Status of $\mathcal{CP}$ Violation in the Flavour Sector

(B-mesons)

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Outline

CP violation in the Standard Model

CKM elements from semileptonic decays: $|V_{ub}|$

CP violation in mixing: a_{sl}

CP violation in interference: $\sin(2\beta)$, φ_s

Measuring γ

CP violation in charmless decays

Looking forward

$\mathcal{CP}$ violation in the SM

Standard Model describes interaction of all fundamental particles

- Weak interactions in the SM: flavour eigenstates
- Particles evolve in time: mass eigenstates
- mass ⟶ flavour: *Cabibbo-Kobayashi-Maskawa* (CKM) matrix[1]

$$[\mathit{flavour}] = V_{CKM}\,[\mathit{mass}]$$

$$V_{CKM} = \begin{bmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-\iota\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4-\frac{1}{2}A^2\lambda^4 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-\iota\bar{\eta}) & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho-\iota\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{bmatrix} + \mathcal{O}(\lambda^5)$$

  - 4 parameters: λ, A, ρ, η

[1] Similar to the PMNS matrix in the lepton sector

$\mathcal{CP}$ violation in the SM

Standard Model describes interaction of all fundamental particles

- Weak interactions in the SM: flavour eigenstates
- Particles evolve in time: mass eigenstates
- mass $\longrightarrow$ flavour: *Cabibbo-Kobayashi-Maskawa* (CKM) matrix[1]

$$[flavour] = V_{CKM}\,[mass]$$

$$V_{CKM} = \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\,e^{-\iota\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\,e^{-\iota\beta} & -|V_{ts}|\,e^{\iota\beta_s} & |V_{tb}| \end{bmatrix} + \mathcal{O}(\lambda^5)$$

- 4 parameters: λ, A, ρ, η
- Complex elements $\longrightarrow$ $\mathcal{CP}$ violating phases: γ, β, β_s
- 6 unitarity relations $\Longrightarrow$ 6 CKM triangles

$$\sum_k V_{ik}V_{jk}^* = \delta_{ij}$$

[1] Similar to the PMNS matrix in the lepton sector

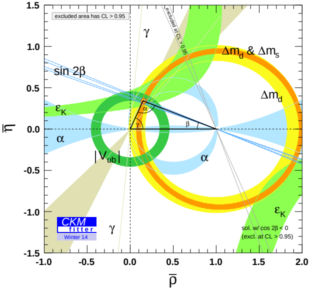
The CKM triangle & CP violating phases

b–d triangle

- Constrain apex on the "unitarity clock":

$$R_b \propto \left| \frac{V_{ub}}{V_{cb}} \right|$$

- Obtained from semileptonic *tree level* B decays



- Check for internal consistency
- Constrain angles: α, β, γ (φ_2, φ_1, φ_3)
- Time integrated / dependent CP asymmetries, mixing, etc
- Look for NP

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

The CKM triangle & CP violating phases

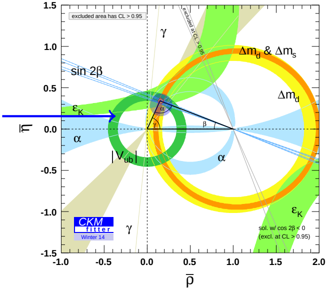
b–d triangle

$|\mathbf{V_{ub}}|$

Decay with $b \longrightarrow ul\nu$ transition

$\mathbf{\Lambda^0_b \longrightarrow p\mu\nu, \Lambda_c\mu\nu}$ **(LHCb)**

LHCb-PAPER-2015-013 (Apr '15)



$\boldsymbol{\alpha}$ Decays with V_{ub} + V_{td} i.e. $\gamma+\beta$

$\mathbf{B^0 \longrightarrow \eta\pi^0}$ **(Belle)**

arxiv:1502.07550 (Apr '15)

- Implications on α determination

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

The CKM triangle & CP violating phases

b–d triangle

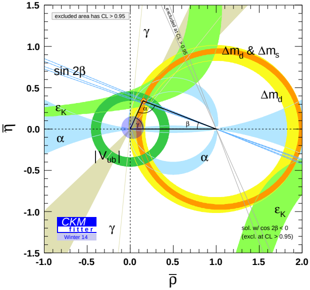
γ interference with V_{ub}, least precisely measured

Time averaged
decay rate ratios, asymmetries:
ADS, GLW, GGSZ, ...

Time dependent
CP observables in the B_s system

Tree decays
establishes SM baseline

Loop decays
sensitive to NP



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

$B^\pm \longrightarrow Dh^\pm$ (LHCb)
LHCb-PAPER-2015-014 (Apr '15)
JHEP 10 (2014) 097 ...

$B_s \longrightarrow D_sK$ (LHCb)
JHEP 11 (2014) 060

γ combination (LHCb)
LHCB-CONF-2014-004

$B^0 \longrightarrow D^0K^*$ (Belle)
arxiv:1502.07550

$B^0 \longrightarrow D^0K^*$ (LHCb)
PRD 90 (2014) 112002

The CKM triangle & CP violating phases

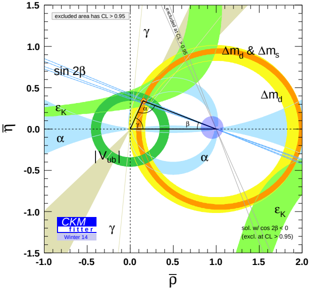
b–d triangle

sin(2β)
time-dependent CP observables in the B^0 system

$B^0 \longrightarrow D^{(*)}_{CP} h^0$ (BaBar & Belle)
arxiv:1505.04147
(May ’15)

$B^0 \longrightarrow J/\psi K_S$ (LHCb)
LHCB-PAPER-2015-004
(March ’15)

$B_s \longrightarrow J/\psi K_S$ (LHCb)
LHCB-PAPER-2015-005



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

Very sensitive to NP

a_{sl}/A_{CP}
flavour specific semileptonic asymmetry in the B^0 and B_s system

$B_s \longrightarrow D_s \mu\nu X$ (LHCb)
PLB 728 (2014) 607–615

$B^0 \longrightarrow D^{(*)}\mu\nu X$ (LHCb)
PRL 114 (2015) 041601

B^0–$\overline{B^0} \longrightarrow l^{\pm}l^{\pm}X$ (BaBar)
PRL 114 081801 (2015)

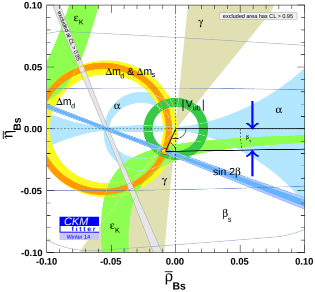
$B^0 \longrightarrow D^* X l\nu$ (BaBar)
PRL 111 101802 (2013)

The CKM triangle & CP violating phases

b–s triangle

φ_s time-dependent CP observables in the B_s system

CP violation in mixing time dependent CP observables, semileptonic asymmetries



$B_s \longrightarrow J/\psi KK$ **(LHCb)** PRL 114 (2015) 041801

$B_s \longrightarrow J/\psi\pi\pi$ **(LHCb)** PLB 736 (2014) 186

$B_s \longrightarrow J/\psi\varphi$ **(ATLAS)** PRD 90 (2014) 052007

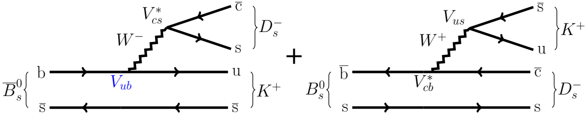
$B_s \longrightarrow J/\psi\varphi$ **(CMS)** CMS-PAS-BPH-13-012

$B_s \longrightarrow D_s D_s$ **(LHCb)** PRL 113 (2014) 211801

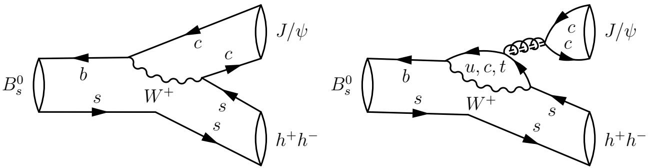
$$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0$$

Typical diagrams

SM: tree diagrams interfering



Loops could hide NP



CKM elements from semileptonic decays: $|V_{ub}|$

$|V_{ub}|$: status and LHCb strategy

- Constrains apex of the triangle
  - Measured from decays with $b \longrightarrow ul\nu$ transitions
- Current status: inconsistent

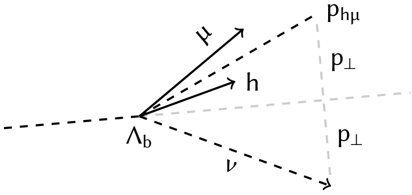
	$\lvert V_{ub}\rvert$
exclusive ($B \longrightarrow \pi l\nu$)	$(3.28\pm0.29) \times 10^{-3}$
inclusive (all $b \longrightarrow ul\nu$)	$(4.41\pm0.15) \times 10^{-3}$

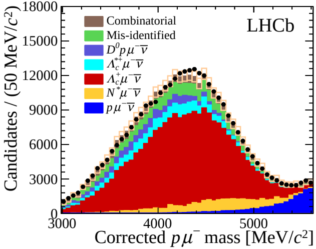
- Use baryonic decays at LHCb

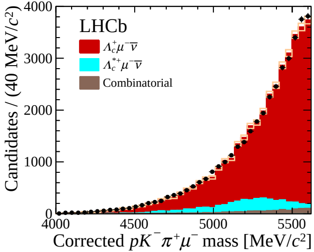
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu})} R_{FF}$$

Form factor ratio from Lattice QCD

$|V_{ub}|$: $\Lambda_b \rightarrow p\mu\nu$ (LHCb)







- Missing particle: ν
- Observable: *corrected mass*

$$m_{corr} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$$

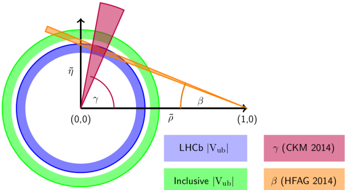
- Lattice QCD input
  - most precise for high q^2, $m_{inv}^2(\mu+\nu)$
  - Λ_b mass & flight direction $\Rightarrow$ 2 solutions
  - both solutions > 15 GeV/c²

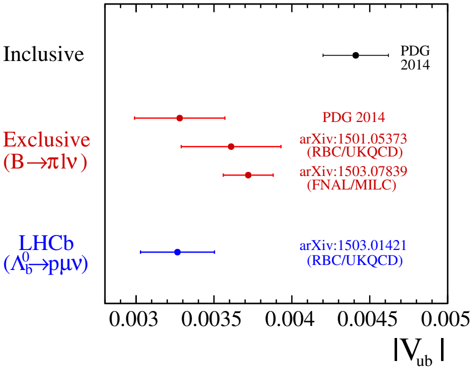
$|V_{ub}|$: $\Lambda_b \longrightarrow p\mu\nu$ results (LHCb)

LHCb-PAPER-2015-013

Using $|V_{cb}|$ from world avg:

$|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$





$C\!P$ violation in mixing: a_{sl}

Flavour mixing in neutral mesons

$\text{Prob}(B^0 \longrightarrow \overline{B^0}) \neq \text{Prob}(\overline{B^0} \longrightarrow B^0)$

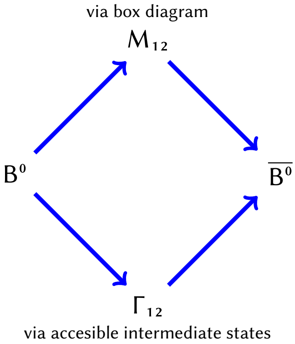
- Neutral mesons mix

$$|B_{H/L}\rangle = p|B^0\rangle \mp q|\overline{B^0}\rangle \quad \mathcal{H} = M + \imath\Gamma$$

- Asymmetry in flavour specific decays
  - $B^0 \longrightarrow D\mu X$, $B_s \longrightarrow D_s\mu X$, ...

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

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

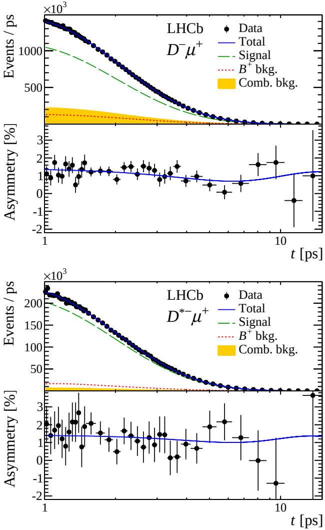


a_{sl}^d: $B^0 \longrightarrow D^{(*)}\mu\nu X$ (LHCb)

$$A_{meas} \equiv \frac{\Gamma[\overline{B^0} \to f] - \Gamma[B^0 \to \bar{f}]}{\Gamma[\overline{B^0} \to f] + \Gamma[B^0 \to \bar{f}]}$$

$$N(t) \propto e^{-\Gamma t}\left[1 + \xi A_D + \xi \frac{a_{sl}}{2} - \xi\left(A_P - \frac{a_{sl}}{2}\right)\cos(\Delta m t)\right]$$

- a_{sl}^d: time dependent
  PRL 114 (2015) 041601
- Need to correct for detection asymmetry, A_D
- $\xi = \pm 1$, depending on B flavour
- $a_{sl}^d = (-0.02 \pm 0.19 \pm 0.30)\%$
- SM[2]: $(-0.041 \pm 0.006)\%$

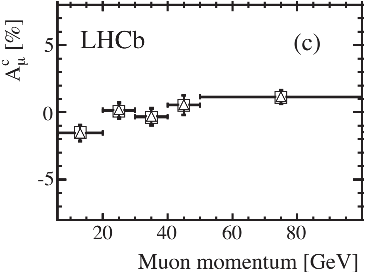


[2] arxiv:1205.1444

a_{sl}^s: $B_s \longrightarrow D_s \mu \nu X$ (LHCb)

$$\begin{aligned} A_{meas} \equiv & \frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} \\ = & \frac{a_{sl}}{2} + \left[A_P - \frac{a_{sl}}{2}\right] \frac{\int e^{-\Gamma_s t} \cos(\Delta m_s t)\epsilon(t)\,\mathrm{d}t}{\int e^{-\Gamma_s t} \cosh(\frac{\Delta\Gamma_s t}{2})\epsilon(t)\,\mathrm{d}t} \Bigg\} \Delta m_s \ll \Delta m_d \\ = & A_\mu^c - A_{track} - A_{bkg} \end{aligned}$$

- a_{sl}^s: time averaged
  PLB 728 (2014) 607–615
- A_μ^c = corrected μ asymmetry
- A_{track} = track reconstruction asymmetry
- A_{bkg} = asymmetry introduced by backgrounds



- a_{sl}^s = (-0.06±0.50±0.36)%
- SM[3]: (0.0019±0.0003)%

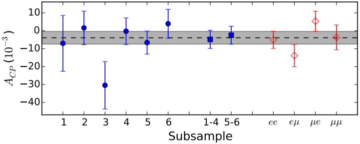
[3] arxiv:1205.1444

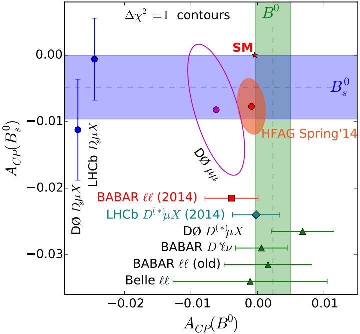
A_{CP} measurements at BaBar

- Same-sign dileptonic A_{CP}
  PRL 114 081801 (2015)
- Produces entangled B^0–$\overline{B^0}$ pairs
  - $l^\pm l^\pm$ in the final state $\Longrightarrow$ one of the B's oscillated
  - $l \in \{e, \mu\}$, assume e–μ universality

$$A_{CP} = \frac{P_{ll}^{++} - P_{ll}^{--}}{P_{ll}^{++} + P_{ll}^{--}} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

- A_{CP} = (-0.39±0.35±0.19)%
- SM: (-0.041±0.006)%



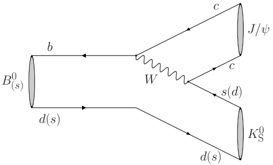


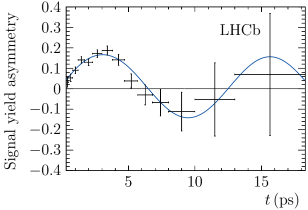
CP violation in interference: $\sin(2\beta)$, φ_s

sin(2β): $B^0 \longrightarrow J/\psi K_S$ (LHCb)

$$\begin{tikzcd} B^0 \arrow[r] \arrow[d] & f_{CP} \\ \overline{B^0} \arrow[ur] & \end{tikzcd}$$

Decay to
CP eigenstates





$$\mathcal{A}(t) = \frac{\Gamma[\overline{B^0} \to f_{CP}] - \Gamma[B^0 \to f_{CP}]}{\Gamma[\overline{B^0} \to f_{CP}] + \Gamma[B^0 \to f_{CP}]} = \frac{S\sin(\Delta m t) - C\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A^{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

- Assuming negligible CP violation in mixing
- $\Delta\Gamma \sim 0$ for B^0:
  $A(t) = S\sin(\Delta m t) - C\cos(\Delta m t)$
- In the SM: $S \sim \sin(2\beta)$, $C \approx 0$

$B^0 \longrightarrow J/\psi K_S$

S = 0.731±0.035±0.020

C = -0.038±0.032±0.005

LHCB-PAPER-2015-004

sin(2β): $B^0 \longrightarrow D^{(*)}_{CP} h^0$ (BaBar & Belle)

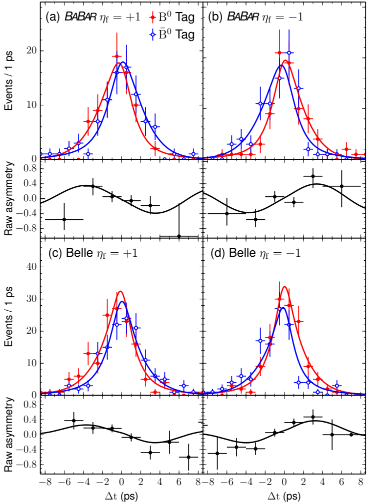
arxiv:1505.04147 (May '15)

Combined BaBar and Belle data

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{\mathrm{BaBar}} + \sum_j \ln \mathcal{P}_j^{\mathrm{Belle}}$$

- More than 1/ab data!
- Different treatment of time resolution, otherwise very similar selection and time model

sin(2β) = 0.66±0.10±0.06

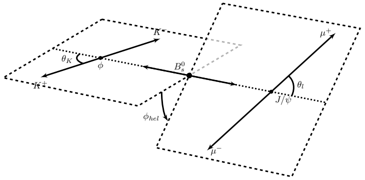


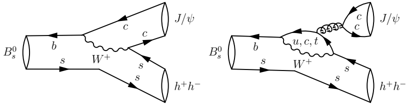
φ_s: $B_s \longrightarrow J/\psi KK$, $J/\psi\pi\pi$ (LHCb)

$$\begin{tikzcd} B^0 \arrow[r] \arrow[d] & f_{CP} \\ \overline{B^0} \arrow[ur] & \end{tikzcd}$$

Decays to CP eigenstates

SM: weak phase $\varphi_s = -2\beta_s$





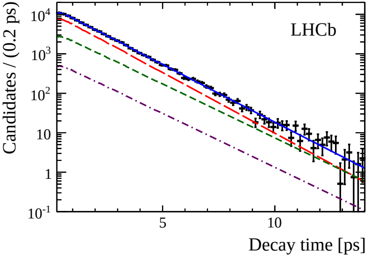
Intermediate vector boson resonances

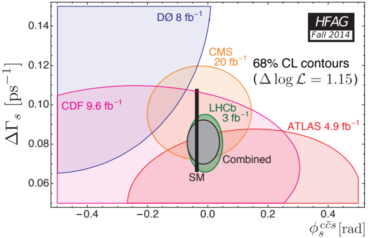
Model angular dependence to disentangle CP eigenstates

$$\frac{d\Gamma[B_s^0 \to J/\psi KK]}{dt\, d\Omega} = \sum_k h_k(t) f_k(\Omega)$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right]$$

φ_s: $B_s \longrightarrow J/\psi KK$, $J/\psi\pi\pi$ – results





	LHCb PRL 114 (2015) 041801	ATLAS PRD 90 (2014) 052007	CMS CMS-PAS-BPH-13-012
φ_s (rad)	-0.058±0.049±0.006	0.12±0.25±0.05	-0.03±0.11±0.03
$\Delta\Gamma_s$ (ps^{-1})	0.0805±0.0091±0.0032	0.053±0.021±0.010	0.096±0.014±0.007
Γ_s (ps^{-1})	0.6603±0.0027±0.0015	0.677±0.007±0.004	—

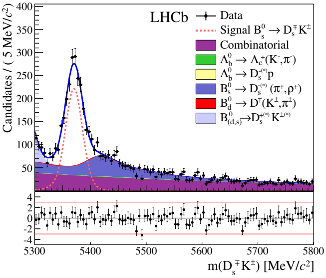
$B_s \longrightarrow J/\psi KK$, $J/\psi\pi\pi$ combined: φ_s = -0.010±0.039 (LHCb)

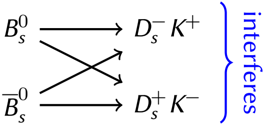
Combined φ_s = -0.015±0.035 (HFAG)

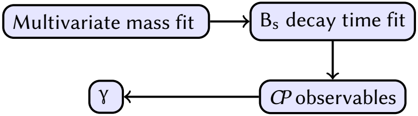
Measuring γ

γ: $B_s \longrightarrow D_s K$ (LHCb)

time dependent





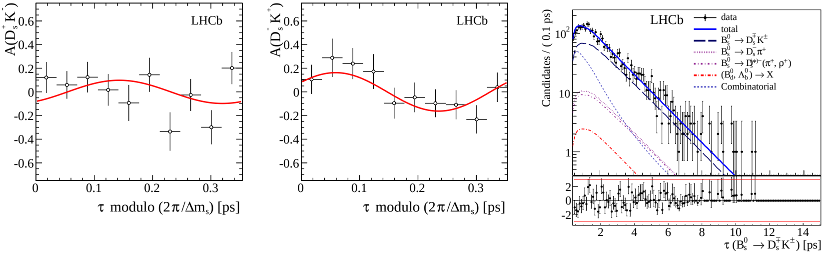


$$\Gamma_{B^0_s \to f}(t) \simeq e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A^{\Delta\Gamma}_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right]$$

For $\overline{B}^0_s \to \overline{f}$, you get corresponding CP conjugated observables.

γ: $B_s \longrightarrow D_s K$ – result

B_s decay-time asymmetry and decay-time distributions



Params	*s*Fit	*c*Fit
C_f	0.52 ± 0.25 ± 0.04	0.53 ± 0.25 ± 0.04
$A_f^{\Delta\Gamma}$	0.29 ± 0.42 ± 0.17	0.37 ± 0.42 ± 0.20
$A_{\bar{f}}^{\Delta\Gamma}$	0.14 ± 0.41 ± 0.18	0.20 ± 0.41 ± 0.20
S_f	-0.90 ± 0.31 ± 0.06	-1.09 ± 0.33 ± 0.08
$S_{\bar{f}}$	-0.36 ± 0.34 ± 0.06	-0.36 ± 0.34 ± 0.08

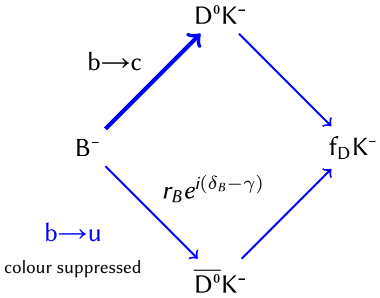
JHEP 11 (2014) 060

Physics parameters like Γ, $\Delta\Gamma_s$, Δm_s, etc are fixed to measured values[4].

[4] PRD 86 (2012) 010001, PRD 87 (2013) 112010

γ: $B^\pm \longrightarrow Dh^\pm$

time integrated



r_B small for $B^- \longrightarrow D^0\pi^-$

Observables:

- Asymmetries (A)
- Yield ratios (R)

Multitude of D^0 decay modes:

- GGSZ: $K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$
- GLW: K^+K^-, $\pi^+\pi^-$ (CP-even)
- ADS: π^-K^+
- quasi-GLW: hh + neutral
  - $\pi^0\pi^+\pi^-$, $\pi^0K^+K^-$, $\pi^+\pi^-\pi^+\pi^-$
- GLS (ADS-like): πK + neutral
  - $\pi^-K^+\pi^+\pi^-$, $\pi^-K^+\pi^0$, $\pi^-K^+K^0_S$

$$R_{GLW} = 1 + r_B^2 + 2(2F_+^{h'h'\pi^0} - 1) r_B \cos\delta_B \cos\gamma$$

$$A_{GLW} = 2(2F_+^{h'h'\pi^0} - 1) r_B \sin\delta_B \sin\gamma \;/\; R_{GLW}$$

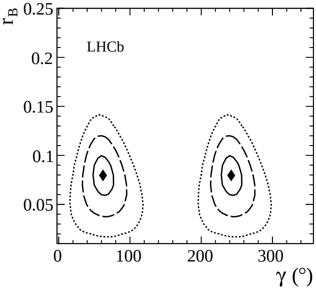
$$R_{ADS} = r_B^2 + r_D^2 + 2\kappa_D^{K\pi\pi^0} r_B r_D \cos(\delta_B + \delta_D) \cos\gamma$$

$$A_{ADS} = 2\underset{\uparrow}{\kappa_D^{K\pi\pi^0}} r_B r_D \sin(\delta_B + \delta_D) \sin\gamma \;/\; R_{ADS}$$

Dilution factors

GLW/ADS/GGSZ (LHCb)

well established methods



JHEP 10 (2014) 097

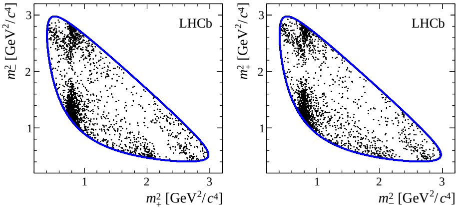
$r_B = 0.080^{+0.019}_{-0.021}$

$\gamma = (62^{+15}_{-14})^\circ$

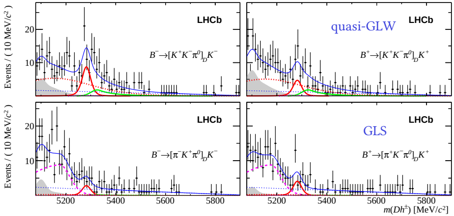
$\delta_B = (134^{+14}_{-15})^\circ$

LHCb-PAPER-2015-014

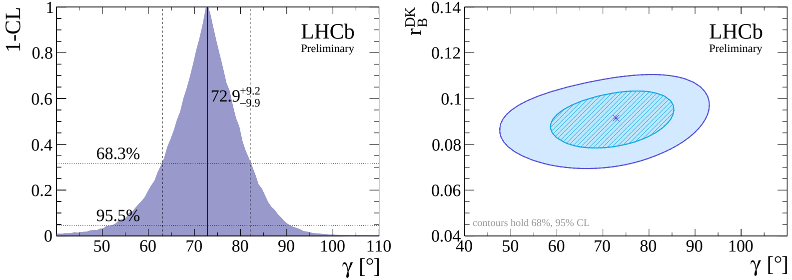
GGSZ $D \to K^0_S h^+ h^-$ ($h = \pi/K$)



quasi-GLW/GLS $D \to KK\pi^0, \pi\pi\pi^0/K\pi\pi^0$



Combining γ measurements



- LHCB-CONF-2014-004
- χ^2 combination of experimental inputs
  - 1/fb & 3/fb: $B^\pm \longrightarrow DK^\pm$ (ADS, GLW, GGSZ, GLS)
  - 1/fb: $B_s \longrightarrow D_s K$
- $\gamma = (73^{+9}_{-10})^\circ$: ~30% improvement over the past!

CP violation in charmless decays

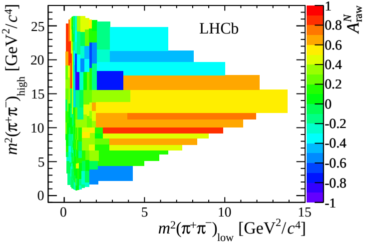
Direct $\mathcal{CP}$ violation in $B^{\pm} \longrightarrow h'^{\pm} h^{+} h^{-}$

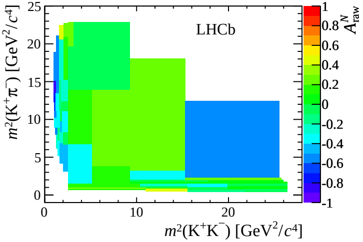
PRD 90 (2014) 112004

- Interference between tree and penguin diagrams (sensitive to NP)
- $h, h' \in \{\pi, K\}$

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

- A_P = production asym
- A_D = detection asym (π/K diff.)
- Possible $\pi\pi \leftrightarrow KK$ rescattering[5]





$A_{\mathcal{CP}}(B^{\pm} \longrightarrow K^{\pm}\pi^{+}\pi^{-}) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007$
$A_{\mathcal{CP}}(B^{\pm} \longrightarrow K^{\pm}K^{+}K^{-}) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007$
$A_{\mathcal{CP}}(B^{\pm} \longrightarrow \pi^{\pm}\pi^{+}\pi^{-}) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007$
$A_{\mathcal{CP}}(B^{\pm} \longrightarrow \pi^{\pm}K^{+}K^{-}) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$

[5] PLB 726 (2013) 337, PRD 89 (2014) 094013

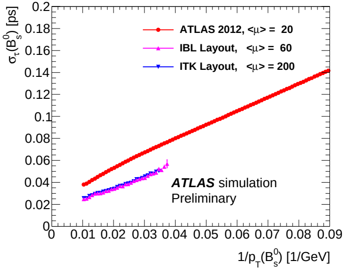
Looking forward

φ_s at ATLAS and LHCb

		ATLAS $\sigma(\varphi_s)$	LHCb $\sigma(\varphi_s)$
Run I	2010–12	0.12	0.049
Run II	2015–18	0.054	0.025
		0.10	
Run III	2020–22	0.064	0.009
HL-LHC	2023–30	0.022	–

- New IBL and ITK improve σ_t
  - with high p_T: $\sigma_t \downarrow$, but eff. $\downarrow$
- Trigger thresholds for μ p_T

nominal	6+6 GeV
pessimistic	11+11 GeV

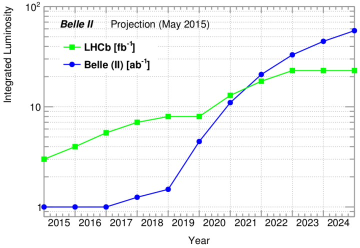


ATLAS-PHYS-PUB-2013-010

LHCb-PUB-2014-040

talk by Greig Cowan @ HL-LHC

LHCb & Belle II



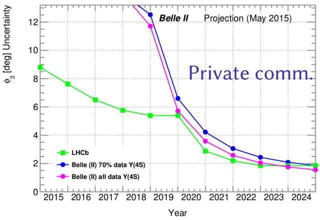
- Belle II will have larger dataset eventually:

Belle II	50 ab^{-1}
LHCb	50 fb^{-1}

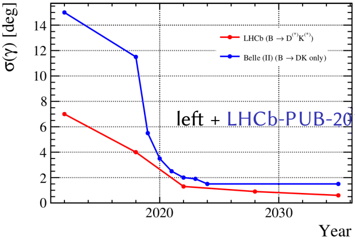
- Complement each other
- Modes with γ/π^0 in the final state: $B^\pm \to [D\gamma]_{D^*}K^\pm$
  - Easier at Belle II/e^+e^- colliders
- Time dependent B_s decays and baryonic decays
  - Only feasible at LHCb
- LHCb already exploring extensions to well established techniques
  - quasi-GLW/GLS: $D \to \pi K \pi^0$, $D \to hh\pi^0$ ($h \in \{K,\pi\}$)
  - CKM angle γ (φ_3) from $B^0 \to D^0K^*$, $B^0 \to D^0K\pi$[6]

[6]LHCb-PAPER-2015-017

LHCb & Belle II in the context of γ (or φ₃)



Private comm.



left + LHCb-PUB-2014-040

Table: LHCb precision on γ (or φ₃)

$\longmapsto$ LHCb upgrade (from 2022)

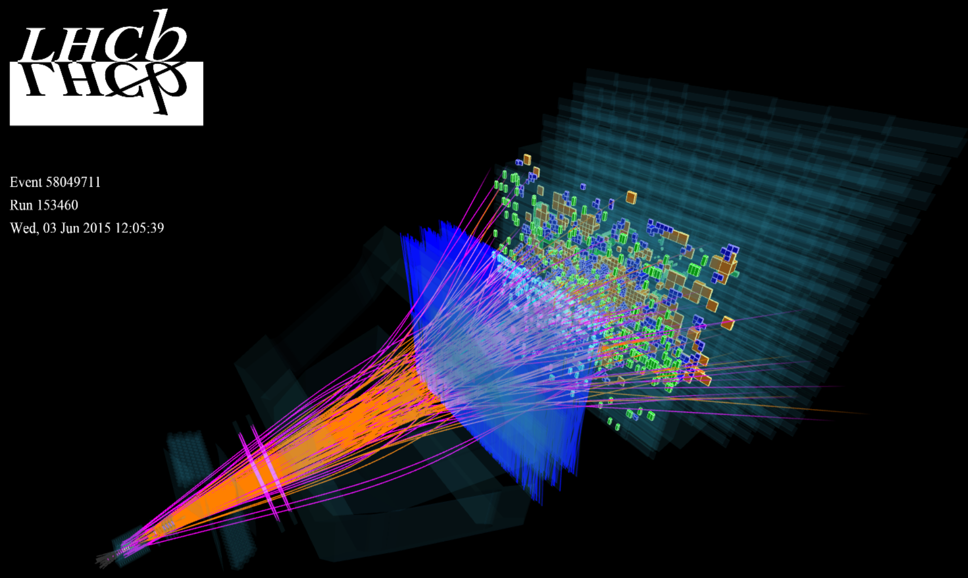
year	2012	2018	2022	2028	2035
γ(°)	7	4	1.3	0.9	0.6

$\longmapsto$ HL-LHC (from 2028)

- Belle II: considering only $B \longrightarrow DK$ decays
- see also: talk by Greig Cowan @ HL-LHC

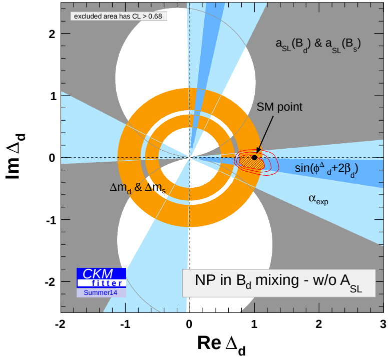
Conclusion

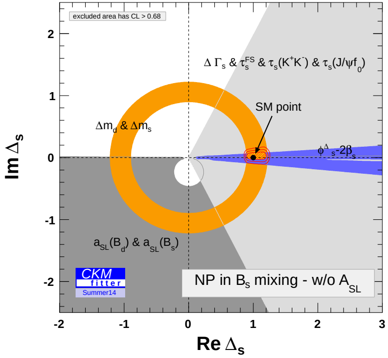
- a_{sl}, $\sin(2\beta)$, φ_s: Results from the LHC experiments and B-factories find them to be consistent with the SM
- Charmless 3-body decay: Unexplained *CP* asymmetry in final state
- γ: LHCb improved on previous γ measurements by ~30%, more yet to come.
- ATLAS: Although not designed for B-physics, and large number of PVs, good φ_s prospects due to new inner tracker layer.
- LHCb & Belle II: physics programmes complement each other.


LHCb
Event 58049711
Run 153460
Wed, 03 Jun 2015 12:05:39

Fin

a_{sl} & NP





$$a_{sl}^q = \Im\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) \simeq \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_{12}^q$$

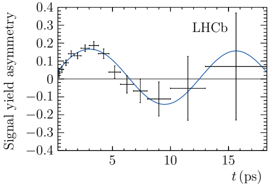
$$M_{12}^q \equiv M_{12}^{SM,q}\cdot\Delta_q, \qquad \Delta_q \equiv \left|\Delta_q\right| e^{\iota\phi_q^{\Delta}}$$

SM $\Delta_q = 1$

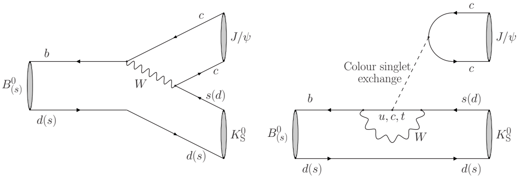
NP $\Im(\Delta_q) \neq 0$

CKMfitter: arxiv:1501.05013

$\sin(2\beta)$ from $B^0_{(s)} \to J/\psi K_S$ (LHCb)



$B^0 \to J/\psi K_S$ vs $B^0_s \to J/\psi K_S$: $\varphi \to \varphi + \Delta\varphi$ (penguin)



$B^0 \to J/\psi K_S$

$S = 0.731 \pm 0.035 \pm 0.020$

$C = -0.038 \pm 0.032 \pm 0.005$

LHCB-PAPER-2015-004

$B^0_s \to J/\psi K_S$

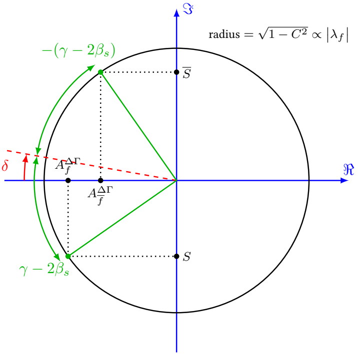
$A^{\Delta\Gamma} = 0.49 \pm^{0.77}_{0.65} \pm 0.06$

$C = -0.28 \pm 0.41 \pm 0.08$

$S = -0.08 \pm 0.40 \pm 0.08$

LHCB-PAPER-2015-005

γ: $B_s \longrightarrow D_s K$ – observables



$$\left.\begin{aligned} B_s^0 &\to D_s^{\mp} K^{\pm} \\ \overline{B}_s^0 &\to D_s^{\pm} K^{\mp} \end{aligned}\right\} \text{interferes}$$

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

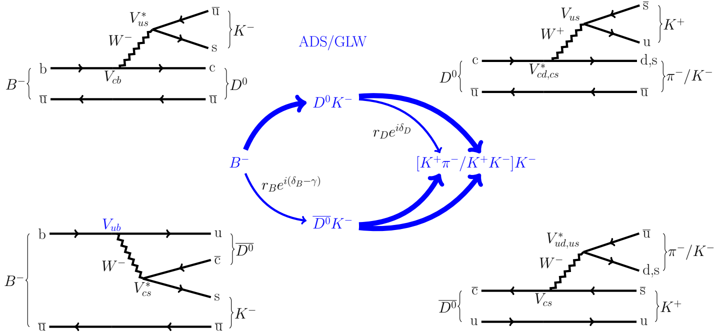
$$A_f^{\Delta\Gamma} = \frac{-2\Re(\lambda_f)}{1+|\lambda_f|^2} \qquad S_f = \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}$$

$$\Re(\lambda_f) = \cos(\delta - (\gamma - 2\beta_s))$$
$$\Im(\lambda_f) = \sin(\delta - (\gamma - 2\beta_s))$$

$$\Gamma_{B_s^0\to f}(t) \simeq e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right]$$

For $\overline{B}_s^0 \to \bar{f}$, you get corresponding CP conjugated observables.

ADS/GLW

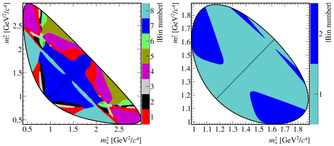


V^*_{us}
W^-
V_{cb}
B^-
b
c
ū
s
K^-
D^0
ADS/GLW
V_{us}
W^+
$V^*_{cd,cs}$
D^0
s̄
u
d,s
π^-/K^-
K^+
D^0K^-
$r_D e^{i\delta_D}$
B^-
$r_B e^{i(\delta_B-\gamma)}$
$[K^+\pi^-/K^+K^-]K^-$
$\overline{D^0}K^-$
V_{ub}
W^-
V^*_{cs}
c̄
$\overline{D^0}$
$V^*_{ud,us}$
V_{cs}

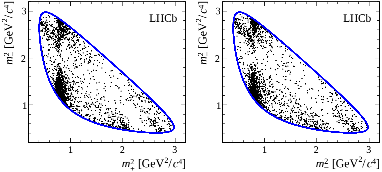
GGSZ

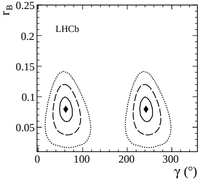
$$N^{-}_{\pm i} = h_{B^-}\left[F_{\pm i} + r_B^2 F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})\right]$$

- $D \longrightarrow K^0_S h^+ h^-$ ($h = \pi/K$)
- Bins in phase space (m_+, m_-)



- F_i: fraction of events in bin i
- c_i, s_i: cos, sin of avg. strong phase (input from CLEO-c)





$r_B = 0.080^{+0.019}_{-0.021}$

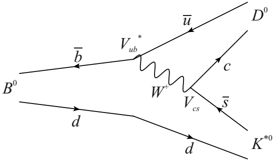
$\gamma = (62^{+15}_{-14})^\circ$

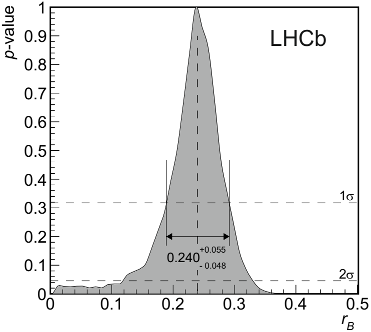
$\delta_B = (134^{+14}_{-15})^\circ$

JHEP 10 (2014) 097

$B^0 \longrightarrow D^0K^*$

extensions





Both diagrams, colour suppressed $\Rightarrow$ larger r_B

$r_B = 0.240^{+0.055}_{-0.048}$

Future γ measurement

Note: r_B and δ_B, different from $B^\pm \longrightarrow Dh^\pm$ modes

PRD 90 (2014) 112002 (LHCb)

arxiv:1502.07550
(Dalitz analysis @ Belle)

List of more results

$a_{sl}/A_{\mathcal{CP}}$ measurements

$B^0 \longrightarrow D^*Xl\nu$ (BaBar)
PRL 111 101802 (2013)

$B \longrightarrow X_s ll$ (BaBar)
PRL 112 211802

$B \longrightarrow X_s\gamma$ (BaBar)
PRD 90 092001

φ_s measurements

$B_s \longrightarrow D_sD_s$ (LHCb) PRL 113 (2014) 211801

$B_s \longrightarrow J/\psi KK,\pi\pi$ (LHCb) PRD 87 (2013) 112010

γ & related measurements

$B^{\pm} \longrightarrow Dh^{\pm}$ (LHCb)
LHCb-PAPER-2015-014
($D \longrightarrow hh'\pi^0$)
JHEP 10 (2014) 097
PLB 723 (2013) 44 (ADS)
PLB 712 (2012) 203–21

$B_s \longrightarrow D_sK$ (LHCb)
JHEP 11 (2014) 060

γ combination (LHCb)
LHCB-CONF-2014-004

$B^0 \longrightarrow D^0K^*$ (Belle)
arxiv:1502.07550

$B^0 \longrightarrow D^0K^*$ (LHCb)
PRD 90 (2014) 112002

γ & related (contd.)

$B^- \longrightarrow DK^-\pi\pi, D\pi^-\pi\pi$ (LHCb)
LHCb-PAPER-2015-020

$B^0 \longrightarrow D^0K\pi$ (LHCb)
LHCb-PAPER-2015-017

Charmless decays

$B^+ \longrightarrow p\bar{p}K^+$ (LHCb) PRL 113 (2014) 141801

$B_s \longrightarrow K^{*0}\overline{K}^{*0}$ (LHCb)
LHCB-PAPER-2014-068

$B^+ \longrightarrow K_s\pi\pi$ (BaBar)
arxiv:1501.00705

γ & $-2\beta_s$ from $B \longrightarrow hh$ (LHCb)
PLB 741 (2015) 1