FLAVOUR PHYSICS AT LHCb

ICNFP 2015 : 4th International Conference on New Frontiers in Physics

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on behalf of the LHCb Collaboration
**Quark flavour mixing**

\[ V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \]

\[ V_{CKM} \text{ originates from MISALIGNMENT between UP and DOWN quark couplings to the Higgs boson} \]

- KM theory is highly predictive
  - huge range of phenomena, over many orders of magnitude in energy with only 4 independent parameters (not including quark masses)
- CKM matrix has minimal flavour violation
  - extended theories do not replicate in general such flavour structure
- KM mechanism introduces CP violation
  - it is THE standing theory of CP violation, in absence of neutrino masses or \( \theta_{QCD} \)
The Unitarity Triangles

- CKM matrix must be UNITARY for a given number of quark generations (3): \( V_{\text{CKM}}^+ = V_{\text{CKM}} \)
- which provides many relationships, prominently:
  \[
  |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \\
  V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0
  \]
- only one independent phase, but 4 measurable combinations can be formed of the type \( V_{\alpha i}V_{\alpha j}^*V_{\beta j}V_{\beta i}^* \) such as \( \beta \) (BaBar, Belle 2001, this talk), \( \beta_s \) (LHCb 2013), \( \gamma \) (this talk)

- consistency of measurements are tests of the Standard Model and provide model-independent constraints on New Physics

see also http://www.utfit.org
Two roads to travel the same path
in quark flavour physics

is KM theory perturbed?

- not necessarily in quark sector
- unpredicted scale
- CPV in NEUTRINOS now realistic, with sizable $\theta_{13}$

Non appearance at ATLAS/CMS makes the case more compelling

can be seen in RARE DECAYs
through quantum loops

NEW HEAVY PARTICLES
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CP VIOLATION
extra sources must be there
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Topics covered in this talk

Towards New SM In 12 Steps

- \( B \rightarrow X_s \nu \bar{\nu} \)
- \( B \rightarrow K^*(K) \nu \bar{\nu} \)
- \( K \rightarrow \pi \nu \bar{\nu} \)
- \( B \rightarrow X_s l^+l^- \)
- \( B \rightarrow K^*(K) l^+l^- \)
- \( K^{*0} \rightarrow \mu^+\mu^- \)
- \( B_s \rightarrow \Phi \mu^+\mu^- \)
- \( B \rightarrow X_s \gamma \)
- \( B \rightarrow K^* \gamma \)
- \( B^+ \rightarrow \tau^+ \nu_\tau \)
- \( B \rightarrow D^* \tau \nu \)
- \( \Delta F = 2 \) Observables
- \( \sin(2\beta) \)
- \( B_{s,d} \rightarrow \mu^+\mu^- \)
- \( B_s \rightarrow \mu^+\mu^- \)
- \( \gamma \) & \( V_{ub} \)
- LFV, EDMs \((g-2)_{\mu,e}\)
- CKM from Trees
- Lattice
- \( \varepsilon'/\varepsilon \)

Clock from Buras & Girbach, RPP (2014) 086201
The LHCb apparatus

LHCb Detector
Weight: 5,600 tonnes
Height: 10 m
Length: 20 m

Electromagnetic Calorimeter

RICH1

Vertex Locator

Tracker Turicensis

Dipole Magnet

Tracking Stations

RICH2

Hadron Calorimeter

Muon Chambers

a
CP VIOLATION
Why $\gamma$ from $B \rightarrow DK$ is important

- $\gamma$ plays a unique role in flavour physics
  - it can be measured from tree diagrams alone
    (probably the only such CP violating parameter)
- Therefore a reference point for the Standard Model
  - particularly important after New Physics is discovered

- A final state COMMON to $D^0$ and $\bar{D}^0$ is required. Different possibilities are characterized in the literature (GLW,ADS,GGSZ)
Most precise channel is $D_{CP}K$ (awaiting LHCb update with full Run 1 data sample)

- LHCb only combination, without latest results (but including measurements on $DK^*$ and time dependent $D_{s}^{\pm}K_{\pm}$) gives $\gamma = (73^{+9}_{-10})^0$, best single-experiment result (CKM2014 update)

- New LHCb measurements with competitive sensitivity
New decays modes for $\gamma$ at LHCb

- Highly significant signals in CP modes $B^- \to DK^-\pi^+\pi^-$, $D \to K^+\pi^-$, $K^+K^-$, $\pi^+\pi^-$

- New independent, additional LHCb measurement:
  
  $\gamma = (74^{+20}_{-18})^o$

- First observation of the suppressed ADS mode $B^- \to (K^+\pi^-)_D K^-\pi^+\pi^-$, very sensitive to $\gamma$

arXiv:1505.07044, submitted to PRD
Further analysis strategies by LHCb on the neutral modes $B^{-} \rightarrow DK^{-}$ with $D \rightarrow \pi^{+}\pi^{-}\pi^{0}$, $D \rightarrow K^{+}K^{-}\pi^{0}$ and $D \rightarrow K^{-}\pi^{+}\pi^{0}$ (ADS)

Recent analysis of coherently produced $D\bar{D}$ at $\psi(3770)$ has shown that $D \rightarrow \pi^{+}\pi^{-}\pi^{0}$ is very close to a CP-even eigenstate (CP-even fraction $F_{+} = 0.968 \pm 0.017$), which makes it particularly suitable for $\gamma$ analysis (so called quasi-GLW)


No evidence of CP violation has been obtained yet at LHCb, but good consistency with other measurements has been shown

\[ V_{ub}/V_{cb} \text{ from } \Lambda_b \rightarrow p\mu\nu / \Lambda_b \rightarrow \Lambda_c^{+}\mu\nu \]

- \(|V_{ub}|\) governs the most sensitive misalignment between up/down quark flavor couplings to the Higgs boson.
- Excellent measurements from \( B^{-} \rightarrow \pi^{0}\ell^{-}\bar{\nu} \) and \( B^{0} \rightarrow \pi^{+}\ell^{-}\bar{\nu} \) at B-factories, but long standing discrepancy between exclusive and inclusive (containing all \( b \rightarrow u\ell^{-}\bar{\nu} \) transitions) measurements, at 3.8σ level:

\[
|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \quad |V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3} \quad \text{(incl.)}
\]

\[
|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \quad |V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \quad \text{(excl.)}
\]

- LHCb at a hadron collider uses the corrected mass:

\[
M_{\text{corr}} = \sqrt{M_{h\mu}^{2} + p_{\perp}^{2}} + p_{\perp}
\]

and directly compares \( \Lambda_b \rightarrow p\mu^{-}\bar{\nu} \) with \( \Lambda_b \rightarrow \Lambda_c^{+}(pK^{-}\pi^{+})\mu^{-}\bar{\nu} \)
Lattice QCD form factors, needed in the calculation of $|V_{ub}|$, are most precise at high $q^2$ ($\mu\nu$), select $q^2 > 15$ GeV$^2$

$q^2$ can be determined using $\Lambda_b$ flight direction and mass, up to a two-fold ambiguity

vertex isolation is used, $\Lambda_c^+ \rightarrow pK^-\pi^+$ cross-feed is the main background

fit $M_{corr}$ to get the signal yields
V_{ub}/V_{cb} \text{ from } \Lambda_b \rightarrow p\mu\nu / \Lambda_b \rightarrow \Lambda_c^+\mu\nu

- New physics claimed to explain the puzzle with extra RH currents

\[ \mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L (\bar{u}\gamma_\mu P_L b + \epsilon_R \bar{u}\gamma_\mu P_R b) (\bar{\nu}\gamma_\mu P_L l) + h.c. \]

F. Bernlochner et al. PRD 90, 094003 (2014)

LHCb:

\[ \frac{B(\Lambda_b \rightarrow p\mu\nu)}{B(\Lambda_b \rightarrow \Lambda_c^+\mu\nu)} \times 10^{-2} = (1.00 \pm 0.04\,(\text{stat}) \pm 0.08\,(\text{syst})) \times 10^{-2} \]

Nature Physics 10.1038 arXiv:1504.01568

- LHCb results do not support RH currents, agree with exclusive

- \[ |V_{ub}| \approx 0.083 \pm 0.004\,(\text{exp}) \pm 0.004\,(\text{lattice}) \]

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New Frontiers in Physics

Kolymbari

24 August 2015
- time evolution of $B^0 / \bar{B}^0$ asymmetry, 41500 decays
- LHCb is now competitive: $\sin(2\beta) = 0.731 \pm 0.035 \pm 0.020$
- similar statistical precision to B-factories
- result consistent with world averages and with other measurements constraining $\sin(2\beta)$: $0.771^{+0.017}_{-0.041}$ CKMfitter, arXiv:1501.05013
- significant improvement will require understanding of higher-order contributions
RARE AND SEMI-RARE DECAYS
B → μ⁺μ⁻ decays are an acid test for New Physics models

Very suppressed (10⁻⁹-10⁻¹⁰) in SM due to:
- GIM mechanism (Z⁰)
- chirality of W±
- minimal flavor violation (H⁰)

Features not generally respected by generic extensions!

Painstakingly searched for over 30 years...

Predictions are sharp:

B(B_s → μ⁺μ⁻)_{SM} = (3.66 ± 0.23) \times 10⁻⁹

B(B⁰ → μ⁺μ⁻)_{SM} = (1.06 ± 0.09) \times 10⁻¹⁰

Exemplary sensitivity for SUSY:

B(B_s → μ⁺μ⁻) ≈ (tanβ)⁶/M_{A⁰}
$B_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$

- LHCb / CMS collaborative upshot
  - complementary angular regions with respect to LHC beams
  - designed for different purposes: higher instantaneous $\mathcal{L}$ compensates lower $B \rightarrow \mu\mu$ efficiency (CMS)
  - dimuon mass resolution different: uniform $\approx 25$ MeV/$c^2$ for LHCb and angle dependent ranging from 32-76 MeV/$c^2$ for CMS

- Combination of CMS and LHCb data results in conclusive evidence for $B_s \rightarrow \mu^+\mu^-$, and in a $3\sigma$ effect for $B^0 \rightarrow \mu^+\mu^-$

- Results consistent with SM at $2\sigma$ level: A NEW PHASE OF PRECISION MEASUREMENTS IS INITIATED
Lepton universality can be broken by new physics with $\tau$ lepton, and ratios like $R(D^*) = \frac{B(B \rightarrow D^*\tau\nu)}{B(B \rightarrow D^*\mu\nu)}$ are sensitive to it.

- In two Higgs doblet models (2HDM), the $D/D^*$ helicity amplitudes $H_s$ become:

$$H_s^{2HDM} \approx H_s^{SM} \left(1 + (S_R \pm S_L) \frac{q^2}{m_\tau(m_b \mp m_c)} \right)$$

with scalar NP contributions $S_{L,R}$ proportional to $(\bar{c} P_{L,R} b) (\bar{\tau} P_{L,R} \nu_\tau)$ $P_{L,R} = (1 \mp \gamma_5)/2$

- BaBar reported anomalous high values of $R(D^*)$ and $R(D)$:

PRD 88 (2013) 072012, also PRL 109 101802

Those exclude 2HDM where $S_L = 0$ (type II, minimal SUSY) in the full $\tan\beta$-$m_{H^\pm}$ plane, but are compatible with general 2HDM having $|S_R + S_L| < 1.4$
First $b \to \tau$ reco at a hadron collider: $\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$ and $B^0 \to D^{*+} \mu^- \bar{\nu}_\mu$

identical final state topologies with $D^{*+} \to D^0 (\to K^- \pi^+) \pi^+$ and $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

$LHCb$ result confirms the excess to the SM value $0.252 \pm 0.003$. Fit also extracts form factor parameters, which appear to agree with world averages.

- $B^0$ rest-frame variables ($m_{\text{miss}}^2, E_{\mu}^*, q^2$) are measured with $(15-20\%)$ resolution thanks to $p_B$
- Control samples of various backgrounds allow precise corrections
  - good prospects for Run 2, systematics expected to scale with sample sizes

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

arXiv:1504.01568, submitted to PRL
\[ B \rightarrow D^{(*)}\tau\nu \]

Tension with SM seems to persist

\[ \Delta \chi^2 = 1.0 \]

SM prediction from PRD 85 (2012) 094025

thanks to M. Rotondo

unofficial average, very preliminary

\[ R(D^*) = 0.322 \pm 0.021 \]
\[ R(D) = 0.390 \pm 0.047 \]

statistical or systematic correlations not accounted for
Angular analysis of $B^0 \to K^{*0} \mu^+\mu^-$

- $b \to s \mu^+\mu^-$ FCNC transition allowed in SM via electroweak penguin and box diagrams, subject to contamination by new heavy particles ($Z'$, extra $H...$)

- Angular observables in $K^{*0}(K^+\pi^-)\mu^+\mu^-$ characterized by 6 amplitudes: $A_{0,||,\perp}^{L,R}$ for $K^{*0}$ helicities and $\mu^+\mu^-$ chiralities (L,R)

- Full set of 8 observables analysed (3 fb$^{-1}$) as function of $q^2(\mu^+\mu^-)$, only some are shown largely in agreement with SM, however ... see next

Zero crossing point $q_0^2$ OK with SM, very sensitive to some MSSM models arXiv:0811.1214
Earlier publication by LHCb with 2011 dataset PRL 111 (2013) 191801 found a local deviation from SM prediction with 3.7σ significance in one particular observable: $P_5'$.

Possible interpretations of this discrepancy was widely discussed in the literature (over 13 papers in 2014). The full datasample with 3 fb$^{-1}$ confirms a 3.7σ statistical discrepancy.

$P_5'$ is related to the L/R asymmetry of the interference between $A_0$ and $A_\perp$:

$$P_5' = \sqrt{2} Re \left( A_0^L A_\perp^* - A_0^R A_\perp^* \right) / \sqrt{F_L(1 - F_L)} = S_5 / \sqrt{F_L(1 - F_L)}$$

$$F_L = |A_0^L|^2 + |A_0^R|^2$$

Contrary to $B^0 \rightarrow K^{*0} \mu^+\mu^-$, $B_s \rightarrow \Phi(K^+K^-)\mu^+\mu^-$ is not self-tagging. Good complementarity (yield $\approx 1/6$)

Full angular analysis as function of $q^2(\mu^+\mu^-)$, all of the 8 observables are determined for the first time

- physics-wise, the observables are different from $K^* \mu\mu$ (new CP-violating asymmetries, no $S_s$ or $A_{FB}$)

All angular observables are consistent with the SM, but tension seen in the branching fraction

- a similar trend is also seen for the branching fractions of other $b \rightarrow s \mu^+\mu^-$ decays at LHCb ($B^0 \rightarrow K^{(*)}\mu^+\mu^-$, JHEP 06 (2014) 133, $B^+ \rightarrow K^+\pi^+\pi^-\mu^+\mu^-$, JHEP 10 (2014) 064.
Summary

- Appreciable amount of Flavour Physics results by LHCb this year, not everything has been covered in this talk (absent were charm CPV, other rare decays, $B \rightarrow$ no charm, etc)
- Sensitivity to $B_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ has reached the $10^{-10}$ level and will continue to improve
- A few interesting "tensions" with the SM to follow up very closely:
  - hints on $\tau$-lepton non-universality in $R(D^*)$ and $R(D)$
  - $S_5$ observable in $B \rightarrow K^{*0} \mu\mu$ deviated from SM, also $b \rightarrow s \mu\mu$ rates too low.
  - inclusive/exclusive tension in $|V_{ub}|$ still there, although RH currents are not supported
- Much to know in the short and longer terms:
  - Run 2 has just started at LHC (LHCb & ATLAS &CMS)
  - LHCb upgrade & Belle II will take over from 2018 on
THE END
Global fits performed on the new LHCb $B^0 \rightarrow K^{*0} \mu^+\mu^-$ data


Angular observables, branching fractions and combination

Consistently, data favour $C^\text{NP}_9 \neq 0$ at 3-4 $\sigma$