CPV IN HEAVY-FLAVOUR hadrons at LHCb

6th Symposium on Prospects in the Physics of Discrete Symmetries

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On behalf of the LHCb collaboration

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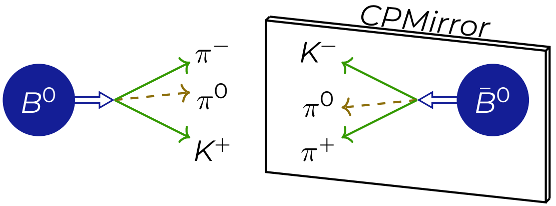
What is *CP* Violation?

C – Charge conjugation

$$Ce_L^- \rightarrow e_L^+$$

P – Parity

$$Pe_L^- \rightarrow e_R^-$$



CP violation distinguishes matter from antimatter

Well established in the Standard Model, but searching also for beyond-SM sources.

Sources of CP violation

$$A_{CP} = \frac{\Gamma(X \to f) - \Gamma(\overline{X} \to \bar{f})}{\Gamma(X \to f) + \Gamma(\overline{X} \to \bar{f})}$$

In first order:

$$A_{CP} = a_{\text{dir}} + a_{\text{mix}} + a_{\text{int}}$$

- CPV in decay
- CPV in mixing
- Interference between mixing and decay

direct CPV
decay-specific

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

indirect, not decay specific,
only neutral mesons

$$p/q = |p/q|e^{i\phi} \neq 1$$

CPV and CKM

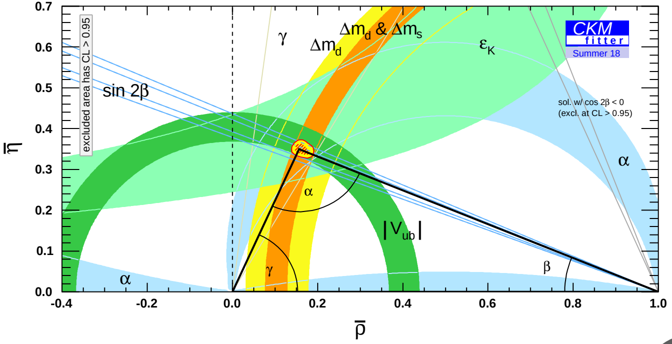
All SM CPV contained in the CKM matrix (complex phase)

Unitarity gives a triangle in the complex plane:

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

Area corresponds to total CPV in SM.

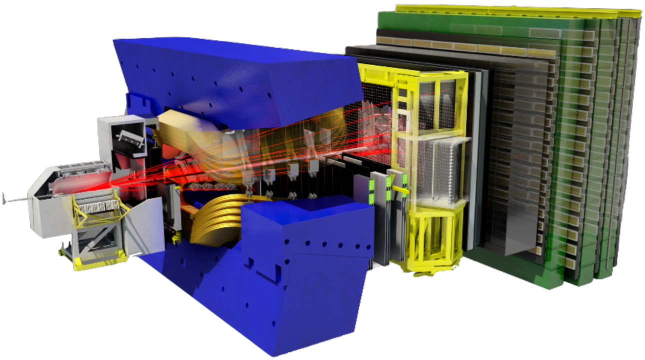
$$\alpha + \beta + \gamma = 180^\circ$$



Any discrepancies would indicate New Physics!

LHCb

JINST 3 (2008) S08005



One-arm spectrometer

Optimised for B and D decays
100k $b\overline{b}$ pairs per second
$\sigma(c\overline{c}) = 20 \times \sigma(b\overline{b})$

Data samples:
Run1: 3fb^{-1}, 7,8 TeV (2011,2012)
Run2: 6fb^{-1}, 13 TeV (2015-2018)
Run3: 25fb^{-1}, (2021-2024)
Run4: 50fb^{-1}, (2027-2030)
Run5: 300fb^{-1},(2031-2034)

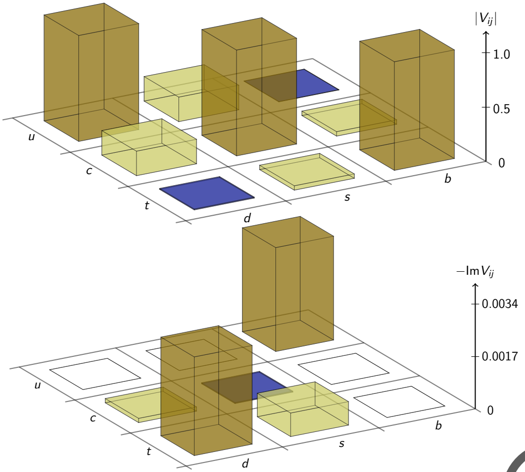
CPV in charm

CPV in charm

Not measured yet

- Unique: probes the up-sector
- ~Only first 2 generations of quarks (b contribution is CKM suppressed)
- Relevant elements almost real

- SM prediction $< \mathcal{O}(10^{-3})$ - high precision needed!
- LHCb: world leading sample of charm hadrons



LHCb publications in charm CPV

Search for CP violation through an amplitude analysis of $D^0 \to K^+K^-\pi^+\pi^-$ decays

subm. JHEP, arXiv:1811.08304

Measurement of the charm-mixing parameter y_{CP}

subm. PRL, arXiv:1810.06874

Measurement of the time-integrated CP asymmetry in $D^0 \to K^0_S K^0_S$ decays

JHEP 11(2018)048

Measurement of angular and CP asymmetries in $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays

PRL 121, 091801 (2018)

A measurement of the CP asymmetry difference in $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays

JHEP 03 (2018) 182

Measurement of the CP violation parameter A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

PRL 118, 261803 (2017)

Updated determination of $D^0 - \overline{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$ decays

PRD 97, 031101 (2018)

AND MORE

Time-integrated measurements

- In first order measure $a^f_{\text{dir}} + a_{ind}$
- Golden mode: $D^0 \rightarrow K^+K^-,\ \pi^+\pi^-$
- Start by measuring ΔA_{CP}: other asymmetries cancel in first order
- LHCb has the world best measurements to date!

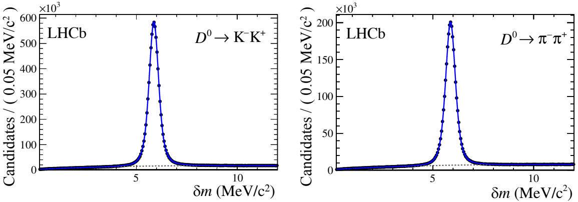
D^{*+} Decays
(pion tag)
PRL 116 (2016) 191601
Run1 data
$7.7 \times 10^6\ (K^+, K^-)$
$2.5 \times 10^6\ (\pi^+, \pi^-)$

semileptonic B decays
(muon tag)
JHEP 07 (2014) 041
Run1 data
$2.1 \times 10^6\ (K^+, K^-)$
773k (π^+, π^-)
measured also single-mode A_{CP}

Time-integrated measurements: ΔA_{CP}

PRL 116 (2016) 191601, JHEP 07 (2014) 041

prompt



$$\Delta A_{CP} = (-0.10 \pm 0.08(stat.) \pm 0.03(syst))\%$$

most precise single-experiment measurement

Still no evidence of CPV...

Expected scaling of stat. unc.:

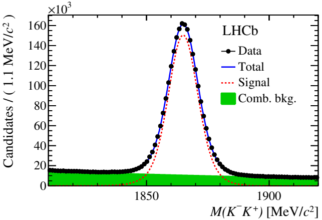
Run 1-2 (9fb^{-1}): 0.03%

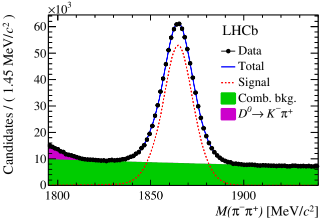
Run 1-5 (300fb^{-1}): 0.003%

LHCB-PUB-2018-009

semileptonic

$$\Delta A_{CP} = (+0.14 \pm 0.16(stat.) \pm 0.08(syst))\%$$





Time-dependent measurements

- Primarily probes indirect CPV
- Measure asymmetry in eff. lifetimes in decays to CP eigenstates
  $D^0 \to K^+K^-, \pi^+\pi^-$
- Measure difference in (eff.) lifetimes of CP and flavour eigenstates
  $D^0 \to K^-\pi^+$

$$A_\Gamma = \frac{\tau_{\overline{D}^0} - \tau_{D^0}}{\tau_{\overline{D}^0} + \tau_{D^0}} \approx -a_{\text{ind}} + \frac{1}{2} a_{\text{dir}} y_{CP}$$

$$y_{CP} = \frac{\tau(D^0 \to \text{flavour eigenstate})}{\tau(D^0 \to CP\,\text{eigenstate})} - 1$$

How to interpret?

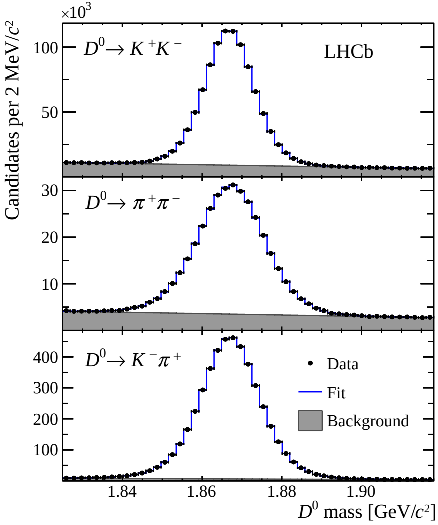
$$A_\Gamma = \frac{1}{2}\left(\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right)$$

$$y_{CP} = \frac{1}{2}\left(\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x\sin\phi\right)$$

- Need also precise measurements of mixing parameters

Time-dependent measurements: y_{CP}

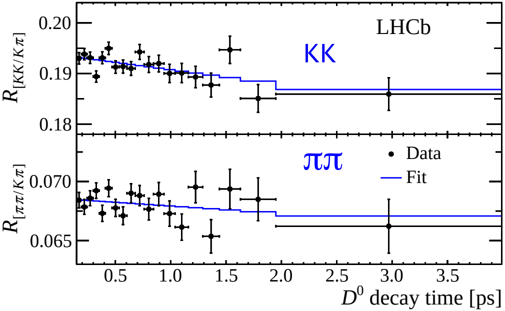
Submitted to PRL, arXiv:1810.06874



- Run1 data, semileptonic tag
- Extract y_{CP} from ratios of decays $D^0 \to K^+K^-(\pi^+\pi^-)$ and $D^0 \to K^-\pi^+$:
- Get ratio of yields in bins of decay time
  - fit to extract $\Delta\Gamma$
  - 878.2k K^+K^-
  - 311.6k $\pi^+\pi^-$
  - 4579.5k $K^-\pi^+$
- Calculate y_{CP} from $\Delta\Gamma$ and W.A. value of $\Gamma = 2.4284\ \text{ps}^{-1}$

Time-dependent measurements: y_{CP}

Submitted to PRL, arXiv:1810.06874



Decay	Δ_Γ [ps^{-1}]	y_{CP} [%]
$D^0 \to K^+K^-$	$0.0153 \pm 0.0036 \pm 0.0027$	$0.63 \pm 0.15 \pm 0.11$
$D^0 \to \pi^+\pi^-$	$0.0093 \pm 0.0067 \pm 0.0038$	$0.38 \pm 0.28 \pm 0.15$

- KK: best precision from single experiment.
- Combined: $y_{CP} = (0.57 \pm 0.13(stat.) \pm 0.09(syst.))\%$
  - As precise as the world-average value!
- Consistent with W.A. value and with no CPV

CPV in B sector

CPV in *B* sector

Everything we have mentioned so far, and more...

CP violation in *B* mesons confirmed since 2001.

Main interest today:
New physics
Measuring also other parameters, like CKM angles

LHCb publications on CPV in B sector

Search for CP violation in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays
PLB 787 (2018) 124-133

Measurement of CP asymmetries in two-body $B^0_{(s)}$-meson decays to charged pions and kaons
PRD 98, 032004 (2018)

Measurement of the CKM angle γ using $B^\pm \to DK^\pm$ with $D \to K^0_S\pi^+\pi^-, K^0_S K^+K^-$ decays
JHEP 08 (2018) 176

Search for CP violation using triple product asymmetries in $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$ and $\Xi_b^0 \to pK^-K^-\pi^+$ decays
JHEP 08 (2018) 039

Measurement of CP violation in $B^0 \to D^\mp\pi^\pm$ decays
JHEP 06 (2018) 084

Measurement of CP asymmetry in $B^0_s \to D_s^\mp K^\pm$ decays
JHEP 03 (2018) 059

Measurement of the CP asymmetry in $B^- \to D_s^- D^0$ and $B^- \to D^- D^0$ decays
JHEP 05 (2018) 160

AND MORE

B to charm: measuring CKM angle γ

Measurements of γ

- γ is the phase between $V_{ud}V^*_{ub}$ and $V_{cd}V^*_{cb}$.
- Theoretically very clean: $\delta\gamma/\gamma = \mathcal{O}(10^{-7})$
- Excellent New Physics probe!
- Experimentally more challenging: from tree level $B \to DX$ decays
- LHCb contribution is substantial:

World average	LHCb combination	Pre-LHCb
$\gamma = (73.5^{+4.2}_{-5.1})^\circ$	$\gamma = (74.0^{+5.0}_{-5.8})^\circ$	$\gamma = (73^{+22}_{-25})^\circ$

LHCb-CONF-2018-002

- Precision predictions:
  - End of Run 3 $\sim 1.5^\circ$ uncertainty ($\sim 23\ fb^{-1}$)
  - End of Run 4 $\sim 0.9^\circ$ uncertainty ($\sim 50\ fb^{-1}$)
  - End of Run 5 $\sim 0.3^\circ$ uncertainty ($\sim 300\ fb^{-1}$)

Many methods and techniques

$D^0 \rightarrow$ CP eigenstates

GLW

e.g. KK, $\pi\pi$
very sensitive but
multiple solutions

$D^0 \rightarrow$ multi body

GGSZ

e.g. $K^0_S\pi\pi$ golden mode

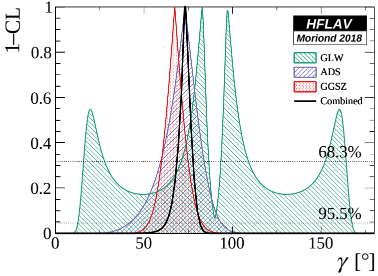
$D^0 \rightarrow$ flavour specific

ADS

e.g. $K\pi$
more susceptible
to systematics

time-dependant

e.g. $B^0_s \rightarrow D^-_s K^+$
interf. mix., dec.



$B^0 \rightarrow$ multibody

Dalitz

e.g. $B^0 \rightarrow D^0K^+\pi^-$
will become important

GGSZ: $D^0 \to K_S^0\pi\pi, KK$

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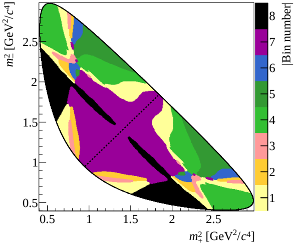
- GGSZ observable:

$$d\Gamma_{B^\pm}(x) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}[x_\pm c_i + y_\pm s_i)]$$

- Single solution, excellent sensitivity from interference between various contributions.

$$x_\pm = r_B \cos(\delta_B \pm \gamma) \qquad c_i = \cos(\delta_{D_{(\pm,\mp)}})$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma) \qquad s_i = \sin(\delta_{D_{(\pm,\mp)}})$$



- 2fb^{-1} at 13 TeV
  - Method: model-independent fit of the Dalitz plot in bins.
  - Bins from CLEO-c, minimised δ_D variation; c_i, s_i given.
  - Compare D Dalitz plot distribution for B^+, B^-.

GGSZ: $D^0 \to K^0_S\pi\pi, KK$

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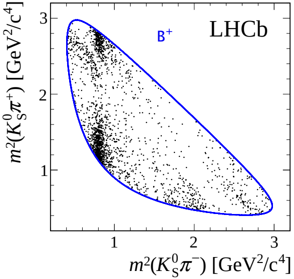
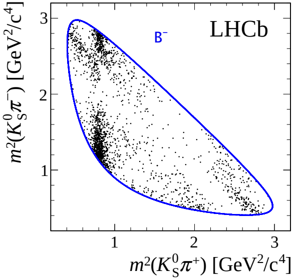
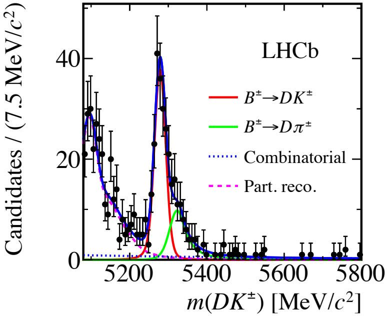
- B^+, B^- yields in bin i : $f(N_{tot}, F_i, c_i, s_i, x_{+(-)}, y_{+(-)})$
- Simultaneous fit for both B charges, D decay modes (and K^0_S categories)







- Yields: 3900 $K^0_S\pi\pi$ and 530 $K^0_S KK$

GGSZ: $D^0 \to K^0_S\pi\pi, KK$

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$$x_- = (\ \ 9.0 \pm 1.7 \pm 0.7 \pm 0.4) \times 10^{-2},$$
$$y_- = (\ \ 2.1 \pm 2.2 \pm 0.5 \pm 1.1) \times 10^{-2},$$
$$x_+ = (-7.7 \pm 1.9 \pm 0.7 \pm 0.4) \times 10^{-2},$$
$$y_+ = (-1.0 \pm 1.9 \pm 0.4 \pm 0.9) \times 10^{-2},$$

- CP violation: $(x_+, y_+) \neq (x_-, y_-)$: 6.4σ deviation!
- First observation of CPV in $B^\pm \to DK^\pm$, $D \to K^0_S h^+ h^-$.
- Fit $x_\pm, y_\pm$ to obtain γ, r_B, δ_B:

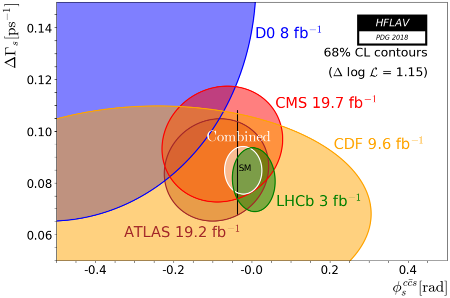
$$\gamma = 87^\circ\,{}^{+11^\circ}_{-12^\circ}\left({}^{+22^\circ}_{-23^\circ}\right),$$
$$r_B = 0.086\,{}^{+0.013}_{-0.014}\left({}^{+0.025}_{-0.027}\right),$$
$$\delta_B = 101^\circ\,{}^{+11^\circ}_{-11^\circ}\left({}^{+22^\circ}_{-23^\circ}\right).$$

- Most precise γ measurement from a single analysis
- Can combine result with previous LHCb analysis (Run1)

Charmless $B_{(s)}$: measuring ϕ_s

ϕ_s

- B_s unitarity triangle: $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$
- ϕ_s = phase diff. between amplitudes decaying to CP eigenstates and those that do after mixing
- SM: $\phi_s^{c\bar{c}} \approx -2\beta_s$
- Recent first evidence of CPV in $B_s \to K^+K^-$! PRD 98 (2018) 032004
- Golden mode: $B_s \to J/\psi\phi$ measured by CDF, D0, ATLAS, CMS



- LHCb taking it further: $B_s \to J/\psi KK$, $B_s \to \psi(2S)\phi$, $B_s \to J/\psi\pi\pi$, $B_s \to D_sD_s$
- LHCb $B_s \to J/\psi KK$ dominates the world-average. PRL 114, 041801 (2015)
- LHCb also measured $\phi_s^{s\bar{s}}$ in $B_s \to \phi\phi$ PRD 90, 052011 (2014), LHCb-CONF-2018-001

$\phi_s^{d\overline{d}} : B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

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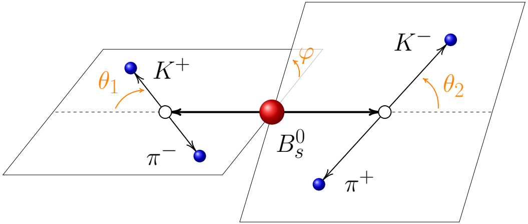
- 3fb^{-1}, 7 and 8 TeV
- First measurement of $\phi_s^{d\overline{d}}$
- 9 quasi-two-body states are considered; CPV effects assumed to be same for all, and CPV in mixing is neglected
- $\phi_s^{d\overline{d}} = \phi_M - 2\phi_D$ expected small in SM
- ϕ_M = $B_s - \overline{B}_s$ mixing phase, ϕ_D = CPV weak phase in decay



$\phi_s^{dd}: B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

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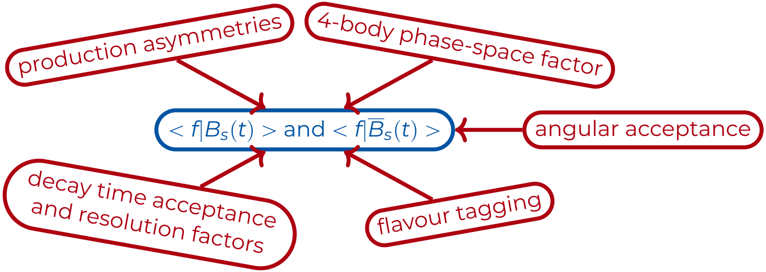
- Fit to 4-body invariant mass; obtain signal weights through *sPlot* to perform the CP fit on a sample representing only signal.



- Extremely complex fit

$\phi_s^{dd} : B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

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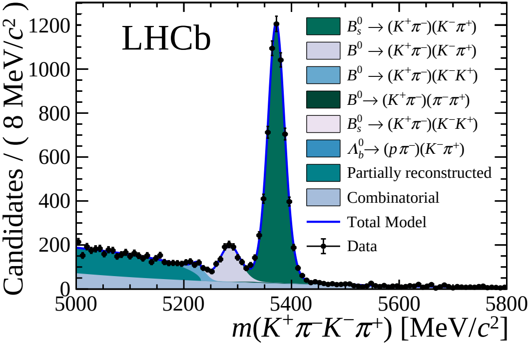

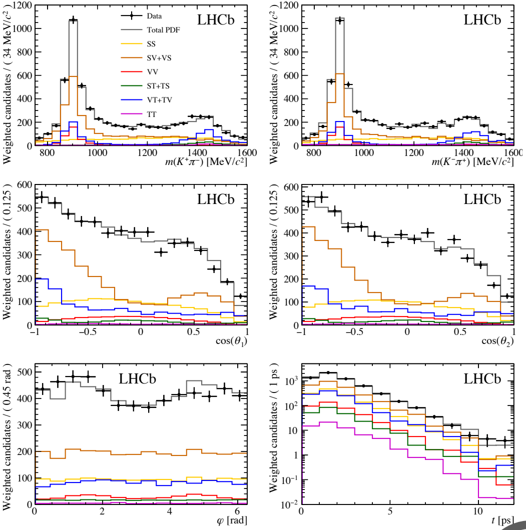

$\phi_s^{d\bar{d}} = -0.10 \pm 0.13 \pm 0.14$

consistent with SM

CP violation in baryons

- First evidence of CPV in baryons:

  LHCb, $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$ 3.3σ

  Nature Physics 13, 391-396 (2017)

- In general expected CPV in baryons to be of similar levels as in mesons

Triple product asymmetries

- T-violation + CPT conservation -> CP violation
- Construct a triple-product C_T, odd under T-reversal
- Complementary dependence on the strong phase difference than decay rate asymmetries
- Largely insensitive to production and detection asymmetries

$$A_T = \frac{\Gamma(X, C_T > 0) - \Gamma(X, C_T < 0)}{\Gamma(X, C_T > 0) + \Gamma(X, C_T < 0)}$$

$$\overline{A}_T = \frac{\Gamma(\overline{X}, -C_T > 0) - \Gamma(\overline{X}, -C_T < 0)}{\Gamma(\overline{X}, -C_T > 0) + \Gamma(\overline{X}, -C_T < 0)}$$

- The CP-violating observable:

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

T-odd asymmetries: $\Lambda_b^0 \to pK^-h^+h^-, \Xi_b^0 \to pK^-K^-\pi^+$

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- Rich resonant structure enhances sensitivity to CPV
- T-odd observable:

$$\begin{aligned} C_T &= \mathbf{p}_p(\mathbf{p}_{h_1} \times \mathbf{p}_{h_2}) \\ h_{1,2} &= K^-\pi^+ \quad (\Lambda_b^0 \to pK^-\pi^+\pi^-) \\ h_{1,2} &= K^-_{\text{fast}}K^+ \quad (\Lambda_b^0 \to pK^-K^+K^-) \\ h_{1,2} &= K^-_{\text{fast}}\pi^+ \quad (\Xi_b^0 \to pK^-K^-\pi^+) \end{aligned}$$

- Simultaneous fit to $m(pKhh)$ to 4 samples for each mode.
- 9877 ± 195 $(\Lambda_b^0 \to pK^-\pi^+\pi^-)$
- 5297 ± 83 $(\Lambda_b^0 \to pK^-K^+K^-)$
- 709 ± 45 $(\Xi_b^0 \to pK^-K^-\pi^+)$

T-odd asymmetries: $\Lambda_b^0 \to pK^-h^+h^-, \Xi_b^0 \to pK^-K^-\pi^+$

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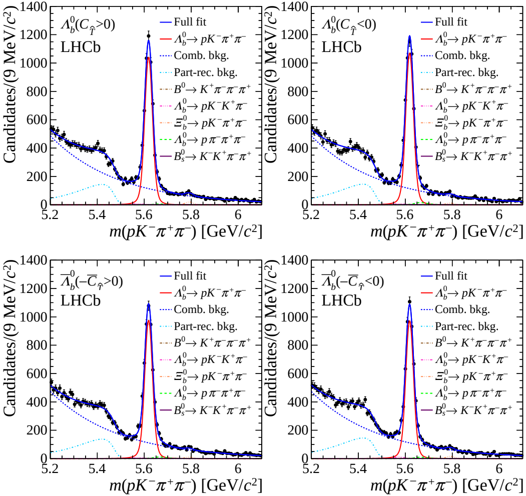

	$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to pK^-K^+K^-$	$\Xi_b^0 \to pK^-K^-\pi^+$
$a_P^{\widehat{T}\text{-odd}}$ (%)	$-0.60 \pm 0.84 \pm 0.31$	$-1.56 \pm 1.51 \pm 0.32$	$-3.04 \pm 5.19 \pm 0.36$
$a_CP^{\widehat{T}\text{-odd}}$ (%)	$-0.81 \pm 0.84 \pm 0.31$	$1.12 \pm 1.51 \pm 0.32$	$-3.58 \pm 5.19 \pm 0.36$

- CP asymmetries may vary over phase-space due to interference between resonant contributions
- Repeat analysis in specific phase-space regions with different binning schemes. No CPV observed

Summary

CHARM

CPV not measured yet!
Approaching SM sensitivity
Many LHCb results still only with Run1!
Main issue: huge statistics, controlling systematics...

B SECTOR

Not probing only CPV directly, but also other parameters: CKM angles
Searches for New Physics
Extremely rich field

BARYONS

Still largely unexplored
Expected similar CPV levels as in mesons

LHCb is an invaluable player in the CPV field