b decaimientos hadrónicos

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on behalf of the LHCb collaboration

XXXVIII Physics in Collision

Bogota, Colombia

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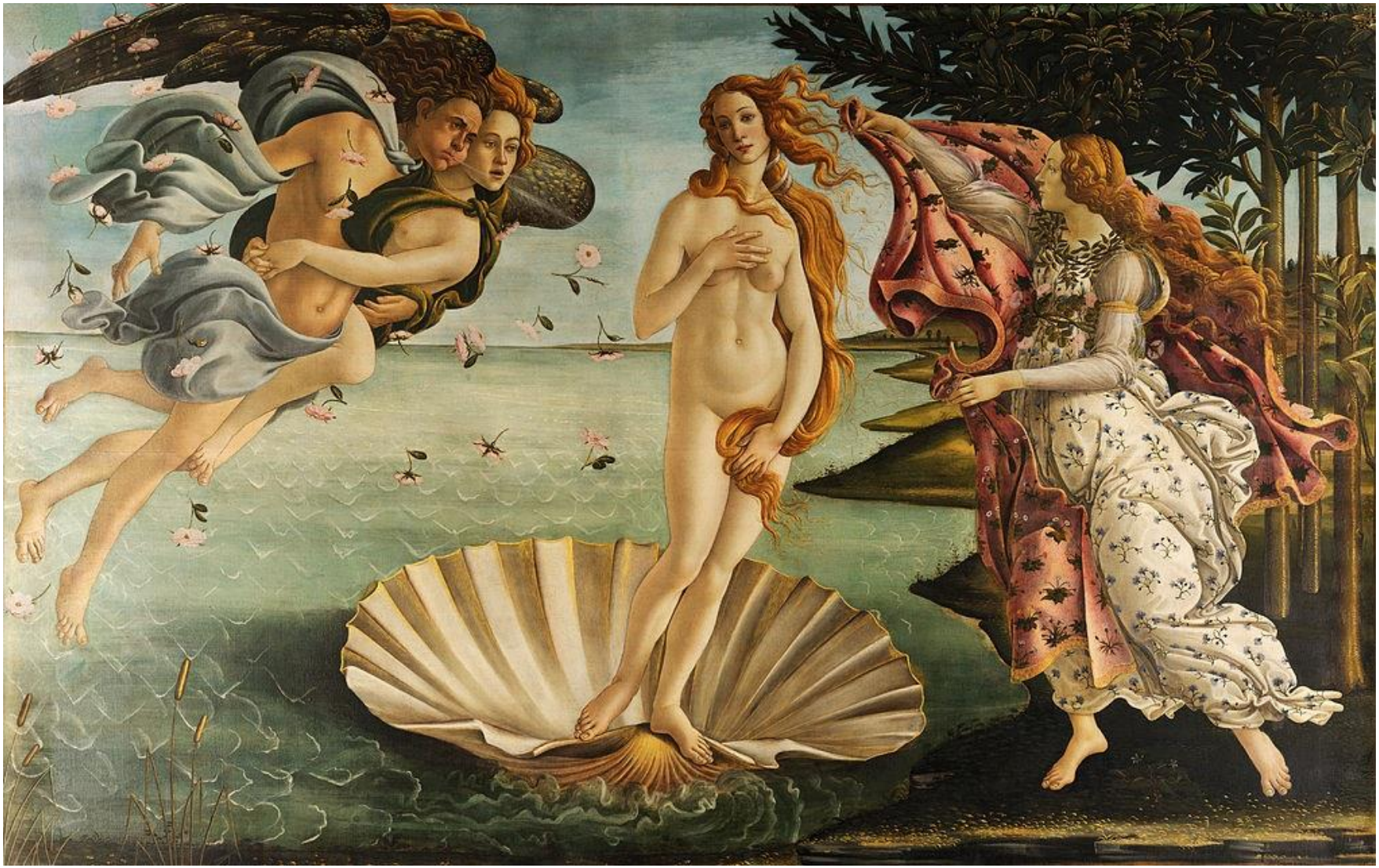
Selected results since PIC 2017
from BaBar, Belle, CMS and LHCb

B-decays also in talk of Paoti Chang

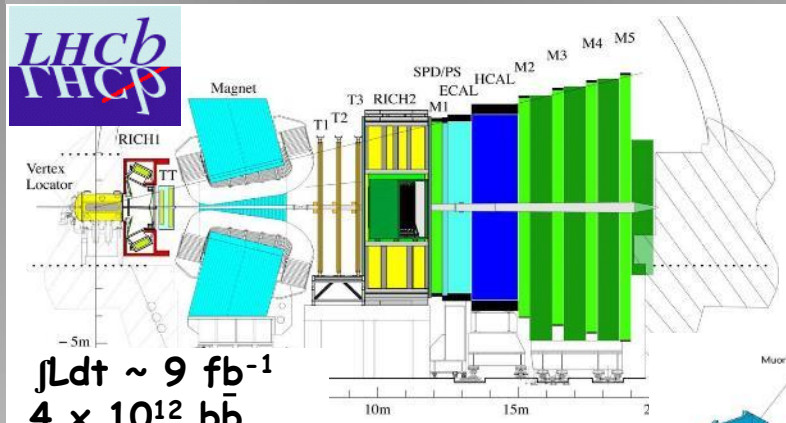
In this talk, new results on

CP-parity violation and **QCD tests** with multibody beauty decays



Sources of modern beauty

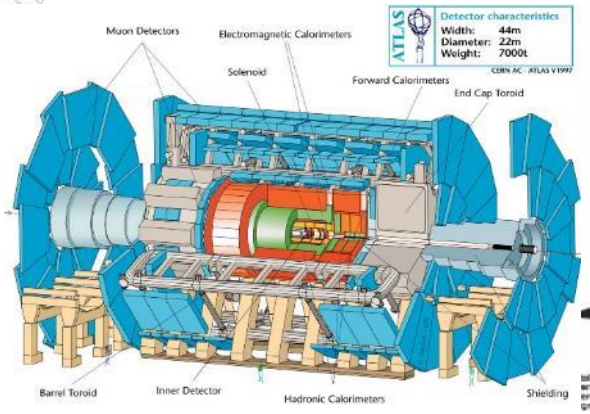
Hadron colliders

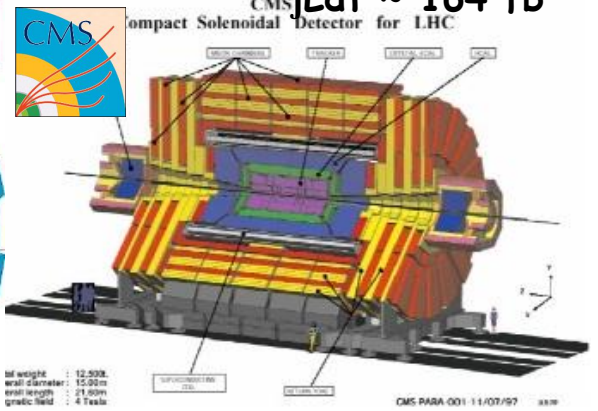


$\int Ldt \sim 9\ fb^{-1}$
$4 \times 10^{12}\ b\bar{b}$

- Excellent lifetime resolution
  due to LARGE boost, ~0.03 τ_B
- Large $b\bar{b}$ production cross section

General purpose experiments





$\int Ldt \sim 164\ fb^{-1}$

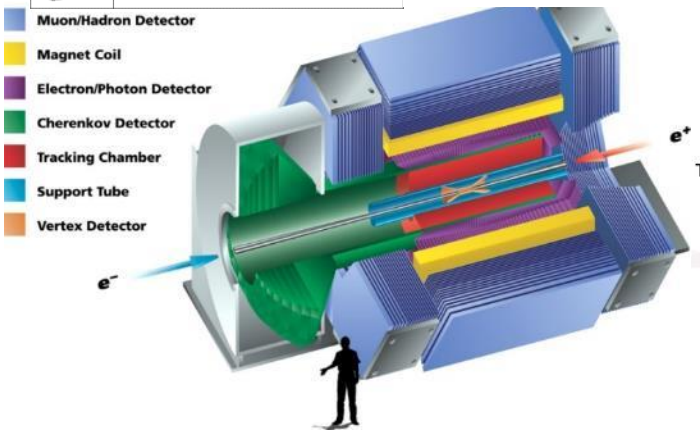
- Large combinatorial backgrounds
- Decays with neutrals and missing particles more difficult

e^+e^- colliders

- Clean environment
- Excellent performance for modes with neutrals/neutrinos
- Lower boost, poorer lifetime resolution

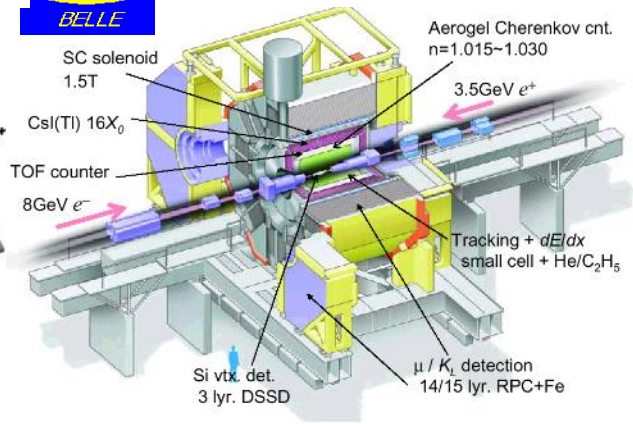
BABAR

$\int Ldt \sim 550\ fb^{-1}$
$0.7 \times 10^9\ b\bar{b}$



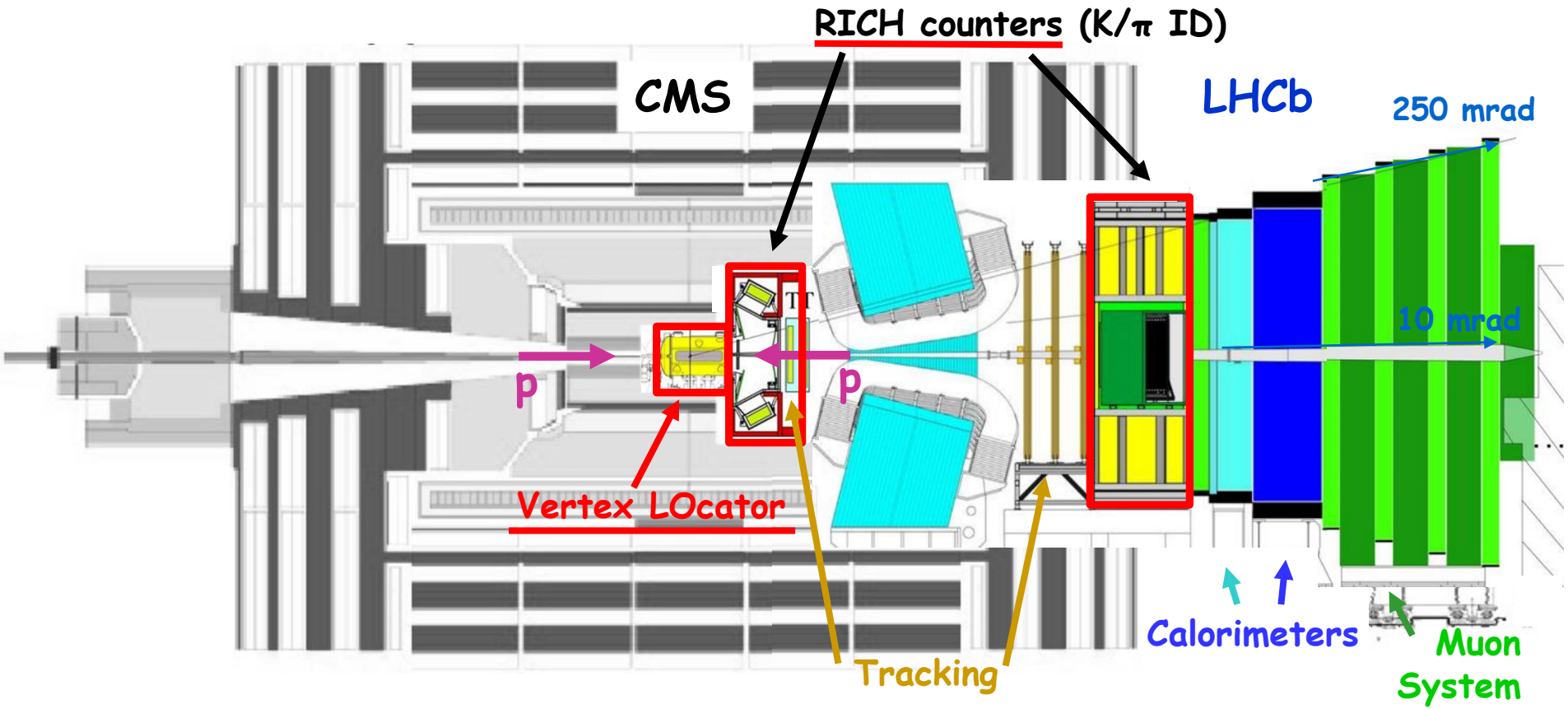
BELLE

$\int Ldt \sim 1\ ab^{-1}$
$1.2 \times 10^9\ b\bar{b}$



JINST 8 (2013) P08002, INT.J.MOD.PHYS.A30 (2015) 1530022

- **LHCb**: dedicated flavour physics experiment
- Acceptance 1.9 < η < 4.9, **~4% of solid angle**, but **~40% of beauty production x-section**

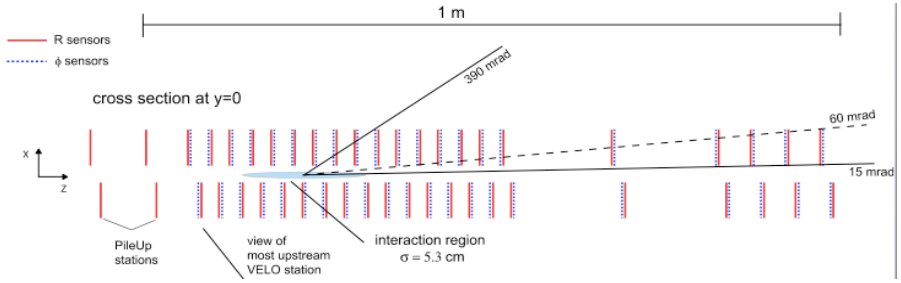


- Key detector systems for hadronic final states: **vertex reconstruction (VELO), particle identification (RICHs), trigger**

Vertex reconstruction in LHCb: VErtex LOcator

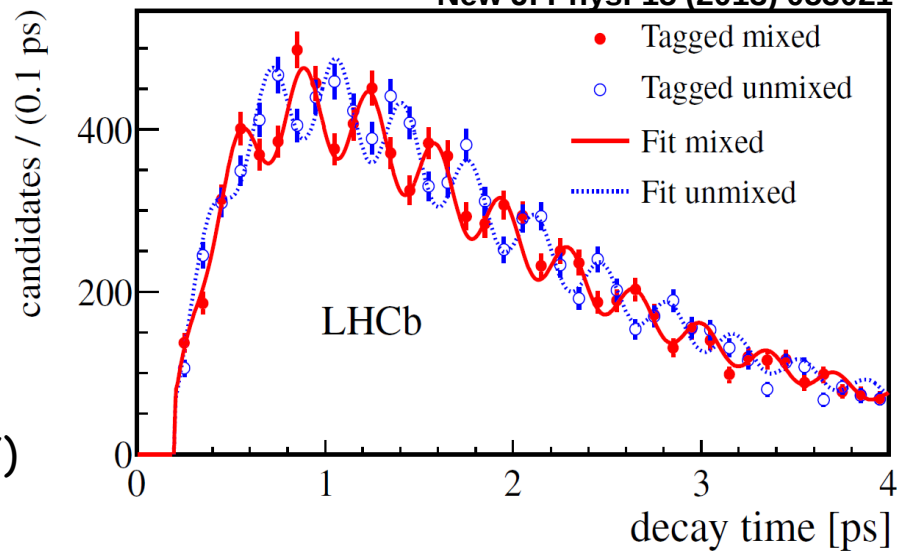
JINST 8 (2013) P08002, JINST 9 (2014) P09007

- 88 semi-circular **microstrip Si sensors**
- Double-sided, **R and φ** layout
- 300μm thick n-on-n sensors, strip pitches from 40 to 120μm
- **First active strip at 8.2mm from beam axis**



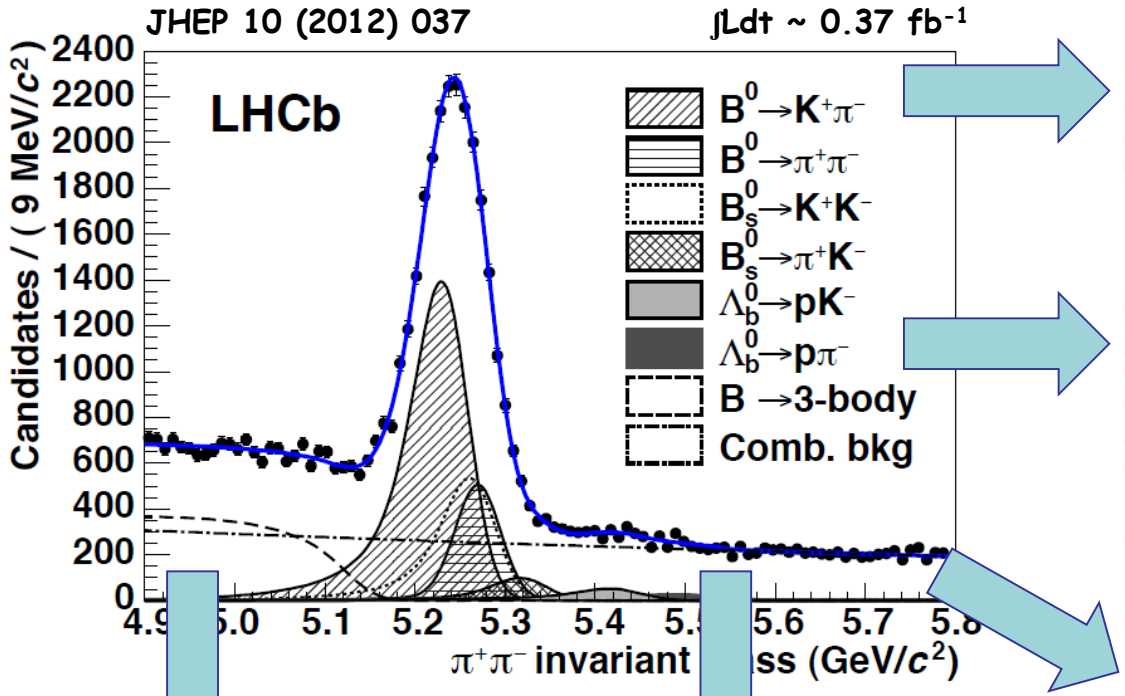
- Excellent **spatial resolution**, down to 4μm for single tracks
- Precise **impact parameter** measurement, $\sigma_{IP} = 11.6 + 23.4/pT$ [μm]
- Precise **primary vertex** reconstruction, $\sigma_{x,y} = 13\mu m$, $\sigma_z = 69\mu m$ for vertex of 25 tracks
- VELO provides excellent **proper time** resolution
- **Vertex resolution** allows to resolve fast (x~27) $B_s\bar{B}_s$ oscillations

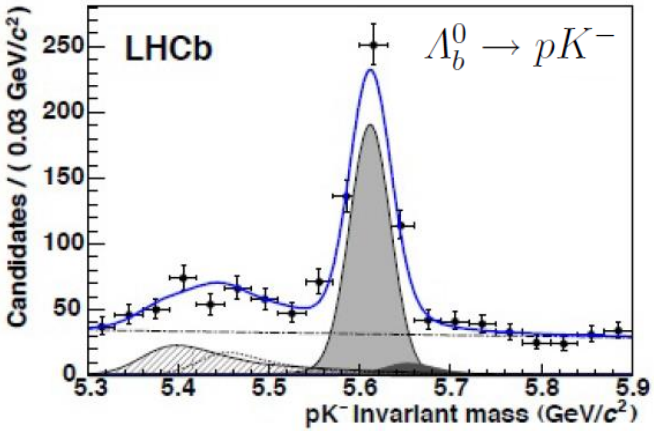
New J. Phys. 15 (2013) 053021

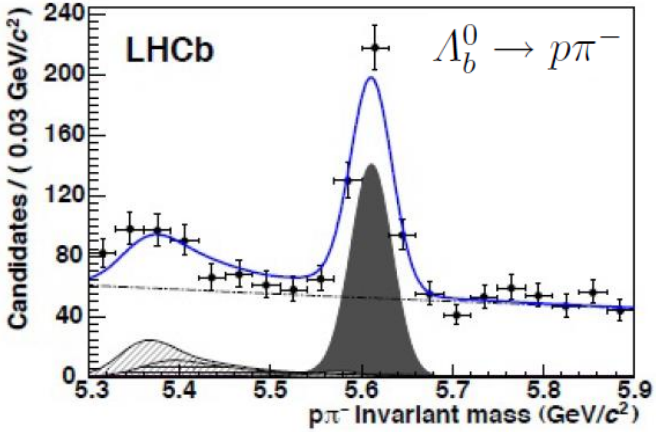


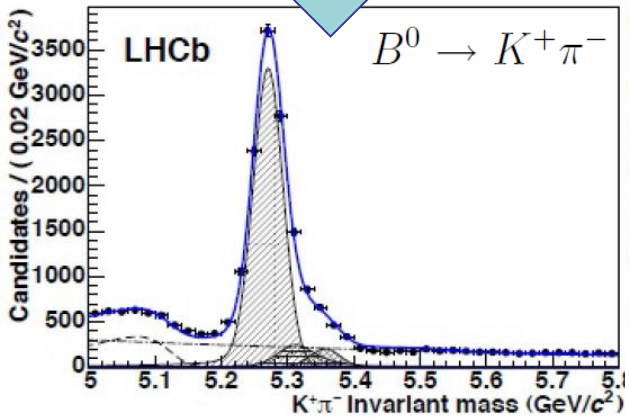
Charged hadron ID in LHCb: Cherenkov light detectors

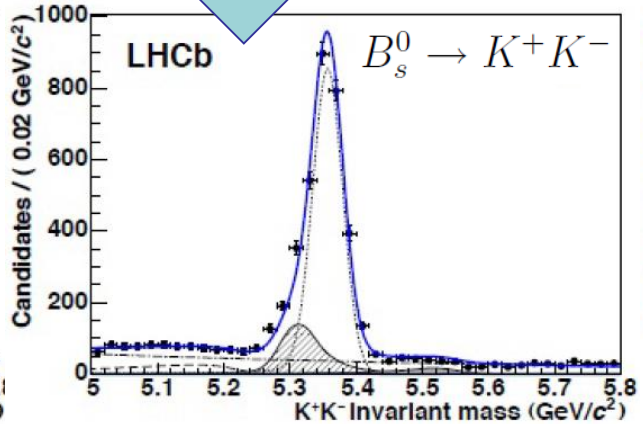
- **2 Ring Imaging Cherenkov Detectors**, Cerenkov light recorded by HPD
- Charged hadron ID, **charmless 2-body b-hadron decays**

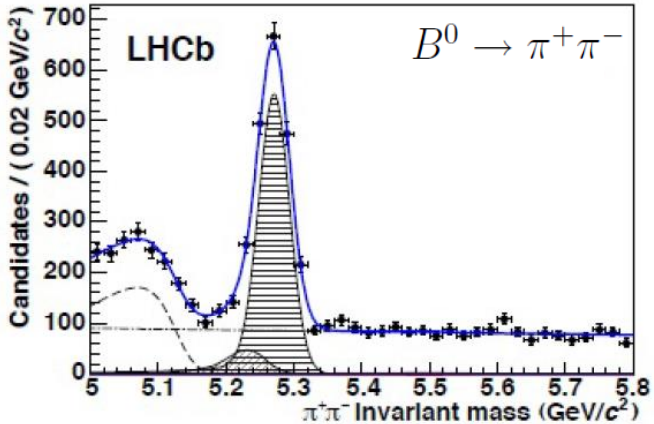












Selected results on hadronic b-decays since PIC 2017 – B-factories

Search for the decay mode $B^0 \to p\bar{p}\bar{p}$, arXiv:1803.10378

Measurement of cos(2β) in $B \to D^{(*)} h^0$ with $D \to K_S \pi^+\pi^-$ decays by a combined time-dependent Dalitz plot analysis of BaBar and Belle data, arXiv:1804.06153

First evidence of cos(2β)>0 and resolution of the CKM unitarity triangle ambiguity by a time-dependent Dalitz plot analysis of $B^0 \to D^{(*)} h^0$ with $D \to K_S \pi^+\pi^-$ decays, arXiv:1804.06152

Observation of $B^+ \to p \bar{\Lambda} K^+K^-$ and $B^+ \to \bar{p} \Lambda K^+K^+$ decays, arXiv:1807.10503

Evidence of charged $\Xi_c(2930)$ and updated measurement of $B^0 \to K^0 \Lambda_c^+ \bar{\Lambda}_c^-$ at Belle, arXiv:1806.09182

Measurement of time-dependent CP asymmetries in $B^0 \to K_S \eta\gamma$ decays, PRD 97 (2018) 092003

Observation of $\Xi_c(2930)^0$ and updated measurement of $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ at Belle, EPJC 78 (2018) 252

Measurements of the absolute branching fractions of $B^+ \to X_{c\bar{c}} K^+$ and $B^+ \to \bar{D}^{*0} \pi^+$, PRD 97 (2018) 012005

Selected results on hadronic b-decays since PIC 2017 - LHC

Measurement of production cross sections times branching fraction of $B_c \to J/\psi\, \pi^+$ and $B_c \to J/\psi\, K^+$ in pp collisions at $\sqrt{s}$=7 TeV, CMS-PAS-BPH-13-002

Observation of the $B^*_{s2} \to B^0 K_s$ decay and study of excited B_s mesons in pp collisions at $\sqrt{s}$=8 TeV, CMS-PAS-BPH-16-003

Search for CPV in charmless 2-body Λ_b decays, arXiv:1807.06544

Observation of $B_s \to \bar{D}^{*0}\, \varphi$ and search for $B^0 \to \bar{D}^0\, \varphi$ decays, arXiv:1807.01892

Observation of the decay $\bar{B}_s \to \chi_{c2}\, K^+\, K^-$, arXiv:1806.10576

Observation of the decay $\Lambda_b \to \psi(2S)\, p\pi^-$, JHEP 1808 (2018) 131

Measurement of the CKM angle γ using $B^\pm \to DK^\pm$ with $D \to K_S\pi^+\pi^-$, $K_SK^+K^-$ decays, arXiv:1806.01202

Measurement of CP asymmetries in 2-body $B_{(s)}$-meson decays to charged pions and kaons, PRD 98 (2018) 032004

Search for CPV using triple product asymmetries in $\Lambda_b \to pK^-\pi^+\pi^-$, $\Lambda_b \to pK^-K^+K^-$, $\Xi_b \to pK^-K^-\pi^+$, JHEP 08 (2018) 039

Measurement of CP violation in $B^0 \to D\pi$ decays, JHEP 1806 (2018) 084

Observation of the decay $\Lambda_b^0 \to \Lambda_c^+\, p\bar{p}\pi^-$, PLB 784 (2018) 101

Measurement of the CP asymmetry in $B^- \to D_s^-\, D^0$ and $B^- \to D^-\, D^0$ decays, JHEP 1805 (2018) 160

Amplitude analysis of the decay $\bar{B}^0 \to K_S\pi^+\pi^-$ and first observation of the CP asymmetry in $\bar{B}^0 \to K^*(892)^-\pi^+$, PRL 120 (2018) 261801

First measurement of the CP-violating phase $\varphi_s^{d\bar{d}}$ in $B_s \to (K^+\pi^-)(K^-\pi^+)$ decays, JHEP 1803 (2018) 140

Measurement of CP asymmetry in $B_s \to D_sK$ decays, JHEP 1803 (2018) 059

Search for B_c decays to two charm mesons, Nucl. Phys. B930 (2018) 563

First observartion of $B^+ \to D_s^+\, K^+K^-$ decays and a search for $B^+ \to D_s^+\varphi$ decays, JHEP 1801 (2018) 131

Measurement of branching fractions of charmless 4-body Λ_b and Ξ_b decays, JHEP 1802 (2018) 098

Measurement of CP observables in $B^\pm \to DK^{*\pm}$ decays using 2-body and 4-body D final states, JHEP 1711 (2017) 156

Measurement of CP violation in $B \to J/\psi\, K_s$ and $B \to \psi(2S)\, K_s$ decays, JHEP 1711 (2017) 170

First observartion of the rare purely baryonic decay $B^0 \to p\bar{p}$, PRL 119 (2017) 232001

Measurement of CP observables in $B^\pm \to D^{(*)}\, K^\pm$ and $B^\pm \to D^{(*)}\, \pi^\pm$ decays, PLB 777 (2018) 16

Updated branching fraction measurements of $B_{(s)} \to K_S\, h^+\, h'^-$ decays, JHEP 1711 (2017) 027

Study of charmonium production in b-hadron decays and first evidence for decay $B_s \to \varphi\varphi\varphi$, EPJC 77 (2017) 609

Search for CPV in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays, Nature 13 (2017) 391

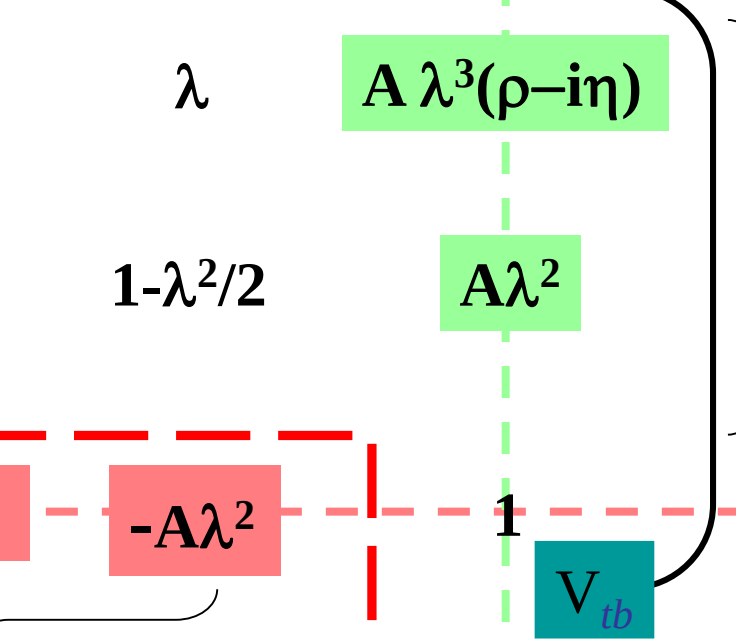
CP-parity violation in Stardard Model

Bruno Touschek

Cabibbo-Kobayashi-Maskawa matrix in Wolfenstein parametrization

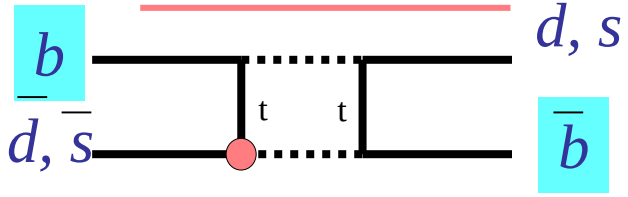
- Mass eigenstates related to weak eigenstates via **CKM mixing matrix**
- 3 generations → 4 parameters (**3 real parameters and 1 complex phase**): λ, A, ρ, η

	d	s	b
u	$1-\lambda^2/2$	λ	$A\lambda^3(\rho-i\eta)$
c	$-\lambda$	$1-\lambda^2/2$	$A\lambda^2$
t	$A\lambda^3(1-\rho-i\eta)$	$-A\lambda^2$	1



$$\lambda = 0.2257^{+0.0009}_{-0.0010}$$
$$\bar{\rho} = 0.135^{+0.031}_{-0.016}$$
$$\bar{\eta} = 0.349^{+0.015}_{-0.017}$$
$$A = 0.814^{+0.021}_{-0.022}$$

B Oscillations



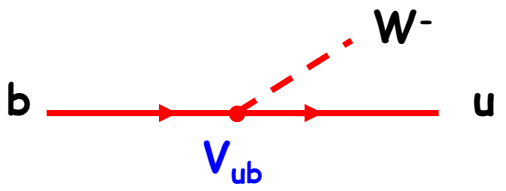
V_{td}, V_{ts}

- **Single complex parameter** in the CKM matrix **responsible for CPV**
  → strong predictive power !
- **B-physics** solely capable to determine **CKM mixing parameters of 3rd quark generation** and **for CPV up to** λ^3

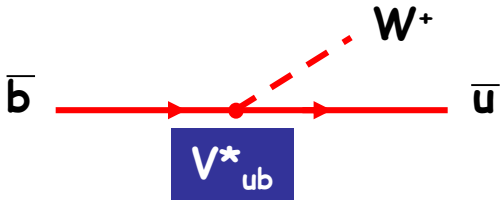
- **CP symmetry** describes the invariance under charge conjugation C and parity operation P

Non-zero η in CKM matrix ➔ **CP symmetry violation**:

Transition amplitude between i and j quarks : V_{ij}



Transition amplitude between i and j anti-quarks : V_{ij}^*



Irreducible phase ➔ $V^*_{ub} \neq V_{ub}$

➔ matter behaves differently from anti-matter

i.e. **CP symmetry violation**

however, not visible when considering $|V_{ub}|^2$

Original idea *in: M.Kobayashi and T.Maskawa, Prog. Theor. Phys. 49 (1973) 652*

3 family flavour mixing in quark sector needed for CP violation.

Before the discovery of the charm quark !

- Unitarity of the CKM matrix : $V V^{\dagger} = V^{\dagger} V = 1$ → 9 relations $\sum_{k=1}^{n} V_{ik} V_{jk}^{*} = \delta_{ij},$

- The non-diagonal elements of the matrix products correspond to 6 triangle equations :

(a) $\frac{V_{ud} V_{us}^{*}}{V_{cd} V_{cs}^{*}}$ with $V_{td} V_{ts}^{*}$

$V_{ud}^{*} V_{us} + V_{cd}^{*} V_{cs} + V_{td}^{*} V_{ts} = 0$ $\quad \lambda\ \lambda\ \lambda^{5}$

$V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0$ $\quad \lambda^{3}\ \lambda^{3}\ \lambda^{3}$

$V_{us}^{*} V_{ub} + V_{cs}^{*} V_{cb} + V_{ts}^{*} V_{tb} = 0$ $\quad \lambda^{4}\ \lambda^{2}\ \lambda^{2}$

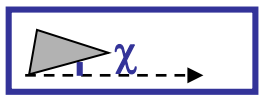
$V_{ud}^{*} V_{td} + V_{us}^{*} V_{ts} + V_{ub}^{*} V_{tb} = 0$ $\quad \lambda^{3}\ \lambda^{3}\ \lambda^{3}$

$V_{td} V_{cd}^{*} + V_{ts} V_{cs}^{*} + V_{tb} V_{cb}^{*} = 0$ $\quad \lambda^{4}\ \lambda^{2}\ \lambda^{2}$

$V_{ud}^{*} V_{cd} + V_{us}^{*} V_{cs} + V_{ub}^{*} V_{cb} = 0$ $\quad \lambda\ \lambda\ \lambda^{5}$

(b) $\frac{V_{ud} V_{ub}^{*}}{V_{cd} V_{cb}^{*}}$ with $V_{td} V_{tb}^{*}$

(c) $\frac{V_{ts} V_{tb}^{*}}{V_{cs} V_{cb}^{*}}$ with $V_{us} V_{ub}^{*}$



Area of each UT = |J|/2

Jarlskog invariant:

$J \equiv c_{12} c_{23} c_{13}^{2} s_{12} s_{23} s_{13} \sin\delta = (3.115 \pm 0.093) \times 10^{-5}$

$$V_{ub}^{*}V_{ud} + V_{cb}^{*}V_{cd} + V_{tb}^{*}V_{td} = 0$$

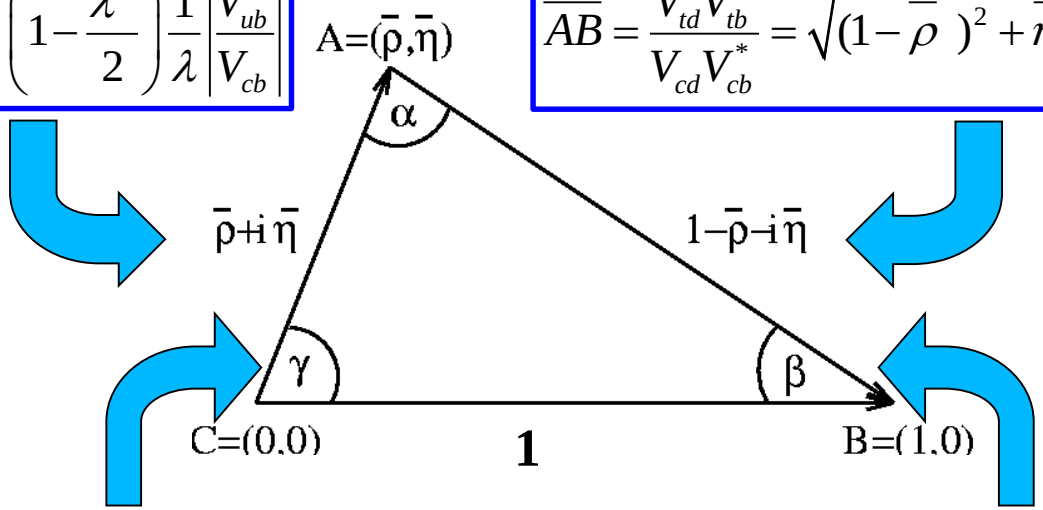
$$V_{ud}\,V_{ub}^{*} = A\lambda^{3}(\bar{\rho} + i\bar{\eta}) \qquad V_{cd}\,V_{cb}^{*} = -A\lambda^{3} \qquad V_{td}\,V_{tb}^{*} = A\lambda^{3}(1 - \bar{\rho} - i\bar{\eta})$$

$$\overline{AC} = \frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} = \sqrt{\bar{\rho}^{2} + \bar{\eta}^{2}} = \left(1 - \frac{\lambda^{2}}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

(b→u transitions)

$$\overline{AB} = \frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}} = \sqrt{(1-\bar{\rho})^{2} + \bar{\eta}^{2}} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right| \sim \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|$$

(B mixing)



$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right) = \operatorname{atan}\left(\frac{\bar{\eta}}{\bar{\rho}}\right)$$

(b→u phase)

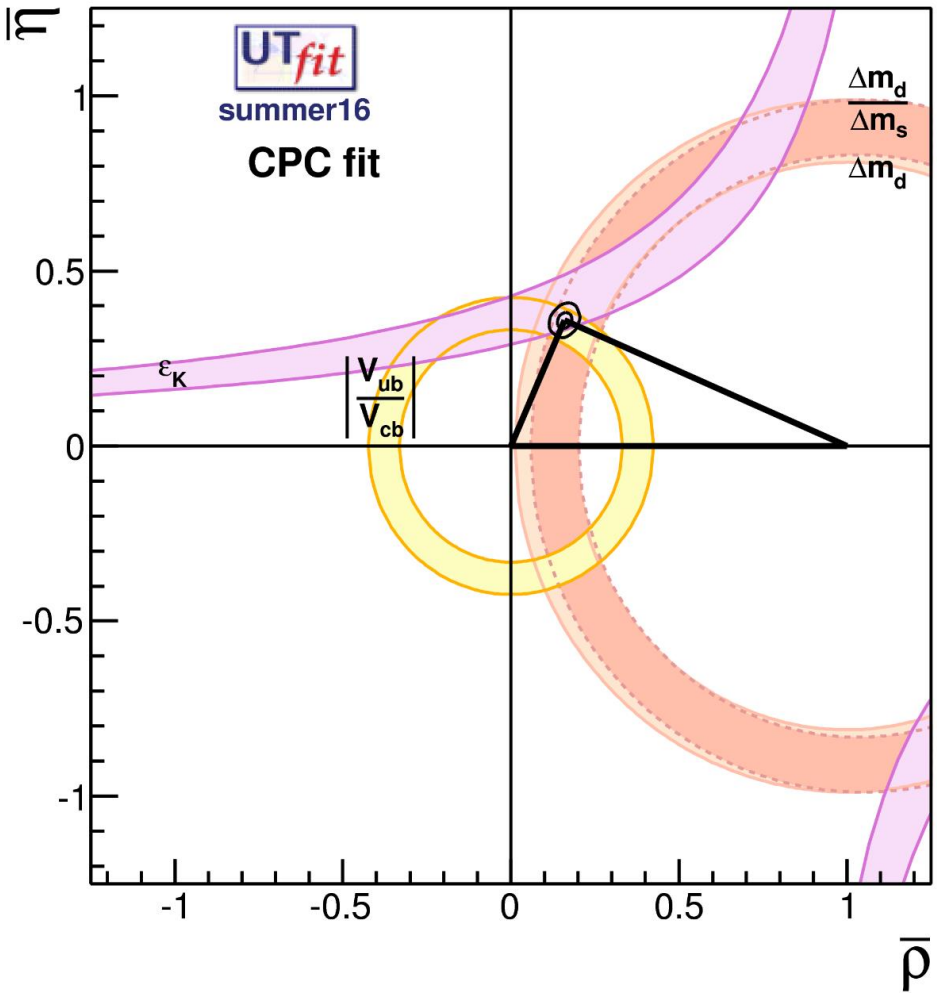
$$\beta = \arg\left(\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}}\right) = \operatorname{atan}\left(\frac{\bar{\eta}}{(1-\bar{\rho})}\right)$$

(B mixing phase)

$$\alpha + \beta + \gamma = \pi$$

Building UT from b-decays and BB mixing …

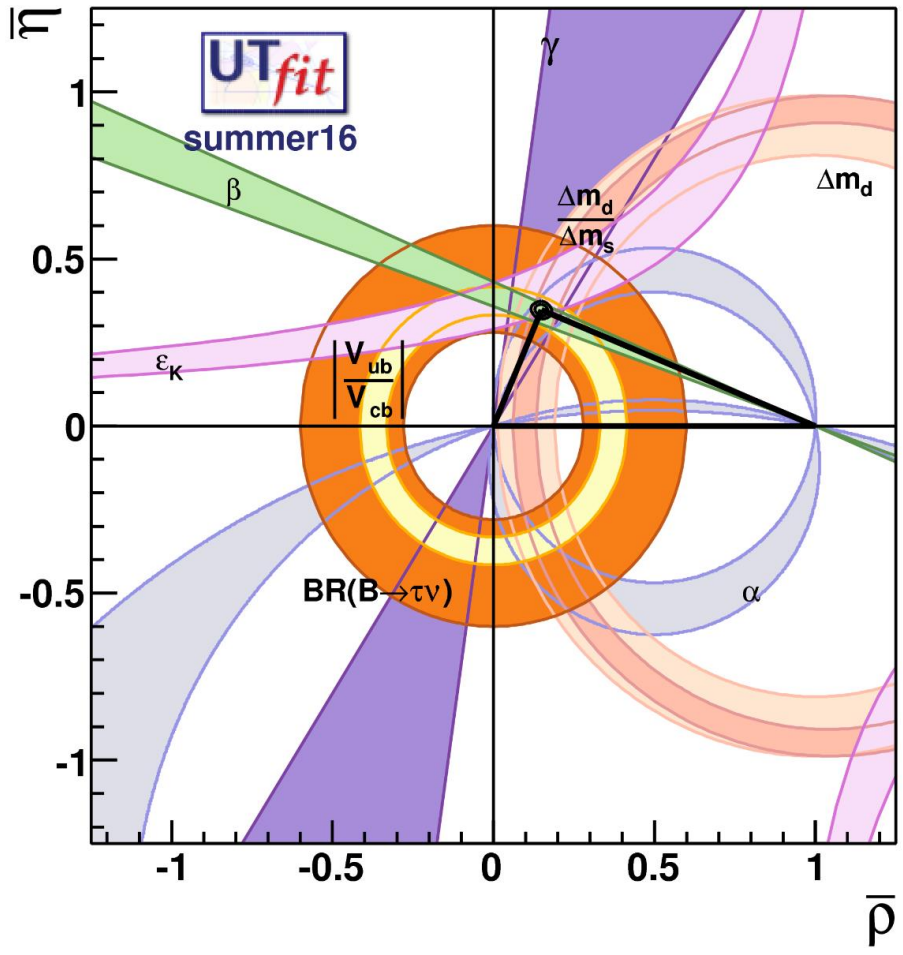
… and kaon CPV …



… non-degenerated triangle → CPV !

Measurements of:

$\Delta m_d, \Delta m_s, V_{ub}, V_{cb}, \varepsilon_K$ + cos2β + β + α + γ + 2β+γ



ρ = 0.153 ± 0.013
η = 0.343 ± 0.011

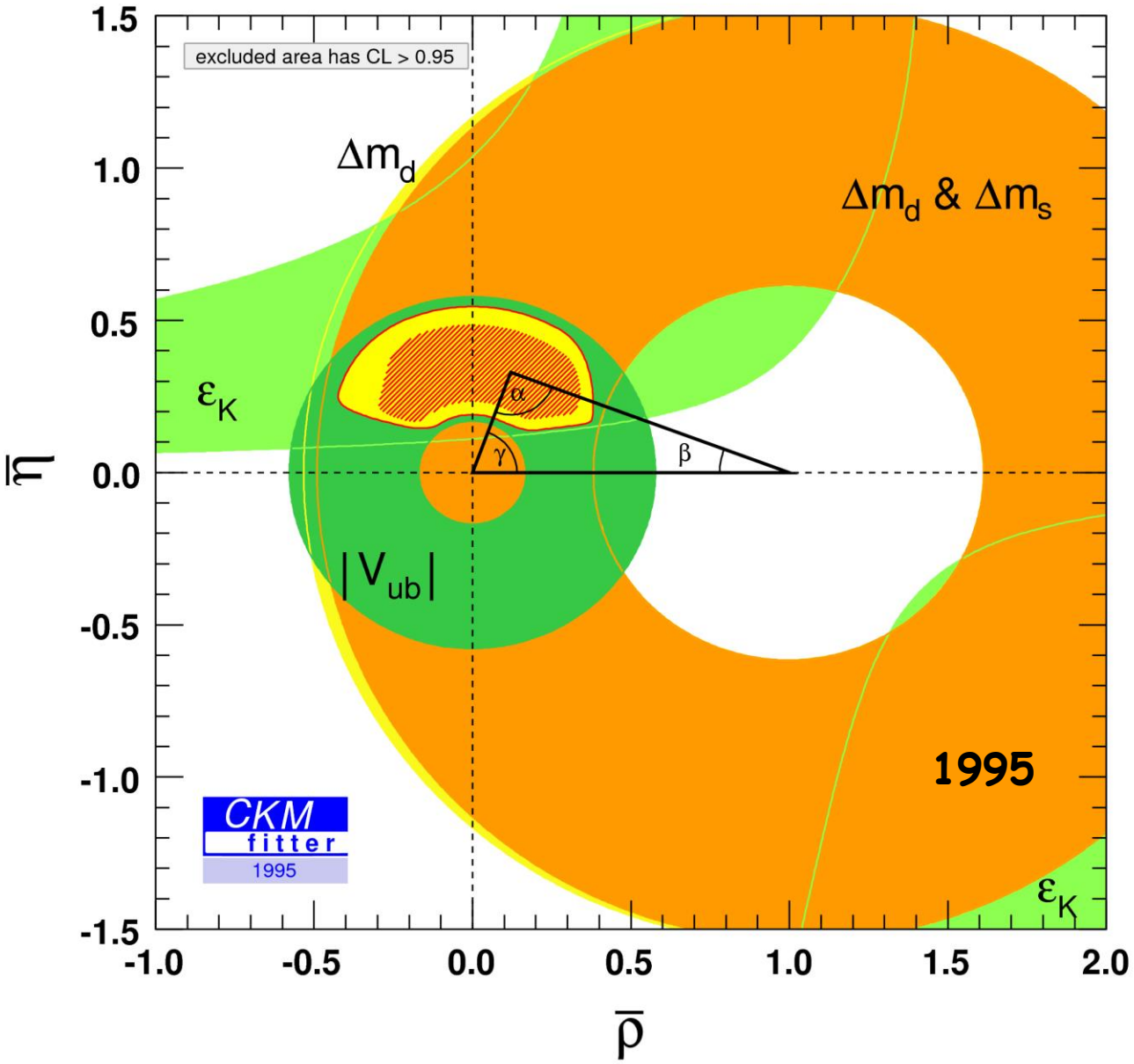
~3% precision !

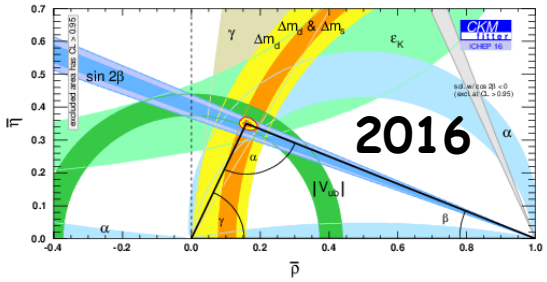
- ALL the measurements are (so far) consistent …

… but progress further :

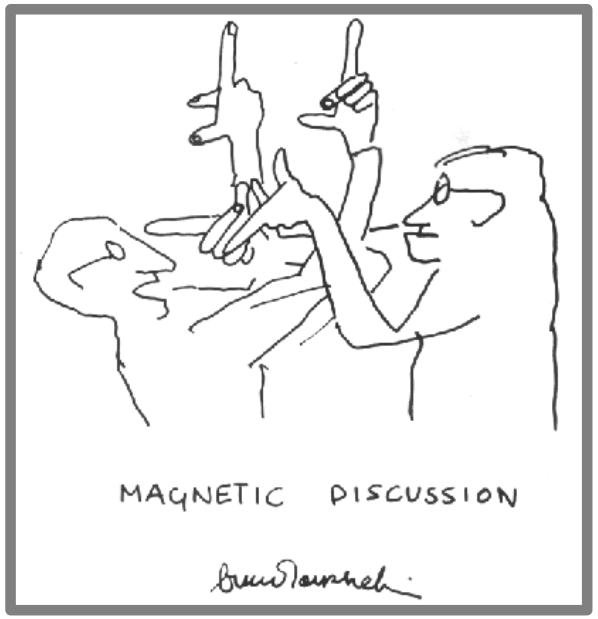
- Over-constrain UT, check that UT closes
- Compare measurements involving CPV (angles) to decay-probability measurements (sides)
- Compare CPV in tree-mediated processes to CPV in processes involving loops

Evolution of the UT constraints





CP-parity violation studies with B mesons



Bruno Touschek

CP-conjugated amplitudes : $\begin{cases} A_f = A(B \to f) \\ \bar{A}_f = A(\bar{B} \to \bar{f}) \end{cases}$

Starting from the time evolution of the B^0 and $\bar{B}^0$ mesons
time-dependent rates of an initially pure flavor state :

$$\left|\langle f|H|B^0(t)\rangle\right|^2 = |A_f|^2 \cdot |g_+(t) + \lambda_f g_-(t)|^2 \text{ and } \left|\langle f|H|\bar{B}^0(t)\rangle\right|^2 = \left|\frac{p}{q}\right|^2 \cdot |A_f|^2 \cdot |g_-(t) + \lambda_f g_+(t)|^2$$

$$g_+(t) = e^{-i(m_B - i\frac{\Gamma_B}{2})t}\left[\cosh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} - i\sinh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right],$$

$$g_-(t) = e^{-i(m_B - i\frac{\Gamma_B}{2})t}\left[-\sinh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} + i\cosh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right]$$

$$\lambda_f = \frac{q}{p}\frac{< f \mid H \mid \bar{B}^0 >}{< f \mid H \mid B^0 >} \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

and after some trigonometry and assuming no CPV in mixing ($|q/p| = 1$)

$$\left|\langle f|H|B^0(t)\rangle\right|^2 = e^{-t/\tau_B} \cdot |A_f|^2 \frac{1+|\lambda_f|^2}{2}\left[1 + C_f\cos(\Delta m_d t) - S_f\sin(\Delta m_d t)\right]$$

$$\left|\langle f|H|\bar{B}^0(t)\rangle\right|^2 = e^{-t/\tau_B} \cdot |A_f|^2 \frac{1+|\lambda_f|^2}{2}\left[1 - C_f\cos(\Delta m_d t) + S_f\sin(\Delta m_d t)\right]$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\,\mathrm{Im}[\lambda_f]}{1+|\lambda_f|^2}$$

- $|\lambda_f|^2 \neq 1$: direct CP
- $|q/p|^2 \neq 1$: CP violation in mixing
- $\mathrm{Im}[\lambda_f] \neq 0$: CPV in the interference

*In all cases **two different paths** (different strong and weak phases) to achieve final state.*

- CP-violating asymmetry from comparing mixing probabilities

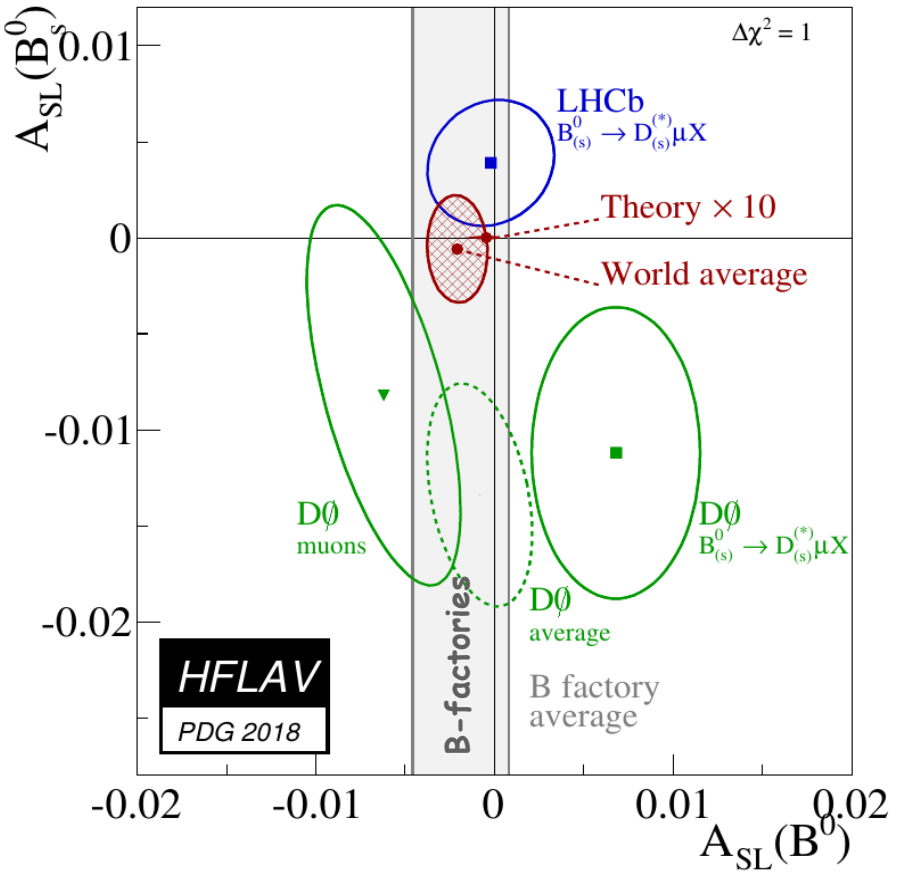
$$a_{sl}^q = \frac{\Gamma(\bar{B}^0_{(s)} \to f) - \Gamma(B^0_{(s)} \to \bar{f})}{\Gamma(\bar{B}^0_{(s)} \to f) + \Gamma(B^0_{(s)} \to \bar{f})} \approx \frac{\Delta\Gamma_{(s)}}{\Delta m_{(s)}} \tan\phi_{12}^q$$

- SM predictions:

$$a_{sl}^s = (2.2 \pm 0.27) \cdot 10^{-5} \quad a_{sl}^d = (-4.7 \pm 0.6) \cdot 10^{-4}$$

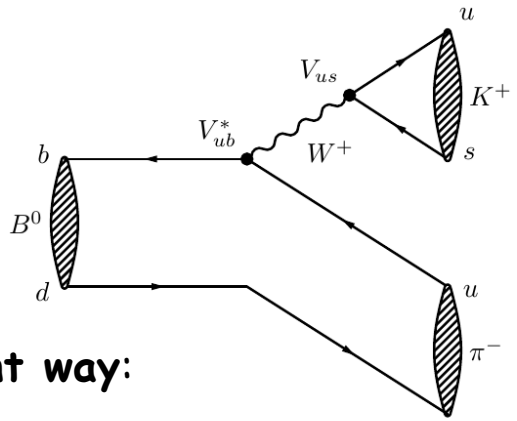
PRD 83 (2011) 036004

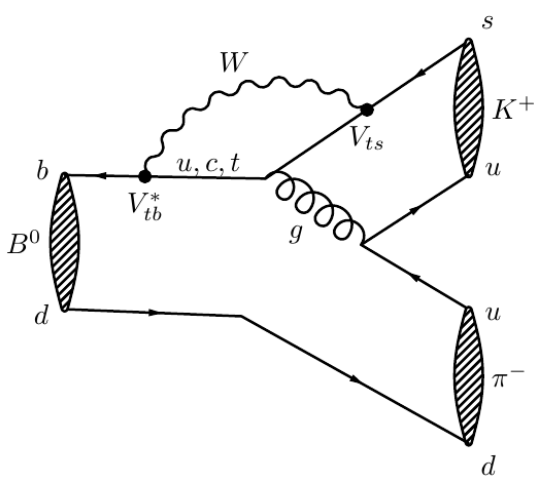
- Two **major techniques**: same-sign dilepton asymmetry and untagged time-dependent asymmetry
- **Measurements of a^d_{sl} and a^s_{sl} compatible with SM predictions**



- **No significant CPV in B-mixing** observed so far

- Direct CPV in $B_{(s)} \to K\pi$ decays
- **Interference between b→u tree and b→s(d) penguin diagrams**





- **SM prediction in a model-independent way:**

$$\Delta = \underbrace{\frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)}}_{\text{measurement}} + \underbrace{\frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s}}_{\text{external values}} \underbrace{\equiv}_{\text{SM}} 0$$

H.J.Lipkin, PLB 621 (2005) 126

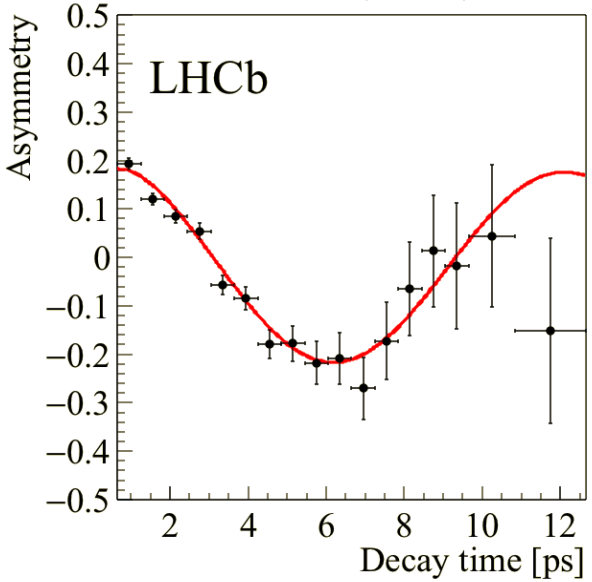
- First evidence of direct CPV → BaBar 2004

PRL 93 (2004) 131801

PRD 98 (2018) 032004

- LHCb measured **time-dependent asymmetries**:

$$A_{CP}^{B^0} = -0.084 \pm 0.004 \pm 0.003$$
$$A_{CP}^{B_s^0} = 0.213 \pm 0.015 \pm 0.007$$



- Using also HFLAV arXix:1612.07233 and JHEP 1304 (2013) 001:

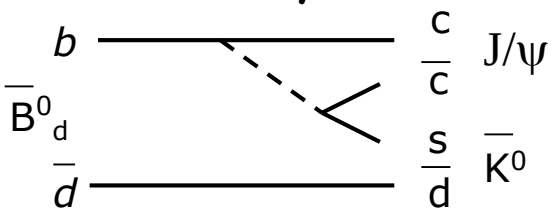
$$\Delta = -0.11 \pm 0.04 \pm 0.03$$

- **Compatible with SM expectation**

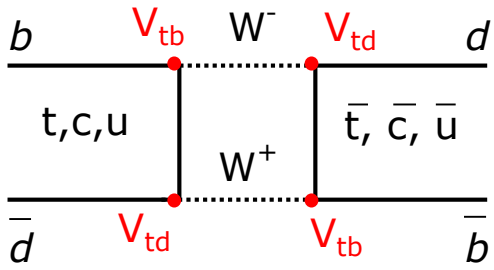
B → J/ψK$_s$: the angle β

- Common CP eigenstate

- decay -



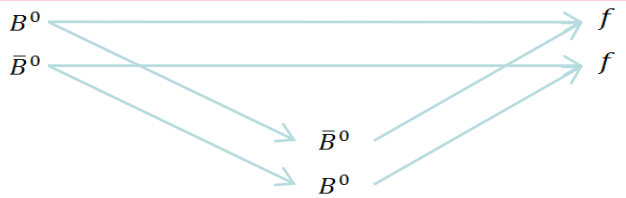
- mixing -



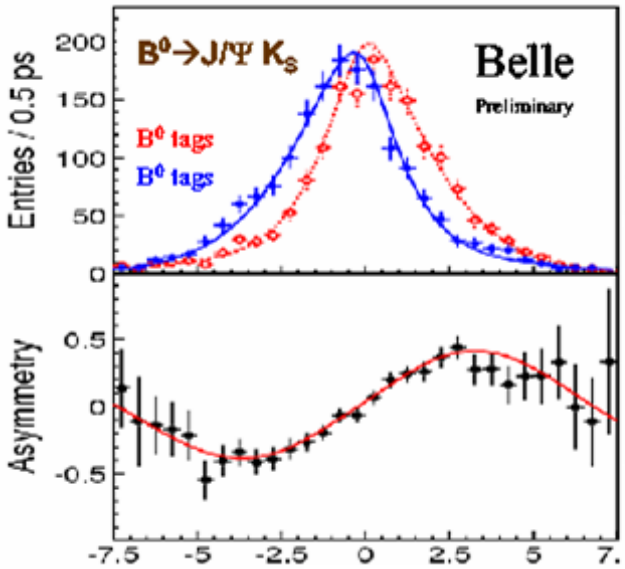
- Decay + B-mixing + K-mixing

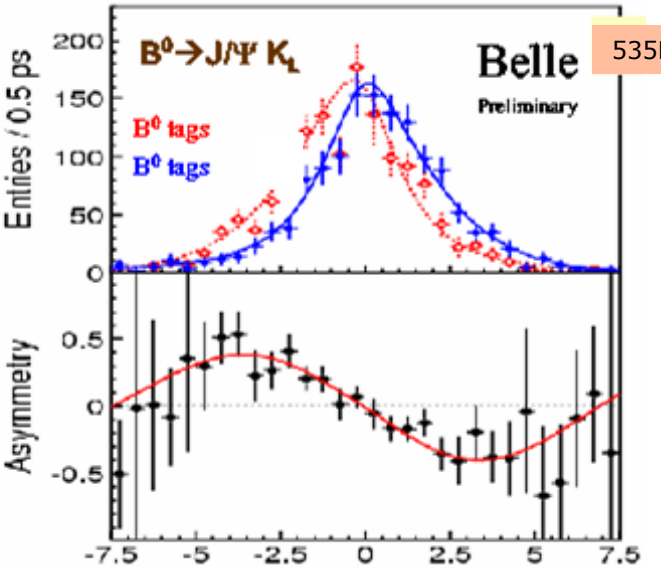
Im $\lambda^{CP}(J/\psi K_s) = \eta_{CP}(J/\psi K_s)$ sin2β

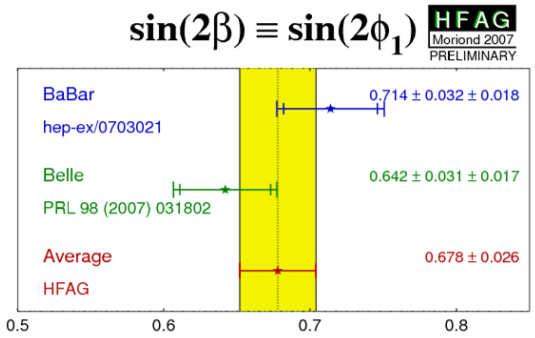
CP violation in the interference between mixing and decay:



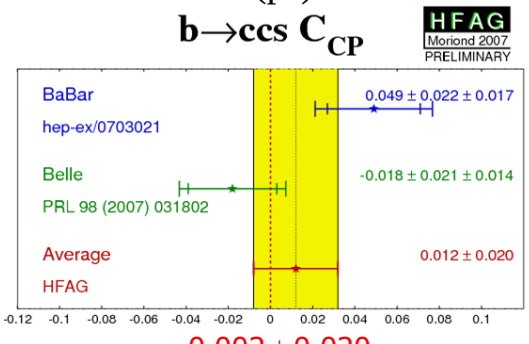
Canonical plots, B-factories in 2007







0.678 ± 0.026

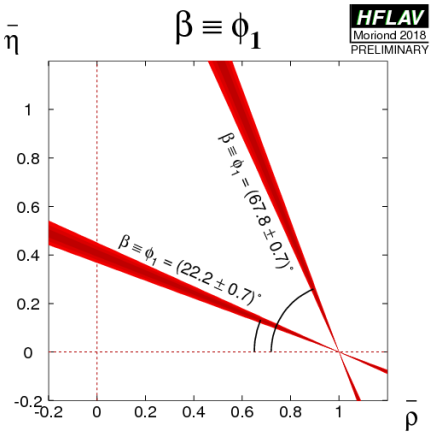


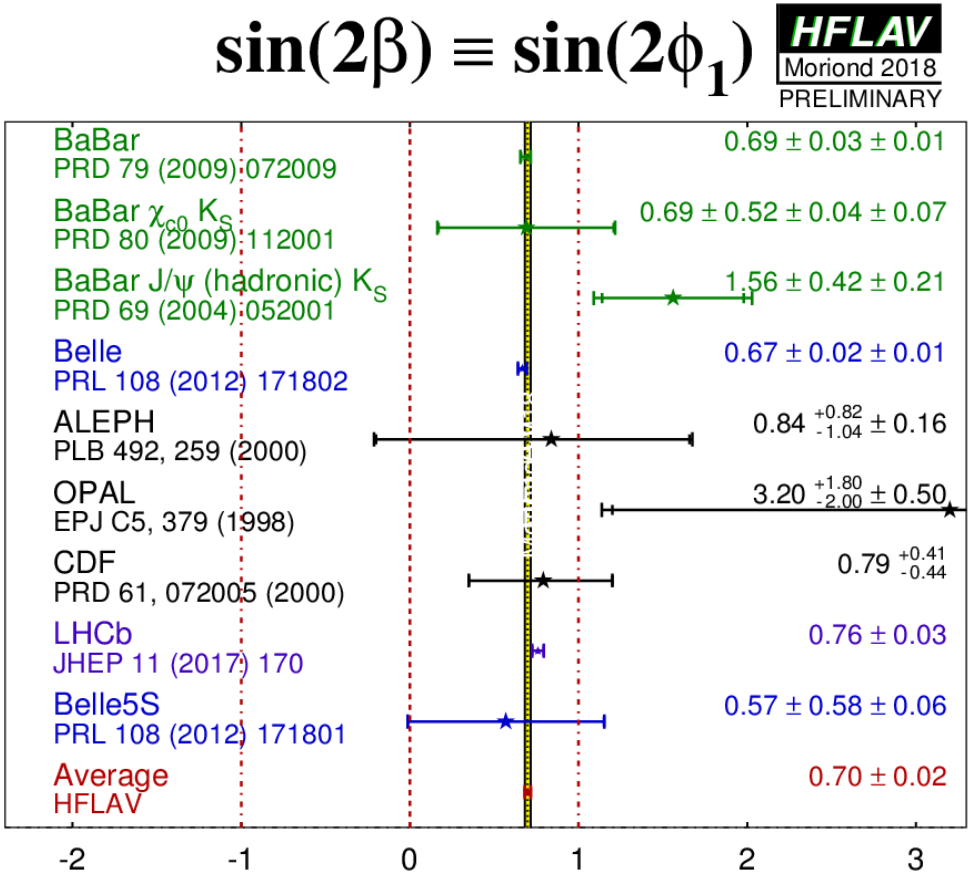
0.002 ± 0.020

- Uncertainty of the LHCb result with 3 fb^{-1} competitive with Belle and BaBar results
- **Indirect sin2β prediction** from $UTFit_{2016}$
  $sin2\beta_{(indirect)} = 0.724 \pm 0.028$
  compatible with the average of direct sin2β measurements
- **Two solutions** of
  $sin2\beta_{(HFLAV)} = 0.699 \pm 0.017$

$\beta_1 = (22.2 \pm 0.7)^o$

$\beta_2 = (67.8 \pm 0.7)^o$





- **Ambiguity on the UT apex position resolved by B-factories**

arXiv:1804.06152

arXiv:1804.06153

cos2β in $B^0 \to D^{(*)}h^0$ with $D \to K_S\pi^+\pi^-$ by a time-dependent Dalitz plot analysis

arXiv:1804.06152
arXiv:1804.06153

- Multi-body final states to **resolve trigonometric amgiguity** **1.24 x 10^9 $B\bar{B}$ pairs**
- $B^0 \to D^{(*)}h^0$ decay mediated by tree-level colour suppressed $b \to c\bar{u}d$ tree amplitude
- Following **$D \to K_S\pi^+\pi^-$ exhibits complex interference structures** recieving resonant and non-resonant contributions from variety of intermediate CP eigenstates ; information on relative strong phase over the 3-body Dalitz plot phase space needed

- Study **time evolution of $B^0 \to [K_S\pi^+\pi^-]_D h^0$ multibody final state**
- Low branching fractions, $BR_B \sim O(10^{-4})$ and $BR_D \sim O(10^{-2})$; decay model over Dalitz plot phase space → challenging analysis
- **$D \to K_S\pi^+\pi^-$ amplitude analysis** with Belle data
- **Time-dependent Dalitz-plot analysis** using combined BaBar and Belle data

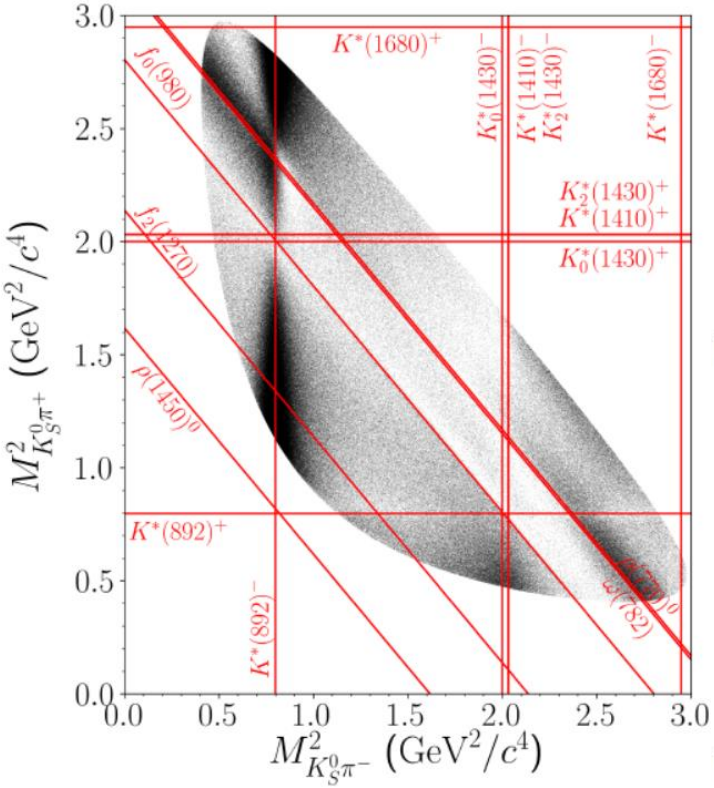
$$\frac{e^{\frac{-|\Delta t|}{\tau_{B^0}}}}{2}\Big\{ \left[|\mathcal{A}_{\overline{D}^0}|^2 + |\mathcal{A}_{D^0}|^2\right] - q\left(|\mathcal{A}_{\overline{D}^0}|^2 - |\mathcal{A}_{D^0}|^2\right)\cos(\Delta m_d \Delta t) + 2q\eta_{h^0}(-1)^L \underbrace{\mathrm{Im}\left(e^{-2i\beta}\mathcal{A}_{D^0}\mathcal{A}^*_{\overline{D}^0}\right)}_{\mathrm{Im}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\overline{D}^0}\right)\boxed{\cos 2\beta} - \mathrm{Re}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\overline{D}^0}\right)\boxed{\sin 2\beta}} \sin(\Delta m_d \Delta t)\Big\}$$

cos2β in $B^0 \to D^{(*)}h^0$ with $D \to K_S\pi^+\pi^-$ by a time-dependent Dalitz plot analysis

arXiv:1804.06152
arXiv:1804.06153

1.24×10^9 $B\bar{B}$ pairs

- Results of **amplitude analysis** using Belle data



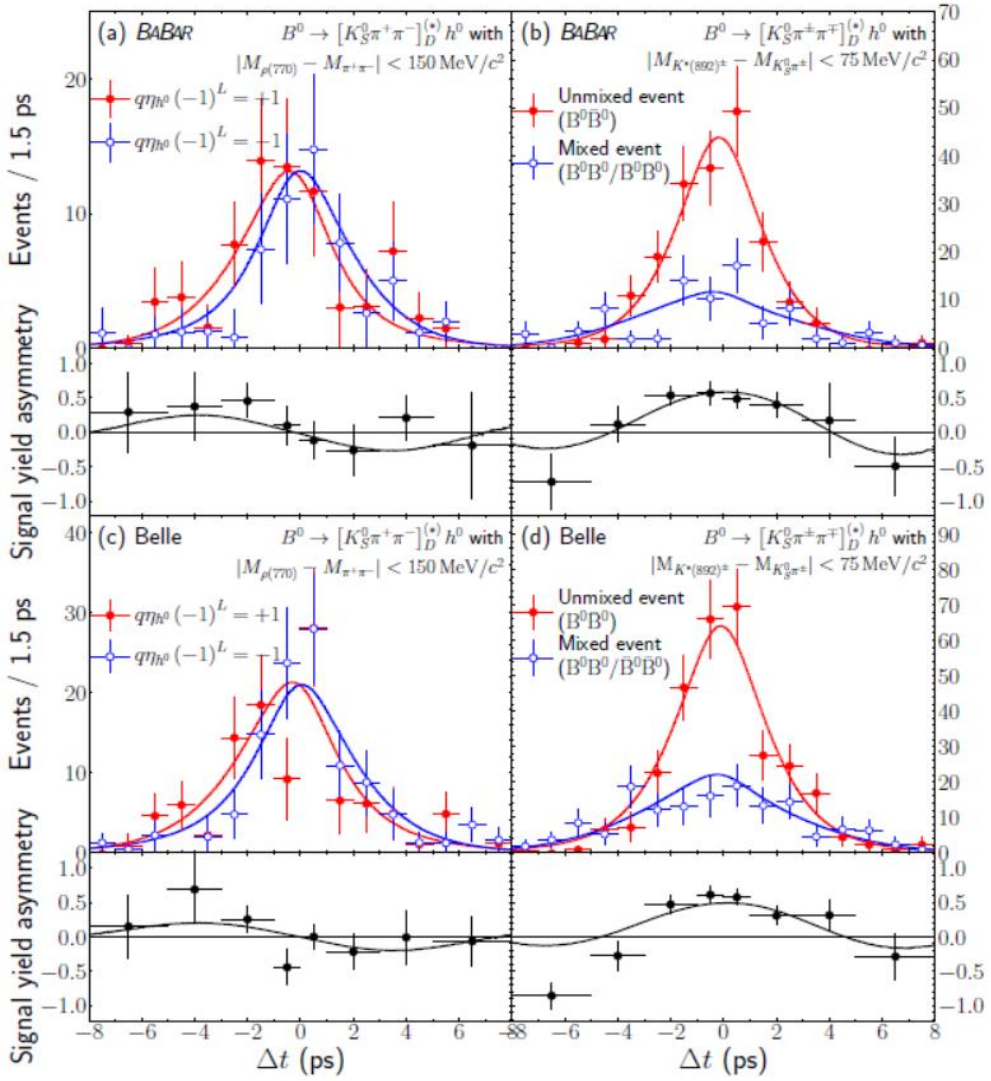
Resonance	Amplitude	Phase (deg)	Fit Fraction (%)
$K^0_S\rho(770)^0$	1 (fixed)	0 (fixed)	20.4
$K^0_S\omega(782)$	0.0388 ± 0.0005	120.7 ± 0.7	0.5
$K^0_S f_2(1270)$	1.43 ± 0.03	-36.3 ± 1.1	0.8
$K^0_S\rho(1450)^0$	2.85 ± 0.10	102.1 ± 1.9	0.6
$K^*(892)^-\pi^+$	1.720 ± 0.006	136.8 ± 0.2	59.9
$K_2^*(1430)^-\pi^+$	1.27 ± 0.02	-44.1 ± 0.8	1.3
$K^*(1680)^-\pi^+$	3.31 ± 0.20	-118.2 ± 3.1	0.5
$K^*(1410)^-\pi^+$	0.29 ± 0.03	99.4 ± 5.5	0.1
$K^*(892)^+\pi^-$	0.164 ± 0.003	-42.2 ± 0.9	0.6
$K_2^*(1430)^+\pi^-$	0.10 ± 0.01	-89.6 ± 7.6	< 0.1
$K^*(1410)^+\pi^-$	0.21 ± 0.02	150.2 ± 5.3	< 0.1
$\pi^+\pi^-$ *S*-wave Parameters			10.0
β_1	8.5 ± 0.5	68.5 ± 3.4	
β_2	12.2 ± 0.3	24.0 ± 1.4	
β_3	29.2 ± 1.6	-0.1 ± 2.5	
β_4	10.8 ± 0.5	-51.9 ± 2.4	
$f_{11}^{\rm prod}$	8.0 ± 0.4	-126.0 ± 2.5	
$f_{12}^{\rm prod}$	26.3 ± 1.6	-152.3 ± 3.0	
$f_{13}^{\rm prod}$	33.0 ± 1.8	-93.2 ± 3.1	
$f_{14}^{\rm prod}$	26.2 ± 1.3	-121.4 ± 2.7	
$s_0^{\rm prod}$	-0.07 (fixed)		
$K\pi$ *S*-wave Parameters			
$K_0^*(1430)^-\pi^+$	2.36 ± 0.06	99.4 ± 1.7	7.0
$K_0^*(1430)^+\pi^-$	0.11 ± 0.01	162.3 ± 6.6	< 0.1
$M_{K_0^*(1430)^\pm}$ (GeV/c^2)	1.441 ± 0.002		
$\Gamma_{K_0^*(1430)^\pm}$ (GeV)	0.193 ± 0.004		
F	$+0.96 \pm 0.07$		
R	1 (fixed)		
a	$+0.113 \pm 0.006$		
r	-33.8 ± 1.8		
ϕ_F (deg)	0.1 ± 0.3		
ϕ_R (deg)	-109.7 ± 2.6		
$K^*(892)^\pm$ Parameters			
$M_{K^*(892)^\pm}$ (GeV/c^2)	0.8937 ± 0.0001		
$\Gamma_{K^*(892)^\pm}$ (GeV)	0.0472 ± 0.0001		

cos2β in B⁰ → D^(*)h⁰ with D → $K_S\pi^+\pi^-$ by a time-dependent Dalitz plot analysis

- Yields and asymmetries for **ρ(770) and K*(892) regions** of Dalitz plot regions

arXiv:1804.06152
arXiv:1804.06153

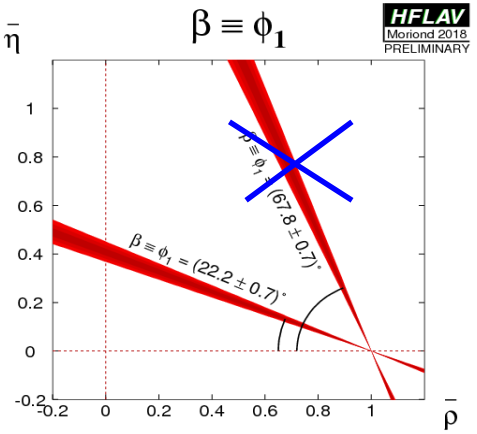
1.24 x 10⁹ $B\bar{B}$ pairs



- Background subtracted using sPlot

$$\sin 2\beta = 0.80 \pm 0.14 \pm 0.06 \pm 0.03_{\text{model}}$$
$$\cos 2\beta = 0.91 \pm 0.22 \pm 0.09 \pm 0.07_{\text{model}}$$
$$\beta = (22.5 \pm 4.4 \pm 1.2 \pm 0.6_{\text{model}})^\circ$$

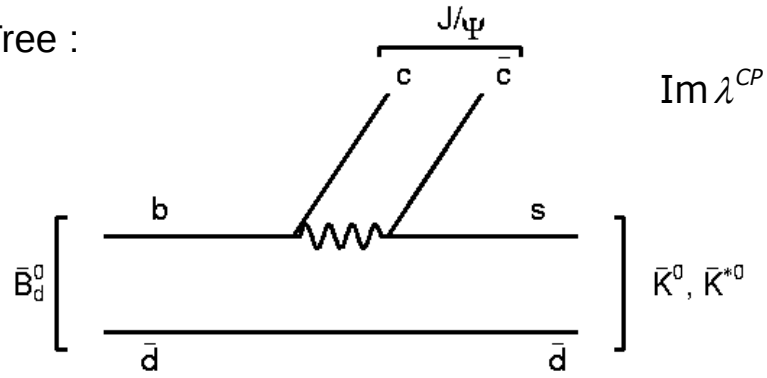
- The results agree with more precise measurements with b→cc̄s transitions
- β = 0° excluded at 5.1σ, observation of CPV in B⁰ → D^(*)h⁰



- **cos2β >0 at 3.7σ, β_2 excluded at 7.3σ, thus resolving ambiguity on the UT apex position**

Comparison of sin(2β) measurements from tree and penguin diagrams

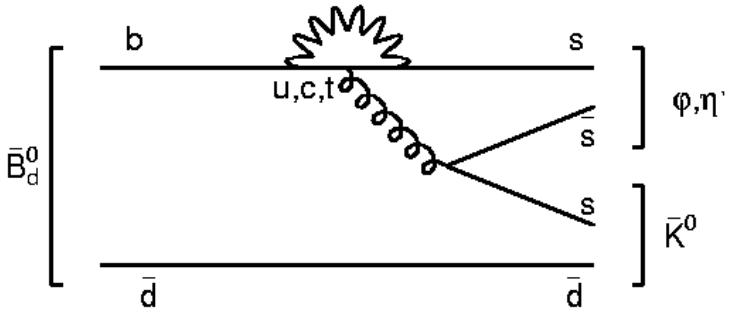
Tree :



$$\mathrm{Im}\,\lambda^{CP}(J/\psi K_S^0) = \eta_{CP}^{J/\psi K_S^0}\,\mathrm{Im}\left(\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\,\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\,\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right) = \eta_{CP}^{J/\psi K_S^0}\sin 2\beta$$

B^0 mixing **K^0 mixing**

Penguin :



$$\mathrm{Im}\,\lambda^{CP}(\phi K_S^0) = \eta_{CP}^{\phi K_S^0}\,\mathrm{Im}\left(\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\,\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}\,\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right) \sim \eta_{CP}^{\phi K_S^0}\sin 2\beta$$

Unitarity : $V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0$

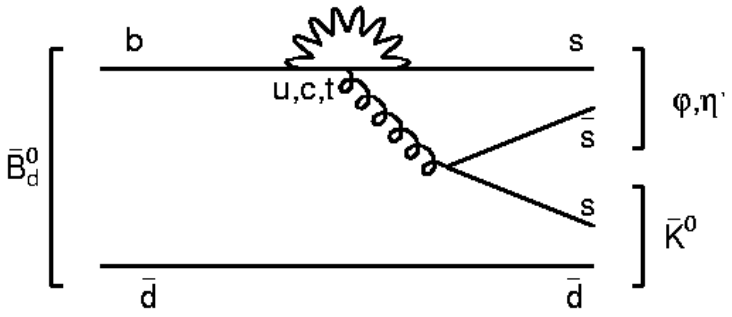
λ^4

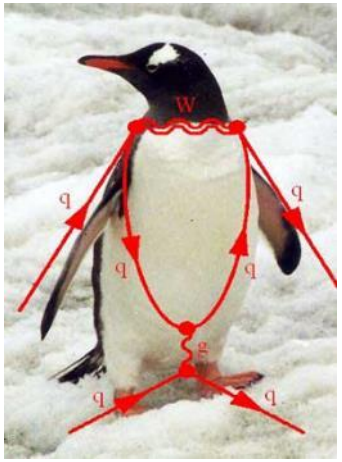
$\Rightarrow V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0$

sin(2β) charmonium tree $\overset{?}{=}$ sin(2β) s-penguin

Comparison of sin(2β) measurements from tree and penguin diagrams

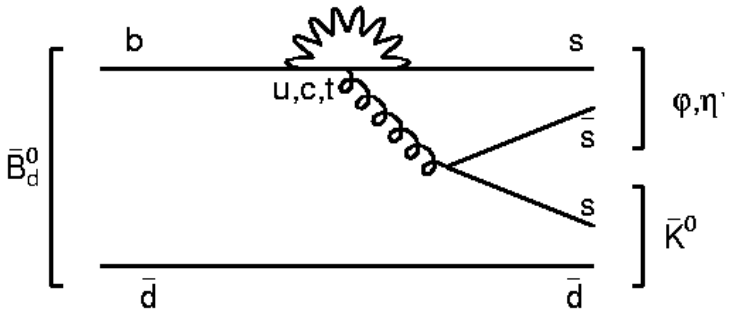
Why penguin ?



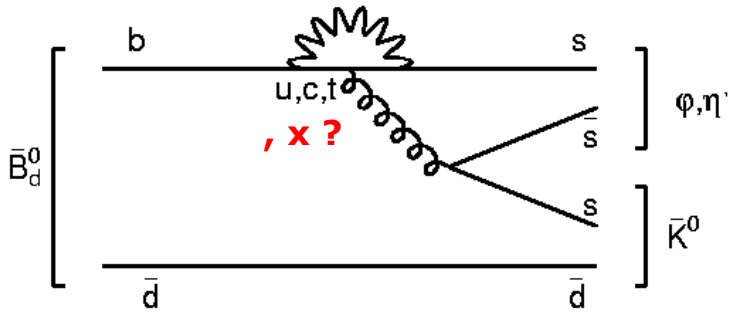


Comparison of sin(2β) measurements from tree and penguin diagrams

Penguin :

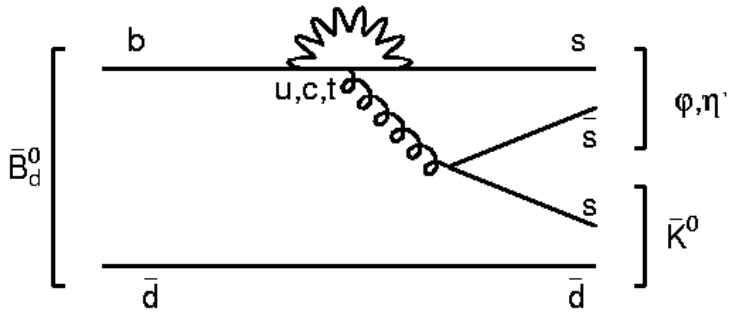


Penguin :

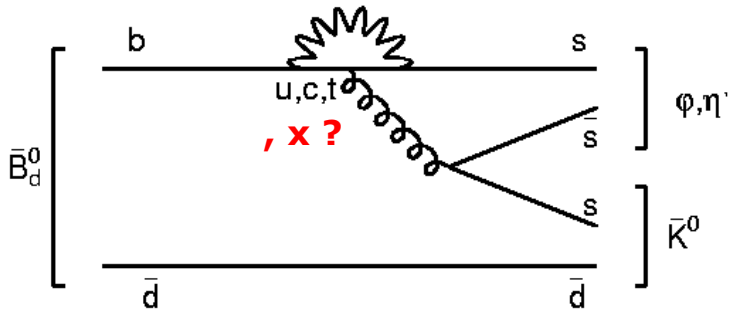


Comparison of sin(2β) measurements from tree and penguin diagrams

Penguin :

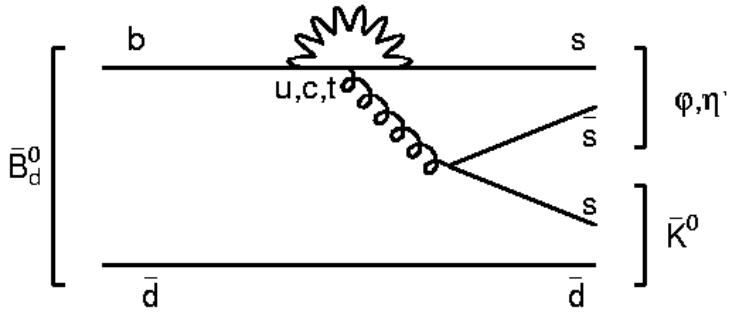


Penguin :

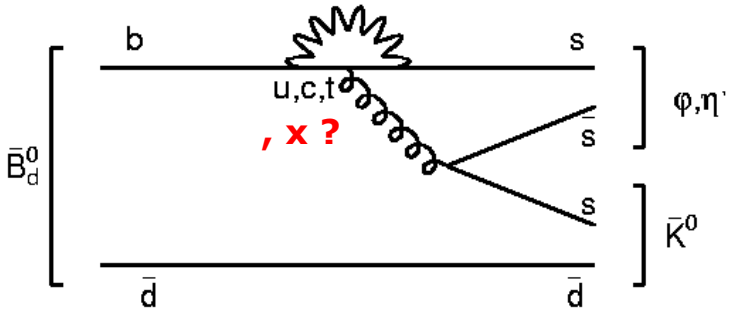


Comparison of sin(2β) measurements from tree and penguin diagrams

Penguin :



Penguin :



… with my compliments to the Microsoft/Linux battle …

Measurement of time-dependent CP asymmetry in $B^0 \to K_S\eta\gamma$

PRD 97 (2018) 092003
0.77 x 10^9 $B\bar{B}$ pairs

- $B^0 \to K_S\eta\gamma$ dominated by **EM penguin diagram**, search for new physics contribution in the penguin loop
- Left-handed photon, right-handed contribution suppressed by m_s/m_b
- Measure **photon polarization via time-dependent CPV study**
- Mixing induced CPV generated by interference between B^0 and $\bar{B}^0$ decays:

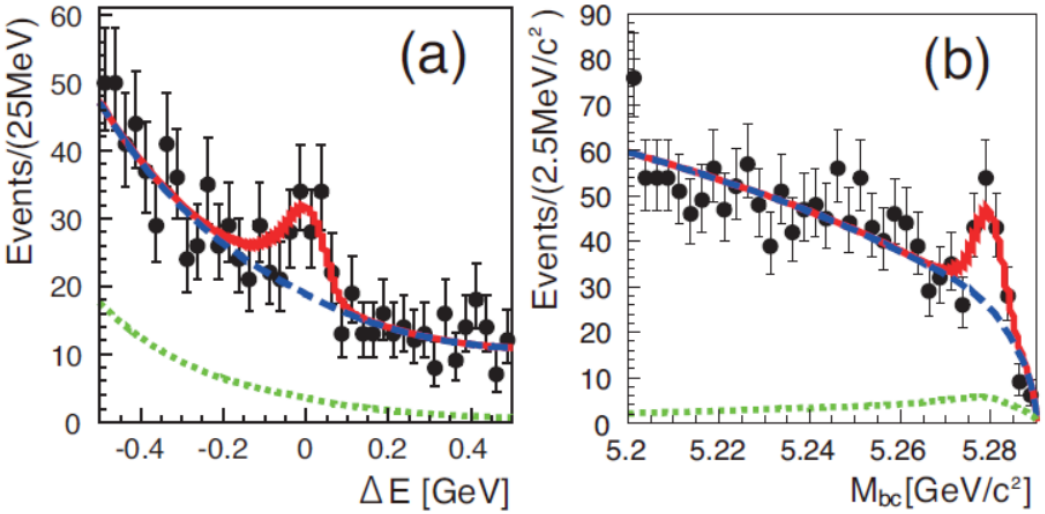
$$S \sim -2\,\zeta_{CP}\,(m_s/m_b)\sin 2\beta = -0.02\,\zeta_{CP}$$

- Proper time difference

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q\,[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)]\}$$

$$\Delta t \simeq (z_{\rm rec} - z_{\rm tag})/\beta\gamma c \equiv \Delta z/\beta\gamma c$$

- Neural-network based selection
- **Helicity angle** and mass distributions from studying $B^+ \to K^+\eta\gamma$
- Signal extracted from **3D unbinned maximum-likelihood fit**

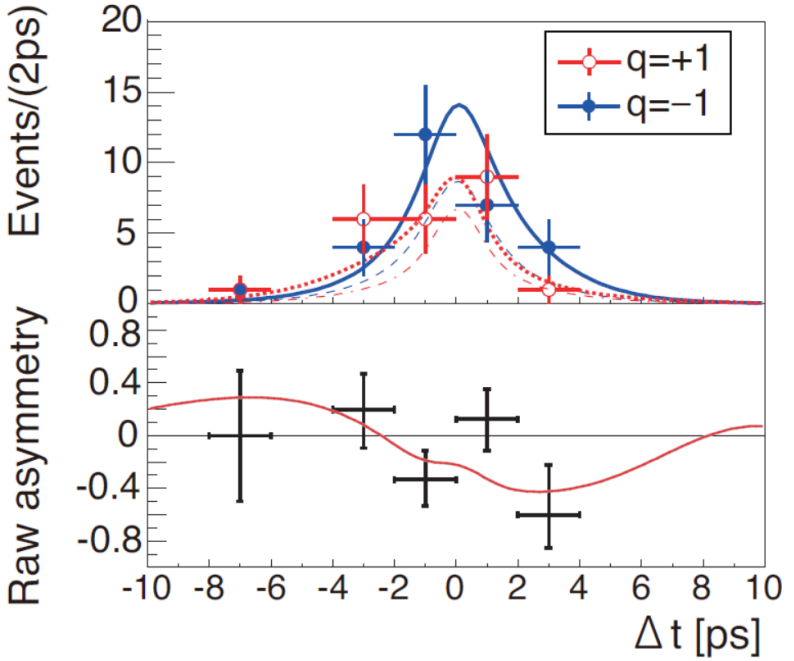


Measurement of time-dependent CP asymmetry in $B^0 \to K_S\eta\gamma$

PRD 97 (2018) 092003

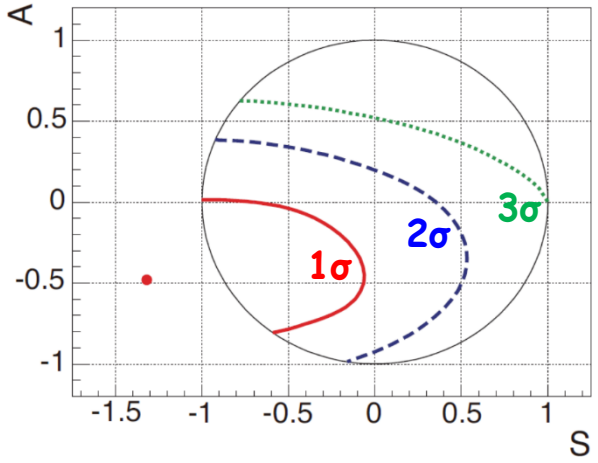
0.77 x 10^9 $B\bar{B}$ pairs

- Fit to the **Δt distribution in the signal region**



- Measure **S and A parameters** and establish confidence levels

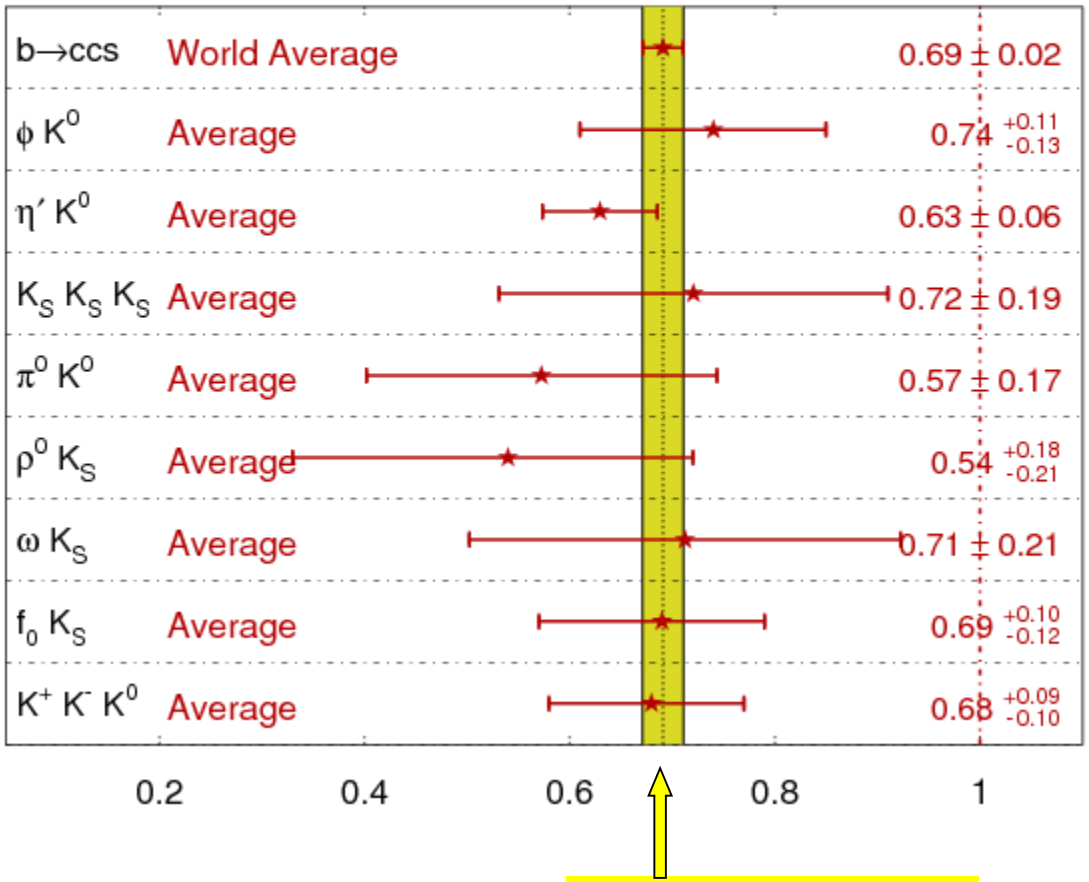
$$\mathcal{S} = -1.32 \pm 0.77(\text{stat.}) \pm 0.36(\text{syst.})$$
$$\mathcal{A} = -0.48 \pm 0.41(\text{stat.}) \pm 0.07(\text{syst.})$$



- Result **consistent with no asymmetry hypothesis within 2σ** and with SM predictions
- Improved precision with Belle II

Comparison of sin(2β) measurements from tree and penguin diagrams

$$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$$ HFLAV Summer 2016

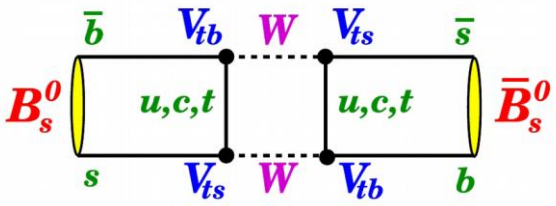


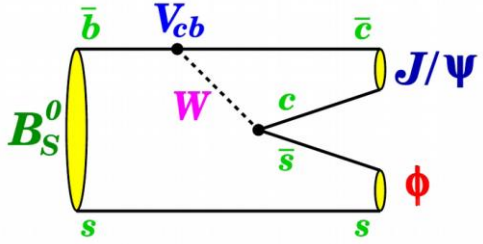
sin(2β) from charmonium $(J/\Psi)K^0$

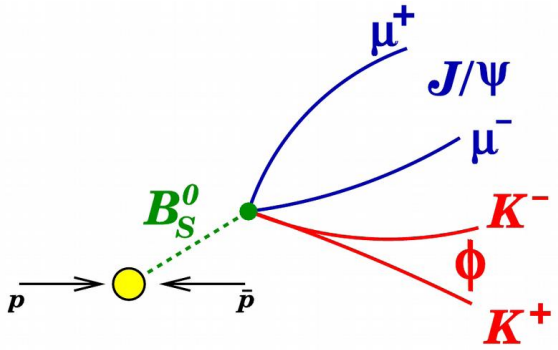
No contradiction between sin2β from b→cc̄s and b→qq̄s

φ_s and $\Delta\Gamma_s$ measurements

- Similar to B^0 system, interference of mixing and decay gives access to **CPV phase of B_s mixing** $\varphi_s = -2\beta_s$ (neglecting penguin contribution)
- Measured via $B_s \rightarrow J/\psi\varphi$, $J/\psi\, K^+K^-$, $J/\psi\, \pi^+\pi^-$ by CDF and D0, LHCb, ATLAS and CMS







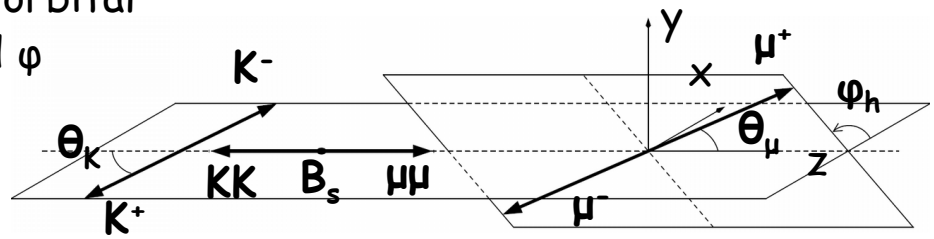
- Time-dependent flavour-tagged **angular anaysis**
- φ_s and $\Delta\Gamma_s$ from maximum likelihood fit
- Distinguish CP aigenstates

$\varphi_s \rightarrow K^+K^-$, in P wave → CP-even, CP-odd

$\varphi_s \rightarrow K^+K^-$, in S wave → CP-odd

depending on relative orbital momentum of J/ψ and φ

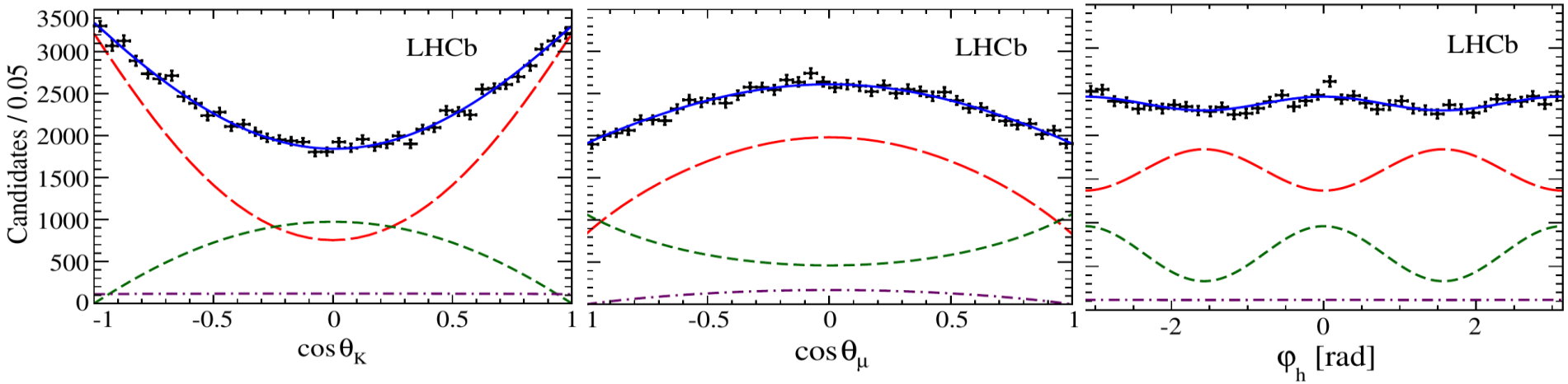
helicity angles $\Omega = (\theta_\mu, \theta_K, \varphi_h)$

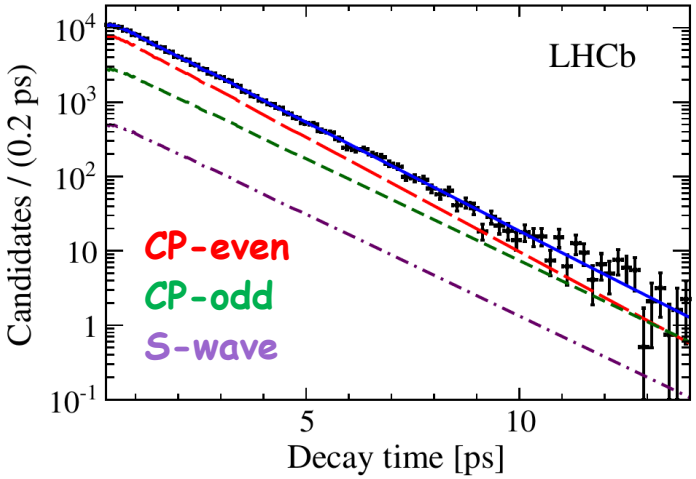


φ_s and $\Delta\Gamma_s$ measurements

- Time-dependent flavour tagged **angular anaysis**

PRL 114 (2015) 041801





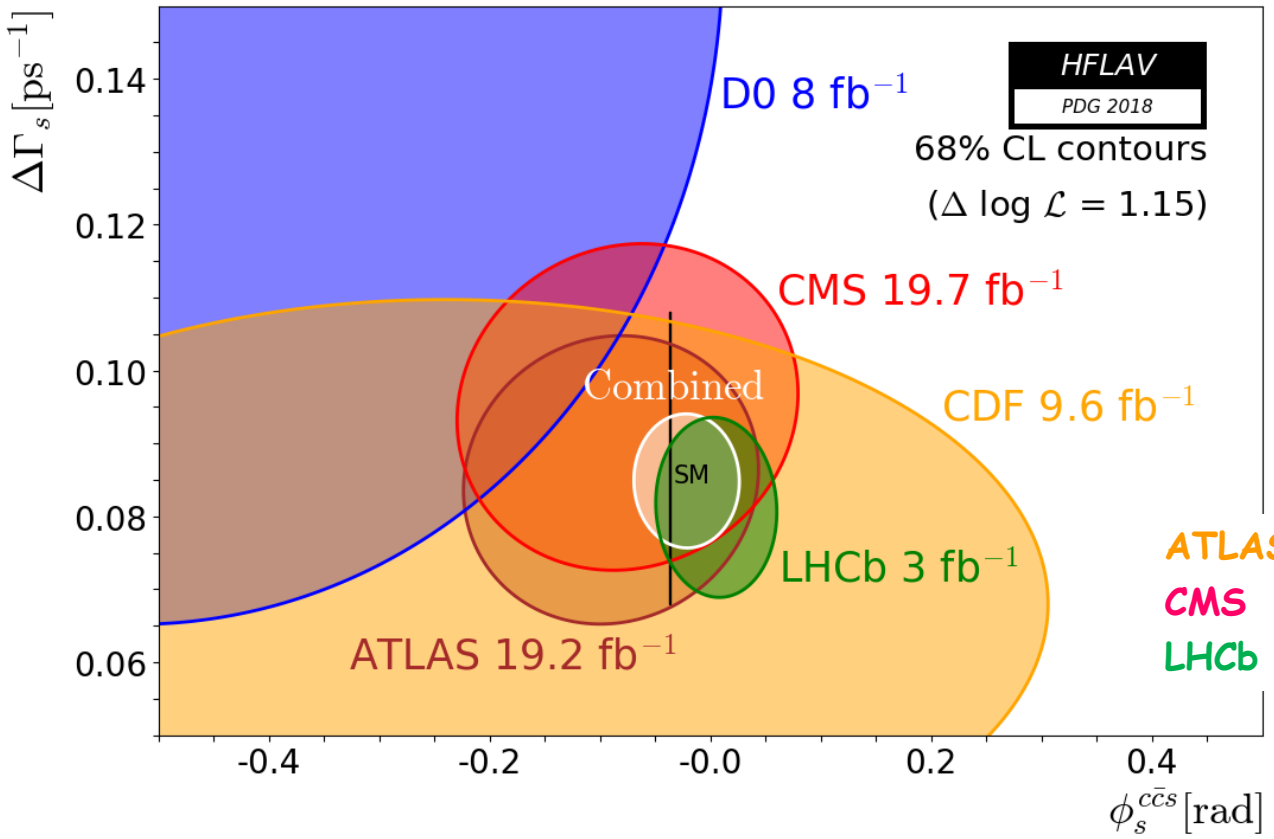
- **Time-dependent** flavour tagged angular anaysis
- Event-by-event decay time resolution

- **LHCb average** with Run I data of $B_s \to J/\psi\varphi$, $J/\psi\, K^+K^-$, $J/\psi\, \pi^+\pi^-$

JHEP 1708 (2017) 037

$$\phi_s = 1 \pm 37\,\text{mrad}$$
$$|\lambda| = 0.973 \pm 0.013$$
$$\Gamma_s = 0.6588 \pm 0.0022 \pm 0.0015\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0813 \pm 0.0073 \pm 0.0036\,\text{ps}^{-1}$$

HFLAV average for $\varphi_s^{c\bar{c}}$ and $\Delta\Gamma_s$



ATLAS PLB 757 (2016) 97
CMS JHEP 1608 (2016) 147
LHCb JHEP 1708 (2017) 037

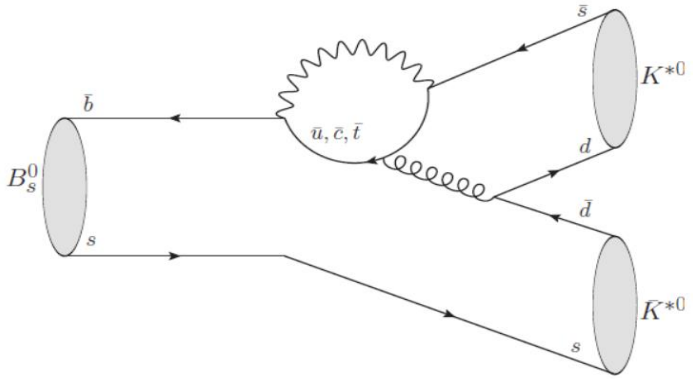
- Precision on φ_s of 33 mrad with Run I LHC data
- Good **agreement with SM** expectations

Measurement of φ_s in $B_s \to (K^+\pi^-)(K^-\pi^+)$

JHEP 1803 (2018) 140

$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$=7 and 8 TeV

- Decay first observed by LHCb
  PLB 709 (2012) 50, update JHEP 1507 (2015) 166
- Decay **dominated by a gluonic penguin diagram** (complementary to measurements with EW penguins)



- **Time-dependent amplitude analysis**

$$\Gamma \sim \Sigma e^{-\Gamma_s t} [a_{ij} \cosh(\tfrac{1}{2}\Delta\Gamma_s t) + b_{ij} \sinh(\tfrac{1}{2}\Delta\Gamma_s t) + c_{ij} \cosh(\tfrac{1}{2}\Delta m_s t) + d_{ij} \sinh(\tfrac{1}{2}\Delta m_s t)]$$

First time with tensor components

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

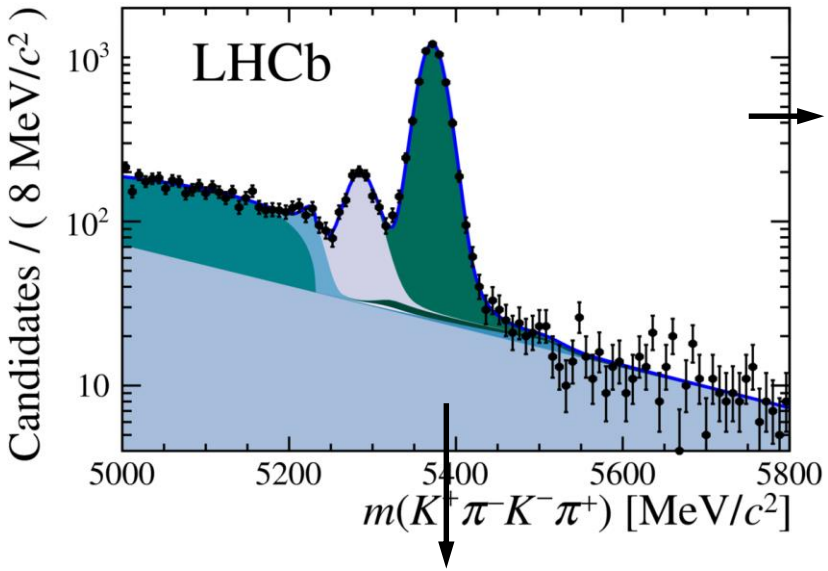
- 19 amplitudes

Measurement of φ_s in $B_s \rightarrow (K^+\pi^-)(K^-\pi^+)$

JHEP 1803 (2018) 140

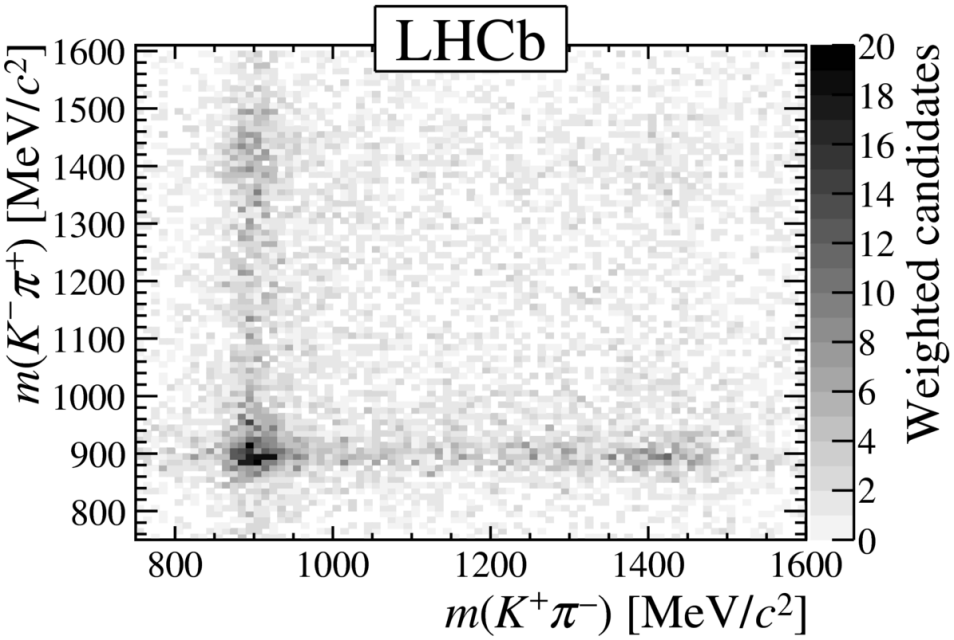
$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$=7 and 8 TeV

- BDT-based selection, signal weights using sPlots technique



- B-yields extraction

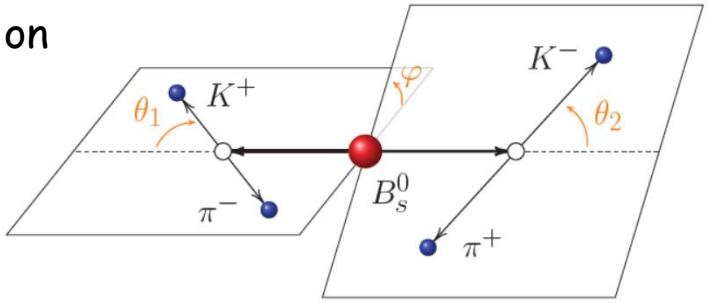
Channel	Yield	Yield in Signal Region
$B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$	6080 ± 83	6004
$B^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$	1013 ± 49	103
$B^0 \rightarrow (K^+\pi^-)(K^-K^+)$	281 ± 47	1
$B_s^0 \rightarrow (K^+\pi^-)(K^-K^+)$	8 ± 3	4
$B^0 \rightarrow (K^+\pi^-)(\pi^-\pi^+)$	57 ± 13	33
$\Lambda_b^0 \rightarrow (p\pi^-)(K^-\pi^+)$	44 ± 10	13
Partially reconstructed	2580 ± 151	0
Combinatorial	2810 ± 214	372



- $(K^+\pi^-)$ invariant masses after applying signal weights

Measurement of φ_s in $B_s \to (K^+\pi^-)(K^-\pi^+)$

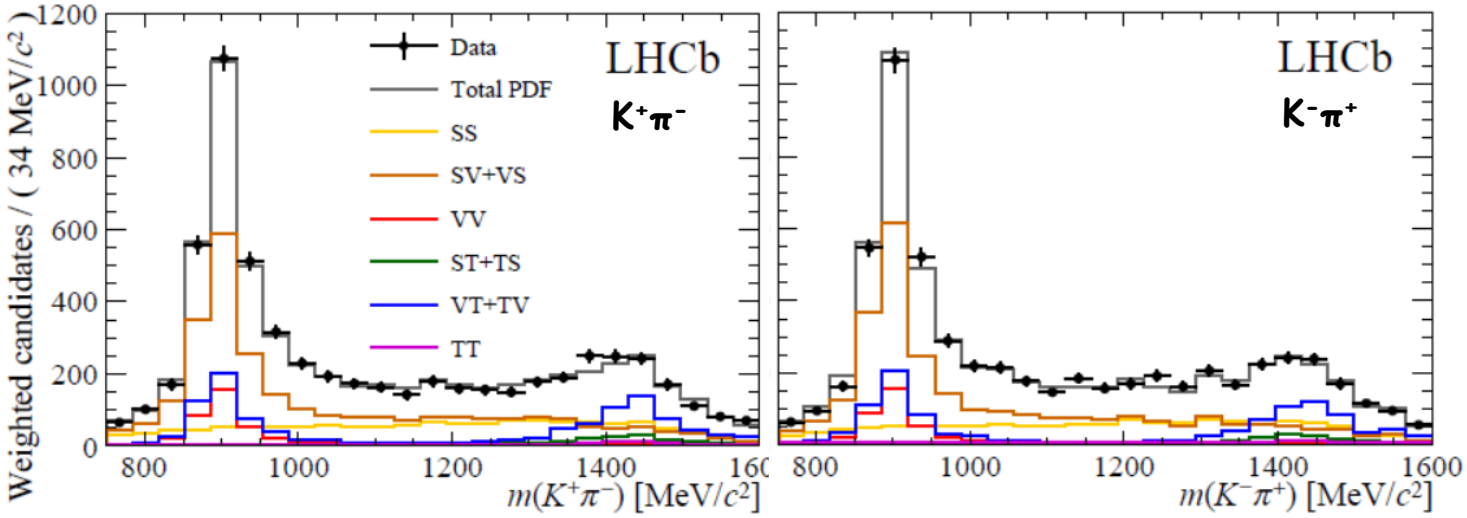
- Amplitudes depend on masses and angles



JHEP 1803 (2018) 140

$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$=7 and 8 TeV

- **Projections** of decay-time-dependent, flavour-tagged fit to the sPlot weighted data



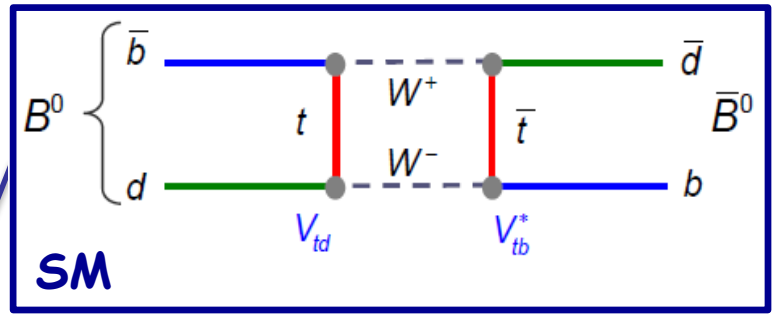
$$\varphi_s^{d\bar{d}} = -0.10 \pm 0.13 \pm 0.14$$

- **Consistent with SM prediction, $B_s \to \varphi\varphi$ measurement and** $\varphi_s^{c\bar{c}} = -0.021 \pm 0.031$

PRD 90 (2014) 052011 HFLAV

Flavour transitions probe high mass scales in quantum loops (e.g. FCNC)

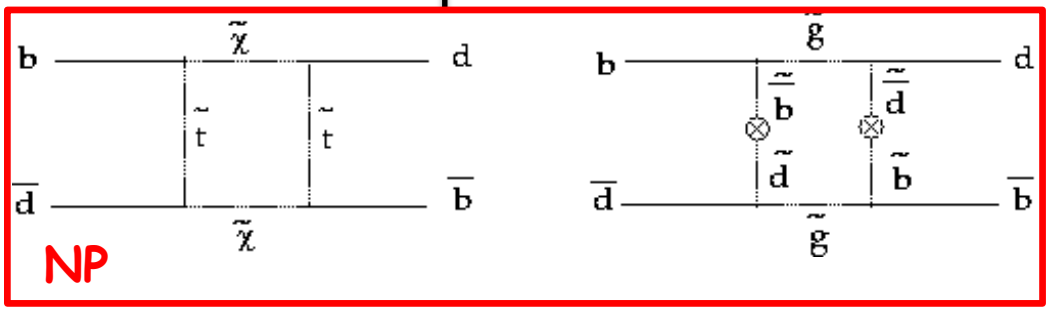
Standard Model scale and **couplings** (CKM matrix elements):



B$\bar{\text{B}}$ mixing:

$$A_0\left[\frac{C_{SM}}{M_W^2}+\frac{C_{NP}}{\Lambda_{NP}^2}\right]$$

New Physics scale and **coupling:**

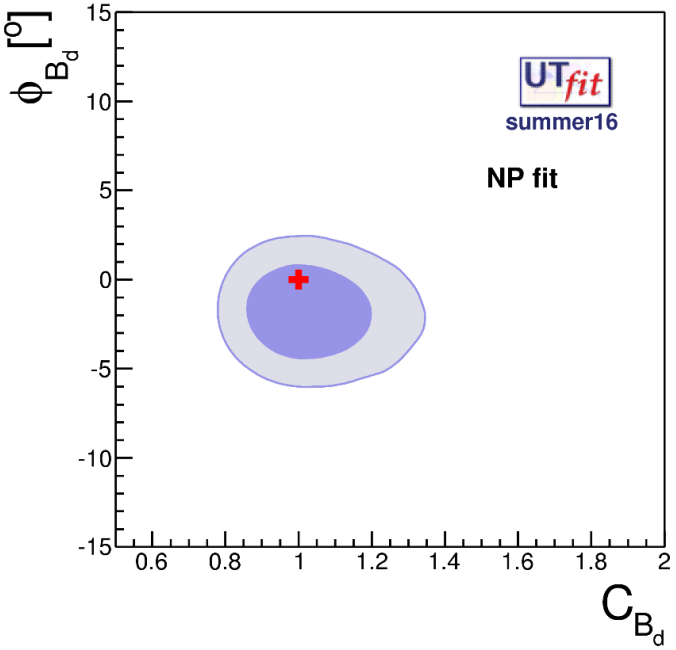


- For NP in ΔB=2 transitions :

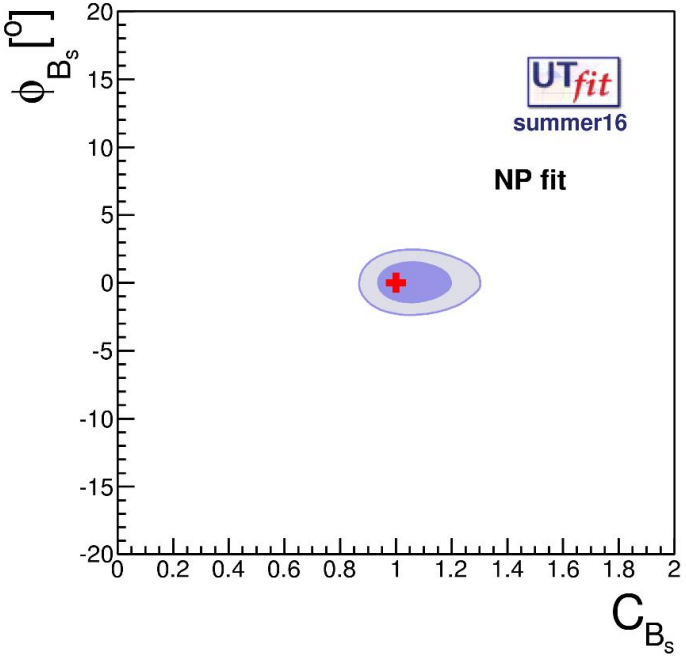
$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\rm eff}^{\rm full} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\rm eff}^{\rm SM} | \bar{B}_q^0 \rangle},$$

$$\begin{aligned}
\Delta m_d^{\rm exp} &= C_{B_d} \Delta m_d^{\rm SM}, \\
\sin 2\beta^{\rm exp} &= \sin(2\beta^{\rm SM} + 2\phi_{B_d}), \\
\alpha^{\rm exp} &= \alpha^{\rm SM} - \phi_{B_d}, \\
\Delta m_s^{\rm exp} &= C_{B_s} \Delta m_s^{\rm SM}, \\
\phi_s^{\rm exp} &= (\beta_s^{\rm SM} - \phi_{B_s}),
\end{aligned}$$

B_d sector



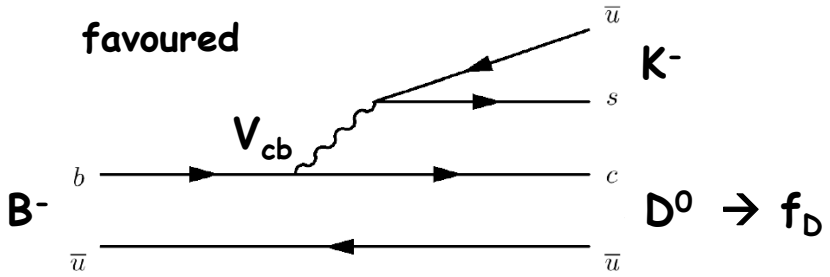
B_s sector

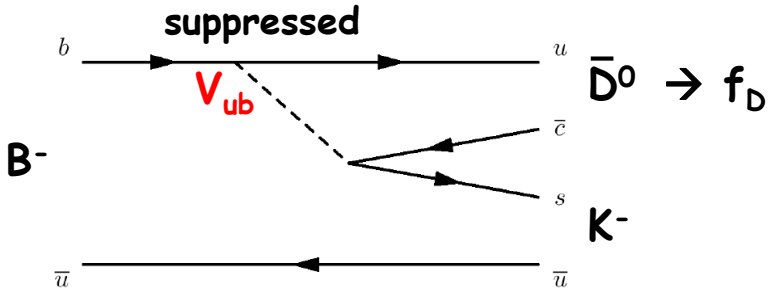


- No sign of NP at the 10%-20% level …

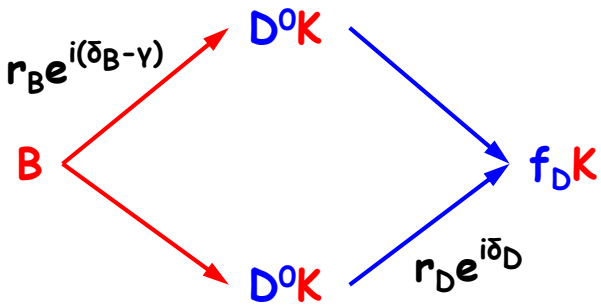
Angle γ from B→DK decays

- B→DK decays probe **angle γ**





- Interference since both D^0 and $\bar{D}^0$ decay to a common final state f_D
- Parameters: weak phase **γ**, relative strong phases and magnitude ratios of the amplitudes **(δ_B, r_B)** and **(δ_D, r_D)**
- SM benchmark since **tree-mediated process**



$$\frac{A_{suppressed}}{A_{favoured}} = r_B e^{i(\delta_B-\gamma)}$$

- Measure asymmetries and average partial decay rate ratios → fit for **γ**, **r_B**, **δ_B**
- **Methods of γ extraction** depending on f_D:

  GLW (Gronau, London, Wyler) – suppressed CP eigenstate (K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$)

  ADS (Atwood, Dunietz, Soni) – interference of suppressed B / favoured D and favoured B / doubly suppressed D decays ($K^-\pi^+$, $K^+\pi^-$)

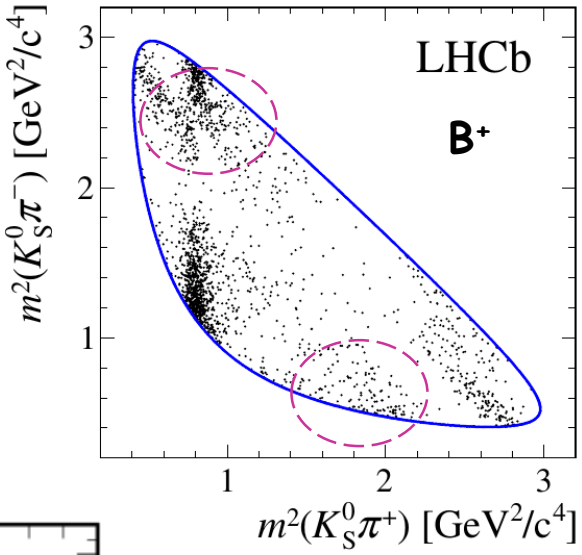
  GGSZ (Giri, Grossman, Sofer, Zupan) – interference on Dalitz plot for multibody f_D ($K_S\,\pi^+\pi^-$, $K_S\,K^+K^-$)

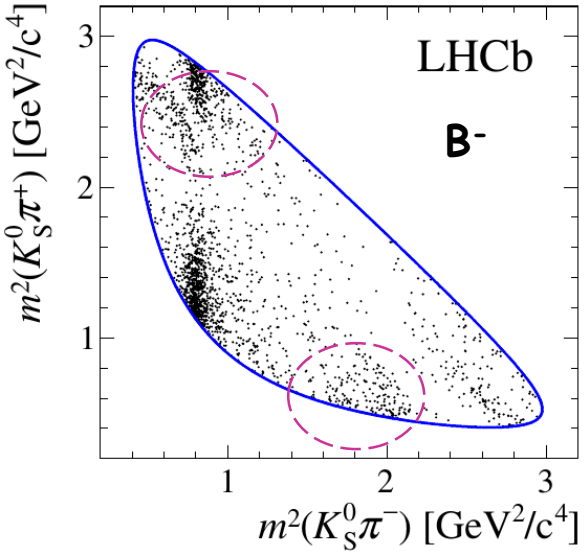
arXiv:1806.01202

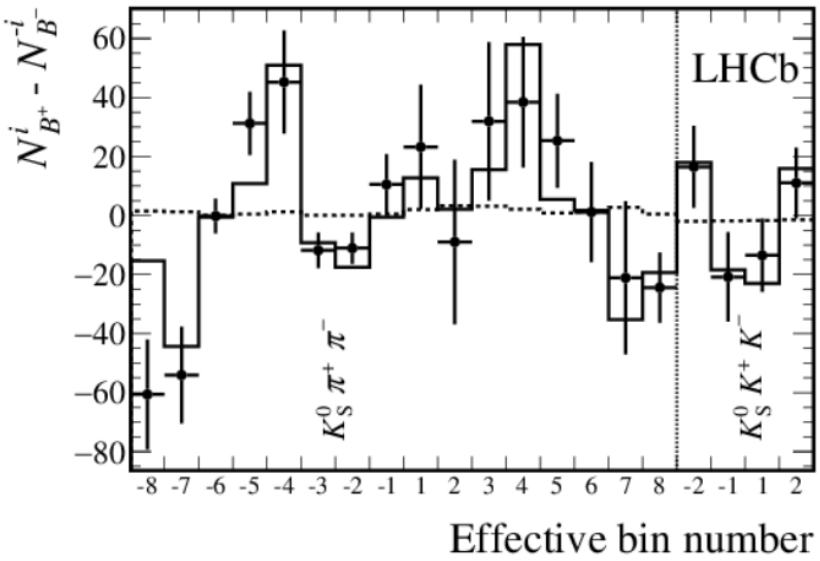
∫Ldt = 2.0 fb^{-1} at √s=13 TeV

- **GGSZ** – interference of suppressed and favoured B decays followed by D decays → amplitude and phase variations across the Dalitz plane
- Measure B^+ and B^- yields and calculate **asymmetries in bins across the Dalitz plane**
- Use external (CLEO-c) strong phase measurement

  PRD 82 (2010) 112006
- Compare yield differences in Dalitz plane bins







No CPV

- Study CP-violating observables

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

arXiv:1806.01202

∫Ldt = 2.0 fb^{-1} at √s=13 TeV

- The CP-observables are measured to be

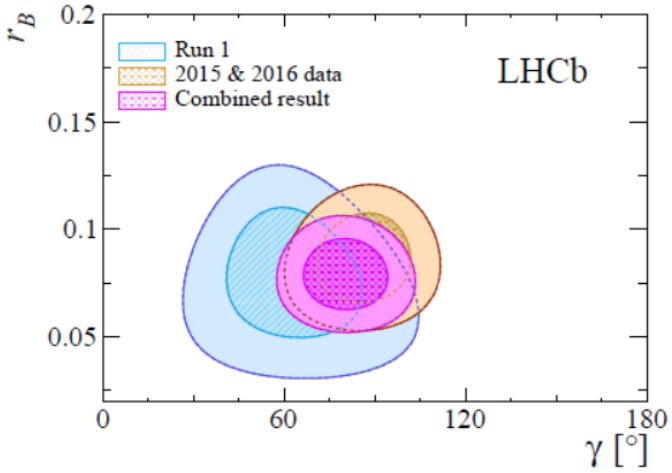
$$x_- = (\ \ 9.0 \pm 1.7 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_- = (\ \ 2.1 \pm 2.2 \pm 0.5 \pm 1.1) \times 10^{-2}$$
$$x_+ = (-7.7 \pm 1.9 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_+ = (-1.0 \pm 1.9 \pm 0.4 \pm 0.9) \times 10^{-2}$$

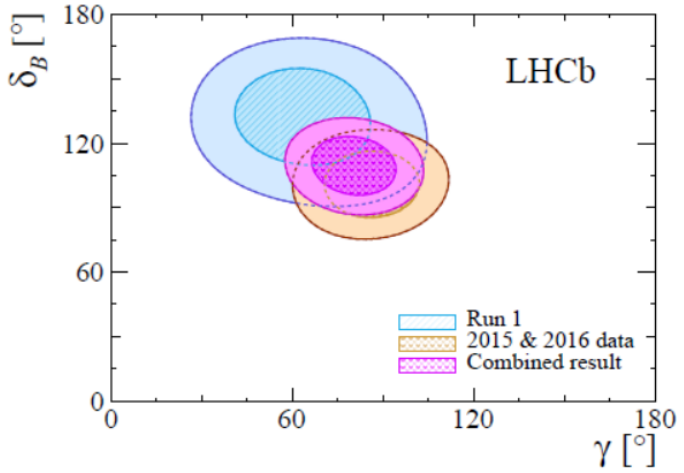
- These values are translated to

$$\gamma = 87^\circ\ ^{+11^\circ}_{-12^\circ}\ \left(^{+22^\circ}_{-23^\circ}\right),$$
$$r_B = 0.087\ ^{+0.013}_{-0.014}\ \left(^{+0.025}_{-0.027}\right)$$
$$\delta_B = 101^\circ\ ^{+11^\circ}_{-11^\circ}\ \left(^{+22^\circ}_{-23^\circ}\right).$$

- **Most precise determination of γ from a single analysis**
- These results are consistent with the LHCb results from run I, JHEP 1410 (2014) 097 and the two results are combined

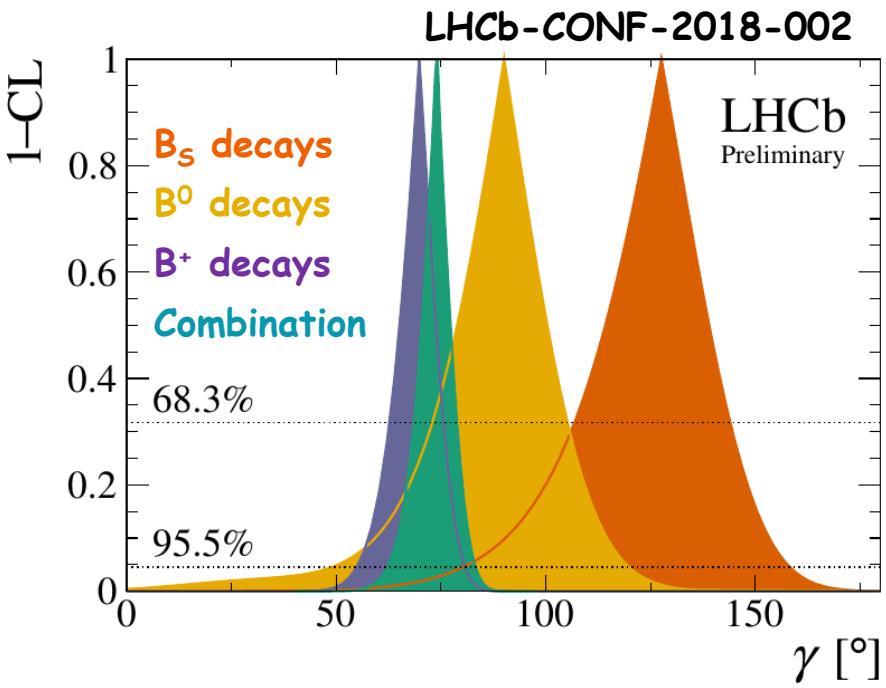
$$\gamma = 80^\circ\ ^{+10^\circ}_{-9^\circ}\ \left(^{+19^\circ}_{-18^\circ}\right),$$
$$r_B = 0.080\ ^{+0.011}_{-0.011}\ \left(^{+0.022}_{-0.023}\right)$$
$$\delta_B = 110^\circ\ ^{+10^\circ}_{-10^\circ}\ \left(^{+19^\circ}_{-20^\circ}\right).$$





Angle γ from LHCb measurements

- Combine 16 measurements to obtain **global LHCb average**
- Determine **γ, hadronic amplitude ratio and phase difference**
- To achieve optimal sensitivity, use 94 observables with a likelihood ansatz for the combination

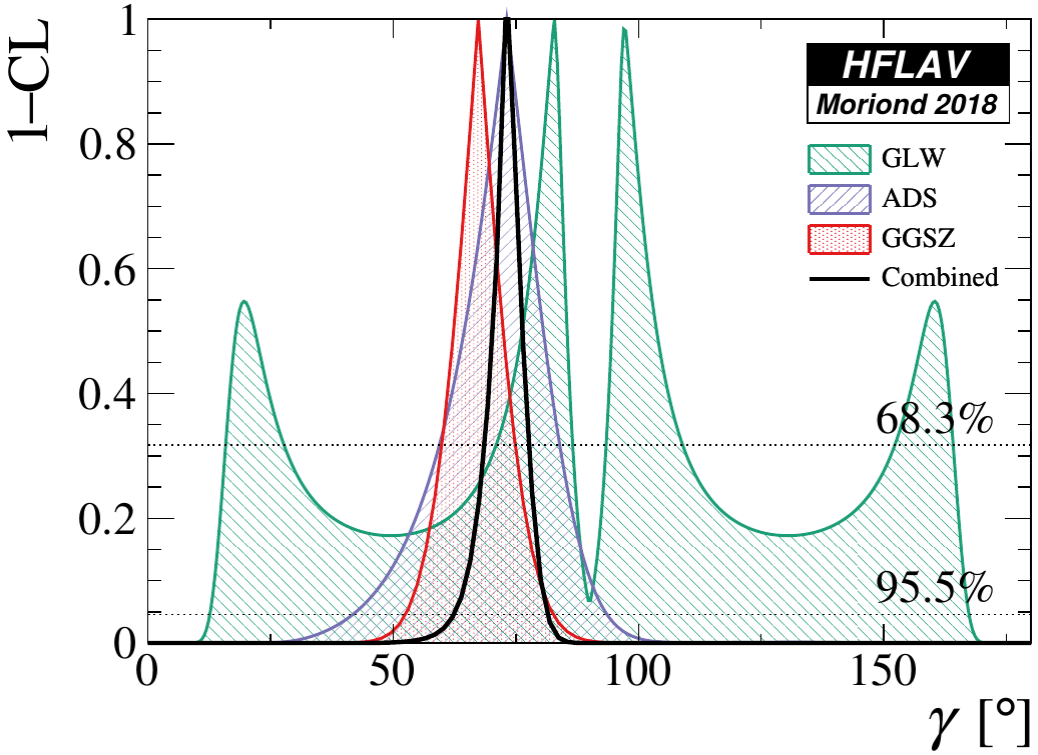


$$\gamma = (74.0\,^{+5.0}_{-5.8})^\circ$$

$B^+ \to DK^+$	$D \to h^+h^-$	GLW	Run 1 & 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	Run 1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	Run 1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	Run 2
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	Run 1
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	Run 1 & 2
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	Run 1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	Run 1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	Run 1
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	Run 1
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	Run 1

World average of angle γ measurements

- **Combine measurements from different experiments**
- Uncertainties on the averages are dominated by the LHCb results



- **HFLAV average:**

$$\gamma_{HFLAV} = (73.5\ ^{+\ 4.2}_{-\ 5.1})^{o}$$

- **Indirect prediction from Utfit 2016:**

$$\gamma_{prediction} = (65.3 \pm 2.0)^{o}$$

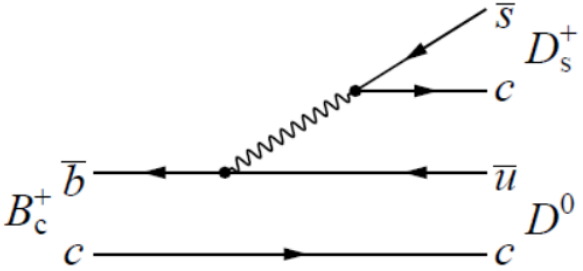
- **Direct and indirect determination yield compatible γ values**

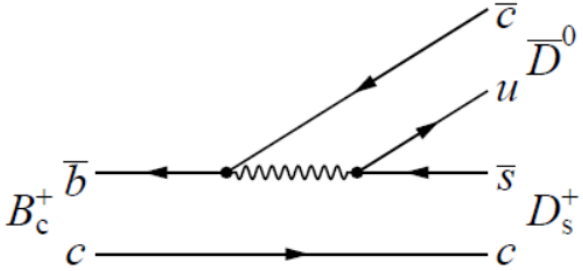
Search for B_c decays to two charm mesons

Nucl. Phys. B930 (2018) 563

$\int Ldt$ = 3.0 fb^{-1}

- Sensitive to **angle γ**
- b→c transition colour-suppressed





- **Large r-values**

$$r_{B_c^+} \equiv |A(B_c^+ \to D^0 D_s^+)/A(B_c^+ \to \overline{D}^0 D_s^+)| \approx 1$$

and potentially large CPV for D-decays to CP eigenstates

- Theory predictions for $B_c \to D^+_{(s)} \overline{D}^{0}_{(-)}$

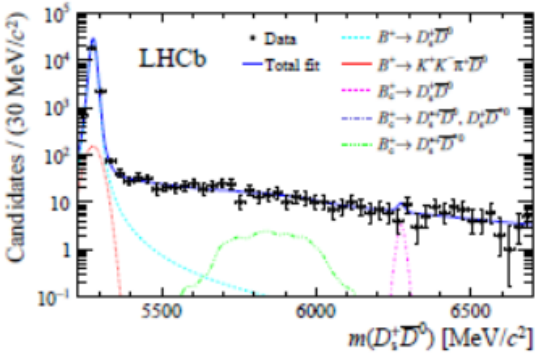
	Prediction for the branching fraction $[10^{-6}]$			
Channel	Ref. [9]	Ref. [10]	Ref. [11]	Ref. [12]
$B_c^+ \to D_s^+ \overline{D}^0$	2.3 ± 0.5	4.8	1.7	2.1
$B_c^+ \to D_s^+ D^0$	3.0 ± 0.5	6.6	2.5	7.4
$B_c^+ \to D^+ \overline{D}^0$	32 ± 7	53	32	33
$B_c^+ \to D^+ D^0$	0.10 ± 0.02	0.32	0.11	0.32

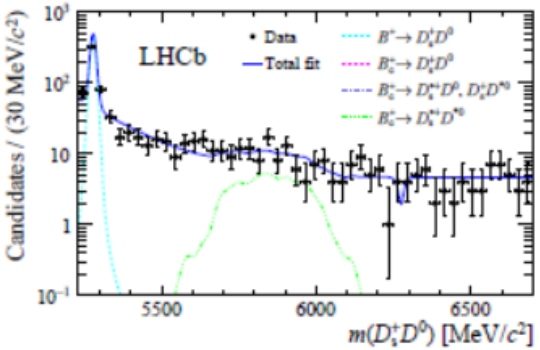
Z.Rui, Z.Zhitian, C.-D.Lu, PRD 86 (2012) 074019

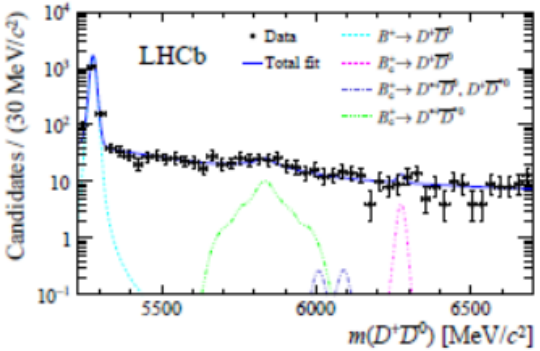
V.V.Kiselev, arXiv:hep-ph/0211021

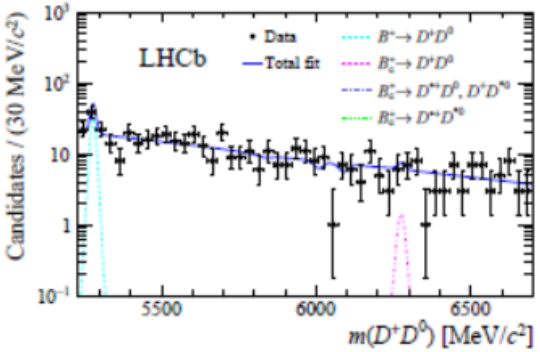
M.A.Ivanov, J.G.Korner, O.N.Pakhomova, PLB 555 (2003) 189

M.A.Ivanov, J.G.Korner, P.Santorelli, PRD 73 (2006) 054024









Search for B_c decays to two charm mesons

Nucl. Phys. B930 (2018) 563

$\int Ldt$ = 3.0 fb^{-1}

- BDT-based analysis
- Normalization using
  $B \to D^+_{(s)} \bar{D}^0$ decay modes
- **Upper limits at 90% CL**
  set on the ratios

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ \bar{D}^0)}{\mathcal{B}(B^+ \to D_s^+ \bar{D}^0)} < 0.9 \times 10^{-3}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ D^0)}{\mathcal{B}(B^+ \to D_s^+ \bar{D}^0)} < 3.7 \times 10^{-4}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+ \bar{D}^0)}{\mathcal{B}(B^+ \to D^+ \bar{D}^0)} < 1.9 \times 10^{-2}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+ D^0)}{\mathcal{B}(B^+ \to D^+ \bar{D}^0)} < 1.2 \times 10^{-2}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^{*+} \bar{D}^0) + \mathcal{B}(B_c^+ \to D_s^+ \bar{D}^{*0})}{\mathcal{B}(B^+ \to D_s^+ \bar{D}^0)} < 2.8 \times 10^{-3}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^{*+} D^0) + \mathcal{B}(B_c^+ \to D_s^+ D^{*0})}{\mathcal{B}(B^+ \to D_s^+ \bar{D}^0)} < 3.0 \times 10^{-3}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to (D^{*+} \to D^+\pi^0, \gamma)\bar{D}^0) + \mathcal{B}(B_c^+ \to D^+ \bar{D}^{*0})}{\mathcal{B}(B^+ \to D^+ \bar{D}^0)} < 5.5 \times 10^{-2}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to (D^{*+} \to D^+\pi^0, \gamma)D^0) + \mathcal{B}(B_c^+ \to D^+ D^{*0})}{\mathcal{B}(B^+ \to D^+ \bar{D}^0)} < 2.2 \times 10^{-2}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^{*+} \bar{D}^{*0})}{\mathcal{B}(B^+ \to D_s^+ \bar{D}^0)} < 1.1 \times 10^{-2}$$

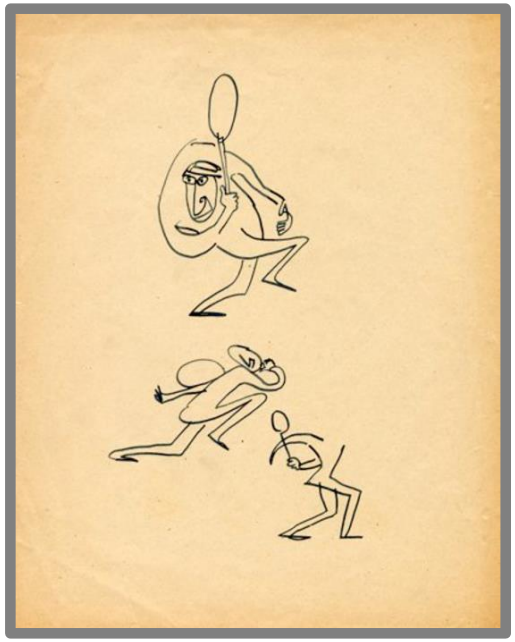
$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^{*+} D^{*0})}{\mathcal{B}(B^+ \to D_s^+ \bar{D}^0)} < 2.0 \times 10^{-2}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^{*+} \bar{D}^{*0})}{\mathcal{B}(B^+ \to D^+ \bar{D}^0)} < 6.5 \times 10^{-1}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^{*+} D^{*0})}{\mathcal{B}(B^+ \to D^+ \bar{D}^0)} < 1.3 \times 10^{-1}$$

- Upper limits still above theory predictions
- Assuming f_c/f_u = 1.2%, BR($B_c \to D^+\bar{D}^0$) < 6.0 x 10^{-4} @ 90% CL

CP-parity violation studies with b-baryons



Bruno Touschek

Search for CPV in charmless 2-body Λ_b decays

arXiv:1807.06544

- Measure **direct CP asymmetries** in $\Lambda_b \to p\pi^-$ and $\Lambda_b \to pK^-$ decays — $\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV
- Asymmetries predicted between few (generalized factorization) and 30% (pQCD) — Y.K.Hsiao, C.Q.Geng, PRD 91 (2015) 116007; A.Ali, G.Kramer, C.-D.Lu, PRD 58 (1998) 094009; C.-D.Lu et al., PRD 80 (2009) 034011
- First study by CDF PRL 113 (2014) 242001
- **CP asymmetries** deduced as

$$A_{CP}^{pK^-} = A_{\rm raw}^{pK^-} - A_{\rm D}^{p} - A_{\rm D}^{K^-} - A_{\rm PID}^{pK^-} - A_{\rm P}^{\Lambda_b^0} - A_{\rm trigger}^{pK^-},$$
$$A_{CP}^{p\pi^-} = A_{\rm raw}^{p\pi^-} - A_{\rm D}^{p} - A_{\rm D}^{\pi^-} - A_{\rm PID}^{p\pi^-} - A_{\rm P}^{\Lambda_b^0} - A_{\rm trigger}^{p\pi^-},$$

- **Raw asymmetries**:

$$A_{\rm raw}^{f} \equiv \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda}_b^0 \to \overline{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda}_b^0 \to \overline{f})}$$

- **Detection asymmetries**: kaon and pion asymmetries determined using charm-meson control samples; proton asymmetry from simulation
- **Particle ID asymmetries** determined using calibration samples
- Λ_b **production asymmetry** from LHCb, PLB 774 (2017) 139
- **Trigger asymmetries** estimated using data-driven techniques

Search for CPV in charmless 2-body Λ_b decays

arXiv:1807.06544

$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV

- BDT-based event selection
- Raw asymmetries:

$$A_{\rm raw}^{pK^-} = (1.0 \pm 1.3)\%$$
$$A_{\rm raw}^{p\pi^-} = (0.5 \pm 1.7)\%$$

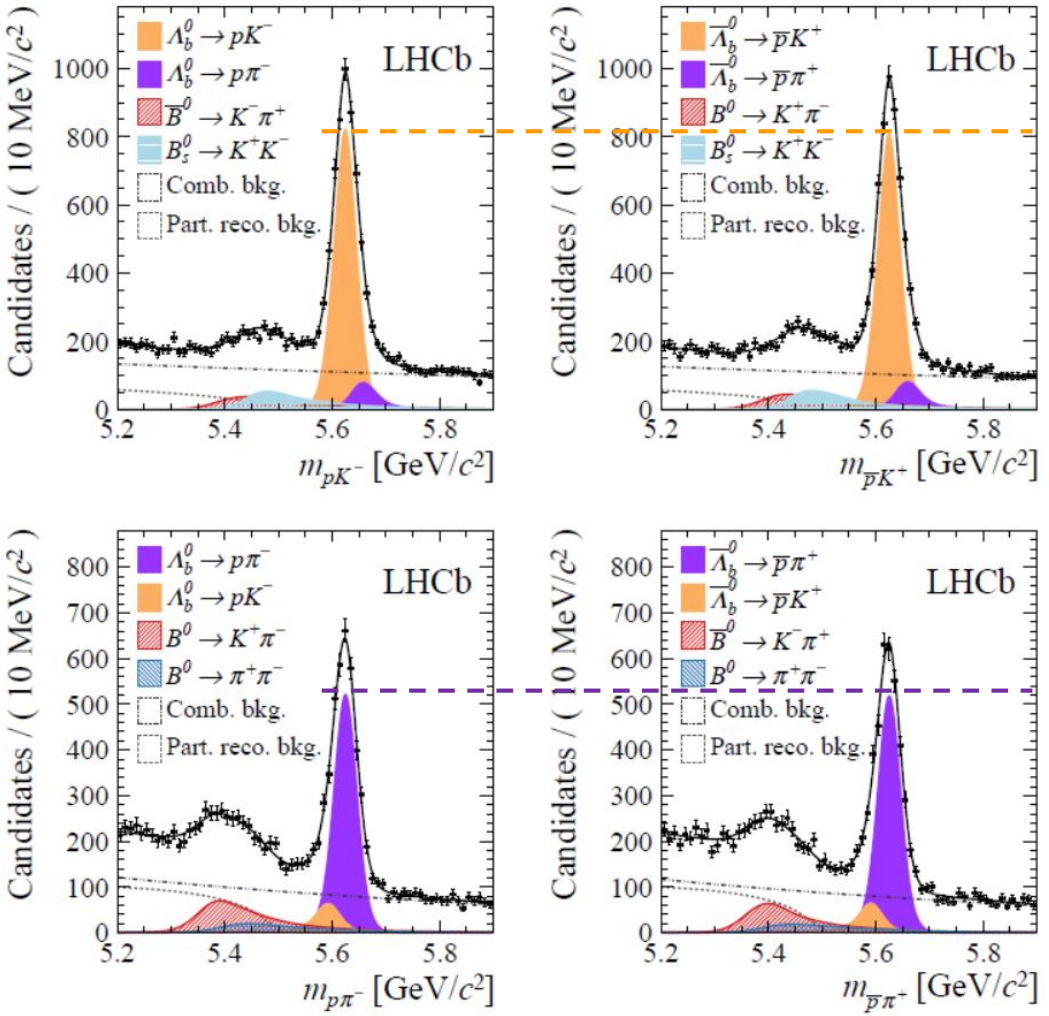
- Resulting **CP asymmetries**:

$$A_{CP}^{pK^-} = -0.020 \pm 0.013 \pm 0.019$$
$$A_{CP}^{p\pi^-} = -0.035 \pm 0.017 \pm 0.020$$

- ΔA_{CP} independent from the proton detection and Λ_b production asymmetries; PID, detection and raw asymmetries partially cancel

$$\Delta A_{CP} \equiv A_{CP}^{pK^-} - A_{CP}^{p\pi^-} = A_{\rm raw}^{pK^-} - A_{\rm D}^{K^-} - A_{\rm PID}^{pK^-} - A_{\rm trigger}^{pK^-} - A_{\rm raw}^{p\pi^-} + A_{\rm D}^{\pi^-} + A_{\rm PID}^{p\pi^-} + A_{\rm trigger}^{p\pi^-}.$$

$$\Delta A_{CP} = 0.014 \pm 0.022 \pm 0.013$$



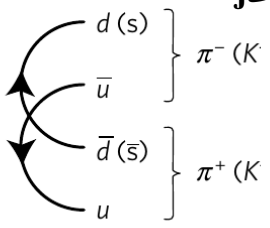
- Most precise measurement to date, compatible with **no direct CPV**

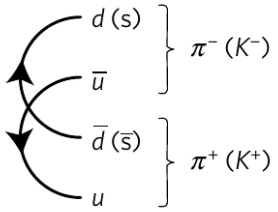
Search for CPV in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays

Nature 13 (2017) 391

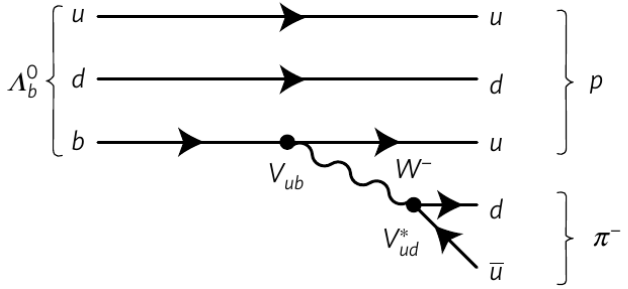
$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV

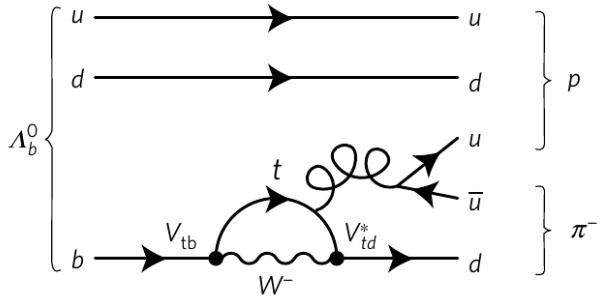
- CPV from interference of two amplitudes with comparable magnitudes





- Measure **P and CP violation** observables using **triple products** of final state particle momenta in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays in the Λ_b c.m.s.





- Λ_b : $C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+})$ $\quad A_{\hat{T}}(C_{\hat{T}}) = \dfrac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$

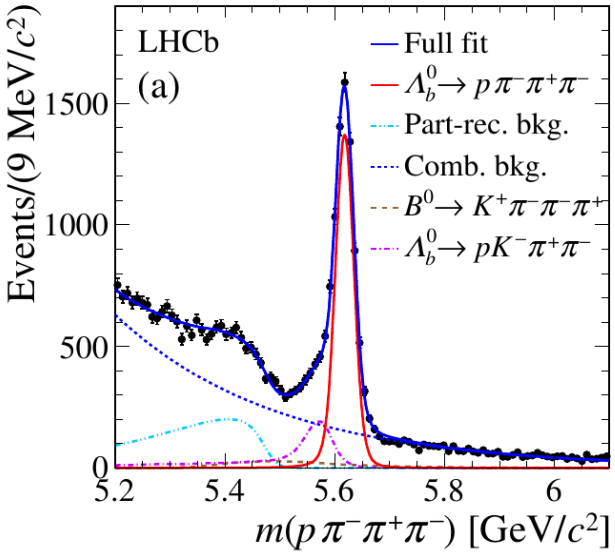
- Λ_b : $\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})$ $\quad \overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \dfrac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}$

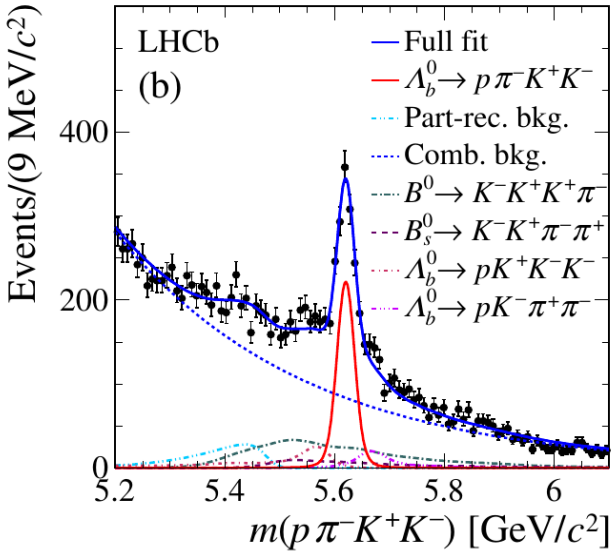
- T-odd observables : $a_P^{\hat{T}\text{-odd}} = \dfrac{1}{2}\left(A_{\hat{T}} + \overline{A}_{\hat{T}}\right)$ $\quad a_{CP}^{\hat{T}\text{-odd}} = \dfrac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)$

Non-zero values indicate P / CP violation.

Search for CPV in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays

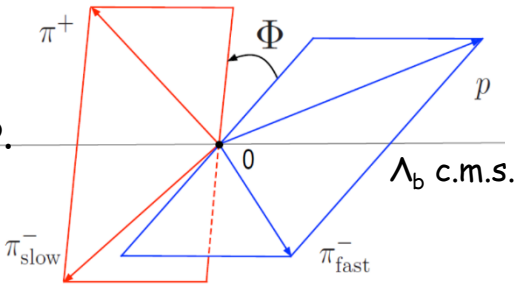
Nature 13 (2017) 391
$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7, 8 TeV



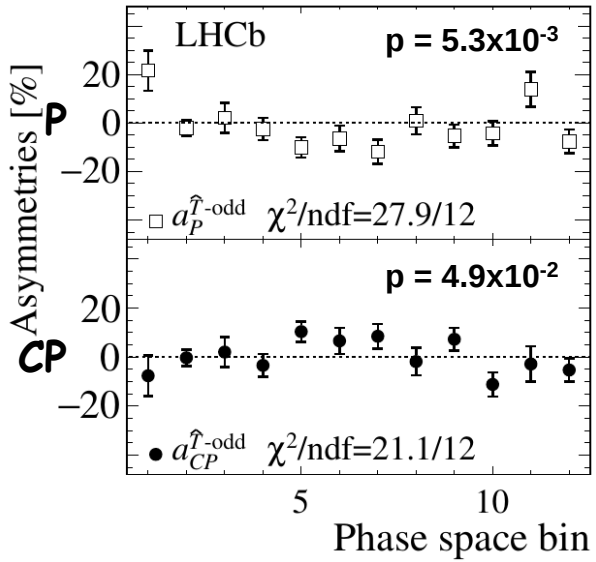


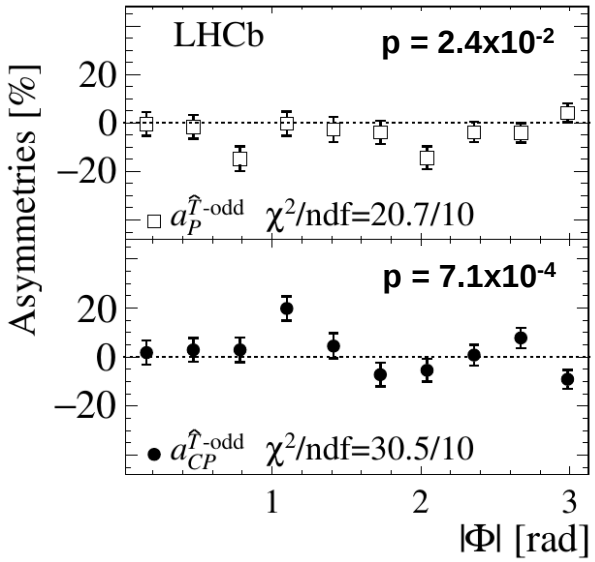
- The Λ_b 4-body decays have a rich resonance structure
- $\Lambda_b \to p\pi^-\pi^+\pi^-$ dominated by $\Delta(1232)^{++} \to p\pi^+$ and $\rho^0(770) \to \pi^+\pi^-$ contributions

- CP asymmetries vary over the phase space → binning in a phase space and Φ.



$\Lambda_b \to p\pi^-\pi^+\pi^-$



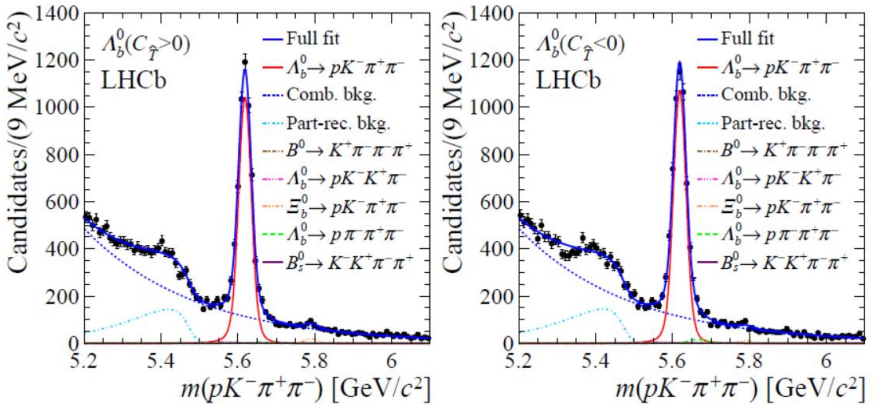


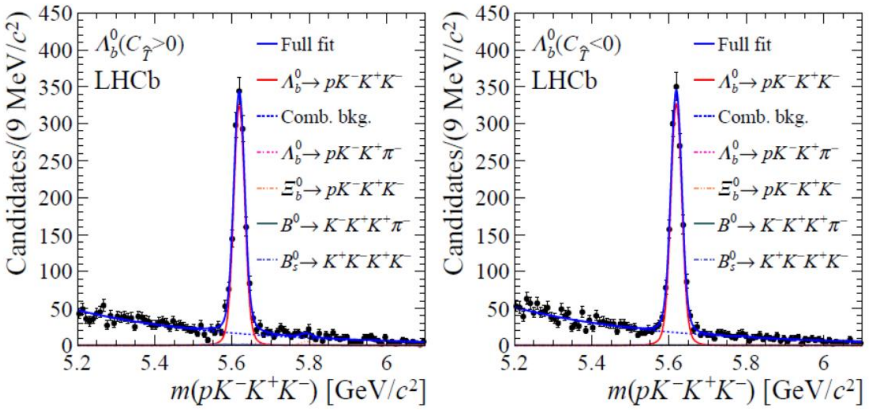
- Asymmetry measurements over the entire phase space do not show P / CP violation
- **First evidence for CPV in the baryon sector** at 3.3σ in localized asymmetry measurements

Search for CPV in $\Lambda_b \to pK^-\pi^+\pi^-$, $\Lambda_b \to pK^-K^+K^-$, $\Xi_b \to pK^-K^-\pi^+$ decays

JHEP 1808 (2018) 039
$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV

- CPV from interference of two amplitudes with comparable magnitudes, tree b→u and penguin b→s
- Sensitive to angle γ
- Search for CPV using **triple product asymmetries**

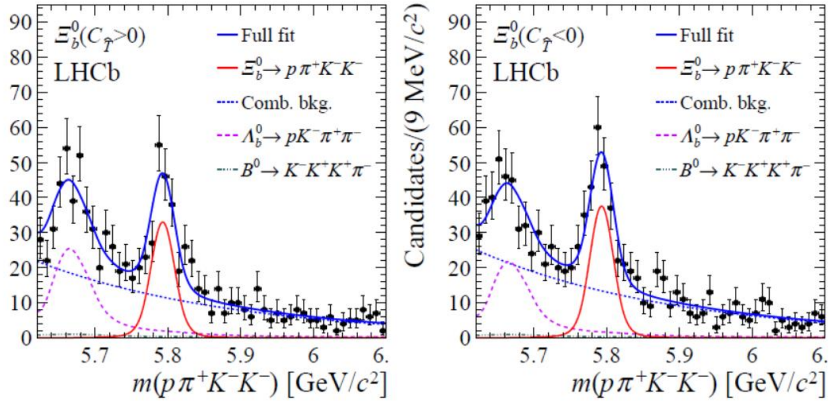




- Measurements in the **integrated phase space region** compatible with P and CP symmetries

	$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to pK^-K^+K^-$	$\Xi_b^0 \to pK^-K^-\pi^+$
$a_P^{\hat{T}\text{-odd}}$ (%)	$-0.60 \pm 0.84 \pm 0.31$	$-1.56 \pm 1.51 \pm 0.32$	$-3.04 \pm 5.19 \pm 0.36$
$a_{CP}^{\hat{T}\text{-odd}}$ (%)	$-0.81 \pm 0.84 \pm 0.31$	$1.12 \pm 1.51 \pm 0.32$	$-3.58 \pm 5.19 \pm 0.36$

- Sensitivity ranges from 0.8% to 5.2%

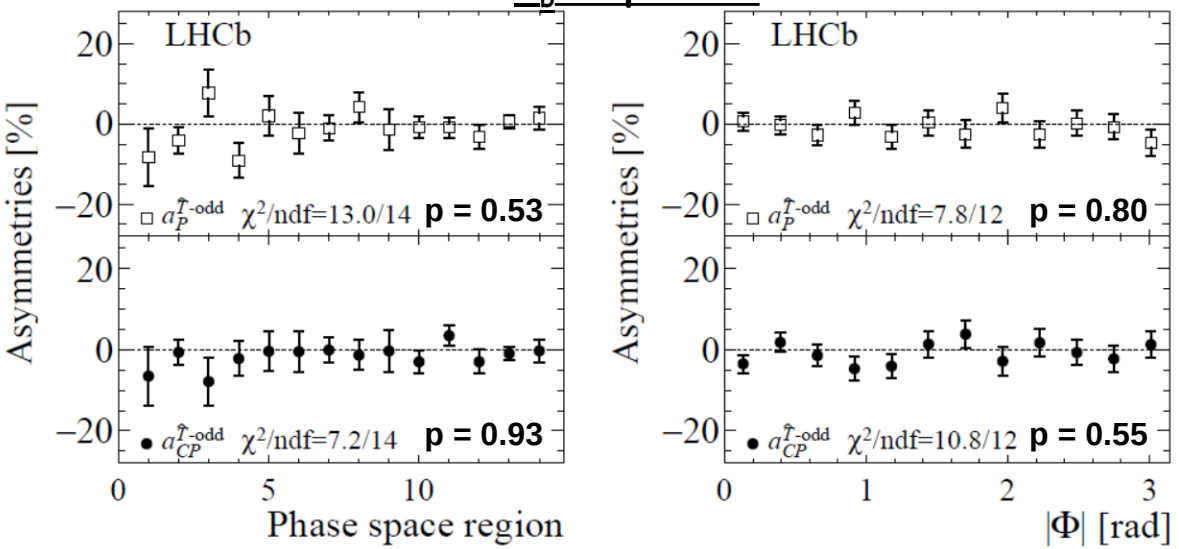


JHEP 1808 (2018) 039
$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV

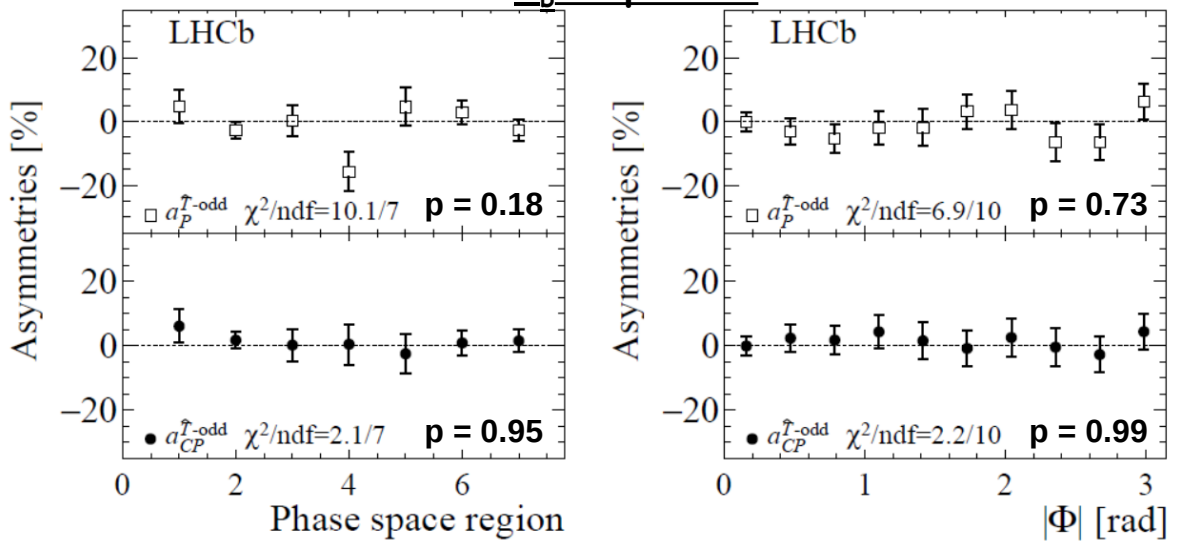
- Study P and CP asymmetries **in bins of the phase space and Φ**

- The measurements across the phase space and Φ are all **consistent with P and CP conservation**

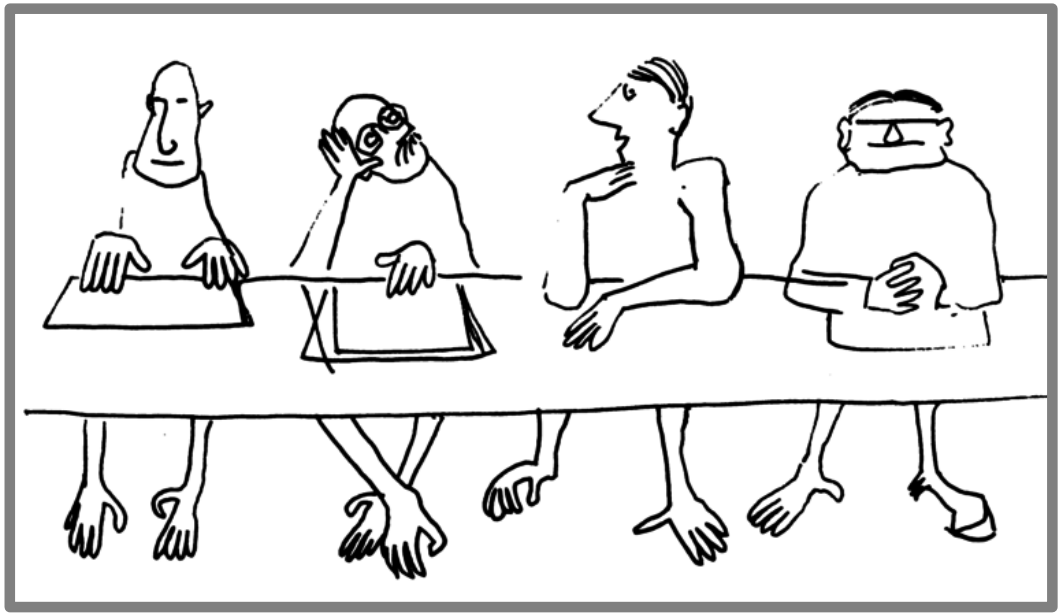
$\Lambda_b \to pK^-\pi^+\pi^-$



$\Lambda_b \to pK^-K^+K^-$



QCD tests via hadronic b-decays



Bruno Touschek

First observation of the $B^0 \to p\bar{p}$ decay

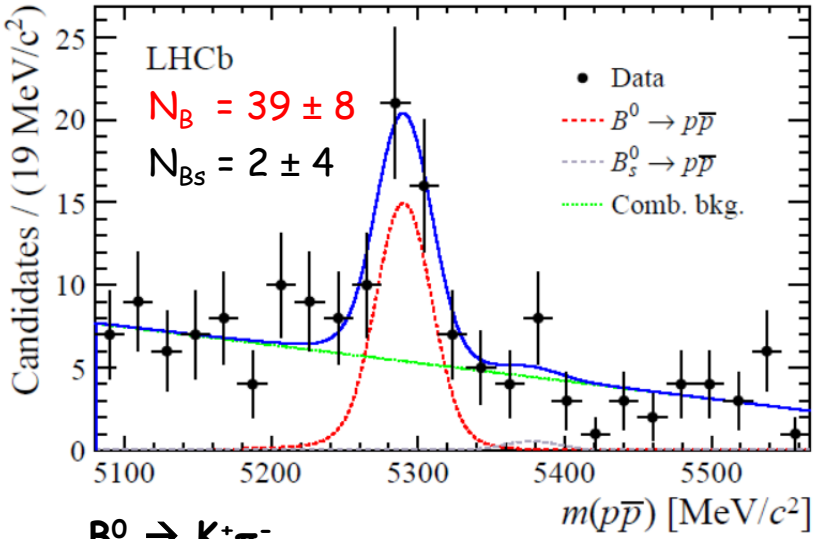
PRL 119 (2017) 232001

$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV

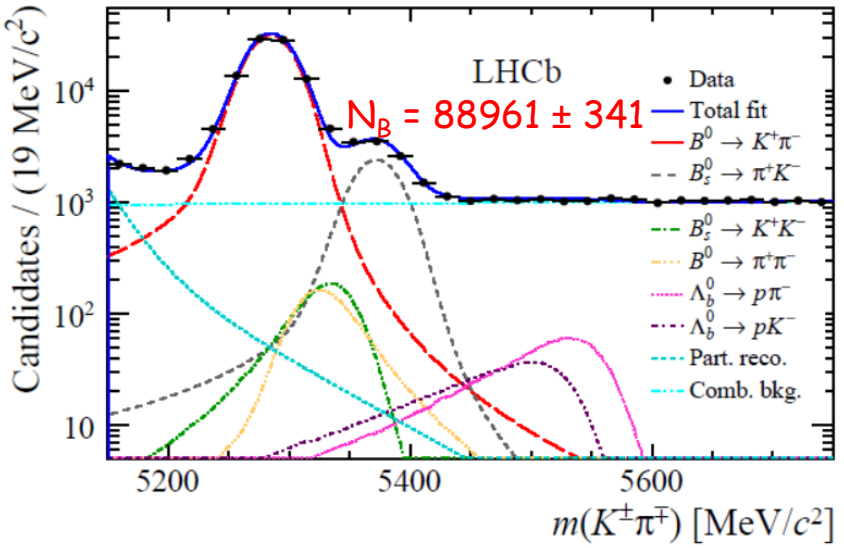
- Understanding of **suppression of 2-body baryonic decays**; of **characteristic threshold enhancement** in the baryon-antibaryon mass spectrum
- Tests of **QCD-based models** describing hadronization
- **Tree and penguin amplitudes of charmless 2-body baryonic decays** from the information on BR($B^0 \to p\bar{p}$) and on BR($B^+ \to p\bar{\Lambda}$)
- Particle ID efficiencies determined from data control samples
- Multilayer perceptron (MLP) classier based on TMVA
- "Blind" analysis to avoid biases
- Normalization channel $B^0 \to K^+\pi^-$

- **BR($B^0 \to p\bar{p}$) = (1.25 ± 0.27 ± 0.18) x 10^{-8}**
- **BR($B_s \to p\bar{p}$) < 1.5 x 10^{-8} @ 90% CL**, using Feldman-Cousins frequentist method

$B^0 \to p\bar{p}$



$B^0 \to K^+\pi^-$

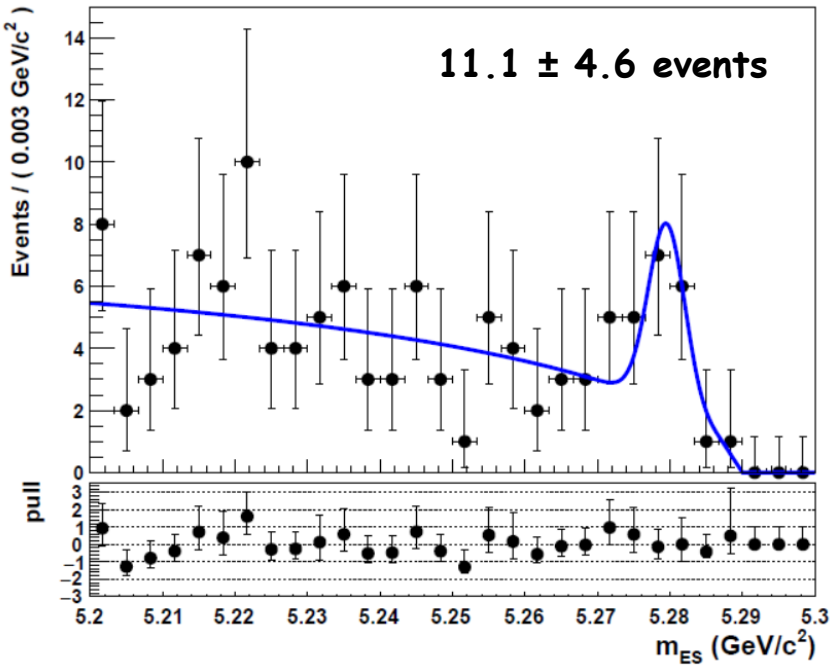


Search for the decay mode $B^0 \to p\bar{p}\bar{p}$

arXiv:1803.10378

4.71×10^8 $B\bar{B}$ pairs

- Limited number of **exclusive baryonic B-decays** are measured
- Tests of QCD-based models
- Study exclusive baryonic B-decays to better understand mechanism of **hadronisation into baryons**; to better understand **threshold dynamical enhancement effect**
- Search for $B^0 \to p\bar{p}\bar{p}$ to better understand **hierarchy trend** for 2-body vs. 3-body vs. 4-body decays



- "Blind", BDT-based analysis
- Potential feed-down from $B^0 \to p\bar{p}hh$ decays found to be negligible

- $BR(B^0 \to p\bar{p}\bar{p}) = (1.1 \pm 0.5 \pm 0.2) \times 10^{-7}$
- Statistical significance 2.9σ
- **$BR(B^0 \to p\bar{p}\bar{p}) < 2.0 \times 10^{-7}$ @ 90% CL**

First observation of the $\bar{B}^0_s \to \chi_{c2} K^+ K^-$ decay

arXiv:1806.10576

$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV

$\int Ldt$ = 1.9 fb^{-1} at $\sqrt{s}$ = 13 TeV

- QCD tests via 2-body b-decays to charmonium states
- **b-decays to χ_c states (J=0,1,2)**: suppression of decays to χ_{c1} with respect to decays to χ_{c0} and χ_{c2} within the factorization approach
- Experimentally, **factorization does not provide a proper description** in some cases

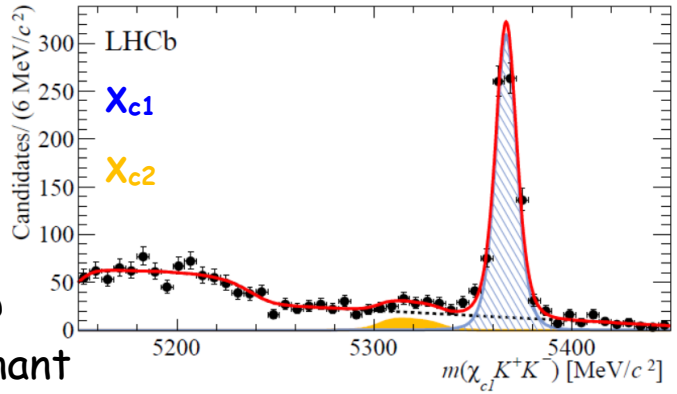
$$\mathcal{B}(B^+ \to \chi_{c2} K^+)/\mathcal{B}(B^+ \to \chi_{c1} K^+) = (2.25^{+0.73}_{-0.69}\,(\text{stat}) \pm 0.17\,(\text{syst})) \times 10^{-2}$$ BELLE, PRL 107 (2011) 091803

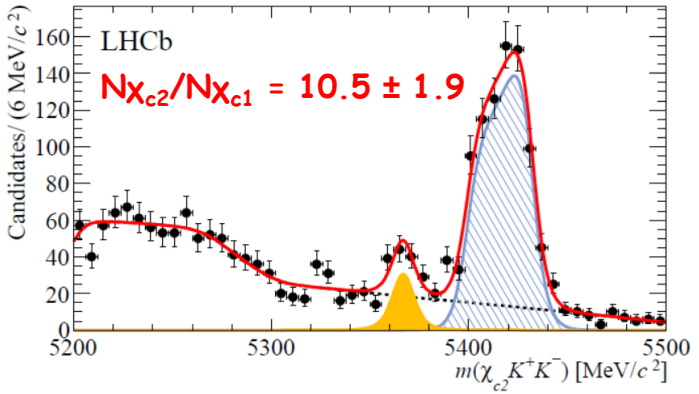
$$\mathcal{B}(B^0 \to \chi_{c2} K^*(892)^0)/\mathcal{B}(B^0 \to \chi_{c1} K^*(892)^0) = (17.1 \pm 5.0\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 1.1\,(\mathcal{B})) \times 10^{-2}$$ LHCb, Nucl. Phys. B874 (2013) 663

$$\mathcal{B}(B^+ \to \chi_{c2} K^+\pi^+\pi^-)/\mathcal{B}(B^+ \to \chi_{c1} K^+\pi^+\pi^-) = 0.36 \pm 0.05$$ BELLE, PRD 93 (2016) 052016

$$\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)/\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-) = 1.02 \pm 0.10\,(\text{stat}) \pm 0.02\,(\text{syst}) \pm 0.05\,(\mathcal{B})$$ LHCb, PRL 119 (2017) 062001

- Constraints on pointing associated collision vertex, J/ψ and χ_c masses
- MVA-based analysis
- M(K^+K^-) in ±15 MeV/c^2 window around known φ mass
- **K^+K^- dominated by φ resonance** (non-resonant S-wave fraction < 21% @ 90%CL)





- First observation, **significance 6.7σ**

$$\frac{\mathcal{B}(\bar{B}^0_s \to \chi_{c2} K^+K^-)}{\mathcal{B}(\bar{B}^0_s \to \chi_{c1} K^+K^-)} = (17.1 \pm 3.1\,(\text{stat}) \pm 0.4\,(\text{syst}) \pm 0.9\,(\mathcal{B}))\%$$

J/ψ and $\eta_c(1S)$ production in inclusive b-decays

Usachov,Kou,SB, LAL-17-051

- From EPJC 75 (2015) 311; Chin. Phys. C40 (2016) 100001:

$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)} = 0.691 \pm 0.090 \pm 0.024 \pm 0.103$$

- Relation between LDME from HQSS:

$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle.$$

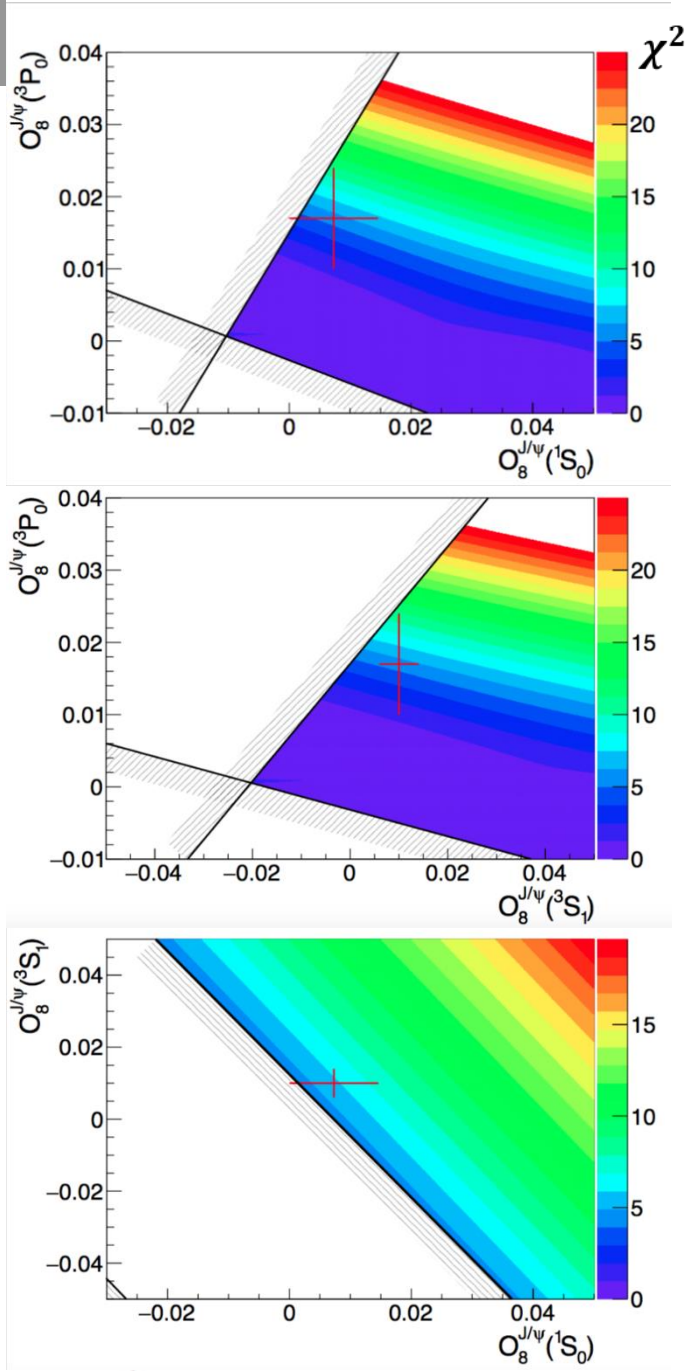
- Branching fractions calculated in
  Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003

- 4 LDME and **2 measurements:**

$$\mathcal{B}(b \to J/\psi^{direct} X)$$

$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)}$$

- **Fit two LDME to measurements**
- Consecutively fix two remaining LDME from
  Han et al., PRL 114 (2015) 092005
- Theory uncertainties conservatively taken into account
- Points with error bars correspond to the matrix elements determined from prompt production in
  Han et al., PRL 114 (2015) 092005



$$\langle O_1^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$$

J/ψ and $\eta_c(1S)$ production in inclusive b-decays

Usachov,Kou,SB, LAL-17-051

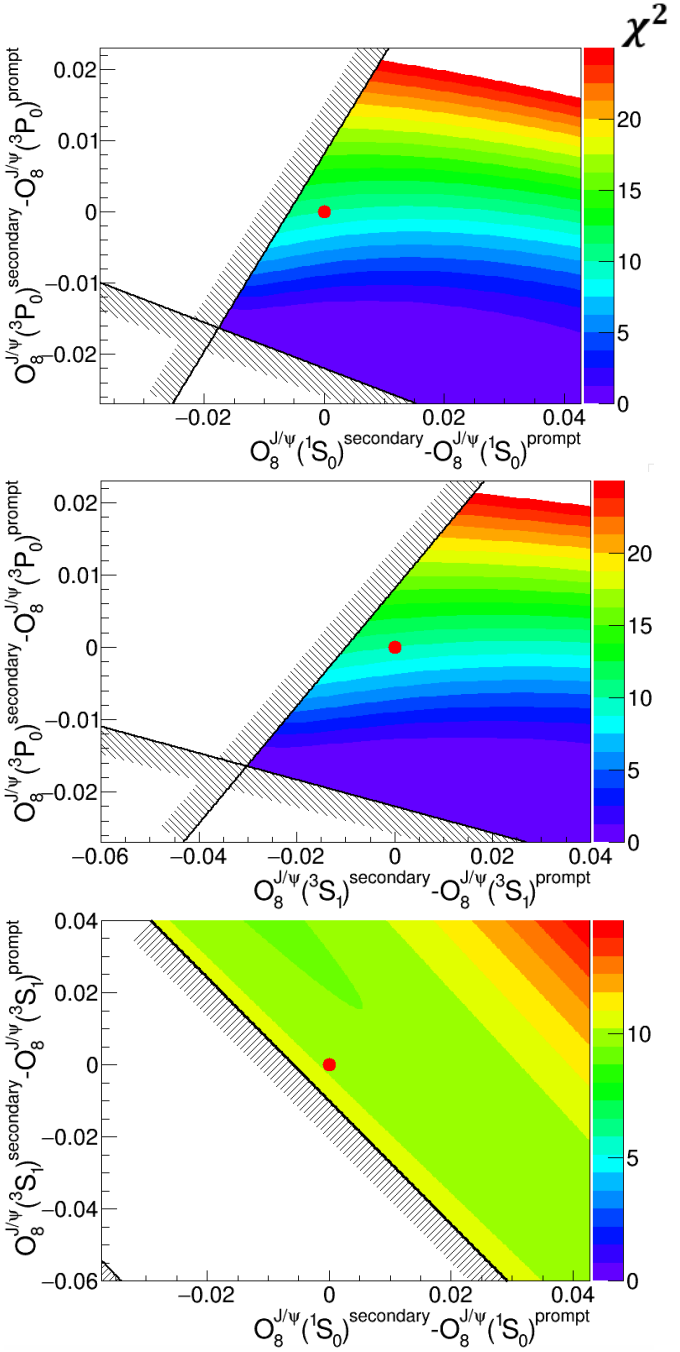
- Fit two LDME to measurements
- Shown are **differences between matrix elements determined from charmonium production in b-decays and those from prompt charmonium production**

  Han et al., PRL 114 (2015) 092005
- Consecutively fix two remaining LDME from

  Han et al., PRL 114 (2015) 092005
- Theory uncertainties conservatively taken into account
- Red points correspond to identical matrix elements in b-decays and in prompt production

$$\langle O_1^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$$

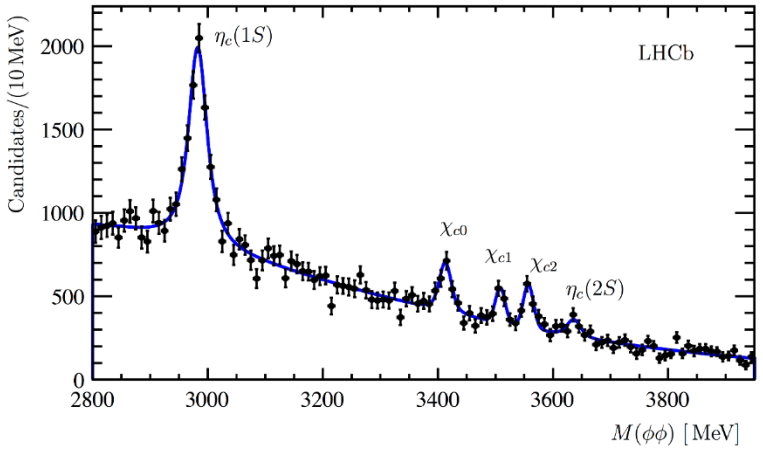
- Important to improve precision of the $\eta_c(1S)$ hadroproduction measurement

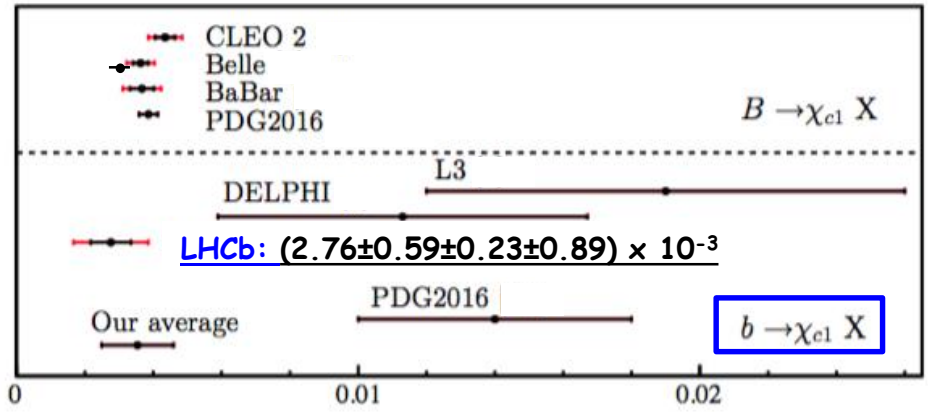


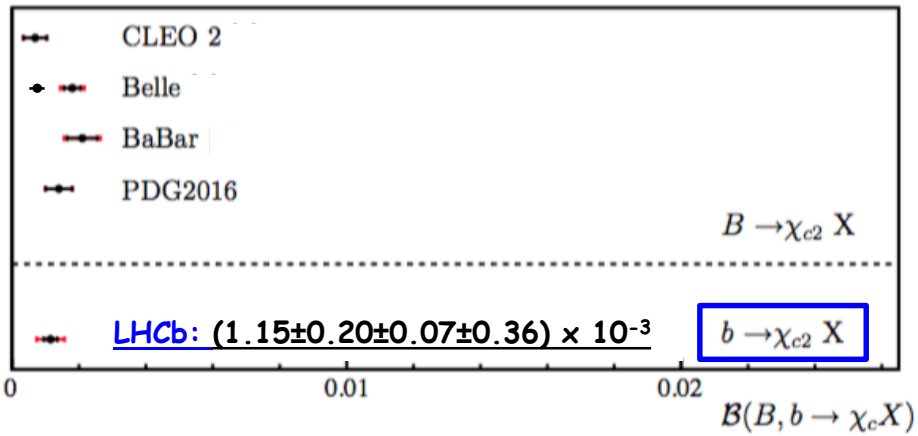
Inclusive b-decays to χ_c and $\eta_c(2S)$

EPJC 77 (2017) 609
$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV

- Charmonium reconstructed via **decays to φφ**; true φφ combinations using 2D fit technique
- First measurement of χ_{c0} production in b-hadron decays: **BR(b→χ_{c0}X)=(3.02±0.47±0.23±0.94)x10^{-3}**
- Most precise measurements of χ_{c1} and χ_{c2} production in b-decays, consistent with B-factories







- First measurement of $\eta_c(2S)$ production in b-decays; first evidence for $\eta_c(2S)$→φφ

$$\frac{\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi)}{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to \phi\phi)} = 0.040 \pm 0.011 \pm 0.004$$

- Important to **measure hadroproduction of $\eta_c(2S)$** Lansberg, Shao, Zhang arXiv:1711.00265

Inclusive b-decays to χ_c

Usachov,Kou,SB, LAL-17-051

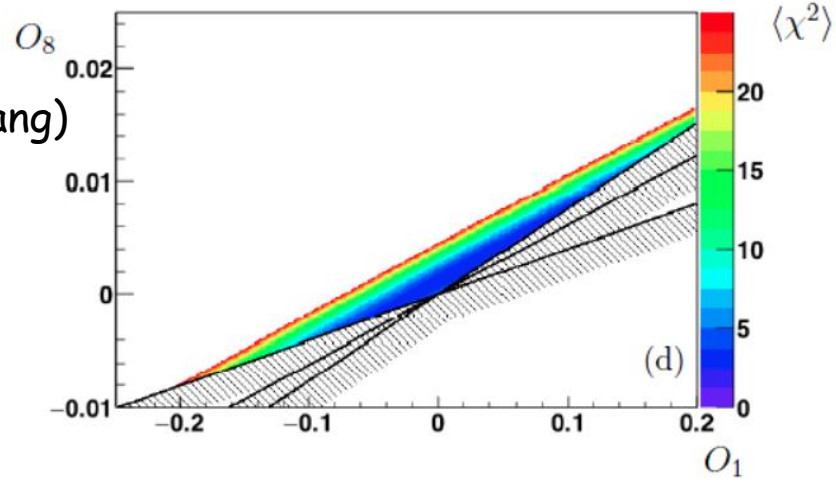
- From **EPJC 77 (2017) 609** and **Chin. Phys. C40 (2016) 100001**:

$$\mathcal{B}(b \to \chi_{c0}{}^{direct} X) = (2.74 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1}{}^{direct} X) = (2.49 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2}{}^{direct} X) = (0.89 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3}$$

- Relation between LDME from HQSS:

$$O_1 \equiv \langle O_1^{\chi_{c0}}(^3P_0)\rangle / m_c^2,$$
$$O_8 \equiv \langle O_8^{\chi_{c0}}(^3S_1)\rangle,$$
$$\langle O_1^{\chi_{cJ}}(^3P_J)\rangle / m_c^2 = (2J+1) O_1,$$
$$\langle O_8^{\chi_{cJ}}(^3S_1)\rangle = (2J+1) O_8.$$

- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**
- **Fit two LDME to three measurements**
- Important to revisit theory calculations (H.-F. Zhang)
- This technique constrains theory using **simultaneously** results on **charmonia hadroproduction and** on **charmonia from b-inclusive decays** under **assumptions of factorization, universality and HQSS**, with **different charmonium states**.



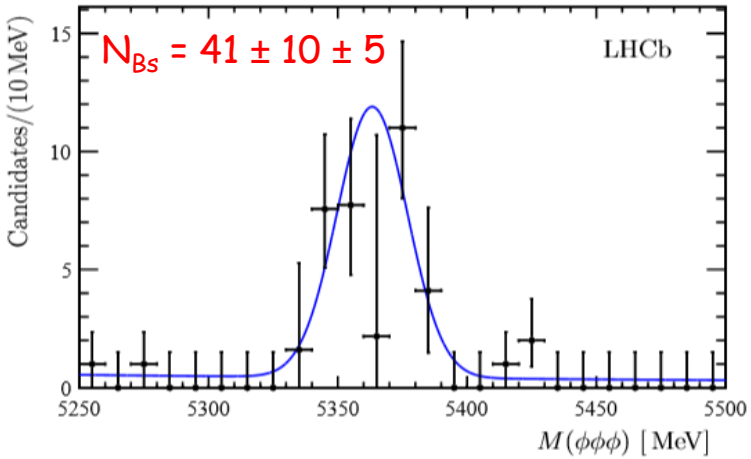
- Alternatively, once hadroproduction and production in b-decays measured for charmonium states with linked LDMEs, the above **assumptions can be tested quantitatively**.

First evidence of $B_s \to \phi\phi\phi$ decays

Eur.Phys.J. C77 (2017) 609

$\int Ldt$ = 3.0 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV

- B_s candidates reconstructed via **decays to φφφ**; true φφφ combinations using 3D fit technique
- Normalization channel $B_s \to \phi\phi$
- First evidence, **significance 4.9σ**



$$\frac{\mathcal{B}(B_s^0 \to \phi\phi\phi)}{\mathcal{B}(B_s^0 \to \phi\phi)} = 0.117 \pm 0.030 \pm 0.015$$

$$\mathcal{B}(B_s^0 \to \phi\phi\phi) = (2.15 \pm 0.54 \pm 0.28 \pm 0.21_{\mathcal{B}}) \times 10^{-6}$$

- No resonant structure is observed in M(φφ)
- In $B_s \to \phi\phi\phi$ decays, φ transverse polarization is preferred

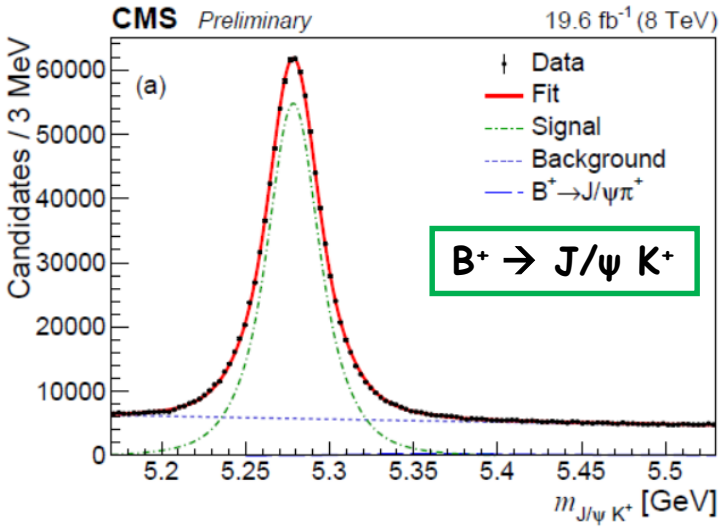
Observation of the $B^*_{s2}(5840)^0 \to B^0K^0_S$ decay

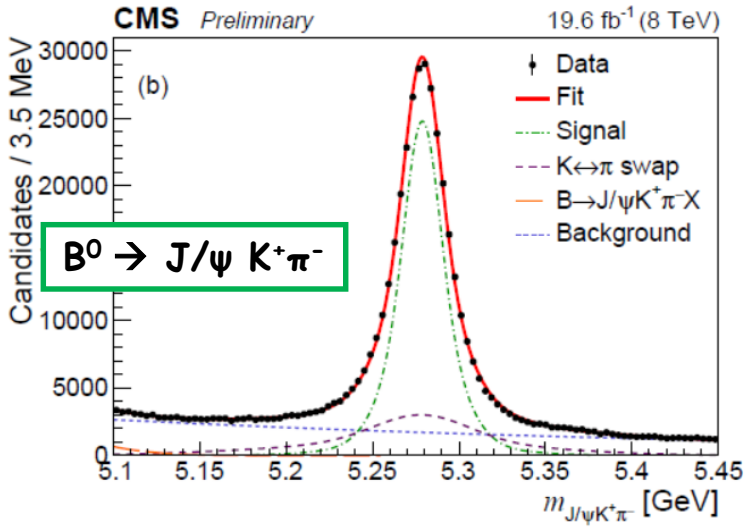
CMS-PAS-BPH-16-003

❑ Search for missing **D-wave decays** of $B_{s1}(5830)^0$ ($j=3/2$, $J^P=1^+$) and $B_{s2}^*(5840)^0$ ($j=3/2$, $J^P=2^+$) predicted by HQET

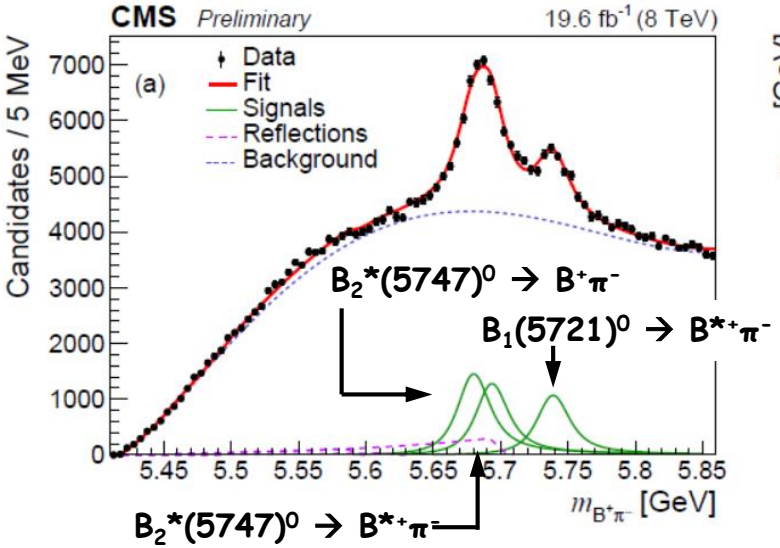
$\int Ldt = 19.6\ fb^{-1}$ at $\sqrt{s}=8$ TeV

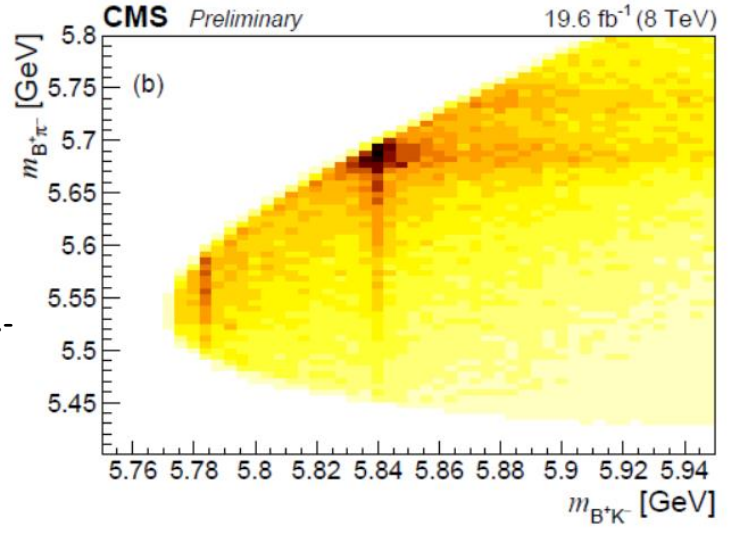
❑ Large samples of reconstructed ground state B-mesons





❑ Clear signals of reconstructed excited B^0 states

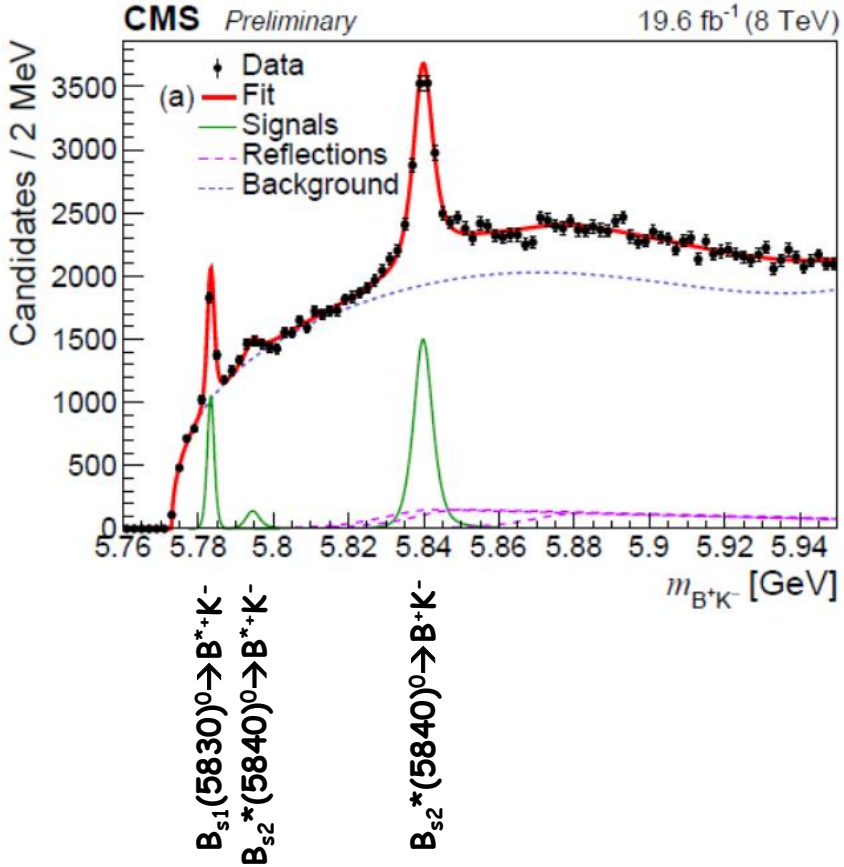


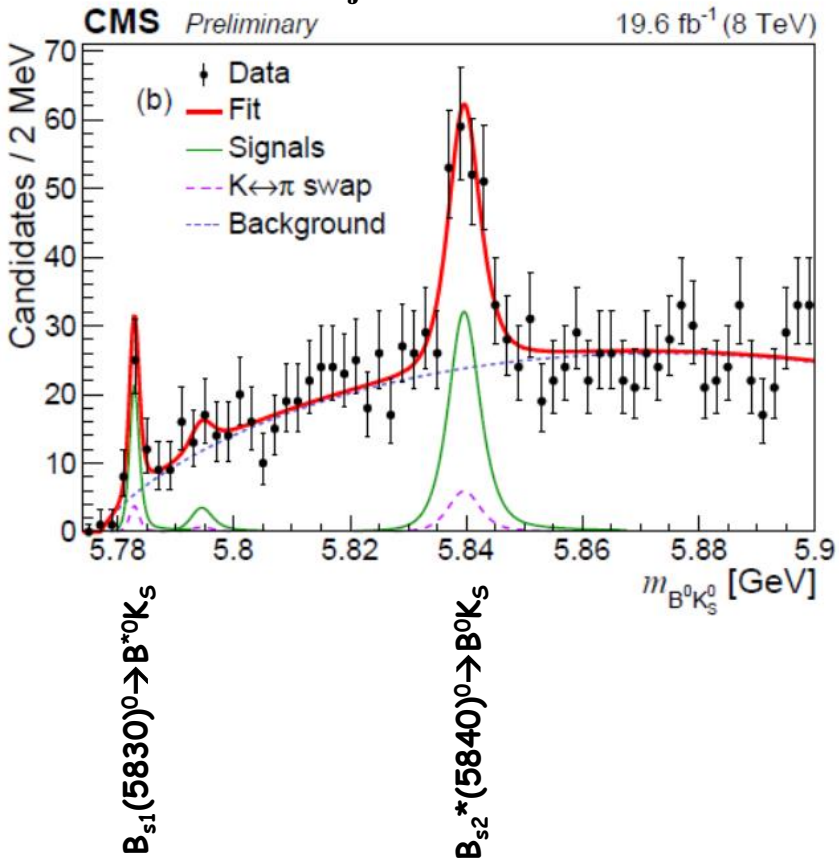


Observation of the $B^*_{s2}(5840)^0 \to B^0K^0_S$ decay

CMS-PAS-BPH-16-003

$\int Ldt = 19.6\ fb^{-1}$ at $\sqrt{s}=8$ TeV





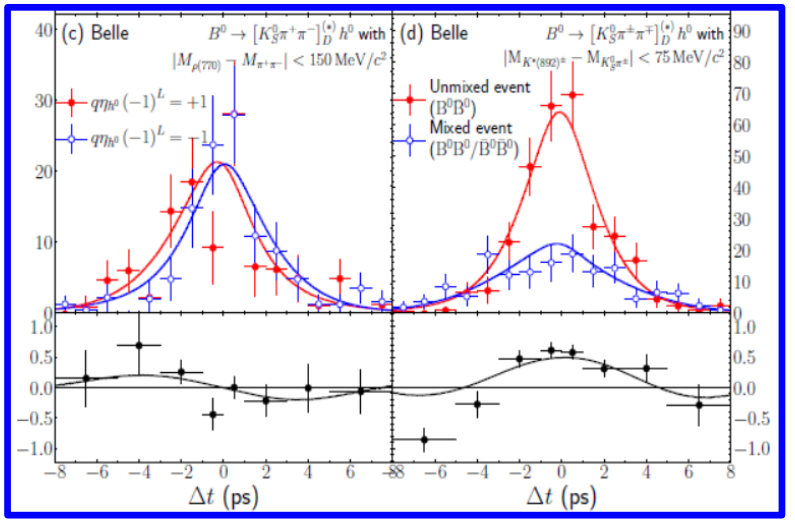
- First observation of $B^*_{s2}(5840)^0 \to B^0K_S$, statistical significance 6.3σ
- First evidence of $B_{s1}(5830)^0 \to B^{*0}K_S$, statistical significance 3.9σ

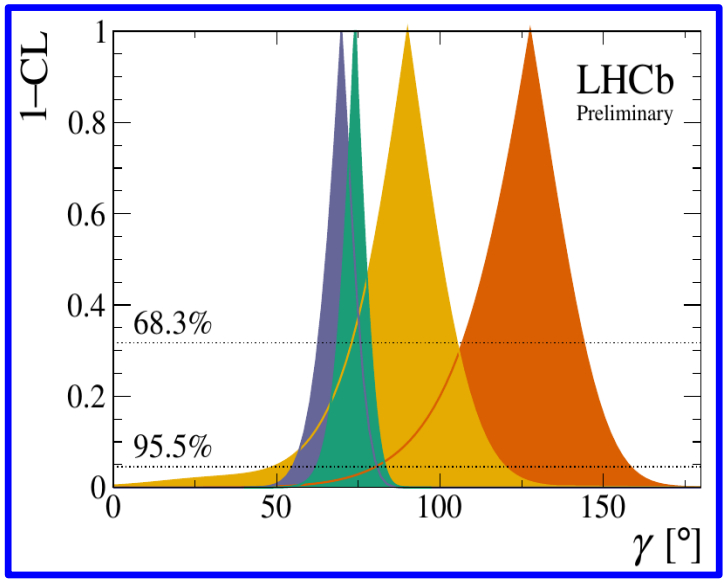
$$\frac{\mathcal{B}(B^*_{s2} \to B^0K^0_S)}{\mathcal{B}(B^*_{s2} \to B^+K^-)} = 0.432 \pm 0.077\,(\text{stat}) \pm 0.075\,(\text{syst}) \pm 0.021\,(\text{PDG})$$

$$\frac{\mathcal{B}(B_{s1} \to B^{*0}K^0_S)}{\mathcal{B}(B_{s1} \to B^{*+}K^-)} = 0.492 \pm 0.122\,(\text{stat}) \pm 0.068\,(\text{syst}) \pm 0.024\,(\text{PDG})$$

Summary

- b-hadron decays play a key role in **precision determination of the CKM parameters**
- They provide a series of **consistency checks of Standard Model**
- Being described by a single parameter in the Standard Model, **CP-parity violation** in b-sector (B and Bs) and also charm and strange sectors provides a powerful test of the model



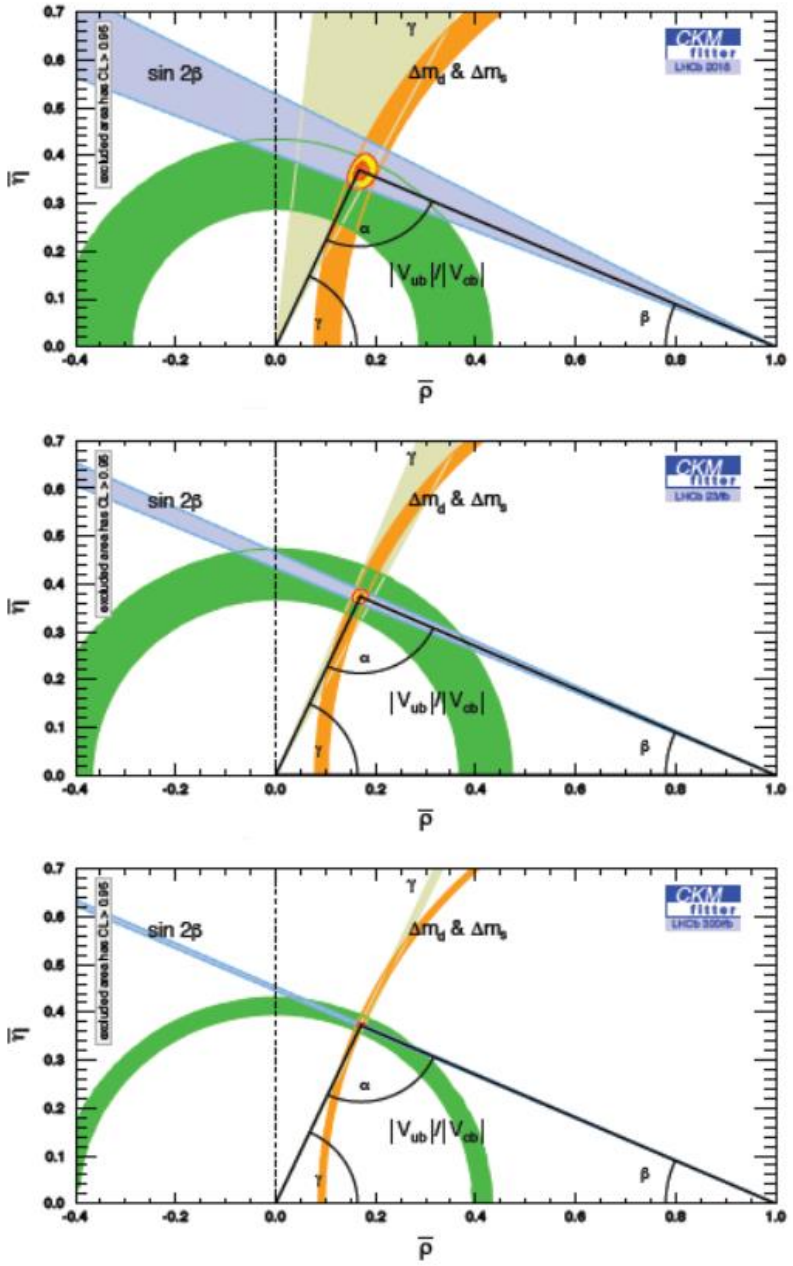


- **Hadronic b-decays** allows applying a wide range of techniques to constrain Standard Model parameters
- Precision achieved by the experiments allows a systematic **verification of QCD-based models**

- Numerous new results, impressive **progress since PIC 2017**
- Further improving precision with the analysis of **LHC Run II** data, new data from **HL-LHC** and **Belle II**

Backup

- **Prospective CKM profile (LHCb only !) for 23/fb and 300/fb**
- Educated prospective values for hadronic parameters used to describe the oscillation frequencies by V. Vagnoni (from LQCD community)



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