# Charmless two-body b-meson decays at LHCb

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# Charmless $b$ decays

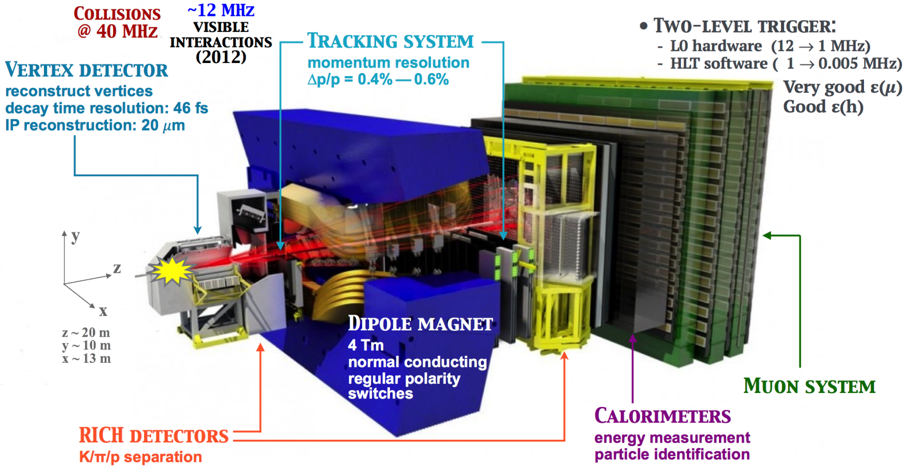
## Suppressed decays in the Standard Model (SM)

- $\mathbf{b} \to \mathbf{u}$ transitions are mediated by **tree diagrams**
- $\mathbf{b} \to \mathbf{d}, \mathbf{s}$ procceed through diagrams with **loops** (penguins)
- $|\mathbf{V_{ub}}|$ makes both **amplitudes of similar magnitude**
- **Relative weak phase** difference between these diagrams within the SM framework is $\gamma_{\text{CKM}}$

## Rich scenario to search for New Physics (NP) effects:

- **New particles** may contribute in the **loops**
- Rare modes, sensitive to **variations** of $\mathcal{B}$ w.r.t. SM predictions
- Similar amplitudes lead to **sizeable CP violation effects**
- **NP** could also provide **additional sources** of **CP violation**
- **Flavor symmetries** can be exploited to **deal with QCD**

# The LHCb detector



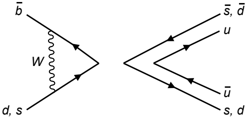
# $\mathbf{B^0 \to K^+K^-}$ and $\mathbf{B_s^0 \to \pi^+\pi^-}$

# Introduction to the $B^0 \to K^+K^-$ Decay

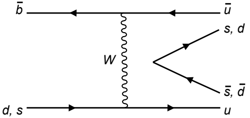
LHCb-PAPER-2016-036 in preparation

## Motivation

- The $\mathbf{B^0 \to K^+K^-}$ **decay mode** was **never observed**
- $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$ are **U-spin partners**
  - The relation $\frac{\mathcal{B}(B^0 \to K^+K^-)}{\mathcal{B}(B_s^0 \to \pi^+\pi^-)}$ may bring information on the U-spin symmetry
  - Both are **very suppressed** decays (PA, E)
- Final states containing hadrons $\to$ complicated QCD phenomenology
  - Huge efforts have been put in this area...
  - But several QCD computations remain affected with **sizeable uncertainties** $\to$ **experimental input very useful**
  - Both decays affected by **final state reescattering**




**Penguin Annihilation (PA)**




**W-Exchange(E)**

Previous knowledge on $\mathcal{B}(B^0 \to K^+K^-)$ and $\mathcal{B}(B_s^0 \to \pi^+\pi^-)$ ($\mathcal{B} \times 10^6$):

| Decay mode | BaBar | Belle | CLEO | CDF | LHCb | Average |
|---|---|---|---|---|---|---|
| $B^0 \to K^+K^-$ | $< 0.5$ | $0.10 \pm 0.08 \pm 0.04$ | $< 0.8$ | $0.23 \pm 0.10 \pm 0.10$ | $0.12^{+0.08}_{-0.07} \pm 0.01$ | $0.13^{+0.06}_{-0.05}$ |
| $B_s^0 \to \pi^+\pi^-$ | – | $< 12$ | – | $0.60 \pm 0.17 \pm 0.04$ | $0.98^{+0.23}_{-0.19} \pm 0.07$ | $0.76 \pm 0.13$ |

References

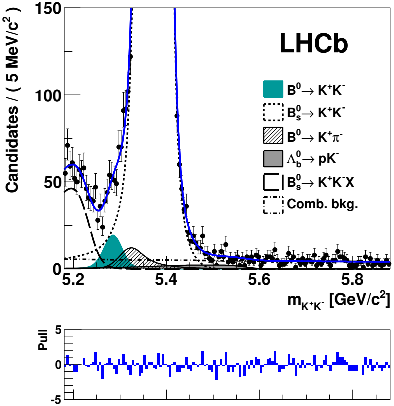
# Analysis Strategy

LHCb-PAPER-2016-036 in preparation

- **Analized data**: full **LHCb Run 1** data sample, corresponding to an integrated luminosity of $1fb^{-1}$ at $\sqrt{s} = \mathbf{7TeV}$ and $2fb^{-1}$ at $\sqrt{s} = \mathbf{8TeV}$
- The regions $\mathbf{5.22 < m_{KK} < 5.34[GeV/c^2]}$ and $\mathbf{5.33 < m_{\pi\pi} < 5.45[GeV/c^2]}$ are disregarded during selection optimization → **blind analysis**
- **Event selection** is performed in several steps:
  - **Pre-selection** (trigger): mainly using track and vertex fit qualities, kinematic information and decay topology
  - **Offline** selection: boosted decision tree (BDT) multivariate classifier and particle identification (PID) criteria
  - **Simultaneous optimization of the BDT and PID** requeriments aiming at the best sensitivity on the signal yields → 2 selections (A: $B^0 \to KK$ and B: $B^0 \to \pi\pi$)
- **Signal yields** are obtained from a **simultaneous 2-body invariant mass fit** to several mutually exclusive subsamples (PID requeriments): $K\pi, pK, p\pi, \pi\pi$ and $KK$
- **PID calibration** is done via a **data-driven method**, using $D^{*+}$, $\Lambda$ and $\Lambda_c^+$ decays
- $\mathcal{B}(\mathbf{B \to K^+\pi^-})$ is used as **normalization** for the measurements

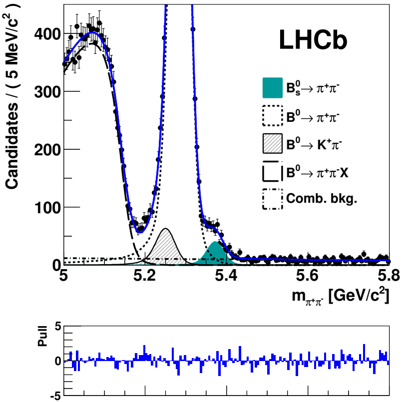
# Preliminary Results from the 2-body Invariant Mass Fit

Selection A




Selection B

LHCb-PAPER-2016-036 in preparation




$$\mathbf{N_{B^0 \to K^+K^-} = 201.1 \pm 32.7 \pm 13.5}$$
$$N_{B^0 \to K^+\pi^-} = 105010 \pm 430 \pm 990$$

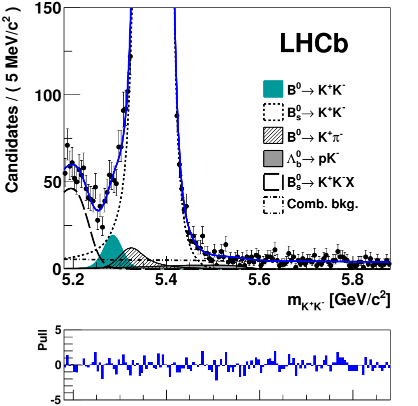
$\to$ **5.8$\sigma$** significance achieved!
(inc. systematics)

$$\mathbf{N_{B_s^0 \to \pi^+\pi^-} = 455.0 \pm 35.2 \pm 24.2}$$
$$N_{B^0 \to K^+\pi^-} = 71300 \pm 310 \pm 610$$

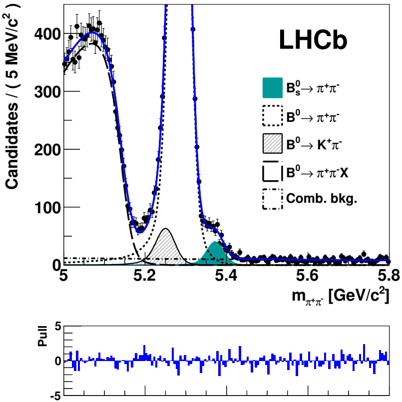
Uncertainties: $\pm$ stats. $\pm$ syst.

# Preliminary Results from the 2-body Invariant Mass Fit

Selection A




Selection B LHCb-PAPER-2016-036 in preparation




$\mathcal{B}(B^0 \to K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8}$

$\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$

Uncertainties: $\pm$ stats. $\pm$ syst. $\pm \mathcal{B}(B^0 \to K^+\pi^-) \pm f_s/f_d$

HFAG LHCb

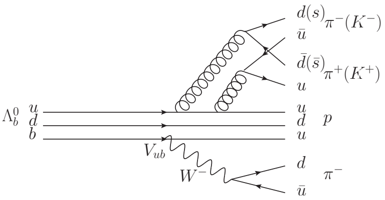
# $\Lambda_b \to p\pi^-h^+h^-(h = \pi, K)$

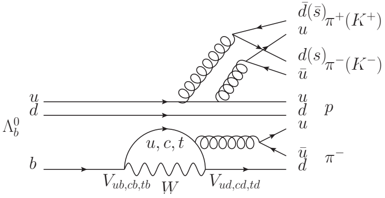
# Analysis of $\Lambda_b \to p\pi^- h^+ h^- (h = \pi, K)$

LHCb-PAPER-2016-030 in preparation

**Motivation**

- **Direct CP violation** (CPV) has **never been observed** in baryon decays
- Large CPV effects are expected in charmless $\Lambda_b$ decays ($A_{CP} \sim 20\%$) Y. K. Hsiao et al.
- Both tree and penguin diagrams contribute with similar amplitudes
- Measurements of CPV on these decays can be used to **test the SM** and to **place constraints** on SM **extensions**.




**Tree** $\propto |V_{ub}| \sim \lambda^3$

**Penguin** $\propto \sum_{x=u,c,t} V_{bx}V_{xd} \sim \lambda^3$

# Analysis Strategy

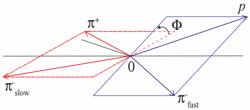
LHCb-PAPER-2016-030 in preparation

- Analized data $\to$ full **LHCb Run 1**
- Search for CPV in $\Lambda_b \to p\pi^-h^+h^-(h=\pi,K)$ using **triple product asymmetries**
- Look at **regions of phase space** for increased sensitivity to **localised CPV effects** (strong phases variations)
- $\mathbf{\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-}$ decay (no CPV is expected) is used as **control sample**
- **Event selection**: trigger, BDT, charm vetoes, and PID requeriments
- **Signal yields** are obtained from a **simultaneous fit** to $\mathbf{M(p\pi^-h^+h^-)}$

## Observables construction

**Triple products** in the $\Lambda_b$ rest frame:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+}) \propto \sin\Phi$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h^+} \times \vec{p}_{h^-}) \propto \sin\overline{\Phi}$$




**$\hat{\mathbf{T}}$-odd asymmetries**:

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}}>0) - N_{\Lambda_b^0}(C_{\hat{T}}<0)}{N_{\Lambda_b^0}(C_{\hat{T}}>0) + N_{\Lambda_b^0}(C_{\hat{T}}<0)}$$

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

**CP-violating observable:**

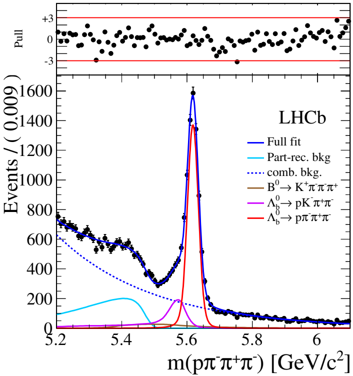
$$\mathbf{a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})}$$

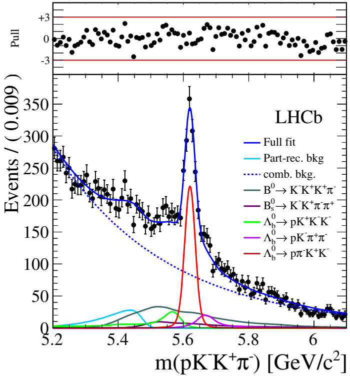
**P-violating observable:**

$$\mathbf{a_{P}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}})}$$

# Preliminary Results from the 4-body Invariant Mass Fit

LHCb-PAPER-2016-030 in preparation




$$N_{\Lambda_b^0 \to p\pi^-\pi^+\pi^-} = 6646 \pm 105(\text{stat}) \qquad N_{\Lambda_b^0 \to p\pi^- K^+K^-} = 1030 \pm 56(\text{stat})$$

**Definition of the signal categories:**

$$N_{\Lambda_b^0}(C_{\hat{T}} > 0) = \tfrac{1}{2} N_{\Lambda_b^0}(1 + A_{\hat{T}}) \qquad N_{\Lambda_b^0}(C_{\hat{T}} < 0) = \tfrac{1}{2} N_{\Lambda_b^0}(1 - A_{\hat{T}})$$

$$N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) = \tfrac{1}{2} N_{\overline{\Lambda}_b^0}(1 + \overline{A}_{\hat{T}}) \qquad N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0) = \tfrac{1}{2} N_{\overline{\Lambda}_b^0}(1 - \overline{A}_{\hat{T}})$$

# Two $a_{CP}^{\hat{T}-odd}$ Measurements

LHCb-PAPER-2016-030 in preparation

1.- **Measurement integrated over the phase space:**

$a_{CP}^{\hat{T}-odd}$ obtained from the fits in the previous slide
Results are **compatible** with **P and CP conservation**

| Decay | $A_{\widehat{T}}$ (%) | $\bar{A}_{\widehat{T}}$ (%) | $a_{CP}^{\widehat{T}-\mathrm{odd}}$ (%) |
|---|---|---|---|
| $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ | $-2.56 \pm 2.06 \pm 0.45$ | $-4.86 \pm 2.06 \pm 0.44$ | $1.15 \pm 1.45 \pm 0.32$ |
| $\Lambda_b^0 \to p\pi^-K^+K^-$ | $2.68 \pm 6.76 \pm 0.85$ | $4.55 \pm 6.07 \pm 0.52$ | $-0.93 \pm 4.54 \pm 0.42$ |

2.- **Local measurements:**

Limited statistics on the $\mathbf{\Lambda_b^0 \to p\pi^-K^+K^-}$ allows for 2 divisions only:

- $\Lambda^{*0}$ dominated interval: $1.0 < m(pK^-) < 2.0 GeV/c^2$
- Its complementary region: $2.0 < m(pK^-) < 5.0 GeV/c^2$

$\rightarrow$ results are **compatible** with **P and CP conservation**

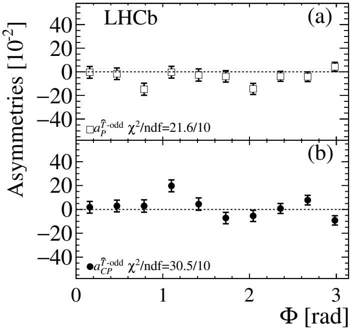
For the $\mathbf{\Lambda_b^0 \to p\pi^-\pi^+\pi^-}$ two different schemes are studied:

- **Scheme A**: 12 regions dominated by **2-body resonances** ($\rho^0(770), \Delta^{++}, N^*$)
- **Scheme B**: 10 **uniform bins in** $\mathbf{\Phi}$

$\rightarrow$ **3.3$\sigma$ evidence for CPV** is found when **combining both schemes**

# A closer look on $a_{CP}^{\hat{T}-odd}$ (Preliminary)

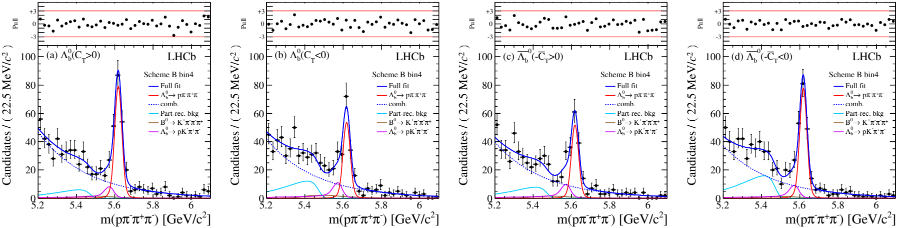
**LHCb-PAPER-2016-030 in preparation**




← $a_P^{\hat{T}-odd}$ and $a_{CP}^{\hat{T}-odd}$ measurements in Φ bins for the $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decay

◇ **CPV patterns have been searched for**, and several cross-checks have been studied, but **no specific amplitude could be associated to this effect**.

↓ **Fit projections** for the four signal categories for the candidates **in the bin where the largest CPV effect is observed** ($\frac{3}{10}\pi < \Phi < \frac{4}{10}\pi$)



# Summary

Two of the latest results by LHCb were presented

- $\mathbf{B^0_{(s)} \to h^+h^-}$ modes:
  - **First observation** of the rarest fully hadronic decay ever seen, the $\mathbf{B^0 \to K^+K^-}$ decay (**$5.8\sigma$** significance, including systematical uncertainties)
  - **Most precise measurements** of $\mathcal{B}(\mathbf{B_s^0 \to \pi^+\pi^-})$ and $\mathcal{B}(\mathbf{B^0 \to K^+K^-})$
  - $\mathcal{B}(B^0 \to K^+K^-)$ determination provides a very useful **reference** for a better understanding of the **QCD effects involving PA diagrams.**

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- $\mathbf{\Lambda_b \to p\pi^-h^+h^-}$ decays:
  - Search for P and CP violation using triple products asymmetries
  - $\mathbf{\Lambda_b \to p\pi^-K^+K^-}$ measurements are **compatible with P and CP conservation**
  - $\mathbf{\Lambda_b \to p\pi^-\pi^+\pi^-}$ channel shows **evidence for localised CP violation**, with a significance up to $\mathbf{3.3\sigma}$ (when combining results from different binning schemes)
  - Both results are in **agreement with SM** predictions for CPV in charmless $\Lambda_b^0$ decays
  - **First evidence of CPV in baryon decays!**

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  - Both results are in **agreement with SM** predictions for CPV in charmless $\Lambda_b^0$ decays
  - **First evidence of CPV in baryon decays!**

Thanks for your attention!

# Backup slides

# References ($B^0_{(s)} \to h^+h^-$)

| Decay mode | BaBar | Belle | CLEO | CDF | LHCb | Average |
|---|---|---|---|---|---|---|
| $B^0 \to K^+K^-$ | $< 0.5$ | $0.10 \pm 0.08 \pm 0.04$ | $< 0.8$ | $0.23 \pm 0.10 \pm 0.10^{\dagger}$ | $0.12^{+0.08}_{-0.07} \pm 0.01^{\dagger}$ | $0.13^{+0.06}_{-0.05}$ |
| $B_s^0 \to \pi^+\pi^-$ | – | $< 12$ | – | $0.60 \pm 0.17 \pm 0.04^{\dagger}$ | $0.98^{+0.23}_{-0.19} \pm 0.07^{\dagger}$ | $0.76 \pm 0.13$ |


- BaBar collaboration, B. Aubert et al., Improved Measurements of the Branching Fractions for $B^0 \to \pi^+\pi^-$ and $B^0 \to K^+\pi^-$, and a search for $B^0 \to K^+K^-$, Phys. Rev. D75 (2007) 012008
- Belle collaboration, Y. T. Duh et al., Measurements of branching fractions and direct CP asymmetries for $B^0 \to K^+\pi^-$, $B^0 \to \pi^+\pi^-$ and $B^0 \to K^+K^-$ decays, Phys. Rev. D87 (2013) 031103
- CLEO collaboration, A. Bornheim et al., Measurements of charmless hadronic two body B meson decays and the ratio $\mathcal{B}(B^0 \to DK)/\mathcal{B}(B^0 \to D\pi)$, Phys. Rev. D68 (2003) 052002
- CDF collaboration, T. Aaltonen et al., Evidence for the charmless annihilation decay mode $B_s^0 \to \pi^+\pi^-$, Phys. Rev. Lett. 108 (2012) 211803
- LHCb collaboration, R. Aaij et al., Measurement of b-hadron branching frac- tions for two-body decays into charmless charged hadrons, JHEP 10 (2012) 037
- Heavy Flavor Averaging Group, Y. Amhis et al., Averages of b-hadron, c-hadron, and $\tau$-lepton properties as of summer 2014

# Systematical uncertaities in the $B_{(s)}^0 \to h^+ h^-$ analyses

- $B \to h^+ h^-$ **yields**: toys are generated with the baseline model and fitted back with alternative models

- **PID efficiencies**: their systematic is assessed again by running pseudoexperiments, and then fitting the output distributions using PID efficiencies randomly extracted according to their estimated uncertainties

| Systematic uncertainty | $N(B^0 \to K^+K^-)$ | $N(B_s^0 \to \pi^+\pi^-)$ |
|---|---|---|
| Final state radiation | 6.05 | 5.42 |
| Signal mass shape | 10.10 | 3.16 |
| Comb. back. mass shape | 5.48 | 2.58 |
| Part. reco. back. mass shape | 1.33 | 23.06 |
| Crossfeed back. mass shape | negligible | negligible |
| PID efficiencies | 3.43 | 2.52 |
| Sum in quadrature | 13.50 | 24.17 |

(Preliminary results)

# Binning schemes for the $\Lambda_b^0 \to p\pi\pi\pi$ measurements

| Scheme A Region | $m_{p\pi^+}$ ( GeV/$c^2$) | $m_{p\pi^-_{slow}}$ ( GeV/$c^2$) | $m_{\pi^+\pi^-_{slow}}$, $m_{\pi^+\pi^-_{fast}}$ ( GeV/$c^2$, GeV/$c^2$) | $\Phi$ |
|---|---|---|---|---|
| 1 | $(1.00, 1.23)$ | | | $(0, \frac{\pi}{2})$ |
| 2 | $(1.00, 1.23)$ | | | $(\frac{\pi}{2}, \pi)$ |
| 3 | $(1.23, 1.35)$ | | | $(0, \frac{\pi}{2})$ |
| 4 | $(1.23, 1.35)$ | | | $(\frac{\pi}{2}, \pi)$ |
| 5 | $(1.35, 5.40)$ | $(0.90, 2.00)$ | $(m_{\pi^+\pi^-_{slow}} < 0.78 \vert\vert m_{\pi^+\pi^-_{fast}} < 0.78)$ | $(0, \frac{\pi}{2})$ |
| 6 | $(1.35, 5.40)$ | $(0.90, 2.00)$ | $(m_{\pi^+\pi^-_{slow}} < 0.78 \vert\vert m_{\pi^+\pi^-_{fast}} < 0.78)$ | $(\frac{\pi}{2}, \pi)$ |
| 7 | $(1.35, 5.40)$ | $(0.90, 2.00)$ | $!(m_{\pi^+\pi^-_{slow}} < 0.78 \vert\vert m_{\pi^+\pi^-_{fast}} < 0.78)$ | $(0, \frac{\pi}{2})$ |
| 8 | $(1.35, 5.40)$ | $(0.90, 2.00)$ | $!(m_{\pi^+\pi^-_{slow}} < 0.78 \vert\vert m_{\pi^+\pi^-_{fast}} < 0.78)$ | $(\frac{\pi}{2}, \pi)$ |
| 9 | $(1.35, 5.40)$ | $(2.00, 4.00)$ | $(m_{\pi^+\pi^-_{slow}} < 0.78 \vert\vert m_{\pi^+\pi^-_{fast}} < 0.78)$ | $(0, \frac{\pi}{2})$ |
| 10 | $(1.35, 5.40)$ | $(2.00, 4.00)$ | $(m_{\pi^+\pi^-_{slow}} < 0.78 \vert\vert m_{\pi^+\pi^-_{fast}} < 0.78)$ | $(\frac{\pi}{2}, \pi)$ |
| 11 | $(1.35, 5.40)$ | $(2.00, 4.00)$ | $!(m_{\pi^+\pi^-_{slow}} < 0.78 \vert\vert m_{\pi^+\pi^-_{fast}} < 0.78)$ | $(0, \frac{\pi}{2})$ |
| 12 | $(1.35, 5.40)$ | $(2.00, 4.00)$ | $!(m_{\pi^+\pi^-_{slow}} < 0.78 \vert\vert m_{\pi^+\pi^-_{fast}} < 0.78)$ | $(\frac{\pi}{2}, \pi)$ |
| **Scheme B Region** | | | | |
| $i$ | $(i = 1, 2, ..., 10)$ | | | $(\frac{i-1}{10}\pi, \frac{i}{10}\pi)$ |