Theoretical issues in heavy flavor physics

A biased sampling

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Lepton-Photon 2011
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Flavor physics: a wall of the SM edifice

Building up the Standard Model

- GIM mechanism ⇔ no FCNC
- CKM paradigm ⇔ three quark families
- Large B–$\overline{B}$ mixing ⇔ heavy top quark

Precision tests of the Standard Model

- CKM elements: do they explain all CP violation ?
- Rare decays: do new particles contribute through loop processes ?
- Asymmetries: are the predicted SM relations obeyed ?

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Window to New Physics beyond the SM

Puzzles that may lead directly to NP

- The $K - \pi$ puzzle: is it just matrix elements calculation ?
- Anomalous like-sign-dimuon anomaly
- $B \rightarrow \tau\nu_\tau$: loss of universality ?
- Lifetime difference and CP phase in B_s decay

Questions that may not have quick answers

- Why three generations ? *(Only three, are we sure ?)*
- Why the extreme hierarchy of masses ?
- What is the source of CP violation ?
- What about baryon asymmetry ?

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Caveats, excuses and apologies

- Mainly B decays, partly D decays, top had its own session
- Most of the data, but not all, updated till EPS 2011. Theoretical plots often use older data.
- Will focus on measurements at the border of SM and beyond, which could be a bit unfair to all those beautiful measurements that are consistent with the SM.
- Omit items that have been covered in earlier talks

  Tim Gershon, Rick van Kooten, Youngjoon Kwon, Gerhard Raven
- Apologies for inadvertant omissions

Contents

Outline

1. Standard Model calculations
   - Masses, decay constants and bag parameters
   - CKM matrix elements
   - Mass differences and width differences
2. New physics: what does the data indicate ?
   - Enhanced contribution to $\Delta\Gamma_s$
   - Fourth generation of quarks
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A typical B-decay rate calculation ($b \to s\mu\mu$)

The effective Hamiltonian: Operator Product Expansion

$$\begin{aligned}\mathcal{H}_{\text{eff}}^{SM} &= -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \Big\{ \sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + C_7 \frac{e}{16\pi^2} (\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R) b)\, F^{\mu\nu} \\ &\quad + C_9 \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)\, \bar{\mu}\gamma_\mu \mu + C_{10} \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)\, \bar{\mu}\gamma_\mu \gamma_5 \mu \Big\}\end{aligned}$$

Decay rate:

$$\Gamma(B \to f) = [\textit{phase space})] |\langle f | H_{\text{eff}}^{SM} | B \rangle|^2$$

Quantities involved:

• masses, • decay constants, • bag factors,
• Wilson coefficients, • Hadronic matrix elements (form factors),
• CKM elements

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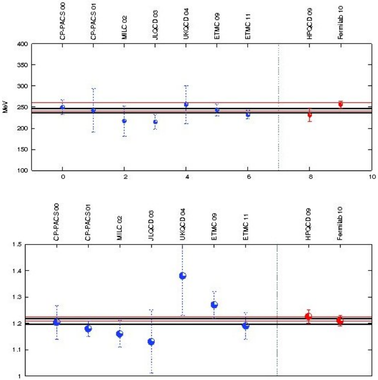
Decay constants f_B and f_{B_s}

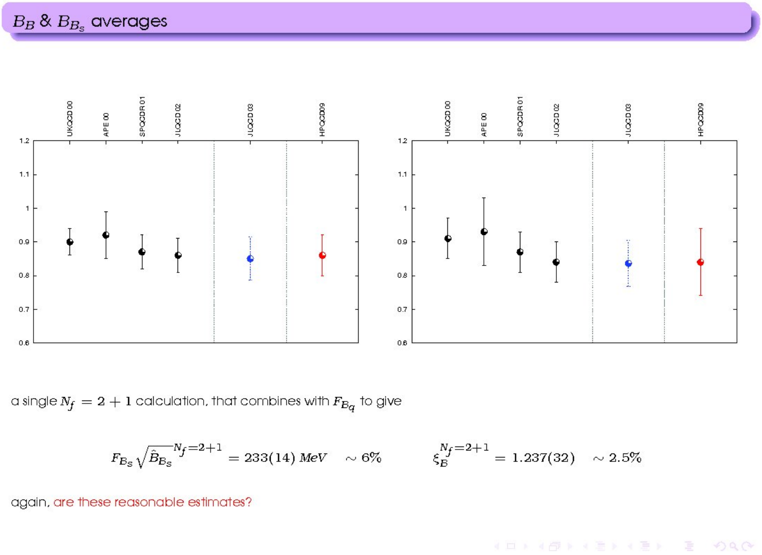


$\boxed{N_f = 2+1 \text{ results}}$

- $F_B = 205(12)$ MeV $\sim 6\%$
- $F_{B_s} = 250(12)$ MeV $\sim 5\%$
- $(F_{B_s}/F_B) = 1.215(19)$ $\sim 1.5\%$

N. Tantalo, EPS 2011

Bag parameters



B_B & B_{B_s} averages

a single $N_f = 2+1$ calculation, that combines with F_{B_q} to give

$$F_{B_s}\sqrt{\hat{B}_{B_s}}^{N_f=2+1} = 233(14)\ MeV \quad \sim 6\% \qquad \xi_B^{N_f=2+1} = 1.237(32) \quad \sim 2.5\%$$

again, are these reasonable estimates?

N. Tantalo, EPS 2011

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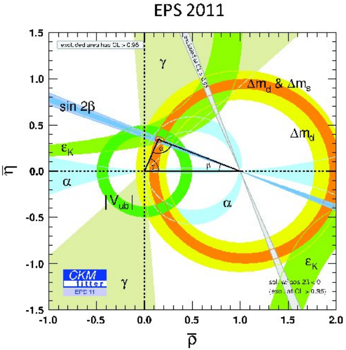
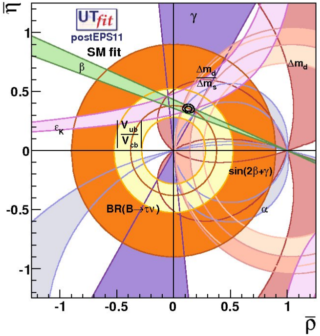
Global fits to CKM elements

CKMfitter:



UTfit:



Issues involved in CKM element determination

Measurements of individual elements

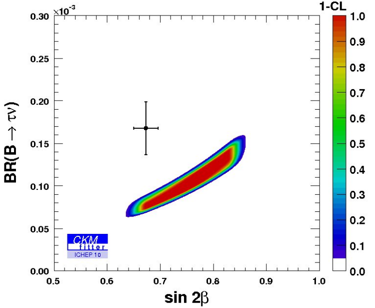
- V_{ub}: inclusive vs. exclusive vs. $B \to \tau\nu$
- V_{cs}: semileptonic K decays vs. hadronic τ decays
- V_{ts} and V_{td}: Form factors and Bag factors essential

Tests of unitarity

- 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

Measurements that may indicate NP

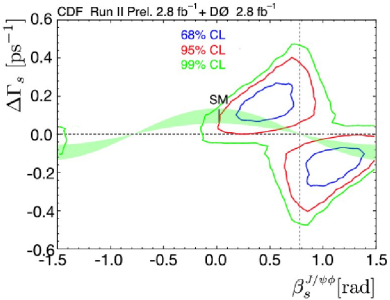
$B(B \to \tau\nu)$ and $\sin 2\beta$



$\Delta\Gamma_s$ and $\beta_s^{J/\psi\phi}$ in $B_s \to J/\psi\phi$

CDF-D0 combined fit, 2010

Update + LHCb not included



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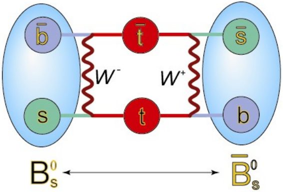
Mass difference in neutral B systems



$$
\begin{aligned}
M_{12} &= \frac{1}{2M_{B_s}}\langle \bar{B}_s|\mathcal{H}_{eff}^{\Delta B=2}|B_s\rangle \left[1+O\left(m_b^2/m_W^2\right)\right] \quad , \\
\mathcal{H}_{eff}^{\Delta B=2} &\sim G_F^2\,(V_{tb}V_{ts}^*)^2 C^Q(m_t, m_W, \mu)Q(\mu) + h.c. \\
Q &= (\bar{b}_i s_i)_{V-A}(\bar{b}_j s_j)_{V-A},
\end{aligned}
$$

ΔM Measurements

- $\Delta M_d/\Gamma_d = 0.771 \pm 0.008 \Rightarrow V_{td}$
- $\Delta M_s/\Gamma_s = 26.92 \pm 0.15 \pm 0.10 \Rightarrow V_{ts}$
- $\Delta M_D/\Gamma_D = 0.63 \pm 0.2$ (LD contributions significant)

Talk by Youngjoon Kwon

Width differences: theory and experiment

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

- $\Delta\Gamma_s/\Gamma_s = 0.137 \pm 0.027$
- $\Delta\Gamma_d/\Gamma_d = (42 \pm 8) \times 10^{-4}$ Lenz et al, 2011
- $\Delta\Gamma_d/\Delta\Gamma_s \approx |V_{td}/V_{ts}|^2 \approx 0.04$

$\Delta\Gamma_d$ measurement: possible? worthwhile?

- $\Delta\Gamma_d/\Gamma_d = 0.009 \pm 0.037$ (BaBar + Delphi)
- $\Delta\Gamma_d/\Gamma_d = 0.017 \pm 0.018 \pm 0.11$ (Belle)
- May increase upto 2.5% with new physics
- $\Delta\Gamma_d$ neglected in theoretical calculations – OK as long as the accuracy of experiments is below per cent level.

$\Delta\Gamma_D$

- Very small: not many common final states for D and $\overline{D}$ decay

$\Delta\Gamma_s$: Can new physics increase it ?

Measurement from $B_s \to J/\psi\phi$

- $\Delta\Gamma_s/\Gamma_s = 0.154^{+0.067}_{-0.065}$
- Values much larger than predictions are still allowed
  (This point will be useful soon)

NP contribution to $\Delta\Gamma_s$

- $\Delta\Gamma_q = 2\mathrm{Re}(\Gamma^*_{12} M_{12})/|M_{12}| = -2|\Gamma_{21}|_q \cos(\Theta_q - \Phi_q)$
  $\Theta_q \equiv \mathrm{Arg}(\Gamma_{21})_q, \Phi_q \equiv \mathrm{Arg}(M_{21})_q$
- $[\Theta_s - \Phi_s](\mathrm{SM}) \approx 0$
- $\Delta\Gamma_s$ can only decrease by new physics effects !!

  Grossman 1996

  Caveat: Flavor-dependent NP contributions to Γ_{12} ?
- Third generation scalar leptoquark models

  AD, Kundu, Nandi, 2007
- Left-right symmetric models

  Badin, Gabbiani, Petrov, 2007

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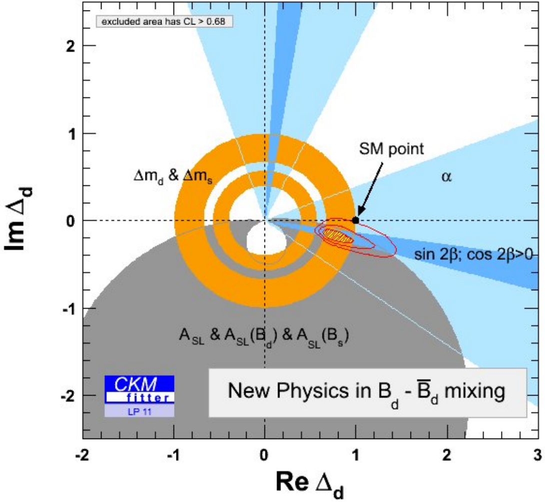
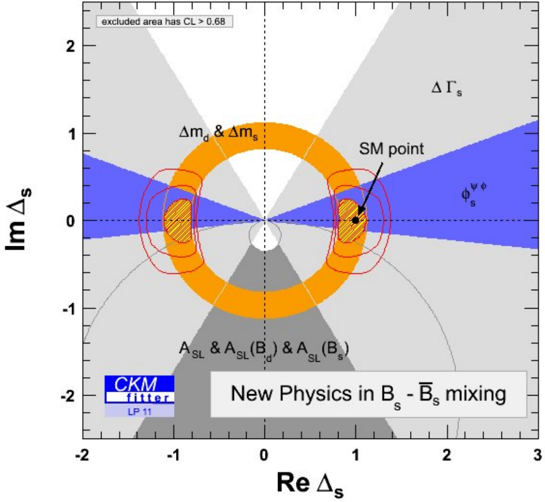
Like-sign dimuon asymmetry and $B \to J/\psi\phi$: for B_d

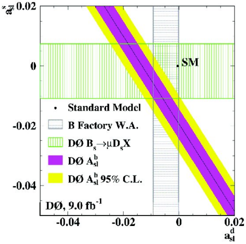


Like-sign dimuon asymmetry and $B \to J/\psi\phi$: for B_s



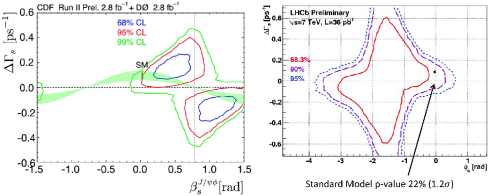
Large $\Delta\Gamma_s$ and ϕ_s indicated ?

Like-sign Dimuon asymmetry:



- SM $\Rightarrow A^b_{sl} = (-0.023^{+0.005}_{-0.006})\%$
- $A^b_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$
  $\Rightarrow 3.9\sigma$ deviation
- B_s sector: $a^s_{sl} = (-1.81 \pm 1.06)\%$
- $a^s_{sl} = (\Delta\Gamma_s/\Delta M_s)\ \tan\phi^{sl}_s$
- Large $\Delta\Gamma_s$ and/or large ϕ_s

$B_s \to J/\psi\phi$ angular analysis:



Standard Model p-value 22% (1.2σ)

- Results getting closer to SM
- Large $\Delta\Gamma_s$ and $\beta_s^{J/\psi\phi}$ still possible

The Tale of Two Betas

β from $B_s \to J/\psi\phi$

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

β 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}.
- $\phi_s^{sl}(SM) = 0.0041 \pm 0.0007$
- $\beta_s^{sl}(SM) = -0.0020 \pm 0.0003$

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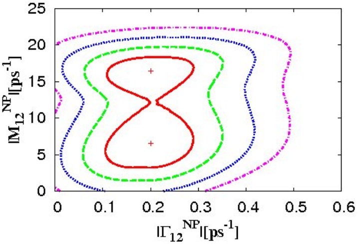
$\Gamma_{12}^{NP} = 0$ highly disfavored

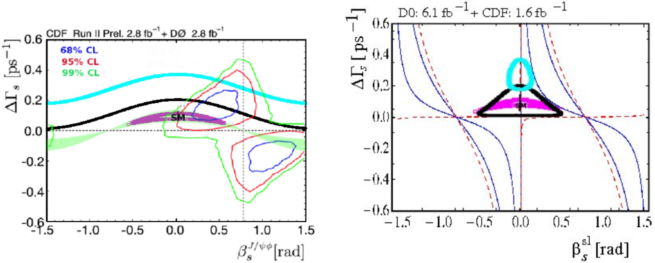


Poster by S. Patra

- $B_s \to J/\psi\phi$ and likesign dimuon asymmetry favor large ϕ_s values (especially the latter)
- Moreover, they favor different ϕ_s regions $\Rightarrow$ Tension that can be reduced only with larger $\Delta\Gamma_s$
- If no NP contribution to Γ_{12s}, difficult to be consistent with data

Implications of nonzero Γ_{12}^{NP}

Possible to go outside the “green band”:



Scalar leptoquarks that couple only to τ

AD, Kundu, Nandi, 2010

Z’, RPV SUSY

Deshpande, He, Valencia 2010

- $b \to s\tau\tau$ the only unconstrained operator Bauer et al, 2010
- Enhanced BR for $B_s \to \tau^+\tau^-$ predicted
- $BR(B_s \to \tau\tau) \sim 5\%$ still allowed

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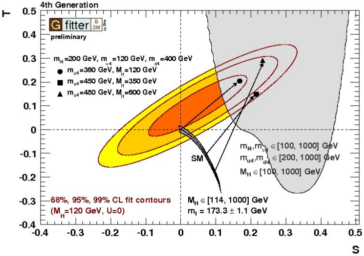
Electroweak constraints

Fourth generation still allowed with precision constraints



Electroweak constraints on fourth generation

- Masses cannot be too high, unitarity constraints
- Higgs mass and θ_{34} correlated

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 $B \to X_s\gamma$ and $B \to X_c e\bar{\nu}$
- the branching ratio of $B \to X_s\mu^+\mu^-$ in the high-q^2 and low-q^2 regions

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.

Table of Constraints from flavor data

Magnitude	SM	$m_{t'} = 400$ GeV	$m_{t'} = 600$ GeV
$\lvert\tilde{V}_{ud}\rvert$	0.9743 ± 0.0002	0.9743 ± 0.0002	0.9743 ± 0.0002
$\lvert\tilde{V}_{us}\rvert$	0.227 ± 0.001	0.227 ± 0.001	0.227 ± 0.001
$\lvert\tilde{V}_{ub}\rvert$	$(3.55 \pm 0.17) \times 10^{-3}$	$(3.90 \pm 0.38) \times 10^{-3}$	$(3.91 \pm 0.39) \times 10^{-3}$
$\lvert\tilde{V}_{ub'}\rvert$	–	0.017 ± 0.014	0.016 ± 0.018
$\lvert\tilde{V}_{cd}\rvert$	0.227 ± 0.001	0.227 ± 0.001	0.227 ± 0.001
$\lvert\tilde{V}_{cs}\rvert$	0.9743 ± 0.0002	0.9743 ± 0.0002	0.9743 ± 0.0002
$\lvert\tilde{V}_{cb}\rvert$	0.042 ± 0.001	0.041 ± 0.001	0.041 ± 0.001
$\lvert\tilde{V}_{cb'}\rvert$	–	$(8.4 \pm 6.2) \times 10^{-3}$	$(6.0 \pm 3.8) \times 10^{-3}$
$\lvert\tilde{V}_{td}\rvert$	0.0086 ± 0.0003	0.009 ± 0.002	0.009 ± 0.001
$\lvert\tilde{V}_{ts}\rvert$	0.041 ± 0.001	0.041 ± 0.001	0.040 ± 0.001
$\lvert\tilde{V}_{tb}\rvert$	1	0.998 ± 0.006	0.999 ± 0.003
$\lvert\tilde{V}_{tb'}\rvert$	–	0.07 ± 0.08	0.04 ± 0.06
$\lvert\tilde{V}_{t'd}\rvert$	–	0.01 ± 0.01	0.01 ± 0.02
$\lvert\tilde{V}_{t's}\rvert$	–	0.01 ± 0.01	0.004 ± 0.010
$\lvert\tilde{V}_{t'b}\rvert$	–	0.07 ± 0.08	0.04 ± 0.06
$\lvert\tilde{V}_{t'b'}\rvert$	–	0.998 ± 0.006	0.999 ± 0.003

Quantity	SM	$m_{t'} = 400$ GeV	$m_{t'} = 600$ GeV
$\lvert\tilde{V}_{tb}^{*}\tilde{V}_{td}\rvert$	0.0086 ± 0.0003	0.009 ± 0.002	0.009 ± 0.001
$\mathrm{Arg}(\tilde{V}_{tb}^{*}\tilde{V}_{td})$	$(-21.5 \pm 1.0)^{\circ}$	$(-30.4 \pm 10.3)^{\circ}$	$(-27.9 \pm 8.0)^{\circ}$
$\lvert\tilde{V}_{tb}^{*}\tilde{V}_{ts}\rvert$	0.041 ± 0.001	0.040 ± 0.001	0.040 ± 0.001
$\mathrm{Arg}(\tilde{V}_{tb}^{*}\tilde{V}_{ts})$	$(-178.86 \pm 0.06)^{\circ}$	$(-178.12 \pm 1.14)^{\circ}$	$(-178.12 \pm 0.57)^{\circ}$
$\lvert\tilde{V}_{t'b}^{*}\tilde{V}_{t'd}\rvert$	–	0.0010 ± 0.0015	0.0006 ± 0.0011
$\mathrm{Arg}(\tilde{V}_{t'b}^{*}\tilde{V}_{t'd})$	–	$(-107.1 \pm 106.5)^{\circ}$	$(-102.5 \pm 112.8)^{\circ}$
$\lvert\tilde{V}_{t'b}^{*}\tilde{V}_{t's}\rvert$	–	0.0005 ± 0.0010	0.0002 ± 0.0005
$\mathrm{Arg}(\tilde{V}_{t'b}^{*}\tilde{V}_{t's})$	–	$(37.8 \pm 120.3)^{\circ}$	$(40.1 \pm 174.1)^{\circ}$

Alok et al, 2011

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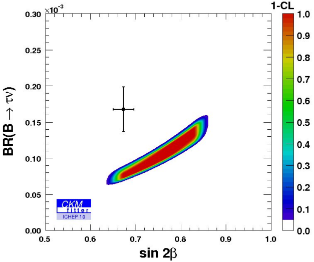
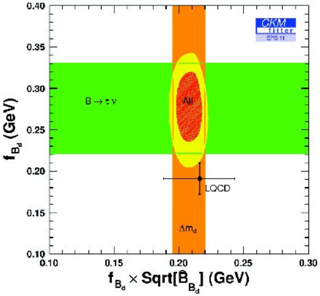
Implications of the $B \to \tau\nu$ anomaly

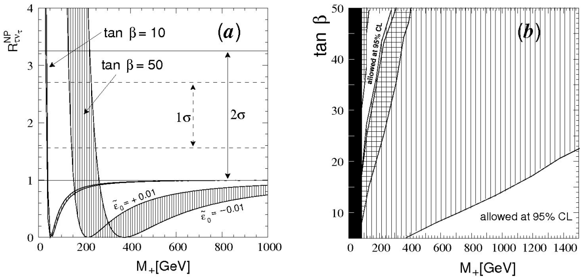




- SM: $\mathrm{BR}(B^+ \to \tau^+\nu_\tau)_{\mathrm{SM}} = (0.81 \pm 0.15) \times 10^{-4}$
- Measured: $\mathrm{BR}(B^+ \to \tau^+\nu_\tau) = (1.68 \pm 0.31) \times 10^{-4}$
- More than 2σ enhancement: difficult to explain by f_{B_d}
- New physics ? large V_{ub} ?
- But $K^+ \to \mu\nu$ looks fine. Universality violation ?
- $B \to D\tau\nu$ and $B \to D^*\tau\nu$ show similar (1.8σ) excess (See talk by Tim Gershon)

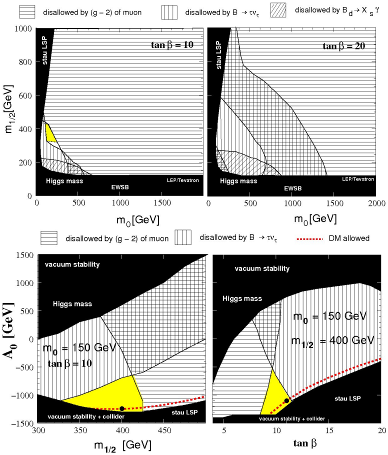
If $B \to \tau\nu$ is indeed enhanced:

$$\mathrm{BR}(B^+ \to \tau^+\nu_\tau)_{\mathrm{NP}} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2\,|\widetilde{V}_{ub}|^2\,\tau_B\left(1 - \tan^2\beta\,\frac{m_B^2}{M_+^2}\right)^2$$



- Large M_{H^+}, small $\tan\beta$ to barely survive
- Small M_{H^+}, large $\tan\beta$ to explain the anomaly

Constraints on cMSSM



- cMSSM cannot explain the anomaly
- Only a small region in parameter space survives
- This “golden” region is still consistent with neutralino dark matter !

Bhattacharjee et al, 2011

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

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4. Concluding remarks

The $K\pi$ puzzle

The puzzle

$$\Delta_{K\pi} = A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-)$$
$$= 0.121 \pm 0.022 \Rightarrow 5.5\sigma \text{ from SM} (P.Chang, EPS2011)$$

Is it just matrix element calculation ?

- C and P_{EW} corrections may be high
- QCDF: large imaginary values for C and P_{EW} amplitudes
- Evidence for large P_{EW} should have been found from $B(B^+ \to \pi K)/B(B^0 \to \pi K)$ and $B(B^+ \to \rho K)/B(B^0 \to \rho K)$; not found
- Large C $\Rightarrow$ breakdown of power-counting in SCET
  But SCET seems to hold for all other modes !
- pQCD claims that higher order corrections resolve the problem, but there is no consensus on this.

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Lorentz structure of NP models

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

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

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

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

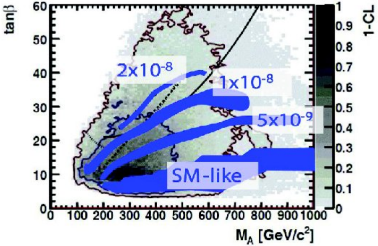
- Branching ratio, longitudinal polarization fraction f_L
- Many angular asymmetries: $A_{FB}, A_T^{(2)}, A_{LT}$
- Triple Product (TP) asymmetries: $A_T^{(im)}, A_{LT}^{(im)}$
- CP asymmetries for all of these

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

- SM: BR $= (0.32 \pm 0.02) \times 10^{-8}$
- CDF measurement: BR $= (1.8^{+1.1}_{-0.9}) \times 10^{-8}$
- CMS+LHCb limit: BR $< 1.1 \times 10^{-8}$

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

⇒ Strong bounds on Scalar and pseudoscalar operators



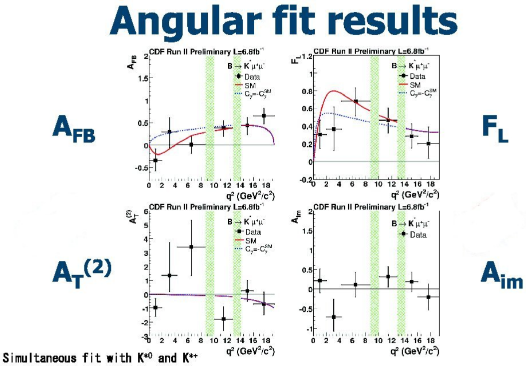
Specific model (cMSSM):

Buchmueller et al

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

CDF results:

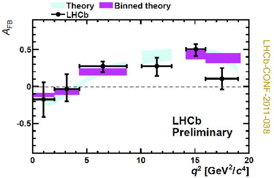
Talk by Youngjoon Kwon



Angular fit results

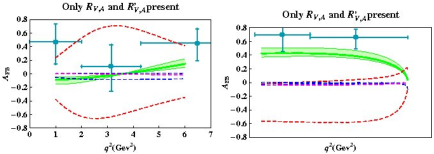
Simultaneous fit with K^{*0} and K^{*+}

LHCb measurements:

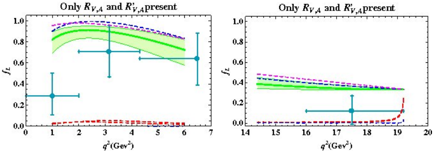


New VA operators: effect on $K^*\mu\mu$ observables

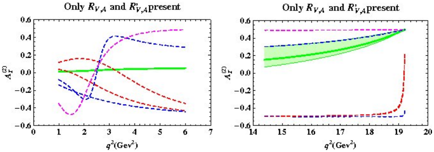
Forward-backward asymmetry



Longitudinal polarization fraction



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



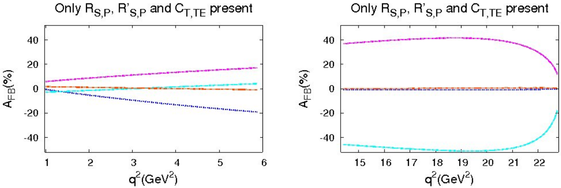
Poster by D. Ghosh

New SP and T operators

Limits (updated pre-EPS 2011):

- $|R_s - R'_S|^2 + |R_P - R'_P|^2 < 0.44$
- $|C_T|^2 + 4|C_{TE}|^2 < 1.0$

Forward-backward asymmetry in $K\mu\mu$:



- Zero in the SM
- Enhancement at low q^2: due to S, P operators
- Enhancement at high q^2: due to T operators

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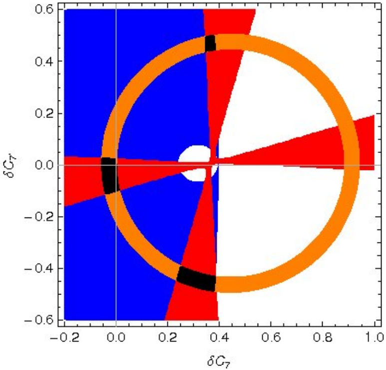
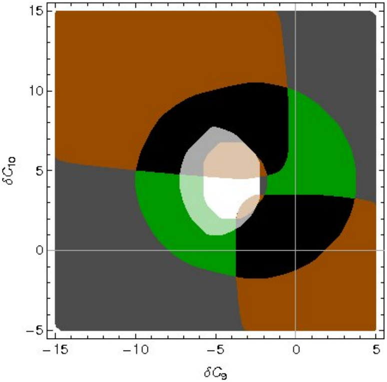
Changes in Wilson coefficients due to NP

$$\boxed{C_i O_i \to (C_i + \delta C_i) O_i}$$



A_I, $S_{K^*\gamma}$, $B \to X_s\gamma$



$B \to X_s\mu^+\mu^-$, A_{FB}, f_L

Descotes-Genon et al, 2011

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Concluding remarks

- Flavor physics: a window and a magnifying glass
- Flavor physics bounds already significant enough to constrain new physics at the energy frontier
- Hints of new physics in B_s sector: indications of NP that contribute to $\Delta\Gamma_s$? (Measure $B_s \to \tau\tau$)
- Model-independent combined analyses of multiple modes needed to get an handle on new physics
- We are at the mercy of data

The End of Flavor Physics (talk)

backup slides

Time evolution of a tagged B_q or $\bar{B}_q$ decay

$$A_f \equiv \langle f|B_q\rangle, \ \overline{A}_f \equiv \langle f|\overline{B}_q\rangle \ , \quad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

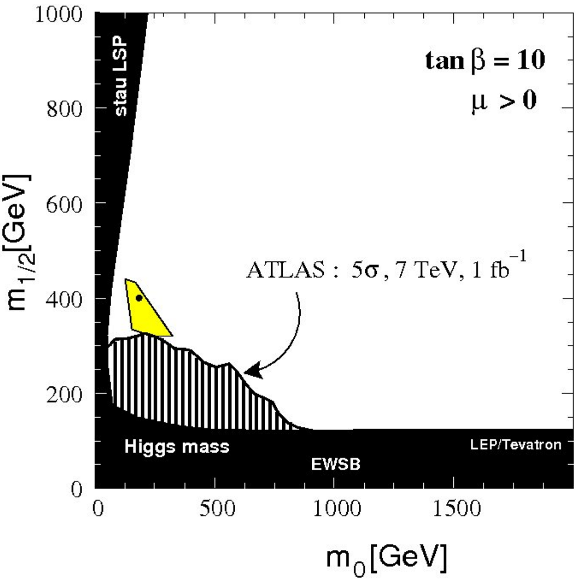
(λ_f independent of the unphysical phase φ)

$$\Gamma(B_q(t)\to f) = \mathcal{N}_f\,|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\,e^{-\Gamma t}\times$$
$$\left[\cosh\frac{\Delta\Gamma_q\,t}{2} + \mathcal{A}_{\rm CP}^{\rm dir}\,\cos(\Delta m\,t) + \mathcal{A}_{\Delta\Gamma}\,\sinh\frac{\Delta\Gamma_q\,t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\,\sin(\Delta m\,t)\right],$$

$$\Gamma(\overline{B}_q(t)\to f) = \mathcal{N}_f\,|\bar{A}_f|^2\,\frac{1+|\lambda_f|^2}{2}\,e^{-\Gamma t}\times$$
$$\left[\cosh\frac{\Delta\Gamma_q\,t}{2} - \mathcal{A}_{\rm CP}^{\rm dir}\,\cos(\Delta m\,t) + \mathcal{A}_{\Delta\Gamma}\,\sinh\frac{\Delta\Gamma_q\,t}{2} - \mathcal{A}_{\rm CP}^{\rm mix}\,\sin(\Delta m\,t)\right].$$

$$\mathcal{A}_{\rm CP}^{\rm dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad \mathcal{A}_{\rm CP}^{\rm mix} = -\frac{2\,{\rm Im}\lambda_f}{1+|\lambda_f|^2} \quad \mathcal{A}_{\Delta\Gamma} = -\frac{2\,{\rm Re}\lambda_f}{1+|\lambda_f|^2},$$

The golden region and LHC reach



Calculation of Γ_{12}

Only internal c and u quarks contribute $\Rightarrow$

$$\Gamma_{12} = \frac{1}{2M_{B_d}} < \bar{B}_d | \mathcal{I}m \, i \int d^4x \, T \mathcal{H}_{eff}^{\Delta B=1}(x) \, \mathcal{H}_{eff}^{\Delta B=1}(0) \, | B_d >$$

$$\mathcal{H}_{eff}^{\Delta B=1} \sim G_F \left(V_{ub}^* V_{ud} \sum_{i=1,2} C_i Q_i^{uu} + V_{cb}^* V_{ud} \sum_{qi=1,2} C_i Q_i^{cu} + \right.$$
$$\left. + V_{ub}^* V_{cd} \sum_{i=1,2} C_i Q_i^{uc} + V_{cb}^* V_{cd} \sum_{i=1,2} C_i Q_i^{cc} - V_{tb}^* V_{td} \sum_{i=3}^{6} C_i Q_i^{penguins} \right).$$

$$Q_1^{qq'} = (\bar{b}_i q_j)_{V-A} (\bar{q}'_j d_i)_{V-A}, \quad Q_2^{qq'} = (\bar{b}_i q_i)_{V-A} (\bar{q}'_j d_j)_{V-A},$$

$$\begin{aligned} \Gamma_{12}(B_s) &= -\mathcal{N} \times [(V_{cb}^* V_{cs})^2 f(z,z) \\ &+ (V_{cb}^* V_{cs})(V_{ub}^* V_{us}) f(z,0) + (V_{ub}^* V_{us})^2 f(0,0) \;] \end{aligned}$$