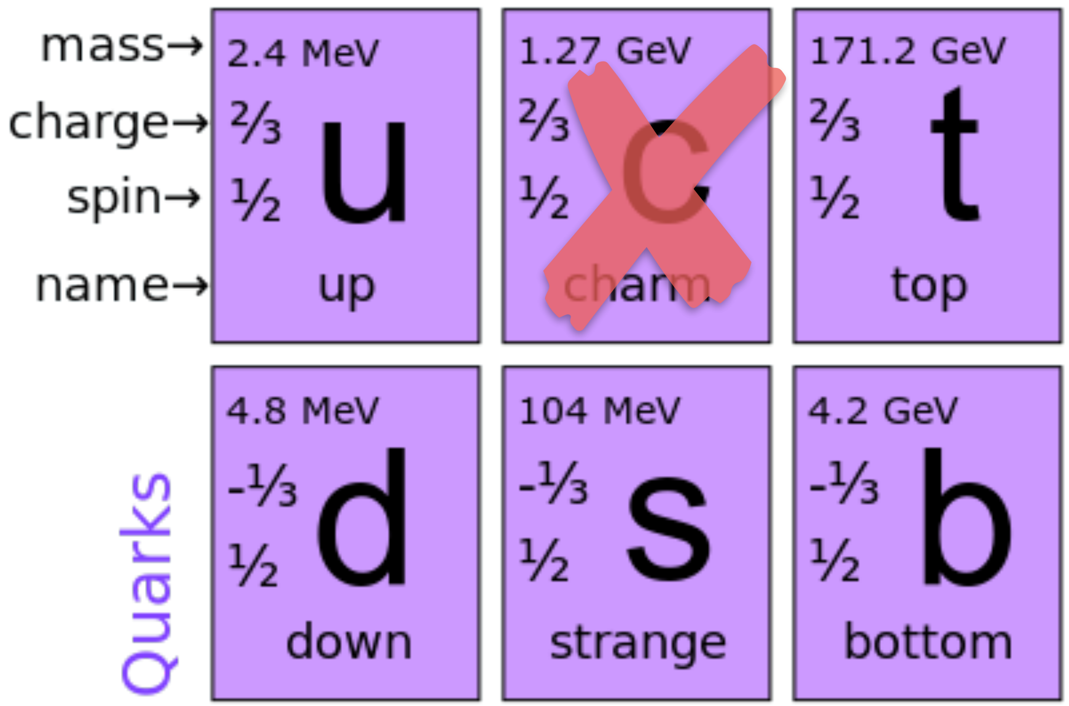
CP violation in charmless hadronic B decays

Wenbin Qian
University of Warwick

UK Flavour 2017, Durham

Charmless b decays



No charm quark in final state particles

~ 1% of b decay

Large CPV from mixing and decay or with other diagrams from different resonant structures over Dalitz plot

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

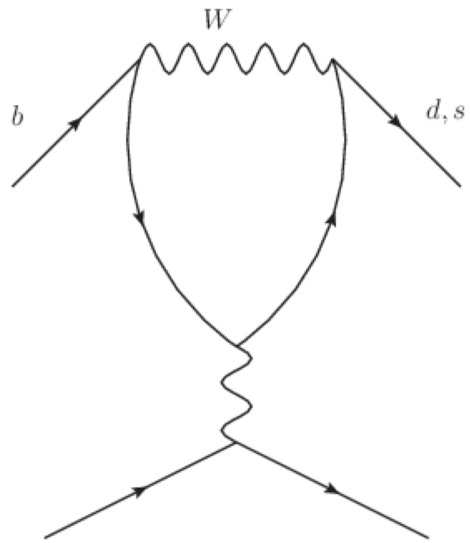
P + T

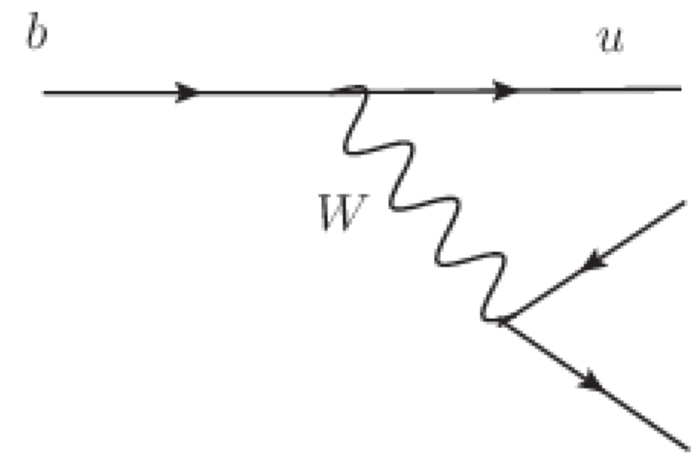
$$b \to d\bar{u}u$$

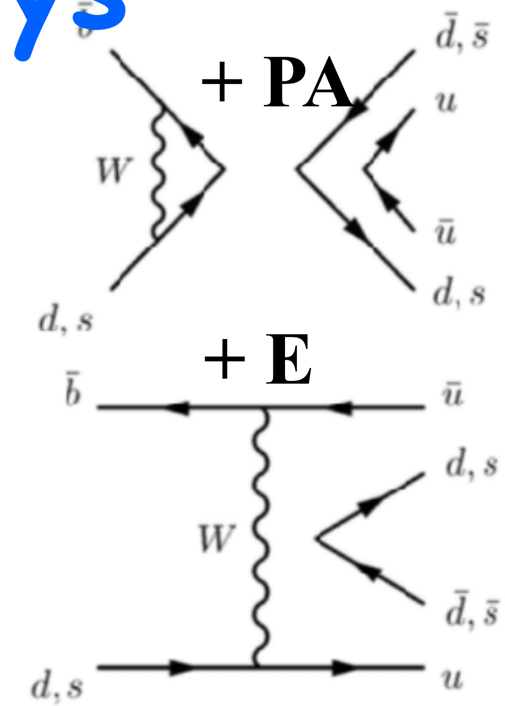
$b \to s\bar{d}d$	$b \to s\bar{s}s$
P	**P**
$b \to d\bar{s}s$	$b \to d\bar{d}d$

U-spin related

CPV in charmless B decays







$|V_{td}|e^{i\beta}$ or $-|V_{ts}|e^{-i\beta_s}$ $|V_{ub}|e^{-i\gamma}$

+ New Physics

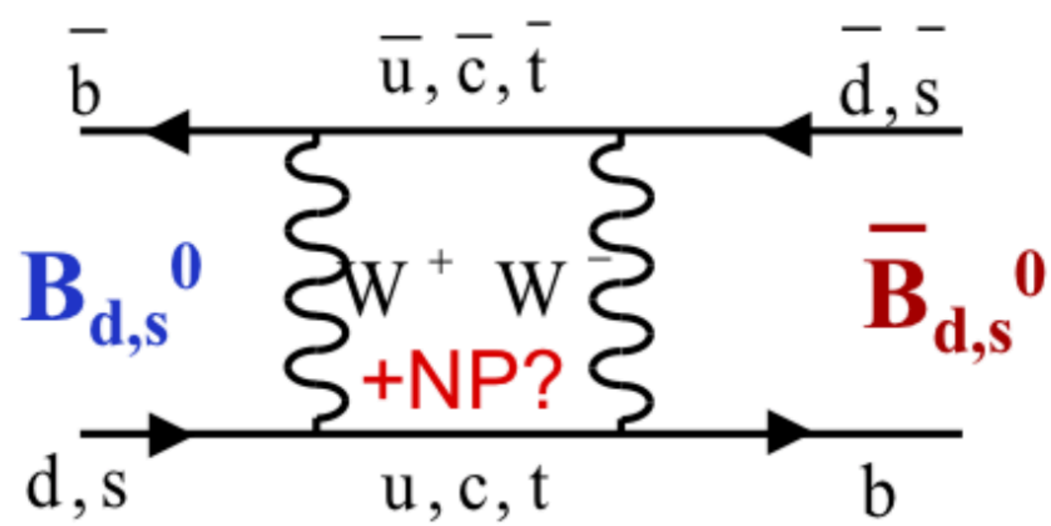
- **CPV appears when there are two competitive contributions:**

$$A = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)} \qquad \bar{A} = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

- **Additional weak phase through mixing**

- **QCD plays an important role in the game**



$|V_{td}|^2 e^{-2i\beta}$ or $|V_{ts}|^2 e^{2i\beta_s}$

Two body charmless B decays

- ➢ **Main contributions for $B^0 \to K^+K^-$ and $B_s \to \pi^+\pi^-$, $\pi^0\pi^0$: PA/E processes, very rare decay; two charged modes have been found by LHCb recently**

  PRL 118 (2017) 081801, JHEP 10 (2012) 037

- ➢ **While $B_s \to K_s\pi^0$, $\pi^0\pi^0$ not observed yet, other decay modes are extensively studied by B factories and LHCb**

- ➢ **$B \to \pi\pi$ system: extract CKM angle α through Isospin relationship**

  arXiv:1705.02981

- ➢ **$B \to \pi\pi$, $B_s \to K^+K^-$ system: extract CKM angle γ and $2\beta_s$ through U-spin and U-spin + Isospin analyses**

  PLB 741 (2015) 1 and references therein

- ➢ **Recently, Belle has updated the Branching fraction and A_{CP} measurements on $B^0 \to \pi^0\pi^0$ and LHCb on $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$**

Measurements on $B^0 \to \pi^0\pi^0$ from Belle

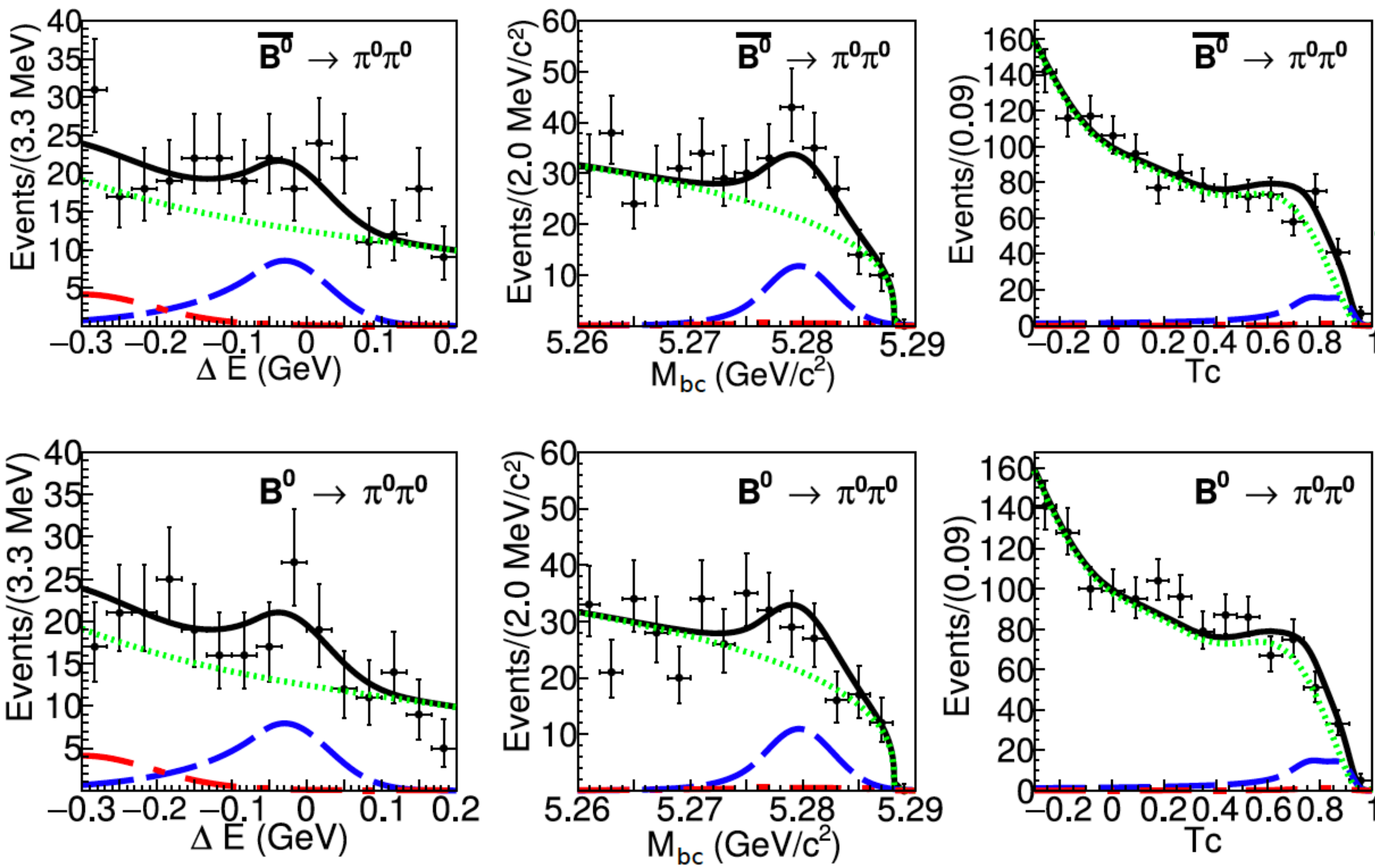
➢ **Measurements with 752×10^6 $B\bar{B}$ (693 fb^{-1}) to replace previous results; Time-integrated measurements; initial flavor from the other B**

$$\Delta E = E_B^* - E_{BEAM}^*$$

$$M_{bc} = \sqrt{E_{BEAM}^{*2} - \vec{p}_B^{\,*2}}$$

Fisher + angle info.

arXiv: 1705.02083



Continuum background

Signal

$B^+ \to \rho^+\pi^0$ and others

Projections in signal enhanced areas of other two variables

Results from $B^0 \to \pi^0\pi^0$

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.31 \pm 0.19 \pm 0.18) \times 10^{-6}$$

arXiv: 1705.02083

$$\mathcal{A}_{CP} = +0.14 \pm 0.36 \pm 0.12$$

Some recent Predictions:

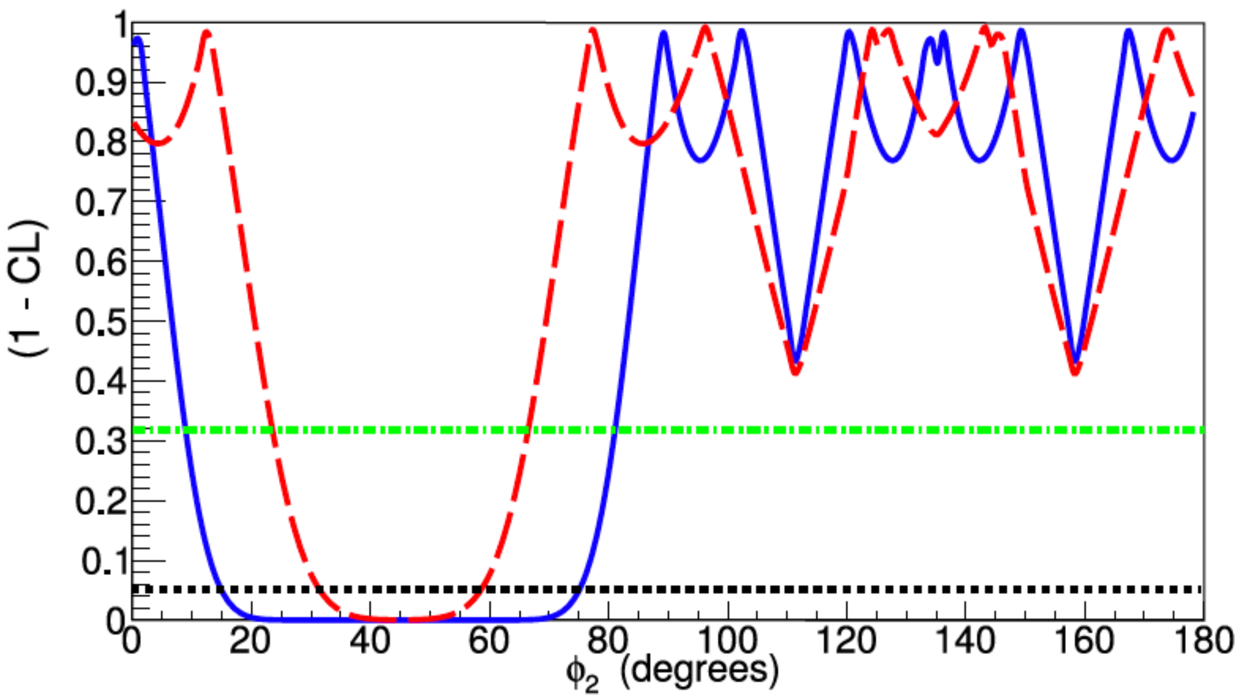
$$Br(B^0 \to \pi^0\pi^0) = [0.23^{+0.08}_{-0.05}(\omega_b)^{+0.05}_{-0.04}(f_B)^{+0.04}_{-0.03}(a_2^\pi)] \times 10^{-6},$$ PRD 90 (2014) 014029

$$\mathcal{B}(B_d \to \pi^0\pi^0)|_{\text{PMC}} = \left(0.98^{+0.44}_{-0.31}\right) \times 10^{-6},$$ PLB 749 (2015) 422

$$\text{Br}(\bar{B}^0(B^0) \to \pi^0\pi^0) = (1.17^{+0.11}_{-0.12}) \times 10^{-6}.$$ PRD 95 (2017) 034023

Measured values lower and predicted values higher, though still have tensions

α excluded at 95% for [15.5°, 75°]



+ Belle results on $B^0 \to \pi^+\pi^-$ and $B^+ \to \pi^+\pi^0$

Previous from Belle

- PRD 88 (2013) 092003
- PRL 94 (2005) 181803 (253 fb^{-1})
- PRD 87 (2013) 031103(R)

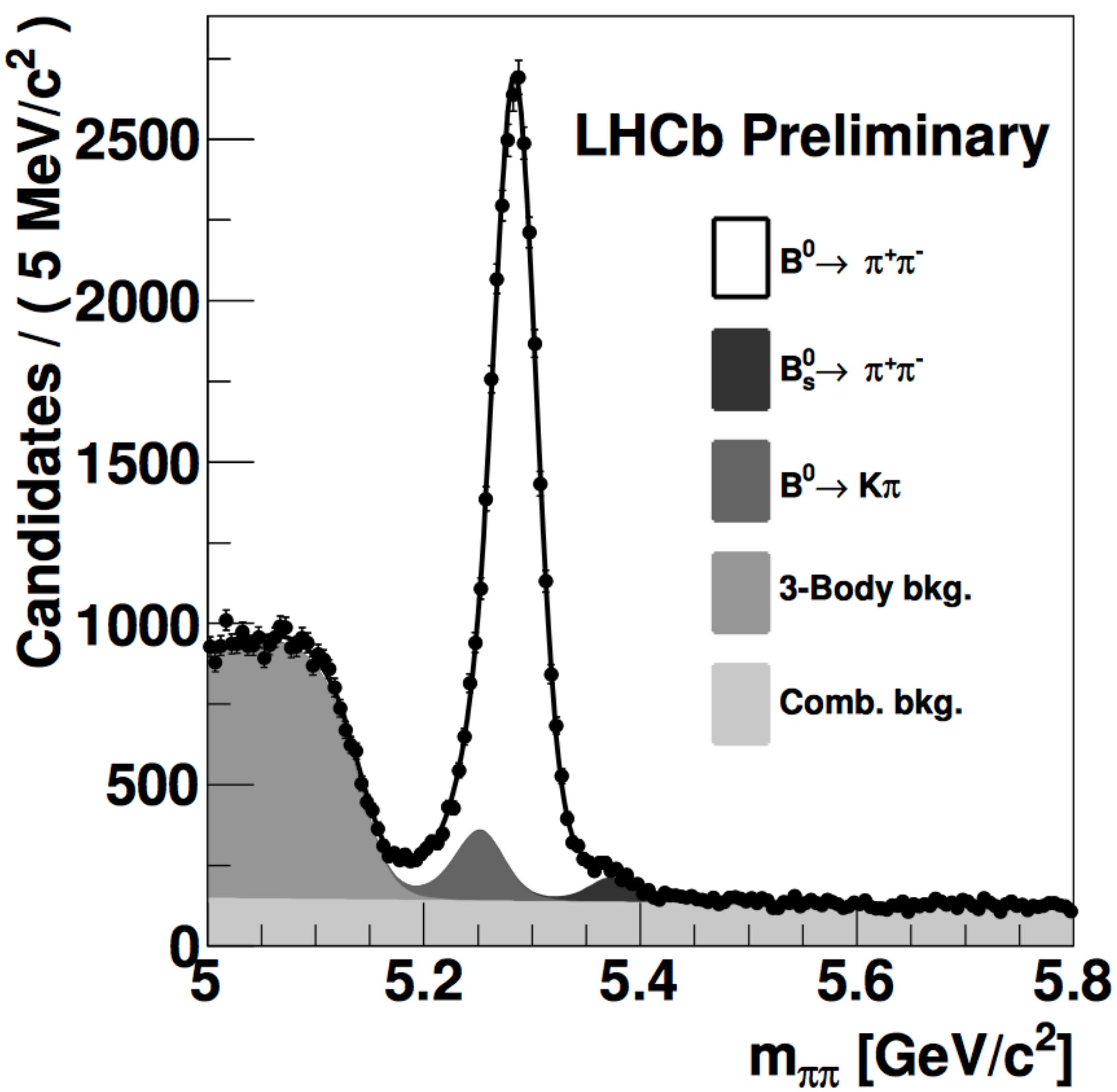
Including new results

$B^0 \to \pi\pi$ and $B_s \to KK$ measurements from LHCb

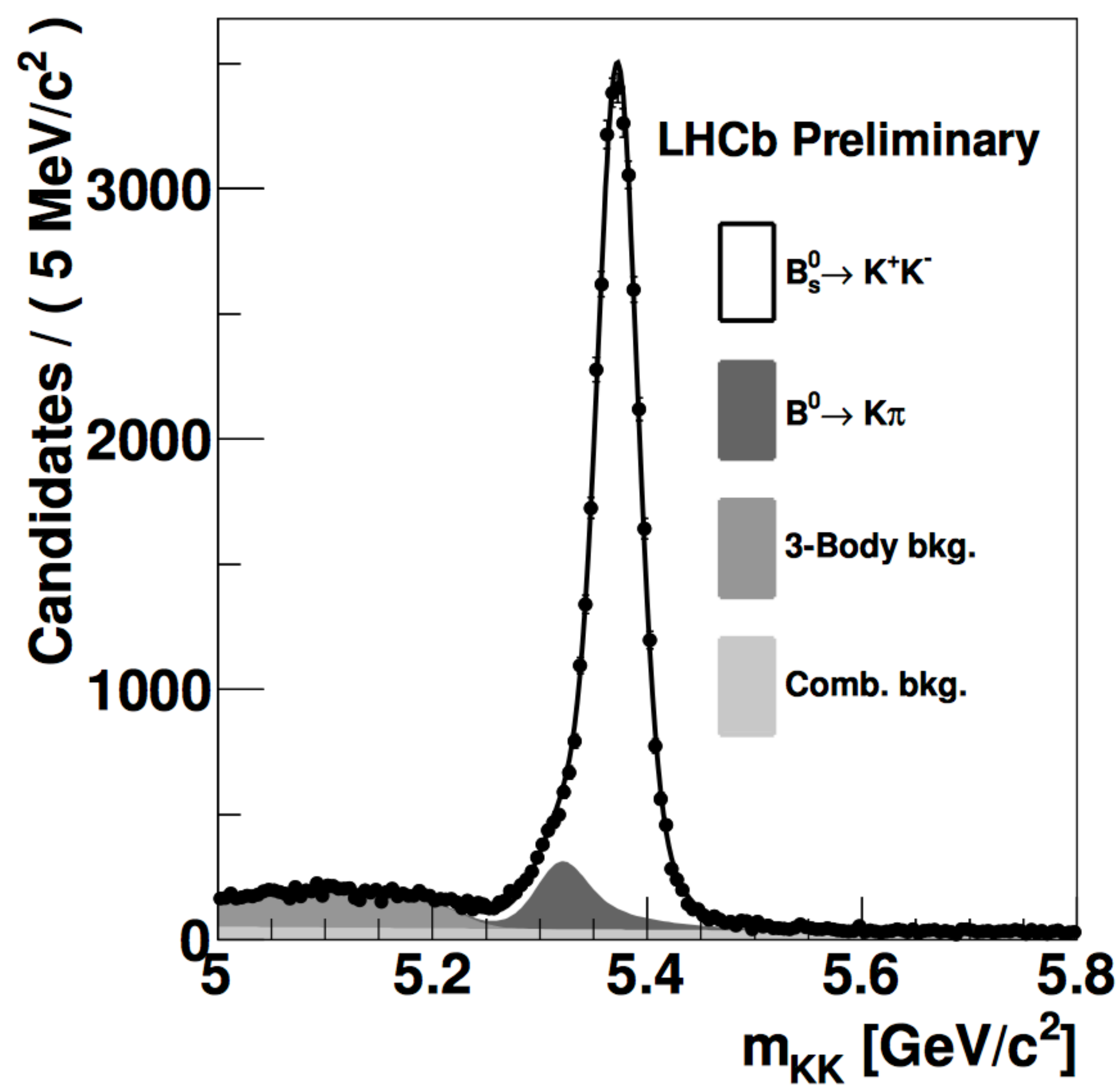
LHCb-CONF-2016-018

- Time-dependent analysis with 3 fb^{-1} data;

$B^0 \to \pi^+\pi^-$ 28652±226



$B_s \to K^+K^-$ 36840±222



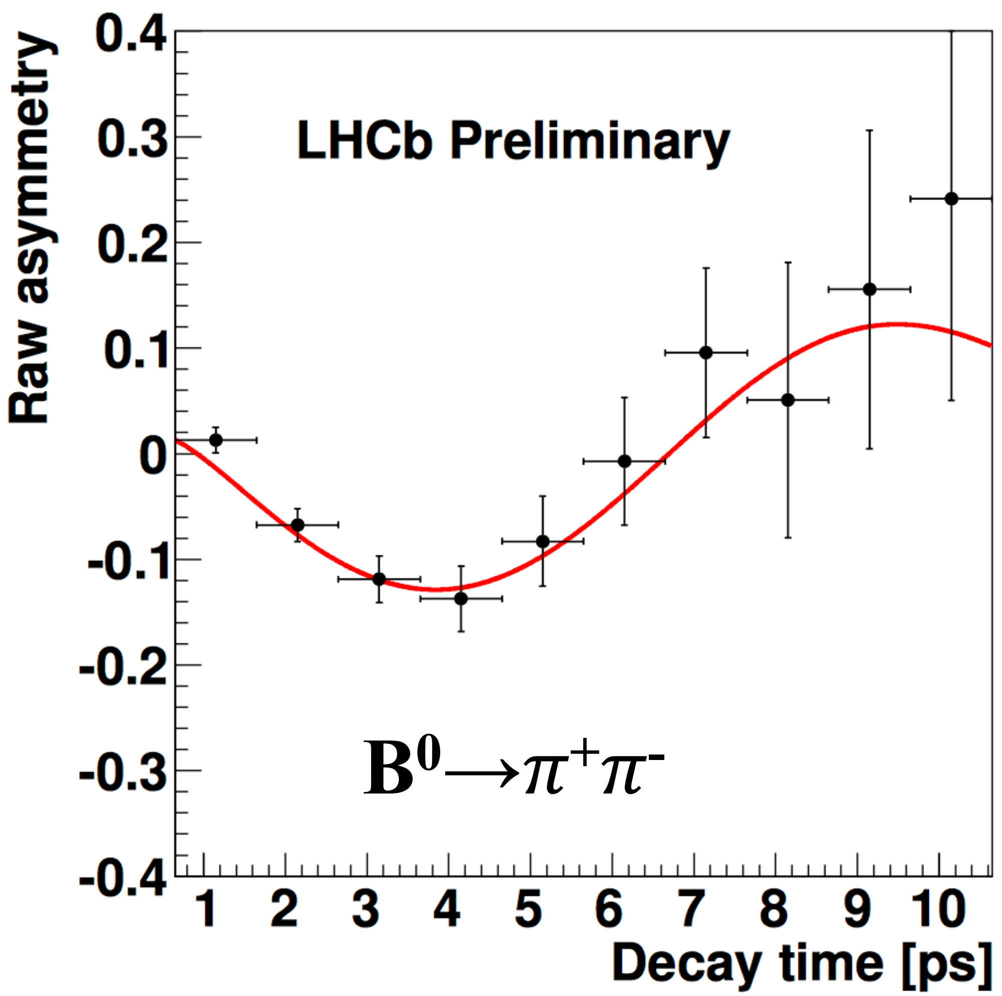
- Production asymmetries of $B_{d(s)}$ determined from $B_{d(s)} \to K\pi$

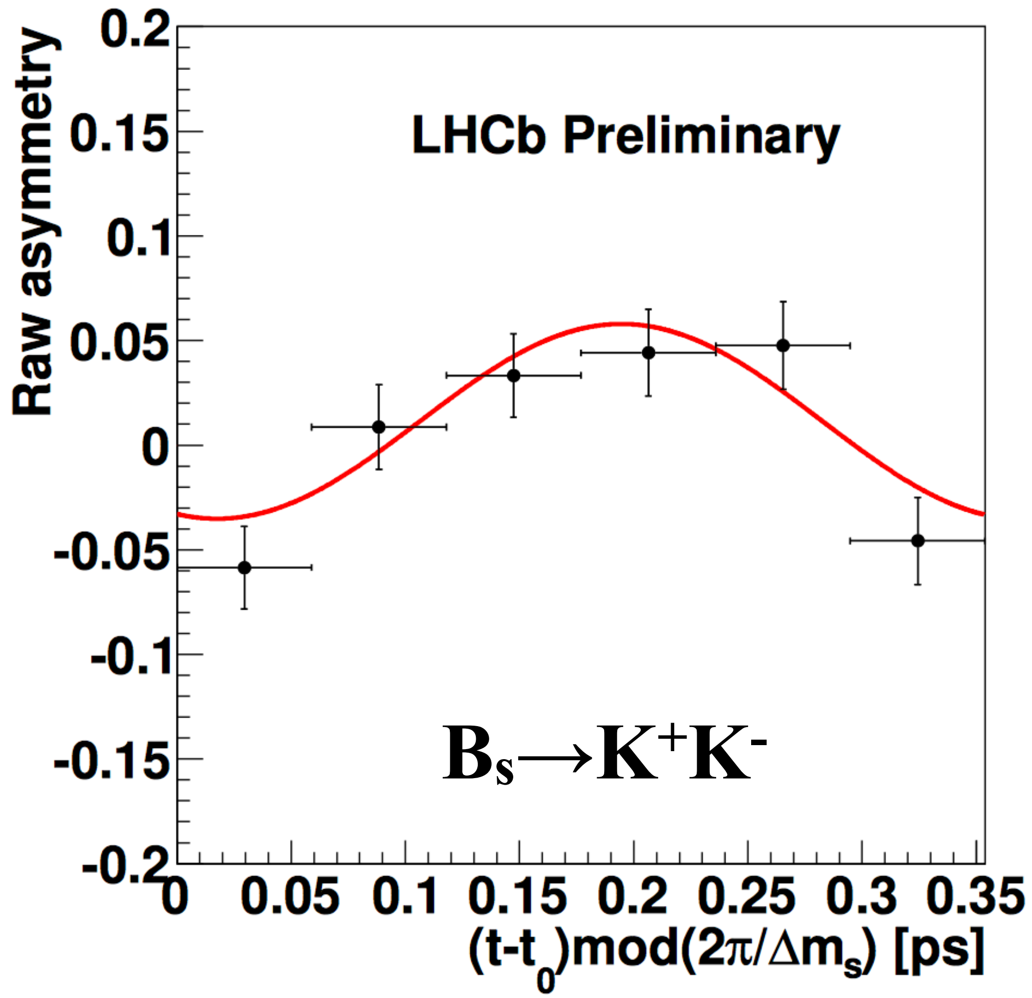
Time dependent asymmetries

LHCb-CONF-2016-018

➢ $\Delta m_{d(s)}$, $\Delta\Gamma_{d(s)}$ and $\Gamma_{d(s)}$ fixed from measured values

$$\mathcal{A}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f\cos(\Delta m_{d,s}t) + S_f\sin(\Delta m_{d,s}t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right)},$$





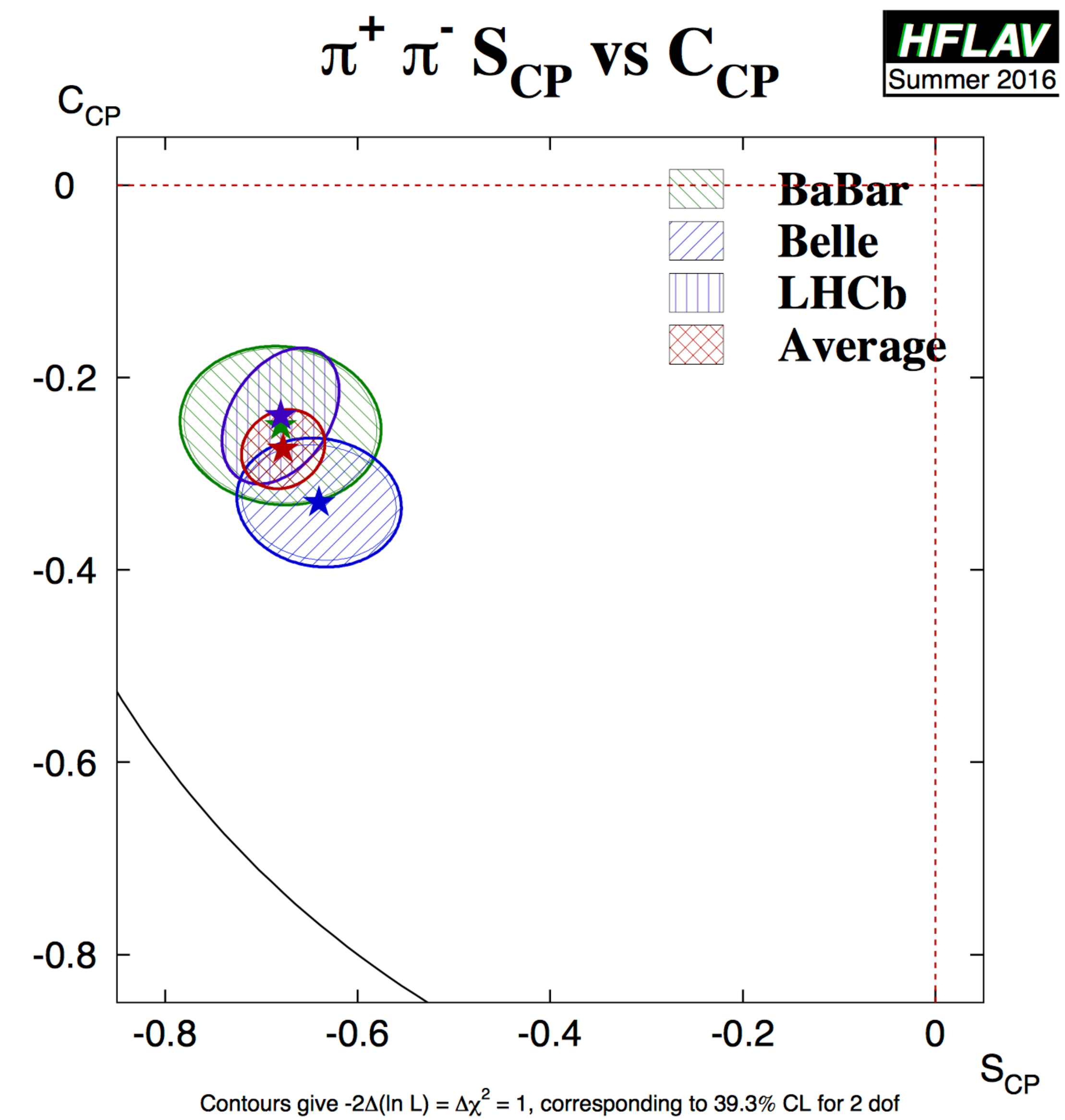
➢ $B_{(s)}\to K\pi$ used for calibration channels of flavor tagging

Results from $B^0 \to \pi\pi$ and $B_s \to KK$ measurements

LHCb-CONF-2016-018

$$C_{\pi^+\pi^-} = -0.24 \pm 0.07 \pm 0.01,$$
$$S_{\pi^+\pi^-} = -0.68 \pm 0.06 \pm 0.01,$$
$$C_{K^+K^-} = 0.24 \pm 0.06 \pm 0.02, \quad 3.6\sigma$$
$$S_{K^+K^-} = 0.22 \pm 0.06 \pm 0.02, \quad 3.3\sigma$$
$$A^{\Delta\Gamma}_{K^+K^-} = -0.75 \pm 0.07 \pm 0.11,$$

Evidence of CPV for B_s mode at 4.6σ



arXiv:1612.07233

- **Recent updates into paper ongoing (3 fb^{-1}):**

BDT selections re-optimized to gain more statistic power

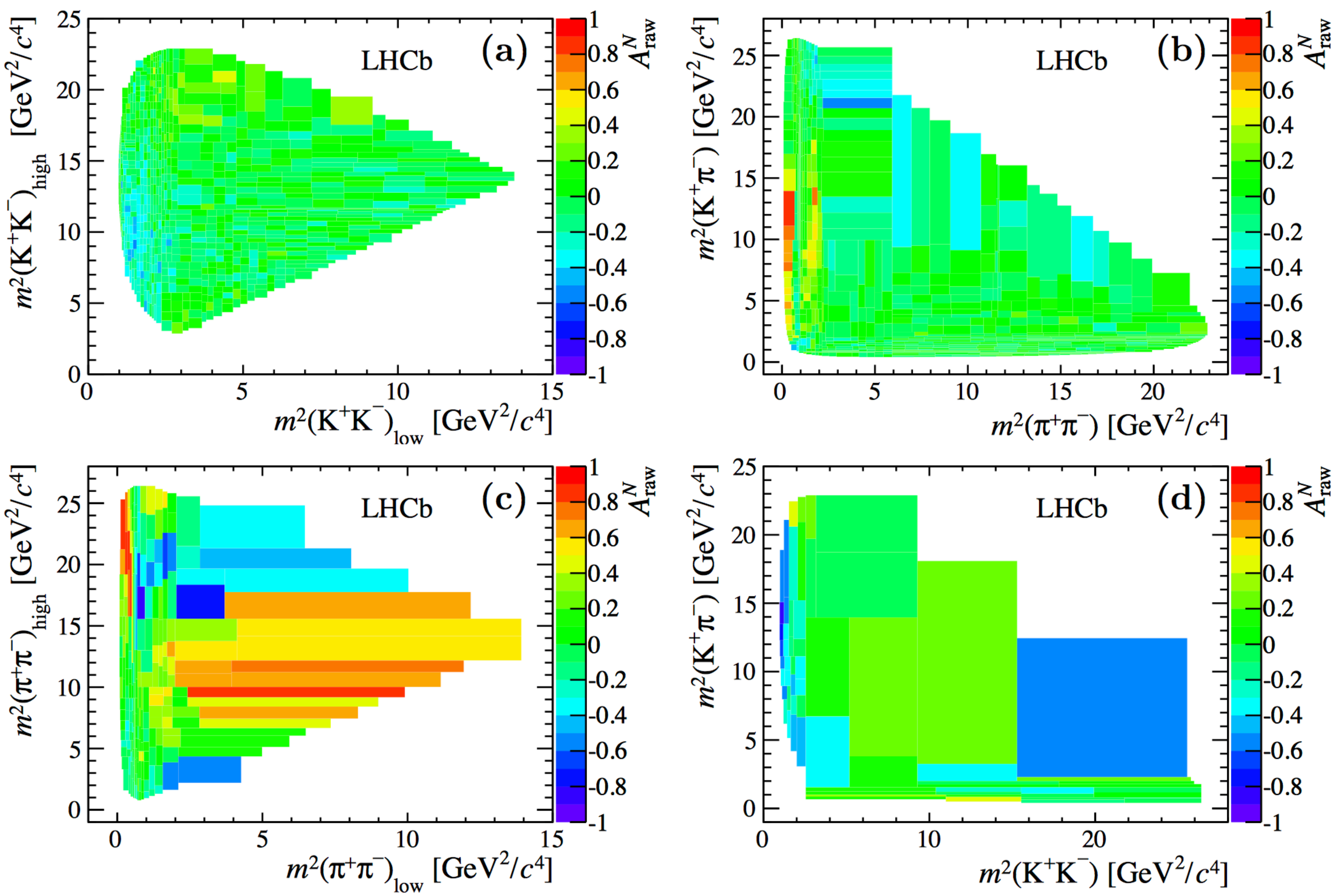
Adding SS flavor taggers

Three body charmless B decays

➢ Three body $B_{d(s)}$ charmless decays involve one or more neutral final state (π^0 or K_s): extensively studied by B factories with limited statistics; π^0 mode hard for LHCb but not fully impossible

➢ Three body B^- charmless decays with charged final states much easier experimentally; increasing interests after LHCb's CPV measurements over Dalitz plot

PRD 90, 112004 (2014)



➢ Amplitude analyses needed to extract CPV information; $B\to\pi\pi\pi$, $K\pi\pi$ and KKK have been performed by B factories

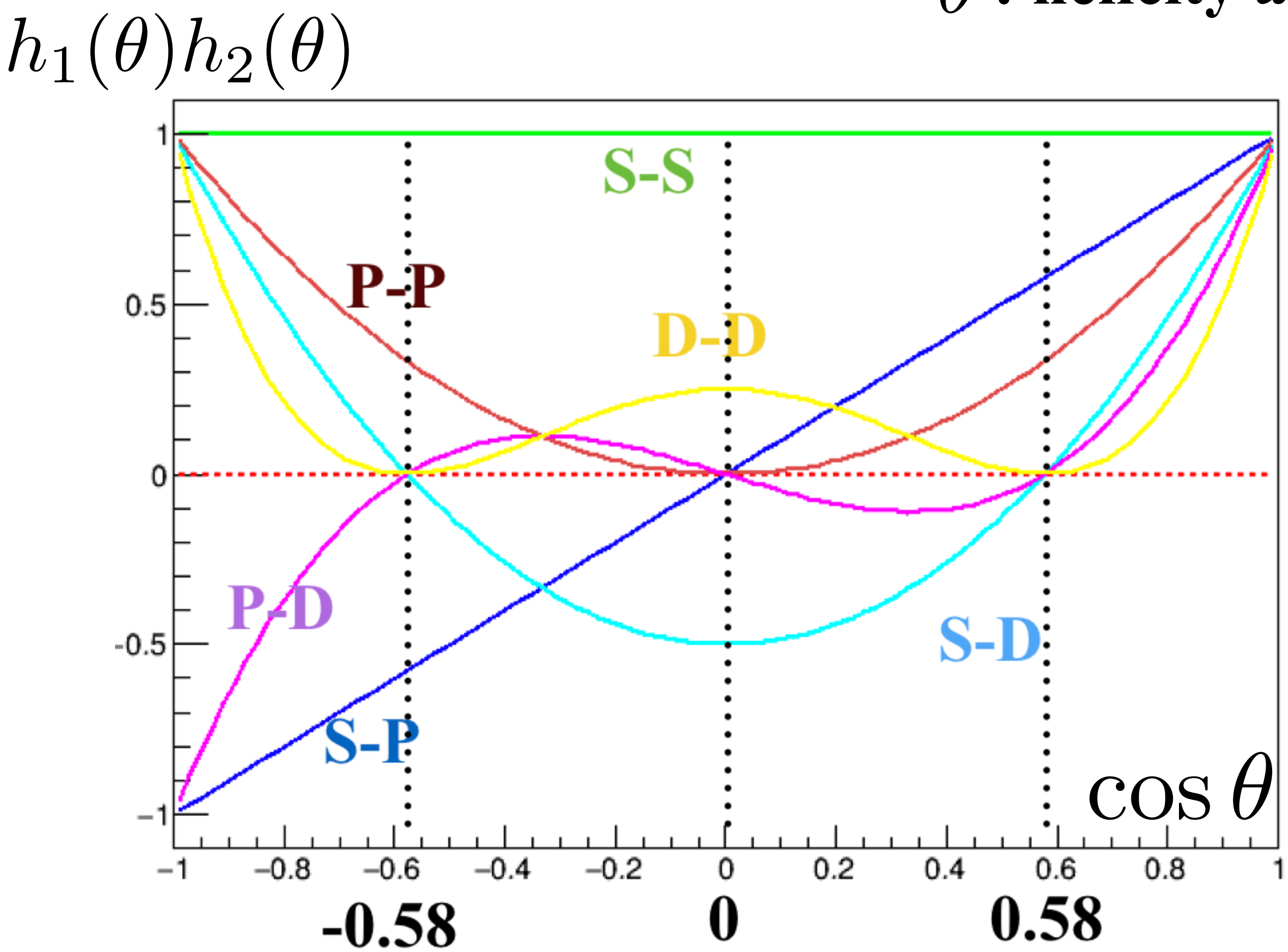
➢ Large data set collected by LHCb will show more interesting results

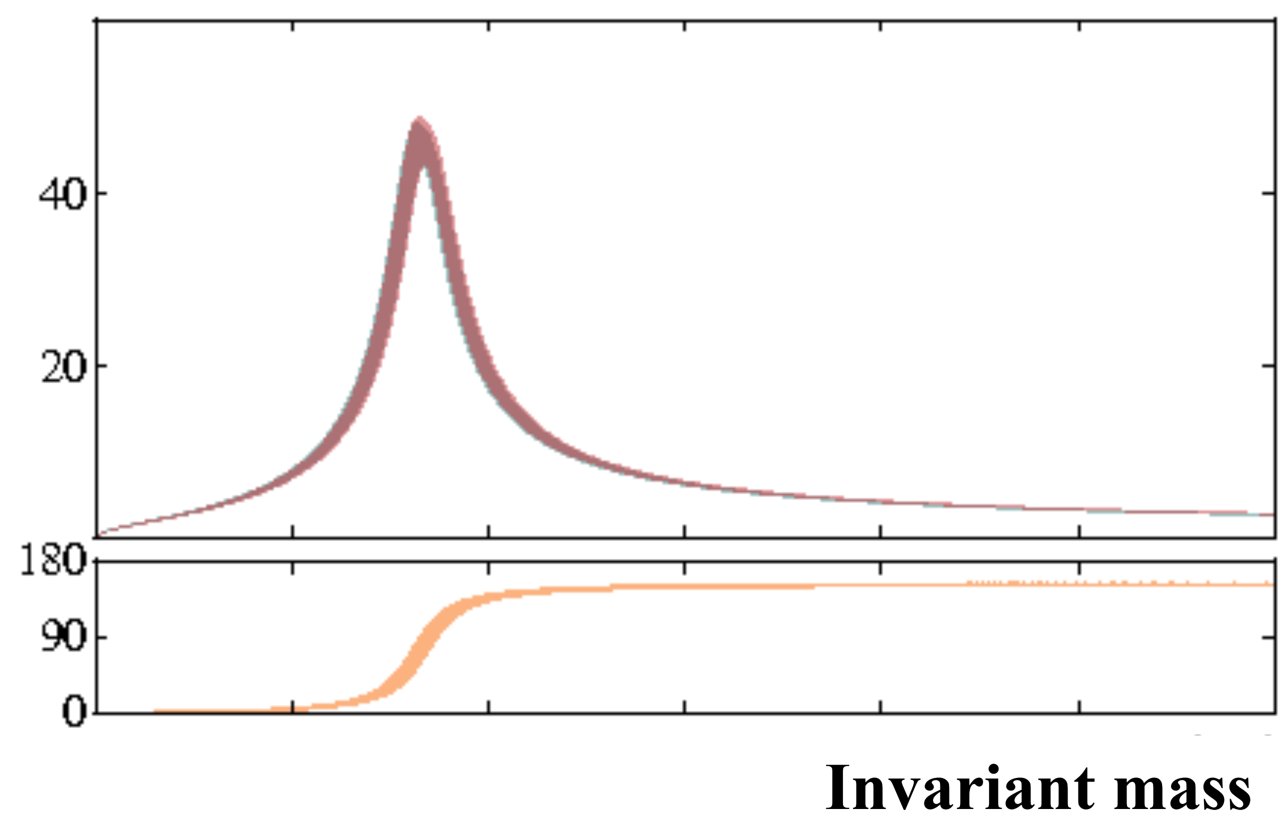
Resonant effect over Dalitz plot

- Full version of A_{CP} in slide 3 (also including angular distributions)

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{2a_1 a_2 h_1(\theta) h_2(\theta) \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)}{a_1^2 h_1^2(\theta) + a_2^2 h_2^2(\theta) + 2a_1 a_2 h_1(\theta) h_2(\theta) \cos(\delta_1 - \delta_2) \cos(\phi_1 - \phi_2)}$$

θ : **helicity angle** $h(\theta)$: **angular distribution of resonance**





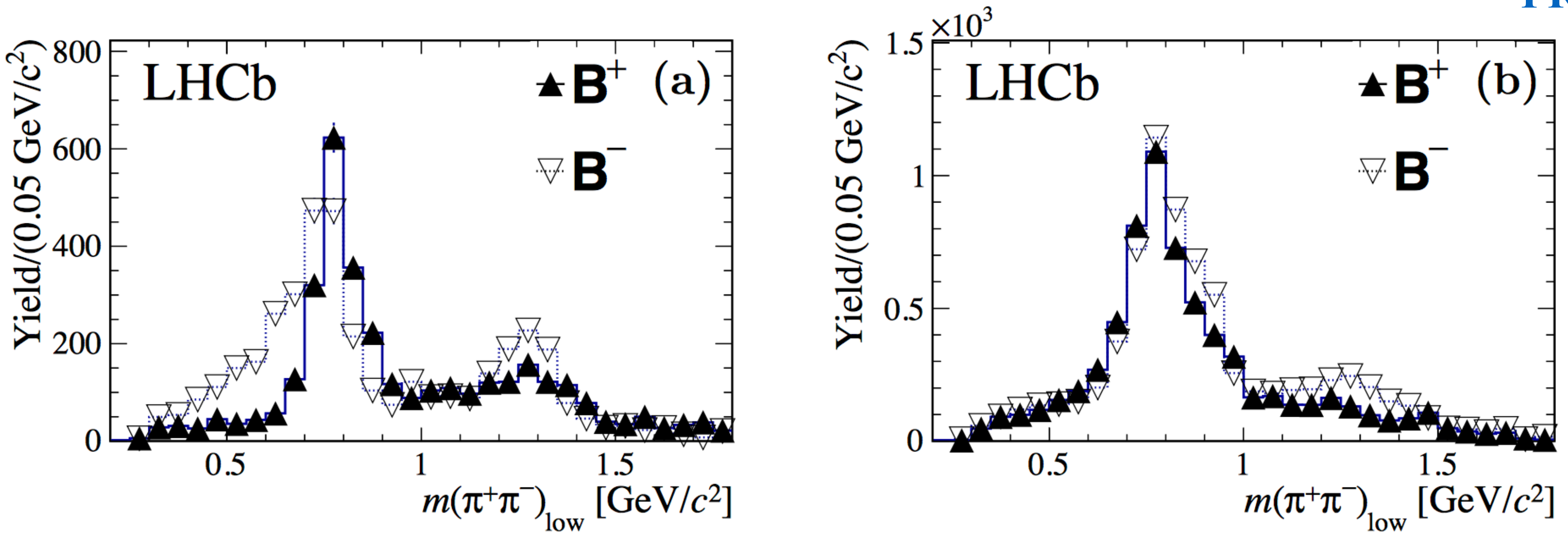
- 180° phase changing for Breit-Wigner ➜ CPV sign flip

- CPV sign flip when different wave (S-P, S-D, P-D etc) components interference

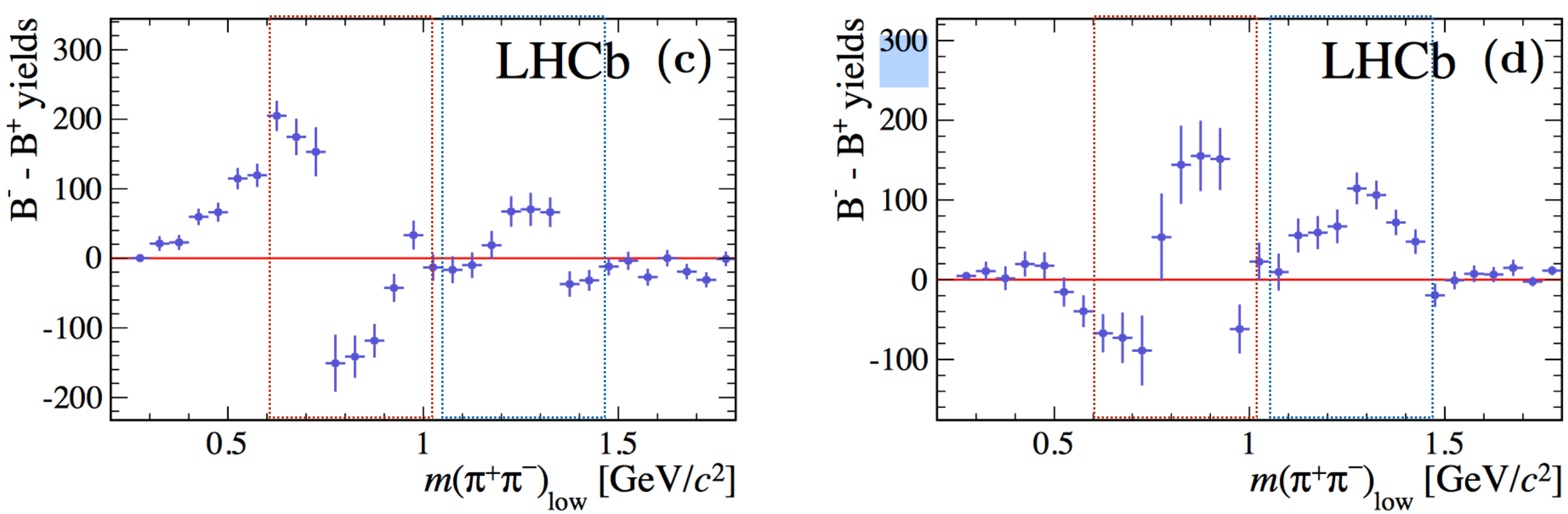
An Example: P-S interference

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{2a_1 a_2 h_1(\theta) h_2(\theta)\sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)}{a_1^2 h_1^2(\theta) + a_2^2 h_2^2(\theta) + 2a_1 a_2 h_1(\theta) h_2(\theta)\cos(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2)}$$

PRD 90, 112004 (2014)



RBW phase shift **RBW phase shift**

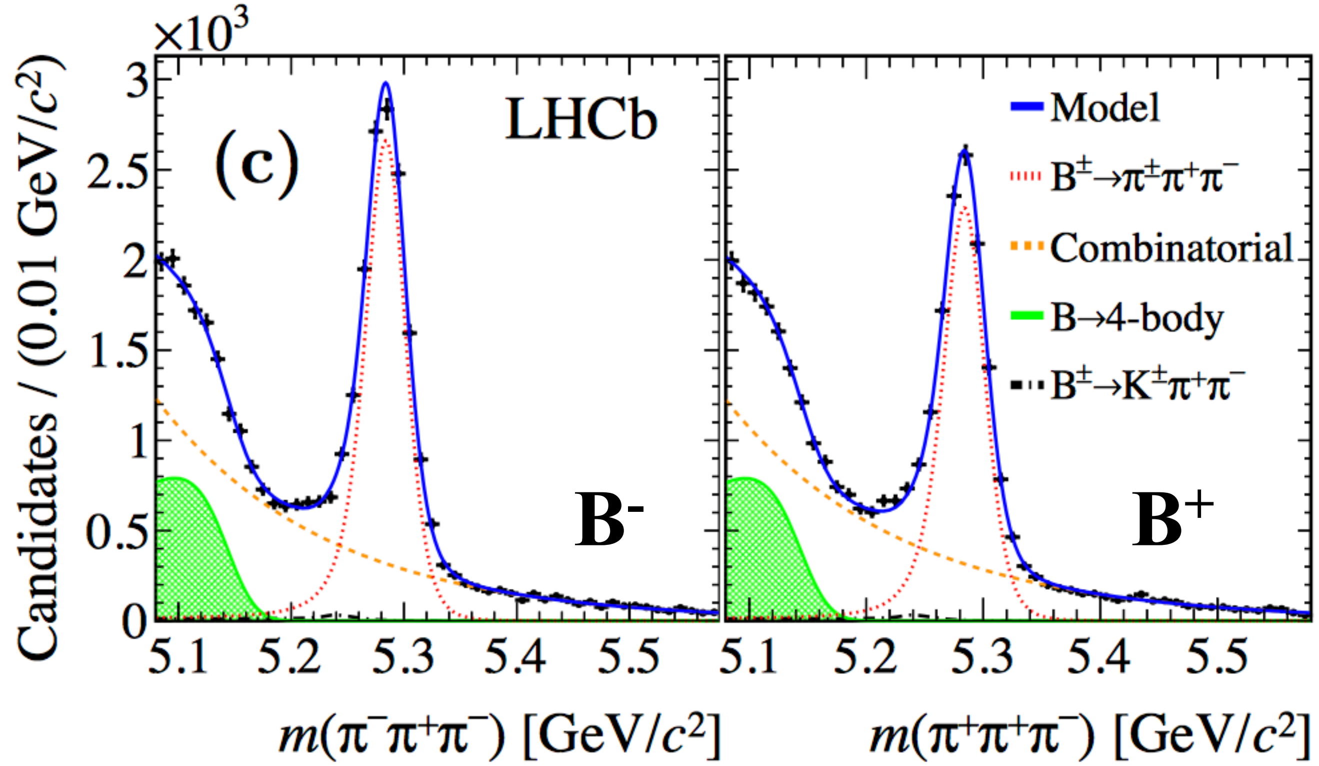


Large CP in $f_2(1270)$, but dividing w.r.t $\cos\theta = 0$ may not be ideal as shown in previous slide

$\cos\theta < 0$ **$\cos\theta > 0$**

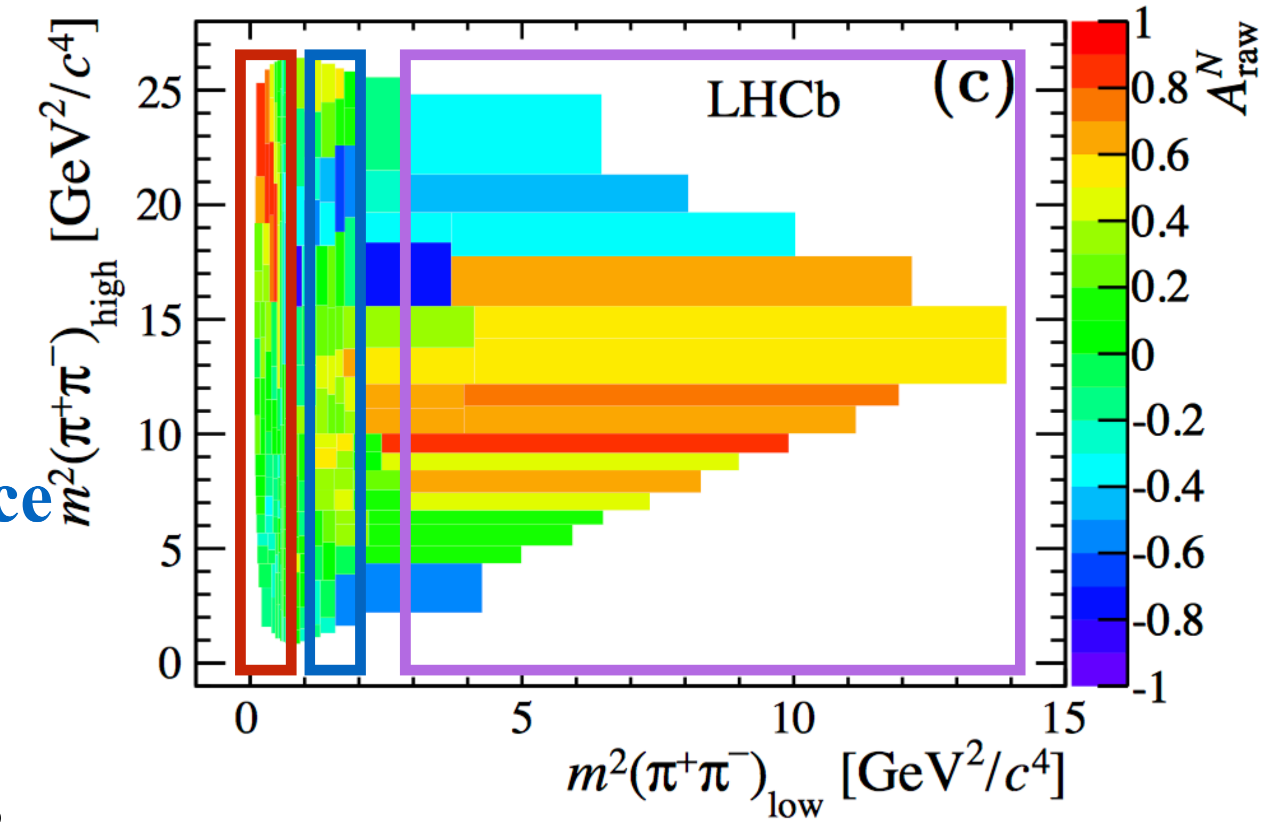
θ : helicity angle

Amplitude analysis of B→$\pi\pi\pi$ from LHCb



Plots from PRD 90, 112004 (2014) for instruction

- ➢ **RUN 1 LHCb data: ~21K signals with 4.4K background vs Babar: 1219 signals with 2.3K background**



- ➢ **Resonant contributions:**

  ρ-ω, $f_0(500)$, $f_0(980)$ region: S-P wave interference

  $f_2(1270)$ region: D-S, P wave interference

  High mass: KK-$\pi\pi$ rescattering

$\pi\pi$ S-wave description

➢ General agreed descriptions (RBW, GS) for $\pi\pi$ P- and D-waves;

➢ More complicated $\pi\pi$ S-wave, modeled in three different approaches:

➢ Isobar model: different S-wave contributions are explicitly modeled:

$f_0(500)$: RBW, complex pole parameterization

$$T_\sigma(m_{13}) = \frac{1}{m_\sigma^2 - m_{13}^2},$$

PRD 71 (2005) 054030

$f_0(980)$: Flatte parametrization

non-resonant: flat, Belle model, re-scattering model etc

$$T_{nr}(m_{13}, m_{23}) = c_{nr}(e^{-\alpha_{nr} m_{13}^2} e^{i\delta_1^{nr}} + e^{-\alpha_{nr} m_{23}^2} e^{i\delta_2^{nr}}),$$

PRL 96 (2006) 251803

$$T_{nr}(m_{13}) = \frac{a^{nr}}{1 + \frac{m_{13}^2}{\Lambda^2}} e^{i\delta^{nr}}$$

arXiv:hep-ph/1506.08332

➢ K-Matrix approach: 5 poles and 5 decay channels; parameters from global fit to previous data while production vector parameters from fit to data

EPJA 16 (2003) 229

➢ Model independent approach (QMI): $\pi\pi$ S-wave binned into 13 bins; amplitudes in each bin obtained from fit to data (26 free parameters)

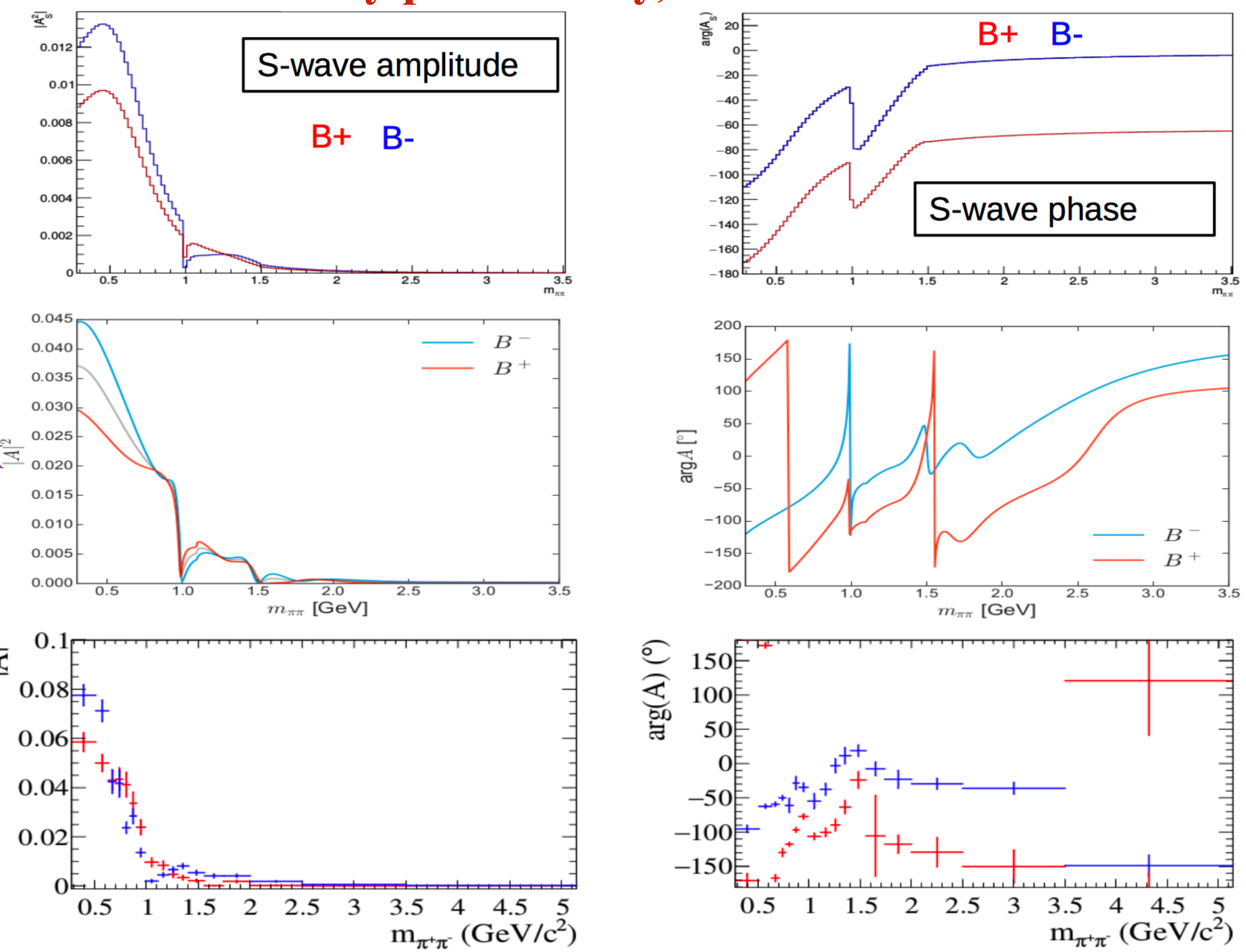
$\pi\pi$ S-wave from data

Very preliminary, un-official results

Isobar

K-Matrix

QMI



Similar pictures between different models over broad range

CPV modeling and results

- ➢ **Amplitude over Dalitz plot will be expressed as:**

$$A \equiv A(m^2_{\max}, m^2_{\min}) \;=\; \sum_j c_j F_j(m^2_{\max}, m^2_{\min})\,,$$
$$\bar{A} \equiv \bar{A}(m^2_{\max}, m^2_{\min}) \;=\; \sum_j \bar{c}_j \bar{F}_j(m^2_{\max}, m^2_{\min})\,.$$

With

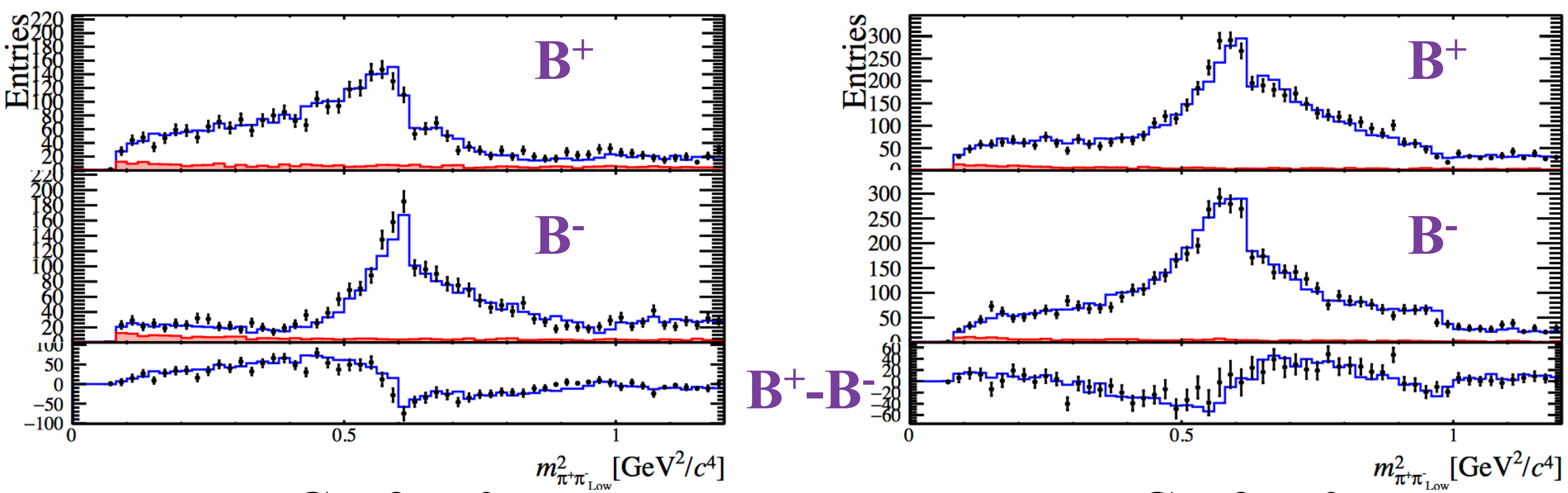
c_i w.r.t. ρ(770)

$$c_i = (x_i + \Delta x_i) + i(y_i + \Delta y_i)$$
$$\overline{c_i} = (x_i - \Delta x_i) + i(y_i - \Delta y_i)$$

- ➢ **Results on c_i, A_{CP} and fit fractions will be given**

$$\mathcal{A}_{CP} = -2\left[\frac{x\ \delta_x + y\ \delta_y}{x^2 + \delta_x^2 + y^2 + \delta_y^2}\right],$$

- ➢ **A fit example of ρ-ω region**



Cosθ < 0 **Cosθ > 0**

Very preliminary, un-official results

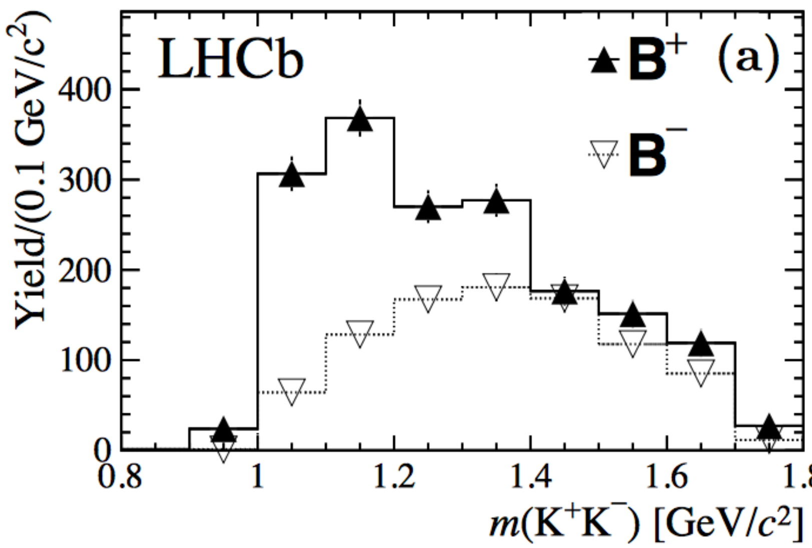
θ : helicity angle

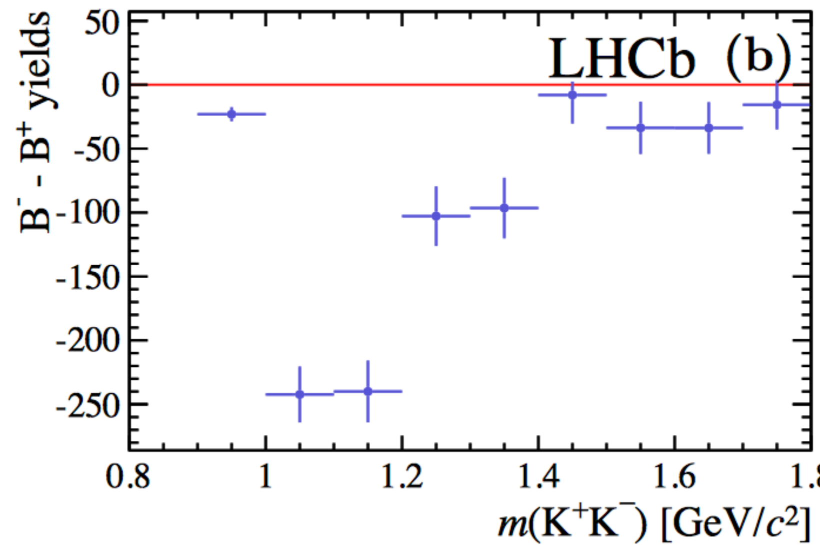
Measurements with B→KKπ

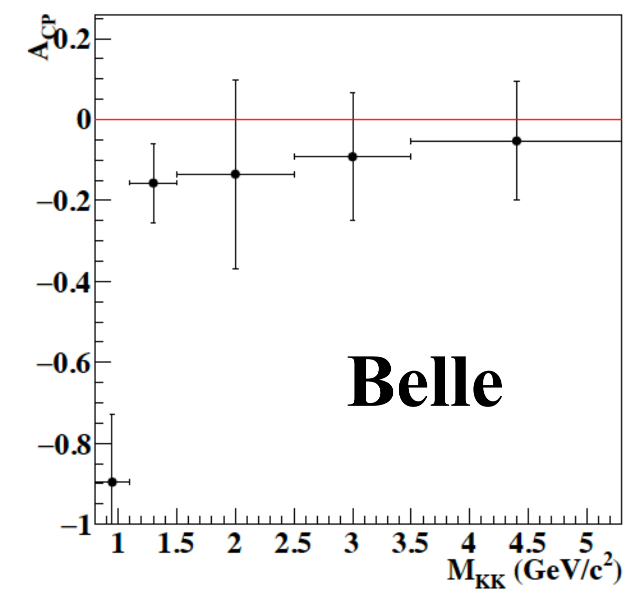
- ➢ Previous LHCb A_{CP} measurement with 6k signals:

PRD 90, 112004 (2014)

arXiv:1705.02640







- ➢ Belle join the game recently with around 660 signal events: results consistent with LHCb

arXiv:1705.02640

- ➢ LHCb is also working on amplitude analysis; reasonable fit has already achieved

Kπ resonances: $K^*(800)$, $K^*(892)$, $K_0^*(1430)$

KK resonances: $f_0(980)$, $f_0(1370)$, $f_2(1270)$, $\rho^0(1450)$, possible P-wave contribution

Alternative models also tried: like rescattering model for KK S-wave

PRD 92 (2015) 054010, PRD 71 (2005) 074016

Branching fraction updates for $B_{d(s)} \to K_s hh^{(')}$

JHEP 10 (2013) 143

➢ Previous LHCb measurements with 1 fb^{-1} data observes $B_s \to K_s K\pi$, $K_s\pi\pi$ and confirms $B^0 \to K_s K\pi$

arXiv:1707.01665

➢ Updates performed with full Run 1 data, aiming at finding $B_s \to K_s KK$; though a bit unlucky, only 2.5σ significance

➢ Measurements normalized to $B^0 \to K_s\pi\pi$ channel

Branching fraction (stat. sys. normalization)	Decay outside VELO	Decay inside VELO
Normalization: $B^0 \to K_s\pi\pi$	2766±66	1411±45
$\mathcal{B}(B^0 \to \overset{(-)}{K}{}^0 K^\pm \pi^\mp) = (6.1 \pm 0.5 \pm 0.7 \pm 0.3) \times 10^{-6}$,	261±24	160±17
$\mathcal{B}(B^0 \to K^0 K^+ K^-) = (27.2 \pm 0.9 \pm 1.6 \pm 1.1) \times 10^{-6}$,	1133±39	685±29
$\mathcal{B}(B_s^0 \to K^0 \pi^+ \pi^-) = (9.5 \pm 1.3 \pm 1.5 \pm 0.4) \times 10^{-6}$,	146±19	74±11
$\mathcal{B}(B_s^0 \to \overset{(-)}{K}{}^0 K^\pm \pi^\mp) = (84.3 \pm 3.5 \pm 7.4 \pm 3.4) \times 10^{-6}$,	1100±41	568±28
$\mathcal{B}(B_s^0 \to K^0 K^+ K^-) \in [0.4 - 2.5] \times 10^{-6}$ at 90% C.L. ,	12±6	7±4

➢ Dalitz-plot analyses of $B^0 \to K_s\pi\pi$, $K_s KK$ and $B_s \to K_s K\pi$ underway

CPV in charmless baryon decays

- **Similar as B^+ mode, only direct CPV in baryon sector expected**

- **Two body charmless baryon decays have small Br; only one CPV measurement from CDF where no clear CPV found; Potential large CPV expected in $b \to s u \bar{u}$ and $b \to d u \bar{u}$**

  PRL113 (2014) 242001, PRD 91 (2015) 116007

- **Several CPV measurements have been performed on three body charmless baryon decays by LHCb and no clear CPV found**

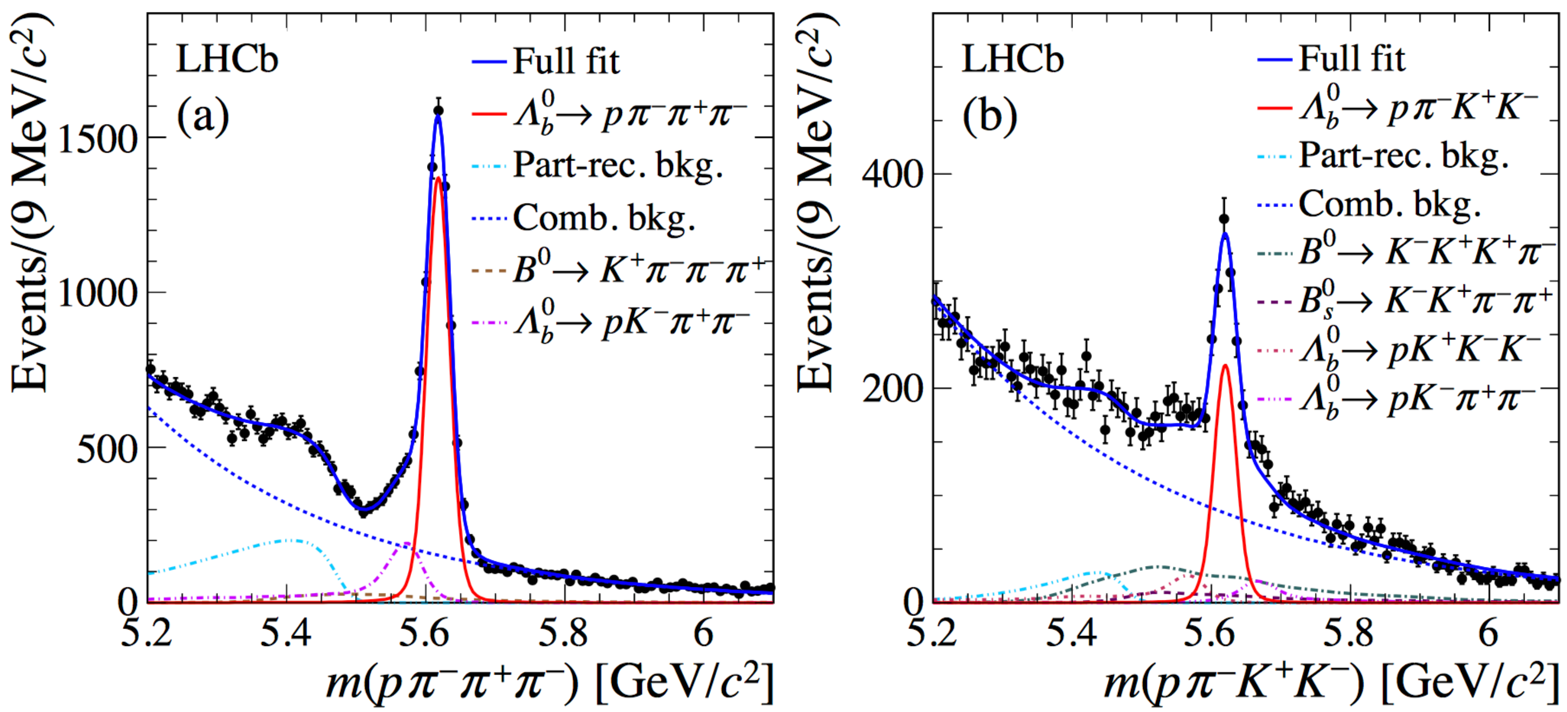
  JHEP 04 (2014) 087, JHEP 05 (2016) 08, PLB 759 (2016) 282

- **CPV measurements in baryon sectors limited by statistics; Unlike meson decays, baryon decays tend to have larger Br for final states with more tracks (4 body > 3 body > 2 body); rich resonant interference and strong phase variation over phase space offer larger chance to have large CPV and interesting CPV pattern**

- **CPV measurement in four body baryon decays can be performed either similarly as those for $B \to hhh$ (ongoing) or using technics like triple product; ultimate procedure is full amplitude analysis**

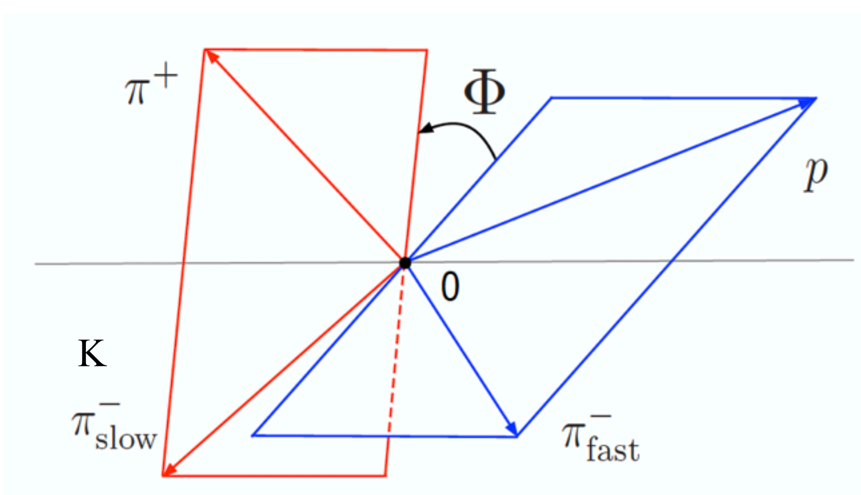
CPV in $\Lambda_b \to p\pi hh$ decays from LHCb

Nature Physics 13 (2017) 391



$p\pi\pi\pi$: 6.6k signals
$pK\pi\pi$: 1k signals
vs
three body decays: less than 1k signals

➢ **Phase space integrated CPV:**



$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin\Phi \text{, for } \Lambda_b^0$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin\overline{\Phi} \text{, for } \overline{\Lambda}_b^0$$

CP violation observable: $a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$

P-violating observable: $a_{P}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}}>0) - N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0) + N(C_{\hat{T}}<0)} \text{, for } \Lambda_b^0$$

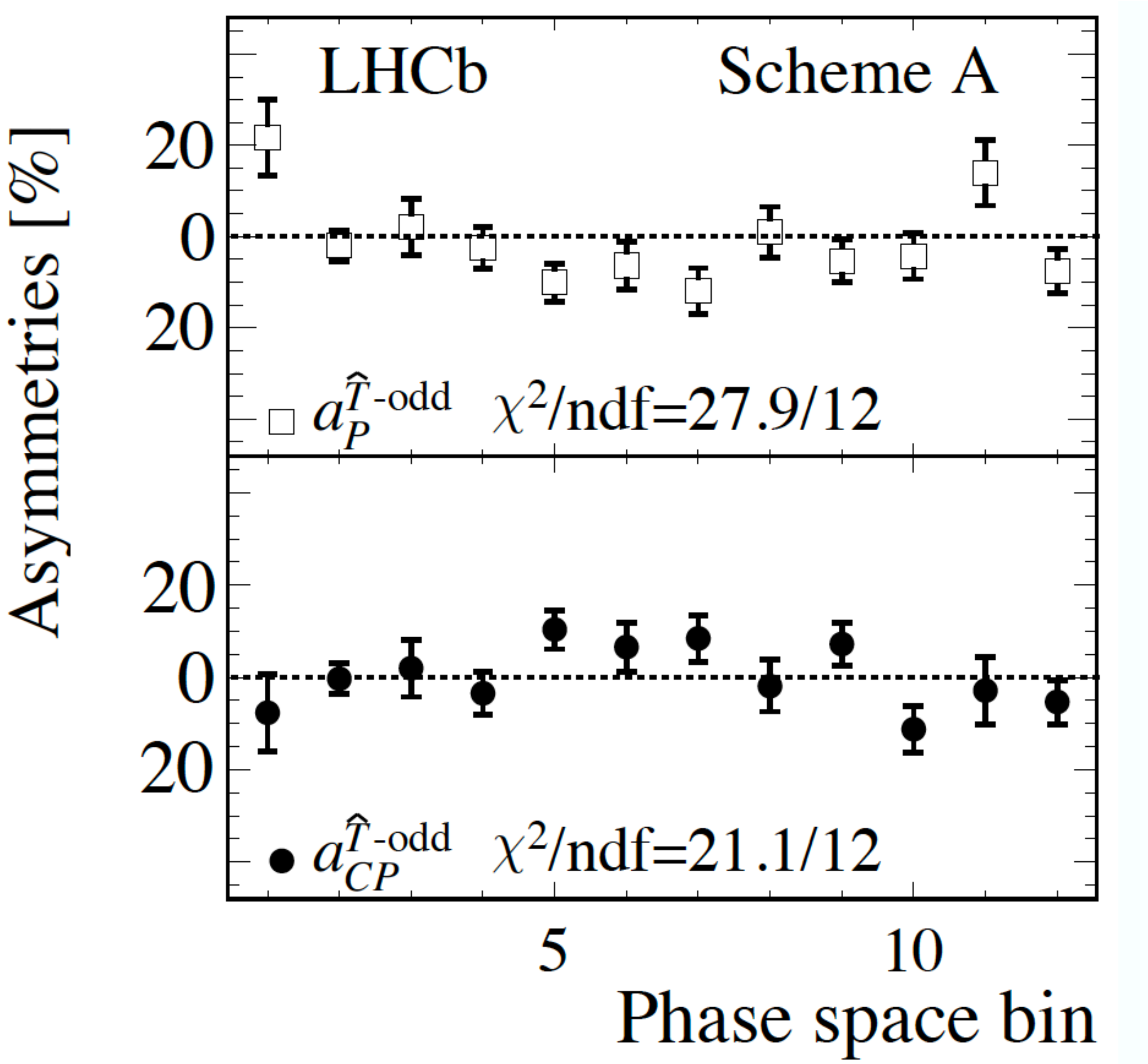
$$\overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \frac{\overline{N}(-\overline{C}_{\hat{T}}>0) - \overline{N}(-\overline{C}_{\hat{T}}<0)}{\overline{N}(-\overline{C}_{\hat{T}}>0) + \overline{N}(-\overline{C}_{\hat{T}}<0)} \text{, for } \overline{\Lambda}_b^0$$

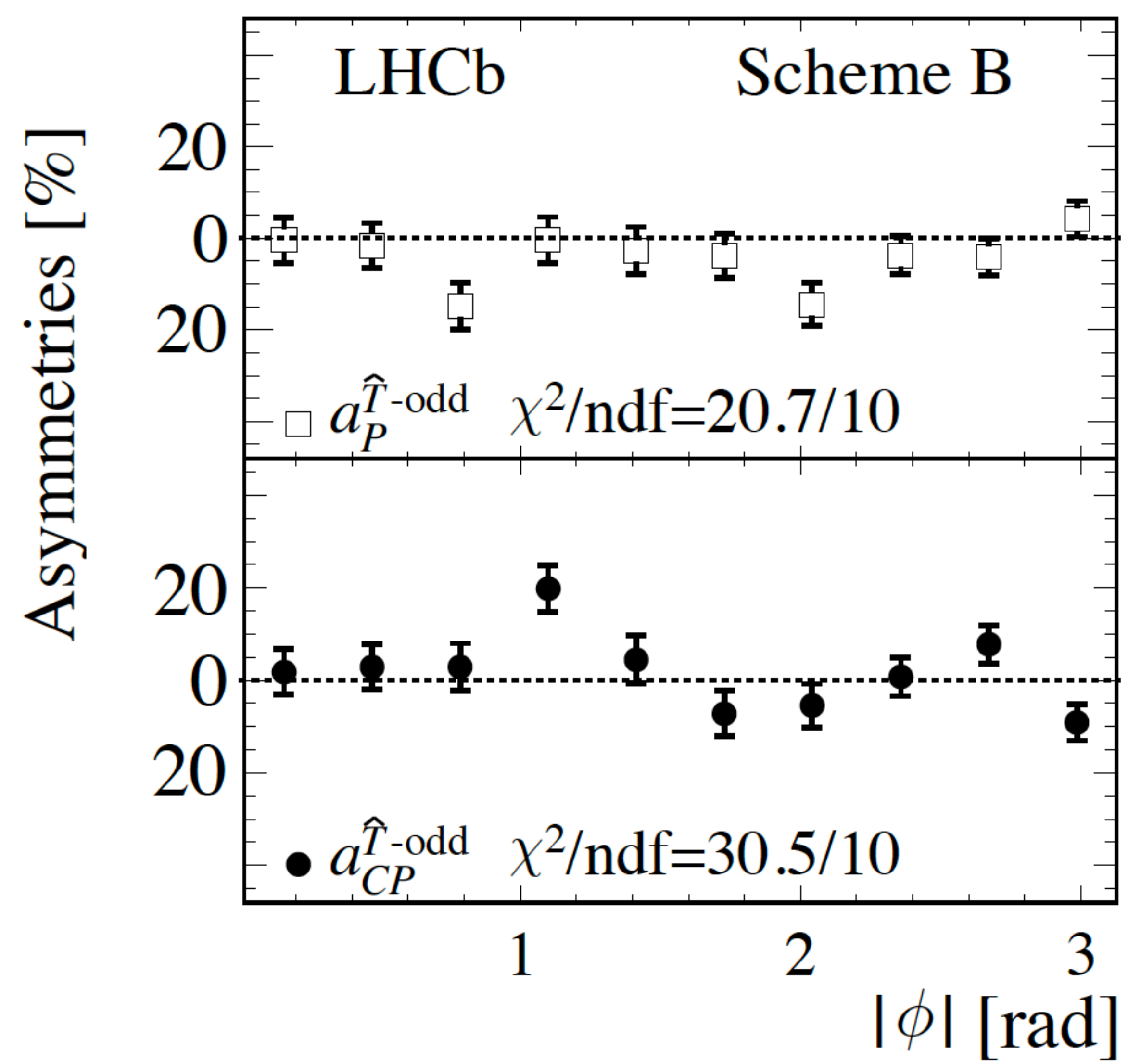
$$a_P^{\hat{T}-\mathrm{odd}} = (-3.71 \pm 1.45 \pm 0.32)\%$$

$$a_{CP}^{\hat{T}-\mathrm{odd}} = (1.15 \pm 1.45 \pm 0.32)\%$$

CPV in different regions

Nature Physics 13 (2017) 391





Binning based on resonant structures, e.g. ρ(770), N*, Δ^{++}

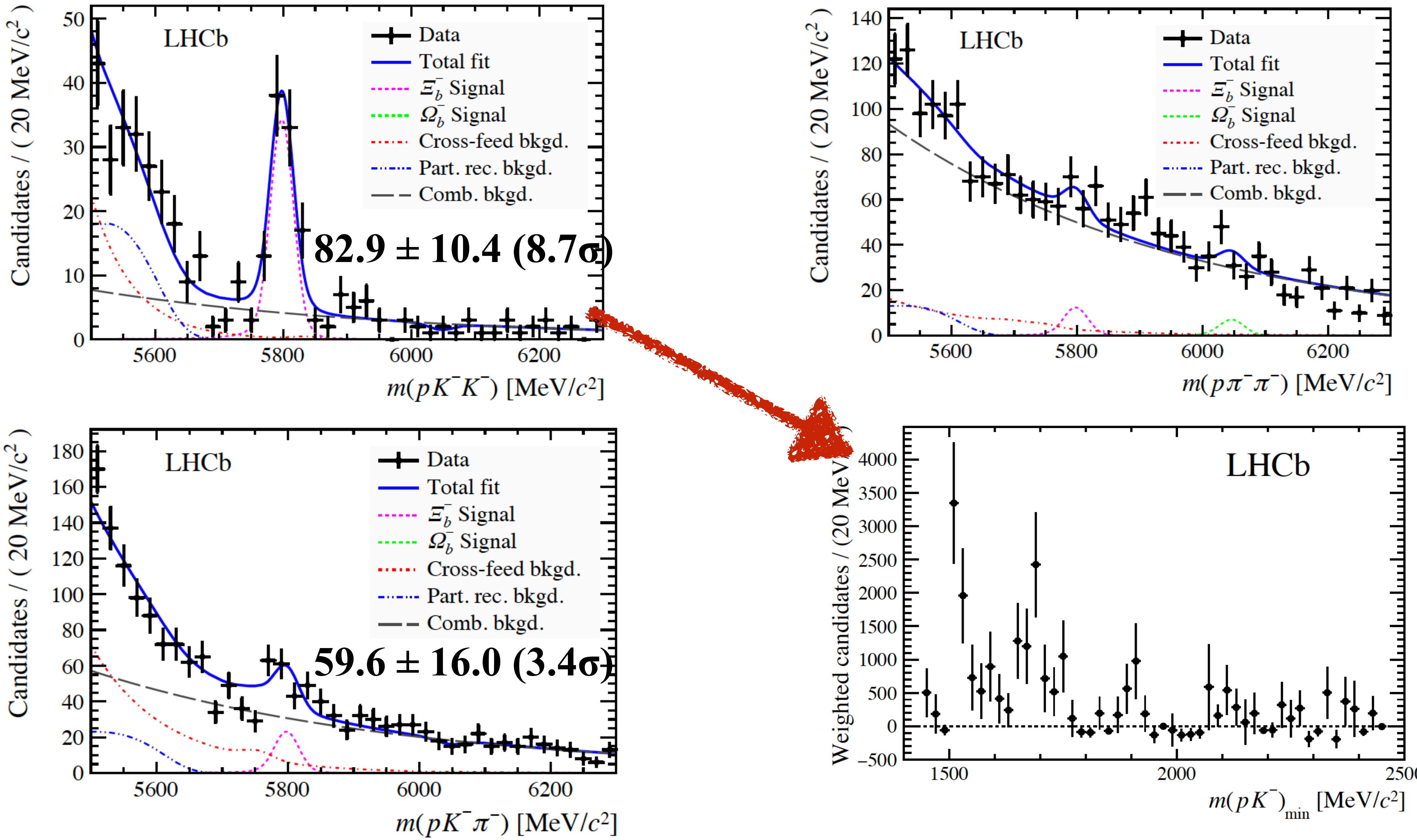
Binning based on ϕ angle

First evidence for CPV with 3.3σ

Search for $\Xi_b, \Omega_b \rightarrow phh^{(')}$

➢ **Decays interesting CPV measurement from P and T interference**

PRL 118 (2017) 071801



➢ **Interesting resonant structures over m(pK) and amplitude analysis with Run 2 data is planned**

Baryonic B decays

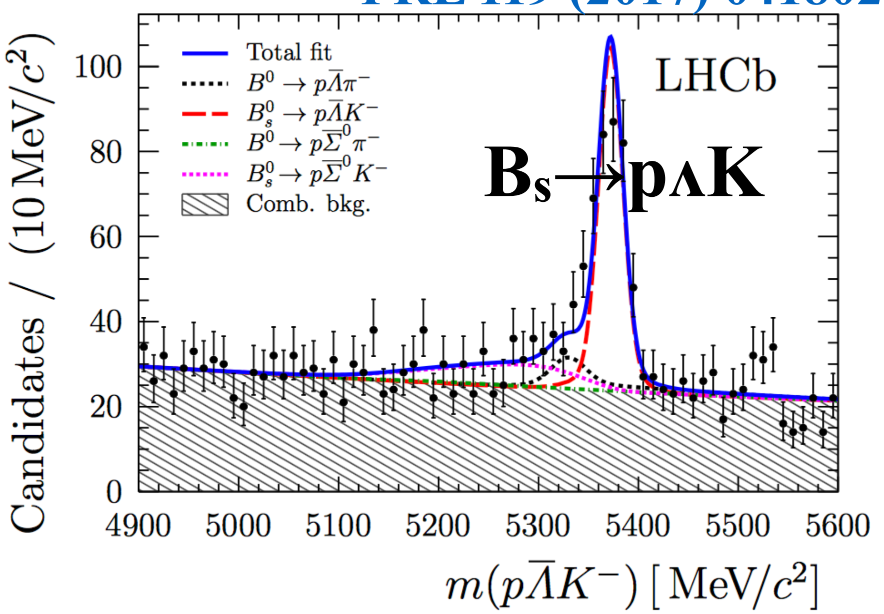
PRL 88 (2002) 181803

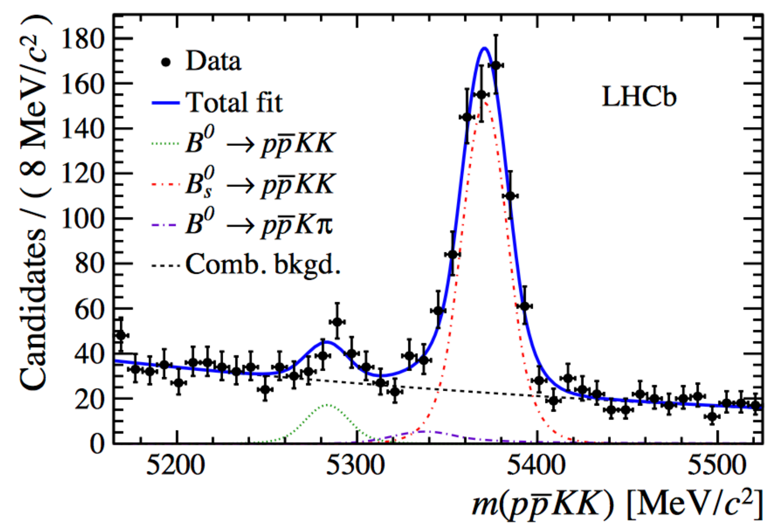
➢ First baryonic B decay ($p\bar{p}K$) has been observed in 2002 by B factories

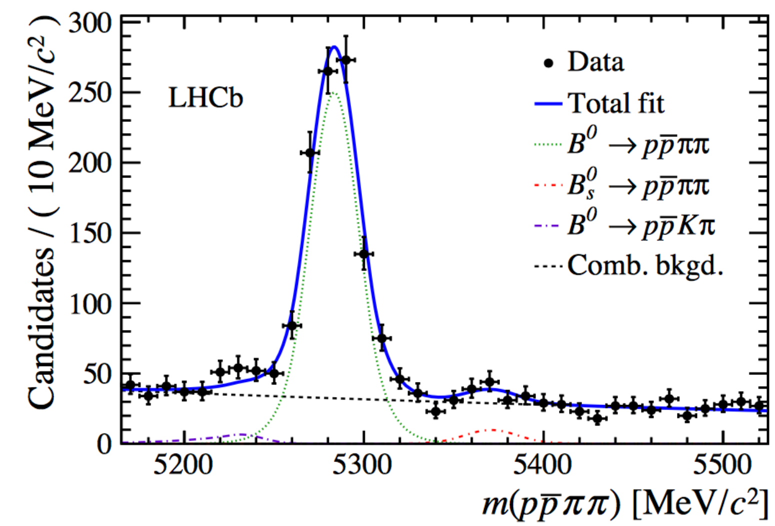
➢ First CPV evidence seen in 2013 by LHCb also in $p\bar{p}K$ decay PRL 113 (2014) 141801

➢ More interesting baryonic B decays found recently, potential place for CPV studies

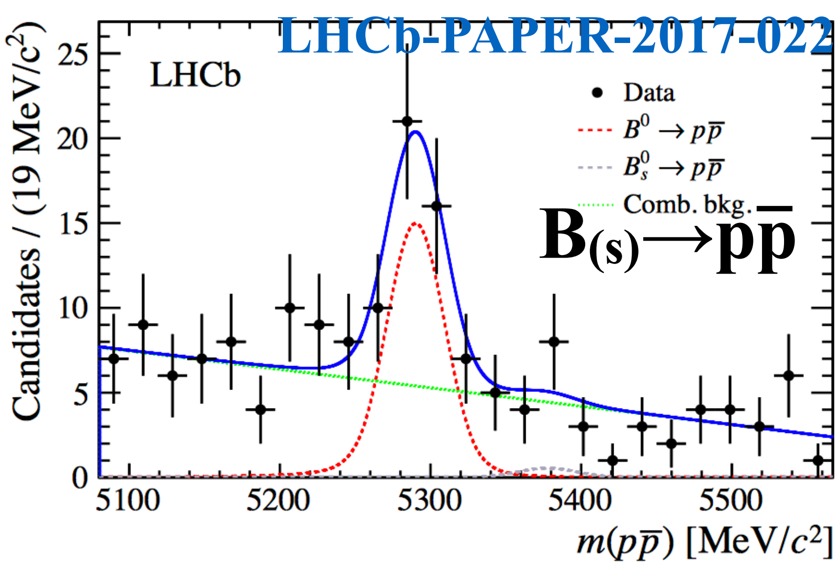
PRL 119 (2017) 041802

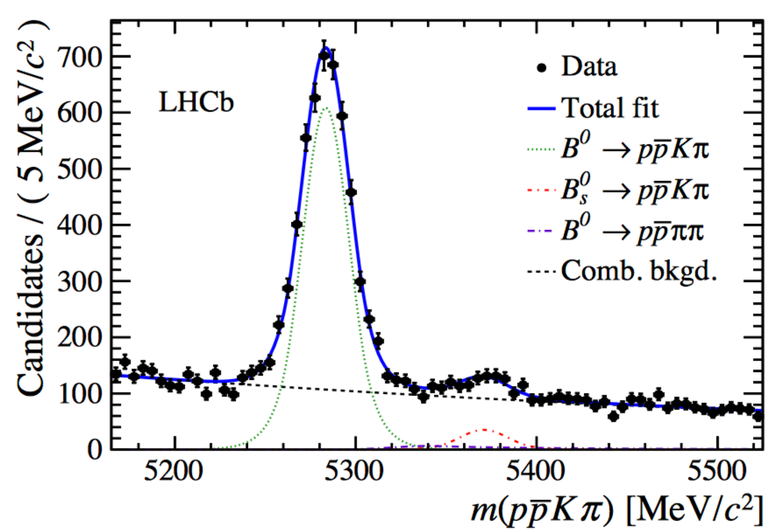






LHCb-PAPER-2017-022





$B_{(s)} \to p\bar{p}hh^{(\prime)}$

arXiv:1704.08497

Conclusion

➢ **Many interesting CPV measurements/searches have been performed by LHCb (Run 1 data) and B factories**

➢ **Already put useful information in determining CKM angle precisely and in constraining new physics**

➢ **More new/interesting results are in the pipeline from LHCb (including Run 2 data) and from Belle (Belle II soon)**

➢ **Stay tuned!!!**

Many Thanks

Measurement on $B_s \to \phi\phi$

PRD 90 (2014) 052011

➢ **$B_s \to \phi\phi$ decay dominated by $b \to s s \bar{s}$ penguin contribution: no large direct CPV expected; weak phase from mixing and decay cancels ➜ excellent place for new physics search**

➢ **Time dependent amplitude analysis performed with 3 fb^{-1} LHCb data**

➢ **Using 4000 signal events, the CPV phase is measured to be**

$$\phi_s = -0.17 \pm 0.15\,(\text{stat}) \pm 0.03\,(\text{syst})\,\text{rad}$$

➢ **Triple-product asymmetries offered complementary information; the measurement is consistent with CP conservation**

$$A_U \equiv \frac{\Gamma(U>0)-\Gamma(U<0)}{\Gamma(U>0)+\Gamma(U<0)} \qquad U = \sin\phi\cos\phi$$

$$A_V \equiv \frac{\Gamma(V>0)-\Gamma(V<0)}{\Gamma(V>0)+\Gamma(V<0)} \qquad V = \sin(\pm\phi)$$

$$\sin\Phi = (\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1}$$

+ for $\cos\theta_1 \cos\theta_2 \geq 0$

- for $\cos\theta_1 \cos\theta_2 \leq 0$

$$A_V = -0.017 \pm 0.017\,(\text{stat}) \pm 0.006\,(\text{syst}) \qquad A_U = -0.003 \pm 0.017\,(\text{stat}) \pm 0.006\,(\text{syst})$$

➢ **Updates with RUN1 + 2015 + 2016 data ongoing and at least twice signal expected**

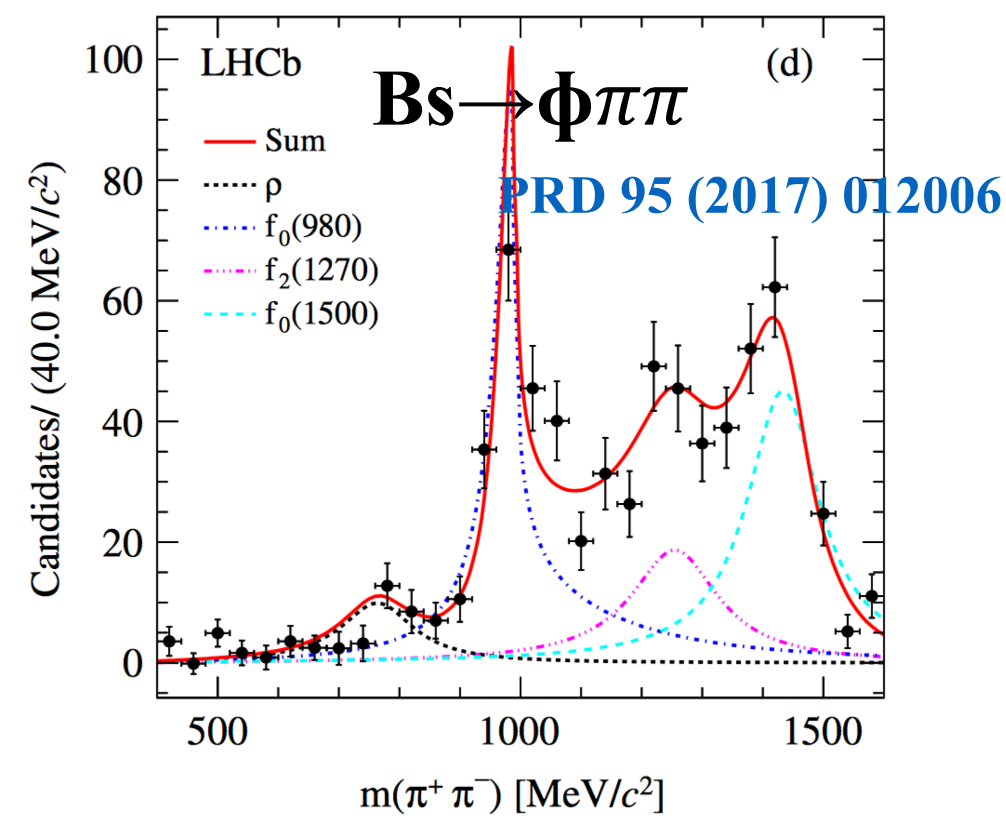
Other recent studies in $B_s \to \phi X$ sector by LHCb

- Search on $B_s \to \phi\eta'(\pi\pi\gamma)$ performed with full Run 1 data: JHEP 05 (2017) 158

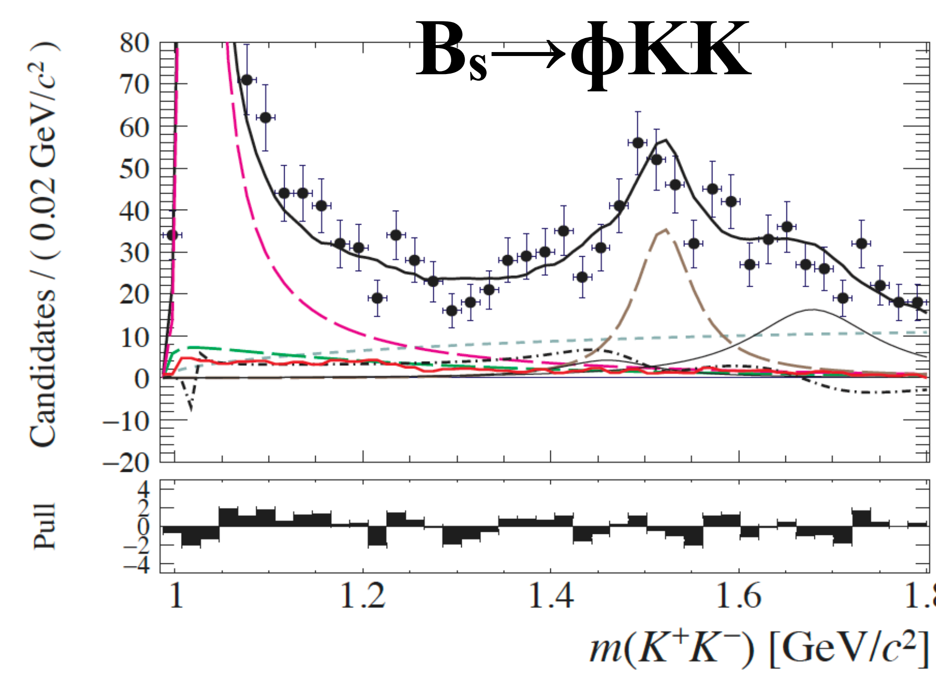
$$\mathcal{B}(B_s^0 \to \eta'\phi) < 0.82\,(1.01) \times 10^{-6} \quad \text{at} \quad 90\%\ (95\%)\ \text{CL}$$

- Observation of $B_s \to \phi\pi\pi$ and evidence for $B^0 \to \phi\pi\pi$ with Run 1 data

  Time-independent amplitude analysis performed and resonance structures like $\rho(770)$, $f_0(980)$, $f_2(1270)$ and $f_0(1500)$ identified



- Studies also expands to higher KK mass and a time-independent amplitude analysis ongoing with Run 1 3 fb^{-1} data in LHCb



- New quasi-two body decays observed in higher mass region could be interesting for future CPV measurements