Outlook for direct CP violation measurements at LHCb

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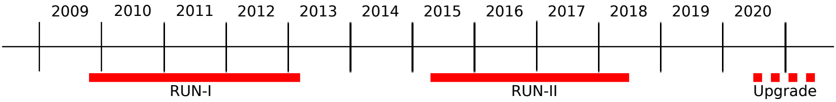
Overview

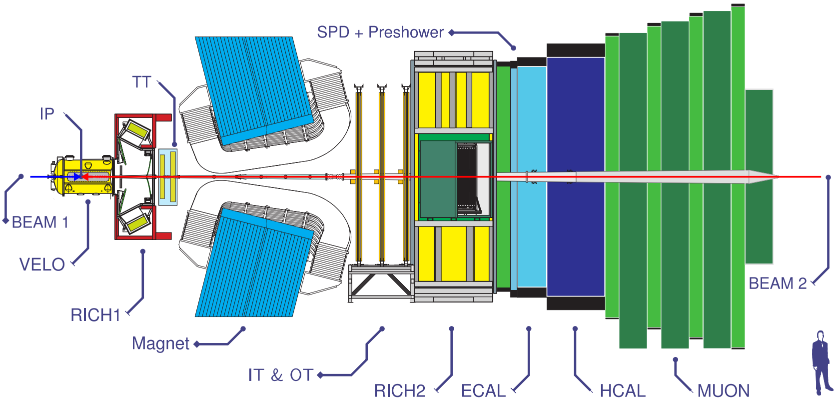
- Outlook for Run-II (period after LS1 – 2015–2018)
  - LHC running parameters
  - LHCb improvements
- Upgrade (beyond LS2 – 2020–)
  - New detectors
  - Trigger and DAQ upgrade
  - Higher luminosity
- Benchmark DCPV measurements at LHCb
  - γ measurements (tree processes)
  - EW penguins (Rare decays): $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$
  - EW penguins (Radiative decays) $B^0 \to K^{*0}\gamma$
  - Gluonic penguins: ($B \to VV$ decays) $B_s^0 \to \phi\phi$

First discuss Run-II and Upgrade, and look at performance for "benchmark channels"



LHCb detector

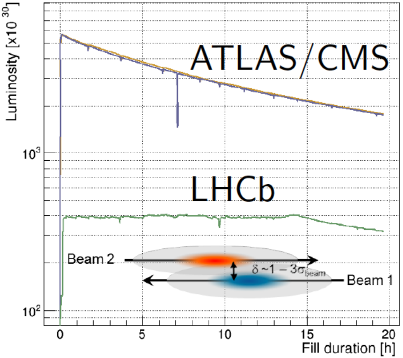
- LHCb: single arm spectrometer with acceptance $2 < \eta < 5$
  - optimized for b physics (rare decays, CPV, spectroscopy)
  - also well suited for c physics



LHCb Run-II prospects 2015–2018

Changes with respect to Run-I

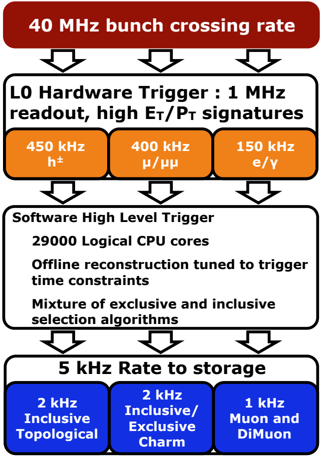
- luminosity at LHCb $L = 4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$
  - kept constant within $\pm 5\%$
  - compare to $L = 2 - 4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ for Run-I (2011–2012)
- higher $b\bar{b}$ cross-section at 13 TeV
  - assume factor 1.6
- higher multiplicity and inelastic cross-section
- 25 ns bunch spacing



Run-II: expect $\approx 5\,\text{fb}^{-1}$

- Optimize trigger scheme
  - Push decision to later stages in the trigger (improve purity)
  - Effectively more CPU power for the trigger ($\approx 2\times$)

Architecture of LHCb trigger for Run-I



Three stages:

Hardware (“L0”) max output 1 MHz

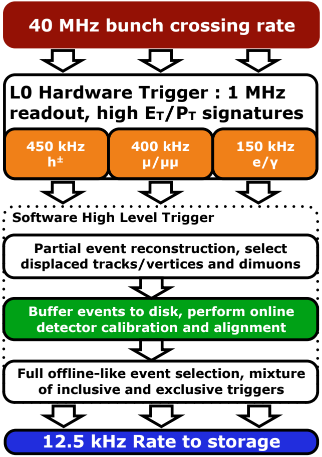
Software (“HLT1”) fast reconstruction and initial selection

Software (“HLT2”) almost off-line reconstruction and final selection

Output rate up to 5 kHz (design 2 kHz)

Hlt1 and Hlt2 are run in sequence on the same event in one task

Architecture of LHCb trigger for Run-II



Three stages:

Hardware (“L0”) max output 1 MHz

Software (“HLT1”) fast reconstruction and initial selection

Software (“HLT2”) “off-line” reconstruction and final selection

Output rate of HLT2 12.5 kHz

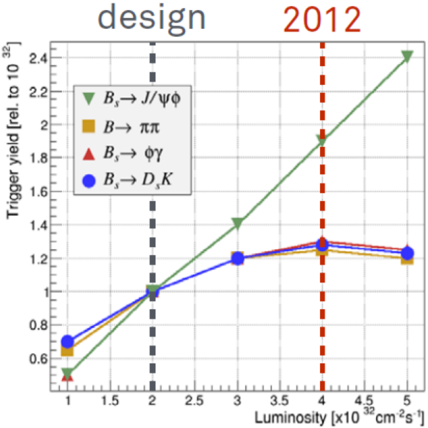
HLT1 writes events to local storage
Do calibration/alignment before HLT2
Hlt2 can reach off-line performance

enriched selection!

LHCb Upgrade objectives

UPGRADE: Higher luminosity
Main trigger limitation: 1MHz hardware trigger limit
Rate, occupancy and radiation damage ...

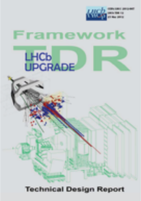
- Remove limitation of 1 MHz hardware trigger
  - All reconstructed in software trigger – 30 MHz
  - Trigger redesign
  - New front end electronics and DAQ system
- Luminosity $L = 2 \times 10^{33}$cm^{-2}s^{-1}
- High particle densities
  - Replace sub-detectors to reduce occupancy
- Radiation damage issues

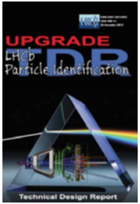


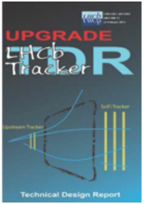
Charm trigger will also profit!

LHCb Upgrade documentation

- LHCb upgrade (LOI): CERN/LHCC 2011-001
- Framework TDR for the LHCb Upgrade (TDR): CERN/LHCC 2012-007
- LHCb VELO Upgrade (TDR): CERN/LHCC 2013-021
- LHCb PID Upgrade (TDR): CERN/LHCC 2013-022
- LHCb Tracker Upgrade (TDR): CERN/LHCC 2014-001
- LHCb Trigger and Online Upgrade (TDR): CERN/LHCC 2014-016

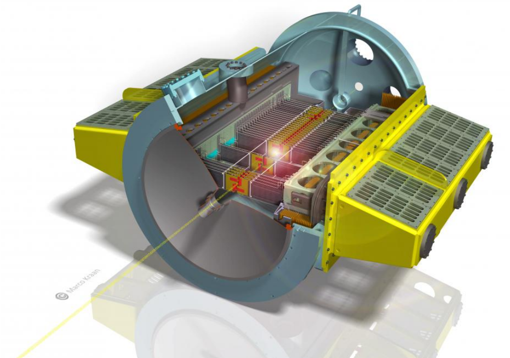




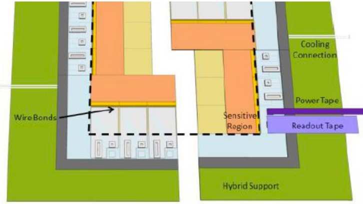


Upgraded Vertex Locator

- 40 MHz readout
- $55 \times 55\ \mu m^2$ pixel size (VeloPix: development from TimePix)
- increased radiation hardness
- microchannel CO_2 cooling



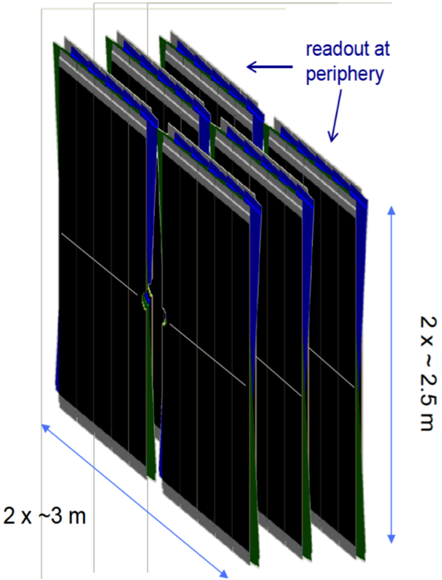
Vertex Detector: replace $r - \phi$ strip geometry with pixel geometry



Fibre Tracker

Scintillating Fibres (SciFi) with Silicon Photo-Multiplier (SiPM) readout

- 250 μm diameter fibres
- fast track reconstruction in trigger
- radiation damage: fibres OK up to 50 fb^{-1}
- dark current: SiPM cooled to -40^o



Selected DCPV measurements

Recent LHCb results:

- γ measurements (tree processes) Dalitz plot analysis
- EW penguins (Rare decays): $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$
- EW penguins (Radiative decays): $B^0 \to K^{*0}\gamma$
- Gluonic penguins: ($B \to VV$ decays) $B_s^0 \to \phi\phi$

γ measurement: Dalitz analysis

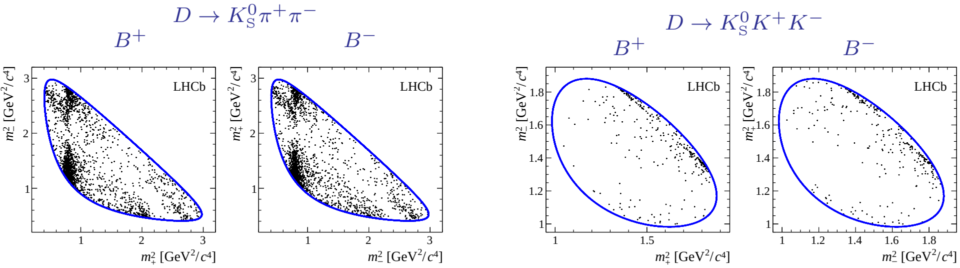
Use predefined binning of Dalitz plot in $B^\pm \to DK^\pm$ decays with $D \to K^0_S h^+ h^-$
Model independent analysis using strong phase difference measured by CLEO-c

[Phys. Rev. D82 (2010) 112006, arXiv:1010.2817]

Measured inputs from $B^0 \to D^* \mu X$ with $D^* \to D\pi$ to remove detection asymmetries

Remove model-dependent inputs

Recent LHCb result: subm. JHEP, [arXiv:1408.2748]



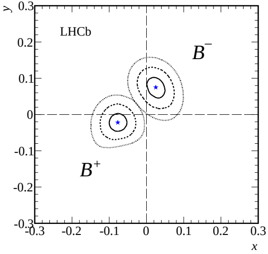
m^2_+ and m^2_-: m^2 of $K^0_S h^-$ and $K^0_S h^+$ combinations

Results of γ measurement

Simultaneous fit to all bins to $x_\pm$ and $y_\pm$:

$x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$ and $y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$

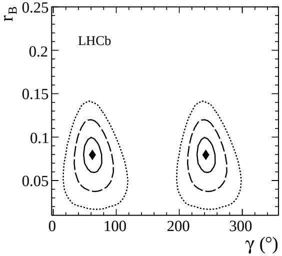
$$x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \quad \times 10^{-2}$$
$$x_- = (\ \ 2.5 \pm 2.5 \pm 1.0 \pm 0.5) \quad \times 10^{-2}$$
$$y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \quad \times 10^{-2}$$
$$y_- = (\ \ 7.5 \pm 2.9 \pm 0.5 \pm 1.4) \quad \times 10^{-2}$$

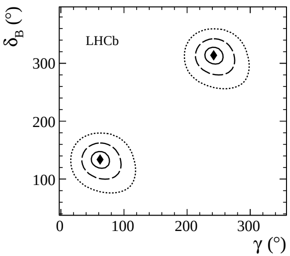


First two uncertainties are statistical and systematic
third is due to strong phases from CLEO-c

$$r_B = 0.080\,^{+0.019}_{-0.021}$$
$$\gamma = (62\,^{+15}_{-14})^\circ$$
$$\delta_B = (134\,^{+14}_{-15})^\circ$$

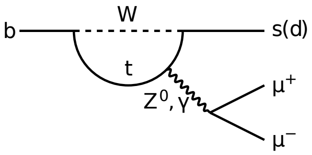
Most precise γ from single DCPV measurement





Electroweak Penguins

$B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$
$b \to s(d)l^+l^-$ decays



flavour changing neutral currents (FCNC)
forbidden at tree level in the SM – only loops and boxes
NP effect can be relatively large

Observables:

Studies of isospin asymmetry LHCb paper [JHEP, arXiv:1403.8044], [JHEP 06 (2014) 133]
Zero crossing point, LHCb: $\mu^+\mu^-$ forward-backward asymmetry [JHEP 05 (2014) 082] [JHEP 08 (2013) 131]

new measurement of the direct CP asymmetry $\mathcal{A}^{CP}$

$$\mathcal{A}^{CP} \equiv \frac{\Gamma(\overline{B} \to \overline{K}^{(*)}\mu^+\mu^-) - \Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(\overline{B} \to \overline{K}^{(*)}\mu^+\mu^-) + \Gamma(B \to K^{(*)}\mu^+\mu^-)}$$

LHCb: subm. JHEP, [arXiv:1408.0978]

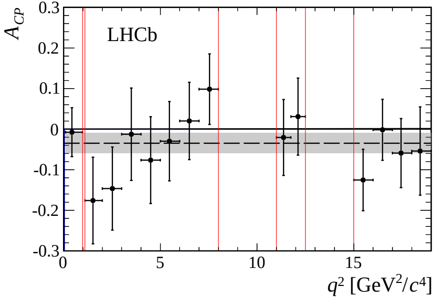
Electroweak Penguins
$\mathcal{A}^{CP}$ in $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$

Counting experiment: Measure: CP asymmetries

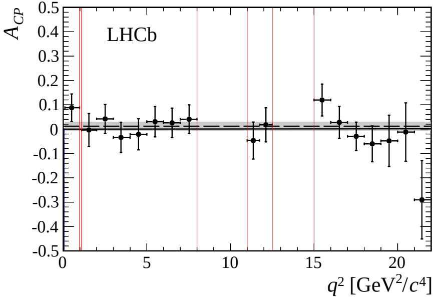
$$\mathcal{A}^{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.035 \pm 0.024 \pm 0.003,$$
$$\mathcal{A}^{CP}(B^+ \to K^+\mu^+\mu^-) = 0.012 \pm 0.017 \pm 0.001,$$

Systematic uncertainties much smaller than statistical errors
SM expects a very small asymmetry: sensitivity to NP

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

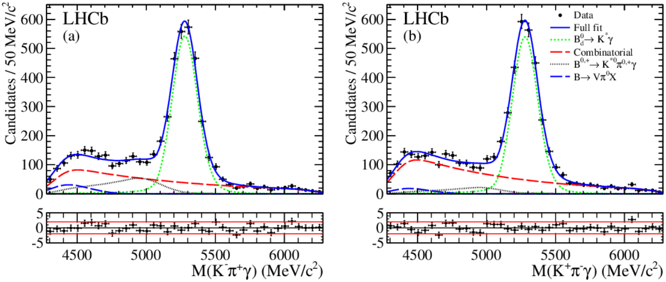


$B^\pm \to K^\pm\mu^+\mu^-$



Electroweak Penguins
Radiative decays

Direct CP asymmetry in $B^0 \to K^{*0}\gamma$ decay
Electroweak penguin
Sensitive to photon polarization



$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (0.8 \pm 1.7\,(\text{stat.}) \pm 0.9\,(\text{syst.}))\%$$

Experimental syst. error will also improve with larger data samples
LHCb: [Nucl. Phys. B867 (2013) 1-18] (1 fb^{-1} data set)

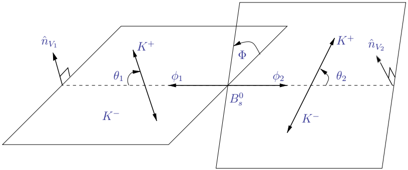
SM prediction: $A_{SM}(B^0 \to K^{*0}\gamma) = (-0.61 \pm 0.43)\%$

M. Matsumori, A. I. Sanda, and Y. Y. Keum, Phys. Rev. D72 (2005) 014013, arXiv:hep-ph/0406055

Gluonic Penguins
Direct CPV in $B_s^0 \to \phi\phi$

Triple-product asymmetries in $B_s^0 \to \phi\phi$ decay:
T-odd combinations

$U = \sin(\Phi)\cos(\Phi)$
$V = \sin(\pm\Phi)$
V positive if $\cos(\theta_1)\cos(\theta_2) \geq 0$



CP violation in a decay time integrated method
asymmetries from mixing strongly suppressed: (M. Gronau and J. L. Rosner, Phys. Rev. D84 (2011) 096013, arXiv:1107.1232)
SM close to zero – sensitivity to NP: (A. Datta, M. Duraisamy, and D. London, Phys. Rev. D86 (2012) 076011, arXiv:1207.4495)

new LHCb results: subm. JHEP, [arXiv:1407.2222]

The triple-product asymmetries (decay time integrated fit)

$$A_U = -0.003 \pm 0.017(stat) \pm 0.006(syst)$$
$$A_V = -0.017 \pm 0.017(stat) \pm 0.006(syst)$$

Measurement still dominated by statistical uncertainties

Physics prospects for the Upgrade

Type	Observable	LHC Run 1	LHCb 2018	**Upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\boldsymbol{\phi_s^{\rm eff}(B_s^0 \to \phi\phi)}$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\boldsymbol{\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)}$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	$0.2\,\%$
Electroweak penguin	$\boldsymbol{S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)}$	0.04	0.020	**0.007**	0.02
	$\boldsymbol{q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)}$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\boldsymbol{\gamma(B \to D^{(*)}K^{(*)})}$	7°	4°	$\boldsymbol{1.1^\circ}$	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	$\boldsymbol{2.4^\circ}$	negligible
	$\beta(B^0 \to J/\psi\ K_S^0)$	1.7°	0.8°	$\boldsymbol{0.31^\circ}$	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

LHCb Run 1: $3\,{\rm fb}^{-1}$
LHCb 2018: assuming $5\,{\rm fb}^{-1}$
LHCb Upgrade: assuming $50\,{\rm fb}^{-1}$
Estimate of the theoretical uncertainty

Conclusions

- Many direct CPV measurements are statistically limited after LHCb Run-I
- Run-II will provide three times more $b\bar{b}$ – reduce errors by factor two
- Running after the Upgrade will provide a further order of magnitude more data
- Many systematic uncertainties will also be reduced with more data
- Many of these measurements will not be systematics-limited
- Theoretical errors also small