Exploring CP violation in heavy flavor physics: recent results and future prospects

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LFC24, SISSA (Italy)
18 September 2024

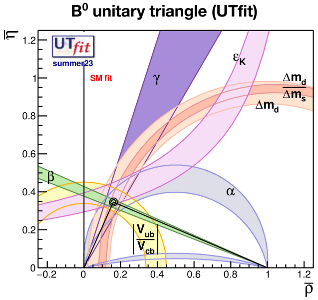
Introduction

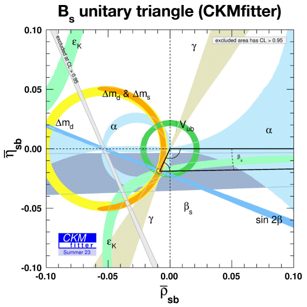
Why we need CP violation?

- **Baryon asymmetry remains one of the great mysteries of modern physics**
- Half a century ago, Andrei **Sakharov** proposed three necessary **conditions** for a baryon-generating process:
  1. Baryon number violation
  2. C and **CP violation (CPV)**
  3. Non thermal equilibrium
- In the Standard Model (SM) CP is **conserved** **by the strong and electromagnetic interactions**, but it is **violated** **by the weak force**
  - CPV was first observed in 1964 by Fitch and Cronin using neutral kaons
    - P violation was proposed by Lee and Yang (1956) and experimentally observed by Wu (1957)
- CPV is **allowed** in the SM, but the amount is **insufficient** to account for the observed baryon asymmetry of the universe
  - Sources of CPV beyond the SM have to exist
  - CPV observables are often precisely predicted and very sensitive to new physics

CP violation in the SM

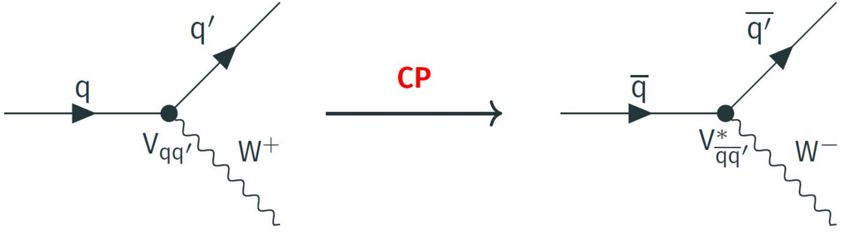
- In the SM quark transitions are possible through flavor-changing weak interactions
- **Information about the strength of the transition is contained in the Cabibbo-Kobayashi-Maskawa (CKM) matrix** 
  - Parameters: 3 angles + 1 complex phase
- **The single complex phase allows for CP violation**
- In the SM, the CKM matrix is **unitary**
  - Unitary conditions can be represented by "unitary triangles"





$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Flavour **CKM** **Mass**



E.g.: u ➔ b amplitude ~ $|V_{ub}|$ exp($-i\delta_{CP}$)

E.g.: $\bar{u}$ ➔ $\bar{b}$ amplitude ~ $|V_{ub}|$ exp($+i\delta_{CP}$)

Types of CP violation

- **Observable CP violation in weak interaction can be classified into three different types**
  1. *Direct* CPV in **decays** $Pr(M \to f) \neq Pr(\overline{M} \to \overline{f})$
     - Observed in K, B, and D mesons
  2. *Indirect* CPV in **mixing** $Pr(M^0 \to \overline{M}^0) \neq Pr(\overline{M}^0 \to M^0)$
     - Observed in K^0 oscillations
  3. CPV in decay/mixing **interference** $Pr(M^0_{(\rightsquigarrow \overline{M}^0)} \to f_{CP}) \neq Pr(\overline{M}^0_{(\rightsquigarrow M^0)} \to f_{CP})$
     - Observed in K^0, B^0 and B_s mesons

- Defining A_f the M ➜ f amplitude, the CPV information can be coded in the **rephasing invariant complex parameter λ**, with $|M^0_{L,H}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle \quad (|q|^2 + |p|^2 = 1)$

$$\boxed{\lambda \equiv \frac{q}{p}\frac{\overline{A}_{\overline{f}}}{A_f}} \begin{cases} |\overline{A}_{\overline{f}}/A_f| \neq 1 & \to \text{direct CPV} \\ |q/p| \neq 1 & \to \text{indirect CPV} \\ |\lambda| = 1,\ \mathrm{Im}(\lambda) \neq 0 & \to \text{interference CPV} \end{cases}$$

CP violation in the charm sector

Overview of charm CPV

- **First observed** in 2019 by LHCb [ref]
  - CPV differences between two modes
- **Complicated SM prediction** due to strong interaction effects
- Expected to be **small**
  - CKM and GIM suppressed
- **Single mode evidence only in $D^0 \to \pi^+\pi^-$ decays** [ref]
- Goal: discover CPV in charm mixing

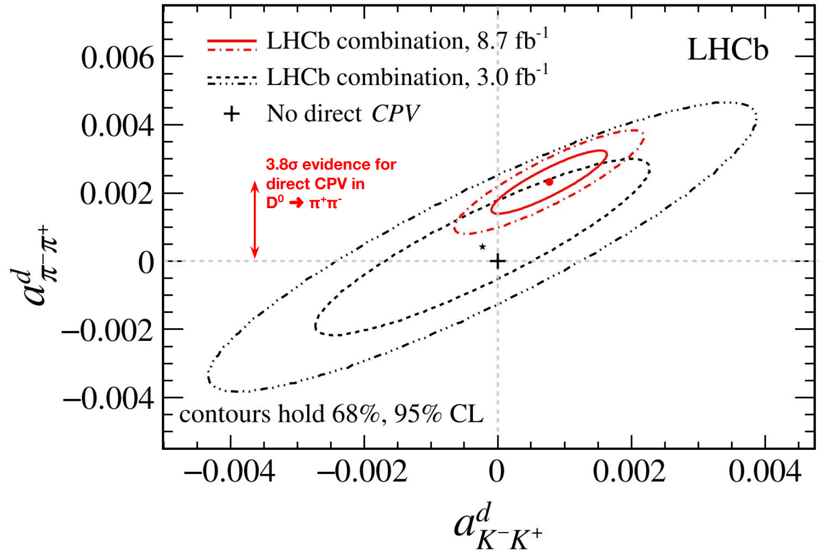


Fig from: [PRL131(2023)091802]

[CMS] CPV in $D^0 \to K_S K_S$

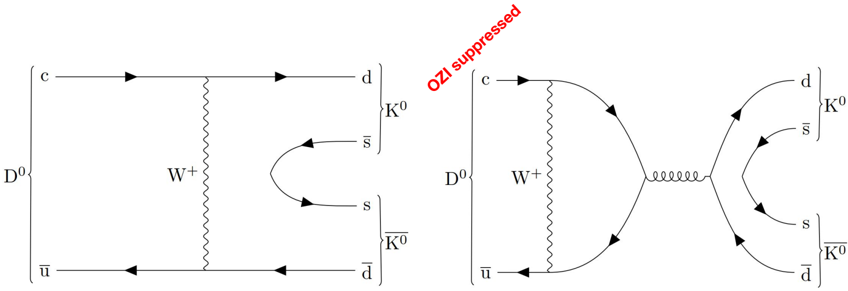
- **Measuring**

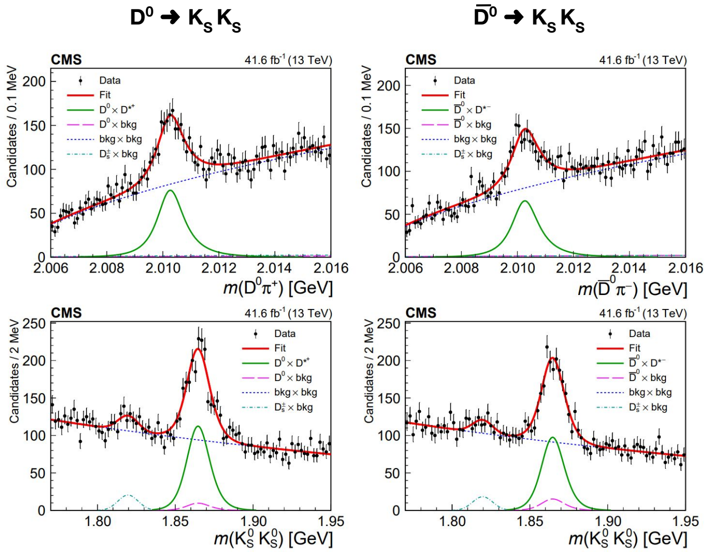
$$A_{CP} = \frac{\Gamma(D^0 \to K^0_S K^0_S) - \Gamma(\overline{D}^0 \to K^0_S K^0_S)}{\Gamma(D^0 \to K^0_S K^0_S) + \Gamma(\overline{D}^0 \to K^0_S K^0_S)}$$

- Observation of a significant CPV ➜ hints of BSM physics
  - From theory, CPV could be as large as *O(1%)* [ref]
- **Strategy**: measure $\Delta A_{CP} = A_{CP}(D^0 \to K_S K_S) - A_{CP}(D^0 \to K_S \pi^+\pi^-)$
  - Detector and production asymmetries canceled
  - CPV in $D^0 \to K_S \pi^+\pi^-$ already measured consistent with 0 [ref]
- **Results:** $\Delta A_{CP} = 6.3 \pm 3.0\,(\text{stat}) \pm 0.2\,(\text{syst})\,\%$
- **Using the world-average value of $A_{CP}(K_S \pi^+\pi^-) = (-0.1 \pm 0.8)\%$, $A_{CP}(K_S K_S)$ is found to be**

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

- Consistent with
  - no CP violation at 2σ,
  - LHCb (-3.1 ± 1.3)% at 2.7σ [ref]
  - Belle (0.0 ± 1.5)% at 1.8σ [ref]

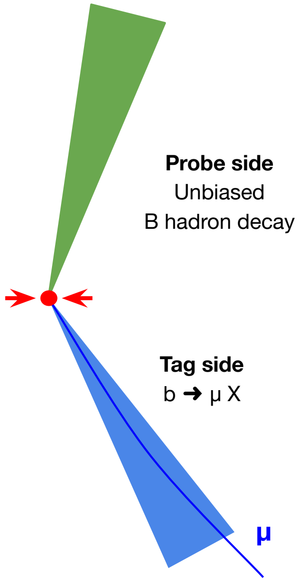


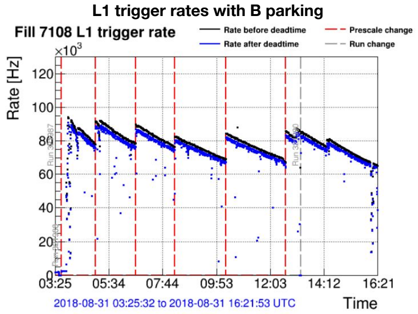


[CMS-EXO-23-007]
[CMS-BPH-22-005]

Technical interlude: the CMS B parking dataset

- **Designed to allow CMS to perform B physics measurements on difficult/impossible to trigger final states** (e.g. fully hadronic final states)
- Achieved with a set of **single muon triggers** (tags) with different thresholds in p_T and impact parameter
  - Luminosity decreases during a run ➜ less restrictive triggers enabled
    - Maximises the available trigger bandwidth
  - Events are *parked* for later reconstruction
  - Very high purity of ~80%
- No impact on the *standard* CMS physics programme
- **10 billion unbiased B hadron** decays collected in 2018 (L_{int} ~ 41 fb^{-1})





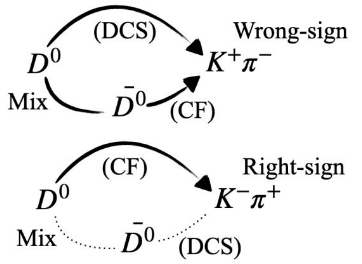
[LHCb] Charm mixing CPV

- **Never observed**
- **$D^0 \rightarrow K^+\pi^-$**: discovery channel for charm mixing
- Fit the time-dependent ratios
  - Probe for: CPV in mixing, $SU(3)_F$ breaking, rescattering effects and BSM

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

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

decay CPV; interference CPV; mixing CPV

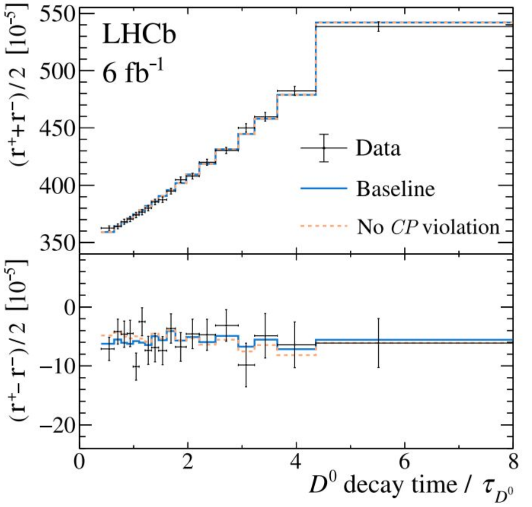


- Flavor of the D^0 tagged via $D^{*+} \rightarrow D^0 \pi^+$
- **Results**
  - No evidence of CPV
  - Evidence at 3.4σ on the quadratic term
  - Improved precision by 60% compared to previous measurements

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

First evidence of quadratic behaviour ($c'_{K\pi}$)

No evidence of CPV ($A_{K\pi}$, $\Delta c_{K\pi}$, $\Delta c'_{K\pi}$)



[LHCb] Charm CPV in decay/mixing interference

- CPV arising from the **interference** between decay with and without mixing to a CP finalstate
- Search in the Cabibbo-suppressed decay $D^0 \to \pi^+\pi^-\pi^0$ (CP eigenstate)
  - Flavor tagged using $D^*(2010)^+ \to D^0\pi^+$
- **Results**
  - No evidence of CP violation

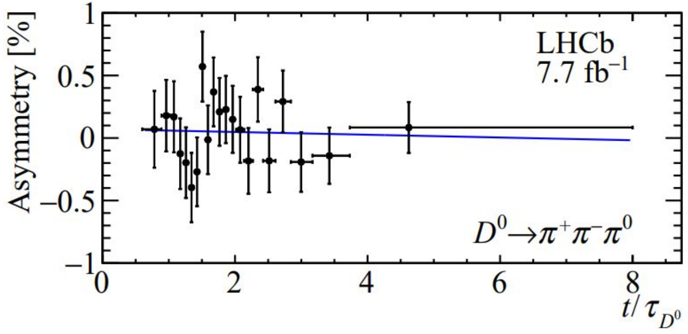
$$\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}.$$

$$A_{CP}(f_{CP}, t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)} \approx a^{\text{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}}.$$

decay CPV ($a^{\text{dir}}_{f_{CP}}$)

interference CPV ($\Delta Y_{f_{CP}}$)

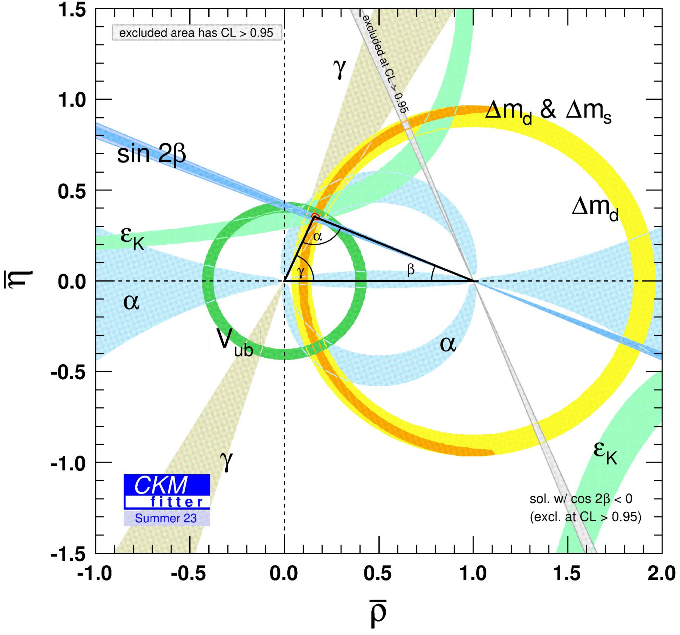
$$\Delta Y_{f_{CP}} \approx \frac{\eta_{f_{CP}}}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi\right]$$



CP violation in B decays

Overview of beauty CPV

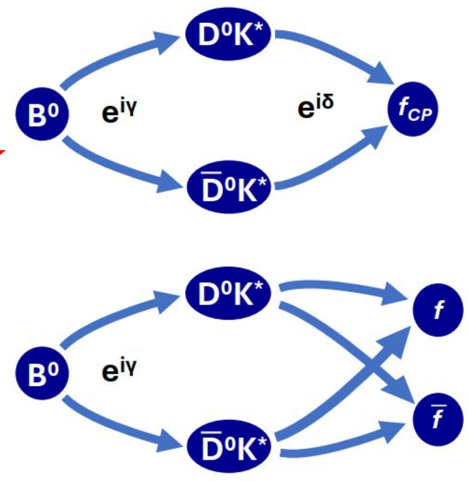
- **Extensively studied at beauty factories and LHC**
  - Observed in decays and decay/mixing interference
  - Not observed in mixing
- **Clean SM predictions** (usually)
- Strong test for the Standard Model
  - **High sensitivity** to new physics contribution
- Can be very large (e.g. in $B^0 \to J/\psi\ K_s$)



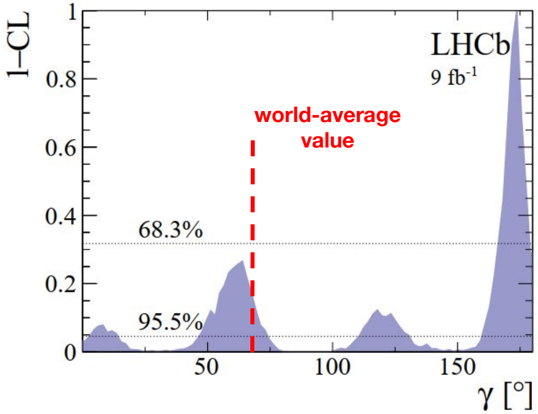
Deep link between CPV observables and the CKM matrix

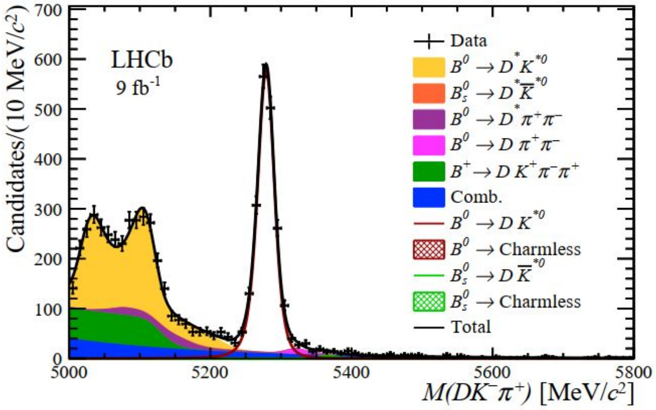
[JHEP05(2024)025]

[LHCb] CPV in $B^0 \rightarrow D^0 K^{*0}$ decays

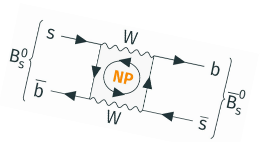


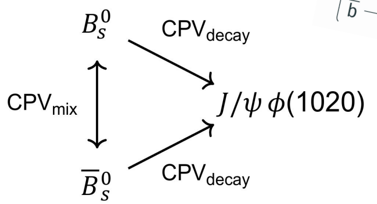
- **Direct measurement of the CKM angle γ via the study of the CP asymmetries**
- Use D decays to (14 samples fitted)
  - CP-eigenstates ($\pi^+\pi^-$, K^+K^-, $4\pi^\pm$)
  - via Cabibbo-favored ($D^0 \rightarrow K^- \pi^+$) and doubly Cabibbo-suppressed ($\bar{D}^0 \rightarrow K^- \pi^+$)
- **Results**: significant evidence of CPV was detected
  - 60% improvement w.r.t. previous results
- Four solutions for γ are found, one compatible with the world-average: γ = (62 ± 8)°





[CMS] CPV in B_s decay/mixing interference

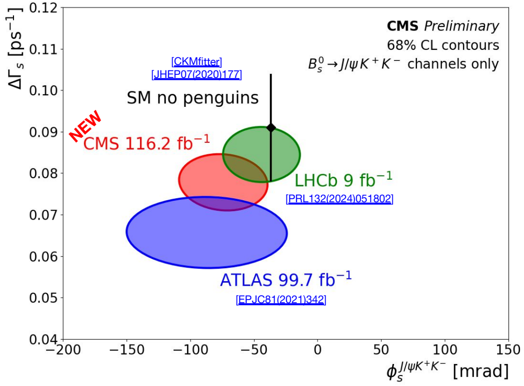




$$\Gamma\left(B^0_{s\,(\rightsquigarrow \overline{B}^0_s)} \to f\right)(t) \overset{?}{\neq} \Gamma\left(\overline{B}^0_{s\,(\rightsquigarrow B^0_s)} \to f\right)(t)$$

- **Flagship CPV analysis at LHC**
  - ATLAS, LHCb and CMS in the game
- **Motivations**
  - Precise SM prediction: $\phi_s \approx -2\beta_s = -37 \pm 1$ mrad
  - Very sensitive to new physics
- **Precise characterization of the B_s ➜ J/ψ ϕ decay** (mixing, CPV, B_s system properties)
  - Time- and flavor-dependent angular analysis
- Innovative flavor tagging algorithm based on machine learning
  - Performance improved by 400%
- (First) evidence at 3σ of CPV in B_s ➜ J/ψ ϕ decays (when combined with Run1 results)

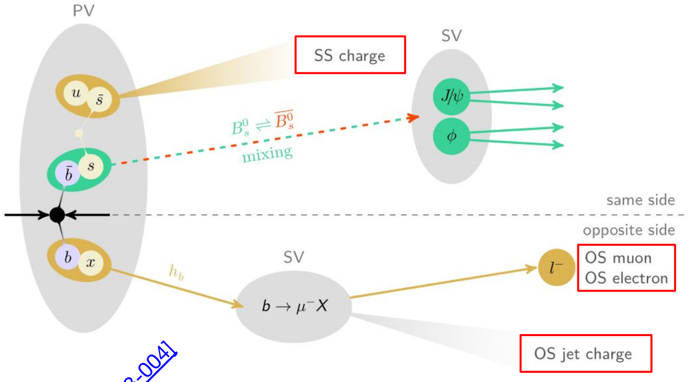
$$\phi_s = -74 \pm 23 \text{ [mrad]}$$
$$\Delta\Gamma_s = 0.0780 \pm 0.0045 \text{ [ps}^{-1}\text{]}$$



Technical interlude: CMS inclusive flavor tagging

- A **cutting-edge** **flavor tagging framework** has been engineered for flavor-sensitive measurements to extract the best possible results from data
- **Four DNN-based algorithms are used**, divided into two main classes
  - **Same side (SS):** exploits the B_s fragmentation
    1. **SS tagger**: leverages charge asymmetries in the B_s fragmentation
  - **Opposite side (OS)**: exploits decay products of the other *b*-hadron in the event
    2. **OS muon**: leverages $b \rightarrow \mu^- X$ decays
    3. **OS electron**: leverages $b \rightarrow e^- X$ decays
    4. **OS jet**: capitalizes on charge asymmetries in the OS *b*-jet
- **The combined flavor tagging framework achieves a tagging power of P_{tag} = 5.6%** when applied to the B_s data sample
  - Among the highest ever recorded at LHC

Schematic representation of a generic $B_s \rightarrow J/\psi\ \phi$ event



[CMS-PAS-BPH-23-004]

Flavor tagging performance in $B_s \rightarrow J/\psi\ \phi$ events
(mutually exclusive categories)

Category	ε_{tag} [%]	$\mathcal{D}^2_{eff}$	P_{tag} [%]
Only OS muon	6.07 ± 0.05	0.212	1.29 ± 0.07
Only OS electron	2.72 ± 0.02	0.079	0.214 ± 0.004
Only OS jet	5.16 ± 0.03	0.045	0.235 ± 0.003
Only SS	33.12 ± 0.07	0.080	2.64 ± 0.01
SS + OS muon	0.62 ± 0.01	0.202	0.125 ± 0.003
SS + OS electron	2.77 ± 0.02	0.150	0.416 ± 0.005
SS + OS jet	5.40 ± 0.03	0.124	0.671 ± 0.006
Total	55.9 ± 0.1	0.100	5.59 ± 0.02

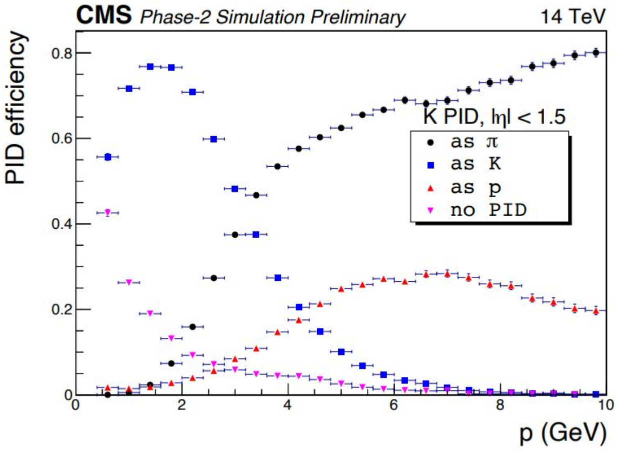
Future prospects at HL-LHC

[CERN-CMS-DP-2022-025]

Flavor tagging in CMS Phase-2 with timing

- **The planned MTD (Mip Timing Detector) will provide CMS Phase-2 with the time information of charged tracks**
- The reconstruction algorithm utilizes compatible times of tracks from a vertex to offer time-of-flight-based particle identification (PID) as a natural byproduct
- **Same-side tagging could utilize charge correlation between the light quark in the B meson and a nearby soft hadron for flavor tagging**
- The PID from MTD, when integrated into the Phase-2 extrapolation of this analysis, shows a significant improvement in the tagging performance

Simulated PID efficiencies



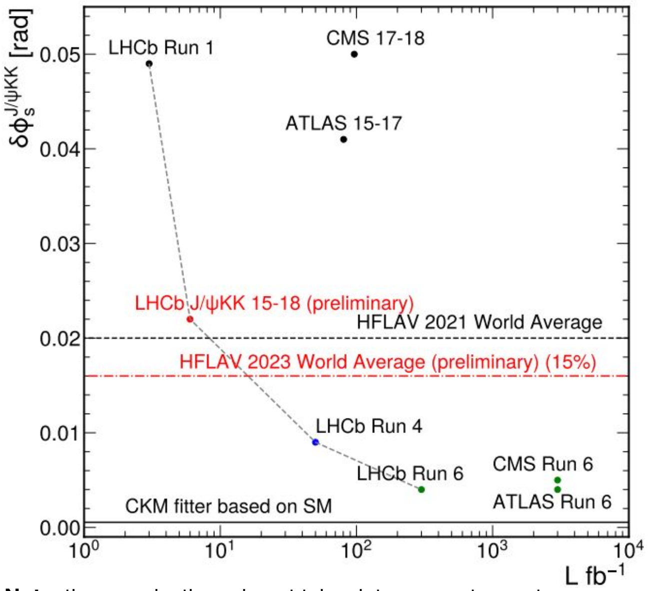
Relative gain in P_{tag} (only SS)

PID scenario	Gains in P_{tag}
MC truth (perfect PID < 3 GeV)	+66%
PID with σ_{BTL} = 40 ps	+24%
PID with σ_{BTL} = 70 ps	+14%

Projecting ϕ_s to HL-LHC

- **Current status:** with an uncertainty of $\sigma(\phi_s)$ =14 mrad the world average is consistent with SM-based predictions, though new physics contributions of ~10% are still possible
- **HL-LHC will enable an exceptionally precise measurement of ϕ_s**, opening new avenues for probing physics beyond the Standard Model
- The planned detector improvements in all three experiments are critical to deliver these requirements despite the much higher HL-LHC pileup
- **HL-LHC experiments aim for a combined $\sigma(\phi_s)$ ~ 2 mrad and $\sigma(\Delta\Gamma_s)$ ~ 5 ps^{-1} in**
  - Individual experiments: $\sigma(\phi_s)$ ~ 3-5 mrad
- **Challenges**: precise control over hadronic effects and penguin pollution (more on this later)

Projected ϕ_s precision

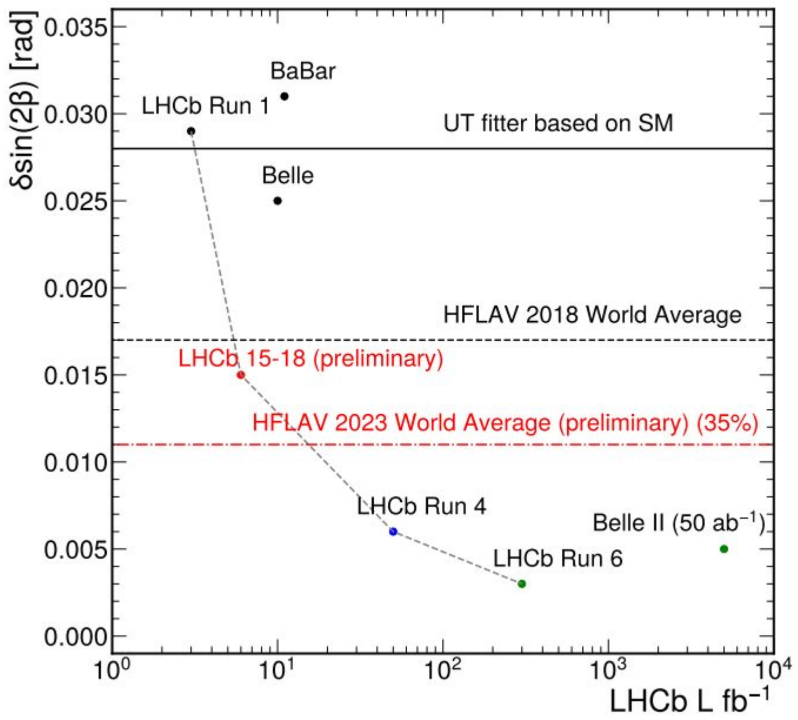


Note: these projections do not takes into account recent development in flavor/tagging and trigger

[Yellow Report on Flavor Physics]

Projecting sin(2β) to HL-LHC

- **Current status:** with a precision of 0.011, the world-average value is in excellent agreement with SM-based predictions
- After Upgrade-II LHCb will be able to reach a statistical precision below 0.003, while Belle-II with 50 ab^{-1} projects σ(sin2β) ~ 0.005
    - CMS has expressed the intention of pursuing sin(2β)
- **Systematic uncertainties** will need to be controlled, especially from CP violation in K^0–$\overline{K}^0$ mixing and nuclear cross-section differences.
- Controlling the penguin effects will be essential to derive insightful boundaries on new physics effects



[J.Phys.G48(2021)6,065002]

March of the penguins

We measure this — Assuming this is negligible — Trying to probe this

$$\phi_s = \phi_s^{tree} + \Delta\phi_s^{penguin} + \Delta\phi_s^{NP}$$

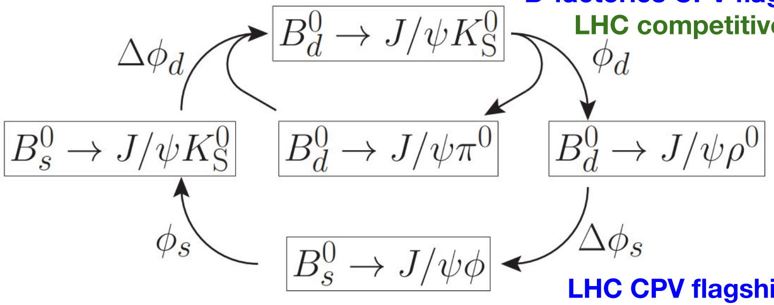
$$\sin(2\beta) = \sin(2\beta^{tree} + \Delta\phi_d^{penguin} + \Delta\phi_d^{NP})$$

- Penguin pollutions are expected to be small but they are not well constrained and will be the leading source of systematic at HL-LC

$$\Delta\phi_s^{penguin} \approx 3 \pm 10\ mrad \quad vs \quad \sigma(\phi_s) \approx 15\ mrad$$

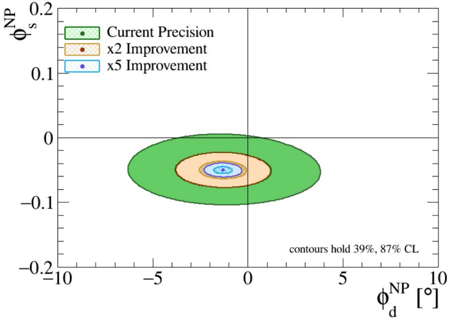
$$\Delta\phi_d^{penguin} \approx -10 \pm 10\ mrad \quad vs \quad \sigma(2\beta) \approx 15\ mrad$$

- Analysis of penguin and NP contributions is possible using Cabibbo-favored control channels



B-factories CPV flagship
LHC competitive

LHC CPV flagship
B-factories not competitive



[Yellow Report on Flavor Physics]

Penguins at HL-LHC

ϕ_s

- The best constraint on penguin pollution in ϕ_s comes from $B^0 \to J/\psi\, \rho^0$

$$\Delta\phi_s^{c\bar{c}s} \approx -\epsilon \left(\phi_d{}^{J/\psi\,\rho^0} - 2\beta\right) \qquad \epsilon = |V_{us}|^2/(1-|V_{us}|^2) = 0.0534$$

- The LHCb collaboration foresee to be able to measure $\phi_d^{J/\psi\,\rho0}$ with a precision $\lesssim$1°, corresponding to an uncertainty on the penguin pollution $\lesssim$ 1.5 mrad (reminder: $\sigma(\phi_s)$ ~ 2 mrad at HL-LHC)

sin(2β)

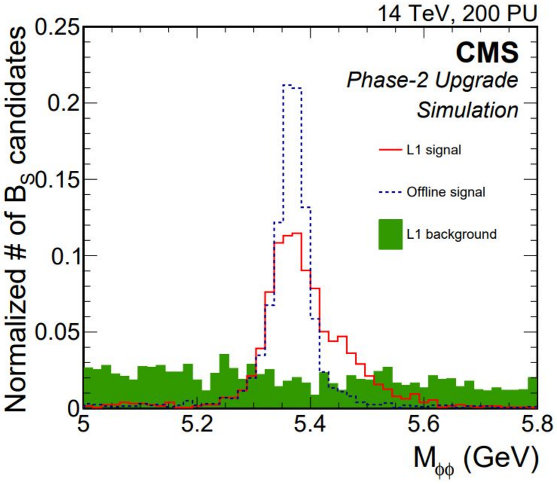
- A first analysis of $B_s \to J/\psi\, K_s$ has been performed [ref] as a proof of concept for constraining $\Delta\phi_d$
- However, the penguin pollutants will be mostly kept in check by Belle-II using $B^0 \to J/\psi\, \pi^0$ decays

[Yellow Report on Flavor Physics]

Other CPV opportunities

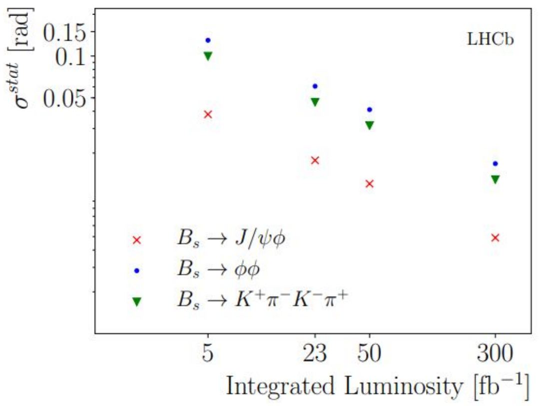
B_s ➜ ϕϕ ➜ KKKK

- **Penguin dominated decay**
- **Benchmark for CPV in FCNC**
- **CMS** Phase-2 will be able to access tracking information at the first stages of the trigger process, allowing the direct trigger of fully hadronic final states
  - For B_s ➜ ϕϕ a 30~35% efficiency at L1 trigger is expected
- **LHCb** Upgrade II can achieve a statistical uncertainty on ϕ_s^{sss} of 11 mrad with 300 fb^{-1} of data collected



Other charmless decays

- At HL-LHC LHCb can also access
  - ϕ_s^{dds} via B_s ➜ $(K^+\pi^-)(K^-\pi^+)$, with a precision of 9 mrad
  - ϕ_s^{duu} via B_s ➜ $K_s\pi^+\pi^-$, with a precision of 70 mrad



Outlook

Summary and outlook

- **CP violation has been an extremely successful field in recent years and has a clear road for the upcoming colliders**
- The upgrade to HL-LHC offers promising opportunities to push the boundaries of CPV measurements
  - **But** penguins are always lurking
- **The future is not only a simple *luminosity scaling***: detector upgrades, additional possibilities in triggering and new analysis techniques are going to be a key part of future collider programmes
  - Thallenge will be to continue refining our experimental approaches while controlling systematic uncertainties
- With these advancements, the study of CP violation will remain at the forefront of probing fundamental physics

Stay tuned in the future for other exciting results on CPV!

Thanks for the attention

Backup

Clavor mixing

- **Neutral K, D, and B mesons are subject to flavor mixing, that is oscillations between their C-conjugate states before decay**
- They propagate as light and heavy mass eigenstates which are described by a superposition of flavor states:

$$|M^0_{L,H}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle \qquad (|q|^2 + |p|^2 = 1)$$

- The system is characterized by the parameters

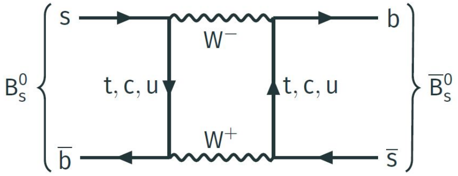
$$m \equiv \frac{m_H + m_L}{2} \qquad \Gamma \equiv \frac{\Gamma_H + \Gamma_L}{2}$$

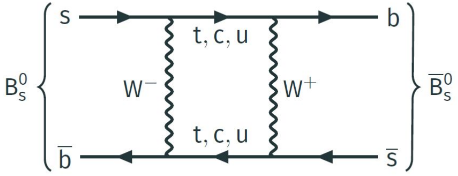
$$\Delta m \equiv m_H - m_L \qquad \Delta\Gamma \equiv \Gamma_L - \Gamma_H$$

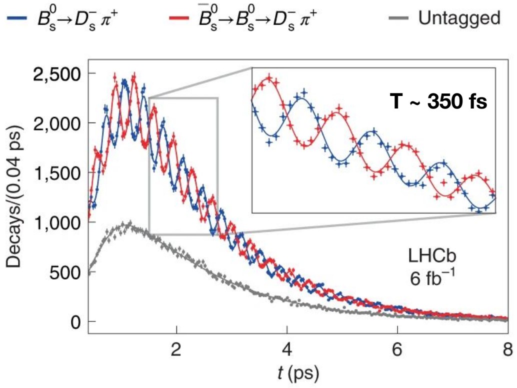
Definition may vary

  - The flavor eigenstates oscillate with period T = 2π/Δm
- **CPV in mixing**, i.e. $Pr(M^0 \to \overline{M}^0) \neq Pr(\overline{M}^0 \to M^0)$, **implies |q/p| ≠ 1**

Example: B_s meson mixing







Ref: LHCb Collab. Nat.Phys.18(2022)1-5

$D^0 \rightarrow K_s K_s$ measurement strategy

- **Use D^0 from $D^{*+} \rightarrow D^0 \pi^+$ and $D^{*-} \rightarrow \overline{D}^0 \pi^-$**, so that the pion charge tags the D^0 flavor
- This introduces the D^{*+}/D^{*-} differences in the measurement

What we want

$$A_{CP} = A_{raw} - A_{prod} - A_{det}$$

What we measure

$$A_{raw} = \frac{N(D^0) - N(\overline{D}^0)}{N(D^0) + N(\overline{D}^0)}$$

$$A_{prod} = \frac{\sigma_{pp \rightarrow D^{*+}X} - \sigma_{pp \rightarrow D^{*-}X}}{\sigma_{pp \rightarrow D^{*+}X} + \sigma_{pp \rightarrow D^{*-}X}}$$??

$$A_{det} \approx \frac{\epsilon_{\pi^+} - \epsilon_{\pi^-}}{\epsilon_{\pi^+} + \epsilon_{\pi^-}}$$??

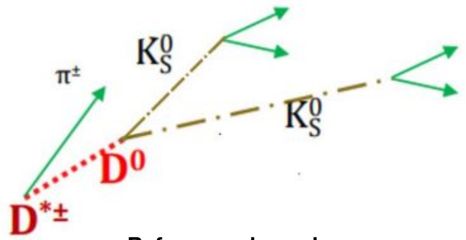
- **Strategy: measure $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K_S K_S) - A_{CP}(D^0 \rightarrow K_S \pi^+ \pi^-)$**
  - Reference channel is very similar in kinematics and topology ➜ A_{prod} and A_{det} cancel out
  - CPV in $D^0 \rightarrow K_s \pi^+\pi^-$ already measured consistent with zero [PRD86(2012)032007]

$$\Delta A_{CP} = A_{raw}(D^0 \rightarrow K_S K_S) - A_{raw}(D^0 \rightarrow K_S \pi^+ \pi^-)$$

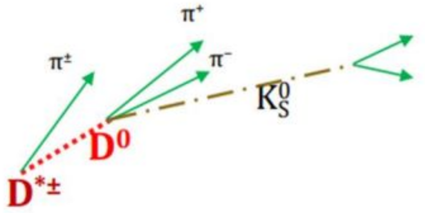
$D^0 \rightarrow K_s\, K_s$ event selection

- **First, $K_S \rightarrow \pi^+\pi^-$** are reconstructed fitting the π tracks to a common vertex
  - $|m(\pi^+\pi^-) - m(K_s^{w.a.})| < 20$ MeV, $p_T(K_S) > 2.2(1.0)$ GeV
- In the **signal channel**, two K_S candidates are required and fitted to a common vertex to form $D^0 \rightarrow K_S K_S$ candidates
  - $1.7 \text{ GeV} < m(K_S K_S) < 2.0$ GeV
  - K_S displacement in *xyz* from the D^0 vertex $>9\sigma$ and $>7\sigma$
  - D^0 displacement in *xyz* (*xy*) from the PV $>9\sigma$ ($>2\sigma$)
- In the **reference channel**, two track with $p_T > 0.6$ GeV are used to form the $D^0 \rightarrow K_S\pi^+\pi^-$ candidate
  - $1.823 < m(K_S\pi^+\pi^-) < 1.908$ GeV
- **Finally**, an additional track with $-1.2 < |\eta| < 1.2$ and $p_T > 0.36$ GeV is added to form $D^{*+} \rightarrow D^0\pi^+$ candidates
  - $m(D^0\pi^+) = m(D^0\pi^+) - m(D^0) + m_{PDG}(D^0)$

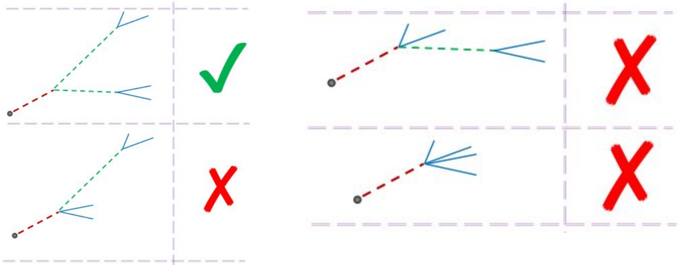
Signal channel



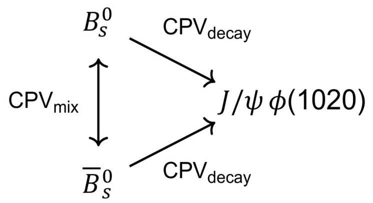
Reference channel



- **Background suppression**: several fits corresponding to incorrect topologies are performed and vertex probabilities requirements are imposed

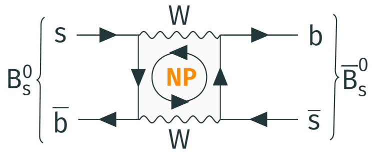


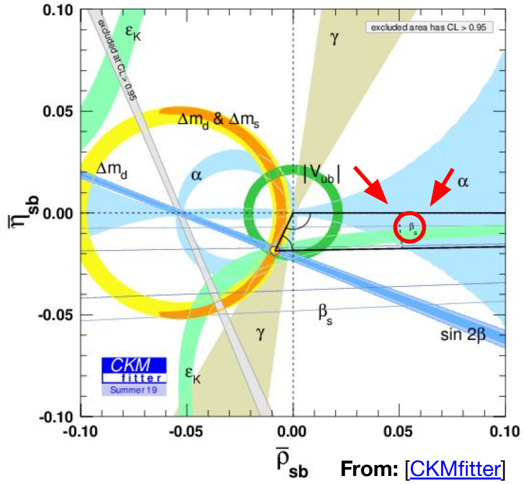
ϕ_s motivations



$$\Gamma\left(B_{s\,(\rightsquigarrow \overline{B}_s^0)}^0 \to f\right)(t) \overset{?}{\neq} \Gamma\left(\overline{B}_{s\,(\rightsquigarrow B_s^0)}^0 \to f\right)(t)$$

- **B_s mesons decays allow us to study the time-dependent CP violation generated by the interference between direct decays and flavor mixing**
  - CPV in the interference is possible even if there is no CPV in decay and mixing
- **The weak phase ϕ_s is the main CPV observable**
  - Predicted by the SM to be $\boldsymbol{\phi_s \approx -2\beta_s}$ (β_s ➜ angle of the B_s unit. triangle)
    - Neglecting contributions from higher-order diagrams ($\Delta\phi_s^{loop} \approx 3\pm10$ mrad)
  - β_s determined by CKM global fits to be **$-2\beta_s$ = -37 ± 1 mrad** [CKMfitter, UTfit]
- **New physics** can change the value of ϕ_s up to ~100% via new particles contributing to the flavor oscillations [RMP88(2016)045002]





From: [CKMfitter]

- This seminar presents the latest CMS results with the *golden* channel $B_s \to J/\psi\,\phi(1020) \to \mu^+\mu^- K^+K^-$

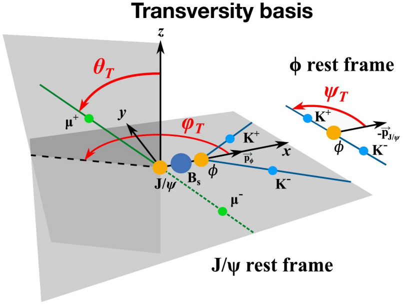
ϕ_s: a time-, flavor- and angular-dependent measurement

final-state CP eigenvalue

CP violation

flavor oscillations

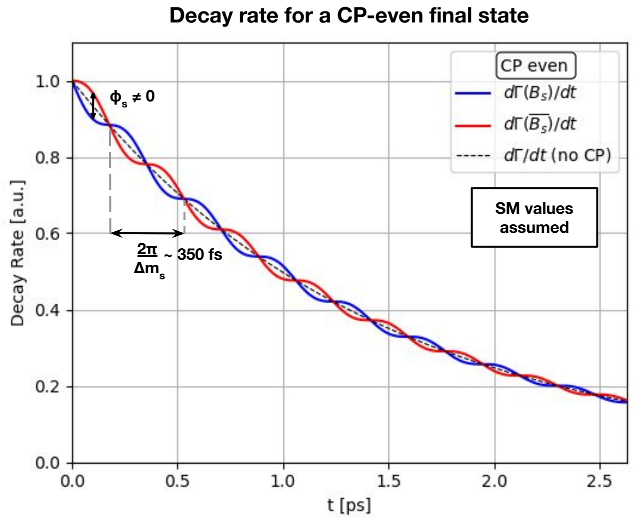
$$a_{CP}(t) = \frac{-\eta_{fs}\sin(\phi_s)\sin(\Delta m_s t)}{\cosh(\frac{1}{2}\Delta\Gamma_s t) - \eta_{fs}\cos(\phi_s)\sinh(\frac{1}{2}\Delta\Gamma_s t)}$$



Core ingredients

- **Time-dependent angular analysis** to separate the CP eigenstates (“transversity basis” used)
- **Time-dependent flavor analysis** to resolve the B_s mixing oscillations (T ~ 350 fs)

$$\text{sensistivity} \propto \sqrt{\frac{\epsilon_{tag}\mathcal{D}^2_{tag}N_{sig}}{2}}\sqrt{\frac{N_{sig}}{N_{sig}+N_{bkg}}}\,e^{-\frac{\sigma_t^2\Delta m_s^2}{2}}$$



$B_s \to J/\psi\ \phi$ decay rate model

Flavor tag decision (flips c_i and d_i signs)

Mistag probability

Decay time

$$\frac{d^4\Gamma(B_s)}{d\Theta dt} \propto \sum_{i=1}^{10} \mathcal{O}_i(t,\alpha)\, g_i(\Theta)$$

$$\mathcal{O}_i(t,\alpha) = N_i e^{-\Gamma_s t}\left[a_i \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + b_i \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + c_i\xi(1-2\omega)\cos(\Delta m_s t) + d_i\xi(1-2\omega)\sin(\Delta m_s t)\right]$$

Angular variables

Most sensitive terms for SM ϕ_s (column d_i, rows 1–3)

i	$g_i(\theta_T, \psi_T, \varphi_T)$	N_i	a_i	b_i	c_i	d_i
1	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$	$k_{SP}\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$	$k_{SP}\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$k_{SP}\lvert A_S(0)\rvert\lvert A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad S = -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2} \qquad D = -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}$$

Sensitive to direct CPV

Sensitive to $\phi_s \sim 0$

Sensitive to $\phi_s \sim \pi/2$

Conventions

- $|A_{//}|^2 = |A_0|^2 - |A_\perp|^2$
- $\delta_0 = 0$
- $\delta_{S\perp} = \delta_S - \delta_\perp$
- $\Delta\Gamma_s > 0$

Physics parameters

- ϕ_s, $|\lambda|$
- $\Delta\Gamma_s$, Γ_s, Δm_s
- $|A_0|^2$, $|A_\perp|^2$, $|A_S|^2$
- $\delta_{//}$, $\delta_\perp$, $\delta_{S\perp}$

S-P wave effective coupling $k_{SP} \approx 0.54$

- Introduced since $m(K^+K^-)$ is not fitted
- Evaluated from the S- and P-wave lineshape interference

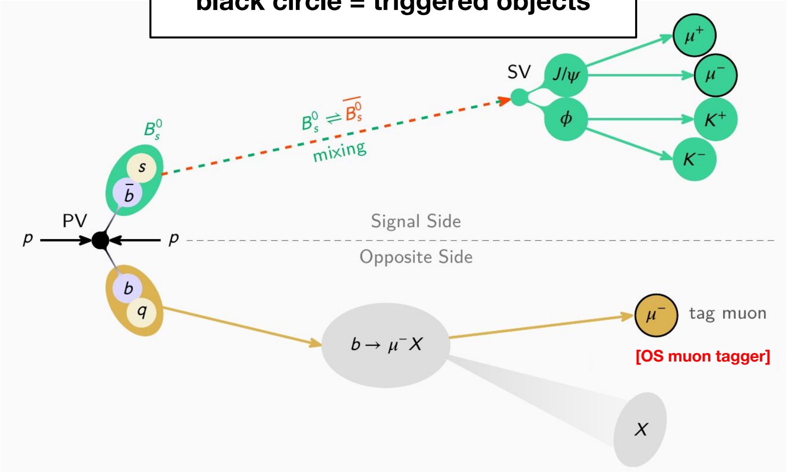
ϕ_s: trigger strategy

PLB816(2021)136188 (superseded)

black circle = triggered objects

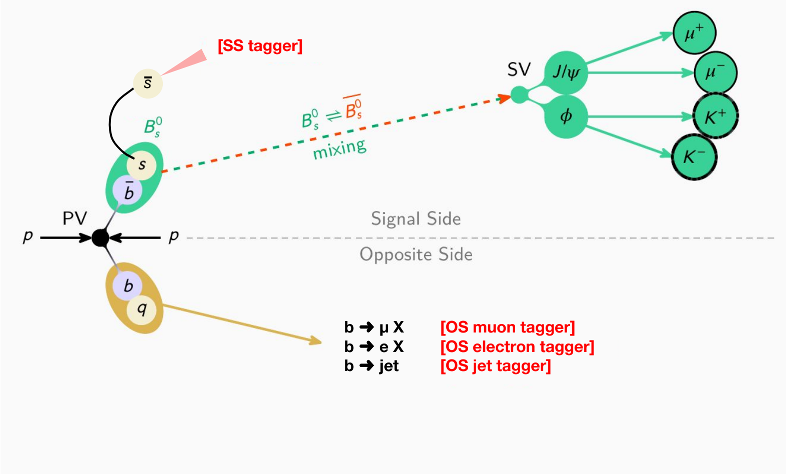
Muon-tagging trigger

- $J/\psi \to \mu^+\mu^-$ candidate plus an additional muon (for tagging)
- **≈50 000** signal candidates
- Used for time resolution modeling
- Tagging algorithms deployed: OS-muon
  - P_{tag} ~ **10%** (muon at trigger level enhance tagging efficiency)



Standard trigger

- Displaced $J/\psi \to \mu^+\mu^-$ candidate + $\phi(1020) \to K^+K^-$
- **≈450 000** signal candidates
- Tagging algorithms deployed: OS-muon, OS-electron, OS-jet, Same Side
  - P_{tag} ~ **5%**



ϕ_s: decay time and its resolution

- The time dependence of the decay rate is parametrized with the **proper decay length** ct, measured in the transverse plane as

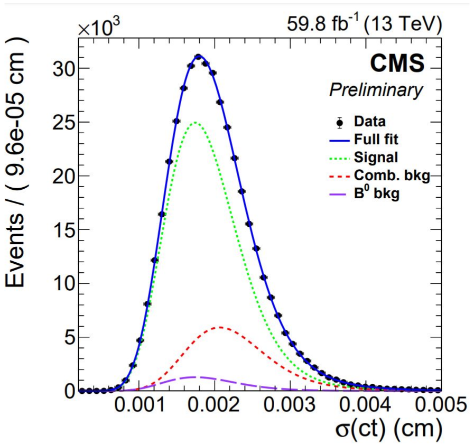
$$ct = c \cdot \frac{m_{Bs}^{w.a.} \cdot L_{xy}}{p_T} \quad \text{with} \quad L_{xy} \equiv ||\bar{r}_{xy}(SV) - \bar{r}_{xy}(PV)||$$

- Its **uncertainty** is obtained by fully propagating the uncertainties in L_{xy} and p_T
  - The uncertainty on L_{xy} dominates for most of the ct spectrum, with $\sigma(p_T)$ taking over at high values (ct ≳ 3 mm)
- **The ct uncertainty is calibrated in a prompt data sample** of $B_s \to J/\psi\ \phi$, obtained by removing the displacement requirement in the *muon-tagging* data sets
  - Modeled with two gaussians to obtain the effective dilution and resolution

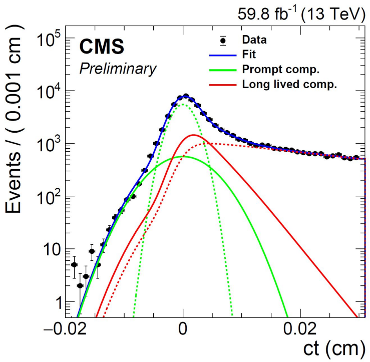
$$\delta_{\text{eff}} = \sqrt{\frac{-2\ln\mathcal{D}}{\Delta m_s^2}} \quad \text{with} \quad \mathcal{D} = \sum_{i=1}^{2} f_i \exp\left(-\frac{\sigma_i \Delta m_s^2}{2}\right)$$

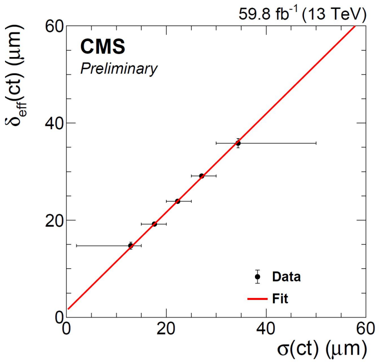
- **Excellent agreement** found, with corrections ~5%

Proper decay length uncertainty distribution for the *standard* trigger (2018)



Time resolution calibration for 2018 data





ϕ_s: acceptance and efficiency effects

- **The efficiency in selecting and reconstructing the B_s candidates is not independent of the decay time and angular observables**
    - To properly fit the decay rate model an efficiency parametrization is needed

Time efficiency

- Modeled in the $B^0 \rightarrow J/\psi\, K^{*0}$ data control channel with corrections from simulations
- Ultimately parametrized with Bernstein's polynomials

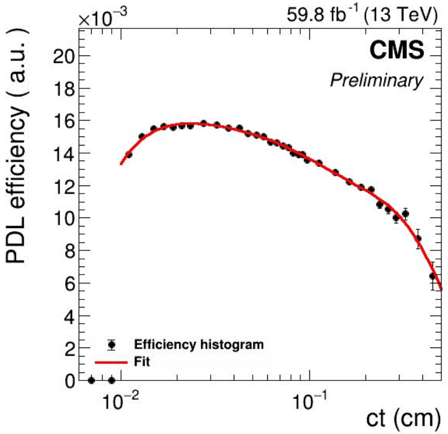
$$\varepsilon^{\text{data}}_{B^0}(ct) = \frac{N_{B^0}(ct)}{e^{-\Gamma^{\text{w.a.}}_{d}} \otimes P_{B^0}(\sigma_{ct})}$$

$$\varepsilon^{\text{data}}_{B_s}(ct) = \varepsilon^{\text{data}}_{B^0}(ct) \cdot \frac{\varepsilon^{\text{MC}}_{B_s}(ct)}{\varepsilon^{\text{MC}}_{B^0}(ct)}$$

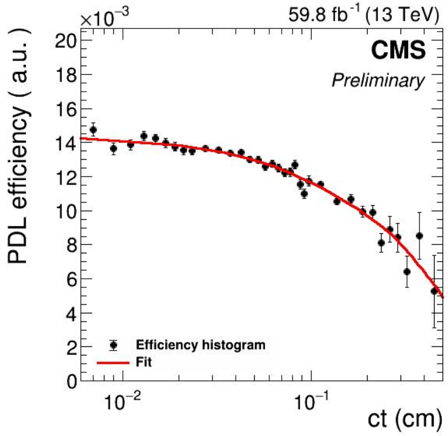
Angular efficiency

- Estimated with KDE distributions in simulated events
- The simulated data samples are corrected to match the data
    - An iterative procedure is used to simultaneously correct the kinematics of the final state particles and the differences in the physics parameters set in the MC with respect to what measured in the data

ct efficiency for the *standard* trigger category (2018)



ct efficiency for the *muon-tagging* trigger category (2018)



Flavor, neural networks, and probabilities

- The **tagging inference logic** differs between algorithms
  - **Lepton taggers** (OS muon, OS electron)
    - Lepton charge ➜ ξ_{tag}; DNN score ➜ ω_{tag} *(DNN trained for correct-tag vs mistag)*

$$\text{OS } \ell^- \to \text{OS } b \xrightarrow{tag} \text{signal } B_s$$
$$\text{OS } \ell^+ \to \text{OS } \overline{b} \xrightarrow{tag} \text{signal } \overline{B}_s$$
$$\omega_{tag} = 1 - s_{DNN}$$

DNN score

  - **Charge-based taggers** (OS jet, SS)
    - DNN score ➜ Prob(B_s) ➜ ξ_{tag}, ω_{tag} *(DNN trained for B_s vs $\overline{B}_s$)*

$$s_{DNN} > 0.5 + \epsilon \xrightarrow{tag} \text{signal } B_s \quad \text{with} \quad \omega_{tag} = 1 - s_{DNN}$$
$$s_{DNN} < 0.5 - \epsilon \xrightarrow{tag} \text{signal } \overline{B}_s \quad \text{with} \quad \omega_{tag} = s_{DNN}$$

    - ϵ is used to remove events with ω_{tag} ~ 50%
- **The algorithms are optimized and trained in simulated events and calibrated in data with self-tagging B^+ ➜ $J/\psi K^+$ decays**
  - The calibration is performed by comparing ω_{tag} predicted by the DNN and the one measured in data

Tagging calibration strategy (and other tricks)

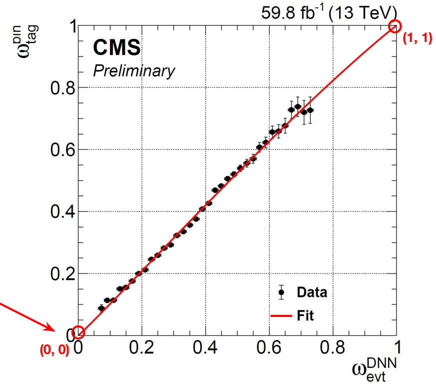
- **A multi-pronged strategy has been devised to improve the ω_{tag} estimation and suppress systematic effects**
  1. All models are constructed from the start as *probability estimators*, i.e. score~ω_{tag}
     - Loss function: *cross-entropy*, which is the likelihood for the probability P(true class | score)
     - Output layer: *Sigmoid* function, which normalizes the output to a probability distribution
  2. All DNNs are calibrated with the *Platt scaling*, which ensures that the calibrated score is still a probability
     - The Platt scaling is a linear calibration of the score before the last sigmoid layer
  3. In calibrating the charge-based taggers (which provide a probability for B_s vs $\overline{B}_s$):
     A. The output is *symmetrized* due to the initial LHC charge imbalance

$$s_{DNN}^{sym}(x) = \frac{s_{DNN}(x) + [1 - s_{DNN}(\overline{x})]}{2}$$

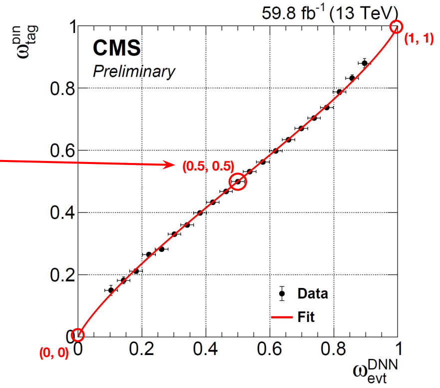
     B. The symmetry is explicitly forced in the calibration function by removing the constant term

This strategy cancels almost all the systematic effects associated with flavor tagging

OS-Muon calibration (*muon-tagging* trigger 2018)



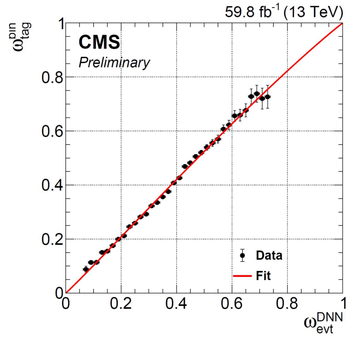
OS-jet calibration (2018)



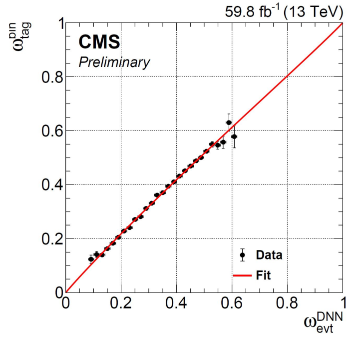
ϕ_s: OS-lepton tagging

- **OS-lepton tagging techniques search for b ➜ ℓ^-X decays of the other B hadron in the event**
- The **charge** of the lepton is used as tagging feature and a fully connected DNN is used to estimate the mistag probability
- **Lepton selection**
  - Loose kinematic cuts
  - Separated from the signal B meson
  - MVA discriminator against fakes
  - OS-electrons are searched only if no OS-muon is found in the event (explicit orthogonality)
- **Mistag estimation**
  - Fully connected DNN with ReLU activation and dropout
  - Inputs: lepton kinematics and surrounding activity
- **Trained on simulated B_s ➜ J/ψ ϕ(1020) events and calibrated in B^+ ➜ J/ψ K^+ data**

OS-Muon calibration (*muon-tagging* trigger 2018)



OS-Electron calibration (2018)

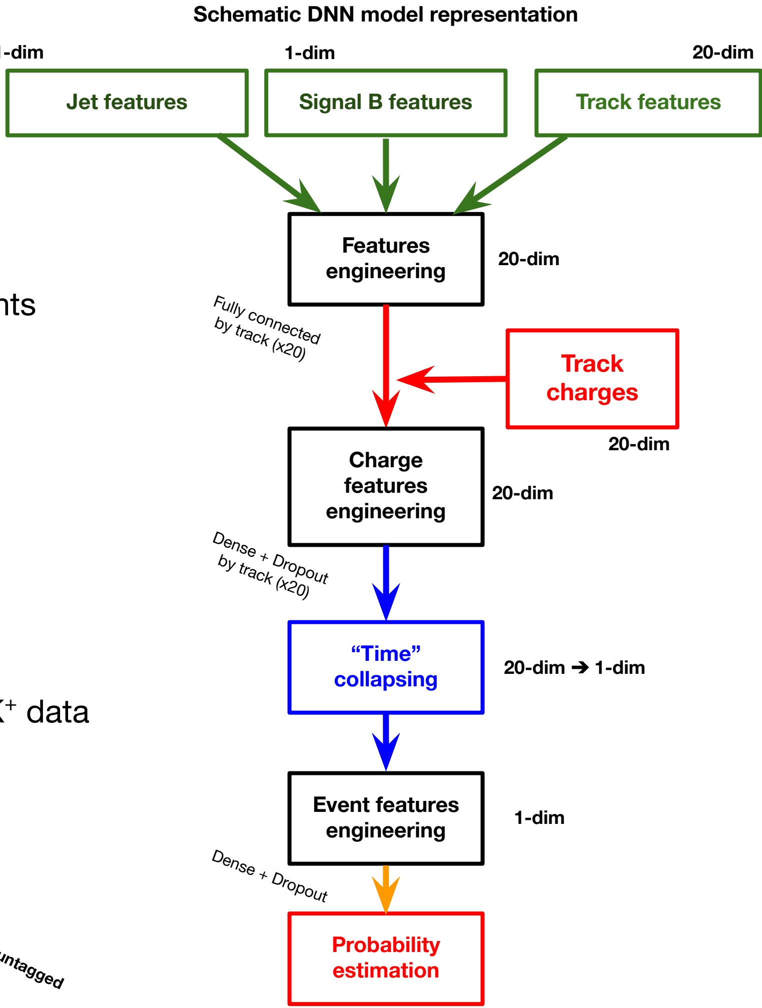


ϕ_s: OS-jet tagging

- **The OS-jet algorithm exploits charge asymmetries in the jet structure and is based on a DNN called *DeepJetCharge***
  - Inputs: features from signal B meson, OS jet and its constituents
    - NB: The only flavor asymmetry is in the charges
  - Based on the *DeepSets* architecture [ref]
- **Jet selection**
  - No OS-lepton candidate
  - At least 2 tracks with $|IP_z| < 1$ cm
  - Separated from the signal B meson
  - jet b-tagging discriminator
- Additional nearby tracks are used due to the poor jet clustering performance in the kinematic region of interest ($p_T < 20$ GeV)
- Trained on simulated $B_s \rightarrow J/\psi\ \phi$ events and calibrated in $B^+ \rightarrow J/\psi\ K^+$ data
- **The trained network produces the probability of signal B meson containing a $\bar{b}$ quark (i.e. being a B_s)**
- The score is finally used to compute both ξ_{tag} and ω_{tag}

$$s_{DNN} > 0.52 \xrightarrow{\text{tag}} \text{signal } B_s \quad \text{with} \quad \omega_{tag} = 1 - s_{DNN}$$
$$s_{DNN} < 0.48 \xrightarrow{\text{tag}} \text{signal } \overline{B}_s \quad \text{with} \quad \omega_{tag} = s_{DNN}$$

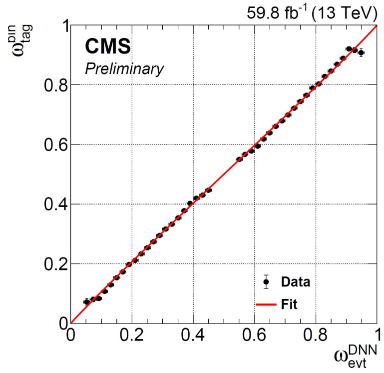
$\omega_{tag} > 0.48 \rightarrow$ untagged



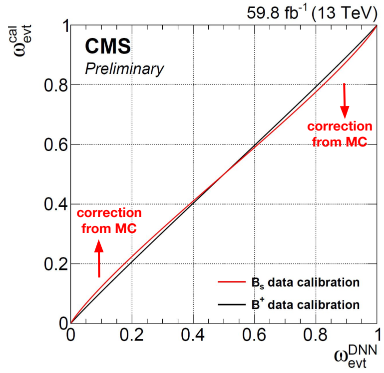
ϕ_s: SS tagger

- **The SS tagger consists of a DNN (*DeepSSTagger*), derived from *DeepJetCharge,* able to probe the fragmentation products of a B meson and exploit tracks with high flavor correlation**
- *DeepSSTagger* uses the kinematic information from up to 20 tracks (ordered by $|IP_z|$) around the reconstructed B meson
- **Track selection**
  - $\Delta R(trk, B) < 0.8$, $|IP_z(PV)| < 0.4$ cm, $|IP_{xy}(PV)|/\sigma_{dxy} < 1$
  - Overlap with signal and OS is carefully avoided with geometrical cuts and vetos
- **Trained on an equal-weight mixture** of $B_s \to J/\psi\, \phi$ and $B^+ \to J/\psi\, K^+$ to make the model invariant for $B_s \leftrightarrow B^+$ for calibration purposes
  - Calibration directly in B_s was found to be not feasible in CMS
    - Tested: $B_s \to D_s^- \pi^+$ (not enough stat.) and $B_s^{**} \to B^{+(*)}K^-$ (too much uncer. from B^{0**} bkg)
  - The trained network produces the probability of signal B meson containing a negatively charged quark alongside the b quark (i.e., being a B_s or B^-)
- **Calibration**
  - The SS is calibrated $B^+ \to J/\psi\, K^+$ data, with residual differences ~10% corrected with simulations
  - Events with $\omega_{tag} > 0.46$ are removed before the calibration and assumed untagged

Same-side tagger calibration (B^+ data 2018)



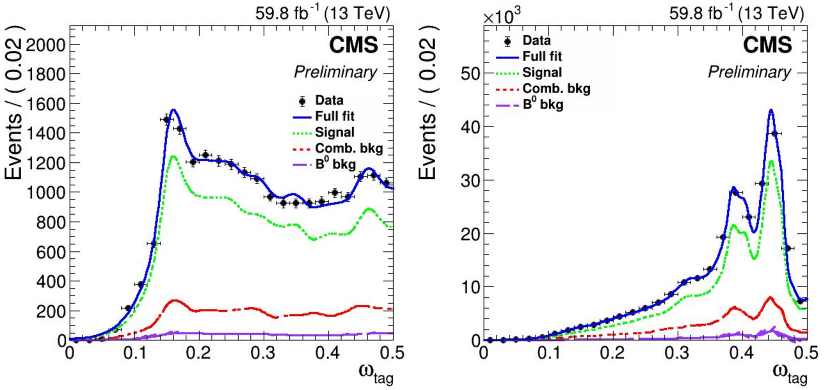
Comparison between Same-side tagger B^+ and B_s calibrations (2018)



ϕ_s: flavor tagging performance

- The SS and any one of the OS algorithms overlap in about 20% of the events
  - In these cases, the information is combined to improve the tagging inference
- **The combined flavor tagging framework achieves a tagging power of P_{tag} = 5.6%** when applied to the B_s data sample
  - Among the highest ever recorded at LHC
  - x3~4 improvement with respect to prev. CMS results
- **This is the first CMS implementation of the OS jet and same-side tagging techniques**
  - SS accounts for half of the performance
- Largest ever effective statistics $N_{Bs} \cdot P_{tag}$ (490k · 5.6% ≈ 27.5k) for a single ϕ_s measurement
- The flavor tagging framework is validated in the $B^0 \rightarrow J/\psi K^{*0}$ data control channel with flavor mixing measurements, both integrated and time-dependent

ω_{tag} distribution in the *muon-tagging* trigger category (left) and the *standard* one (right) for 2018 data



Flavor tagging performance (mutually exclusive categories)

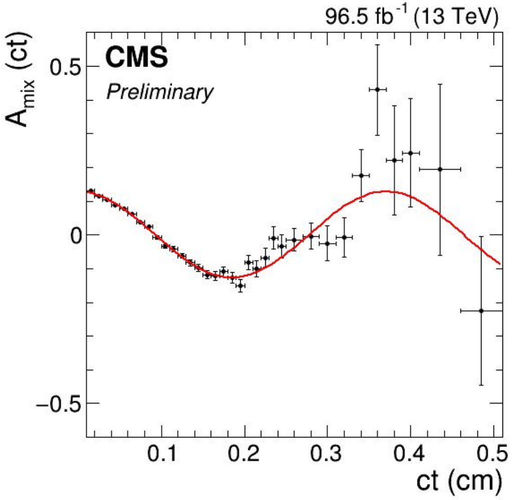
Category	ε_{tag} [%]	$\mathcal{D}^2_{eff}$	P_{tag} [%]
Only OS muon	6.07 ± 0.05	0.212	1.29 ± 0.07
Only OS electron	2.72 ± 0.02	0.079	0.214 ± 0.004
Only OS jet	5.16 ± 0.03	0.045	0.235 ± 0.003
Only SS	33.12 ± 0.07	0.080	2.64 ± 0.01
SS + OS muon	0.62 ± 0.01	0.202	0.125 ± 0.003
SS + OS electron	2.77 ± 0.02	0.150	0.416 ± 0.005
SS + OS jet	5.40 ± 0.03	0.124	0.671 ± 0.006
Total	55.9 ± 0.1	0.100	5.59 ± 0.02

ϕ_s: tagging validation with B^0 events

- **The flavor tagging framework is validated in the $B^0 \rightarrow J/\psi\, K^{*0}$ control channel** (~2M events)
- The time-dependent **mixing asymmetry** is measured to extract the flavor mixing oscillation frequency Δm_d with a precision of ~*1%* (comparable with BaBar and Belle)
  - Excellent agreement with world-averages is observed
    ➜ **No bias in mixing frequency measurements**
- Study performed also in each tagging category (see backup)
- The **time-integrated mixing** is also measured for each tagger and their dependency on the expected tagging dilution is compared
  - The dependency between the measured A_{mix} and the estimated D_{tag} is found to be well described by a linear relationship, indicating that all four techniques behave in the same predictable way

B^0 flavor mixing asymmetry

$$A_{mix}(ct) = \frac{N_{unmix}(ct) - N_{mix}(ct)}{N_{unmix}(ct) + N_{mix}(ct)}$$



ϕ_s: fit model

- The physics parameters are extracted with **unbinned multidimensional extended maximum-likelihood (UML) fit** performed simultaneously on **12 data sets** (2 trig. cat. x 2 years x 3 ξ_{tag} values)
  - *Physics parameters*: ϕ_s, $|\lambda|$, $\Delta\Gamma_s$, Γ_s, Δm_s, $|A_0|^2$, $|A_\perp|^2$, $|A_S|^2$, $\delta_{//}$, $\delta_\perp$, $\delta_{S\perp}$
  - *Observables*: m_{Bs}, ct, σ_{ct}, cos θ_T, cos ψ_T, ϕ_T, ω_{tag}
- **Fit model**

$$P = f_{sig} P_{sig} + f_{bkg} P_{bkg} + f_{bkg\ B^0} P_{bkg\ B^0}$$

Angular eff

$B_s \rightarrow J/\psi\ \phi$ decay rate

Observables pdfs

SIGNAL $\quad P_{sig} = \varepsilon(\Theta)\,[\tilde{f}(\Theta, ct\,|\,\alpha, \xi_{tag}, \omega_{tag}) \otimes G(ct, \sigma_{ct})]\, P_{sig}(m_{B_s})\, P_{sig}(\sigma_{ct})\, P_{sig}(\omega_{tag})$

COMBINATORIAL BKG $\quad P_{bkg} = [P_{bkg}(ct) \otimes G(ct, \sigma_{ct})]\, P_{bkg}(\Theta)\, P_{bkg}(m_{B_s})\, P_{bkg}(\sigma_{ct})\, P_{bkg}(\omega_{tag})$

$B^0 \rightarrow J/\psi\ K^{0*}$ BKG $\quad P_{bkg\ B^0} = [P_{bkg\ B^0}(ct) \otimes G(ct, \sigma_{ct})]\, P_{bkg\ B^0}(\Theta)\, P_{bkg\ B^0}(m_{B_s})\, P_{bkg\ B^0}(\sigma_{ct})\, P_{bkg\ B^0}(\omega_{tag})$

Bkg time pdf

Time resolution convolution

- The time efficiency is implemented as a *re-weighting* of the data events to drastically improve fit time
- The statistical uncertainties and fit bias are estimated with **1300 *bootstrap* distributions**
- The yield for the **$B^0 \rightarrow J/\psi\ K^{*0}$ is estimated directly in data** with a 2D fit to the B_s invariant mass and its B^0 reflection
- The background from **$\Lambda_b \rightarrow J/\psi\ K^- p^+$ is found to be negligible** and is treated as a systematic uncertainty

ϕ_s: systematic uncertainty overview

	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	Δm_s [$\hbar$ps^{-1}]	$\|\lambda\|$	$\|A_0\|^2$	$\|A_\perp\|^2$	$\|A_S\|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]
Statistical uncertainty	23	0.0043	0.0015	0.035	0.014	0.0016	0.0021	0.0033	0.074	0.089	0.15
Model bias	4	0.0011	0.0002	0.004	0.006	0.0012	0.0022	0.0006	0.015	0.017	0.03
Flavor tagging	4	$<10^{-4}$	0.0005	0.007	0.002	$<10^{-4}$	$<10^{-4}$	0.0006	0.012	0.016	0.03
Angular efficiency	4	0.0002	$<10^{-4}$	0.015	0.011	0.0042	0.0019	0.0001	0.017	0.044	0.02
Time efficiency	<1	0.0014	0.0026	$<10^{-3}$	$<10^{-3}$	0.0004	0.0005	$<10^{-4}$	0.001	0.002	$<10^{-2}$
Time resolution	<1	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	0.001	$<10^{-3}$
Model assumptions	—	0.0005	0.0006	—	—	—	—	—	—	—	—
B^0 background	<1	0.0002	0.0003	$<10^{-3}$	$<10^{-3}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$
Λ_b^0 background	—	—	0.0004	—	—	0.0004	0.0003	—	—	—	—
S-P wave interference	<1	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$
$P(\sigma_{ct})$ uncertainty	<1	0.0002	0.0003	$<10^{-3}$	$<10^{-3}$	0.0001	0.0001	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$
Total systematic uncertainty	7	0.0019	0.0028	0.017	0.012	0.0044	0.0030	0.0009	0.025	0.050	0.05

- **Model bias, flavor tagging, and angular efficiency are found to be the leading systematic sources for ϕ_s**
- The measurement is still heavily statistically limited for ϕ_s

ϕ_s: results

Fit results

Parameter	Fit value	Stat. uncer.	Syst. uncer.
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
$\|\lambda\|$	1.011	± 0.014	± 0.012
$\|A_0\|^2$	0.5300	± 0.0016	± 0.0044
$\|A_\perp\|^2$	0.2409	± 0.0021	± 0.0030
$\|A_S\|^2$	0.0067	± 0.0033	± 0.0009
$\delta_\parallel$	3.145	± 0.074	± 0.025
$\delta_\perp$	2.931	± 0.089	± 0.050
$\delta_{S\perp}$	0.48	± 0.15	± 0.05

- **ϕ_s and $\Delta\Gamma_s$ are found in agreement with the SM**

$$\phi_s^{SM} \simeq -37 \pm 1 \text{ mrad} \qquad \Delta\Gamma_s^{SM} = 0.091 \pm 0.013 \text{ ps}^{-1}$$

- **Γ_s and Δm_s are consistent with the latest world averages**

$$\Gamma_s^{WA} = 0.6573 \pm 0.0023 \text{ ps}^{-1} \qquad \Delta m_s^{WA} = 17.765 \pm 0.006\ \hbar\text{ps}^{-1}$$

- **$|\lambda|$ is consistent with no direct CPV ($|\lambda| = 1$)**

- This measurement utilizes the **largest ever** effective statistics $N_{Bs} \cdot P_{tag}$ for a single ϕ_s measurement
    - The precision on ϕ_s is comparable with the world's most precise single measurement by LHCb (ϕ_s = -39 ± 22 (stat) ± 6 (syst) mrad) [PRL132(2024)051802]
    - This is the most precise single measurement of $\Delta\Gamma_s$ to date in this channel