Challenges for New Physics in the Flavor Sector

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Flavor Physics & CP violation 2015

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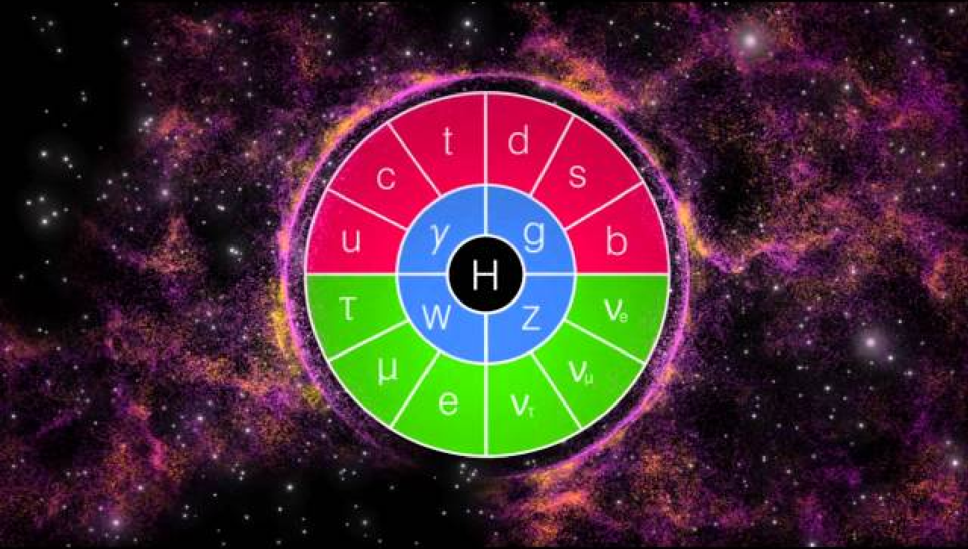
The Standard Model of Particle Physics



particlefever.com

The Standard Model as Effective Theory

$$\mathcal{L}_{\text{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$
$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$+ Y H \bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim6}}$$

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CC problem (Λ^4)

Hierarchy problem ($\Lambda^2 H^2$)

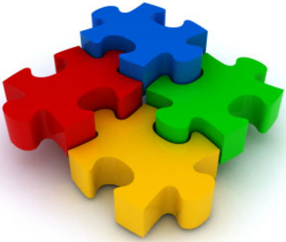
Vacuum stability? (λH^4)

Strong CP problem ($F_{\mu\nu}\tilde{F}^{\mu\nu}$)

SM flavor puzzle ($Y H \bar{\Psi}\Psi$)

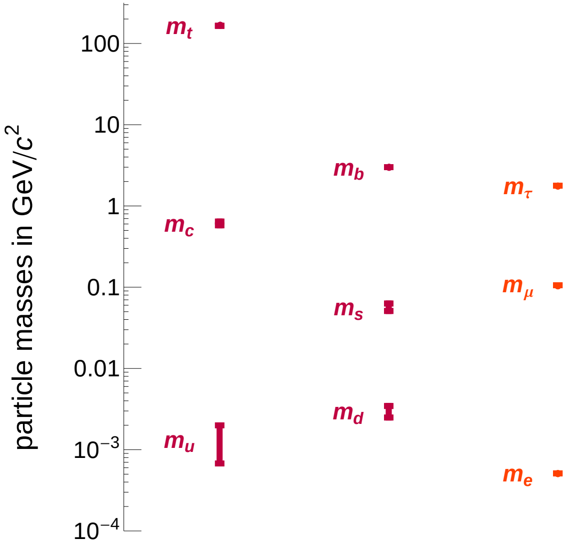
Neutrino masses ($\frac{1}{\Lambda}(LH)^2$)

NP flavor puzzle ...



The Standard Model Flavor Puzzle

Flavor Hierarchies



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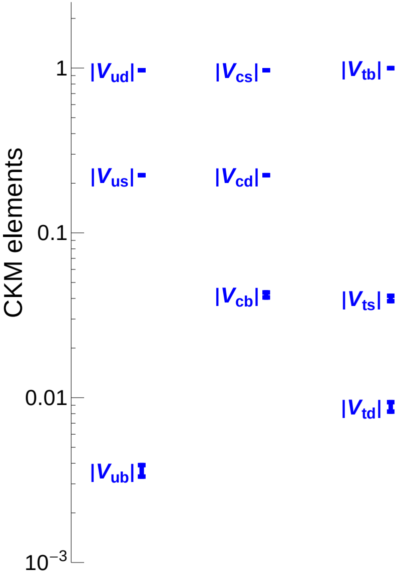
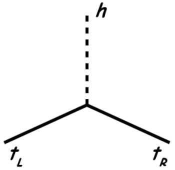
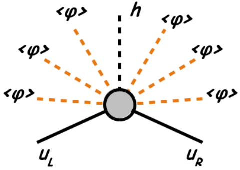


Hierarchy from Symmetry

(Froggatt, Nielsen ’79; ...)

fermion masses are forbidden by flavor symmetries
and arise only after spontaneous breaking of the symmetry





Simple U(1) model:

$Q(t_L)=Q(t_R)=0$
$Q(u_L)=-Q(u_R)=3$
$Q(h)=0$
$Q(\varphi)=-1$

$h\bar{t}_R t_L$ $\qquad$ $\frac{\varphi^6}{M^6} h\bar{u}_R u_L$

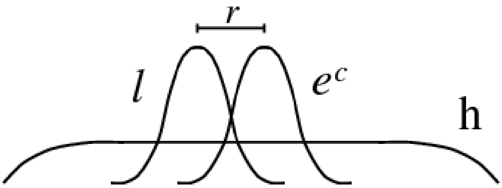
mass and mixing hierarchies given by powers of the spurion $\langle\varphi\rangle/M$

$$\frac{m_u}{m_t} \sim \left(\frac{\langle\varphi\rangle}{M}\right)^n$$

Hierarchy without Symmetry: Geometry

(Arkani-Hamed, Schmaltz '99; ...)

fermions are localized at different positions in an extra dimension

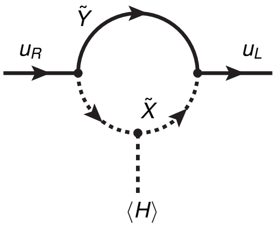


hierarchies from exponentially small wave-function overlap between left-handed and right-handed fermions and the Higgs

$$\frac{m_u}{m_t} \sim e^{-\Delta}$$

(Weinberg ’72; ...)

light fermion masses arise only from quantum effects



light fermions do not couple
to the Higgs directly

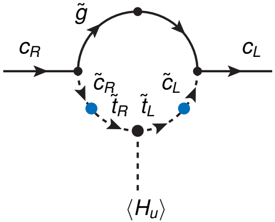
couplings are loop-induced
by flavor violating new particles

mass and mixing hierarchies from loop factors

$$\frac{m_u}{m_t} \sim \left(\frac{1}{16\pi^2} \right)^n$$

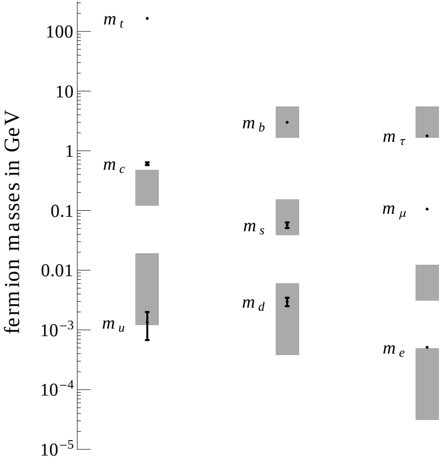
A simple setup for
loop induced fermion masses:

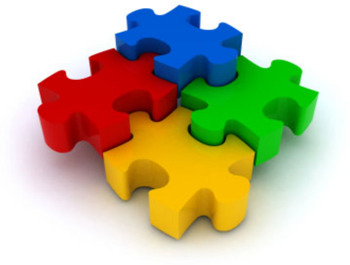
- MSSM field content
- rank 1 Yukawa couplings
- flavor anarchic sfermion masses



Works remarkably well!
(muon mass can be fixed by
adding new gauge interactions)

WA, Frugiuele, Harnik '14



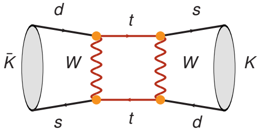


The New Physics
Flavor Puzzle

Sensitivity to High Scales

Example: CP Violation in Kaon mixing

- Standard Model amplitude is loop suppressed and CKM suppressed



$$\propto \frac{g^4}{16\pi^2} \frac{m_t^2}{M_W^4} (V_{td} V_{ts}^*)^2$$

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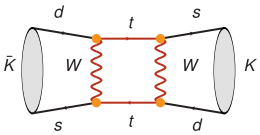
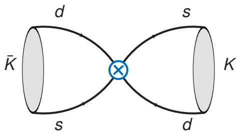


$$\propto \frac{g^4}{16\pi^2} \frac{m_t^2}{M_W^4} (V_{td} V_{ts}^*)^2$$

- Generic New Physics amplitude only suppressed by New Physics scale



$$\propto \frac{1}{\Lambda_{\rm NP}^2}$$

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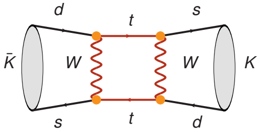

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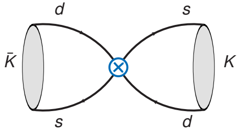
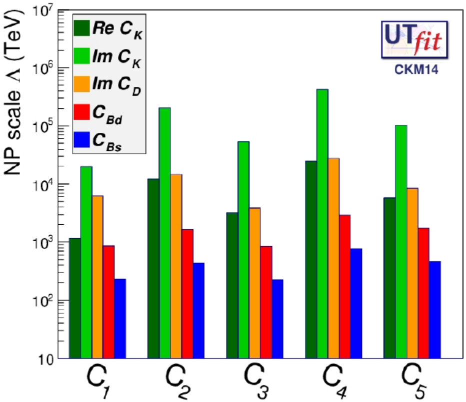


$$\propto \frac{1}{\Lambda_{\rm NP}^2}$$

- CP Violation in Kaon Mixing can probe extremely high scales

$$\Lambda_{\rm NP} \sim \frac{M_W^2}{m_t}\frac{4\pi}{g^2}\frac{1}{|V_{td}V_{ts}^*|} \sim 10^4 \text{ TeV}$$

The New Physics Flavor Puzzle

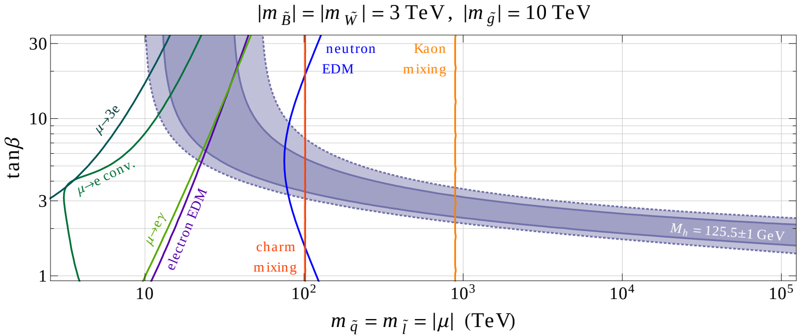


$$\frac{1}{\Lambda_{\rm NP}^2}\sum_i \mathcal{C}_i \mathcal{O}_i^{\rm dim6} \quad \text{with} \quad \mathcal{C}_i = 1$$

If New Physics has generic flavor violating couplings of $O(1)$, it has to be at extremely high scales

If there is New Physics at the TeV scale, it has to have a highly non-generic flavor structure

WA, Harnik, Zupan '13 (also Moroi, Nagai '13; McKeen, Pospelov, Ritz '13; Fuyuto, Hisano, Nagata, Tsumura '13; Ibrahim, Itani, Nath '14)



a large host of low energy observables can probe squarks and sleptons with masses far above the direct reach of current and future colliders (IF they have anarchic flavor structure)

Low Energy Probes of PeV Scale Sfermions (Future)

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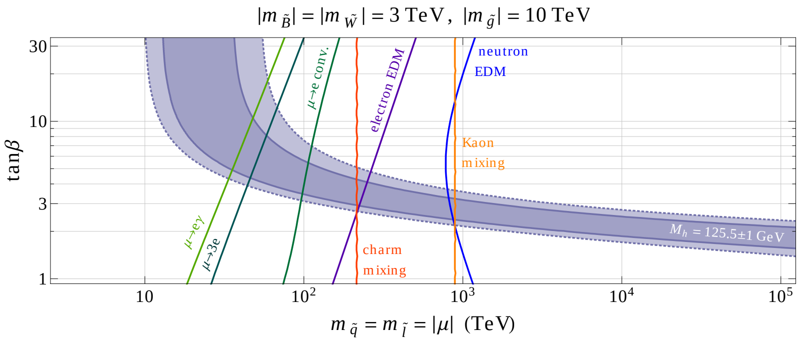

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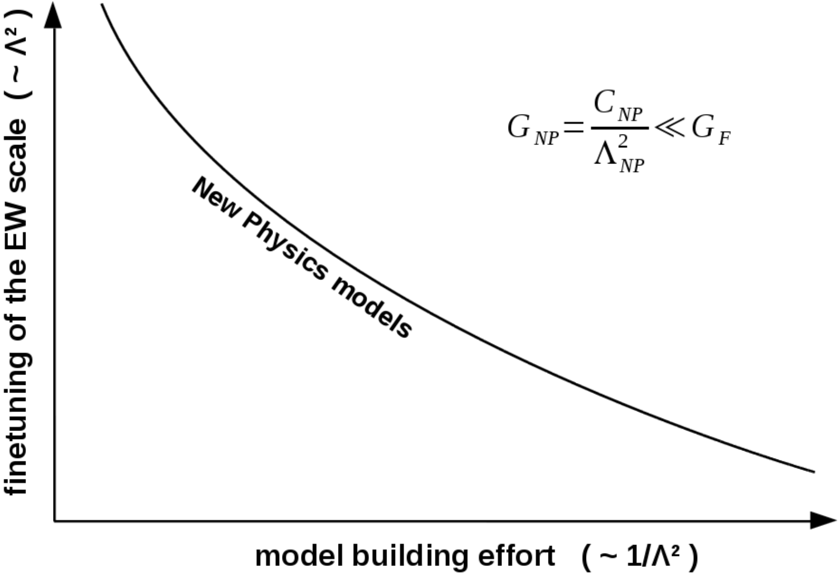
experimental sensitivities are expected to improve significantly in the next decade

Approaches to the New Physics Flavor Puzzle



$$G_{NP} = \frac{C_{NP}}{\Lambda_{NP}^2} \ll G_F$$

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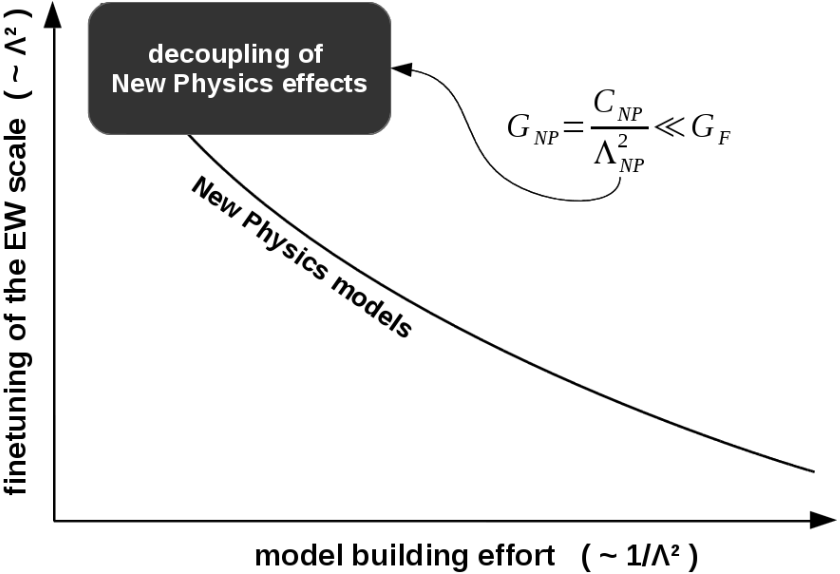
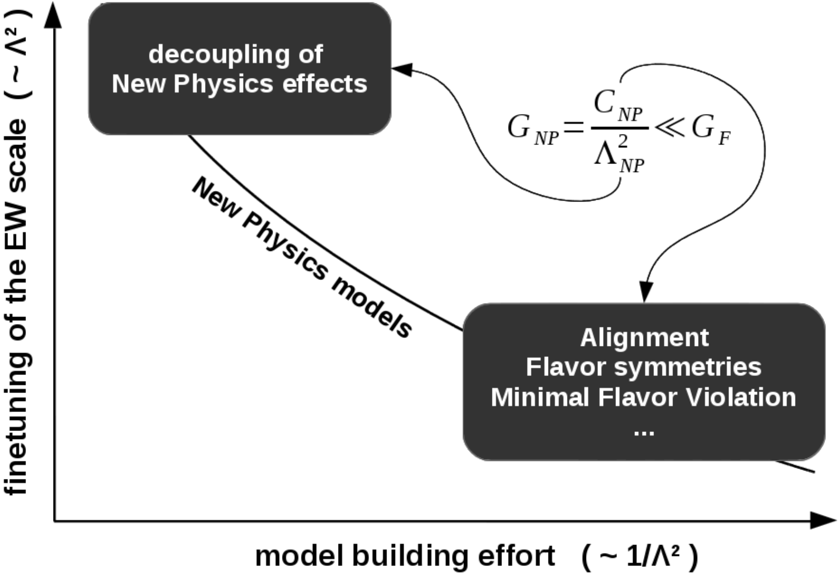
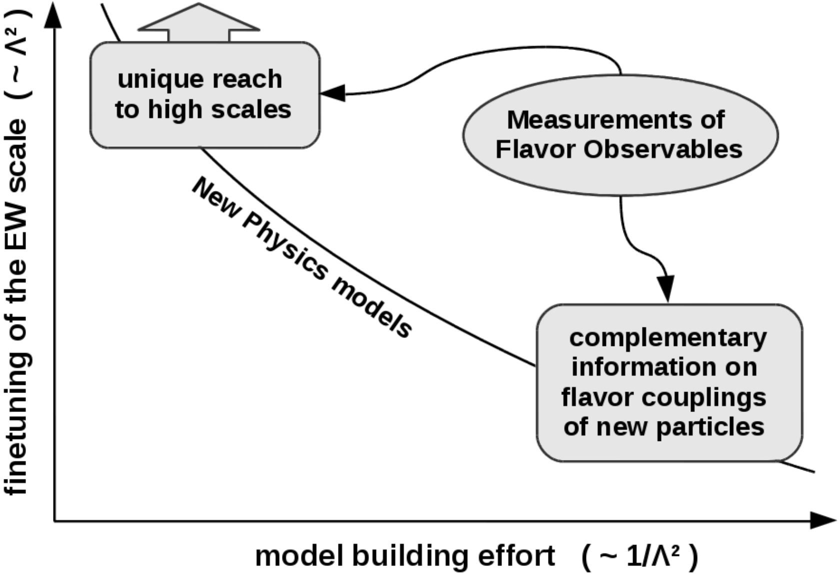
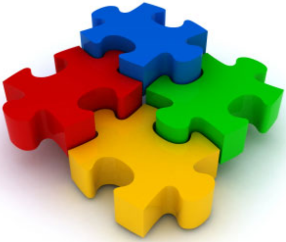




finetuning of the EW scale (~ Λ²)
decoupling of New Physics effects
$G_{NP} = \frac{C_{NP}}{\Lambda^2_{NP}} \ll G_F$
New Physics models
Alignment
Flavor symmetries
Minimal Flavor Violation
...
model building effort (~ 1/Λ²)

The Role of Flavor Physics





Flavor Anomalies

(Incomplete) List of Anomalies in Flavor Physics

★ anomaly in $B \to K^* \mu^+ \mu^-$ angular distributions

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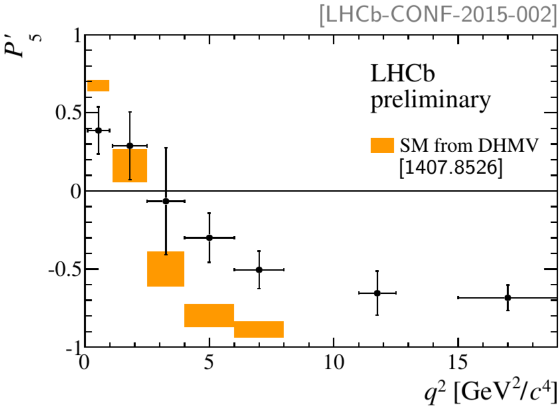
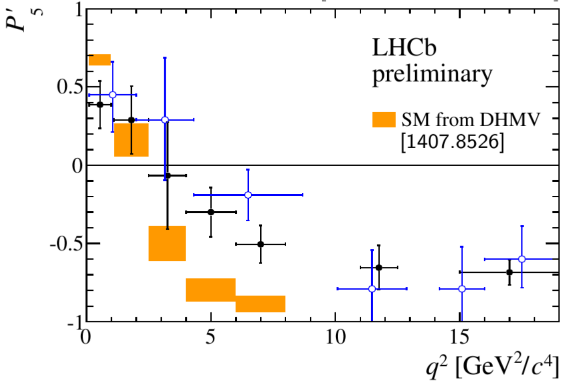


2.9σ in [4,6] GeV^2 bin (+2.9σ in [6,8] GeV^2 bin)

[LHCb-CONF-2015-002]



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More $b \to s\ell\ell$ Anomalies

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

\+ indication for violation of lepton flavor universality (LFU)

$$R_K = \frac{\text{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\text{BR}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓

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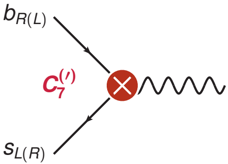
	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

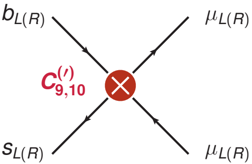
$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators



$\propto 1/q^2$

semileptonic operators



$\propto 1$

	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'
$B \to (X_s, K^*)\,\gamma$	★		
$B \to (X_s, K, K^*)\,\mu^+\mu^-$	★	★	★
$B_s \to \phi\,\mu^+\mu^-$	★	★	★
$B_s \to \mu^+\mu^-$			★

neglecting tensor operators (secretly dimension 8)

neglecting scalar operators (strongly constrained by $B_s \to \mu^+\mu^-$)

(Alonso, Grinstein, Martin Camalich '14) many processes and many observables are modified simultaneously

$\Rightarrow$ global fits are required

WA, Straub, Paradisi ’11; Bobeth, Hiller, van Dyk, Wacker ’11; WA, Straub ’12, ’13, ’14;

Beaujean, Bobeth, van Dyk, Wacker; ’12; Descotes-Genon, Matias, Virto ’13, ’14;

Beaujean, Bobeth, van Dyk ’13; Hurth, Mahmoudi ’13; Ghosh, Nardecchia, Renner ’14;

Hurth, Mahmoudi, Neshatpour ’14; Jäger, Martin Camalich ’14; ...

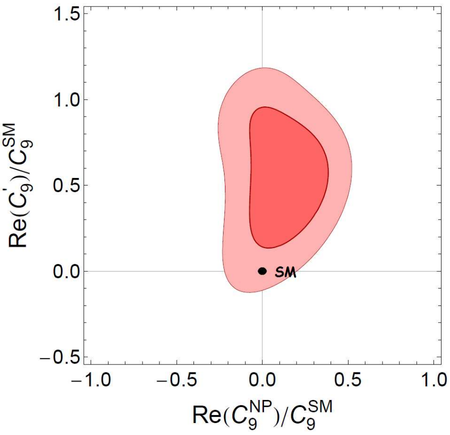
2011

favored new physics parameter space

$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$$

muonic vector current

(WA, Straub '11 - '15)



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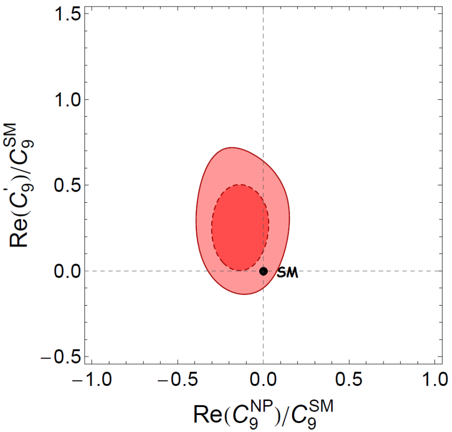
2012



The C_9 - C_9' Plane

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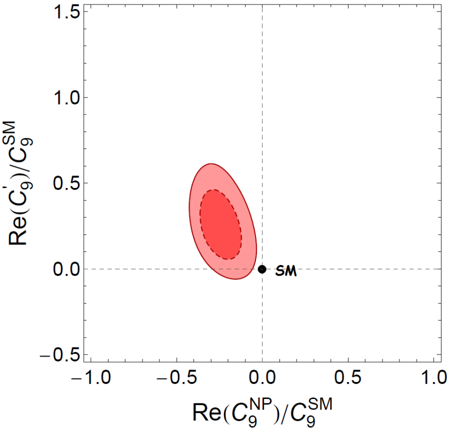
2013



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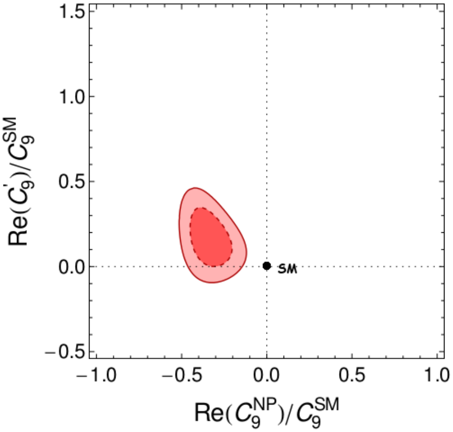
2014



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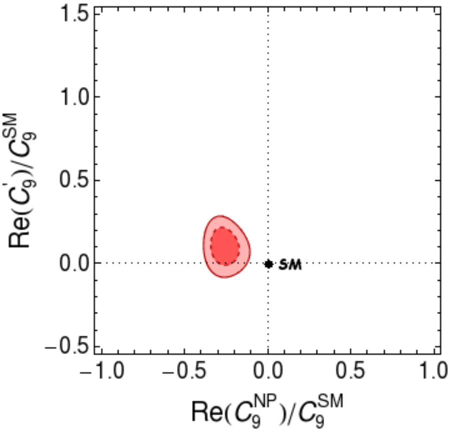
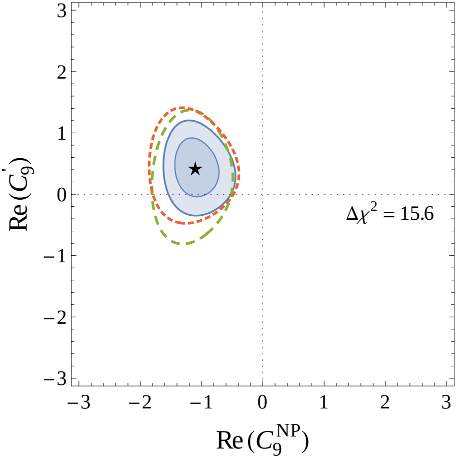
(WA, Straub '11 - '15)

2015





WA, Straub 1411.3161 / 1503.06199

$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$$

muonic vector current

- NP contributions to C_9 give best description of the data
- (NP with $C_9 = -C_{10}$ works almost equally well)
- best fit point

$$\chi^2/\#_{\mathrm{dof}} = 101.3/86$$

- compare to SM

$$\chi^2/\#_{\mathrm{dof}} = 116.9/88$$

	LFU violation
hadronic effects?	✗
New Physics?	✓

Distinguishing New Physics from Hadronic Effects

	LFU violation	CP violation
hadronic effects?	✗	✗
New Physics?	✓	✓

Distinguishing New Physics from Hadronic Effects

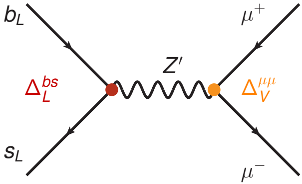
	LFU violation	CP violation	non-trivial q^2 dependence
hadronic effects?	✗	✗	✓
New Physics?	✓	✓	✗

Implications for the New Physics Scale

generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\; V_{tb}V_{ts}^*\; (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\; V_{tb}V_{ts}^*\; (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$

(assumes New Physics has O(1) coupling to muons)

Models with Flavor Changing Z' Bosons



many Z' models in the literature:

(WA, Straub '13/'14; Gauld, Goertz, Haisch '13; Buras et al. '13/'14; WA, Gori, Pospelov, Yavin '14; Glashow, Guadagnoli, Lane '14; Crivellin, D'Ambrosio, Heeck '14/'15; Niehoff, Stangl, Straub '15; Aristizabal Sierra, Staub, Vicente '15; Boucenna, Valle, Vicente '15; Celis et al. '15; Crivellin et al. '15; ...)

alternatives:

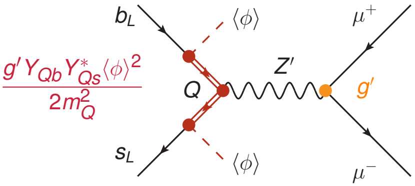
(Datta, Duraisamy, Ghosh '13; Hiller, Schmaltz '14; Biswas et al. '14; Gripaios, Nardecchia, Renner '14; Buras et al. '14; Bhattacharya et al. '14; Becirevic, Fajfer, Kosnik '15; Alonso, Grinstein, Martin Camalich '15; ...)

$$C_9^{\rm NP} = \frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*}\,\frac{v^2}{M_{Z'}^2}\,\frac{4\pi^2}{e^2} \simeq \frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*}\,\frac{(5~\text{TeV})^2}{M_{Z'}^2}$$

muon number - tau number
is anomaly free
gauging it leads to the wanted
vector couplings with muons

$$\mathcal{L} \supset g'(\bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau)Z'_\mu$$

couple the Z' to quarks only
indirectly, by mixing with
heavy vector-like fermions
charged under $U(1)'$



WA, Gori, Pospelov, Yavin 1403.1269

A Simple Model Based on Gauged $L_\mu - L_\tau$

muon number - tau number
is anomaly free
gauging it leads to the wanted
vector couplings with muons

$$\mathcal{L} \supset g'(\bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau)Z'_\mu$$

couple the Z' to quarks only
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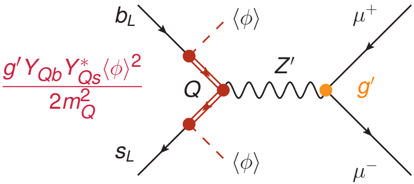


contributions to $B \to K^* \mu^+\mu^-$ are
independent of the $U(1)'$ gauge
coupling and the Z' mass

$$C_9 \simeq \frac{Y_{Qb} Y^*_{Qs}}{2m_Q^2} \quad , \quad C'_9 \simeq -\frac{Y_{Db} Y^*_{Ds}}{2m_D^2}$$

WA, Gori, Pospelov, Yavin 1403.1269

I look forward to an exciting conference!

Back Up

Probing the $L_\mu - L_\tau$ Z'

$(g-2)$ of the muon

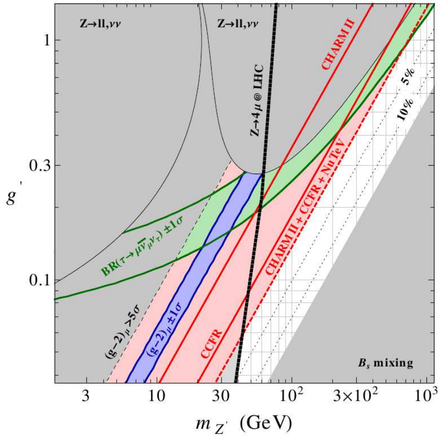
tau decays

Z couplings to leptons

$Z \to 4\mu$ @ LHC

B_s mixing

neutrino trident production



WA, Gori, Pospelov, Yavin 1403.1269 / 1406.2332

($g - 2$) of the muon

tau decays

Z couplings to leptons

$Z \to 4\mu$ @ LHC

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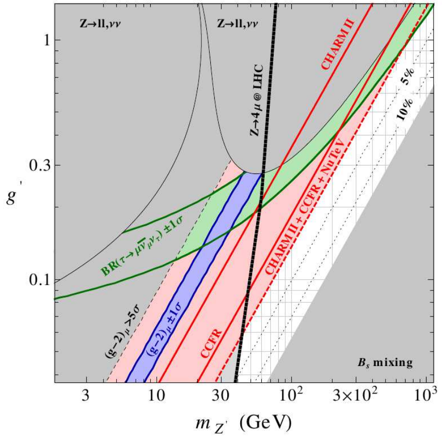
neutrino trident production



B_s mixing leads to an upper bound on the $U(1)'$ breaking vev.
neutrino tridents lead to a lower bound.

WA, Gori, Pospelov, Yavin 1403.1269 / 1406.2332