CERN

LHCb Overview

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on behalf of the LHCb collaboration

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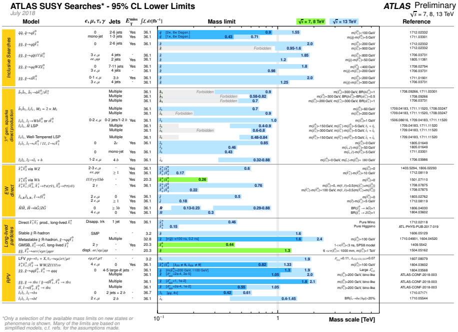
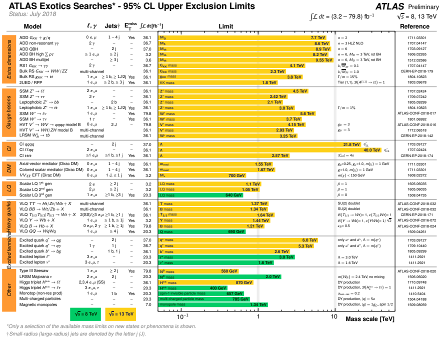
Implications Workshop 2018
October 17th – 19th, 2018

Searches for New Physics

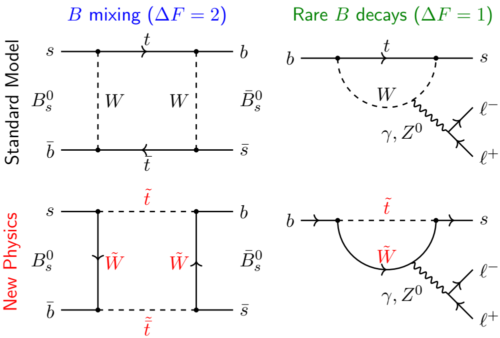




From [ATLAS SUSY summary] and [ATLAS Exotics summary], similar plots also from CMS

- With Higgs discovery all SM particles are found, however SM is an incomplete theory (DM, matter-antimatter asymmetry, . . .)
- However, no signs for BSM physics from direct searches at the LHC so far
- Precision searches with flavour probe virtual corrections to the SM
- FCNC observables can be significantly affected by new heavy BSM particles
- Allows to access mass scales well beyond direct searches ($\mathcal{O}(100\,\text{TeV})$)

Searches for New Physics



$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{SM}} + \frac{\kappa^2}{\Lambda^2_{\text{NP}}}\mathcal{O}$$

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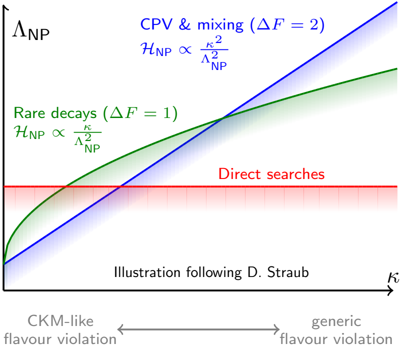
Exclusion limits for NP searches



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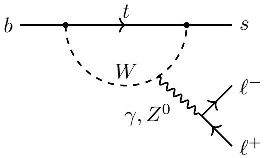
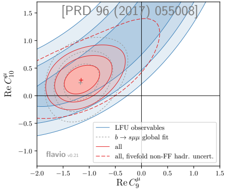
Flavour Anomalies

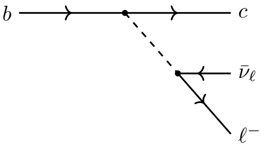
Loop-level $b \to s\ell\ell$ FCNCs



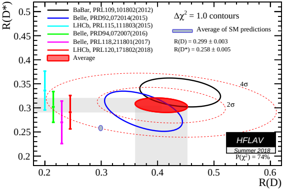
- $B^0 \to K^{*0}\mu^+\mu^-$ angular: $\sim 3.4\,\sigma$
  [LHCb, JHEP 02 (2016) 104]
- $\mathcal{B}(b \to s\mu^+\mu^-)$: $\sim 3\,\sigma$
  [LHCb, JHEP 09 (2015) 179]
- LFU in R_K, R_{K^*}: $2.6\,\sigma$, $2.4\,\sigma$
  [LHCb, PRL 113 (2014) 151601] [LHCb, JHEP 08 (2017) 055]


[PRD 96 (2017) 055008]

Tree-level $b \to c\tau\nu$ decays



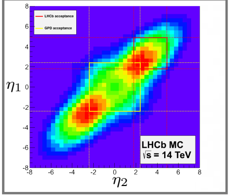
- $R(D)$: $2.3\,\sigma$ [BaBar, PRL 109 (2012) 101802]
  [BaBar, PRD 88 (2013) 072012] [Belle, PRD 92 (2015) 072014]
- $R(D^*)$: $3.0\,\sigma$ [LHCb, PRL 115 (2015) 111803] [LHCb, PRL 120 (2017) 171802
  [BaBar, PRL 109 (2012) 101802] [BaBar, PRD 88 (2013) 072012] [Belle, PRD 92 (2015) 072014]
  [Belle, PRD 94 (2016) 072007] [Belle, PRL 118 (2017) 211801] [Belle, PRD 97 (2018) 012004]
- Combination $\sim 3.8\sigma$

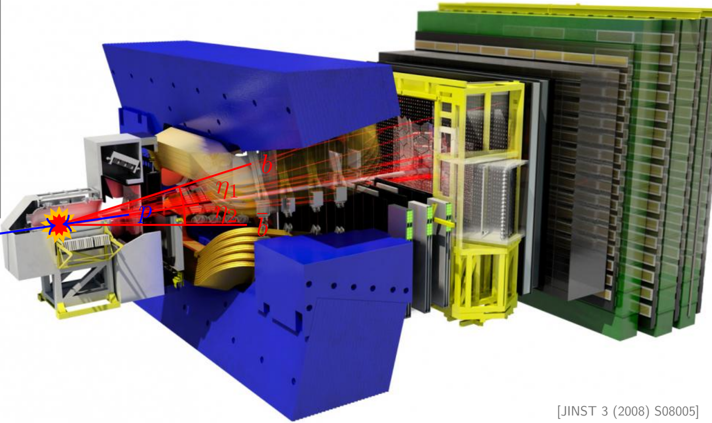


- No single measurement at the level of an observation
- However, interesting pattern emerges

LHCb: Optimized for precision flavour measurements

$b\bar{b}$ production





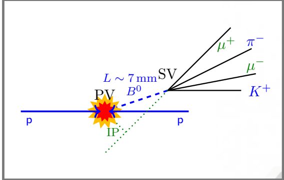
[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

- $b\bar{b}$ produced in forward/backward direction → Optimized acceptance $2 < \eta < 5$
- Huge production cross-sections in LHCb acceptance 1.4×10^{11} $b\bar{b}$-pairs per fb^{-1} (Run 2)
- All beauty, charm and strange hadrons produced (B_s^0, Λ_b^0, B_c^+, D_s^+, Λ_c^+, Σ^+, $\ldots$)

	$\sqrt{s} = 7\,\mathrm{TeV}$	$\sqrt{s} = 13\,\mathrm{TeV}$
$\sigma_{b\bar{b}}^{\text{acc.}}\,[\,\mu\mathrm{b}]$	75.3 ± 14.1	$144 \pm 1 \pm 21$
$\sigma_{c\bar{c}}^{\text{acc.}}\,[\,\mu\mathrm{b}]$	1419 ± 134	2940 ± 241
Refs.	[PLB 694:209 (2010)] [NPB 871 (2013) 1-20]	[PRL 118 (2017) 052002] [JHEP 03 (2016) 159]

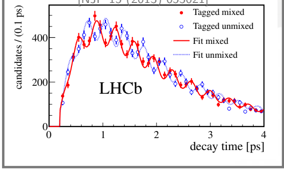
LHCb: Optimized for precision flavour measurements

Heavy flavour signature

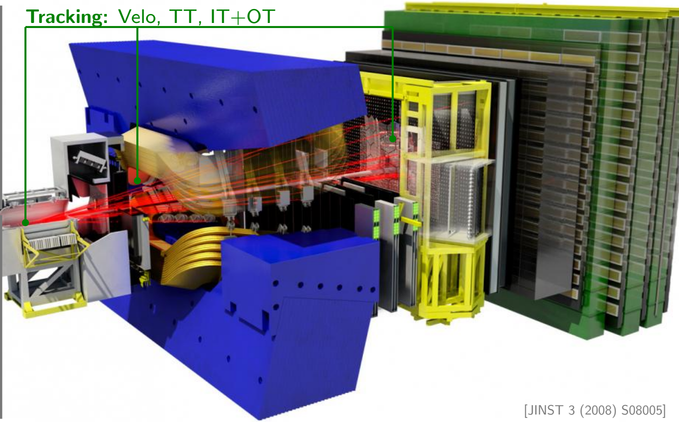


B_s^0 mixing

[NJP 15 (2013) 053021]



Tracking: Velo, TT, IT+OT

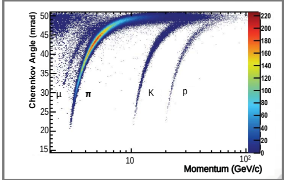


[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

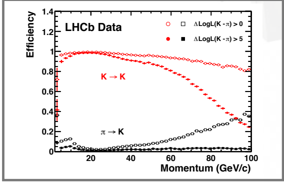
- Excellent IP resolution $\sim 20\,\mu\mathrm{m}$ to identify B decay vertices
- Decay time resolution $\sim 45\,\mathrm{fs}$
- Resolutions $\sigma(p)/p = 0.5 - 1\%$, $\sigma(m) \sim 22\,\mathrm{MeV}$ for two-body B-decays
  $\rightarrow$ Low combinatorial backgrounds

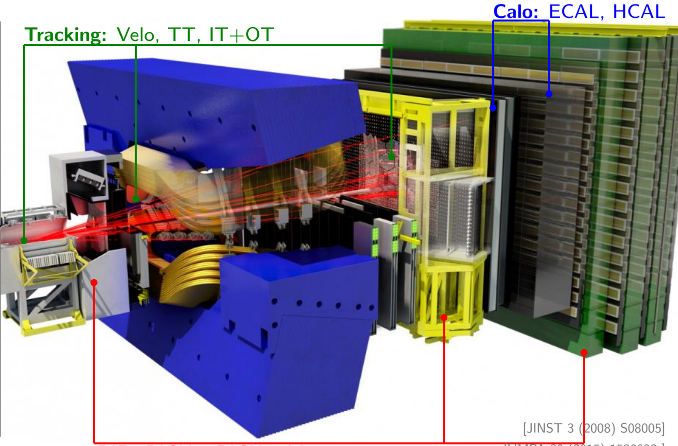
LHCb: Optimized for precision flavour measurements

Cherenkov angle *vs.* momentum



K identification/π misidentification





Calo: ECAL, HCAL

Tracking: Velo, TT, IT+OT

PID: RICH1, RICH2, Muon

[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

- Excellent particle identification through RICH detectors and muon system
- High identification efficiencies $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\mu\to\mu} \sim 97\%$
- Low misidentification probabilities $\epsilon_{\pi\to K} \sim 5\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
  → Low backgrounds from misidentification

LHCb: Optimized for precision flavour measurements

LHCb Run 2 trigger

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$	**400 kHz $\mu/\mu\mu$**	**150 kHz e/γ**

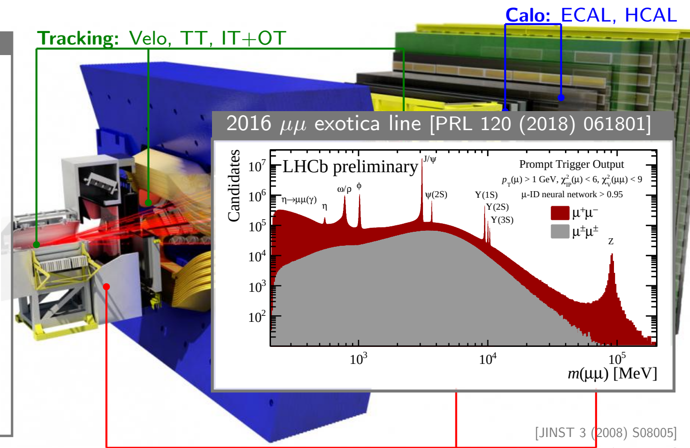
Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage



Calo: ECAL, HCAL

Tracking: Velo, TT, IT+OT

2016 $\mu\mu$ exotica line [PRL 120 (2018) 061801]

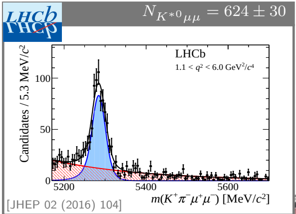
[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

PID: RICH1, RICH2, Muon

- Flexible trigger system with low thresholds: $p_\mathrm{T}(\mu) > 1.8\,\mathrm{GeV}$, $E_\mathrm{T}(e) > 3.0\,\mathrm{GeV}$
- High efficiencies, *e.g.* $\epsilon_\mathrm{trigger}(B \to J/\psi\, X) \sim 90\%$
- Since Run 2: Online calibration and alignment, allows use of PID in trigger
- Allows low p_T physics: charm, strange, exotica, . . .

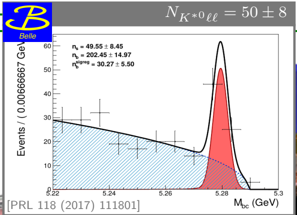
LHCb: Optimized for precision flavour measurements

$N_{K^{*0}\mu\mu} = 624 \pm 30$



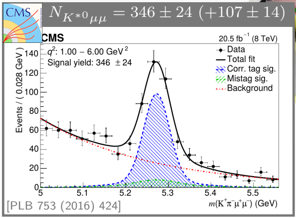
[JHEP 02 (2016) 104]

$N_{K^{*0}\ell\ell} = 50 \pm 8$



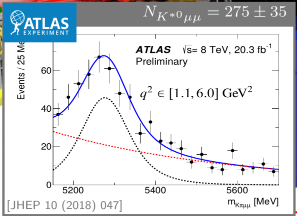
[PRL 118 (2017) 111801]

$N_{K^{*0}\mu\mu} = 346 \pm 24\ (+107 \pm 14)$

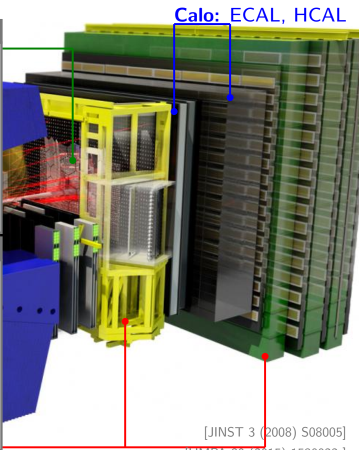


[PLB 753 (2016) 424]

$N_{K^{*0}\mu\mu} = 275 \pm 35$



[JHEP 10 (2018) 047]



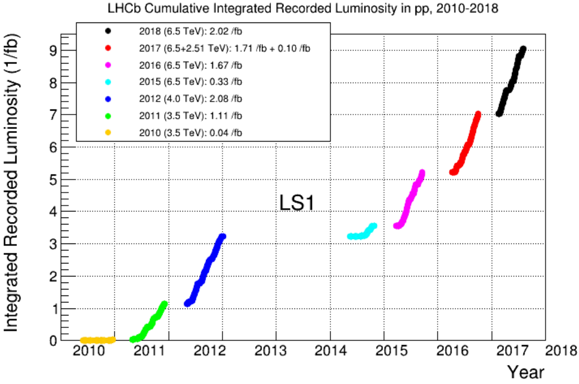
Calo: ECAL, HCAL

PID: RICH1, RICH2, Muon

[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

- Performance comparison using $B^0 \to K^{*0}\mu^+\mu^-$ Run 1 results as example
- LHCb compares very favourably
  - Largest yields ($b\bar{b}$ cross-section, large acceptance and high trigger efficiencies)
  - Excellent mass resolution and low combinatorial backgrounds
  - Negligible peaking backgrounds due to powerful particle identification

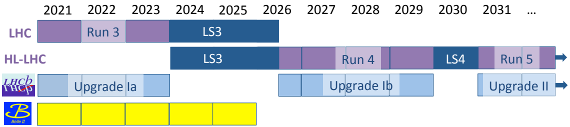
LHCb current: Run 1 and 2

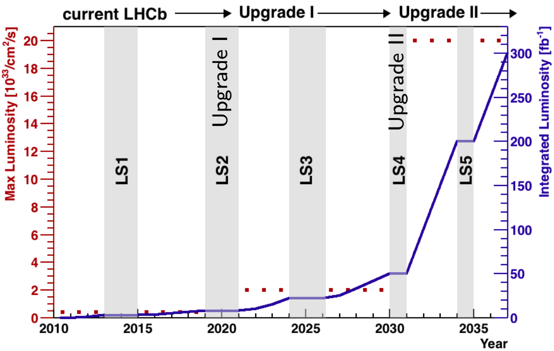


- A wealth of results published with Run 1 data
- Several new results published or upcoming include Run 2 data
- $> 9\,\mathrm{fb}^{-1}$ data by end of Run 2: Look forward to many exciting new results!

→ Accounting for $\sigma_{b\bar{b}}$ increase expect gain factor ~ 5 of Run 1+2 *wrt.* Run 1

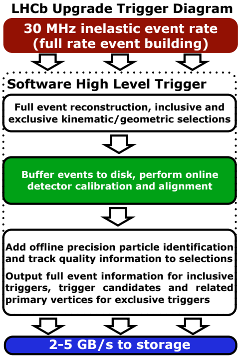
LHCb Upgrade schedule





- Upgrade I a+b: $50\,\mathrm{fb}^{-1}$ after Run 3+4 at $\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Upgrade II: $300\,\mathrm{fb}^{-1}$ after Run 5+6 at $\mathcal{L} = 2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Full Belle 2 detector data taking starting 2019, $50\,\mathrm{ab}^{-1}$ sample 2025

LHCb Upgrade I: $50\,\mathrm{fb}^{-1}$ at $2\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$



LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

LHCb UPGRADE
Letter of Intent

Framework TDR
LHCb UPGRADE
Technical Design Report

UPGRADE
LHCb TDR
Trigger and Online
Technical Design Report

UPGRADE
LHCb TDR
Tracker
SciFi Tracker
Upstream Tracker
Technical Design Report

UPGRADE
LHCb TDR
Particle Identification
Technical Design Report

UPGRADE
LHCb TDR
VELO
VERTEX LOCATOR
Technical Design Report

UPGRADE
LHCb TDR
Software & Computing
Technical Design Report

- Removal of L0 bottleneck and move to full software trigger will increase efficiencies, by a factor of ~ 2 for hadronic modes
- Upgrade I replaces frontend electronics: readout at inelastic $30\,\mathrm{MHz}$ rate
- Far reaching detector upgrades to improve occupancy, radiation hardness
  Vertex Locator → Pixel; Main trackers → SciFi Tracker, UT; RICH photodetectors
  → Replacing 90% of active channels!

LHCb Upgrade I: $50\,\mathrm{fb}^{-1}$ at $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

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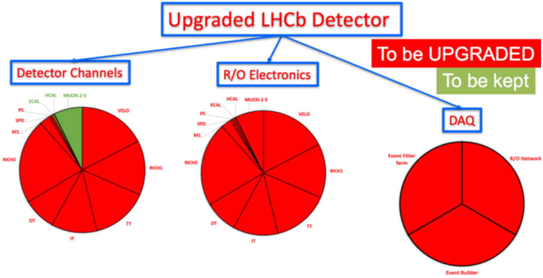

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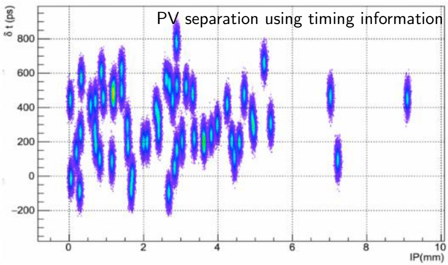
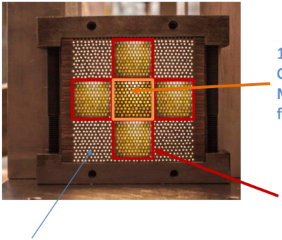
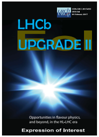
LHCb Upgrade II: $300\,\mathrm{fb}^{-1}$ at $2\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$


PV separation using timing information


1 cell GaGG:ce, Mg, Ti fibers from FOMOS

4 cells YAG fibers from Crytur

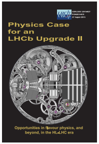
Plastic fibers


LHCb UPGRADE II

EoI

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

Expression of Interest


Physics Case for an LHCb Upgrade II

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

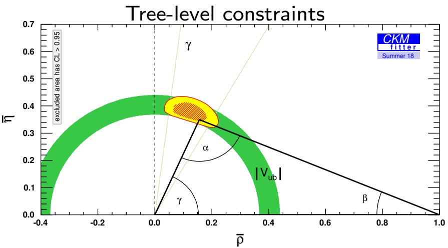
- Upgrade II will collect $300\,\mathrm{fb}^{-1}$ to fully exploit the flavour physics potential of the HL-LHC
- EoI [CERN-LHCC-2017-003] and Physics case [CERN-LHCC-2018-027] received very positive response, Framework TDR requested
- Pileup of ~ 50 requires upgrades to cope with radiation and occupancy
- Use of timing information to separate primary vertices
- Reduced material in Vertex Detector to improve IP resolution
- Studies ongoing for improved ECAL with higher granularity

NP searches using CKM precision measurements

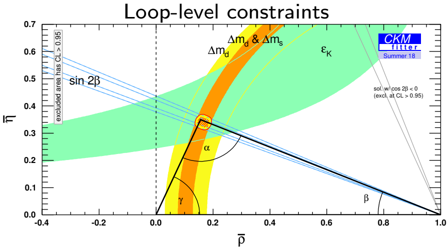
$$\begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3\left(\rho-i\eta\right) \\ -\lambda & 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}\left(1+4A^2\right) & A\lambda^2 \\ A\lambda^3\left(1-\rho-i\eta\right) & -A\lambda^2+A\frac{\lambda^4}{2}\left(1-2\left(\rho+i\eta\right)\right) & 1-A^2\frac{\lambda^4}{2} \end{pmatrix} + \mathcal{O}(\lambda^5)$$

- Quark flavour in SM described by 6 couplings and 4 CKM parameters
- A, λ, ρ, η not predicted by SM, need to be measured

Tree-level constraints

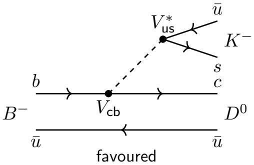


Loop-level constraints



- Compare tree-level constraints with loop-level constraints
- Still a lot of room for NP → More precise determinations needed

Determining γ from $B^- \to \overset{(-)}{D}{}^0 K^-$ tree-level decays



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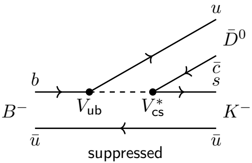

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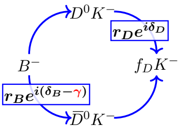
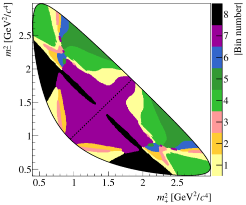
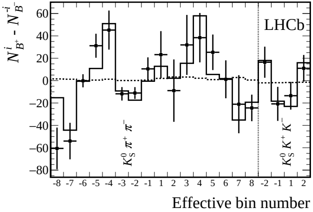
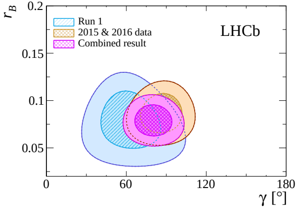


- Access γ with common $\overset{(-)}{D}{}^0$ final state f_D
  1. ADS flavour specific [PRL 78 (1997) 3257]
  2. GLW CP eigenstate [PLB 265 (1991) 172] [PLB 253 (1991) 483]
  3. GGSZ Dalitz analysis [PRD 68 (2003) 054018]



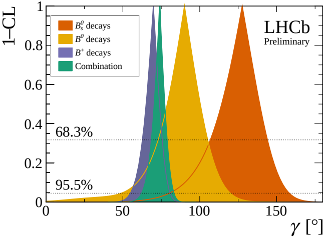


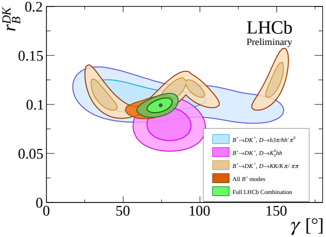


- Dalitz plot analysis of ~ 4500 $B^- \to D(K^0_S h^+h^-)K^-$ decays ($2\,\mathrm{fb}^{-1}$ Run 2)
- Most precise single measurement $\gamma = (87^{+11}_{-12})^\circ$ [JHEP 08 (2018) 176]

LHCb γ combination exploits complementarity of inputs

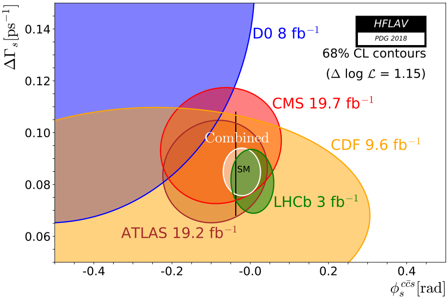
	B decay	D decay	Method	Ref.	Dataset[†]
	$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
	$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1
	$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1
	$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1
	$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1
New	$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2
	$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1
	$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
	$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2
New	$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2
	$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1
	$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1
	$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1
	$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1
	$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1
New	$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1



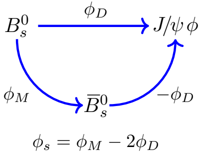


- LHCb γ combination yields $\gamma = (74.0^{+5.0}_{-5.8})^\circ$ [LHCb-CONF-2018-002]
- Dominating the world average $\gamma = (73.5^{+4.2}_{-5.1})^\circ$ [HFLAV winter 2018]
- Slight tension with loop-determination $\gamma = (65.6^{+1.0}_{-3.4})^\circ$ [CKMfitter 2018]
- 3–4° precision with full Run 2, 1.5° with $23\,\mathrm{fb}^{-1}$, 0.35° with Upgrade II

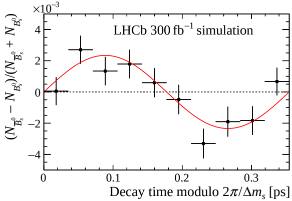
V_{ts} phase ϕ_s



[PRL 109 (2012) 171802]
[PRL 94 (2005) 101803]
[PRD 85 (2012) 032006]
[PRL 102 (2009) 032001]
[PRD 90 (2014) 052007]
[JHEP 08 (2016) 147]
[PLB 757 (2016) 97]
[PRL 114 (2015) 041801]
[PLB 736 (2014) 186]
[JHEP 08 (2017) 037]
[PLB 762 (2016) 253]
[PRL 113 (2014) 211801]
[PRD 87 (2013) 112010]



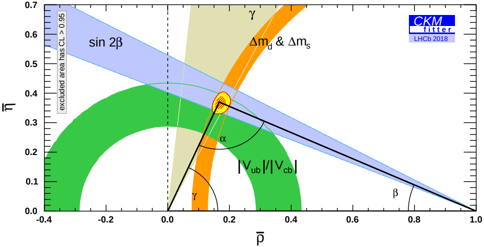
$$\phi_s = \phi_M - 2\phi_D$$



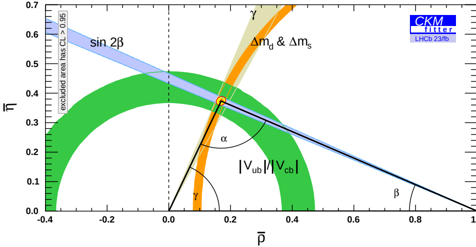
- Combination $\phi_s = -0.021 \pm 0.031\,\mathrm{rad}$ [HFLAV 2018]
- Compare with $\phi_s = -0.037 \pm 0.001\,\mathrm{rad}$ from indirect constraints
- Combination dominated by $B_s^0 \to J/\psi\,\phi$ time-dependent angular analysis by LHCb [PRL 114 (2015) 041801], stat. limited
- LHCb Upgrade II expects sensitivity of $0.004\,\mathrm{rad}$ with $300\,\mathrm{fb}^{-1}$

CKM prospects

LHCb now



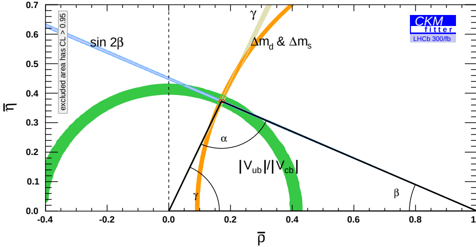
LHCb Upgrade Ia $23\,\mathrm{fb}^{-1}$



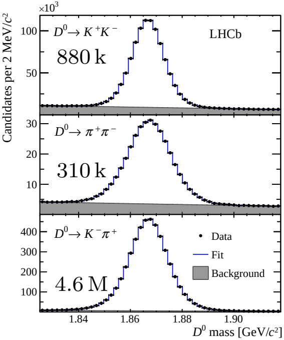
Inputs

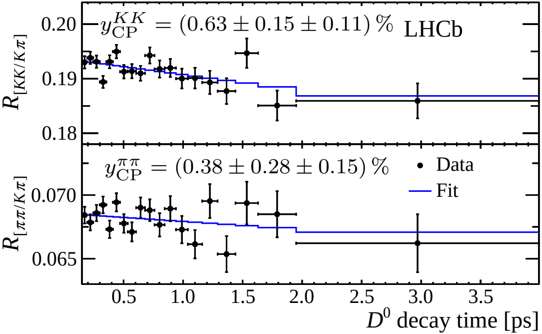
	LHCb (now)	LHCb 23 fb^{-1}	LHCb 300 fb^{-1}
CKM inputs (LHCb)			
$\sin 2\beta$	0.760 ± 0.034	0.7480 ± 0.0095	0.7480 ± 0.0024
γ rad	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.025	1.136 ± 0.005
$\lvert V_{\mathrm{ub}}\rvert/\lvert V_{\mathrm{cb}}\rvert$	15%	6%	1%
$\Delta m_d(\,\mathrm{ps}^{-1})$	0.5065 ± 0.0020	same	same
$\Delta m_s(\,\mathrm{ps}^{-1})$	17.757 ± 0.021	same	same
Hadronic input (LQCD)			
$\xi = \frac{f_{B_d}\sqrt{B_{B_d}}}{f_{B_s}\sqrt{B_{B_s}}}$	-	0.6%	0.2%

LHCb Upgrade II $300\,\mathrm{fb}^{-1}$



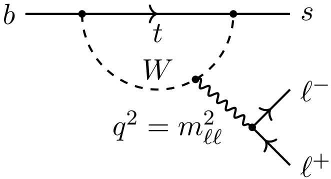
Mixing and CPV in Charm: y_{CP}

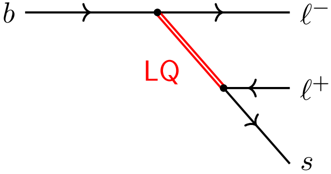




- Mixing parameters: $x = \frac{m_2 - m_1}{\Gamma}$, $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$
$$y_{\mathrm{CP}} = \frac{\Gamma_{\mathrm{CP}+}}{\Gamma} - 1 \overset{\text{no CPV}}{=} y$$
- Measured using time-dependent ratio between $\pi^+\pi^-$ (K^+K^-) and $K^-\pi^+$ yields, using semileptonic tag $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$
- Result: $y_{\mathrm{CP}} = (0.57 \pm 0.13 \pm 0.09)\,\%$ [LHCb-PAPER-2018-038] compatible with current world average $(0.84 \pm 0.16)\,\%$ and as precise
- Appearance of this result on the arXiv is imminent!

Rare decays as probes for NP





- Rare FCNC decays are loop-suppressed in the SM
- NP can contribute, affect decay rates and angular distributions
- Model independent description in effective field theory

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^{*} \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i} + \frac{\boxed{\kappa}}{\boxed{\Lambda_{\text{NP}}^2}} \mathcal{O}$$

Local operator

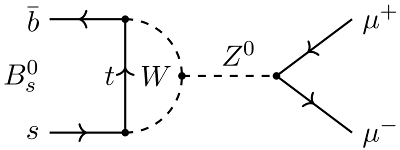
Wilson coefficient (“effective coupling”)

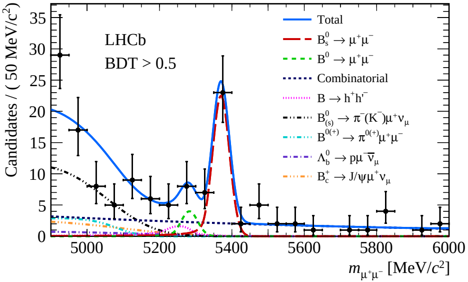
NP coupling

NP scale

$i = 1, 2$	Tree
$i = 3-6, 8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9, 10$	EW penguin
$i = S, P$	(Pseudo)scalar penguin

The very rare decay $B_s^0 \to \mu^+\mu^-$





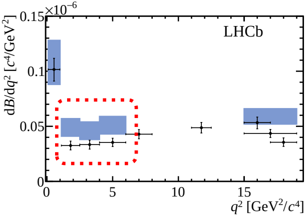
- Loop- and helicity suppressed with purely leptonic final state: Experimentally and theoretically clean probe of new (pseudo)scalars
- First observation of $B_s^0 \to \mu^+\mu^-$ ($7.8\,\sigma$) by single experiment with $4.4\,\text{fb}^{-1}$ of data (incl. $1.4\,\text{fb}^{-1}$ Run 2) by LHCb [PRL 118 (2017) 191801]:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9} \qquad \mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}) \times 10^{-10}$$

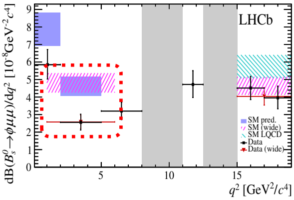
- Eff. lifetime $\tau(B_s^0 \to \tau^+\tau^-) = 2.04 \pm 0.44 \pm 0.05\,\text{ps}$ complementary probe
- Upgrade II: 4% uncertainty on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$, 10% on B^0/B_s^0 ratio, 2% uncertainty on τ, time-dep. CP-violation $\sigma(S_{\mu\mu}) \sim 0.2$

Branching fractions of rare $b \to s\mu^+\mu^-$ decays

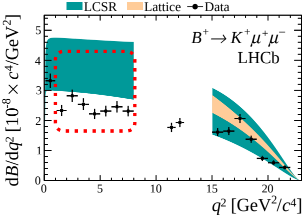
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



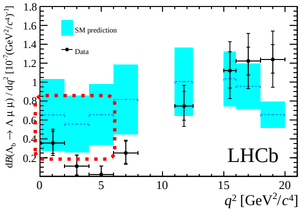
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



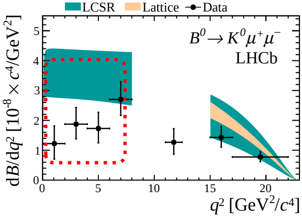
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



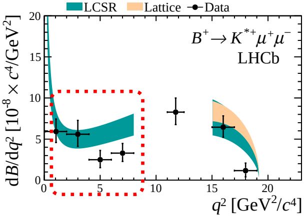
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



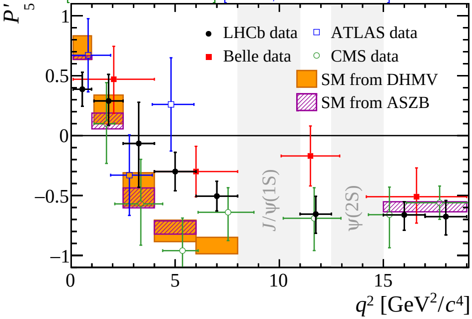
$B^+ \to K^{*+}\mu^+\mu^-$ [JHEP 06 (2014) 133]

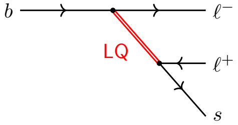


- Pattern: Data consistently below SM predictions
- But sizeable hadronic theory uncertainties
- Tensions at $1-3\,\sigma$ level

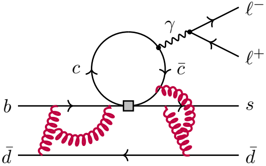
Angular analyses of $b \to s\mu^+\mu^-$ decays: P_5' and friends

[LHCb, JHEP 02 (2016) 104] [Belle, PRL 118 (2017) 111801]
[CMS-PAS-BPH-15-008] [ATLAS, arXiv:1805.04000]





NP or SM $c\bar{c}$-loop?



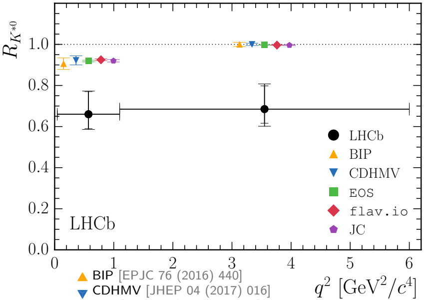
- $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ exhibits rich angular structure, one example the less form-factor dependent observable P_5'
- In q^2 bins $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ local deviations of $2.8\,\sigma$ and $3.0\,\sigma$ LHCb only global $B^0 \to K^{*0}\mu^+\mu^-$ analysis corresponds to $3.4\,\sigma$
- Significances depend on hadronic charm-loop uncertainties
- Run 2 update in preparation, q^2-unbinned approaches also pursued

[JHEP 11 (2017) 176] [EPJC 78 (2018) 453] [arXiv:1805.06378] [arXiv:1805.06401]

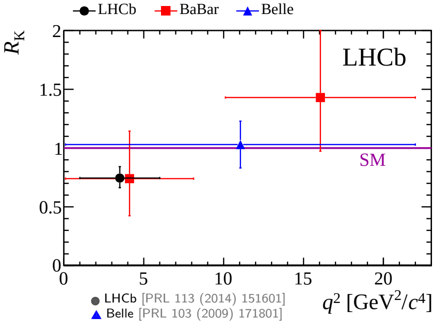
Lepton Flavour Universality tests R_{K^*} and R_K

- $R_X = \int \frac{\mathrm{d}\Gamma(B\to X\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2 / \int \frac{\mathrm{d}\Gamma(B\to Xe^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2 \overset{\text{SM}}{=} 1 \pm \mathcal{O}(1\%)$ [EPJC 76 (2016) 8,440]
  unaffected by hadronic uncertainties

[JHEP 08 (2017) 055]



▲ BIP [EPJC 76 (2016) 440]
▼ CDHMV [JHEP 04 (2017) 016]
■ EOS [PRD 95 (2017) 035029]
◆ flav.io [EPJC 77 (2017) 377]
⬟ JC [PRD 93 (2016) 014028]

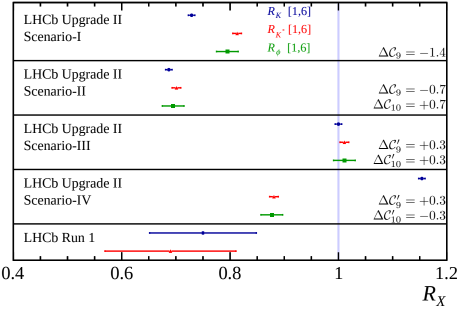


● LHCb [PRL 113 (2014) 151601]
▲ Belle [PRL 103 (2009) 171801]
■ BaBar [PRD 86 (2012) 032012]

- Numerical result and compatibility with SM prediction(s):

$R_{K^*}(0.045 < q^2 < 1.1\,\mathrm{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03$ at low q^2: $2.1\text{-}2.3\,\sigma$
$R_{K^*}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$ at central q^2: $2.4\text{-}2.5\,\sigma$
$R_K(1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$ at central q^2: $2.6\,\sigma$

Prospects for rare decays



Observable	Current	LHCb 23 fb^{-1}	 300 fb^{-1}	Belle II
R_K	0.1	0.025	0.007	0.036
R_{K^*}	0.1	0.031	0.008	0.032
R_ϕ	-	0.08	0.02	-
R_{pK}	-	0.06	0.02	-
R_π	-	0.18	0.05	-

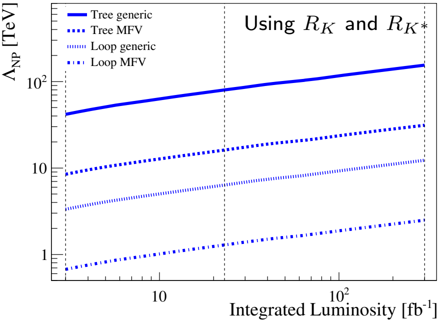
- R_K and R_{K^*} updates with Run 2 data in preparation,
  In addition, other R_X will be measured *e.g.* R_{pK}, R_ϕ, $R_{K\pi\pi}$, ...
- Upgrade II samples will reduce R_{K,K^*} uncertainties below %-level
- Huge samples in Upgrade II:

Mode	$K^+\mu^+\mu^-$	$K^{*0}\mu^+\mu^-$	$K^+e^+e^-$	$K^{*0}e^+e^-$
Yield	862 000	435 000	46 000	20 000

- Upgrade II NP reach up to $\mathcal{O}(100\,\mathrm{TeV})$
  Λ_{NP} reach factor ~ 2 higher than Upgrade Ia

Prospects for rare decays

Integrated Luminosity	$3\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K and R_{K^*} measurements			
$\sigma(C_9)$	0.44	0.12	0.03
$\Lambda_{\rm NP}^{\rm tree\,generic}$ [TeV]	40	80	155
$\Lambda_{\rm NP}^{\rm tree\,MFV}$ [TeV]	8	16	31
$\Lambda_{\rm NP}^{\rm loop\,generic}$ [TeV]	3	6	12
$\Lambda_{\rm NP}^{\rm loop\,MFV}$ [TeV]	0.7	1.3	2.5
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis			
$\sigma^{\rm stat}(S_i)$	0.034–0.058	0.009–0.016	0.003–0.004
$\sigma(C'_{10})$	0.31	0.15	0.06
$\Lambda_{\rm NP}^{\rm tree\,generic}$ [TeV]	50	75	115
$\Lambda_{\rm NP}^{\rm tree\,MFV}$ [TeV]	10	15	23
$\Lambda_{\rm NP}^{\rm loop\,generic}$ [TeV]	4	6	9
$\Lambda_{\rm NP}^{\rm loop\,MFV}$ [TeV]	0.8	1.2	1.9

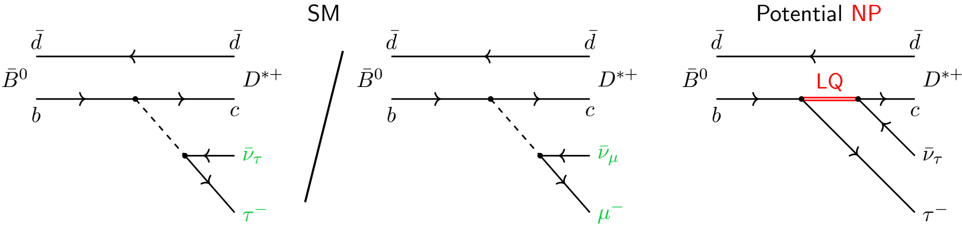


- R_K and R_{K^*} updates with Run 2 data in preparation,
  In addition, other R_X will be measured *e.g.* R_{pK}, R_ϕ, $R_{K\pi\pi}$, ...
- Upgrade II samples will reduce R_{K,K^*} uncertainties below %-level
- Huge samples in Upgrade II:

Mode	$K^+\mu^+\mu^-$	$K^{*0}\mu^+\mu^-$	$K^+e^+e^-$	$K^{*0}e^+e^-$
Yield	862 000	435 000	46 000	20 000

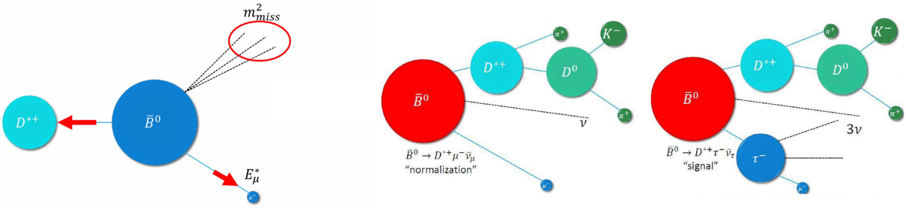
- Upgrade II NP reach up to $\mathcal{O}(100\,\text{TeV})$
  $\Lambda_{\rm NP}$ reach factor ~ 2 higher than Upgrade Ia

Lepton universality test in tree-level decays



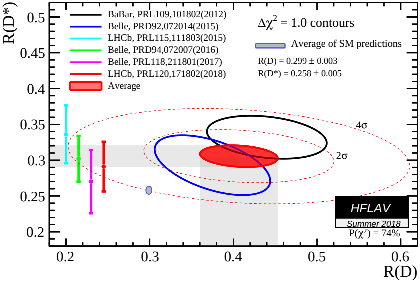
- Lepton universality can also be tested in $b \to c\ell\nu$ tree-level decays
- Modified coupling in particular possible to third generation τ
- Theoretically clean tests possible in B decays:
  $$R_{D^*} = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} \overset{\text{SM}}{=} 0.252 \pm 0.003$$ [PRD 85 (2012) 094025]
- Dependence on V_{cb} cancels in ratio

Current experimental status

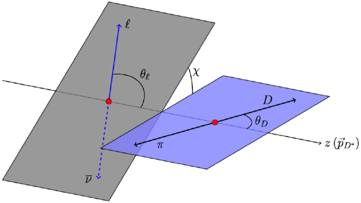


- LHCb also has access to other b-hadron species: B^0_s, B^+_c, Λ^0_b, ...
- So far LHCb has published analyses of
  - $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$ with $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ compatible with the SM at $2.1\,\sigma$ [PRL 115 (2015) 111803]
  - $R_{D^*} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ compatible with the SM at $1\,\sigma$ [PRL 120 (2018) 171802]
  - $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ using B^+_c decays compatible with the SM at $\sim 2\,\sigma$ [PRL 120 (2018) 121801]

$R_{D^{(*)}}$ combination and prospects



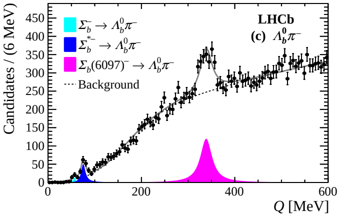
	LHCb			
Observable	Current	23 fb^{-1}	300 fb^{-1}	Belle II
R_{D^*}	0.026	0.0072	0.002	0.005
$R_{J/\psi}$	0.24	0.071	0.02	-



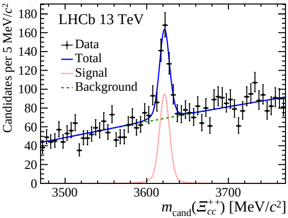
- All measurements see excess wrt. SM prediction
- Tension of R_D/R_{D^*} combination corresponds to $\sim 3.8\,\sigma$
- Run 2 updates ongoing, additional modes in preparation $(R_{D_s},\ R_{\Lambda_c^+},\ \ldots)$
- Upgrade II will allow angular analysis to determine spin structure of NP
- Profits from vertexing improvements and higher trigger ϵ in the Upgrade(s)

Spectroscopy Results

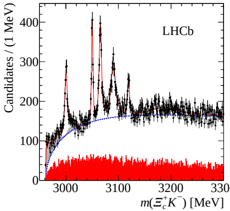
$\Lambda_b^0\pi^\pm$ resonances [arXiv:1809.07752]



Ξ_{cc}^{++} observation [PRL 119 (2017) 112001]

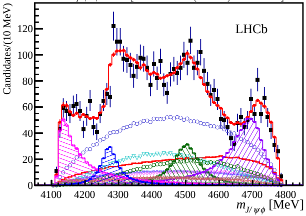


Ω_c states [PRL 118 (2017) 182001]

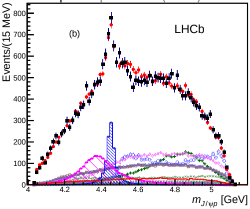


And many more!

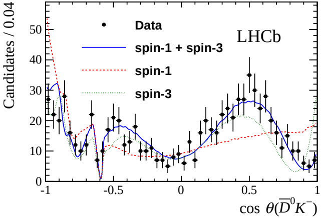
$B^+ \to J/\psi\,\phi K^+$ [PRL 118 (2017) 022003]



Pentaquarks [PRL 115 (2015) 072001]

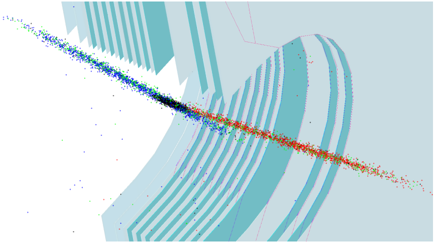


$\bar{D}^0K$ resonances [PRL 113 (2014) 162001]

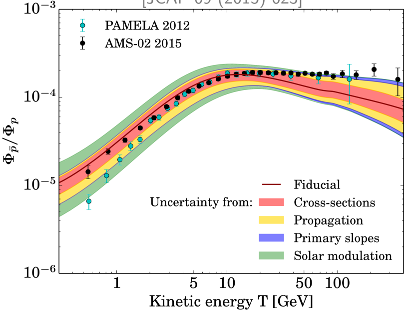


- Many very interesting recent results from spectroscopy, unfortunately no time to go into detail here
- Detailed presentations following this talk in the very same session

LHCb is ~~not~~ a fixed target experiment



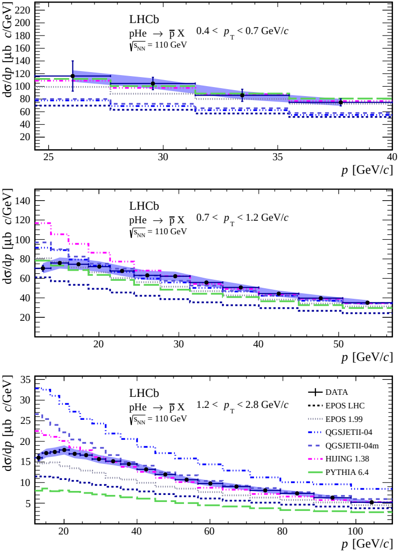
[JCAP 09 (2015) 023]



- LHCb can be turned into fixed target experiment using SMOG (**S**ystem for **M**easuring **O**verlap with **G**as) system [JINST 9 (2014) P12005]
- Originally developed for beam profile measurements for $\mathcal{L}$ determination
- Target: Noble Gas injected close to vertex detector $(\mathrm{He}, \mathrm{Ne}, \mathrm{Ar}, \ldots)$
- Allows very useful measurements connected to astroparticle physics
  - AMS-02 and PAMELA measure cosmic ray flux of $\bar{p}$ with high precision
  - Requires knowledge of $\bar{p}$ production in interaction of cosmic rays with interstellar medium $(\mathrm{H}, \mathrm{He})$

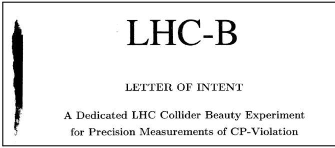
$\bar{p}$ production in $p\mathrm{He}$ collisions at $\sqrt{s_{\mathrm{NN}}} = 110\,\mathrm{GeV}$

- LHCb performed first measurement of $\sigma(p + \mathrm{He} \to \bar{p} + X)$ at $\sqrt{s_{\mathrm{NN}}} = 110\,\mathrm{GeV}$ [arXiv:1808.06127]
- Exploiting particle identification to separate $K^-/\pi^-/\bar{p}$
- Determine σ in bins of p and p_{T}
- Uncertainty $< 10\%$ for most bins, lower than spread from various predictions,
- Result will significantly improve future predictions of $\bar{p}$ flux



Conclusions

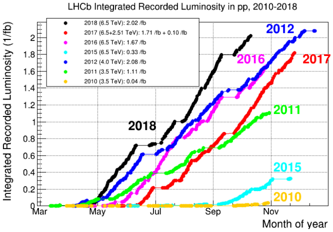
- LHCb has shown excellent performance in Run 1 and 2 resulting in large high quality data samples
- The LHCb Physics programme is unique and diverse, far beyond CP violation and rare decays
- Many results in agreement with SM prediction setting strong constraints on NP
- But some intriguing tensions remain, the *Flavour anomalies*
    - $b \to s\mu^+\mu^-$ $\mathcal{B}$ and angular observables
    - LFU tests in rare decays: R_K and R_{K^*}
    - LFU tests in $b \to c\ell\nu$ decays: $R_{D^{(*)}}$
- Updates with Run 2 data coming soon that will clarify the situation
- Data already on tape corresponds to an effective signal yield increase by factor ~ 5 *wrt.* Run 1



LHC-B

LETTER OF INTENT

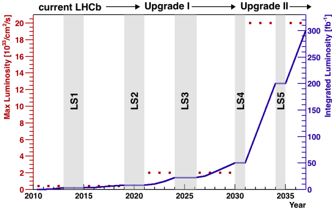
A Dedicated LHC Collider Beauty Experiment
for Precision Measurements of CP-Violation

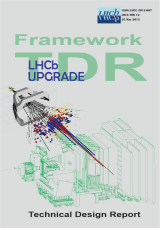


LHCb Integrated Recorded Luminosity in pp, 2010-2018

Outlook

- LHCb well positioned for the future LHC Runs
- Upgrade I will deliver $50\,\text{fb}^{-1}$ that will be essential to precisely study potential deviations, trigger efficiency for hadronic modes increases by a factor 2
- Upgrade II will provide unprecedented $300\,\text{fb}^{-1}$ sample to fully exploit the strength of precision measurements
- Will allow to probe NP scales Λ_{NP} a factor ~ 2 higher than with the Run 3 sample
- We welcome Belle II joining with full detector soon, increased efforts from ATLAS/CMS very welcome
- Apologies to all results I could not mention due to time

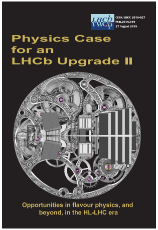



CERN/LHCC 2012-007
LHCb TDR 12
25 May 2012

Framework TDR

LHCb UPGRADE

Technical Design Report


CERN/LHCC 2018-027
PUB-2018-019
27 August 2018

Physics Case for an LHCb Upgrade II

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

Backup

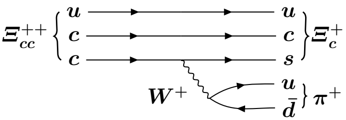
Prospects summary

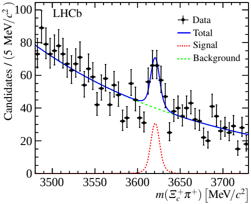
Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

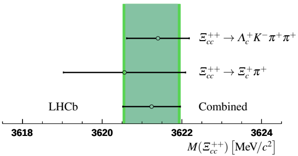
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_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 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Doubly charmed baryon Ξ_{cc}^{++}

- Douly charmed baryon Ξ_{cc} observed for the first time in decay $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [PRL 119 (2017) 112001]
- Lifetime measured relative to $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^- \pi^+$ ($1.7\,\mathrm{fb}^{-1}$ Run 2) consistent with expectations from weak decay
  $\tau(\Xi + cc^{++}) = \left(0.256^{+0.024}_{-0.022} \pm 0.014\right)$ ps [PRL 121 (2018) 052002]
- Recently re-observed in the decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ ($1.7\,\mathrm{fb}^{-1}$ Run 2) [arXiv:1807.01919]



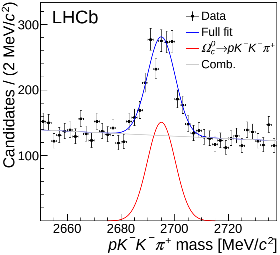


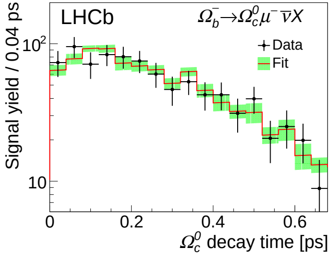


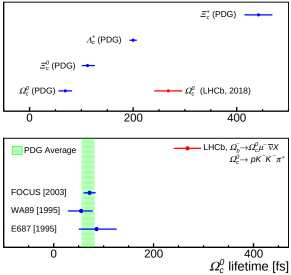
- Combined mass $m(\Xi_{cc}^{++}) = (3621.24 \pm 0.65 \pm 0.31)\ \mathrm{MeV}/c^2$

Ω_c lifetime

- Ω_c lifetime least well measured charmed baryon lifetime
- Around $1000\ \Omega_b \to \Omega_c(\to pK^-K^-\pi^+)\mu^-\bar{\nu}_\mu X$ decays in $3\,\text{fb}^{-1}$
- Lifetime measured relative to D^+ from $B \to D^+(\to K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$ decays
- $\tau(\Omega_c) = (268 \pm 24_{\text{stat.}} \pm 10_{\text{syst.}} \pm 2_{D\,\text{lifetime}})$ fs [PRL 121 (2018) 092003]







- Four times larger, inconsistent with current world average $(69 \pm 12\,\text{fs})$