CP violation with B mesons at LHCb

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On behalf of the LHCb collaboration

Epiphany, 8-10 jan 2014

CP violation

Violation of CP symmetry

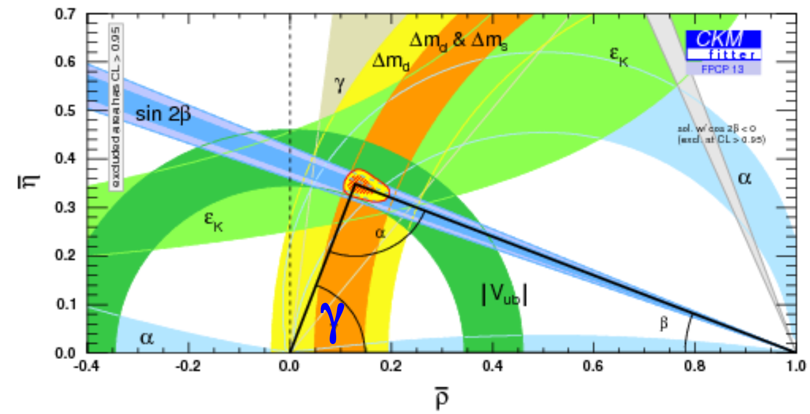
- Particles behave different than anti-particles
- Within the Standard Model (SM) only weak interactions violate CP
- Flavour changing weak interactions characterised by **CKM matrix**

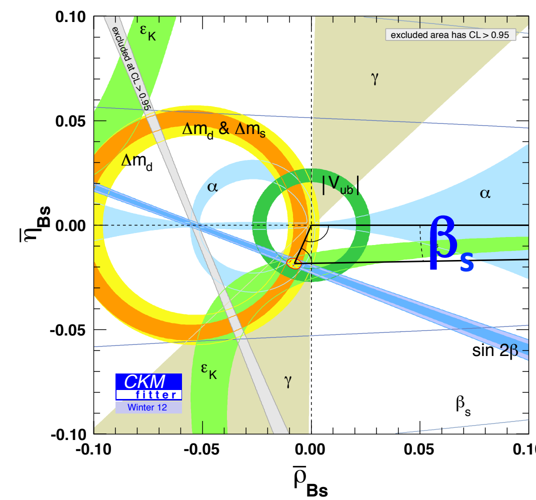
Unitary (3x3)

→ 3 real parameters
1 complex phase

→ Orthogonality relations
6 **unitarity triangles**

- Test SM by over-constraining CKM parameters





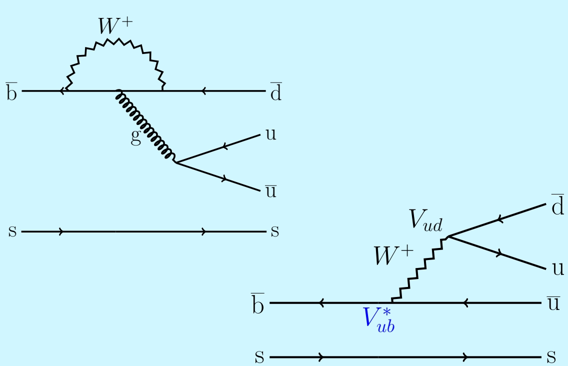
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \approx \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\,e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\,e^{-i\beta} & -|V_{ts}|\,e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Classification of CPV

CPV IN DECAY

$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$

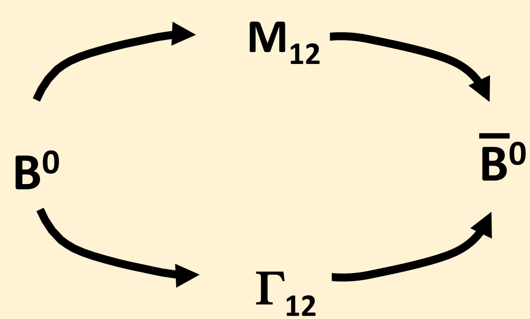
Interference trough multiple decay paths



CPV IN MIXING

$$\text{Prob}(B^0_{(s)} \to \bar{B}^0_{(s)}) \neq \text{Prob}(\bar{B}^0_{(s)} \to B^0_{(s)})$$

Interference trough virtual (loops) and real (intermediate states) contributions

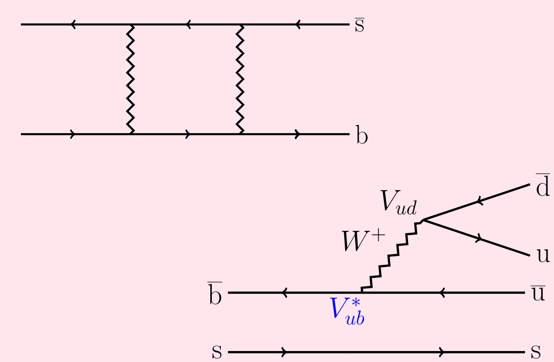


CPV IN DECAY+MIXING

$$\Gamma(B^0(\to \bar{B}^0) \to f) \neq \Gamma(\bar{B}^0(\to B^0) \to \bar{f})$$

Interference in mixing and decay

Time dependent measurements



Overview CPV 2013

76 LHCb papers in 2013, ~25% of these on CP violation with B mesons

Combined γ from $B^+ \to D^0 h^+$
PLB 726 (2013) 151

A_{CP} from $B^\pm \to K \pm \pi^\mp \pi^\pm \gamma$
Conf: EPS HEP 2013

$R/A_{CP/ADS}$ from $B^+ \to D^0 K^+$
PLB 712 (2012), 203–212

r_B^K from $B^\pm \to [\pi^\pm K^\mp \pi^+ \pi^-]_D K^\pm$
PLB 723 (2013) 44–53)

r_B from $B^\pm \to [K_S^0 h^+ h^-]_{D^0} K^\pm$
PLB 718 (2012) 43–55)

C, S from $B_s^0 \to J/\psi K_S^0$
PLB 721 (2013) 24–31

A_{CP} from $B^0 \to K^{*0}\gamma$
NPB 867 (2013), 1–18

A/R_d^{KK} from $B^0 \to [K^+K^-]_{D^0} K^{*0}$
JHEP 1303 (2013) 067

$\phi_s, \Gamma_s, \Delta\Gamma_s$ from $B_s^0 \to J/\psi h^+ h^-$
PRD 87, 112010 (2013)

$A/\delta_{\perp/\parallel}$ from $B^0 \to J/\psi K^*(892)^0$
PRD 88, 052002 (2013)

A_{CP} from $B^\pm \to \pi^\pm h^+ h^-$
arXiv:1310.4740 [hep-ex]

C_{KK}, S_{KK} from $B_s^0 \to K^+K^-$
JHEP 10 (2013) 183

A_{CP} from $B^0 \to K^{*0}\mu^+\mu^-$
PRL 110, 031801 (2013)

A_{CP} from $B^\pm \to K^\pm h^+ h^-$
PRL 111, 101801 (2013)

A_{CP} from $B_{d,s}^0 \to K^+\pi^-$
PRL 110 (2013) 221601

A_{CP} from $B^+ \to K^+\mu^+\mu^-$
PRL 111, 151801 (2013)

A_{CP} from $B^+ \to p\bar{p}h^+$
PRD 88, 052015 (2013)

A_{CP} from $B^+ \to K_S^0 h^+$
PLB 726 (2013) 646–655

CPV phase from $B_s^0 \to \phi\phi$
PRL 110, 241802 (2013)

a_{sl}^s from $B_s^0 \to D_s^+ X \mu^- \nu$
arXiv:1308.1048 [hep-ex]

Outline

(My) highlights 2013

- 1 fb^{-1} LHCb 2011 dataset
- $\sqrt{s}$ = 7 TeV

CPV IN DECAY

- Charmless B decays
  - $B^0_{(s)} \longrightarrow K\pi$
  - $B^\pm \longrightarrow h^+h^-\pi^\pm$
- Charmed B decays
  - $B^\pm \longrightarrow D^0h^\pm$

CPV IN MIXING

- $B_s^0 \longrightarrow D_s^- X\mu^+\upsilon_\mu$

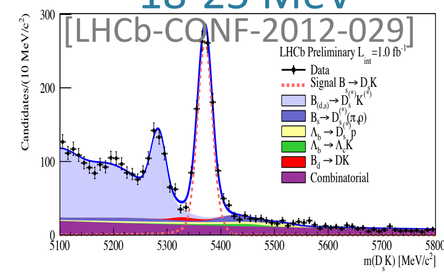
CPV IN DECAY+MIXING

- γ with loops
  - $B_s^0 \longrightarrow K^+K^-$
- ϕ_s
  - $B_s^0 \longrightarrow J/\psi\ \phi$

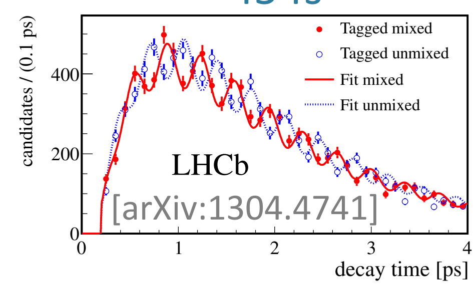
Selection of Beauty events

- Separation between primary and secondary vertex
- PID cuts on tracks
  RICH – pion, kaon identification
- Multivariate analysis, like boosted decision trees
  Typical variables – or their χ^2 – are:
  - Track quality
  - Secondary vertex quality
  - Kinematic variables

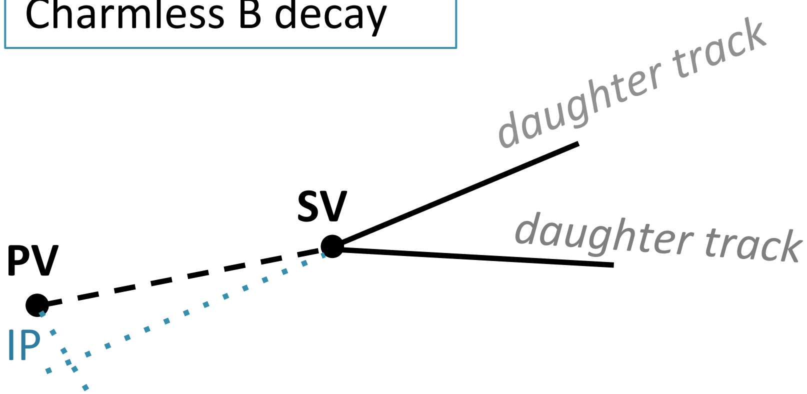
Mass resolution
18-25 MeV



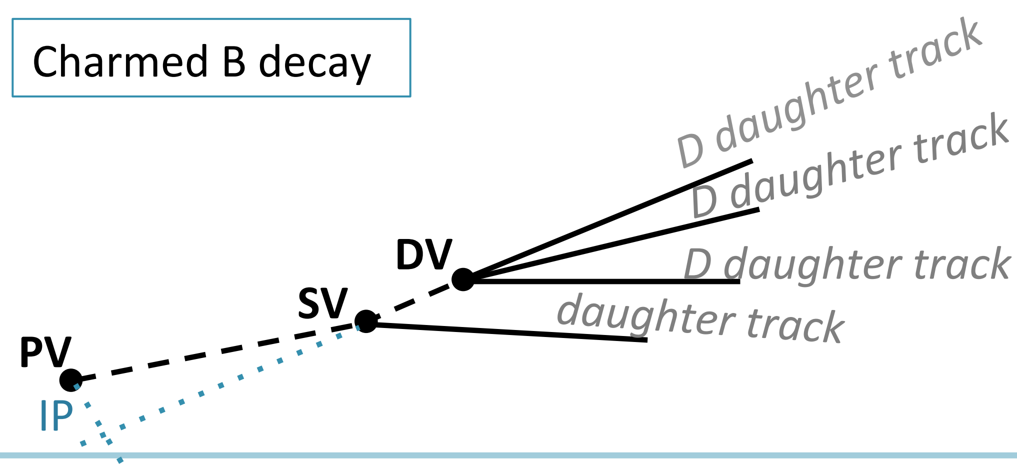
Time resolution
~45 fs



Charmless B decay



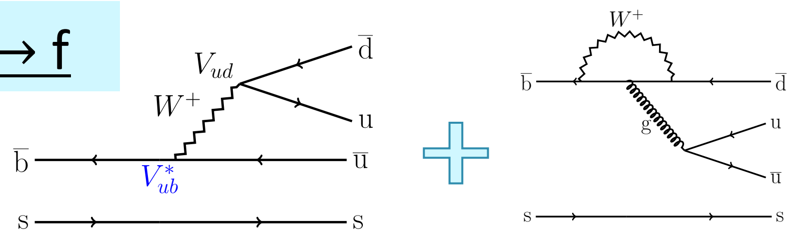
Charmed B decay



CP violation in decay

$$\Gamma(B \to f) \neq \Gamma(\overline{B} \to \overline{f}) \qquad \left| \frac{\overline{A}_{\overline{f}}}{A_f} \right| \neq 1$$

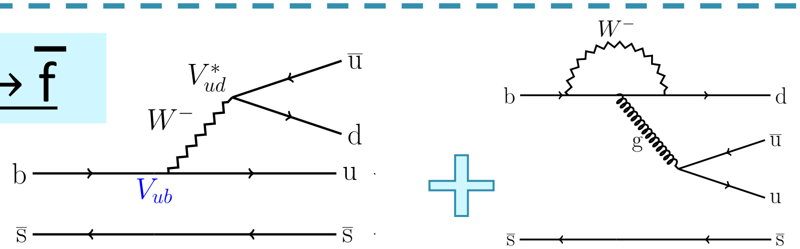
$B \longrightarrow f$



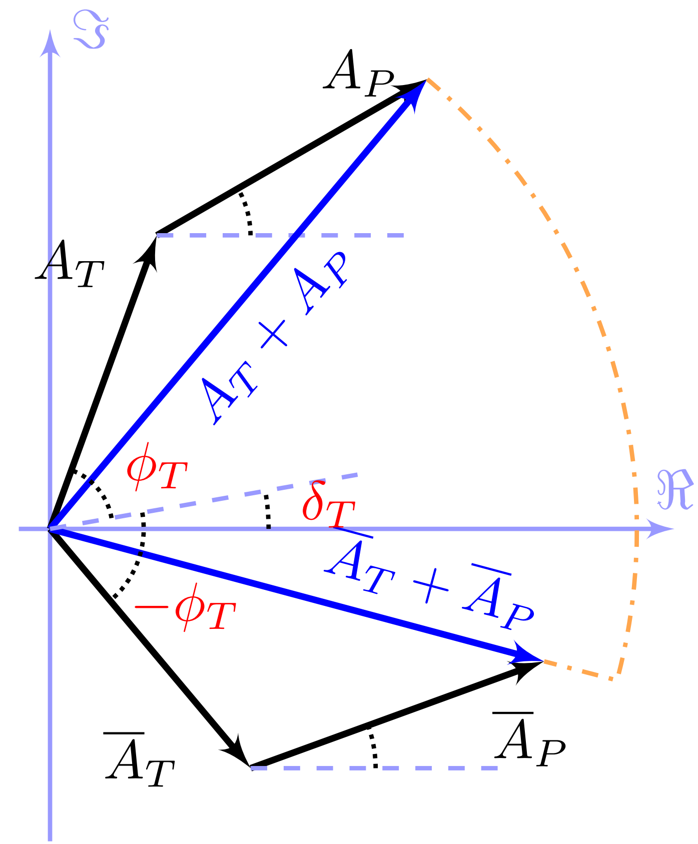
$$A \propto A_T e^{i(\phi_T + \delta_T)} + A_P e^{i(\phi_P + \delta_P)}$$

CP

$\overline{B} \longrightarrow \overline{f}$



$$A \propto A_T e^{i(-\phi_T + \delta_T)} + A_P e^{i(-\phi_P + \delta_P)}$$



Experimental observable:

$$A_{CP} = \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f})}{\Gamma(B \to f) + \Gamma(\overline{B} \to \overline{f})}$$

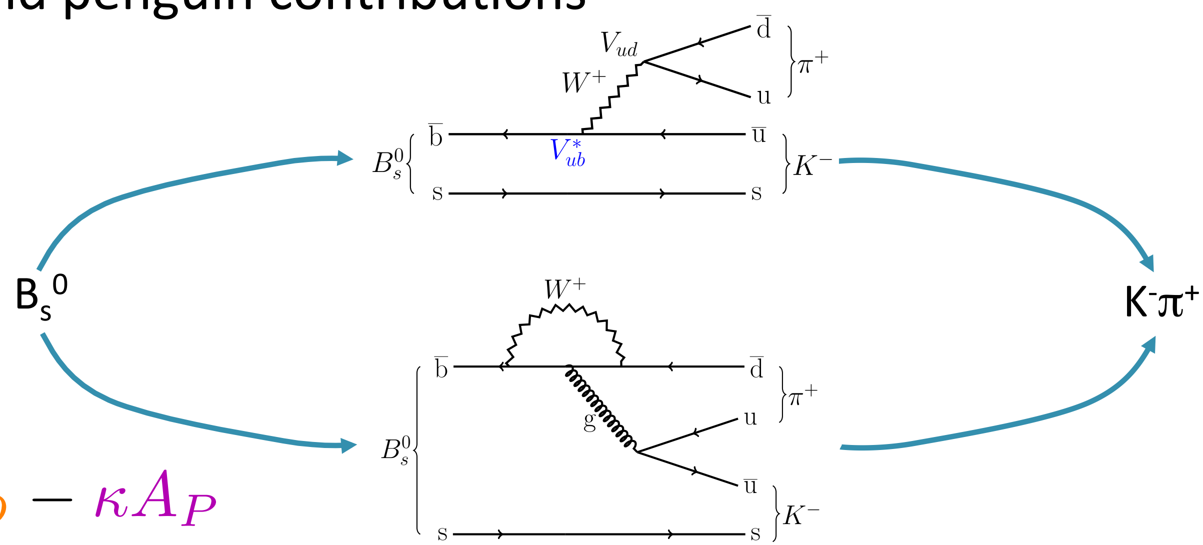
$B^0_{(s)} \longrightarrow K\pi$

[PRL 110 (2013) 221601]

$B_s^0 \longrightarrow K^-\pi^+$

$$A_{CP}(B_s^0 \to K^-\pi^+) = \frac{\Gamma(\bar{B}_s^0 \to K^+\pi^-) - \Gamma(B_s^0 \to K^-\pi^+)}{\Gamma(\bar{B}_s^0 \to K^+\pi^-) + \Gamma(B_s^0 \to K^-\pi^+)}$$

- First measurement of CP violation with B_s decays
- Also measure $A_{CP}(B^0 \longrightarrow K^+\pi^-)$ $\longrightarrow$ test SM
- Interference of tree and penguin contributions
  - Sensitivity to γ



$$A_{raw} = A_{CP} - A_D - \kappa A_P$$

Detector efficiency asymmetry

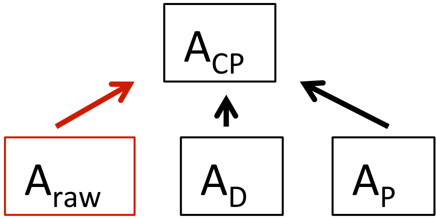
B,$\bar{\text{B}}$ production asymmetry, times dilution factor

$B^0_{(s)} \longrightarrow K\pi$

[PRL 110 (2013) 221601]

Raw event asymmetry

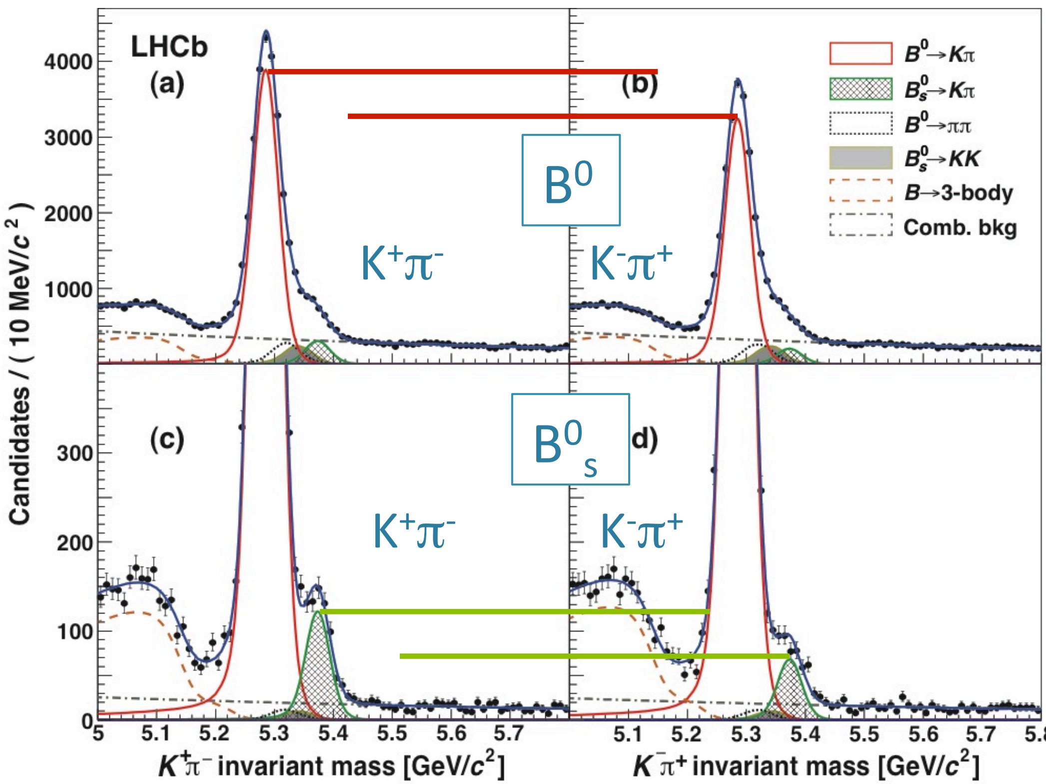
$$A_{raw} = \frac{N(K^+\pi^-) - N(K^-\pi^+)}{N(K^+\pi^-) + N(K^-\pi^+)}$$



- Untagged sample
- Extract yields from mass fit

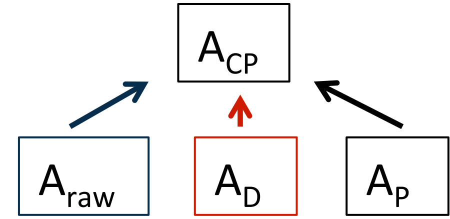
$N(B^0 \longrightarrow K^+\pi^-) = 41420 \pm 300$
$A_{raw}(B^0 \longrightarrow K^+\pi^-) = -0.091 \pm 0.006$

$N(B_s^0 \longrightarrow K^-\pi^+) = 1065 \pm 55$
$A_{raw}(B_s^0 \longrightarrow K^+\pi^-) = 0.28 \pm 0.04$



[PRL 110 (2013) 221601]

Instrumental asymmetry



$$A_D = \frac{\epsilon_D(K^-\pi^+) - \epsilon_D(K^+\pi^-)}{\epsilon_D(K^-\pi^+) + \epsilon_D(K^+\pi^-)}$$

- Measured from data

$$D^{*+} \to D^0(K^-\pi^+)\pi^+ \quad : \quad A^*_{raw}(K\pi) = A^*_D(\pi_s) + A_P(D^*) + A^*_D(K\pi)$$

$$D^{*+} \to D^0(K^-K^+)\pi^+ \quad : \quad A^*_{raw}(KK) = A^*_D(\pi_s) + A_P(D^*) + A_{CP}(KK)$$

$$A^*_{raw}(K\pi) - A^*_{raw}(KK) = A^*_D(K\pi) - A_{CP}(KK)$$

- Reweight for differences in kinematic properties B and D meson

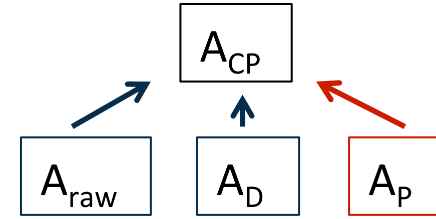
$$A_D(K\pi) = (-1.15 \pm 0.23)\% \qquad (B^0_s)$$

$$A_D(K\pi) = (-1.22 \pm 0.21)\% \qquad (B^0)$$

$B^0_{(s)} \longrightarrow K\pi$

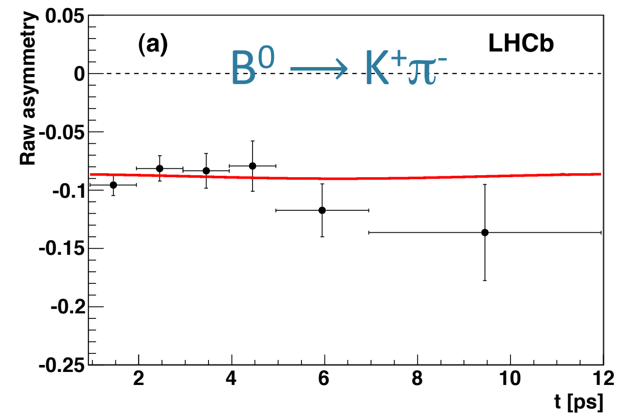
[PRL 110 (2013) 221601]

Production asymmetry

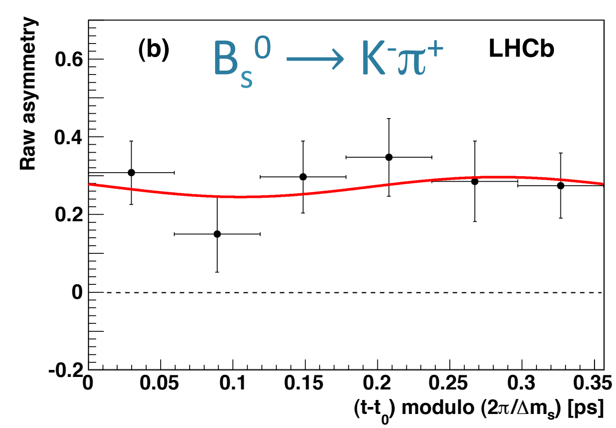


- Measured in data using time dependence
  - Assume negligible mixing

$$\mathcal{A}(t) \approx A_{CP} + A_D + A_P \cos(\Delta m_{s(d)} t)$$



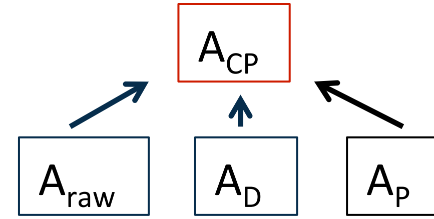
$$A_P = (4 \pm 8)\% \qquad (B_s^0)$$
$$A_P = (0.1 \pm 1.0)\% \qquad (B^0)$$



$B^0_{(s)} \longrightarrow K\pi$

[PRL 110 (2013) 221601]

CP asymmetry



- First observation (6.5σ) of CP violation in B_s system

$$A_{CP}(B^0_s \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat.}) \pm 0.01\,(\text{syst.})$$

- Most precise measurement of

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat.}) \pm 0.003\,(\text{syst.})$$

- Consistent with standard model (Δ = 0)

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B^0_s \to K^-\pi^+)} + \frac{\mathcal{B}(B^0_s \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = -0.02 \pm 0.05 \pm 0.04$$

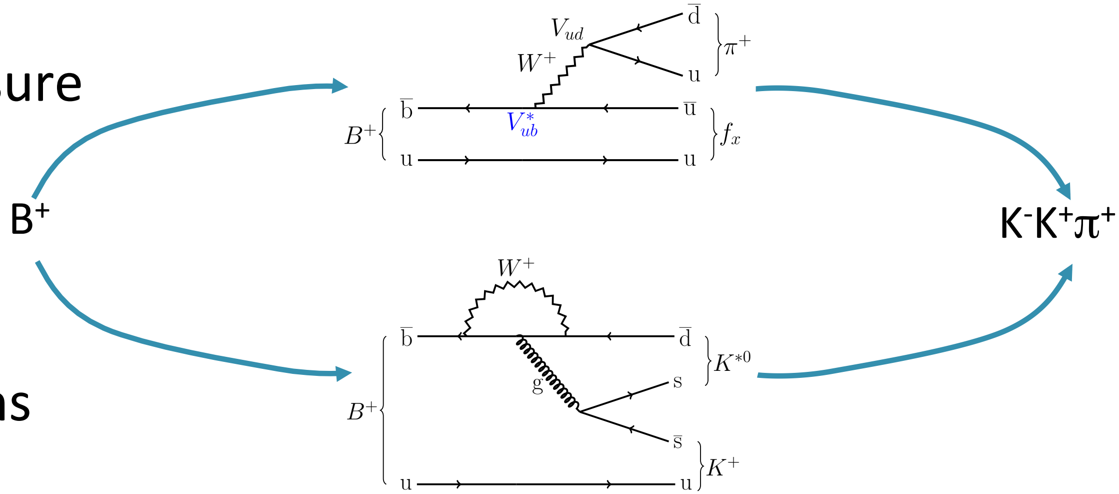
$B^{\pm} \longrightarrow h^{+}h^{-}\pi^{\pm}$

arXiv:1310.4740 [hep-ex]

$$A_{CP}(B^{\pm} \to f^{\pm}) = \frac{\Gamma(B^{-} \to f^{-}) - \Gamma(B^{+} \to f^{+})}{\Gamma(B^{-} \to f^{-}) + \Gamma(B^{+} \to f^{+})} \qquad f^{\pm} = \begin{cases} K^{+}K^{-}\pi^{\pm} \\ \pi^{+}\pi^{-}\pi^{\pm} \end{cases}$$

New mechanism to measure CP asymmetries

Interference of tree and penguin contributions



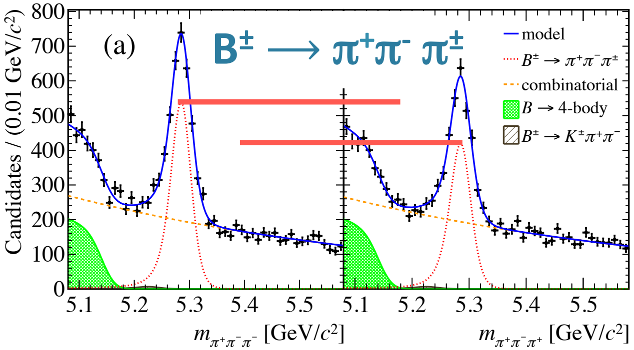
$$A_{raw} = A_{CP} - A_{D} - A_{P}$$

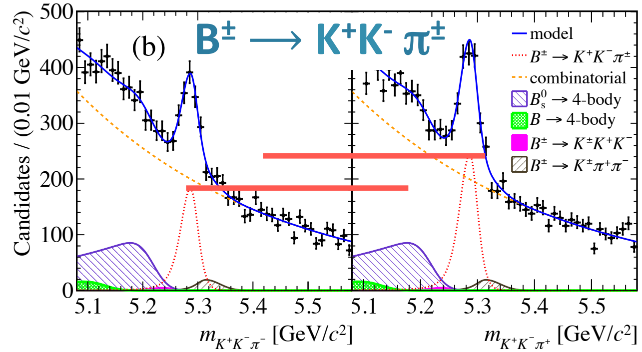
<u>Raw asymmetry</u>
Mass fit

<u>Detector asymmetry</u>
$A_D = -0.010 \pm 0.007$

<u>B^{+},B^{-} production asymmetry</u>
Measured in $B^{\pm} \longrightarrow J/\psi\ (\mu\mu)K^{\pm}$ data
$A_P = -0.004 \pm 0.004$

$B^\pm \longrightarrow h^+h^- \pi^\pm$

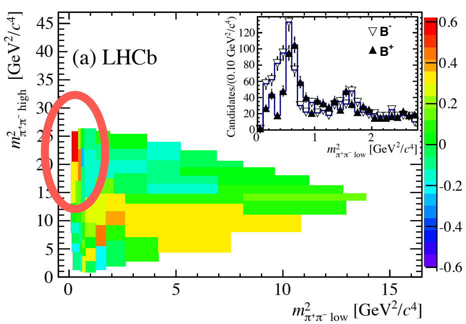


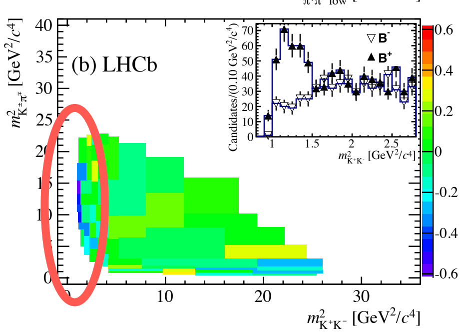


arXiv:1310.4740 [hep-ex]

$A_{CP}(B^\pm \longrightarrow \pi^+\pi^-\pi^\pm) = 0.117 \pm 0.021 \pm 0.009 \pm 0.007$

$A_{CP}(B^\pm \longrightarrow K^+K^-\pi^\pm) = -0.141 \pm 0.040 \pm 0.018 \pm 0.007$





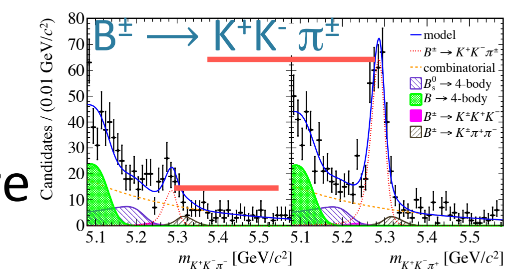
Dalitz plane analysis

Larger asymmetries in localized regions of phase space

- $\pi\pi\pi$: $A_{CP} = 0.584 \pm 0.082 \pm 0.027 \pm 0.007$
- $KK\pi$: $A_{CP} = -0.648 \pm 0.070 \pm 0.013 \pm 0.007$

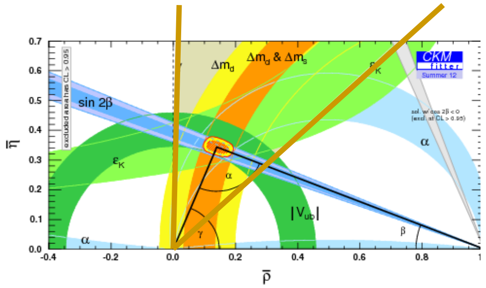
- Large strong phase differences
- Final state $KK \leftrightarrow \pi\pi$ rescattering

new mechanisms to measure CP asymmetries



$B^\pm \longrightarrow D^0h^\pm$

[PLB 726 (2013) 151]



γ from $B^\pm \longrightarrow D^0h^\pm$

- Over-constraining the UT: test SM
- Tree diagrams: not sensitive to NP

Combination of 3 measurements by LHCb

- Frequentist approach
- Maximise combined likelihood of experimental observables

Input measurements

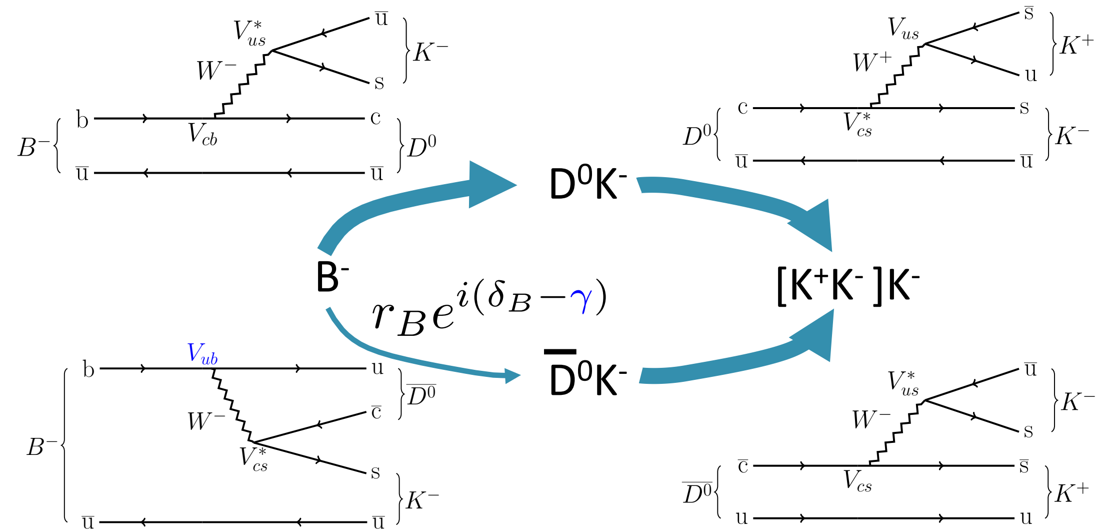
1. $B^\pm \longrightarrow D^0K^+$ and $B^\pm \longrightarrow D^0\pi^+$, with $D^0 \longrightarrow K^+K^-, \pi^+\pi^-, K^\pm\pi^\mp$ [PLB 712 (2012) 203-212]
2. $B^\pm \longrightarrow D^0K^+$ and $B^\pm \longrightarrow D^0\pi^+$, with $D^0 \longrightarrow K^\pm\pi^\mp\pi^\pm\pi^\mp$ [PLB 723 (2013) 44-53]
3. $B^\pm \longrightarrow D^0K^+$, with $D^0 \longrightarrow K_S^0K^+K^-, K_S^0\pi^+\pi^-$ [PLB 718 (2012) 43-55]

$B^\pm \longrightarrow D^0 h^\pm$

[PLB 712 (2012) 203-212]

GLW

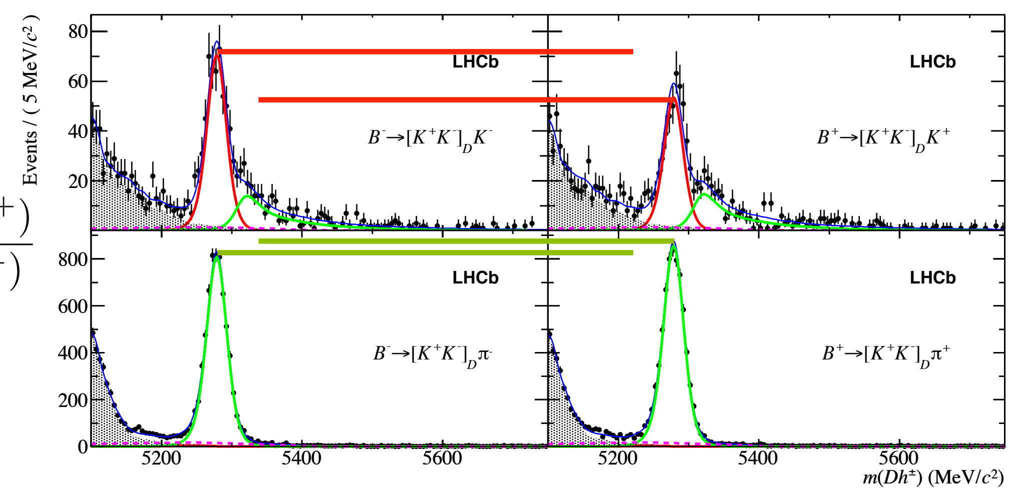
- f is CP eigenstate: K^+K^-, $\pi^+\pi^-$
- Large event rate, small interference



- Observables:

$$A_{CP+} = \frac{\Gamma(B^- \to f_D K^-) - \Gamma(B^+ \to f_D K^+)}{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to f_D K^+)} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma}$$

$$R_{CP+} = \frac{\Gamma(B^- \to f_{D,CP} K^-) + \Gamma(B^+ \to f_{D,CP} K^+)}{\Gamma(B^- \to f_{D,tot} K^-) + \Gamma(B^+ \to f_{D,tot} K^+)} = 1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma$$



- Unknown variables

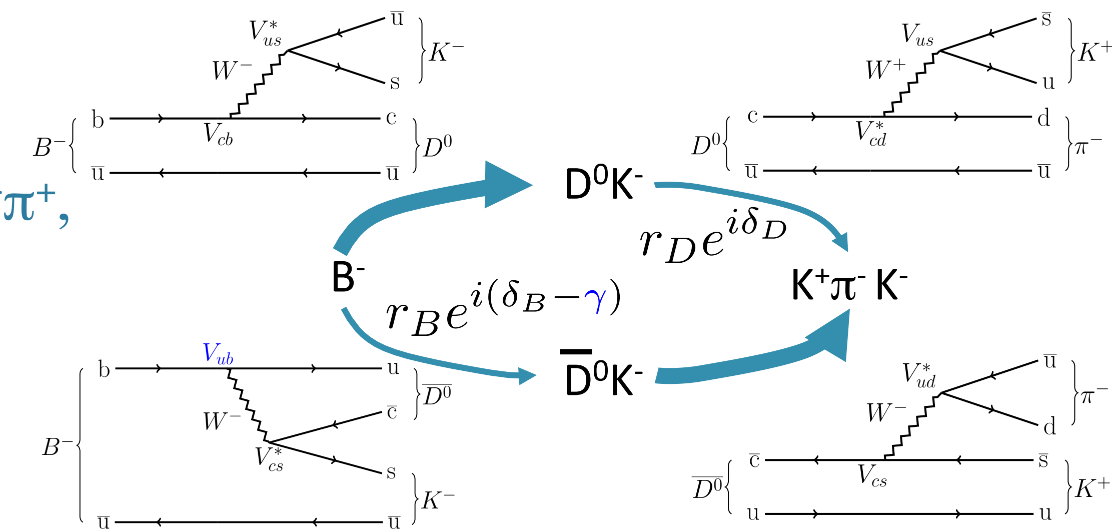
$$r_B, \delta_B, \gamma$$

$B^{\pm} \longrightarrow D^0 h^{\pm}$

[PLB 712 (2012) 203-212]

ADS

- *f* common final state: $K^+\pi^-$, $K^-\pi^+$, $K^{\pm}\pi^{\mp}\pi^+\pi^-$
- Lower event rate, large interference



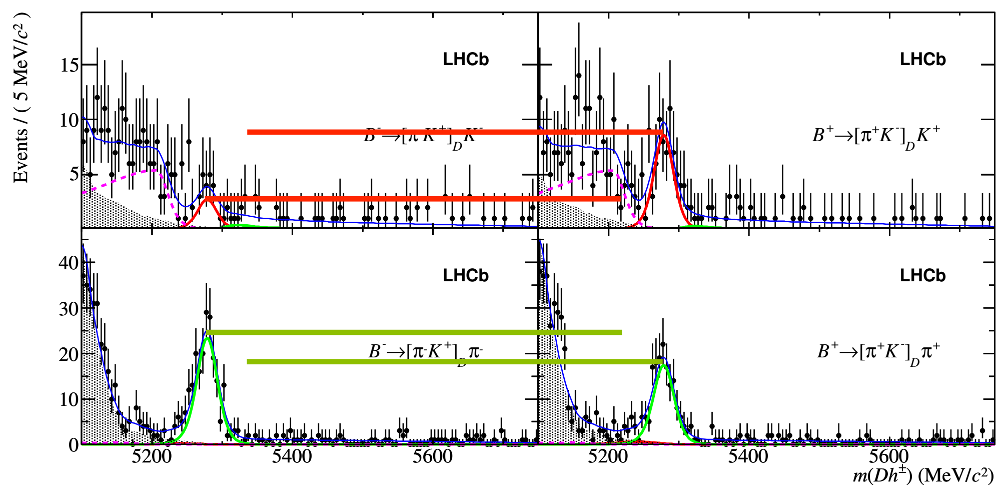
- Observables:

$$A_{ADS} = \frac{\Gamma(B^- \to f_D K^-) - \Gamma(B^+ \to \bar{f}_D K^+)}{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to \bar{f}_D K^+)}$$

$$= \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}$$

$$R_{ADS} = \frac{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to \bar{f}_D K^+)}{\Gamma(B^- \to \bar{f}_D K^-) + \Gamma(B^+ \to f_D K^+)}$$

$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

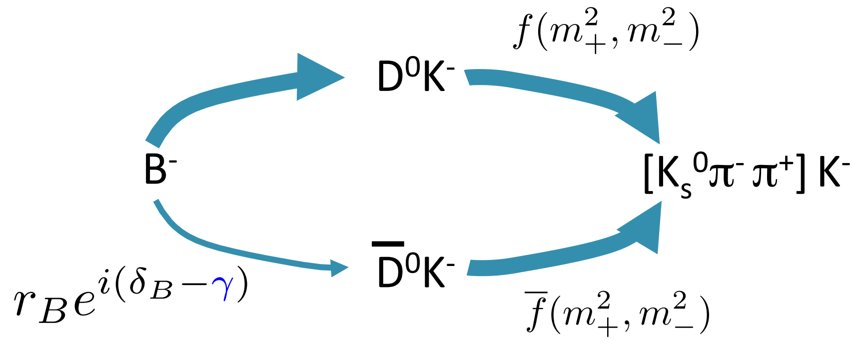


- Unknown variables

$$r_B, r_D, \delta_B, \delta_D, \gamma$$

[PLB 718 (2012) 43-55]

GGSZ



- *f* common final state: $K_s^0\pi^+\pi^-$, $K_s^0K^-K^+$
- Measure decay amplitude in bins Dalitz plane

$$A_B(m_+^2, m_-^2) = f + r_B e^{i(\delta_B - \gamma)}\overline{f}$$

$$\Gamma_{\pm i}(B^-) = h_{B^-}\left[K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_{-i}, K_{+i}}(x_- c_{\pm i} + y_- s_{\pm i})\right]$$

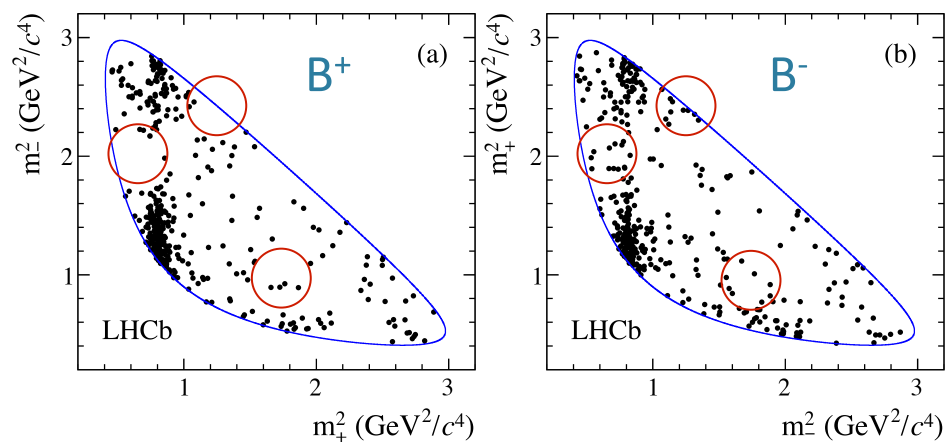
$$\Gamma_{\pm i}(B^+) = h_{B^+}\left[K_{\mp i} + r_B^2 K_{\pm i} + 2\sqrt{K_{-i}, K_{+i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$

i: dalitz-bin

- $D^0 \longrightarrow K_s^0h^-h^+$ decay described by K, c, s (CLEO)
- Observables:

$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$

$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$



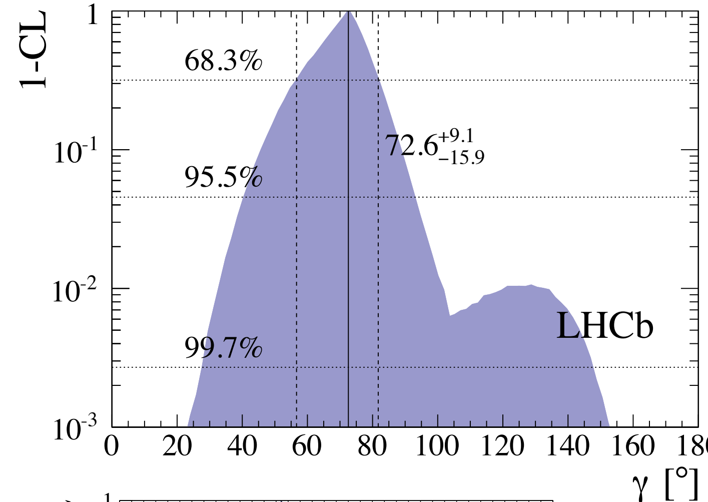
$B^{\pm} \longrightarrow D^0 h^{\pm}$

[PLB 726 (2013) 151]

Combination

- Combining $B^{\pm} \longrightarrow D^0K^{\pm}$ and $B^{\pm} \longrightarrow D^0\pi^{\pm}$
- GLW/ADS/GGSZ, $1fb^{-1}$
- Includes information from covariance matrices
- Includes D^0-mixing
- Limited by statistics

$$\gamma = 72.6^{\circ}$$
$$\gamma \in [55.4, 82.3]^{\circ} \quad \text{at } 68\% \text{ CL}$$

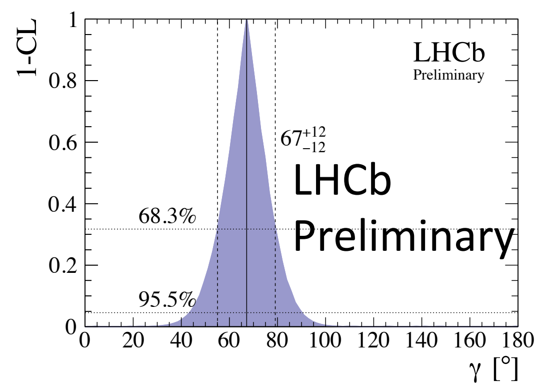


Update

[LHCb-CONF-2013-006]

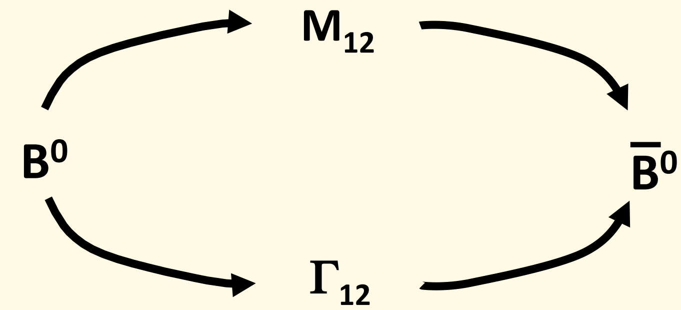
- Include $3fb^{-1}$ data for GGSZ analysis
- Only use $B^{\pm} \longrightarrow D^0K^{\pm}$

$$\gamma = 67.2^{\circ}$$
$$\gamma \in [55.1, 79.1]^{\circ} \quad \text{at } 68\% \text{ CL}$$



CP violation in mixing

Off shell states: weak box diagram



On shell states: $B^0 \longrightarrow f \longrightarrow \bar{B}^0$

$$\mathrm{Prob}(B^0_{(s)} \to \bar{B}^0_{(s)}) \neq \mathrm{Prob}(\bar{B}^0_{(s)} \to B^0_{(s)})$$

Relative phase between on and off shell states

$$\phi_{12} = \arg\left(\frac{-M_{12}}{\Gamma_{12}}\right)$$

$$\frac{q}{p} = -\sqrt{\frac{M^*_{12} - \frac{i}{2}\Gamma^*_{12}}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

$$B_H = pB^0 - q\overline{B}^0$$
$$B_L = pB^0 + q\overline{B}^0$$

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

Experimental: *flavour specific* final states

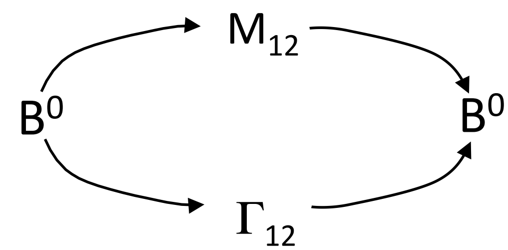
$B_s^0 \longrightarrow D_s^- \mu^+ \nu$

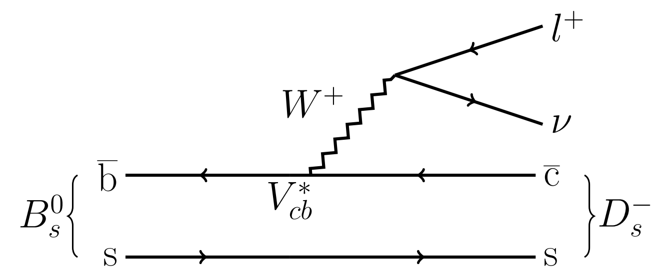
[arXiv:1308.1048 [hep-ex]]

- Sensitive probe to new physics: SM $\phi_{12} \approx 0.2°$
- Flavour specific CP violating asymmetry

$$a_{sl} = 1 - \left|\frac{q}{p}\right|^2 = \frac{\Delta\Gamma}{\Delta M} \tan\phi_{12}$$

$$\phi_{12} = \arg\left(\frac{-M_{12}}{\Gamma_{12}}\right)$$





- Untagged final state asymmetry

$$A_{\text{meas}} \equiv \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]}$$

$$= \frac{a_{\text{sl}}^s}{2} + \left[a_{\text{P}} - \frac{a_{\text{sl}}^s}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s\, t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s\, t}{2})\epsilon(t)dt}$$

$A_P \approx 1\%$

Integral ratio ≈ 0.2%, due to fast oscillations. Evaluated on MC.

$$A_{meas} \approx \frac{a_{sl}}{2}$$

$B_s^0 \longrightarrow D_s^- \mu^+ \nu$

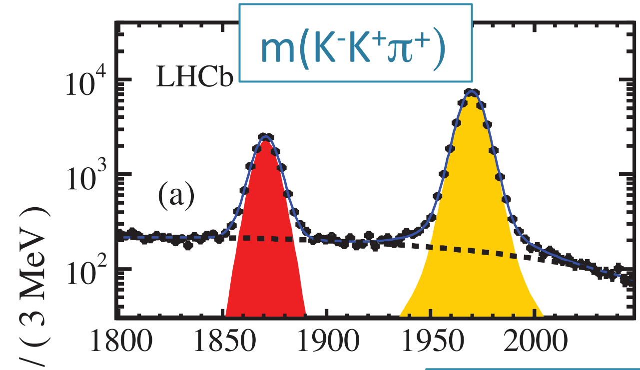
$$A_{meas} = A_\mu^c - A_{track} - A_{bkg}$$

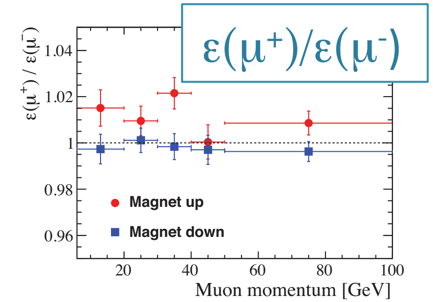
[arXiv:1308.1048 [hep-ex]]

- Measured yield asymmetry, corrected for muon PID and trigger efficiency
- Charge asymmetry due to tracking
- Charge asymmetry due to backgrounds

$$A_\mu^c = \frac{N(D_s^+\mu^-)/\epsilon(\mu^-) - N(D_s^-\mu^+)/\epsilon(\mu^+)}{N(D_s^+\mu^-)/\epsilon(\mu^-) + N(D_s^-\mu^+)/\epsilon(\mu^+)}$$

- **N** measured by fitting KKπ invariant mass distribution
- ε measured using sample of $J/\psi \longrightarrow \mu\mu$ decays





$$A_{track} = A_{track}^{\pi\mu} + A_{track}^{KK}$$

- Pion and muon reconstruction very similar
- Small contribution from kaons

$$A_{bkg}$$

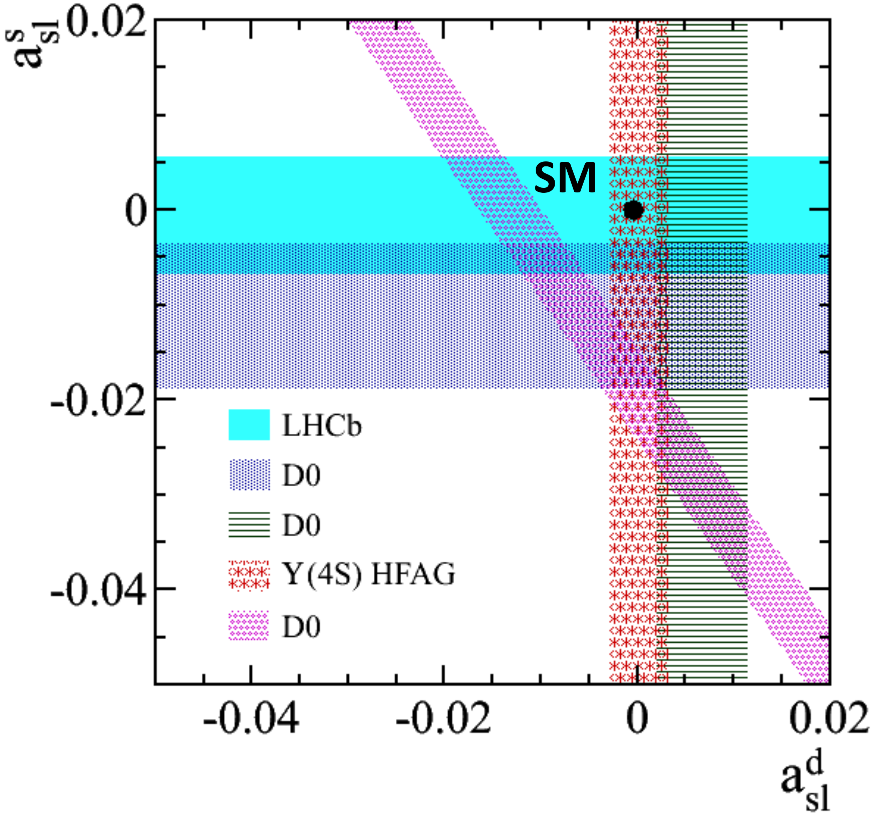
- 3 sources of background: prompt charm, misIDed background, $B \longrightarrow DD_s$
- Background for $D_s^-\mu^+$ slightly different than for $D_s^+\mu^-$

[arXiv:1308.1048 [hep-ex]]

Result

$$A_{meas} = (-0.03 \pm 0.25 \pm 0.18)\%$$

$$a_{\rm sl}^{s} = (-0.06 \pm 0.50 \pm 0.36)\%$$



CPV in interference

Interference between mixing and decay

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

There can be CPV in interference between mixing and decay, without there being CPV in mixing and/or decay!

CP violation if $\Im\lambda_f \neq 0$

$\bar{A}_f \neq 0 \longrightarrow \overline{B}^0 \to f$ i.e. no flavour specific final state

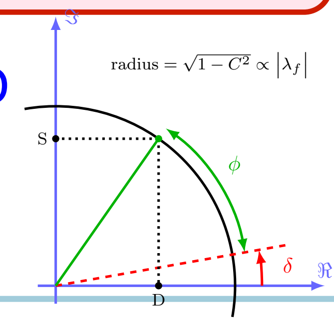
Decay equations - B_s^0 decay to *CP eigenstate*

$$\Gamma(B_s^0 \to f)(t) \propto |A_f|^2(1+|\lambda_f|^2)\left[\cosh(\Delta\Gamma_s t) + D_f\sinh(\Delta\Gamma_s t) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right]$$

$$\Gamma(\overline{B}_s^0 \to f)(t) \propto \left|\frac{q}{p}\right| |A_f|^2(1+|\lambda_f|^2)\left[\cosh(\Delta\Gamma_s t) + D_f\sinh(\Delta\Gamma_s t) - C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)\right]$$

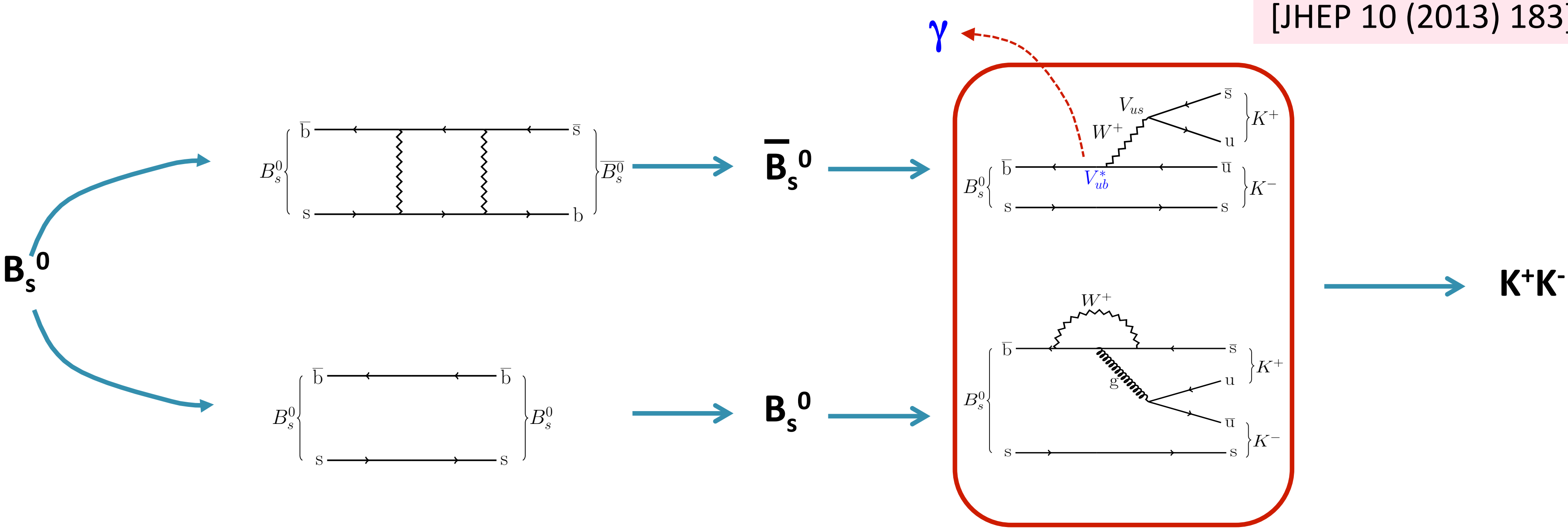
$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2} \qquad D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2}$$

- Physics information is contained in CP observables C, S, D
- Time dependent CP violation



$B_s^0 \longrightarrow K^+K^-$

[JHEP 10 (2013) 183]



- Sensitive to γ
  - Diagrams with loops sensitive to new physics

- Time dependent CP asymmetry

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

Decay time distribution

[JHEP 10 (2013) 183]

$$\Gamma(B_s^0 \to f)(t) \propto |A_f|^2(1+|\lambda_f|^2)\left[\cosh(\Delta\Gamma_s t) + D_f \sinh(\Delta\Gamma_s t) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right]$$

$$\Gamma(\overline{B}_s^0 \to f)(t) \propto \left|\frac{q}{p}\right| |A_f|^2(1+|\lambda_f|^2)\left[\cosh(\Delta\Gamma_s t) + D_f \sinh(\Delta\Gamma_s t) - C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t)\right]$$

$$f(t,\xi) = K\left\{\left[(1-A_{\mathrm{P}})\Omega_\xi^B + (1+A_{\mathrm{P}})\bar{\Omega}_\xi^B\right] I_+(t) + \left[(1-A_{\mathrm{P}})\Omega_\xi^B - (1+A_{\mathrm{P}})\bar{\Omega}_\xi^B\right] I_-(t)\right\}$$

$$I_+(t) = \left\{e^{-\Gamma_s t}\left[\cosh(\Delta\Gamma_s t/2) + D_f \sinh(\Delta\Gamma_s t/2)\right]\right\} \otimes R(t)\varepsilon_{\mathrm{acc}}(t)$$

$$I_-(t) = \left\{e^{-\Gamma_s t}\left[C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right]\right\} \otimes R(t)\varepsilon_{\mathrm{acc}}(t)$$

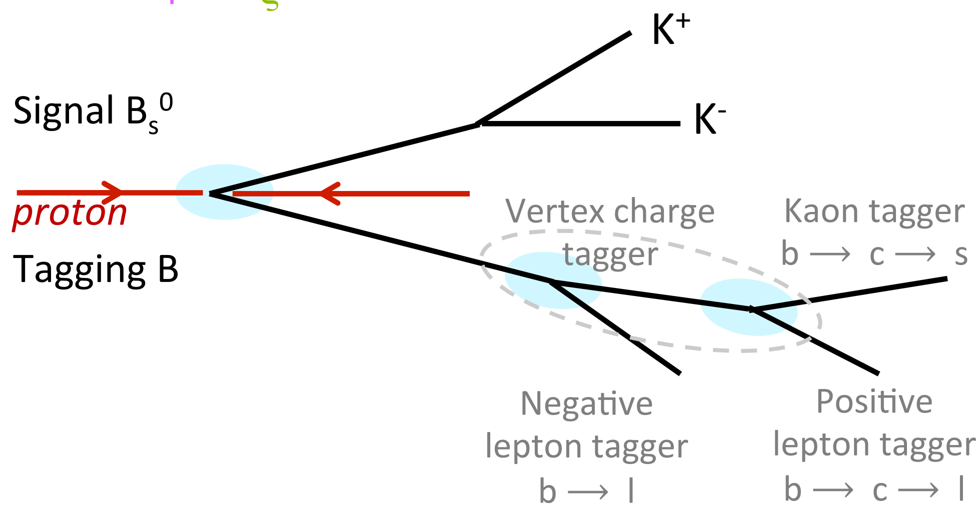
- A_P: Production asymmetry
- Ω_ξ^B: Probability to tag a B as a B
- R(t): Resolution model
- $\varepsilon_{acc}(t)$: Acceptance function

$B_s^0 \longrightarrow K^+K^-$

[JHEP 10 (2013) 183]

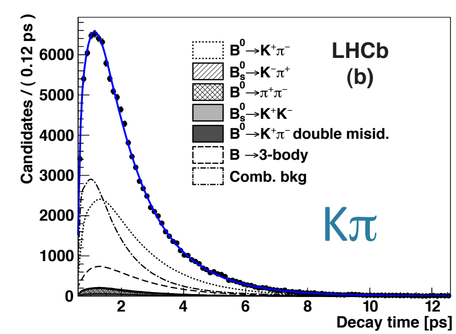
Production asymmetry and flavour tagging: A_P, Ω_ξ^B

- Analyse 'other' B in event to determine initial flavour signal B
- Mis-tag probability (η) is determined by a neural network
- Calibrated using flavour specific $B \longrightarrow K\pi$ decays



Decay time resolution: R(t)

- Resolution estimated from MC $B_s \longrightarrow KK$ events
- Quantify data/MC differences using prompt charmonium and bottomonium data



Acceptance: $\varepsilon_{acc}(t)$

- Dependence reconstruction efficiency on decay time
- Studied on simulated events

$B_s^0 \longrightarrow K^+K^-$

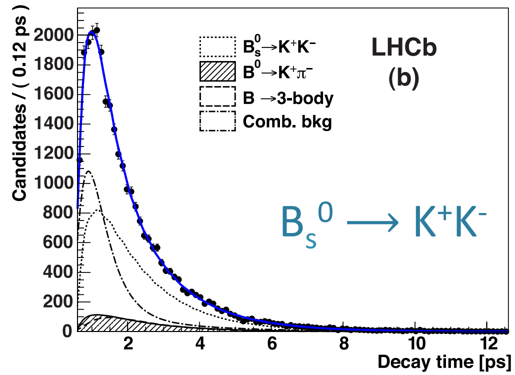
[JHEP 10 (2013) 183]

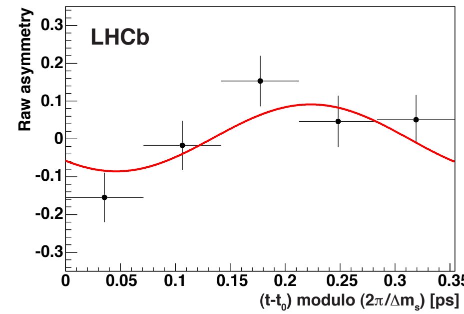
Results

$B_s^0 \longrightarrow K^+K^-$

$$C_{KK} = 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst})$$
$$S_{KK} = 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst})$$

First measurement of C_{KK} and S_{KK}

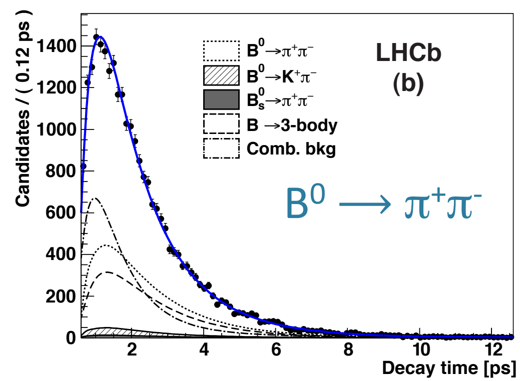


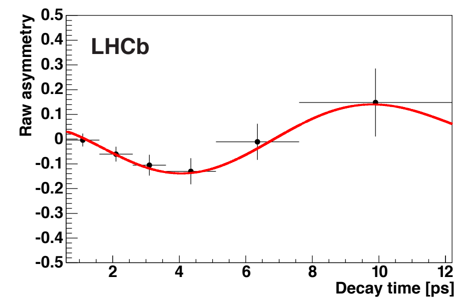


$B^0 \longrightarrow \pi^+\pi^-$

$$C_{\pi\pi} = -0.38 \pm 0.15\,(\text{stat}) \pm 0.02\,(\text{syst})$$
$$S_{\pi\pi} = -0.71 \pm 0.13\,(\text{stat}) \pm 0.02\,(\text{syst})$$

$C_{\pi\pi}$ and $S_{\pi\pi}$ in good agreement with existing measurements

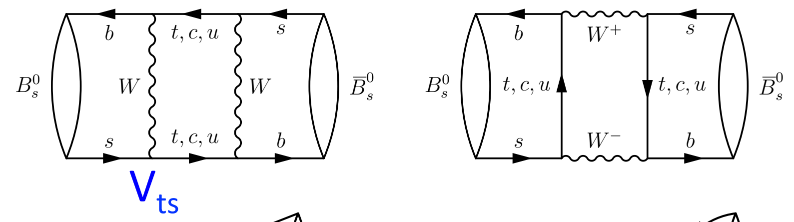


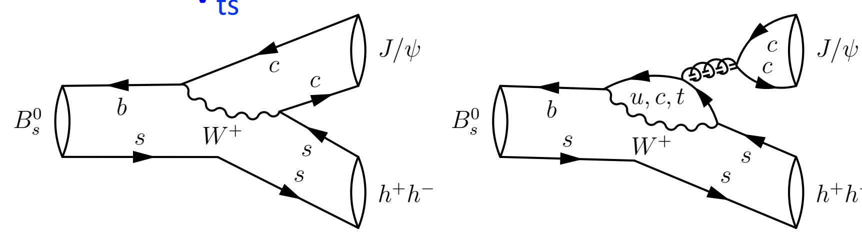


Motivation

[PRD 87, 112010 (2013)]

- Current knowledge on β_s
  $2\beta_s = 0.0364 \pm 0.0016$ rad
- New Physics can contribute to the box diagram
  $\longrightarrow$ enhancement of phase
- SM prediction
  $\phi_s = -2\beta_s$



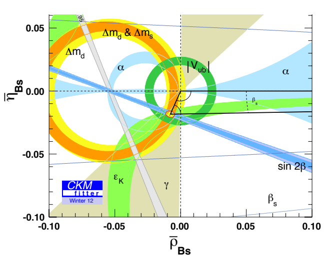


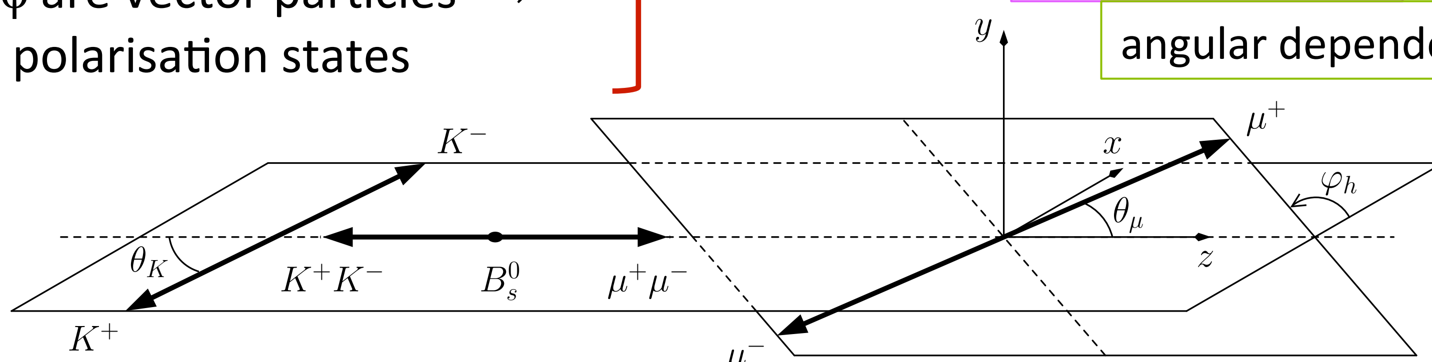
- Dominated by resonant decay mode $J/\psi\phi$, where $\phi \longrightarrow KK$
- J/ψ and ϕ are vector particles $\longrightarrow$ multiple polarisation states

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

time dependence

angular dependence

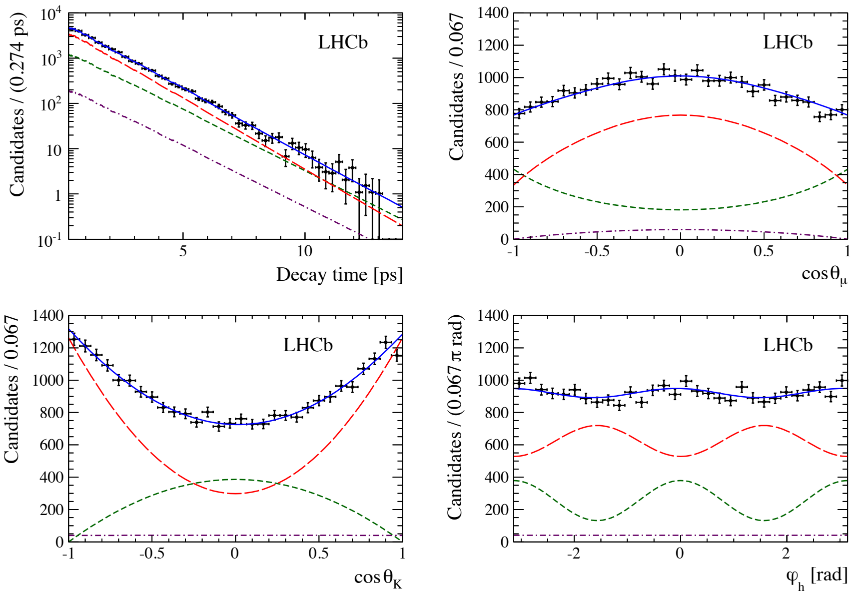




$B_s^0 \longrightarrow J/\psi\, K^+K^-$

[PRD 87, 112010 (2013)]

Results



$B_s^0 \longrightarrow J/\psi\, K^+K^-$ *only*

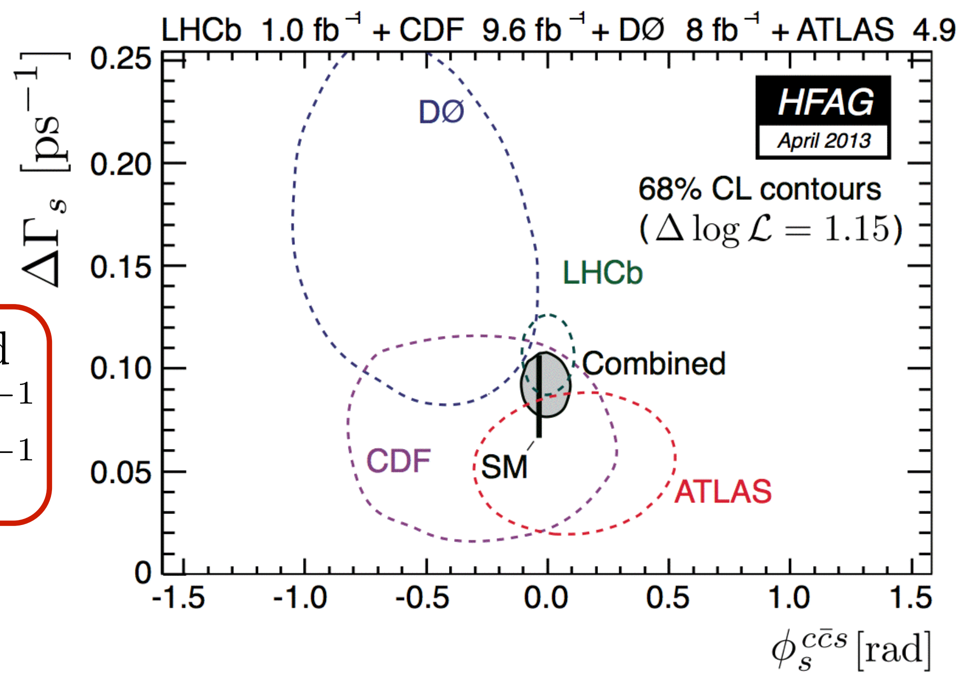
$$
\begin{array}{lcccccl}
\phi_s & = & 0.07 & \pm 0.09 & \pm 0.01 & \text{rad} \\
\Gamma_s & = & 0.663 & \pm 0.005 & \pm 0.006 & \text{ps}^{-1} \\
\Delta\Gamma_s & = & 0.100 & \pm 0.016 & \pm 0.003 & \text{ps}^{-1}
\end{array}
$$

World's most precise single measurement

Combination with $B_s^0 \longrightarrow J/\psi\, \pi^+\pi^-$

$$
\begin{array}{lcccccl}
\phi_s & = & 0.01 & \pm 0.07 & \pm 0.01 & \text{rad} \\
\Gamma_s & = & 0.661 & \pm 0.004 & \pm 0.006 & \text{ps}^{-1} \\
\Delta\Gamma_s & = & 0.106 & \pm 0.011 & \pm 0.007 & \text{ps}^{-1}
\end{array}
$$

Measurement agrees with SM prediction

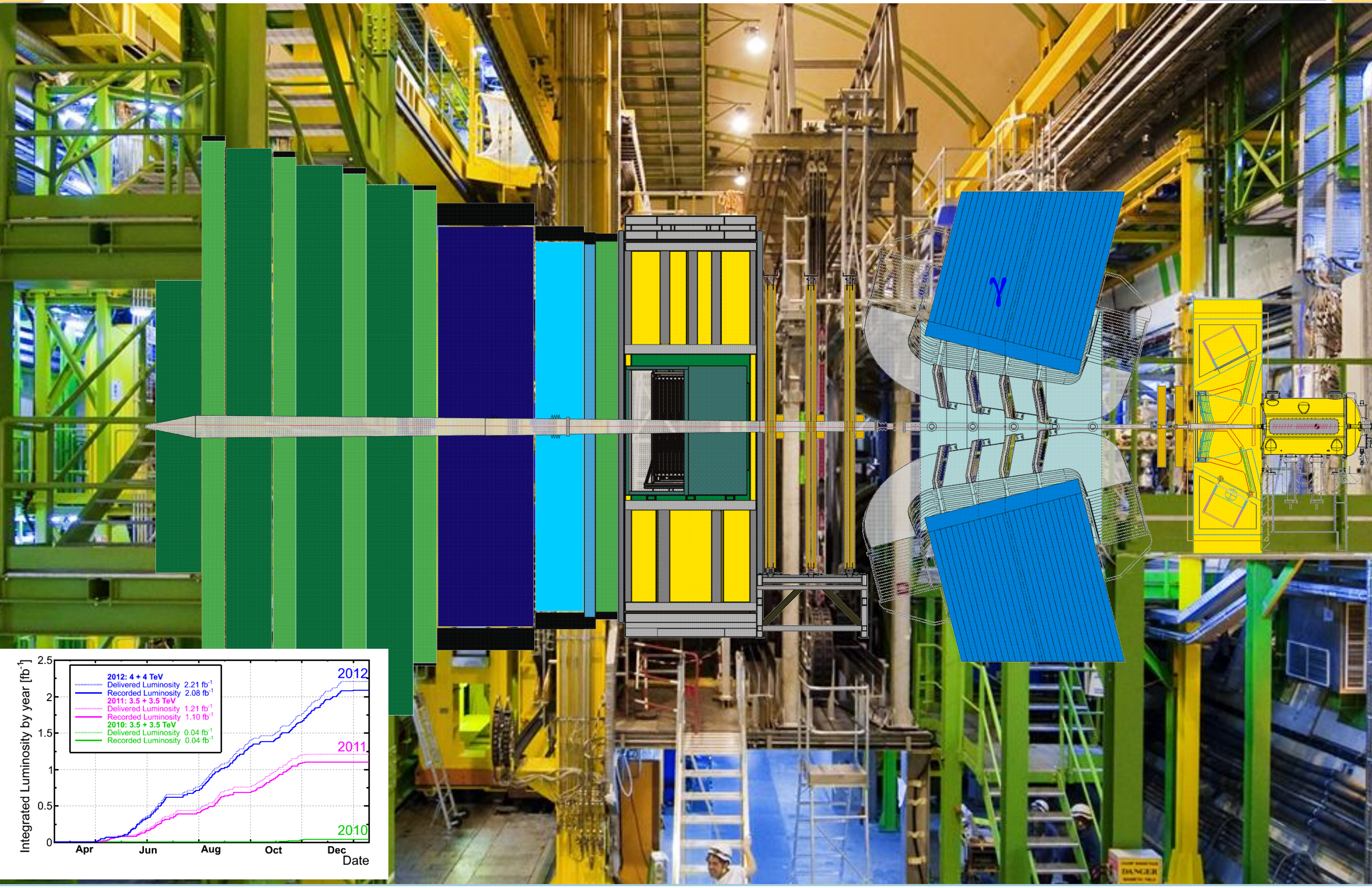


Conclusion

- LHCb has produced many first and world's best CP asymmetry measurements, in many different B decay modes
- Most of the LHCb results are limited by their statistical uncertainty
- All results presented here are based on $1fb^{-1}$ dataset collected in 2011. The $2fb^{-1}$ dataset collected in 2012 is currently being studied.
- More data to be collected in Run2 (start mid 2015) and after the upgrade.
- More/Updated results expected soon. Stay tuned!

Thank you!

LHCb


γ
Integrated Luminosity by year [fb^{-1}]
2012: 4 + 4 TeV
Delivered Luminosity 2.21 fb^{-1}
Recorded Luminosity 2.08 fb^{-1}
2011: 3.5 + 3.5 TeV
Delivered Luminosity 1.21 fb^{-1}
Recorded Luminosity 1.10 fb^{-1}
2010: 3.5 + 3.5 TeV
Delivered Luminosity 0.04 fb^{-1}
Recorded Luminosity 0.04 fb^{-1}
2012
2011
2010
0
0.5
1
1.5
2
2.5
Apr
Jun
Aug
Oct
Dec
Date

CP violation

Violation of CP symmetry

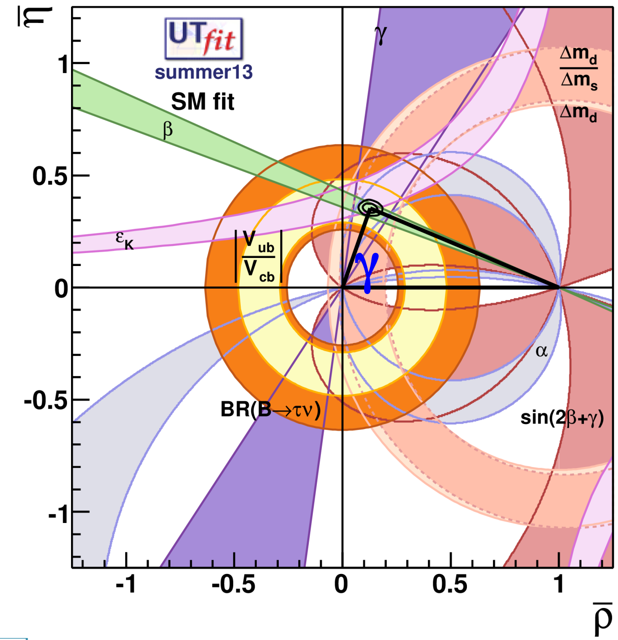
- Particles behave different than anti-particles
- Within the Standard Model (SM) only weak interactions violate CP
- Flavour changing weak interactions characterised by **CKM matrix**

Unitary (3x3)

→ 3 real parameters
1 complex phase

→ Orthogonality relations
6 **unitarity triangles**

UT fit



- Test SM by over-constraining CKM parameters

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \approx \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\,e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\,e^{-i\beta} & -|V_{ts}|\,e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$