Heavy flavour decays

the mundane and the exotic

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The mundane vs the exotic

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Outline

1. The mundane: precision tests of the SM
   - CKM matrix elements
   - $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing
   - Rare FCNC decays $b \to s\mu\mu$
2. Specific new physics models: constraints
   - Fourth generation of quarks
   - MFV models with charged Higgs
   - Constrained MSSM
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   - Models contributing to Γ_{12}^{s}
   - Lorentz structure of new physics
4. Concluding remarks

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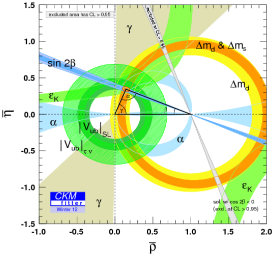
Global fits to CKM elements

CKMfitter:

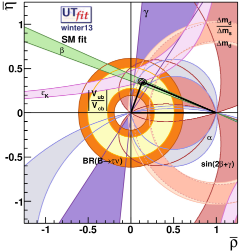


Constraints in the $\bar{\rho}$–$\bar{\eta}$ plane:

- the ratio $|V_{ub}/V_{cb}|$
- ϵ_K from $K \to \pi\pi$
- Mass differences ΔM_d and ΔM_s
- Angles α, β, γ (or ϕ_2, ϕ_1, ϕ_3) of the unitarity triangle

UTfit:

Pre-Moriond13 fits



KM paradigm
mostly vindicated !

************** Not so fast ! *************

***** Devil may be in the details ! *****

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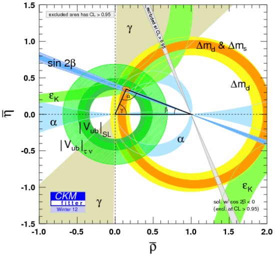

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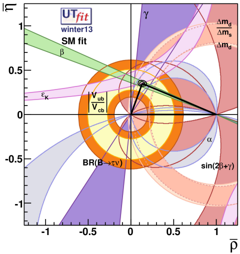

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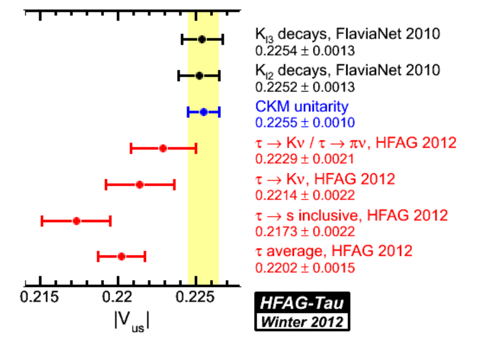
***** Devil may be in the details ! *****

Precision measurements of $|V_{us}|$

Unitarity vs. semileptonic K decays vs. hadronic τ decays

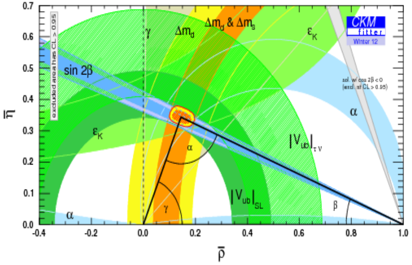
- Semileptonic K decays $\Rightarrow |V_{us}| = 0.2254 \pm 0.0013$
- Strange vs. non-strange hadronic τ decays
  $\Rightarrow |V_{us}| = 0.2202 \pm 0.0015$
- $\sim 3\sigma$ discrepancy !



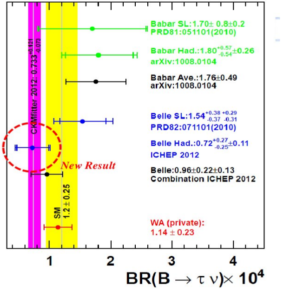
The tale of three $|V_{ub}|$'s

V_{ub}: inclusive vs. exclusive vs. leptonic

- $|V_{ub}|(\text{excl}) = (3.38 \pm 0.36) \times 10^{-3}$
- $|V_{ub}|(\text{incl}) = (4.27 \pm 0.38) \times 10^{-3}$
- $|V_{ub}|(\tau\nu) = ??$

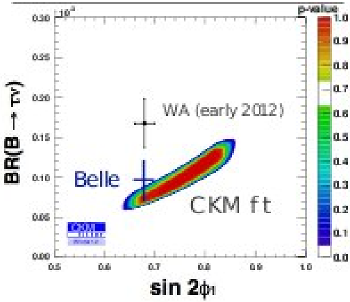


pre-Moriond13



Y. Yook, ICHEP12

Effective $|V_{ub}|$: correlation b/w $\sin 2\beta$ and $B(B \to \tau\nu)$



Before new Belle results

- Branching ratio of $B^+ \to \tau^+\nu$ too large $\Rightarrow$ enhanced V_{ub} ?
- $K \to \mu\nu$ OK with the SM. lepton-universality violation ?

After new Belle results

Seems consistent with the SM for now...

Effective $|V_{cb}|$: semileptonic $B \to D\tau\nu$ and $B \to D^*\tau\nu$

Babar 2012

$R(D) = B(B \to D\tau\nu)/B(B \to D\ell\nu)$

- SM Prediction: $R(D) = 0.297 \pm 0.017$
- Measurement: $R(D) = 0.440 \pm 0.058 \pm 0.042$
  $\Rightarrow$ 2.2σ enhancement

$R(D^*) = B(B \to D^*\tau\nu)/B(B \to D^*\ell\nu)$

- SM Prediction: $R(D) = 0.252 \pm 0.003$
- Measurement: $R(D) = 0.332 \pm 0.024 \pm 0.018$
  $\Rightarrow$ 2.7σ enhancement

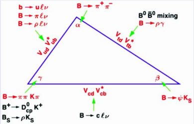
- Affect $b \to c\tau\nu$, indicate lepton-universality violation ?

Tests of unitarity

With magnitudes of elements

- $|V_{ud}| = 0.97425 \pm 00022 \quad , |V_{us}| = 0.2254 \pm 0.0013$
- Unitarity holds to one part in 10^{-3}

With unitarity angles



- The trivial unitarity relation (more a test of our calculations):

$$\alpha + \beta + \gamma = \pi$$

- The nontrivial unitarity relation:

$$\sin \beta_s = \left| \frac{V_{us}}{V_{ud}} \right|^2 \frac{\sin \beta \ \sin(\gamma + \beta_s)}{\sin(\beta + \gamma)} \left[1 + \mathcal{O}(\lambda^4)\right]$$

Aleksan et al, 1994

- We will soon be close to testing this

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Mass and width differences: theory and experiment

ΔM Measurements

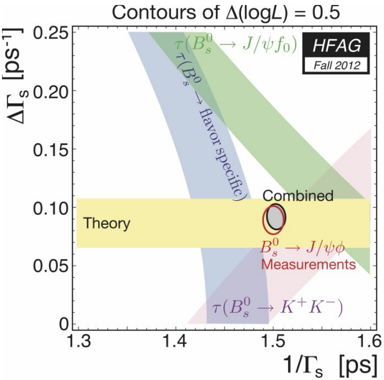
- $\Delta M_d/\Gamma_d = 0.770 \pm 0.008 \Rightarrow |V_{td}|$
- $\Delta M_s/\Gamma_s = 26.74 \pm 0.22 \Rightarrow |V_{ts}|$

$\Delta\Gamma_d$ and $\Delta\Gamma_s$: predictions and measurements

- In SM, $\Delta\Gamma_d/\Gamma_d = (42 \pm 8) \times 10^{-4}$
- Current limit: $\Delta\Gamma_d/\Gamma_d = 0.015 \pm 0.018$
  (BaBar + Delphi + Belle)

- In SM, $\Delta\Gamma_s/\Gamma_s = 0.137 \pm 0.027$
- Measurement: $\Delta\Gamma_s/\Gamma_s = 0.159 \pm 0.023$
  (mainly from $B_s \to J/\psi\phi$ at LHCb)

Lifetime difference in B_s decays



Slight tension among Γ, ΔΓ measured through

- B_s to flavor-specific modes
- $B_s \to K^+K^-, J/\psi f_0$
- $B_s \to J/\psi\phi$

The tale of two betas in B_s-$\bar{B}_s$ mixing

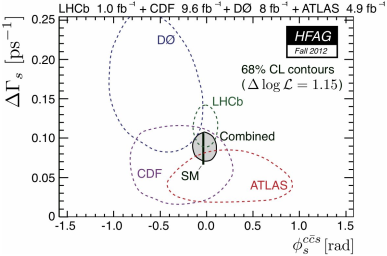
$\beta_s^{J/\psi\phi}$ from $B_s \to J/\psi\phi$

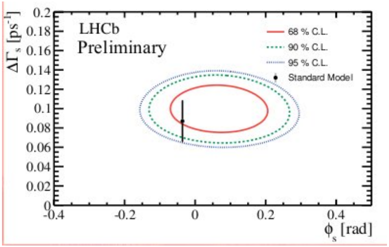
- $\beta_s^{J/\psi\phi} \approx \frac{1}{2}\mathrm{Arg}\left(-\frac{(V_{cb}V_{cs}^*)^2}{M_{12s}}\right)$
- $\beta_s^{J/\psi}(SM) = 0.019 \pm 0.001$

β_s^{sl} from a_{sl}

- $a_{sl} = (\Delta\Gamma_s/\Delta M_s)\ \tan\phi_s^{sl}$
- $\phi_s^{sl} = \mathrm{Arg}(-M_{12s}/\Gamma_{12s})$
- $\mathrm{Arg}(\Gamma_{12}) \neq \mathrm{Arg}(V_{cb}V_{cs}^*)^2$ since the (c-u) and (u-u) intermediate states contribute to Γ_{12}.
- $\phi_s^{sl}(SM) = 0.0041 \pm 0.0007$
- $\beta_s^{sl}(SM) = -0.0020 \pm 0.0003$

$\phi_s^{J/\psi\phi}$: Angular analysis of $B_s \to J/\psi\phi$

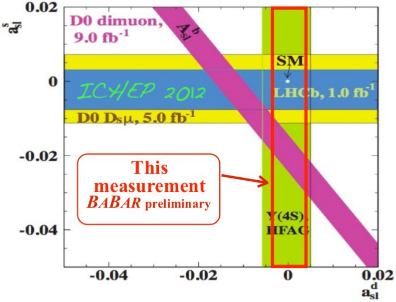


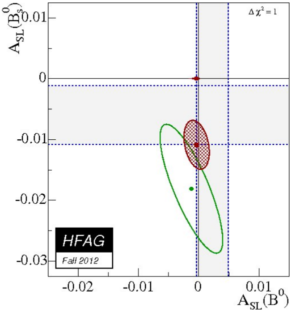


$$\phi_s = -2\beta_s^{J/\psi\phi}$$

- Results close to SM now
- Discrete ambiguity in the sign of $\Delta\Gamma$ removed.
- Enhancement in $\Delta\Gamma_s$ possible only by a few tens of percent
- Enhancement in $\beta_s^{J/\psi\phi}$ also highly restricted, but due to its small and precisely predicted SM value, measurements of deviation possible.

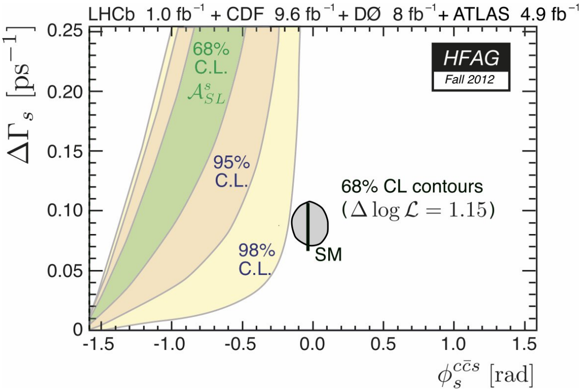
β_s^{sl}: Like-sign dimuon asymmetry





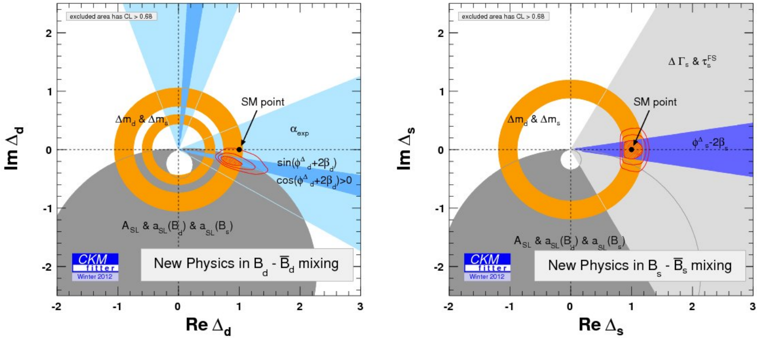
- SM $\Rightarrow A_{sl}^b = (-0.023^{+0.005}_{-0.006})\%$
- $A_{sl}^b = (-0.787 \pm 0.172 \pm 0.093)\% \Rightarrow 3.9\sigma$ deviation

A_{sl}^{s} and SM



- B_s sector: $a_{sl}^{s} = (-1.81 \pm 1.06)\%$
- $a_{sl}^{s} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s^{sl}$
- Large $\Delta\Gamma_s$ and/or large ϕ_s !

Consolidated B_d and B_s results



- $\Delta_d = \frac{M_{12d}}{M_{12d}(SM)}$, $\Delta_s = \frac{M_{12s}}{M_{12s}(SM)}$,
- $\Gamma_{12d/s}(NP) = 0$ assumed (not true in general)

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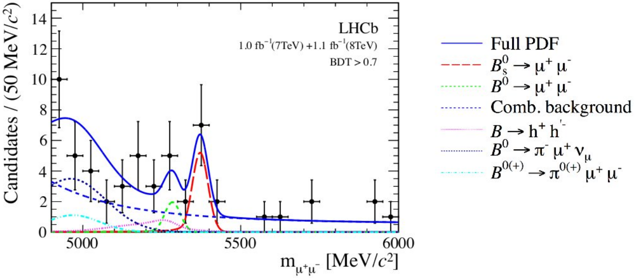
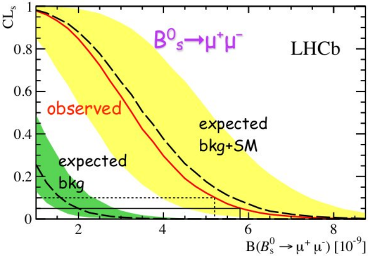
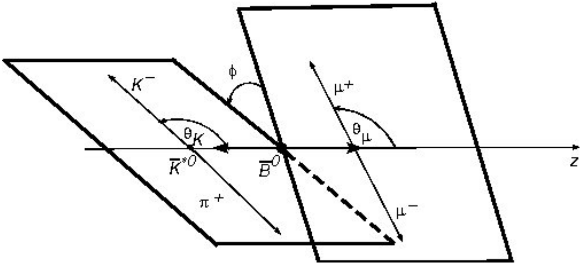
Branching ratio of $B_s \to \mu^+\mu^-$





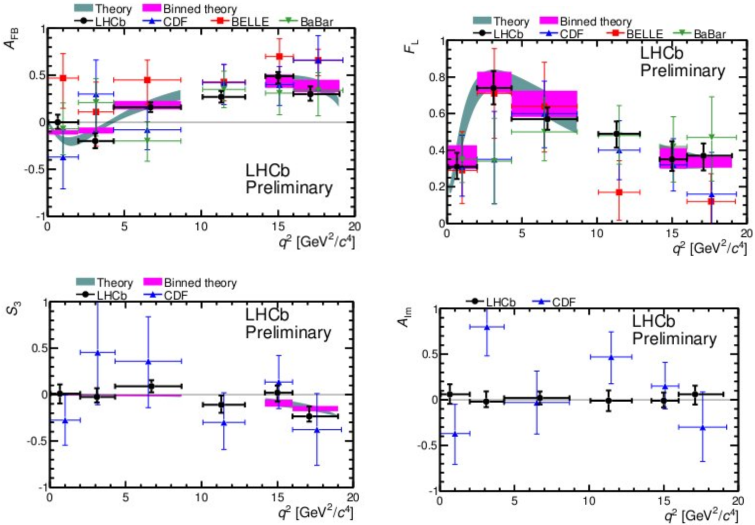
- SM: BR $= (3.2 \pm 0.2) \times 10^{-9}$
- Measurement: BR $= 3.2^{+1.5}_{-1.2} \times 10^{-9}$
- Already constraining many NP models severely

Angular variables in $B \to K^* \mu^+ \mu^-$

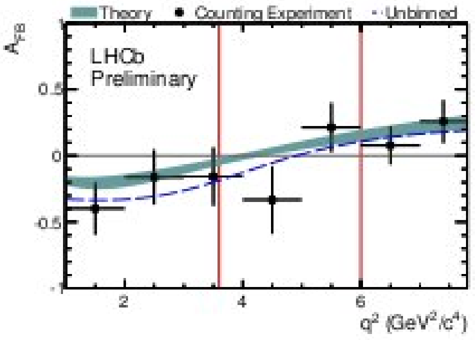


$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{16\pi}\Big[F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell-1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Big]$$

Angular asymmetries in $B \to K^* \mu^+ \mu^-$



$A_{\rm FB}$ in $B \to K^* \mu^+ \mu^-$



- From the interference between γ- and Z-penguin
- Zero of $A_{\rm FB}$ is a clean observable: the form factor dependence cancels at LO to give

$$\mathrm{Re}[C_9^{\rm eff}(q_0^2)] = -(2 m_B m_b / q_0^2)\, C_7^{\rm eff}$$

- At NLO, $q_0^2 = 3.90 \pm 0.12\ \mathrm{GeV}^2$
- Observation: $q_0^2 = 4.9^{+1.1}_{-1.3}\ \mathrm{GeV}^2$

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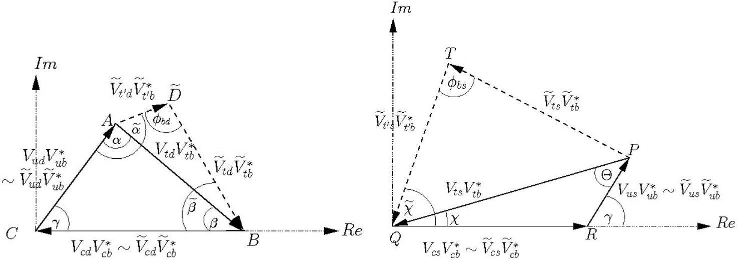
Desirability for flavor physics

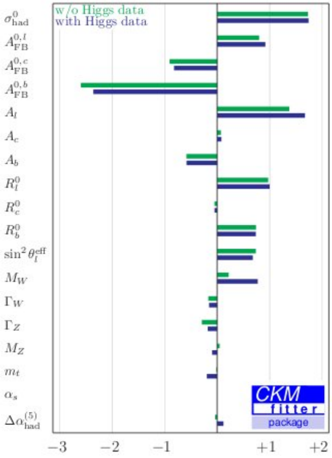
- Unitarity quadrilaterals: allow extra sources of CP violation



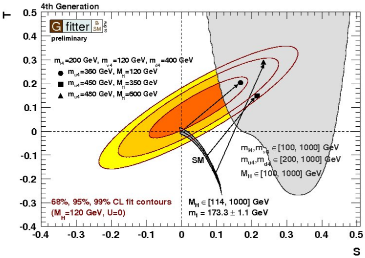
AD, CSKim, 2007; Alok, AD, Ray 2009

- Makes possible deviations in both, β and β_s ($= \chi$ in figure)
- May help in accounting for the $\sin 2\beta$ anomaly
- Predicts deviation of β_s from SM

Electroweak constraints



- Three generations give a good fit to precision data
- Fourth generation still allowed



Chanowitz, Erler, Hou, Kribs, Langacker, Soni et al

Constraints from the flavor data

Observables that impact CKM_4 in a clean manner:

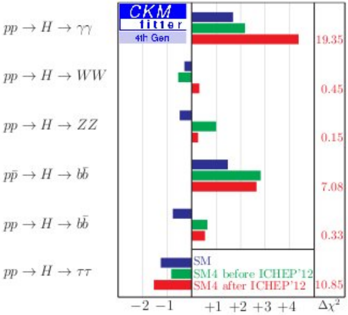
- R_{bb} and A_b from $Z \to b\bar{b}$
- ϵ_K from $K_L \to \pi\pi$
- the branching ratio of $K^+ \to \pi^+ \nu\bar{\nu}$
- the mass differences in the B_d and B_s systems
- the time-dependent CP asymmetry in $B_d \to J/\psi K_S$
- γ from tree-level decays
- the branching ratios of $B \to X_s\gamma$, $B \to X_c e\bar{\nu}$, and $B \to X_s\mu^+\mu^-$

Constraints and implications

- $|\tilde{V}_{ub'}| < 0.06$, $|\tilde{V}_{cb'}| < 0.027$, $|\tilde{V}_{tb'}| < 0.31$ at 3σ
- NP signals for B, D and rare K decays are still possible

AD, Alok, London 2011

Constraints from the Higgs data



(red numbers: decrease in χ^2 if channel is removed from the analysis)

- Data 5.3σ away from SM4
- Fourth generation in serious trouble, mainly from $H \to \gamma\gamma$

Eberhardt et al, arXiv:1209.1101

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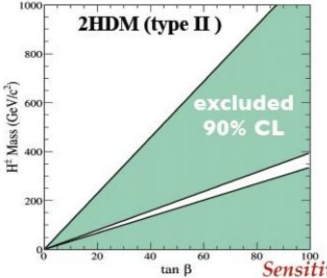
If $B \to \tau\nu$ is indeed enhanced



$$\mathcal{B}(B^+ \to \tau^+\nu) = \mathcal{B}_{\rm SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2$$

W. Hou, PRD 48, 2342 (1993)

for this plot, we use

$B_{\rm SM}(B^+ \to \tau^+ \nu) = (1.20 \pm 0.25)\times 10^{-4}$

using f_B (HPQCD), $|V_{ub}|$ (HFAG)

Note:

$\mathcal{B}_{\rm SM} = 0.83 \pm 0.08$ (UTfit)

$\mathcal{B}_{\rm SM} = 0.733^{+0.121}_{-0.073}$ (CKMfitter)

Sensitivity to H⁺ is complementary to LHC direct searches

Y. Yook, ICHEP12

- Large tan β – large M_{H^+} solution is the decoupling limit: not better than the SM.
- Only the sliver can actively account for the enhancement

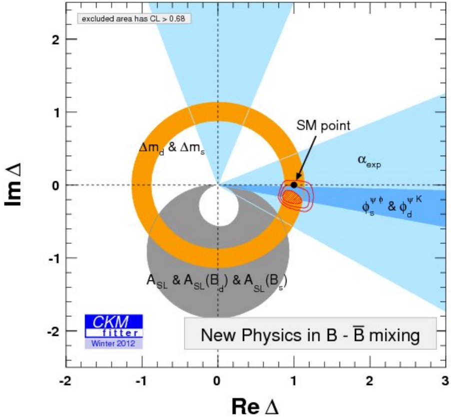
(Note: above figure with older $B \to \tau\nu$ data)

If $B \to D\tau\nu$ and $B \to D^*\tau\nu$ are also enhanced

- Type-II 2HDM cannot account for $B \to D\tau\nu$ and $B \to D^*\tau\nu$ simultaneously.
- Type-III HDM can account for $B \to D\tau\nu$ and $B \to D^*\tau\nu$ simultaneously, but not $B \to \tau\nu$ at the same time.
- With Type-III HDM, with MSSM-like Higgs potential and flavor violation in the up sector, all three measurements can be accounted for.

Crivellin, Greub, Kokulu, 2012

MFV constraints from *Bd* and *Bs* mixing



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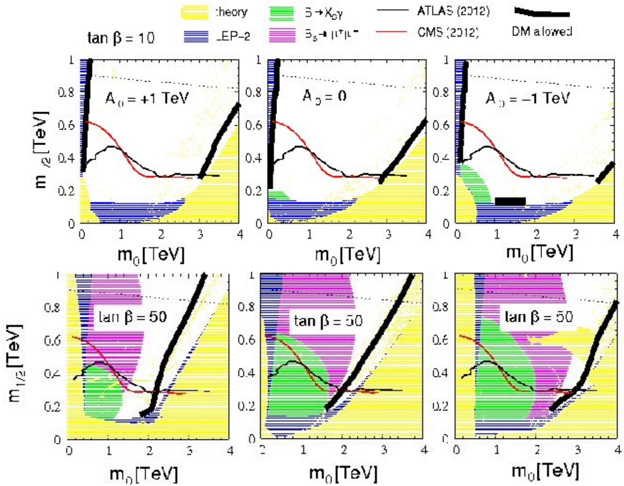
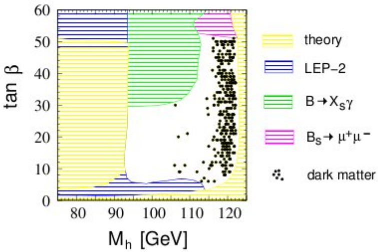
Flavour-physics limits in m_0–$m_{1/2}$ plane



- At large tan β, constraints from flavor physics become more and more stringent

Ghosh et al, 2012

Constraints in the M_h-tan β plane



- The analysis was done before the Higgs announcement
- The theoretical constraints assume $|A_0| < 1$ TeV
- With $A_0 < -5$ TeV, 125 GeV Higgs become allowed
- Flavor-physics data points towards large negative A_0

Ghosh et al, 2012

Flavor physics is now encroaching on the territory of high-energy collider physics !

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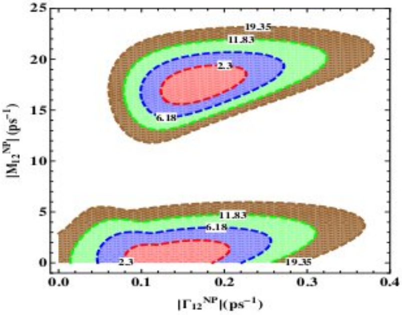
Desirability of $\Gamma_{12s}^{NP} = 0$



- $B_s \to J/\psi\phi$ and like-sign dimuon asymmetry favor different ϕ_s regions
- The tension can be reduced only with larger $\Delta\Gamma_s$
- If no NP contribution to Γ_{12s}, difficult to be consistent with data

AD, Ghosh, Kundu, Patra, 2011; AD, Ghosh, 2012

Γ_{12s}^{NP} and $b \to s\tau\tau$

- NP contributing to $b \to s\tau\tau$ can enhance $\Delta\Gamma_s$

  AD, A. Kundu, S, Nandi, 2007

- Such NP can also account for the dimuon anomaly, if it can make $B(B_s \to \tau^+\tau^-) \sim 5 - 10\%$

  AD, A. Kundu, S, Nandi, 2010

- $b \to s\tau\tau$ the only unconstrained operator that can contribute significantly to Γ_{12s}

  Bauer et al, 2010

- $B(B_s \to \tau^+\tau^-)$ is not measured yet. Is that the missing link to NP ?

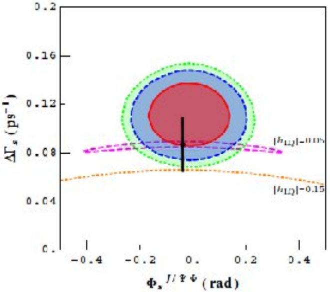
How much enhancement of $B_s \to \tau\tau$ possible ?

- Enhancement of $B_s \to \tau^+\tau^-$ (but not of $B_d \to \tau^+\tau^-$) would contribute to the difference in B_s and B_d lifetimes.
- SM predicts $|\tau_{B_s}/\tau_{B_d} - 1| \lesssim 1\%$
- Measured lifetime ratio: $\tau_{B_s}/\tau_{B_d} = 1.002 \pm 0.014 \pm 0.012$
- $B(B_s \to \tau^+\tau^-)$ up to 3.5% possible even without considering effect on other decays
- But $b \to s\tau\tau$ also enhances $B_d \to X_s\tau\tau$, which allows a cancellation, so that $B(B_s \to \tau^+\tau^-) \lesssim 15\%$ possible
- Limit from direct limit on $B^+ \to K^+\tau^+\tau^-$ easily evaded

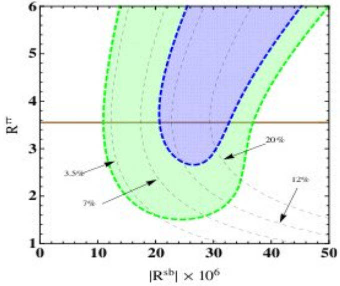
AD, Ghosh, 2012

How well do specific models work ?

Leptoquarks

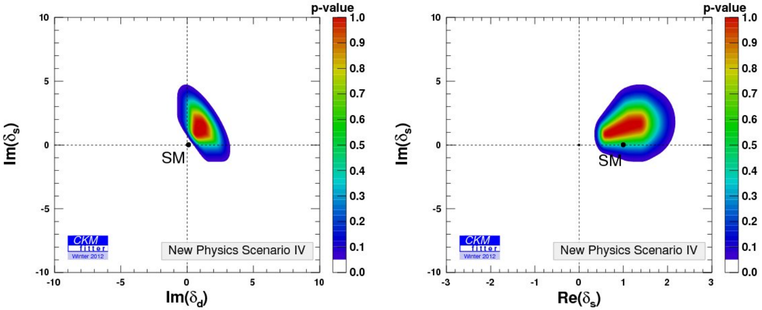


Flavor-dependent Z'



- Leptoquarks cannot enhance the BR to percent level.
- With flavor-dependent Z' model, enhancement upto 5% allowed (limits from τ_{B_s}/τ_{B_d} and $B(B^+ \to K^+\tau\tau)$)
- Perhaps NP in B_d system is also needed ? Where can it come from ?

Constraints with NP both in B_d and B_s sectors



- Defined earlier: $\Delta_d = \frac{M_{12d}}{M_{12d}(SM)}$, $\Delta_s = \frac{M_{12s}}{M_{12s}(SM)}$
- $\delta_q = \frac{(\Gamma^q_{12}/M^q_{12})}{\mathrm{Re}[(\Gamma^q_{12}/M^q_{12})]_{\mathrm{SM}}}$
- 8-dim fit: $\Delta_d, \Delta_s, \delta_d, \delta_s$
- SM disfavoured at 2.6σ

Outline

Lorentz structure of NP models

$$\mathcal{H}_{\rm eff}(b \to s\mu^+\mu^-) = \mathcal{H}_{\rm eff}^{SM} + \mathcal{H}_{\rm eff}^{VA} + \mathcal{H}_{\rm eff}^{SP} + \mathcal{H}_{\rm eff}^{T} \ ,$$

$$\begin{aligned}
\mathcal{H}_{\rm eff}^{SM} &= -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \Big\{ \sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + C_7 \frac{e}{16\pi^2} (\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R)b)\, F^{\mu\nu} \\
&\quad + C_9 \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)\, \bar{\mu}\gamma_\mu\mu + C_{10} \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)\, \bar{\mu}\gamma_\mu\gamma_5\mu \Big\} \\
\mathcal{H}_{\rm eff}^{VA} &= \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}^* V_{ts} \Big\{ R_V\, \bar{s}\gamma_\mu P_L b\, \bar{\mu}\gamma_\mu\mu + R_A\, \bar{s}\gamma_\mu P_L b\, \bar{\mu}\gamma_\mu\gamma_5\mu \\
&\qquad + R'_V\, \bar{s}\gamma_\mu P_R b\, \bar{\mu}\gamma_\mu\mu + R'_A\, \bar{s}\gamma_\mu P_R b\, \bar{\mu}\gamma_\mu\gamma_5\mu \Big\} \ , \\
\mathcal{H}_{\rm eff}^{SP} &= \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}^* V_{ts} \Big\{ R_S\, \bar{s}P_R b\, \bar{\mu}\mu + R_P\, \bar{s}P_R b\, \bar{\mu}\gamma_5\mu \\
&\qquad + R'_S\, \bar{s}P_L b\, \bar{\mu}\mu + R'_P\, \bar{s}P_L b\, \bar{\mu}\gamma_5\mu \Big\} \ , \\
\mathcal{H}_{\rm eff}^{T} &= \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}^* V_{ts} \Big\{ C_T\, \bar{s}\sigma_{\mu\nu} b\, \bar{\mu}\sigma^{\mu\nu}\mu + i C_{TE}\, \bar{s}\sigma_{\mu\nu} b\, \bar{\mu}\sigma_{\alpha\beta}\mu\, \epsilon^{\mu\nu\alpha\beta} \Big\}
\end{aligned}$$

$b \to s\mu^+\mu^-$ decay modes: inter-related observables

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

- Branching ratio

$B \to X_s\mu^+\mu^-$, $B \to \mu^+\mu^-\gamma$, $B \to K\mu^+\mu^-$

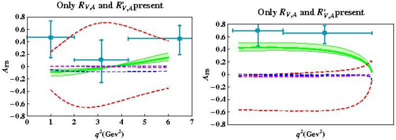
- Branching ratio, Forward-backward asymmetry A_{FB}, CP asymmetry

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

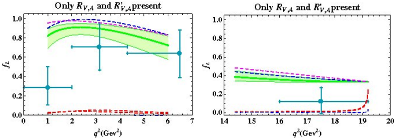
- Branching ratio, longitudinal polarization fraction f_L
- Many angular asymmetries: A_{FB}, $A_T^{(2)}$, A_{LT}
- Triple Product (TP) asymmetries: $A_T^{(im)}$, $A_{LT}^{(im)}$
- CP asymmetries for all of these

New VA operators: effect on $K^*\mu\mu$ observables

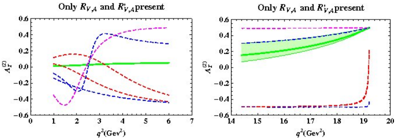
Forward-backward asymmetry



Longitudinal polarization fraction



The angular observable $A_T^{(2)}$:



Alok et al 2011

New SP operators: $B_s \to \mu^+\mu^-$ branching ratio

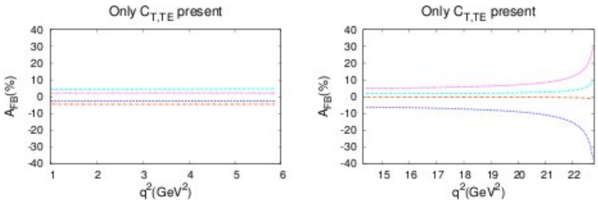
- SM: $\mathrm{BR} = (3.2 \pm 0.2) \times 10^{-9}$
- LHCb: $\mathrm{BR} = 3.2^{+1.5}_{-1.2} \times 10^{-9}$

$$B(\bar{B}_s \to \mu^+\mu^-) = \frac{G_F^2 \alpha_{em}^2 m_{B_s}^5 f_{B_s}^2 \tau_{B_s}}{64\pi^3} |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} \times \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) \left| \frac{R_S - R_S'}{m_b + m_s} \right|^2 + \left| \frac{R_P - R_P'}{m_b + m_s} + \frac{2m_\mu}{m_{B_s}^2} (C_{10} + R_A - R_A') \right|^2 \right\}.$$

$\Rightarrow$ Strong bounds on Scalar and pseudoscalar operators

$$|R_s - R_S'|^2 + |R_P - R_P'|^2 < 0.05$$

New T operators: A_{FB} in $B \to K\mu\mu$



- Zero everywhere in the SM, new VA operators do not help
- SP operators are severely bounded
- T operators can cause enhancement at high q^2
- From $B \to X_s\mu\mu$: $|C_T|^2 + 4|C_{TE}|^2 < 1.0$.
- Can enhance $A_{FB}(q^2)$ to $\sim 20\%$ for large q^2

Alok et al 2011

Outline

1. The mundane: precision tests of the SM
   - CKM matrix elements
   - $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing
   - Rare FCNC decays $b \to s\mu\mu$
2. Specific new physics models: constraints
   - Fourth generation of quarks
   - MFV models with charged Higgs
   - Constrained MSSM
3. Model-independent new-physics search
   - Models contributing to Γ_{12}^s
   - Lorentz structure of new physics
4. Concluding remarks

Concluding remarks

- B physics: a magnifying glass for testing SM
- Rare decays and precision measurements constrain specific NP models as well as indicate what classes of NP may be present
- Bounds from low-energy data getting significant enough to constrain new physics at the energy frontier
- Hints of NP in A^b_{sl}, $B \to \tau\nu$, $B \to D^{(*)}\tau\nu$:
  - Universality-breaking $b \to u\tau\nu$ / $b \to c\tau\nu$ / $b \to s\tau\tau$?
  - Indications of NP that contribute to $\Delta\Gamma_s$?
  - $B_s \to \tau\tau$ may turn out to be crucial
- Only data will tell.

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