CKM and CPV measurements in the beauty and charm sector

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On behalf of the LHCb collaboration

LHCP 2023
Large Hadron Collider Physics Conference

Outlines

- Introduction.
- Measurement of the CKM angle ϕ_s
  - $B_s \to J/\psi\phi$ → ATLAS, CMS and LHCb
- Measurement of the CKM angle $\phi_s^{s\bar{s}s}$
  - $B_s \to \phi\phi$
- CKM angle γ measurement
  - $B^{\pm} \to \left[h^+h^-\pi^{\pm}\pi^{\mp}\right]_D h^{\pm}(h = K, \pi)$

beauty

charm

- CP violation in charm sector.
  - CP violation in multibody D decay.

LHCb

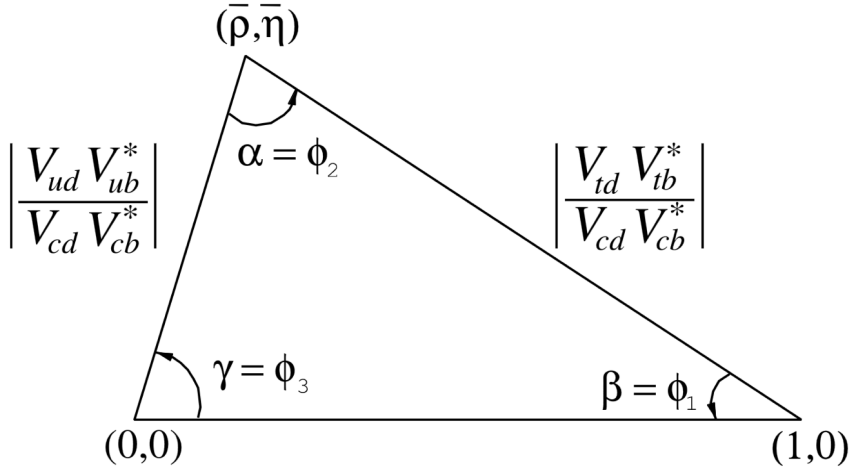
- Summary.

CKM matrix and CP violation

- CKM matrix is a 3×3 unitary matrix, elements represent the strength of flavor-changing weak interactions.

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = V_{\mathrm{CKM}} \begin{bmatrix} d \\ s \\ b \end{bmatrix}, \text{ where } V_{\mathrm{CKM}} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix}$$

- Parameterized by 3 mixing angles and CP violating phase.
- $V_{\mathrm{ud}}V_{\mathrm{ub}}^{*} + V_{\mathrm{cd}}V_{\mathrm{cb}}^{*} + V_{\mathrm{td}}V_{\mathrm{tb}}^{*} = 0$
- CKM phases are related to CP violation (CPV).
  - $\alpha = \arg\left(-\frac{V_{\mathrm{td}}V_{\mathrm{tb}}^{*}}{V_{\mathrm{ud}}V_{\mathrm{ub}}^{*}}\right);\ \beta = \arg\left(-\frac{V_{\mathrm{cd}}V_{\mathrm{cb}}^{*}}{V_{\mathrm{td}}V_{\mathrm{tb}}^{*}}\right);\ \gamma = \arg\left(-\frac{V_{\mathrm{ud}}V_{\mathrm{ub}}^{*}}{V_{\mathrm{cd}}V_{\mathrm{cb}}^{*}}\right).$
- CKM matrix unitarity: test consistency of the CKM mechanism.
  - Sensitive to New Physics (NP).

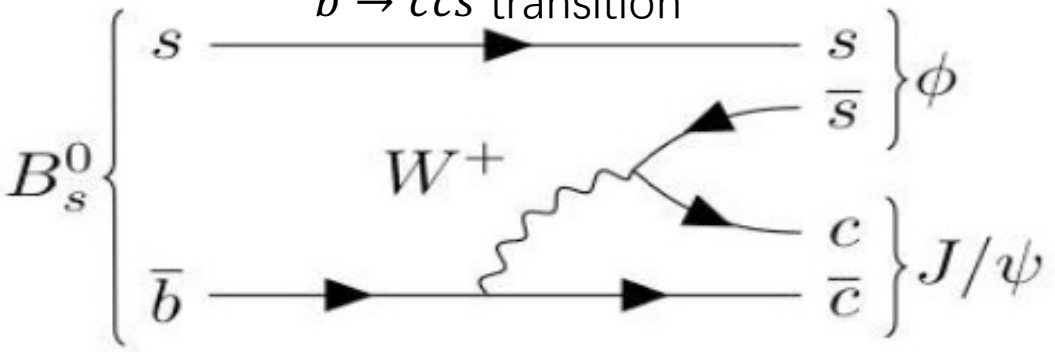


CP violating ϕ_s and $\Delta\Gamma_s$ in $B_s \to J/\psi\phi$ decays

- ϕ_s: weak phase difference between direct decays and decays through mixing of B_s^0.
- $\phi_s \approx -2\beta_s$, $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$.
- Sensitive to NP.

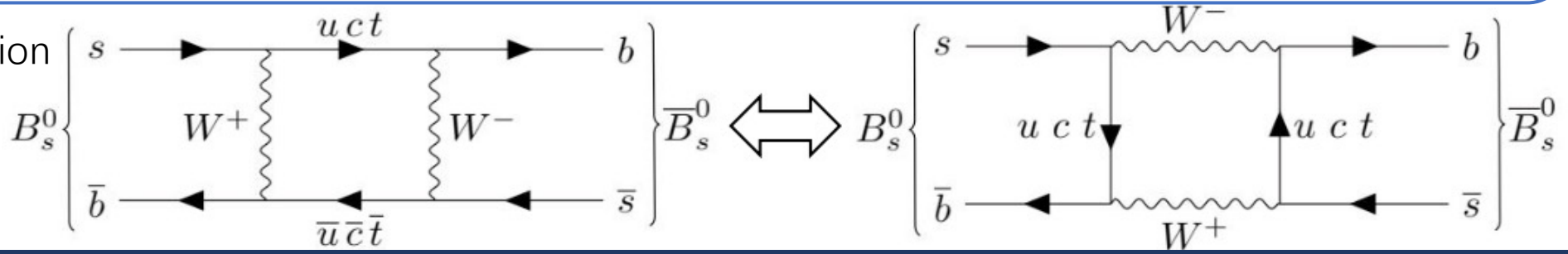
	ϕ_s
CKMfitter	$-0.0365^{+0.0013}_{-0.0012}$rad
UTfit	-0.03700 ± 0.0014rad

$\bar{b} \to \bar{c}cs$ transition



- $\Delta\Gamma_s$: decay widths difference between mass eigenstates.
- Standard Model (SM) prediction: $(0.085 \pm 0.015)\text{ps}^{-1}$ [arXiv:1511.09466].
- Sensitive to NP.

$B_s^0 - \overline{B_s}^0$ oscillation

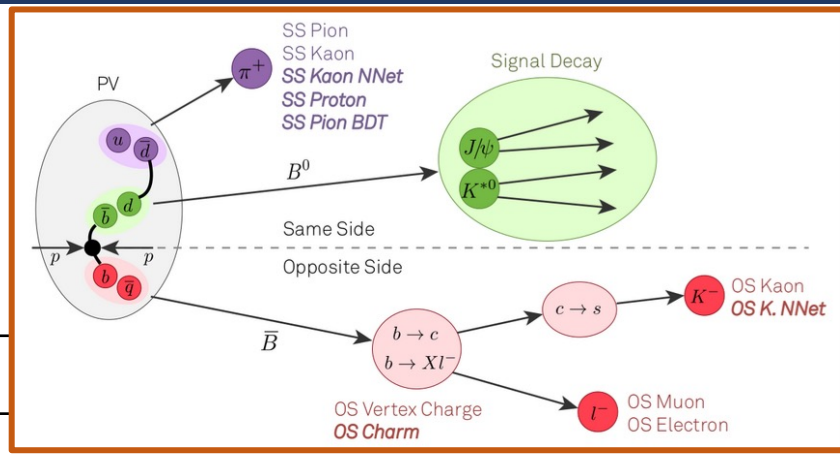


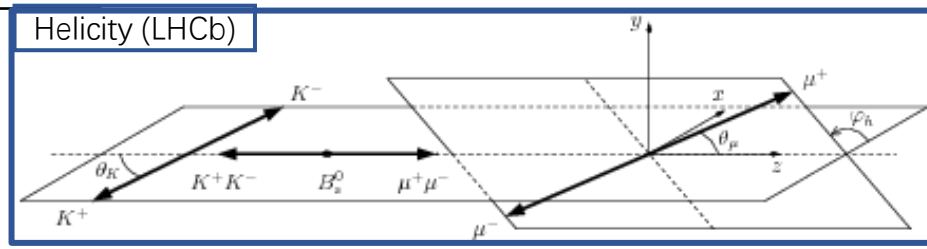
Measurement with $B_s \to J/\psi K^+ K^-$ decay

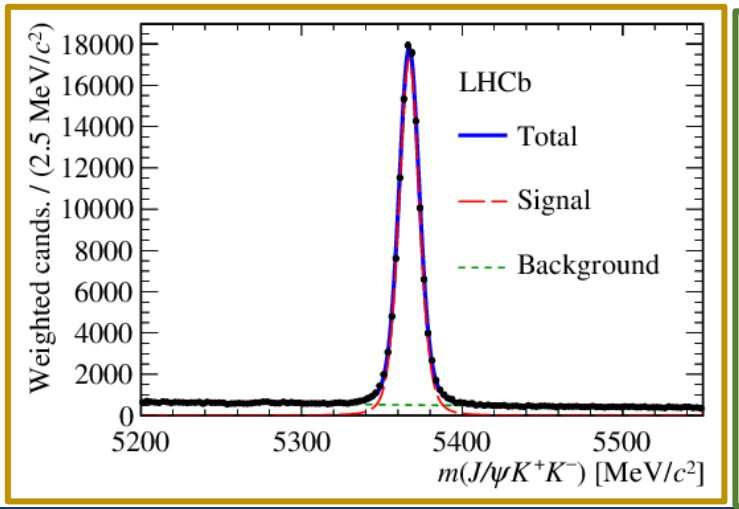
[Phys. Lett. B 816 (2021) 136188]
[Eur. Phys. J. C 81 (2021) 342]
[arXiv:1906.08356]
[arXiv:2105.14738]

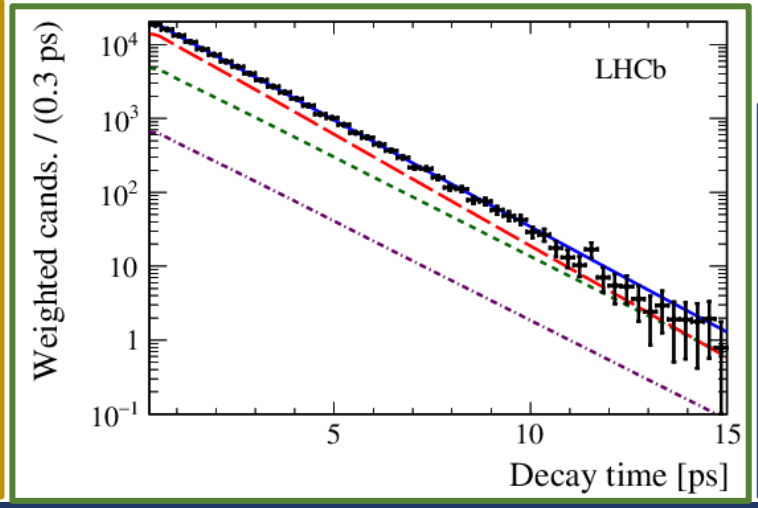
LHCb	ATLAS	CMS
Same-side (SS) and opposite-side (OS) tagger	OS tagger	
Helicity	Transversity	

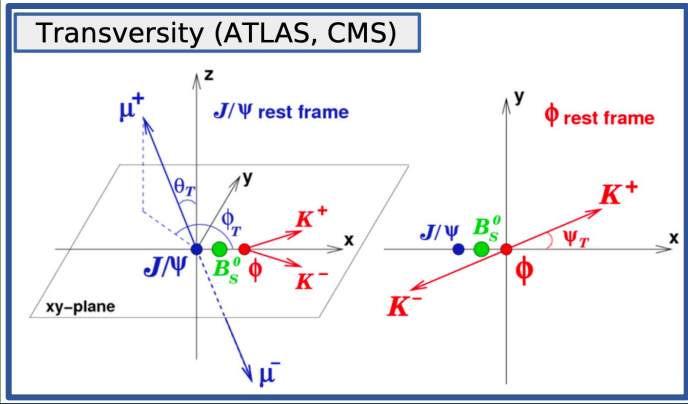
time-dependent angular analysis for signal from mass distribution.











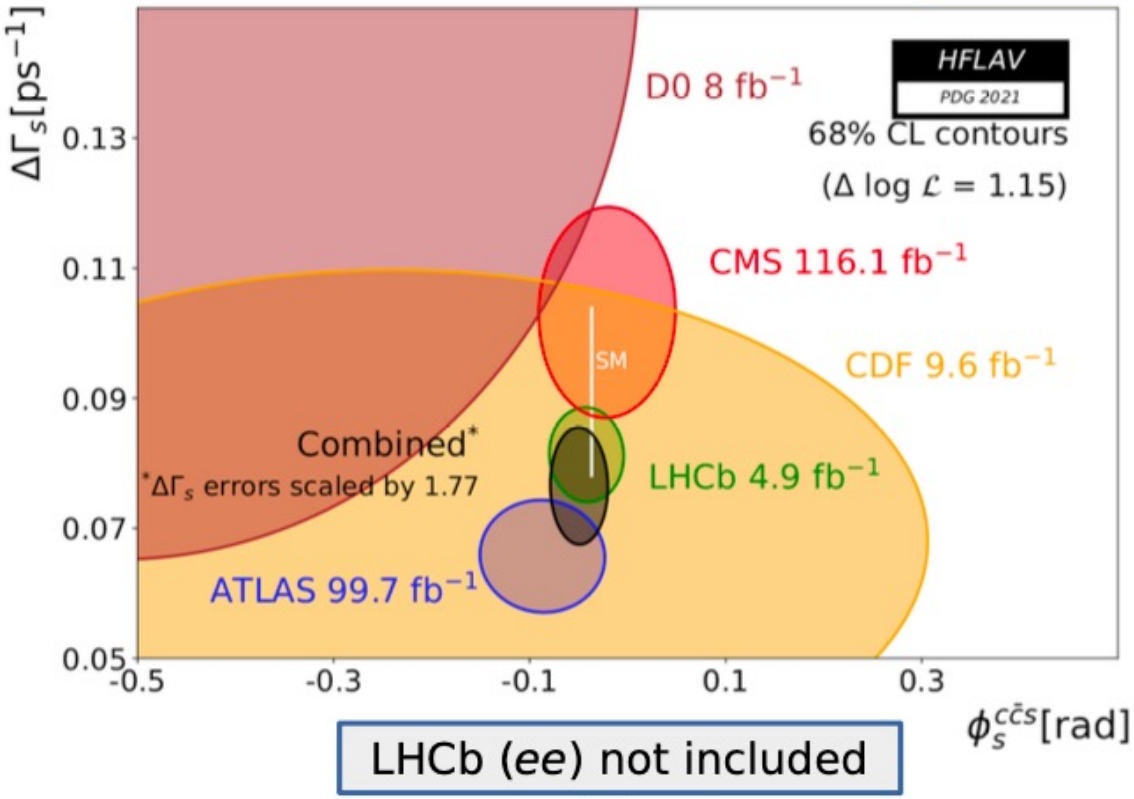
Comparison between CMS, ATLAS and LHCb Results

Measurement of ϕ_s	
CDF, D0, ATLAS and CMS	LHCb
$B_s \to J/\psi\phi$	$B_s \to J/\psi K^+K^-$ (including $B_s \to J/\psi\phi$), $B_s \to \psi(2S)\phi$, $B_s \to J/\psi\pi^+\pi^-$, $B_s \to D_s^+D_s^-$.

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]
ATLAS	$-0.087 \pm 0.036 \pm 0.021$	$0.0657 \pm 0.0043 \pm 0.0037$
CMS	$-0.021 \pm 0.044 \pm 0.010$	$0.1032 \pm 0.0095 \pm 0.0048$
LHCb (all mumu)	-0.042 ± 0.025	0.0813 ± 0.0048
LHCb (ee)	$0.00 \pm 0.28 \pm 0.07$	$0.115 \pm 0.045 \pm 0.011$

Important check for the results with muons, because the systematic uncertainties are independent, while the studied mechanism of the CPV is the same.

[LHCb Public results]
[ATLAS Public results]
[CMS Public results]



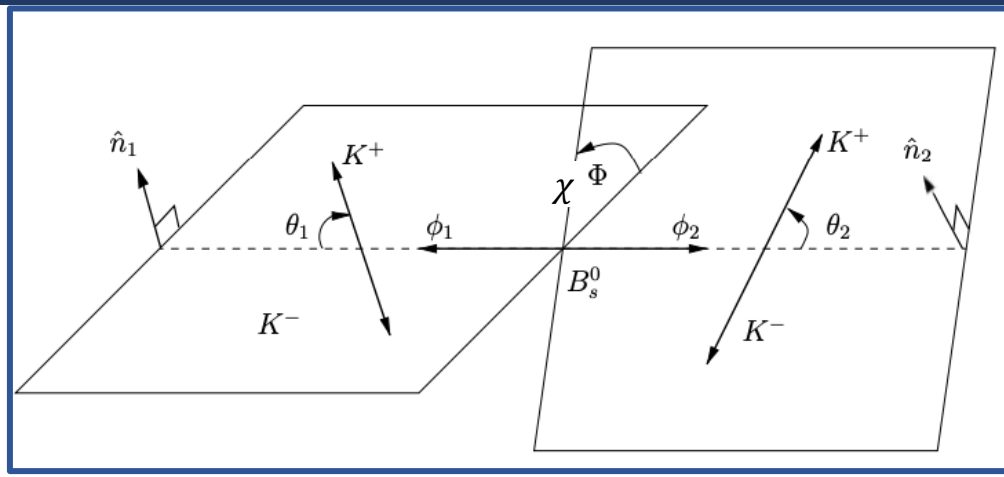
LHCb (*ee*) not included

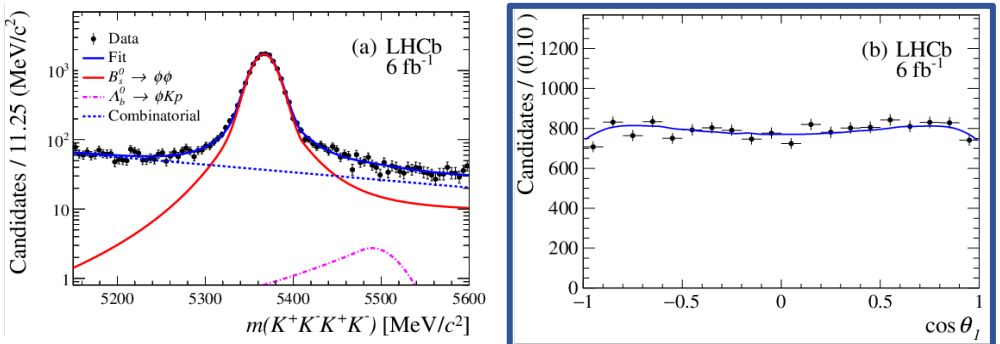
- The combined result is consistent with SM predictions.

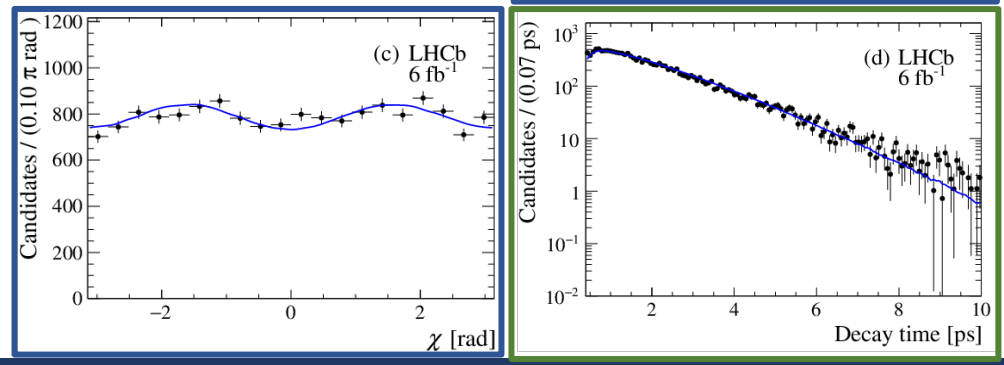
CP violation in $B_s^0 \to \phi\phi$

arXiv:2304.06198

- $b \to s\bar{s}s$ is benchmark to study CPV in FCNC decays.
- CPV arises from the interference between decay and mixing, characterised by the phase $\phi_s^{s\bar{s}s}$ and $|\lambda|$.
- Final state has 3 linear polarisation states.
- $6\ \mathrm{fb}^{-1}$, 13 TeV
  - Flavour-tagged time-dependent angular analysis.
  - 15840 signal yields.
    - Signal weight is used to subtract background in the fit to decay-time and angular distributions.
    - $\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009$ rad
    - $|\lambda| = \quad 1.004 \pm 0.030 \pm 0.009$



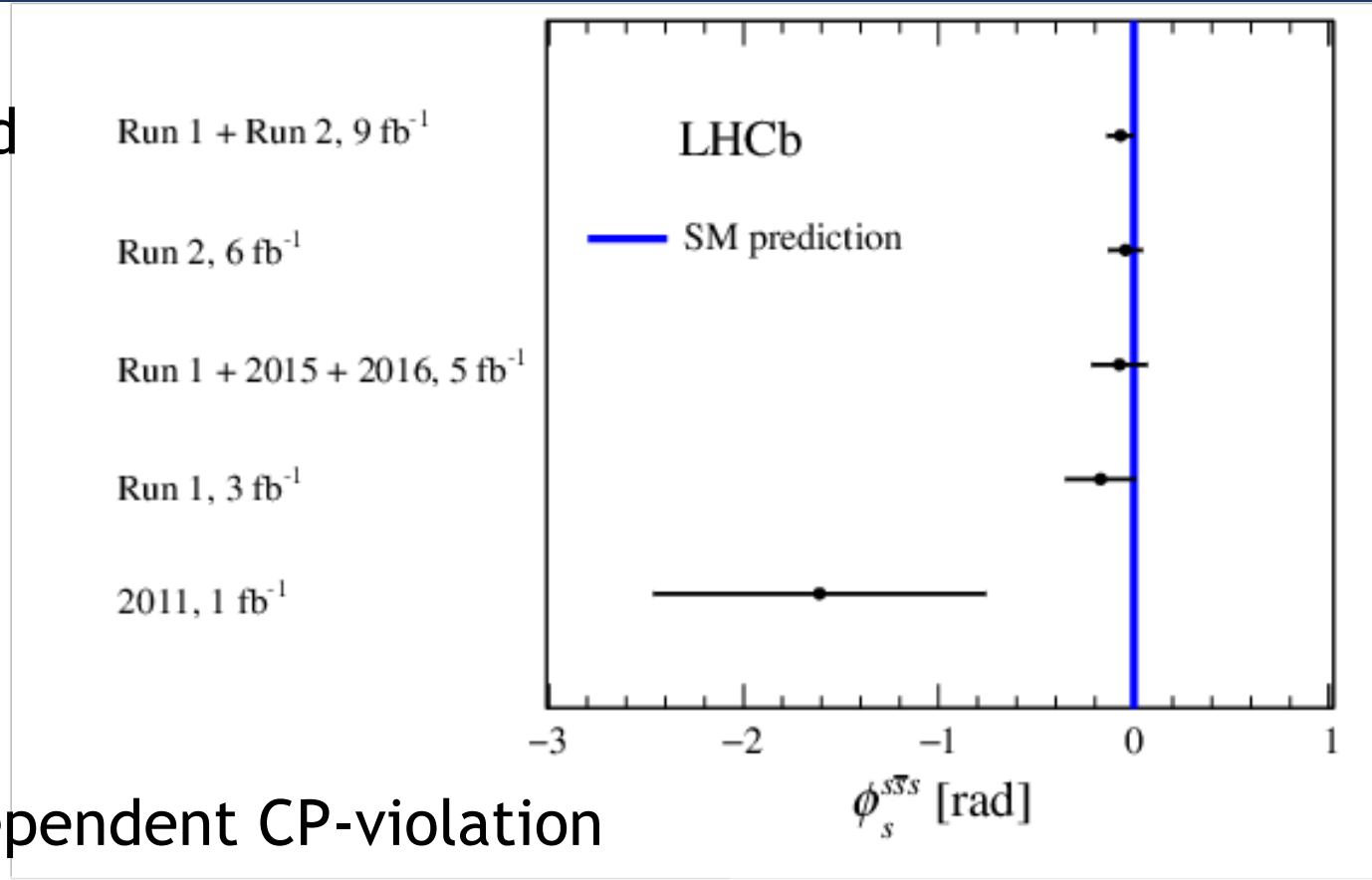




Combined results in $B_s^0 \to \phi\phi$

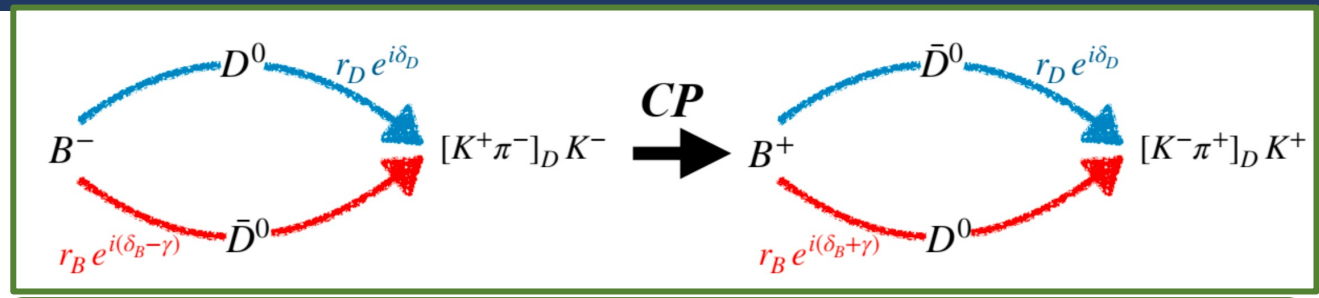
arXiv:2304.06198

- Combined with data taken in 2011 and 2012
  - $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069\,\text{rad}$
  - $|\lambda| = 1.009 \pm 0.030.$
- The most precise measurement.
- Consistent with and supersedes the previous measurement.
- Agree with the SM expectation.
- The first time that the polarization-dependent CP-violation parameters are measured
  - Show no significant difference between the three polarization states of $B_s^0 \to \phi\phi$ decays.
  - Constrain new physics contributions in $b \to s$ transitions.



Direct measurement of γ

- CKM γ is the only angle that can be determined using tree-level B meson decays with negligible theoretical uncertainty.



$r_{B(D)}, \delta_{B(D)}$ are ratio of amplitudes of and strong phase difference between $B^+(D^0)$ and $B^-(\bar{D}^0)$ decays, respectively.

- Direct measurement of γ can probe NP beyond SM.
- Several time-independent modes: $B \to D^{(*)}h$, D^0 and $\bar{D}^0$ decay to the same final state.
  - GLW: CP eigenstates ($D \to K^+K^-/\pi^+\pi^-$).
  - ADS: Cabibbo-favoured (CF) or Cabibbo-suppressed (CS) decays ($D \to K^+\pi^-$).
  - BPGGSZ: multi-body D decays, study CP asymmetry over phase space ($D \to K^0_S\pi^+\pi^-$).
- Time-dependent (interference between mixing and decay): $B^0 \to D^{\mp}\pi^{\pm}$…

Combination of γ measurements

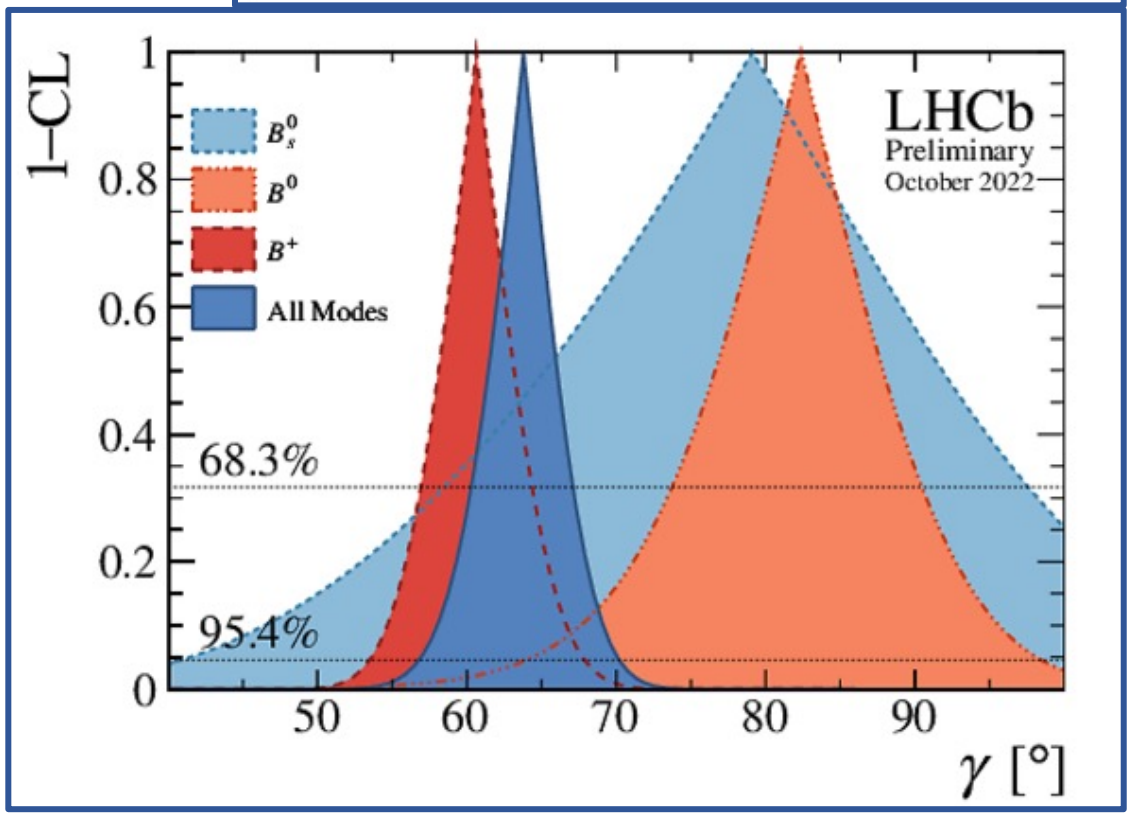
LHCb-CONF-2022-003

- Combination of measurements sensitive to the CP violation angle γ and charm sector is performed.
- Include new and updated measurements from B decay
  - $B^{\pm} \to \left[K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}\right]_{D} h^{\pm}$ arXiv:2209.03692
  - $B^{\pm} \to \left[h^{\pm}h'^{\mp}\pi^{0}\right]_{D} h^{\pm}$ arXiv:2112.10617
  - $\gamma = \left(63.8^{+3.5}_{-3.7}\right)^{\circ}$
- Compatibility with indirect determination
  - $\gamma = (65.5^{+1.1}_{-2.7})^{\circ}$ CKMfitter
- Compatible with previous combination
  - $\gamma = \left(65.4^{+3.8}_{-4.2}\right)^{\circ}$ arXiv:2110.02350
- The most precise determination from a single experiment.

Split by initial B meson species

Species	Value [°]	68.3% CL Uncertainty	68.3% CL Interval
B^+	60.6	$^{+4.0}_{-3.8}$	[56.8, 64.6]
B^0	82.0	$^{+8.1}_{-8.8}$	[73.2, 90.1]
B^0_s	79	$^{+21}_{-24}$	[55, 100]

2.2σ tension

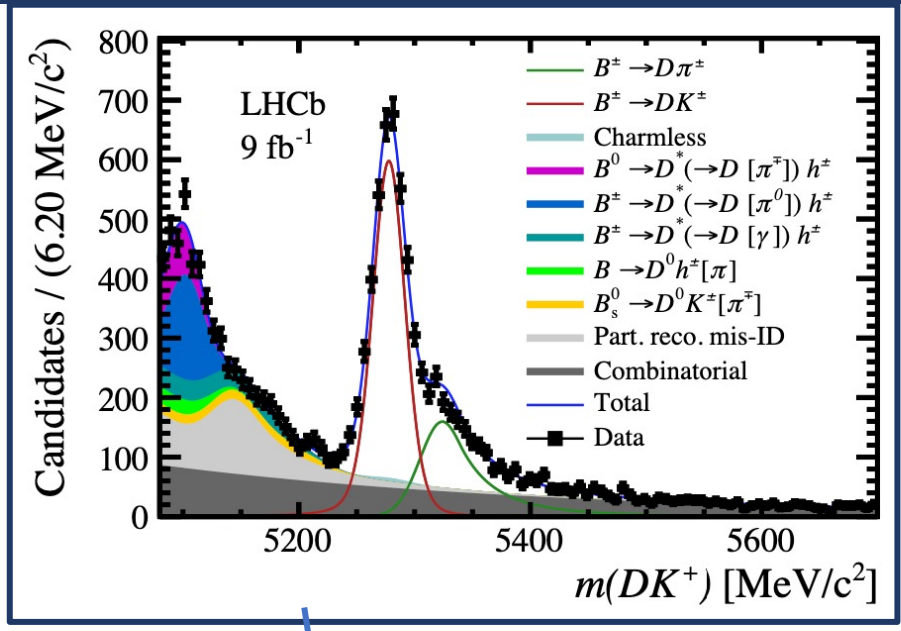


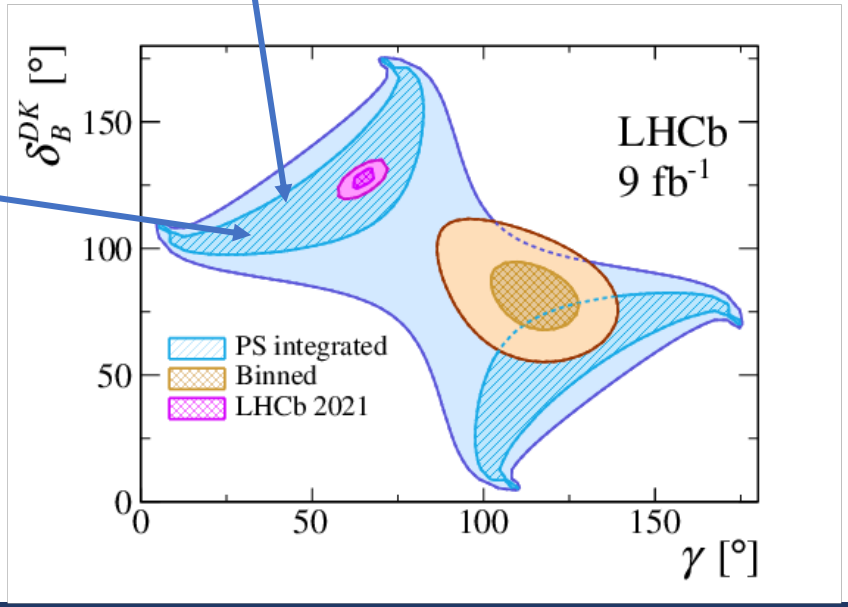
γ measurement with $B^{\pm} \to \left[h^+h^-\pi^{\pm}\pi^{\mp}\right]_D h^{\pm}$

arXiv:2301.10328

- The first study of CP violation in $B^{\pm} \to \left[K^+K^-\pi^{\pm}\pi^{\mp}\right]_D h^{\pm} (h = K, \pi)$.
- Phase space integrated analysis for $K^+K^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$.
  - supersede the previous $B \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$ measurement. arXiv:2012.09903

CP-violating observable	Fit results
$A_K^{KK\pi\pi}$	$0.093 \pm 0.023 \pm 0.002$
$A_\pi^{KK\pi\pi}$	$-0.009 \pm 0.006 \pm 0.001$
$A_K^{\pi\pi\pi\pi}$	$0.060 \pm 0.013 \pm 0.001$
$A_\pi^{\pi\pi\pi\pi}$	$-0.0082 \pm 0.0031 \pm 0.0007$
$R_{CP}^{KK\pi\pi}$	$0.974 \pm 0.024 \pm 0.015$
$R_{CP}^{\pi\pi\pi\pi}$	$0.978 \pm 0.014 \pm 0.010$





γ measurement with $B^{\pm} \to \left[h^+h^-\pi^{\pm}\pi^{\mp}\right]_D h^{\pm}$

arXiv:2301.10328

External information on charm parameters, currently from amplitude model.

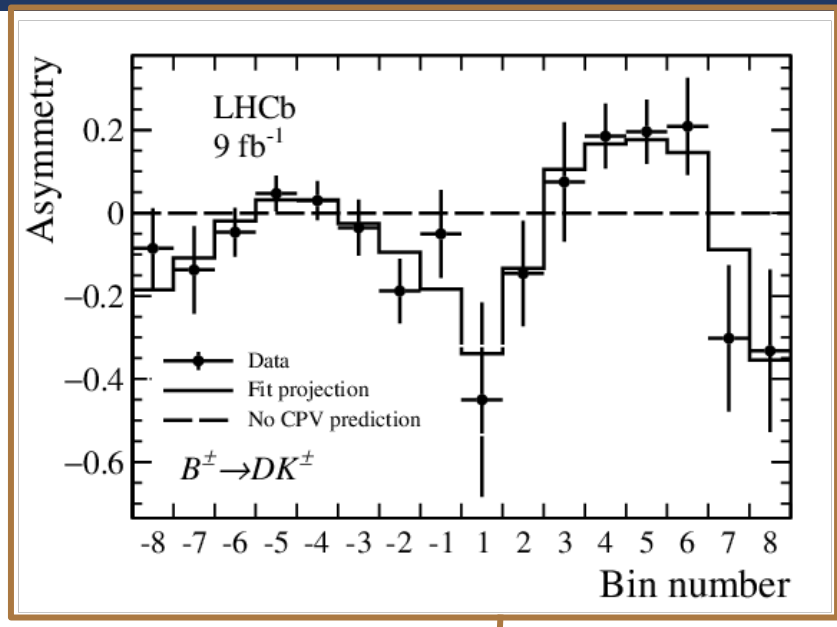
Direct measurement of charm parameters allow the CP-violating observables to be determined model-independently.

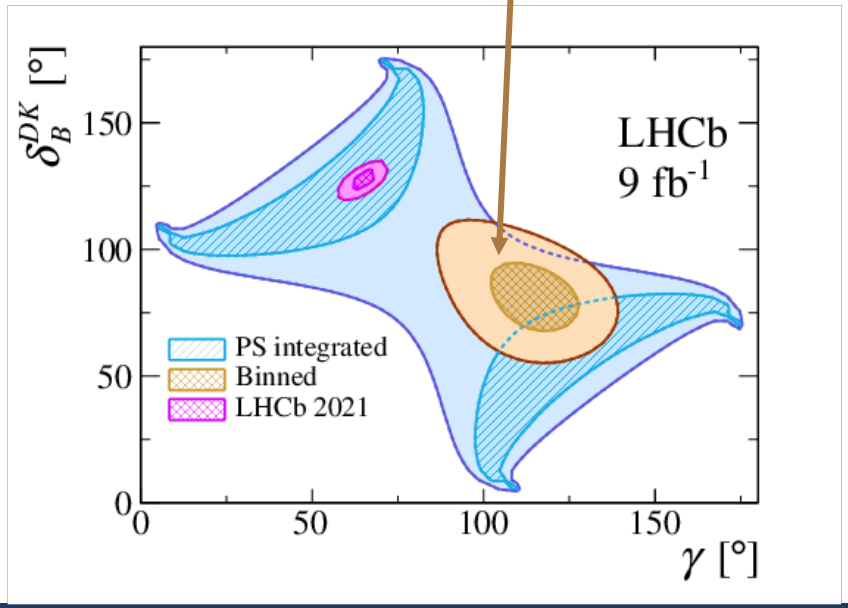
- Binned analysis for $K^+K^-\pi^+\pi^-$.
  - Local asymmetries confirm presence of CP violation effects.
  - $\gamma = (116^{+12}_{-14})^\circ$

3σ agreement with previous LHCb determinations using other channels.

Result will evolve after charm model-independent measurement.

arXiv:2110.02350





CP violation in charm sector

- CP violation in up-type quark decays in charm sector.
- CP violation is expected to be tiny in Standard Model(SM) due to CKM elements and GIM mechanism: $A_{CP} \sim 10^{-4} - 10^{-3}$.
- Types of CP violation.
  - direct CP violation in decay
  - CP violation in mixing
  - Interference between decay and mixing
- LHCb has reported the first observation of CP asymmetry in $D^0 \to h^+h^-$ decays in March 2019 [PRL 122 (2019) 211803].
- Further studies are ongoing in charm sector.

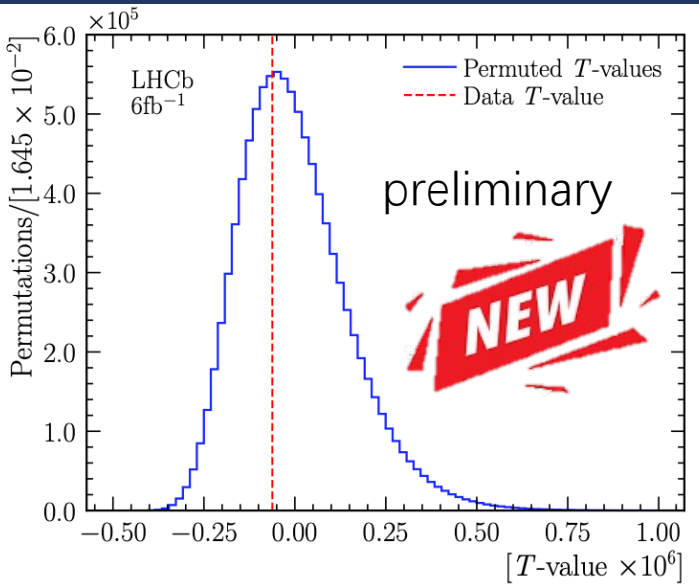
More will be given by D.Friday's talk on CPV and mixing in c decays.

Search for CP violation in multi-body D decays

- Direct CPV arises from different weak and strong phases between the amplitudes involved in the decay
- 3-body charm decays
  - Resonances provide a source of strong phase difference.
  - Enhance sensitivity to CPV in localized regions of the phase space.

Search for CP violation in multi-body D decays

- model-independent approach.
  - Compare Dalitz distributions of D^0 and $\overline{D}^0$ decays.
    - $D^0 \to \pi^-\pi^+\pi^0$ decay (unbinned) LHCb-PAPER-2023-005
      - p-value is obtained by comparing nominal result to the expected distribution under CP symmetry.
        - p-value is 0.62
      - No indication of any CPV in localized region of the phase space.
    - $D^+_{(s)} \to K^-K^+K^+$ decay (binned) arXiv: 2303.04062
      - p-value is defined as the probability of obtaining a test variable (Dalitz-plot distribution comparison of D^0 and $\overline{D}^0$) that is at least as high as the value observed under CP conservation.
        - D^+_s mode: p-value = 13.3%
        - D^+ mode: p-value = 31.6%
      - No local CP violation observed and the first search for CP violation in the $D^+_{(s)} \to K^-K^+K^+$ decays.



Summary

- The measurements of ϕ_s from LHCb and so on are in an agreement with the SM, results with final state containing electrons are an important check.
- New precise $\phi_s^{s\bar{s}s}$ tests of SM in B_s decay, in agreement with the SM.
- The most precise single measurement of β is performed.
- Direct measurement of γ in B decays improve precision in LHCb.
  - Uncertainty < $4°$
  - Further improvements expected with other decay modes and more knowledge of charm hadronic parameters.
- New search of local CP violation in charm sector.

Thanks for your attention!

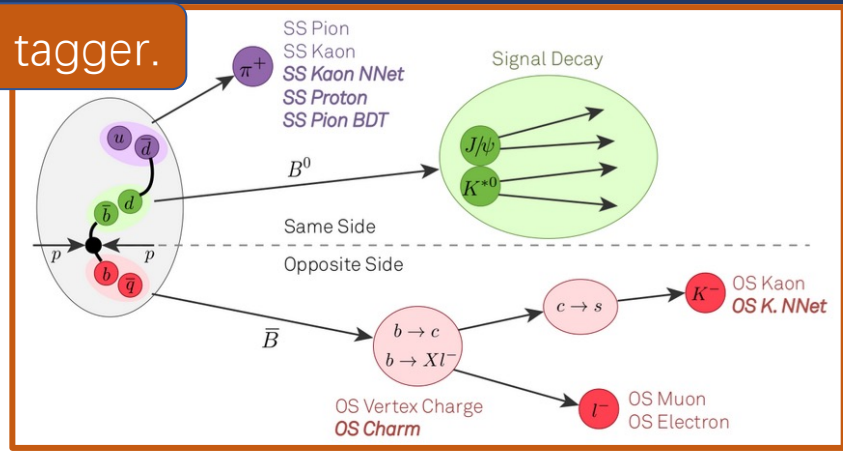
11th Edition of the Large Hadron Collider Physics Conference

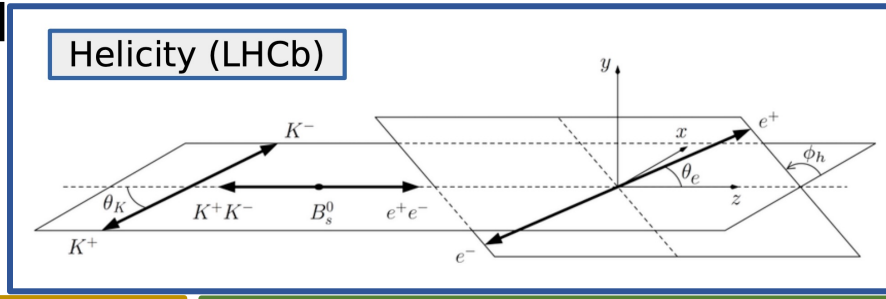
BACKUP

LHCb Result - $B_s \to J/\psi(e^+e^-)\phi$ decay

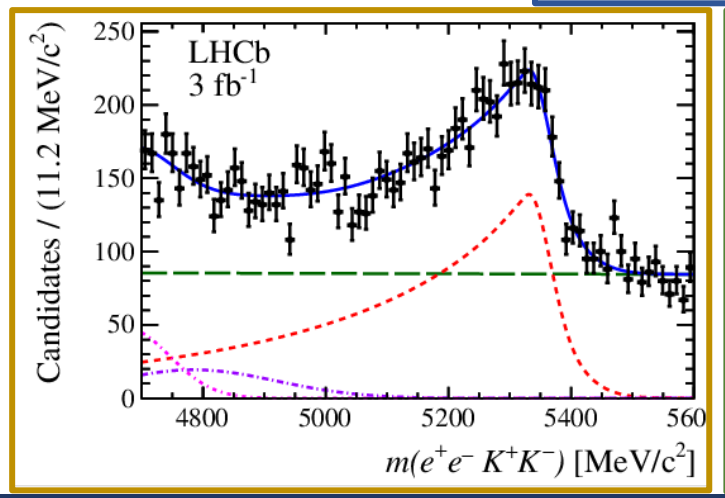
- 3fb^{-1}, 7&8 TeV arXiv:2105.14738
  - Admixture of CP-even and CP-odd components, disentangled by time-dependent angular analysis.
  - $(1.27 \pm 0.05)\times 10^4$ $B_s \to J/\psi(e^+e^-)\phi$ decays from the fit to $m(e^+e^-K^+K^-)$ distribution.
  - CP observables are determined by fit to background-subtracted candidates in B_s^0 decay time and helicity angles distributions.
    - $\phi_s = 0.00 \pm 0.28 \pm 0.07\,\text{rad}$
    - $\Delta\Gamma_s = 0.115 \pm 0.045 \pm 0.011\,\text{ps}^{-1}$

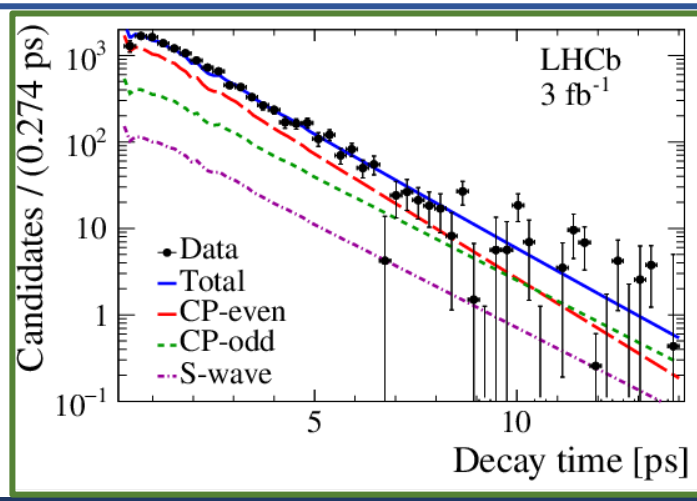
Same-side tagger and opposite-side tagger.





- The first time that ϕ_s measured with the final state containing electrons
- No evidence for direct CPV.

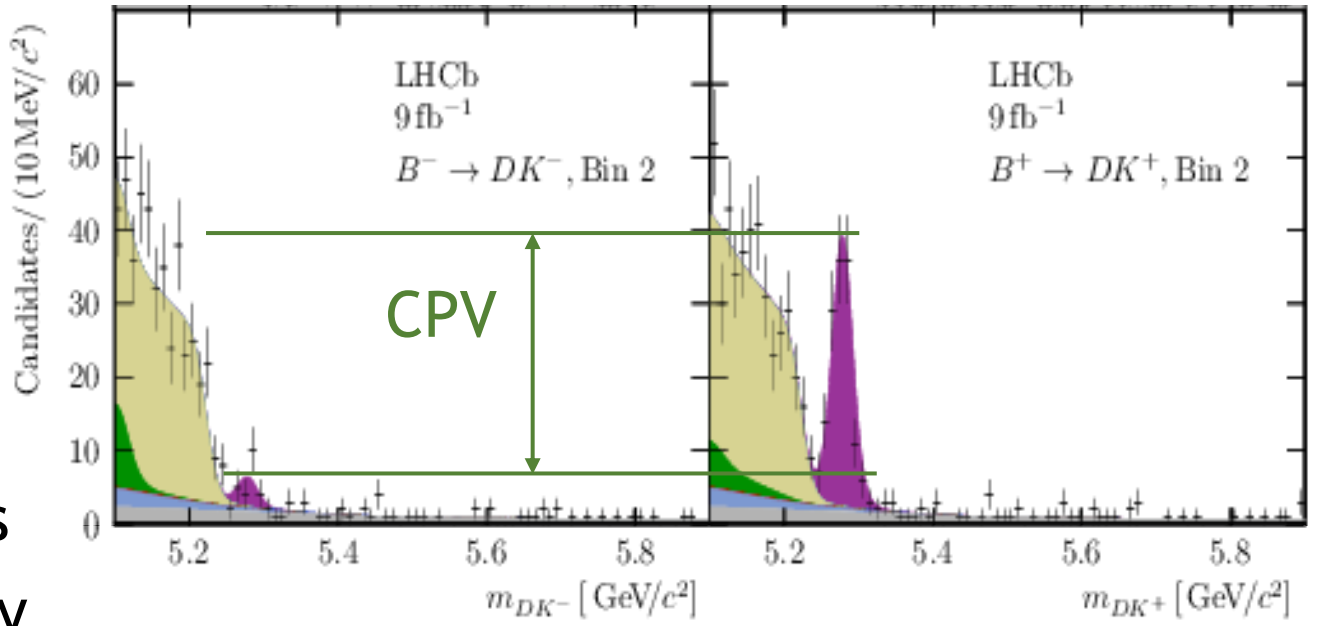




γ measurement with $B^{\pm} \to \left[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}\right]_D h^{\pm}$

arXiv:2209.03692

- $9\ \mathrm{fb}^{-1}$, 7,8 and 13 TeV
- Through CF and DCS amplitudes
  - high branching fractions and only charged particles
- First measurement of parameters in this decay in bins of phase space of D^0 decay



- Magnitude of CP violation in one of bins is the largest yet observed.
- $\gamma = \left(54.8^{+6.0+0.6\,+6.7}_{-5.8\,-0.6\,-4.3}\right)^{\circ}$
  - One of the most precise determinations (2nd).
  - Compatible with current averages.
- Have a strong impact on the overall knowledge of γ.

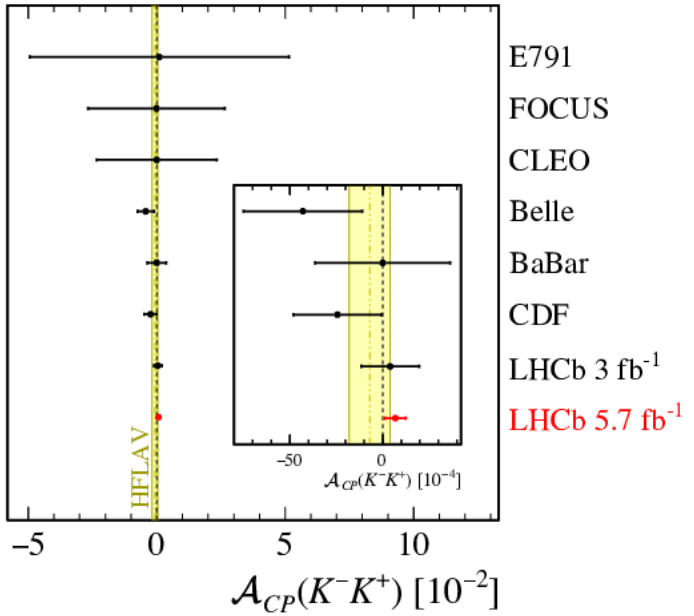
From external inputs for hadronic D decay parameters determined from CLEO-c and BESIII

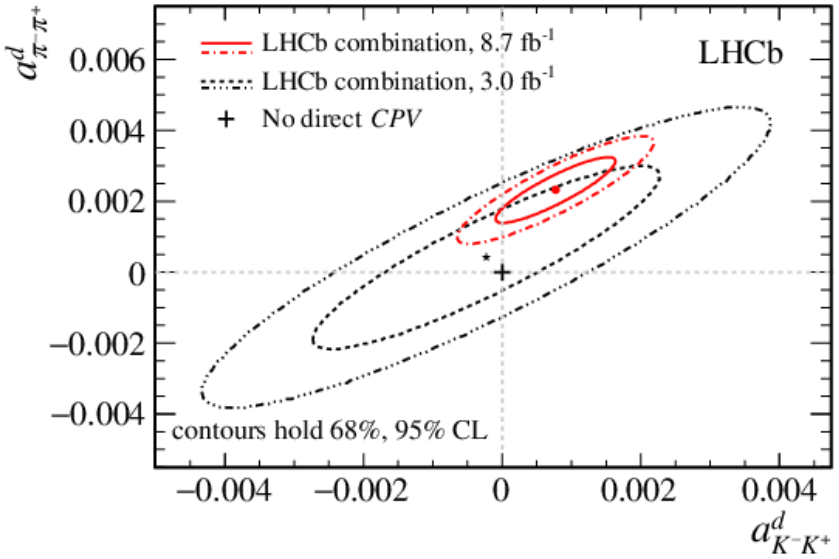
Improvement from incoming BESIII $\psi(3770)$ data.

Measurement of CP asymmetry in $D^0 \to K^-K^+$

arXiv:2209.03179

- 5.7fb^{-1}, 13 TeV
  - $\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$
  - Consistent with the previous LHCb results.
  - Comparison with the world average gives a compatibility of 1.3σ.
  - The most precise measurement of time-integrated CP asymmetry in $D^0 \to K^-K^+$.





- Combination of charm CP asymmetries by LHCb
  - $a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4}$
  - $a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$
- Departure from U-spin symmetry is 2.7σ.
- The first evidence of direct CP violation in $D^0 \to \pi^+\pi^-$ at the level of 3.8σ.