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LHCb status and prospects

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on behalf of the LHCb collaboration

20 December 2014

Conference on elementary particles, astrophysics, and cosmology (Miami 2014)
December 17 – 23, 2014, Fort Lauderdale, USA



- 1 Introduction
- 2 The LHCb detector
- 3 Selected physics results
- 4 LHCb plans
- 5 Conclusions and prospects

Introduction

- LHCb is the LHC experiment dedicated to beauty and charm hadrons.

Wide physics program:

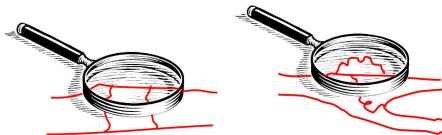
- 1 CKM and CP violation with b and c hadrons
- 2 Rare decays of b and c hadrons
- 3 Spectroscopy in pp interactions and B decays
- 4 Electroweak and QCD measurements in the forward region
- 5 Heavy quark production
- 6 Exotica searches

In 25 minutes, will concentrate on items 1 and 2...

- Power of flavour physics: loop processes (box and penguins) are sensitive to energy scales well beyond the ones of the accelerators, thanks to virtual contributions.

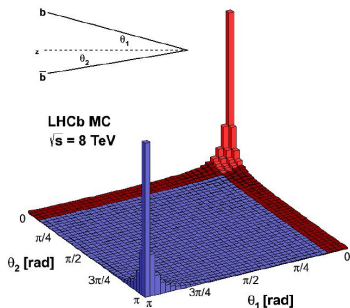
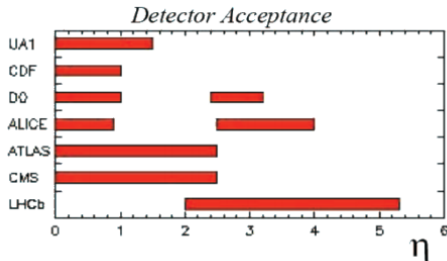
e.g. Argus 1987, $B^0-\bar{B}^0$ mixing \Rightarrow heavy top quark

\rightarrow Indirect search for New Physics



LHCb: super b and c factory at the LHC

- LHC is a proton-proton collider, $\sqrt{s} = 7 \text{ TeV}$ (2011), 8 TeV (2012)
- Large $b\bar{b}$ production cross-section: $\sigma(pp \rightarrow b\bar{b}) = 286 \mu\text{b}$ at 7 TeV
[PLB 694 (2010) 209]
- $\sigma(pp \rightarrow c\bar{c})$ 20 times larger!
- All kinds of b -hadrons produced (B^+ , B^0 , B_s^0 , B_c^+ , b -baryons, ...)
- b -hadrons produced mainly at low angle: LHCb detector installed in the forward region; unique pseudo-rapidity range



- Single-arm forward spectrometer:

- Tracking system

- IP resolution $\sim 15\mu\text{m}$ (at high p_T)

- $\delta p/p \sim 0.45\%$

- RICH system

- Very good $K - \pi$ identification for

- $p \sim 2 - 100 \text{ GeV}/c$

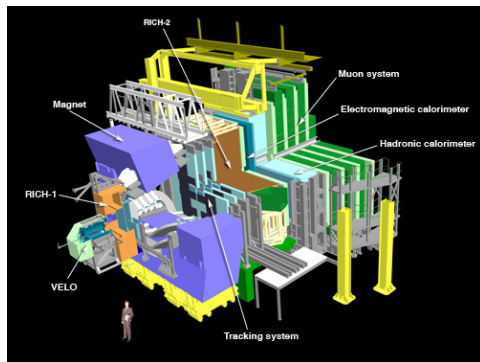
- Calorimeters

- Energy measurement, identify π^0, γ, e

- + trigger

- Muon detector

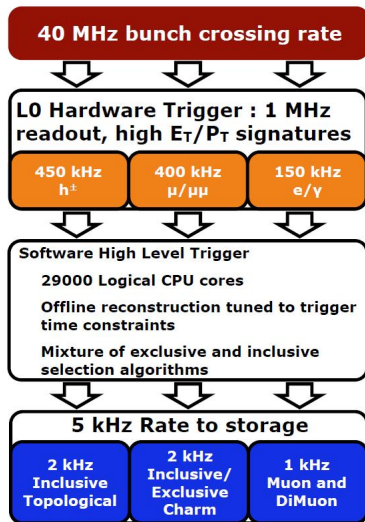
- muon identification + trigger



- Integrated lumi 1 fb^{-1} (2011), 2 fb^{-1} (2012)
Instantaneous lumi $\sim 1 - 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

The LHCb Trigger in 2011–2012

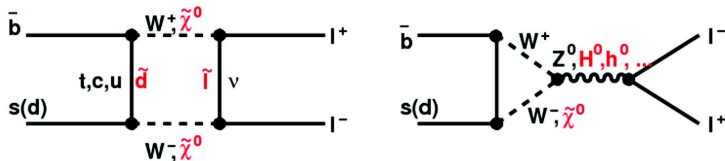
- L0 hardware trigger:
 - Find lepton, hadron with high p_T
 - Reduce the rate from 40 MHz to 1 MHz
- HLT1 software trigger:
 - Finds vertices in VELO
 - Tracks with high IP & p_T
- HLT2 software trigger:
 - Reconstruct all tracks in event
 - Select inclusive/exclusive b-hadrons
 - Output rate = 5 kHz



Few selected physics results

- Rare decays
 - $B \rightarrow \mu^+ \mu^-$
 - Lepton universality with $B^+ \rightarrow K^+ \ell^+ \ell^-$ (R_K)
 - $B \rightarrow K^* \mu^+ \mu^-$ (P'_5)
- CP violation
 - γ angle
 - Mixing-induced CP violation (ϕ_s)
 - Semileptonic asymmetries (A_{SL}^s, A_{SL}^d)
- Other

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



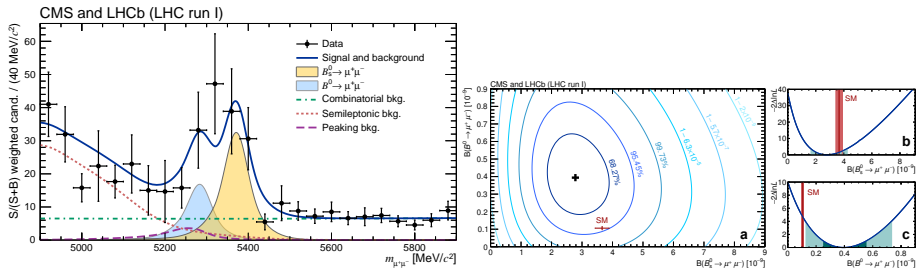
- $B_{s,d}^0 \rightarrow \mu^+ \mu^-$ are loop processes very suppressed in the SM. Precise theoretical prediction [C. Bobeth et al, PRL 112, 101801]:

$$\mathcal{B}^{\text{SM}}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23)^{-9}$$

$$\mathcal{B}^{\text{SM}}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09)^{-10}$$
- Sensitive to new physics
 e.g. $\mathcal{B}^{\text{MSSM}}(B_s^0 \rightarrow \mu^+ \mu^-) \propto \tan^6 \beta$, where $\tan \beta = v_2/v_1$ is the ratio of neutral Higgs field vacuum expectation values
- Intensive searches over the past 30 years...

$B \rightarrow \mu^+ \mu^-$ combined analysis of CMS and LHCb

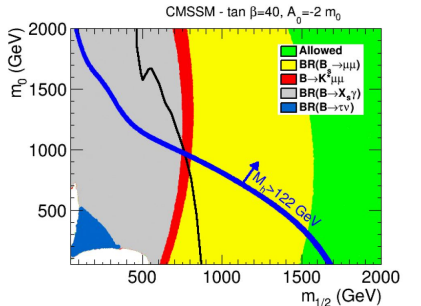
[CMS and LHCb, arXiv:1411.4413, submitted to Nature]



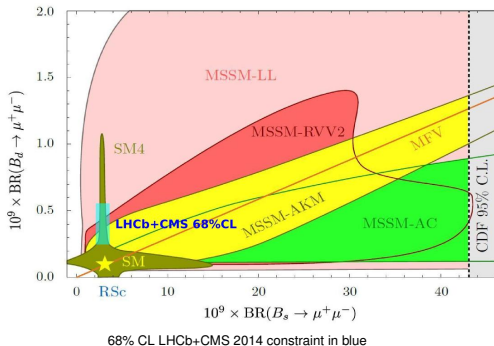
- $\mathcal{B}(B_S^0 \rightarrow \mu^+ \mu^-) = 2.8_{-0.6}^{+0.7} \times 10^{-9}$ (6.2σ), **first observation!**
- $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = 3.9_{-1.4}^{+1.6} \times 10^{-10}$ (3.2σ) evidence for $B^0 \rightarrow \mu^+ \mu^-$
- $\frac{\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_S^0 \rightarrow \mu^+ \mu^-)} = 0.14_{-0.06}^{+0.08}$ (2.3σ of SM)

$B \rightarrow \mu^+ \mu^-$ consequences

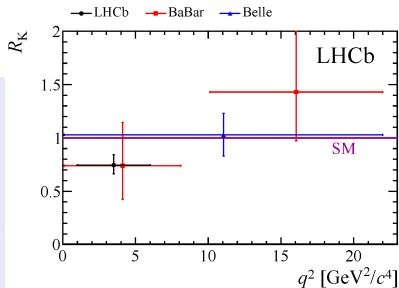
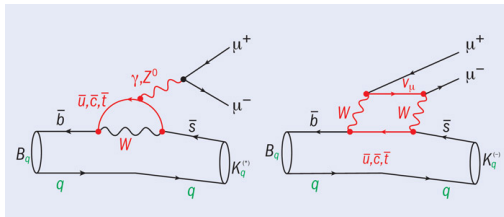
[Mahmoudi et al, arXiv1401.2145]



Modified from [D. Straub, Nuovo Cim. C035N1 (2012) 249] UNOFFICIAL



Strong constraints on many NP models, in particular those with large $\tan \beta$



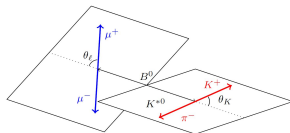
- Search for NP in the above loops

$$(q^2 = m_{\ell\ell}^2)$$

$$R_K \equiv \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-3}) \text{ in the SM}$$

- $R_K(\text{LHCb}, 1 < q^2 < 6 \text{ GeV}^2/c^4) = 0.745_{-0.074}^{+0.090} \pm 0.036$ (2.6σ from SM)
- To be watched out with more statistics

- Same motivations as $B^- \rightarrow K^- \ell^+ \ell^-$
(same SM loops, but with a vector in the final state)
- Complicated angular analysis with many observables:

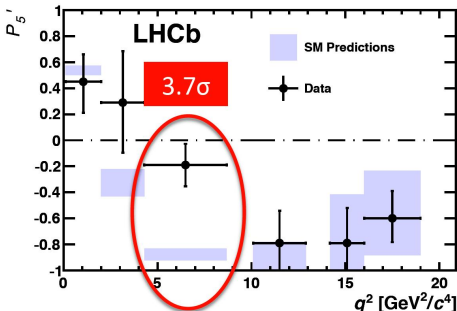
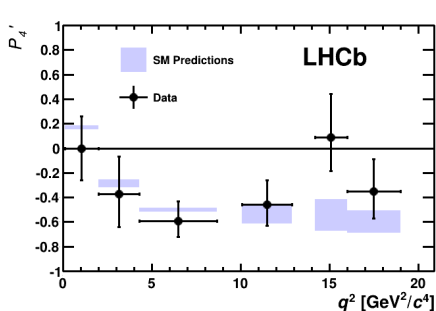


$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d \cos \theta_\ell d \cos \theta_K d\phi dq^2} = \frac{9}{32\pi} \left[\frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ \left. - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \right. \\ \left. + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \right. \\ \left. + S_6 \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \right. \\ \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

- Can parameterize the angular coeff to be largely free of form factor uncertainties

[S. Descotes-Genon et al, arXiv:1303.5794]

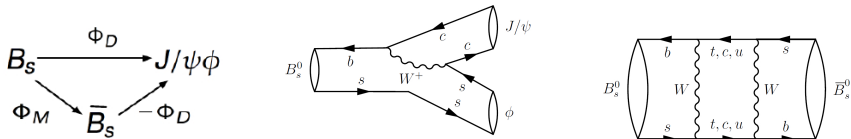
e.g. $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ where F_L is the fraction of longitudinal polarization,
 S_5 is the coefficient of $\sin 2\theta_K \sin \theta_\ell \cos \phi$ in the decay rate.



- Mainly compatible with the SM expect one angular variable
- Local 3.7σ discrepancy LHCb with SM prediction in 3rd bin of P'_5
- Look-elsewhere-effect-corrected SM p-value of this analysis is 0.5%
- Theoretical work ongoing to better understand this bin.
NP contribution to EW penguin Wilson coeff C_9 ?
- LHCb update with full Run 1 data expected soon

Mixing induced CPV in B_s^0

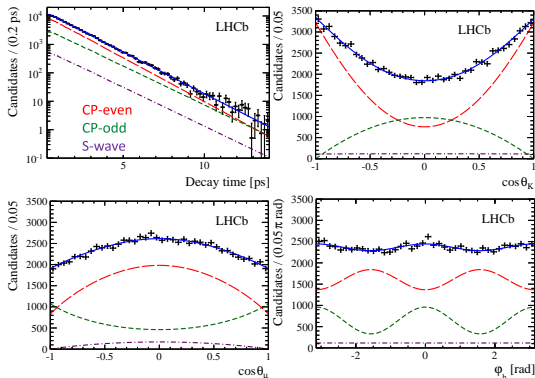
- Interference between B_s^0 decay to $J/\psi \phi$ either directly or via $B_s^0 - \bar{B}_s^0$ oscillation gives rise to a CP violating phase $\phi_s^{J/\psi \phi} \equiv \phi_s = \Phi_M - 2\Phi_D$



- In SM, $\phi_s \simeq -2\beta_s = -(0.0363 \pm 0.0013)$ rad, $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
- Neglecting sub-leading diagrams, the same phase is expected in $B_s^0 \rightarrow D_s^+ D_s^-$ and $B_s^0 \rightarrow J/\psi \pi \pi$
- Measured by fitting differential decay rates for B_s^0 and \bar{B}_s^0 :

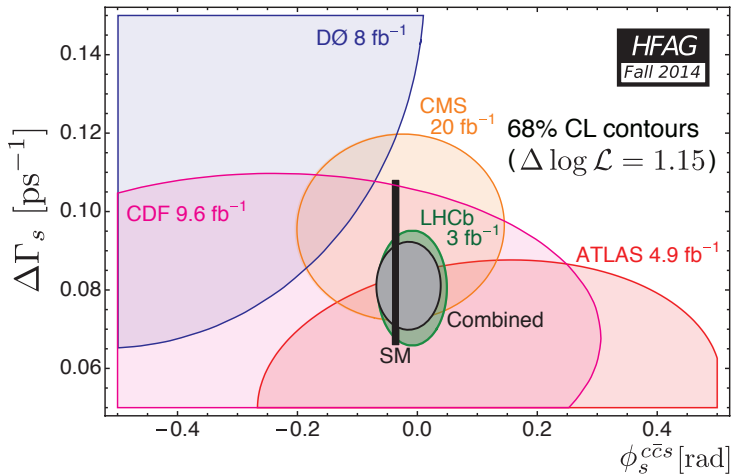
$$\frac{d^4\Gamma(B_s^0 \rightarrow J/\psi \phi)}{dt d\cos\theta_\mu d\varphi_h d\cos\theta_K} = f(\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, M(B_s^0), |A_\perp|, |A_\parallel|, |A_S|, \delta_\perp, \delta_\parallel, \dots)$$

- Unbinned maximum likelihood fit (time, mass, angles, initial flavour)



- $\phi_S = -0.058 \pm 0.049 \pm 0.006$ rad,
- $\Gamma_S \equiv (\Gamma_L + \Gamma_H)/2 = 0.6603 \pm 0.0027 \pm 0.0015$ ps⁻¹
- $\Delta\Gamma_S \equiv \Gamma_L - \Gamma_H = 0.0805 \pm 0.0091 \pm 0.0032$ ps⁻¹
- Combined with $B_S^0 \rightarrow J/\psi \pi^+ \pi^-$: $\phi_S = -0.010 \pm 0.039$

Mixing-induced CPV in B_s^0



- LHCb is dominating the world average:
- $\phi_s^{\text{HFAG WA}} = -0.015 \pm 0.035$
- Compatible with SM, but still room for NP!

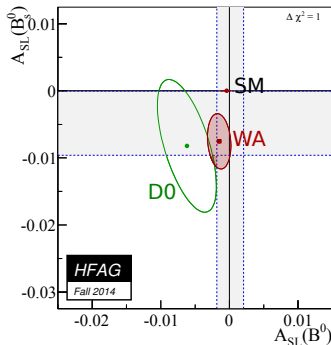
CPV in B^0 and B_s^0 mixing

- Semileptonic asymmetry $A_{SL}^q = \frac{\Gamma(\bar{B}_q \rightarrow B_q \rightarrow f) - \Gamma(B_q \rightarrow \bar{B}_q \rightarrow \bar{f})}{\Gamma(\bar{B}_q \rightarrow B_q \rightarrow f) + \Gamma(B_q \rightarrow \bar{B}_q \rightarrow \bar{f})}$ very small in the SM
- DØ measures the di-muon asymmetry, A_{SL}^b , mixture of semileptonic asymmetries in B_s^0 (A_{SL}^s) and B^0 (A_{SL}^d). $\sim 3\sigma$ from SM [DØ, PRD 89 (2014) 012002]
- Same approach delicate at pp collider due to production asymmetries. LHCb measures individually:

$$A_{SL}^s = (-0.06 \pm 0.50 \pm 0.36)\%, 1 \text{ fb}^{-1}, [\text{LHCb, PLB 728 (2014) 607}]$$

$$A_{SL}^d = (-0.02 \pm 0.19 \pm 0.30)\%, 3 \text{ fb}^{-1}, [\text{arXiv:1409.8586}]$$

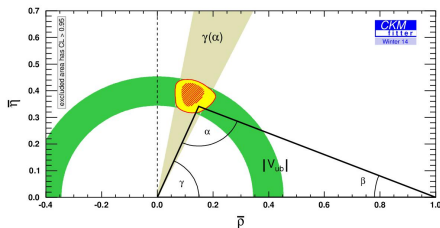
Compatible with both SM and DØ



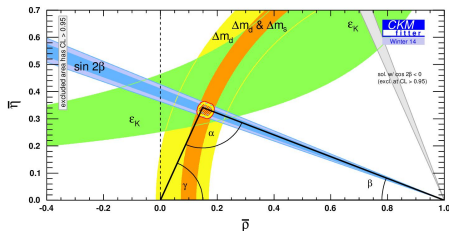
- $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is the least known of the CKM unitarity angles.

Can be determined by:

- tree level processes, nearly insensitive to NP. Act as reference
Very precise theoretical prediction, $\delta\gamma/\gamma \simeq 10^{-7}$ [J. Brod et al, JHEP 1401 (2014) 051]
 - loop processes, sensitive to NP
- Comparing the two can reveal NP



Constraints from "Trees"



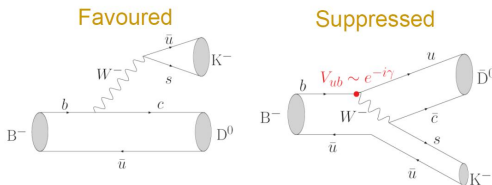
Constraints from "Loops"

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at:

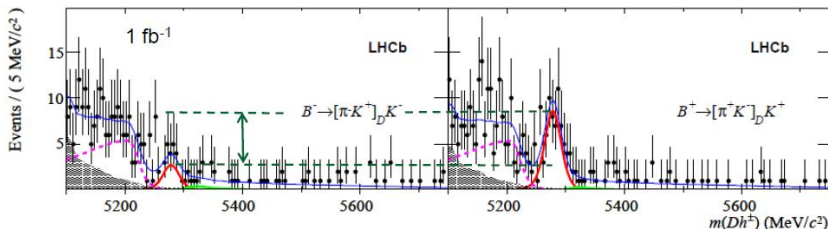
<http://ckmfitter.in2p3.fr>

γ angle measured with tree processes

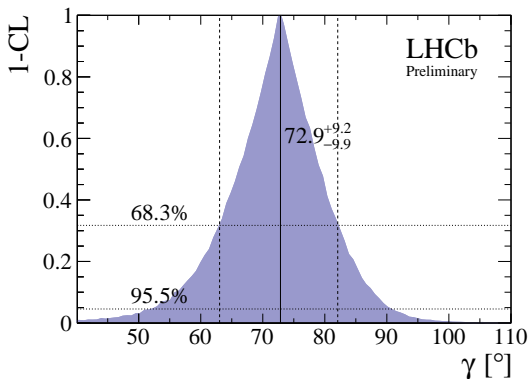
- γ -from-tree measures using interferences between suppressed and favored $B \rightarrow Dh$ decays
- Many modes uses: $D \rightarrow KK$, $D \rightarrow K\pi$, $D \rightarrow K_S^0 \pi\pi$, $D \rightarrow K_S^0 K\pi$, $B_s^0 \rightarrow D_s^{\mp} K^{\pm}$



- Typical BR are small around 10^{-7}
- e.g. "suppressed ADS mode": very clean easy to interpret information on γ :



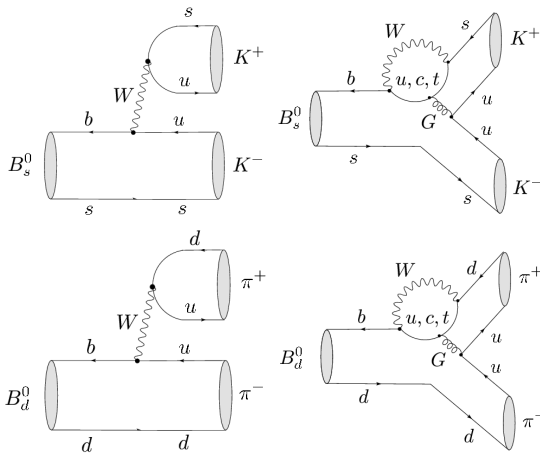
[PLB 712 (2012) 203]



- LHCb combination of many modes, using $B_{(s)} \rightarrow D_{(s)} K^{(*)}$ (mixture of 1 and 3 fb^{-1})
- $\gamma = (72.9^{+9.2}_{-9.9})^\circ$, world best measurement, better than B -factories legacy!

γ -angle measured with loop processes [arXiv:1408.4368, 1 fb⁻¹]

- γ extracted from $B_s^0 \rightarrow K^+ K^-$, $B^0 \rightarrow \pi^+ \pi^-$, $B^+ \rightarrow \pi^+ \pi^0$ and $B^0 \rightarrow \pi^0 \pi^0$ using U-spin + isospin analyses. [e.g. R. Fleischer, PLB459 (1999) 306, Ciuchini, JHEP 10 (2012) 029]
- Experimental result: $\gamma = (63.5_{-6.7}^{+7.2})^\circ$
- Compatible with “ γ from tree” so far



Few other physics results (amongst ~ 235 papers...!)

- First observation of the excited baryons $\Xi_b^{('*)-}$ (bsd), [PRL 113, 242002 (2014)]
- First observation of a heavy flavored spin-3 particle: $D_{sJ}^*(2860)^-$, [PRD 90 (2014) 072003]
- First observation of Z production in proton-lead collisions at LHCb, [JHEP 09 (2014) 030]
- Quantum numbers of the first confirmed tetraquark ($cu\bar{c}\bar{d}$) $Z(4430)^-$, [PRL 112, 222002 (2014)]
- First observation of photon polarization in $b \rightarrow s\gamma$ transition, [PRL 112, 161801 (2014)]
- Search for direct and indirect CP violation and measurement of mixing parameter in charm, [PRL 111, 251801 (2013), PRL 112, 041801 (2014), PRL 110, 101802 (2013)]
- Determination of the $X(3872)$ meson quantum numbers, [PRL 110, 222001 (2013)]
- First observation of CP violation in B_s^0 , [PRL 110 (2013) 221601]
- World best limit on $\mathcal{B}(K_s^0 \rightarrow \mu^+ \mu^-)$, [JHEP 01 (2013) 090]
- Electroweak physics in the forward region, [arXiv:1411.1264, JHEP 02 (2013) 106, JHEP 01 (2013) 111, JHEP 06 (2012) 058]

LHCb plans

- **Run 2** (2016-2018): 5 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$, improved trigger
- Some major experimental measurements (e.g. γ , $B_s^0 \rightarrow \phi\phi$) are not yet at the level of theoretical prediction
- Above a luminosity of $\sim 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, our efficiency to trigger hadronic modes saturates, because of the L0-trigger bottleneck which can not cope more than 1 MHz output rate.

⇒ We will **upgrade** the LHCb experiment in 2018–2019:

- Full software trigger: read all detector at 40 MHz → $\times 2$ efficiency for hadronic final state.
- Luminosity up to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, new challenges: high pile-up, large occupancies, radiation damages
- Detector upgrades: VELO (pixels), tracker (Silicon strips and scintillating fibers), RICH (multi-anode PMTs), CALO& MUON (new electronics), ...
- Aim to collect $\sim 50 \text{ fb}^{-1}$. Annual yields wrt published analyses: $\times 10$ for muonic final states and $\times 20$ for hadronic modes.



APPROVED



APPROVED



APPROVED



APPROVED



APPROVED

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb ⁻¹)	Theory uncertainty
B_S^0 mixing	$2\beta_S(B_S^0 \rightarrow J/\psi \phi)$	0.035	0.025	0.008	~ 0.003
	$2\beta_S(B_S^0 \rightarrow J/\psi f_0(980))$	0.17	0.045	0.014	~ 0.01
	$A_{FB}(B_S^0)$	6.4×10^{-3}	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_S^{\text{eff}}(B_S^0 \rightarrow \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_S^{\text{eff}}(B_S^0 \rightarrow K^{*0}K^{*0})$	–	0.13	0.02	< 0.02
	$2\beta_S^{\text{eff}}(B^0 \rightarrow \phi K_S^0)$	0.17	0.30	0.05	0.02
Right-handed currents	$2\beta_S^{\text{eff}}(B_S^0 \rightarrow \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_S^0 \rightarrow \phi\gamma)/\tau_{B_S^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \rightarrow K^{*0}\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.08	0.025	0.008	0.02
	$s_0 A_{FB}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$	25 %	6 %	2 %	7 %
	$A_1(K\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.25	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \rightarrow \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$	25 %	8 %	2.5 %	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_S^0 \rightarrow \mu^+\mu^-)$	1.5×10^{-9}	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_S^0 \rightarrow \mu^+\mu^-)$	–	$\sim 100\%$	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \rightarrow D^{(*)}K^{(*)})$	$\sim 10\text{--}12^\circ$	4°	0.9°	negligible
	$\gamma(B_S^0 \rightarrow D_S K)$	–	11°	2.0°	negligible
	$\beta(B^0 \rightarrow J/\psi K_S^0)$	0.8°	0.6°	0.2°	negligible
Charm	A_Γ	2.3×10^{-3}	0.40×10^{-3}	0.07×10^{-3}	–
\mathcal{CP} violation	ΔA_{CP}	2.1×10^{-3}	0.65×10^{-3}	0.12×10^{-3}	–

- $2\beta_S^{\text{eff}}(B_S^0 \rightarrow \phi\phi)$ with a precision of 0.03
- γ with a precision below 1°

Conclusions and prospects

- LHCb has worked extremely well during Run 1 and collected 3 fb^{-1} with which outstanding results were obtained, e.g.:
 - Measurements of CPV phase ϕ_s : $\sigma(\phi_s) < 39 \text{ mrad}$
 - Measurement of γ angle: $\sigma(\gamma) < 10^\circ$
 - Observation of charm mixing
 - Some interesting “tensions” to be watched out with more statistics:
 - P'_5 in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ (3.7σ local)
 - $\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)$ (2.6σ)
 - $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) / \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ (2.3σ)
 - + much more!
- More results are still expected from Run 1
- Run 2 of LHC (2015-2018) should bring us $\simeq 5$ more fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$
- The LHCb upgrade phase (2020-2028) is actively being prepared and will open an unprecedented physics potential in heavy flavour (50 fb^{-1})