Evidence of CP violation in $B^{\pm} \rightarrow h^{\pm}h^{+}h^{-}$ charmless decays

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Outline

- Theory Overview
  - The $B^{\pm} \rightarrow h^{\pm}h^{+}h^{-}$ charmless decays.
  - Dalitz plot.
  - The CPT theorem.

- The LHCb experiment.

- Evidence of direct CP violation in $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$ decays.

LHCb-CONF-2012-018 preliminary $\mathcal{L} = 1.0\ fb^{-1}$

- Evidence of direct CP violation in $B^{\pm} \rightarrow \pi^{\pm}K^{+}K^{-}$ and $B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ decays.

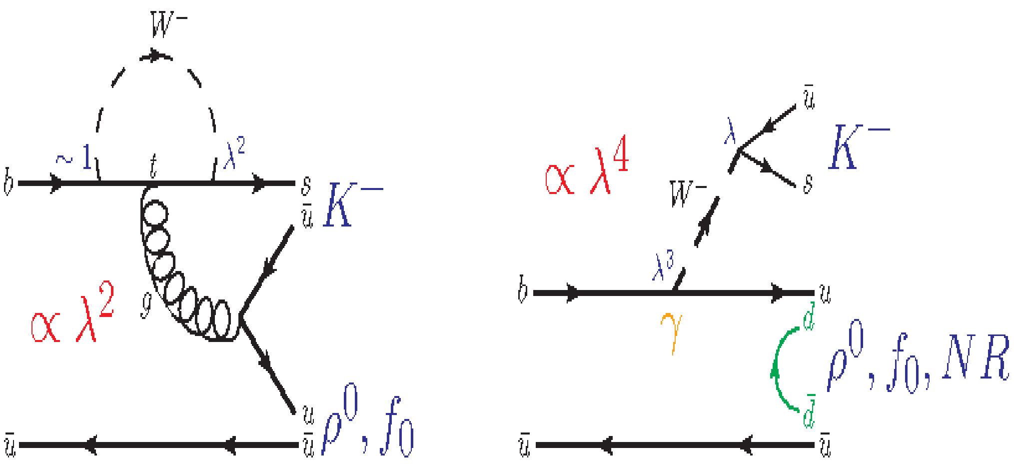
LHCb-CONF-2012-028 preliminary $\mathcal{L} = 1.0\ fb^{-1}$

- Discussions and perspectives.

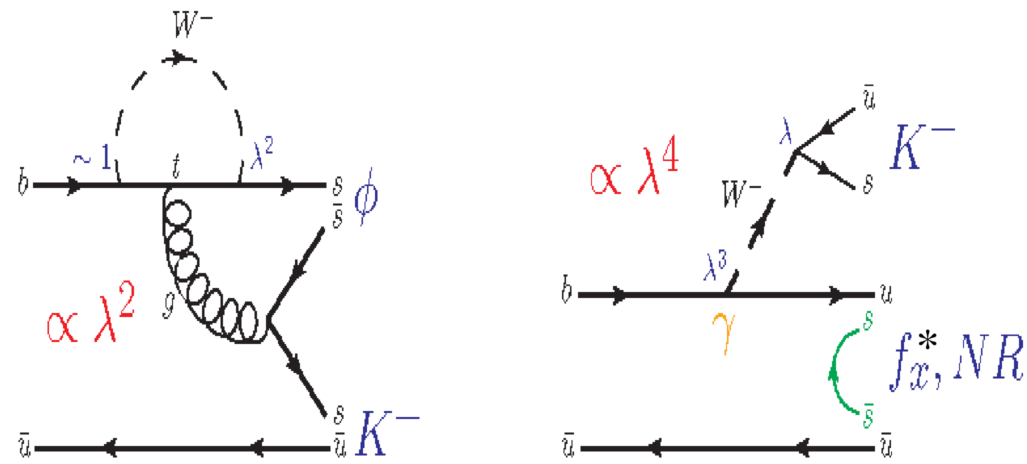
- Conclusions

Theory Overview I

$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ BR $\propto 10^{-5}$



$B^{\pm} \to K^{\pm}K^{+}K^{-}$ BR $\propto 10^{-5}$

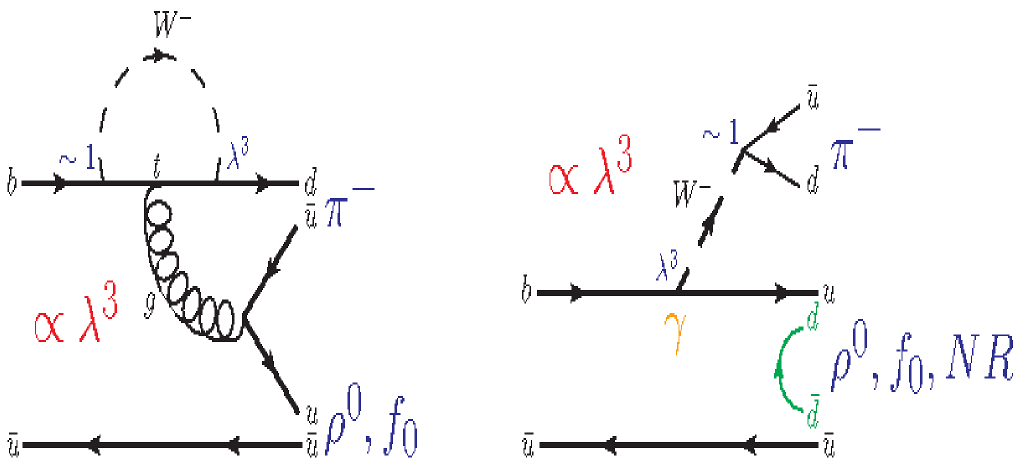


- Access to t → s (P) and the CKM phase b → u (T) transitions.
  - γ at tree level.
- CP violation (CPV) expected from interference between tree ($\propto \lambda^4$) and penguin ($\propto \lambda^2$) diagrams in both channels. Type I
- For Kππ:
  - CP violation expected also from ρ^0, f_0 and K* interferences in the phase space. Type II
- For KKK:
  - φ resonance only from penguin contribution.
  - CPV expected only from interference between φ and f_x (or no-resonant). Type II
- Note that Type I and Type II are two different sources of CPV.

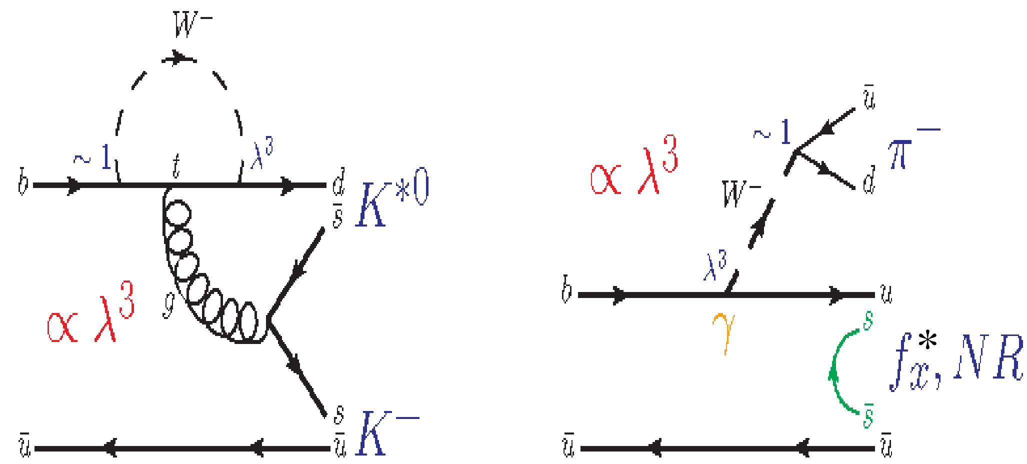
* fx holds for any resonance with the K^+K^- final state.

Theory Overview II

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ BR $\propto 10^{-5}$



$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ BR $\propto 10^{-6}$

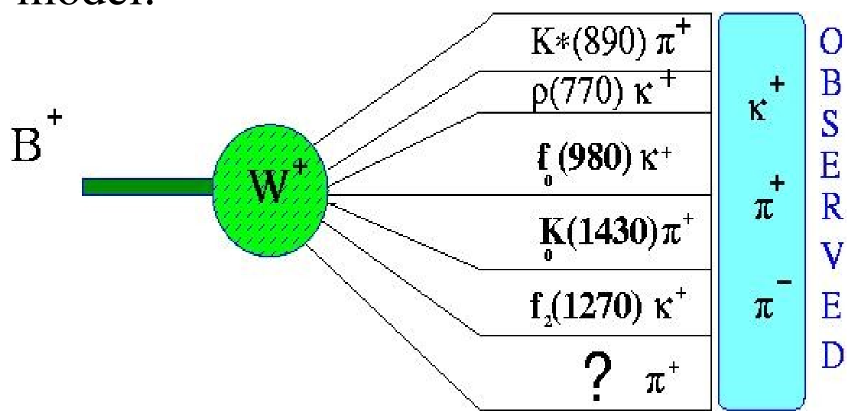


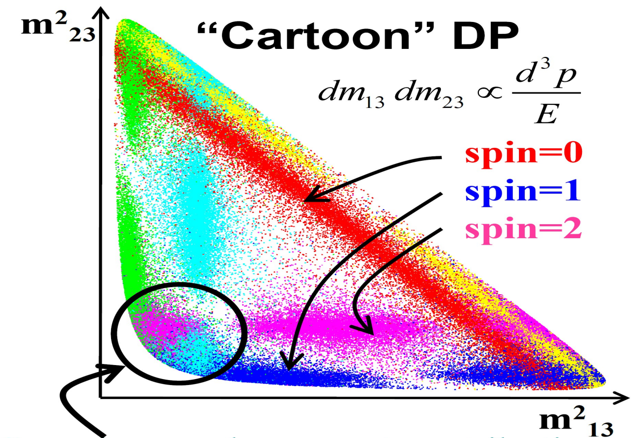
- Access to t → d (P) and the CKM phase b → u (T) transitions.
  - γ at tree level.
- CPV expected from interference between tree ($\propto \lambda^3$) and penguin ($\propto \lambda^3$) diagrams in both channels. Type I
- For πππ:
  - CP violation expected also from ρ^0 and f_0 interferences in the phase space. Type II
- For πKK:
  - ϕ resonance not expected for this mode (for current LHCb statistics).
  - CPV expected only from interference between K* and f_x (or no-resonant). Type II
- Note that Type I and Type II are two different sources of CPV.

* fx holds for any resonance with the K^+K^- final state.

Theory Overview III

- CPV in Dalitz plot (DP) is commonly studied through an amplitude analysis using the isobar model:





$$\mathcal{A}(B \to f) = \Sigma\, a_r e^{i(\varphi)} \mathcal{M}_r + \Sigma\, a_r e^{i(\varphi + \gamma)} \mathcal{M}_r + a_{nr} e^{i\delta} \mathcal{M}_{nr}$$

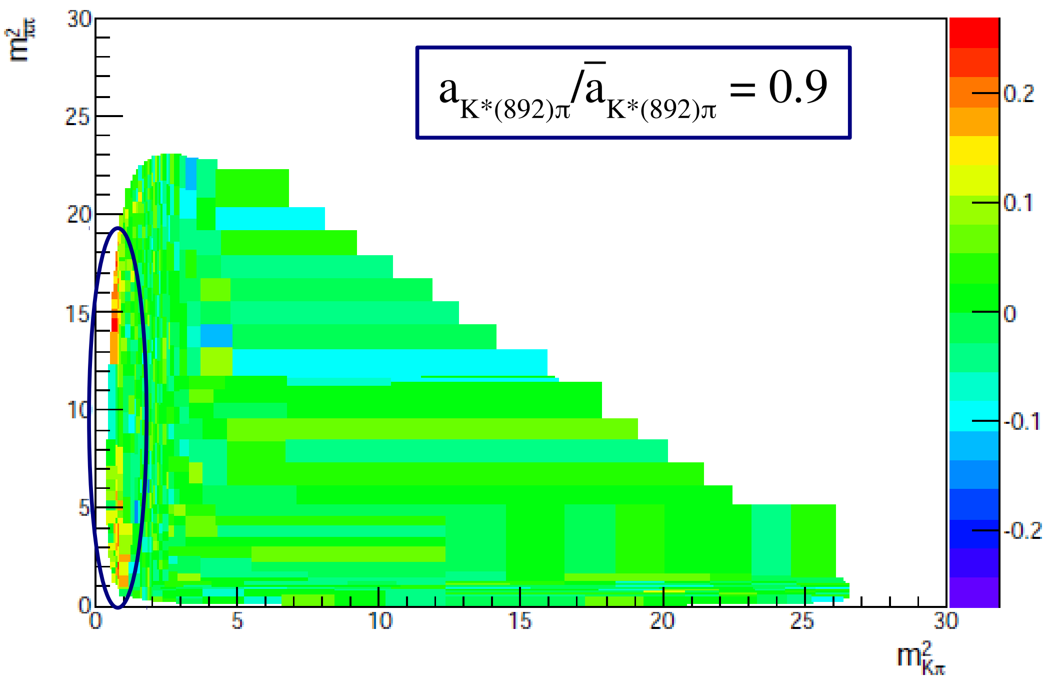
- Each resonance is included in a coherent sum for the total decay.
- Resonance interferences (parallel or crossing) → probe for CPV.
- CPV comes from differences in the amplitudes and phases for $\mathcal{A}$ and $\overline{\mathcal{A}}$.
  - Strong phase φ don't change sign under $\mathcal{A} \to \overline{\mathcal{A}}$.
  - Weak phase γ changes the under $\mathcal{A} \to \overline{\mathcal{A}}$.
- Some results in these modes:
  - Belle and BaBar: Evidence of CPV in $B^\pm \to \rho K^\pm$ (Kππ final state).
  - BaBar: Evidence of CPV in $B^\pm \to \phi K^\pm$ (KKK final state)

Belle: PRL **96**, (2006) 251803
BaBar: PR **D78**, (2008) 012004
BaBar: PR **D85**, (2012) 112010

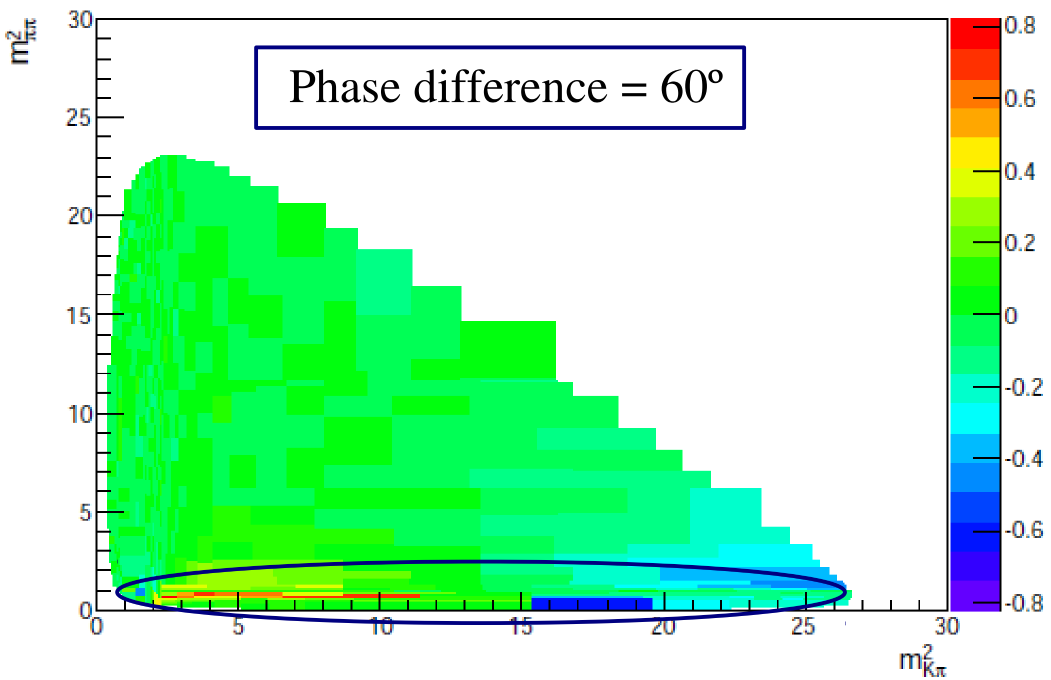
Theory Overview IV

- Amplitude analysis has a characteristic feature:
  - Difference in the amplitude for a resonance implies a difference in the total number of events for that resonance.
  - Difference in weak phase for a resonance implies a change in the shape of the resonance band in the phase space.
- Both effects must be seen where the resonance exists.

Fast MC with amplitude difference in $K^*\pi$



Fast MC with phase difference in ρK_s



Figures from I. Bediaga et. al: PR **D86**, (2012) 036005

Theory Overview V

- Other factors may influence the CPV measurement in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays.

- For instance, the CPT theorem implies:

From CPT theorem

$$\sum_{f_\alpha^{(i)} \in F_i} \Gamma(P \to f_\alpha^{(i)}) = \sum_{\bar{f}_\alpha^{(i)} \in \bar{F}_i} \Gamma(\bar{P} \to \bar{f}_\alpha^{(i)})$$

In F_i all f_α are connected via strong interactions

I. I. Bigi, A. I. Sanda , "CP Violation", 2nd edition, Cambridge University Press, 2009.

- As an example, consider the kaon decay:

$$\Gamma(K^+ \to 3\pi) \equiv \Gamma(K^+ \to \pi^+\pi^+\pi^-) + \Gamma(K^+ \to \pi^0\pi^0\pi^+)$$
$$= \Gamma(K^- \to \pi^-\pi^-\pi^+) + \Gamma(K^- \to \pi^0\pi^0\pi^-) \equiv \Gamma(K^- \to 3\pi)$$

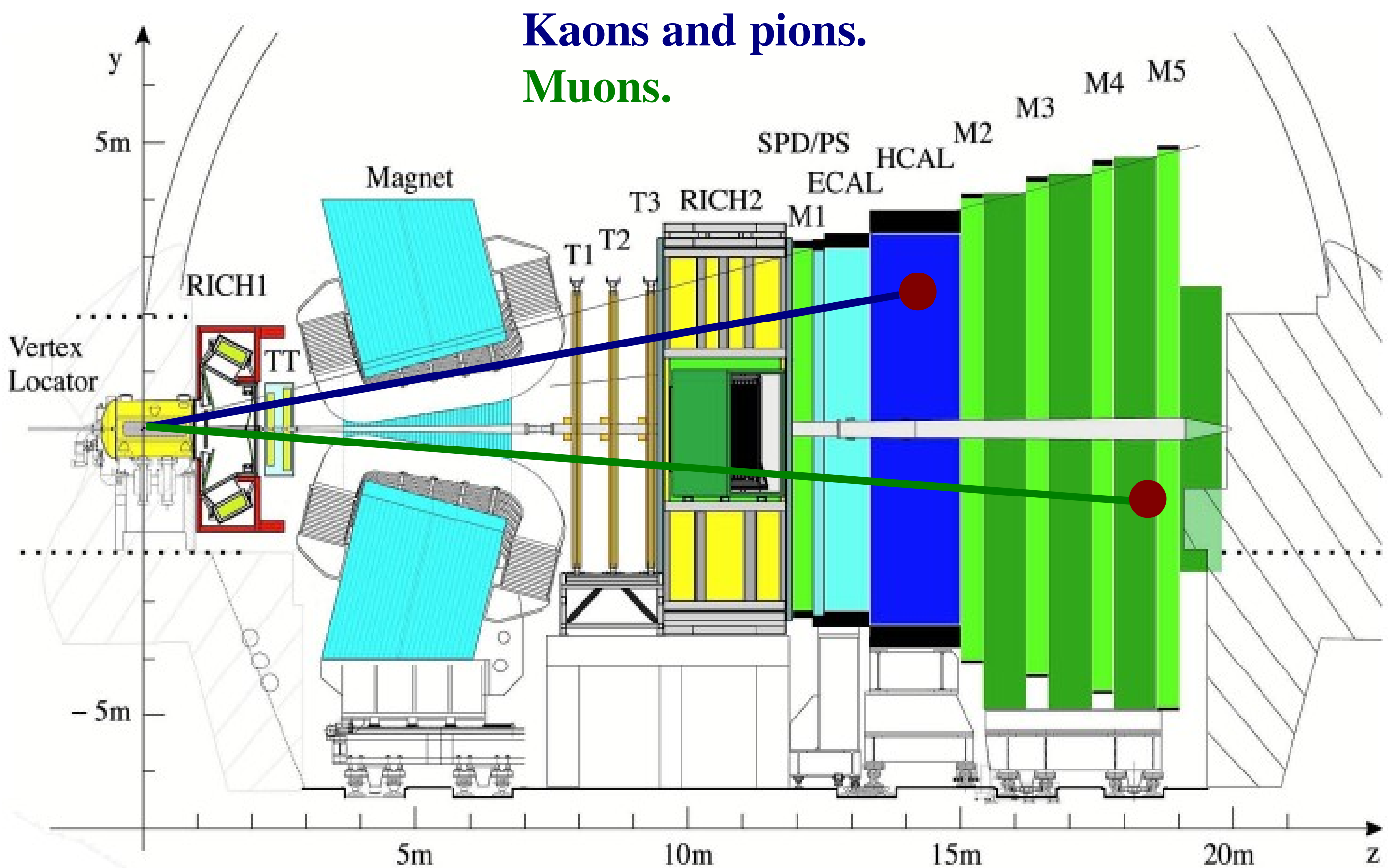
Marshak et. al , "Theory of weak interaction in particle physics", Wiley & Sons, 1969.

- Some excess (or *deficit*) of $K^+ \to \pi^+\pi^+\pi^-$ with respect to $K^- \to \pi^-\pi^-\pi^+$ may be balanced if the π^0 modes are included in the analysis.

- Due to CPT theorem, one must think about all final states together in order to understand the CPV distribution over the Dalitz plot.

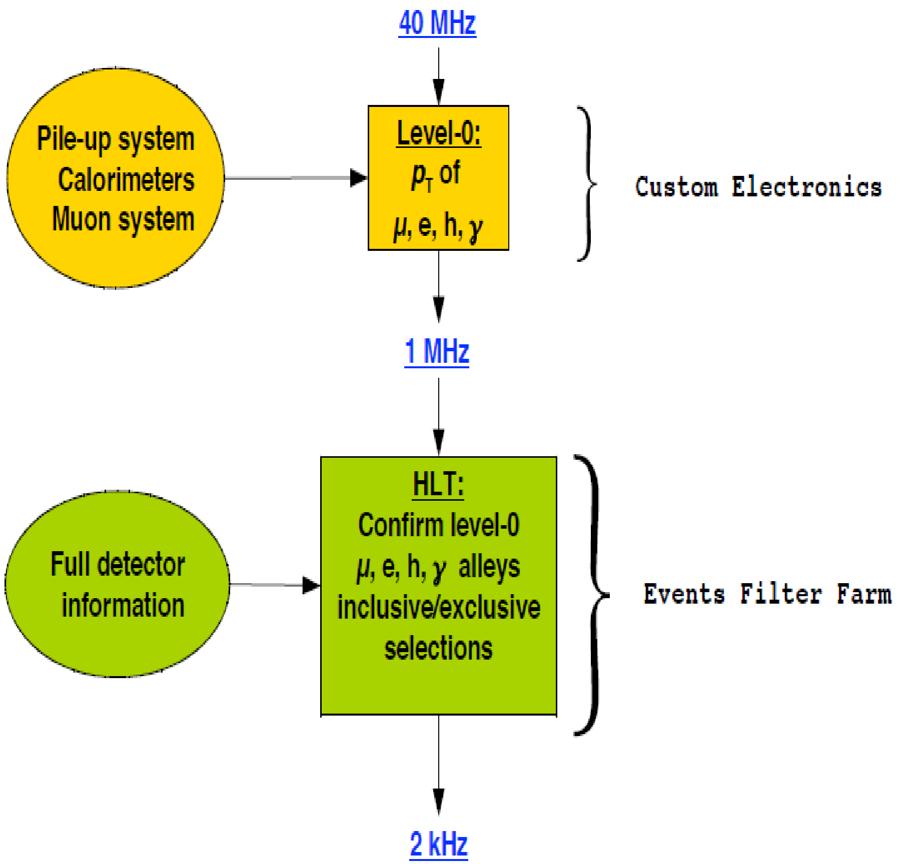
LHCb Overview

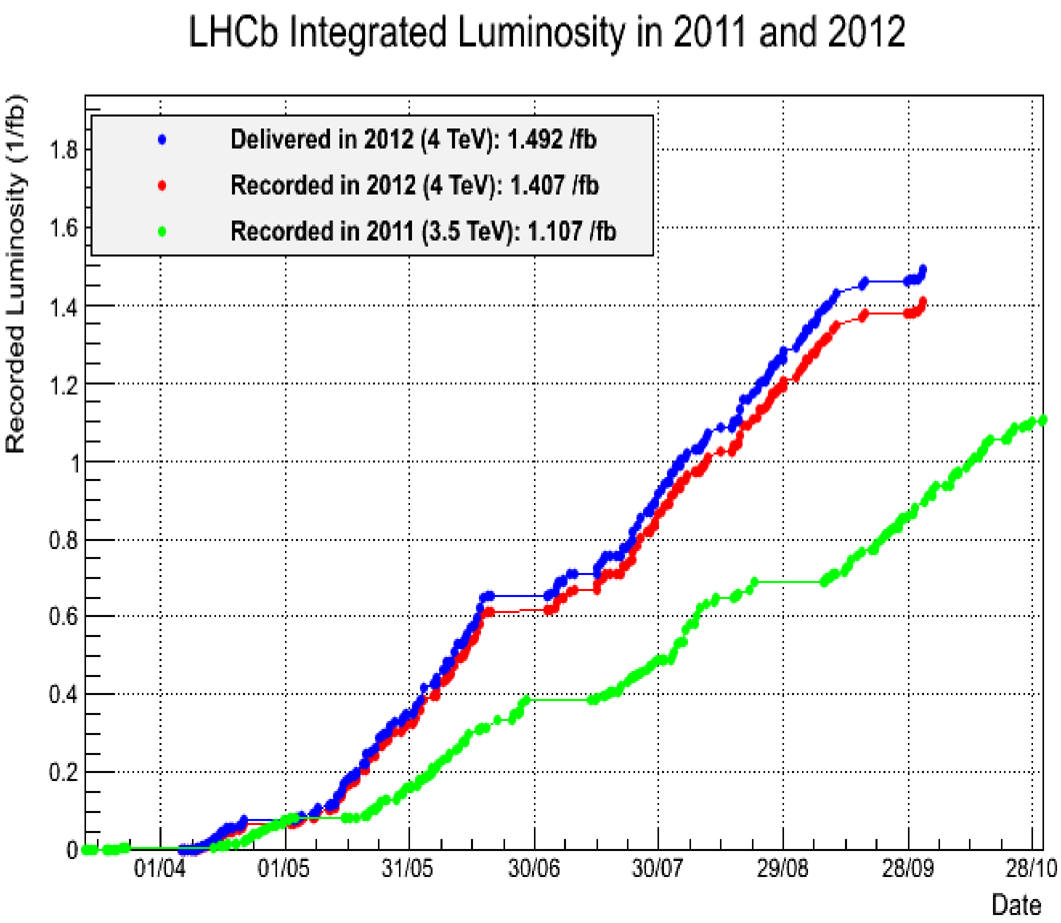
JINST **3** (2008) S08005



- Excellent tracking and vertexing for B and D decays.
- Excellent particle identification.
- Kaons and pions travels through substantial amount of material.
  - Possible detection asymmetry is accounted for.

LHCb trigger and DAQ





- Total integrated luminosity in 2011: 1.1 fb^{-1}.
- Expected for 2012: ~ 2.0 fb^{-1}.

$B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+K^-$

preliminary $\mathcal{L} = 1.0\ fb^{-1}$ LHCb-CONF-2012-018

- Selection explores the decay topology (see backup for full description):
  - Tracks with high momentum and transverse momentum.
  - Tracks with large impact parameters with respect to the interaction point.
  - B candidate with large flight distance, momentum and impact parameter with respect to interaction point.
- Particle ID used to separate kaons from pions and to veto muons.
- Different samples based on different trigger decisions used for the measurement.
- The $B^\pm \to K^\pm\pi^+\pi^-$ is connected to $B^\pm \to K^\pm K^+K^-$ through the final state interaction $\pi^+\pi^- \to K^+K^-$. Surovtsev, et. al: PRD **81**, (2010) 016001
- Same selection except for particle ID and background vetoes
- Observable:

$$A_{cp} = \frac{\Gamma(B^- \to f) - \Gamma(B^+ \to f)}{\Gamma(B^- \to f) + \Gamma(B^+ \to f)}$$

CPV measurement strategy

- The raw asymmetry can be interpreted as:

$$A_{cp}^{RAW}(K^{\pm}h^{+}h^{-}) = A_{cp}(K^{\pm}h^{+}h^{-}) + A_{P}(B^{\pm}) + A_{I}(K^{\pm})$$

- Where:
  - A_{cp} is the physical CPV.
  - A_{P} is the B^{+}/B^{-} production asymmetry.
  - $A_{I}(K^{\pm})$ is the instrumental asymmetry that holds for kaon detection and reconstruction.

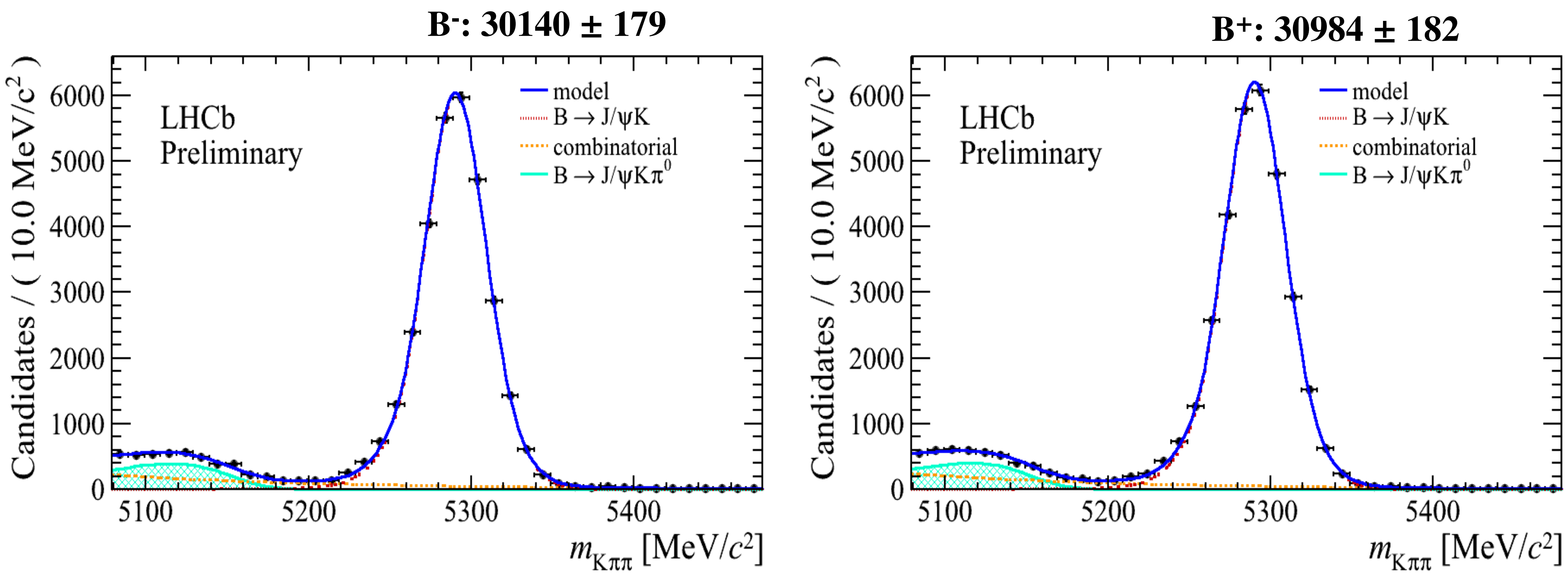
- The $B^{\pm} \rightarrow J/\psi K^{\pm}$ mode is used to extract the A_{I} and A_{P} asymmetries.
  - Same decay topology as $B^{\pm} \rightarrow h^{\pm}h^{+}h^{-}$ decays.
  - A_{P} is independent of the final state.
  - No CPV expected: $A_{CP} = 0.001 \pm 0.007$. PDG
  - Same selection applied.
  - Statistical error from PDG will be account separately since it is not measured by LHCb.

- Hence:

$$A_{P}(B^{\pm}) + A_{I} = A_{cp}^{RAW}(J/\psi K^{\pm}) - A_{cp}(J/\psi K^{\pm})$$

$$A_{cp}(K^{\pm}h^{+}h^{-}) = A_{cp}^{RAW}(K^{\pm}h^{+}h^{-}) - A_{cp}^{RAW}(J/\psi K^{\pm}) + A_{cp}(J/\psi K^{\pm})$$

$B^{\pm} \rightarrow J/\psi K^{\pm}$ raw asymmetry

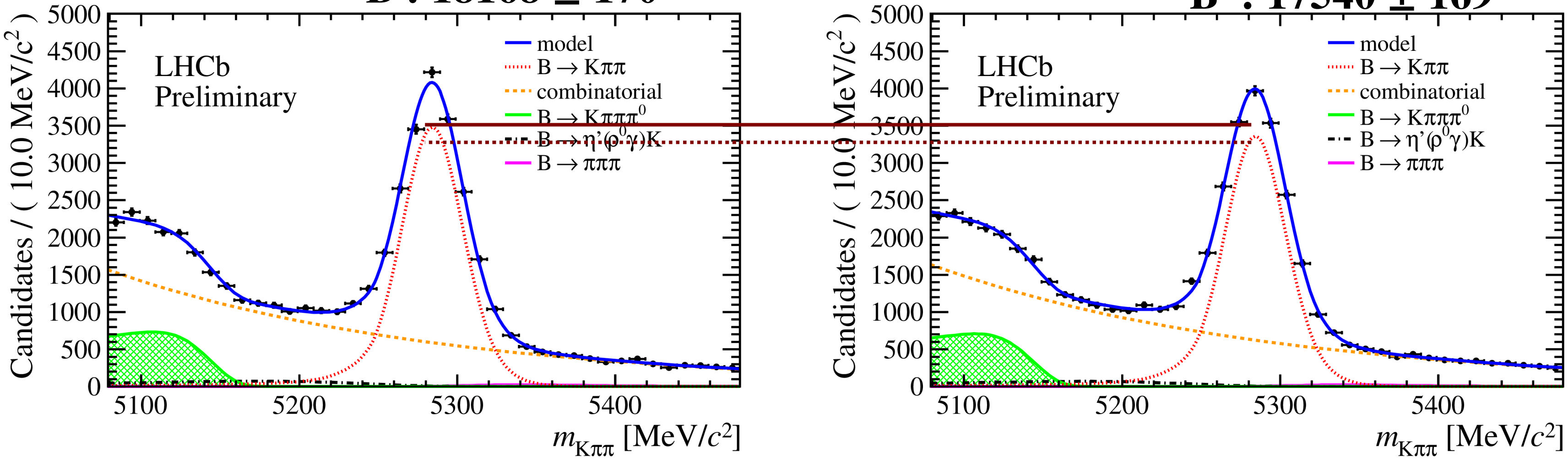


- Same selection as signal modes except for particle identification.

$$A^{raw}_{cp} = \frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} = A^{raw}_{cp}(J/\psi K) = -0.014 \pm 0.004$$

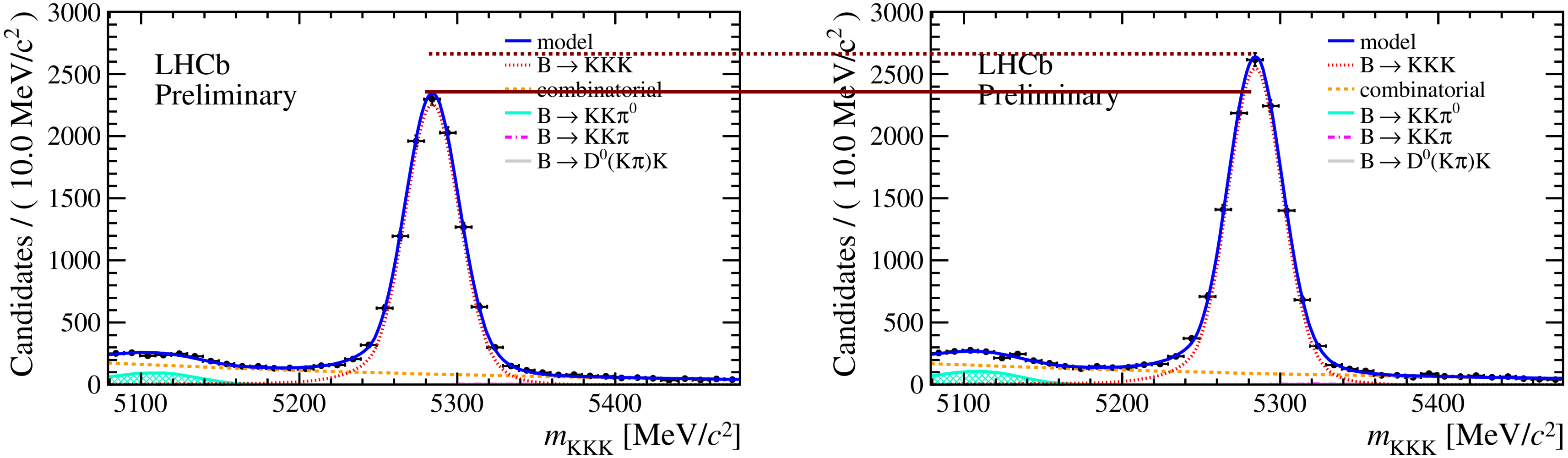
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ raw asymmetries

B^{-}: 18168 ± 170 **B^{+}: 17540 ± 169**



$A_{cp}^{raw}(K\pi\pi) = +0.018 \pm 0.007$

B^{-}: 10289 ± 110 **B^{+}: 11606 ± 117**



$A_{cp}^{raw}(KKK) = -0.060 \pm 0.007$

$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ systematics and results

- The main sources of systematic uncertainties are:
  - Subtraction method: kinematic variables of the kaon from control channel were weighted to match the same distribution from the signal kaon.
  - Trigger correction: the measurement was performed using samples from different trigger decision.
- Final result:

$$A_{cp}(B^{\pm} \to K\pi\pi) = +0.034 \pm 0.009(\text{stat}) \pm 0.004(\text{syst}) \pm 0.007(J/\psi K)$$
$$A_{cp}(B^{\pm} \to KKK) = -0.046 \pm 0.009(\text{stat}) \pm 0.005(\text{syst}) \pm 0.007(J/\psi K)$$

2.8σ

3.7σ

- Previous measurements:

$A_{cp}(B^{\pm} \to K\pi\pi) = +0.038 \pm 0.022$

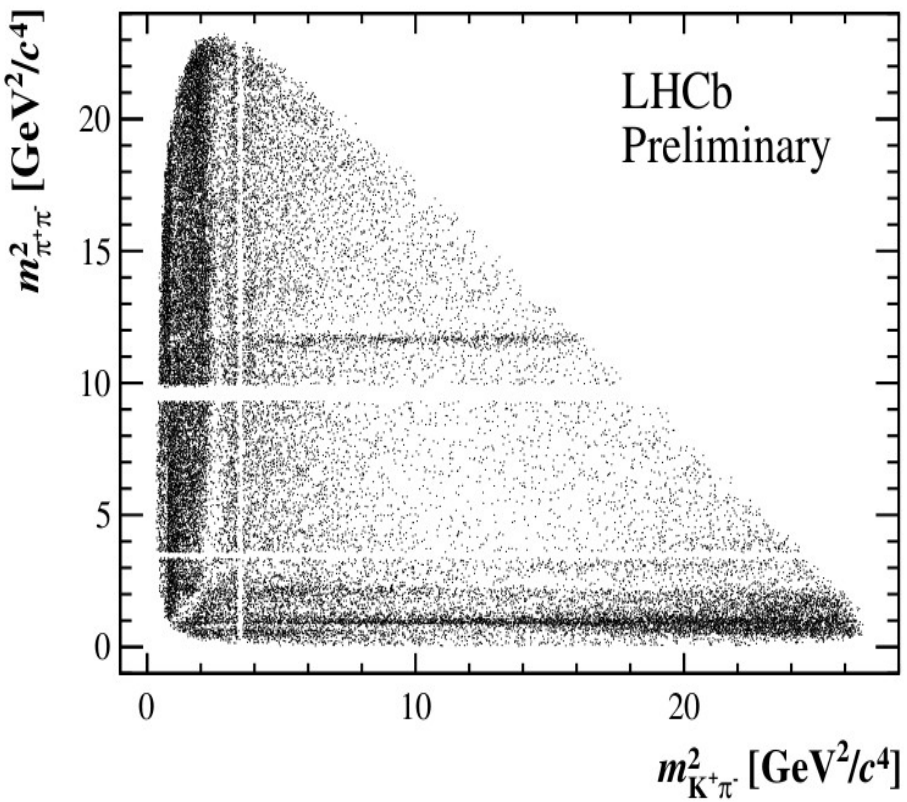
$A_{cp}(B^{\pm} \to KKK) = -0.017 \pm 0.030$

PDG

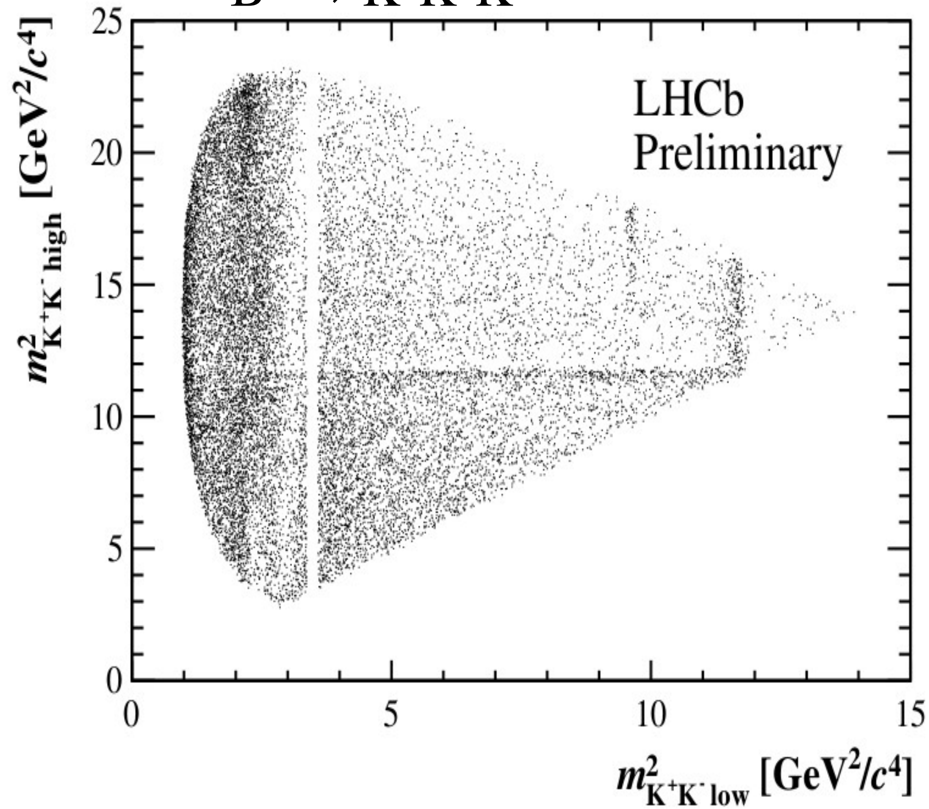
First evidence of global CPV in charmless three-body B decays.

$B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$ Dalitz plot

*$B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$



*$B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$

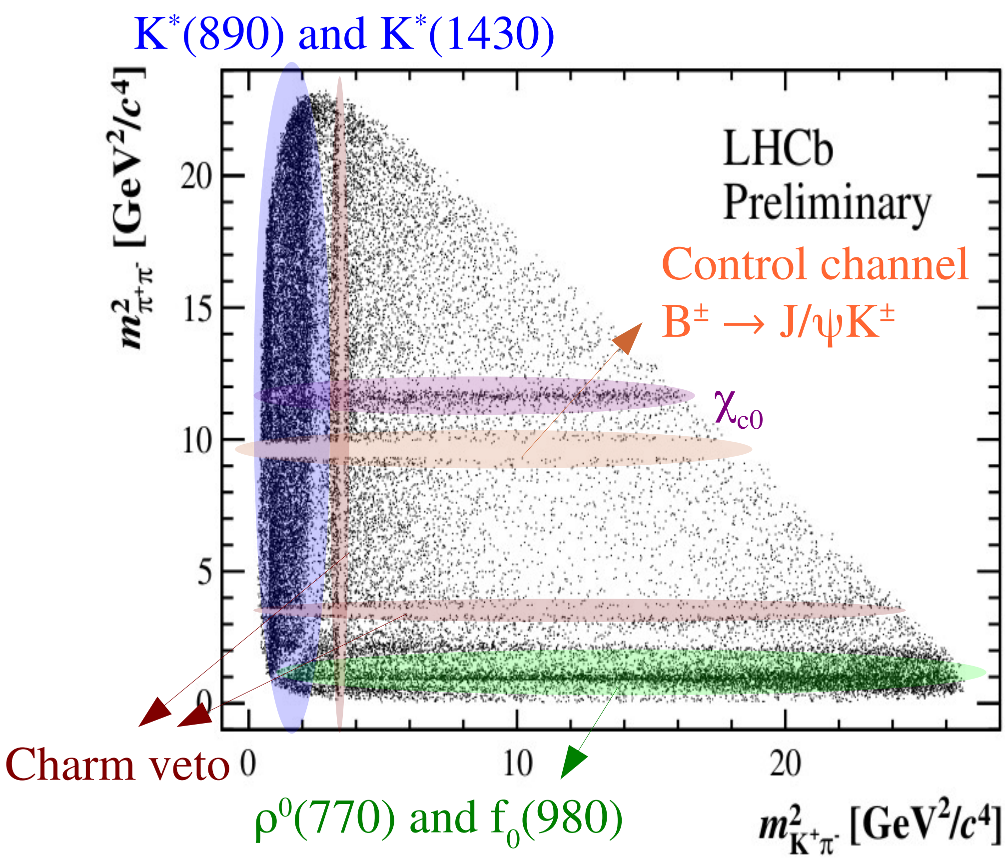


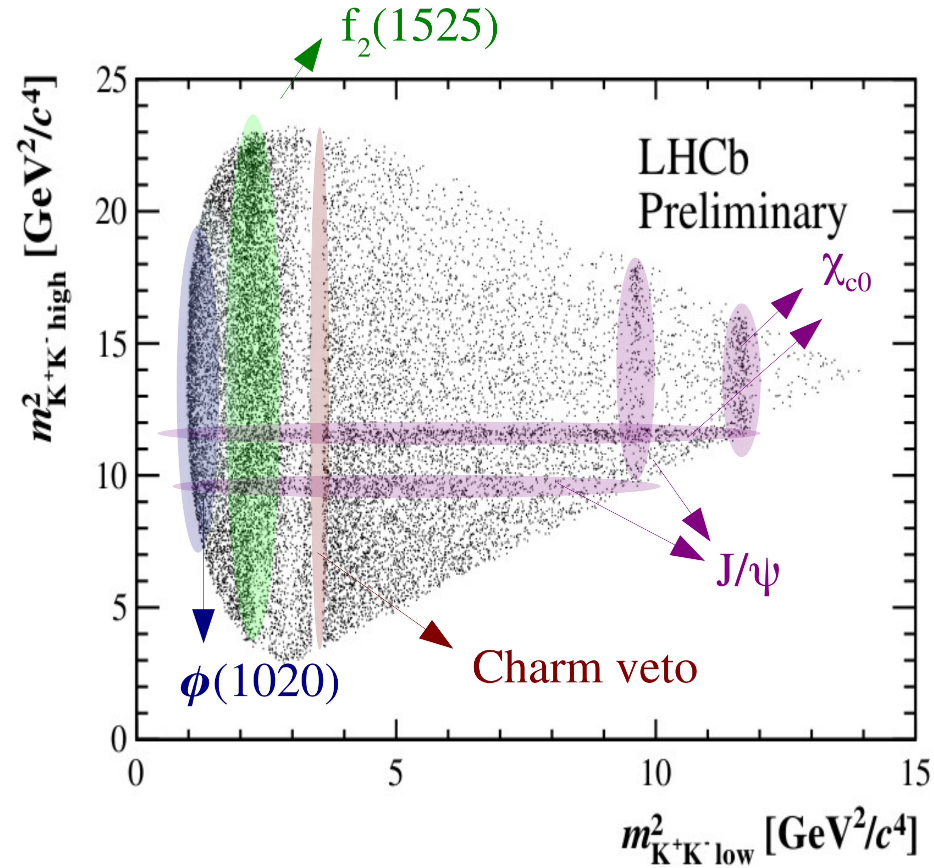
$$m^2_{K^{\pm}K^{\mp}Low} < m^2_{K^{\pm}K^{\mp}High}$$

- Phase space without B mass constraint.
- Phase space not background subtracted.
- D^0 contribution removed.
- J/ψ contribution removed from $K\pi\pi$ sample since it is the control channel.
- Acceptance efficiency is flat over the Dalitz plot

*±40 MeV^2 m_B mass window

$B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$ Dalitz plot





$$m^2_{K^{\pm}K^{\mp}Low} < m^2_{K^{\pm}K^{\mp}High}$$

- Phase space without B mass constraint.
- Phase space not background subtracted.
- D^0 contribution removed.
- J/ψ contribution removed from Kππ sample since it is the control channel.
- Acceptance efficiency is flat over the Dalitz plot

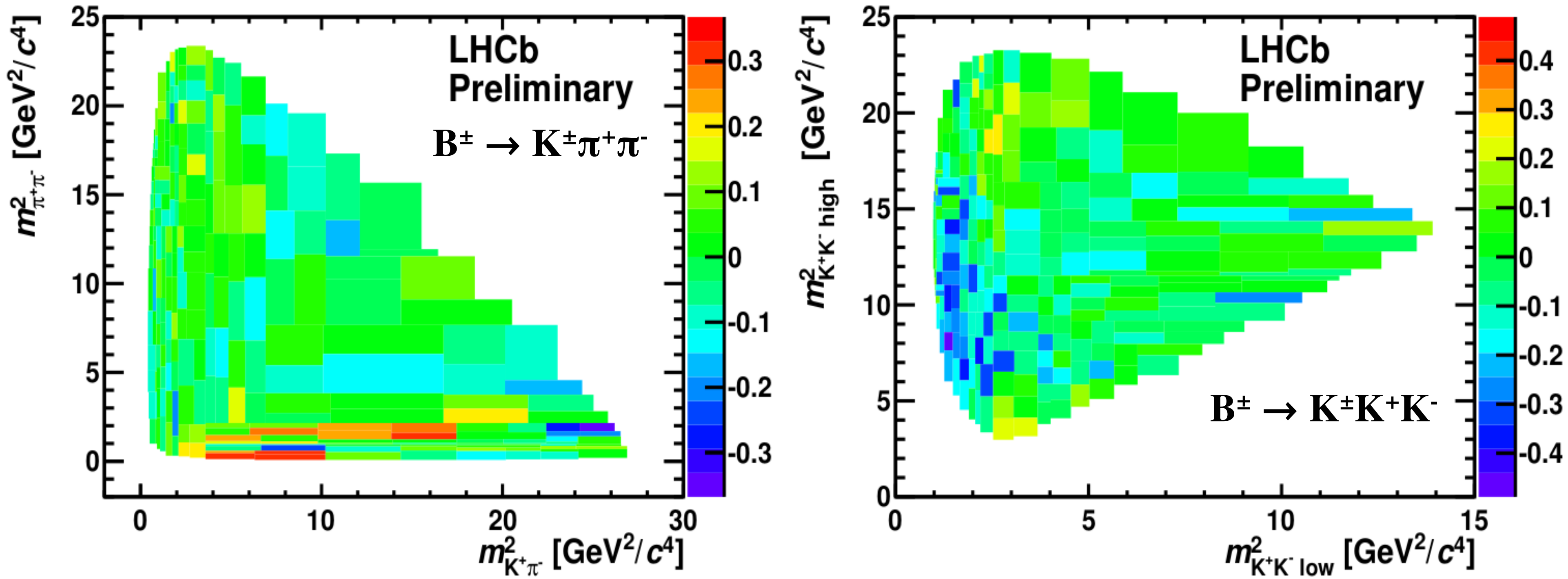
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ Dalitz plot

- Different approaches for Dalitz plots:
  - Adaptive binning applied to define bins with equal number of entries for the total sample.

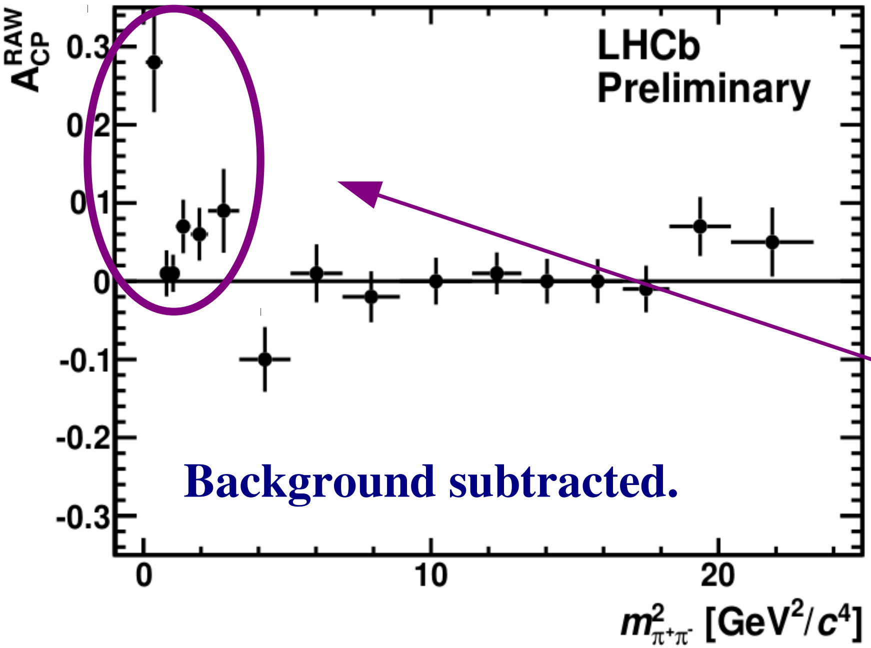
- Asymmetry per bin (including background):

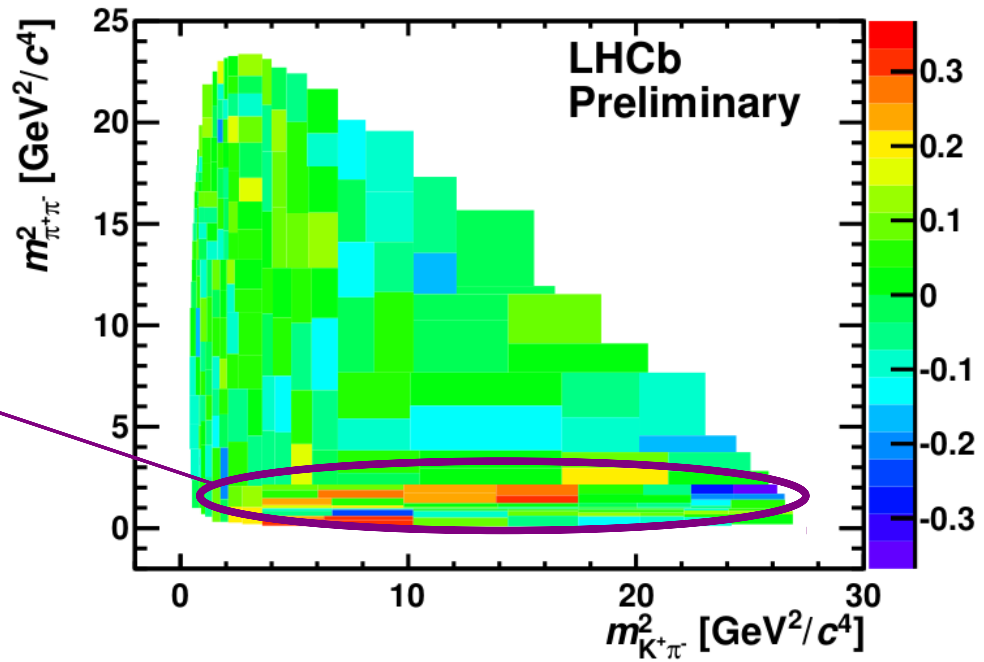
$$A_{cp}^{N}(s,b) = \frac{(s+b)^{-} - (s+b)^{+}}{(s+b)^{-} + (s+b)^{+}}$$

- The A^{n}_{cp} for each bin was computed:



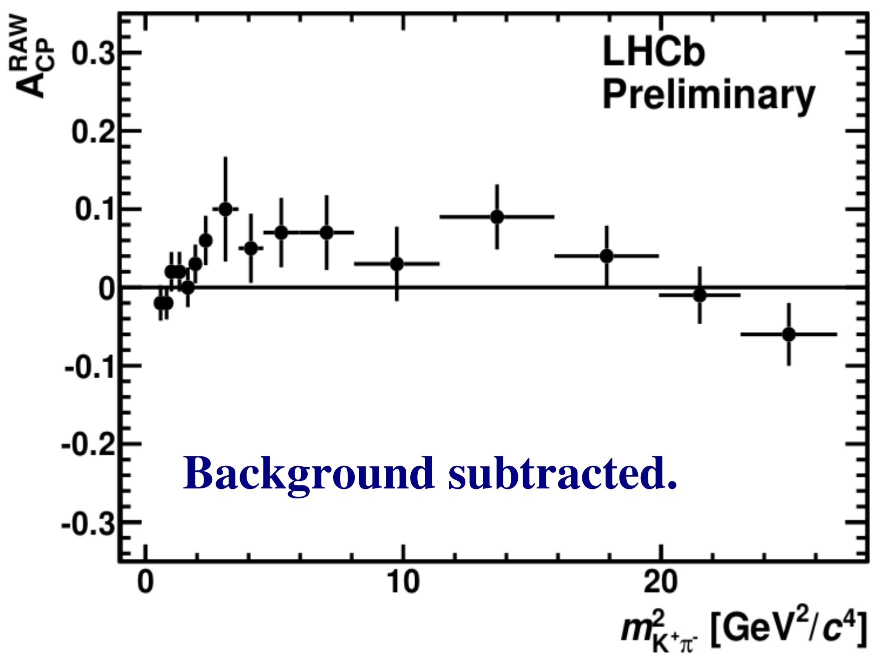
$B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ Dalitz plot



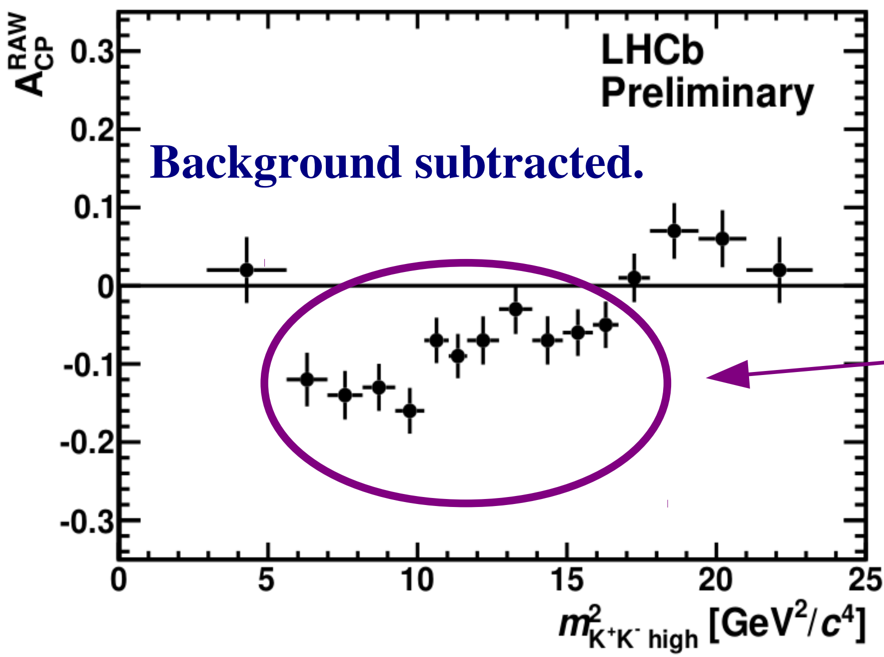


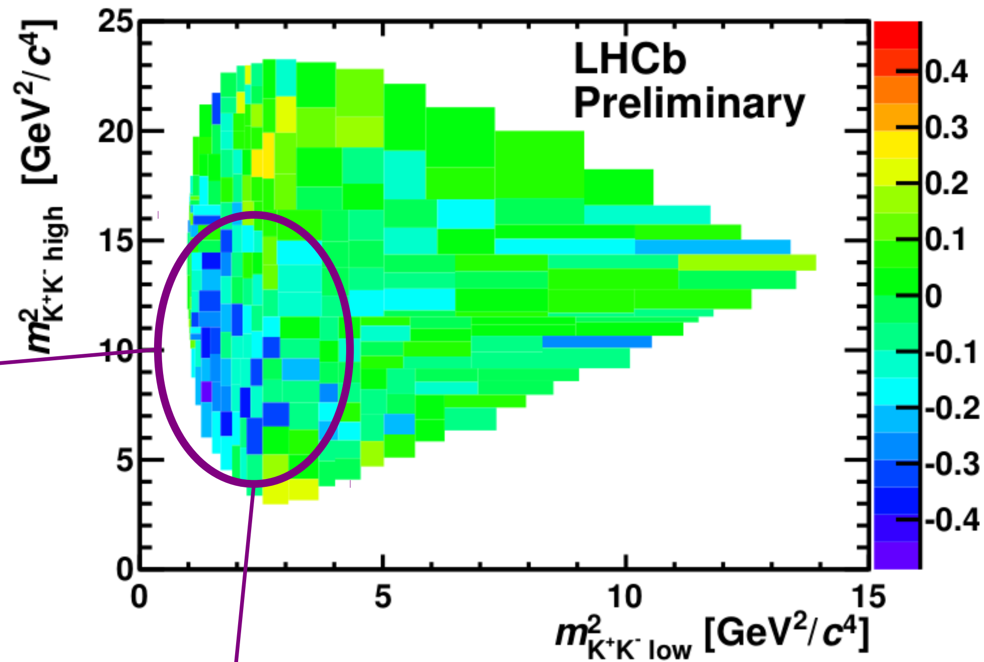
- Agrees with B factories results.
- No signature of CPV in the $K\pi$ invariant mass

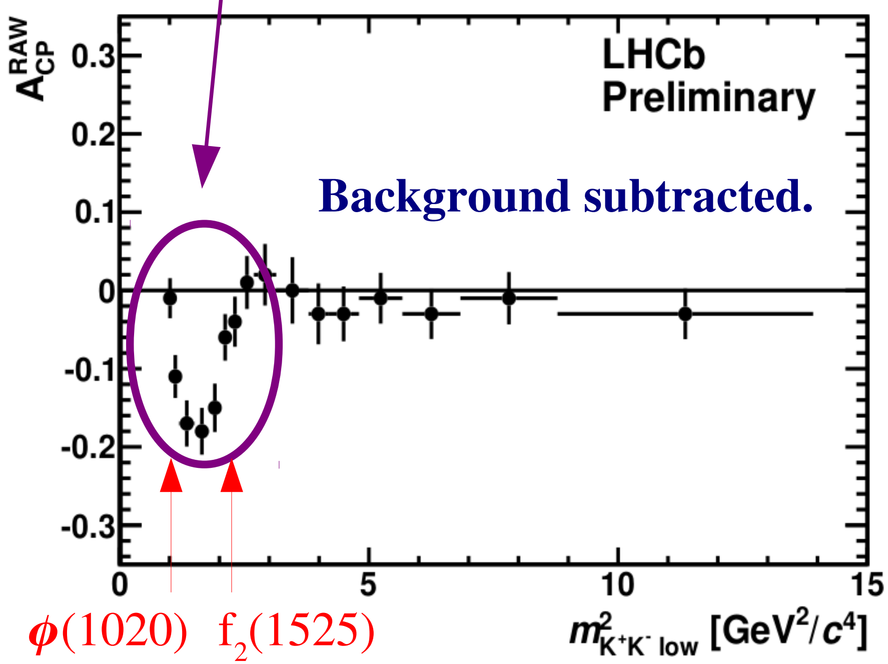
Large positive CPV at low $m^2_{\pi+\pi-}$



$B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$ Dalitz plot







- No similar report from B factories.

Very large CPV at low $m^2_{K+K-\ low}$ not clearly associated to a resonance

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$

LHCb-CONF-2012-028

- Same selection applied on $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ analysis.

- Particle ID used to separate kaons from pions and to veto muons.

- Different samples based on different trigger decisions used for the measurement.

- Similar statistics
  - Large background.

- Same selection except for particle ID and background vetoes.

- Instrumental and productions asymmetries:
  - Even number of kaons.
  - Instrumental asymmetry for pions extracted from a large D* sample.
  - $B^{\pm}$ production asymmetry extracted using previous analysis results.

CPV measurement strategy

- The raw asymmetry can be interpreted as:

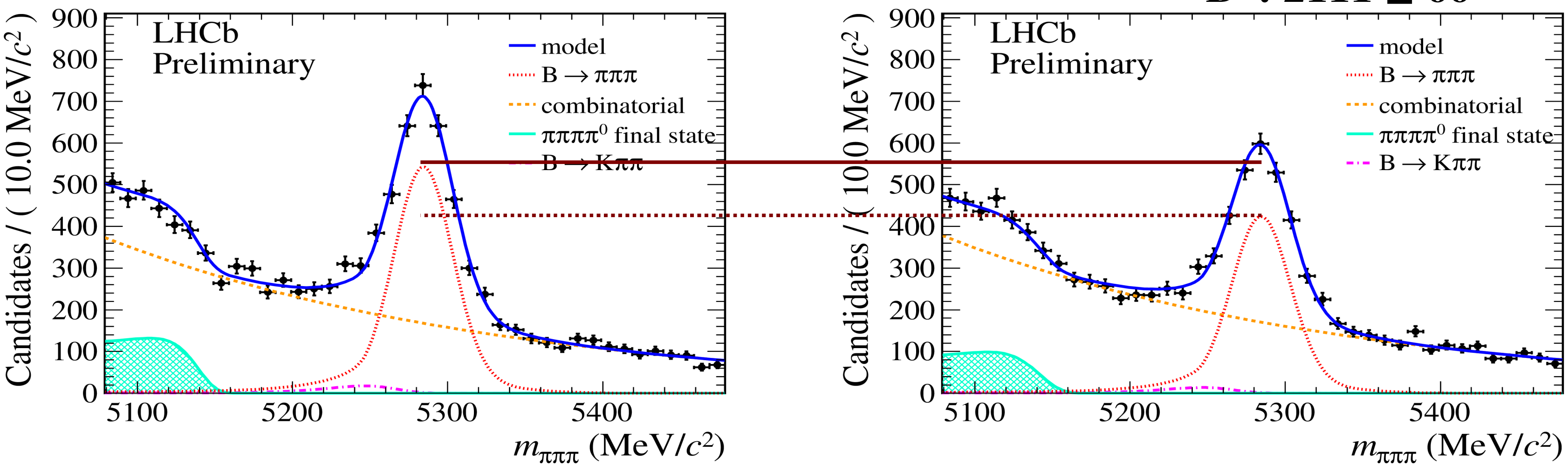
$$A_{cp}^{RAW}(\pi^{\pm}h^{+}h^{-}) = A_{cp}(\pi^{\pm}h^{+}h^{-}) + A_P + A_I$$

- Where:
  - A_{cp} is the physical CPV.
  - A_P is the B^+/B^- production asymmetry.
  - A_I is the instrumental asymmetry that holds for detection and reconstruction.
  - A_{cp}^{RAW} is the raw asymmetry and it was corrected by the acceptance in the Dalitz plot.

- Base measurements:
  - A_p extracted from $B^{\pm} \rightarrow J/\psi K^{\pm}$ control channel. LHCb-CONF-2012-018
  - Large sample of $D^0 \rightarrow K^{\pm}\pi^{\mp}$ and $D^0 \rightarrow K^+K^-$ used to measure the $A_I(K^{\pm})$. LHCb: PRL **108**, (2012) 201601.
  - $A_I(\pi^{\pm})$ for pions extracted from a large $D^{*\pm}$ sample. LHCb: PL **B713**, (2012) 186.

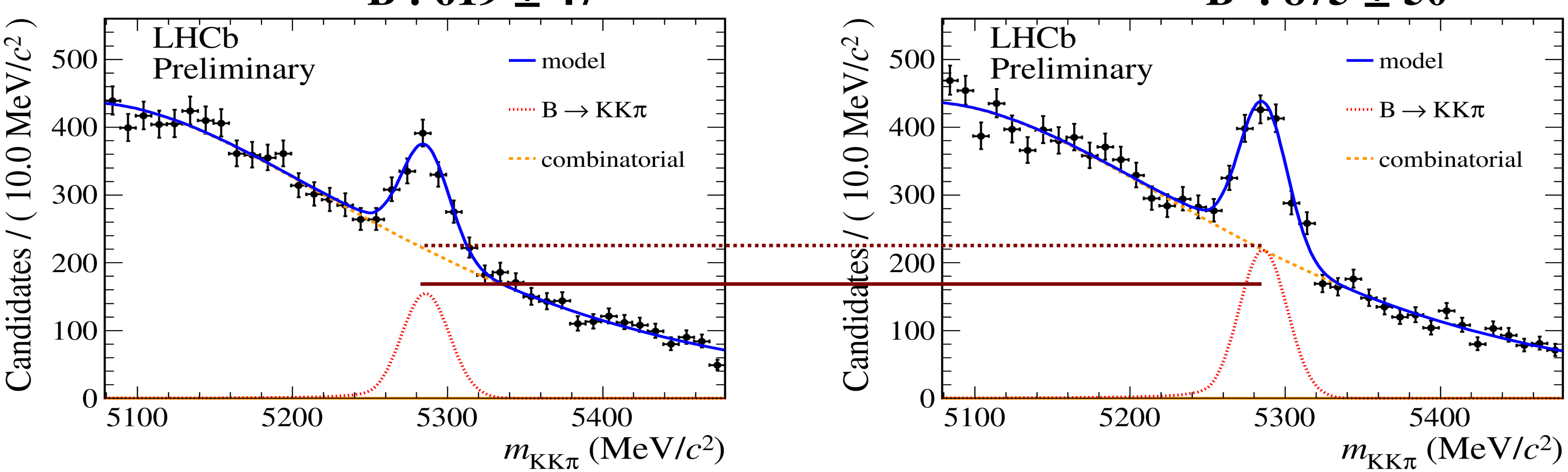
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ raw asymmetry

B^{-}: 2718 ± 71 **B^{+}: 2111 ± 66**



$A_{cp}^{raw}(\pi\pi\pi) = +0.125 \pm 0.020$

B^{-}: 619 ± 47 **B^{+}: 875 ± 50**



$A_{cp}^{raw}(\pi KK) = -0.171 \pm 0.046$

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ systematics and results

- The main sources of systematic uncertainties are:
  - Acceptance efficiency: the acceptance over the Dalitz plot was corrected for the B^{+} and B^{-} detection and reconstruction efficiencies.
  - Kaon kinematics: the $B^{\pm} \to J/\psi K^{\pm}$ raw asymmetry in bins of kaon momentum is weighted by the ratio of K^{-} and K^{+} efficiencies from $D^{0} \to K^{+}K^{-}$ sample.
- Final result:

$$A_{cp}(B^{\pm} \to \pi\pi\pi) = +0.120 \pm 0.020(\text{stat}) \pm 0.019(\text{syst}) \pm 0.007(J/\psi K)$$
$$A_{cp}(B^{\pm} \to \pi KK) = -0.153 \pm 0.046(\text{stat}) \pm 0.019(\text{syst}) \pm 0.007(J/\psi K)$$

4.2σ

3.0σ

- Previous measurements:

$$A_{cp}(B^{\pm} \to \pi\pi\pi) = +0.032 \pm 0.044(\text{stat})\ ^{+0.040}_{-0.037}(\text{syst})$$
$$A_{cp}(B^{\pm} \to \pi KK) = -0.00 \pm 0.10(\text{stat}) \pm 0.03(\text{syst})$$

PDG

First evidence of global CPV in charmless three-body B decays.

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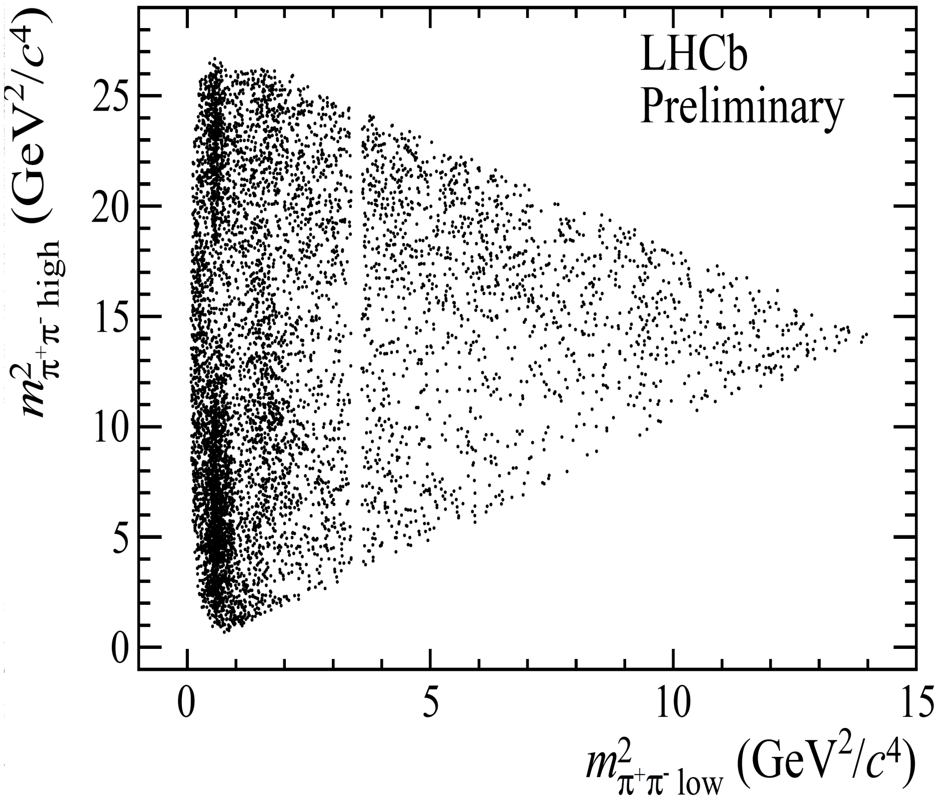
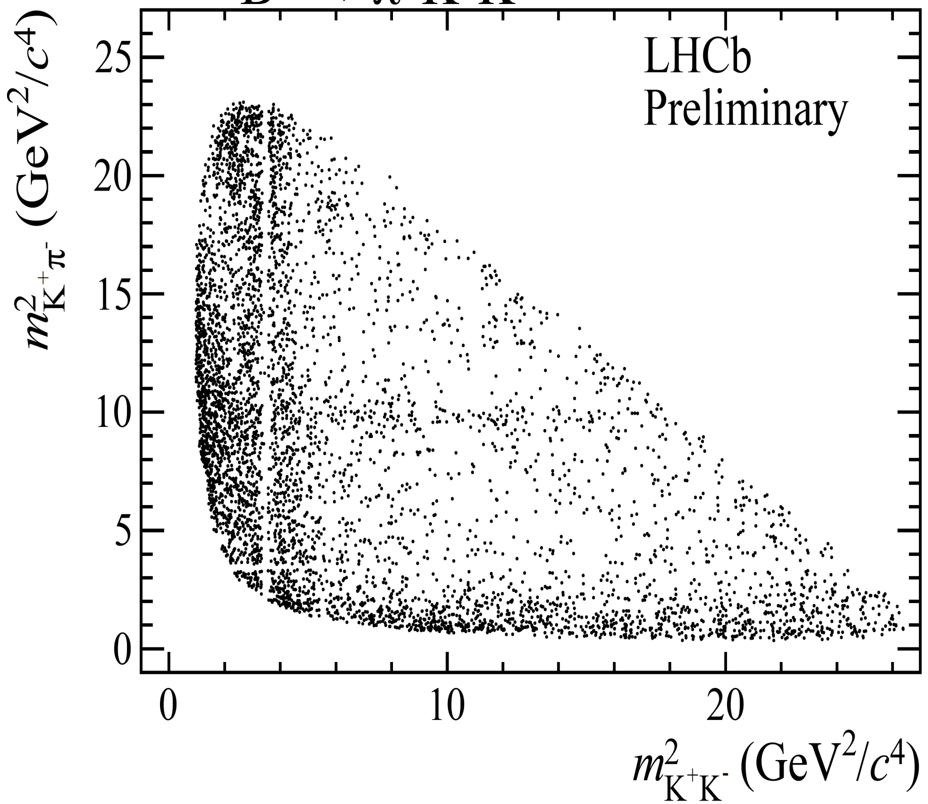
*$B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$



$$m^2_{\pi^+\pi^- \text{low}} < m^2_{\pi^+\pi^- \text{high}}$$

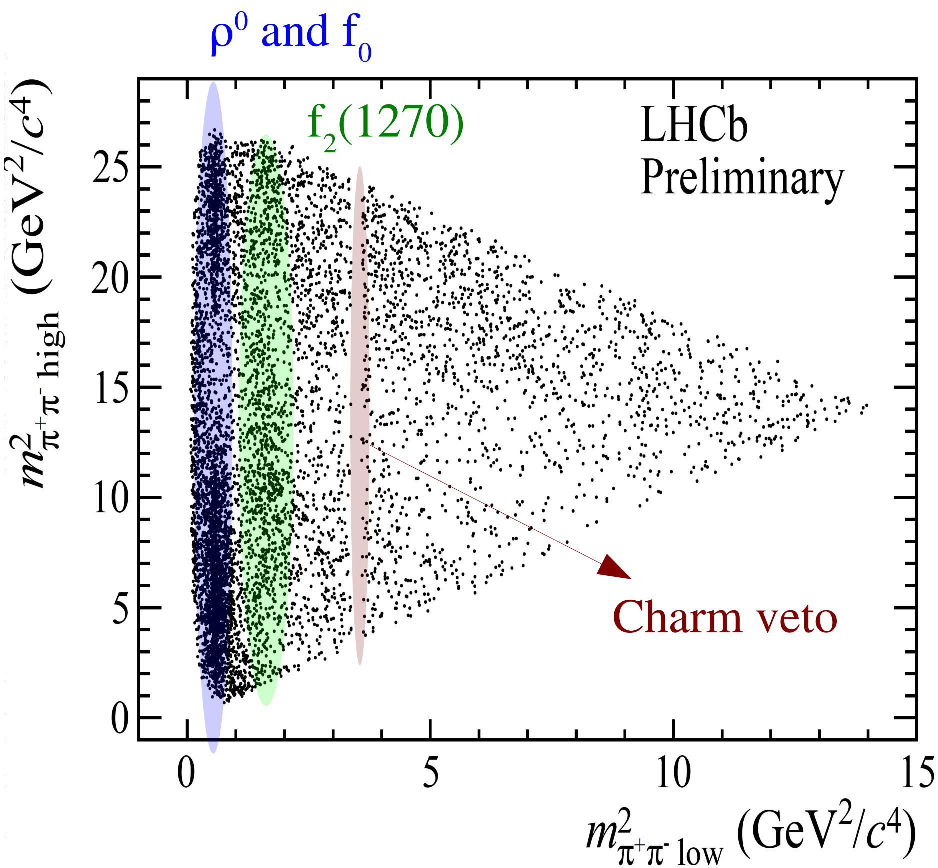
*$B^{\pm} \rightarrow \pi^{\pm}K^{+}K^{-}$

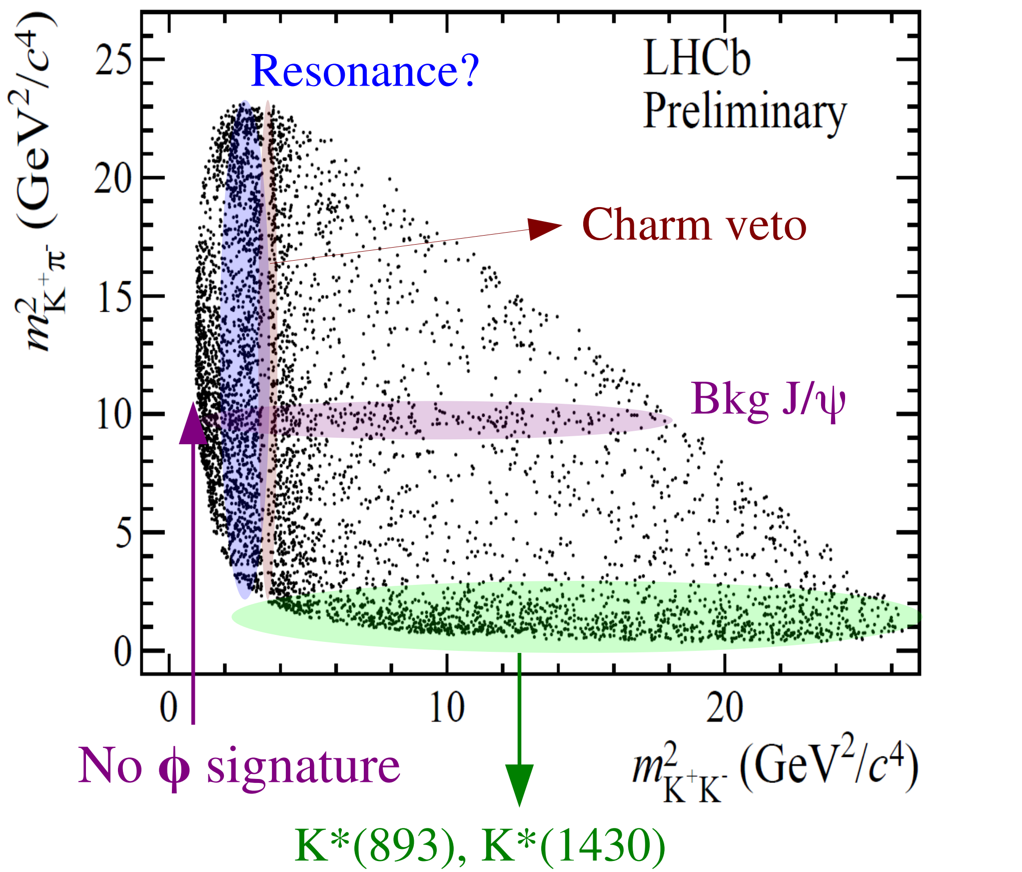


- Phase space without B mass constraint.
- Phase space not background subtracted.
- D^0 contribution removed.
- Acceptance efficiency is flat over the Dalitz plot

*±40 MeV^2 m_B mass window

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ Dalitz plot





$$m^2_{\pi^+\pi^-\,\mathrm{low}} < m^2_{\pi^+\pi^-\,\mathrm{high}}$$

- Phase space without B mass constraint.
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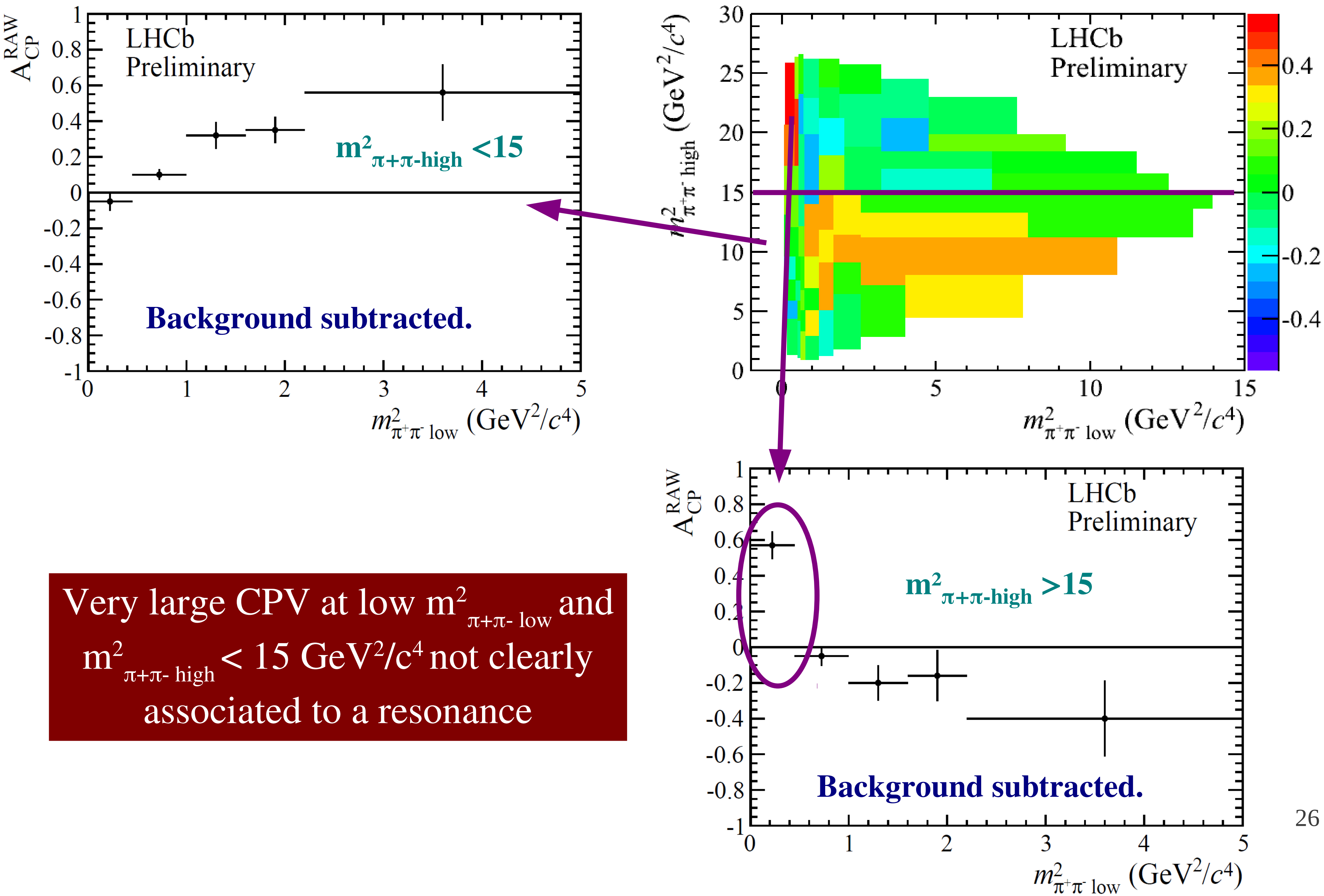
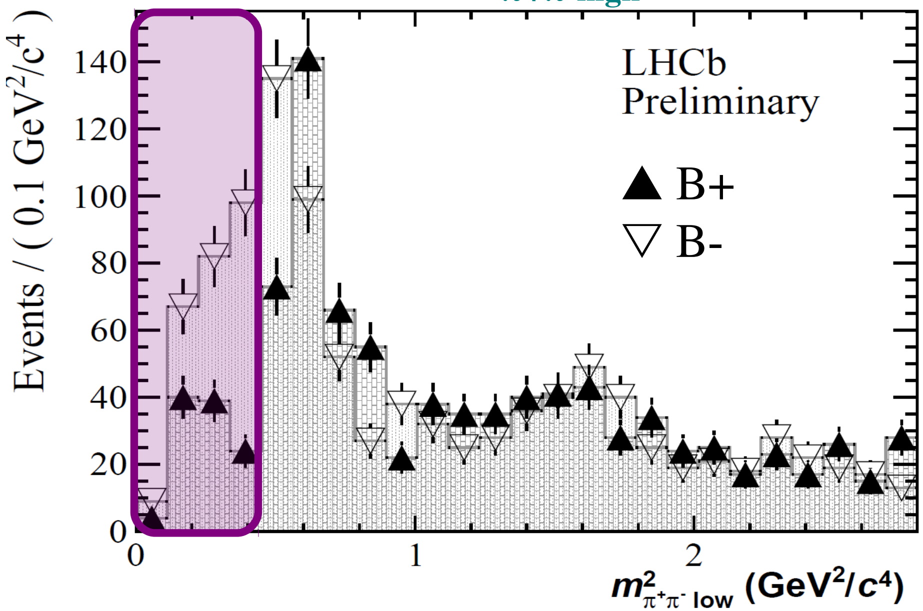
$B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot



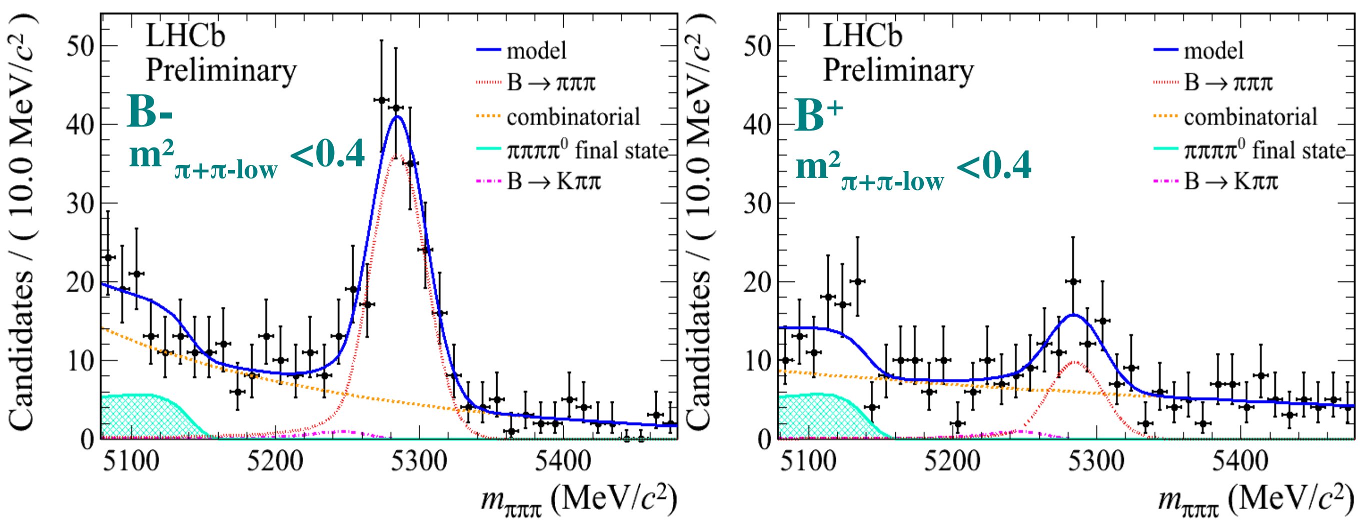
Very large CPV at low $m^2_{\pi+\pi-\ low}$ and $m^2_{\pi+\pi-\ high}$ < 15 GeV^2/c^4 not clearly associated to a resonance

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ zoom in large CPV region

Event yield for $m^2_{\pi+\pi\text{-high}} > 15$



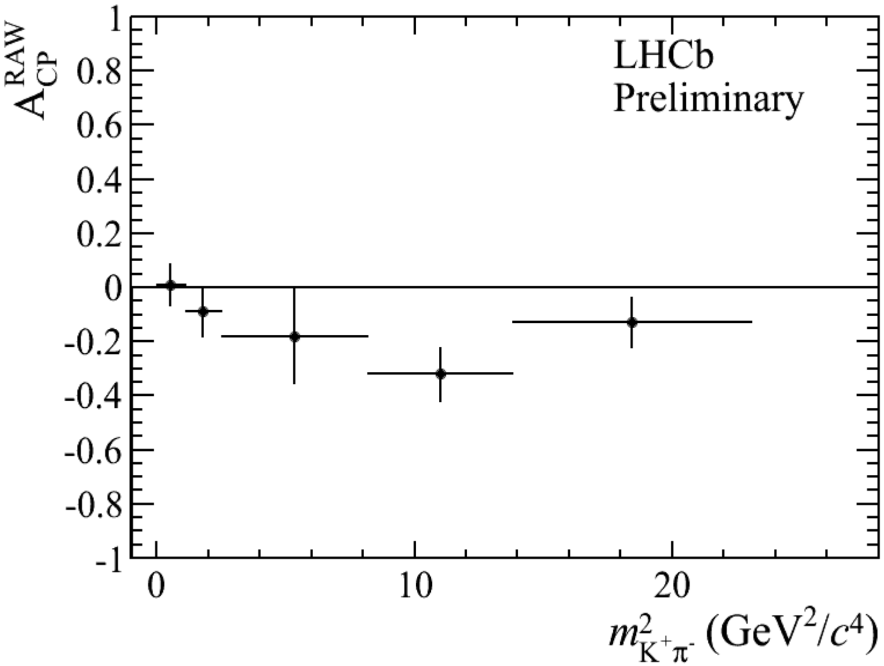
Very large CPV in a region of the phase space not associated to a resonance

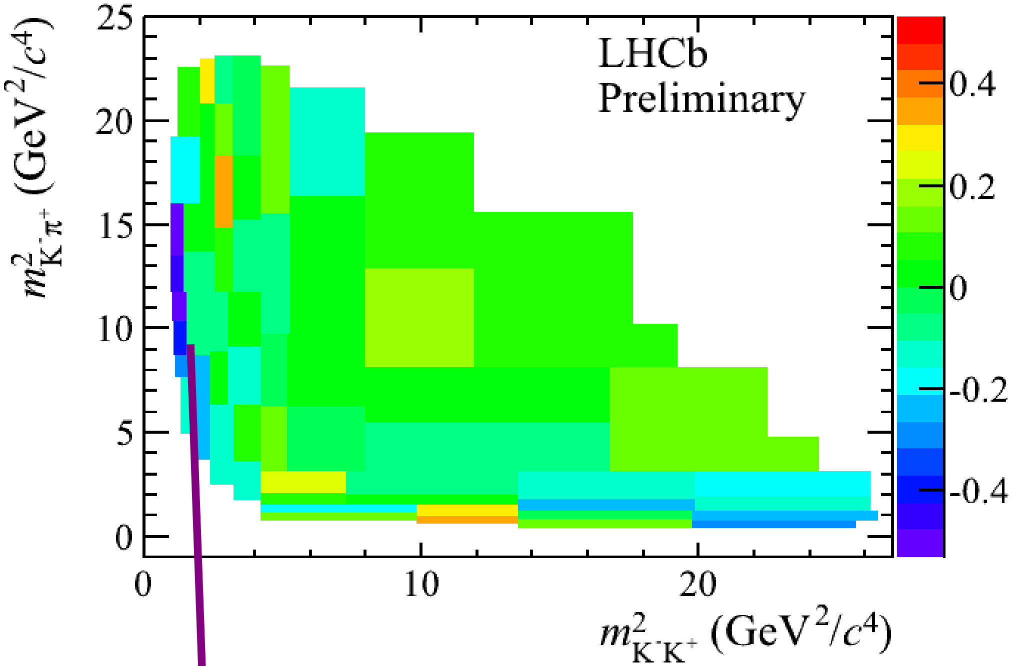


$A_{cp}(B^{\pm} \to \pi\pi\pi \text{ region}) = +0.622 \pm 0.075(\text{stat}) \pm 0.032(\text{syst}) \pm 0.007\ (J/\psi K^{\pm})$

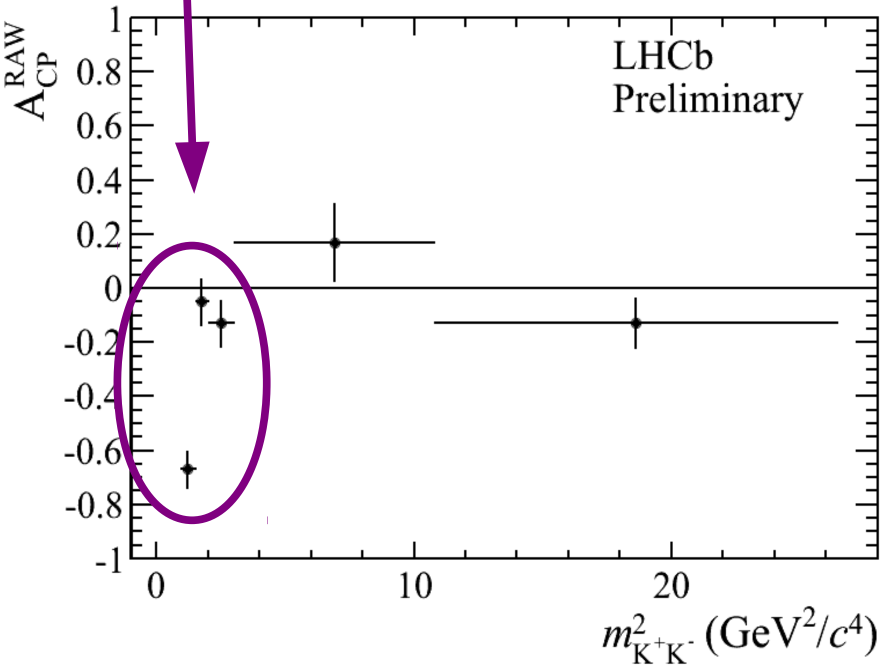
7.6σ

$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ Dalitz plot



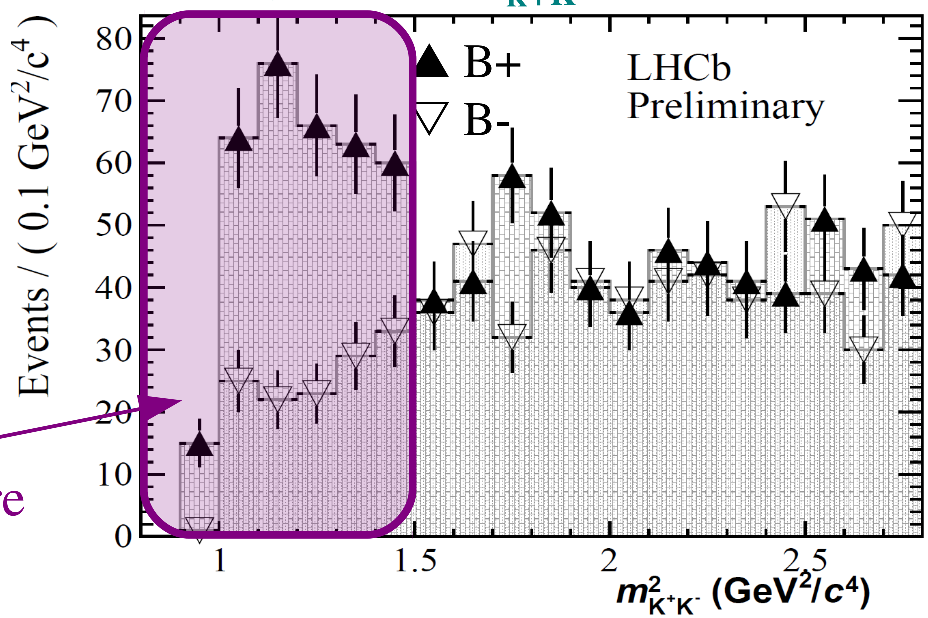


Very large CPV at low m^2_{K+K-}



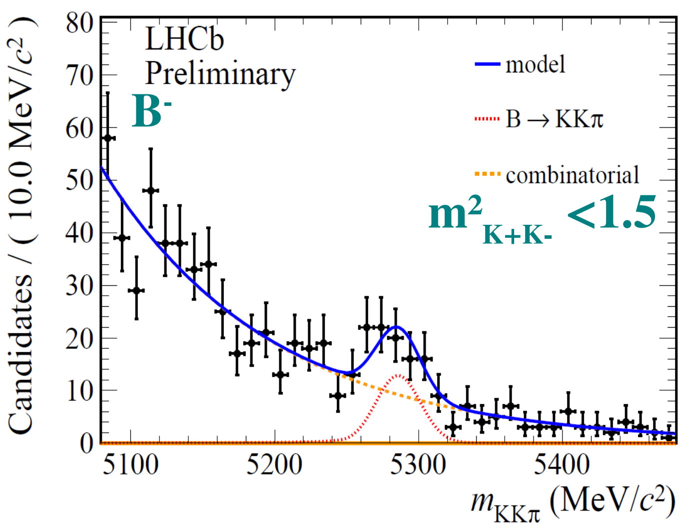
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ zoom in large CPV region

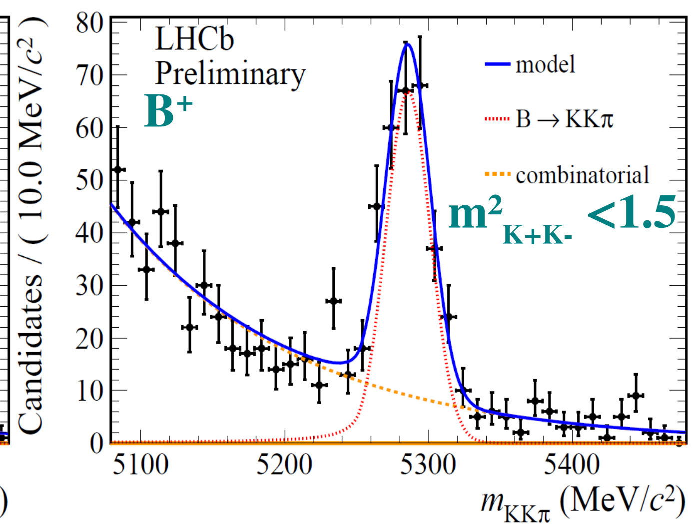
Event yield for $m^2_{K+K-} < 3$



No φ signature

Very large CPV in a region of the phase space not associated to a resonance



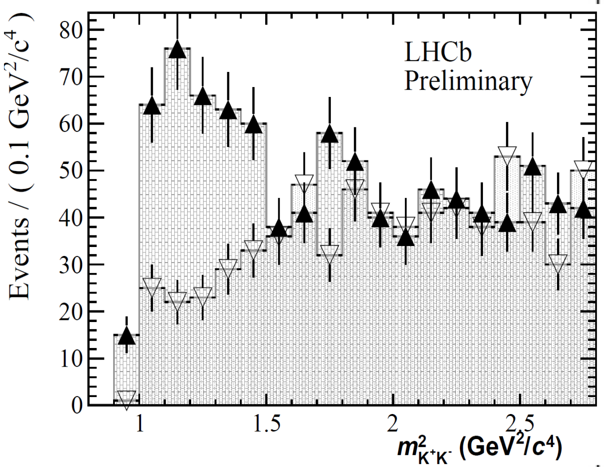


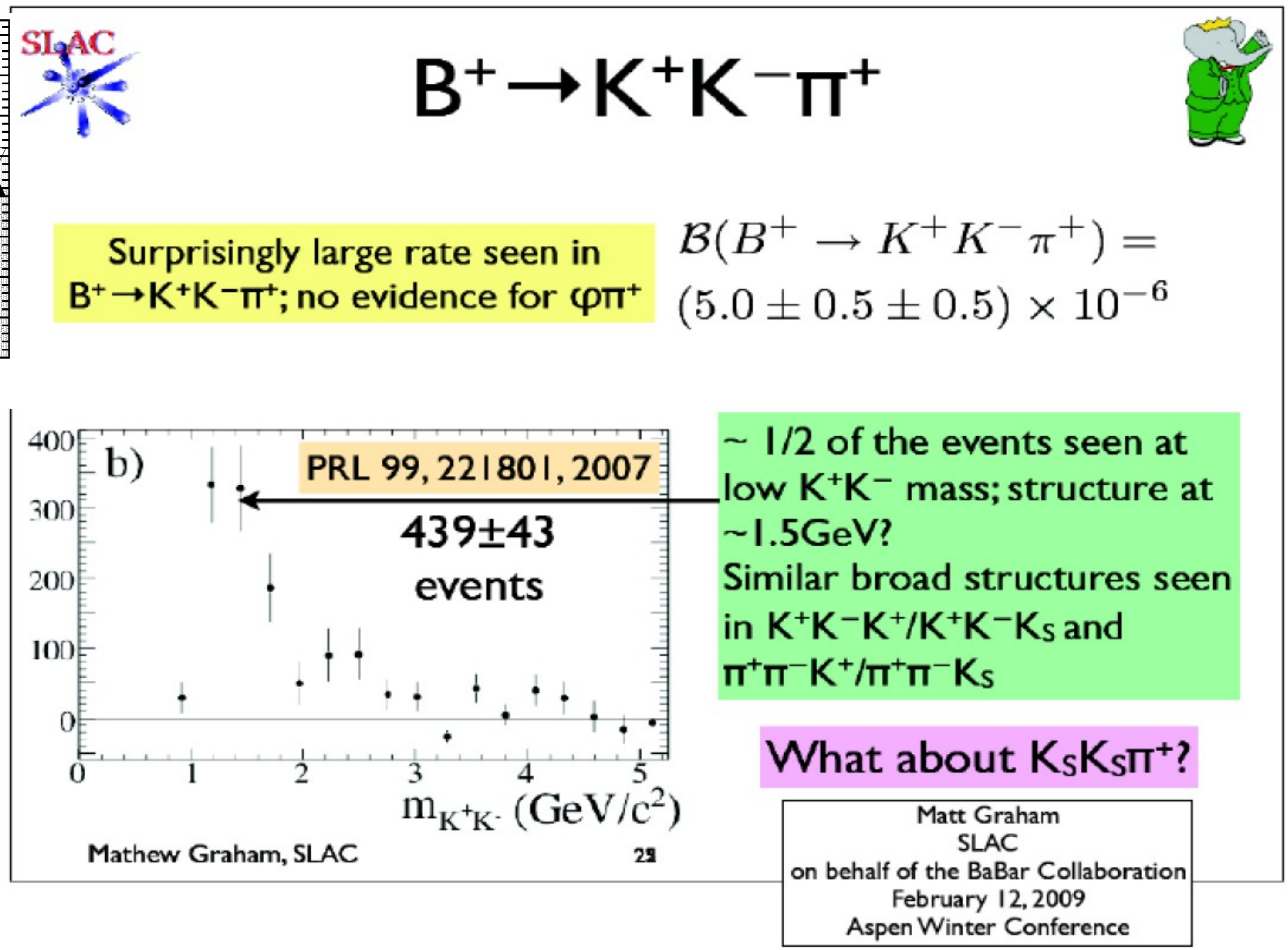
$A_{cp}(B^{\pm} \to \pi KK \text{ region}) = -0.671 \pm 0.067(\text{stat}) \pm 0.028(\text{syst}) \pm 0.007\ (J/\psi K^{\pm})$

9.2σ

BaBar results on $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$

- BaBar have similar results (but they didn't divide their sample in B^+ and B^-):





Remarks I

- Evidence of CPV in all 4 channels.

- Larger CPV in $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ and $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ as compared to $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$.
  - Large CPV also observed in the two body decays $B_s \to K^{-}\pi^{+}$ and $B^0 \to K^{+}\pi^{-}$

LHCb: PRL **108**, (2012) 201601

$$A_{cp}(B^0 \to K\pi) = -0.088 \pm 0.011(stat) \pm 0.008(syst)$$
$$A_{cp}(B_s \to \pi K) = +0.27 \pm 0.08(stat) \pm 0.02(syst)$$

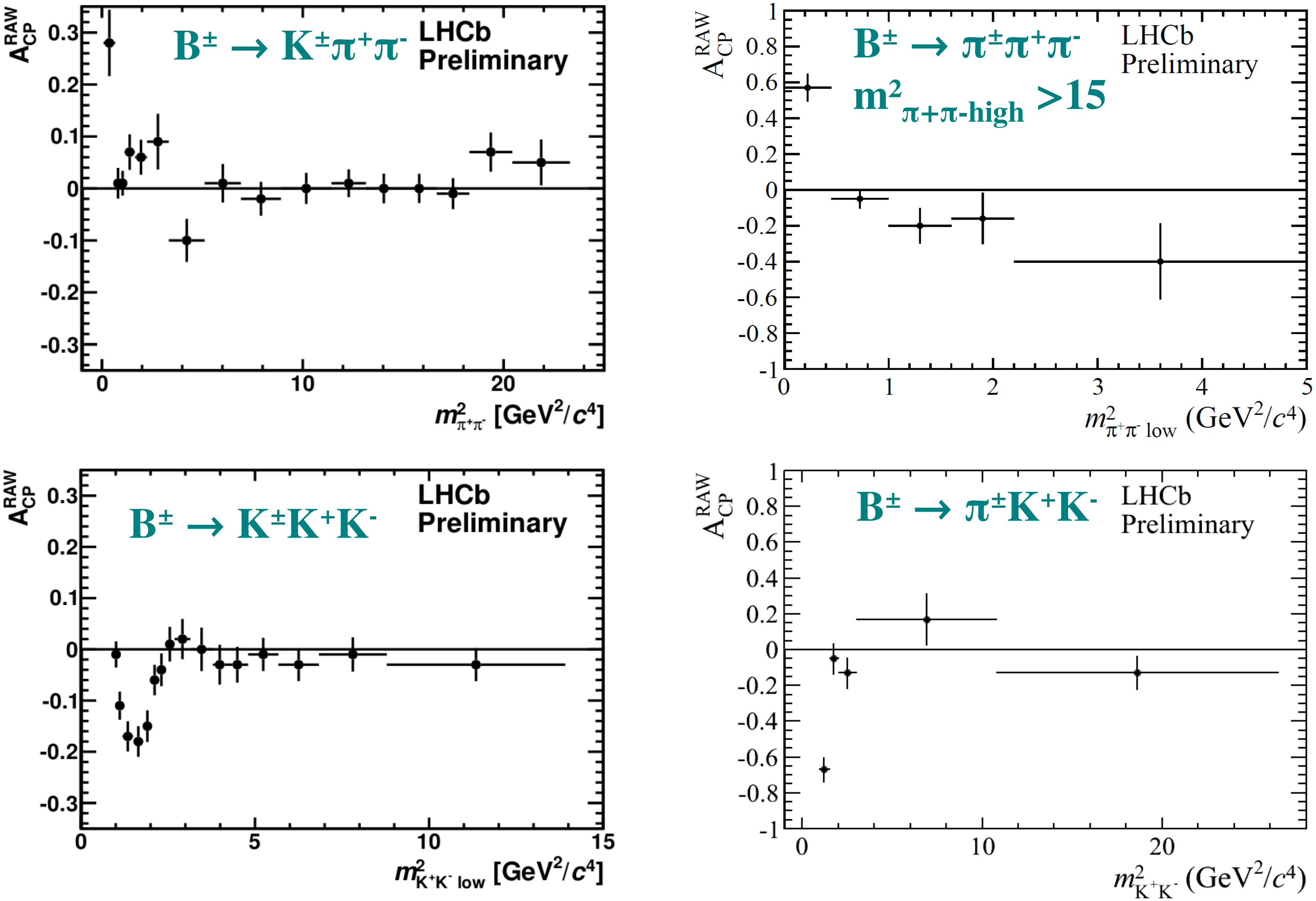
- Positive CPV in $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$.

- Negative CPV in $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$.

First evidence of global CPV in charmless three-body B decays.

Remarks II

- CPV not uniform in the Dalitz plot.
  - Large CPV in the low KK and ππ invariant mass regions and not significant elsewhere
- CPV not clearly associated to resonance structure.
  - **Future amplitude analysis will need to incorporate this feature.**



- Positive CPV at low ππ invariant mass.
- Negative CPV at low KK invariant mass.

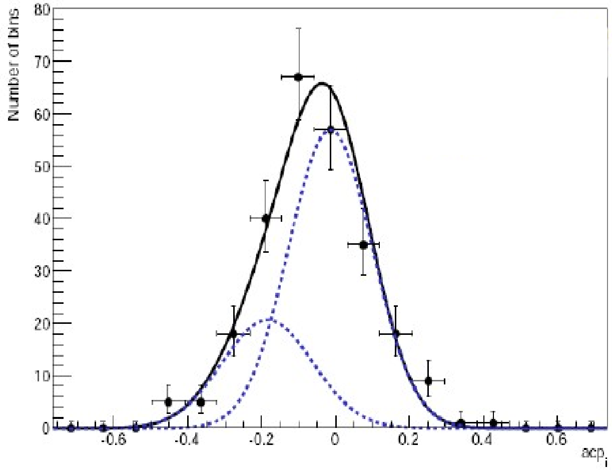
Perspectives

- Dalitz plot may have positive and negative sources of CPV.
- Global CPV measurements: integral over m_{12} and m_{23} (three body mass plot).
  - May hide large asymmetries.
- Projected CPV measurement: integral over m_{12} or m_{23}.
  - Reveal large local asymmetries (if they exist).
- If each bin of the Dalitz plot has the same total number of events N:

I. Bediaga et. al: PR **D86**, (2012) 036005

$$A_{cp}(i) = \frac{N^+(i) - N^-(i)}{N^+(i) + N^-(i)}$$

→ $A_{cp}(i)$ distribution is a Gaussian centered at zero and with width $1/\sqrt{N}$ in case of CP conserved.



→ In the presence of CPV, not only the CP conserved Gaussian will appear but also a Gaussian for each CPV source.

Model independent.

Call for les Nabis

- Theorists and experimentalists mixture → formation of the working group les Nabis.

From Theory

I. Bigi, S. Gardner (USA)
C. Hanhart, Th. Mannel, U-G. Meißner, W. Ochs, A. Sibirts (Germany)
J. A. Oller, J. R. Pelaez (Spain)
M. R. Pennington (UK)

From Experiment

I. Bediaga (Brazil)
A.E. Bondar (Russia)
A. Denig, W. Gradl, K. Peters, U. Wiedner (Germany)
T. J, Gershon, G. Wilkinson (UK)
B. T. Meadows (USA)

The talisman Paul Serusier, 1888

Conclusions

- Evidence of CPV in $B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+K^-$
  LHCb-CONF-2012-018 preliminary $\mathcal{L} = 1.0\ \mathrm{fb}^{-1}$

$$A_{cp}(B^\pm \to K\pi\pi) = +0.034 \pm 0.009(\mathrm{stat}) \pm 0.004(\mathrm{syst}) \pm 0.007(J/\psi K^\pm)$$ **2.8σ**

$$A_{cp}(B^\pm \to KKK) = -0.046 \pm 0.009(\mathrm{stat}) \pm 0.005(\mathrm{syst}) \pm 0.007(J/\psi K^\pm)$$ **3.7σ**

- Evidence of CPV in $B^\pm \to \pi^\pm\pi^+\pi^-$ and $B^\pm \to \pi^\pm K^+K^-$
  LHCb-CONF-2012-028 preliminary $\mathcal{L} = 1.0\ \mathrm{fb}^{-1}$

$$A_{cp}(B^\pm \to \pi\pi\pi) = +0.120 \pm 0.020(\mathrm{stat}) \pm 0.019(\mathrm{syst}) \pm 0.007(J/\psi K^\pm)$$ **4.2σ**

$$A_{cp}(B^\pm \to \pi KK) = -0.153 \pm 0.046(\mathrm{stat}) \pm 0.019(\mathrm{syst}) \pm 0.007(J/\psi K^\pm)$$ **3.0σ**

- Observation of very high CPV in regions of the Dalitz plot

$$A_{cp}(B^\pm \to \pi\pi\pi\ \mathrm{region}) = +0.622 \pm 0.075(\mathrm{stat}) \pm 0.032(\mathrm{syst}) \pm 0.007(J/\psi K^\pm)$$ **7.6σ**

$$A_{cp}(B^\pm \to \pi KK\ \mathrm{region}) = -0.671 \pm 0.067(\mathrm{stat}) \pm 0.028(\mathrm{syst}) \pm 0.007(J/\psi K^\pm)$$ **9.2σ**

Three times more statistics at the end of 2012.
Stay tuned!

Backup

Final selection for B → hhh

- Trigger decision:
  - Hardware trigger (L0) to select a hadron with high transverse energy.
  - Software trigger (Hlt) to select hadrons with high transverse momentum and coming from the same decaying vertex

- PID selection:
  - $\Delta\log\mathcal{L}_{K\pi} > 4$ for kaons and $\Delta\log\mathcal{L}_{K\pi} < 0$ for pions.
  - Muon veto : $\Delta\log\mathcal{L}_{\mu\pi} < 5$ to exclude the control channel (see below).
  - Cuts on invariant masses $m_{\pi\pi}$, $m_{K\pi}$ and m_{KK} to exclude charm background.

- Offline selection explore the decay topology:
  - Tracks momenta and impact parameter with respect to interaction point and decaying vertex.
  - B candidate flight distance, momentum and impact parameter with respect to interaction point.

Variables	Selection cuts
Tracks P_T	> 0.1 GeV/c
Tracks P	> 1.5 GeV/c
Tracks $IP\chi^2$	> 1
Tracks χ^2/n.d.f.	< 3
Sum of P_T of tracks	> 4.5 GeV/c
Sum of $IP\chi^2$ of tracks	> 200
P_T of the highest-P_T track	> 1.5 GeV/c
P_T of the second highest-P_T track	> 0.9 GeV/c
IP of the highest-P_T track	> 0.05 mm
Maximum DOCA	< 0.2 mm
$B^\pm$ candidate M_{KKK}	$5.05 - 6.30$ GeV/c^2
$B^\pm$ candidate M_{KKK}^{COR}	$4 - 7$ GeV/c^2
$B^\pm$ candidate M^{COR}	< 5.8 GeV/c^2
$B^\pm$ candidate IP χ^2	< 10
$B^\pm$ candidate P_T	> 1.7 GeV/c
Distance from SV to any PV	> 3 mm
Secondary Vertex χ^2	< 12
$B^\pm$ candidate $\cos(\theta)$	> 0.99998
$B^\pm$ Pointing angle	< 0.1
$B^\pm$ Flight Distance χ^2	> 700
Number of long tracks in the event	< 200

$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ Fit function

- We performed an unbinned extended likelihood fit to the $B^{\pm}$ invariant mass
- Signal PDF model:
  - Sum of a Crystal Ball and a Gaussian
  - Common mean and different widths for the two functions.
  - Fractions and Crystal Ball parameters extracted from MC and fixed to data.
  - Widths for both Crystal Ball and Gaussian determined from the fit to full data.
- Combinatorial background PDF model:
  - Exponential function with one free parameter for the slope.
- Peaking and partial backgrounds PDF model:
  - Modified Gaussian with shapes extracted from MC and fixed to data for peaking and partial backgrounds.
  - Fractions extracted from MC for peaking background and left float in the fit for partial background.

Signal PDF: Gaussian + Crystal Ball.

$$F_S(m) = f_{\text{sig}}\mathcal{G}(m; m_0, \sigma_1) + (1 - f_{\text{sig}})\mathcal{C}(m; m_0, \sigma_2, a, n)$$

Background PDF: Modified Gaussian.

$$F_i(m) = N_i \exp\left[\frac{-(m-\mu_i)^2\beta_i(m)}{2\sigma_{Ri}^2}\right], \qquad \beta_i(m) = \exp(-2\lambda_i(m-\mu_i))$$

$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ systematics and results

- Signal PDF: floated parameters in the fit procedure and two Crystal Balls used.
- Signal shape: signal yield from the difference between the total number of events and the background integral inside signal region.
- Background model: background fraction varied for both $K\pi\pi$ and KKK modes.
- Background charge asymmetry: fit with 100% charge asymmetry for the peaking background components.
- Acceptance: raw asymmetry corrected by the efficiency in each bin of the phase space.
- Subtraction method: kinematic variables of the kaon from control channel were weighted to match the same distribution from the signal kaon.

Contribution	Syst($K^{\pm}\pi^{+}\pi^{-}$)	Syst($K^{\pm}K^{+}K^{-}$)
Signal fixed parameters	0.002	0.002
Signal model	0.0001	0.0001
Signal shape	0.0012	0.0001
Background model	0.0003	0.00002
Background asymmetry	0.0002	0.0001
Acceptance	0.001	0.0015
Trigger correction	0.0011	0.001
Subtraction method	0.0035	0.0012
Total	0.0045	0.0030

$A_{cp}(B^{\pm} \to K\pi\pi) = +0.034 \pm 0.009(\text{stat}) \pm 0.004(\text{syst}) \pm 0.007^{*}$

$A_{cp}(B^{\pm} \to KKK) = -0.046 \pm 0.009(\text{stat}) \pm 0.005(\text{syst}) \pm 0.007^{*}$

* $J/\psi K$ A_{cp} uncertainty quoted separately.

$A_{cp}(B^{\pm} \to K\pi\pi) = +0.038 \pm 0.022$

$A_{cp}(B^{\pm} \to KKK) = -0.017 \pm 0.030$

PDG

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ Fit function

- We performed an unbinned extended likelihood fit to the $B^{\pm}$ invariant mass
- Signal PDF model:
  - Crystal Ball function.
  - Crystal Ball radiative tail parameters extracted from MC and fixed to data.
  - Crystal Ball mean and width extracted from the combined B^{+}/B^{-} data and fixed to the individual B^{+} and B^{-} fits.
- Combinatorial background PDF model:
  - Exponential function with one free parameter for the slope for $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$.
  - A modified Gaussian for $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$.
- Peaking and partial backgrounds PDF model:
  - Modified Gaussian with shapes extracted from MC and fixed to data for peaking and partial backgrounds for $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$.
  - Negligible for $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$.

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ systematics and results

- Fit function: signal yield from the difference between the total number of events and the background integral inside signal region.
- Acceptance efficiency: error of the efficiency correction R.
- Kaon kinematics: the $B^{\pm} \to J/\psi K^{\pm}$ raw asymmetry in bins of kaon momentum is weighted by the ratio of K^{-} and K^{+} efficiencies from $D^{0} \to K^{+}K^{-}$ sample.
- Kaon instrumental asymmetry: the statistical uncertainty of the kaon instrumental asymmetry was included as a systematic since it came from another analysis.
- Pion instrumental asymmetry: the statistical uncertainty of the pion instrumental asymmetry was included as a systematic since it came from another analysis.

Contribution	$\pi\pi\pi$	$KK\pi$
Fit function model	0.008	0.009
Acceptance	0.015	0.014
A_D^K kaon kinematics	0.008	0.008
A_D^K stat. uncertainty	0.002	0.002
A_D^π stat. uncertainty	0.003	0.003
Total	0.019	0.019

$A_{cp}(B^{\pm} \to \pi\pi\pi) = +0.120 \pm 0.020(stat) \pm 0.019(syst) \pm 0.007^{*}$

$A_{cp}(B^{\pm} \to \pi KK) = -0.153 \pm 0.046(stat) \pm 0.019(syst) \pm 0.007^{*}$

* $J/\psi K$ A_{cp} uncertainty quoted separately.

$A_{cp}(B^{\pm} \to \pi\pi\pi) = +0.032 \pm 0.044(stat)\ ^{+0.040}_{-0.037}(syst)$

$A_{cp}(B^{\pm} \to \pi KK) = -0.00 \pm 0.10(stat) \pm 0.03(syst)$

PDG

Systematic for B → hh

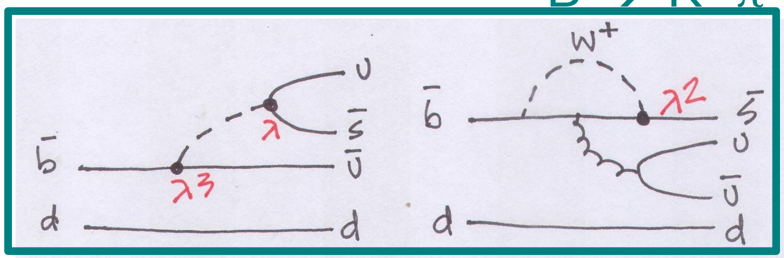
TABLE II. Summary of systematic uncertainties on $A_{CP}(B^0 \to K\pi)$ and $A_{CP}(B_s^0 \to K\pi)$. The categories (a), (b), and (c) defined in the text are also indicated. The total systematic uncertainties given in the last row are obtained by summing the individual contributions in quadrature.

Systematic uncertainty	$A_{CP}(B^0 \to K\pi)$	$A_{CP}(B_s^0 \to K\pi)$
(a) PID calibration	0.0012	0.001
(b) Final state radiation	0.0026	0.010
(b) Signal model	0.0004	0.005
(b) Combinatorial background	0.0001	0.009
(b) 3-body background	0.0009	0.007
(b) Cross-feed background	0.0011	0.008
(c) Instr. and prod. asym. (A_Δ)	0.0078	0.005
Total	0.0084	0.019

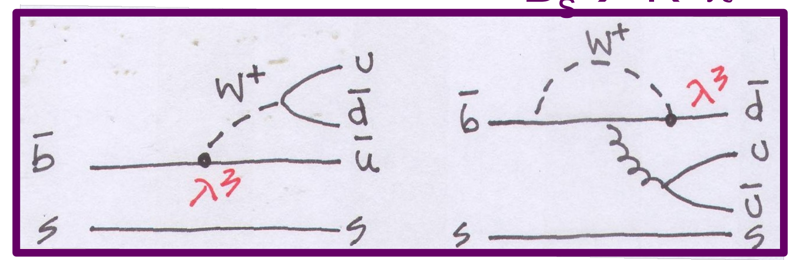
$B_s \to K^-\pi^+$ and $B^0 \to K^+\pi^-$

$\mathcal{L} = 0.35\ \mathrm{fb}^{-1}$ PRL **108**, (2012)201601

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



$B_s \to K^- \pi^+$



- Access to CKM CP violation (CPV) transition $b \to u$ and $t \to d(s)$.
  - γ at tree level.
- CPV expected from interference between tree and penguin diagrams.
- Similar diagrams for two and three body
- Extensively studied by b factories and Tevatron and yet new intriguing results.
- Observable:

$$A_{cp} = \frac{\Gamma(B^- \to f) - \Gamma(B^+ \to f)}{\Gamma(B^- \to f) + \Gamma(B^+ \to f)}$$

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

$\mathcal{L} = 0.35\ fb^{-1}$ PRL **108**, (2012)201601

TABLE II. Summary of systematic uncertainties on $A_{CP}(B^0 \to K\pi)$ and $A_{CP}(B_s^0 \to K\pi)$. The categories (a), (b), and (c) defined in the text are also indicated. The total systematic uncertainties given in the last row are obtained by summing the individual contributions in quadrature.

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(b) Cross-feed background	0.0011	0.008
(c) Instr. and prod. asym. (A_Δ)	0.0078	0.005
Total	0.0084	0.019

- No prior evidence of CPV in B_s system.
  - $A_{cp}(B^0) = -0.097$ +- 0.012. PDG
  - $A_{cp}(B_s) = 0.39$ +- 0.17. PRL 106, (2011) 181802
- Strategy:

$$A_{CP} = A_{\text{raw}} \pm A_D(K\pi) - \kappa_{d(s)} A_P(B^0_{(s)})$$

- Corrections:
  - Instrumental from D* and untagged $D \to hh$: $A_D = 0.01 \pm 0.02$.
  - Mixing: $\kappa_d = 0.303 \pm 0.005$ and $\kappa_s = -0.033 \pm 0.003$.
  - Production from $B^0 \to J/\psi K^{*0}$: $A_P(B^0) = 0.010 \pm 0.013$.

$A_{cp}(B^0 \to K\pi) = -0.088 \pm 0.011(\text{stat}) \pm 0.008(\text{syst})$ **Most precise >6σ**

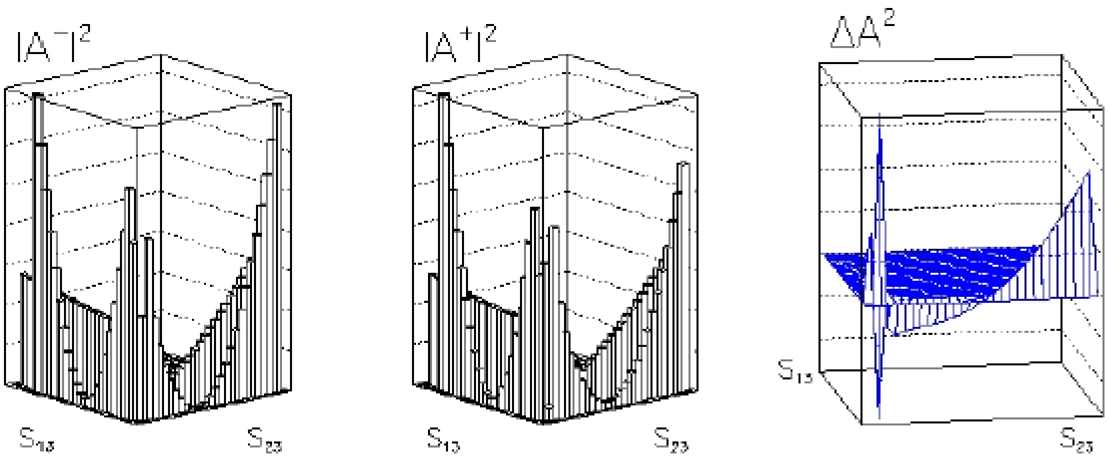
$A_{cp}(B_s \to \pi K) = +0.27 \pm 0.08(\text{stat}) \pm 0.02(\text{syst})$ **First evidence 3.3σ**

- Same large CPV as $B^\pm \to h^\pm h^+ h^-$ decays.

Perspectives I

- One Dalitz plot may have positive and negative sources of CPV:

Fast MC



- Global CPV measurement: integral over S_{12} and S_{23} (three body mass plot).
  - May hide large local asymmetries.

- Projected CPV measurement: integral over S_{12} or S_{23}.
  - Reveals large local asymmetries (if exists).