On the recent flavour anomalies

Marco Nardecchia

DAMTP and Cavendish Laboratory,
University of Cambridge

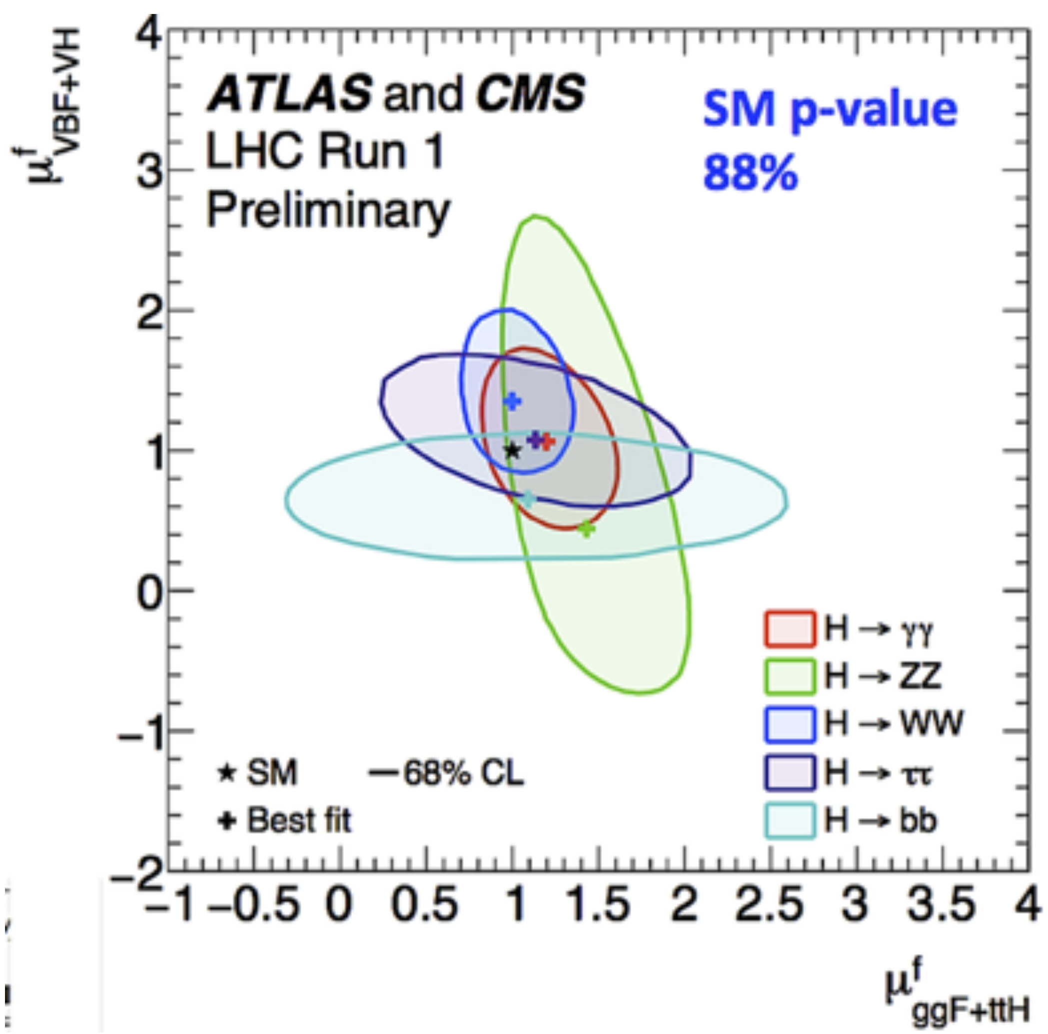
4 July 2016, Rome

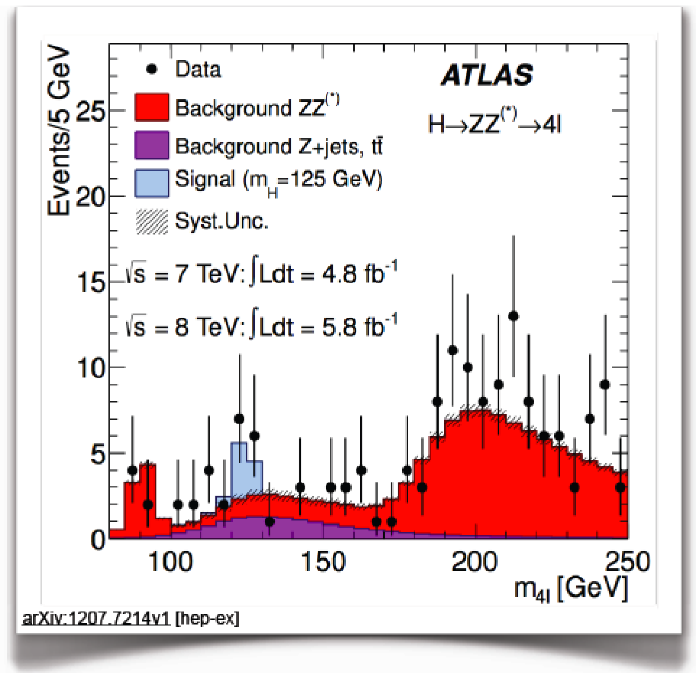
Outline

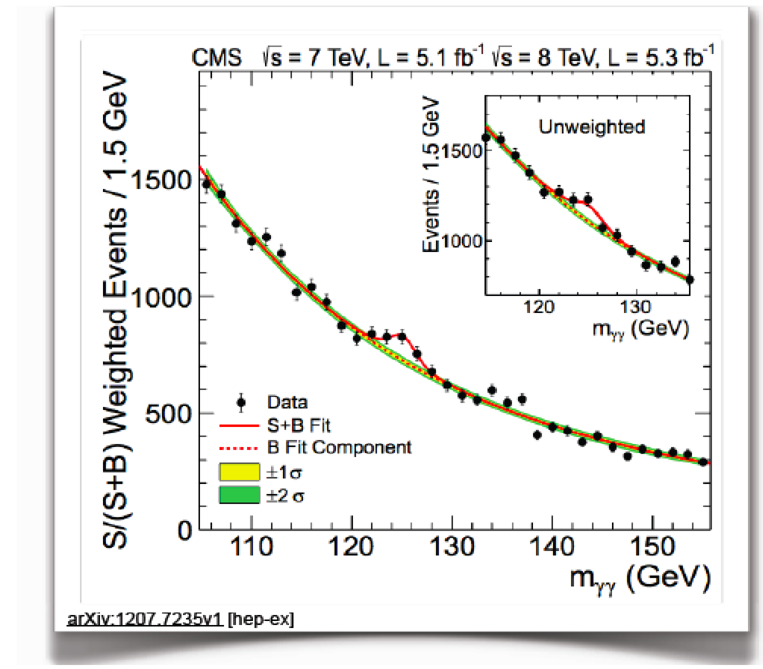
- BSM and (Minimal) Flavour Violation: a review
- Flavour Anomalies
- New Physics in semi-leptonic B-decays
- Conclusions

A brief summary

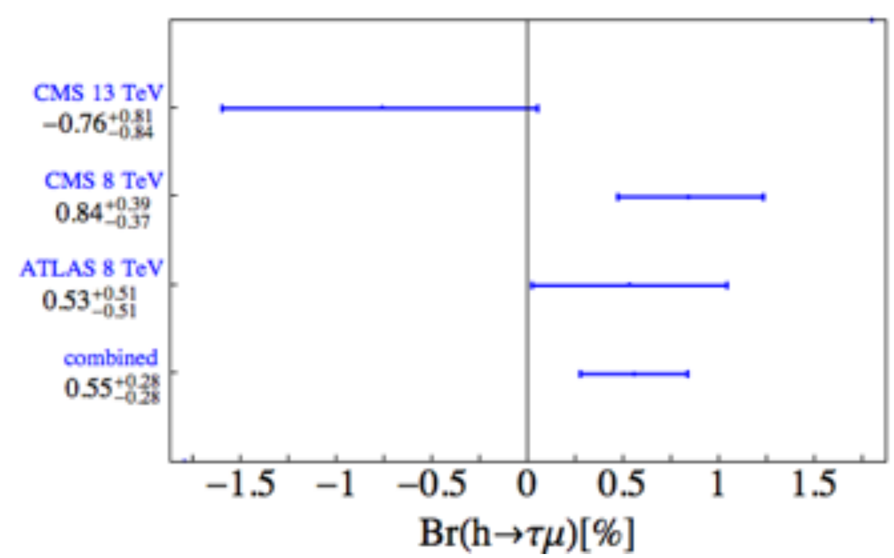
1) Discovery of a SM Higgs-like scalar*







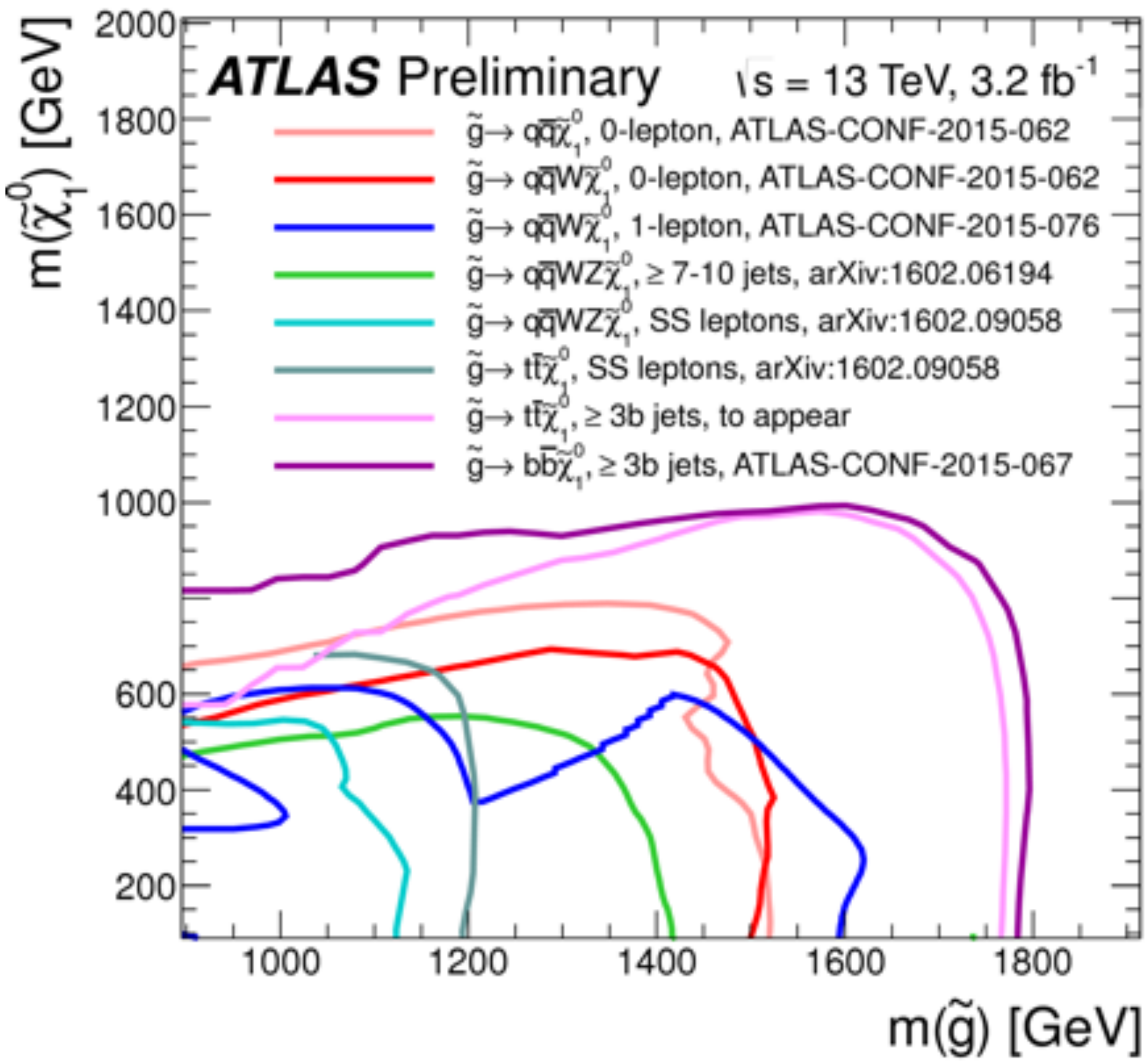
*however $h \to \tau\mu$

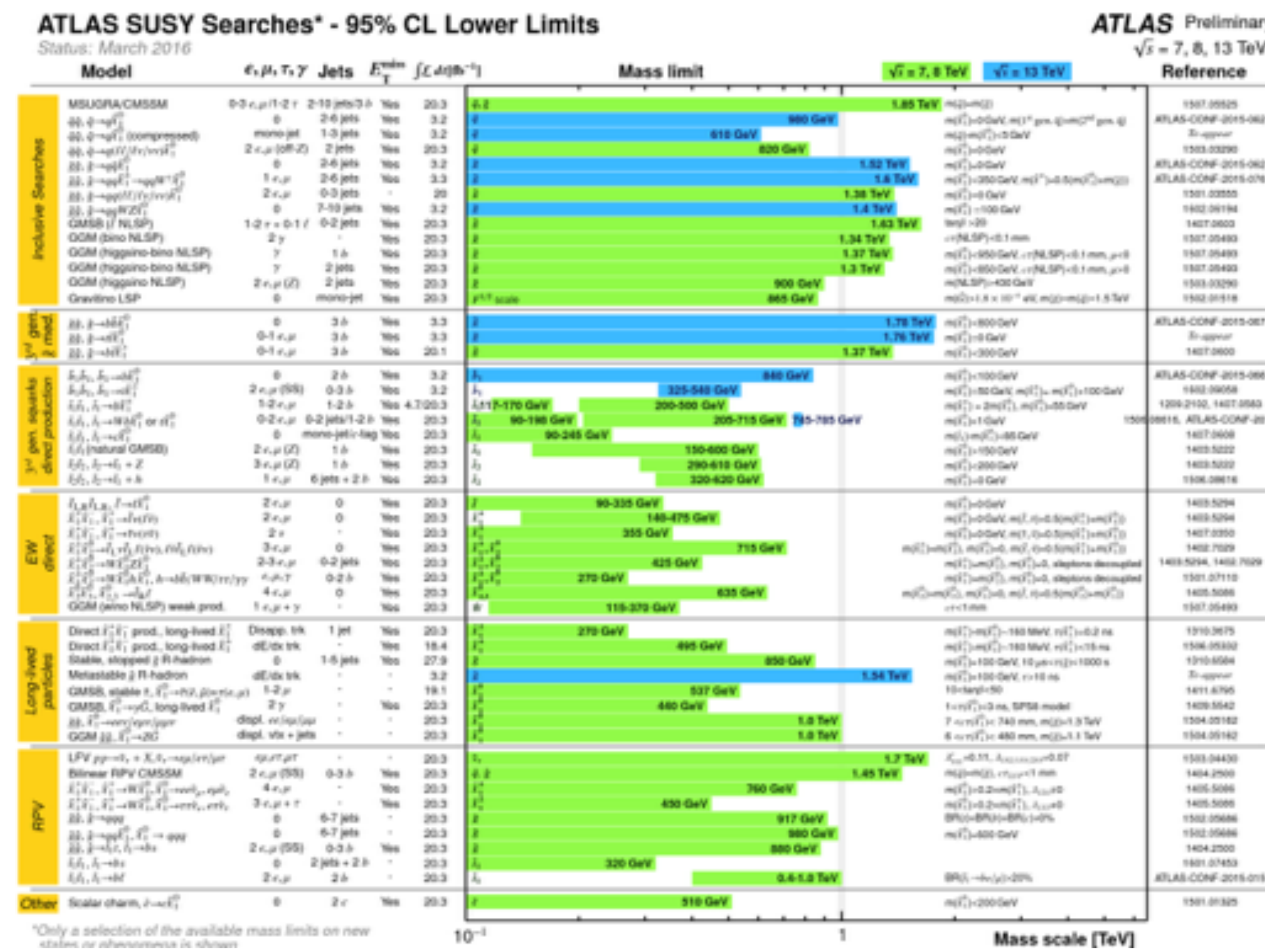


[From Adam Falkowski's blog]

A brief summary

2) No evidence of New Physics from direct searches*

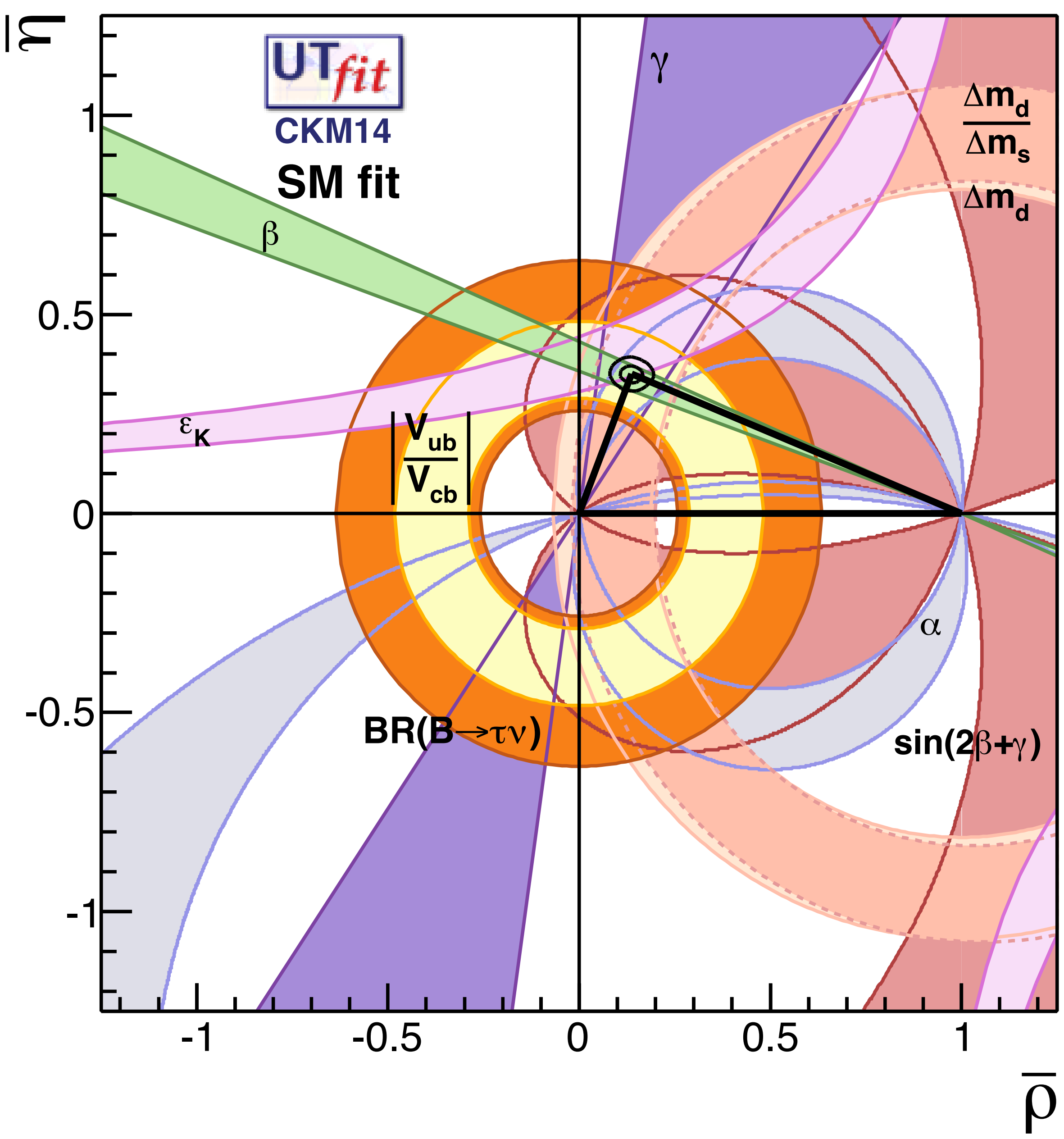




* however…. an interesting 750 GeV di-photon anomaly from Run-2

A brief summary

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 $\Lambda?$

- 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

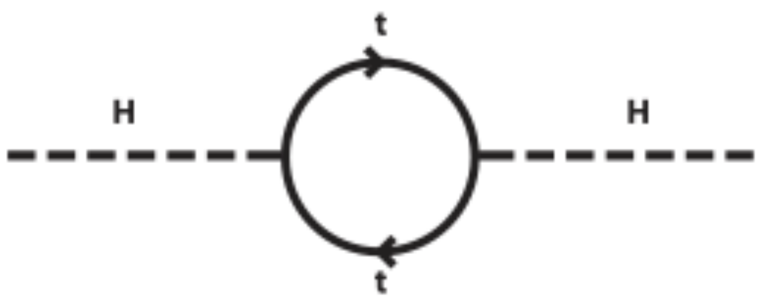
- However we have some indications….

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

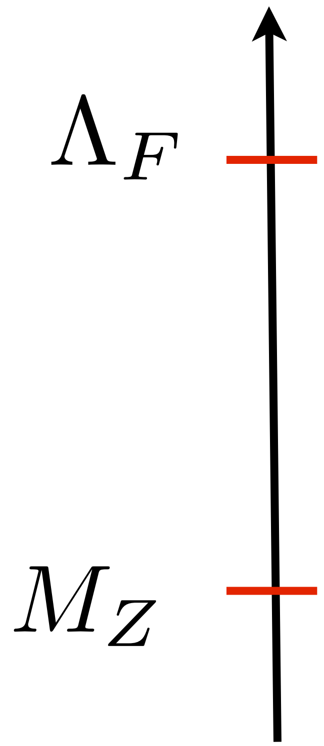
(i) the full EFT is formally invariant with respect to the flavor symmetry

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

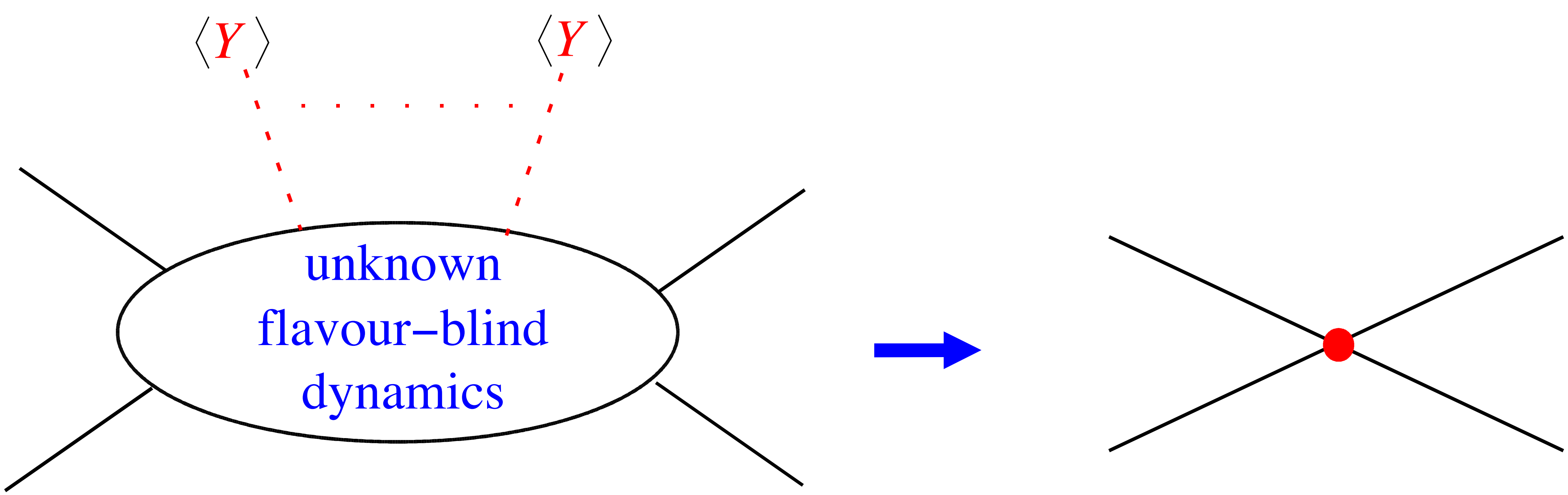
(ii) the SM Yukawa couplings are the only irreducible source of flavor breaking

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

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 $y_u = V_{\rm CKM}^\dagger \frac{\hat{m}_u}{v},\ y_d = \frac{\hat{m}_d}{v},\ y_e = \frac{\hat{m}_e}{v}$

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

- Consequences

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

(ii) predictive hypothesis with correlations among observables

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

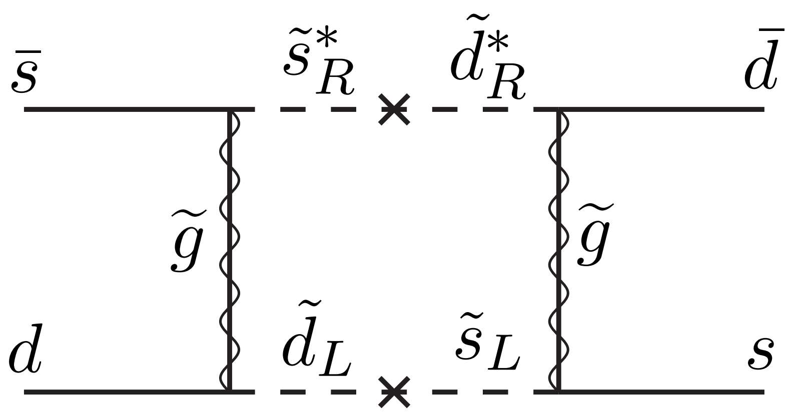
(iv) there is no flavor violation in the lepton sector

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

SUSY-MFV

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



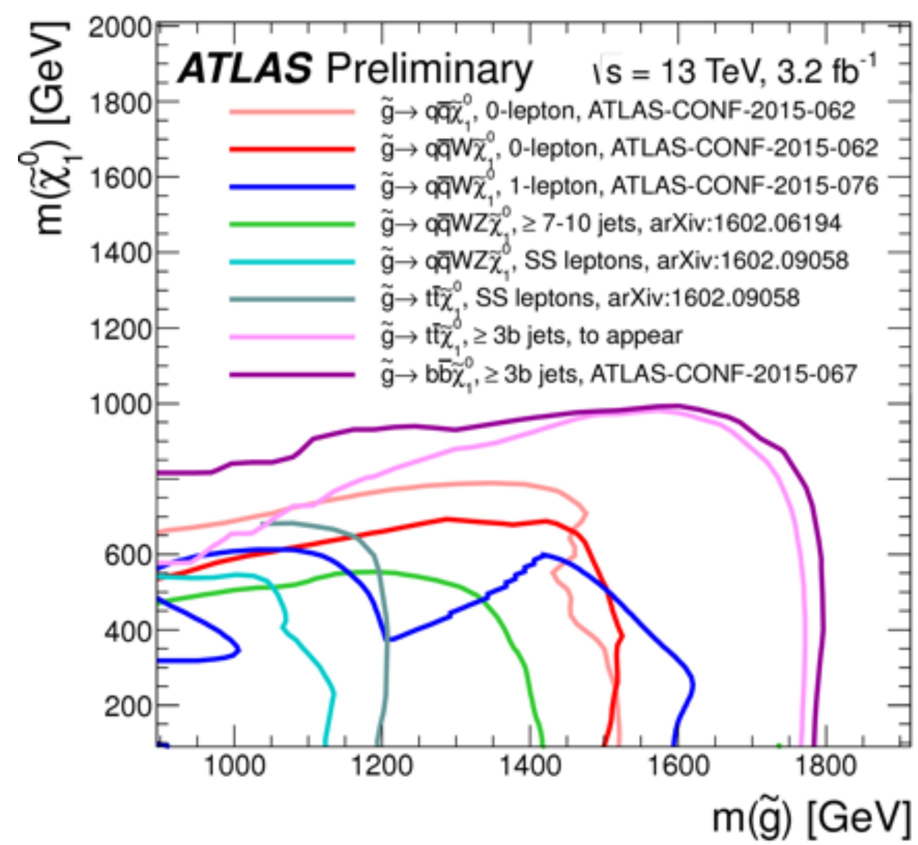
$$\frac{c_{ij}\mathcal{O}_{ij}}{\Lambda^2}$$

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

$$\Lambda = m_{susy}$$

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

Direct Searches $m_{susy} > 1000 \text{ GeV}$



Tiny NP effects in the flavour sector from MFV

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

Simplifying a complicated multi-dim. problem...

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:

Flavor Structure	< 1 TeV	few TeV	> few TeV
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%]

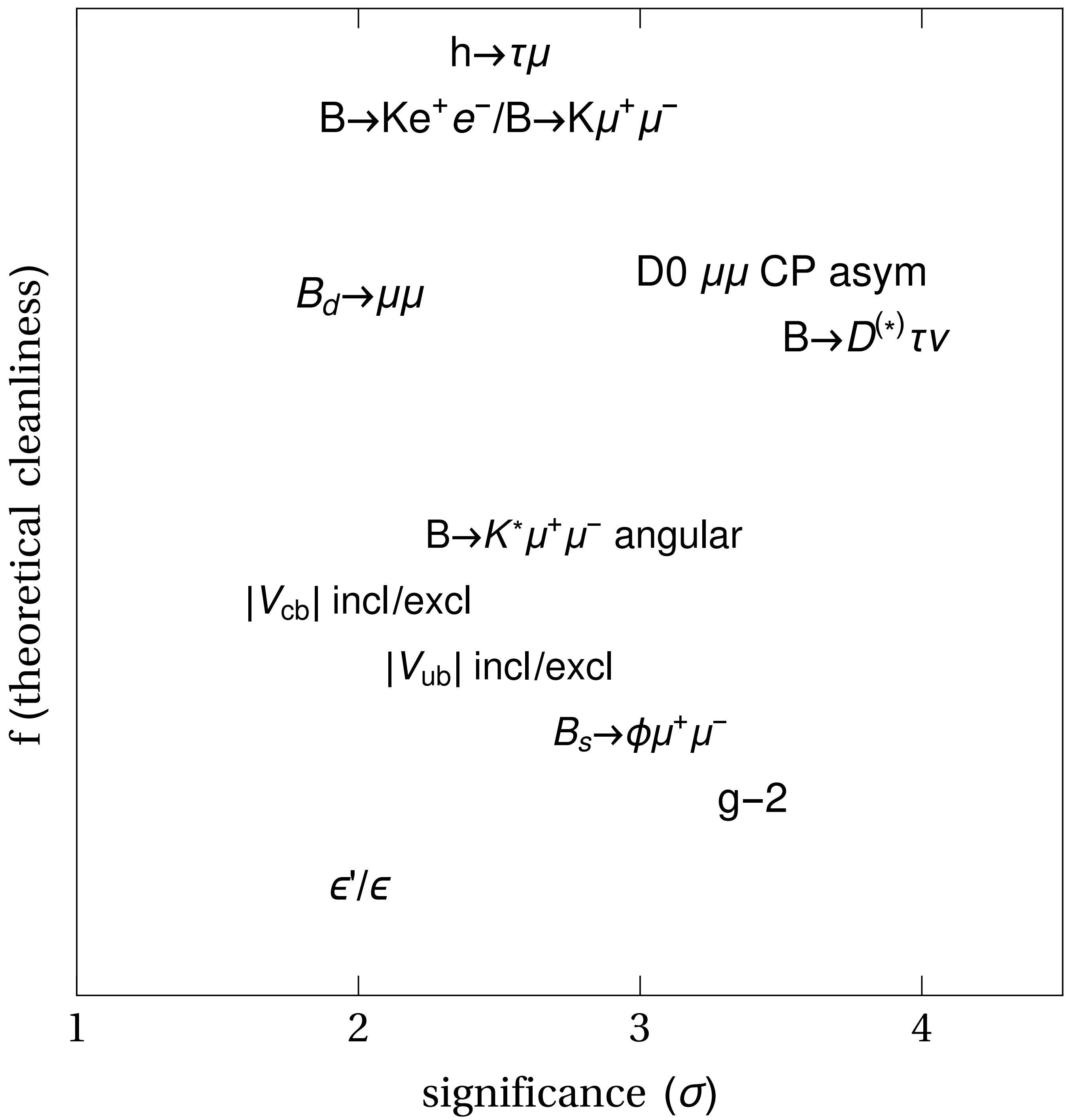
Mass scale of New Physics (*new colored & flavored particles*)

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

Flavour Anomalies



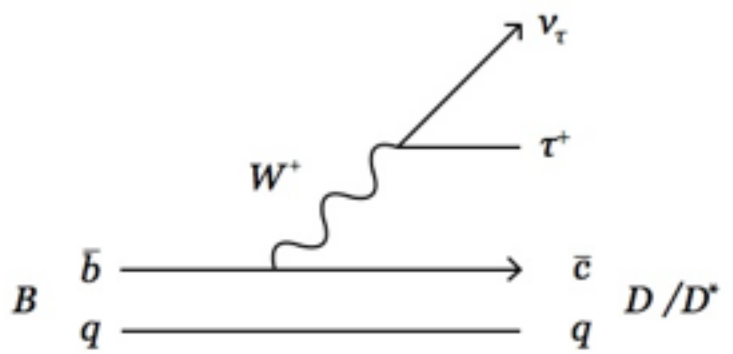
Z. Ligeti, Moriond QCD 2016

- "True" significance? Complicated and subjective
- No clear evidence for New Physics
- Some channels are very clean, only limiting factor is statistics
- Other channels requires careful assessment of the theoretical error. We need correlations
- New particles, are new probes of flavour physics
- Interesting pattern of anomalies…

Flavour Anomalies (B-decays)

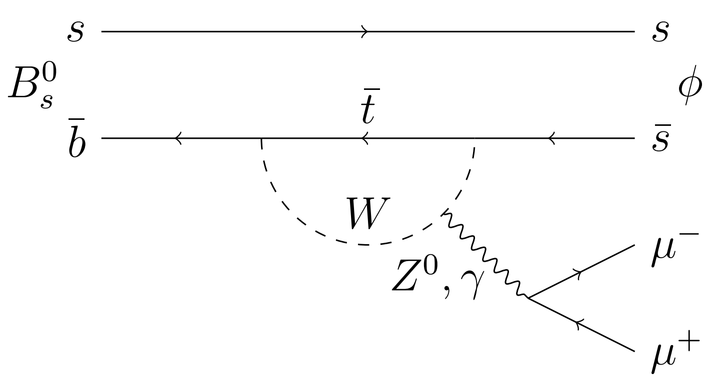
Two different set of measurements

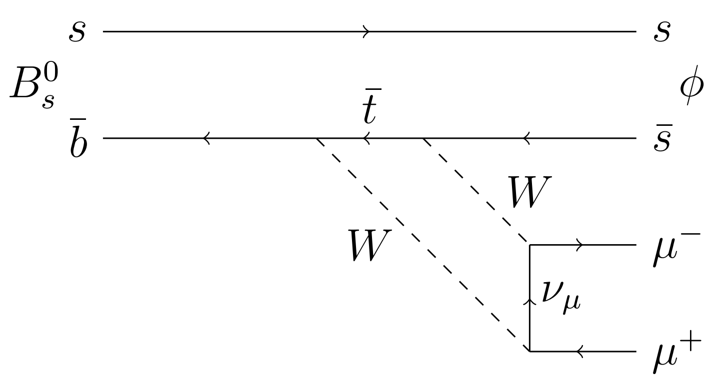
1) Flavour Changing Charged Current $b \to c\,\ell\,\nu_\ell$ $(B \to D^{(*)}\tau\nu, \ldots)$



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

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

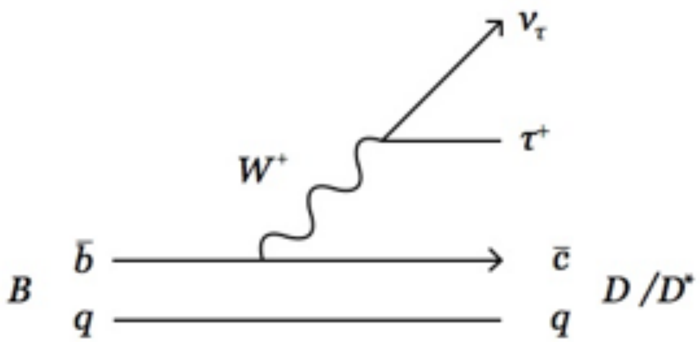




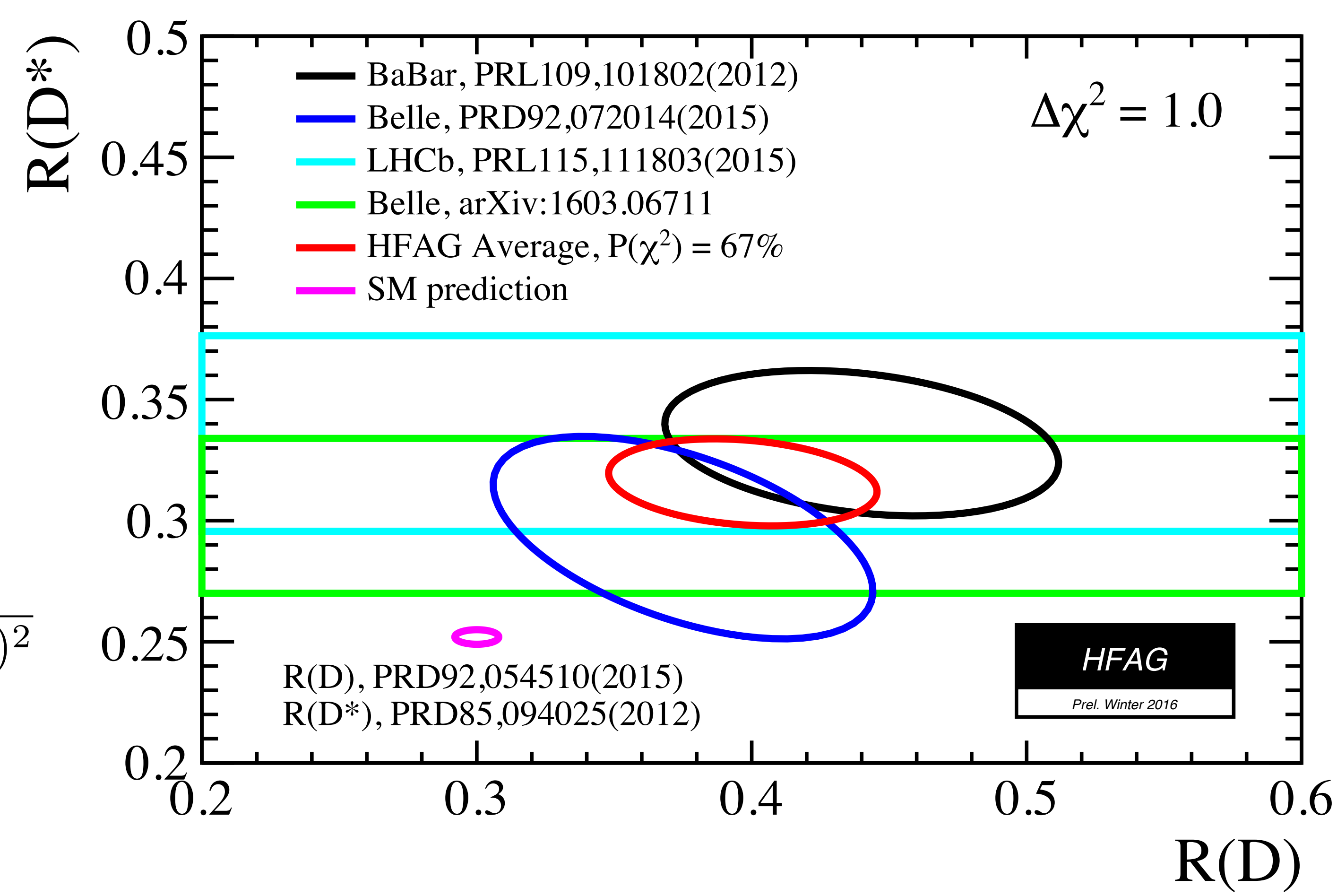
$b \to c\tau\nu$

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

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



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



- SM prediction quite solid (taking ratios helps)
- Seen in 3 different experiments in a consistent way, combined significance 4.0σ (HFAG website)
- Measurements are consistent with e/mu universality
- In the SM the flavour transition is unsurpassed by loop factor (tree-level charged current)
- Assuming central values, NP has to be large, easier to have interference with SM (left current)
- Data could be fitted by new interactions with mediator at the EW scale
- Various constraints on model building, EWPT, other flavour observables, direct searches

$b \to s\ell\ell$

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

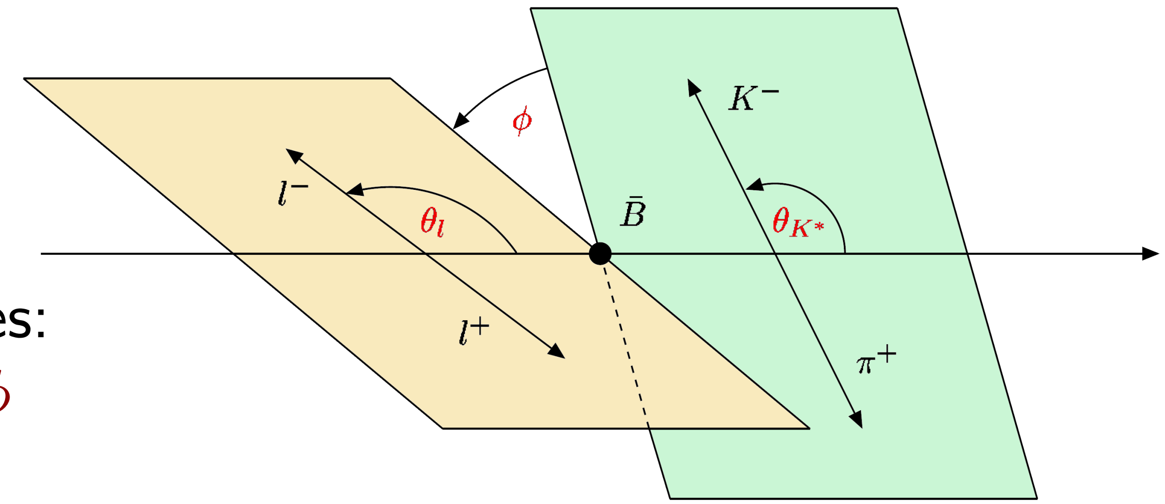
(in particular $B_S^0 \to \phi\mu^+\mu^-$)

3) Hint of violation of lepton universality in R_K

[4) Leptonic decay $B_s \to \mu^+\mu^-$]

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

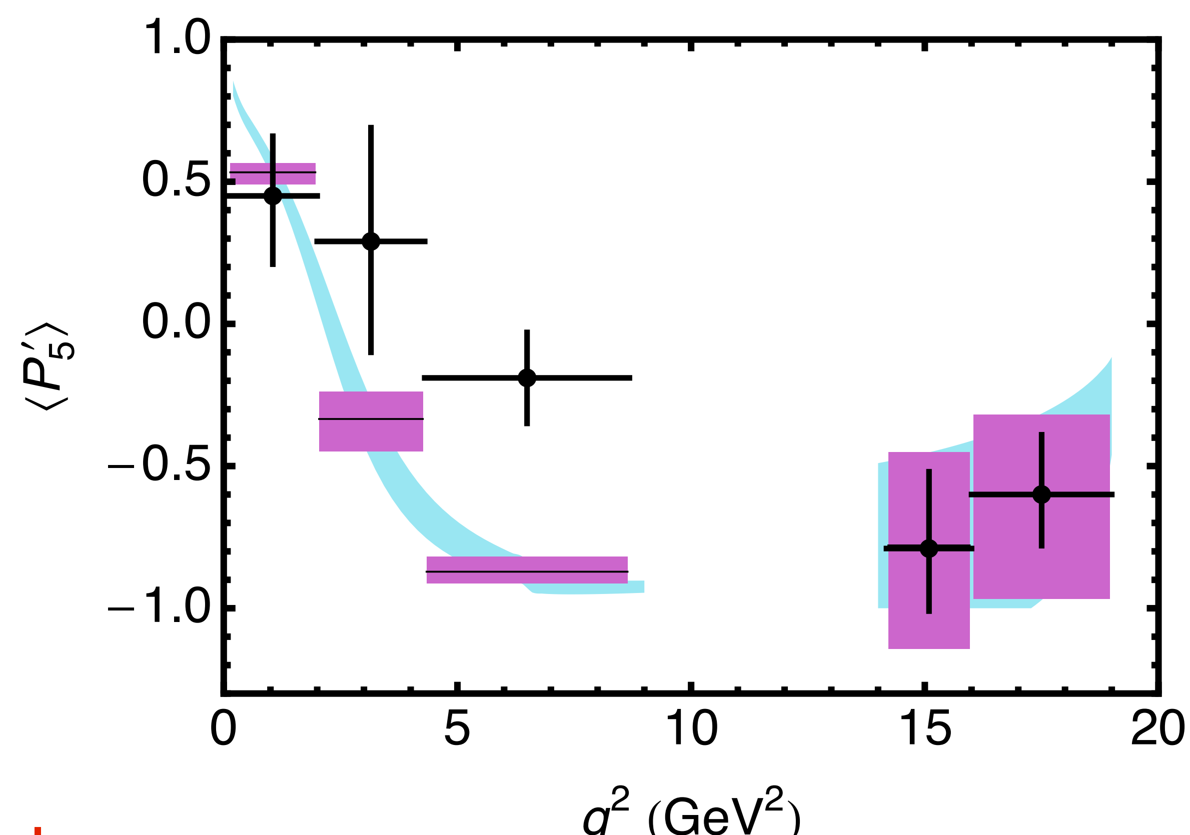
Angular distributions



$\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ ($\bar{K}^{*0} \to K^-\pi^+$) 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:

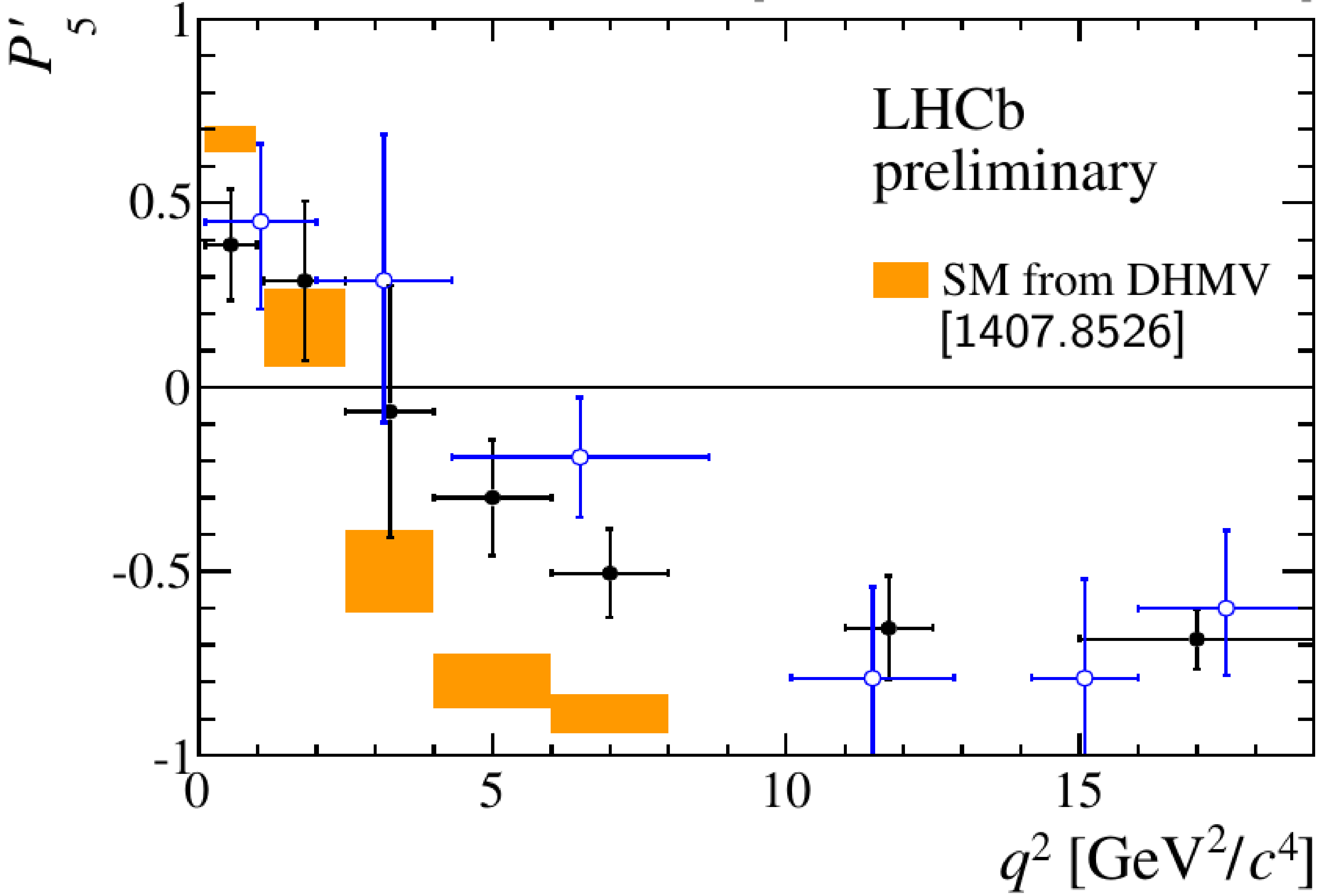
1. Statistical fluctuation
2. Hadronic uncertainties
3. New Physics

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

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

Moriond EW 2015

[LHCb-CONF-2015-002]



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

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

Branching ratios

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

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P'_5	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P'_5	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \ \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \ \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \ \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \ \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$
[recently updated, LHCB 1506.08777]				0.26 ± 0.04		$+3.5$

[Altmannshofer, Straub 1503.06199]

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

R_K

LHCb, 1406.6482, PRL

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

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

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

$$R_K^{SM} = 1 + \delta_{R_K}$$

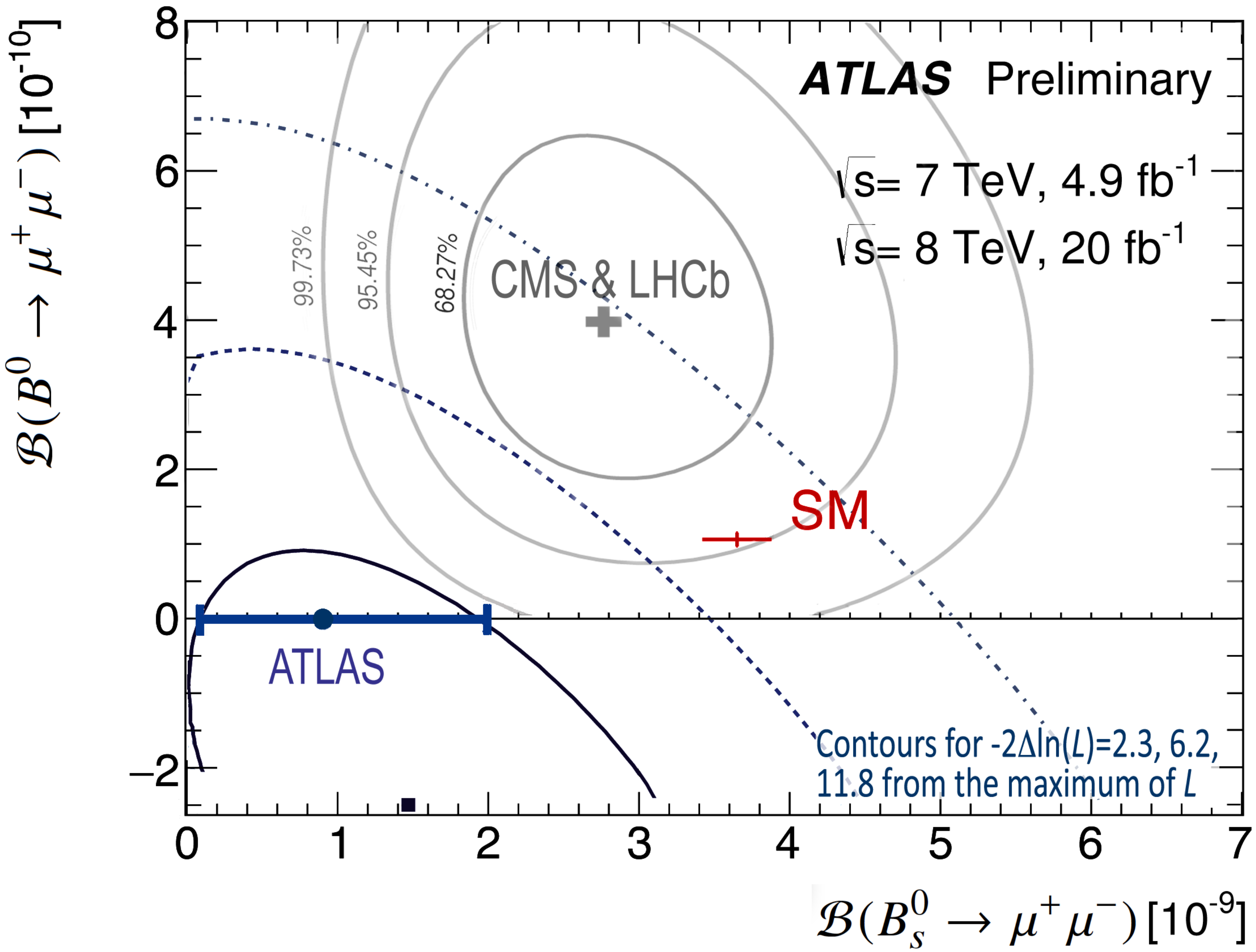
$$|\delta_{R_K}| < 1\%$$

[Bordone, Isidori, Pattori, 1605.07633]

Explanations:

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

(Leptonic decays)



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

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

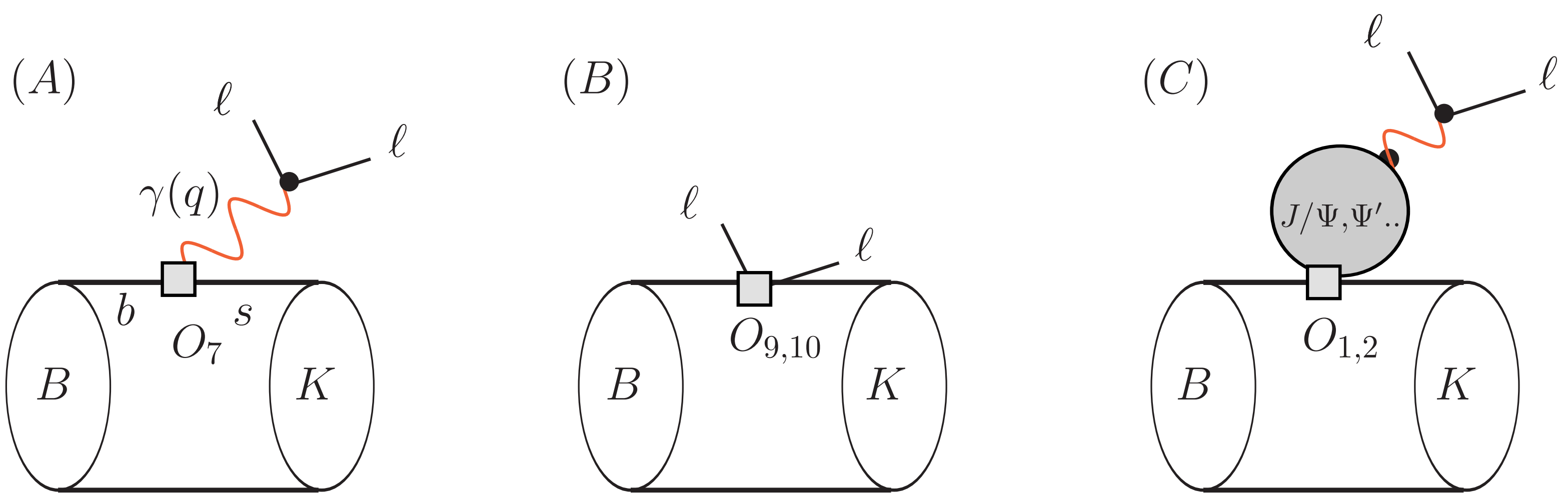
$$\mathcal{O}_7^{(\prime)} = \frac{e}{16\pi^2}\, m_b\,(\bar{s}\sigma_{\alpha\beta}P_{R(L)}b)\,F^{\alpha\beta}\,, \qquad C_7^{SM} = -0.319,$$

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

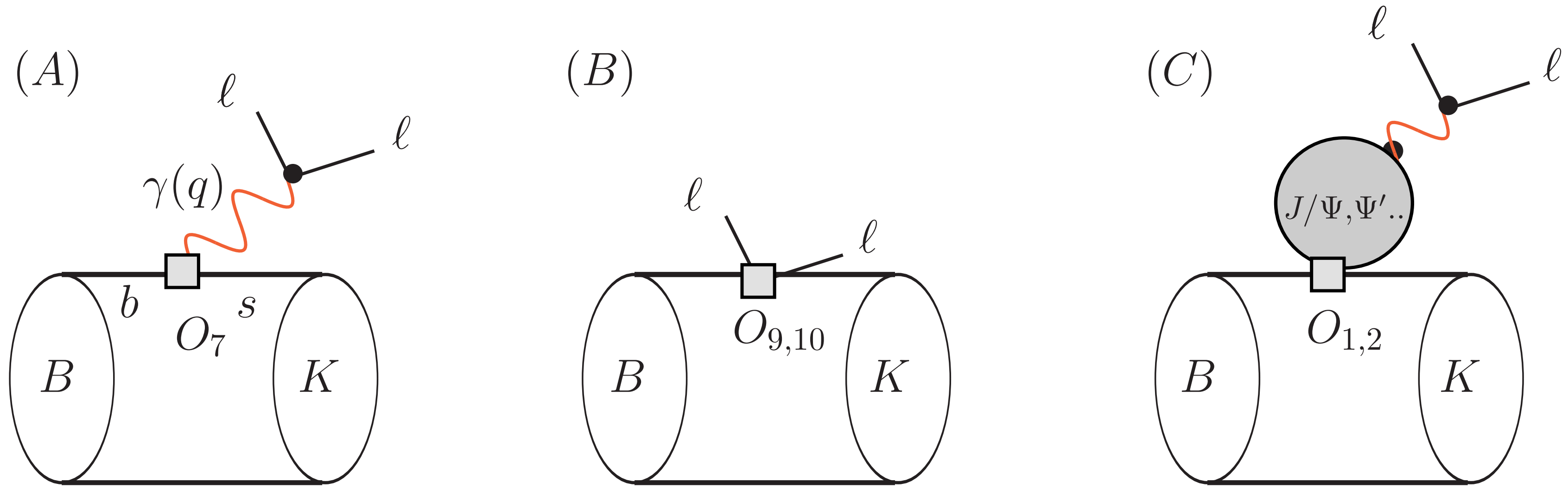
$$\mathcal{O}_{10}^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi}\,(\bar{s}\gamma_\alpha P_{L(R)}b)\,(\bar{\ell}\gamma^\alpha\gamma_5\ell). \qquad C_{10}^{SM} = -4.41.$$

SM gives lepton flavour universal contribution

- Relevant contribution, add hadronic weak interaction



Theoretical uncertainties



1. Form factors, however at low q^2 can use Light-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)

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

- Difficult to evaluate
- Some effects have been estimated (like charm loops) in 1006.4945

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
....
....]

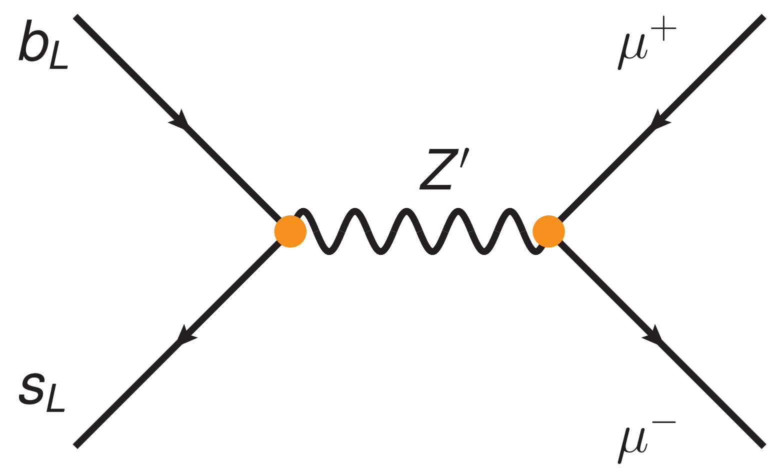
- Assuming only one source of NP at high scale, data prefers effects in the muon sector
- If only one Wilson coefficient is allowed to be non vanishing, various groups agree that NP in $\mathcal{O}_9^\mu$ is preferred by the data. $C_9^{\mu,NP} \approx -1$
- Short distance effects from New Physics are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

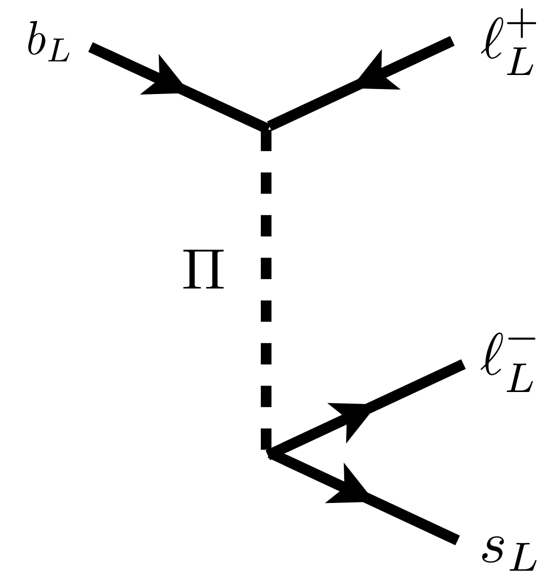
$$\begin{matrix} \bar{\ell}\gamma^\alpha\ell \\ \bar{\ell}\gamma^\alpha\gamma_5\ell \end{matrix} \longrightarrow \begin{matrix} \bar{\ell}_L\gamma^\alpha\ell_L \\ \bar{\ell}_R\gamma^\alpha\ell_R \end{matrix}$$

Best Fit with
Left-Left currents

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

Simplified Models





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

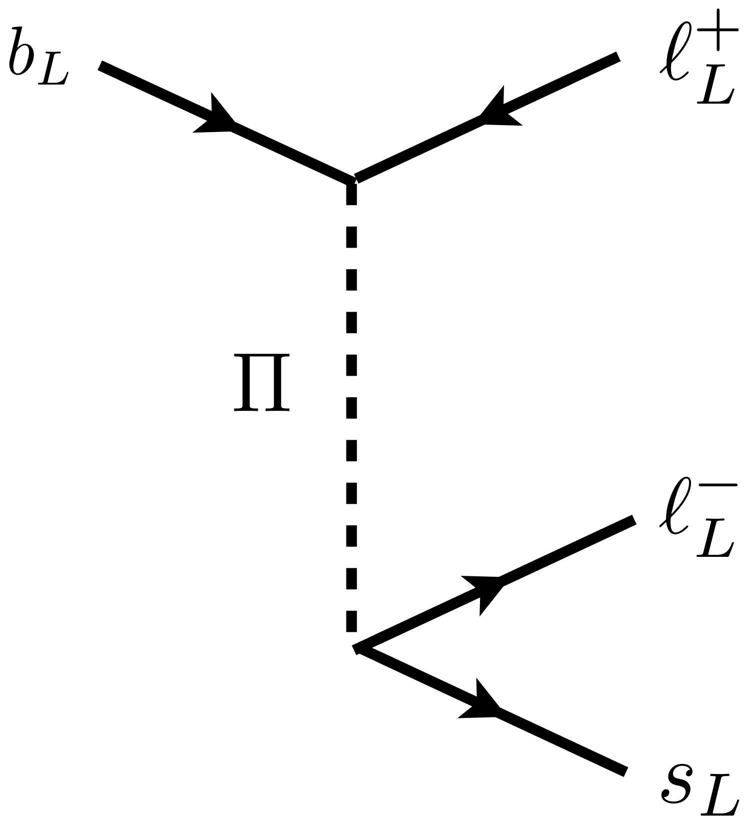
$$\frac{\lambda_{b\mu}\lambda_{s\mu}}{m_{\Pi}^2} \approx \frac{1}{(30\ \mathrm{TeV})^2}$$

Gauld, Goertz, Haisch, 1308.1959 + 1310.1082
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
…….

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



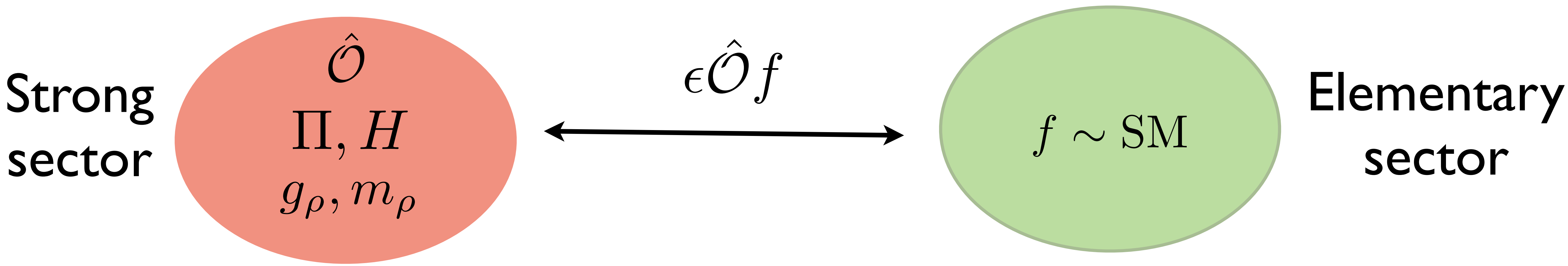
- Quantum number of the new states, uniquely determined by the the Left-Left structure

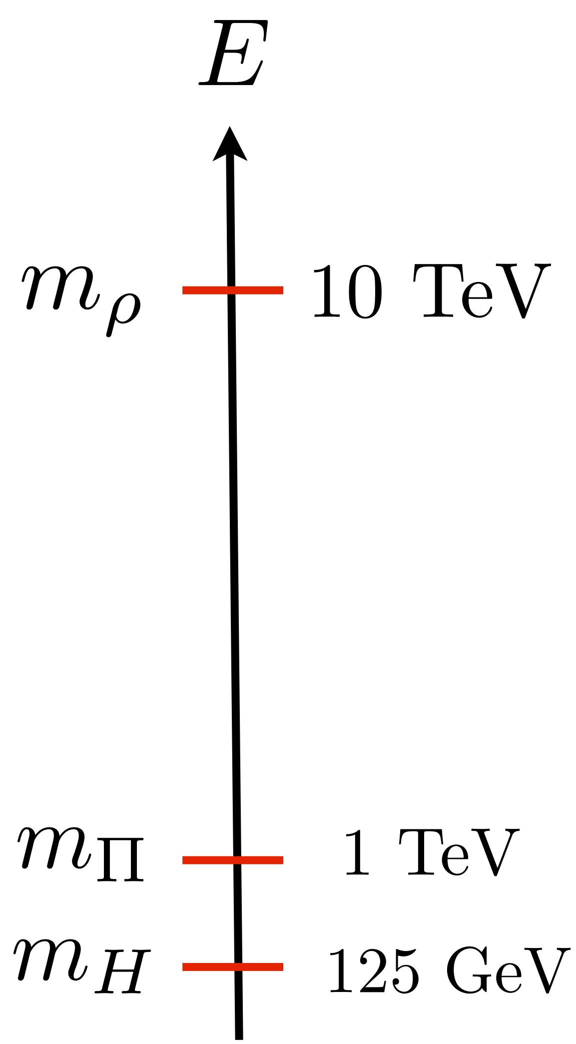
$$\Pi \sim (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

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

- 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





- 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

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

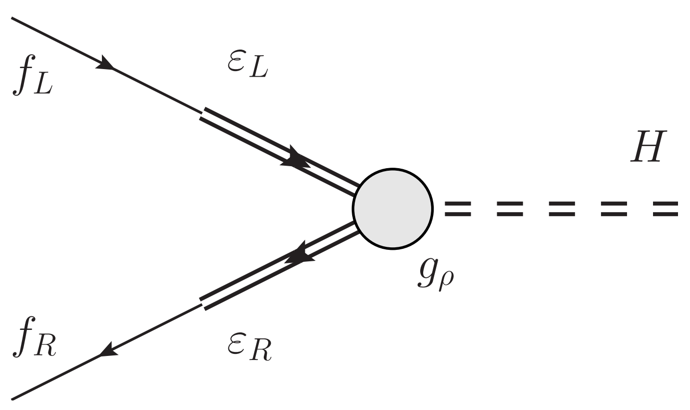
- BSM Flavour violation regulated by the same mechanism

- Naturalness (…)

Based on 1412.5942, JHEP,
Ben Gripaios and Sophie Renner

Partial Compositeness in CH models

- Yukawa sector:



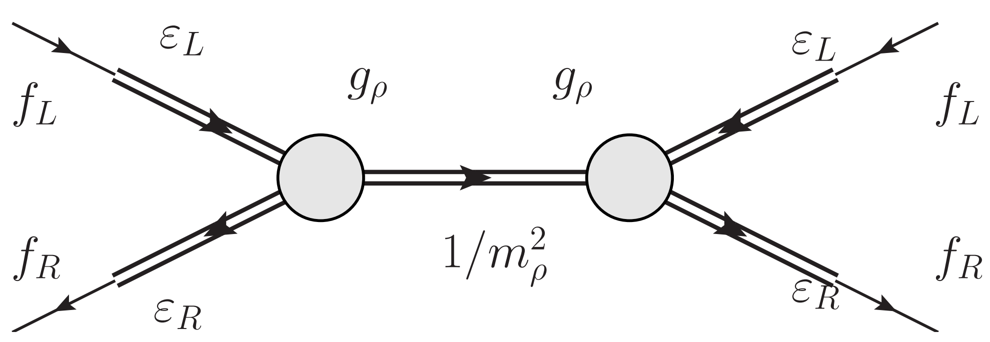
$$\mathcal{L}_{\text{elem}} = i\bar{f}\gamma^\mu D_\mu f$$

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

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

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

- 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

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)

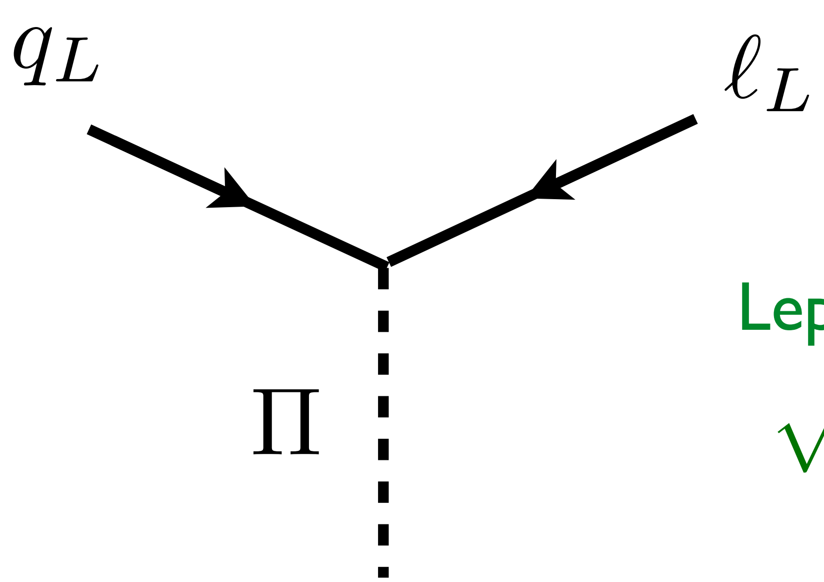
- In the lepton sector parameters cannot be univocally connected to physical inputs, due to our ignorance on neutrino masses, will assume that left and right mixing have similar size

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

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



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!

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

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

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

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

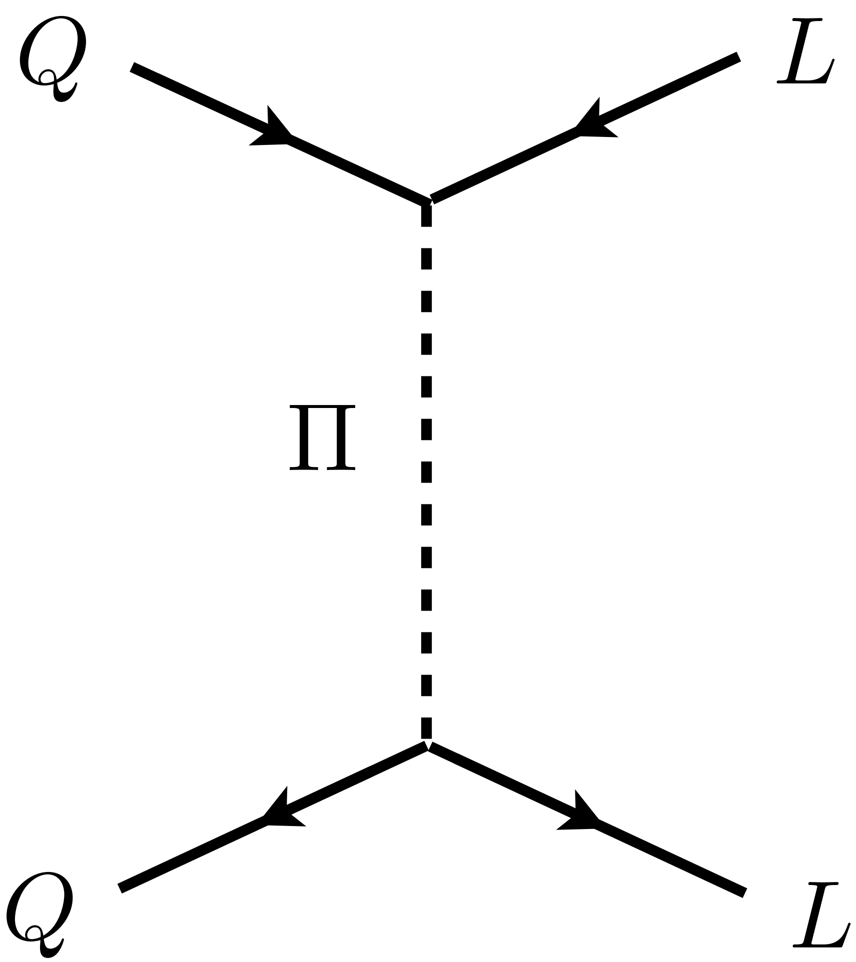
- Due to the partial compositeness structure, negligible contribution to observables involving electrons like $\text{BR}(B \to K e^+ e^-)$. R_K is easily accommodated.

- 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

Flavour violation at the tree level

- Integrating away the leptoquarks fields we get



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

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

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

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

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

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

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

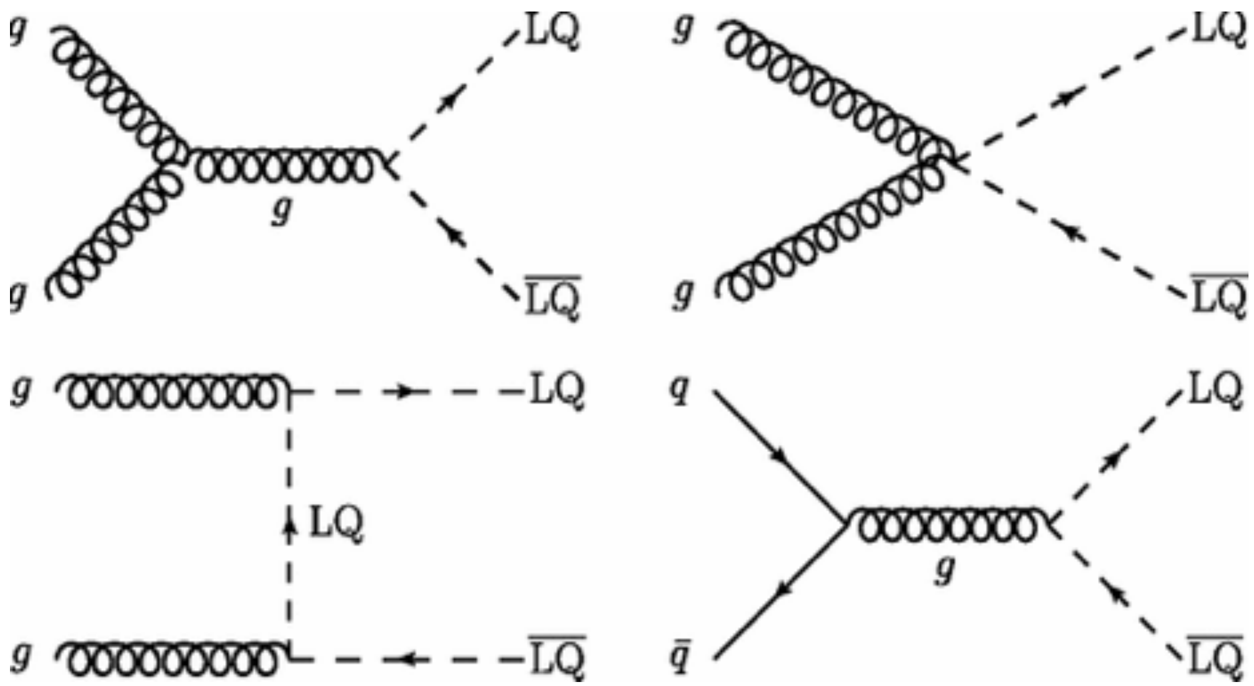
Present bound $\delta C_{\nu\bar{\nu}} \in [-6.3, 2.3]$ NA62 expected sensitivity $\delta C_{\nu\bar{\nu}} \in [-0.2, 0.2]$

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

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

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

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]

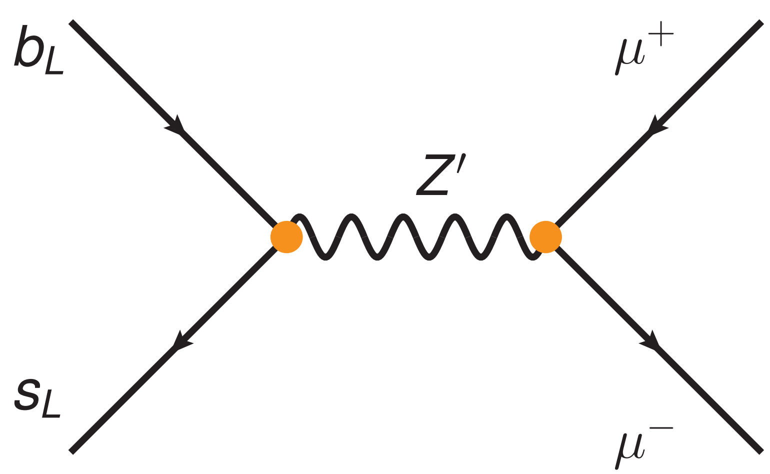
$$M > 720 \text{ GeV}$$

Z’ from a U(2) flavour symmetry

Some aspects of flavour symmetry

Based on 1509.01249, JHEP
with A. Falkowski and R. 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



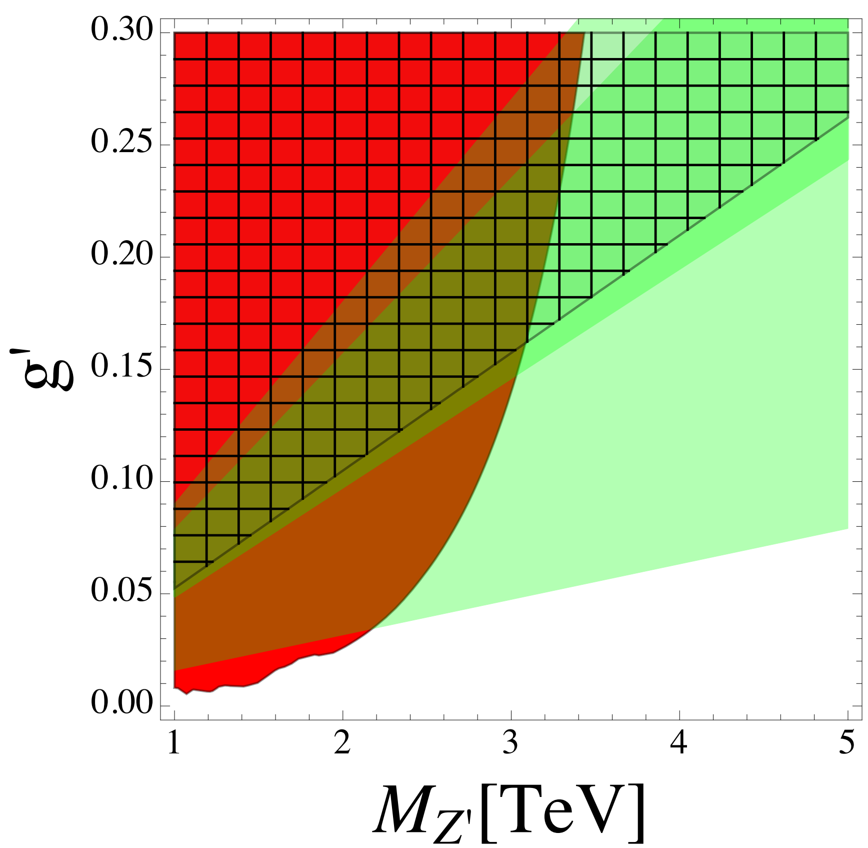
$$\mathcal{L} \supset g' \Delta_{L,R}^{f_i f_j} f_i^\dagger \overline{\sigma}^\mu f_j Z'_\mu$$

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

λ = Cabibbo angle

Predictions

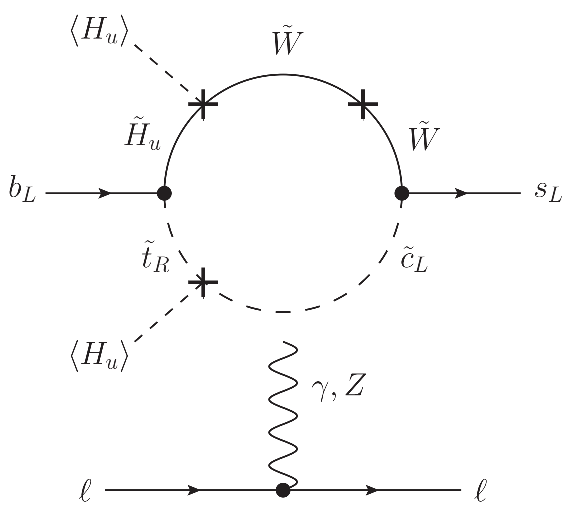
- Constructive effect in electron channels
- LFV, mu-e conversion in the nuclei
- Z’ at LHC main decay in dielectron…

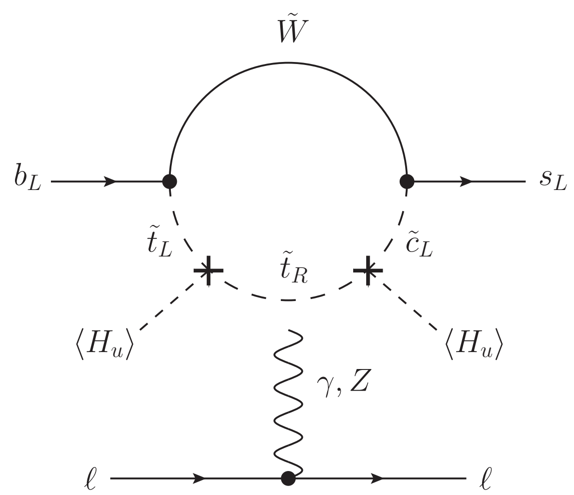


MSSM (ask me)

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

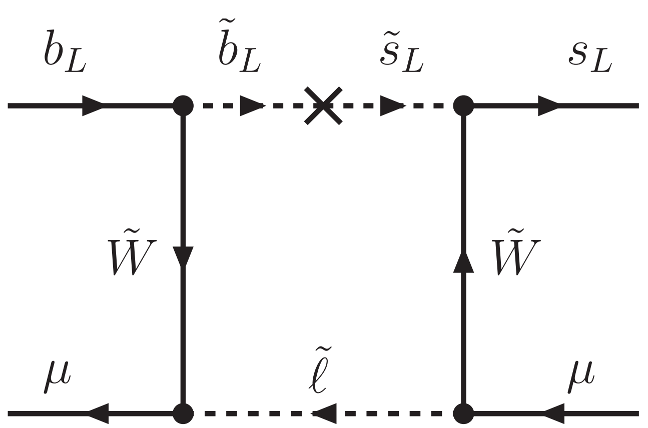
Altmannshofer, Straub
arXiv:1308.1501, arXiv:1411.3161





- 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

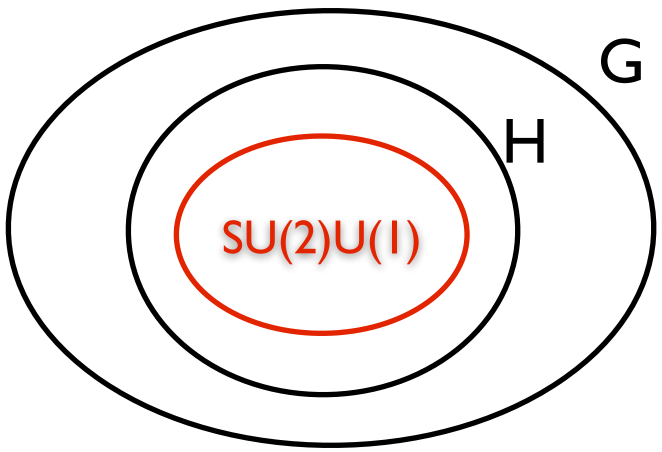
- Motivated models connecting FV in the SM and the NP exist giving rise to interesting and testable predictions at LHC and other colliders.

Backup

Composite Higgs

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

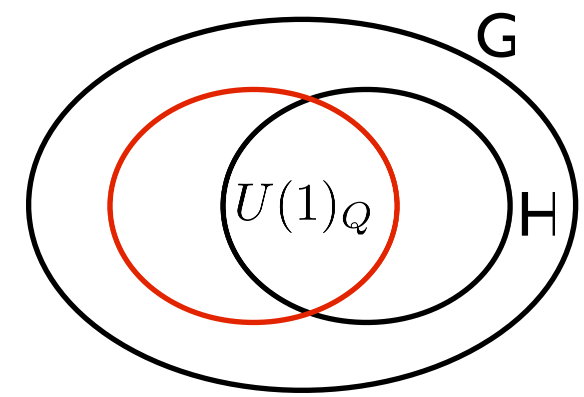
- The Higgs is a pseudo Goldstone boson
- Pattern of symmetry breaking:



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

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 $G/H = SO(5)/SO(4)$

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

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

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

Parameters (quark sector)

- Yukawas are given by

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

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

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

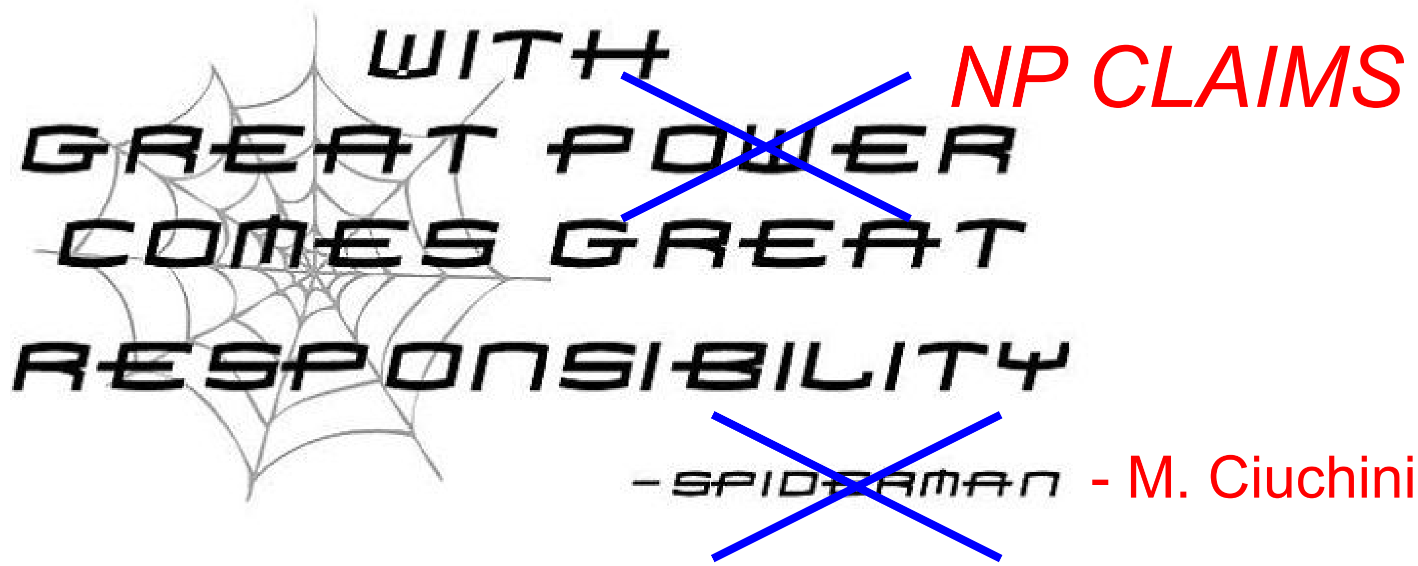
(g_ρ, ϵ_3^q) in what follows

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

$$\frac{G_W}{\sqrt{2}}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\left\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar{e}\gamma^\mu e+\tfrac{3}{2}\bar{e}\gamma^\mu\gamma_5 e\right\}.$$

If $g \gg e$ then $g \gg g'$, and this is just the usual e-ν scattering matrix element times an extra factor $\frac{3}{2}$. If $g \simeq e$ then $g \ll g'$, and the vector interaction is multiplied by a factor $-\frac{1}{2}$ rather than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be taken very seriously, but it is worth keeping in mind that the standard calculation[8] of the electron-neutrino cross section may well be wrong.



FIRST EVIDENCE OF NEW PHYSICS IN b $\leftrightarrow$ s TRANSITIONS

(**UT***fit* Collaboration)

M. Bona,[1] M. Ciuchini,[2] E. Franco,[3] V. Lubicz,[2,4] G. Martinelli,[3,5] F. Parodi,[6]
M. Pierini,[1] C. Schiavi,[6] L. Silvestrini,[3] V. Sordini,[7] A. Stocchi,[7] and V. Vagnoni[8]

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.