Particle and Astroparticle Theory Seminar, MPIK Heidelberg, 20 January 2014

Status of new physics in rare *B* decays

Presented by David M. Straub

Junior Research Group “New Physics”
Excellence Cluster Universe, Munich

Outline

1. $B_s \to \mu^+\mu^-$
   - Experiment vs. Standard Model
   - Supersymmetry
   - Partial compositeness
2. $B \to K^*\mu^+\mu^-$
   - Global analyses
   - New physics?

Two hot topics

12 November 2012 Last updated at 13:30 GMT

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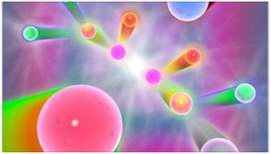
Popular physics theory running out of hiding places

By Pallab Ghosh
Science correspondent, BBC News

Researchers at the Large Hadron Collider have detected one of the rarest particle decays seen in nature.



Supersymmetry predicts heavy versions of all the particles we know about - "super particles"

The finding deals a significant blow to the theory of physics known as supersymmetry.

Many researchers had hoped the LHC would have confirmed this by now.

Supersymmetry, or Susy, has gained popularity as a way to explain some of the inconsistencies in the traditional theory of subatomic physics known as the Standard Model.

The new observation, reported at the **Hadron Collider Physics conference in Kyoto** and outlined in **an as-yet unpublished paper**, is not consistent with many of the most likely models of Susy.

Prof Chris Parkes, who is the spokesperson for the UK participation in the

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Rare particle decay delivers blow to supersymmetry

14 November 2012

By **Lucie Bradley**
Cosmos Online

The popular physics theory of supersymmetry has been called into question by new results from CERN.

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SYDNEY: The popular physics theory of supersymmetry has been called into question by new results from CERN.

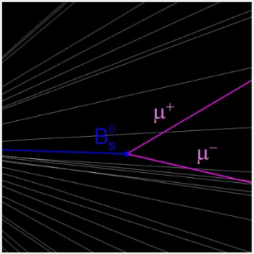
Physicists working at CERN's Large Hadron Collider (LHC) near Geneva, Switzerland, have announced the discovery of an extremely rare type of particle decay.

While discoveries are usually accompanied by excitement there is also a tinge of uncertainty surrounding this latest finding from CERN. It has dealt a hefty blow to the popular physics theory of supersymmetry.

The results were presented at the Hadron Collider Physics Symposium in Kyoto, Japan, and will also be submitted to the journal *Physical Review Papers*.

A three in one billion chance

Scientists have been searching for this type of particle decay for the last decade and so the results from CERN have "generated a lot of excitement now that it has been found," according to physicist Mark Kruse, from Duke



A typical decay of the Bs (B sub s) meson into two muons. The two muons traversed the whole LHCb detector, which originated from the B0s decay point 14 mm from the proton-proton collision. Credit: LHCb

Two hot topics

New rare decay tightens the screw on supersymmetry

November is a peak tourist time for Kyoto and I can see why. After a rainy first evening, the sky is now clear blue and the autumn leaves are glorious. The news in the hunt for physics beyond the standard model is less cheery

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Kyoto autumn for supersymmetry

Posted by
Jon Butterworth
Tuesday 13 November
2012 04.32 GMT
guardian.co.uk
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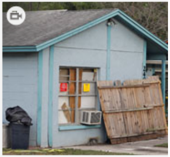
Here at the Hadron Collider Physics symposium in Kyoto, three experimental talks on searches for physics beyond the Standard Model have just finished, all with the same result: nothing so far.

Today's best video



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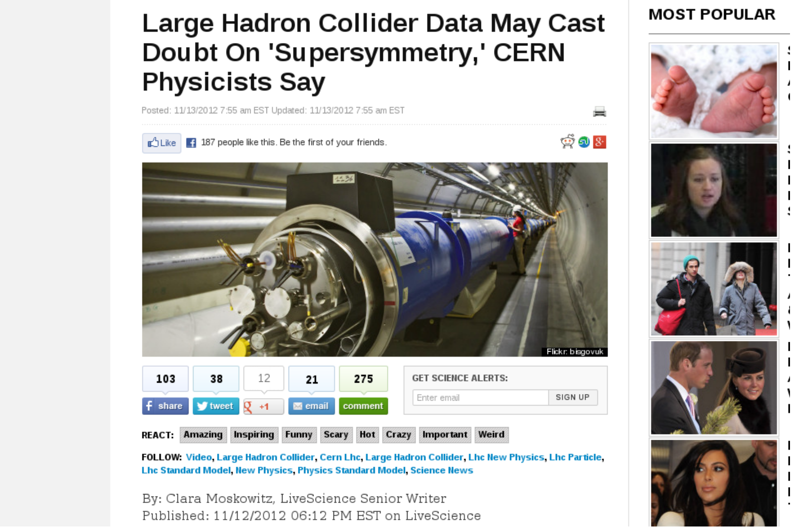

Large Hadron Collider Data May Cast Doubt On 'Supersymmetry,' CERN Physicists Say

Posted: 11/13/2012 7:55 am EST Updated: 11/13/2012 7:55 am EST

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By: Clara Moskowitz, LiveScience Senior Writer
Published: 11/12/2012 06:12 PM EST on LiveScience

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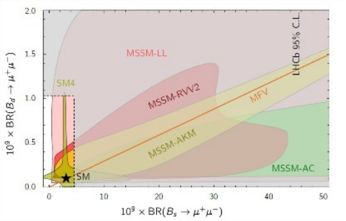
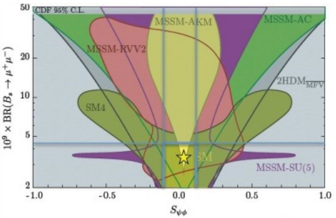
Two hot topics

30 March 2012: LHCb strongly squeezes SUSY parameter space.

Results presented by the LHCb Collaboration at the Rencontres de Moriond EW and QCD conferences allowed theorists to squeeze strongly the parameters of supersymmetric extensions of the Standard Model (SUSY), the most popular new physics model. The simplest version of this model, called the Minimal Supersymmetric Standard Model (MSSM), predicted the frequencies with which B_s and B_d mesons decay into pairs of oppositely charged muons to have values significantly different from the Standard Model (SM) prediction. This is shown in the left image below, which was presented by David Straub (SNS and INFN, Pisa) at the Moriond EW conference. The predictions for both frequencies (branching ratios BR) depend on different parameters of the MSSM and cover nearly all of the left image surface. The LHCb results, see 5 March 2012 news, limit the predictions that are still allowed to a small region around the SM expected value. It is interesting to note that certain combinations of MSSM parameters allow lower BR values than those predicted by the SM. The LHCb measurements of the parameter φ_s, which sets the scale for the difference between properties of matter and antimatter for the strange beauty B_s mesons, see 5 March 2012 news, also strongly limits the SUSY parameter space that is still allowed, as shown by the vertical lines on the right image below.





SUSY contributions to observables that can be measured in experiments depend, in general, on more than 100 free parameters. Therefore in order to be able to analyse experimental data physicists are using a simplified model, the Constrained MSSM (CMSSM), with 5 parameters m_0, $m_{1/2}$, A_0, $\tan\beta$ and $\mu/|\mu|$. Nazila Mahmoudi (Clermont-Ferrand and CERN) presented the left image below at the Moriond QCD conference. The

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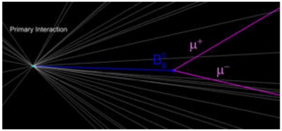
Rare Particle Discovery Dims Hopes for Exotic Theories

LiveScience By by Clara Moskowitz, LiveScience Senior Writer
July 19, 2013 2:12 PM



This diagram illustrates the collision of two protons inside the Large Hadron Collider, creating a spray …

Physicists have measured an extremely rare particle decay inside the world's largest atom smasher — a discovery that bolsters the leading model of particle physics and leaves little room for undiscovered particles beyond this theory.

Inside the Large Hadron Collider (LHC), a 17-mile-long (27 kilometers) circular tunnel under France and Switzerland, particles are sped up to near the speed of light and then smashed together. The collisions give rise to an array of pedestrian particles, as well as some exotic rarities. It is one of these rare particles, called B-sub-s, that physicists recently measured.

B-sub-s particles are made of two flavors of quarks: bottom quarks and anti-strange quarks (the antimatter counterparts to strange quarks). They last only a very short while after being created inside the LHC, quickly decaying into lighter particles. Now, physicists say they've observed B-sub-s particles decaying into two particles called muons (cousins of electrons). [Beyond Higgs: 5 Elusive Particles That May Lurk in the Universe]

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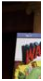

Lates

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TPM LIVEWIRE

'Big Bang Machine' Observes Rare Strange Beauty Particle Decay, Bolstering Standard Model

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CARL FRANZEN – NOVEMBER 12, 2012, 10:29 AM EST 14

Evidence consistent with the so-called "God Particle" Higgs boson was but one of the "Big Bang Machine" Large Hadron Collider's major discoveries this year: On Monday, the European Organization for Nuclear Research (CERN), the agency in charge of the collider, which is the world's largest and most powerful particle accelerator, announced at a conference in Tokyo that it had observed one of the rarest ever predicted particle decays -- a strange beauty quark decaying into a muon and antimuon -- which is only expected to occur three times in every billion decays, according to the Standard Model, the prevailing particle physics theory that explains the laws of the universe.

"This measurement is a sort of checkup of the Standard Model and today it appears healthier

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Two hot topics

Discovery of rare decay narrows space for new physics

Jul 19, 2013

After a quarter of a century of searching, physicists have discovered a rare particle decay that gives them an indirect way to test models of new physics.

Researchers on the CMS and LHCb collaborations at the Large Hadron Collider at CERN announced today at the EPS-HEP Conference in Stockholm, Sweden, that their findings agreed closely with the Standard Model of particle physics, ruling out several models that predict new particles.

In this result, physicists showed for the first time enough evidence to declare the discovery of a decay of a particle made up of two kinds of quarks—bottom quarks and anti-strange quarks—into a pair of particles called muons.

The U.S. Department of Energy's Fermi National Accelerator Laboratory serves as the U.S. hub for more than 1,000 scientists and engineers who participate in the CMS experiment. DOE and the National Science Foundation support involvement by about 2,000 scientists and students from U.S. institutions in the LHC experiments CMS, ATLAS, LHCb and ALICE—the vast majority participating at their home institutions via a powerful broadband network that ships data from CERN.

"This is a victory for the Standard Model," said CMS physicist Joel Butler of Fermi National Accelerator Laboratory. "But we know the Standard Model is incomplete, so we keep trying to find things that disagree with it."

The Standard Model predicts that the particle, called B-sub-s, will decay into two

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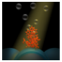
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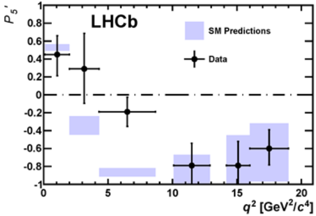
Two hot topics

9 August 2013: LHCb results hint at new physics?

The LHCb Collaboration has just published the results of a new analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay, with $K^{*0} \to K^+\pi^-$. These results were presented three weeks ago at the European Physical Society Conference on High Energy Physics, EPSHEP, Stockholm, Sweden, and triggered very interesting discussions. The analysis of the $B^0 \to K^*\mu\mu$ decay is considered as a very promising channel to search for new physics effects, see the 14 June 2013 news for an introduction. A contribution from new physics particles could modify the angular distributions of the decay products. LHCb physicists have studied different variables related to these angular distributions as functions of the $\mu^+\mu^-$ invariant mass squared. In previously published results, no significant deviation from the Standard Model prediction has been found, see the 13 March 2012 news. In order to increase sensitivity to new physics effects LHCb physicists started to analyse additional observables (the so called P_i' observables) which are considered theoretically clean. This means that they are less sensitive than other observables to some theoretical parameters that are not precisely known (form-factors for experts). Four such observables, labelled P_4', P_5', P_6' and P_8', have been studied.



The image shows the distribution of the P_5' observable as a functio of the $\mu^+\mu^-$ invariant mass squared q^2. The black data points are compared with the Standard Model prediction. A 3.7σ deviation of data above the prediction is observed for the third bin corresponding to q^2 between 4.3 and 8.68 GeV^2/c^4. Taking into account that this deviation is observed in one out of 24 bins investigated in this work (the so-called look-elsewhere effect), the significance of the deviation becomes 2.8σ.

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click the image for higher resolution

These new results are of great interest to theorists, who are combining results from several measurements to search for

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A Four-Sigma Evidence Of New Physics In Rare B Decays Found By LHCb, And Its Interpretation

By Tommaso Dorigo | July 24th 2013 01:31 PM | 5 comments | Print | E-mail | Track Comments

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Tommaso Dorigo

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Today I received news of an interesting measurement of angular distributions of the decay products in the rare decay of the B meson to a K* and a muon pair - one of the specialties of the LHCb collaboration, which has more horse-power in some of these low-energy measurements than ATLAS and CMS.

As I described in the two previous posts, (where I discussed the recent measurements of the Bs->μμ decay and the Bd one) when you look at rare decays of heavy mesons which occur within the Standard Model thanks to quantum loops of virtual particles, you get sensitive to possible new physics effects - new particles that circulating in those quantum loops may produce a visible deviation of the decay

A Quantum Diaries Survivor

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ABOUT TOMMASO

I am an experimental particle physicist working with the CMS experiment at CERN. In my spare time I

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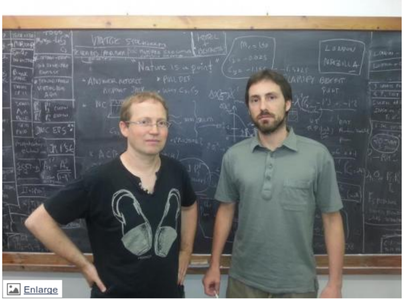
First experimental signs of a New Physics beyond the Standard Model

Jul 31, 2013



Enlarge

This is Joaquim Matias (left) and Javier Virto at the Universitat Autònoma de Barcelona. Credit: UAB

The Standard Model, which has given the most complete explanation up to now of the universe, has gaps, and is unable to explain phenomena like dark matter or gravitational interaction between particles. Physicists are therefore seeking a more fundamental theory that they call "New Physics", but up to now there has been no direct proof of its existence, only indirect observation of dark matter, as deduced, among other things, from the movement of the galaxies.

Outline

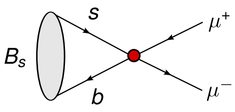
1. $B_s \to \mu^+\mu^-$
   - Experiment vs. Standard Model
   - Supersymmetry
   - Partial compositeness

2. $B \to K^*\mu^+\mu^-$
   - Global analyses
   - New physics?

$B_s \to \mu^+\mu^-$ in the SM

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \, C_{10} O_{10} + \text{h.c.}$$

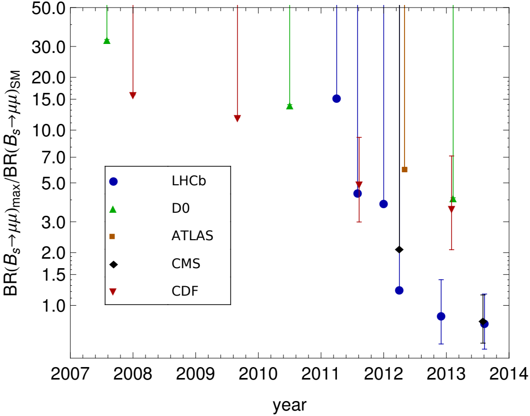
$$O_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



- Flavour-changing neutral current
  - Loop suppression
  - CKM suppression
- B_s is a pseudoscalar
  - Helicity suppression, m_μ^2/m_B^2
  - Only 1 operator – no γ penguin or vector operator

$\Rightarrow$ One of the rarest B decays!

History: search for $B_s \to \mu^+\mu^-$



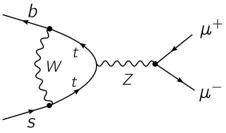
- Hope for order-of-magnitude enhancement was disappointed
- Precision of SM prediction becomes crucial

Computing the branching ratio

Schematically:

$$\text{BR} \propto \tau_{B_s} \left| V_{tb} V_{ts}^* \, C_{10} \, \langle \mu\mu | O_{10} | B_s \rangle \right|^2$$

$C_{10}(\mu_W) =$



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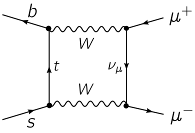

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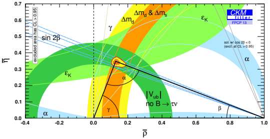
$$\langle 0 | \bar{s}\gamma_\mu\gamma_5 b | \bar{B}_s(p) \rangle = i p_\mu f_{B_s}$$

$V_{tb} V_{ts}^* \Leftarrow$



Some subtle points

- Bremsstrahlung emission (soft final-state photons): to be taken care of by experiment [Buras et al. 1208.0934]
- Direct emission of photons can be suppressed by appropriate invariant mass cut and is then negligible [Buras et al. 1208.0934, Aditya et al. 1212.4166]
- B_s mesons oscillate & the 2 mass eigenstates have quite different width: $y_s = \Delta\Gamma_s/(2\Gamma_s) = (8 + 1)\%$
  - Difference between the (flavour-averaged) BR at $t = 0$ and the (flavour averaged) time-integrated $\overline{\text{BR}}$ [De Bruyn et al. 1204.1735]

$$\overline{\text{BR}} = \frac{1 + \mathcal{A}^{\mu\mu}_{\Delta\Gamma} y_s}{1 - y_s^2} \, \text{BR}$$

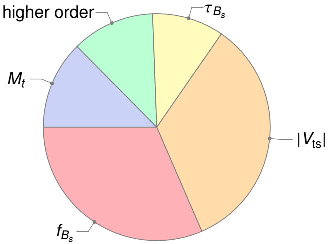
  - $A^{\mu\mu}_{\Delta\Gamma} = 1$ in the SM, potentially sensitive to NP [De Bruyn et al. 1204.1737]
  - $\overline{\text{BR}}_{\text{SM}} \approx 1.09 \, \text{BR}_{\text{SM}}$

Recent progress in the SM calculation

- f_{B_s} computed on the lattice to 2% precision [HPQCD, FLAG]
- NLO electroweak corrections to C_{10}
  Uncertainty in the BR: 7% $\to$ 1% [Bobeth et al. 1311.1348]
- NNLO QCD corrections to C_{10}
  Uncertainty in the BR: 2% $\to$ 0.2% [Hermann et al. 1311.1347]

State of the art [Bobeth et al. 1311.0903]

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$



$$\text{cf.: } \overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{LHCb+CMS}} = (2.9 \pm 0.7) \times 10^{-9}$$

$B_s \to \mu\mu$ vs. $B_d \to \mu\mu$

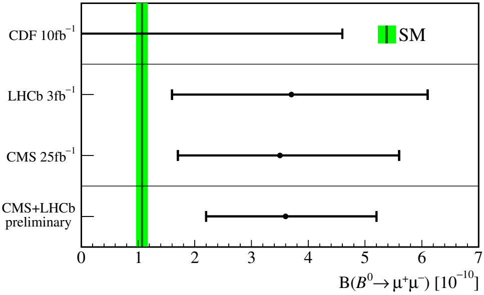
- In the SM (and all models with Minimal Flavour Violation), BRs differ only by CKM elements and overall factor

$$\frac{\text{BR}(B_s \to \mu^+\mu^-)}{\text{BR}(B_d \to \mu^+\mu^-)} = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s} |V_{ts}|^2}{\tau_{B_d} f_{B_d}^2 m_{B_d} |V_{td}|^2}$$

$$\overline{\text{BR}}(B_d \to \mu^+\mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$

$$\text{cf.: } \overline{\text{BR}}(B_d \to \mu^+\mu^-)_{\text{LHCb+CMS}} = (3.3^{+1.6}_{-1.4}) \times 10^{-10}$$

$B_d \to \mu^+\mu^-$ experiment vs. SM



- 2.4σ above 0, 1.6σ above SM. If NP: no MFV!

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$B_s \to \mu^+\mu^-$ beyond the SM

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\sum_i C_i O_i + C_i' O_i' + \text{h.c.}$$

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

$$O_S^{(\prime)} = \frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\ell)$$

$$O_P^{(\prime)} = \frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)$$

$$\text{BR}(B_s \to \mu^+\mu^-) \propto \left[|S|^2\left(1-\frac{4m_\mu^2}{m_{B_s}^2}\right)+|P|^2\right]$$

$$S = \frac{m_{B_s}}{2}C_S \qquad P = \frac{m_{B_s}}{2}C_P + m_\mu C_{10}$$

Higgs couplings in the MSSM: tree level

- At tree level, the MSSM is a type-II 2HDM

$$-\mathcal{L}_Y = Y_u^{ij} \, H_u \bar{q}_L^i \, u_R^j + Y_d^{ij} \, H_d \bar{q}_L^i \, d_R^j + \text{h.c.}$$

$$m_u = v_u Y_u \qquad\qquad m_d = v_d Y_d$$

- Higgs couplings are diagonal in the mass basis.

Higgs couplings in the MSSM: *loop* level

- At 1-loop level, non-holomorphic couplings are induced
- MSSM becomes a type-III 2HDM

$$-\Delta\mathcal{L}_Y = \epsilon_u^{ij}\, H_d^* \bar{q}_L^i\, u_R^j + \epsilon_d^{ij}\, H_u^* \bar{q}_L^i\, d_R^j + \text{h.c.}$$

$$m_u = v_u Y_u + v_d \epsilon_u \qquad\qquad m_d = v_d Y_d + v_u \epsilon_d$$

- $\tan\beta$-enhanced correction to down-type masses and Higgs couplings
- Flavour-changing Higgs couplings in the mass basis

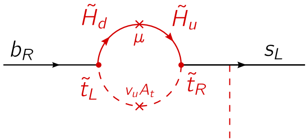
Higgs couplings in the MSSM: *loop* level

- At 1-loop level, non-holomorphic couplings are induced
- MSSM becomes a type-III 2HDM

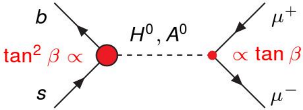
$$-\Delta\mathcal{L}_Y = \epsilon_u^{ij}\, H_d^* \bar{q}_L^i\, u_R^j + \epsilon_d^{ij}\, H_u^* \bar{q}_L^i\, d_R^j + \text{h.c.}$$

$$m_u = v_u Y_u + v_d \epsilon_u \qquad m_d = v_d Y_d + v_u \epsilon_d$$

- $\tan\beta$-enhanced correction to down-type masses and Higgs couplings
- Flavour-changing Higgs couplings in the mass basis
- $\bar{s}_L^i b_R H^0$ coupling $\propto \tan^2\beta$



(Pseudo-)scalar operators in the MSSM

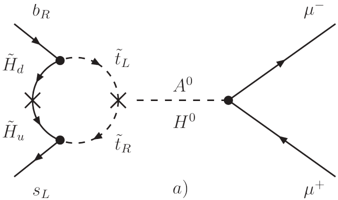


$$C_S \approx -C_P \propto \frac{\tan^3\beta}{M_A^2}$$

$$C'_S \approx C'_P \propto \frac{\tan^3\beta}{M_A^2}$$

(Pseudo-)scalar operators in the MSSM with MFV

Even for a degenerate spectrum: Higgsino contribution



$$C_S^{\tilde{H}} \propto \frac{\tan\beta^3}{M_A^2} \frac{A_t \mu}{m_{\tilde{t}}^2} f_{\tilde{H}}\left(\frac{|\mu|^2}{m_{\tilde{t}}^2}\right)$$

- Constructive interference for $\text{sgn}(\mu A_t) = -1$
- NB: in the CMSSM, $A_t \approx 0.8 A_0 - 2.2 m_{1/2}$
- Subleading Wino and gluino contributions also in MFV

(Pseudo-)scalar operators in the MSSM *without* MFV

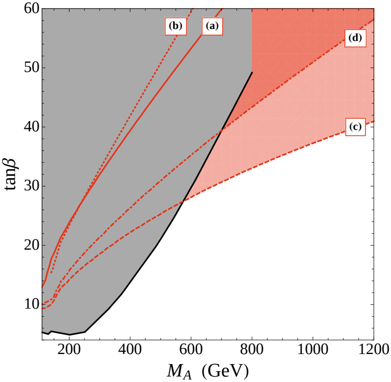
$$C_S^{\tilde{W}} \propto (\delta_d^{LL})_{32} \frac{\tan\beta^3}{M_A^2} \frac{M_2 \mu}{m_{\tilde{t}}^2} f_{\tilde{W}}\left(\frac{|\mu|^2}{m_{\tilde{t}}^2}, \frac{|M_2|^2}{m_{\tilde{t}}^2}\right)$$

$$C_S^{\tilde{g}} \propto -(\delta_d^{LL})_{32} \frac{\tan\beta^3}{M_A^2} \frac{M_3 \mu}{m_{\tilde{b}}^2} f_{\tilde{g}}\left(\frac{|M_3|^2}{m_{\tilde{b}}^2}\right)$$

$$C_S^{\prime\,\tilde{g}} \propto -(\delta_d^{RR})_{32} \frac{\tan\beta^3}{M_A^2} \frac{M_3 \mu}{m_{\tilde{b}}^2} f_{\tilde{g}}\left(\frac{|M_3|^2}{m_{\tilde{b}}^2}\right)$$

- $(\delta_d^{LL})_{32}$ strongly constrained by $b \to s\gamma$
- $(\delta_d^{RR})_{32}$ constrained by $b \to s\gamma$ and ΔM_s

Complementarity with Higgs searches



[Altmannshofer et al. 1211.1976]

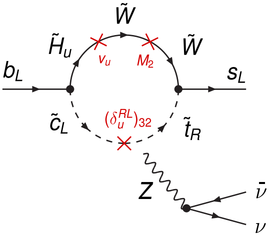
$m_{\tilde{q}} = 2$ TeV, $6M_1 = 3M_2 = M_3 = 1.5$ TeV

Scenario	(a)	(b)	(c)	(d)	(e)
μ [TeV]	1	4	-1.5	1	-1.5
sign(A_t)	+	+	+	-	-

- Large tan β + light Higgs spectrum disfavoured
- Direct Higgs searches more constraining for tan $\beta \lesssim 25$
- Milder bounds for $\mu A_t > 0$ (destructive interference with SM)

Finally: C_{10} in SUSY

- Only way to get sizable C_{10} in SUSY: Z penguin with chargino loop



- At most 25% effect in BR
- NB: C'_{10} negligible throughout parameter space

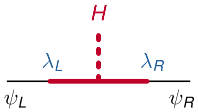
Outline

1. $B_s \to \mu^+\mu^-$
   - Experiment vs. Standard Model
   - Supersymmetry
   - Partial compositeness
2. $B \to K^*\mu^+\mu^-$
   - Global analyses
   - New physics?

Partial compositeness

- Solving the hierarchy problem without SUSY: the Higgs is composite
- Successful theory of flavour requires quarks to be partially composite

$$\mathcal{L} \supset \lambda_L \bar{\psi}_L \mathcal{O}_R + \lambda_R \bar{\psi}_R \mathcal{O}_L$$



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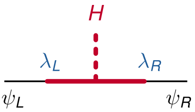
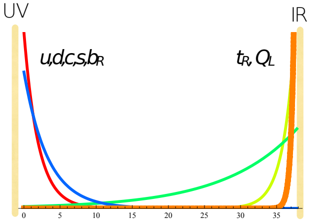


Related by AdS/CFT to models with a warped extra dimension

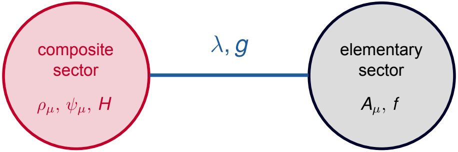


[A. Weiler]

The two-site picture

[Contino et al. hep-ph/0612180]

A simple 4D theory realizing the partial compositeness paradigm

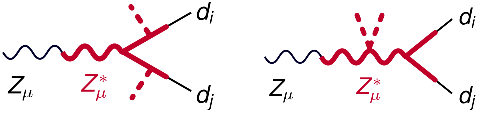


$$\mathcal{L}_s = -\bar{Q}_L\, m_Q\, Q_R - \bar{U}_L\, m_U\, U_R - \bar{D}_L\, m_D\, D_R$$
$$+\bar{Q}_L \mathcal{H}\, Y_U\, U_R + \bar{Q}_L \mathcal{H}\, Y_D\, D_R + \text{h.c}$$
$$\mathcal{L}_{\text{mix}} = \lambda_L\, \bar{q}_L Q_R + \lambda_{Ru}\, \bar{U}_L u_R + \lambda_{Rd}\, \bar{D}_L d_R$$

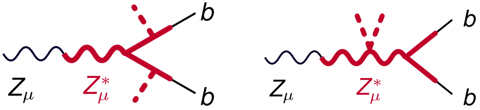
$$q^{\text{phys}} = c_L\, q + s_L\, Q \qquad \frac{s_L}{c_L} = \frac{\lambda_L}{m_Q} \qquad m_{q^{\text{phys}}} = \frac{v}{\sqrt{2}} Y\, s_L\, s_R \qquad \text{etc.}$$

Z penguins from partial compositeness

After EWSB, composite-elementary mixing leads to correlated tree-level contributions to flavour-changing Z couplings . . .



. . . and $Z \to b\bar{b}$



Numerical analysis of Z penguins in 3 models

- Two choices for the fermion content (irreps of $SU(2)_L \times SU(2)_R \times U(1)_X$) to protect T parameter and $Z \to b\bar{b}$
  - $(2,2)_{2/3} + (2,2)_{-1/3} + (1,1)_{2/3} + (1,1)_{-1/3}$ (“**bidoublet** model”)
  - $(2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$ (“**triplet** model”)
- Two choices for the flavour structure
  - flavour **anarchy**
  - $\boldsymbol{U(2)^3}$ flavour symmetry

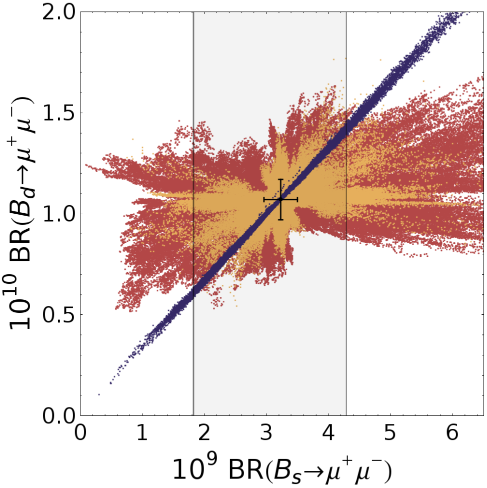
see [Barbieri et al. 1203.4218, Barbieri et al. 1211.5085, Straub 1302.4651] and ref. therein

Pattern of flavour-changing Z couplings

- triplet model: P_{LR} forbids g_L^{ij}
- bidoublet model: P_C forbids g_R^{ij}
- $U(2)^3$ forbids g_R^{ij}

		K		$B_{d,s}$		D	
		L	R	L	R	L	R
Ⓐ	triplet		$\mathbb{C}$		$\mathbb{C}$	$\mathbb{C}$	
	bidoublet	$\mathbb{C}$		$\mathbb{C}$		$\mathbb{C}$	
$U(2)^3_{\text{LC}}$	triplet					$\mathbb{R}$	
	bidoublet	$\mathbb{R}$		$\mathbb{C}$		$\mathbb{R}$	

$B_s \to \mu\mu$ vs. $B_d \to \mu\mu$



Partial compositeness:

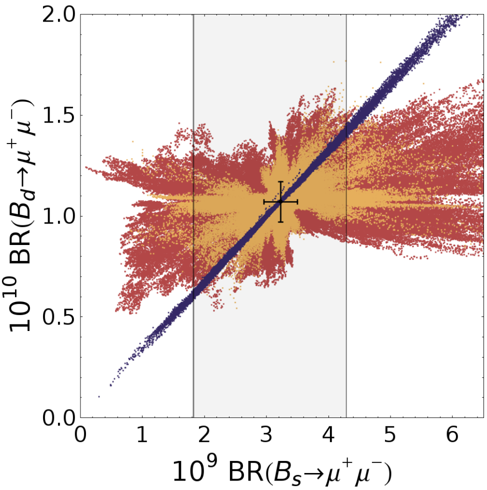
triplet + anarchy

bidoublet + anarchy

bidoublet + $U(2)^3$

[Straub 1302.4651]

$B_s \to \mu\mu$ vs. $B_d \to \mu\mu$



Partial compositeness:

triplet + anarchy

bidoublet + anarchy

bidoublet + $U(2)^3$

[Straub 1302.4651]

- Experiments *start* to probe interesting region
- MFV-like correlation in $U(2)^3$

Outline

1. $B_s \to \mu^+\mu^-$
   - Experiment vs. Standard Model
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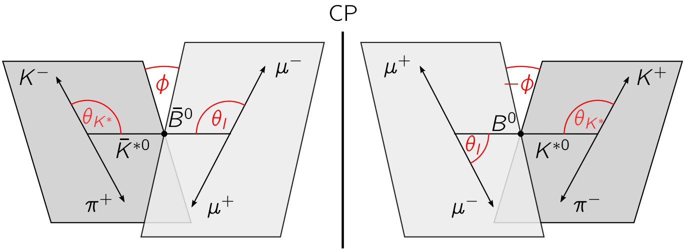
   - Global analyses
   - New physics?

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



- exclusive semi-leptonic decay probing the $b \to s$ transition
- 4-body decay: angular distribution with many observables sensitive to NP
- “self-tagging”: sensitive to CP violation

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular decay distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} \times$$
$$\Big\{ I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*}) \cos 2\theta_l$$
$$+ I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi + \left(I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*}\right) \cos\theta_l$$
$$+ I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi + I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi \Big\}$$

- Full set of observables: 12 angular coefficient functions $I_i(q^2)$

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular decay distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} \times$$
$$\Big\{ + I_2^s \sin^2\theta_{K^*}(3+\cos 2\theta_l) - I_2^c 2\cos^2\theta_{K^*}\sin^2\theta_l$$
$$+ I_3 \sin^2\theta_{K^*}\sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*}\sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_{K^*}\sin\theta_l\cos\phi + I_6 \sin^2\theta_{K^*}\cos\theta_l$$
$$+ I_7 \sin 2\theta_{K^*}\sin\theta_l\sin\phi + I_8 \sin 2\theta_{K^*}\sin 2\theta_l\sin\phi + I_9 \sin^2\theta_{K^*}\sin^2\theta_l\sin 2\phi \Big\}$$

- Full set of observables: 12 angular coefficient functions $I_i(q^2)$
- Neglecting lepton mass, scalar/tensor operators: 9 independent $I_i(q^2)$

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular decay distribution

$$\frac{d^4\bar{\Gamma}}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} \times$$
$$\Big\{ + \bar{I}_2^s \sin^2\theta_{K^*} (3 + \cos 2\theta_l) - \bar{I}_2^c 2\cos^2\theta_{K^*} \sin^2\theta_l$$
$$+ \bar{I}_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + \bar{I}_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi$$
$$- \bar{I}_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi - \bar{I}_6 \sin^2\theta_{K^*} \cos\theta_l$$
$$+ \bar{I}_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi - \bar{I}_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi - \bar{I}_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi \Big\}$$

- Full set of observables: 12 angular coefficient functions $I_i(q^2)$
- Neglecting lepton mass, scalar/tensor operators: 9 independent $I_i(q^2)$
- CP-conjugate decay: another 9 independent functions $\bar{I}_i(q^2)$

Basis of observables

- consider sums and differences of I_i, $\bar{I}_i$ to separate CP violating and CP conserving NP effects
- normalize to CP-averaged decay rate to reduce th. & exp. uncertainties

CP-averaged angular coefficients

$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2)\right) \Bigg/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

CP asymmetries

$$A_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) - \bar{I}_i^{(a)}(q^2)\right) \Bigg/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

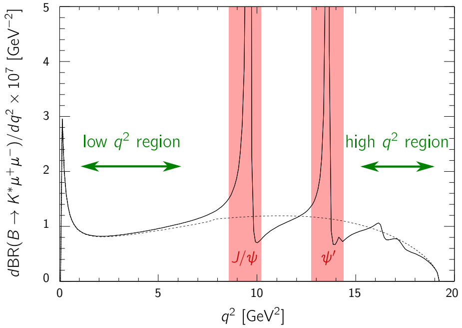
[Kruger et al. hep-ph/9907386, Bobeth et al. 0805.2525, Altmannshofer et al. 0811.1214]

Experimental status of angular observables

Observable	NP-sensitive?	measured
$d\mathrm{BR}/dq^2$	yes	Belle, BaBar, CDF, LHCb, CMS
$F_L = -S_2^c$	yes	Belle, BaBar, CDF, LHCb, ATLAS, CMS
S_3	yes	CDF, LHCb
S_4	yes	LHCb
S_5	yes	LHCb
$A_{\mathrm{FB}} = \frac{3}{4} S_6$	yes	Belle, BaBar, CDF, LHCb, ATLAS, CMS
S_7	no	LHCb
S_8	no	LHCb
S_9	no	LHCb
A_{CP}	no	CDF, LHCb
$A_{3\ldots8}$	$7, 8$	–
A_9	yes	CDF, LHCb

red = updated this year

Kinematical regions



- low $q^2 \lesssim 6$ GeV^2: expansion in m_{K^*}/E_{K^*}
- intermediate $q^2 \in [6, 15]$ GeV^2: $c\bar{c}$ resonances, $B \to K^*\psi(\to \mu^+\mu^-)$
- high $q^2 \gtrsim 15$ GeV^2: expansion in $E_{K^*}/\sqrt{q^2}$

Alternative bases of observables

To reduce theory uncertainties related to form factors, one can change the normalization of the $S_i^{(a)}$ and $A_i^{(a)}$ and find “optimized” observables for low *or* high q^2

Low q^2

$$P_4' = \frac{2\,S_4}{\sqrt{F_L(1-F_L)}}$$

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

$\dots$

[Descotes-Genon et al. 1303.5794]

High q^2

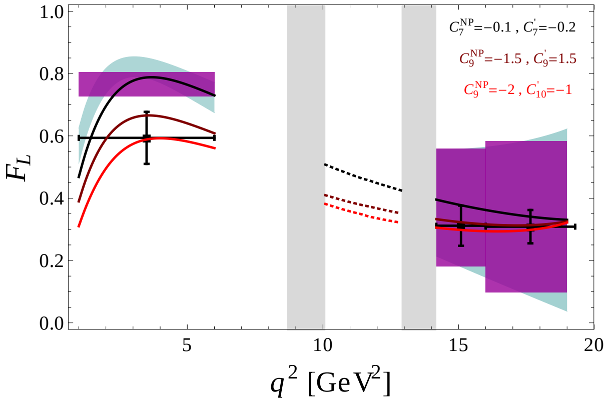
$$H_T^{(1)} = \frac{2\,S_4}{\sqrt{F_L(1-F_L-S_3)}}$$

$$H_T^{(2)} = \frac{S_5}{\sqrt{F_L(1-F_L+S_3)}}$$

$\dots$

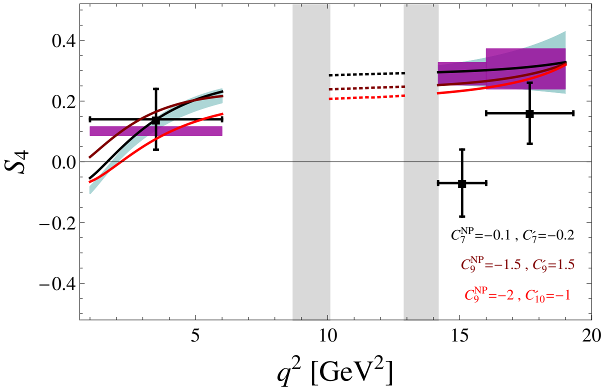
[Bobeth et al. 1006.5013]

SM vs. data: F_L [Altmannshofer and DS 1308.1501]



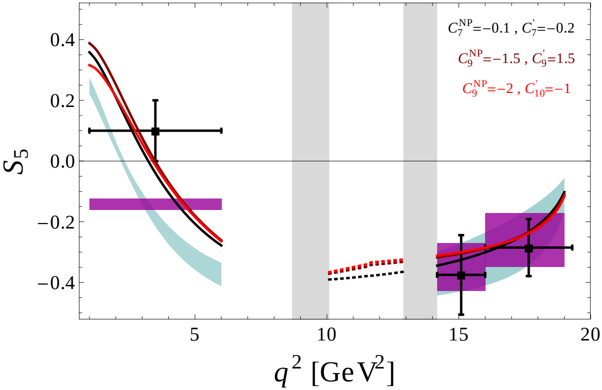
1.9σ tension at low q^2

SM vs. data: S_4 [Altmannshofer and DS 1308.1501]



2.8σ tension at high q^2

SM vs. data: S_5 [Altmannshofer and DS 1308.1501]



2.4σ tension at low q^2

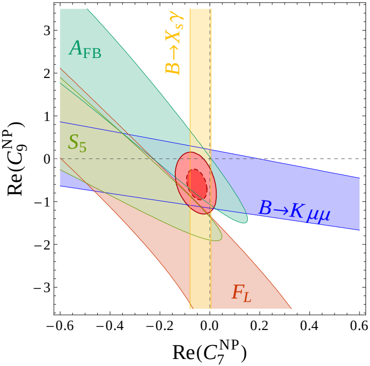
Global analysis of $b \to s$ transitions

$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu} \quad O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell) \quad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

- $b \to s$ operators contribute to many observables measured by B factories and/or at LHC
- global analysis necessary

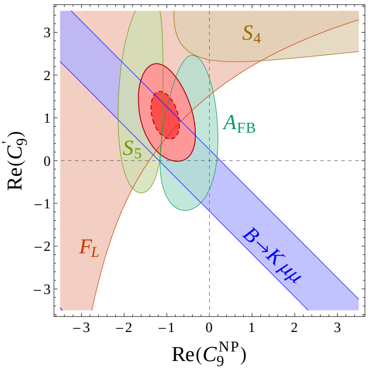
Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
$B \to X_s\gamma$	X		
$B \to K^*\gamma$	X		
$B \to X_s\mu^+\mu^-$	X	X	X
$B \to K\mu^+\mu^-$	X	X	X
$B \to K^*\mu^+\mu^-$	X	X	X
$B_s \to \mu^+\mu^-$			X

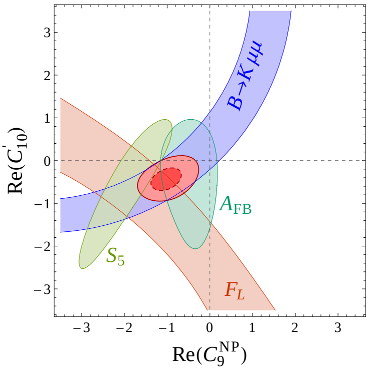
Fitting C_7 and C_9



- Although the S_5 and F_L tensions could be solved with NP in C_7 or C_9 only, this is strongly disfavoured by the bounds from BR($B \to X_s\gamma$) and BR($B \to K\mu^+\mu^-$), respectively

Fitting C_9 and $C'_{9,10}$





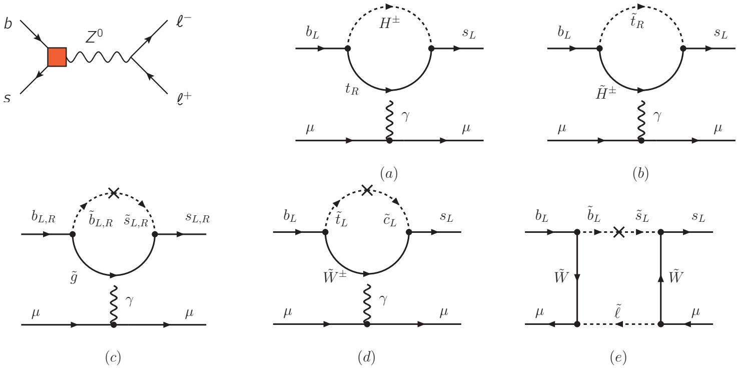
Fit results and $\Delta\chi^2$

Scenario	C_7^{NP}	C_7'	C_9^{NP}	C_9'	C_{10}'	$\Delta\chi^2(\text{SM})$
(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	$+0.7$	-0.2	**10.8**

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

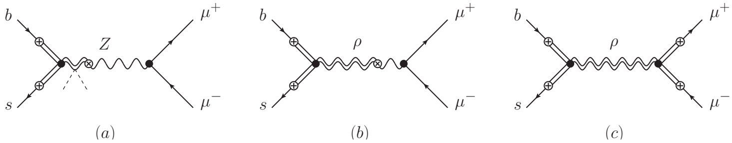
- There is a tension in some angular observables $B \to K^*\mu^+\mu^-$ that could be due to new physics (or statistical fluctuation, or underestimated theory errors)
- If due to NP, it requires a simultaneous contribution to the Wilson coefficients C_9 and C_9' in order not to violate constraints from other processes
- Which actual NP model could explain such an effect?

1st try: MSSM



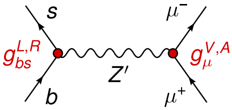
By systematically studying all relevant contributions, one can show that the effect in C_9 and C_9' is negligible throughout the MSSM parameter space, in particular once LHC direct bounds and other flavour constraints (B_s mixing) taken into account

2nd try: partial compositeness



- $C_9^{(\prime)}$ are generated at tree level from vector resonance exchange
- also here, contributions numerically negligible

Solving the anomaly with a Z' boson

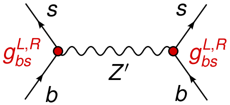


$$\mathcal{L} \supset \frac{g_2}{2c_W}\left[\bar{s}\gamma^\mu(g_{bs}^L P_L + g_{bs}^R P_R)b + \bar{\mu}\gamma^\mu(g_\mu^V + \gamma_5 g_\mu^A)\mu\right]Z'_\mu\,,$$

$$\left\{C_9^{\text{NP}}, C_9'\right\} \propto \frac{m_Z^2}{m_{Z'}^2}\left\{(g_{bs}^L)(g_\mu^V), (g_{bs}^R)(g_\mu^V)\right\}$$

[Descotes-Genon et al. 1307.5683, Altmannshofer and DS 1308.1501, Gauld et al. 1308.1959, Buras and Girrbach 1309.2466, Gauld et al. 1310.1082, Buras et al. 1311.6729]

Simultaneous contribution to B_s mixing



$$\frac{\Delta M_s}{\Delta M_s^{\text{SM}}} - 1 \propto \frac{m_Z^2}{m_{Z'}^2}\left[(g_{bs}^L)^2 + (g_{bs}^R)^2 - 9.7(g_{bs}^L)(g_{bs}^R)\right]$$

- The requirement to solve the $B \to K^*\mu\mu$ anomaly + the ΔM_s constraint lead to an upper bound on $M_{Z'}$:

$$C_9^{\text{NP}} = -1,\, C_9' = 1 \quad \Rightarrow M_{Z'} < g_\mu^V \times 0.9\,\text{TeV}$$

$$C_9^{\text{NP}} = -1.5 \quad \Rightarrow M_{Z'} < g_\mu^V \times 2.0\,\text{TeV}$$

Conclusions

1. $B_s \to \mu^+\mu^-$ closing in on the SM
    - Not there yet! After several improvements, theory unc. well below exp.; exp. still statistics dominated
    - Implications for SUSY: large $\tan\beta$ with light Higgses disfavoured
    - Implications for partial compositeness: starts to probe the parameter space
2. $B \to K^*\mu^+\mu^-$ showing a few tensions with the SM
    - If due to NP, requires contribution to C_9 and C_9'
    - Impossible to explain in SUSY or partial compositeness
    - Only known explanation: light flavour-changing Z'