Recent Results on CP Violation in Charm mesons at LHCb

Maurizio Martinelli (Università di Milano Bicocca and CERN)
on behalf the LHCb Collaboration

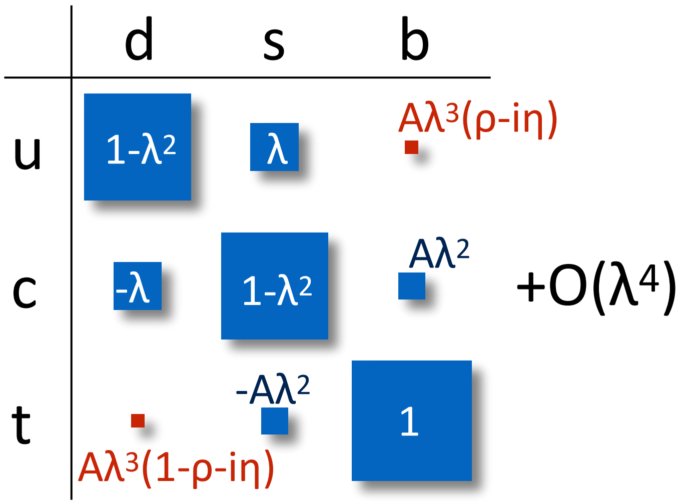
Weak Interactions and Neutrino 2019
Bari, 04.06.2019

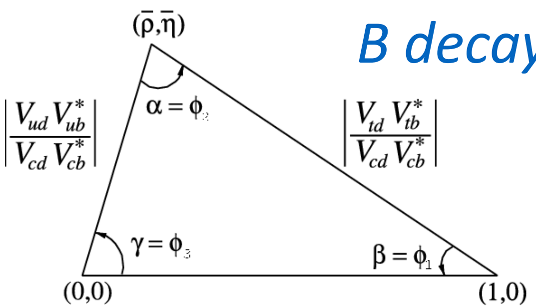
CP Violation in Charm

CP Violation in The Standard Model

CKM Matrix

- CPV is naturally introduced by the irreducible complex phase of the CKM matrix
- Relatively large effects in transitions involving the third generation of quarks



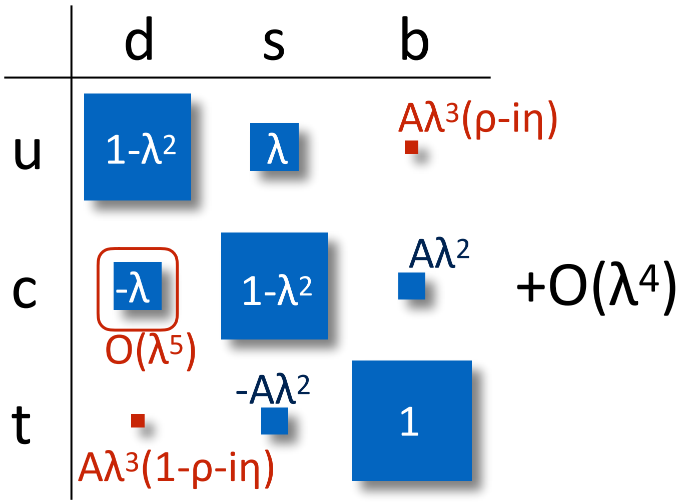


B decays

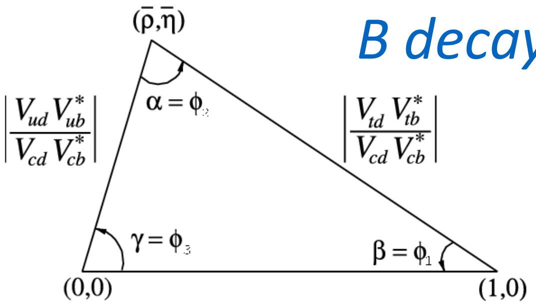
CP Violation in The Standard Model

CKM Matrix

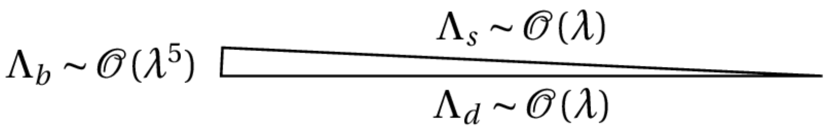
- CPV is naturally introduced by the irreducible complex phase of the CKM matrix
- Relatively large effects in transitions involving the third generation of quarks
- Highly suppressed in Charm



B decays



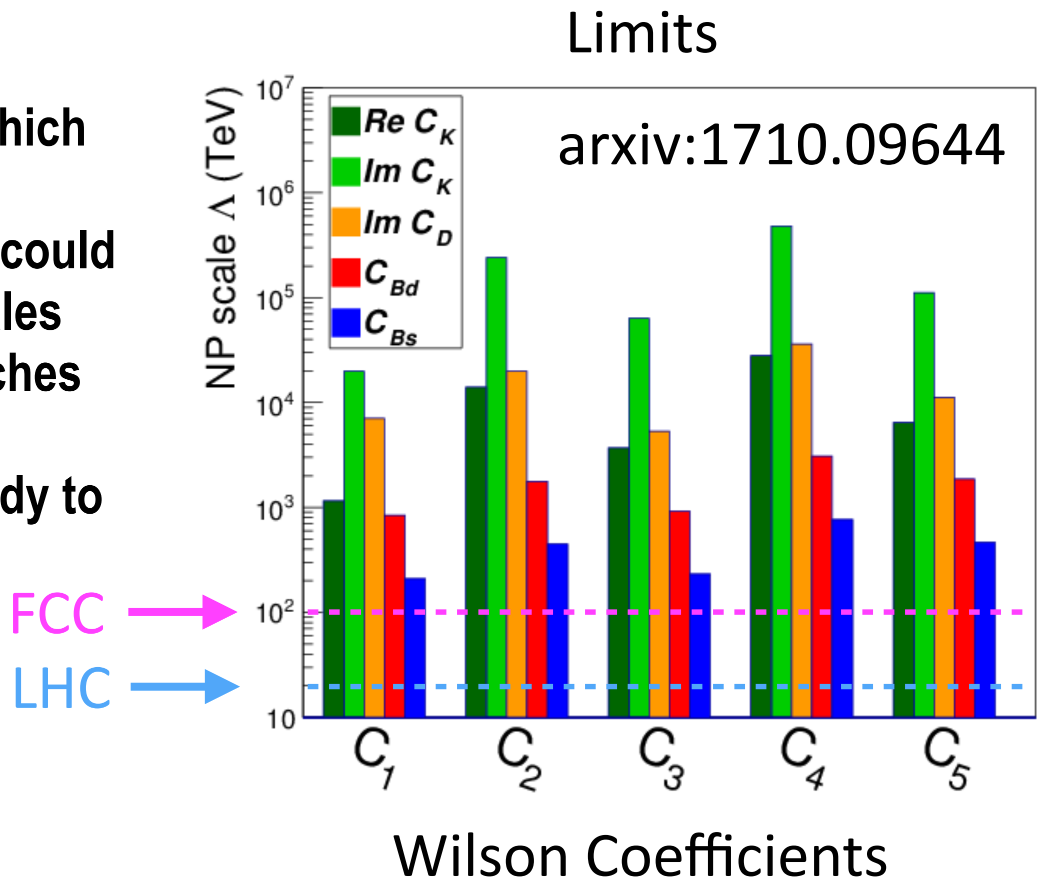
D decays



Why Studying CPV in Charm Decays?

Charming

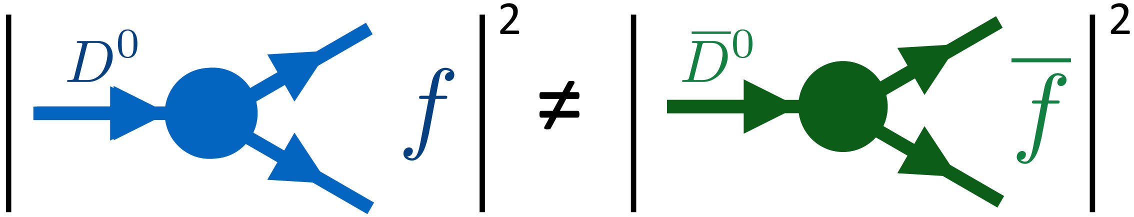
- Only up-type quark decay in which CPV can be probed
- Indirect CPV in Charm decays could probe extremely high BSM scales
- Complementary to direct searches for BSM particles
- We have billions of decays ready to be studied at LHCb!



CP Violation in Charm

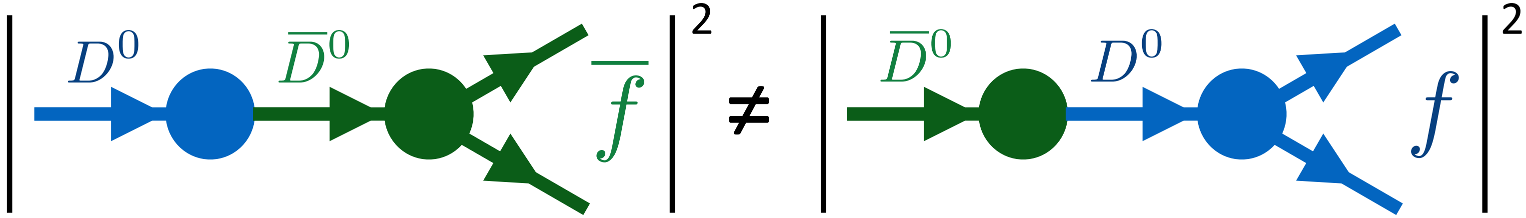
Decay

Direct

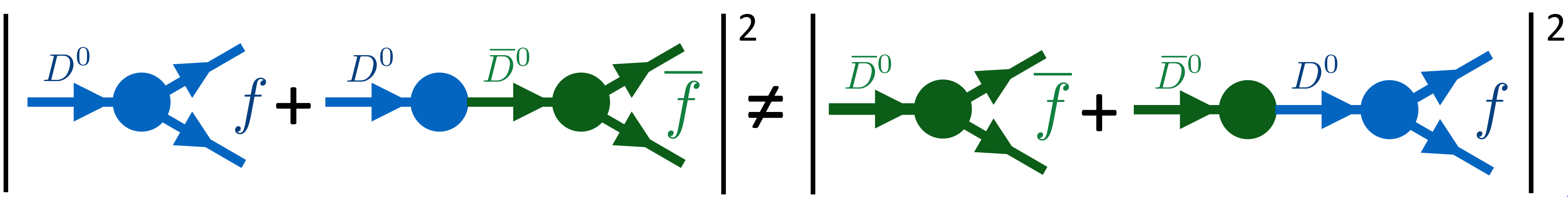


Mixing

Indirect



Interference Mixing and Decay



Charm at LHCb

The LHCb Experiment

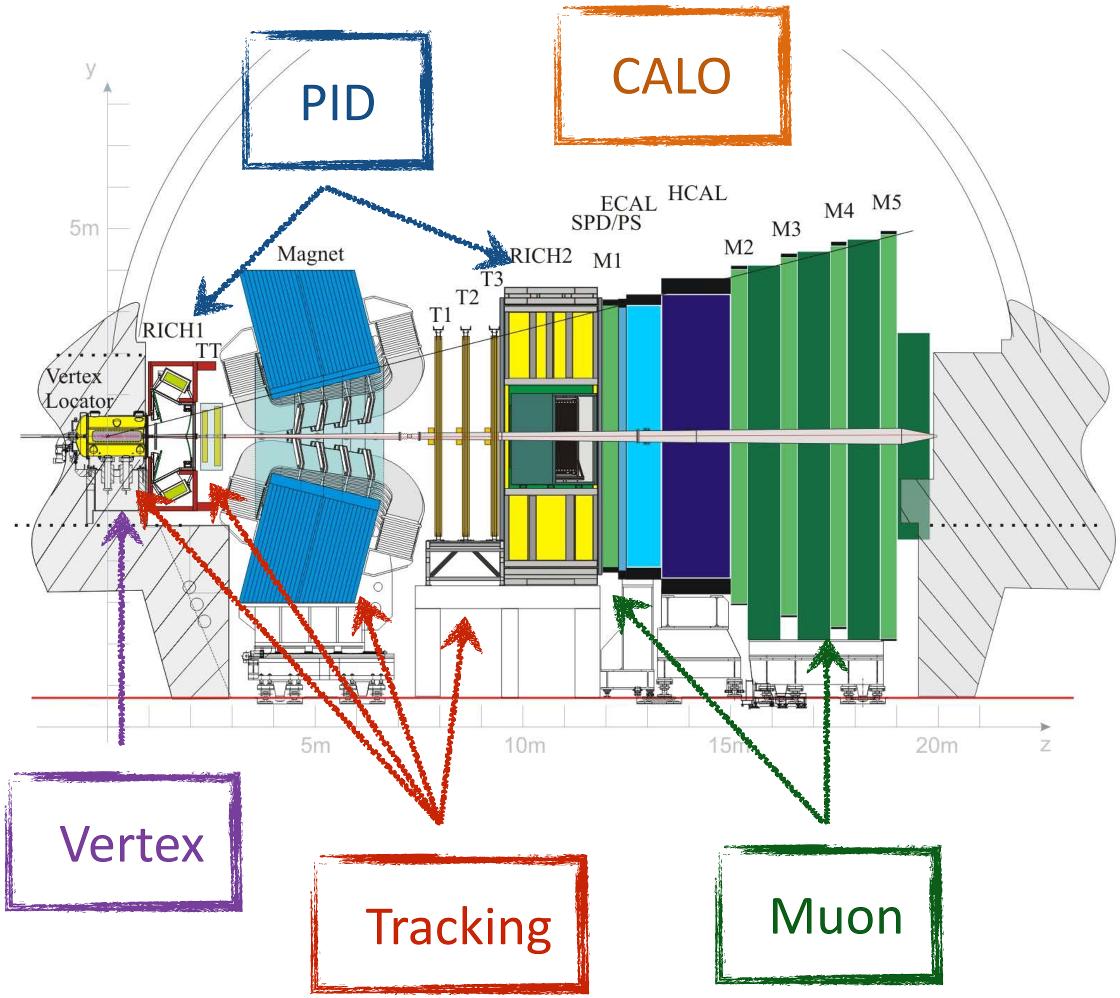
JINST 3 (2008) S08005

Charm quarks produced in low η at LHC
$\sigma(pp \to c\bar{c}) \sim 20\sigma(pp \to b\bar{b})$

$\varepsilon_{VELO} \approx 98\%$
$\delta t/t = 45fs$
$\sigma(IP) \approx 20\mu m$
$\delta p/p \approx 0.5\%$

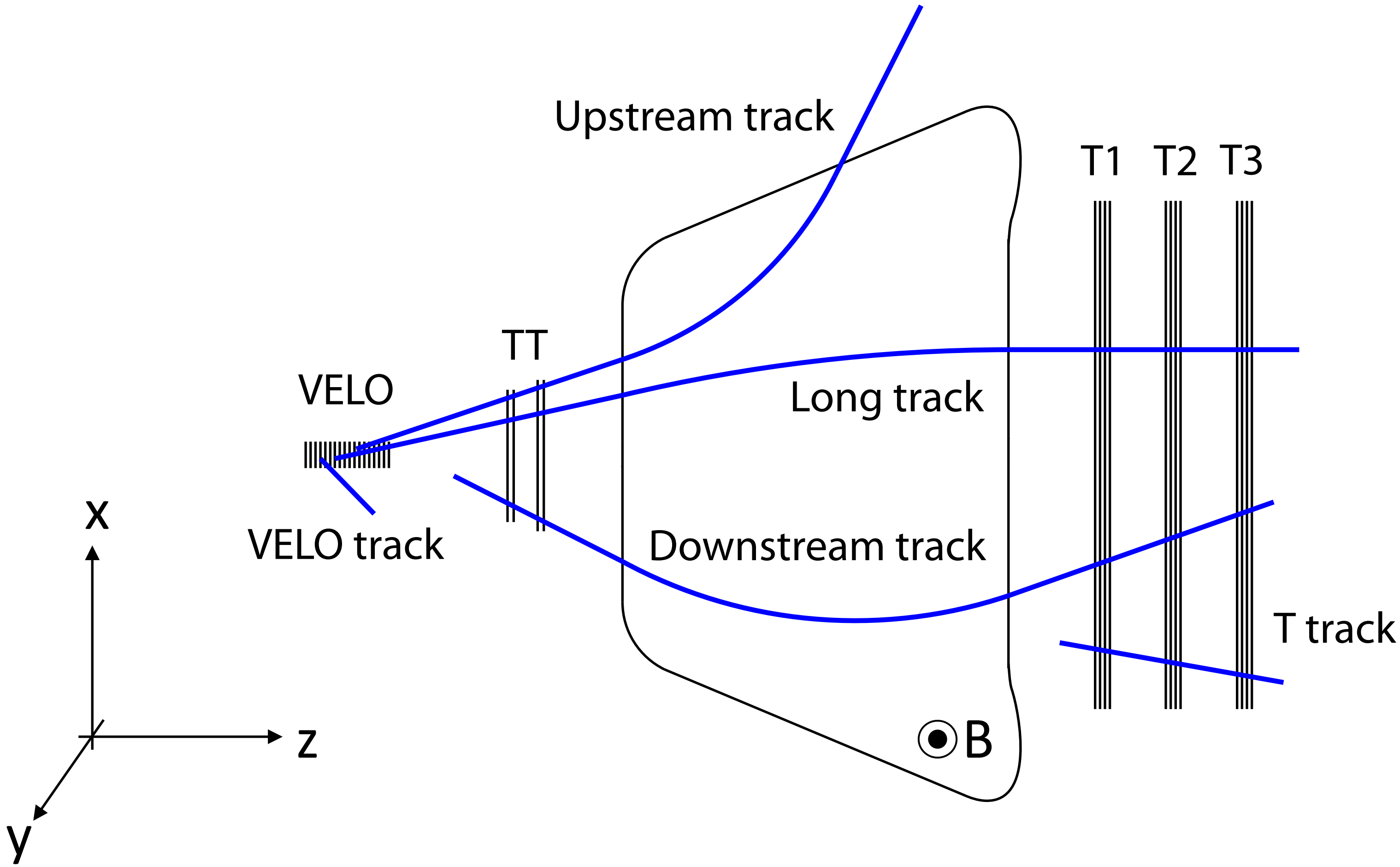
$\varepsilon_{Track} \approx 95\%$
$\varepsilon_{PID}(K) \approx 95\%$
$\varepsilon_{PID}(\mu) \approx 97\%$
$\varepsilon_{PID}(e) \approx 90\%$

Int.J.Mod.Phys. A30 (2015) no.07, 1530022



Tracking Reconstruction at LHCb

JINST 10 (2015) P02007

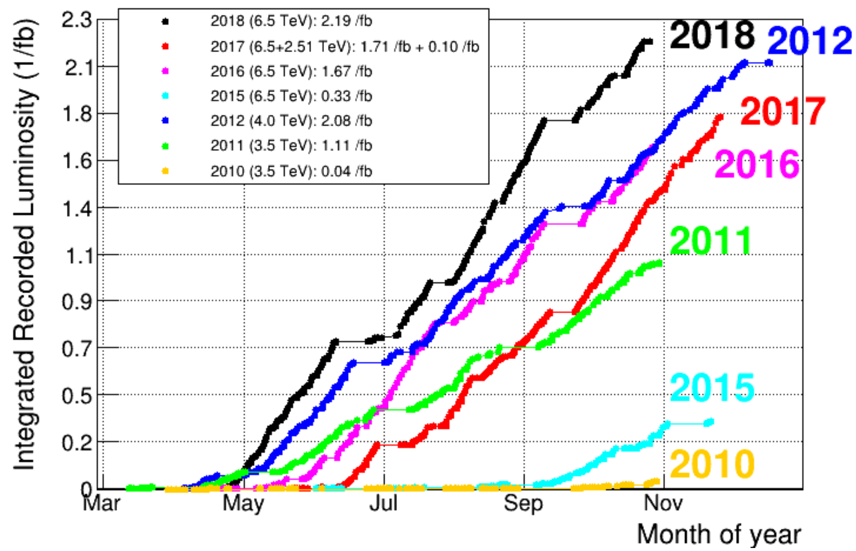


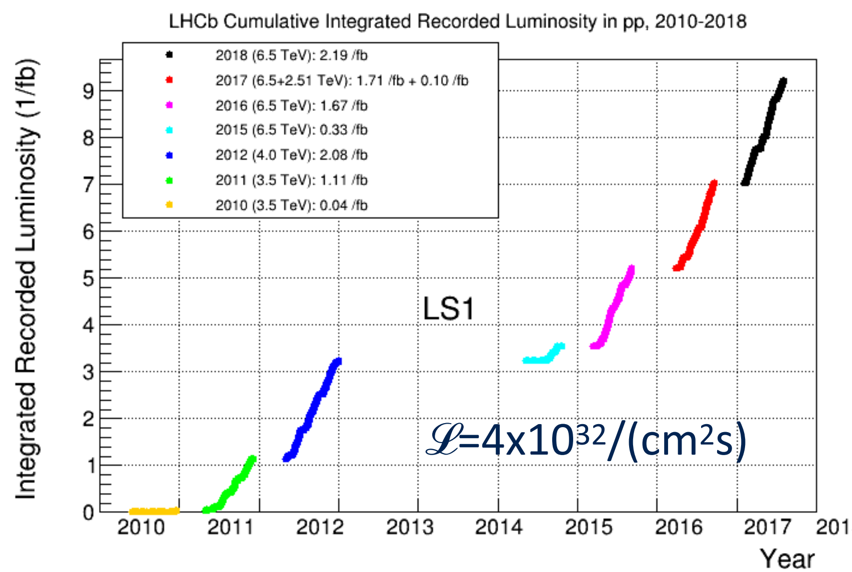
LHCb Dataset

Year	Luminosity (1/fb)	CM Energy (TeV)
2010	0.04	7
2011	1.11	7
2012	2.08	8
2015	0.33	13
2016	1.67	13
2017	1.71	13
2018	2.19	13

Run1 (2010–2012)

Run2 (2015–2018)





Charm Physics at LHCb

An Experiment By Itself

- **With the charm production cross-section at LHCb and our ability of triggering it we have a vast physics program in Charm**

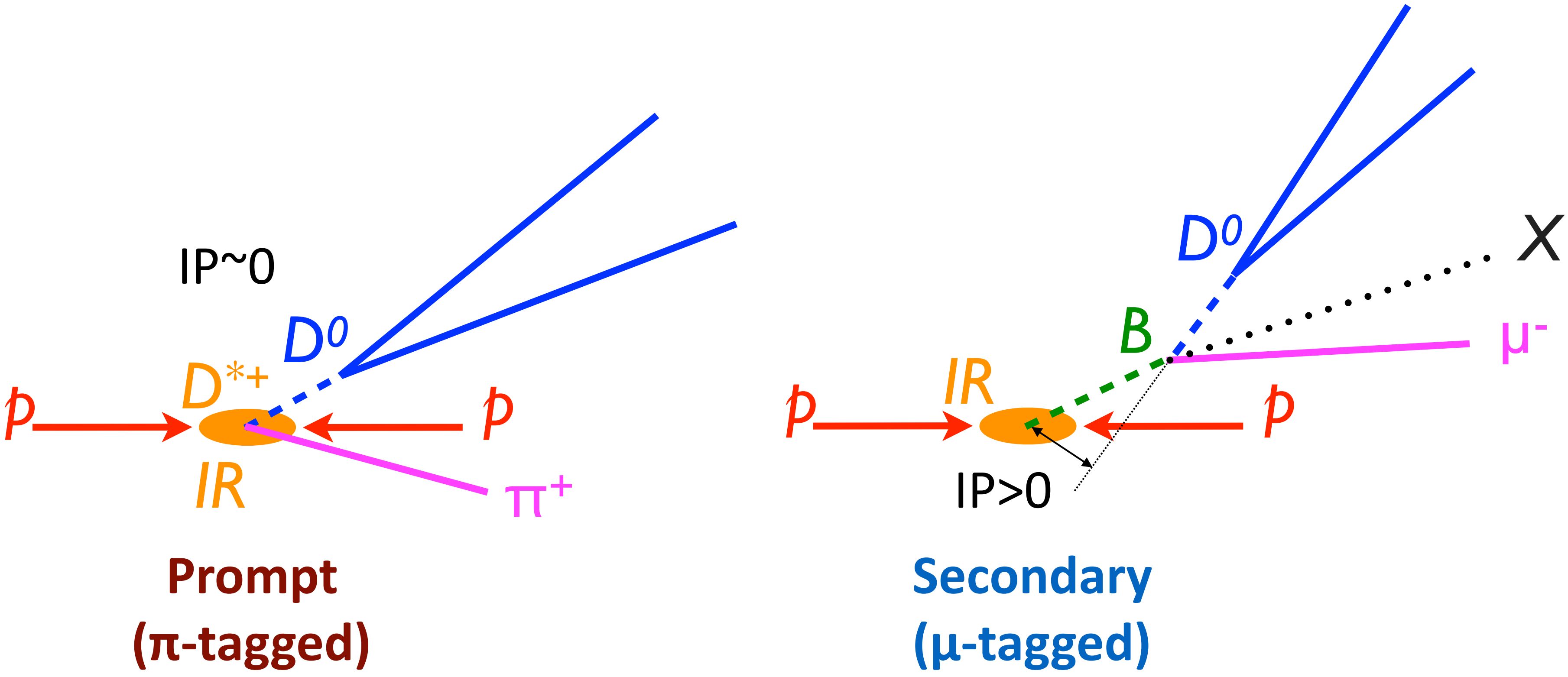
Mixing
CPV

Rare
Decays

Production
Spectroscopy
Amplitude Analyses

- **Pro: huge yields (10^9 $D^0 \to K^- \pi^+$ CF decays in LHCb with 9/fb)**
- **Cons: poor neutrals reconstruction**
  Focus on hadronic and semileptonic decays

Charm Production at LHCb



Recent CPV Measurements by LHCb

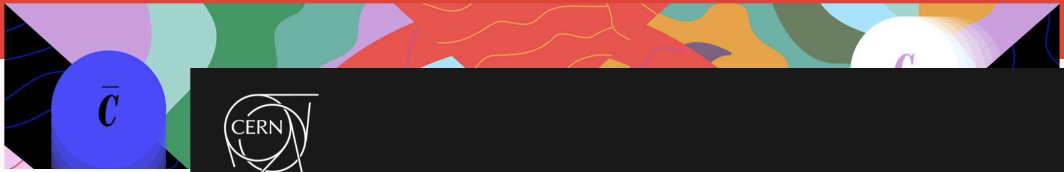
First Observation of CPV in Charm!

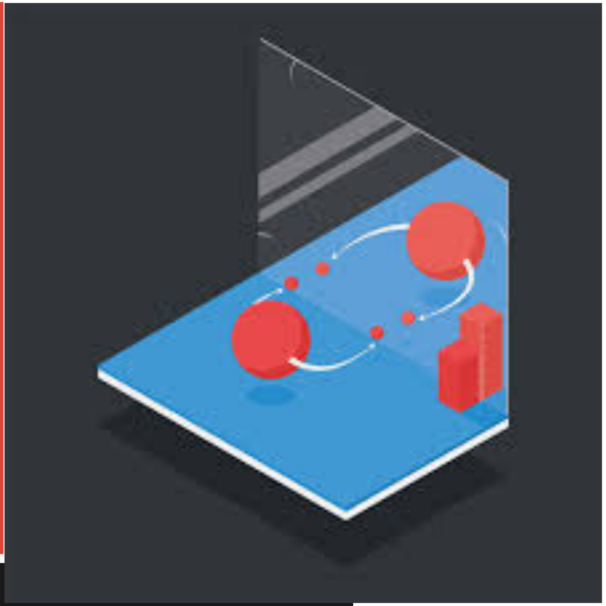
symmetry
dimensions of particle physics
topics
follow +
A joint Fermilab/SLAC publication

LHCb discovers matter-antimatter asymmetry in charm quarks

03/21/19 | By Sarah Charley

A new observation by the LHCb experiment finds that charm quarks behave differently than their antiparticle counterparts.





CERN
ABOUT

News › Press release › Topic: Physics

Voir en français

LHCb sees a new flavour of matter–antimatter asymmetry

The LHCb collaboration has observed a phenomenon known as CP violation in the decays of a particle known as a D0 meson for the first time

21 MARCH, 2019

Why ΔA_{CP} and How to Measure it

Correcting for Instrumental Asymmetries

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

Why ΔA_{CP} and How to Measure it

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$$A_{h^+h^-} = A_{CP}(h^+h^-) + A_D + A_P \quad (*)$$

- $A_{CP}(h^+h^-)$: The asymmetry we want to measure
- A_D: Detection Asymmetry of tagging track ($\mu^\pm$ or $\pi^\pm$)
- A_P: Production Asymmetry (D^* or B)

(*) Valid only if A_{hh} small

Why ΔA_{CP} and How to Measure it

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$$A_{h^+h^-} = A_{CP}(h^+h^-) + A_D + A_P \quad (*)$$

The asymmetry we want to measure

Detection Asymmetry of tagging track ($\mu^\pm$ or $\pi^\pm$)

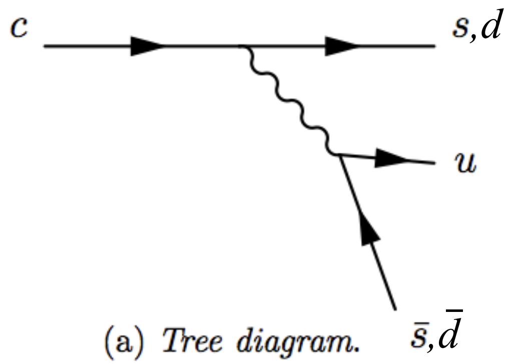
Production Asymmetry (D* or B)

$$\Delta A_{CP} = A_{K^+K^-} - A_{\pi^+\pi^-} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

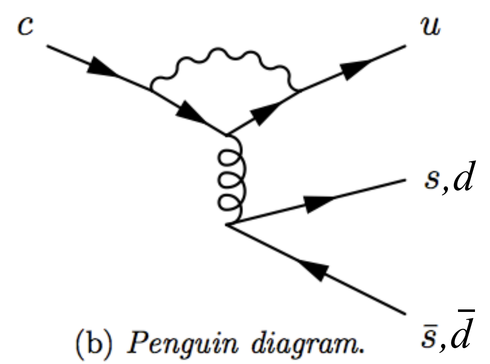
(*) Valid only if A_{hh} small

Why is $\Delta A_{CP} \neq 0$?

CPV Arising from Interference



(a) *Tree diagram.*



(b) *Penguin diagram.*

SU(3) Symmetry

- **In this limit, $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ are equal and opposite in sign, resulting in $\Delta A_{CP} \sim 10^{-3}$**

Phys. Lett. B774 (2017) 235-242

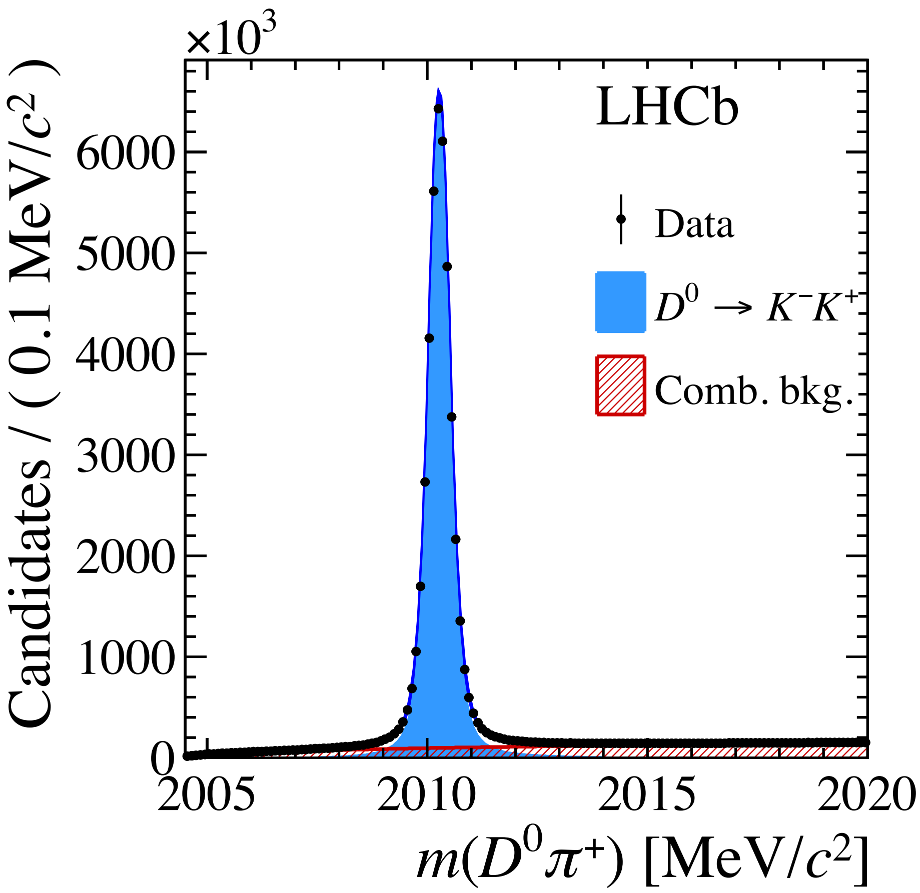
Phys. Rev. D75 (2007) 036008

Phys. Lett. B712 (2012) 81

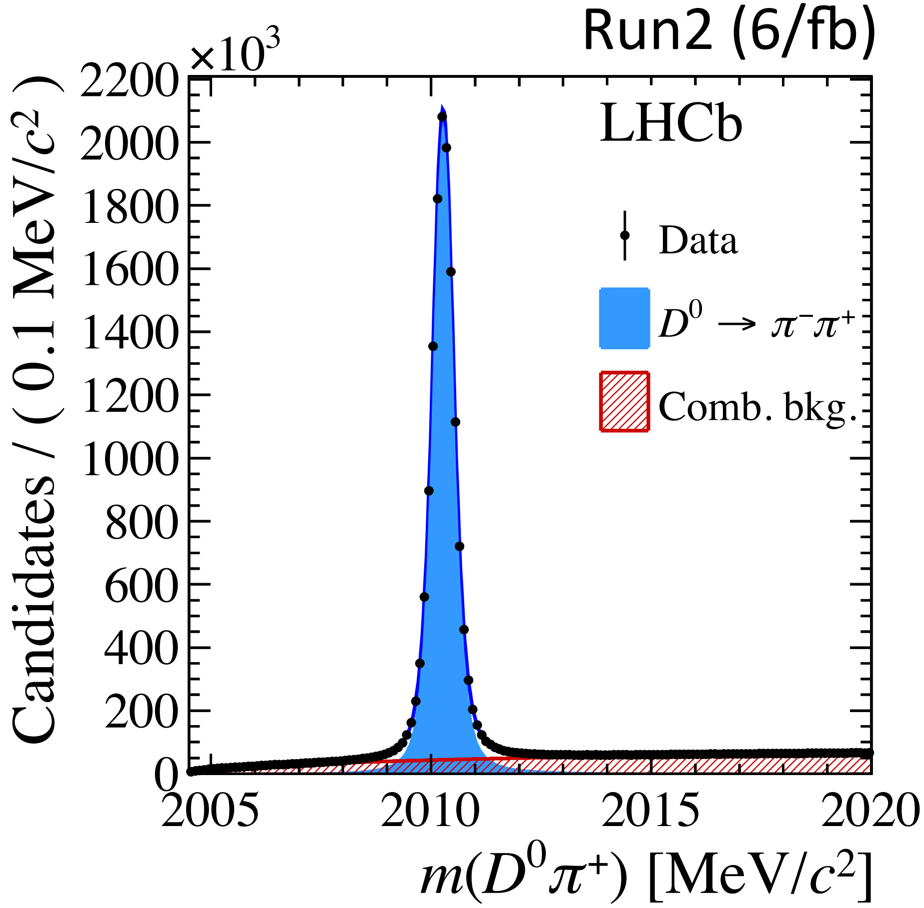
ΔA_{CP} Dataset (π-tagged)

PRL122 (2019) 211803

Run2 (6/fb)



44M

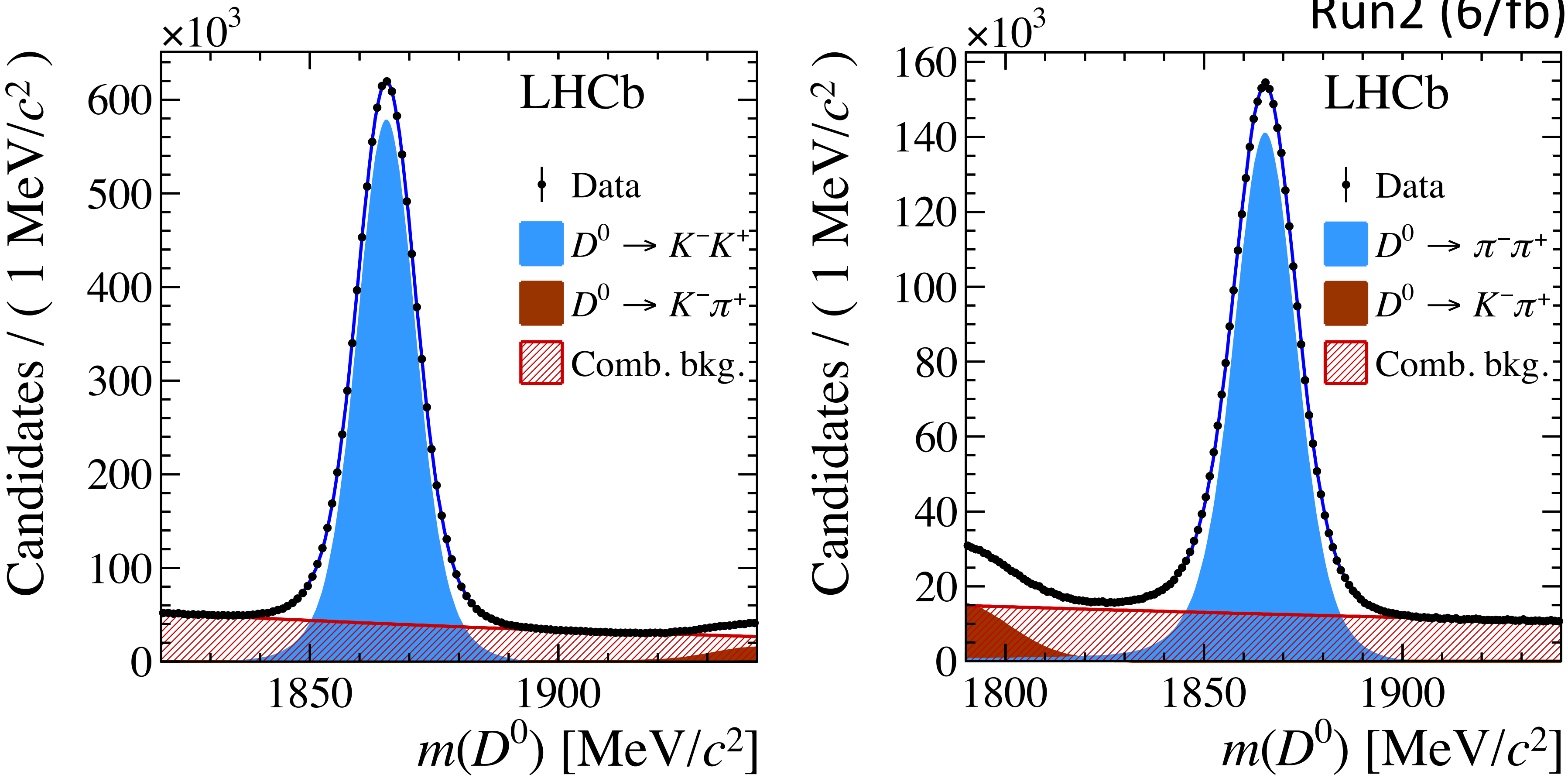


14M

ΔA_{CP} Dataset (μ-tagged)

PRL122 (2019) 211803

Run2 (6/fb)



9M

3M

Tracking Asymmetries

Sources of Inefficiency

- **Material Interactions**
  15% nuclear interaction length before end of tracker
- **Geometry**
  Trajectories through dead-channels, beam-pipe or out of the detector
- **Tracking**
  High occupancy, low p_T

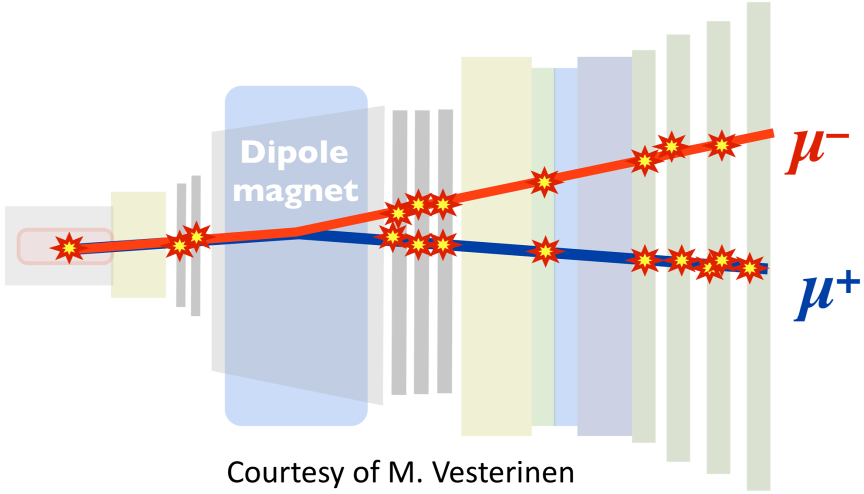
Depend on charge (+kinematics, detector/ machine conditions)

Uncertainty

- **10% on material budget, detector conditions over time, beam positions, detector simulation**

Strategies

- **Avoidance**
  Use observables non-sensitive to detection asymmetries (e.g. ΔA_{CP})
- **Calibration**
  Measure and correct the asymmetries
- **Ignore it**
  When statistical uncertainty much larger than residual asymmetry after averaging the two polarities

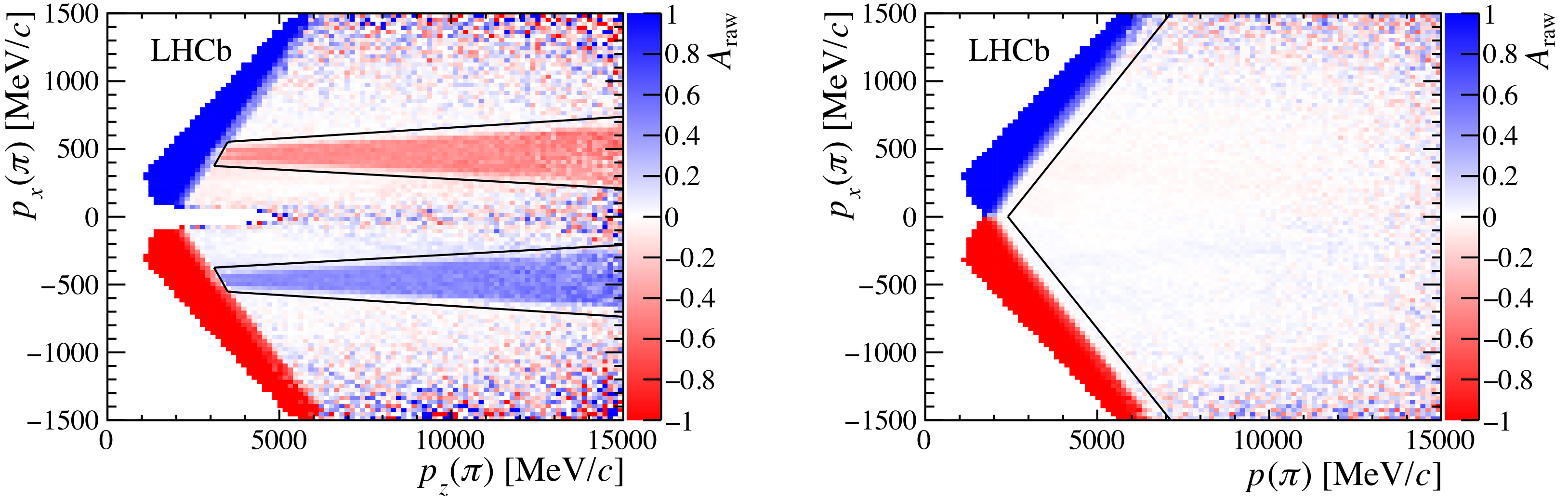


Courtesy of M. Vesterinen

Correcting Tracking Asymmetries

PRL122 (2019) 211803

Remove Areas with Large Asymmetry

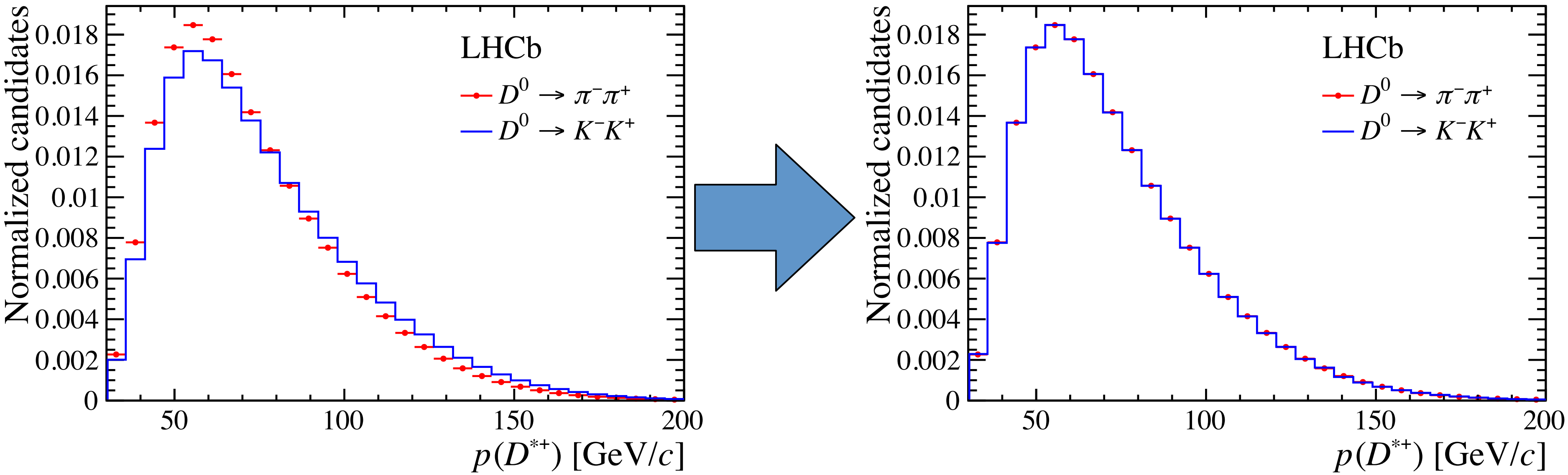


- Regions in which only D^{*+} or D^{*-} are possible since low momentum pion escapes detection
- Break the assumption that A_{hh} is small

Correcting Tracking Asymmetries

PRL122 (2019) 211803

Reweight By Momenta Distributions



- **Detection and production asymmetry dependent on the kinematics of the reconstructed particles**
- **Variables (p, p_T, ϕ) for D^{*+} and D^0**

Systematic Uncertainties

π-tagged

- **Fit Model**
  Evaluated by fitting pseudo experiments with alternative models
- **Peaking Background:**
  $D^0 \to K^- \pi^+ \pi^0$ and $D^0 \to \pi^- l^+ \nu$ peak in the $m(D^0\pi)$ signal region
  Estimated by measuring the yields and asymmetries of backgrounds in the $m(D^0)$ distributions

μ-tagged

- **Mistag (wrong muon assignment)**
  Estimated from a control sample of $B \to D^0(\to K^- \pi^+)\mu X$

$\times 10^{-4}$

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

ΔA_{CP} Results

PRL122 (2019) 211803

π-tagged (6/fb)

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2(\text{stat.}) \pm 0.9(\text{syst.})] \times 10^{-4}$$

μ-tagged (6/fb)

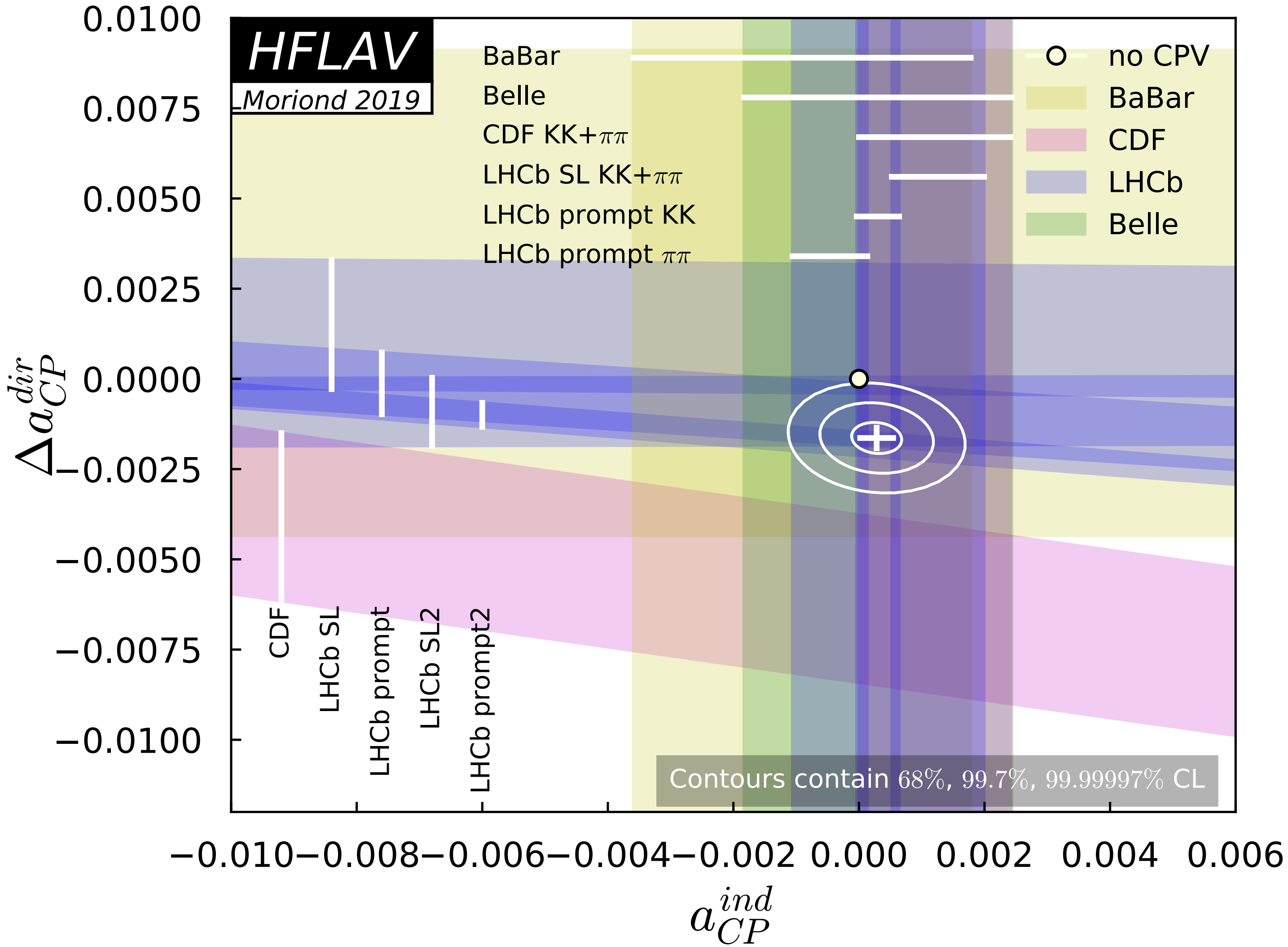
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8(\text{stat.}) \pm 5(\text{syst.})] \times 10^{-4}$$

Combination with Run1 data

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

5.3 std dev significance

CPV in Charm World Average



What Does It Tell Us?

Compatible with SM arXiv:1812.07638

- **Predictions range between 10^{-4} and 10^{-2}**
  Most of them in the 10^{-3} ball park

Other Channels?

- **Observation in other channels would provide a nice confirmation of the effect**
  And help its interpretation

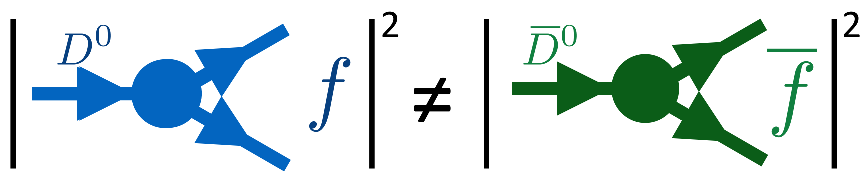
Indirect CPV

- **Still missing**
  Expected $\sim 10^{-5}$
- **Could still be sensitive to BSM effects**

Where to look for Direct CPV?

<u>*Decay*</u>

Direct



A_{CP} in $D^0 \to hh$

Measurement of individual CPV

- With ΔA_{CP} we know that there is CPV up to a certain level
- But what is its exact value?
- Individual measurement is needed
- But adds layers of complication

$$\begin{aligned} A_{CP}(D^0 \to K^+K^-) &= A_{\rm raw}(D^0 \to K^+K^-) - A_P(D^{*+}) - A_D(\pi_s^+) \\ &= A_{\rm raw}(D^0 \to K^+K^-) - A_{\rm raw}(D^0 \to K^-\pi^+) \\ &+ A_{\rm raw}(D^+ \to K^-\pi^+\pi^+) - A_{\rm raw}(D^+ \to \overline{K}^0\pi^+) + A_D(\overline{K}^0) \end{aligned}$$

Run1 Result PLB 767 (2017) 177

- $A_{CP}(KK) = (0.04 \pm 0.12 \pm 0.10)\%$
  $A_{CP}(\pi\pi) = (0.07 \pm 0.14 \pm 0.11)\%$

Prospects

- Run2 analysis ongoing
- Main challenge is keeping the systematic uncertainties low
  Largest uncertainties due to weighting technique

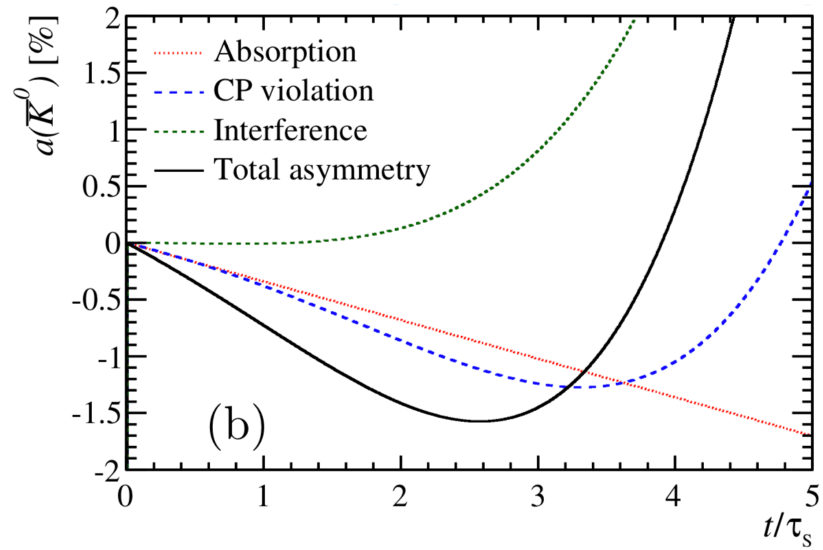
K^0 Asymmetries

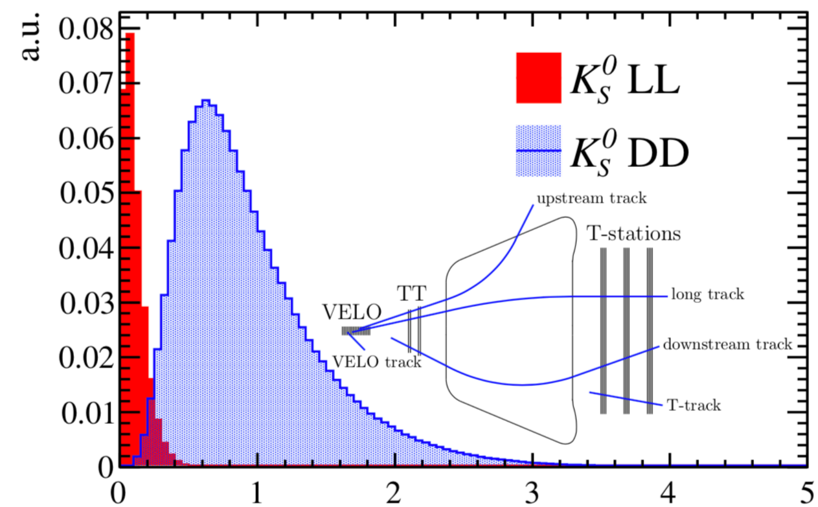
The Effect

- **K^0 violate CP and interacting with the detector may show K^0_S from K^0_L regeneration**
- **Result is a detection asymmetry**
  $A(K^0_S\ LL) = (-0.73 \pm 0.05) \times 10^{-3}$
  $A(K^0_S\ DD) = (-6.2 \pm 0.3) \times 10^{-3}$

Uncertainty

- **From knowledge of detector material**
- **Currently using only LL K^0_S for asymmetry measurements**
  1/3 total K^0_S in LHCb detector





CERN-THESIS-2014-274

Quasi-Two-Body Decays - $D_{(s)}^+ \to K^0_S(\phi)h^+$

PRL122 (2019) 191803

$D_{(s)}^+ \to K^0_S K(\pi)^+$ and $D^+ \to \phi\pi^+$

- The measured asymmetry can be factorised in the limit of small asymmetries

$$A(D^+_{(s)} \to f^+) \approx A_{CP}(D^+_{(s)} \to f^+) + A_P(D^+_{(s)}) + A_D(f^+)$$

- Use control samples to correct for production and detection asymmetries

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

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

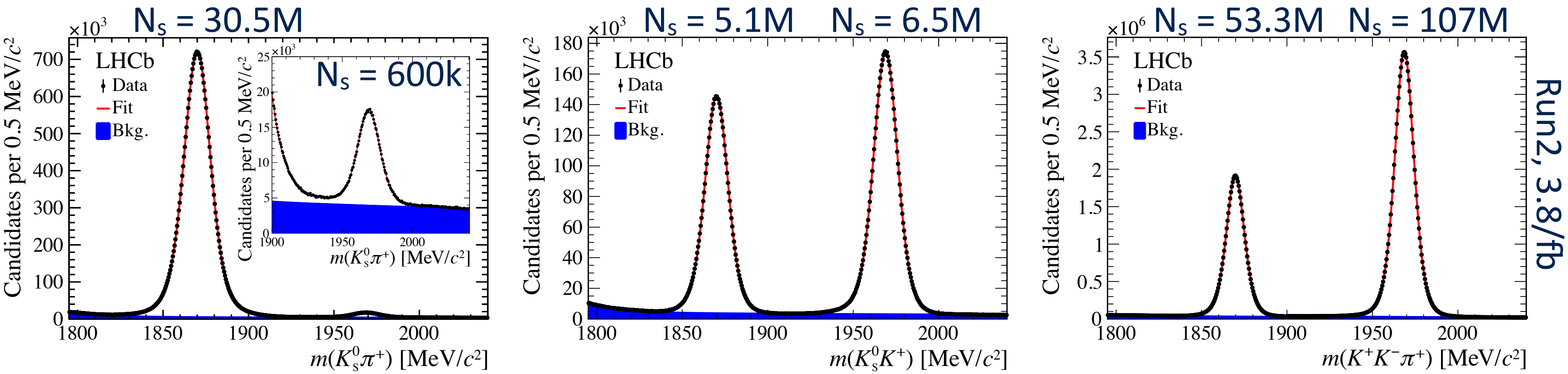
$$A_{CP}(D^+ \to \phi\pi^+) \approx A(D^+ \to \phi\pi^+) - A(D^+ \to K^0_S\pi^+)$$

- Crucial to measure very well K^0_S and K/π reconstruction asymmetries, and $D_{(s)}^+$ production asymmetries

Quasi-Two-Body Decays - $D_{(s)}^+ \to K^0_S(\phi)h^+$

PRL122 (2019) 191803

Results



- **High yields, sensitivity already lower than 10^{-3} for $D^+ \to K^0_S K^+$ and $D^+ \to \phi\pi^+$**

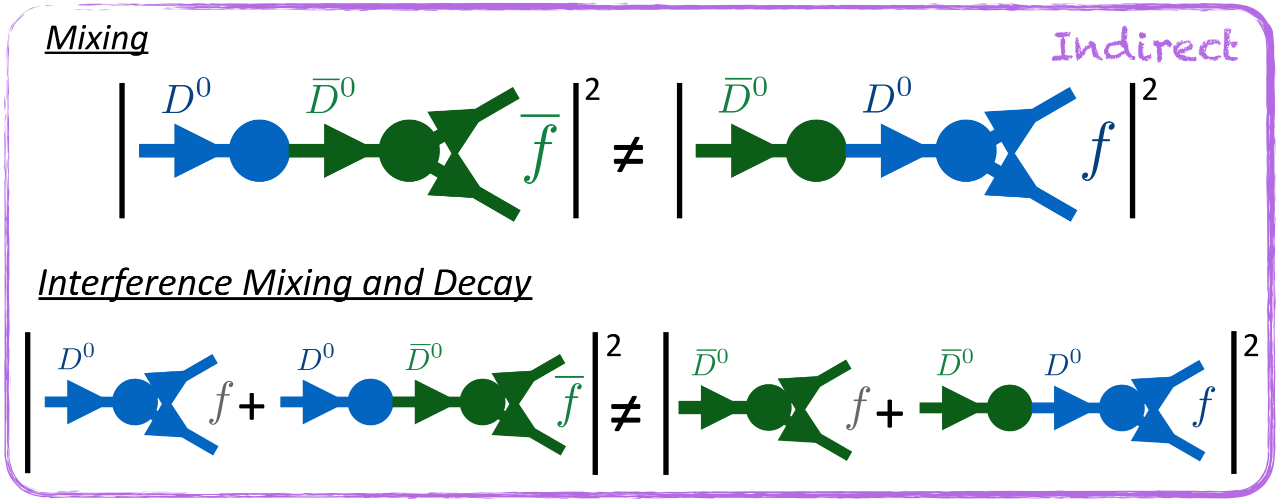
$$a_{CP}(D_s^+ \to K^0_S \pi^+) = (1.6 \pm 1.7 \pm 0.5) \times 10^{-3}$$

$$a_{CP}(D^+ \to K^0_S K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3}$$

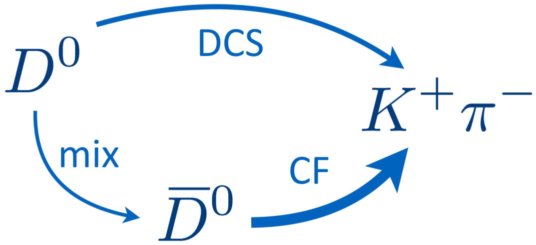
$$a_{CP}(D^+ \to \phi\pi^+) = (0.03 \pm 0.40 \pm 0.29) \times 10^{-3}$$

- **Major systematics from fit model**

Search for Indirect CPV



CPV in the $D^0 \to K\pi$ WS Mixing



$$R = \frac{N_{WS}}{N_{RS}}$$

$$R_{K\pi} \approx R_{K\pi} + \sqrt{R_{K\pi}} y'(\Gamma t) + \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$

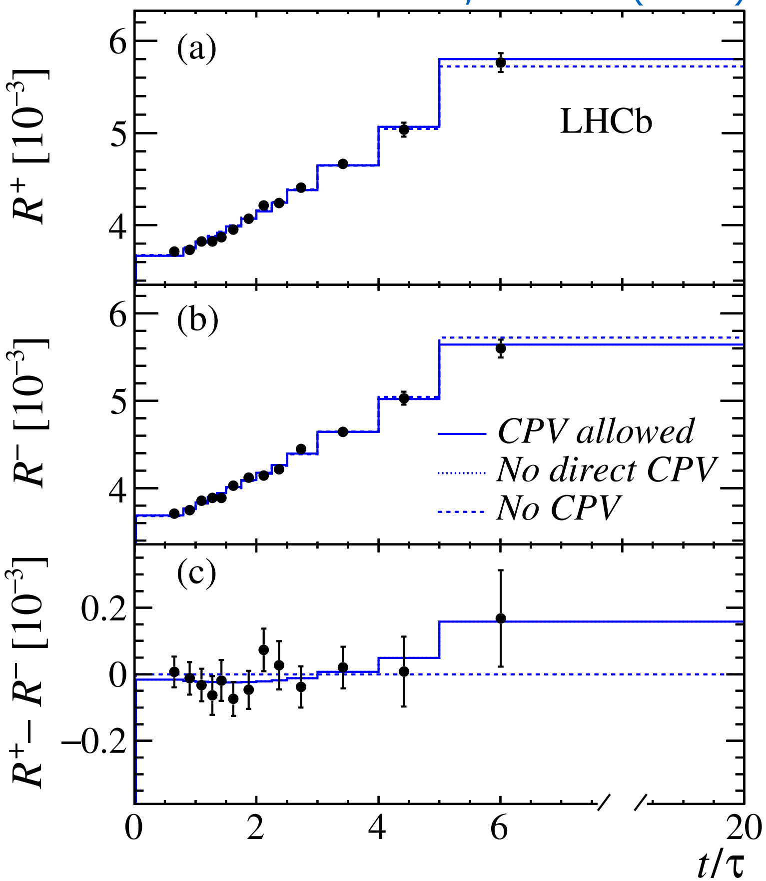
Previous result (Run1+2015/6)

- **Established technique with small systematic uncertainties based on control samples**
- **Technique originally developed to measure mixing, extended to extract CP asymmetry parameters**
  By comparing the mixing parameters for D^0 and $\overline{D}^0$

Run1+Run2 Expectations

- **Direct CPV will be probed up to 0.5% from ratio of WS/RS decays at t=0**
- **CPV in mixing from x', y'$\Longrightarrow\sigma(|q/p|)\sim0.1$, $\sigma(\phi)\sim10^\circ$**

PRD 97, 031101 (2018)



5/fb

$R_D = (3.454\pm0.031)\times10^{-3}$ $A_D = (-0.1\pm9.1)\times10^{-3}$

$x'^2=(3.9\pm2.7)\times10^{-5}$ $y'=(5.28\pm0.52)\times10^{-3}$ $1.00 < |q/p| < 1.35$ @68.3% CL

A_Γ in $D^0 \to h^+h^-$

Indirect CPV Measurement

PRL 118, 261803 (2017)
LHCB-CONF-2019-001 (2019)

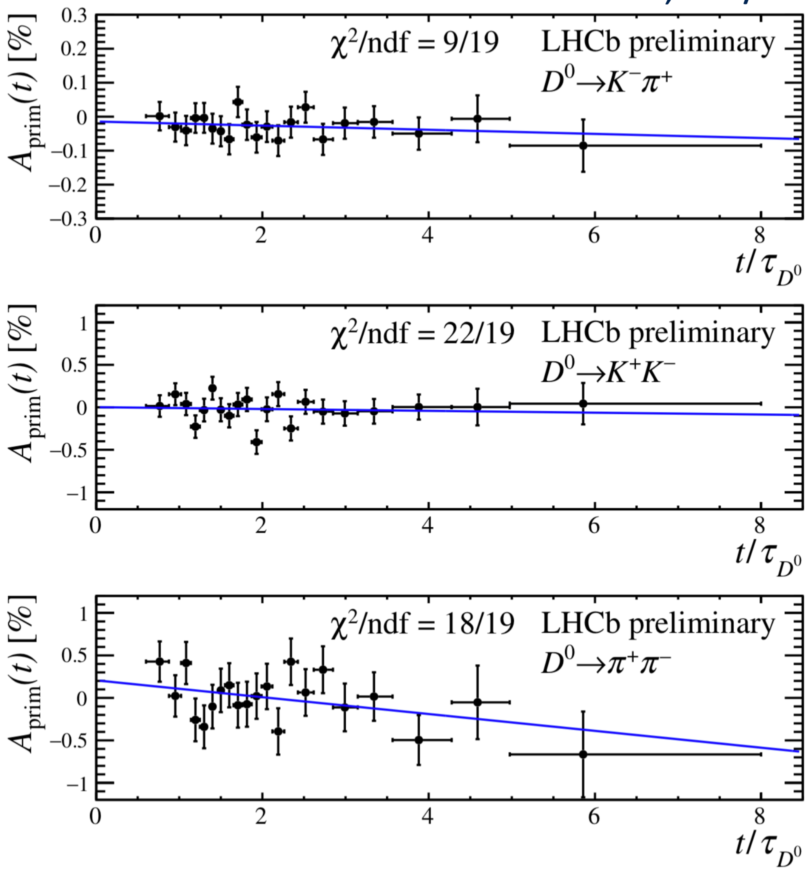
- $A_\Gamma \sim -a_{CP}^{ind}$

$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to h^+h^-) - \hat{\Gamma}(\overline{D}^0 \to h^+h^-)}{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\overline{D}^0 \to h^+h^-)}$$

- Important input to the interpretation of ΔA_{CP}

$$\Delta A_{CP} \simeq \Delta A_{CP}^{dir}\left(1 + \frac{\overline{\langle x \rangle}}{\tau_{D^0}} y_{CP}\right) + \frac{\Delta\langle x \rangle}{\tau_{D^0}} a_{CP}^{ind}$$

2015+2016, 1.9/fb



Challenging Systematics

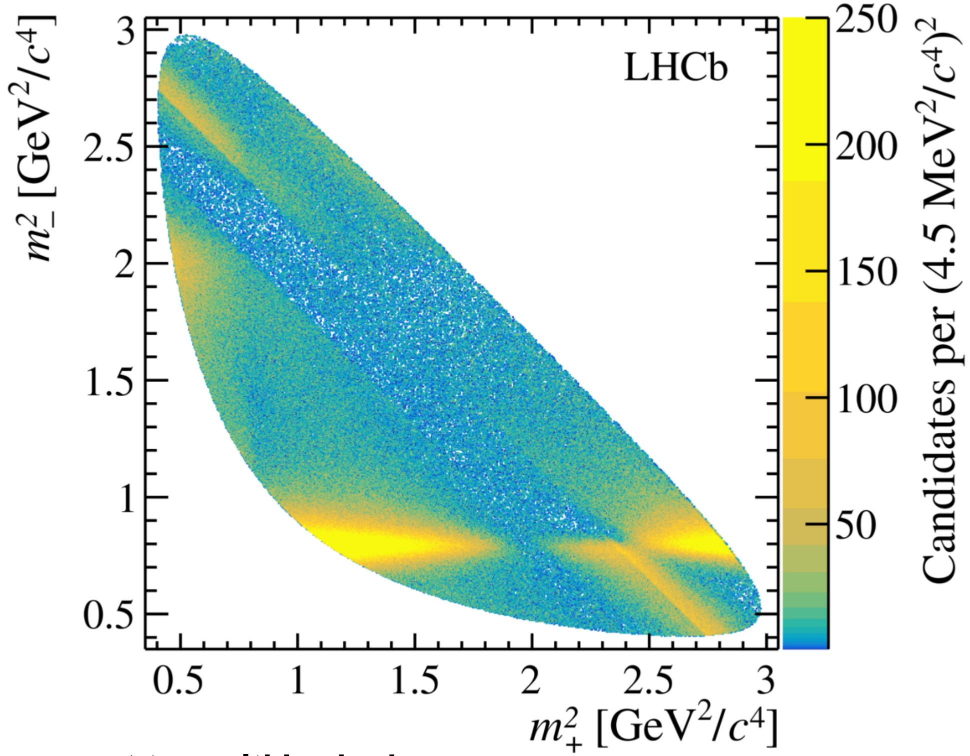
- **Need to control any potential source of asymmetry in decay time**
  Luckily CF $D^0 \to K^-\pi^+$ comes at help
- **Secondary D^0 decays need precise estimate**

2015-2016 result and Prospects

- $A_\Gamma(KK) = (\ 1.3 \pm 3.5 \pm 0.7) \times 10^{-4}$
  $A_\Gamma(\pi\pi) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}$
- **Averaged and combined with Run1: $A_\Gamma(KK+\pi\pi) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}$**
- **With full LHCb dataset (adding 4/fb) a precision of 1.6×10^{-4} is achievable**

The Golden Channel: $D^0 \to K^0_S \pi^+ \pi^-$

arXiv:1903.03074



Mixing and indirect CPV

- **Allows to measure directly x**
- **Indirect CPV from measurement of q/p**

Analysis Approaches

- **Time-dependent amplitude analysis**
- **Bin-flip**

Bin-flip PRD 99, 012007 (2019)

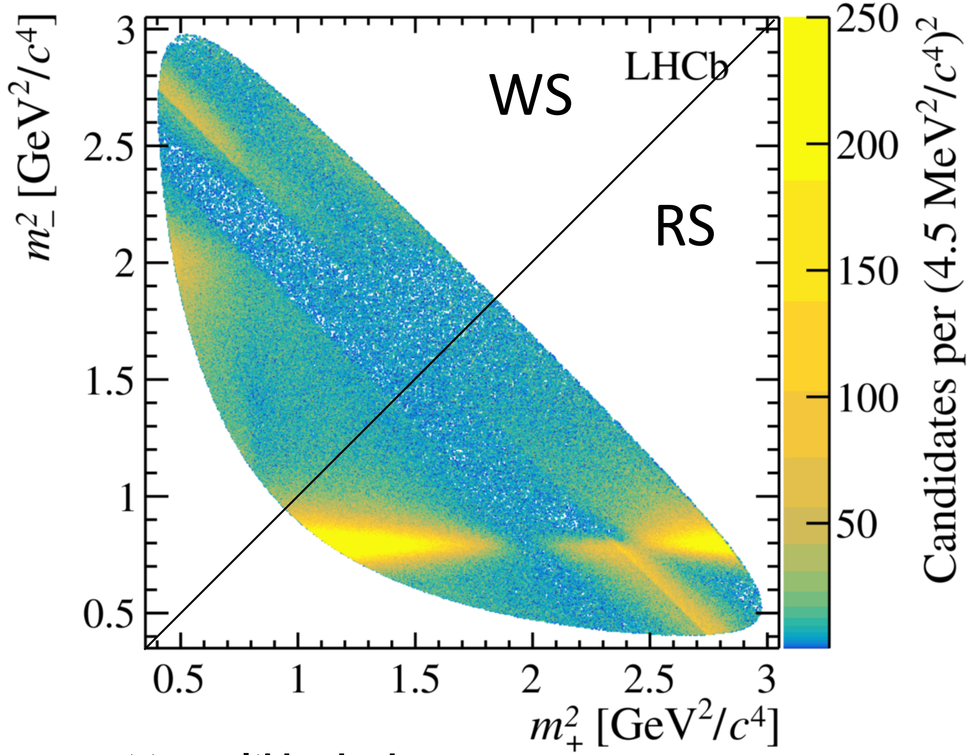
- **An extension of the WS mixing measurement concept to multi body decays**

$$R_b \approx r_b - \sqrt{r_b}\left[(1-r_b)c_b y - (1+r_b)s_b x\right]\Gamma t$$

- **Hadronic parameters constrained by external input**
  From measurement of quantum-correlated D^0-$\overline{D}^0$ pairs (e.g. CLEO, BESIII)
- **Slightly degraded precision with respect to amplitude analysis approach**
  At the advantage of significantly simplified analysis

The Golden Channel: $D^0 \to K^0_S \pi^+ \pi^-$

arXiv:1903.03074



Mixing and indirect CPV

- **Allows to measure directly x**
- **Indirect CPV from measurement of q/p**

Analysis Approaches

- **Time-dependent amplitude analysis**
- **Bin-flip**

Bin-flip PRD 99, 012007 (2019)

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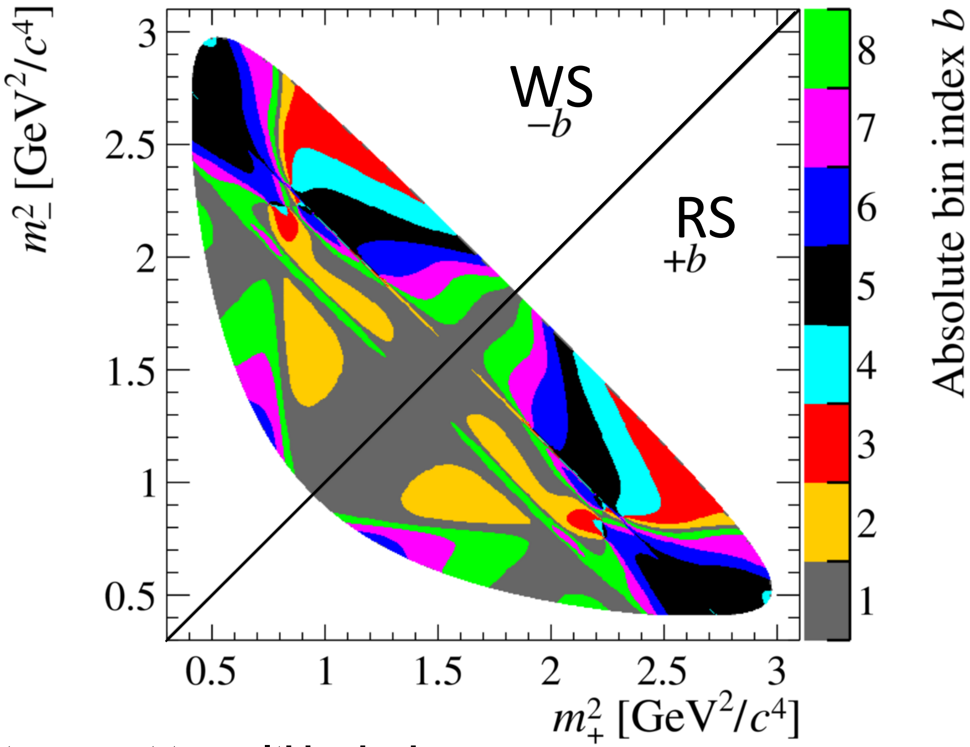

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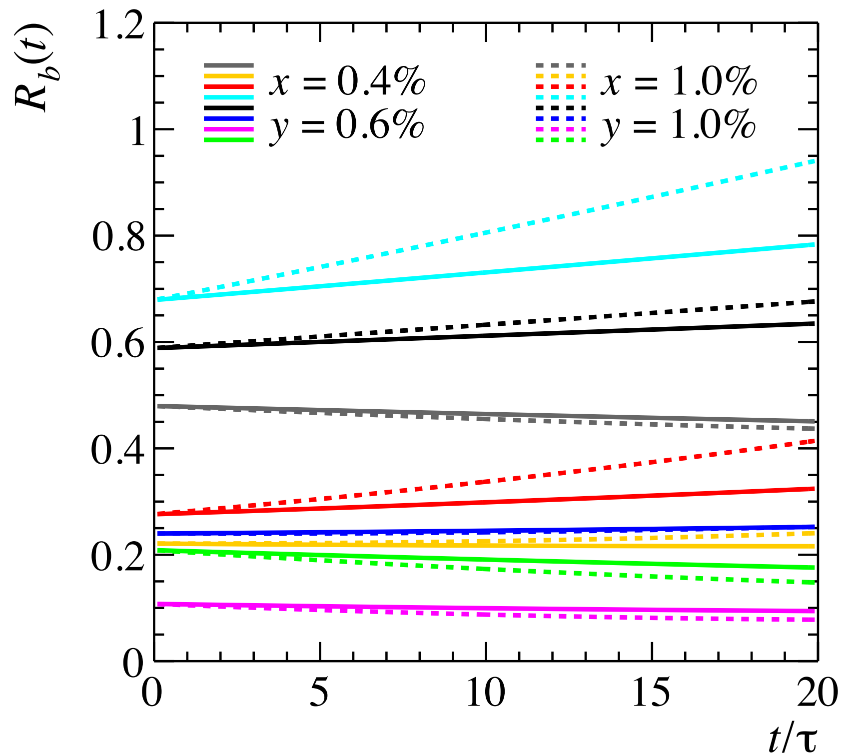

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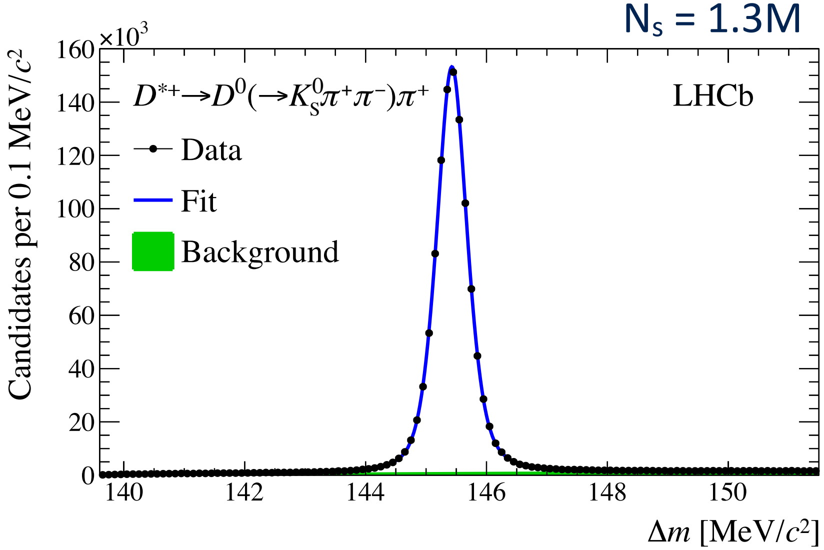
$D^0 \to K^0_S \pi^+ \pi^-$ Bin-Flip Analysis

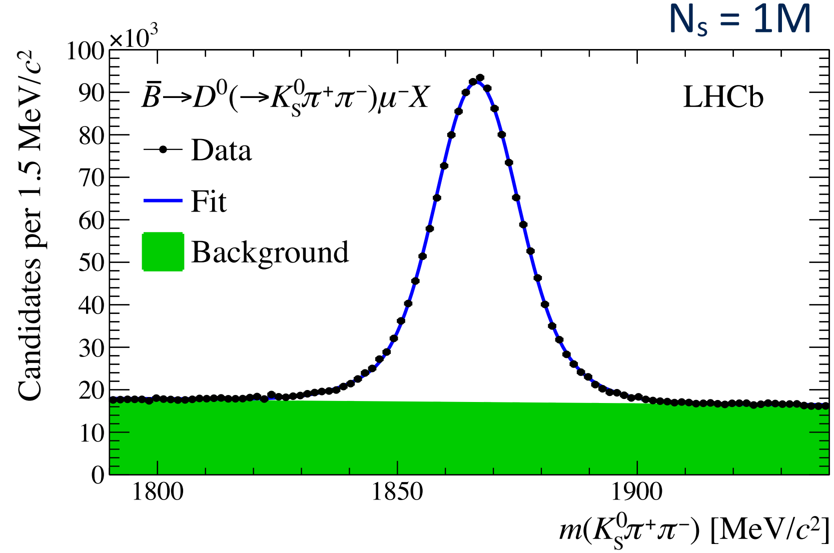
arXiv:1903.03074

Run1 Data (3/fb)

N_s = 1.3M



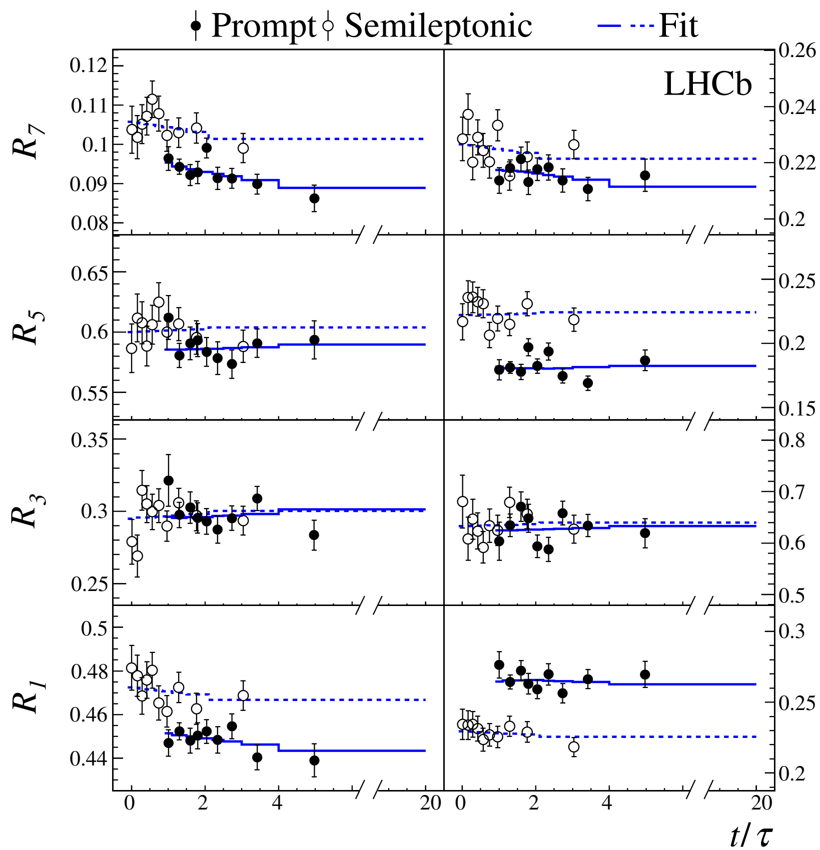
N_s = 1M



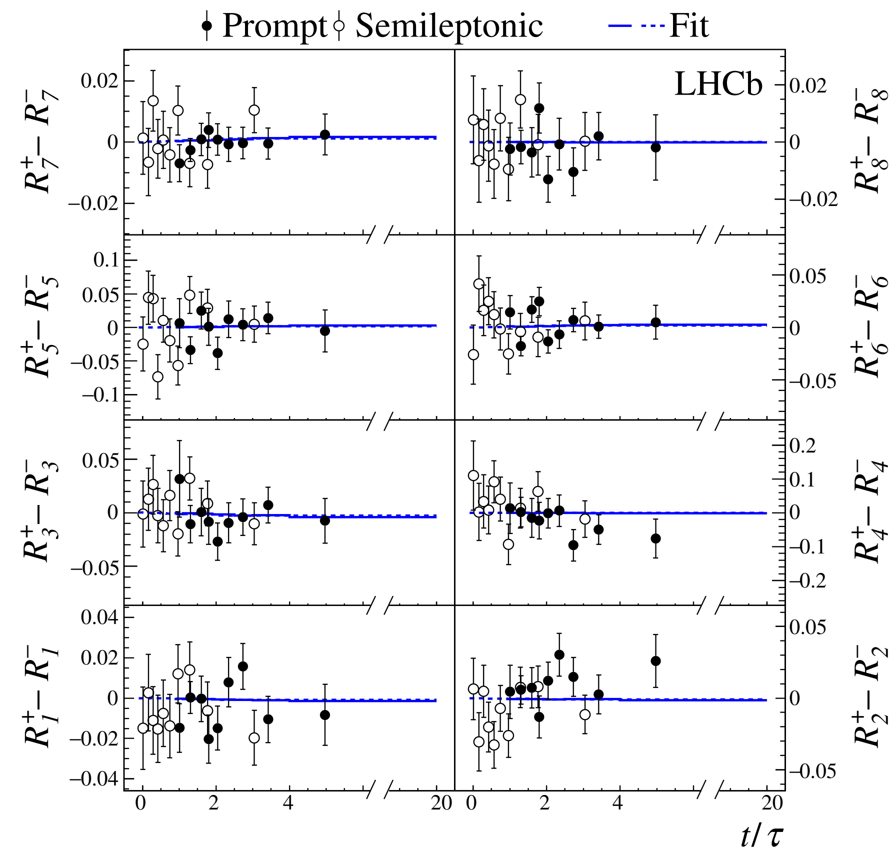
- **Two categories of K^0_S candidates (LL and DD)**

$D^0 \rightarrow K^0_S \pi^+ \pi^-$ Bin-Flip Results

arXiv:1903.03074



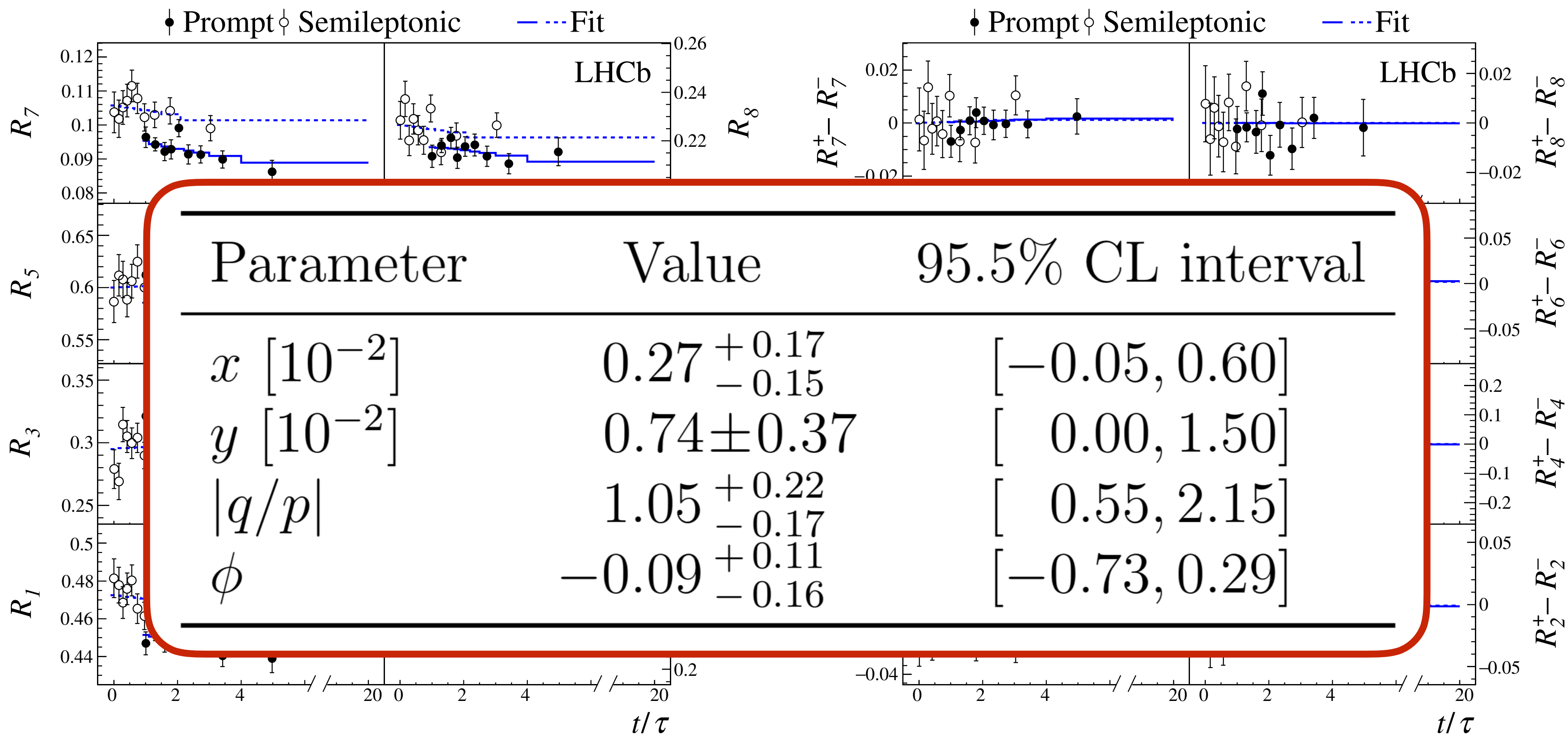
Mixing: $D^0 + \overline{D}^0$



CPV: $D^0 - \overline{D}^0$

$D^0 \to K^0_S \pi^+ \pi^-$ Bin-Flip Results

arXiv:1903.03074



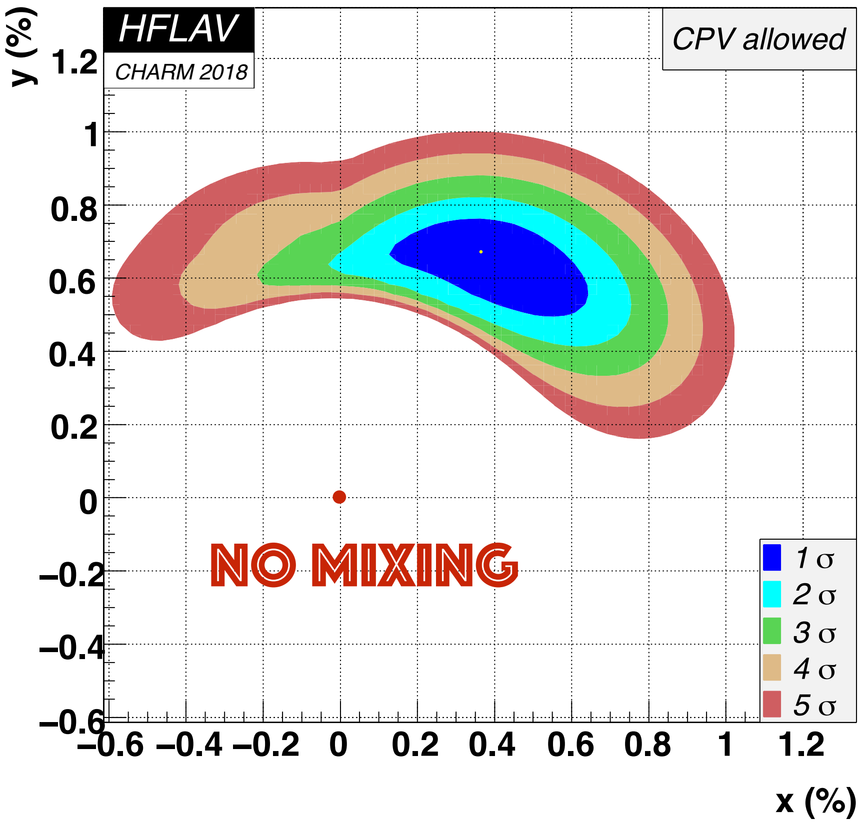
Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p \rvert$	$1.05^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

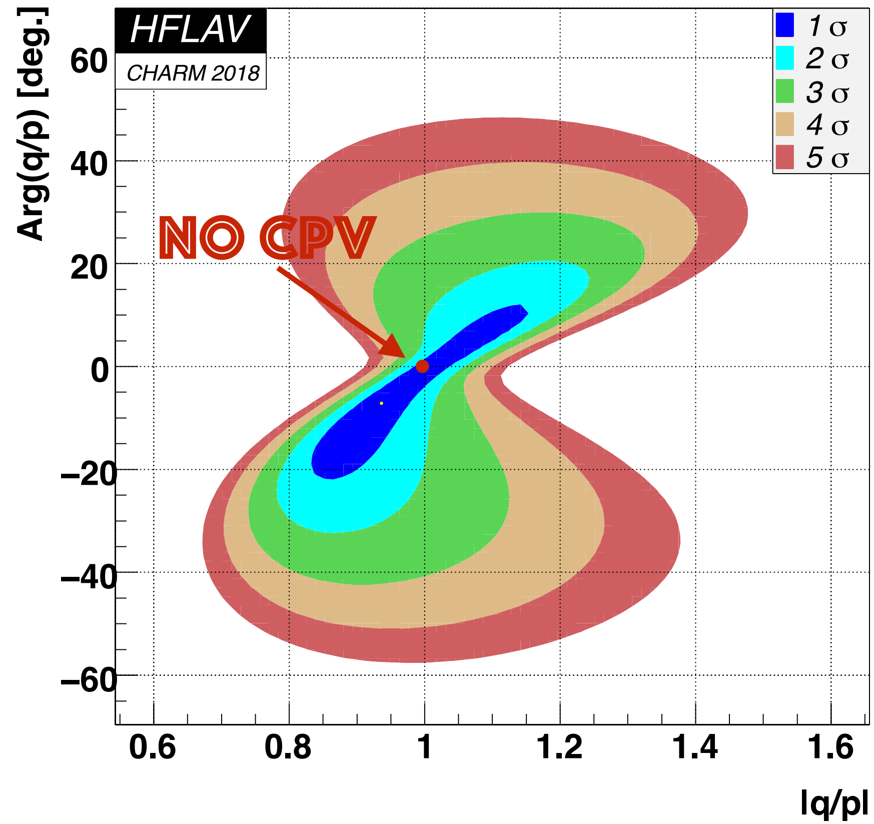
Mixing: $D^0 + \overline{D}^0$

CPV: $D^0 - \overline{D}^0$

World's most precise measurement of x, |q/p|, and ϕ

Impact on World Average





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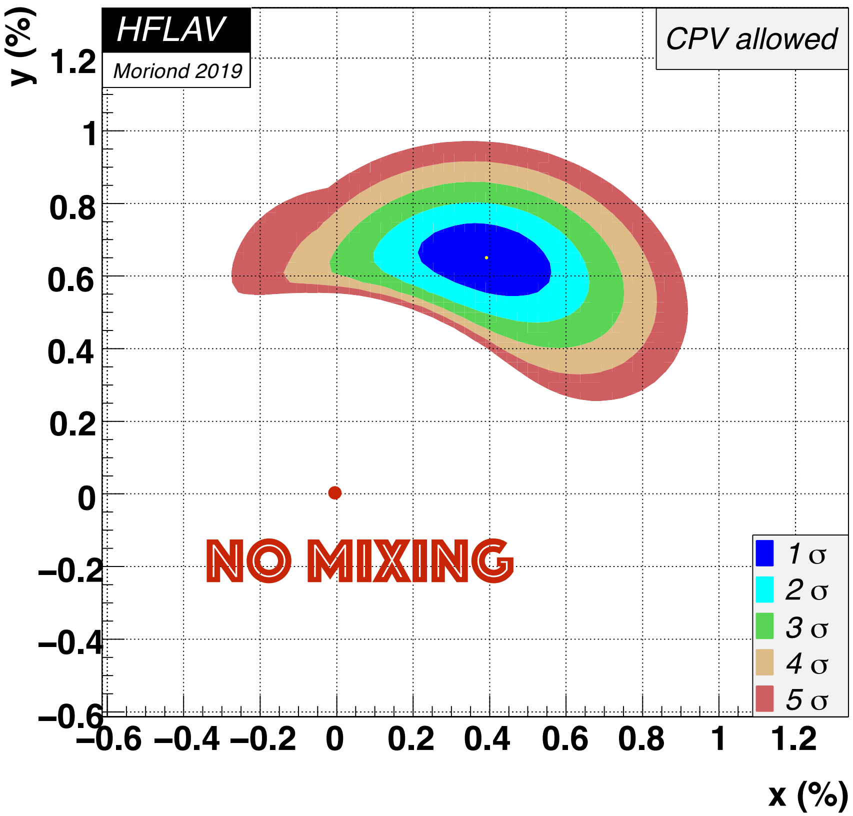
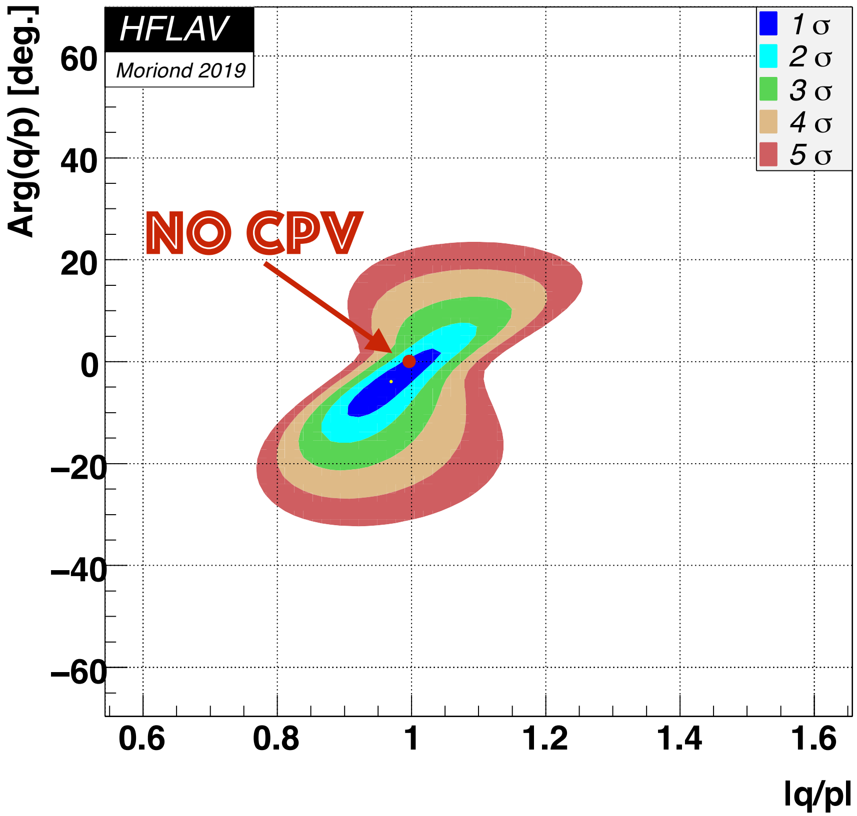




$$x = \left(0.39^{+0.11}_{-0.12}\right)\,\%$$

$$y = \left(0.651^{+0.063}_{-0.069}\right)\,\%$$

$$|q/p| = \left(0.969^{+0.050}_{-0.045}\right)$$

$$\phi = \left(-3.9^{+4.5}_{-4.6}\right)^{\circ}$$

Off the Beaten Path

Multibody Decays

Pro and Cons

- **Rich resonant structure may favour interference giving rise to CPV effects**
- **Difficult to perform ΔA_{CP}-like measurements**

Techniques

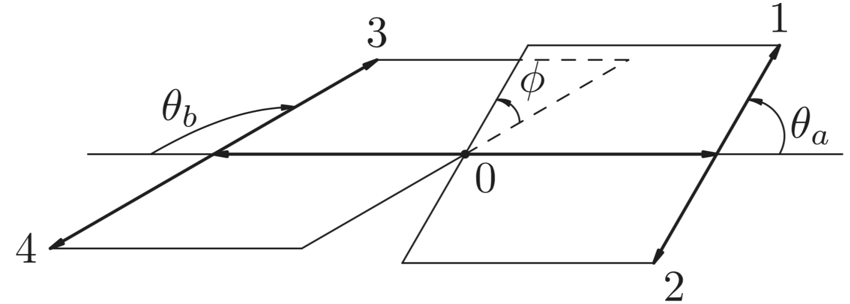
- **Triple Products** JHEP 10 (2014) 005
  $\sigma a_{CP}^{Todd}(D^0 \to K^+K^-\pi^+\pi^-) = 2.9 \times 10^{-3}$
  Analysis ongoing on Run2 LHCb dataset
  $\sigma(D^0 \to K^+K^-\pi^+\pi^-) \sim 5.4 \times 10^{-4}$
  $\sigma(D^0 \to \pi^+\pi^-\pi^+\pi^-) \sim 2.4 \times 10^{-4}$
- **Energy Test** PLB 769 (2017) 345-356
  Compares distribution in the phase-space
  Discovery tool, does not identify source of CPV

$$A_T = \frac{N(D^0, \Phi > 0) - N(D^0, \Phi < 0)}{N(D^0, \Phi > 0) - N(D^0, \Phi < 0)}$$

$$\overline{A}_T = \frac{N(\overline{D}^0, -\overline{\Phi} > 0) - N(\overline{D}^0, -\overline{\Phi} < 0)}{N(\overline{D}^0, -\overline{\Phi} > 0) - N(\overline{D}^0, -\overline{\Phi} < 0)}$$

$$a_{CP}^{T\text{-odd}} = \frac{1}{2}(A_T - \overline{A}_T)$$

$$\Phi = \Phi_{lmn} = P_l(\cos\theta_a) P_m(\cos\theta_b) \sin n\phi$$



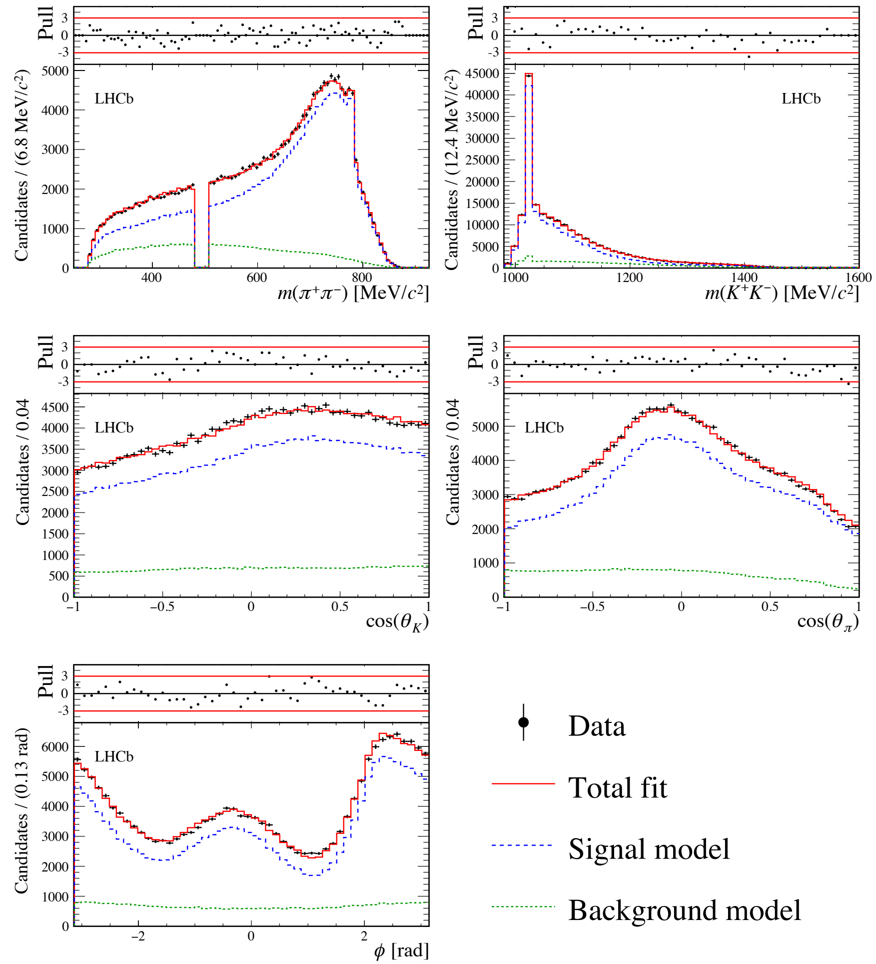
PRD 92, 076013 (2015)

CPV Searches with Amplitude Analyses - $D^0 \to K^+K^-\pi^+\pi^-$

JHEP 02 (2019) 126

N_s = 160k

Run1, 3/fb



Advantages

- **Clear identification of responsible processes**
- **Possibility to probe regions of phase space with different strong phase difference**

Challenges

- **Model building complexity**
- **Model-dependent results**

Results

- **Most precise amplitude modelling of $D^0 \to K^+K^-\pi^+\pi^-$**
- **Compatible with CP symmetry**
  Sensitivity ranging from 1% ($\phi\rho$, $K_1^+K^-$) to 15%

CPV Searches with Amplitude Analyses - $D^0 \to K^+K^-\pi^+\pi^-$

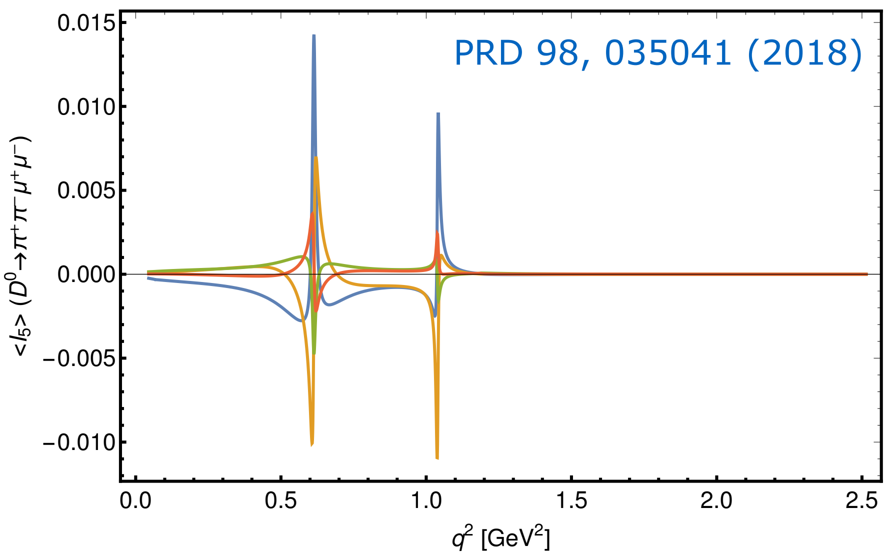
JHEP 02 (2019) 126

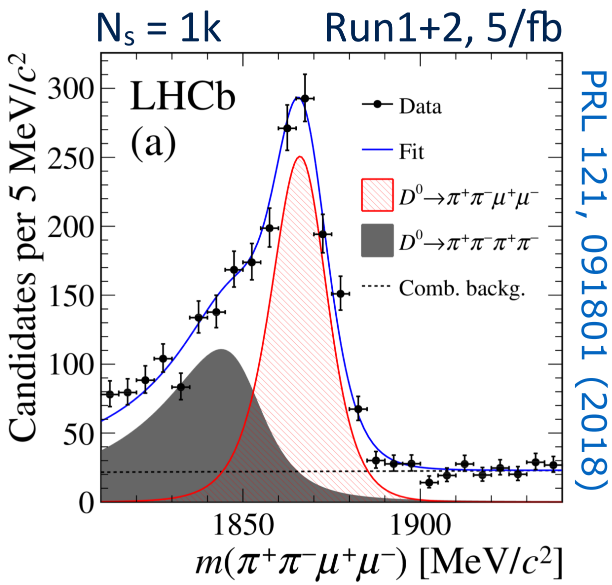
Amplitude	$A_{\lvert c_k \rvert}$ [%]	$\Delta\arg(c_k)$ [%]	$A_{\mathcal{F}_k}$ [%]
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=0}$	0 (fixed)	0 (fixed)	$-1.8 \pm 1.5 \pm 0.2$
$D^0 \to K_1(1400)^+K^-$	$-1.4 \pm 1.1 \pm 0.2$	$1.3 \pm 1.5 \pm 0.3$	$-4.5 \pm 2.1 \pm 0.3$
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$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

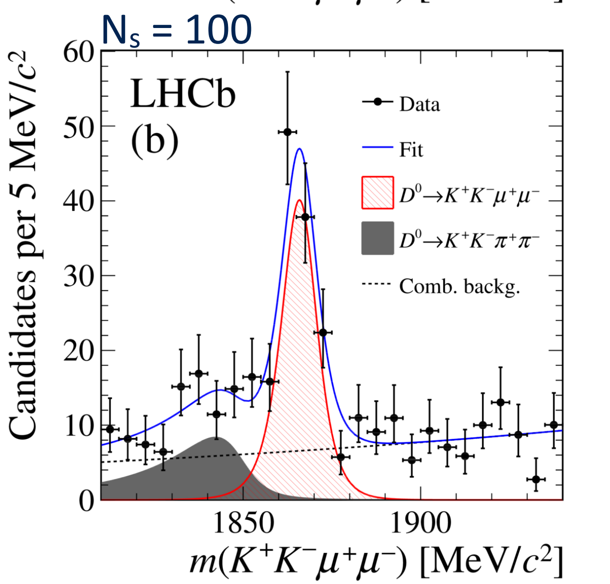
CPV in Rare Decays

Rarest Charm Decay Observed So Far

- **$BF(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97)\times10^{-7}$**
  $BF(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16)\times10^{-7}$
- **Studied triple product and Forward-Backward asymmetries**
  Null with 4(11)% sensitivity for $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$
- **With full LHCb dataset expected factor 2 better sensitivity**
- **Further null tests of the SM are suggested**
  An amplitude analysis may be needed to control hadronic uncertainties
- **Suggested to test Lepton Universality with $D^0 \to h^+h^-e^+e^-$**

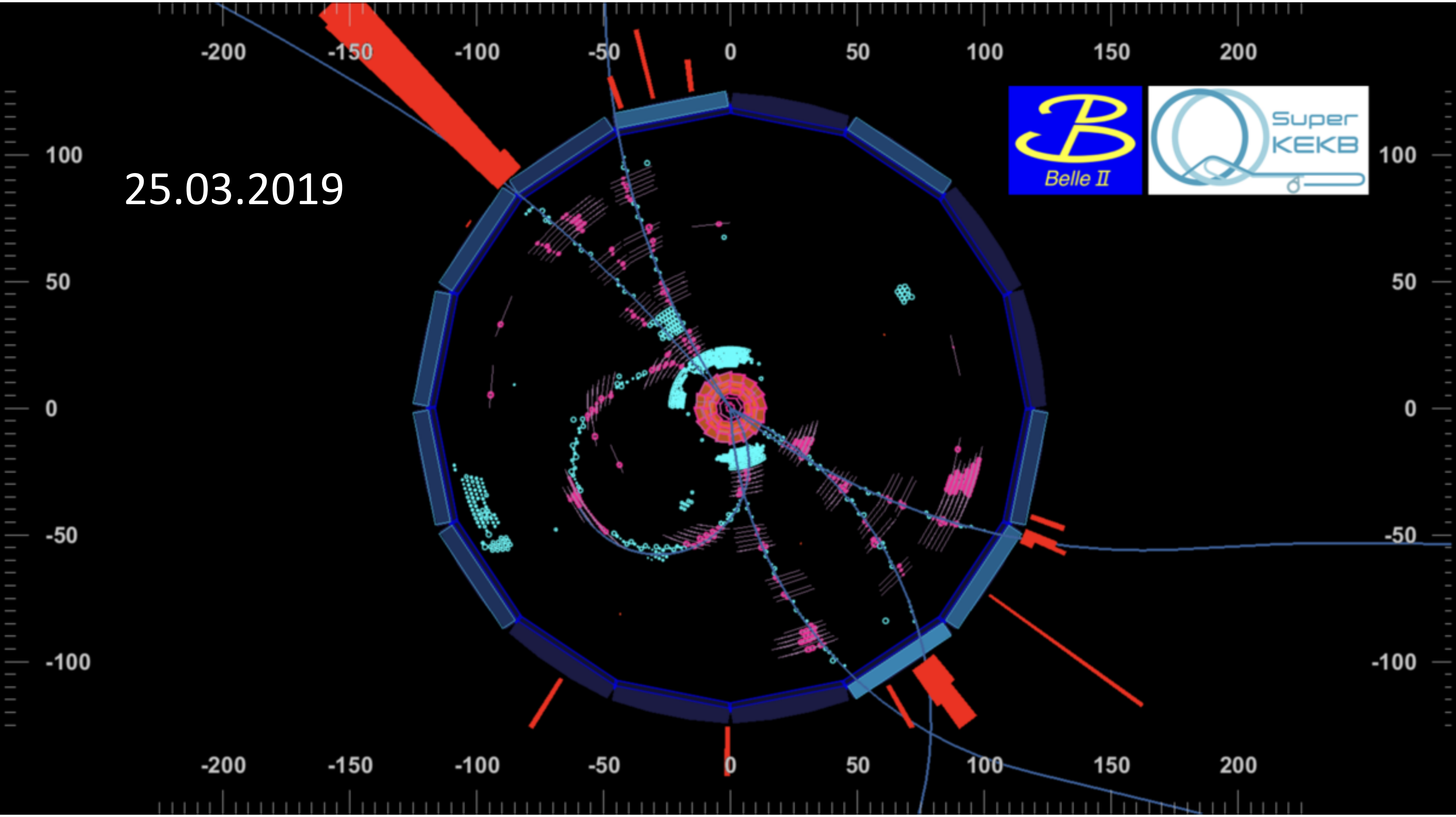






(Long-Term) Future

Upcoming Competition - Belle II



LHCb Upgrade and Belle II

LHCb (Upgrade)

BelleII

HADRONIC CHANNELS

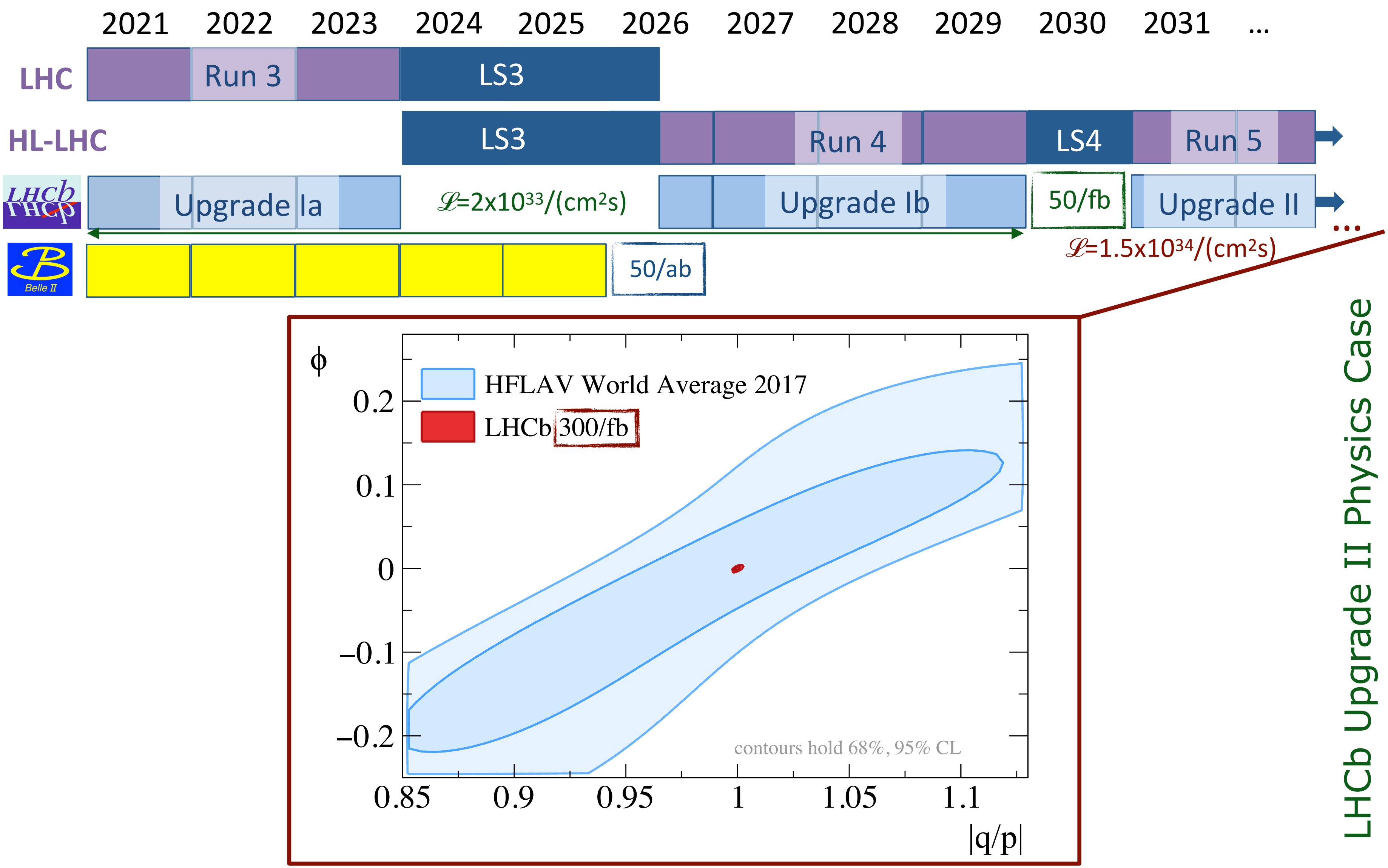
CHANNELS WITH K^0_S

CHANNELS WITH NEUTRALS

LHCb Upgrade II Physics Case

Belle II Physics Book

Towards Ultimate Precision



Conclusions

CP Violation in Charm Finally Discovered

- Much effort is needed to fully understand the impact on our knowledge of the Standard Model
- Observing it in other decay channels will surely help and should be LHCb aim with its full dataset

Indirect CP Violation Still Escaping Detection

- We have many ways to find it and we can still explore them all with full LHCb dataset (9/fb)

Further Challenges Ahead

- The LHCb Upgrade will collect 50/fb by 2030
- Belle-II will join the competition in the same period
- LHCb Upgrade-II (300/fb) will provide the ultimate precision in flavour physics

Exciting Times Ahead!