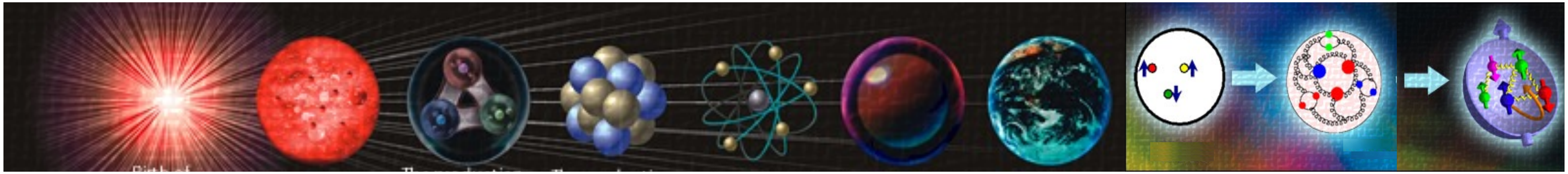


Recent CPV results at LHCb(eauty)

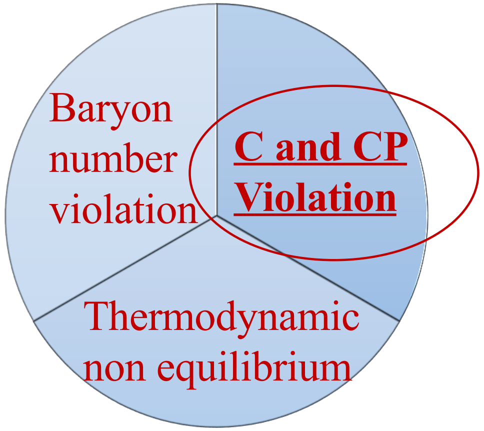
Yanxi ZHANG/张艳席
Peking University/北京大学

13/Nov./2021

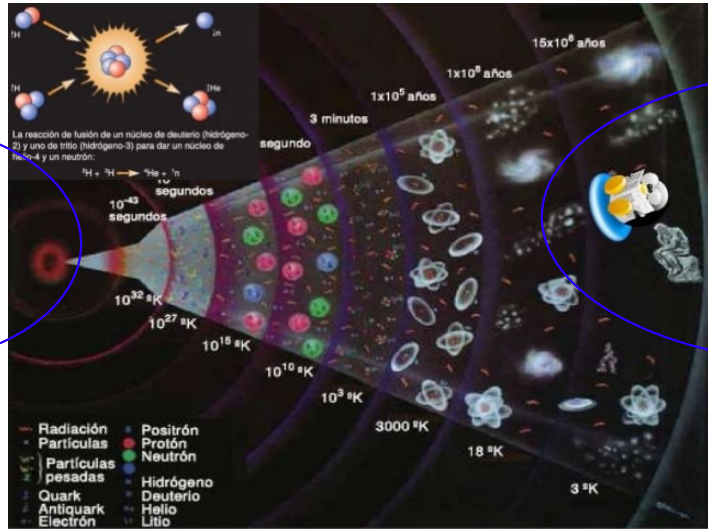
第18届重味物理和CP破坏研讨会
暨南大学 2021年11月10-14

CP violation

- Baryogenesis: Sakharov conditions



Matter = Antimatter



$\frac{\text{Matter}}{\text{Antimatter}} - 1 \sim 10^{-10}$

- CKM mechanism

Quark eigenstates interacting with H different from eigenstates interacting with W bosons

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

- More than three quarks?
- Sole source of CPV?

If only three generations of quarks:

- ✓ Unitary in 3×3
- ✓ 3 rotation angles
- ✓ 1 phase, giving CPV

Over constrain (3×3) CKM (unitarity) with extensive independent measurements

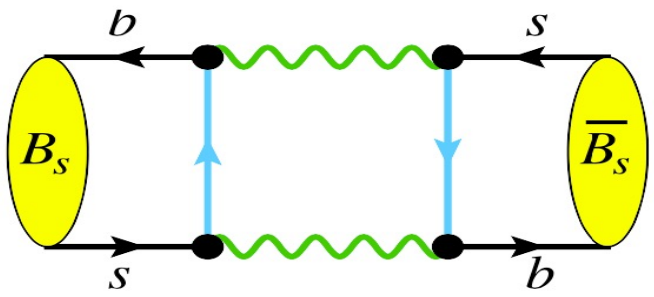
Actually CKM insufficient to explain baryon asymmetry in Universe, search for new CPV

Three types of CPV

- Mixing

$$\mathcal{P}(\bar{B}_s^0 \to B_s^0) \neq \mathcal{P}(B_s^0 \to \bar{B}_s^0)$$

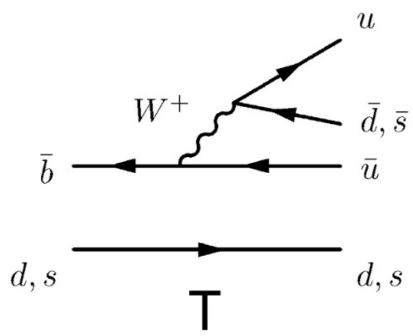
Off shell $\mathrm{Arg}(M_{12}) \neq \mathrm{Arg}(\Gamma_{12})$ On shell

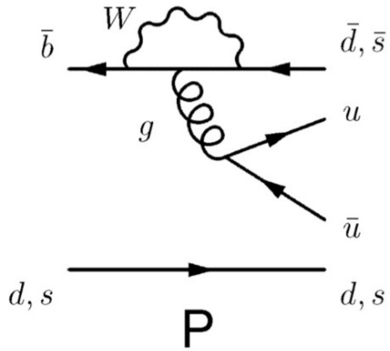


- Decay

$$\mathcal{P}(B \to f) \neq \mathcal{P}(\bar{B} \to \bar{f})$$

At least two interfering amplitudes with different strong and different weak phases

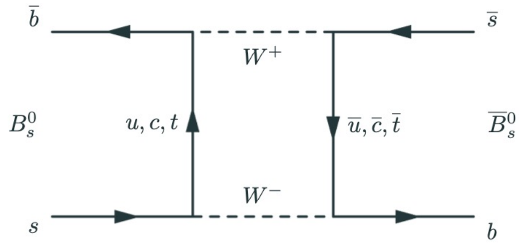




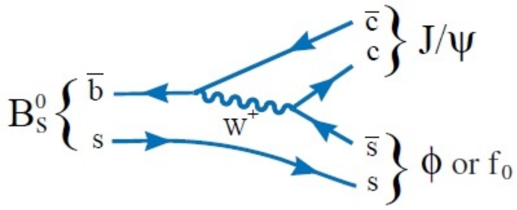
- Mixing and decay

$$\mathcal{P}(B \to \bar{B} \to f) \neq \mathcal{P}(\bar{B} \to B \to \bar{f})$$

Different weak phases in mixing and decay



$\propto (V_{tb}^* V_{ts})^2$



$\propto V_{cb}^* V_{cs}$

Constraining CKM matrix elements in SM and probing NP

Mixing and CPV

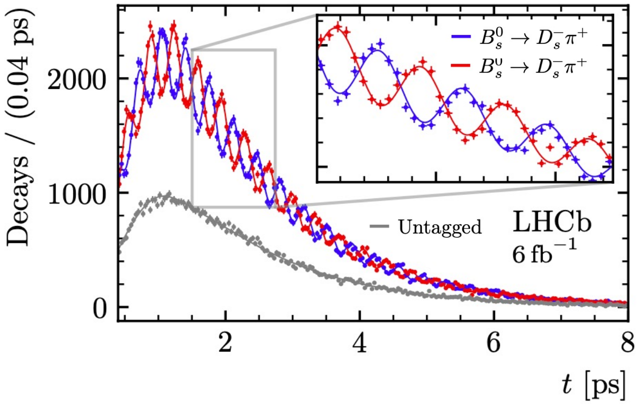
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

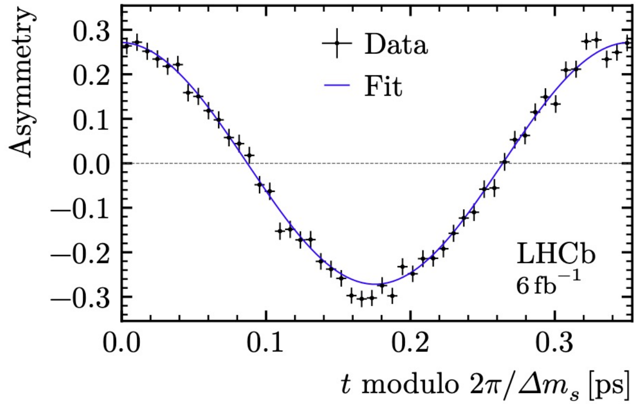
ΔM_s of $B_s^0 - \bar{B}_s^0$ oscillation

Time dependent rate of flavor specific decays

$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cdot\cos(\boxed{\Delta m_s}t)\right] \qquad C = \begin{cases} -1 & \text{if mixing occurs} \\ 1 & \text{if not mixed} \end{cases}$$

Degraded by initial b-flavor tagging: $\epsilon(1-\omega)^2 \sim 6\%$

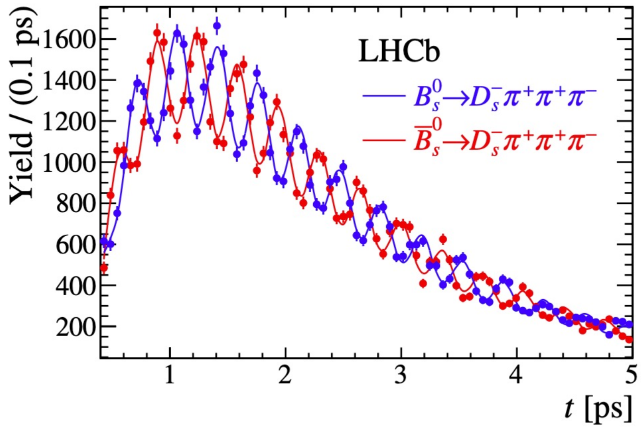


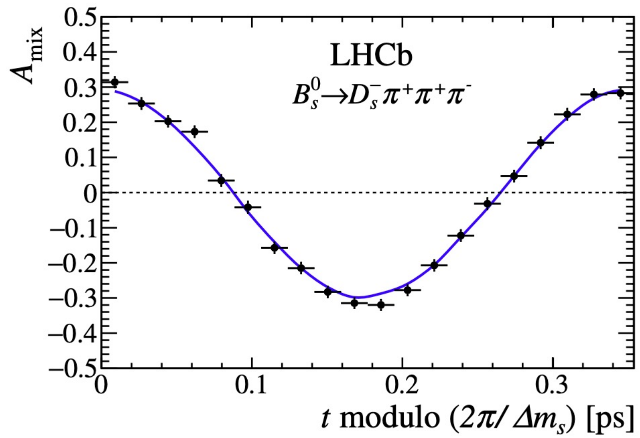


$B_s \to D_s^{\pm}\pi^{\mp}$

Giving most precise single measurement

arXiv:2104.04421





$B_s \to D_s^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$

JHEP 03 (2021) 137

LHCb average: $\Delta M_s = 17.7656 \pm 0.0057\ \text{ps}^{-1}$

Lattice and sum rule Prediction: $18.4^{+0.7}_{-1.2}\ \text{ps}^{-1}$

B_s^0 mixing angle $\phi_s = -2\beta_s^{\text{eff}}$

- ϕ_s sensitive to new physics, SM prediction: $\phi_s = -37 \pm 1$ mrad

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

- Time dependent CP asymmetry:

$$A_{\text{CP}}(t) = \frac{\Gamma_{\bar{B}_s^0 \to f}(t) - \Gamma_{B_s^0 \to f}(t)}{\Gamma_{\bar{B}_s^0 \to f}(t) + \Gamma_{B_s^0 \to f}(t)} \propto -\eta_f \sin\phi_s \sin(\Delta M_s t)$$

f: common final state

- LHCb combination of five measurements

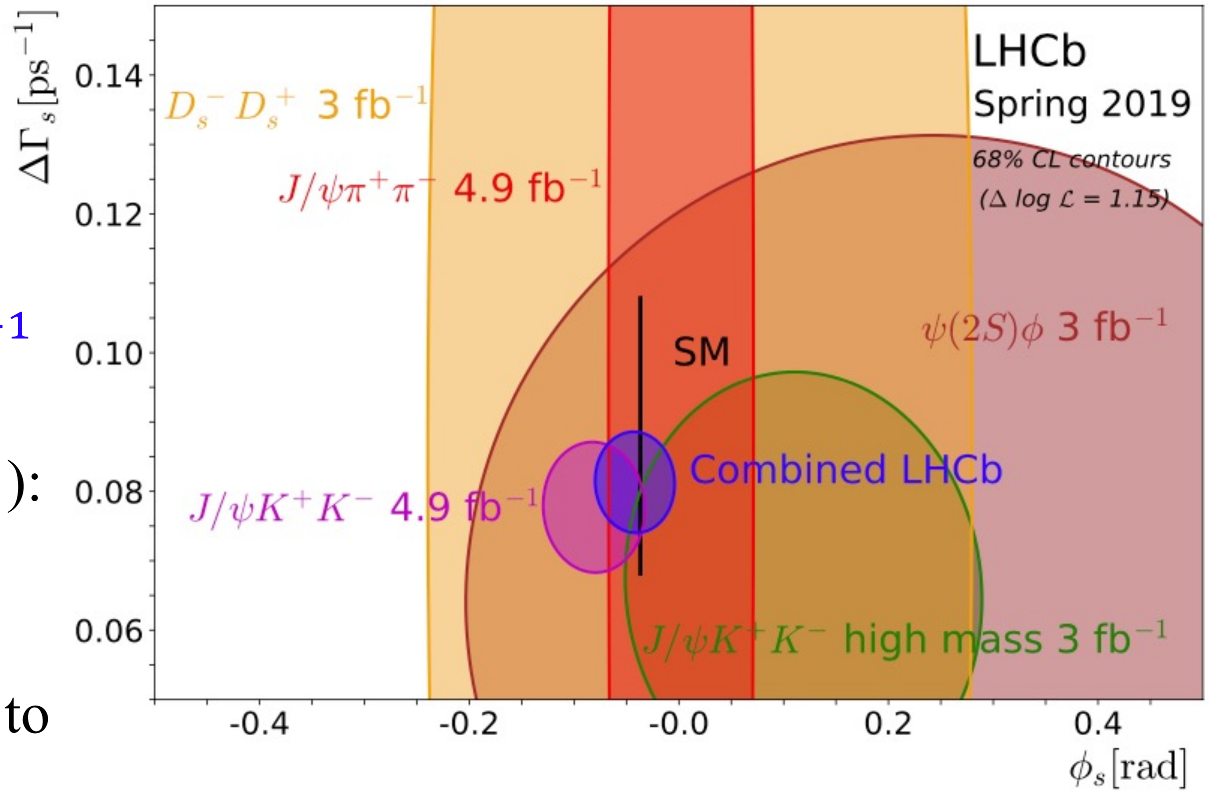
$\phi_s = -42 \pm 25$ mrad
$\Delta\Gamma_s = 0.0813 \pm 0.0048\ \text{ps}^{-1}$

New world average (PDG 2021):

$\phi_s = -50 \pm 19$ mrad

Consistent with SM, but need to gain experimental precision

EPJC 79 (2019) 706



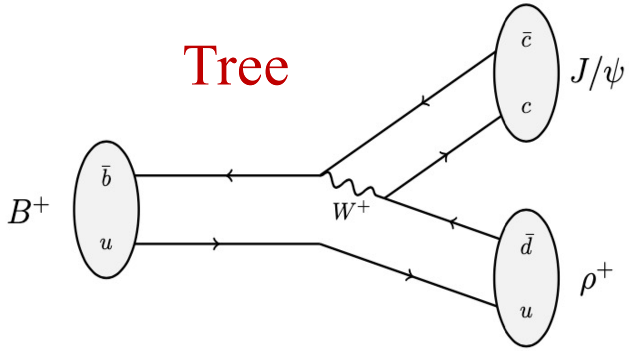
Control of penguin pollution

EPJC 79 (2019) 537

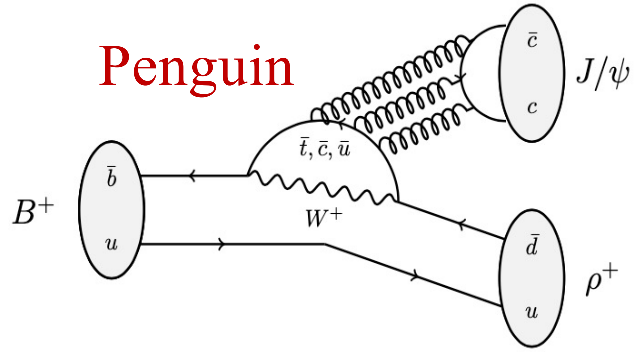
- Uncertainty on ϕ_s from penguin diagram: $\phi_s \rightarrow \phi_s + \Delta\phi^P$
- Magnitude of penguin evaluated using A_{CP} of $B^+ \rightarrow J/\psi\rho^+$ decays

$A_{\text{CP}} \propto |\mathcal{A}_P/\mathcal{A}_T|$

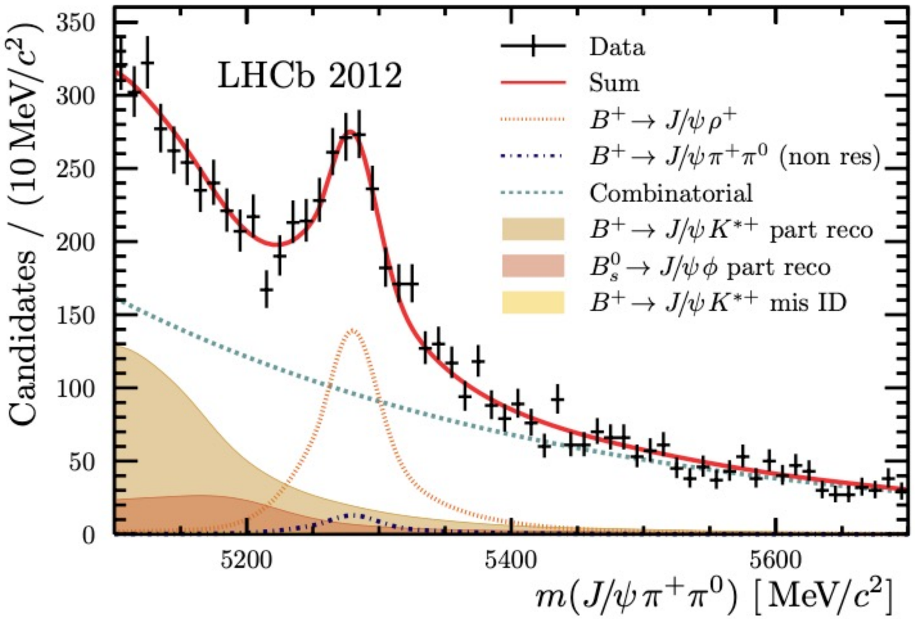
Tree



Penguin



Counting signals from mass spectrum



$$A_{\text{CP}} = -0.045^{+0.056}_{-0.057} \pm 0.008$$

Compatible with $A_{\text{CP}}(B^0 \rightarrow J/\psi\rho^0)$
No evidence of CPV

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

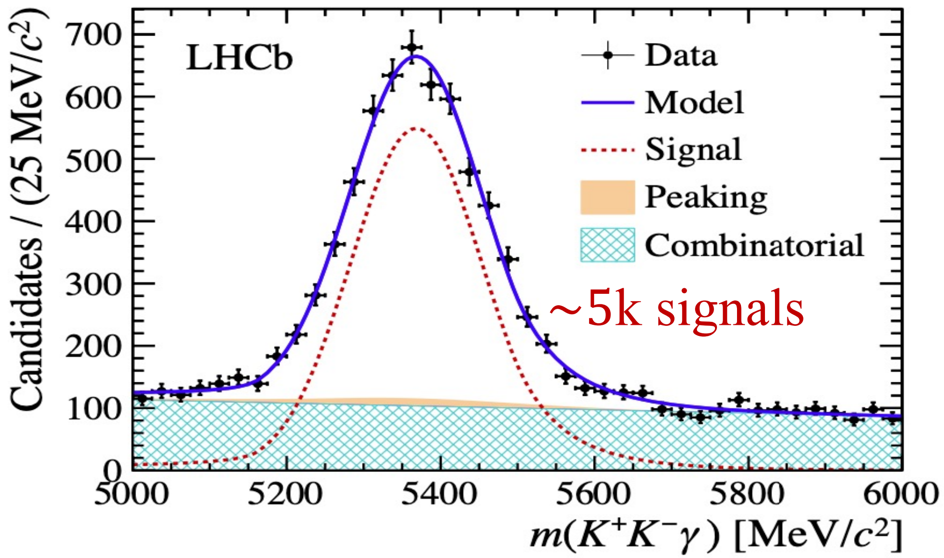
PRL 123 (2019) 081802

- γ dominantly left handed, right-handed component $\propto m_s/m_b$
- Time dependent decay rate:

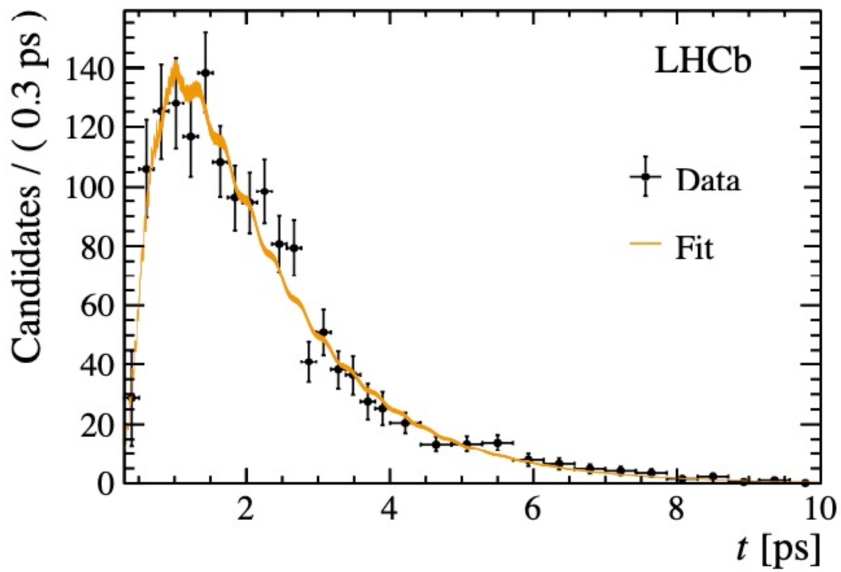
$$\mathcal{P}_{\pm} \propto e^{-\Gamma_s t}\left[\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2) \pm C\cos(\Delta M_s t) \mp S\sin(\Delta M_s t)\right]$$

$\mathcal{A}^{\Delta}, C, S$ sensitive to photon helicity, almost 0 in SM , may be modified by NP

Mass distribution



Decay time distribution



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

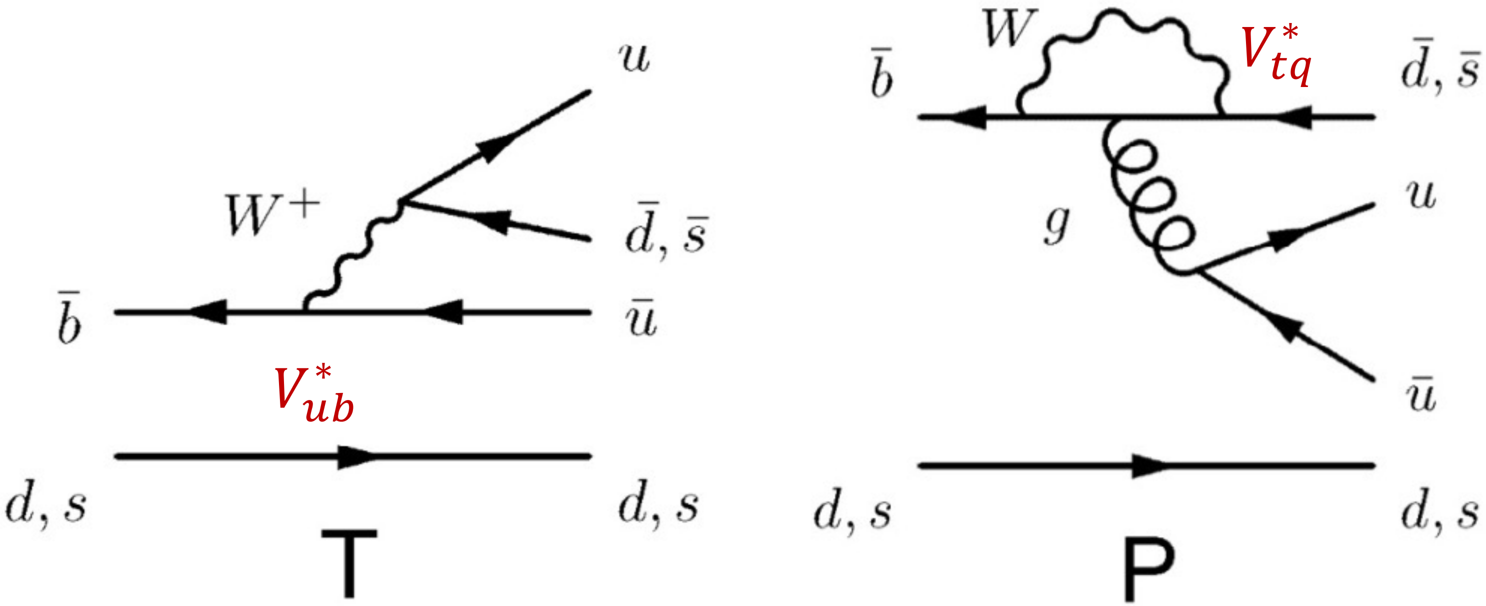
No evidence of CPV
Compatible with SM within 1.9σ

CPV in charmless decays

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Charmless b-hadron decays

- Mediated by $b \to u$ tree and $b \to d(s)$ penguin diagrams with comparable magnitude and large weak phases → expecting direct CPV



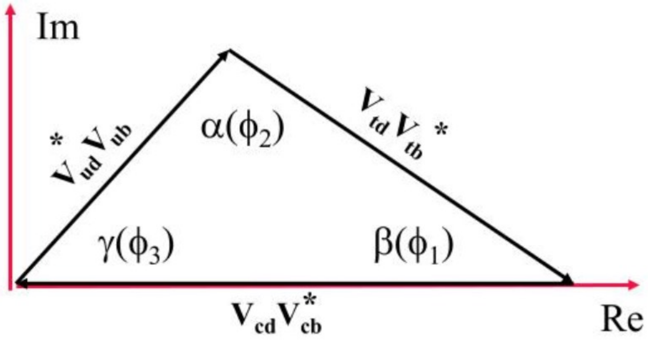
$$V_{\mathrm{CKM}} = \begin{array}{ccc} & & V_{ub}^{*} \\ \multicolumn{3}{c}{\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}} \\ V_{td}^{*} & V_{ts}^{*} & \end{array} + \mathcal{O}(\lambda^4)$$

CPV in $B^0 \to \pi^+\pi^-$ decays

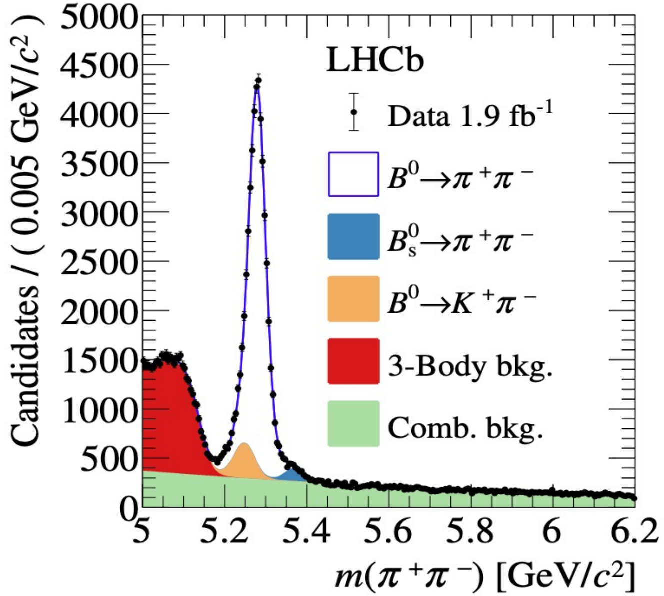
JHEP 03 (2021) 075

- Input to $\alpha(\phi_2)$ angle measurement
- Time dependent asymmetry

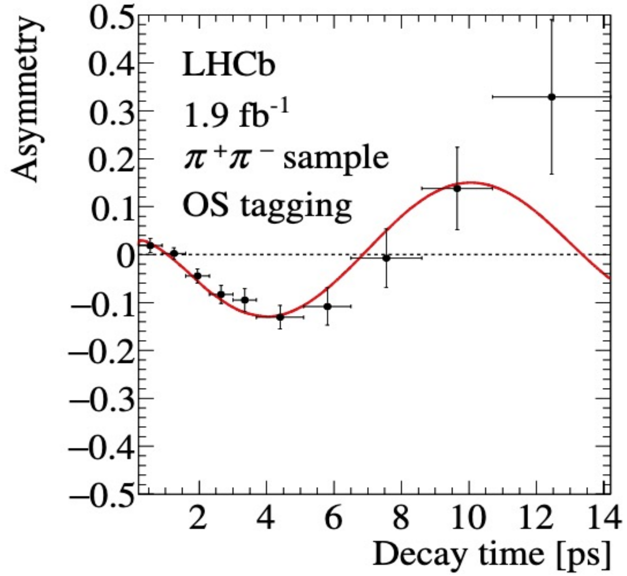
$$A_{\mathrm{CP}}(t) = \frac{-C_f \cos(\Delta M t) + S_f \sin(\Delta M t)}{\cosh(\Delta\Gamma t/2) + A_f^{\Delta\Gamma} \sinh(\Delta\Gamma t/2)}$$



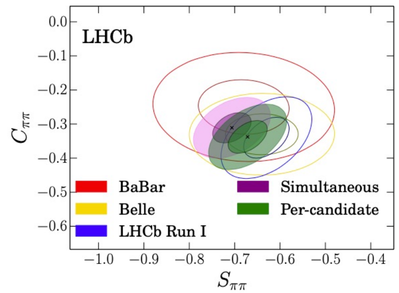
Mass distribution



Time dependent asymmetry



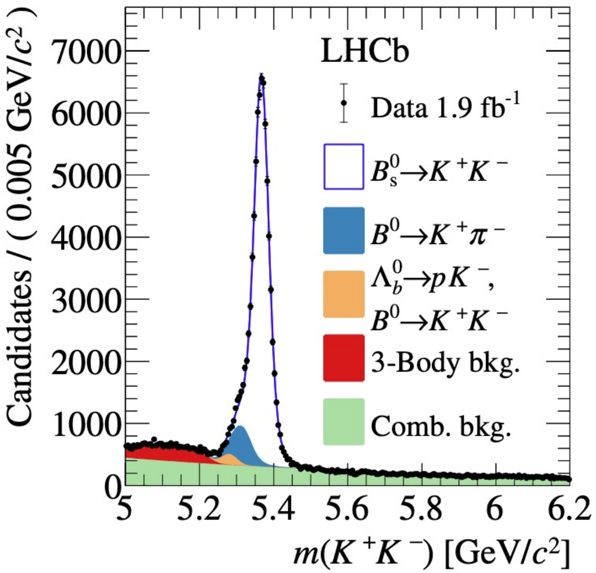
$$C_{\pi^+\pi^-} = -0.311 \pm 0.045 \pm 0.15$$
$$S_{\pi^+\pi^-} = -0.706 \pm 0.042 \pm 0.13$$



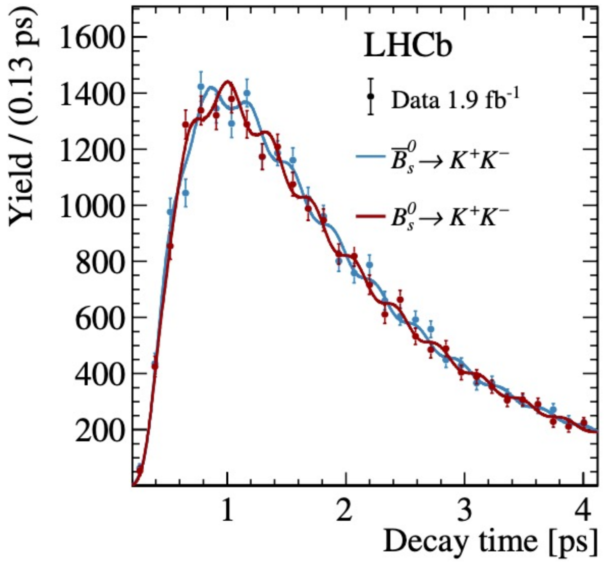
Consistent with previous measurements

CPV in $B_s^0 \to K^+K^-$ decays

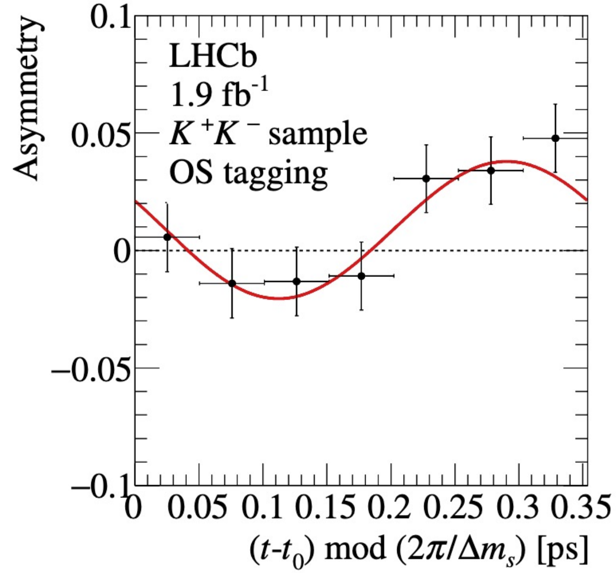
Mass distribution



Decay time distribution



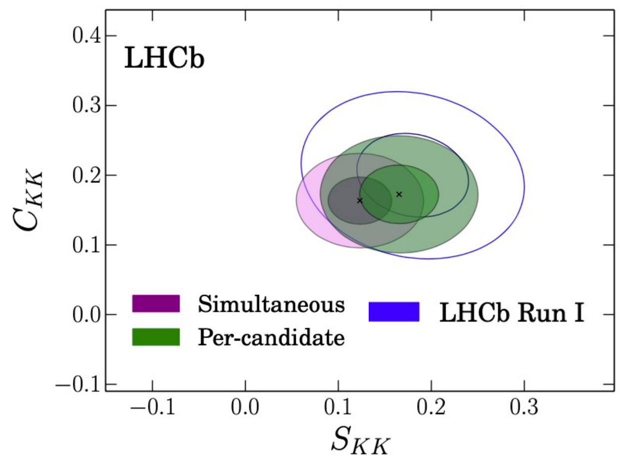
Time dependent asymmetry



$$C_{K^+K^-} = 0.164 \pm 0.034 \pm 0.14$$
$$S_{K^+K^-} = 0.123 \pm 0.034 \pm 0.15$$
$$A_{KK}^{\Delta\Gamma} = -0.83 \pm 0.05 \pm 0.09$$

$$\sqrt{C_{K^+K^-}^2 + S_{K^+K^-}^2 + \left(A_{KK}^{\Delta\Gamma}\right)^2} = 0.93 \pm 0.08$$

Consistent with Run I results



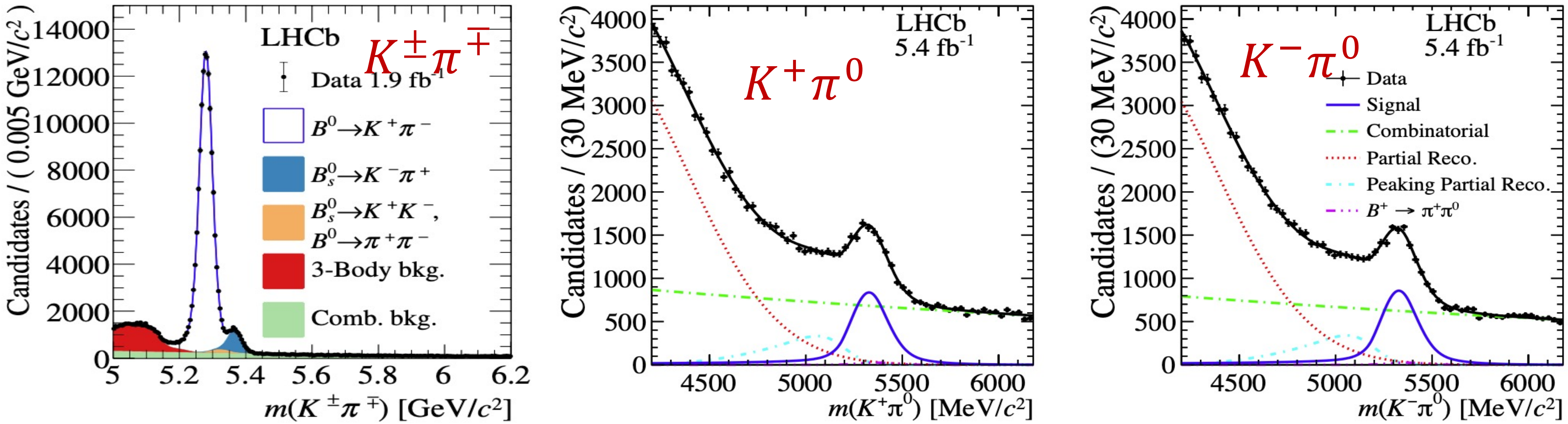
Direct CPV in $B \to K\pi$ system

JHEP 03 (2021) 075
PRL 126 (2021) 091802

- Isospin symmetry implies $A_{\mathrm{CP}}(B^0 \to K^+\pi^-) \approx A_{\mathrm{CP}}(B^+ \to K^+\pi^0)$

  Experiment: $\Delta A_{\mathrm{CP}}^{K\pi} \neq 0$ at 5.5σ so called "$K\pi$" puzzle

- New measurements



$$A_{\mathrm{CP}}(B^+ \to K^+\pi^0) = +0.025 \pm 0.015 \pm 0.006 \pm 0.003$$
$$A_{\mathrm{CP}}(B^0 \to K^+\pi^-) = -0.0824 \pm 0.0033 \pm 0.0033$$

New value of $\Delta A_{\mathrm{CP}}^{K\pi} = 0.115 \pm 0.014$, nonzero at $> 8\sigma$

Measurement of $A_{\mathrm{CP}}(B_s^0 \to K^-\pi^+) = 0.236 \pm 0.013 \pm 0.011$

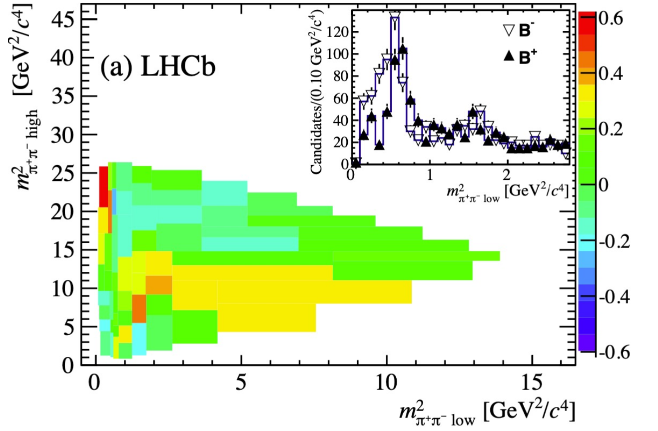
$$\Delta \equiv \frac{A_{\mathrm{CP}}(B^0 \to K^+\pi^-)}{A_{\mathrm{CP}}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B \to K^+\pi^-)}\frac{\Gamma_s}{\Gamma_d} = -0.085 \pm 0.043,$$ nonzero at 2σ

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

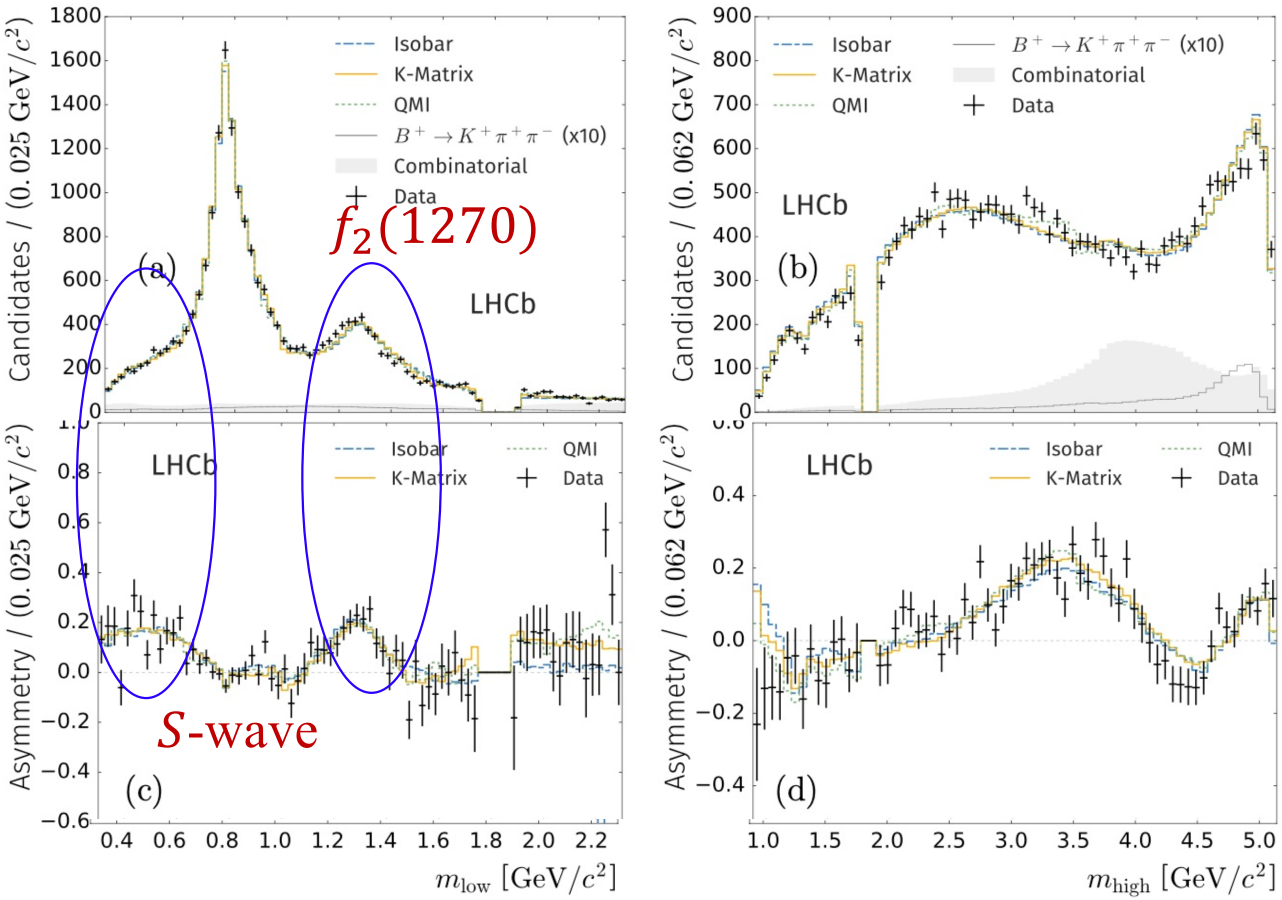
PRL 124 (2020) 031081
PRD 101 (2020) 012006

- CPV observed in phase space of $B \to hhh$ decays, better understanding with Dalitz plot analysis

$$A^{\pm}(m_{13}^2, m_{23}^2) = \sum_{j=1}^{N} c_j^{\pm} F_j(m_{13}^2, m_{23}^2)$$



Mass projections and CP



Components and quasi-two-body A_{CP}

Component	Isobar
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 0.6 \pm 1.5$
$\omega(782)$	$-4.8 \pm 6.5 \pm 1.3 \pm 3.5$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 1.5 \pm 4.4$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 3.6 \pm 35.7$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 7.8 \pm 24.1$
S-wave	$+14.4 \pm 1.8 \pm 1.0 \pm 1.9$

$S - P$ wave interference

PRL 124 (2020) 031081
PRD 101 (2020) 012006

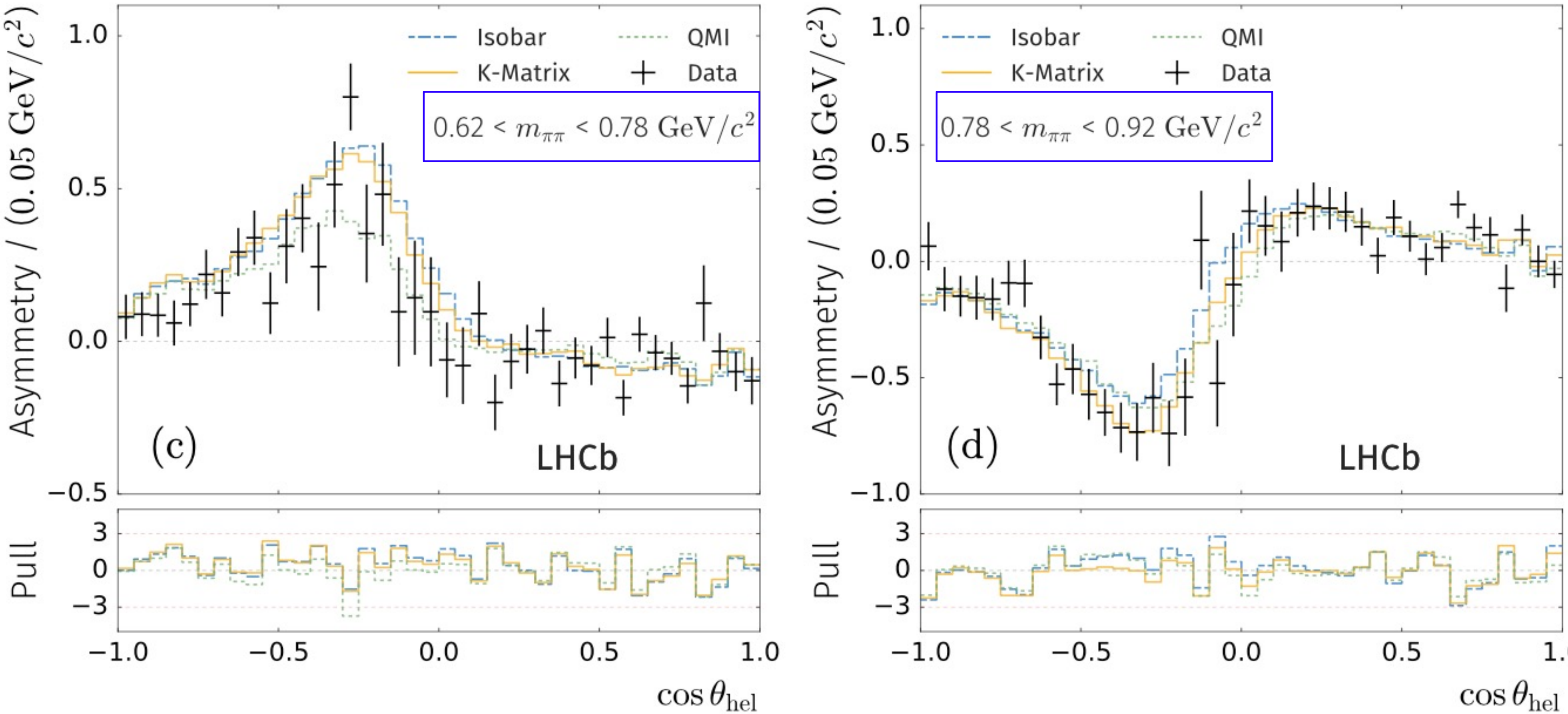
- Evaluation of strong phase in Breit-Wigner with energy $\sqrt{s}$

$$A_{\mathrm{CP}} \propto \cos\theta \times (m_S^2 - S) \times (m_P^2 - S) + \cdots$$

A_{CP} in bins of helicity angle

Below $\rho(770)^0$ mass

Above $\rho(770)^0$ mass



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

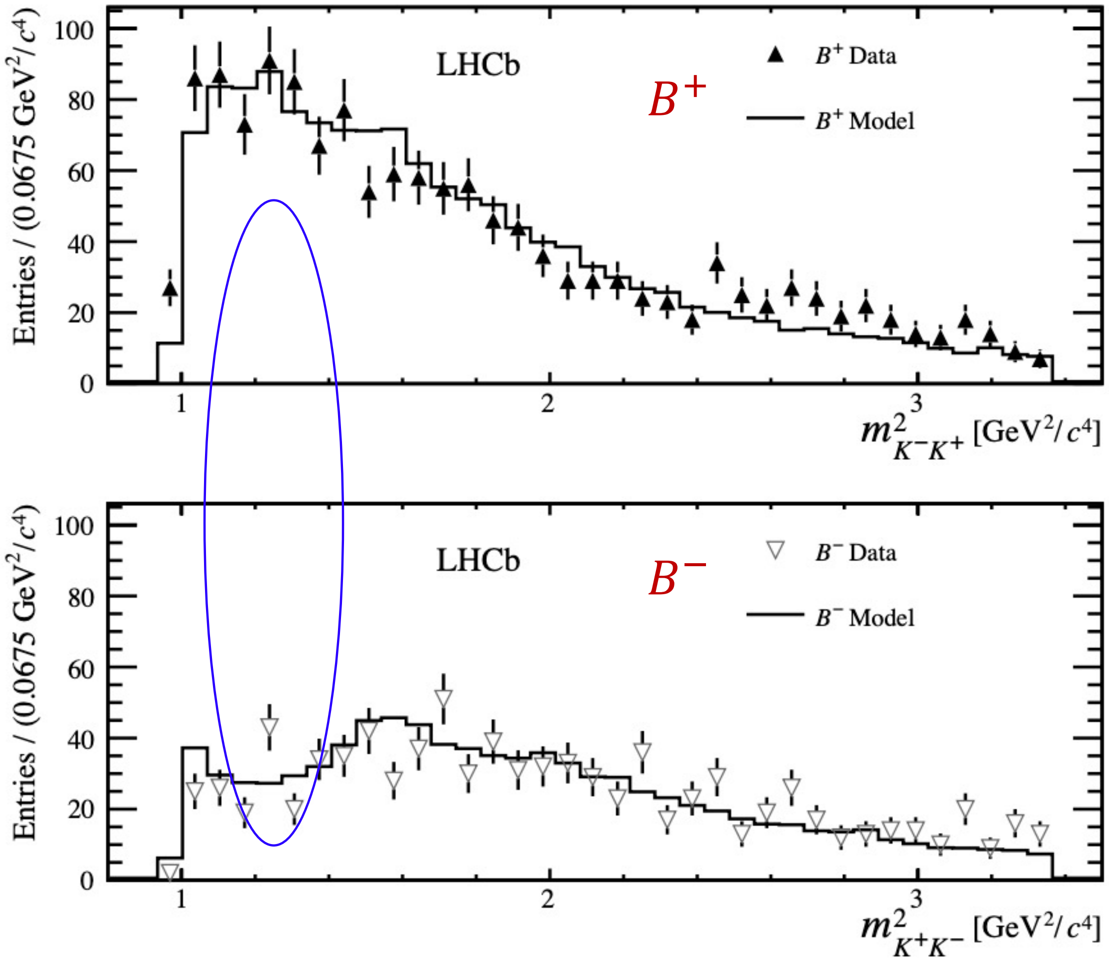
PRL 123 (2019) 231802

- Amplitude model: large S-wave contribution, modeled by non-resonant single pole and $\pi^+\pi^- \to K^+K^-$ rescattering

Large asymmetry observed for rescattering in region $0.95 < m_{K^+K^-} < 1.42$ GeV

Mass and fit projections

$A_{CP} = (-66 \pm 4 \pm 2)\%$



Quasi-two-body A_{CP}

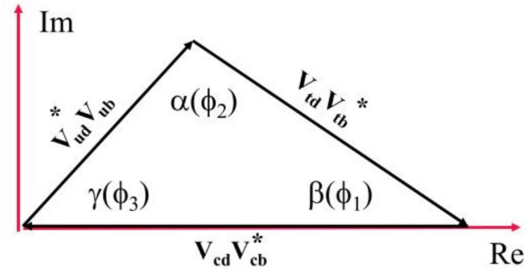
Contribution	Fit Fraction(%)	A_{CP}(%)
$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$
$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$
Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$
$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$
$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$
Rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$

Measurement of $\gamma(\phi_3)$ angle

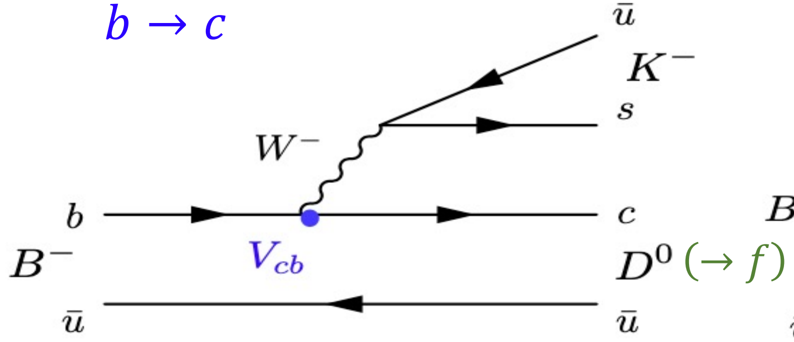
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Measurement of γ angle

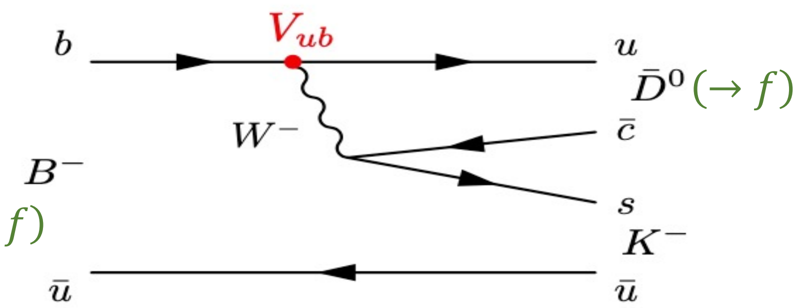
- $\gamma = \arg\left[-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right]$ measured via interference of $b \to c$ and $b \to u$ tree-level diagrams



$b \to c$



$b \to u$



V_{cb} favored, $\mathcal{A}_c \propto r_D e^{-i\delta_D}$ V_{ub} suppressed, $\mathcal{A}_u \propto r_B e^{-i\gamma + i\delta_B}$

Decay rates: $\Gamma(B^\pm \to f h^\pm) \propto r_D^2 + r_B^2 + 2 r_B r_D \cos(\delta_B + \delta_D \pm \gamma)$ giving direct A_{CP}

- D decay final state:

GLW: $f = KK, \pi\pi$ etc, CP eigenstates
PLB 253 (1991) 483, PLB 265 (1991) 172

GGSZ: $f = K_s\pi\pi$ etc, self-conjugate multi-body PRD 68 (2003) 054018

ADS: $f = K\pi, K3\pi$ etc, quasi-flavor-specific sates PRL 78 (1997) 3257

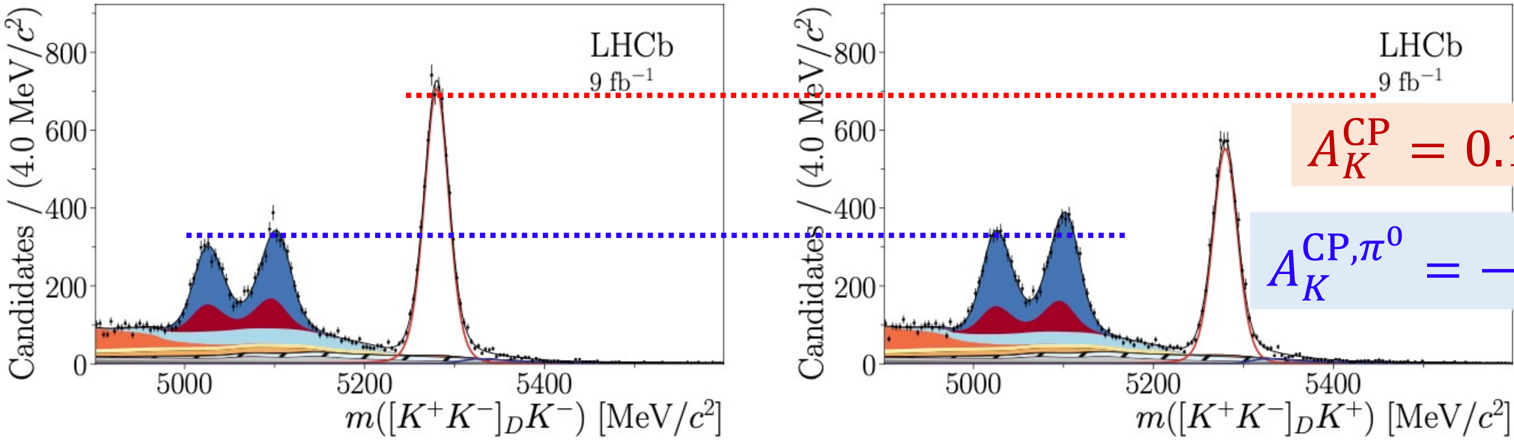
…

Two-body D decays

JHEP 04 (2021) 081

- $B \to DK, D\pi$ and partially reconstructed $B \to D^*K, D^*\pi$ decays

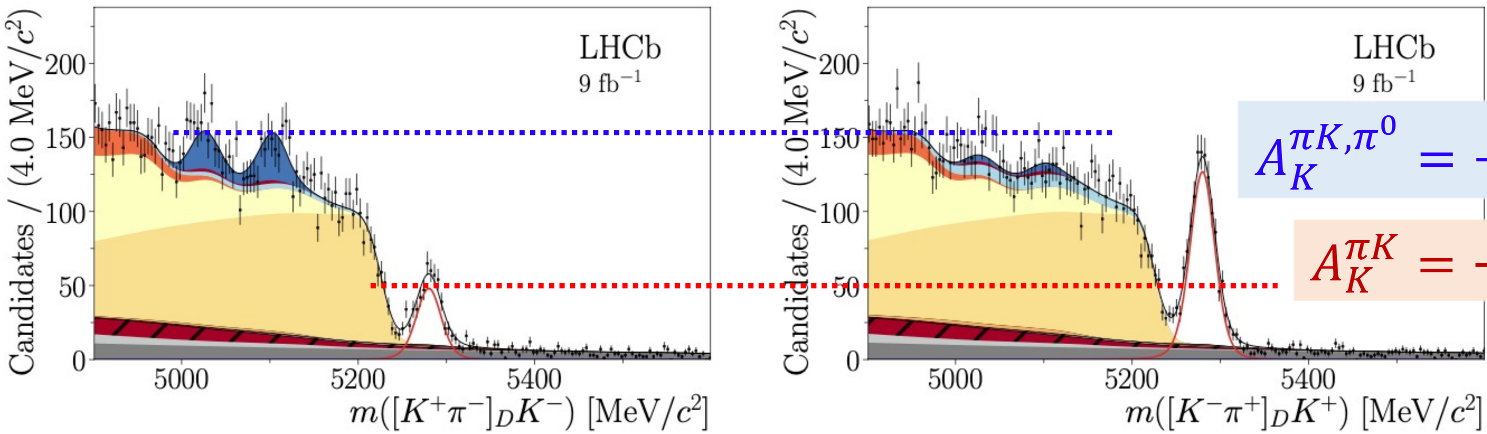
$B^\pm \to [K^-K^+]_D K^\pm$, CP eigenstate of D



$A_K^{\mathrm{CP}} = 0.136 \pm 0.009$

$A_K^{\mathrm{CP},\pi^0} = -0.115 \pm 0.021$

$B^\pm \to [K^\pm\pi^\pm]_D K^\pm$, doubly Cabibbo suppressed decay of D



$A_K^{\pi K,\pi^0} = +0.717 \pm 0.286$

$A_K^{\pi K} = -0.451 \pm 0.026$

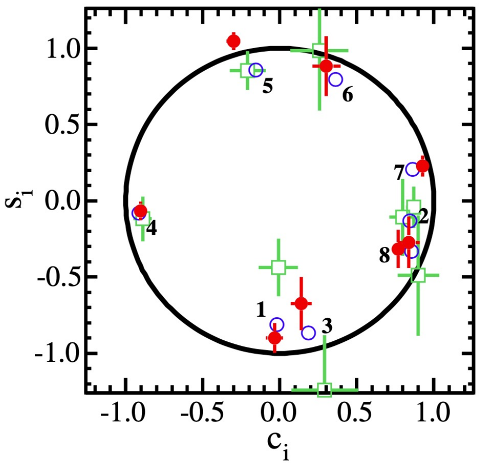
Three-body D decays

JHEP 02 (2021) 169

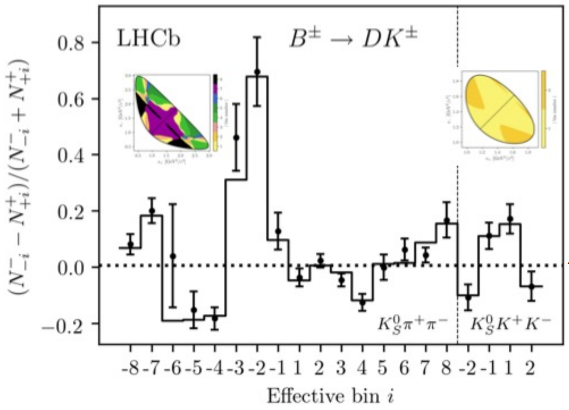
- $B^\pm \to DK^\pm,\ D \to K_s h^+ h^-$, interference between D^0 and $\overline{D}^0$ at each Dalitz point

$$A_B\left(m^2_{K_s h^+}, m^2_{K_s h^-}\right) = A_D\left(m^2_{K_s h^+}, m^2_{K_s h^-}\right) + r_B e^{i(\delta_B - \gamma)} A_{\overline{D}}\left(m^2_{K_s h^-}, m^2_{K_s h^+}\right)$$

External inputs for D interference: CLEO-c, BESIII



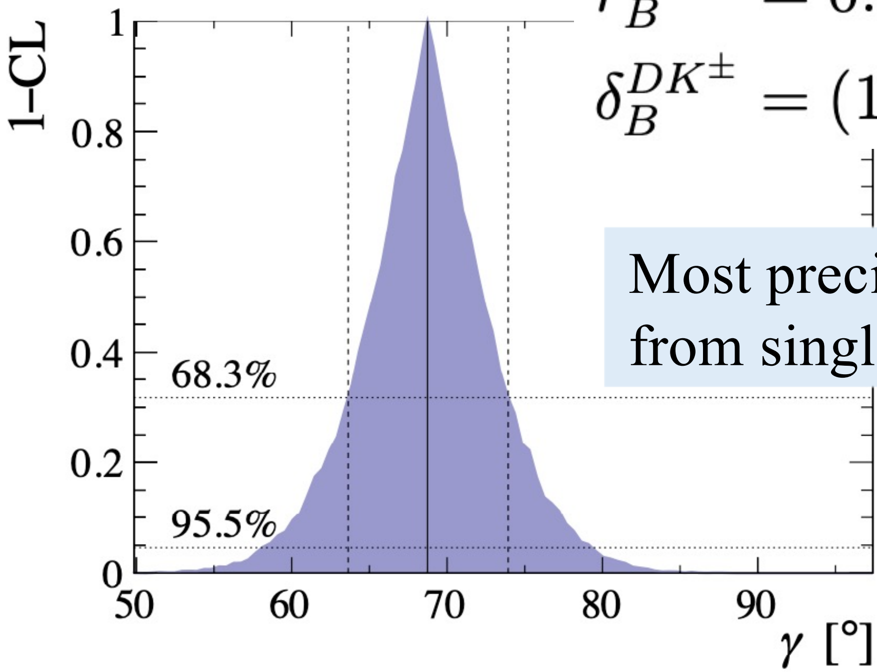
PRD101 (2020) 112002
PRD102 (2020) 052008



Asymmetry in Dalitz bins

If no CPV

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ,$$
$$r_B^{DK^\pm} = 0.0904^{+0.0077}_{-0.0075},$$
$$\delta_B^{DK^\pm} = (118.3^{+5.5}_{-5.6})^\circ,$$



Most precise value of γ from single analysis

γ from $B_s^0 \to D_s^- K^+ \pi^+ \pi^-$ decays

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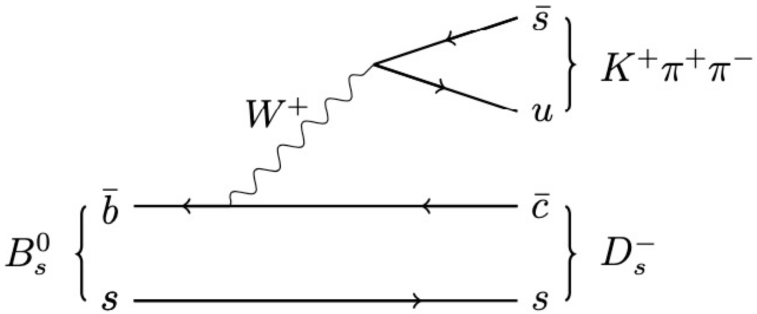
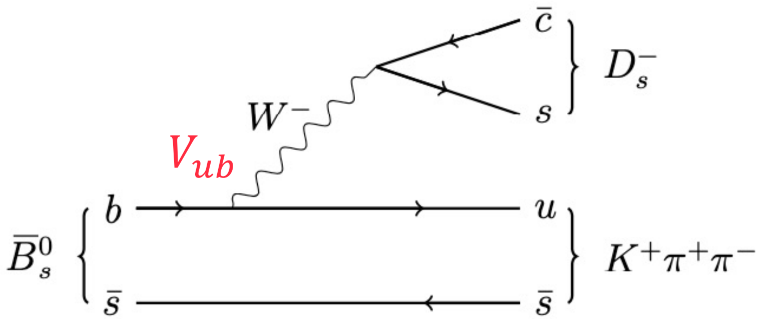
- Interference between direct and oscillated B_s^0 decays

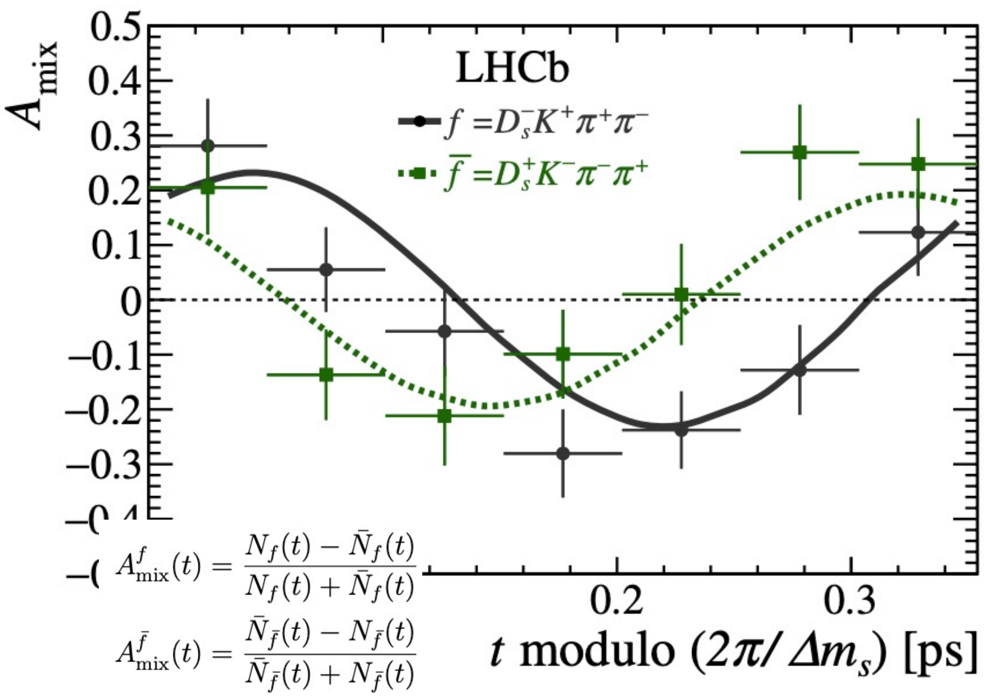




$\mathcal{A}(B_s^0 \to f) \propto V_{cb}^* V_{us}$

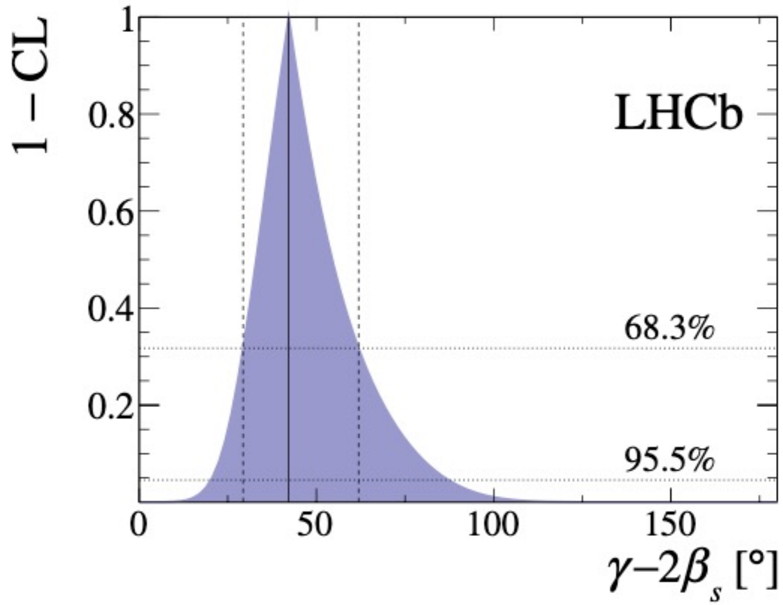
$\mathcal{A}(B_s^0 \to \bar{B}_s^0 \to f) \propto e^{2\beta_s} \times V_{cs}^* V_{ub}$

- Time dependent asymmetry



$$A_{\rm mix}^f(t) = \frac{N_f(t) - \bar{N}_f(t)}{N_f(t) + \bar{N}_f(t)}$$

$$A_{\rm mix}^{\bar{f}}(t) = \frac{\bar{N}_{\bar{f}}(t) - N_{\bar{f}}(t)}{\bar{N}_{\bar{f}}(t) + N_{\bar{f}}(t)}$$



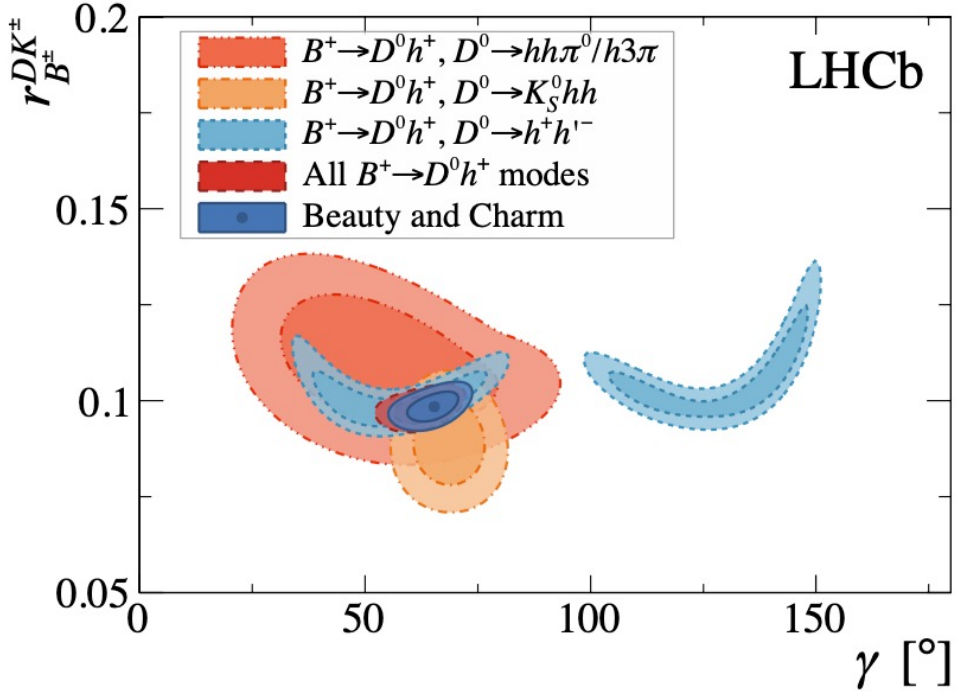
$\gamma - 2\beta_s = 42 \pm 10 \pm 4 \pm 5°$

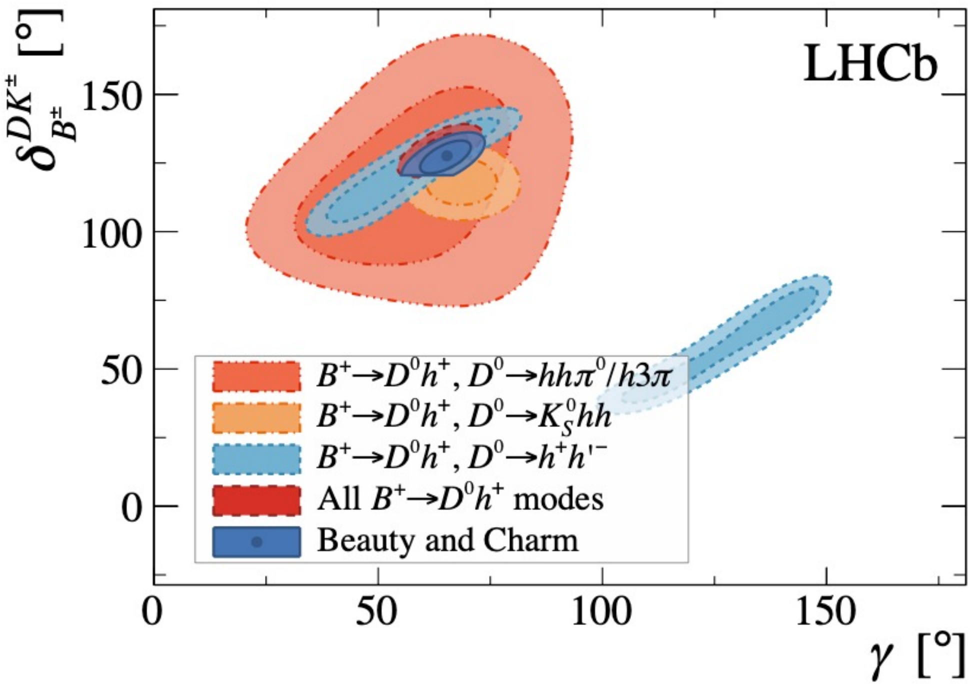
LHCb γ combination

arXiv:2110.02350

- Combine measurements from more than 20 $B \to Dh^{(*)}$ analysis

$\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$, becomes closer to global fitter $(65.7^{+0.9}_{-2.7})^{\circ}$





$r_B^{DK^\pm} = 0.0984^{+0.0027}_{-0.0026}$

$\delta_B^{DK^\pm} = (127.6^{+4.0}_{-4.2})^{\circ}$

CPV in beauty baryons

A new terrain for CPV and CKM matrix

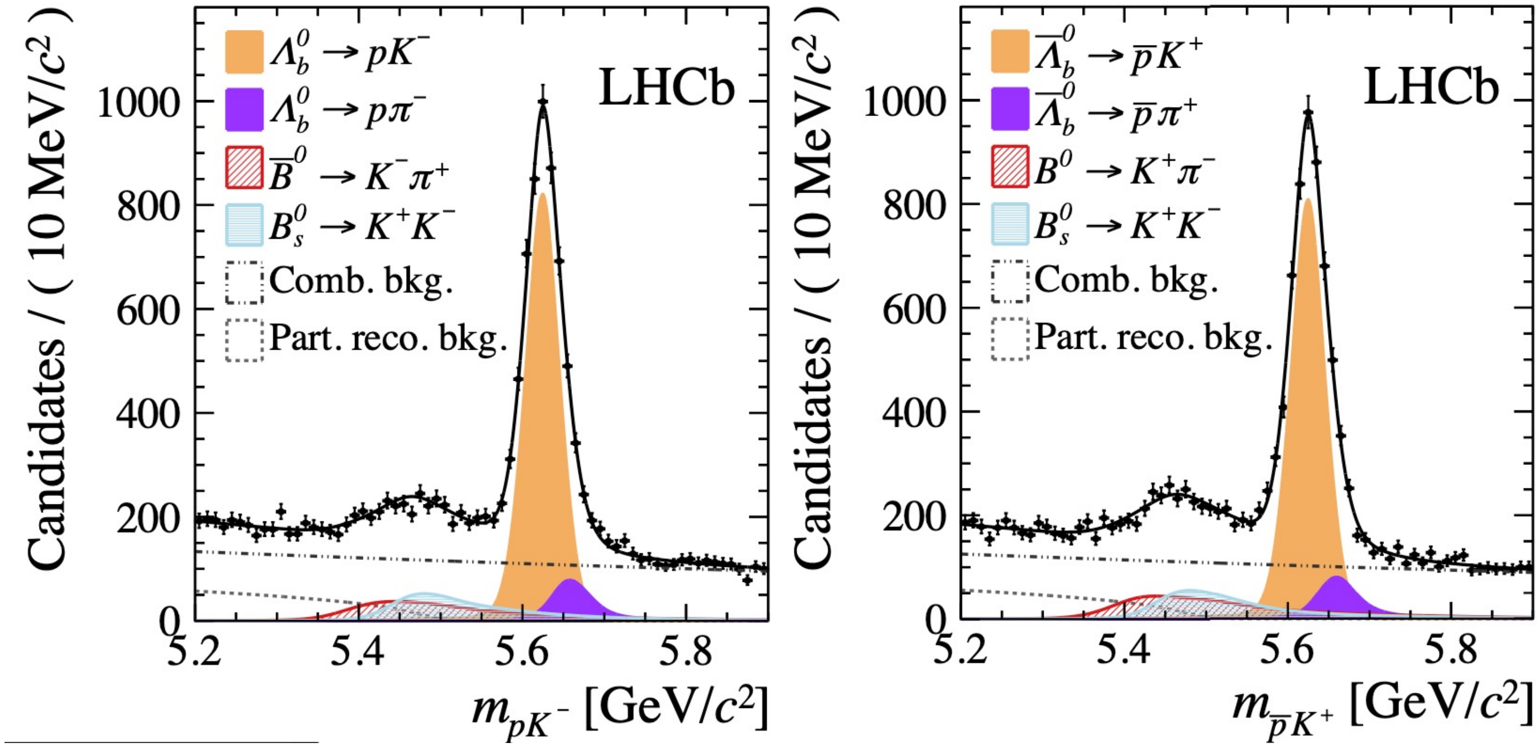
CPV in baryons

- Expected in SM but not observed yet
- Consistent with CKM mechanism?
- Strong phase too small?

Previous measurement in $\Lambda_b^0 \to p h^-$

$$A_{\mathrm{CP}}(pK^-) = -0.020 \pm 0.013 \pm 0.019$$
$$A_{\mathrm{CP}}(p\pi^-) = -0.035 \pm 0.017 \pm 0.020$$

But $A_{\mathrm{CP}}(B^0 \to K^+\pi^-) = -0.0824 \pm 0.0047$, $A_{\mathrm{CP}}(B_s^0 \to K^-\pi^+) = 0.236 \pm 0.017$



Phys. Lett. B784 (2018) 124

CPV in $\Lambda_b^0 \to DpK^-$ decays

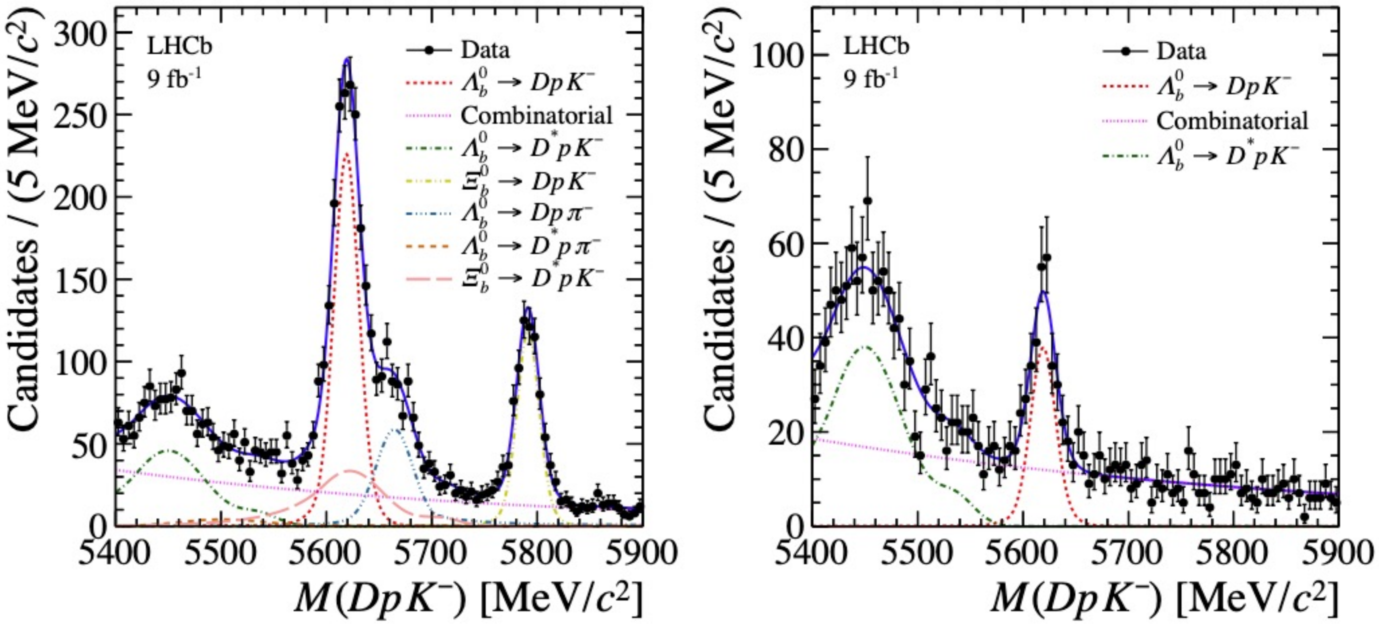
arXiv:2109.02621

- A new channel sensitive to γ angle

Favored ($b \to c$)
$\Lambda_b^0 \to [K^-\pi^+]_D pK^-$

Suppressed ($b \to u$)
$\Lambda_b^0 \to [K^+\pi^-]_D pK^-$

No relative color suppression



$$R \equiv \frac{\mathcal{B}([K^-\pi^+]_D pK^-)}{\mathcal{B}([K^+\pi^-]_D pK^-)} = 7.1 \pm 0.8^{+0.4}_{-0.3} \qquad A_{CP}([K^+\pi^-]_D pK^-) = 0.12 \pm 0.09^{+0.02}_{-0.03}$$

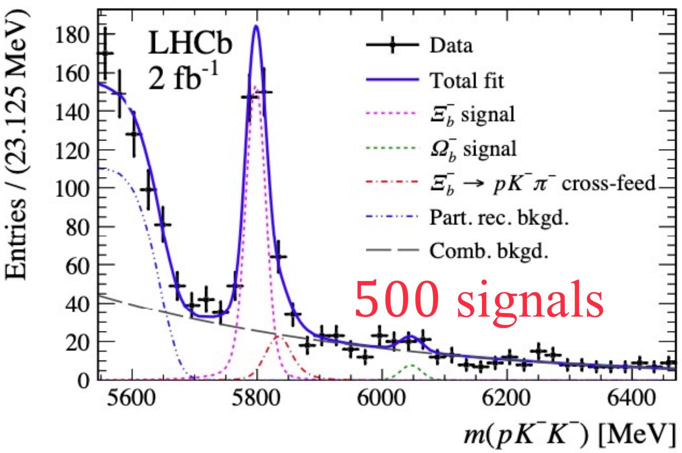
Interference and CP may be large

CPV in $\Xi_b^- \to pK^-K^-$ decays

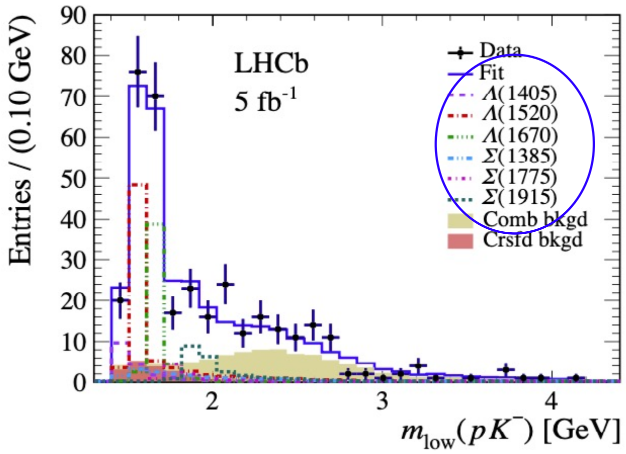
PRD 104 (2021) 052010

- Charmless $b \to s$ transition, CPV as for $B \to hhh$ in mesons?
- Amplitude analysis with 6 resonances

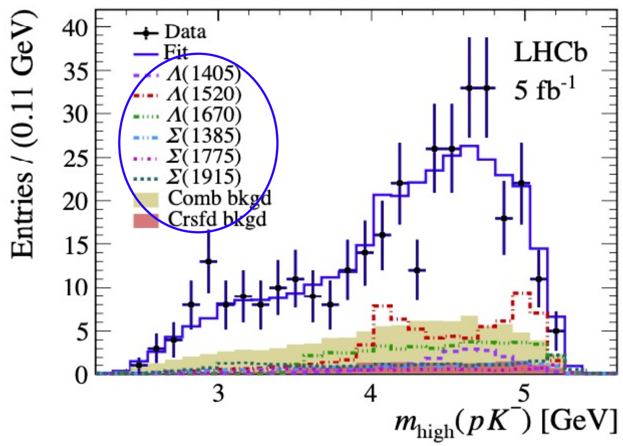
Mass spectrum



$m_{\mathrm{low}}(pK^-)$



$m_{\mathrm{high}}(pK^-)$



Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

No evidence of CPV

$$\mathcal{B}\left(\Xi_b^- \to pK^-K^-\right) = (2.3 \pm 0.9) \times 10^{-6}$$

Magnitude similar to $\mathcal{B}(B \to 3h)$

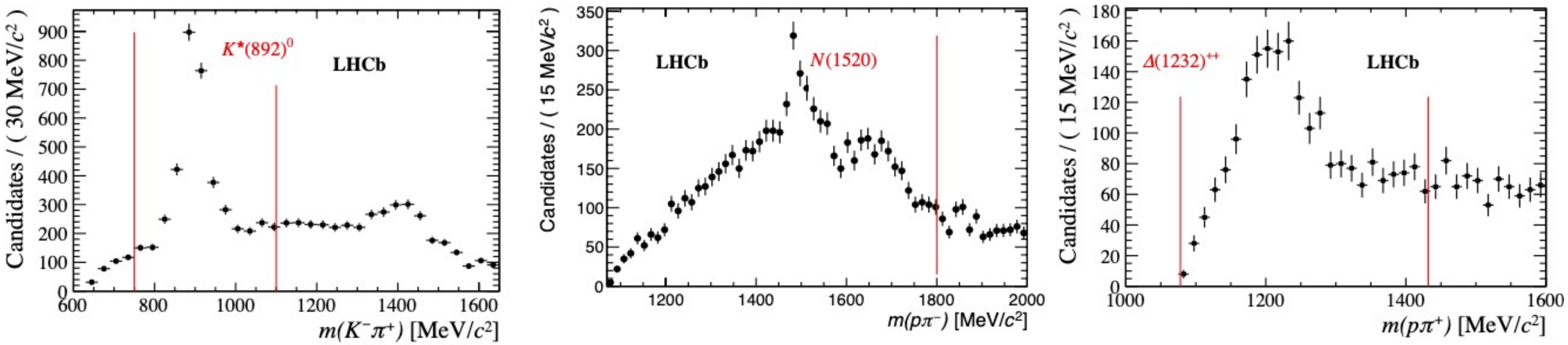
CPV in $\Xi_b^0, \Lambda_b^0 \to phhh$ decays

EPJC 79 (2019) 745

- Six decay modes from 0.5-10K signals (3 fb^{-1})
- Abundant resonant structures

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$
$\Lambda_b^0 \to pK^-\pi^+\pi^-$
$\Xi_b^0 \to pK^-\pi^+\pi^-$ $\quad$ $\Lambda_b^0 \to pK^-K^+\pi^-$
$\Xi_b^0 \to pK^-\pi^+K^-$ $\quad$ $\Lambda_b^0 \to pK^-K^+K^-$

Example: $\Lambda_b^0 \to pK^-\pi^+\pi^-$



- Global and local $A_{\rm CP}$ around resonances studied, relative to CKM favored modes

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+1.1 \pm 2.5 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.2 \pm 1.1 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-6.9 \pm 4.9 \pm 0.8)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (+0.2 \pm 1.8 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+\pi^-) = (-17 \pm 11 \pm 1)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+K^-) = (-6.8 \pm 8.0 \pm 0.8)\,\%$$

- With experimental precision of $\geq 1\%$ no evidence of $A_{\rm CP}$ found.
- Baryon $A_{\rm CP}$ small compared to mesons

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

PRD 102 (2020) 051101

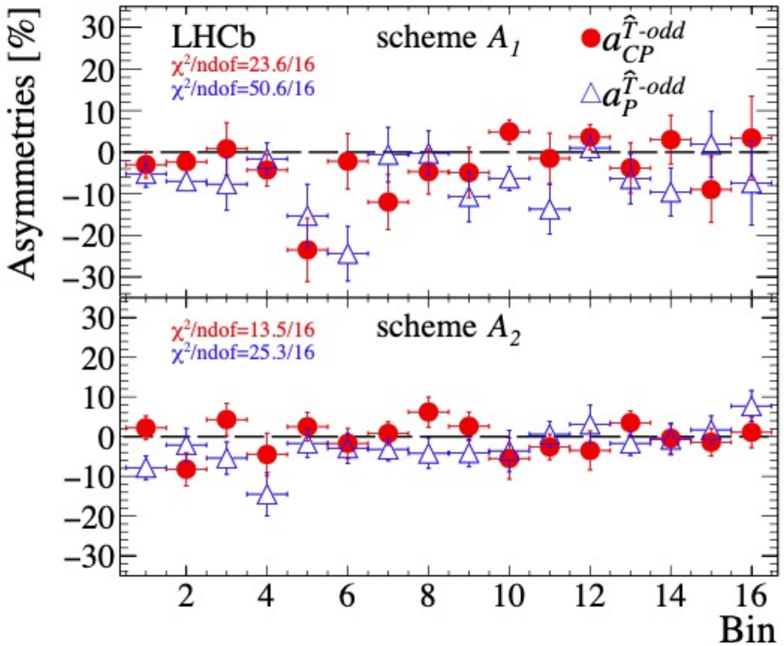
- Triple product $C_{\hat{T}} \equiv \vec{P}_p \cdot (\vec{p}_{\pi^-_{\text{fast}}} \times p_{\pi^+}),\ \bar{C}_{\hat{T}} \equiv \vec{P}_p \cdot \left(\vec{p}_{\pi^+_{\text{fast}}} \times p_{\pi^-}\right)$
- Triple product asymmetry: $A_{\hat{T}} = \langle C_{\hat{T}} \rangle,\ \bar{A}_{\hat{T}} = \langle -\bar{C}_{\hat{T}} \rangle$

CP violating: $a_{\text{CP}} = (A_{\hat{T}} - \bar{A}_{\hat{T}})/2 = (-0.7 \pm 0.7 \pm 0.2)\%$. No hint of CPV

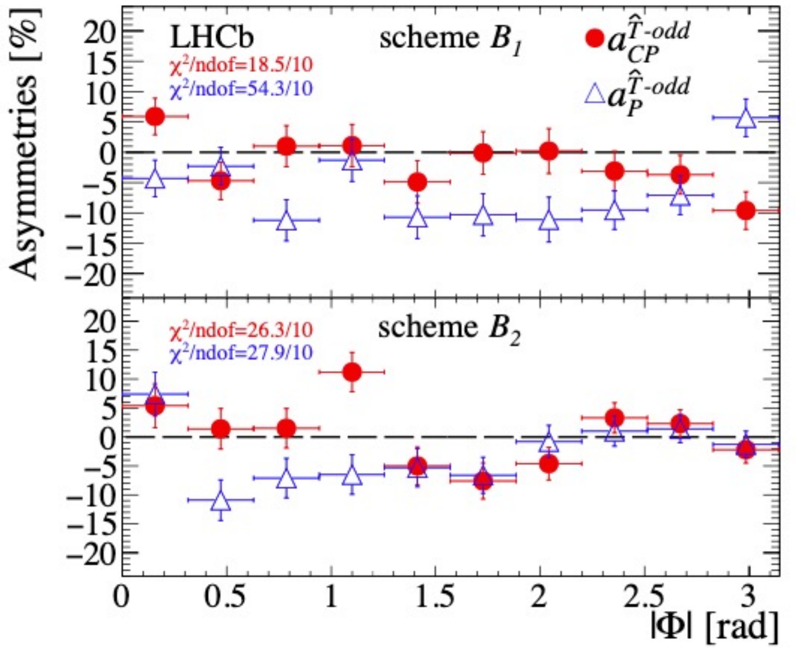
Parity violation observed: $a_{\text{P}} = (A_{\hat{T}} + \bar{A}_{\hat{T}})/2 = (-4.0 \pm 0.7 \pm 0.2)\%$

No CPV of triple product asymmetry in phase space either

Binning according to N^{*+}/Δ^{++} resoances



Φ: angle between $\vec{p}_p \times \vec{p}_{\pi^-_{\text{fast}}}$ and $\vec{p}_{\pi^+} \times \vec{p}_{\pi^-_{\text{slow}}}$

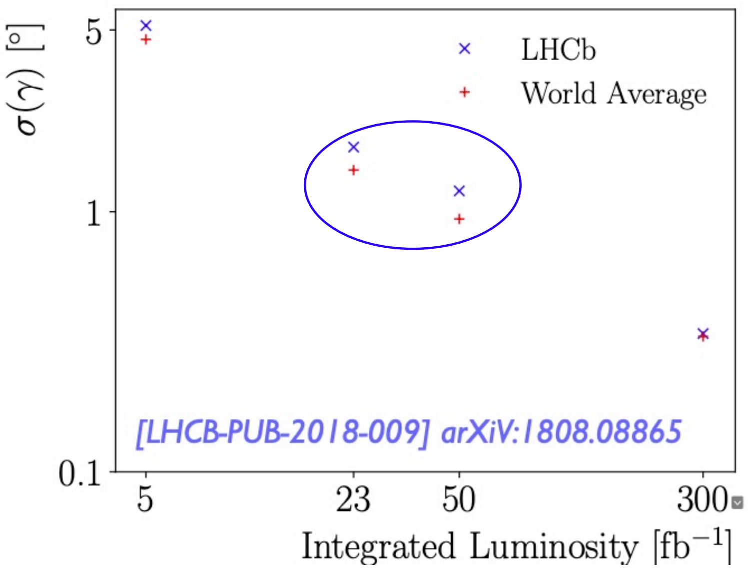


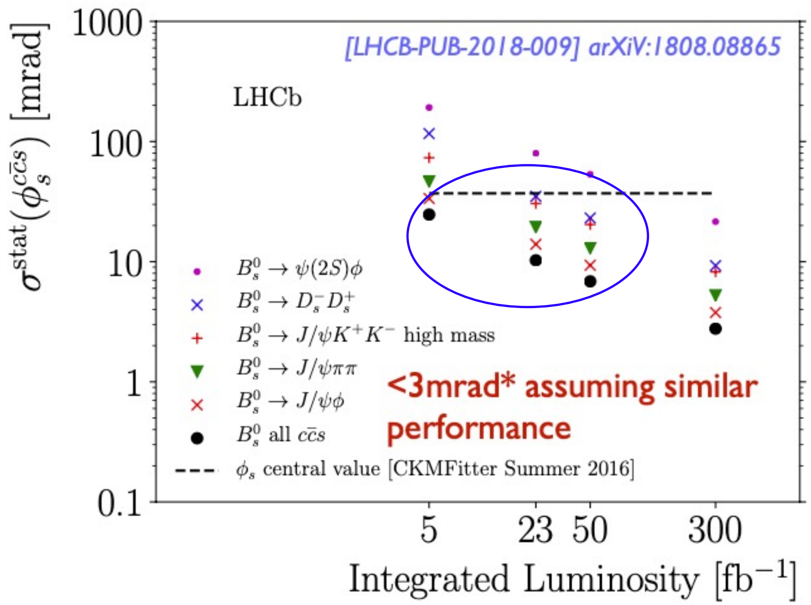
Summary

- New results on mixing parameters, direct CPV in $b \to D$ and charmless decays

  $\Delta M_s = 17.7656 \pm 0.0057\ \mathrm{ps}^{-1}, \phi_s = -42 \pm 25\ \mathrm{mrad}, \gamma = (65.4^{+3.8}_{-4.2})^\circ, A_{CP}(hh(h))\ldots$

  Even new ones are coming with full run 1+ run 2data
- No CPV in beauty baryons observed, but started to be sensitive at % level
- The future:





And baryon CPV

Backup slides

CKM matrix up to λ^6

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

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

JHEP 03 (2020) 147

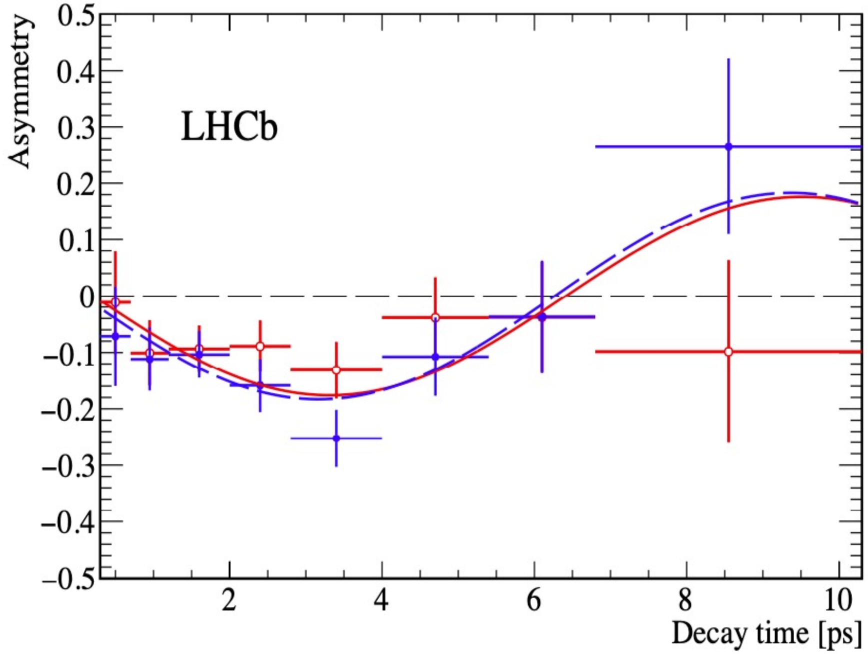
- Decay via $b \to c\bar{c}d$ tree transition causing only CPV in mixing, other processes may induce direct CPV
- Time dependent decay rate:

$$\mathcal{P}(B,f) \propto (1 \underbrace{\pm}_{f \text{ or } \bar{f}} A_{\rm CP})[1 \pm C_f \cos(\Delta M_d t) \mp S_f \sin(\Delta M_d t)]$$

B^0 or $\bar{B}^0$

For $b \to c\bar{c}d$: $A_{\rm CP}, C_f = 0$

Time dependent CP asymmetry for $f = D^{*+}D^-$ and $\bar{f} = D^{*-}D^+$



$A_{\rm CP} = +0.008 \pm 0.014 \pm 0.006$

$(S_f + S_{\bar{f}})/2 = -0.861 \pm 0.077 \pm 0.019$

$(S_f - S_{\bar{f}})/2 = +0.019 \pm 0.075 \pm 0.012$

$(C_f + C_{\bar{f}})/2 = -0.059 \pm 0.092 \pm 0.020$

$(C_f - C_{\bar{f}})/2 = -0.031 \pm 0.092 \pm 0.016$

Mixing induced CPV

Consistent with no direct CPV

$B_s^0 \to D_s^- K^+ \pi^+ \pi^-$

$$\frac{\mathrm{d}\Gamma(B_s^0 \to f)}{\mathrm{d}t} \propto \left[\cosh\left(\frac{\Delta\Gamma_s\, t}{2}\right) + C_f \cos(\Delta m_s\, t) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s\, t}{2}\right) - S_f \sin(\Delta m_s\, t)\right] e^{-\Gamma_s\, t}$$

$$\frac{\mathrm{d}\Gamma(\bar{B}_s^0 \to f)}{\mathrm{d}t} \propto \left[\cosh\left(\frac{\Delta\Gamma_s\, t}{2}\right) - C_f \cos(\Delta m_s\, t) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s\, t}{2}\right) + S_f \sin(\Delta m_s\, t)\right] e^{-\Gamma_s\, t}$$

$$C_f = \frac{1-r^2}{1+r^2},$$

$$A_f^{\Delta\Gamma} = -\frac{2\, r\, \kappa \cos(\delta - (\gamma - 2\beta_s))}{1+r^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = -\frac{2\, r\, \kappa \cos(\delta + (\gamma - 2\beta_s))}{1+r^2}$$

$$S_f = +\frac{2\, r\, \kappa \sin(\delta - (\gamma - 2\beta_s))}{1+r^2}, \quad S_{\bar{f}} = -\frac{2\, r\, \kappa \sin(\delta + (\gamma - 2\beta_s))}{1+r^2}$$

γ combination

B decay	D decay	Ref.	Dataset	Status since Ref. [24]
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[28]	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$	[29]	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^+h^-$	[26]	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$	[30]	Run 1&2	**Updated**
$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^{\pm} \to DK^{*\pm}$	$D \to h^+h^-$	[31]	Run 1&2(*)	As before
$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[31]	Run 1&2(*)	As before
$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h^-$	[32]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[33]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[34]	Run 1	As before
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	[35]	Run 1	As before
$B^0_s \to D^{\mp}_s K^{\pm}$	$D^+_s \to h^+h^-\pi^+$	[36]	Run 1	As before
$B^0_s \to D^{\mp}_s K^{\pm}\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[37]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[38–40]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[41]	Run 1	**New**
–	$D^0 \to h^+h^-$	[42–45]	Run 1&2	**New**
–	$D^0 \to K^+\pi^-$	[46]	Run 1	**New**
–	$D^0 \to K^+\pi^-$	[47]	Run 1&2(*)	**New**
–	$D^0 \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	[48]	Run 1	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[49, 50]	Run 1&2	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[51]	Run 1	**New**