CP violation @ LHCb

B. Souza de Paula on behalf of the LHCb Collaboration

LISHEP 2015– 7/8/2015 – Manaus

Why CP violation?

- Our Universe is made of matter
- CP violation (CPV) is one of the ingredients needed to allow the lack of antimatter
- CPV was introduced in the Standard Model (SM)
- Weak CPV measured is not enough to explain the lack of antimatter
- Good place to look for Physics Beyond the (BSM)

CKM matrix

- The Cabibbo-Kobayashi-Maskawa matrix is how CP violation was introduced in the SM
- The quark flavour (weak interaction) and mass eigenstates are different
  - CKM matrix gives the mixture between them

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- CP violation → $V_{CKM} \neq V^*_{CKM}$
  - Need a complex phase

How to measure CPV?

- Only 4 free parameters in the matrix (Wolfenstein parametrisation)

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda\left\{1-\frac{1}{2}A^2\lambda^4\left[1-2(\rho+i\eta)\right]\right\} & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4\left[1+4A^2\right] & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2\left\{1-\frac{1}{2}\lambda^2\left[1-2(\rho+i\eta)\right]\right\} & 1-\frac{1}{2}A^2\lambda^2 \end{pmatrix} + O(\lambda^6)$$

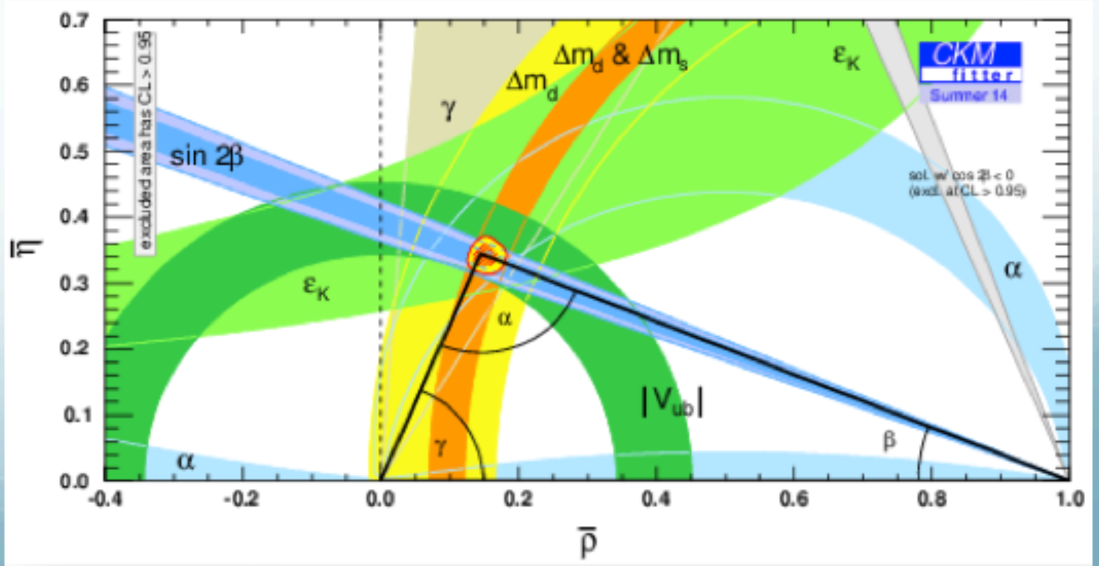
- Measurements to over-constraint them
- Larger CPV in b sector

Triangles

- CPT invariance ➔ $V_{CKM}^{\dagger} V_{CKM} = 1$

$$V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0 \qquad V_{ub}^{*} V_{us} + V_{cb}^{*} V_{cs} + V_{tb}^{*} V_{ts} = 0$$

- Triangles in the complex plane
- Global fit including angles, sizes, meson oscillation

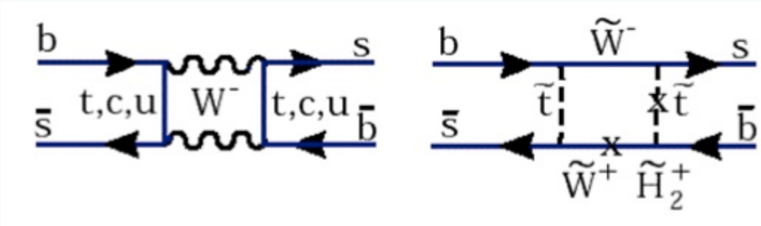


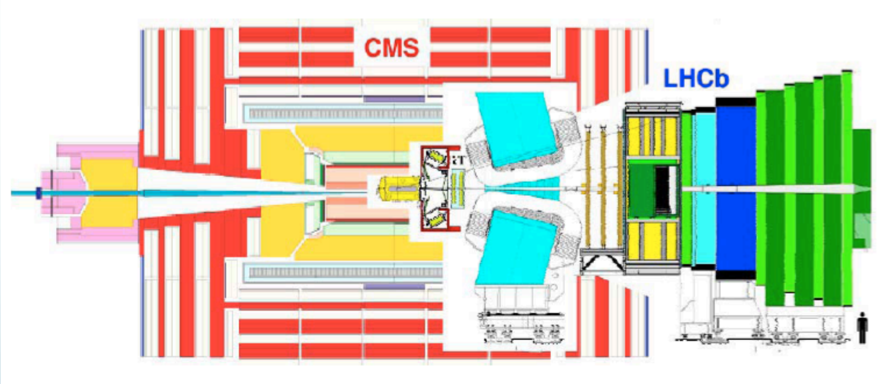
Types of measurements

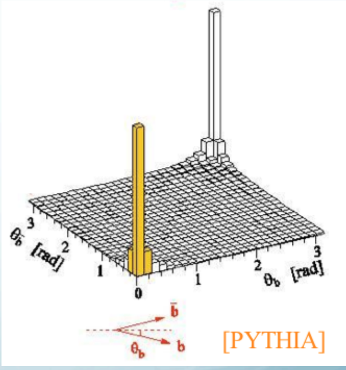
- Whenever a flavour change occurs we can have CPV
- Always need interference between processes
- Direct CPV (in decays) $\left|B \rightarrow f\right| \neq \left|\bar{B} \rightarrow \bar{f}\right|$
- CPV in mixing $\left|B \rightarrow \bar{B}\right| \neq \left|\bar{B} \rightarrow B\right|$
- Interplay between mixing and decay
  - Time dependent decay rates in common decays to both states

LHCb experiment

- Extends to B Factories program (looks also for B_s sector)
- Complementary to ATLAS and CMS
  - Dedicated to flavour physics in B (and D) sector(s)
  - LHCb searches for <u>indirect</u> effect of New Physics through loop diagrams sensitive to higher mass scales
  - Forward spectrometer as $b\bar{b}$ are boosted along beam axis $2<\eta<5$

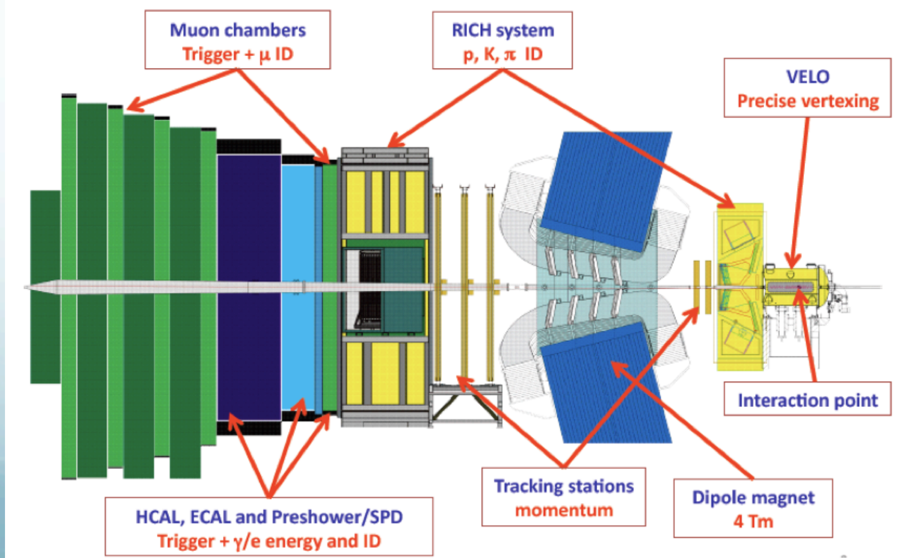






LHCb performance

- Large cross-section: $\sigma(\bar{b}b) \sim 300\mu b$
- Excellent triggers and flavour tagging
- Tracking system gives an efficiency of ~96% for long tracks
- 2 RICH detectors give better particle identification (p/K/π)
- In run I: 3.0 fb^{-1} recorded: ~10^{12} *bb* pairs produced



Results to be presented

- Direct CPV
  - $B_{d,s} \to K\pi$
  - $B^{\pm} \to K^{\pm}\pi\pi, K^{\pm}KK$
- Indirect CPV in B
  - $\sin 2\beta$ from $B^0 \to J/\psi K_s$
  - ϕ_s from $B_s \to J/\psi K^+ K^-$
- Combination of γ
- All results presented with 3.0fb^{-1} recorded in run I
- Many other results left aside for lack of time

$$a_{sl}^s, B_s \to \phi\phi, |V_{ub}/V_{cb}|, charm...$$

CP in $B \rightarrow K\pi$

- Direct integrated CP asymmetry

$$A_{CP} = \frac{\Gamma(\overline{B}_{d,s} \to K^+\pi^-) - \Gamma(B_{d,s} \to K^-\pi^+)}{\Gamma(\overline{B}_{d,s} \to K^+\pi^-) + \Gamma(B_{d,s} \to K^-\pi^+)}$$

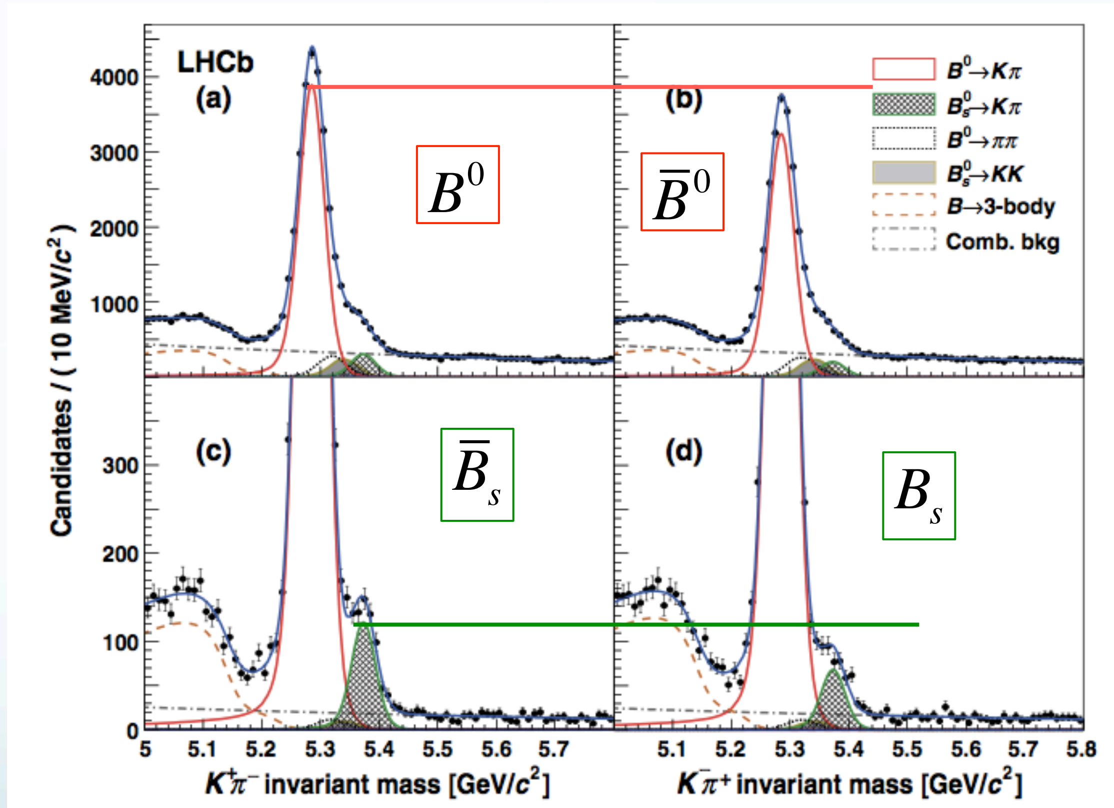
- First observation of $\not{CP}$ in B_s system

- Large asymmetries

$$A_{CP}(B^0) = (-8.0 \pm 0.7 \pm 0.3)\%$$
$$A_{CP}(B_s) = (27 \pm 4 \pm 1)\%$$

- Consistent with SM

- $A_{CP}(B^0) - A_{CP}(B^+ \to K^+\pi^0) \neq 0$

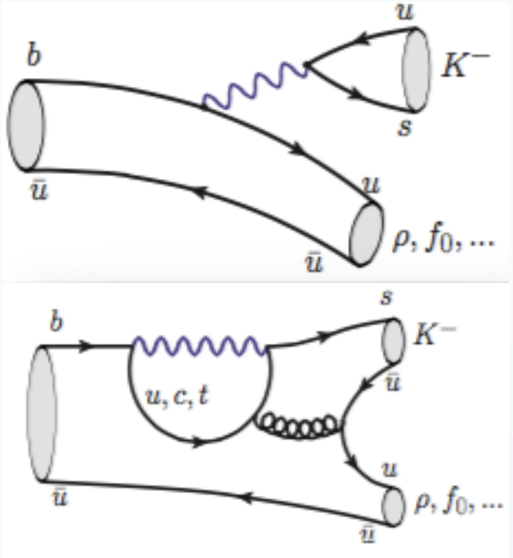


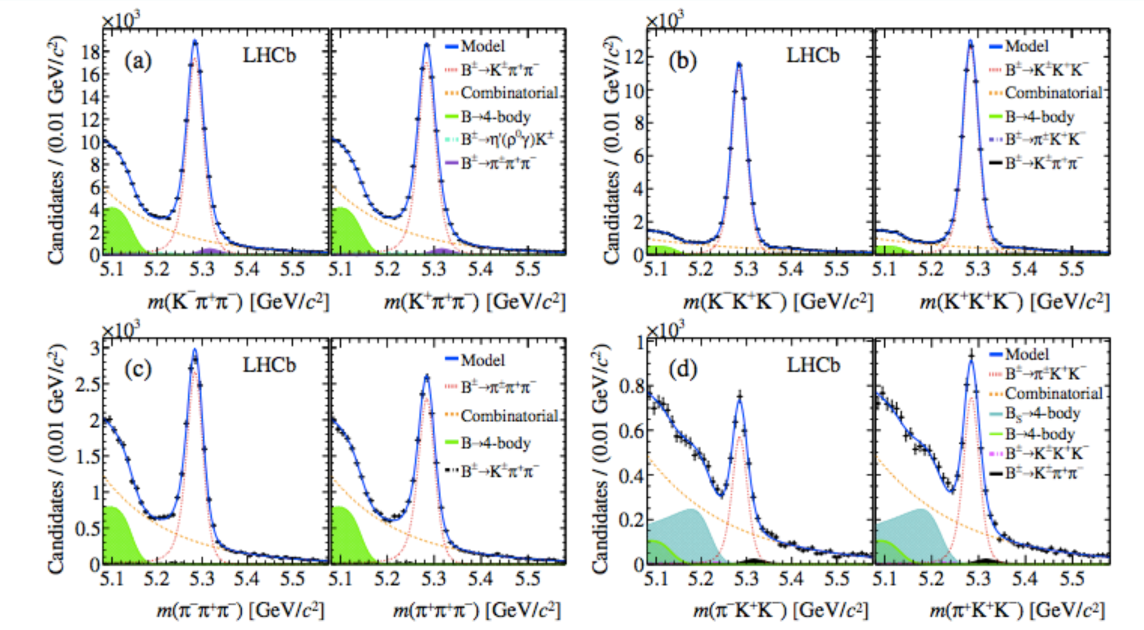
$$A_{CP} = \frac{\Gamma[B^- \to f^-] - \Gamma[B^+ \to f^+]}{\Gamma[B^- \to f^-] + \Gamma[B^+ \to f^+]} = A_{raw} - A_P - A_D$$

PRL 110, 221601 (2015)

Direct CP in $B^{\pm} \rightarrow 3h$

- Interference between Tree and Penguin diagrams (sensitive to BSM)
- Final states: $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$, $K^{\pm}K^{+}K^{-}$, $\pi^{\pm}\pi^{+}\pi^{-}$, $\pi^{\pm}K^{+}K^{-}$



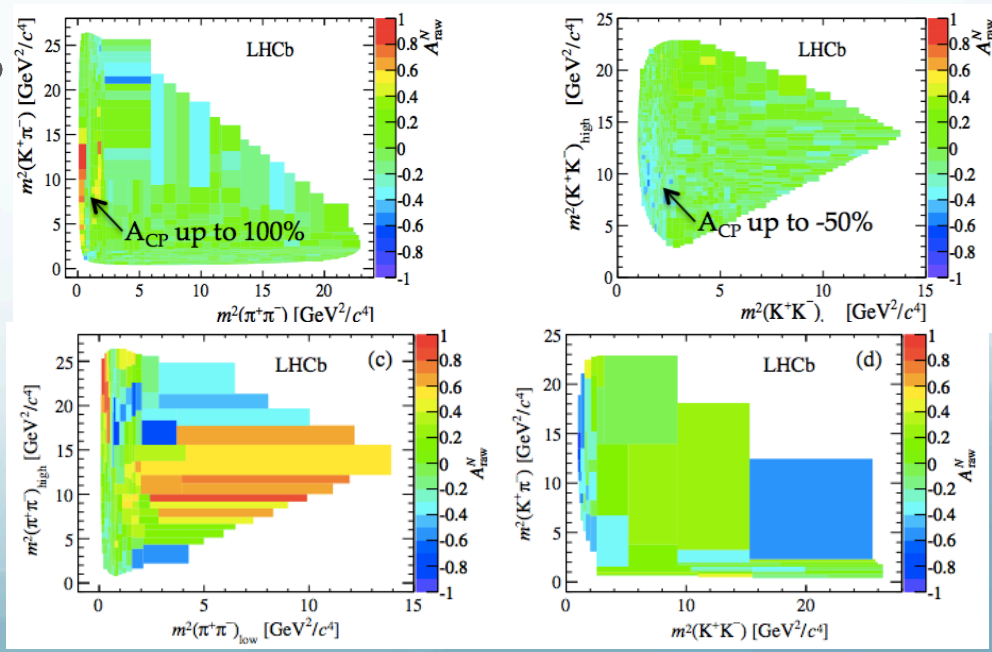


PRD 90, 112004 (2014)

$B^\pm \rightarrow K^\pm\pi^+\pi^-, K^\pm K^+K^-, \pi^\pm\pi^+\pi^-, \pi^\pm K^+K^-$

- Many resonances in final state
  - Strong and weak phases interplay
- Asymmetries looked for in Dalitz plots
- Large A_{CP} in low mass region
- Final state rescattering?

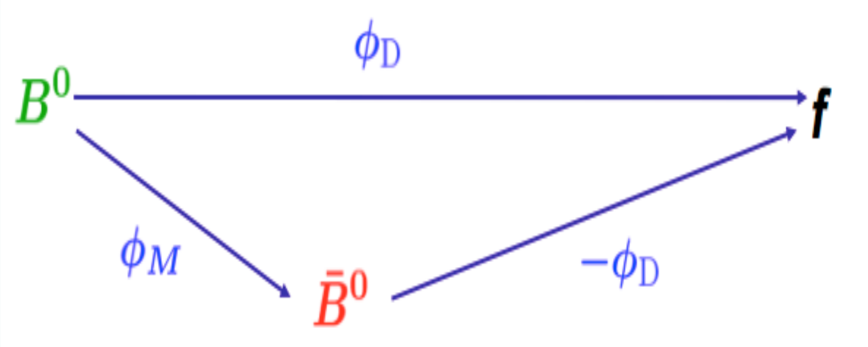
$$A_{CP} = \frac{\Gamma[B^- \to f^-] - \Gamma[B^+ \to f^+]}{\Gamma[B^- \to f^-] + \Gamma[B^+ \to f^+]} = A_{raw} - A_P - A_D$$



PRD 90, 112004 (2014)

Indirect ~~CP~~

- When both $B_{(d,s)}$ and $\overline{B}_{(d,s)}$ have the same final state we can have CP asymmetry in the interference between decay and mixing



$$\Phi_f = \Phi_M - 2\,\Phi_D$$

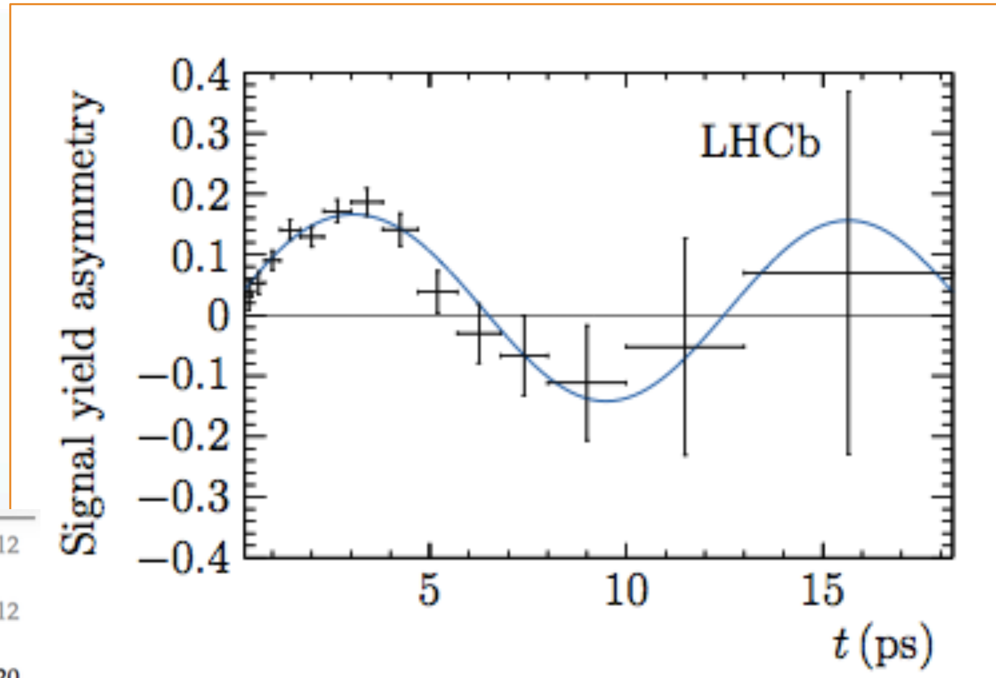
- Same is true for B_s
- Relies heavily on flavour tagging

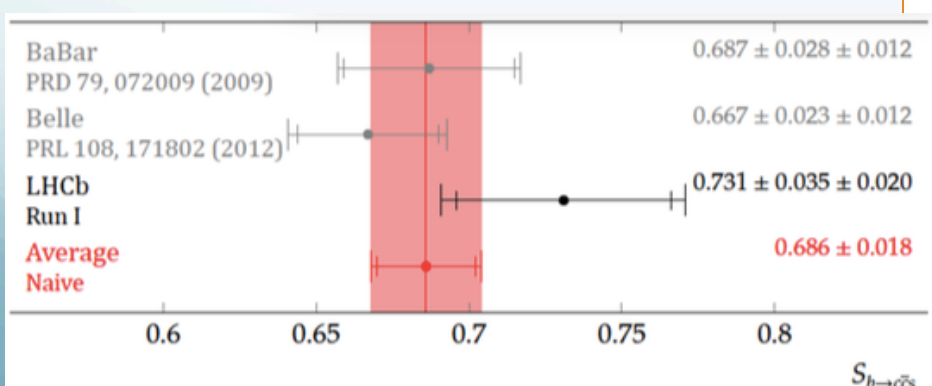
CPV in $B^0 \rightarrow J/\Psi K_S$

- Time-dependent asymmetry ($\Delta\Gamma=0$)
- SM: $C_{J/\psi KS}=0$ $S_{J/\psi KS}=\sin 2\beta$
- One of the most precisely CP parameter measured before LHC

$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)} = S_{J/\psi K^0_S}\sin(\Delta m_d t) - C_{J/\psi K^0_S}\cos(\Delta m_d t).$$

$$S = 0.731 \pm 0.035\,(\text{stat}) \pm 0.020\,(\text{syst})$$
$$C = -0.038 \pm 0.032\,(\text{stat}) \pm 0.005\,(\text{syst})$$



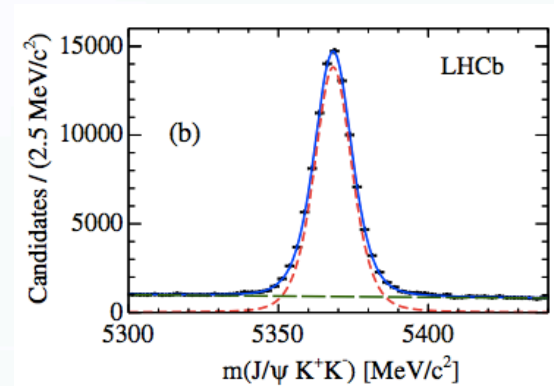


PRL 115, 631601 (2015)

Φ_s in $B_s \rightarrow J/\psi K^+K^-$

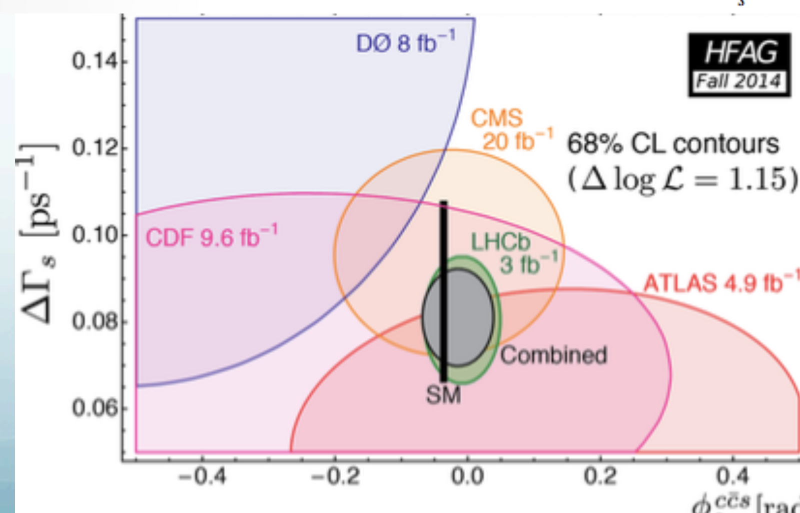
- Analogue to $\sin 2\beta$ in B_s system
- Time-dependent analysis
- Small & well predicted in SM $\Phi_s = -2\beta_s = (-3.6 \pm 0.1)$ mrad
- Is not a CP eigenstate needs to separate CP odd and even components with angular analysis (~1% s-wave)

$$\phi_s = (-0.058 \pm 0.049 \pm 0.006)rad$$



$$A(t) = \frac{\Gamma\left[\overline{B_s^0}(t)\right] - \Gamma\left[B_s^0(t)\right]}{\Gamma\left[\overline{B_s^0}(t)\right] - \Gamma\left[B_s^0(t)\right]} \sim -\sin\phi_s \sin(\Delta m_s t) + \cosh\left(\frac{\Delta\Gamma_s t}{2}\right)$$

$$\Delta\Gamma_s \equiv \Gamma(B_{s,H}) - \Gamma(B_{s,L})$$



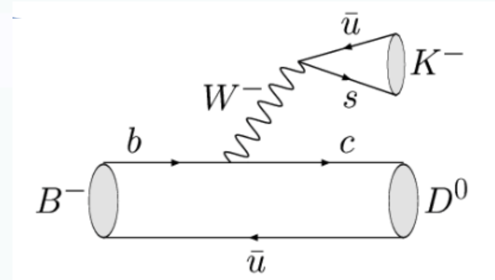
γ combination in $B^{\pm} \rightarrow DK^{\pm}$

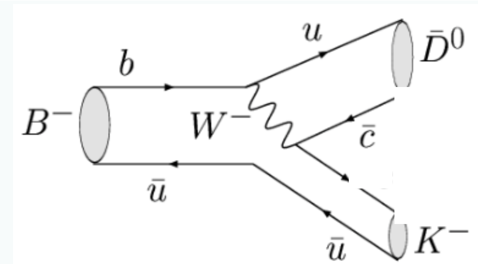
- Only CPV parameter from tree decays
- Many different final states
- Some are exclusively measured by LHCb

D→ (quasi)CP-eigenstates: K^+K^-, $\pi^+\pi^-$, $KK\pi^0$, $\pi\pi\pi^0$

D→ flavour specific: $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K_SK^+\pi^-$

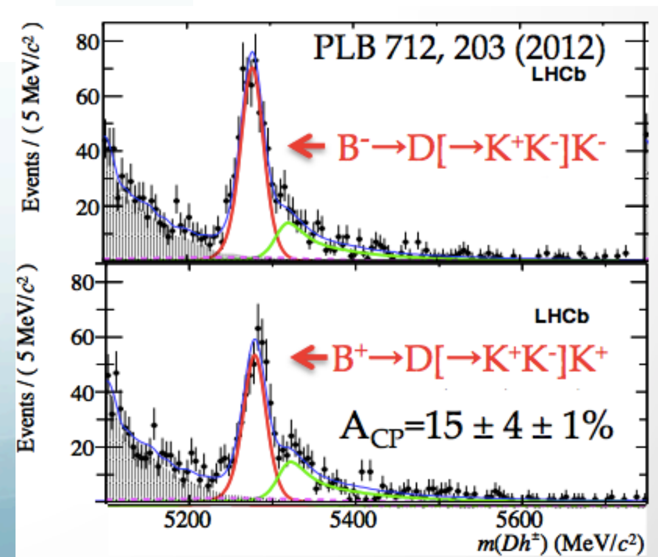
D→ 3-body self-conjugated: $K_S\pi^+\pi^-$, $K_SK^+K^-$





- χ^2 Combination (also $B_s \rightarrow D_sK$)

$$\gamma = (73 \pm ^{+9}_{-10})^{o}$$



Belle: $\gamma = 73 \pm 14°$ BaBar: $\gamma = 70 \pm 18°$

Conclusions

- LHCb had many precise CPV measurements in LHC Run I
  - Direct CPV measurements
  - CKM angles: $\sin 2\beta = 0.731 \pm 0.035 \pm 0.020; \gamma = (73 \pm^{+9}_{-10})^{o}$
  - First precise measurements in the B_s sector
    $\phi_s = (-0.058 \pm 0.049 \pm 0.006) rad$
- Everything consistent with SM
- Some places to look for in ongoing Run II
  - Why $A_{CP}(B^0) - A_{CP}(B^+ \to K^+\pi^0) \neq 0$?
  - Low mass A_{CP} in B➔hhh
  - Better precision in γ and Φ_s

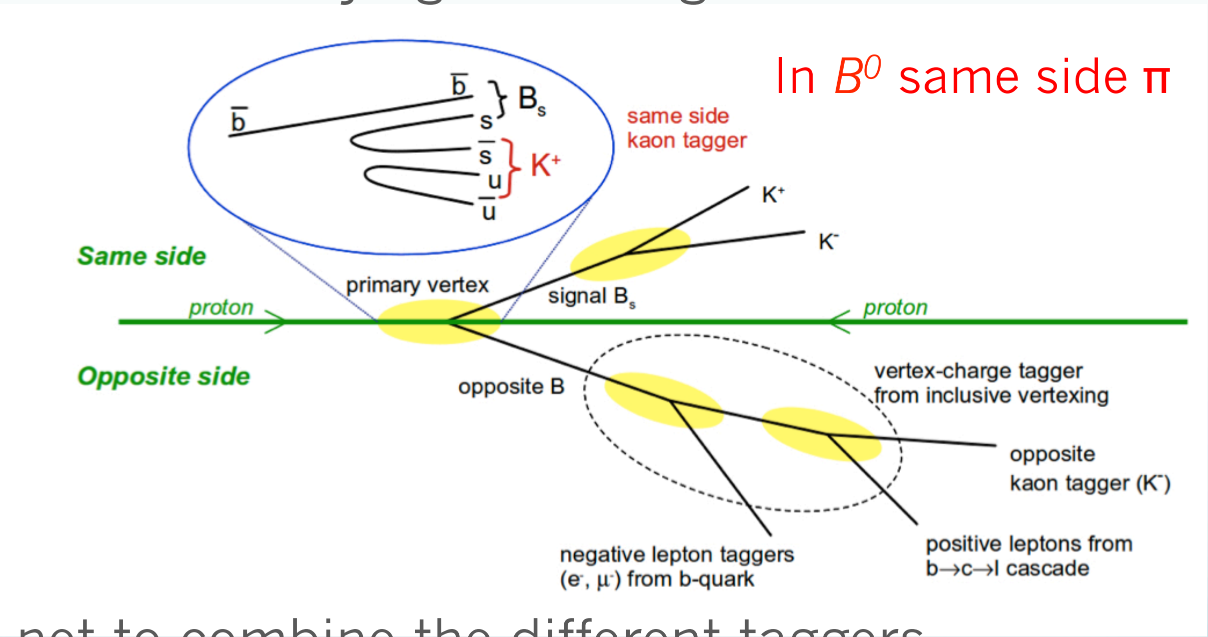

Thank you!

Backup

Tagging system

- Flavour Tagging is the procedure to determine the flavour of the reconstructed B meson at production

- Looks for the underlying event to get an answer



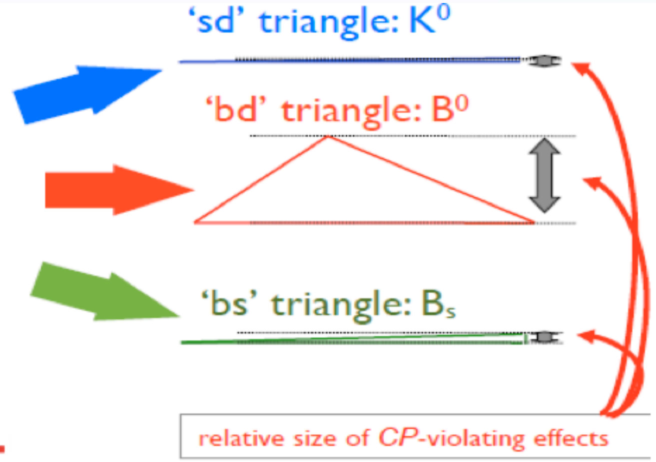
- Neural net to combine the different taggers

CKM triangles

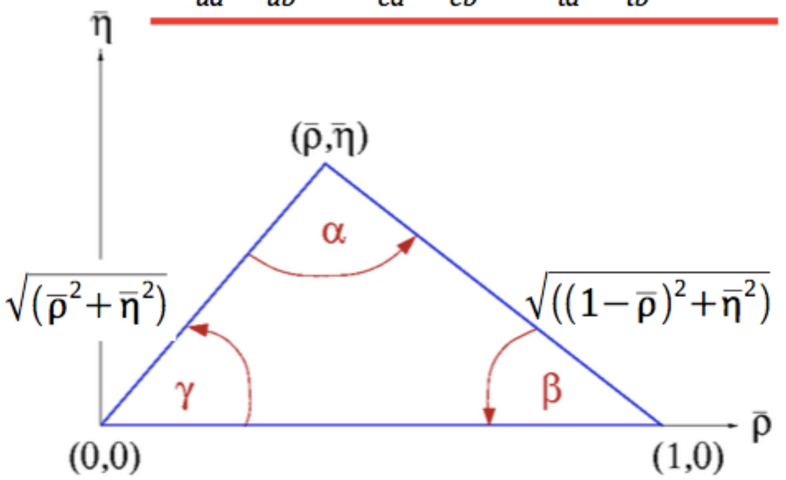
$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0$$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0$$



$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$



$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

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

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$

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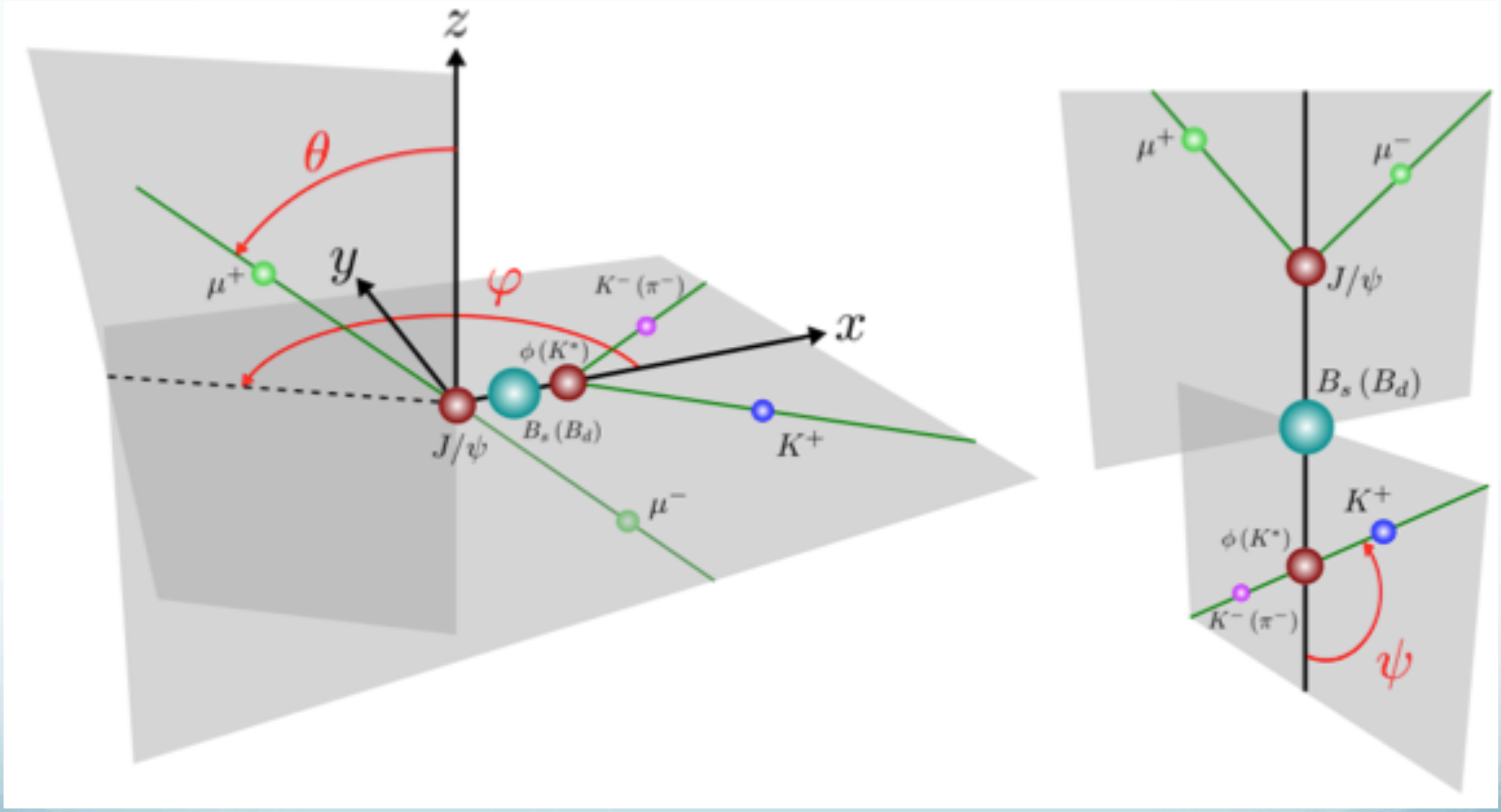
Φ_s

- In SM

$$\phi_s = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = (-0.036 \pm 0.001)rad$$

- Many NP terms can be added to Φ_s due to mixing: eg. SUSY, extra dimensions, 4^{th} generation

Angles definition



CP-even and CP-odd