Flavour physics after LHC-1, what's next?

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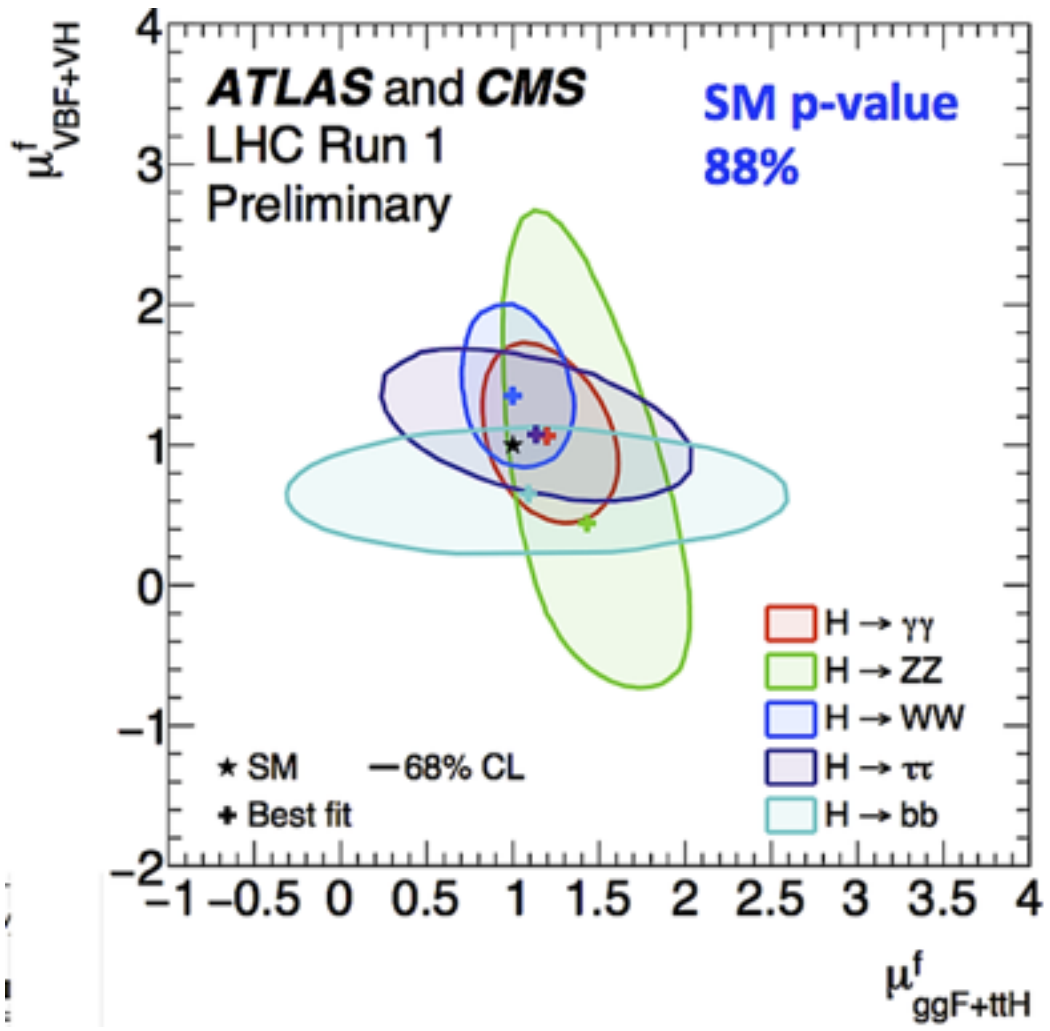
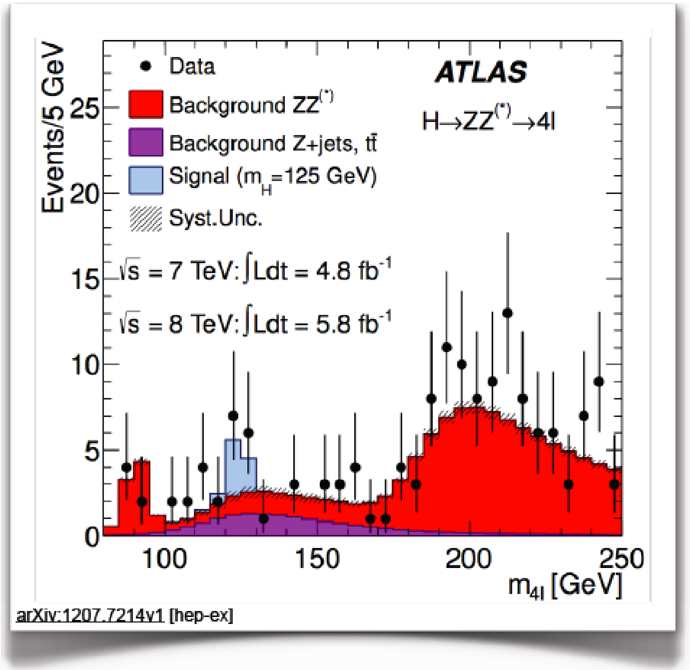
Outline

- (Minimal) Flavour Violation after LHC-1
- “Anomalies” in semileptonic B-decays
- New Physics
- Conclusions

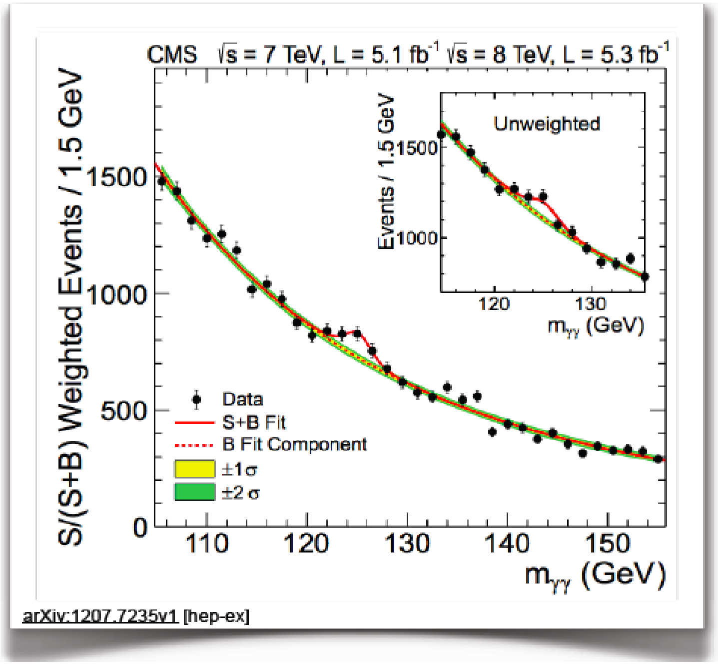
After LHC-1

1) Discovery of a SM Higgs-like scalar*



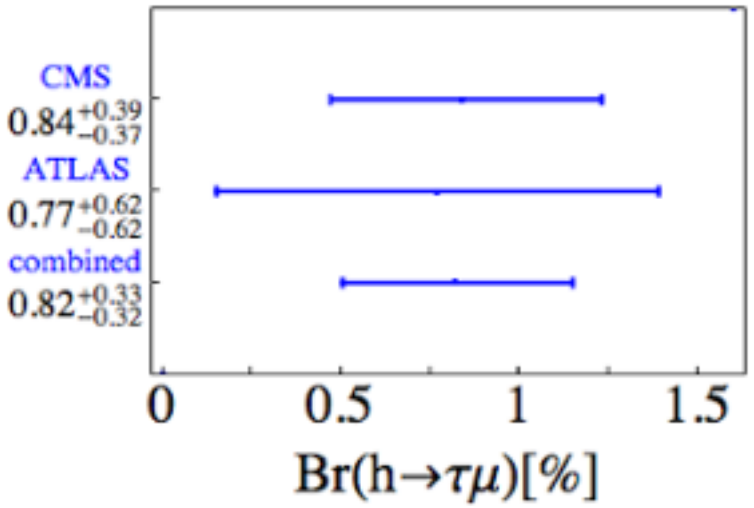


arXiv:1207.7214v1 [hep-ex]



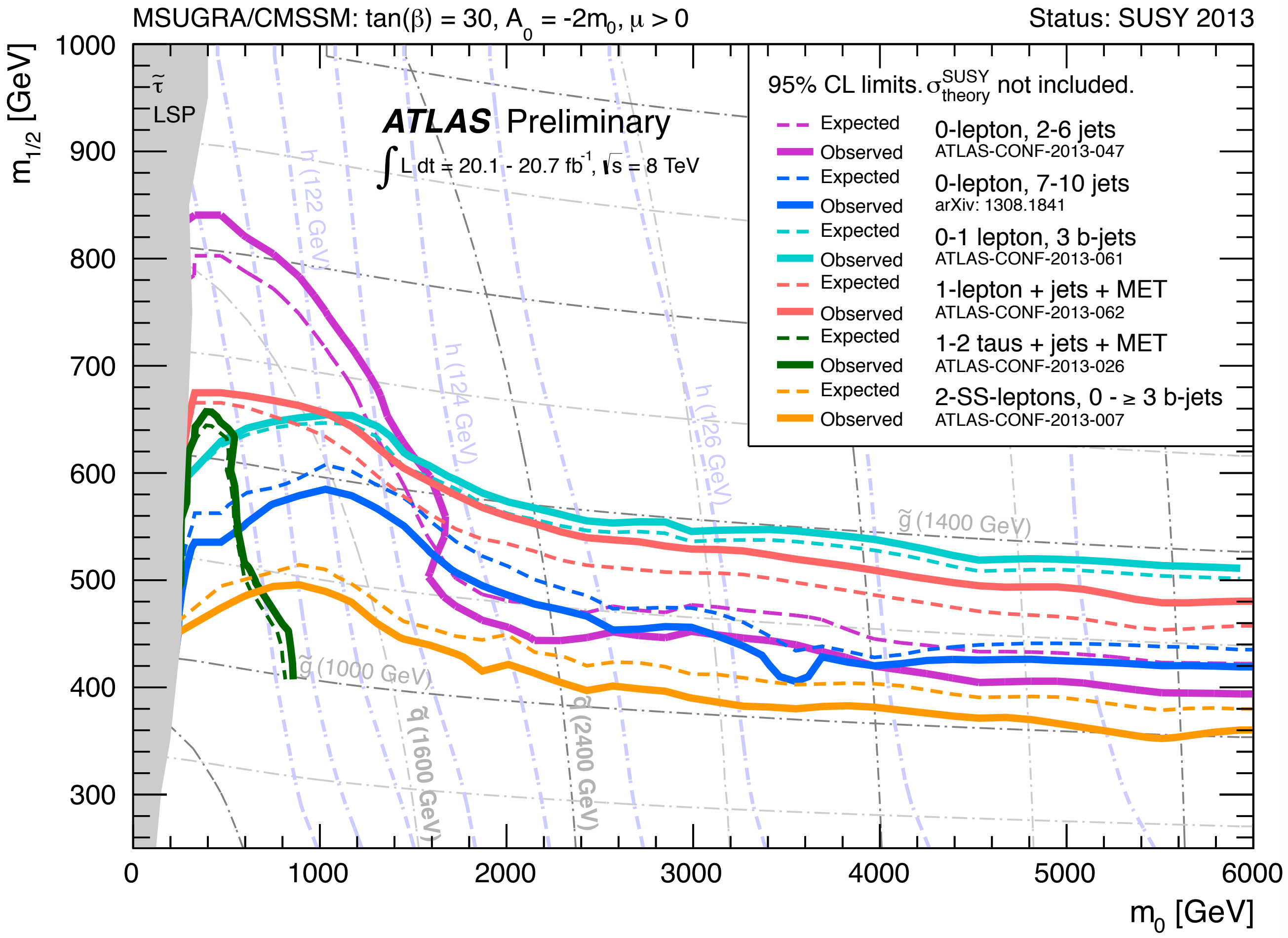
arXiv:1207.7235v1 [hep-ex]

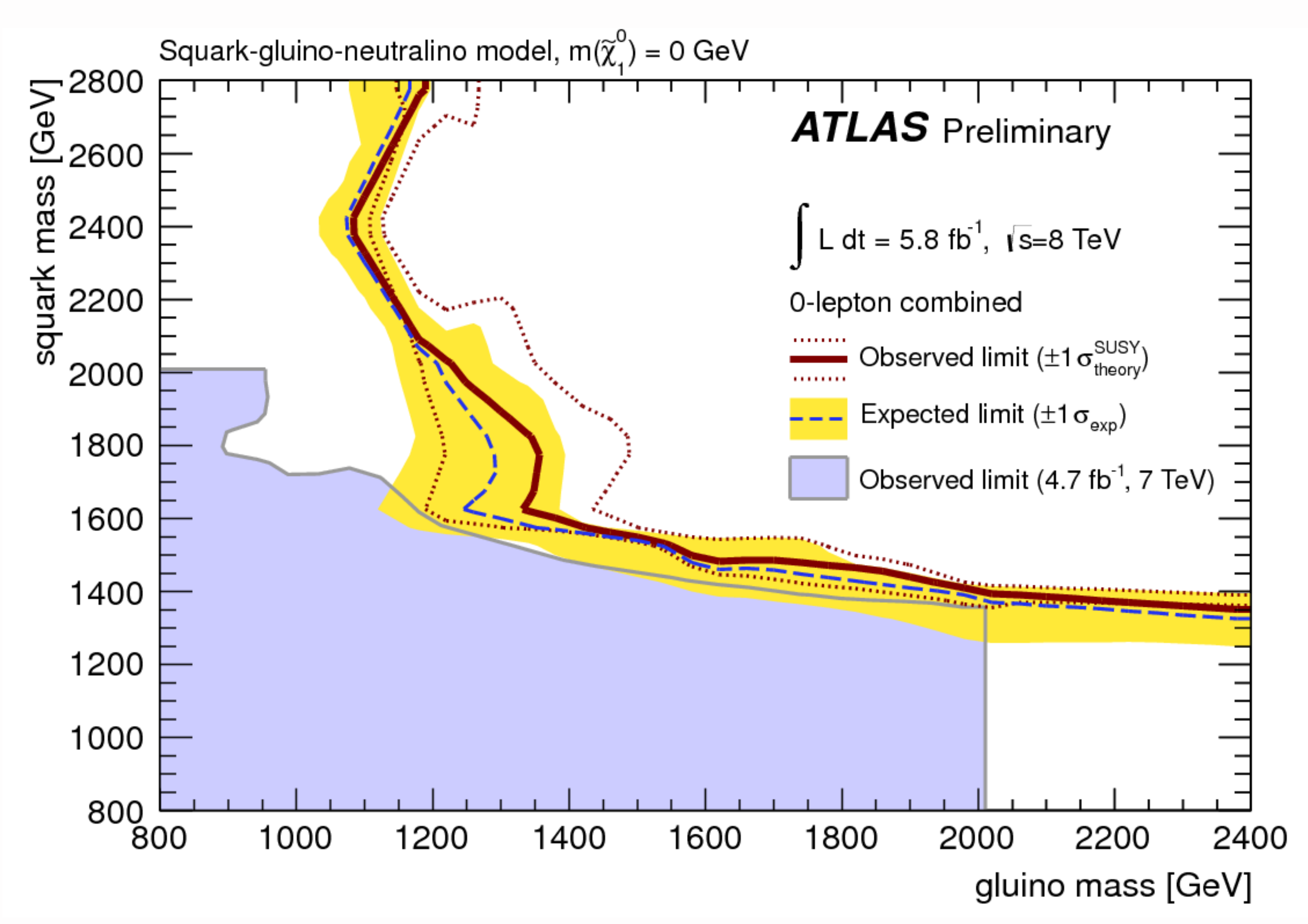
*however see CMS 1502.07400 and ATLAS 1508.03372



After LHC-1

2) No evidence of New Physics from direct searches*





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

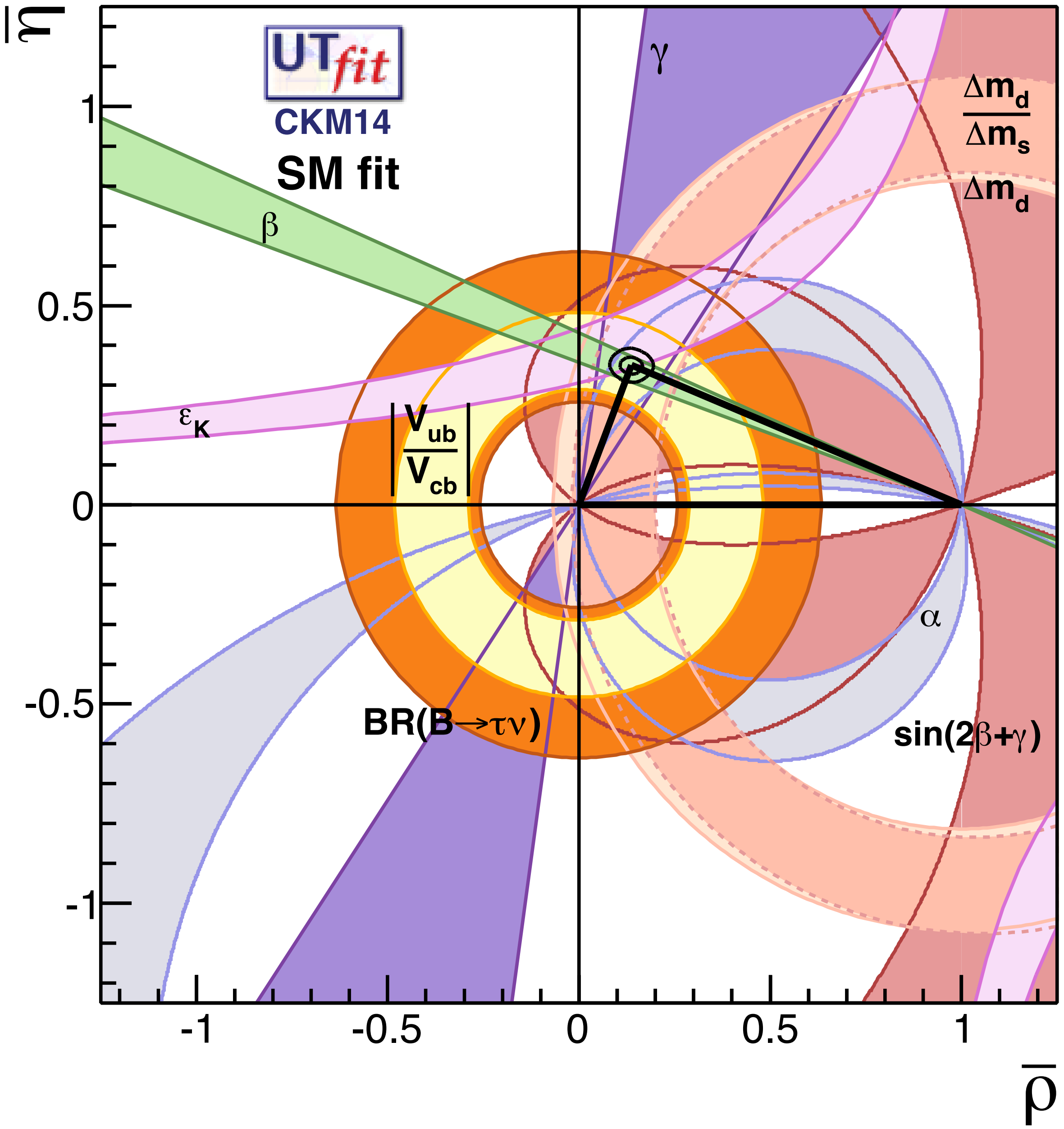
* however see the very recent di-bosons story triggered by ATLAS 1506.00962

A spin-1 resonances at around 1.8 TeV?

$$pp \to X \to V_{SM} V_{SM} \to (JJ)$$

After LHC-I

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



*more details in a few slides

New Physics

- 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

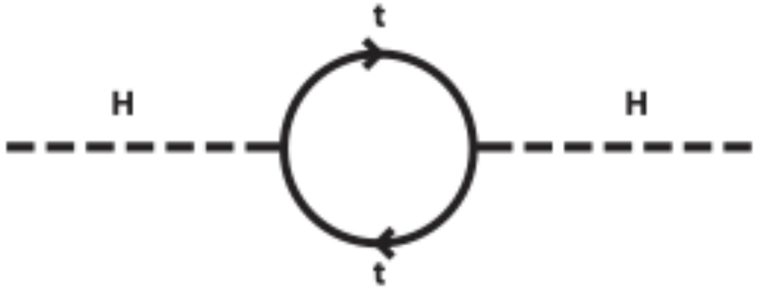
- However we have some indications….

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, ...)

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

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



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

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

- Lower bounds from FCNC

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

- 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, Giudice, Isidori, Strumia
hep-ph/0207036

- MFV hypothesis consists in the assumptions that

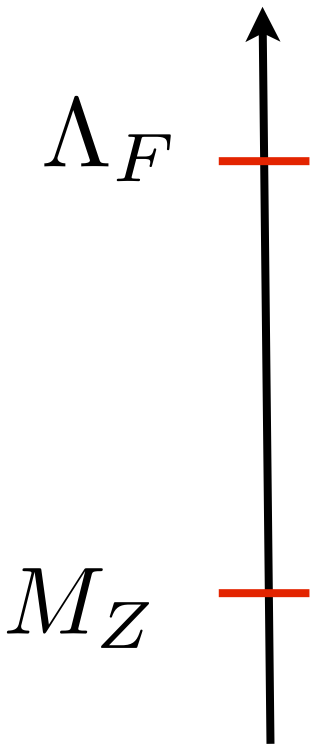
(i) the full EFT is formally invariant with respect to the flavor symmetry

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

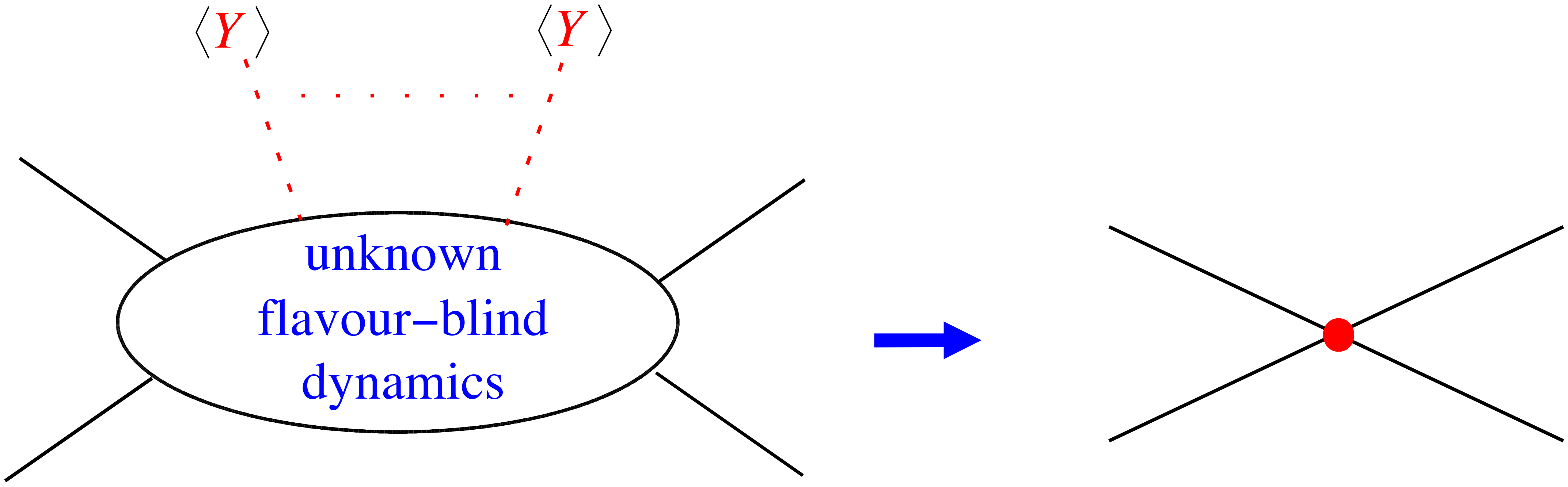
(ii) the SM Yukawa couplings are the only irreducible source of flavor breaking

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

Minimal Flavour Violation and UV



- Flavor Theory
- Flavor blind dynamics, RGE effects
- Low energy MFV lagrangian



MFV consequences

- Let us work in a basis where $y_u = V^\dagger_{\rm CKM}\frac{\hat{m}_u}{v}, \; y_d = \frac{\hat{m}_d}{v}, \; y_e = \frac{\hat{m}_e}{v}$

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

- Consequences

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

  (ii) predictive hypothesis with correlations among observables

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

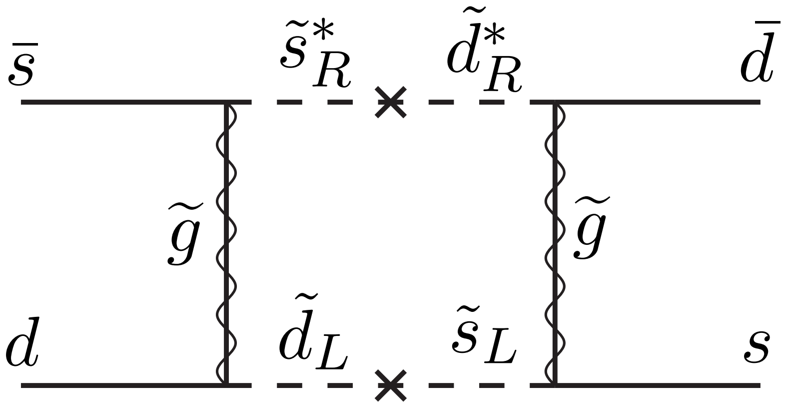
  (iv) there is no flavor violation in the lepton sector

Operator	Bound on Λ	Observables
$H^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)\left(eF_{\mu\nu}\right)$	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	$\epsilon_K,\ \Delta m_{B_d},\ \Delta m_{B_s}$
$H_D^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)\left(g_s G^a_{\mu\nu}\right)$	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	$B \to X_s\ell^+\ell^-,\ B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)\left(eD_\mu F_{\mu\nu}\right)$	1.5 TeV	$B \to X_s\ell^+\ell^-$

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

SUSY-MFV after LHC-1

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



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

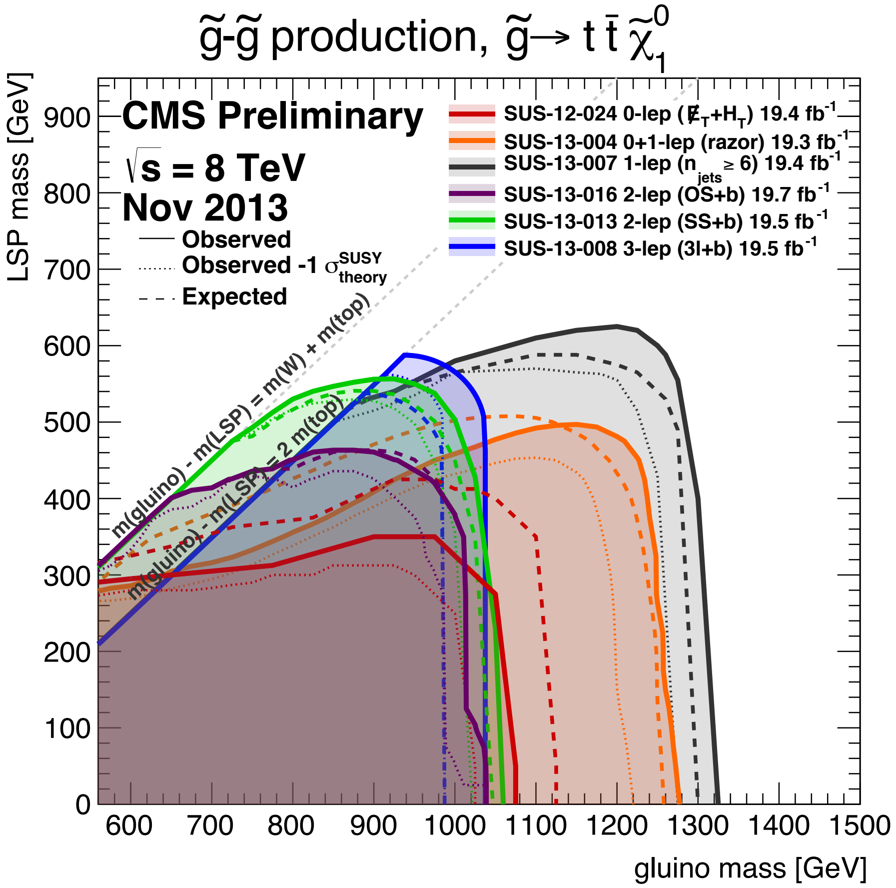
$$c_{ij} = \frac{\alpha_s}{4\pi}\left(y_u y_u^\dagger\right)_{ij}$$

$$\Lambda = m_{susy}$$

Flavour $m_{susy} > 500$ 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...

Flavor Structure

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%]

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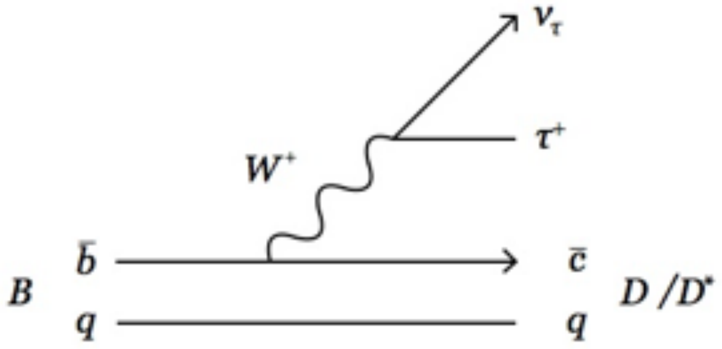
Anarchic	~~huge [> O(1)]~~	~~sizable [O(1)]~~	sizable/small [< O(1)]
Small misalignment (*e.g. partial compositeness*)	~~sizable [O(1)]~~	small [O(10%)]	small/tiny [O(1-10%)]
Aligned to SM (*MFV*)	~~small [O(10%)]~~	tiny [O(1%)]	not visible [< 1%]

Flavour Anomalies

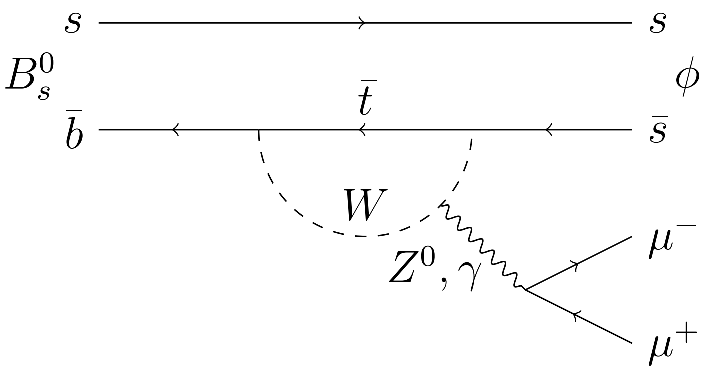
Two different set of measurements

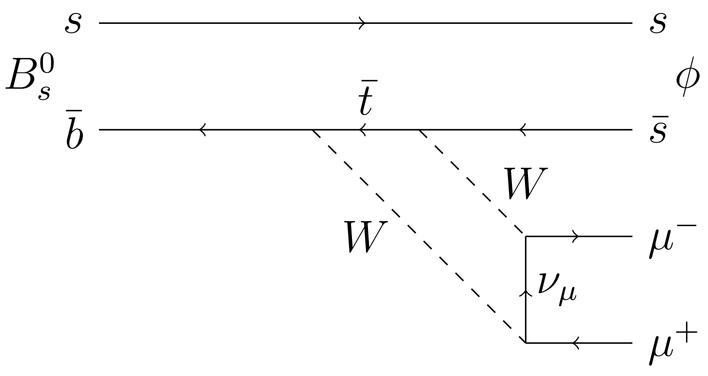
1) Flavour Changing Charged Current $b \to c\,\ell\,\nu_\ell$ $(B \to D^{(*)}\tau\nu, \dots)$



2) Flavour Changing Neutral Current $b \to s\ell\ell$

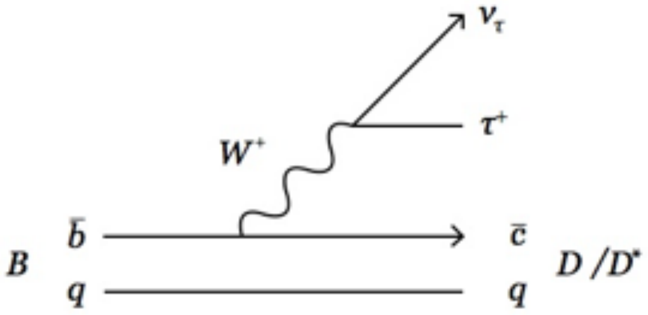
$$(B \to K^*\mu\mu, B \to \phi\mu\mu, R_K, \dots)$$





$b \to c\tau\nu$

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



[Freytsis, Ligeti, Ruderman 1506.08896]

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Exp. average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50 ab^{-1}	± 0.010	± 0.005

arXiv

[1205.5442, 1303.0571]

[talk, FPCP 2015]

[1506.08614]

[1503.07237,1505.03925,1203.2654]

- More than 3σ deviation from the SM prediction, seen in 3 different experiments
- Measurements are consistent with e/mu universality
- In the SM the flavour transition is unsurpassed by loop factor
- Assuming central values, NP has to be very large
- Data could be fitted by new interactions with mediator at the EW scale
- Various constraints on model building, EWPT, other flavour observables, direct searches

$b \to s\ell\ell$

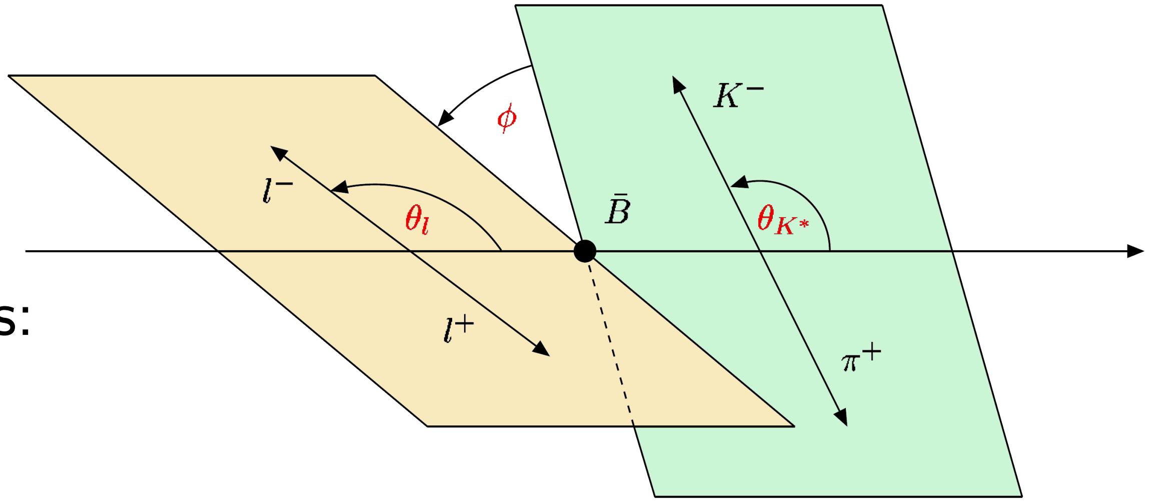
1) Tension in the LHCb data coming from $B \to K^* \mu^+ \mu^-$ angular observables

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

(in particular $B_S^0 \to \phi \mu^+ \mu^-$)

3) Hint of violation of lepton universality in R_K

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

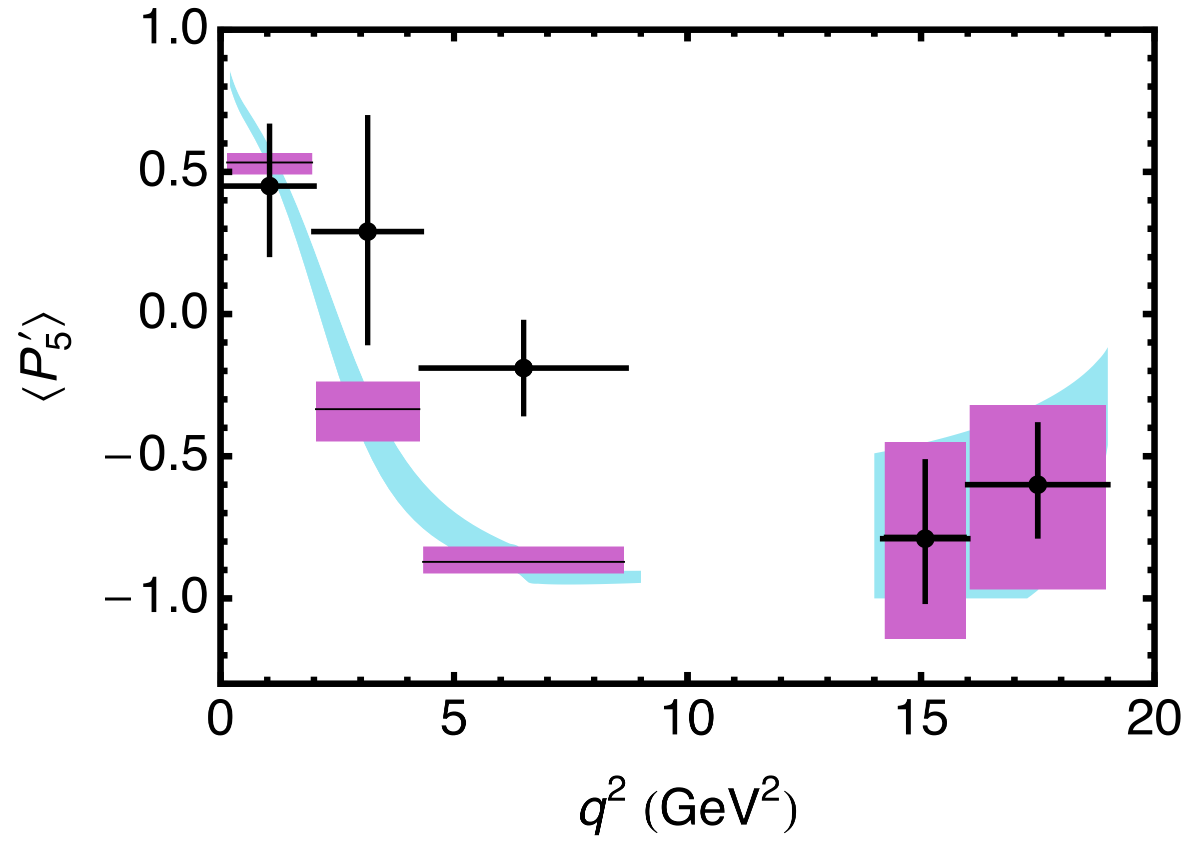


Angular distributions

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

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

LHCb, 1308.1707, PRL



3.7σ discrepancy in one of q^2 bins

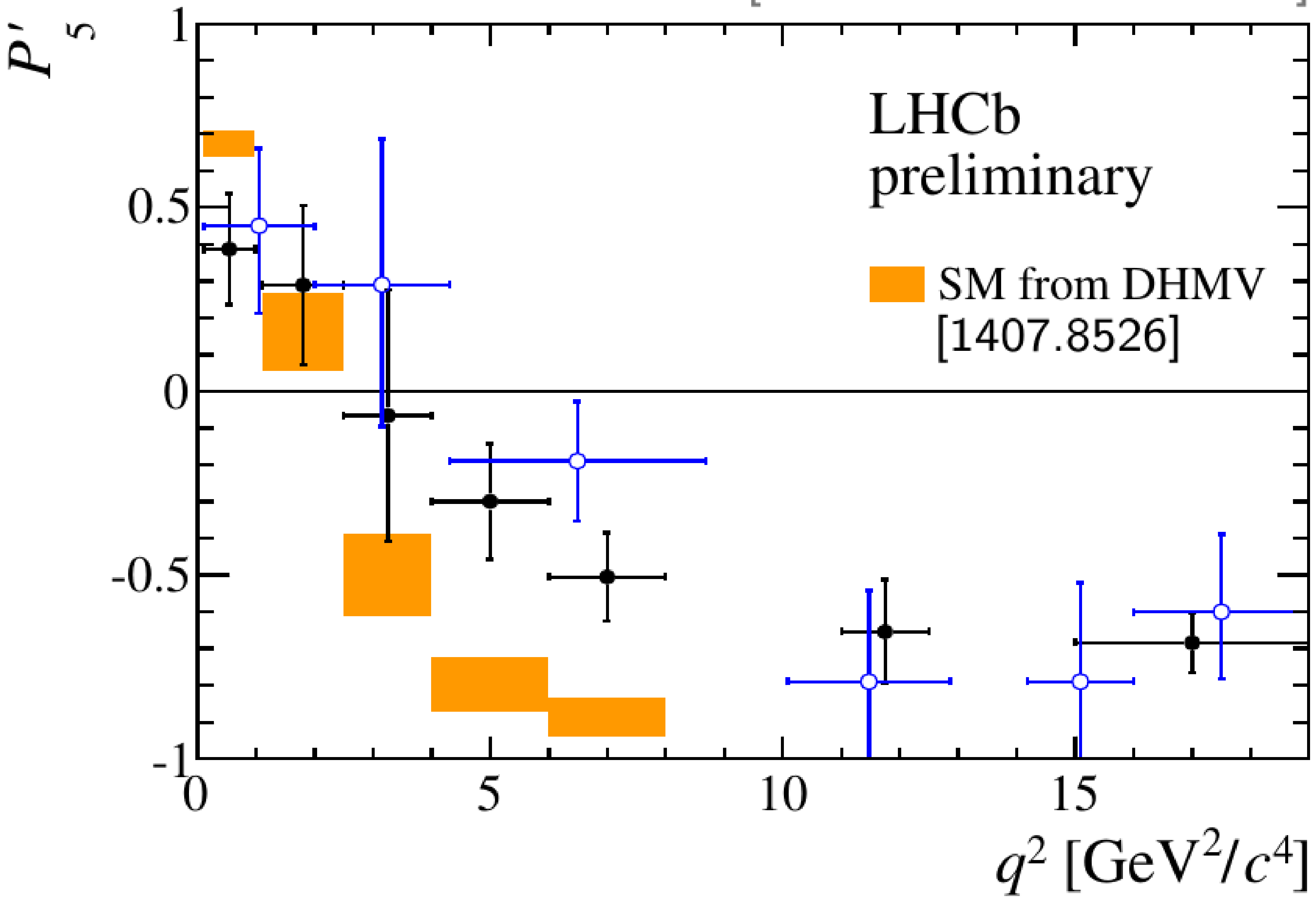
Explanations:

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

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

Moriond EW
2015

[LHCb-CONF-2015-002]



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

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

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
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{d\mathrm{BR}}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8\ \frac{d\mathrm{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8\ \frac{d\mathrm{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{d\mathrm{BR}}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

[Altmannshofer, Straub
1503.06199]

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

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

R_K

LHCb, 1406.6482, PRL

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

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

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

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

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

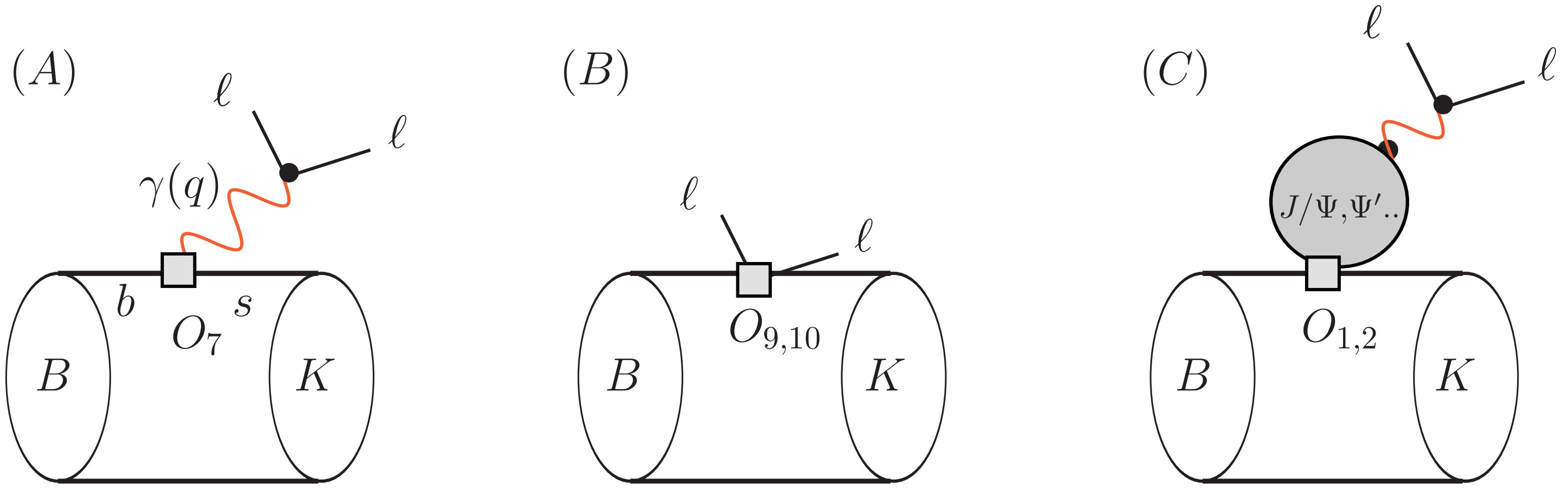
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} (V_{ts}^* V_{tb}) \sum_i C_i^\ell(\mu)\, \mathcal{O}_i^\ell(\mu)$$

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

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

SM gives lepton flavour universal contribution

- Relevant contribution, add hadronic weak interaction



Fits

Coeff.	best fit	1σ	2σ	p [%]
$C_7^{\rm NP}$	-0.05	$[-0.08, -0.02]$	$[-0.11, 0.01]$	2.4
C_7'	-0.05	$[-0.14, 0.04]$	$[-0.22, 0.13]$	1.8
$C_9^{\rm NP}$	-1.31	$[-1.65, -0.95]$	$[-1.98, -0.58]$	11.3
C_9'	0.26	$[-0.02, 0.53]$	$[-0.29, 0.81]$	2.0
$C_{10}^{\rm NP}$	0.60	$[0.32, 0.90]$	$[0.06, 1.23]$	3.2
C_{10}'	-0.18	$[-0.40, 0.03]$	$[-0.62, 0.24]$	2.0
$C_9^{\rm NP} = C_{10}^{\rm NP}$	-0.09	$[-0.36, 0.20]$	$[-0.61, 0.53]$	2.0
$C_9^{\rm NP} = -C_{10}^{\rm NP}$	-0.55	$[-0.74, -0.36]$	$[-0.95, -0.19]$	7.1
$C_9' = C_{10}'$	-0.06	$[-0.36, 0.24]$	$[-0.67, 0.52]$	1.8
$C_9' = -C_{10}'$	0.13	$[-0.00, 0.25]$	$[-0.13, 0.38]$	2.0

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

[Fits by various groups,
Ghosh, MN, Renner, 1408.4097,
Hurth, el al., 1410.4545,
Altmannshofer, Straub, 1411.3161, 1503.06199]

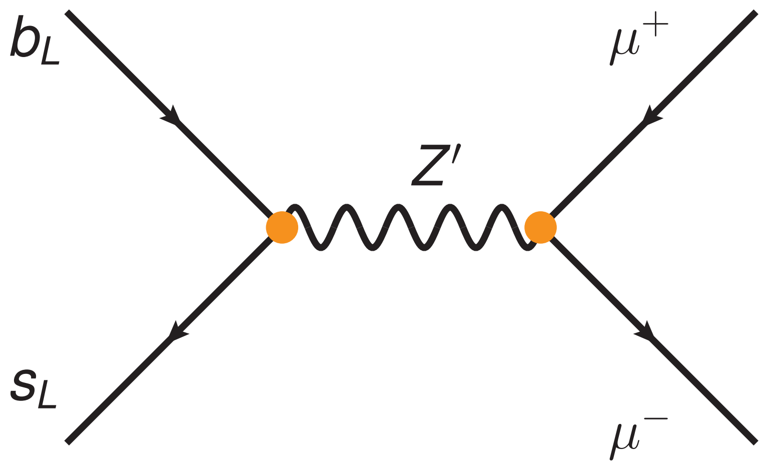
- Assuming only one source of NP at high scale, data prefers effects in the muon sector
- If only one Wilson coefficient is allowed to be non vanishing, various groups agree that NP in $\mathcal{O}_9^\mu$ is preferred by the data. $C_9^{\mu,NP} \approx -1$
- Short distance effects from New Physics are expected to have a chiral structure

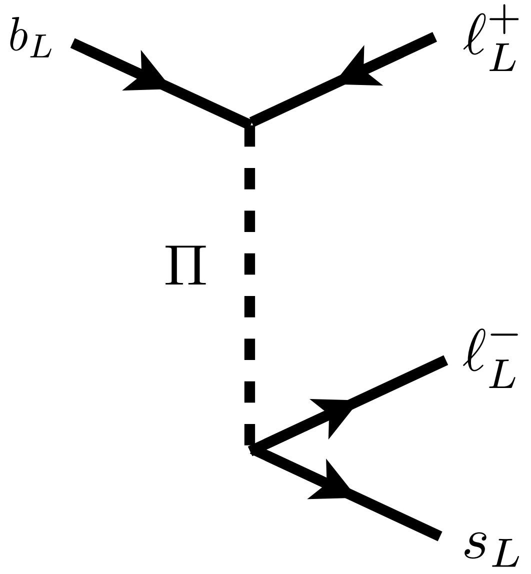
$$\begin{array}{c} \bar{\ell}\gamma^\alpha\ell \\ \bar{\ell}\gamma^\alpha\gamma_5\ell \end{array} \longrightarrow \begin{array}{c} \bar{\ell}_L\gamma^\alpha\ell_L \\ \bar{\ell}_R\gamma^\alpha\ell_R \end{array}$$

Best Fit with
Left-Left currents

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

Simplified Models





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

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

Altmannshofer, Gori, Pospelov, Yavin 1403.1269
Glashow, Guadagnoli, Lane 1411.0565
Crivellin, D'ambrosio, Heeck 1501.00993, 1503.03477
Niehoff, Stangl, Straub 1503.03865, 1508.00569
Aristizabal Sierra, Staub, Vicente 1503.06077
Crivellin, Hofer, Matias, Nierste, Pokorski, Rosiek 1504.07928
Celis, Fuentes-Martin, Jung, Serodio 1505.03079
Greljo, Isidori, Marzocca 1506.01705
Belanger, Delaunay, Westhoff 1507.0660
Altmannshofer, Yavin 1508.07009
Falkowski, Nardecchia, Ziegler, 1509.01249
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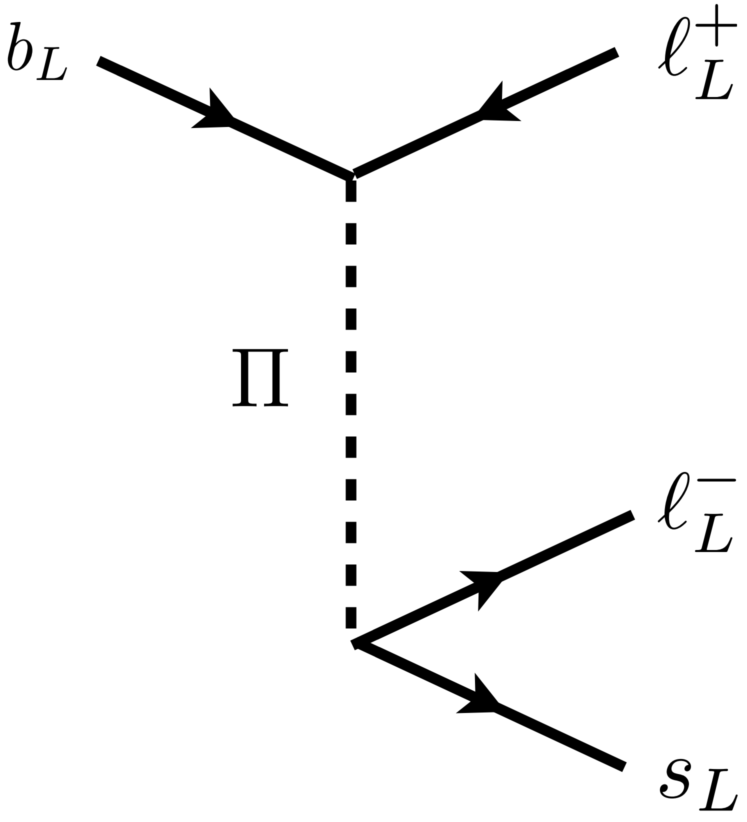
Hiller, Schmaltz, 1408.1627
Biswas, Chowdhury, Han, Lee 1409.0882
Gripaios. Nardecchia, Renner 1411.0565
Sahoo, Mohanta 1501.05193
Medeiros Varzielas, Hiller 1503.01084
Becirevic, Fajfer, Kosnic, 1503.09024
Alonso, Grinstein, Camalich 1505.05164
Sahoo, Mohanta 1507.020700
…….

New Physics (Model Dependent)

- A leptoquark interpretation Hiller, Schmaltz 1408.1627



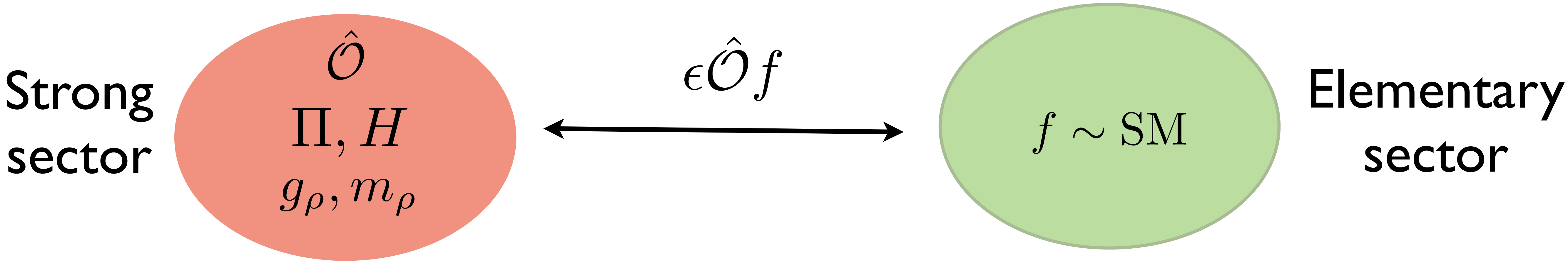
- Quantum number of the new states, uniquely determined by the the Left-Left structure

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

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

- Anomalies are fitted when $\dfrac{\lambda_{b\mu}\lambda_{s\mu}}{m_\Pi^2} \approx \dfrac{1}{(30\,\mathrm{TeV})^2}$
- Just two, non-vanishing leptoquark coupling
- Scale of New Physics not predicted
- No connection with FV in the SM

Composite Higgs Framework



Strong sector

$\hat{\mathcal{O}}$

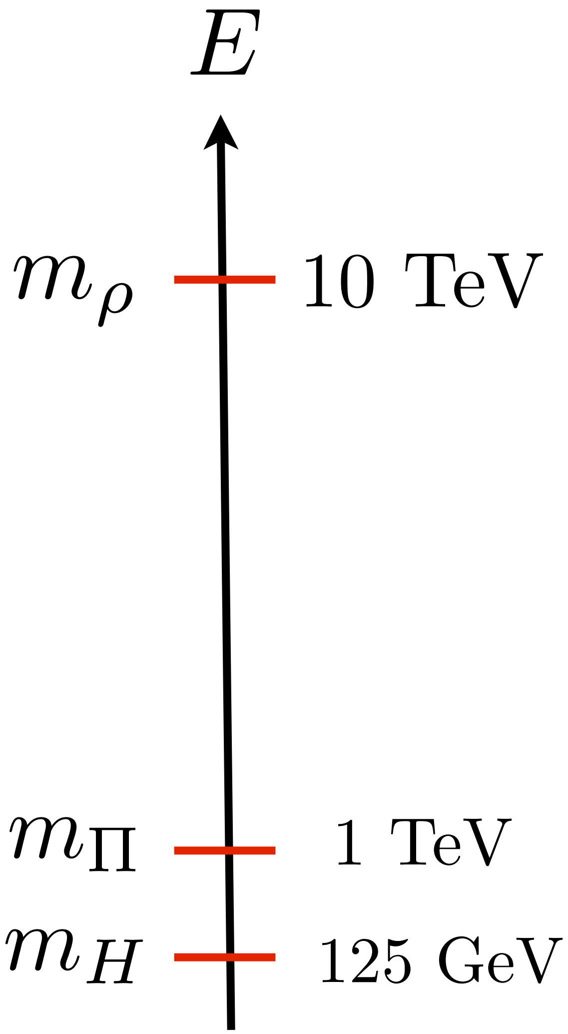
Π, H

g_ρ, m_ρ

$\epsilon \hat{\mathcal{O}} f$

$f \sim \mathrm{SM}$

Elementary sector



E

m_ρ — $10\ \mathrm{TeV}$

m_Π — $1\ \mathrm{TeV}$

m_H — $125\ \mathrm{GeV}$

- 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

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

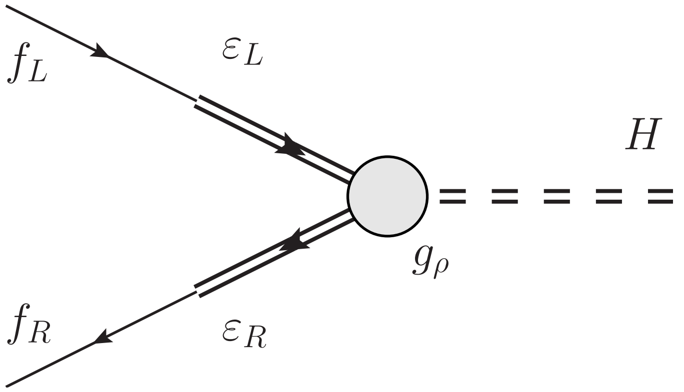
- BSM Flavour violation regulated by the same mechanism

- Naturalness (…)

Based on 1412.5942, JHEP,
Ben Gripaios and Sophie Renner

Partial Compositeness in CH models

- Yukawa sector:



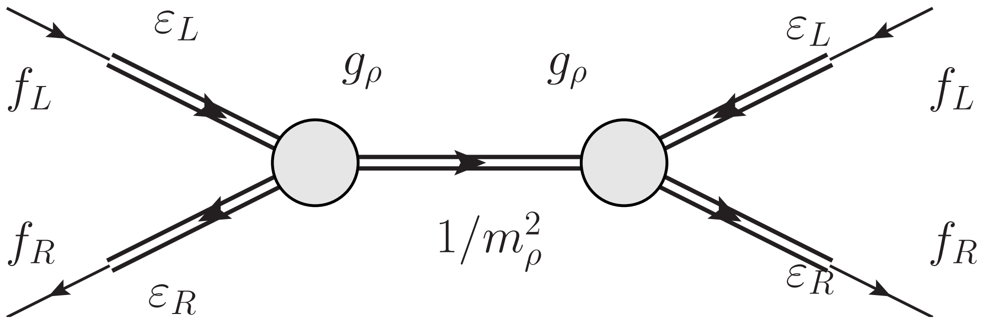
$$\mathcal{L}_{\text{elem}} = i\overline{f}\gamma^\mu D_\mu f$$

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

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

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

- 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

Mixing parameters

- Mixing parameters are related to values of fermion masses and mixing

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d \qquad (Y_e)_{ij} \sim g_\rho \epsilon_i^\ell \epsilon_j^e,$$

- In the quarks sector everything is fixed up to 2 parameters, (g_ρ, ϵ_3^q)

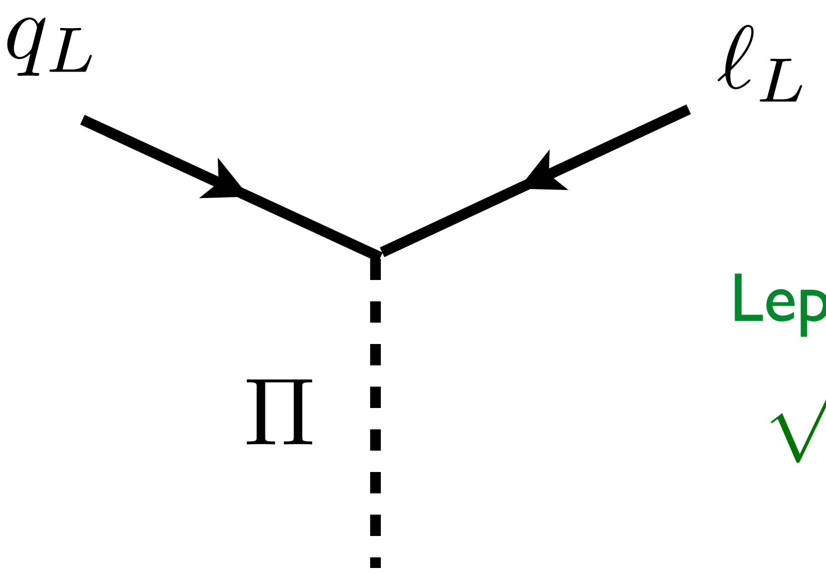
- In the lepton sector parameters cannot be univocally connected to physical inputs, due to our ignorance on neutrino masses, will assume that left and right mixing have similar size

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

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



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! $(g_\rho, \epsilon_3^q, M) \to \sqrt{g_\rho} \epsilon_3^q / M$

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

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

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

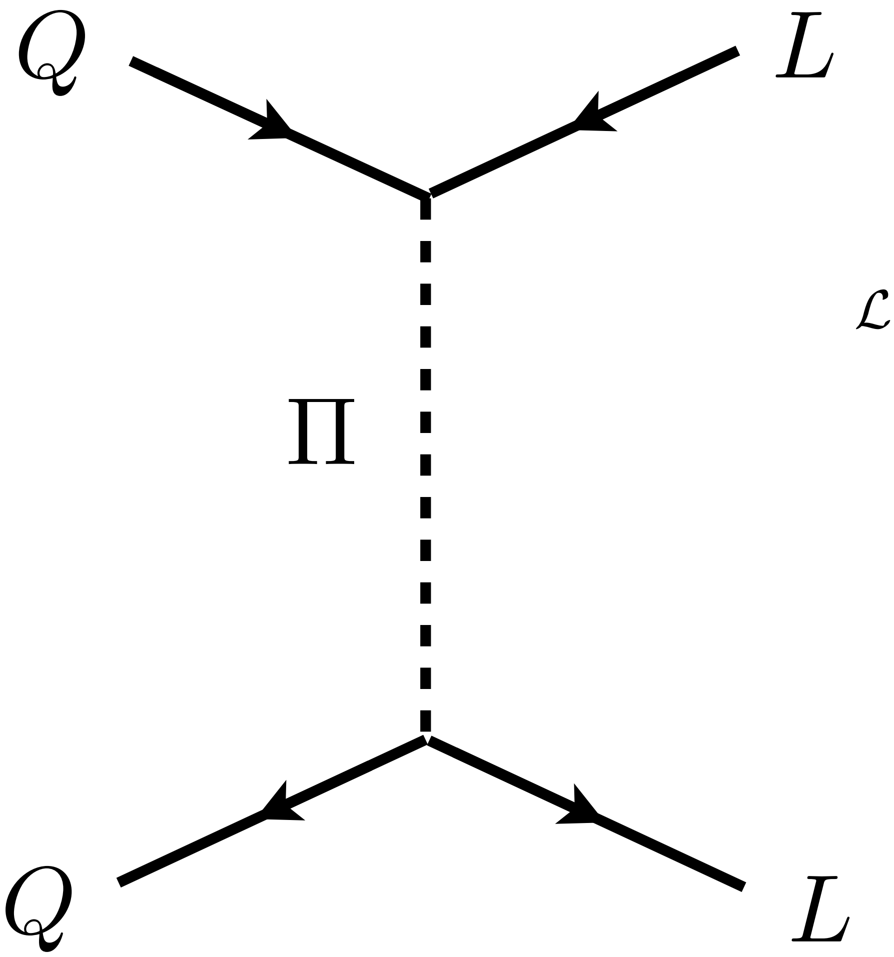
- Due to the partial compositeness structure, negligible contribution to observables involving electrons like $\mathrm{BR}(B \to K e^+ e^-)$. R_K is easily accommodated.

- 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, $M \lesssim 1\ \mathrm{TeV}$

Flavour violation at the tree level

- Integrating away the leptoquarks fields we get



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

$$u'^j_L = V^{\dagger jk}_{CKM} u^k_L$$

- “Vertical” correlations induced by SM gauge invariance
- “Horizontal” correlations induced by partial compositeness

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 $b \longrightarrow s\tau^+\tau^-$

- 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 $B \longrightarrow K^*\overline{\nu}_\mu\nu_\mu$ gives

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

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

Testable at Belle II

See 1002.5012

Predictions

- Rare Kaon decay

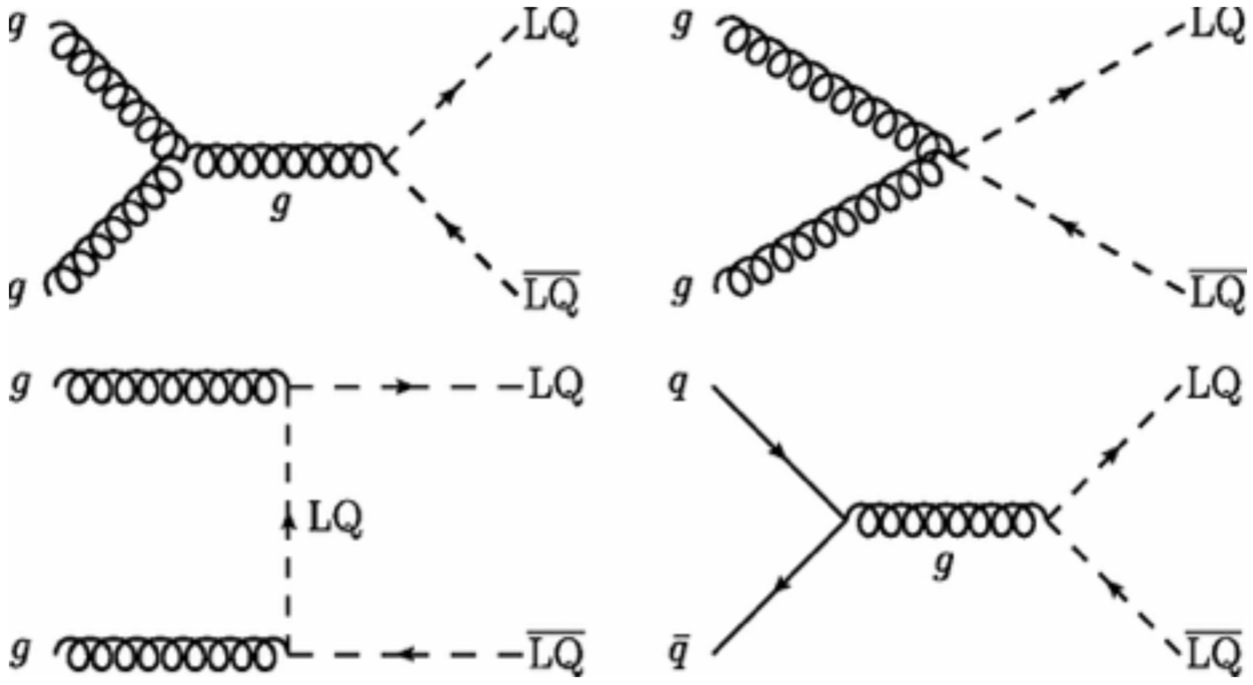
Hurt et al 0807.5039
NA62 1411.0109

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

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

LHC



- Production via strong interaction

- Decay to fermions of the third family

$$\Pi_{4/3} \to \overline{\tau}\,\overline{b}, \quad M > 720 \text{ GeV}$$
$$\Pi_{1/3} \to \overline{\tau}\,\overline{t} \text{ or } \Pi_{1/3} \to \overline{\nu_\tau}\,\overline{b}, \quad M > 410 \text{ GeV}$$
$$\Pi_{-2/3} \to \overline{\nu_\tau}\,\overline{t}. \quad M > 640 \text{ GeV}$$

- Stop and sbottom + dedicated leptoquark searches

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

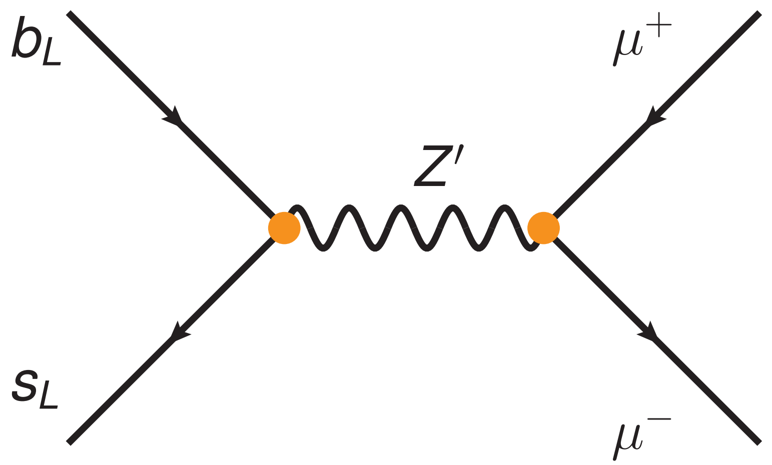
$$M > 720 \text{ GeV}$$

Z' from a U(2) flavour symmetry

Some aspects of flavour symmetry

Based on 1509.01249 with
Adam Falkowski and Robert Ziegler

- Allow for an understanding of the hierarchy of masses and mixing in the SM
- Create a connection between BSM and SM flavour violation
- Scale of the flavour dynamics not predicted… but can be fitted with the anomalies



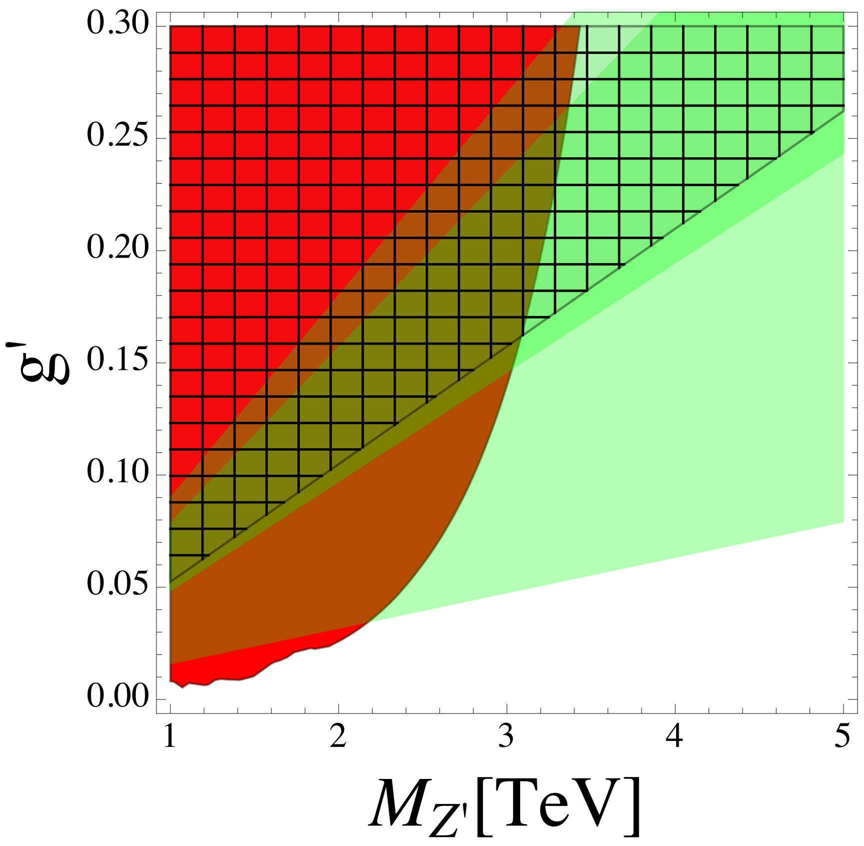
$$\mathcal{L} \supset g' \Delta^{f_i f_j}_{L,R}\, f_i^\dagger \overline{\sigma}^\mu f_j\, Z'_\mu$$

$$\Delta^{d_i d_j}_L \sim \begin{pmatrix} 1 & \lambda^5 & \lambda^3 \\ \lambda^5 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^4 \end{pmatrix}$$

λ = Cabibbo angle

Predictions

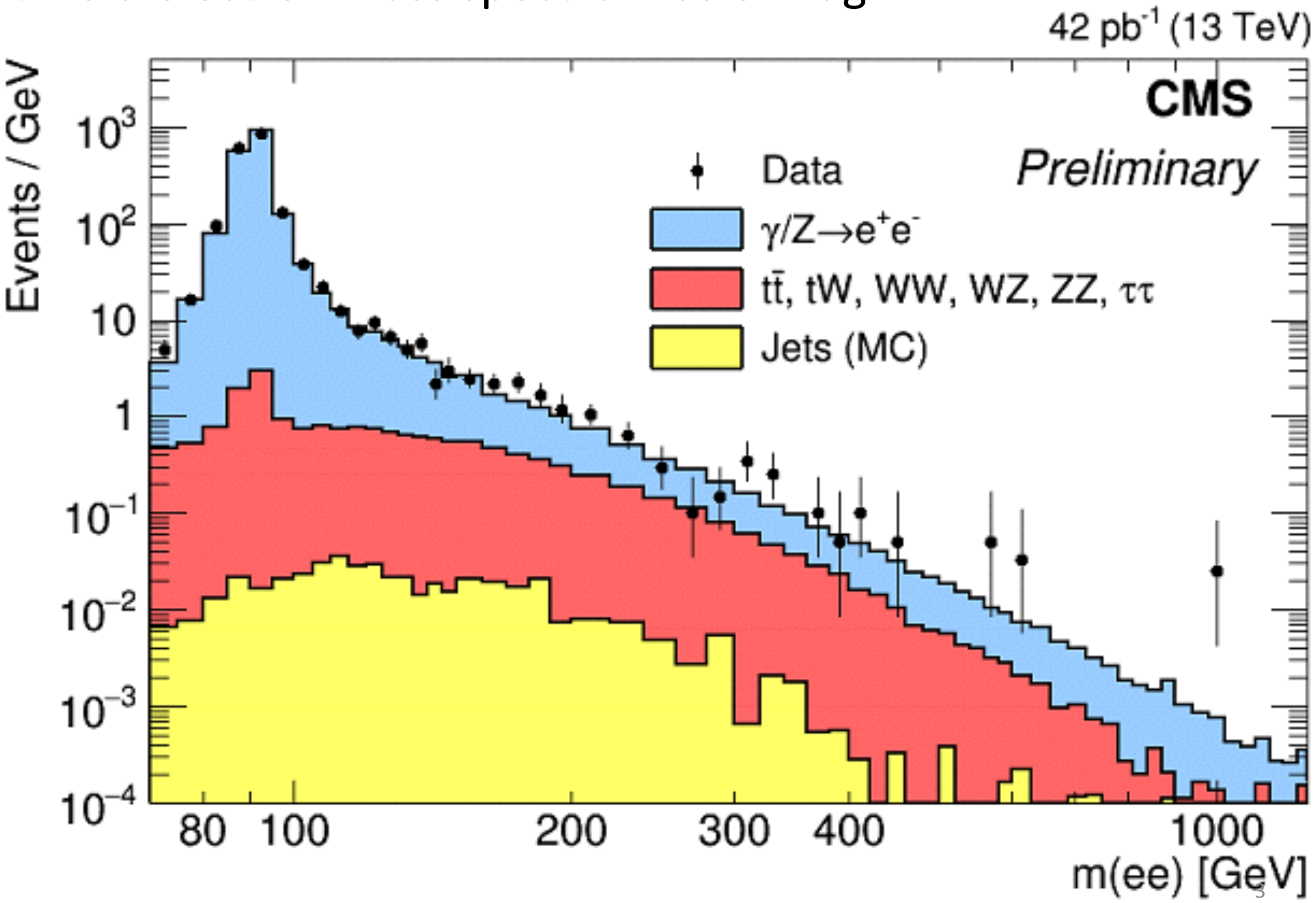
- Constructive effect in electron channels
- LFV, mu-e conversion in the nuclei
- Z' at LHC main decay in dielectron…



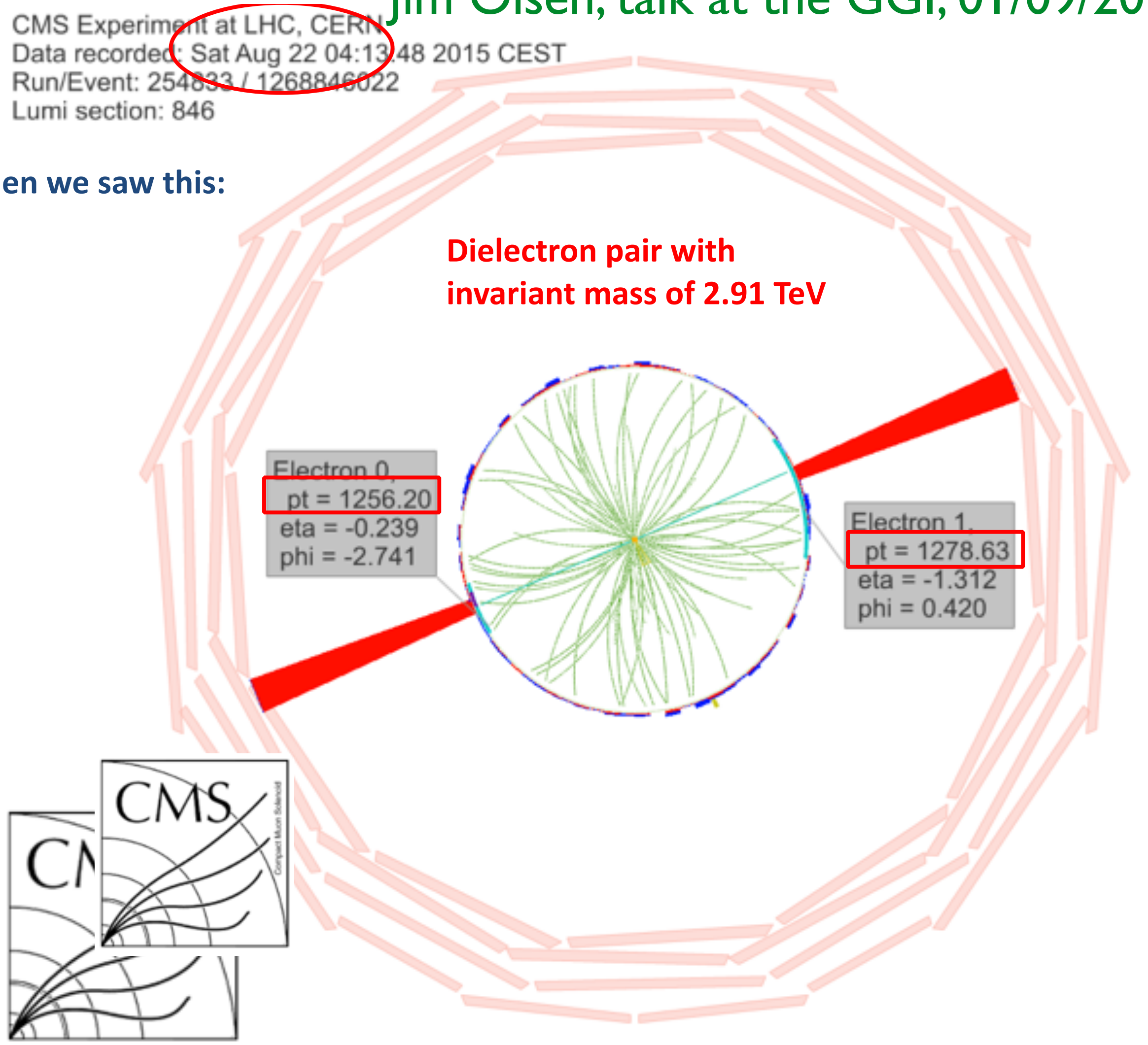
(JUST FOR FUN….)

Jim Olsen, talk at the GGI, 01/09/2015

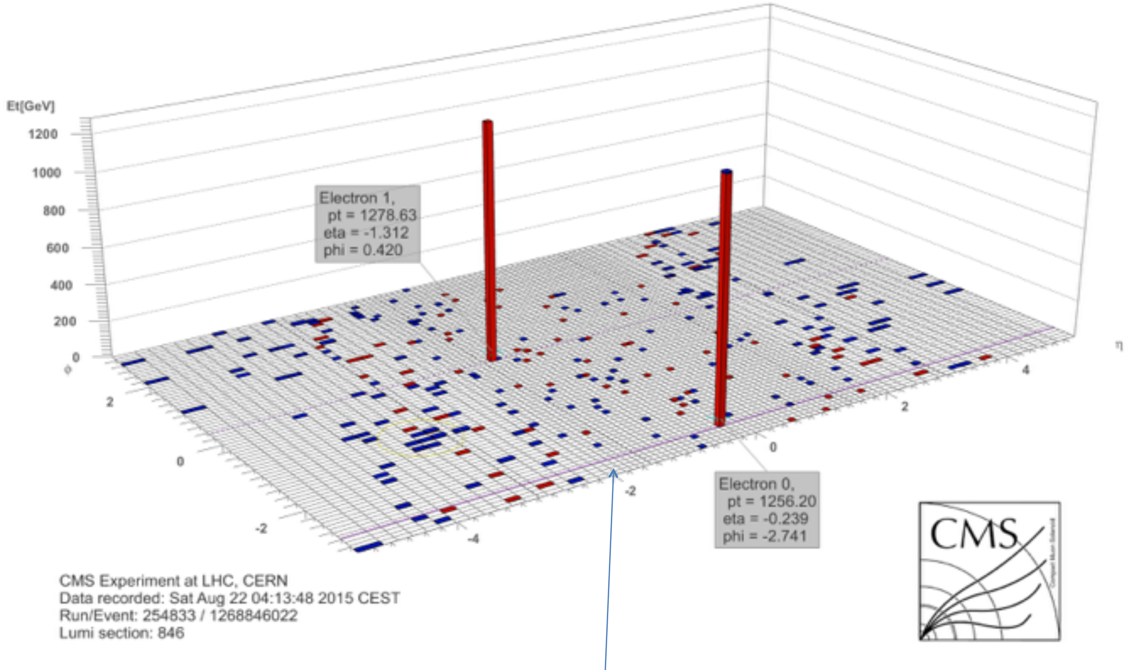
CMS dielectron mass spectrum as of Aug. 22



And then we saw this:



Dielectron pair with invariant mass of 2.91 TeV

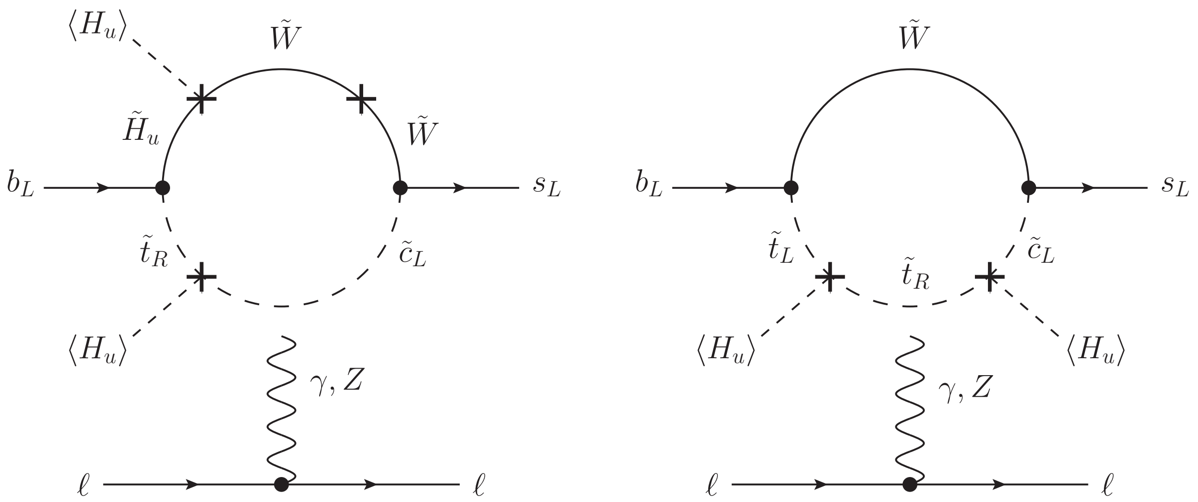


mass range	SM Bkg Expection
>1 TeV	*0.21*
> 2 TeV	*0.007*
> 2.5 TeV	*0.002*

MSSM

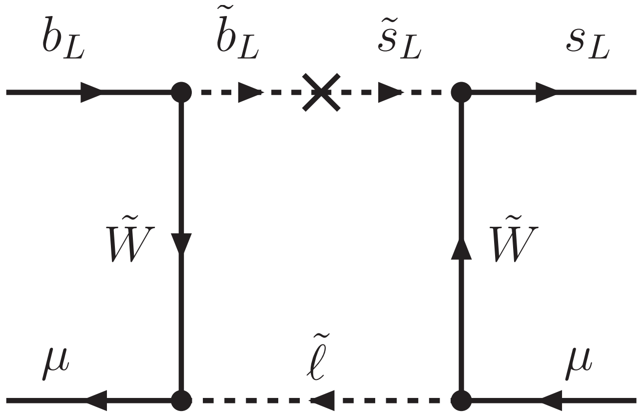
- $B \to K^* \mu^+ \mu^-$

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 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

Conclusions

- First run of LHC left us with the Higgs, no strong evidence for New Physics, but a series of interesting "anomalies"

- Still premature to claim a discovery of New Physics in B-physics. However if hints are confirmed we need NP beyond MFV

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

- Anomalies can be explained through the tree level exchange of a leptoquark or a Z' boson

- Motivated models connecting FV in the SM and the NP exist giving rise to interesting and testable predictions at LHC and other colliders.