LHCb Status and Overview

A story in three chapters
Marina Artuso, Syracuse University
On behalf of the LHCb collaboration
The LHCb trilogy

LHCb: Phase I
(an ever-growing physics scope)

LHCb Upgrade I
(the software trigger edition)

LHCb Upgrade II
(exploiting timing to reach the highest sensitivity)

6/3/2024
M. Artuso LHCP 2024
Chapter I – Physics Highlights from Run I & II
LHCb physics: beauty, charm and beyond
New leaves are still growing on this rich “tree of knowledge”

- CP Violation in charm and beauty decays
- Magnitude of quark mixing angles
- Rare b and c decays
- Neutral meson oscillations
- Lepton flavor universality
- Conventional and exotic spectroscopy
- Search for exotic new particles, axions, dark sector...
- Electroweak physics in the forward direction
- Heavy ion physics

New leaves are still growing on this rich “tree of knowledge”
The origin story: beauty as a tool for discovery

- Old paradigm: tree diagrams are dominated by Standard Model processes, and loops can unveil new physics manifestations through interference with new particles (maybe not the whole story)
- Also: things are more complicated: we observe hadron decays effective Hamiltonian

\[ \mathcal{H} (b \rightarrow s \ell^+ \ell^-) = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1}^{10} C_i(\mu)\mathcal{O}_i(\mu) \]
The long and winding road: disentangle the amplitudes contributing to these decays

\[ \mathcal{A}_{\lambda}^{L,R}(B \rightarrow M_\lambda \ell^+ \ell^-) = N_\lambda \left( (C_9 \mp C_{10}) F_\lambda(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right) \]

Old approach: exclude regions where non-local effects expected to be dominant

Local form factors

Non-local form factors
Experimental study of local and non-local amplitudes

LHCb-PAPER-2024-011, in preparation

- Full $q^2$ range of $B^0 \to K^{*0} \mu^+ \mu^-$ used in the fit
- Fit model encompasses signal (local, one and two-particle non-local amplitudes & interference terms) & gives:

<table>
<thead>
<tr>
<th>Wilson Coefficient results</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_9$</td>
<td>$3.56 \pm 0.28 \pm 0.18$</td>
</tr>
<tr>
<td>$C_{10}$</td>
<td>$-4.02 \pm 0.18 \pm 0.16$</td>
</tr>
<tr>
<td>$C'_9$</td>
<td>$0.28 \pm 0.41 \pm 0.12$</td>
</tr>
<tr>
<td>$C'_{10}$</td>
<td>$-0.09 \pm 0.21 \pm 0.06$</td>
</tr>
<tr>
<td>$C_{9\tau}$</td>
<td>$(1.0\pm 2.6 \pm 1.0) \times 10^{-2}$</td>
</tr>
</tbody>
</table>

$B^0 \to K^{*0}[\tau^+ \tau^- \to \mu^+ \mu^-]$ rescattering
Lepton flavor violation

- Lepton flavor is conserved in decays mediated by the Standard Model
- New physics models predict deviations especially involving the 3rd family ⇒ it is important to look!

First limit of this lepton flavor violating decay

\[ \mathcal{B}(B_s^0 \to \phi \mu^+ \tau^-) < 1.0 \times 10^{-5} \text{ at 90\% CL,} \]
\[ \mathcal{B}(B_s^0 \to \phi \mu^+ \tau^-) < 1.1 \times 10^{-5} \text{ at 95\% CL.} \]
Lepton flavor universality – the tauonic semileptonic story

- Would require new physics at tree level
- Most recent example: simultaneous measurement of $\mathcal{R}(D^+)$ and $\mathcal{R}(D^{*+})$
- Challenging measurement: multi $\nu$ in the final state!

$$R(D^+) = \frac{\overline{B} \to D^* \tau^- \nu}{\overline{B} \to D \pi^+}$$

- Complex template 3D fit in $q^2, m_{\text{miss}}, E_{\ell}^*$ gives
  $$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
  $$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$
- Correlation coefficient -0.39
Where are we now?

- The result shown is 0.78σ from SM and 1.09σ from the world average.
- The combined average is 3.3σ tension with the Standard Model.
Unitarity constraints: the triangles

\[ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2 / 2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \]
Mixing and CP Violation in $D^0 \to K^+\pi^-$ decays

- Analysis using Run II data set (6fb$^{-1}$)
- Fit time-dependent ratios $R_{K\pi}^+(t) \equiv \frac{\Gamma(D^0(t)\to K^+\pi^-)}{\Gamma(D^0(t)\to K^+\pi^-)}$ and $R_{K\pi}^-(t) \equiv \frac{\Gamma(D^0(t)\to K^-\pi^+)}{\Gamma(D^0(t)\to K^-\pi^+)}$
Q1: Can we organize the zoo of known hadrons into a well-motivated structures \((q\bar{q}, qq, q\bar{q}q\bar{q}, qqqq\bar{q}\ldots)\) with specific quantum numbers and masses consistent with a theoretical model?

Q2: Study manifestations of QCD in collective nuclear phenomena

Q3: Validate effective theories based on QCD (or lattice QCD calculations) to extract fundamental SM parameters
Q3: how well do the predictive tools in-hand work?

- **Heavy quark expansion** has been crucial to the extraction of quark mixing parameters from **inclusive measurements**, determination of **flavor oscillation parameters**

- Lifetime measurements have been one of the important testing ground of HQE predictions

- Measure ratio $R(t)$ with respect to $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$

$$R(t) = \frac{N[\Xi_b^- \rightarrow \Xi^0_c \pi^-](t)}{N[\Lambda^0_b \rightarrow \Lambda^+_c \pi^-](t)} \cdot \frac{\varepsilon[\Lambda^0_b \rightarrow \Lambda^+_c \pi^-](t)}{\varepsilon[\Xi_b^- \rightarrow \Xi^0_c \pi^-](t)} = R_0 \exp(\lambda t)$$

$$\lambda = \frac{1}{\tau_{\Lambda^0_b}} - \frac{1}{\tau_{\Xi_b^-}}$$

**RUN I-II average:**

- $\tau_{\Xi_b^-} = 1.078 \pm 0.012 \pm 0.007$
- $\tau_{\Xi_b^-} = 1.578 \pm 0.018 \pm 0.010 \pm 0.011 \text{ ps}$
Chapter II

The software trigger edition
RUN 3 & 4

Now

Upgrade I
Goals: higher luminosity (~×5) + higher sensitivity

\[ \mathcal{L} = 4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1} \]
\[ \mathcal{L}_{int} = 9 \text{ fb}^{-1} \]
\[ \mu \approx 1 \]

\[ \mathcal{L} = 2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} \]
\[ \mathcal{L}_{int} = 50 \text{ fb}^{-1} \]
\[ \mu \approx 5 \]

\[ \mathcal{L} = 1.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1} \]
\[ \mathcal{L}_{int} = 300 \text{ fb}^{-1} \]
\[ \mu \approx 40 \]
A new detector!

Highlights:
1. New Tracking system: pixel-based VELO closer to the beam pipe (8.2mm → 5.1mm) + Upstream tracker with higher granularity + New SciFi
2. RICH with new mechanics, optics and PMT readout
3. New luminometer (PLUME)
4. New SMOG2 system for fixed target physics
The tracking system

For PID see M. Atzeni PID at LHCb

C. Trippl SciFi Tracker

Image of new VELO RF box and modules via hadronic interaction vertices

Normalised entries

- SciFi modules + mats alignment with mat-end contraction calibration
- SciFi modules alignment
- Before alignment

LHCb Preliminary 2024

# SciFi hits on long tracks

SciFi modules + mats alignment with mat-end contraction calibration
SciFi modules alignment
Before alignment

LHCb Preliminary 2024
The Software Trigger

To exploit a higher luminosity, we needed to get rid of the hardware first level trigger (hadron, calorimeter objects and muon threshold).

Write ~10GB/s at 1 MHz

K. Richardson Real time Analysis

https://arxiv.org/abs/1903.01360
New opportunities in search for exotic particles

• Probing the dark sector:

Dark sector physics at high-intensity experiments

Sensitivity projections for dark photon

Electron ID in the HLT

Other experiments

LHCb

Software trigger offers the opportunity to enhance sensitivity

Electron ID in the HLT

Craik, Ilten, Johnson, Williams [arXiv:2203.07048v1]
Moving towards the integrated luminosity goals

Integrated luminosity over the years

This year’s plans
Software trigger at work

- Removing the L0 trigger selection improves charm reconstruction efficiency
B decays in 2024 data

\[ B^+ \rightarrow J/\psi K^+ [J/\psi \rightarrow \mu^+ \mu^-] \]

\[ B^+ \rightarrow J/\psi K^+ [J/\psi \rightarrow e^+ e^-] \]

Trigger improvement also in hadronic B decays with electrons in the final state
Heavy ion program: 2023 PbPb data

- VELO in open position and no UT reached 30% centrality (70% saturation in Run II)

About 20K $D^0$ decays
Chapter III: LHCb Upgrade 2

Tackling the challenge of the high luminosity (operation at high pile-up)
The LHCb upgrade II

- Use $\mathcal{O}(10 \text{ ps})$ timing in vertex reconstruction and particle identification to mitigate pile-up
- Increase granularity in UT & add MAPs sectors to the SCIFI
- Add tracking stations in the magnet to increase efficiency for low-momentum tracks
Detector R&D

Timepix4 telescope: studies of per hit time resolution

SPACAL technology for the innermost section of the ECAL being studied in test beams

TORCH prototype test beam

Test beam Mighty Tracker prototype

D. Manuzzi PicoCAL
Our goal is to **fully exploit the HL-LHC discovery potential using flavor as a probe of quantum imprints of new phenomena** and, more broadly, LHCb as a general-purpose detector in the forward direction exploiting a trigger strategy that can adapt the experiment strategy to the lesson learned in the course of the data taking, well aligned with one of the science drivers emerging from the Snowmass community study and cited in the P5 report.
Future prospects: CP violation and rare decays will probe subtle deviations from SM expectations.
## Sensitivity projections

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb (up to 9 fb(^{-1}))</th>
<th>Upgrade I (23 fb(^{-1}))</th>
<th>Upgrade II (50 fb(^{-1}))</th>
<th>Upgrade III (300 fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CKM tests</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>(\gamma (B \rightarrow DK, \text{ etc.}))</td>
<td>4(^\circ) [9, 10]</td>
<td>1.5(^\circ)</td>
<td>1(^\circ)</td>
<td>0.35(^\circ)</td>
</tr>
<tr>
<td>(\phi_\chi (B_s^0 \rightarrow J/\psi \phi))</td>
<td>32 mrad [8]</td>
<td>14 mrad</td>
<td>10 mrad</td>
<td>4 mrad</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>(A_0^0 \rightarrow p\mu^- \nu_\mu, \text{ etc.}))</td>
</tr>
<tr>
<td>(\sigma_3^D (B^0 \rightarrow D^- \mu^+ \nu_\mu))</td>
<td>36 \times 10(^{-4}) [34]</td>
<td>8 \times 10(^{-4})</td>
<td>5 \times 10(^{-4})</td>
<td>2 \times 10(^{-4})</td>
</tr>
<tr>
<td>(\sigma_5^D (B_s^0 \rightarrow D_s^\pm \mu^+ \nu_\mu))</td>
<td>33 \times 10(^{-4}) [35]</td>
<td>10 \times 10(^{-4})</td>
<td>7 \times 10(^{-4})</td>
<td>3 \times 10(^{-4})</td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>(\Delta A_{CP} (D^0 \rightarrow K^+K^-, \pi^+\pi^-))</td>
<td>29 \times 10(^{-5}) [5]</td>
<td>13 \times 10(^{-5})</td>
<td>8 \times 10(^{-5})</td>
<td>3.3 \times 10(^{-5})</td>
</tr>
<tr>
<td>(A_T (D^0 \rightarrow K^+K^-, \pi^+\pi^-))</td>
<td>11 \times 10(^{-5}) [38]</td>
<td>5 \times 10(^{-5})</td>
<td>3.2 \times 10(^{-5})</td>
<td>1.2 \times 10(^{-5})</td>
</tr>
<tr>
<td>(\Delta x (D^0 \rightarrow K_{2\pi}^0 \pi^+\pi^-))</td>
<td>18 \times 10(^{-5}) [37]</td>
<td>6.3 \times 10(^{-5})</td>
<td>4.1 \times 10(^{-5})</td>
<td>1.6 \times 10(^{-5})</td>
</tr>
<tr>
<td><strong>Rare Decays</strong></td>
<td></td>
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<tr>
<td>(B(B^0 \rightarrow \mu^+\mu^-)/B(B_s^0 \rightarrow \mu^+\mu^-))</td>
<td>69% [40, 41]</td>
<td>41%</td>
<td>27%</td>
<td>11%</td>
</tr>
<tr>
<td>(S_{\mu\mu} (B_s^0 \rightarrow \mu^+\mu^-))</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.2</td>
</tr>
<tr>
<td>(A_{L2} (B^0 \rightarrow K^{*0}e^+e^-))</td>
<td>0.10 [52]</td>
<td>0.060</td>
<td>0.043</td>
<td>0.016</td>
</tr>
<tr>
<td>(A_{Lm} (B^0 \rightarrow K^{*0}e^+e^-))</td>
<td>0.10 [52]</td>
<td>0.060</td>
<td>0.043</td>
<td>0.016</td>
</tr>
<tr>
<td>(A_{ST} (B^0 \rightarrow \phi \gamma))</td>
<td>10.41 [41]</td>
<td>10.44 [51]</td>
<td>0.124</td>
<td>0.083</td>
</tr>
<tr>
<td>(S_{\phi\gamma} (B_s^0 \rightarrow \phi \gamma))</td>
<td>0.32 [51]</td>
<td>0.093</td>
<td>0.062</td>
<td>0.025</td>
</tr>
<tr>
<td>(\alpha_{\gamma} (B^0 \rightarrow A\gamma))</td>
<td>40.17 [53]</td>
<td>0.148</td>
<td>0.097</td>
<td>0.038</td>
</tr>
<tr>
<td><strong>Lepton Universality Tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(R_{K^+} (B^+ \rightarrow K^+\ell^+\ell^-))</td>
<td>0.044 [12]</td>
<td>0.025</td>
<td>0.017</td>
<td>0.007</td>
</tr>
<tr>
<td>(R_{K^0} (B^0 \rightarrow K^{0*}\ell^+\ell^-))</td>
<td>0.12 [61]</td>
<td>0.034</td>
<td>0.022</td>
<td>0.009</td>
</tr>
<tr>
<td>(R(D^+) (B^0 \rightarrow D^*\ell^+\nu_\ell))</td>
<td>0.026 [62, 64]</td>
<td>0.007</td>
<td>0.005</td>
<td>0.002</td>
</tr>
</tbody>
</table>
LHCb

An exciting and diverse physics

Rooted on a versatile detector offering a dynamic trigger strategy

A story in progress

Fueled by a dedicated and vibrant community

Thank you for your attention!
The end

Back-up material follows
LHCb Methodology: study \( b \) and \( c \) in the forward direction at the LHC

- In the forward region at LHC the \( b\bar{b} \) production \( \sigma \) is large.
- The hadrons containing the \( b \) & \( b \) quarks are both likely to be in the acceptance. Essential for “flavor tagging”.
- LHCb uses the forward direction where the \( B \)’s are moving with considerable momentum \( \sim 100 \) GeV, thus minimizing multiple scattering.
- At \( \mathcal{L}=2 \times 10^{32}/\text{cm}^2/\text{s} \), we get \( 10^{12} \) \( B \) hadrons in \( 10^7 \) sec.
$B_{(s)}^0 \rightarrow \mu^+ \mu^-(\gamma)$

A $\gamma$ in the final state adds complexity to the reconstruction but also new opportunities (e.g. sensitivity to additional Wilson coefficients). This is the first search with full reconstruction of the final state in different $\alpha^2$ (i.e. $m_{\mu\mu}^2$) intervals.

$B_s^0 \rightarrow \mu^+ \mu^-$, the well-studied “golden mode”
Several tensions currently reported in $B \to K^{(*)}\mu^+\mu^-$

Angular distribution $B^0 \to K^{*0}\mu^+\mu^-$

Nicola Serra’s talk

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$

$\lambda_b \to pK^{-}\ell^+\ell^-$

Angular distribution

$B^0 \to K^0\ell^+\ell^-$

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

$B^{0} \to K^{0}\ell^{+}\ell^{-}$

$B^{+} \to K^{+}\ell^{+}\ell^{-}$

$\alpha_{b} \to p K^{-} \ell^{+} \ell^{-}$

**References**

- JHEP 10 (2018) 047
- JHEP 05 (2020) 040
- arXiv:2103.11789
- arXiv:2110.09501

M. Artuso LHCP 2024
The angle $\gamma$

- Accessible from tree level processes (good Standard Model probe)

Key processes in charged B decays

Key processes in $B^0$ decays
LHCb average:

\[ \gamma = (65.4^{+3.8}_{-4.2})^\circ \]

<table>
<thead>
<tr>
<th>Species</th>
<th>Value [^\circ]</th>
<th>68.3% CL</th>
<th>95.4% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ )</td>
<td>61.7</td>
<td>( ^{+4.4}_{-4.8} )</td>
<td>[56.9, 66.1]</td>
</tr>
<tr>
<td>( B^0 )</td>
<td>82.0</td>
<td>( ^{+8.1}_{-8.8} )</td>
<td>[73.2, 90.1]</td>
</tr>
<tr>
<td>( B^0_s )</td>
<td>79</td>
<td>( ^{+21}_{-24} )</td>
<td>[55, 100]</td>
</tr>
</tbody>
</table>

More details in D. Manuzzi’s talk

\[ x \equiv \frac{\Delta M}{\Gamma} = 0.400^{+0.052}_{-0.053} \]

\[ y \equiv \frac{\Delta \Gamma}{2 \Gamma} = (0.630^{+0.033}_{-0.030})\% \]

\[ \left| \frac{q}{p} \right| = 0.997 \pm 0.016 \]
The $B_s^0$ triangle

Current status

CPV in $B_s^0 \ b \rightarrow [c\bar{c}s]$ decays

$\Delta \Gamma_s [\text{ps}^{-1}]$

HFLAV

PDG 2021

68% CL contours
$(\Delta \log \mathcal{L} = 1.15)$

D0 8 fb$^{-1}$

CMS 116.1 fb$^{-1}$

CDF 9.6 fb$^{-1}$

LHCb 4.9 fb$^{-1}$

ATLAS 99.7 fb$^{-1}$

Combined$^*$

$\Delta \Gamma_s$ errors scaled by 1.77
Fixed target program at LHCb

SMOG detector allows pursuit of fixed target program: gas injection system (H₂, He, Ne…)

LHCb-Figure-2024-005

Recorded luminosity [nb⁻¹]

<table>
<thead>
<tr>
<th>Collision system</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH₂</td>
<td>1</td>
</tr>
<tr>
<td>pD₂</td>
<td>1.5</td>
</tr>
<tr>
<td>pHe</td>
<td>3</td>
</tr>
<tr>
<td>pNe</td>
<td>5</td>
</tr>
<tr>
<td>pO₂</td>
<td>10</td>
</tr>
<tr>
<td>pAr</td>
<td>15</td>
</tr>
</tbody>
</table>

LHCb preliminary, $\sqrt{s_{NN}} = 113$ GeV
May 2024

Candidates / (0.3 MeV/c²)

LHCb preliminary 2024, pNe
$\sqrt{s_{NN}} = 113$ GeV

Data
Signal + background
Signal
Background

m (pπ) [MeV/c²]

1100 1110 1120 1130

×10⁶
CKM: the sides – old tensions to be resolved

A multidecade puzzle: both $|V_{ub}|$ and $|V_{cb}|$ determination encompass a persisting tension between the values extracted from inclusive or exclusive final state

$|V_{ub}|_{incl} \times 10^3 = 4.32 \pm 0.29$

$|V_{ub}|_{excl} \times 10^3 = 3.74 \pm 0.19$

$|V_{ub}|_{ave} \times 10^3 = 3.89 \pm 0.25$

$|V_{cb}|_{incl} \times 10^3 = 42.16 \pm 0.50$

$|V_{cb}|_{excl} \times 10^3 = 39.44 \pm 0.63$

$|V_{cb}|_{ave} \times 10^3 = 41.1 \pm 1.3$