Flavour Physics: Theoretical Status and Prospects

ROBERT FLEISCHER

Nikhef & Vrije Universiteit Amsterdam

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• Setting the Stage
• Theoretical Framework
• Studies of CP Violation
• Studies of Rare Decays
• Concluding Remarks
Setting the Stage
Status @ LHC High-Energy Frontier

- Examples of New Physics searches @ ATLAS: → no signals  (CMS similar)

- SUSY:

- Exotics:
... but “Higgs-like” particle @ ATLAS and CMS

- Combined ATLAS and CMS measurement of the Higgs mass:

\[ m_H = [(125.09 \pm 0.21\text{ (stat)} \pm 0.11\text{ (syst)}) \text{ GeV}] \]

[ATLAS & CMS Collaborations, PRL 114 (2015) 191803]

- Key question: is the new particle really the SM Higgs particle?
Status @ LHC High-Precision Frontier

- **Flavour Physics:**
  - Observables are globally consistent with the Standard Model.
  - Some “tensions” with respect to the SM have recently emerged:
    \[
    \rightarrow \text{not (yet?) conclusive, but hot topics for this conference!}
    \]

- **Implications for the general structure of NP:**
  \[
  \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{NP}}(\varphi_{\text{NP}}, g_{\text{NP}}, m_{\text{NP}}, ...)
  \]
  - Large characteristic NP scale \( \Lambda_{\text{NP}} \), 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).*

- **Much more is yet to come:**
  \[
  \rightarrow \text{LHC run II, Belle II, LHCb upgrade}
  \]
  \[
  \ldots \text{but prepare to deal with “smallish/challenging” NP effects!}
  \]
The Quark-Flavour Code

• Quark flavour physics and CP violation in the Standard Model (SM):

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} =
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

quark-mixing matrix, also known as the Caibibo–Kobayashi–Maskawa (CKM) matrix → unitary matrix; complex phase → CP violation

• New Physics (NP): typically new sources for flavour and CP violation.

⇒ encoded in weak decays of $K$, $D$ and $B$ mesons ...
→ before searching for NP, understand the SM picture ...

• The key problem:
  
  – The theory is formulated in terms of quarks, while flavour-physics experiments use their QCD bound states, i.e. $B$, $D$ and $K$ mesons.
  
  – Impact of strong interactions (QCD) → “hadronic” uncertainties

• 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 clean SM relations that could be spoiled by NP ...

• This feature led to the “rise of the $B$ mesons”: → focus of this talk

... after $K$ decays had dominated for 35 years!
→ very rich phenomenology, as complex as the Tokyo Subway Map:

⇒ have to make a selection: challenges, progress & hot topics
Theoretical Framework

... in a nutshell
Hierarchy of Scales

\[ \Lambda_{NP} \sim 10^{(0\ldots?) \text{ TeV}} \gg \Lambda_{EW} \sim 10^{-1} \text{ TeV} \gg \gg \Lambda_{QCD} \sim 10^{-4} \text{ TeV} \]

(very) short distances

long distances

• Powerful theoretical concepts/techniques:

  → “Effective Field Theories”

  – Heavy degrees of freedom (NP particles, top, Z, W) are “integrated out” from appearing explicitly: \( \rightarrow \) short-distance loop functions.

  – Calculation of perturbative QCD corrections.

  – Renormalization group allows the summation of large \( \log(\mu_{SD}/\mu_{LD}) \).

• Applied to the SM and various NP scenarios, such as the following:

  – MSSM, UED, WED, LH, LHT, \( Z' \) models, ...
Low-Energy Effective Hamiltonians

• Separation of short-distance from long-distance contributions (OPE):

\[ \langle f | \mathcal{H}_{\text{eff}} | B \rangle = \frac{G_F}{\sqrt{2}} \sum_j \lambda_{\text{CKM}}^j \sum_k C_k(\mu) \langle f | Q_j^k(\mu) | B \rangle \]

\[ [G_F: \text{Fermi's constant, } \lambda_{\text{CKM}}^j: \text{CKM factors, } \mu: \text{renormalization scale}] \]

• Short-distance physics: [Buras et al.; Martinelli et al. ('90s); ...]

\[ \rightarrow \text{Wilson coefficients } C_k(\mu) \rightarrow \text{perturbative quantities } \rightarrow \text{known!} \]

• Long-distance physics:

\[ \rightarrow \text{matrix elements } \langle f | Q_j^k(\mu) | B \rangle \rightarrow \text{non-perturbative } \rightarrow \text{“unknown”!} \]
Theoretical Challenges ...

- Theoretical precision is generally limited by *strong interactions*:
  - Non-perturbative methods of QCD needed: QCD sum rules, lattice ...

- **Impressive recent progress in Lattice QCD:**
  - $B_K$ parameter (kaon physics), decay constants, form factors, ...
    - $rare \, B_{s,d}^0 \rightarrow \mu^+\mu^-$ decays, semileptonic $B$ decays.
  - Flavour Lattice Averaging Group (FLAG):
    - [http://itpwiki.unibe.ch/flag/](http://itpwiki.unibe.ch/flag/)

- **However, still a big challenge for Lattice QCD:**
  - *non-leptonic* $B$ decays
Theoretical Framework for Non-Leptonic $B$ Decays

\[ |A_j| e^{i\delta_j} \propto \sum_k C_k(\mu) \times \langle f | Q_{ij}^k(\mu) | B \rangle \]

- **QCD factorization (QCDF):**
  Beneke, Buchalla, Neubert & Sachrajda (99–01); Beneke & Jäger (05); ... Bell & Huber (14)

- **Perturbative Hard-Scattering (PQCD) Approach:**
  Li & Yu ('95); Cheng, Li & Yang ('99); Keum, Li & Sanda ('00); ... 

- **Soft Collinear Effective Theory (SCET):**
  Bauer, Pirjol & Stewart (2001); Bauer, Grinstein, Pirjol & Stewart (2003); ...

- **QCD sum rules:**
  Khodjamirian (2001); Khodjamirian, Mannel & Melic (2003); ...

⇒ Lots of (technical) progress, still a theoretical challenge...
Studies of CP Violation
Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements (→ typically strategies to determine the UT angle $\gamma$):

- **Exact relations:** class of pure “tree” decays (e.g. $B \to DK$).
- **Approximate relations,** which follow from the *flavour symmetries of strong interactions*, i.e. $SU(2)$ isospin or $SU(3)_F$:
  \[
  B \to \pi\pi, \ B \to \pi K, \ B_{(s)} \to KK.
  \]

- **Decays of neutral $B_d$ or $B_s$ mesons:**
  - Lead to “mixing-induced” CP violation $S(f)$, in addition to “direct” CP violation $C(f)$ (caused by interference between decay amplitudes).
  - If one CKM amplitude dominates:
    \[
    \Rightarrow \text{hadronic matrix elements cancel in } S(f), \text{ while } C(f) = 0.
    \]
A Brief Roadmap of Quark-Flavour Physics

• CP-B studies through various processes and strategies:

\[ B \to \pi\pi \text{ (isospin), } B \to \rho\pi, B \to \rho\rho \]

\[ R_b \ (b \to u, c\ell\bar{\nu}_\ell) \]

\[ R_t \ (B_q^0 - \bar{B}_q^0 \text{ mixing}) \]

\[ B \to \pi K \text{ (penguins)} \]

\[ B_u^\pm \to K^\pm D \]
\[ B_d \to K^{*0} D \]
\[ B_c^\pm \to D_s^\pm D \quad \text{only trees} \]

\[ B_d \to D^{(*)\pm} \pi^\mp : \gamma + 2\beta \]
\[ B_s \to D_s^\pm K^\mp : \gamma + \phi_s \quad \text{only trees} \]

• Moreover “rare” decays: \( B \to X_s\gamma, B_{d,s} \to \mu^+\mu^-, K \to \pi\nu\bar{\nu}, \ldots \)
  – Originate from loop processes in the SM.
  – Interesting correlations with CP-B studies.

\[
\begin{array}{|c|c|}
\hline
\text{New Physics (NP)} & \Rightarrow \text{Discrepancies (!?)} \\
\hline
\end{array}
\]
• Status of global fits:

– *CKMfitter* Collaboration [http://ckmfitter.in2p3.fr/];
– *UTFit* Collaboration [http://www.utfit.org/UTfit/WebHome]:

⇒ \( \gamma \) has currently still sizeable errors ...
Prospects for Extracting $\gamma$

- Pure tree decays: $B \to D^{(*)} K^{(*)}$ and $B_s \to D_s K$

- The corresponding determinations of $\gamma$ are theoretically clean, i.e. the hadronic matrix elements cancel out (simply speaking).

- Decays are very robust with respect to New-Physics contributions:
  \[ \Rightarrow \text{reference for the “true” Standard Model value of } \gamma. \]

- Excellent prospects for the era of Belle II and the LHCb upgrade:
  \[ \Rightarrow \text{uncertainty of } \Delta \gamma_{\text{exp}} \sim 1^\circ (!) \]
• Decays with loops, i.e. penguin contributions:
  \[ B_s \rightarrow \pi\pi, \pi K, KK \]

\[ \propto A\lambda^4 R_b e^{i\gamma} \]


– Complemented through QCD factorization/SCET/PQCD, calculations of \( SU(3) \)-breaking corrections, etc., [Beneke and Neubert (2003); ...]

• **Goal:** extraction of \((\gamma)_{\text{loops}}\) and comparison with \((\gamma)_{\text{tree}}\)

\[ \Rightarrow \text{will discrepancies show up?} \]

\[ \rightarrow \text{particularly (most) promising method ...} \]
The $B^0_s \to K^+K^-$, $B^0_d \to \pi^+\pi^-$ System

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

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

$\Rightarrow \quad s \leftrightarrow d$
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:

$U$-spin symmetry $\Rightarrow d' = d$, $\theta' = \theta$

- Determination of $\gamma$ and hadronic parameters $d(=d')$, $\theta$ and $\theta'$.
- Internal consistency check of the $U$-spin symmetry: $\theta \equiv \theta'$.

[Determined by R.F. (1999, 2007)]

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

$37k$ $B_s \to K^+K^-$ events/year ($\theta \approx 5^\circ$)

$26k$ $B^0 \to \pi^+\pi^-$ events/year ($\theta_1 \approx 7^\circ$)

$37k$ $B_s \to K^+K^-$ events/year ($\theta \approx 5^\circ$)

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$\gamma$ ($\circ$) vs. $d$ ($\hat{\text{arbitrary units}}$)

$\gamma$ ($\circ$) vs. $\theta$ ($\hat{\text{arbitrary units}}$)

$\gamma$ ($\circ$) vs. $\theta$ ($\hat{\text{arbitrary units}}$)

- Experimental accuracy for $\gamma$ of a few degrees!

[LHCb Collaboration (B. Adeva et al.)
Extraction of $\gamma$

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

\[
\Rightarrow \gamma = (67.7^{+4.5}_{-5.0}|_{\text{input}} + 5.0 |_{\xi} + 0.1 |_{\Delta \theta})^\circ
\]

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

- **“Tree-level” results:** $\gamma = (73.2^{+6.3}_{-7.0})^\circ$ [CKMfitter], $(68.3 \pm 7.5)^\circ$ [UTfit].

**Prospects: “Optimal” Determination of $\gamma$**

- **Measurement of the CP asymmetries of $B_s^0 \rightarrow K^+K^-$:**

  ![Graphs showing CP asymmetries](image)

  - **Green bands:** current SM projection
  - **Current LHCb result**

- $\gamma$ and the hadronic parameters $d = d'$ and $\theta, \theta'$ [→ $U$-spin test] can be determined through the intersection of two *theoretically clean* contours.

- Information on the branching ratios (form factors, etc.) is not needed, but rather provides valuable further insights into $U$-spin-breaking effects.

⇒ look forward to high-precision CPV measurements in $B_s^0 \rightarrow K^+K^-$
Interesting Variant of the Method

- Combines the $B_s \rightarrow K^+K^-$, $B_d \rightarrow \pi^+\pi^-$ U-spin method (see above) with the Gronau–London isospin $B \rightarrow \pi\pi$ analysis:
  - Reduces the sensitivity to $U$-spin-breaking effects.
  - Provides a competitive determination of $\phi_s = -2\beta_s$.

[Ciuchini, Franco, Mishima & Silvestrini (2012)]

- Pioneering LHCb analysis: [$\kappa$ parametrises $U$-spin-breaking effects]

$$\gamma = (63.5^{+7.2}_{-6.7})^\circ, \quad \phi_s \equiv -2\beta_s = - (6.9^{+9.2}_{-8.0})^\circ$$

[LHCb Collaboration, V. Vagnoni et al., arXiv:1408.4368 [hep-ex]]
Application of the U-spin method to $B \rightarrow PPP$ decays:

- Utilises the following decays:

$$B_{d,s}^0 \rightarrow K_S h^+ h^- \ (h = K, \pi)$$

- Time-dependent Dalitz plot analyses allow the measurement of the corresponding branching ratios and CP asymmetries.

- The $U$-spin method – analogous to the $B_s^0 \rightarrow K^+ K^-$, $B_d^0 \rightarrow \pi^+ \pi^-$ system – to extract $\gamma$ can be applied to each point of the Dalitz plot.

- A potential advantage of using three-body decays is that the effects of $U$-spin breaking may be reduced by averaging over the Dalitz plot.

NP could be present, but still cannot be resolved!

Key problem: control hadronic uncertainties ...
Particularly Interesting Decay: $B^0 \rightarrow \pi^0 K^0$

- Isospin relation between neutral $B \rightarrow \pi K$ amplitudes:

$$\sqrt{2} A(B^0 \rightarrow \pi^0 K^0) + A(B^0 \rightarrow \pi^- K^+) = -\left[ (\hat{T} + \hat{C}') e^{i\gamma} + \hat{P}_{ew} \right] \equiv 3A_{3/2}$$

- Implies a correlation between the CP asymmetries:

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

Electroweak “penguin” contribution → NP?

[R.F., S. Jäger, D. Pirjol and J. Zupan ('08); confirmed by Gronau & Rosner ('08)]
Hot Topic in view of $B_d^0 \to K^{*0}\mu^+\mu^-$ @ LHCb:

- Puts also other non-leptonic $B$-meson decays with sensitivity to Electroweak Penguins (again...) into the spotlight:

$$B^+ \to \pi^0 K^+, \quad B_s^0 \to \phi\phi, \quad B_s^0 \to \pi^0\phi, \quad B_s^0 \to \rho^0\phi, \ldots$$
Precision Measurements of the $B^0_q - \bar{B}^0_q$ Mixing Phases
Current Experimental Situation

- $B^0_s - \bar{B}^0_s$ mixing phase:

\[
\phi_{c\bar{c}s} = \phi_s = \phi_{s}^{SM} + \phi_{s}^{NP} = -2\lambda^2\eta + \phi_{s}^{NP}
\]

- HFAG average of the current experimental data:

\[
\phi_s = -(0.86 \pm 2.01)° \quad \text{vs.} \quad \phi_{s}^{SM} = -(2.086^{+0.080}_{-0.069})°
\]
**CP Violation in** $B^0_d \rightarrow J/\psi K_S$

- **SM corrections:** $\rightarrow$ *doubly Cabibbo-suppressed penguins*

\[ A(B^0_d \rightarrow J/\psi K_S) = \left(1 - \frac{\lambda^2}{2}\right) A' \left[1 + \epsilon a' e^{i\theta'} e^{i\gamma}\right] \]  
\[ \epsilon \equiv \frac{\lambda^2}{1 - \lambda^2} \sim 0.05 \]

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

\[ \frac{S(B_d \rightarrow J/\psi K_S)}{\sqrt{1 - C(B_d \rightarrow J/\psi K_S)^2}} = \sin(\phi_d + \Delta\phi_d) \]

\[ \sin \Delta\phi_d \propto 2\epsilon a' \cos \theta' \sin \gamma + \epsilon^2 a'^2 \sin 2\gamma \]
\[ \cos \Delta\phi_d \propto 1 + 2\epsilon a' \cos \theta' \cos \gamma + \epsilon^2 a'^2 \cos 2\gamma \]

[S. Faller, R.F., M. Jung & T. Mannel (2008)]
Towards High-Precision Analyses

• **Era of Belle II and the LHCb upgrade**
  
  – Experimental precision requires the control of the penguin corrections to reveal possible CP-violating NP contributions to $B^0_d - \bar{B}^0_d$ mixing.
  
  – The topic receives increasing interest in the theory community:
    
    R.F., (99); Ciuchini, Pierini & Silvestrini (05, 11); Faller, R.F., Jung & Mannel (08); Gronau & Rosner(08); De Bruyn, R.F. & Koppenburg; Jung (2012); De Bruyn & R.F. (15); Frings, Nierste & Wiebusch (15); ...

• **The hadronic phase shift $\Delta\phi_d$ cannot be calculated in a reliable way:**

  \[ \Rightarrow \text{use data for } B^0_s \rightarrow J/\psi K_S: \]

  – Key feature: → "magnified" penguin parameters (no $\epsilon$ suppression)

  \[ A(B^0_s \rightarrow J/\psi K_S) \propto [1 - ae^{i\theta}e^{i\gamma}] \]

  – $U$-spin flavour symmetry: \[ ae^{i\theta} = a'e^{i\theta'} \]
Constraints on the Penguin Parameters: $\chi^2$ Fit

\( \rightarrow \) uses $SU(3)$ and currently available data on $B \rightarrow J/\psi X$ decays:

- Internal consistency checks look fine, i.e. not any “anomalous” feature.
- The global fit yields $\chi^2_{\text{min}} = 2.6$ for four degrees of freedom $(a, \theta, \phi_d, \gamma)$, indicating good agreement between the different input quantities:

\[
\begin{align*}
a &= 0.19^{+0.15}_{-0.12}, \\
\theta &= (179.5 \pm 4.0)^\circ, \\
\phi_d &= (43.2 \pm 1.8)^\circ
\end{align*}
\]

• Illustration through intersecting contours for the different observables:

\[ a = 0.19^{+0.15}_{-0.12} \]
\[ \theta = (179.5 \pm 4.0) \degree \]
\[ \phi_d = (43.2 \pm 1.8) \degree \]

39 % C.L.
68 % C.L.
90 % C.L.

Constraints on $\Delta \phi_{d}^{\psi K^0_S}$

$\Delta \phi_{d}^{\psi K^0_S} = -(1.10^{+0.70}_{-0.85})^\circ$

$\chi^2$ fit gives "guidance" for the importance of penguin effects.

Prospects: CP Violation in $B_{s}^{0} \rightarrow J/\psi K_{S}$

\[
A(B_{s}^{0} \rightarrow J/\psi K_{S}) = -\lambda A \left[ 1 - ae^{i\theta}e^{i\gamma} \right]
\]

- CP asymmetries allow clean determination of $a$ and $\theta$.
- $U$-spin partner of the $B_{d}^{0} \rightarrow J/\psi K_{S}$ decay:

\[
ae^{i\theta} \overset{U \text{ spin}}{=} a'e^{i\theta'}
\]

[no further dynamical assumptions ($E$ and $PA$)]

- Cleanest penguin control for determination of $\phi_{d}$ from $B_{d}^{0} \rightarrow J/\psi K_{S}$.

• Confidence contours for the CP asymmetries of $B_s^0 \to J/\psi K_S^0$ in the Standard Model following from the global $\chi^2$ fit:

![Confidence contours](image)

\[ A_{CP}^{\text{dir}}|_{SM} = 0.003 \pm 0.021 \]
\[ A_{CP}^{\text{mix}}|_{SM} = -0.29 \pm 0.20 \]
\[ A_{\Delta \Gamma}|_{SM} = 0.957 \pm 0.061 \]

• Pioneering LHCb analysis: [LHCb, K. De Bruyn et al., arXiv:1503.07055 [hep-ex]]

→ first measurement of the CP asymmetries:

\[ A_{CP}^{\text{dir}}(B_s \to J/\psi K_S^0) = -0.28 \pm 0.41(\text{stat}) \pm 0.08(\text{syst}) \]
\[ A_{CP}^{\text{mix}}(B_s \to J/\psi K_S^0) = 0.08 \pm 0.40(\text{stat}) \pm 0.08(\text{syst}) \]
\[ A_{\Delta \Gamma}(B_s \to J/\psi K_S^0) = 0.49^{+0.77}_{-0.65}(\text{stat}) \pm 0.06(\text{syst}) \]
**LHCb Upgrade Era:**

→ *benchmark scenario for the* \( B_{d,s}^0 \rightarrow J/\psi K_S^0 \) *analysis:*

- Assumes the following future measurements: [see also arXiv:1208.3355]
  - Clean \( \gamma \) determination from tree decays \( B \rightarrow D^{(*)}K^{(*)} \): \( \gamma = (70 \pm 1) ^\circ \)
  - \( \phi_s \) measured from \( B_s^0 \rightarrow J/\psi\phi \) and penguin strategies (see below):
    \[
    \phi_s = -(2.1 \pm 0.5)_{\text{exp}} \pm 0.3_{\text{theo}} ^\circ = -(2.1 \pm 0.6) ^\circ .
    \]
  - CP violation in the \( B_s \rightarrow J/\psi K_S^0 \) decay:¹
    \[
    A_{\text{CP}}^{\text{dir}}(B_s \rightarrow J/\psi K_S^0) = 0.00 \pm 0.05 \\
    A_{\text{CP}}^{\text{mix}}(B_s \rightarrow J/\psi K_S^0) = -0.28 \pm 0.05
    \]


¹These uncertainties were extrapolated from the current LHCb measurements of the CP violation in \( B_s^0 \rightarrow D_s^{\pm}K^{\mp} \) decays, corrected for the \( B_s^0 \rightarrow J/\psi K_S^0 \) event yield (no official LHCb study).
• Comments:
  – This determination of $a$ and $\theta$ is theoretically clean.
  – Relation to $a'$, $\theta'$ (enter $B_d \rightarrow J/\psi K_S$) through $U$-spin symmetry.
... conversion into $\Delta \phi_d$

- $U$-spin relation between $B_s^0 \to J/\psi K_s^0$ and $B_d^0 \to J/\psi K_S^0$:

\[
a' = \xi a, \quad \theta' = \theta + \delta
\]

$\to$ allow for $U$-spin breaking (non-fact.): $\xi = 1.00 \pm 0.20, \delta = (0 \pm 20)^\circ$:

\[
\Delta \phi_{\psi K_S^0} = -\left[1.09 \pm 0.20 \text{ (stat)}^{+0.20}_{-0.24} \text{ (U spin)}\right]^\circ = -\left[1.09 \pm 0.30\right]^\circ
\]
Using Branching Ratio Information

It is important to emphasise that BRs are not required in this analysis:

- Knowing \((a, \theta) \rightarrow \text{clean!}\), the following quantity can be determined:

\[
H = \frac{1 - 2a \cos \theta \cos \gamma + a^2}{1 + 2\epsilon a' \cos \theta' \cos \gamma + \epsilon^2 a'^2} \propto \frac{\mathcal{B}(B_s \rightarrow J/\psi K_S)}{\mathcal{B}(B_d \rightarrow J/\psi K_S)}
\]

\[
\Rightarrow \quad H_{(a,\theta)} = 1.172 \pm 0.037 (a, \theta) \pm 0.0016 (\xi, \delta)
\]

- We may then extract the following amplitude ratio from the BRs:

\[
\left| \frac{A'}{A} \right| = \sqrt{\epsilon H_{(a,\theta)} \frac{\text{PhSp}(B_s \rightarrow J/\psi K_S^0) \tau_{B_s} \mathcal{B}(B_d \rightarrow J/\psi K_S^0)_{\text{theo}}}{\text{PhSp}(B_d \rightarrow J/\psi K_S^0) \tau_{B_d} \mathcal{B}(B_s \rightarrow J/\psi K_S^0)_{\text{theo}}}}
\]

- \(\mathcal{B}(B_s \rightarrow f)\) measurements @ LHCb limited by \(f_s/f_d = 0.259 \pm 0.015\):

\[
\Rightarrow \quad \text{assuming no improvement of } f_s/f_d, \text{ which is conservative } \Rightarrow
\]

\[
\left| \frac{A'}{A} \right|_{\exp} = 1.160 \pm 0.035 \quad \text{vs} \quad \left| \frac{A'}{A} \right|_{\text{LCSR}} = 1.16 \pm 0.18 \quad (!)
\]
Control Channel for Belle II: $B_d^0 \rightarrow J/\psi \pi^0$

![Diagram showing the control channel for Belle II: $B_d^0 \rightarrow J/\psi \pi^0$]

* Replace $s$ spectator of $B_s^0 \rightarrow J/\psi K_S$ by $d$ quark $\Rightarrow B_d^0 \rightarrow J/\psi \pi^0$

- CKM amplitude structure of $B_d^0 \rightarrow J/\psi \pi^0$ is analogous to $B_s^0 \rightarrow J/\psi K_S$:
  $\Rightarrow$ shows also “magnified penguins”!

- Exchange and penguin annihilation amplitudes have to be neglected in $B_d^0 \rightarrow J/\psi \pi^0$ as they have no counterpart in $B_d^0 \rightarrow J/\psi K_S$:
  - Expected to be tiny, but can be probed through $B_s^0 \rightarrow J/\psi \pi^0$ and $B_s^0 \rightarrow J/\psi \rho^0$ [no evidence in the current LHCb data].

[R.F. (1999): $B_d^0 \rightarrow J/\psi \rho^0$; Ciuchini, Pierini & Silvestrini (2005, 2011)]
Prospects for Measuring $\phi_d$

Sources:
- Belle II – Talk at Krakow
- LHCb Upgrade – arXiv: 1208.3355
- $\Delta \phi_d$ – arXiv: 1412.6834

[Compilation: Kristof De Bruyn]
$B^{0}_{s,d} \rightarrow J/\psi V$ Decays:

- $B^{0}_{s} \rightarrow J/\psi \phi$: benchmark decay to extract $\phi_{s}$
- $B^{0}_{d} \rightarrow J/\psi \rho^{0}$: penguin probe $\rightarrow$ CPV @ LHCb
- $B^{0}_{s} \rightarrow J/\psi \bar{K}^{*0}$: yet another penguin probe
The $B^0_s \rightarrow J/\psi \phi$ Decay

- **Final state is mixture of CP-odd and CP-even states:**

  → disentangle through $J/\psi \rightarrow \mu^+ \mu^- \phi \rightarrow K^+ K^-$ angular distribution

- **Impact of SM penguin contributions:** $f \in \{0, ||, \perp\}$

  \[
  A\left(B^0_s \rightarrow (J/\psi \phi)_f\right) = \left(1 - \frac{\lambda^2}{2}\right) A'_f \left[1 + \epsilon a'_f e^{i\theta'_f} e^{i\gamma}\right]
  \]

  \* CP-violating observables $\Rightarrow \phi^\text{eff}_{s,(\psi \phi)_f} = \phi_s + \Delta \phi^{(\psi \phi)_f}_s$

- **Smallish $B^0_s - \bar{B}^0_s$ mixing phase $\phi_s$ (indicated by data ...):**

  $\Rightarrow \Delta \phi^f_s$ at the 1$^\circ$ level would have a significant impact ...

[Faller, R.F. & Mannel (2008)]
News on $B_s^0 \rightarrow J/\psi\phi$

- **Penguin parameters:**
  - $(a'_f, \theta'_f)$ are expected to differ for different final-state configurations $f$.
  - Simplified arguments along the lines of factorisation:

$$
\Rightarrow a'_f \equiv a'_{\psi\phi}, \quad \theta'_f \equiv \theta'_{\psi\phi} \quad \forall f \in \{0, \parallel, \perp\}
$$

$$
\implies \text{interesting to test through data!} \quad \text{[R.F. (1999)]}
$$

- **New LHCb results for $B_s \rightarrow J/\psi\phi$:** [LHCb, arXiv:1411.3104]
  - First polarisation-dependent results for $\phi_{s,f}^{\text{eff}}$: → pioneering character:

$$
\begin{align*}
\phi_{s,0}^{\text{eff}} &= -0.045 \pm 0.053 \pm 0.007 = -(2.58 \pm 3.04 \pm 0.40)\degree \\
\phi_{s,\parallel}^{\text{eff}} - \phi_{s,0}^{\text{eff}} &= -0.018 \pm 0.043 \pm 0.009 = -(1.03 \pm 2.46 \pm 0.52)\degree \\
\phi_{s,\perp}^{\text{eff}} - \phi_{s,0}^{\text{eff}} &= -0.014 \pm 0.035 \pm 0.006 = -(0.80 \pm 2.01 \pm 0.34)\degree
\end{align*}
$$

- Assuming a universal value of $\phi_{s}^{\text{eff}}$:

$$
\phi_{s}^{\text{eff}} = \phi_{s} + \Delta \phi_{s} = -0.058 \pm 0.049 \pm 0.006 = -(3.32 \pm 2.81 \pm 0.34)\degree
$$
• Further polarisation-dependent LHCb results for $B^0_s \rightarrow J/\psi\phi$:

$$|\lambda_f| \equiv \left| \frac{A(\bar{B}^0_s \rightarrow (J/\psi\phi)_f)}{A(B^0_s \rightarrow (J/\psi\phi)_f)} \right| = \frac{1 + \epsilon a'_f e^{i\theta'_f e^{-i\gamma}}}{1 + \epsilon a'_f e^{i\theta'_f e^{+i\gamma}}}$$

$$|\lambda^0| = 1.012 \pm 0.058 \pm 0.013$$
$$|\lambda^\perp/\lambda^0| = 1.02 \pm 0.12 \pm 0.05$$
$$|\lambda^\parallel/\lambda^0| = 0.97 \pm 0.16 \pm 0.01$$

* Assuming a universal $|\lambda^f| \equiv |\lambda_{\psi\phi}|$: \Rightarrow $|\lambda_{\psi\phi}| = 0.964 \pm 0.019 \pm 0.007$

• Constraints in the $\theta'_{\psi\phi}$–$a'_{\psi\phi}$ plane following from the “universal” LHCb values of $\phi^\text{eff}_s$ and $|\lambda_{\psi\phi}|$, assuming the SM value of $\phi_s$:
Controlling the Penguin Effects in $B^0_s \rightarrow J/\psi\phi$:

• Use the $SU(3)$ flavour symmetry.

• Neglect certain $E$ and $PA$ topologies:
  – Probed through $B^0_d \rightarrow J/\psi\phi$ and $B^0_s \rightarrow J/\psi\rho^0$.
  – No evidence for enhancement in LHCb data:
    $\rightarrow$ stronger bounds in the future ...

The $B_{d}^{0} \rightarrow J/\psi \rho^{0}$ Decay

- **Decay amplitude:**

$$\sqrt{2} A \left( B_{d}^{0} \rightarrow (J/\psi \rho^{0})_{f} \right) = -\lambda A_{f} \left[ 1 - a_{f} e^{i\theta_{f}} e^{i\gamma} \right]$$

- **CKM structure similar to** $B_{s}^{0} \rightarrow J/\psi K_{S}$ and $B_{d}^{0} \rightarrow J/\psi \pi^{0}$:

  → “magnified penguin contributions”

  - Hardonic parameters in $B_{s,d}^{0} \rightarrow J/\psi K_{S}^{0}$ and $B_{d}^{0} \rightarrow J/\psi \rho^{0}$ are generally expected to differ from one another.

- **CP violation:** $\phi_{d,f}^{\text{eff}} \equiv 2\beta_{f}^{\text{eff}}$ (in general polarisation dependent)
Extracting CKM phases from angular distributions of $B_{d,s}$ decays into admixtures of $CP$ eigenstates

Robert Fleischer

Theory Division, CERN, CH-1211 Geneva 23, Switzerland

(Received 27 April 1999; published 8 September 1999)

The time-dependent angular distributions of certain $B_{d,s}$ decays into final states that are admixtures of $CP$-even and $CP$-odd configurations provide valuable information about CKM phases and hadronic parameters. We present the general formalism to accomplish this task, taking also into account penguin contributions, and illustrate it by considering a few specific decay modes. We give particular emphasis to the decay $B_d \rightarrow J/\psi \rho^0$, which can be combined with $B_s \rightarrow J/\psi \phi$ to extract the $B_d^0 - \bar{B}_d^0$ mixing phase and—if penguin effects in the former mode should be sizeable—also the angle $\gamma$ of the unitarity triangle. As an interesting by-product, this strategy allows us to take into account also the penguin effects in the extraction of the $B_s^0 - \bar{B}_s^0$ mixing phase from $B_s \rightarrow J/\psi \phi$. Moreover, a discrete ambiguity in the extraction of the CKM angle $\beta$ can be resolved, and valuable insights into $SU(3)$-breaking effects can be obtained. Other interesting applications of the general formalism presented in this paper, involving $B_d \rightarrow \rho \rho$ and $B_{s,d} \rightarrow K^* \bar{K}^*$ decays, are also briefly noted.

PACS number(s): 12.15.Hh, 13.25.Hw
• First experimental results for CP violation in the $B_d^0 \rightarrow J/\psi \rho^0$ channel:

$\rightarrow$ pioneering polarisation-dependent analysis:

$$\phi_{d,0}^{\text{eff}} = + (44.1 \pm 10.2^{+3.0}_{-6.9})^\circ$$
$$\phi_{d,||}^{\text{eff}} - \phi_{d,0}^{\text{eff}} = - (0.8 \pm 6.5^{+1.9}_{-1.3})^\circ$$
$$\phi_{d,\perp}^{\text{eff}} - \phi_{d,0}^{\text{eff}} = - (3.6 \pm 7.2^{+2.0}_{-1.4})^\circ$$


• Assuming polarisation-independent penguin parameters:

$$\phi_d^{\text{eff}} = (41.7 \pm 9.6^{+2.8}_{-6.3})^\circ$$

$$A_{\text{CP}}^{\text{dir}}(B_d \rightarrow J/\psi \rho) \equiv C_{J/\psi \rho} = -0.063 \pm 0.056^{+0.019}_{-0.014}$$
$$A_{\text{CP}}^{\text{mix}}(B_d \rightarrow J/\psi \rho) \equiv S_{J/\psi \rho} = -0.66^{+0.13+0.09}_{-0.12-0.03}$$

• Using $\gamma = (70.0^{+7.7}_{-9.0})^\circ$ [CKMfitter] and $\phi_d = (43.2^{+1.8}_{-1.7})^\circ$ determined from our $B \rightarrow J/\psi P$ analysis (see above), a $\chi^2$ fit to the data yields:

$$a_{\psi \rho} = 0.037^{+0.097}_{-0.037}, \quad \theta_{\psi \rho} = - (67^{+181}_{-141})^\circ, \quad \Delta \phi_d^{J/\psi \rho^0} = - (1.5^{+12}_{-10})^\circ$$
Illustration of the determination of $a_f$ and $\theta_f$ from the $\chi^2$ fit through intersecting contours derived from the CP observables in $B_d^0 \rightarrow J/\psi \rho^0$:}
Further Implications of the $B^0_d \to J/\psi \rho^0$ Analysis:

- Conversion into the $B^0_s \to J/\psi \phi$ penguin parameters:

  \[ a'_\psi \phi = \xi a_{\psi \rho} \quad \theta'_\psi \phi = \theta_{\psi \rho} + \delta \quad [\xi = 1.00 \pm 0.20, \delta = (0 \pm 20)^\circ] \]

  \[ \Rightarrow \Delta \phi^\psi_{\psi \phi} = \left[ 0.08^{+0.56}_{-0.72} \text{(stat)}^{+0.15}_{-0.13} \text{(SU(3))} \right] \]° (I)

  ... to be compared with $\phi^\text{eff} = \phi_s + \Delta \phi^\psi_{\psi \phi} = -(3.32 \pm 2.81 \pm 0.34)^\circ$.

  [In agreement with LHCb Collaboration, S. Stone et al., arXiv:1411.1634]

- Extraction of hadronic amplitude ratios: [→ $B^0_{s,d} \to J/\psi K_S$ discussion]

\[
\begin{align*}
\frac{A'_0(B_s \to J/\psi \phi)}{A_0(B_d \to J/\psi \rho^0)} & = 1.06 \pm 0.07 \text{(stat)} \pm 0.04 (a_0, \theta_0) \quad \text{(fact)} = 1.43 \pm 0.42 \\
\frac{A'_||(B_s \to J/\psi \phi)}{A_||(B_d \to J/\psi \rho^0)} & = 1.08 \pm 0.08 \text{(stat)} \pm 0.05 (a_||, \theta_||) \quad \text{(fact)} = 1.37 \pm 0.20 \\
\frac{A'_\perp(B_s \to J/\psi \phi)}{A_\perp(B_d \to J/\psi \rho^0)} & = 1.24 \pm 0.15 \text{(stat)} \pm 0.06 (a_\perp, \theta_\perp) \quad \text{(fact)} = 1.25 \pm 0.15
\end{align*}
\]

[Naive “fact” refers to LCSR form factors [Ball & Zwicky ('05)]; recent PQCD calculation: X. Liu, W. Wang and Y. Xie (2014)]
A Penguin Roadmap

\[ \mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow J/\psi \rho^0) \]
\[ \mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow J/\psi \rho^0) \]

\[ \Delta \phi_s^{(\psi \phi)} \]

\[ \mathcal{A}_{\text{CP}}^{\text{dir}}(B_s \rightarrow J/\psi \phi) \]
\[ \mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \rightarrow J/\psi \phi) \]

\[ a_f, \theta_f \]

\[ \mathcal{B}(B_d \rightarrow J/\psi \rho^0) \]
\[ \mathcal{B}(B_s \rightarrow J/\psi K^{*0}) \]
\[ |\mathcal{A}'_f/\mathcal{A}_f| \]

\[ |\mathcal{A}'_f/\bar{\mathcal{A}}_f| \]

\[ \text{Test} \]
\[ \text{Extended Fit} \]
\[ \text{Old Input} \]

QCD Calculations

Interplay Between the $\phi_d$ and $\phi_s$ Analyses

$B_0^d \rightarrow J/\psi K_{S}^0$
$B_0^d \rightarrow J/\psi \rho^0$
$B_0^s \rightarrow J/\psi K_{S}^0$
$B_0^s \rightarrow J/\psi \phi$

Studies of Rare Decays
New Observables \[\rightarrow\] LHCb Upgrade Era
General Features of $B_s^0 \rightarrow \mu^+ \mu^-$

- **Situation in the Standard Model (SM):** \( \rightarrow \) only loop contributions:

- Moreover: helicity suppression \( \rightarrow \) BR \( \propto m_{\mu}^2 \)

\[ \Rightarrow \text{strongly suppressed decay} \]

- **Hadronic sector:** \( \rightarrow \) very simple, only the $B_s$ decay constant $F_{B_s}$ enters:

\[ \langle 0 | \bar{b} \gamma_5 \gamma_\mu s | B_s^0(p) \rangle = i F_{B_s} p_\mu \]

\[ \Rightarrow B_s^0 \rightarrow \mu^+ \mu^- \text{ belongs to the cleanest rare } B \text{ decays} \]
Highlight of LHC Run I: Observation of $B_s^0 \rightarrow \mu^+\mu^-$

- Combined analysis of CMS and LHCb:

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}, \quad \mathcal{B}(B_d^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \]


- Most recent theoretical Standard Model analysis:

\[
\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9},
\]

\[
\mathcal{B}(B_d^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}
\]

Interesting situation to monitor:

Figure 4 | Variation of the test statistic $-2\Delta \ln L$ as a function of the ratio of branching fractions $R \equiv \mathcal{B}(B^0 \to \mu^+ \mu^-)/\mathcal{B}(B_s^0 \to \mu^+ \mu^-)$. The dark and light (cyan) areas define the $\pm 1\sigma$ and $\pm 2\sigma$ confidence intervals for $R$, respectively. The value and uncertainty for $R$ predicted in the SM, which is the same in BSM theories with the minimal flavour violation (MFV) property, is denoted with the vertical (red) band.

LHCb Upgrade Era: $B_s^0 \rightarrow \mu^+\mu^-$

- Branching ratio measurement requires normalization:

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

→ ratio of fragmentations functions $f_s/f_d$ is the major limiting factor...

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

- Is there an observable beyond the branching ratio?: yes ...
  
  - Exploit the sizeable $B_s$ decay width difference $\Delta \Gamma_s$:

$$y_s = \frac{\Delta \Gamma_s}{2 \Gamma_s} \equiv \frac{\Gamma_{L}^{(s)} - \Gamma_{H}^{(s)}}{2 \Gamma_s} = 0.075 \pm 0.012$$

  - Provides access to another observable:

$$A_{\Delta \Gamma}^{\mu \mu} = \frac{|P|^2 \cos(2\varphi_P - \phi_{s}^{NP}) - |S|^2 \cos(2\varphi_S - \phi_{s}^{NP})}{|P|^2 + |S|^2} \quad \text{SM} \rightarrow 1$$

[De Bruyn, R.F., Knegjens, Koppenburg, Merk, Pellegrino & Tuning (2012)]
Comments on $A_{\Delta \Gamma}^{\mu\mu}$: theoretically clean

- $A_{\Delta \Gamma}^{\mu\mu}$ involves the following New Physics parameters:

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2} \pi} V_{ts}^* V_{tb} \alpha \left[ C_{10} O_{10} + C_S O_S + C_P O_P + C_{10}' O_{10}' + C_S' O_S' + C_P' O_P' \right]$$

$$P \equiv |P| e^{i\varphi_P} \equiv \frac{C_{10} - C_{10}'}{C_{10}^{\text{SM}}} + \frac{M_{B_s}^2}{2m_{\mu}} \left( \frac{m_b}{m_b + m_s} \right) \left( \frac{C_P - C_P'}{C_{10}^{\text{SM}}} \right) \overset{\text{SM}}{\rightarrow} 1$$

$$S \equiv |S| e^{i\varphi_S} \equiv \sqrt{1 - 4 \frac{m_{\mu}^2 M_{B_s}^2}{M_{B_s}^2 2m_{\mu}} \left( \frac{m_b}{m_b + m_s} \right) \left( \frac{C_S - C_S'}{C_{10}^{\text{SM}}} \right)} \overset{\text{SM}}{\rightarrow} 0$$

- $A_{\Delta \Gamma}^{\mu\mu}$ can be extracted from a time-dependent untagged analysis:

$$\langle \Gamma(B_s(t) \to \mu^+ \mu^-) \rangle \equiv \Gamma(B_s^0(t) \to \mu^+ \mu^-) + \Gamma(\bar{B}_s^0(t) \to \mu^+ \mu^-)$$

$$\propto e^{-t/\tau_{B_s}} \left[ \cosh(y_{st}/\tau_{B_s}) + A_{\Delta \Gamma}^{\mu\mu} \sinh(y_{st}/\tau_{B_s}) \right]$$

- Currently only time-integrated analyses $\to$ BR measurement.

- Need to correct for $\Delta \Gamma_s$ when comparing with theory BR calculation.
New Degree of Freedom to Probe New Physics

• Useful to introduce the following ratio:

\[
R \equiv \frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{exp}}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{SM}}} = \left[ \frac{1 + A_{\Delta \Gamma}^{\mu\mu} y_s}{1 - y_s^2} \right] (|P|^2 + |S|^2) \\
= \left[ \frac{1 + y_s \cos(2\varphi_P - \phi_{sNP}^P)}{1 - y_s^2} \right] |P|^2 + \left[ \frac{1 - y_s \cos(2\varphi_S - \phi_{sNP}^S)}{1 - y_s^2} \right] |S|^2
\]

– Current situation: \[ R = 0.82 \pm 0.21 \]

– \( R \) does not allow a separation of the \( P \) and \( S \) contributions:

\[ \Rightarrow \text{sizeable NP could be present ...} \]

• Further information from the measurement of \( A_{\Delta \Gamma}^{\mu\mu} \):

\[
|S| = |P| \sqrt{\frac{\cos(2\varphi_P - \phi_{sNP}^P) - A_{\Delta \Gamma}^{\mu\mu}}{\cos(2\varphi_S - \phi_{sNP}^S) + A_{\Delta \Gamma}^{\mu\mu}}}
\]

\[ \Rightarrow \text{offers a new window for NP in } B_s \to \mu^+\mu^- \]
• Current constraints in the $|P| - |S|$ plane and illustration of those following from a future measurement of the $B_s \to \mu^+ \mu^-$ observable $A_{\Delta \Gamma}^{\mu \mu}$:

- Assumes no NP phases for the $A_{\Delta \Gamma}$ curves (e.g. MFV without flavour-blind phases).

[De Bruyn, R.F., Knegjens, Koppenburg, Merk, Pellegrino & Tuning (2012)]
• Detailed analysis within specific NP scenarios:

\[
\bar{R} = \frac{\text{BR}(B_s \rightarrow \mu^+\mu^-)}{\text{BR}_{\text{SM}}(B_s \rightarrow \mu^+\mu^-)}
\]

\[0.79^{+0.20}_{-0.20}\]

[Buras, R.F., Girrbach & Knegjens (2013)]

• \(A_{\Delta\Gamma}^{\mu\mu}\) is encoded in the effective \(B_s^0 \rightarrow \mu^+\mu^-\) lifetime:

\[
\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t \langle \Gamma(B_s(t) \rightarrow \mu^+\mu^-) \rangle \, dt}{\int_0^\infty \langle \Gamma(B_s(t) \rightarrow \mu^+\mu^-) \rangle \, dt} = \frac{\tau_{B_s}}{1 - y_s^2} \left[ 1 + 2 A_{\Delta\Gamma}^{\mu\mu} y_s + y_s^2 \right]
\]

\(\rightarrow\) promising observable for the LHCb upgrade era!
New Observables in $B_s^0 \rightarrow \phi \ell^+ \ell^-$

- In analogy to the $B_s^0 \rightarrow \mu^+ \mu^-$, the decay width difference $\Delta \Gamma_s$ can also be utilized in the rare decay $B_s^0 \rightarrow \phi \ell^+ \ell^-$:
  - Angular analysis is required.
  - Much more involved than $B_s^0 \rightarrow \mu^+ \mu^-$: form factors, resonances, etc.,
  - Interesting to complement the search for NP with $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$. 

- Discuss also the observables of the time-dependent analysis of the angular distribution of the $B_d^0 \rightarrow K^{*0} (\rightarrow \pi^0 K_S)$ decay.

$\rightarrow \left\{ \begin{array}{l}
\text{interesting to fully exploit the physics potential of semileptonic rare } B_{(s)} \text{ decays in the era of Belle II and the LHCb upgrade.}
\end{array} \right.$

“Puzzles” in Semileptonic Rare $B$ Decays
Results from LHCb: $\bar{B}^0 \to \bar{K}^{*0} \mu^+ \mu^-$

- “Optimised” observables of the angular distribution: focus on $P_5'$

[Descotes-Genon, Matias & Virto ('13); Buras & Girrbach ('13); Jäger & Martin Camalich ('13); Hurth & Mahmoudi ('14); Lyon & Zwicky ('14); Hiller & Zwicky ('14); Descotes-Genon, Hofer, Matias & Virto, ...]


→ guideline for the following discussion + results
Many more observables provided by $b \to s$ semileptonic rare decays:

<table>
<thead>
<tr>
<th>Decay</th>
<th>obs.</th>
<th>$q^2$ bin</th>
<th>SM pred.</th>
<th>measurement</th>
<th>pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to \bar{K}^{*0}\mu^+\mu^-$</td>
<td>$F_L$</td>
<td>[2, 4.3]</td>
<td>0.81 ± 0.02</td>
<td>0.26 ± 0.19</td>
<td>ATLAS</td>
</tr>
<tr>
<td>$B^0 \to \bar{K}^{*0}\mu^+\mu^-$</td>
<td>$F_L$</td>
<td>[4, 6]</td>
<td>0.74 ± 0.04</td>
<td>0.61 ± 0.06</td>
<td>LHCb</td>
</tr>
<tr>
<td>$B^0 \to \bar{K}^{*0}\mu^+\mu^-$</td>
<td>$S_5$</td>
<td>[4, 6]</td>
<td>−0.33 ± 0.03</td>
<td>−0.15 ± 0.08</td>
<td>LHCb</td>
</tr>
<tr>
<td>$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$</td>
<td>$P'_5$</td>
<td>[1.1, 6]</td>
<td>−0.44 ± 0.08</td>
<td>−0.05 ± 0.11</td>
<td>LHCb</td>
</tr>
<tr>
<td>$B^0 \to \bar{K}^{*0}\mu^+\mu^-$</td>
<td>$P'_5$</td>
<td>[4, 6]</td>
<td>−0.77 ± 0.06</td>
<td>−0.30 ± 0.16</td>
<td>LHCb</td>
</tr>
<tr>
<td>$B^- \to K^{*-}\mu^+\mu^-$</td>
<td>$10^7 \frac{dBR}{dq^2}$</td>
<td>[4, 6]</td>
<td>0.54 ± 0.08</td>
<td>0.26 ± 0.10</td>
<td>LHCb</td>
</tr>
<tr>
<td>$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$</td>
<td>$10^8 \frac{dBR}{dq^2}$</td>
<td>[0.1, 2]</td>
<td>2.71 ± 0.50</td>
<td>1.26 ± 0.56</td>
<td>LHCb</td>
</tr>
<tr>
<td>$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$</td>
<td>$10^8 \frac{dBR}{dq^2}$</td>
<td>[16, 23]</td>
<td>0.93 ± 0.12</td>
<td>0.37 ± 0.22</td>
<td>CDF</td>
</tr>
<tr>
<td>$B_s \to \phi\mu^+\mu^-$</td>
<td>$10^7 \frac{dBR}{dq^2}$</td>
<td>[1, 6]</td>
<td>0.48 ± 0.06</td>
<td>0.23 ± 0.05</td>
<td>LHCb</td>
</tr>
</tbody>
</table>

Table 1: Observables where a single measurement deviates from the SM by $1.9\sigma$ or more (cf.\textsuperscript{15} for the $B \to K^{*}\mu^+\mu^-$ predictions at low $q^2$).

Complemented by yet another puzzling LHCb measurement: \[\to see below\]

$R_K \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathcal{B}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$

$\Rightarrow$ indication for lepton flavour non-universality (!?)
Global fit to the $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow se^+e^-$ data:

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>best fit</th>
<th>$1\sigma$</th>
<th>$2\sigma$</th>
<th>$\sqrt{\chi^2_{b.f.} - \chi^2_{SM}}$</th>
<th>$p$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_7^{NP}$</td>
<td>-0.04</td>
<td>$[-0.07, -0.02]$</td>
<td>$[-0.10, 0.01]$</td>
<td>1.52</td>
<td>1.1</td>
</tr>
<tr>
<td>$C_7'$</td>
<td>0.00</td>
<td>$[-0.05, 0.06]$</td>
<td>$[-0.11, 0.11]$</td>
<td>0.05</td>
<td>0.8</td>
</tr>
<tr>
<td>$C_9^{NP}$</td>
<td>-1.12</td>
<td>$[-1.34, -0.88]$</td>
<td>$[-1.55, -0.63]$</td>
<td>4.33</td>
<td>10.6</td>
</tr>
<tr>
<td>$C_9'$</td>
<td>-0.04</td>
<td>$[-0.26, 0.18]$</td>
<td>$[-0.49, 0.40]$</td>
<td>0.18</td>
<td>0.8</td>
</tr>
<tr>
<td>$C_{10}^{NP}$</td>
<td>0.65</td>
<td>$[0.40, 0.91]$</td>
<td>$[0.17, 1.19]$</td>
<td>2.75</td>
<td>2.5</td>
</tr>
<tr>
<td>$C_{10}'$</td>
<td>-0.01</td>
<td>$[-0.19, 0.16]$</td>
<td>$[-0.36, 0.33]$</td>
<td>0.09</td>
<td>0.8</td>
</tr>
<tr>
<td>$C_9^{NP} = C_{10}^{NP}$</td>
<td>-0.20</td>
<td>$[-0.41, 0.05]$</td>
<td>$[-0.60, 0.33]$</td>
<td>0.82</td>
<td>0.8</td>
</tr>
<tr>
<td>$C_9^{NP} = -C_{10}^{NP}$</td>
<td>-0.57</td>
<td>$[-0.73, -0.41]$</td>
<td>$[-0.90, -0.27]$</td>
<td>3.88</td>
<td>6.8</td>
</tr>
<tr>
<td>$C_9' = C_{10}'$</td>
<td>-0.08</td>
<td>$[-0.33, 0.17]$</td>
<td>$[-0.58, 0.41]$</td>
<td>0.32</td>
<td>0.8</td>
</tr>
<tr>
<td>$C_9' = -C_{10}'$</td>
<td>-0.00</td>
<td>$[-0.11, 0.10]$</td>
<td>$[-0.22, 0.20]$</td>
<td>0.03</td>
<td>0.8</td>
</tr>
</tbody>
</table>

$\chi^2_{SM} = 125.8$ for 91 measurements ($p = 0.92\%$)

[W. Altmannshofer @ Portorož 2015]
- **Constraints on Wilson coefficient functions:**

  ![Graphs of Re(C_{9}^{NP}) vs. Re(C_{10}^{NP}) and Re(C_{9}^{NP}) vs. Re(C'_{9})](image)

  Figure 1 – Allowed regions in the $\text{Re}(C_{9}^{NP})$-$\text{Re}(C_{10}^{NP})$ plane (left) and the $\text{Re}(C_{9}^{NP})$-$\text{Re}(C'_{9})$ plane (right). The blue contours correspond to the 1 and 2$\sigma$ best fit regions from the global fit. The green and red contours correspond to the 1 and 2$\sigma$ regions if only branching ratio data or only data on $B \to K^{*}\mu^{+}\mu^{-}$ angular observables is taken into account.

  → $Z'$ boson could do the job ...

**Key question:** → **Standard Model or New Physics?**

- **Sources of hadronic uncertainties:**
  - Power corrections $\Lambda_{\text{QCD}}/m_b$ affecting form-factor relations.
  - Influences of hadronic resonances ...
  - Complicated hadronic setting ...

- **Important to have critical analyses:** → example ... [S. Jäger @ Portorož 2015]

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**Angular observable $P_5'$**

- Red line: heavy-quark limit, **no power corrections**
- Pink: full scan over all theory errors
- Light blue: "68% Gaussian" theory error (a la Descotes-Genon, Hofer, Matias, Virto)
- Yellow: add theory errors in quadrature

---

Pure heavy-quark limit (!) describes data surprisingly well.

Within errors there appears to be no significant discrepancy

Cannot support LHCb claim of 2.9 sigma effect in the 4..6 GeV² bin

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Wednesday, 8 April 15
- **Interesting experimental probe:** $\rightarrow q^2$ dependence of $C_{9}^{\text{NP}}$

![Graph showing $C_{9}^{\text{NP}}$ dependence on $q^2$](image)

Figure 2 – Purple: ranges preferred at 1σ for a new physics contribution to $C_{9}$ from fits to all $B \rightarrow K^*\mu^+\mu^-$ observables in different bins of $q^2$. Blue: 1σ range for $C_{9}^{\text{NP}}$ from the global fit (cf. tab. 2). Green: 1σ range for $C_{9}^{\text{NP}}$ from a fit to $B \rightarrow K^*\mu^+\mu^-$ observables only. The vertical gray lines indicate the location of the $J/\psi$ and $\psi'$ resonances, respectively.

- Should $C_{9}^{\text{NP}}$ be found to be $q^2$ independent: $\Rightarrow$ support for NP
- Should $C_{9}^{\text{NP}}$ show $q^2$ dependence: $\Rightarrow$ support for hadronic effects...

$\Rightarrow$ stay tuned ...

Closer Look @ Testing Lepton Flavour Universality

- **Observable in the current spot light:**

\[
R_K \equiv \frac{\mathcal{B}(B \rightarrow K\mu^+\mu^-)[1,6]}{\mathcal{B}(B \rightarrow Ke^+e^-)[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036
\]


- **Standard Model prediction:** \( R_K = 1 \) → excellent approximation

\[
\Rightarrow 2.6\sigma \text{ deviation from LHCb (!?)}
\]


- **Differences with respect to the \( \bar{B}^0 \rightarrow \bar{K}^{*0}\mu^+\mu^- \) observables:**
  
  - Hadronic effects cannot explain the LHCb central value...
  
  - Is it an experimental fluctuation?

  - Is it New Physics? → Various studies in the literature:

    *leptoquarks, Z' models, composite Higgs models, ...*

[Hiller & Schmaltz (2014); Gripaios & Nardecchia (2014); Niehoff, Stangl & Straub (2015); Becirevic, Fajfer & Kosnik (2015); De Medeiros Varzielas & Hiller (2015); Crivellin (2015); Celis et al. (2015); Alonso, Grinstein & Martin Camalich ('15); ...]
Concluding Remarks
Great Opportunities for Flavour Physics

→ many more interesting topics than covered in this talk: ...

- **Leptonic and semileptonic** $B$ **decays with** $\tau$ **leptons:**
  
  $\Rightarrow$ intriguing data for $B \to \tau \bar{\nu}_\tau$, $D(\ast)\tau \bar{\nu}_\tau$: extended Higgs sector (?)

  - First LHCb $\bar{B} \to D^\ast \tau \bar{\nu}$ result and Belle update @ FPCP 2015:
    $\Rightarrow$ (still) inconclusive situation ...

- **Charm physics:** → complementay to the $B$-meson system:

  $\Rightarrow$ *down-type quarks in FCNC loop processes*

  - Pattern of tiny CP violation in the SM model.
  - Difference $\Delta A_{CP}$ of CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
    has received a lot of attention some time ago: looks now SM-like ...
  - Hadronic uncertainties are challenging, $SU(3)$ is a useful tool...

- **Search for lepton-flavour-violating processes:**

  $B \to K \mu e$, $B \to K \mu \tau$, $B_s \to \mu e$, $B_s \to \mu \tau$, ...

  - Would be unambiguous signals of New Physics.
  - Links to violation of lepton flavour universality?
• **Kaon physics:** → focus on rare kaon decays:

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ and } K_L \rightarrow \pi^0 \nu \bar{\nu} \]

- NA62 (CERN) and KOTO (J-PARC) aim to measure the BRs.
- Theoretically very clean and interesting probes for New Physics:

Towards New Frontiers in Precision Flavour Physics

• Crucial for the full exploitation of flavour physics in the next $\sim 10$ years:

  ◊ (continued) strong interaction theory ↔ experiment:

  – Hadronic physics: factorization, $SU(3)$-breaking corrections, data...
  – Think further about new observables to probe the SM/NP.
  – Explore correlations/patterns between processes in specific NP models.

• Exciting times for (quark) flavour physics:

  $(2–3)\sigma$ deviations seem to accumulate: $\rightarrow$ first footprints of NP (?

  – First signals for $B_d^0 \rightarrow \mu^+\mu^-$ (?)
  – Anomalies in $B_d^0 \rightarrow K^{*0}\mu^+\mu^-$ (?)
  – $R_K = \mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)/\mathcal{B}(B^+ \rightarrow K^+e^+e^-)$ (?)
  – Data for $B \rightarrow \tau\nu$ decays, $B \rightarrow D^{(*)}\tau\nu$ decays (?)

$\Rightarrow$ hot topics for discussions @ WIN 2015