The first evidence of CP violation in the B_s -> J/ψ ϕ system, obtained by CMS

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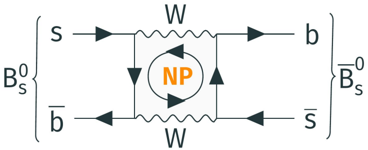
XVIth Quark Confinement and the Hadron Spectrum

Motivations

- **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 **$\phi_s \approx -2\beta_s = -37 \pm 1$ mrad** ([CKMfitter, UTfit])
    β_s ➜ angle of the B_s unit. triangle
- **New physics** can change the value of ϕ_s up to ~100% via new particles contributing to the flavor oscillations [RMP88(2016)045002]



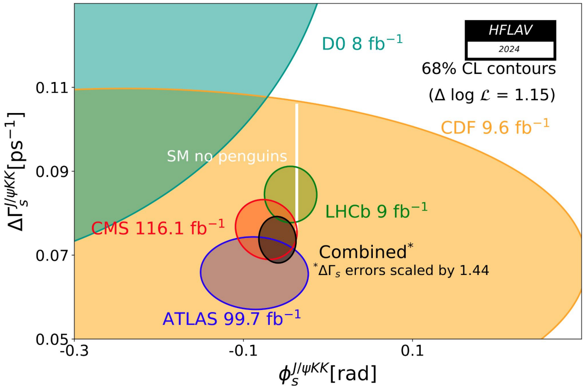
- ϕ_s has been **first measured** by the **Tevatron** experiments D0 and CDF
- At LHC ϕ_s has been measured several times by ATLAS, LHCb, and CMS
- This presentation is about the latest CMS results with the *golden* channel B_s ➜ $J/\psi\ \phi(1020)$ ➜ $\mu^+\mu^- K^+K^-$

$$\begin{tikzcd}
B_s^0 \arrow[dr, "\text{CPV}_{\text{decay}}"] \arrow[dd, leftrightarrow, "\text{CPV}_{\text{mix}}"'] & \\
& J/\psi\,\phi(1020) \\
\bar{B}_s^0 \arrow[ur, "\text{CPV}_{\text{decay}}"'] &
\end{tikzcd}$$

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

$$\downarrow$$

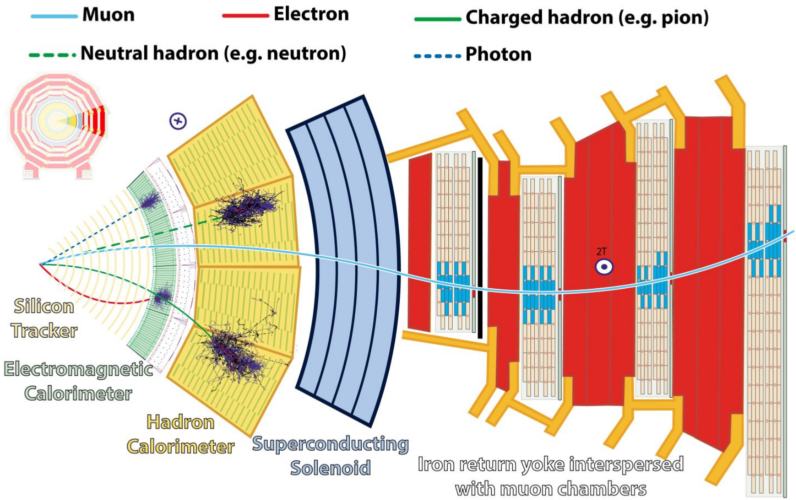
$$\boxed{\begin{aligned} a_{CP}(t) &\propto \Gamma_{\bar{B}_s\to f}(t) - \Gamma_{B_s\to f}(t) \\ &\propto -\eta_{fs}\sin(\phi_s)\sin(\Delta m_s t) \end{aligned}}$$



Dataset and detector

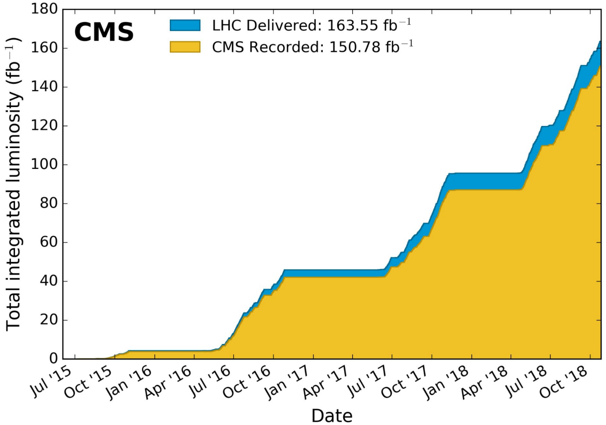
CMS is a general purpose detector able to perform a vast range of physics studies, including flavor physics

- \+ **Excellent tracking system** able to reconstruct vertices with high decay time resolution
- \+ **Enormous amount of data collected**
    - ~ 7.5 · 10^{13} bb pairs produced inside CMS during Run 2
- – High pile up N_{PV} ~ 40 (in Run 2)
- – No reliable hadronic particle identification available

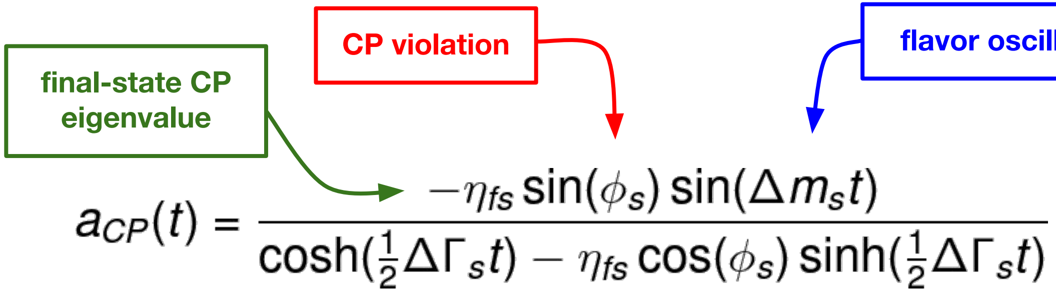


- **Dataset**: L_{int} = 96 fb^{-1} collected in 2017-2018
- Signal **candidates: 491 270 ± 950**

CMS luminosity in Run-2



A time-, flavor- and angular-dependent measurement

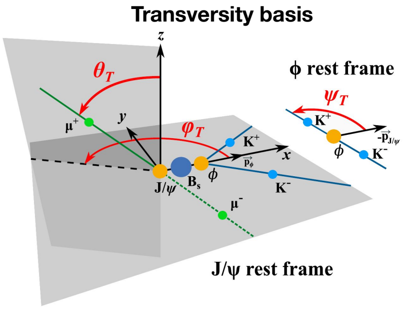


final-state CP eigenvalue

CP violation

flavor oscillations

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

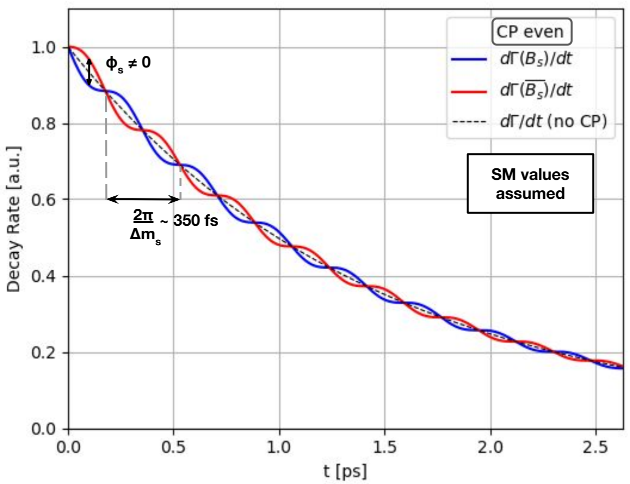


Core ingredients

- **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, CMS σ_t ~ 65 fs)

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

Decay rate for a CP-even final state



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

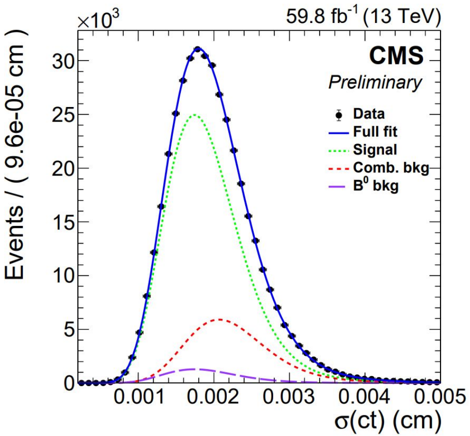
$$ct = c \cdot \frac{m_{Bs}^{w.a.} \cdot L_{xy}}{p_T} \quad \text{with} \quad L_{xy} \equiv ||\bar{r}_{xy}(SV) - \bar{r}_{xy}(PV)||$$

- 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 $B_s \rightarrow J/\psi\, \phi$, obtained by removing the displacement requirement in the data set
    - Modeled with two gaussians to obtain the effective dilution and resolution

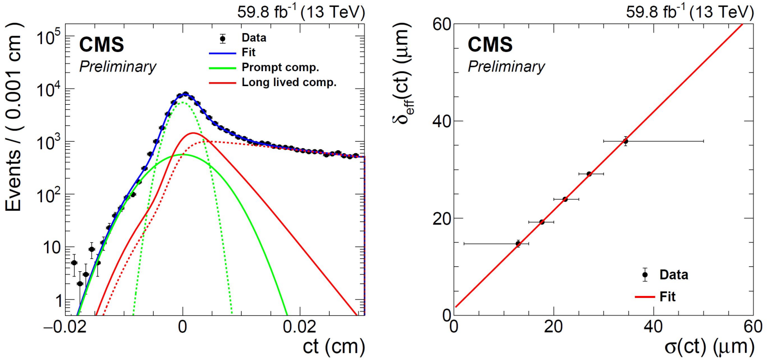
$$\delta_{\text{eff}} = \sqrt{\frac{-2\ln\mathcal{D}}{\Delta m_s^2}} \quad \text{with} \quad \mathcal{D} = \sum_{i=1}^{2} f_i \exp\left(-\frac{\sigma_i \Delta m_s^2}{2}\right)$$

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

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



Time resolution calibration for 2018 data



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

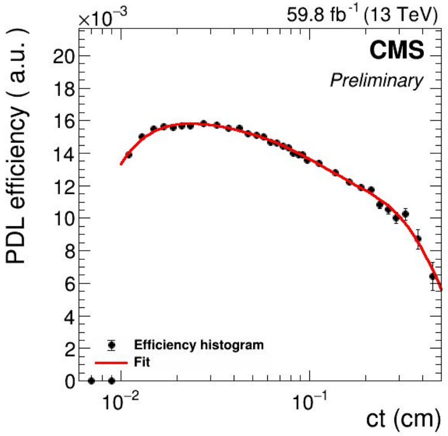
$$\varepsilon_{B^0}^{\text{data}}(ct) = \frac{N_{B^0}(ct)}{e^{-\Gamma_d^{\text{w.a.}}} \otimes P_{B^0}(\sigma_{ct})}$$

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

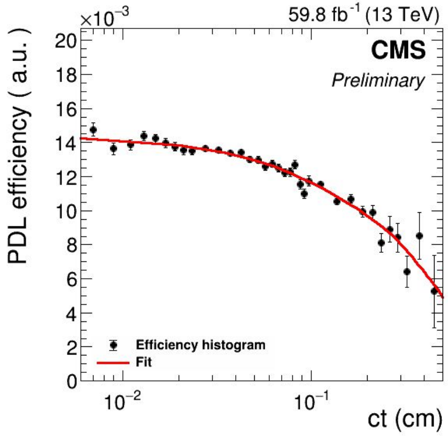
Angular efficiency

- 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)



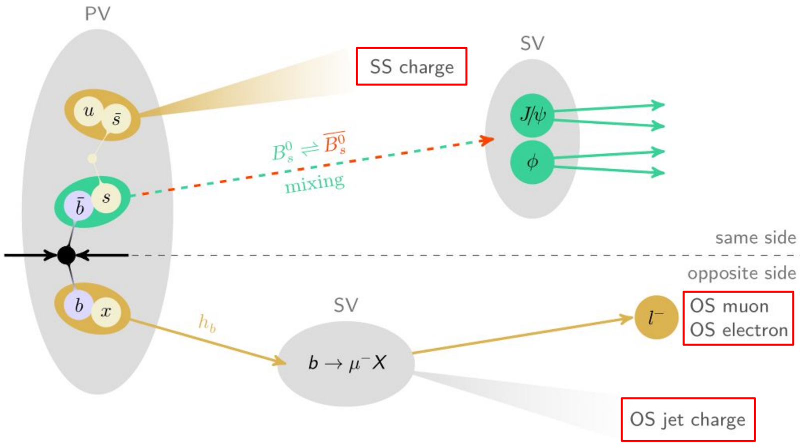
ct efficiency for the *muon-tagging* trigger category (2018)



Flavor tagging overview

- A **cutting-edge flavor tagging framework** has been engineered to extract the best possible results from data
- **Four DNN-based algorithms are used**, divided into two main categories
  - **Opposite side (OS)**: exploits decay products of the other B hadron in the event
    1. **OS muon**: leverages $b \rightarrow \mu^- X$ decays
    2. **OS electron**: leverages $b \rightarrow e^- X$ decays
    3. **OS jet**: capitalizes on charge asymmetries in the OS *b*-jet
  - **Same side (SS):** exploits the B_s fragmentation
    4. **SS tagger**: leverages charge asymmetries in the B_s fragmentation

Schematic representation of a generic event



Useful definitions

$$\xi_{tag} = \begin{cases} +1 & \text{for } B_s \\ -1 & \text{for } \overline{B}_s \\ 0 & \text{if no tagging decision is made} \end{cases}$$

$$\epsilon_{tag} = \frac{N_{tag}}{N_{tot}}, \quad \omega_{tag} = \frac{N_{mistag}}{N_{tag}}, \quad \mathcal{D}_{tag} = 1 - 2\omega_{tag}, \quad P_{tag} = \epsilon_{tag}\mathcal{D}_{tag}^2$$

Calibration strategy (and other tricks)

A multi-pronged strategy has been devised to improve the ω_{tag} estimation and suppress systematic effects

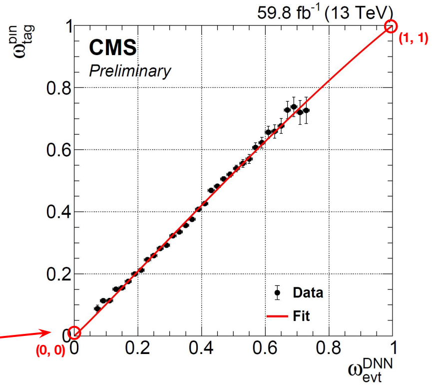
1. All models are constructed from the start as *probability estimators*, i.e. score ~ ω_{tag}
    - Loss function: *cross-entropy*, which is the likelihood for the probability P(true class | score)
    - Output layer: *Sigmoid* function, which normalizes the output to a probability distribution
2. All 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

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

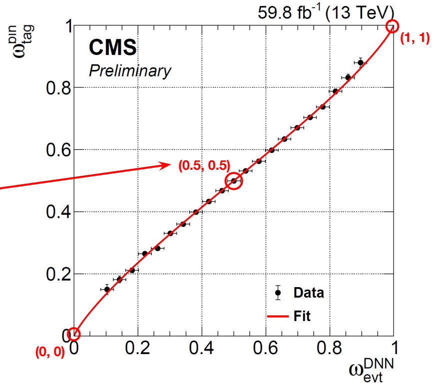
    B. The symmetry is explicitly forced in the calibration function by removing the constant term

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

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



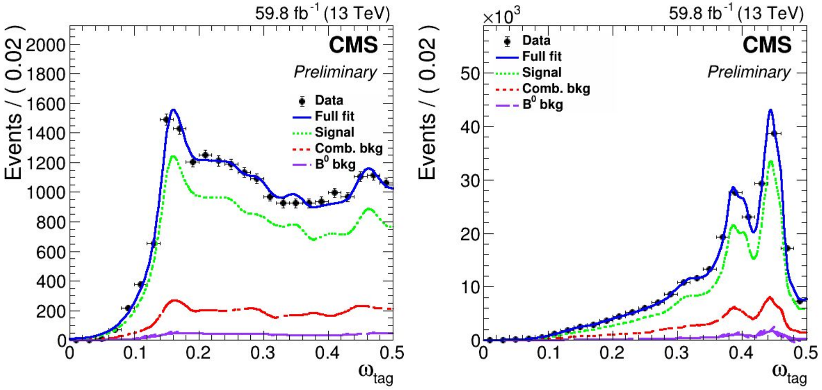
OS-jet calibration (2018)



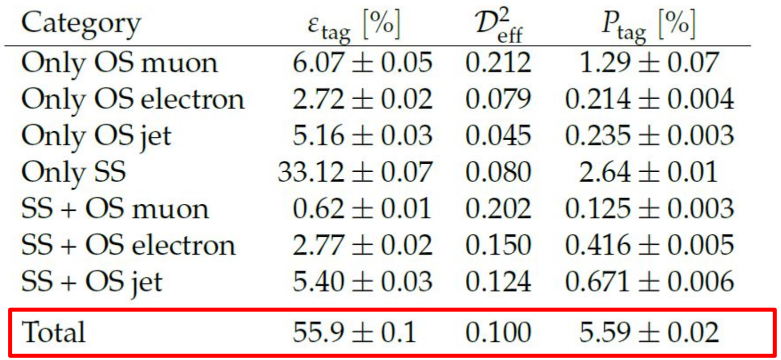
Flavor tagging performance

- The SS and any one of the OS algorithms overlap in about 20% of the events
  - In these cases, the information is combined to further 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

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



Flavor tagging performance (mutually exclusive categories)



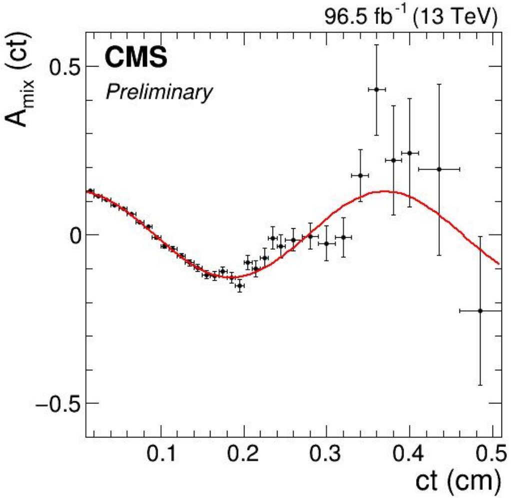
Category	ε_{tag} [%]	$\mathcal{D}^2_{eff}$	P_{tag} [%]
Only OS muon	6.07 ± 0.05	0.212	1.29 ± 0.07
Only OS electron	2.72 ± 0.02	0.079	0.214 ± 0.004
Only OS jet	5.16 ± 0.03	0.045	0.235 ± 0.003
Only SS	33.12 ± 0.07	0.080	2.64 ± 0.01
SS + OS muon	0.62 ± 0.01	0.202	0.125 ± 0.003
SS + OS electron	2.77 ± 0.02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

Tagging validation with B^0 events

- **The flavor tagging framework is validated in the B^0 ➜ J/ψ 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
- 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

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

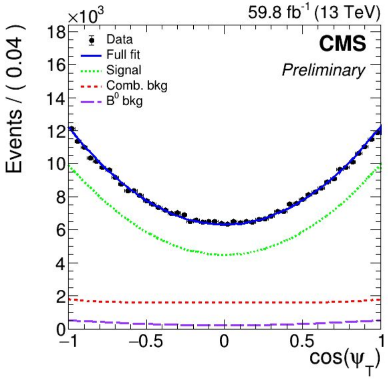


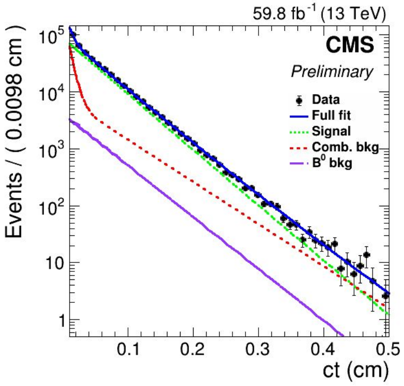
Fit strategy

- The physics parameters are extracted with **unbinned multidimensional extended maximum-likelihood (UML) fit**
    - *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}, t, σ_t, $\cos\theta_T$, $\cos\psi_T$, ϕ_T, ω_{tag}
- **Fit model**

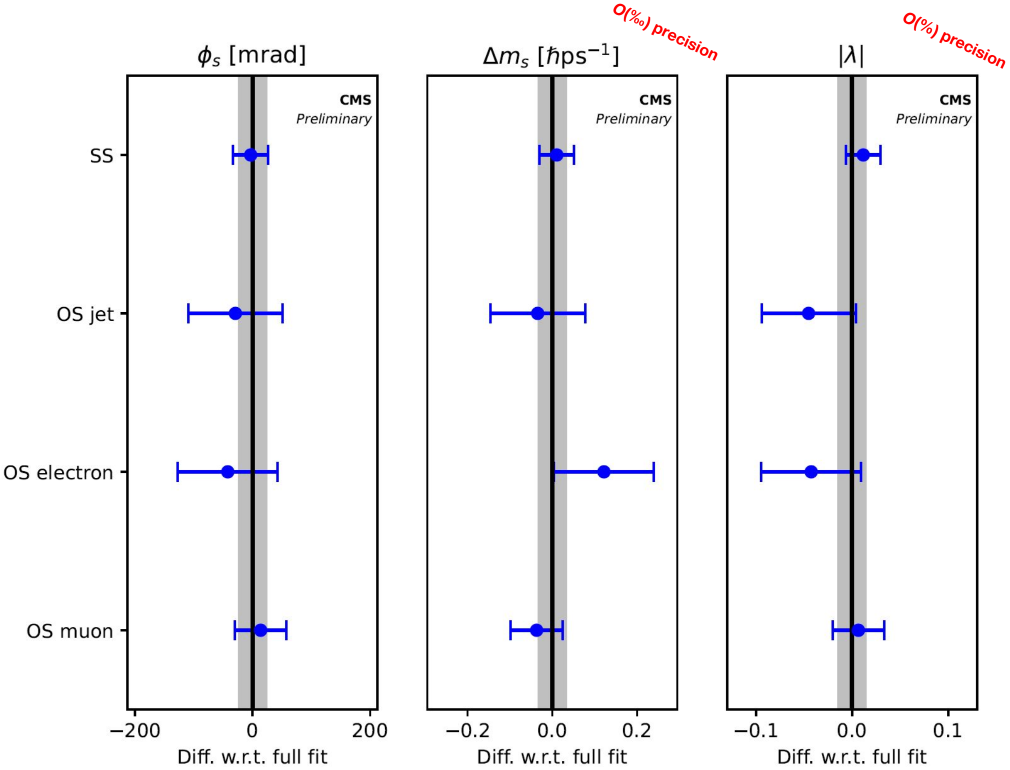
$$\frac{P(t,\sigma_t,\Theta,\xi_{tag},\omega_{tag},m\,|\,\alpha)}{\boxed{\epsilon(t)}} = \left[\boxed{\Gamma(t,\Theta,\xi_{tag},\omega_{tag}\,|\,\alpha)}\otimes\boxed{G(t\,|\,\sigma_t)}\right]\cdot\boxed{\epsilon(\Theta)}\cdot P(\sigma_t)P(m)P(\omega_{tag})+P_{bkg}(\dots)$$

- **Analytical decay rate**
- **Time resolution** (extracted from prompt background)
- **Angular efficiency** (extracted from MC)
- **Time efficiency** (from B^0 ➔ $J/\psi\, K^*$ events in data)
    - Implemented as reweighting
- **Backgrounds sources:**
    - 75%: combinatorial
    - 25%: B^0 ➔ $J/\psi\, K^*$ ➔ $\mu\mu\, K\pi$
    - negligible: Λ_b ➔ $J/\psi\, \Lambda^0$ ➔ $\mu\mu\, Kp$ (treated as systematic uncertainty)
- The statistical uncertainties and fit bias are estimated with 1300 bootstrap distributions





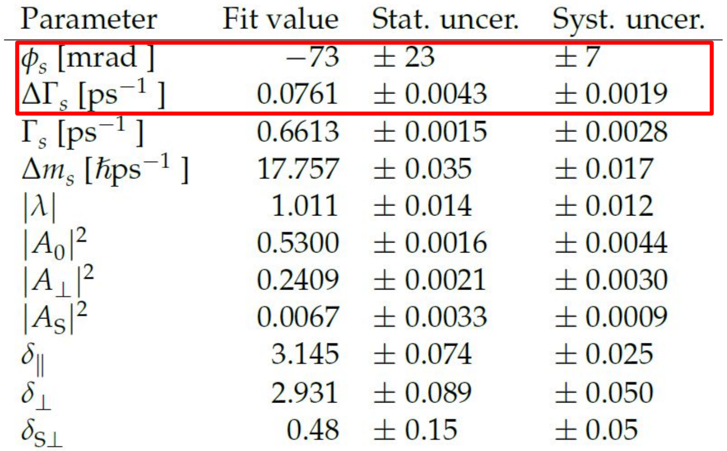
Validation: fit with individual tagging techniques



- **To check the consistency and stability of the tagging framework, the fit to data is repeated with only one tagging algorithm deployed at a time**
  - The grey area represents the result and statistical uncertainty of the full fit
  - Only flavor-sensitive parameters are presented
- **Excellent agreement between the various tagging techniques**

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
$\lvert\lambda\rvert$	1.011	± 0.014	± 0.012
$\lvert A_0\rvert^2$	0.5300	± 0.0016	± 0.0044
$\lvert A_\perp\rvert^2$	0.2409	± 0.0021	± 0.0030
$\lvert A_S\rvert^2$	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 (~27.5k)
  - 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

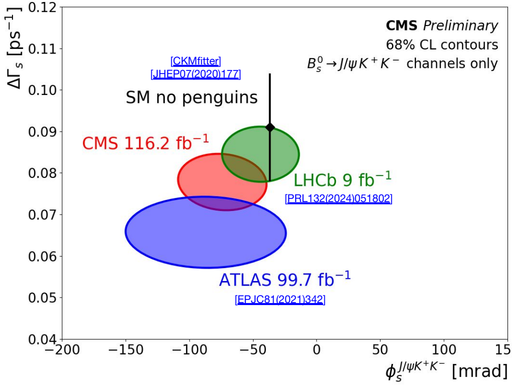
Combination with 8 TeV results

- These results supersede PLB816(2021)136188 and are further combined with those obtained CMS at 8 TeV [PLB757(2016)97], yielding

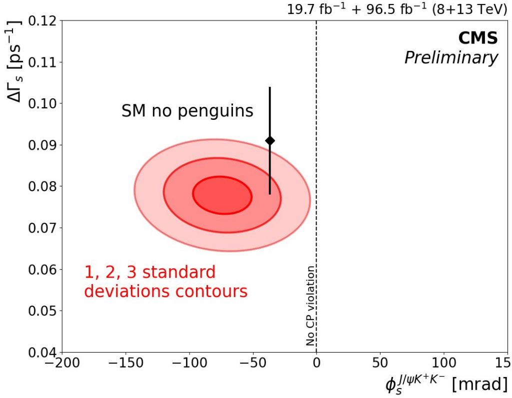
$$\boxed{\begin{aligned}\phi_s &= -74 \pm 23\ [\text{mrad}]\\ \Delta\Gamma_s &= 0.0780 \pm 0.0045\ [\text{ps}^{-1}]\end{aligned}}$$

- Due to the high difference in statistical power between the two results the sensitivity gain is small
- **The combined value for the weak phase ϕ_s is consistent with the SM prediction, the latest world average, and with zero (no CPV) at 3.2 s.d.**
    - **This is the first evidence of CPV in $B_s \rightarrow J/\psi\ K^+K^-$ decays**
- These results helps to further constrain possible BSM effects in the B_s system

Comparison with other LHC experiments



1, 2, 3 standard deviations contours



Summary and outlook

- This presentation showed the **measurement of the time-dependent CP violation in B_s ➜ J/ψ ϕ**
- Thanks to the advancements in trigger strategies and flavor tagging techniques, this resulted in the **first evidence for CP violation in B_s ➜ J/ψ K^+K^-**
- CMS recent contributions in flavor physics prove that it can be one of the leading actors in several key areas of study, such as rare decays and CP violation and that it is able to compete in measurements for which the detector was not designed

- **Run 3 will provide unique opportunities thanks of a revamped trigger strategy, which will lead to the collection of an unprecedented amount of data suitable for flavor physics studies**

Stay tuned in the future for other exciting CMS results!

Backup

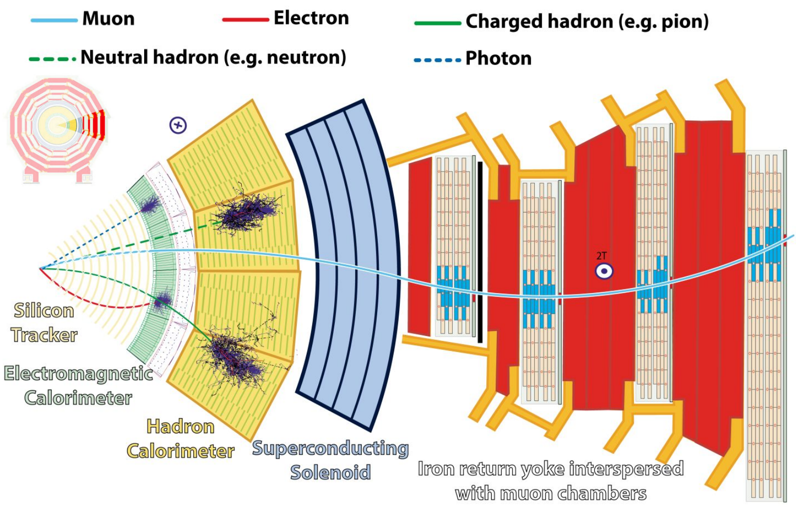
The CMS detector

CMS is a general purpose detector able to perform a vast range of physics studies, including flavor physics

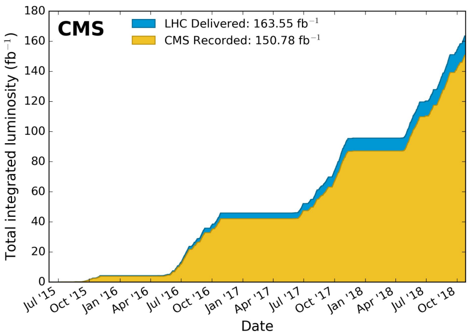
- \+ **Excellent tracking system** able to reconstruct vertices with high decay time resolution (e.g., **σ_t ~ 65 fs** for $B_s \rightarrow J/\psi\ \phi$) up to $|\eta| < 2.5$
- \+ **Enormous amount of data collected**
  - ~ $7.5 \cdot 10^{13}$ bb pairs produced inside CMS during Run 2
- – High pile up N_{PV} ~ 40 (in Run 2)
- – No reliable hadronic particle identification available

Some **CMS flavor physics highlights** from recent years

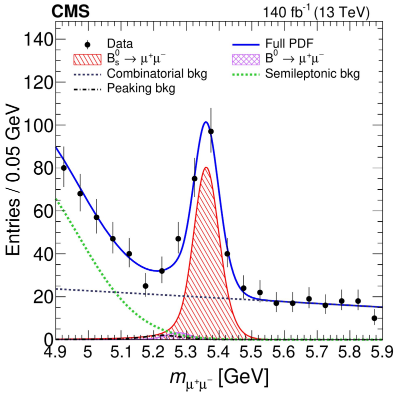
- $B_s \rightarrow \mu^+\mu^-$ (world's most precise) [PLB842(2023)137955]
- $\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$ observation [PRL131(2023)091903]
- f_s/f_u measurements [PRL131(2023)121901]
- Triple J/ψ production observation [Nat.Phys.19(2023)338]
- R(K) LFU test [BPH-22-005]
- R(J/ψ) LFU test [BPH-22-012]



CMS luminosity in Run-2



$B_s \rightarrow \mu^+\mu^-$



Theory reference: J.Phys.G48(2021)6,065002

Penguin contributions

Assuming this is negligible

We measure this

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

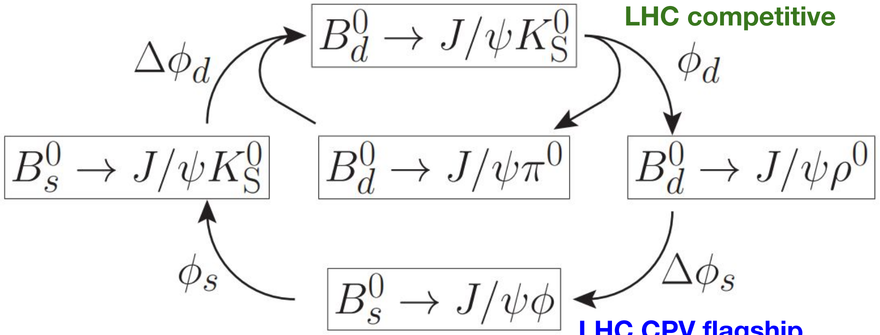
$$\boxed{\sin(2\beta)} = \sin(2\beta^{tree} + \boxed{\Delta\phi_d^{penguin}} + \boxed{\Delta\phi_d^{NP}})$$

Trying to probe this

- Penguin pollutions are expected to be small for B_s, but they are not well constrained

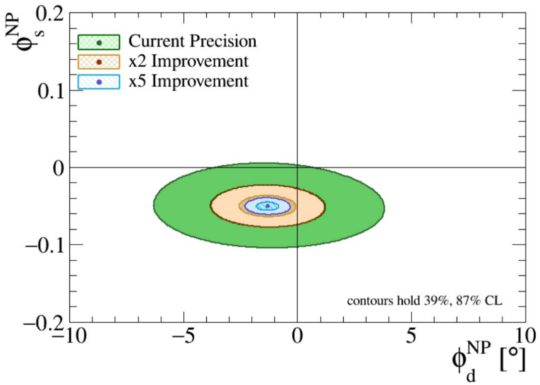
$$\Delta\phi_s^{penguin} \approx 3 \pm 10 \text{ mrad}$$

- 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



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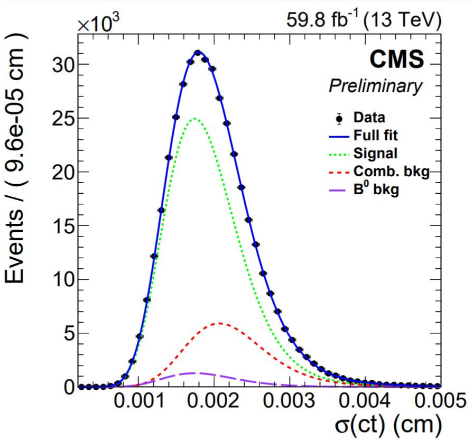
- Its **uncertainty** is obtained by fully propagating the uncertainties in L_{xy} and p_T
  - The uncertainty on L_{xy} dominates for most of the ct spectrum, with $\sigma(p_T)$ taking over at high values (ct $\gtrsim$ 3 mm)
- **The ct uncertainty is calibrated in a prompt data sample** of $B_s \rightarrow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

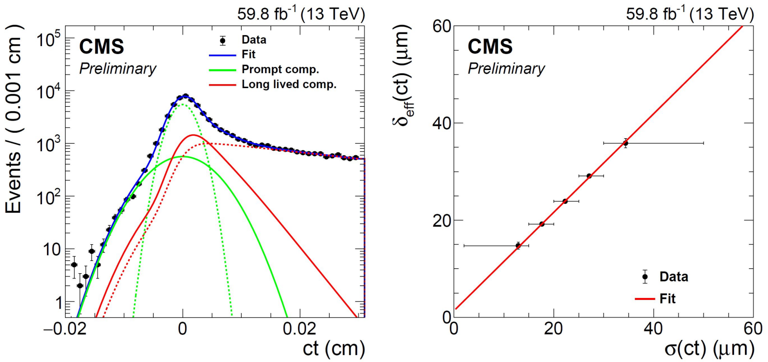
$$\delta_{\text{eff}} = \sqrt{\frac{-2 \ln \mathcal{D}}{\Delta m_s^2}} \quad \text{with} \quad \mathcal{D} = \sum_{i=1}^{2} f_i \exp\left(-\frac{\sigma_i \Delta m_s^2}{2}\right)$$

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

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



Time resolution calibration for 2018 data



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

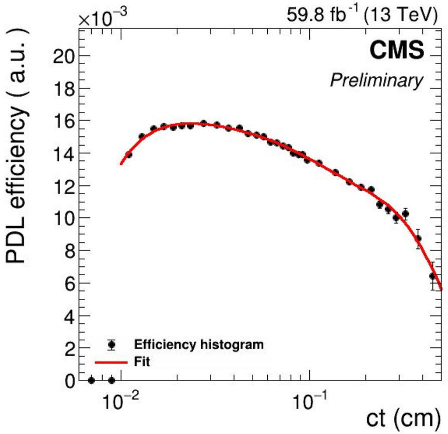
$$\varepsilon^{\text{data}}_{B^0}(ct) = \frac{N_{B^0}(ct)}{e^{-\Gamma^{\text{w.a.}}_{d}} \otimes P_{B^0}(\sigma_{ct})}$$

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

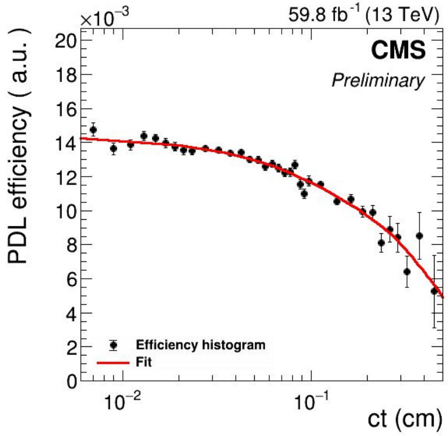
Angular efficiency

- 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)



Decay rate model

Flavor tag decision
(flips c_i and d_i signs)

Mistag probability

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

Decay time

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

Angular variables

Most sensitive terms for SM ϕ_s

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

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

Sensitive to direct CPV

Sensitive to ϕ_s ~ 0

Sensitive to ϕ_s ~ π/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

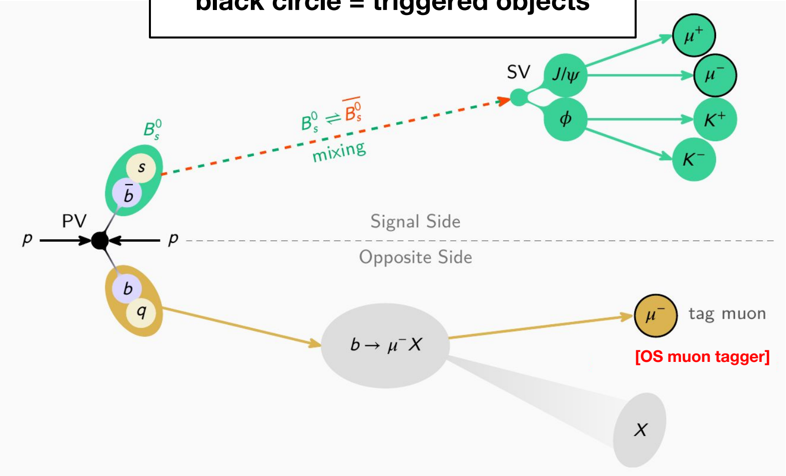
Trigger strategy

PLB816(2021)136188
(superseded)

black circle = triggered objects

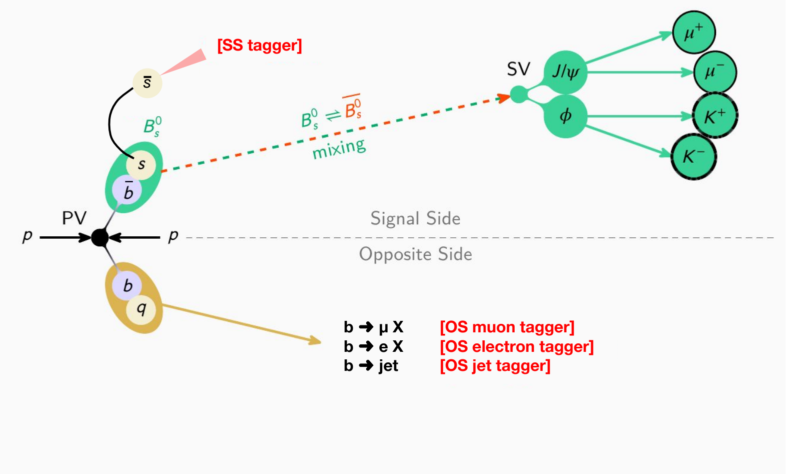
Muon-tagging **trigger**

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



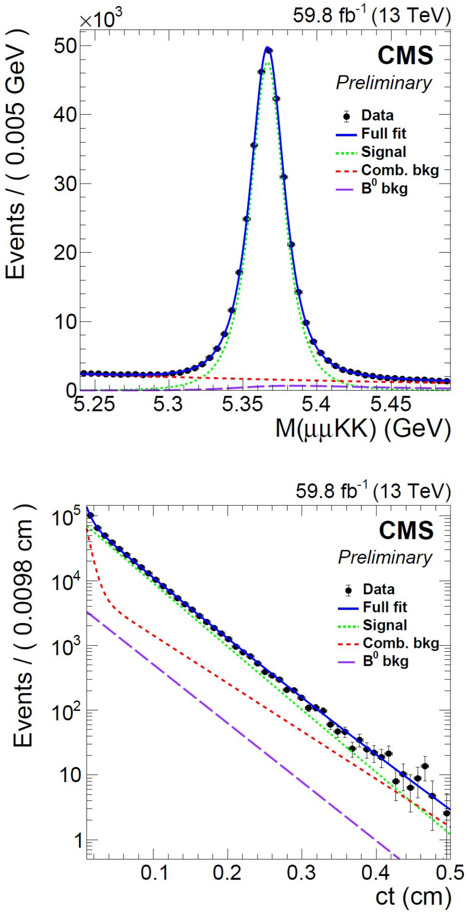
Dataset and selection

- **Dataset**: L_{int} = 96 fb^{-1} collected in 2017-2018
    - Why no 2016 data? Very different data set (old inner tracker detector with worse time resolution and different trigger menu)
- **Signal candidates: 491 270 ± 950**
- Notable selection requirements:

Variable	Requirement
ct (*muon-tagging* HLT)	$> 60\ \mu$m
ct (*standard* HLT)	$> 100\ \mu$m
ct/σ_{ct} (*standard* HLT)	> 3
$\lvert m(K^+K^-) - m_{\phi(1020)} \rvert$	< 10 MeV
$\lvert m(\mu^+\mu^-) - m_{J/\psi} \rvert$	< 150 MeV

- To avoid **overlaps**, events that pass both trigger category selections are placed only in the *muon-tagging* one
    - This depletes the *standard* trigger category of OS muons
- The PV of choice is the closest in 3D to the line that passes through the SV and parallel to the B_s momentum

Invariant mass and proper decay length distributions for the *standard* trigger (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)

$$\boxed{\begin{array}{l} \text{OS } \ell^- \to \text{OS } b \xrightarrow{\text{tag}} \text{signal } B_s \\ \text{OS } \ell^+ \to \text{OS } \bar{b} \xrightarrow{\text{tag}} \text{signal } \bar{B}_s \end{array}} \qquad \boxed{\omega_{tag} = 1 - \boxed{s_{DNN}}}$$

DNN score

-
    - **Charge-based taggers** (OS jet, SS)
        - DNN score ➜ Prob(B_s) ➜ ξ_{tag}, ω_{tag}

(DNN trained for B_s vs $\bar{B}_s$)

$$\begin{array}{llll} \boxed{s_{DNN}} > 0.5 + \epsilon \xrightarrow{tag} \text{signal } B_s & \text{with} & \omega_{tag} = 1 - & \boxed{s_{DNN}} \\ \boxed{s_{DNN}} < 0.5 - \epsilon \xrightarrow{tag} \text{signal } \bar{B}_s & \text{with} & \omega_{tag} = & \boxed{s_{DNN}} \end{array}$$

-
    -
        - 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

Calibration strategy (and other tricks)

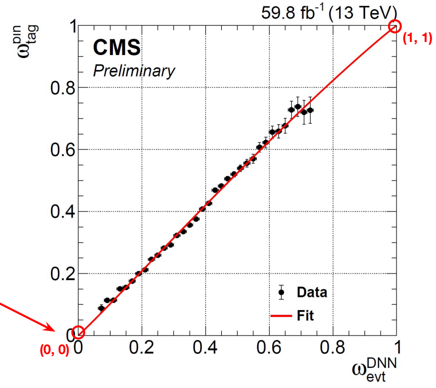
- **A** **multi-pronged strategy** **has been devised to improve the ω_{tag} estimation and suppress systematic effects**
  1. All models are constructed from the start as *probability estimators*, i.e. score~ω_{tag}
     - Loss function: *cross-entropy*, which is the likelihood for the probability P(true 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

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

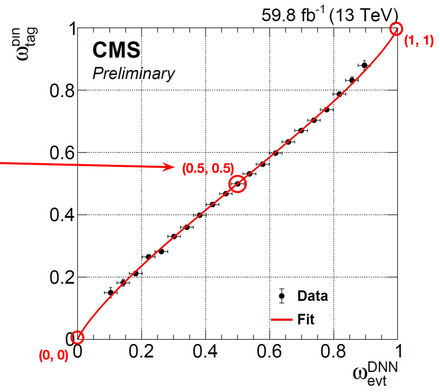
     - B. The symmetry is explicitly forced in the calibration function by removing the constant term

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

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



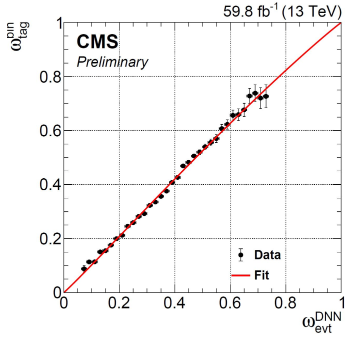
OS-jet calibration (2018)



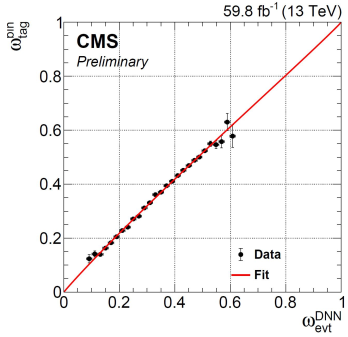
OS-lepton tagging

- **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)



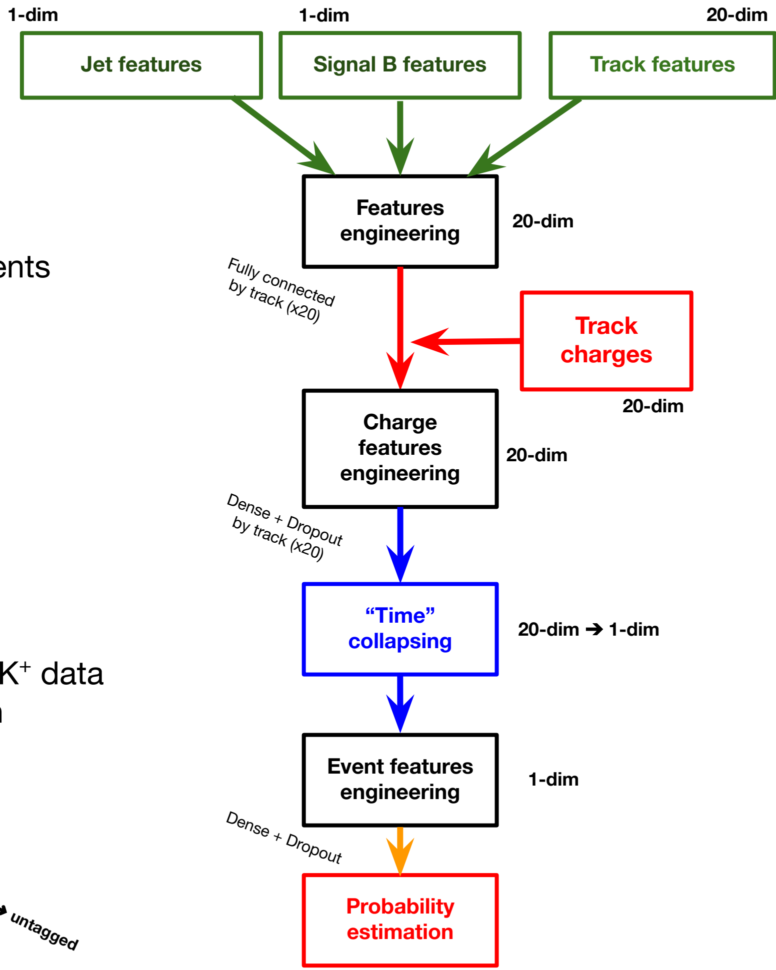
OS-jet tagging

- **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 $\overline{b}$ quark (i.e. being a B_s)**
- The score is finally used to compute both ξ_{tag} and ω_{tag}

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

$\omega_{tag} > 0.48$ → untagged

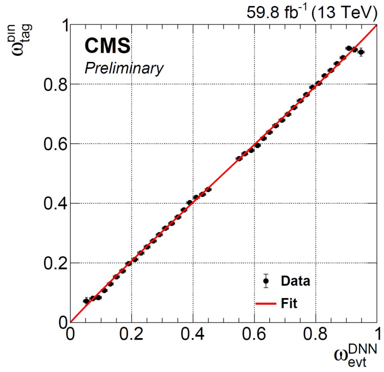
Schematic DNN model representation



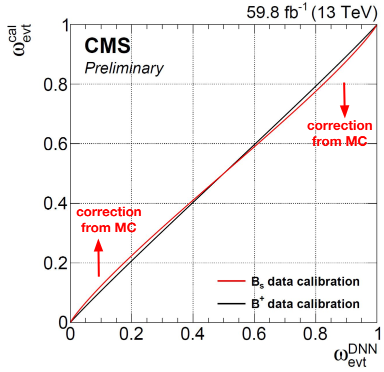
SS tagger

- **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**
  - $\Delta R(\mathrm{trk}, B) < 0.8$, $|IP_z(PV)| < 0.4$ 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)



Offline selection

Requirements common between the two HLTs

- $5.24 < m(\mu\mu KK) < 5.49$ GeV
- $p_T(B_s) > 9.5$ GeV
- Vertex probability > 2%
- $\sigma(ct) < 50$ µm
- $|\eta(\mu)| < 2.4$
- $|\eta(K)| < 2.5$
- $|m(\mu\mu) - m(J/\psi^{PDG})| < 150$ MeV
- $|m(KK) - m(\phi(1020)^{PDG})| < 10$ MeV

Requirements specific to the *muon-tagging HLT*

- $p_T(\mu) > 3.5$ GeV
- $p_T(K) > 1.15$ GeV
- $ct > 60$ µm

Requirements specific to the *standard* HLT

- *muon-tagging* trigger vetoed
- $p_T(\mu) > 4$ GeV
- $p_T(K) > 0.9$ GeV
- $p_T(\mu\mu) > 6.9$ GeV
- $ct > 100$ µm, $ct/\sigma(ct) > 3$

- **Selection requirement optimized** with the a genetic algorithm to maximize $S/\sqrt{(S + B)}$
- **To avoid overlaps, the *muon-tagging* trigger is vetoed in the *standard* trigger category**
- The **PV** of choice is the closest in 3D to the line that passes through the SV and parallel to the B_s momentum

OS-lepton taggers selection

OS Muon

- **Requirements**
  - $p_T > 2$ GeV
  - $|\eta| < 2.4$
  - $|d_z(PV)| < 1$ cm
  - $\Delta R(B_s) > 0.4$
  - Discriminators vs fakes

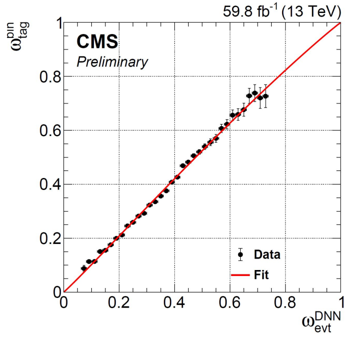
- Deployed in **both trigger categories**
- Dense DNN for ω_{tag} estimation
  - Inputs: kinematics, IP, surrounding activity

OS electron

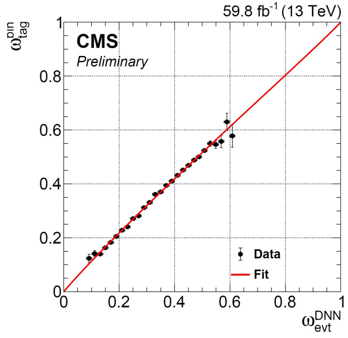
- **Requirements**
  - No OS muon selected in the event
  - $p_T > 2.5$ GeV
  - $|\eta| < 2.4$
  - $|d_z(PV)| < 0.2$ cm
  - $|d_{xy}(PV)| < 0.08$ cm
  - $\Delta R(B_s) > 0.4$
  - Discriminators vs fakes

- Deployed **only in the *standard* trigger** category
- Dense DNN for ω_{tag} estimation
  - Inputs: kinematics, IP, surrounding activity

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



OS-Electron calibration (2018)



Taggers combination

- **Overlap logic**

Overlap	OS muon	OS electron	OS jet	SS
OS muon		X	X	✓
OS electron	X		X	✓
OS jet	X	X		✓
SS	✓	✓	✓	

- **Tag decision combination**

$$\xi(\xi_1, \xi_2, \omega_1, \omega_2) = \begin{cases} \xi_1 & \text{if} \quad \omega_1 < \omega_2 \\ \xi_2 & \text{if} \quad \omega_2 < \omega_1 \end{cases}$$

- **Mistag combination**

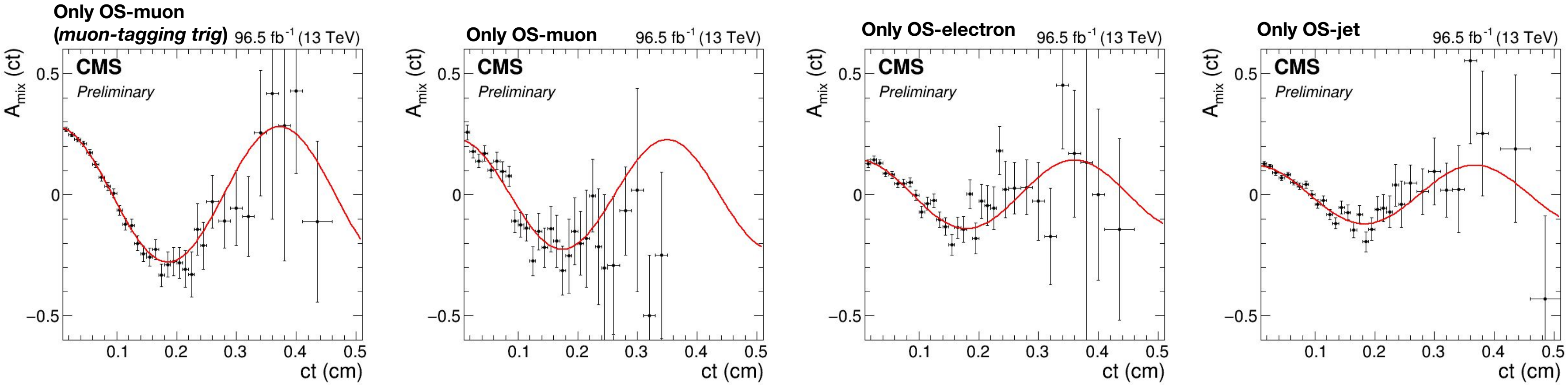
$$p(\overline{b}) = \prod_{i=1}^{2} \left(\frac{1 - \xi_i}{2} + \xi_i (1 - \omega_i) \right) \qquad p(b) = \prod_{i=1}^{2} \left(\frac{1 + \xi_i}{2} - \xi_i (1 - \omega_i) \right)$$

$$P(\overline{b}) = \frac{p(\overline{b})}{p(\overline{b}) + p(b)} \qquad P(b) = \frac{p(b)}{p(\overline{b}) + p(b)}$$

All categories are mutually exclusive

All, but the first,refers to the *standard* trigger category

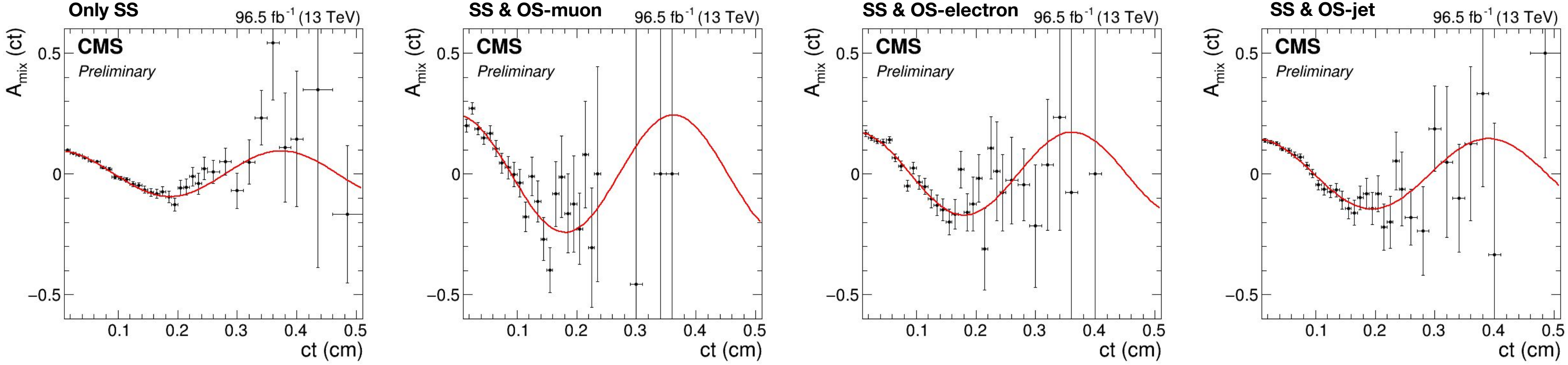
Mixing asymmetry for different tagging categories


Only OS-muon (*muon-tagging trig*)

Only OS-muon

Only OS-electron

Only OS-jet

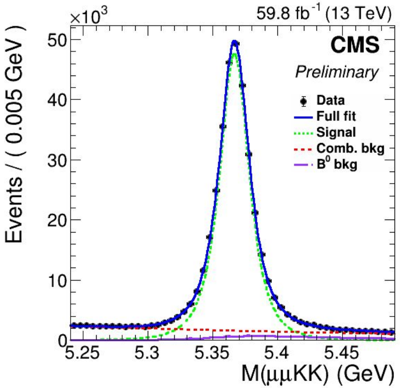

Only SS

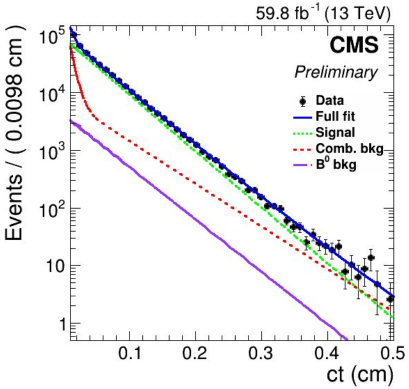
SS & OS-muon

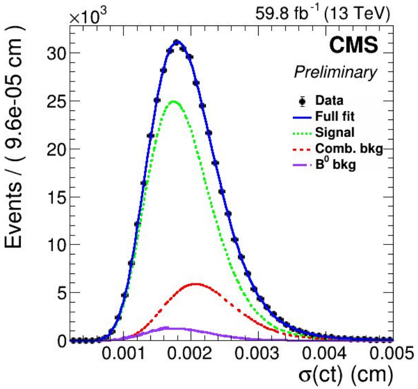
SS & OS-electron

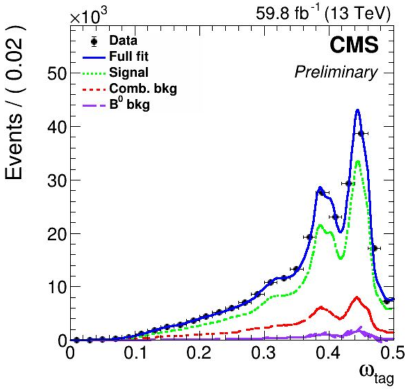
SS & OS-jet

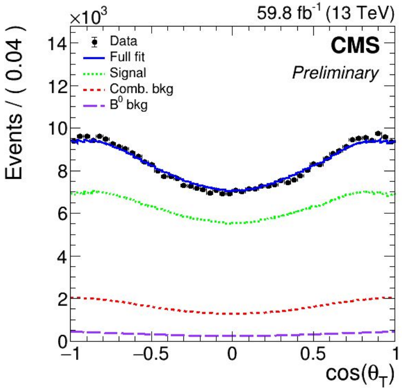
Fit projections (*standard* trigger category 2018)

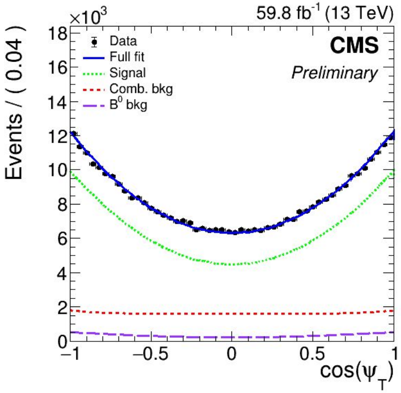


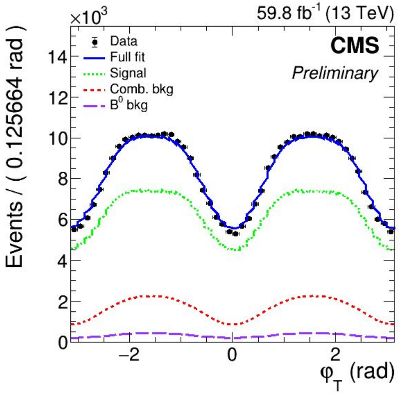










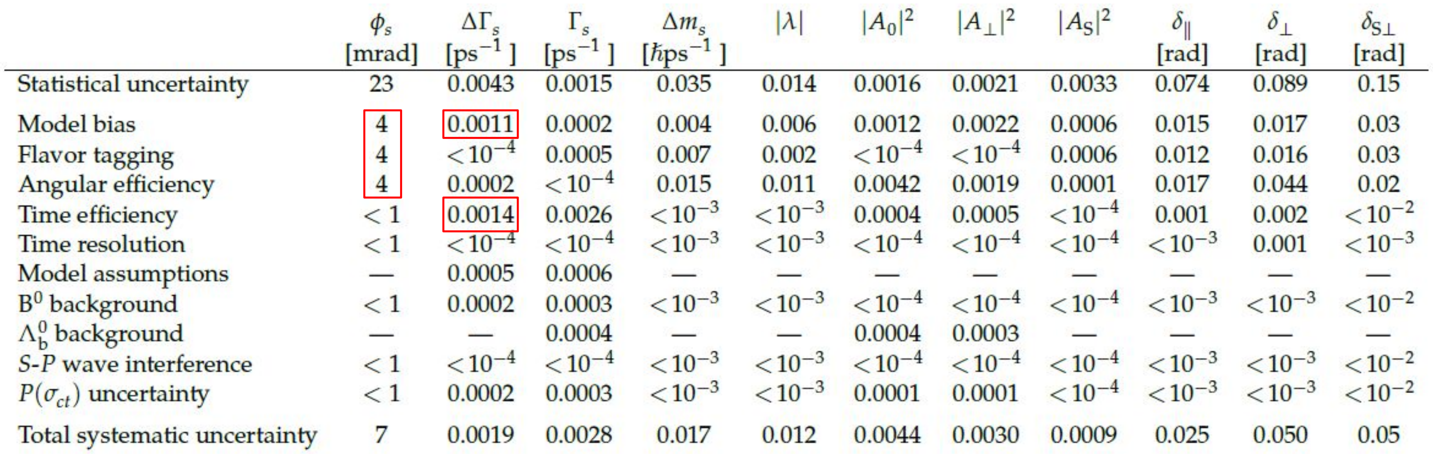


Systematic uncertainty classification

- **Type-I: unaccounted uncertainties**
  - Account for the finite statistics of simulated/control samples and uncertainties in calibrations and efficiency
  - **Always** propagated to the final results
  - Evaluated with two procedures
    1. *Type-I full*: obtained by sampling the samples/parameters of interest ~100 times, repeating the fit each time, and taking the RMS of the results as uncertainty
    2. *Type-I simple:* obtained by sampling a parameter only two times at $\pm 1\sigma_{\text{stat}}$
- **Type-II: method and model assumptions**
  - Account for **possible** bias induced by the assumptions made in the fit model and the analysis methods
  - Evaluated only if a **significant** bias is observed while testing an alternative (good) hypothesis
  - A significant bias for a parameter V is defined as a difference Δ in the fit results of **more than 20% of its σ_{stat}**
  - In these cases, **half of the bias** is taken as uncertainty, assuming that the *true* bias is uniformly distributed between 0 and Δ

The fit bias does not fall into either of these two categories

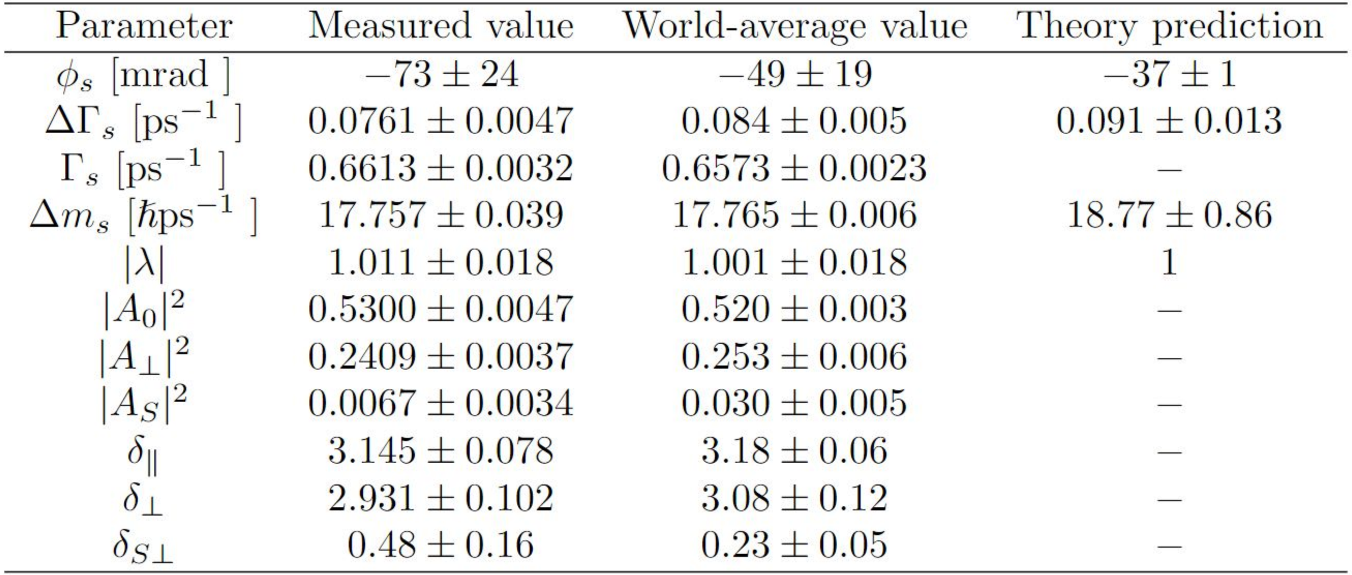
Systematic uncertainty overview



	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	Δm_s [$\hbar\text{ps}^{-1}$]	$\lvert\lambda\rvert$	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$\lvert A_S\rvert^2$	$\delta_\parallel$ [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

Comparison with theory and world averages



Parameter	Measured value	World-average value	Theory prediction
ϕ_s [mrad]	-73 ± 24	-49 ± 19	-37 ± 1
$\Delta\Gamma_s$ [ps^{-1}]	0.0761 ± 0.0047	0.084 ± 0.005	0.091 ± 0.013
Γ_s [ps^{-1}]	0.6613 ± 0.0032	0.6573 ± 0.0023	–
Δm_s [$\hbar$ps^{-1}]	17.757 ± 0.039	17.765 ± 0.006	18.77 ± 0.86
$\lvert\lambda\rvert$	1.011 ± 0.018	1.001 ± 0.018	1
$\lvert A_0\rvert^2$	0.5300 ± 0.0047	0.520 ± 0.003	–
$\lvert A_\perp\rvert^2$	0.2409 ± 0.0037	0.253 ± 0.006	–
$\lvert A_S\rvert^2$	0.0067 ± 0.0034	0.030 ± 0.005	–
$\delta_\parallel$	3.145 ± 0.078	3.18 ± 0.06	–
$\delta_\perp$	2.931 ± 0.102	3.08 ± 0.12	–
$\delta_{S\perp}$	0.48 ± 0.16	0.23 ± 0.05	–

[CKMfitter, UTfit]

[Lenz & Tetlalmatzi-Xolocotzi]

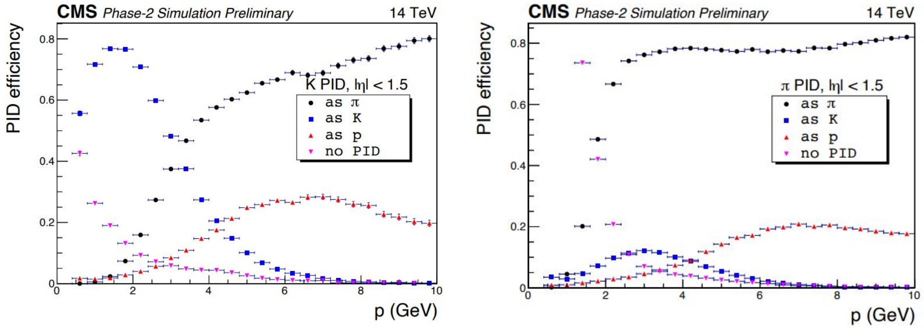
[Lenz & Tetlalmatzi-Xolocotzi]

Reference: CERN-CMS-DP-2022-025

Flavor tagging in Phase-2 with MTD

- The MTD (Mip Timing Detector) provides time information of charged tracks at its surface
- 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 *s*-quark in the B_s and a nearby soft kaon for flavor tagging
- The PID from MTD, when integrated in the Phase-2 extrapolation of this analysis, shows a significant improvement of the tagging performances

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%