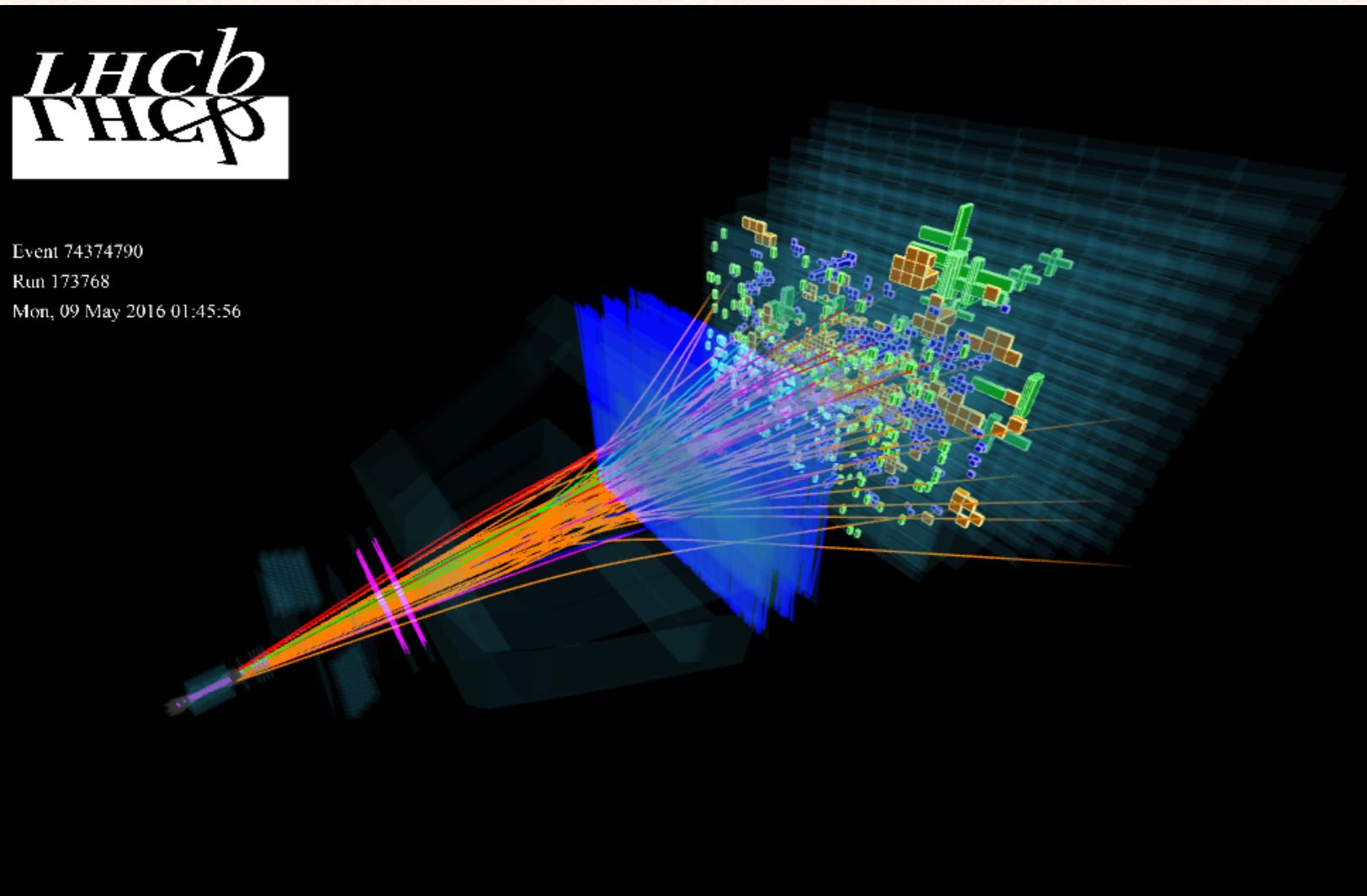




Event 74374790
Run 173768
Mon, 09 May 2016 01:45:56



University
of Glasgow



17/04/18 – DIS 2018, Kobe, Japan

CP Violation in Beauty and Charm at LHCb

Cameron Dean on behalf of
the LHCb Collaboration

Contents

- Neutral Meson Oscillations and CP Violation
- Current Global Status of the CKM Matrix
- Flavour Physics at LHCb
- Latest Results in CP Violation from LHCb

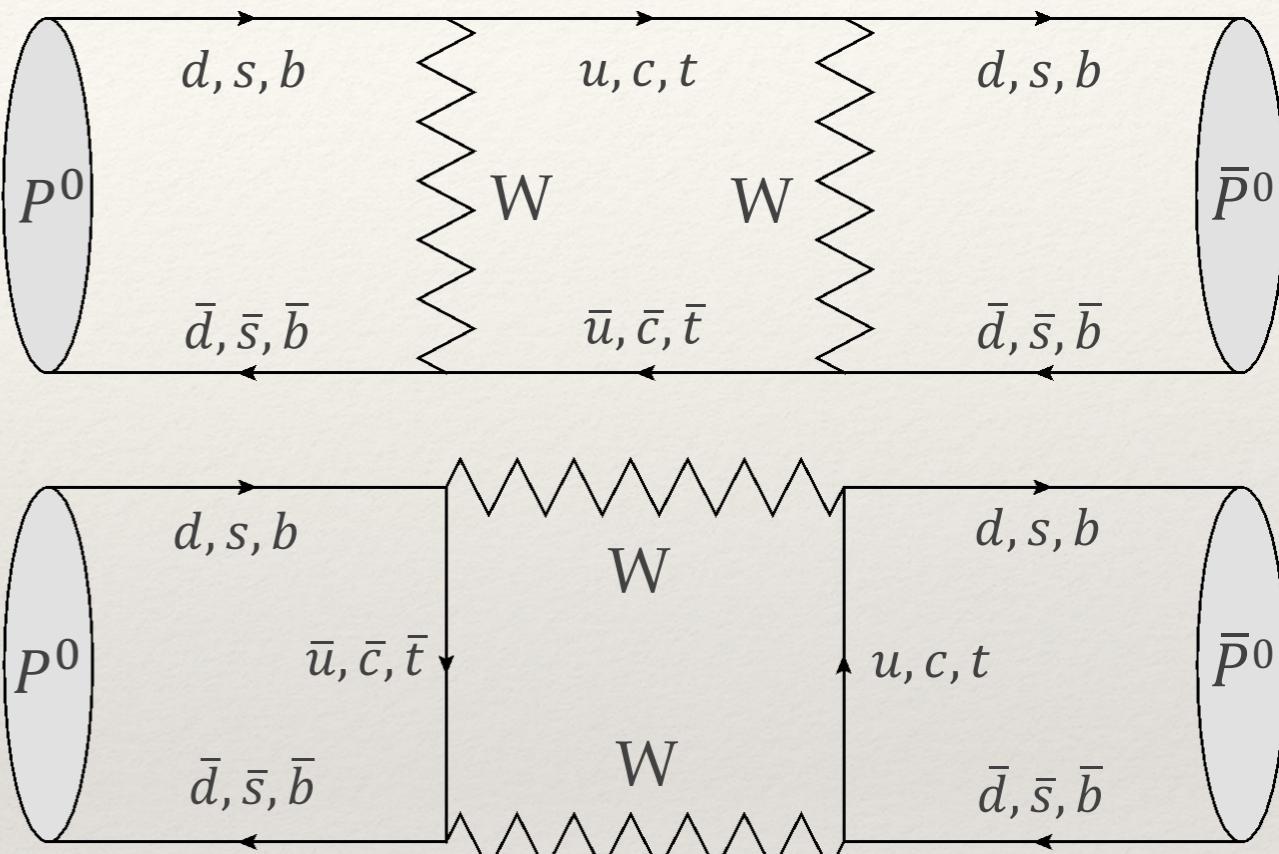
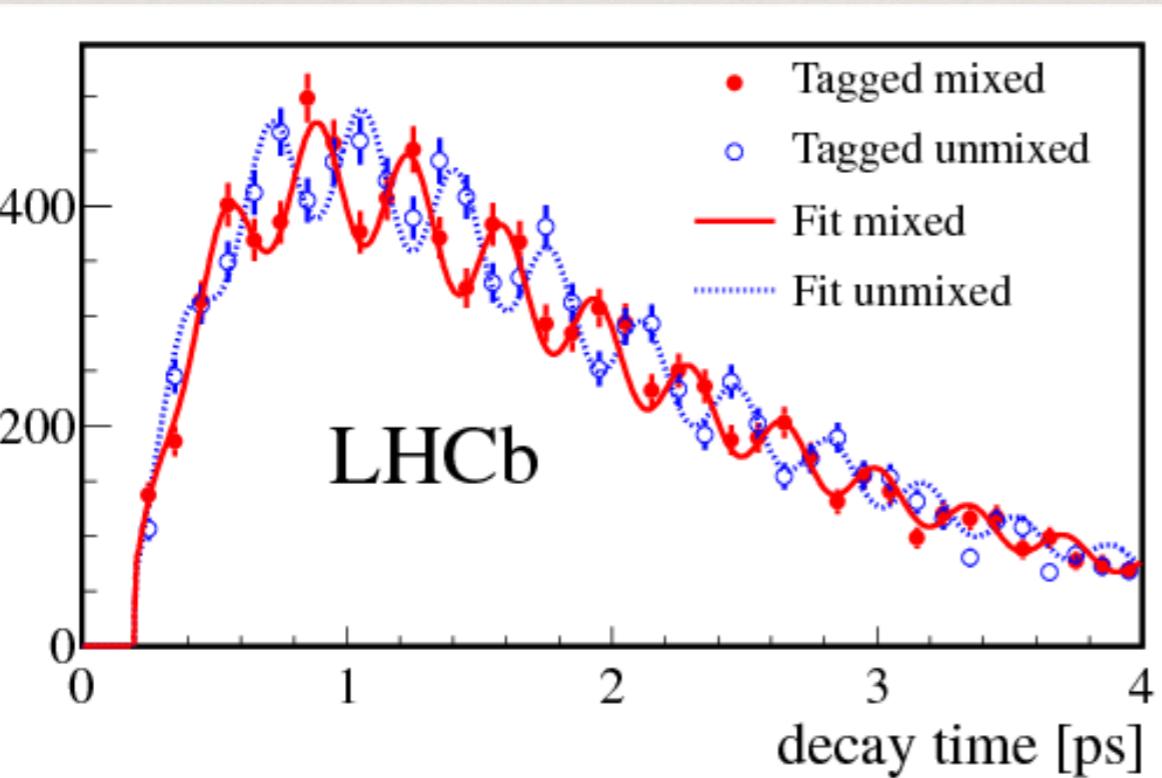
Neutral Meson Oscillations

$$|P_1\rangle = p|P^0\rangle + q|\bar{P}^0\rangle$$

Eigenstates Weak Eigenstates

$$|P_2\rangle = p|P^0\rangle - q|\bar{P}^0\rangle$$

$$B_s^0 \rightarrow D_s^- \pi^+ \text{ Decay Time}^+$$



Oscillation period measured:
 $D^0(661^{+285}_{-306}\text{ ps})^*$
 $B^0(12.39 \pm 0.05\text{ (syst.)} \pm 0.02\text{ (stat.)} \text{ ps})^\diamond$
 $B_s^0(353.6 \pm 0.5\text{ (syst.)} \pm 0.1\text{ (stat.)} \text{ fs})^\diamond$

CP Violation

Three types of CP Violation

1. CPV in the decay (right)

$$\left| \frac{A_f}{\bar{A}_{\bar{f}}} \right| \neq 1$$

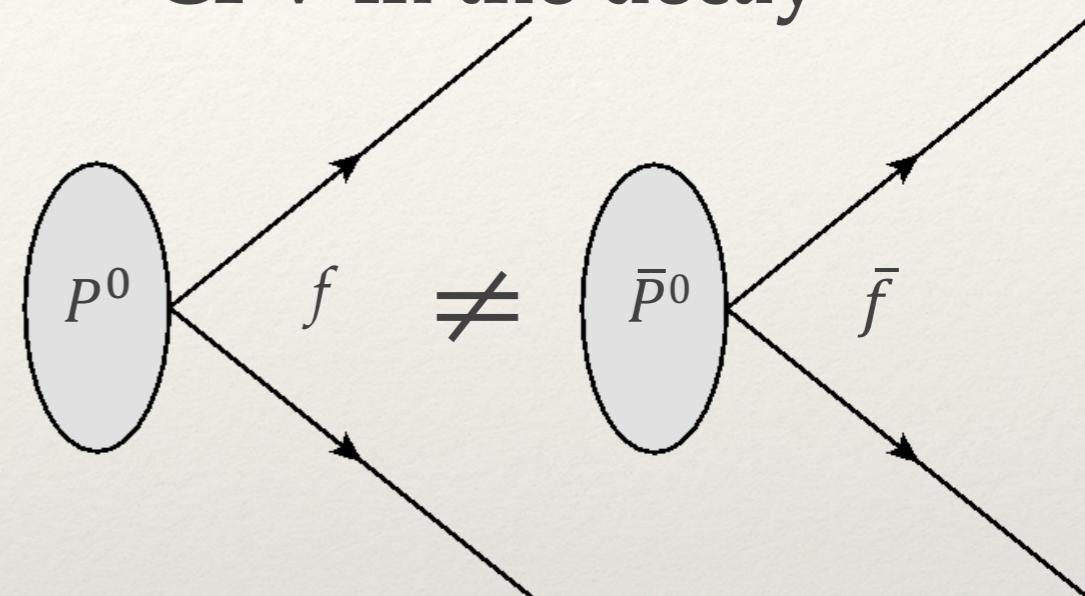
2. CPV in the mixing (previous slide)

$$\left| \frac{q}{p} \right| \neq 1$$

3. CPV in the interference
between the decay and mixing

$$A_{\text{CP}} = \frac{\Gamma[\bar{P} \rightarrow \bar{f}, t] - \Gamma[P \rightarrow f, t]}{\Gamma[\bar{P} \rightarrow \bar{f}, t] + \Gamma[P \rightarrow f, t]} = \frac{S_f \sin(\Delta m t) - C_f \cos(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma}{2}t\right)}$$

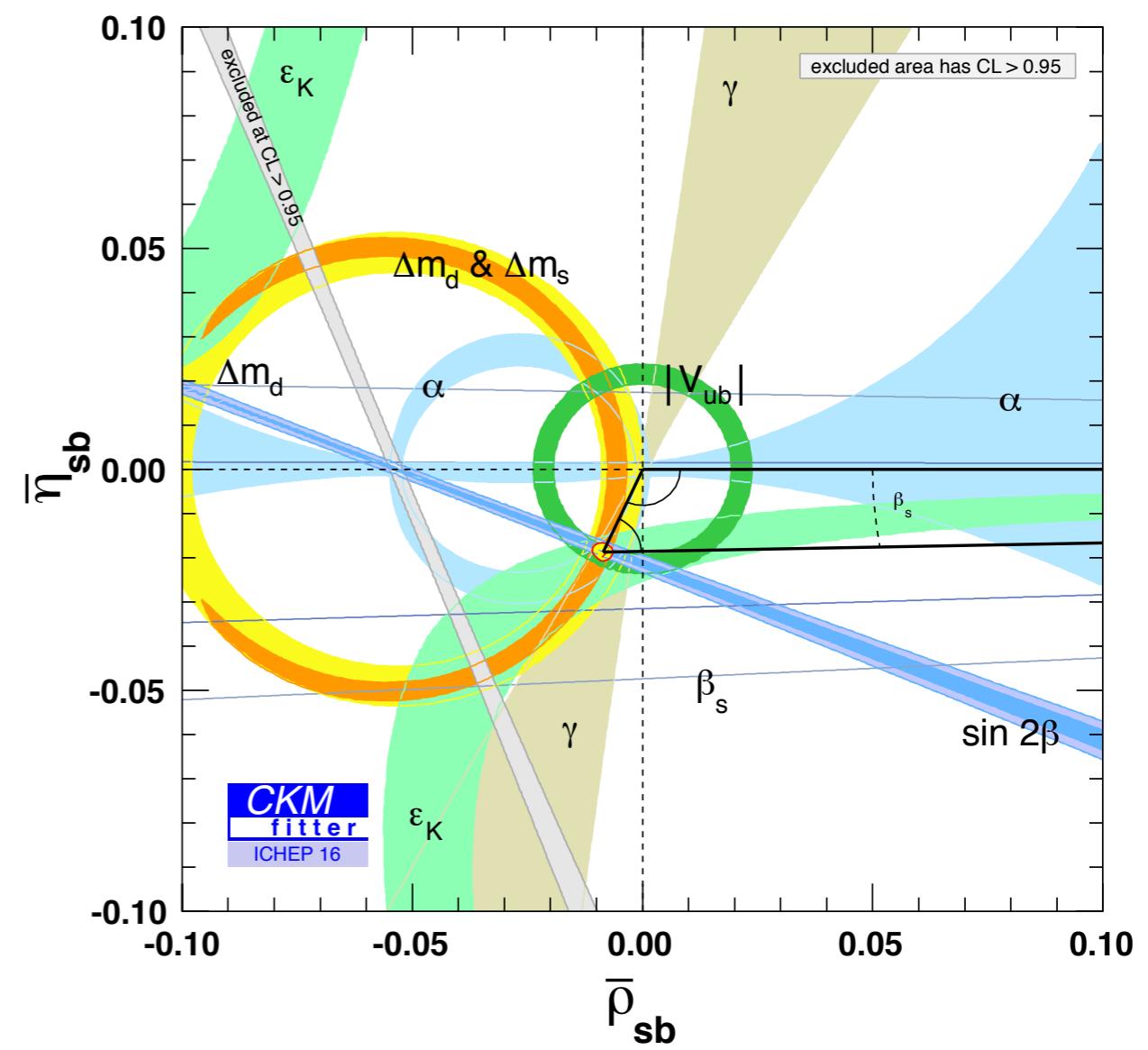
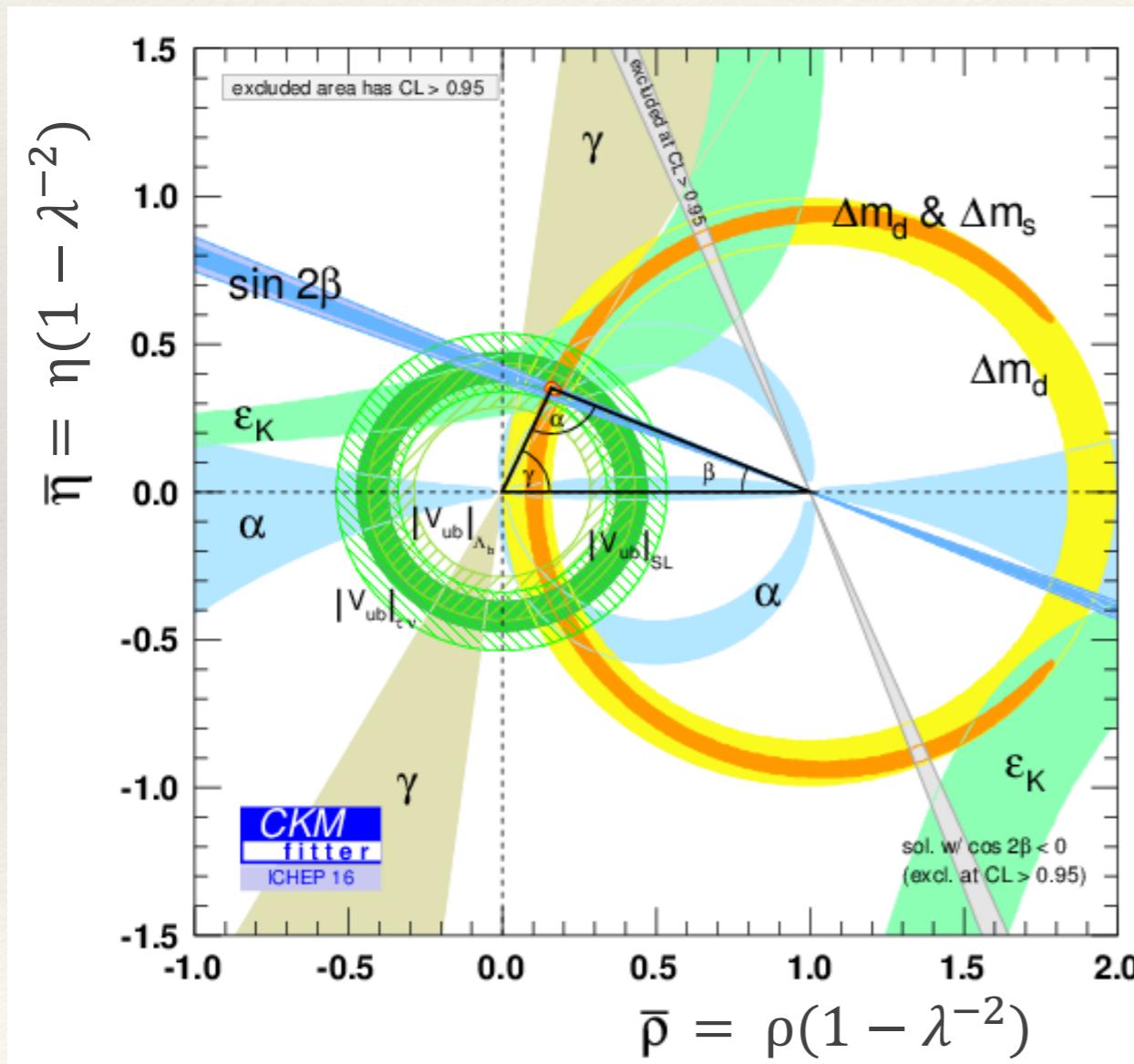
CPV in the decay



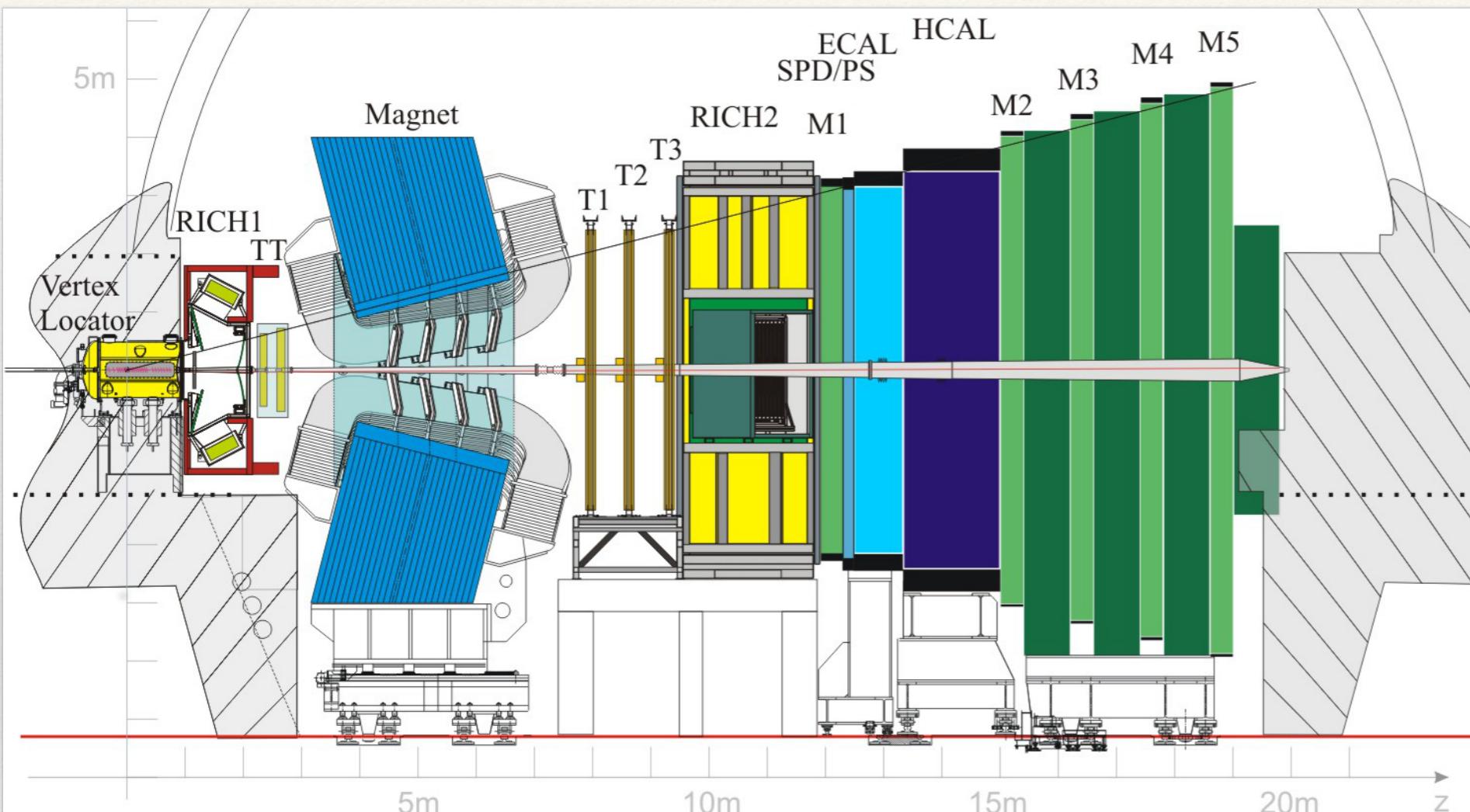
Decay Amplitudes $\longrightarrow A_f = \langle f | \hat{H} | P^0 \rangle$
 $\longrightarrow \bar{A}_{\bar{f}} = \langle \bar{f} | \hat{H} | \bar{P}^0 \rangle$

The Unitarity Triangles

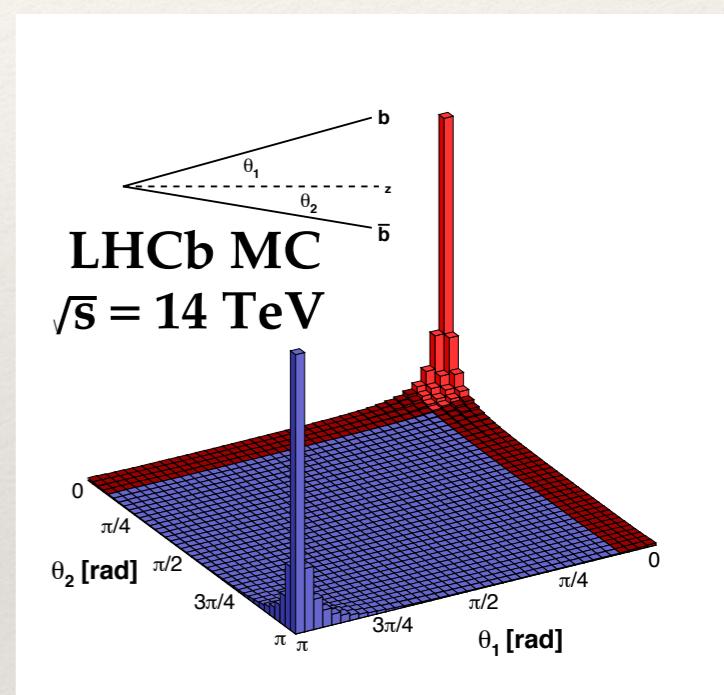
$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4) \quad \bar{\rho} + i\bar{\eta} = \frac{|V_{ud}V_{ub}^*|}{|V_{cd}V_{cb}^*|} e^{i\gamma}$$



The LHCb Detector

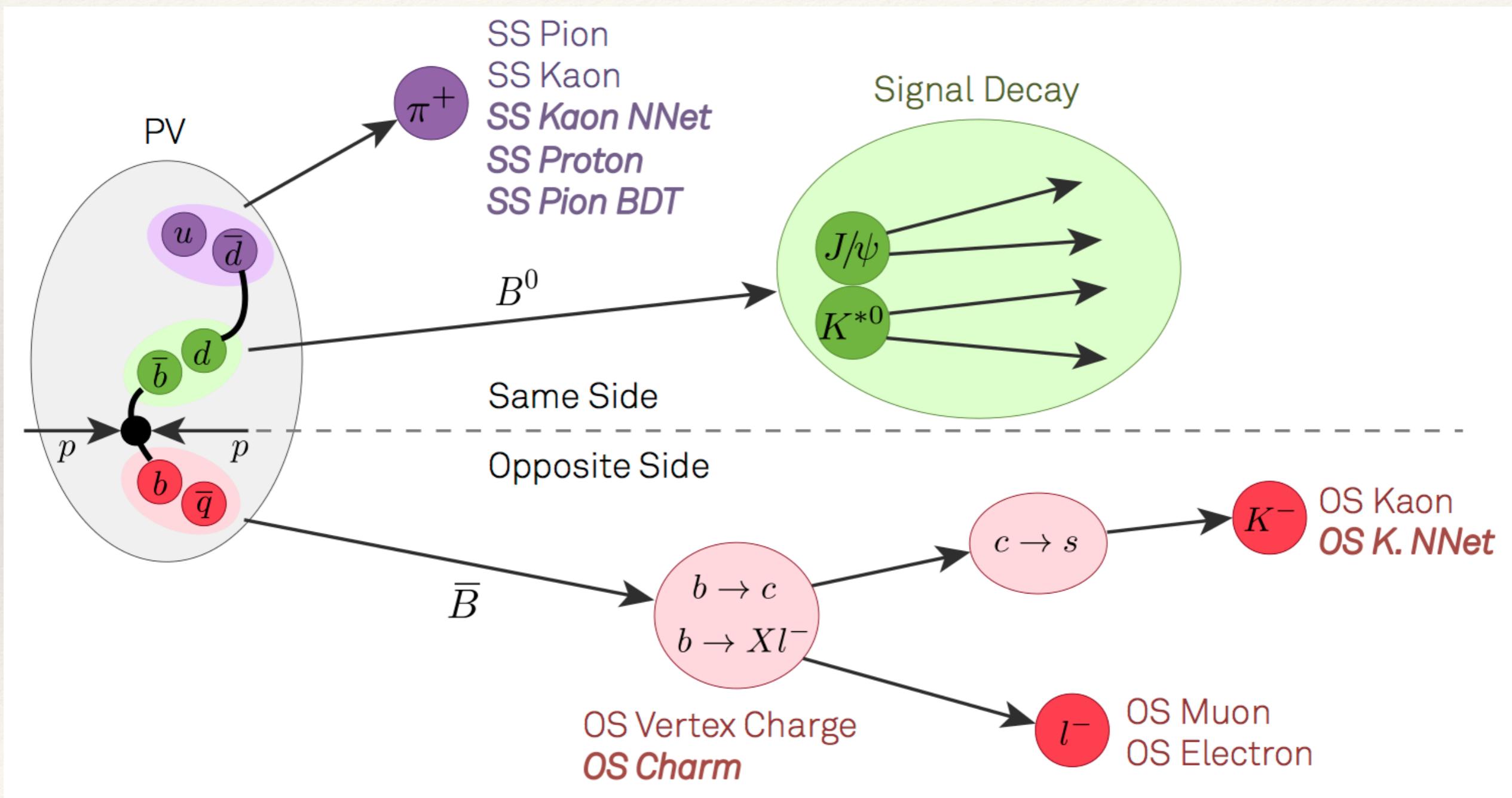


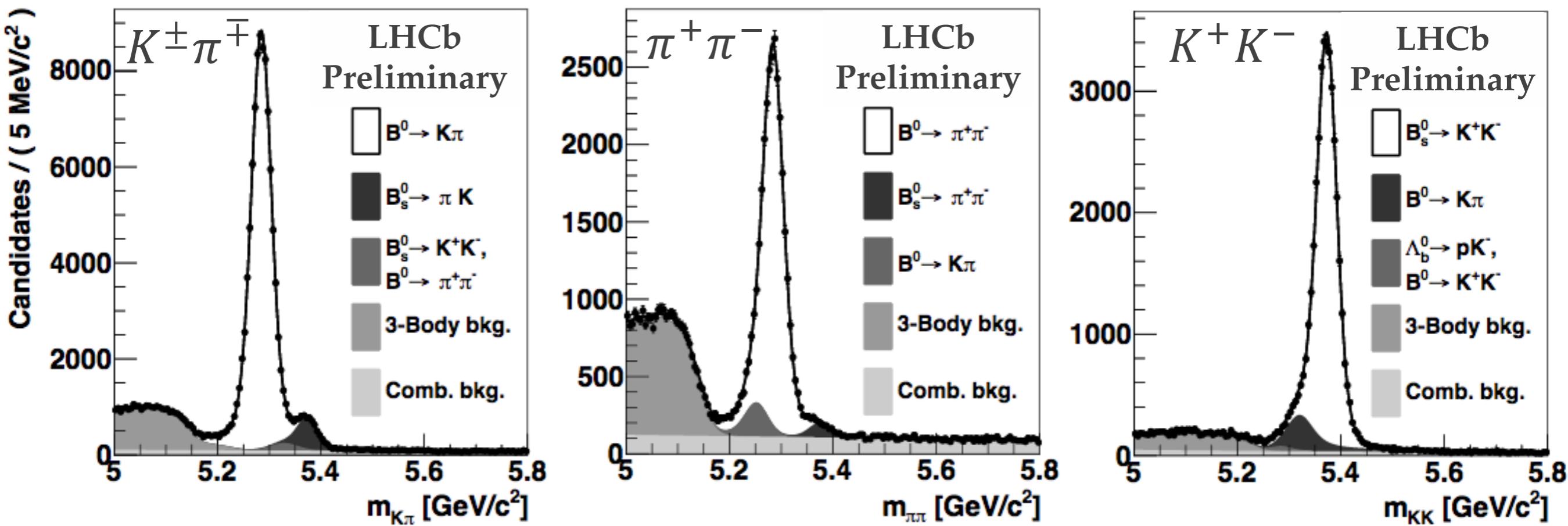
b-quark Production Angle



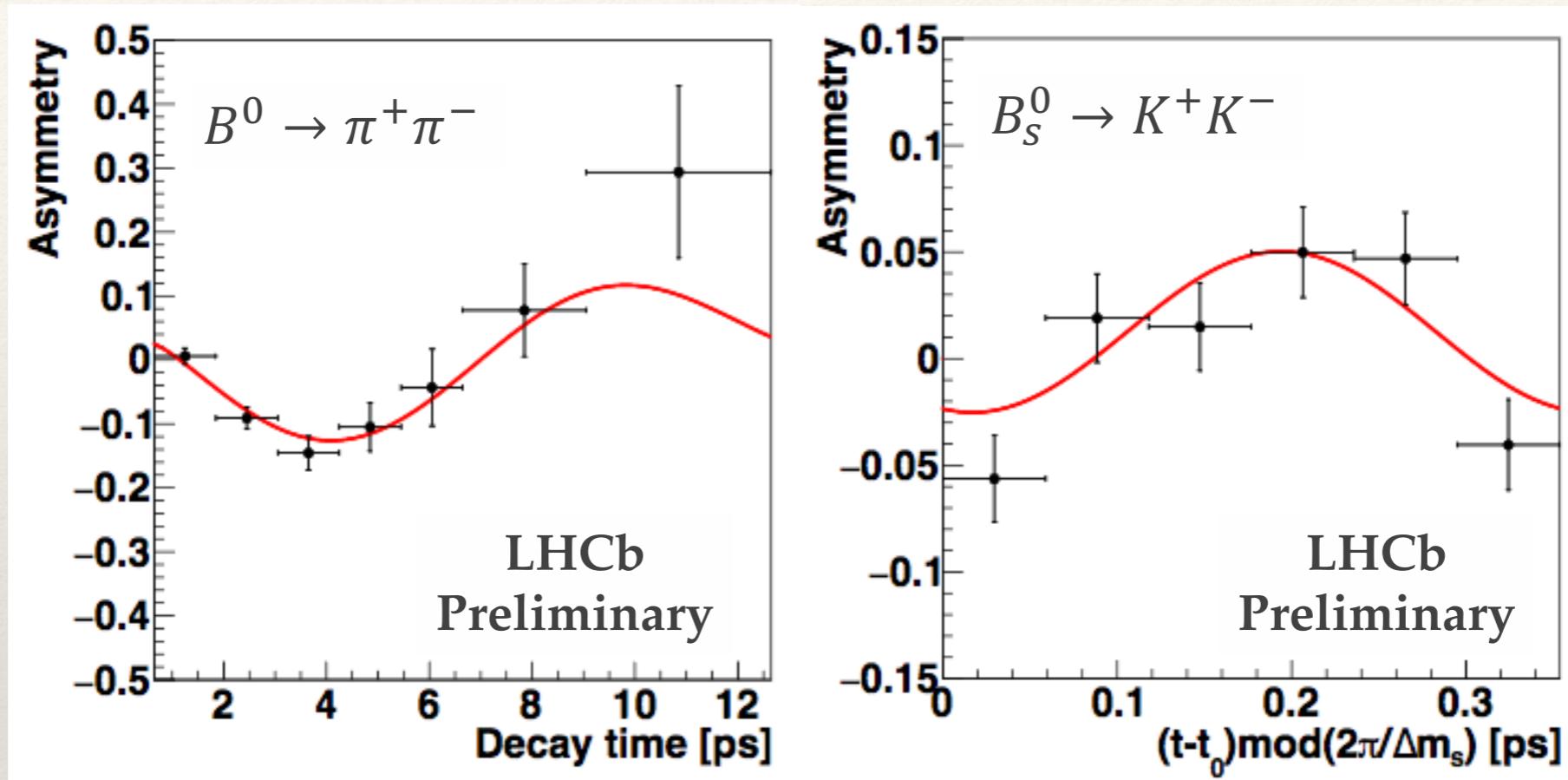
- Very rich physics program; see other LHCb talks for more information, [lepton universality studies](#), [particle production](#), [W, Z & top production](#), [hadron production](#) and [heavy flavour spectroscopy & exotics](#)

Flavour Tagging



$B_{(s)}^0 \rightarrow h^+ h^-$ 

- Measurements on $B_s^0 \rightarrow K^+K^-$, $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$
- Due to Cabibbo suppression at Tree Level, Loop Level contributes equally
- Sensitive probe of New Physics and Unitarity Triangle angle γ

$B_{(s)}^0 \rightarrow h^+ h^-$ 

$C_{\pi\pi} = -0.34 \pm 0.06 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$

$S_{\pi\pi} = -0.63 \pm 0.05 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$

$C_{KK} = 0.20 \pm 0.06 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$

$S_{KK} = 0.18 \pm 0.06 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$

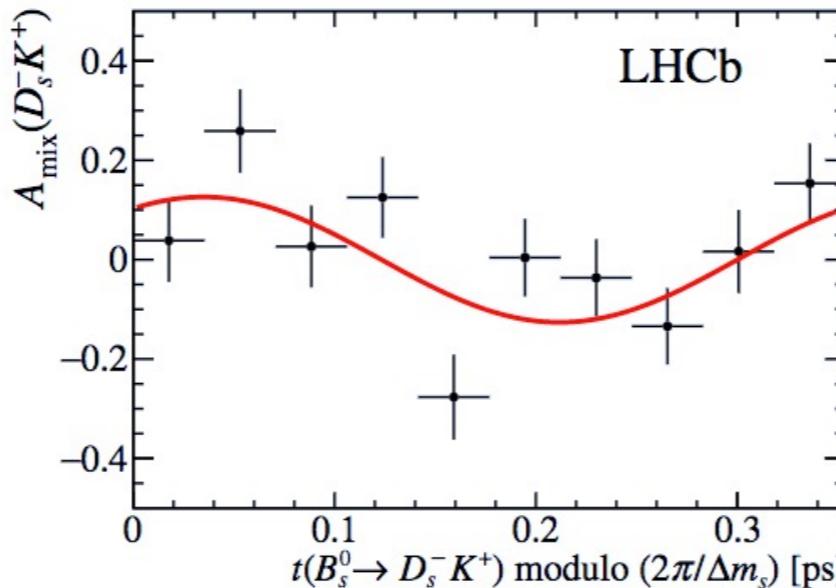
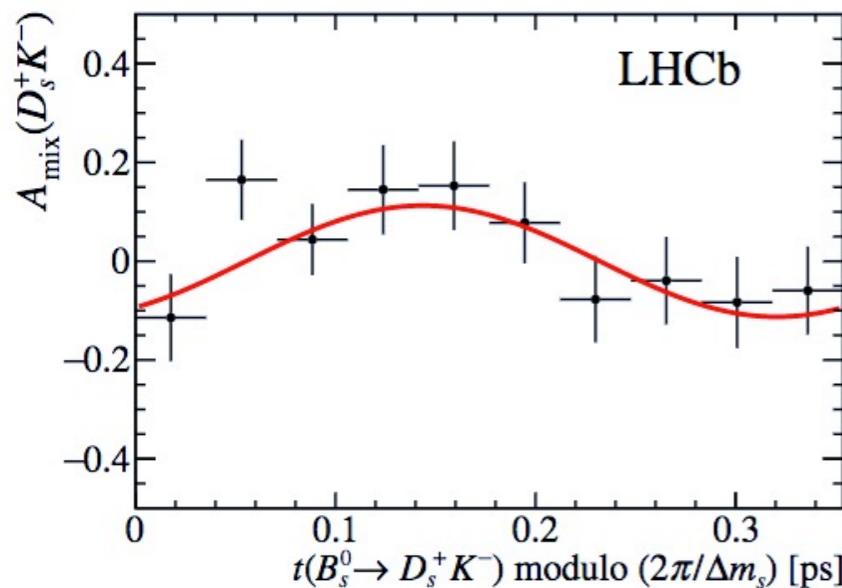
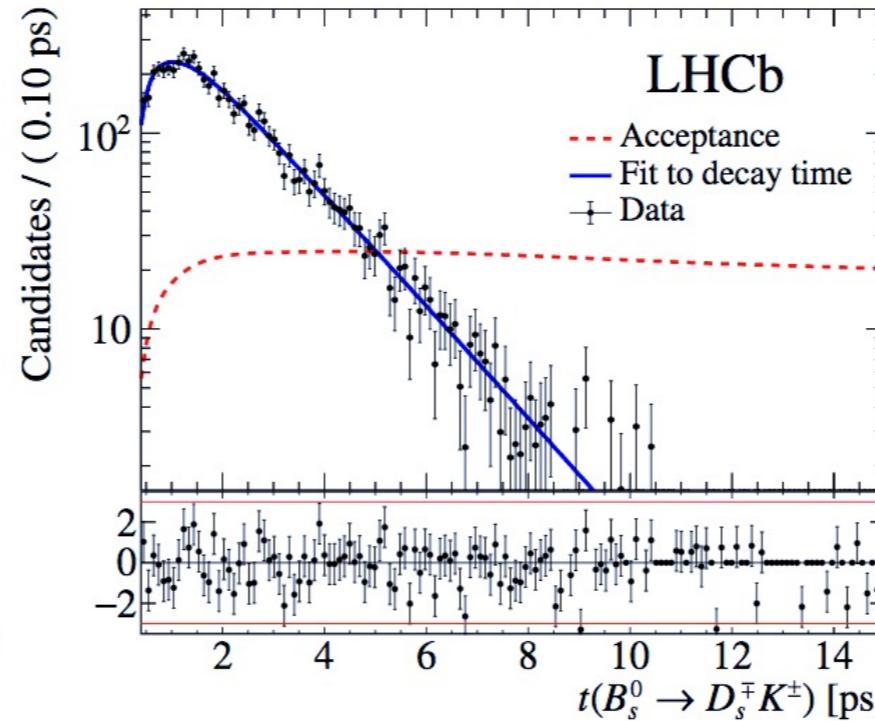
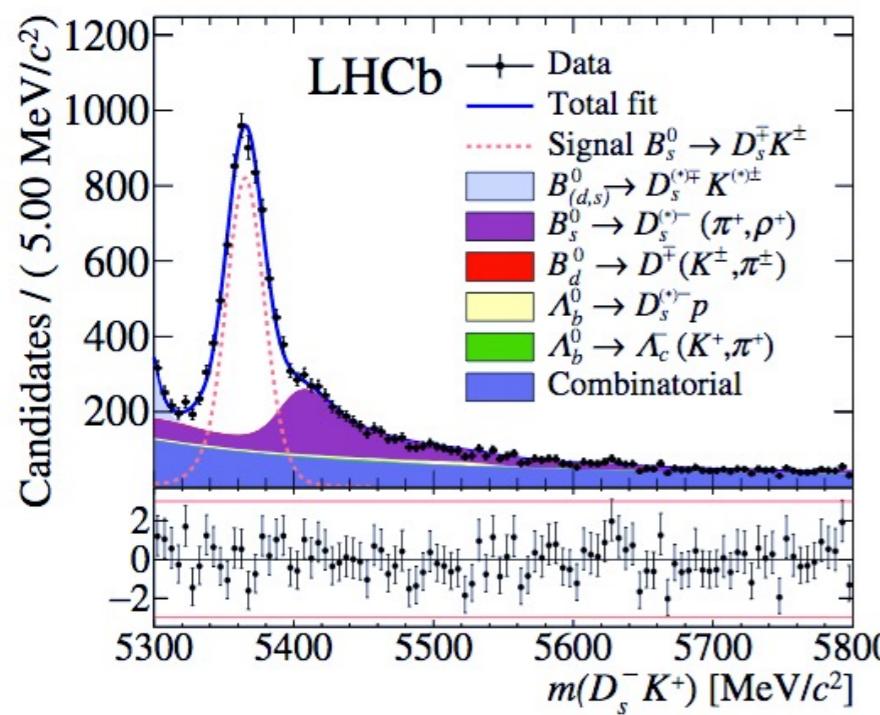
$A_{KK}^{\Delta\Gamma} = -0.79 \pm 0.07 \text{ (stat.)} \pm 0.10 \text{ (syst.)}$

$A_{CP}(B^0 \rightarrow K^+ \pi^-) = -0.084 \pm 0.004 \text{ (stat.)} \pm 0.003 \text{ (syst.)}$

$A_{CP}(B_s^0 \rightarrow \pi^+ K^-) = 0.213 \pm 0.015 \text{ (stat.)} \pm 0.007 \text{ (syst.)}$

- Combined measurement on $B_s^0 \rightarrow K^+ K^-$ is 4.0σ
- Strongest evidence of time-dependent CPV in B_s^0 mesons

$$B_s^0 \rightarrow D_s^\mp K^\pm$$

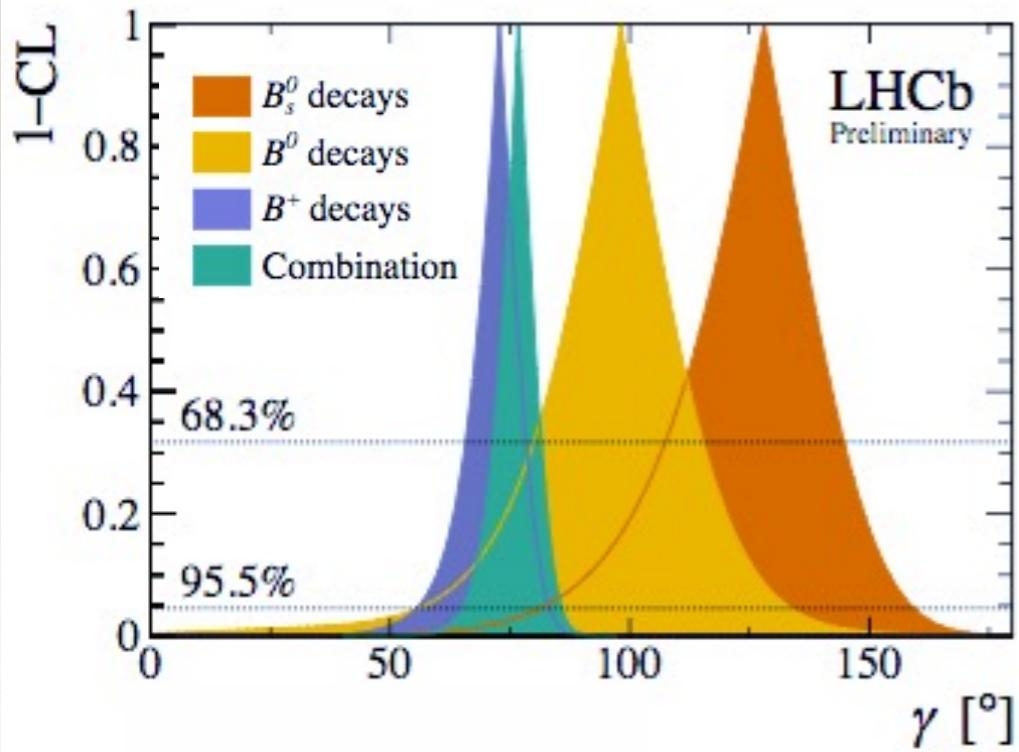
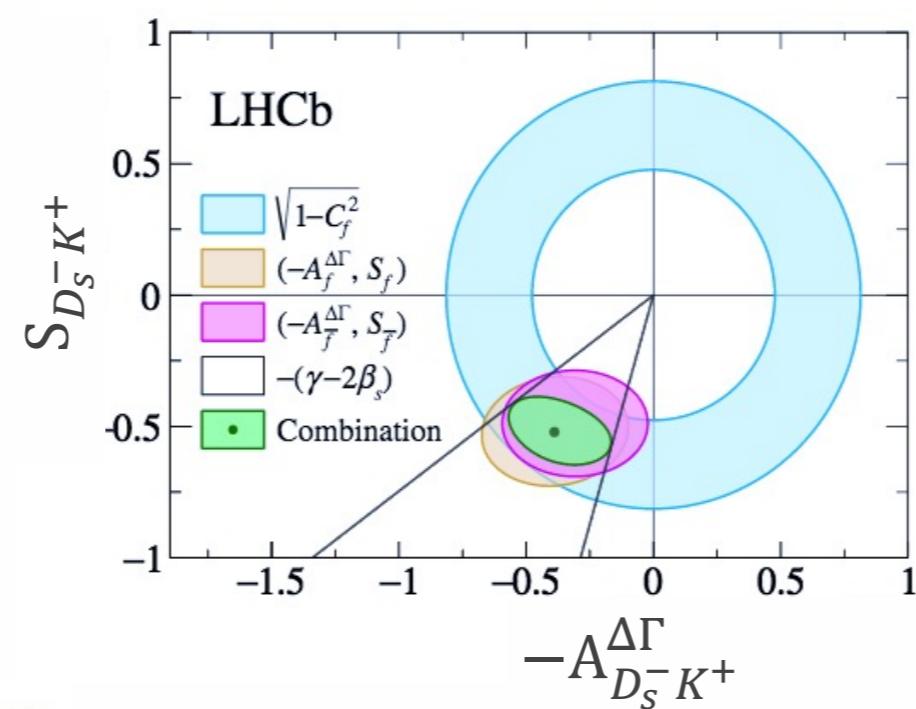
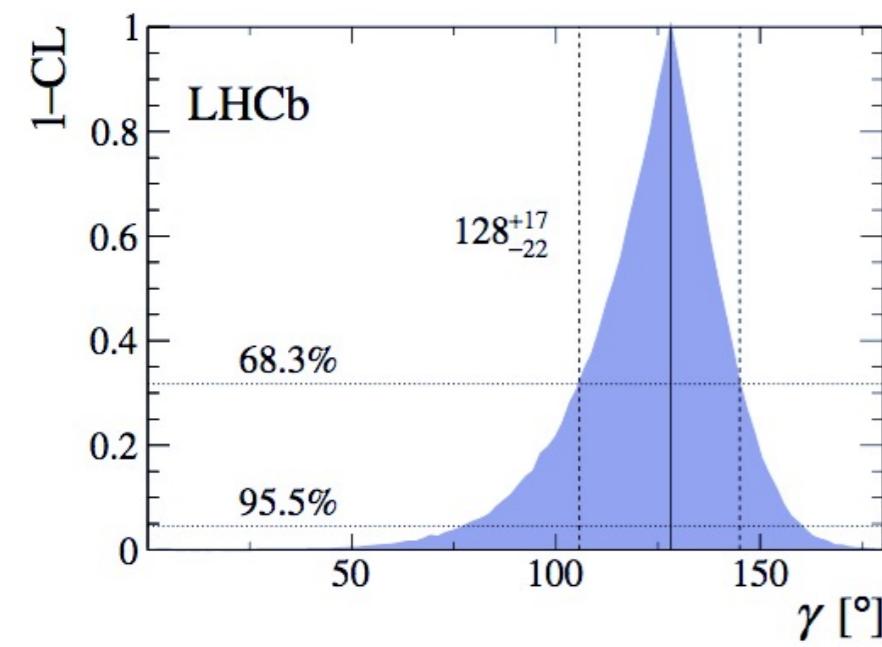


Top Left - $D_s^\mp K^\pm$
Invariant Mass
Distribution

Top Right -
 $B_s^0 \rightarrow D_s^\mp K^\pm$ Lifetime

Bottom Left -
Asymmetry from
 $B_s^0 \rightarrow D_s^+ K^-$

Bottom Right -
Asymmetry from
 $B_s^0 \rightarrow D_s^- K^+$

$B_s^0 \rightarrow D_s^\mp K^\pm$ 

Top Left - 1-CL distribution for γ
Top Right - Contributions of observables to measurement of γ
Bottom - Combined LHCb measurements on γ

$$\gamma(\text{LHCb Avg.}) \blacktriangle = (76.8^{+5.1}_{-5.7})^0$$
$$\gamma(B_s^0 \rightarrow D_s^\mp K^\pm) \blacklozenge = (128^{+17}_{-22})^0$$

Compatible at 2.8σ with combined measurement

$$B^\pm \rightarrow D_{(s)}^\pm D^0$$

- This is a measure of direct CP Violation

$$A_{\text{raw}}(f) = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})} = A_{\text{CP}} + A_{\text{P}} + A_{\text{D}}$$

where:

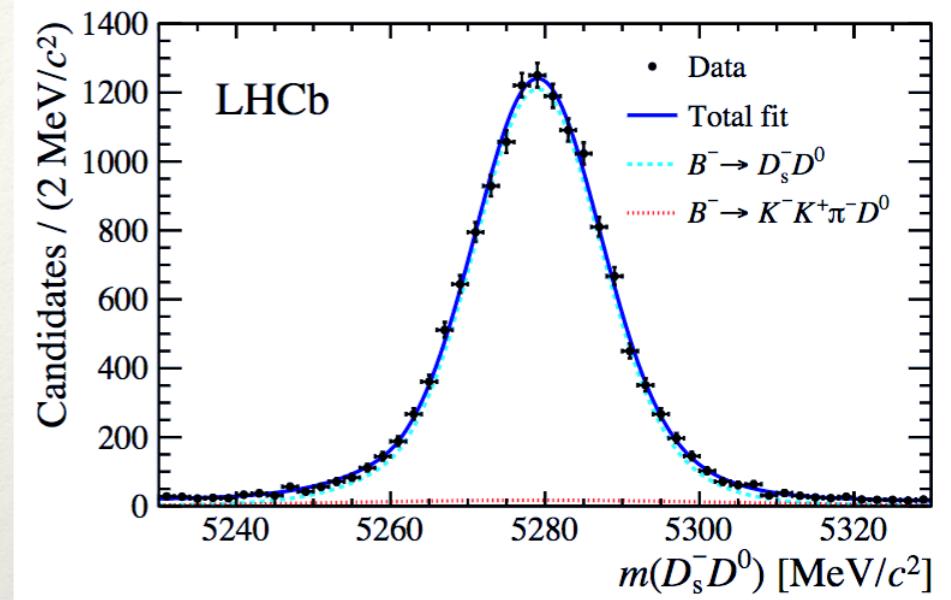
A_{CP} is the asymmetry due to CPV

A_{P} is the production asymmetry

A_{D} is the detection asymmetry

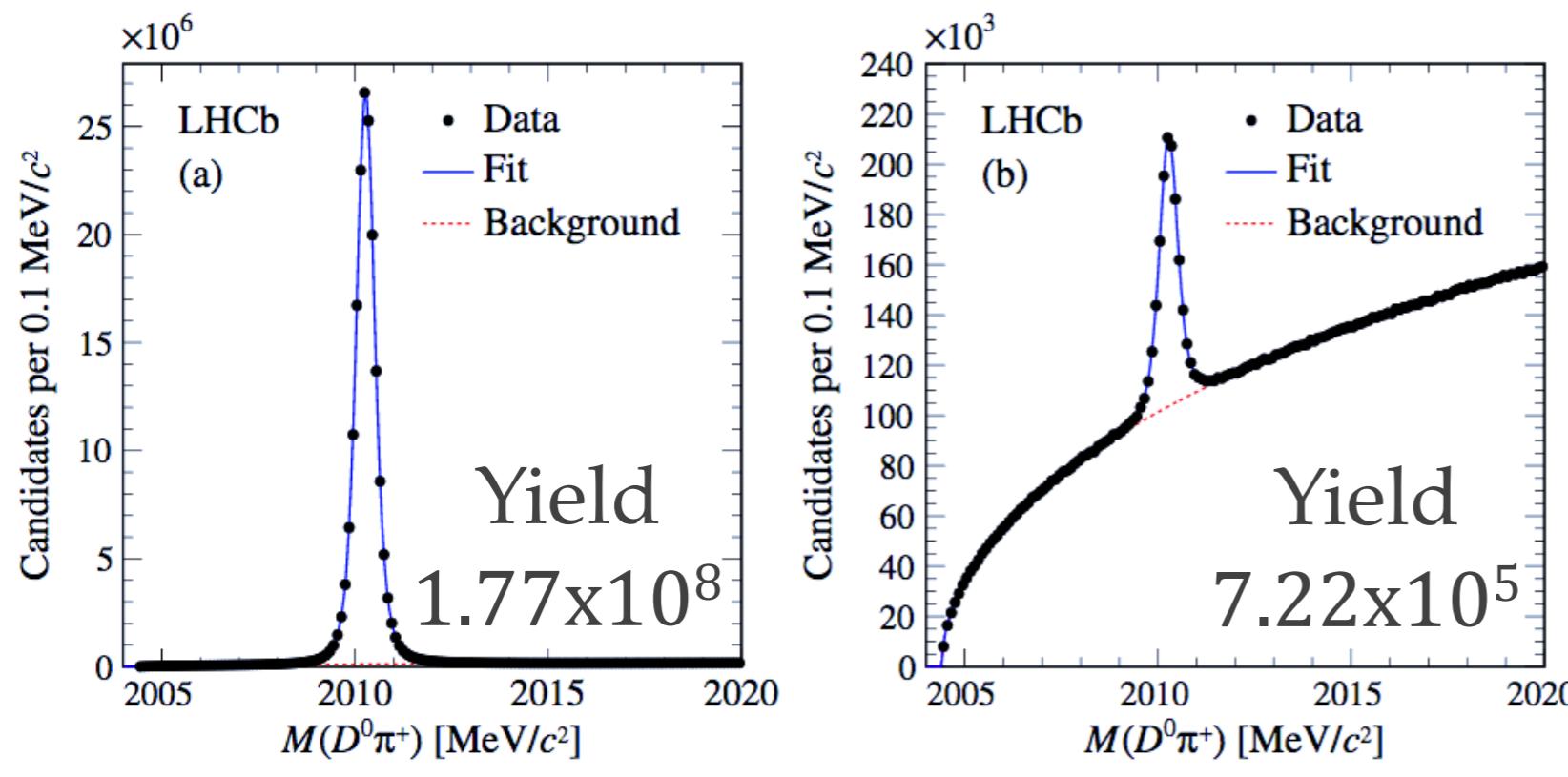
- No CPV found

- $A_{\text{P}} + A_{\text{D}} = \begin{cases} (-1.4 \pm 0.5)\% \text{ for } B^- \rightarrow D_s^- D^0 \\ (-0.3 \pm 0.4)\% \text{ for } B^- \rightarrow D^- D^0 \end{cases}$
- $A_{\text{CP}}(B^- \rightarrow D_s^- D^0) = (-0.4 \pm 0.5 \text{ (stat.)} \pm 0.5 \text{ (syst.)})\%$
- $A_{\text{CP}}(B^- \rightarrow D^- D^0) = (-2.3 \pm 2.7 \text{ (stat.)} \pm 0.4 \text{ (syst.)})\%$



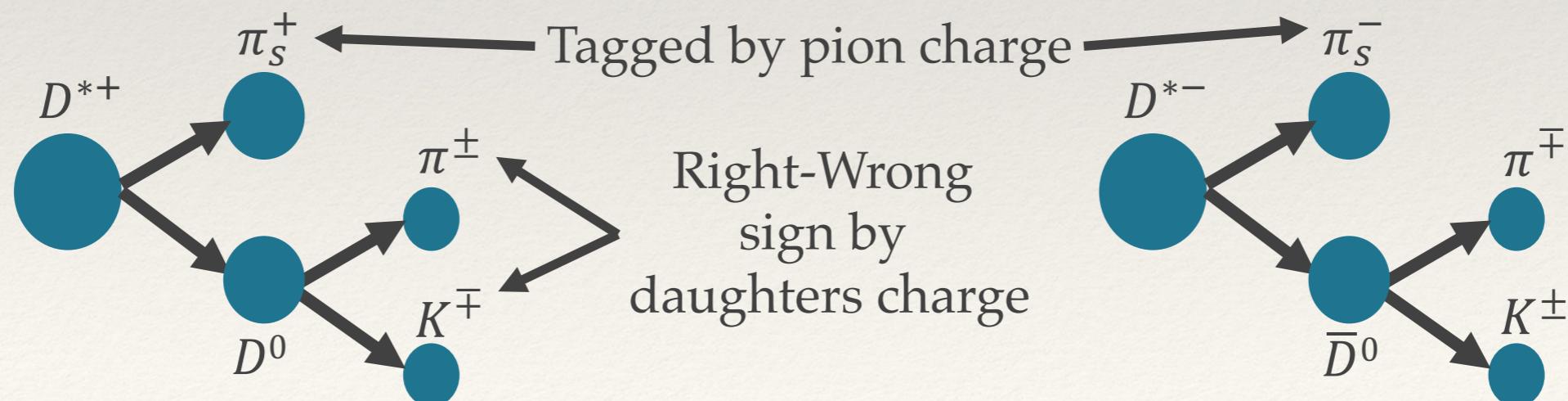
Channel	$N(B^-)$	$N(B^+)$
$B^- \rightarrow D_s^- D^0$	21375 ± 165	22153 ± 168
$B^- \rightarrow D^- D^0$	1047 ± 40	1005 ± 39

D^0 Mixing and $D^0 \rightarrow K^+ \pi^-$



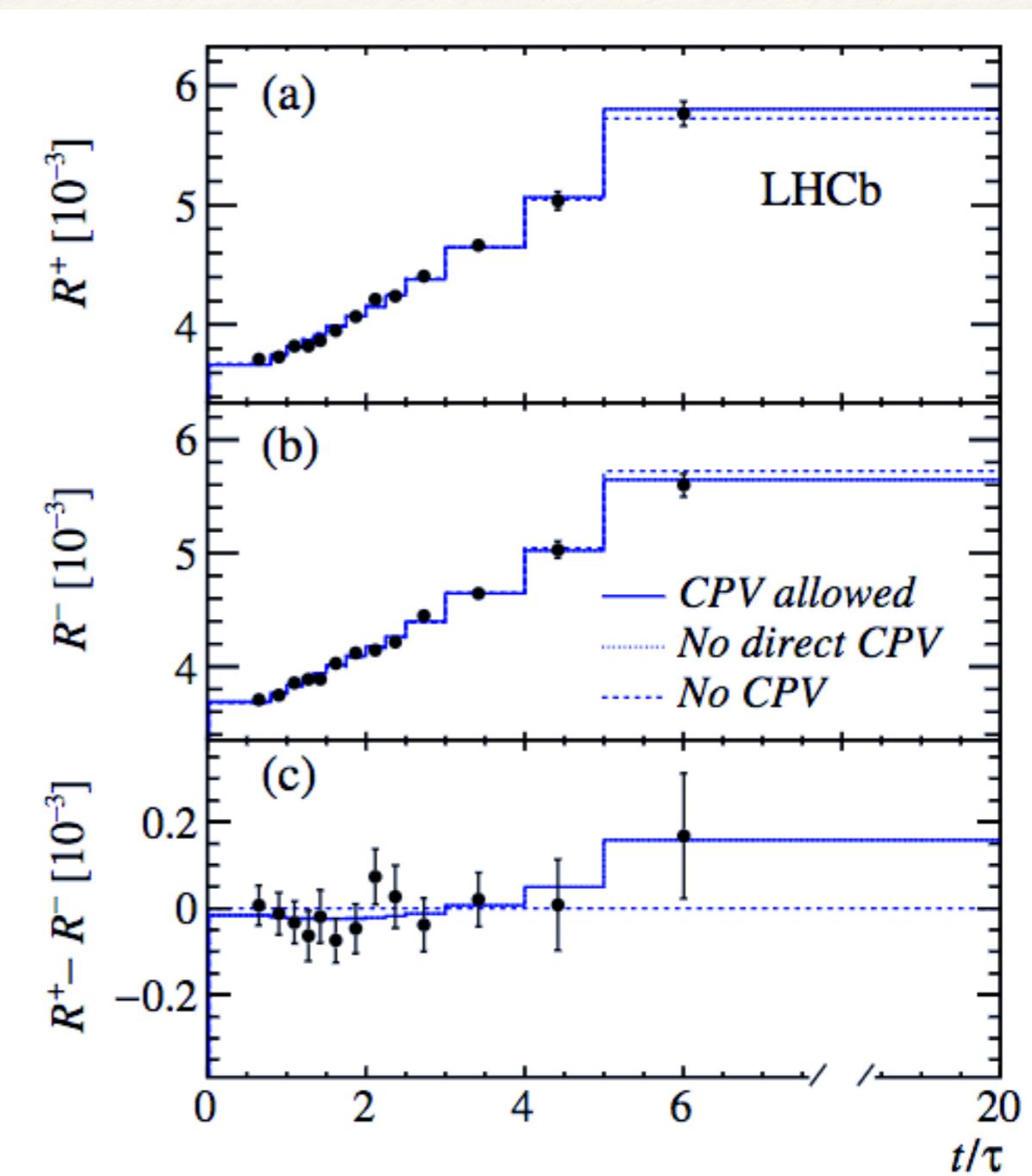
Left - Invariant mass distribution of right-sign ($D^0 \rightarrow K^- \pi^+$) decays
Right - Invariant mass distribution of wrong sign ($D^0 \rightarrow K^+ \pi^-$) decays

How is this done?



D^0 Mixing and $D^0 \rightarrow K^+ \pi^-$

- $R_D^\pm(t) \approx R_D^\pm + \sqrt{R_D^\pm} y'^\pm \frac{t}{\tau} + \frac{(x'^\pm)^2 + (y'^\pm)^2}{4} \frac{t^2}{\tau^2}$
 - $x'^\pm = \left| \frac{q}{p} \right|^{\pm 1} (x' \cos \phi \pm y' \sin \phi)$
 - $y'^\pm = \left| \frac{q}{p} \right|^{\pm 1} (x' \sin \phi \mp y' \cos \phi)$
 - $x' = x \cos \delta + y \sin \delta$
 - $y' = y \cos \delta - x \sin \delta$
 - $x = \frac{\Delta m}{\Gamma}$
 - $y = \frac{\Delta \Gamma}{2\Gamma}$
- $x'^2 = (3.9 \pm 2.7) \times 10^{-3}$
 $y' = (5.28 \pm 0.52) \times 10^{-3}$

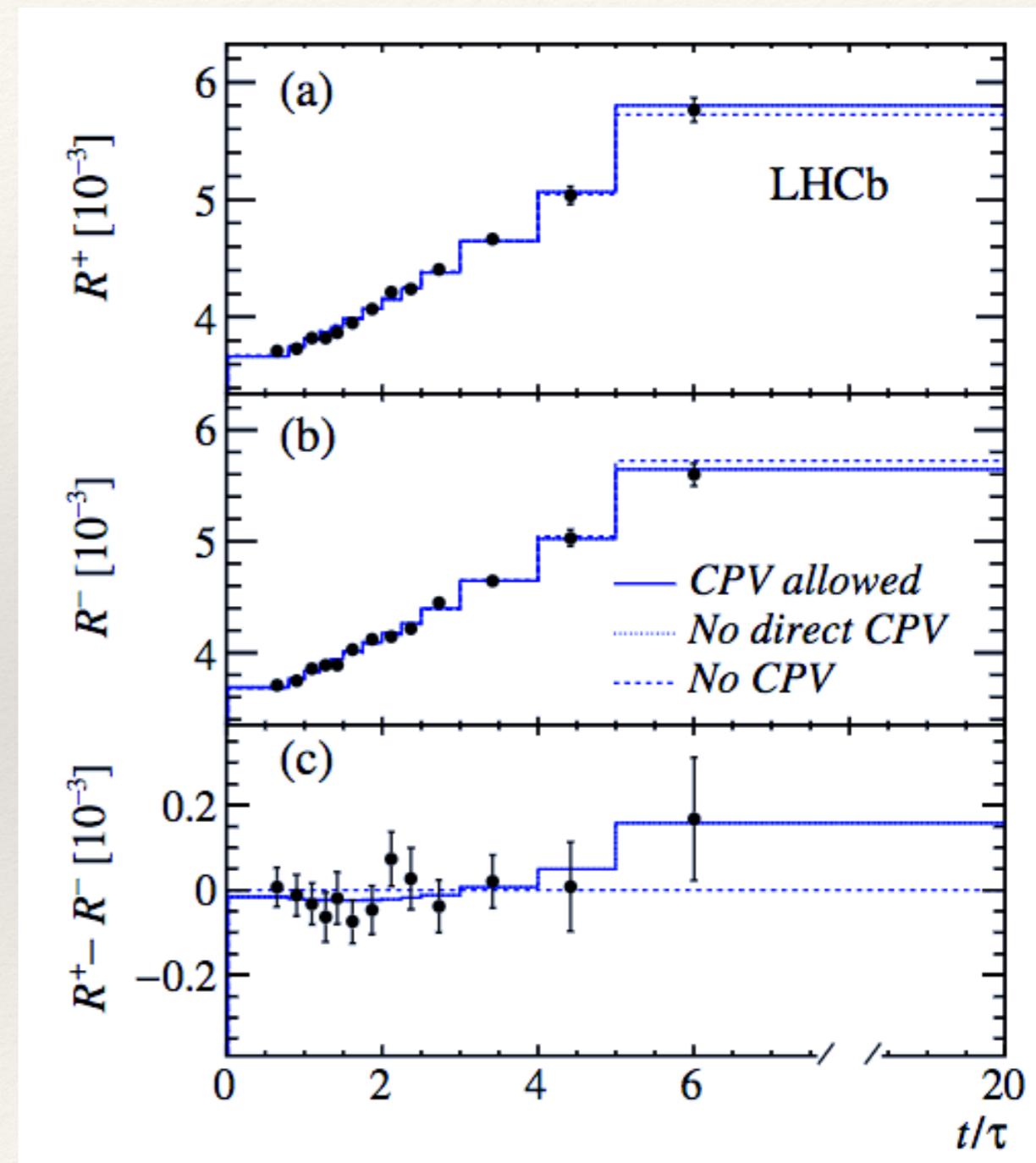


D^0 Mixing and $D^0 \rightarrow K^+ \pi^-$

- The asymmetry is defined as:

$$A_{\text{CP}}^{\text{Dir}} = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 9.1) \times 10^{-3}$$

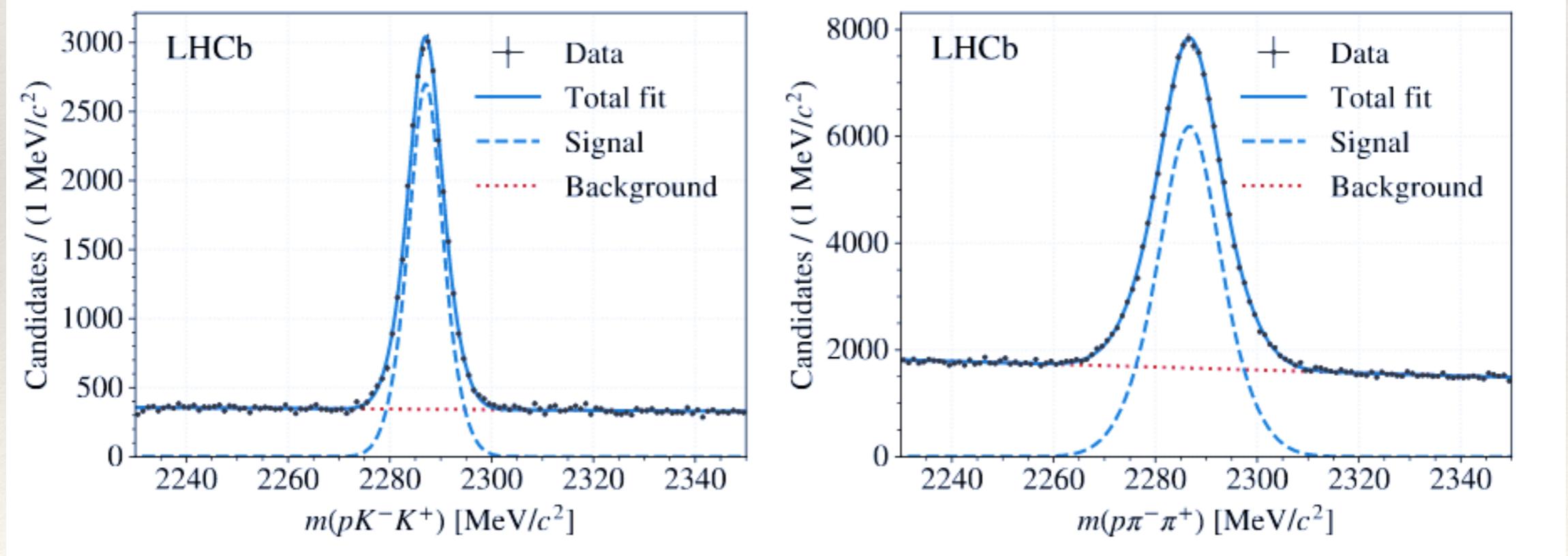
No evidence for CPV (direct or indirect)



$\Lambda_c^+ \rightarrow ph^+h^-$

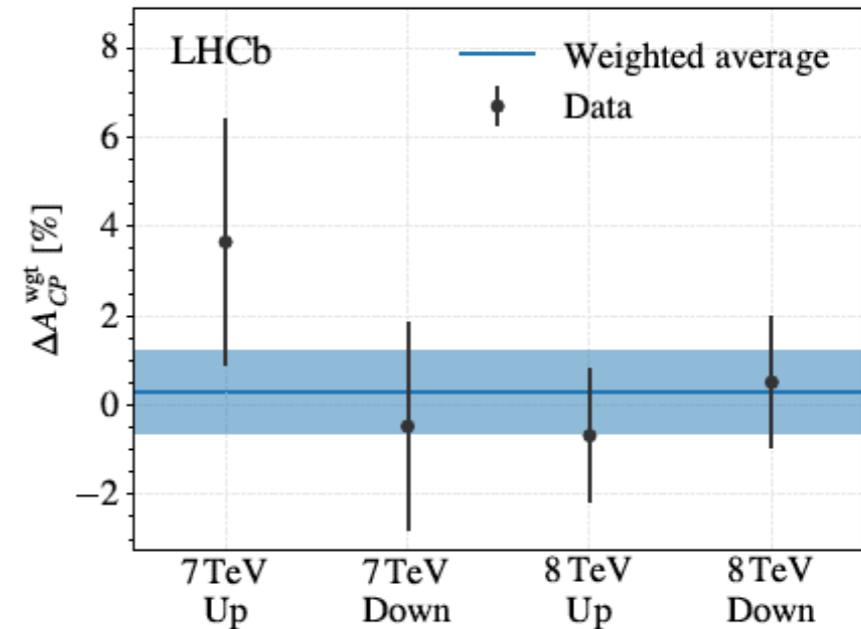
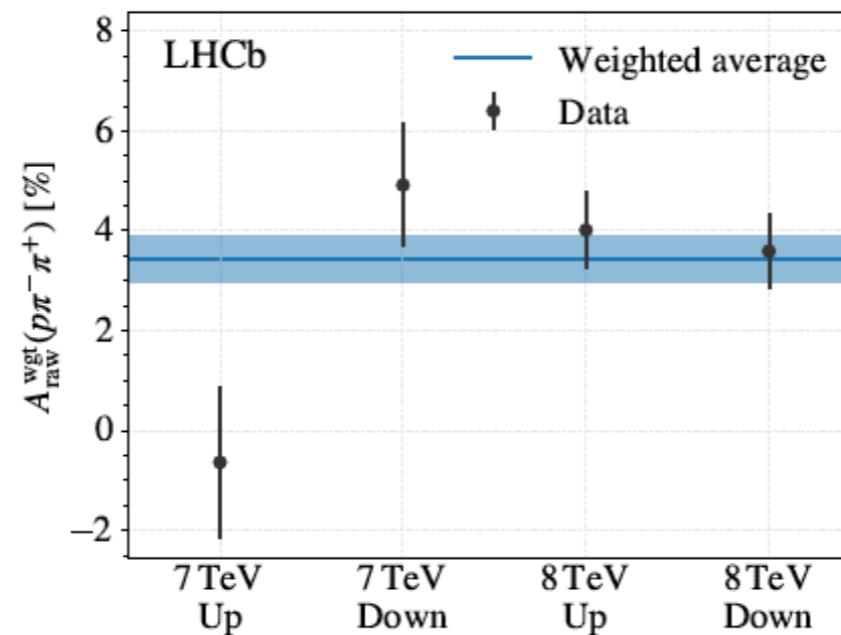
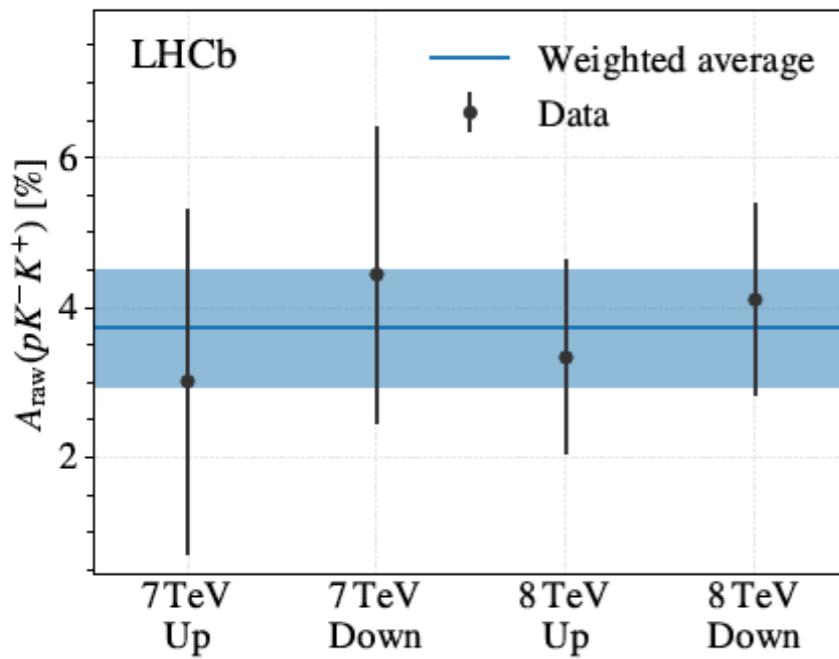
- CPV is compared in two decay chains: $\Lambda_b^0 \rightarrow (\Lambda_c^+ \rightarrow pK^+K^-)\mu^-X$ and $\Lambda_b^0 \rightarrow (\Lambda_c^+ \rightarrow p\pi^+\pi^-)\mu^-X$
- Proton charge is used to split data into Λ_c^+ and Λ_c^-
- Asymmetry defined as:

$$\Delta A_{\text{CP}}^{\text{wgt}} = A_{\text{CP}}(pK^+K^-) - A_{\text{CP}}^{\text{wgt}}(p\pi^+\pi^-)$$



Yield = $(2.52 \pm 0.04) \times 10^4$

Yield = $(1.62 \pm 0.01) \times 10^5$

$\Lambda_c^+ \rightarrow ph^+ h^-$ 

$$A_{CP}(pK^+K^-) = (3.72 \pm 0.78)\%$$

$$A_{CP}^{wgt}(p\pi^+\pi^-) = (3.42 \pm 0.47)\%$$

$$\Delta A_{CP}^{wgt} = (0.30 \pm 0.91 \text{ (stat.)} \pm 0.61 \text{ (syst.)})\%$$

No evidence for CP violation in charm baryons

Summary

- CP Violation is an important requirement to explain the matter anti-matter asymmetry but SM predictions not enough
- Wide range of channels studied by the LHCb collaboration
 1. $B_s^0 \rightarrow K^+ K^-$ show a 4σ significance for time-dependant CPV
 2. $B_s^0 \rightarrow D_s^\mp K^\pm$ measured γ to be compatible with combined measurements
 3. No evidence yet for CPV in $B^\pm \rightarrow D_{(s)}^\pm D^0$
 4. No evidence yet for CPV in the charm sector
- Many Run I analyses undergoing updates with Run II data
- LHCb upgrade in LSII, many channels pushed from discovery to precision and yield on increased statistically limited channels

Thank You

Backup

$$B_s^0 \rightarrow D_s^\mp K^\pm$$

Measured CP Parameters

$$C_{D_s^- K^+} = -C_{D_s^+ K^-} = 0.73 \pm 0.14 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$$

$$S_{D_s^- K^+} = -0.52 \pm 0.20 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$$

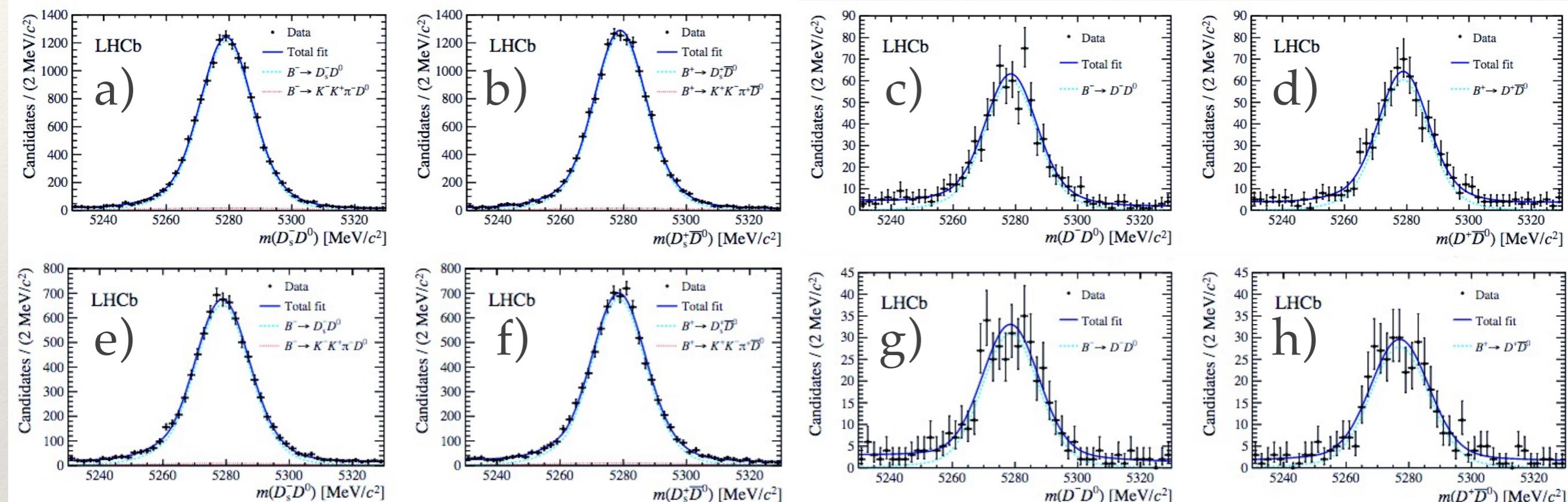
$$S_{D_s^+ K^-} = -0.49 \pm 0.20 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$$

$$A_{D_s^- K^+}^{\Delta\Gamma} = 0.39 \pm 0.28 \text{ (stat.)} \pm 0.15 \text{ (syst.)}$$

$$A_{D_s^+ K^-}^{\Delta\Gamma} = 0.31 \pm 0.28 \text{ (stat.)} \pm 0.15 \text{ (syst.)}$$

$$\gamma = (128^{+17}_{-22})^0$$

$$B^\pm \rightarrow D_{(s)}^\pm D^0$$



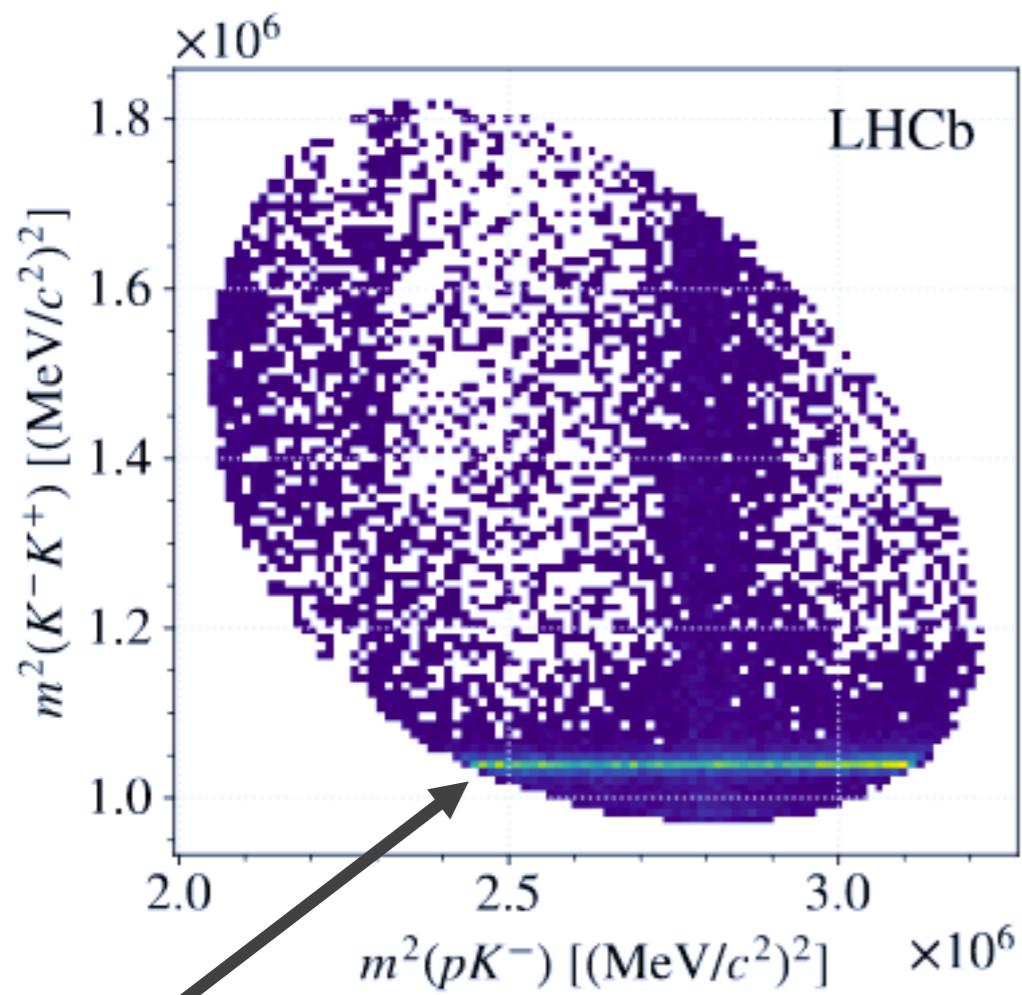
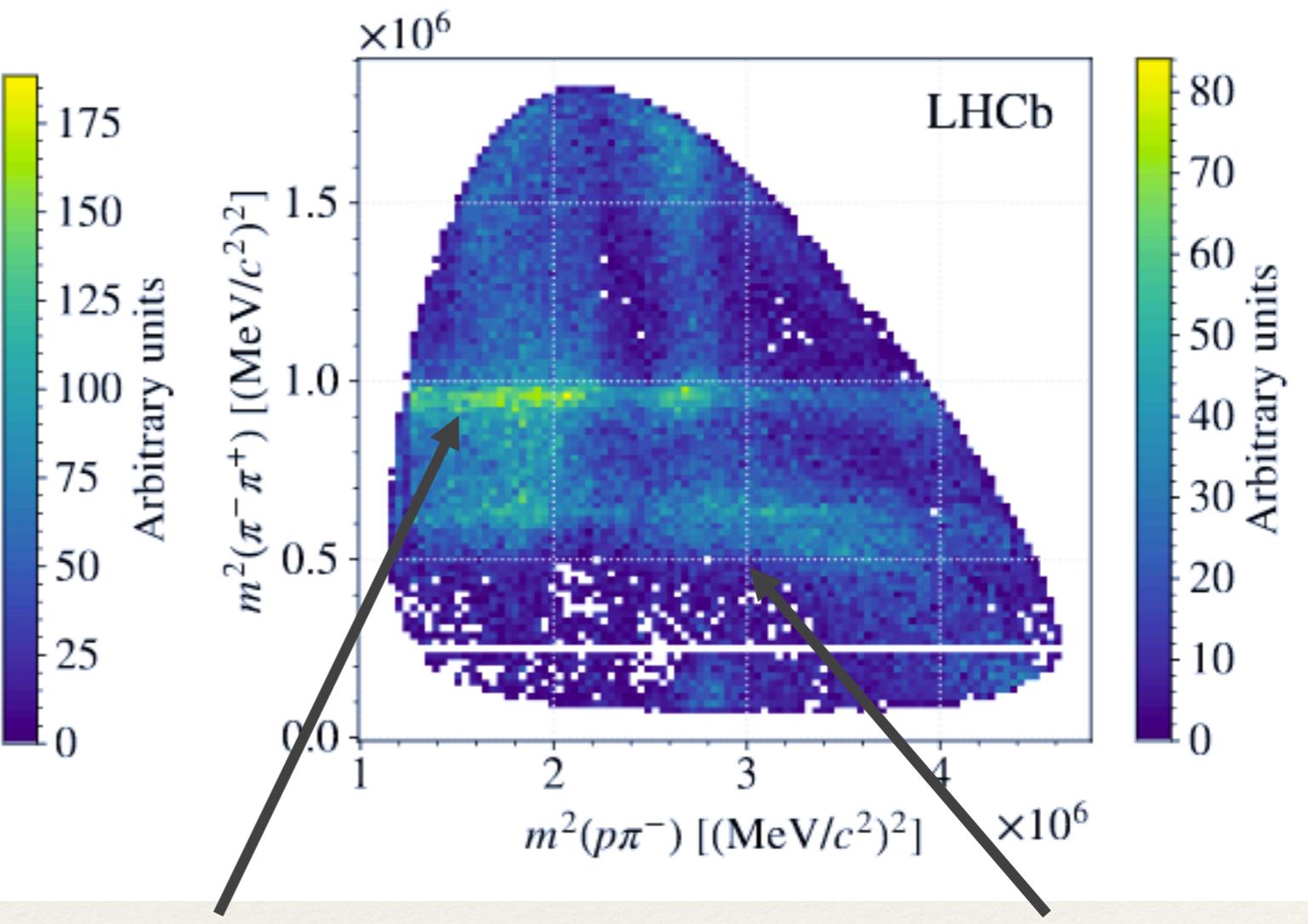
- | | |
|--|--|
| a) $B^- \rightarrow D_s^- (D^0 \rightarrow K^+ \pi^-)$ | b) $B^+ \rightarrow D_s^+ (D^0 \rightarrow K^- \pi^+)$ |
| c) $B^- \rightarrow D^- (D^0 \rightarrow K^+ \pi^-)$ | d) $B^+ \rightarrow D^+ (D^0 \rightarrow K^- \pi^+)$ |
| e) $B^- \rightarrow D_s^- (D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-)$ | f) $B^+ \rightarrow D_s^+ (D^0 \rightarrow K^- \pi^+ \pi^- \pi^+)$ |
| g) $B^- \rightarrow D^- (D^0 \rightarrow K^+ \pi^- \pi^- \pi^-)$ | h) $B^+ \rightarrow D^+ (D^0 \rightarrow K^- \pi^+ \pi^- \pi^+)$ |

$$\Lambda_c^+ \rightarrow ph^+h^-$$

Resonant Background Analysis

$$\Lambda_c^+ \rightarrow pK^+K^-$$

$$\Lambda_c^+ \rightarrow p\pi^+\pi^-$$

 $\phi \rightarrow K^+K^-$  $f_0(980) \rightarrow \pi^+\pi^-$ $\rho(770)/\omega(782) \rightarrow \pi^+\pi^-$

CKM Matrix

Chau and Keungs Parametrisation

$$V_{CKM} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

- δ_{13} is a complex phase allowing CP violation in the standard model
- $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$
- Noting $c_{13} \approx c_{23} \approx 1$ and $c_{12} = \sqrt{1 - s_{12}^2} \approx 1 - \lambda^2/2$ we get the Wolfenstein Parameterisation of the CKM matrix
- $V_{cb} = A\lambda^2$ and $s_{12}e^{i\delta} = A\lambda^2(\rho - i\eta)$ where $A \approx 4/5$

Wolfenstein Parametrisation

$$V_{CKM} = \begin{bmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

Status of CKM Matrix

Observable	central \pm CL $\equiv 1\sigma$
A	$0.8250^{+0.0071}_{-0.0111}$
λ	$0.22509^{+0.00029}_{-0.00028}$
$\bar{\rho}$	$0.1598^{+0.0076}_{-0.0072}$
$\bar{\eta}$	$0.3499^{+0.0063}_{-0.0061}$
α [°]	$92.0^{+1.3}_{-1.1}$
α [°] (!)	$92.1^{+1.5}_{-1.1}$
α [°] (dir. meas.)	$-2.2^{+3.7}_{-4.9} 88.8^{+2.3}_{-2.3}$
β [°]	$22.60^{+0.36}_{-0.35}$
β [°] (!)	$23.74^{+1.13}_{-0.98}$
β [°] (dir. meas.)	$21.85^{+0.68}_{-0.67}$
γ [°]	$65.40^{+0.97}_{-1.16}$
γ [°] (!)	$65.33^{+0.96}_{-2.54}$
γ [°] (dir. meas.)	$72.1^{+5.4}_{-5.8}$

Observable	central \pm CL $\equiv 1\sigma$
$ V_{ud} $	$0.974334^{+0.000064}_{-0.000068}$
$ V_{us} $	$0.22508^{+0.00030}_{-0.00028}$
$ V_{ub} $	$0.003715^{+0.000060}_{-0.000060}$
$ V_{cd} $	$0.22494^{+0.00029}_{-0.00028}$
$ V_{cs} $	$0.973471^{+0.000067}_{-0.000067}$
$ V_{cb} $	$0.04181^{+0.00028}_{-0.00060}$
$ V_{td} $	$0.008575^{+0.000076}_{-0.000098}$
$ V_{ts} $	$0.04108^{+0.00030}_{-0.00057}$
$ V_{tb} $	$0.999119^{+0.000024}_{-0.000012}$

Observables

The decay of neutral mesons follow

$$\Gamma[B \rightarrow f, t] = N_B \omega e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \mathcal{A}^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma}{2}t\right) - S_f \sin(\Delta m t) + C_f \cos(\Delta m t) \right]$$

$$\Gamma[\bar{B} \rightarrow f, t] = N_{\bar{B}} (1 - \omega) e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \mathcal{A}^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma}{2}t\right) + S_f \sin(\Delta m t) - C_f \cos(\Delta m t) \right]$$

Observables are related to different CPV parameters

$$\lambda = \frac{q}{p} \frac{\bar{A}_f}{A_f} = \left| \frac{q}{p} \right| \left| \frac{\bar{A}_f}{A_f} \right| e^{i(\phi_{\frac{q}{p}} + \phi_{\bar{A}_f} - \phi_{A_f})}$$

q and p come from the coefficients of the Weak eigenstates and thus are related to mixing. A_f comes from the decay amplitudes

$$C_f = \frac{1 - |\lambda|^2}{1 + |\lambda|^2} = \frac{1 - (|\frac{q}{p}| |\frac{\bar{A}_f}{A_f}|)^2}{1 + (|\frac{q}{p}| |\frac{\bar{A}_f}{A_f}|)^2}$$

C_f describes CPV in the decay

$$S_f = \frac{2Im(\lambda)}{1 + |\lambda|^2} = \frac{2|\frac{q}{p}| |\frac{\bar{A}_f}{A_f}| \sin(\phi_{\frac{q}{p}} + \phi_{\bar{A}_f} - \phi_{A_f})}{1 + (|\frac{q}{p}| |\frac{\bar{A}_f}{A_f}|)^2}$$

S_f describes CPV from interference between the mixing and the decay

$$\mathcal{A}_f^{\Delta\Gamma} = \frac{-2Re(\lambda)}{1 + |\lambda|^2} = \frac{-2|\frac{q}{p}| |\frac{\bar{A}_f}{A_f}| \cos(\phi_{\frac{q}{p}} + \phi_{\bar{A}_f} - \phi_{A_f})}{1 + (|\frac{q}{p}| |\frac{\bar{A}_f}{A_f}|)^2}$$

The LHCb Upgrade

- ❖ Upgrade will installed in LS2
- ❖ Removing the hardware trigger, full 40 MHz readout at a luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- ❖ Upgrading to a new detector rated to 50 fb^{-1}
- ❖ Increasing pileup (μ) from 1.2 to > 5
- ❖ Will extend the discovery and precision ability for many channels

