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FERMI NATIONAL ACCELERATOR LABORATORY

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CKM and CP Violation at the LHC

Lepton Photon 2025, Madison, WI, USA

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On behalf of the ATLAS, CMS and LHCb Collaborations

U.S. DEPARTMENT of ENERGY

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OUTLINE

- Introduction
- Cabibbo-Kobayashi-Maskawa (CKM) elements and *CP* Violation
  - Beauty sector (B^0, B_s^0)
  - Charm sector (D^0)
  - Top sector
- Prospects
- Concluding remarks

Presenting results from ATLAS, CMS and LHCb released in the past ~18 months

Introduction

- In the Standard Model (SM) *CP* violation (CPV) occurs thanks to the imaginary phases in quark and neutrino flavor mixing matrices of the weak interaction.
- The magnitude associated to these SM sources is insufficient to account for the baryon asymmetry observed in the universe.
- Studying CPV provides a unique opportunity to uncover interactions beyond the SM.
- CPV can happen in the decay, in the mixing and in the interference between mixing and decay.
- The LHC experiments continue a vigorous multiprong study in the Beauty, Charm and Top sectors searching for CPV and defining better the CKM matrix.
- Some of the latest results and prospects will be presented here.

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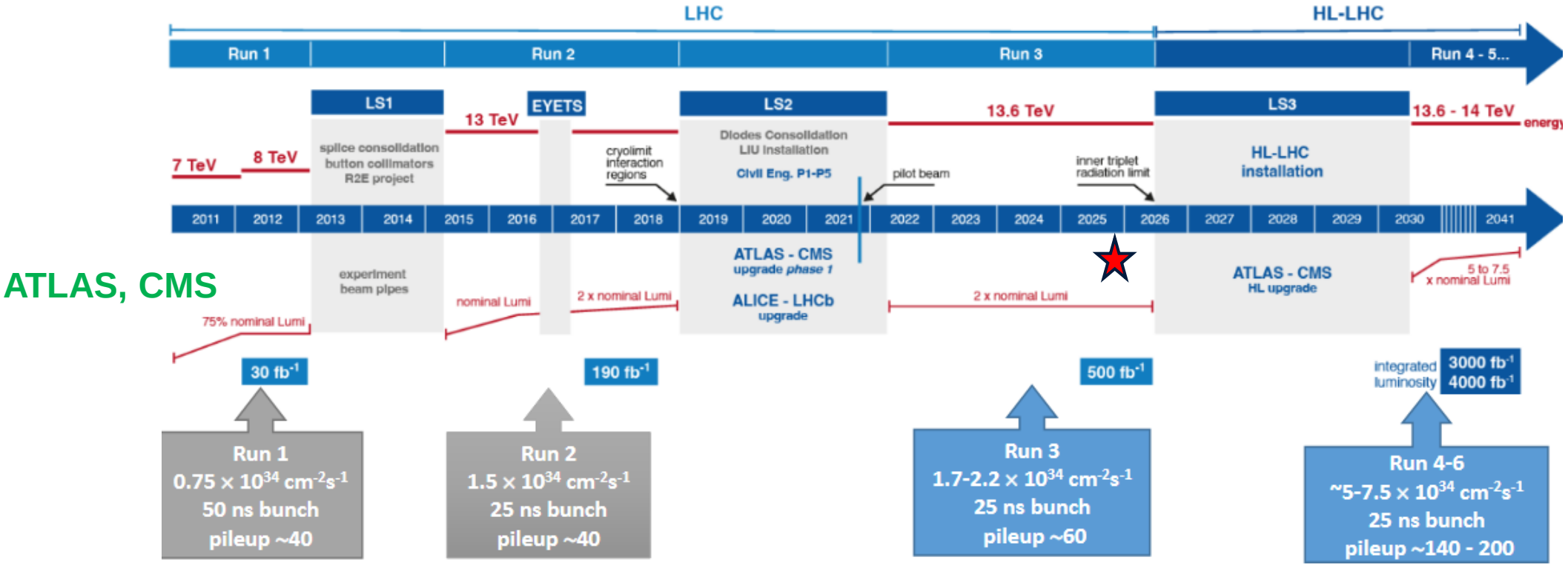
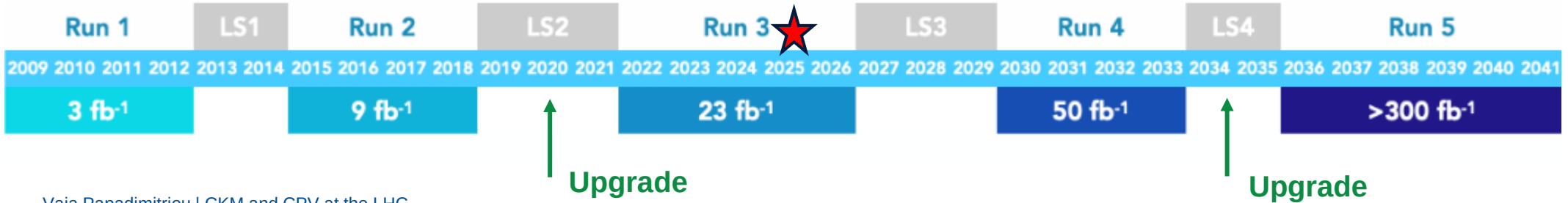
LHC and HL-LHC (past, present, future)



ATLAS, CMS



LHCb

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Measurement of the time-dependent CP violation in B^0 mesons

$$B^0 \rightarrow \psi K_s^0 \rightarrow \mu^+\mu^-(e^+e^-)\pi^+\pi^-$$

PRL 132(2024) 021801

$\sqrt{s} = 13$ TeV, 6 fb^{-1}

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Determining angle β

- Measurement of *CP* violation in the interference of B^0 decays with and without mixing implies the measurement of the periodic change of decay rate differences of initial B^0 and $\bar{B}^0$ mesons to a common, *CP*-invariant final state, *f*, with time:

Mixing frequency

$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = \frac{S \sin(\Delta m_d t) - C \cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma} \sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

  - $S = \sin(2\beta + \Delta\phi_d + \Delta\phi_d^{NP})$
  - Contributions from penguin diagrams to the decay amplitude that cause a phase shift $\Delta\phi_d$ are CKM suppressed, so deviations of S from sin(2β) are expected to be small in the SM.
    - Interesting to check

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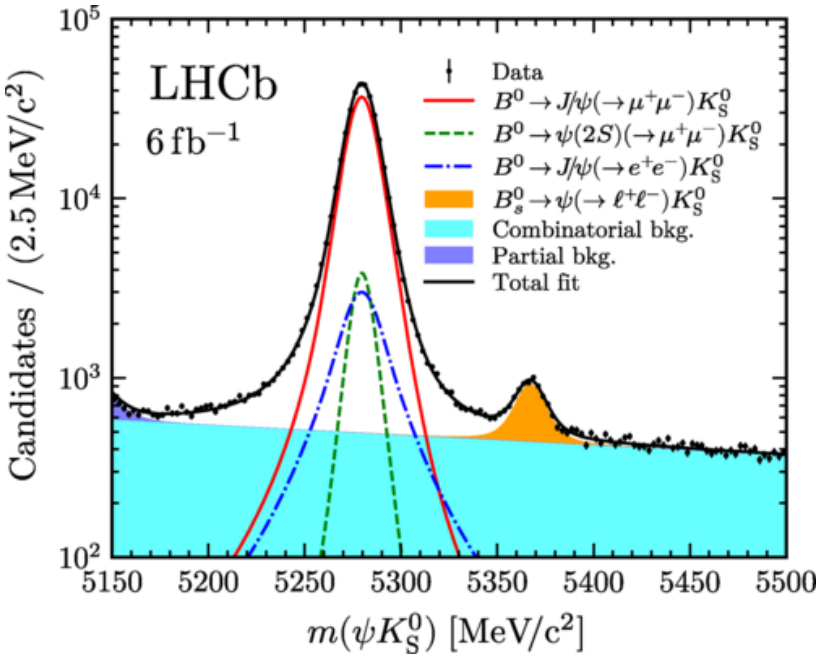
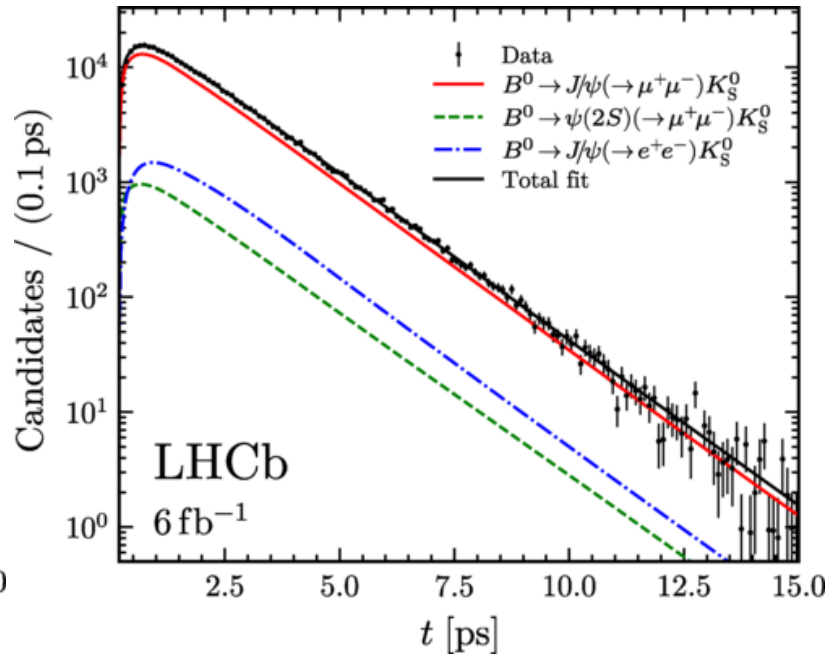
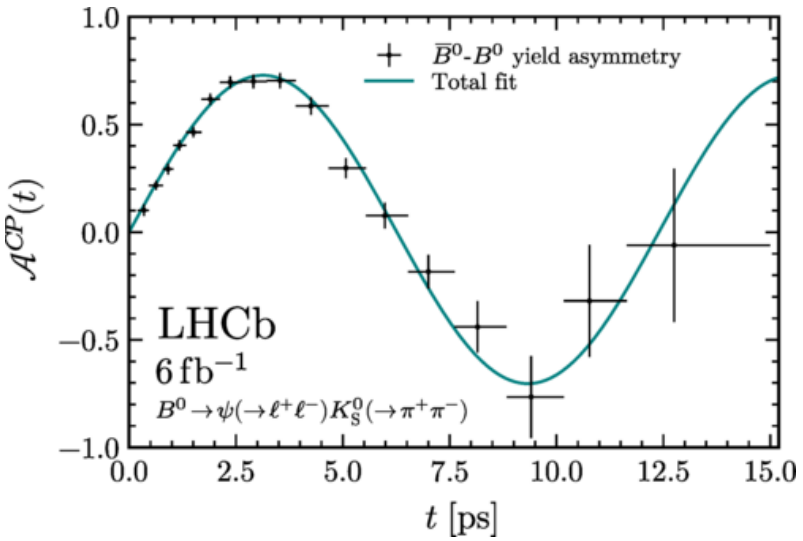
Latest measurement of S by LHCb







- Signal yield: ~ 370k events

Channel	ϵ_{tag} (%)	$\mathcal{D}^2$ (%)
$B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$	85.34 ± 0.05	4.661 ± 0.013
$B^0 \to J/\psi(\to e^+e^-)K^0_S$	92.20 ± 0.08	6.462 ± 0.032
$B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S$	84.81 ± 0.15	4.59 ± 0.04

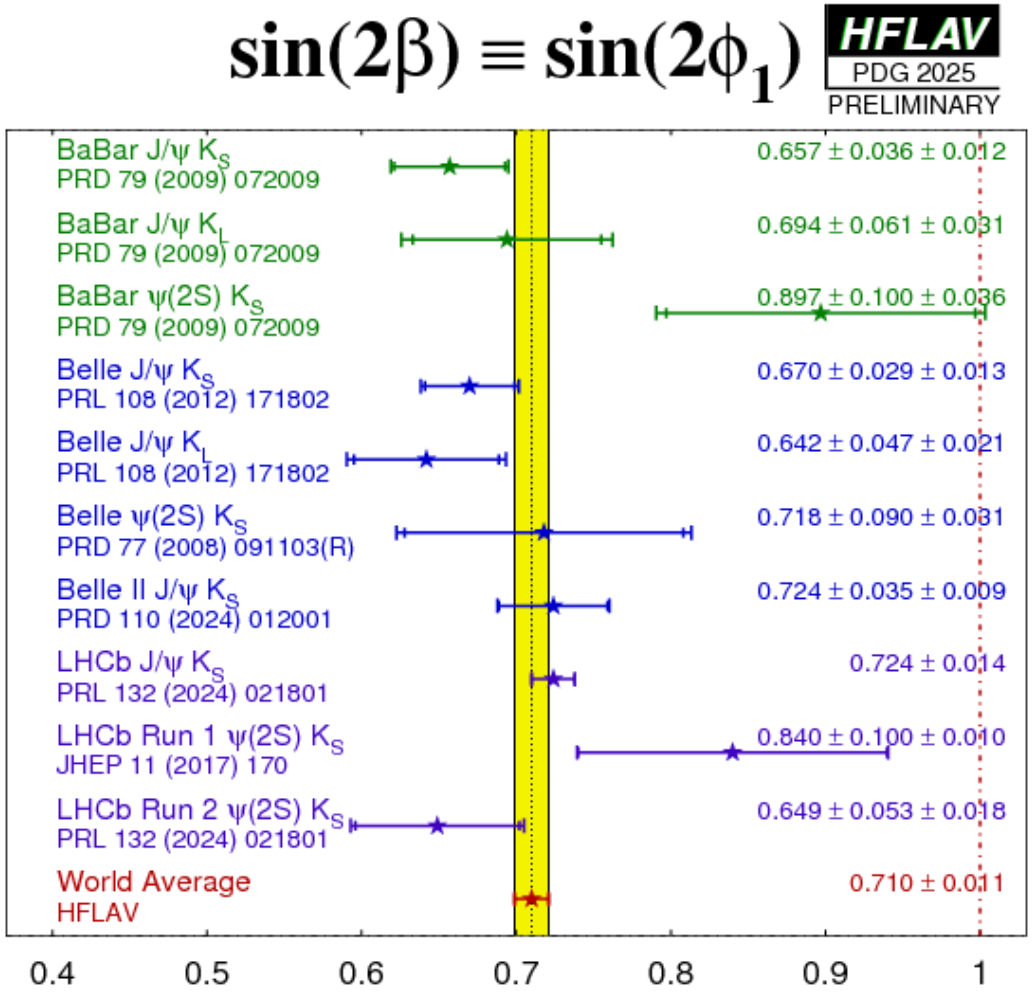
$$S^{\text{Run 1\&2}}_{\psi K^0_S} = 0.724 \pm 0.014(\text{stat} + \text{syst})$$
$$C^{\text{Run 1\&2}}_{\psi K^0_S} = 0.004 \pm 0.012(\text{stat} + \text{syst})$$

$$S_{\psi K^0_S} = 0.717 \pm 0.013(\text{stat}) \pm 0.008(\text{syst})$$
$$C_{\psi K^0_S} = 0.008 \pm 0.012(\text{stat}) \pm 0.003(\text{syst})$$

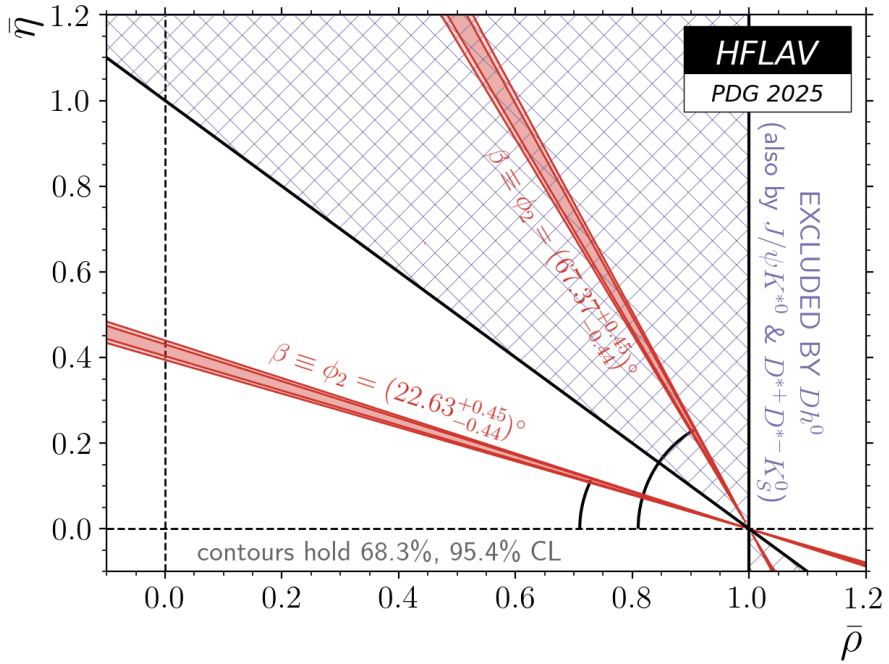
- Most precise single measurement of the CKM angle β.
- Consistent with the Belle II measurement (PRD 111(2024) 012001)

$$S = 0.724 \pm 0.035 \pm 0.009$$
$$C = -0.035 \pm 0.026 \pm 0.029$$

World Average of *S* for $b \to c\bar{c}s$



S for $B^0 \to J/\psi\, K_s^0$ is equal to 0.712 ± 0.011



- Investigate further the closeness of *S* to sin(2β)
- Within SM, use flavor-SU(3) relations and measurements of $B_{u,d,s} \to J/\psi\pi(K)$ *CP* asymmetries to make predictions for yet unmeasured observables (see e.g. arxiv: 2506.21675)

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First Evidence for Direct CP violation in Beauty to Charmonium Decays

CKM suppressed – penguin enhanced $B^+ \to J/\psi\pi^+$

(Relative to favored $B^+ \to J/\psi K^+$)

PRL 134 (2025) 101801

$\sqrt{s} = 13$ TeV, 5.4 fb^{-1}

Analysis Results

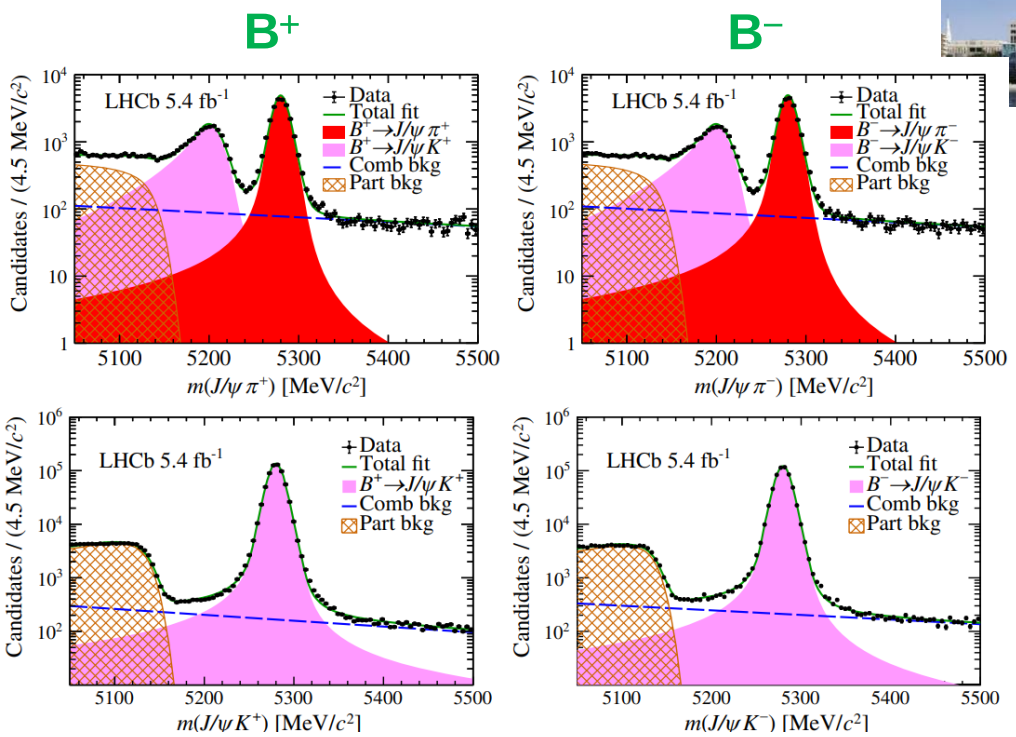
$\mathcal{A}^{CP}$ is the decay rate asymmetry between the B^- and B^+ mesons.

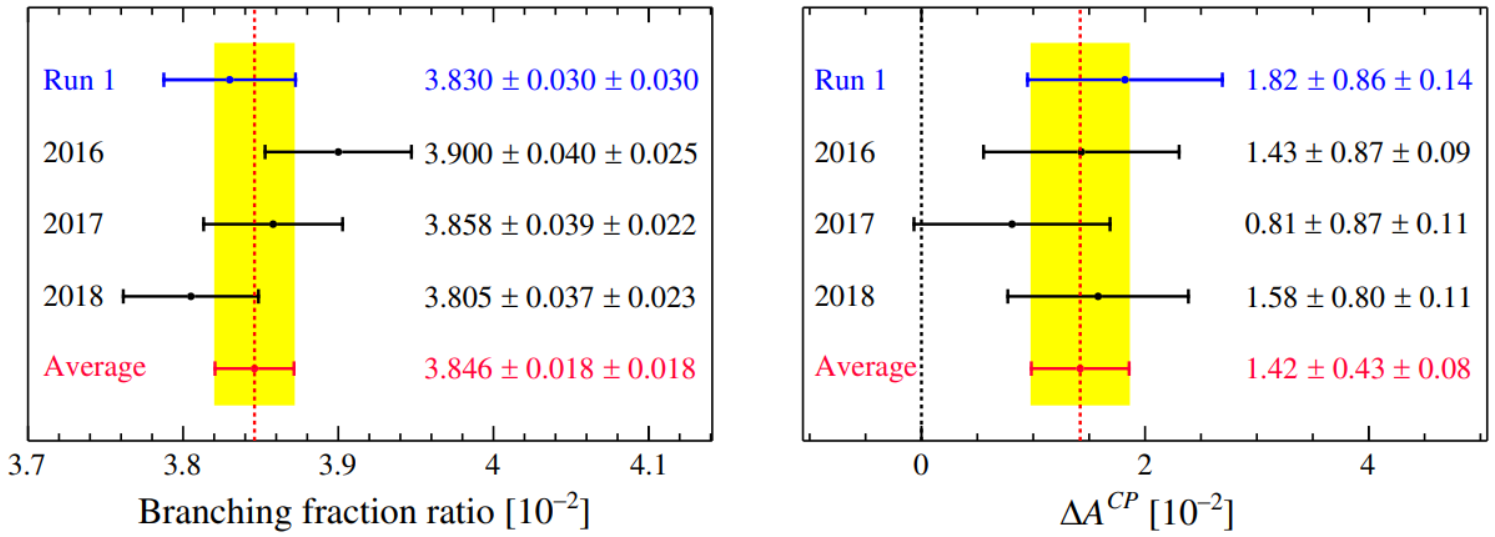
$$\Delta\mathcal{A}^{CP} \equiv \mathcal{A}^{CP}(B^+ \to J/\psi\pi^+) - \mathcal{A}^{CP}(B^+ \to J/\psi K^+)$$

$$\mathcal{R}_{\pi/K} \equiv \frac{\mathcal{B}(B^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$$

$$\mathcal{R}_{\pi/K} = (3.852 \pm 0.022 \pm 0.018) \times 10^{-2},$$
$$\Delta\mathcal{A}^{CP} = (1.29 \pm 0.49 \pm 0.08) \times 10^{-2}.$$

Run 2 avg





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Analysis results

- Combining the Run 1 and Run 2 LHCb results yields:

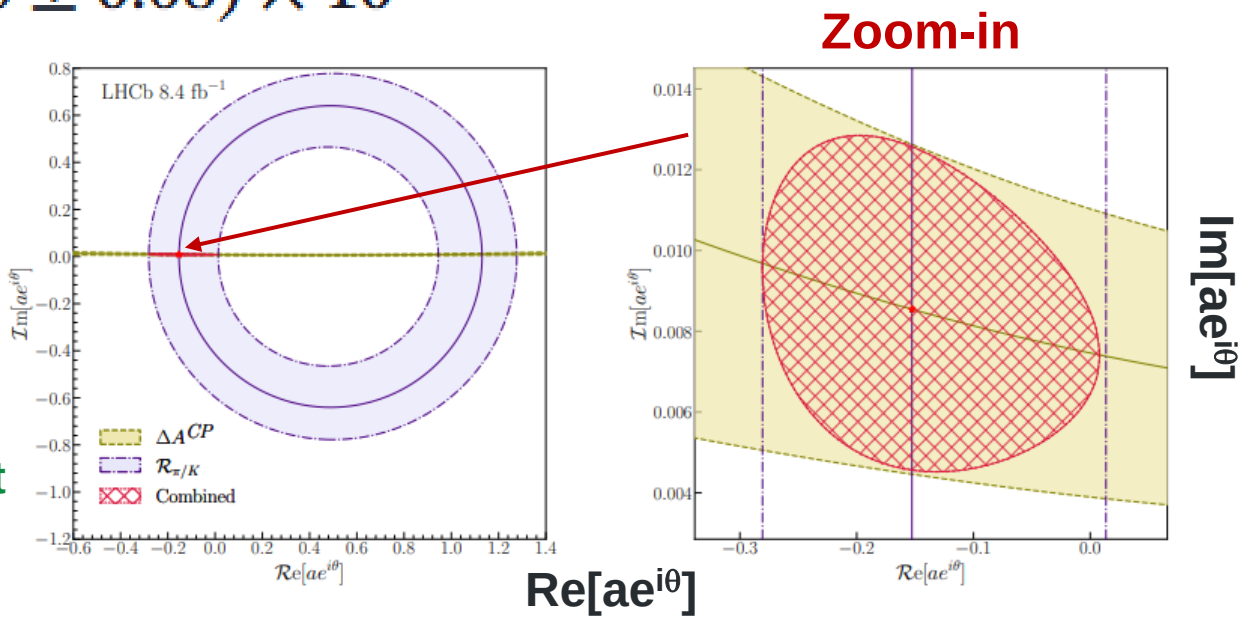
$$\mathcal{R}_{\pi/K} = (3.846 \pm 0.018 \pm 0.018) \times 10^{-2},$$
$$\Delta\mathcal{A}^{CP} = (1.42 \pm 0.43 \pm 0.08) \times 10^{-2}.$$

- $\Delta\mathcal{A}^{CP}$ deviates from zero by 3.2 standard deviations
- **First evidence** for direct CP violation in Beauty decays to charmonium

$$\mathcal{A}^{CP}(B^+ \to J/\psi\pi^+) = (1.51 \pm 0.50 \pm 0.08) \times 10^{-2}$$

- Follow-up constraints on the relative size and strong phase diff between the penguin contribution and the tree contribution

$\Delta\mathcal{A}^{CP}$ **: Strong constraint on imaginary part**



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Measurement of the time-dependent CP violation in B_s^0 mesons

$B_s^0 \rightarrow J/\psi\, \varphi(1020) \rightarrow \mu^+\mu^- K^+ K^-$

(final state is a mixture of CP-even and CP-odd components)

arXiv: 2412.19952

$\sqrt{s} = 13$ TeV, 96.5 fb^{-1}

PRL 132(2024) 051802

$\sqrt{s} = 13$ TeV, 6 fb^{-1}

EPJ C81(2021) 342

$\sqrt{s} = 13$ TeV, 80.5 fb^{-1}

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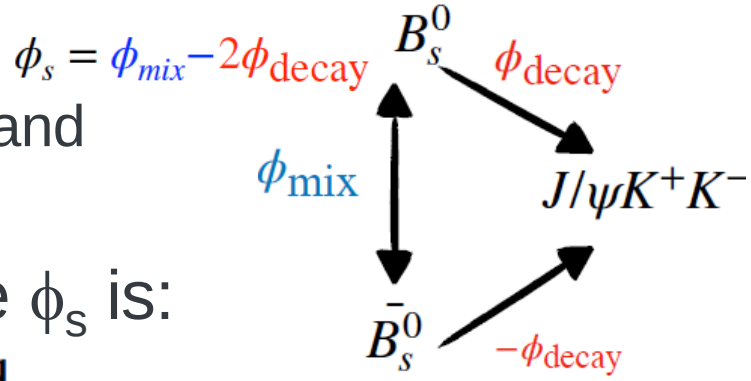
Motivation and SM expectation

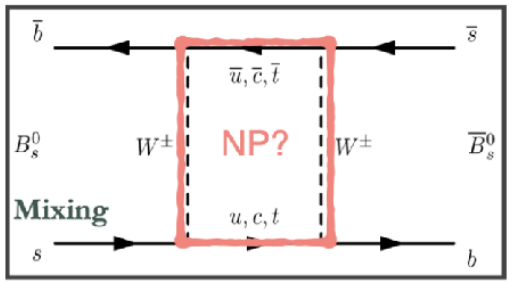
- Decays of the B_s^0 meson allow for the study of time-dependent *CP* violation generated by the interference between direct decays and flavor mixing.
  - This requires a measurement that depends on time, flavor and angular distributions



- The Standard Model (SM) prediction for the weak phase ϕ_s is:

$$\phi_s \approx -2\beta_s = -2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx -37 \pm 1\,\text{mrad}$$

- New Physics (NP) can change ϕ_s significantly (up to O(100%))



$$a_{CP}(t) \propto \Gamma_{\bar{B}_s \to f}(t) - \Gamma_{B_s \to f}(t)$$
$$\propto -\eta_{fs} \sin(\phi_s) \sin(\Delta m_s t)$$

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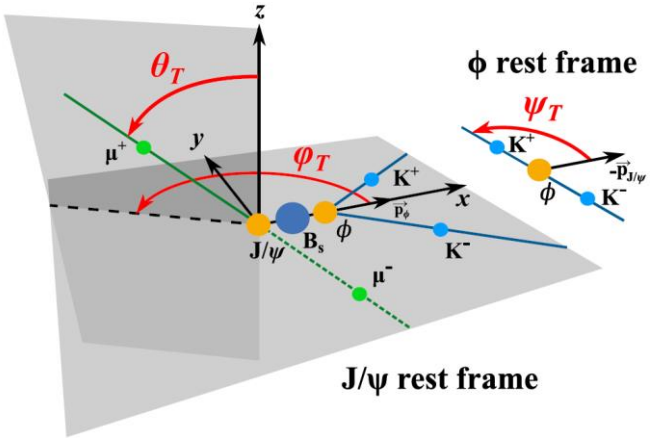
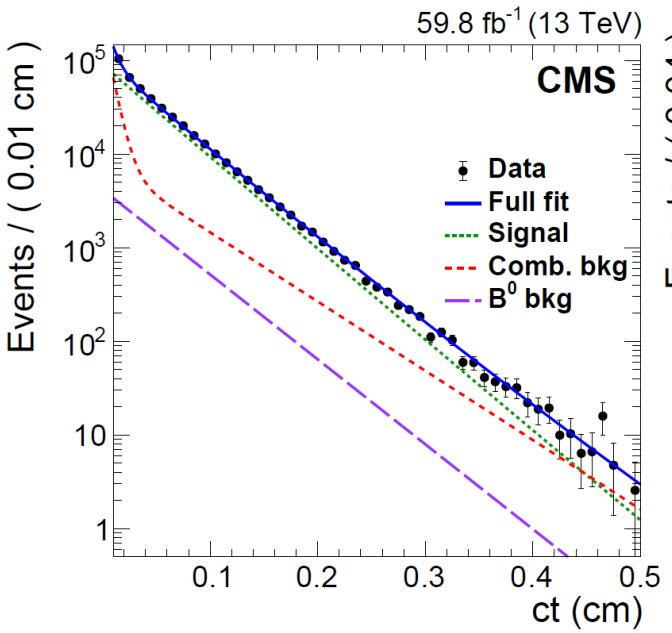
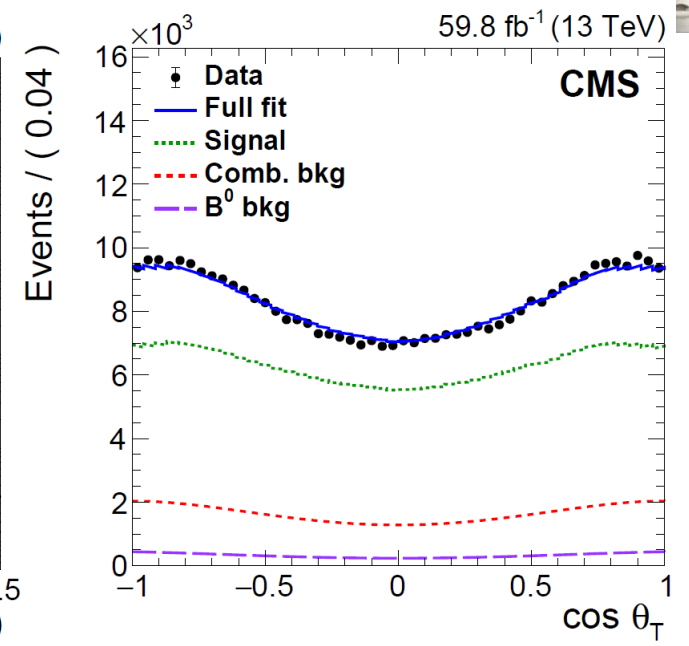
ϕ_s in CMS

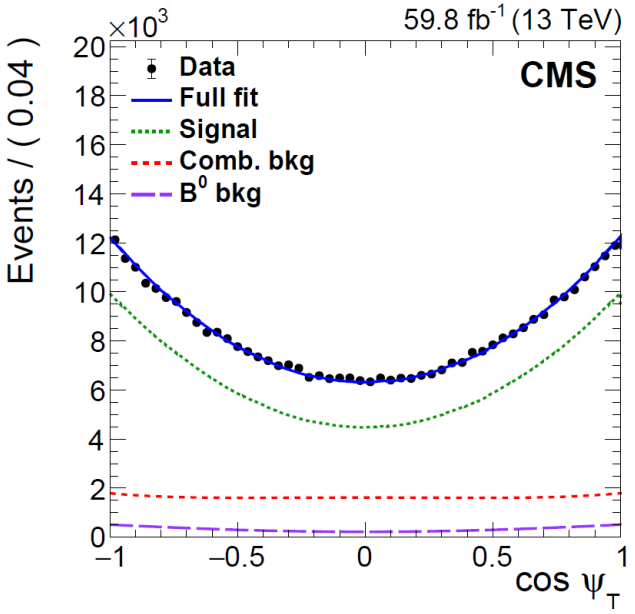


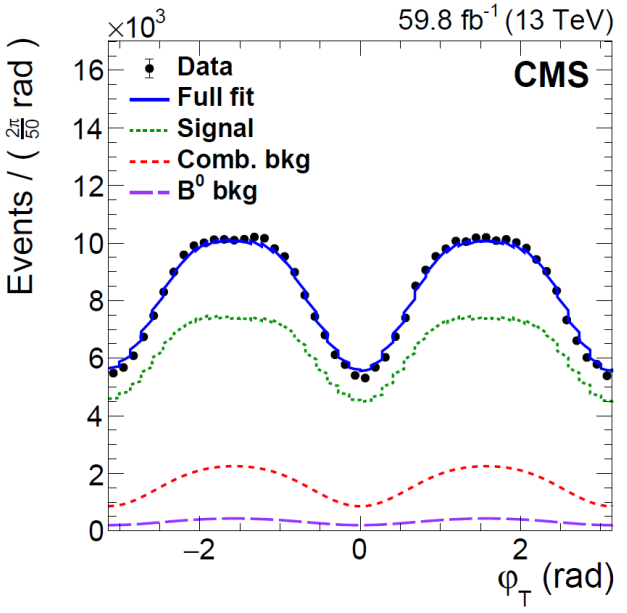
- Signal yield: ~ 491k events
- Tagging power: ~5.6%

Parameter	Fit value	Stat. unc.	Syst. unc.
ϕ_s [mrad]	−73	± 23	± 7
$\Delta\Gamma_s$ [ps^{-1}]	0.0761	± 0.0043	± 0.0019
Γ_s [ps^{-1}]	0.6613	± 0.0015	± 0.0028
Δm_s [$\hbar$ps^{-1}]	17.757	± 0.035	± 0.017
$\lvert\lambda\rvert$	1.011	± 0.014	± 0.012









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ϕ_s in CMS - Combining with 8 TeV results

- These 13 TeV results are combined with the similar CMS results at 8 TeV (PLB8TeV) yielding:

$$\phi_s = -74 \pm 23 \text{ [mrad]}$$
$$\Delta\Gamma_s = 0.0780 \pm 0.0045 \text{ [ps}^{-1}\text{]}$$

- Both values above are compatible with SM predictions
- The ϕ_s value is consistent with zero (no CPV) at 3.2 standard deviations
- **First evidence** for mixing induced CPV in $\mathbf{B_s^0 \to J/\psi\, \varphi(1020)}$ decays

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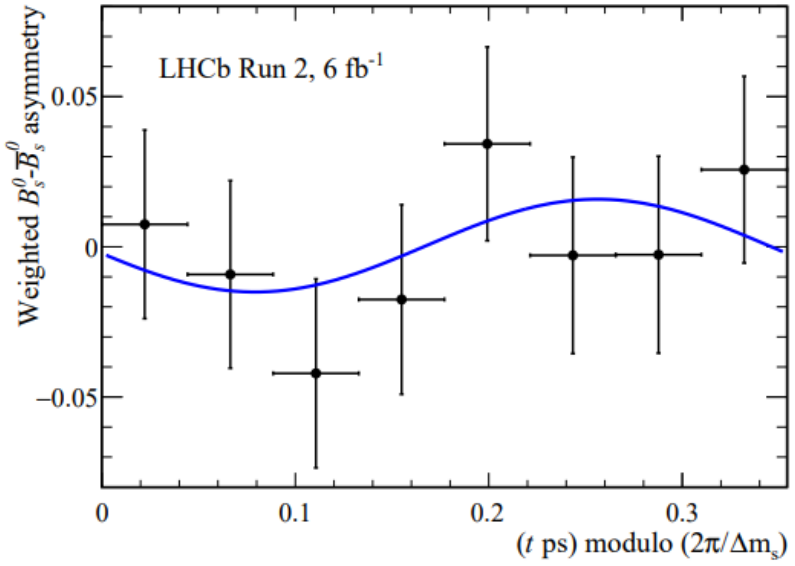
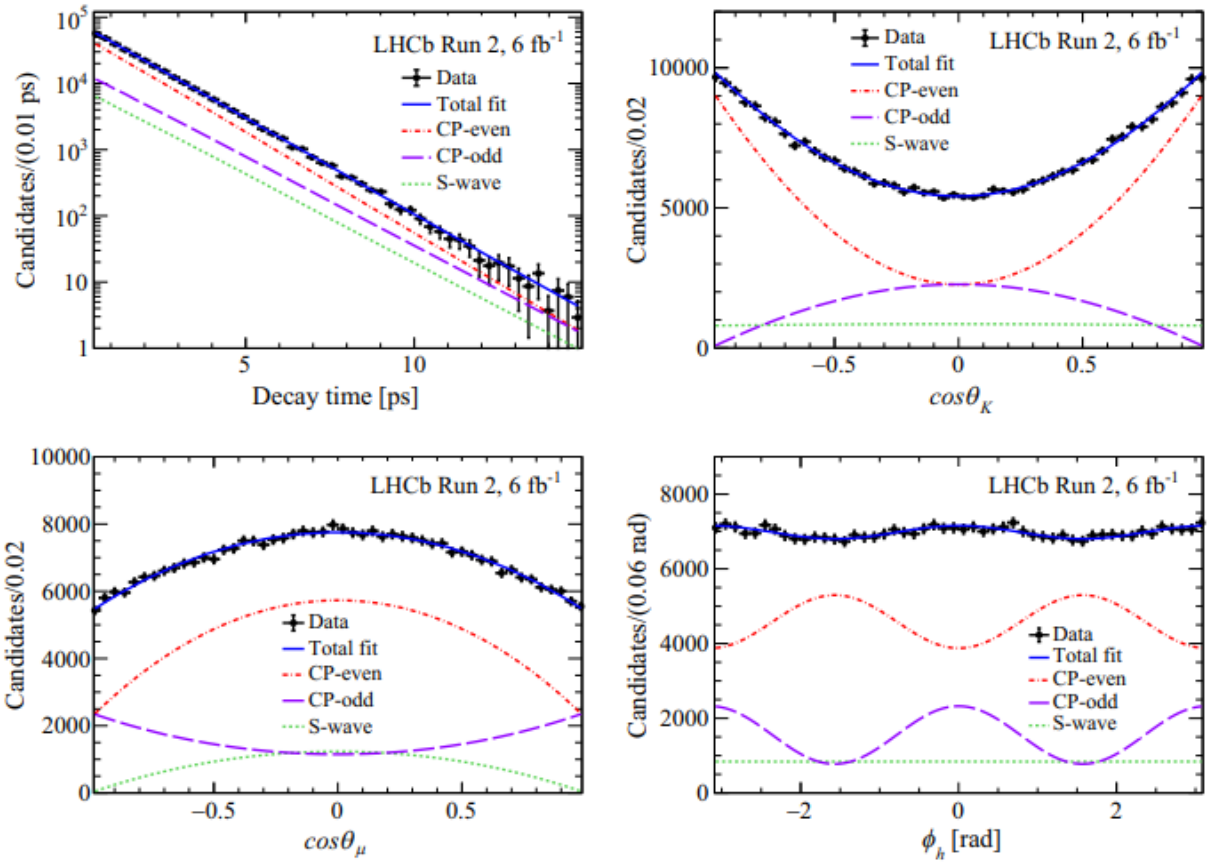
ϕ_s in LHCb

- Signal yield: ~ 349k events
- Tagging power: ~4.3%
  - See also **talk by Jonah E. Blank** at the Computing AI/ML 1 parallel session

Asymmetry between B_s^0 and $\bar{B}_s^0$ decays as a function of the decay time





Parameter		Values	
ϕ_s [rad]	−0.039	±0.022	±0.006
$\lvert\lambda\rvert$	1.001	±0.011	±0.005
$\Gamma_s - \Gamma_d$ [ps^{-1}]	−0.0056	$^{+0.0013}_{-0.0015}$	±0.0014
$\Delta\Gamma_s$ [ps^{-1}]	0.0845	±0.0044	±0.0024

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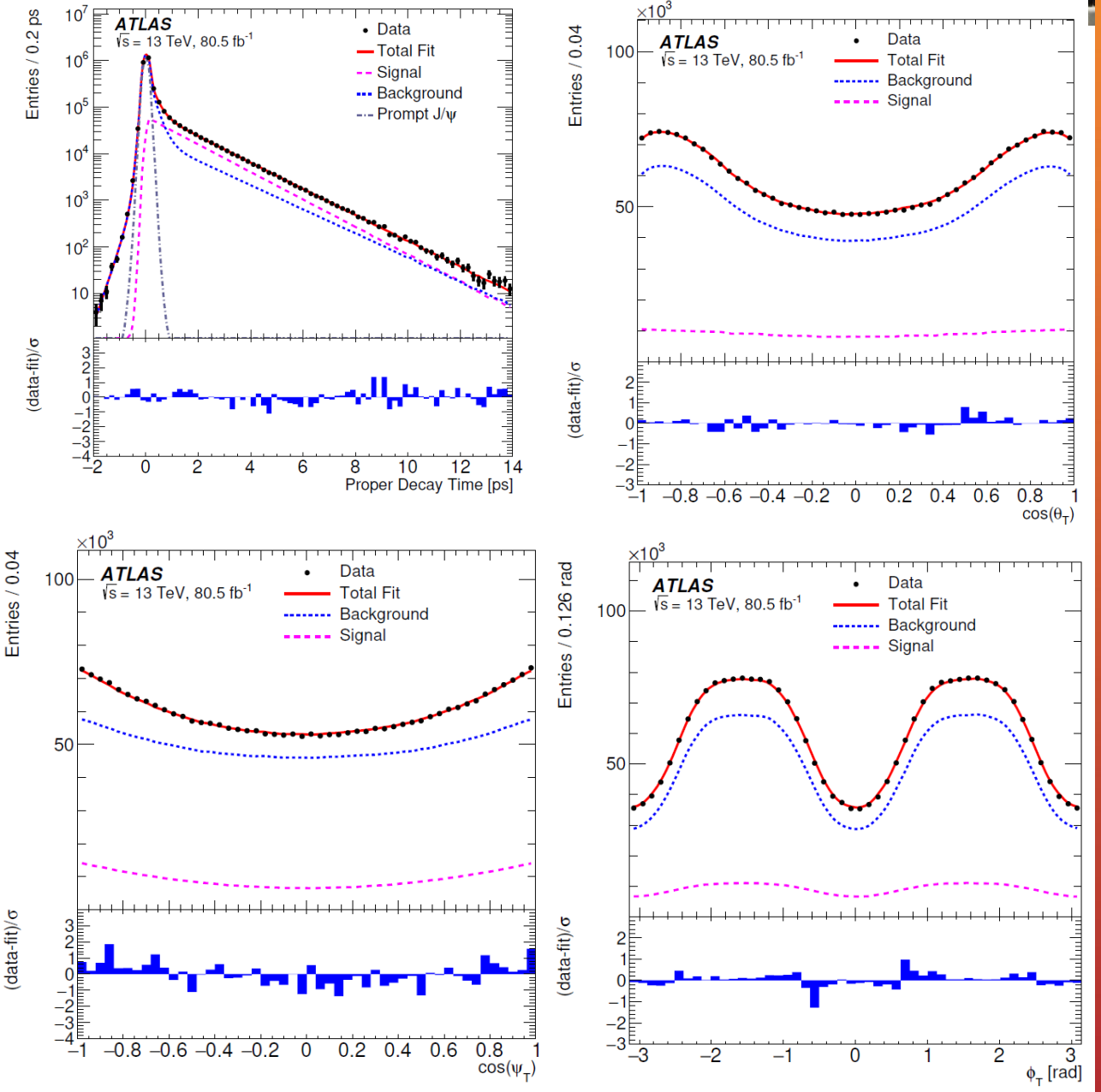
ϕ_s in ATLAS

- Signal yield: ~ 450k events
- Tagging power: ~1.8%

$$\phi_s = -0.087 \pm 0.036 \text{ (stat.)} \pm 0.021 \text{ (syst.) rad}$$
$$\Delta\Gamma_s = 0.0657 \pm 0.0043 \text{ (stat.)} \pm 0.0037 \text{ (syst.) ps}^{-1}$$
$$\Gamma_s = 0.6703 \pm 0.0014 \text{ (stat.)} \pm 0.0018 \text{ (syst.) ps}^{-1}$$



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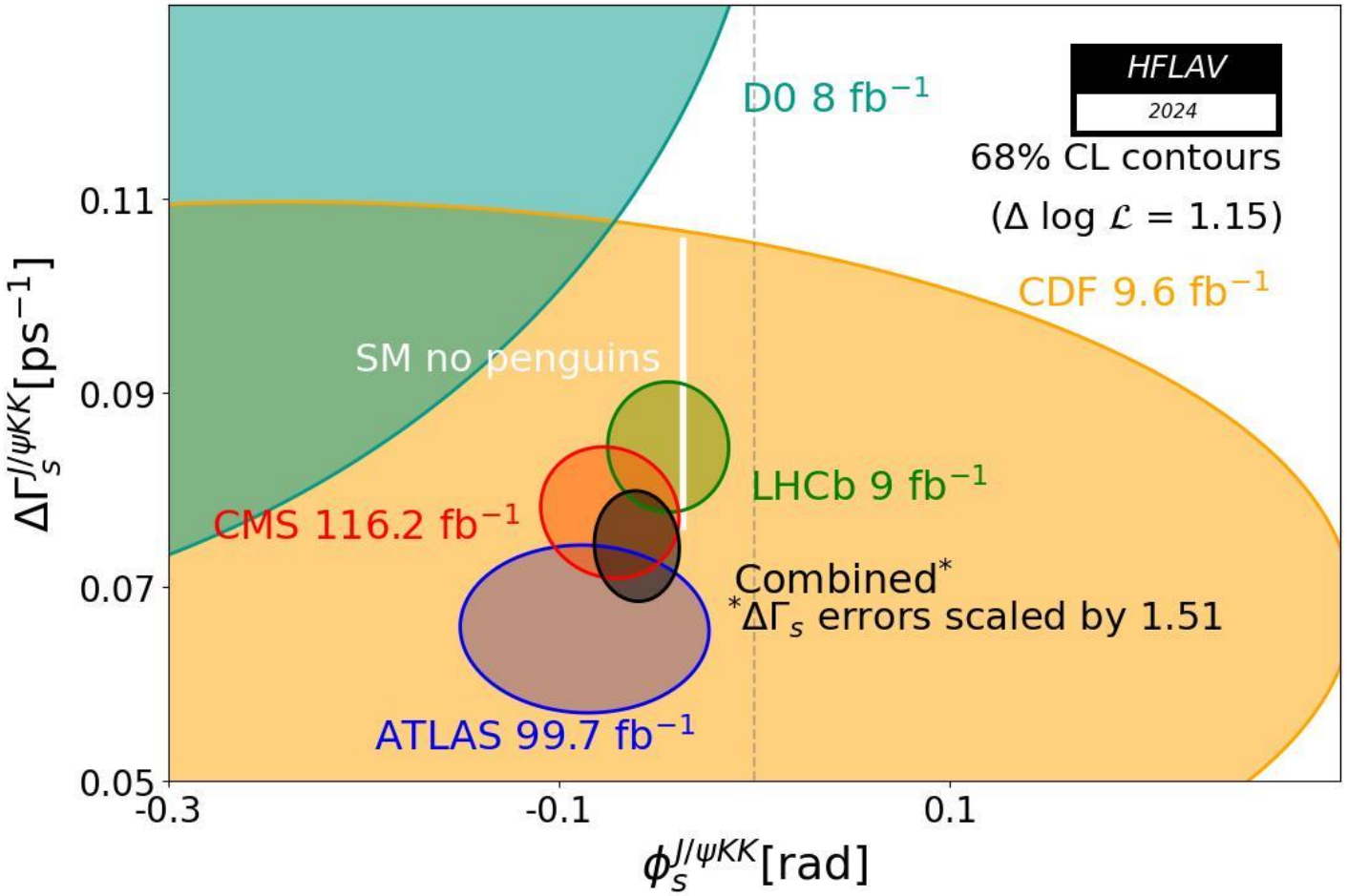
World average of ϕ_s - $B_s^0 \rightarrow J/\psi\ \varphi(1020)$



$$\beta_s = \arg(-(V_{ts}\, V_{tb}^*)/(V_{cs}\, V_{cb}^*))$$

$$\phi_s\ (B_s^0 \rightarrow J/\psi\ \varphi(1020)) \approx -2\beta_s\ (B_s^0 \rightarrow J/\psi\ \varphi(1020)) = -\ 0.060 \pm 0.014\ \text{rad}$$

$\varphi_s^{\bar{c}cs}$	-0.052 ± 0.013 rad

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Updated Measurement of CP violation and polarization in $B_s^0 \to J/\psi \overline{K}^*(892)^0$ decays

$K^-\pi^+$

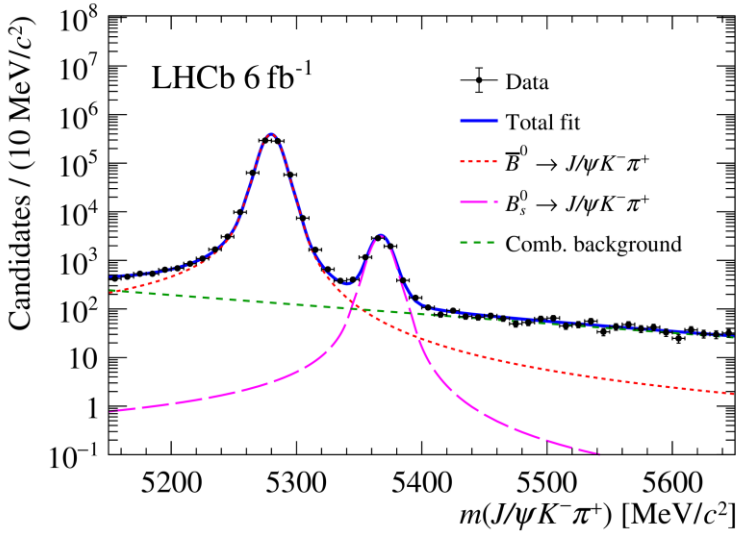
ArXiv:2506.22090

$\sqrt{s} = 13$ TeV, 6.0 fb^{-1}

Time integrated angular analysis performed

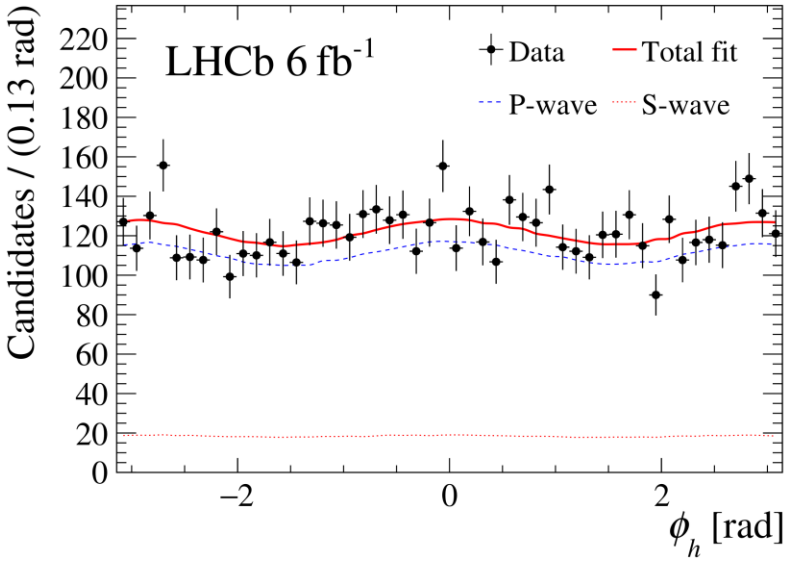
Measurement can be used to control the penguin pollution in the ϕ_s measurement with $B_s \to J/\psi\phi$

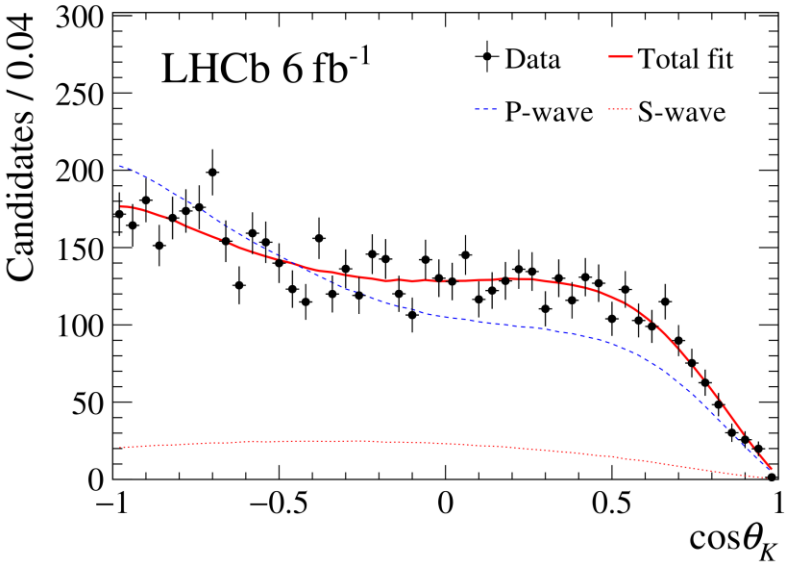
Analysis Results

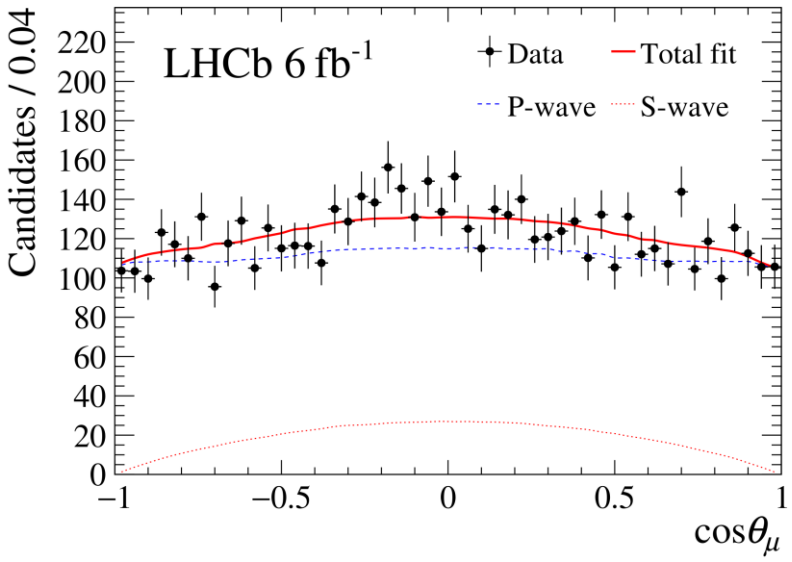


- B^0 yield: ~ 727k events
- B_s^0 yield: ~ 6.1k events

- Un-binned maximum-likelihood fit to the three helicity angles performed
- Projections of the angular fit result onto the helicity angles for the background subtracted data sample







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Analysis Results

- P-wave polarization fractions:

$$f_0 = 0.534 \pm 0.012\,(\text{stat}) \pm 0.009\,(\text{syst})$$ Longitudinal
$$f_\parallel = 0.211 \pm 0.014\,(\text{stat}) \pm 0.005\,(\text{syst})$$ Parallel

- P-wave direct CP asymmetries, consistent with zero

$$A_0^{CP} = 0.014 \pm 0.029\,(\text{stat}) \pm 0.007\,(\text{syst})$$
$$A_\parallel^{CP} = -0.055 \pm 0.065\,(\text{stat}) \pm 0.007\,(\text{syst})$$
$$A_\perp^{CP} = 0.060 \pm 0.057\,(\text{stat}) \pm 0.016\,(\text{syst})$$

Partial decay rates

$$A_k^{CP} = \frac{\overline{\Gamma}_k - \Gamma_k}{\overline{\Gamma}_k + \Gamma_k} \quad (k = 0, \parallel, \perp, S)$$

Phases

$\delta_\parallel = 2.879 \pm 0.087$

$\delta_\perp = 0.057 \pm 0.068$

- Combining with Run 1:

$$f_0 = 0.528 \pm 0.011\,(\text{stat}) \pm 0.009\,(\text{syst})$$
$$f_\parallel = 0.205 \pm 0.012\,(\text{stat}) \pm 0.005\,(\text{syst})$$
$$A_0^{CP} = 0.021 \pm 0.026\,(\text{stat}) \pm 0.007\,(\text{syst})$$
$$A_\parallel^{CP} = -0.073 \pm 0.060\,(\text{stat}) \pm 0.007\,(\text{syst})$$
$$A_\perp^{CP} = 0.057 \pm 0.049\,(\text{stat}) \pm 0.014\,(\text{syst})$$

Most accurate to date

Additional improvements coming with larger datasets and better precision

$$\frac{\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})} = (3.12 \pm 0.09\,(\text{stat}) \pm 0.06\,(\text{syst}) \pm 0.10\,(\frac{f_d}{f_s}))\%$$

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Measurement of time-dependent *CP* asymmetry in $B_s^0 \to D_s^{\pm} K^{\mp}$ decays

Determine angle γ

JHEP 2503 (2025) 139

$\sqrt{s} = 13$ TeV, 6.0 fb^{-1}

More information presented on Tuesday in the "*Quark Flavor 1*" parallel session by Aidan Wiederhold

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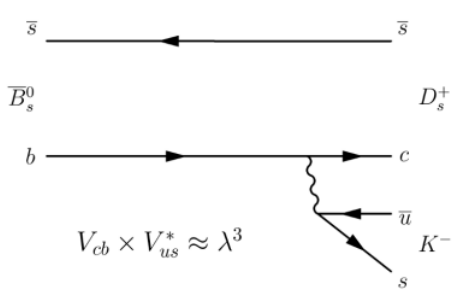
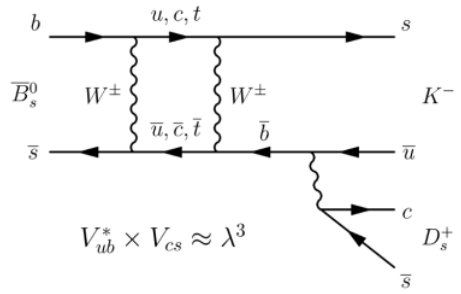
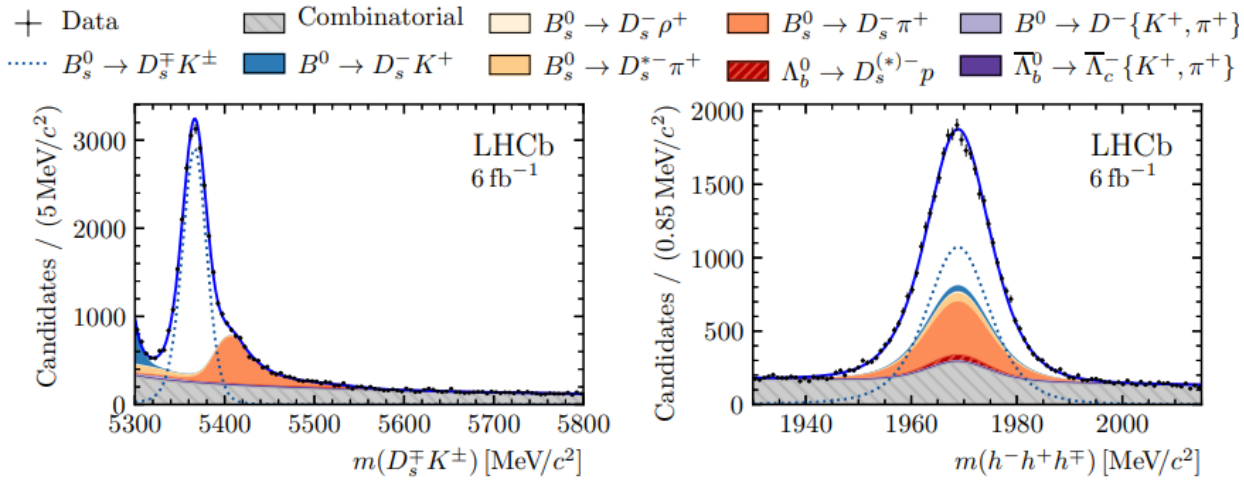
Analysis Results

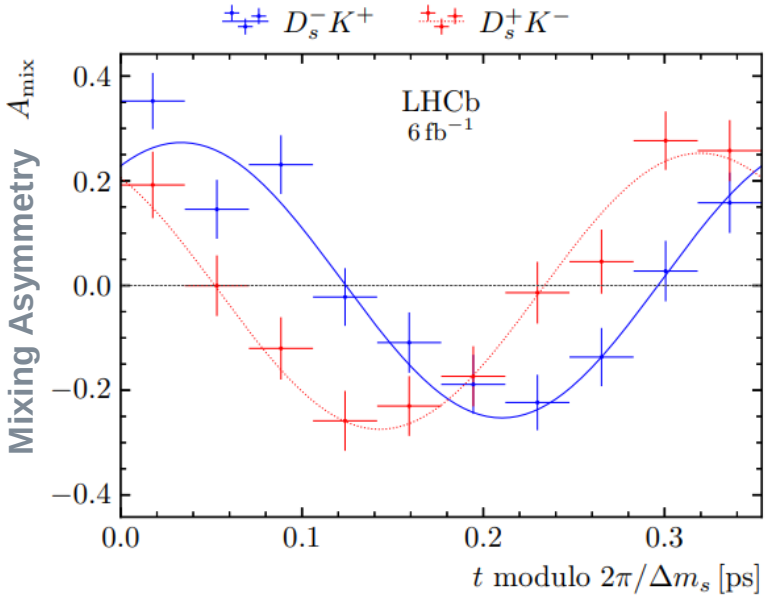
~21k $B_s^0 \to D_s^{\pm} K^{\mp}$

With B_s^0–$\overline{B}_s^0$ mixing









$$\frac{\mathrm{d}\Gamma_{B_s^0 \to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos\left(\Delta m_s t\right) - S_f\sin\left(\Delta m_s t\right)\right]$$

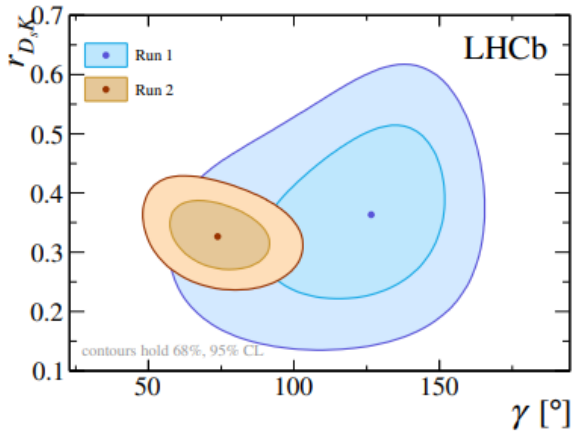
Parameter	Value
C_f	$0.791 \pm 0.061 \pm 0.022$
$A_f^{\Delta\Gamma}$	$-0.051 \pm 0.134 \pm 0.058$
$A_{\bar{f}}^{\Delta\Gamma}$	$-0.303 \pm 0.125 \pm 0.055$
S_f	$-0.571 \pm 0.084 \pm 0.023$
$S_{\bar{f}}$	$-0.503 \pm 0.084 \pm 0.025$

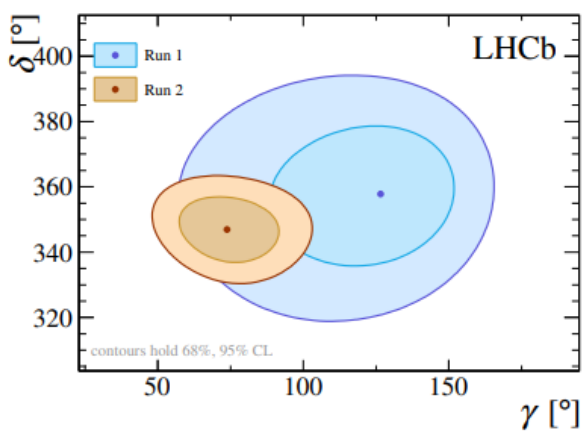
CPV in the Interference between B_s^0–$\overline{B}_s^0$ mixing and $B_s^0 \to D_s^{\mp} K^{\pm}$ decays is observed with significance of 8.6σ

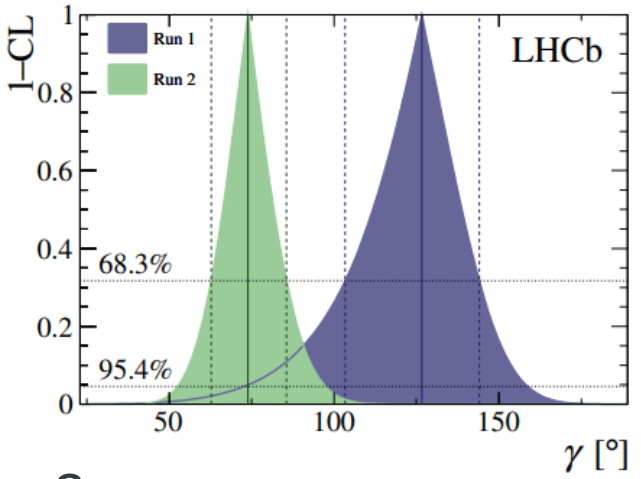
$S_f \neq -S_{\bar{f}}$

Analysis Results

- The results are used to determine the CKM angle γ, the strong-phase difference δ and the magnitude of the ratio r_{DsK} between the $B_s^0 \to D_s^+ K^-$ and the $B_s^0 \to D_s^- K^+$ decay amplitudes







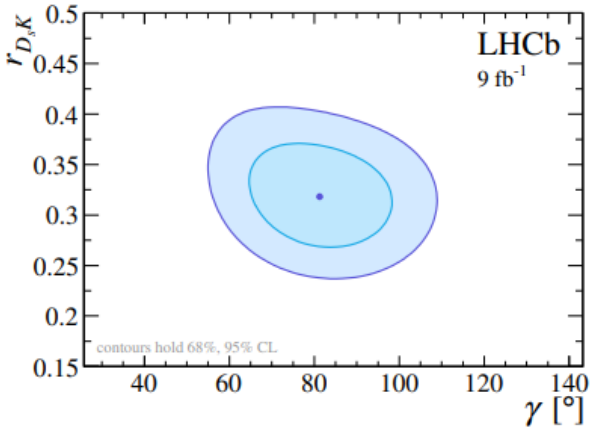
$$\gamma = (127^{+18}_{-26})^\circ\,,$$
$$\delta = (358^{+14}_{-15})^\circ\,,$$
$$r_{D_sK} = 0.364^{+0.095}_{-0.094}$$

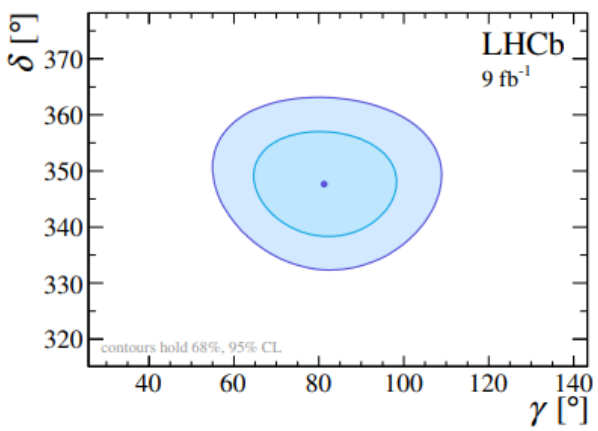
Run 1

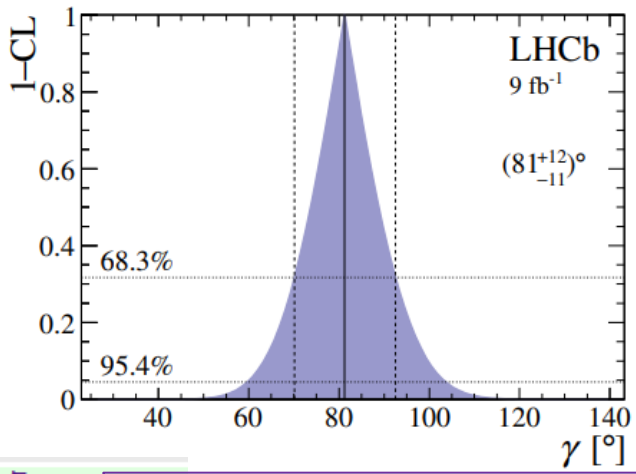
$$\gamma = (74 \pm 12)^\circ\,,$$
$$\delta = (346.9^{+6.8}_{-6.6})^\circ\,,$$
$$r_{D_sK} = 0.327^{+0.039}_{-0.037}\,,$$

Run 2

- Combining Run 1 (JHEP 03 (2018) 059) with Run 2:







$$\gamma = (81^{+12}_{-11})^\circ\,,$$
$$\delta = (347.6 \pm 6.3)^\circ$$
$$r_{D_sK} = 0.318^{+0.034}_{-0.033}\,.$$

The most precise determination of angle γ in B_s^0 meson decays

$$\gamma \equiv \phi_3 = (66.4^{+2.7}_{-2.8})^\circ$$ WA: HFLAV, August 2025

Measurement of $D^0 - \bar{D}^0$ mixing and search for *CP* violation with $D^0 \to K^+\pi^-$ decays

PRD 111 012001 (2025)

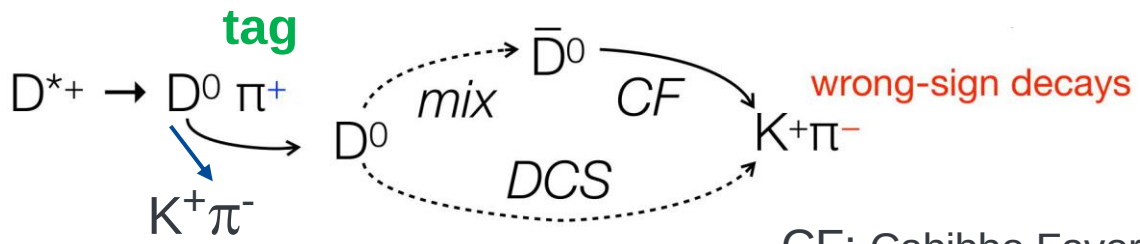
$\sqrt{s} = 13$ TeV, 6 fb^{-1}

Search for *CP* violation in semileptonically tagged $D^0 \to K^+\pi^-$ decays

ArXiv:2501.11635 , JHEP(2025)149

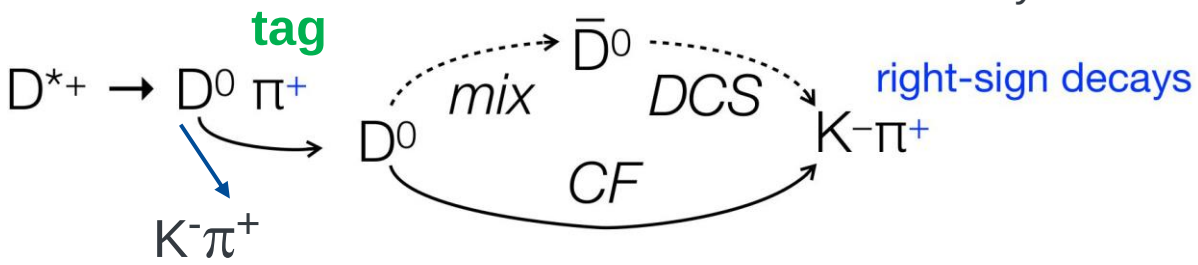
$\sqrt{s} = 13$ TeV, 5.4 fb^{-1}

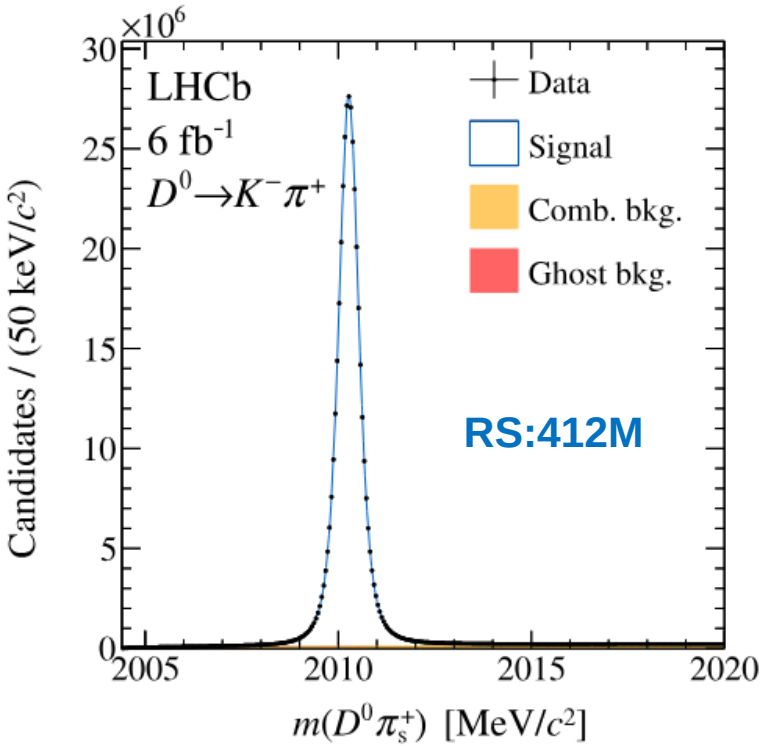
D^0 – $\bar{D}^0$ mixing and decay rates



CF: Cabibbo Favored

DCS: Doubly Cabibbo Suppressed





Measuring as a function of time:

$$R^{+}_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\bar{D}^0(t) \to K^+\pi^-)}$$

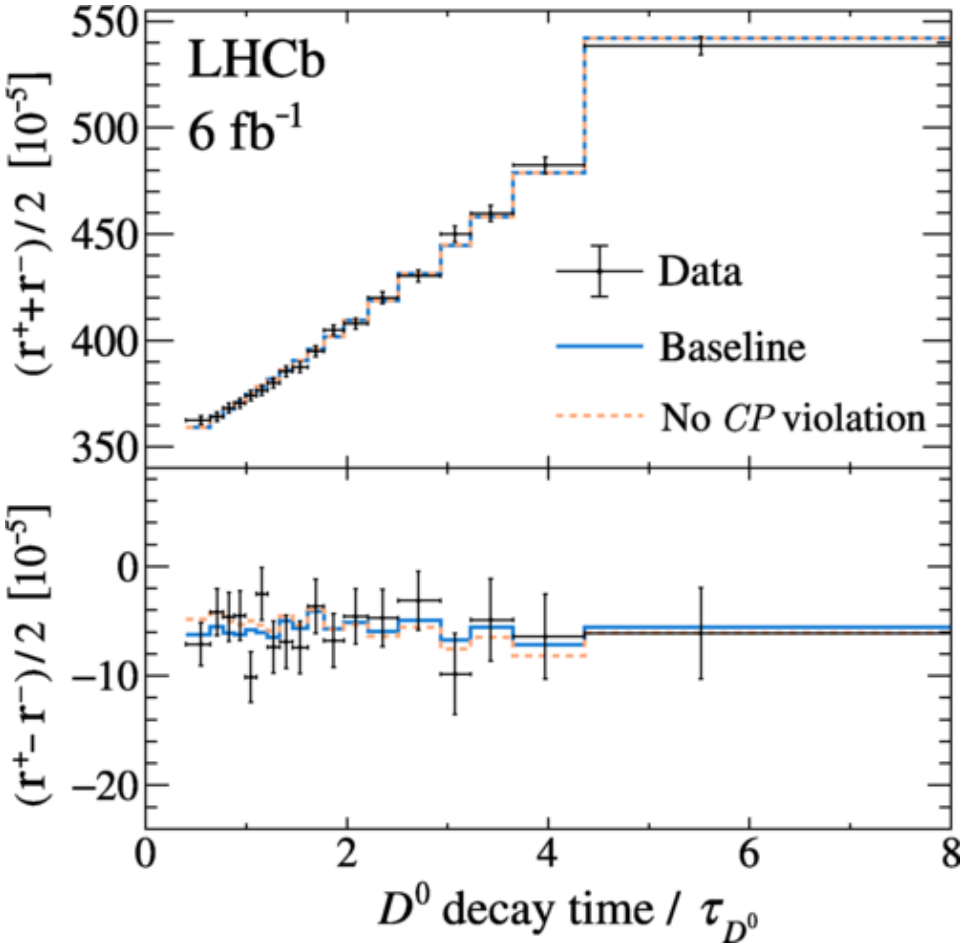
$$R^{-}_{K\pi}(t) \equiv \frac{\Gamma(\bar{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})t + (c'_{K\pi} \pm \Delta c'_{K\pi})t^2$$

No CPV implies: $A_{K\pi} = 0$, $\Delta c_{K\pi} = 0$ and $\Delta c'_{K\pi} = 0$

Analysis results – “single-tagged”

Prompt

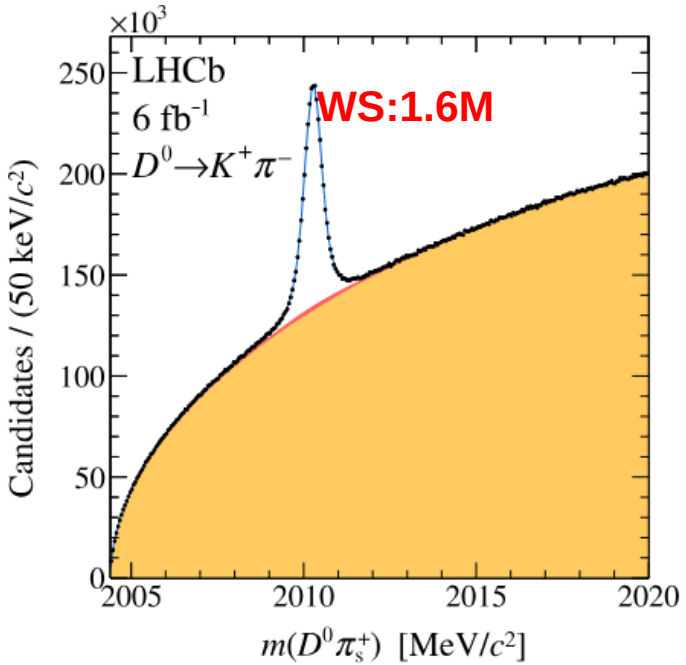


Half sum and half difference of measured WS to RS yields ratio vs decay time

$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

Non-zero t^2 term: 3.4 stand. dev.

Consistent with no CPV



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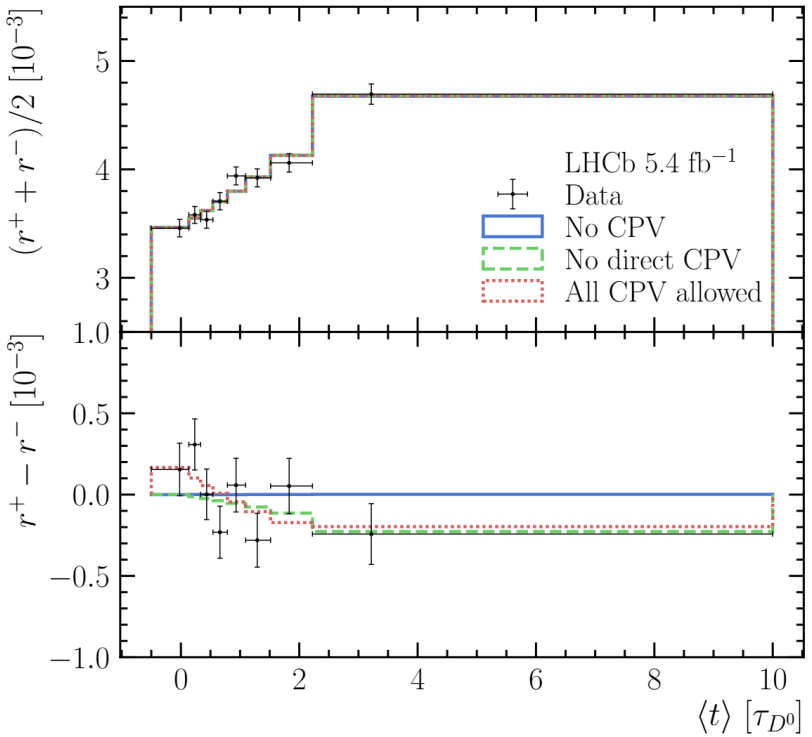
Analysis results – "double-tagged"

Smaller sample but larger purity

$$\overline{B} \to D^*(2010)^+ \mu^- X$$
$$D^0 \pi^+$$

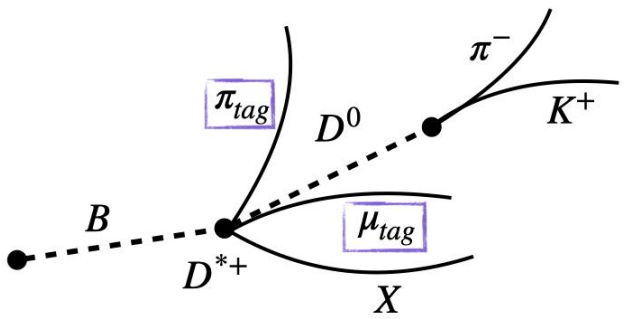


Half sum and half difference of measured WS to RS yields ratio vs decay time

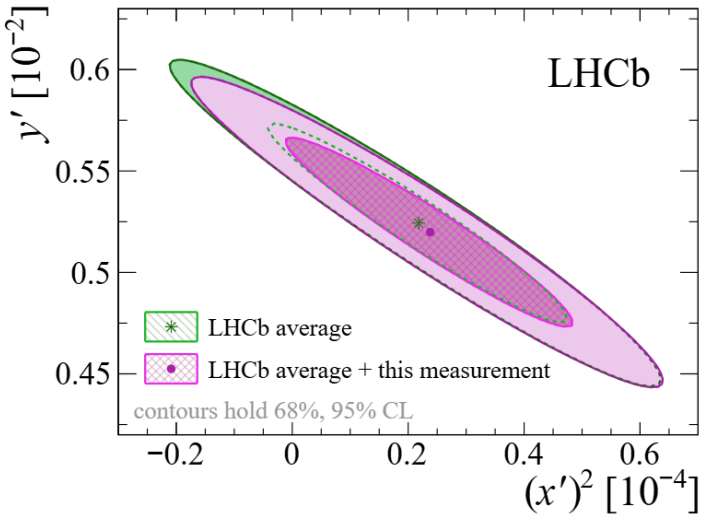
R_D	$(347.2 \pm 5.8) \times 10^{-5}$
$c_{K\pi}$	$(5.8 \pm 1.6) \times 10^{-3}$
$c'_{K\pi}$	$(0.9 \pm 2.6) \times 10^{-5}$
A_D	$(2.3 \pm 1.7) \times 10^{-2}$
$\Delta c_{K\pi}$	$(-2.3 \pm 1.6) \times 10^{-3}$
$\Delta c'_{K\pi}$	$(2.1 \pm 2.6) \times 10^{-5}$

Direct CP asymmetry

Consistent with no CPV



$$x \equiv \frac{\Delta M}{\overline{\Gamma}}$$
$$y \equiv \frac{\Delta \Gamma}{2\overline{\Gamma}}$$



$y' = (5.8 \pm 1.6 \pm 0.2) \times 10^{-3}$
$(x')^2 = (0.0 \pm 1.2 \pm 0.1) \times 10^{-4}$

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Search for *CP* violation in events with top quarks and Z bosons

(in the BSM context)

ArXiv:2505.21206

$\sqrt{s} = 13$ TeV & 13.6 TeV; 173 fb^{-1}

Run 3

More information presented earlier today in the "*Top Physics 3*" parallel session by Santosh Bhandari

ATLAS and CMS have published information on constraints and measurements of the $|V_{tb}|$, $|V_{td}|$ and $|V_{ts}|$ elements both within SM and BSM context that I will not cover here

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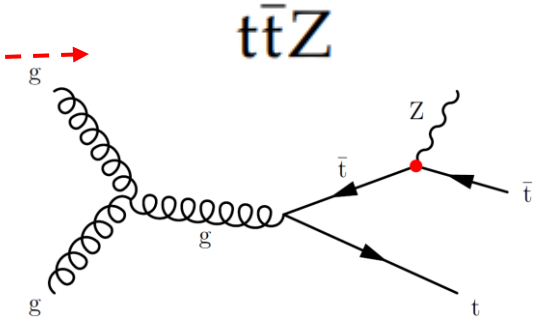
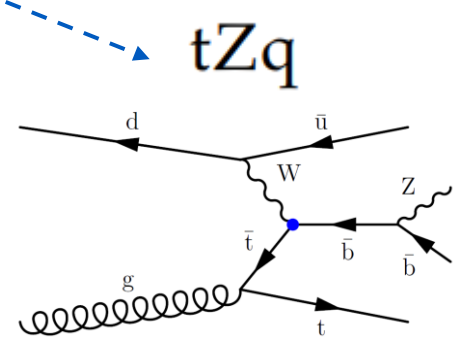
Motivation

- Explore CPV in associated production of a Z boson with a top quark pair or a single top quark.
- Inclusive & differential production xsec measured by ATLAS and CMS to be consistent with SM in observables that are invariant under *CP.*
- Search for CPV via Effective Field Theory (EFT) *CP*-odd operators.
- The highlighted (red/blue) couplings could be modified by $\mathcal{O}^{I}_{tW}$ and $\mathcal{O}^{I}_{tZ}$ dim-6 operators.
- For first time introducing CP-odd observables that enable direct access to the linear (interference) contribution from the operator.
- Sensitive to NP effects that do not modify the total xsec

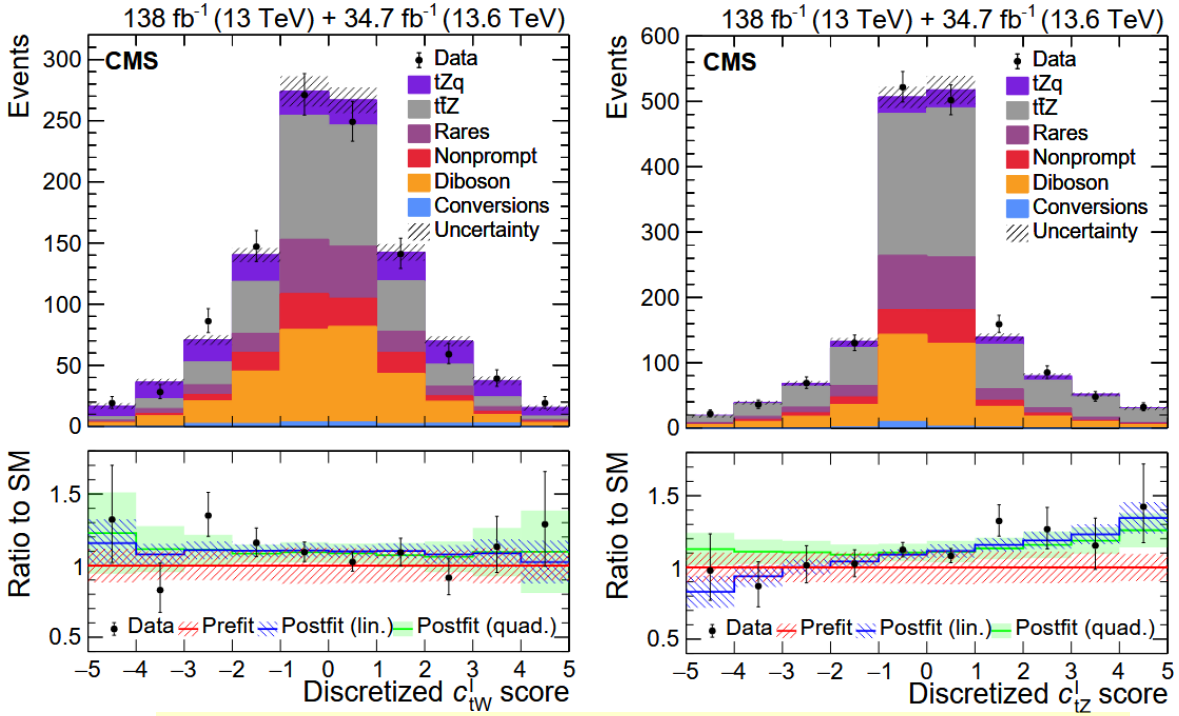




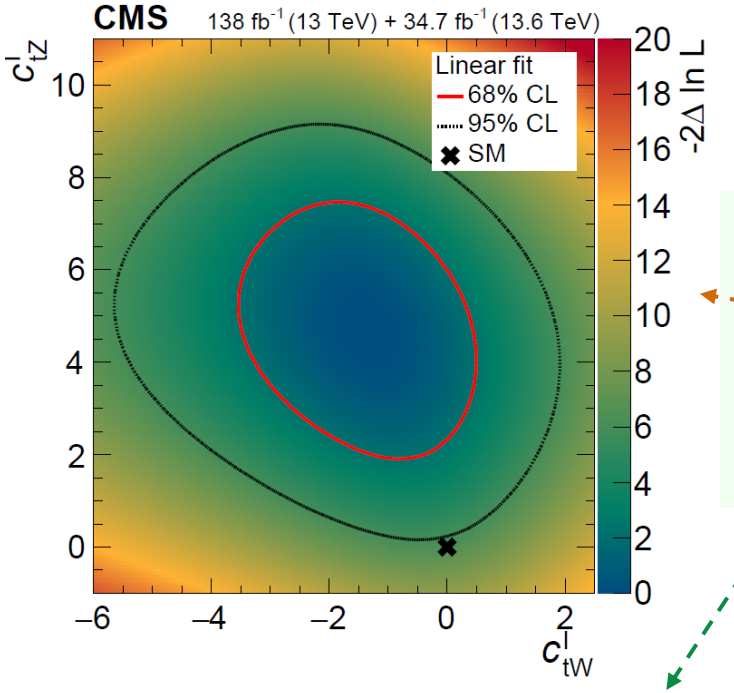
$$\frac{d\sigma}{d\mathcal{O}} \propto \underbrace{|\mathcal{M}_{\mathbf{SM}}|^2}_{\mathbf{SM}} + \underbrace{\sum_i \frac{C_i}{\Lambda^2} \cdot 2\,\mathrm{Re}\left[\mathcal{M}_{\mathbf{SM}}\mathcal{M}_i^*\right]}_{\mathbf{Interference\ (linear)}} + \underbrace{\sum_{i,j} \frac{C_i C_j}{\Lambda^4} \cdot \mathrm{Re}\left[\mathcal{M}_i \mathcal{M}_j^*\right]}_{\mathbf{Quadratic\ (pure\ EFT)}}$$

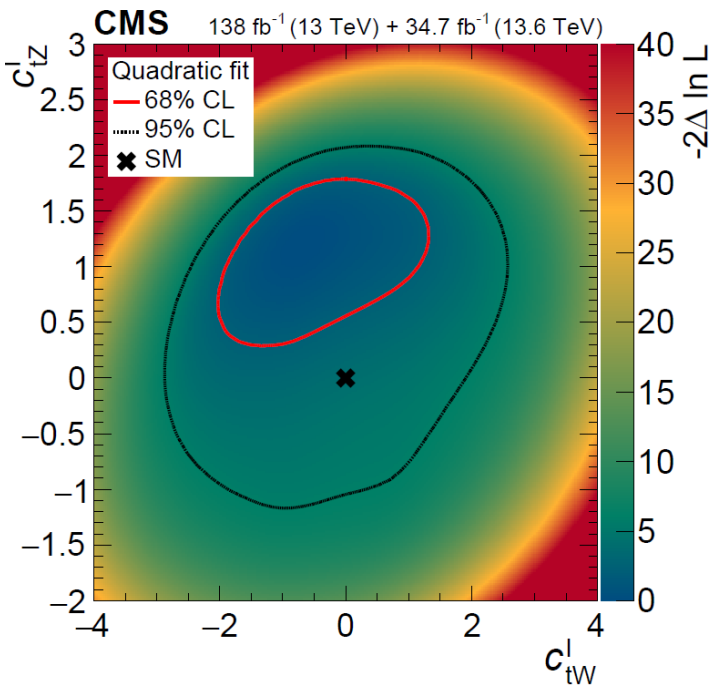
Analysis Results

- Events with at least 3 charged leptons and additional jets are selected
- Using Physics-informed Machine Learning (ML) techniques



Distributions of discretized scores of Wilson coefficients compared with predictions





Likelihood scans as functions of Wilson coefficients with linear contributions (top) and linear + quadratic (bottom)

Results consistent with the SM prediction within 2 standard deviations

At 95% CL

$$-2.7 < c^{I}_{tW} < 2.5$$

$$-0.2 < c^{I}_{tZ} < 2.0$$

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CKM Triangle – present and future

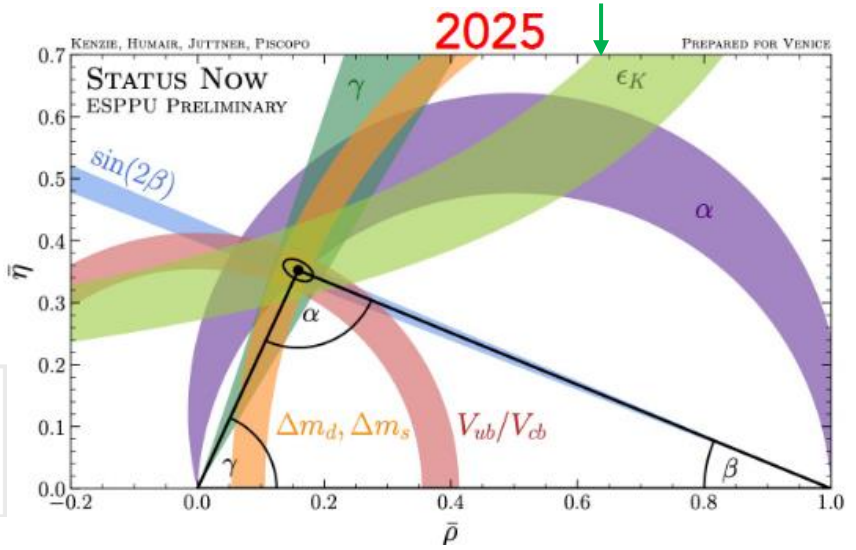
- Update from the European Strategy for Particle Physics, June 2025, Venice meeting
  - Measured uncertainties on selected key observables (arXiv:2503.24346v2)

Experiment Assumed data sample	ATLAS 20.3-99.7 fb^{-1}	CMS 116-140 fb^{-1}	LHCb 2-9 fb^{-1}	Belle II 364-1075 fb^{-1}
CKM angles				
β	—	—	0.57° [15]	1.2° [16]
α	—	—	—	6.6° [17]
γ	—	—	2.8° [18]	13° [17]
ϕ_s [mrad]	42 [19]	23 [20]	20 [21]	—

WA: HFLAV, August 2025

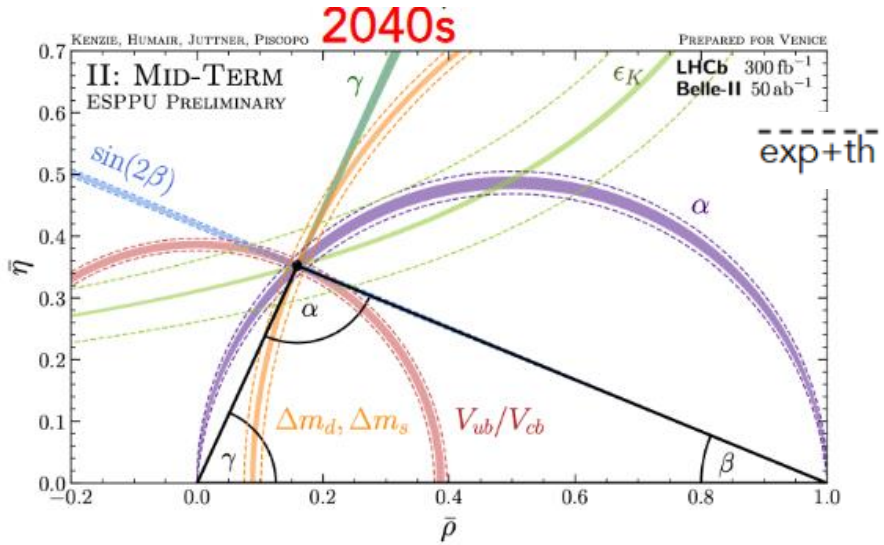
Parameters: $(\bar{\rho}, \bar{\eta})$ apex of Unitarity Triangle
$\bar{\rho} = 0.139 \pm 0.014$
$\bar{\eta} = 0.360 \pm 0.008$

Talk by M-H Schune



  - Sensitivity to selected key observables (arXiv:2503.24346v2)

Experiment Assumed data sample	ATLAS 3000 fb^{-1}	CMS 3000 fb^{-1}	LHCb 300 fb^{-1}	Belle II 50 ab^{-1}
CKM angles				
β	—	—	0.08°	0.3°
α	—	—	—	0.6°
γ	—	—	0.3°	1.0°
ϕ_s [mrad]	(4 – 9)	3	3	—



- A lot of additional work in the experiments beyond the ESPPU document

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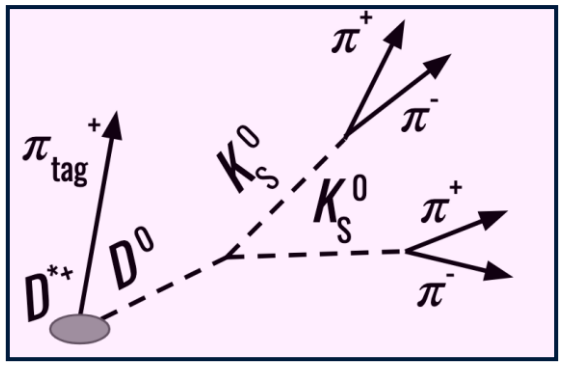
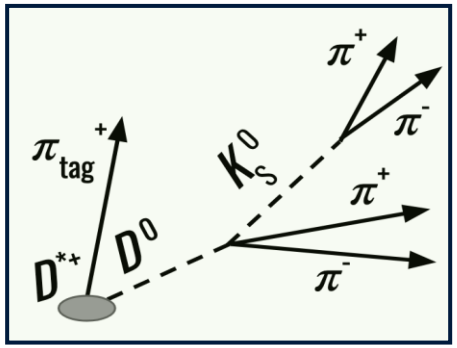
Search for *CP* violation in $D^0 \to K_S^0 K_S^0$ decays



Signal channel



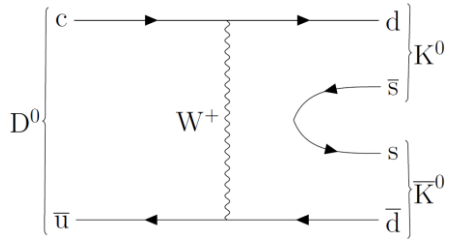
Reference channel

[ArXiv:2405.11606](), [EPJC 84 (2024) 1264]()

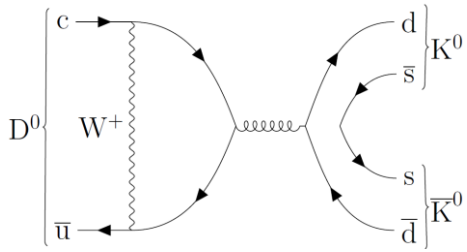
$\sqrt{s} = 13$ TeV, 41.6 fb^{-1}

Fully hadronic final state

W boson exchange



Penguin annihilation



More information to be presented in this session on similar results from LHCb and Belle at the talk by Alex Gilman

Motivation and theory expectation

- CPV in charm mesons is severely suppressed by the GIM mechanism and the magnitude of the CKM elements
  - Observation of significant CPV in D decays may indicate contributions from NP which can be different from those related to d-quark systems
- Theoretical expectation (PRD92_054036) points to:

$$|a_{CP}^{\mathrm{dir}}| \leq 1.1\% \quad (95\% \quad \mathrm{C.L.})$$

- We are measuring direct CPV in $D^0 \to K_s^0 K_s^0$ decays and the *CP* asymmetry difference, ΔA_{CP}, between the signal channel and reference channels

$$A_{CP}(K_S^0 K_S^0) = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}$$

- Reference channel A_{CP} has been measured to be consistent with zero as expected (decay not CKM-suppressed)
- Any significant deviation of ΔA_{CP} from zero would indicate CPV in the $D^0 \to K_s^0 K_s^0$ decay

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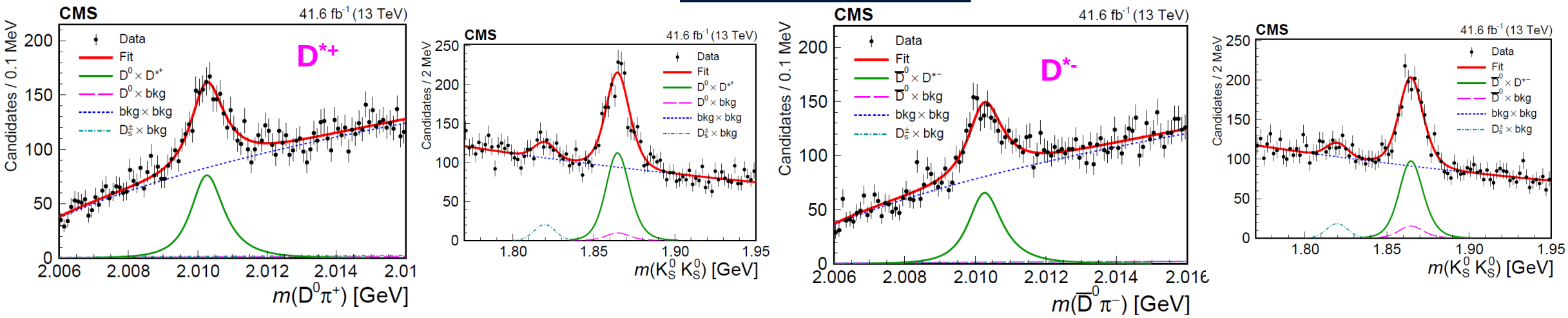
Analysis results

Decay	N
$D^{*+} \to D^0\pi^+$	1095 ± 46
$D^{*-} \to \overline{D}^0\pi^-$	951 ± 44



$$\Delta A_{CP} \equiv A_{CP}(K_S^0 K_S^0) - A_{CP}(K_S^0 \pi^+ \pi^-) = (6.3 \pm 3.0\,(\text{stat}) \pm 0.2\,(\text{syst}))\,\%$$

- Using the world-average value of $A_{CP}(K_s^0\pi^+\pi^-) = (-0.1 \pm 0.8)\%$, $A_{CP}(K_s^0 K_s^0)$ results to:

$$A_{CP}(D^0 \to K_s^0 K_s^0) = (6.2 \pm 3.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.8\,(A_{CP}(K_s^0\pi^+\pi^-)))\%$$

- Consistent with no CP violation within 2.0 standard deviations
- Consistent with recent LHCb and Belle/Belle II measurements (see next talk)
- This paves the way for future CPV searches in the charm sector using more data, new techniques and different channels

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Concluding Remarks

- Many achievements by the LHC experiments in setting CKM constraints and *CP* violation measurements in the past few years
  - Extensive work in the Beauty, Charm and Top sectors within both SM and BSM scenarios
    - Several highlights reported today (e.g. CPV observed in the interference between B_s^0–$\overline{B}_s^0$ and $B_s^0 \to D_s^{\mp} K^{\pm}$ decays and measurement of angle γ)
- Upgrades in the detectors, trigger, DAQ systems and algorithm improvements will enhance the capabilities of ATLAS, CMS and LHCb in the years ahead.
- No stone should be left unturned!
- Very interesting prospects ahead!

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THANKS

- ATLAS: Nedaa Alexandra Asbah, Josh McFayden, Radek Novotny, Semen Turchikhin
- CMS: Alexander Grohsjean, Georgios Karathanasis, Dmytro Kovalsky, Valentina Mariani, Sergio Sanchez Kruz, Robert Schoefbeck
- LHCb: Chen Chen, Alex Gilman, Daniele Manuzzi, Abhijit Mathad, Biljana Mitreska, Ozlem Ozcelik, Tommaso Pajero, G. Punzi
- HFLAV: Tim Gershon, Matt W. Kenzie

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BACKUP

CKM matrix elements – 3rd generation

- Direct, model independent measurement of the modulus of the CKM matrix element $|V_{tb}|$, $|V_{td}|$ and $|V_{ts}|$ in final states enriched in single quark t-channel events (*Phys. Lett. B* 808 (2020) 135609)

$$|V_{tb}| > 0.970$$
$$|V_{td}|^2 + |V_{ts}|^2 < 0.057$$

At 95% CL

Under the SM assumption of CKM unitarity

- Two BSM models:

Additional quark families heavier than top quark

$$|V_{tb}| = 0.988 \pm 0.051$$
$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$$

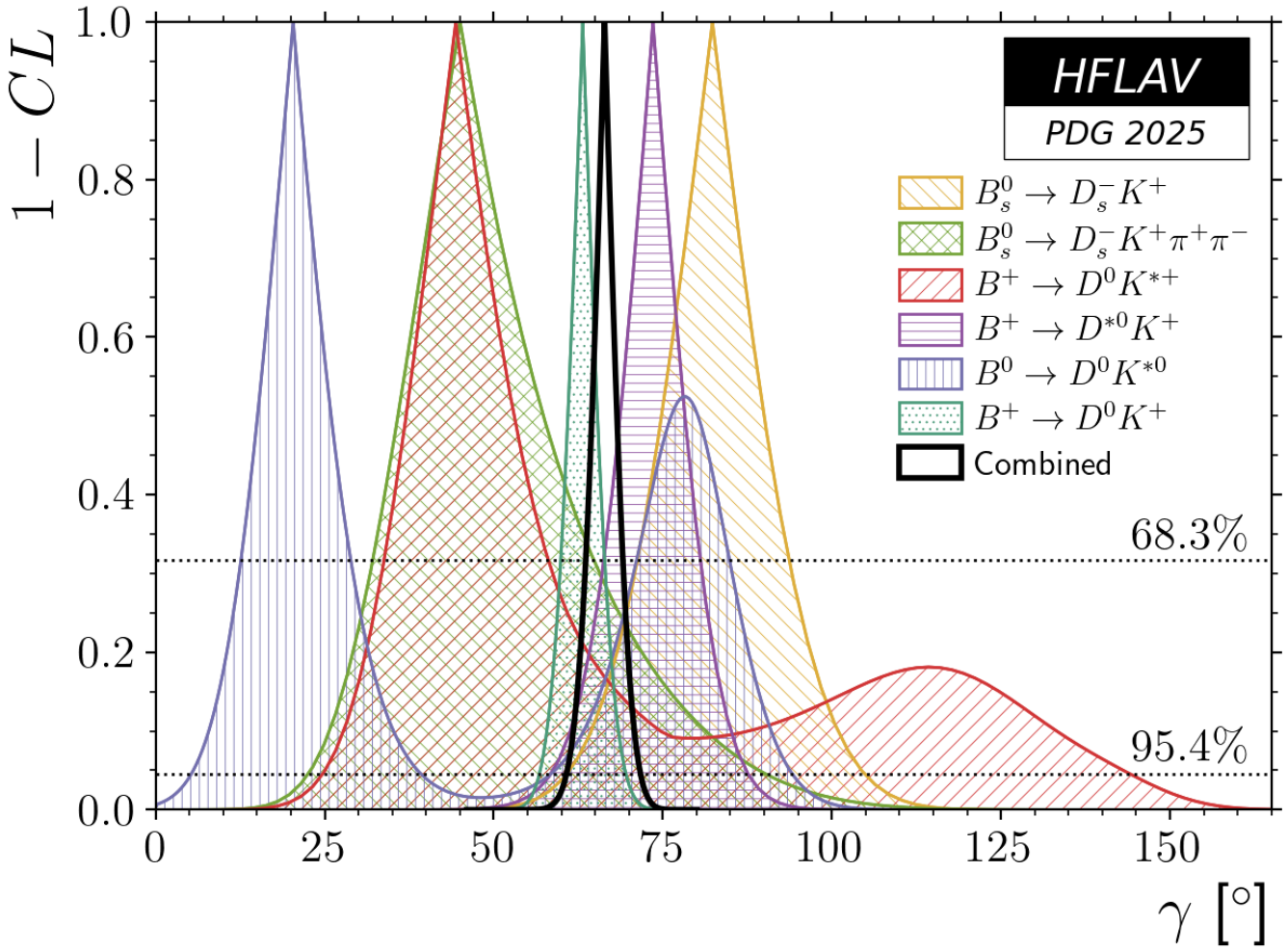
Top quark width unconstrained

$$|V_{tb}| = 0.988 \pm 0.024,$$
$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06,$$
$$\frac{\Gamma_t^{obs}}{\Gamma_t} = 0.99 \pm 0.42,$$

Related work by ATLAS described in [1] and [2]

World Average of angle γ

- From HFLAV – August 2025 (Input to PDG 2025)



$$\gamma \equiv \phi_3 = (66.4^{+2.7}_{-2.8})^\circ$$

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