Future of charm, strangeness, $\tau^\pm$ at LHCb

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General aspects for a HL/HE LHCb

Many challenges ahead

- Improve tracking system/trigger to fit in timing constraints
- Maintain or improve the current resolutions (mass, impact parameter, $p_T$, ...)
- Development of faster simulation methods
Tracking performance

\[ \mathcal{L} \times 10 \] is challenging for tracking:

- Expected pile-up \( \sim 50 \)
- Selection of \( b \) and \( c \) hadrons is based on the flight distance
- Requires correct association of production vertex and decay vertices
- 13% mismatching for \( b \)-hadron decays if we keep the Phase-I Upgrade configuration
- With a track hit time resolution of \( \sim 200 \) ps, we recover the current levels

[CERN-LHCC-2017-003]
The VELO RF foil

- The RF foil separates VELO vacuum from primary LHC vacuum
- Isolates sensors from radio-frequency pickup
- Introduces a lot of material right in front of the interaction point
- Increases the resolution on the impact parameter due to multiple scattering
Removal of the VELO RF foil

- A lot of effort has been put on reducing the amount of material

- For charm and $\tau$ decays (and partially reconstructed B decays), the impact parameter resolution is crucial

- RF foil removal is risky, but the improvement is very big!

Scenario 1: With RF foil

Scenario 2: No RF foil
Improvements on the trigger

For the Phase-I Upgrade:

- Loose $E_T$ and $p_T$ cuts, increase the efficiencies to study soft processes (charm, strange and $\tau$ decays)
- Dynamic mix of inclusive and exclusive lines
- Only the requested information from the event is saved [arXiv:1604.05596]
- More efficient particle identification and reconstruction algorithms
- Efficiencies up to $\sim 90\%$ are possible

For Phase-II...

- Tighter throughput constraint
- Maybe need to restructure the trigger
- Usage of GPUs, FPGAs, etc... for simple processes
Interest on charm decays

- Charmed hadrons provide the only way to study CP violation (CPV) with up-type quarks
- After the Phase-II Upgrade, LHCb will have recorded the largest sample of charm hadrons ever
- This would constitute over 2 orders of magnitude of what is expected for Belle II in $D^0 \to h^+h^-$, $D^0 \to K^0_S h^+h^-$ ($h = \pi, K$)
- To study CPV, huge statistics needed for both real data and simulated samples

$$A_{\text{CP}} \equiv \frac{\Gamma_{D^0 \to f} - \Gamma_{\bar{D}^0 \to \bar{f}}}{\Gamma_{D^0 \to f} + \Gamma_{\bar{D}^0 \to \bar{f}}}$$

$$D_1 = p \left| D^0 \right\rangle - q \left| \bar{D}^0 \right\rangle$$

$$D_2 = p \left| D^0 \right\rangle + q \left| \bar{D}^0 \right\rangle$$

$$\phi \equiv \arg\left(\frac{q}{p}\right)$$

$$x \equiv \frac{m_1 - m_2}{\Gamma}$$

$$y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$m_i \Rightarrow$ mass of $D_i$

$\Gamma_i \Rightarrow$ decay width of $D_i$
Direct CPV

- Direct CPV is not so cleanly predicted, smaller than $\sim 10^{-3}$ [arXiv:1608.06528], close to the current sensitivity.

- LHCb has the best measurements of $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$ asymmetries:
  
  \[
  A_{CP}(D^0 \to K^+ K^-) = (0.04 \pm 0.12 \pm 0.10)\%
  \]
  
  \[
  A_{CP}(D^0 \to \pi^+ \pi^-) = (0.07 \pm 0.14 \pm 0.11)\%
  \]

- The main systematic comes from the statistics of the control samples, like $D^+ \to K_S^0 \pi^+$

For Phase-II Upgrade

\[
\sigma(A_{CP}^{\pi\pi} - A_{CP}^{KK}) \sim 10^{-5}
\]

Opportunity to measure CP asymmetries with charmed baryons:

- $\Lambda_c^+$ sensitivity $\sigma(A_{CP}) \sim 10^{-4}$
- $\Xi_{cc}^{++}$ sensitivity $\sigma(A_{CP}) \sim 10^{-3}$
Indirect CPV

- CPV in mixing-related phenomena are predicted to be $\sim 10^{-4}$ or less [arXiv:1510.05797]
- Direct access to CPV observables like $x$, $y$, $|q/p|$ and $\phi$
- Current results are limited by statistics
- Improving the $K_S^0$ reconstruction would help to study $D^0 \rightarrow K_S^0 h^+ h^-$

For Phase-II, the expectation is to bring these parameters down to:

$$\sigma(x) \sim 10^{-5} \quad \sigma(y) \sim 10^{-5}$$
$$\sigma(|q/p|) \sim 10^{-3} \quad \sigma(\phi) \sim 10^{-3}(^\circ)$$

No-mixing $\Rightarrow x = y = 0$
No CP violation $\Rightarrow \phi = 0^\circ$ and $|q/p| = 1$

[CERN-LHCC-2017-003]
Rare decays

- Rare charm decays constitute a unique probe for New Physics in the up-quark sector
- Relatively unexplored
- Higher-order diagrams are very suppressed
- $b$-anomalies make progress on studying $c \rightarrow u$ more pressing
Rare decays

\[ D^0 \rightarrow h^+ h^- \mu^+ \mu^- \]

- Observed the first signal of leptonic decays of \( c \) mesons \[ \text{[Phys. Rev. Lett. 119, 181805]} \]
- In Phase-II, high-statistics amplitude and angular analysis (disentangle between SD, LD)

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

- Expectation for Phase-II:
  \[ \mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) \sim 10^{-10} \]
- Particle identification is crucial to reduce the background from \( D^0 \rightarrow h^+ h^- \)

Searches also for \( D \rightarrow hll, \Lambda_c^+ \rightarrow p\mu^+ \mu^-, \ldots \)

Possibility to explore the electron modes starting in Run-II

With an improved ECAL, search for radiative charm decays?
The magnet stations

**LHCb dipole magnet**

**Magnet Station**

**low-momentum tracker**

- $D^0$ mesons are usually tagged using $D^{*+} \rightarrow D^0 \pi^+_{soft}$

- The track of the $\pi^+_{soft}$ has a high chance of running outside the detector

- Aim to place tracking stations in the magnet region

- Gain of 21% for $D^{*+} \rightarrow D^0(K\pi)\pi^+_{soft}$

- Improvements also for $R(D^*)$, Heavy Ion, ...
Strange decays at LHCb

- Huge production of strange hadrons at LHCb
- Larger lifetimes
- $\mathcal{O}(10^{13})/\text{fb}^{-1}$ $K_S^0$ decay inside the VELO
- Efficiencies have been proved to be high enough already in 2011, using the $K_S^0 \rightarrow \mu^+\mu^-$ analysis as a benchmark
- Many possibilities to study: $K_S^0$, $\Lambda^0$, $\Sigma^+$, $\Xi^-$, ...
- Currently developing tracking, particle identification and tagging algorithms
$K^0_S \rightarrow \mu^+ \mu^-$

- Flavour-changing neutral current (FCNC) transition

- Dominated by long distance contributions through $K^0 \rightarrow \gamma\gamma$

- $\mathcal{B} \left( K^0_S \rightarrow \mu^+ \mu^- \right)$ helps to kill models with leptoquarks [arXiv:1712.01295], or supersymmetric contributions [arXiv:1711.11030], [arXiv:1712.04959]

- Study of the interference between $K^0_L \rightarrow \mu^+ \mu^-$ and $K^0_S \rightarrow \mu^+ \mu^-$ allows to determine $\text{sign}(A_{L\gamma\gamma}^{\mu})$:

\[
\mathcal{B} \left( K^0_S \rightarrow \mu^+ \mu^- \right) = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}
\]

\[
\mathcal{B} \left( K^0_L \rightarrow \mu^+ \mu^- \right) = \begin{cases} 
(6.85 \pm 0.80 \pm 0.06) \times 10^{-9} & \text{if } A_{L\gamma\gamma}^{\mu} > 0 \\
(8.11 \pm 1.49 \pm 0.13) \times 10^{-9} & \text{if } A_{L\gamma\gamma}^{\mu} < 0
\end{cases}
\]

\[
A_{L\gamma\gamma}^{\mu} = \text{sign} \left( \frac{A(K^0_L \rightarrow \gamma\gamma)}{A(K^0_L \rightarrow (\pi^0)^* \rightarrow \gamma\gamma)} \right)
\]

$K^0_S \rightarrow \mu^+ \mu^-$ invariant mass

- Backgrounds are currently under control

- $K^0_S \rightarrow \pi^+ \pi^-$ with the two pions misidentified as muons dominates the spectrum

- Benefit from improvements on muon identification at low-$p_T$

- Currently we have a very good resolution around the $K^0_S$ mass ($\sim 4\text{MeV}/c^2$). Maintaining it is completely necessary.
At high luminosity, another enemy appears...

- $K^0_L \rightarrow \mu^+ \mu^-$ is an irreducible background
  $(B = (5.8 \pm 0.6 \pm 0.4) \times 10^{-9}$ [Phys. Rev. Lett. 63, 2185])

- For Run-I, $B_{\text{eff}} \left( K^0_L \rightarrow \mu^+ \mu^- \right)$ was out of the sensitivity $\sim 10^{-11}$

- With $300 \text{ fb}^{-1}$, both branching fractions will be of the same order of magnitude

- Need to define a strategy to differentiate $K^0_S \leftrightarrow K^0_L$

- Having a good proper time resolution is crucial!

Now we are here!

$K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$

- SM prediction of $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$
  depends on the measurement of
  \[ \mathcal{B}(K_S^0 \rightarrow \pi^0 \mu^+ \mu^-) = 2.9^{+1.5}_{-1.2} \times 10^{-9} \]

- Current kaon experiments do not expect to improve such measurement

- A sensitivity study was performed at LHCb

- Low $\pi^0$ reconstruction efficiency at LHCb

- The $K_S^0$ mass does not depend too much on the information from the $\pi^0$

Two possible strategies

- **FULL**: fully reconstruct the candidate
- **PARTIAL**: omit the $\pi^0$ reconstruction

[CERN-LHCb-PUB-2016-017]
$K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$ prospects

- Beating the NA48 measurement [Phys. Lett. B599 (2004) 197] is possible in the upgrade $\mathcal{L}_{\text{eff}} > 5$ fb$^{-1}$

- Best strategy omitting the $\pi^0$ reconstruction

- Maybe benefit from an upgraded ECAL
Other strange friends

There are many other interesting studies that can be done at LHCb:

- $K^0_S \rightarrow x^+x^-l^+l^-$: highly suppressed in the SM ($\sim 10^{-14}$ for muons)

- $K^+ \rightarrow \pi^+\mu^+\mu^-$: maybe competitive with NA62 (LFU)

- Semileptonic/rare Hyperon Decays ($\Lambda^0 \rightarrow p\mu^-\bar{\nu}$, $\Sigma^+ \rightarrow p\mu^+\mu^-$, ...)

- $K^0_S \rightarrow \pi^+\mu^-\bar{\nu}$: no measurement at present ($V_{us}$, CPT, LFU)

For the moment, everything very preliminary in most cases:

- No dedicated trigger lines for SHD or $K^0_S \rightarrow \pi^+\mu^-\bar{\nu}$ ($\mathcal{B} \sim 10^{-4}$)

- Apart from $\Sigma^+ \rightarrow p\mu^+\mu^-$, nothing published so far, set benchmarks for Run-II

- Tracking is challenging for $K^+$ studies (flight distance $\sim m$)
τ decays

• LHCb was the first experiment to search for LFV τ decays on a hadron collider

• Inclusive production of τ leptons, mainly from b and c hadron decays

• Calibration and normalization channel $D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-$
\[ \tau^- \rightarrow \mu^+ \mu^- \mu^- \]

- Getting close to B-factories (ongoing studies with Run-II data samples)

- With \( \sim 300 \text{ fb}^{-1} \), we expect \( B(\tau^- \rightarrow \mu^+ \mu^- \mu^-) < 3 \times 10^{-9} \), similar to what is expected for Belle 2 with 50 \( \text{ab}^{-1} \)

- Irreducible background of \( D_s^- \rightarrow \eta(\mu^+ \mu^- \gamma)\mu^- \bar{\nu}_\mu \), reduced with cuts in \( m_{\mu^+ \mu^-} \)

- Benefit from any improvement on the ECAL
τ^− → \bar{p}\mu^+\mu^- and τ^− → p\mu^−\mu^−

- Test for models where \( |\Delta(B - L)| = 0, 2 \)
- Analysis done using the data sample from 2011 (no update since then)
- Clean signature, no expected peaking backgrounds
- We might expect a factor of 20 of improvement using the full Run-(I - V) samples

\[ B(\tau^- \rightarrow \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7} \]

\[ B(\tau^- \rightarrow p\mu^-\mu^-) < 4.4 \times 10^{-7} \]
Conclusions

• LHCb has a big power of adaptation to new fields

• Tracking and trigger improvements are crucial:
  - Tracking efficiency
  - Ghost removal
  - Low-$p_T$ reconstruction
  - Full software trigger

• An upgraded ECAL allows to better control backgrounds and use other normalization channels

• Larger samples of both real and simulated data allows approaching SM predictions for CPV in charm decays

• New possibilities to study strange decays at LHCb, reach SM prediction for $K^0_S \rightarrow \mu^+\mu^-$

• Expected a very big improvement on $\tau$ decays, competitive with B-factories
BACKUP
The LHCb detector in Phase-II Upgrade

Future of charm, strangeness, $\tau^{\pm}$ at LHCb

(CERN-LHCC-2017-003)

Miguel Ramos Pernas

(HL/HE LHC meeting, Fermilab, April 5, 2018)
Future of charm, strangeness, $\tau^{\pm}$ at LHCb

(HL/HE LHC meeting, Fermilab, April 5, 2018)
Track types at LHCb

- VELO track
- Downstream track
- Long track
- Upstream track
- T track

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Trigger definitions

- **Signal candidate tracks (S)**
- **The rest of the event (R)**

**Trigger?**
- **yes**
  - **TOS**
  - **Trigger?**
  - **yes**
    - **TIS**
  - **no**
    - **Trigger?**
    - **yes**
      - **TOS**
      - **Trigger?**
      - **yes**
      - **TIS**
    - **no**
      - **S+R**
      - **Trigger?**
      - **yes**
      - **TOS**
      - **Trigger?**
      - **yes**
      - **TIS**

Where:
- \( a = N^{TRIG} - N^{TIS} - N^{TOS} + N^{TISTOS} \)
- \( b = N^{TOS} - N^{TISTOS} \)
- \( c = N^{TIS} - N^{TISTOS} \)
- \( d = N^{TISTOS} \)
LHCb trigger diagrams

LHCb 2012 Trigger Diagram
- 40 MHz bunch crossing rate
- L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu\mu$
- 150 kHz $e/\gamma$
- Software High Level Trigger
  - 29000 Logical CPU cores
  - Offline reconstruction tuned to trigger time constraints
  - Mixture of exclusive and inclusive selection algorithms
- 5 kHz (0.3 GB/s) to storage
  - 2 kHz Inclusive Topological
  - 2 kHz Inclusive/Exclusive Charm
  - 1 kHz Muon and DiMuon
- 1 kHz Charm
- 2 kHz Inclusive/Exclusive Muon

LHCb 2015 Trigger Diagram
- 40 MHz bunch crossing rate
- L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu\mu$
- 150 kHz $e/\gamma$
- Software High Level Trigger
  - Partial event reconstruction, select displaced tracks/vertices and dimuons
- Full offline-like event selection, mixture of inclusive and exclusive triggers
- 12.5 kHz (0.6 GB/s) to storage

LHCb Upgrade Trigger Diagram
- 30 MHz inelastic event rate (full rate event building)
- Software High Level Trigger
  - 2-5 GB/s to storage
  - Full event reconstruction, inclusive and exclusive kinematic/geometric selections
  - Add offline precision particle identification and track quality information to selections
  - Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

Buffer events to disk, perform online detector calibration and alignment

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$D^0 \to \mu^+ \mu^-$ mass distributions

![Graph](image)


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\[ \Lambda_c^+ \rightarrow pK^+K^- \text{ and } \Lambda_c^+ \rightarrow p\pi^+\pi^- \]
The di-muon triggers for Run-II

<table>
<thead>
<tr>
<th></th>
<th>$K_S^0 \rightarrow \mu^+ \mu^-$</th>
<th>$K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>0.361 $\pm$ 0.004</td>
<td>0.344 $\pm$ 0.009</td>
</tr>
<tr>
<td>HLT1/L0</td>
<td>0.699 $\pm$ 0.007</td>
<td>0.705 $\pm$ 0.015</td>
</tr>
<tr>
<td>HLT1/L0 (old)</td>
<td>0.274 $\pm$ 0.006</td>
<td>0.299 $\pm$ 0.015</td>
</tr>
<tr>
<td>HLT2/HLT1</td>
<td>0.9898 $\pm$ 0.0017</td>
<td>0.983 $\pm$ 0.005</td>
</tr>
<tr>
<td>HLT2/HLT1 (old)</td>
<td>0.293 $\pm$ 0.013</td>
<td>0.26 $\pm$ 0.03</td>
</tr>
<tr>
<td>global</td>
<td>0.250 $\pm$ 0.004</td>
<td>0.238 $\pm$ 0.008</td>
</tr>
<tr>
<td>global (old)</td>
<td>0.0290 $\pm$ 0.0015</td>
<td>0.026 $\pm$ 0.003</td>
</tr>
</tbody>
</table>

green: trigger with new lines  
red: trigger without new lines

- Big increase on the efficiencies: a factor $\sim 2.4$ for HLT1 and $\sim 3.5$ for HLT2
- Total efficiency increased by a factor $\sim 10$
$K^0_S \rightarrow \pi^0 \mu^+ \mu^-$

$\mathcal{B} (K^0_L \rightarrow \pi^0 \mu^+ \mu^-)$ has a variation of $\sim 1$ order of magnitude in models with extra dimensions.

$\mathcal{B} (K^0_L \rightarrow \pi^0 l^+ l^-)_{SM} = \left( C^l_{\text{dir}} \pm C^l_{\text{int}} |a_S| + C^l_{\text{mix}} |a_S|^2 + C^l_{\gamma\gamma} + C^l_{\gamma S} \right) \times 10^{-12}$

$|a_S| = 1.2 \pm 0.2$ dominates the theoretical uncertainty. Comes from the measurements of $\mathcal{B} (K^0_S \rightarrow \pi^0 l^+ l^-)$.

Large uncertainties on $\mathcal{B} (K^0_S \rightarrow \pi^0 \mu^+ \mu^-) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$ (NA48) [Phys. Lett. B599 (2004) 197]

Randall-Sundrum model

[JHEP 1009:017,2010]