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Precision flavour physics at LHCb: CP violation and CKM constraints



Sevda Esen
on behalf of the LHCb collaboration

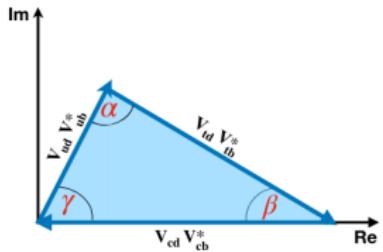


Les Rencontres de Physique de la Vallée d'Aoste
March 10, 2021

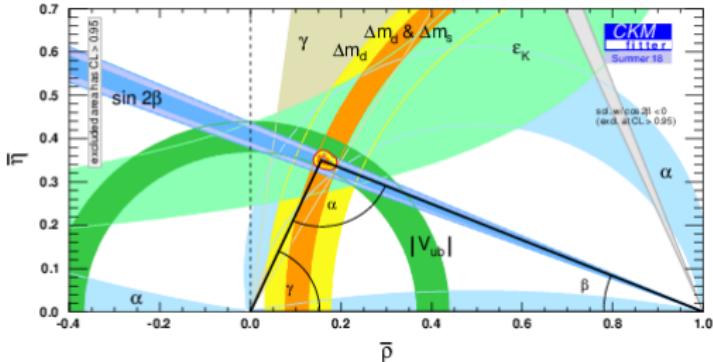
CKM MATRIX AND CP VIOLATION IN SM

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| e^{-i\beta} & -|V_{ts}| e^{i\beta s} & |V_{tb}| \end{pmatrix} = \begin{pmatrix} \text{blue square} & \text{blue square} & \text{blue square} \\ \text{blue square} & \text{blue square} & \text{blue square} \\ \text{blue square} & \text{blue square} & \text{blue square} \end{pmatrix}$$

- Key test of the SM: Verify unitarity of CKM matrix
 - Magnitudes: Measure branching fractions or mixing frequencies
 - Phases: Measure CPV
- Sensitivity to BSM effects from global consistency of various measurements



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



- CPV in charm decays: three world best measurements
- CPV in beauty: latest γ measurement and more $K - \pi$ puzzle
- V_{ub}/V_{cb} : first V_{ub} measurement from B_s^0 decay
- ϕ_s : first time with electrons in the final state
- Δm_s : world best measurement

- Cabibbo-suppressed decays of D^0 into CP eigenstates $K^+ K^-$ and $\pi^+ \pi^-$

$$A_{CP}(f, t) \equiv \frac{\Gamma(D^0 \rightarrow f, t) - \Gamma(\bar{D}^0 \rightarrow f, t)}{\Gamma(D^0 \rightarrow f, t) + \Gamma(\bar{D}^0 \rightarrow f, t)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}$$

$x_{12}, y_{12} \ll 1$

$$y_{12} = \frac{2|\Gamma_{12}|}{\Gamma}$$

$$x_{12} = \frac{2|M_{12}|}{\Gamma}$$

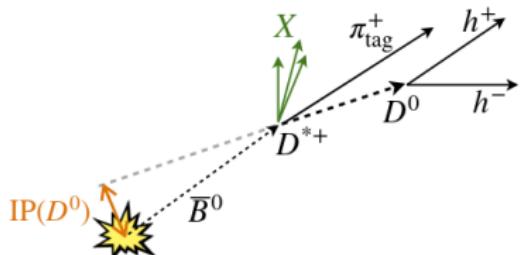
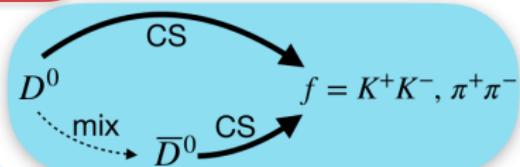
$$\Delta Y_f \approx -x_{12} \sin \phi_2^M$$

$$\phi_2^M \sim \arg(M_{12})$$

$\mathcal{O}(10^{-5} - 10^{-4})$ in the SM

current experimental precision: 2×10^{-4}

Kagan & Silvestrini 2020,
Grossman et al. (in preparation),
Li, Umeeda, Xu, Yu 2020

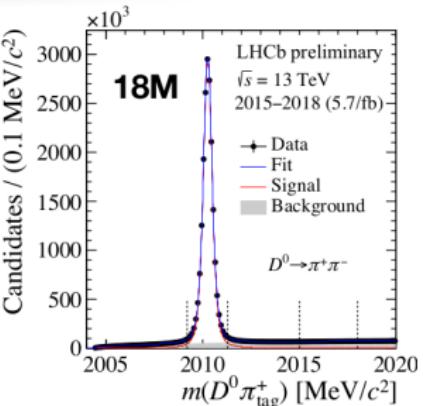
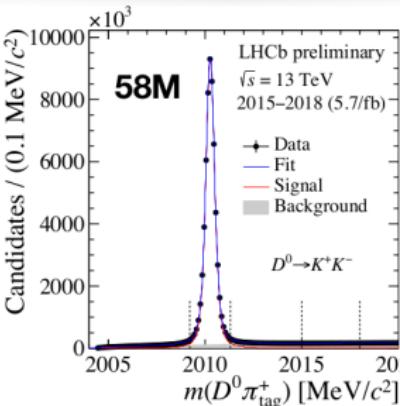
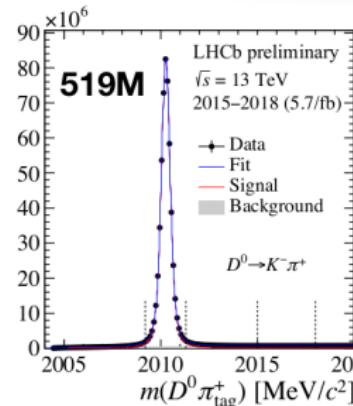


- Contribution from B decays reduced with $IP(D^0) < 60\mu m$
- $D^0 - \bar{D}^0$ and $\pi^+ \pi^-$ kinematics weighted to remove detection asymmetries

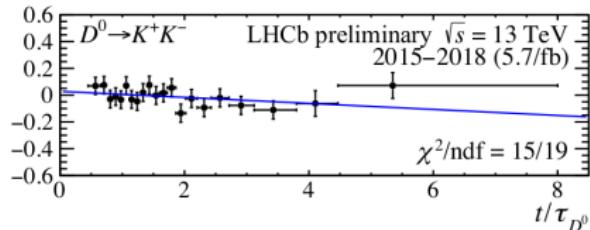
\mathcal{CP} VIOLATION IN $D^0 \rightarrow h^+ h^-$ [LHCb-PAPER-2020-045 IN PREPARATION]

LHCb
THCP

PRELIMINARY



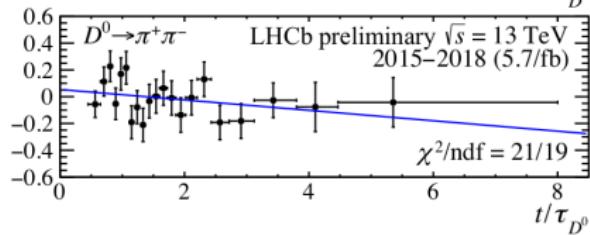
Asymmetry [%]



$$\Delta Y_{K^+ K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$$

$$\Delta Y_{\pi^+ \pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$

Asymmetry [%]

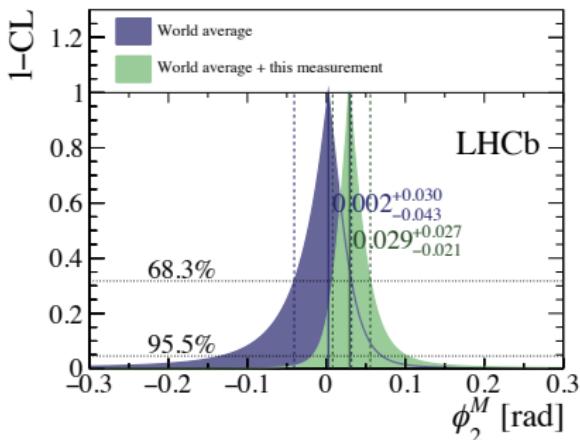
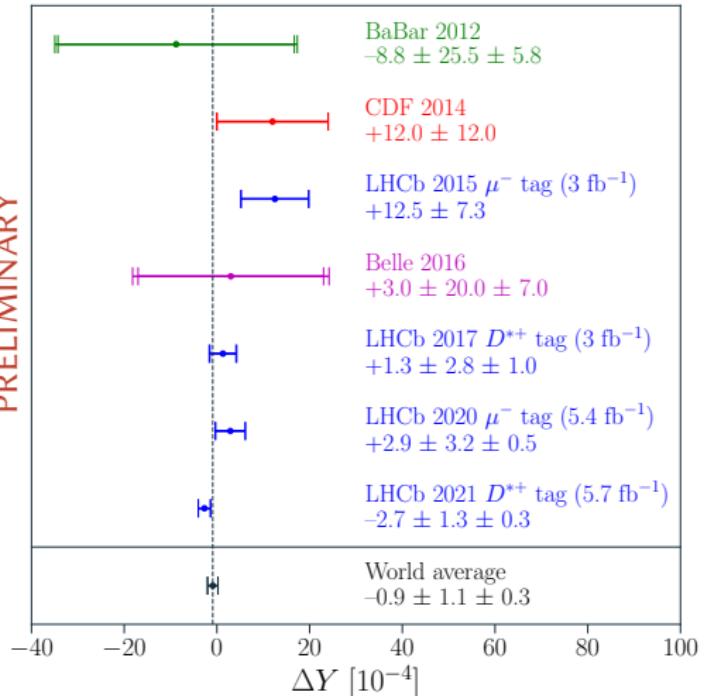


Sys. < 20% of stat.

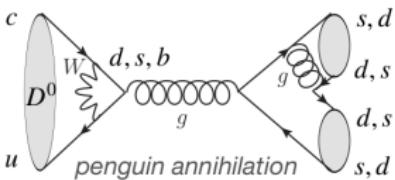
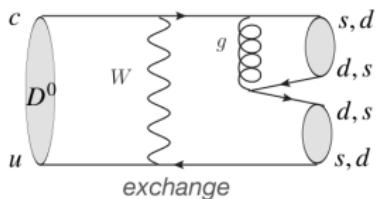
Agree with each other within 0.5σ
 Compatible with zero within 2σ



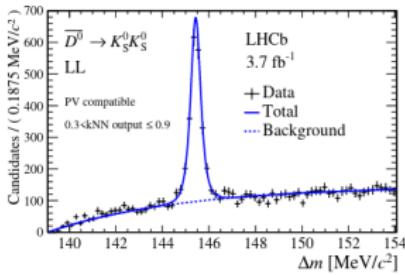
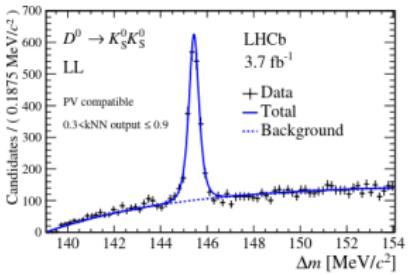
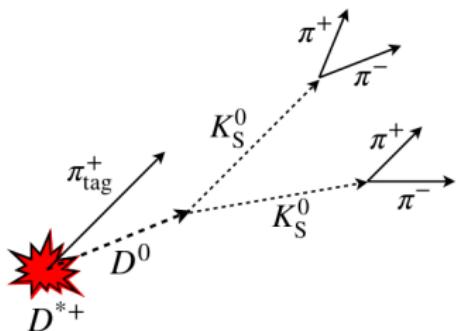
PRELIMINARY



- Only exchange diagrams contribute at the tree level (vanishing at $SU(3)_F$ limit)



Figures from Cheng & Chiang 2012



Sample	2017 + 2018			2015 + 2016		
	\mathcal{A}^{CP} [%]	Yield	\mathcal{A}^{CP} [%]	Yield		
LL PV-comp.	-4.3 ± 1.6 ± 0.6	4056 ± 77	0.3 ± 2.5 ± 1.3	1388 ± 41		
LL PV-inc.	-3.0 ± 7.9 ± 1.4	430 ± 41	-11 ± 17 ± 3	178 ± 31		
LD PV-comp.	-2.9 ± 3.8 ± 0.9	1145 ± 49	-7.2 ± 5.8 ± 1.7	411 ± 25		
LD PV-inc.	-5 ± 17 ± 2	349 ± 64	-10 ± 31 ± 4	58 ± 18		
DD	-35 ± 47 ± 6	87 ± 28	-	-		

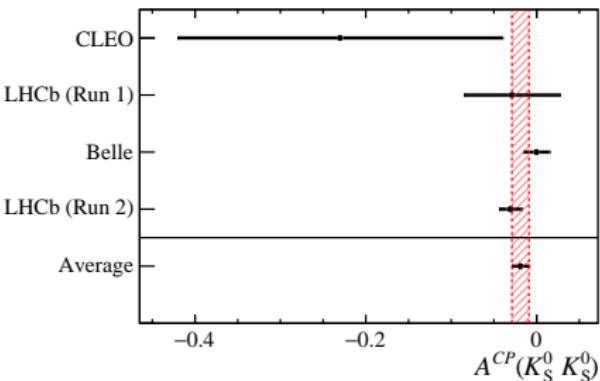
$$A_{\text{raw}}(K_S^0 K_S^0) = A_{CP}(K_S^0 K_S^0) + A_D(\pi_{\text{tag}}^+) + A_P(D^{*+})$$

$$A_{\text{raw}}(K^+ K^-) = A_{CP}(K^+ K^-) + A_D(\pi_{\text{tag}}^+) + A_P(D^{*+})$$

< 0.2%

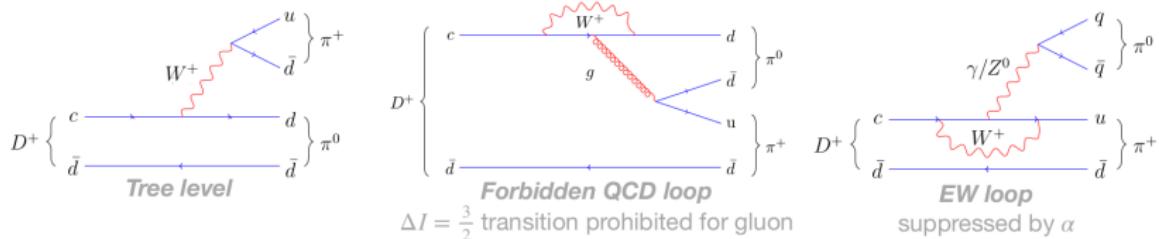
PLB 767 (2017) 177–187

$$\mathcal{A}_{K_S^0 K_S^0}^{CP} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

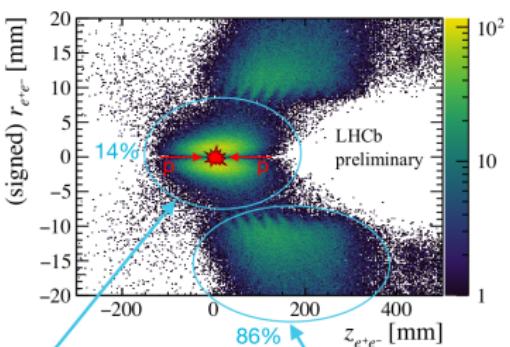


CP VIOLATION IN $D_{(s)}^\pm \rightarrow h^\pm \pi^0/\eta$ DECAYS [LHCb-PAPER-2021-001 IN PREP]

- $\mathcal{A}^{CP}(D^+ \rightarrow \pi^+ \pi^0) < 10^{-5}$ in SM due to isospin symmetry

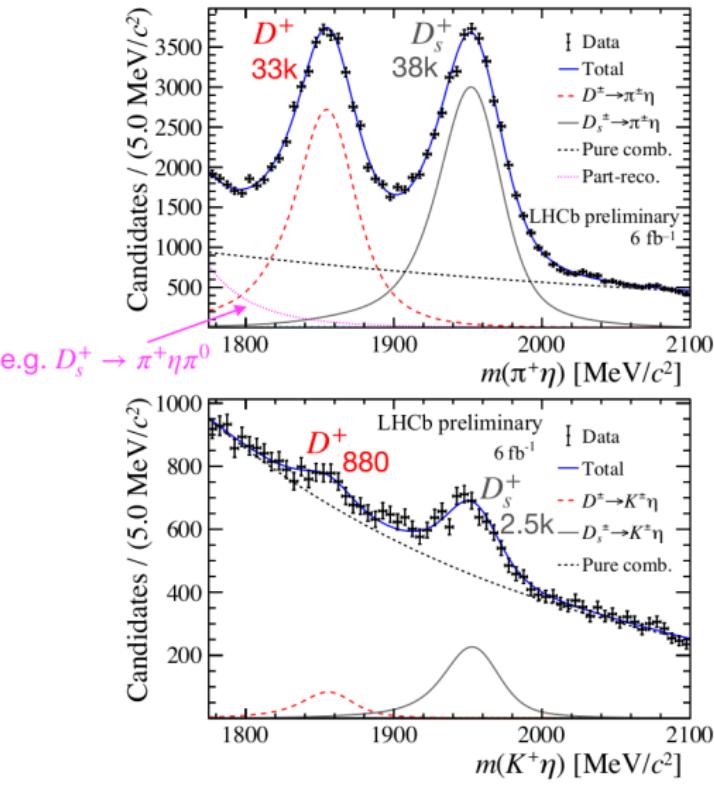
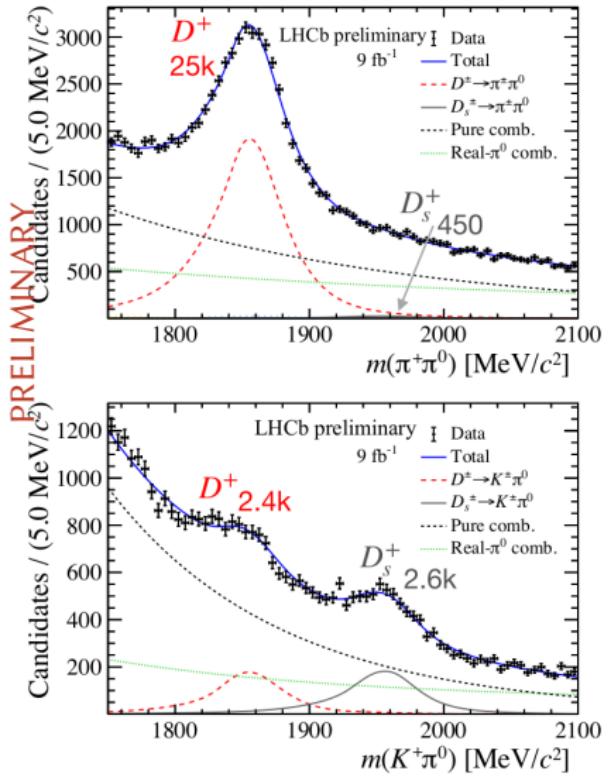


- Use $h^0 \rightarrow e^+ e^- \gamma$ to have a decay vertex
- Bremsstrahlung correction for electrons and positrons
- Nuisance asymmetries are removed using $D_s^+ \rightarrow h^+ K_s^0$
- 2D fit to $D_{(s)}^+$ and h^0 masses



CP VIOLATION IN $D_{(s)}^{\pm} \rightarrow h^{\pm}\pi^0/\eta$ DECAYS [LHCb-PAPER-2021-001 IN PREP]

LHCb
THCP



CP VIOLATION IN $D_{(s)}^{\pm} \rightarrow h^{\pm}\pi^0/\eta$ DECAYS [LHCb-PAPER-2021-001 IN PREP]

LHCb

$$A_{CP}(D^+ \rightarrow \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$

$$A_{CP}(D^+ \rightarrow K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%$$

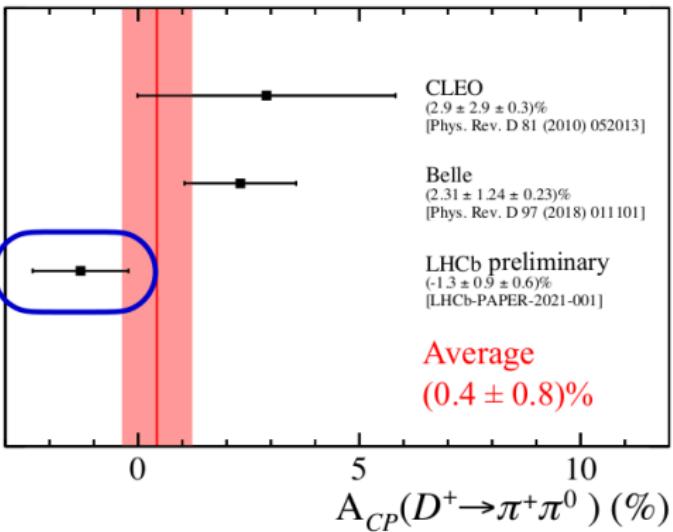
$$A_{CP}(D_s^+ \rightarrow K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%$$

$$A_{CP}(D^+ \rightarrow \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%$$

$$A_{CP}(D_s^+ \rightarrow \pi^+\eta) = (-0.8 \pm 0.7 \pm 0.5)\%$$

$$A_{CP}(D^+ \rightarrow K^+\eta) = (-6 \pm 10 \pm 4)\%$$

$$A_{CP}(D_s^+ \rightarrow K^+\eta) = (-0.9 \pm 3.7 \pm 1.1)\%$$

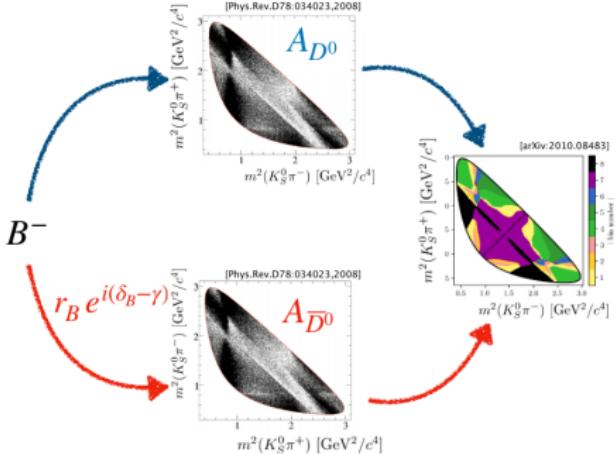
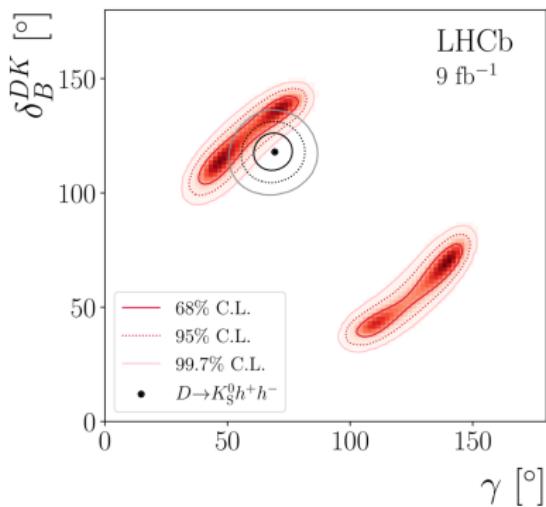


MEASUREMENT OF γ WITH $B^\pm \rightarrow D^{(*)} h^\pm$ [ARXIV:2012.09903]

LHCb
THCP

- $B^\pm \rightarrow D(\rightarrow K_s^0 h^+ h^-) h^\pm$

- Mass fit in each Dalitz plot bin
- D strong phase from CLEO and BESIII
- $\gamma = (68.7^{+5.2}_{-5.1})^\circ$



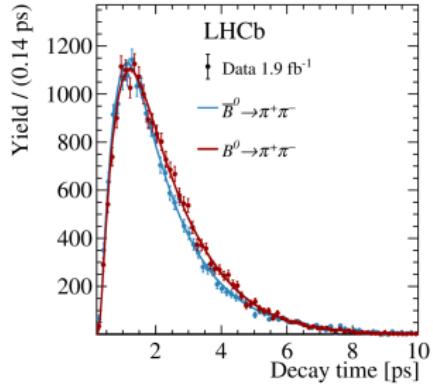
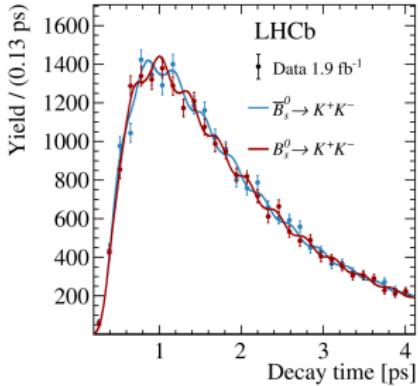
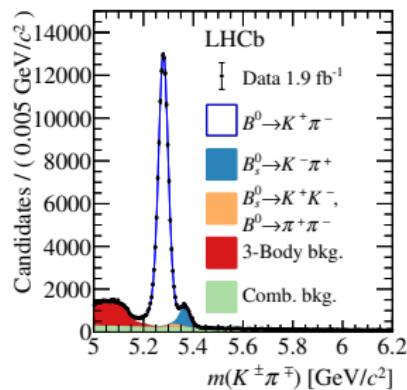
- $B^\pm \rightarrow D^{(*)} h^\pm$,
 $D \rightarrow K^+ K^-$, $\pi^+ \pi^-$, $K^\mp \pi^\pm$
- 30 observables measured
- Strong constraints on γ
- LHCb combination: $\gamma = (67 \pm 4)^\circ$
[LHCb-CONF-2020-003]



CP VIOLATION IN $B_{(s)} \rightarrow h^+ h^+$ DECAYS [ARXIV:2012.05319]

LHCb
THCP

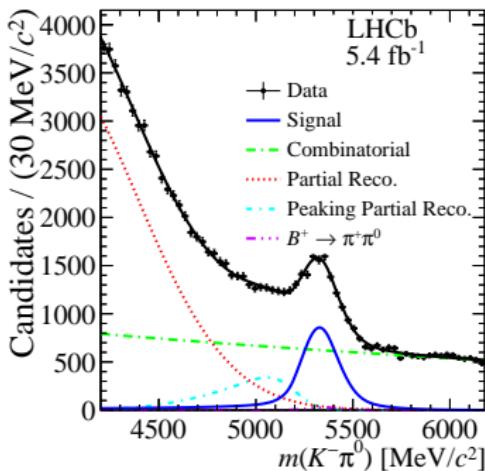
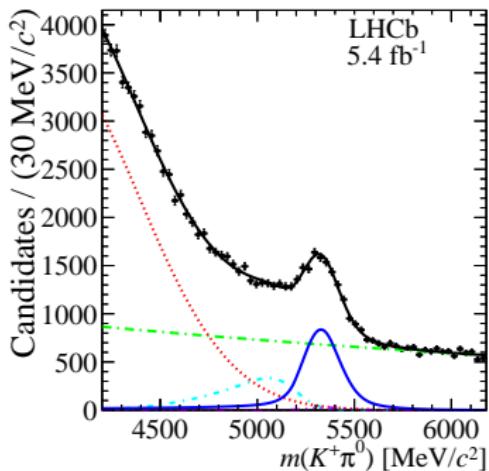
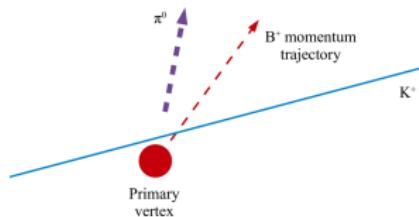
- Time dependent CP asymmetries in $B^0 \rightarrow \pi^+ \pi^-$, $B_s^0 \rightarrow K^+ K^-$
- Time integrated CP in $B_{(s)}^0 \rightarrow K\pi$
- Sensitive to $\beta_s, \gamma, \Delta M_{d.s}$
- Combination with run 1: $C_{KK} = 0.172 \pm 0.031$, $S_{KK} = 0.139 \pm 0.032$
- First observation of time dependent CP violation in B_s



\mathcal{CP} VIOLATION IN $B^+ \rightarrow K^+\pi^0$ DECAYS [ARXIV:/2012.12789]

LHCb
THCP

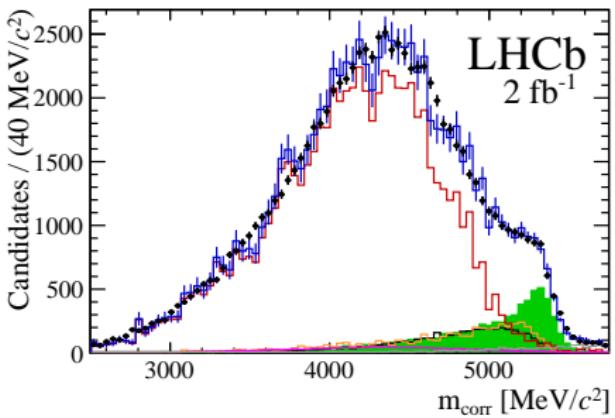
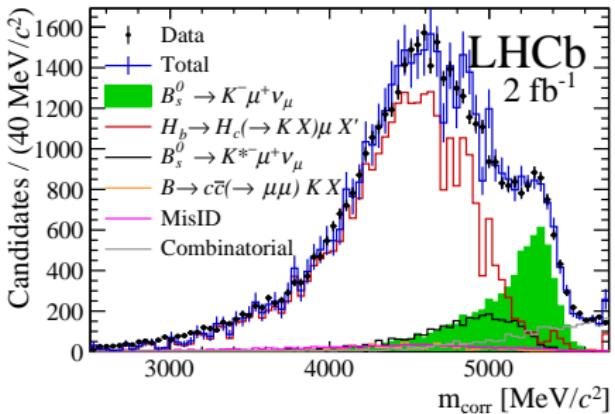
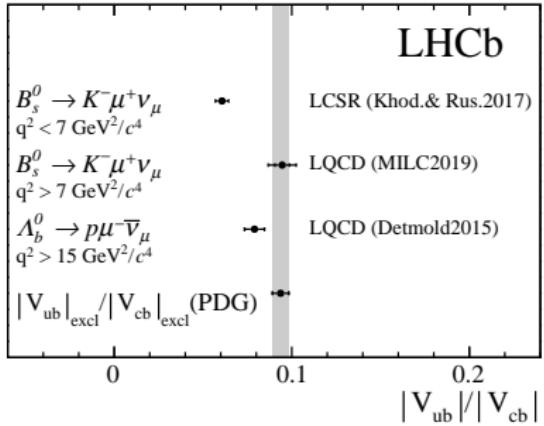
- $\mathcal{A}^{\mathcal{CP}}(B^0 \rightarrow K^+\pi^-) = \mathcal{A}^{\mathcal{CP}}(B^+ \rightarrow K^+\pi^0)$ from isospin symmetry
5.5 σ deviation from equality seen
- Production and detection asymmetries from $B^+ \rightarrow J/\psi K^+$
- $\mathcal{A}^{\mathcal{CP}}(B^+ \rightarrow K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$
- $\mathcal{A}^{\mathcal{CP}}(B^0 \rightarrow K^+\pi^-) \neq \mathcal{A}^{\mathcal{CP}}(B^+ \rightarrow K^+\pi^0)$ by 8.8 σ



MEASUREMENT OF V_{ub}/V_{cb} [ARXIV:2012.05143]

LHCb
lhcb

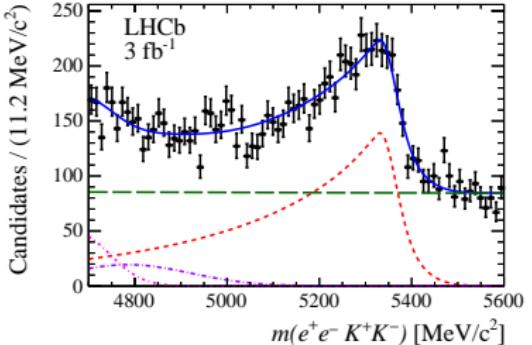
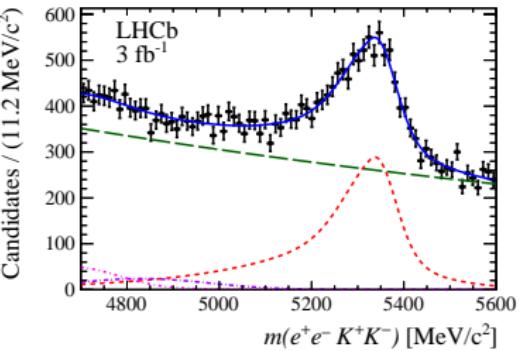
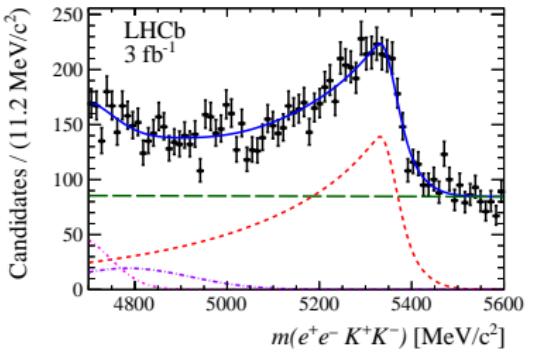
- Using 2 fb^{-1} of data at $\sqrt{s} = 8 \text{ TeV}$
- Signal: $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$
- Normalization: $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$
- $R = \frac{B(B_s^0 \rightarrow K^- \mu^+ \nu_\mu)}{B(B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu)} = \frac{|V_{ub}|}{|V_{cb}|} \times \frac{FF_K}{FF_{D_s}}$
- Bins: $q^2 < 7$ and $q^2 > 7 \text{ GeV}^2/c^4$



NEW

- Follows similar strategy as $J/\psi \rightarrow \mu^+\mu^-$ analysis
- First time dependent angular analysis with an electron final state

PRELIMINARY

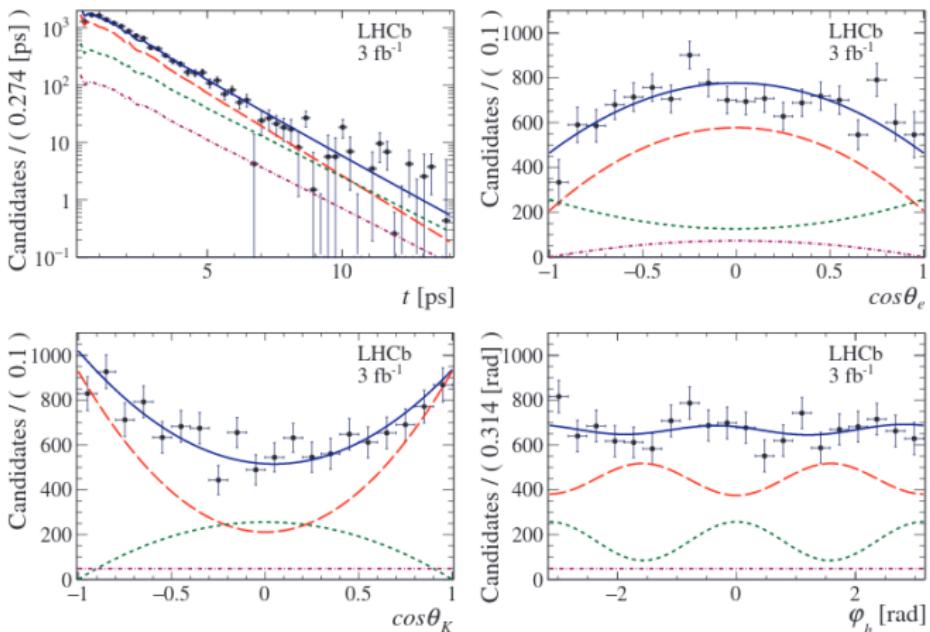


+	Data
—	Total fit
- - -	$B_s^0 \rightarrow J/\psi ee\phi$
- - -	Combinatorial
- - -	$B_s^0 \rightarrow \psi(2S)\phi$
- - -	$B_s^0 \rightarrow \chi_c(1P)\phi$

NEW

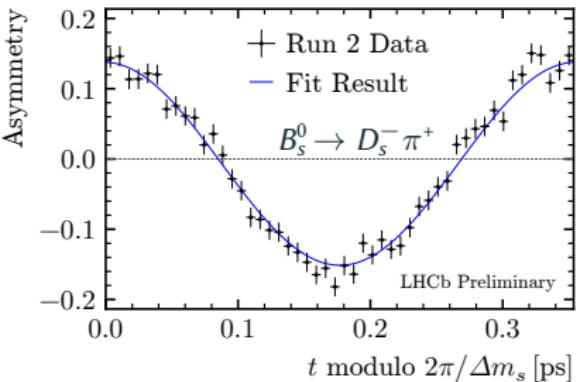
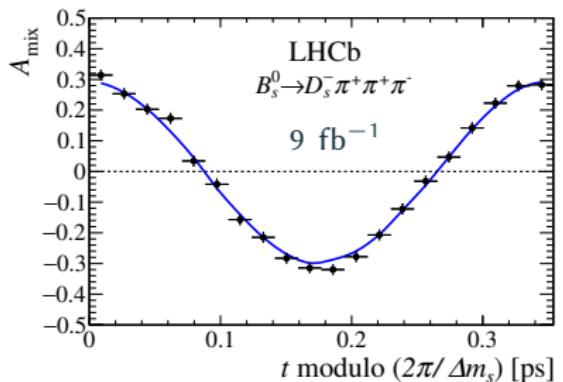
- Follows similar strategy as $J/\psi \rightarrow \mu^+\mu^-$ analysis
- First time dependent angular analysis with an electron final state
- $\phi_s = (0.00 \pm 0.28 \pm 0.05) \text{ rad}$

PRELIMINARY



NEW

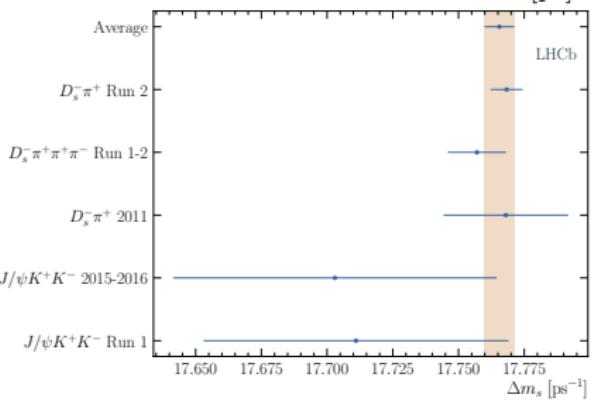
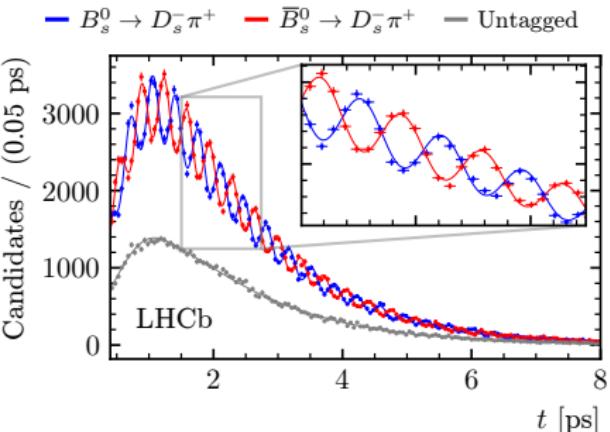
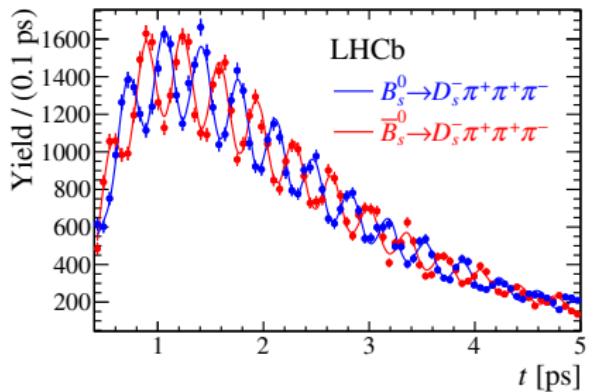
- Mixing asymmetry $\frac{\text{unmixed} - \text{mixed}}{\text{unmixed} + \text{mixed}}$ proportional to $(1 - 2\omega) \cos(\Delta m_s t)$
- Tagging power $\varepsilon_{\text{tag}}(1 - 2\omega)^2 \approx 6\%$
- Two decay modes: $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow D_s^- \pi^+ \pi^- \pi^+$



MEASUREMENT OF Δm_s [ARXIV:2011.12041] AND [LHCb-PAPER-2021-005 IN PREP]

NEW

PRELIMINARY



Decay mode	Data sample	Δm_s ps^{-1}
$B_s^0 \rightarrow D_s^- \pi^+$	2011	$17.768 \pm 0.023 \pm 0.006$
$B_s^0 \rightarrow D_s^- \pi^- \pi^+ \pi^+$	2011-2018	$17.757 \pm 0.007 \pm 0.008$
$B_s^0 \rightarrow D_s^- \pi^+$	2015-2018	$17.7683 \pm 0.0051 \pm 0.0032$
Average		17.7666 ± 0.0057



- CPV in charm decays: three world best measurements
- CPV in beauty: latest γ measurement and more $K - \pi$ puzzle
- V_{ub}/V_{cb} : first V_{ub} measurement from B_s^0 decay
- ϕ_s : first time with electrons in the final state **NEW!**
- Δm_s : world best measurement **NEW!**