Franz Muheim
University of Edinburgh and CERN
on behalf of the LHCb collaboration

- Introduction
- Selected physics highlights
- LHCb upgrade
- Conclusions
Great Vertex Resolution! Primary/secondary separation, proper time resolution.
Excellent momentum and mass resolution.
Outstanding PID (K-π) and μ reconstruction.
Dedicated Trigger system for beauty and charmed hadrons
- **LHCb collaboration**
  - 1500 members and > 1000 authors
  - 86 institutes, 19 Countries

- **Data samples**
  - Run 1 and 2 with 3 fb$^{-1}$ and 6 fb$^{-1}$

- **Physics output**
  - 575 papers submitted, 558 published
  - ~20 new papers for this summer

- **LHCb talks at EPS**
  - Rare decays and CP violation
    - Paula Alvarez, Thu 29/7 15:15

28/07/2021
Franz Muheim - LHCb highlights
Rare decays
Electroweak penguin decays

- Flavour changing neutral currents
  - $b \to s \ell^+\ell^-$
  - Forbidden at tree level in SM
  - Branching fractions at $10^{-6}$ to $10^{-10}$
  - Powerful probe of New Physics

- Significant part of physics programme
  - 7 papers already in 2021
  - Branching fractions, angular analysis, Lepton flavour universality or violation

<table>
<thead>
<tr>
<th>Report</th>
<th>Title</th>
<th>Observed</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003.04352</td>
<td>Search for the lepton flavour violating decay $B^+ \to K^+\mu^+\tau^+$ using $B_{s,0}^0$ decays</td>
<td>Limit</td>
<td>Lepton Flavour Viol.</td>
</tr>
<tr>
<td>2003.03999</td>
<td>Search for the rare decays $B_{s,0}^0 \to e^+\mu^-$ and $B_{s,0}^0 \to e^-\mu^+$</td>
<td>Limit</td>
<td>Rare decay</td>
</tr>
<tr>
<td>2003.04831</td>
<td>Measurement of CP-averaged observables in the $B^+ \to K^+\mu^+\mu^-$ decay</td>
<td>$P_{\gamma}$</td>
<td>Angular asymmetry</td>
</tr>
<tr>
<td>2010.06011</td>
<td>Strong constraints on the $b\to s\gamma$ photon polarisation from $B_{s,0}^0 \to \mu^+\mu^-$ decays</td>
<td>$C_7'$</td>
<td>Wilson coefficient</td>
</tr>
<tr>
<td>2012.13241</td>
<td>Angular analysis of the $B^+ \to K^+\mu^+\mu^-$ decay</td>
<td>$P_{\gamma}$</td>
<td>Angular asymmetry</td>
</tr>
<tr>
<td>2021.030</td>
<td>Search for the $\Xi_b \to \Xi\gamma$ radiative decay</td>
<td></td>
<td>Limit</td>
</tr>
</tbody>
</table>

28/07/2021 Franz Muheim - LHCb highlights
Test of lepton flavour universality

- **Lepton flavour universality**
  - $B^+ \to K^+\mu^+\mu^-$ vs $B^+ \to K^+e^+e^-$ decays
  - Clean theoretical prediction
    \[
    R_K = \frac{B(B \to K\mu\mu)}{B(B \to Ke e)} \bigg|_{q^2_{\text{min}}, q^2_{\text{max}}} = 1 \pm O(10^{-4})_{\text{QCD}} \pm O(10^{-2})_{\text{QED}}
    \]
  - Measuring double ratio with $J/\psi$ modes reduces systematic uncertainties

- **Result**
  - $R_K = 0.846^{+0.044}_{-0.041}$
  - $3.1\sigma$ evidence for LFU
  - More measurements and more data needed

- #CautiouslyExcited

Franz Muheim - LHCb highlights 28/07/2021

LHCb-PAPER-2021-004, arXiv:2103.11769
99 citations

Lepton flavour universality tests at LHCb Michael McCann
**b → s e^+e^- branching fractions**

- **Differential branching fractions**
  - Decay rate of $b \to s \ell^+\ell^-$ sensitive to BSM
  - Branching fractions low for muons ($B^+, B^0, B_s^0$ and $\Lambda_b^0$)
- $B_s^0 \to \phi\mu^+\mu^-$
  - $d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/dq^2 = (2.88 \pm 0.21) \times 10^{-8}/(\text{GeV}^2/c^4)$ for $q^2 \in [1.1, 6.0] \text{ GeV}^2/c^4$
  - In agreement with Run 1 result
  - 3.6$\sigma$ deviation tension with SM

Electroweak penguin decays at LHCb

**NEW** LHCb-PAPER-2021-014
arXiv:2105.14007

Franz Muheim - LHCb highlights
Angular observables

- Polarisation, asymmetries vs $q^2$
- $B^0 \rightarrow K^{*0}\mu^+\mu^-$
  - Local tension 2.5σ and 2.9σ in asymmetry $P_{5'}$
    with SM in $q^2$ bins [4,6] and [6,8] GeV²/c⁴
  - Global analysis finds tension 3.3σ
  - Consistent with ATLAS, Belle, CMS results

- $B^+ \rightarrow K^{*+}\mu^+\mu^-$
  - First LHCb measurement
  - Local tension with SM up to 3.0σ in $P_2(\sim A_{FB})$
    in $q^2$ bin [6,8] GeV²/c⁴
  - Global tension 3.1σ determined in fit to effective field theory Wilson coefficient $Re(C_9)$
**b → s ℓ+ℓ- angular analysis**

- **B⁺ → K⁺μ⁺μ⁻**
  - First angular analysis in this mode
  - Observables F_L and coefficients S_i
  - Compatible with SM, tension in F_L
  - Compatibility 1.9σ using "Flavio" package to fit for shift of EFT coefficient ΔRe(C_9) i.e. vector coupling from SM

**Summary**

- Internally consistent trends observed for ΔRe(C_9) in B⁰ → K*⁰μ⁺μ⁻, B⁺ → K⁺μ⁺μ⁻ and B_s⁰ → φμ⁺μ⁻
- Negative shift of ΔRe(C_9) from SM preferred 2 to 3σ level

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**NEW**

**LHCb-PAPER-2021-022**

- Electroweak penguin decays at LHCb
- Christoph Langenbruch

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**PRL 125 (2020) 011802**

- B⁰ → K*⁰μ⁺μ⁻ 3.4σ

**PRL 126 (2021) 161802**

- B⁺ → K⁺μ⁺μ⁻ 3.1σ

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Franz Muheim - LHCb highlights
**Very rare leptonic decay**

- Helicity and CKM suppressed
- Sensitive to New Physics

**$B_s^0 \rightarrow \mu^+\mu^-$**

- $B(B_s^0 \rightarrow \mu^+\mu^-) = 3.09^{+0.46}_{-0.43} \times 10^{-9}$
- Significance $> 10 \sigma$
- in agreement with SM

**$B^0 \rightarrow \mu^+\mu^-$**

- $B(B^0 \rightarrow \mu^+\mu^-) < 2.6 \times 10^{-10}$ at 95% CL

**First search for $B_s^0 \rightarrow \mu^+\mu^-\gamma$**

- $B(B_s^0 \rightarrow \mu^+\mu^-\gamma) < 2.0 \times 10^{-9}$ at 95% CL for $m_{\mu\mu} > 4.9 \text{ GeV}/c^2$

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Very rare decays at LHCb
Miguel Ramos Pernas

Franz Muheim - LHCb highlights
Oscillations, \( \text{CP} \) and charm

\[ B_s^0 \rightarrow D^- \pi^+ \quad \text{and} \quad \overline{B}_s^0 \rightarrow B_s^0 \rightarrow D^- \pi^+ \quad \text{Untagged} \]
**B_s Oscillations**

- **B_s^0 mass difference \( \Delta m_s \)**
  - Measured by oscillation frequency with \( B_s^0 \rightarrow D_s^{\mp} \pi^\pm \) decays
  - Flavour tagging identifies \( B_s^0 \) / anti-\( B_s^0 \) at production

- **Legacy measurement**
  - \( \Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032 \) ps\(^{-1}\)
  - Precision 3 x 10\(^{-4}\)
  - Including \( B_s^0 \rightarrow D_s^{\mp} h^{\mp} \pi^{\pm} \pi^{\mp} \) et al.
  - \( \Delta m_s = 17.7656 \pm 0.0057 \) ps\(^{-1}\)

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**Measurement of the CKM angle \( \gamma \) at LHCb**

Franz Muheim - LHCb highlights
Charm mixing

- **Charm D⁰ Mixing**
  - Unique: up-type quarks
  - Small mixing, sensitive to \( \mathcal{CP} \)
  - \( |D_{1,2}| = p|D^0| \pm q|\bar{D}^0| \)
  - \( x = (m_1 - m_2)c^2/\Gamma \)
  - \( y = (\Gamma_1 - \Gamma_2)/(2\Gamma) \)
  - No measurement of \( x \neq 0 \) until this summer

- **Charm at LHCb**
  - Large cross section - \( \sigma_{cc} \sim 5 \text{ mb} \), charm rate \( \sim 2 \text{ MHz} \)
  - Run 2 - dedicated Turbo trigger - 15 kHz to tape

- **D⁰ \( \rightarrow K_S^0 \pi^+\pi^- \)**
  - 30.6M decays & very small background

- **Bin-flip method**
  - Measure asymmetry between D⁰ and anti-D⁰ in binned Dalitz plot \( m^2(K_S^0\pi^-) \) vs \( m^2(K_S^0\pi^+) \)
  - In each bin approx. constant strong-phase difference between D⁰ and anti-D⁰ amplitude
Observation of mass difference

- **Observation**
  - of small mass difference in neutral charm meson eigenstates

\[
x = (3.98^{+0.56}_{-0.54}) \times 10^{-3}, \\
y = (4.0^{+1.5}_{-1.4}) \times 10^{-3}, \\
|q/p| = 0.996 \pm 0.052, \\
\phi = 0.0576^{+0.047}_{-0.051}.
\]

- \(m_1 - m_2 = 6.4 \times 10^{-6} \text{ eV} = 1 \times 10^{-38} \text{ g}\)
- Significance > 7 \(\sigma\)

- No evidence for \(\mathcal{C}\mathcal{P}\) at \(2 \times 10^{-4}\)

**Acknowledgements**

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and NERSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and ARDC (Australia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); RFBR, RSF and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

**References**


Neutral particle oscillations

Timeline

- **B^0**: ARGUS
  - Observation of B^0 oscillations

- **D^0**: Belle & BaBar
  - Evidence of D^0 oscillations

- **D^0**: LHCb
  - Observation of D^0 mass difference
  - LHCb-PAPER-2021-009

- **K^0**
  - Behavior of neutral particles
  - e.g., Phys. Rev. 97 (1955) 1387

- **B^0_s**: CDF
  - Observation of B_s^0 oscillations

- **D^0**: LHCb
  - Observation of D^0 oscillations
**CKM angle $\gamma$ and charm mixing**

- **New method**
  - First simultaneous determination of CKM angle $\gamma$ and charm mixing parameters
  - 151 observables, 52 parameters
- **CKM angle $\gamma$**
  - $\gamma = (65.4^{+3.8}_{-4.2})^\circ$
  - Most precise measurement
- **Comparison**
  - Excellent agreement with indirect global CKM fits
    - $\gamma = (65.8 \pm 2.2)^\circ$ UTfit
- **Charm mixing**
  - $y = (0.630^{+0.033}_{-0.030})%$
  - $x = (0.400^{+0.052}_{-0.053})%$
  - Precision on $y$ improved by factor 2

Measurement of the CKM angle gamma at LHCb
Mark Whitehead
Charmed Ω_c^0 baryon lifetime

- **Charmed baryon lifetimes**
  - \( \Lambda_c^+ (udc), \Xi_c^+ (usc), \Xi_c^0 (dsc), \Omega_c^0 (ssc) \)
  - Hierarchy (PDG 2018)
    \( \tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) \)
  - 2018 - LHCb measures longer \( \tau(\Omega_c^0) \) in semileptonic b-baryon decays

- **Promptly produced c-baryons**
  - \( \Omega_c^0 \rightarrow p K^− K^− \pi^- \)
  - \( \Xi_c^0 \rightarrow p K^− K^− \pi^- \)
  - \( \tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7 \text{ fs} \)
  - \( \tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2 \text{ fs} \)
  - Confirms \( \tau(\Omega_c^0) \) is 4x longer

- **New lifetime hierarchy**
  - \( \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+) \)

LHCb-PAPER-2021-021
PRL 121 (2018) 092003

28/07/2021 Franz Muheim - LHCb highlights
Exotic Spectroscopy

- **Baryon**
- **Meson**
- **Tetraquark**
- **Pentaquark**

Exotic objects such as tetraquarks and pentaquarks are discussed to explain the difference in mass compared to the expected mass of baryons and mesons. They are built from quark-antiquark combinations and can arise due to the spontaneous breaking of the SU(3) confinement symmetry. Typical states are described in terms of spin, charge, etc., and the SU(3) representation of the baryon theory is deduced from the SU(3) young tableaux. A spin-0 anti-triplet with zero charge is specified, which is the only choice that gives the right unitarity and weak interactions. Of course, the symmetries of the baryon theory are needed to make sense of the spin and charge of all objects.
Overview

- Discovery of $X(3872)$ - now $\chi_{c1}(3872)$ - by Belle in 2003 started new era in exotic spectroscopy
- Observation of $c\bar{c}uud$ pentaquarks $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$
- Observation of two $\bar{c}c\bar{u}s$ tetraquarks $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$
- Evidence for two $c\bar{d}u\bar{s}$ tetraquarks $X_0(2900)$ and $X_1(2900)$
Observation of excited $\Xi_b^0$ baryons

- $\Xi_b^0 \rightarrow \Lambda_b^0 K^- \pi^+$ spectrum
  - Using 1.6 M $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ decays

- Observation
  - Two new excited $\Xi_b^0$ states
    - Intermediate structures
      - $\Xi_b^0 (6327)$: $\Sigma_b^+ \rightarrow \Lambda_b^0 \pi^+$
      - $\Xi_b^0 (6333)$

$$m_{\Xi_b(6327)^0} = 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24 \text{ MeV},$$
$$m_{\Xi_b(6333)^0} = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22 \text{ MeV},$$
$$\Gamma_{\Xi_b(6327)^0} < 2.20 (2.56) \text{ MeV at 90\% (95\%) CL},$$
$$\Gamma_{\Xi_b(6333)^0} < 1.55 (1.85) \text{ MeV at 90\% (95\%) CL},$$

Data: Total fit
- $\Xi_b(6327)^0$
- $\Xi_b(6333)^0$

Beauty-hadron spectroscopy at LHCb
Hongjie Mu
Evidence for structure in $J/\psi p$

- **Amplitude analysis**
  - using 800 $B_s^0 \to J/\psi p\bar{p}$ decays
  - Observe structure in $J/\psi p$ and $J/\psi\bar{p}$ spectrum
  - Significance of $3.1\sigma$ to $3.7\sigma$ depending on $J^p$ assignment

- **Evidence**
  - For $P_c(4337)^+$ state
  - Consistent with a (c\bar{c}uud) pentaquark
  - Mass and width

\[
M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst}) \text{ MeV}, \\
\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst}) \text{ MeV},
\]
Exotic Spectroscopy

- **Categories of observed resonance states**
  - Excited states: $b\bar{q}$, $c\bar{q}$, $bqq$, $cqq$
  - Exotic states: $cc(q\bar{q})$, $cc\bar{c}$, $c\bar{q}q\bar{q}$, $c\bar{c}qq$
  - Evidence for two $\bar{c}du\bar{s}$ tetraquarks
  - Natural width varies from $O(1)$ to $O(100)$ MeV

- **Heavy quark symmetry**
  - Predicts doubly heavy tetraquark hadron $cc\bar{q}\bar{q}$ or $bb\bar{q}\bar{q}$ to be long-lived with respect to strong interaction

- **Doubly charmed tetraquark $T_{cc}^+$**
  - Ground state $T_{cc}^+$ with $J^P = 1^+$
  - Many models predict $T_{cc}^+$ mass close to the $D^*D$ threshold

- **Observation strategy**
  - Search for narrow exotic state in same sign doubly charmed mass spectrum
The study is based on proton-proton (pp) collision data, corresponding to integrated luminosities of two heavy quarks $Q$ and two light antiquarks $q$, and their masses resolution and to make the determination of hadronic matter, the so-called mesons and baryons. While Quantum Chromodynamics (QCD), the theory of the strong force, describes the formation of hadronic matter, the landscape of the field. Along with baryons formed of three quarks ($qqq$), states with other quark content, known as exotic hadrons, have been actively discussed since the birth of the constituent quark model. Theoretical predictions for the mass of the ground state of a meson containing $b$ or $c$ quarks and is further described in Methods.

Recent LHCb results on exotic meson candidates

Franz Muheim - LHCb highlights
Observation of $T_{cc}^+$ state

- **First observation of a same-sign doubly charmed tetraquark $T_{cc}^+$**
  - Very narrow state in $D^0 D^0 \pi^+$ mass spectrum
  - Consistent with $cc\bar{u}\bar{d}$ tetraquark
  - Mass very close to $D^{*+}D^0$ mass thresholds
  - Manifestly exotic

- **Parameters of $T_{cc}^+$**
  - Fit structure with P-wave relativistic Breit-Wigner

\[
\begin{align*}
\delta m_{BW} &= -273 \pm 61 \pm 5^{+11}_{-14} \text{ keV/c}^2, \\
\Gamma_{BW} &= 410 \pm 165 \pm 43^{+18}_{-38} \text{ keV},
\end{align*}
\]

- Uncertainties stat, syst and due $J^P = 1^+$ assumption
- Significance for signal $> 10 \sigma$
- Significance for $\delta m_{BW} < 0$ $4.3 \sigma$

Recent LHCb results on exotic meson candidates
Ivan Polyakov
Spectroscopy at the LHC

- Status 28 July 2021

62 new hadrons at the LHC
55 new hadrons at LHCb

Franz Muheim - LHCb highlights
A MODEL OF LEPTONS*

Steven Weinberg†

Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the problem of renormalization:

\[ R = \left[ \frac{1}{2} (1 - \gamma_5) \right] e. \]  

The largest group that leaves invariant the kinematic terms \(-\bar{L}\gamma^{\mu}\partial_{\mu}L - \bar{R}\gamma^{\mu}\partial_{\mu}R\) of the Lagrangian consists of the electronic isospin \(T\) acting on \(L\), plus the numbers \(N_L\), \(N_R\) of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge \(Q = T_3 - N_R - \frac{1}{2} N_L\), and the electron number \(N = N_R + N_L\). But the gauge field corresponding to an unbroken sym-
• W boson mass
  – Fundamental parameter of Standard Model
  – Sensitivity to new physics limited by direct $m_W$ measurements
  – Most precise results from ATLAS, CDF and D0

• LHCb parton distributions

Global electroweak fit
EPJC 78, 675 (2018) GFitter
**W mass measurement**

### Method

- \( W^+ \rightarrow \mu^+ \nu_\mu \) decay mode
- Transverse momentum \( p_T \) of muon with charge \( q \) peaks at \( \sim m_W/2 \)
- Shift in \( m_W \) distorts \( q/p_T \) spectrum
- Muon \( p_T \) depends on transverse momentum \( p_T^W \) of \( W \) boson
- \( Z \rightarrow \mu^+\mu^- \) decays measured simultaneously

\[
\phi^* = \frac{\tan((\pi - \Delta \phi)/2)}{\cosh(\Delta \eta/2)} \sim \frac{p_T^Z}{M},
\]

### \( m_W \) determination

- Simultaneous fit to \( q/p_T \) and \( \phi^* \) of \( W \) and \( Z \)
- Precision: 23 MeV stat. uncertainty
- Systematic uncertainties from PDF, theory and experiment

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28/07/2021  
Franz Muheim - LHCb highlights
• **W boson mass**
  - Using 2016 data sample 1.6 fb\(^{-1}\)
  - \(m_W = 80364 \pm 23_{\text{stat}} \pm 11_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \) MeV

• **Discussion and outlook**
  - First LHCb measurement of W boson mass \(m_W\)
  - Pathfinder analysis: 32 MeV precision using \(~1/3\) of Run 2 data sample
  - Expect LHCb precision < 20 MeV with full Run 1&2 data set
  - Average LHCb with ATLAS could profit from –ve PDF correlations

**EPJC 75 12, 601 (2015)**
**Intrinsic charm of proton**

- **Z boson and charm jets**
  - $\sigma(Zc)/\sigma(Zj)$ fraction of $Z$+jet events where jet originates from a charm quark
- **Charm-jet**
  - Displaced vertex DV, corrected mass $m_{\text{cor}}$
  - Calibrated with tag and probe
- **Result**
  - Sizable enhancement of c-jets at high $Z$ rapidity
  - Consistent with 1% intrinsic charm in proton

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**NEW**

LHCb-PAPER-2021-029

PRD 93 (2016) 074008

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*QCD physics measurements at the LHCb experiment*

Lorenzo Sestini
Heavy Ion Physics

- **PbPb collisions at \(\sqrt{s} = 5\) TeV**
  - Coherent production of \(J/\psi\) ultraperipheral lead-lead collisions
  - \(J/\psi \rightarrow \mu^+\mu^-\) rapidity \(2.0<y<4.5\)
  - Cross-section \(\sigma = 4.45\pm0.24\pm0.18\pm0.58\) mb
  - Comparison to phenomenological models

- **Charged particle production at \(\sqrt{s} = 5\) TeV**
  - Comparison of pPb and pp data samples
  - Nuclear modification factor
    \[
    R_{pPb}(\eta, p_T) = \frac{1}{A} \frac{d^2\sigma_{pPb}(\eta, p_T)/dp_Td\eta}{d^2\sigma_{pp}(\eta, p_T)/dp_Td\eta}
    \]
  - Continuous evolution of \(R_{pPb}\) vs \(x_{\text{exp}}\)
    between forward, central and backward \(\eta\)

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Franz Muheim - LHCb highlights

28/07/2021
Upgrades present and future

Physics Case for an LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era
LHCb upgrade

- LHCb upgrade
  - new detector
  - Installation ongoing
  - Huge challenge
  - intensified due to Covid

- Status of Installation
  - Significant progress under difficult circumstances
  - Travel restrictions are still a concern
  - Commissioning has started RICH, CALO, Muons
## VELO and UT

### VELO modules
- 40 of 52 modules produced
- Assembly of half-VELO starting

### UT modules
- Production nearly complete
- Module mounting next

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**UT stave**

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Franz Muheim - LHCb highlights 28/07/2021
SciFi tracker

- SciFi half detector installed
  - Happened 10 days ago – a major milestone
  - 6/12 C-frames installed
RICH, CALO, Muons Commissioning

- **RICH 2 installed**
  - 1st detector in commissioning

- **CALO**
  - Front-end board installation progressing well

- **Muons**
  - A side switched on
  - DCS and DAQ
  - Electronics installed
  - Commissioning ongoing

28/07/2021
Franz Muheim - LHCb highlights
LHCb Upgrade I – Online & Trigger

- **Software High Level Trigger**
  - 30 MHz event rate
  - 10 GB/s to Storage

- **Online installation**
  - Event builder PC servers & FPGA DAQ cards completed
  - Event builder network > 100 Tb/s achieved
    (200 x Run2, 32 Tb/s required)
  - Commissioning of Muon, RICH, CALO underway

- **GPU HLT1 trigger**
  - Event reconstruction In trigger achieved in single GPU card
  - Full reconstruction in trigger achieved required CPU event rate
LHCb Upgrade II

- LHC flavour physics facility
  - Fully exploit HL-LHC luminosity for flavour physics & beyond
  - Expression of interest (2017)
  - Physics Case (2018)
  - Strong support in European Strategy (2020)

- Framework TDR
  - Drafting in progress, delivery later this year
Conclusions

- **LHCb is producing lots of exciting physics results**
  - in many areas - rare decays, CP violation, charm, spectroscopy, electroweak, QCD, exclusive production, heavy ion, fixed target, > 30 papers in 2021

- **Flavour anomalies**
  - Cautious excitement
  - More results on lepton flavour universality, and under way

- **Highlights of highlights this week**
  - First observation of a doubly charmed same-sign tetraquark $T_{cc}^+$
  - Measurement of $W$ mass
  - Indication of intrinsic charm in proton

- **LHCb upgrade**
  - Huge progress during last year despite difficult circumstances
  - RICH, CALO and Muon in commissioning
  - Planning for future upgrade in ~2030 is gaining momentum
Backup
Excited $\Omega_c^0$ baryons

- Discovery of 5 excited $\Omega_c^0$ states
  - In prompt $\Xi_c^+ K^-$ production
- Observation in $b$-baryon production
  - $\Omega_b^- \to \Xi_c^+ K^- \pi^-$
  - Observe 4 of 5 states
    and a structure at threshold
  - Measure quantum numbers
  - Spin $\frac{1}{2}$ excluded at 2.5σ and 3.9σ
    for $\Omega_c^0(3050)$ and $\Omega_c^0(3065)$

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LHCb results in charm baryons

Franz Muheim - LHCb highlights
Branching fraction measurements

- consistently below Standard Model predictions
**Very rare leptonic decay**
- Helicity and CKM suppressed
- Sensitive to New Physics

**$B_s^0 \rightarrow \mu^+\mu^-$**
- $B(B_s^0 \rightarrow \mu^+\mu^-) = 3.09^{+0.46}_{-0.43} \times 10^{-9}$
- Significance $> 10 \sigma$, in agreement with SM

**$B^0 \rightarrow \mu^+\mu^-$**
- $B(B^0 \rightarrow \mu^+\mu^-) < 2.6 \times 10^{-10}$ at 95% CL

**First search for $B_s^0 \rightarrow \mu^+\mu^-\gamma$**
- $B(B_s^0 \rightarrow \mu^+\mu^-\gamma) < 2.0 \times 10^{-9}$ at 95% CL
  for $m_{\mu\mu} > 4.9$ GeV/c$^2$

**Effective lifetime**
- $\tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03$ ps

Very rare decays at LHCb
Miguel Ramos Pernas

Franz Muheim - LHCb highlights