What would permille constraints on flavour observables bring us?

Uli Haisch
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Flavour Run I summary on a slide

\[ \mu_{B_s \rightarrow \mu^+ \mu^-} = 0.78 \pm 0.18 \]
Flavour: new-physics scale?

\[ \mu_{B_s \to \mu^+ \mu^-} \simeq 1 \pm \frac{4\pi}{g^2 |V_{tb}^* V_{ts}|^2} \frac{\nu^2}{\Lambda^2} \]

\[ \Lambda \gtrsim \frac{\nu}{\sqrt{0.2}} \times \left\{ \frac{\sqrt{4\pi}}{g |V_{tb}^* V_{ts}|} \right\} \simeq \left\{ 50 \text{ TeV} \right\} \]

anarchic tree
Flavour: new-physics scale?

\[ \Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \frac{\sqrt{4\pi}}{g \left| V_{tb}^* V_{ts} \right|} & \approx \begin{cases} 50 \text{ TeV} , \quad \text{anarchic tree} \\ 0.6 \text{ TeV} , \quad \text{MFV loop} \end{cases} \\ 1 \end{cases} \]
Estimating new-physics reach

\[ \Lambda \gtrsim \frac{v}{\sqrt{\delta}} \times \left\{ \frac{\sqrt{4\pi}}{g|V_{tb}^*V_{ts}|} \right\} \approx \left\{ \begin{array}{c} \frac{25 \text{ TeV}}{\sqrt{\delta}}, \quad \text{anarchic tree} \\ \frac{0.3 \text{ TeV}}{\sqrt{\delta}}, \quad \text{MFV loop} \end{array} \right\} \]

To predict future just need to know total relative uncertainty \( \delta \), that’s all
If one takes $\delta$ to be a $\%$, bounds on new-physics scale improve by a factor of around 15 compared to LHC Run I limits.

$$\Lambda \gtrsim \frac{v}{\sqrt{100}} \times \left\{ \frac{\sqrt{4\pi}}{g |V_{tb}^* V_{ts}|} \right\} \simeq \left\{ \begin{array}{ll} 700 \text{ TeV}, & \text{anarchic tree} \\ 8.5 \text{ TeV}, & \text{MFV loop} \end{array} \right.$$
How realistic is a %?

Even if we get enough statistics what about systematics?

Are you sure we understand QCD well enough at scales of a few GeV?

[more on experimental issues in talks by Marc & Patrick]
$B_s \rightarrow \mu^+ \mu^-$: current SM errors

Calculation of 3-loop QCD & 2-loop EW effects reduces perturbative uncertainties to 0.5%. Relative errors due to $f_{B_s}$ & CKM both around 4%.

[Bobeth et al., 1311.0903, 1311.1348; Hermann et al., 1311.1347]
$B_s \rightarrow \mu^+ \mu^-$: future SM errors

Improvements in lattice QCD calculations may reduce errors due to $f_{B_s}$ & $V_{cb}$, leading to a future total uncertainty of 3%.

[Blum et al., http://www.usqcd.org/documents/13flavor.pdf]
B$\to$K$^*$μ$^+$μ$^-$: current SM errors

For $P_5'$ in [4, 6] GeV$^2$ bin:

\[-0.82^{+0.01+0.02+0.03+0.06+0.07}_{-0.01-0.02-0.06-0.06-0.08}\]

- parametric
- non-factorisable power corrections
- form factors
- factorisable power corrections
- long-distance $c\bar{c}$ effects

[Matias, Moriond EW 2015]
For $P_5'$ in $[4, 6]$ GeV$^2$ bin:

$$-0.82^{+0.01+0.02+0.03+0.06+0.07}_{-0.01-0.02-0.06-0.06-0.08}$$

Dominant uncertainty of $O(10\%)$ due to long-distance $c\bar{c}$ contribution cannot be calculated from first principles at present. Achieving % level precision in $B\to K^*\mu^+\mu^-$ & related modes would require breakthrough in our understanding of non-perturbative QCD. Maybe experiment can help by measuring long-distance $c\bar{c}$ effects

[see Patrick's talk & Petridis, Rare B Decays: Theory and Experiment 2016]
### Flavour precision observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Error</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \gamma$</td>
<td>$\mathcal{O}(10^{-7})$</td>
<td>[Bordone et al., 1605.07633]</td>
</tr>
<tr>
<td>$\delta \beta$</td>
<td>$\mathcal{O}(1%)$</td>
<td>[Ciuchini et al., hep-ph/0507290]</td>
</tr>
<tr>
<td>$\delta R_{D^*}$</td>
<td>$\mathcal{O}(1%)$</td>
<td>[Fajfer et al., 1203.2654]</td>
</tr>
<tr>
<td>$\delta R_K, \delta R_{K^*}, \ldots$</td>
<td>$\mathcal{O}(1%)$</td>
<td>[Bordone et al., 1605.07633]</td>
</tr>
</tbody>
</table>

Theoretical errors in some observables at % level or below. If measured with a comparable precision one could learn a lot about exotic tree-level effects, penguin pollution, lepton-flavour universality violating couplings, etc.
B mixing: present & future

\[ M_{12}^q = (M_{12}^q)_{SM} \left( 1 + h_q e^{2i\sigma_q} \right) \]

\[ h_d \lesssim 30\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 0.8 \cdot 10^3 \text{TeV, anarchic tree} \\ 0.6 \text{TeV, MFV loop} \end{cases} \]
B mixing: present & future

\[ M_{12}^q = (M_{12}^q)_{SM} \left( 1 + h_q e^{2i\sigma_q} \right) \]

\[ h_d \lesssim 5\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 2 \cdot 10^3 \text{TeV}, \text{ anarchic tree} \\ 1.4 \text{TeV}, \text{ MFV loop} \end{cases} \]
Constraints on 2HDM-II

Present 95% CL exclusions:
- $B \rightarrow X_s \gamma$
- $B \rightarrow \tau \nu$
- $B_s \rightarrow \mu^+ \mu^-$

- $\bar{t} \rightarrow \bar{b} H^+ (\rightarrow \tau^+ \bar{\nu}_\tau, \bar{t}b)$

MSSM updated $m_h^\text{max}$

[CMS, 1508.07774]

Flavour physics provides stringent indirect constraints in $m_{H^\pm}$-tan$\beta$ plane. Restrictions highly complementary to direct searches by ATLAS & CMS
Constraints on 2HDM-II

Excluded by

\[
\frac{\text{Br}(B_s \rightarrow \mu^+\mu^-)}{\text{Br}(B_s \rightarrow \mu^+\mu^-)_{SM}} \in [0.46, 1.16]
\]

[0.46, 1.16]

[0.46, 0.55]

Any precision measurement of $B_s \rightarrow \mu^+\mu^-$ compatible with Run I 95% CL limit will significantly reduce allowed parameter space in $m_{H^\pm}$-$\tan \beta$ plane.
Constraints on 2HDM-II

Excluded by

\[
\frac{\text{Br}(B_s \to \mu^+\mu^-)}{\text{Br}(B_s \to \mu^+\mu^-)_{\text{SM}}} \in
\]

- [0.46, 1.16]
- [0.93, 1.16]

Any precision measurement of $B_s \to \mu^+\mu^-$ compatible with Run I 95% CL limit will significantly reduce allowed parameter space in $m_{H^\pm}$-$\tan \beta$ plane.
Constraints on 2HDM-II

Excluded by

$$\frac{\text{Br}(B_s \to \mu^+\mu^-)}{\text{Br}(B_s \to \mu^+\mu^-)_{\text{SM}}} \in$$

[0.46, 1.16]

[0.9, 1.1]

Any precision measurement of $B_s \to \mu^+\mu^-$ compatible with Run I 95% CL limit will significantly reduce allowed parameter space in $m_{H^\pm}$-tan $\beta$ plane.
Since flavour observables involve typically a handful of MSSM parameters such as $m_{\tilde{\tau}}, \mu, A_t$, etc. always more model-dependent than direct searches
**B_s \rightarrow \mu^+ \mu^- constraints on MSSM**

![Graph showing constraints on tan(β) vs. M_A (GeV)]

(a) \( \mu = 1 \text{ TeV}, \ A_t > 0 \)
(b) \( \mu = 4 \text{ TeV}, \ A_t > 0 \)
(c) \( \mu = -1.5 \text{ TeV}, \ A_t > 0 \)
(d) \( \mu = 1 \text{ TeV}, \ A_t < 0 \)

all squarks degenerate with 2 TeV, \( A_t \) such that \( m_h = 125 \text{ GeV} \)

- included by LHC Run I
- \( H, A \rightarrow \tau^+ \tau^- \) searches

Interference of Higgsino with SM contribution make \( B_s \rightarrow \mu^+ \mu^- \) sensitive probe of \( \mu A_t \). Currently \( \mu A_t < 0 \) stronger constrained as interference constructive
$B_s \rightarrow \mu^+ \mu^-$ constraints on MSSM

(a) $\mu = 1$ TeV, $A_t > 0$

all squarks degenerate with 2 TeV, $A_t$ such that $m_h = 125$ GeV

- excluded by LHC Run I
- $H, A \rightarrow \tau^+ \tau^-$ searches

- parameters leading to $\text{Br}(B_s \rightarrow \mu^+ \mu^-) \in [3.2, 4.2] \cdot 10^{-9}$

However also choices with $\mu A_t > 0$ will be constrained significantly if a lower bound of $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ above half of SM prediction is established in future
\[ B_s \rightarrow \mu^+ \mu^- \text{ vs. } B_d \rightarrow \mu^+ \mu^- \]

in scenarios with MFV deviations in \( B_{s,d} \rightarrow \mu^+ \mu^- \) modes very constrained

\[ \frac{\text{Br}(B_d \rightarrow \mu^+ \mu^-)/\text{Br}(B_d \rightarrow \mu^+ \mu^-)_\text{SM}}{\text{Br}(B_s \rightarrow \mu^+ \mu^-)/\text{Br}(B_s \rightarrow \mu^+ \mu^-)_\text{SM}} \]

CMS & LHCb, 1411.4413

68% CL

95% CL

MFV
$B_s \to \mu^+ \mu^- \text{ vs. } B_d \to \mu^+ \mu^-$

At HL-LHC can rule out or provide precision test of MFV hypothesis

- MFV
- little Higgs model with T parity
  [Blanke et al., 1507.06316]
- Randall-Sundrum model without custodial protection
  [Bauer et al., 0912.1625]

In models beyond MFV, modes are uncorrelated.
Currently only real parts of Wilson coefficients constrained by global fits. Weak sensitivity to $\text{Im}(C_7)$ from $B \to K^*\gamma$. Precise measurements of CP-violating observables in $B \to K^* \mu^+ \mu^-$ thus important goal of LHCb.
Future directions in $B \to K^* \mu^+ \mu^-$

Low-$q^2$ observables in $B \to K^* \mu^+ \mu^-/e^+e^-$ over clean & orthogonal tests of $C'_7$. Together with $b \to s \gamma$ can probe full $C'_7$ sector
Y production at LHCb

LHCb $\sqrt{s} = 8$ TeV
$3 < p_T < 4$ GeV/$c$
$3.0 < y < 3.5$

Precision measurement of dimuon spectrum for invariant masses in $\Upsilon$ region with only 3% of 8 TeV data set
Existing $\Upsilon$ data provides best bound on 2HDM-II for $m_A \in [8.6, 11]$ GeV. With more data should be possible to improve & extend limits notably.

[for other new-physics searches in dimuon sample see Patrick’s talk & backup slides]
Constraining SM parameters


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>fine structure constant</td>
<td>$\frac{1}{137.035999139(31)}$</td>
<td>0.23 ppb</td>
</tr>
<tr>
<td>electron mass</td>
<td>0.5109989461(31) MeV</td>
<td>6.2 ppb</td>
</tr>
<tr>
<td>Fermi constant</td>
<td>$1.1663787(6) \cdot 10^{-5}$ GeV$^{-2}$</td>
<td>500 ppb</td>
</tr>
<tr>
<td>$W$-boson mass</td>
<td>80.385(15) GeV</td>
<td>0.2%</td>
</tr>
<tr>
<td>strong coupling constant</td>
<td>0.1185(6)</td>
<td>0.5%</td>
</tr>
<tr>
<td>top-quark mass</td>
<td>173.21(87) GeV</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Flavour physics obviously allows to constrain CKM elements. But what about other SM parameters like for instance $\alpha_s$ or $m_t$?
Boxes & Z penguins

[see e.g. Buras, hep-ph/9806471]

Within SM, only two 1-loop topologies lead to a quadratic dependence on top mass

\[ \Delta m_K, \Delta m_{B_d}, \Delta m_{B_s}, \epsilon_K \]

\[ B_{d,s} \rightarrow \mu^+ \mu^-, B \rightarrow K^{(*)}, X_s \mu^+ \mu^-, \]

\[ K \rightarrow \pi \nu \bar{\nu}, K \rightarrow \pi \mu^+ \mu^-, \epsilon'/\epsilon, Z \rightarrow b\bar{b} \]
Top mass from $B_s \rightarrow \mu^+\mu^-$

$$\text{Br} \left( B_s \rightarrow \mu^+\mu^- \right)_{\text{SM}} = 3.65 \left( \frac{m_t^{\text{pole}}}{173.1 \text{ GeV}} \right)^{3.06} (1 \pm 3\%) \cdot 10^{-9}$$

$$\text{Br} \left( B_s \rightarrow \mu^+\mu^- \right)_{\text{exp}} = 3.65 (1 \pm 4\%) \cdot 10^{-9}$$

$$\downarrow$$

$$m_t^{\text{pole}} = (173.1 \pm 2.8) \text{ GeV}$$

Indirect determination less stringent than direct measurements, but useful given theoretical ambiguities in extraction of $m_t$ at colliders

[UH, Top at Twenty; Giudice et al., 1508.05332]
## Constraining SM couplings

[LEPEWWG, hep-ex/0509008; CMS, 1303.3239; Falkowski et al., 1508.00581]

<table>
<thead>
<tr>
<th>Couplings</th>
<th>Accuracy (Left, Right)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ze^+e^-$</td>
<td>(0.1%)$_L$, (0.1%)$_R$</td>
</tr>
<tr>
<td>$Zcar{c}$</td>
<td>(1.0%)$_L$, (3.2%)$_R$</td>
</tr>
<tr>
<td>$Zbar{b}$</td>
<td>(0.4%)$_L$, (6.5%)$_R$</td>
</tr>
<tr>
<td>$Ztar{t}$</td>
<td>&gt; 100%</td>
</tr>
<tr>
<td>$WWZ$ coupling</td>
<td>2.3%</td>
</tr>
<tr>
<td>$WW\gamma$ coupling</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

Only couplings of W- & Z-bosons to leptons known with a precision below 1%. Which accuracy can flavour precision measurements achieve?
HL-LHC $B_s \rightarrow \mu^+\mu^-$ measurements have potential to constrain $Zt\bar{t}$ couplings at few % level. Direct measurements only able to reach $O(30\%)$ precision.

[Röntsch & Schulze, 1404.1005] [UH based on Brod et al., 1408.0792]
LHCb has measured forward-central $b\bar{b}$ asymmetry with $O(50\%)$ precision using $1 \text{ fb}^{-1}$ of 7 TeV data, while SM prediction has uncertainty of $O(15\%)$.

$Zb\bar{b}$ couplings from $A_{\text{FC}}^{b\bar{b}}$ at LHCb

$\sqrt{s} = 7 \text{ TeV}$

$\Delta\phi > 2.6$

$2.0 < \eta < 4.0$

$E_T > 20 \text{ GeV}$

$\alpha_s(m_Z^2) = 0.119$

NNPDF2.3 (N)LO
Zb$b\bar{b}$ couplings from $A_{FC}^{b\bar{b}}$ at LHCb

To reach LEP sensitivity need to achieve total relative error on forward-central b$b$ asymmetry at % level. A challenge for both LHCb & theory.
WWZ/γ couplings from flavour

As deviations in WWZ coupling logarithmically enhanced in $B_s \rightarrow \mu^+\mu^-$ may get $O(1\%)$ precision at HL-LHC. Only $O(10\%)$ sensitivity in case of $WW\gamma$
Conclusions

• To shed further light on existing flavour anomalies one needs measurements with higher statistics. LHC upgrade is able to deliver such precision measurements, which can lead to important interplay & complementarity with ATLAS, CMS, Belle II, NA62, etc.

[see Jernej’s talk]

• Anomalies could be due to new flavour dynamics at relatively low scale & in such a case one can learn a lot about it at HL-LHC. Conversely if deviations disappear, LHC upgrade will significantly push up effective scale of flavour violation
Backup
Future of lattice calculations

[Blum et al., http://www.usqcd.org/documents/13flavor.pdf]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>CKM element</th>
<th>Present</th>
<th>2007 forecast</th>
<th>Present</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_K/f_\pi$</td>
<td>$</td>
<td>V_{us}</td>
<td>$</td>
<td>0.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$f^K_{\pi}(0)$</td>
<td>$</td>
<td>V_{us}</td>
<td>$</td>
<td>0.2%</td>
<td>–</td>
</tr>
<tr>
<td>$f_D$</td>
<td>$</td>
<td>V_{cd}</td>
<td>$</td>
<td>4.3%</td>
<td>5%</td>
</tr>
<tr>
<td>$f_{Ds}$</td>
<td>$</td>
<td>V_{cs}</td>
<td>$</td>
<td>2.1%</td>
<td>5%</td>
</tr>
<tr>
<td>$D \to \pi \ell \nu$</td>
<td>$</td>
<td>V_{cd}</td>
<td>$</td>
<td>2.6%</td>
<td>–</td>
</tr>
<tr>
<td>$D \to K \ell \nu$</td>
<td>$</td>
<td>V_{cs}</td>
<td>$</td>
<td>1.1%</td>
<td>–</td>
</tr>
<tr>
<td>$B \to D^* \ell \nu$</td>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
<td>1.3%</td>
<td>–</td>
</tr>
<tr>
<td>$B \to \pi \ell \nu$</td>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
<td>4.1%</td>
<td>–</td>
</tr>
<tr>
<td>$f_B$</td>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
<td>9%</td>
<td>–</td>
</tr>
<tr>
<td>$\xi$</td>
<td>$</td>
<td>V_{ts}/V_{td}</td>
<td>$</td>
<td>0.4%</td>
<td>2-4%</td>
</tr>
<tr>
<td>$\Delta M_s$</td>
<td>$</td>
<td>V_{ts}V_{tb}</td>
<td>^2$</td>
<td>0.24%</td>
<td>7-12%</td>
</tr>
<tr>
<td>$B_K$</td>
<td>Im$(V_{td}^2)$</td>
<td>0.5%</td>
<td>3.5-6%</td>
<td>1.3%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>
Impact of theory improvement

NNLO QCD & NLO EW effects in $B_{s,d} \rightarrow \mu^+ \mu^-$ phenomenologically relevant

[Bobeth et al., 1311.0903, 1311.1348; Hermann et al., 1311.1347]
Calculation of 3-loop QCD & 2-loop EW effects reduces perturbative uncertainties to 0.5%. Relative errors due to $f_{Bd}$ & CKM are 4.5% & 6.9%.

[Bobeth et al., 1311.0903, 1311.1348; Hermann et al., 1311.1347]
$B_d \rightarrow \mu^+ \mu^-$: future SM errors

Improvements in lattice QCD calculations may reduce errors due to $f_{B_d}$ leading to a future total uncertainty of 7%.

[Blum et al., http://www.usqcd.org/documents/13flavor.pdf]
FIG. 1. The past (2003, top left) and present (top right) status of the unitarity triangle in the presence of NP in neutral-meson mixing. The lower plots show future sensitivities for Stage I and Stage II described in the text, assuming a consistent with the SM. The combination of all constraints in Table I yields the red-hatched regions, yellow regions, and dashed red contours at 68.3% CL, 95.5% CL, and 99.7% CL, respectively.

Stage I projection refers to a time around or soon after the end of LHCb Phase I, corresponding to an anticipated 7 fb$^{-1}$ LHCb data and 5 ab$^{-1}$ Belle II data, towards the end of this decade. The Stage II projection assumes 50 fb$^{-1}$ LHCb and 50 ab$^{-1}$ Belle II data, and probably corresponds to the middle of the 2020s, at the earliest. Estimates of future experimental uncertainties are taken from Refs. [17, 18, 21, 22]. (Note that we display the units as given in the LHCb and Belle II projections, even if it makes some comparisons less straightforward; e.g., the uncertainties of both $\beta$ and $\beta'$ will be $\sim 0.2^\circ$ by Stage II.) For the entries in Table I where two uncertainties are given, the first one is statistical (treated as Gaussian) and the second one is systematic (treated through the Rfit model [8]). Considering the difficulty to ascertain the breakdown between statistical and systematic uncertainties in lattice QCD inputs for the future projections, for simplicity, we treat all such future uncertainties as Gaussian.

The fits include the constraints from the measurements of $A_{d,s}^{SL}$ [10, 11], but not their linear combination [23], nor from $\Delta \Gamma_s$, whose effects on the future constraints on NP studied in this paper are small. While $\Delta \Gamma_s$ is in agreement with the CKM fit [10], there are tensions for $A_{d,s}^{SL}$ [23]. The large values of $\Delta \Gamma_s$ allowed until recently, corresponding to $(M_s^{NP}) \sim -2(M_s^{SM})$, are excluded by the LHCb measurement of the sign of $\Delta \Gamma_s$ [24]. We do not consider $K$ mixing for the fits shown in this Section.

[Charles et al., 1309.2293]
Stage I:

- 7 fb$^{-1}$ of LHCb data
- 5 ab$^{-1}$ of Belle II data
- $\delta f_{Bq} = O(1\%)$, $\delta V_{ub} = O(2\%)$

Lattice QCD improvements crucial to obtain such tight constraints
CKM fit in 10 years

Stage II:
- 50 fb$^{-1}$ of LHCb data
- 50 ab$^{-1}$ of Belle II data
- $\delta f_{Bq} = O(1\%)$,
  $\delta V_{ub} = O(2\%)$

Lattice QCD improvements crucial to obtain such tight constraints
New-physics reach in B mixing

[Charles et al., 1309.2293]

<table>
<thead>
<tr>
<th>Couplings</th>
<th>NP loop order</th>
<th>Scales (in TeV) probed by $B_d$ mixing</th>
<th>$B_s$ mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>C_{ij}</td>
<td>=</td>
<td>V_{ti}V_{tj}^*</td>
</tr>
<tr>
<td></td>
<td>one loop</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>$</td>
<td>C_{ij}</td>
<td>= 1$ (no hierarchy)</td>
<td>tree level</td>
</tr>
<tr>
<td></td>
<td>one loop</td>
<td>$2 \times 10^2$</td>
<td>40</td>
</tr>
</tbody>
</table>
Flavour constraints on 2HDM-II

$B \rightarrow D^* \tau \nu$ would require very small $m_H$ & large $\tan\beta$. No region in parameter space compatible with all measurements.
Deviations in $B \to D^{(*)}\tau\nu$ can be explained, using coupling $\epsilon_{32}^u$ of left-handed top to right-handed charm quarks.
MSSM: indirect probes

\[ \Delta C_7^\chi \propto -\mu A_t t_\beta \frac{m_t^2}{m_t^4} \]

\[ C_S \approx -C_P \propto \mu A_t t_\beta^3 \frac{m_t^2}{m_t^4} \frac{m_b m_\mu}{M_W^2 M_A^2} \]

\[ \Delta a_\mu^\chi \propto \frac{G_F M_W^2}{\sqrt{2} \pi^2} \mu M_2 t_\beta \frac{m_\mu^2}{m_\nu^4} \]
MSSM: Higgs properties

\[(\Delta M^2_{h})_t \approx \frac{3G_F}{\sqrt{2\pi^2}} m_t^4 \left[ -\ln \left( \frac{m_t^2}{m_t^2} \right) + \frac{X_t^2}{m_t^2} \left( 1 - \frac{X_t^2}{12m_t^2} \right) \right] \]

\[\kappa_{\tilde{q}} \approx \frac{1}{4} m_q^2 \frac{\partial}{\partial m_q^2} \ln \left[ \det (\mathcal{M}_{\tilde{q}}^2) \right] \]

\[
\approx \left\{ \begin{array}{c}
\frac{m_t^2}{4} \left( \frac{1}{m_{t_1}^2} + \frac{1}{m_{t_2}^2} - \frac{X_t^2}{m_{t_1}^2 m_{t_2}^2} \right), \quad \tilde{q} = \tilde{t} \\
- \frac{m_b^2 X_b^2}{4m_{b_1}^2 m_{b_2}^2}, \quad \tilde{q} = \tilde{b}
\end{array} \right\}
\]
\[ R_{\mu^+\mu^-} = \frac{\text{Br}(B_s \to \mu^+\mu^-)_{\text{MSSM}}}{\text{Br}(B_s \to \mu^+\mu^-)_{\text{SM}}} \simeq 1 - 13.2 C_P + 43.6 \left(C_S^2 + C_P^2\right) \]

\[ C_S \simeq -C_P \]

\[ \frac{dR_{\mu^+\mu^-}}{dC_P} = -13.2 + 174.4 C_P = 0 \quad \implies \quad C_P \simeq 0.076 \]

\[ \implies \]

\[ (R_{\mu^+\mu^-})_{\text{min}} \simeq 0.5 \]
Probing $\mu$ & $M_{\tilde{Q}_3}$ with $B_s \rightarrow \mu^+\mu^-$

[Altmannshofer et al., 2011.1976]

LHCb 1+1.5+4 fb$^{-1}$, positive $A_t$

LHCb 1+1.5+4 fb$^{-1}$, negative $A_t$

Allowed for degenerate squarks

Excluded by LEP chargino searches

Allowed for $M_{Q_{1,2}} > 2 M_{\tilde{Q}_3}$
Stop sector probes

\[
\Delta C_7^\chi \approx \frac{5}{288} \frac{m_t^2}{m_{\tilde{t}_1}^2} - \frac{2}{9} t_\beta s_\tilde{t} \frac{\mu m_t}{m_{\tilde{t}_1}^2}
\]

\[
\frac{\Delta C}{C_{SM}} \approx \frac{m_t^2 X_t^2}{12 s_\beta^2 m_{\tilde{t}_1}^4}
\]
Stop sector probes

\[
\frac{\epsilon_K}{(\epsilon_K)_{\text{SM}}} \approx 1 + 0.16 \frac{m_t^2}{m_{\tilde{t}_1}^2}
\]

\[
\Delta \rho \approx \frac{G_F}{24\sqrt{2}\pi^2} \frac{m_t^4}{m_{\tilde{t}_1}^2} \left( 1 - s_{\tilde{t}}^2 \frac{\delta m_{\tilde{t}}^2}{m_{\tilde{t}_1}^2} \right)
\]
Indirect bounds on stop sector

Depending on choice of parameters in stop sector, combination of indirect measurements can provide limits on mass of lightest stop eigenstate of around 300 GeV

\[ t_\beta = 10 \]
\[ \mu = 0.2 \text{ TeV} \]
\[ \theta \bar{t} = 0 \]
Depending on choice of parameters in stop sector, combination of indirect measurements can provide limits on mass of lightest stop eigenstate of around 300 GeV.

\[ t_\beta = 10 \]
\[ \mu = 0.2 \text{ TeV} \]
\[ \theta_{\tilde{t}} = \pi/4 \]
Indirect bounds on stop sector

\[ t_\beta = 2 \]
\[ \mu = -0.2 \text{ TeV} \]
\[ \theta_i = \pi/4 \]

But if constraint from Higgs-boson mass measurement is ignored (only applies in SUSY with minimal Higgs sector), no relevant model-independent lower bound on stop mass can be found.
Implications of $b \to s \mu^+ \mu^-$ anomalies

Simplest new-physics explanations of $P'_5$ & $R_K$ anomalies would lead to $O(-20\%)$ shifts in $\text{Br}(B \to X_s \mu^+ \mu^-)$. Should be observable at Belle II

$$\delta \text{Br}_{[1,6] \ \text{GeV}^2} = -17\%$$

$$\delta \text{Br}_{>14.4 \ \text{GeV}^2} = -25\%$$
Implications of $b \to s \mu^+ \mu^-$ anomalies

Zero of forward-backward asymmetry shifted by even $O(35\%)$. Belle II measurements of $B \to X_s \mu^+ \mu^-$ crucial to shed light on $P_5$ & $R_K$ anomalies
Low-$q^2$ observable in $b \rightarrow s l^+ l^-$

$$S_{K^* \gamma} \simeq \frac{2 \text{Im} \left( e^{-2i\beta} C_7 C_7' \right)}{|C_7|^2 + |C_7'|^2}$$

$$P_1 \simeq \frac{2 \text{Re} \left( C_7 C_7' \right)}{|C_7|^2 + |C_7'|^2} \quad P_3^{CP} \simeq \frac{2 \text{Im} \left( C_7 C_7' \right)}{|C_7|^2 + |C_7'|^2}$$

LHCb will reach theoretical limit by end of HL-LHC for $P_1$ but not for $P_3^{CP}$ which is CP violating but does not require a strong phase
CP violation in $B \rightarrow K^* \mu^+ \mu^-$

\[
\langle A_7 \rangle_{[1,6]} \simeq -0.44 \text{Im}(C_7^{NP}) + 0.44 \text{Im}(C_7') + 0.07 \text{Im}(C_{10}^{NP}) - 0.07 \text{Im}(C_{10}')
\]
CP violation in $B \to K^* \mu^+ \mu^-$

\[ \langle A_8 \rangle_{1,6} \simeq +0.25 \text{Im}(C_7^{\text{NP}}) + 0.23 \text{Im}(C'_7) + 0.04 \text{Im}(C_9^{\text{NP}}) + 0.02 \text{Im}(C'_9) - 0.06 \text{Im}(C'_{10}) \]
**CP violation in \( B \to K^* \mu^+ \mu^- \)**

\[
\langle A_9 \rangle_{[1,6]} \simeq +0.12 \text{Im}(C_7') + 0.04 \text{Im}(C_{10}')
\]

**[Altmannshofer & Straub, 1308.1501]**

![Graph showing CP violation](image-url)
Constraints from radiative decays

[Paul & Straub, 1608.02556]
Axions in dimuon spectrum

Can use dimuon spectrum as measured by LHCb to set interesting constraint on axion-top couplings in axion-portal models

[Freytsis et al., 0911.5355]  

[LHCb, 1508.04094]

Axions in dimuon spectrum

Can use dimuon spectrum as measured by LHCb to set interesting constraint on axion-top couplings in axion-portal models

[Freytsis et al., 0911.5355]
Dark photons at LHCb

\[
\mathcal{L} \supset - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + e e A'_\mu J^\mu_{\text{EM}}
\]

LHCb will have sensitivity to large regions of unexplored dark photon $A'$ parameter space via inclusive dimuon analysis, especially in $[210, 520]$ MeV & $[10, 40]$ GeV mass ranges.
Flavour-changing transitions provide another way to test light spin-0 states. Bounds depend however strongly on assumption on structure of couplings between spin-0 states & SM fermions.
Figure 3. Excluded parameter regions for a pseudoscalar $A$ with Yukawa-like couplings to all fermions (left) and Yukawa-like couplings only to quarks (right); the coupling $g_{Yq}$ was defined in Eq. (2.3).

In particular, there are strong constraints from BaBar on new states $A$ produced in the radiative decay $A \rightarrow \mu^+ \mu^-$, which apply for a wide range of different final states. For Yukawa-like couplings the strongest bound comes from $A \rightarrow \mu^+ \mu^-$ for $m_A < 2 m_{\tau}$ [95] and from $A \rightarrow \tau^+ \tau^-$ above the kinematic threshold [96]. For universal quark couplings, strong bounds can still be obtained from hadronic decays of $A$ by searching for a bump in the momentum spectrum of the photon [97].

4 Excluded parameter regions

The parameter regions excluded by the various experimental results discussed above are presented in Fig. 3 for the case of Yukawa-like couplings and Yukawa-like quark couplings, and in Fig. 4 for the case of universal quark couplings and third generation quark couplings. Let us briefly discuss the different cases in more detail.

4.1 Yukawa-like couplings

A straight-forward bound on $g_Y$ can be obtained from $K \mu^2$, which gives \( \text{BR}(K \rightarrow \pi^+ A) < 10^{-6} \) for $m_A$. Substituting the value for $h_s$ from Eq. (2.11) into Eq. (A.2), we obtain the prediction \( \text{BR}(K_L \rightarrow \pi^0 A) \ll 0.06 g_Y^2 \) in this mass region. Consequently, the bound from $K \mu^2$ implies \( g_Y < 0.005 \) for $m_A \ll 100 \text{MeV}$. As many other searches, this bound is significantly weakened for $m_A \ll m_{\tau}$.

Most of the experimental constraints that we consider depend on the pseudoscalar branching ratios and its decay length. For example, the bound \( \text{BR}(B \rightarrow K^{+} \text{inv}) \approx 5 \times 10^{-5} \) implies $g_Y < 0.3$. However, for $m_A$ so close to the pion mass, the pseudoscalar mediator would significantly enhance the pion decay rate, disfavouring such a set-up.

[Light spin-0 states & flavour] [Dolan et al., 1412.5174]
Figure 4. Excluded parameter regions for a pseudoscalar $A$ with universal couplings to quarks; the coupling $g_{q}$ was defined in Eq. (2.4). The left panel shows the constraints when $A$ couples to all quarks, while the right panel shows the constraints when $A$ couples only to third generation quarks $Q = \{b, t\}$.

For the case of universal quark couplings, the constraints on $g_{q}$ are considerably stronger than the corresponding ones for $g_{Y}$. This is partially due to the fact that there is no factor $p^{2}m_{f}/v$ in the couplings, but more importantly due to larger flavour-changing effects resulting from the non-MFV coupling structure. The former reason also implies that experiments probing rare kaon decays become more important compared to experiments probing rare $B$ meson decays. The enhancement of flavour-changing effects, on the other hand, implies that bounds from processes like $b \rightarrow s\gamma$ give stronger bounds than processes like $\phi \rightarrow \gamma$ hadrons.

For small pseudoscalar masses, we again find a clear complementarity between searches for $K_{L} \rightarrow \pi^{0}\gamma\gamma$ and searches for $K^{+} \rightarrow \pi^{+}+\text{inv}$ (see left panel of Fig. 4), ruling out the entire parameter region $m_{A} < m_{K}m_{\pi}$ and $g_{q} > 10^{-7}$.

To close the gap between $m_{A} < m_{K}m_{\pi}$ and $m_{A} > 3m_{\pi}$, we again show the bound corresponding to $\text{BR}(B \rightarrow K\gamma\gamma) < 10^{-2}$. By assumption, we take photonic decays to be negligible above the hadronic decay threshold. Consequently, the dominant bound comes from $b \rightarrow s\gamma$ for $m_{A}$. For $m_{B} < m_{A}$, and from BaBar for $m_{A} < m_{\phi}$.

4.4 Universal couplings to $b$ and $t$ quarks only

If we assume that the pseudoscalar couples only to bottom and top quarks with the same coupling strength $g_{Q}$, then the effective flavour changing coupling $h_{S}$ is reduced by more than...
t\bar{t} production at LHCb

Figure 1. Ratio of production mechanisms of pseudotop as a function of pseudorapidity at 7 (left) and 14 TeV (right). The blue band corresponds to the uncertainty associated to scale variation.

There have been large efforts in the QCD community to improve the precision of top quark pair production predictions. In particular, the completion of the full next-to-next-to-leading order (NNLO) calculation \[3, 4, 5, 6\] as well as resummation of soft gluon emissions to next-to-next-to-leading log (NNLL) accuracy \[7, 8, 9\]. The reduced scale uncertainty in these predictions is crucial to gaining information on other sources of theoretical uncertainty such as the high-x gluon PDF, and the top mass. A recent study of the impact of these uncertainties on the inclusive cross-section at NNLO+NNLL accuracy can be found in Ref. \[10\], where it is observed that such a measurement, with minimal scale uncertainties, has the potential to strongly constrain the gluon PDF. It is clear that a differential result to the same accuracy is highly desirable and will be available in the not-too-distant future.

In fact, differential cross-section results and studies using approximate NNLO calculations and resummation techniques have already been obtained in \[11, 12, 13, 14\]. To this end, we demonstrate the increased sensitivity of pair production cross-section measurements at high rapidity to the gluon PDF at NLO accuracy.

2 LHCb analysis at 7, 14 TeV

This section aims to provide an estimate of the potential statistical precision of a cross-section measurement achievable with the current 7 TeV data (\(R_L dt = 1 fb^{-1}\)) as well as the projected 14 TeV data sample after 1 year of running (\(R_L dt = 5 fb^{-1}\)). As pointed out in Ref. \[1\], top quarks can be identified through their decay \(t \rightarrow W \rightarrow \mu \nu b\), where the muon and the b are registered by the detector. Indeed, in the full \(t\bar{t}\) decay it is also possible to reconstruct a b, \(\mu\) along with W decay products, radiated jets (which tend to –2– [Gauld, 1311.1810]

\[Gauld, 1311.1810\]

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Why $t\bar{t}$ production at LHCb?

In new-physics scenarios in which top production proceeds via $t$-channel exchange, cross section enhanced at large $\eta$

[in LHCb context see Kagan et al., 1103.3747]
Why $\bar{t}t$ production at LHCb?

Even if no new physics hides in top sector, could make use of LHCb data by improving our understanding of gluon PDF.
Single-lepton asymmetry

Single-lepton channel statistically more promising than dilepton mode. As background low, second signal should still be looked for
Single-lepton asymmetry

LHCb can do it, if backgrounds are under control!

$$\sigma_{14\text{ TeV}} \simeq 4.9\, \text{pb} \quad \Rightarrow \quad A^l = ([1.4, 2.0] \pm 0.3)\%$$

50 fb$^{-1}$, 2030 (?)

$$\epsilon_b = 70\%$$

$$\epsilon_l = 75\%$$

[Gauld, 1409.8631]
Dominant 1-loop corrections due to top exchange & proportional to $m_t^2$. In contrast, Higgs contribution scales as $g_1^2 \ln(m_h^2/m_Z^2)$.
Top mass from EW fit

$\Delta \chi^2$

- SM fit w/o $m_t$ measurement
- SM fit w/o $m_t$ and $M_H$ measurements
- $m_t^{\text{pole}}$ world average [arXiv:1403.4427]
- $m_t^{\text{pole}}$ from Tevatron $\alpha_s$ [arXiv:1207.0980]
- $m_t^{\text{pole}}$ from CMS, $\alpha_s$ (CMS) [arXiv:1307.1907]
- $m_t^{\text{pole}}$ from ATLAS, $\alpha_s$ [arXiv:1406.5375]
- $m_t^{\text{pole}}$ from ATLAS, $\alpha_s^{\text{jet}}$ [ATLAS-CONF-2014-053]

$m_t^{\text{pole}} = (177.0 \pm 2.5) \text{ GeV}$