Flavour elements of the HL/HE-LHC workshop

J. Martin Camalich

4th Workshop on LHCb Upgrade II

April 8th 2019
Main Goal

Study the **physics potential** of the High-Luminosity LHC and possible upgrade to the High-Energy LHC

- **HL-LHC:** 14 TeV, 3 ab\(^{-1}\) \((\text{LHCb: } 300 \text{ fb}\(^{-1}\))\)
- **HE-LHC:** 27 TeV, 15 ab\(^{-1}\) \((\text{LHCb: } 3 \text{ ab}\(^{-1}\))\)

**Global effort:** Five working groups

- **SC:** M. Mangano & G. Salam (TH), A. Dainese (ALICE), A. Nisati (ATLAS), A. Meyer (CMS), M. Vesterinen (LHCb)
- **WG1:** Standard Model physics
- **WG2:** Higgs physics
- **WG3:** Beyond the Standard Model physics
- **WG4:** Flavour physics
- **WG5:** High-density QCD with heavy-ion and proton beams

**More than one year of work!**

**Workshop meetings:**

- **Kick-off plenary meeting:** CERN, 3 days on 20, 31 October and 1st November 2017 [link](#)
- Joint meeting of WG2, 3 and 4: FNAL April 4-6, 2018, [Web page](#)
- **Second plenary meeting:** CERN, 3 days on 18-20 June, 2018 [link](#)
- **Final Jamboree:** CERN, March 1 2019 [link](#)
Opportunities in Flavour Physics
at the HL-LHC and HE-LHC

Report from Working Group 4 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

- **arXiv number:** 1812.07638
  - Cnv’s: A. Cerri (ATLAS), S. Malvezzi (CMS), V. Gligorov (LHCb), JMC & J. Zupan (TH)
  - 303 signing authors
    - 70 TH contributors
    - 33 TH referees
  - 213 pages (+78 pages of references)

Complements “LHCb Upgrade II” document (arXiv:1808.08865) including . . .
  - Theoretical interpretation of projections
  - Interplay with ATLAS and CMS
What have we learned from the LHC so far?

- **Two blunt evidences**
  - A light SM-like Higgs
  - No new particles directly at $\sqrt{s} \sim 1$ TeV

- **SM becomes a “self-consistent” renormalizable theory up to $m_{\text{Planck}}$ . . .**

  *(Modulo stability of EW vacuum)*

  - EW hierarchy problem
  - What is the astrophysical/cosmological dark matter
  - . . .
Flavor physics was instrumental in discovering and shaping the SM

- Nuclear $\beta$-decays: Discovery weak interactions and neutrino
- Rare Kaon-decays: Discovery of the charm quark
- Kaon decays: Discovery of $CP$ violation $\Rightarrow$ Discovery of 3 generations

● Expect the unexpected ...

PROPOSAL FOR $K^0_2$ DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of $K^0_1$ mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^0_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. 

Thanks to Zoltan Ligeti for sharing this
Flavour Physics in the HL-LHC era

- **Prototypical example:** FCNCs

\[ \mathcal{M}_{\text{SM}} \sim G_F \frac{y_t^2}{16\pi^2} (V_{ts}^* V_{tb})^2 \]

- Flavour observables probe (indirectly) very high energy scales!

**What is the reach in \( \Lambda \) of flavour physics at HL(HE)-LHC?**
CKM metrology in the HL-LHC era: Tree-level inputs

- Overconstrain CKM: Tree-level inputs (SM) vs. loop-level (NP)
- LHCb prospects in tree-level

- Measurements of $|V_{ub}|/|V_{cb}|$

$\Lambda_b \rightarrow (p, \Lambda_c^+)\mu^-\bar{\nu}$

- Current: $\pm 0.0050$
- Phase I: $\pm 0.0025$
- Phase II: $\pm 0.0008$

- Other: e.g. $B_c^+ \rightarrow D^0\mu^-\bar{\nu}$

- Measurements of $\gamma$
  Open competition with Belle II

Big impact on UT!

L. Silvestrini, HL/HE-LHC Kick-off
CKM metrology in the HL-LHC era: CPV in the $B$ system

- **Measurements of $\phi_s$**

  \[ \phi_s^{\text{direct}} = -0.21(31) \text{ mrad}, \quad \phi_s^{\text{SM}} = -0.037(1) \text{ mrad} \]

- **Tree-level dominated decays**

- **Strong interplay between Expt's**

  ![Graph showing SM 68% CL contours with Combined Projection and current experimental constraint]

- **Measurement of $\phi_d$ with $B^0 \to J/\psi K_S^0$**

  \[
  \sin \phi_d^{c\bar{c}s} \text{ (stat.)}
  \]

  - **Current:** $\pm 0.029$
  - **BELLE II:** $\pm 0.005$
  - **LHCb - II:** $\pm 0.003$

  ![Graph showing signal yield asymmetry with LHCb 300 fb$^{-1}$ simulation]
Impact of HL-LHC in Unitarity Triangle

Current

Projection HL-LHC only

Projection on bounds on New Physics

- Generic
- MFV and loop

Improvements on $\Lambda$ by a factor 2-3
Search of NP in rare $B$-decays: Rates and angular observables

1. **Pure leptonic decay** $B_q \rightarrow \mu^+ \mu^-$
   - **Branching fr.** (SM pred. by $|V_{cb}|$)
   - **Effective lifetime**

2. **Angular analyses** $B \rightarrow K^* \mu^+ \mu^-$

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J. Martin Camalich (IAC)  Flavour elements of the HL/HE-LHC workshop  April 8th 2019  10 / 21
Projection of fits to $B_s \rightarrow \mu^+ \mu^-$ and angular analyses using ATLAS, CMS and LHCb projections

- Much more explored in the document

1. **Other decays:** $B_s \rightarrow \phi \mu^+ \mu^-$, $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$, $B_s \rightarrow \gamma \mu^+ \mu^-$, ...
2. **Radiative decays:** $B_s \rightarrow \phi \gamma$, $B \rightarrow K^* e^+ e^-$, $\Lambda_b \rightarrow \Lambda \gamma$, ...
3. $b \rightarrow d \mu^+ \mu^-$ transitions: 17K events of $B \rightarrow \pi \mu^+ \mu^-$!
**LFUV in** $b \rightarrow s \ell^+ \ell^-$

- CLFV also generically expected: e.g. $\mathcal{B}(B^0 \rightarrow e^\pm \mu^\mp) \lesssim 2 \times 10^{-10}$ at LHCb Ph. II

**LFUV in** $b \rightarrow c \tau^- \bar{\nu}$

- Prospects to measure angular distributions!
The $B$-anomalies: Interplay with high $p_T$ searches

- **The anomalies in CC’s:** $\Lambda \sim 1$ TeV
  
  - Leptoquarks only survivor
    
    Vector LQ model for $B$-anomalies
  
    - Parameter space probed at HL-LHC (direct only at HE-LHC)

- **The anomalies in FCNC’s:** $\Lambda \sim 10$ TeV
  
  - $Z'$ or leptoquarks
  
    - @HL-LHC only if loop-level or combined with CC anomalies
Flavour connection to top-quark and Higgs-boson physics

- **Top-quark flavor transitions**

  1. **Top FCNCs**

     | B limit at 95% C.L. | 3 ab⁻¹, 14 TeV | 15 ab⁻¹, 27 TeV | Ref. |
     |---------------------|----------------|----------------|-----|
     | $t \to q u$         | $3.8 \times 10^{-6}$ | $5.6 \times 10^{-7}$ | [1194] |
     | $t \to q c$         | $32.1 \times 10^{-6}$ | $19.1 \times 10^{-7}$ | [1194] |
     | $t \to Z q$         | $2.4 - 5.8 \times 10^{-5}$ | | [1195] |
     | $t \to \gamma u$    | $8.6 \times 10^{-6}$ | | [1196] |
     | $t \to \gamma c$    | $7.4 \times 10^{-5}$ | | [1196] |
     | $t \to H q$         | $10^{-4}$ | | [1195] |

     - Limits relevant for BSM (Sec.10)

  2. **Anomalous $Wtb$ couplings**

     | Coeff. | $c_{tW}$ | $c_{bW}$ | $c_{\nu tb}$ |
     |--------|----------|----------|--------------|
     | Current | Re(...)  | [-0.70, 0.82] | [-2.2, 2.2]  | [-8.9, 10.9] |
     |         | Im(...)  | [-1.5, 2.2]   | [-2.1, 2.2]  | [-9.9, 9.9]  |
     | 3000 fb⁻¹ | Re(...) | [-0.23, 0.58] | [-2.2, 2.0]  | [-9.3, 10.6] |
     |         | Im(...)  | [-1.2, 1.3]   | [-2.2, 2.1]  | [-9.9, 9.9]  |

     - **Weaker** than $B \to X_s \gamma$:
       $c_{\nu tb} \in [-4.6, 4.9] \times 10^{-2}$

- **Higgs-flavor physics**

  1. **Diagonal yukawas**

  2. **Off-diagonal and CPV yukawas**

     - Limits typically weaker than CLFV decays ($\mu \to e\gamma$) or EDM
     - **Exception:** $\tau\mu$-Higgs coupling!
     - **Direct limits** on CPV from asymmetries in $ttH$ and $h \to \tau\tau$
The tau, kaons and hyperons

- Flavour physics with the $\tau$-lepton

1. Collider bounds on high $p_T$ tails

- CLFV: $\tau \to 3\mu$

- Competitive bounds on taus with valence quarks $\Lambda \sim 20$ TeV!

- The LHCb strangeness-physics program

- Best bound on $K_S \to \mu^+ \mu^-$

- Broad program complementary with “kaon factories”
  - LFUV: e.g. $K^\pm \to \pi^\pm \ell^+ \ell^-$
  - Hyperon decays: $\Sigma^+ \to p\mu^+ \mu^-$

Greljo et al. PRL122, 131803

\[ B(K_0^S \to \mu^+ \mu^-) \text{ limit at 95\% CL } \times 10^{-9} \]
Charm physics at HL-LHC

- **Probing GIM in up quark system**
  - Indirect CPV

- **Direct CPV**

- **Rare decays and null-tests of the SM**
  - Large long-distance cont’s

- **Null tests and isospin relations**

\[ D^0 \to \mu^+ \mu^- \]

**Current:** \( 6.2 \times 10^{-9} \)

**LHCb-II:** \( 1.8 \times 10^{-10} \)

**SM:** \( \lesssim 10^{-10} \)

Charm-systems are very challenging for theory
Flavor physics and nonperturbative QCD

- **Hadronic contributions “plague” interpretation of flavour observables**
  - Decay constants and **form factors** in exclusive decays
  - Long-distance contributions to rare processes
  - Penguin pollution conts. to CPV in $B_q^0$
  - QED corrections to hadron decays
  - ...

- **Progress in QCD crucial for the flavor physics program**
  - Program **spearheaded by lattice QCD community** ... (Sec. 11)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Published averages</th>
<th>Reference</th>
<th>error (to be published/not in FLAG-2016)</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{K^+}$</td>
<td>1.193(3)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.25% (0.15%, symmet. [822])</td>
<td>0.15%</td>
<td>0.15%</td>
</tr>
<tr>
<td>$f_{K^+} / f_{K^0}$</td>
<td>0.9706(27)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.28% (0.20% [1527])</td>
<td>0.12%</td>
<td>0.12%</td>
</tr>
<tr>
<td>$f_{K}^{(*)}(0)$</td>
<td>0.7625(97)</td>
<td>$N_f = 2 + 1$</td>
<td>1.3%</td>
<td>0.7%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$B_K$</td>
<td>248.83(1.27)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.5% (0.16% [822])</td>
<td>0.16%</td>
<td>0.16%</td>
</tr>
<tr>
<td>$f_{D_s} / f_{D_s}$</td>
<td>1.1716(32)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.27% (0.14% [822])</td>
<td>0.14%</td>
<td>0.14%</td>
</tr>
<tr>
<td>$f_{D_s}$</td>
<td>228.4(3.7)</td>
<td>$N_f = 2 + 1$ [66]</td>
<td>1.6% (0.56% [822])</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$f_{B_s}$/ $f_{B_s}$</td>
<td>0.6(50)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.6% (0.4% [822])</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$f_{B_s}$</td>
<td>2.05(7)</td>
<td>$N_f = 2 + 1 + 1$ [66]</td>
<td>0.5%</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>$f_{B_d}$/ $f_{B_d}$</td>
<td>0.53(10)/1.35(6)</td>
<td>$N_f = 2/N_f = 2 + 1$ [66]</td>
<td>~4%</td>
<td>0.8%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$B_{D_s}$/ $B_{B_d}$</td>
<td>1.007(21)/1.032(28)</td>
<td>$N_f = 2/N_f = 2 + 1$ [66]</td>
<td>2.1% (2.7%)</td>
<td>0.5%</td>
<td>0.3%</td>
</tr>
<tr>
<td>$\xi$</td>
<td>1.206(17)</td>
<td>$N_f = 2 + 1$ [66]</td>
<td>1.4%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>$\overline{m}_u(\overline{m}_s)$</td>
<td>1.275(8) GeV</td>
<td>$N_f = 2 + 1$ [66]</td>
<td>0.6%</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

**B → π** for $|V_{ub}\text{thor}|$

**B → D** for $|V_{ub}\text{thor}|$

(first param. BCL z-exp.)

**B → D** for $|V_{ub}\text{thor}|$

$|V_{ub}\text{thor}|$

$|V_{ub}/V_{ub}\text{thor}|$

B → K

(first param. BCL z-exp.)

$|V_{ub}/V_{ub}\text{thor}|$

(first param. BCL z-exp.)
Spectroscopy and QCD exotica

**SU(3)_c-singlet combinations of q and \( \bar{q} \) allowed by QCD dynamics?**

**Quark Model VS. QCD exotica**

- **Experimentally very promising**
  - Many states to be discovered!
    - e.g. for the pentaquark ...
  - **HL-LHC:** Argand plot \( Z^- (4430) \)

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**Pappagallo’s talk HL/HE-LHC Kick-off**

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LHCb
Spectroscopy and QCD exotica

**SU(3)_{c}-singlet combinations of q and q̄ allowed by QCD dynamics?**

**Quark Model VS. QCD exotica**

- **Theoretically challenging**
  - **X(3872) still controversial**
    - e.g. prompt production at colliders
  - **TH’s charted interesting states and channels**

<table>
<thead>
<tr>
<th>Excited single-heavy baryons</th>
<th>A whole SU(3) family; determination of spin and parity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X(3872)</strong></td>
<td>$D^0\bar{D}^0\pi^0$, $D\bar{D}\gamma$, Line shapes; decay width; production rates</td>
</tr>
<tr>
<td></td>
<td>$J/\psi\pi^+\pi^-$, $J/\psi3\pi$,</td>
</tr>
<tr>
<td></td>
<td>$J/\psi\gamma$, $\psi'\gamma$</td>
</tr>
<tr>
<td>$X_2$ (?)</td>
<td>$DD$, $DD^* + c.c.$, $J/\psi\omega$</td>
</tr>
<tr>
<td>$\chi_{c1}(2P)$ (?)</td>
<td>$DD^* + c.c.$, $J/\psi\eta$, $J/\psi\eta'$</td>
</tr>
<tr>
<td>$h_c(2P)$ (?)</td>
<td>$DD^* + c.c.$, $J/\psi\eta$, $J/\psi\eta'$</td>
</tr>
<tr>
<td>$X_b$ (?)</td>
<td>$\Upsilon\omega$, $\chi_{b1}\pi^+\pi^-$, $BB\gamma$, $\Upsilon\gamma$</td>
</tr>
<tr>
<td>$X_{b2}$ (?)</td>
<td>$BB$, $\Upsilon\omega$</td>
</tr>
<tr>
<td>$Z_c$ structures</td>
<td>$(c\bar{c})\pi^\pm$, $(D^{(<em>)}\bar{D}^{(</em>)})\pm$</td>
</tr>
<tr>
<td></td>
<td>Line shapes; production rates; Argand plots</td>
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<td></td>
<td>Sensitivity to kinematics</td>
</tr>
</tbody>
</table>

Anderlini’s talk HL/HE-LHC Kick-off
Flavor physics at HL/HE-LHC: Promising program for discoveries!

- Addresses fundamental questions!
- **Strong experimental program** extending for the next **two decades**
- **Strong interplay** with Higgs Physics, Collider Physics, Hadron physics, ... 

- **Document will be an important input for European Strategy of HEP**
List of topics

Only contributors to the TH content are listed!

1. **Introduction**  G. Isidori, Z. Ligeti
4. **Strange-quark probes of NP**  G. D’Ambrosio, D. Guadagnoli, T. Kitahara, D. Martínez-Santos
5. **Tau leptons**  V. Cirigliano, M. González-Alonso, A. Falkowski, E. Passemar
7. **Bottom-quark probes of NP**  W. Altmannshofer, D. Straub, J. Virto; M. Freytsis, M. Jung, D. Robinson, S. Schacht
8. **Top quark & flavour (WG1)**  G. Durieux, T. Kitahara, C. Zhang; F. Deliot, W. Dekens; M. Estévez, D. Faroughy, J. Kamenik

**This talk**

**Glimpse at TH interpretation of Flavour @ HL/HE-LHC!**