LHCb status and prospects

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on behalf of the LHCb collaboration

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Outline

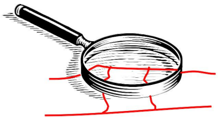
1. Introduction
2. The LHCb detector
3. Selected physics results
4. LHCb plans
5. Conclusions and prospects

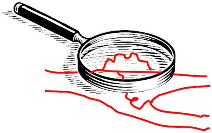
Introduction

- 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–$\overline{B}^0$ mixing $\Rightarrow$ heavy top quark
  $\rightarrow$ Indirect search for New Physics

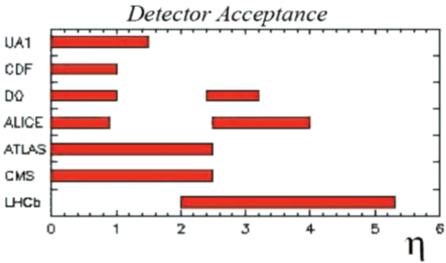


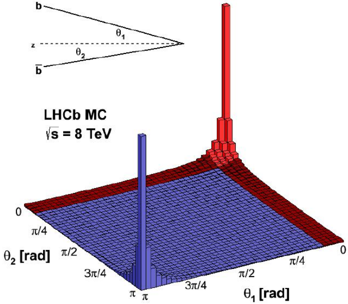


LHCb: super *b* and *c* factory at the LHC

- LHC is a proton-proton collider, $\sqrt{s} = 7\,\mathrm{TeV}$ (2011), $8\,\mathrm{TeV}$ (2012)
- Large $b\bar{b}$ production cross-section: $\sigma(pp \to b\bar{b}) = 286\mu$b at 7 TeV

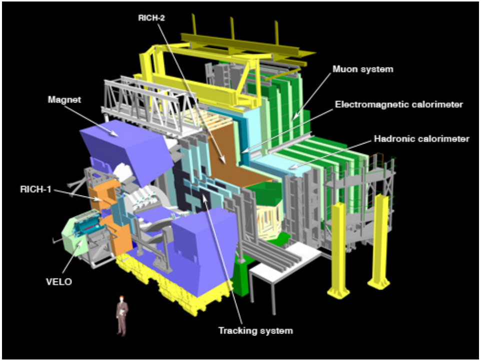
  [PLB 694 (2010) 209]
- $\sigma(pp \to c\bar{c})$ 20 times larger!
- All kinds of *b*-hadrons produced (B^+, B^0, B_s^0, B_c^+, *b*-baryons, ...)
- *b*-hadrons produced mainly at low angle: LHCb detector installed in the forward region; unique pseudo-rapidity range





The LHCb detector [JINST 3 (2008 S08005)]

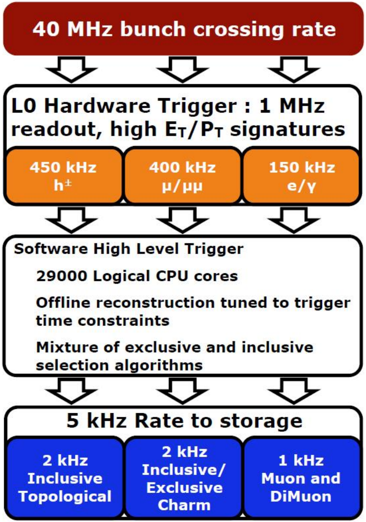
- Single-arm forward spectrometer:
  - Tracking system
    IP resolution $\sim$ 15μm (at high p_{T})
    $\delta p/p \sim 0.45\%$
  - RICH system
    Very good $K-\pi$ identification for
    $p \sim 2-100\,\mathrm{GeV}/c$
  - Calorimeters
    Energy measurement, identify π^0,γ,e
    + trigger
  - Muon detector
    muon identification + trigger



- Integrated lumi 1 fb^{-1} (2011), 2 fb^{-1} (2012)
  Instantaneous lumi $\sim 1-4\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

The LHCb Trigger in 2011–2012

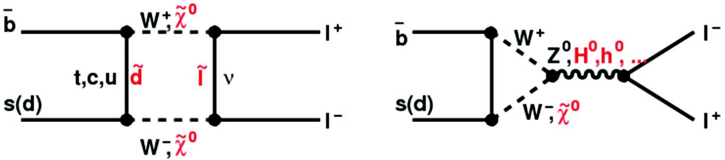
- L0 hardware trigger:
  - Find lepton, hadron with high p_{T}
  - Reduce the rate from 40 MHz to 1 MHz
- HLT1 software trigger:
  - Finds vertices in VELO
  - Tracks with high IP & p_{T}
- HLT2 software trigger:
  - Reconstruct all tracks in event
  - Select inclusive/exclusive b-hadrons
  - Output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



Few selected physics results

- Rare decays
  - $B \to \mu^+\mu^-$
  - Lepton universality with $B^+ \to K^+\ell^+\ell^-$ (R_K)
  - $B \to K^*\mu^+\mu^-$ (P_5')
- CP violation
  - γ angle
  - Mixing-induced CP violation (ϕ_s)
  - Semileptonic asymmetries (A^s_{SL}, A^d_{SL})
- Other

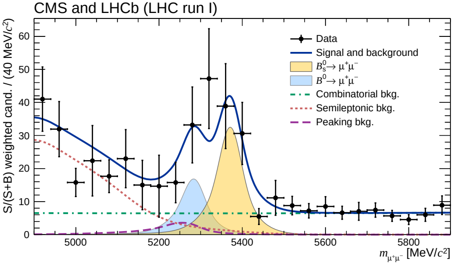
$B \to \mu^+\mu^-$

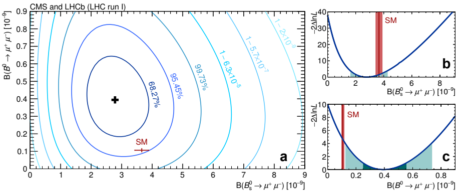


- $B^0_{s,d} \to \mu^+\mu^-$ are loop processes very suppressed in the SM.
  Precise theoretical prediction [C. Bobeth et al, PRL 112, 101801]:
  $\mathcal{B}^{\rm SM}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23)^{-9}$
  $\mathcal{B}^{\rm SM}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09)^{-10}$
- Sensitive to new physics
  e.g. $\mathcal{B}^{\rm MSSM}(B^0_s \to \mu^+\mu^-) \propto \tan^6\beta$, where $\tan\beta = v_2/v_1$ is the ratio of neutral Higgs field vacuum expectation values
- Intensive searches over the past 30 years...

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

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

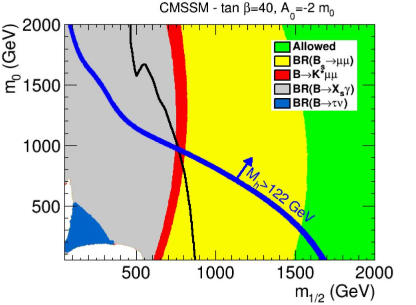




- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$ (6.2σ), first observation!
- $\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$ (3.2σ) evidence for $B^0 \to \mu^+\mu^-$
- $\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = 0.14^{+0.08}_{-0.06}$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

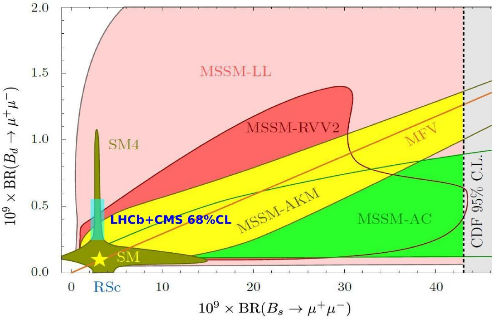
$B \to \mu^+\mu^-$ consequences

[Mahmoudi et al, arXiv1401.2145]



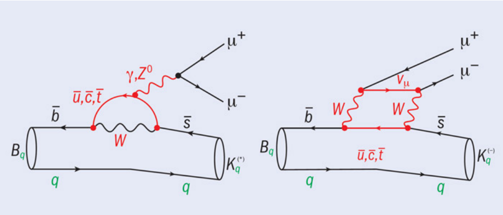
Black line corresponds to the direct limit by ATLAS 20.3 fb^{-1}

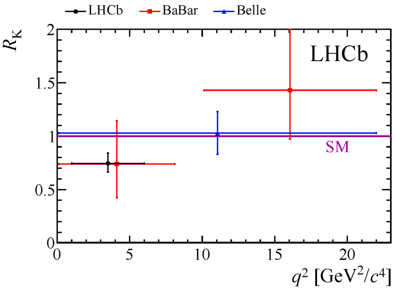
Modified from [D. Straub, Nuovo Cim. C035N1 (2012) 249] UNOFFICIAL



68% CL LHCb+CMS 2014 constraint in blue

Strong constraints on many NP models, in particular those with large tan β





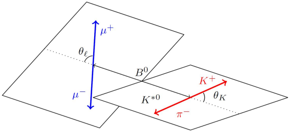
- Search for NP in the above loops $(q^2 = m^2_{\ell\ell})$

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

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

$B^0 \to K^*\mu^+\mu^-$ [JHEP 08 (2013) 131, PRL 111 (2013) 191801]

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



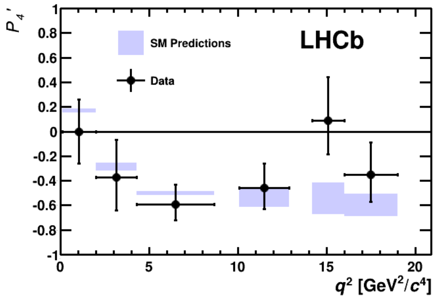
$$
\begin{aligned}
\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\
&- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\
&+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\
&+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\
&+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]
\end{aligned}
$$

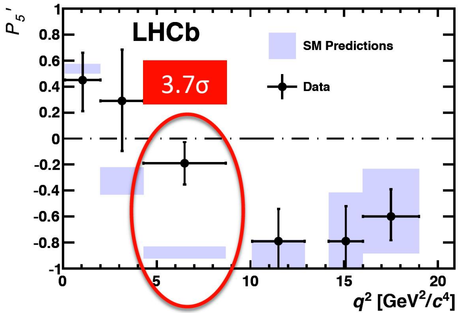
- Can parameterize the angular coeff to be largely free of form factor uncertainties

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

  e.g. $P_5' = \frac{S_5}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$ 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.

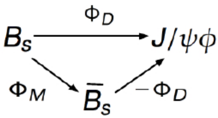


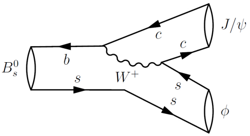


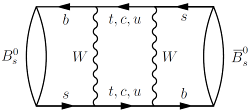
- Mainly compatible with the SM expect one angular variable
- Local 3.7σ discrepancy with SM prediction in 3rd bin of P_5'
- Look-elsewhere-effect-corrected SM p-value of this analysis is 0.5%
- Theoretical work ongoing to better understand this bin.
  NP contribution to EW penguin Wilson coeff C_9?
- 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–$\overline{B}_s^0$ oscillation gives rise to a CP violating phase $\phi_s^{J/\psi\,\phi} \equiv \phi_s = \Phi_{\rm M} - 2\Phi_{\rm D}$







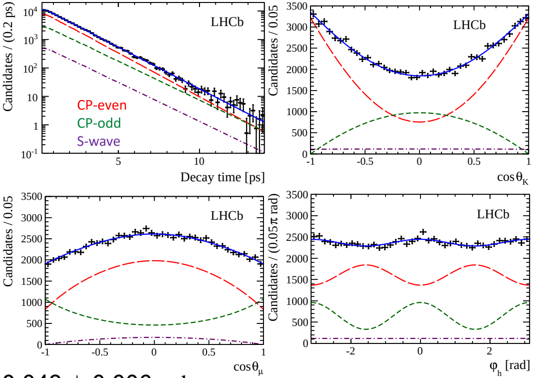
- In SM, $\phi_s \simeq -2\beta_s = -(0.0363 \pm 0.0013)\,\mathrm{rad}$, $\beta_s = \arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right)$
- Neglecting sub-leading diagrams, the same phase is expected in $B_s^0 \to D_s^+ D_s^-$ and $B_s^0 \to J/\psi\pi\pi$

- Measured by fitting differential decay rates for B_s^0 and $\overline{B}_s^0$:

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

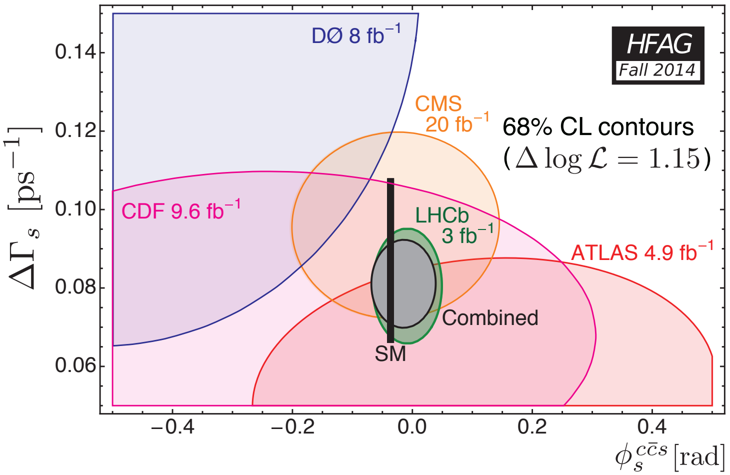
Mixing-induced CPV in $B_s^0 \to J/\psi\, h^+ h^-$ [arXiv:1411.3104]

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



- $\phi_s = -0.058 \pm 0.049 \pm 0.006\,\mathrm{rad}$,
- $\Gamma_s \equiv (\Gamma_\mathrm{L} + \Gamma_\mathrm{H})/2 = 0.6603 \pm 0.0027 \pm 0.0015\,\mathrm{ps}^{-1}$
- $\Delta\Gamma_s \equiv \Gamma_\mathrm{L} - \Gamma_\mathrm{H} = 0.0805 \pm 0.0091 \pm 0.0032\ \mathrm{ps}^{-1}$
- Combined with $B_s^0 \to J/\psi\pi^+\pi^-$: $\phi_s = -0.010 \pm 0.039$

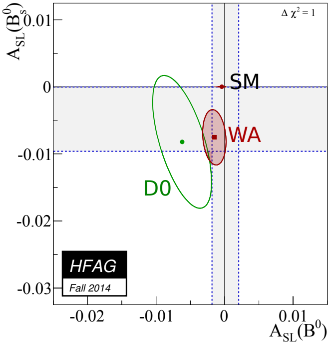
Mixing-induced CPV in B_s^0



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

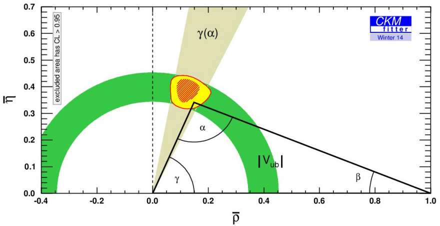
CPV in B^0 and B_s^0 mixing

- Semileptonic asymmetry $A_{\rm SL}^q = \frac{\Gamma(\bar{B}_q \to B_q \to f) - \Gamma(B_q \to \bar{B}_q \to \bar{f})}{\Gamma(\bar{B}_q \to B_q \to f) + \Gamma(B_q \to \bar{B}_q \to \bar{f})}$ very small in the SM
- DØ measures the di-muon asymmetry, A_{SL}^b, mixture of semileptonic asymmetries in B_s^0 ($A_{\rm SL}^s$) and B^0 ($A_{\rm SL}^d$). $\sim 3\sigma$ from SM [D0, PRD 89 (2014) 012002]
- Same approach delicate at *pp* collider due to production asymmetries. LHCb measures individually:
  $A_{\rm SL}^s = (-0.06 \pm 0.50 \pm 0.36)\%$, 1 fb^{-1}, [LHCb, PLB 728 (2014) 607]
  $A_{\rm SL}^d = (-0.02 \pm 0.19 \pm 0.30)\%$, 3 fb^{-1}, [arXiv:1409.8586]
  Compatible with both SM and DØ

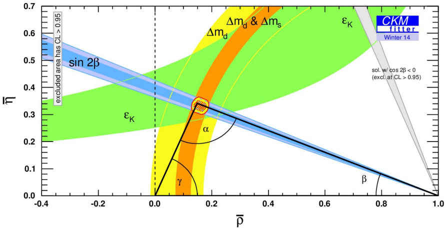


γ angle

- $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ 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"



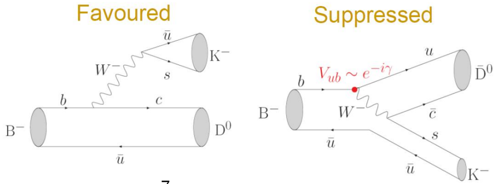
Constraints from "Loops"

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

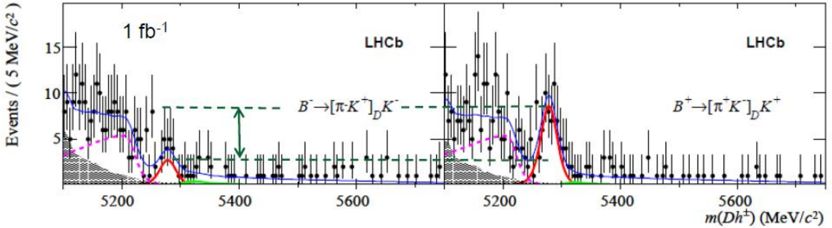
http://ckmfitter.in2p3.fr

γ angle measured with tree processes

- γ-from-tree measures using interferences between suppressed and favored $B \to Dh$ decays
- Many modes uses: $D \to KK$, $D \to K\pi$, $D \to K^0_S\pi\pi$, $D \to K^0_S K\pi$, $B^0_s \to D_s^\mp K^\pm$

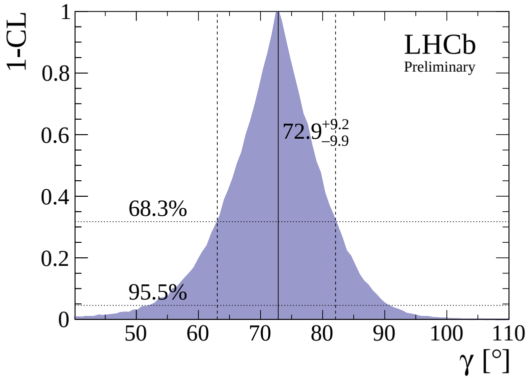


- Typical BR are small around 10^{-7}
- e.g. “suppressed ADS mode”: very clean easy to interpret information on γ:



[PLB 712 (2012) 203]

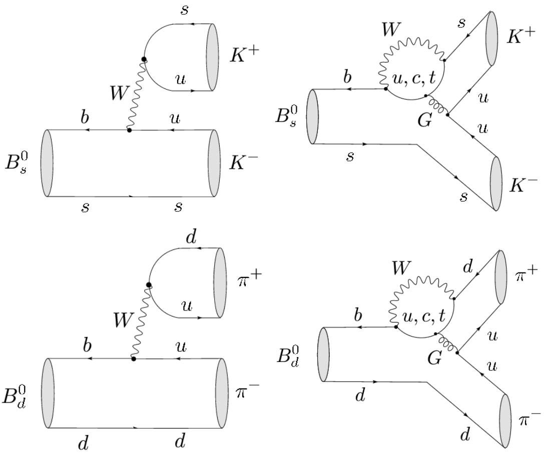
γ-angle measured with tree processes [LHCb-CONF-2014-004]



- LHCb combination of many modes, using $B_{(s)} \to D_{(s)} K^{(*)}$ (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 $B_s^0 \to K^+K^-$, $B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$ using U-spin + isospin analyses. [e.g. R. Fleischer, PLB459 (1999) 306, Ciuchini, JHEP 10 (2012) 029]
- Experimental result: $\gamma = (63.5^{+7.2}_{-6.7})^\circ$
- Compatible with "γ from tree" so far



Few other physics results (amongst $\sim$ 235 papers...!)

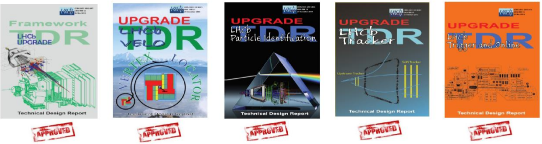
- First of observation of the excited baryons $\Xi_b^{('*)-}$ (bsd), [PRL 113, 242002 (2014)]
- First observation of of a heavy flavored spin-3 particle: $D_{sJ}^*(2860)^-$, [PRD 90 (2014) 072003]
- First observation of Z production in proton-lead collisions at LHCb, [JHEP 09 (2014) 030]
- Quantum numbers of the first confirmed tetraquark ($cu\bar{c}\bar{d}$) $Z(4430)^-$, [PRL 112, 222002 (2014)]
- First observation of photon polarization in $b \to s\gamma$ 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 $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$, [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 $\sqrt{s} = 13\,\mathrm{TeV}$, improved trigger
- Some major experimental measurements (e.g. γ, $B_s^0 \to \phi\phi$) are not yet at the level of theoretical prediction
- Above a luminosity of $\sim 4 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, our efficiency to trigger hadronic modes saturates, because of the L0-trigger bottleneck which can not cope more than 1 MHz output rate.

$\Rightarrow$ We will upgrade the LHCb experiment in 2018–2019:

- Full software trigger: read all detector at 40 MHz $\to$ $\times 2$ efficiency for hadronic final state.
- Luminosity up to $2\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 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 fb^{-1}. Annual yields wrt published analyses: $\times$10 for muonic final states and $\times$20 for hadronic modes.



Expected performances of LHCb upgrade CERN-LHCC-2012-007

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

- $2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$ 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: $\sigma(\phi_s) < 39\,\mathrm{mrad}$
  - 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 $B^0 \to K^{*0}\mu^+\mu^-$ (3.7σ local)
    - $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ (2.6σ)
    - $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (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 $\sqrt{s} = 13\,\mathrm{TeV}$
- The LHCb upgrade phase (2020-2028) is actively being prepared and will open an unprecedented physics potential in heavy flavour (50 fb^{-1})