CP violation in B decays

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ON BEHALF OF LHCb (and ATLAS/CMS for a few results) COLLABORATION

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Outline

- Introduction
- Selected results from **LHCb (a few results from ATLAS/CMS)**
  - **Publications in 2017**

PLB 777 (2018) 16-30
LHCb-PAPER-2017-030
LHCb-CONF-2017-004
JHEP 11 (2017) 170
JHEP 08 (2017) 037
LHCb-PAPER-2017-048

- Summary

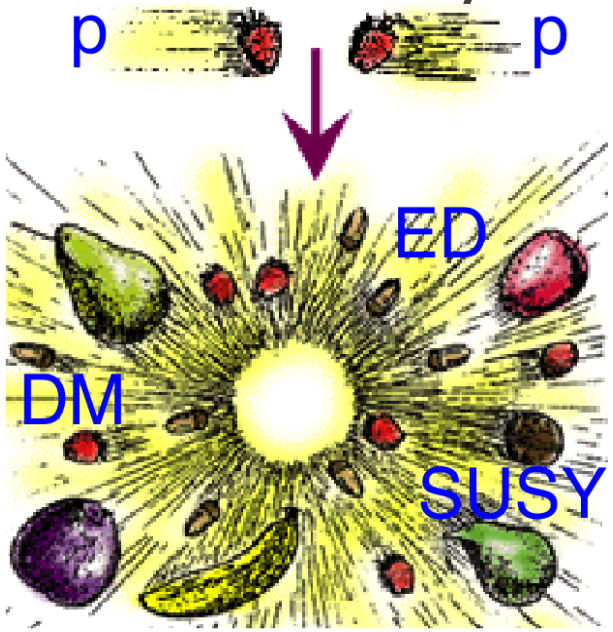
CP violation

- **Standard Model (SM)** works beautifully up to few hundred GeV, must be an effective theory valid up to some scale
- Sources of CP violation:
  - **Beyond the standard model (BSM)** are needed to explain the large **matter/antimatter asymmetry** observed in the universe
- Most BSM physics models predict **additional heavy particles**:
  - Enter in internal loops (Box and Penguin diagrams)
  - Lead to sizeable modification of observables such as CP violating phases
- Precise measurements of CP observables, compared with SM can probe the presence of BSM physics

Paths to new Physics at LHC

Direct search

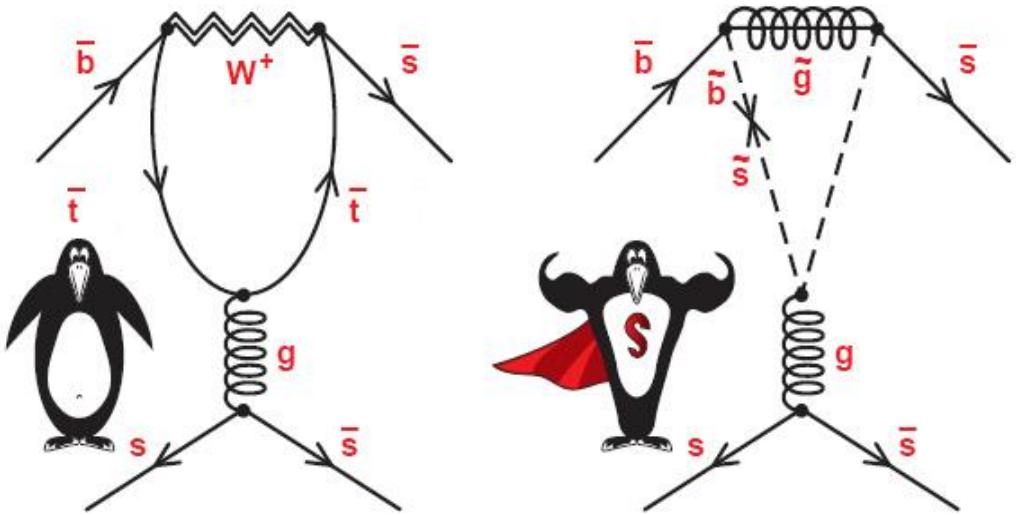
The "relativistic" way



Masses and production cross section limited by collision energy

Indirect search (Flavour physics)

The "quantum" way



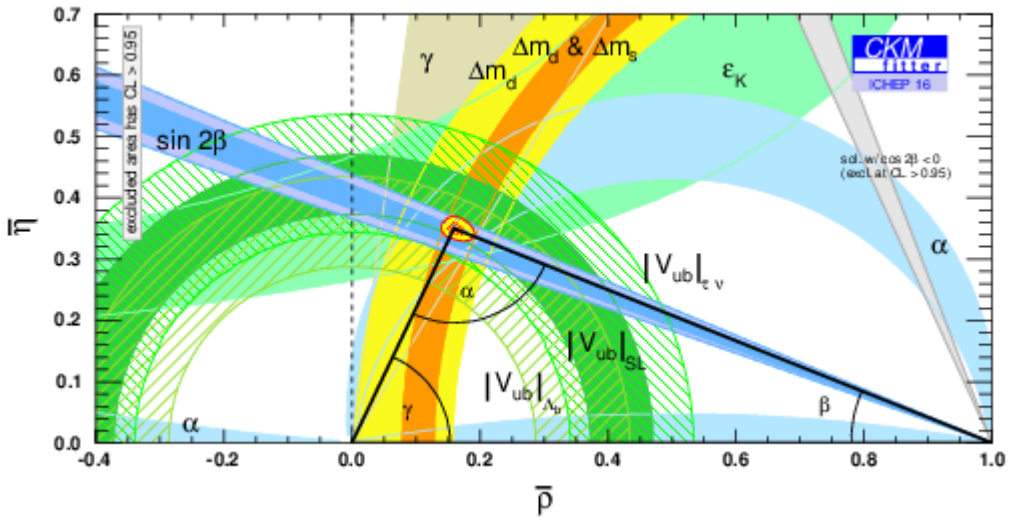
Sensitive to much higher mass scales O(10 - 100TeV)

CP violation measurements!

CP violation in the Standard Model

- **CKM matrix: unitary, 3*3 matrix describing charged-current weak interactions (3 angles, one phase).**

$$\begin{array}{c} \\ u \\ c \\ t \end{array}\begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$

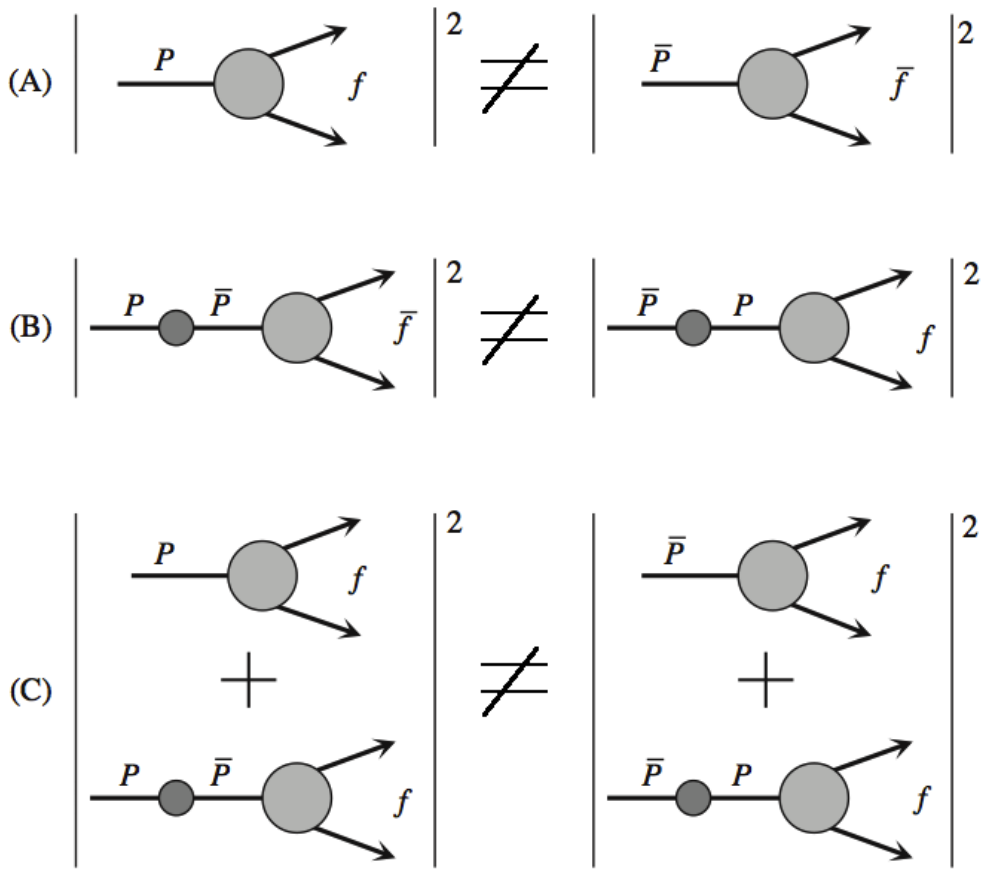


- **CKM phase:**
  - **The only source of CPV in the SM quark sector**

- **Why B decays?**
  - **Measurements overconstrain the SM picture of CPV**
  - **Larger angles, similar size sides $V_{ud}V_{ud}^* + V_{cd}V_{cd}^* + V_{td}V_{td}^* = 0$**

A huge success

CP violation phenomenology



➢ CPV in decays:

- Need CP invariant (strong) phase δ and CPV (weak) phase ϕ
- Example: $B^{\pm} \to J/\psi K^{\pm}$

$$A(P \to f) = a_1 e^{i\delta_1} e^{i\phi_1} + a_2 e^{i\delta_2} e^{i\phi_2}$$
$$A(\bar{P} \to \bar{f}) = a_1 e^{i\delta_1} e^{-i\phi_1} + a_2 e^{i\delta_2} e^{-i\phi_2}$$
$$\to \Delta|A|^2 \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

➢ CPV in mixing:

- Mass eigenstates vs flavour eigenstates:
- Example: lepton charge asym in $B_s^0 \to D_s^{\mp}\mu^{\pm}\nu_\mu X$ decays

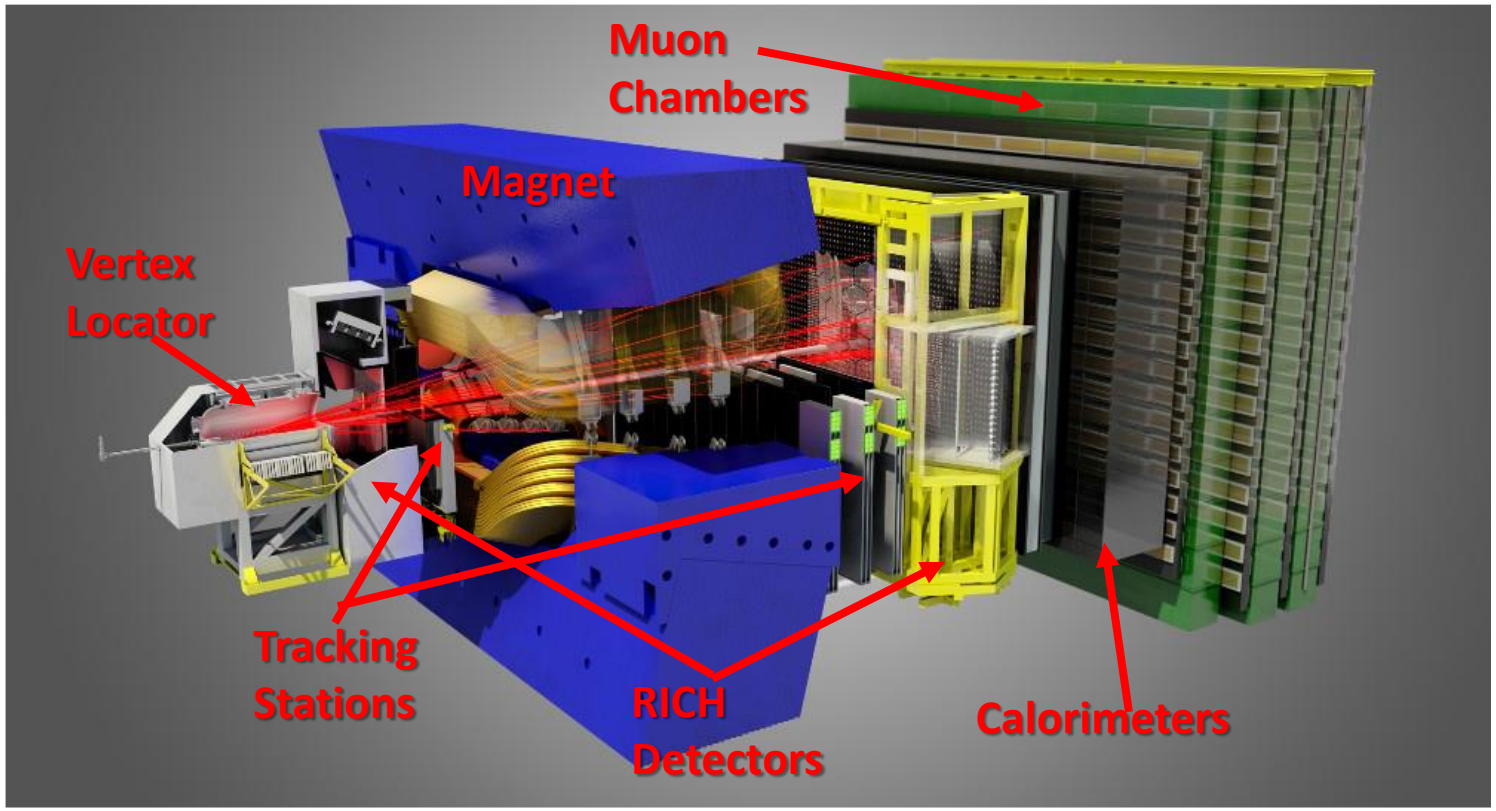
$$|P_{L,H}\rangle = p\,|P^0\rangle \pm q\,|\bar{P}^0\rangle$$
$$\to \text{CPV if } |q/p| \neq 1$$

➢ CPV in interference between mixing and decay:

- Neutral meson decaying
- S_f: interference between mixing and decay
- C_f: direct CPV
- Example: ϕ_s

$$\frac{A(\bar{P} \to f) - A(P \to f)}{A(\bar{P} \to f) + A(P \to f)} = \frac{C_f \cos(\Delta m t) - S_f \sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

LHCb detector



LHCb is a forward spectrometer initially designed for b , c physics

Unique acceptance: $2 < \eta < 5$

Momentum resolution:

- 0.4% at 5 GeV, 0.6% at 100 GeV

Excellent track and vertex reconstruction

Good PID separation

Flexible trigger

- trigger low momentum objects

JINST 3 (2008) S08005

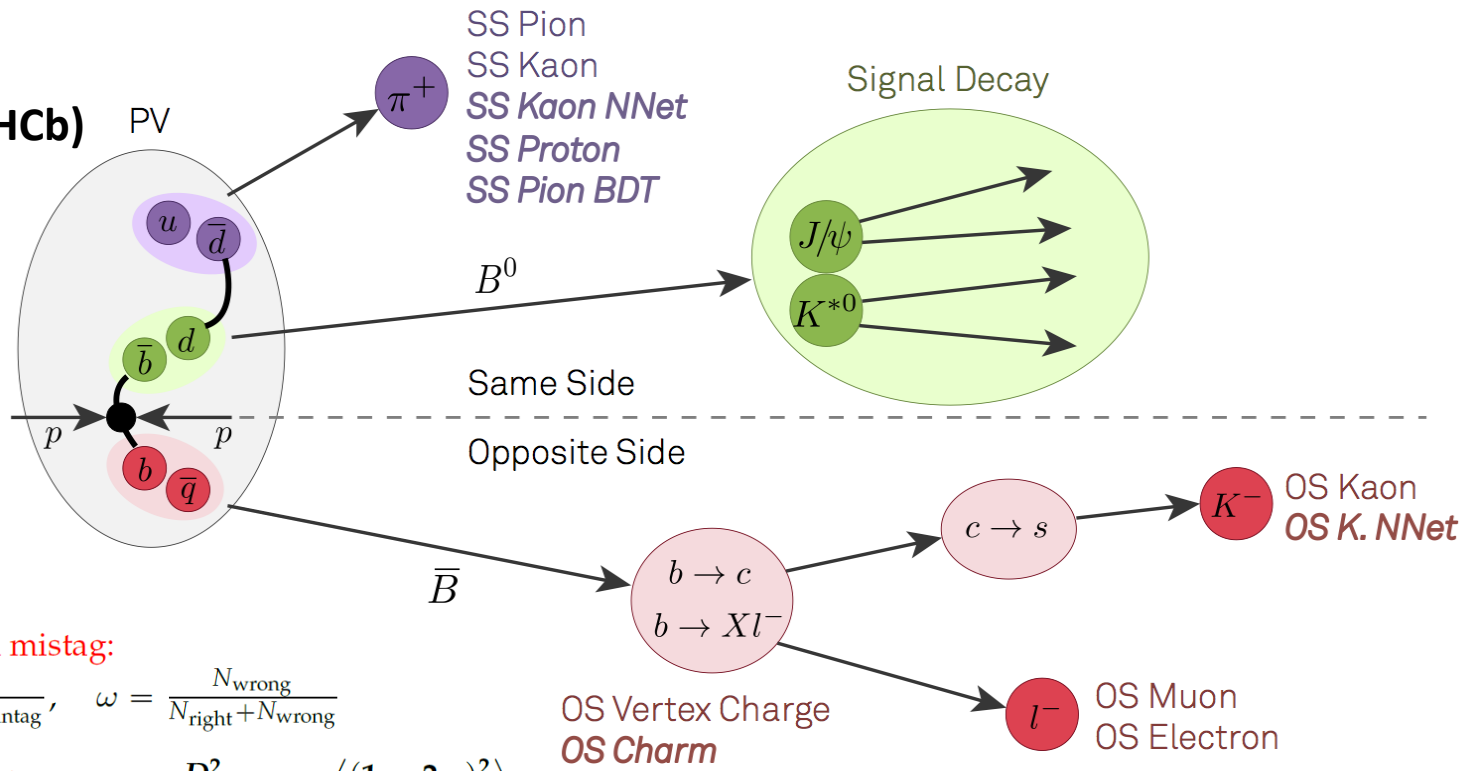
Measuring B meson

Typical requirements:

- Excellent decay time resolution (~ 45 fs @LHCb)
- Modelling decay time efficiency
- Production and detection asymmetry
- Tagging of meson flavour@ production

Tagging power:

- ~ 4% LHCb (J/ψ modes)
- ~ 8% LHCb (open charm modes)



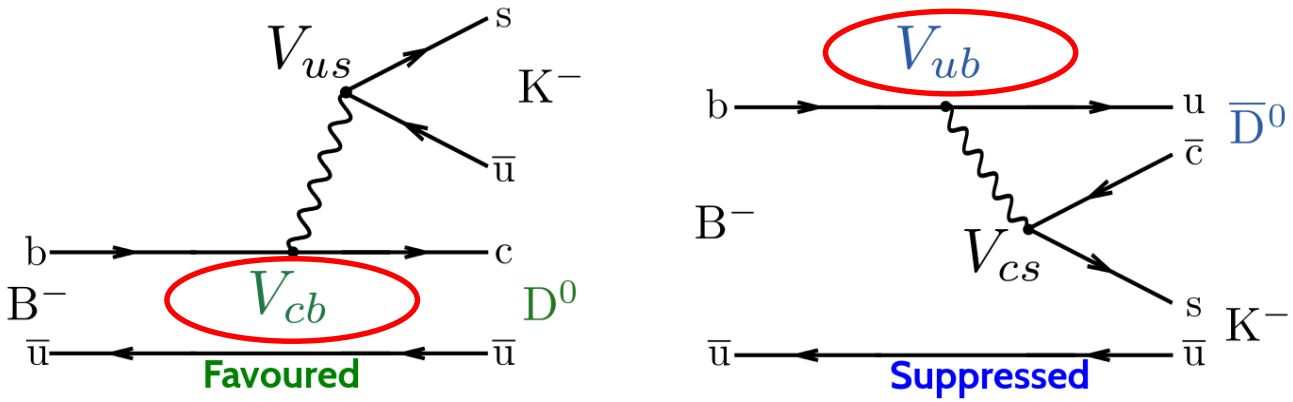
Efficiency and mistag:

$$\epsilon_{\text{tag}} = \frac{N_{\text{tag}}}{N_{\text{tag}}+N_{\text{untag}}}, \quad \omega = \frac{N_{\text{wrong}}}{N_{\text{right}}+N_{\text{wrong}}}$$

Tagging power: $\epsilon_{\text{eff}} = \epsilon_{\text{tag}} D^2 = \epsilon_{\text{tag}} \langle (1-2\omega)^2 \rangle$

CKM angle γ

- $\gamma = -\arg(V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$
  - γ is still the least known angle of the Unitarity Triangle
  - Only CP-violating parameter that can be measured from tree-level decays
  - Theoretically clean: $|\delta_\gamma \leq O(10^{-7})|$



Two main routes:

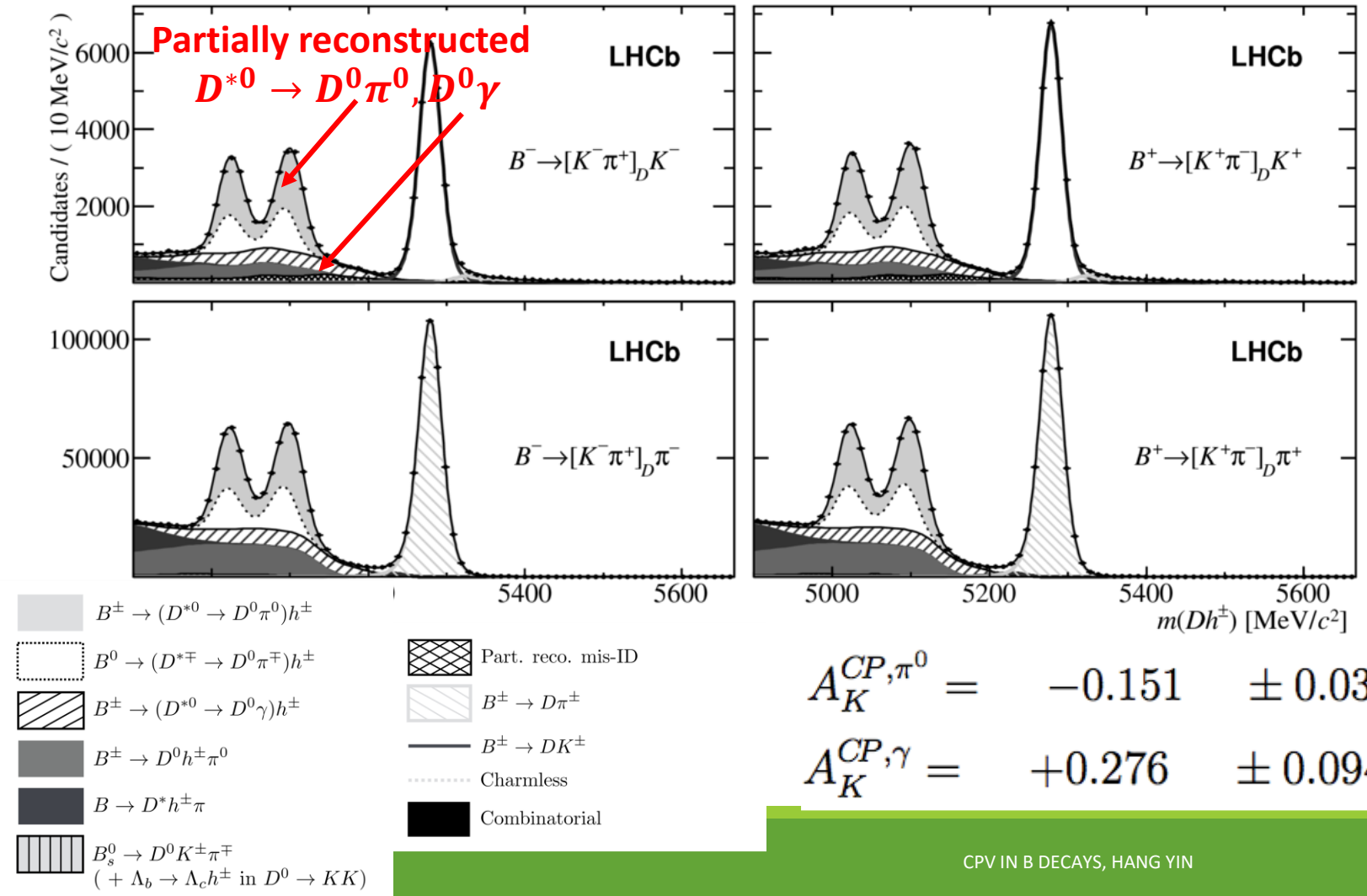
Time-independent measurements: e.g. $B \to DK$

Time-dependent analyses with B_s decays: $B_s \to D_s K$

Signal yields are small (BR $\approx 10^{-7}$), interference between favoured and suppressed decays is small

PLB 777 (2018) 16-30

CP observables in $B^{\pm} \to D^{(*)}K^{\pm}$ and $B^{\pm} \to D^{(*)}\pi^{\pm}$



Experimental challenge: π^0, γ reconstruction at LHCb → these particles are ignored in the analysis

Uses 5 fb-1 (Run 1 + Run 2)

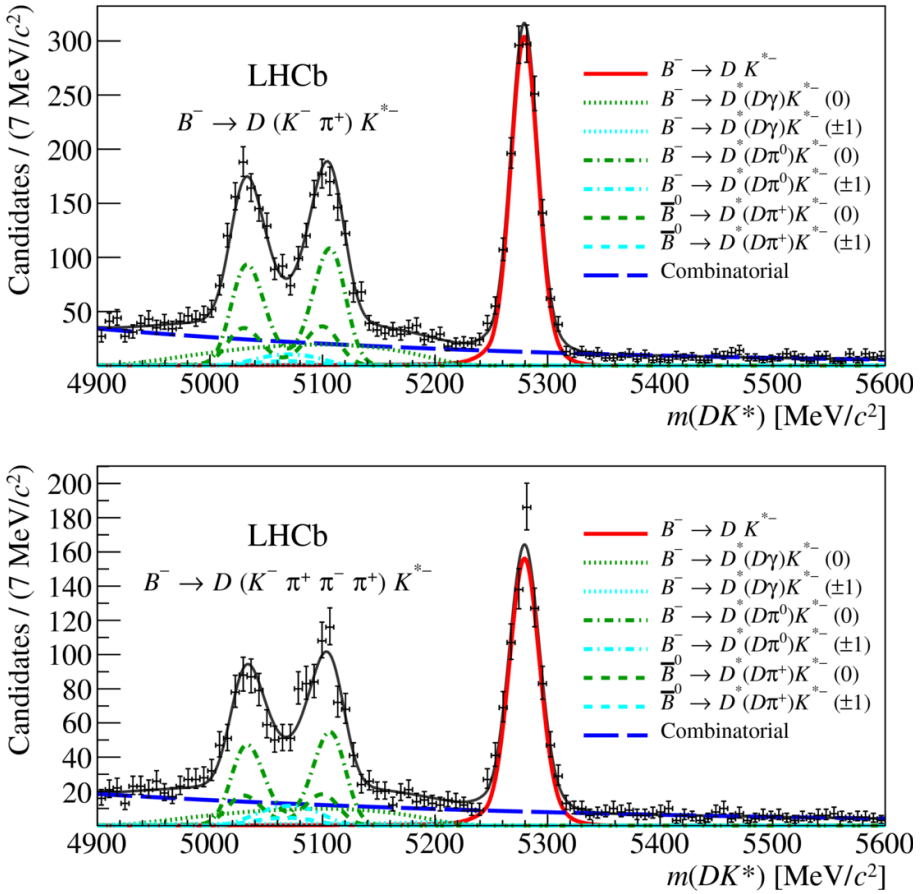
For the first time, part-reco approach used.

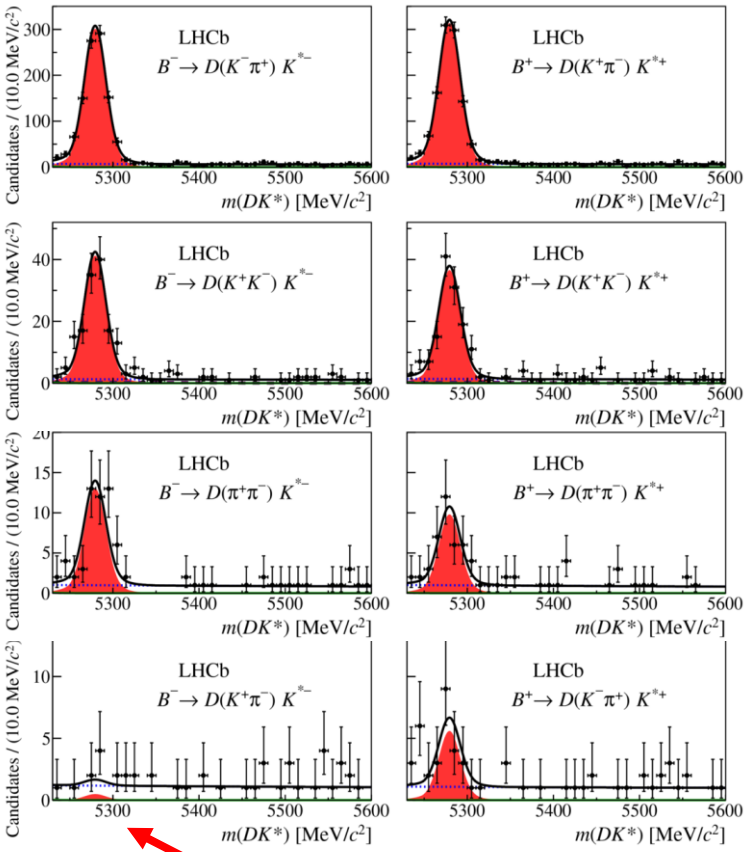
$$A_K^{CP,\pi^0} = -0.151 \pm 0.033\ (\text{stat}) \pm 0.011\ (\text{syst}) \quad 4.3\,\sigma$$

$$A_K^{CP,\gamma} = +0.276 \pm 0.094\ (\text{stat}) \pm 0.047\ (\text{syst}) \quad 2.4\,\sigma$$

LHCb-PAPER-2017-030
Submitted to JHEP

CP observables in $B^{\pm} \to DK^{*\pm}$





Uses 2- and 4-body D^0 decay modes (+Run2 data)

Constraint r_B, δ_B and γ from the measurement of ratio of rates and CP asymmetries

Results in 2-body modes consistent and more precise than Babar

$$R_{CP+} = 1.18 \pm 0.08 \pm 0.01$$
$$A_{CP+} = 0.08 \pm 0.06 \pm 0.01$$
$$R_{ADS}^{K\pi} = 0.011 \pm 0.004 \pm 0.001$$
$$A_{ADS}^{K\pi} = -0.81 \pm 0.17 \pm 0.04$$

4.3σ evidence of suppressed ADS mode

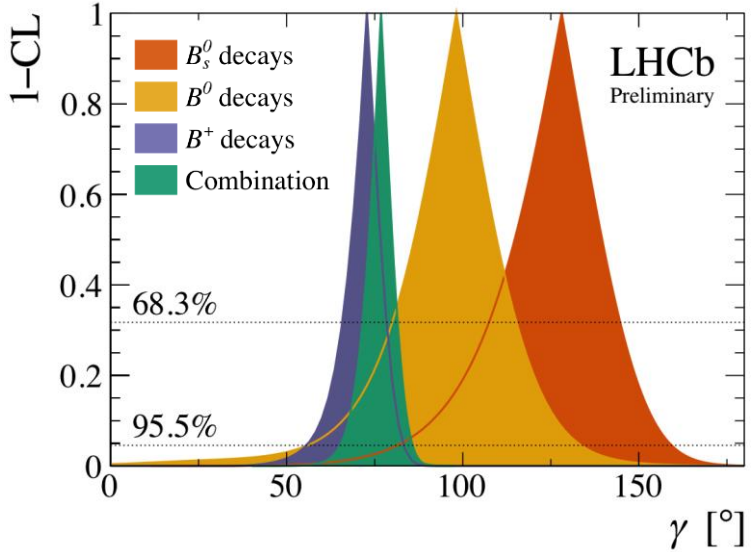
LHCb-CONF-2017-004

Followed the same strategy as previous LHCb combination: JHEP 12 (2016) 087

γ LHCb combination

- Use several $B \to DK$ measurements (85 observables, 37 parameters)

B decay	D decay	Method	Ref.	Status since last combination [1]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[16]	Updated to Run 1 + 2 fb^{-1} Run 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[18]	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[19]	As before
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[20]	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[16]	New
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[21]	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[22]	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[23]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[24]	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[25]	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[26]	Updated to 3 fb^{-1} Run 1

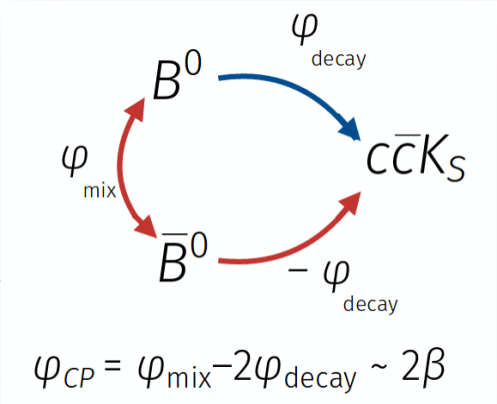


LHCb combination: $(76.8^{+5.1}_{-5.7})^o$

CKM indirect constraint: $(65.3^{+1.0}_{-2.5})^o$

LHCb can reach 4° end of Run II and better than 0.4^o precision with phase-2 upgrade. CERN-LHCC-2017-003 (2017)

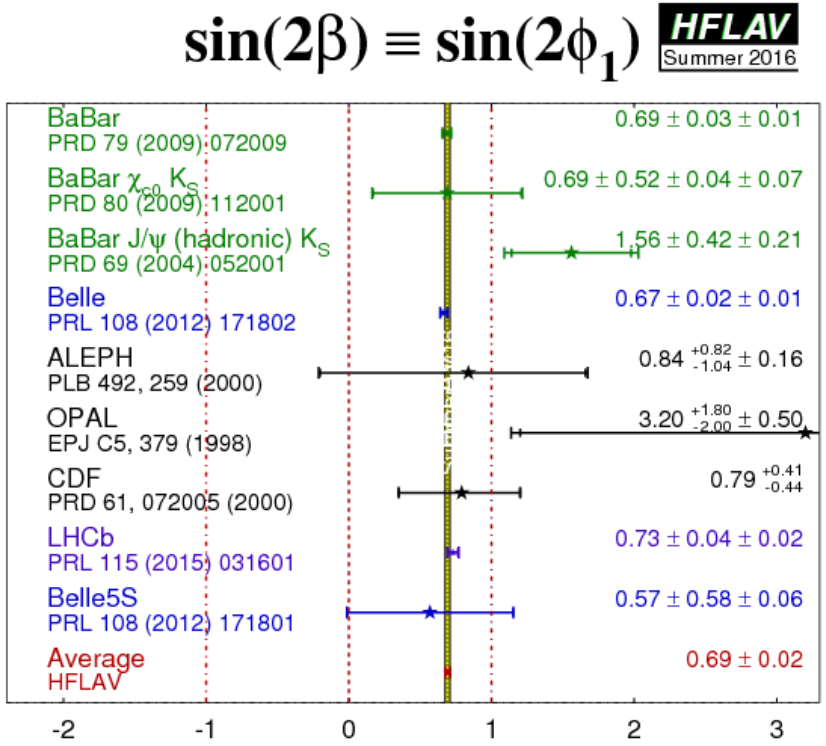
Determination of β



- $\beta = -arg(V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$: $\sim 22^o$ (indirect determination in SM)
  - Interference between mixing and decay in $B^0 \to (c\bar{c})K_s$ is sensitive to β

- The B-factories still dominate the world average
  - $\beta = (21.9 \pm 0.7)^o$ [HFLAV]
  - LHCb Run 1 results close to it

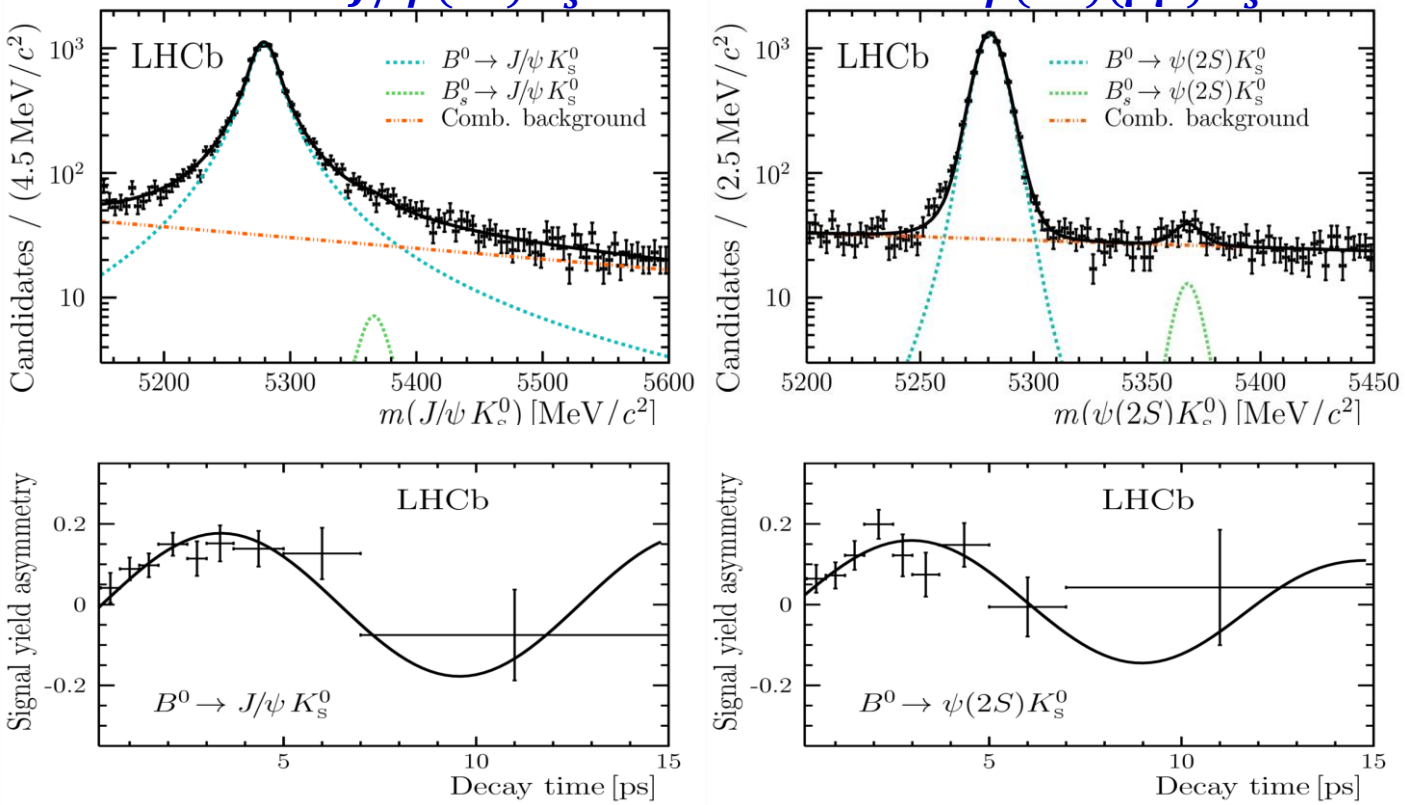
- LHCb is expected to reach 0.6^o (0.2^o) precision with Run 2 (phase-1 upgrade)

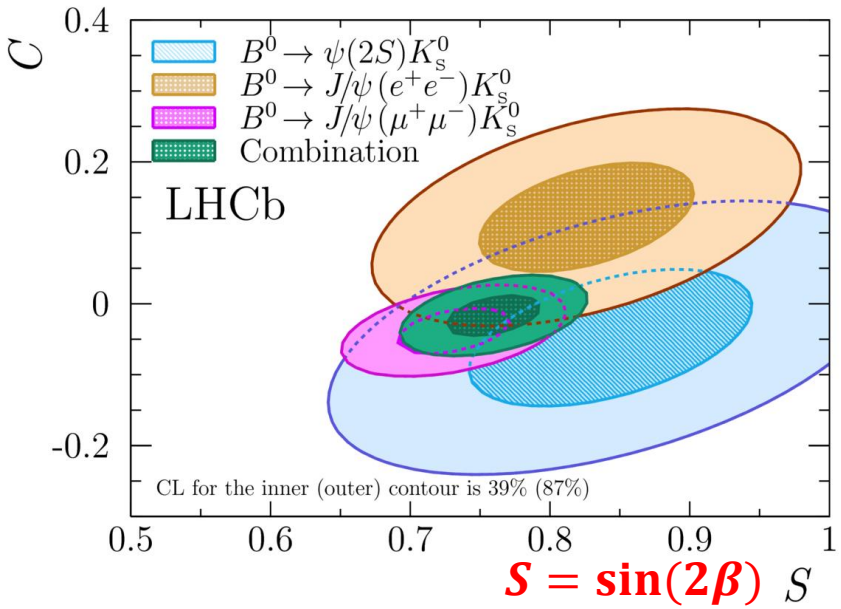


$\sin(2\beta)$ from $B^0 \to (c\bar{c})K_s$

- Additional channels from Run 1 data

$B^0 \to J/\psi(ee)K_s$ $\qquad$ $B^0 \to \psi(2S)(\mu\mu)K_s$





$S = \sin(2\beta)$

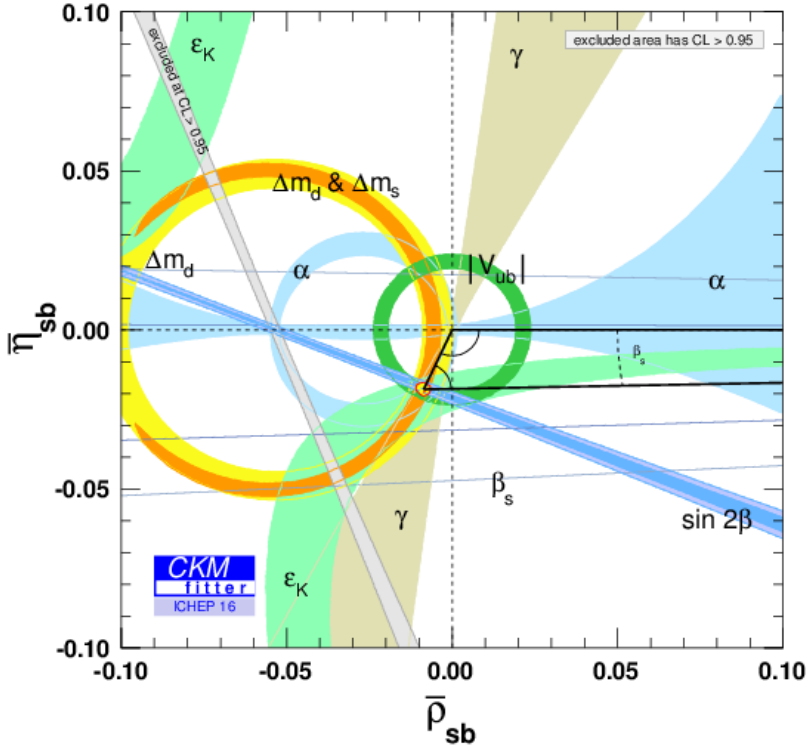
$$C\left(B^0 \to [c\bar{c}]K^0_S\right) = -0.017 \pm 0.029\,,$$
$$S\left(B^0 \to [c\bar{c}]K^0_S\right) = \quad 0.760 \pm 0.034\,,$$

About 20% improvement in precision wrt previous result [PRL 115 (2015) 031601]

$$A_{CP}(t) = S\sin(\Delta m t) - C\cos(\Delta m t)$$
$$S \approx \sin(2\beta)$$

CP violation in the B_s system

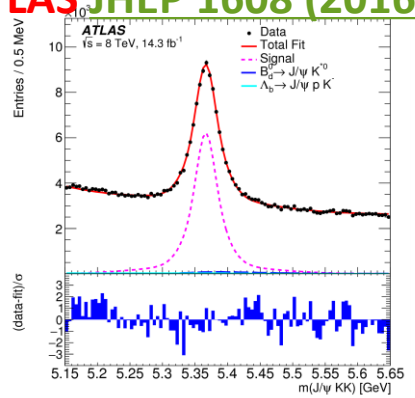
- $\beta_S = -\arg(V_{cs}V_{cb}^*/V_{ts}V_{tb}^*)$: SM prediction $\phi_s = -2\beta_s = -36.5^{+1.3}_{-1.2}$ mrad
  - $B_S \to J/\psi\phi$ is a golden channel for measure β_S
  - Additional sensitivity comes from other $b \to c\bar{c}s$ transitions
  - Tevatron results have been improved by > 10 by LHC

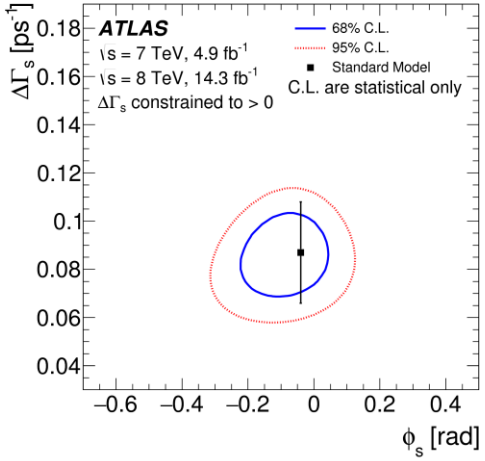


- **LHCb:**
  - $J/\psi\phi$: PRL 114, 041801 (2015)
  - $J/\psi KK$: JHEP 08 (2017) 037
  - $J/\psi\pi\pi$: PLB 736 (2014) 186
  - $\psi(2S)\phi$: PLB 762 (2016) 253-262
  - $D_S^+D_S^-$: PRL 113, 211801 (2014)
- **CMS:** $J/\psi\phi$ PLB 757 (2016) 97
- **ATLAS:** $J/\psi\phi$: JHEP 08 (2016) 147

ϕ_s measurements from LHC

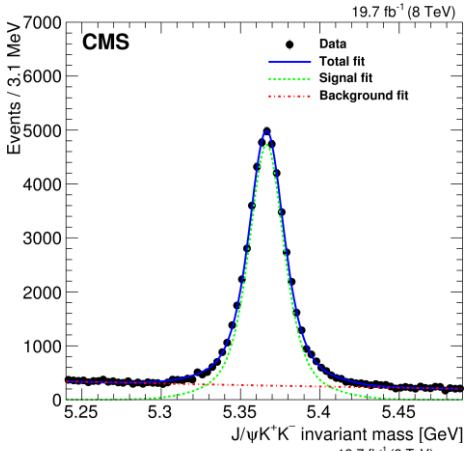
ATLAS JHEP 1608 (2016) 147

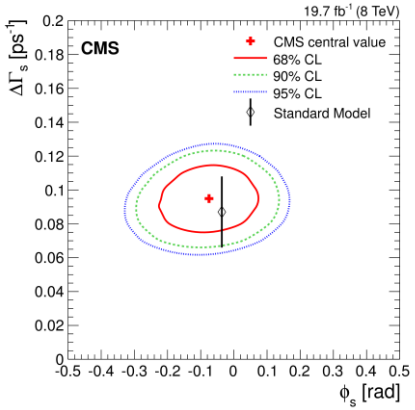




$\phi_s = -0.090 \pm 0.078 \pm 0.041$

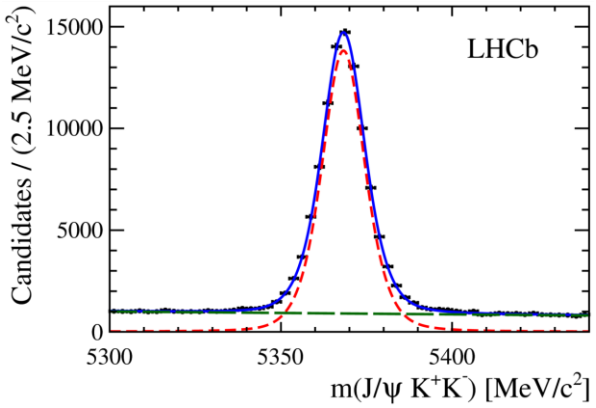
CMS PLB 757 (2016) 97

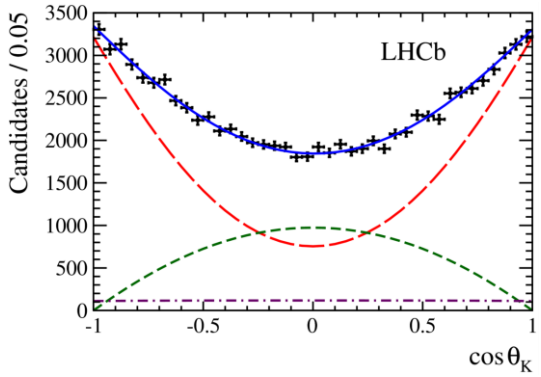




$\phi_s = -0.075 \pm 0.097 \pm 0.031$

LHCb PRL 114, 041801 (2015)





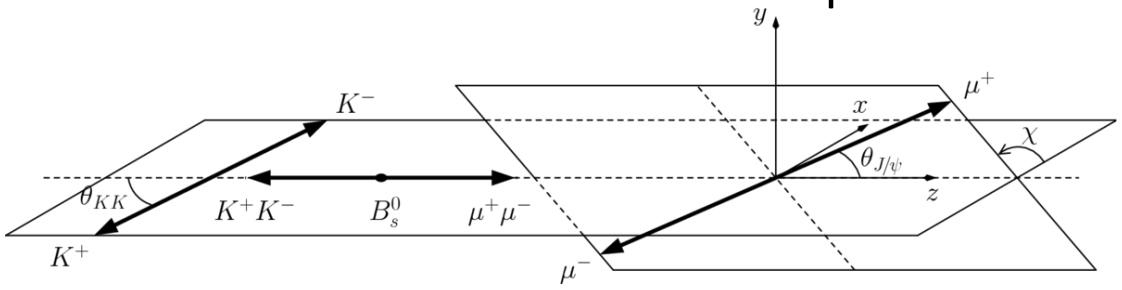
$\phi_s = -0.058 \pm 0.049 \pm 0.006$

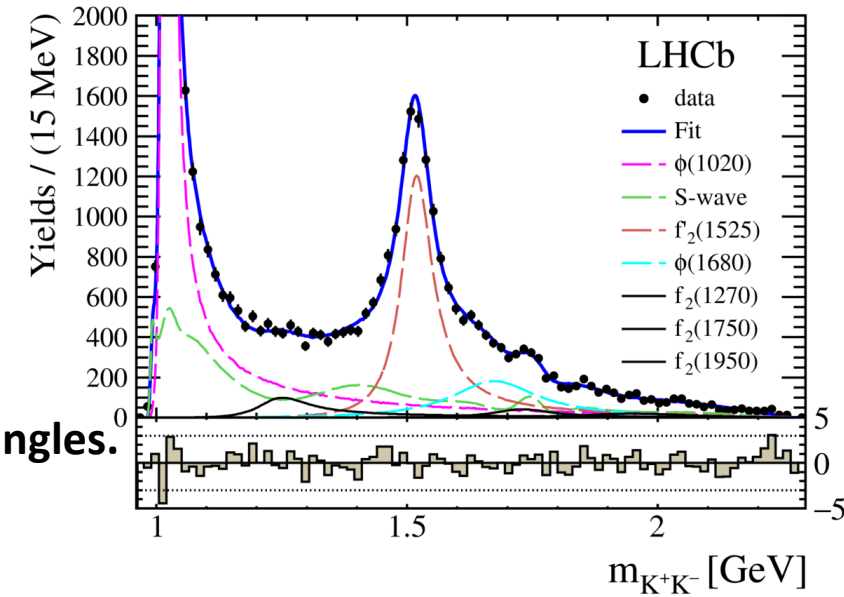
JHEP 08 (2017) 037

First time that ϕ_s is measured in the final states dominated by a tensor

Measurement of $\phi_s^{c\bar{c}s}$ in $B_s^0 \to J/\psi K^+K^-$ above $\phi(1020)$

- Flavour-tagged, time-dependent amplitude analysis with $m_{K^+K^-}$ above the $\phi(1020)$ threshold with full LHCb Run I data sample.





Selection using MVA analysis, background subtraction via sWeight in $m(J/\psi K^+K^-)$ and multi-dimensional fit to decay time, $m_{K^+K^-}$ and the helicity angles.

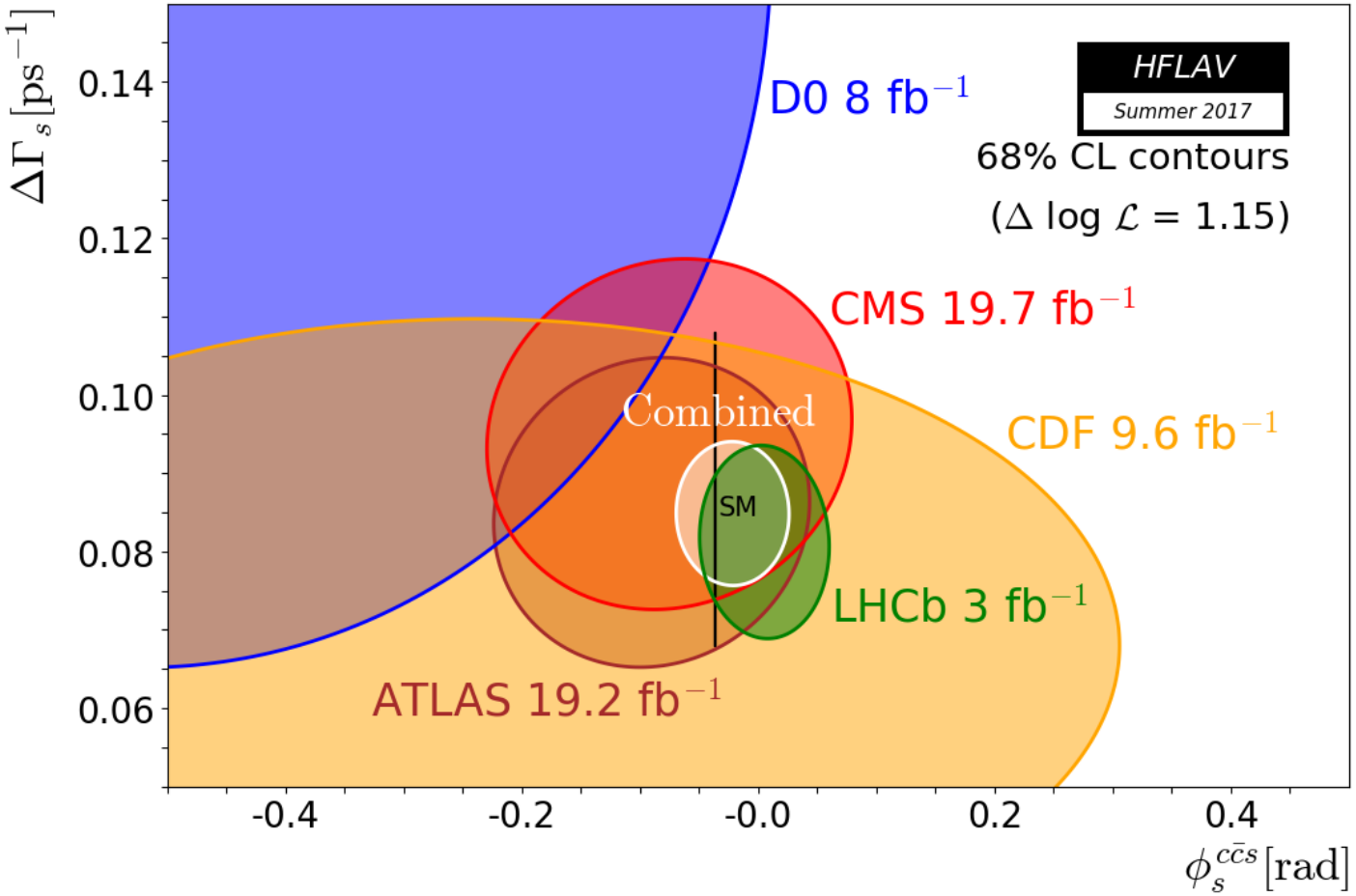
Efficiencies and decay time control channel: $B^0 \to J/\psi K^{*0}(\to K^+\pi^-)$

Dominant systematic uncertainty: resonance modelling and background subtraction

New LHCb average (including $J/\psi\phi$ and $J/\psi\pi\pi$): $\phi_s = 1 \pm 37\,\mathrm{mrad}$

$$\phi_s = 119 \pm 107 \pm 34\,\mathrm{mrad},$$
$$|\lambda| = 0.994 \pm 0.018 \pm 0.006,$$
$$\Gamma_s = 0.650 \pm 0.006 \pm 0.004\,\mathrm{ps}^{-1},$$
$$\Delta\Gamma_s = 0.066 \pm 0.018 \pm 0.010\,\mathrm{ps}^{-1}.$$

State of art of ϕ_s



Precision improved by > 10 since Tevatron results

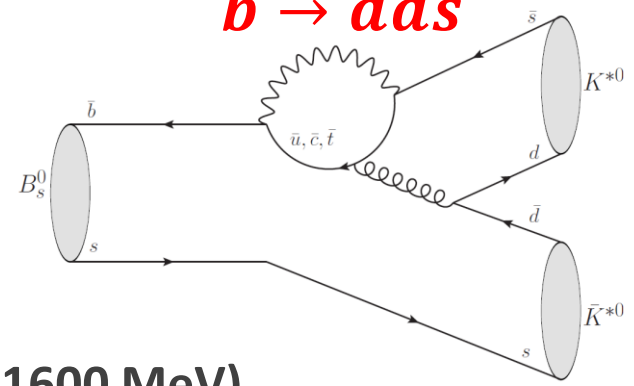
New Physics is not large, the uncertainty needs to be further reduced

HFLAV: $\phi_s = -21 \pm 31$ mrad (preliminary)

- ✓ **Atlas expects a significant increase in sensitivity with a new innermost pixel detector**
- ✓ **LHCb sensitivity with phase-2 upgrade expected to be < 3 mrad [CERN-LHCC-2017-0023 (2017)]**
- ✓ **Important to control size of the penguin diagram contribution**

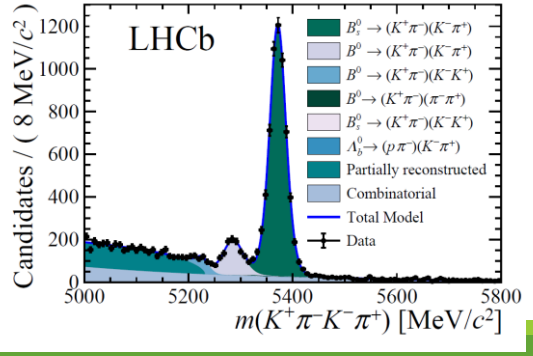
First measurement of ϕ_s using $B_s \to (K^+\pi^-)(K^-\pi^+)$ decays

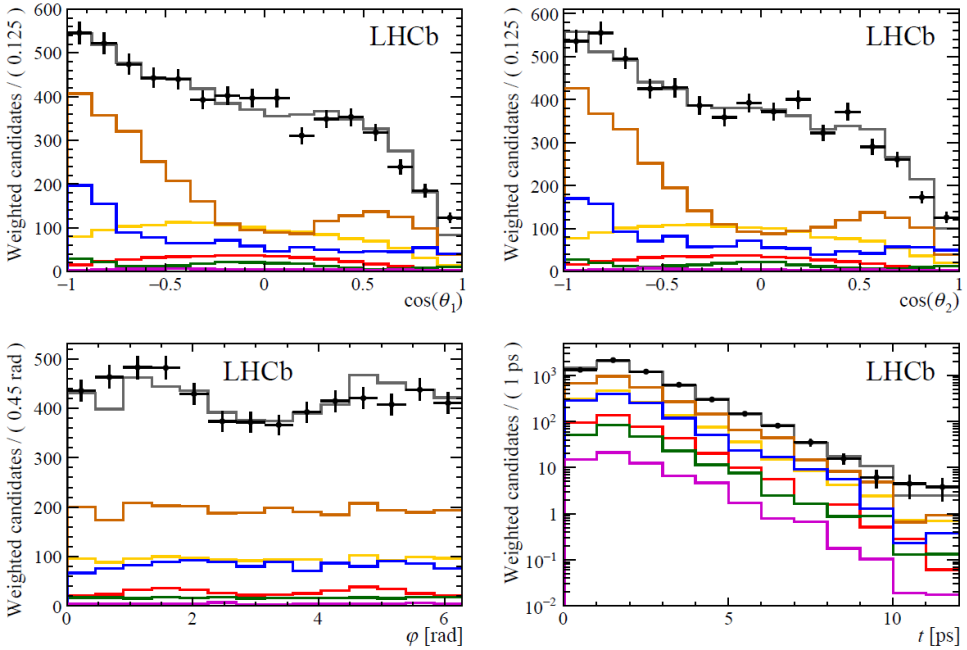
$b \to d\bar{d}s$



- Gluonic penguin decay: new physics could enter both mixing and decay
- Very complicated time-dependent angular analysis: many resonants (750-1600 MeV)

Decay	Mode	j_1	j_2	Allowed values of h	Number of amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	scalar-scalar	0	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	scalar-vector	0	1	0	1
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	vector-scalar	1	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}_2^*(1430)^0$	scalar-tensor	0	2	0	1
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	tensor-scalar	2	0	0	1
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	vector-vector	1	1	$0, \parallel, \perp$	3
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	vector-tensor	1	2	$0, \parallel, \perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	tensor-vector	2	1	$0, \parallel, \perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	tensor-tensor	2	2	$0, \parallel_1, \perp_1, \parallel_2, \perp_2$	5





$$\phi_s^{d\bar{d}} = -0.10 \pm 0.13 \pm 0.14 \text{ rad}$$

CP violation in B mixing

- **D0** reported an anomalous like-sign dimuon asymmetry with **~3 σ from SM** [Phys. Rev. D 89, 012002 (2014)]

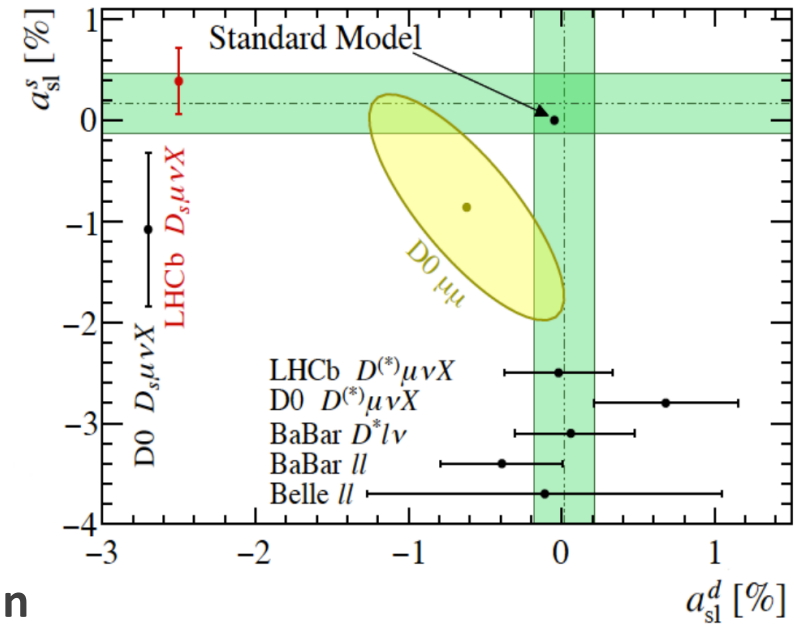
- Consider a flavour-specific final state f:

$$B^0_{(s)} \to f \quad \text{or} \quad \overline{B}^0_{(s)} \to B^0_{(s)} \to f$$

$$\overline{B}^0_{(s)} \to \overline{f} \quad \text{or} \quad B^0_{(s)} \to \overline{B}^0_{(s)} \to \overline{f}$$

$$a_{sl} \equiv \frac{\Gamma(\overline{B}^0_{(s)}(t)\to f)-\Gamma(B^0_{(s)}(t)\to \overline{f})}{\Gamma(\overline{B}^0_{(s)}(t)\to f)+\Gamma(B^0_{(s)}(t)\to \overline{f})} \simeq \frac{\Delta\Gamma}{\Delta M}\tan\phi_M$$

CPV in mixing is very small in the SM



- **LHCb** measured results are consistent with SM prediction [Phys. Rev. Lett. 117, 061803 (2016), Phys. Rev. Lett. 114, 041601 (2015)]

- **ATLAS** measured same- and opposite-sign charge asymmetries based on the μ charge from a top and the charge of the soft μ from b-hadron in $t\bar{t}$ events [JHEP 02 (2017) 071]
  - **Four CP asymmetries (one mixing and three direct) consistent with SM**

Summary

- Results found so far are compatible with SM prediction
  - New Precision measurements in b mesons

- Many of them are within the physics program of LHCb and its upgrade, ATLAS and CMS also start to contribute to these physics

- With the statistics achieved by LHC during the Run-1 and Run-2, more results are coming
  - Stay tuned for many interesting new results!

Backup

ϕ_s combination (2017 summer)

LHCb:

- $J/\psi\phi$ [PRL114, 041801 (2015)]
- $J/\psi K^+K^-$ [arXiv:1704.08217 (2017)]
- $J/\psi\pi^+\pi^-$ [Phys. Lett. B736, (2014) 186]
- $\psi(2S)\phi$ [Phys. Lett. B762 (2016) 253-262]
- $D_s^+D_s^-$ [PRL113, 211801 (2014)]

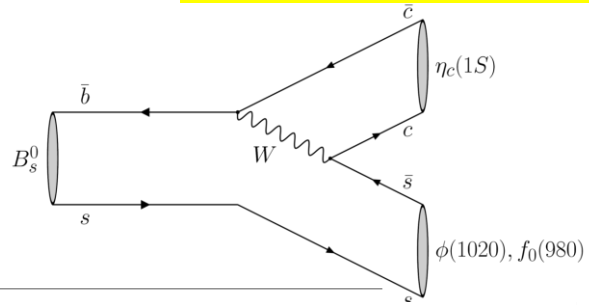
CMS:

- $J/\psi\phi$ [Phys. Lett. B 757 (2016) 97]

ATLAS:

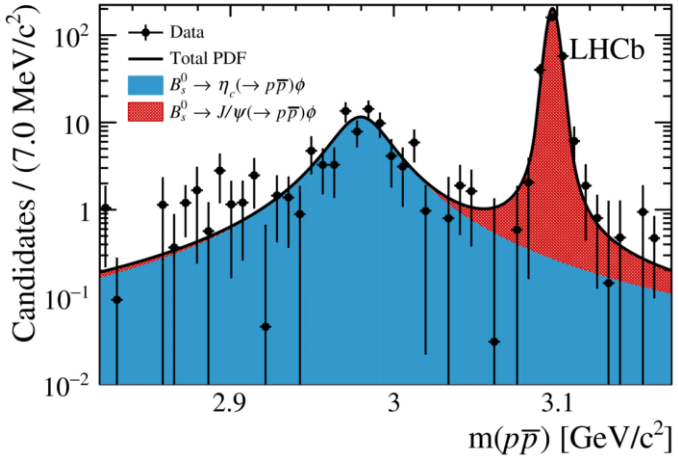
- $J/\psi\phi$ [JHEP 08 (2016) 147]

JHEP 07 (2017) 021



Observation of the $B_s^0 \to \eta_c \phi$

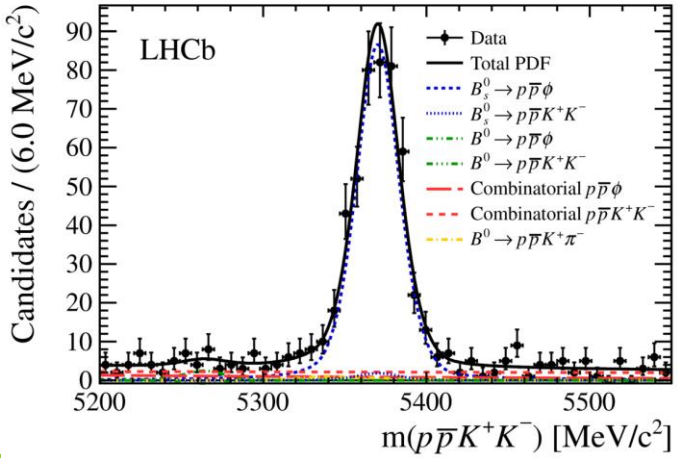
- $\eta_c \phi$ final state is CP-even: no need angular analysis
- Using Run-I data, which is not enough to perform ϕ_s measurement
- Branching ratio measurement is presented



- $\eta_c \to p\bar{p}, K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-, K^+K^-K^+K^-$
- $\phi \to K^+K^-$

$$\mathcal{B}(B_s^0 \to \eta_c\phi) = (5.01 \pm 0.53 \pm 0.27 \pm 0.63) \times 10^{-4},$$
$$\mathcal{B}(B_s^0 \to \eta_c\pi^+\pi^-) = (1.76 \pm 0.59 \pm 0.12 \pm 0.29) \times 10^{-4},$$

4.6σ

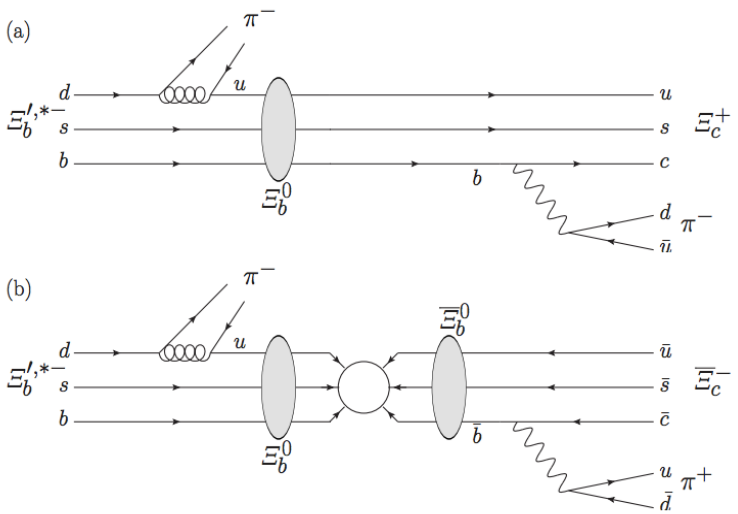


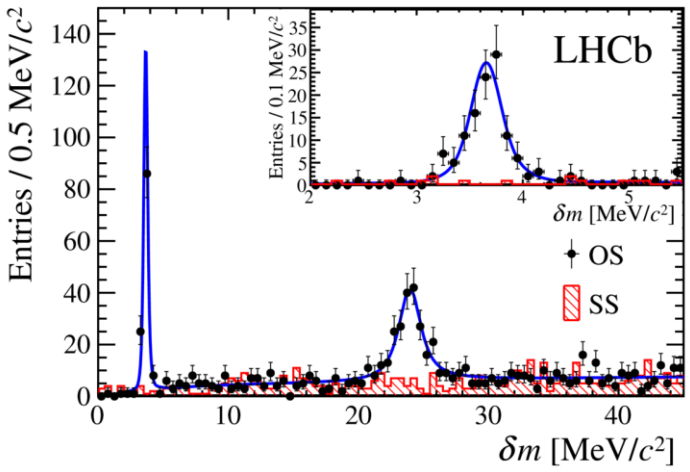
In the future with significant improvement of the hadronic trigger efficiencies, could become of interest to add sensitivity to ϕ_s

Phys. Rev. Lett. 119, 181807 (2017)

Baryon-number violation

- BNV never been seen experimentally → strong constraints from photon lifetime
- **BSM models with flavour-diagonal six fermion vertices allow BNV without violating constraints [PRD 85, 036005 (2012), PLB 721 82 (2013)]**
- **Unambiguous experimental evidence:**
  - **baryon-antibaryon oscillations of hadrons that contain quarks of all three generations (usb)**





No evidence of BNV oscillations

Nature Physics 13, 391–396 (2017)

CP violation in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays

- Direct CPV had never been observed in baryon decays
- Large CPV effects are expected in charmless Λ_b decays ($A_{CP}\sim 20\%$)
  - Y.K. Hsiao and C.Q. Geng [PRD 91, 116007 (2015)]
- Both tree and penguin diagrams contribute with similar amplitudes
- $a_{CP} \neq 0$ at 3.3σ was seen