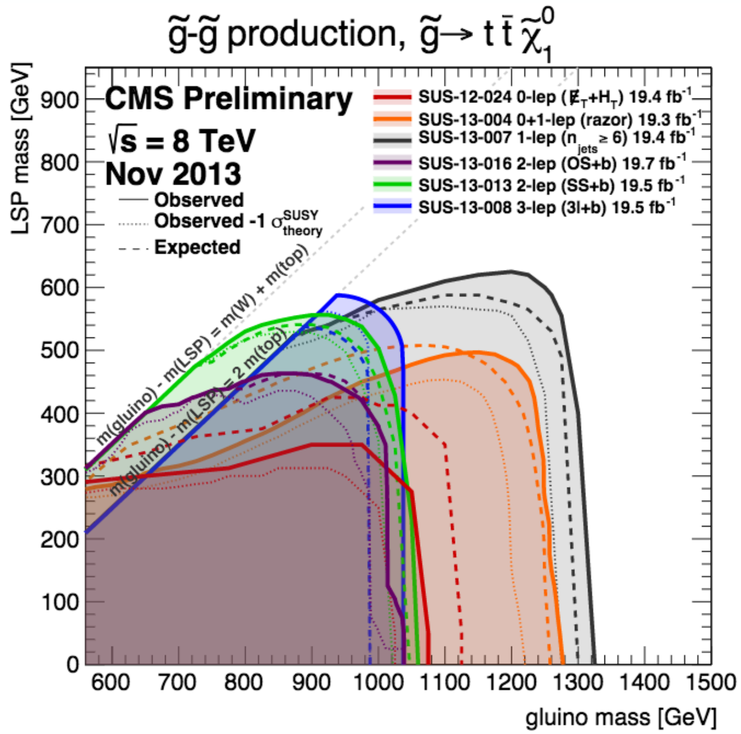
$$c_{ij} = \frac{\alpha_s}{4\pi}\left(y_u y_u^\dagger\right)_{ij}$$



$$\frac{}{\Lambda^2} \qquad \Lambda = m_{susy}$$

Flavour $m_{susy} > 500$ GeV

Direct Searches $m_{susy} > 1000$ GeV



Tiny NP effects in the flavour sector from MFV

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

Simplifying a complicated multi-dim. problem...	< 1 TeV	few TeV	> few TeV
	Direct New Physics searches @ high pT:		
	NP within direct	NP within reach	NP beyond direct

c_{ij} / Λ	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

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

Simplifying a complicated multi-dim.

	< 1 TeV	few TeV	> few TeV
	Direct New Physics searches @ high pT:		

problem... Λ / c_{ij}	NP within direct reach @ 8 TeV	NP within reach @ 14 TeV	NP beyond direct searches @ LHC
	NP effects in Quark Flavor Physics:		
Flavor Structure			
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%]

"Anomalies"

1) Tension in the LHCb data coming from $B \to K^* \mu^+ \mu^-$ angular observables

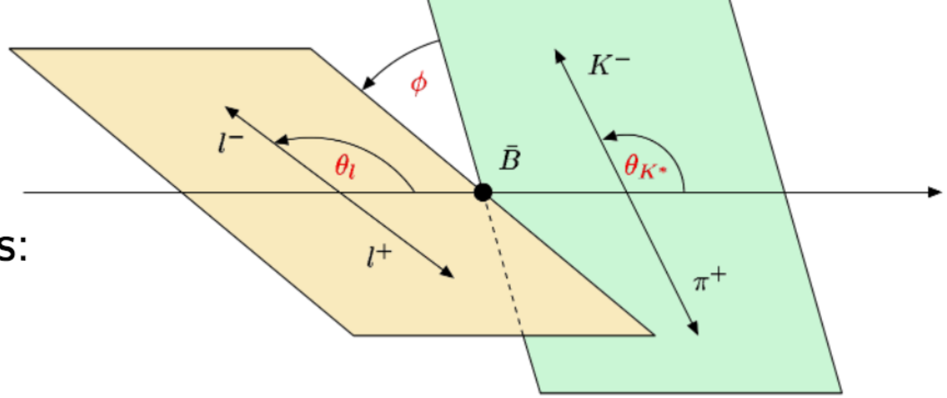
2) Various measurements of branching ratios are low compared to the SM prediction

3) Hint of violation of lepton universality in R_K

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

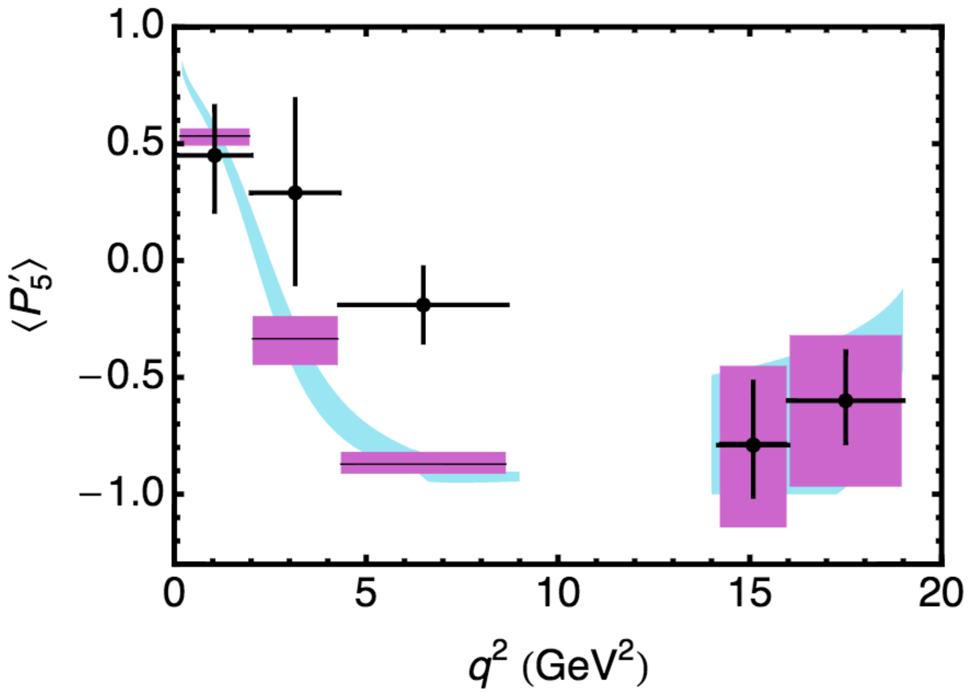
Angular distributions

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



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

LCHb, 1308.1707, PRL



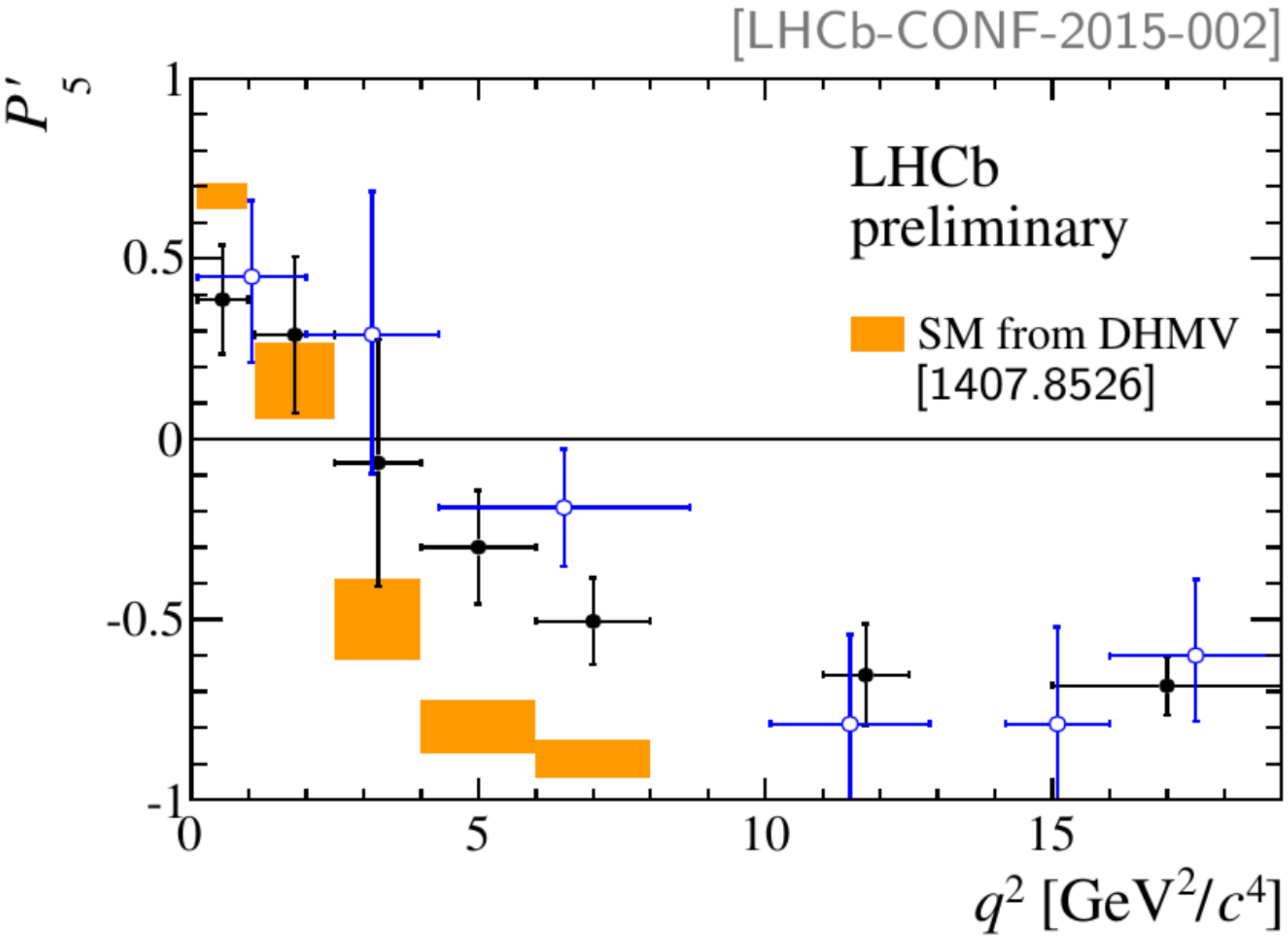
3.7σ discrepancy in one of q^2 bins

Explanations:

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

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

Moriond EW
21 March 2015



$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

2.9σ in [4,6] GeV^2 bin   ($+2.9\sigma$ in [6,8] GeV^2 bin)

Branching ratios

Branching ratios

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

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[16, 19.25]$	0.47 ± 0.05	0.31 ± 0.07	CDF	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	A_{FB}	$[2, 4.3]$	-0.04 ± 0.03	-0.20 ± 0.08	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.79 ± 0.03	0.26 ± 0.19	ATLAS	$+2.7$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[2, 4.3]$	-0.16 ± 0.03	0.12 ± 0.14	LHCb	-2.0
$\bar{B}^- \to \bar{K}^{*-}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[4, 6]$	0.50 ± 0.08	0.26 ± 0.10	LHCb	$+1.9$
$\bar{B}^- \to \bar{K}^{*-}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[15, 19]$	0.59 ± 0.06	0.40 ± 0.08	LHCb	$+1.8$
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.53	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 ± 0.10	0.37 ± 0.22	CDF	$+2.3$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[1, 6]$	0.39 ± 0.06	0.23 ± 0.05	LHCb	$+2.0$

[Altmannshofer, Straub 1411.3161]

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

R_K

LCHb, 1406.6482, PRL

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{{\rm d}\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{{\rm d}q^2} {\rm d}q^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{{\rm d}\Gamma[B^+ \to K^+ e^+ e^-]}{{\rm d}q^2} {\rm d}q^2}$$

$$1 < q^2 < 6\,{\rm GeV}^2/c^4$$

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

$$R_K^{SM} \simeq 1.00$$

Explanations:

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

New Physics (Model Independent)

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

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

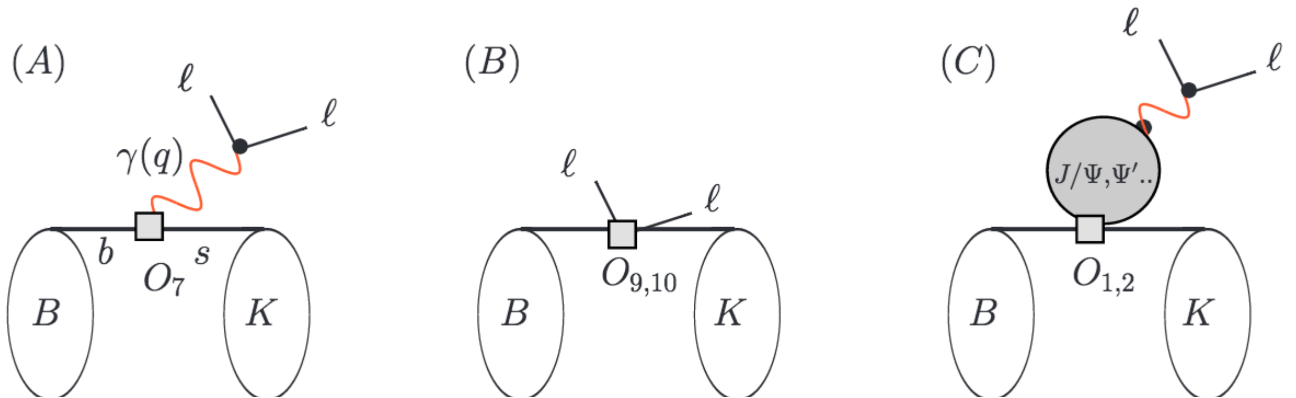
$$\mathcal{O}_7^{(\prime)} = \frac{e}{16\pi^2}\, m_b \left(\bar{s}\sigma_{\alpha\beta} P_{R(L)} b\right) F^{\alpha\beta}\,, \qquad C_7^{SM} = -0.319,$$

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

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

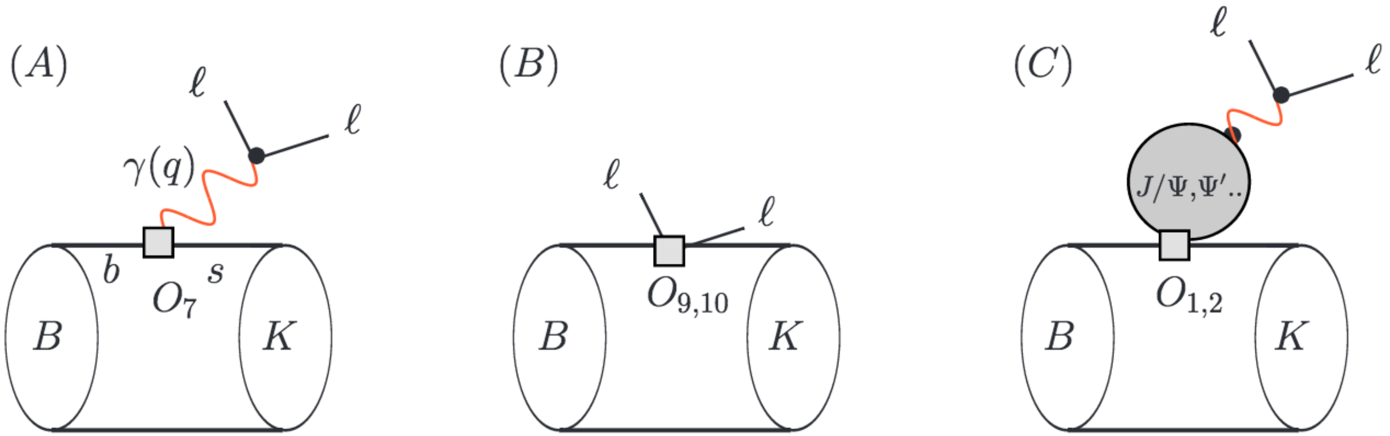
SM gives lepton flavour universal contribution

- Relevant contribution, add hadronic weak interaction



[figure from Lyon,Zwicky, 1406.0566]

Theoretical uncertainties



1. From factors, however at low q^2 can use Ligh-Cone Sum Rules (LCSR) and at high q^2 lattice result [Ball, Zwicky hep-ph/0412079, Horgan, Liu, Meinel, Wingate arXiv:1310.3722, arXiv:1310.3887]

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

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

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

“Ad hoc fix” $C_9 \to C_9^{eff} = C_9 + Y(q^2)$

From now on, I assume New Physics, SM prediction and numerical analysis I will use

[Altmannshofer, Straub, 1411.3161]

Fits

Coeff.	best fit	1σ	2σ	$\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}$
C_7^{NP}	-0.05	$[-0.08, -0.02]$	$[-0.11, 0.01]$	3.2
C_7'	-0.05	$[-0.14, 0.04]$	$[-0.22, 0.13]$	0.3
C_9^{NP}	-1.31	$[-1.65, -0.95]$	$[-1.98, -0.58]$	12.9
C_9'	0.26	$[-0.02, 0.53]$	$[-0.29, 0.81]$	0.9
C_{10}^{NP}	0.60	$[0.32, 0.90]$	$[0.06, 1.23]$	5.1
C_{10}'	-0.18	$[-0.40, 0.03]$	$[-0.62, 0.24]$	0.7
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.09	$[-0.36, 0.20]$	$[-0.61, 0.53]$	0.1
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.55	$[-0.74, -0.36]$	$[-0.95, -0.19]$	9.7
$C_9' = C_{10}'$	-0.06	$[-0.36, 0.24]$	$[-0.67, 0.52]$	0.
$C_9' = -C_{10}'$	0.13	$[-0.00, 0.25]$	$[-0.13, 0.38]$	0.9

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

[Fits by various groups,
Gosh, MN, Renner, 1408.4097,
Hurth, el al., 1410.4545,
Altmannshofer, Straub, 1411.3161]

- Assuming only one source of NP at high scale, data prefers effects in the muon sector
- If only one Wilson coefficient is allowed to be non vanishing, various groups agree that NP in $\mathcal{O}_9^\mu$ is preferred by the data $C_9^{\mu,NP} \simeq -1$

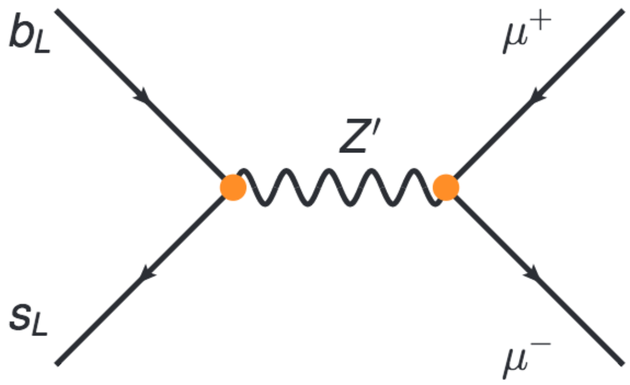
in C_9 is preferred by the data: $C_9 \approx -1$

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

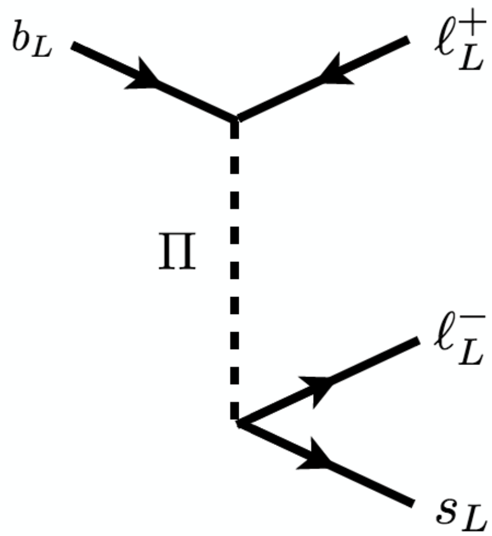
$$\begin{matrix} \bar{\ell}\gamma^\alpha \ell \\ \bar{\ell}\gamma^\alpha\gamma_5 \ell \end{matrix} \longrightarrow \begin{matrix} \bar{\ell}_L\gamma^\alpha \ell_L \\ \bar{\ell}_R\gamma^\alpha \ell_R \end{matrix}$$

Best Fit with Left-Left currents $\quad C_9^{\mu,NP} = -C_{10}^{\mu,NP}$

Simplified Models



Altmannshofer, et al. 1403.1269
Glashow, Guadagnoli, Lane 1411.0565
Altmannshofer, Straub 1411.3161
Niehoff, Stangl, Straub 1503.03865
…….



Hiller, Schmaltz, et al. 1403.1269
Gripaios. MN, Renner 1411.0565
Becirevic, Fajfer, Kosnic, 1503.09024
…….

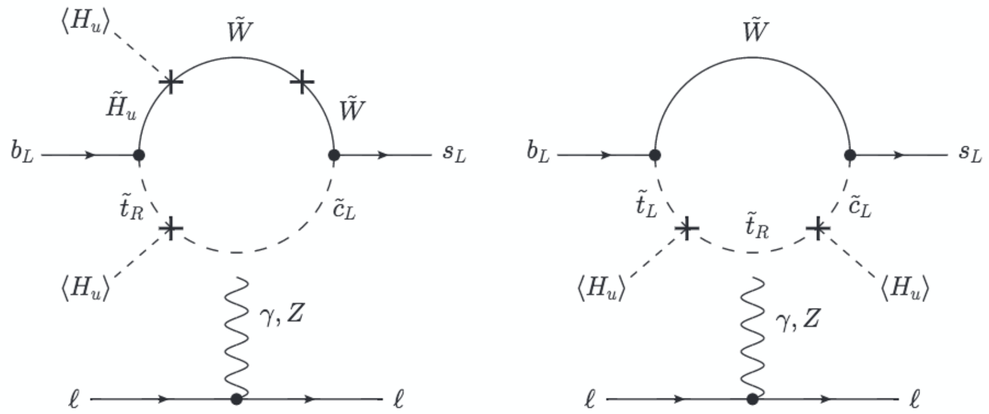
• New Physics at the LHC motived by Naturalness problem of the EW scale

Which is the interpretation of these anomalies in the context of SUSY and Composite Higgs?

MSSM

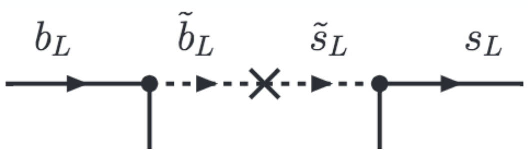
• $B \to K^* \mu^+ \mu^-$

Altmannshofer, Straub
arXiv:1308.1501, arXiv:1411.3161

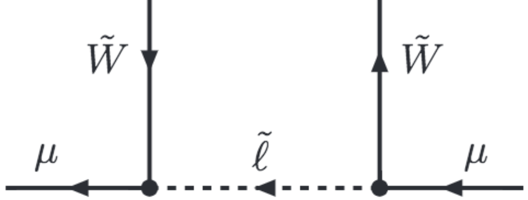


• Large effects possible in C_{10}^Z
• Better than SM but worse than NP in C_9^μ
• Lepton universal

• R_K



• Lepton universality is broken by slepton masses $m_{\tilde{e}} \gg m_{\tilde{\mu}}$
• Box diagrams are numerically small, very light particles in



• Box diagrams are numerically small, very light particles in the loop

• Direct searches (LHC+LEP) give strong constraints, probably no holes left (but a careful analysis is required)

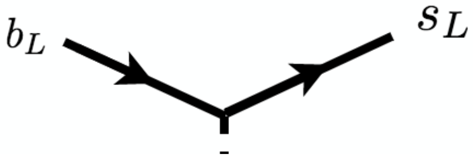
The LHCb results suggest an extensions of the MSSM

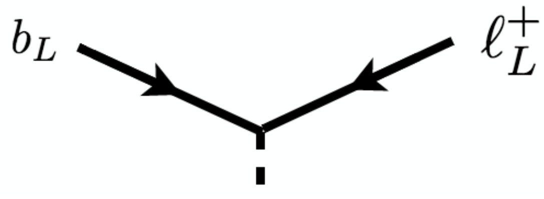
Composite Higgs

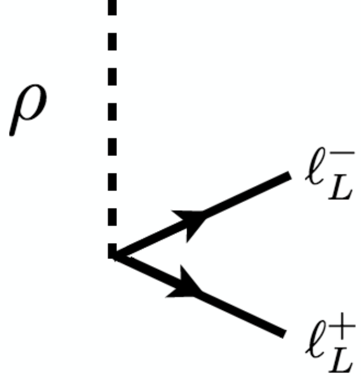
Strong sector	$\hat{\mathcal{O}}$ g_ρ, m_ρ	$\epsilon \hat{\mathcal{O}} f$ ⟷	$f \sim \mathrm{SM}$	Elementary sector

• The Higgs is a pseudo Goldstone boson

• Possible contributions to semileptonic B decays

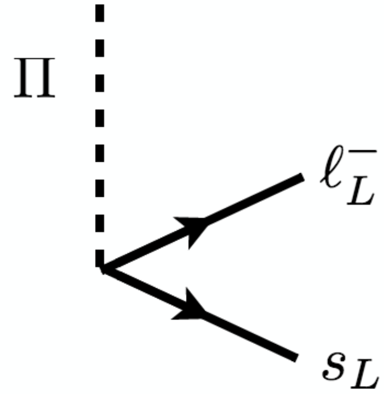






- Spin-1 Vector exchange

Niehoff, Stangl, Straub
1503.03865

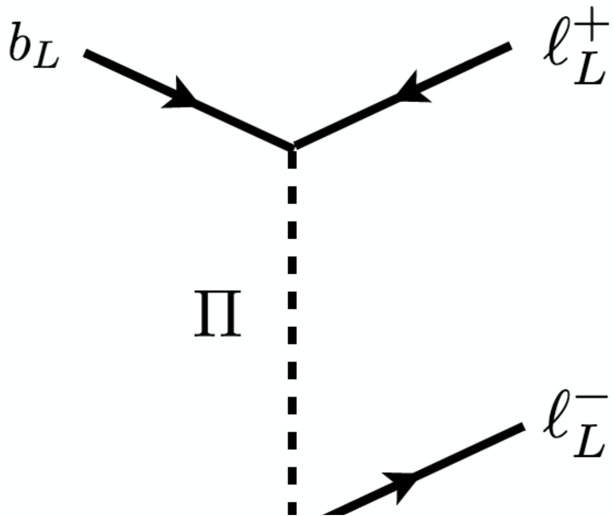


- Scalar leptoquark

Based on 1412.5942, JHEP,
Ben Gripaios and Sophie Renner

New Physics (Model Dependent)

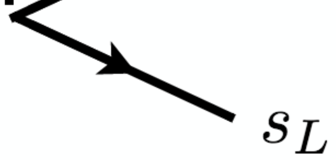
- A leptoquark interpretation   Hiller, Schmaltz 1408.1627



- Quantum number of the new states, uniquely determined by the the Left-Left structure

$$\Pi \sim (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

$$\lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2\tau_a \ell_{Li}\, \Pi$$



- Anomalies are fitted when $\sqrt{|\lambda^*_{s\mu}\lambda_{b\mu}|} \simeq M/(48\,\mathrm{TeV})$

- Just two, non-vanishing leptoquark coupling

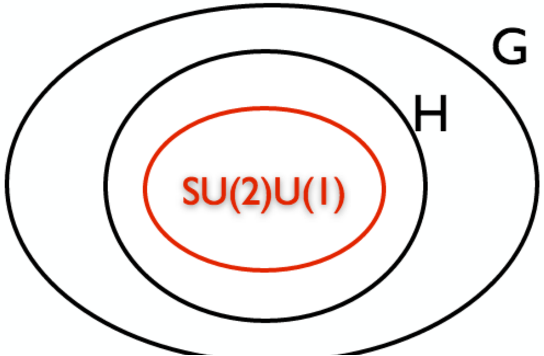
- Scale of New Physics not predicted

Composite Higgs

Georgi, Kaplan (1984)
Agashe, Contino, Pomarol hep-ph/0412089
Contino, 1005.4269
Bellazzini, Csaki, Serra 1401.2457

- The Higgs is a pseudo Goldstone boson

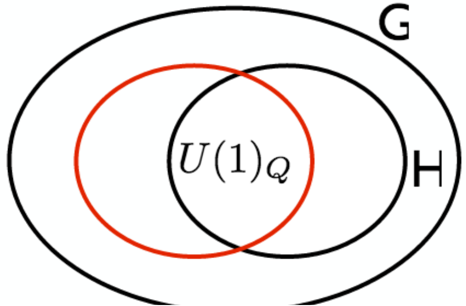
- Pattern of symmetry breaking:



$$G \underset{f>v}{\longrightarrow} H$$

by strong interactions g_ρ, m_ρ

Comparing with TC



- Explicit breaking of G due to the Yukawa sector and an effective potential for H is generated:
    1. EW symmetry is broken
    2. Higgs mass is generated

$$V(H) \sim \frac{m_\rho^4}{g_\rho^2} \times \frac{y_{L,R}^2}{16\pi^2} \times \hat{V}(H/f)$$

- EW tuning is characterised by $\xi \equiv \frac{v^2}{f^2}$

- Minimal realisation
    1. H contains EW group and the custodial symmetry $H = SO(4)$
    2. G/H contains only one Higgs doublet $G/H = SO(5)/SO(4)$

Theoretical Framework

Strong sector

$\hat{\mathcal{O}}$

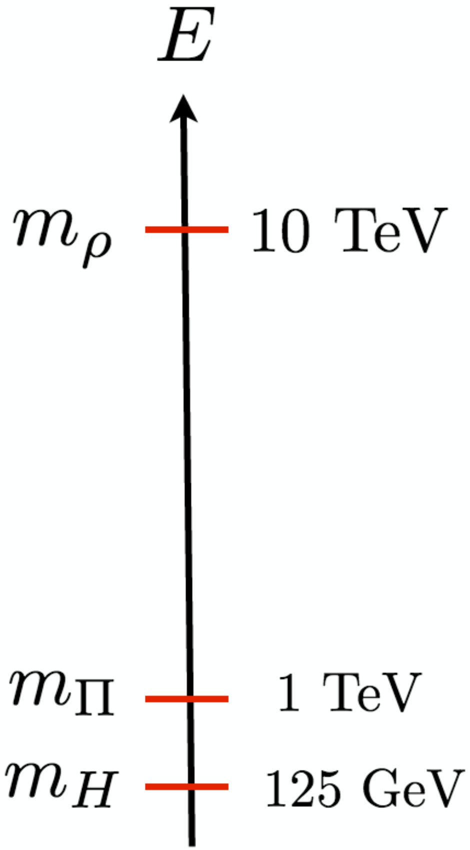
Π, H

g_ρ, m_ρ

$\epsilon \hat{\mathcal{O}} f$ ⟷

$f \sim \mathrm{SM}$

Elementary sector



- 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 (…)

Leptoquarks as PNGB

- Partial compositeness requires the presence of coloured composite state, plausible to expect coloured PNGB

Gripaios 0910.1789

- Depending on the quantum numbers of the PNGB, diquark and leptoquark couplings are expected

Gripaios, Giudice, Sundrum 1105.3189

- Colour gauge group can be part of the symmetries of the strong sector (in analogously to the EW group)
- Coset structure $(\mathbf{1},\mathbf{2},1/2)+(\overline{\mathbf{3}},\mathbf{3},1/3)+(\mathbf{3},\mathbf{3},-1/3)$

$$SO(5)\to SU(2)_H\times SU(2)_R \qquad H\sim(\mathbf{2},\mathbf{2})$$

$$SO(9)\to SU(4)\times SU(2)_\Pi \qquad (\Pi+\Pi^\dagger)\sim(\mathbf{6},\mathbf{3})$$

- SM embedding

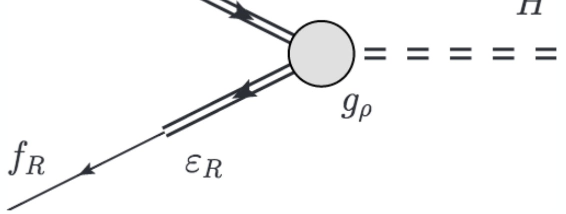
$$\begin{array}{rcl} SU(3)_C\times U(1)_\psi & \supset & SU(4) \\ SU(2)_L & = & (SU(2)_H\times SU(2)_\Pi)_D \\ T_Y & = & -\frac{1}{2}T_\psi+T_{3R} \end{array}$$

- Mass term generated by the colour gauge interactions $m_\Pi^2\sim\frac{\alpha_s}{4\pi}m_\rho^2$

Partial Compositeness in CH models

- Yukawa sector:

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

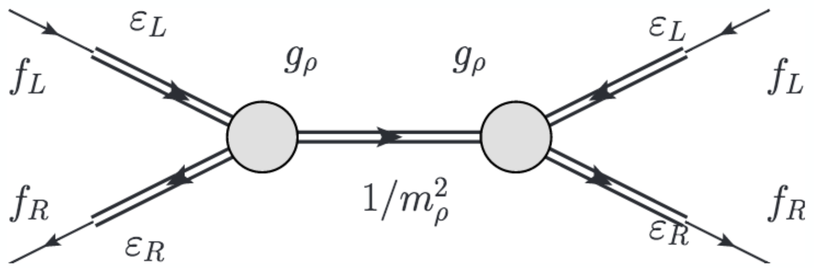


$$\mathcal{L}_{\rm comp} = \mathcal{L}_{\rm comp}(g_\rho, m_\rho, H)$$

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

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

- 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

- Focus on Leptoquark resonance

Parameters (quark sector)

- Yukawas are given by

$$(Y_u)_{ij} \sim g_\rho \epsilon^q_i \epsilon^u_j \qquad (Y_d)_{ij} \sim g_\rho \epsilon^q_i \epsilon^d_j$$

$$(Y_u)_{ij} \sim g_\rho \epsilon_i \epsilon_j \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i \epsilon_j$$

- And diagonalized by

$$(L_u^\dagger Y_u R_u)_{ij} = g_\rho \epsilon_i^u \epsilon_i^q \delta_{ij} \equiv y_i^u \delta_{ij} \,, \qquad (L_d^\dagger Y_d R_d)_{ij} = g_\rho \epsilon_i^d \epsilon_i^q \delta_{ij} \equiv y_i^d \delta_{ij} \,,$$

$$(L_u)_{ij} \sim (L_d)_{ij} \sim \min\left(\frac{\epsilon_i^q}{\epsilon_j^q}, \frac{\epsilon_j^q}{\epsilon_i^q}\right) \,, \qquad (R_{u,d})_{ij} \sim \min\left(\frac{\epsilon_i^{u,d}}{\epsilon_j^{u,d}}, \frac{\epsilon_j^{u,d}}{\epsilon_i^{u,d}}\right)$$

- Link with the CKM $\quad V_{CKM} = L_d^\dagger L_u \sim L_{u,d}$

$$\frac{\epsilon_1^q}{\epsilon_2^q} \sim \lambda \qquad \frac{\epsilon_2^q}{\epsilon_3^q} \sim \lambda^2 \qquad \frac{\epsilon_1^q}{\epsilon_3^q} \sim \lambda^3$$

- Everything is fixed up to 2 parameters

$$g_\rho, \epsilon_i^q, \epsilon_i^u, \epsilon_i^d \qquad 1+3+3+3=10$$

$$m_i^u, m_i^d, V_{CKM} \qquad 3+3+2=8$$

(g_ρ, ϵ_3^q) in what follows

Lepton sector

- Yukawas for charged leptons $\quad (Y_e)_{ij} \sim g_\rho \epsilon_i^\ell \epsilon_j^e,$

• Parameters cannot be univocally connected to physical inputs, due to our ignorance on neutrino masses

• The phenomenologically most favourable scenario is obtained when

$$\frac{\epsilon_i^\ell}{\epsilon_j^\ell} \sim \frac{\epsilon_i^e}{\epsilon_j^e} \sim \sqrt{\frac{m_i^e}{m_j^e}}.$$

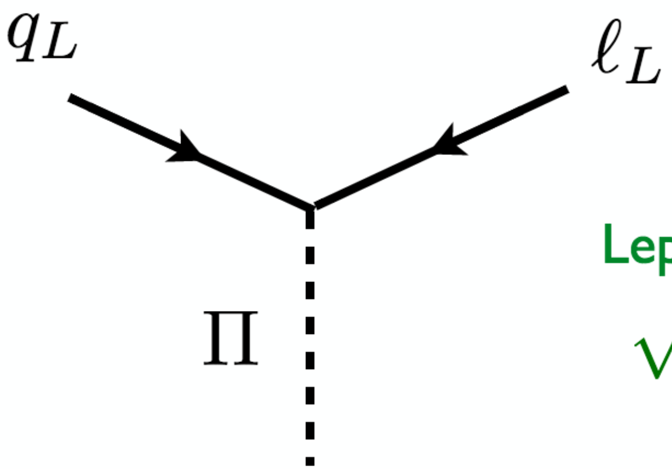
• We will assume that left (ϵ_i^ℓ) and right (ϵ_i^e) mixings have similar size

Mixing Parameter	Value
$\epsilon_1^q = \lambda^3 \epsilon_3^q$	$1.15 \times 10^{-2}\, \epsilon_3^q$
$\epsilon_2^q = \lambda^2 \epsilon_3^q$	$5.11 \times 10^{-2}\, \epsilon_3^q$
$\epsilon_1^u = \frac{m_u}{v g_\rho} \frac{1}{\lambda^3 \epsilon_3^q}$	$5.48 \times 10^{-4}/(g_\rho \epsilon_3^q)$
$\epsilon_2^u = \frac{m_c}{v g_\rho} \frac{1}{\lambda^2 \epsilon_3^q}$	$5.96 \times 10^{-2}/(g_\rho \epsilon_3^q)$
$\epsilon_3^u = \frac{m_t}{v g_\rho} \frac{1}{\epsilon_3^q}$	$0.866/(g_\rho \epsilon_3^q)$
$\epsilon_1^d = \frac{m_d}{v g_\rho} \frac{1}{\lambda^3 \epsilon_3^q}$	$1.24 \times 10^{-3}/(g_\rho \epsilon_3^q)$
$\epsilon_2^d = \frac{m_s}{v g_\rho} \frac{1}{\lambda^2 \epsilon_3^q}$	$5.29 \times 10^{-3}/(g_\rho \epsilon_3^q)$
$\epsilon_3^d = \frac{m_b}{v g_\rho} \frac{1}{\epsilon_3^q}$	$1.40 \times 10^{-2}(g_\rho \epsilon_3^q)$
$\epsilon_1^\ell = \epsilon_1^e = \left(\frac{m_e}{g_\rho v}\right)^{1/2}$	$1.67 \times 10^{-3}/g_\rho^{1/2}$
$\epsilon_2^\ell = \epsilon_2^e = \left(\frac{m_\mu}{g_\rho v}\right)^{1/2}$	$2.43 \times 10^{-2}/g_\rho^{1/2}$
$\epsilon_3^\ell = \epsilon_3^e = \left(\frac{m_\tau}{g_\rho v}\right)^{1/2}$	$0.101/g_\rho^{1/2}$

Flavour Violation & Leptoquarks

- Comment later about the flavour physics associated with m_ρ
- Relevant Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + (D^\mu \Pi)^\dagger D_\mu \Pi - M^2 \Pi^\dagger \Pi + \lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2 \tau_a \ell_{Li}\, \Pi + \text{ h.c.}$$



Quarks →

Leptons $\sqrt{Y_\ell}$ ↓

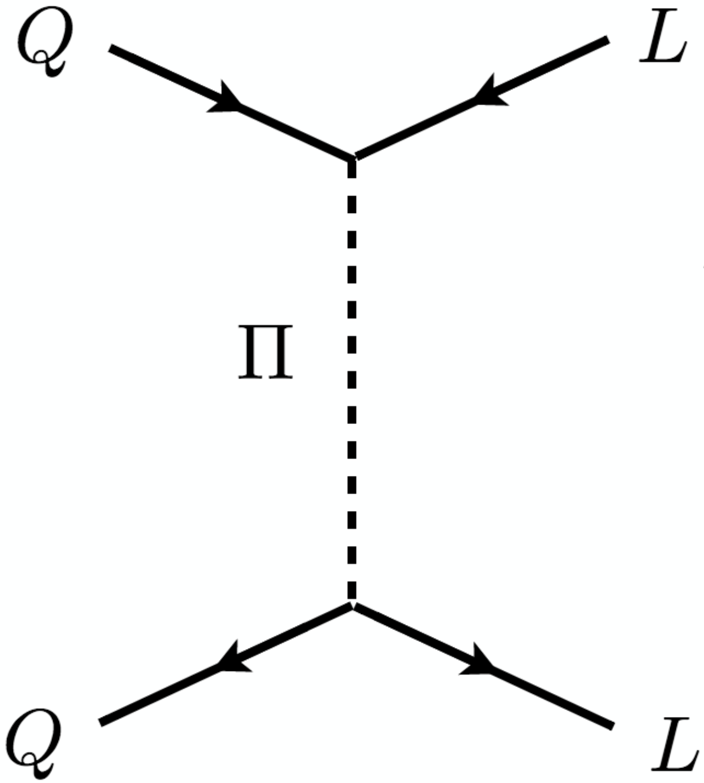
$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

- c are O(1) parameters
- Only 3 fundamental parameters reduced to a single combination in all the flavour observable! $(g_\rho, \epsilon_3^q, M) \to \sqrt{g_\rho}\epsilon_3^q / M$

Flavour violation at the tree level

Flavour violation at the tree level

- Integrating away the leptoquarks fields we get



$$\mathcal{L}_{LQ}^{eff} = \sum_{ij\ell k} \frac{\lambda_{ij}(\lambda_{\ell k})^*}{2M^2} \Big[2\left(\overline{d}_L \gamma^\mu d_L\right)_{kj} \left(\overline{e}_L \gamma_\mu e_L\right)_{\ell i} + 2\left(\overline{u}'_L \gamma^\mu u'_L\right)_{kj} \left(\overline{\nu}_L \gamma_\mu \nu_L\right)_{\ell i}$$

$$+ \left(\overline{d}_L \gamma^\mu d_L\right)_{kj} \left(\overline{\nu}_L \gamma_\mu \nu_L\right)_{\ell i} + \left(\overline{u}'_L \gamma^\mu u'_L\right)_{kj} \left(\overline{e}_L \gamma_\mu e_L\right)_{\ell i}$$

$$+ \left(\overline{u}'_L \gamma^\mu d_L\right)_{kj} \left(\overline{e}_L \gamma_\mu \nu_L\right)_{\ell i} + \left(\overline{d}_L \gamma^\mu u'_L\right)_{kj} \left(\overline{\nu}_L \gamma_\mu e_L\right)_{\ell i} \Big] ,$$

$$u_L'^{j} = V_{CKM}^{\dagger jk} u_L^k$$

- "Vertical" correlations induced by SM gauge invariance
- "Horizontal" correlations induced by partial compositeness

Fit to the anomalies

- The analysis of $b \to s\mu^+\mu^-$ observable gives

$$C_9^{NP\mu} = -C_{10}^{NP\mu} \in [-0.84, -0.12] \quad (\text{at } 2\sigma)$$

Altmannshofer, Straub 1411.3161

- In our framework gives

$$C_9^{\mu NP} = -C_{10}^{\mu NP} = \left[\frac{4G_F e^2 (V_{ts}^* V_{tb})}{16\sqrt{2}\pi^2}\right]^{-1} \frac{\lambda_{22}^* \lambda_{23}}{2M^2} = -0.49\, c_{22}^* c_{23} (\epsilon_3^q)^2 \left(\frac{M}{\text{TeV}}\right)^{-2} \left(\frac{g_\rho}{4\pi}\right)$$

$$\text{Re}(c_{22}^* c_{23}) \in [0.24, 1.71] \left(\frac{4\pi}{g_\rho}\right) \left(\frac{1}{\epsilon_3^q}\right)^2 \left(\frac{M}{\text{TeV}}\right)^2 \quad (\text{at } 2\sigma)$$

- Due to the partial compositeness structure, negligible contribution to observables involving electrons like $\text{BR}(B \to K e^+ e^-)$. R_K is easily accommodated.

- 3 immediate implications

1) the composite sector is genuinely strong interacting, $g_\rho \sim 4\pi$
2) that left-handed quark doublet should be largely composite, $\epsilon_3^q \sim 1$
3) the mass of the leptoquark states should be low, $M \lesssim 1$ TeV

Predictions

- We expect large effects coming from third families of leptons

Lepton $\sqrt{Y_\ell}$ ↓

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

- Decay channels with taus are difficult to be reconstructed $b \to s\tau^+\tau^-$

- More interesting are channels with tau neutrinos in the final state

Buras et al.
arXiv:1409.4557

$$R_K^{*\nu\nu} \equiv \frac{\mathcal{B}(B \to K^* \nu\overline{\nu})}{\mathcal{B}(B \to K^* \nu\overline{\nu})_{SM}} < 3.7,$$

$$R_K^{\nu\nu} \equiv \frac{\mathcal{B}(B \to K \nu\overline{\nu})}{\mathcal{B}(B \to K \nu\overline{\nu})_{SM}} < 4.0.$$

- Considering just $B \to K^* \overline{\nu}_\mu \nu_\mu$ gives

$$\Delta R_K^{(*)\nu\nu} < \text{ few } \%$$

- Including $\mathrm{BR}(B \to K \nu_\tau \overline{\nu}_\tau)$, large deviation $\Delta R_K^{(*)\nu\nu} \sim 50\%$

Testable at Belle II   See 1002.5012

Predictions

- Rare Kaon decay

Hurt et al 0807.5039
NA62 1411.0109

$$\mathcal{B}(K^+ \to \pi^+ \nu\nu) = 8.6(9) \times 10^{-11}[1 + 0.96\delta C_{\nu\bar{\nu}} + 0.24(\delta C_{\nu\bar{\nu}})^2]$$

Present bound $\delta C_{\nu\bar{\nu}} \in [-6.3, 2.3]$ NA62 expected sensitivity $\delta C_{\nu\bar{\nu}} \in [-0.2, 0.2]$

Composite leptoquark prediction $$\delta C_{\nu\bar{\nu}} = 0.62\ \mathrm{Re}(c_{31}c_{32}^*) \left(\frac{g_\rho}{4\pi}\right) (\epsilon_3^q)^2 \left(\frac{M}{\mathrm{TeV}}\right)^{-2}$$

- Radiative decay $\mu \longrightarrow e\gamma$

$$|c_{23}^* c_{13}| < 1.4 \left(\frac{4\pi}{g_\rho}\right) \left(\frac{M}{\mathrm{TeV}}\right)^2 \left(\frac{1}{\epsilon_3^q}\right)^2$$

- Meson mixing ΔM_{B_s}

$$\left(\frac{4\pi}{\ldots}\right)^2 \left(\frac{M}{\ldots}\right)^2 \left(\frac{1}{\ldots}\right)^4$$

$$|c_{33}c_{23}^*| < 4.2 \left(\frac{4\pi}{g_\rho}\right) \left(\frac{M}{\text{TeV}}\right) \left(\frac{1}{\epsilon_3^q}\right)$$

Constraints

Decay	(ij)(kl)*	$\lvert\lambda_{ij}\lambda_{kl}^*\rvert / \left(\frac{M}{\text{TeV}}\right)^2$	$\lvert c_{ij}c_{kl}^*\rvert \left(\frac{g_\rho}{4\pi}\right)(\epsilon_3^q)^2 / \left(\frac{M}{\text{TeV}}\right)^2$
$K_S \to e^+e^-$	(12)(11)*	< 1.0	$< 4.9 \times 10^7$
$K_L \to e^+e^-$	(12)(11)*	$< 2.7 \times 10^{-3}$	$< 1.3 \times 10^5$
† $K_S \to \mu^+\mu^-$	(22)(21)*	$< 5.1 \times 10^{-3}$	$< 1.2 \times 10^3$
$K_L \to \mu^+\mu^-$	(22)(21)*	$< 3.6 \times 10^{-5}$	< 8.3
$K^+ \to \pi^+e^+e^-$	(11)(12)*	$< 6.7 \times 10^{-4}$	$< 3.3 \times 10^4$
$K_L \to \pi^0e^+e^-$	(11)(12)*	$< 1.6 \times 10^{-4}$	$< 7.8 \times 10^3$
$K^+ \to \pi^+\mu^+\mu^-$	(21)(22)*	$< 5.3 \times 10^{-3}$	$< 1.2 \times 10^3$
$K_L \to \pi^0\nu\bar{\nu}$	(31)(32)*	$< 3.2 \times 10^{-3}$	< 42.5
† $B_d \to \mu^+\mu^-$	(21)(23)*	$< 3.9 \times 10^{-3}$	< 46.0
$B_d \to \tau^+\tau^-$	(31)(33)*	< 0.67	$< 4.6 \times 10^2$
† $B^+ \to \pi^+e^+e^-$	(11)(13)*	$< 2.8 \times 10^{-4}$	$< 6.9 \times 10^2$
† $B^+ \to \pi^+\mu^+\mu^-$	(21)(23)*	$< 2.3 \times 10^{-4}$	< 2.7

- With a breaking of lepton universality is generically associated a breaking of the lepton flavour. [Glashow, Guadagnoli, Lane, 1411.0565]

- In our framework, all the LFV decays are below the current experimental sensitivity

Naturalness

- From the B-meson decays anomalies we get $M \sim \ 1 \text{ TeV}, \ g_\rho \sim 4\pi$

- We can infer the scale of the strong sector from $M \sim \frac{\alpha_s}{4\pi} m_\rho^2 \longrightarrow \quad m_\rho \sim 10 \text{ TeV}$

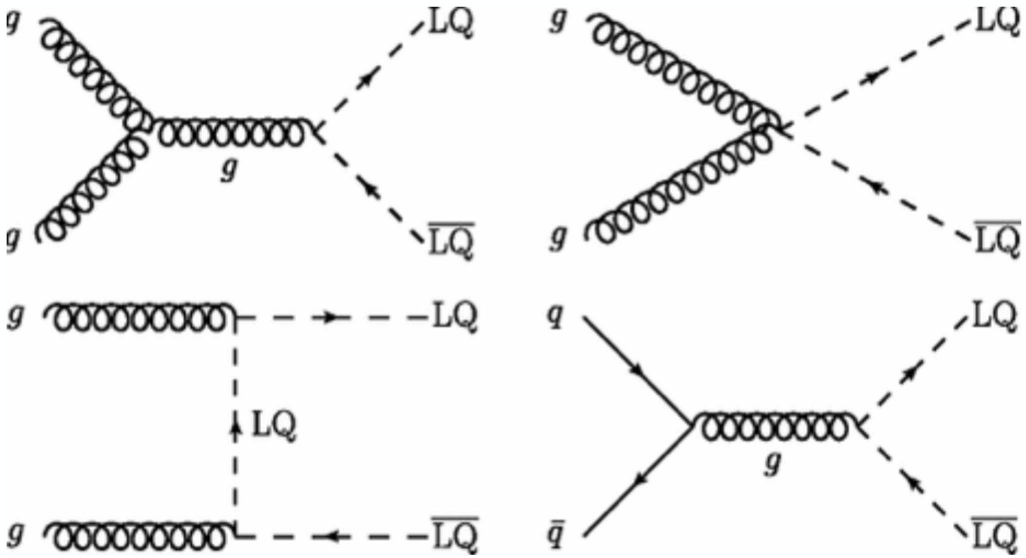
- Flavour physics is (almost) fine in the quark sector, but we need a departure from flavour anarchy in the lepton sector See Rattazzi, etal. arXiv:1205.5803

- Higgs potential $V(H) \sim \frac{3}{4\pi^2} (\epsilon_3^{q,u})^2 m_\rho^4 \, \overline{V} \left(\frac{g_\rho H}{m_\rho} \right)$

natural value $v \sim f = \frac{m_\rho}{g_\rho} \sim 1 \text{ TeV}$ EW tuning $\xi \equiv \frac{v^2}{f^2} = \text{few}\%$

- In general, a larger tuning is required to obtain a light physical Higgs

LHC



- Production via strong interaction

- Decay to fermions of the third family

- Stop and sbottom +

$$\Pi_{4/3} \to \overline{\tau}\, b, \quad M > 720 \text{ GeV}$$

$$\Pi_{1/3} \to \overline{\tau}\, \bar{t} \text{ or } \Pi_{1/3} \to \overline{\nu_\tau}\, \bar{b}, \quad M > 410 \text{ GeV}$$

$$\Pi_{-2/3} \to \overline{\nu_\tau}\, \bar{t}. \quad M > 640 \text{ GeV}$$

dedicated leptoquark searches

[ATLAS arXiv:1407.0583]
[CMS arXiv:1408.0806]
[CMS-PAS-EXO-13-010]

$$M > 720 \text{ GeV}$$

Conclusions

- Still premature to claim a discovery of New Physics

- Current anomalies in B decays have as simple and economic interpretation at the EFT level, NP in the muon sector

- Can be explained in the context of a composite Higgs model featuring an additional (light) leptoquark as pseudo-Goldstone boson.

- Considering the present sensitivity and the future prospects, indirect effects could show up in various observables:

$$\mathrm{BR}(B \to K^{(*)}\nu\overline{\nu}),\ \mathrm{BR}(K^+ \to \pi^+\nu\overline{\nu}),\ \mathrm{BR}(\mu \to e\gamma)$$

- Composite leptoquarks could be within the reach of LHC13

- Tuning is below the *per cent* level