Recent results on CP Violation in Charm sector by LHCb

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SAUR Miroslav
(On behalf of the LHCb collaboration)

University of Chinese Academy of Sciences

I. LHCb detector and data

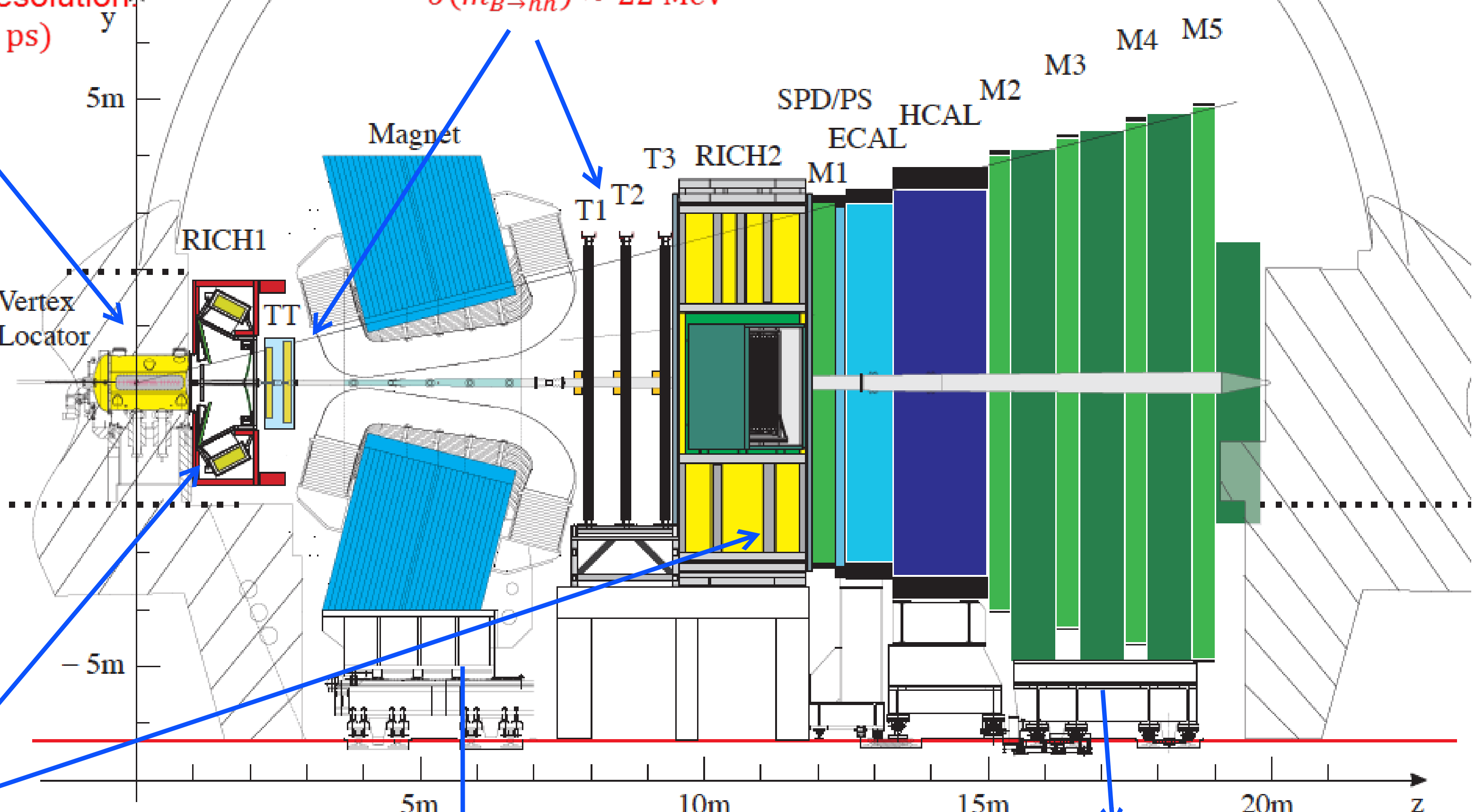
LHCb detector 2010-2018

- Single-arm forward spectrometer focused on heavy flavor (*b*, *c*) physics
- Effective as multi-purpose detector in forward region

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



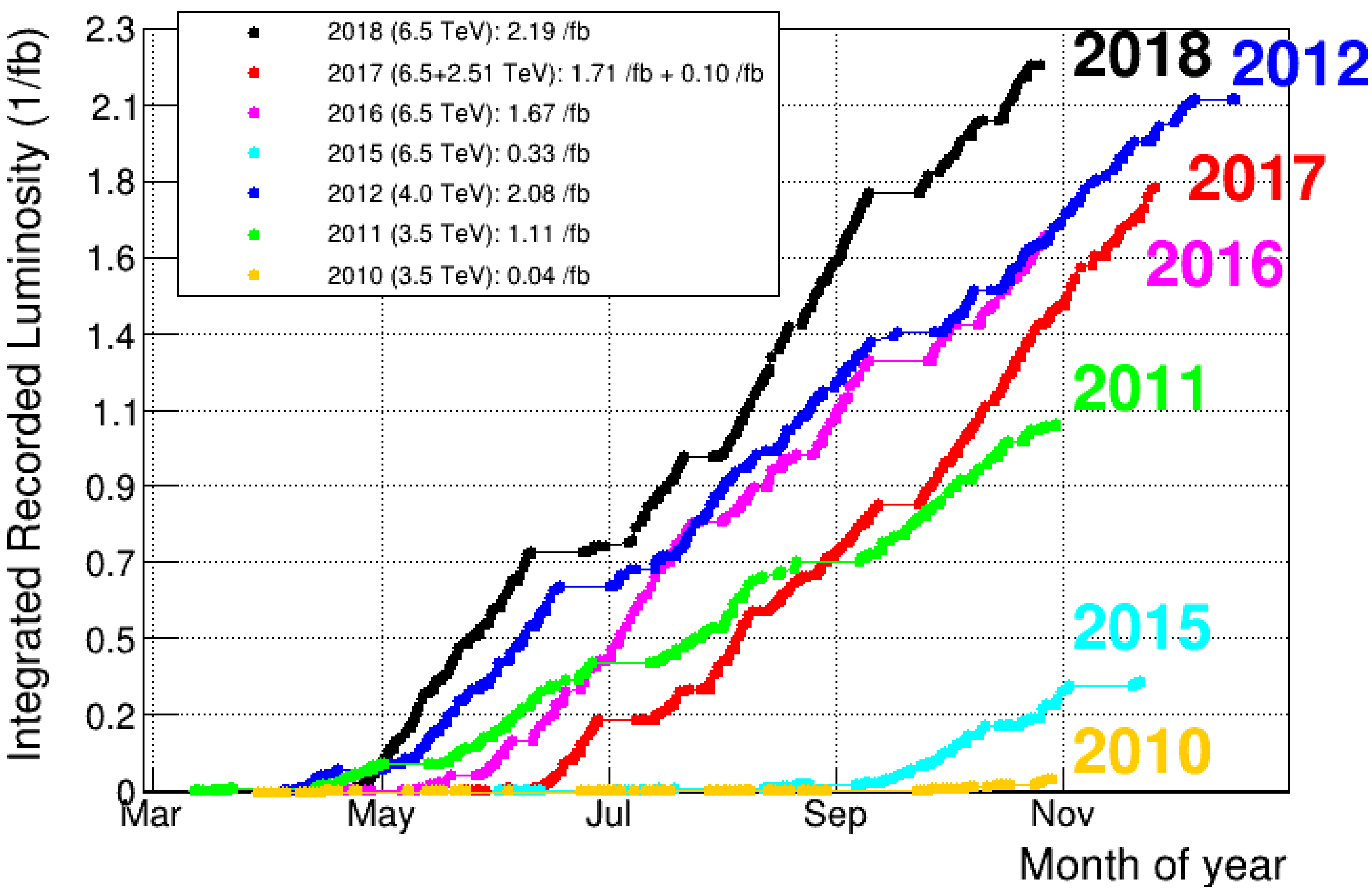
RICH: particle ID
- $\varepsilon(K\to K)$ ~95%
- Mis-ID: $\varepsilon(\pi\to K)$ ~5%

Magnet
- Bending power: 4 Tm

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

Data taking 2010-2018

- Run I (7-8 TeV, 2010-2012) and Run II (13 TeV, 2015-2018)
- Average efficiency of the data taking > 90 %
- Various systems: pp, p-Pb, Pb-Pb, SMOG (fixed target)



Measurement of charm at LHCb

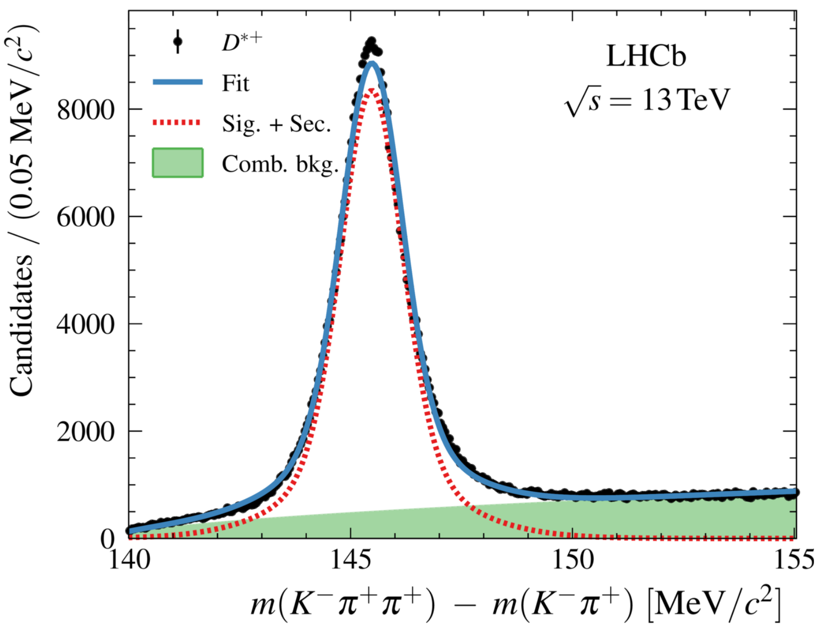
NPB 871 1 (2016), JHEP05 074 (2017)

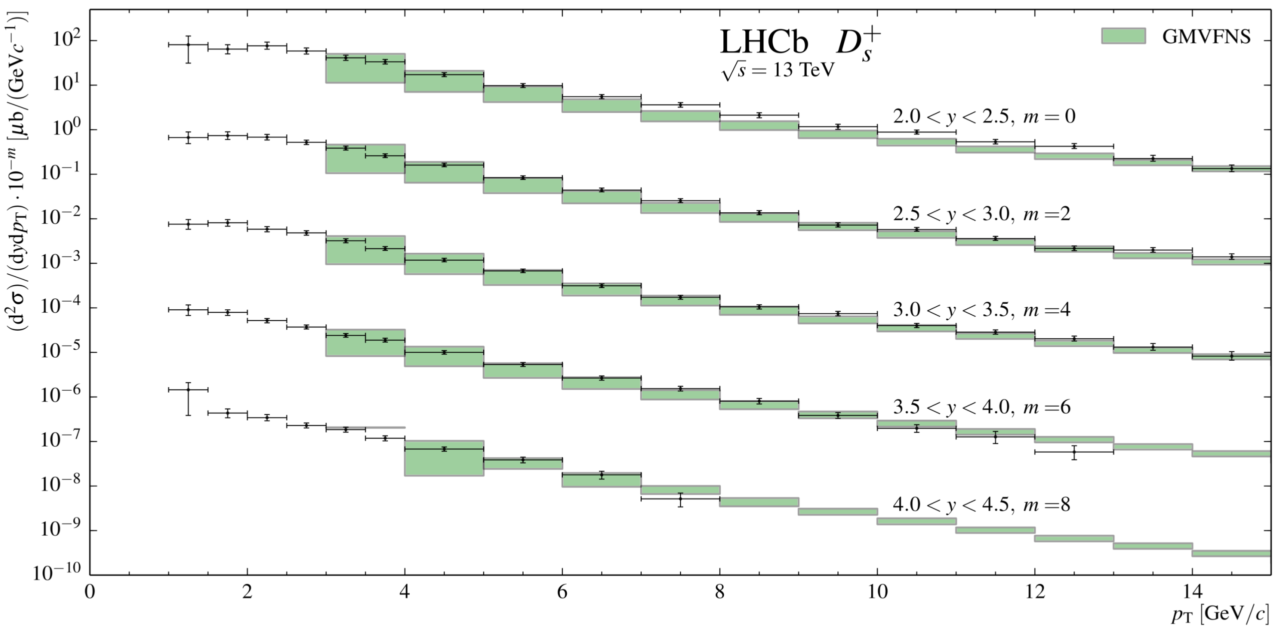
- Large charm cross section at LHCb:

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

$p_T < 8GeV/c, 2.0 < y < 4.5$

- Significant statistics collected already during the Run I:
  - 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

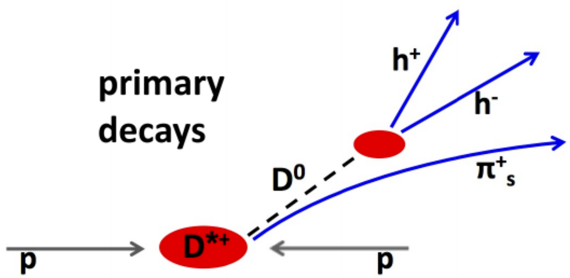


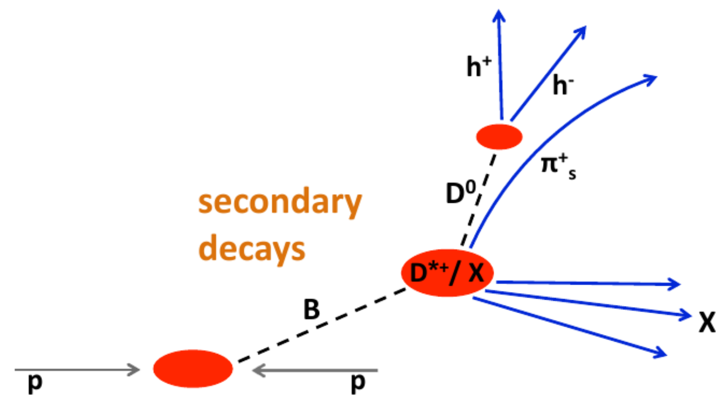


JHEP 05 074 (2017)

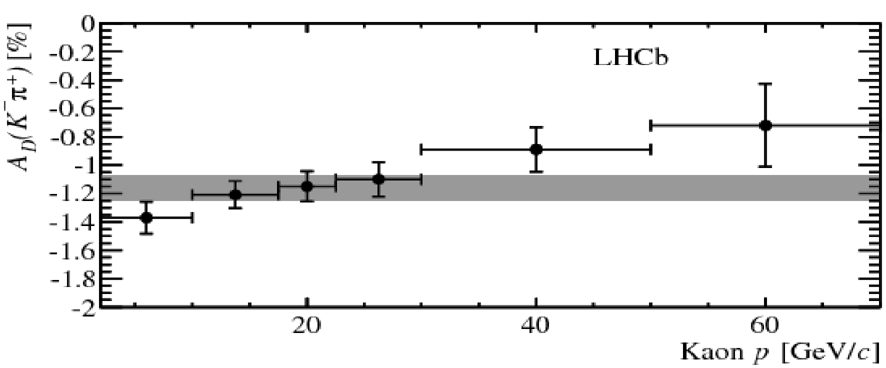
Experimental aspects at LHCb

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

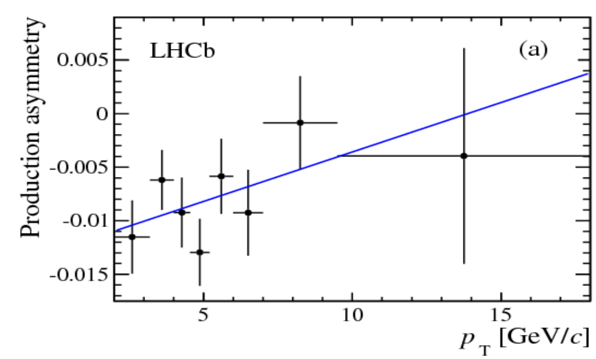




- Production asymmetries (charge dependent):
  - Different cross-section for $D^+_{(s)}/D^-_{(s)}$, Λ_c^+/Λ_c^- , …
- Detection asymmetries (charge and momentum dependent):
  - Different interactions with the detector material (K^+ vs K^-, π^+ vs π^-)



JHEP 07 041 (2014)

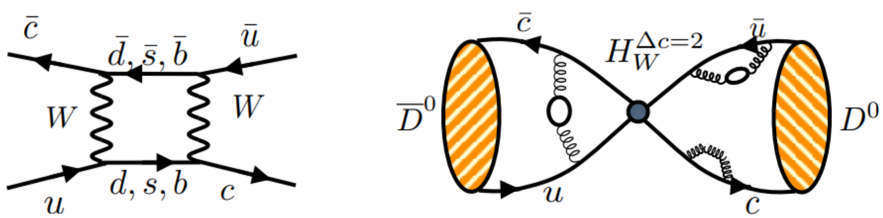


PLB 718 902 (2013)

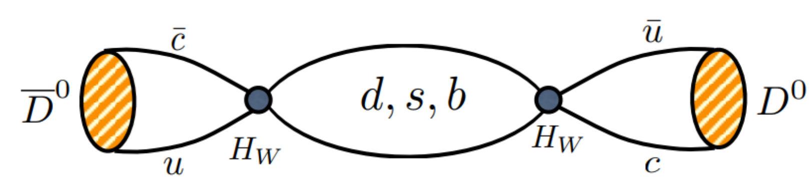
II. Charge-Parity Violation

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



short distance



long distance

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

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

CPV classification

- CPV is present in the SM via Cabibbo-Kobayashi-Maskawa (CKM) mechanism, but is too weak to explain the Baryon asymmetry of the Universe
- CPV has been firstly observed at Strange [PRL 13 138 (1964)] and Bottom [NP A 675 (2000), 398-403] sector, first observation in Charm sector (PRL 122 (2019) 211803)
- 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
- **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*

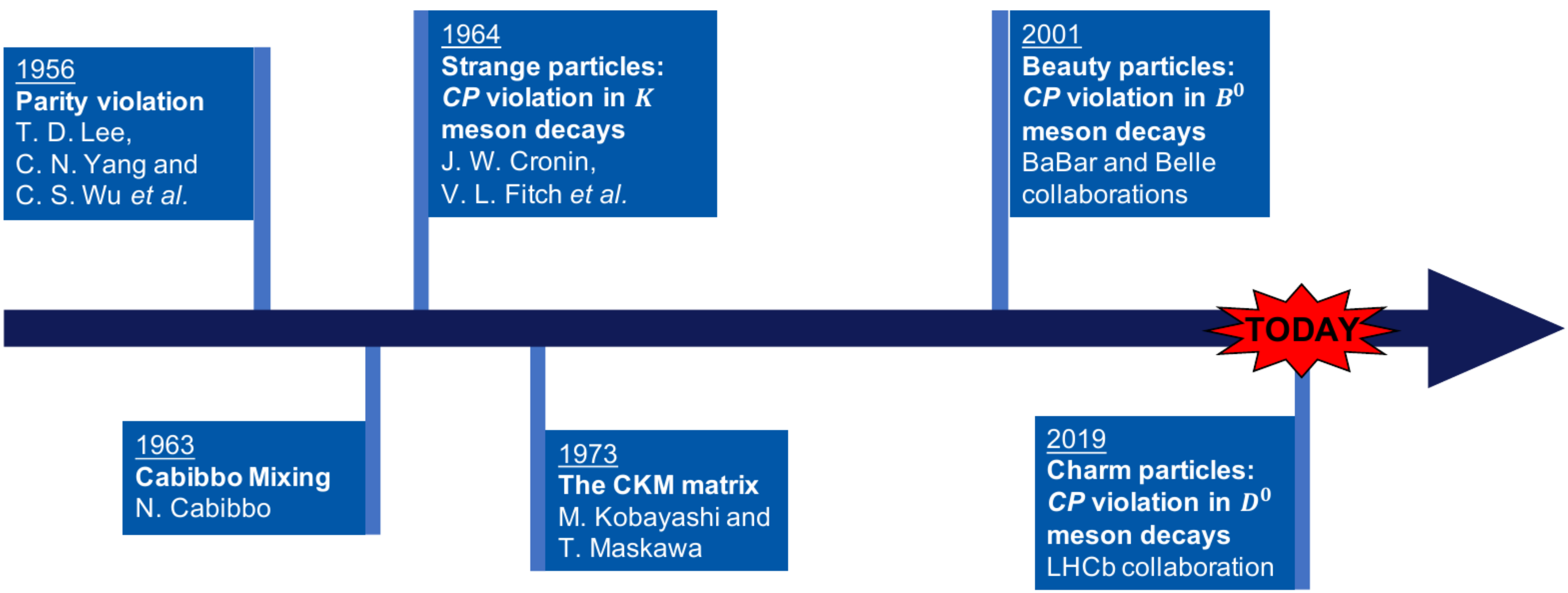
- Only possible *CPV* for charged hadrons
- Occurs in the case:

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

- Typically (for SCS modes): $A_{CP} < 10^{-4} - 10^{-3}$

Charm sector and *CPV*

- Charm is unique, gives sensitivity to new physics coupling to up-type quark
- Charm is also difficult for theory calculations
- Complementary to direct searches for BSM particles
- BSM contributions could be hidden in loops
- Assuming generic BSM scenarios, much larger scale are accessible with respect to direct searches
- Flavour physics and *CPV* lead to breakthrough in particle physics many times



II. Recent LHCb results on *CP* violation in Charm

1. Measurement of the mass difference between neutral charm-meson eigenstates (PHYS. REV. LETT. 122 (2019) 231802)

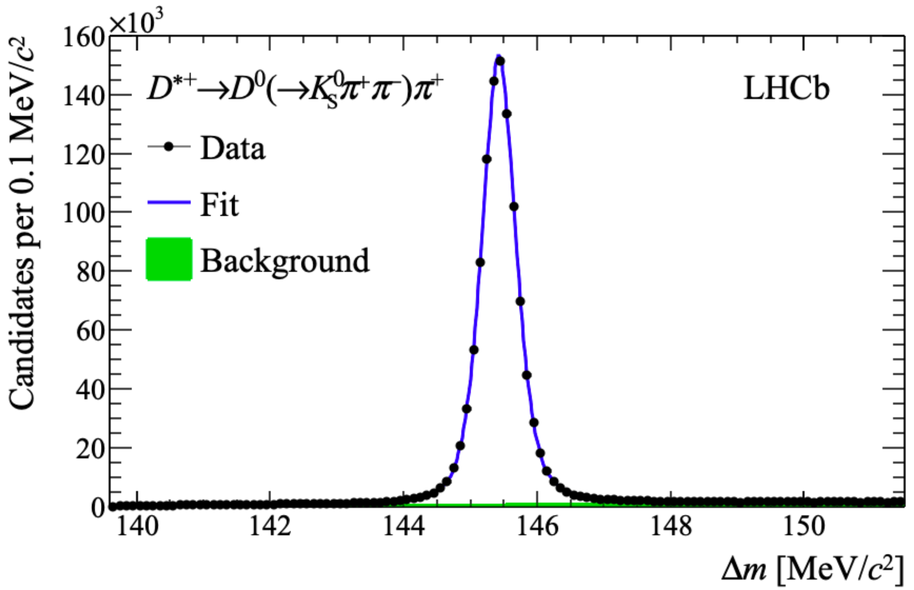
2. Search for time-dependent *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays (LHCB-CONF-2019-001; INSPIRE: 1735332)

3. Observation of *CP* violation in charm decays (PHYS. REV. LETT. 122 (2019) 211803)

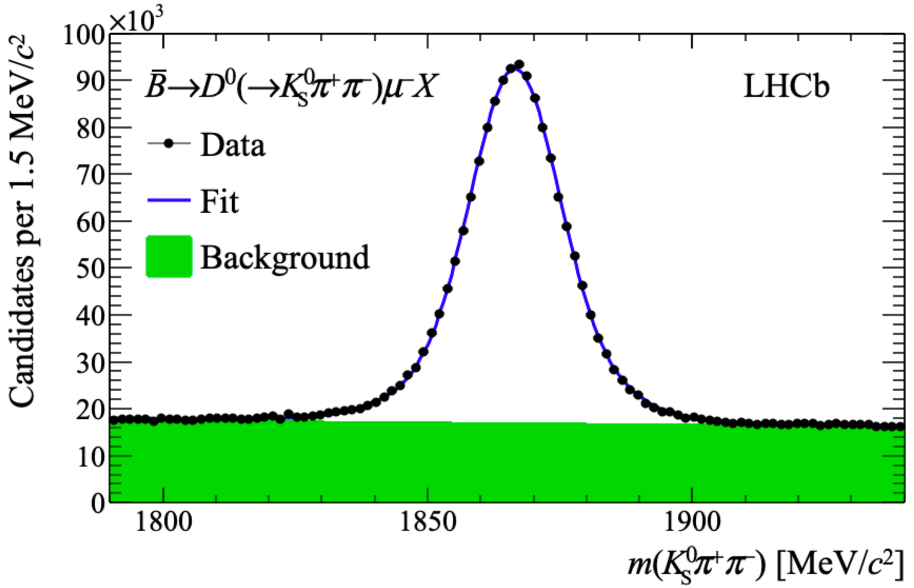
1. Measurement of the mass difference between neutral charm-meson eigenstates (PHYS. REV. LETT. 122 (2019) 231802)

D^0 mass eigenstates Δm: introduction

- *CPV* is an interference effect
- How to enhance our sensitivity?
- LHCb Run I full sample
- Prompt and semileptonic production of $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-$
- Around 1.3×10^6 signal candidates for prompt production and around 1.0×10^6 for semileptonic decays
- Channel with a rich resonance spectrum
- Good sensitivity to mixing and time-dependent *CPV* parameters via varying strong phases
- Experimentally complicated (decay dynamics and acceptance effects)

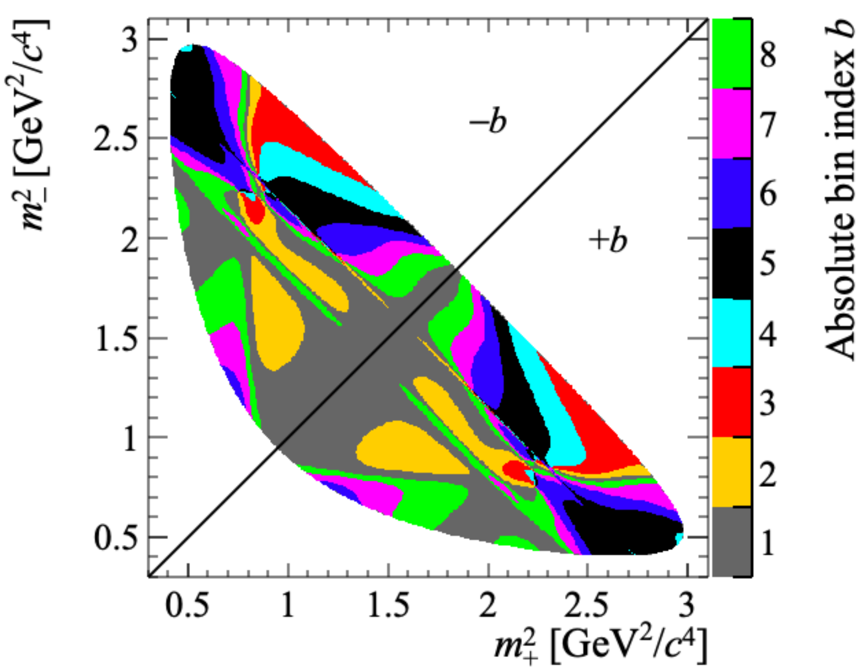


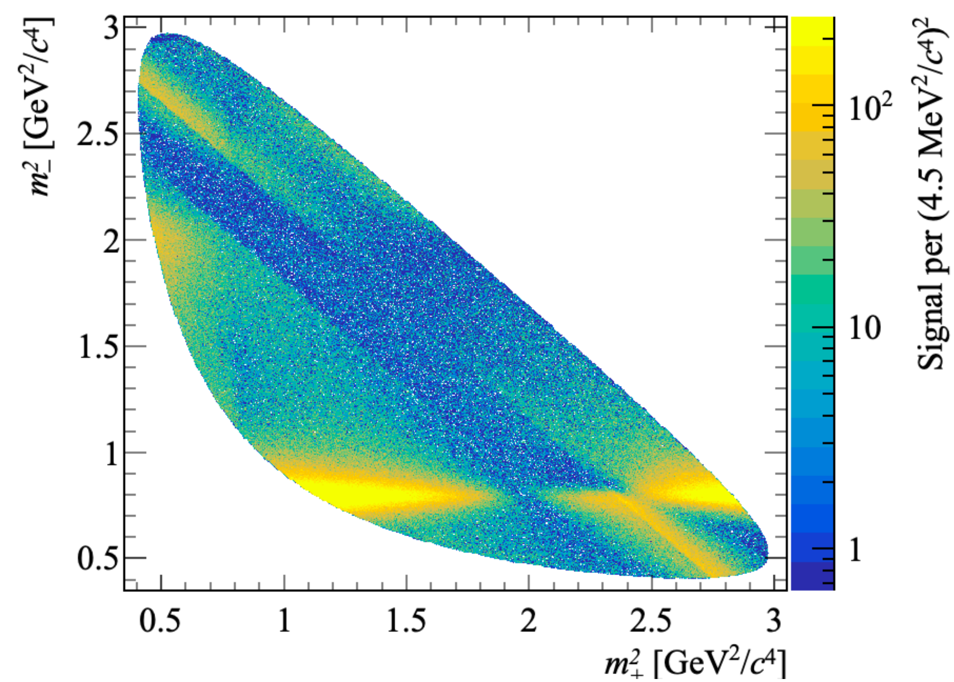
PHYS. REV. LETT. 122 (2019) 231802



D^0 mass eigenstates Δm: method

- Bin flip method (Phys. Rev. D 99, 012007): a novel approach minimizing dependence on amplitude model and detector acceptance
- Data are binned in Dalitz plane ($R^{+/-}_{1-8}$) to keep strong phases approximately constant; input is taken from CLEO (Phys. Rev. D 82, 112006)
- Data are also binned in decay time (20 bins)
- Ratio of yields in opposition bins across the bisection is measured
  - Cancellation of acceptance effects, also a good sensitivity to *x*





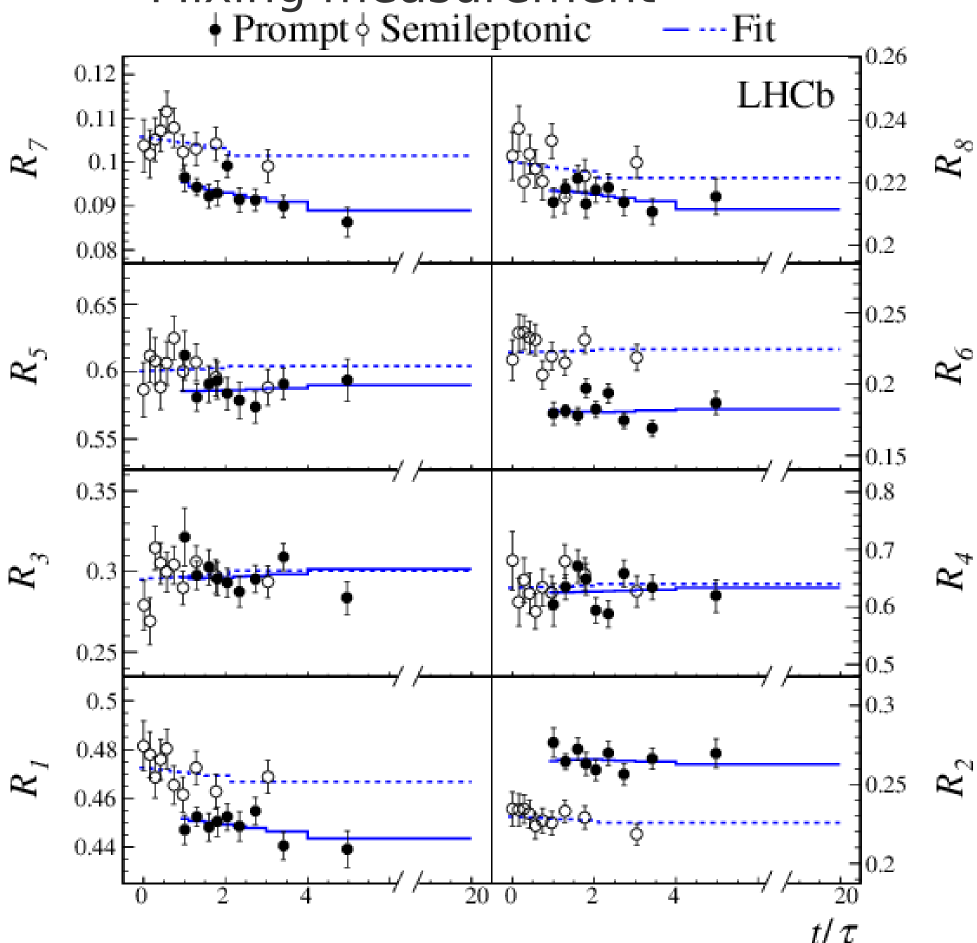
PHYS. REV. LETT. 122 (2019) 231802

D^0 mass eigenstates Δm: fits

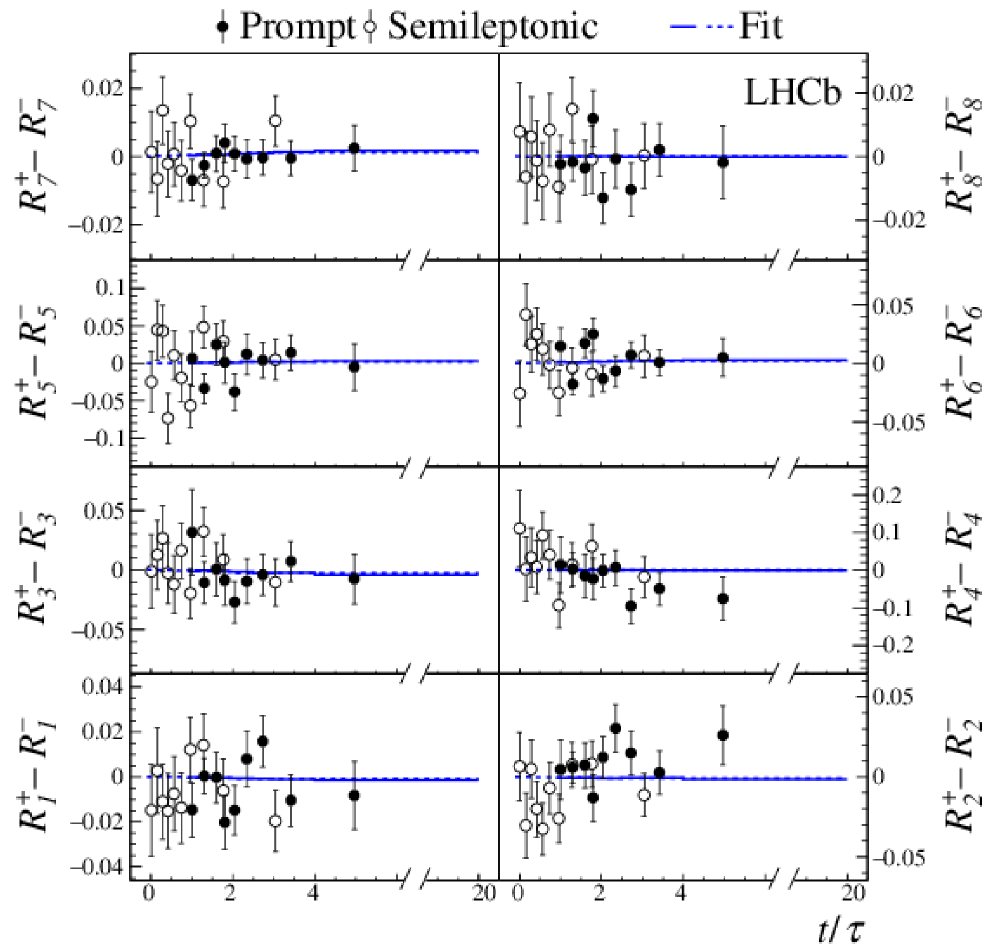
- Simultaneous least-squares fit* to prompt and semileptonic data
- Offset due to sample-specific efficiency variations across Dalitz plot

* details in backup slide 40

- *CP*-averaged yield ratios as function of *t/τ*
- Mixing measurement



- Differences of D^0 and anti-D^0 yield ratios as function of *t/τ*
- Search for *CP* violation

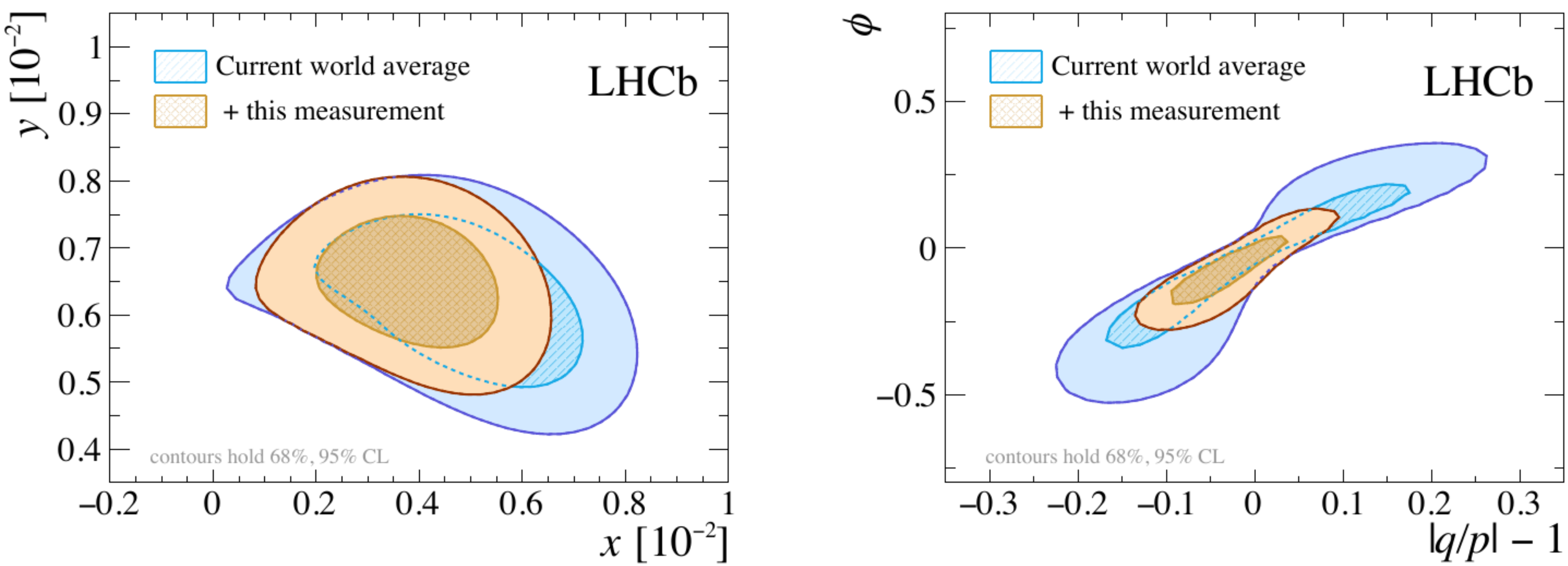


D^0 mass eigenstates Δm: results

- The most precise measurement of *x* done by a single experiment, consistent with *CP* symmetry scenario

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	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

- Combined with the world average, first evidence of $x > 0$ larger than 3σ



2. Search for time-dependent *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays (LHCB-CONF-2019-001; INSPIRE: 1735332)

CPV(t) in $D^0 \to h^+h^-$: introduction

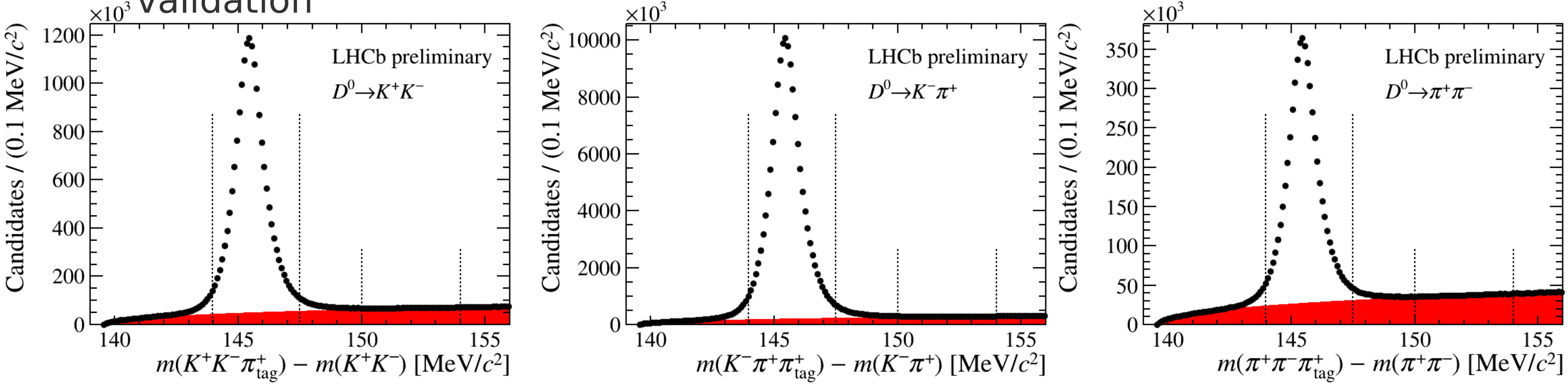
$$A_\Gamma = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx y(|\frac{q}{p}| - 1) - x\phi_f - yA_{CP}^{decay}(f)$$

CPV in interference

CPV in mixing

CPV in decay
Negligible with current exp.
Precision (3×10^{-4} vs 1×10^{-5})

- LHCb 2015-2016 data, prompt D^{*+} decays utilized for a tagging of D0 decays
- Analysis done using two signal channels $D^0 \to K^+K^-/\pi^+\pi^-$ ($17\times10^6/5\times10^6$)
- $D^0 \to K^-\pi^+$ control channel (146×10^6) used for a full analysis procedure validation



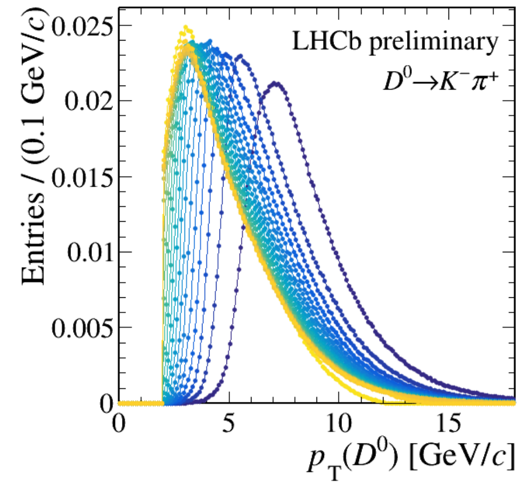
- Asymmetry measured in 21 decay time bins

LHCb-CONF-2019-001

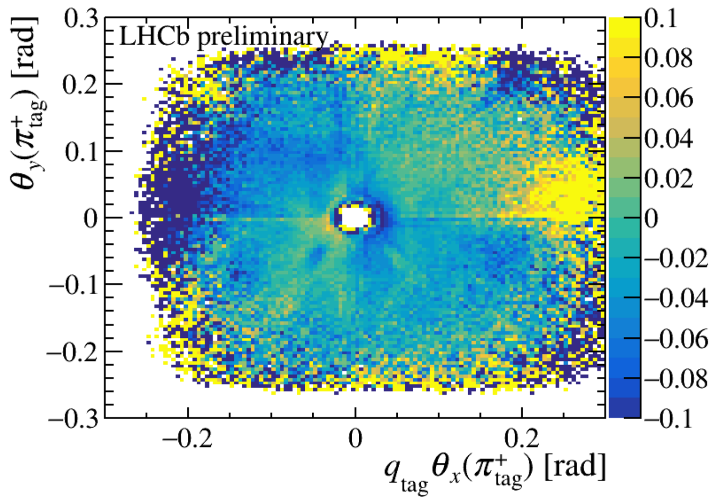
- Current world average, $(-3.2 \pm 2.6)\times10^{-4}$, dominated by LHCb Run I measurement (Phys. Rev. Lett. 118, 261803)

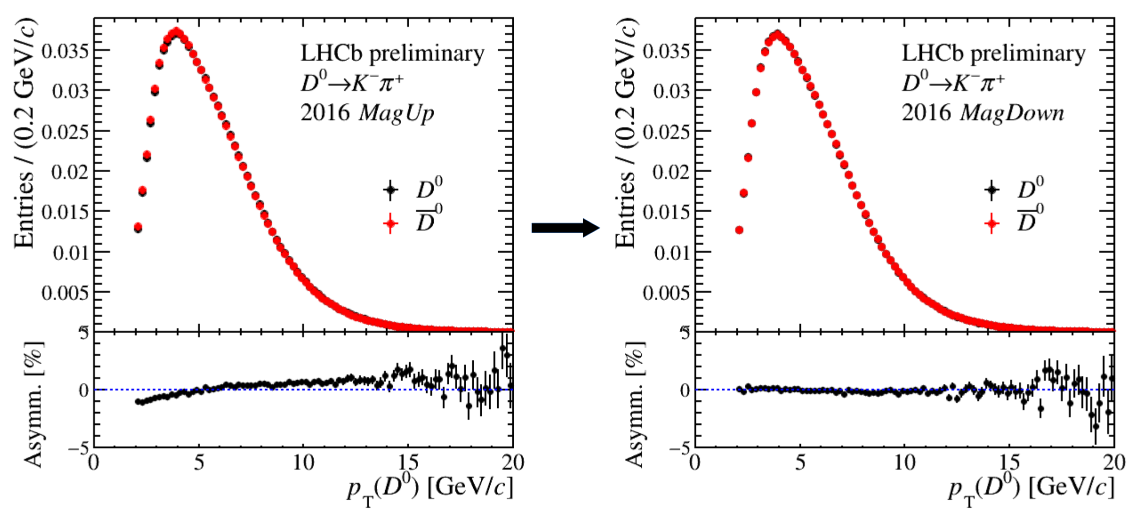
CPV(t) in $D^0 \to h^+h^-$: detector asymm.

- Time and momentum-dependent asymmetries arise from two main sources
  - Momentum-dependent detection asymmetry from tagging pion
  - Correlation between the measured decay time and the momentum of the D^0 due to trigger requirements

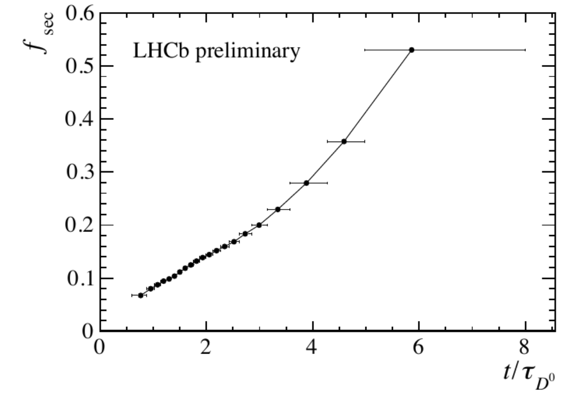


- Effect can be cancelled by weighting events between D^0 and anti-D^0 candidates
  - Separate weighting for different experimental conditions (magnet polarity, year)
  - 3D momentum weighting





$CPV(t)$ in $D^0 \rightarrow h^+h^-$: systematic



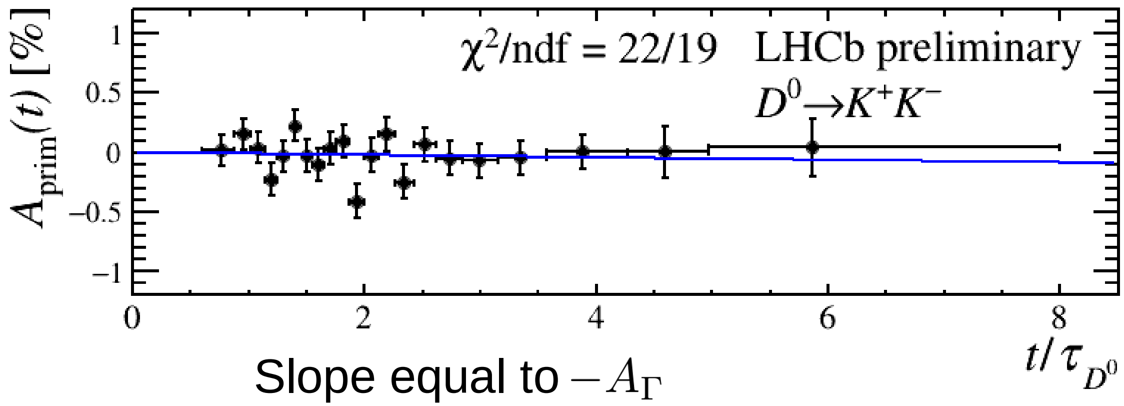
- Contamination of D^{*+} by the secondary decays
  - Measured decay time of secondary decays biased to longer decay time
  - Fraction of secondary decays increases as a function of time
- Kinematic weighting depends on the exact binning
  - Bins has be to kept large enough to avoid large statistical fluctuations
  - Control channel used for bin size optimization

Source	$A_\Gamma(D^0 \rightarrow K^+K^-)$	$A_\Gamma(D^0 \rightarrow \pi^+\pi^-)$
Secondary decays	0.4	0.4
Δm background	0.3	0.5
$m(h^+h^-)$ background	0.3	0.2
Kinematic weighting	0.3	0.3
Sum in quadrature	0.7	0.8

LHCb-CONF-2019-001

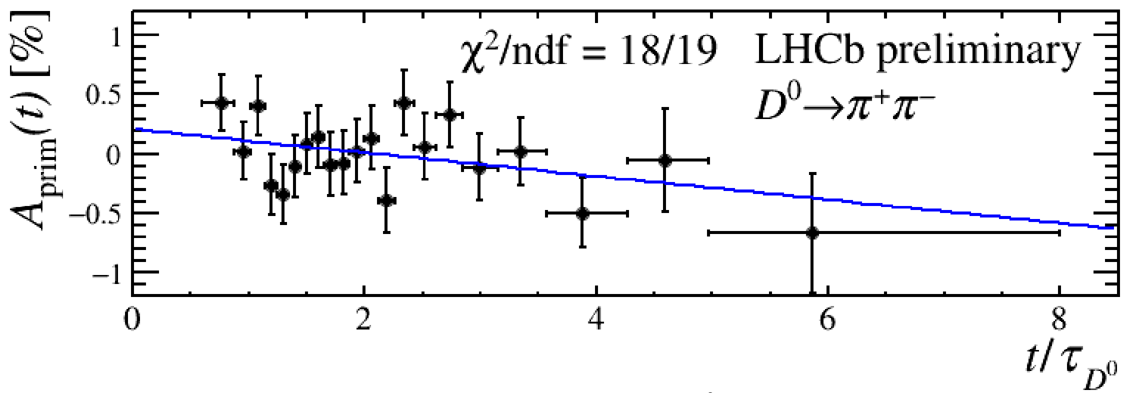
CPV(t) in $D^0 \rightarrow h^+h^-$: results

$$\mathbf{A_\Gamma}(\mathrm{K^+K^-}) = (\mathbf{1.3} \pm \mathbf{3.5} \pm \mathbf{0.7}) \times \mathbf{10^{-4}}$$



Slope equal to $-A_\Gamma$

$$\mathbf{A_\Gamma}(\pi^+\pi^-) = (\mathbf{11.3} \pm \mathbf{6.9} \pm \mathbf{0.8}) \times \mathbf{10^{-4}}$$



$$\mathbf{A_\Gamma}(\mathrm{K^+K^-} + \pi^+\pi^-) = (\mathbf{3.4} \pm \mathbf{3.1} \pm \mathbf{0.6}) \times \mathbf{10^{-4}}$$

LHCb-CONF-2019-001

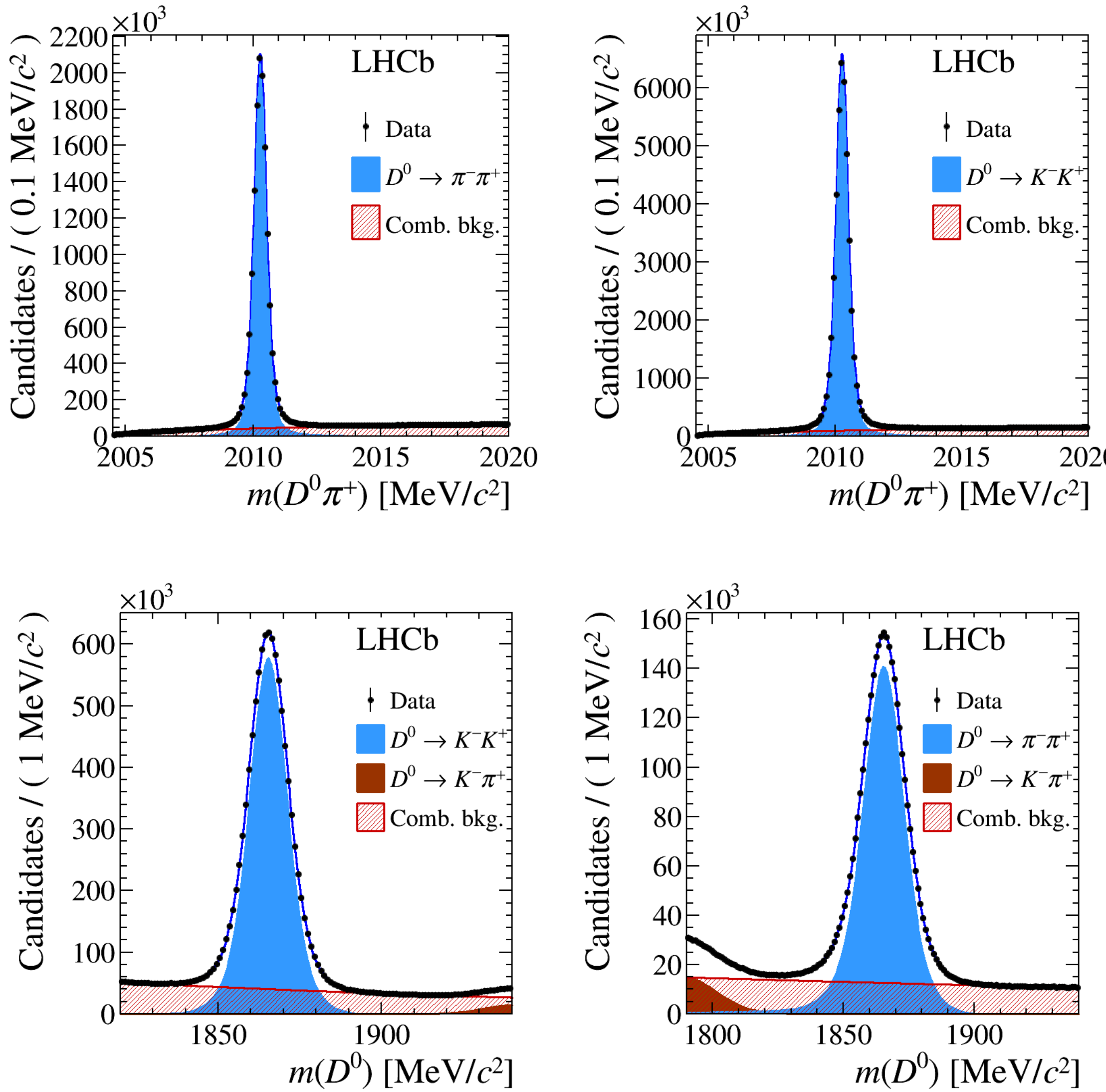
$$\mathbf{A_\Gamma}(\mathrm{K^+K^-} + \pi^+\pi^-,\ 2011-2016) = (\mathbf{0.9} \pm \mathbf{2.1} \pm \mathbf{0.7}) \times \mathbf{10^{-4}}$$

- Systematic uncertainty reduced by 30 % with respect to previous LHCb analysis (Phys. Rev. Lett. 118, 261803)
- Consistent with *CP* symmetry
- Dominated by statistical uncertainty → full Run II analysis in progress

3. Observation of *CP* violation in charm decays (PHYS. REV. LETT. 122 (2019) 211803)

CPV in Charm: introduction

- Full LHCb Run II data set
- $D^0 \to K^+K^-/\pi^+\pi^-$ decays
- Prompt ($44 \times 10^6/13 \times 10^6$) and semileptonic production ($9 \times 10^6/3 \times 10^6$)
- Using Turbo data stream – online reconstruction of data (Comput. Phys. Commun. 208 (2016) 35)
- Fit to invariant mass distribution to extract the raw asymmetries
- However, raw asymmetries are influenced by the production and detection asymmetries



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CPV in Charm: experimental issues

- Detection and production asymmetries can be cancelled using suitable experimental procedure for prompt / semileptonic decays:

$$\mathrm{A_{raw}(f) \approx A_{CP}(f) + A_D(D^0) + A_D(\pi/\mu) + A_P(D^{*+}/B)}$$

- $\mathrm{A_{raw}(f) = \dfrac{N(D^0 \to f) - N(\overline{D^0} \to f)}{N(D^0 \to f) + N(\overline{D^0} \to f)}}$ - experimentally accessible asymmetry

- $\mathrm{A_{CP}(f)}$ - physical *CP* asymmetry of final state *f*
- $\mathrm{A_D(D^0)}$ - D^0 detection asymmetry, cancelled due to symmetric final states
- $\mathrm{A_D(\pi/\mu)}$ - detection asymmetry of tagging particle
- $\mathrm{A_P(D^{*+}/B)}$ - production asymmetry of mother particle
- Under the assumption of small experimental asymmetries, *CP* can be obtained as

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

CPV in Charm: fiducial selection

- Due to LHCb geometry, low momentum particle can be kicked out from the detector acceptance
- Such a regions of phase space generate very large raw detector asymmetries

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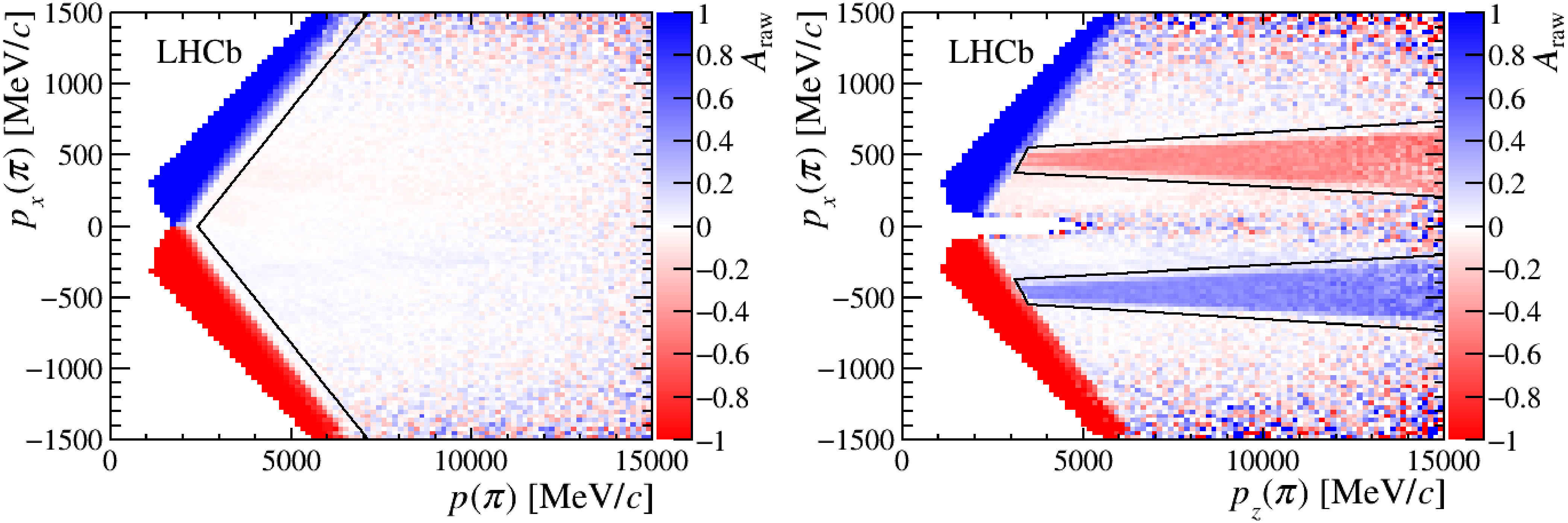
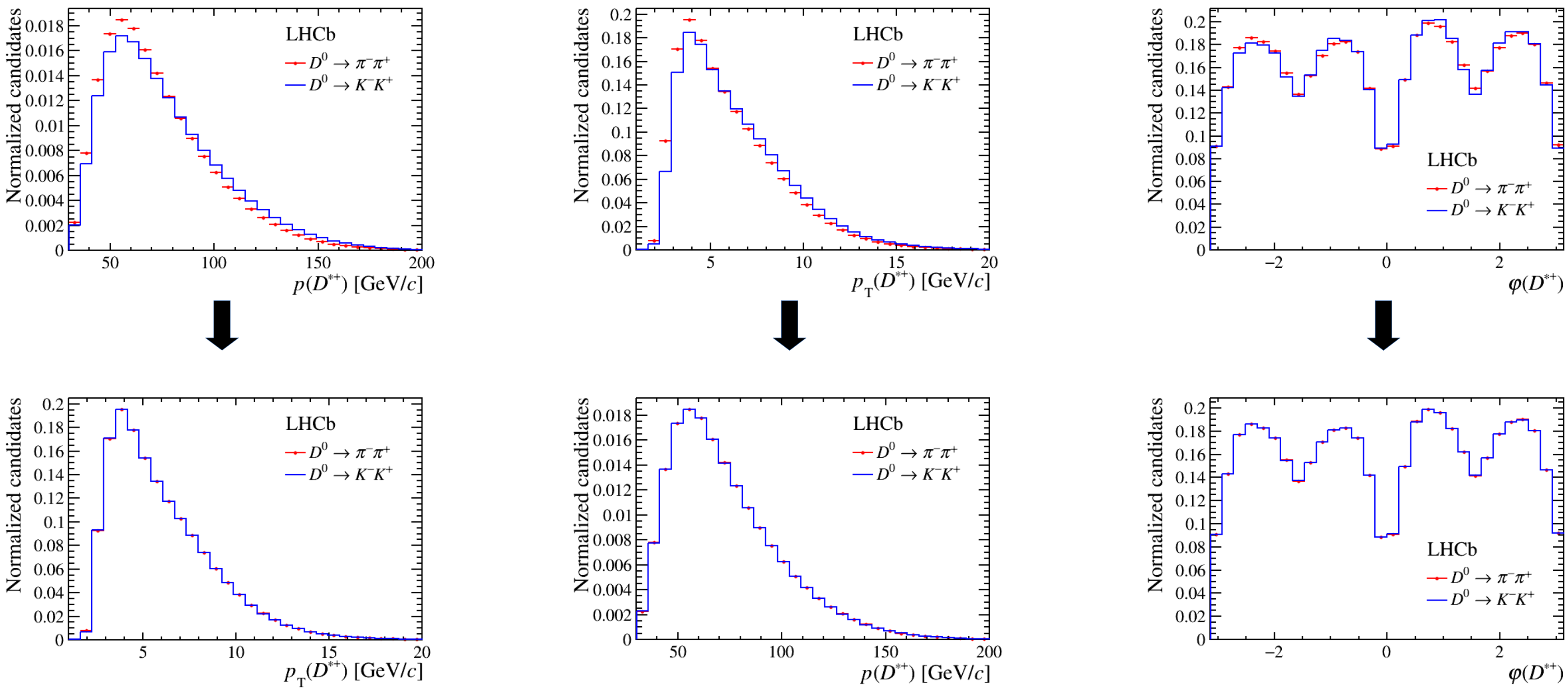


- This part of phase space must be removed in order of kinematic equalization
- Same procedure for prompt/semileptonic decays (π/μ)

CPV in Charm: kinematic weighting

- Detection and production asymmetries depend on the kinematic of the reconstructed particles
- Weighting procedure between modes to assure same kinematic
- Variables prompt/semileptonic: $p_{\mathrm{T}}(\mathrm{D}^*), p(\mathrm{D}^*), \phi(\mathrm{D}^*)$ / $p_{\mathrm{T}}(\mathrm{D}^0), p(\mathrm{D}^0), \phi(\mathrm{D}^0)$



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CPV in Charm: systematic

- Prompt mode dominated by:
  - Fit model
    - Default model: Sum of three Gaussian and Johnson Su function (prompt) and two Gaussians convolved with a power-law function (sl)
    - Alternative: Fitting pseudoexperiments with alternative models
  - Misreconstructed background
- Semileptonic mode dominated by mistagging of muon
  - Evaluated using control sample $\mathrm{B} \to \mathrm{D}^0(\to \mathrm{K}^-\pi^+)\mu\mathrm{X}$

Source	π-tagged $[10^{-4}]$	μ-tagged $[10^{-4}]$
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B^0 fraction	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

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CPV in Charm: results

- Run II results:

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

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

- Compatible with the previous LHCb results and the world average values
- When combined with Run I LHCb results:

$$\Delta A_{CP}^{\text{RunI+RunII}} = [-15.4 \pm 2.9] \times 10^{-4}$$

- *CP* violation at 5.3 σ level
- ΔA_{CP} is mostly sensitive to direct *CPV*

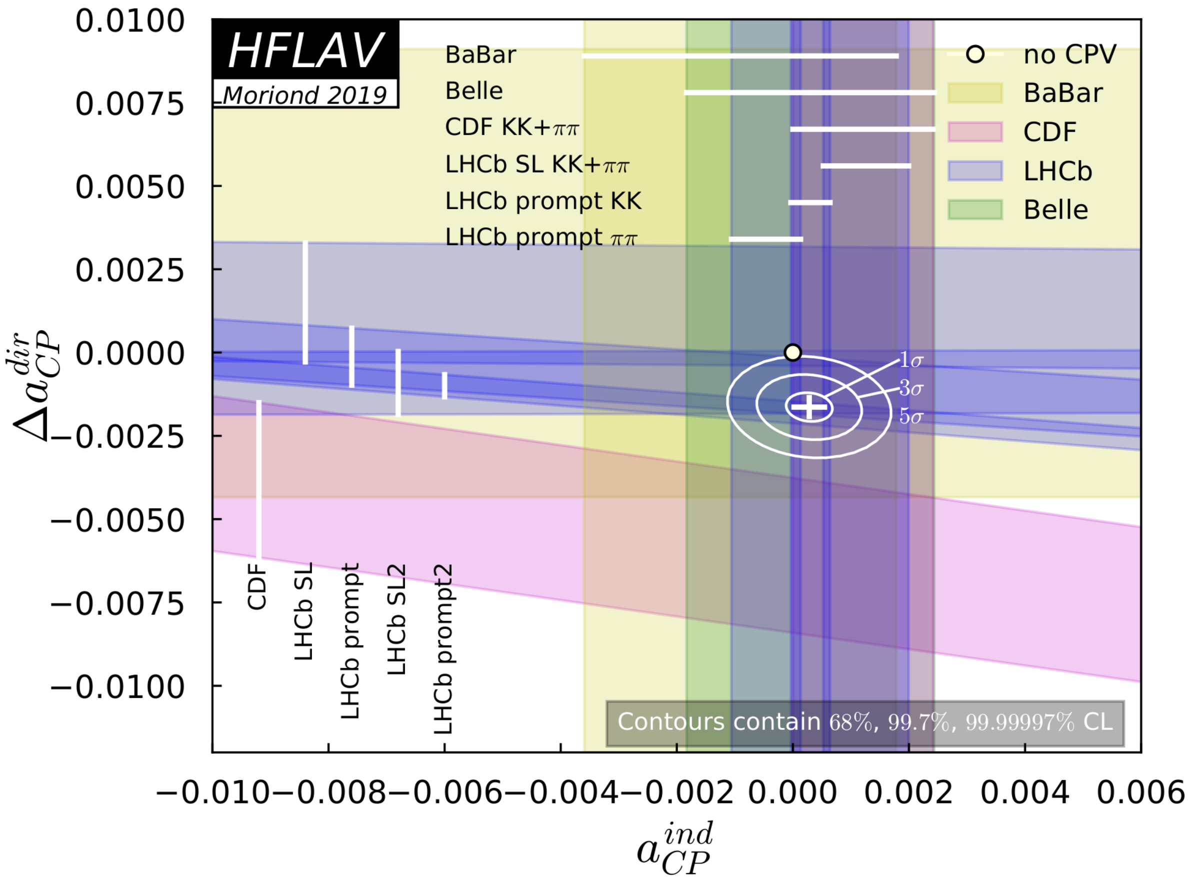
CPV in Charm: world average

- Updated HFLAV fit

$$\Delta a_{CP}^{dir} = (-16.4 \pm 2.8) \times 10^{-4}$$

$$\Delta a_{CP}^{ind} = (2.8 \pm 2.6) \times 10^{-4}$$

- Compatible with SM
  - Most predictions on 10^{-4} - 10^{-3} level
- Progress in theory calculations needed
- Observation in other channels could provide a confirmation of this effect
- Thorough study needs to be done to decide if SM or BSM effect
- Indirect *CPV* still missing



Conclusion and Outlook

- Different mass between *CP*-even and *CP*-odd D^0 states
- Direct *CPV* in Charm observed for the first time
- Inconclusive if SM or BSM effects
- Indirect *CPV* still unobserved

Future prospects

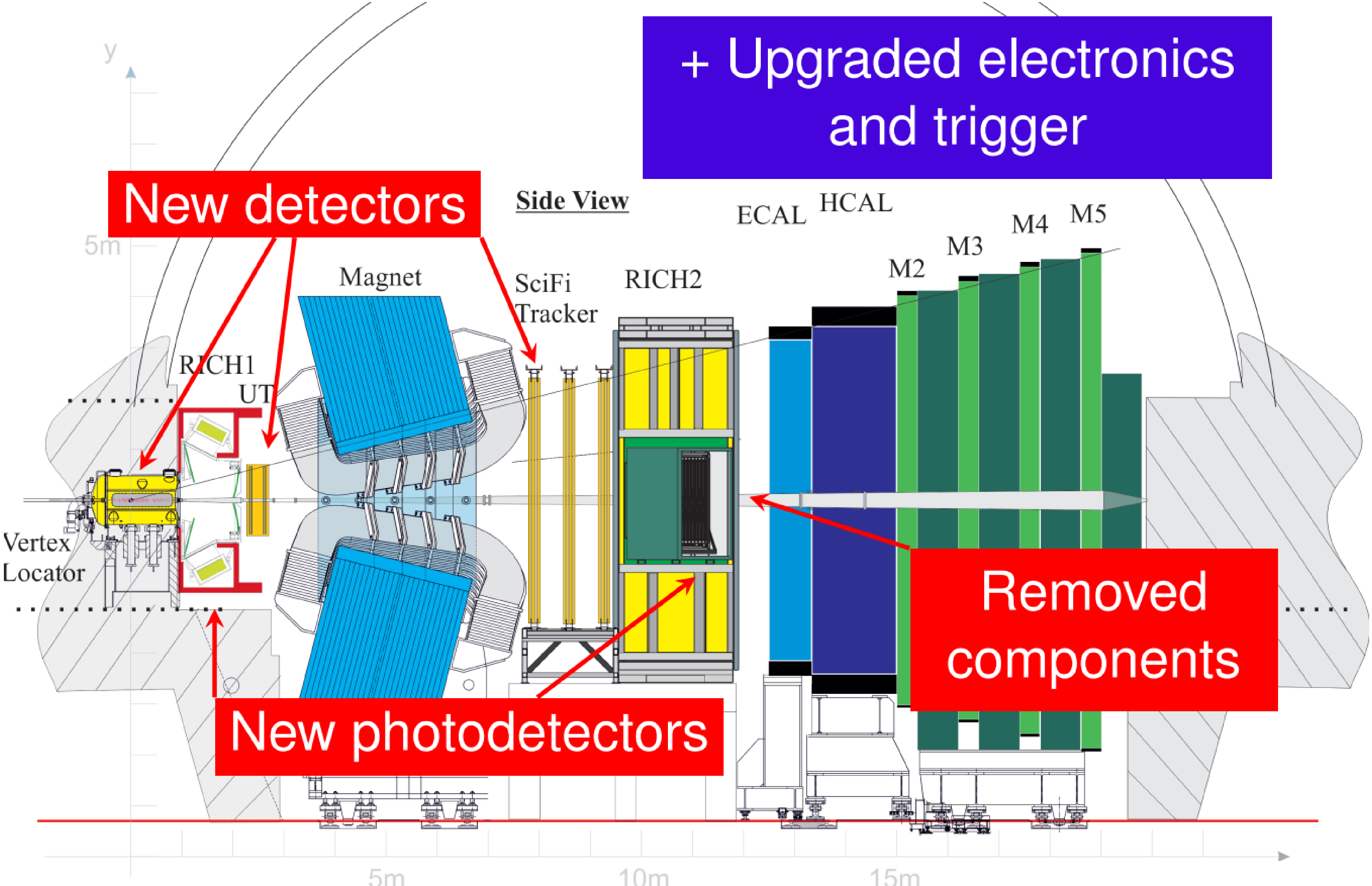
- LHCb has access to the world largest Charm sample – analyses now have to exploit it
- Belle-II is now preparing for data taking
- Ongoing LHCb Upgrade – 5x higher luminosity and new software trigger
- 50/fb will be collected by 2030
- Expected statistical uncertainty: $\mathcal{O}(10^{-4})$
- Also a possibilities to utilize rare and multi-body decays

Thank you for your attention

BACKUP
Slides

Planned LHCb upgrades

LHCb upgrade Phase I (Run III)



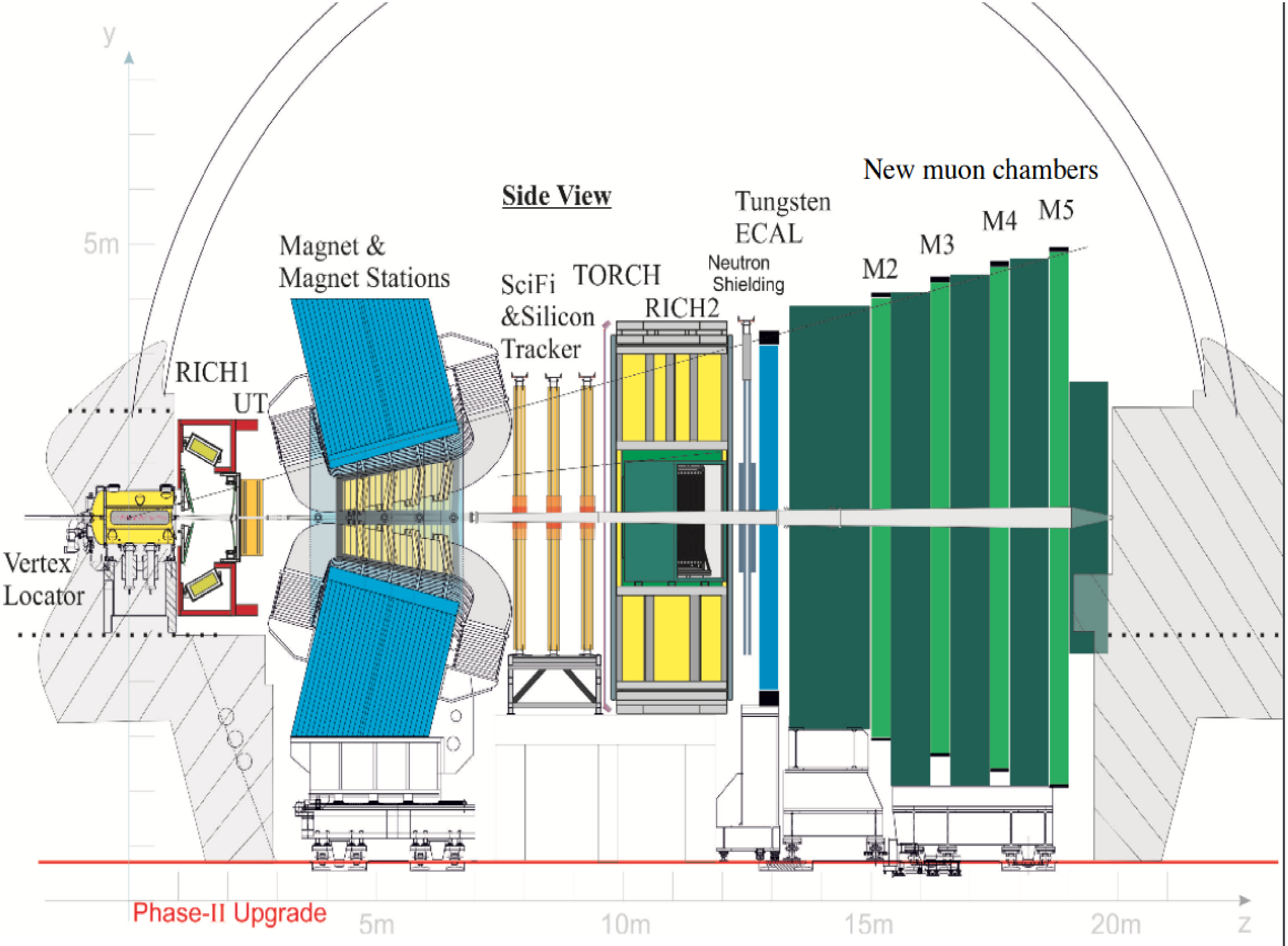
LHCb-TALK-2017-232

LHCb upgrade Phase I (Run III)

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	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
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\,A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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 %	$\sim 10\,\%$
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}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\, K_S^0$)	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)



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LHCb upgrade Phase II (Run V)

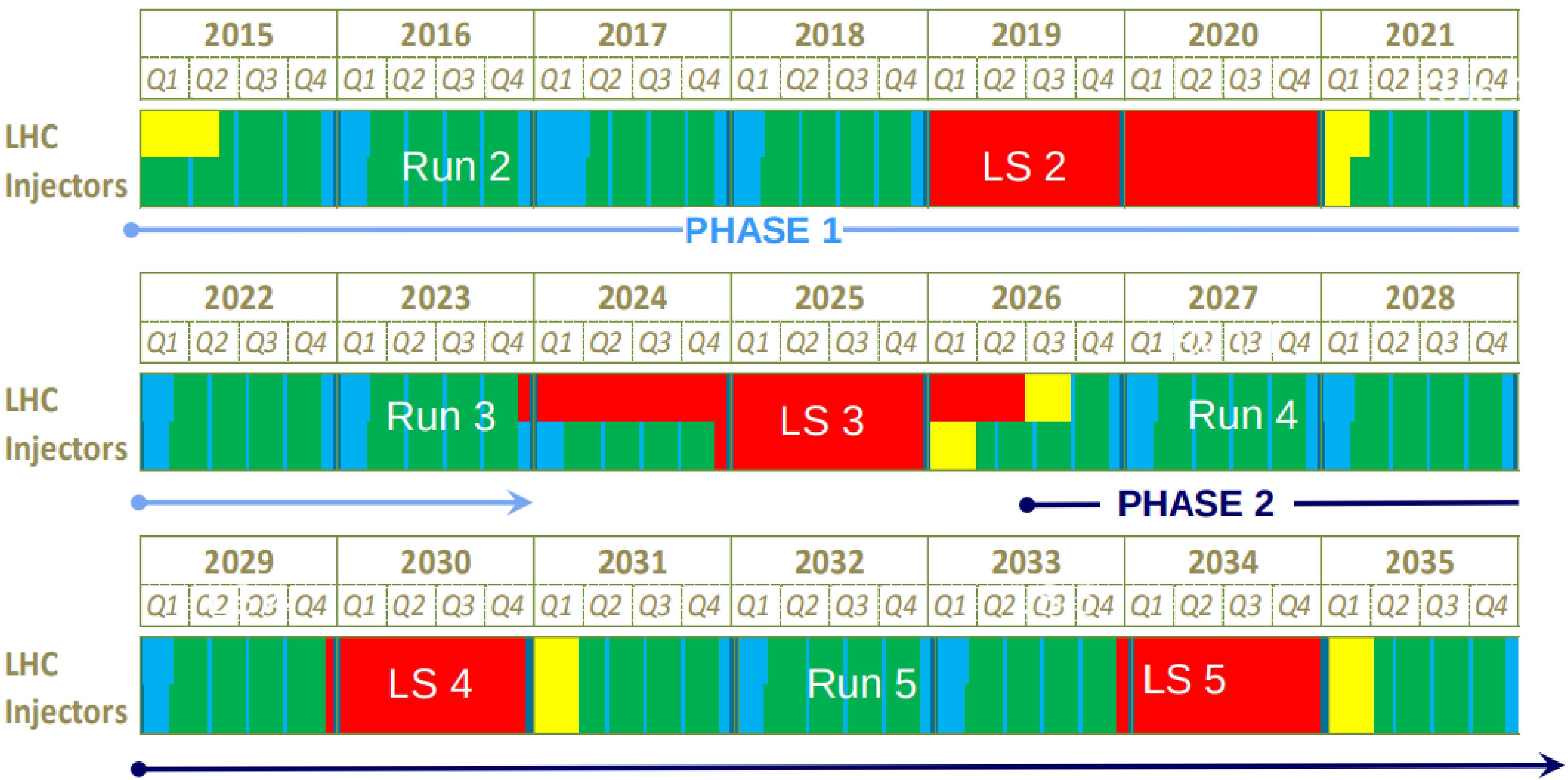
Topics and observables	Experimental reach	Remarks
EW Penguins		
Global tests in many $b \to s\mu^+\mu^-$ modes with full set of precision observables; lepton universality tests; $b \to dl^+l^-$ studies	*e.g.* 440k $B^0 \to K^*\mu^+\mu^-$ & 70k $\Lambda_b^0 \to \Lambda\mu^+\mu^-$; Phase-II $b \to d\mu^+\mu^- \approx$ 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.

LHC timeline

LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

- Physics
- Shutdown
- Beam commissioning
- Technical stop



D^0 mass eigenstates Δm: fits

- Simultaneous least-squares fit* for prompt and semileptonic data
- Offset due to sample-specific efficiency variations across Dalitz plot

$$\chi^2 = \sum_{\mathrm{Pr,\,SL}} \sum_{\mathrm{LL,\,DD}} \sum_{b,j} \left[\frac{(N^+_{-bj} - N^+_{bj} R^+_{bj})^2}{(\sigma^+_{-bj})^2 + (\sigma^+_{bj} R^+_{bj})^2} + \frac{(N^-_{-bj} - N^-_{bj} R^-_{bj})^2}{(\sigma^-_{-bj})^2 + (\sigma^-_{bj} R^-_{bj})^2} \right] + \chi^2_X,$$

$$\chi^2_X = \sum_{a,b} \left[X_a^{\mathrm{CLEO}} - X_a \right] (V^{-1}_{\mathrm{CLEO}})_{ab} \left[X_b^{\mathrm{CLEO}} - X_b \right].$$

- Simultaneously applied for prompt/semileptonic data, D^0/anti-D^0
- Two fits: *CP* symmetry scenario and indirect *CPV* allowed

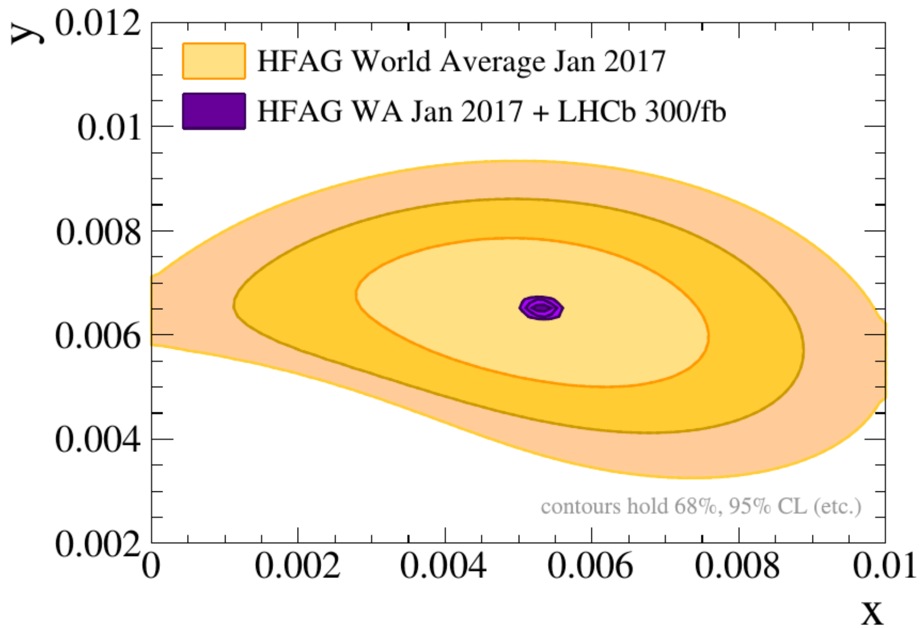
VI. Future prospects for Run III and beyond

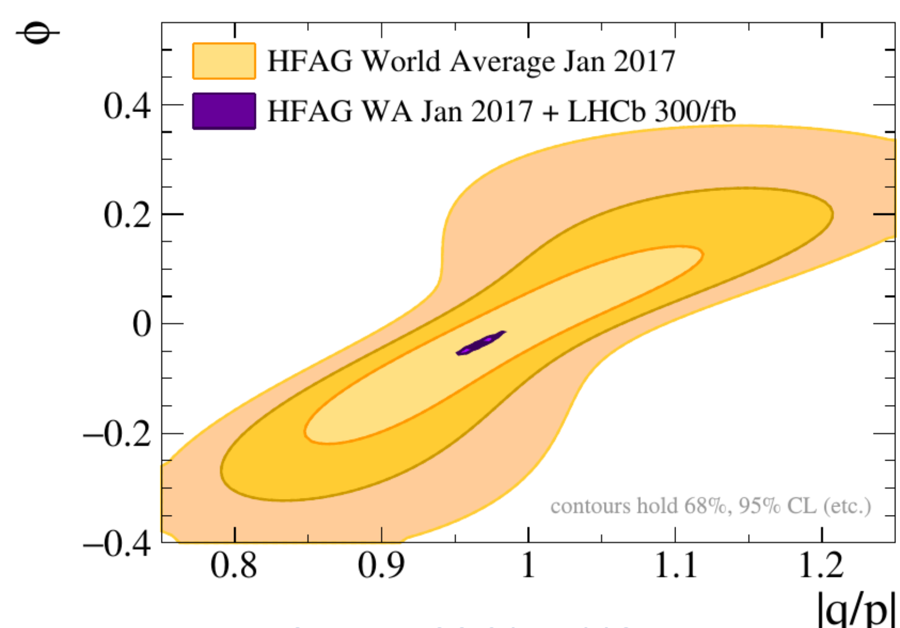
Prospect for indirect *CPV* searches

→ 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





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Prospects for direct *CPV* searches

- Precision is already at $\mathcal{O}(10^{-3})$ level, one 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: $\mathrm{D}^0 \to \pi^0\pi^0,\ \mathrm{D}^0 \to \mathrm{K_S K_S},\ \mathrm{D}^0 \to \pi^0\pi^+$

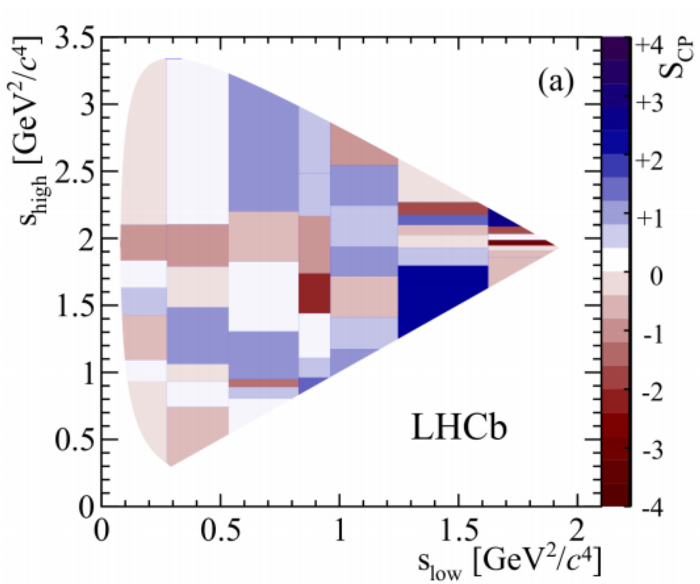
1) Multibody decays [slide: 42-43]
2) Rare decays (radiative, leptonic) [slide: 45]
3) Double Cabibbo Suppressed (DCS) decays (e.g. $\mathrm{D}^+ \to \mathrm{K}^+\pi^+\pi^-/\mathrm{K}^+\mathrm{K}^-\mathrm{K}^+$)
4) Exploring charm baryons [slide: 46-47]
   - Measured 1st evidence for *CPV* in baryons: $\Lambda_\mathrm{b} \to \mathrm{p}3\pi$ [Nature Phys. 13, 391-396 (2017)]

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:

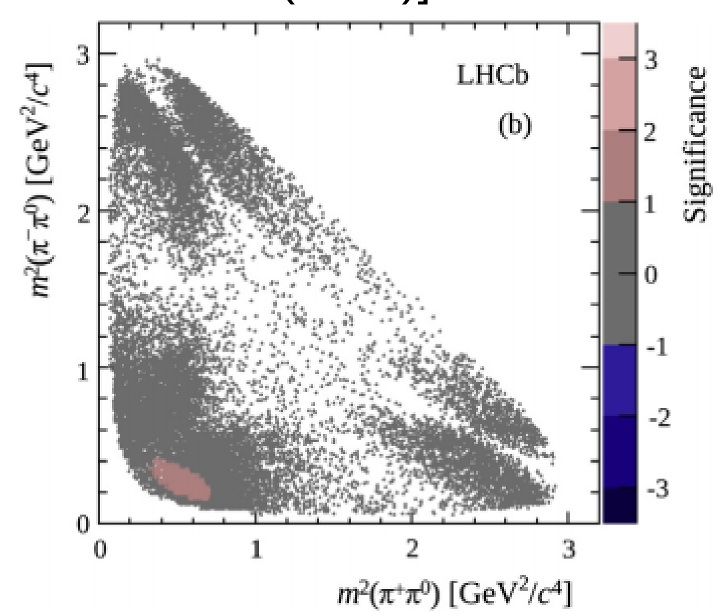
Binned approach

- 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)]



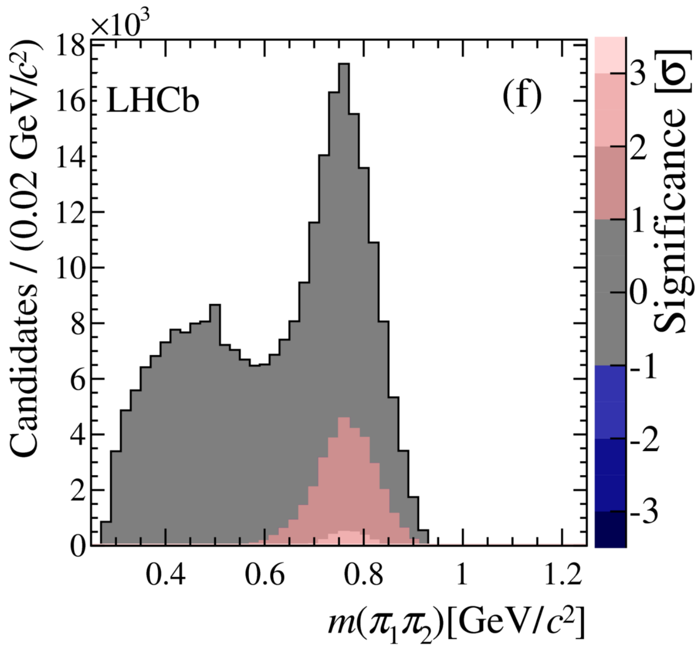
Prospect: direct *CPV* 4-body decays

- 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)]



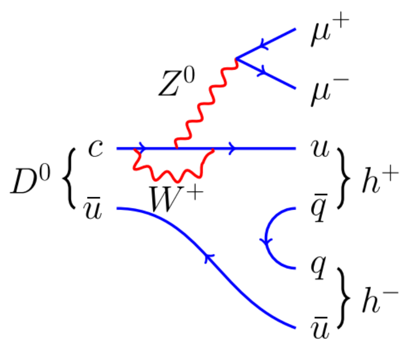
Mode	$A_{CP}^{P-odd}\ [10^{-3}]$	Exp.	Ref.
$\mathrm{D}^+ \to \mathrm{K_S K^+}\pi^+\pi^-$	$-12 \pm 10 \pm 5$	BaBar	PRD 84 031103
$\mathrm{D}^0 \to \mathrm{K^+K^-}\pi^+\pi^-$	$1.8 \pm 2.9 \pm 0.4$	LHCb	JHEP 10 005 (2014)
$\mathrm{D}^0 \to \mathrm{K_S}\pi^+\pi^-\pi^0$	$-0.3 \pm 1.4^{+0.2}_{-0.8}$	Belle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

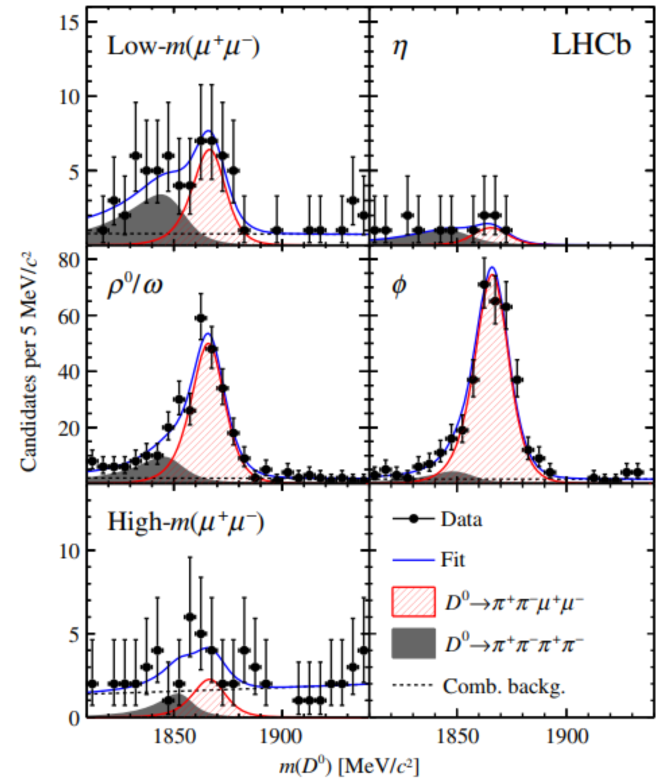
Prospect: *CPV* in rare decays

- 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 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

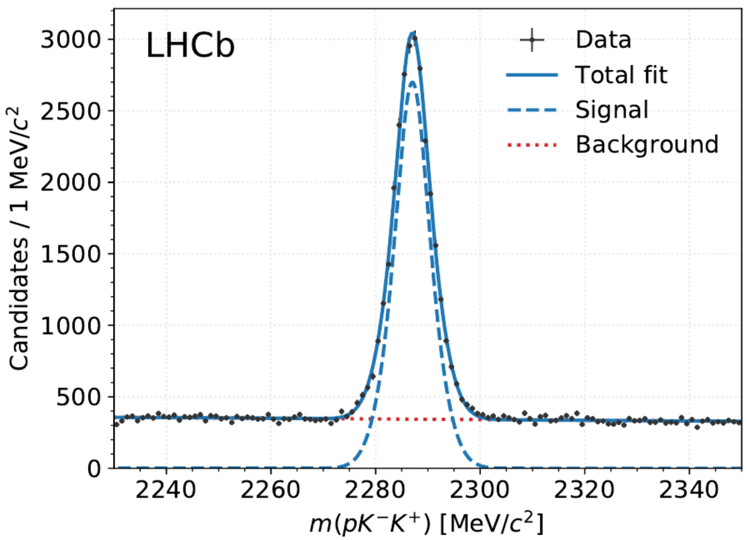
- **SM** amplitudes are less suppressed, lower sensitivity to BSM amplitudes
- Suggested channels: $\Lambda_c \to p\pi^+\pi^-/pK^+K^-,\ \Xi_c^+ \to pK^-\pi^+$

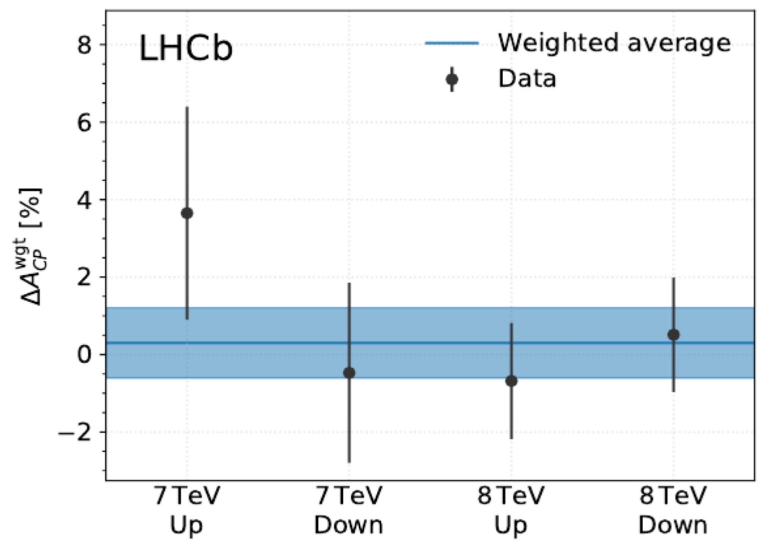
DCS

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

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





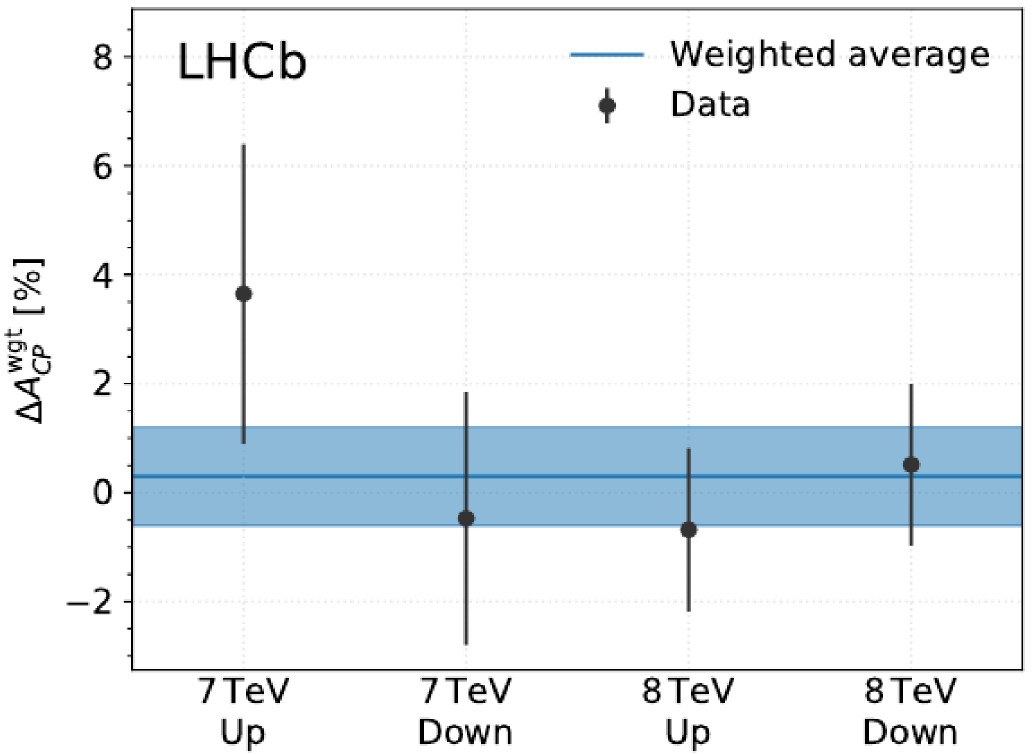
arXiv: 1712.07051

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

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