Heavy Quarks & Leptons 2014

Measurements of CP violating phases at LHCb

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on behalf of the LHCb collaboration

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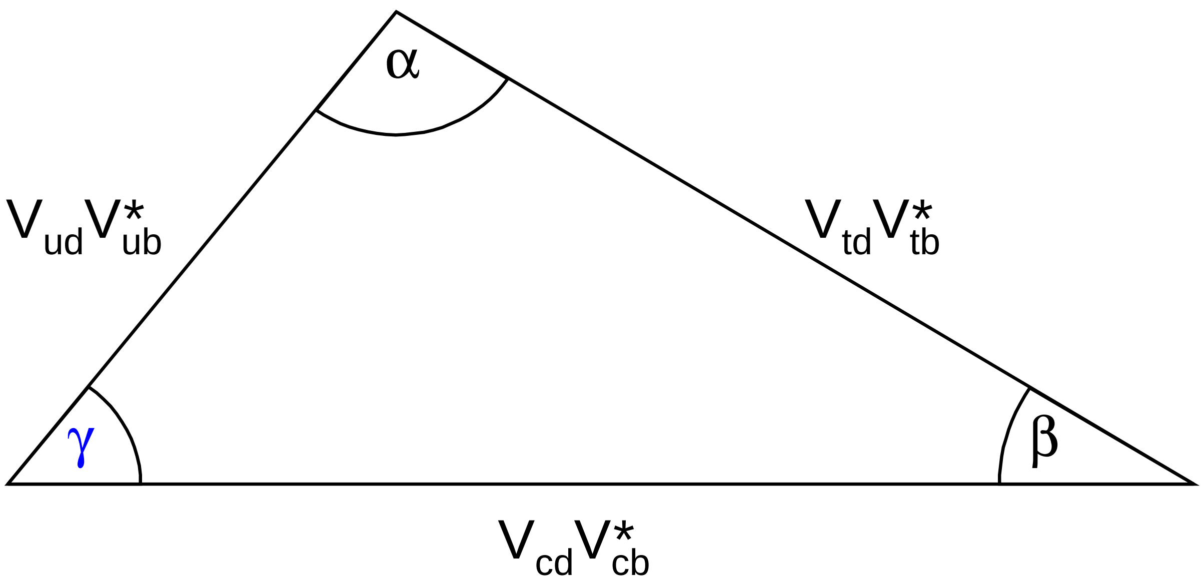
Outline

1. $B^{\pm} \to D[K^0_S \pi^+ \pi^-] K^{\pm}$
2. $B^{\pm} \to D[K^0_S K^{\pm} \pi^{\pm}] K^{\pm}$
3. $B^0_s \to J/\psi \pi^+ \pi^-$
4. $B^0_s \to \phi\phi$
5. $B \to hh$

$$\phi_3 = \gamma \equiv -\arg\left(\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)$$

$$\phi_s \equiv -\arg(M_{12}/\Gamma_{12})$$



γ from B Decays

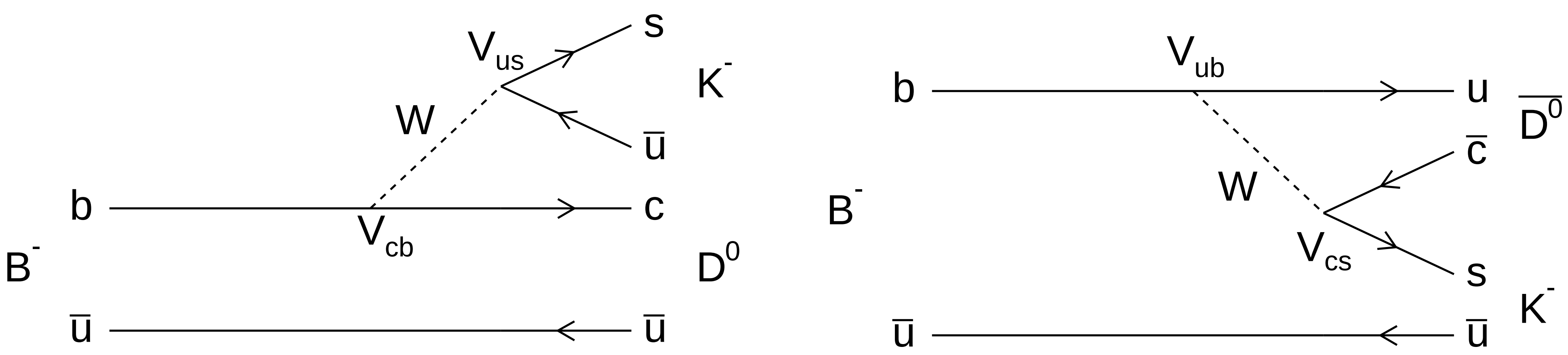
Theoretically cleanest Standard Model measurement of γ from $B \to DK$ decays

$|\delta\gamma|/\gamma \lesssim \mathcal{O}(10^{-7})$ from electroweak corrections: J. Brod and J. Zupan, JHEP **1401** (2014) 051

When D^0 and $\bar{D}^0$ decay to the same final state, f

Interference between the dominant $b \to c\bar{u}s$ with the corresponding DCS $b \to u\bar{c}s$

$$A_{B^-} \propto A_f \quad + \quad r_B e^{i(\delta_B - \gamma)} \bar{A}_f$$



Amplitude ratio: $r_B = |A(B \to \bar{D}K)| \div |A(B \to DK)|$

Strong phase difference between $A(B \to \bar{D}K)$ and $A(B \to DK)$: δ_B

GGSZ Method

Measure r_B, δ_B and γ, through interference in the Dalitz plot of D decays to CP eigenstates

A. Bondar, Proceedings of BINP Special Analysis Meeting on Dalitz Analysis, 24-26 Sep. 2002, unpublished

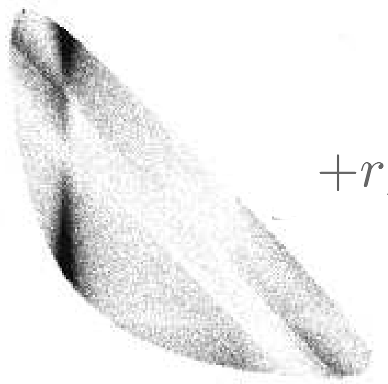
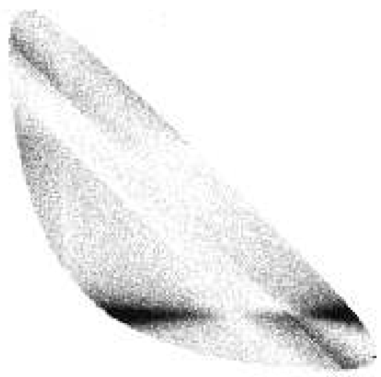
A. Giri, Y. Grossman, A. Soffer, J. Zupan, Phys. Rev. D **68** (2003) 054018

eg. $D^0 \rightarrow K^0_S\pi^+\pi^-$ and $\bar{D}^0 \rightarrow K^0_S\pi^+\pi^-$

Dalitz plots defined as scatterplot of $m^2_+(K^0_S\pi^+)$ vs $m^2_-(K^0_S\pi^-)$

Contains complete quantum information of the decay including phase relationships

$$|A(B^- \rightarrow DK^-)|^2 = | \quad A_{D^0} \quad + r_B e^{i(\delta_B - \gamma)} \quad A_{\bar{D}^0} \quad |^2$$

$= \Big|$  $+ r_B e^{i(\delta_B - \gamma)}$  $\Big|^2$

Yield Extraction

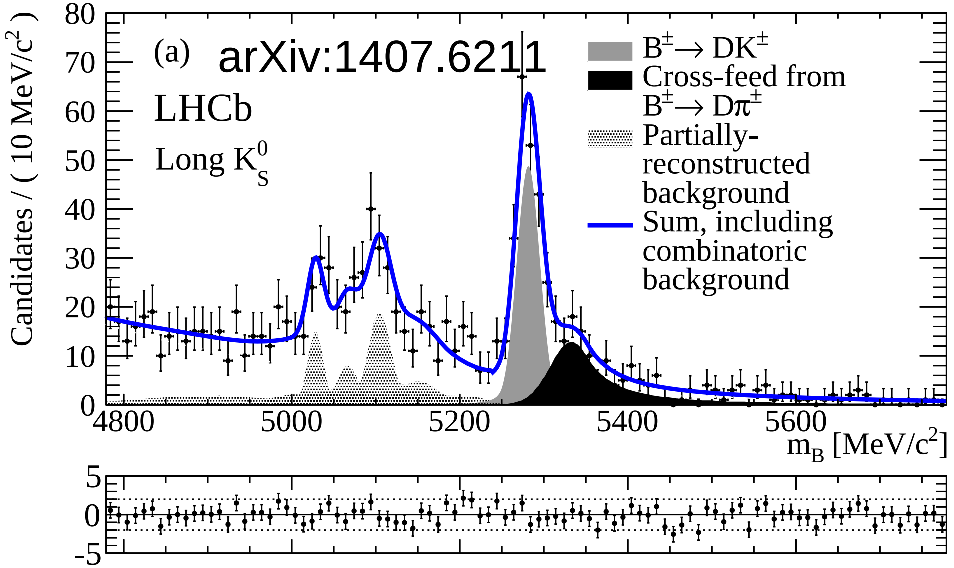
First model-dependent measurement of γ from LHCb using the GGSZ method

Integrated data sample of 1 fb^{-1} recorded at centre-of-mass energy of 7 TeV

Determine signal yield to obtain signal and background fractions for subsequent Dalitz analysis

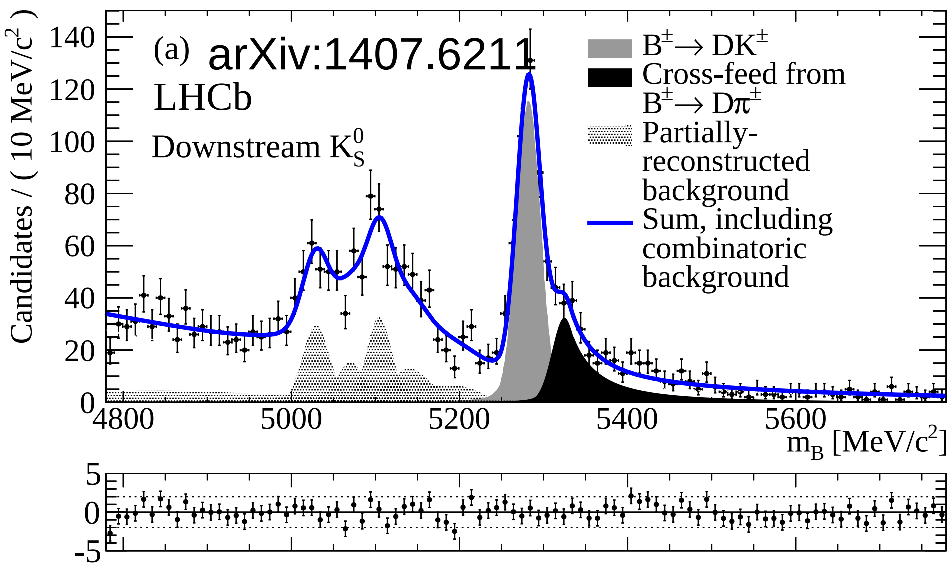
Excellent RICH PID performance suppresses $B^{\pm} \rightarrow D[K^0_S\pi^+\pi^-]\pi^{\pm}$ by $\mathcal{O}(10^2)$

"Long" K^0_S



$B^{\pm} \rightarrow DK^{\pm}$ yield: 217 ± 17 events

"Downstream" K^0_S



$B^{\pm} \rightarrow DK^{\pm}$ yield: 420 ± 27 events

Dalitz Amplitude

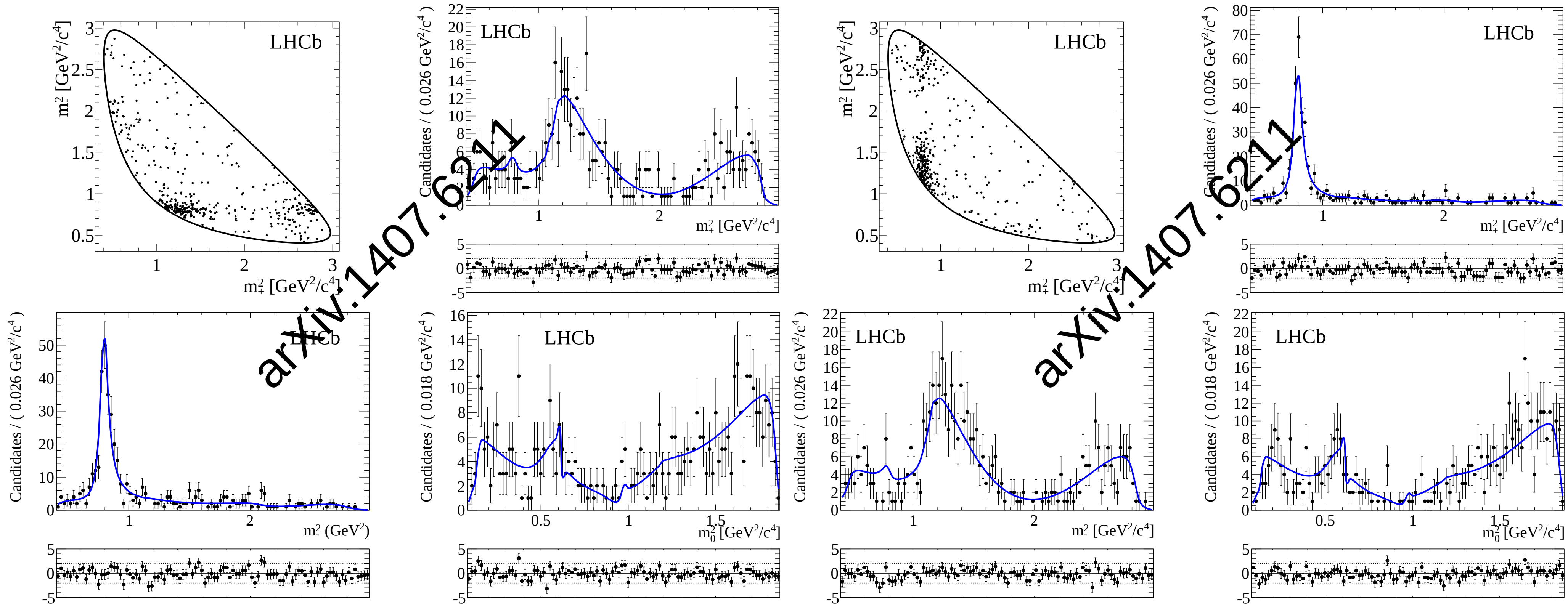
Amplitude model fixed to that determined by the BaBar Collaboration

P. del Amo Sanchez *et al*. (BaBar Collab.), Phys. Rev. Lett. 105 (2010) 081803

Restrict fit region to $\sim 3\sigma$ around B^+ mass

γ manifests as a difference in the structure between these 2 Dalitz plots

$B^- \to DK^-$ $\qquad\qquad$ $B^+ \to DK^+$



Results

Technical detail: Instead of fitting for r_B, δ_B and γ directly

Fit for transformed parameters

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

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

$$x_+ = -0.084 \pm 0.045 \pm 0.009 \pm 0.003$$

$$y_+ = -0.032 \pm 0.048 \pm 0.009 \pm 0.007$$

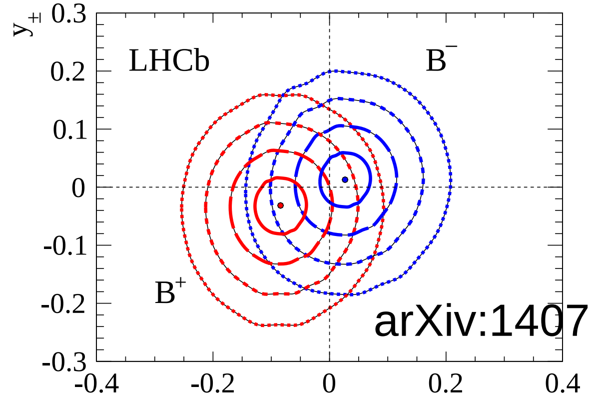
$$x_- = +0.027 \pm 0.044^{+0.010}_{-0.008} \pm 0.001$$

$$y_- = +0.013 \pm 0.048^{+0.008}_{-0.006} \pm 0.003$$

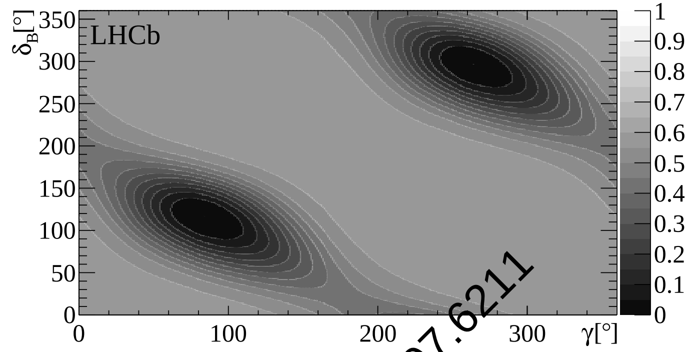
Uncertainties

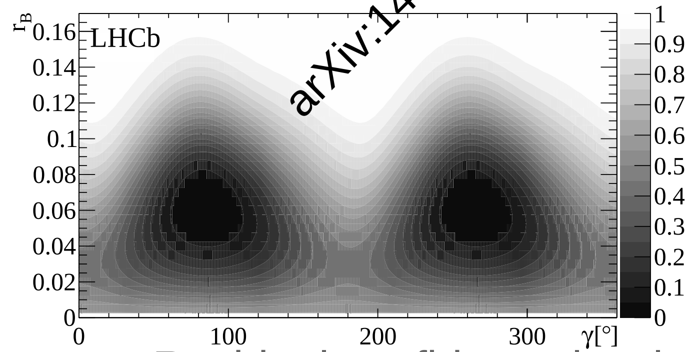
1: statistical, 2: systematic, 3: model

Convert to γ, negligible D^0 mixing effect



Likelihood contours





Residual confidence level

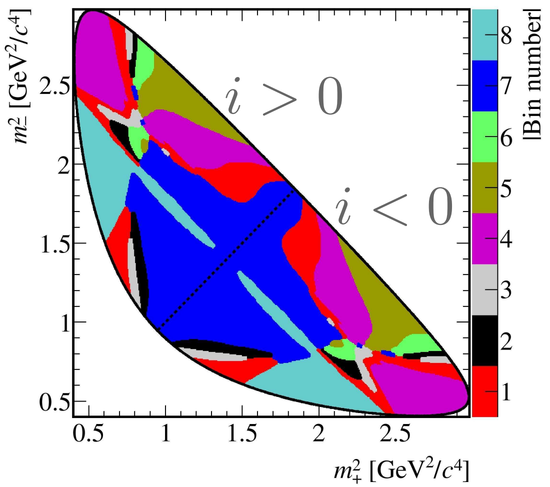
Model-Independent GGSZ

Amplitude model uncertainty is the dominant systematic error on γ

Remove using a binned Dalitz method: Phys. Rev. D **68** 054018 (2003)

Binning scheme inspired by model, uniform division of strong phase difference $\Delta\delta_D$, is optimal

Choice of binning affects γ precision, but not γ itself



Measure B^+, B^- yield in each bin i, compare in a χ^2 fit with expected number of $B^\pm \to DK^\pm$ events in bin i: $N_i^\pm$

$$B^+ \colon N_i^+ \propto F_{-i} + (x_+^2 + y_+^2)F_i + 2\sqrt{F_i F_{-i}}(x_+ c_i + y_+ s_i)$$

$x_+ = r_B \cos(\delta_B + \gamma)$, $y_+ = r_B \sin(\delta_B + \gamma)$

F_i: Fraction of pure D^0 events in a given bin i

From flavour-tagged sample

Must have same Dalitz efficiency profile as signal

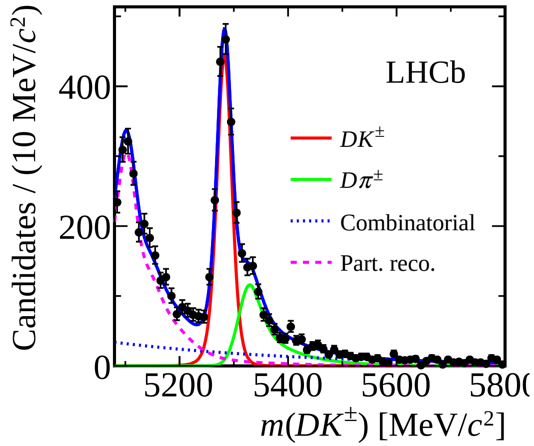
c_i, s_i: Amplitude weighted average of strong phase difference in bin i

$c_i = \langle \cos \Delta\delta_D \rangle_i$, $s_i = \langle \sin \Delta\delta_D \rangle_i$

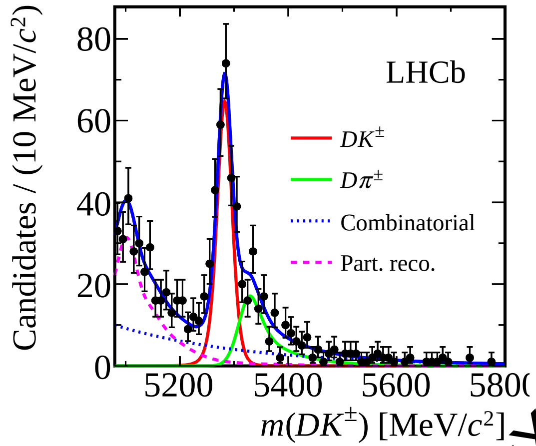
Measured at CLEO-c with $\psi(3770) \to D^0 \bar{D}^0$: Phys. Rev. D **82**, 112006 (2010)

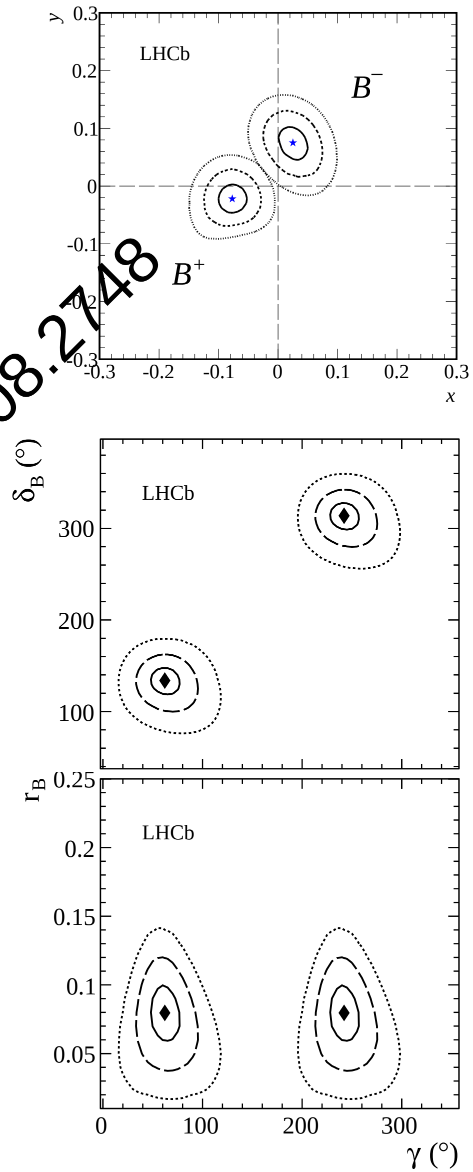
Model-Independent Results

"Downstream": $K^0_S\pi^+\pi^-$



"Downstream": $K^0_S K^+ K^-$





World's most precise measurements of $x_\pm, y_\pm$

$x_+ = [-7.7 \pm 2.4$ (stat) ± 1.0 (syst) ± 0.4 (CLEO-c)$] \times 10^{-2}$

$x_- = [+2.5 \pm 2.5$ (stat) ± 1.0 (syst) ± 0.5 (CLEO-c)$] \times 10^{-2}$

$y_+ = [-2.2 \pm 2.5$ (stat) ± 0.4 (syst) ± 1.0 (CLEO-c)$] \times 10^{-2}$

$y_- = [+7.5 \pm 2.9$ (stat) ± 0.5 (syst) ± 1.4 (CLEO-c)$] \times 10^{-2}$

Convert to γ, negligible D^0 mixing effect

Results

Model-dependent measurements

LHCb: 1 fb^{-1}

New Results!

$\gamma = (84^{+49}_{-42})^{\circ}$

Belle: 657M $B\bar{B}$ pairs

PRD **81** (2010) 112002

$\gamma = (78^{+14}_{-15})^{\circ}$

Includes $B \to D^{(*)}K$

BaBar: 468M $B\bar{B}$ pairs

PRL 105 (2010) 121801

$\gamma = (68 \pm 15)^{\circ}$

Includes $B \to D^{(*)}K^{(*)}$

Includes $D \to K_S^0 K^+ K^-$

Model-independent measurements

LHCb: 3 fb^{-1}

New Results!

$\gamma = (62^{+15}_{-14})^{\circ}$

Includes $D \to K_S^0 K^+ K^-$

Belle: 772M $B\bar{B}$ pairs

PRD **85** (2012) 112014

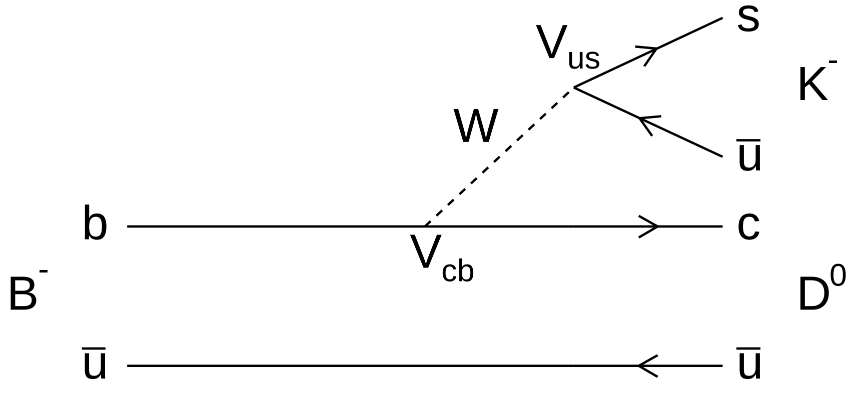
$\gamma = (77 \pm 16)^{\circ}$

γ solution consistent with Standard Model chosen

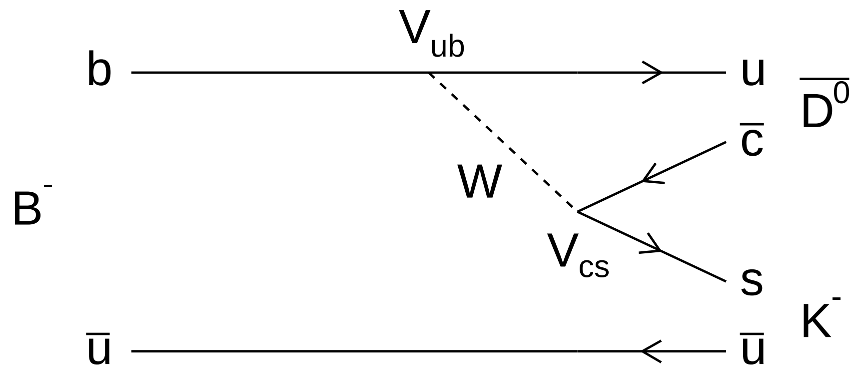
LHCb uncertainties comparable now comparable with B factories

ADS-Like Adaptation

Colour-favoured

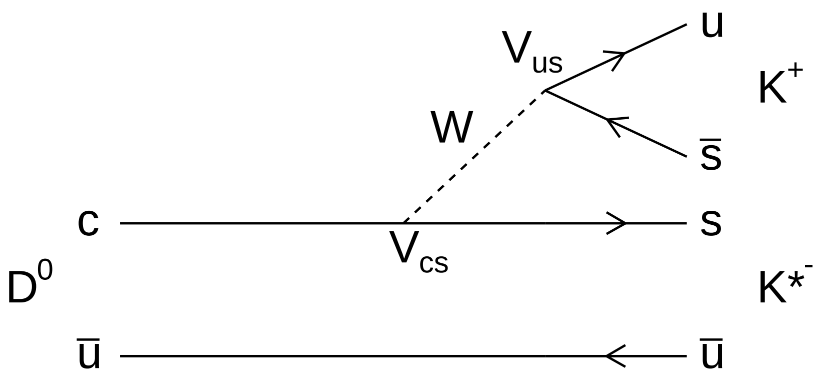


Colour-suppressed

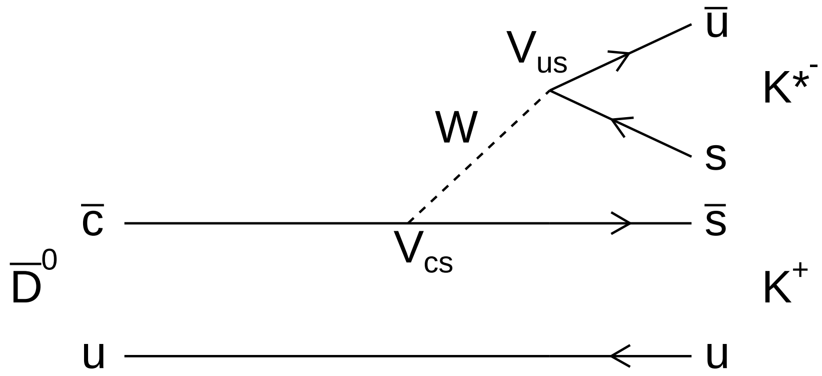


Difference in magnitudes mean that resulting asymmetries tend to be small, however

$K^*(892)^-$ from spectator (suppressed)



$K^*(892)^-$ from W (favoured)



Amplitudes of similar magnitude can enhance the effect of CP asymmetries

D. Atwood, I. Dunietz, A. Soni, Phys. Rev. Lett. **78** (1997) 3257

ADS Method

Singly Cabibbo Suppressed (SCS) D decays across the Dalitz plot

Y. Grossman, Z. Ligeti and A. Soffer, Phys. Rev D **67** (2003) 071301

Consider $B^- \to DK^-$ followed by $D \to K^0_S K^+ \pi^-$

For a given B charge, 2 possibilities for kaon charge configuration

Charged kaons with Opposite Sign (OS)

$$\Gamma^-_{\mathrm{OS}} \propto r_B^2 + {r_D}^2 + 2 r_B r_D \kappa_f \cos(\delta_B - \gamma + \delta_f)$$

Charged kaons with Same Sign (SS)

$$\Gamma^-_{\mathrm{SS}} \propto 1 + r_B^2 {r_D}^2 + 2 r_B r_D \kappa_f \cos(\delta_B - \gamma - \delta_f)$$

Amplitude ratio: $r_D = |A(D^0 \to K^0_S K^+ \pi^-)| \div |A(\bar{D}^0 \to K^0_S K^+ \pi^-)|$

3-body decay, so resonant structure varies across the Dalitz plot, $m^2_{K^0_S K}$ vs $m^2_{K^0_S \pi}$

Decay rate in region of a resonance depends on integral of the interference term in that region

Coherence factor κ_f, and average strong phase difference δ_f

ADS Method

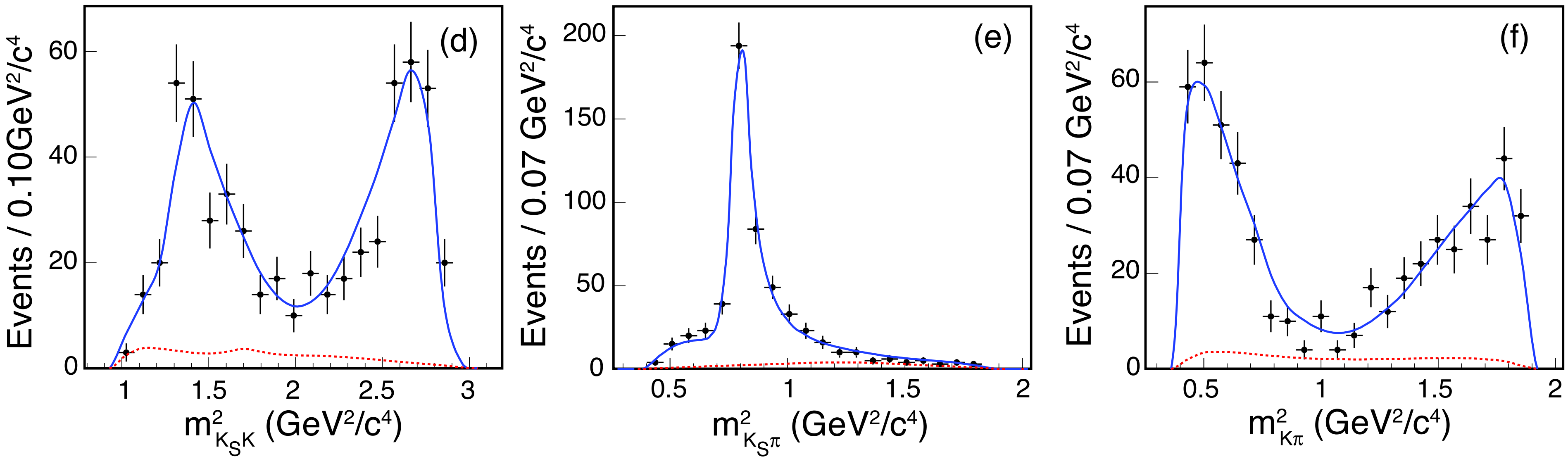
$$\kappa_f e^{-i\delta_f} \propto \int A^*_{K^0_S K^- \pi^+}(m^2_{K^0_S K}, m^2_{K^0_S \pi}) A_{K^0_S K^+ \pi^-}(m^2_{K^0_S K}, m^2_{K^0_S \pi}) dm^2_{K^0_S K} dm^2_{K^0_S \pi}$$

$K^0_S K^- \pi^+$ and $K^0_S K^+ \pi^-$ are flavour non-specific final states

Correlated $D^0 \bar{D}^0$ pairs can tag the D flavour

Amplitudes measured by the CLEO Collaboration

J. Insler *et al*. (CLEO Collab.) Phys. Rev. D. **85** (2012) 092016



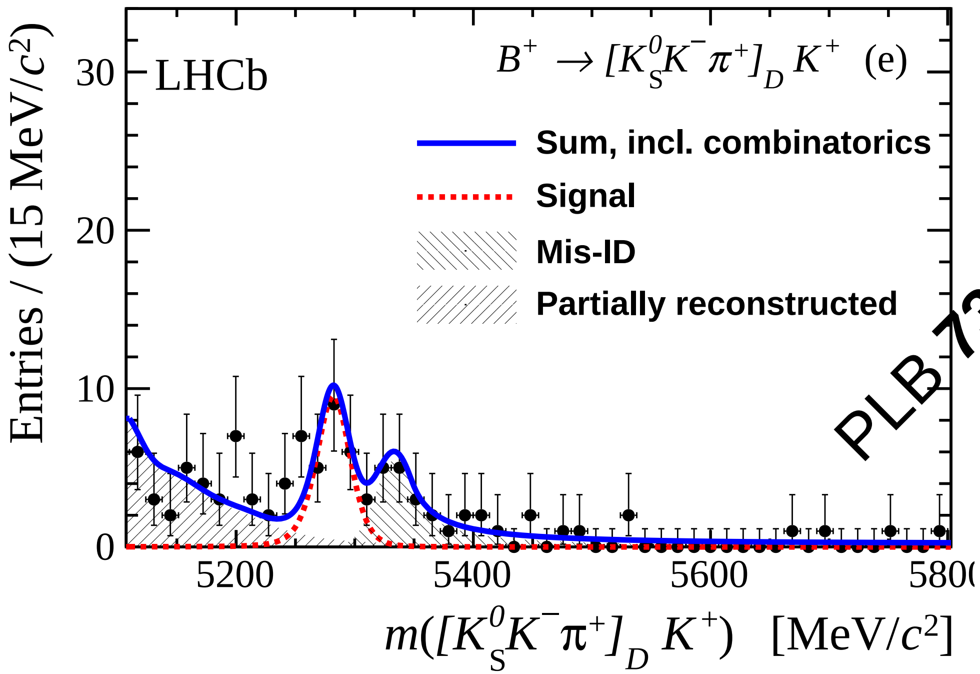
Results

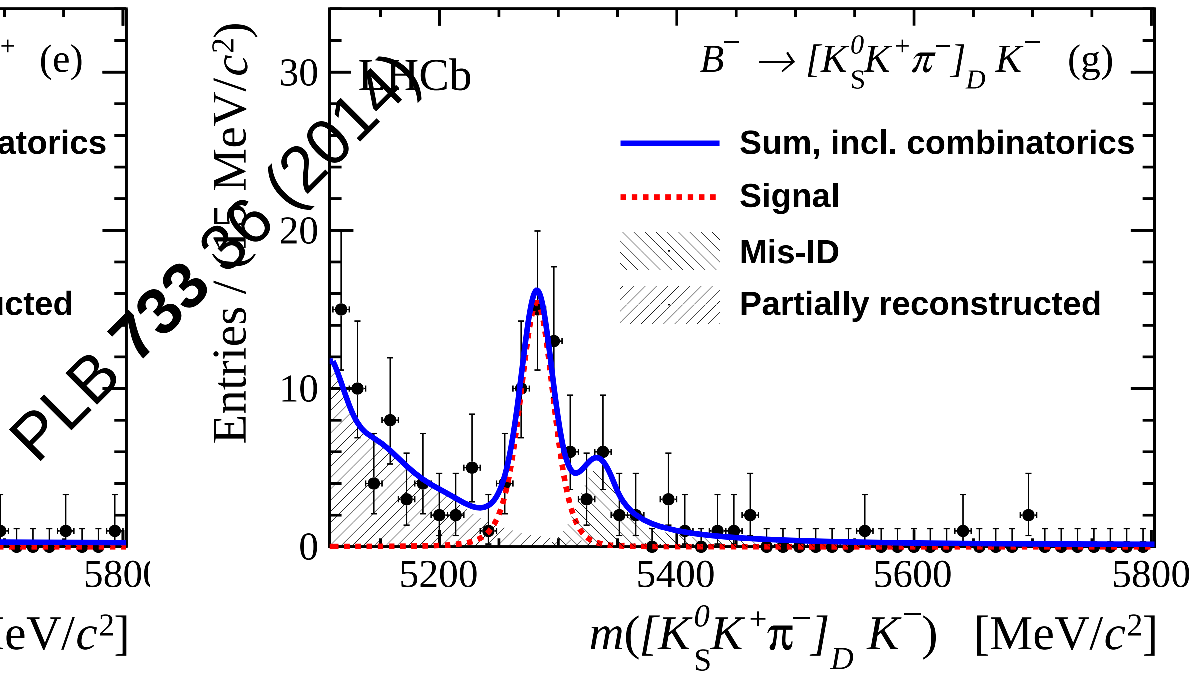
World's first measurement of γ using SCS $D \to K^0_S K^+ \pi^-$ decays

Full LHCb data sample of 3 fb^{-1}: 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV

R. Aaij *et al.* (LHCb Collab.) Phys. Lett. B **733** 36 (2014)

$\Gamma^{+}_{\mathrm{OS}} \propto r_B^2 + r_D^2 + 2 r_B r_D \kappa_f \cos(\delta_B + \gamma + \delta_f)$ $\quad$ $\Gamma^{-}_{\mathrm{OS}} \propto r_B^2 + r_D^2 + 2 r_B r_D \kappa_f \cos(\delta_B - \gamma + \delta_f)$



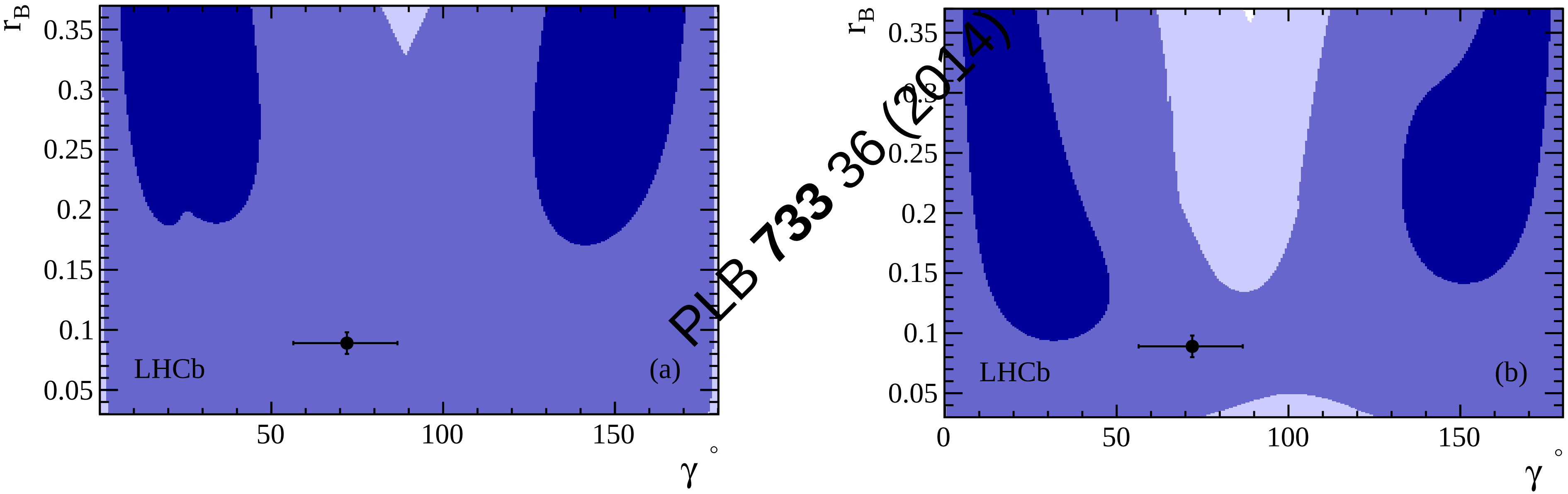


γ manifests as a difference in the rates when 2 kaons have opposite charge

Results

γ constraint accounting for D^0 mixing effects, contours represent change in likelihood

Whole Dalitz plot | $K^*(892)$ region



$n\sigma$ contours with $n = 1$ (dark blue), $n = 2$ (medium blue) and $n = 3$ (light blue)

Data point: LHCb average from other $B \to DK$ modes
R. Aaij *et al*. (LHCb Collab.) Phys. Lett. B **726** (2013) 151

Agreement within 2σ

Constraint tighter in $K^*(892)$ region because coherence factor is larger

Neutral Meson Mixing

Mixing arises from a difference between the mass and flavour eigenstates

$$|P_H\rangle = p|P^0\rangle + q|\bar{P}^0\rangle, \qquad |P_L\rangle = p|P^0\rangle - q|\bar{P}^0\rangle$$

p, q are complex mixing parameters

Mixing can be described by the effective 2x2 Hamiltonian

$$H_{ij} = M_{ij} - i\Gamma_{ij}/2$$

M is the mass term

Γ provides the decay term due to the $-i$

Solving the Schrödinger Equation

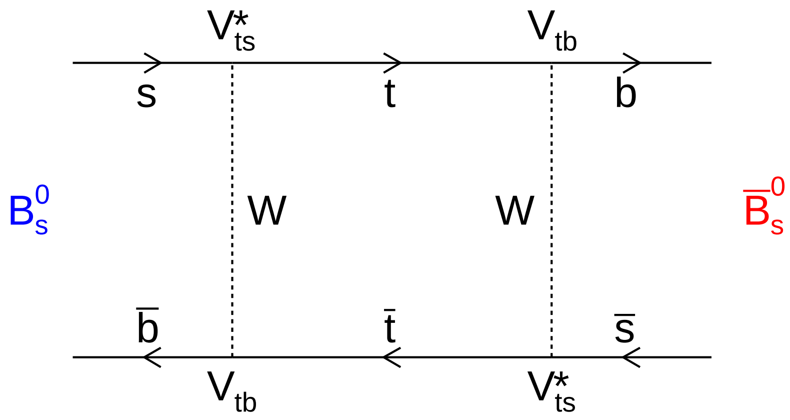
3 mixing physical observables

$\Delta m \equiv m_H - m_L$: mixing frequency in time evolution

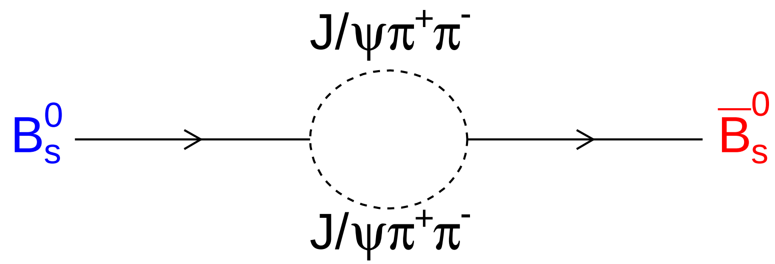
$\Delta\Gamma \equiv \Gamma_H - \Gamma_L$: lifetime difference

$\phi_{\mathrm{mix}} = -\arg(M_{12}/\Gamma_{12})$: CP-violating mixing phase

M_{12}: short-distance off-shell



$-i\Gamma_{12}/2$: long-distance on-shell



CP Violation in Neutral Mesons

CP violation in neutral meson system governed by complex parameter

$$\lambda_{CP} \equiv \frac{q}{p}\frac{\bar{A}(\bar{P}^0 \to f_{CP})}{A(P^0 \to f_{CP})}$$

Access experimentally through time-dependent rate asymmetry in neutral mesons

$$a_{CP}(t) \equiv \frac{\Gamma(\bar{P}^0 \to f_{CP}) - \Gamma(P^0 \to f_{CP})}{\Gamma(\bar{P}^0 \to f_{CP}) + \Gamma(P^0 \to f_{CP})} = \frac{\mathcal{A}_{CP}\cos(\Delta m t) + \mathcal{S}_{CP}\sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

Sensitive to 3 physical observables

$\mathcal{A}_{CP}$: CP violation in the decay, $|\bar{A}| \neq |A|$

$$\mathcal{A}_{CP} \equiv \frac{|\lambda_{CP}|^2 - 1}{|\lambda_{CP}|^2 + 1}$$

$\mathcal{S}_{CP}$: Mixing-induced CP violation, $\arg(\lambda_{CP}) \neq 0$

$$\mathcal{S}_{CP} \equiv -\eta_{CP}\frac{2\Im(\lambda_{CP})}{|\lambda_{CP}|^2 + 1}$$

$\mathcal{A}_{\Delta\Gamma}$: Admixture of P_H and P_L that decay to final state

$$\mathcal{A}_{\Delta\Gamma} \equiv -\frac{2\Re(\lambda_{CP})}{|\lambda_{CP}|^2 + 1}$$

CP Violation in $B_s^0 \to J/\psi\pi^+\pi^-$

Expectation for λ_{CP} depends on amplitudes present

$$\lambda_{CP} \equiv \frac{q_s}{p_s}\frac{\bar{A}(\bar{B}_s^0 \to J/\psi\pi^+\pi^-)}{A(B_s^0 \to J/\psi\pi^+\pi^-)}$$

Phases generated by CKM mechanism

Decay amplitudes, $A, \bar{A}$ depend on V_{cb}

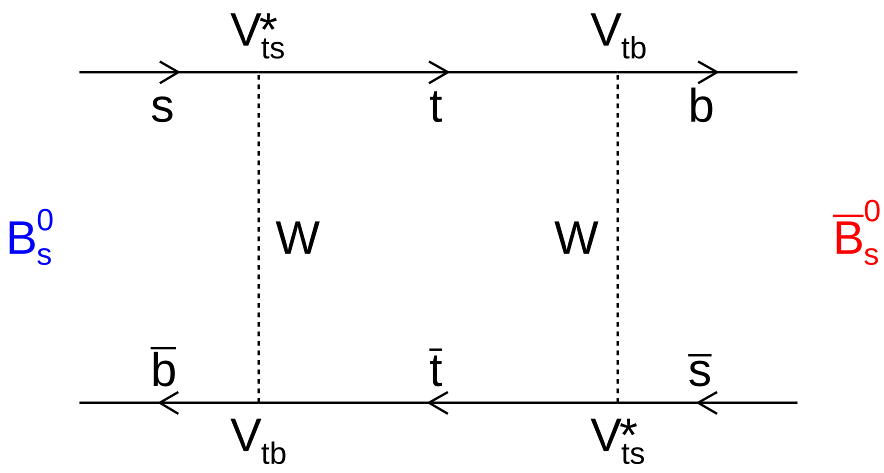
V_{cb} aligned along the real axis by convention

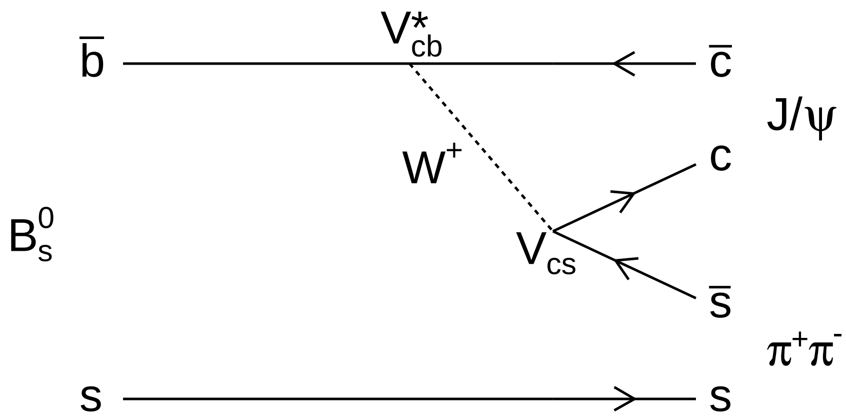
For leading decay diagram,

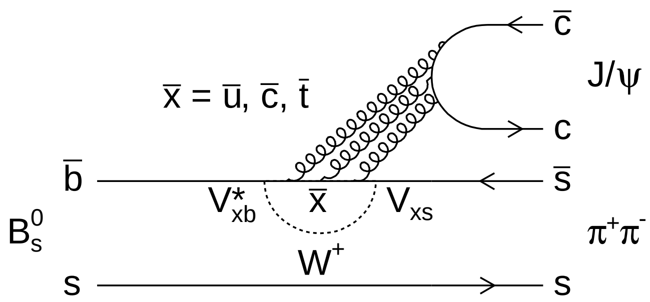
Expect $\lambda_{CP} = |q_s/p_s|\exp(i\phi_s)$

However in reality, some distortion is possible

From SM, or New Physics in the mixing loop







$B_s^0 \to J/\psi\pi^+\pi^-$

- ϕ_s is very precisely predicted in the Standard Model
  - $\phi_s^{\mathrm{SM}} = -0.0364 \pm 0.0016$ rad: J. Charles *et al.*, Phys. Rev. D **84**, 033005 (2011)
- Precise predictions gives excellent opportunity to probe for New Physics phases
  - $\phi_s^{\mathrm{exp}} = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$
- Previous LHCb result with 1/3 the current data set $1\ \mathrm{fb}^{-1}$
  - $\phi_s^{\mathrm{exp}} = +0.01 \pm 0.07$ (stat) $\pm\, 0.01$ (syst) rad: Phys. Rev. D **87**, 112010 (2013)
  - Performed assuming that $B_s^0 \to J/\psi\pi^+\pi^-$ was a pure CP-odd eigenstate
  - CP-odd component greater than 97.7% at 95% CL: Phys. Rev. D **86**, 052006 (2012)
  - Could ultimately dominate the systematic uncertainty
- Simultaneously measure CP-even/odd components with time-dependent amplitude analysis
- Perform with full LHCb data sample $3\ \mathrm{fb}^{-1}$

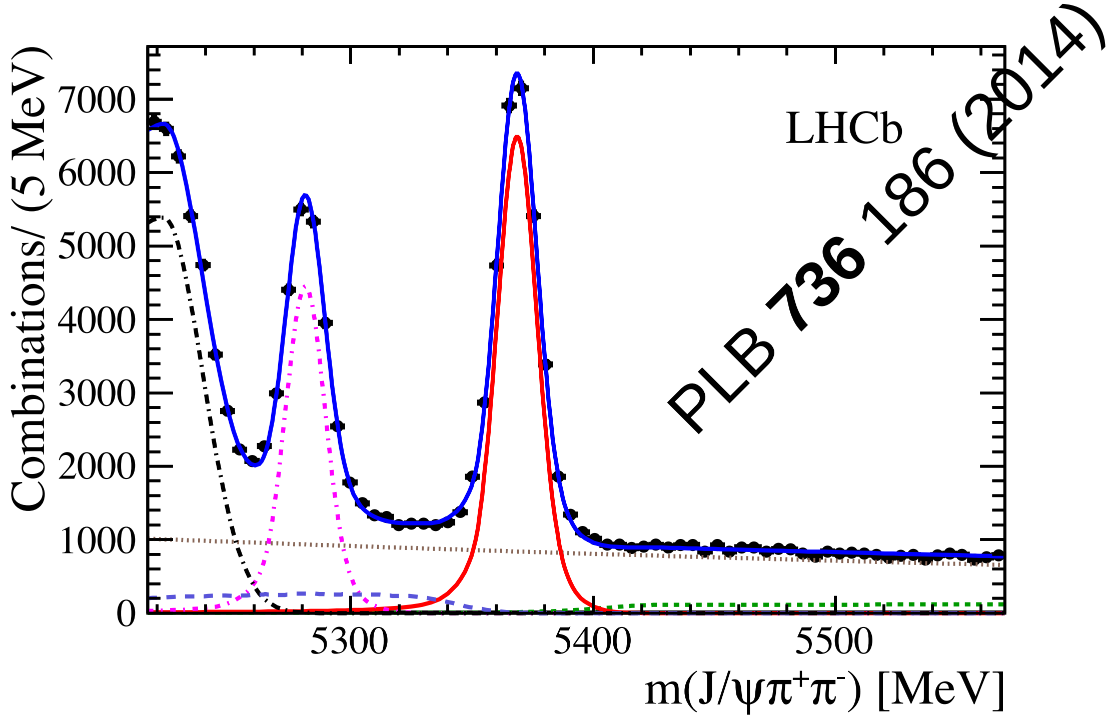
$B_s^0 \to J/\psi\pi^+\pi^-$ Yield

Reconstructed as $B_s^0 \to J/\psi[\mu^+\mu^-]\pi^+\pi^-$

Selections based on Boosted Decision Tree trained with MC (signal) and data (background)

Signal yield: 27100 ± 200 events

Retain events within ± 20 MeV for further analysis



Red: $B_s^0 \to J/\psi\pi^+\pi^-$

Pink: $B^0 \to J/\psi\pi^+\pi^-$

Green: $B^- \to J/\psi K^-$

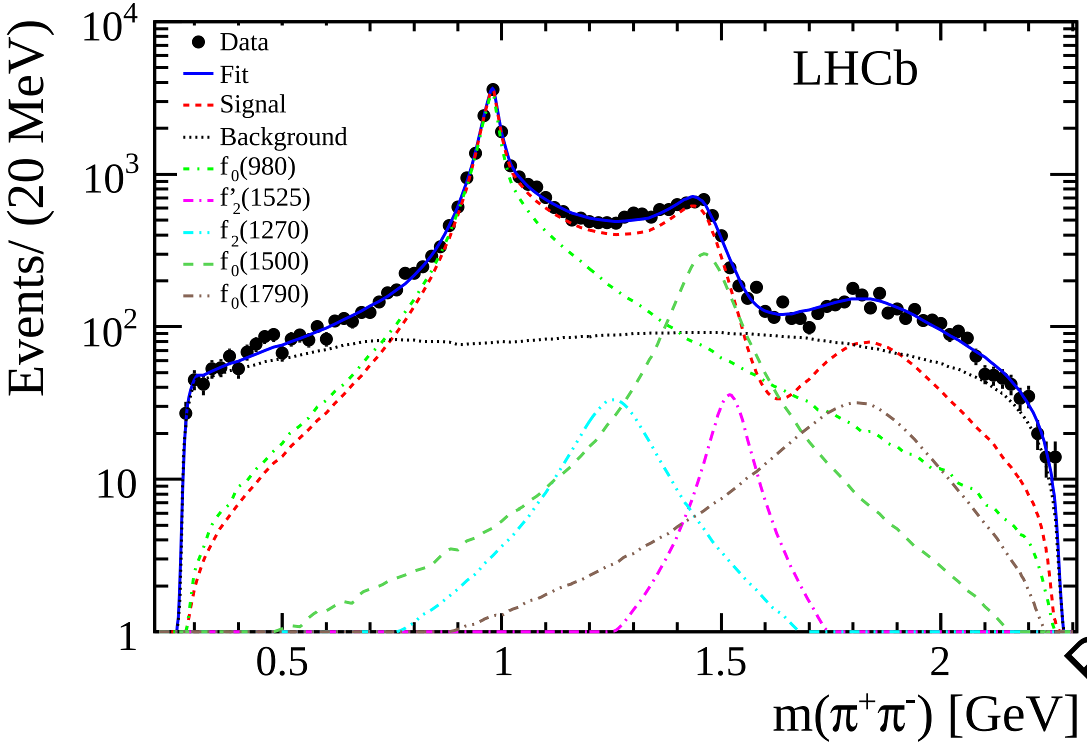
Black: $B^0 \to J/\psi K^\mp\pi^\pm$ reflection

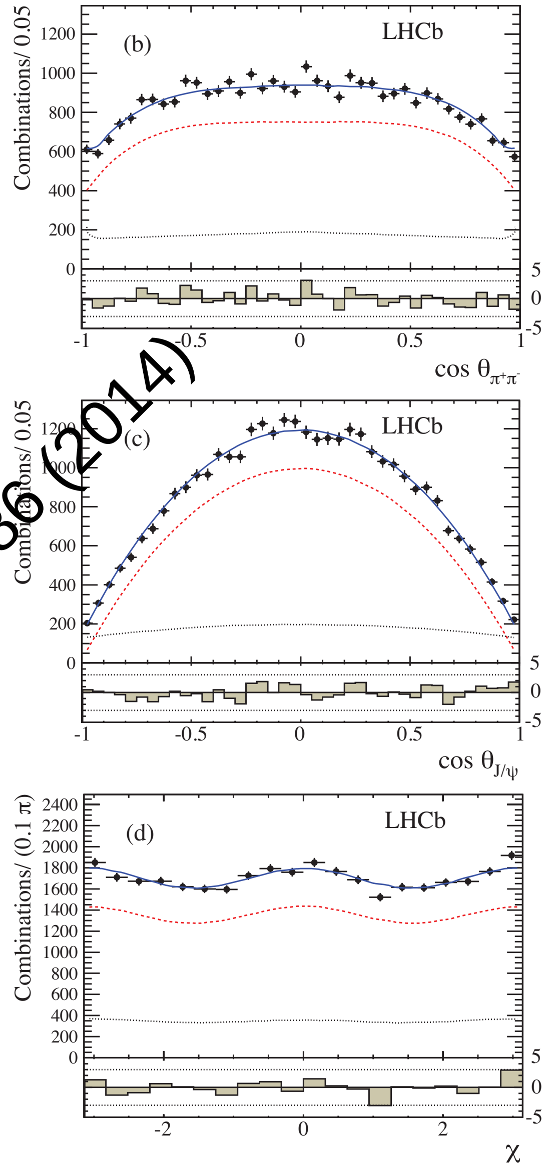
Purple: Other misreconstructed decays

Brown: Combinatorial background

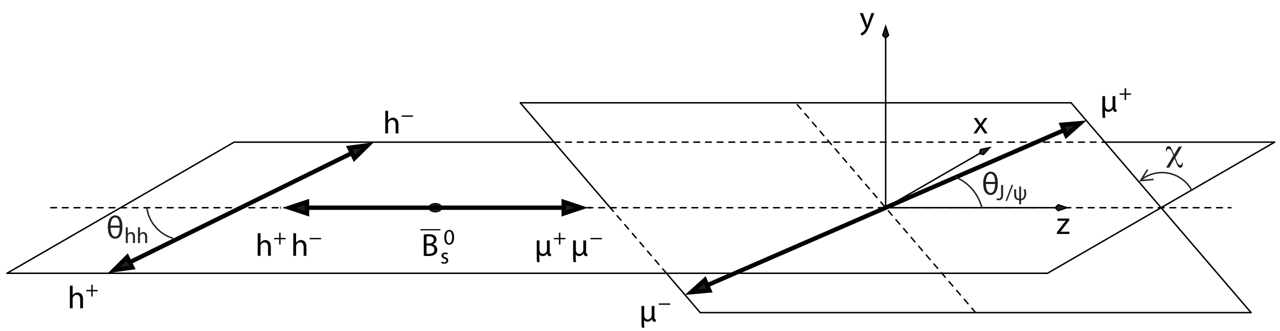
$B_s^0 \to J/\psi\pi^+\pi^-$ Amplitude Analysis

Disentangle CP-odd/even contributions





PLB 736 186 (2014)



$B_s^0 \to J/\psi\pi^+\pi^-$ Time Distribution

Time-dependent decay rate

$$\Gamma(t) = \mathcal{N}e^{-\Gamma_s t}\left\{\frac{|\mathcal{A}|^2+|\overline{\mathcal{A}}|^2}{2}\cosh\frac{\Delta\Gamma_s t}{2}+\frac{|\mathcal{A}|^2-|\overline{\mathcal{A}}|^2}{2}\cos(\Delta m_s t) - \mathcal{R}e(\mathcal{A}^*\overline{\mathcal{A}})\sinh\frac{\Delta\Gamma_s t}{2} - \mathcal{I}m(\mathcal{A}^*\overline{\mathcal{A}})\sin(\Delta m_s t)\right\},$$

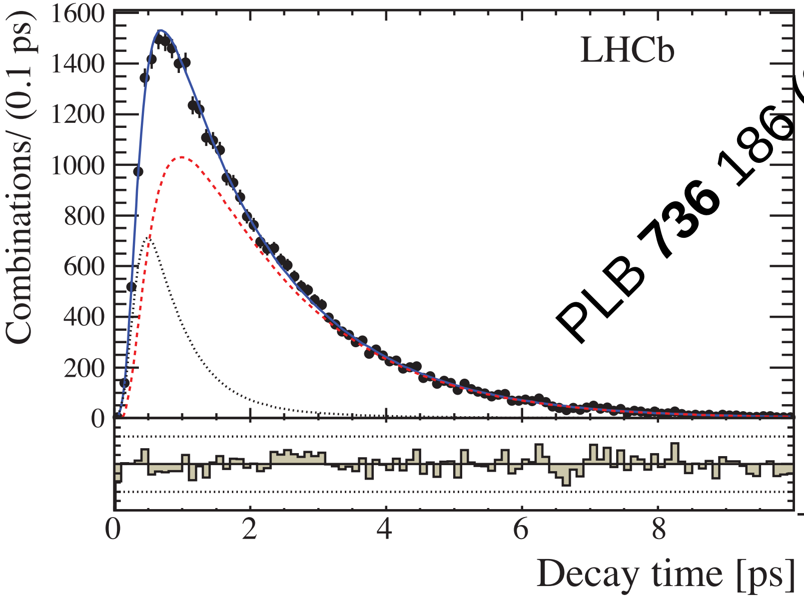
$$\overline{\Gamma}(t) = \left|\frac{p}{q}\right|^2\mathcal{N}e^{-\Gamma_s t}\left\{\frac{|\mathcal{A}|^2+|\overline{\mathcal{A}}|^2}{2}\cosh\frac{\Delta\Gamma_s t}{2}-\frac{|\mathcal{A}|^2-|\overline{\mathcal{A}}|^2}{2}\cos(\Delta m_s t) - \mathcal{R}e(\mathcal{A}^*\overline{\mathcal{A}})\sinh\frac{\Delta\Gamma_s t}{2} + \mathcal{I}m(\mathcal{A}^*\overline{\mathcal{A}})\sin(\Delta m_s t)\right\},$$

Sum over number of isobars

$$\mathcal{A} \equiv \sum_i A_i$$

$$\bar{\mathcal{A}} \equiv \sum_i \lambda_i^{CP} A_i$$

$$\lambda_i^{CP} \equiv \eta_i \frac{q_s}{p_s}\frac{\bar{A}_i}{A_i}$$



PLB 736 186 (2014)

Per-event resolution model

Effective resolution: 40.3 fs

Opposite-side and Same-side flavour tagging

Effective tagging efficiency: $(3.89 \pm 0.25)\%$

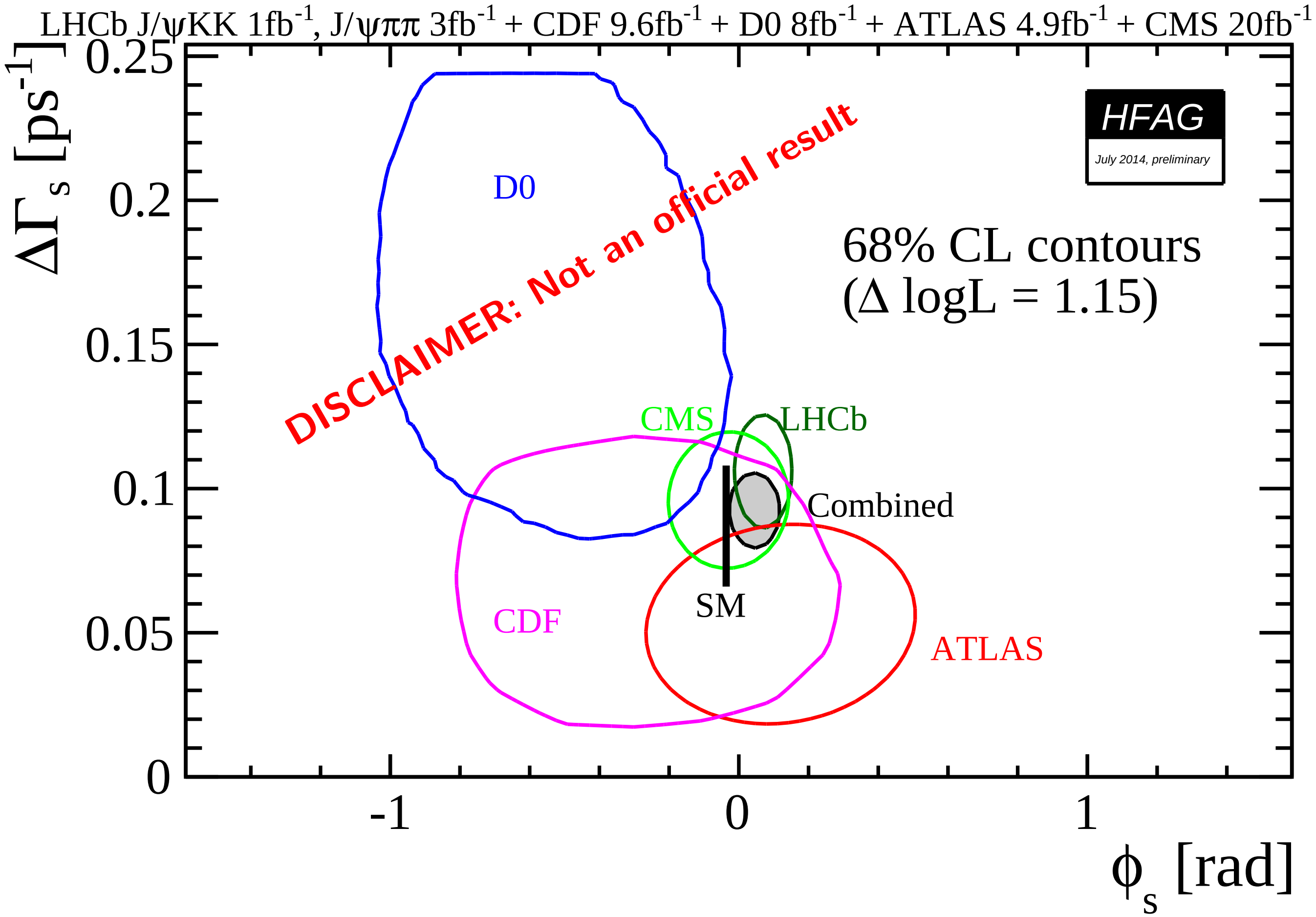
$\phi_s = +0.070 \pm 0.068$ (stat) $\pm\, 0.008$ (syst)

$|\lambda_{CP}| = 0.89 \pm 0.05$ (stat) $\pm\, 0.01$ (syst)

ϕ_s Average

New LHCb results consistent with SM expectation

World's most precise result



$B_s^0 \to \phi\phi$

Forbidden at tree level in the Standard Model

Dominant contribution to $\bar{b} \to \bar{s}s\bar{s}$ transitions from gluonic penguins

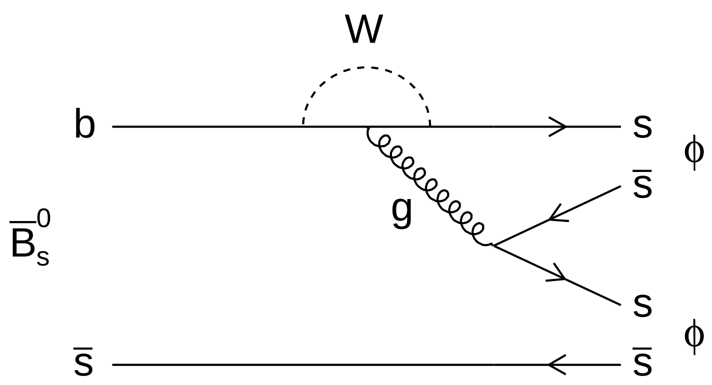
Pure loop processes highly sensitive to New Physics

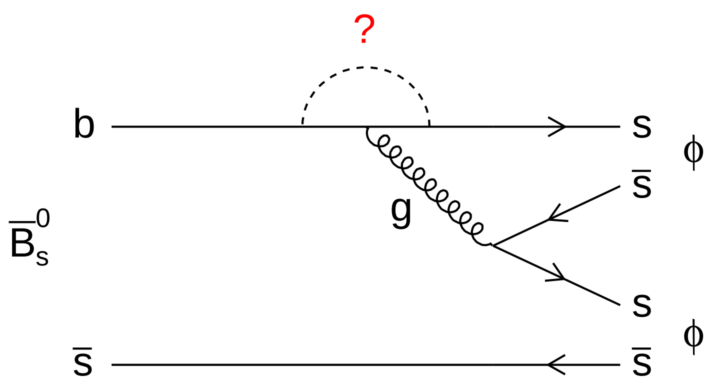
CP final state

$$\lambda_{CP} \equiv \frac{q_s}{p_s}\frac{\bar{A}(\bar{B}_s^0 \to \phi\phi)}{A(B_s^0 \to \phi\phi)} = |\lambda_{CP}|e^{i\phi_s^{\text{eff}}}$$

SM predictions: M. Bartsch, G. Buchalla, C. Kraus, arXiv:0810.0249 [hep-ph] (2008)

$$\mathcal{A}_{CP} \equiv \frac{|\lambda_{CP}|^2 - 1}{|\lambda_{CP}|^2 + 1} \lesssim -0.02, \qquad \mathcal{S}_{CP} \equiv -\eta_{CP}\frac{2\Im(\lambda_{CP})}{|\lambda_{CP}|^2 + 1} \lesssim 0.02$$





$B_s^0 \to \phi\phi$ Results

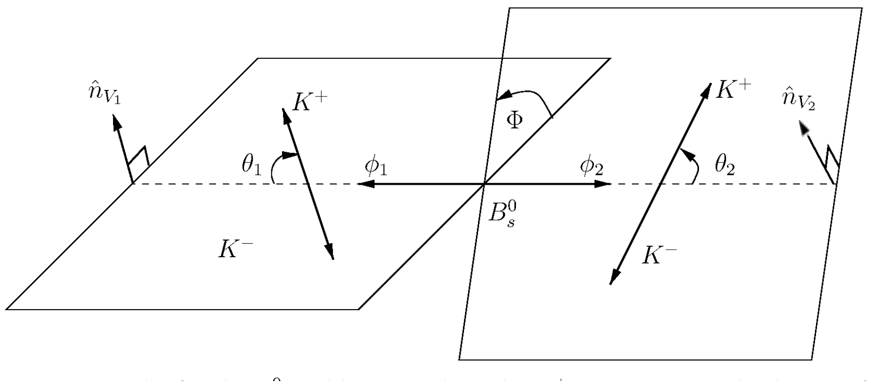
$B_s^0 \to \phi\phi$ is a Vector-Vector final state and $\mathcal{S}_{CP}$ depends on the CP eigenvalue

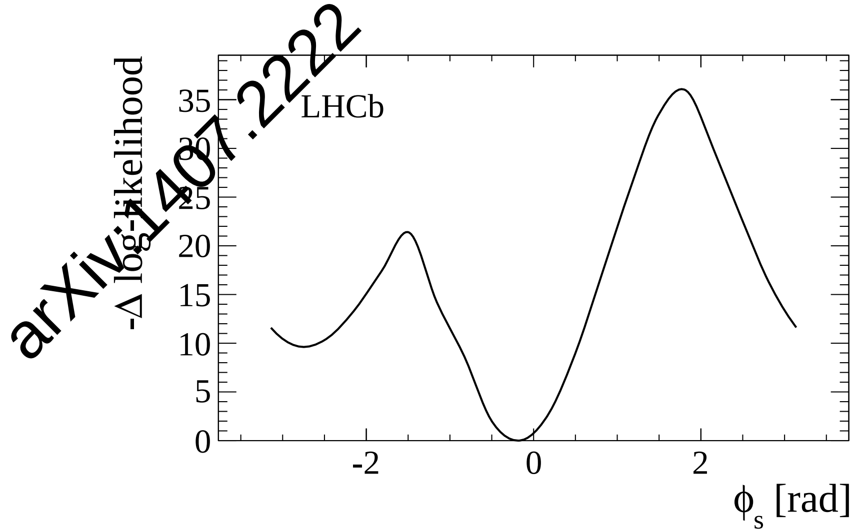
- Depends on the relative orbital angular momentum between the 2 ϕ resonances

Transversity basis can isolate definite CP states: $A_0, A_{||}$ (CP-even), $A_\perp$ (CP-odd)

Need to consider interference when one or both K^+-K^- systems are in an S-wave

3950 ± 67 signal events





$\phi_s^{\mathrm{eff}} = -0.17 \pm 0.15$ (stat) $\pm\ 0.03$ (syst), $|\lambda_{CP}| = 1.04 \pm 0.07$ (stat) $\pm\ 0.03$ (syst)

Consistent with Standard Model predictions, no indication of either type of CP violation

U-spin Symmetry

SU(2) subgroup of SU(3) under which d and s can be interchanged

$\Delta S = 0$ ($b \to d$) effective Hamiltonian same as corresponding $\Delta S = 1$ ($b \to s$) with $d \leftrightarrow s$

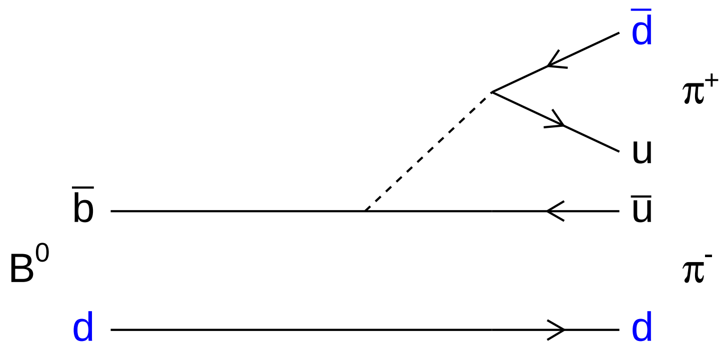
Using CKM unitarity relation $\Im(V_{ub}^* V_{us} V_{cb} V_{cs}^*) = -\Im(V_{ub}^* V_{ud} V_{cb} V_{cd}^*)$

U-spin Theorem relating $\Delta S = 0$ and $\Delta S = 1$ decays

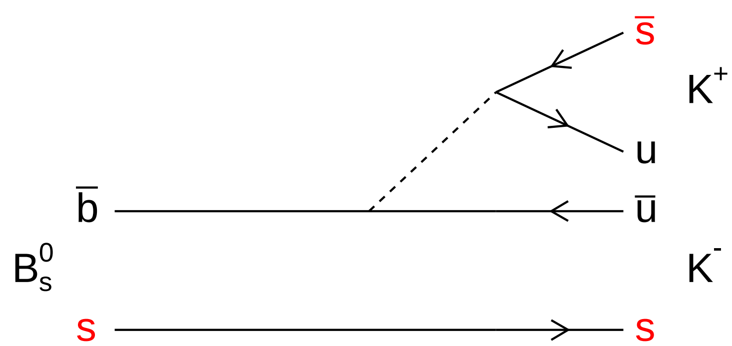
$$\Delta\Gamma(B \to f) = -\Delta\Gamma(\hat{U}B \to \hat{U}f)$$

U-spin breaking around 30% level: PLB **727**, 136 (2013), Mod. Phys. Lett. A **23**, 1175 (2008)

$\Delta S = 0$



$\Delta S = 1$



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

U-spin symmetry between these 2 decay channels give sensitivity to γ and ϕ_s

Additional constraints from isospin considerations in the $B \to \pi^+\pi^-/\pi^0\pi^0/\pi^+\pi^0$ system

Experimental results on branching fractions and CP violation parameters as input

Constrain using Bayesian approach, flat prior probability distributions for hadronic parameters

Introduce U-spin breaking percentage parameter

$$C_{\pi^+\pi^-} = -\frac{2d\sin(\vartheta)\sin(\gamma)}{1-2d\cos(\vartheta)\cos(\gamma)+d^2},$$

$$S_{\pi^+\pi^-} = -\frac{\sin(2\beta+2\gamma)-2d\cos(\vartheta)\sin(2\beta+\gamma)+d^2\sin(2\beta)}{1-2d\cos(\vartheta)\cos(\gamma)+d^2},$$

$$C_{\pi^0\pi^0} = -\frac{2dq\sin(\vartheta_q-\vartheta)\sin(\gamma)}{q^2+2dq\cos(\vartheta_q-\vartheta)\cos(\gamma)+d^2},$$

$$\mathcal{A}_{\pi^+\pi^0} = 0,$$

$$C_{K^+K^-} = \frac{2\tilde{d}'\sin(\vartheta')\sin(\gamma)}{1+2\tilde{d}'\cos(\vartheta')\cos(\gamma)+\tilde{d}'^2},$$

$$S_{K^+K^-} = -\frac{\sin(-2\beta_s+2\gamma)+2\tilde{d}'\cos(\vartheta')\sin(-2\beta_s+\gamma)+\tilde{d}'^2\sin(-2\beta_s)}{1+2\tilde{d}'\cos(\vartheta')\cos(\gamma)+\tilde{d}'^2},$$

$$A^{\Delta\Gamma}_{K^+K^-} = -\frac{\cos(-2\beta_s+2\gamma)+2\tilde{d}'\cos(\vartheta')\cos(-2\beta_s+\gamma)+\tilde{d}'^2\cos(-2\beta_s)}{1+2\tilde{d}'\cos(\vartheta')\cos(\gamma)+\tilde{d}'^2}.$$

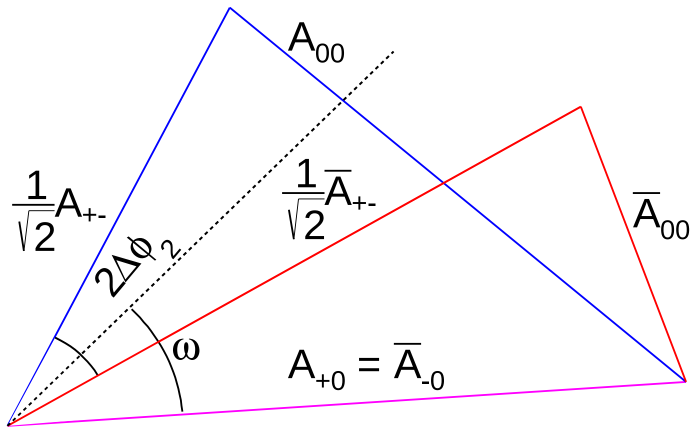
$$\mathcal{B}_{\pi^+\pi^-} = F(B^0\to\pi^+\pi^-)|D|^2(1-2d\cos(\vartheta)\cos(\gamma)+d^2),$$

$$\mathcal{B}_{\pi^0\pi^0} = F(B^0\to\pi^0\pi^0)\frac{|D|^2}{2}(q^2+2dq\cos(\vartheta_q-\vartheta)\cos(\gamma)+d^2),$$

$$\mathcal{B}_{\pi^+\pi^0} = F(B^+\to\pi^+\pi^0)\frac{|D|^2}{2}(1+q^2+2q\cos(\vartheta_q)),$$

$$\mathcal{B}_{K^+K^-} = F(B_s^0\to K^+K^-)\frac{\lambda^2}{(1-\lambda^2/2)^2}|D'|^2(1+2\tilde{d}'\cos(\vartheta')\cos(\gamma)+\tilde{d}'^2),$$

9 observables
10 unknowns



Motivated by first measurement of time-dependent CP violation in $B_s^0 \to K^+K^-$ at LHCb

JHEP **10**, 183 (2013)

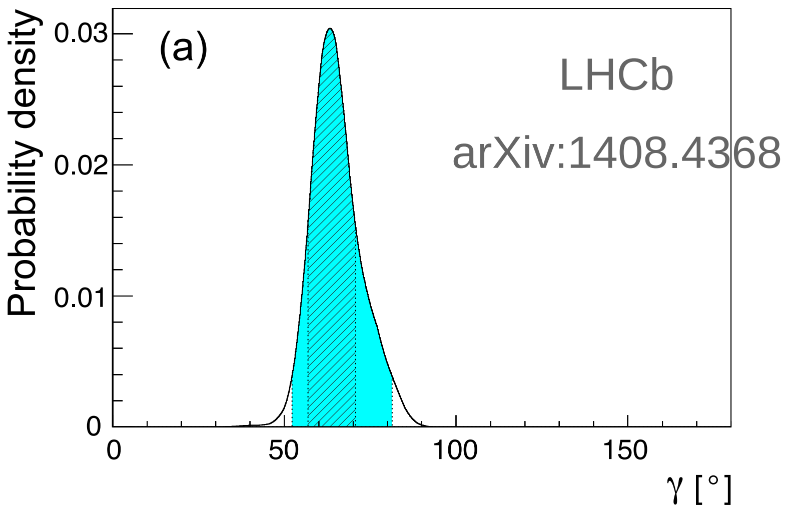
Penguin contributions may cause deviations

Results

Two analyses assuming 50% U-spin symmetry breaking: arXiv:1408.4368 (New!)

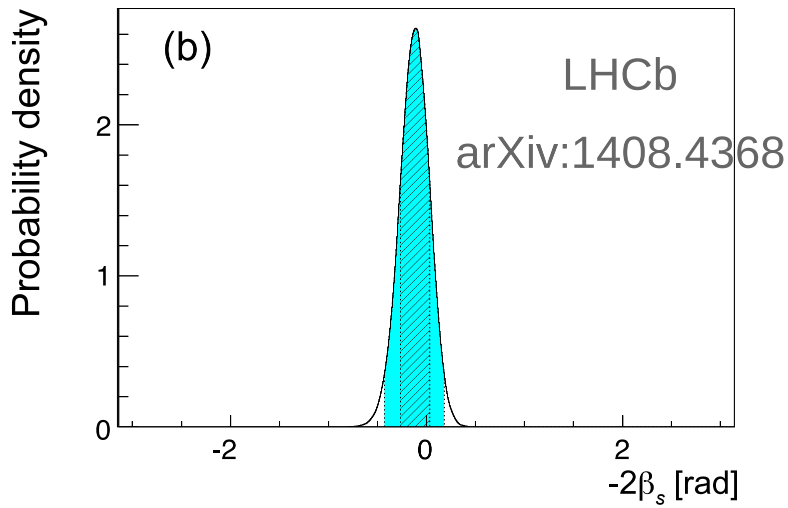
1. Constrain $\phi_s \equiv -2\beta_s$ from unitarity triangle parameters, determine γ
2. Constrain γ to world average, determine $-2\beta_s$

Analysis 1



$$\gamma = (63.5^{+7.2}_{-6.7})^{\circ}$$

Analysis 2



$$\phi_s = -0.12^{+0.14}_{-0.16} \text{ rad}$$

Hatched (Shaded): 68% (95%) posterior probability intervals

No significant deviation from pure tree measurements, competitive uncertainties

Summary

First model-dependent measurement of γ at LHCb using $B^{\pm} \to D[K^0_S\pi^+\pi^-]K^{\pm}$

- Consistent with Standard Model expectations

Best model-independent measurement of γ at LHCb using $B^{\pm} \to D[K^0_S\pi^+\pi^-]K^{\pm}$

- Uncertainty now similar to that achieved by the B factories

First ADS-like constraint of γ with $B^{\pm} \to D[K^0_S K^{\pm}\pi^{\pm}]K^{\pm}$

- Amplitude from CLEO
- γ consistent with other LHCb measurements

Best measurement of ϕ_s in $B^0_s \to J/\psi\pi^+\pi^-$ and $B^0_s \to \phi\phi$ decays

- Consistent with the Standard Model, no evidence for New Physics

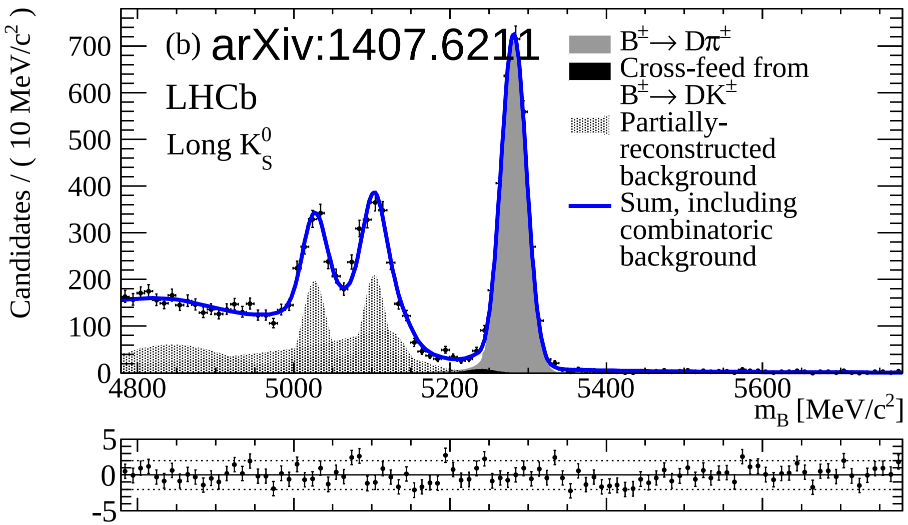
First measurement of ϕ_s and γ using U-spin and isospin constraints in $B \to hh$ system

- U-spin breaking under control, uncertainties competitive with tree-level determinations

Backup

$B^{\pm} \to D[K^0_S \pi^+ \pi^-]\pi^{\pm}$

"Long" K^0_S



"Downstream" K^0_S

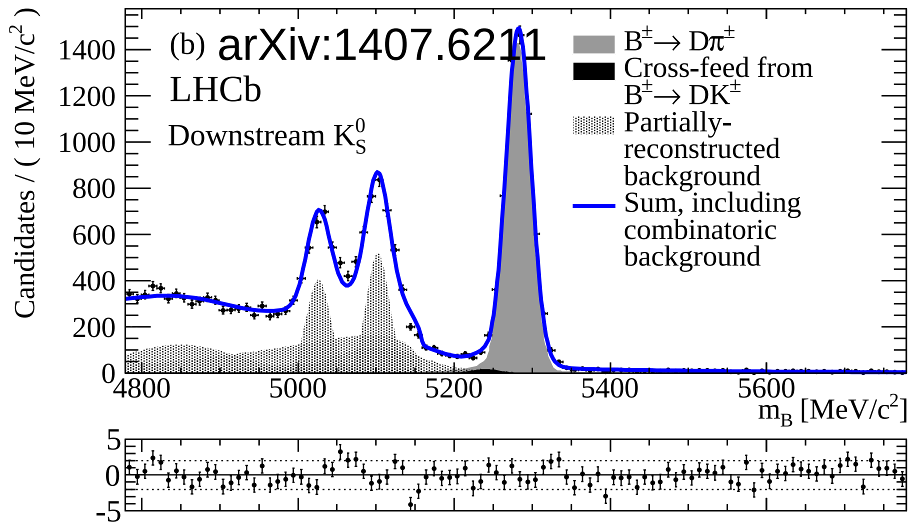


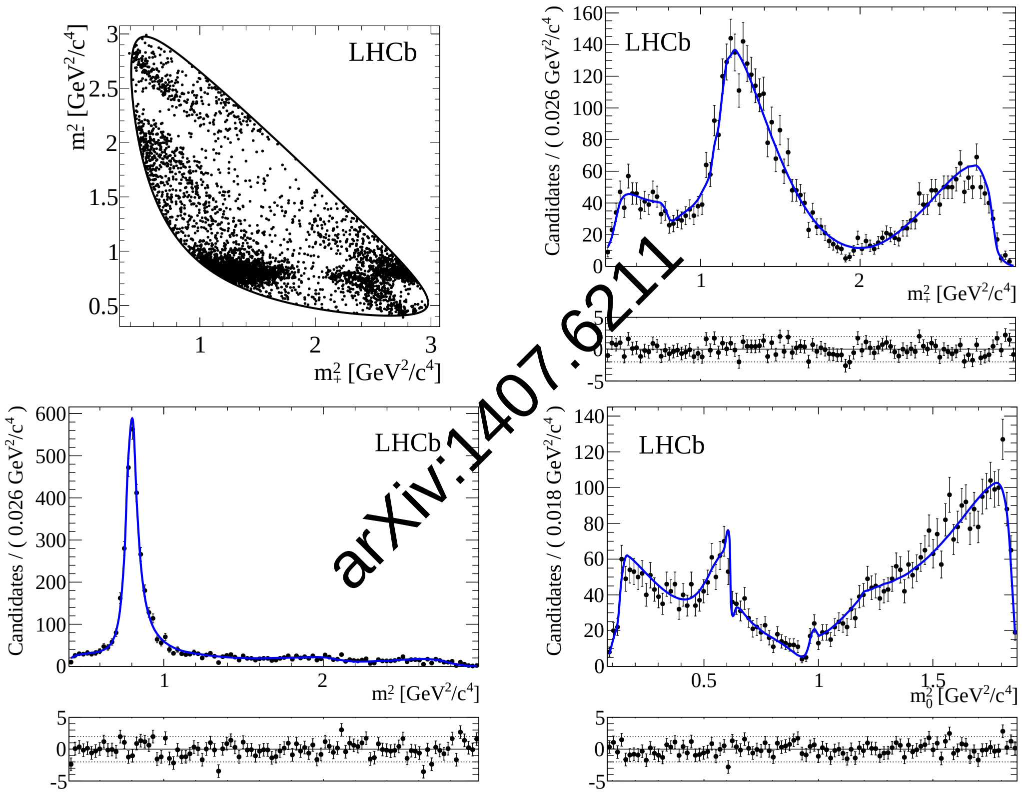
Table 1: Fitted signal and background yields in the signal invariant mass region (|B mass after refit - world average| $< 50\,\mathrm{MeV}/c^2$) for components contributing to the CP fit.

Fit component	$B^\pm \to DK^\pm$, *long*	$B^\pm \to DK^\pm$, *downstream*
Signal	217±17	420±27
Cross-feed background (from $B^\pm \to D\pi^\pm$)	35.9±0.7	76±1
Combinatoric D background	5^{+7}_{-3}	31^{+11}_{-9}
Random Dh background	28^{+5}_{-8}	45^{+18}_{-19}
D$^*\pi$ background	0.36±0.08	6±7
Dρ background	2.2±0.5	4±11
$B_s \to DK^*$ background	0.9±0.2	4±2

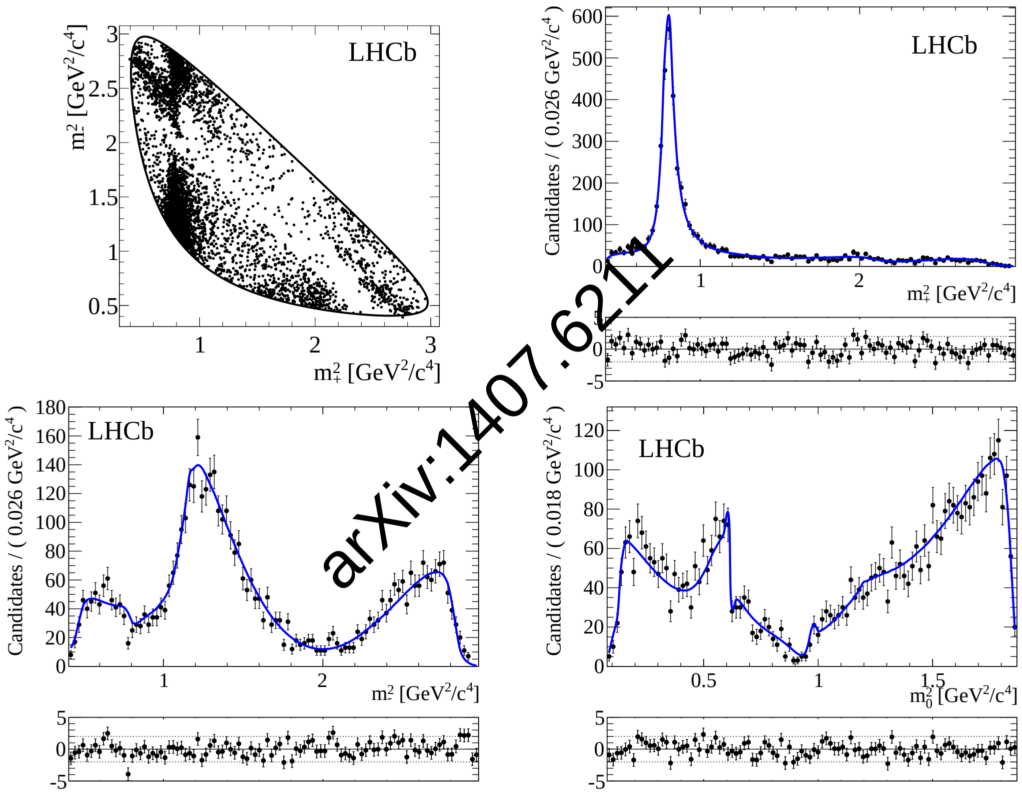
Fit component	$B^\pm \to D\pi^\pm$, *long*	$B^\pm \to D\pi^\pm$, *downstream*
Signal	2906±56	5960±80
Cross-feed background (from $B^\pm \to DK^\pm$)	27±2	53±3
Combinatoric D background	15^{+19}_{-10}	99^{+36}_{-27}
Random Dh background	76^{+15}_{-22}	146^{+33}_{-41}
D$^*\pi$ background	6.6±0.4	22.0±0.7

$B^{\pm} \to D[K^0_S \pi^+ \pi^-]\pi^{\pm}$

$B^- \to D\pi^-$



$B^+ \to D\pi^+$



$B^\pm \to D[K^0_S\pi^+\pi^-]K^\pm$

	Description		$\delta x_-(\times 10^{-3})$	$\delta y_-(\times 10^{-3})$	$\delta x_+(\times 10^{-3})$	$\delta y_+(\times 10^{-3})$
(a)	K-matrix 1st solution		-0.132	0.044	0.250	-2.346
(b)	K-matrix 2nd solution		-0.086	-0.339	0.122	-0.528
(c)	Remove slowly varying part in P-vector		-0.144	-0.317	0.097	-0.762
(d)	Generalised LASS $\to$ relativistic Breit-Wigner		-0.713	-1.846	3.042	6.584
(e)	Gounaris-Sakurai $\to$ relativistic Breit-Wigner		0.077	-0.849	0.145	0.818
(f)	$K^\star(1680)$	$m+\delta m$	-0.063	-0.561	0.181	0.256
(g)		$m-\delta m$	-0.128	-0.161	-0.098	-1.104
(h)		$\Gamma+\delta\Gamma$	-0.059	-0.365	-0.048	-0.423
(i)		$\Gamma-\delta\Gamma$	-0.158	-0.333	0.273	-0.489
(j)	$f_2(1270)$	$m+\delta m$	-0.106	-0.346	0.096	-0.464
(k)		$m-\delta m$	-0.102	-0.351	0.085	-0.456
(l)		$\Gamma+\delta\Gamma$	-0.102	-0.344	0.081	-0.467
(m)		$\Gamma-\delta\Gamma$	-0.105	-0.351	0.097	-0.453
(n)	$K_2^\star(1430)$	$m+\delta m$	-0.082	-0.355	0.078	-0.421
(o)		$m-\delta m$	-0.125	-0.342	0.106	-0.498
(p)		$\Gamma+\delta\Gamma$	-0.100	-0.369	0.071	-0.432
(q)		$\Gamma-\delta\Gamma$	-0.109	-0.328	0.112	-0.489
(r)	$r_{\rm BW} = 0.0\,{\rm GeV}^{-1}$		-0.154	-0.385	-0.116	-0.338
(s)	$r_{\rm BW} = 3.0\,{\rm GeV}^{-1}$		-0.308	-0.281	1.225	-0.386
(t)	Add $K^\star(1410)$ and $\rho(1450)$		-0.124	-0.286	0.023	-0.701

Table 2: Summary of the model related systematic uncertainties for each alternative model.

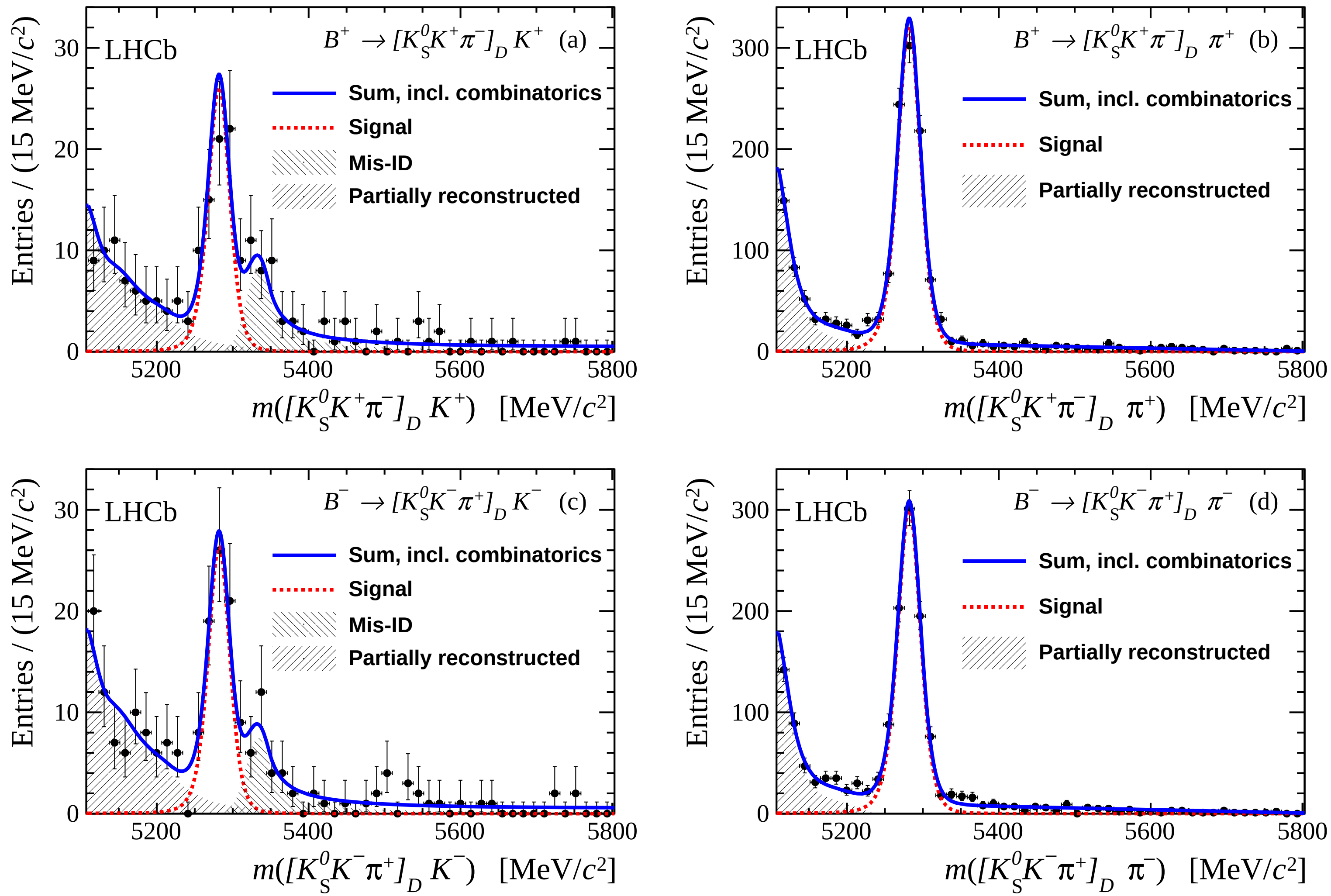
$B^{\pm} \to D[K_S^0\pi^+\pi^-]K^{\pm}$

Source of uncertainty	$\delta x_-(\times 10^{-3})$	$\delta y_-(\times 10^{-3})$	$\delta x_+(\times 10^{-3})$	$\delta y_+(\times 10^{-3})$
Combinatoric D yield estimate	1.0	4.3	2.7	4.9
Inclusion of semileptonic background	3.1	2.8	0.63	3.2
Charged kaon detection asymmetry	0.022	0.030	0.0041	0.025
Amplitudes for backgrounds				
Combinatoric D	3.5	3.4	4.7	6.4
Random Dh	0.10	0.16	0.066	0.16
B_s partially-reconstructed	0.59	0.59	0.15	0.73
$r_{B^{\pm}\to D\pi^{\pm}}$	1.8	1.9	1.6	1.1
Efficiency over the phase space	5.7	0.35	6.9	0.31
CP fit bias	5.7	5.1	-1.3	2.6
Total experiment or fit related	$^{+9.6}_{-7.7}$	$^{+8.2}_{-6.4}$	$^{+9.0}_{-9.1}$	$^{+9.2}_{-8.8}$
Total model related	0.9	2.5	3.3	7.4

Table 3: Summary of absolute values of systematic uncertainties.

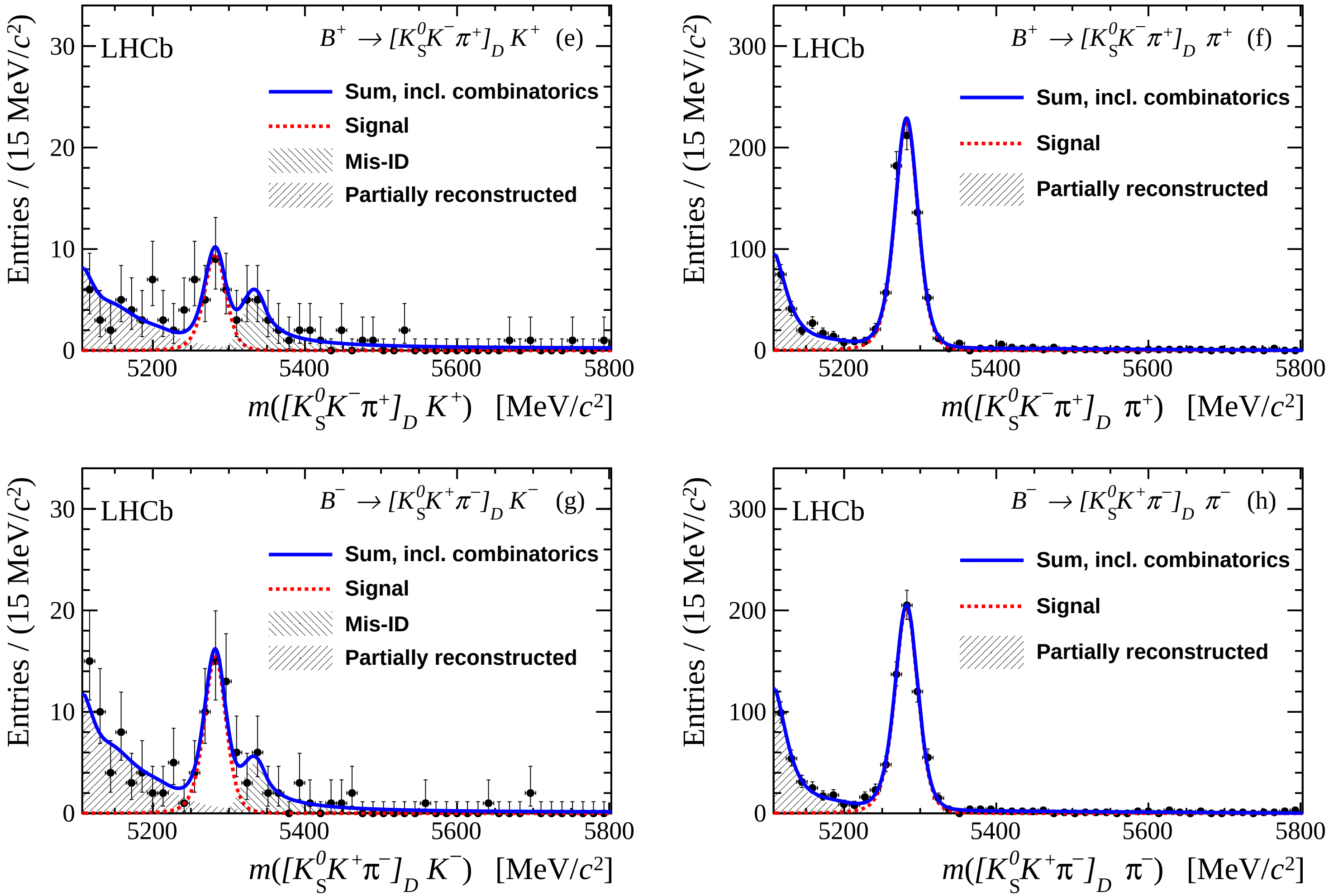
$B^{\pm} \to D[K^0_S K^{\pm}\pi^{\pm}]K^{\pm}$

SS candidates



$B^{\pm} \to D[K^0_S K^{\pm} \pi^{\pm}] K^{\pm}$

OS candidates



$B^{\pm} \to D[K^0_S K^{\pm}\pi^{\pm}]K^{\pm}$

Table 1: Signal yields and their statistical uncertainties derived from the fit to the whole Dalitz plot region, and in the restricted region of phase space around the $K^*(892)^{\pm}$ resonance.

	Whole Dalitz plot		$K^*(892)^{\pm}$ region	
Mode	$DK^{\pm}$	$D\pi^{\pm}$	$DK^{\pm}$	$D\pi^{\pm}$
SS	145 ± 15	1841 ± 47	97 ± 12	1365 ± 38
OS	71 ± 10	1267 ± 37	26 ± 6	553 ± 24

Table 2: Results for the observables measured in the whole Dalitz plot region, and in the restricted region of phase space around the $K^*(892)^{\pm}$ resonance. The first uncertainty is statistical and the second is systematic. The corrections for production and detection asymmetries are applied, as is the efficiency correction defined in Eq. (5).

Observable	Whole Dalitz plot	$K^*(892)^{\pm}$ region
$\mathcal{R}_{\mathrm{SS/OS}}$	$1.528 \pm 0.058 \pm 0.025$	$2.57 \pm 0.13 \pm 0.06$
$\mathcal{R}_{DK/D\pi,\,\mathrm{SS}}$	$0.092 \pm 0.009 \pm 0.004$	$0.084 \pm 0.011 \pm 0.003$
$\mathcal{R}_{DK/D\pi,\,\mathrm{OS}}$	$0.066 \pm 0.009 \pm 0.002$	$0.056 \pm 0.013 \pm 0.002$
$\mathcal{A}_{\mathrm{SS},\,DK}$	$0.040 \pm 0.091 \pm 0.018$	$0.026 \pm 0.109 \pm 0.029$
$\mathcal{A}_{\mathrm{OS},\,DK}$	$0.233 \pm 0.129 \pm 0.024$	$0.336 \pm 0.208 \pm 0.026$
$\mathcal{A}_{\mathrm{SS},\,D\pi}$	$-0.025 \pm 0.024 \pm 0.010$	$-0.012 \pm 0.028 \pm 0.010$
$\mathcal{A}_{\mathrm{OS},\,D\pi}$	$-0.052 \pm 0.029 \pm 0.017$	$-0.054 \pm 0.043 \pm 0.017$

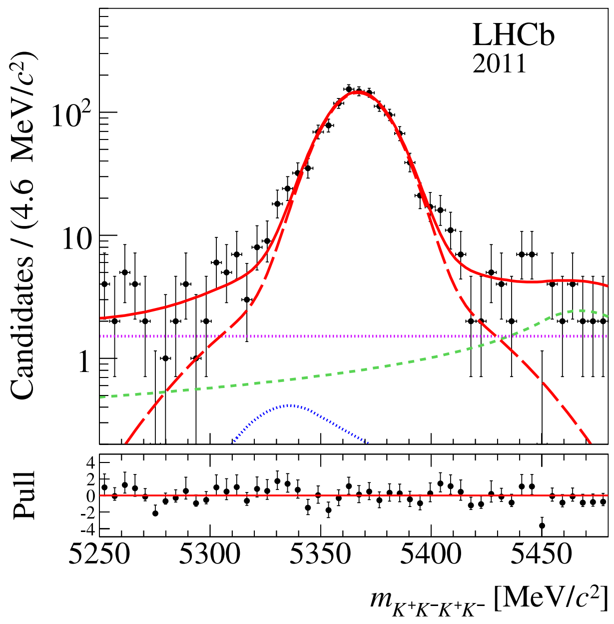
$B_s^0 \to \phi\phi$ Yield

Reconstructed as $B^0 \to \phi[K^+K^-]\phi[K^+K^-]$

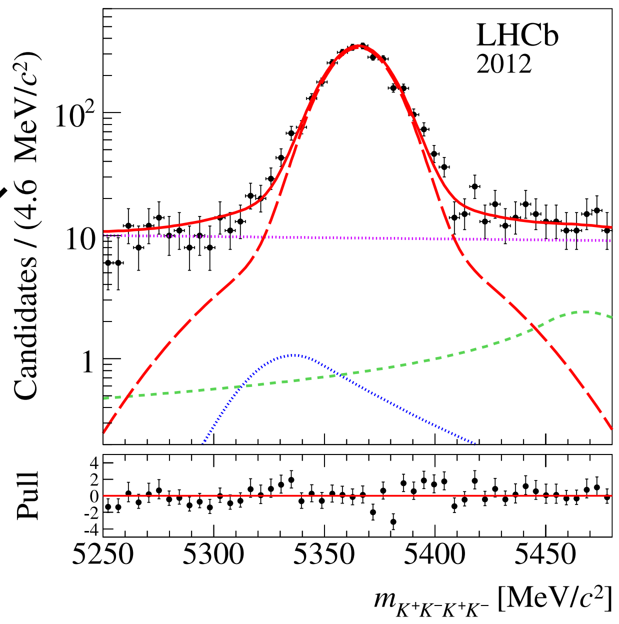
ϕ candidates required to be within 25 MeV$/c^2$ of nominal ϕ pole mass

Fit to 4 kaon mass used to assign signal weights for subsequent time-dependent analysis

$N_{\text{Sig}} = 1185 \pm 35$



$N_{\text{Sig}} = 2765 \pm 57$



arXiv:1407.2222

Red: $B^0 \to \phi\phi$ signal

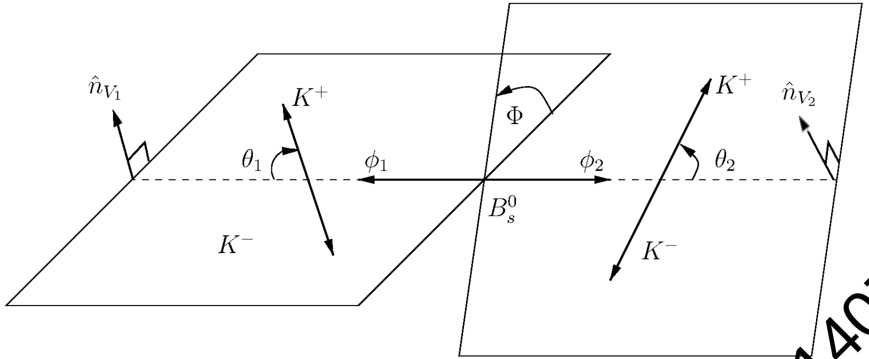
Green: $B^0 \to \phi p K^-$ peaking background

Blue: $B^0 \to \phi K^{*0}$ peaking background

Pink: Combinatorial background

$B_s^0 \to \phi\phi$ Angular Analysis

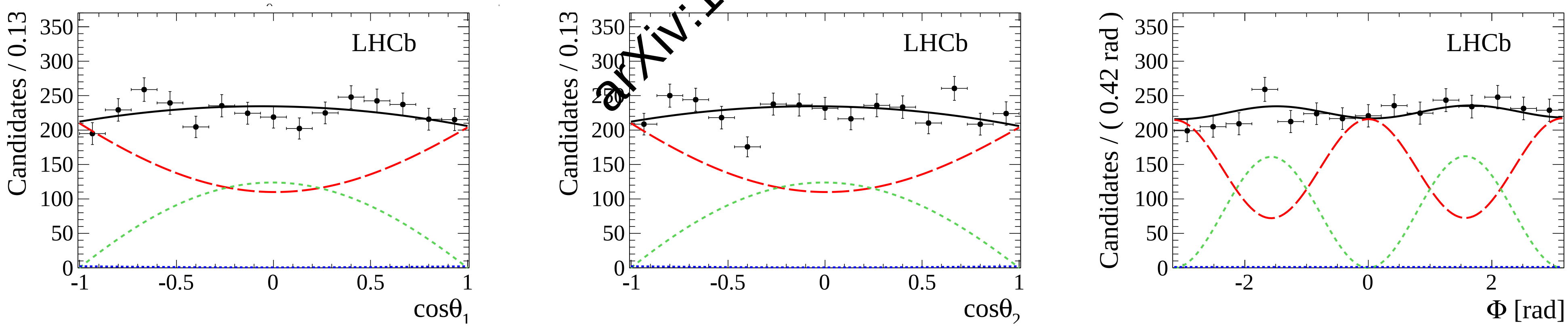
- $B_s^0 \to \phi\phi$ is a Vector-Vector final state and $\mathcal{S}_{CP}$ depends on the CP eigenvalue
  - Depends on the relative orbital angular momentum between the 2 ϕ resonances
- Transversity basis can isolate definite CP states: $A_0, A_{||}$ (CP-even), $A_\perp$ (CP-odd)
- Need to consider interference when one or both K^+-K^- systems are in an S-wave



Red: CP-even

Green: CP-odd

Blue: S-wave K^+-K^- components

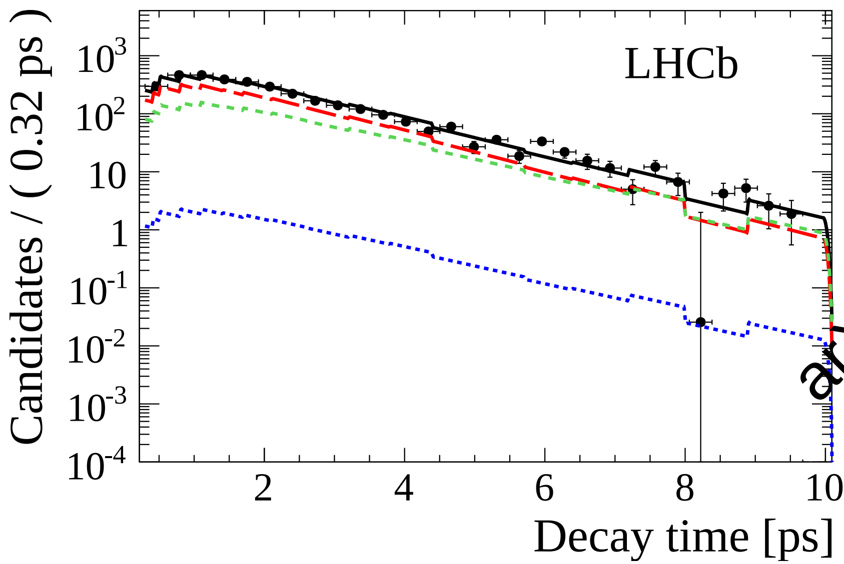


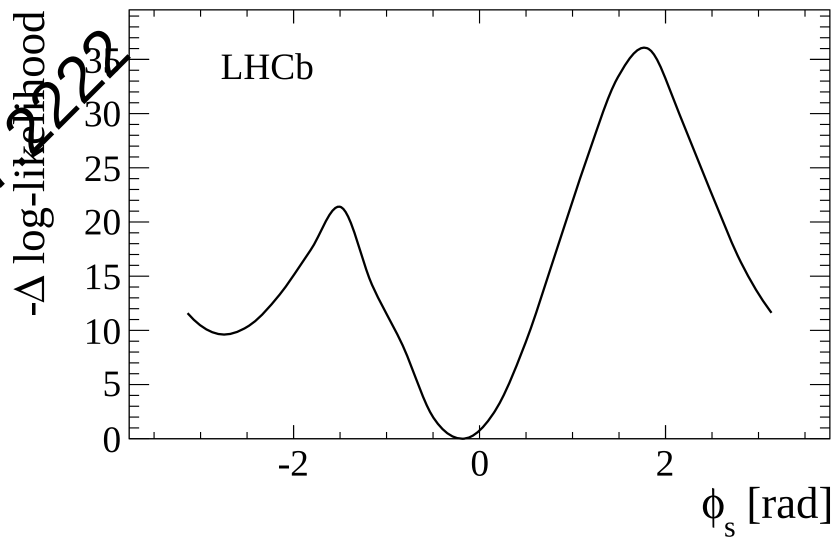
$B_s^0 \to \phi\phi$ Time Distribution

Decay time acceptance determine from topologically similar channel

$$B_s^0 \to D_s^-[K^+K^-\pi^-]\pi^+$$

Barely any S-wave K^+-K^- components (blue) seen





$\phi_s^{\text{eff}} = -0.17 \pm 0.15$ (stat) $\pm\, 0.03$ (syst), $|\lambda_{CP}| = 1.04 \pm 0.07$ (stat) $\pm\, 0.03$ (syst)

Consistent with Standard Model predictions

No indication of either type of CP violation

$B^{\pm} \to D[K^0_S K^{\pm} \pi^{\pm}] K^{\pm}$

Table 3: Absolute values of systematic uncertainties, in units of 10^{-2}, for the fit to the whole Dalitz plot.

Observable	Eff. correction	Fit PDFs	Prod. and det. asymms.	PID	Total
$\mathcal{R}_{\mathrm{SS/OS}}$	2.40	0.50	–	0.01	2.45
$\mathcal{R}_{DK/D\pi,\ \mathrm{SS}}$	0.01	0.38	–	0.02	0.38
$\mathcal{R}_{DK/D\pi,\ \mathrm{OS}}$	0.01	0.19	–	0.01	0.19
$\mathcal{A}_{\mathrm{SS},\ DK}$	0.14	0.44	1.71	0.01	1.78
$\mathcal{A}_{\mathrm{OS},\ DK}$	0.36	2.13	0.99	0.01	2.37
$\mathcal{A}_{\mathrm{SS},\ D\pi}$	0.02	0.05	0.99	< 0.01	0.99
$\mathcal{A}_{\mathrm{OS},\ D\pi}$	0.03	0.10	1.71	< 0.01	1.72

Table 4: Absolute values of systematic uncertainties, in units of 10^{-2}, for the fit in the restricted region.

Observable	Eff. correction	Fit PDFs	Prod. and det. asymms.	PID	Total
$\mathcal{R}_{\mathrm{SS/OS}}$	6.08	0.53	–	0.01	6.10
$\mathcal{R}_{DK/D\pi,\ \mathrm{SS}}$	0.01	0.25	–	0.02	0.25
$\mathcal{R}_{DK/D\pi,\ \mathrm{OS}}$	0.01	0.21	–	0.01	0.21
$\mathcal{A}_{\mathrm{SS},\ DK}$	0.13	2.27	1.71	0.01	2.85
$\mathcal{A}_{\mathrm{OS},\ DK}$	0.04	2.38	0.99	0.01	2.57
$\mathcal{A}_{\mathrm{SS},\ D\pi}$	0.04	0.17	0.99	< 0.01	1.00
$\mathcal{A}_{\mathrm{OS},\ D\pi}$	0.06	0.09	1.71	< 0.01	1.72

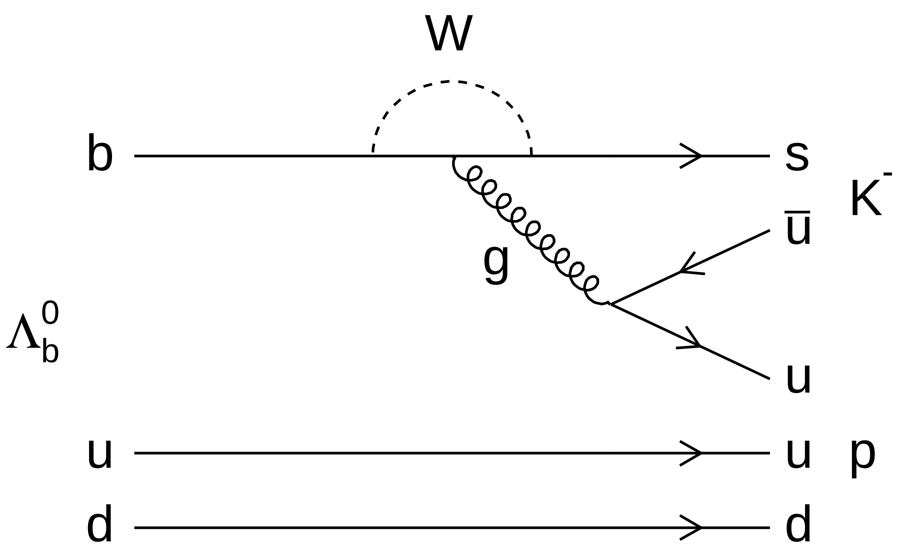
$\Lambda_b^0 \to \bar{K}^0 p \pi^-$

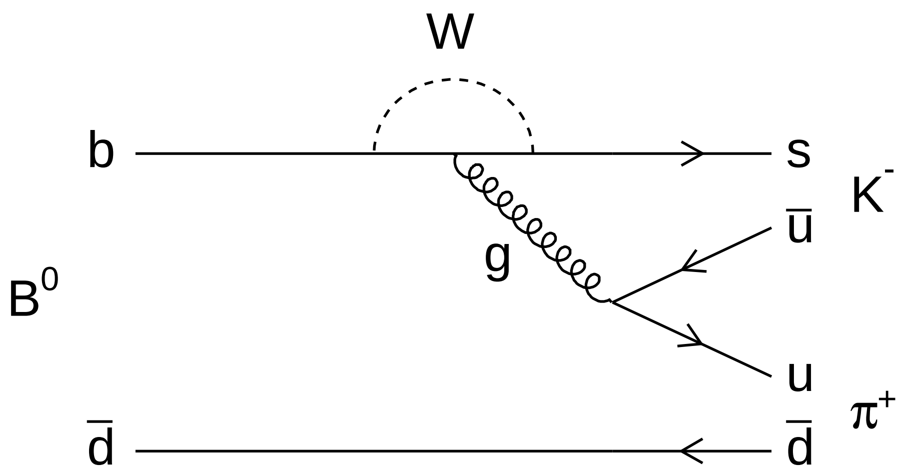
No hadronic charmless 3-body decays yet observed in b baryons

Interesting area to search for CP violating effects

Analogous to large CP violating effects in hadronic charmless 3-body B mesons decays

R. Aaij *et al*. (LHCb Collab.), PRL **111** (2013) 101801; PRL **112** (2014) 011801





Unknown heavy particle in the loop may cause unexpected CP violating effects

Potential for New Physics

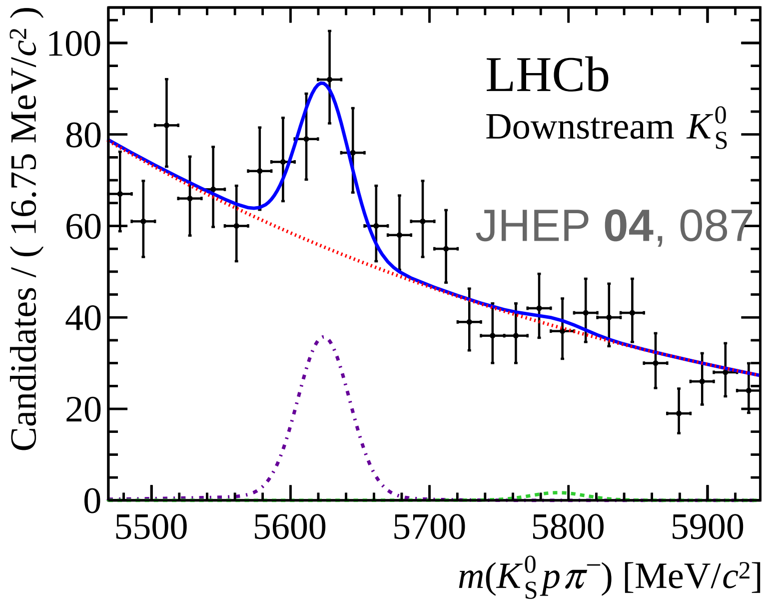
Results

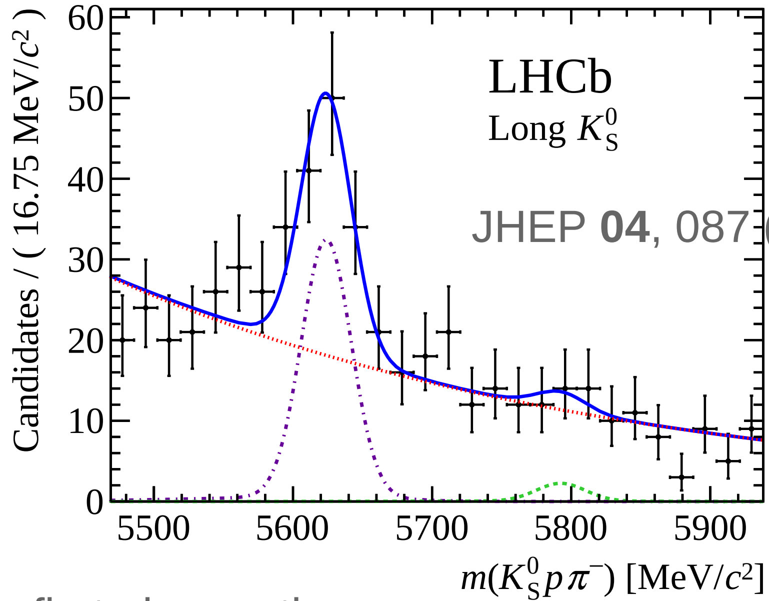
LHCb data sample of 1 fb^{-1} @ 7 TeV

R. Aaij *et al*. (LHCb Collab.), JHEP **04**, 087 (2014)

Veto significant background from $\Lambda_b^0 \rightarrow \Lambda_c^+[pK_S^0]h^-$

$B^0 \rightarrow K_S^0\pi^+\pi^-$ used as normalisation channel

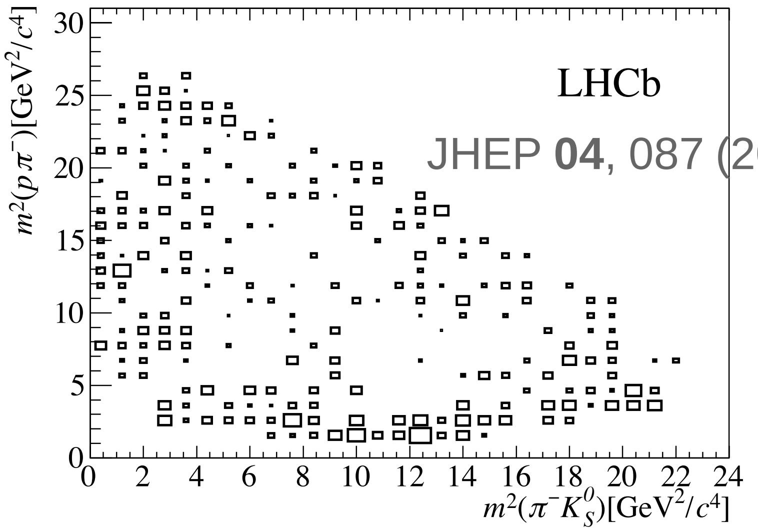




8.6σ significance including systematic uncertainties, first observation

Green curve shows concurrent search for Ξ_b^0 (usb) baryon, not significant

Results



JHEP **04**, 087 (2014)

Background subtracted $\Lambda_b^0 \to \bar{K}^0 p \pi^-$ Dalitz plot

Signal detection efficiency weighted by Dalitz plot

No clear peaking structure except for low $p\pi^-$ mass

Could be from excited nucleon states

$$\mathcal{B}(\Lambda_b^0 \to \bar{K}^0 p \pi^-) = (1.26 \pm 0.19 \pm 0.09 \pm 0.34 \pm 0.05) \times 10^{-5}$$

Uncertainties 1: statistical, 2: systematic, 3: $f_{\Lambda_b^0}/f_d$, 4: $\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)$

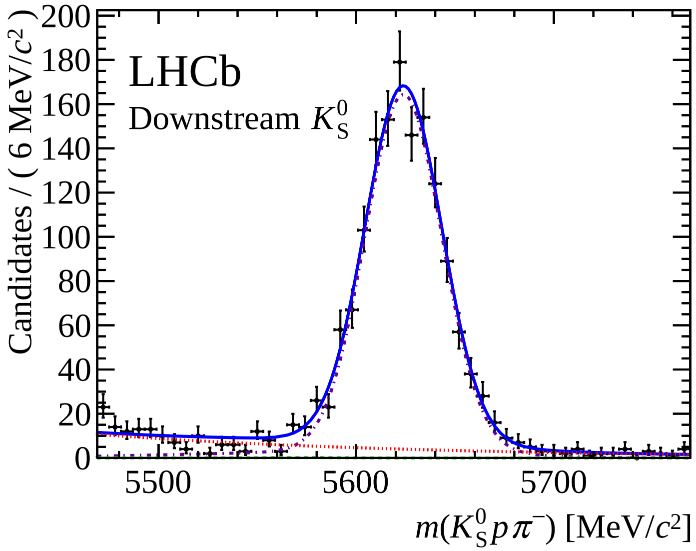
Measure integrated direct CP violation over the Dalitz plot

$$\mathcal{A}_{CP}^{\mathrm{Raw}} = (N_{\bar{f}} - N_f)/(N_{\bar{f}} + N_f)$$

Remove production and detection asymmetries with $\Lambda_b^0 \to \Lambda_c^+[\bar{K}^0 p]\pi^-$ control sample

$\mathcal{A}_{CP}(\Lambda_b^0 \to \bar{K}^0 p \pi^-) = 0.22 \pm 0.13$ (stat) $\pm\ 0.03$ (syst)

$\Lambda_b^0 \to \Lambda_c^+[\bar{K}^0 p]\pi^-$



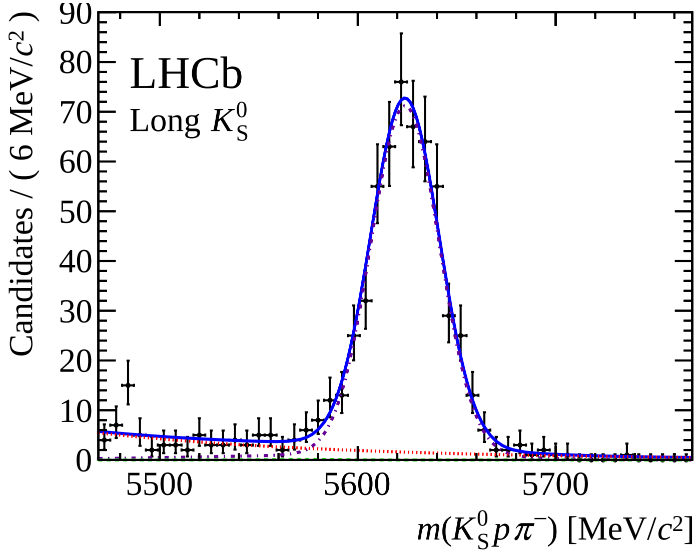
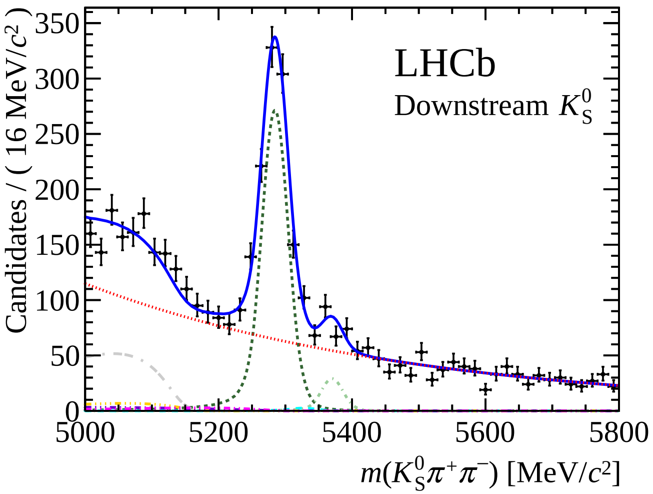


Table 1: Fitted yields and efficiency for each channel, separated by K_S^0 type. Yields are given with both statistical and systematic uncertainties, whereas for the efficiencies only the uncertainties due to the limited Monte Carlo sample sizes are given. The three rows for the $B^0 \to K_S^0\pi^+\pi^-$ decay correspond to the different BDT selections for charmless signal modes and the channels containing Λ_c^+ or D_s^- hadrons.

Mode	Downstream		Long	
	Yield	Efficiency ($\times10^{-4}$)	Yield	Efficiency ($\times10^{-4}$)
$\Lambda_b^0 \to K_S^0 p\pi^-$	$106.1 \pm 21.5 \pm 3.7$	5.40 ± 0.12	$90.9 \pm 14.6 \pm 1.0$	2.26 ± 0.06
$\Lambda_b^0 \to K_S^0 pK^-$	$11.5 \pm 10.7 \pm 1.2$	5.34 ± 0.11	$19.6 \pm 8.5 \pm 0.8$	2.87 ± 0.07
$\Xi_b^0 \to K_S^0 p\pi^-$	$5.3 \pm 15.7 \pm 0.7$	5.35 ± 0.10	$6.4 \pm 8.5 \pm 0.5$	2.67 ± 0.07
$\Xi_b^0 \to K_S^0 pK^-$	$10.5 \pm 8.8 \pm 0.5$	6.12 ± 0.10	$6.3 \pm 5.6 \pm 0.4$	2.91 ± 0.07
$\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)\pi^-$	$1391.6 \pm 39.6 \pm 24.8$	4.85 ± 0.09	$536.8 \pm 24.6 \pm 3.5$	1.71 ± 0.05
$\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)K^-$	$70.0 \pm 10.3 \pm 3.3$	4.69 ± 0.07	$37.4 \pm 7.1 \pm 2.7$	1.66 ± 0.03
$\Lambda_b^0 \to D_s^- p$	$6.3 \pm 5.1 \pm 0.6$	2.69 ± 0.05	$6.5 \pm 3.7 \pm 0.2$	0.89 ± 0.03
$B^0 \to K_S^0\pi^+\pi^-$ ($K_S^0 ph$)	$913.5 \pm 45.0 \pm 12.2$	5.57 ± 0.09	$495.7 \pm 31.8 \pm 7.5$	2.86 ± 0.06
$B^0 \to K_S^0\pi^+\pi^-$ ($\Lambda_c^+ h$)	$1163.8 \pm 60.7 \pm 18.8$	7.38 ± 0.11	$589.0 \pm 33.3 \pm 17.3$	3.27 ± 0.06
$B^0 \to K_S^0\pi^+\pi^-$ ($D_s^- p$)	$1317.8 \pm 77.1 \pm 25.7$	7.76 ± 0.11	$614.1 \pm 38.3 \pm 14.8$	3.47 ± 0.07

$\Lambda_b^0 \to \bar{K}^0 p\pi^-$

Control sample $B^0 \to K^0\pi^+\pi^-$ with selection criteria of $\Lambda_b^0 \to \bar{K}^0 p\pi^-$



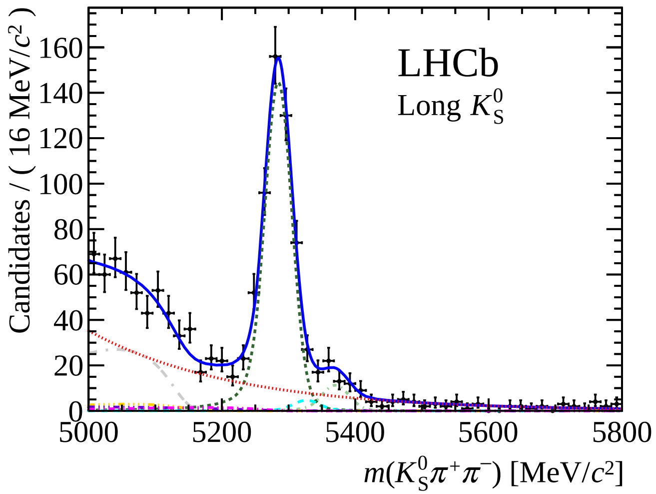


Table 2: Relative systematic uncertainties on the branching fraction ratios (%) with respect to $B^0 \to K_S^0\pi^+\pi^-$ decays. The total is obtained from the sum in quadrature of all contributions except that from knowledge of the fragmentation fractions.

Downstream	Simulation	Δ_{PHSP}	PID	Fit model	Fit bias	Vetoes	Total	$f_{\Lambda_b^0}/f_d$
$\mathcal{B}(\Lambda_b^0 \to K_S^0 p\pi^-)$	6	4	6	1	<1	3	10	27
$\mathcal{B}(\Lambda_b^0 \to K_S^0 pK^-)$	6	58	2	8	4	4	59	27
$\mathcal{B}(\Xi_b^0 \to K_S^0 p\pi^-)$	4	64	6	12	7	–	66	–
$\mathcal{B}(\Xi_b^0 \to K_S^0 pK^-)$	4	47	2	4	3	–	47	–
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)\pi^-)$	5	–	6	2	<1	<1	8	27
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)K^-)$	5	–	4	5	<1	1	8	27
$\mathcal{B}(\Lambda_b^0 \to D_s^-(\to K_S^0 K^-)p)$	6	–	6	7	6	–	12	27
Long								
$\mathcal{B}(\Lambda_b^0 \to K_S^0 p\pi^-)$	6	3	4	2	1	<1	8	27
$\mathcal{B}(\Lambda_b^0 \to K_S^0 pK^-)$	6	42	4	4	1	1	43	27
$\mathcal{B}(\Xi_b^0 \to K_S^0 p\pi^-)$	5	47	5	8	2	–	49	–
$\mathcal{B}(\Xi_b^0 \to K_S^0 pK^-)$	5	37	5	6	4	–	39	–
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)\pi^-)$	6	–	4	3	<1	<1	8	27
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)K^-)$	5	–	6	8	1	<1	11	27
$\mathcal{B}(\Lambda_b^0 \to D_s^-(\to K_S^0 K^-)p)$	6	–	8	4	2	–	11	27