Studio di decadimenti rari a LHCb

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100° Congresso SIF, Pisa 2014
Indirect searches for New Physics

• High energy
  “real” new particles can be produced and discovered via their decays

• High precision
  “virtual” new particles can be discovered in loop processes, such as Flavor Changing Neutral Current (FCNC)

Direct and indirect approach complement each other

Recent LHCb results on FCNC $b$ decays:
- Photon polarization in $b \rightarrow s \gamma$
- Branching fractions and angular distributions of $b \rightarrow s \mu^+ \mu^-$
- The very rare decays $B^0(s) \rightarrow \mu^+ \mu^-$

• Lepton Flavour Violating decays
FCNC decays

• In the Standard Model FCNC decays are forbidden at tree level, and occur at loop level only → strongly suppressed!

• SM diagrams for $b \to s \mu^+ \mu^-$: “electroweak penguins”

• Contribution from New Physics as correction to the SM

$$A = A_0 \left( \frac{C_{SM}}{m_W^2} + \frac{C_{NP}}{\Lambda_{NP}^2} \right)$$

What is the scale of $\Lambda_{NP}$?
What is its coupling $c_{NP}$?
Three impersonations of the EW penguin

“Photon penguin”

\[ b \rightarrow s \gamma \]

\[ \bar{b} \rightarrow \bar{t}, \bar{c}, \bar{u} \]

\[ C_7^{(l)} \]

\[ \alpha_{\text{QED}} \text{ suppression} \]

\[ \text{BR} \sim 3 \times 10^{-4} \]

BR, \( \gamma \) polarization

“Electroweak penguin”

\[ b \rightarrow s \mu^+ \mu^- \]

\[ \bar{b} \rightarrow \bar{t}, \bar{c}, \bar{u} \]

\[ W^+ \]

\[ C_7^{(l)}, C_9^{(l)}, C_{10}^{(l)} \]

angular distributions

\[ \text{BR} \sim 10^{-6} \]

“Higgs penguin”

\[ B_{0(s)}^0 \rightarrow \mu^+ \mu^- \]

\[ B_{0(s)}^0 \rightarrow W \]

\[ \text{helicity suppression} \]

\[ \text{BR} \sim 3.6 \times 10^{-9} \]
FCNC processes in effective field theory

- Effective Hamiltonian for $b \rightarrow s$ FCNC transitions

$$
\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i O_i + C_i' O_i')
$$

- Wilson coefficients $C_i$ encode short-distance physics and possible NP effects, computed perturbatively

- Local operators $O_i$ with different Lorentz structure absorb long distance effects

- $O_i'$ helicity flipped operators, $m_s/m_b$ suppressed in SM

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_7^{(r)}$</td>
<td>$\frac{e}{g^2} m_b (\bar{s} \sigma_{\mu \nu} P_{R(L)} b) F^{\mu \nu}$</td>
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<tr>
<td>$O_9^{(r)}$</td>
<td>$\frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\mu} \gamma^\mu \mu)$</td>
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<tr>
<td>$O_{10}^{(r)}$</td>
<td>$\frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\mu} \gamma^\mu \gamma_5 \mu)$</td>
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<td>$O_8^{(r)}$</td>
<td>$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b) (\bar{\mu} \mu)$</td>
</tr>
<tr>
<td>$O_P^{(r)}$</td>
<td>$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b) (\bar{\mu} \gamma_5 \mu)$</td>
</tr>
</tbody>
</table>
photon polarization in $b \to s\gamma$
The SM predicts that the photon emitted in $b \to s \gamma$ decays is predominantly left-handed (up to order $m_s^2/m_b^2$), since the recoil $s$-quark that couples to a $W$-boson is left-handed.

Several models beyond the SM predict the photon to acquire a significant right-handed component due to the exchange of heavy fermions in the electroweak penguin loop.

[Atwood et al PRL 79 (1997) 185]
[Yu et al. JHEP12 (2013) 102]
Photon polarization in $B^+ \rightarrow K^+\pi^-\pi^+\gamma$

- Can infer the photon polarization from the up-down asymmetry of the photon direction in the $K^+\pi^-\pi^+$ rest-frame. Unpolarized photons would have no asymmetry (conceptually similar to Mme. Wu experiment)

The up-down asymmetry is defined as:

$$A_{ud} = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_1^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}} ,$$

where

$$\frac{d\Gamma}{ds ds_{13} ds_{23} d\cos\theta} \propto \sum_{i=0,2,4} a_i(s, s_{13}, s_{23}) \cos^i \theta + \lambda_\gamma \sum_{j=1,3} a_j(s, s_{13}, s_{23}) \cos^j \theta ,$$

$$\lambda_\gamma = \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2} ,$$

Where $s_{ij} = (p_i + p_j)^2$ and the $a_i$ contain the information about the $K^+\pi^-\pi^+$ resonances and their interference: the odd terms is $\cos\theta$ carry the photon polarization: if $\lambda_\gamma \neq 0$ the photon is polarized. In SM $\lambda_\gamma \approx -1 (1)$ for radiative $B$ (anti-$B$) decays, up to $O(m_s^2/m_b^2)$ corrections.
Photon polarization in $B^+ \rightarrow K^+\pi^-\pi^+\gamma$

- At LHCb we look at $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ decays using calorimeter photons, observe $\sim$13k signal candidates in 3 fb$^{-1}$

- There are a large number of overlapping resonances in the $m(K^+\pi^-\pi^+)$ mass spectrum. No attempt is made to separate these in the analysis, we simply bin in 4 bins of $m(K^+\pi^-\pi^+)$
Up-down asymmetry

- Combining the four $m(K^+\pi^-\pi^+)$ bins, the up-down asymmetry $A_{ud}$ is different from zero at $5.2\sigma$

- This is the first observation of photon polarization in $b\rightarrow s\gamma$ decays

- To extract the polarization value from the up-down asymmetry theory input is needed about the amplitude composition of the hadronic system (ongoing)

- Alternative approach is being finalized at LHCb: extraction of $\lambda_\gamma$ from mixing-induced CP violation in $B^0_s \rightarrow \phi\gamma$

[Reference: PRL 112 (2014) 161801]
$b \rightarrow s \mu^+ \mu^-$ decays
# Experimental data on $b \rightarrow s \mu^+ \mu^-$

<table>
<thead>
<tr>
<th># of evts</th>
<th>BaBar</th>
<th>Belle</th>
<th>CDF</th>
<th>LHCb</th>
<th>CMS</th>
<th>ATLAS</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>471 M $\bar{B}B$</td>
<td>605 fb$^{-1}$</td>
<td>9.6 fb$^{-1}$</td>
<td>1 (+2) fb$^{-1}$</td>
<td>5 (+20) fb$^{-1}$</td>
<td>5 fb$^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>BaBar</th>
<th>Belle</th>
<th>CDF</th>
<th>LHCb</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0} \bar{\ell} \ell$</td>
<td>$137 \pm 44^{+\dagger}$</td>
<td>$247 \pm 54^{+\dagger}$</td>
<td>$288 \pm 20$</td>
<td>$2361 \pm 56$</td>
<td>$415 \pm 70$</td>
<td>$426 \pm 94$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+} \bar{\ell} \ell$</td>
<td>$153 \pm 41^{+\dagger}$</td>
<td>$162 \pm 38^{+\dagger}$</td>
<td>$319 \pm 23$</td>
<td>$4746 \pm 81$</td>
<td>not yet</td>
<td>not yet</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ \bar{\ell} \ell$</td>
<td>$24 \pm 6$</td>
<td>$162 \pm 16$</td>
<td>$176 \pm 17$</td>
<td>$174 \pm 15$</td>
<td>emerging</td>
<td>emerging</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^0_S \bar{\ell} \ell$</td>
<td>$32 \pm 8$</td>
<td>$176 \pm 17$</td>
<td>not yet</td>
<td>not yet</td>
<td>limit</td>
<td>limit</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \phi \bar{\ell} \ell$</td>
<td>$62 \pm 9$</td>
<td>$174 \pm 15$</td>
<td>emerging</td>
<td>emerging</td>
<td>limit</td>
<td>limit</td>
</tr>
<tr>
<td>$B^+_s \rightarrow \bar{\mu} \mu$</td>
<td>$51 \pm 7$</td>
<td>$78 \pm 12$</td>
<td>$25 \pm 7$</td>
<td>$25 \pm 7$</td>
<td>limit</td>
<td>limit</td>
</tr>
<tr>
<td>$B^+_d \rightarrow \bar{\mu} \mu$</td>
<td>$51 \pm 7$</td>
<td>$78 \pm 12$</td>
<td>$25 \pm 7$</td>
<td>$25 \pm 7$</td>
<td>limit</td>
<td>limit</td>
</tr>
</tbody>
</table>

## Outlook / Prospects

- **Belle** reprocessed all data 711 fb$^{-1}$ → no final analysis yet!
- **LHCb** $\sim 2$ fb$^{-1}$ from 2012 to be analysed and $\gtrsim 8$ fb$^{-1}$ by the end of 2018
- **ATLAS / CMS** $\sim 20$ fb$^{-1}$ from 2012 to be analysed
- **Belle II** expects about (10-15) K events $B \rightarrow K^{*} \bar{\ell} \ell$ ($\gtrsim 2020$)

[Bevan arXiv:1110.3901]

great interest, big effort...
Angular analysis of $B^0 \rightarrow K^{*0} \rightarrow K^+\pi^- \mu^+\mu^-$

- $B^0 \rightarrow K^* \mu^+\mu^-$ is the golden mode to test new vector (-axial) couplings in $b \rightarrow s$ transitions: sensitivity to $O_7$, $O_9$ and $O_{10}$ and their primed counterparts.

- $K^* \rightarrow K\pi$ is self tagged, hence angular analysis ideal to test helicity structure

- Decay described by 3 helicity angles and $q^2 = m(\mu^+\mu^-)$

  \[
  \frac{d^4\Gamma}{d \cos \theta_{\ell} \ d \cos \theta_K \ d \phi \ dq^2} \propto F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_K) + F_L \cos^2 \theta_K (2 \cos^2 \theta_{\ell}) + \\
  \frac{1}{4} (1 - F_L)(1 - \cos^2 \theta_K)(2 \cos^2 \theta_{\ell} - 1) + S_3 (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_{\ell}) \cos 2\phi + \\
  \frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_{\ell} + \\
  A_{Im}(1 - \cos^2 \theta_K)(1 - \cos^2 \theta_{\ell}) \sin 2\phi
  \]

  folding technique ($\phi \rightarrow \phi + \pi$ for $\phi < 0$) applied to reduce the number of fit parameters

  $F_L$: fraction of $K^*$ longitudinal polarization
  $A_{FB}$: Forward-Backward lepton asymmetry
  $S_3$: Asymmetry in $K^*$ transverse polariz.
  $A_{Im}$: T-odd CP asymmetry

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Results based on 900 signal events from 1 fb$^{-1}$ at 7 TeV (angular analysis on 3 fb$^{-1}$ being finalized)

SM prediction from [C. Bobeth et al. JHEP 07 (2011) 067]

Zero crossing point of $A_{FB}$ free from leading FF uncertainties

we measure $q_0^2 = 4.9 \pm 0.9$ GeV$^2$

to be compared with $q_{0,SM}^2 = 4.36^{+0.33}_{-0.31}$ GeV$^2$
$B^0 \to K^{*0}\mu^+\mu^-$ angular observables (1 fb$^{-1}$)

ATLAS (prelim.) [ATLAS-CONF-2013-038], CMS 5.2 fb$^{-1}$ [PLB 727 (2013) 77], LHCb 1 fb$^{-1}$ [JHEP 08 (2013) 131]

- And fortunately also ATLAS and CMS with $\sim$0.4k candidates in 5 fb$^{-1}$ start to contribute to this analysis. They particularly competitive at large $q^2$. 

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B⁰ → K*⁰μ⁺μ⁻ angular observables (1 fb⁻¹)

• Can also apply different angular foldings to access different angular terms: focus on observables where leading form-factor uncertainties cancel, e.g.

\[ P'_{4,5} = S_{4,5}/\sqrt{F_L(1 - F_L)} \]

[Decotes-Genon et al. JHEP 05 (2013) 137]

• SM prediction from [Decotes-Genon et al. JHEP 05 (2013) 137]

• In 1 fb⁻¹, LHCb observes a local \(4.3 < q^2 < 8.7 \text{ GeV}^2\) discrepancy of 3.7\(\sigma\) in \(P'_{5}\) (the probability that at least one bin varies by this much is 0.5%) 

eagerly await for LHCb 3 fb⁻¹ analysis!
Understanding the $P'_{5}$ anomaly?

- Several global fits to the available $b\rightarrow s\gamma$ and $b\rightarrow s\ell^+\ell^-$ have been attempted, which include the observed anomaly $\Rightarrow$ discrepancy with SM is $3-4.5 \sigma$. Fits favour $C_{9}^{NP} \sim -1.5$ (non-SM vector current), and can also be explained by introducing a flavour-changing $Z'$ boson $\sim 1-7$ TeV

[Decotes-Genon, Matias, Virto ’13
Altmannshofer, Straub ’13
Gaul, Goertz, Haisch ’14

- By introducing form-factor uncertainties as nuisance parameters in the global fit, the discrepancy wrt SM is reduced to $2\sigma$

Beaujean, Bobeth, van Dyk ’13

- Form-factor uncertainties are being rediscussed, especially in the large recoil region, with appreciable impact on the comparison with data, and different opinions, of course!

Jaeger, Camalich ’13
Lyon, Zwicky ’14
Hofer, Matias ’14

(4.3 < q^2 < 8.7 GeV^2)
Understanding the P'\text{5} anomaly?

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- Form-factor uncertainties are being rediscussed, especially in the large recoil region, with appreciable impact on the comparison with data, and different opinions, of course!

looks interesting but we need more data, and better understanding of theoretical uncertainties...

(4.3 < q^2 < 8.7 \text{ GeV}^2)
$B^0_{s,d} \rightarrow \mu^+\mu^-$
**B^0_{(s)} \to \mu^+\mu^-** decays

- **B^0_{(s)} \to \mu^+\mu^-** decays are a particular interesting case of EW penguin. The helicity suppression of the vector(-axial) terms, makes these decays very sensitive to new (pseudo-)scalar interactions
- **Higgs penguin!**

  e.g. in MSSM, branching fraction scales as $\tan^6 \beta / M_A^4$

- **Predicted precisely in the SM:**

  $$B(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
  $$B(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

  [Bobeth et al. PRL 112 (2014) 101801]

- The $B^0/B^0_s$ ratio is also powerful to discriminate among NP models: a deviation from the value predicted by SM, $\sim (V_{td}/V_{ts})^2$, would indeed also imply the breaking of the **Minimal Flavour Violation hypothesis**
It’s a long history...with great contributors!
CMS vs LHCb

- Good trigger and muon ID
- No hadron PID
- Excellent silicon tracking to resolve signal decays in the high pile-up environment
- Di-muon mass resolution 32-75 MeV/c²
- CMS: $5+20$ fb\(^{-1}\) at 7 and 8 TeV

- Efficient muon trigger
- Good muon and hadron PID
- Track impact parameter resolution $\leq 20\mu m$
- Luminosity levelling at $4\times10^{32}$ cm\(^{-2}\)s\(^{-1}\)
- Di-muon mass resolution 25 MeV/c²
- LHCb: $1+2$ fb\(^{-1}\) at 7 and 8 TeV

$\sim 1$ fb\(^{-1}\) at LHCb is equivalent to $\sim 10$ fb\(^{-1}\) at CMS
$\mathcal{B}(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}) = 3.0^{+1.0}_{-0.9} \times 10^{-9} \ (4.3\sigma)$

$\mathcal{B}(B^{0} \rightarrow \mu^{+}\mu^{-}) = 3.5^{+2.1}_{-1.8} \times 10^{-10} \ (2.0\sigma)$

Nov. 2012: LHCb found the first evidence of the $\mathcal{B}(B_{s}^{0} \rightarrow \mu^{+}\mu^{-})$ with 2.1 fb$^{-1}$
Combined CMS and LHCb results at CKM2014

- Full simultaneous fit of CMS and LHCb data

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

- Statistical significance (Wilks’ theorem):
  - 6.2 \sigma for the $B_s^0 \rightarrow \mu^+\mu^-$ (Expected SM 7.6 \sigma)
  - First observation
  - 3.2 \sigma for the $B^0 \rightarrow \mu^+\mu^-$ (Expected SM 0.8 \sigma)
Comparison with SM

Signal strength

- 2D LL scan performed for the signal strength BR/BR_{SM}:

\[ S_{B^0}^{B_s} = 0.76^{+0.20}_{-0.18} \]
\[ S_{SM}^{B^0} = 3.7^{+1.6}_{-1.4} \]

- Compatibility with SM:

  1.2\sigma for B^0_s  
  2.2\sigma for B^0

\[ \mathcal{R} = 0.14^{+0.08}_{-0.06} \]

B^0/B^0_s ratio

- 1D LL scan of the B^0/B^0_s ratio:

CMS and LHCb

- Compatibility with SM (and MFV):

  2.3\sigma for B^0/B^0_s ratio

theoretical errors included in the fits
Implications

- Latest results on $B^0(s) \rightarrow \mu^+\mu^-$ strongly constrain the parameter space for many NP models, complementing direct searches from ATLAS/CMS: in particular, large $\tan\beta$ with light pseudo-scalar Higgs in CMSSM is strongly disfavored

\[\text{Figure 1: Flavour constraints in the CMSSM, in the } (m_{1/2}, m_0) \text{ parameter plane with } A_0 = -2m_0, \text{ for } \tan\beta = 30 \text{ in the left and } \tan\beta = 50 \text{ in the right. The black lines delimit the ATLAS SUSY direct search limits with 20.3 fb}^{-1} \text{ of data and the white lines show where the Higgs mass can reach a value of 122 GeV.}\]

- Start to explore less constrained (and more "natural") SUSY models: "split-family" SUSY, pMSSM

Barbieri et al. ’14
Althmanshofer et al. ’13
Mamhoudi ’13
More implications

- **Model independent constraints:**
  the precision achieved now is such that $B^0_{(s)} \to \mu^+\mu^-$ sensitivity to $(Z, \gamma)$ penguin cannot longer be considered sub-leading, and starts to compete with the golden mode $B^0 \to K^*\mu^+\mu^-$. 

  - Test the MFV hypothesis:
    flavour breaking in NP model described by CKM matrix → naturally small effects in FCNC observables

  $B^0/B^0_s$ ratio fixed by MFV to SM value: it is therefore very relevant to clarify the experimental picture on $B^0$.
Lepton Flavour Violation and exotic searches
The quest for lepton flavour violation

- The discovery of neutrino oscillations implies charged-LFV at some level. Many extensions of the SM introduce large cLFV effects.

- Important advantage wrt the quark sector: the reach for NP energy scale is not much affected by QCD uncertainties in the SM predictions.

- The MEG collaboration at PSI using $3.6 \times 10^{14}$ stopped muons reached an amazing sensitivity to $\mu \rightarrow e\gamma$:

  $$B(\mu^\pm \rightarrow e^\pm \gamma) < 5.7 \times 10^{-13} \text{ at 90\% C.L.}$$

  [PRL 110 (2014) 201801]

- In principle, $\tau$ are more sensitive per event than $\mu$ since mass typically decreases GIM suppression, >500; however production rate is much lower.
Search for lepton flavour violation in $\tau \rightarrow \mu\mu\mu$

- Possible as penguin with neutrino oscillation; SM prediction $\sim 10^{-40}$, beyond experimental reach

- (some) NP predictions: SUSY $\sim 10^{-10}$, mSUGRA+seesaw $\sim 10^{-9}$, non universal $Z'$ $\sim 10^{-8}$

- With $\sim 1.4 \times 10^9 \tau$ at the B-factories the current limits are:

  **Belle:** $\text{BR}(\tau \rightarrow \mu\mu\mu) < 2.1 \times 10^{-8}$ at 90%CL  
  \hspace{1cm} \text{arXiv:1001.3221}

  **BaBar:** $\text{BR}(\tau \rightarrow \mu\mu\mu) < 3.3 \times 10^{-8}$ at 90%CL  
  \hspace{1cm} \text{arXiv:1002.4550}

- At the LHC $\tau$ are copiously produced (mainly from charm decays, $D_s \rightarrow \tau\nu$): $\sim 10^{11} \tau/fb^{-1}$ ($\sim 5 \times 10^{14}$ at HL-LHC!).

  Few days ago, LHCb presented at TAU2014 the search based on 3 fb$^{-1}$

  $\text{BR}(\tau \rightarrow \mu\mu\mu) < 4.6 \times 10^{-8}$ at 90% CL
Search for Majorana neutrinos

- Observation of neutrino oscillations is a strong theoretical motivation for Majorana neutrinos to exist
- In LHCb, heavy Majorana neutrinos can be sought in $B^- \rightarrow \pi^+ \mu^- \mu^-$ decay, which is forbidden in SM but can proceed via production of on-shell massive neutrinos
- Limit on $\text{BR}(B^- \rightarrow \pi^+ \mu^- \mu^-)$ from 3$\text{fb}^{-1}$ can be translated (with a model-dependent assumption on the decay width) to an upper limit on the coupling between muon and fourth generation neutrino

![Graph of neutrino mass vs. coupling strength](image)

decay width from Atre et al. JHEP 05 (2009) 030 + S. Stone, Z. Xing '13
Search for Majorana neutrinos - implications

- Limit on BR can be translated to a model-dependent upper limit on the coupling between muon and fourth generation neutrino

\[ [\text{JHEP} 05 (2009) 030] \]

- With this result LHC join the search for Heavy Neutral Leptons performed all around the world, both at colliders and fixed target experiments.
Conclusions
Conclusions

• Flavor-changing transitions represent a unique window on physics beyond the SM: there is still a lot to learn and explore
  LHC (and LHCb) is acting as a fantastic flavour-factory

• There are few interesting anomalies, but in general the agreement with the SM is excellent: large NP contributions, \(O(\text{SM})\), ruled out in many cases
  need combined th+exp precision at the few % level

• Ambitious program for upgrading integrated luminosity in the next years at LHC: LHCb aims at \(\sim 50\text{fb}^{-1}\)

• Interplay between low energy precision measurements and direct searches as strong as ever
Conclusions

• Flavor-changing transitions represent a unique window on physics beyond the SM: there is still a lot to learn and explore
  - LHC & LHCb are acting as a fantastic flavour-factory

- We don’t know yet what is the scale of NP: cast a wide net!

• Interplay between low energy precision measurements and direct searches as strong as ever
SPARES
Photon polarization in $B^+ \to K^+\pi^-\pi^+\gamma$

- From theory, the decay rate of $B \to (K_{res} \to P_1P_2P_3)\gamma$

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos\theta} = |A|^2 \left\{ \frac{1}{4} |\vec{J}|^2 (1 + \cos^2 \theta) + \frac{1}{2} \lambda' \text{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)] \cos \theta \right\} \rightarrow 1^+$$

$$+ |B|^2 \left\{ \frac{1}{4} |\vec{K}|^2 (\cos^2 \theta + \cos^2 2\theta) + \frac{1}{2} \lambda' \text{Im}[\vec{n} \cdot (\vec{K} \times \vec{K}^*)] \cos \theta \cos 2\theta \right\} + |C|^2 \frac{1}{2} \sin^2 \theta$$

$$+ \left\{ \frac{1}{2} (3 \cos^2 \theta - 1) \text{Im}[AB^*\vec{n} \cdot (\vec{J} \times \vec{K}^*)] + \lambda' \text{Re}[AB^*(\vec{J} \cdot \vec{K}^*)] \cos^3 \theta \right\} \rightarrow 1^-$$


- $J$ and $K$ are the helicity amplitude that carry the $s_{13}$ and $s_{23}$ dependence
- $s_{ij} = (p_i + p_j)^2$
- $p_i$ = final state particles momenta
- $\lambda'$ is the photon polarization ($\lambda' \sim 1$ in the SM for $B^+$)
- $\vec{n}$ is the normal to the decay plane
- $\cos \theta$ from triple product $\cos \theta \equiv \left( \frac{p_1 \times p_2}{|p_1 \times p_2|} \right)_z$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass [MeV/c²]</th>
<th>Full width [MeV/c²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1(1270)^+$</td>
<td>1272 ± 7</td>
<td>90 ± 20</td>
</tr>
<tr>
<td>$K_1(1400)^+$</td>
<td>1403 ± 7</td>
<td>174 ± 13</td>
</tr>
<tr>
<td>$K_2(1430)^+$</td>
<td>1425.6 ± 1.5</td>
<td>98.5 ± 2.7</td>
</tr>
<tr>
<td>$K_1(1520)^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_2(1770)^+$</td>
<td>1773 ± 8</td>
<td>186 ± 14</td>
</tr>
<tr>
<td>$K_3(1780)^+$</td>
<td>1776 ± 7</td>
<td>159 ± 21</td>
</tr>
</tbody>
</table>
Photon polarization in $B^+ \to K^+\pi^-\pi^+\gamma$

Best fit, Fit with $(C'_7 - C_7)/(C'_7 + C_7) = 0$

- [PRL 112 (2014) 161801]
\(B^0 \rightarrow K^{*0} \mu^- \mu^+\) angular distribution

- Angular distribution depends on 11 angular terms:

\[
\frac{d^4\Gamma[B^0 \rightarrow K^{*0} \mu^+ \mu^-]}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[ J_3^s \sin^2\theta_K + J_4^s \cos^2\theta_K + J_5^s \sin^2\theta_K \cos 2\theta_\ell + J_6^s \cos^2\theta_K \cos 2\theta_\ell + J_7^s \cos^2\theta_\ell + J_8^s \cos^2\theta_\ell \cos 2\phi + J_9^s \cos^2\theta_\ell \sin\phi \right]
\]

where the \(J_i^s\)'s are bilinear combinations of seven decay amplitudes \(A_{\parallel}^{L,R}, A_{\perp}^{L,R}, A_0^{L,R}\) & \(A_t\) (\(L/R\) for the chirality of the \(\mu^+ \mu^-\) system).

- Large number of terms, simplified by angular folding, e.g. \(\phi \rightarrow \phi + \pi\) if \(\phi < 0\) to cancel terms in \(\cos \phi\) and \(\sin \phi\) (LHCb).

OR by integrating over two of the three angles (ATLAS and CMS):

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\phi} = \frac{1}{2\pi} \left( 1 + S_3 \cos 2\phi + A_9 \sin 2\phi \right),
\]

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2} F_L \cos^2\theta_K + \frac{3}{4} (1 - F_L) (1 - \cos^2 \theta_K),
\]

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4} F_L (1 - \cos^2\theta_\ell) + \frac{3}{8} (1 - F_L) (1 + \cos^2\theta_\ell) + A_{FB} \cos\theta_\ell.
\]

- in [PRL 111 (2013) 191801] fit \(P'_{4,5,6,8}=S_{4,5,7,8}/\sqrt{F_L(1-F_L)}\) with different angular foldings; e.g. for \(P'_{5}\):

  \(\varphi \rightarrow \varphi\) for \(\varphi < 0\); \(\theta_I \rightarrow \pi - \theta_I\) for \(\theta_I > \pi/2\)

- 24 bins in total
Understanding the P'\textsubscript{5} anomaly?

- Several global fits to the available $b\to s\gamma$ and $b\to s\ell^+\ell^-$ have been attempted, which include the observed anomaly.
  - Fits favour slightly negative $C_9^{NP}$ (non-SM vector current), and can also be explained by introducing a flavour-changing $Z'$ boson $\sim 1-7$ TeV.

- By introducing form-factor uncertainties as nuisance parameters in the global fit, the discrepancy wrt SM is reduced to $2\sigma$.

- Form-factor uncertainties are being rediscussed, especially in the large recoil region, with appreciable impact on the comparison with data, and different opinions, of course!

Against NP:
- Main effect in $P_5'$ not far from cc threshold
- Significance reduced with conservative estimates of non-factoriz. corr. [but not everybody agree → talk by Hofer]
- NP in photon-penguins only is "suspicious" [personal opinion]

G. Isidori at ICHEP 2014

Jaeger, Camalich '13
Lyon, Zwicky '14
Hofer, Matias '14

(4.3<q^2<8.7 GeV^2)
Differential BRs at high $q^2 (>14\text{GeV}^2)$

Hints of deviation from SM predictions also in the differential BRs of $B \rightarrow K^{*0}\mu^+\mu^-$ and $B_s \rightarrow \phi\mu^+\mu^-$ decays could be explained by the same value of $C_9(\text{NP})$ [Horgan et al., arXiv:1310.3887]

CDF: Public note 10894
CMS: arXiv: 1308.3409
ATLAS: ATLAS-CONF-2013-038
B $\to$ K$^{(*)}\mu^-\mu^+$ isospin asymmetry

Isospin asymmetry $A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+} \mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+} \mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$

SM prediction for $A_I$ is $\mathcal{O}(1\%)$

![Graphs showing $A_I$ vs $q^2$ for LHCb $B \to K\mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$]

- Results with 3 fb$^{-1}$ consistent with SM
- p-value for deviation of $A_I(B \to K\mu\mu)$ from 0 is 11% (1.5$\sigma$)
- Tensions seen in the 1 fb$^{-1}$ analysis reduced due to
  1. Updated reco./selection
  2. Stat. approach
  3. Isospin symmetry in $J/\psi$ modes

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**B^+ \rightarrow K^+\mu^-\mu^+** angular distribution

- Single angle and two parameters describe the decay:

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta} = \frac{3}{4} (1 - F_H) + \frac{1}{2} F_H + A_{FB} \cos \theta
\]

- \(F_H\) corresponds to the fractional contribution of (pseudo)scalar and tensor operators to \(\Gamma\).
- Angular distribution is only +ve for \(A_{FB} \leq F_H/2\) and \(F_H \geq 0\).
- Unfortunately the angular distribution is insensitive to \(C_9^{NP}\).
- It is also consistent with the SM expectation of \(A_{FB} \approx 0\) and \(F_H \approx 0\).
Lepton universality in $B^+ \to K^+ \ell^+\ell^-$

$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ e^+e^-)} = 1 \pm \mathcal{O}(10^{-3}) \text{ in the SM}$$

- Experimental challenges for $B^+ \to K^+ e^+e^-$ mode
  1. Trigger
  2. Bremsstrahlung
- Use double ratio to cancel systematic uncertainties
  $$\mathcal{R}_K = \left( \frac{N_{K^+\mu^+\mu^-}}{N_{K^+e^+e^-}} \right) \left( \frac{N_{J/\psi (e^+e^-) K^+}}{N_{J/\psi (\mu^+\mu^-) K^+}} \right) \left( \frac{\varepsilon_{K^+e^+e^-}}{\varepsilon_{K^+\mu^+\mu^-}} \right) \left( \frac{\varepsilon_{J/\psi (\mu^+\mu^-) K^+}}{\varepsilon_{J/\psi (e^+e^-) K^+}} \right)$$

- Correct for bremsstrahlung using calorimeter photons (with $E_T > 75$ MeV).
- Migration of events into/out-of the $1 < q^2 < 6$ GeV$^2/c^4$ window is corrected using MC.
- Take double ratio with $B^+ \to J/\psi K^+$ decays to cancel possible systematic biases.
- In 3 fb$^{-1}$ LHCb determines
  $$R_K = 0.745_{-0.074}^{+0.099} \text{(stat)}_{-0.036}^{+0.036} \text{(syst)}$$
  which is consistent with SM at 2.6$\sigma$.

LHCb-PAPER-2014-024 [Preliminary].
Belle [PRL 103 (2009) 171801].
BaBar [PRD 86 (2012) 032012]
$B^0_{(s)} \to \mu^+\mu^-$ decays

**SM**

![SM diagram](image1)

**NP**

![NP diagram](image2)

Relevant for $\text{BR} = \mathcal{O}(\text{SM})$

Possible large enhancement (e.g. SUSY @ large $\tan\beta$)

\[
B(B^0_q \to \mu^+\mu^-) \approx \frac{G_F\alpha^2 M^3_{B^0} f^2_{B^0} \tau_{B^0}^q}{64\pi^3 \sin^4 \theta_W} |V_{tb}V^*_{tq}|^2 \left(1 - \frac{4m^2_\mu}{M^2_{B^0}} \right)^{1/2} \times \\
\left[ \left(1 - \frac{4m^2_\mu}{M^2_B} \right) |C_S - C'_S|^2 + |C_P - C'_P| + \frac{2m_\mu}{M_B} (C_{10} - C'_{10}) \right]^2
\]
**$B^0_{(s)} \rightarrow \mu^+\mu^-$ time-integrated BR**

Time-integrated BR vs CP-averaged BR

$$B(B^0_{(s)} \rightarrow \mu^+\mu^-)_{TH, \langle \phi \rangle} = \frac{1 + y_s A_{\Delta \Gamma}}{1 - y_s^2} \times B(B^0_{(s)} \rightarrow \mu^+\mu^-)_{CP}$$

$$= SM \quad \frac{1}{1 - y_s} \times B(B^0 \rightarrow \mu^+\mu^-)_{CP}$$

$$y_s = \frac{\Delta \Gamma \tau_s}{2 \Gamma_s} = 0.0615 \pm 0.0085$$

$$A_{\Delta \Gamma} = \frac{\Gamma_{B^0_{(s), \tau} \rightarrow \mu \mu} - \Gamma_{B^0_{(s), \mu} \rightarrow \mu \mu}}{\Gamma_{B^0_{(s), \tau} \rightarrow \mu \mu} + \Gamma_{B^0_{(s), \mu} \rightarrow \mu \mu}} = 1$$

Lifetime bias in the analysis efficiency

$$\epsilon = \frac{\int_0^\infty \Gamma(B^0_{(s)}(t) \rightarrow \mu^+\mu^-, A_{\Delta \Gamma}, y_s) \epsilon(t) dt}{\int_0^\infty \Gamma(B^0_{(s)}(t) \rightarrow \mu^+\mu^-, A_{\Delta \Gamma}, y_s) dt},$$

$$\delta_{\epsilon} = \frac{\epsilon^{A_{\Delta \Gamma}, \mu \mu}}{\epsilon^{M C}} = \frac{\int_0^\infty \Gamma(B^0_{(s)}(t) \rightarrow \mu^+\mu^-, A_{\Delta \Gamma}, y_s) \epsilon(t) dt}{\int_0^\infty \Gamma(B^0_{(s)}(t) \rightarrow \mu^+\mu^-, A_{\Delta \Gamma}, y_s) dt} \cdot \frac{\int_0^\infty e^{-\Gamma_{M C} t} \epsilon(t) dt}{\int_0^\infty e^{-\Gamma_{M C} t} \epsilon(t) dt}$$

Correction for $B_s = 4.50 \pm 0.03\%$

Correction for $B^0 = 1.48 \pm 0.01\%$

a residual dependence vs analysis lifetime-dependent cuts is also corrected
- $b\bar{b}$ produced correlated predominantly in forward (backward) direction → single arm forward spectrometer ($2 < \eta < 5$)

- Large $b\bar{b}$ production cross section
  $\sigma_{b\bar{b}} = (75.3 \pm 14.1) \, \mu b$ [Phys. Lett. B694 (2010)] in acceptance

  $\sim 10^{11}$ b-bbar couples per fb$^{-1}$

  $\sim 3$ fb$^{-1}$ accumulated so far
$B_{(s)}^0 \rightarrow \mu^+\mu^-$ at LHCb

1) Run the experiment at $4 \times 10^{32}$ cm$^{-2}$s$^{-1}$ with 1262 colliding bunches
   - twice the design luminosity with half number of bunches
     $\rightarrow$ 4 times more collisions per crossing than design: $<\mu>_{8\text{TeV}} = 1.7$
   - higher occupancy in the detector
     $\rightarrow$ challenging for the trigger

2) Large acceptance, efficient muon trigger
   - acceptance $\times$ reconstruction efficiency for signal is $\sim 10\%$
   - L0: single muon $p_T > 1.76$ GeV/c, dimuon $\sqrt{(p_T1^2 + p_T2^2)} > 1.6$ GeV/c
   - HLT: IP and invariant mass cuts
   - overall trigger efficiency $\sim 90\%$

3) Background reduction:
   - Very good momentum resolution: $\delta p/p \sim 0.4\% \rightarrow 0.6\%$ for $p=(5-100)$ GeV/c
   - Muon identification: matching between tracks reconstructed in the spectrometer and hits in the muon stations + moderate requirements on global PID likelihood (RICH+CALO+MUON);
     for this analysis: $\varepsilon(\mu \rightarrow \mu) \sim 98\%, \varepsilon(\pi \rightarrow \mu) \sim 0.6\%, \varepsilon(K \rightarrow \mu) \sim 0.3\%, \varepsilon(p \rightarrow \mu) \sim 0.3\%$

4) Excellent vertex and IP resolution:
   - to separate signals from background: $\sigma(\text{IP}) \sim 25 \mu m$ @ $p_T = 2$ GeV/c

$\sim B_{s}^0 \rightarrow \mu^+\mu^-$

12 SM evts/fb$^{-1}$

LHCb instantaneous luminosity

luminosity leveling at work!
Lepton flavour violation in $\tau \rightarrow \mu\mu\mu$

First search at a hadron collider:
- Possible thanks to the very low pT thresholds of the LHCb muon triggers

Huge cross section: $\sigma(pp \rightarrow \tau X) \sim 80 \mu b$ at $\sqrt{s} = 7$ TeV
- $8 \times 10^9 \tau$ produced in 1 fb$^{-1}$ almost exclusively from B and D$_s$

But also huge background:
- Cut based analysis followed by multivariate one in the PID and kinematical plane

Normalization using $D_s \rightarrow \phi(\mu\mu)\pi$ (very similar topology):

$$BR(\tau^\rightarrow \mu^-\mu^+\mu^-) = BR(D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-) \times \frac{f_{D_s}^{D_s}}{BR(D_s^- \rightarrow \tau^-\bar{\nu}_\tau)} \times \frac{\epsilon_{cal}}{\epsilon_{sig}} \times \frac{N_{sig}}{N_{cal}}$$

Fraction of $\tau$ leptons which originate from Ds decays, calculated using bb and cc cross section as measured by LHCb [1,2] and the inclusive $b \rightarrow \tau$ and $c \rightarrow \tau$ branching fractions as measured by LEP experiments [3]

Search for Majorana neutrinos

- BR upper limits as a function of mass and lifetime in [1-1000]ps

- Limit on BR can be translated to a model-dependent upper limit on the coupling between muon and fourth generation neutrino

\[
B(B^- \rightarrow \pi^+ \mu^- \mu^-) = \frac{G_F f_B^2 f^2_{\pi\mu} m_B^5}{128 \pi^2 \hbar} |V_{ub}V_{ud}|^2 \tau_B \left(1 - \frac{m_N^2}{m_B^2}\right) \frac{m_N}{\Gamma_N} |V_{\mu 4}|^4,
\]

where: \[\Gamma_N = [3.95m_N^3 + 2.00m_N^5(1.44m_N^3 + 1.14)] \times 10^{-13}|V_{\mu 4}|^2,\]

decay width from
Atre et al. JHEP 05 (2009) 030
+ S. Stone, Z. Xing ’13
Search for lepton flavour violation in $B_{(s)} \rightarrow \mu e$

• Decays of the type $B_{(s)} \rightarrow \mu e$ are allowed in models with a local gauge symmetry between quarks and leptons, with lepto-quark linking different quark/lepton generations

\[ \text{[Pati, Salam PRD 10 (1974) 275]} \]

• With 1 fb$^{-1}$ LHCb has put limits x20 more stringent than the previous best limits set by CDF

\[ \text{BR}(B^0_{s} \rightarrow \mu e) < 1.1 \times 10^{-8} \text{ at 90\% CL} \]
\[ \text{BR}(B^0 \rightarrow \mu e) < 2.8 \times 10^{-9} \text{ at 90\% CL} \]

\[ \text{[PRL 111 (2013) 141801]} \]

• These limits can be translated into limits on the value of the lepto-quark mass in the framework of the Pati-Salam model:

\[ m_{LQ}(B_{s} \rightarrow \mu e) > 101 \text{ TeV/c}^2 \text{ at 95\% CL} \]
\[ m_{LQ}(B \rightarrow \mu e) > 126 \text{ TeV/c}^2 \text{ at 95\% CL} \]
### Projections

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb⁻¹)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s$ mixing</td>
<td>$2\beta_s$ ($B^0_s \rightarrow J/\psi \phi$)</td>
<td>0.10 [9]</td>
<td>0.025</td>
<td>0.008</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s$ ($B^0_s \rightarrow J/\psi f_0(980)$)</td>
<td>0.17 [10]</td>
<td>0.045</td>
<td>0.014</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{fs}(B^0_s)$</td>
<td>$6.4 \times 10^{-3}$ [18]</td>
<td>0.6 $\times 10^{-3}$</td>
<td>0.2 $\times 10^{-3}$</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$2\beta^\text{eff}_{s}(B^0_s \rightarrow K^+K^-)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta^\text{eff}_{s}(B^0_s \rightarrow K^*0K^*0)$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta^\text{eff}_{s}(B^0_s \rightarrow K^0\pi^0)$</td>
<td>0.17 [18]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$2\beta^\text{eff}_{s}(B^0_s \rightarrow \phi\gamma)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau^\text{eff}<em>{s}(B^0_s \rightarrow \phi\gamma)/\tau</em>{B^0}$</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>$S_3(B^0 \rightarrow K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.08 [14]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$A_{FB}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$</td>
<td>25% [14]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>$A_1(K\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.25 [15]</td>
<td>0.08</td>
<td>0.025</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \rightarrow \pi^+\mu^+\mu^-)/B(B^+ \rightarrow K^+\mu^+\mu^-)$</td>
<td>25% [16]</td>
<td>8%</td>
<td>2.5%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B^0_s \rightarrow \mu^+\mu^-)$</td>
<td>$1.5 \times 10^{-9}$ [2]</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma(B \rightarrow D^{(<em>)}K^{(</em>)})$</td>
<td>$\sim 10$–$12$° [19, 20]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma(B^0_s \rightarrow D_sK)$</td>
<td>–</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta(B^0 \rightarrow J/\psi K^0\bar{s})$</td>
<td>0.8° [18]</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T$</td>
<td>$2.3 \times 10^{-3}$ [18]</td>
<td>0.40 $\times 10^{-3}$</td>
<td>0.07 $\times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td>$CP$ violation</td>
<td>$\Delta A_{CP}$</td>
<td>$2.1 \times 10^{-3}$ [5]</td>
<td>0.65 $\times 10^{-3}$</td>
<td>0.12 $\times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>

2012: LHCb Upgrade Framework TDR


Matteo Palutan, INFN-LNF