Status and perspective of CPV and CKM measurements at ATLAS and CMS

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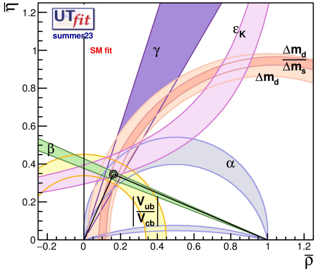
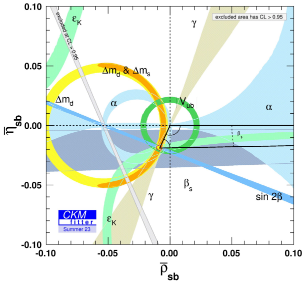
CP violation in the SM

- 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"

B^0 unitary triangle (UTfit)

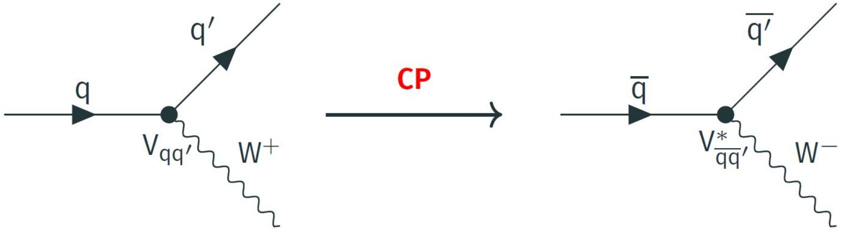


B$_s$ unitary triangle (CKMfitter)



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

Flavour **CKM** **Mass**



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

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

Search for CP violation in $D^0 \rightarrow K_S K_S$

CMS: arXiv:2405.11606

Dataset: 2018 B Parking (41 fb^{-1})

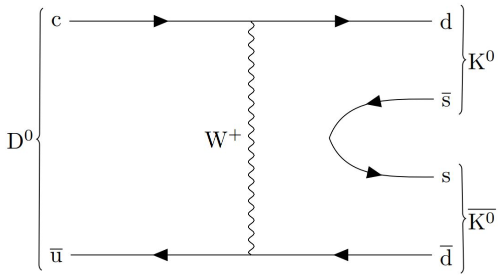
Motivations

- **CP violation in the up-quark sector is not studied as well as in the down-quark one**
  - Expected to be suppressed by the GIM mechanism and CKM element size
- **Observation of a significant CPV ➜ hints of BSM physics**
  - First observation of CPV in D mesons in 2019 by LHCb with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays [PRL122(2019)211803]
- Presented here: **measurement of the direct CPV in $D^0 \to K_S K_S$ decays**

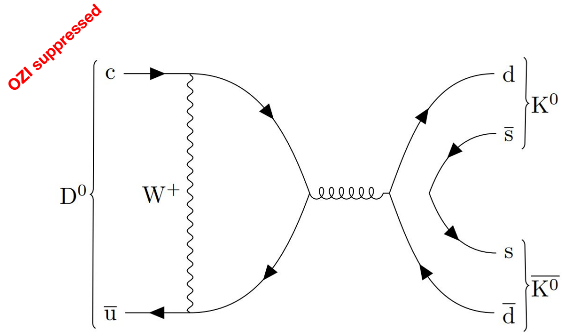
$$A_{CP} = \frac{\Gamma(D^0 \to K^0_S K^0_S) - \Gamma(\overline{D}^0 \to K^0_S K^0_S)}{\Gamma(D^0 \to K^0_S K^0_S) + \Gamma(\overline{D}^0 \to K^0_S K^0_S)}$$

- From theory, CPV in $D^0 \to K_S K_S$ could be as large as *O(1%)* [PRD92(2015)054036]

W exchange diagram for D^0



Penguin annihilation diagram for D^0



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 additional asymmetries due to the D^{*+}/D^{*-} differences in the measurement

What we want

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

Measured

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

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

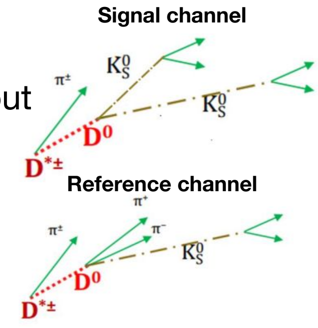
??

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

??

- **Need a reference channel: $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K_S K_S) - A_{CP}(D^0 \rightarrow K_S \pi^+ \pi^-)$**
  - 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]

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



A_{CP} extraction

To extract the CP asymmetry a **2D maximum-likelihood fit is performed on the invariant mass of the D^{*+} and D^0**

- Fit is done simultaneously on the D^{*+} and D^{*-} samples with only the yields left to float
- **Main fit components** (signal channel):
  - D^0 x D^{*+}, the signal component
  - D^0 x *bkg*, real D^0 but fake D^{*+}
  - *bkg* x *bkg*, background in both dimensions
- **Notable selections:** $m(\pi^+\pi^-) \in$ PDG ± 20 MeV, $m(K_S K_S) \in [1.7,2.0]$ GeV, displaced by >9(2)σ in xyz(xy)
- **Background suppression:** fit alternative topologies, select based on vertex probabilities
- **Yields:**

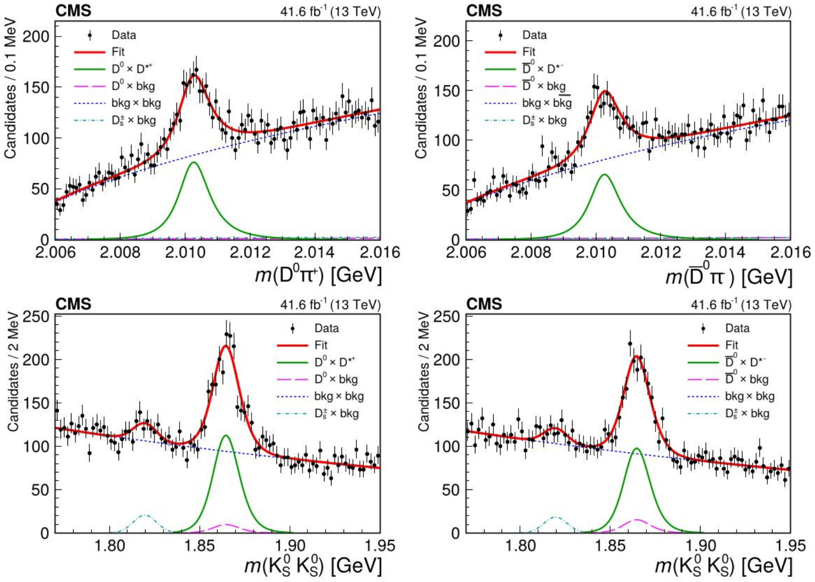
Reference channel

Pion charge	N
π^+	944 800 ± 3 500
π^-	930 150 ± 3 400

Signal channel

Pion charge	N
π^+	1095 ± 46
π^-	951 ± 44

$D^0 \rightarrow K_S K_S$ $\quad$ $\overline{D}^0 \rightarrow K_S K_S$



Systematic uncertainties

Source	Uncertainty, %
$m(D\pi^\pm)$ signal model	0.10
$m(D\pi^\pm)$ background model	0.02
$m(K^0_S K^0_S)$ signal model	0.04
$m(K^0_S K^0_S)$ background model	0.02
$m(K^0_S K^0_S)$ fit range	0.04
Reweighting	0.09
ΔA_{CP} in MC	0.13
Total	0.20

Results and outlook

- Putting everything together, ΔA_{CP} is measured

$$\Delta A_{CP} = 6.3 \pm 3.0\,(\text{stat}) \pm 0.2\,(\text{syst})\,\%$$

- **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, with LHCb [PRD104(2021)L031102] [(-3.1 ± 1.3)%] at 2.7σ and Belle [PRL119(2017)171801] [(0.0 ± 1.5)%] at 1.8σ
- **This is the first CMS study of CP violation in the charm sector, paving the way for future measurements using**
  - More data
  - Refined techniques
  - Different channels

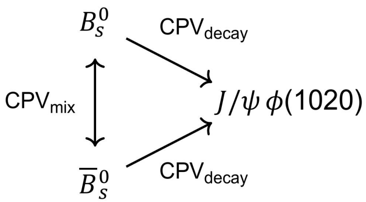
Measurement of the time-dependent CP violation in B_s mesons

CMS: [CMS PAS BPH-23-004]

ATLAS: [EPJC81(2021)342]

Dataset:
CMS: 2017-18 (96 fb^{-1})
ATLAS: 2015-17 (80 fb^{-1})

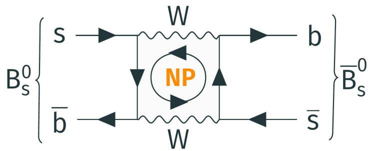
Motivations



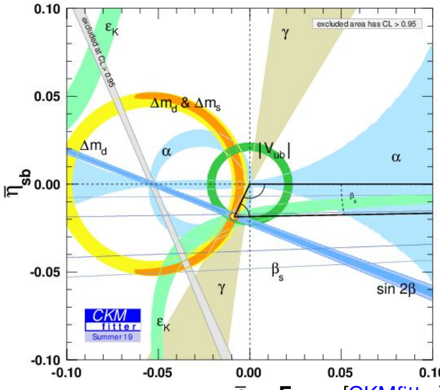
$$\Gamma\left(B^0_{s\,(\rightsquigarrow \overline{B}^0_s)} \to f\right)(t) \overset{?}{\neq} \Gamma\left(\overline{B}^0_{s\,(\rightsquigarrow B^0_s)} \to f\right)(t)$$

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

- **B_s mesons decays allow us to study the time-dependent CP violation generated by the interference between direct decays and flavor 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 measurements in the *golden* channel B_s ➜ $J/\psi\ \phi(1020)$ ➜ $\mu^+\mu^- K^+K^-$
  - **CMS:** 96.4 fb^{-1} 2017 - 18 + 19.7 fb^{-1} Run1
  - **ATLAS:** 80 fb^{-1} 2015 - 17 + 19.2 fb^{-1} Run1
    - 60 fb^{-1} from 2018 to be added



From: [CKMfitter]

A time-, flavor- and angular-dependent measurement

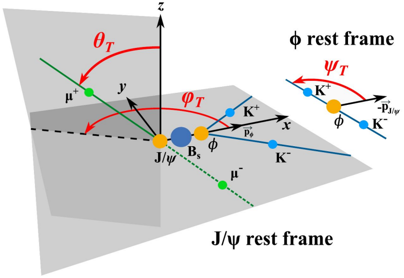
final-state CP eigenvalue

CP violation

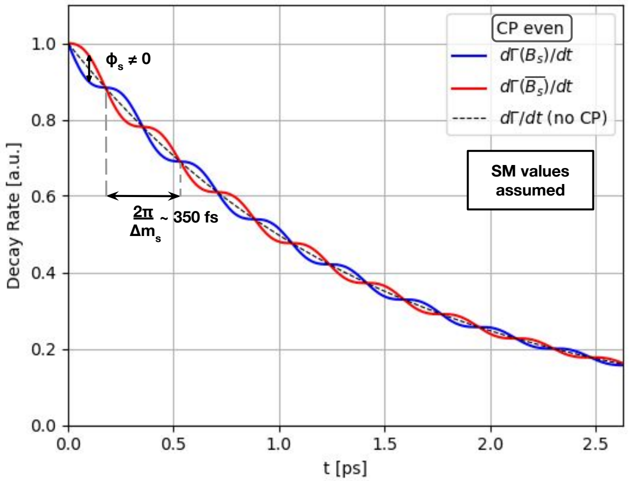
flavor oscillations

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

Transversity basis



Decay rate for a CP-even final state



Core ingredients

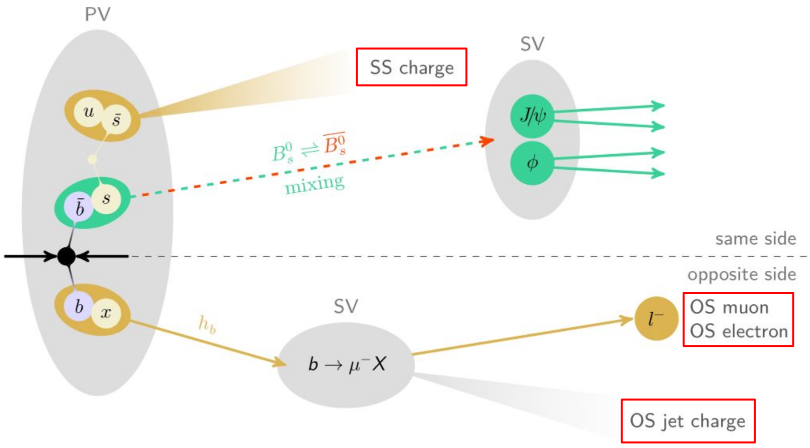
- **Time-dependent** **angular** **analysis** to separate the CP eigenstates ("transversity basis" used)
- **Time-dependent** **flavor** **analysis** to resolve the B_s mixing oscillations (T ~ 350 fs, CMS/ATLAS σ_t ~ 65 fs)

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

Flavor tagging overview

- **Flavor tagging algorithms** can be divided into two main categories
  - **<u>Opposite side (OS)</u>**: exploits decay products of the other B hadron in the event
    - **OS muon**: leverages $b \rightarrow \mu^- X$ decays
    - **OS electron**: leverages $b \rightarrow e^- X$ decays
    - **OS jet**: capitalizes on charge asymmetries in the OS *b*-jet
  - **<u>Same side (SS):</u>** exploits the B_s fragmentation
    - **SS tagger**: leverages charge asymmetries in the B_s fragmentation
      - Main contributor to the tagging perf.
    - Currently not used in ATLAS
- Flavor tagging information is converted to a probability and propagated to the Likelihood

Schematic representation of a generic event



Useful definitions

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

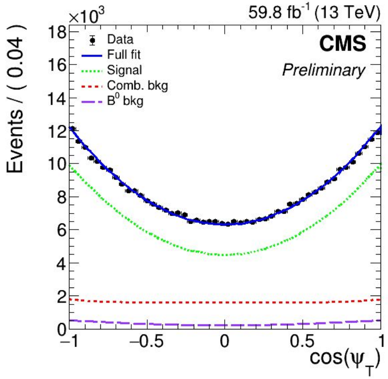
$$\epsilon_{tag} = \frac{N_{tag}}{N_{tot}}, \quad \omega_{tag} = \frac{N_{mistag}}{N_{tag}}, \quad \mathcal{D}_{tag} = 1 - 2\omega_{tag}, \quad P_{tag} = \epsilon_{tag}\mathcal{D}^2_{tag}$$

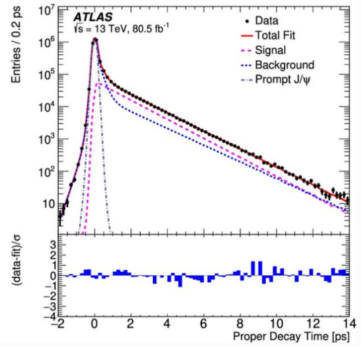
Fit strategy

- The physics parameters are extracted with **unbinned multidimensional extended maximum-likelihood (UML) fit**
  - *Physics parameters*: ϕ_s, $\Delta\Gamma_s$, Γ_s, $|A_{(0,\perp,//)}|^2$, $|A_S|^2$, $\delta_{(\perp,//)}$, δ_S, $|\lambda|^\dagger$, $\Delta m_s{}^\dagger$
  - *Observables*: m_{Bs}, t, σ_t, $\cos\theta_T$, $\cos\psi_T$, ϕ_T, ω_{tag}, $\sigma_{mBs}{}^*$, $p_T{}^*$
- **Fit model**

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

- **Analytical decay rate**
- **Time resolution**
  - In ATLAS, conditional to the p_T of the candidate
- **Angular efficiency**
- **Time efficiency**
- **Backgrounds sources:**
  - combinatorial
  - B^0 ➔ J/ψ K* ➔ μμ Kπ
  - Λ_b ➔ J/ψ Λ^0 ➔ μμ Kp (negligible in CMS)





†: CMS only, fixed to PDG value in ATLAS

*: ATLAS only

Fit results

Fit results

CMS

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

ATLAS

Parameter	Solution (a)		
	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018
$\|A_\parallel(0)\|^2$	0.2220	0.0017	0.0021
$\|A_0(0)\|^2$	0.5152	0.0012	0.0034
$\|A_S\|^2$	0.0343	0.0031	0.0045
$\delta_\perp$ [rad]	3.22	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.09
$\delta_\perp - \delta_S$ [rad]	-0.24	0.05	0.04

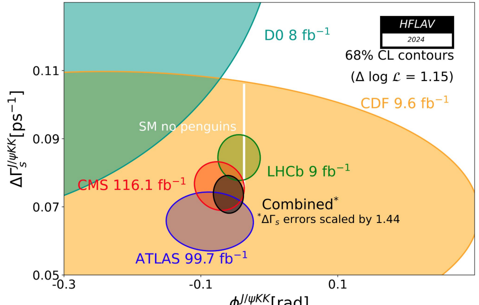
- **ϕ_s and $\Delta\Gamma_s$ are found in agreement with the SM**

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

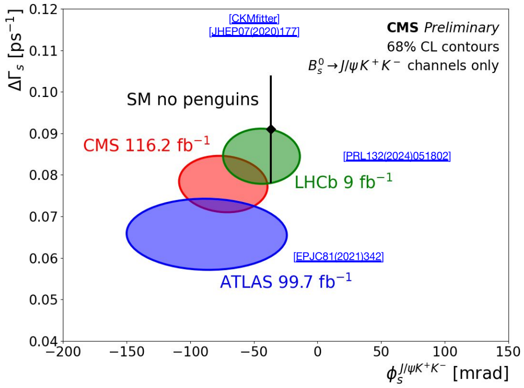
- **Γ_s and Δm_s are consistent with the latest world averages in CMS**

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

- **Some tension is observed in ATLAS in Γ_s w.r.t. the world average**
- Still dominated by statistical uncertainty
- **First evidence of CPV** in this channel by CMS, at **3.2 σ**



Comparison between LHC experiments



Results and outlook

- After combination with Run1 results, the current best results for the measurement of ϕ_s and $\Delta\Gamma_s$ in CMS and ATLAS are

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

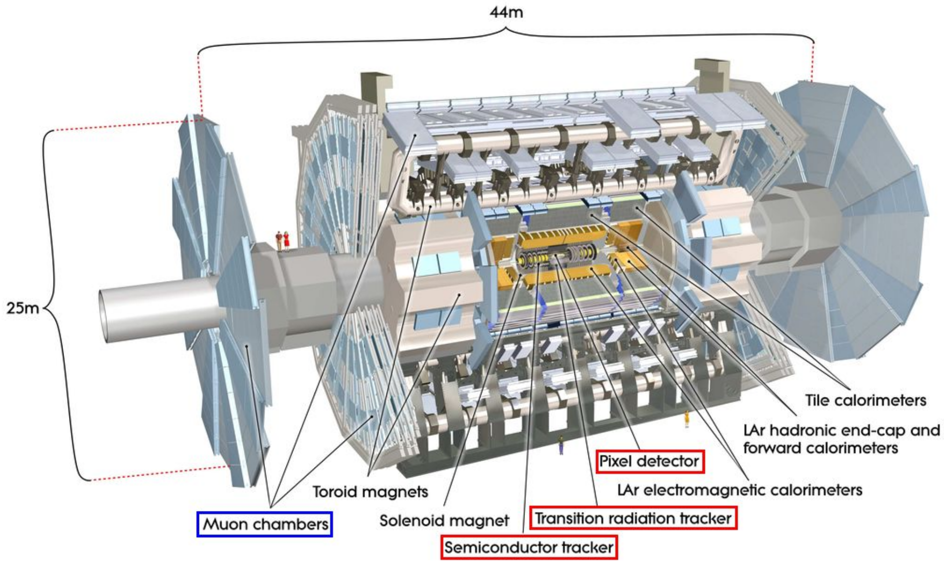
ATLAS: $\phi_s = 0.087 \pm 0.036(\text{stat.}) \pm 0.021(\text{syst.})$ [mrad], $\Delta\Gamma_s = 0.0657 \pm 0.0043(\text{stat.}) \pm 0.0037(\text{syst.})$ [ps^{-1}]

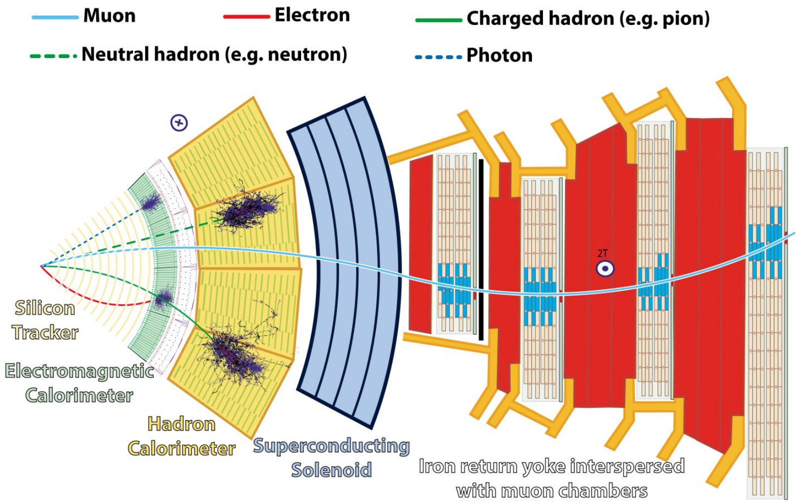
- Both measurements are still limited by statistics
  - ATLAS is still missing a large part of Run2 + all of Run3
  - CMS has completed the Run2 analysis and is looking at Run3
- New opportunities will come in Run3 using additional trigger strategies, like the Scouting/Trigger Level analysis or the Delayed Reconstruction/Parking streams which have been expanded to include B-Physics
- Phase2 will provide an unprecedented amount of data, which will push the uncertainty on ϕ_s to the O(mrad) level
  - New strategies will be required to deal with the currently negligible systematics (e.g. penguin contributions)

Backup

ATLAS and CMS

General purpose detector able to perform a vast range of physics studies, including flavor physics

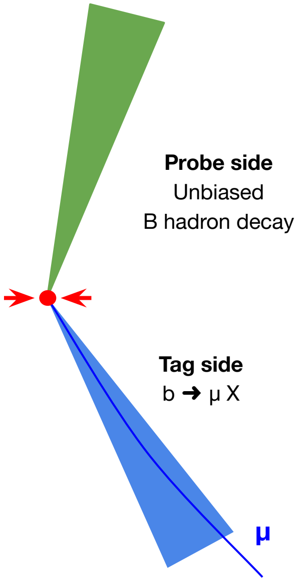


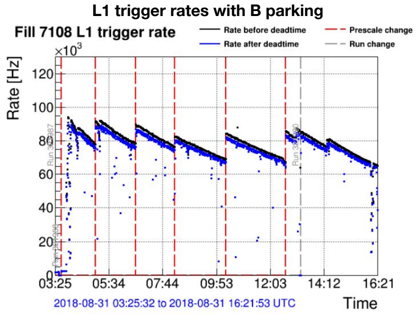


References
[CMS-EXO-23-007]
[CMS-BPH-22-005]

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})



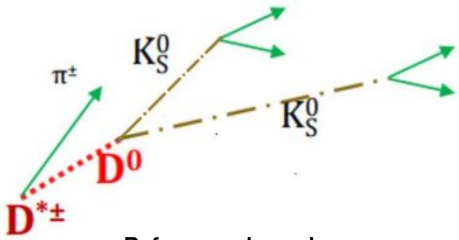


Event selection

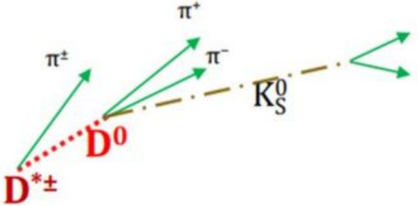
- **First, K_S ➜ $\pi^+\pi^-$** are reconstructed fitting the π tracks to a common vertex
  - $|m(\pi^+\pi^-) - m(K_s^{w.a.})| < 20$ MeV, $p_T(K_S) > 2.2(1.0)$ GeV
- In the **signal channel**, two K_S candidates are required and fitted to a common vertex to form D^0 ➜ K_SK_S candidates
  - 1.7 GeV < $m(K_SK_S)$ < 2.0 GeV
  - K_S displacement in *xyz* from the D^0 vertex >9σ and >7σ
  - D^0 displacement in *xyz* (*xy*) from the PV >9σ (>2σ)
- In the **reference channel**, two track with $p_T > 0.6$ GeV are used to form the D^0 ➜ $K_S\pi^+\pi^-$ 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^{*+} ➜ $D^0\pi^+$ candidates
  - $m(D^0\pi^+) = m(D^0\pi^+) - m(D^0) + m_{PDG}(D^0)$

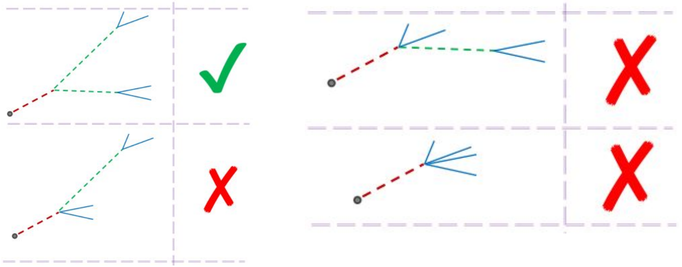
- **Background suppression**: several fits corresponding to incorrect topologies are performed and vertex probabilities requirements are imposed

Signal channel



Reference channel





Selection

Table 1: Optimized selection criteria in the signal channel $D^0 \to K^0_S K^0_S$.

Variable	Requirement
p_T of tagging pion from $D^{*\pm} \to D\pi^\pm$	> 0.35 GeV
η of tagging pion from $D^{*\pm} \to D\pi^\pm$	$-1.2 < \eta < 1.2$
$p_T(K^0_S)$	> 2.2 GeV and > 1.0 GeV
$P_{vtx}(D\pi^\pm)$	$> 5\%$
$P_{vtx}(K^0_S K^0_S)$	$> 1\%$
$P_{vtx}(\pi^+\pi^-)$ for $K^0_S \to \pi^+\pi^-$	$> 1\%$
D^0 vertex displacement from the PV in xy	> 2 s.d.
D^0 vertex displacement from the PV in xyz	> 9 s.d.
K^0_S vertex displacement from the D^0 vertex in xyz	> 9 s.d. and > 7 s.d.
angle between D^0 momentum and displacement from PV in xyz	< 0.205 rad
angle between D^0 momentum and displacement from PV in xy	< 0.237 rad
angle between D^0 momentum and displacement from BX in xy	< 0.237 rad

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

Penguin contributions

Assuming this is negligible

We measure this

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

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

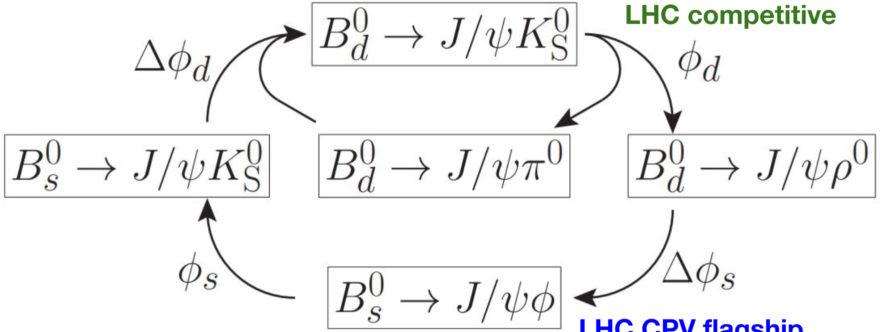
Trying to probe this

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

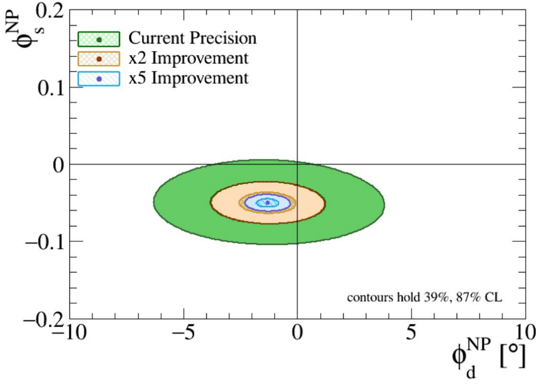
$$\Delta\phi_s^{penguin} \approx 3 \pm 10 \text{ mrad}$$

- 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



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	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_0(0)\rvert^2$	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