## **Recent Flavour results from LHCb**

V.Tisserand (LPC Clermont-Ferrand) IN2P3/CNRS-UCA On behalf of the LHCb@CERN collaboration



58th International Winter Meeting on Nuclear Physics January 20 to 24, 2020 Bormio, Italy









UNIVERSITÉ Clermont Auvergne

### **Introduction:** LHC is a heavy flavour quarks factory

The LHCb detector has been designed for the study of hadrons decays containing the b and c quarks. Huge cross-sections @LHC and largest samples, mainly produced in pairs in tight cones around either beam. In LHCb acceptance (forward arm detector for precision measurements in the range  $2 < \eta < 5$ ):

- $1.4 \ge 10^{11} b\overline{b}$  pairs per fb<sup>-1</sup> ( $\sqrt{s}$  =13 TeV)  $\mathcal{O}(10^{12})$   $c\overline{c}$  pairs per fb<sup>-1</sup>  $\mathcal{O}(10^{13})$   $K^{0}_{s}$  mesons per fb<sup>-1</sup>

As opposed to B-factories (BABAR & Belle(-II)), all species of b-hadrons produced: B<sup>+</sup> & B<sup>0</sup> ("B<sub>11</sub> & B<sub>d</sub>"), **B**<sub>s</sub>, **B**<sub>c</sub>,  $\Lambda_{\rm b}$ ,  $\Sigma_{\rm b}$ ,  $\Omega_{\rm b}$  ... (i.e. including b baryons). In the rough proportion : 40% B<sup>+</sup>, 40% B<sup>0</sup>, 10% B<sub>s</sub>, 0.1% B<sub>c</sub> & 10% b baryons. (see e.g. Phys.Rev. D100 (2019) no.3, 031102; arXiv:1902.06794).  $\Rightarrow$  LHCb does physics in s-, c-, b-hadron decays (not only\*).

\*e.g.: EW and QCD physics in large  $\eta$  @ LHC, Heavy quark production, conventional and exotic spectroscopy (Paolo Gandini) and lon and fixed target physics (Valery Pugatch).











Menie degustazione

Per principiare : antipasti

CKM parameters & CP Violation (CPV): •  $|V_{cb}|$  from  $B_s^0 \rightarrow D_s^{(*)-} \mu^+ \upsilon_{\mu}$ (LHCb-PAPER-2019-041, arXiv:2001:03225 & sub. to Phys.Rev. D)

• CP & P violation in  $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ (<u>LHCb-PAPER-2019-028</u>, <u>arXiv:1912.10741</u> & sub. to Phys.Rev.Lett.)

Piatto principale & dolce del giorno

Rare decays & Beyond the Standard Model (BSM) studies:

• Test Lepton Universality in  $\Lambda_b^0 \rightarrow pK^-l^+l^-$ (<u>LHCb-PAPER-2019-040</u>, <u>arXiv:1912.08139</u> & sub. to JHEP)

• Search for the very rare  $K_s^0 \rightarrow \mu^+ \mu^-$  decay (<u>LHCb-PAPER-2019-038</u>, to be sub. to Phys.Rev.Lett.)



### **Detector & Data**



#### Multipurpose detector in the forward region

- tracking efficiency > 96% (multibody final states!)
- excellent vertexing: impact parameter  $\sigma$ (IP)=15+29/P<sub>T</sub> µm & decay time resolution ~ 45 fs
- very good momentum resolution:  $dp/p \sim$  0.5 1.0%  $\sigma(m_{B}){\sim}25 MeV/c^{2}$  for 2-body
- excellent PID: (µ/K ID 97/70 % for ( $\pi \to \mu, K)$  misID of few%)
- Hardware (L0: calo and muons )+ Software flexible trigger (HLT) input rate: 1 MHz small P<sub>T</sub> and low mass objects
- stable running conditions constant number of PVs
- online real time analysis alignment and calibration fully automated

#### Ever increasing integrated data/year rate

LHCb has recorded about 9 fb<sup>-1</sup> of pp collisions:

- 1 fb<sup>-1</sup> @ 7 TeV
- 2 fb<sup>-1</sup> @ 8 TeV
- 6 fb<sup>-1</sup> @ 13 TeV Run 2 total is 5-6 times Run1 (2017+2018 are 2/3 of the total dataset, given the

cross-sections increases and trigger changes)

#### $\Rightarrow$ LHCb has yet submitted more than 500 papers



#### The Standard Model (SM) & the Unitary CKM Matrix → mixing of the 3 quarks families & CP violation

• the Higgs boson gives mass to elementary bosons & fermions (quarks, leptons) through Yukawa couplings, but there is not only that ! :

$$\mathcal{L}_{cc}^{\mathrm{quarks}} = rac{g}{2\sqrt{2}} W^{\dagger}_{\mu} [\sum_{ij} \bar{u}_i(q_2) \gamma^{\mu} (1 - \gamma^5 V_{ij} d_j] + \mathrm{h.c}$$



charged currents (EW) imply transitions between quark families : quarks decays [there are no neutral current changing flavour (FCNC) at tree level (i.e. GIM mechanism )].

$$V_{CKM} = \begin{pmatrix} d & s & b \\ u & 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ c & -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ t & A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \quad (VV^{\dagger} = 1)$$

• strong hierarchy in EW  $V_{ij}$  couplings for the 3 families (wrt diagonal couplings  $\infty \lambda^{N} \approx (0.225)^{N}$  :  $\rightarrow$  Cabibbo angle).

• KM (Kobayashi-Maskawa) mechanism :

3 generations  $\rightarrow$  <u>4 parameters</u>: A,  $\lambda$ ,  $\rho$ & 1 complex part  $\eta$  which phase is the unique source of CPV in SM.



The CKM Matrix : the unitary triangle & the very rich phenomenolgy of quark flavors



→4 parameters (A,  $\lambda$ ,  $\rho$  &  $\eta$ ) to be obtained/tested wrt data: nucleons, K, D, B<sub>(s)</sub> & top quark physics.

→ unitarity relation in B<sub>d</sub> system (1<sup>rst</sup> line/3<sup>rd</sup> column):

$$rac{V_{ud} \, V_{ub}^*}{V_{cd} \, V_{cb}^*} + 1 + rac{V_{td} \, V_{tb}^*}{V_{cd} \, V_{cb}^*} = 0 \ O(1) + O(1) + O(1)$$



 $|V_{cb}|$  from  $B_{s}^{0} \rightarrow D_{s}^{(*)} \mu^{+} \upsilon_{\mu}$ 



### Introducing $|V_{cb}|$ (i.e. $b \rightarrow c$ transition)



- Long standing discrepancy : slight tension between averages!
- Caprini-Lellouch-Neubert (CLN) FF parametrization used in excl. measurements cause of tension (i.e. Bigi et al. Phys. Lett. B769 (2017) 441& Grinstein et al. Phys. Lett. B771 (2017) 359) ?
- New measurements with B<sup>+</sup> and B<sup>0</sup> by <u>Babar</u> (2019) and <u>Belle</u>(2018) uses also Boyd-Grinstein-Lebed (BGL) FF param. (more general, but truncation of series in BGL somewhat arbitrary).

#### ➔ need to compare both parametrizations

- → LHCb can help with  $B_s^0 \rightarrow D_s^{(*)} \mu^+ \upsilon_{\mu}$  decays that have interesting features:
- Easier lattice QCD calculation of FF ("heavy" valence quark) allows for better precision
- Expected less contamination from D<sup>\*\*</sup><sub>s</sub> feed-down, mostly decaying to DK<sup>(\*)</sup>

#### [LHCb-PAPER-2019-041]

- □ Model decays with : CLN and BGL parameterisations to investigate possible differences
- Side-products: measure also BF of the two B<sup>0</sup><sub>s</sub> exclusive decays
- Need to:
  - Extract signal yields of exclusive  $B_s^0$  decays from inclusive  $D_s^-(\rightarrow \phi(KK)\pi^-)\mu^+$  sample
  - Normalize to a reference decay. Use  $D^{-}(\rightarrow KK\pi^{-})\mu^{+}$ : same final state and similar kinematic to suppress efficiency biases, measure the ratios
  - Take as external input  $f_s/f_d$ , BF of B<sup>0</sup> and  $D^{*}_{(s)}$  decays these external inputs will bring the dominant uncertainty

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)},$$
$$\mathcal{R}^* \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)}$$



- Decay rates :
- 4-D, vector case:

can be decomposed in terms of 3 helicity amplitudes that in turn depend on 3 FF:  $h_{A1}$  (w),

$$\frac{\mathrm{d}^4 \Gamma(B \to D^* \mu \nu)}{\mathrm{d}w \,\mathrm{d}\cos\theta_\mu \,\mathrm{d}\cos\theta_D \,\mathrm{d}\chi} = \frac{3m_B^3 m_{D^*}^2 G_{\mathrm{F}}^2}{16(4\pi)^4} \eta_{\mathrm{EW}}^2 \left[ V_{cb} \right]^2 \left[ \mathcal{A}(w, \theta_\mu, \theta_D, \chi) \right]^2$$

1-D, scalar case:

can be written as a function of 1 FF

$$\frac{\mathrm{d}\Gamma(B \to D\mu\nu)}{\mathrm{d}w} = \frac{G_{\mathrm{F}}^2 m_D^3}{48\pi^3} (m_B + m_D)^2 \eta_{\mathrm{EW}}^2 (V_{cb})^2 (w^2 - 1)^{3/2} \mathcal{G}(w)^2$$

The 4-velocity  $\omega \equiv (m_{B}^{2}+m_{D(*)}^{2}-q^{2})/(2m_{B}m_{D(*)})$ , where  $q^{2}$  is the square of the  $\mu \upsilon$  invariant mass  $\rightarrow$  but,  $q^{2}$  can not be measured directly  $\otimes$ , because of the neutrino...



 $R_1(w)$  &  $R_2(w)$ 

[LHCb-PAPER-2019-041] Run 1 data only

→ final state not fully reconstructed ( $\gamma/\pi^0$  from D<sup>\*-</sup><sub>(s)</sub> and also  $\upsilon_{\mu}$ ): employ novel strategy to constraint  $\omega$ (i.e. q<sup>2</sup>). Use reconstructed variables correlated with q<sup>2</sup> which preserve information on the FF  $\rightarrow p_{\perp}(D_{(s)})$ 

Separate signal/remaining Bckgds after selections in 2-D view.

➔ fit signal and reference yields (expressed from decay rates) and MC simulation templates of FF for CLN and BGL :

- $p_{\perp}(D_{s}^{-}\mu^{+})$  (i.e. transverse to the  $B_{s}^{0}$  flight direction)
- $\mathbf{m}_{corr} \equiv (\mathbf{m}^2 (\mathbf{D}_s \mu^+) + \mathbf{p}_{\perp}^2 (\mathbf{D}_s \mu^+))^{1/2} + \mathbf{p}_{\perp} (\mathbf{D}_s \mu^+)$







 $\rightarrow D_{S}^{-}\mu^{+}\nu_{\mu}$ 

 $B_{S}^{0}$ 

 $\rightarrow D_s^{*-}\mu^+\nu_\mu$ 

 $B_{S}^{0}$ 

#### [LHCb-PAPER-2019-041] Run 1 data only

→ cannot fully reconstruct recoil variable  $\omega$  (for form factors!),

but  $p_{\perp}(D_{s}^{-} \mu^{+})$  is a good proxy. & also has some small correlations for the  $B_{s}^{0} \rightarrow D_{s}^{*-}$  $\mu^{+} \upsilon_{\mu} \operatorname{decay}$  with helicity angles  $\cos \theta_{D}$  and  $\cos \theta_{\mu}$ 

→ white line: average/profile



1950

 $m_{K^+K^-\pi^\pm}$  [MeV/ $c^2$ ]

2000 2050

1850

1900

1800

- Selection inherited from <u>LHCb-PAPER-2017-004</u> ( $B_s$  and  $D_s$  lifetime measurements)
- Cut m(KK) around the φ mass for both D and D<sub>s</sub> to have same kinematics for signal and reference decays
- Select also same-sign D<sup>-</sup><sub>(s)</sub> μ<sup>-</sup> combinations to model combinatorial bckgd

 $\times 10^3$ 22X11  $\rightarrow$  first, fit reference channel, keeping  $GeV/c^2$ GeV/c LHCb LHCb  $' \rightarrow D^{-} \mu^{+} \nu_{\mu}$ total signal yields floating N<sup>(\*)</sup><sub>ref</sub>  $' \rightarrow D \ \mu^+ v_{\mu}$ 10 Phys. bkg. 0.23 2 o. Comb. bkg. per per <u>×10'</u> Candidates andidates GeV/c GeV/o LHCb-LHCb  $35 = B_s^0 \rightarrow D_s^- \mu^+ v_\mu$ 20Ē  $B_s^0 \rightarrow D_s^- \mu^+ v_\mu$ 18 Phys. bkg. 6E o. Comb. bkg. 5.5 4.5 0.5 2.5 4 4  $p_{|}(D^{-}) [\text{GeV}/c]$ 20F per 0  $m_{\rm corr}$  [GeV/ $c^2$ ] Candidates per 15F andidates 10E  $\rightarrow$  for signal fit: express signal yields 4.5 5.5 0.5  $m_{\rm corr} \, [{\rm GeV}/c^2]$  $p_{\perp}(D_{s})$  [GeV/c] N<sup>(\*)</sup><sub>sig</sub> in terms of N<sup>(\*)</sup><sub>ref</sub>



[LHCb-PAPER-2019-041] Run 1 data only

[LHCb-PAPER-2019-041] Run 1 data only

CLN form factor (FF) fit			
Parameter	Value		
$ V_{cb} $ [10 <sup>-3</sup> ]	$41.4 \pm 0.6 \text{ (stat)} \pm 1.2 \text{ (ext)}$	)	
$\mathcal{G}(0)$	$1.102 \pm 0.034 (\mathrm{stat}) \pm 0.004 (\mathrm{ext})$	)	
$ ho^2(D_s^-)$	$1.268 \pm 0.047 (\mathrm{stat}) \pm 0.001 (\mathrm{ext})$	)	
$\rho^2(D_s^{*-})$	$1.23 \pm 0.17 \text{ (stat)} \pm 0.01 \text{ (ext)}$	)	
$R_1(1)$	$1.34 \pm 0.25 \text{ (stat)} \pm 0.02 \text{ (ext)}$	)	
$R_{2}(1)$	$0.83 \pm 0.16 \text{ (stat)} \pm 0.01 \text{ (ext)}$	)	

### → Very nice compatibility



<u>Note</u>: (details in backup) Here external inputs systematic errors only (dominated by  $f_s/f_d$ ) & when adding experim. syst. largest systematic on  $|V_{cb}|$  is from  $D_{(s)}^- \rightarrow KK\pi^-$  model



BGL form factor (FF) fit		
Parameter	Value	
$ V_{cb}  \ [10^{-3}]$	42.3 $\pm 0.8$ (stat) $\pm 1.2$ (ext)	
$\mathcal{G}(0)$	$1.097 \pm 0.034 \text{ (stat)} \pm 0.008 \text{ (ext)}$	
$d_1$	$-0.0172 \pm 0.0074 (\text{stat}) \pm 0.0007 (\text{ext})$	
$d_2$	$-0.256 \pm 0.047 \text{ (stat)} \pm 0.002 \text{ (ext)}$	
$b_1$	$-0.060 \pm 0.068 \text{ (stat)} \pm 0.013 \text{ (ext)}$	
$a_0$	$0.0374 \pm 0.0086 (\mathrm{stat}) \pm 0.0008 (\mathrm{ext})$	
$a_1$	$0.28 \pm 0.26 $ (stat) $\pm 0.08 $ (ext)	
$c_1$	$0.0031 \pm 0.0022 (\text{stat}) \pm 0.0006 (\text{ext})$	

1-

[LHCb-PAPER-2019-041] Run 1 data only

Summary: in this novel approach for exclusive determination of  $|V_{cb}|$   $\Rightarrow$  exploit ratio  $B_s^0 \rightarrow D_s^{(*)} \mu^+ \upsilon_{\mu} / B^0 \rightarrow D^{(*)} \mu^+ \upsilon_{\mu}$  to cancel systematics  $\Rightarrow$  MC template-based fit in plane:

- helps to suppress Bckgds
- express FF dependence in terms of observed quantities



### Search for CPV in *b*-baryon decay $\Lambda^0_b \rightarrow p\pi^-\pi^+\pi^-$





### Search for CPV in *b*-baryon decay $\Lambda^0_b \rightarrow p\pi^-\pi^+\pi^-$

- Violation of C/CP (C/CPV) symmetry is one of the necessary 3 Sakharov conditions for the matter wrt anti-matter asymmetry in baryogenesis after the early Universe.
- The predicted amount of CPV in the Standard Model (SM) is far too small to explain the absence of antimatter in the Universe. As-of-yet no CP violation in bbaryons has been observed, though the CKM mechanism predicts sizeable amount of violation.
- Possibly there are other sources of CPV beyond the SM. Need to search for CPV effects extensively as large LHCb dataset opens new field in heavy flavour physics precision measurements and <u>many searches yet</u> performed.



- Transitions governed  $b \rightarrow u d\bar{u}$  tree and  $b \rightarrow d\bar{u}u$  penguin amplitudes of similar size
- Large relative CKM weak phase  $\alpha$ =Arg(V\*<sub>tb</sub>V<sub>td</sub>/V\*<sub>ub</sub>V<sub>ud</sub>) in SM

→ Potential non negligible CPV effects in the SM





### Search for CPV in *b*-baryon decay $\Lambda^0_{\ b} \rightarrow p\pi^-\pi^+\pi^-$

- CPV can be measured by comparing yields between baryon and antibaryon decays (i.e. direct CP violation): but highly diluted by experimental effect (i.e. *b*-hadron production and charged particles reconstruction asymmetries).
- Rather use integrated and triple-product asymmetry (TPA) measurements :

Measure *CPV* via  $\hat{T}$ -(P-)violating aymmetries in  $\Lambda_b \rightarrow p \pi_{fast}^{-} \pi^{+} \pi_{slow}^{-}$ T = spin and momentum reversal operator • Triple products in  $\Lambda_{\rm b}$  rest frame  $C_{\hat{T}} = \overrightarrow{p}_{p} \cdot \left(\overrightarrow{p}_{\pi_{fast}} \times \overrightarrow{p}_{\pi^{+}}\right) \propto \sin \Phi$  $\pi^+$ Φ  $\overline{C}_{\hat{T}} = \overrightarrow{p}_{\overline{p}} \cdot \left( \overrightarrow{p}_{\pi_{true}^+} \times \overrightarrow{p}_{\pi^-} \right) \propto \sin \overline{\Phi}$ p $\hat{T}(P)$ -odd asymmetries: n  $A_{\hat{T}} = \frac{N_{\Lambda_{b}^{0}} \left( C_{\hat{T}} > 0 \right) - N_{\Lambda_{b}^{0}} \left( C_{\hat{T}} < 0 \right)}{N_{\Lambda_{c}^{0}} \left( C_{\hat{T}} > 0 \right) + N_{\Lambda_{c}^{0}} \left( C_{\hat{T}} < 0 \right)}$  $\pi_{\rm slow}^ \pi_{\text{fast}}$  $\overline{A}_{\widehat{T}} = \frac{N_{\overline{\Lambda}_{b}^{0}}\left(-\overline{C}_{\widehat{T}} > 0\right) - N_{\overline{\Lambda}_{b}^{0}}\left(-\overline{C}_{\widehat{T}} < 0\right)}{N_{\overline{\Lambda}_{b}^{0}}\left(-\overline{C}_{\widehat{T}} > 0\right) + N_{\overline{\Lambda}_{b}^{0}}\left(-\overline{C}_{\widehat{T}} < 0\right)}$  $a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2} \left( A_{\hat{T}} - \overline{A}_{\hat{T}} \right)$ CP-violating observable:  $a_P^{\hat{T}-\text{odd}} = \frac{1}{2} \left( A_{\hat{T}} + \overline{A}_{\hat{T}} \right)$ *P*-violating observable:



PA

### First indication of CPV in *b*-baryon decay $\Lambda^0_{\ b} \rightarrow p\pi^-\pi^+\pi^-$



- Integrated results compatible with CP (@  $3.3\sigma$ ) & P ( $2.2\sigma$ ) conservation
- Largely insensitive to production & decay asymmetries
- Low systematic uncertainties <1%</li>

• Already triggered some theorists (e.g.: JHEP 10 (2016) 005, Nature Phys. 13 (2017) 322, PoS ICHEP (2016) 531, Phys.Rev. D95 (2017) 09300).



#### New search for CPV in *b*-baryon decay $\Lambda^0_b \rightarrow p\pi^-\pi^+\pi^$ with 2011-2017 datset

General Science (Run2) → signal yield = x4 signal yield Run1
 Applied 2 different methods to search for CPV:

[LHCb-PAPER-2019-028]

- Triple Product Asymmetries (TPA), new optimization
- Energy Test [(test statistics), thermodynamics independent model like, or statistical two-sample comparison technique (Energy=0 if similar samples)] applied here for the first time
- Improved understanding of decay dynamics:
- Simplified Λ<sup>0</sup><sub>b</sub> → pπ<sup>-</sup>π<sup>+</sup>π<sup>-</sup> amplitude model including main contributions N<sup>\*+</sup>π<sup>-</sup> (p a<sub>1</sub>(1260)<sup>-</sup>) with m(pπ<sup>+</sup>π<sup>-</sup><sub>slow</sub>) < (>) 2.8 GeV/c<sup>2</sup> (plus other and also : Δ\*(1234)<sup>++</sup>(→pπ<sup>+</sup>)π<sup>-</sup> & a<sub>1</sub> → ρπ) → identified interesting regions for CPV-odd and separate it to avoid dilution → 2 new binning schemes
   Λ<sup>0</sup><sub>b</sub> → Λ<sup>+</sup><sub>c</sub>(pK<sup>-</sup>π<sup>+</sup>)π<sup>-</sup> validiation control sample (i.e. no CPV expected)



### New results for CPV in *b*-baryon decay $\Lambda^0_b \rightarrow p\pi^-\pi^+\pi^-$

#### [LHCb-PAPER-2019-028]

**TPA method** (systematic negligible wrt to statistical uncertainties) Scheme A: based on helicity angles Scheme B: on  $\Phi$  angle intervals Asymmetries [%] % 30E  $ullet a_{CP}^{\widehat{T} ext{-odd}}$  $a_{CP}^{\hat{T}-odd}$ LHCb scheme  $A_{I}$ scheme  $B_1$ LHCb  $\chi^2/ndof=18.5/10$  $\chi^2$ /ndof=23.6/16 20 $\Delta a_{P}^{\hat{T}-odd}$ symmetries  $\triangle a_{P}^{\hat{T}-odd}$  $\chi^2/ndof=50.6/16$  $\chi^2$ /ndof=54.3/10 1010 a<sub>1</sub> region a₁<sup>-</sup> region -30 30 scheme  $A_{2}$ 20 scheme  $B_{2}$ /ndof=26.3/10  $\chi^2$ /ndof=25.3/16  $v^2/ndof=27.9/1$ 2010 -10-20 N<sup>\*+</sup> region N<sup>\*+</sup> region -302 8 12 14 16 0.5 1.5 2 2.5 3 10Δ 6 0  $|\Phi|$  [rad] Bin

Integrated TPA measurements :

$$\begin{aligned} a_{CP}^{\widehat{T}\text{-odd}} &= -0.70 \pm 0.70 \pm 0.17 \\ a_{P}^{\widehat{T}\text{-odd}} &= -3.98 \pm 0.70 \pm 0.17 \end{aligned}$$

- Both TPA and Energy Test methods (i.e. search for non-null asymmetries):
  - suggest CP conservation at 2.8-2.9 σ
  - first observation of P violation in b-baryon decay at the level of 5.5  $\sigma$  !



### Test of Lepton Universality with $\Lambda_{b}^{0} \rightarrow pK^{-}l^{+}l^{-}$





#### Rare b-hadron decays & $b \rightarrow sll$ anomalies



#### FCNC ( $|\Delta F|=1$ , forbidden at Tree level) sensitive to indirect effects of "New Physics" (NP or BSM) in loops/penguin diagrams :

- → Quantum corrections due to virtual effects ( $\Delta E.\Delta t \sim \hbar$ ) ⇒ deviations wrt SM predictions precise measurements and precise calculations.
- → Open gates to yet inaccessible energy scales at accelerators :  $\Lambda_{NP}$  > 0.5-2×10<sup>4</sup> TeV
- → Accessing new couplings/phases in loops/boxes : CPV &/or rare decays
- → Many observables: asymmetries ( $A_{FB}$ , direct, time dep: C, S, ...), angular/amplitude analyses (transversity/helicity), structure of currents (V-A), polarization (RH  $\gamma$ ?), Lepton Universality, BFs > or < SM pred. ?



#### Rare b-hadron decays & $b \rightarrow sll$ anomalies

#### LCSR Lattice -Data LCSR Lattice - Data LCSR Lattice -Data $dB/dq^2 [10^{-8} \times c^4/GeV^2]$ $dB/dq^2 [10^{-8} \times c^4/\text{GeV}^2]$ $c^4/\text{GeV}^2$ $B^+ \rightarrow K^+ \mu^+ \mu^-$ LHCb $B^0 \rightarrow K^0 \mu^+ \mu^-$ LHCb $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ LHCb $b \rightarrow sll$ decay rates × systematically below $dB/dq^2 [10^{-8}]$ the SM predictions $q^{15} = \frac{20}{[\text{GeV}^2/c^4]}$ $q^{15} q^{20} [\text{GeV}^2/c^4]$ 10 10 10 $q^2 \,[{\rm GeV}^2/c^4]$ [JHEP 06 (2015) 115] [JHEP 09 (2018) 146] [JHEP 04 (2017) 142] $dB/dq^2 [c^4/\text{GeV}^2]$ $\times 10^{-6}$ $dB(B_s^0 \rightarrow \phi \mu \mu)/dq^2 [10^{-8} GeV^{-2}c^4]$ LHCb LHCb 1.4 $\mathrm{d}\mathcal{B}$ $[10^{-7}~{\rm GeV^{-2}}]$ SM pred. $\overline{\mathrm{d}q^2}$ 1.2 7 6 5 4 3 2 2 0. - Data 1.0 0.8 0.6 0.0 0.4 LHCb (3fb<sup>-1</sup>) 0.2 SM prediction 10 $q^{2} [\text{GeV}^{2}/c^{4}]$ 15 20 10 5 $q^{15} q^{2} \, [{\rm GeV^2}/c^4]$ $q^2 \, [\text{GeV}^2]$ $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Ā S LHCb data ATLAS data $b \rightarrow sll$ angular analysis • CMS data Belle data 0.5 Local tension with SM predictions SM from DHMV SM from ASZB (2.8 and 3.0 $\sigma$ ) [LHCb, JHEP 02 (2016) 104] -0.5 5 10 15 0 5 $q^{2} \,[{\rm GeV}^{2}/c^{4}]$

#### [JHEP 06 (2014) 133]



- LHCb deviations @ 2-2.5  $\sigma$  (R<sub>K\*</sub> with Run1 only data and R<sub>K</sub> with Run1 + 2016)
- Crucial to add more data and measure LU in other modes and b-hadron decays
- Also some tensions in b->clv in  $B \rightarrow D(*)\tau v$  wrt  $B \rightarrow D(*)\mu/ev$

(i.e. 3<sup>rd</sup> vs 1<sup>rst</sup> & 2<sup>nd</sup> family)



Method for Test of Lepton Universality (LU) in  $\Lambda_{b}^{0} \rightarrow pK^{-}l^{+}l^{-}$ 

[LHCb-PAPER-2019-040] Run 1 + 2016 data

#### 1) In the SM:

$$R_{H} = \frac{BR(B \to H\mu^{+}\mu^{-})}{BR(B \to He^{+}e^{-})} = 1 + \mathcal{O}(10^{-2})$$

#### 2) Experimentally:

3) Exploit the well test LU in  $J/\psi$  modes:

$$r_{J/\psi}=rac{BR(B
ightarrow HJ/\psi(\mu^+\mu^-))}{BR(B
ightarrow HJ/\psi(e^+e^-))}=1$$

- as stringent cross-check
- to build double ratio  $\rightarrow$  cancel systematic effects

$$\begin{split} R_{H} \propto \frac{N(B \rightarrow H\mu^{+}\mu^{-})}{N(B \rightarrow He^{+}e^{-})} \times \frac{\epsilon(B \rightarrow He^{+}e^{-})}{\epsilon(B \rightarrow H\mu^{+}\mu^{-})} \\ \text{From mass fit} & \text{From MC simu.} \\ + \text{ calibration samples} \end{split} \qquad R_{H} = \frac{N(B \rightarrow H\mu^{+}\mu^{-})}{\frac{N(B \rightarrow HJ/\psi(\mu^{+}\mu^{-}))}{N(B \rightarrow HJ/\psi(\mu^{+}e^{-}))}} \times \frac{\epsilon(B \rightarrow He^{+}e^{-})}{\epsilon(B \rightarrow HJ/\psi(e^{+}e^{-}))} \\ \frac{R_{H}}{R_{pK}} = \frac{\mathcal{B}(\Lambda_{b}^{0} \rightarrow pK^{-}e^{+}e^{-})}{\mathcal{B}(\Lambda_{b}^{0} \rightarrow pK^{-}J/\psi(\rightarrow e^{+}e^{-}))} / \frac{\mathcal{B}(\Lambda_{b}^{0} \rightarrow pK^{-}\mu^{+}\mu^{-})}{\mathcal{B}(\Lambda_{b}^{0} \rightarrow pK^{-}J/\psi(\rightarrow \mu^{+}\mu^{-}))} \end{split}$$

 $\Rightarrow$ First test of LU with b-baryons, using  $\Lambda_{b}^{0} \rightarrow pK^{-}\mu^{+}\mu^{-}$  and  $\Lambda_{b}^{0} \rightarrow pK^{-}e^{+}e^{-}$  decays



$$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))} \bigg/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))}$$

Note : use of inverse definition due to expected small yields in rare electron mode (better LLH numerical behavior)

- R<sub>pK</sub> is expected to be unity in the SM [Fuentes-Martin et al.]
- Complementary to  $R_{K(*)}$  due to fractional baryon spin

#### $\Rightarrow$ Side-products:

- $\bullet \ \Lambda_b {\rightarrow} \ pK^-e^+e^-$  never observed before  $\rightarrow$  first observation
- BF( $\Lambda_b \rightarrow pK^- \mu^+ \mu^-$ ) never measured before  $\rightarrow$  first measurement



#### Test of Lepton Universality (LU) in $\Lambda_{b}^{0} \rightarrow pK^{-}l^{+}l^{-}$

- → Simulation describes hadronic pK<sup>-</sup> structure (pentaquarks) → Selection adapted form  $\Lambda_{b}^{0} \rightarrow \Lambda l^{+}l^{-}$  angular analysis [JHEP 09 (2018) 146] &  $R_{K^{*}}$  LU Test [JHEP 08 (2017) 055]
  - ⇒ LU test performed in the region (J/ $\psi \in [6,11]$  GeV<sup>2</sup>/c<sup>4</sup>):
  - $100 \text{ MeV}^2/c^4 < q^2 < 6 \text{ GeV}^2/c^4$
  - m(pK) < 2.6 GeV/c<sup>2</sup>



Bremsstrahlung effects in the *ee* channel (even with corrections)
 Special electron/muon Hardware trigger



#### Test of Lepton Universality (LU) in $\Lambda_b^0 \rightarrow p K^- l^+ l^-$

[LHCb-PAPER-2019-040] Run 1 + 2016 data

#### **Resonant modes q<sup>2</sup>** $\in$ [6,11] GeV<sup>2</sup>/c<sup>4</sup> (pKJ/ $\psi$ ): mass fit

Constrain m(ee/µµ) to known J/ $\psi$  mass  $\rightarrow$  better mass resolution for m( $\Lambda^0_h$ )



Efficiency cross-check: single ratio r<sub>J/w</sub> known to be LU

 $r^{-1}_{J/w} = 0.96 \pm 0.05$ 

$$r_{J/\psi}^{-1} = \frac{N(\Lambda_b^0 \to pK^- J/\psi(\to e^+ e^-))}{N(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+ \mu^-))} \times \frac{\epsilon(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+ \mu^-))}{\epsilon(\Lambda_b^0 \to pK^- J/\psi(\to e^+ e^-))}$$

including stat. and syst.

• **Compatible with 1** (validated to be flat in kine & topo vars:  $P_T(\Lambda^0, lmax), m(pK), \theta_{ll}$ )

• Also checked with  $\psi(2S)$ 





#### Non-resonant modes: mass fit



Mass constraint not possible  $\rightarrow$  larger

In 0.1 <  $q^2$  < 6 GeV<sup>2</sup>/c<sup>4</sup> and m(pK<sup>-</sup>) < 2.6 GeV/c<sup>2</sup>:

- First measurement of  $\Lambda^0_{\ b} \rightarrow p K^{-} \mu^{+} \mu^{-}$  branching fraction
- Then derive first observation of  $\Lambda_b^0 \rightarrow pK^-e^+e^-$  decay mode (significance >7 $\sigma$ )

 $\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (2.65 \pm 0.14 \pm 0.12 \pm 0.29^{+0.38}_{-0.23}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}) \times 10^{-7} \mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)\Big|_{0.1 < q^2 < 6 \text{ GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.3 \pm 0$ 

uncertainty dominated by knowledge of  $\Lambda_{\rm b}$  hadronization fraction at LHC

Result for test of Lepton Universality (LU) in  $\Lambda^0_b \rightarrow pK^-l^+l^-$ 

[LHCb-PAPER-2019-040] Run 1 + 2016 data

In 0.1 <  $q^2$  < 6 GeV<sup>2</sup>/c<sup>4</sup> and m(pK<sup>-</sup>)<2.6 GeV/c<sup>2</sup>: log(likelihood) LHCb • first test of LU in b-baryons (stat. dominates ~15% & main syst. from fit model, MC corrections, norm. mode):  $\left. R_{pK}^{-1} \right|_{0.1 < q^2 < 6 \,\mathrm{GeV}^2/c^4} = 1.17^{+0.18}_{-0.16} \pm 0.07$ stat stat+syst inverting likelihood profile:  $R_{pK}|_{0.1 < q^2 < 6 \,\mathrm{GeV}^2/c^4} = 0.86 \,{}^{+\,0.14}_{-\,0.11} \pm 0.05$  $R_{pK}$  $\Rightarrow$ Test of LU:  $R_{Kp}$  compatible with unity @1 $\sigma$  & previous R<sub>K(\*)</sub> 1.0 measurements (i.e. <1) 0.8- So far, the puzzle remains and all the Test LHCb 0.6 of LU favours lower than 1 R<sub>h</sub> values - Need to add more data (add 2017+2018 part of  $q^2 \, [{\rm GeV}^2/c^4]$ Run2 (i.e. x2) + Run 3 after 2021):

- to study m(pK<sup>-</sup>) spectrum
- to split q<sup>2</sup> ranges for higher sensitivity

### Search for the very rare decay $K^0{}_s \rightarrow \mu^+ \mu^-$







#### Introducing the very rare decay $K_{s}^{0} \rightarrow \mu^{+}\mu^{-}$

• Strongly suppressed Flavour-changing Neutral Current (FCNC) transition

the cousin of  $B^0_{(s)} \rightarrow \mu^+ \mu^-$ 

- Dominated by long distance contributions through  $K^0 \rightarrow \gamma \gamma$ .
- BF( $K_L^0 \rightarrow \mu^+ \mu^-$ )= (6.84± 0.11)x10<sup>-9</sup>, in agreement with the SM.
- Allows to set model-independent bounds on the CP-violating phase of the  $s \rightarrow dll$  amplitude.
- SM prediction: BF( $K_s^0 \rightarrow \mu^+ \mu^-$ ) = (5.18 ± 1.50<sub>LD</sub> ± 0.02<sub>SD</sub>)10<sup>-12</sup>



Some constraints already in-place for many BSM scenarios (possible large virtual effects in loop/boxes) : leptoquarks [JHEP 02 (2018) 101], SUSY [JHEP 04 (2018) 019] [JHEP 05 (2018) 024] and extensions of the SM [PRL 119:201802].

→ Still room, with the present constraints

[JHEP 05 (2018) 024], [JHEP 01(2004) 009], [NPB 366 (1991) 189].



### Measuring the BF of the very rare decay $K_s^0 \rightarrow \mu^+ \mu^-$

[LHCb-PAPER-2019-038]

Use huge 2016-2018 Run 2 LHCb Ks dataset (5.6 fb-1 @ 13 TeV & K<sup>0</sup><sub>s</sub> x-sec~ 0.6 barn !!

[JHEP 05 (019) 048])

New reconstruction and triggering since Run 1 :

✓ New muons tracks implemented at HLT1 software trigger (use relatively low occupancy in muon chamber for µ-ID online) : down to  $P_T$ = 80 MeV/c & re-optimization of HLT1,2 → gain about 1 order of magnitude on  $K_s^0 \rightarrow \mu^+\mu^-$  rate wrt Run1

#### Use $K_{s}^{0} \rightarrow \pi^{+}\pi^{-}$ as control/normalization sample

- Similar selection to that of  $K_s^0 \rightarrow \mu^+ \mu^-$
- Only trigger and particle identification requirements are different.
- BF from ratio (most of the systematic effects cancel):







### **Results** for the very rare decay $K^0_{,} \rightarrow \mu^+\mu^-$

#### [LHCb-PAPER-2019-038]



4 among the 20 fitting bins (10 MVA x 2trigger types) with highest S/B ratio

result obtained from the posterior probability of the branching fraction in the fit (Run2 data only):

 $\mathcal{B}\left(K_{S}^{0} \to \mu^{+}\mu^{-}\right) < 2.2(2.6) \times 10^{-10} \text{ at } 90(95)\% \text{ CL}$ 

Minimum:  $\mathcal{B}(K_S^0 \to \mu^+ \mu^-) = 1.03^{+0.76}_{-0.68} \times 10^{-10}$ 

 $\mathcal{B}(K_S^0 \to \mu^+ \mu^-) < 2.1(2.4) \times 10^{-10}$  at 90(95)% CL

Minimum:  $\mathcal{B}(K_S^0 \to \mu^+ \mu^-) = 0.94^{+0.72}_{-0.64} \times 10^{-10}$ 

→ 18-40 times the SM predictions



## **Conclusions & outlook**

LHCb exploits an unprecedented dataset of b-,c-,s-hadrons, of any kinds, to challenge the Standard Model of Particle Physics :

- **CKM and CP violation physics:**
- New exclusive methode to measure  $|V_{cb}|$  from  $B_s^0 \rightarrow D_s^{(*)} \mu^+ \upsilon_{\mu}$ (LHCb-PAPER-2019-041, arXiv:2001:03225 & sub. to Phys. Rev. D)
- Search for CP & observation of P violation in  $\Lambda^0_{b} \rightarrow p\pi^{-}\pi^{+}\pi^{-}$

(<u>LHCb-PAPER-2019-028</u>, <u>arXiv:1912.10741</u> & sub. to Phys. Rev. Lett.)

- □ Rare decays for test of beyond the SM studies:
- Many intriguing indication of deviations in  $b \to sl^+l^-$  decays  $\rightarrow$  perform Test of Lepton Universality in  $\Lambda_b^0 \to pK^-l^+l^-$

(<u>LHCb-PAPER-2019-040</u>, <u>arXiv:1912.08139</u> & sub. to JHEP)

• Search for the very rare  $K_s^0 \rightarrow \mu^+ \mu^-$  decay: more than 3 orders of magnitude gained on the upper limit (i.e. SM x 20-40) since the beginning of LHCb (LHCb-PAPER-2019-038, to be sub. to Phys. Rev. Lett.)

Yet the statistics is a still a key issue. Many more to come with first phase of LHCb upgradre of LHCb Run3-Run4 (2021-2030):  $\approx$  50 fb<sup>-1</sup> and second phase of LHCb upgrade after (2030-2038):  $\approx$  300 fb<sup>-1</sup>  $\Rightarrow$  towards ultimate test of flavour physics on many subjects.



# **BACKUPs**




[LHCb-PAPER-2019-038] Run 1 data only

### Data sample, selection:

**a** analysis based on 7 and 8 TeV data (3  $fb^{-1}$ )

• use  $B_s^0 \rightarrow D_s^{(*)-} \mu^+ \nu_{\mu}$  decays

- trigger on high  $p_T \mu$  associated with 1-3 charged displaced tracks ■ offline, select  $\mu^+$  plus three tracks consistent with  $D^-_{(s)} \rightarrow K^+ K^- \pi^-$ 
  - $m_{K^+K^-} \in [1008, 1032] \text{ MeV}/c^2$  to suppress BG under  $D^-_{(s)}$  peaks, and keep signal and reference channel kinematics similar
  - $\blacksquare$   $m_{K^+K^-\pi^-}$  mass in  $D^-$  or  $D_s^-$  range
- produce clean  $D_{(s)}^-$  peaks by optimising selection using track/vertex quality, vertex displacement,  $p_T$  and PID criteria
- measure yields relative to reference decays ( $B^0 \rightarrow D^{(*)-} \mu^+ \nu_{\mu}$ )
- only partial reconstruction:  $D^-_{(s)} (\rightarrow \phi(K^+K^-)\pi^-)\mu^+$ 
  - cross-contamination between  $D^-\mu^+$  and  $D_s^-\mu^+$  samples below 0.1% (based on simulation)
  - combinatorial BG from same-sign  $D^-_{(s)}\mu^-$  candidates
  - veto misreconstructed/mis-IDed  $B_s^0 \to \psi^{(')}(\to \mu^+\mu^-)\phi(\to K^+K^-)$ ,  $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu}_{\mu}X$  and  $B_{(s)}^0 \to D_{(s)}^-\pi^+$



[LHCb-PAPER-2019-038] Run 1 data only

## Analysis strategy:

signal and reference yields from fit to 2D distribution of  $p_{\perp}$ ,  $m_{corr}$ 

- use  $B_s^0$  modes are signal
  - easier LQCD calculation due to heavier s quark
  - FF theory calculations available for whole  $q^2$  spectrum
  - less contamination due to less contamination from partially reconstructed decays)
- 2D templates from simulation (signal, reference decays and physics bkg) and same-sign data (combinatorial bkg)
  - floating FF parameters used to rebuild the 2D templates for signal and reference decays at each fit iteration
- $B_s^0 \rightarrow D_s^{(*)-} \mu^+ \nu_{\mu}$  yields expressed as a function of  $|V_{cb}|$  by integrating over the respective differential decay rates (equations in 2 slides)
  - FF described by either the CLN or BGL parametrization, with some parameters constrained to their LQCD determinations
- all other yields left free to float in the fit



V. Tisserand, LHCb, LPC Clermont FD

[LHCb-PAPER-2019-038] Run 1 data only

## Analysis strategy illustration:



recalculate 2D templates in  $p_{\perp}(D_{s}^{-} \mu^{+}) - m_{corr}$  for each FF parameter change



V. Tisserand, LHCb, LPC Clermont FD

[LHCb-PAPER-2019-041] Run 1 data only

→ first, fit reference channel, keeping total signal yields floating  $N^{(*)}_{ref}$ 



[LHCb-PAPER-2019-038] Run 1 data only

## External inputs:

# external inputs (experimental/theory, preliminary):

Parameter	Value	
$f_S/f_d \times b(D_S^- \to K^- K^+ \pi^-) \times \tau [ps]$	$0.01913 \pm 0.00076$	
$\mathscr{B}(D^- \to K^- K^+ \pi^-)$	$0.00993 \pm 0.00024$	
$\mathscr{B}(D^{*-} \to D^{-}X)$	$0.323 \pm 0.006$	
$\mathscr{B}(B^0 \to D^- \mu^+ \nu \mu)$	$0.0231 \pm 0.0010$	
$\mathscr{B}(B^0 \to D^{*-} \mu^+ \nu \mu)$	$0.0505 \pm 0.0014$	
$B_s^0$ mass [GeV/ $c^2$ ]	$5.36688 \pm 0.00017$	
$D_s^-$ mass [GeV/ $c^2$ ]	$1.96834 \pm 0.00007$	
$D_{s}^{*-}$ mass [GeV/ $c^{2}$ ]	$2.1122 \pm 0.0004$	

Parameter	Value
$\eta_{EW}$	$1.0066 \pm 0.0050$
$h_A(1)$	$0.902 \pm 0.013$
CLN parametrisation	
$\mathcal{G}(0)$	$1.073 \pm 0.037$
$\rho^2(D_s^-)$	$1.299\pm0.051$
BGL parametrisation	
$\mathcal{G}(0)$	$1.072 \pm 0.037$
$d_1$	$-0.0117 \pm 0.0081$
$d_2^{-1}$	$-0.239 \pm 0.048$



## Systematics:

							Uncerta	inty						
	CLN parametrization				BGL parametrization									
	$ V_{cb} $	$\rho^2(D_s^-)$	$\mathcal{G}(0)$	$\rho^2(D_s^{*-})$	$R_1(1)$	$R_{2}(1)$	$ V_{cb} $	$d_1$	$d_2$	$\mathcal{G}(0)$	$b_1$	$C_1$	$a_0$	$a_1$
Source	$[10^{-3}]$	$[10^{-2}]$	$[10^{-2}]$	$[10^{-1}]$	$[10^{-1}]$	$[10^{-1}]$	$[10^{-3}]$	$[10^{-3}]$	$[10^{-2}]$	$[10^{-2}]$	$[10^{-2}]$	$[10^{-3}]$	$[10^{-3}]$	$[10^{-1}]$
$f_s/f_d \times \mathscr{B}(D_s^- \to K^+ K^- \pi^-)(\times \tau)$	0.8	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.3	0.0	0.2	0.1
$\mathscr{B}(D^- \to K^- K^+ \pi^-)$	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.3	0.0	0.2	0.1
$\mathscr{B}(D^{*-} \to D^- X)$	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.2	0.0	0.1	0.5	0.2	0.5	0.3
$\mathscr{B}(B^0 \to D^- \mu^+ \nu_\mu)$	0.4	0.1	0.3	0.1	0.2	0.1	0.5	0.6	0.1	0.1	1.3	0.4	1.1	0.7
$\mathscr{B}(B^0 \to D^{*-} \mu^+ \nu_{\mu})$	0.3	0.1	0.2	0.1	0.1	0.1	0.2	0.4	0.1	0.1	0.8	0.3	0.7	0.4
$m(B_s^0), m(D^{(*)-})$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.2	0.1
$\eta_{EW}$	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.0	0.2	0.1
$h_{A_1}(1)$	0.3	0.1	0.2	0.1	0.1	0.1	0.3	0.4	0.1	0.1	0.9	0.3	0.8	0.5
External inputs (ext)	1.2	0.1	0.4	0.1	0.2	0.1	1.2	0.7	0.2	0.8	1.3	0.6	0.8	0.8
$D^- \rightarrow K^+ K^- \pi^-$ model	0.8	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Background	0.4	3.2	2.2	0.5	0.9	0.7	0.1	4.9	1.5	2.3	6.9	2.0	5.2	2.0
Fit bias	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	1.8	0.4	1.6	0.4
Corrections to simulation	0.0	0.1	0.5	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.2	0.1
Form-factor parametrization	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Experimental (syst)	0.9	3.2	2.2	0.5	0.9	0.7	0.9	4.9	1.5	2.3	7.2	2.1	5.4	2.0
Statistical (stat)	0.6	4.7	3.4	1.7	2.5	1.6	0.8	7.4	4.7	3.4	6.8	2.2	8.6	2.6

preliminary, [LHCb-PAPER-2019-041] in preparation

# ■ largest systematic uncertainties on $|V_{cb}|$ from $f_s/f_d$ and $D^-_{(s)} \rightarrow K^+K^-\pi^-$ model



 CPV can be measured by comparing yields between baryon and antibaryon decays δ: strong phase

$$A_{CP} = \frac{N(B \to f) - N(\overline{B} \to \overline{f})}{N(B \to f) + N(\overline{B} \to \overline{f})} \propto \frac{\sin(\delta_1 - \delta_2)\sin(\theta_1 - \theta_2)}{\sin(\theta_1 - \theta_2)}$$

- The decay receives contributions from at least two amplitudes
- Sensitive to baryon-antibaryon production asymmetries  $A_P(B)$
- ✓ Sensitive to charged particle reconstruction asymmetries  $A_D(f)$
- Measure  $\Delta A_{CP} = A_{CP}(B \rightarrow f) A_{CP}(B \rightarrow f')$  to mitigate the effect of the experimental effects
- P-even CPV test



[LHCb-PAPER-2019-028]

### Measure *CPV* via $\hat{T}$ -(P-)violating aymmetries in $\Lambda_b^0 \rightarrow ph^-h^+h^-$ :



- Is the P violation different between particle and antiparticle?
- P-odd CPV test



# Sensitivity to CPV

[LHCb-PAPER-2019-028]

- Complementary approach to other measurements
  - $a_{CP}^{\hat{T}-\text{odd}} \propto \cos\left(\delta_{even} \delta_{odd}\right) \sin\left(\theta_{even} \theta_{odd}\right)$ not sensitive if  $\delta_{even} - \delta_{odd} = \pi/2 \text{ or } 3\pi/2$

δ: strong phase
 θ: weak phase
 amplitudes

*T*-even

<del>Î</del>-odd

Phys. Rev. D 92 (2015) 076013

- By construction,  $A_{\widehat{T}}$ ,  $\overline{A}_{\widehat{T}}$ ,  $a_{CP}^{\widehat{T}-\text{odd}}$  and  $a_P^{\widehat{T}-\text{odd}}$  are largely insensitive to
  - ✓ particle/antiparticle production asymmetries
  - detector-induced charge asymmetries
  - $\implies$  reduced systematic uncertainties
- Sensitive to potential new physics effects

W. Bensalem, A. Datta, and D. London, New physics effects on triple product correlations in Ab decays, Phys. Rev. D66 (2002) 094004, arXiv:hep-ph/0208054



[LHCb-PAPER-2019-028]

# Phase-space integrated results

## TPA method

- First observation of P violation at 5.50 in a b-baryon decay
- No sign of CPV integrated over phase space

Acummotru	Dataset					
Asymmetry	Run1+Run2 (2011-2017)	Run 1 (2011-2012)				
$A_{\widehat{T}}$ (%)	$-4.68 \pm 0.99 \pm 0.24$	$-2.56 \pm 2.05 \pm 0.44$				
$\overline{A}_{\widehat{T}}$ (%)	$-3.29 \pm 0.99 \pm 0.24$	$-4.86 \pm 2.05 \pm 0.44$				
$a_P^{\widehat{T}\text{-odd}}$ (%)	$-3.98 \pm 0.70 \pm 0.17$	$-3.71 \pm 1.45 \pm 0.32$				
$a_{CP}^{\widehat{T}}$ -odd (%)	$-0.70 \pm 0.70 \pm 0.17$	$1.15 \pm 1.45 \pm 0.32$				



LHCb-PAPER-2019-028

# Results in bins of phase space

## TPA method

Comparison wrt the previous result



Compatibility at the level of 2.6σ checked with pseudo experiments



V. Tisserand, LHCb, LPC Clermont FD

## Results in bins of phase space

### TPA method

LHCb-PAPER-2019-028

Binning scheme	Dominant contribution	Hypothesis	p-value	
$A_1$	$40 \times ma^{-}$	CP-conserving	$9.8 \times 10^{-2}$	-
(helicity angles)	$M_b \rightarrow pa_1$	P-conserving	$1.8 \times 10^{-5}$	
$A_2$	$\Lambda 0 \rightarrow \Lambda t * + -$	CP-conserving	$6.4 \times 10^{-1}$	
(helicity angles)	$\Lambda_b \to N^{++} \pi$	P-conserving	$6.4 \times 10^{-2}$	
В	Entine generale	CP-conserving	$5.0 \times 10^{-3}$	
$(in  \Phi )$	Entire sample	P-conserving	$3.5 \times 10^{-7}$	
$B_1$	$40  ma^{-}$	CP-conserving	$4.7 \times 10^{-2}$	
$(in  \Phi )$	$M_b \rightarrow pa_1$	P-conserving	$4.3 \times 10^{-8}$	5.50
$B_2$	$A0 \rightarrow N^{*+}\pi^{-}$	CP-conserving	$3.4 \times 10^{-3}$	2.90
$(in  \Phi )$	$M_b \rightarrow M \rightarrow M$	P-conserving	$1.9 \times 10^{-3}$	-



## Second Approach: Energy Test

[LHCb-PAPER-2019-028]

- Model independent, statistical two-sample comparison technique
- $\bullet$  Samples  $\rightarrow$  matter/antimatter events in the Phase Space
- $\psi(d_{ij}) = e^{-d_{ij}^2/2\delta^2}$  : Weighting function
- $n, \bar{n}$ : number of  $\Lambda_b, \bar{\Lambda}_b$  candidates
- *d<sub>ij</sub>*: distance in phase space
- $\delta$ : distance parameter to be optimized







Second Approach: Energy Test

[LHCb-PAPER-2019-028]

- Going from sample (I to III) or (II to IV) constitutes a CP transformation
- Can look for CPV in two combinations:
   P-even (I + II) vs (III + IV)
   P-odd (I + IV) vs (II + III)
- P-violation: (I + III) vs (II + IV)
- By construction insensitive to global production and detection asymmetries





[LHCb-PAPER-2019-028]

Sensitivity studies: Energy Test method choice of  $\delta$ 

Three values of  $\delta$  chosen:

- 13GeV<sup>2</sup>/c<sup>4</sup> mean distance between events in the phase space
- 2.7 $GeV^2/c^4$  mean distance to the 600th nearest neighbour
- 3  $1.6 \text{GeV}^2/c^4$  mean distance to the 600th nearest neighbour with  $m^2(p\pi^+\pi^-_{slow}) < 6 \text{GeV}^2/c^4$



P-odd CPV included in  $sin(\phi)$  amplitude of the  $N^{*+}$  cascade topology



# Energy Test results

[LHCb-PAPER-2019-028]

• CP(P)-symmetry hypothesis (with permutation test)

δ	$1.6 \ \mathrm{GeV^2}/c^4$	$2.7~{\rm GeV^2}/c^4$	$13~{\rm GeV^2}/c^4$
p-value ( $CP$ -conservation, $P$ -even)	$3.1 \times 10^{-2}$	$2.7 \times 10^{-3}$	$1.3 \times 10^{-2}$
p-value ( $CP$ -conservation, $P$ -odd)	$1.5 \times 10^{-1}$	$6.9 \times 10^{-2}$	$6.5 \times 10^{-2}$
p-value ( $P$ -conservation)	$1.3 \times 10^{-7}$	$4.0 \times 10^{-7}$	$1.6 \times 10^{-1}$

Permutation test to take into account LEE



- Visualise the regions where CPV is concentrated
- Select events that contribute mostly to the Test Statistic





Test of Lepton Universality (LU) in  $\Lambda_{b}^{0} \rightarrow pK^{-}l^{+}l^{-}$ 

# **Electrons at LHCb**

#### Hardware trigger

Larger ECAL occupancy  $\rightarrow$  tighter thresholds for electrons:

- e p<sub>T</sub> > 2700/2400 MeV in 2012/2016
- μ p<sub>T</sub> > 1700/1800 MeV in 2012/2016 [LHCb-PUB-2014-046, 2019 [INST 14 P04013]

Mitigated by including events triggered independently of the signal (TIS)



 $\rightarrow$  analysis performed in 2 trigger categories

#### Interaction with detector material

Electrons radiate much more Bremsstrahlung

#### Recovery procedure in place



- miss some photons and add fake ones
- ECAL resolution worse than tracking
- → worse mass resolution for electron modes



### Test of Lepton Universality (LU) in $\Lambda_b^0 \rightarrow pK^-l^+l^-$

- → Simulation describes hadronic pK<sup>-</sup> structure: phase-space in MC + PHOTOS final state QED radiation, rich structure in data. Correct MC following amplitude analysis of  $\Lambda_b \rightarrow pKJ/\psi$  in data (Pentaquark discovery [PRL 115 (2015) 072001])
- → Selection adapted form  $\Lambda_{b}^{0} \rightarrow \Lambda_{l+l}^{-}$  angular analysis [HEP 09 (2018) 146] and  $R_{K^{*}}$  <u>LU Test</u> [JHEP 08 (2017) 055]
  - Preselection: p and p<sub>T</sub> requirements, acceptance, PID
  - Mass vetoes:  $\phi$ ,  $\Lambda_c$ ,  $D^0$ ,  $\gamma \rightarrow e^+e^-$ ,  $B^+ \rightarrow K^+ll$  and  $p \leftrightarrow K$  swaps
  - BDT against combinatorial background using kinematic information suppresses ~97% of the bckgd while retaining ~85% of the signal
  - Corrected mass cut against partially reconstructed backgrounds

### in the region (J/ $\psi \in$ [6,11] GeV<sup>2</sup>/c<sup>4</sup>):

0.1 < q<sup>2</sup> < 6 GeV<sup>2</sup>/c<sup>4</sup>
m(pK) < 2.6 GeV/c<sup>2</sup>

→ Bremsstrahlung effects in the *ee* channel (even with corrections)

➔ Special electron/muon Hardware trigger





Test of Lepton Universality (LU) in  $\Lambda_{b}^{0} \rightarrow pK^{-}l^{+}l^{-}$ 

# **Corrections to simulation**

- Hadronic pK<sup>-</sup> structure: phase-space in MC, rich structure in data
  - $\circ$  correct MC following amplitude analysis of  $\Lambda_{b} \rightarrow pKJ/\psi$  in data (Pentaquark discovery)
- Λ<sub>b</sub> kinematics and lifetime
- Particle identification (PID) response
- Event multiplicity
- Trigger response

Very good agreement between data and MC after all the corrections

Efficiency extraction from corrected MC



Phys. Rev. Lett. 115 (2015) 072001



# **Selection and backgrounds**

- <u>Preselection</u>: p and  $p_{T}$  requirements, acceptance, PID
- <u>Mass vetoes</u>:  $\Phi$ ,  $\Lambda_c$ ,  $D^0$ ,  $\gamma \rightarrow e^+e^-$ ,  $B^+ \rightarrow K^+II$  and  $p \leftarrow \rightarrow K^-$  swaps
- <u>BDT</u> against combinatorial background using kinematic information
  - ° trained on  $\Lambda_{\rm b}$  → pK<sup>-</sup>II MC and data side-band: m(pK<sup>-</sup>II) > 5825 MeV/c<sup>2</sup>
  - $\circ$  separated BDTs for e and  $\mu$  final states and run periods
  - suppress ~97% of the background while retaining ~85% of the signal
- <u>Corrected mass</u> cut against partially reconstructed backgrounds





Test of Lepton Universality (LU) in  $\Lambda_{b}^{0} \rightarrow pK^{-}l^{+}l^{-}$ 

[LHCb-PAPER-2019-040] Run 1 + 2016 data

# Nonresonant modes: extracting R<sup>-1</sup><sub>pK</sub>

Simultaneous fit to electron and muon mode, in various data-taking and trigger categories. Observables are fit parameters:

$$N^{i}(\Lambda_{b}^{0} \to pK^{-}\mu^{+}\mu^{-}) = r_{\mathcal{B}} \times \underbrace{\frac{N^{i}(\Lambda_{b}^{0} \to pK^{-}J/\psi(\to \mu^{+}\mu^{-}))}{\mathcal{B}(J/\psi \to \ell^{+}\ell^{-})}}_{\mathcal{B}(J/\psi \to \ell^{+}\ell^{-})} \times \underbrace{\frac{\epsilon^{i}(\Lambda_{b}^{0} \to pK^{-}\mu^{+}\mu^{-})}{\epsilon^{i}(\Lambda_{b}^{0} \to pK^{-}J/\psi(\to \mu^{+}\mu^{-}))}}_{\mathcal{B}(J/\psi \to \ell^{+}\ell^{-})} \times \underbrace{\frac{\epsilon^{i}(\Lambda_{b}^{0} \to pK^{-}e^{+}e^{-})}{\epsilon^{i}(\Lambda_{b}^{0} \to pK^{-}e^{+}e^{-})}}_{\epsilon^{i}(\Lambda_{b}^{0} \to pK^{-}J/\psi(\to e^{+}e^{-}))}$$

observables from resonant-mode fit from corrected MC from PDG

$$r_{\mathcal{B}} \equiv \mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)/\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi)$$



Test of Lepton Universality (LU) in  $\Lambda_b^0 \rightarrow pK^-l^+l^-$ 

# **Systematic uncertainties**

R<sup>-1</sup><sub>pK</sub> measurement statistically dominated, main systematic uncertainties:

- <u>Fit model</u>: partially reconstructed background shape in  $\Lambda_b \rightarrow pK^-ee$ • nominal:  $\Lambda_b \rightarrow pK^+ee$ ,  $K^{*-} \rightarrow K^-\pi^0$ ; alternative: nonresonant  $\Lambda_b \rightarrow pK^-\pi^0ee$  decay
- <u>Corrections to simulation</u>: alternative binning, control modes, etc
- <u>Normalisation mode</u> uncertainties: yields and efficiencies
- <u>Others</u>: m<sub>corr</sub> cut efficiency, q<sup>2</sup> migration



# **Systematic uncertainties**

Uncertainty treatment depending on whether there is correlation between data taking and trigger categories:

- <u>uncorrelated</u>: gaussian constraints included in the mass fit
  - MC corrections, normalisation mode uncertainties
- <u>correlated</u>: gaussian smearing of likelihood profile
  - $\circ$  decay model corrections, fit model, m<sub>corr</sub> cut efficiency, q<sup>2</sup> migration



BSM in  $K^0_s \rightarrow \mu^+ \mu^-$ 





## the very rare decay $K_{s}^{0} \rightarrow \mu^{+}\mu^{-}$

#### [LHCb-PAPER-2019-038]

- Main background from  $\pi \rightarrow \mu$  mis-ID (including decay in flight)
- Veto inelastic interactions with the detector material VELO and RF foil
- Use a Boosted decision tree MVA discriminator
  - → Analysis done in 10 bins of the classier for each trigger category (20 bins in total, as 2 types of L0 triggers: trigger on signal TOS or on the rest on the event TIS).
- For bckgds description see back-up slides  $(K_{s}^{0} \rightarrow \pi^{+}\pi^{-}, K_{s}^{0} \rightarrow \pi^{-}\mu^{+}\upsilon_{\mu}, K_{L}^{0} \rightarrow \mu^{+}\mu^{-}(\gamma)...)$
- Main systematic uncertainties comes from the determination of the trigger efficiency:

Hardware trigger (L0): 11% Software trigger (HLT): 13%

• Total systematic varies between 19% and 23%, depending on the trigger category and BDT bin.





the very rare decay  $K^0_{,} \rightarrow \mu^+\mu^-$ 

#### [LHCb-PAPER-2019-038]

#### Backgrounds from other strange decays



• Very rare decays.

thresholds.

•  $\mathcal{B}_{\text{eff.}} (K_L^0 \to \mu^+ \mu^-) \sim 10^{-11}.$ 

• 5 SM candidates expected in the final dataset.

Di-muon mass below the

plane [Phil. Mag. 45 (1954) 13].

Considered in the di-muon mass fit.

•  $\mathcal{B}_{SM} \left( K_S^0 \to \mu^+ \mu^- \gamma \right) = (1.45 \pm 0.27) \times 10^{-9}$ 

• 
$$\mathcal{B}\left(K_L^0 \to \mu^+ \mu^- \gamma\right) = (3.59 \pm 0.11) \times 10^{-7}$$

- Di-muon spectrum displaced to the left, no candidates in the fit region.
- $K_S^0 \to \mu^+ \mu^- \gamma \gamma$  even more suppressed.



V. Tisserand, LHCb, LPC Clermont FD

### the very rare decay $K_{s}^{0} \rightarrow \mu^{+}\mu^{-}$

#### [LHCb-PAPER-2019-038]

#### **Backgrounds from resonances**

Decays from resonances have been considered as possible backgrounds [PDG]:

Decay	Branching fraction
$\omega (782) \to \pi^0 \mu^+ \mu^-$	$(1.34 \pm 0.18) \times 10^{-4}$
$\eta  ightarrow \mu^+ \mu^- \gamma$	$(3.1 \pm 0.4) \times 10^{-4}$
$\omega (782) \to \pi^0 \pi^+ \pi^-$	$(89.3 \pm 0.6) \%$
$\eta  ightarrow \pi^+\pi^-\gamma$	$(4.22 \pm 0.08) \%$

- These resonances decay promptly.
- Only those coming from c and b hadron decays could survive the trigger and selection requirements.
- Decays in the pionic mode are not visible in the  $K^0_S \to \pi^+\pi^-$  selection.
- MC studies showed that none of them is expected to appear in the final selection.





#### Systematic uncertainties

Biggest systematic comes from the determination of the trigger efficiency:

- Hardware trigger (L0): 11%
- Software trigger (HLT): 13%

Other sources of systematic uncertainties are:

- Efficiency of the muon-identification, cross-checked using  $J/\psi \rightarrow \mu^+\mu^-$  real and simulated data. Low statistics for low- $p_T$  muons, so also need to use  $K_S^0 \rightarrow \pi \mu \nu$  to cross-check.
- Systematic on the correction for data-simulation differences.
- Efficiency ratio between  $K_S^0 \to \mu^+ \mu^-$  and  $K_S^0 \to \pi^+ \pi^-$ .
- BDT response across the years.
- Determination of the no-bias trigger rates.

Total systematic varies between 19% and 23%, depending on the trigger category and BDT bin. Lowest values are in the TIS category and higher BDT bins.



the very rare decay  $K_{s}^{0} \rightarrow \mu^{+}\mu^{-}$ 

#### Summary of the analysis strategy

Analysis using data from 2016, 2017 and 2018 using:

- Two trigger categories defined by the hardware trigger (L0):
  - TIS: candidates from triggered events where the signal decay  $(K_S^0 \rightarrow \mu^+ \mu^-)$  could (or not) have satisfied the trigger requirements.
  - xT0S: candidates from events exclusively triggered due to the presence of the signal decay.
- HLT selection common for both trigger categories.
- Topological selections, followed by cuts in the Armenteros-Podolanski plane [Phil. Mag. 45 (1954) 13] to reduce contamination from  $\Lambda^0$  decays.
- One BDT classifier trained for each trigger category (common across the years).
- Analysis done in 20 bins of the BDT classifiers.
- Use muon-identification optimized for strange decays.
- Normalization channel is  $K_S^0 \to \pi^+\pi^-$ , taken from trigger-unbiased events.
- Fit to the di-muon invariant mass, calculating the limit on the branching fraction from the posterior probability.



### LHCb upgrade schedule towards 50/fb and 300/fb in 12 and 20 years !



### LHCb upgrade schedule phase 1

### Software trigger





## LHCb: Trigger/detector upgrade phase 1 for Run 3 starting in 2021



Removal of L0 bottleneck and move to full software trigger will increase efficiencies, by a factor of  $\sim 2$  for hadronic modes

- Upgrade I replaces frontend electronics: readout at inelastic 30 MHz rate
- Far reaching detector upgrades to improve occupancy, radiation hardness Vertex Locator → Pixel; Main trackers → SciFi Tracker, UT; RICH photodetectors

### LHCb: upgrade Phase 2 (U2)

Physics case for an LHCb Upgrade II Opportunities in flavour physics, and beyond, in the HL-LHC era

The LHCb collaboration



#### Abstract

The LHCb Upgrade II will fully exploit the flavour-physics opportunities of the HL-LHC, and study additional physics topics that take advantage of the forward acceptance of the LHCb spectrometer. The LHCb Upgrade I will begin operation in 2020. Consolidation will occur, and modest enhancements of the Upgrade I detector will be installed, in Long Shutdown 3 of the LHC (2025) and these are discussed here. The main Upgrade II detector will be installed in long shutdown 4 of the LHC (2030) and will build on the strengths of the current LHCb experiment and the Upgrade I. It will operate at a luminosity up to  $2 \times 10^{34} \,\mathrm{cm^{-2}s^{-1}}$ , ten times that of the Upgrade I detector. New detector components will improve the intrinsic performance of the experiment in certain key areas. An Expression Of Interest proposing Upgrade II was submitted in February 2017. The physics case for the Upgrade II is presented here in more depth. CP-violating phases will be measured with precisions unattainable at any other envisaged facility. The experiment will probe  $b \to s\ell^+\ell^-$  and  $b \to d\ell^+\ell^-$  transitions in both muon and electron decays in modes not accessible at Upgrade I. Minimal flavour violation will be tested with a precision measurement of the ratio of  $\mathcal{B}(B^0 \to \mu^+ \mu^-)/\mathcal{B}(B^0_s \to \mu^+ \mu^-)$ . Probing charm *CP* violation at the 10<sup>-5</sup> level may result in its long sought discovery. Major advances in hadron spectroscopy will be possible. which will be powerful probes of low energy QCD. Upgrade II potentially will have the highest sensitivity of all the LHC experiments on the Higgs to charm-quark couplings. Generically, the new physics mass scale probed, for fixed couplings, will almost double compared with the pre-HL-LHC era; this extended reach for flavour physics is similar to that which would be achieved by the HE-LHC proposal for the energy frontier.



### Ideas for LHCb: upgrade Phase 2 (U2)







## LHCb: upgrade Phase 2 (U2)

#### CERN-LHCC-2018-027 LHCB-PUB-2018-009

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
$\overline{R_K \ (1 < q^2 < 6 \mathrm{GeV}^2 c^4)}$	0.1 [274]	0.025	0.036	0.007	
$R_{K^*} \ (1 < q^2 < 6 \mathrm{GeV}^2 c^4)$	0.1 [275]	0.031	0.032	0.008	-
$R_{\phi}, R_{pK}, R_{\pi}$	-	0.08,  0.06,  0.18	-	0.02,  0.02,  0.05	-
CKM tests					
$\gamma$ , with $B_s^0 \to D_s^+ K^-$	$\binom{+17}{-22}^{\circ}$ [136]	$4^{\circ}$	-	$1^{\circ}$	-
$\gamma$ , all modes	$\binom{+5.0}{-5.8}^{\circ}$ [167]	$1.5^{\circ}$	$1.5^{\circ}$	$0.35^{\circ}$	_
$\sin 2\beta$ , with $B^0 \to J/\psi K_s^0$	0.04 [609]	0.011	0.005	0.003	_
$\phi_s$ , with $B_s^0 \to J/\psi\phi$	49  mrad [44]	14 mrad		$4 \mathrm{mrad}$	22 mrad [610]
$\phi_s$ , with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	-	9 mrad	-
$\phi_s^{s\bar{s}s}$ , with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	—	$11 \mathrm{mrad}$	Under study [611]
$a_{ m sl}^s$	$33  imes 10^{-4}$ [211]	$10 imes 10^{-4}$	-	$3 imes 10^{-4}$	-
$\left V_{ub} ight /\left V_{cb} ight $	$6\% \ [201]$	3%	1%	1%	_
$B^0_s, B^0 { ightarrow} \mu^+ \mu^-$					
$\overline{\mathcal{B}(B^0 \to \mu^+ \mu^-)}/\mathcal{B}(B^0_* \to \mu^+ \mu^-)$	90% [264]	34%	_	10%	21% [612]
$\tau_{B^0 \rightarrow u^+ u^-}$	22% [264]	8%	_	2%	-
$S_{\mu\mu}^{a}$	-	_	-	0.2	-
$b \rightarrow c \ell^- \bar{\nu} \mu$ LUV studies					
$\frac{B(D^*)}{B(D^*)}$	0.026 [215, 217]	0.0072	0.005	0.002	_
$R(J/\psi)$	0.24 [220]	0.071	_	0.02	_
Charm	1				
$\Delta A_{CP}(KK - \pi\pi)$	$8.5 \times 10^{-4}$ [613]	$1.7  imes 10^{-4}$	$5.4 \times 10^{-4}$	$3.0 \times 10^{-5}$	_
$A_{\Gamma} (\approx x \sin \phi)$	$2.8 \times 10^{-4}$ [240]	$4.3 \times 10^{-5}$	$3.5 \times 10^{-4}$	$1.0 \times 10^{-5}$	_
$x \sin \phi$ from $D^0 \to K^+ \pi^-$	$13 \times 10^{-4}$ [228]	$3.2 \times 10^{-4}$	$4.6 \times 10^{-4}$	$8.0 \times 10^{-5}$	_
$x \sin \phi$ from multibody decays		$(K3\pi)$ 4.0 × 10 <sup>-5</sup>	$(K_{\rm s}^0\pi\pi)$ 1.2 × 10 <sup>-4</sup>	$(K3\pi)$ 8.0 × 10 <sup>-6</sup>	- designed
, , , , , , , , , , , , , , , , , , , ,					4 1