Flavour physics results at the LHC

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on behalf of the LHCb collaboration

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Flavour physics results at the LHC

- Flavour physics in the quark sector
  - what is it? why is it important? how does LHC contribute?

- A few B-physics results from the LHC experiments, including textbook examples and current “flavour anomalies”
  - Measurements of CP violation and CKM observables
  - Search for new phenomena in rare $b \rightarrow s$ transitions
  + lepton-flavour universality

showing LHC Run 1 data from ATLAS, CMS and (mostly) LHCb

(sorry for having to omit many results, including from the charm sector)
Standard Model (SM) of particles

- Matter is made of fermions (spin 1/2) of different "flavours"
- Each fermion has an anti-matter partner

<table>
<thead>
<tr>
<th>Leptons</th>
<th>electron e</th>
<th>muon $\mu$</th>
<th>tau $\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>neutrino $\nu_e$</td>
<td>neutrino $\nu_\mu$</td>
<td>neutrino $\nu_\tau$</td>
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<table>
<thead>
<tr>
<th>Quarks</th>
<th>up $u$</th>
<th>charm $c$</th>
<th>top $t$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>down $d$</td>
<td>strange $s$</td>
<td>bottom $b$</td>
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<table>
<thead>
<tr>
<th>Electric charge [e]</th>
<th>Colour charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-1$</td>
<td>no</td>
</tr>
<tr>
<td>$0$</td>
<td></td>
</tr>
<tr>
<td>$+2/3$</td>
<td>yes</td>
</tr>
<tr>
<td>$-1/3$</td>
<td></td>
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</tbody>
</table>

- Quarks only appear in colourless combinations (=hadrons), bound by the strong force:

- Forces are described as exchanges of bosons (gluons, photon, $W^\pm$ and $Z^0$ for strong, e.m. weak interactions, respectively)

- Flavour physics = study of transitions between fermions of different flavours

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SM Higgs boson generates masses of particles
Quark mass eigenstates are different from weak eigenstates
→ quark mixing matrix (Cabibbo, Kobayashi, Maskawa)

Different mixing matrix for quarks and anti-quarks ⇒ CP violation

\[
\begin{align*}
\text{Quarks} & : & \begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} &= 
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix} 
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix} \\
\text{Anti-quarks} & : & \begin{pmatrix}
    \bar{d}' \\
    \bar{s}' \\
    \bar{b}'
\end{pmatrix} &= \begin{pmatrix}
    V_{ud}^* & V_{us}^* & V_{ub}^* \\
    V_{cd}^* & V_{cs}^* & V_{cb}^* \\
    V_{td}^* & V_{ts}^* & V_{tb}^*
\end{pmatrix} 
\begin{pmatrix}
    \bar{d} \\
    \bar{s} \\
    \bar{b}
\end{pmatrix}
\end{align*}
\]
CP violation in the Standard Model (SM)

- **CKM matrix:**
  - complex and unitary
  - \(4\) parameters (e.g. 3 angles and 1 phase)

\[
V_{\text{CKM}} V_{\text{CKM}}^\dagger = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}
\]

\[\Rightarrow V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0\]

- \(6\) unitarity triangles

- most sensitive experimental tests on the two unsquashed triangles, with transitions involving b quarks

**“The Unitarity Triangle”**
(area \(\propto\) CP violation)
Discoveries of CP violation

1964:
- Cronin & Fitch in $K^0$ decays

2001:
- BaBar & Belle in $B^0$ decays

2013:
- LHCb in $B_s$ decays

still awaited:
- in $D^0$ decays
- in baryon decays

LHCb, PRL 110 (2013) 221601

LHCb-PAPER-2016-030

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CP violation visualized in the simplest way

- **C** = charge conjugation
  - replacing all particles with their anti-particles
- **P** = parity (space reversal)
  - swapping left and right (like a mirror does)

\[ B^0 \rightarrow K^+\pi^- \neq B^0 \rightarrow K^-\pi^+ \]

| LHCb, PRL 110 (2013) 221601 | Encontro de Física 2016, Natal, Brasil | O. Schneider | 7 |
Global CKM fit

- Fit all available data to constrain the position of the apex of the unitary triangle
  - this needs theory input, e.g. from QCD calculations on the lattice (LQCD)

- Available measurements in 2001:
  - CP violation in $K^0$ decays
    - $|\varepsilon_K|$
  - sides of the triangle
    - $|V_{ub}/V_{cb}|$, $\Delta m_d$ and $\Delta m_s$
  - very first B-factory measurements of CP violation in $B^0$ decays
    - $\sin 2\beta$

Complex plane, where base of triangle is normalized to 1 and taken as real

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Global CKM fit

- Status in 2006

- 2008 Nobel prize awarded to Kobayashi & Maskawa!

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Status in 2010, before LHC comes into play
Global CKM fit

- **Status ~now**
  - substantial reduction of many experimental and theoretical uncertainties
  - large impact of LHCb

- **All measurements beautifully consistent within SM!**
This is not enough!

- **SM cannot be the ultimate theory**
  - Too many free parameters (quark and lepton masses and mixing parameters) pattern must be governed by a hidden mechanism yet to be discovered
  - SM believed to be a low-energy effective theory of a more fundamental theory at a certain high energy scale $\Lambda$, in the TeV region or above

- **Plenty of extensions of the SM introduce new particles, dynamics, symmetries, … at a higher scale $\Lambda$**

  **We must search for New Physics (NP), i.e.**
  - new particles and interactions
  - new sources of CP violation

- **Two compelling cosmological reasons**
  - existence of dark matter
    → no candidate in SM
  - matter-antimatter asymmetry of the Universe
    → CP violation in SM totally insufficient to explain baryogenesis
Two approaches to New Physics search

- New particles could
  ① be produced and observed directly as real particles with specific signatures
     • e.g. multiple jets and/or leptons with large amount of missing energy
     ⇒ Need high energy
  ② appear as virtual particles in loop processes, leading to observable deviations from the SM expectations
     • e.g. decay probability of known heavy hadrons (containing a b or c quark)
     ⇒ Need high precision (statistics)

- The two approaches are complementary
Strengths of indirect searches

- Can access higher scales and therefore sense new effect earlier:
  - Example: third quark generation inferred by Kobayashi and Maskawa (1973) to explain small CP violation measured with kaons (1964), but only directly observed in 1977 (b) and 1995 (t)

- Can access phases
  - if NP is discovered, it is important to measure the phases of the new couplings

NB: phase measurements (e.g. CP violation) need quantum interference of two amplitudes
The flavour problem

- Flavour-Changing Neutral Currents (FCNC) suppressed in the SM
  - cannot happen at the tree level, but only at loop level (higher-order)

- At the start of LHC
  - NP scale $\Lambda$ was thought to be $O(\text{TeV})$, where NP with generic flavour structure should have large FCNC effects

- Today
  - no NP discovered (yet)
  - current data exclude NP with large FCNC effects

- So …
  - either NP sits at a much larger scale, out of collider reach
  - or NP has a mechanism to suppress FCNC effects (SM-like flavour structure and/or very small couplings $c_{\text{NP}}$)

Amplitude in terms of couplings and scales

$$\Lambda \sim \frac{c_{\text{SM}}}{M_W^2} + \frac{c_{\text{NP}}}{\Lambda^2}$$
Strategy for indirect NP search

- Improve precision of CKM measurements
  - measure all angles and sides of UTs in many different ways
    - different observables may or may not be sensitive to NP
  - test consistency within SM
    - needs theory input to relate measurements to CKM elements
    - any inconsistency is a sign of NP

- Measure FCNC transitions, where NP could still emerge (at 10–20% level)
  - e.g. rare decays, neutral meson mixing
  - favour observables with clean SM predictions

Note:
- flavour physics is often hindered by hadronic (QCD) effects, which are difficult to calculate
LHCb
(LHCb, violation of CP)

LHC ring (27 km = 0.09 ms)

Geneva

CERN

LHC = CERN’s Flavour Factory

The world’s most intense source of b and c quarks

pp collisions:
7–8 TeV during Run 1 (2010–2012)

Lake
Huge production

- $\sigma_{bb} = 300 \, (500) \, \mu b$ at $\sqrt{s} = 8 \, (13) \, \text{TeV}$
- All $b$-hadron species produced

"Asymmetric" flavour factory:

- Gluon-gluon fusion

<table>
<thead>
<tr>
<th>ATLAS/CMS</th>
<th>LHCb</th>
</tr>
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<tbody>
<tr>
<td>Detector geometry</td>
<td>central</td>
</tr>
<tr>
<td>Angular coverage</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>~40% of $bb$ pairs</td>
</tr>
<tr>
<td>Heavy flavour physics with</td>
<td>dimuon decays only,</td>
</tr>
<tr>
<td></td>
<td>high $p_T$ thresholds</td>
</tr>
<tr>
<td>7 TeV sample</td>
<td>~5 fb$^{-1}$</td>
</tr>
<tr>
<td>8 TeV sample</td>
<td>~20 fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>1 fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2 fb$^{-1}$</td>
</tr>
</tbody>
</table>

- $\theta_1$ [rad]
- $\theta_2$ [rad]
- $\eta$ [rad]
- $\phi$ [rad]
- $z$ [rad]

LHCb MC
$\sqrt{s} = 8 \, \text{TeV}$
Experiment optimized for flavour physics:
- angular coverage
- efficient trigger for hadronic and leptonic modes
- precision tracking and vertexing (mass, proper time)
- excellent particle identification (e.g. \( \pi, K, p \))
Measurements of CP violation and CKM observables
\[ \Delta m_d \text{ and } \Delta m_s \]

- \( B_{d,s} \) and \( \bar{B}_{d,s} \) are quantum superpositions of two mass state with splitting \( \Delta m_{d,s} \)

\[ \Rightarrow B_{d,s} - \bar{B}_{d,s} \text{ oscillations} \]

- in the SM

\[ \Delta m_s / \Delta m_d = \frac{m_{B_s}}{m_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 (1.206 \pm 0.019)^2 \]

- Theory uncertainty dominates

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CP-violating phase $\phi_s$

— phase difference between the $B_s$ mixing amplitude and the $b \rightarrow c\bar{c}s$ decay amplitude of the $B_s$ meson

— small in SM, very sensitive to NP contributions to $B_s$ mixing:

$$\phi_s^{SM} \equiv -2\beta_s \equiv -2 \arg \left(-\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*}\right) = -37.6^{+0.8}_{-0.7} \text{ mrad}$$

Best mode is $B_s \rightarrow J/\psi K^+K^-$

— final state is mixture of CP+ and CP− need time-dependent angular analysis of flavour-tagged events

— extract $\phi_s$, $\Delta \Gamma_s$, $\Delta m_s$, ...

World average $\phi_s = -30 \pm 33 \text{ mrad}$
CPV in $B_s \to J/\psi K^+K^-$

- ATLAS
  - PRD 90 (2014) 052007
  - arXiv:1601.03297
- CMS
  - PLB 757 (2016) 97
- LHCb (shown here)
  - PRL 114 (2015) 041801
  - also $B_s \to \psi(2S)K^+K^-$
  - arXiv:1608.04855
  - + pure CP final states
  - PLB 736 (2014) 186
  - PRL 113 (2014) 211801

3 fb$^{-1}$
~ 100k signal events (background subtracted)

Decay time [ps]

Candidates / 0.05 ps

Candidates / (0.2 ps)

1000
2500
3000
3500

Candidates / 0.05

10
500

Candidates / (0.05π rad)

- total fit
- CP-even P-wave component
- CP-odd P-wave component
- CP-odd S-wave component

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|\text{V}_{ub}| \text{ from } \Lambda_{b} \rightarrow p\mu\nu

- Suppressed \(b \rightarrow u\) transition rate measured with respect to \(b \rightarrow c\)
- New LHCb measurement with \(\Lambda_{b}\) decays

\[
|V_{ub}|^2 = \frac{BR(\Lambda_{b} \rightarrow p\mu\bar{\nu}_{\mu})}{BR(\Lambda_{b} \rightarrow \Lambda_{c}^{+}\mu\bar{\nu}_{\mu})} \times R_{FF}
\]

\(R_{FF}\) = form factor ratio from LQCD

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Long-standing discrepancy (~3σ) between two world averages
- $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$ from excl. $B \to \pi \ell \nu$
- $|V_{ub}| = (4.41 \pm 0.22) \times 10^{-3}$ from incl. $B \to X \ell \nu$

New LHCb measurement
- $|V_{ub}| = (3.27 \pm 0.15_{\text{exp}} \pm 0.16_{\text{LQCD}} \pm 0.06_{V_{cb}}) \times 10^{-3}$ from exclusive $\Lambda_b \to p \mu \nu$
- consistent with excl. average
- inconsistent with incl. average (3.5σ)

Assume a fractional right-handed contribution $\varepsilon_R$ to the SM weak current
- $|V_{ub}|$ determinations now depend on $\varepsilon_R$
- exclusive determinations consistent with SM ($\varepsilon_R=0$)

\( \gamma \) from \( B^\pm \rightarrow DK^\pm \)

\( \gamma \) is the only CP-violating parameter that can be measured from tree-level decays → important NP-free reference

- most powerful method is using \( B^\pm \rightarrow DK^\pm \) decays
- two tree-level amplitudes (favoured \( b \rightarrow c \) and suppressed \( b \rightarrow u \))

- make them interfere by considering final states \( f_D \) accessible to both \( D^0 \) and \( D^0 \) (e.g. \( f_D = K^+K^-, \pi^+\pi^-, K^\pm\pi^\mp, \pi^\pm\pi^\mp \))

- measure the relative rates of \( B^- \rightarrow f_D K^- \) and \( B^+ \rightarrow f_D K^+ \)

- solve for all unknowns and extract \( \gamma \)

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GLW: Gronau, London, Wyler

ADS: Atwood, Dunietz, Soni,
PRL 78 (1997) 3257

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ADS favoured modes
— 29'470 ± 230 B± → (K±π∓)K± events

ADS suppressed modes
— 553 ± 34 B± → (π±K∓)K±
— CP violation at 8σ

GLW modes
— 1'162 ± 48 B± → (ππ)K±
— 3'816 ± 92 B± → (KK)K±
— CP violation at 5σ (combined)

etc
— … (also B± → Dπ±)
Many measurements of $\gamma$ with tree decays
- several $B \to DX$ and $D$ decays modes
- no single golden mode, need to combine results

LHCb
- Combine all $B \to DK$ measurements
  - 72 observables, 32 parameters

$\gamma = \left( 70.9 \pm 7.1 \right)^\circ$

B factories:
- BaBar $(69^{+17}_{-16})^0$
- Belle $(68^{+15}_{-14})^0$

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Search for New Physics
in rare $b \rightarrow s$ transitions
+ lepton flavour-violation
**Very rare FCNC decay in the SM**
- loop (higher-order) decay
- CKM suppression
- helicity suppression
  - Lorentz structure of weak interaction

**Clean SM predictions**
- $\text{BR}_{\text{SM}}(B_s \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$
- $\text{BR}_{\text{SM}}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

**Can be strongly enhanced in many NP models, e.g. with new (pseudo)scalars**
- Minimal Supersymmetric SM (MSSM) with large $\tan\beta$

\[
\text{BR} \propto \left(C^{\text{MSSM}}_{S,P}\right)^2 \propto \frac{\tan^6\beta}{M_A^4}
\]
Combined CMS and LHCb analysis from Run 1 data

- **First observation** of $B_s \rightarrow \mu^+\mu^-$
  - $\text{BR} = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$

- **First evidence** of $B^0 \rightarrow \mu^+\mu^-$
  - $\text{BR} = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$

- Overall consistency with SM at 2$\sigma$ level

- Recent result from ATLAS
  - No significant $B_s$ signal (1.4$\sigma$), no $B^0$ signal
  - 95% CL upper limits close to CMS+LHCb central values
  - Compatible with SM at 2$\sigma$ level
3 decades of experimental efforts …

... supersymmetric models with large tanβ now ruled out
Suppressed loop decay, sensitive to NP

- Kinematics in terms of $q^2 = m(\mu\mu)^2$ and 3 helicity angles

- Angular analysis offers many $q^2$-dependent observables with clean SM predictions

LHCb

- Full angular analysis of $B^0$ and $\bar{B}^0$
  - Complete set of observables
  - Measured for the first time
  - $K\pi$ S-wave taken into account

CMS

- Partial angular analysis (less observables)

$B^0 \rightarrow K^{*0}\mu^+\mu^-, \ K^{*0} \rightarrow K^{+}\pi^-$

Candidates / 11 MeV/c$^2$

LHCb, JHEP 02 (2016) 104

$B^0 \rightarrow K^{*}\mu\mu$

LHCb

$\psi(2S)$ veto

J/$\psi$ veto

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LHCb

- no significant CP asymmetries
- all CP-averaged observables, except $P_5'$, agree individually with SM predictions
- $P_5'$ anomaly (already seen with first 1 fb$^{-1}$) is confirmed: 3.4σ from SM prediction

Belle

- sees deviation in $P_5'$ (2.1σ) consistent with LHCb

Fluctuations,
underestimated hadronic effect,
… or New Physics?

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ anomaly

- $q^2$ [GeV$^2$/c$^4$]
- $P_5'$
- LHCb 3 fb$^{-1}$
- SM from DHMV
- LHCb fit of the EW penguin Wilson coeff $C_9$,
including $S_3 S_9$,
$F_L$, $A_{FB}$:
3.4σ from SM

Theoretical work ongoing to better understand this effect:
NP or unexpectedly large hadronic effect?

See e.g. [Descotes-Genon et al., arXiv:1510.04239]

Channel also studied by
BaBar [arXiv:1508.07960],
Belle [PRL 103, 171801],
CMS [PLB 753(2016)424],
ATLAS [ATLAS-CONF-2013-038] and CDF [PRL 108, 081807]
Other $b \rightarrow s \mu^+ \mu^-$ decays

- $B_s \rightarrow \phi \mu^+ \mu^-$
  - 432 ± 24 signal events
  - angular observables agree with SM
  - differential BR in the region $1 < q^2 < 6$ GeV$^2$ is 3σ below SM

- $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$
  - 285 ± 21 signal events
  - first measurements of forward-backward asymmetries
  - rate again below SM in low $q^2$ region

Intriguing picture with consistent deficit in many $b \rightarrow s \mu^+ \mu^-$ modes
Lepton Flavour Universality (LFU) in the SM

- same EW couplings for $\ell = e, \mu, \tau$

LHCb

- electron reconstruction challenging,
  huge tail due to energy loss

$B^+ \to K^+ \mu^+ \mu^-$

$B^+ \to K^+ e^+ e^-$

- for low $q^2$ region ($1 < q^2 < 6 \text{ GeV}^2/c^4$):

$$R_K = \frac{\text{BR}(B^+ \to K^+ \mu^+ \mu^-)}{\text{BR}(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

2.6$\sigma$ from SM value of $1 \pm O(10^{-3})$
Test of LFU in tree decays

- LFU can also be tested with $B \to D^{(*)}\ell^-\nu$
  - not rare decays (no loop), sensitive to NP (charged Higgs) at tree level

- Observables $R(D)$ and $R(D^*)$

$$R(D^{(*)}) = \frac{BR(B^0 \to D^{(*)}\tau^+\nu_\tau)}{BR(B^0 \to D^{(*)}\ell^+\nu_\ell)}$$

with $\ell = e, \mu$

- LHCb
  - CHALLENGING ENVIRONMENT FOR $\tau$ RECONSTRUCTION (MISSING $\nu$)

- 2D world average
  - $4.0\sigma$ away from SM

Non universality implies lepton flavour violation in many NP models
Conclusion and prospects

- **Flavour physics = essential component in the search for New Physics**
  - great boost in precision/reach from the analyses of LHC Run 1 data

- **A few interesting 3–4σ deviations from the SM predictions**
  - incl. vs excl. $|V_{ub}|$, $P_5$’ in $B^0 \rightarrow K^{*0}\mu^+\mu^-$, $b \rightarrow s\mu^+\mu^-$ rates, lepton universality

- **Results limited by statistics, but plans to collect much more data**
  - **LHCb**: $3 \rightarrow 8 \text{ fb}^{-1}$ by 2018, $\rightarrow 50 \text{ fb}^{-1}$ by ~2030
    - upgraded detector in 2021 with improved efficiency and DAQ capabilities
  - **ATLAS, CMS**: $25 \rightarrow 300 \text{ fb}^{-1}$ by 2024, ultimate upgrade goal is $3000 \text{ fb}^{-1}$
    - flavour physics program will depend on ability to maintain low $p_T$ thresholds for dimuons and cope with increased pileup
  - **Belle 2** at Super-KEKB: ramp up in 2019, $\rightarrow 5 \text{ ab}^{-1}$ ($= 50 \times \text{Belle}$) by 2025

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Exciting times ahead, stay tuned