Experimental progress and prospect on Charm CPV search

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High Intensity Electron-Positron Accelerator
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Outline

Introduction

I. Charm physics and BSM

II. *CPV* theory introduction

III. LHCb detector

Results

IV. Mixing and indirect CPV

V. Direct CPV

Future

VI. Future prospects

I. Charm physics and BSM

Charm physics and BSM

1) Charm hadrons are the only particles with the up-type type quark where mixing and Charge-Parity violation (*CPV*) can occur

2) Standard model (**SM**) predicts little to none *CPV* in charm sector

3) Perfect place where to look for Beyond Standard Model (BSM) effects

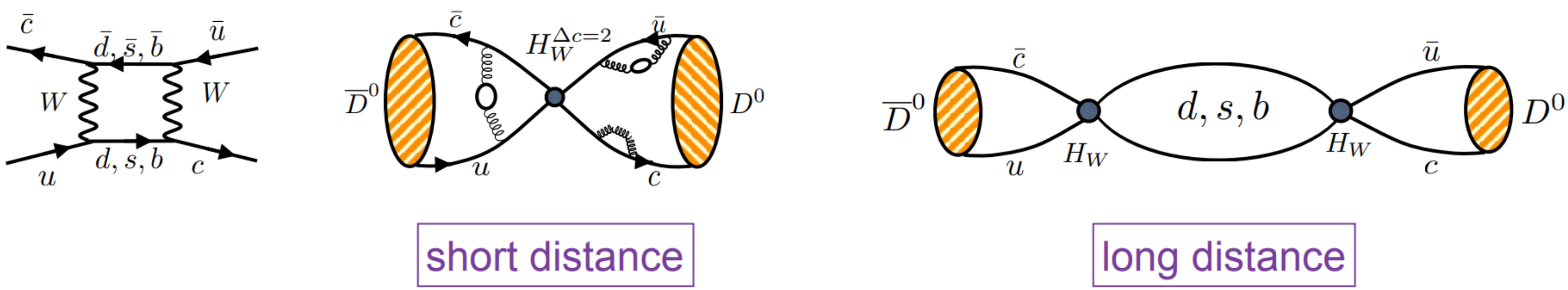
4) Due to mass of charm quark theoretical calculations are challenging

5) In addition many studies in charm sector are important inputs for b-physics

II. *CP* violation theory introduction

Mixing of $\mathrm{D}^0 - \bar{\mathrm{D}}^0$

- D^0 mesons are produced as a flavor eigenstates, but decays as mass eigenstates D_1 and D_2: $|\mathrm{D}_1\rangle = p|\mathrm{D}^0\rangle + q|\bar{\mathrm{D}}^0\rangle$, $|\mathrm{D}_2\rangle = p|\mathrm{D}^0\rangle - q|\bar{\mathrm{D}}^0\rangle$, $|q|^2 + |p|^2 = 1$
- Mixing occurs in the case: $\Delta M = M_1 - M_2 \neq 0$ or $\Delta\Gamma = \Gamma_1 - \Gamma_2 \neq 0$
- Associated mixing parameters: $x = \frac{\Delta M}{\Gamma}$, $y = \frac{\Delta\Gamma}{2\Gamma}$, where: $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$
- Influence of short and long distance effects



- For the small mixing parameters ($x,\ y\ <\ 10^{-2}$) the time-dependent asymmetry can be approximated as:

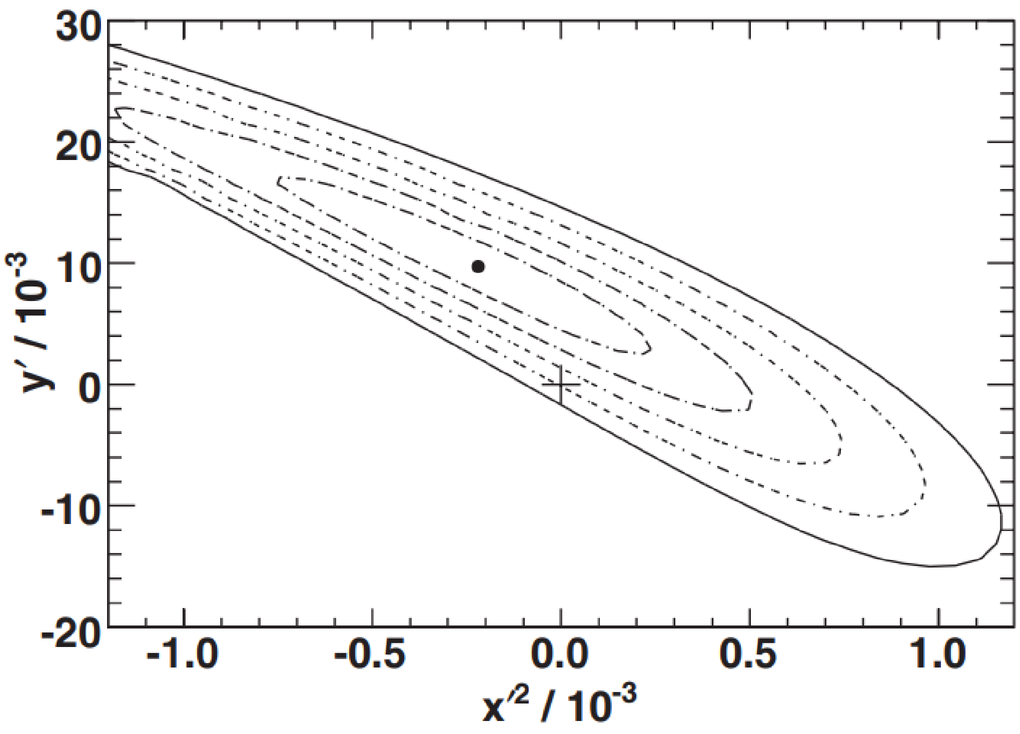
$$A_{CP}(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \simeq A_{CP}^{dir,f} - A_\Gamma \frac{f}{t_D}$$

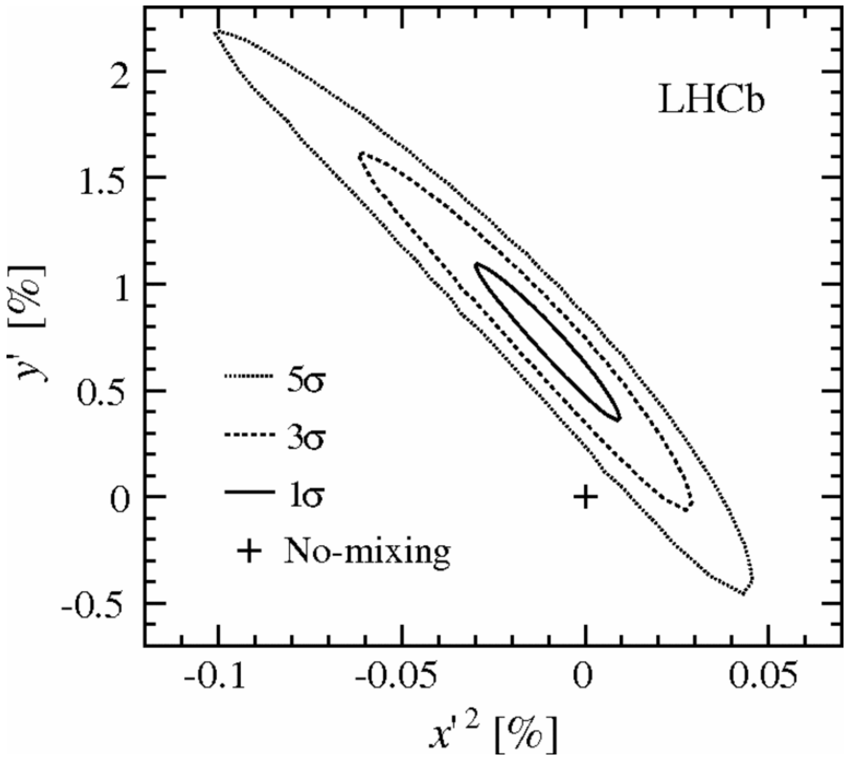
where A_Γ is the asymmetry between effective decay widths of D^0 and $\bar{\mathrm{D}}^0$

$$A_\Gamma = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

Mixing of $\mathrm{D}^0 - \bar{\mathrm{D}}^0$: introduction

- First evidence of $\mathrm{D}^0 - \bar{\mathrm{D}}^0$ mixing measured by the BaBar and Belle experiments [PRL 98 211802 (2007) and PRL 98 211803 (2007)]
- Mixing observed by the LHCb experiment [PRL 110 101802 (2013)]





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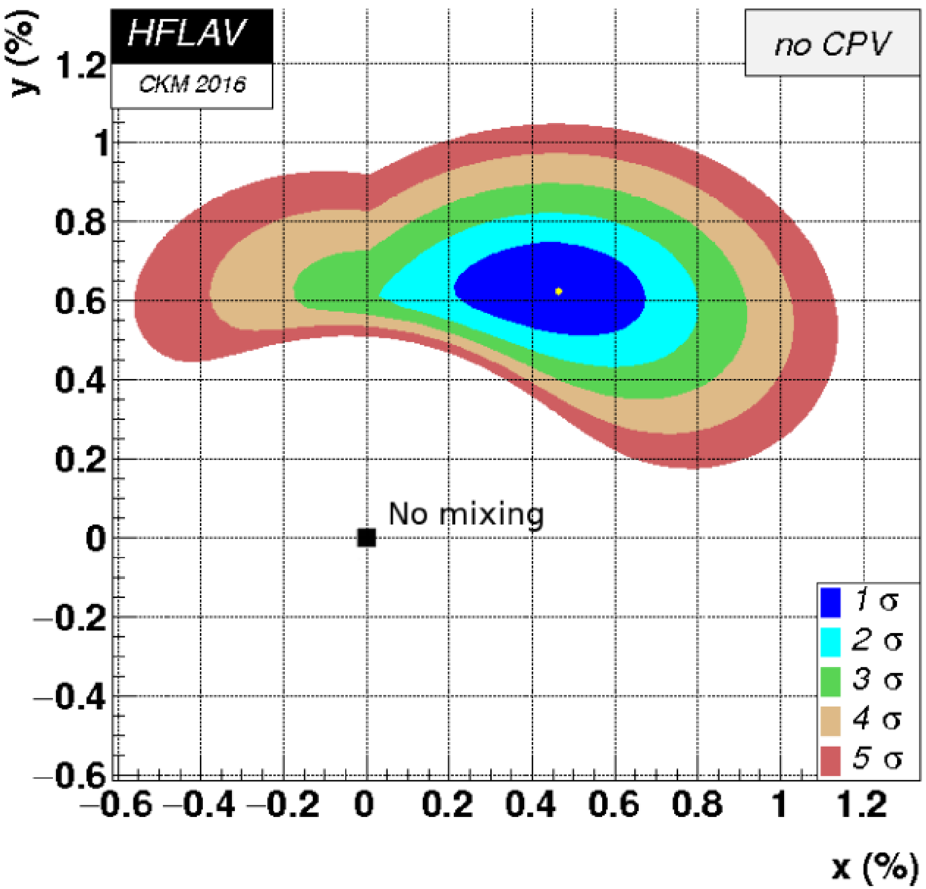
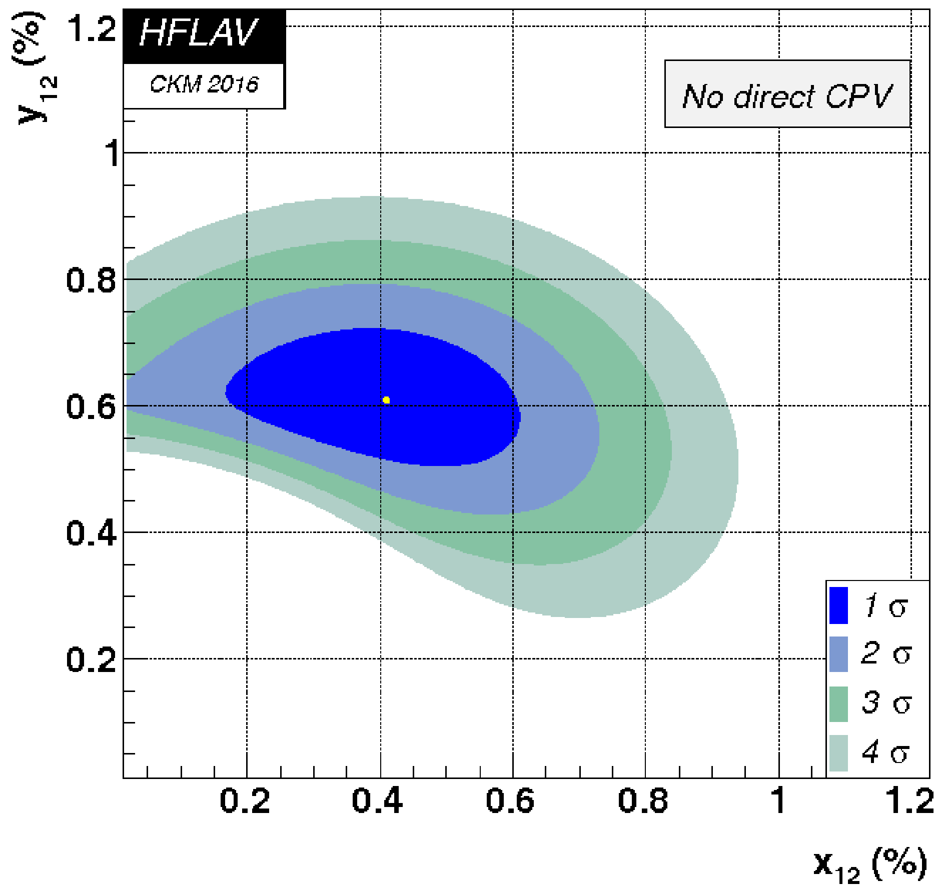




- Mixing established as a 11.5 σ effect

CPV classification

- *CPV* is present in the **SM** via Cabibbo-Kobayashi-Maskawa (CKM) mechanism, but is too weak to explain the Baryon asymmetry
- Today *CPV* is confirmed at strange [PRL 13 138 (1964)] and bottom [NP A 675 (2000), 398-403] sector, no observation in charm
- Two types of *CPV*: Indirect (*CPV* in mixing, *CPV* in interference) and Direct

CPV in mixing

- Independent on final state
- Different mixing rates $\mathrm{D}^0 \to \bar{\mathrm{D}}^0$ and $\bar{\mathrm{D}}^0 \to \mathrm{D}^0$

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

- Accessible via the using flavor specifics decays
- No mass difference or *CPV* in mixing observed so far
- **SM** prediction: $\mathcal{O}(10^{-4})$

CPV in interference

- Possibility of interference between mixing and decay amplitudes

$$\phi = arg(\frac{q\bar{A}_f}{pA_f})$$

- Can be observed as a decay-time-dependent difference in decay rates and as a time-integrated difference
- **SM** prediction: $\mathcal{O}(10^{-4})$

Direct *CPV*

- Only possible *CPV* for charged hadrons
- Occurs in the case:

$$|\frac{\bar{A}_{\bar{f}}}{A_f}| \neq 1$$

- Typically (for SCS modes): $A_{CP} < 10^{-4} - 10^{-3}$
- Time dependent measurements
- Experimentally challenging

III. LHCb detector

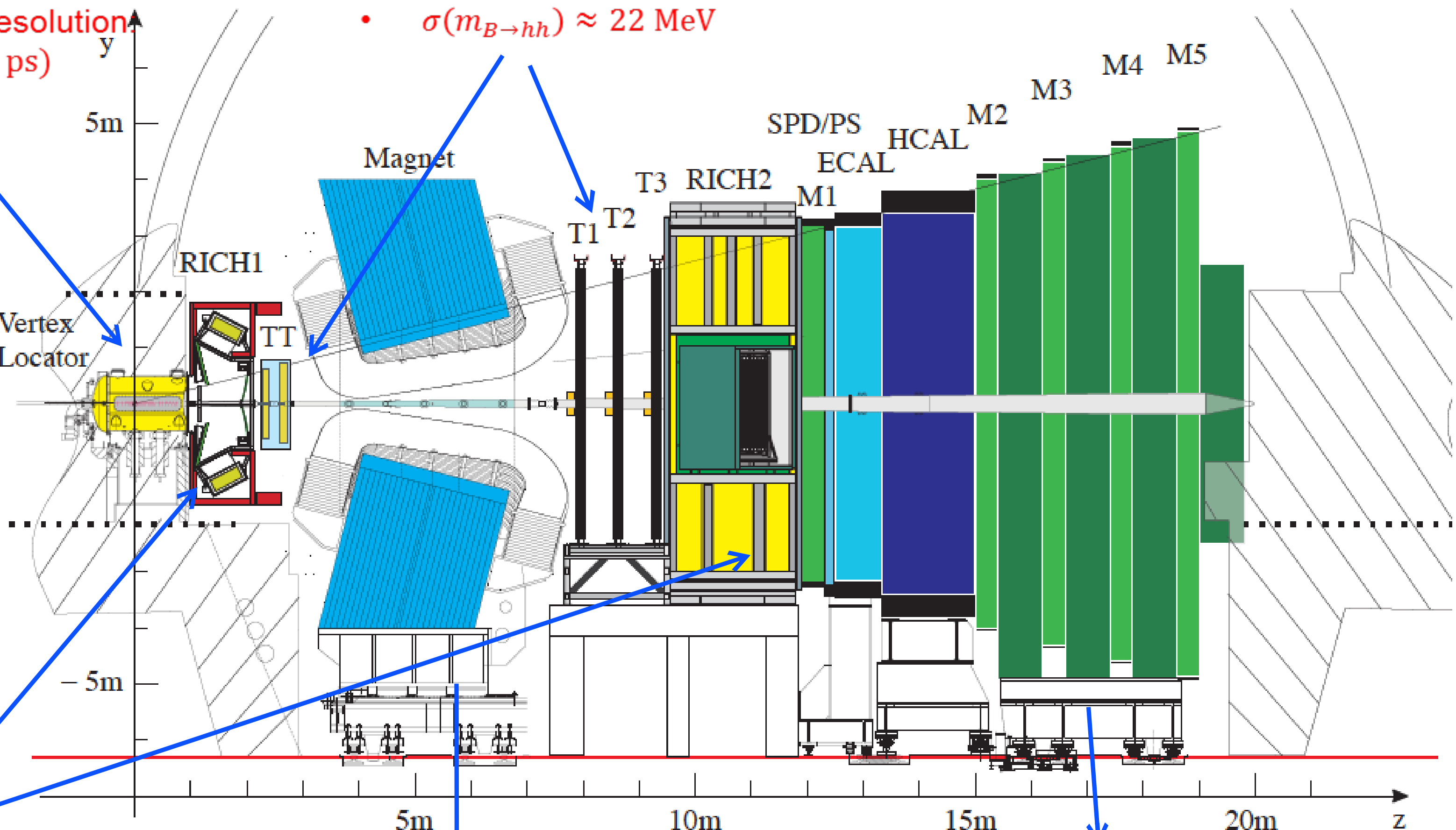
LHCb detector

- Single-arm forward spectrometer focused on heavy flavor (*b*, *c*) physics

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Vertex Locator(vertex reconstruction)
- Impact parameter resolution: 20 μm
- Decay time resolution 45 fs (τ_B~1.5 ps)

Tracking system(particle reconstruction)
- ϵ(Tracking) ~96%
- $\delta p/p$ ~0.5%-1%(5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV



RICH: particle ID
- $\varepsilon(K \to K)$ ~95%
- Mis-ID: $\varepsilon(\pi \to K)$ ~5%

Magnet
- Bending power: 4 Tm

Muon system
- μ ID: $\varepsilon(\mu \to \mu)$ ~97%
- Mis-ID: $\varepsilon(\pi \to \mu)$ ~1-3%

Measurement of charm at LHCb

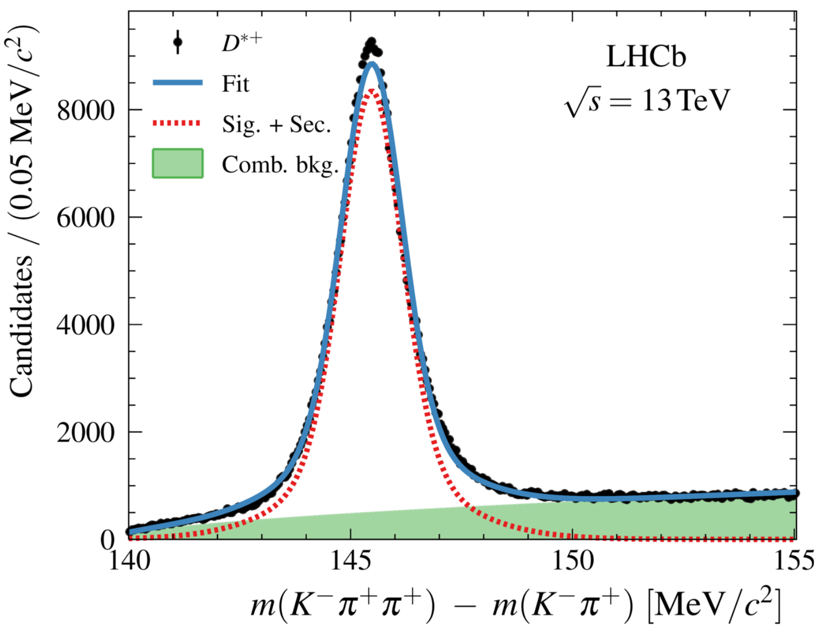
NPB 871 1 (2016), JHEP05 074 (2017)

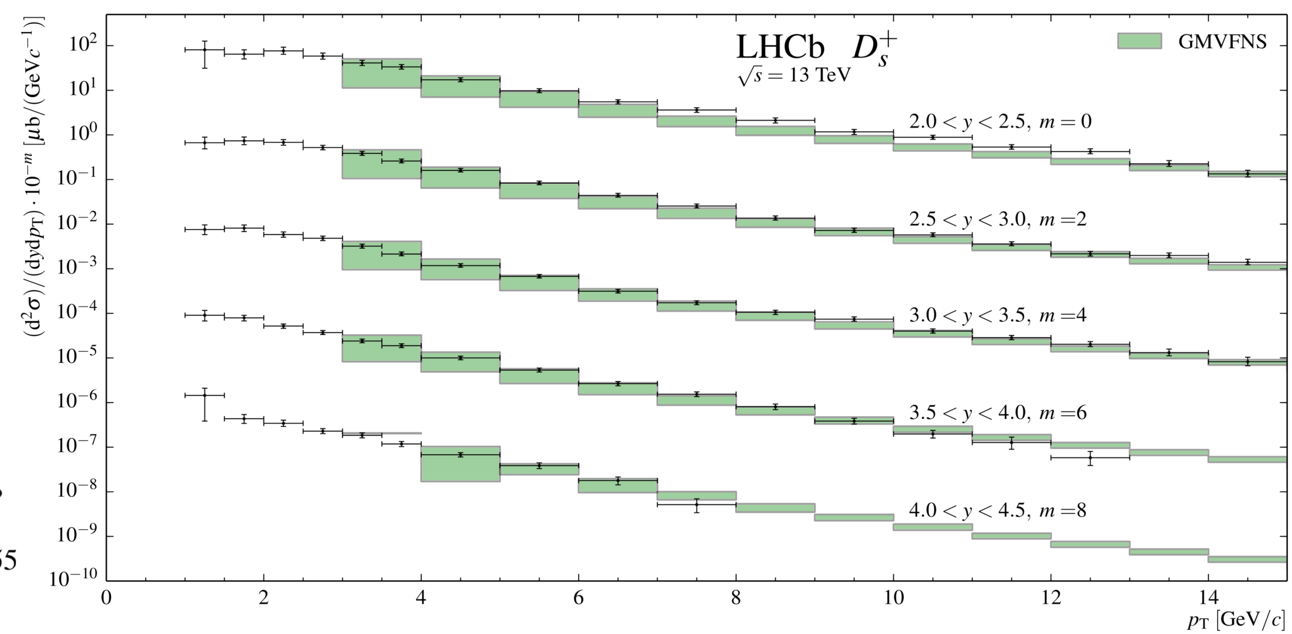
- Large charm cross section at LHCb:

$$\sigma(pp \to c\bar{c}) = \begin{matrix}[1419 \pm 12\ (stat.) \pm 116\ (syst.) \pm 65\ (frag.)]\mu\text{b} \ @\ 7\ \text{TeV} \\ [2369 \pm 3\ (stat.) \pm 152\ (syst.) \pm 118\ (frag.)]\mu\text{b} \ @\ 13\ \text{TeV}\end{matrix}$$

$p_\mathrm{T} < 8GeV/c, 2.0 < y < 4.5$

- Significant statistics collected during Run I (2011-2012, 7+8 TeV, 3 fb^{-1}):
  - About 5×10^{12} D^0 and 2×10^{12} D^{*+} collected
- Run II: higher collision energy and improved trigger → more statistics than Run I

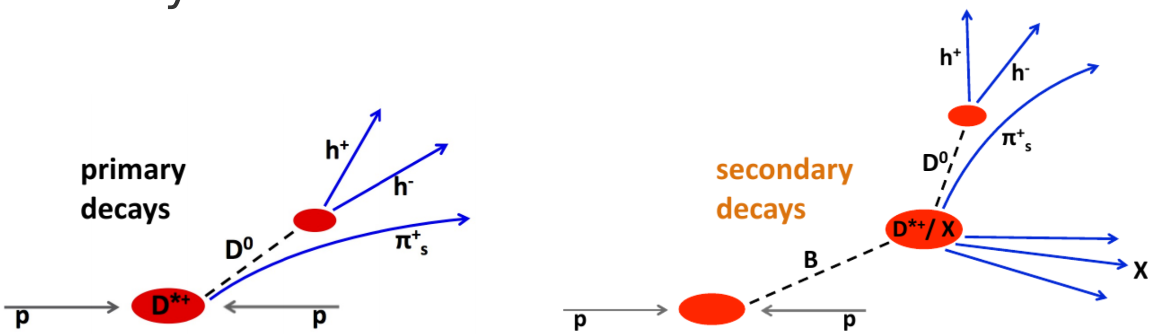




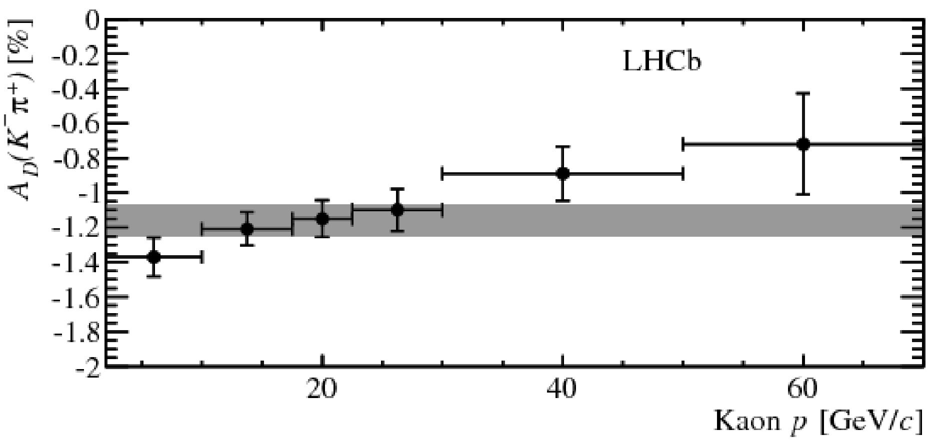
JHEP 05 074 (2017)

Experimental aspects at LHCb

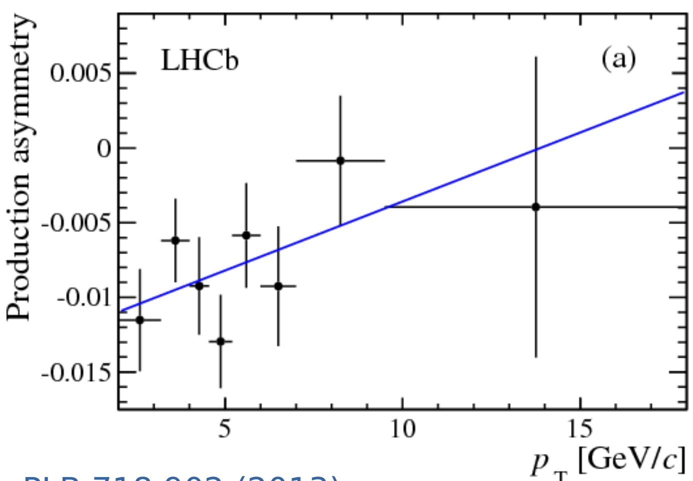
- Flavor tagging: prompt vs secondary → LHCb uses both methods



- Production asymmetries:
  - Different cross-section for $D^+_{(s)}/D^-_{(s)}$, Λ^+_c/Λ^-_c , ...
- Detection asymmetries:
  - Different interactions with the detector material (K^+ vs K^-, π^+ vs π^-)
  - Depends on the particle momentum



JHEP 07 041 (2014)

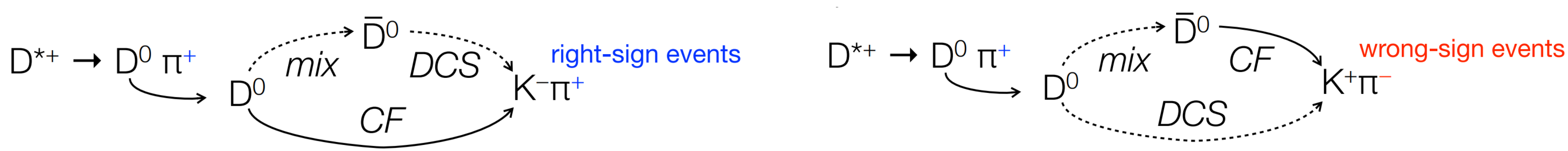


PLB 718 902 (2013)

IV. $\mathrm{D}^0 - \bar{\mathrm{D}}^0$ mixing and indirect CPV

Mixing of $\mathbf{D^0 - \bar{D}^0}$

- The latest results from LHCb using data from Run I (3 fb^{-1}) and from part of Run II (2015-2016, 2 fb^{-1})
- Using the prompt charm production: $\mathrm{D}^{*+} \to \mathrm{D}^0(\to \mathrm{K}^+\pi^-)\pi^+$
- Study of $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ (Right-sign) and $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$ (Wrong-sign) decays:



- Significant yields: 1.77×10^8 RS and 7.22×10^5 WS decays
- The *CP*-averaged decay-time-dependent ratio of WS-to-RS rates:

$$R^{\pm}(t) \approx R_D^{\pm} + \sqrt{R_D^{\pm}} y' \frac{t}{\tau} + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} (\frac{t}{\tau})^2$$

where $x' \equiv x \cos\delta + y \sin\delta$ and $y' \equiv y \cos\delta - x \sin\delta$

- Fit obtained by minimizing a χ^2 variable

Mixing of $\mathrm{D}^0 - \bar{\mathrm{D}}^0$

$$R^{\pm}(t) \approx R_D^{\pm} + \sqrt{R_D^{\pm}} y' \frac{t}{\tau} + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} (\frac{t}{\tau})^2$$

$R^+ \neq R^-$ direct CPV
$x'^+ \neq x'^-$ CPV in mixing
$y'^+ \neq y'^-$ and interference

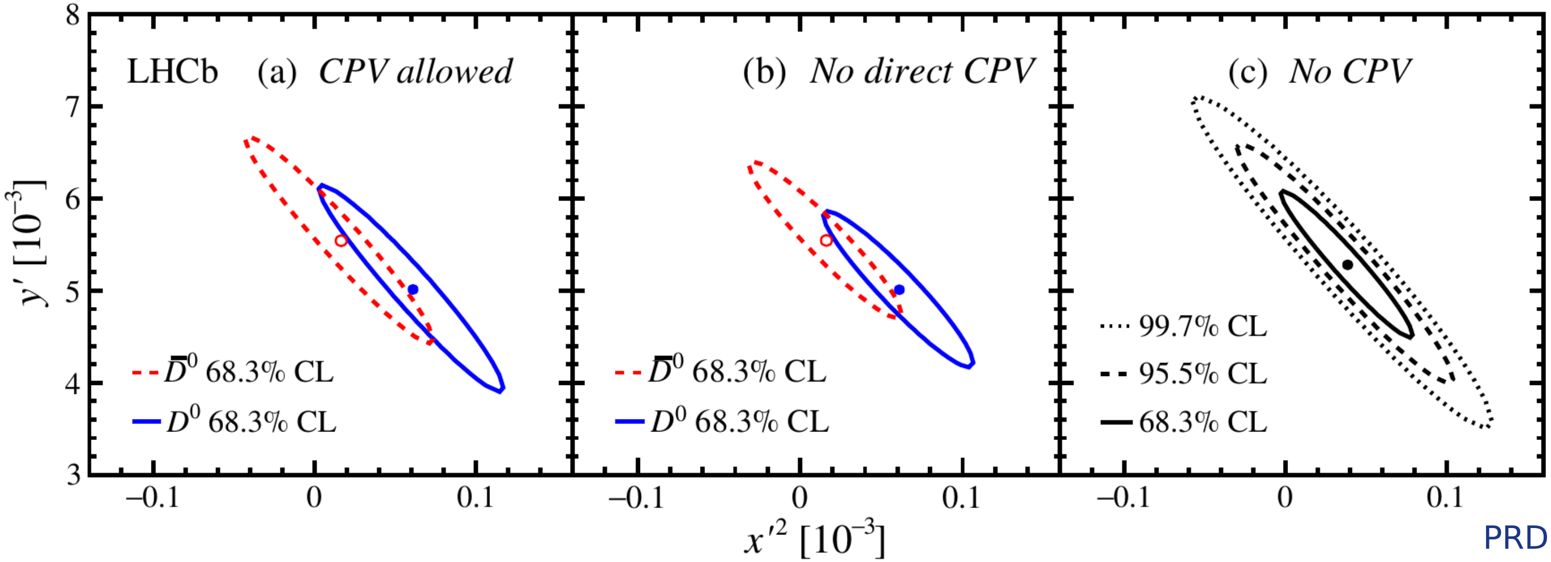
$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

→ Three scenarios were studied:

a) *CPV* allowed - direct and indirect *CPV* allowed

b) No Direct *CPV* - imposed condition $R_D^+ = R_D^-$

c) No *CPV* - *CP*-conservation hypothesis fit (all mix. parameters same for D^0 and $\bar{\mathrm{D}}^0$)



PRD 97 031101 (R)

→ *CPV* parameter: $A_D = (-0.1 \pm 9.1) \times 10^{-3}$

→ Determination of $|q/p|$: $1.00 < |q/p| < 1.35$ at $68.3\ \%$ confidence level
$0.82 < |q/p| < 1.45$ at $95.5\ \%$ confidence level

Mixing of $\mathrm{D}^0 - \bar{\mathrm{D}}^0$

$$R^{\pm}(t) \approx R_D^{\pm} + \sqrt{R_D^{\pm}} y' \frac{t}{\tau} + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} (\frac{t}{\tau})^2$$

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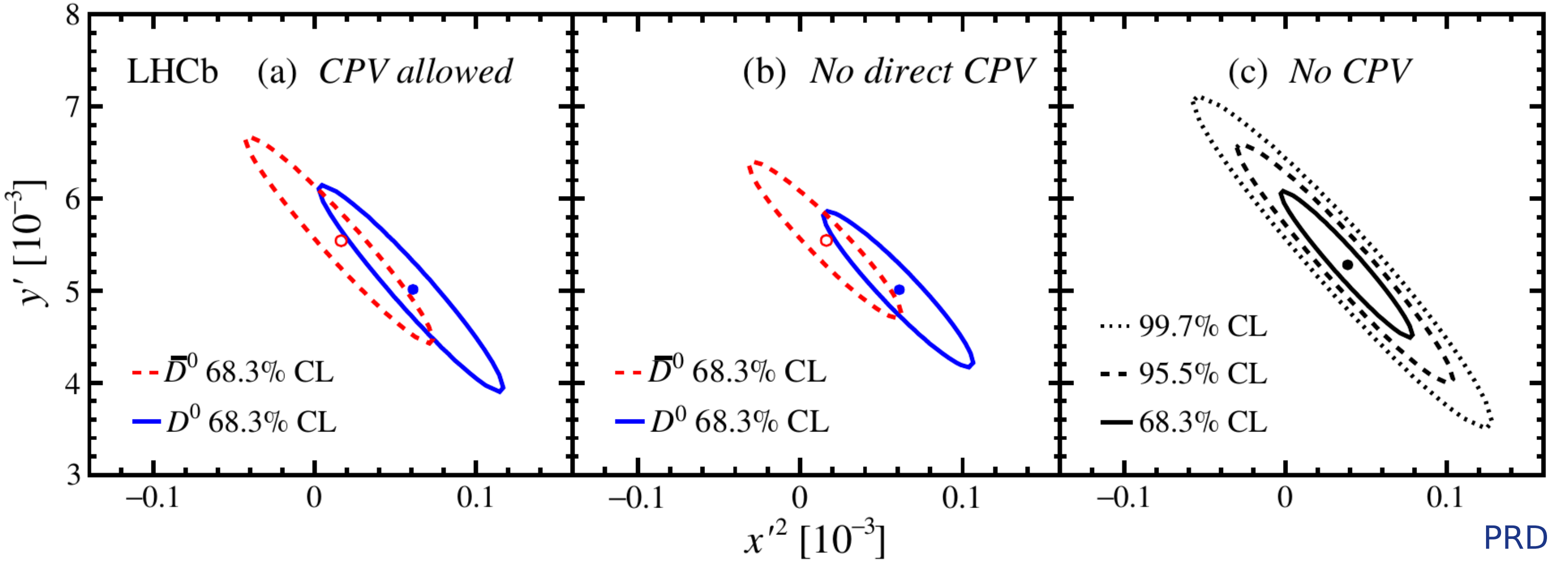


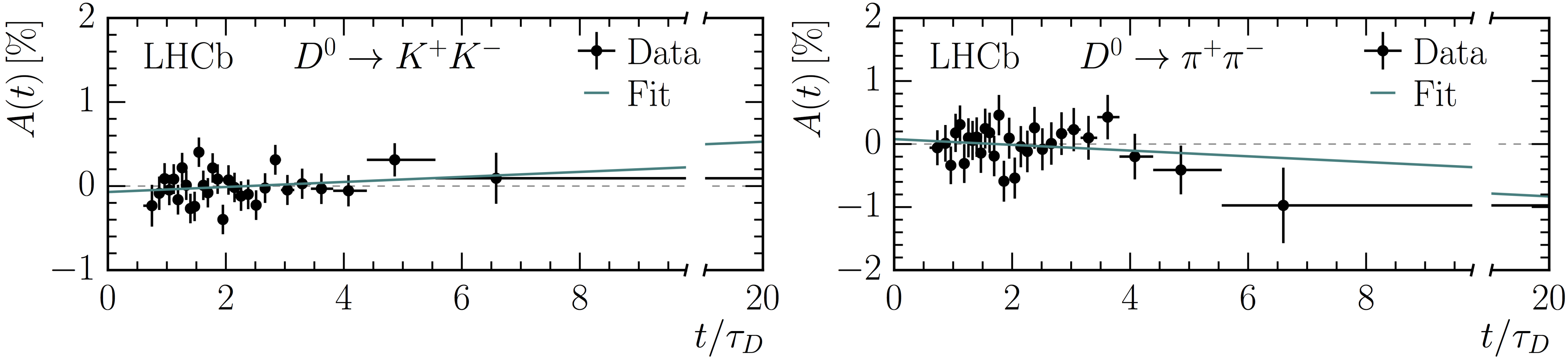
PRD 97 031101 (R)

- The results are twice as precise as previous LHCb results based only on Run I data [PRL 111 251801 (2013)]
- <u>No evidence for CPV observed</u>

A_Γ measurement: direct charm

- The SM prediction: $\mathcal{O}(10^{-4})$
- Enhancement possible by the several NP models up to the order $\mathcal{O}(10^{-3} - 10^{-2})$
- Measurement done via $\mathrm{D}^0 \to \mathrm{K}^-\mathrm{K}^+$ and $\mathrm{D}^0 \to \pi^-\pi^+$ decays from D^*
- Full Run I data set (3 fb^{-1})

$$A_{CP}(t) \equiv A_{CP}^{dir} - A_\Gamma \frac{t}{\tau}$$



- Previous measurement improved by nearly a factor of two.

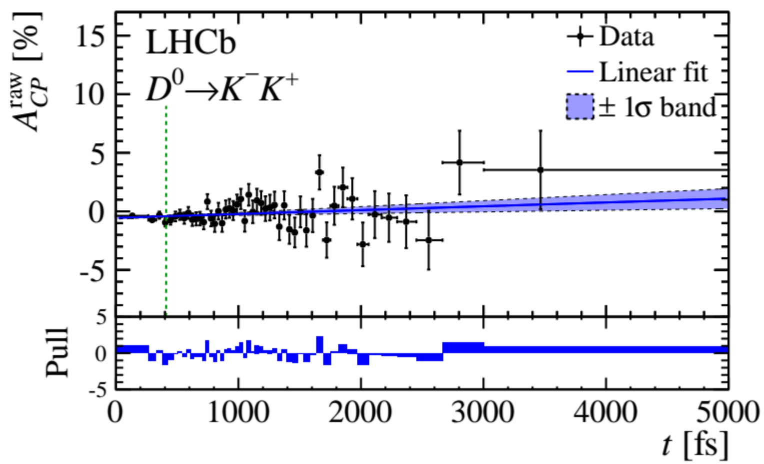
PRL 118 261803 (2017)

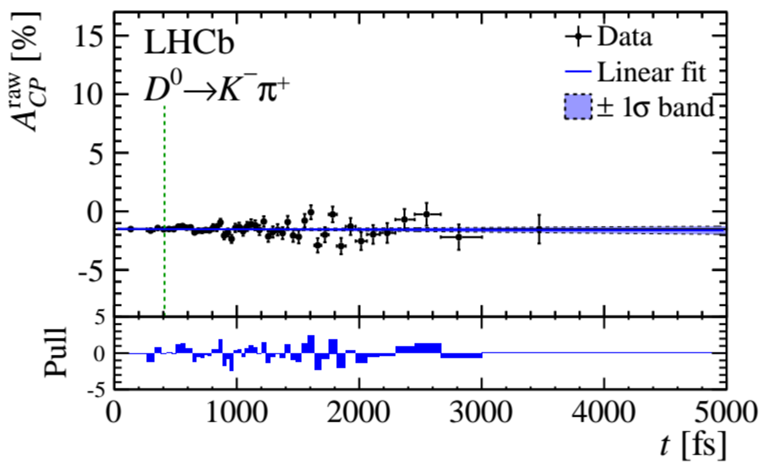
$$A_\Gamma(\mathrm{D}^0 \to \mathrm{K}^-\mathrm{K}^+) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\mathrm{D}^0 \to \pi^-\pi^+) = (+0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$

- Single combined value: $A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$
- No evidence for CPV observed

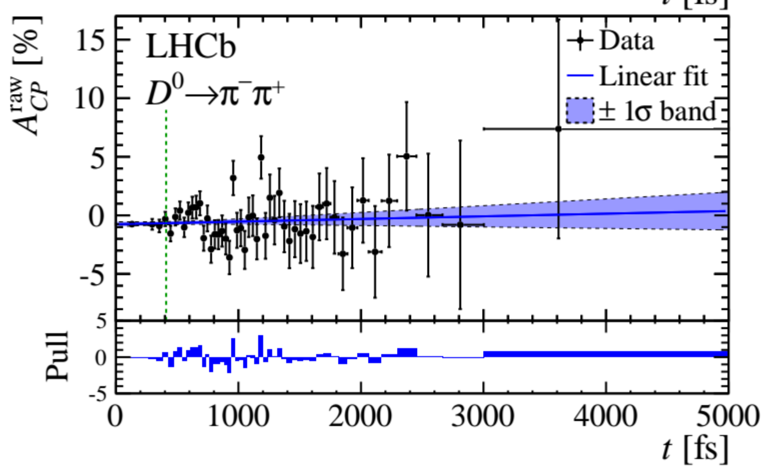
A_Γ measurement: muon tagged

- Using the secondary charm production for cross-check of direct charm results → prompt and secondary charm results are uncorrelated
- Used the *b*-hadron decays, data set is dominated by the $\mathrm{B}^- \to \mathrm{D}^0 \mu \bar{\nu}_\mu \mathrm{X}$ and $\bar{\mathrm{B}}^0 \to \mathrm{D}^0 \mu \bar{\nu}_\mu \mathrm{X}$ (around 40 %) decays, full Run I data-set (3 fb^{-1})
- D meson reconstructed via $\mathrm{K}^-\mathrm{K}^+$, $\pi^-\pi^+$ channels





JHEP 04 043 (2015)



- The $\mathrm{K}^-\pi^+$ decay used as a control channel (no CPV expected)
- D^0 lifetime fixed to $\tau = 410.1$ fs
- Time dependent fit:

$$A_{CP}(t) \equiv A_{CP}^{dir} - A_\Gamma \frac{t}{\tau}$$

A_Γ measurement: muon tagged

- Using the secondary charm production for cross-check of prompt charm results → prompt and secondary charm results are uncorrelated
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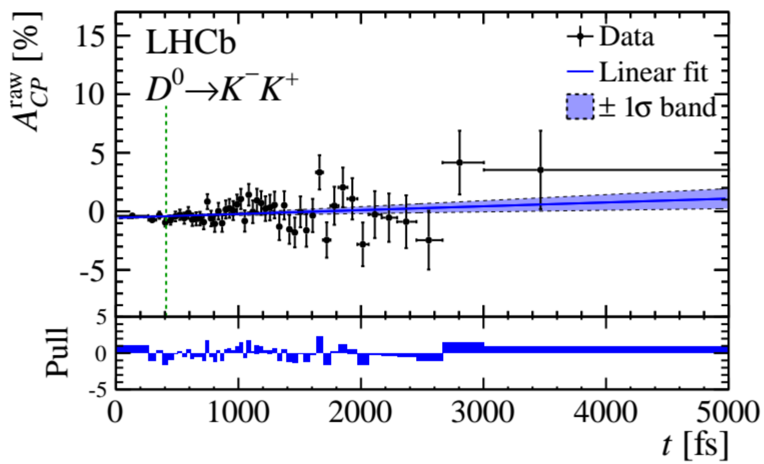

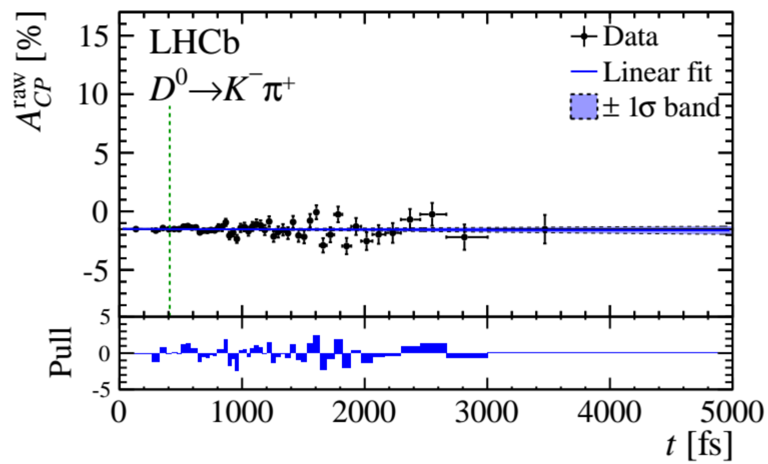

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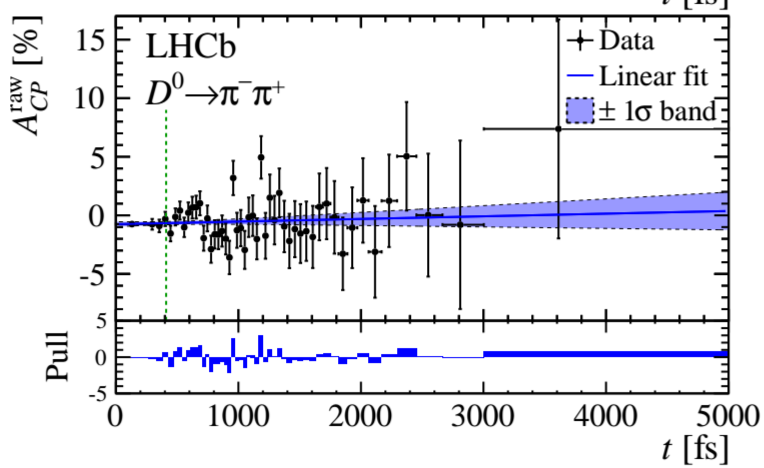


- Final results:

$$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077 \,{}^{+0.026}_{-0.034})\ \%$$
$$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145 \,{}^{+0.025}_{-0.033})\ \%$$

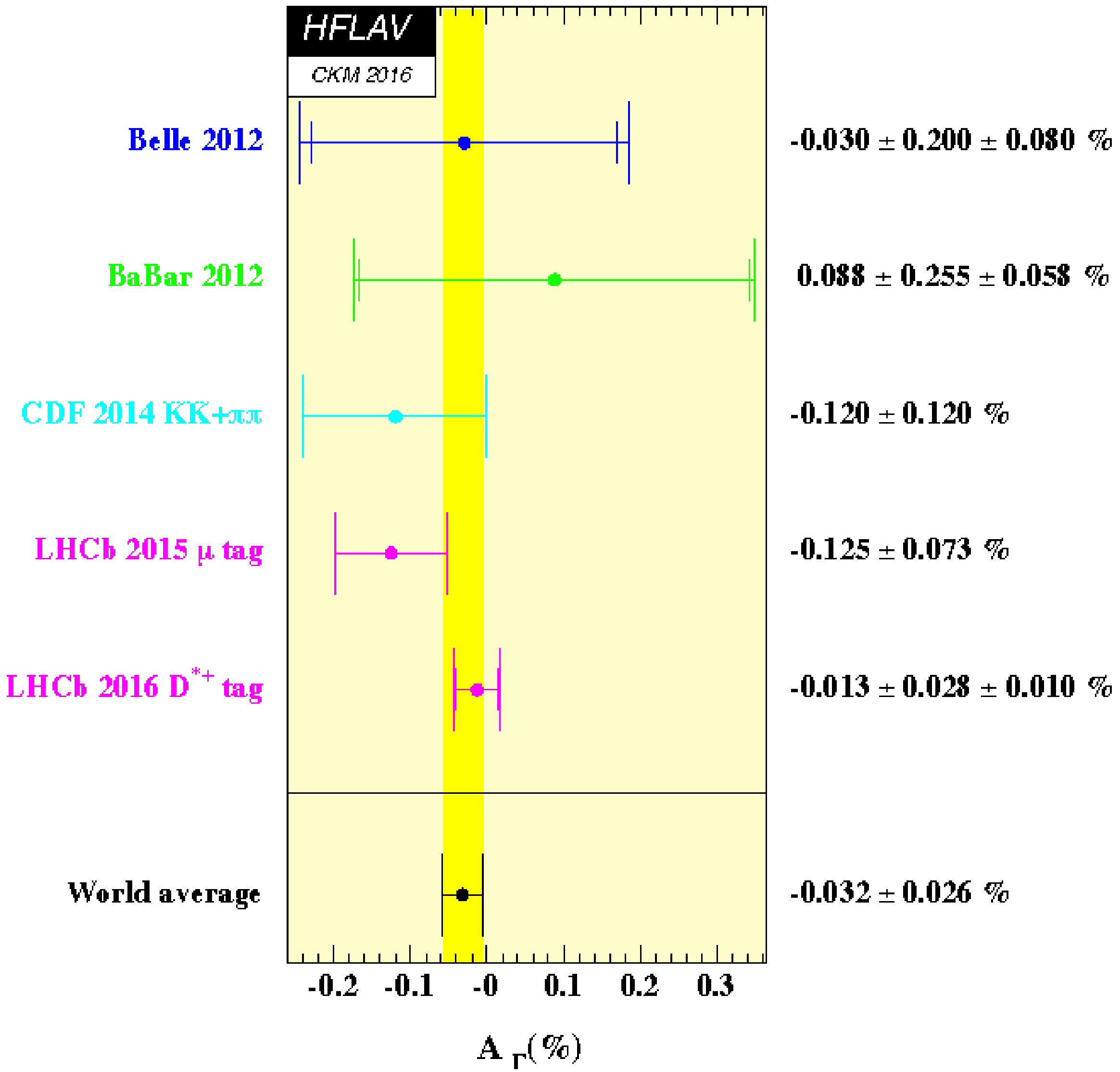
- Compatible with prompt charm measurements of A_Γ

HFLAV A_Γ average (2016)

- The world average value of A_Γ measurements
- SM prediction: $\mathcal{O}(10^{-4})$
- Measurements entering the SM area
- Overall combined LHCb Run I value:

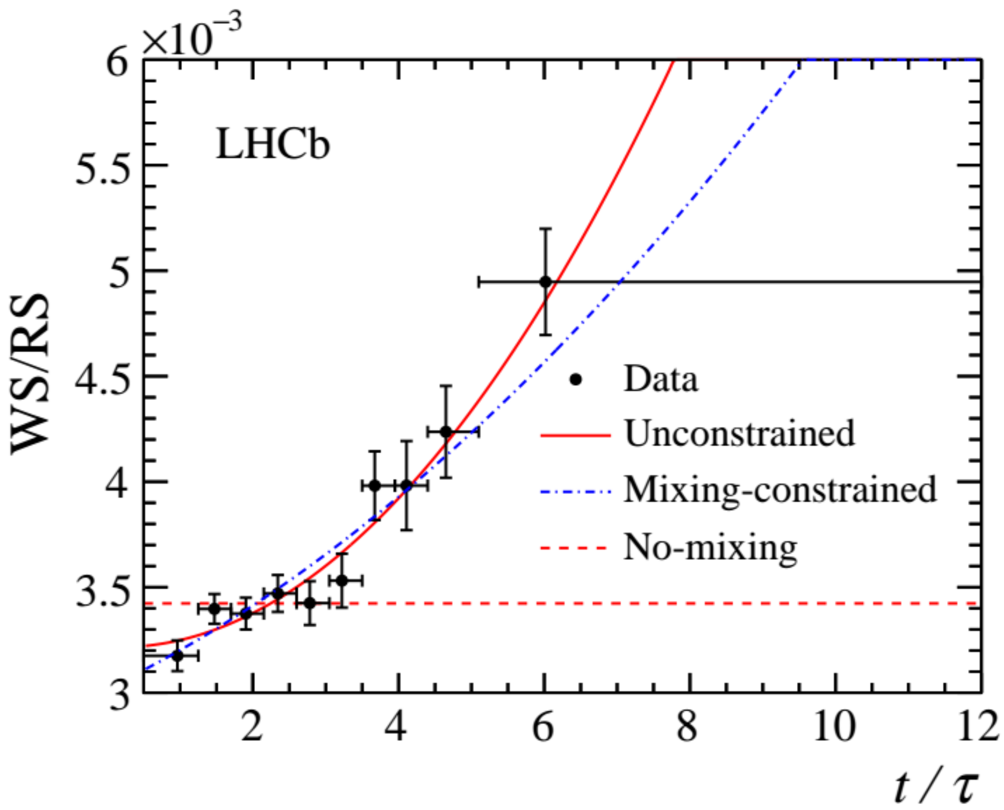
  $$A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$$

  The most precise measurement to this day
- The average is compatible with the no-*CPV* hypothesis



Multibody decays

- Measurement of time evolution of phase space → time dependent Dalitz plot
- Direct access to many variables: $x, y, |q/p|, \phi$; access to amplitudes and phases, sensitivity for interferences $D^0 \to f$ & $D^0 \to \bar{f}$
- However the description is model-dependent



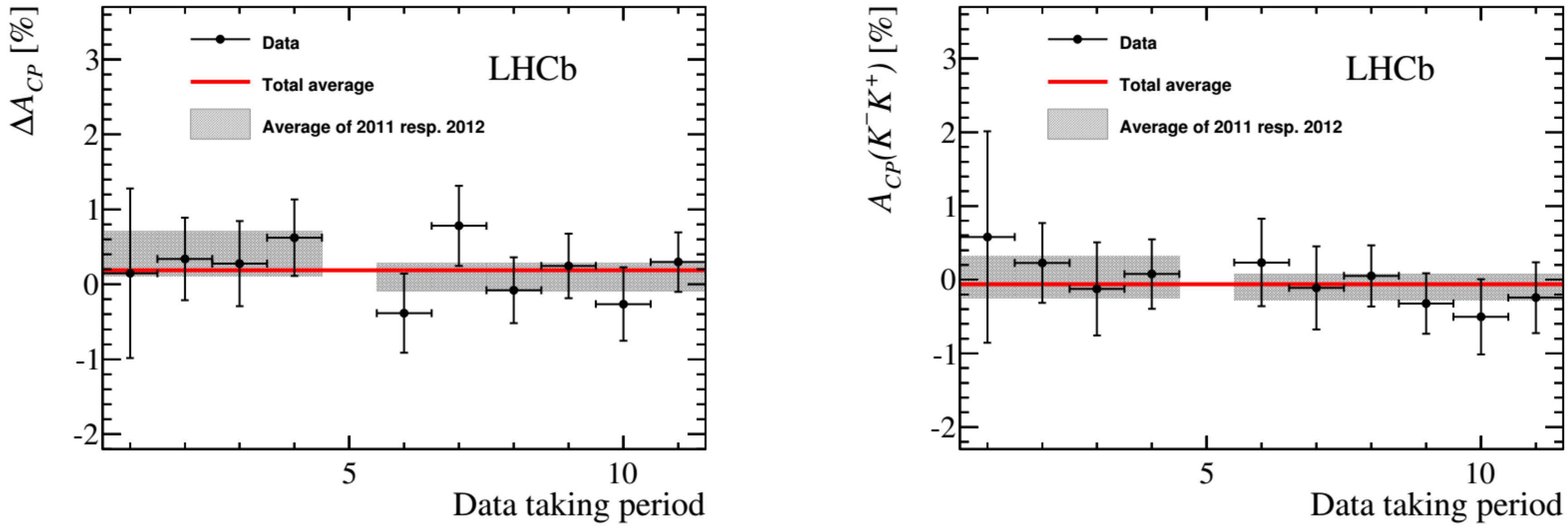
PRL 116 241801

- $D^0 \to K^+\pi^-\pi^+\pi^-$ Run I data
- Time-integrated study
- Wrong-sign: $D^0 \to K^+\pi^-\pi^+\pi^-$
- Right-sign: $D^0 \to K^-\pi^+\pi^+\pi^-$
- Most precise measurement of $D^0 \to K^+\pi^-\pi^+\pi^-$ branching ratio
- Mixing in this mode: 8.2 σ
- More thorough study including Run II data is in progress

V. Direct CPV

$\Delta A_{CP}(\mathrm{D}^0 \to \mathrm{K}^-\mathrm{K}^+/\pi^-\pi^+)$ muon tagged

- Secondary charm production: $\bar{\mathrm{B}}^0 \to \mathrm{D}^0(\to \mathrm{K}^-\mathrm{K}^+/\pi^-\pi^+)\mu\bar{\nu}_\mu \mathrm{X}$, Run I (3 fb^{-1}) data
- Individual raw asymmetries depends on muon reconstruction efficiency $A_D(\mu^-)$ and asymmetry in B hadrons production $A_P(B)$: $A_{raw} = A_{CP} + A_D(\mu^-) + A_P(B)$
- Difference of asymmetries: $\Delta A_{CP} = A_{raw}(K^-K^+) - A_{raw}(\pi^-\pi^+)$



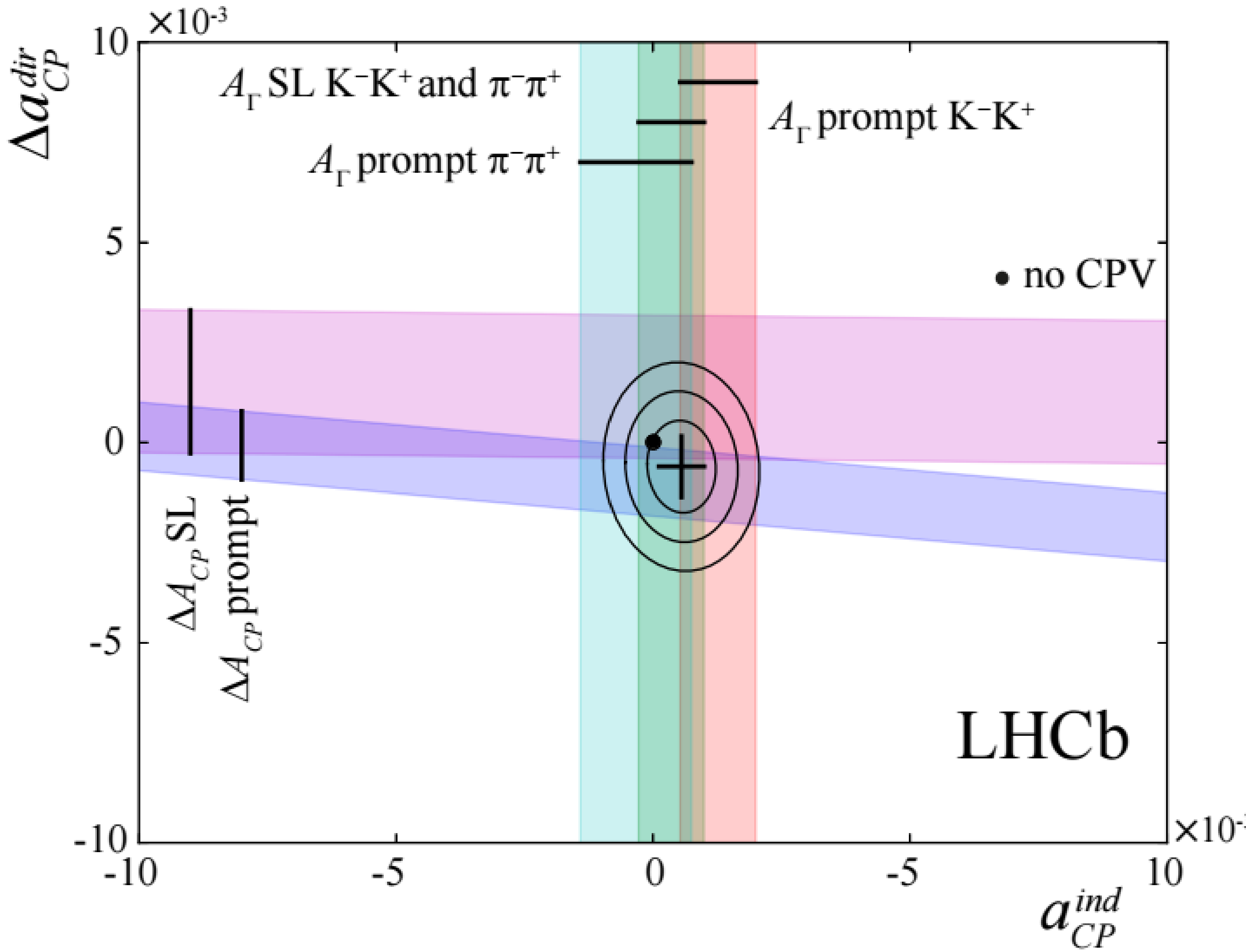
JHEP 07 041 (2014)

$$\mathbf{\Delta A_{CP}} = (+\mathbf{0.14} \pm \mathbf{0.16} \pm \mathbf{0.08})\ \%$$
$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15 \pm 0.10)\ \%$$
$$A_{CP}(\pi^-\pi^+) = (-0.20 \pm 0.19 \pm 0.10)\ \%$$

- Result from the prompt charm production: $\mathbf{\Delta A_{CP}} = (-\mathbf{0.10} \pm \mathbf{0.08} \pm \mathbf{0.03})\ \%$ [PRL 116 191601 (2016)]

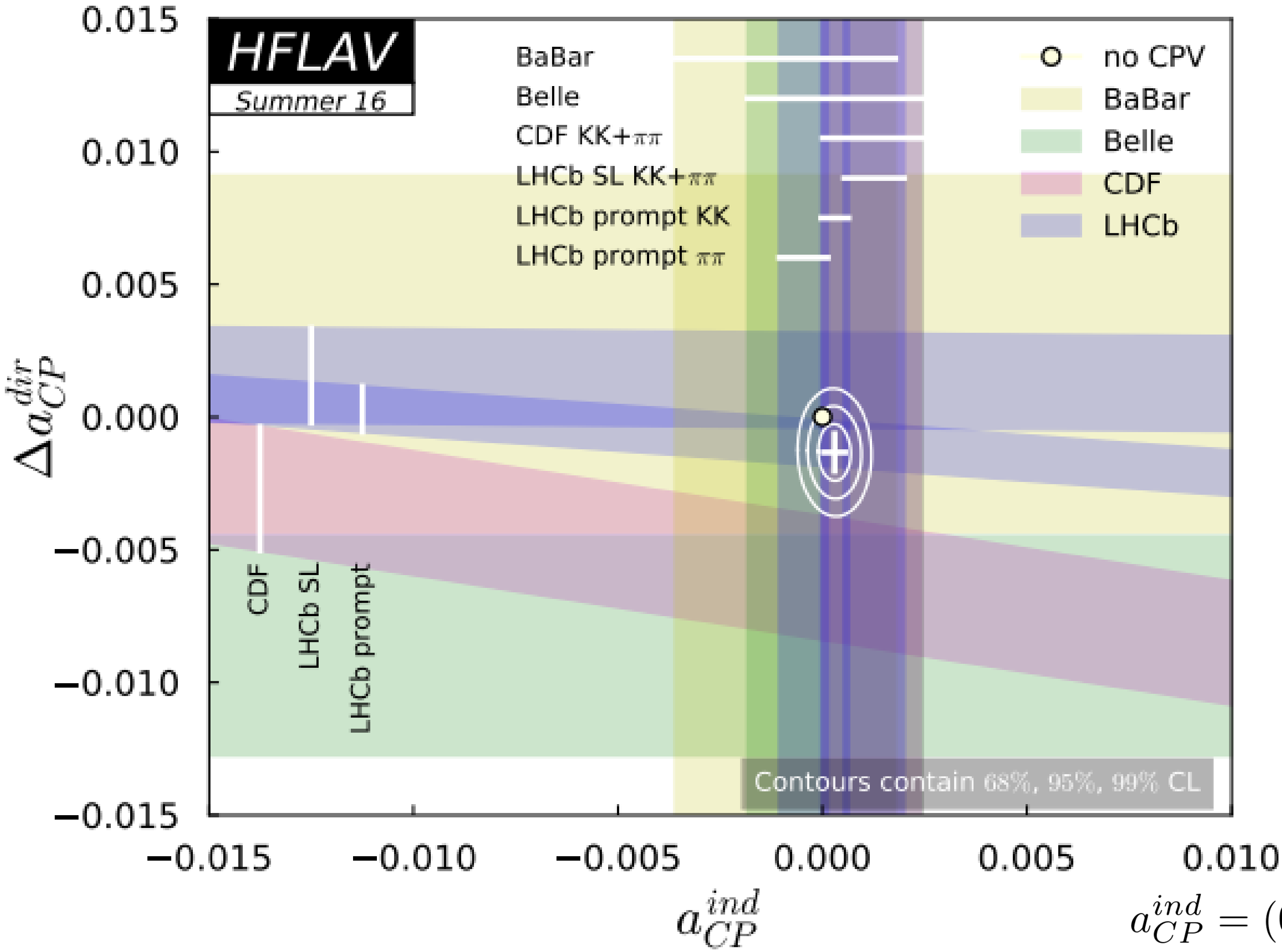
LHCb summary average (2016)

→ Average of the *CPV* searches $\mathrm{D}^0 \to \mathrm{h}^-\mathrm{h}^+$ at LHCb



PRL 116 191601 (2016)

HFLAV world average (2016)



$$a_{CP}^{ind} = (0.056 \pm 0.040)\ \%$$

$$\Delta a_{CP}^{dir} = (-0.137 \pm 0.070)\ \%$$

Compatible with no-*CPV* hypothesis in the charm sector at 6.5 % CL

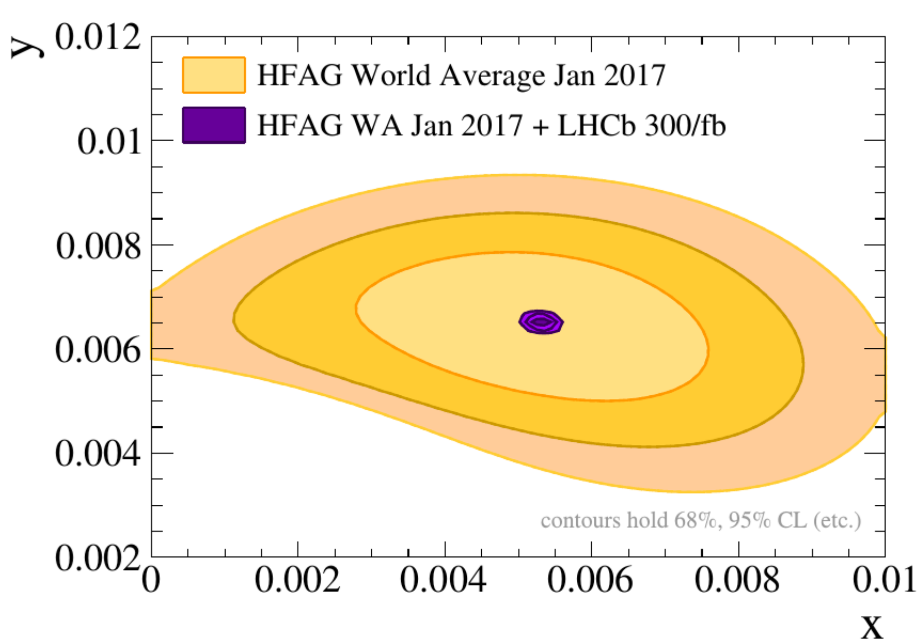
VI. Future prospects for Run II and beyond

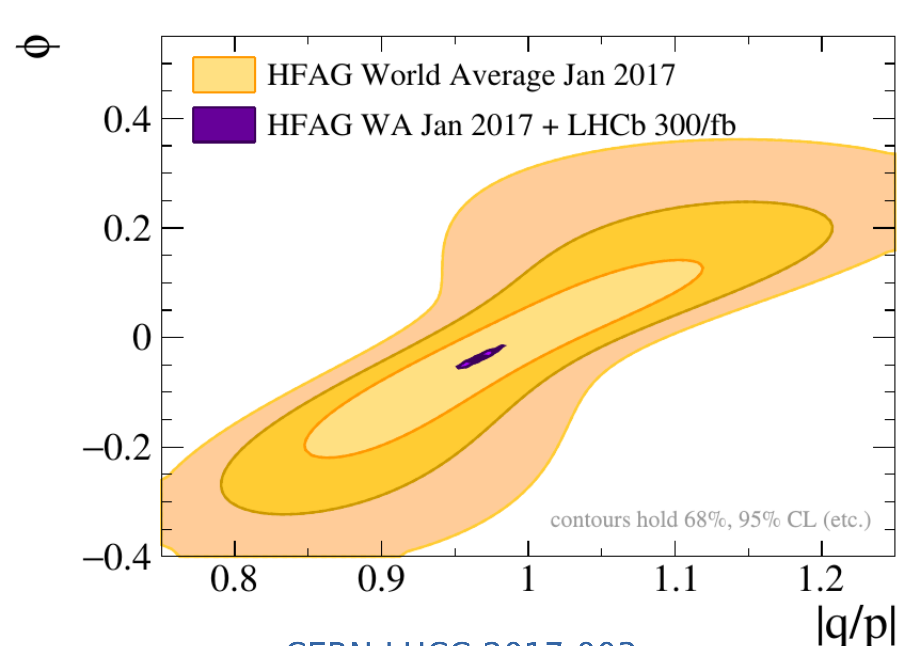
Prospect for indirect *CPV* searches

→ Results on the indirect *CPV* is already dominated by LHCb

1: BELLE2-TALK-CONF-2017-080

	$\sigma(x)$ $[10^{-3}]$	$\sigma(y)$ $[10^{-3}]$	$\sigma(q/p)$ $[10^{-3}]$	$\sigma(\phi)$ $[mrad]$
HFAG 2016	1.4	0.7	80	173
Run II	0.8	0.6	47	83
Run III	0.3	0.2	17	32
Belle II (50 ab^{-1})[1]	0.8	0.5	60	70





CERN-LHCC-2017-003

Prospects for direct *CPV* searches

→ Precision is already at $\mathcal{O}(10^{-3})$ level, so far no evidence for *CPV* in charm

→ With the the Run III data (50 fb^{-1} in combination with Run I+II) the precision will be comparable with the **SM** prediction at $\mathcal{O}(10^{-4})$ level

→ Need for precise BR input by Belle II/HIEPA: $\mathrm{D}^0 \to \pi^0\pi^0,\ \mathrm{D}^0 \to \mathrm{K_S K_S},\ \mathrm{D}^0 \to \pi^0\pi^+$

1) Multibody decays [slide: 30-31]

2) Rare decays (radiative, leptonic) [slide: 32]

3) Double Cabibbo Suppressed (DCS) decays (e.g. $\mathrm{D}^+ \to \mathrm{K}^+\pi^+\pi^-/\mathrm{K}^+\mathrm{K}^-\mathrm{K}^+$)

4) Exploring charm baryons [slide: 33-34]

  → Measured 1st evidence for *CPV* in baryons: $\Lambda_\mathrm{b} \to \mathrm{p}3\pi$ [Nature Phys. 13, 391-396 (2017)]

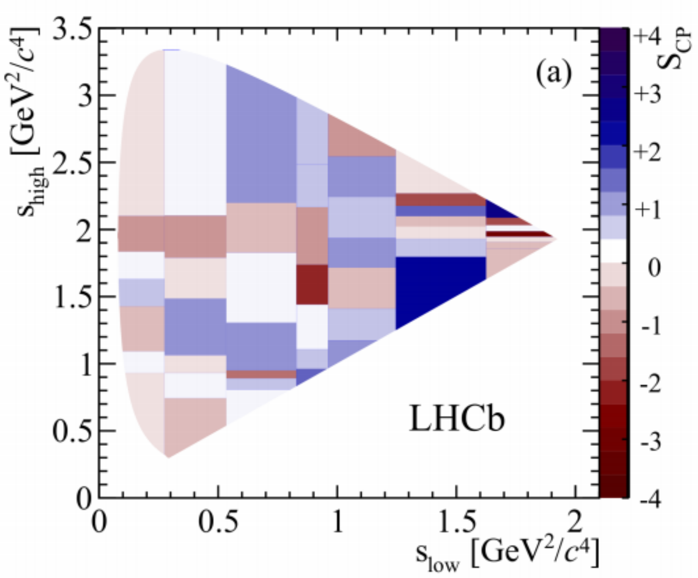
→ Need of detector upgrades [slide: backup]

Prospect: *CPV* in N-body decays

- Strong phase vary in Phase Space → this leads to local *CPV* asymmetries
- Need for detailed study of Phase space
- Model dependent: amplitude analysis
- Model independent approach:

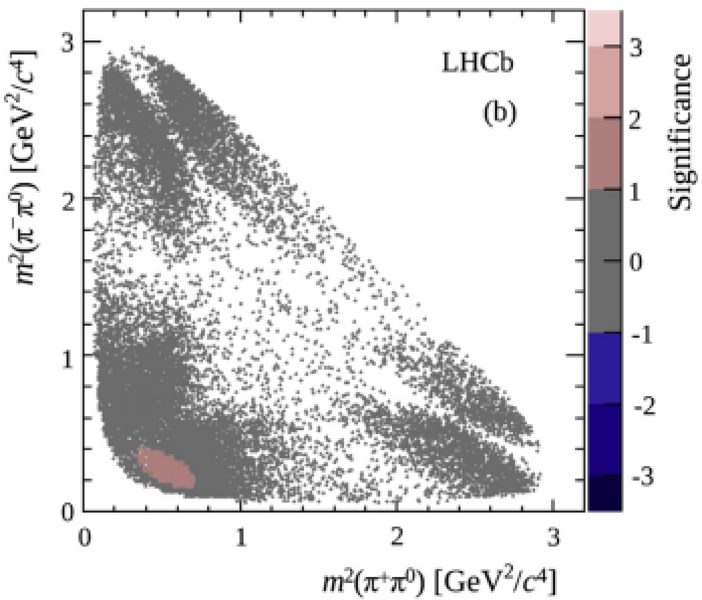
Binned approach

- S_{cp} approach
- Significance of asymmetry in Dalitz plot
  [PLB 728 585 (2014)]



Unbinned approach (Energy test)

- Testing data consistency with no-*CPV* hypothesis
- Significance of asymmetry for each event
  [PLB 740 158 (2015)]



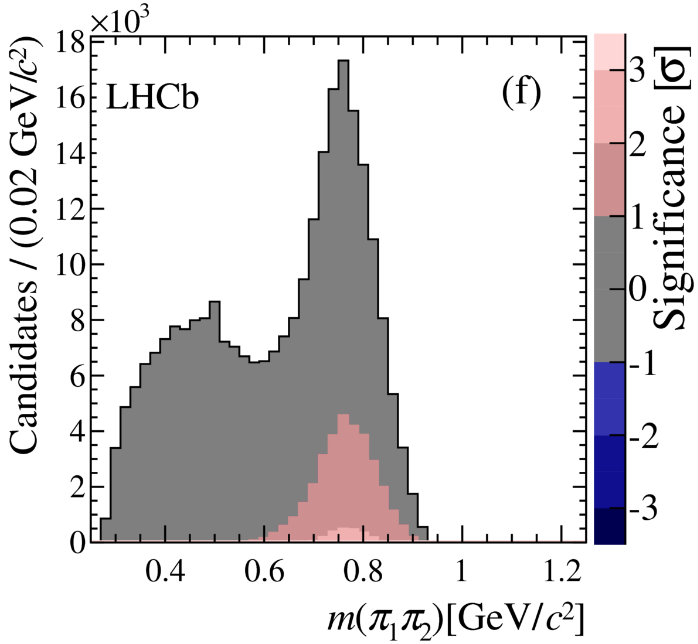
Prospect: direct *CPV* 4-body decays

- The more precise detector → more possibilities with the study of D multi-body decays
- The 2+3-body decays: only P-even amplitude accessible → *CPV* via *C*-violation
- The 4-body decays: also P-odd amplitudes → *CPV* via *P*-violation
- We can write:

$$A_{CP}^{P-even} \approx \sin\Delta\phi_{weak} \sin\Delta\phi_{strong}$$
$$A_{CP}^{P-odd} \approx \sin\Delta\phi_{weak} \cos\Delta\phi_{strong}$$

- First measurement: $\mathrm{D}^0 \to \pi^+\pi^-\pi^+\pi^-$, *P*-odd *CPV* with the 2.7 σ significance

  [PLB 769 345-356 (2017)]



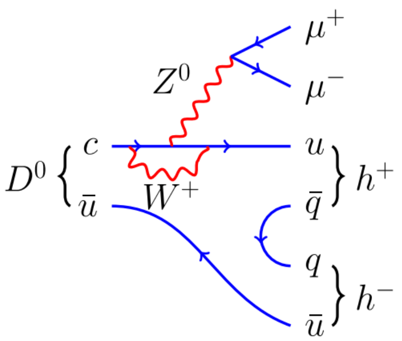
Mode	A_{CP}^{P-odd} $[10^{-3}]$	Exp.	Ref.
$\mathrm{D}^+ \to \mathrm{K_S K^+}\pi^+\pi^-$	$-12 \pm 10 \pm 5$	BaBar	PRD 84 031103
$\mathrm{D}^0 \to \mathrm{K^+K^-}\pi^+\pi^-$	$1.8 \pm 2.9 \pm 0.4$	LHCb	JHEP 10 005 (2014)
$\mathrm{D}^0 \to \mathrm{K_S}\pi^+\pi^-\pi^0$	$-0.3 \pm 1.4^{+0.2}_{-0.8}$	Belle	PRD 95 091101

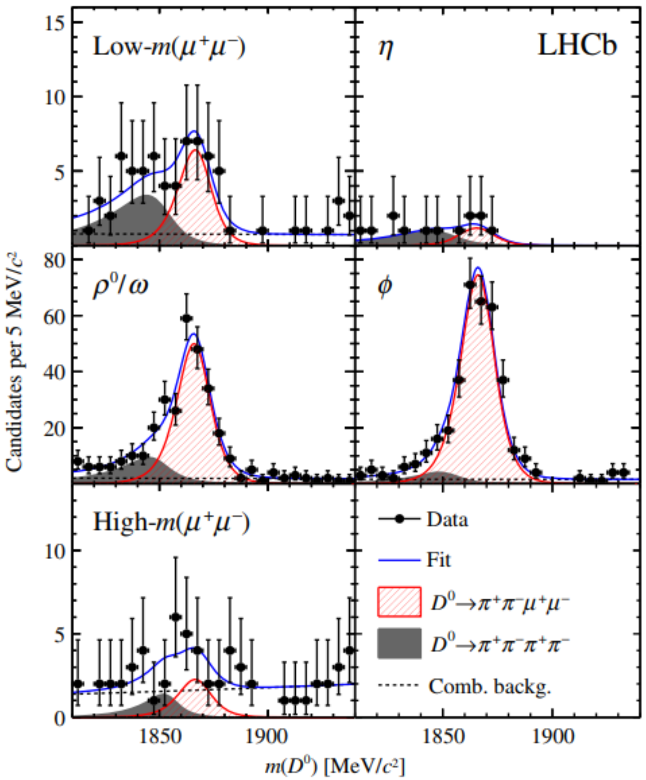
Prospect: *CPV* in rare decays

- Large contribution from penguin diagrams → larger values of *CPV* expected
- Two main categories: Leptonic and Radiative decays

<u>Leptonic decays</u>

- First observation of $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\mu^+\mu^-$ and $\mathrm{D}^0 \to \pi^+\pi^-\mu^+\mu^-$
- 5.4 σ signal
- *CPV* up to $\mathcal{O}(10^{-2})$





PRL 119 181805

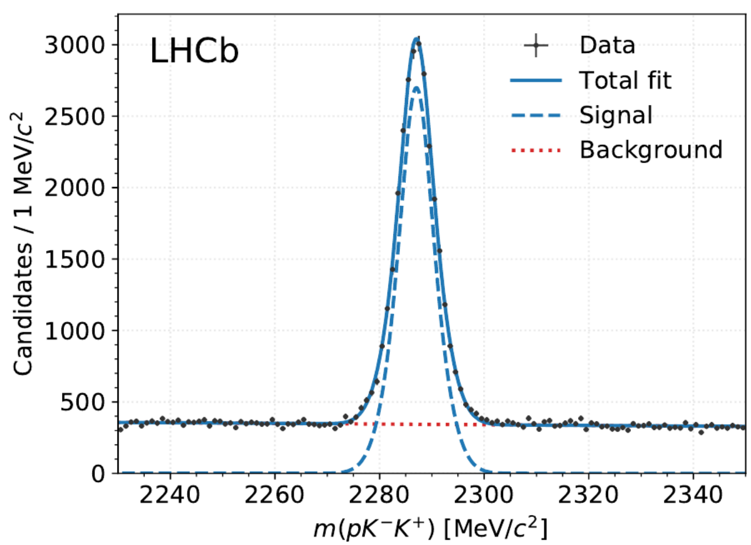
<u>Radiative decays</u>

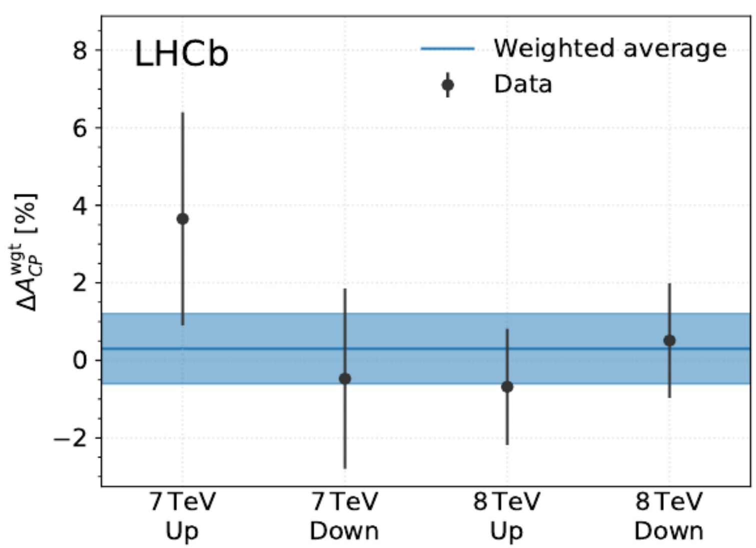
- Large *CPV* within SM, up to 10 %
- With the upgrade, LHCb will be competitive in $\mathrm{D}^0 \to \rho\gamma, \phi\gamma, \mathrm{K}^*\gamma$
- Belle measurement[1]: $A_{CP}(\mathrm{D}^0 \to \rho^0\gamma) = (+5.6 \pm 15.1 \pm 0.6)\%$

1: PRL 118 051801

CPV in $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^+\pi^-$

- First measurement of CPV parameters in three-body Λ_c^+ decays
- Full Run I (3 fb^{-1}) data used
- The $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ decay channel used in order to reduce prompt background
- Two SCS decays studied: $\Lambda_c^+ \to pK^-K^+$ (25 k) $\Lambda_c^+ \to p\pi^-\pi^+$ (160 k)
- Measurement of difference $\Delta\mathcal{A}_{CP} = \mathcal{A}_{raw}(pK^-K^+) - \mathcal{A}_{raw}(p\pi^-\pi^+)$ in order to cancel production and detection asymmetry





LHCb-PAPER-2017-044

- Final result: $\boldsymbol{\Delta\mathcal{A}_{CP} = (0.30 \pm 0.91 \pm 0.61)}$ %

CPV in charmed baryons

- Several theoretical works about *CPV* in charmed baryons
- Multibody decays are preferred due to larger BR and access to *CPV*-odd observables

SCS

- **SM** amplitudes are less suppressed, lower sensitivity to BSM amplitudes
- Suggested channels: $\Lambda_c \to p\pi^+\pi^-/pK^+K^-,\ \Xi_c^+ \to pK^-\pi^+$

DCS

- Significant suppression of **SM** amplitudes
- No CP asymmetry from **SM** in such amplitudes
- Suggested channel: $\Lambda_c^+ \to pK^+\pi^-$

Conclusion

- Charm physics is still of a great importance
- Precision measurements of *CPV* are a fundamental tools to probe **SM**

  at energy scales and couplings unaccessible at the energy frontier
- Still <u>no signal of *CPV* (Direct or Indirect) in charm sector observed</u>
  - obtained strong constraints for many BSM models
- Key measurements are mainly limited by the statistics $\rightarrow$ with Run II data the $\mathcal{O}(10^{-3} - 10^{-4})$ precision is now becoming possible
- Several new analysis methods are now used for Run II data
- With several major upgrades planned for Run III and Run V, LHCb will be one of the main driving forces in the heavy flavor physics during coming years
  - after 2025 only dedicated heavy flavor experiment!

Thank you for your attention

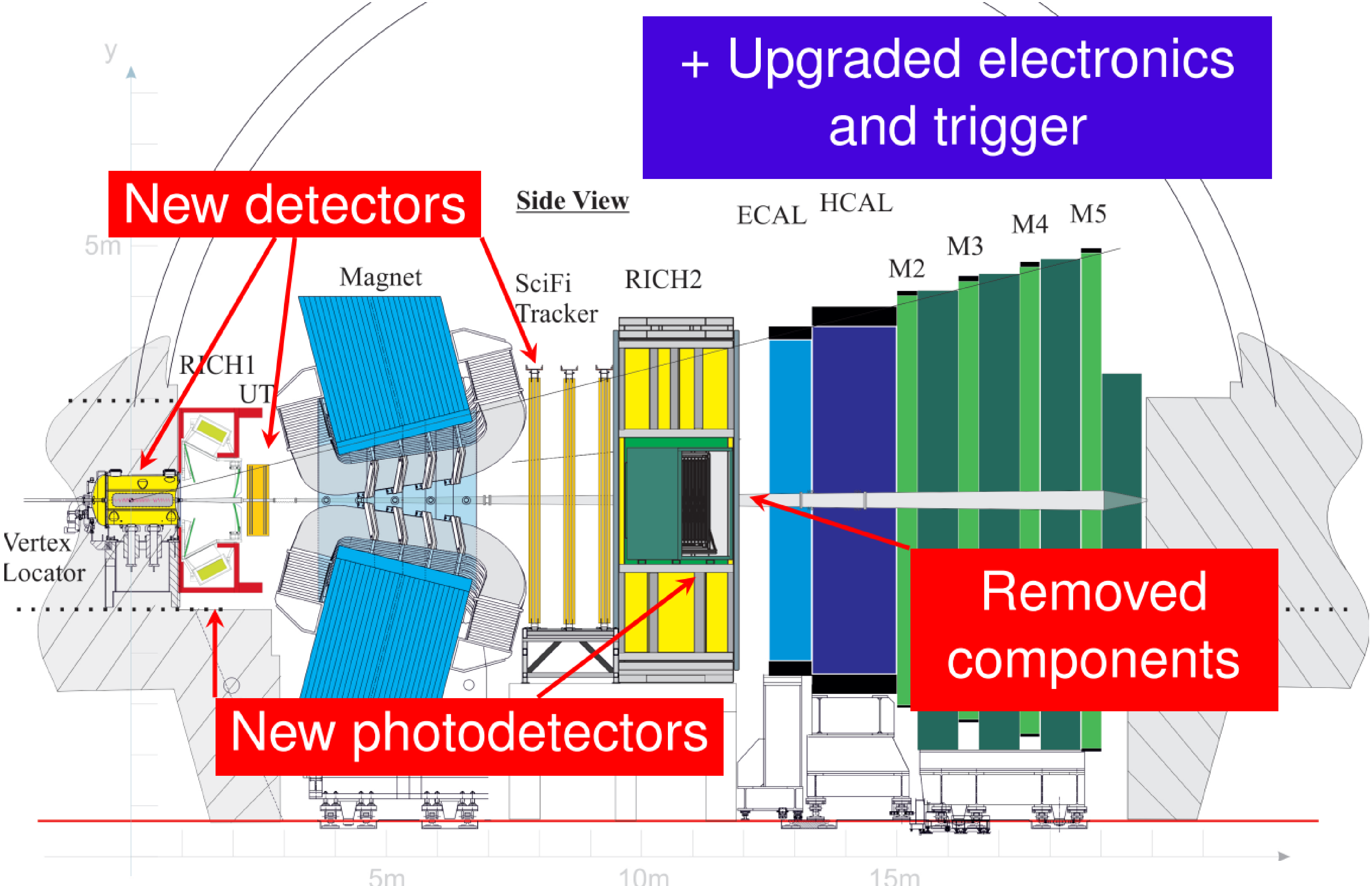
BACKUP
Slides

Planned LHCb upgrades

LHCb upgrade Phase I (Run III)

- Hardware upgrade for Run III:
  - VELO upgrade: 40 MHz readout (1 MHz), 790k channels/module (4096), $C0_2$ internal cooling
  - New Scintillating Fibre Tracker (SciFi)
- Software upgrade for Run 3:
  - Fully software trigger, 40 MHz event rate frequency
  - Full event reconstruction at the HLT level – output rate in Gbs^{-1}
- Upgrade I construction on track for Run III
- Expected recorded luminosity: 5 fb^{-1} per year
- Before Run IV (LS3):
  - Phase I(b) upgrade: consolidation of Phase I upgrade
  - Replace of innermost parts of ECAL
  - Adding of Magnet side stations
  - Same luminosity as during Run III

LHCb upgrade Phase I (Run III)



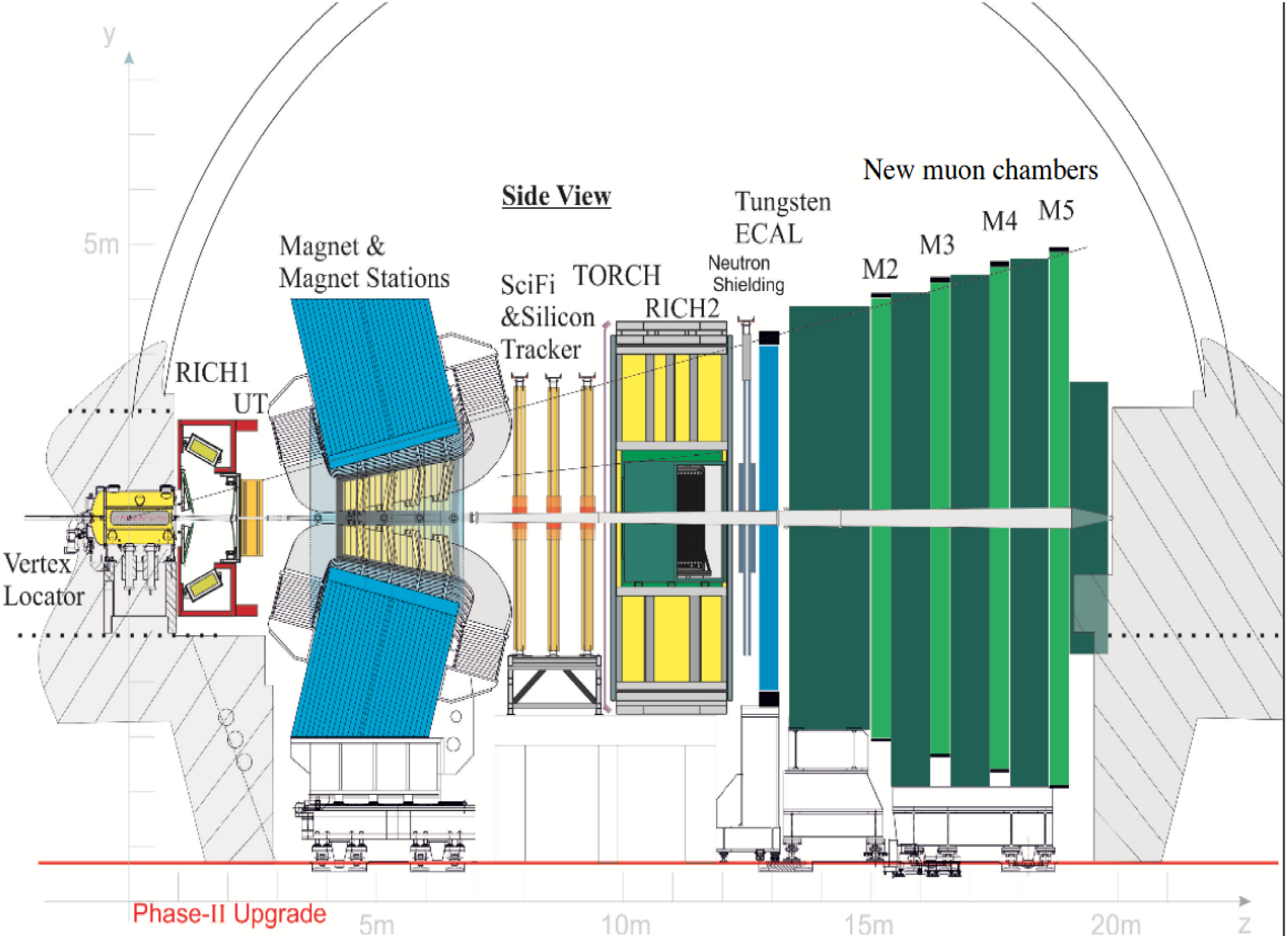
LHCb-TALK-2017-232

LHCb upgrade Phase I (Run III)

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\, K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

CERN/LHCC 2012-007

LHCb upgrade Phase II (Run V)



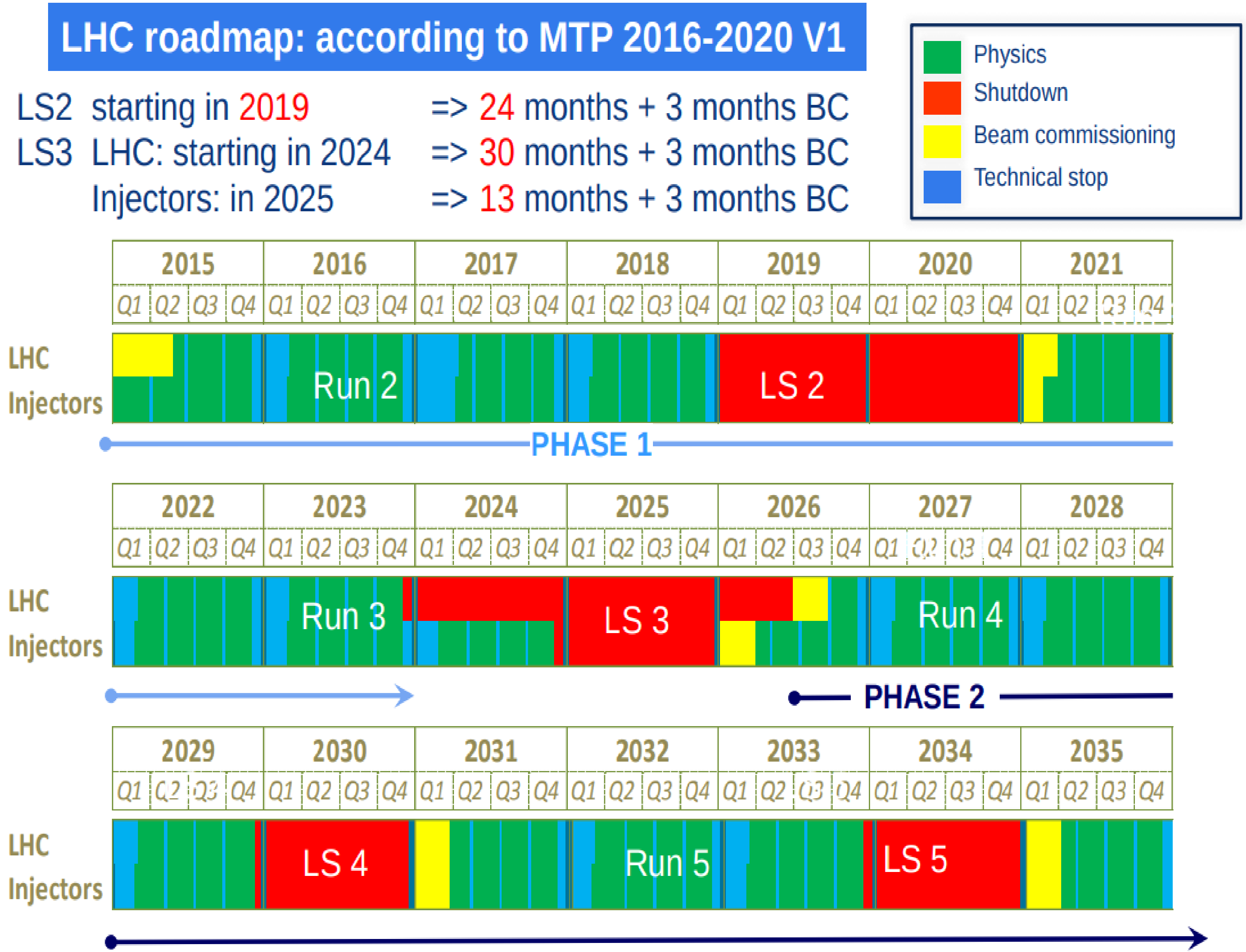
CERN-LHCC-2017-003

LHCb upgrade Phase II (Run V)

Topics and observables	Experimental reach	Remarks
EW Penguins		
Global tests in many $b \to s\mu^+\mu^-$ modes with full set of precision observables; lepton universality tests; $b \to dl^+l^-$ studies	*e.g.* 440k $B^0 \to K^*\mu^+\mu^-$ & 70k $\Lambda_b^0 \to \Lambda\mu^+\mu^-$; Phase-II $b \to d\mu^+\mu^- \approx$ Run-1 $b \to s\mu^+\mu^-$ sensitivity.	Phase-II ECAL required for lepton universality tests.
Photon polarisation		
$\mathcal{A}^\Delta$ in $B_s^0 \to \phi\gamma$; $B^0 \to K^* e^+e^-$; baryonic modes	Uncertainty on $\mathcal{A}^\Delta \approx 0.02$; $\sim 10k$ $\Lambda_b^0 \to \Lambda\gamma$, $\Xi_b \to \Xi\gamma$, $\Omega_b^- \to \Omega\gamma$	Strongly dependent on performance of ECAL.
$b \to cl^-\bar{\nu}_l$ lepton-universality tests		
Polarisation studies with $B \to D^{(*)}\tau^-\bar{\nu}_\tau$; τ^-/μ^- ratios with B_s^0, Λ_b^0 and B_c^+ modes	*e.g.* 8M $B \to D^*\tau^-\bar{\nu}_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ & $\sim 100k$ $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$	Additional sensitivity expected from low-p tracking.
$B_s^0, B^0 \to \mu^+\mu^-$		
$R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$; $\tau_{B_s^0\to\mu^+\mu^-}$; CP asymmetry	Uncertainty on $R \approx 20\%$; Uncertainty on $\tau_{B_s^0\to\mu^+\mu^-} \approx 0.03\,\mathrm{ps}$	
LFV τ decays		
$\tau^- \to \mu^+\mu^-\mu^-$, $\tau^- \to h^+\mu^-\mu^-$, $\tau^- \to \phi\mu^-$	Sensitive to $\tau^- \to \mu^+\mu^-\mu^-$ at 10^{-9}	Phase-II ECAL valuable for background suppression.
CKM tests		
γ with $B^- \to DK^-$, $B_s^0 \to D_s^+K^-$ *etc.*	Uncertainty on $\gamma \approx 0.4°$	Additional sensitivity expected
ϕ_s with $B_s^0 \to J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$	Uncertainty on $\phi_s \approx 3\,\mathrm{mrad}$	in CP observables from Phase-II
$\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$	Uncertainty on $\phi_s^{s\bar{s}s} \approx 8\,\mathrm{mrad}$	ECAL and low-p tracking.
$\Delta\Gamma_d/\Gamma_d$	Uncertainty on $\Delta\Gamma_d/\Gamma_d \sim 10^{-3}$	Approach SM value.
Semileptonic asymmetries $a_{\mathrm{sl}}^{d,s}$	Uncertainties on $a_{\mathrm{sl}}^{d,s} \sim 10^{-4}$	Approach SM value for a_{sl}^d.
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ with Λ_b^0, B_s^0 and B_c^+ modes	*e.g.* $120k$ $B_c^+ \to D^0\mu^-\bar{\nu}_\mu$	Significant gains achievable from thinning or removing RF-foil.
Charm		
CP-violation studies with $D^0 \to h^+h^-$, $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K^\mp\pi^\pm\pi^+\pi^-$	*e.g.* 4×10^9 $D^0 \to K^+K^-$; Uncertainty on $A_\Gamma \sim 10^{-5}$	Access CP violation at SM values.
Strange		
Rare decay searches	Sensitive to $K_S^0 \to \mu^+\mu^-$ at 10^{-12}	Additional sensitivity possible with downstream trigger enhancements.

CERN-LHCC-2017-003

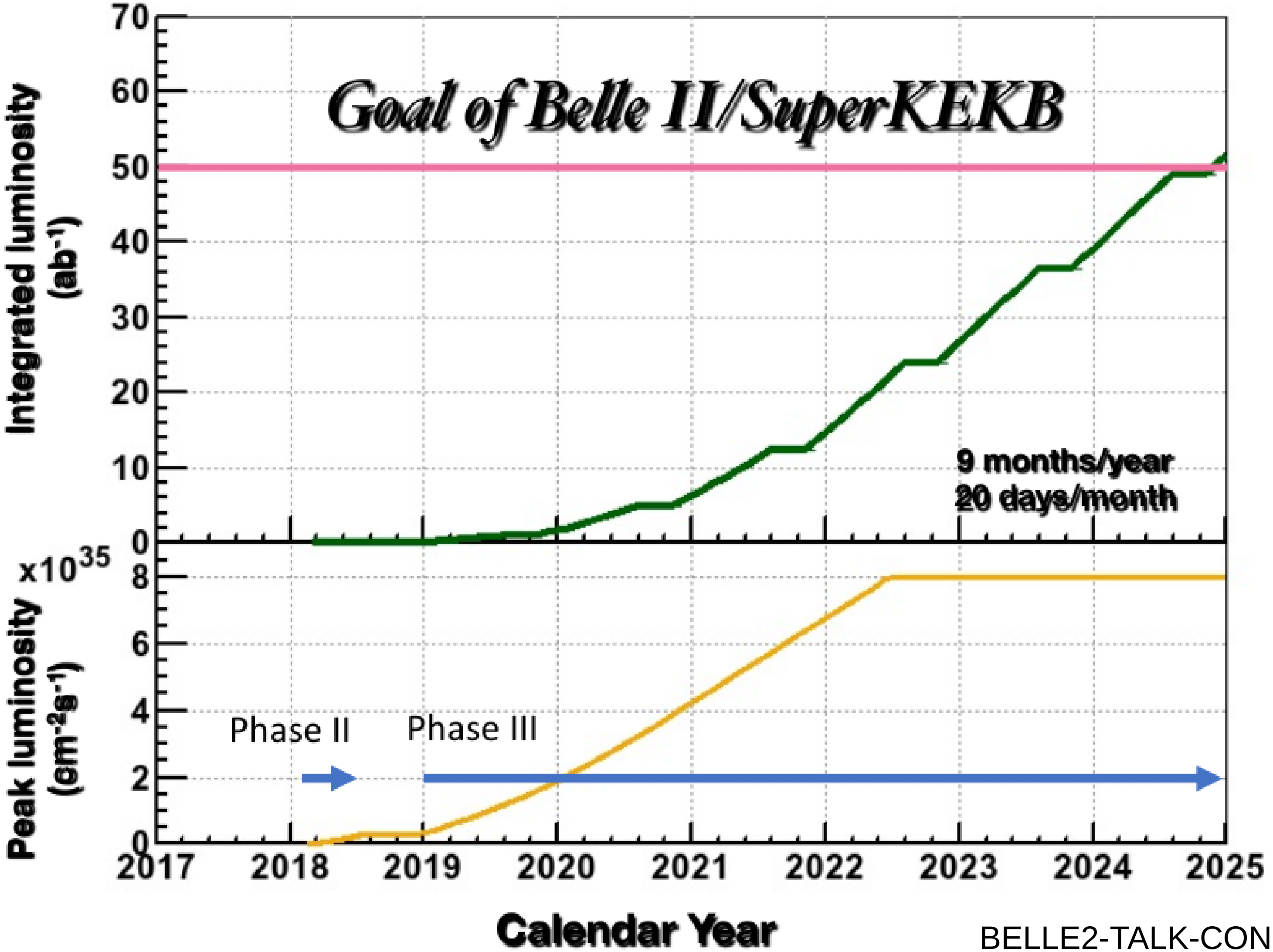
LHC timeline



Belle II status

Belle II – status of the experiment

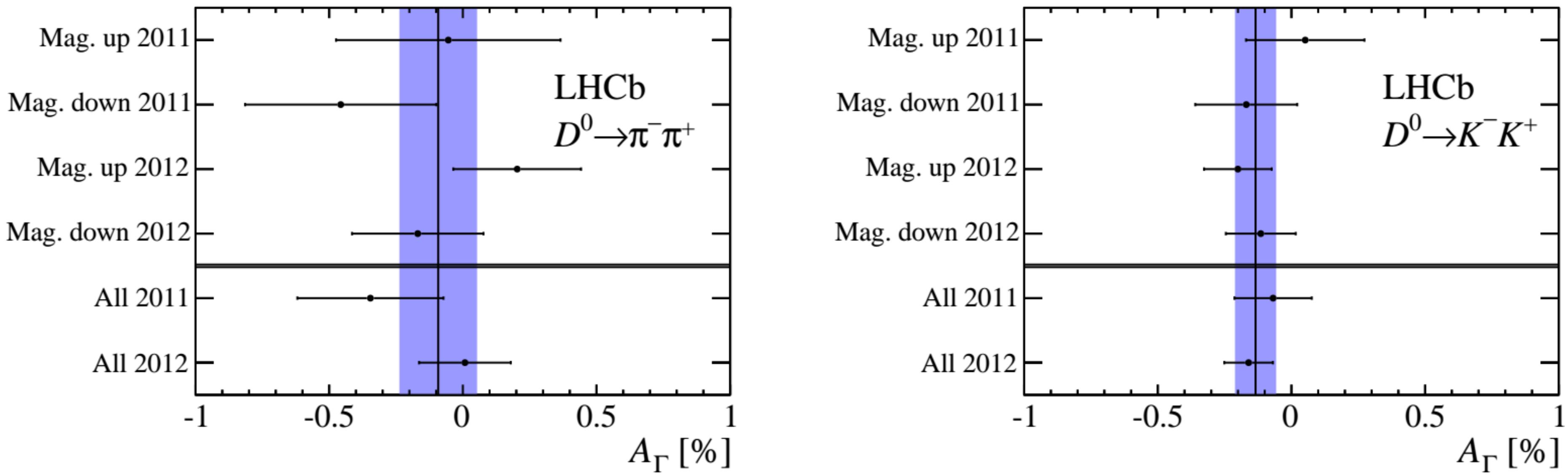
- Phase II (2018): first collisions, measurement of background, no PXD
- Phase III (2019): Full detector, physical run



BELLE2-TALK-CONF-2018-012

A_Γ measurement: muon tagged

- Results by the year and magnet polarity:



- Final results:

$$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077\ ^{+0.026}_{-0.034})\ \%$$
$$A_\Gamma(\pi^-\pi^+) = \ (-0.092 \pm 0.145\ ^{+0.025}_{-0.033})\ \%$$

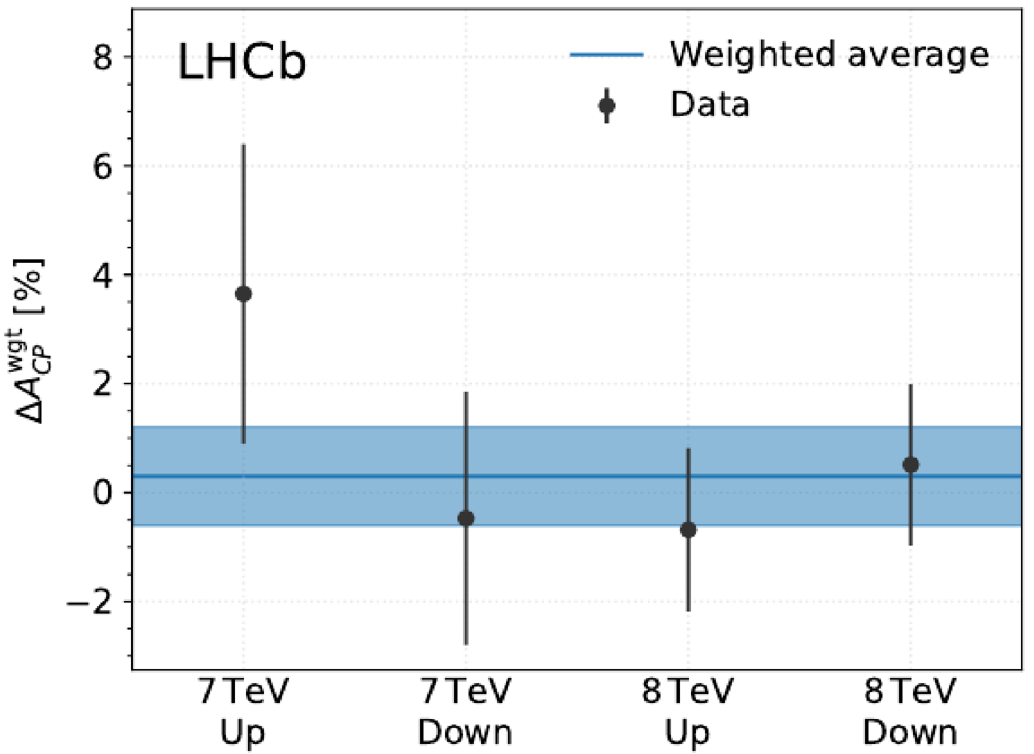
JHEP 04 (2015) 043

- Compatible with direct charm A_Γ measurements
- No CPV observed

CPV in $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^+\pi^-$

- Obtained results in the 4 bins: collision energy and magnet polarity
- First result of search for direct *CPV* search in three-body Λ_c^+ decays:

$$\boldsymbol{\Delta\mathcal{A}_{CP}} = [\mathbf{0.30 \pm 0.91\ (stat.) \pm 0.61\ (syst.)}]\ \%$$

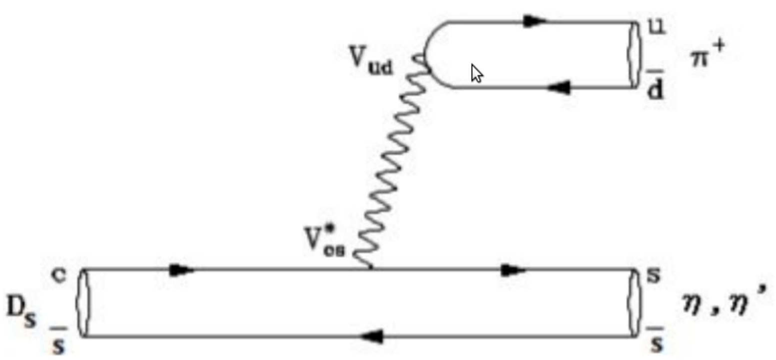


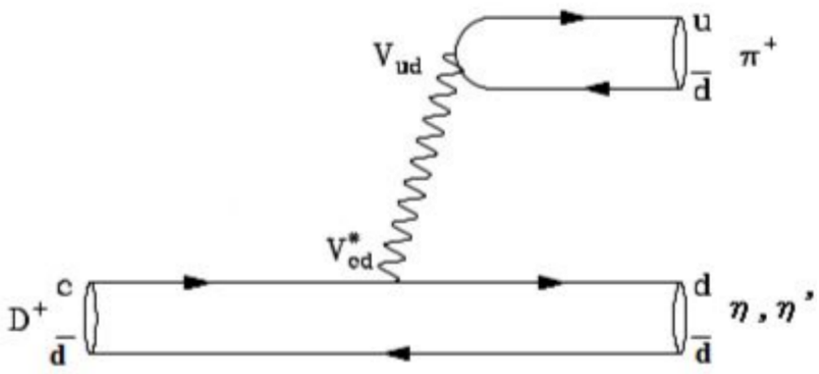
arXiv: 1712.07051

- Result shows no sign of direct *CPV*
- More data required for more precise measurement

CPV in $\mathbf{D}^+_{(\mathbf{s})} \to \eta'\pi^+$

- Study of CF $\mathbf{D}_s^+ \to \eta'\pi^+$ and SCS $\mathbf{D}^+ \to \eta'\pi^+$ decays:

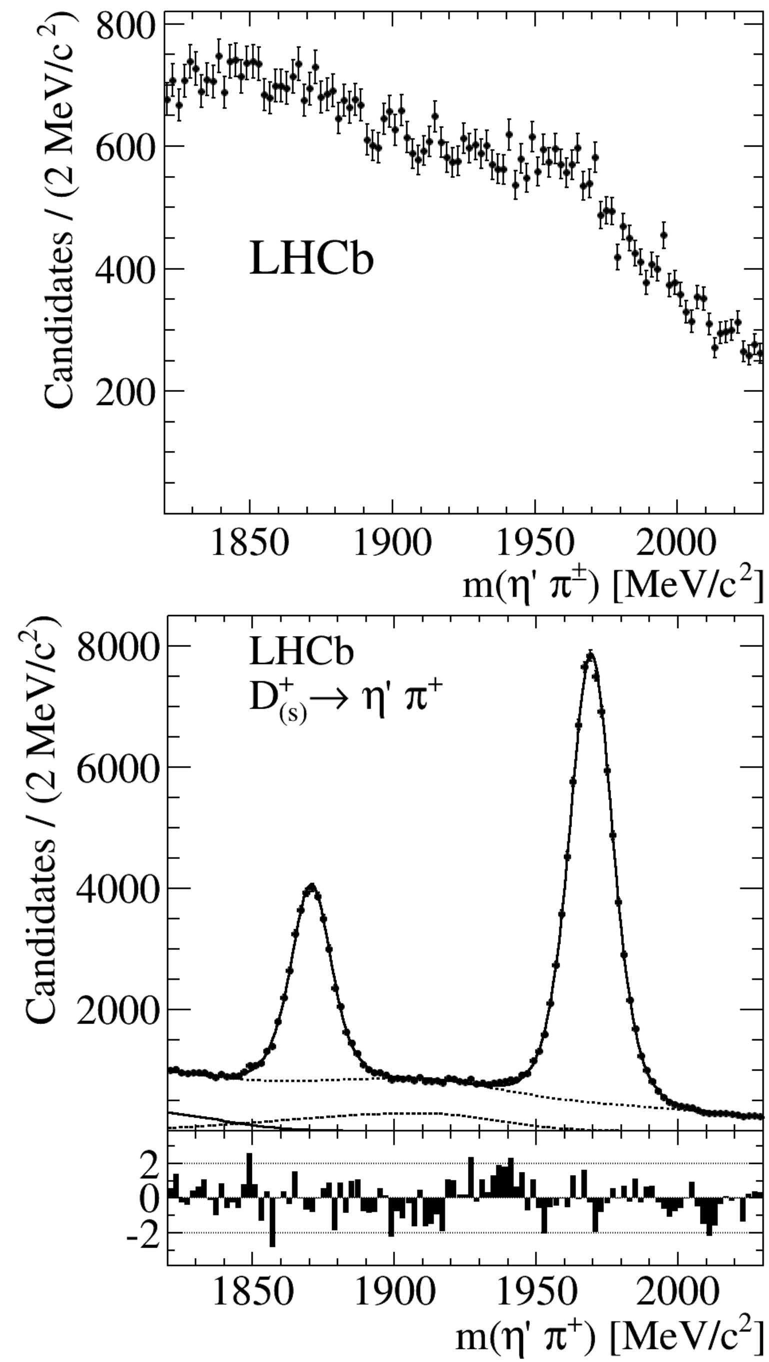




- Full reconstruction chain: $\mathrm{D}^+_{(\mathrm{s})} \to \eta'(\to \pi^+\pi^-\gamma)\pi^+$
- First measurement at hadron collider (very challenging photon background)
- Measurement is done via the difference parameter $\Delta\mathcal{A}_{CP}$
- For difference (and for tracking and detection asymmetries canceling) the control channels $\mathrm{D}^+ \to \mathrm{K}^0_\mathrm{s}\pi^+$ and $\mathrm{D}^+_\mathrm{s} \to \phi\pi^+$ are used
- Systematics is very limited by the photonic background

CPV in $D^+_{(s)} \to \eta' \pi^+$

- Data from Run I (2011-2012, 3 fb^{-1})
- Full reconstruction chain:
  $D^+_{(s)} \to \eta'(\to \pi^+\pi^-\gamma)\pi^+$
- First measurement at hadron collider (very challenging photon background)
- Data divided into 12 subsamples:
  - Energy (7 and 8 TeV)
  - Magnet polarity (Up and Down)
  - 3 Trigger selections
- Each subsample then divided into $3(p_T)$ x $3(\eta)$ bins based on bachelor pion
- Systematics limited by the background



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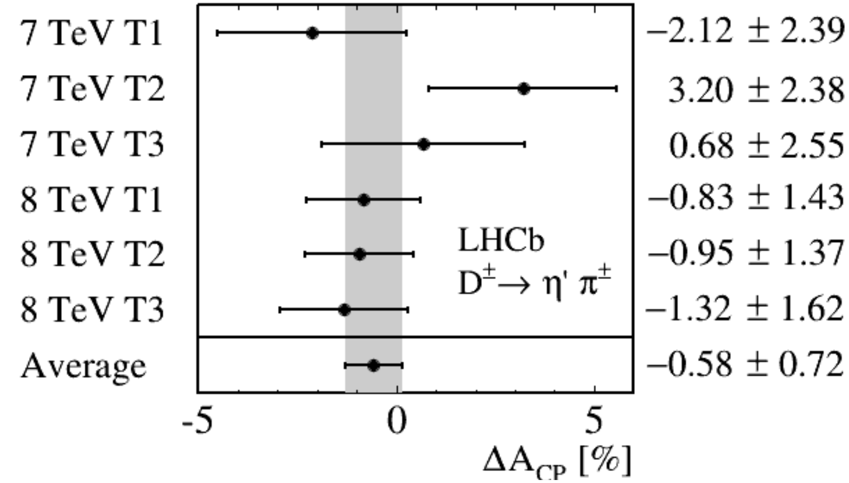
CPV in $\mathrm{D}^{+}_{(\mathbf{s})} \to \eta'\pi^{+}$

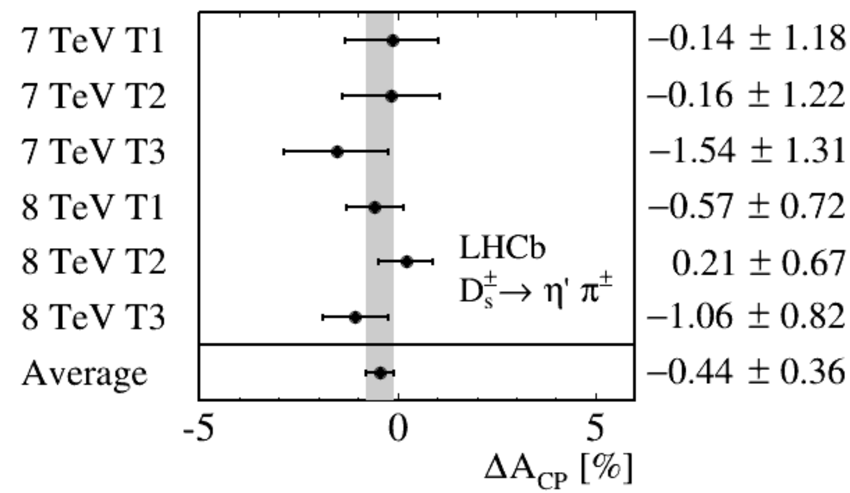
- Based on Run I data (2011-2012, 3 fb^{-1})
- Systematics is very limited by the photonic background
- CP asymmetries is then calculated as:

$$\Delta\mathcal{A}_{CP}(\mathrm{D}^{\pm} \to \eta'\pi^{\pm}) \equiv \mathcal{A}_{CP}(\mathrm{D}^{\pm} \to \eta'\pi^{\pm}) - \mathcal{A}_{CP}(\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\pi^{\pm})$$
$$= \mathcal{A}_{raw}(\mathrm{D}^{\pm} \to \eta'\pi^{\pm}) - \mathcal{A}_{raw}(\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}) + \mathcal{A}(\bar{\mathrm{K}}^0 - \mathrm{K}^0)$$
$$\Rightarrow \mathcal{A}_{CP} \approx \Delta\mathcal{A}_{CP}(\mathrm{D}^{\pm} \to \eta'\pi^{\pm}) + \mathcal{A}_{CP}(\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\pi^{\pm})$$

$$\Delta\mathcal{A}_{CP}(\mathrm{D}^{\pm}_\mathrm{s} \to \eta'\pi^{\pm}) \equiv \mathcal{A}_{CP}(\mathrm{D}^{\pm}_\mathrm{s} \to \eta'\pi^{\pm}) - \mathcal{A}_{CP}(\mathrm{D}^{\pm}_\mathrm{s} \to \phi\pi^{\pm})$$
$$= \mathcal{A}_{raw}(\mathrm{D}^{\pm}_\mathrm{s} \to \eta'\pi^{\pm}) - \mathcal{A}_{raw}(\mathrm{D}^{\pm}_\mathrm{s} \to \phi\pi^{\pm})$$
$$\Rightarrow \mathcal{A}_{CP} \approx \Delta\mathcal{A}_{CP}(\mathrm{D}^{\pm}_\mathrm{s} \to \eta'\pi^{\pm}) + \mathcal{A}_{CP}(\mathrm{D}^{\pm}_\mathrm{s} \to \phi\pi^{\pm})$$

Trigger selections: T1, T2, T3





- The most precise results to date:

$$\mathcal{A}_{\mathbf{CP}}(\mathrm{D}^{\pm} \to \eta'\pi^{\pm}) = [-\mathbf{0.61} \pm \mathbf{0.72}\ (\mathbf{stat.}) \pm \mathbf{0.53}\ (\mathbf{syst.}) \pm \mathbf{0.12}\ (\mathrm{K}^0_\mathrm{s}\pi^{\pm})]\ \%$$

$$\mathcal{A}_{\mathbf{CP}}(\mathrm{D}^{\pm}_\mathrm{s} \to \eta'\pi^{\pm}) = [-\mathbf{0.82} \pm \mathbf{0.36}\ (\mathbf{stat.}) \pm \mathbf{0.22}\ (\mathbf{syst.}) \pm \mathbf{0.27}\ (\phi\pi^{\pm})]\ \%$$

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