Searching for New Physics with B Mesons

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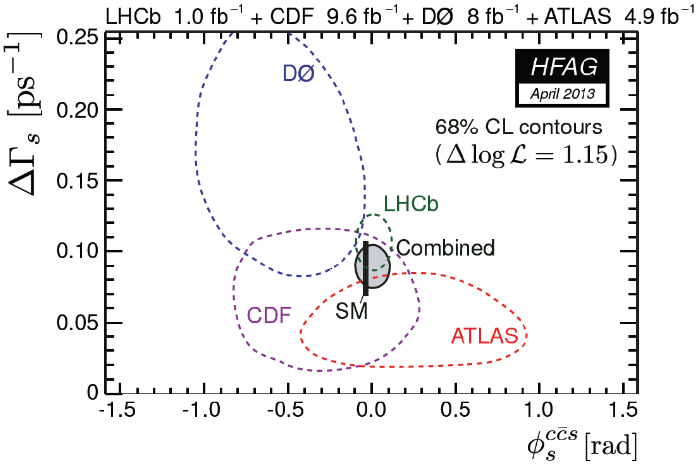
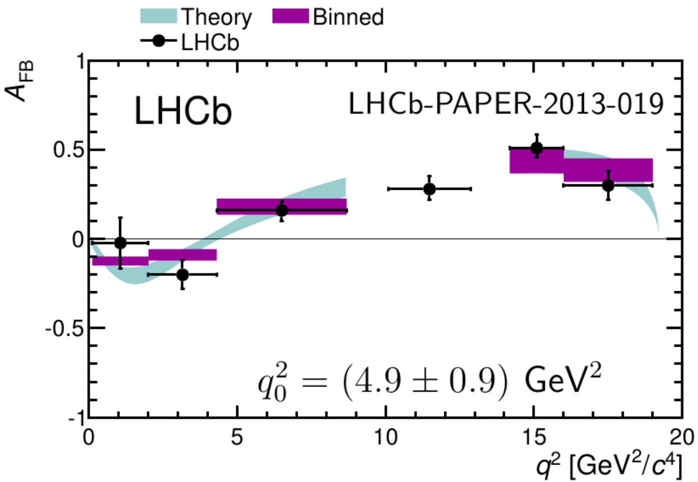
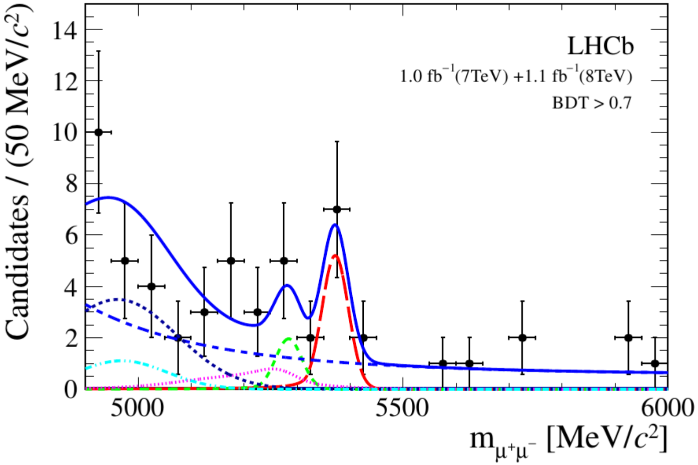
Strong Constraints on CP Violation in B_s Mixing



Forward Backward Asymmetry in $B \to K^*\mu^+\mu^-$



First Evidence for $B_s \to \mu^+\mu^-$



No Sign of New Physics Yet...

It's not the End, it's the Beginning

- Spectacular effects in processes like
  B_s mixing, $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \mu^+\mu^-$, etc.
  are excluded...

  ...but in many cases NP contributions of O(50%) are starting to be probed only now

- many B physics observables can be predicted with high accuracy in the SM

$\rightarrow$ even modest NP contributions can be identified

- in the absence of any direct sign of NP at the LHC, indirect probes of NP are more important than ever

Discussed in this Talk

$b \to s\gamma$

$b \to s\ell^+\ell^-$

$B_s \to \mu^+\mu^-$

$B_d \to \mu^+\mu^-$

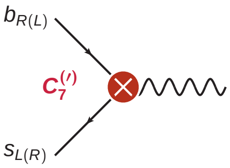
$b \to s\nu\bar{\nu}$

$B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$

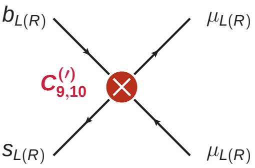
Radiative and Semi-Leptonic B Decays

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

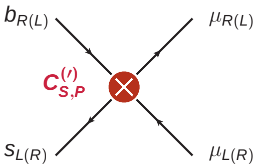
magnetic dipole operators



semileptonic operators



scalar operators

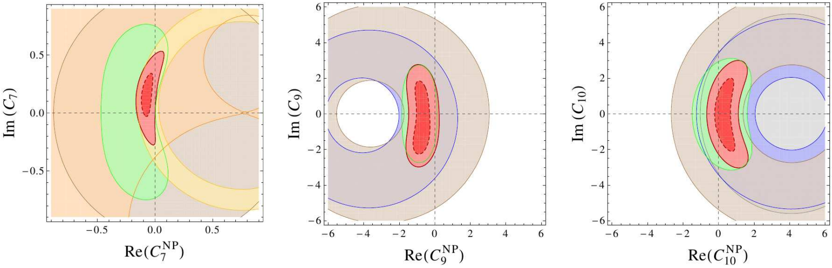


	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'	C_S, C_S', C_P, C_P'
$B \to (X_s, K^*)\, \gamma$	★			
$B \to (X_s, K, K^*)\, \ell^+\ell^-$	★	★	★	(★)
$B_s \to \mu^+\mu^-$			★	★

neglecting tensor operators

Model-Independent Constraints on New Physics

WA, Straub ’12 (see also Beaujean, Bobeth, van Dyk, Wacker ’12; Descotes-Genon et al. ’12; ...)



$B_s \to \mu^+\mu^-$

$B \to X_s \ell^+\ell^-$

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

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

$B \to X_s\gamma$ (BR)

$B \to X_s\gamma$ ($A_{\rm CP}$)

$B \to K^*\gamma$

- data shows good agreement with SM: $\chi^2_{\rm SM}/N_{\rm dof} = 20.9/24$
- complementary information on RH currents from the different exclusive decays
- imaginary parts less constrained $\to$ need to measure T-odd CP asymmetries

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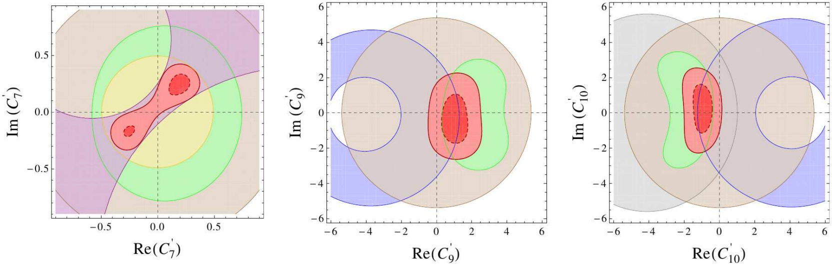

$B_s \to \mu^+\mu^-$

$B \to X_s \ell^+\ell^-$

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

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

$B \to X_s\gamma$ (BR)

$B \to X_s\gamma$ (A_{CP})

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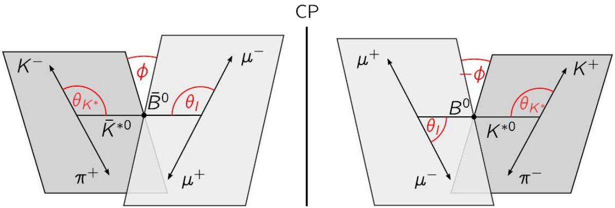


normalized 4-fold differential decay distributions

$$\frac{32\pi}{9} \frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} \Big/ \left(\frac{d(\Gamma+\bar{\Gamma})}{dq^2}\right)$$

$$= S_1^s \sin^2\theta_{K^*} + S_1^c \cos^2\theta_{K^*} + (S_2^s \sin^2\theta_{K^*} + S_2^c \cos^2\theta_{K^*}) \cos 2\theta_\ell$$
$$+ S_3 \sin^2\theta_{K^*} \sin^2\theta_\ell \cos 2\phi + S_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos\phi$$
$$- S_5 \sin 2\theta_{K^*} \sin\theta_\ell \cos\phi - (S_6^s \sin^2\theta_{K^*} + S_6^c \cos^2\theta_{K^*}) \cos\theta_\ell$$
$$+ A_7 \sin 2\theta_{K^*} \sin\theta_\ell \sin\phi$$
$$- A_8 \sin 2\theta_{K^*} \sin 2\theta_\ell \sin\phi - A_9 \sin^2\theta_{K^*} \sin^2\theta_\ell \sin 2\phi$$

example: impact of dipole operators $C_7 m_b (\bar{s}_L (\sigma F) b_R)$, $C_7' m_b (\bar{s}_R (\sigma F) b_L)$

	$q_0^2(S_4)$	$q_0^2(S_5)$	$q_0^2(S_6^s)$	$\langle A_7 \rangle$	$\langle A_8 \rangle$	S_3	A_9
$\mathrm{Re}(C_7^{\mathrm{NP}}) > 0$	$\Downarrow$	$\Downarrow$	$\Downarrow$	–	–	–	–
$\mathrm{Re}(C_7^{\mathrm{NP}}) < 0$	$\Uparrow$	$\Uparrow$	$\Uparrow$	–	–	–	–
$\mathrm{Im}(C_7^{\mathrm{NP}}) > 0$	–	–	–	$\Downarrow$	$\Uparrow$	–	–
$\mathrm{Im}(C_7^{\mathrm{NP}}) < 0$	–	–	–	$\Uparrow$	$\Downarrow$	–	–
$\mathrm{Re}(C_7'^{\mathrm{NP}}) > 0$	$\Uparrow$	$\Downarrow$	–	–	–	$\Updownarrow$	–
$\mathrm{Re}(C_7'^{\mathrm{NP}}) < 0$	$\Downarrow$	$\Uparrow$	–	–	–	$\Updownarrow$	–
$\mathrm{Im}(C_7'^{\mathrm{NP}}) > 0$	–	–	–	$\Uparrow$	$\Uparrow$	–	$\Updownarrow$
$\mathrm{Im}(C_7'^{\mathrm{NP}}) < 0$	–	–	–	$\Downarrow$	$\Downarrow$	–	$\Updownarrow$

every operator has its own characteristic “score card”

$B \to K^* \mu + \mu^-$ has exceptional “model disrciminating power”

2 parameters

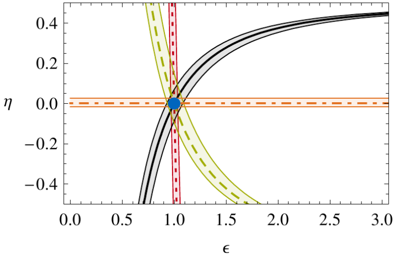
$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|C_{L,\text{SM}}^\nu|} \;,\quad \eta = \frac{\text{Re}(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

η parametrizes
RH currents in $b \to s\nu\bar{\nu}$

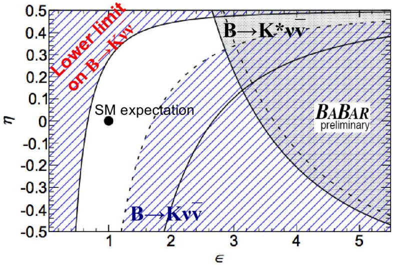
4 observables

$B(B \to X_s\nu\bar{\nu})$, $B(B \to K\nu\bar{\nu})$
$B(B \to K^*\nu\bar{\nu})$, $F_L(B \to K^*\nu\bar{\nu})$

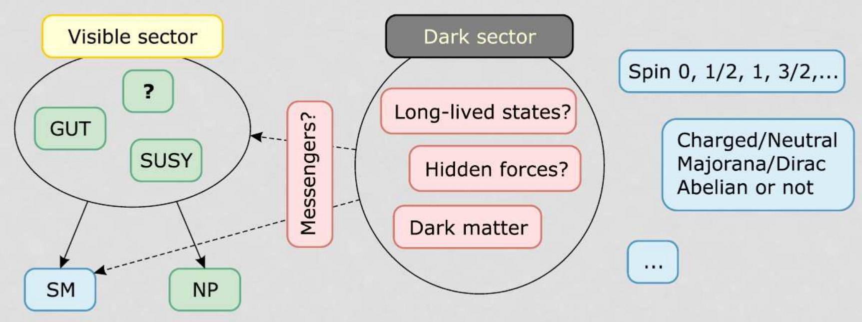
K^* polarization F_L
measures RH currents



WA, Buras, Straub, Wick ’09



$b \to s\nu\bar{\nu}$ as Portal to Dark Sectors (I)

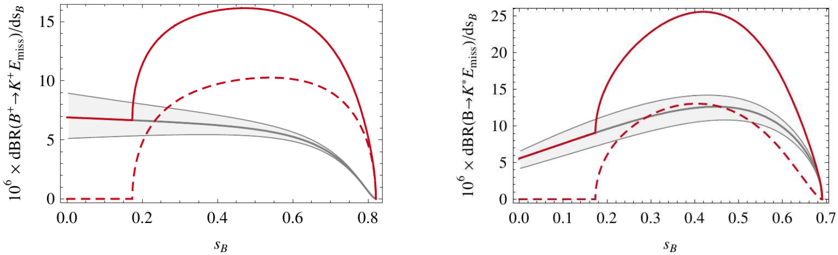


talk by Philippe Mertens, Project X Physics Study '12; Kamenik, Smith '11

- there might be new, light, and very weakly coupled states (dark matter, axions, ...)
- $b \to s\nu\bar{\nu}$ decays can provide a portal to hidden sector experimental signature: $B \to K^{(*)} + \not{E}$
- model dependent distortion the missing energy spectrum compared to $B \to K^{(*)}\nu\bar{\nu}$

concrete example:

light scalar singlet (could be dark matter)with mass $m_S = 1.1$ GeV
and flavor changing $b \to s$ coupling $(\bar{s}P_R b)\, S^2$



WA, Buras, Straub, Wick '09

$B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$

thanks to remarkable progress on the lattice,
B meson decay constants are not anymore the main uncertainty
in the SM predictions
(largest uncertainty comes now from CKM elements)

Buras, Fleischer, Girrbach, Knegjens '13

$$\text{BR}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.56 \pm 0.18) \times 10^{-9} \;, \quad \text{BR}(B_d \to \mu^+\mu^-)_{\text{SM}} = (1.03 \pm 0.07) \times 10^{-10}$$

(in addition: $\pm$ 5% uncertainty from unknown higher order electro-weak corrections)

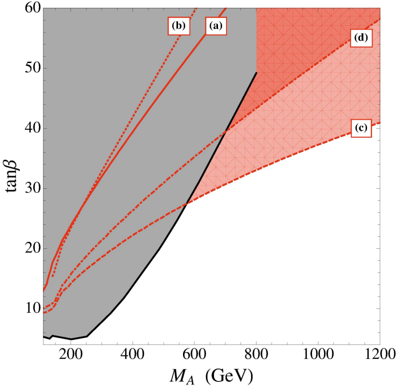
current experimental results

$$\text{BR}(B_s \to \mu^+\mu^-)_{\text{LHCb}} = (3.2^{+1.5}_{-1.2}) \times 10^{-9} \;, \quad \text{BR}(B_d \to \mu^+\mu^-)_{\text{LHCb}} < 9.4 \times 10^{-10} \text{ @ 95\% C.L.}$$

expected future experimental sensitivities before 2018

$\sim \pm 15\%$ for $B_s \to \mu^+\mu^-$, $\sim \pm 100\%$ for $B_d \to \mu^+\mu^-$

WA, Carena, Shah, Yu '12



- dominant contribution from Higgs penguins

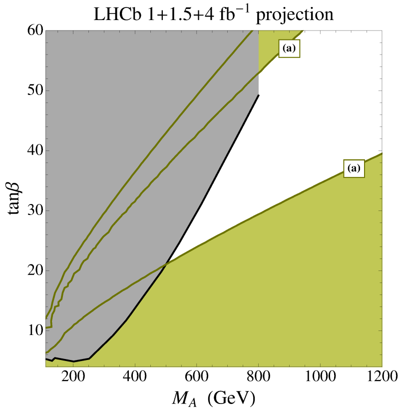
$$C_S^{\tilde{H}} \simeq -C_P^{\tilde{H}} \propto \frac{y_t^2}{16\pi^2} \frac{\mu A_t}{m_{\tilde{t}}^2} \frac{\tan\beta^3}{M_A^2} (V_{tb} V_{ts}^*)$$

- in gray: region excluded by direct $H, A \to \tau\tau$ searches
- for $\mu A_t > 0$ *destructive interference* of Higgsino loop with SM amplitude
- for $\mu A_t < 0$ *constructive interference* of Higgsino loop with SM amplitude $\to$ currently stronger constraint

———	(a)	$\mu = 1\text{TeV}, A_t > 0$	- - - - - -	(c)	$\mu = -1.5\text{TeV}, A_t > 0$
· · · · · ·	(b)	$\mu = 4\text{TeV}, A_t > 0$	- · - · - ·	(d)	$\mu = 1\text{TeV}, A_t < 0$

all squarks degenerate $\tilde{m} = 2\text{TeV}$, $|A_t|$ such that $M_h = 125\text{GeV}$

WA, Carena, Shah, Yu '12



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- for $\mu A_t > 0$ *destructive interference* of Higgsino loop with SM amplitude
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- projected LHCb sensitivity $\delta\text{BR} \sim 0.5 \times 10^{-9}$

(a) $\mu = 1\text{TeV}, A_t > 0$ (c) $\mu = -1.5\text{TeV}, A_t > 0$
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$B_s \to \mu^+\mu^-$ vs $B_d \to \mu^+\mu^-$

"Golden" MFV Relation

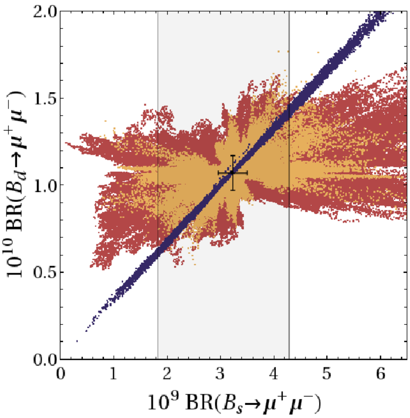
(Buras '03; Hurth, Isidori, Kamenik, Mescia '08)

$$\frac{BR(B_s \to \mu^+\mu^-)}{BR(B_d \to \mu^+\mu^-)} \simeq \frac{f_{B_s}^2}{f_{B_d}^2}\frac{\tau_{B_s}}{\tau_{B_d}}\frac{|V_{ts}|^2}{|V_{td}|^2} \simeq 32$$

- relation holds in the SM, models with MFV, and models with minimally broken $U(2)^3$ flavor symmetry
- experimental results on $B_s \to \mu^+\mu^-$ put upper and lower bounds on $BR(B_d \to \mu^+\mu^-)$

$$BR(B_d \to \mu^+\mu^-) \gtrsim 0.3 \times 10^{-10} \text{ @ 95\% C.L.}$$
$$BR(B_d \to \mu^+\mu^-) \lesssim 1.8 \times 10^{-10} \text{ @ 95\% C.L.}$$

- violation of these bounds implies sources of flavor violation beyond the CKM matrix



Straub '13:
analysis of several models
with partial compositness

More Observables in $B_s \to \mu^+\mu^-$

- full time-dependent flavor tagged decay rate

$$\Gamma(B_s(t) \to \mu^+\mu^-) \propto e^{-\Gamma_s t} \times \Big(\pm S_{\mu\mu} \sin(\Delta M_s t) + \cosh(\Gamma_s y_s t) + \mathcal{A}^{\mu\mu}_{\Delta\Gamma} \sinh(\Gamma_s y_s t) \Big)$$

- time-dependent tagged rate asymmetry

$$\frac{\Gamma(B_s(t) \to \mu^+\mu^-) - \Gamma(\bar{B}_s(t) \to \mu^+\mu^-)}{\Gamma(B_s(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s(t) \to \mu^+\mu^-)} = \frac{S_{\mu\mu} \sin(\Delta M_s t)}{\cosh(\Gamma_s y_s t) + \mathcal{A}^{\mu\mu}_{\Delta\Gamma} \sinh(\Gamma_s y_s t)}$$

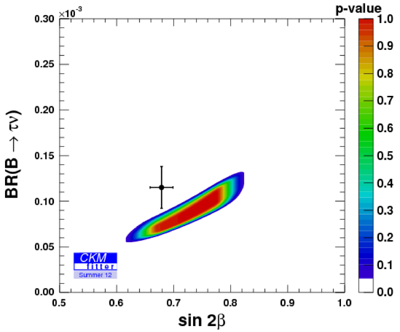
- $S_{\mu\mu}$ is sensitive to CP violation in B_s mixing and in the $B_s \to \mu^+\mu^-$ amplitude
- time dependent flavor tagged rates require *a lot* statistics

- effective lifetime measurement does not need tagging information

$$\tau_{\mu\mu} = \frac{\int_0^\infty dt \; t \, \langle \Gamma(B_s(t) \to \mu^+\mu^-) \rangle}{\int_0^\infty dt \, \langle \Gamma(B_s(t) \to \mu^+\mu^-) \rangle} = \frac{\tau_{B_s}}{1 - y_s^2} \left(\frac{1 + 2\mathcal{A}^{\mu\mu}_{\Delta\Gamma} y_s + y_s^2}{1 + \mathcal{A}^{\mu\mu}_{\Delta\Gamma} y_s} \right)$$

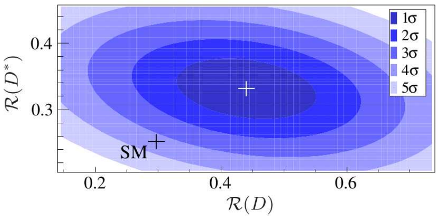
- $\mathcal{A}^{\mu\mu}_{\Delta\Gamma}$ is sensitive to CP conserving NP; BR and $\mathcal{A}^{\mu\mu}_{\Delta\Gamma}$ give complementary information

De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, Tuning '12; De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, Pellegrino, Tuning '12; Buras, Fleischer, Girrbach, Knegjens, '13



"$B \to \tau\nu$ – $\sin 2\beta$ tension"
(used to be $\sim 3\sigma$)

almost disappeared with the latest $B \to \tau\nu$ update from Belle that agrees very well with the SM prediction



new tension emerged in $B \to D^{(*)}\tau\nu$
(Babar '12)

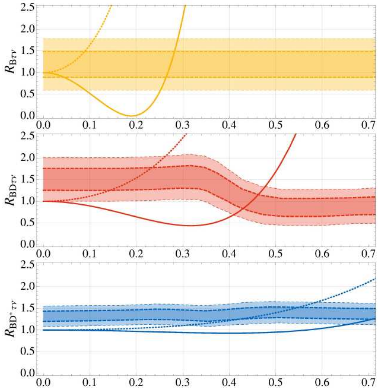
$$R(D) = \frac{\text{BR}(B \to D\tau\nu)}{\text{BR}(B \to D\ell\nu)}$$

$$R(D^*) = \frac{\text{BR}(B \to D^*\tau\nu)}{\text{BR}(B \to D^*\ell\nu)}$$

combination shows a $> 3\sigma$ discrepancy with the SM predictions

$B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$

WA, Carena, Shah, Yu '12



$$R_{B\tau\nu} = \frac{\text{BR}(B \to \tau\nu)}{\text{BR}(B \to \tau\nu)_{\text{SM}}} = \left(1 - m_{B^+}^2 X_B^2\right)^2$$

$$R_{D\tau\nu} = \frac{\text{BR}(B \to D\tau\nu)}{\text{BR}(B \to D\tau\nu)_{\text{SM}}} = \left(1 - 1.5\, m_\tau m_b X_B^2 + 1.0\, m_\tau^2 m_b^2 X_B^4\right)$$

$$R_{D^*\tau\nu} = \frac{\text{BR}(B \to D^*\tau\nu)}{\text{BR}(B \to D^*\tau\nu)_{\text{SM}}} = \left(1 - 0.12\, m_\tau m_b X_B^2 + 0.05\, m_\tau^2 m_b^2 X_B^4\right)$$

- if discrepancies are due to NP, the new states have to be fairly light ($\sim$ EW scale) and have likely flavor structures beyond MFV (e.g. Fajfer et al. '12)
- angular distributions in $B \to D^{(*)}\tau\nu$ and measurement of $B \to \pi\tau\nu$ could help to distinguish between models

Summary

- *it's not the end, it's the beginning*
- few observables left, where spectacular NP effects are still possible: e.g. $B_d \to \mu^+\mu^-$
- many processes are theoretically clean
  $\to$ improved precision can allow to identify
  even modest NP contributions
- a multitude of complementary observables is available
  $\to$ lots of *model discriminating power*
- we don't know where the NP may be hiding

$\to$ Leave No Stone Unturned!

Good Catch!

Back Up

Dimuon Charge Asymmetry

- simplest NP explanations of the dimuon charge asymmetry excluded by LHCb constraint on B_s mixing phase
- what could it be?

  NP in $B_s \to \tau^- \tau^+$?

  (e.g. Bobeth, Haisch '11)

  new light states mixing with B_s?

  (Bai, Nelson '10)

  ...

- latest results on semileptonic asymmetries are not incompatible with the D0 dimuon result ...

  ... but also consistent with the SM

$\rightarrow$ more data needed!

WA, Carena '11