LHCb upgrade: physics perspectives
(or anatomy of the LHCb upgrade)
Gaia Lanfranchi
(LNF-INFN)

The landscape of flavour physics towards the high intensity era, Pisa 9-10 December 2014
The mission of a flavor physicist

To look for New Physics in [mostly FCNC] B, K, charm decays (and cLFV decays) that can be sensitive to quantum corrections from degrees of freedom at and above the electroweak scale.
The success of the CKM picture is impressive....
But how well do we know CKM? Assume $\Delta F=2$ transitions

consider NP in $M_{12q} = M_{12}^{SM,q}(1 + h_q e^{2i\sigma_q})$

independently for $B_d$, $B_s$ with arbitrary flavour structure.

Current status: in most flavor-changing neutral-current processes, NP can still contribute at least at the level of $\sim 20-30\%$ with respect to the SM
Constraints on New Physics from $\Delta F = 2$ transitions

2013

$B_d$

$p$-value

$\sim 20\text{-}25\%$

2018+

LHCb 7 fb$^{-1}$, Belle II: 5 ab$^{-1}$

$p$-value

$\sim 10\%$

2028+

50 fb$^{-1}$ LHCb, 50 ab$^{-1}$ BelleII

$p$-value

$\sim 5\%$

arXiv: 1309.2203 (CKMFitter)
CKMFitter, 1309.2203: a knowledge of CKM at ~5-10% (2028+) could probe new particles with CKM-like couplings with masses, M, → in the 10-20 TeV range if they contribute at tree level (i.e., Λ~ M), → in the 1-2 TeV range if they enter with loop suppression

.. And are in the **ballpark of the gluino masses** explored at LHC @14 TeV
Stop & gluino searches at CMS
[Flaecher, SUSY 2014]

Stop production, \( \tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0 \)

CMS Preliminary
\( \sqrt{s} = 8 \text{ TeV} \)
ICHEP 2014

- Observed
- Expected

Combined of published MVA 1-lepton analysis with preliminary all-hadronic Razor analysis.

Gluino mass [GeV]

[stop mass already excluded at 700-800 GeV, gluino at 1.2 TeV]
For statistically limited measurements, the sensitivity to the NP mass grows as $1/\sqrt{\sigma} \rightarrow 1/N^{1/4}$ → Luminosity matters!
This is why we need to upgrade the detector.

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th>HL-LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, CMS</td>
<td>25 fb⁻¹</td>
<td>100 fb⁻¹</td>
</tr>
<tr>
<td>LHCb</td>
<td>3 fb⁻¹</td>
<td>8 fb⁻¹</td>
</tr>
</tbody>
</table>

2018++: x 4

2030++: L x 20

See talk of A. Cardini
Extrapolations assume:
- Scaling of accuracy with $\sqrt{L}$
- gain x2 for L0 removal for fully hadronic b-decays (a bit more for fully hadronic charm decays)
- same HLT efficiency, reconstruction, stripping, selection, PID efficiencies as in Run I
- same background contamination as in Run I.
Are we going to be dominated by systematic uncertainties?
<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \rightarrow J/\psi\phi)$ (rad)</td>
<td>0.049</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \rightarrow J/\psi f_0(980))$ (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{sl}(B_s^0)$ (10$^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$\phi_s^{\text{eff}}(B_s^- \rightarrow \phi\phi)$ (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.018</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$\phi_s^{\text{eff}}(B_s^0 \rightarrow K^*0K^*0)$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.023</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta^{\text{eff}}(B^0 \rightarrow \phi K_S^0)$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.036</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed</td>
<td>$\phi_s^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)$ (rad)</td>
<td>0.20</td>
<td>0.13</td>
<td>0.025</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>currents</td>
<td>$\tau^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)/\tau_{B_s^0}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak</td>
<td>$S_3(B^0 \rightarrow K^{*}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td>Penguin</td>
<td>$q_0^2 A_{FB}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_1(K\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4)$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</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>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$B(B^0 \rightarrow \mu^+\mu^-)$ (10$^{-9}$)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td>Penguin</td>
<td>$B(B_s^0 \rightarrow \mu^+\mu^-)$ (10$^{-9}$)</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma(B \rightarrow D^{(<em>)}K^{(</em>)})$</td>
<td>$7^\circ$</td>
<td>$4^\circ$</td>
<td>$0.9^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\gamma(B_s^0 \rightarrow D_s^+K^*)$</td>
<td>$17^\circ$</td>
<td>$11^\circ$</td>
<td>$2.0^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta(B^0 \rightarrow J/\psi K_S^0)$</td>
<td>$1.7^\circ$</td>
<td>$0.8^\circ$</td>
<td>$0.31^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_F(D^0 \rightarrow K^+K^-)$ (10$^{-4}$)</td>
<td>3.4</td>
<td>2.2</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$ (10$^{-3}$)</td>
<td>0.8</td>
<td>0.5</td>
<td>0.1</td>
<td>–</td>
</tr>
</tbody>
</table>

A closer look to $\Delta F=2$ transitions
Mixing-induced CP violating phase $\phi_s : B_s \rightarrow J/\psi KK \, \& \, B_s \rightarrow J/\psi \pi \pi$

LHCb, 3 fb$^{-1}$, arXiv 1411.3104

World average: $-15 \pm 36$ mrad
LHCb only: $-10 \pm 40$ mrad
SM : $36 \pm 2$ mrad (Phys. Rev. D 84 (2011) 033005)

\begin{align*}
B_s^0 \rightarrow J/\psi K^+ K^- &:= \phi_s \\
B_s^0 \rightarrow J/\psi \pi^+ \pi^- &:= |\lambda| \\
\text{Combined} &:= -0.010 \pm 0.039
\end{align*}

Fully dominated by statistical uncertainty (x8 syst. uncertainty)
Breakdown of systematic uncertainties for $\phi_s$ in $B_s \rightarrow J/\psi KK$

| Source                                | $\Gamma_s$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] | $|A_\perp|^2$ | $|A_\parallel|^2$ | $\delta_\parallel$ [rad] | $\delta_\perp$ [rad] | $\phi_s$ [rad] | $|\lambda|$ | $\Delta m_s$ [ps$^{-1}$] |
|---------------------------------------|-------------------------|-------------------------------|---------------|-----------------|------------------------|-------------------|----------------|-------------|----------------|
| Nominal stat. uncertainty             | 0.0027                  | +0.0009                       | 0.0031        | 0.0064          | 0.050                  | 0.05              | 0.002          | 0.001       | +0.004          |
| Angular resolution (scale factor)     | 1.001                   | 1.003                         | 1.007         | 1.002           | 1.013                  | 1.009             | 1.003          | 1.003       | 1.006          |
| Total stat. uncertainty               | 0.0027                  | +0.0009                       | 0.0031        | 0.0064          | 0.050                  | 0.05              | 0.002          | 0.001       | +0.004          |
| Mass factorisation                    |                         |                               |               |                 |                        |                   |                |             |                |
| sWeights (stat.)                      | 0.0001                  | 0.0008                        | 0.0001        | 0.0002          | 0.02                   | 0.02              | 0.002          | 0.001       | 0.001          |
| Resonant bkg                          | 0.0001                  | 0.0004                        | 0.0004        | 0.0002          | 0.02                   | 0.02              | 0.002          | 0.003       | 0.001          |
| Ang. acc. (reweighting)               | 0.0001                  | 0.0011                        | 0.0020        | 0.01            |                        |                   | 0.001          | 0.005       | 0.002          |
| Ang. acc. (stat.)                     | 0.0001                  | 0.0002                        | 0.0011        | 0.0004          | 0.02                   | 0.02              | 0.002          | 0.001       | 0.001          |
| Time resolution                       |                         |                               |               |                 |                        |                   |                |             |                |
| Trigger efficiency (stat.)            | 0.0011                  | 0.0009                        |               |                 |                        |                   |                |             |                |
| Track reconstruction (simul.)         | 0.0007                  | 0.0029                        | 0.0005        | 0.0006          | 0.01                   | 0.001             | 0.001          | 0.001       | 0.006          |
| Track reconstruction (stat.)          | 0.0005                  | 0.0002                        |               |                 |                        |                   |                |             | 0.001          |
| Length and mom. scales                | 0.0002                  |                               |               |                 |                        |                   |                |             | 0.005          |
| $C_s$ factors                         |                         |                               |               |                 |                        |                   |                |             |                |
| Angular resolution bias               |                         |                               |               |                 |                        |                   |                |             |                |
| $B_{s+}$ background                   | 0.0005                  |                               |               |                 |                        |                   |                |             |                |
| Fit bias                              |                         |                               |               |                 |                        |                   |                |             |                |
| Quadratic sum of syst.               | 0.0015                  | 0.0033                        | 0.0036        | 0.0067          | 0.0063                 | 0.058             | 0.0055         | 0.0066      | 0.011          |
| Total uncertainties                   | 0.0031                  | 0.0097                        | 0.0061        | 0.0075          | +0.012                 | +0.15             | 0.049          | 0.020       | +0.056         |

Dominant systematic uncertainties:
- $\phi_s$: angular acceptance (MC stat dominated)
- $\Gamma_s, \Delta \Gamma_s$: correction for VELO acceptance (tracking reconstruction) and trigger efficiency
- This should be solved with the upgraded VELO and with the fully lifetime unbiased software trigger foreseen in the upgrade.
**CPV phase in $B_s \to \phi\phi$:**


$B_s \to \phi\phi$ is a FCNC gluonic penguin decay:
- sensitive to CPV phase due to interference between mixing and decay
- phase close to zero in SM (upper limit: 0.02)
- sizeable enhancements due to NP are possible


Result based on 3 fb$^{-1}$:

$$\phi_s = -0.17 \pm 0.15(stat) \pm 0.03(syst) \text{ rad}$$

$$|\lambda| = 1.04 \pm 0.07 \pm 0.03(syst)$$

Agreement with prediction, no evidence of CPV in decay or mixing
Systematic uncertainty dominated by the knowledge of the angular acceptances and time acceptance:

→ This should be solved with the upgraded VELO and with the fully lifetime unbiased software trigger foreseen in the upgrade.
A crucial ingredient is (and will be) the tagging efficiency and its knowledge. Crucial to control the penguin pollution [control modes rely on assumptions on SU(3) breaking corrections].

Large enhancement of the yield expected for removal of the L0 trigger for $B_s \rightarrow \phi \phi$

20-30% relative accuracy

SM : $36 \pm 2$ mrad

<table>
<thead>
<tr>
<th>Process</th>
<th>Run 1 (2010-12)</th>
<th>Run 2 (2015-17)</th>
<th>Upgrade 2030</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \rightarrow J/\psi K^+ K^-$</td>
<td>0.05</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow J/\psi \pi^+ \pi^-$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.016</td>
<td>$\sim 0.001$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \phi \phi$</td>
<td>0.18</td>
<td>0.12</td>
<td>0.026</td>
<td>0.02</td>
</tr>
</tbody>
</table>
$\phi_s$ projections

Upgrade phase

20-30% relative accuracy

SM : $36 \pm 2$ mrad

Will the kaon measurements be at the same level?

$$\frac{\Gamma(K^0_L \rightarrow \pi^0 \nu\bar{\nu})}{\Gamma(K^+ \rightarrow \pi^+ \nu\bar{\nu})} = r_{is} \sin^2(\beta - \beta_s)$$
Here the systematic uncertainties matter!
Dominant systematics: detection asymmetry
Second dominant systematic for Bd is the B⁺ production asymmetry

Mixing in Semi-leptonic asymmetries

\[ a_{s\ell} = \frac{\Gamma(\bar{B} \rightarrow B \rightarrow f) - \Gamma(B \rightarrow \bar{B} \rightarrow f)}{\Gamma(\bar{B} \rightarrow B \rightarrow f) + \Gamma(B \rightarrow \bar{B} \rightarrow f)} \]

- SM predictions [arXiv:1102.4274] are:
  - \( a_{s\ell}^d \) (SM) = \((-4.1 \pm 0.6) \times 10^{-4}\)
  - \( a_{s\ell}^s \) (SM) = \((1.9 \pm 0.3) \times 10^{-5}\)

So far, measured \( a_{s\ell}^d \) with 3 fb\(^{-1}\) [arXiv:1409.8586] and \( a_{s\ell}^s \) with 1 fb\(^{-1}\) [arXiv:1308.1048].

\[
\begin{align*}
  a_{s\ell}^d &= -0.02 \pm 0.19 \text{(stat)} \pm 0.30 \text{(syst)} \% \\
  a_{s\ell}^s &= -0.06 \pm 0.50 \text{(stat)} \pm 0.36 \text{(syst)} \%
\end{align*}
\]

Both consistent with SM
LHCb (naïve) sensitivities in Run I, Run II and upgrade

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \to J/\psi \phi)$ (rad)</td>
<td>0.049</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \to J/\psi f_0(980))$ (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{\text{sl}}(B_s^0)$ ($10^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic</td>
<td>$\phi^\text{eff}(B_s^0 \to \phi \phi)$ (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.018</td>
<td>0.02</td>
</tr>
<tr>
<td>penguin</td>
<td>$\phi^\text{eff}(B_s^0 \to K^{*0}K^{*0})$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.023</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta^\text{eff}(B^0 \to \phi K^0_S)$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.036</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$\phi^\text{eff}(B_s^0 \to \phi \gamma)$ (rad)</td>
<td>0.20</td>
<td>0.13</td>
<td>0.025</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau^\text{eff}(B^0 \to \phi \gamma)/\tau_{\text{pr}}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>ElectroWeak</td>
<td>$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td>penguin</td>
<td>$q_0^2 A_{F3}(B^0 \to K^{*0}\mu^+\mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_1(K\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+\mu^+\mu^-)/B(B^+ \to K^+\mu^+\mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$B(B_s^0 \to \mu^+\mu^-)$ ($10^{-9}$)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td>penguin</td>
<td>$B(B^0 \to \mu^+\mu^-)/B(B^0 \to \mu^+\mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity</td>
<td>$\gamma(B \to D^{(<em>)}K^{(</em>)})$</td>
<td>$7^\circ$</td>
<td>$4^\circ$</td>
<td>$0.9^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>triangle</td>
<td>$\gamma(B_s^0 \to D^+_sK^+)$</td>
<td>17$^\circ$</td>
<td>11$^\circ$</td>
<td>2.0$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\beta(B^0 \to J/\psi K_S)$</td>
<td>1.7$^\circ$</td>
<td>0.8$^\circ$</td>
<td>0.31$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T(D_s^0 \to K^+K^-)$ ($10^{-4}$)</td>
<td>3.4</td>
<td>2.2</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$ ($10^{-3}$)</td>
<td>0.8</td>
<td>0.5</td>
<td>0.1</td>
<td>–</td>
</tr>
</tbody>
</table>

Let’s move into the realm of the rare decays…
FCNC decays are an infinite source of information as they are sensitive to quantum corrections from degrees of freedom at or above the electroweak scale.

NP can modify the Wilson coefficients ($C_i$) affecting observable quantities as angular distributions in $B \to K^{(*)}\mu\mu$ decays ($C_7, C_9, C_{10}$), branching fractions in $B \to \mu\mu$ decays ($C_s, C_p$) and photon polarization ($C'_7$).

\[
H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \sum_i \left[ C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu) \right] 
\]

<table>
<thead>
<tr>
<th>$i$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>Tree</td>
</tr>
<tr>
<td>3 - 6, 8</td>
<td>Gluon penguin</td>
</tr>
<tr>
<td>7</td>
<td>Photon penguin</td>
</tr>
<tr>
<td>9, 10</td>
<td>Electroweak penguin</td>
</tr>
<tr>
<td>S</td>
<td>Higgs (scalar) penguin</td>
</tr>
<tr>
<td>P</td>
<td>Pseudoscalar penguin</td>
</tr>
</tbody>
</table>
Constraints on New Physics from rare decays are looser than mixing

\[ H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i(\mu) O_i(\mu) + C_i'(\mu) O_i'(\mu) \right] \]

- left-handed part
- right-handed part suppressed in SM

The \( C_i^{\text{NP}} \) are all compatible with zero (so far) but one \( C_9^{\text{(NP)}} \)

Tree
- \( i = 1,2 \)

Gluon penguin
- \( i = 3,8 \)

Photon penguin
- \( i = 9 \)

Electroweak penguin
- \( i = 10 \)

Higgs (scalar) penguin
- \( i = S \)

Pseudoscalar penguin
- \( i = P \)

Straub, Altmannshofer
arXiv:1308.1501
Puzzling deviations: $P_5'$ in $B_d \to K^*\mu\mu$

In 2013, the observation by LHCb of a tension with the SM in $B \to K^*\mu\mu$ angular Observables has received considerable attention from theorists and it was shown that the tension could be softened by assuming the presence of new physics (NP).

-3.7 $\sigma$ discrepancy in the region $4.3 < q^2 < 8.68$ GeV$^2$/c$^4$

Can be explained by a negative NP contribution to the Wilson coefficient $C_9$, namely $C_9 = C_9^{\text{SM}} - 1.5$

Descotes-Genon, Virto, Matias PRD 88 (2013) 074002
D. Van Dyck, C. Bobeth, F. Beaujean arXiv 1310.2478
Altmannshofer, Straub (arXiv 1308.1501)
Puzzling deviations: $R_k = \frac{\text{BR}(B^+ \rightarrow K^+\mu^+\mu^-)}{\text{BR}(B^+ \rightarrow K^+e^+e^-)}$

In 2014, another tension with the SM has been observed by LHCb, namely a suppression of the ratio $R_k$ of $B^+ \rightarrow K^+\mu^+\mu^-$ and $B^+ \rightarrow K^+e^+e^-$ branching ratios at low dilepton invariant mass → test of lepton universality

In $3 \text{ fb}^{-1}$ LHCb measures:

$$R_k = 0.745^{+0.090}_{-0.074} \text{(stat)}^{+0.036}_{-0.036} \text{(syst)}$$

which is consistent with SM at $2.6 \sigma$

LHCb, PRL 113 (2014) 151601
Belle, PRL 103 (2009) 171801
Babar, PRD 86 (2012) 032012
Finally, also branching ratio measurements of $B_d \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$ decays published recently seem to be too low compared to the SM predictions when using state-of-the art form factors from lattice QCD or light-cone sum rules (LCSR).

Zwicky et al., Phys. Rev. D71 (2005) 014029,

Average from LHCb, CDF, CMS and ATLAS

Assuming new physics in $B \to K^{(*)}\mu\mu$ only, a consistent description of these anomalies seems possible:

G. Hiller and M. Schmaltz, PRD90 (2014) 054014
S. L. Glashow et al., arXiv:1411.0565 [hep-ph].

Difficult to explain data in SUSY scenarios or using partial compositeness (why only $C_9^{(*)}$?)
Data can be described using $Z'$ with flavour violating couplings, but mass must be $o(7\text{ TeV})$
to avoid direct limits and limits from mixing ($\Delta m_s$).

**PS:** NA62 will probe the same underlying physics with $K \to \pi\nu\nu$ decays
Assuming new physics in $B \to K^{(*)} \mu \mu$ only, a consistent description of these anomalies seems possible:

G. Hiller and M. Schmaltz, PRD90 (2014) 054014
S. L. Glashow et al., arXiv:1411.0565 [hep-ph].

However, while $R_K$ is theoretically extremely clean, predicted to be 1 to an excellent accuracy in the SM, the other observables are plagued by sizable hadronic uncertainties, [different treatments of (factorisable/non-factorisable) corrections can give large variation of $P'_5$]
Rare decays with ew-penguins: prospects

<table>
<thead>
<tr>
<th>Process</th>
<th>3 fb$^{-1}$ (7+8 TeV)</th>
<th>2015</th>
<th>Run II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0} \mu^+ \mu^-$</td>
<td>2.6 k$^\dagger$</td>
<td>1.4 - 2.1 k</td>
<td>8.5 k</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ \mu^+ \mu^-$</td>
<td>4746 ± 81</td>
<td>2.6 - 3.9 k</td>
<td>15.4 k</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+ \mu^+ \mu^-$</td>
<td>100</td>
<td>50 - 80</td>
<td>320</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ e^+ e^- (1 &lt; q^2 &lt; 6)$</td>
<td>256$^{+25}_{-23}$</td>
<td>140 - 210</td>
<td>830</td>
</tr>
</tbody>
</table>

$^\dagger$ with enlarged $q^2$ windows for 3 fb$^{-1}$ analysis

By 2028 the statistical uncertainty on each point will be reduced by a factor 3-4

Zwicky & Lyon in [arXiv:1406.0566]

Will we be able to control the hadronic uncertainties at the same level?
Another puzzling deviation: $\text{BR}(B_d \rightarrow \mu^+\mu^-)$

CMS and LHCb

LHCb and CMS, arXiv:1411.4413

$\text{BR}(B_d) = (3.94^{+1.58}_{-1.41} +0.31^{-0.24}) \times 10^{-10}$

$\text{BR}(B_s) = (2.79^{+0.66}_{-0.60} +0.26^{-0.19}) \times 10^{-9}$

$\text{BR}(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$

$\text{BR}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

 Compatibility with the SM predictions: 2.2 $\sigma$ for $B^0$ and 1.2 $\sigma$ for $B_s$

BR($B_d \rightarrow \mu^+\mu^-$) and BR($B_d \rightarrow \mu^+\mu^-$) in a model independent approach:

LHCb+CMS Bd result out of scale
$$R = \frac{\text{BR}(B^0 \rightarrow \mu^+\mu^-)}{\text{BR}(B_s^0 \rightarrow \mu^+\mu^-)}$$

$$R = 0.14^{+0.08}_{-0.06}$$

$$R \text{ (theory)} = 0.0295^{+0.0028}_{-0.0025} \ ( +8.7\% - 7.7\% )$$

Compatibility with the SM at 2.3 $\sigma$ (including theoretical uncertainty)
Main limiting factor will be the control of the peaking backgrounds (pure particle identification problem)

Expected precision on $R = \frac{\text{BR}(B^0 \rightarrow \mu^+\mu^-)}{\text{BR}(B_s^0 \rightarrow \mu^+\mu^-)}$
Are these extrapolations reliable?

→ a look into the past (LHCb roadmap document, 2009)
→ a look into the future (LHCb upgrade TDRs, 2014)
A look into the past:
“Roadmap document”: LHCb sensitivities pre data taking

Let’s compare with the current results:

For $\varphi_s$ from $B_s^0 \to J/\psi \phi$:

**Roadmap (2 fb$^{-1}$ at 14 TeV):**
- Expected 117,000 decays, $B/S \sim 2.1$,
- $\epsilon_{\text{tag}}(1 - 2\omega)^2 = 4.5\%$ and
- $\sigma(\varphi_s) \sim 0.03$

**Data:** We see 96,000 decays, $B/S \sim 5$,
- $\epsilon_{\text{tag}}(1 - 2\omega)^2 = 3.7\%$ and
- $\sigma(\varphi_s) \sim 0.049$

→ Not there yet

Slightly worse.
A look into the past:
“Roadmap document”: LHCb sensitivities pre data taking

Let’s compare with the current results:

**3σ evidence for B_s → μμ**

Roadmap: Expect 3σ with 3 fb⁻¹ @ 14 TeV
Data: We got 3σ with 2.1 fb⁻¹ @ 7-8 TeV

Better.
A look into the future: performance of the upgraded VELO

Much better IP resolution:
- Intercept is the RF foil thickness,
- slope is due to multiple scattering

Similar time resolution (~ 50 fs)
- important for the dilution factor
D = exp(-σ^2 t Δm^2/2) for B_s CP asymmetries

The upgraded VELO will be a major asset for the LHCb upgrade
A look into the future: performance of the upgraded SciFi tracker

The current tracker would never be able to stand in the upgrade conditions…. 
A look into the future: performance of the upgraded SciFi tracker

However, the upgrade tracker in the upgrade conditions will have worse performance than the current tracker in the current conditions.
A look into the future: performance of the upgraded SciFi tracker

…However the upgrade tracker in the upgrade conditions will have worse performance than the current tracker in the current conditions

Long tracks, p>5 GeV:
→ loss of 4% (5-6%) for double (same) ghost rate for generic long tracks (charm, strange..)
→ loss of 2% (3-4%) for double (same) ghost rate for long tracks from b decays (high pt)

Hence: loss of 8-16% in four body decays
(B_d → K* μμ, B_s → J/ψ φ, B_s → ϕϕ, etc.)
However any increase of hits multiplicity with respect to current simulation can change the results – and we know that the LHCb MC is not tuned (we measured +40\% hits in calorimeters with respect to simulation in Run I)
A look into the future: performance of the MUON system

MuonID performance: pion misidentification and muon efficiency in the upgrade

Extrapolations from data hence more reliable:
- 5 % efficiency/track
- x 2 more background/per track
But no safety factor included.
The numbers from the LHC:
30 MHz of primary interactions, pile-up=7.6
3 b’s, 12 c’s and 41 s per 100 BX

Output rate:
270 (b), 800 (c), 260 (s) kHz of events in LHCb acceptance with mild cuts
( \( p_T > 2 \) GeV, \( \tau > 0.2 \) ps )

The numbers from the upgrade:
money secured to build a farm:
- 13 ms /event @ 30 MHz time budget
- 20 kHz, 2 GB/s output rate

A very challenging project
The upgraded trigger: the name of the game

Time budget: 13 ms/event (*) @ 30 MHz
Tracking possible only applying global event cuts and $p_T$ cuts:

(*) this budget has been estimated assuming that the memory bandwidth grows such that the individual instances of HLT code do not influence each other performance.

[This cut is 60% efficient on charm decays]
Time budget: 13 ms/event @ 30 MHz

[Assuming a more realistic MC with 30% more hits the time to build up the tracks almost saturate the available total time budget. A Global event cut allows to recover a reasonable CPU time but cuts away 30% of Bs → ϕϕ.]
The upgraded trigger: the name of the game

Bandwidth: 20 kHz, 2 GB/sec

<table>
<thead>
<tr>
<th>Selection</th>
<th>Output Rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topological</td>
<td>10 20 50</td>
</tr>
<tr>
<td>Lifetime unbiased</td>
<td>1 4 5</td>
</tr>
<tr>
<td>Exclusive beauty</td>
<td>ε 1 3</td>
</tr>
<tr>
<td>Inclusive di-muon</td>
<td>− − 2</td>
</tr>
<tr>
<td>Charm</td>
<td>9 20 40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20 50 100</strong></td>
</tr>
<tr>
<td><strong>Bandwidth [GBs⁻¹]</strong></td>
<td><strong>2 5 10</strong></td>
</tr>
</tbody>
</table>

With 20 kHz, 2 GB/sec:
- topological trigger (only b-decays, lifetime biased selection)
- handful of lifetime unbiased selections (only b-decays)
- exclusive: only Bs→μμ, Bs→ϕϕ,
- charm: almost nothing fits in 9 kHz
(D⁰→KK: 2 kHz, D⁰→K π: 20 kHz, D⁰→ππ +Cabibbo-suppressed modes: 40 kHz; D⁰→Ks ππ: 9 kHz)

In order to cover the same physics program as in Run I we need either to increase the offline resources or to reduce the event size or to park the data
Conclusions

Flavour physics has been, is and will always be a strategic asset in the quest for new physics… However:
- only a few “hints” of deviations from SM predictions observed so far;
- sensitivity on NP mass scale reachable with LHCb upgrade (2028) is in the same ball park as direct searches at LHC @ 14 TeV (if we assume MFV) and grows (very) slowly with L

Hence:
To do a sizeable step forward in the flavour sector we need high luminosity, highly performing detectors, deep control of systematic uncertainties and reliable theory predictions…

Will the LHCb-upgrade able to keep its promises? Rendez-vous in 2023 for the answer…
Back to the beginning: the mission of a flavor physicist

To look for New Physics in FCNC B, K, charm decays (and cLFV decays) that can be sensitive to quantum corrections from degrees of freedom at and above the electroweak scale.

...but if there was nothing between the EW and Planck scales?

......To be continued.....
SPARES
“Given the absence of unambiguous signal of new physics and the compatibility of the Higgs properties with the SM predictions some doubts arose about the relevance of the naturalness argument as an organizing principle at higher energies.”

C. Grosjean, Future circular collider kick-off meeting, Geneva, February 12-14

“With a mass of the Higgs boson of ~126 GeV the Standard Model could be a self-consistent stable or meta-stable weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles.”

N. Arkani-Hamed, Future circular collider kick-off meeting, Geneva, February 12-14

……To be continued…..
**Sin2β_{eff} from**

$B^0 \rightarrow J/\psi \pi^+\pi^-$

\[
2\beta_{J/\psi}\rho = 2\beta_{eff} = (41.7 \pm 9.6^{+2.8}_{-6.3})^\circ \\
\Delta2\beta_f = 2\beta_{J/\psi}\rho - 2\beta_{J/\psi}K_S^0 = (-0.9 \pm 9.7^{+2.8}_{-6.3})^\circ
\]

Sets limits on the penguin contribution to $\phi_s$ in $B_s^0 \rightarrow J/\psi h^+h^-$

$[-1.05^\circ, 1.18^\circ]$ at 95% CL,*

assuming approximate SU(3) symmetry. The limits depends on the difference of strong phases and relative magnitudes between tree and penguin amplitudes, but do not exceed $\pm 1.8^\circ$.

Effect of penguin contributions in $B^0 \rightarrow J/\psi K_s^0$ should be limited to similar values.

*N.B. Currently, $\sigma(2\beta) = \pm 1.6^\circ$ and $\sigma(\phi_s) = \pm 2^\circ$ [HFAG].
Inputs for CKMfitter results on NP

<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th>2013</th>
<th>Stage I</th>
<th>Stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{ud}</td>
<td>$</td>
<td>$0.9738 \pm 0.0004$</td>
<td>$0.9745 \pm 0.00022$</td>
</tr>
<tr>
<td>$</td>
<td>V_{us}</td>
<td>$ ($K_{\ell 3}$)</td>
<td>$0.2228 \pm 0.0039 \pm 0.0018$</td>
<td>$0.2258 \pm 0.0008 \pm 0.0012$</td>
</tr>
<tr>
<td>$</td>
<td>\epsilon_K</td>
<td>$</td>
<td>$(2.282 \pm 0.017) \times 10^{-3}$</td>
<td>$(2.282 \pm 0.011) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta m_d$ [ps$^{-1}$]</td>
<td>$0.592 \pm 0.006$</td>
<td>$0.597 \pm 0.004$</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$\Delta m_s$ [ps$^{-1}$]</td>
<td>$&gt; 14.5$ [95% CL]</td>
<td>$17.768 \pm 0.024$</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>\times 10^3$ ($b \rightarrow c \ell \nu$)</td>
<td>$41.6 \pm 0.58 \pm 0.8$</td>
<td>$41.15 \pm 0.33 \pm 0.59$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>\times 10^3$ ($b \rightarrow u \ell \nu$)</td>
<td>$3.99 \pm 0.08 \pm 0.68$</td>
<td>$3.75 \pm 0.14 \pm 0.26$</td>
</tr>
<tr>
<td>$\sin 2\beta$</td>
<td>$0.726 \pm 0.037$</td>
<td>$0.679 \pm 0.020$</td>
<td>$0.679 \pm 0.016$ [17]</td>
<td>$0.679 \pm 0.008$ [17]</td>
</tr>
<tr>
<td>$\alpha$ (mod $\pi$)</td>
<td>$-$</td>
<td>$(85.4^{+5.0}_{-4.8})^\circ$</td>
<td>$(91.5 \pm 2)^\circ$ [17]</td>
<td>$(91.5 \pm 1)^\circ$ [17]</td>
</tr>
<tr>
<td>$\gamma$ (mod $\pi$)</td>
<td>$-$</td>
<td>$(68.6^{+8.0}_{-8.5})^\circ$</td>
<td>$(67.1 \pm 4)^\circ$ [17, 18]</td>
<td>$(67.1 \pm 1)^\circ$ [17, 18]</td>
</tr>
<tr>
<td>$\beta_s$</td>
<td>$-$</td>
<td>$0.0065^{+0.0450}_{-0.0415}$</td>
<td>$0.0178 \pm 0.012$ [18]</td>
<td>$0.0178 \pm 0.004$ [18]</td>
</tr>
<tr>
<td>$B(B \rightarrow \tau \nu) \times 10^4$</td>
<td>$-$</td>
<td>$1.15 \pm 0.23$</td>
<td>$0.83 \pm 0.10$ [17]</td>
<td>$0.83 \pm 0.05$ [17]</td>
</tr>
<tr>
<td>$B(B \rightarrow \mu \nu) \times 10^7$</td>
<td>$-$</td>
<td>$3.7 \pm 0.9$ [17]</td>
<td>$3.7 \pm 0.2$ [17]</td>
<td>$3.7 \pm 0.2$ [17]</td>
</tr>
<tr>
<td>$A_{S_L} \times 10^4$</td>
<td>$10 \pm 140$</td>
<td>$23 \pm 26$</td>
<td>$-7 \pm 15$ [17]</td>
<td>$-7 \pm 10$ [17]</td>
</tr>
<tr>
<td>$A_{S_R} \times 10^4$</td>
<td>$-$</td>
<td>$-22 \pm 52$</td>
<td>$0.3 \pm 6.0$ [18]</td>
<td>$0.3 \pm 2.0$ [18]</td>
</tr>
</tbody>
</table>

TABLE I. Central values and uncertainties used in our analysis (see definitions in Ref. [10]). The entries "id" refer to the value in the same row in the previous column. The 2003 and 2013 values correspond to Lepton-Photon 2003 and FPCP 2013 conferences [4]. The assumptions entering the Stage I and Stage II estimates are described in the text.
The uncertainty of CKM matrix elements is now larger than the uncertainty on $f_{Bs,d}$.

**Theory predictions: error budget**

Bobeth et al. ‘13

\[
\begin{align*}
BR(B^0_s \rightarrow \mu^+ \mu^-) &= (3.66 \pm 0.23) \times 10^{-9} (6.3\%) \\
BR(B^0 \rightarrow \mu^+ \mu^-) &= (1.06 \pm 0.09) \times 10^{-10} (8.5\%)
\end{align*}
\]

<table>
<thead>
<tr>
<th>$B^0_s \rightarrow \mu^+ \mu^-$</th>
<th>$f_{B_s}$</th>
<th>CKM</th>
<th>$\tau_H^s$</th>
<th>$M_t$</th>
<th>$\alpha_s$</th>
<th>other param.</th>
<th>non-param.</th>
<th>$\sum$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.0%</td>
<td>4.3%</td>
<td>1.3%</td>
<td>1.6%</td>
<td>0.1%</td>
<td>&lt; 0.1%</td>
<td>1.5%</td>
<td>6.4%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$B^0 \rightarrow \mu^+ \mu^-$</th>
<th>$f_{B_d}$</th>
<th>CKM</th>
<th>$\tau_H^s$</th>
<th>$M_t$</th>
<th>$\alpha_s$</th>
<th>other param.</th>
<th>non-param.</th>
<th>$\sum$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.5%</td>
<td>6.9%</td>
<td>0.5%</td>
<td>1.6%</td>
<td>0.1%</td>
<td>&lt; 0.1%</td>
<td>1.5%</td>
<td>8.5%</td>
</tr>
</tbody>
</table>

- $f_{B_s} = 227.4(4.5) \text{ MeV}$
  [FLAG ’13, arXiv:1310.8555]
- $V_{cb}$ from recent inclusive fit
- $f_{B_d} = 190.5(4.2) \text{ MeV}$
  [FLAG ’13, arXiv:1310.8555]

The uncertainty of CKM matrix elements is now larger than the uncertainty on $f_{Bs,d}$.
Theory predictions: error budget

\[ \text{BR}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9} \ (6.4\%) \]
\[ \text{BR}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10} \ (8.5\%) \]

\[
\begin{array}{|l|l|l|l|l|l|l|l|}
\hline
B_s^0 \to \mu^+\mu^- & f_{B_s} & \text{CKM} & \tau_H^s & M_t & \alpha_s & \text{other param.} & \text{non-param.} & \sum \\
\hline
4.0\% & 4.3\% & 1.3\% & 1.6\% & 0.1\% & < 0.1\% & & 1.5\% & 6.4\% \\
\hline
B^0 \to \mu^+\mu^- & f_{B_d} & \text{CKM} & \tau_H^s & M_t & \alpha_s & \text{other param.} & \text{non-param.} & \sum \\
\hline
4.5\% & 6.9\% & 0.5\% & 1.6\% & 0.1\% & < 0.1\% & & 1.5\% & 8.5\% \\
\hline
\end{array}
\]

\[ R = \frac{\text{BR}(B^0 \to \mu^+\mu)}{\text{BR}(B_s^0 \to \mu^+\mu)} = 0.0295^{+0.0028}_{-0.0025} \ (8.7\% - 7.7\%) \]

The theoretical uncertainty on R is due:
- 8 % uncertainty from CKM elements;
- 3.7 % uncertainty from \( f_{B_s}/f_{B_d} \)
- 1.4 % uncertainty on the \( B_s \) lifetime

These uncertainties do not cancel in the ratio.
CMS and LHCb results: pre-combination

\begin{align*}
\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-) & = (3.0^{+1.0}_{-0.9}) \times 10^{-9} (4.3 \sigma) \\
\text{BR}(B^0 \rightarrow \mu^+ \mu^-) & = (3.5^{+2.1}_{-1.98}) \times 10^{-10} (2.0 \sigma) \\
\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-) & = (2.9^{+1.1}_{-1.9}) \times 10^{-9} (4.0 \sigma) \\
\text{BR}(B^0 \rightarrow \mu^+ \mu^-) & = (3.7^{+2.4}_{-2.1}) \times 10^{-10} (2.0 \sigma)
\end{align*}
Figure 4.2: Top left: Number of primary vertices for simulated data samples generated with \( \nu = 2, \nu = 3.8 \) and \( \nu = 7.6 \). Top right: Number of reconstructible long tracks per primary vertex in an event. Bottom row: Momentum and transverse momentum distributions for all long reconstructible particles in \( B_s \rightarrow \phi\phi \) events at \( \sqrt{s} = 14 \text{ TeV} \).
LHC schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

30 fb⁻¹

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Run 2</td>
<td>YETS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

300 fb⁻¹

<table>
<thead>
<tr>
<th>Year</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>2029</th>
<th>2030</th>
<th>2031</th>
<th>2032</th>
<th>2033</th>
<th>2034</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LHC era

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, CMS</td>
<td>25 fb⁻¹</td>
<td>100 fb⁻¹</td>
<td>300 fb⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS, CMS</td>
<td></td>
<td></td>
<td></td>
<td>3000 fb⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>3 fb⁻¹</td>
<td>8 fb⁻¹</td>
<td>23 fb⁻¹</td>
<td>46 fb⁻¹</td>
<td>100 fb⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

HL-LHC era
How the accuracy on flavour observables translates into M(NP) limits?

General decomposition of flavor-violating observables

\[ A = A_0 \left[ c_{\text{SM}} \frac{1}{M_W^2} + c_{\text{NP}} \frac{1}{M_{\text{NP}}^2} \right] \]

- trivial kinematical factors
- (dimensionless) effective couplings
- effective mass (scale) of NP

E.g.: If \( c_{\text{NP}} \sim c_{\text{SM}} \) [electroweak-MFV-like], then 10% precision \( \leftrightarrow \) \( M_{\text{NP}} \sim 250 \) GeV

Decreasing the error to 2% (~30 x statistics) \( \Rightarrow \)

\[ 250 \text{ GeV} \rightarrow 600 \text{ GeV} \]
\[ \sigma(c_{\text{NP}}) \rightarrow 0.2 \times \sigma(c_{\text{NP}}) \]

Isidori @ ECFA’14
Form-factor uncertainties

- Decay amplitudes depend on 7 $B \to K^*$ form-factors:
  - $A_0$, $A_1$, $A_2$, $T_1$, $T_2$, $T_3$ and $V$.
- Can be reduced to two soft form-factors ($\xi_{||}(q^2)$ and $\xi_{\perp}(q^2)$) at low $q^2$
  - Valid up-to $O(\Lambda/m_B)$, usually assumed to be $O(10\%)$.
- Form observables where $\xi_{||}$ and $\xi_{\perp}$ cancel, e.g. $P_5'$.  

Unfortunately different treatments of (factorisable + non-factorisable) corrections can give large variation of $P_5'$.

Try to constrain the form-factors from the data itself.
\( c\bar{c} \) contributions

- In [Phys. Rev. Lett. 111 (2013) 112003] we showed that there are large \( c\bar{c} \) contributions above the \( \psi(2S) \) e.g. from \( \psi(4160) \). Some debate about whether the level of these was compatible with OPE.

- Zwicky & Lyon in [arXiv:1406.0566] show that the LHCb data can not be explained by naive factorisation, i.e. by taking the vacuum polarisation from BES II.
**c\bar{c} contributions**

- To fit the data, Zwicky & Lyon try global scaling $\eta_c$ and a per-resonance scaling $\rho_c$.
- Data best described by large non-factorisable correction (350%!).
- Receive virtual $c\bar{c}$ contributions to $C_{9}^{\text{eff}}$ below the $J/\psi$,
  
  \[ C_{9}^{\text{eff}} = C_9 + a \cdot \eta_c \cdot h_c(q^2) \, . \]
- Can also see large impact on observables at low $q^2$ (depending on $C_7$ interference) by applying a left- and right-handed scale factor.

$\eta_c = (1, 0)$, $\eta_c = (-1.25, -1.25)$,

$\eta_c = (0, -2.5)$, $\eta_c = (-2.5, 0)$