Flavor Physics
Beyond the Standard Model

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PERIMETER INSTITUTE

Frontiers in Particle Physics:
From Dark Matter to the LHC and Beyond

Aspen Center for Physics

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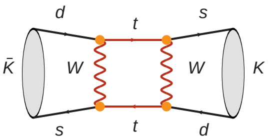
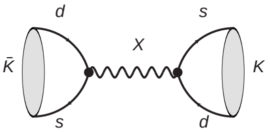
Sensitivity to Very Short Distances

Example: CP Violation in Kaon mixing



$$\sim \frac{g^4}{16\pi^2}\frac{1}{M_W^2}(V_{td}V_{ts}^*)^2$$

SM amplitude is
loop suppressed and
CKM suppressed



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

Generic NP
not necessarily
suppressed

- CP Violation in Kaon Mixing can probe *extremely high scales* far beyond the LHC reach

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

The New Physics Flavor Puzzle

meson mixing observables probe
generic New Physics at very high scales

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

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}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2	2.2×10^2	7.6×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2	7.4×10^2	1.3×10^{-5}	3.0×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

Isidori, Nir, Perez ’10

Many Highly Sensitive Probes

Meson Mixing

Rare Decays

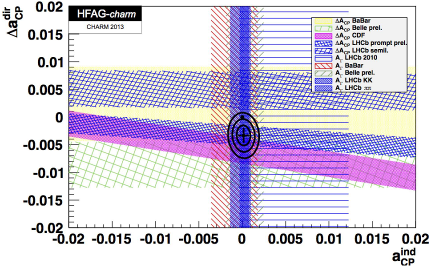
Charged Lepton Flavor Violation

Electric Dipole Moments

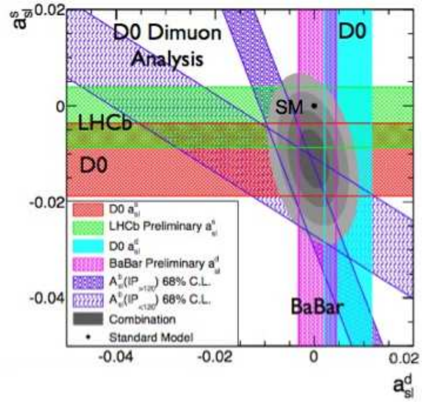
...

Some Anomalies?

- sizable direct CP Violation in charm decays (LHCb)



- sizable direct CP Violation in charm decays (LHCb)
- anomalous like-sign dimuon charge asymmetry (D0)



Some Anomalies?

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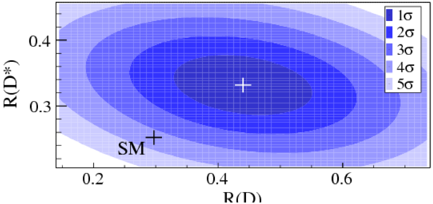
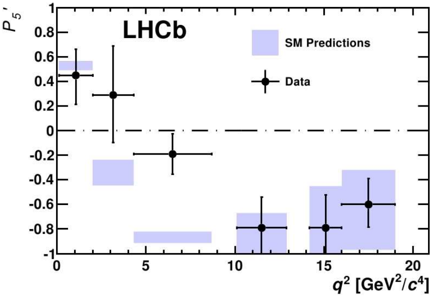
- excess of $B \to D^{(*)}\tau\nu$ decays (BaBar)



Some Anomalies?

- sizable direct CP Violation in charm decays (LHCb)
- anomalous like-sign dimuon charge asymmetry (D0)
- excess of $B \to D^{(*)}\tau\nu$ decays (BaBar)
- the $B \to K^*\mu^+\mu^-$ anomaly (LHCb)
- ...



Outline of the Talk

Part I

flavor observables probe New Physics at high scales

example: mini-split SUSY scenario

Part II

addressing anomalies with New Physics

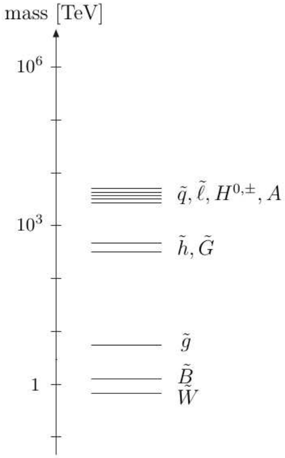
example: the $B \to K^* \mu^+ \mu^-$ anomaly

Low Energy Probes
of PeV Scale Sfermions

WA, Roni Harnik, Jure Zupan

JHEP **1311**, 202 (2013) [arXiv:1308.3653 [hep-ph]]

A “Simply Unnatural” SUSY Spectrum



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

$$\mathcal{L}_{\rm SB} \supset \frac{1}{M_*^2}\int d^4\theta (X^\dagger X)(\Phi^\dagger\Phi + H_u H_d)$$
$$-\frac{\alpha_i b_i}{4\pi}\frac{m_{3/2}}{2}\lambda_i\lambda_i - \frac{m_{3/2}}{2}\tilde{G}\tilde{G} + \int d^4\theta (H_u H_d)$$

- scalar masses of the order $F_X/M_* \gtrsim F_X/M_{\rm Pl} \sim m_{3/2}$
- gaugino masses from anomaly mediation, 1-loop factor below the gravitino mass
- 125 GeV Higgs is “effortless”
- heavy sfermions open up possibilities to generate fermion mass hierarchies radiatively

New Sources of Flavor and CP Violation

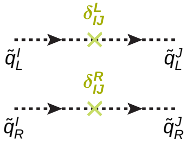
- mini-split SUSY philosophy:
  no model building effort

→ generic flavor mixing for squarks and sleptons

- parametrization in terms of
  mass insertions

$$\hat{M}^2_{\tilde{q}} = m^2_{\tilde{q}} (\mathbb{1} + \delta_q)$$

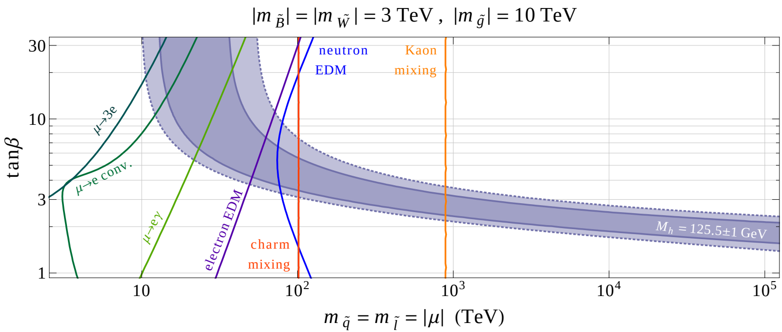
$$\hat{M}^2_{\tilde{\ell}} = m^2_{\tilde{\ell}} (\mathbb{1} + \delta_\ell)$$



- for TeV scale sfermions: SUSY flavor problem
  excessive contributions to many low energy flavor observables
- for 1000 TeV sfermions: flavor opportunity!
  a broad class of low energy processes can be sensitive to sfermions far beyond the reach of LHC

Current Constraints in a Slice of Parameter Space

WA, Harnik, Zupan 1308.3653



- PeV squarks already probed by CP violation in Kaon mixing
- CP violation in charm mixing and the neutron EDM reach up to O(100 TeV)

assumptions for the plot:

- all relevant flavor mixing $|\delta_{ij}| = 0.3$
- all relevant phases $\sin\phi_i = 1$
- no large cancellations between the various contributions

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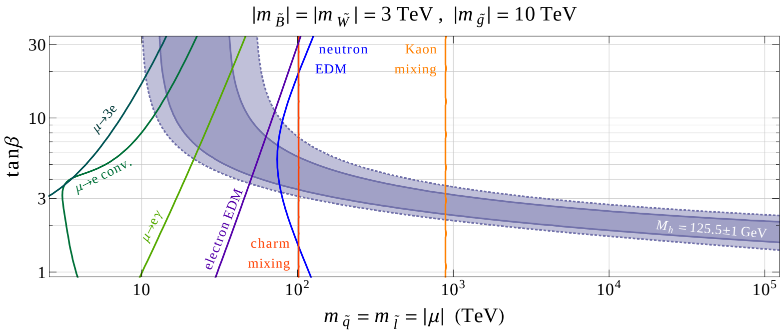
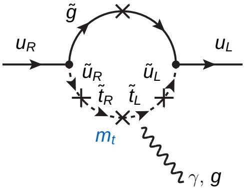
WA, Harnik, Zupan 1308.3653



- PeV squarks already probed by CP violation in Kaon mixing
- CP violation in charm mixing and the neutron EDM reach up to O(100 TeV)
- EDMs particularly interesting: enhanced by m_τ/m_e (d_e) or m_t/m_u (d_n)
  (see also McKeen, Pospelov, Ritz 1303.1172)



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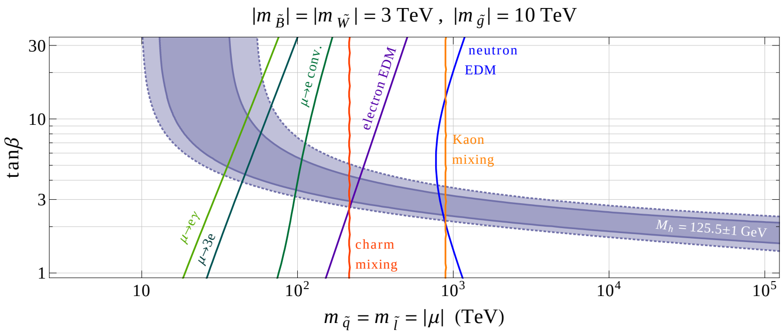


- neutron EDM (in gen. EDMs of hadronic systems) probe squarks at O(PeV)
- electron EDM and $\mu \to e$ conversion probe sleptons above 100 TeV
- SUSY flavor structure is unknown
  $\to$ important to reach the PeV scale
  with as many observables as possible

$^{(*)}$ expected improvements

- CPV in D mixing : factor 10
- d_n : factor 300
- d_e : factor 90
- $\mu \to e$ conv. : factor 10^4

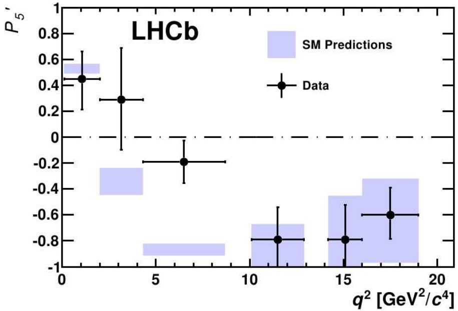
New Physics in $B \to K^* \mu^+ \mu^-$?

WA, David Straub

Eur.Phys.J.C **73**, 2646 (2013) [arXiv:1308.1501 [hep-ph]]

The $B \to K^*\mu^+\mu^-$ "Anomaly"

latest $B \to K^*\mu^+\mu^-$ results
from LHCb (with 1fb^{-1}) 1308.1707
$\to$ talk by Alexander Shires



3.7σ discrepancy
in the $4.3 < q^2 < 8.68$ GeV^2 bin
with respect to a SM prediction
from Descotes-Genon, Hurth, Matias, Virto
1303.5794

- statistical fluctuation?
  (update with full 7+8 TeV data hopefully soon)
- underestimated SM uncertainties?
  (see Jäger, Martin Camalich 1212.2263)
  $\to$ talk by Sebastian Jäger
- New Physics:

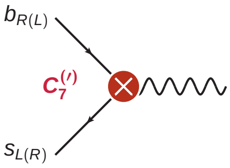
  can anomaly be explained model independently?

  can anomaly be explained in concrete NP models?

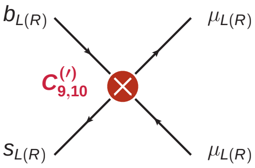
New Physics in $B \to K^* \mu^+ \mu^-$

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

magnetic dipole operators



semileptonic operators



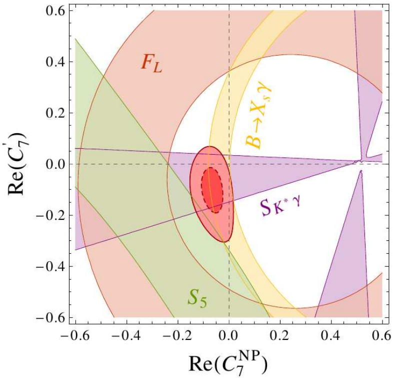
	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'
$B \to (X_s, K^*)\, \gamma$	★		
$B \to (X_s, K, K^*)\, \mu^+\mu^-$	★	★	★
$B_s \to \mu^+\mu^-$			★

neglecting tensor operators

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

C_7 - C_7' plane

$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$



WA, Straub 1308.1501

- new physics in C_7 and C_7' strongly constrained by data on $B \to X_s\gamma$ and $B \to K^*\gamma$
- best fit values

$$C_7^{\rm NP} = -0.06 \pm 0.04$$

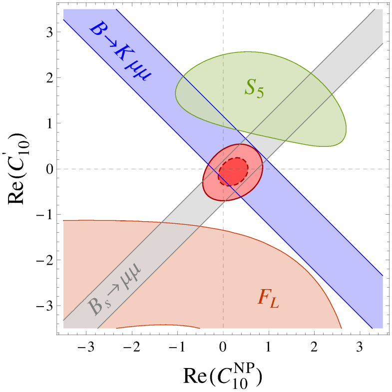
$$C_7' = -0.1 \pm 0.1$$

improve the tension only slightly

(see also: Descotes-Genon, Matias, Virto 1307.5683 and Beaujean, Bobeth, van Dyk 1310.2478
Hurth, Mahmoudi 1312.5267)

C_{10} - C'_{10} plane

$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$



- NP contribution to $C'_{10} \simeq +1.5$ could explain the anomaly in P'_5 ($\sim S_5$)
- would worsen a small tension in F_L
- strong constraints from $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

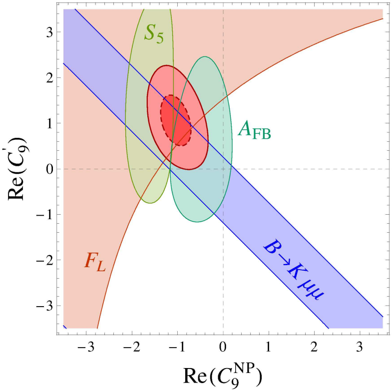
$\to$ no improvement compared to SM

WA, Straub 1308.1501

(see also: Descotes-Genon, Matias, Virto 1307.5683 and Beaujean, Bobeth, van Dyk 1310.2478
Hurth, Mahmoudi 1312.5267)

C_9 - C_9' plane

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



- NP contribution to $C_9^{\rm NP} \simeq -1.5$ would give the best fit to P_5' ($\sim S_5$) (compare $C_9^{\rm SM} \simeq 4.1$)
- the tension in F_L pulls in the same direction
- $A_{\rm FB}$ gives important constraint
- $C_9' \simeq -C_9^{\rm NP}$ helps to avoid constraints from $B \to K\mu^+\mu^-$
- best fit result

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

$$C_9' = +1.0 \pm 0.5$$

WA, Straub 1308.1501

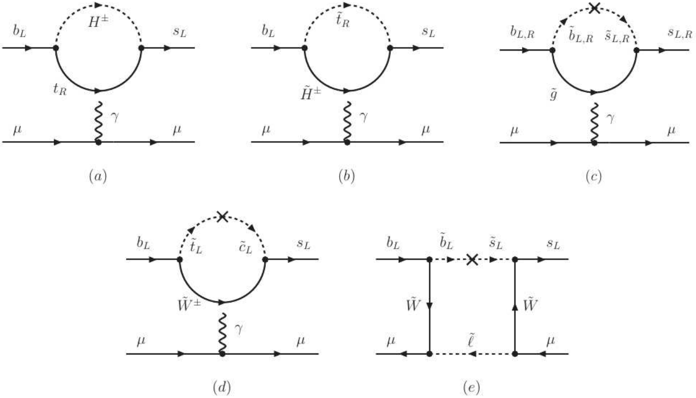
(see also: Descotes-Genon, Matias, Virto 1307.5683 and Beaujean, Bobeth, van Dyk 1310.2478 Hurth, Mahmoudi 1312.5267)

Implications for the NP Scale

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

(assumes NP has O(1) coupling to muons)

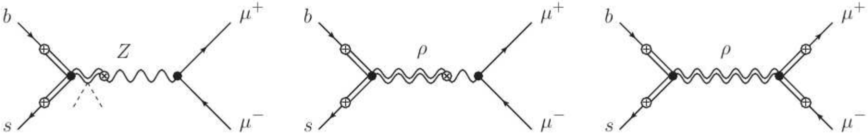
contributions to C_9 and C_9' at the loop level
(Z penguins, photon penguins, boxes)



taking into account bounds from direct searches
$|C_9^{(\prime)}| \simeq 1$ cannot be achieved in the MSSM

C_9 and C_9' in Models with Partial Compositeness

contributions to C_9 and C_9' already at tree level

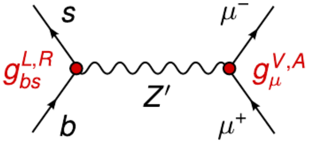


(a) (b) (c)

contributions are suppressed by either
the small vector coupling of the SM Z to muons
or by the small amount of compositness of the muons

$|C_9^{(\prime)}| \simeq 1$ cannot be achieved in models with partial compositness parametrization of generic Z' couplings

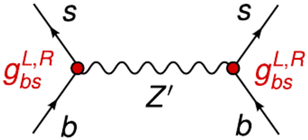
$$\mathcal{L} \supset \frac{g_2}{2c_W}\left[\bar{s}\gamma^\mu(g_{bs}^L P_L + g_{bs}^R P_R)b + \bar{\mu}\gamma^\mu(g_\mu^V + \gamma_5 g_\mu^A)\mu\right]Z'_\mu$$



$$\frac{e^2}{16\pi^2}(V_{ts}^* V_{tb})\left\{C_9^{\rm NP}, C_9', C_{10}^{\rm NP}, C_{10}'\right\} = \frac{m_Z^2}{2m_{Z'}^2}\left\{g_{bs}^L g_\mu^V, g_{bs}^R g_\mu^V, g_{bs}^L g_\mu^A, g_{bs}^R g_\mu^A\right\}$$

(see also: Descotes-Genon, Matias, Virto 1307.5683; Buras, Girrbach 1309.2466; Gauld, Goertz, Haisch 1308.1959; 1310.1082) the Z' contributes also to B_s mixing at tree-level

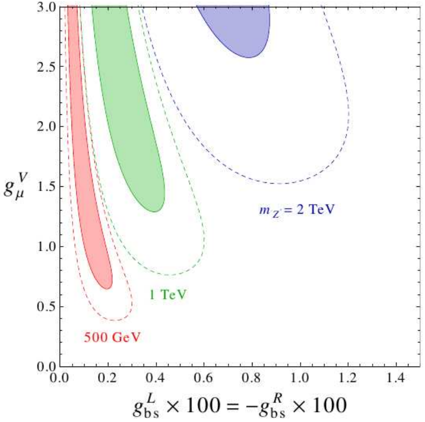
hadronic uncertainties in the SM prediction allow for O(10-15%) new physics contributions



$$\frac{M_{12}}{M_{12}^{\rm SM}} \simeq 1 + \frac{m_Z^2}{m_{Z'}^2}\left[(g_{bs}^L)^2 + (g_{bs}^R)^2 - 9.7(g_{bs}^L)(g_{bs}^R)\right]\left(\frac{g_2^2}{16\pi^2}(V_{ts}^* V_{tb})^2 S_0\right)^{-1}$$

$\rightarrow$ particularly strong constraints if both LH and RH $b \rightarrow s$ couplings are present simultaneously

Upper Bound on the Z' Mass



WA, Straub 1308.1501

combined fit to $B \to K^{(*)}\mu^+\mu^-$ and B_s mixing data

constraint from B_s mixing leads to upper bound on the Z' mass

$$M_{Z'} \lesssim g_\mu^V \times 800\ GeV \quad (C_9 \text{ and } C_9')$$

$$M_{Z'} \lesssim g_\mu^V \times 2\ TeV \quad (\text{only } C_9)$$

$\rightarrow$ di-lepton resonance searches at LHC generically lead to strong constraints on the coupling of the Z' to 1st generation quarks

A Simple Viable Model

Wanted: light Z'
with sizable vector coupling to muons
and small couplings to quarks

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Identify $U(1)'$ with
muon number - tau number
$\rightarrow$ automatically anomaly free

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

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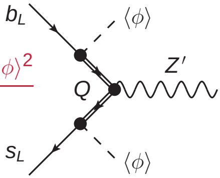
couple to quarks only indirectly,
by mixing with heavy vector-like fermions
charged under $U(1)'$
(see also Fox, Liu, Tucker-Smith, Weiner
1104.4127)

$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{m_Q^2}$$



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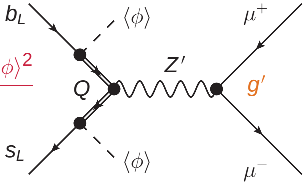


- contributions to $B \rightarrow K^*\mu^+\mu^-$ are independent of the $U(1)'$ gauge coupling and the Z' mass

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

- bounds from B_s mixing constrain the size of the $U(1)'$ breaking vev

$$M_{12} \propto \frac{(Y_{Qb} Y^*_{Qs})^2 \langle\phi\rangle^2}{m_Q^4} + \ldots$$

(work in progress with Stefania Gori, Maxim Pospelov, and Itay Yavin)

Summary

- low energy observables can probe NP at very high scales
- Example: Mini-Split SUSY

  $\rightarrow$ CP Violation in Kaon mixing already probes squarks at the *PeV scale*

  $\rightarrow$ several other observables (charm mixing, EDMs, $\mu \rightarrow e$ in Al) can reach sensitivity to scales of 100 - 1000 TeV in the future

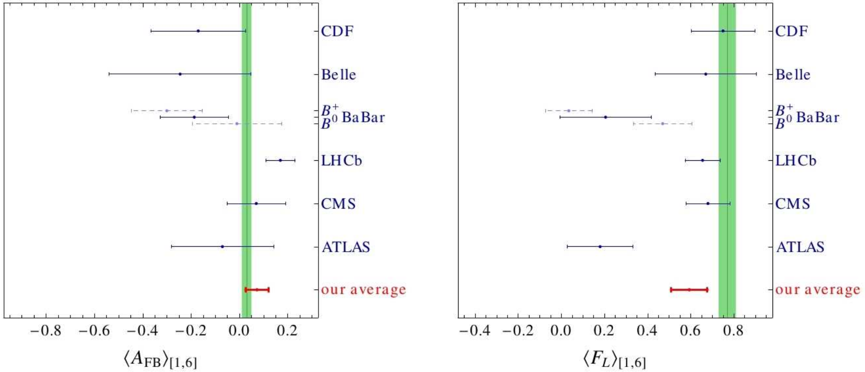
- recent flavor anomalies might already be hinting at NP
- Example: the $B \rightarrow K^* \mu^+ \mu^-$ anomaly

  $\rightarrow$ consistent NP explanation points to the operators $(\bar{s}\gamma_\mu P_{L/R} b)(\bar{\mu}\gamma^\mu \mu)$ with a generic scale of $\sim$ 35 TeV

  $\rightarrow$ models with a flavor changing Z' at (or below) the TeV scale are natural candidates to explain the anomaly

Back Up

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



WA, Straub 1308.1501

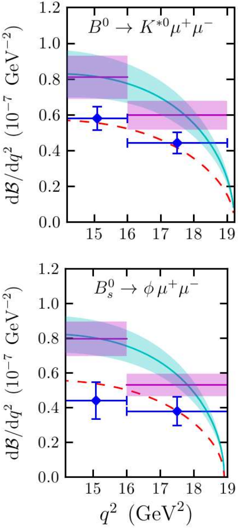
More $B \to K^* \mu^+ \mu^-$ Fits

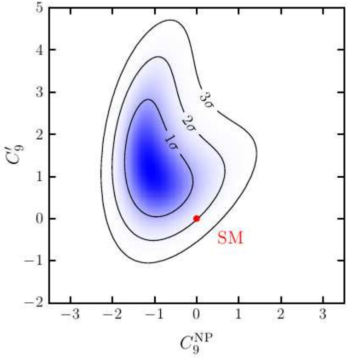
Scenario	C_7^{NP}	C_7'	C_9^{NP}	C_9'	C_{10}^{NP}	C_{10}'	$\Delta\chi^2(SM)$
(7)	-0.07 ± 0.04						3.4
(9)			-0.8 ± 0.3				**4.3**
(77′)	-0.06 ± 0.04	-0.1 ± 0.1					4.7
(97)	-0.05 ± 0.04		-0.6 ± 0.3				6.0
(97′)		-0.1 ± 0.1	-0.7 ± 0.3				5.5
(99′)			-1.0 ± 0.3	$+1.0 \pm 0.5$			**8.3**
(910′)			-1.0 ± 0.3			-0.4 ± 0.2	7.0
Real	-0.03	-0.11	-0.9	$+0.7$	-0.1	-0.2	**10.8**
Complex	$+0.03$ $+0.09i$	-0.23 $-0.23i$	-1.9 $+1.2i$	$+1.2$ $+3.3i$	$+1.6$ $-0.1i$	$+1.0$ $+1.6i$	**14.1**

WA, Straub 1308.1501

the C_9 - C_9' scenario works best

Intriguing Support for New Physics in $C_9^{(\prime)}$

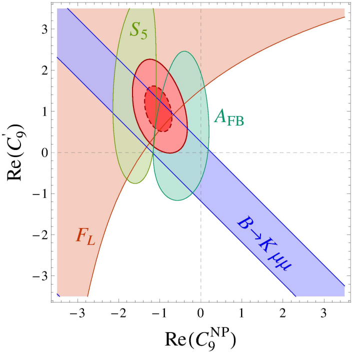




Horgan, Liu, Meinel, Wingate 1310.3887

$C_9^{\rm NP} = -1.1 \pm 0.5\,,\quad C_9' = +1.1 \pm 0.9$

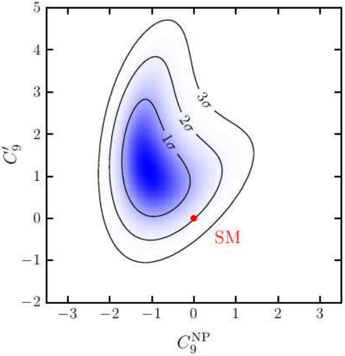
- mainly driven by $B \to K^*\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ BRs at high q^2



WA, Straub 1308.1501

$C_9^{NP} = -1.0 \pm 0.3\,, \quad C_9' = +1.0 \pm 0.5$

- mainly driven by P_5' / S_5 at low q^2



Horgan, Liu, Meinel, Wingate 1310.3887

$C_9^{NP} = -1.1 \pm 0.5\,, \quad C_9' = +1.1 \pm 0.9$

- mainly driven by $B \to K^* \mu^+\mu^-$ and $B_s \to \phi \mu^+\mu^-$ BRs at high q^2

complementary set of observables but same conclusion!