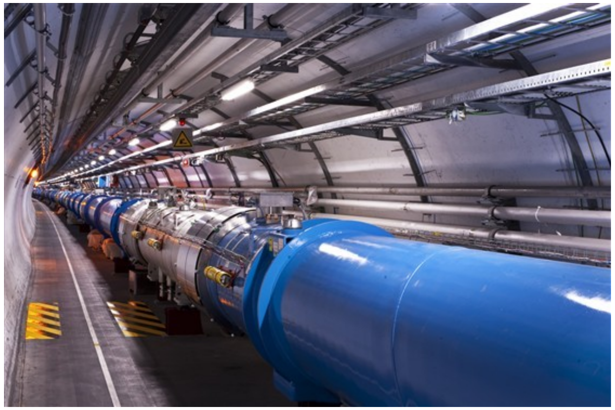
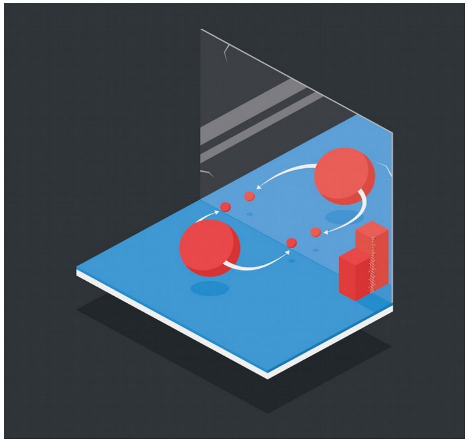
Overview of CP Violation @ LHC





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武漢大學
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CLHCP 2019
Oct. 23-27, 2019, Dalian University of Technology, Dalian

HF

Overview of CP Violation

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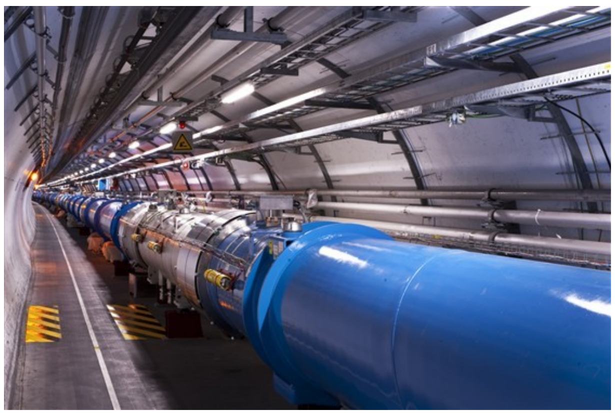

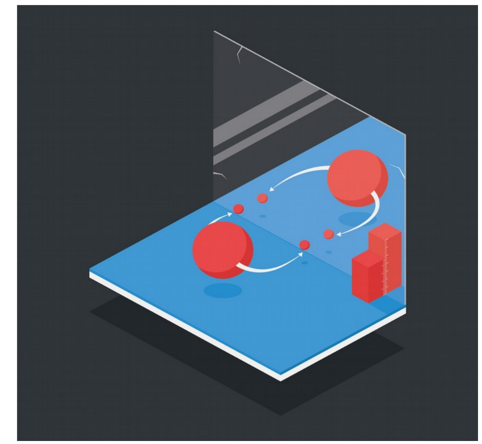

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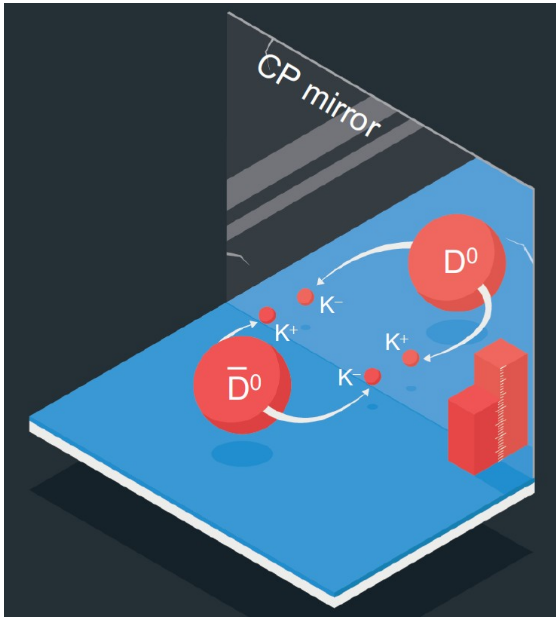
Outline

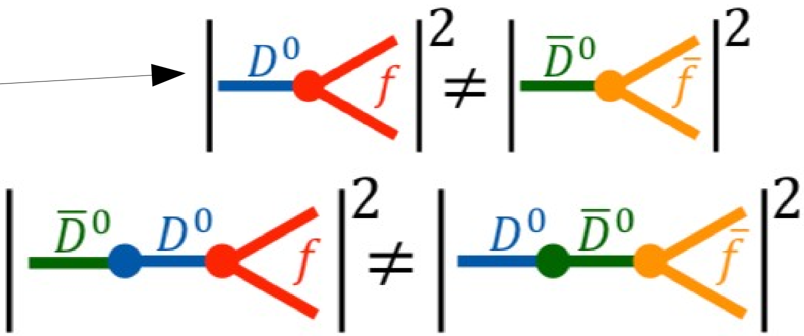
- CPV in charm decays
  - Direct & indirect CPV
  - ΔA_{CP}: first observation!
- CPV in b-hadron decays
  - γ combination
  - Measurements on ϕ_s
  - Multi-body charmless B/Λ_b decays
  - Radiative decays
- Summary & outlook

Predominantly LHCb results

CP violation in charm

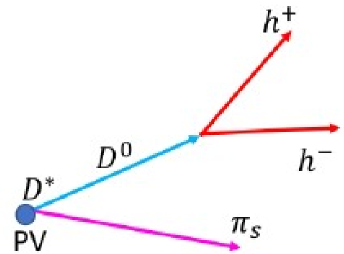


- Charm decays allow CP violation to be probed in the up-sector
  - Complementary to studies in neutral K and $B_{(s)}$ systems
- Expected to be very small in SM (~10^{-3} – 10^{-4})
  - Although theory predictions are not very precise due to large long-distance effects
- CP asymmetries $A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to \bar{f})}$ are sensitive to
  - Direct CP violation a_{CP}^{dir}
  - Indirect CP violation a_{CP}^{ind} (CP violation in mixing or in the interference between mixing and decay)



[PRL 122 (2019) 211803]

ΔA_{CP} measurement



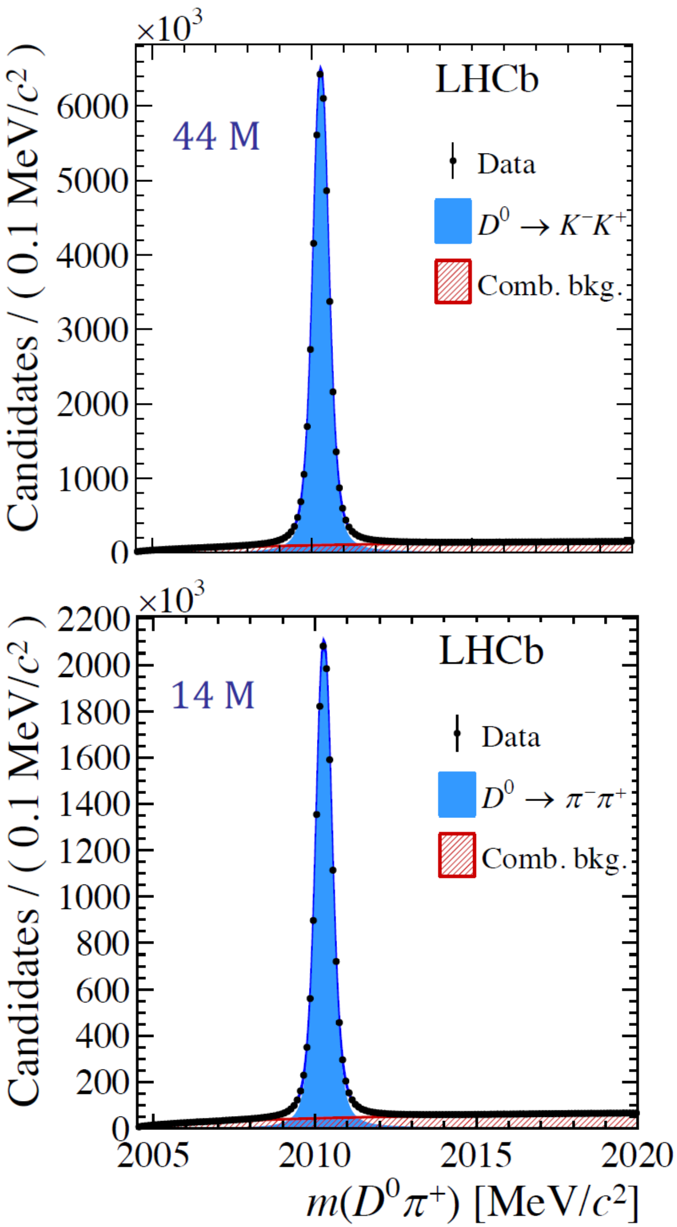
- LHCb uses full Run2 5.9 fb^{-1} data
- Tagging of initial flavor of D^0
  - **Prompt**: coming from PV, i.e., $D^{*+} \to D^0\pi^+$
  - **Semileptonic**: coming from B decays, i.e., $B \to D^0\mu^- X$
- Raw asymmetry for tagged D^0 decays to a final state f (K^+K^-, $\pi^+\pi^-$):

$$A_{\rm raw}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$$

- With many systematics canceled at first order, it is relatively easy to measure time-integrated difference in CP asymmetry

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

Prompt D^0



[PRL 122 (2019) 211803]

ΔA_{CP} measurement

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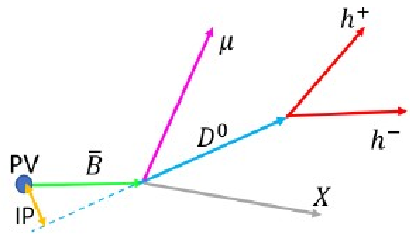

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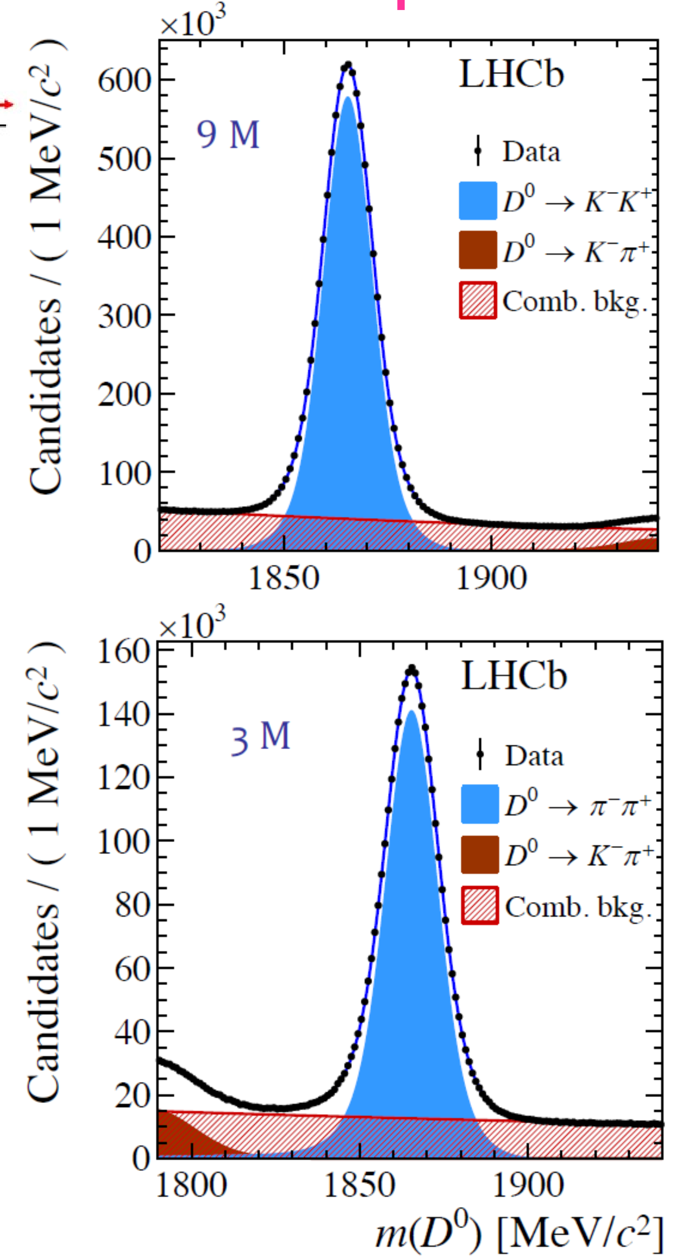
Semileptonic D^0



[PRL 122 (2019) 211803]

Observation of charm CPV

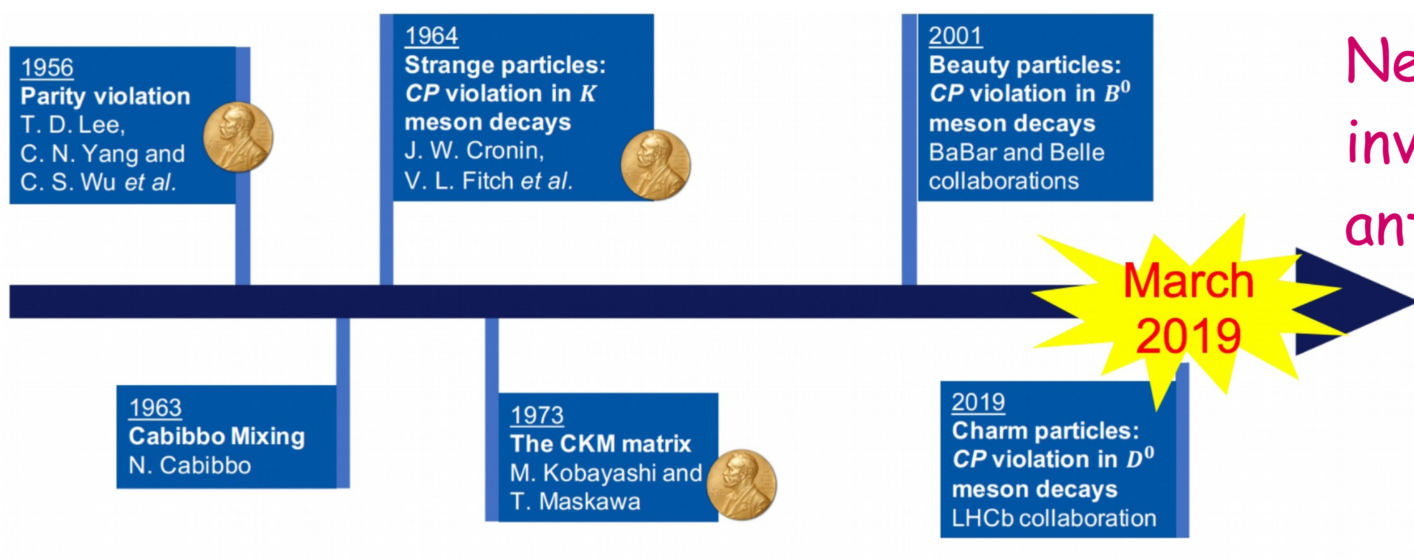
- From full Run2 5.9 fb^{-1} data:

$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4},$$
$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

- Combination with Run1 results:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

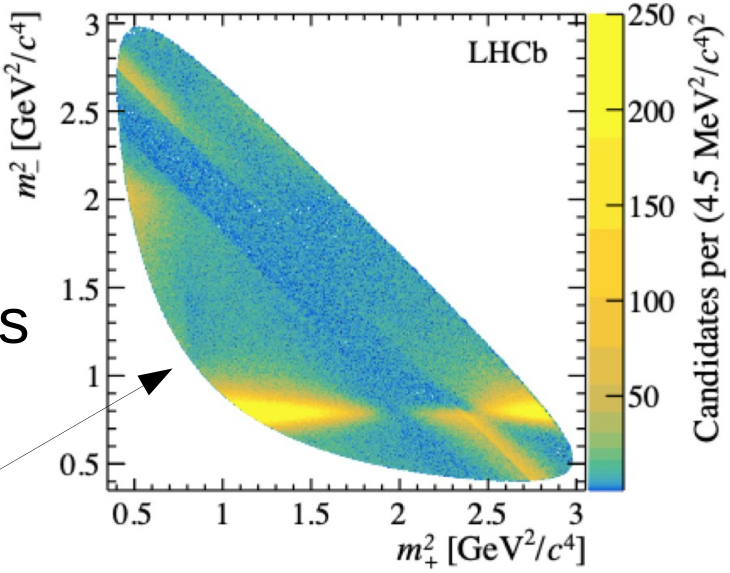
  - Observation of CP violation with **5.3σ** significance!



New window opened to investigate matter-antimatter symmetry!

Oscillations of charm mesons in $D^0 \to K_S^0 \pi\pi$

- D^0 mass eigenstates and their weak eigenstates:
  - $|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\overline{D^0}\rangle$
  - $m_{1,2}$ ($\Gamma_{1,2}$) as mass (width) of $D_{1,2}$
- Mixing parameters: $x \equiv \frac{m_1 - m_2}{\Gamma}; y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$
- x determines the oscillation rate
  - x is very small for D^0, but x and CPV can be enhanced by NP
  - CPV can occur in the mixing → oscillation rates differ for D^0 and $\overline{D}^0$
- LHCb Run1, tagged $D^0 \to K_S^0 \pi\pi$ decay yields
  - Prompt: ~1.3M, Semileptonic: ~1M
- $D^0 \to K_S^0 \pi\pi$ has rich resonance structures



Oscillations of charm mesons in $D^0 \rightarrow K_S^0 \pi\pi$

- Model-independent approach (bin-flip method) [PRD 99 (2019) 012007]
  - To avoid efficiency modeling
- Results with Run1 data:

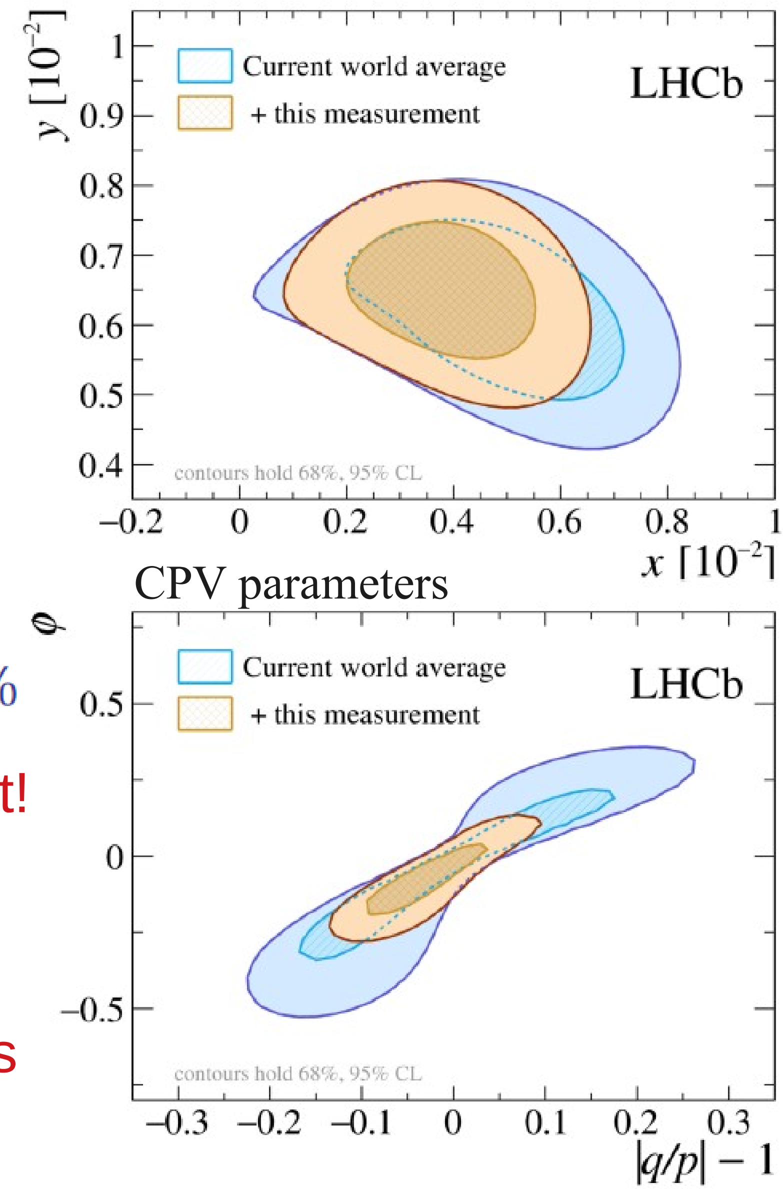
  $y_{CP} = [0.74 \pm 0.36\,(stat) \pm 0.11\,(syst)]\%$

  $\Delta y = [-0.06 \pm 0.16\,(stat) \pm 0.03\,(syst)]\%$

  $x_{CP} = [0.27 \pm 0.16\,(stat) \pm 0.04\,(syst)]\%$

  $\Delta x = [-0.053 \pm 0.070\,(stat) \pm 0.022\,(syst)]\%$

  - Best precision on x from a single experiment!
- Combination with current global knowledge gives x > 0 at more than 3σ
  - First evidence that masses of D^0 eigenstates differ



[LHCb-CONF-2019-001]

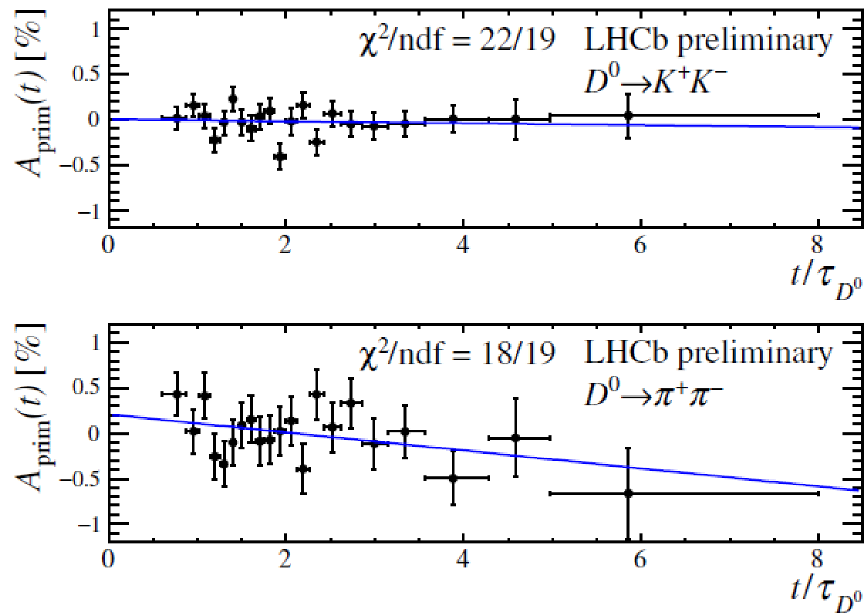
A_Γ in $D^0 \to K^+K^-, \pi^+\pi^-$: Prompt

- A_Γ probes CPV in mixing and interference

$$A_{CP}(f,t) \approx A_{CP}^{\text{decay}}(f) - \boxed{A_\Gamma} \frac{t}{\tau_{D^0}}$$

  - A linear fit to A_{CP} in bins of D^0 decay time extracts A_Γ as slope parameter
- Run2 1.9fb^{-1} (2015-2016) LHCb data have:

$$A_\Gamma(D^0 \to K^+K^-) = (\ 1.3 \pm 3.5 \pm 0.7) \times 10^{-4}$$
$$A_\Gamma(D^0 \to \pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}$$



- A_Γ does not depend on D decay channel, the two values can be combined

$$\mathbf{A_\Gamma(D^0 \to h^+h^-) = (3.4 \pm 3.1 \pm 0.6) \times 10^{-4}} \quad (h = K, \pi)$$

- Combining with Run1 prompt results [PRL 118 (2017) 261803]:

$$\mathbf{A_\Gamma(D^0 \to h^+h^-) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}} \quad (h = K, \pi)$$

A_Γ is consistent with SM!

A_Γ in $D^0 \to K^+K^-, \pi^+\pi^-$: Semileptonic

- A_Γ probes CPV in mixing and interference

$$A_{CP}(f,t) \approx A_{CP}^{\text{decay}}(f) - \boxed{A_\Gamma} \frac{t}{\tau_{D^0}}$$

  - A linear fit to A_{CP} in bins of D^0 decay time extracts A_Γ as slope parameter
- With Run2 5.4 fb^{-1} (2016-2018) data we have

$$A_\Gamma(K^+K^-) = (-4.3 \pm 3.6 \pm 0.5) \times 10^{-4}$$
$$A_\Gamma(\pi^+\pi^-) = (\ \ 2.2 \pm 7.0 \pm 0.8) \times 10^{-4}$$

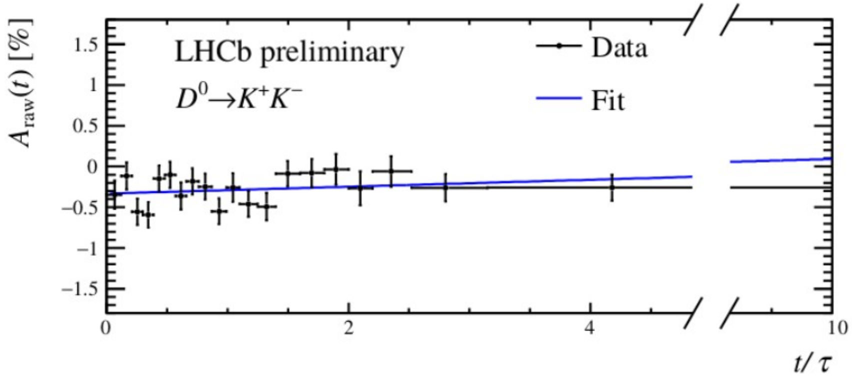
- Combining with Run1 3 fb^{-1} prompt+SL results:

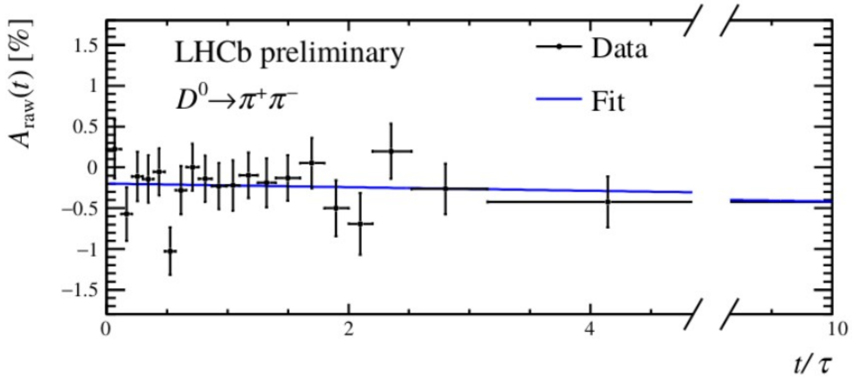
[PRL 118 (2017) 261803, JHEP 04 (2015) 043]

$$A_\Gamma(K^+K^-) = (-4.4 \pm 2.3 \pm 0.6) \times 10^{-4}$$
$$A_\Gamma(\pi^+\pi^-) = (\ \ 2.5 \pm 4.3 \pm 0.7) \times 10^{-4}$$

- Assuming A_Γ to be universal, the averaged result:

$$\mathbf{A_\Gamma(D^0 \to h^+h^-) = (-2.9 \pm 2.0 \pm 0.6) \times 10^{-4}}$$
$$(h = K, \pi)$$





A_Γ is consistent with SM!

Search for CPV in $D_{(s)}^+$ decays

- CPV can arise from interference between $c \to d\bar{d}u$ and $c \to s\bar{s}u$
- Simultaneous fits to extract raw asymmetries

$$A_{CP}(D_s^+ \to K_S^0\pi^+) \approx A(D_s^+ \to K_S^0\pi^+) - A(D_s^+ \to \phi\pi^+)$$

$$A_{CP}(D^+ \to K_S^0K^+) \approx A(D^+ \to K_S^0K^+) - A(D^+ \to K_S^0\pi^+) - A(D_s^+ \to K_S^0K^+) + A(D_s^+ \to \phi\pi^+)$$

$$A_{CP}(D^+ \to \phi\pi^+) \approx A(D^+ \to \phi\pi^+) - A(D^+ \to K_S^0\pi^+)$$

- Results with Run2 3.8 fb^{-1} data:

$$\begin{aligned} A_{CP}(D_s^+ \to K_S^0\pi^+) &= (1.3 \pm 1.9 \pm 0.5) \times 10^{-3} \\ A_{CP}(D^+ \to K_S^0K^+) &= (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3} \\ A_{CP}(D^+ \to \phi\pi^+) &= (0.05 \pm 0.42 \pm 0.29) \times 10^{-3} \end{aligned}$$

- Results with Run1 & Run2 combined:

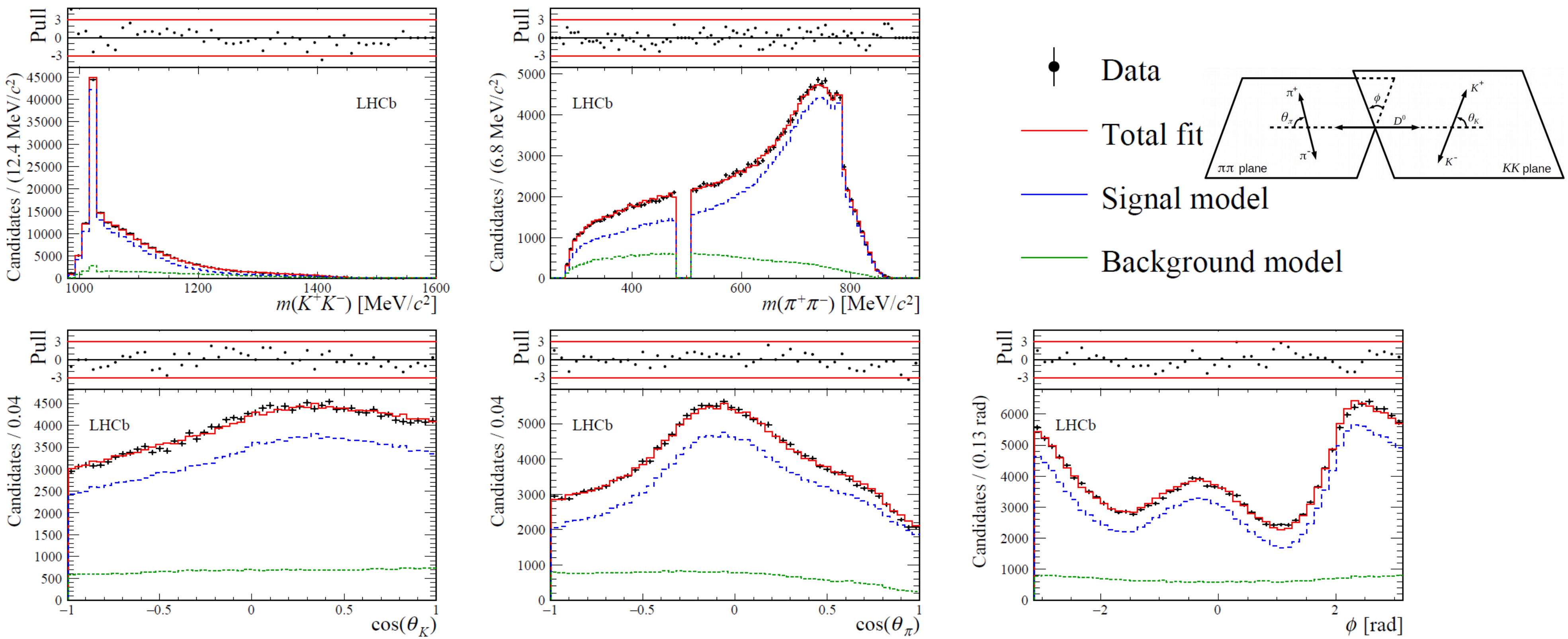
$$\begin{aligned} A_{CP}(D_s^+ \to K_S^0\pi^+) &= (1.6 \pm 1.7 \pm 0.5) \times 10^{-3} \\ A_{CP}(D^+ \to K_S^0K^+) &= (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3} \\ A_{CP}(D^+ \to \phi\pi^+) &= (0.03 \pm 0.40 \pm 0.29) \times 10^{-3} \end{aligned}$$

Best A_{CP} measurements on these channels!

CPV in $D^0 \to K^+K^-\pi^+\pi^-$

- Large number of interfering amplitudes could enhance CPV in multi-body D^0 decays
- 3 fb^{-1} Run1 LHCb data
- 160 k D^0 signal candidates from production mode of $B \to D^0\mu^- X$
- Using isobar model, N=26 amplitudes selected to describe signal in 5D phase space

$$S(\boldsymbol{x};\boldsymbol{c}) = \left|\sum_{k=1}^{N} c_k A_k(\boldsymbol{x})\right|^2$$



[JHEP 02 (2019) 126]

CPV in $D^0 \to K^+K^-\pi^+\pi^-$

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- 3 fb^{-1} Run1 LHCb data
- 160 k D^0 signal candidates from production mode of $B \to D^0 \mu^- X$
- Using isobar model, N=26 amplitudes selected to describe signal in 5D phase space
- Simultaneous fit of D^0 and $\overline{D}^0$ decays to extract CPV parameters for each amplitude
- All parameters consistent with CP conservation with a sensitivity ranging from 1% to 15%

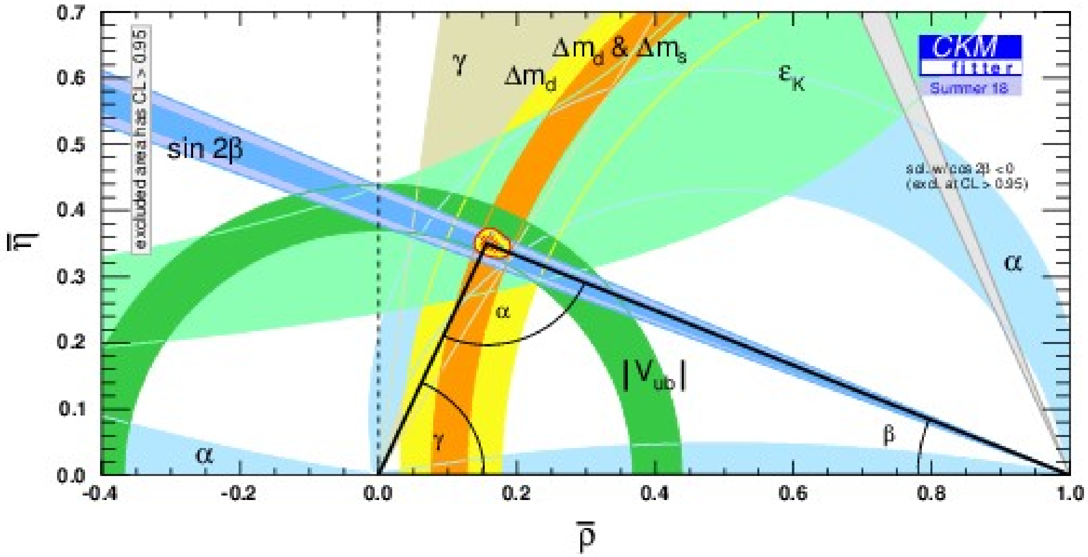
$$S(\boldsymbol{x};\boldsymbol{c}) = \left| \sum_{k=1}^{N} c_k A_k(\boldsymbol{x}) \right|^2$$

$$\overline{|c_k|} = \frac{|c_k|_{D^0} + |c_k|_{\overline{D}^0}}{2}, \qquad A_{|c_k|} = \frac{|c_k|_{D^0} - |c_k|_{\overline{D}^0}}{|c_k|_{D^0} + |c_k|_{\overline{D}^0}},$$

$$\overline{\arg(c_k)} = \frac{\arg(c_k)_{D^0} + \arg(c_k)_{\overline{D}^0}}{2}, \qquad \Delta\arg(c_k) = \frac{\arg(c_k)_{D^0} - \arg(c_k)_{\overline{D}^0}}{2},$$

$$\mathcal{F}_k = \frac{\int |c_k A_k(\boldsymbol{x})|^2 \mathcal{R}_4(\boldsymbol{x}) d^5\boldsymbol{x}}{\int |\sum_{\ell=1}^{N} c_\ell A_\ell(\boldsymbol{x})|^2 \mathcal{R}_4(\boldsymbol{x}) d^5\boldsymbol{x}} \qquad A_{\mathcal{F}_k} = \frac{\mathcal{F}_k^{D^0} - \mathcal{F}_k^{\overline{D}^0}}{\mathcal{F}_k^{D^0} + \mathcal{F}_k^{\overline{D}^0}}$$

CP violation in b-hadron decays



- CKM matrix: origin of CPV in SM
- Test of the Unitarity Triangle: measuring CKM angle γ
- γ Can be measured using exclusively tree-level decays such as $B \rightarrow Dh$ ($h = K, K^*, \pi, \pi\pi$)

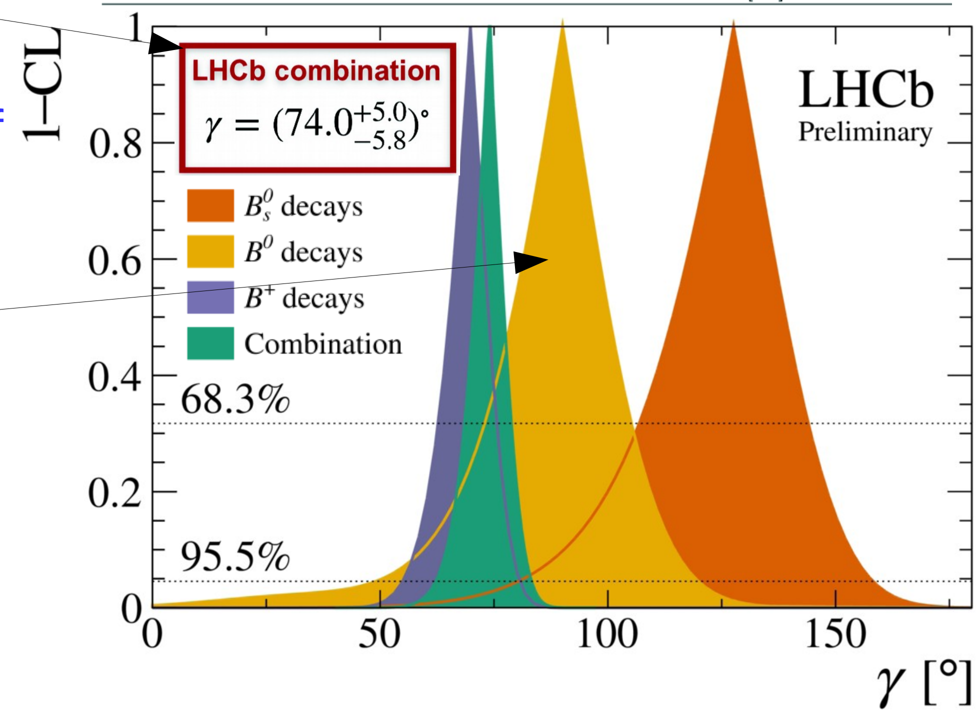
[LHCb-CONF-2018-002]

LHCb γ combination

- Combing many tree-level determinations of γ
  - New and updated results using Run2 2 fb^{-1} data
  - Analyses with full Run2 6 fb^{-1} data yet to come
- The γ world average is currently dominated by the 2018 LHCb combination
  - LHCb combination is dominated by B^+ decays
  - Tension (2σ) between B_s^0 and B^+ results
- New inputs from the ADS/GLW analysis of $B^0 \to DK^{*0}$ ($D \to KK$, $K\pi$, $\pi\pi$, $K\pi\pi\pi$, $\pi\pi\pi\pi$) [JHEP 08 (2019) 041] to be added to the combination
  - Will lead to reduction in the yellow region!

Direct BESIII measurements on strong phase parameters in D decays are important for LHCb γ measurements

B decay	D decay	Method	Ref.	Dataset[†]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1
$B^+ \to DK^+$	$D \to K_S^0h^+h^-$	GGSZ	[17]	Run 1
$B^+ \to DK^+$	$D \to K_S^0h^+h^-$	GGSZ	[18]	Run 2
$B^+ \to DK^+$	$D \to K_S^0K^+\pi^-$	GLS	[19]	Run 1
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ	[24]	Run 1
$B_s^0 \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1

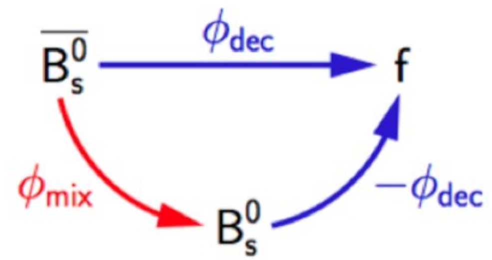


B_s mixing phase ϕ_s

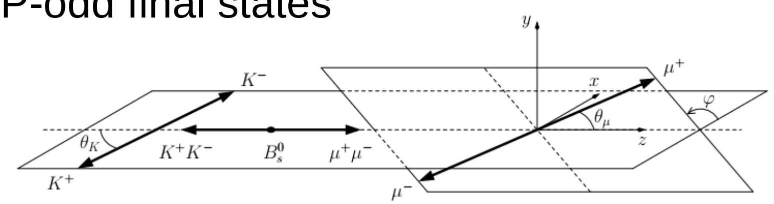
$\lambda \equiv \arg\left[(q/p)\,(\overline{A}/A)\right]$ $\quad \beta_s \equiv \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$

- Mixing-induced CPV phase in $b \to c\bar{c}s$ processes

$$\phi_s = -\arg(\lambda) = \phi_{\rm mix} - 2\,\phi_{\rm dec} \approx -2\beta_s$$

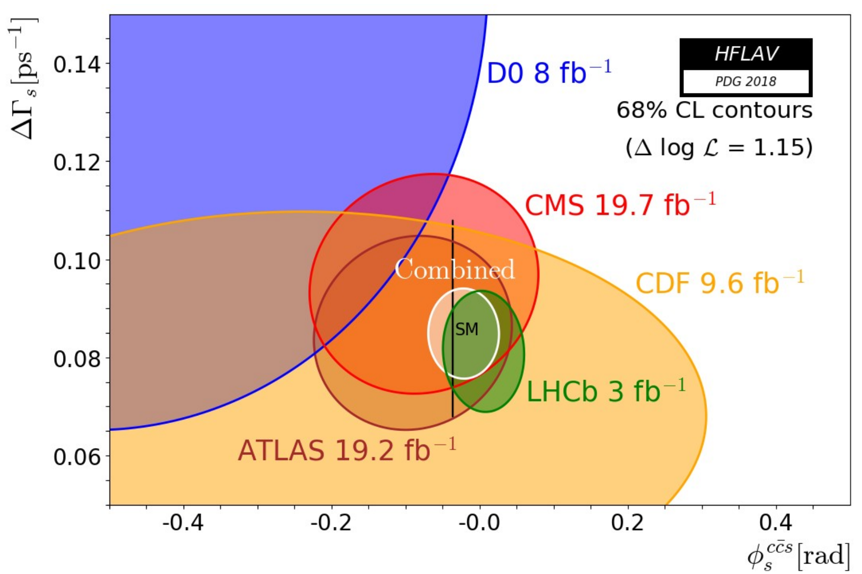


  - Well predicted in SM, NP could bring in sizable contribution
- Accessed through measurements of time-dependent CP asymmetries in B_s decays to CP eigenstates e.g. $B_s \to J/\psi\phi$ with
  - Good decay time resolution (fast B_s oscillation)
  - Efficient flavor tagging power (~5% in LHCb)
  - Angular analysis to disentangle CP-even and CP-odd final states



- World average, then dominated by LHCb Run 1 results, compatible with SM

Status of ϕ_s before Moriond EW 2019

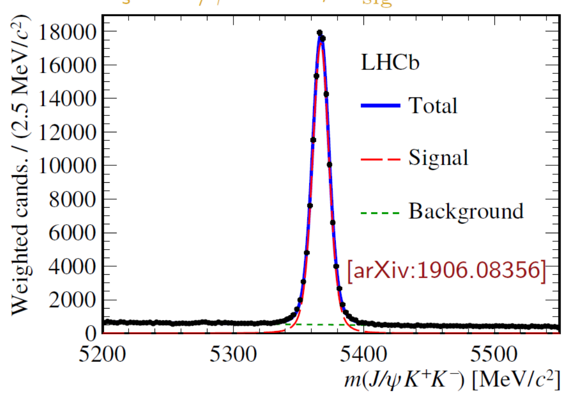


Measurements of ϕ_s with $B_s \to J/\psi hh$

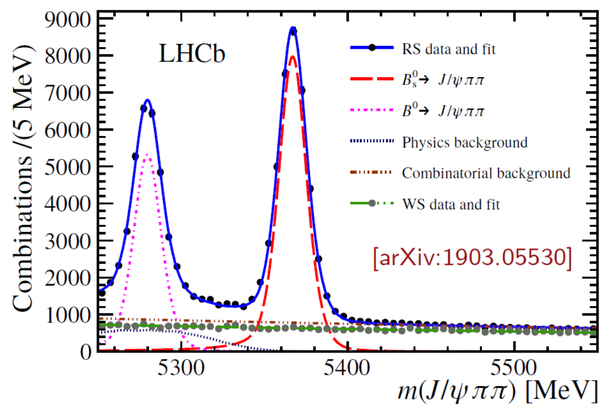
- Update with 2 fb^{-1} Run2 data using $B_s \to J/\psi(\mu\mu)KK$ [EPJC 79 (2019) 706] and $B_s \to J/\psi(\mu\mu)\pi\pi$ decays [PLB 797 (2019) 134789]

See Wenhua Hu's talk in Heavy Flavor session on 24th

$B_s^0 \to J/\psi K^+K^-$, $N_{sig} \sim 117\,000$



$B_s^0 \to J/\psi \pi^+\pi^-$, $N_{sig} \sim 33\,500$



- Combination of Run1 and Run2 gives the most precise ϕ_s result to date, from a single experiment

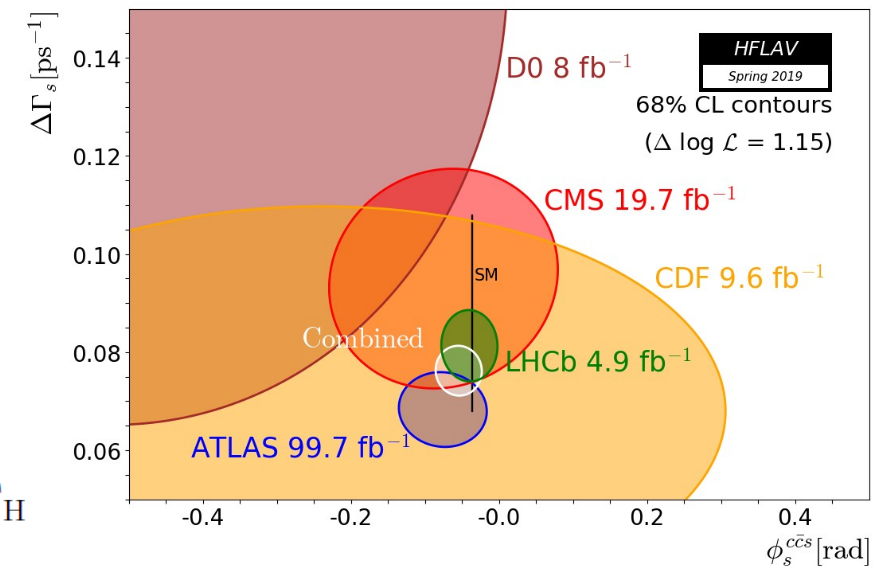
[EPJC 79 (2019) 706]

$$\phi_s = -0.041 \pm 0.025\,\text{rad}$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048\,\text{ps}^{-1}$$

Compatible with SM

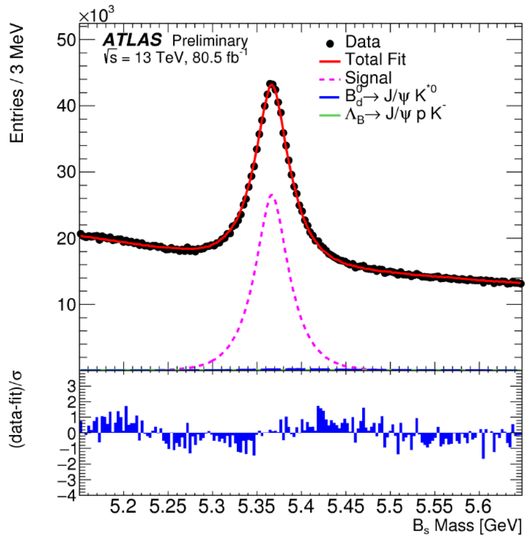
$$\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$$

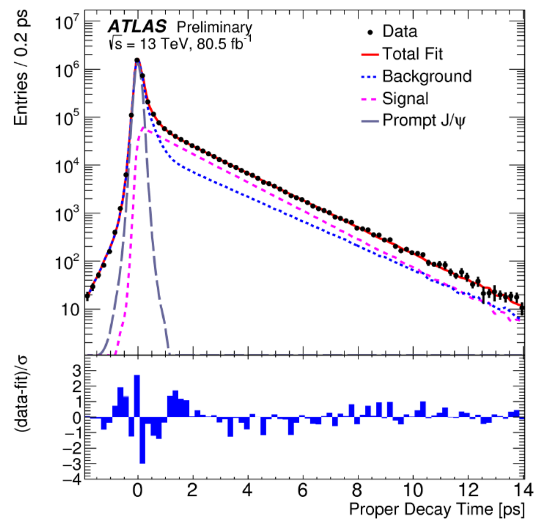
Current status of ϕ_s



Measurement of ϕ_s with $B_s \rightarrow J/\psi KK$

- Update with 80.5 fb^{-1} Run2 (2015-2017) data using $B_s \rightarrow J/\psi(\mu\mu)\phi(KK)$ decays





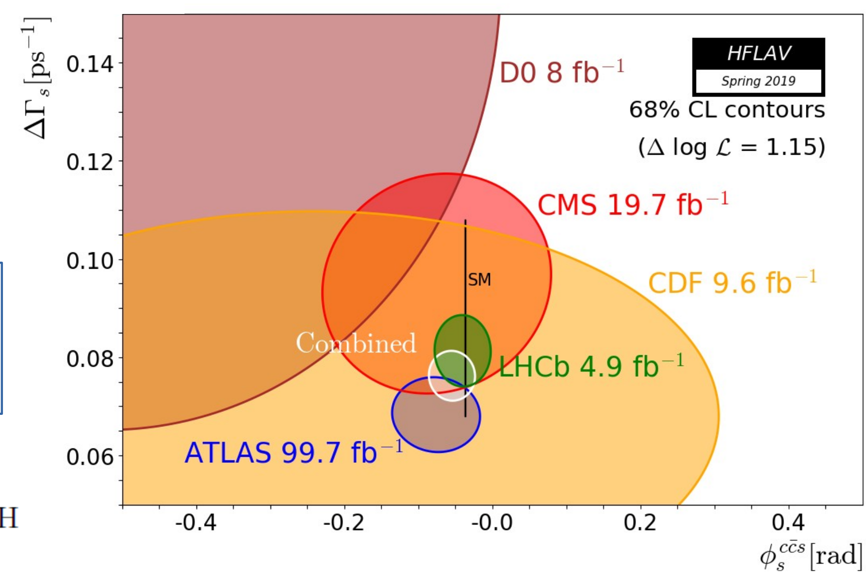
- Combination of Run1 and Run2 gives following results:

$$
\begin{aligned}
\phi_s &= -0.076 \pm 0.034\ (\text{stat.}) \pm 0.019\ (\text{syst.})\ \text{rad} \\
\Delta\Gamma_s &= 0.068 \pm 0.004\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1} \\
\Gamma_s &= 0.669 \pm 0.001\ (\text{stat.}) \pm 0.001\ (\text{syst.})\ \text{ps}^{-1}
\end{aligned}
$$

ATLAS preliminary

$$\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$$

Current status of ϕ_s

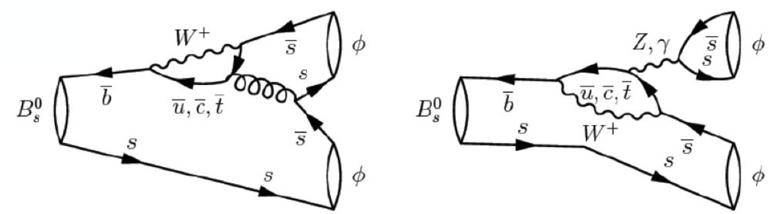


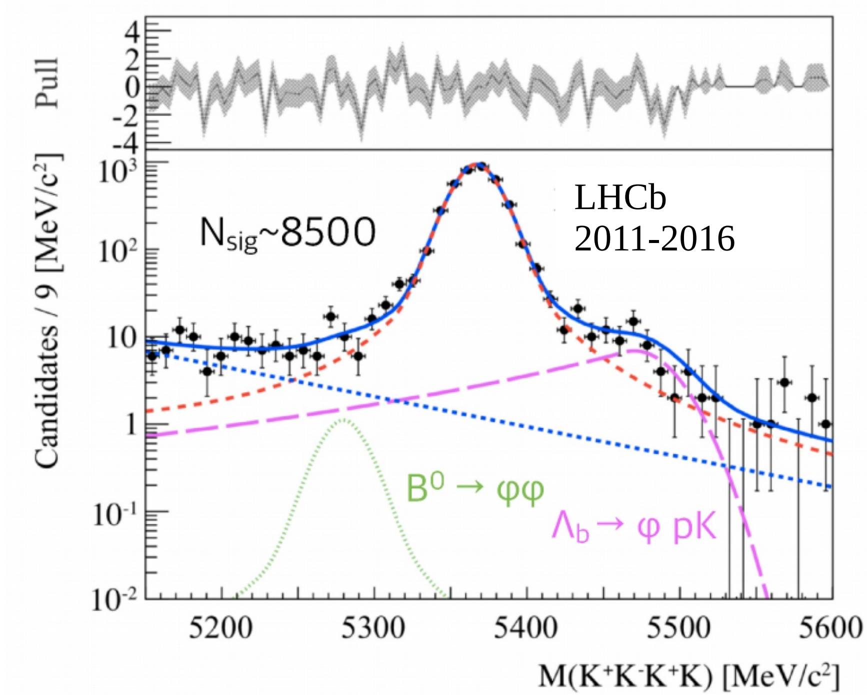
Measurement of CPV in $B_s \to \phi\phi$

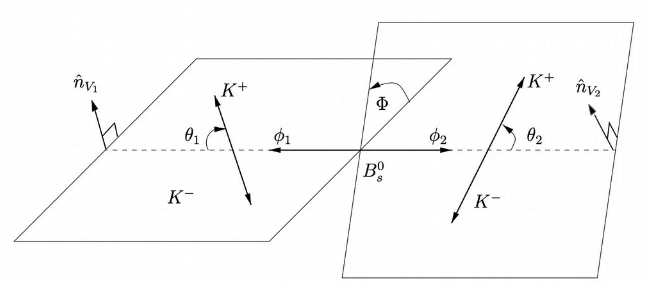
- Enhanced sensitivity to NP since this charmless decay is dominated by $b \to s\bar{s}s$ penguin loop
- Mixing with B_s oscillation could give rise to time-dependent CPV
  - CPV phase $\phi_s^{s\bar{s}s}$ predicted < 0.02 rad

    [PRD 80 (2009) 114026]
- Time-dependent angular analysis to disentangle CP eigenstates SS, SV, VV with Run1 + Run2 (2 fb^{-1}) data

$$\begin{aligned} \phi_s^{s\bar{s}s} &= -0.073 \pm 0.115\,(\text{stat}) \pm 0.027\,(\text{syst})\ \text{rad}, \\ |\lambda| &= 0.99 \pm 0.05\,(\text{stat}) \pm 0.01\,(\text{syst}). \end{aligned}$$



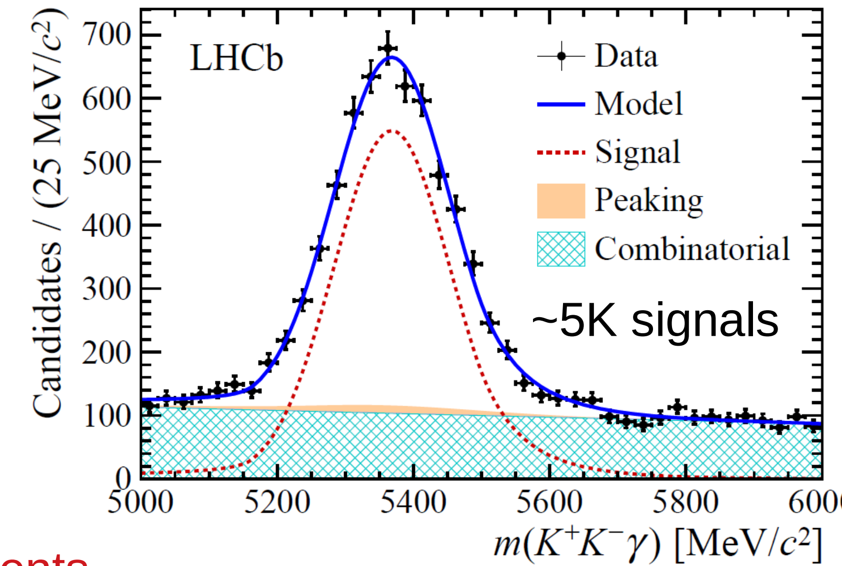




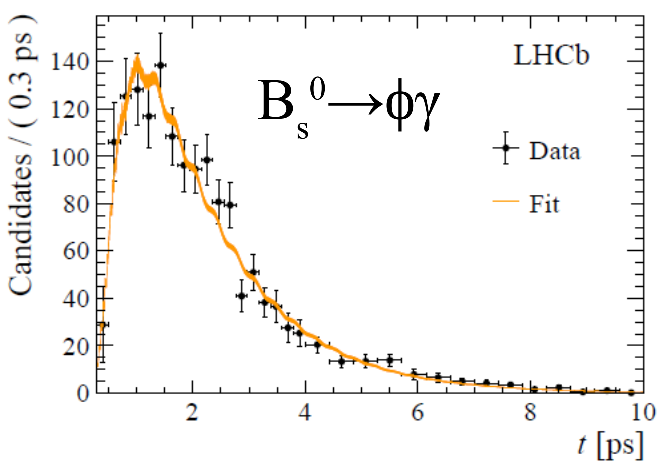
CPV measurements in $B_s^0 \to \phi\gamma$

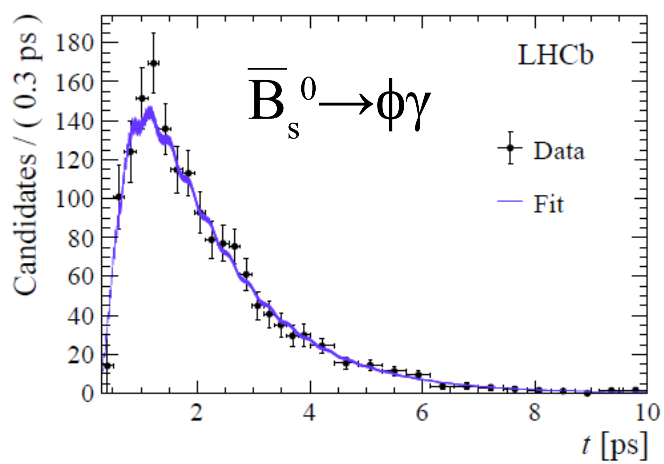
- With $3 fb^{-1}$ Run1 data, and using $B^0 \to K^{*0}\gamma$ as reference channel, LHCb reports:

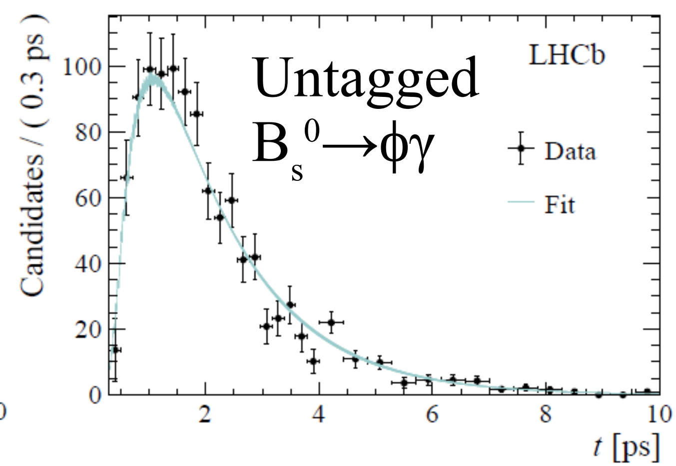
$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$



All consistent with SM, with ***S*** & ***C*** as first measurements

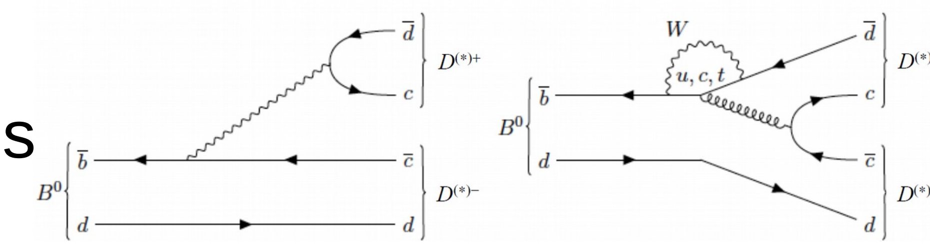




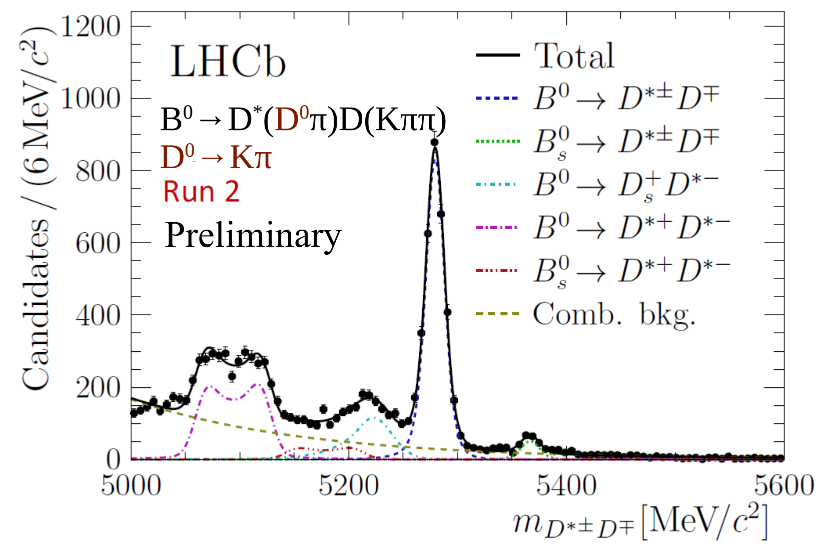


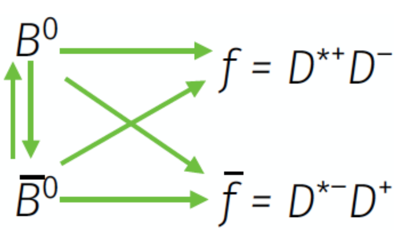
See Jibo He's talk right after this one

CPV measurements in $B^0 \to D^{*\pm}D^{\mp}$



- $b \to c\bar{c}d$ transition with contributions from tree, penguin & exchange diagrams
- Expecting mixing-induced CPV and possible direct CPV contributions
- Using four time-dependent decay rates for B^0 and $\bar{B}^0$ to f and $\bar{f}$ final states to measure 5 parameters:





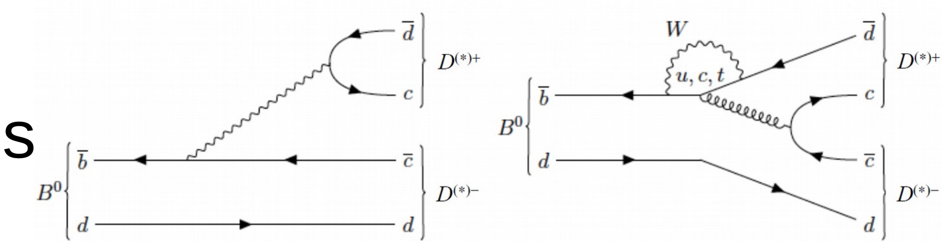
$$S_{D^*D} = \frac{1}{2}(S_{D^{*+}D^-} + S_{D^{*-}D^+}) \qquad C_{D^*D} = \frac{1}{2}(C_{D^{*+}D^-} + C_{D^{*-}D^+})$$

$$\Delta S_{D^*D} = \frac{1}{2}(S_{D^{*+}D^-} - S_{D^{*-}D^+}) \qquad \Delta C_{D^*D} = \frac{1}{2}(C_{D^{*+}D^-} - C_{D^{*-}D^+})$$

$$A_{D^*D} = A_{f\bar{f}}$$

$$\frac{\mathrm{d}\Gamma_{\bar{B}^0,f}(t)}{\mathrm{d}t} = \frac{\mathrm{e}^{-t/\tau_d}}{8\tau_d}(1 + A_{f\bar{f}})\Big[1 + S_f \sin(\Delta m_d t) - C_f \cos(\Delta m_d t)\Big]$$

CPV measurements in $B^0 \to D^{*\pm}D^{\mp}$



- $b \to c\bar{c}d$ transition with contributions from tree, penguin & exchange diagrams
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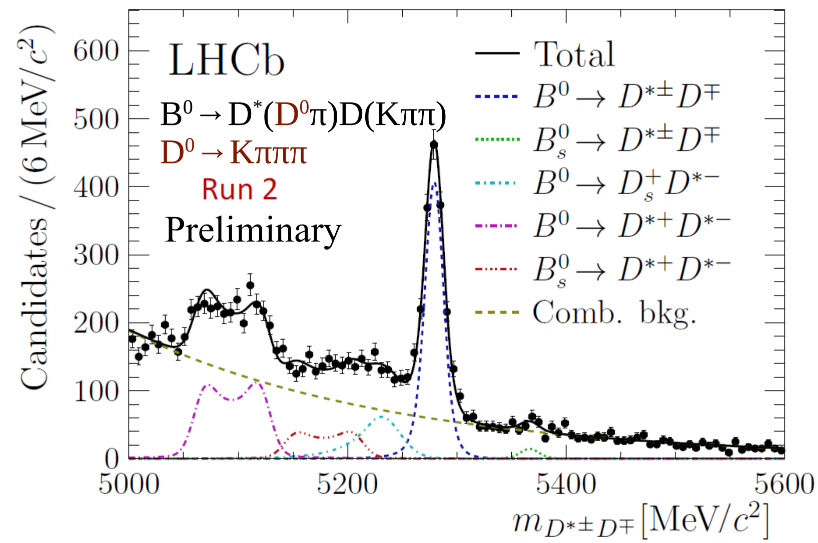

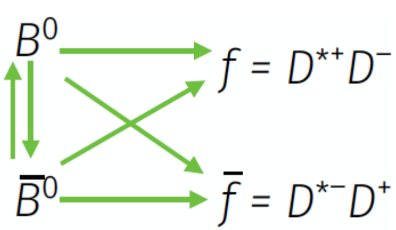

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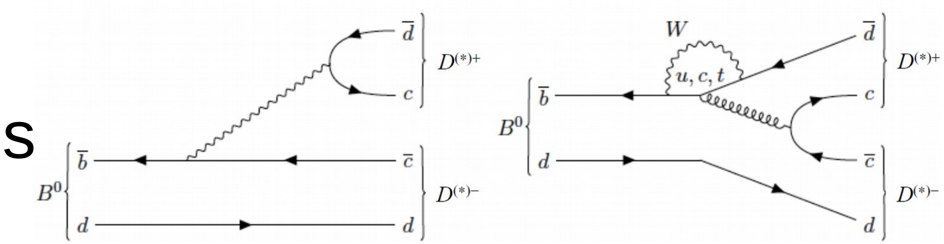


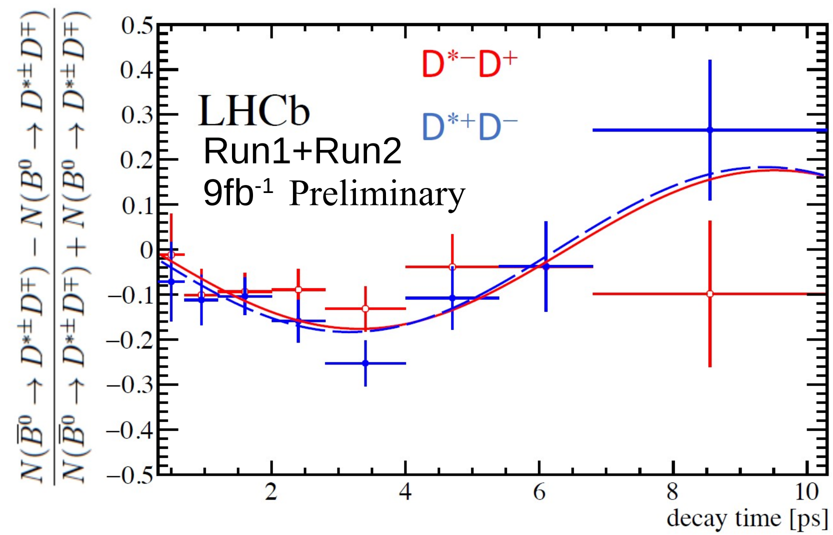
- $b \to c\bar{c}d$ transition with contributions from tree, penguin & exchange diagrams
- Expecting mixing-induced CPV and possible direct CPV contributions
- Using four time-dependent decay rates for B^0 and $\overline{B}^0$ to f and $\bar{f}$ final states to measure 5 parameters:

$$
\begin{aligned}
S_{D^*D} &= -0.861 \pm 0.077\,(\text{stat}) \pm 0.019\,(\text{syst}) \\
\Delta S_{D^*D} &= 0.019 \pm 0.075\,(\text{stat}) \pm 0.012\,(\text{syst}) \\
C_{D^*D} &= -0.059 \pm 0.092\,(\text{stat}) \pm 0.020\,(\text{syst}) \\
\Delta C_{D^*D} &= -0.031 \pm 0.092\,(\text{stat}) \pm 0.016\,(\text{syst}) \\
A_{D^*D} &= 0.008 \pm 0.014\,(\text{stat}) \pm 0.005\,(\text{syst})
\end{aligned}
$$

Preliminary

Main correlations:

$\rho(S_{D^*D}, C_{D^*D}) = 0.44$ $\qquad$ $\rho(\Delta S_{D^*D}, \Delta C_{D^*D}) = 0.46$

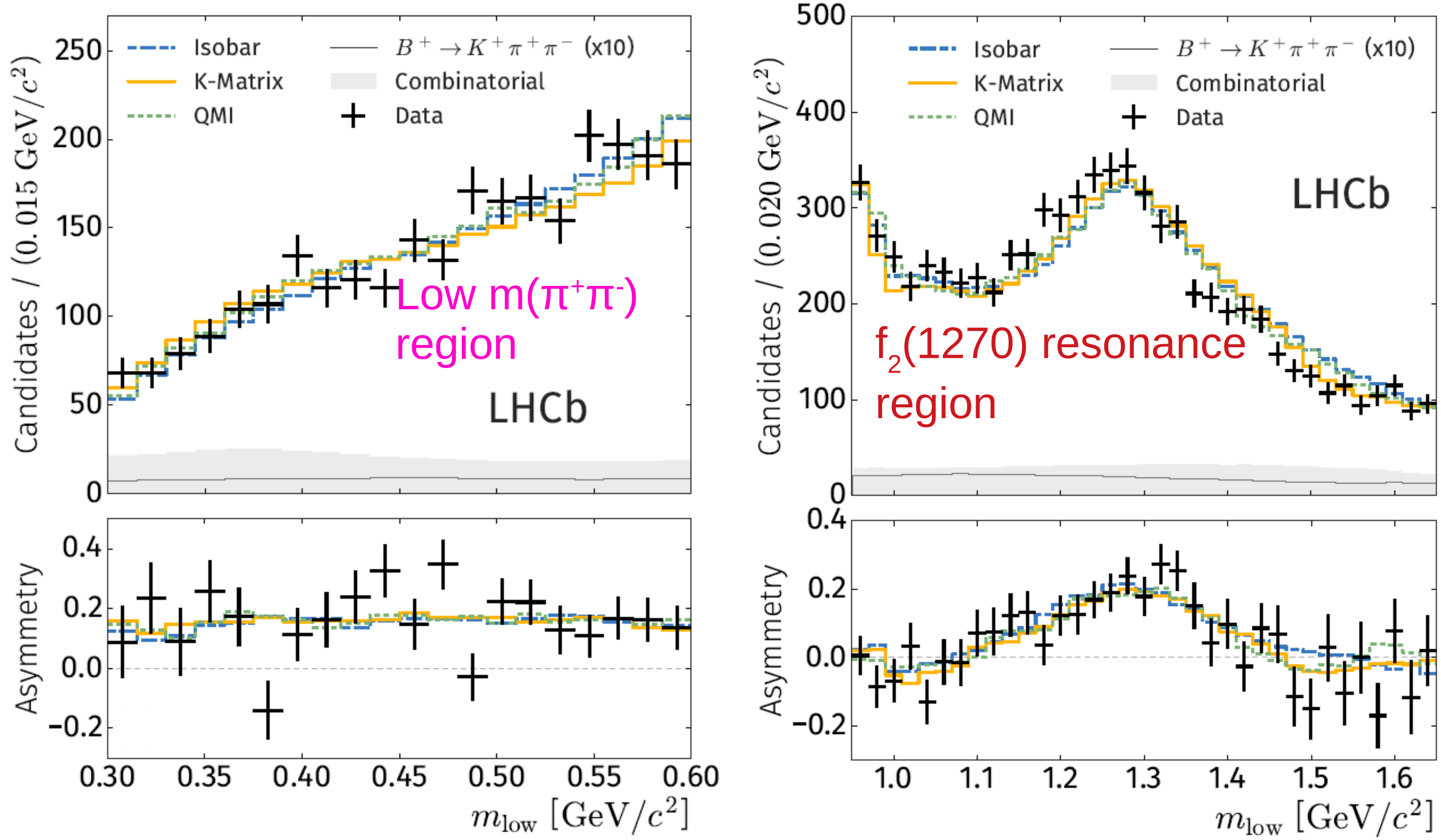


All results are compatible with, and more precise than previous measurements

CPV in $B^+ \to \pi^+\pi^+\pi^-$

- With Run1 3fb^{-1} data, LHCb observes several sources of CPV by performing the amplitude analysis:

Significance CPV observed in the decay amplitudes associated with $f_2(1270)$ and low mass $\pi^+\pi^-$ s-wave

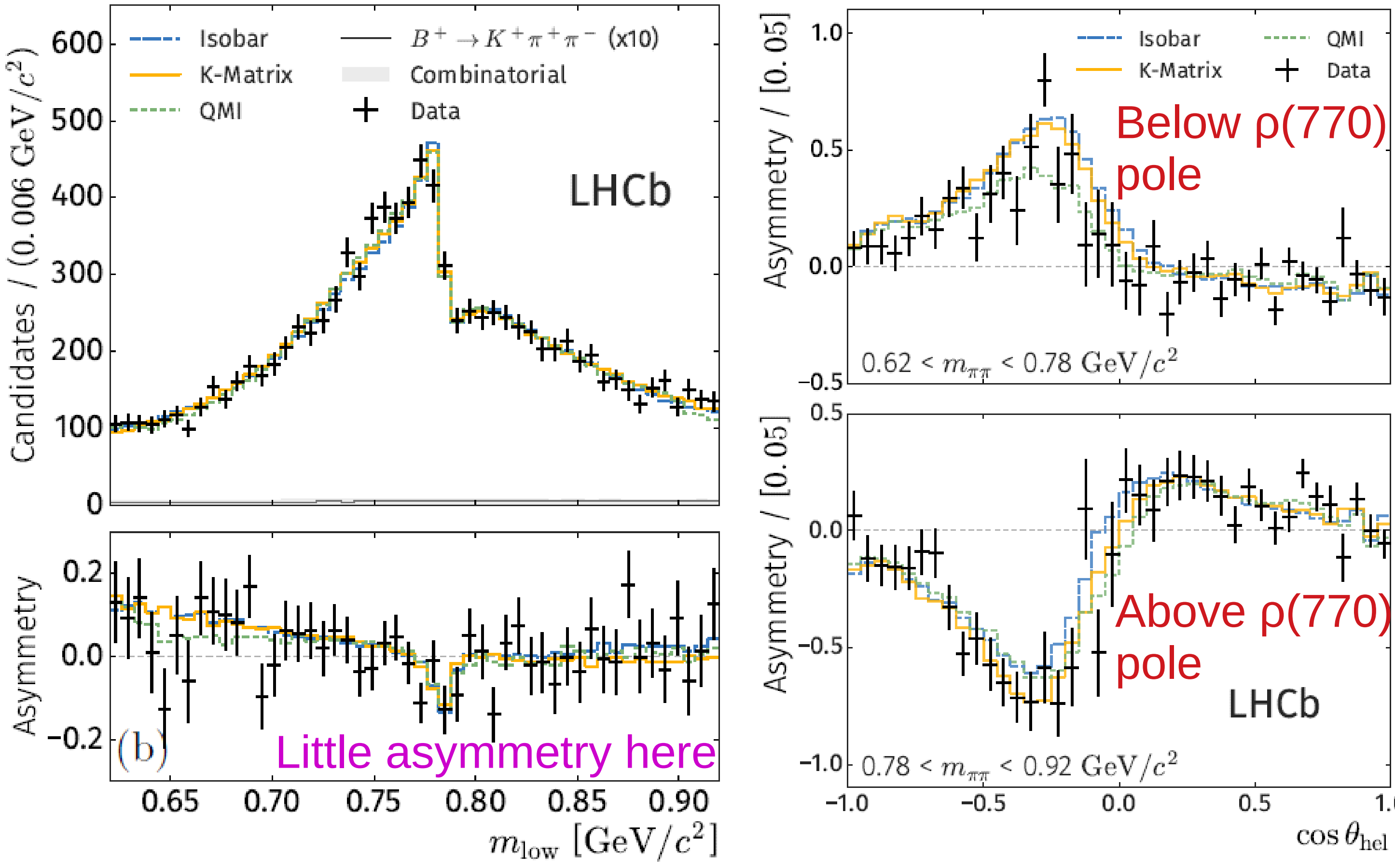


[arXiv:1909.05211, arXiv:1909.05212]

CPV in $B^+ \to \pi^+\pi^+\pi^-$

- With Run1 3fb^{-1} data, LHCb observes several sources of CPV by performing the amplitude analysis:

First observation of CPV characteristic of interference between the spin-1 ρ(770) and spin-0 S-wave



[arXiv:1909.05211, arXiv:1909.05212]

CPV in $B^+ \to \pi^+\pi^+\pi^-$

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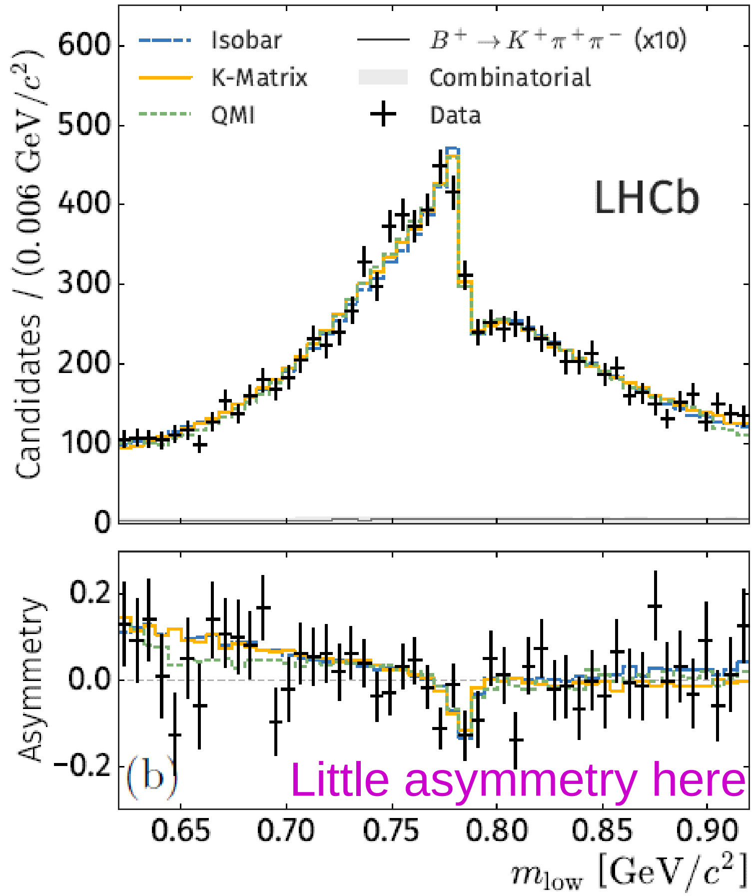
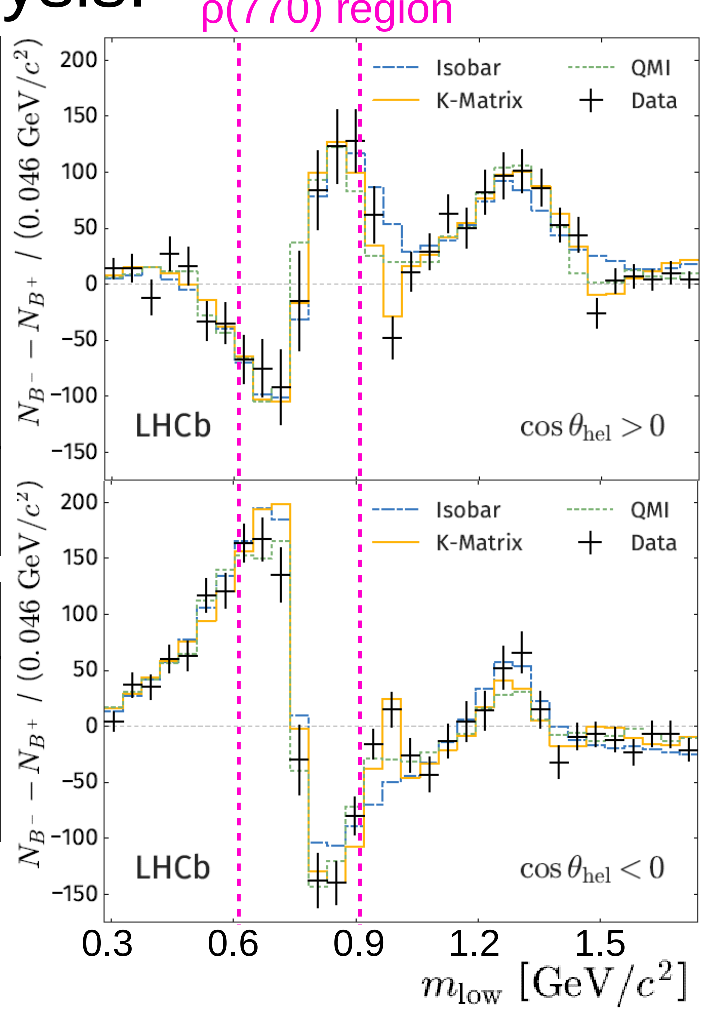
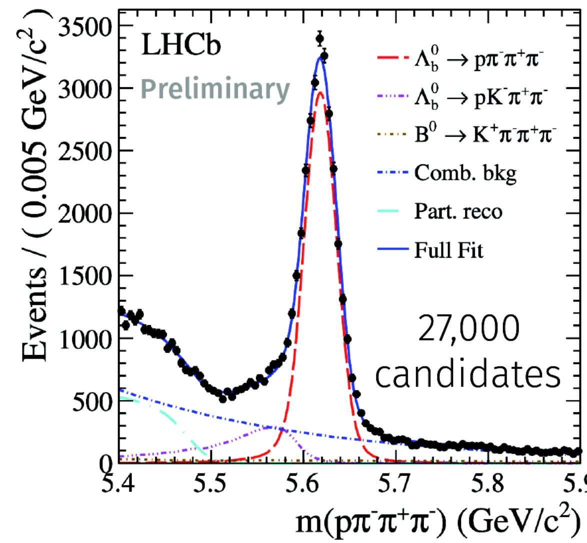
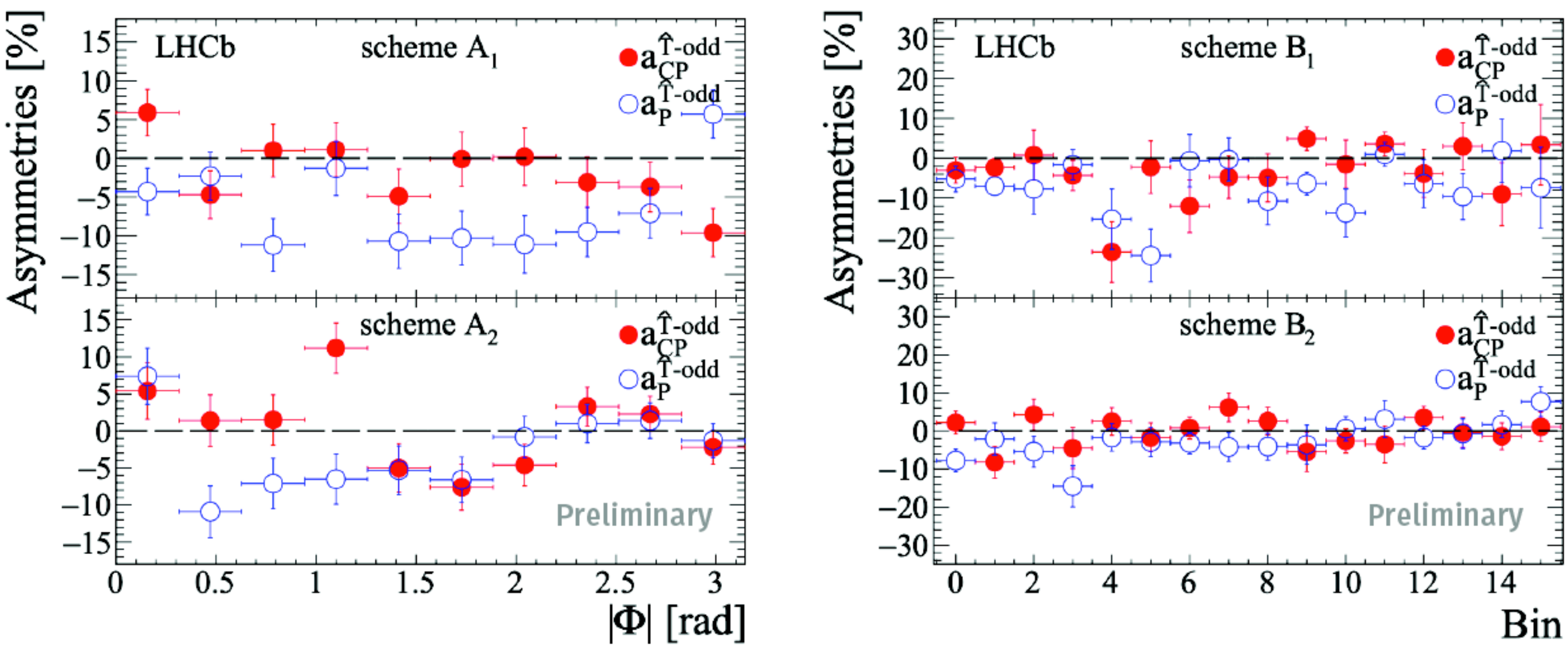




CP and P violation in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$

- CPV yet to be observed in baryon decays
- With 6.6 fb^{-1} Runs1+2 data, LHCb reports the first observation of P violation in b-baryon decay
  - No evidence for **CPV** found, an update to the previous LHCb analysis [Nat. Phy. 13 (2017) 391]
  - Energy test method gives consistent results





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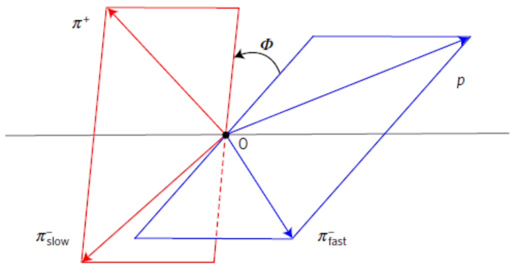
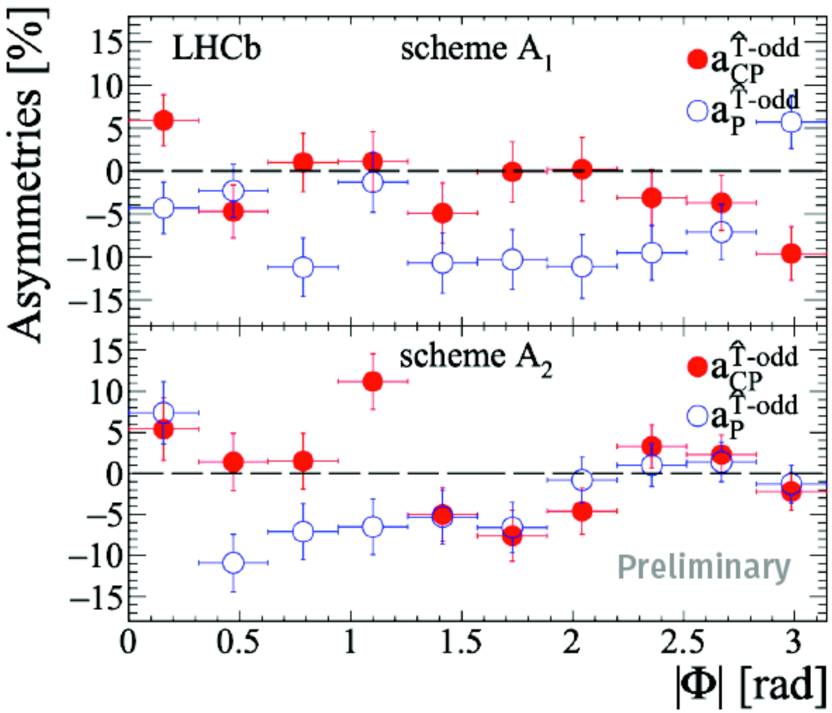


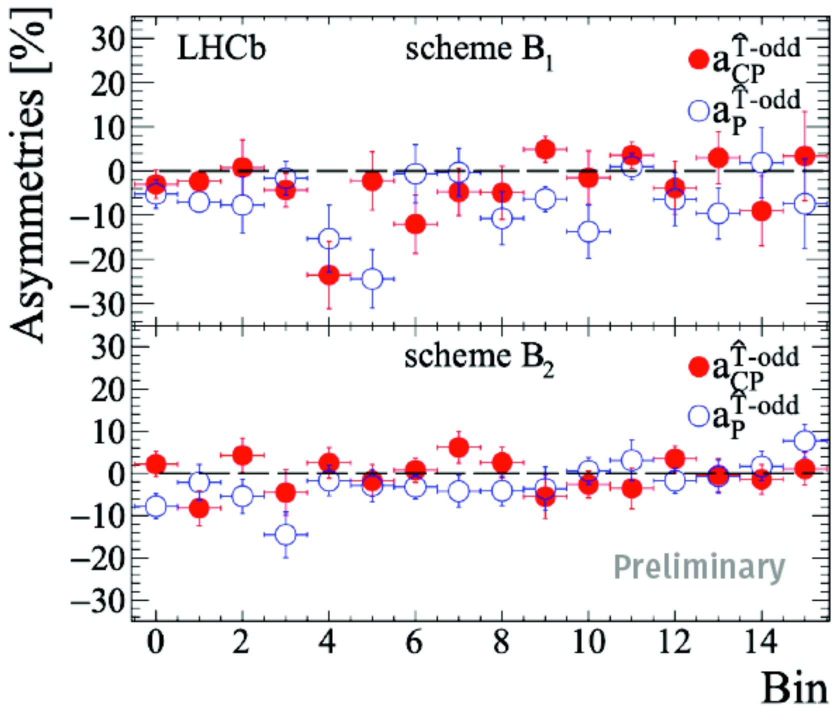
Triple-product asymmetries:

$$C_{\hat{T}} \equiv \vec{p}_{p^+} \cdot (\vec{p}_{\pi^-_{\text{fast}}} \times \vec{p}_{\pi^+})$$

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}, \quad \overline{A}_{\hat{T}} = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)},$$

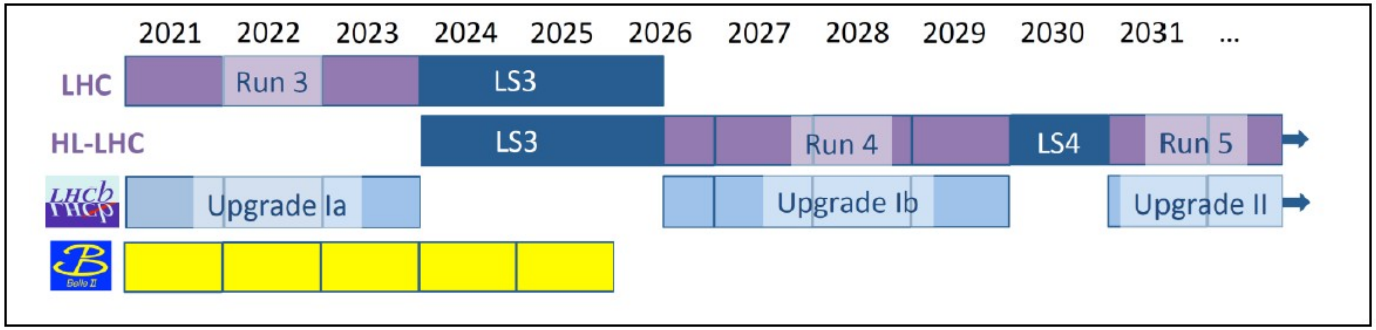
$$a_P^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \overline{A}_{\hat{T}}\right), \; a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)$$

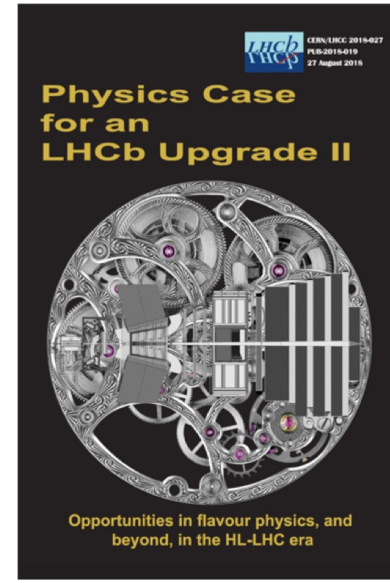




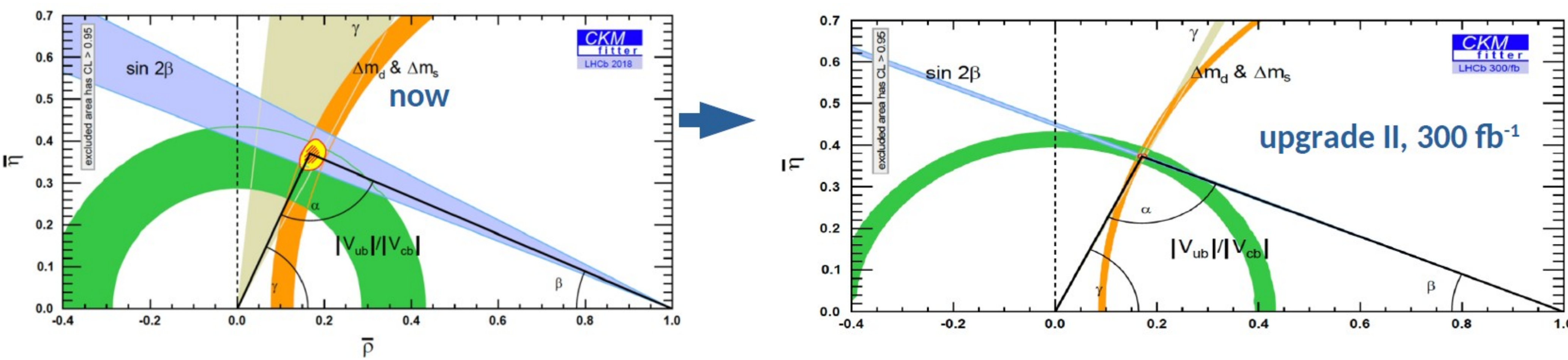
Prospects of LHCb

- Major upgrade phases





  - Upgrade (2020-2023) will provide 3x larger dataset
  - Upgrade (2025-) will be for HL-LHC to collect > 300/fb (30x of current level)

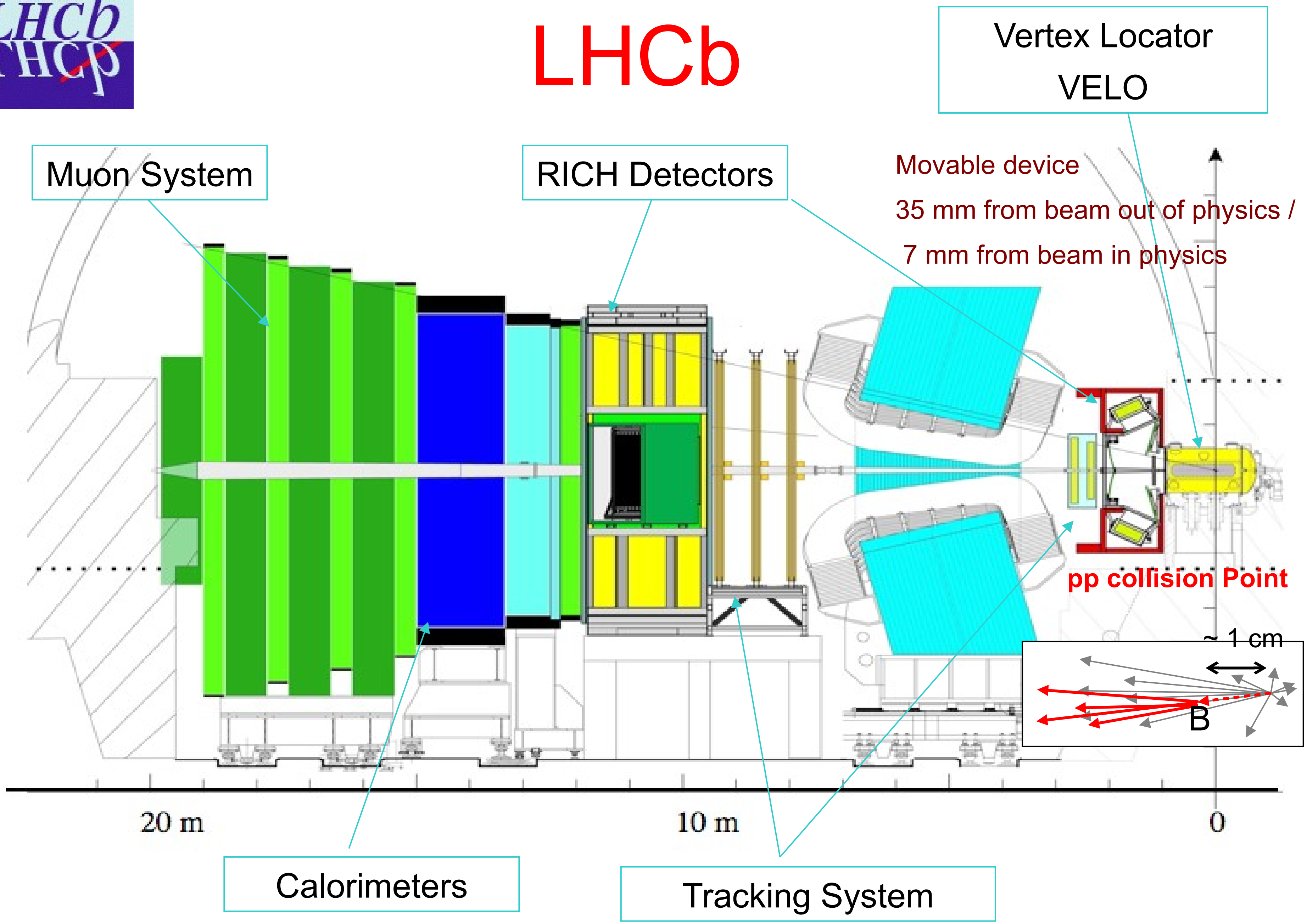


Summary

- For the past few years, LHCb has been quite successful in CPV searches, while ATLAS and CMS have shown their capabilities and potential in the field of heavy flavor physics
  - LHCb highlights 2019: **first observations** of CPV in D^0 decays, and P violation in b-baryon decay, etc.
- Many interesting results from LHC experiments based on Runs1-2 data are still in the pipeline, so stay tuned!
- LHCb upgrade opens up possibilities to many improvements in precision, so interesting times are still ahead on searching for CPV beyond SM

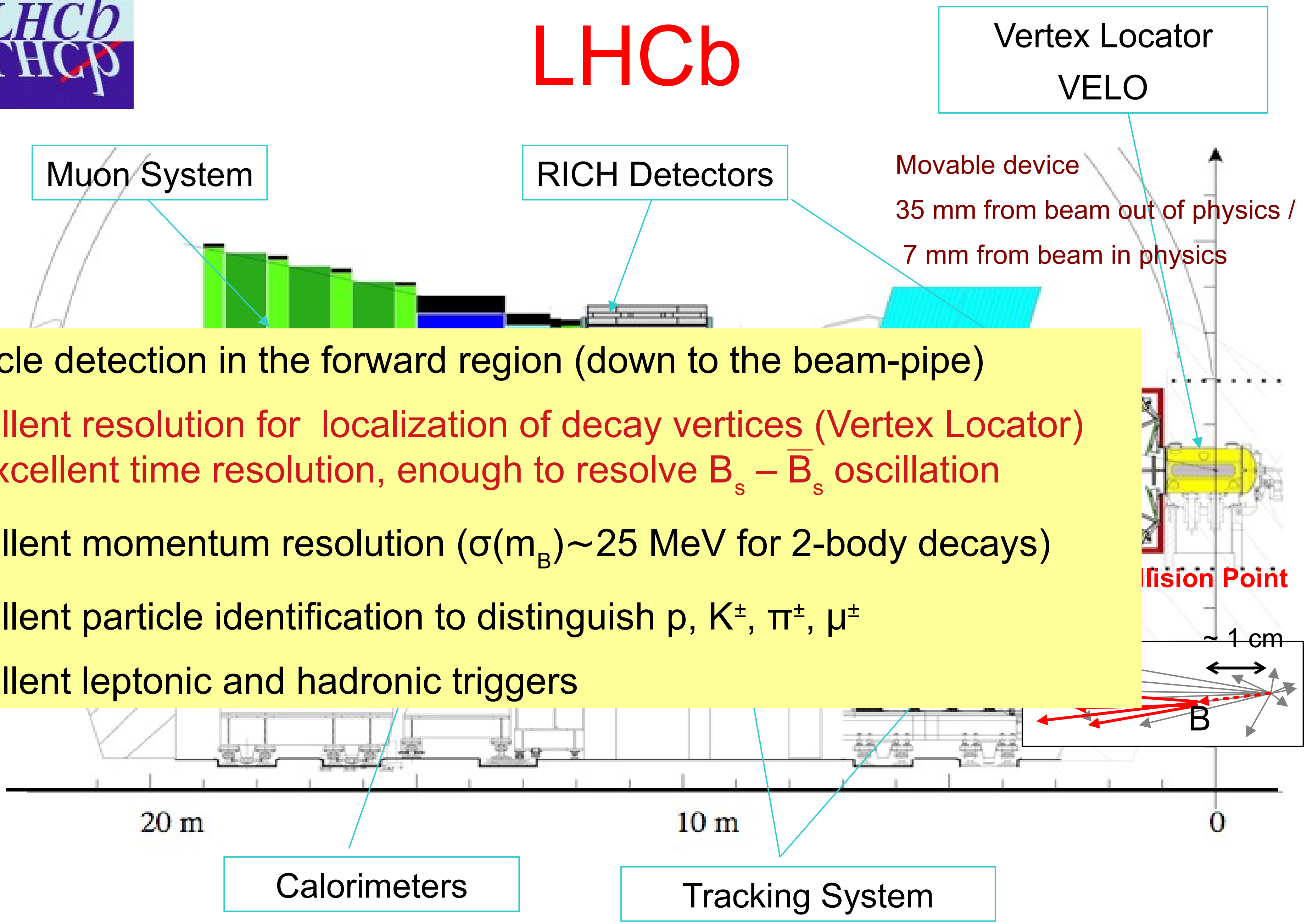
Backup Slides

LHCb


Vertex Locator
VELO
Muon System
RICH Detectors
Movable device
35 mm from beam out of physics /
7 mm from beam in physics
pp collision Point
~ 1 cm
B
20 m
10 m
0
Calorimeters
Tracking System

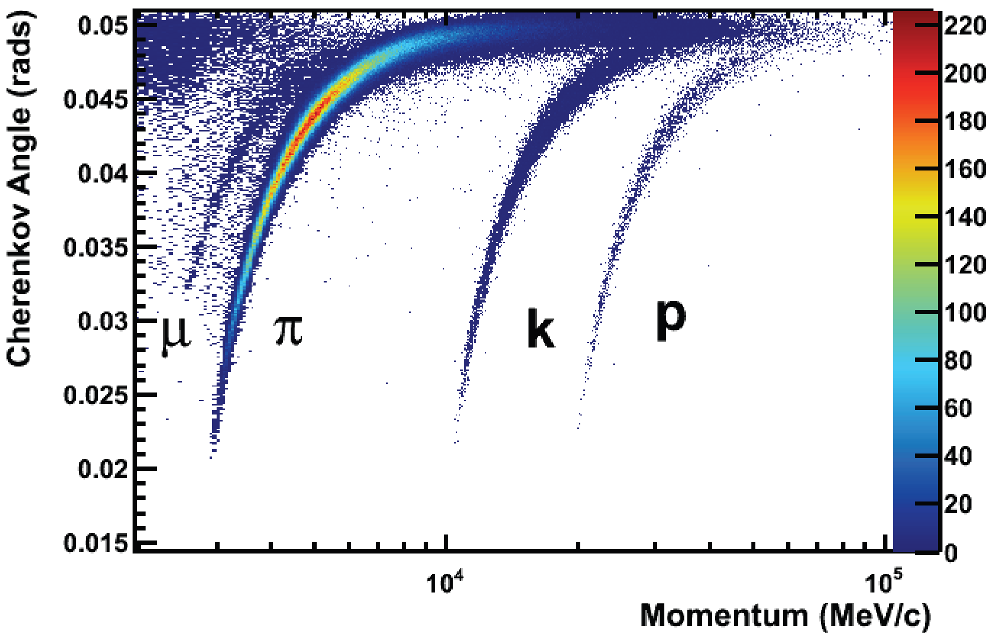
[Int. J. Mod. Phys. A30 (2015)1530022]

LHCb

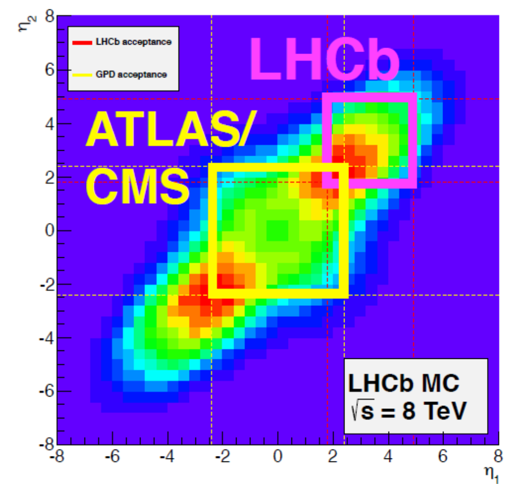


- Particle detection in the forward region (down to the beam-pipe)
- Excellent resolution for localization of decay vertices (Vertex Locator)
  → Excellent time resolution, enough to resolve $B_s - \overline{B}_s$ oscillation
- Excellent momentum resolution ($\sigma(m_B)$~25 MeV for 2-body decays)
- Excellent particle identification to distinguish p, $K^{\pm}$, $\pi^{\pm}$, $\mu^{\pm}$
- Excellent leptonic and hadronic triggers

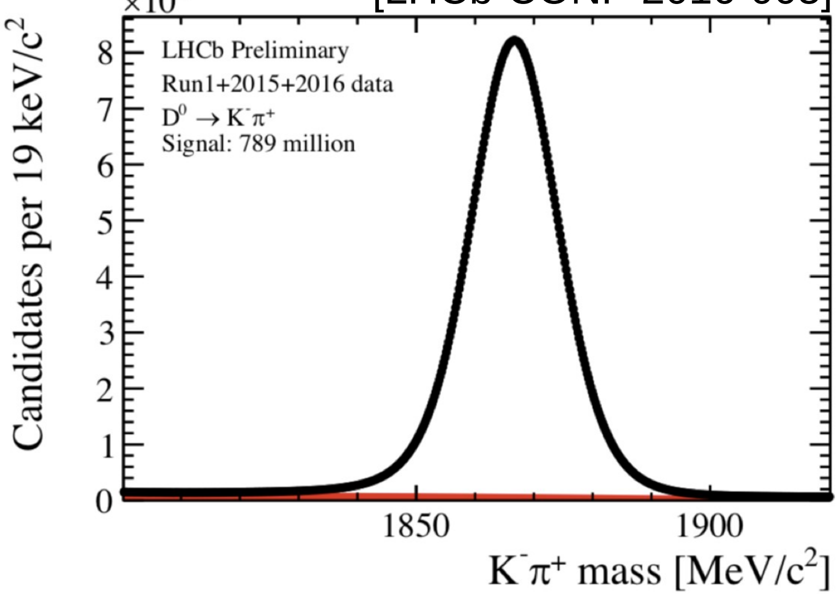
Detector performance



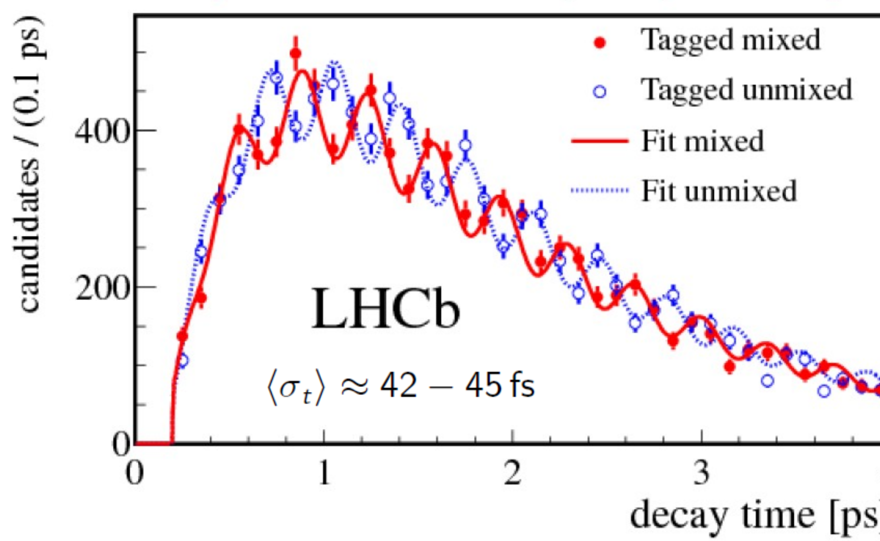
$pp \to b\bar{b}$ cross section



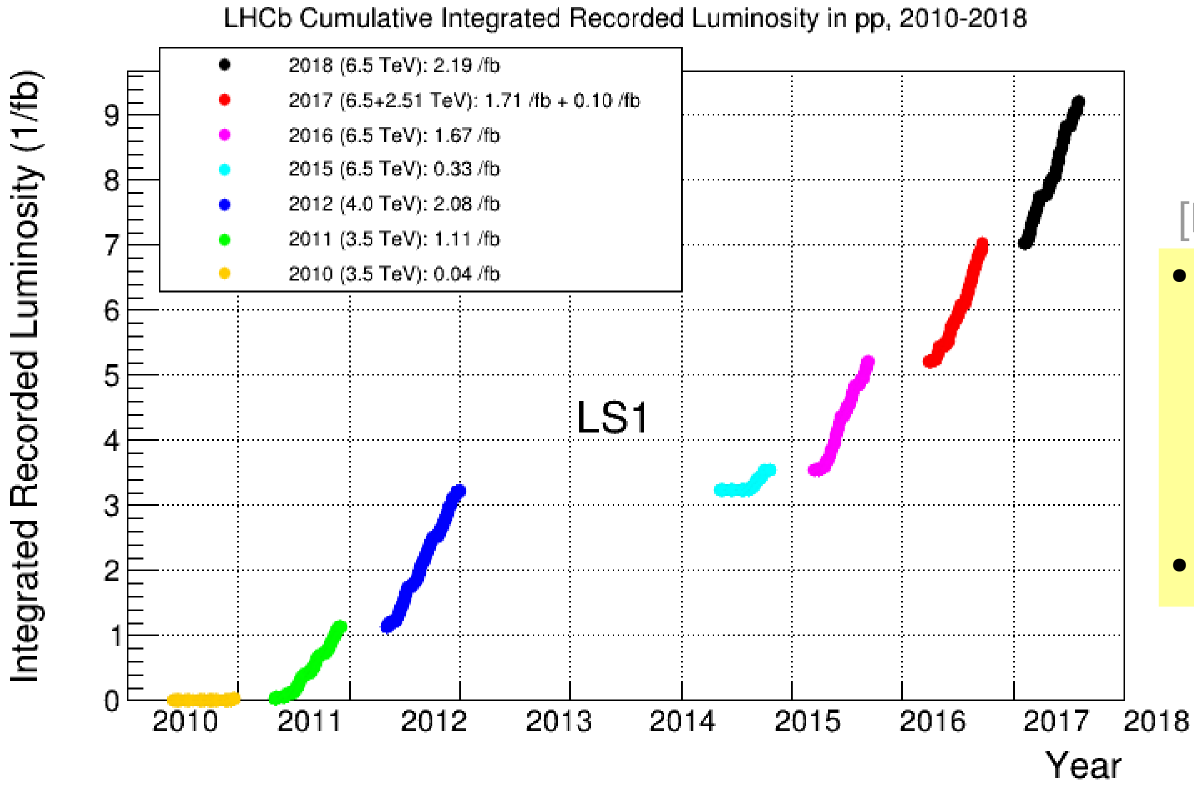
[LHCb-CONF-2016-005]



[New J. Phys. 15 (2013) 053021]



LHCb dataset



[PRL 118 (2017) 052002]

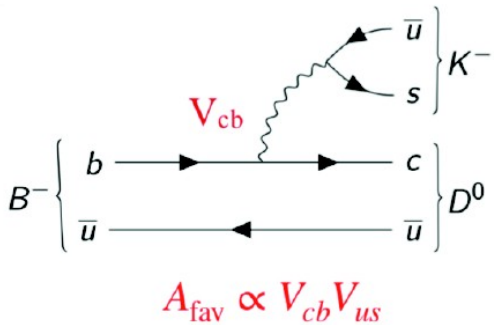
- $b\bar{b}$ cross-section @ $\sqrt{s}$ = 13 TeV: 154.3 ± 1.5 ± 14.3 μb
  - ~10^5 $b\bar{b}$ pairs produced/second and all species of b hadrons: $B^{\pm}$, B^0, B_s^0, B_c^+, Λ_b^0,...
- Charm production ~20x higher

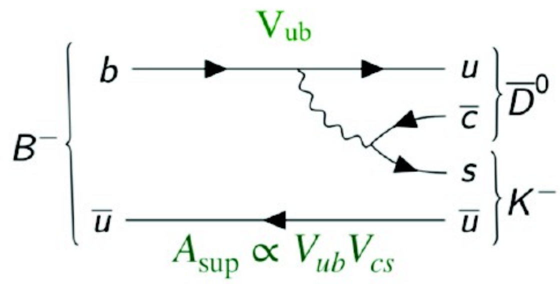
Most of the present analyses use:

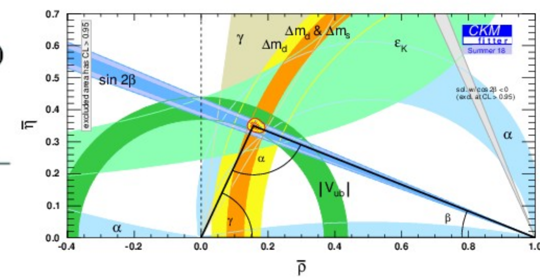
- Run I: 1.0 fb^{-1} @ 7 TeV (2011) + 2.0 fb^{-1} @ 8 TeV (2012)
- Run II: 0.3 fb^{-1} (2015) + 1.7 fb^{-1} (2016) + 1.7 fb^{-1} (2017) + 2.2 fb^{-1} (2018) @ 13 TeV

Test of the Unitarity Triangle: measuring CKM angle γ

- Can be measured using exclusively tree-level decays such as $B \to Dh$ ($h = K, K^*, \pi, \pi\pi$)
  - Interference between $b \to c$ (favored) and $b \to u$ (suppressed) transitions







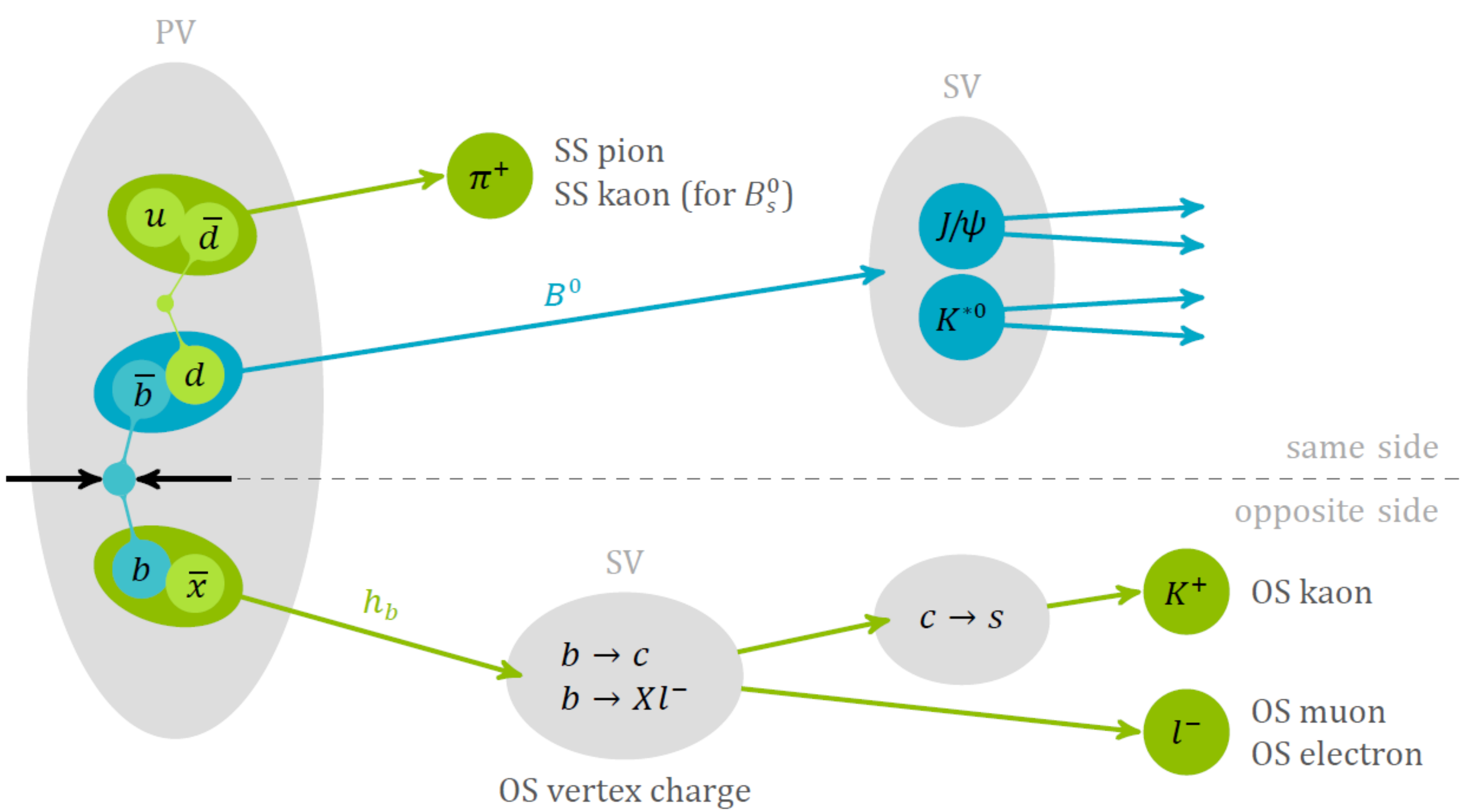
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \qquad \frac{A_{sup}}{A_{fav}} = r_B^{Dh} e^{\delta_B^{Dh} \pm \gamma}$$

where **r** is the ratio of magnitudes and **δ** the strong phase difference

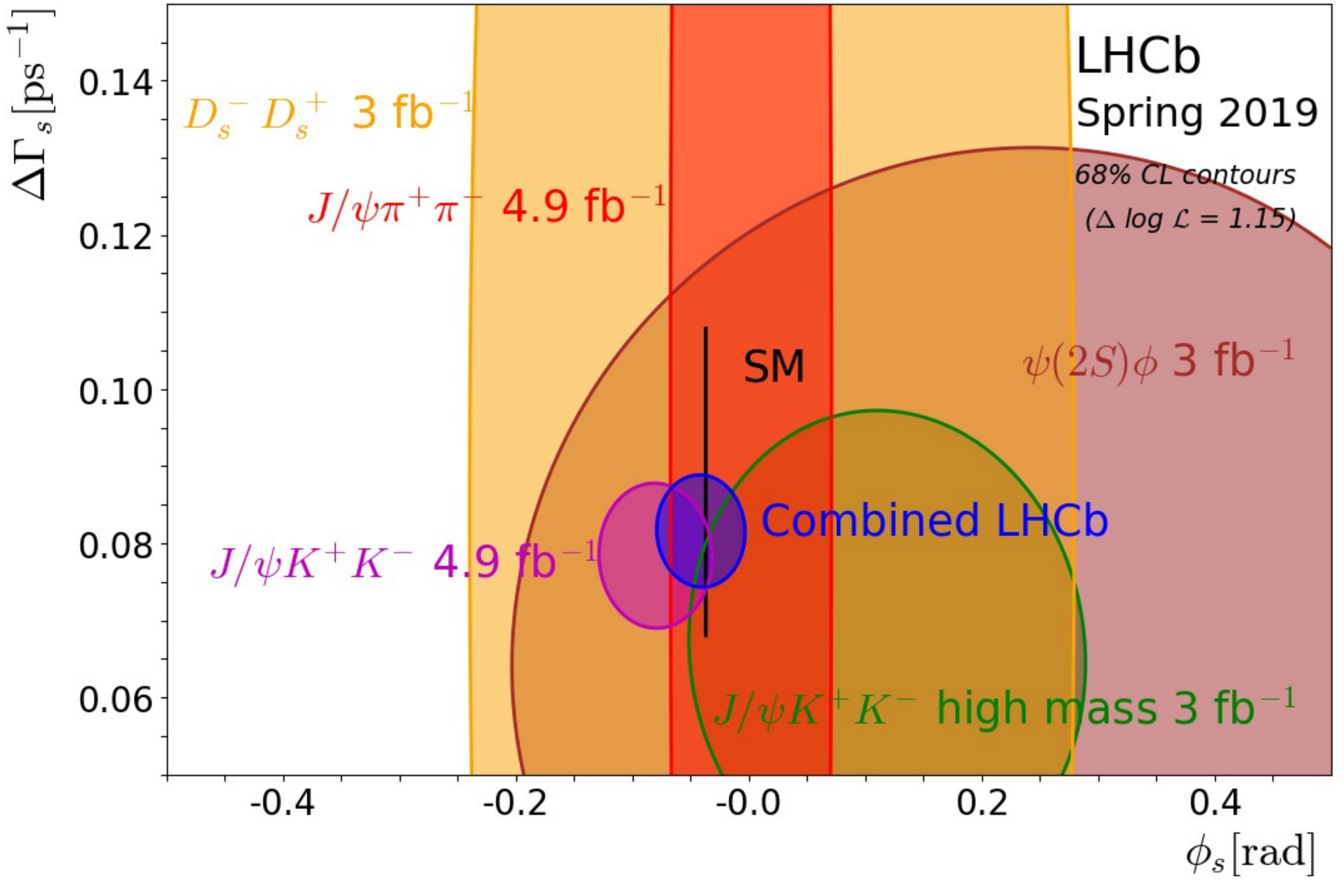
- Can be obtained via time-dependent or time-integrated methods (GLW, ADS, …)
  - Best precision achieved by combing measurements from many decay modes

Flavor tagging [PoS(LHCP2018)230]

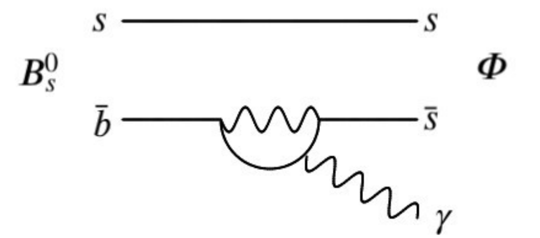
- Tagging in Run 2 improved ⇒ 30% higher tagging power than Run 1
  $\varepsilon_{\rm tag}(B_s^0 \to J/\psi K^+K^-) = 4.73 \pm 0.34\%$ (vs ≈ 3.73% in Run 1)
  $\varepsilon_{\rm tag}(B_s^0 \to J/\psi \pi^+\pi^-) = 5.06 \pm 0.38\%$ (vs ≈ 3.89% in Run 1)

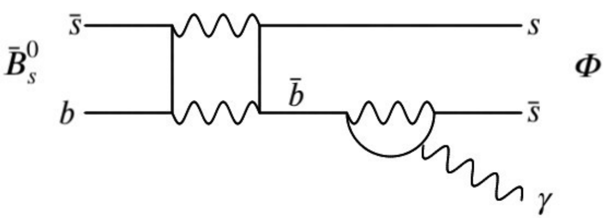


LHCb ϕ_s combination



CPV measurements in $B_s^0 \to \phi\gamma$





- In $b \to s\gamma$ transition, γ is expected in SM to be purely left-handed due to angular momentum conservation, however NP with RH photon may contribute
- Time-dependent rates give access to photon polarization:

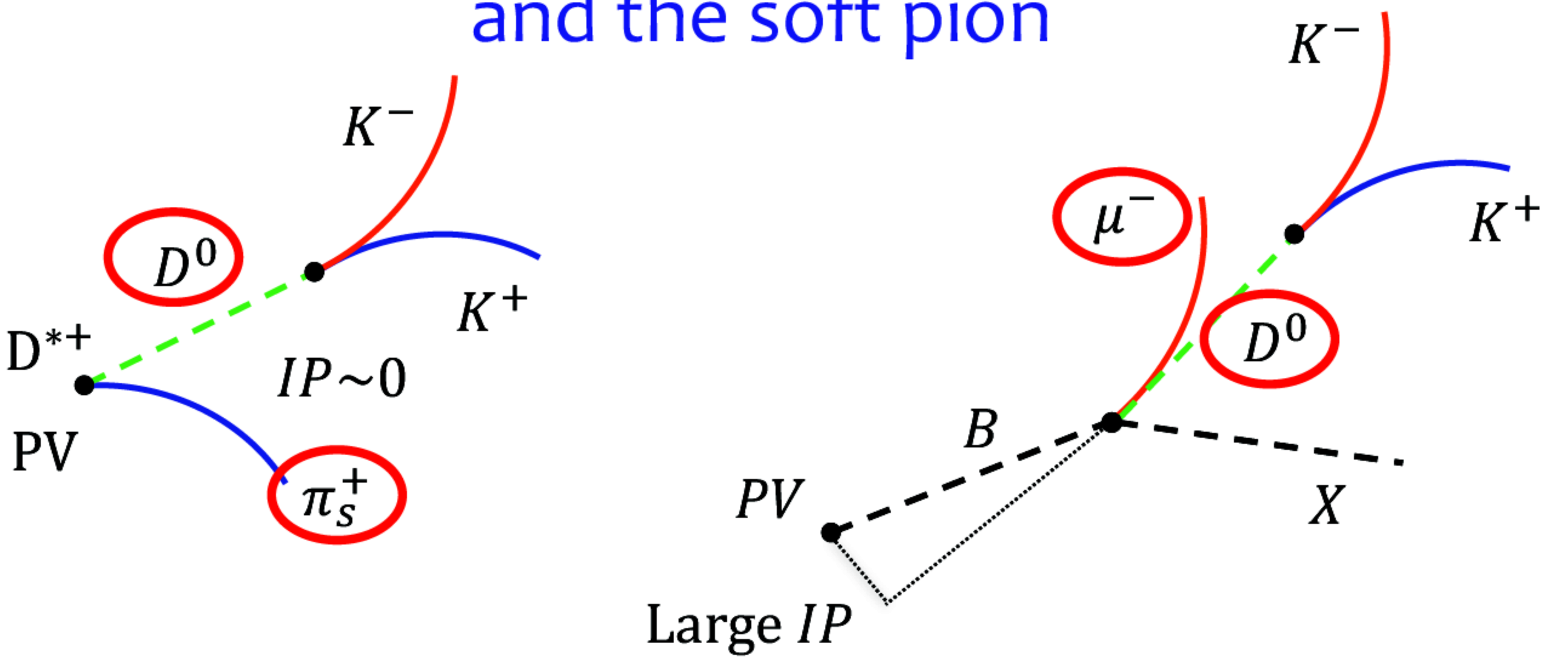
$$\Gamma_{B_s^0 \to \Phi\gamma}(t) \propto \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos(\Delta m_s t) - S\sin(\Delta m_s t)\right]$$

$$\Gamma_{\bar{B}_s^0 \to \Phi\gamma}(t) \propto \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C\cos(\Delta m_s t) + S\sin(\Delta m_s t)\right]$$

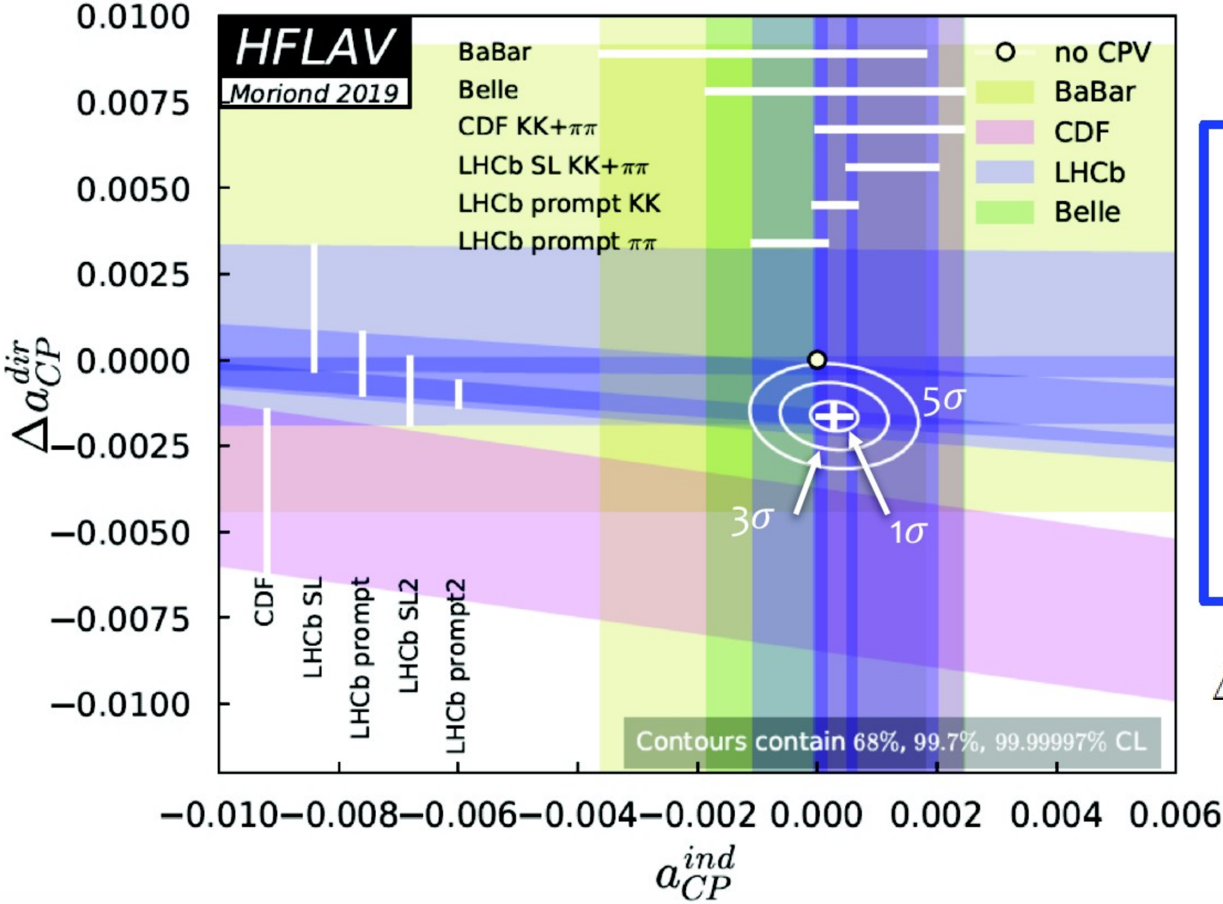
Depend on C_7 and C_7'

  - $\Delta\Gamma_s$ & Δm_s: decay width and mass differences between B_s^0 mass eigenstates
  - ***C***: measure of direct CPV, ***S***: measure of B_s^0 mixing

Experimentally we can tag D^0 flavour at production by means of the charge of the muon and the soft pion



HFLAV updates



HFLAV combination

$a_{CP}^{\text{ind}} = (0.028 \pm 0.026)\%$

$\Delta a_{CP}^{\text{dir}} = (-0.164 \pm 0.028)\%$

Consistency with NO CPV hypothesis: 5×10^{-8}

$$\Delta A_{CP} = \boxed{\left[a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+)\right]} + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\text{ind}}$$

$\Delta\, a_{CP}^{dir}$

World average dominated by LHCb results

provided by the courtesy of M. Gersabeck

Model-independent Bin-flip method

- Used c_b, s_b from CLEO-c

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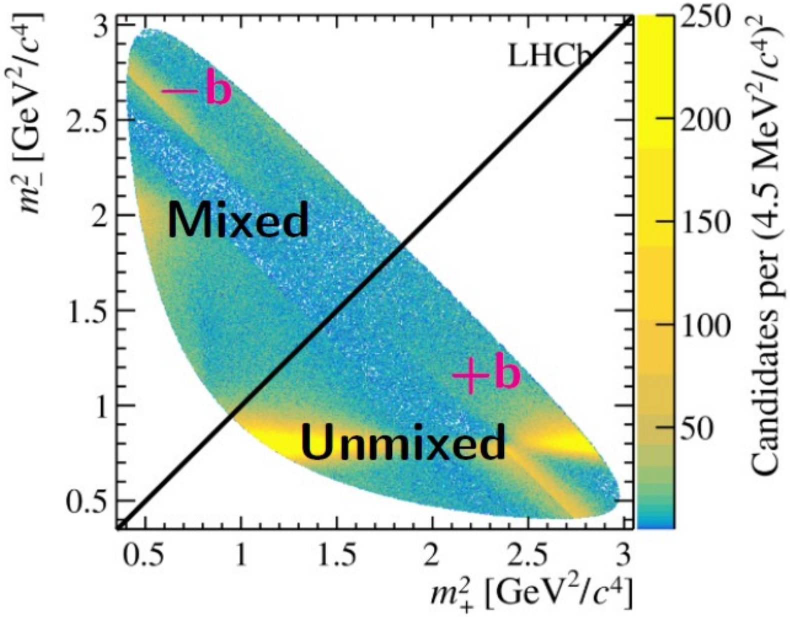


- Bin Dalitz into $\pm b$ about $m_+^2 = m_-^2$
- D decay time into bins j
- Measure ratio of signal in $-b$ and $+b$ in bin j

$$R_{bj}^{\pm} = \frac{r_b\left[1 + \frac{1}{4}t_j^2 Re(z_{CP}^2 - \Delta z^2)\right] + \frac{1}{4}t_j^2 |\ z_{CP} \pm \Delta z\ |^2 + \sqrt{r_b}t_j Re\left[\mathbf{X}_\mathbf{b}^*(z_{CP} \pm \Delta z)\right]}{\left[1 + \frac{1}{4}t_j^2 Re(z_{CP}^2 - \Delta z^2)\right] + r_b\frac{1}{4}t_j^2 |\ z_{CP} \pm \Delta z\ |^2 + \sqrt{r_b}t_j Re\left[\mathbf{X}_\mathbf{b}^*(z_{CP} \pm \Delta z)\right]},$$

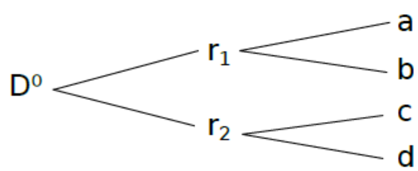
where $z_{CP} \pm \Delta z = -(\frac{q}{p})^{\pm}(y + ix)$ and r_b is ratio without mixing $\mathbf{X_b} = \mathbf{c_b} - \mathbf{is_b}$

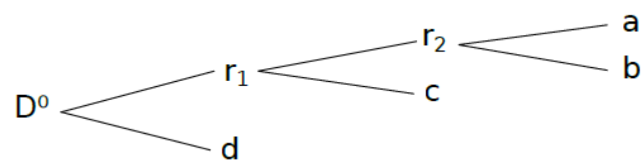
$R^{\pm}$ **changes with time** $\Rightarrow$ **Mixing**
$R^+ \neq R^-$ $\Rightarrow$ **Indirect CPV**

[LHCb-PUB-2018-009]

LHCb upgrade and beyond

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [606]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [607]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [608]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–





Amplitude	$A_{\|c_k\|}$ [%]	$\Delta\,\arg(c_k)$ [%]	$A_{\mathcal{F}_k}$ [%]
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=0}$	0 (fixed)	0 (fixed)	$-1.8 \pm 1.5 \pm 0.2$
$D^0 \to K_1(1400)^+K^-$	$-1.4 \pm 1.1 \pm 0.2$	$1.3 \pm 1.5 \pm 0.3$	$-4.5 \pm 2.1 \pm 0.3$
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$	$1.9 \pm 1.1 \pm 0.3$	$-1.2 \pm 1.3 \pm 0.3$	$2.0 \pm 1.8 \pm 0.7$
$D^0 \to K_1(1270)^+K^-$	$-0.4 \pm 1.0 \pm 0.2$	$-1.1 \pm 1.4 \pm 0.2$	$-2.6 \pm 1.7 \pm 0.2$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=0}$	$-1.3 \pm 1.3 \pm 0.3$	$-1.7 \pm 1.5 \pm 0.2$	$-4.3 \pm 2.2 \pm 0.5$
$D^0 \to K^*(1680)^0[K^-\pi^+]_{L=0}$	$2.2 \pm 1.3 \pm 0.3$	$1.4 \pm 1.5 \pm 0.2$	$2.6 \pm 2.2 \pm 0.4$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=1}$	$-0.4 \pm 1.7 \pm 0.2$	$3.7 \pm 2.0 \pm 0.2$	$-2.6 \pm 3.2 \pm 0.3$
$D^0 \to K_1(1270)^-K^+$	$2.6 \pm 1.7 \pm 0.4$	$-0.1 \pm 2.1 \pm 0.3$	$3.3 \pm 3.5 \pm 0.5$
$D^0 \to [K^+K^-]_{L=0}[\pi^+\pi^-]_{L=0}$	$3.5 \pm 2.5 \pm 1.5$	$-5.5 \pm 2.6 \pm 1.6$	$5.1 \pm 5.1 \pm 3.1$
$D^0 \to K_1(1400)^-K^+$	$0.2 \pm 2.9 \pm 0.7$	$2.5 \pm 3.5 \pm 1.0$	$-1.3 \pm 6.0 \pm 1.0$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=0}$	$4.0 \pm 2.7 \pm 0.8$	$-5.4 \pm 2.8 \pm 0.8$	$6.2 \pm 5.2 \pm 1.5$
$D^0 \to [\overline{K}^*(1680)^0K^*(892)^0]_{L=1}$	$-0.4 \pm 2.1 \pm 0.3$	$0.4 \pm 2.1 \pm 0.3$	$-2.5 \pm 3.9 \pm 0.4$
$D^0 \to \overline{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$2.1 \pm 2.0 \pm 0.6$	$-1.8 \pm 2.2 \pm 0.3$	$2.4 \pm 3.7 \pm 1.1$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=2}$	$0.8 \pm 1.9 \pm 0.3$	$-1.2 \pm 2.0 \pm 0.5$	$-0.1 \pm 3.3 \pm 0.5$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=2}$	$-0.6 \pm 2.5 \pm 0.4$	$0.6 \pm 2.6 \pm 0.4$	$-3.0 \pm 5.0 \pm 0.7$
$D^0 \to \phi(1020)[\pi^+\pi^-]_{L=0}$	$3.8 \pm 3.1 \pm 0.7$	$-0.5 \pm 3.9 \pm 0.7$	$5.8 \pm 6.1 \pm 0.8$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=1}$	$1.6 \pm 2.8 \pm 0.5$	$0.7 \pm 3.0 \pm 0.4$	$1.3 \pm 5.3 \pm 0.6$
$D^0 \to [\phi(1020)\rho(1450)^0]_{L=1}$	$4.6 \pm 4.1 \pm 0.6$	$9.3 \pm 3.3 \pm 0.6$	$7.5 \pm 8.5 \pm 1.1$
$D^0 \to a_0(980)^0 f_2(1270)^0$	$1.6 \pm 3.6 \pm 0.7$	$-7.3 \pm 3.3 \pm 0.8$	$1.5 \pm 7.2 \pm 1.3$
$D^0 \to a_1(1260)^+\pi^-$	$-4.4 \pm 5.6 \pm 3.7$	$9.3 \pm 6.1 \pm 1.3$	$-10.6 \pm 11.7 \pm 7.0$
$D^0 \to a_1(1260)^-\pi^+$	$-3.4 \pm 7.0 \pm 1.9$	$-5.8 \pm 5.6 \pm 4.3$	$-8.7 \pm 13.7 \pm 2.9$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=1}$	$2.1 \pm 5.2 \pm 0.8$	$-12.2 \pm 5.5 \pm 0.6$	$2.4 \pm 11.0 \pm 1.4$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=2}$	$5.2 \pm 7.1 \pm 1.9$	$-5.6 \pm 8.1 \pm 1.3$	$8.5 \pm 14.3 \pm 3.5$
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$11.7 \pm 6.0 \pm 1.9$	$4.8 \pm 6.2 \pm 1.1$	$21.3 \pm 12.5 \pm 2.8$
$D^0 \to [\phi(1020)f_2(1270)^0]_{L=1}$	$2.7 \pm 6.7 \pm 1.7$	$0.9 \pm 6.0 \pm 1.7$	$3.6 \pm 13.3 \pm 3.0$
$D^0 \to [K^*(892)^0\overline{K}_2^*(1430)^0]_{L=1}$	$3.9 \pm 5.2 \pm 1.0$	$6.8 \pm 6.4 \pm 1.4$	$6.1 \pm 10.8 \pm 1.8$

Table 5. *CP*-violation parameters fitted simultaneously to the D^0 and (*CP*-transformed) $\overline{D}^0$ samples. The first uncertainty is statistical and the second is systematic.