B Physics in the LHC Era: Status and Perspectives

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- Setting the Stage
- Theoretical Framework
- B Physics @ LHC: $\rightarrow$ Promising Probes for New Physics
- Conclusions & Outlook

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Setting the Stage

Quark Flavour Physics & CP Violation

$\rightarrow$ key players in the history of the Standard Model (SM):

- 1963: concept of flavour mixing [Cabibbo].
- 1964: discovery of CP violation in $K_{\rm L} \to \pi^+\pi^-$ [Christenson *et al.*].
- 1970: introduction of the charm quark to suppress the flavour-changing neutral currents (FCNCs) [Glashow, Iliopoulos & Maiani].
- 1973: quark-flavour mixing with 3 generations allows us to accommodate CP violation in the SM [Kobayashi & Maskawa].
- 1974: estimate of the charm-quark mass with the help of the K^0–$\bar{K}^0$ mixing frequency [Gaillard & Lee].
- 1980s: the large top-quark mass was first suggested by the large B^0–$\bar{B}^0$ mixing seen by ARGUS (DESY) and UA1 (CERN).

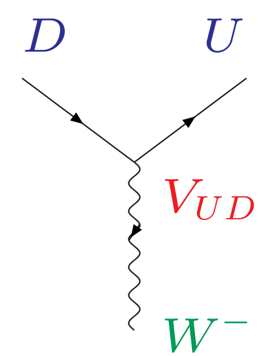
flavour physics has since continued to progress ...

The Quark-Flavour Code

- Quark flavour physics and CP violation: $\rightarrow$ rich phenomenology

flavour eigen-states $\left.\right\}$
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$
$\left\{\right.$ mass eigen-states

quark-mixing matrix, also known as
Cabibbo–Kobayashi–Maskawa matrix $\hat{V}_{\text{CKM}}$
$\rightarrow$ *unitary* matrix



$$\Rightarrow \boxed{\textit{encoded in weak decays of } K,\ D \textit{ and } B \textit{ mesons}}$$

[antiquark–quark boundstates $\bar{q}Q$ with $Q{=}s$, c and b]

- The *key problem:* strong interactions $\rightarrow$ "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 the calculations of the relevant transition amplitudes, we encounter process-dependent, *non-perturbative "hadronic" parameters!?*

    [$\rightarrow$ lattice QCD: lots of progress for some parameters, but still challenging...]

- 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 physics beyond the SM.
- The last decade was governed by the e^+e^- B factories with the BaBar (SLAC) and Belle (KEK) experiments and B results from the Tevatron:
  - *CP-violating phenomena in B-meson decays could be established.*
  - The *interplay with theory* resulted in many new insights.
  - With the exception of a few "flavour puzzles" (not yet conclusive because of large errors), also the SM flavour sector is in good shape.
- However, a large territory of the B-physics landscape was left unexplored:

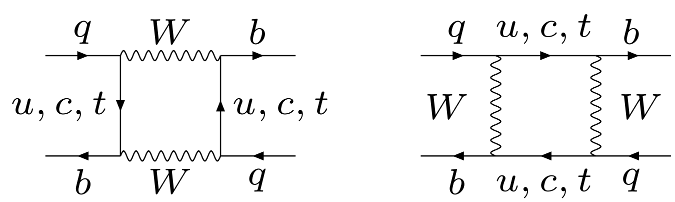
$\rightarrow$ target of another LHC experiment: LHCb [$\rightarrow$ talk by Val Gibson]

Species of B Mesons

- Charged B mesons:
  $$B^+ \sim u\,\bar{b} \qquad B^- \sim \bar{u}\,b$$
  $$B_c^+ \sim c\,\bar{b} \qquad B_c^- \sim \bar{c}\,b$$

- Neutral B mesons:
  $$B_d^0 \sim d\,\bar{b} \qquad \bar{B}_d^0 \sim \bar{d}\,b$$
  $$B_s^0 \sim s\,\bar{b} \qquad \bar{B}_s^0 \sim \bar{s}\,b$$

  – B_q^0–$\bar{B}_q^0$ mixing: $\rightarrow$ *Quantum Mechanics*



$$\Rightarrow \quad \boxed{|B_q(t)\rangle = a(t)|B_q^0\rangle + b(t)|\bar{B}_q^0\rangle\ :}$$

  ∗ Schrödinger equation $\Rightarrow$ mass eigenstates:

$$\boxed{\Delta M_q \equiv M_{\rm H}^{(q)} - M_{\rm L}^{(q)}, \quad \Delta\Gamma_q \equiv \Gamma_{\rm L}^{(q)} - \Gamma_{\rm H}^{(q)}}$$

  ∗ Decay rates: $\Gamma(\overset{(-)}{B_q^0}(t) \rightarrow \overset{(-)}{f})$:

$$\cos(\Delta M_q t)\ \&\ \sin(\Delta M_q t) \quad \rightarrow \quad \text{oscillations!}$$

Hope for New Physics ...

- 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/problems:
  - Hierarchy problem
  - Fine-tuning problem...

  $\rightarrow$ suggest New Physics in the TeV regime
- Popular specific models for physics beyond the SM:
  - Supersymmetry (SUSY)
  - Universal extra dimension (UED)
  - Warped extra dimension (WED)
  - Little Higgs models (LH, with T parity LHT)
  - Z' models
  - 4th generation models

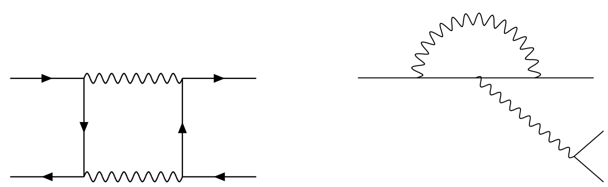
  $\rightarrow$ new sources of flavour & CP violation

How to Search for New Physics (NP) Beyond the SM?

- Search for *direct* signals of NP: $\Rightarrow$ physics @ ATLAS $\oplus$ CMS
  - Produce new particles (e.g. squarks, gauge bosons, ...) at colliders;
  - Study the decays of the new particles in general purpose detectors ...

$\rightarrow$ *high-energy frontier*

- Search for *indirect* footprints of NP: $\Rightarrow$ B (flavour) physics @ LHCb
  - Sensitivity to NP effects through *virtual quantum effects:*



$\rightarrow$ *high-precision frontier*

$\Rightarrow$ expect synergy between both avenues to search for NP

Theoretical Framework:

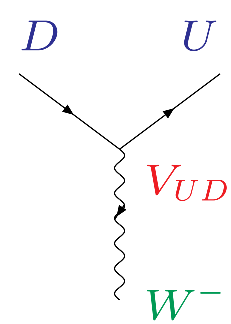
in a nutshell ...

Basic Language: Quantum Field Theory

- Lagrangian:

$$\boxed{\mathcal{L} = \mathcal{L}_{\rm SM}(g_k^{\rm SM}, m_k^{\rm SM}, \hat{V}_{\rm CKM}) + \mathcal{L}_{\rm NP}(g_k^{\rm NP}, m_k^{\rm NP}, \hat{V}_{\rm NP})} \Rightarrow \left\{ \begin{array}{l} \text{Feynman} \\ \text{diagram} \\ \text{calculations} \end{array} \right.$$

- Lagrangian composed of SM and NP fields involves:
  - Couplings: $g_k^{\rm SM} \oplus g_k^{\rm NP}$
  - Particle masses: $m_k^{\rm SM} \oplus m_k^{\rm NP}$, and ...



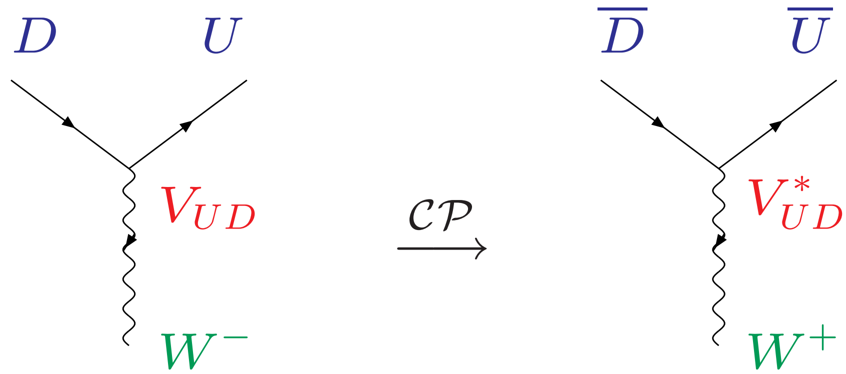
- *Quark flavour mixing:* $[D \in \{d, s, b\}, U \in \{u, c, t\}]$
  - SM: $D \to UW$ described by the Cabibbo–Kobayashi–Maskawa (CKM) matrix $\hat{V}_{\rm CKM}$ connecting the quark flavour states with their mass eigenstates through a *unitary* transformation: $\hat{V}_{\rm CKM}^\dagger \cdot \hat{V}_{\rm CKM} = \hat{1}$.
  - In general, new sources of flavour mixing through NP: $\hat{V}_{\rm NP}$.

- NP may induce flavour-changing neutral currents (FCNCs) @ tree level:

$\rightarrow$ forbidden in the SM [Glashow–Iliopoulos–Maiani (GIM) mechanism ('70)]

CP Violation in the Standard Model

- Behaviour of "charged-current" processes under CP transformations:



$$\boxed{V_{UD} \stackrel{\mathcal{CP}}{\longrightarrow} V^*_{UD}}$$

- Kobayashi & Maskawa (1973): $\boxed{\hat{V}_{\rm CKM}\ \textit{complex}\ \text{for}\ N \geq 3\ \text{generations}}$
  - $N = 2$: (real) quark-mixing-matrix parametrized by the Cabibbo angle.
  - $N = 3$: $\hat{V}_{\rm CKM}$ parametrized by three angles and *one complex phase*:

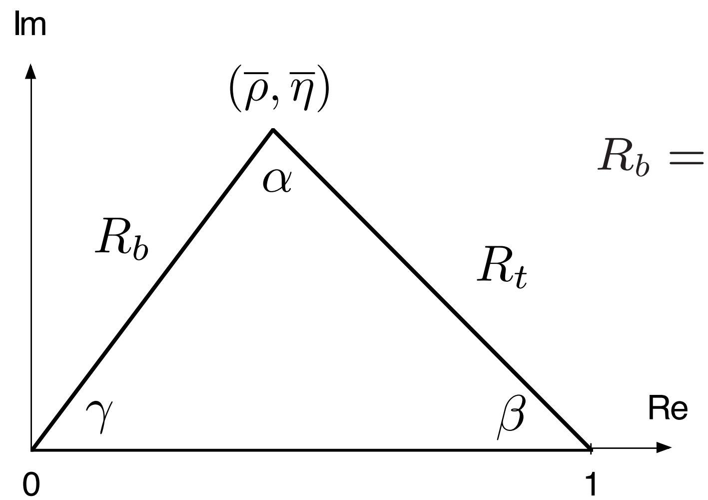
$\Rightarrow$ allows us to accommodate CP violation:[1]

$\rightarrow$ $\boxed{\text{Kobayashi–Maskawa (KM) mechanism}}$

[1] Another source of CP violation: strong CP problem with "QCD vacuum angle" θ (neutron EDM).

The Unitarity Triangle (UT)

- Unitarity of the CKM matrix:[2] $\Rightarrow V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \Rightarrow$



$$R_b = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

$$R_t = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

  - $\lambda \equiv |V_{us}| = 0.22 \rightarrow$ phenomenological expansion of the CKM matrix.
  - $\bar\rho \equiv (1 - \lambda^2/2)\rho$, $\bar\eta \equiv (1 - \lambda^2/2)\eta$ take NLO effects into account, where ρ, η appear in the CKM parametrization by Wolfenstein.

CP violation: non-vanishing height of the UT (i.e. $\gamma \neq 0^\circ$)

- Theoretical interpretation of various flavour-physics observables:

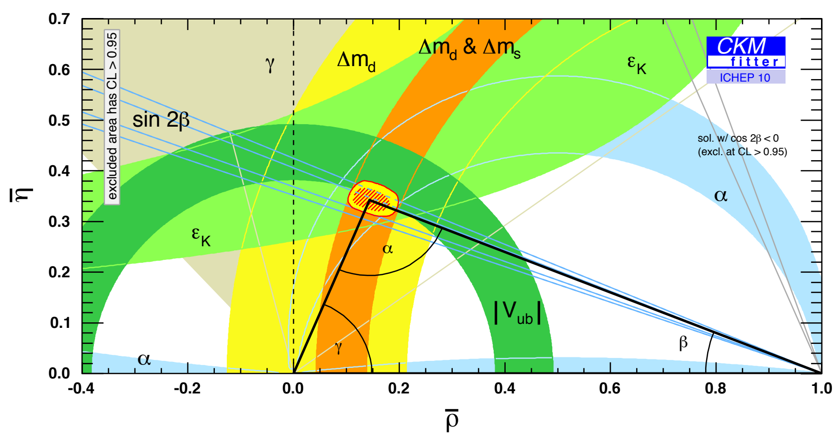
$\Rightarrow$ contours in the $\bar\rho$–$\bar\eta$ plane: $\Rightarrow$ *KM consistency checks* ...

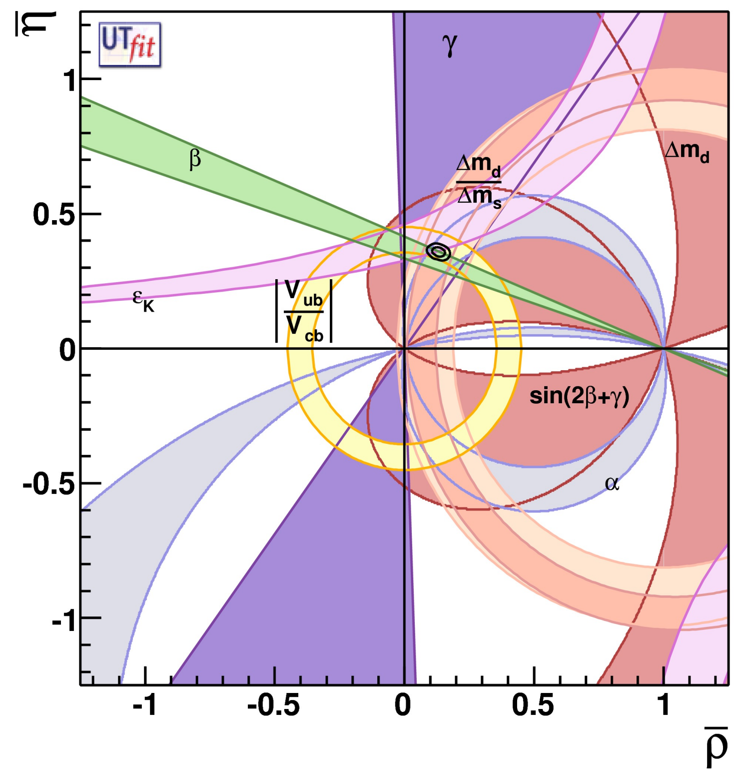
[2] Actually 6 unitarity triangles: 4 are extremely squashed; 2 non-squashed ones agree at LO in $\lambda = 0.22$.

Status of the Unitarity Triangle

- <u>Fits of the UT by two groups:</u> $\rightarrow$ many plots & correlations ...
  - *CKMfitter* Collaboration `[http://ckmfitter.in2p3.fr/]`;
  - *UTfit* Collaboration `[http://www.utfit.org/UTfit/WebHome]`:

$\Rightarrow$ *continuously updated results:*





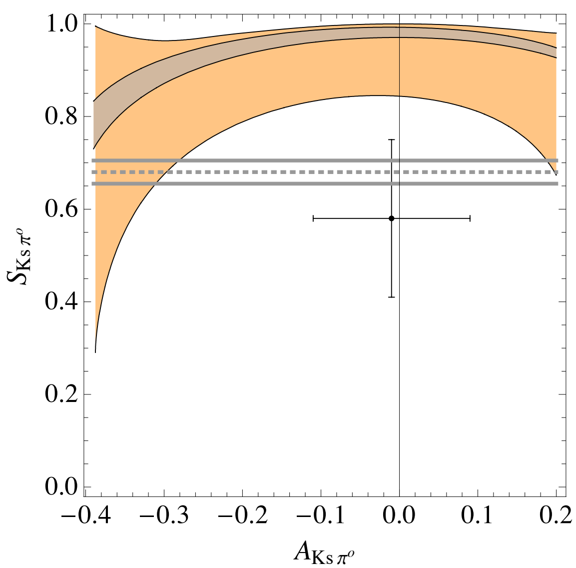
$\Rightarrow$ some tension between β, ε_K, $|V_{ub}/V_{cb}|$ (?)

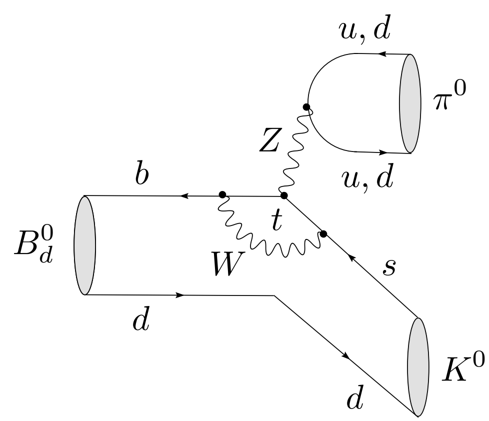
[See, e.g., E. Lunghi & A. Soni ('09–'10); A. Buras & D. Guadagnoli ('09); ...]

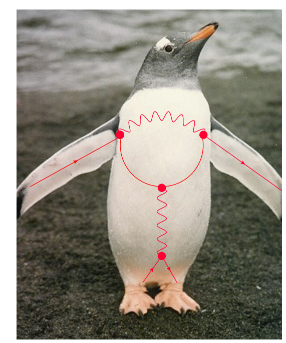
(New) Flavour Physics: Where Do We Stand?

- Lessons from the B, D and K decay 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:
    - $*$ *Example:* CP violation in $B^0 \to \pi^0 K_S$ [Future @ LHCb: $B_s^0 \to \phi\phi$]

$$\frac{\Gamma(\bar{B}^0(t) \to \pi^0 K_S) - \Gamma(B^0(t) \to \pi^0 K_S)}{\Gamma(\bar{B}^0(t) \to \pi^0 K_S) + \Gamma(B^0(t) \to \pi^0 K_S)} = A_{\pi^0 K_S} \cos(\Delta M_d t) + S_{\pi^0 K_S} \sin(\Delta M_d t)$$







Electroweak "penguin" contribution $\to$ NP?

[R.F., S. Jäger, D. Pirjol & J. Zupan ('08)]

- 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):*

    $\rightarrow$ essentially the same CP & flavour violation as in the SM.

- Comments:
  - MFV has not yet been 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

- Excellent news:
  - We are at the beginning of a new era in particle physics: $\rightarrow$ **LHC era**

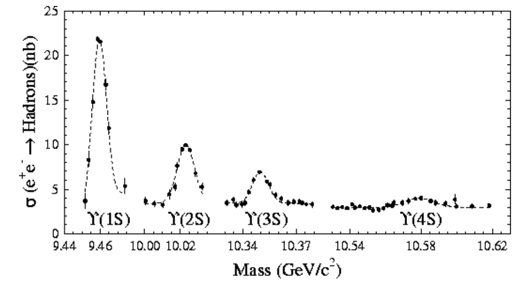
B Physics @ LHC:

$\Rightarrow$ promising probes for New Physics

[$\longrightarrow$ Val Gibson's talk for the experimental aspects]

New Territory: B_s-Meson System

- e^+e^- B factories:



  - Cannot access the B_s system if operated @ $\Upsilon(4S)$: BaBar (SLAC) & Belle (KEK).
  - Belle has collected data @ $\Upsilon(5S)$ as well.

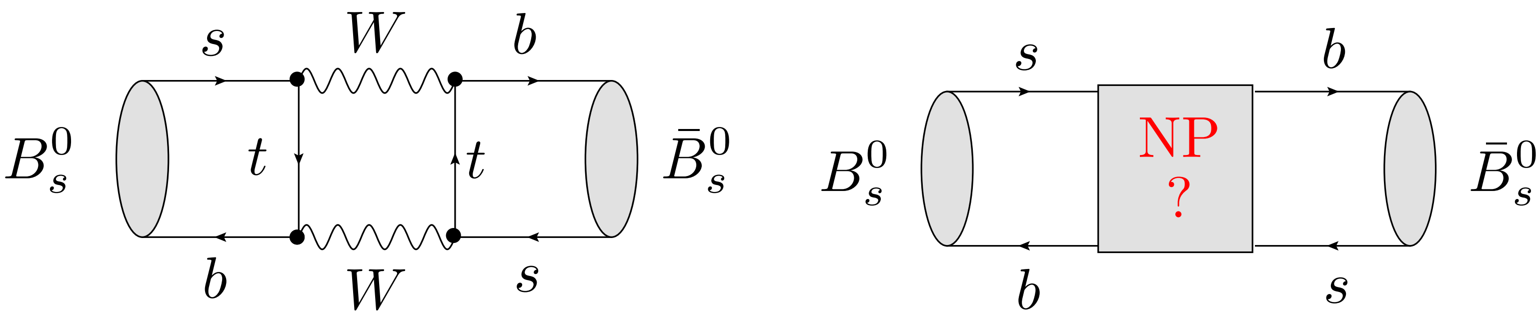
The B_s system is the domain of hadron colliders	$\rightarrow$

- CDF & DØ @ Tevatron:
  - Observation of B_s^0–$\bar{B}_s^0$ mixing in 2006 (after long efforts).
  - Intriguing results for CP violation in $B_s^0 \rightarrow J/\psi\phi$ since about 3 years.

- LHCb: $\rightarrow$ *promising processes for first NP signals:*
  - CP violation in $B_s^0 \rightarrow J/\psi\phi$.
  - Branching ratio of $B_s^0 \rightarrow \mu^+\mu^-$ (ATLAS & CMS are competitive).
  - Various other decays & strategies ...

$\rightarrow$ particularly interesting ...

⋆ Search for NP in B_s^0–$\bar{B}_s^0$ mixing:



Standard Model New Physics (e.g. SUSY, Z' models)

◇ FCNC process: ⇒ strongly suppressed in the SM ("box" diagrams)

⋆ involves a CP-violating phase $\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP}$

→ SM piece is *tiny*: $\phi_s^{\rm SM} \approx -2^\circ$

⇒ **sensitive probe for NP**

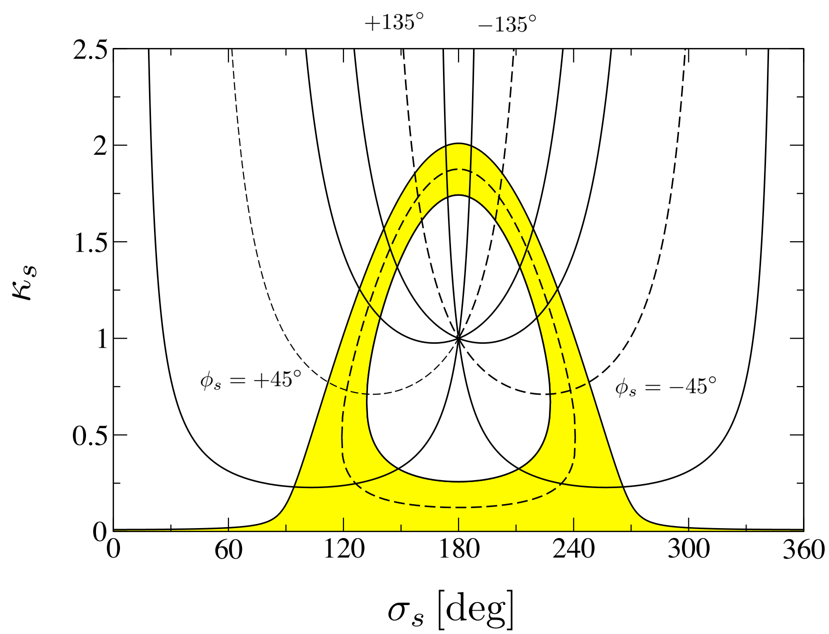
Constraints on NP Parameter Space

- Parameter (complex number) to characterize NP in $B_s^0 - \bar{B}_s^0$ mixing:

$$\boxed{\kappa_s e^{i\sigma_s} \equiv \text{"NP"} / \text{"SM"}} \Rightarrow$$

  – Mass difference: $\Delta M_s = \Delta M_s^{\rm SM} \left|1 + \kappa_s e^{i\sigma_s}\right|$
  – Mixing phase: $\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP} = \phi_s^{\rm SM} + \arg(1 + \kappa_s e^{i\sigma_s})$

- Allowed region in the σ_s–κ_s plane:

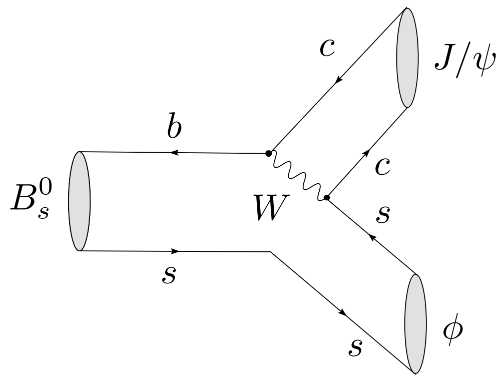


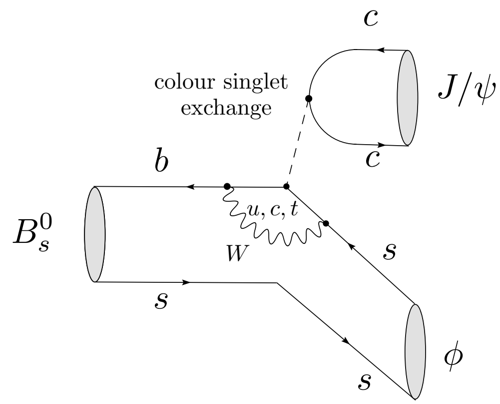
$\Delta M_s \Rightarrow$ yellow band;

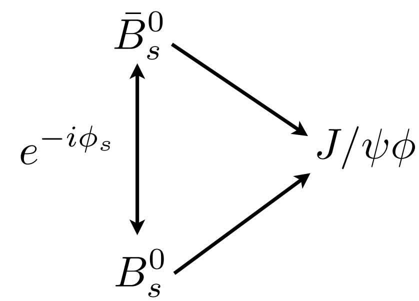
$\phi_s \Rightarrow \ldots$

[Details: P. Ball & R.F. (2006)]

CP Violation in $B_s^0 \to J/\psi\phi$

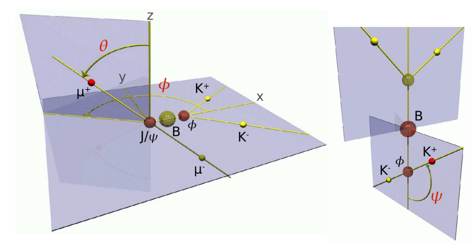






- Interference effects through B_s^0–$\bar{B}_s^0$ mixing:
  - *Mixing-induced* CP violation in time-dependent rates.
  - Hadronic parameters cancel to good approximation:

$$\Rightarrow \boxed{\text{CP asymmetries} \sim \sin\phi_s}$$



- Final state is mixture of CP-odd and -even eigenstates:

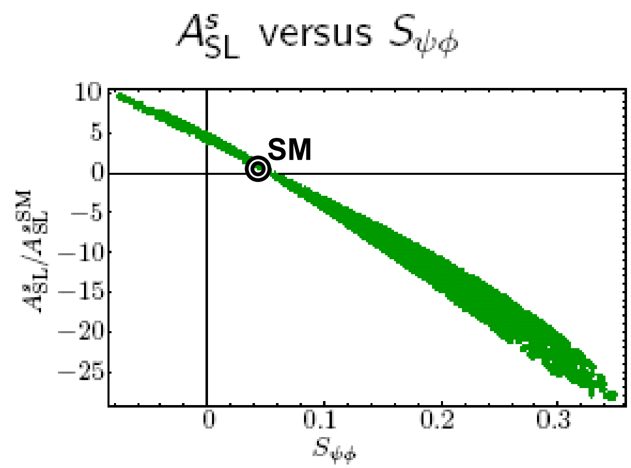
$\to$ disentangle through $J/\psi[\to \mu^+\mu^-]\phi[\to K^+K^-]$ angular distribution.

- *Smallish* CPV in the SM: $\Rightarrow$ $\boxed{\text{sensitive probe for NP in } B_s^0\text{–}\bar{B}_s^0 \text{ mixing}}$

[Dighe, Dunietz & R.F. ('99); Dunietz, R.F. & Nierste ('01); Faller, R.F. & Mannel ('08)]

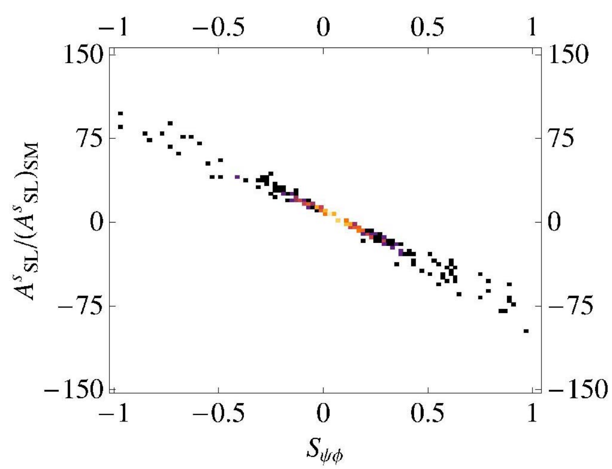
Examples of Specific NP Analyses ($S_{\psi\phi} = -\sin\phi_s$)

- Littlest Higgs Model with T-Parity (LHT):[3]



[Blanke, Buras, Poschenrieder, Recksiegel, Tarantino, Uhlig & Weiler (2007)]

- Warped Extra Dimensions:

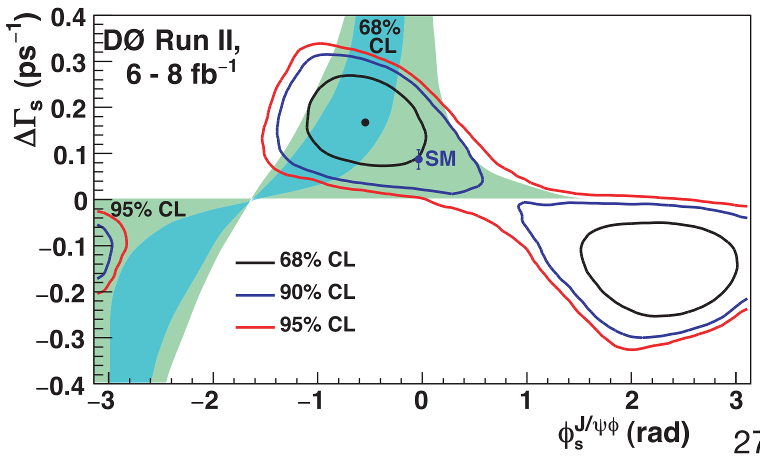


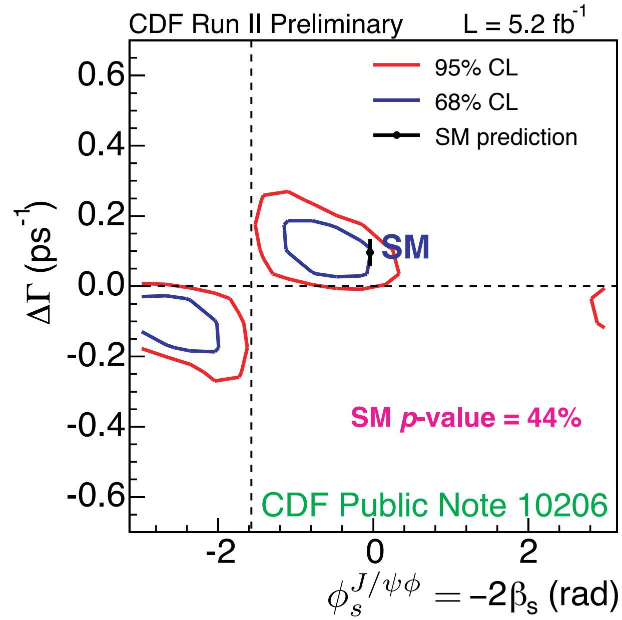
[Blanke, Buras, Duling, Gori & Weiler (2009)]

[3] $A^{sSM}_{SL} \sim 2 \times 10^{-5}$: "wrong-charge" lepton asymmetry measuring CP violation in B^0_s–$\bar{B}^0_s$ oscillations.

Tevatron $B_s^0 \to J/\psi\phi$ Results

- Interesting results on this channel since 2008 ...
- Picture in the Summer of 2011:





$\phi_s^{D\O} = -\left(31.5^{+20.6}_{-21.8}\right)^\circ$ $\qquad$ $\phi_s^{CDF} = [-59.6^\circ, -2.3^\circ]$ (68% C.L.)

  - DØ includes also the anomalous like-sign dimuon charge asymmetry;
  - CDF plot uses only $B_s \to J/\psi\phi$ data.

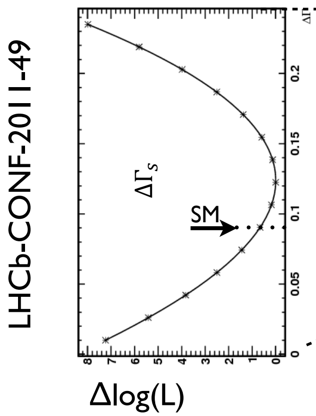
- Bad news: situation is (still...) not conclusive (?)

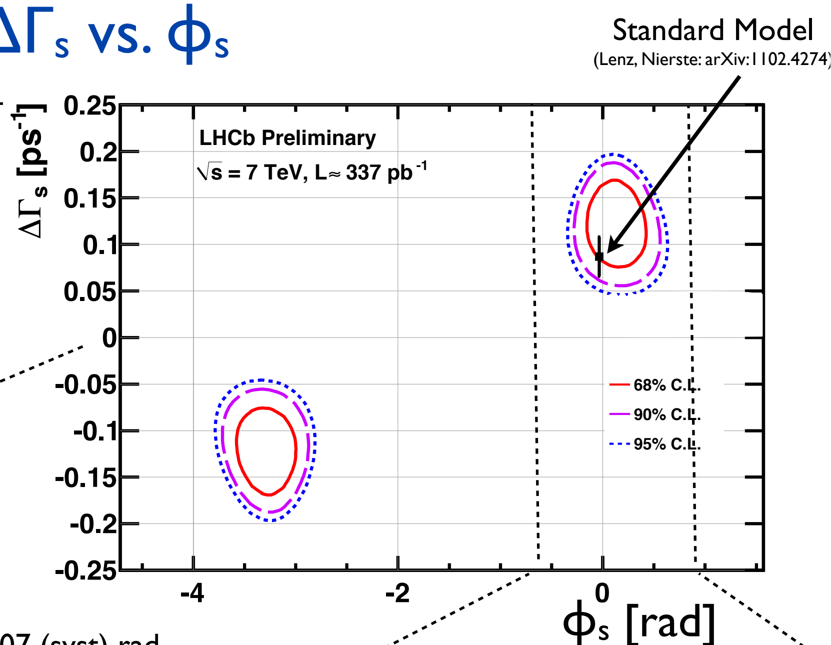
[R. van Kooten @ Lepton–Photon 2011 ⊕ Stefan Söldner-Rembold's talk]

LHCb $B_s^0 \to J/\psi\phi$ Results

- Update at Lepton–Photon 2011:

$B_s \to J/\psi\varphi$: $\Delta\Gamma_s$ vs. ϕ_s



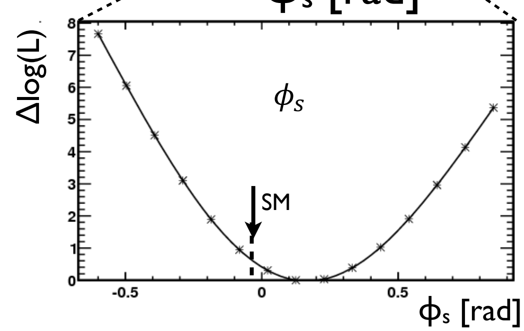


Most precise measurement of ϕ_s

- ϕ_s = 0.13 ± 0.18 (stat) ± 0.07 (syst) rad
- Consistent with SM

4 σ Evidence for $\Delta\Gamma_s \neq 0$:

- $\Delta\Gamma_s$ = 0.123 ± 0.029 (stat) ± 0.008 (syst) ps^{-1}
- Γ_s = 0.656 ± 0.009 (stat) ± 0.008 (syst) ps^{-1}



- $\phi_s = (7.4 \pm 10.3 \pm 4.0)^\circ$ consistent with $\phi_s^{SM} = -2.1^\circ$ $\to$ stay tuned ...

[G. Raven @ Lepton–Photon 2011]

Prospects for $B_s \to J/\psi\phi$

- Experimental reach @ LHCb: *very impressive ...*
  - End of first phase of LHCb ($5\,\text{fb}^{-1} \sim$ 2015): $\sigma(\phi_s)_{\text{exp}} \sim 1^\circ$
  - LHCb upgrade ($50\,\text{fb}^{-1}$): $\sigma(\phi_s)_{\text{exp}} \sim 0.3^\circ$ [M. Merk @ Beauty 2011]

- However: *SM penguin effects were so far fully neglected:*[4]

$$A(B_s^0 \to J/\psi\phi) \propto \mathcal{A}_f \left[1 + \lambda^2(ae^{i\theta})e^{i\gamma}\right]$$

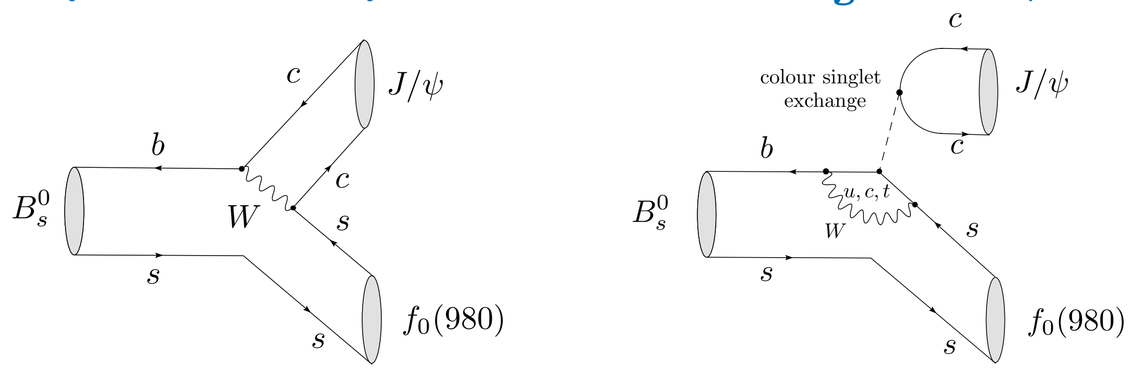
  - Impact of these corrections: $\mathcal{A}_{\text{CP}}^{\text{mix}} = \sin\phi_s \;\to\; \sin(\phi_s + \Delta\phi_s)$.
  - Hadronic shift $\Delta\phi_s$ can be controlled through $B_s^0 \to J/\psi\bar{K}^{*0}$.
    [CDF reported observation of this channel @ ICHEP 2010; LHCb @ Beauty 2011]

- Two scenarios: [$\Delta\phi_s$ must in any case be controlled to match LHCb accuracy]
  - *Optimistic:* $|\mathcal{A}_{\text{CP}}^{\text{mix}}| \sim 40\%$ would be an unambiguous signal of NP!
  - *Pessimistic:* $\mathcal{A}_{\text{CP}}^{\text{mix}} \sim -(5...10)\%$ would require further work from theorists and experimentalists to clarify the picture ...

[Faller, R.F. & Mannel (2009)]

[4] $\lambda \equiv |V_{us}| = 0.22$ is the Wolfenstein parameter of the CKM matrix.

Another (Emerging) Hot Topic: $B_s^0 \to J/\psi f_0(980)$



- $f_0(980)$ is a scalar $J^{PC} = 0^{++}$ state: $\Rightarrow$ no angular analysis is required!

- Dominant mode: $B_s^0 \to J/\psi f_0$ with $f_0 \to \pi^+\pi^-$.

- Recent observation of $B_s^0 \to J/\psi f_0$ at LHCb, Belle, DØ and CDF:

$$R_{f_0/\phi} \equiv \frac{\mathrm{BR}(B_s^0 \to J/\psi f_0; f_0 \to \pi^+\pi^-)}{\mathrm{BR}(B_s^0 \to J/\psi \phi; \phi \to K^+K^-)} \sim 0.25$$

... but as no angular analysis is required:

$\Rightarrow$ $B_s^0 \to J/\psi f_0$ offers an interesting alternative to $B_s^0 \to J/\psi \phi$

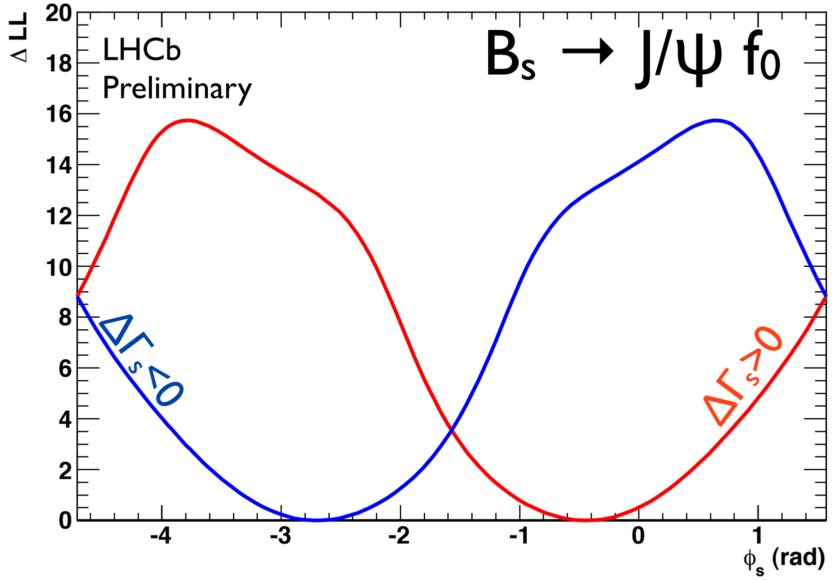
[S. Stone & L. Zhang (2009)]

New Results for $B_s^0 \to J/\psi f_0(980)$

- First measurement of the effective lifetime: [CDF, arXiv:1106.3682 [hep-ex]]

$$\tau_{J/\psi f_0} = \left[1.70^{+0.12}_{-0.11}\,(\text{stat}) \pm 0.03\,(\text{syst})\right] \text{ ps}$$

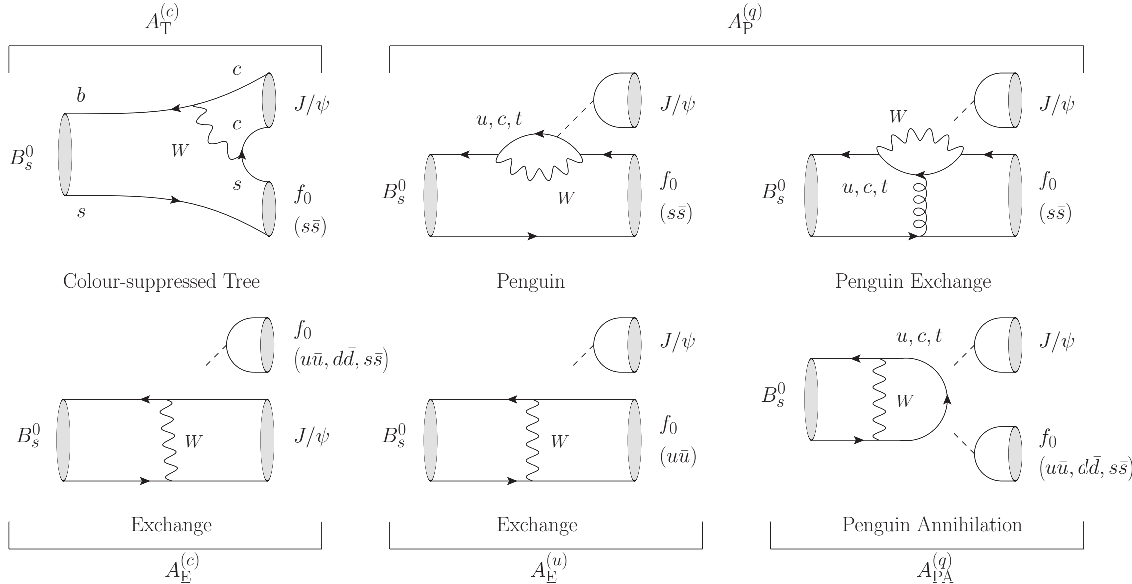
- First study of CP violation in $B_s^0 \to J/\psi f_0$: [LHCb, G. Raven @ LP 2011]



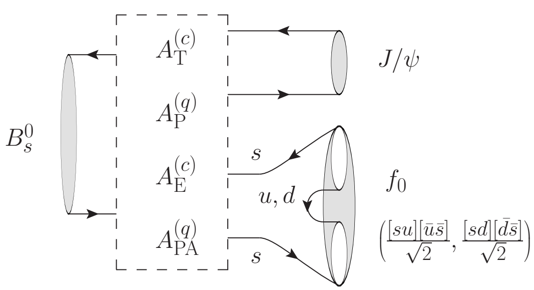
$\to \phi_s = -(25 \pm 25 \pm 1)^\circ \to$ stay tuned ...

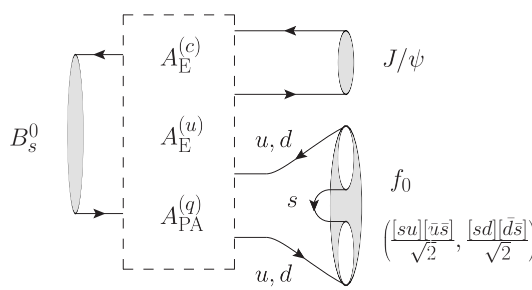
Theoretical Uncertainties?

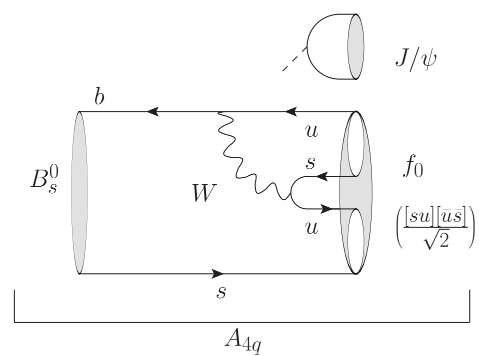
- Decay topologies:



- The composition of the $f_0(980$ is still poorly known: $\to$ 2 benchmarks:
  - Quark–antiquark: $|f_0(980)\rangle = \cos\varphi_{\rm M}|s\bar{s}\rangle + \sin\varphi_{\rm M}\frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)$
  - Tetraquark: $|f_0(980)\rangle = \frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]\right) \to$



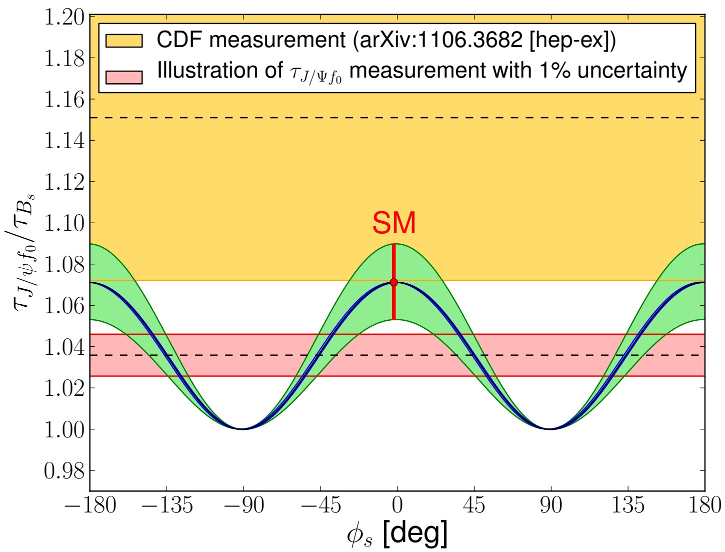


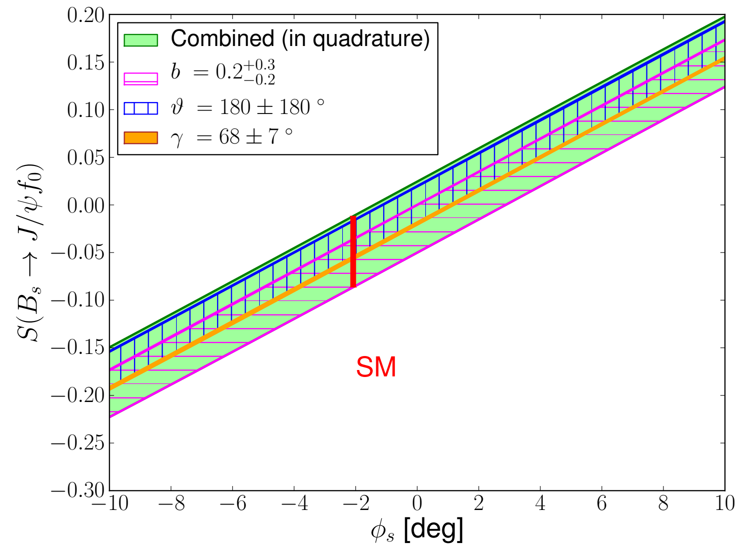


no counterpart in $q\bar{q}$!

[R.F., Rob Knegjens & Giulia Ricciardi, arXiv:1109.1112 [hep-ph]]

- Detailed analysis: $A(B_s^0 \to J/\psi f_0) \propto \left[1 + \lambda^2 (b e^{i\vartheta}) e^{i\gamma}\right]$
  - Effective $B_s^0 \to J/\psi f_0$ lifetime and mixing-induced CP asymmetry S are quite robust with respect to hadronic effects encoded in $be^{i\theta}$:





- Should smallish CPV $-0.1 \lesssim S \lesssim 0$ be found: [LHCb@LP11: $S = -0.43^{+0.43}_{-0.34}$]

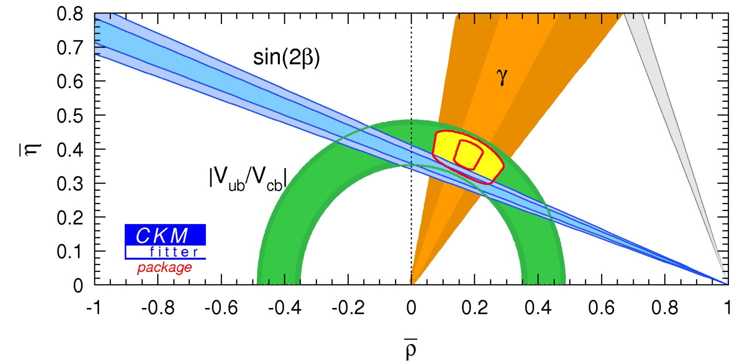
$\Rightarrow$ crucial to constrain hadronic corrections to disentangle NP from SM

- Control channel: $B_d^0 \to J/\psi f_0(980)$ $\Rightarrow$ *search for it & add to agenda!*

[R.F., Rob Knegjens & Giulia Ricciardi, arXiv:1109.1112 [hep-ph]]

Implications of the Data for the B_d^0 System

- Tension in fit of UT: $(\phi_d)_{J/\psi K^0} - 2\beta_{\rm true} = -(8.7^{+2.6}_{-3.6} \pm 3.8)^\circ \to$ NP!?



- SM corrections: doubly Cabibbo-suppressed penguins $(\lambda \equiv |V_{us}| = 0.22) \to$

$$\boxed{A(B_d^0 \to J/\psi\, K_{\rm S}) \propto \left[1 + \epsilon a e^{i\theta} e^{i\gamma}\right]} \quad (\epsilon \equiv \lambda^2/(1-\lambda^2) \sim 0.05)$$

- Generalized expression for mixing-induced CP violation: $[\phi_d = 2\beta + \phi_d^{\rm NP}]$

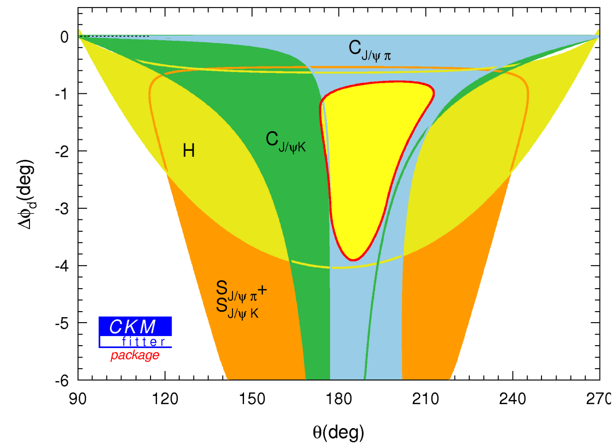
$$\frac{S(B_d \to J/\psi K_{\rm S})}{\sqrt{1 - C(B_d \to J/\psi K_{\rm S})^2}} = \sin(\phi_d + \Delta\phi_d)$$

$$\sin\Delta\phi_d \quad \propto \quad 2\epsilon a \cos\theta \sin\gamma + \epsilon^2 a^2 \sin 2\gamma$$

$$\cos\Delta\phi_d \quad \propto \quad 1 + 2\epsilon a \cos\theta \cos\gamma + \epsilon^2 a^2 \cos 2\gamma$$

- <u>$\Delta\phi_d$ *cannot* be calculated:</u> $\Rightarrow$ use $B_d^0 \to J/\psi\pi^0$ data & $SU(3)$

$$A(B_d^0 \to J/\psi\pi^0) \propto \left[1 - a e^{i\theta} e^{i\gamma}\right]$$



 – Fit to all current data, allowing also for $SU(3)$-breaking corrections:

 $\Rightarrow \Delta\phi_d \in [-6.7, 0.0]^\circ$, i.e. softens the tension in the fit of the UT.

 – NP mixing phase: $\phi_d^{\rm NP} \in [-14.9, 4.0]^\circ$, i.e. no significant effect.

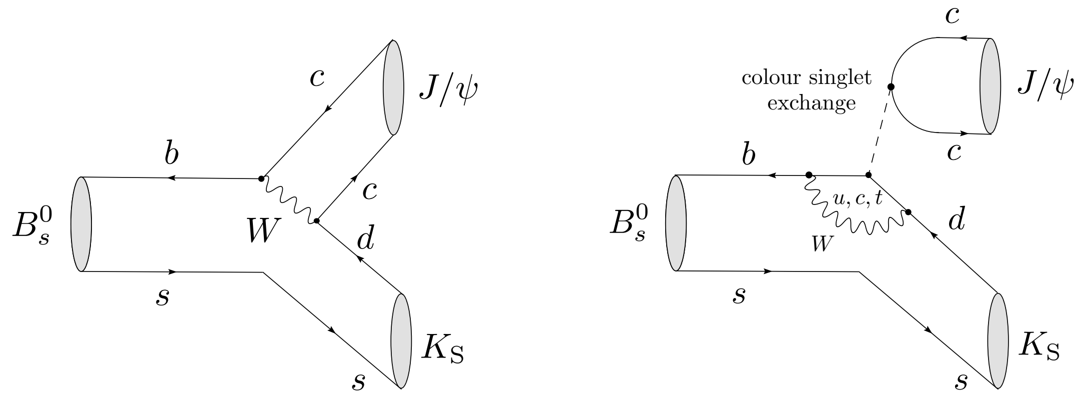
- <u>Observation:</u>

 – The quality of the B-factory data has essentially reached a level of precision where subleading SM effects have to be included!

 – This will be even much more relevant in the LHC era, but $B_d^0 \to J/\psi\pi^0$ is very challenging for this experiment (super-B factory could do) $\Rightarrow$

[S. Faller, R.F., M. Jung & T. Mannel (2008)]

A New Channel for LHCb: $B_s^0 \to J/\psi K_{\rm S}$



$$A(B_s^0 \to J/\psi K_{\rm S}) \propto \mathcal{A}\left[1 - a e^{i\theta} e^{i\gamma}\right]$$

- U-spin symmetry:[5] $\boxed{B_s^0 \to J/\psi K_{\rm S} \Leftrightarrow B_d^0 \to J/\psi K_{\rm S}}$ [R.F. (1999)]
  - Determination of the UT angle γ.
  - Control of penguins in the determination of ϕ_d from $B_d^0 \to J/\psi K_{\rm S}$.

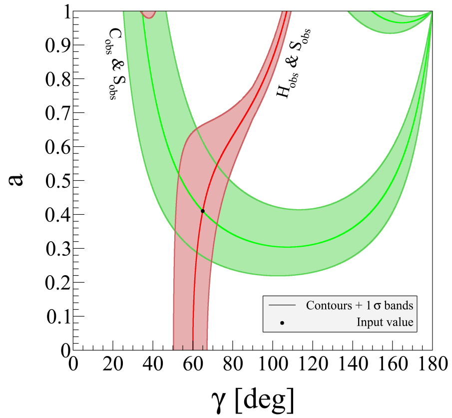
- Experimental status of the $B_s^0 \to J/\psi K_{\rm S}$ decay:
  - Recent news from LHCb [P. Koppenburg @ Physics in Collision 2011]:

$$\frac{\text{BR}(B_s \to J/\psi K_{\rm S})}{\text{BR}(B_d \to J/\psi K_{\rm S})} = 0.0378 \pm 0.0058(\text{stat}) \pm 0.0020(\text{syst}) \pm 0.0030(\text{frag})$$

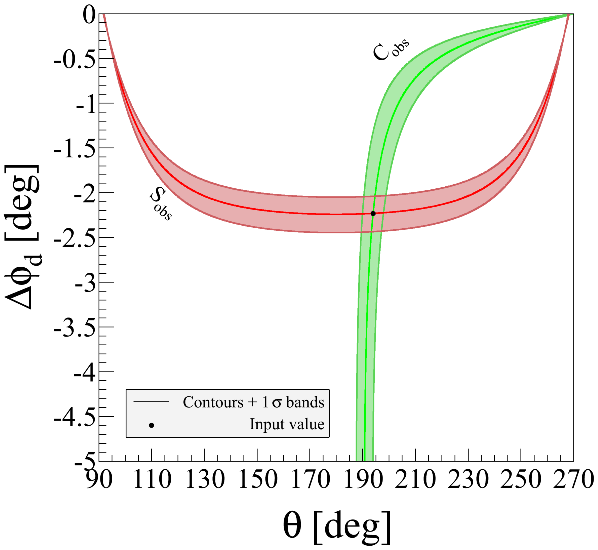
  - First observation by CDF @ ICHEP2010: $0.041 \pm 0.007 \pm 0.004 \pm 0.005$

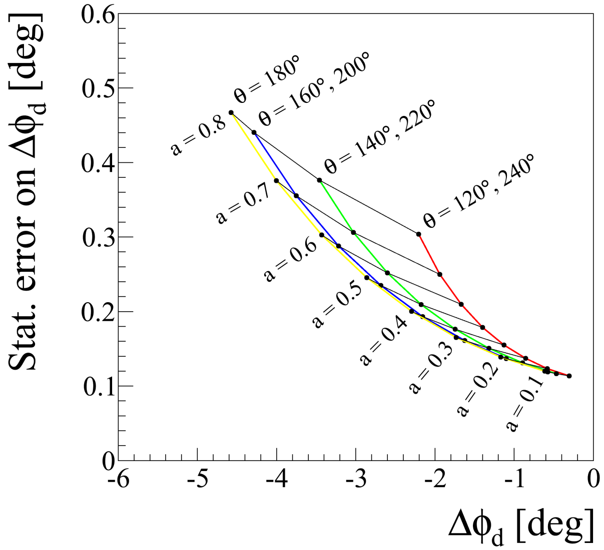
[5] U spin is an $SU(2)$ subgroup of strong $SU(3)_{\rm F}$ relating down and strange quarks to each other.

- Fresh look: [with Kristof De Bruyn & Patrick Koppenburg, arXiv:1010.0089 [hep-ph]]



  - First LHCb (toy) feasibility study: $\to \gamma$ extraction;
  - *Main application:* control of the penguin effects in $(\phi_d)_{J/\psi K_S}$:





$\Rightarrow$ interesting study for the LHCb upgrade $[100\,\mathrm{fb}^{-1}]$

⋆ Further Benchmark Decays

for the

LHCb Experiment

→ very rich physics programme ...

[Detailed studies: LHCb Collaboration, LHCb-PUB-2009-029, arXiv:0912.4179v2]

Two Major Lines of Research

1. Precision measurements of the angle γ of the UT:

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

     current B-factory data: $\gamma|_{D^{(*)}K^{(*)}} = \begin{cases} (71^{+21}_{-25})^\circ & \text{[CKMfitter]} \\ (73 \pm 11)^\circ & \text{[UTfit]} \end{cases}$

   - 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 $B_d^0 \to D_d^+ D_d^-$

2. "Rare" (strongly suppressed) decays which are absent at the SM tree level:

   - $B_s^0 \to \phi\phi$
   - ◇ $B_s^0 \to \mu^+\mu^-$, $B_d^0 \to \mu^+\mu^-$ (ATLAS & CMS are competitive)
   - $B_d^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$; ...

$\to$ let's have a closer look at two of my "favourites" ◇ ...

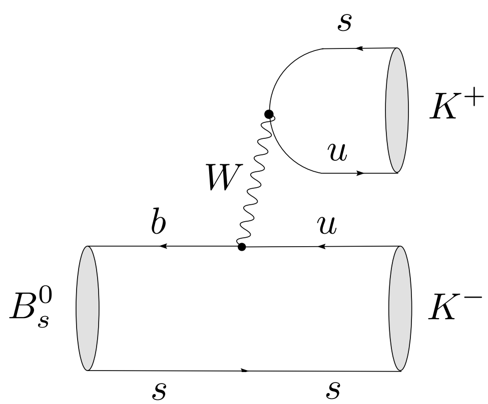
The

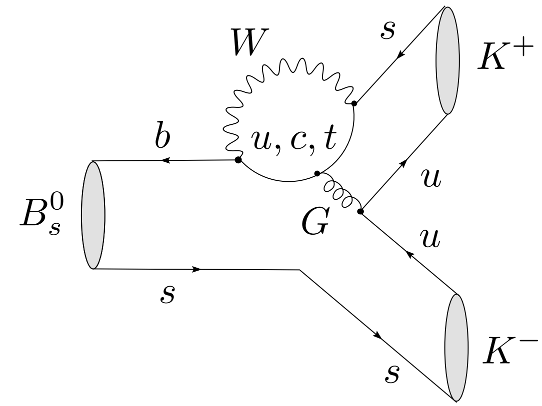
$$\boxed{B_s \to K^+K^-,\, B_d \to \pi^+\pi^-}$$

System

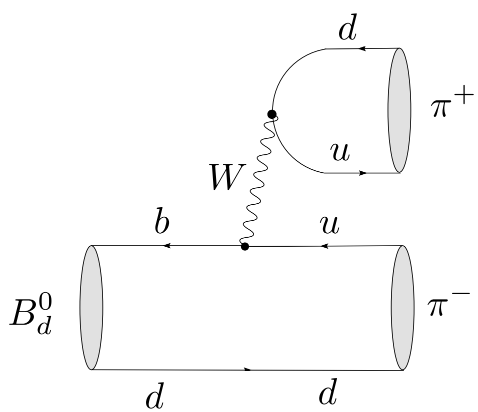
Decay Topologies & Amplitudes

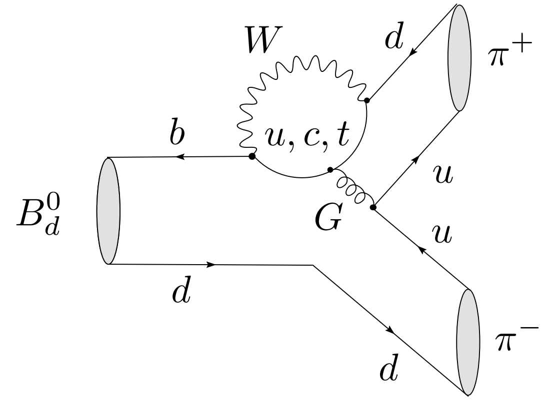
- $B_s^0 \to K^+K^-$: $$A(B_s^0 \to K^+K^-) \propto \mathcal{C}' \left[e^{i\gamma} + \left(\frac{1-\lambda^2}{\lambda^2}\right) d' e^{i\theta'}\right]$$





- $B_d^0 \to \pi^+\pi^-$: $$A(B_d^0 \to \pi^+\pi^-) \propto \mathcal{C} \left[e^{i\gamma} - d\, e^{i\theta}\right]$$





$$\Rightarrow \quad \boxed{s \leftrightarrow d}$$

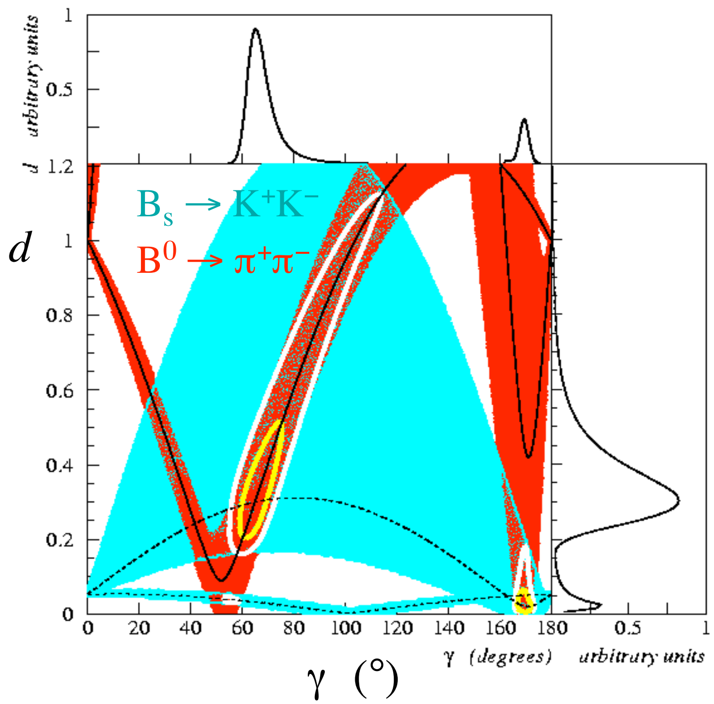
- The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:

$$\boxed{U\text{-spin symmetry}} \quad \Rightarrow \quad d' = d,\ \theta' = \theta$$

  - Determination of γ and hadronic parameters $d (= d')$, θ and θ'.
  - Internal consistency check of the U-spin symmetry: $\theta \stackrel{?}{=} \theta'$.

[R.F. (1999)]

- Detailed studies show that this strategy is very promising for LHCb:



→ experimental accuracy for γ of a few degrees!

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

A Fresh Look:

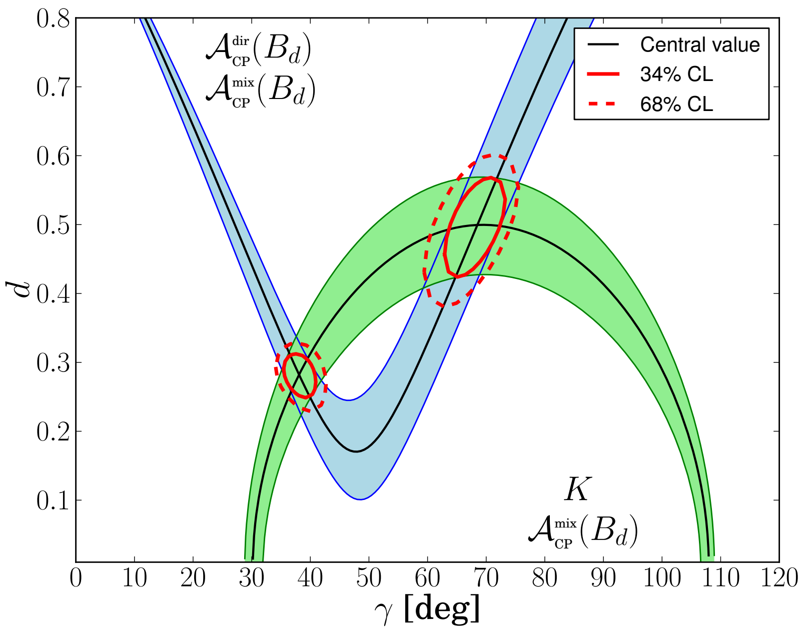
$\rightarrow$ get ready for LHCb data...

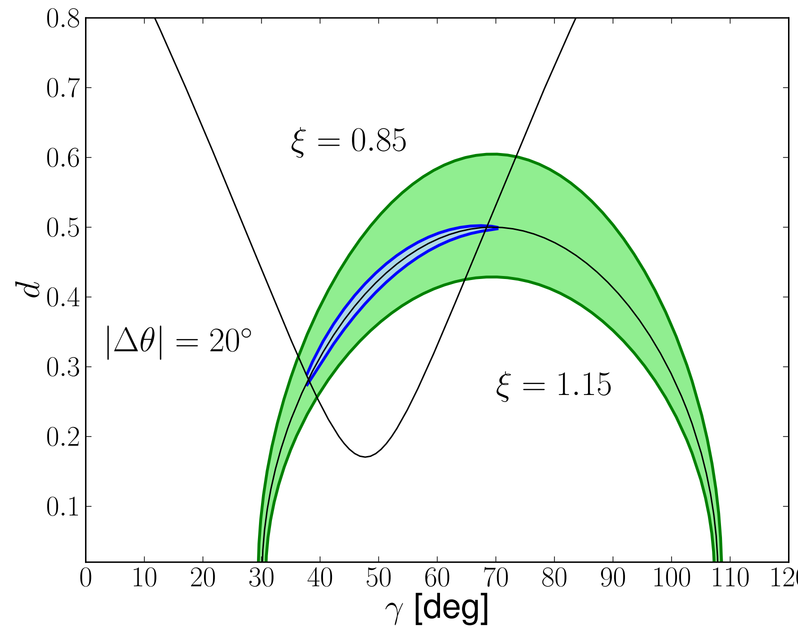
- Use B-factory data as input, as well as ...
- BR($B_s \to K^+K^-$) measurements by CDF and Belle @ $\Upsilon(5S)$,
- updated information of U-spin-breaking form-factor ratios.

[with R. Knegjens, arXiv:1011.1096 [hep-ph]]

Current Picture for γ

- Input data:
  - Information on $K \propto \mathrm{BR}(B_s \to K^+K^-)/\mathrm{BR}(B_d \to \pi^+\pi^-)$;
  - CP violation in $B_d^0 \to \pi^+\pi^-$ and $B_d^0 \to \pi^\mp K^\pm$;
  - U-spin-breaking corrections: $\xi \equiv d'/d = 1 \pm 0.15$, $\Delta\theta \equiv \theta' - \theta = \pm 20^\circ$:





$$\Rightarrow \boxed{\gamma = \left(68.3^{+4.9}_{-5.7}\big|_{\rm input}{}^{+5.0}_{-3.7}\big|_{\xi}{}^{+0.1}_{-0.2}\big|_{\Delta\theta}\right)^\circ}$$

(2-fold ambiguity can be resolved [R.F. ('07)])

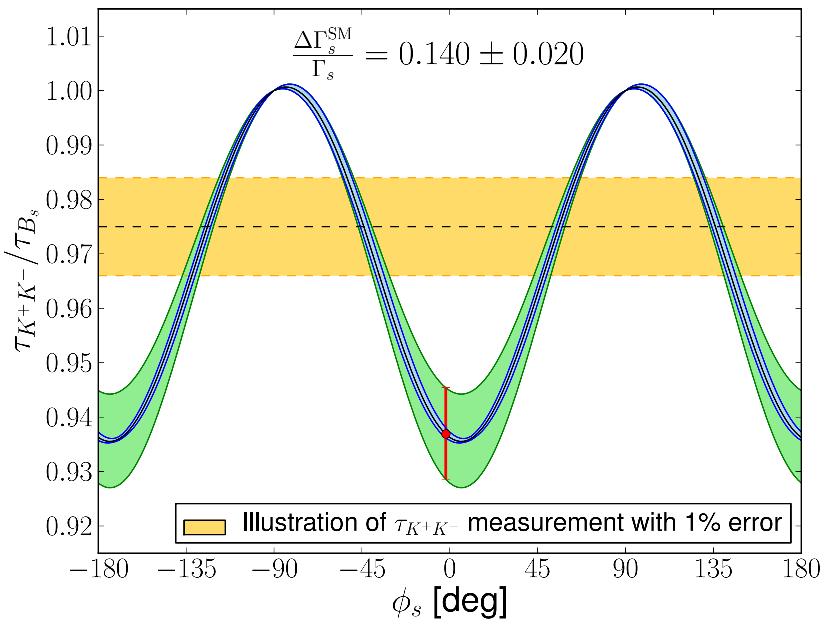
- Fits of the UT: $\gamma = (67.2^{+3.9}_{-3.9})^\circ$ (CKMfitter), $(69.6 \pm 3.1)^\circ$ (UTfit).

The Effective $B_s^0 \to K^+K^-$ Lifetime

- Particularly nice and simple observable: $[\langle\Gamma(B_s(t)\to f)\rangle \to$ "untagged" rate$]$

$$\tau_{K^+K^-} \equiv \frac{\int_0^\infty t\ \langle\Gamma(B_s(t)\to K^+K^-)\rangle\ dt}{\int_0^\infty \langle\Gamma(B_s(t)\to K^+K^-)\rangle\ dt}$$

- Using K, $\mathcal{A}_{\rm CP}^{\rm dir}(B_d\to\pi^\mp K^\pm)$ and $\gamma=(68\pm7)^\circ$ [$\oplus$ U-spin-breaking]: $\Rightarrow$

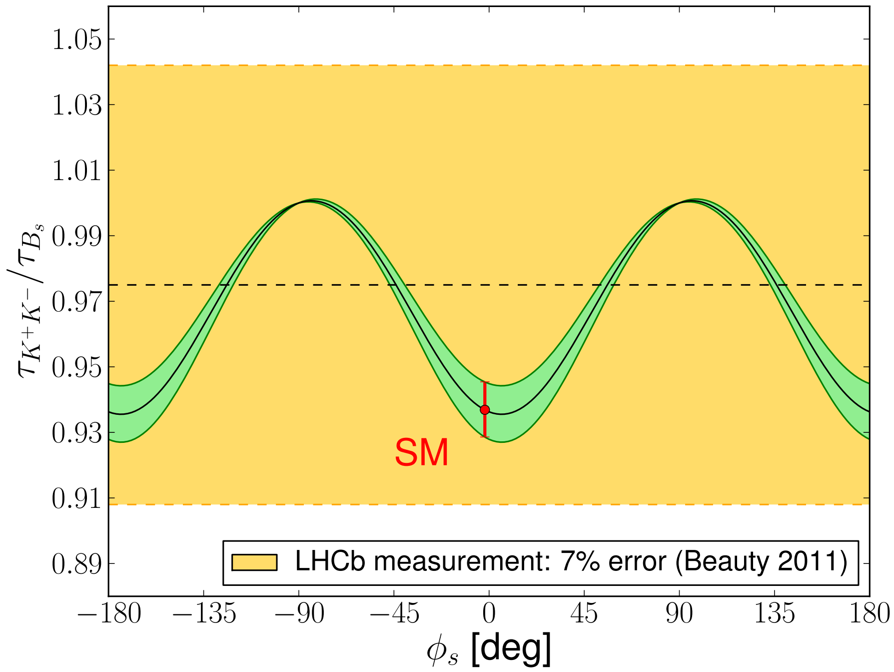


$\Rightarrow$ probe for NP in B_s^0–$\bar{B}_s^0$ mixing

[CDF (2006): $\tau_{K^+K^-} = (1.53\pm0.18\pm0.02)\text{ps}^{-1} \Rightarrow \tau_{K^+K^-}/\tau_{B_s} = 1.04\pm0.12$]

- <u>Recent News from LHCb:</u>

$\rightarrow$ first results on the effective lifetime of $B_s^0 \rightarrow K^+K^-$:



- The error will be reduced soon.
- Analysis to measure CP violation in $B_s^0 \rightarrow K^+K^-$ is also in progress.

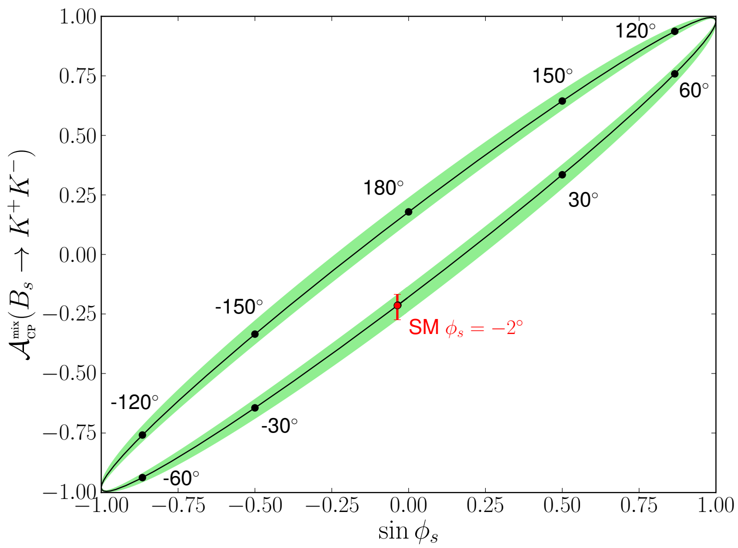
$\rightarrow$ *stay tuned ...*

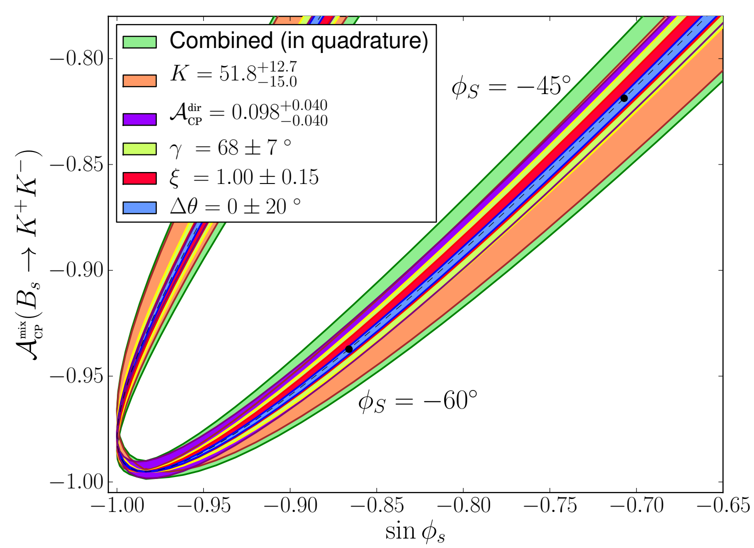
Mixing-Induced $B_s^0 \to K^+K^-$ CP Asymmetry

- The next observable to enter the stage: $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$

$$a_{\rm CP}(t) = \frac{\mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta M_s t) + \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$

- Using K, $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm)$, $\gamma \oplus U$-spin-breaking effects: $\Rightarrow$





– Correlation is very robust with respect to uncertainties.
– Allows also an unambiguous determination of ϕ_s with $\sin\phi_s$.

$\Rightarrow$ **Another interesting probe for NP in B_s^0–$\bar{B}_s^0$ mixing**

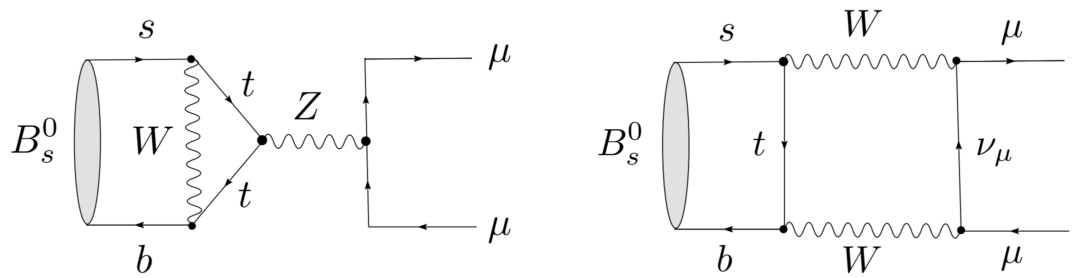
Search for New Physics

in

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

The Rare Decay $B_s^0 \to \mu^+\mu^-$

- Only loop contributions in the SM ("penguins' & "box" diagrams):



$\Rightarrow$ strongly suppressed & sensitive to NP

- Hadronic sector: $\to$ simple situation (only B decay constant f_{B_s} enters):

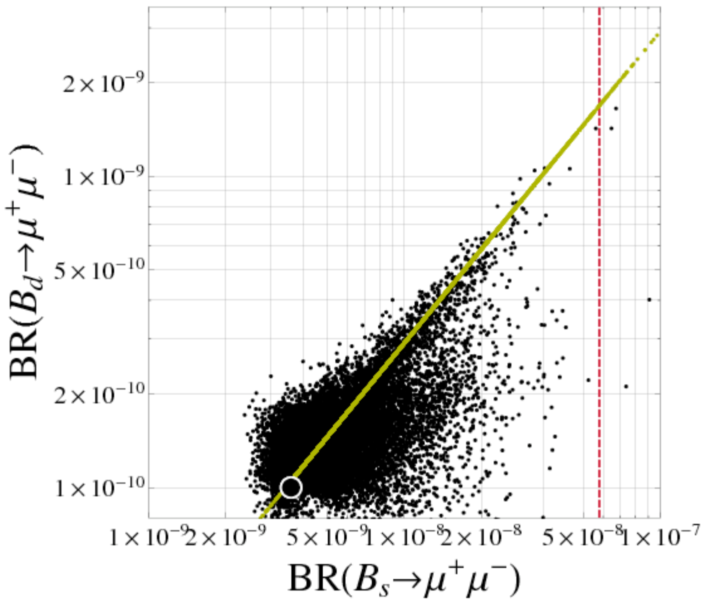
$\Rightarrow$ $B_s^0 \to \mu^+\mu^-$ is one of the cleanest rare B decays

- SM prediction: BR$(B_s \to \mu^+\mu^-) = (3.6 \pm 0.4) \times 10^{-9}$ [A.J. Buras ('09)]

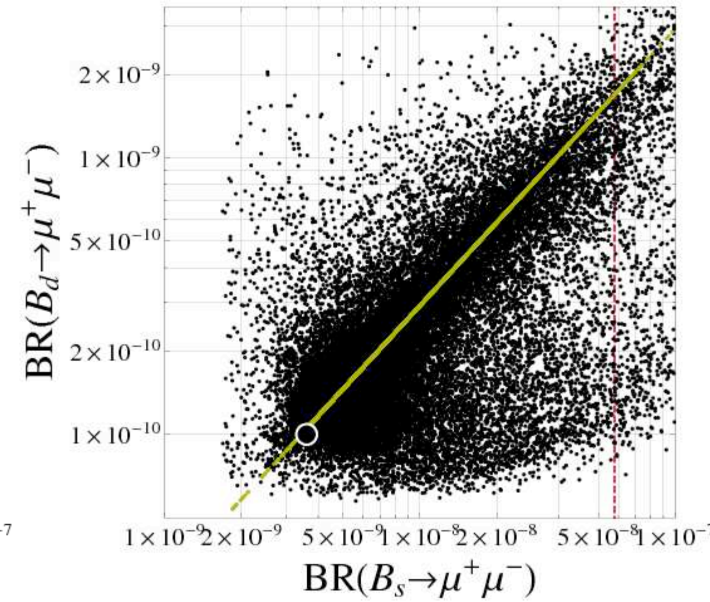
NP may enhance BRs significantly...

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

- <u>Example of a recent analysis:</u> $\rightarrow$ *supersymmetric flavour models:*



(RVV2 model)



(δLL model)

[Altmannshofer, Buras, Gori, Paradisi & Straub (2009);
see also review by A. Buras, arXiv:1012.1447 [hep-ph]]

Experimental Status:

- Tevatron:
  - DØ (2010): BR$(B_s^0 \to \mu^+\mu^-) < 5.1 \times 10^{-8}$ (95% C.L.)
  - CDF (2011): BR$(B_s^0 \to \mu^+\mu^-) < 4.0 \times 10^{-8}$ (95% C.L.)

    $\oplus$ report of observation of an excess of B_s candidates (!):

    $$\text{BR}(B_s^0 \to \mu^+\mu^-) = (18^{+11}_{-9}) \times 10^{-9} \ \ldots$$

- Large Hardon Collider:
  - CMS (2011): BR$(B_s^0 \to \mu^+\mu^-) < 1.9 \times 10^{-8}$ (95% C.L.)
  - LHCb (2011): BR$(B_s^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8}$ (95% C.L.)
  - 1st LHC combined limit: BR$(B_s^0 \to \mu^+\mu^-) < 11 \times 10^{-9}$ (95% C.L.)

    $\to$ LHC upper bound already $\sim 3 \times$ SM value ...

[G. Raven @ Lepton–Photon 2011, LHCb-CONF-2011-047]

The Limiting Factor for the Measurement:

- The analysis of $B_s^0 \to \mu^+\mu^-$ relies on normalization channels:

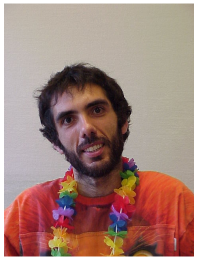
$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B_q \to X)\frac{\epsilon_X}{\epsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}\frac{f_q}{f_s}$$

  - 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_s/f_d *is the major source of uncertainty:*

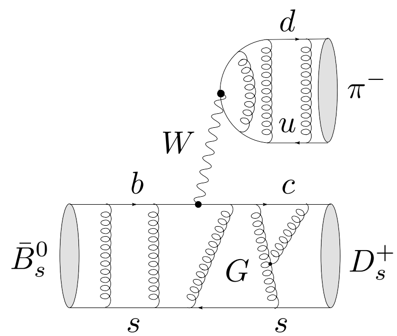
$\Rightarrow$ "boring" non-perturbative, hadronic parameter ...

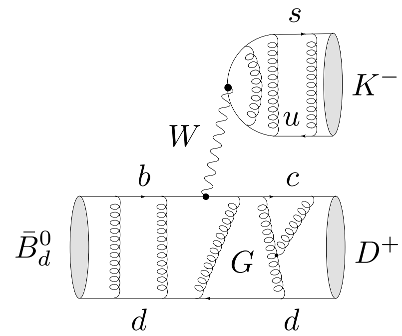
- New method: $\to$ use non-leptonic B decays to *determine* f_s/f_d ...



$\Rightarrow$ U-spin-related $\bar{B}_s^0 \to D_s^+\pi^-$, $\bar{B}_d^0 \to D^+K^-$ system:

[R.F., Nicola Serra & Niels Tuning (2010)]

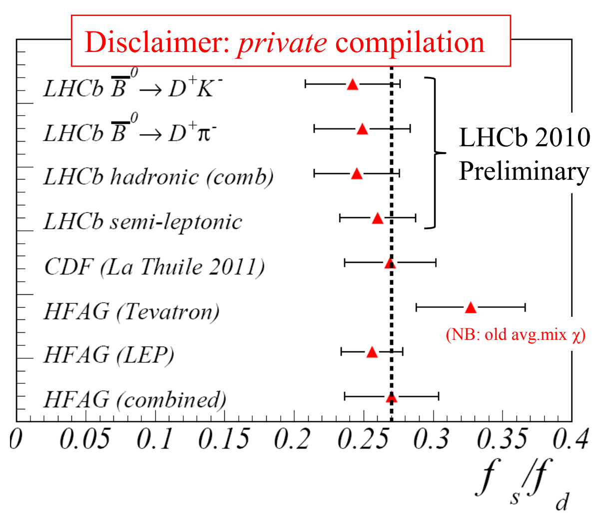




- Prime examples for "factorization" (but so far no application ...) $\Rightarrow$
- Ratio of branching ratios can be calculated:
  - Non-fact. $SU(3)$-breaking corrections: tiny (constrainted through data).
  - Factorizable $SU(3)$-breaking corrections:

    $\rightarrow$ form-factor ratio [QCD sum rules $\oplus$ lattice QCD (in progress)]:

$$\Rightarrow \frac{f_s}{f_d} = \underbrace{\frac{N_s}{N_d} \times \frac{\epsilon(\bar{B}^0_d \to D^+K^-)}{\epsilon(\bar{B}^0_s \to D^+_s\pi^-)}}_{\text{experiment}} \times \underbrace{\frac{\mathrm{BR}(\bar{B}^0_d \to D^+K^-)}{\mathrm{BR}(B_s \to D^+_s\pi^-)}}_{\text{theory}}$$

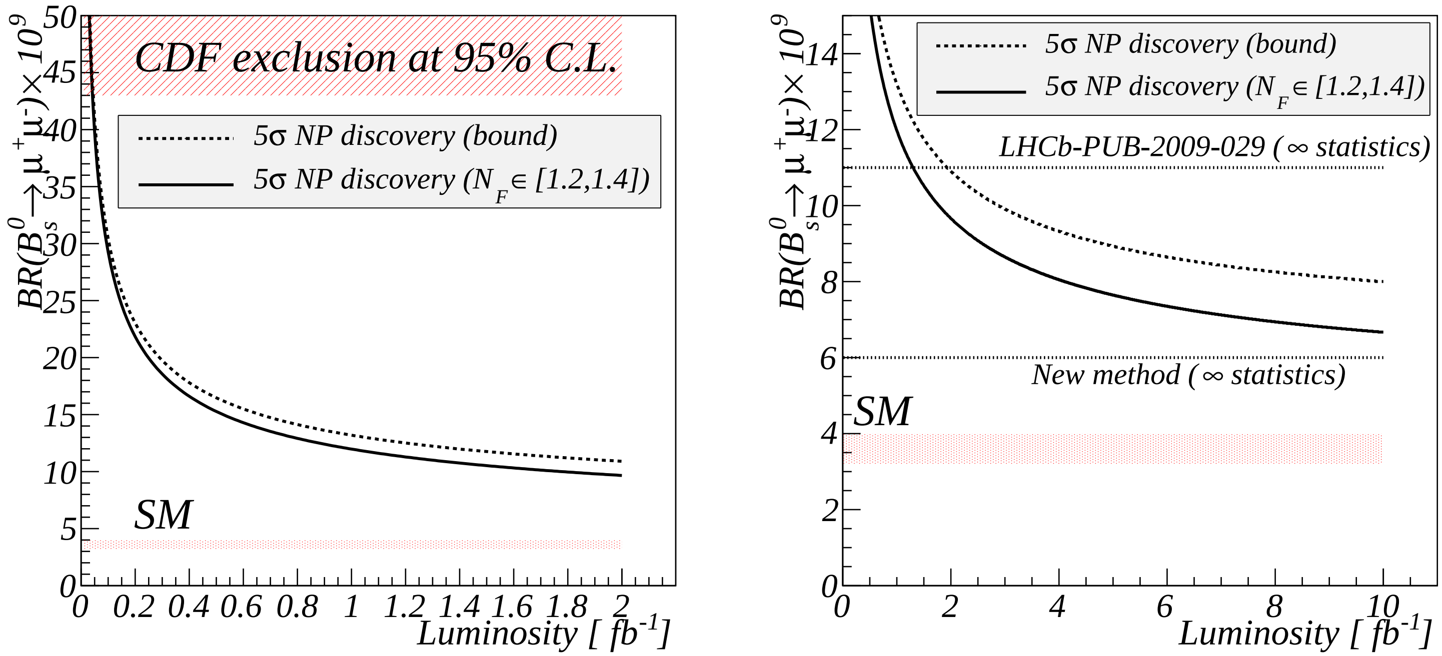


Niels Tuning @ Beauty 2011

[LHCb, arXiv:1106.4435 [hep-ex] $\rightarrow$ PRL]

- Resulting NP Reach at LHCb through New Method for f_s/f_d:

$\rightarrow$ contours for the detection of a 5σ NP signal ("toy" study):



$\Rightarrow$ $B_s \rightarrow \mu^+\mu^-$ NP reach at LHCb is increased by ~ 2

[R.F., N. Serra & N. Tuning (2010)]

Various

other

Interesting Topics ...

Examples

- 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: we have to struggle with 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?

Conclusions & Outlook

Where Do We Stand in B Physics?

- Tremendous progress in B physics in the last decade:

  Fruitful interplay between *theory* $\oplus$ *experiment*

  - e^+e^- B factories: have produced $\sum \mathcal{O}(10^9)$ $B\bar{B}$ pairs;
  - Tevatron: first pioneering B_s results.

  $\rightarrow$ *Data agreed globally with CKM, but also a few potential deviations*

- Towards new frontiers in B physics: LHC $\rightarrow$ already many results:

  - Full exploitation of the B_s physics potential has started!
  - First studies of CP violation: $B^0_s \to J/\psi\phi$, ...
  - New analyses of rare decays: $B^0_s \to \mu^+\mu^-$, $B^0_d \to K^{*0}\mu^+\mu^-$, ...

- Still no signals for New Physics (as from the direct searches):

  - Impressive (also frustrating ...), but we are still at the beginning.
  - We will continue to see more and more precise measurements ...

An Optimistic Scenario: If Nature is Kind (!?) ...

- First unambiguous signs for NP @ LHC in the flavour sector:
  - Could eventually emerge @ LHCb as CP violation in $B_s^0 \to J/\psi\phi$.
  - Would imply *new sources of CP violation!*
  - Study correlations with observables provided by other B decays.

$\to$ NP reach limited by *precision*

- Ideally, NP signals would be complemented by collider physics:
  - Direct signals of new particles @ ATLAS and CMS ($\oplus$ Tevatron).
  - Measure masses, couplings of new particles (e.g. Z' bosons, SUSY).
  - Flavour-physics observables determine then the new flavour- and CP-violating structures (NP particle masses, couplings important input).

$\to$ NP reach limited by the *energy* of the LHC (or ILC, CLIC, ...)

- LHC data collected so far: $\Rightarrow$ *prepare to deal with smallish NP effects...*