Measuring suppressed semileptonic decays at LHCb: testing the CKM picture at tree level

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Warwick seminar
Outline

• The basic ingredients
  • $SU(2) \times U(1)$ in the quark sector and the CKM matrix
  • Unitarity triangle

• Low energy hamiltonians for hadron decays

• Why are SL decays convenient?
  • The role of semileptonic decays in Standard Model testing (and New Physics probing)

• Note:
  • Will not discuss LFUV studies with SL
  • Focus on Cabibbo suppressed SL decays, in particular recent LHCb work
Mass vs Weak eigenstates: CKM matrix

From spontaneous symmetry breaking:

Mass matrices for the quarks: \( m = v \cdot G \) (\( v = \text{Higgs vev, } G \text{ EW constants} \))

\[
\mathcal{L}_{\text{mass}} = -\sum_{i,j}^3 \left[ \tilde{m}_{ij} \overline{U}_{Ri} U_{Lj} + m_{ij} \overline{D}_{Ri} D_{Lj} + h.c. \right]
\]

Diagonalization of the mass matrices to obtain the mass eigenstates, consequence for the charge current kinetic term:

\[
\mathcal{L}_{\text{CC}} = -\left[ \overline{U}_L \gamma^\mu V D_L W^\dagger_\mu + \overline{D}_L \gamma^\mu V^\dagger U_L W^-_\mu \right]
\]

\[ V = P_{U_L}^\dagger P_{D_L} \text{ is the famous Cabibbo-Kobayashi-Maskawa (CKM) matrix} \]

Built with the U and D quarks basis change matrices P (change from weak eigenstates to mass eigenstates)
Discrete symmetries and impact on the CC Lagrangian

**Charge conjugation**

\[ C\psi(\tilde{x})C^{-1} = C\bar{\psi}(\tilde{x})^T \quad C\bar{\psi}(\tilde{x})C^{-1} = \psi(\tilde{x})^TC \quad C = i\gamma^2\gamma^0. \]

**Parity**

\[ \tilde{x} = (t, \bar{x}) \rightarrow \tilde{x}_P = (t, -\bar{x}) \]

\[ \mathcal{P}\psi(\tilde{x})\mathcal{P}^{-1} = \gamma^0\psi(\tilde{x}_P) \quad \mathcal{P}\bar{\psi}(\tilde{x})\mathcal{P}^{-1} = \psi(\tilde{x}_P)^\dagger \]

**Time inversion**

\[ \tilde{x}_T = (-t, \bar{x}) \quad \mathcal{T}\psi(\tilde{x})\mathcal{T}^{-1} = i\gamma^1\gamma^3\psi(\tilde{x}_T) \]

**Charge conjugation + parity = CP (matter to antimatter)**

\[ C\mathcal{P}\psi(\tilde{x})(\mathcal{C}\mathcal{P})^{-1} = C\psi^*(\tilde{x}_P) = C\gamma^0\bar{\psi}^T(\tilde{x}_P) \]

\[ C\mathcal{P}W^{\pm\mu}(\tilde{x})(\mathcal{C}\mathcal{P})^{-1} = -W^{\mp\mu}_\mu(\tilde{x}_P) \]

\[ J^{\mu-} = \bar{U}_L\gamma^\mu VD_L \rightarrow -\bar{D}_L\gamma^\mu V^TU_L \]

\[ J^{\mu+} = \bar{D}_L\gamma^\mu V^\dagger U_L \rightarrow -\bar{U}_L\gamma^\mu V^*D_L \]

\[ \int d^4x \mathcal{L}_{CC} \xrightarrow{CP} \int d^4x - [\bar{D}_L\gamma^\mu V^TU_LW^-_\mu + \bar{U}_L\gamma^\mu V^*D_LW^+_\mu] \]
Important point on V matrix

\[ \mathcal{L}_{CC} = -(\overline{U}_L \gamma^\mu V D_L W_\mu^+ + \overline{D}_L \gamma^\mu V^\dagger U_L W_\mu^-) \]

\[ \int d^4 x \mathcal{L}_{CC} \xrightarrow{CP} \int d^4 x - [\overline{D}_L \gamma^\mu V^T U_L W_\mu^- + \overline{U}_L \gamma^\mu V^* D_L W_\mu^+] \]

The invariance is ensured if and only if V is real

CP violation means at least one complex phase

V has \( N^2 \) complex elements

Unitarity \( V^\dagger V = 1 \) imposes \( N(N-1)/2 \) relations for the phases and \( N(N+1)/2 \) for the magnitudes

2N-1 phases can be absorbed in the redefinition of the fields

At the end, the number of physical phases is \( (N-1)(N-2)/2 \)

One needs to have at least \( N = 3 \) to have CP violating phases!
The current CKM picture

$$V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}$$

Clear hierarchy in the couplings: the further from diagonal, the weaker

Intervention of beyond SM physics: is the flavour hierarchy maintained?
CKM Unitarity triangle(s)

Unitarity condition implies relations, among which:

\[ \sum_k V_{ik} V_{jk}^* = 0 \]

This yields three independent null sums, of which one is particularly interesting:

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

This is « the » famous unitarity triangle, well balanced, with three sides of similar magnitude:

« Bs triangle »: unbalanced, squeezed

\[ V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0 \]

By measuring the sides and angles of the Unitarity triangle, we test the closing relation expected in the Standard Model in presence of CP violation.
b-hadron decays are the privileged ground for testing the CKM picture

Determine angles and sides of the unitary triangle to test its closure

In principle any $b \rightarrow q$ transition should give us access to $V_{qb}$...

But this is the short range level (EW scale)... The long range (hadronization) effects make the game more complicated!
b hadrons

Mass (MeV/c^2)

6277
B_c^+ (b\bar{c})

6071
\Sigma_b^+ (b\bar{s}s)

5813
\Xi_b^+ (b\bar{d}s)

5791
\Xi_b^0 (b\bar{u}s)

5788
\Lambda_b^0 (b\bar{u}d)

5619,4

6277
B_s^0 (b\bar{s})

5366,8
B^0 (b\bar{d})

5279,6
B^+ (b\bar{u})

5279,3

mesons

baryons

All in LHCb program!
(non exhaustive listing here)

Small Belle run at \Upsilon(5S)

BaBar & Belle reach

Not shown here: the excited states of each bound state
Effective Hamiltonians

Derived using Operator Product Expansion + renormalization group to sum up the radiative corrections*

\[ H_{\text{eff}} = \sum_i V_{CKM}^i C_i(\mu) O_i(\mu) \]

Quark flavour couplings (CKM for the SM)

Wilson coefficients, integrate physics from EW scale to \( \mu \) (~ 1 GeV)

6-dim operators (higher orders negligible)

Matrix elements of operators \( O_i \): non perturbative calculations: source of hadronic uncertainties (decay constants, form factors, etc...)

\( C_i/O_i \) mix under RG equations: in practice, use effective \( C_i^{\text{eff}} \)

For right-handed current, use of primed coefficients, \( C_i' \)
(beyond SM contributions)

* For a exhaustive review, see: G.Buchalla et al, Rev.Mod.Phys.68 (1996) 1125-1144
Loop operators and new physics

Loop operators → massive (electroweak) virtual particles: New Physics might intervene. Wilson coefficients affected by NP.

$C_i(\prime) \rightarrow C_i(\prime) + C_{i}^{\text{NP}}$

Electromagnetic penguin

$O_{7\gamma} = (\bar{s}\sigma_{\mu\nu}(m_b R + m_s L)b) F^{\mu\nu}$

$O_{9\gamma} (\prime) = (\bar{s}b)_{V^+A}(\bar{\ell}\ell)_V$

$O_{10\gamma} (\prime) = (\bar{s}b)_{V^+A}(\bar{\ell}\ell)_A$
UT constraints from loop vs tree quantities

Tree quantities

Exclusive $|V_{ub}|$

Inclusive $|V_{ub}|$

Loop quantities

$|V_{ub}|$ measurement is crucial in the tree vs loop test!
The problem of hadronic uncertainties

The effective Hamiltonians in the OPE come as a product of currents $\times$ CKM coupling $\times$ Wilson coefficient

But for the observables, one needs to compute matrix elements between hadronic states! Use of factorization ansatz, e.g. for $B \rightarrow XY$:

$$\langle XY|O_i|B\rangle = \langle XY|j_1 j_2 |B\rangle \approx \langle X|j_1|B\rangle \langle Y|j_2|0\rangle$$

or $$\langle XY|O_i|B\rangle = \langle XY|j_1 j_2 |B\rangle \approx \langle 0|j_1|B\rangle \langle XY|j_2|0\rangle$$

It works exactly or very well for modes where two parts of the decay are well decoupled: (semi)leptonic modes

It needs corrections for the hadronic modes since no decoupling is possible (e.g. soft gluon exchange)

After that, the decoupled matrix elements need some non-perturbative QCD techniques to be computed: QCD sum rules, lattice QCD.

For reviews on QCD sum rules, see:
Extracting EW scale quantities with hadronic decays?

No way with « direct » quantities, or very limited (substantial corrections for non-factorizable effects)

Possible if one uses ratios (asymetries, etc...) : example of $\gamma$ extraction (but still need to deal with strong phases)
Thus....

Channels containing leptons in the final state are preferred due to the (quasi)perfect factorization of the matrix elements (second order electromagnetic effects)

Semileptonic $B \to X \ell \nu$

\[
\langle X \ell \nu | O_{V\ell} | B \rangle = \langle X \ell \nu | j_\ell j_h | B \rangle \approx \langle X | j_h | B \rangle \langle \ell \nu | j_\ell | 0 \rangle
\]

Non perturbative methods treat what happens inside the hadrons, accounting bound states effects: Notion of Form Factor
Form Factors and rates

For $X$ pseudo-scalar, only vector part of the current is relevant

$$\langle X | \bar{q} \gamma^\mu b | B \rangle = f_+ (q^2) \left( p_B^\mu + p_X^\mu - \frac{(m_B^2 - m_X^2)}{q^2} \right) + f_0 (q^2) \frac{(m_B^2 - m_X^2)}{q^2} q^\mu$$

$$q = p_B - p_X = p_\ell + p_\nu$$

$m_{\ell}^2 \leq q^2 \leq m_B^2 - m_X^2$

$$\frac{d\Gamma}{dq}(B \rightarrow X \ell \nu) = \frac{G_F^2 |V_{xb}|^2 (q^2 - m_\ell^2) \sqrt{E_X^2 - m_X^2}}{24 \pi^3 q^4 m_B^2}$$

$$\times \left[ \left( 1 + \frac{m_\ell^2}{2q^2} \right) m_B^2 (E_X^2 - m_X^2) [f_+ (q^2)]^2 + \frac{3m_\ell^2}{8q^2} \left( m_B^2 - m_X^2 \right)^2 [f_0 (q^2)]^2 \right]$$

Since $m_\ell^2 \ll q^2$ in general (for $\ell = e, \mu$), $f_+ \ll \text{pilots}$ the decay rate
Form Factors parametrization and calculation

\[ z(q^2, t_0) = \frac{\sqrt{1 - \frac{q^2}{t_+}} - \sqrt{1 - \frac{t_0}{t_+}}}{\sqrt{1 - \frac{q^2}{t_+}} + \sqrt{1 - \frac{t_0}{t_+}}} \]

\[ t_+ = (m_B + m_X)^2 \]

\[ f_{+,0}(q^2) = \frac{1}{1 - \frac{q^2}{m_B^2}} \sum_{k=0}^{K} b_{+,0}^{(k)}(t_0) z(q^2, t_0)^k \]

\[ t_0 = (m_B + m_X) (\sqrt{m_B} - \sqrt{m_X})^2 \]

Usually \( K=3 \) \( b \) parameters are used for the description

Calculations are done either with Lattice QCD (LQCD), which tends to be accurate at high \( q^2 \) or Light Cone Sum Rule (LCSR), which is more accurate at low \( q^2 \)

*bourrely, caprini, lellouch, phys. rev. d 79 (2009) 013008
Inclusive measurements

$B \to (\Sigma_X X) \ell \nu$

Non-perturbative effects from $B$ only

Use of heavy quark expansion (HQE)

Relevant for $B$ factories
Unitarity triangle before B factories

Situation in 1995, right after the first top quark observation in Fermilab. The top mass intervenes in the $B - \bar{B}$ mixing: use of mixing frequency $\Delta m$ possible.
- First $|V_{cb}|$ measurement at LEP
- Evidence for $|V_{ub}|$ (ARGUS, CLEO)

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + 1 = 0$$
Measurement at B factories

\[ \tilde{p}_{\text{miss}} = \tilde{p}_{\text{beam}} - \sum_i \tilde{p}_i \quad q^2 = (\tilde{p}_{\text{miss}} + \tilde{p}_\ell)^2 \]

**KEY QUANTITY:**

Missing 4-momentum from beam 4-P and sum of visible 4-P

|  \( |V_{cb}| : B \rightarrow D(\ell) \ell \nu, B \rightarrow X_c \ell \nu \) |
|  \( |V_{ub}| : B \rightarrow \pi \ell \nu, B \rightarrow X_u \ell \nu \) |

Clean environment, possibility to do exclusive and inclusive studies

\( B \rightarrow X \ell \nu \)
Measurements from B factories

Example of $B^0 \to \pi^- \ell^+ \nu$

\[
\begin{array}{c|c|c|c|c}
\text{Experiment} & |V_{ub}| (10^{-3}) \\
\hline
Babar (6 bins) & 3.54 \pm 0.12^{+0.38}_{-0.33} & 3.22 \pm 0.15^{+0.55}_{-0.37} & 3.08 \pm 0.14^{+0.34}_{-0.28} & 2.98 \pm 0.31 \\
Babar (12 bins) & 3.46 \pm 0.10^{+0.37}_{-0.32} & 3.26 \pm 0.19^{+0.56}_{-0.37} & 3.12 \pm 0.18^{+0.35}_{-0.29} & 3.22 \pm 0.31 \\
Belle & 3.44 \pm 0.10^{+0.37}_{-0.32} & 3.60 \pm 0.13^{+0.61}_{-0.41} & 3.44 \pm 0.13^{+0.38}_{-0.32} & 3.52 \pm 0.34 \\
Babar + Belle & 3.47 \pm 0.06^{+0.37}_{-0.32} & 3.43 \pm 0.09^{+0.59}_{-0.39} & 3.27 \pm 0.09^{+0.36}_{-0.30} & 3.23 \pm 0.30 \\
Tagged & 3.10 \pm 0.16^{+0.33}_{-0.29} & 3.47 \pm 0.23^{+0.60}_{-0.39} & 3.32 \pm 0.22^{+0.37}_{-0.31} & 3.33 \pm 0.39 \\
\hline
\text{LCSR} & \text{HPQCD} & \text{FNAL/MILC} & \text{FNAL/MILC fit}
\end{array}
\]
UT after B factories mandate

Basically: The B factories established experimentally the CKM picture but a lot of remaining questions (e.g. tree vs loop constraints) and more precision (e.g., $|V_{ub}|$) is needed.
LHC pp collisions and $b\bar{b}$

$\sigma(b\bar{b})$ ranging from 200 $\mu$b (at 7-8 TeV) to 500 $\mu$b (at 13-14 TeV) in the full solid angle, this is $2 \times 10^5$ to $5 \times 10^5$ times the value of the cross section at the B factories!

For a standard luminosity at the LHCb point, $\sim 10^5$ $b\bar{b}$ events per second!

LHC is a mega $b$ factory! But with a noisy environment for the $b$ analyses.... This same environment provides the advantage of a per event primary vertex!

One has to account for the $b$ fragmentation

\[ f_u = f(b \to B^+) = 0.3 - 0.4 \]
\[ f_d = f(b \to B^0) = 0.3 - 0.4 \]
\[ f_s = f(b \to B_s^0) / (f_u + f_d) = 0.134 \pm 0.009 \]
\[ f_{b\text{baryon}} = f(b \to \Lambda_b, \Xi_b, \Omega_b) / (f_u + f_d) = 0.240 \pm 0.022 \]
\[ f_c = \sigma(B_c) = ? \]

LHCb detector

**Forward single-arm spectrometer with warm magnet (possibility to inverse polarity)**

Optimize for b and c hadron studies

**Vertexing**

**Tracking stations**

**Particle ID Ring Imaging Cherenkov**

**Calorimeters and Muon Chambers**

- Acceptance $2 < \eta < 5$
- Momentum resolution $\sim 0.5\%$
- IP resolution $\sim 20 \, \mu m$
- Time resolution $\sim 45 \, \text{fs}$
$|V_{ub}|$ at LHCb

In the deeds, we normalize $b \to u$ decays to corresponding $b \to c$ modes to minimize systematics and control efficiency corrections, etc.. Consequence: we measure $|V_{ub}|/|V_{cb}|$

$\Lambda_b \to p \mu \nu$, normalized to $\Lambda_b \to \Lambda_c(\to pK\pi) \mu \nu$

$B_s \to K \mu \nu$, normalized to $B_s \to D_s(\to KK\pi) \mu \nu$
arXiv:2012.05143, accepted by PRL

*Will concentrate more on this one*
Technique for SL in LHCb

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

Fit variable: binned template histograms for signal and backgrounds

Use Beeston-Barlow method to account for template uncertainty

\[ q^2 = (p_\mu + p_\nu)^2 \]

\[ p_\parallel(\nu) \text{ determined from } p_{H_b}^2 = m(H_b)^2 \]

Two fold ambiguity

Best solution chosen with regression method

JHEP 02 (2017) 021

(other methods to approximate q are also used in SL analyses)
**Method**

Measure:

\[
\frac{BF(H_b \to X_u \mu \nu)}{BF(H_b \to X_c \mu \nu)} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \left( \frac{|V_{ub}|^{-2} \int \frac{d\Gamma_K}{dq^2}}{|V_{cb}|^{-2} \int \frac{d\Gamma_{D_s}}{dq^2}} \right)
\]

Infer: \(\left| \frac{V_{ub}}{V_{cb}} \right|\) using FF calculations (LQCD, QCD SR)

One \(q^2 > 15 \text{ GeV}^2\) region for \(\Lambda_b \to p \mu \nu\)

Two \(q^2\) bins for \(B_s \to K \mu \nu\); \(q^2 < 7 \text{ GeV}^2\)
Boundary chosen to get approximately the same expected number of signal events in each bin

* Measurement of the Branching Fraction for the first time

* Provide a \(\left| \frac{V_{ub}}{V_{cb}} \right|_{\text{excl}}\) measurement to feed in the excl vs incl puzzle AND the Unitarity triangle side
$\Lambda_b \rightarrow p \mu \nu$

$\Lambda_b \rightarrow \Lambda_c(\rightarrow pK\pi) \mu \nu$

$q^2 > 15 \text{ GeV}^2/c^4$ cut to minimize uncertainty from LQCD FF

$|V_{ub}| / |V_{cb}| = 0.083 \pm 0.004 \text{ (exp)} \pm 0.004 \text{ (FF)}$

Central value updated to 0.079 after new $\Lambda_c \rightarrow pK\pi$ BF
$$\Lambda_b \rightarrow p \mu \nu \text{ systematics}$$

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(\Lambda_c^+ \rightarrow pK^+\pi^-)$</td>
<td>+4.7 $\pm$ 5.3</td>
</tr>
<tr>
<td>Trigger</td>
<td>3.2</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.0</td>
</tr>
<tr>
<td>$\Lambda_c^+$ selection efficiency</td>
<td>3.0</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow N^* \mu^- \bar{\nu}_\mu$ shapes</td>
<td>2.3</td>
</tr>
<tr>
<td>$\Lambda_b^0$ lifetime</td>
<td>1.5</td>
</tr>
<tr>
<td>Isolation</td>
<td>1.4</td>
</tr>
<tr>
<td>Form factor</td>
<td>1.0</td>
</tr>
<tr>
<td>$\Lambda_b^0$ kinematics</td>
<td>0.5</td>
</tr>
<tr>
<td>$q^2$ migration</td>
<td>0.4</td>
</tr>
<tr>
<td>PID</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>+7.8 $\pm$ 8.2</strong></td>
</tr>
</tbody>
</table>
Motivation for $\mathcal{B}_s \to K\mu\nu$

Inclusive vs Exclusive puzzle in the plane ($|V_{cb}|, |V_{ub}|$)

UT apex constraint with $\gamma$ and $|V_{ub}|/(|V_{cb}|)$

Exclusive $|V_{ub}|/(|V_{cb}|)$

Inclusive $|V_{ub}|$

$B \to D^{(*)}\ell\nu$

$B \to X_c\ell\nu$

$B \to X_u\ell\nu$

$B \to \pi\ell\nu$
$B \rightarrow \pi$ vs $B_s \rightarrow K$ FF

FF error budgets in LQCD, as reported in Phys. Rev. D 91, 074510 (2015)
Challenge!

$B_s \rightarrow K \mu \nu$

Only two charged tracks in the final state + undetectable neutrino!
Any physics decay with the same tracks + extra tracks or neutral particle is a background!
+ Tracks getting out of acceptance...
Background fighting and characterization involving Machine Learning techniques.
Backgrounds for $B_s \rightarrow K \mu \nu$

- Dominant $V_{cb}: b \rightarrow c (\rightarrow KX) \mu \nu$
- $B_s \rightarrow K^* \mu \nu$: three resonances ($K^*(892)$, $K_0^*(1430)$, $K_2^*(1430)) (\rightarrow K^+ \pi^0)$
  - Neutral isolation, model what passes
- $B \rightarrow c\bar{c} K (X)$
  - Charged isolation MVA output
- MisID background from e.g., $B \rightarrow \pi \mu \nu$
  - Modeled using fake $K/\mu$ selection lines
- Combinatorial (reduced with geometrical cut, removing track pairs with transverse momenta in opposite quadrants)
MVA

Charge BDT

Trained against decay with extra tracks

Neutral BDT

Trained against decay with extra neutrals or long-lived

Neutral BDT optimized after charge BDT selection
Calibration: use of $B^+ \to J/\Psi(\mu\mu) K^+$

**Charge BDT**

- MC $B^0_s \to K\mu^+\nu_\mu$
- MC $B^+ \to J/\Psi K^+$
- Data $B^+ \to J/\Psi K^+$

**Neutral BDT**

- MC $B^0_s \to K\mu^+\nu_\mu$
- MC $B^+ \to J/\Psi K^+$
- Data $B^+ \to J/\Psi K^+$

**$\sigma$(MCorr)**

- MC $B_s \to K\mu^+\nu_\mu$
- MC $B^+ \to J/\Psi K^+$
- Data $B^+ \to J/\Psi K^+$

**Bs_MCORRERR**

$B \to J/\Psi K$ used for Data/MC corrections, reconstructed as $K\mu$ or fully.

After kinematic reweighing, Data/MC shapes agree well.

$K\mu^+\mu^-$ decays where $\mu^-$ is not detected (out of acceptance) are recovered using « neutrino » method: yield of charmonium background constrained.
MisID component(s) estimate

From FakeK (hμ) and FakeMu (Kh) selections

Define μ,π,p,K enriched regions using ID cuts on h

Yields in regions: $N_{i}$

Obtain actual misID yields from Bayes Unfolding

$$N_{i} = \sum_{j} P(\hat{i} | j) \times N_{j}$$

$P(\hat{i} | j)$ obtained from PID calibration samples

Perform the operation across the Mcorr bins to obtain the MisID yields as a function of Mcorr:

$$Y_{i}(\zeta) = N_{i} \times \frac{P(\hat{\zeta} | i)}{P(\hat{i} | i)}$$

$$N(\zeta) = \sum_{i} Y_{i}(\zeta) \quad \zeta = K, \mu$$

This data-driven method enables to infer both the shape and the normalization of the MisID background
Backgrounds for $B_s \rightarrow D_s \mu \nu$

- $B_s \rightarrow D_s^* \mu \nu$ ($D_s^* \rightarrow D_s \gamma$)
- $B_s \rightarrow D_s^{**} \mu \nu$ (higher resonances $\rightarrow D_s X$)
- $B_s \rightarrow D_s \tau \nu$ ($\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$)
- $B \rightarrow D_s D$ ($D \rightarrow \mu \nu X$)
- Note: since the $D_s$ signal is fitted as a function of $M_{\text{corr}}$, no combinatorial or reflections emerging from $D_s \rightarrow KK\pi$ side
Fit of $D_s \rightarrow KK\pi$ in 40 Mcorr bins from 3000 to 6500 MeV/c^2
Bumps clearly showing excess of $B_s \rightarrow K \mu \nu$:

- $N(B_s \rightarrow K \mu \nu) = 6922 \pm 285$ for $q^2 < 7 \text{ GeV}^2$
- $N(B_s \rightarrow K \mu \nu) = 6399 \pm 390$ for $q^2 > 7 \text{ GeV}^2$
- $N(B_s \rightarrow D_s \mu \nu) = 201450 \pm 5200$

Normalization fit to $B_s \rightarrow D_s \mu \nu$:

Uncertainties include fit template limited statistics.
BF results

\[ R_{BF} = \frac{\mathcal{B}(B_s^0 \rightarrow K \mu \nu, \text{ bin})}{\mathcal{B}(B_s^0 \rightarrow D_s \mu \nu)} = \frac{N_K}{N_{D_s}} \times \frac{\epsilon_{D_s}}{\epsilon_K(\text{bin})} \times \mathcal{B}(D_s^+ \rightarrow K^+ K^- \pi^+) \]

\[ R_{BF}(\text{low}) = (1.66 \pm 0.08 \text{ (stat)} \pm 0.07 \text{ (syst)} \pm 0.05 \text{ (} D_s \text{)}) \times 10^{-3} \]

\[ R_{BF}(\text{high}) = (3.25 \pm 0.21 \text{ (stat)} ^{+0.16}_{-0.17} \text{ (syst)} \pm 0.09 \text{ (} D_s \text{)}) \times 10^{-3} \]

\[ R_{BF}(\text{all}) = (4.89 \pm 0.21 \text{ (stat)} ^{+0.20}_{-0.21} \text{ (syst)} \pm 0.14 \text{ (} D_s \text{)}) \times 10^{-3} \]

Low vs High q^2 BF are in the proportions 1:2

Using \[ \mathcal{B}(B_s^0 \rightarrow K \mu \nu, \text{ bin}) = R_{BF} \times \tau_{B_s} \times |V_{cb}|^2 \times FF_{D_s^+} \]

We obtain \[ \mathcal{B}(B_s^0 \rightarrow K^- \mu^+ \nu_{\mu}) = (1.06 \pm 0.05 \text{ (stat)} \pm 0.08 \text{ (syst)}) \times 10^{-4} \]
Systematics

$D_s \rightarrow KK_\pi$ BF brings a 2.8% relative uncertainty

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>All $q^2$</th>
<th>low $q^2$</th>
<th>high $q^2$</th>
</tr>
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<tr>
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<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Particle identification</td>
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<td>1.0</td>
</tr>
<tr>
<td>$\sigma(m_{\text{corr}})$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>Isolation</td>
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<tr>
<td>Charged BDT</td>
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<td>0.6</td>
<td>0.6</td>
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<tr>
<td>Neutral BDT</td>
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<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>$q^2$ migration</td>
<td>–</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Efficiency</td>
<td>1.2</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Fit template</td>
<td>+2.3</td>
<td>+1.8</td>
<td>+3.0</td>
</tr>
<tr>
<td></td>
<td>−2.9</td>
<td>−2.4</td>
<td>−3.4</td>
</tr>
<tr>
<td>Total</td>
<td>+4.0</td>
<td>+4.3</td>
<td>+5.0</td>
</tr>
<tr>
<td></td>
<td>−4.3</td>
<td>−4.5</td>
<td>−5.3</td>
</tr>
</tbody>
</table>

Vary signal(s) and background shapes due to uncertainty related to statistics or FF model or possibly missing components, etc...

Data/MC corrections with control channel
FF calculations $B_s \rightarrow K\mu\nu$

Bouchard et al. (HPQCD2014) shows different behaviour at low $q^2$

High $q^2$ : in general better accuracy for LQCD
LCSR not reliable $> 12$ GeV$^2$
Low $q^2$ : LCSR better

From there, we chose LCSR FF at low $q^2$ and latest LQCD (MILC 2019) for high $q^2$

Error bands : produced as the standard deviation of toys using the correlation matrices of the coefficients of the parametrization
FF calculations $B_s \rightarrow D_s \mu \nu$

Chose McLean et al.

Now published at:


The choice was done BEFORE unblinding

Error bands: produced as the standard deviation of toys using the correlation matrices of the coefficients of the parametrization
Result on $|V_{ub}|/|V_{cb}|$ from $B_s \rightarrow K\mu\nu$

$|V_{ub}|/|V_{cb}|$ (low) = $0.0607 \pm 0.0015$ (stat) $\pm 0.0013$ (syst) $\pm 0.0008$ ($D_s$) $\pm 0.0030$ (FF)

$|V_{ub}|/|V_{cb}|$ (high) = $0.0946 \pm 0.0030$ (stat) $\pm 0.0024$ (syst) $\pm 0.0013$ ($D_s$) $\pm 0.0068$ (FF)

High $q^2$ seems compatible with previous results
Low $q^2$ departs: problem with LCSR calculation (error budget? Normalization with LCSR $D_s\mu\nu$ needed?)
Will contribute to the global fit in the $(|V_{cb}|,|V_{ub}|)$ plane
More FF studies are expected, specially at low $q^2$
Summary/conclusion

SL studies have known a veritable « boom » in LHCb

- Besides the LFUV ratios, not mentioned $|V_{cb}|$ from $B_s$ or the FF measurements of $B_s \rightarrow D_s^{(*)}$, $\Lambda_b \rightarrow \Lambda_c$

  $\Lambda_b \rightarrow p \, \mu \, \nu$ / $B_s \rightarrow K \, \mu \, \nu$ and $|V_{ub}|$

- The unexpected extraction of such a topology will open many doors : the proof of principle is established

- In the future : multi $q^2$ bins analysis so that we constrain the FF variation ourselves

- It is expected that a very precise measurement of $|V_{ub}|$ will be provided and thus the (tree-only) closing relation of UT will be tested at high precision

- Other modes are investigated in view of $|V_{ub}|$ (e.g $B \rightarrow \rho$)
\[ B_s \rightarrow D_s^{(*)} \text{ SL} \]

\[ |V_{cb}| \text{ from } B_s \rightarrow D_s^{(*)} \mu \nu \]

\[ |V_{cb}|(\text{CLN}) = (41.4 \pm 0.6 \text{ (stat)} \pm 1.2 \text{ (ext)}) \times 10^{-3} \]

\[ |V_{cb}|(\text{BGL}) = (42.3 \pm 0.8 \text{ (stat)} \pm 1.2 \text{ (ext)}) \times 10^{-3} \]

\[ \left( \frac{1}{\Gamma} \frac{d\Gamma}{dw} \right)(B_s \rightarrow D_s^{*} \mu \nu) \]

\[ w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}} \]

\[ \text{Phys. Rev. D101 (2020) 072004} \]