Heavy Flavor Physics

Theory Perspectives

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Precision Physics, Fundamental Interactions and Structure of Matter

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An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

Introductory remarks

The extensive experimental and theoretical explorations of flavor-changing processes in the past decades have taught us a great deal about the structure of the fundamental interactions and the properties of elementary particles at and beyond the electroweak scale.

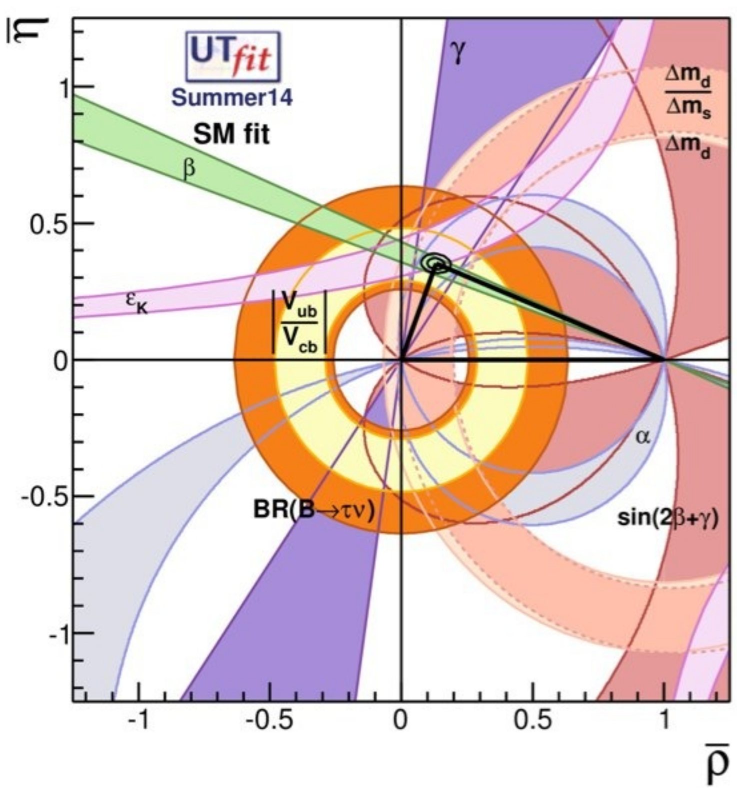
While the discovery of the massive electroweak gauge bosons W and Z (1983), of the last missing third-generation fermions t and ν_τ (1995 and 2000), and of the Higgs boson (2012) have confirmed the particle content of the Standard Model (SM), precision measurements of couplings (in particular the Yukawa couplings) have confirmed the deeper structure of the SM as the correct (effective) quantum theory of the weak scale.

Today, and even more so in the coming decades, flavor physics and precision collider physics (LHC, ILC and beyond) provide complementary and competitive tools to probe for physics beyond the SM.

Flavor physics in the Standard Model

Flavor physics in the Standard Model

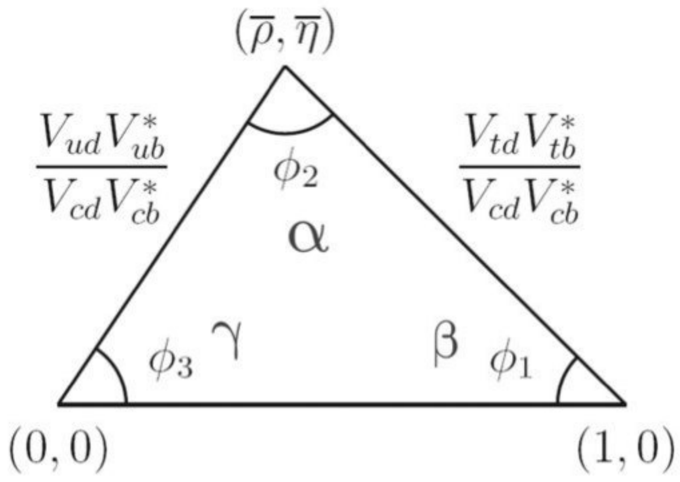
The SM description of flavor and CP violation originating only from the weak charged-current interactions and described by the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix has been spectacularly confirmed by the B-factory program (ARGUS, CLEO, BaBar, Belle, CDF, D0, LHCb, ATLAS, CMS):



$$u_L^i \to U_u^{ij} u_L^j$$

$$d_L^i \to U_d^{ij} d_L^j$$

$$\Rightarrow \quad V_{\text{CKM}} = U_u^\dagger U_d \neq \mathbf{1}$$



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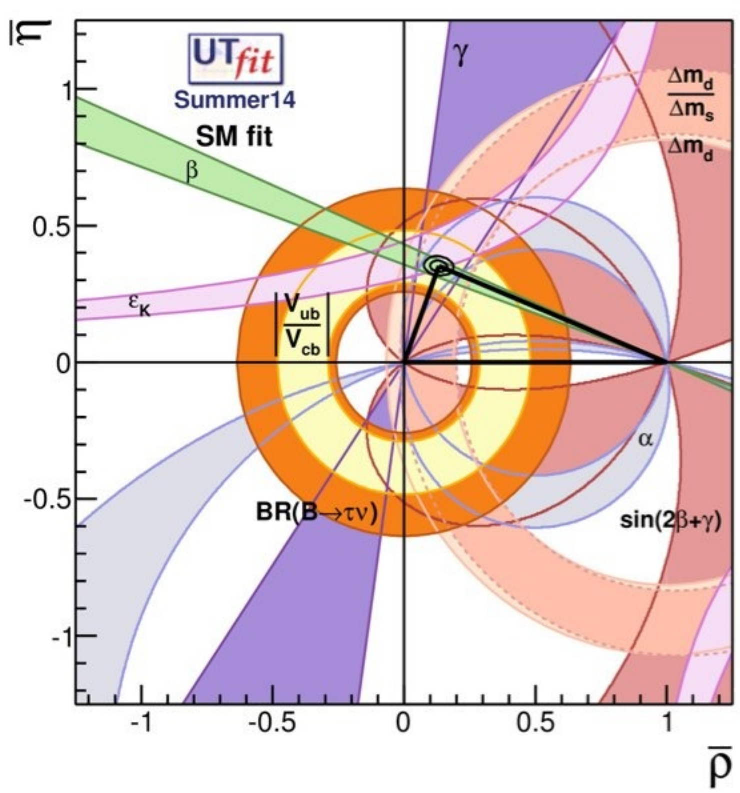
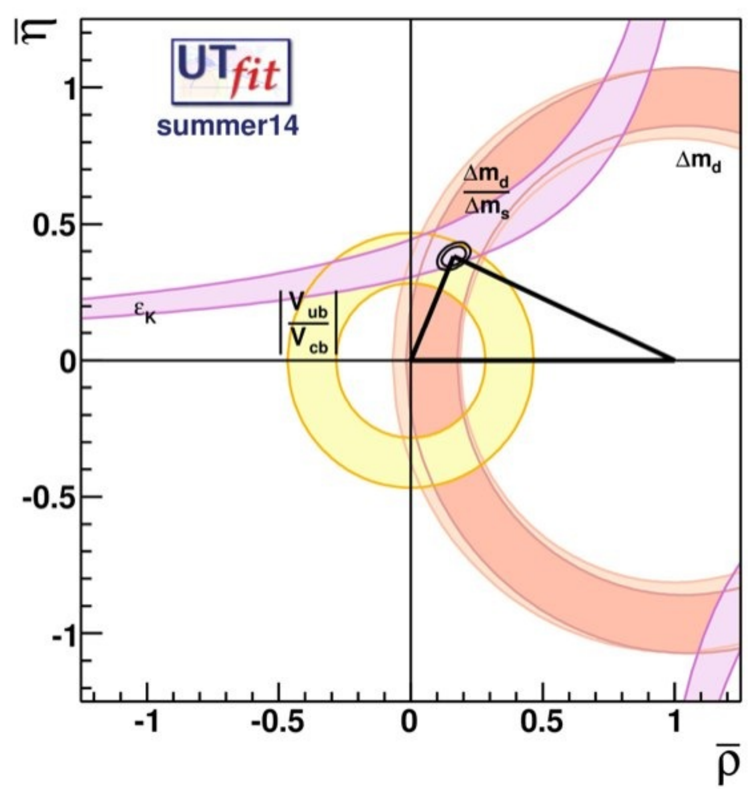
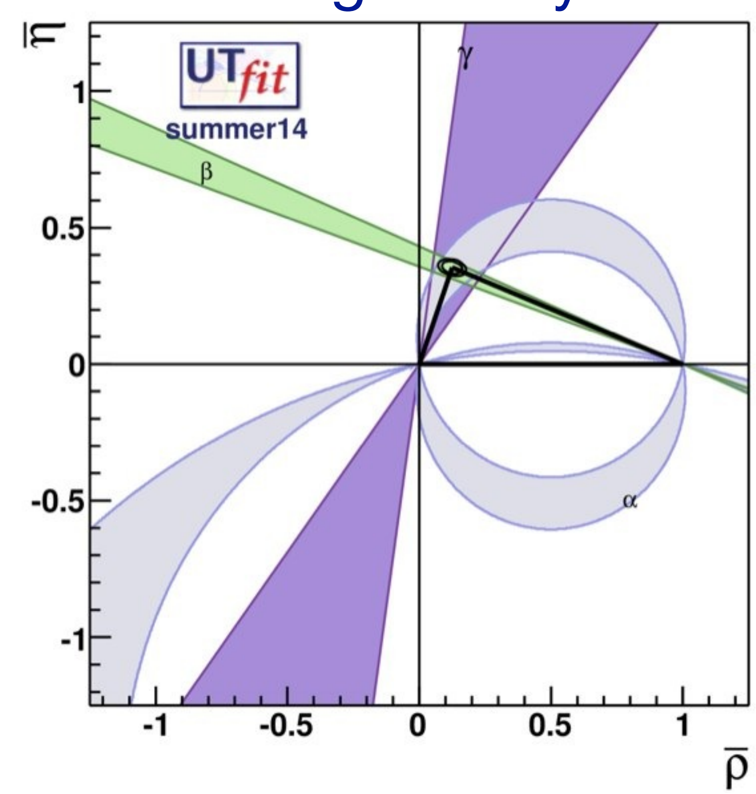


Sides and ε_K



Angles only

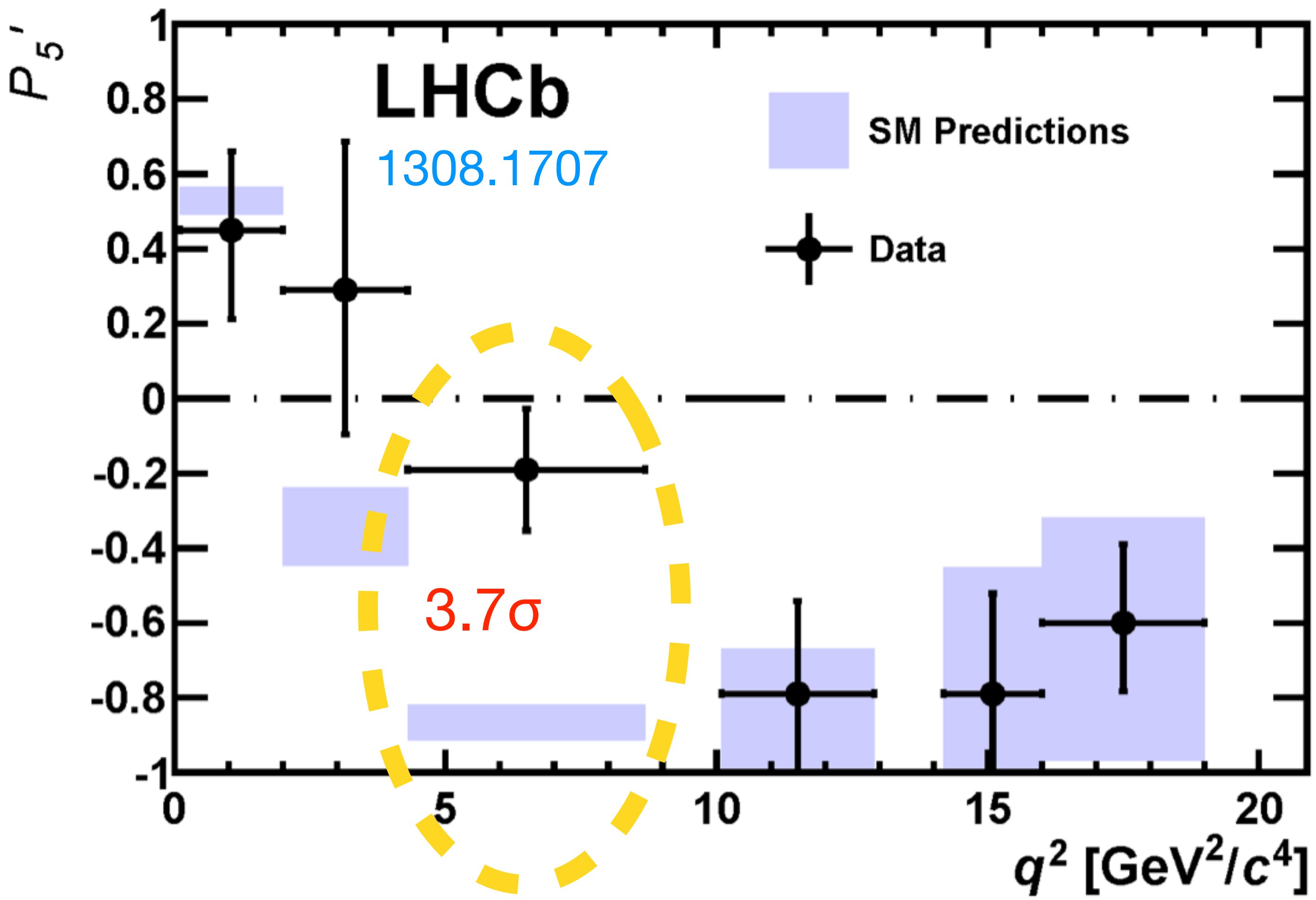


Flavor physics in the Standard Model

The CKM mechanism explains all flavor phenomena studied so far, often with incredible precision.

A few ~3σ "anomalies" exist and should be studied seriously; often such anomalies have disappeared with more data and improved theoretical analyses.

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



Flavor physics in the Standard Model

The CKM paradigm does not explain:

- the **hierarchies** of fermion masses and mixing angles
- the origin of **fermion generations**
- the mechanism of **baryogenesis**
- the **matter-antimatter asymmetry** in the Universe

We do not understand the SM before we have an answer to these questions, which call for a deeper theory of flavor.

The **flavor puzzle** is one of the few robust reasons (besides the existence of dark matter) for why we need to keep searching for new physics!

Flavor physics in the Standard Model

But we have learned much more!

The minimal model of electroweak symmetry breaking via the vacuum expectation value of a **single scalar doublet ϕ** predicts the **absence of tree-level flavor-changing neutral currents** (FCNCs), since the couplings of the neutral bosons Z and H (and, more trivially, of γ and g) are automatically flavor diagonal!

FCNCs in the SM are small due to their **loop and GIM suppression** — a wonderful protection mechanism!

Flavor physics in the Standard Model

Extensions of the SM such as two-Higgs doublet models, SUSY models, extended gauge models (Z'), … tend to predict large FCNCs and can thus give rise to visible effects in many observables:

$$\epsilon_K,\ B\to X_s\gamma,\ B_s\to\mu^+\mu^-,\ K\to\pi\nu\bar{\nu},\ D-\bar{D}\ \text{mixing}, \ldots$$

This is a **huge constraint** on BSM model building!

In fact, flavor data and the existence of dark matter are the **most robust constraints** we have on model building (the role of "naturalness" is currenty being questioned in view of the absence of new colored particles at the LHC).

Flavor physics beyond the Standard Model

Flavor structure beyond the SM

FCNCs provide prime tools to probe the SM at the quantum level and search for (even minute) hints of new interactions or the existence of new virtual particles:

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i$$

Operator	Bounds on Λ [TeV] $(C=1)$		Bounds on C $(\Lambda = 1\,\text{TeV})$		Observables
	Re	Im	Re	Im	
$(\bar s_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar s_R\, d_L)(\bar s_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar c_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar c_R\, u_L)(\bar c_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_R\, d_L)(\bar b_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_L \gamma^\mu s_L)^2$	1.1×10^2	2.2×10^2	7.6×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar b_R\, s_L)(\bar b_L s_R)$	3.7×10^2	7.4×10^2	1.3×10^{-5}	3.0×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

Isidori, Nir, Perez (2010)

Flavor structure beyond the SM

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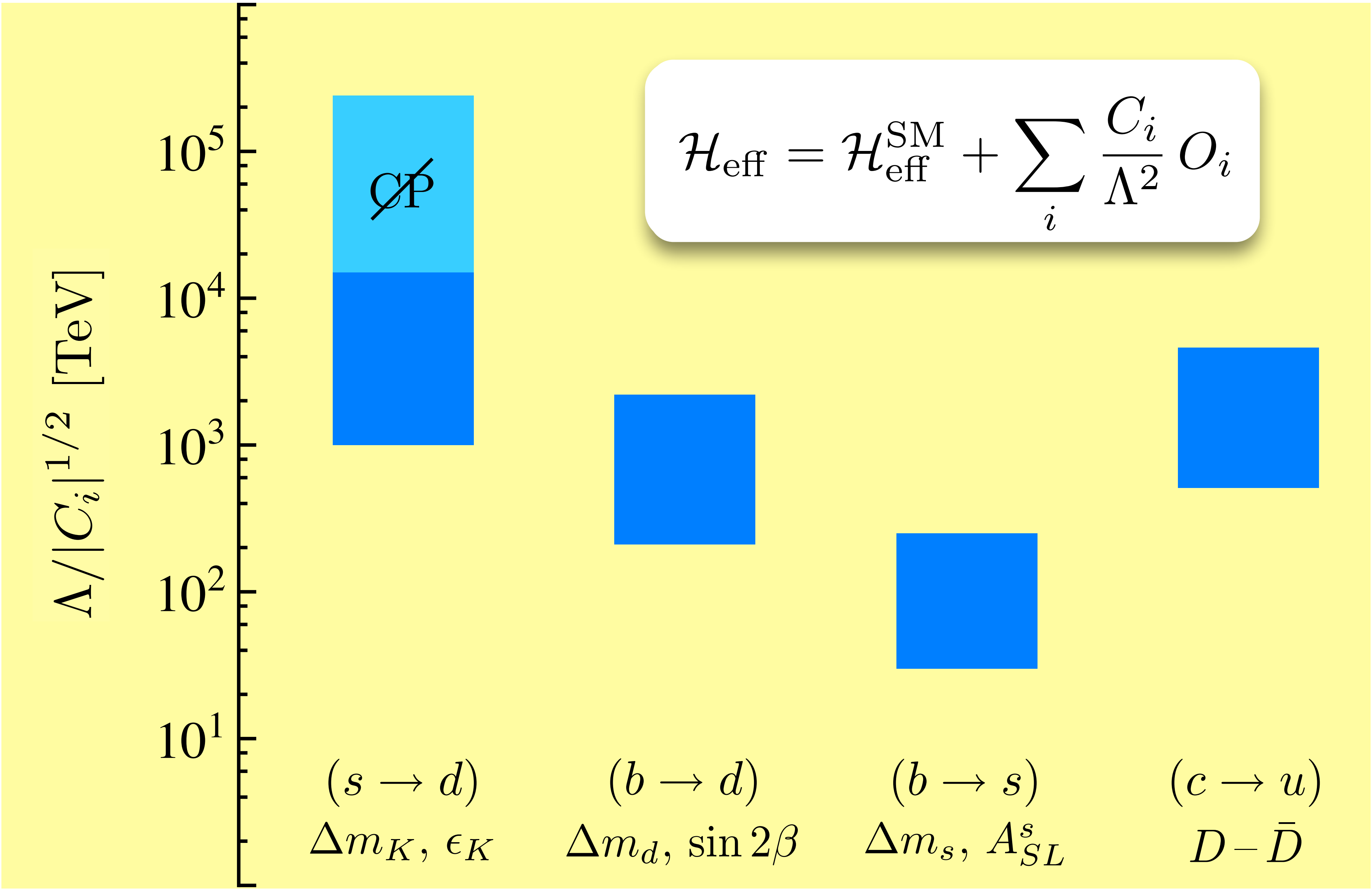
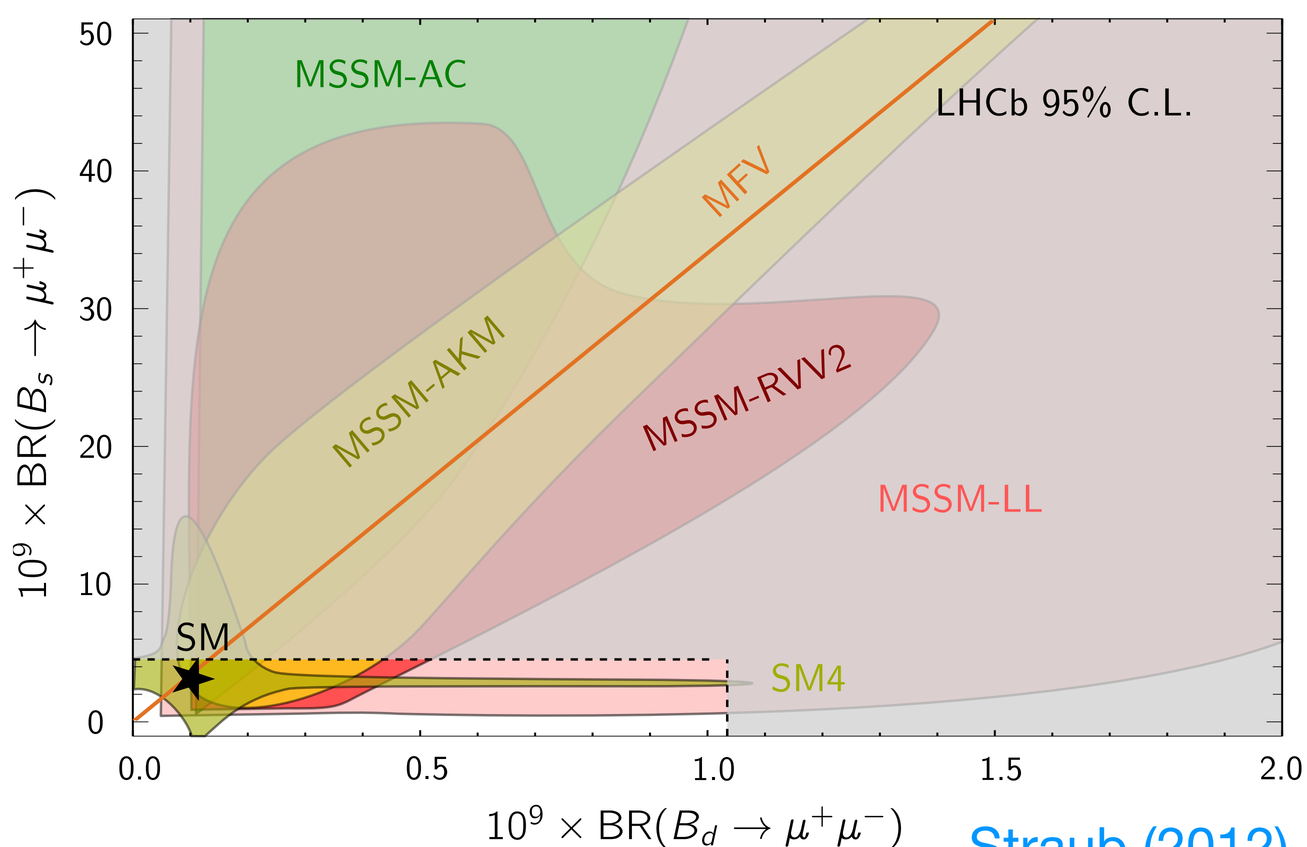


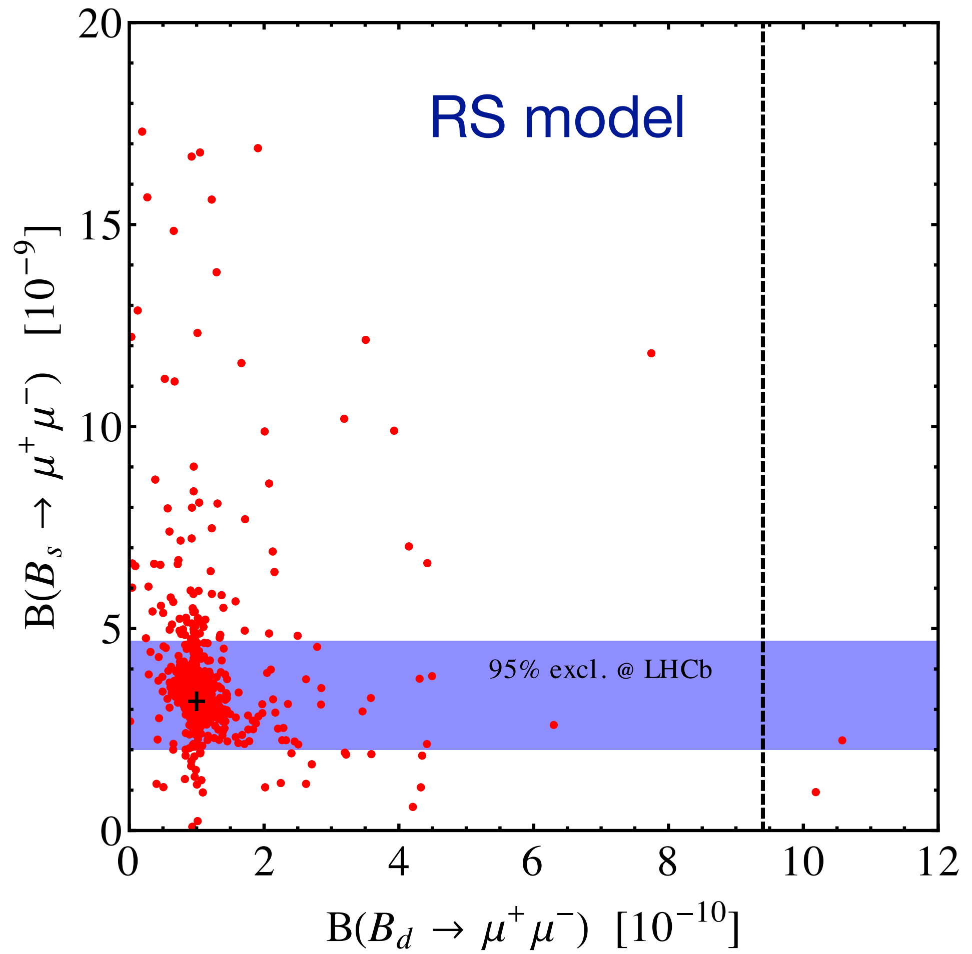
Example 1: Rare leptonic decays $B_{s/d}\to\mu^+\mu^-$

Generically, very large deviations from the SM predictions for the $B_{d,s}\to\mu^+\mu^-$ rates are expected in SUSY models, unless one imposes some *ad hoc* flavor structure such as MFV to keep these corrections small:



Straub (2012)

Much smaller corrections are predicted in dynamical flavor models such as warped extra dimensions (RS models), since the RS-GIM mechanism naturally suppresses flavor-changing interactions of light fermions:



Bauer, Casagrande, Haisch, MN (2009)
Blanke et al. (2008)

$\overline{BR}_{s,SM} = (3.65 \pm 0.23)\times 10^{-9}$

$\overline{BR}_s^{(exp)} = (2.9 \pm 0.7)\times 10^{-9}$

Example 1: Rare leptonic decays $B_{s/d} \to \mu^+\mu^-$

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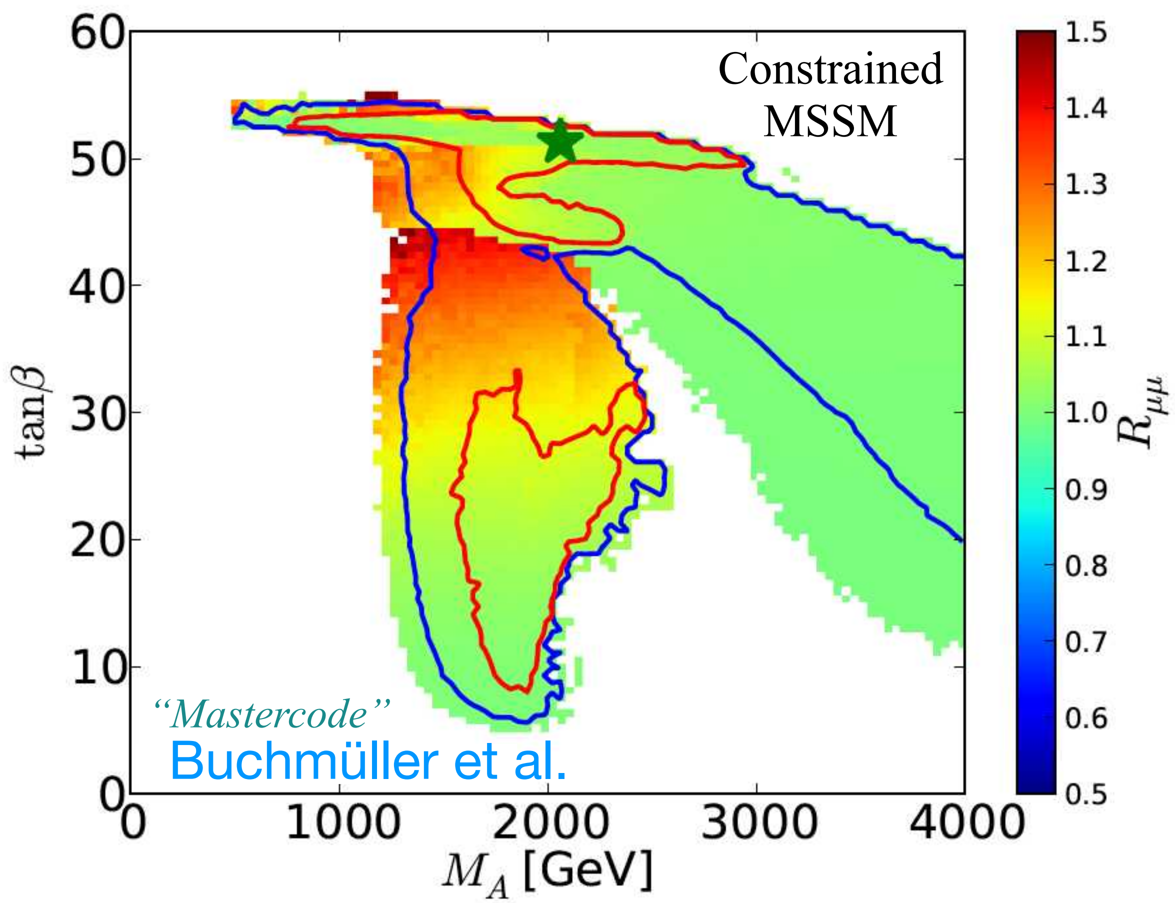

see also: Mahmoudi, Hurth (2012)
Roszkowski et al. (2012)
Altmannshofer et al. (2013)

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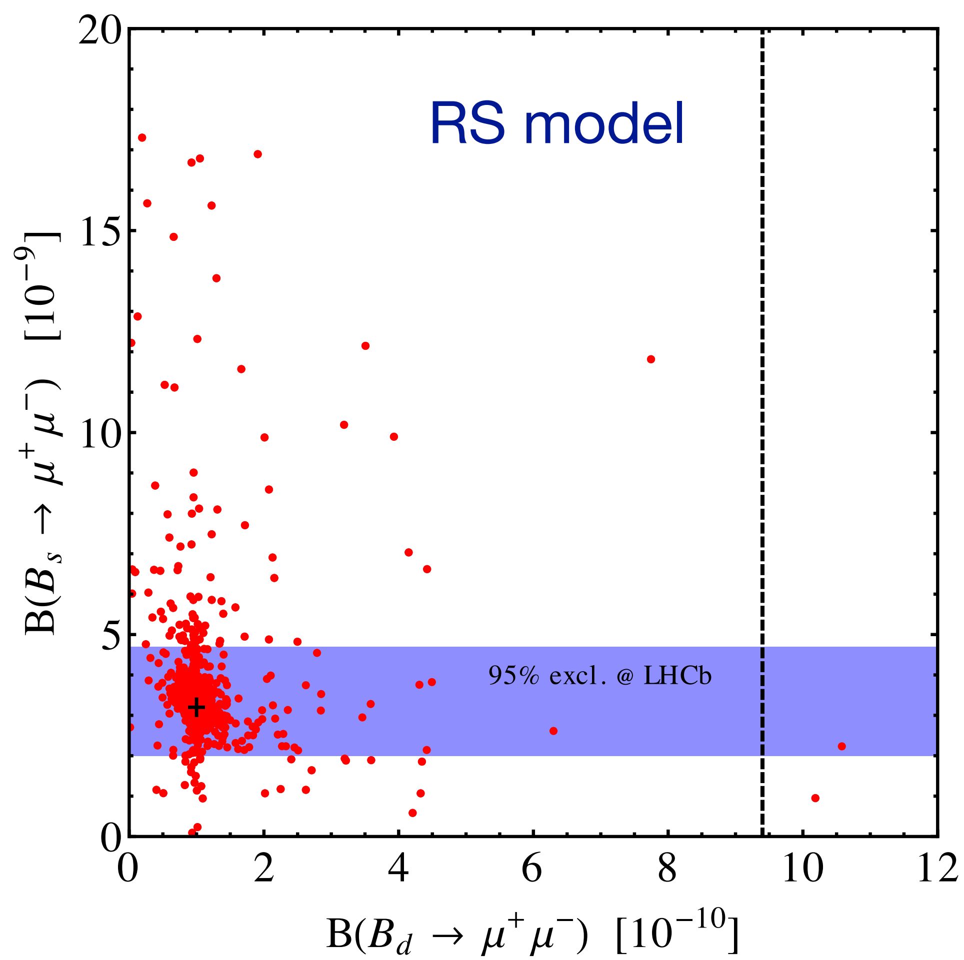


Bauer, Casagrande, Haisch, MN (2009)
Blanke et al. (2008)

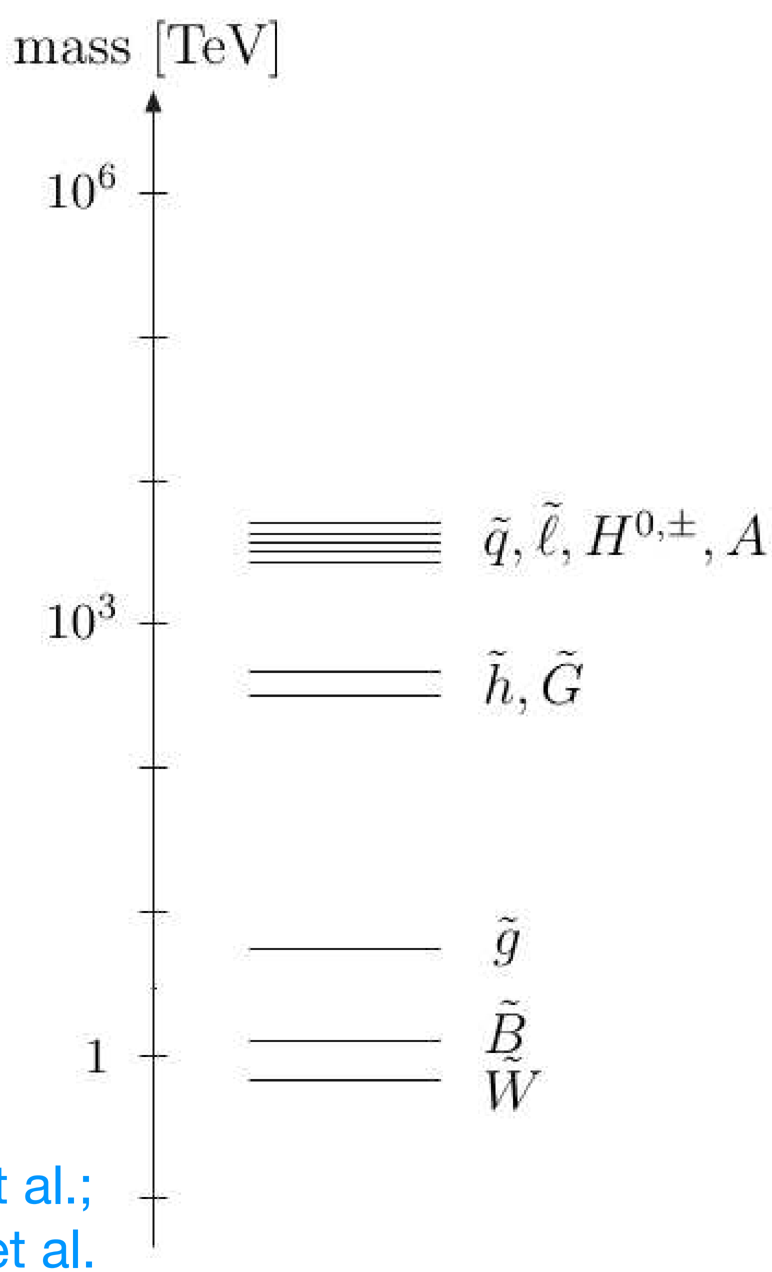
Example 2: Split SUSY with PeV-scale sfermions

Generically large SUSY flavor effects can be tamed by raising the mass scale of scalar super-partners into the 1000-TeV range (which also helps explaining their non-observation at the LHC:-)

This has several advantages:

- a 125 GeV Higgs can be accommodated effortlessly
- heavy sfermions open up the possibility of radiatively generating fermion mass hierarchies
- gaugino masses from anomaly mediation are a loop factor below the gravitino mass

Such split-SUSY models change the perspective on flavor physics, too!



Hall, Nomura; Arvanitaki et al.; Kane et al.; Yanagida et al.; Wells; Arkani-Hamed et al.

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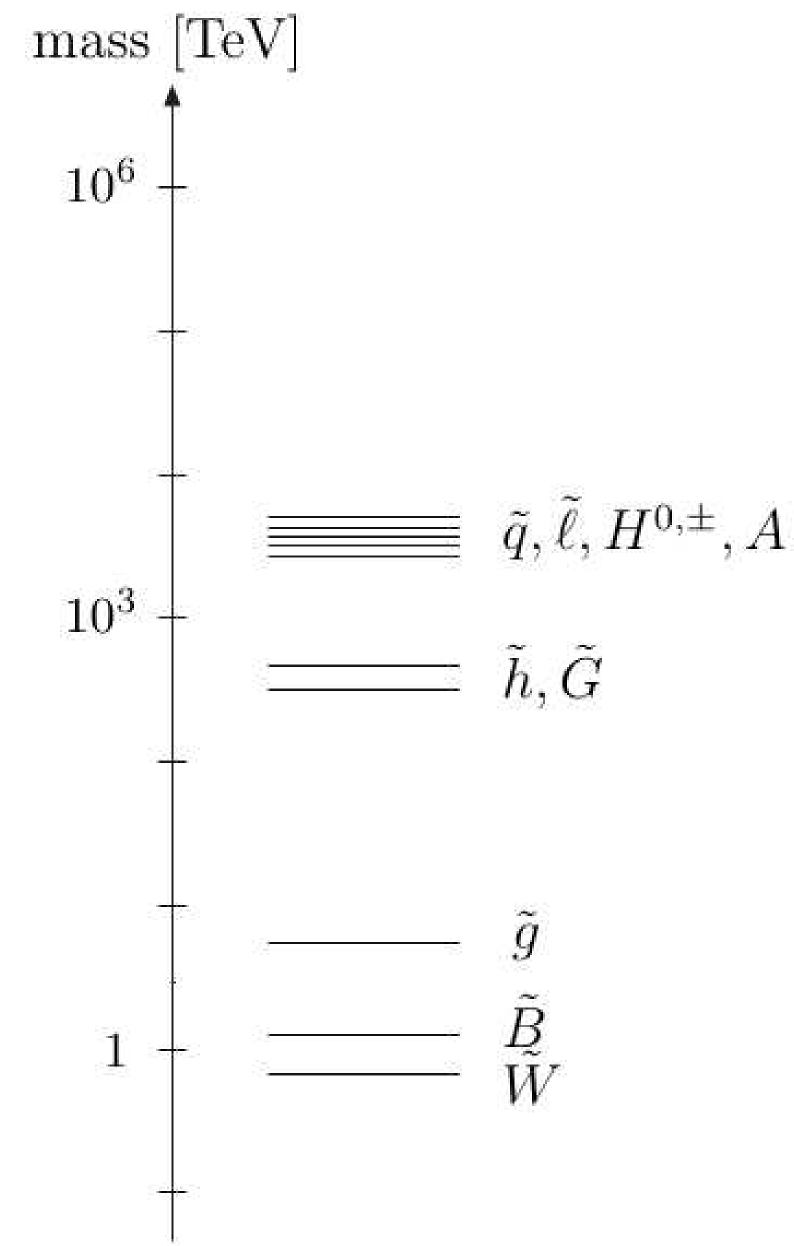
For TeV-scale sfermions:

- **SUSY flavor problem**: extensive contributions to many low-energy observables

For PeV-scale (~1000 TeV) sfermions:

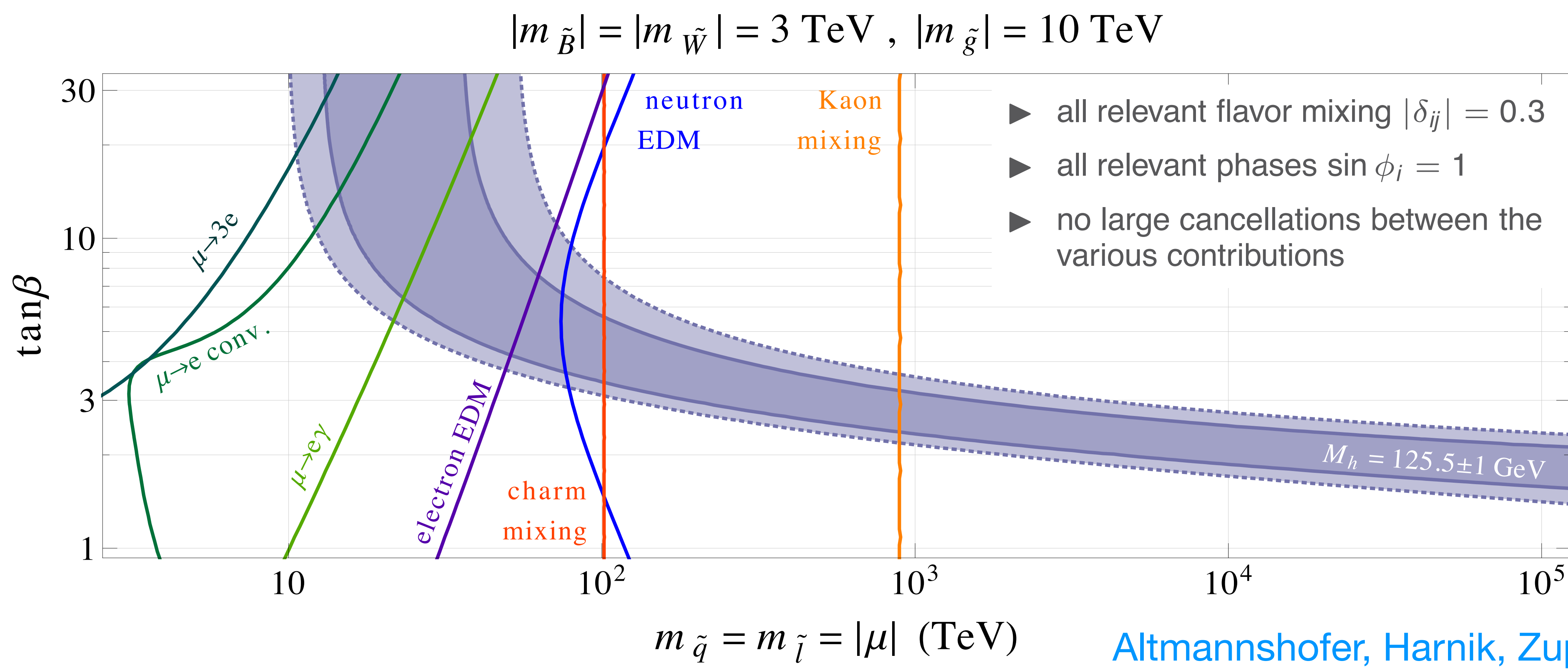
- **SUSY flavor opportunities**: a large number of low-energy observables can be sensitive to sfermion masses far beyond the reach of LHC

Altmannshofer, Harnik, Zupan (2013)



Example 2: Split SUSY with PeV-scale sfermions

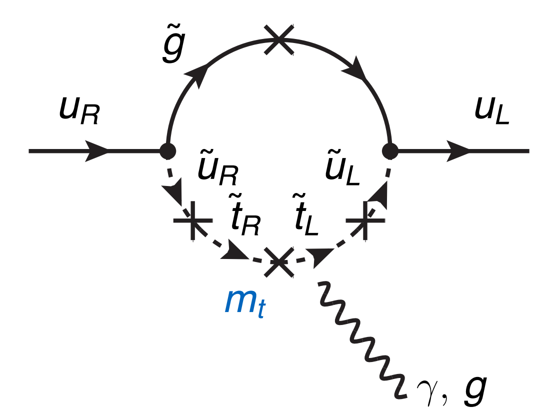
Present constraints:



Altmannshofer, Harnik, Zupan (2013)

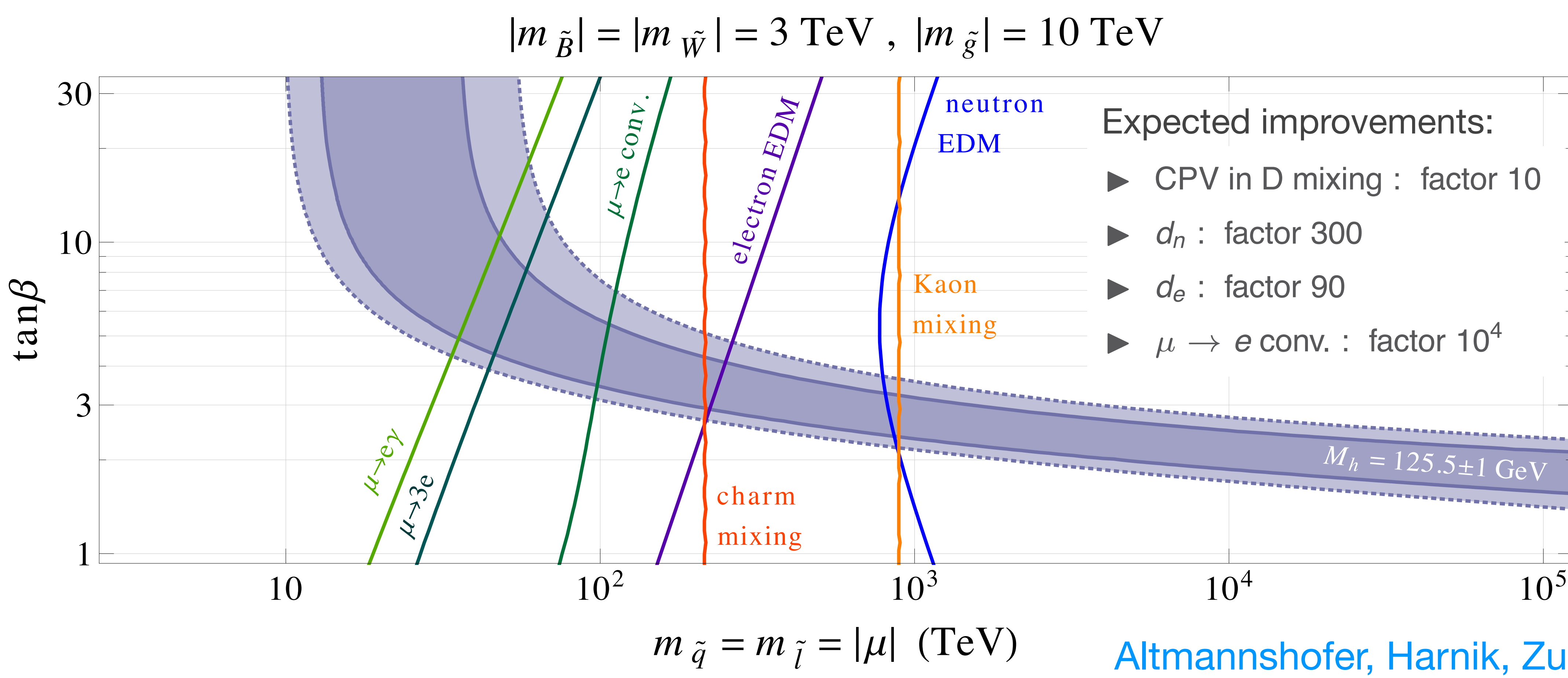
Observations:

- PeV-scale squarks are probed in kaon mixing (ε_K)
- charm mixing and neutron EDM reach up to 100 TeV
- EDMs are particularly interesting, enhanced by m_τ/m_e (d_e) or m_t/m_u (d_n)   McKeen, Pospelov, Ritz (2013)



Example 2: Split SUSY with PeV-scale sfermions

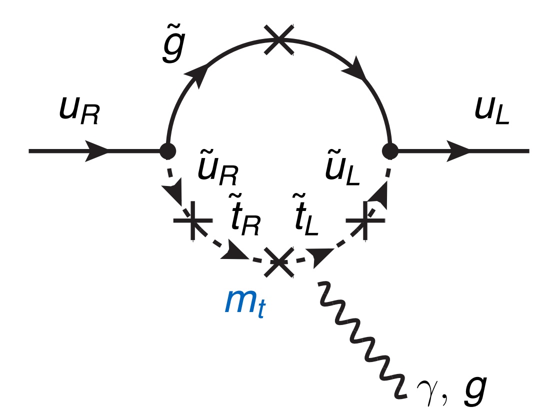
Future constraints:



Altmannshofer, Harnik, Zupan (2013)

Observations:

- neutron EDM will probe 1000 TeV squarks
- electron EDM and μ→e conversion will be sensitive to slepton masses above 100 TeV

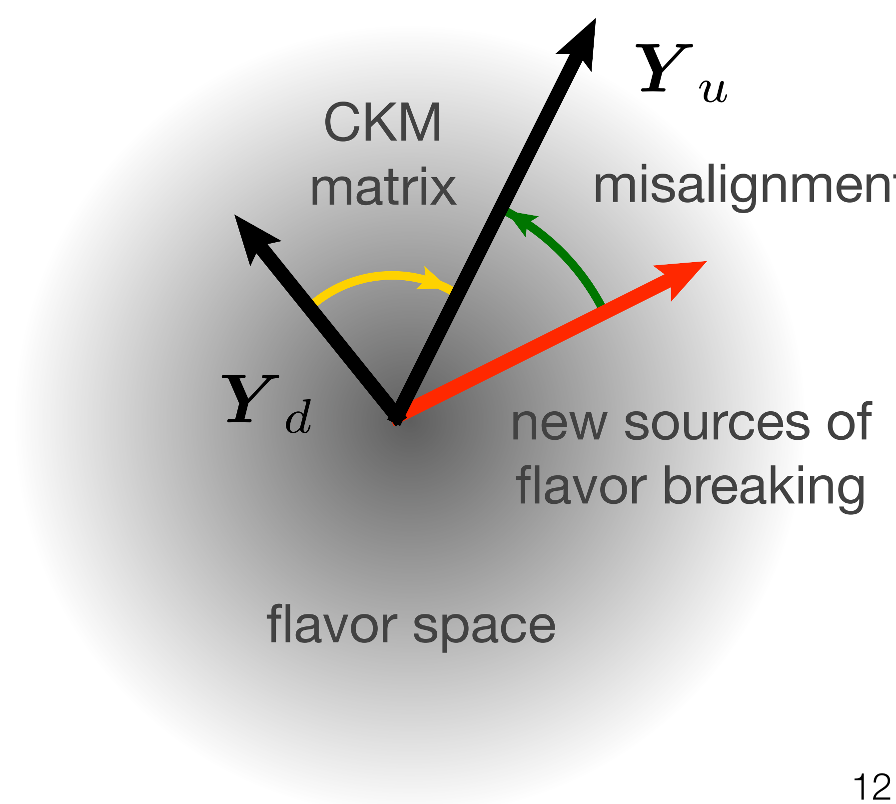


Flavor structure beyond the SM

Flavor violation is a **generic feature** of any BSM physics, since *a priori* there is no reason why the flavor orientation of the couplings of some new particle(s) should be aligned with the CKM matrix!

The concept of minimal flavor violation (MFV) is often invoked to tame flavor effects in BSM models.

Without an underlying theory based on flavor symmetries and their dynamical breaking, MFV is a only paradigm but not a well motivated model.



Flavor structure beyond the SM

Simple example:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\lambda_{ij}}{\Lambda^2}\left(\phi^\dagger\phi\right)\bar{Q}_L^i u_R^j\,\tilde{\phi} + {\rm h.c.}$$

EWSB & rotation to mass basis

$$\mathcal{L} \ni -\sum_{ij} Y_{ij}\,H\bar{u}_L^i u_R^j + {\rm h.c.}$$

Agashe, Contino (2009)
Azatov, Toharia, Zhu (2009)

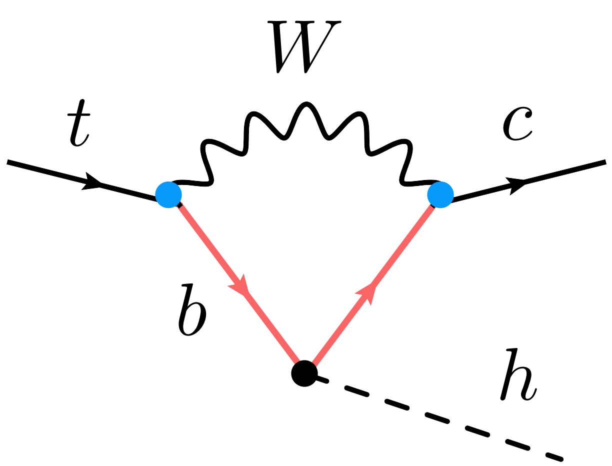
with:

$$Y_{ij} = \frac{\sqrt{2}m_i}{v} + \frac{v^2}{\Lambda^2}\bar{\lambda}_{ij}\,; \quad \bar{\lambda} = U_L \lambda U_R^\dagger$$

This gives rise to flavor-changing Higgs couplings and top-quark FCNCs, unless the matrix λ_{ij} is by chance aligned with the SM Yukawa matrix y_{ij}!

Flavor structure beyond the SM

In the SM, FCNC decays of the top-quark are strongly loop, CKM and GIM suppressed:



$$\mathcal{M} \simeq \frac{3}{32\sqrt{2}\pi^2} V_{tb}^* V_{cb} \, y_t \, \frac{m_b^2}{v^2} \, \bar{c}_L t_R h$$

$$\text{Br}(t \to ch) \simeq 3 \cdot 10^{-15} \,, \qquad \text{Br}(t \to uh) \simeq 2 \cdot 10^{-17}$$

Observing these decays would be a clear signal of new physics, presumably of TeV-scale origin.

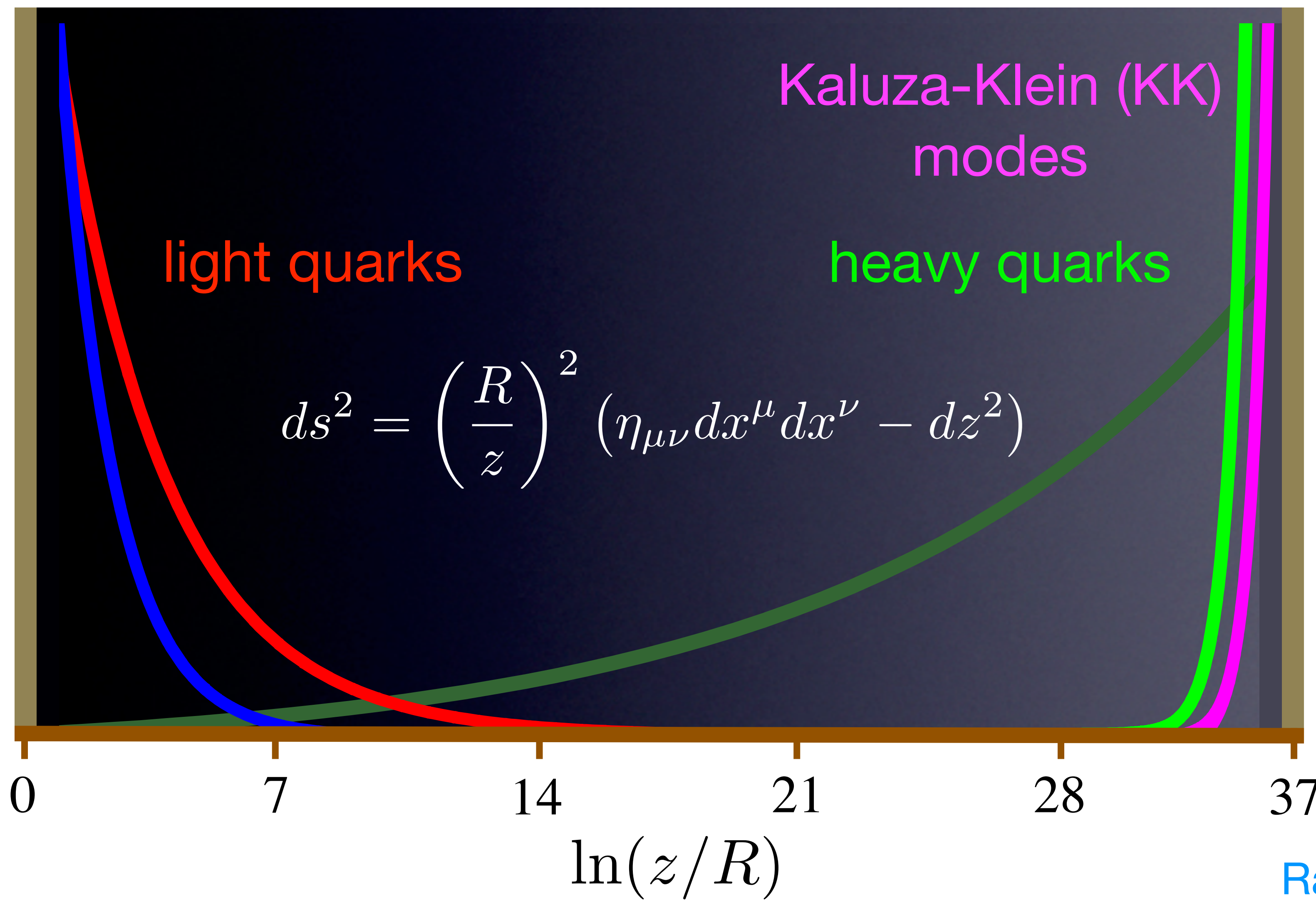
Flavor structure beyond the SM

Concrete models offering a compelling approach to the flavor problem (Froggatt-Nielsen, warped extra dimensions, partial compositeness, …) typically predict some **departures from the MFV paradigm** due to **additional sources of flavor and CP violation** not encoded in the SM Yukawa couplings!

It is important to probe as many flavor observables as possible, without assuming model-dependent correlations!

Flavor structure beyond the SM

Randall-Sundrum (RS) models as an example:

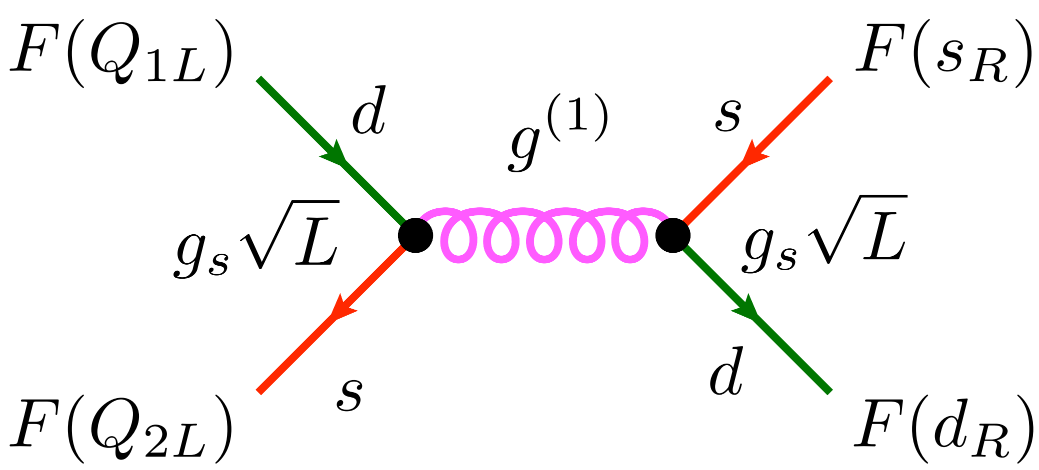


Randall, Sundrum (1999)

The localization of fermions along the extra dimension depends exponentially on O(1) parameters related to the 5D masses. As a result, the overlap integrals with the Higgs profile are exponentially small for light quarks.

Grossman, MN (1999); Ghergetta, Pomarol (2000)

Flavor structure beyond the SM



$$\sim \frac{g_s^2}{M_{\mathrm{KK}}^2}\, L\, F(Q_{1L})F(d_R)\, F(Q_{2L})F(s_R)$$

Tree-level quark FCNCs are induced by the virtual exchange of **Kaluza-Klein (KK) resonances** (including gluons).

Huber (2003); Burdman (2003)
Agashe et al. (2004); Casagrande et al. (2008)

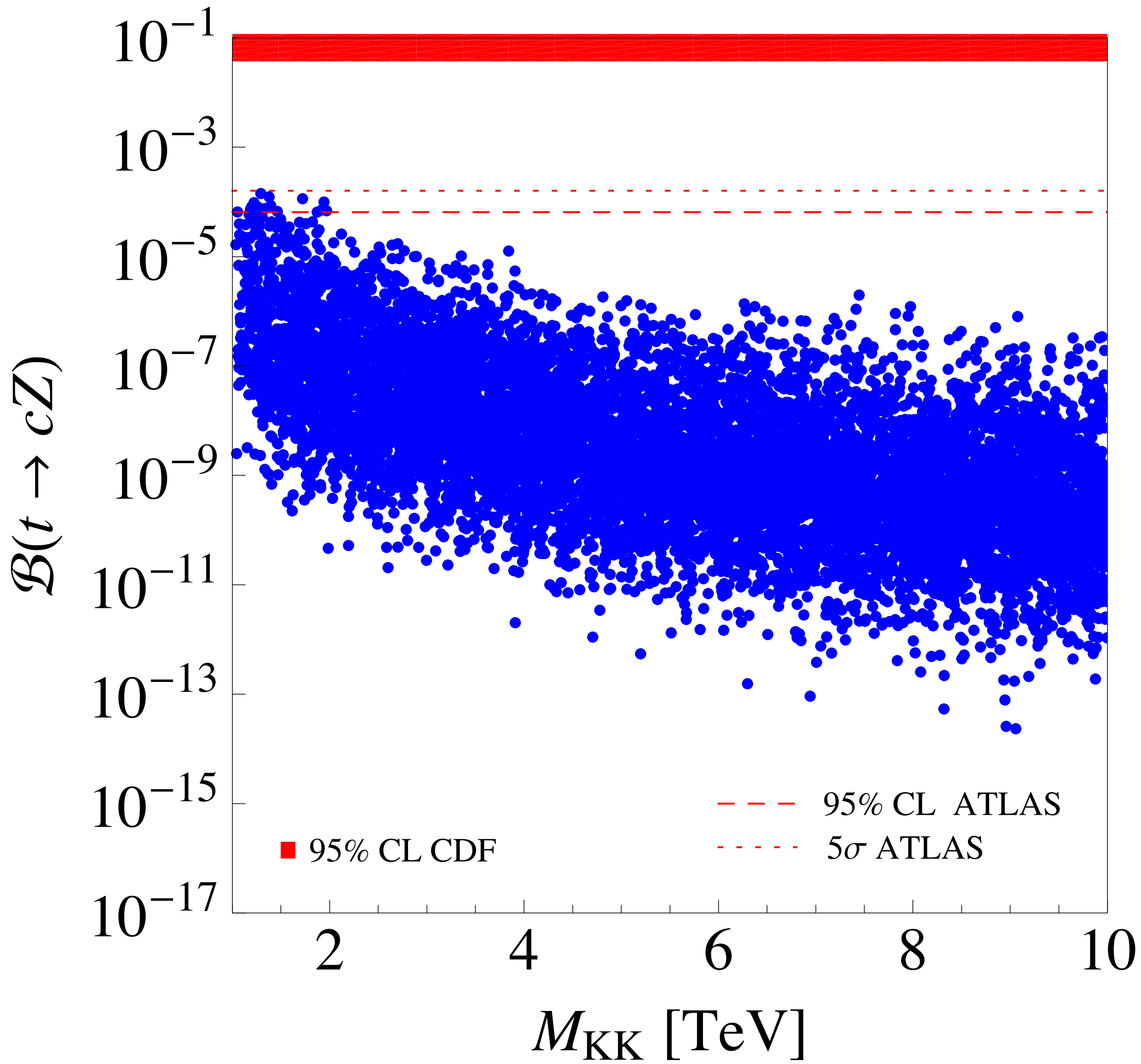
The resulting FCNC couplings depend on the same exponentially small overlap integrals $F(Q_L)$, $F(q_R)$ that generate the fermion masses.

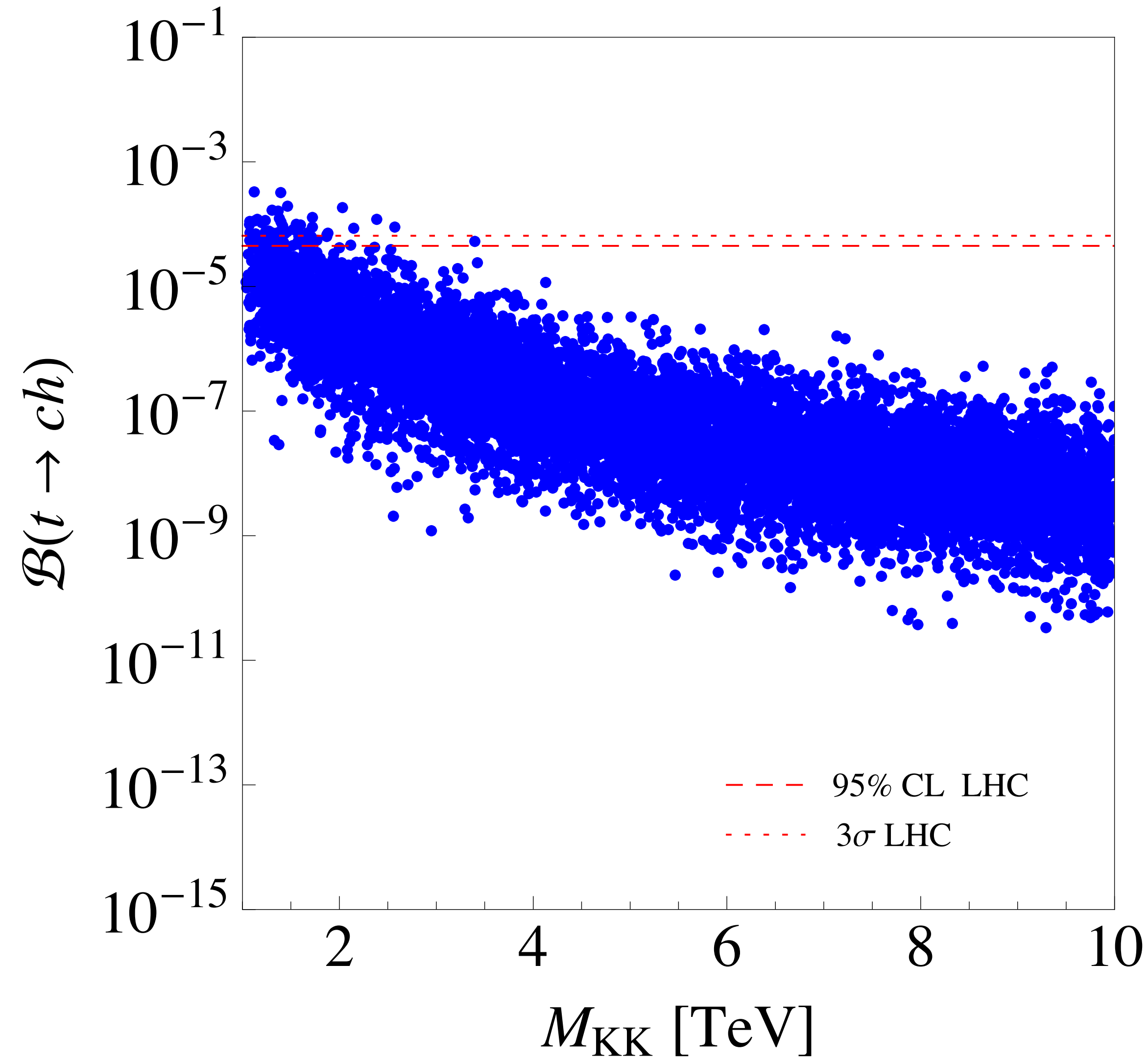
As a result, FCNCs involving light quarks are strongly suppressed: **RS-GIM mechanism** Agashe et al. (2004)

This mechanism suffices to suppress most of the dangerous FCNC couplings!

Flavor structure beyond the SM

Predictions for top-quark FCNCs in the RS model with custodial protection:



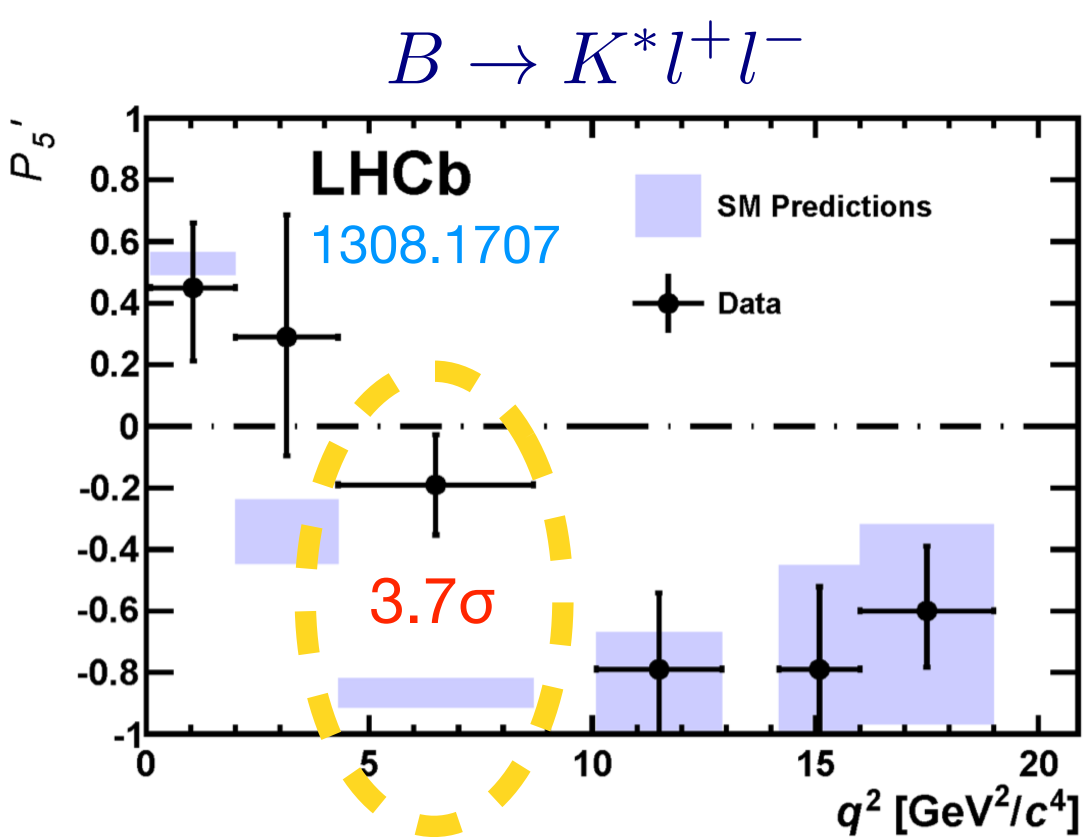


Casagrande et al. (2010)

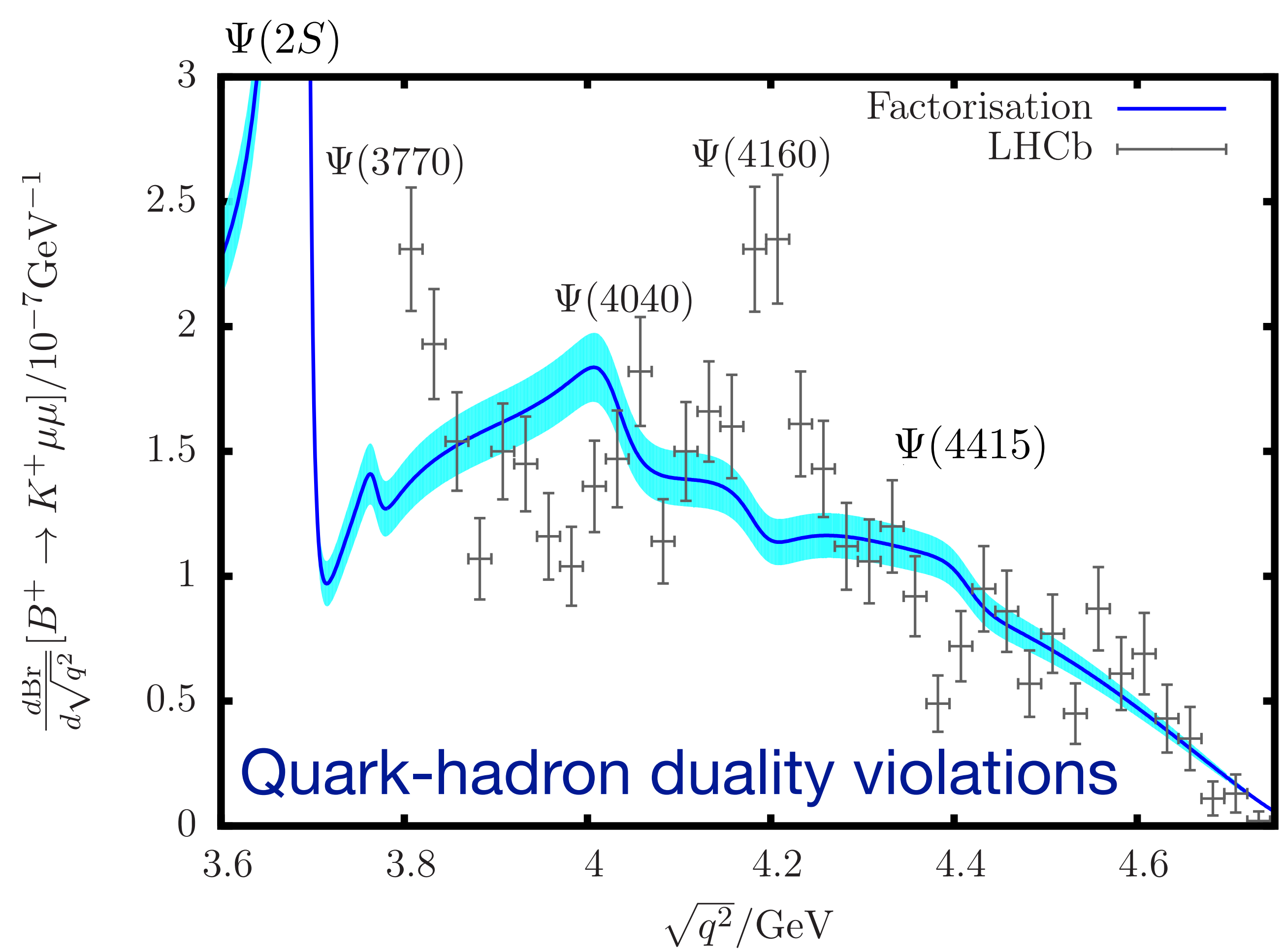
Hints of new physics?

Anomalies: $B \to K^* l^+ l^-$ angular distributions

A few "anomalies" exist in the LHCb data on FCNC processes of the type $b \to s\, l^+ l^-$ and in the global unitarity-triangle fit. Their status is currently under intense debate. New data will help, but also some theory questions need to be addressed.



Matias, Mescia, Ramon, Virto (2012)
Descotes-Genon, Matias, Ramon, Virto (2012)



Lyon, Zwicky (2014)

Anomalies: Lepton non-universality in $B \to K l^+ l^-$

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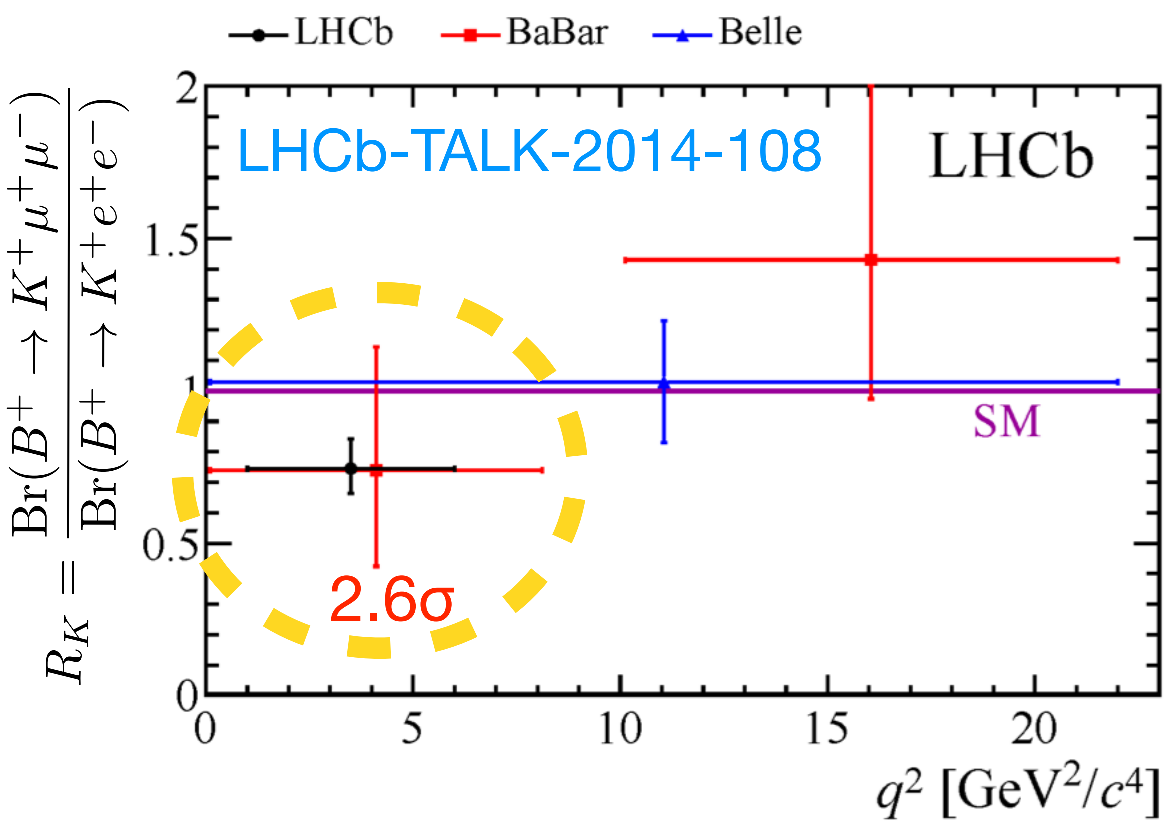
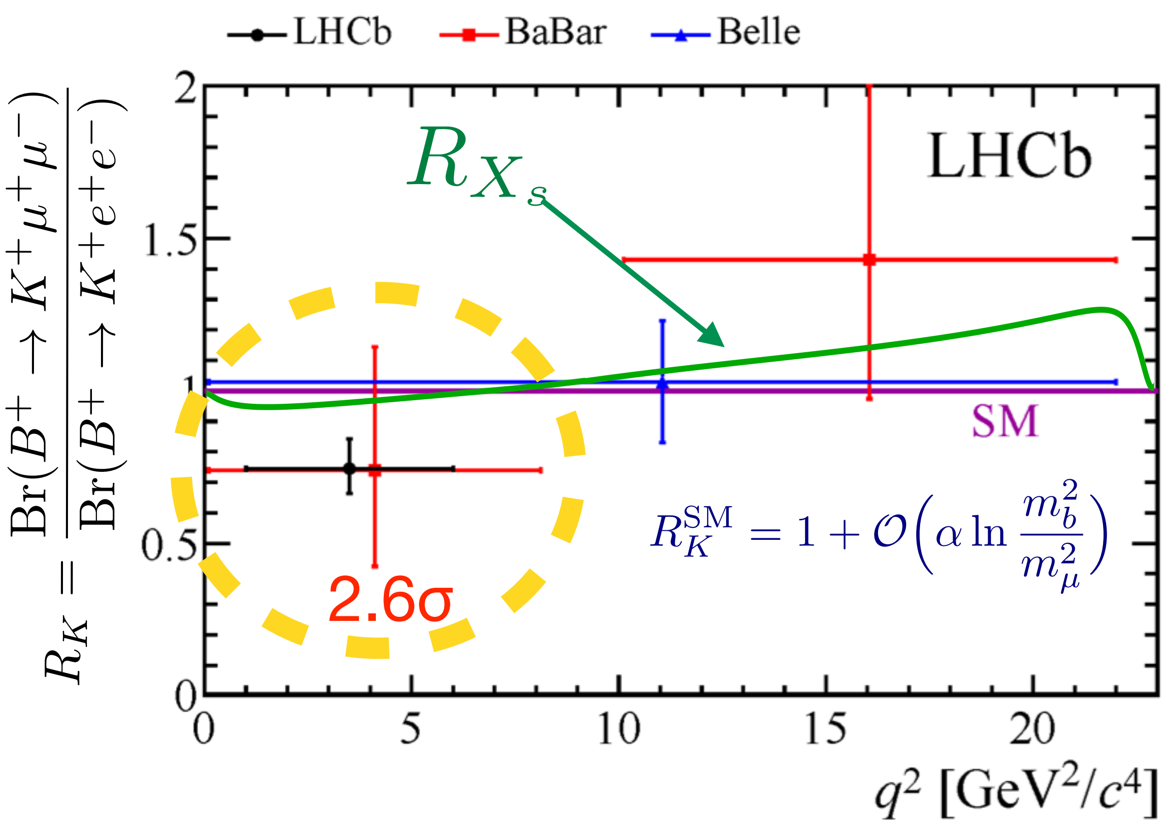


Naive account of QED radiative corrections based on inclusive decay:



Huber, Misiak, Lunghi, Wyler (2005)
Bobeth, Hiller, Piranishvili (2007)
U. Haisch (priv. com.)

Anomalies: Tension in global UT fit (ε_K vs. sin2β)

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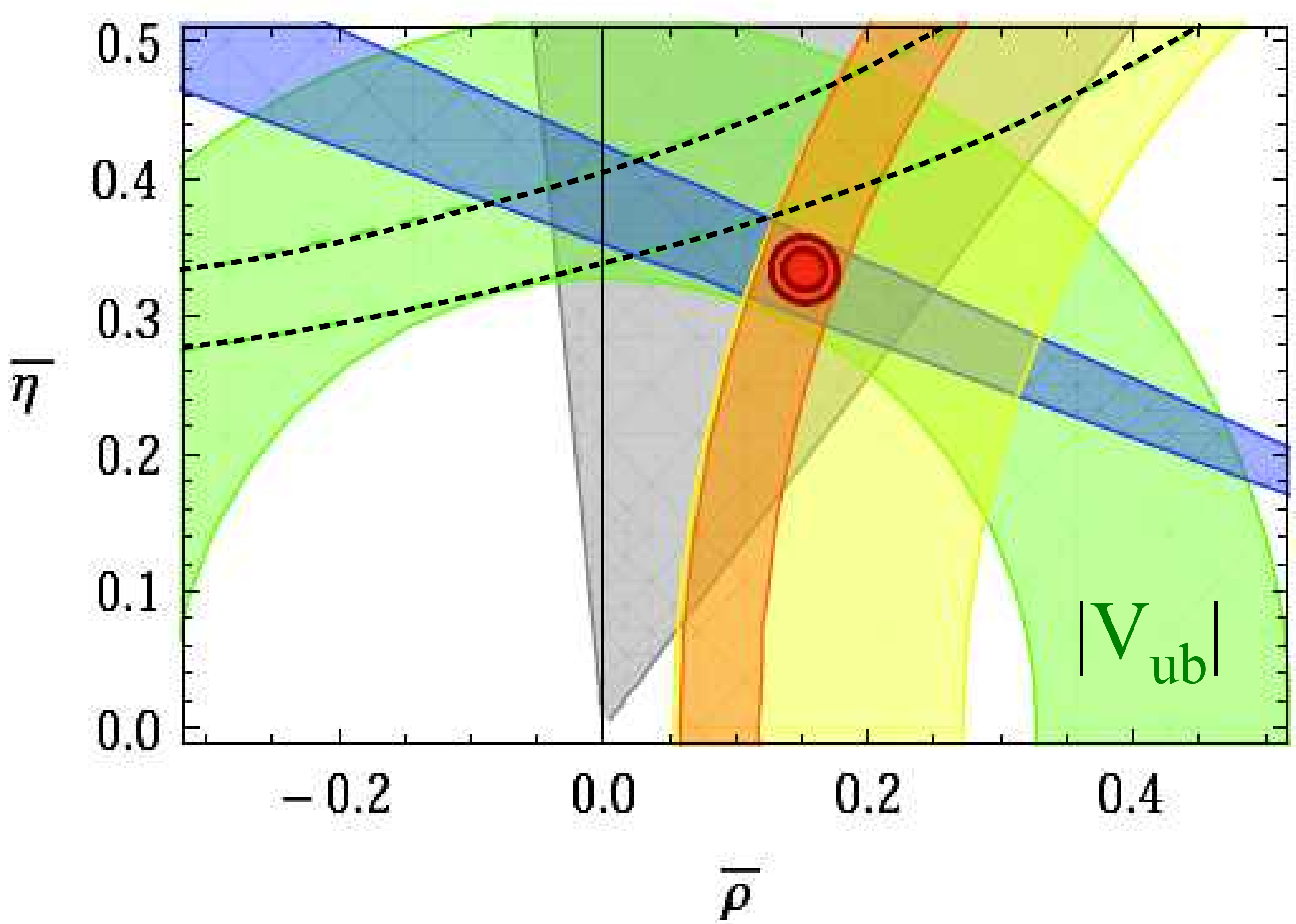
UT fit without ε_K



- Errors from lattice QCD ?
- Problems in the determination of $|V_{ub}|$?

The path to new physics

Exploring *terra incognita* … the tedious way

In the absence of new-physics signals in the form of light (i.e. TeV-scale) new particles, BSM effects can be parameterized **model independently** in terms of **higher-dimensional operators** composed of the known (SM) fields:

- 59 dimension-6 operators for one fermion generation
- **2499 operators** for three generations

Flavor observables are crucial in order to explore this enormous parameter space!

The lepton sector plays a special role, because any signal of lepton flavor violation (such as neutrino oscillations) is an effect of BSM physics!

Exploring *terra incognita* … the tedious way

The effective Lagrangian encoding BSM effects up to operator dimension d=6 reads:

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

unique operator (neutrino masses):

$$Q_{\nu\nu} = (\widetilde{\varphi}^\dagger l_p)^T C (\widetilde{\varphi}^\dagger l_r)$$

Weinberg (1979)

Exploring *terra incognita* … the tedious way

The effective Lagrangian encoding BSM effects up to operator dimension d=6 reads:

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59 operator (× flavor quantum numbers)

Buchmüller, Wyler (1986)
Hagiwara et al. (1987 & 1993)
Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Operators other than four-fermion operators

Exploring *terra incognita* … the tedious way

The effective Lagrangian encoding BSM effects up to operator dimension d=6 reads:

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

59 operator (× flavor quantum numbers)

Buchmüller, Wyler (1986)
Hagiwara et al. (1987 & 1993)
Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

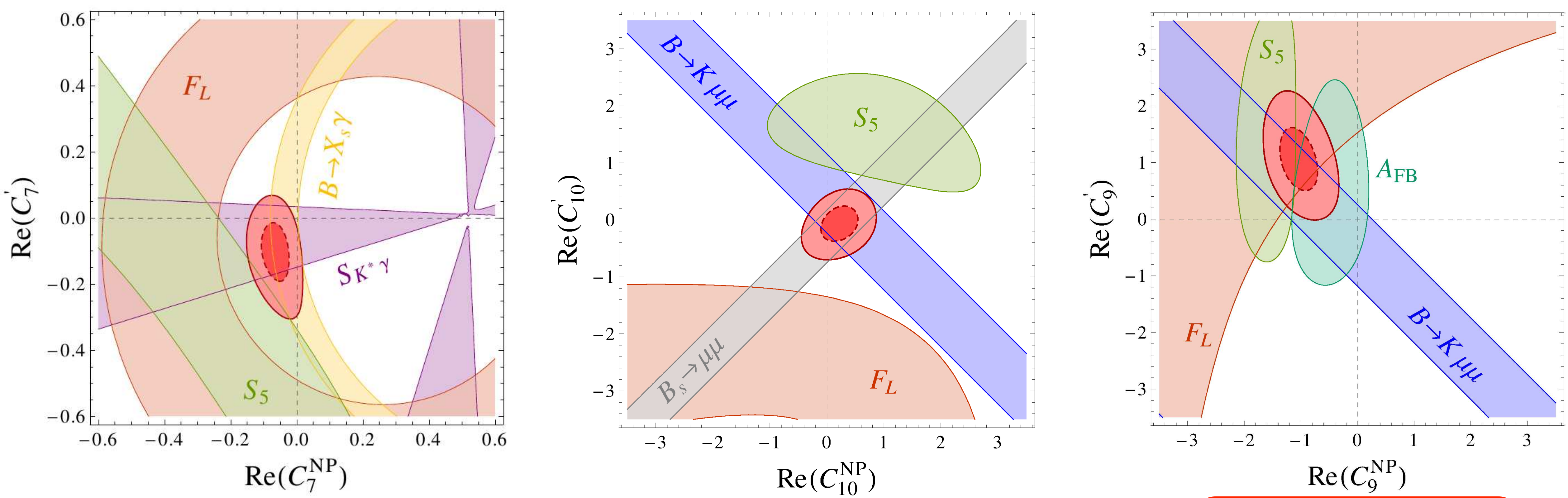
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Four-fermion operators

Global fits of Wilson coefficients in $b \to s\gamma, sl^+l^-$

Flavor observables are crucial in order to **explore the enormous parameter space** of the effective BSM Lagrangian!

A global analysis of the experimental data on $B \to X_s\gamma$, $B \to K^*\gamma$, and $B \to K^{(*)}\mu^+\mu^-$ decay distributions provides information about various operator coefficients (all defined to vanish in the SM):



Altmannshofer, Straub (2013)

$C_9^{\mathrm{NP}} = -1.0 \pm 0.3$

$C_9' = +1.0 \pm 0.5$

A first hint?

Exploring *terra incognita* … the pleasant way

In the fortunate case of the discovery of any new particle, this will directly open up a **new territory** for flavor physics!

In the past years, we have performed extensive searches for flavor-changing Z-boson couplings and probed the flavor-changing top-quark couplings with great accuracy.

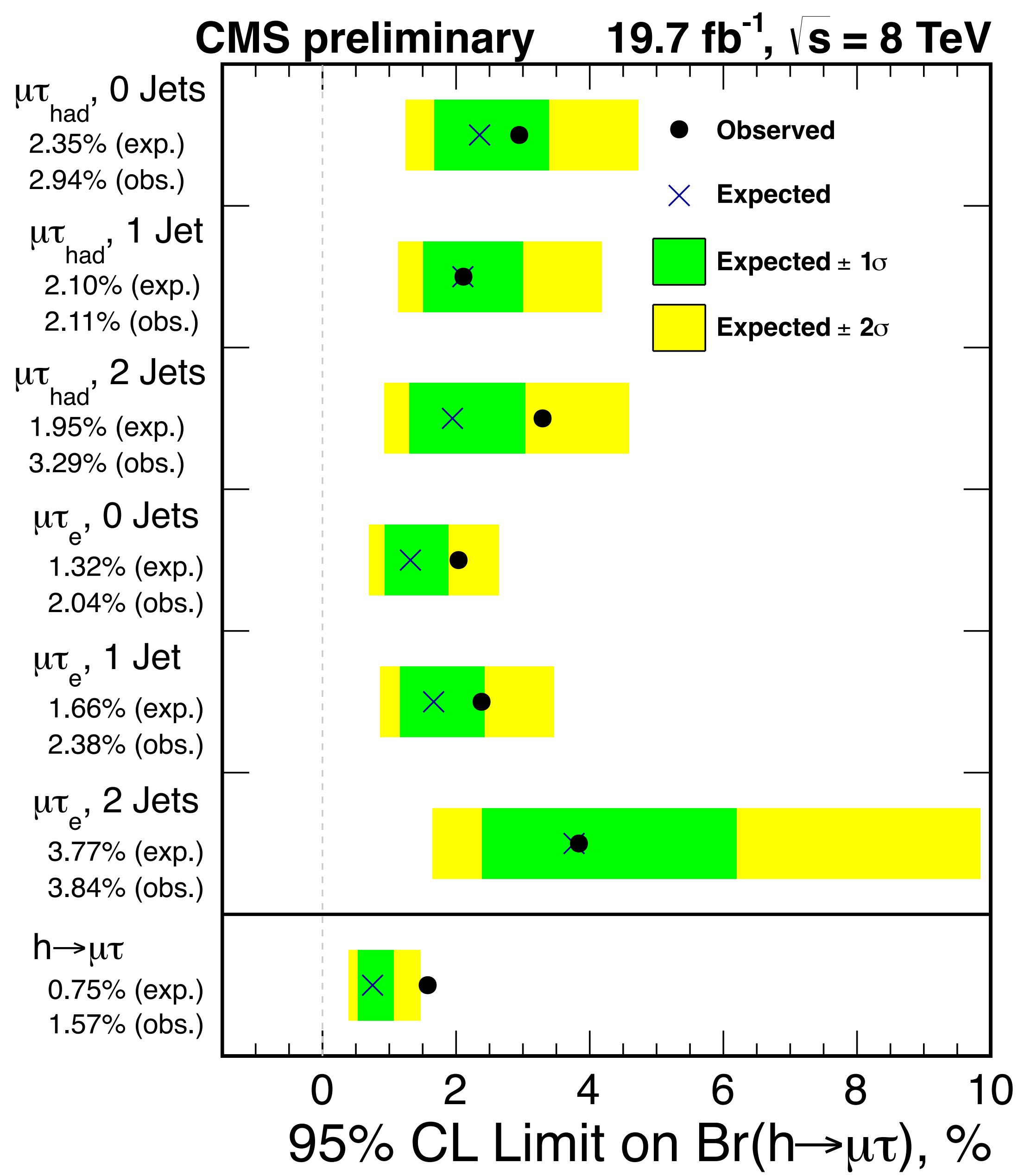
After the Higgs discovery, the study of flavor-changing Higgs couplings is of great importance — this includes lepton-flavor violating modes!

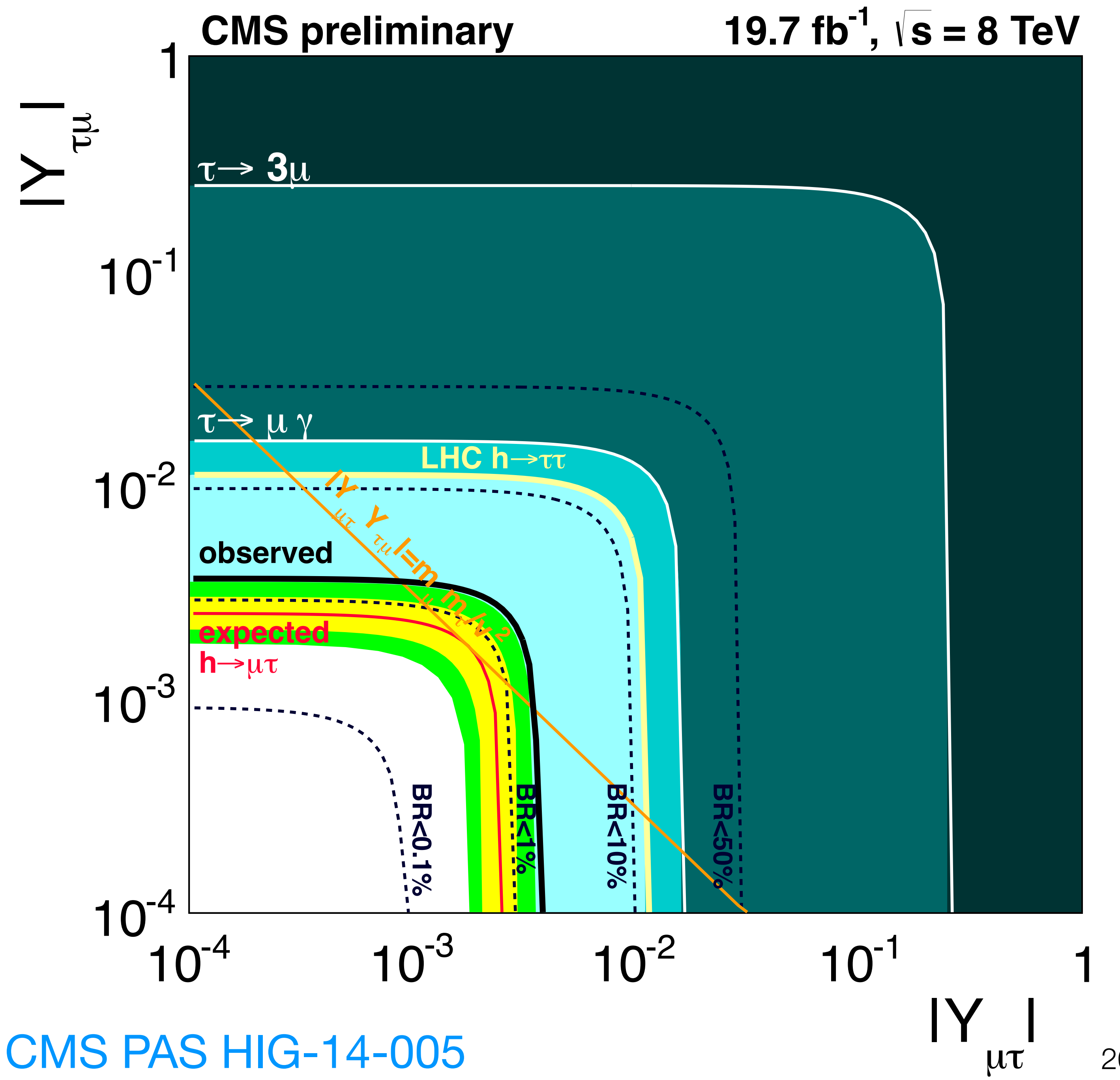
Drey, Efrati, Hochberg, Nir (2013)

The discovery of new particles Z', $\tilde{t}$, $\chi^\pm$, $H^\pm, \ldots$ would open the door to new flavor and CP-violating phenomena!

Exploring *terra incognita* … the pleasant way

A first promising study of the lepton-flavor violating H→τμ decay has recently been reported by CMS:

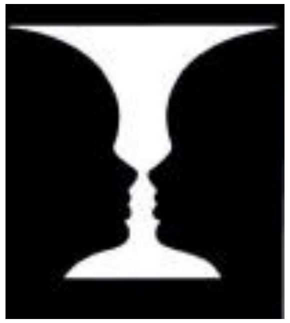




Limit on BR(h → μτ) = 1.57% (0.75 expected)!

CMS PAS HIG-14-005

Complementarity



Complementary ways of probing new physics …

In the 1990s and even well into the era of the B-factories, flavor physics and physics at the energy frontier were too often seen as different branches of particle physics.

Fortunately, this is no longer the case. Now flavor physics is (and should remain) a **crucial component** of a comprehensive high-energy program!

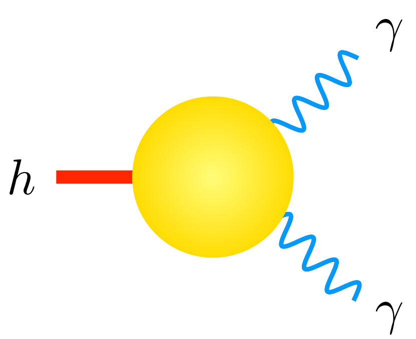
Flavor observables provide **complementary and often competitive indirect probes** of BSM effects, which complement precision studies at the energy frontier.

Examples:

- generic probes
- triple gauge-boson couplings (TGCs)
- $t\bar{t}Z$ vertex
- EDMs

Complementary ways of probing new physics ...

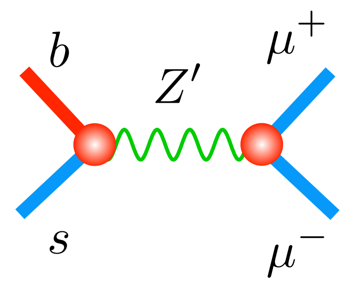
$$\mu_{\text{Higgs}} = 1.1 \pm 0.1$$



$$\mu_{h\to\gamma\gamma} \simeq 1 \pm N\,\frac{v^2}{\Lambda^2}$$

$$\Lambda \gtrsim \sqrt{\frac{N}{0.1}}\,v \simeq \begin{cases} 0.8\,\text{TeV}\,, & N = 1 \\ 3\,\text{TeV}\,, & N = 4\pi \end{cases}$$

$$\mu_{B_s\to\mu^+\mu^-} = 0.8 \pm 0.2$$

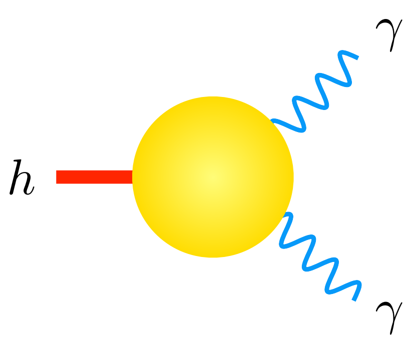


$$\mu_{B_s\to\mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2\,|V_{tb}^*V_{ts}|^2}\,\frac{v^2}{\Lambda^2}$$

$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \left\{ \frac{\sqrt{4\pi}}{g\,|V_{tb}^*V_{ts}|} \right. \simeq \left\{ 50\,\text{TeV}\,, \quad \text{anarchic tree} \right.$$

Complementary ways of probing new physics ...

$$\mu_{\text{Higgs}} = 1.1 \pm 0.1$$



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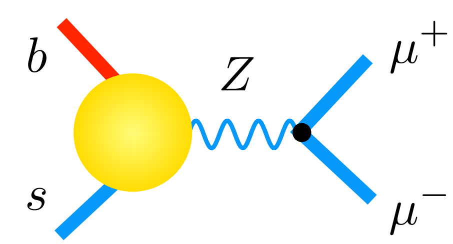


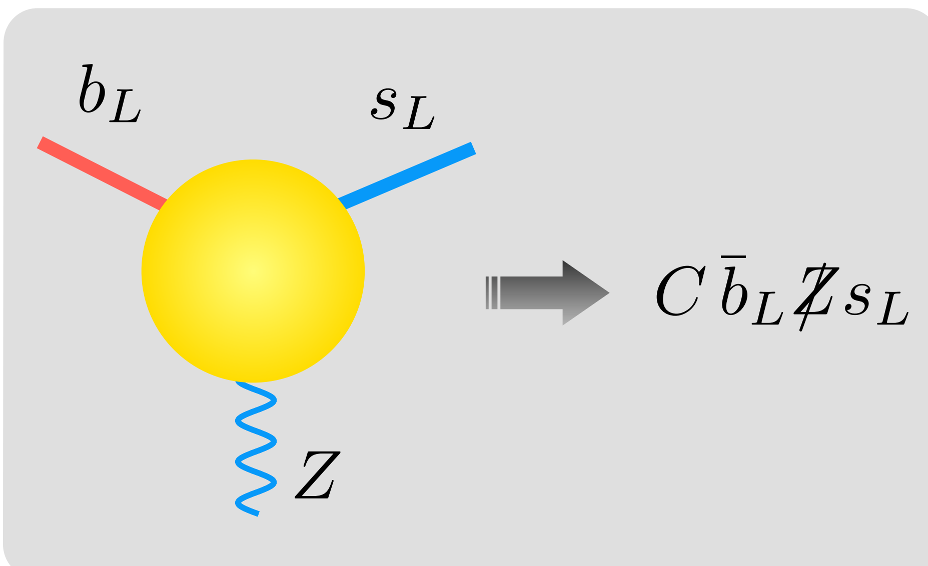
$$\mu_{B_s\to\mu^+\mu^-} \simeq 1 \pm \frac{v^2}{\Lambda^2}$$

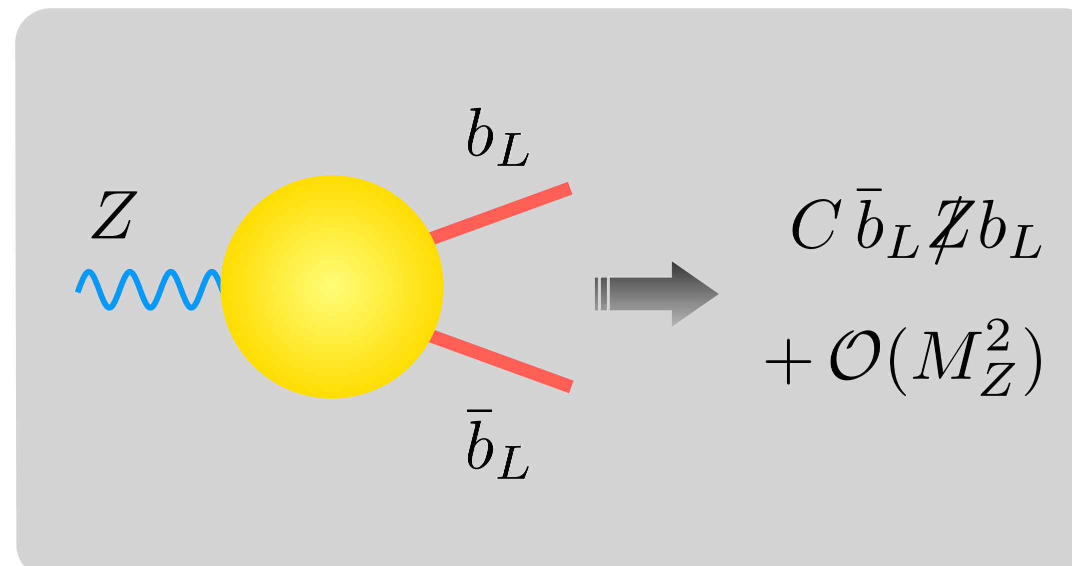
$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\text{TeV}\,, & \text{anarchic tree} \\ 0.6\,\text{TeV}\,, & \text{MFV loop} \end{cases}$$

Even in the most pessimistic scenario, the sensitivity to the NP scale in flavor physics at LHCb is comparable to that of the Higgs-couplings measurements by ATLAS and CMS.

Precision measurements of Z-boson couplings

In many NP models (MFV, SUSY, partial compositeness, …), flavor-changing and flavor-conserving Z-penguin effects are closely related:





$$\Delta C = (-0.16 \pm 0.53)$$

$$\Delta C = -0.04 \pm 0.26$$

Pre LHC, flavor constraints were often not competitive with EWP data.

Bobeth et al. (2005)
Haisch, Weiler (2007)

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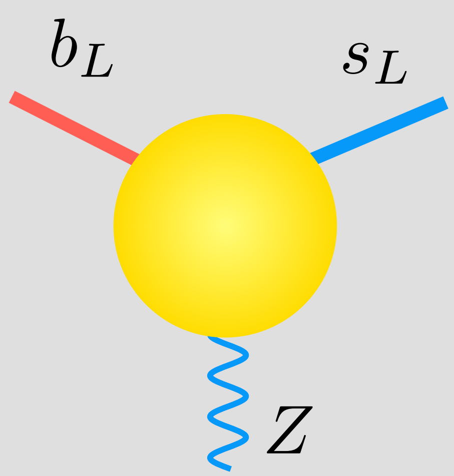
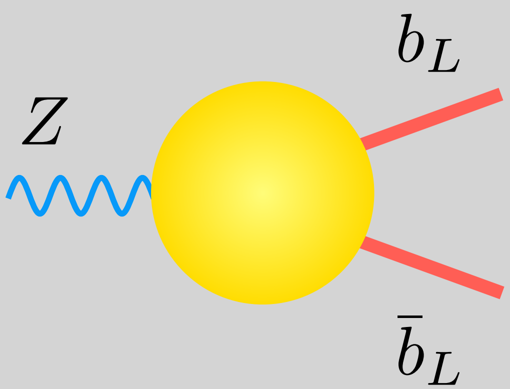


$$C\,\bar{b}_L \not{Z} s_L$$



$$C\,\bar{b}_L \not{Z} b_L + \mathcal{O}(M_Z^2)$$

$$\Delta C = -0.11 \pm 0.11$$

$$\Delta C = 0.28 \pm 0.30$$

Freitas (2012)

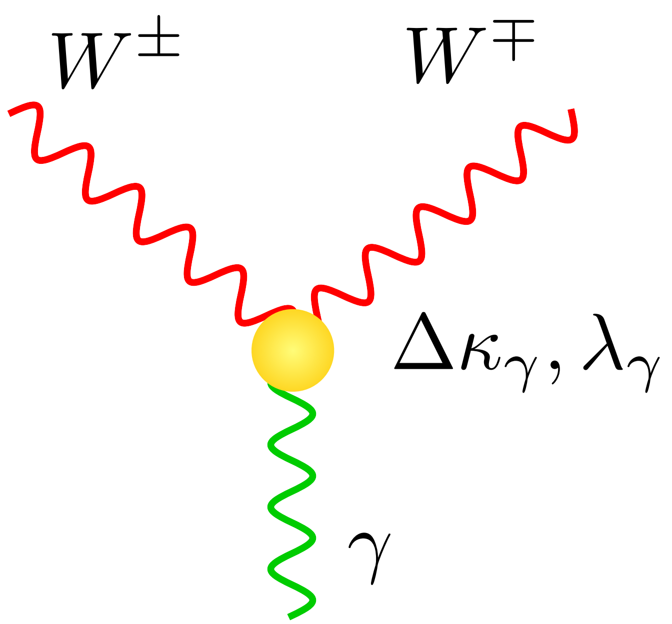
Today, flavor data often provide stronger constraints!

Haisch, Weiler (2007)
Guadagnoli, Isidori (2013)

Triple gauge-boson couplings

Modifications of the non-abelian gauge vertices (coupling 3 or 4 bosons) from d=6 operators such as $(D_\mu \phi)^\dagger (D_\nu \Phi)\, B^{\mu\nu}, \ldots$ could provide subtle hints about NP:

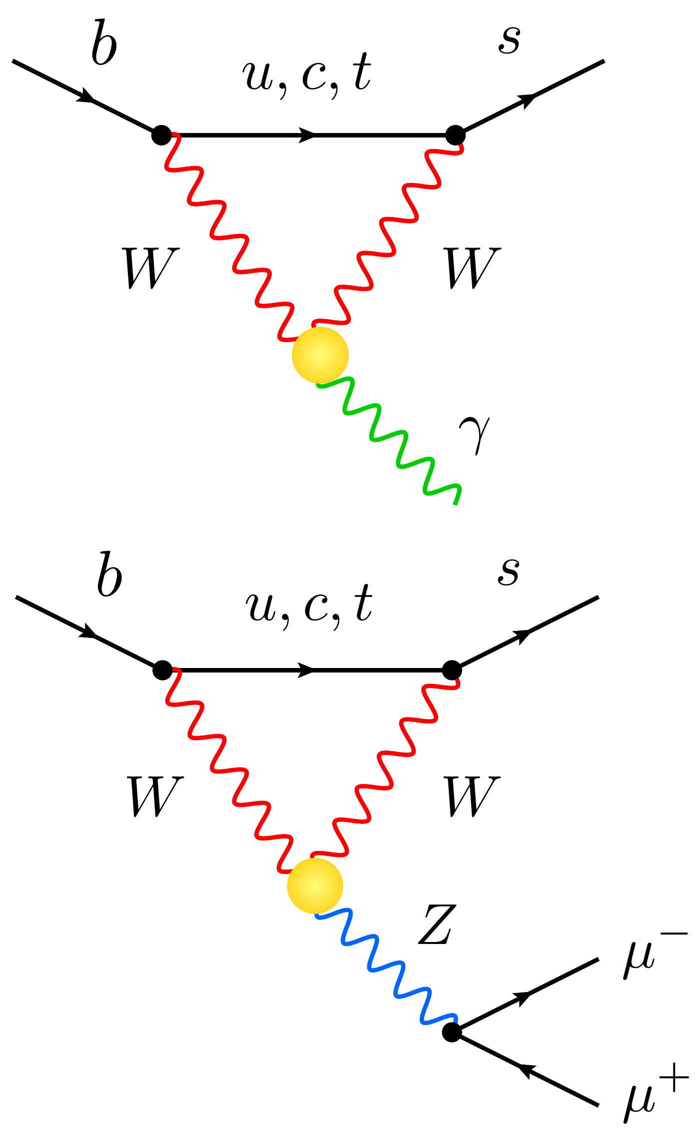
$$\mathcal{L}_{WWV} = -i g_{WWV} \left[g_1^V \left(W^+_{\mu\nu} W^{-\,\mu} V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^{-\,\nu\rho} V_\rho{}^\mu \right]$$

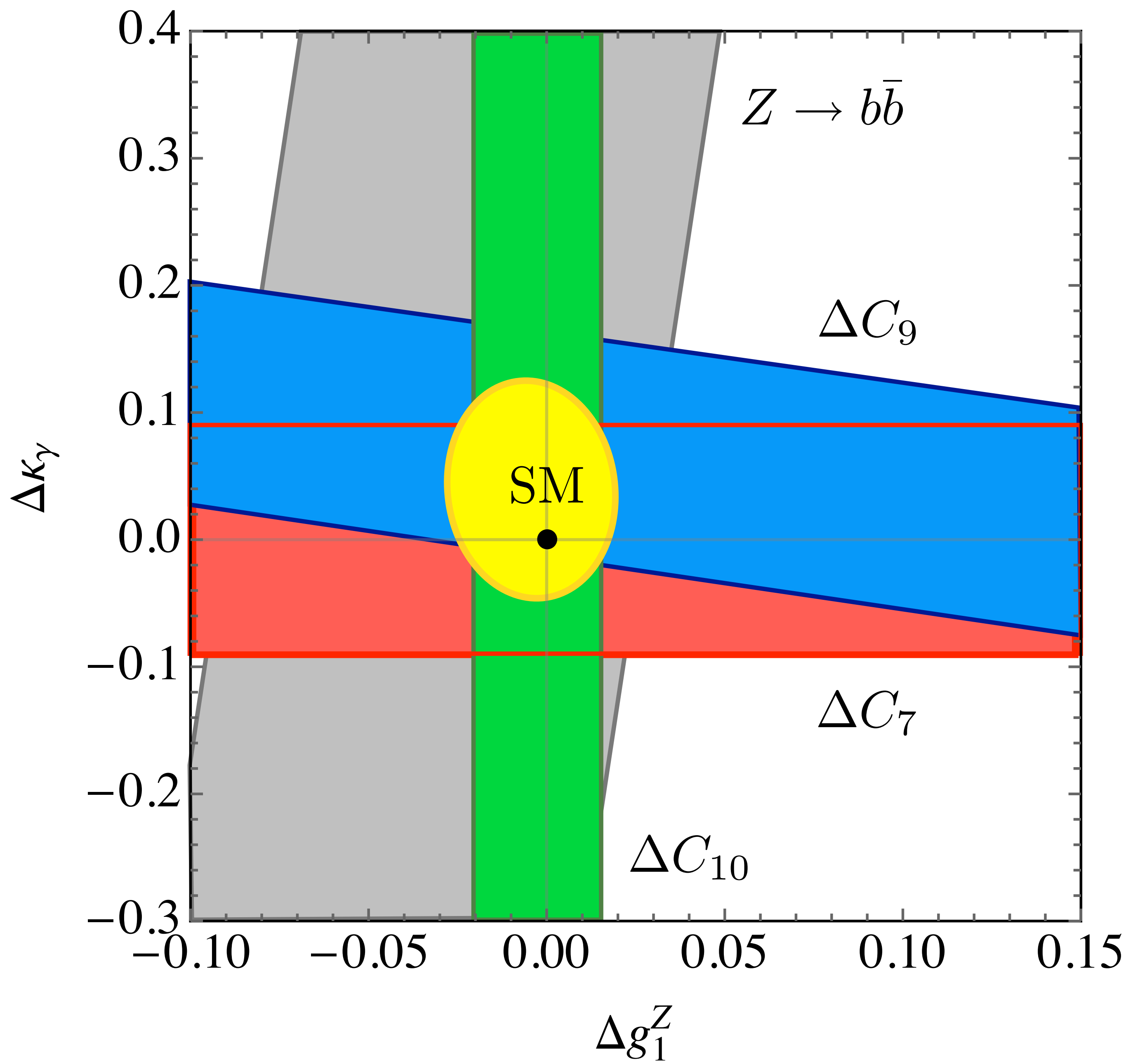


These couplings can be probed “indirectly” in flavor physics and “directly” in di-boson production at colliders.

Triple gauge-boson couplings

Anomalous TGCs contribute to FCNC processes such as $B \to K^* \mu^+ \mu^-$, $B \to X_s \gamma$, $B_s \to \mu^+ \mu^-$, ϵ'/ϵ, and $Z \to b\bar{b}$:

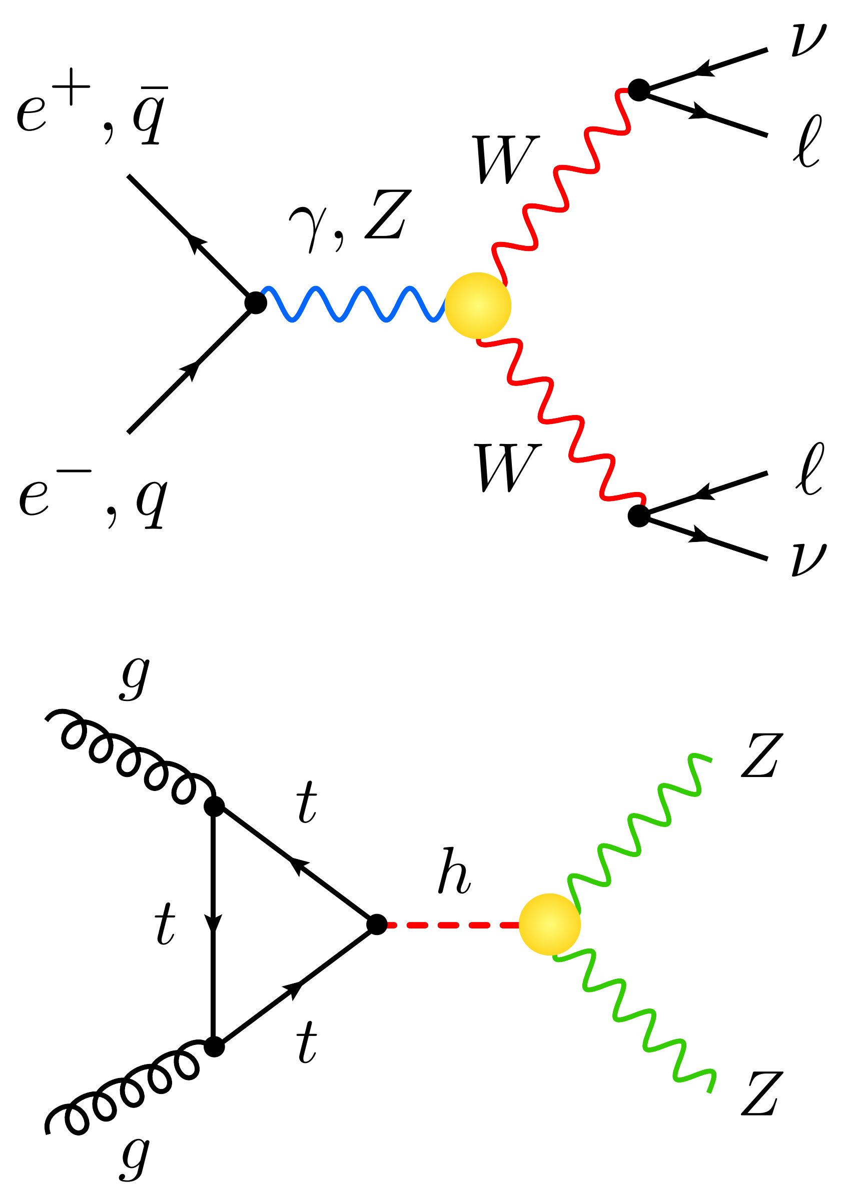


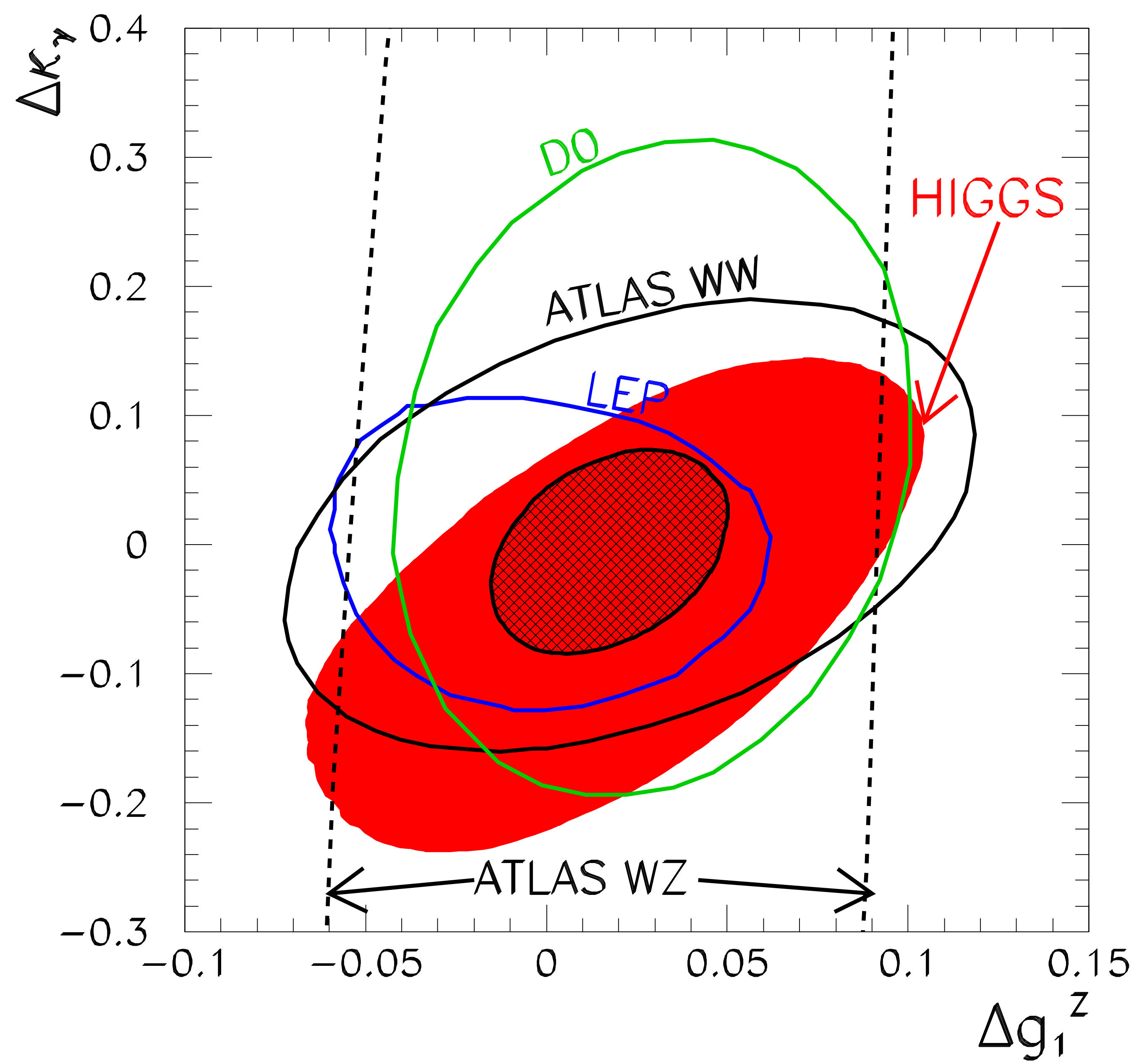


Bobeth, Haisch (priv. com.)

Triple gauge-boson couplings

Direct searches for anomalous TGCs have been performed at Tevatron and LHC (WW, WZ, Wγ, Zγ, … production and H→ZZ, …):





Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia (2013)

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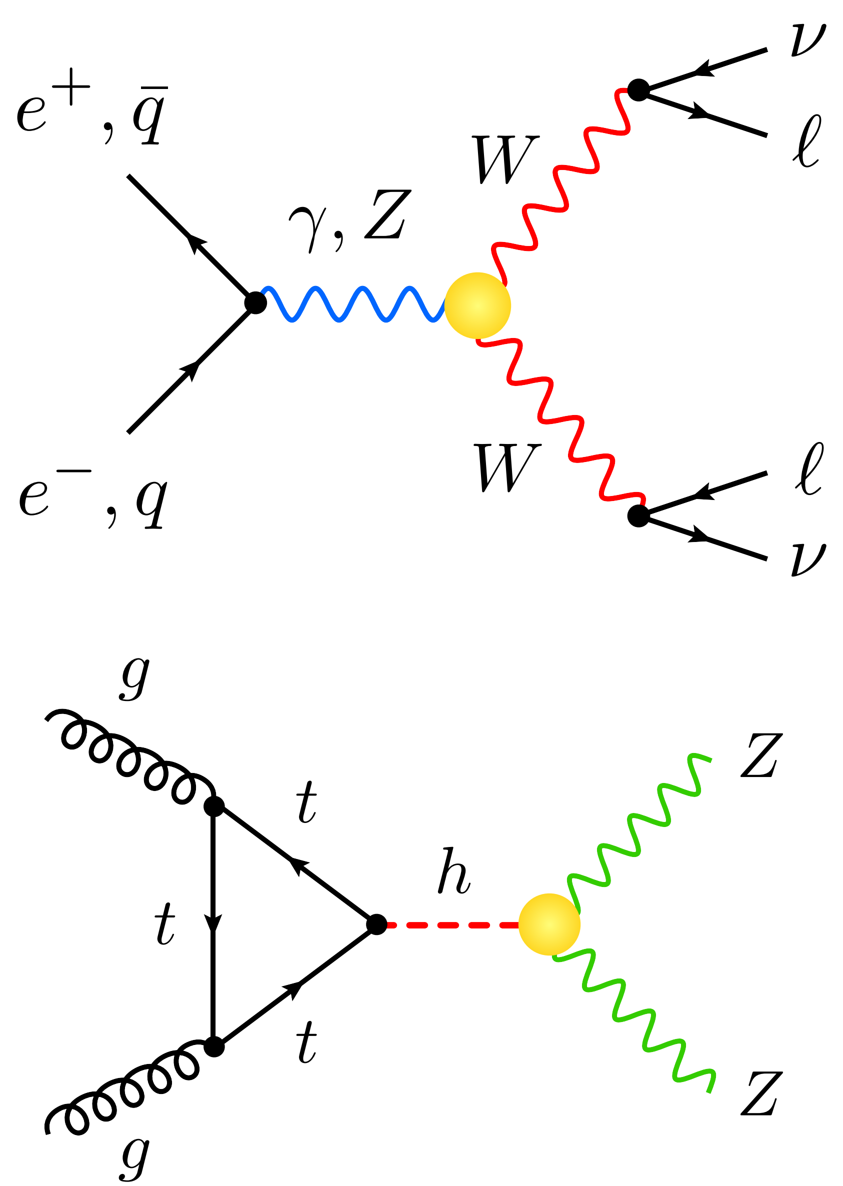
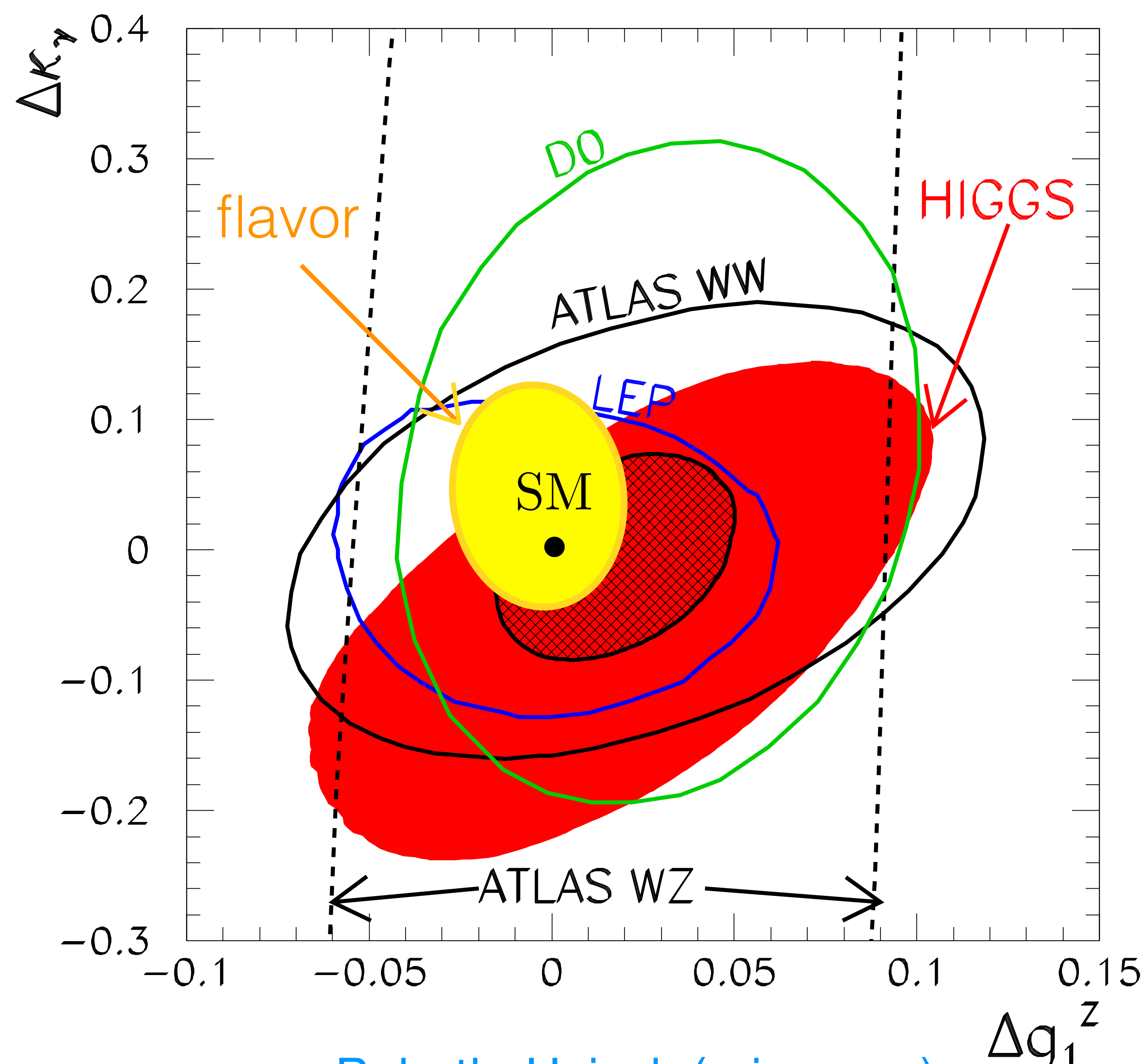


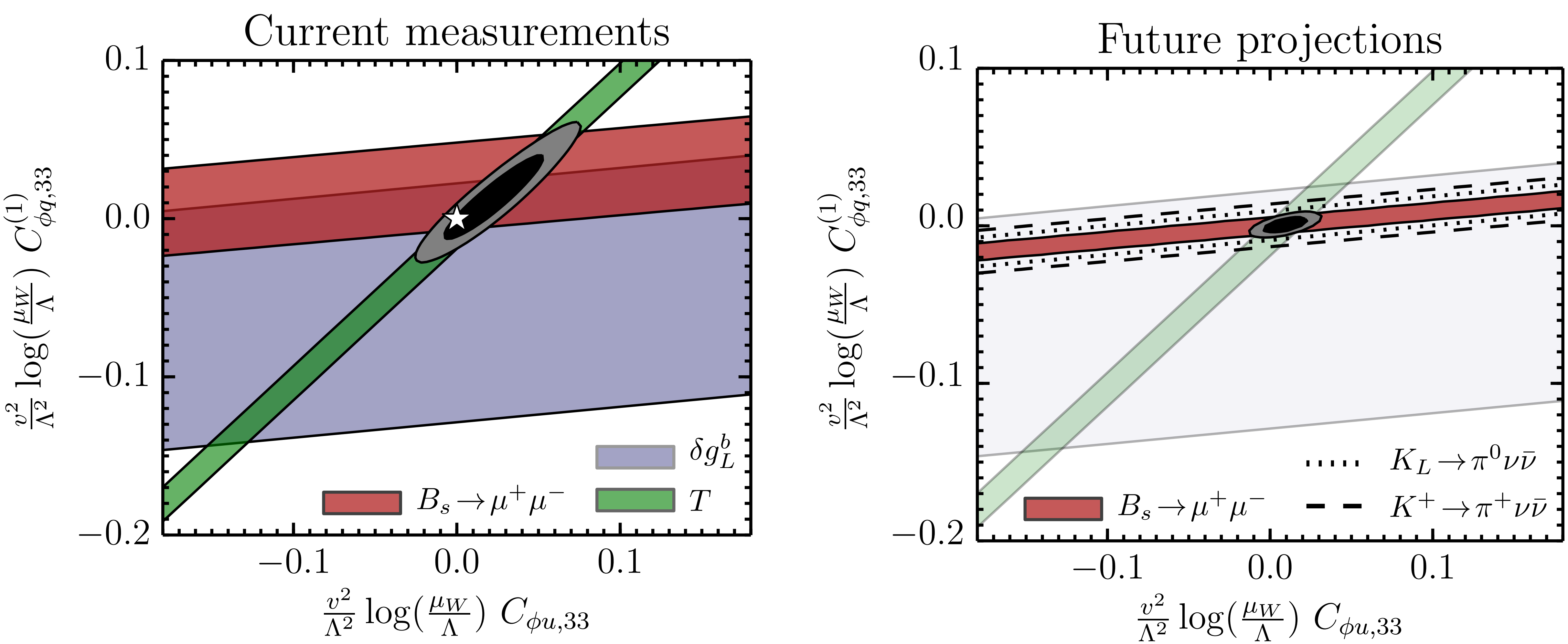


Bobeth, Haisch (priv. com.)

Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia (2013)

Anomalous $t\bar{t}Z$ couplings

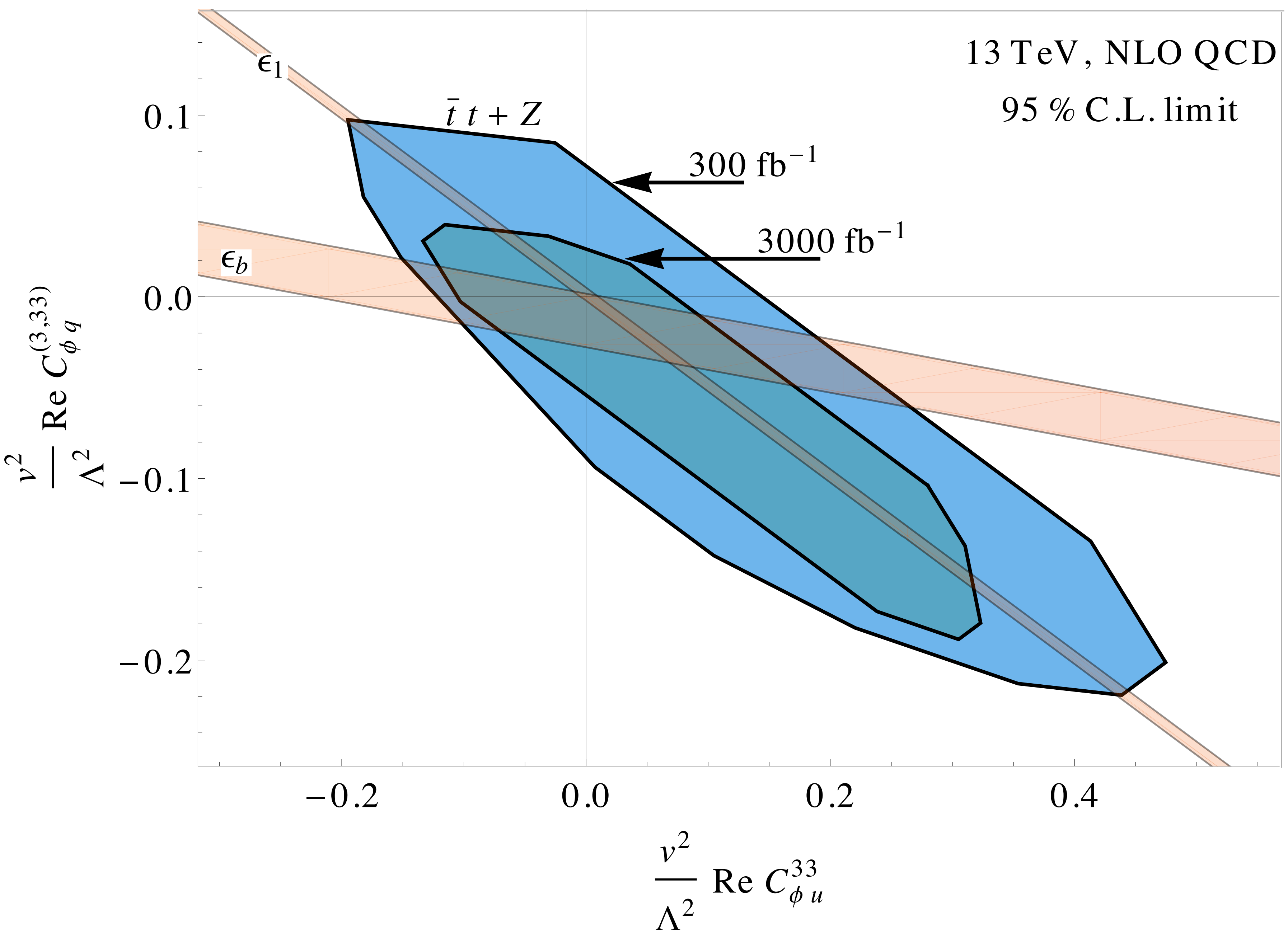
Searches for anomalous Z-boson couplings to the top-quark can be performed using flavor data and EWP tests …



Brod, Greljo, Stamou, Uttayarat (2014)

Anomalous $t\bar{t}Z$ couplings

… but also directly in $pp \to t\bar{t} + Z$ production at the LHC:



Röntsch, Schulze (2014)

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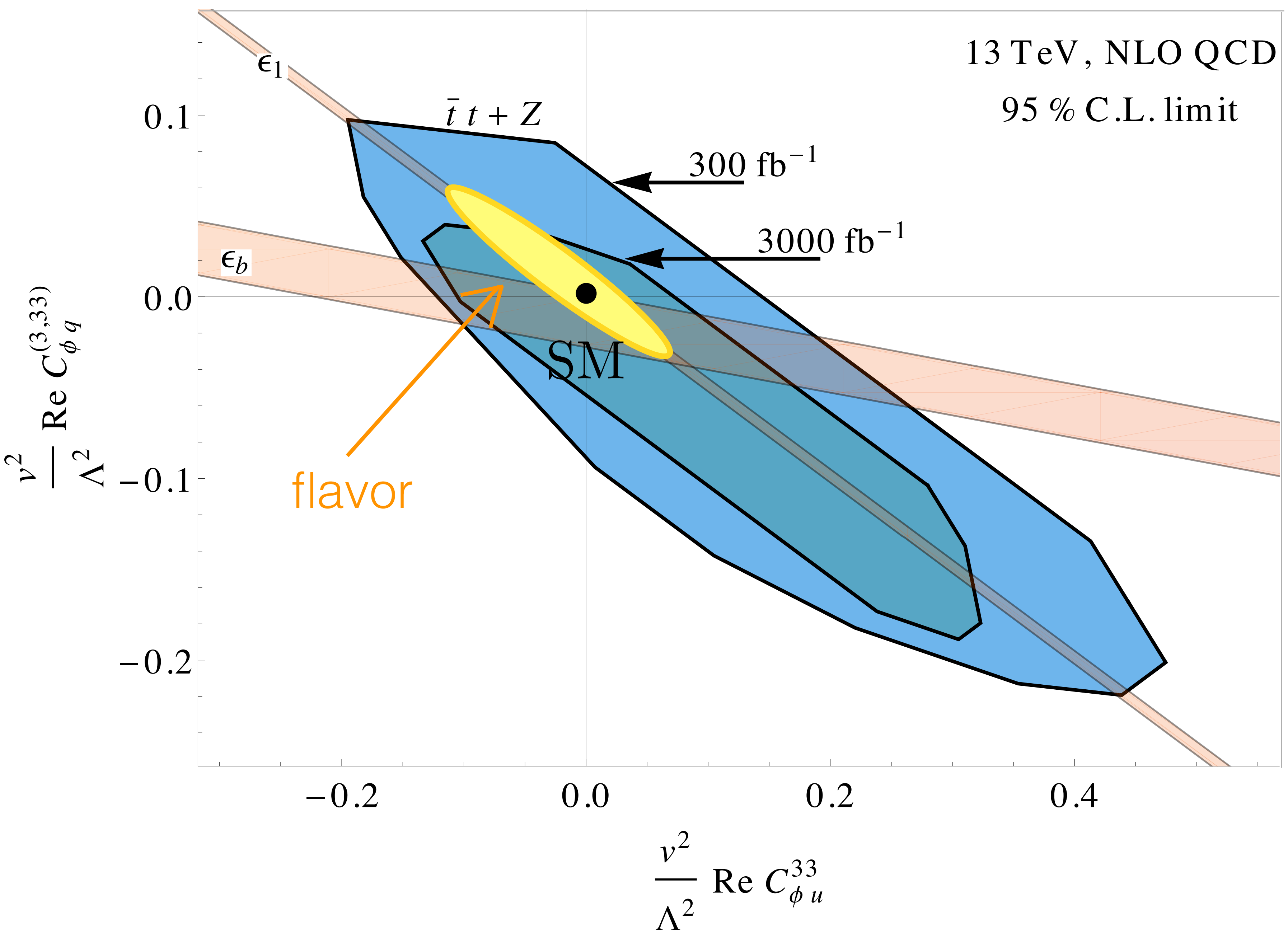

Brod, Greljo, Stamou, Uttayarat (2014)
Röntsch, Schulze (2014)

Summary

The past years have taught us some lessons:

- It pays off to explore theoretically well motivated frontiers of high-energy physics: Higgs (EWSB, unitarity), CKM, dark matter
- But discoveries are not always as easy as predicted by "simple" or "natural" extensions of the SM ("weaker" theoretical motivation).
- Thus a **broad and complementary program** is of utmost importance! It must include all aspects of high-energy physics, but also low-energy probes and astro-particle physics.

Sometimes, breakthrough discoveries can come out of the blue:

- dark energy (who would have thought?)
- imagine we would discover $R_K \neq R_K^{\mathrm{SM}}$ or $\mathrm{Br}(H \to \tau\bar{\mu}) = 1\%$ …

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We need to keep turning all stones to find the next piece of the puzzle!


Thank you!