B Physics in the LHC Era: Selected Topics

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3rd Workshop on Heavy Flavour Physics
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- Setting the Stage
- Focus on two Topics:
  - Search for New Physics in $B_s \to \mu^+\mu^-$
  - Search for New Physics in $B_s \to J/\psi\phi$
- Concluding Remarks

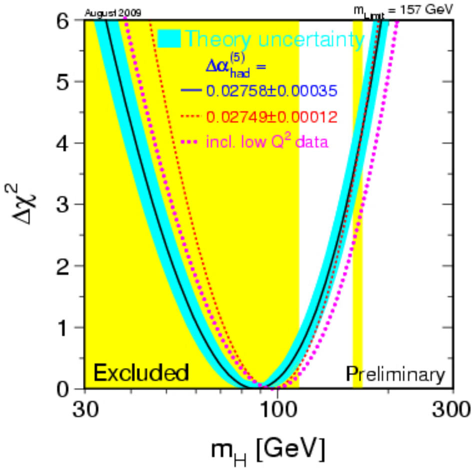
Setting the Stage

Status of the Standard Model

- The Standard Model (SM) is still very healthy:
  - Survived the era of EW precision tests in the ’90s at LEP and SLC!
  - But what causes EW symmetry breaking?
  - Higgs mechanism or an alternative?

    → SM fit $m_H = (87^{+35}_{-26})$GeV.

    CDF & DØ → ATLAS & CMS



- Quark flavour physics and CP violation:
  - Many new insights through data + theory ...
  - Still a large territory is unexplored: → LHCb
- We have indications that the SM *cannot* be complete:
  - Neutrino masses $\neq 0$: suggest see-saw mechanism, GUT scenarios ...
  - Baryon asymmetry of the Universe (SM cannot generate it ...)
  - The long-standing problem of dark matter ...

    ⊕ fundamental theoretical questions (hierarchy problem, ...)

(New) Flavour Physics: Where Do We Stand?

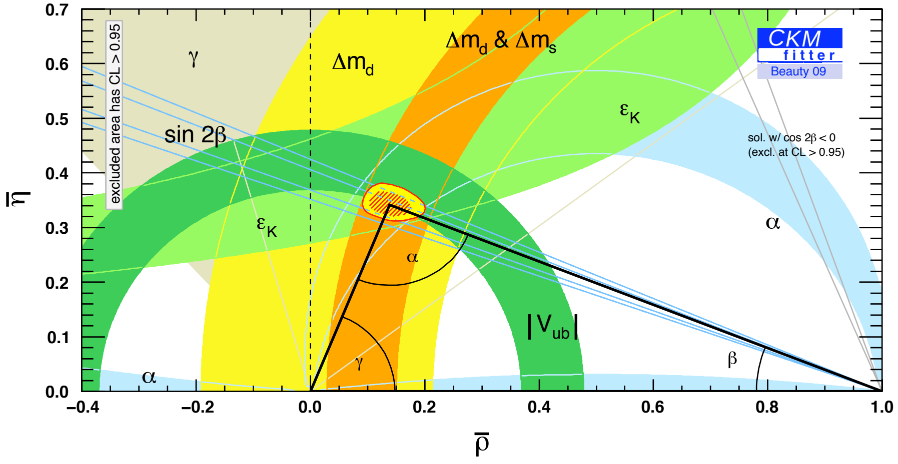
- Lessons from the B, D, K, ... data collected so far:
  - CKM matrix is the dominant source of flavour and CP violation.
  - New effects not yet established, although there are potential signals: hadronic $b \to s$ penguins, B_s^0–$\bar{B}_s^0$ mixing, $B \to \tau\nu$, $(g-2)_\mu$, ...
- Implications for the structure of New Physics:

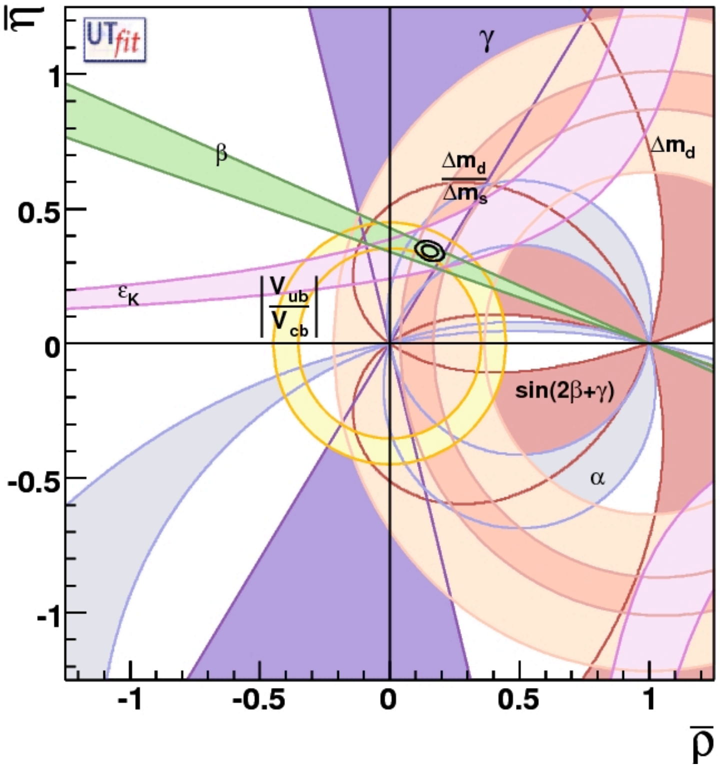
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}(\varphi_{\rm NP}, g_{\rm NP}, m_{\rm NP}, ...)$$

  - Large characteristic NP scale $\Lambda_{\rm NP}$, i.e. not just $\sim$ TeV, which would be bad news for the direct searches at ATLAS and CMS, or (and?) ...
  - Symmetries prevent large NP effects in FCNCs and the flavour sector; most prominent example: *Minimal Flavour Violation (MFV).*
- Comments:
  - MFV is still far from being experimentally established!
  - There are various non-MFV scenarios with room for sizeable effects :-) SUSY, WED, LHT, Z' models, 4th generation, ...
  - Nevertheless, we have to be prepared to deal with “smallish” NP effects :-(

Status of the Unitarity Triangle

- Continuously updated analyses: [→ talk by Marco Ciuchini]
  - *CKMfitter* Collaboration `[http://ckmfitter.in2p3.fr/]`;
  - *UTfit* Collaboration `[http://www.utfit.org]`:





The Challenge to Detect NP in Flavour Physics

- The *key problem:* strong interactions → $\boxed{\text{“hadronic” uncertainties}}$
  - The theory is formulated in terms of quarks, while flavour-physics experiments use their QCD bound states, i.e. B, D and K mesons.
  - In calculations of the relevant transition amplitudes, we encounter process-dependent, *non-perturbative “hadronic” parameters!?*

    [→ lattice QCD: lots of progress (e.g., B_K), but still a long way to go...
    → talk by Jochen Heitger]
- The B-meson system is a *particularly promising* flavour probe:
  - Simplifications through the large b-quark mass $m_b \sim 5\,\text{GeV} \gg \Lambda_{\text{QCD}}$.
  - Offers various strategies to eliminate the hadronic uncertainties and to determine the hadronic parameters from the data.
  - Tests of SM relations that could be spoiled by NP ...
- Two attractive ways for NP to manifest itself: → $\boxed{\text{FCNCs}}$
  - Contributions @ decay amplitude level to rare SM processes.
  - Contributions to B_q^0–$\bar{B}_q^0$ mixing ($q \in \{d, s\}$).

Focus on 2 Topics:

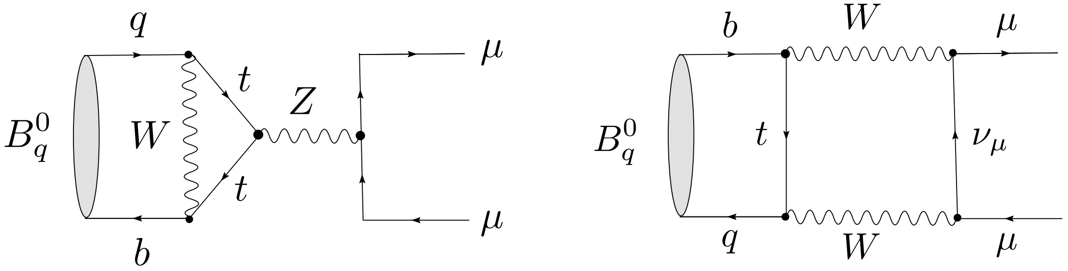
Search for New Physics

in

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

The Rare Decays $B_q \to \mu^+\mu^-$ $(q \in \{d, s\})$

- Originate from Z penguins and box diagrams in the Standard Model:



- Corresponding low-energy effective Hamiltonian: [Buchalla & Buras (1993)]

$$\mathcal{H}_{\rm eff} = -\frac{G_{\rm F}}{\sqrt{2}}\left[\frac{\alpha}{2\pi\sin^2\Theta_{\rm W}}\right] V_{tb}^* V_{tq} \eta_Y Y_0(x_t)(\bar{b}q)_{\rm V-A}(\bar{\mu}\mu)_{\rm V-A}$$

  - α: QED coupling; $\Theta_{\rm W}$: Weinberg angle.
  - η_Y: short-distance QCD corrections (calculated ...)
  - $Y_0(x_t \equiv m_t^2/M_W^2)$: "Inami–Lim function", with top-quark dependence.

- Hadronic matrix element: → very simple situation:
  - Only the matrix element $\langle 0|(\bar{b}q)_{\rm V-A}|B_q^0\rangle$ is required: f_{B_q}

$$\Rightarrow \boxed{\text{belong to the cleanest rare } B \text{ decays!}}$$

- SM predictions: [Buras ('09); lattice input: Lubicz & Tarantino ('09)]
  - Use the data for the ΔM_q to trade f_{B_q} into $\hat{B}_q$:

$$\frac{\text{BR}(B_q \to \mu^+\mu^-)}{\Delta M_q} = 4.4 \times 10^{-10} \frac{\tau_{B_q}}{\hat{B}_q} \frac{Y^2(\nu)}{S(\nu)}$$

  - Expression holds in CMFV models. Application to the SM gives:

$$\begin{aligned} \text{BR}(B_s \to \mu^+\mu^-) &= (3.6 \pm 0.4) \times 10^{-9} \\ \text{BR}(B_d \to \mu^+\mu^-) &= (1.1 \pm 0.1) \times 10^{-10} \end{aligned}$$

  - The error is dominated by the lattice result $\hat{B}_q = 1.22 \pm 0.12$.

- Most recent experimental upper bounds from the Tevatron:
  - CDF collaboration @ 95% C.L.: [CDF Public Note 9892 (2009)]

$$\text{BR}(B_s \to \mu^+\mu^-) < 4.3 \times 10^{-8}, \quad \text{BR}(B_d \to \mu^+\mu^-) < 7.6 \times 10^{-9}$$

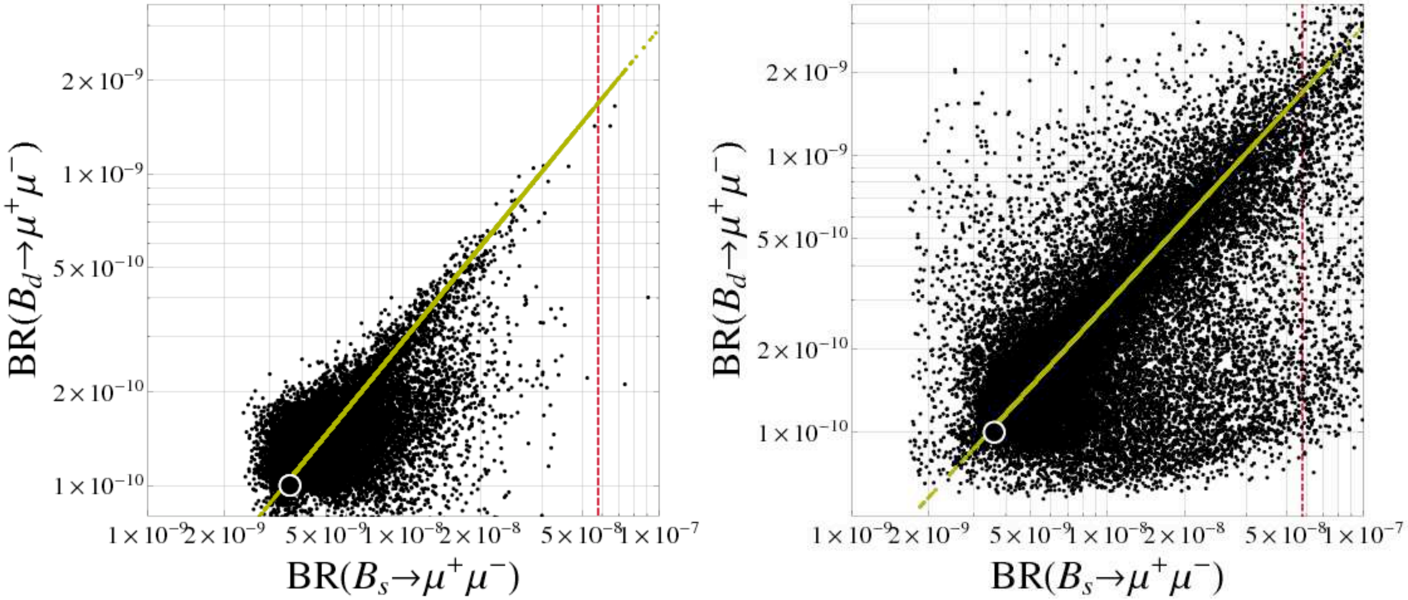
  - DØ collaboration @ 90% C.L. (95% C.L.): [DØ, arXiv:1006.3469 [hep-ex]]

$$\text{BR}(B_s \to \mu^+\mu^-) < 4.2\,(5.1) \times 10^{-8} \Rightarrow \boxed{\text{still a long way (?)}}$$

NP may enhance BRs significantly...

Babu & Kolda, Dedes *et al.*, Foster *et al.*, Carena *et al.*, Isidori & Paradisi, ...

- Example of a recent analysis: → *supersymmetric flavour models:*



(RVV2 model) (δLL model)

[Altmannshofer, Buras, Gori, Paradisi & Straub (2009) → talk by P. Paradisi]

Prospects for $B_s \to \mu^+\mu^-$ @ LHCb

- At LHCb, the extraction of BR$(B_s^0 \to \mu^+\mu^-)$ will rely on normalization channels ($B_u^+ \to J/\psi K^+$, $B_d^0 \to K^+\pi^-$ and/or $B_d^0 \to J/\psi K^{*0}$):

$$\text{BR}(B_s^0 \to \mu^+\mu^-) = \text{BR}(B_q \to X)\frac{\epsilon_X}{\epsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}\frac{f_q}{f_s}$$

  - ϵ factors are total detector efficiencies.
  - N factors denote the observed numbers of events.
  - f_q are fragmentation functions, which describe the probability that a b quark will fragment in a B_q meson ($q \in \{u, d, s\}$).

- A closer look shows: f_q/f_s is the major source of uncertainty
  - Limits the ability to detect a 5σ deviation from the SM at LHCb to BR$(B_s^0 \to \mu^+\mu^-) > 11 \times 10^{-9}$ (assuming $\Delta f_d/f_s = 13\%$).
  - BR(B_s) measurements by Belle$(\Upsilon(5S))$ will also be limited to $\gtrsim 13\%$.
  - Consequently, the determinations of f_d/f_s are not sufficient to meet the high precision at LHCb :-(

  [LHCb Collaboration, B. Adeva *et al.*, LHCb-PUB-2009-029, arXiv:0912.4179v2]

→ Proposal of a New Strategy:

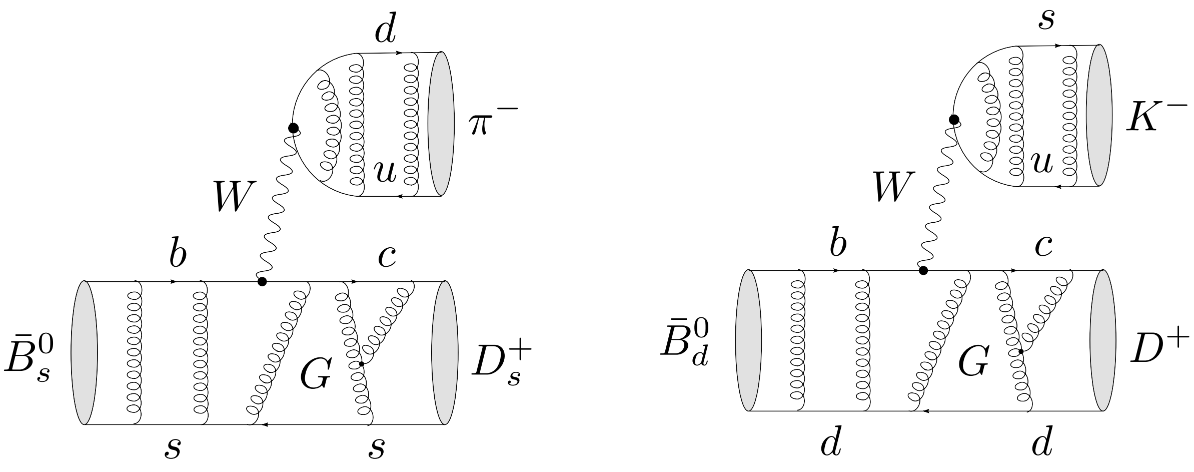
$$\rightarrow \boxed{\textit{measure } f_d/f_s \textit{ at LHCb:}}$$

- Decays should be robust with respect to NP
- Decays should be well suited for LHCb

⇒

R.F., Nicola Serra & Niels Tuning, arXiv:1004.3982 [hep-ph]

$\bar{B}^0_s \to D^+_s \pi^-$ & $\bar{B}^0_d \to D^+ K^-$



- Decays have interesting features:
  - Only contributions from colour-allowed tree-diagram-like topologies.
  - Hadronic amplitudes are related by the U-spin symmetry.
  - Decays are known as prime examples for "factorization":

$$\mathcal{A}(\bar{B}^0_q \to D^+_q P^-) = \frac{G_{\rm F}}{\sqrt{2}} V^*_q V_{cb} a_1(D_q P) f_P F^{(q)}_0(m^2_P)(m^2_{B_q} - m^2_{D_q})$$

[Bjorken ('89); Dugan & Grinstein ('91); Beneke *et al.* ('00); Bauer *et al.* ('01)]

- QCD factorization (QCDF): [Beneke, Buchalla, Neubert & Sachrajda (2000)]
  - a_1 is found as a quasi-universal quantity $|a_1| \simeq 1.05$ with very small process-dependent "non-factorizable" corrections.

$$\rightarrow \boxed{\textit{so far no application, but ...}}$$

- We can use these decays for the determination of f_d/f_s @ LHCb:
  - Ratio of branching ratios:

$$\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+K^-)} \sim \frac{\tau_{B_s}}{\tau_{B_d}} \left|\frac{V_{ud}}{V_{us}}\right|^2 \left(\frac{f_\pi}{f_K}\right)^2 \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2 \left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2$$

  - Ratio of the number of signal events observed in the experiment:

$$\frac{N_{D_s\pi}}{N_{D_dK}} = \frac{f_s}{f_d}\frac{\epsilon_{D_s\pi}}{\epsilon_{D_dK}}\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+K^-)},$$

  - Determination of f_d/f_s:

$$\frac{f_d}{f_s} = 12.88 \times \frac{\tau_{B_s}}{\tau_{B_d}} \times \left[\mathcal{N}_a \mathcal{N}_F \left(\frac{\epsilon_{D_s\pi}}{\epsilon_{D_dK}}\frac{N_{D_dK}}{N_{D_s\pi}}\right)\right]$$

$$\mathcal{N}_a \equiv \left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2, \quad \mathcal{N}_F \equiv \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2$$

Experimental Prospects @ LHCb

- $\bar{B}^0_d \to D^+K^-$ and $\bar{B}^0_s \to D^+_s\pi^-$ can be exclusively reconstructed using the $D^+ \to K^+\pi^+\pi^-$ and $D^+_s \to K^+K^-\pi^+$ channels:

  $\Rightarrow$ identical $K^+K^-\pi^+\pi^-$ final states

  $\Rightarrow$ small uncertainty on $\epsilon_{D_s\pi}/\epsilon_{D_dK}$

- Toy Monte Carlo, generating a 0.2 fb^{-1} sample (→ end of 2010):
  - Expect about 5500 $\bar{B}^0_s \to D^+_s\pi^-$ and 1100 $\bar{B}^0_d \to D^+K^-$ events:

    $\Rightarrow$ 7.5% error for $r \equiv (\epsilon_{D_s\pi}N_{D_dK})/(\epsilon_{D_dK}N_{D_s\pi})$
  - Dominant uncertainty from BR$(D_s \to K^+K^-\pi) = (5.50 \pm 0.28)\%$.

- Extrapolation to 1 fb^{-1} (→ end of 2011):
  - The statistical uncertainty becomes essentially negligible.
  - The total uncertainty is reduced to $\Delta r \sim 5.6\% \to$ $\boxed{\text{looks nice!}}$

[Study with full LHCb simulation in progress (N. Serra & N. Tuning *et al.*)]

Theoretical Uncertainties → U-Spin-Breaking Effects

$$\frac{f_d}{f_s} = 12.88 \times \frac{\tau_{B_s}}{\tau_{B_d}} \times \left[\mathcal{N}_a \mathcal{N}_F \left(\frac{\epsilon_{D_s\pi}}{\epsilon_{D_dK}} \frac{N_{D_dK}}{N_{D_s\pi}} \right) \right]$$

- Non-factorizable, U-spin-breaking effects:

$$\mathcal{N}_a \equiv \left| \frac{a_1(D_s\pi)}{a_1(D_dK)} \right|^2 \approx 1 + 2\Re(a_1^{\rm NF}(D_s\pi) - a_1^{\rm NF}(D_dK))$$

  - $a_1^{\rm NF}$ describe non-universal, i.e. process-dependent, non-factorizable contributions, which cannot be calculated reliably.
  - However, they arise as power corrections to the heavy-quark limit, i.e. they are suppressed by at least one power of $\Lambda_{\rm QCD}/m_b$, and are – in the decays at hand – numerically expected at the few percent level

    [Beneke, Buchalla, Neubert & Sachrajda (2000)]
  - *Moreover:* we are only sensitive to an $SU(3)$-breaking difference:

$$\Rightarrow \boxed{1 - \mathcal{N}_a \text{ conservatively expected to be at most a few percent}}$$

→ $\boxed{\text{Note: } \textit{we can experimentally test factorization:}}$

- The PDG value of BR$(\bar{B}_d^0 \to D^+K^-) = (2.0 \pm 0.6) \times 10^{-4}$ agrees with the QCDF prediction 2.5×10^{-4} in the heavy-quark limit.

- Recent $B_s \to D_s^{(*)}\pi, D_s^{(*)}\rho$ measurements by Belle @ $\Upsilon(5S)$ are also in agreement with factorization [Belle Collaboration, arXiv:1003.5312 [hep-ex]].

- A stringent factorization test will be feasible by combining the LHCb measurement of BR$(\bar{B}_d^0 \to D^+K^-)$ with the BaBar & Belle data for the differential semileptonic $\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell$ rate at $q^2 = M_K^2$:

$$\frac{\text{BR}(\bar{B}_q^0 \to D_q^+P^-)\tau_{B_q}}{d\Gamma(\bar{B}_q^0 \to D_q^+\ell^-\bar{\nu}_\ell)/dq^2|_{q^2=m_P^2}} = 6\pi^2|V_q|^2 f_P^2 |a_1(D_qP)|^2 X_P,$$

where X_P deviates from 1 below the percent level.

[Bjorken ('89); Beneke, Buchalla, Neubert & Sachrajda ('00)]

$\boxed{\text{Factorizable, } U\text{-spin-breaking effects:}}$ $\mathcal{N}_F \equiv \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2$

- $B_s \to D_s$ form factors have so far received only small attention:
  - Heavy-meson chiral perturbation theory [Jenkins & Savage ('92)]
  - QCD sum rules [Blasi *et al.* ('92)]: $\to \mathcal{N}_\mathrm{F} = 1.3 \pm 0.1$
- We can obtain a *lower* bound on BR$(B_s^0 \to \mu^+\mu^-)$:
  - Assumption: $\mathcal{N}_F > 1$ [radius of B_s^0 is smaller than that of the B_d^0]

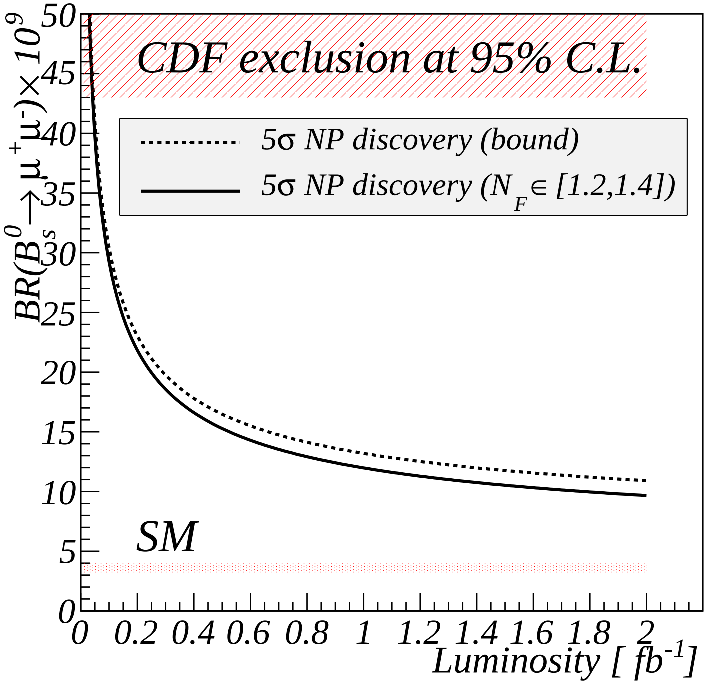
$$\Rightarrow \text{BR}(B_s^0 \to \mu^+\mu^-) > \underbrace{\text{BR}(B_s^0 \to \mu^+\mu^-)_0}_{\text{assumes } \mathcal{N}_F = 1}$$

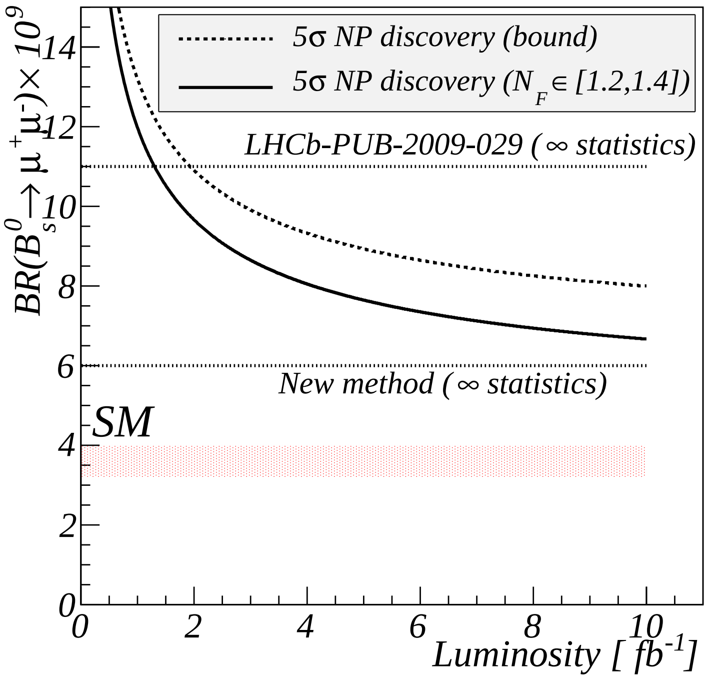
  - Interesting probe for NP.
- Benchmark for non-perturbative calculations: → lattice QCD
  - In order to match experiment, it is sufficient to calculate the U-spin-breaking corrections to $F_0^{(s)}(m_\pi^2)/F_0^{(d)}(m_K^2)$ at the level of 20%.

→ should be feasible.

Resulting NP Reach for $B_s \to \mu^+\mu^-$ at LHCb

- Contours corresponding to the detection of a 5σ NP signal for the bound and the extracted value of the $B_s \to \mu^+\mu^-$ branching ratio:
  - Assuming Gaussian distribution of the errors for branching ratios.
  - Variation of $\mathcal{N}_F \in [1.2, 1.4]$ and $\mathcal{N}_a \in [0.97, 1.03]$ (which does essentially not affect the contours).





$\Rightarrow$ $\boxed{B_s \to \mu^+\mu^- \text{ NP reach at LHCb is increased by } \sim 2}$

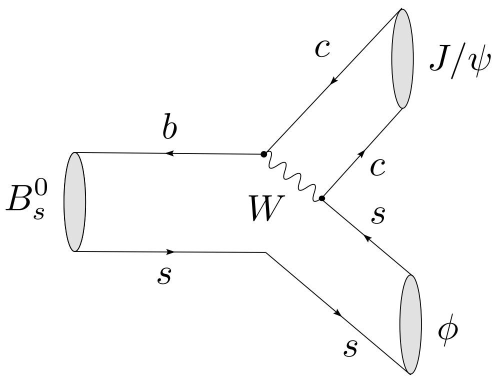
Search for New Physics

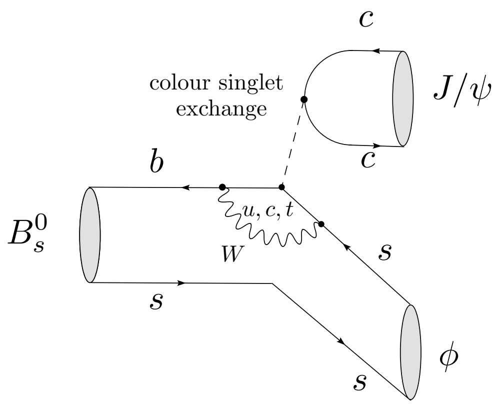
in

$B_s \to J/\psi\phi$

Key Channel: $B_s \to J/\psi\phi$

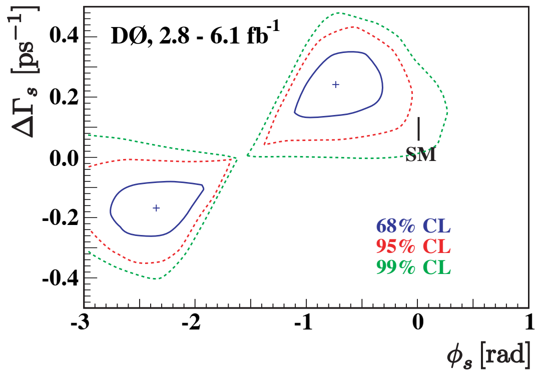
- CP violation in $B_s^0 \to J/\psi\phi$: → probes NP in B_s^0–$\bar{B}_s^0$ mixing

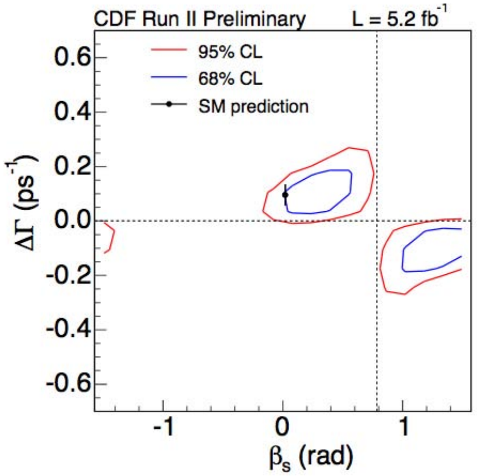




[Dighe, Dunietz & Fleischer (1998); Dunietz, Fleischer & Nierste (2000); ...]

- Recent updates from the Tevatron: $[\phi_s = -2\beta_s]$
  - DØ plot includes the anomalous like-sign dimuon charge asymmetry;
  - CDF plot uses only $B_s \to J/\psi\phi$.





[→ talks by Rick Jesik (DØ) & Diego Tonelli (CDF)]

Prospects for ϕ_s Measurements at the LHC

- Experimental reach @ LHCb: *very impressive ...*
  - One nominal year of operation, i.e. 2 fb^{-1}: $\sigma(\phi_s)_{\rm exp} \sim 1^\circ$
  - LHCb upgrade with integrated lumi of 100 fb^{-1}: $\sigma(\phi_s)_{\rm exp} \sim 0.2^\circ$

- However: *SM penguin effects were so far fully neglected!*

$$\xi^{(s)}_{(\psi\phi)_f} \propto e^{-i\phi_s}\left[1 - \underbrace{2\,i\,\lambda^2 a_f e^{i\theta_f}\sin\gamma + \mathcal{O}(\lambda^4)}_{\text{penguin effects}}\right]$$

  - What is the impact of these corrections?
  - How can they be controlled?
  - Theory has to match experiment ...

[S. Faller, R.F. & T. Mannel (2008); see also M. Ciuchini *et al.* (2005)]

Closer Look @ SM Penguin Effects

- CP asymmetries:

$$\frac{|A_f(t)|^2 - |\overline{A}_f(t)|^2}{|A_f(t)|^2 + |\overline{A}_f(t)|^2} = \frac{\hat{A}^f_{\rm D}\cos(\Delta M_s t) + \hat{A}^f_{\rm M}\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^f_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$

- Impact of hadronic effects:

$$\boxed{\eta_f \hat{A}^f_{\rm M}/\sqrt{1-(\hat{A}^f_{\rm D})^2} = \sin(\phi_s + \Delta\phi^f_s)}$$

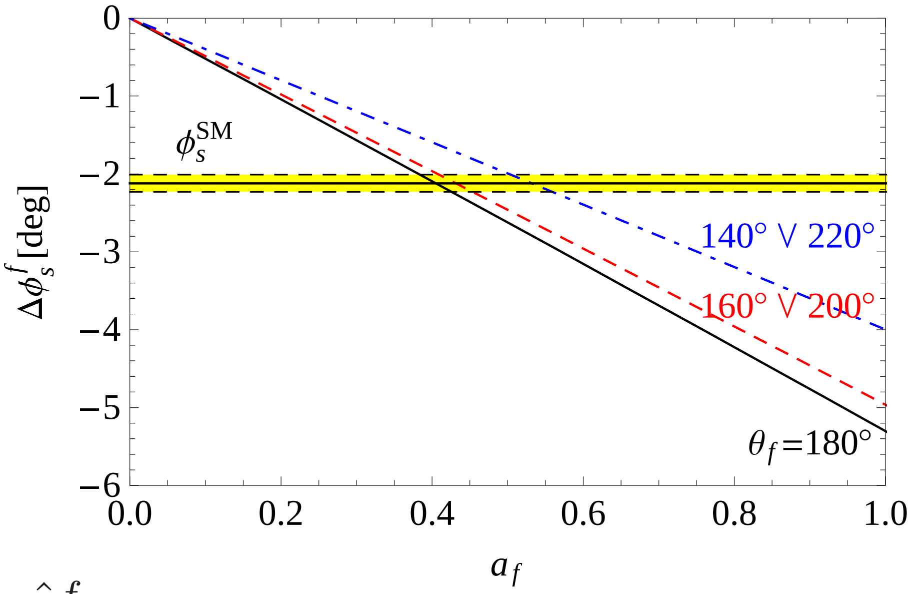
$$\sin\Delta\phi^f_s = \frac{2\epsilon a_f \cos\theta_f \sin\gamma + \epsilon^2 a_f^2 \sin 2\gamma}{N_f\sqrt{1-(\hat{A}^f_{\rm D})^2}}$$

$$\cos\Delta\phi^f_s = \frac{1 + 2\epsilon a_f \cos\theta_f \cos\gamma + \epsilon^2 a_f^2 \cos 2\gamma}{N_f\sqrt{1-(\hat{A}^f_{\rm D})^2}},$$

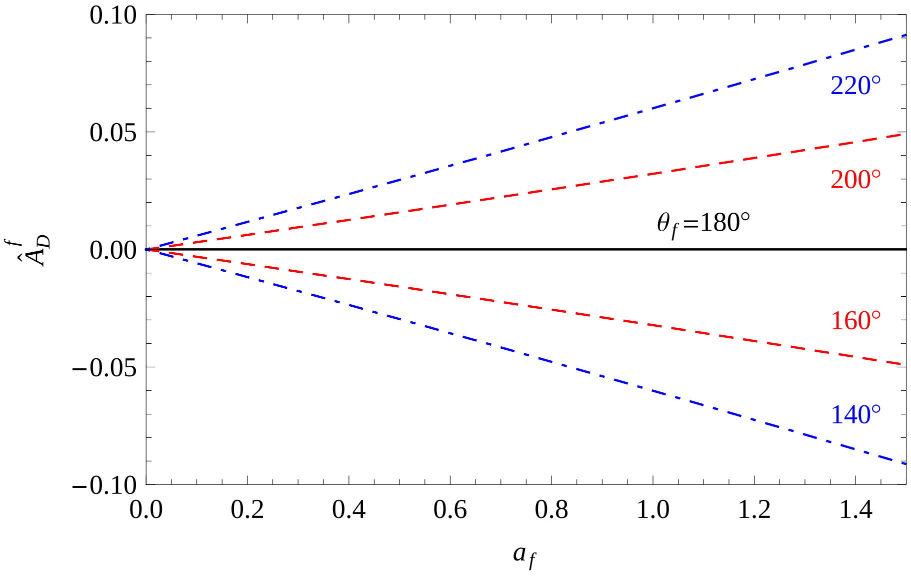
$$N_f \equiv 1 + 2\epsilon a_f \cos\theta_f \cos\gamma + \epsilon^2 a_f^2$$

Illustration of the Effects

- Dependence of $\Delta\phi_s^f$ on a_f for different θ_f:

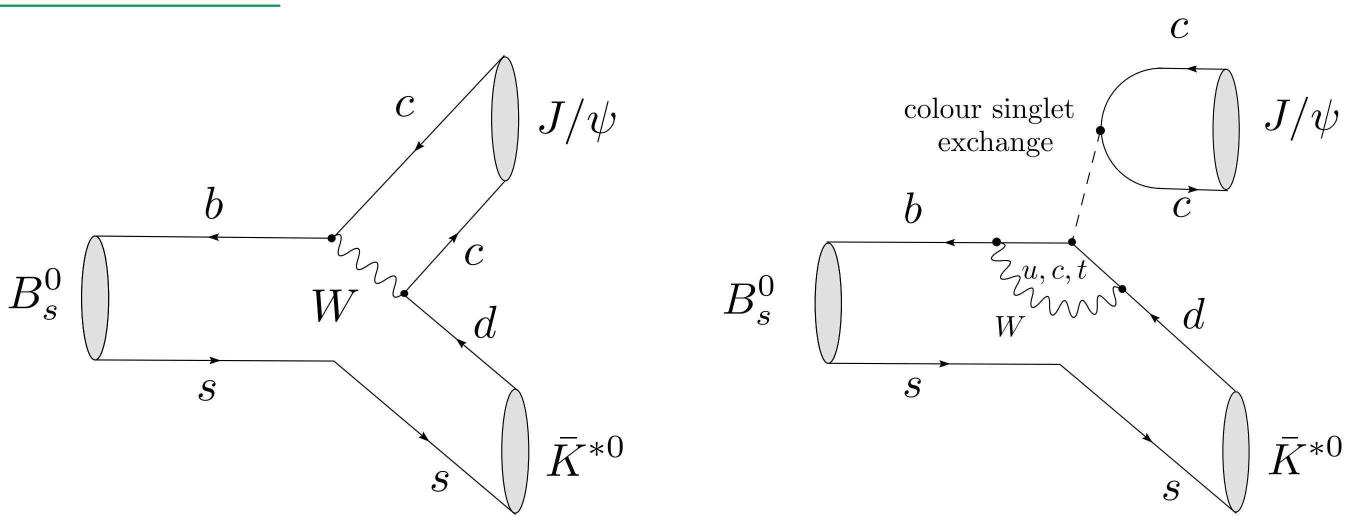


- Dependence of $\hat{A}_{\mathrm{D}}^f$ on a_f for different θ_f:



Control Channel: $B_s^0 \to J/\psi \bar{K}^{*0}$

- Decay topologies:



  - Very similar to the $B_s^0 \to J/\psi\phi$ mode, but different CKM structure: $b \to d$ instead of $b \to s$ transition.
  - Have to neglect PA and E topologies (which can be probed through $B_d^0 \to J/\psi\phi$) when relating both modes through $SU(3)$.

- Decay amplitude: $A(B_s^0 \to (J/\psi \bar{K}^{*0})_f) = \lambda \mathcal{A}'_f \left[1 - a'_f e^{i\theta'_f} e^{i\gamma}\right]$

  - Penguin term is not suppressed by λ^2.
  - Using the working assumption as specified above:

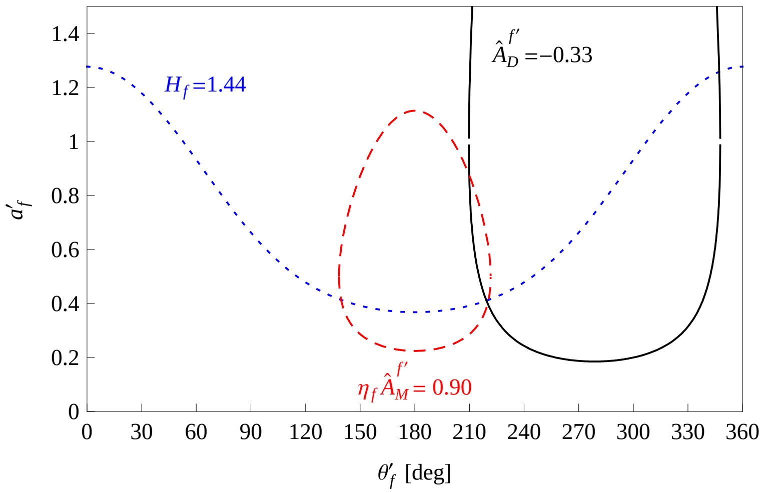
$$\Rightarrow \quad |\mathcal{A}_f| = |\mathcal{A}'_f| \quad \text{and} \quad a_f = a'_f, \quad \theta_f = \theta'_f.$$

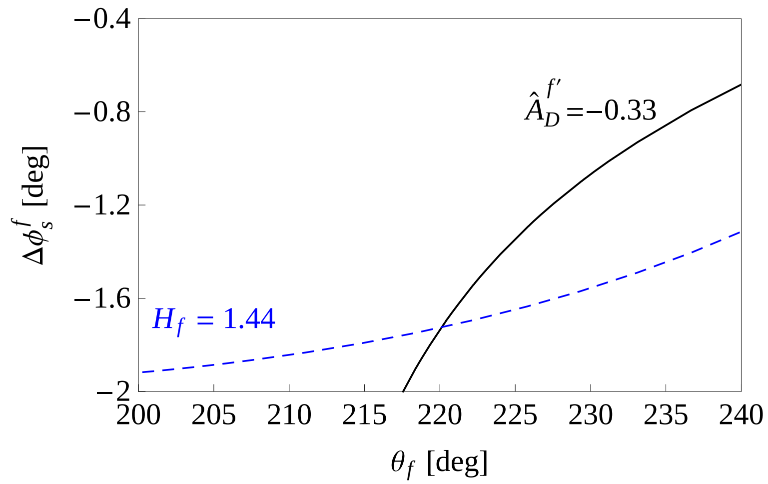
- Control of the effects through $B_s^0 \to J/\psi[\to \ell^+\ell^-]\bar{K}^{*0}[\to \pi^+K^-]$:
  - Ratio of the CP-averaged "untagged" rates $\Gamma[f,t=0]'$ and $\Gamma[f,t=0]$ of the $B_s^0 \to J/\psi\bar{K}^{*0}$ and $B_s^0 \to J/\psi\phi$ modes, respectively:

$$H_f \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}_f}{\mathcal{A}'_f}\right|^2 \frac{\Gamma[f,t=0]'}{\Gamma[f,t=0]} = \frac{1-2a'_f\cos\theta'_f\cos\gamma+a'^2_f}{1+2\epsilon a_f\cos\theta_f\cos\gamma+\epsilon^2 a_f^2}$$

  - Measure the direct CP asymmetries $\hat{A}_{\rm D}^{f'}$, the counterparts of the $\hat{A}_{\rm D}^{f'}$.
  - No mixing-induced CP violation as flavour-specific final state :-(

- Numerical Illustration: $\gamma = 65^\circ$, $a'_f = 0.4$, $\theta'_f = 220^\circ$ (consistent with $a' \in [0.15, 0.67]$ and $\theta' \in [174^\circ, 213^\circ]$ following from a $B^0 \to J/\psi\pi^0$ analysis).





[Detailed discussion, $SU(3)$ breaking, etc.: S. Faller, R.F. & T. Mannel (2008)]

Comments & Observations

- $\Delta\phi_s^f$ is favoured to have negative sign:

$$\Rightarrow \boxed{\text{interferes } \textit{constructively} \text{ with } \phi_s^{\rm SM} = -(2.12 \pm 0.11)^\circ}$$

  - Consequently, the phase shift $\Delta\phi_s^f = -1.7^\circ$ of our example yields

$$\eta_f \hat{A}_{\rm M}^f = -6.7\% \quad \Rightarrow \quad \sim 2 \times \text{naïve SM value!}$$

  - Without the analysis described above: *misinterpretation* as $4\,\sigma$ NP effect with $2\,\mathrm{fb}^{-1}$ @ LHCb, and about $20\,\sigma$ at upgrade with $100\,\mathrm{fb}^{-1}$.
  - Cannot exclude that the hadronic penguin effects are actually more significant than in our example, could lead to $\eta_f \hat{A}_{\rm M}^f \sim -10\%$ ...

- Two scenarios:
  - *Optimistic:* $\eta_f \hat{A}_{\rm M}^f \sim -40\%$ would be an unambiguous signal of NP!
  - *Pessimistic:* $\eta_f \hat{A}_{\rm M}^f \sim -(5...10)\%$ would require more work from TH and EXP to settle the picture...

Much more

Physics

@ LHCb:

Precision Measurements of γ

- Tree strategies, with expected sensitivities after 1 year of taking data:
  - $B_s^0 \to D_s^{\mp} K^{\pm}$: $\sigma_\gamma \sim 14^\circ$
  - $B_d^0 \to D^0 K^*$: $\sigma_\gamma \sim 8^\circ$ ... to be compared with the
  - $B^{\pm} \to D^0 K^{\pm}$: $\sigma_\gamma \sim 5^\circ$
  - ...

  current B-factory data: $\gamma|_{D^{(*)}K^{(*)}} = \begin{cases} (73^{+22}_{-25})^\circ & \text{[CKMfitter]} \\ (78 \pm 12)^\circ & \text{[UTfit]} \end{cases}$

- Decays with penguin contributions:
  - $B_s^0 \to K^+K^-$ and $B_d^0 \to \pi^+\pi^-$: $\sigma_\gamma \sim 5^\circ$
  - $B_s^0 \to D_s^+ D_s^-$ and $B_d^0 \to D_d^+ D_d^-$
  - ...

- Practical challenge:
  - We encounter typically discrete ambiguities for γ: → have to be resolved for the search of NP! [Further info helps, U-spin decays ...]

$\Rightarrow$ $\boxed{\text{Will we encounter discrepancies?}}$ [→ talk by Vincenzo Vagnoni]

Analyses of Rare B Decays

- Non-leptonic: $B_d^0 \to \phi K_{\rm S}$, $B_s^0 \to \phi\phi$, ...
  - Hadronic sector: fix corrections through flavour symmetries.
  - Analyses of CP-violating observables, using also BRs as input.
  - New effects would immediately rule out MFV!
- Semileptonic: $B_d^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$, ...
  - Hadronic sector: quark-current form factors (QCD sum rules, lattice).
  - Search for observables that are particularly robust with respect to the corresponding uncertainties:
    - ∗ Example: 0-crossing of the forward–backward asymmetry.
- Leptonic: $B_s^0 \to \mu^+\mu^-$, $B_d^0 \to \mu^+\mu^-$
  - See discussion given above...

$\Rightarrow$ $\boxed{\text{Will we encounter discrepancies?}}$ [→ talks by U. Egede & G. Buchalla]

Other Interesting Topics

- Charm physics: $D^0 \to K^+K^-$, ...
  - While FCNCs in the B system are sensitive to new effects in the up sector, charm physics probes the down sector (b, s, d in SM loops)!
  - D^0–$\bar{D}^0$ mixing seen in the ball park of the SM, but NP could be hiding there: cannot be resolved because of long-distance QCD effects.
  - Interesting NP probe: search for CP-violating effects, which are tiny in the SM but could be enhanced through NP!

- Search for lepton flavour violation: $B^0_{d,s} \to e^\pm \mu^\mp$, $B^0_{d,s} \to \mu^\pm \tau^\mp$
  - In the SM such processes are forbidden!
  - However, they may arise in NP scenarios, such as SUSY.
  - Studies complement other searches of this phenomenon such as by means of $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$, ...

Will we eventually see signals?

Concluding Remarks

Moving towards New Frontiers ...

- The last decade has seen many interesting B-physics results: ⇒
  - CKM matrix is the dominant source of flavour and CP violation.
  - Potential signals for new phenomena, though not yet established ...
- Flavour takes part in the BIG adventure of this decade: → $\boxed{\text{LHC}}$
  - Specific NP scenarios still leave room for sizeable effects!
  - Promising channels to find *first* NP signals @ LHCb (and the LHC):
    - $B_s^0 \to \mu^+\mu^-$
    - $B_s^0 \to J/\psi\phi$
- Theoretical topics: [↔ strong interaction with LHCb community]
  - Further critically review SM phenomena, develop strategies to control hadronic uncertainties (preferably through data),
  - Explore the patterns in specific NP scenarios:

    ⇒ correlations ⇒ what kind of NP?
  - Bring new channels to the attention of LHCb.
  - Search for synergies, also with high-Q^2 physics @ ATLAS & CMS.