Recent CP violation and lifetime results from CMS

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Agenda

- **Introduction**
- **Direct CPV in $D^0 \rightarrow K_S^0 K_S^0$**
- **Effective lifetime of the $B_s^0 \rightarrow J/\psi K_S^0$**
- **Time-dependent CPV in $B_s^0 \rightarrow J/\psi\ \varphi(1020)$**
- **Summary**

Motivation for CPV and lifetime measurements

- **Baryon asymmetry of the Universe (BAU)** remains one of the great mysteries of modern physics
- Andrei Sakharov proposed three necessary conditions for a BAU generating:
  1. Baryon number violation
  2. C and **CP violation (CPV)**
  3. Non thermal equilibrium
- CP-violation is allowed in the SM, but the amount is insufficient to account for the observed BAU
  - ➢ Sources of CPV beyond the SM have to exist
  - ➢ CPV observables are often precisely predicted, hence, they are very sensitive to *new physics*
- Observable CP violation in weak interaction can be classified into three different types

Direct CPV in decays

$$Pr(M \rightarrow f) \neq Pr(\overline{M} \rightarrow \overline{f})$$

Indirect CPV in mixing

(requires the deviation between CP-eigenstates and flavor states)

$$Pr(M^0 \rightarrow \overline{M}^0) \neq Pr(\overline{M}^0 \rightarrow M^0)$$

CPV in decay+mixing interference

$$Pr(M^0_{(\rightsquigarrow \overline{M}^0)} \rightarrow f_{CP}) \neq Pr(\overline{M}^0_{(\rightsquigarrow M^0)} \rightarrow f_{CP})$$

- We present the results of recent CMS measurements of direct CPV in charm, decay+mixing CPV in B_s^0 and the lifetime measurement of the B_s^0 decay to CP-odd state (useful for better understanding of CPV in mixing)

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., σt ~ 65 fs for B_s^0 → J/ψ φ) up to |η| < 2.5

  - Complementary to LHCb (2 < |η| < 5)

+ Enormous amount of data collected

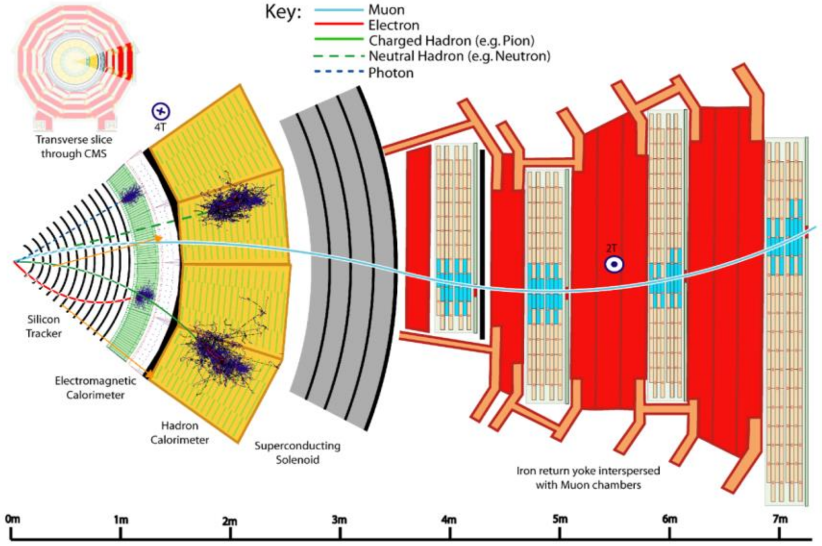
  - ~ $7.5 \cdot 10^{13}$ bb pairs produced at Point 5 during Run 2 (geometric acceptance not considered)

– High pile up NPV ~ 40 (in Run 2)

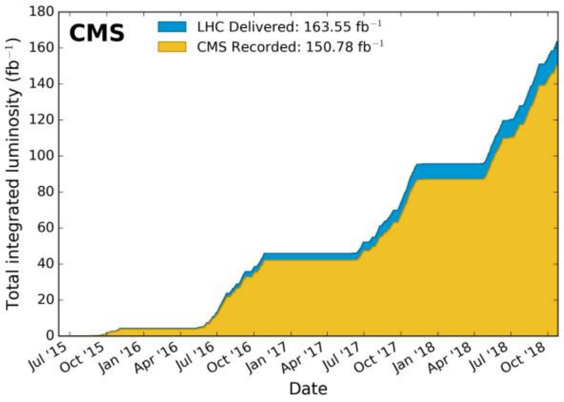
– No reliable hadronic particle identification available

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

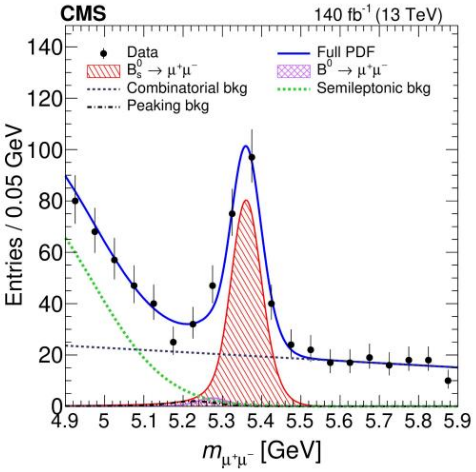
- $B_S \to \mu^+ \mu^-$ (world's most precise) [PLB842(2023)137955]
- $\eta \to \mu^+ \mu^- \mu^+ \mu^-$ observation [PRL131(2023)091903]
- Triple J/ψ production observation [Nat.Phys.19(2023)338]
- Observation of $\Xi_b(6100)^- \to \Xi_b^- \pi^+ \pi^-$ [PRL126(2021)252003]
- Observation of X (6900) → J/ψ J/ψ [PRL132(2024)111901]



CMS luminosity in Run-2



$B_s \to \mu^+\mu^-$



Search for CP violation in $D^0 \to K_S^0 K_S^0$ (CMS-BPH-23-005)

Introduction to the analysis

$$A_{CP}(f) \equiv \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\bar{D}^0 \to f\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\bar{D}^0 \to f\right)}$$

- CP-violation in up-quark sector is heavily suppressed in contrast to down-quark sector
  - Large enhancement would imply the presence of new physics
- Theoretical SM calculations [PRD92(2015)054036] predict CPV in $D^0 \to K^0_S K^0_S$ to be as large as *O(1%)* ← more significant then in in many other D^0 decay channels
- Latest experimental calculation by LHCb [PRL122(2019)211803]:

$A_{CP}(D^0 \to K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$ **← no CPV**

- Many systematic uncertainties in A_{CP} cancel if measured via ΔA_{CP} :

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

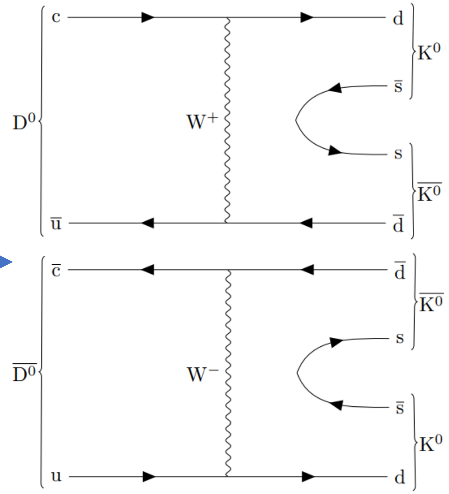
$$\boxed{A_{raw} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)}}$$

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

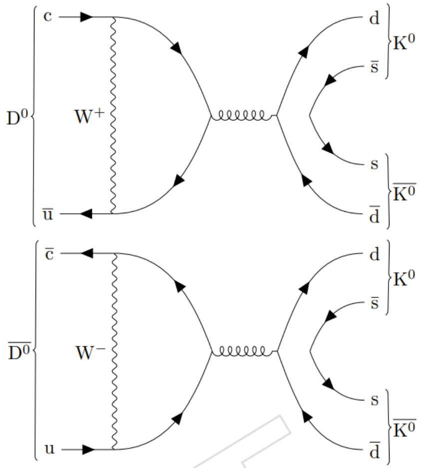
$$\boxed{A_{det} \approx \frac{\epsilon_{\pi^+} - \epsilon_{\pi^-}}{\epsilon_{\pi^+} + \epsilon_{\pi^-}}}$$

- $\mathbf{\Delta A_{CP} = A^{raw}_{CP}(D^0 \to K^0_S K^0_S) - A^{raw}_{CP}(D^0 \to K^0_S \pi^+\pi^-)}$
  - Reference channel is very similar in kinematics and topology → A_{prod} and A_{det} cancel out.
- The **flavor is tagged** by $\mathbf{D^{*\pm} \to D^0 (\bar{D}^0)\pi^\pm}$

Exchange diagram



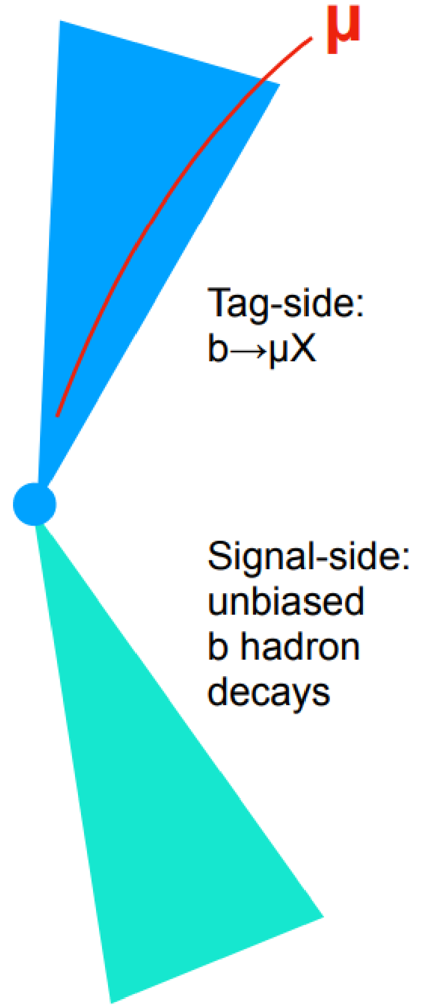
PA diagram



CMS-PAS-BPH-23-005

Bparking miniAOD 2018 data set

- A dedicated data set corresponding to the integral $L = 41\ \mathrm{fb}^{-1}$ is used
- A set of single muon triggers with different thresholds on muon p_T and impact parameter are used
- Due to these thresholds, most(~ 75-80%) of the events in dataset come from beauty semi-leptonic decays $b \to \mu X$
- Almost every time $b \to \mu c \nu X$
- The muon p_T cut at trigger level: 7-12 GeV => D has a high p_T, as both c and μ come from energetic b-hadron
- Thus, b-parking has *$O(10^{10})$* events with charm hadrons with relatively high p_T => it is perfect for CPV search

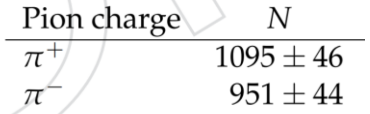


Fits

Fits of “+” and “–” are simultaneous:
all parameters of their pdfs are shared;
only yields are floating

2D UML fit of $(M(D\pi^{\pm}) - M(D) + M_D^{PDG})$ vs $M(K_S^0 K_S^0)$

Projections on $x^+ = m(D\pi^+)$ and $x^- = m(D\pi^-)$ axes of 2d-fit

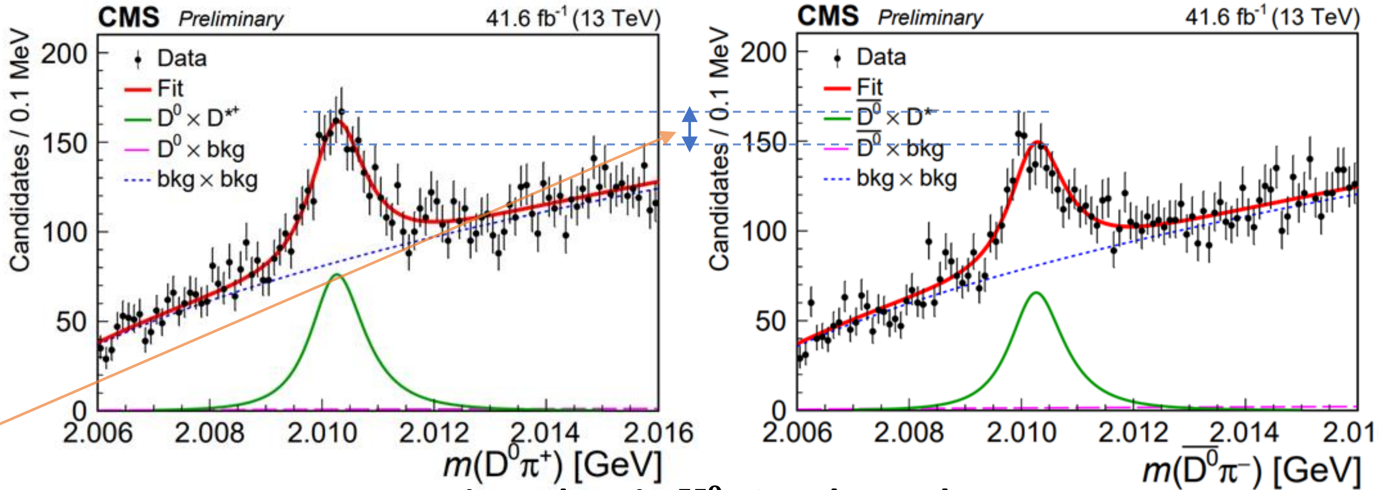


Pion charge	N
π^+	1095 ± 46
π^-	951 ± 44

$$A_{CP}^{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

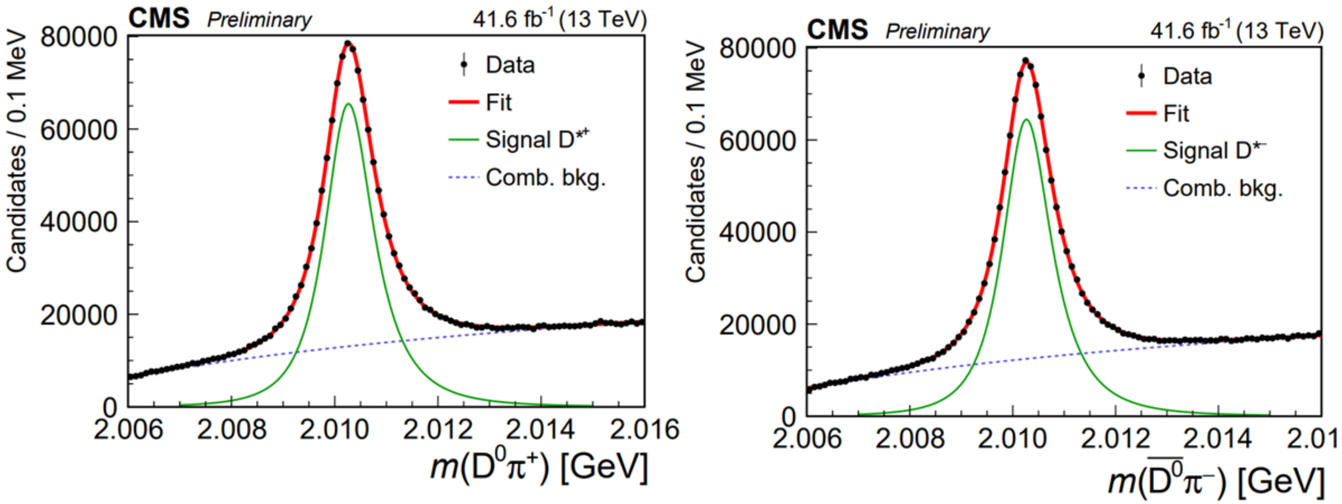
Signal pdf: *Johnson function*
Background pdf: *Threshold function• Pol$_1$*

Fit to data in $K_S^0 K_S^0$ channel



Fit to data in $K_S^0\pi^+\pi^-$ channel

1d-fit of $(M(D\,\pi) - M(D) + M_D^{PDG})$ is applied



Pion charge	N
π^+	$944\,800 \pm 3\,500$
π^-	$930\,150 \pm 3\,400$

CMS-PAS-BPH-23-005 The first CMS study of CP violation in the charm sector!

Results

- This is the first measurement of CP-violation in charm in CMS

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

- Using 2018 b-parking dataset with a lot of charm hadrons produced in semileptonic b decays
- The resulting ΔA_{CP}^{raw}:

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

- Using PDG A_{CP} ($D^0 \rightarrow K_S^0 \pi^+\pi^-$), we derive the A_{CP} ($D^0 \rightarrow K_S^0 K_S^0$):

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

- The result is consistent with **no CPV in $D^0 \rightarrow K_S^0 K_S^0$** at the level of 2.0σ
- The value is consistent with LHCb [PRL122(2019)211803] results at the level of 2.7σ [**(6.2 ± 3.1)%** vs. **(-3.1 ± 1.3)%**] and with Belle [PRL119(2017)171801] measurement at the level of 1.8σ [**(6.2 ± 3.1)%** vs. **(0.0 ± 1.5)%**]

Measurement of effective lifetime of the $B_s^0 \rightarrow J/\psi\ K_S^0$ (CMS-PAS-BPH-22-001)

Dataset: 2016-2018 (140 fb^{-1})

Introduction to the analysis

- B_s mesons are produced in flavor eigenstates, but propagate as mass ones, which, if there is no CPV in mixing, coincide with CP-eigenstates

$B^0_{s,H}$ → CP-odd $\qquad\qquad$ $B^0_{s,L}$ → CP-even

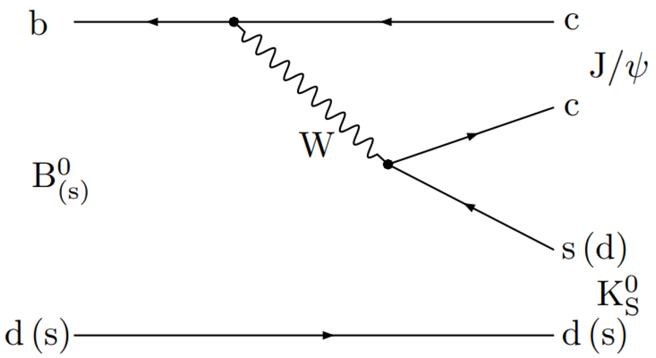
- Nonzero decay difference $\Delta\Gamma$ enables the extraction of information regarding the mass eigenstate rate asymmetry, $A_{\Delta\Gamma}$:

$$\boxed{A_{\Delta\Gamma} = \frac{R_H - R_L}{R_H + R_L} = \frac{-2\mathcal{R}(\lambda)}{1 + |\lambda|^2}}$$

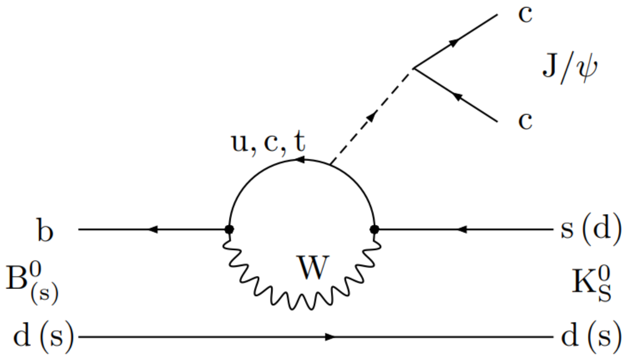
  - R_H and R_L are related to the untagged decay rate as:

$$\Gamma(B_s \to f) + \Gamma(\overline{B}_s \to f) = R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t}$$

- This analysis presents a measurement of the B_s effective lifetime τ in the CP-odd final state $J/\psi\ K^0_S$ with the CMS Run 2 dataset
  - It is a necessary step towards the $A_{\Delta\Gamma}$ measurement
  - The decay is related to $\mathbf{B^0 \to J/\psi\ K^0_S}$ via U-spin symmetry.
    - Can be used to determine penguin contributions in sin2β measurement
    - Can be used to determine γ angle of CKM-matrix



Tree-level diagram



Penguin loop diagram

The effective lifetime

- The effective lifetime is defined as the expected value of the utagged decay rate:

Average lifetime

$$\tau(J/\psi K_S) \equiv \frac{\int_0^\infty t(\Gamma_{B_s\to J/\psi K_S} + \Gamma_{\overline{B}_s\to J/\psi K_S})dt}{\int_0^\infty (\Gamma_{B_s\to J/\psi K_S} + \Gamma_{\overline{B}_s\to J/\psi K_S})dt} = \frac{\tau_{B_s}}{1-y_s^2}\left(\frac{1+2A_{\Delta\Gamma}y_s+y_s^2}{1+A_{\Delta\Gamma}y_s}\right)$$

Normalized decay width difference

$y_s = \tau_{B_s}\Delta\Gamma/2$

- Using the latest measurements and assuming the SM ($A_{\Delta\Gamma} = 0.94 \pm 0.07$, $\tau_{Bs} = 1.520 \pm 0.005$ ps, $\Delta\Gamma = 0.084 \pm 0.005\ \mathrm{ps}^{-1}$):

$$\tau(J/\psi K_S)\big|_{SM} = 1.62 \pm 0.02 \text{ ps}$$

- Available measurement from LHCb [Nucl.Phys.B(2013)873]: $\tau(J/\psi\ K^0_S) = 1.75 \pm 0.14$ ps
- The decay time is measured in the transverse plane as:

$$\boxed{t = \frac{L_{xy}\cdot M_{Bs}}{p_T}}$$

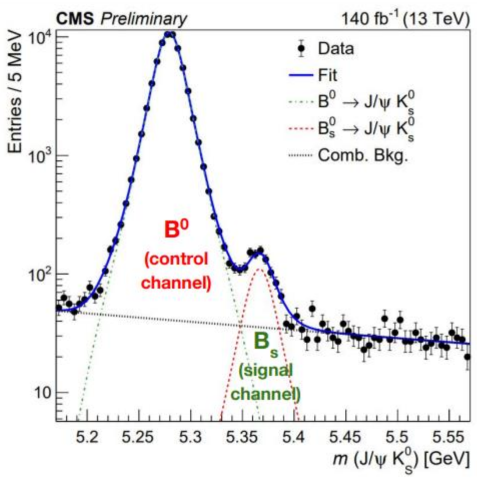
Results

- The **effective lifetime** is measured with a 2D UML fit to the invariant mass and proper decay time
    - ✓ The decay time uncertainty is used as a conditional parameter
    - ✓ Both the effective lifetimes of the signal B_s^0 and control channel B^0 are fitted
    - ✓ The control channel is used to validate most of the measurement components
- Results (using 727 ± 35 B_s^0 signal candidates):

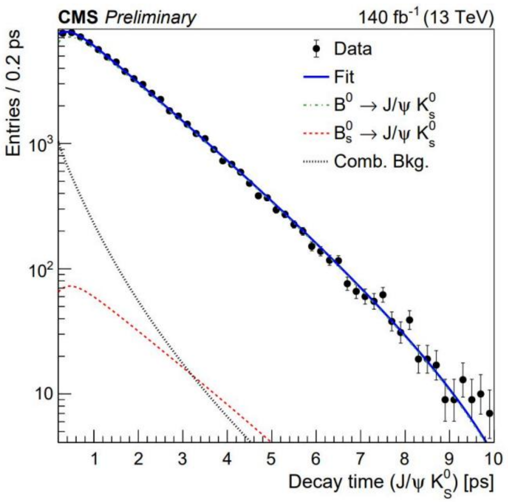
$$\boxed{\tau(J/\psi\ K_S^0) = 1.59 \pm 0.07\ (\text{stat}) \pm 0.03\ (\text{syst})\ \text{ps}}$$

    - ○ The control channel's effective lifetime is found to be in good agreement with the world-average value
- The measured value is in agreement with the SM prediction and compatible with the previous LHCb results at 2.1σ and is twice more precise

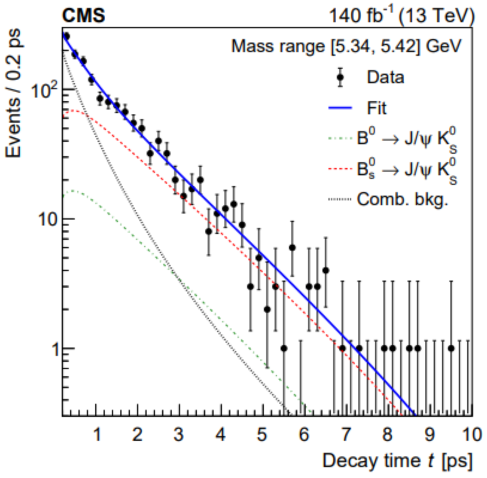
Invariant mass distribution



Proper decay time distribution



Proper decay time distribution (B_s^0 signal region)



CMS-PAS-BPH-22-001 The most precise measurement of this quantity to date!

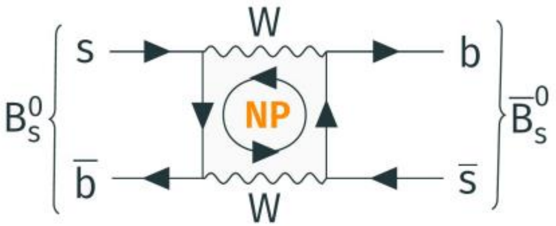
Measurement of time-dependent CP violation in $\mathrm{B_s^0}$ mesons (CMS-BPH-23-004)

CMS-PAS-BPH-23-004

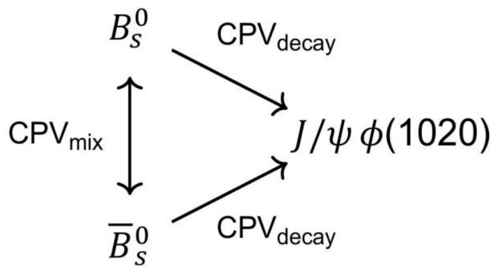
Dataset: 2017-2018 (96 fb^{-1})

Motivation

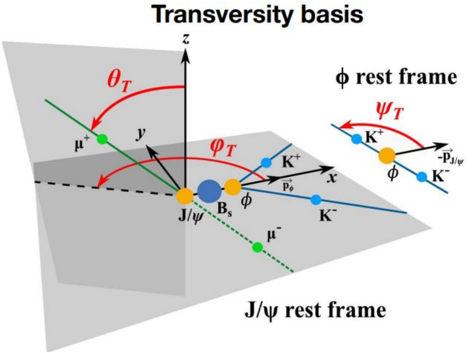
- B_s mesons decays allow us to study the time-dependent CP violation generated by the interference between direct decays and flavor mixing
- The weak phase φ_s is the main CPV observable (Predicted by the SM to be $\varphi_s \approx -2\beta_s$ [β_s → angle of the B_s unit. triangle])
- β_s determined by CKM global fits[CKMfitter, UTfit] to be $-2\beta_s = -37 \pm 1$ mrad
    - **New physics** can change the value of φ_s up to ~100% [RMP88(2016)045002] via new particles contributing to the flavor oscillations



- This analysis presents measurement of time-dependent CPV in B_s^0 via the golden mode $\mathbf{B_s^0 \to J/\psi\ \varphi(1020) \to \mu^+ \mu^- K^+ K^-}$
- The study performs time-dependent **angular analysis** to separate the CP eigenstates ("transversity basis" used) and **flavor analysis** to resolve the B_s mixing oscillations
- The outcome of the analysis: φ_s, $\Delta\Gamma_s$, Γ_s, Δm_s, $|A_0|^2$, $|A_\perp|^2$, $|A_S|^2$, $\delta_\parallel$, $\delta_\perp$, $\delta S_\perp$



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



$$\frac{d^4\Gamma(B_s^0)}{d\Theta\, d(ct)} = \mathcal{F}(\Theta, ct, \alpha) \propto \sum_{i=1}^{10} O_i(ct,\alpha)\, g_i(\Theta)$$

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

Deep neural networks (DNN) for tagging!

CMS-PAS-BPH-23-004

Flavor tagging technique

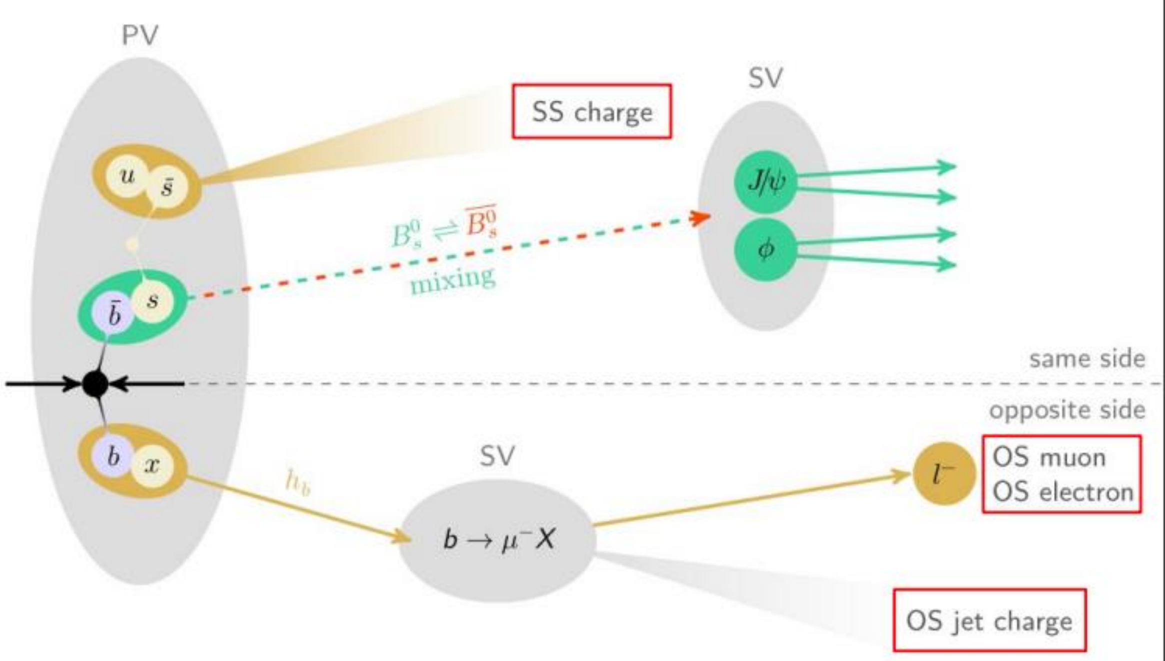
- Four **DNN-based algorithms** are used, divided into two main categories:
  - ❑ **Same side (SS):** exploits the B_s^0 fragmentation
    1. SS tagger: leverages charge asymmetries in the B_s^0 fragmentation
  - ❑ **Opposite side (OS):** exploits decay products of the other B hadron in the event
    1. OS muon: leverages b ➜ μ^-X decays
    2. OS electron: leverages b ➜ e^-X decays
    3. OS jet: capitalizes on charge asymmetries in the OS b-jet
- Logic of taggers:
  1. Lepton taggers (OS muon, OS electron): DNN trained for correct-tag vs mistag; Lepton charge ➜ ξ_{tag}; DNN score ➜ ω_{tag}

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

  2. Charge-based taggers (OS jet, SS): DNN trained for B_s^0 vs $\bar{B}_s{}^0$; DNN score ➜ Prob(B_s) ➜ ξ_{tag} ; ω_{tag}

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

Schematic representation of a generic event



Useful definitions

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

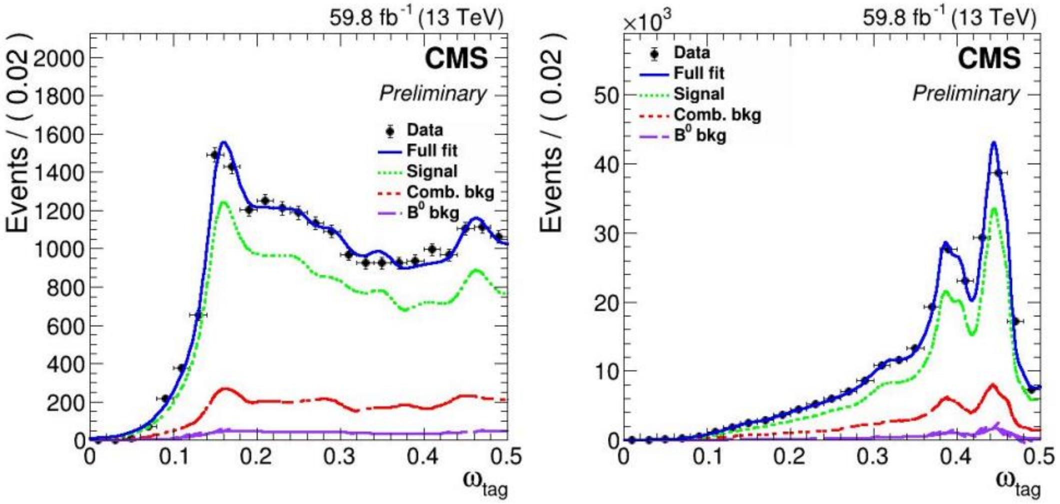
$$\epsilon_{tag} = \frac{N_{tag}}{N_{tot}}, \quad \omega_{tag} = \frac{N_{mistag}}{N_{tag}}, \quad \mathcal{D}_{tag} = 1 - 2\omega_{tag}, \quad P_{tag} = \epsilon_{tag}\mathcal{D}_{tag}^2$$

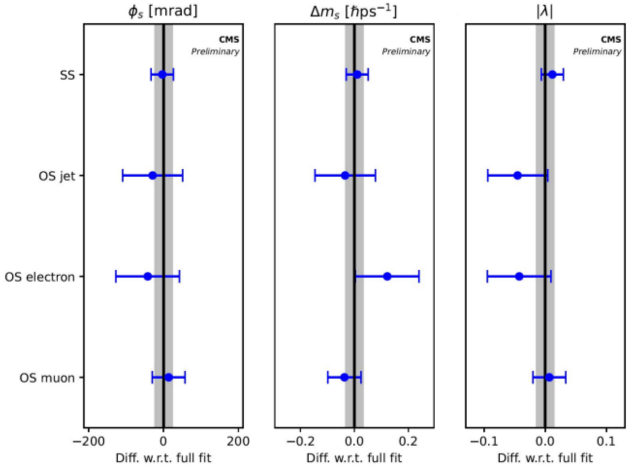
The algorithms are optimized and trained in simulated events and calibrated in data with self-tagging $B^+ \to J/\psi K^+$ decays

Flavor tagging performance

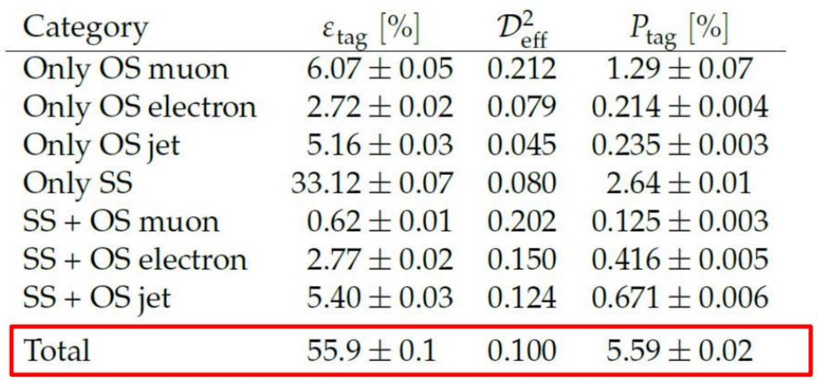
- The SS and any one of the OS algorithms overlap in about 20% of the events
  - In these cases, the information is combined to improve the tagging inference
- The **combined flavor tagging framework** achieves a tagging power of **P_{tag} = 5.6%** when applied to the data sample. Among the highest ever recorded at LHC!
- Largest ever effective statistics $N_{Bs} \cdot P_{tag}$ (490k · 5.6% ≈ 27.5k) for a single φ_s measurement
- The tagging framework is consistent and stable!
  - Validated by repeating the fit to data with only one tagging algorithm deployed at a time

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

CMS-PAS-BPH-23-004

Measured physical parameters

- **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:**

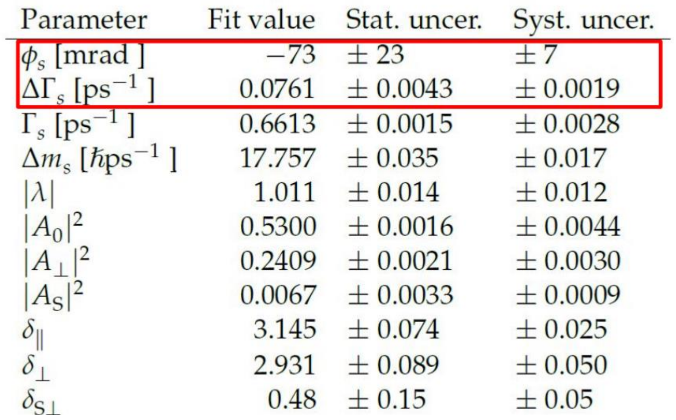
$$\Gamma_s^{WA} = 0.6573 \pm 0.0023 \text{ ps}^{-1} \qquad \Delta m_s^{WA} = 17.765 \pm 0.006\ \hbar\text{ps}^{-1}$$

- **$|\lambda|$** is **consistent** with **no direct CPV** ($|\lambda| = 1$)
- The precision on φ_s is **comparable** with the world's most precise single measurement by LHCb [PRL132(2024)051802] (φ_s = -39 ± 22 (stat) ± 6 (syst) mrad)
- Combined with **8 TeV CMS results**[PLB757(2016)97]:

φ_s = -74 ± 23 mrad
$\Delta\Gamma_s$ = 0.0780 ± 0.0045 [ps]$^{-1}$

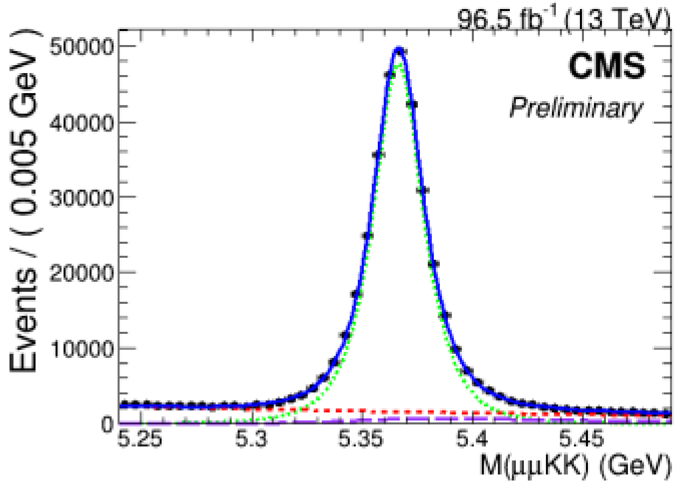
First evidence of CPV in B_s^0 → J/ψ K⁺ K⁻ decays **(3.2 σ)!**

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
$\vert\lambda\vert$	1.011	± 0.014	± 0.012
$\vert A_0\vert^2$	0.5300	± 0.0016	± 0.0044
$\vert A_\perp\vert^2$	0.2409	± 0.0021	± 0.0030
$\vert A_S\vert^2$	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

Fit projection on the input observable of inv. mass M(μ⁺μ⁻K⁺K⁻), the 2018 data.



CMS-PAS-BPH-23-004

Summary

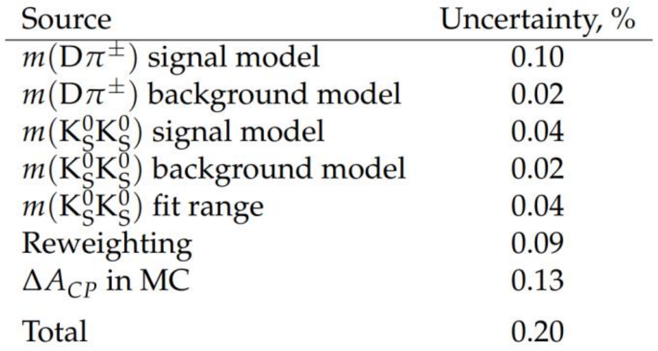
- We present three recent CMS results on the CP violation and lifetime measurements:
  - Search for direct CP violation in $\mathbf{D^0 \rightarrow K^0_S K^0_S}$:
    - First CMS measurement of CP violation in charm: A_{CP} **($D^0 \rightarrow K^0_S K^0_S$) = (6.2 ± 3.0 (stat) ± 0.2 (syst) ± 0.8 (A_{CP} ($D^0 \rightarrow K^0_S \pi^+\pi^-$)))%**
  - Effective lifetime measurement in the CP-odd decay $\mathbf{B_s \rightarrow J/\psi\, K^0_S}$
    - The most precise measurement of this value: $\tau(J/\psi\, K^0_S)$ = **1.59 ± 0.07 (stat) ± 0.03 (syst) ps**
  - Measurement of the time-dependent CP violation in $\mathbf{B^0_s \rightarrow J/\psi\, \varphi}$
    - First evidence of CP violation in $\mathbf{B^0_s \rightarrow J/\psi\, K^+ K^-}$: φ_s **= -74 ± 23 mrad**
- CMS recent contributions to flavor physics prove that it can be one of the leading actors in such areas as rare decays, CP violation measurements and spectroscopy
- New trigger strategies, as well as new refined flavor tagging techniques make the results of CMS in flavor physics compatible with B-factories
- 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

Thank you!

Back-up

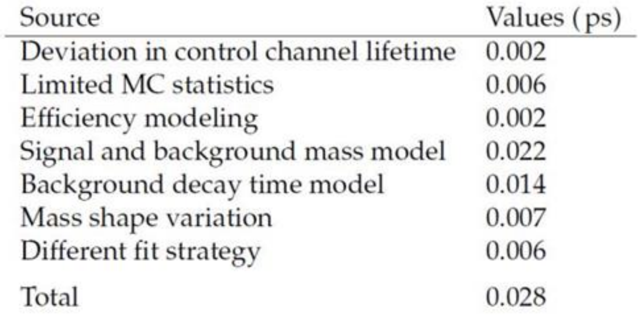
Systematics

Systematic uncertainties in CPV ($D^0 \rightarrow K_S^0 K_S^0$):



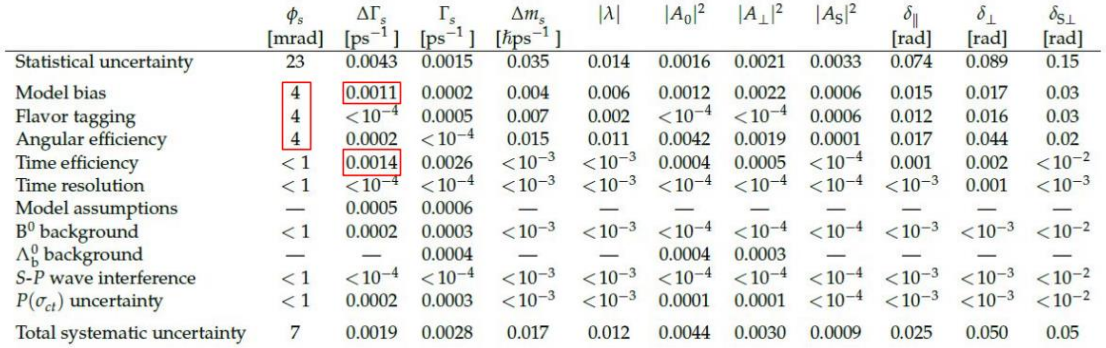
Source	Uncertainty, %
$m(D\pi^\pm)$ signal model	0.10
$m(D\pi^\pm)$ background model	0.02
$m(K_S^0 K_S^0)$ signal model	0.04
$m(K_S^0 K_S^0)$ background model	0.02
$m(K_S^0 K_S^0)$ fit range	0.04
Reweighting	0.09
ΔA_{CP} in MC	0.13
Total	0.20

Systematic uncertainties in $\tau(B_s^0 \rightarrow J/\psi\ K_S^0)$:



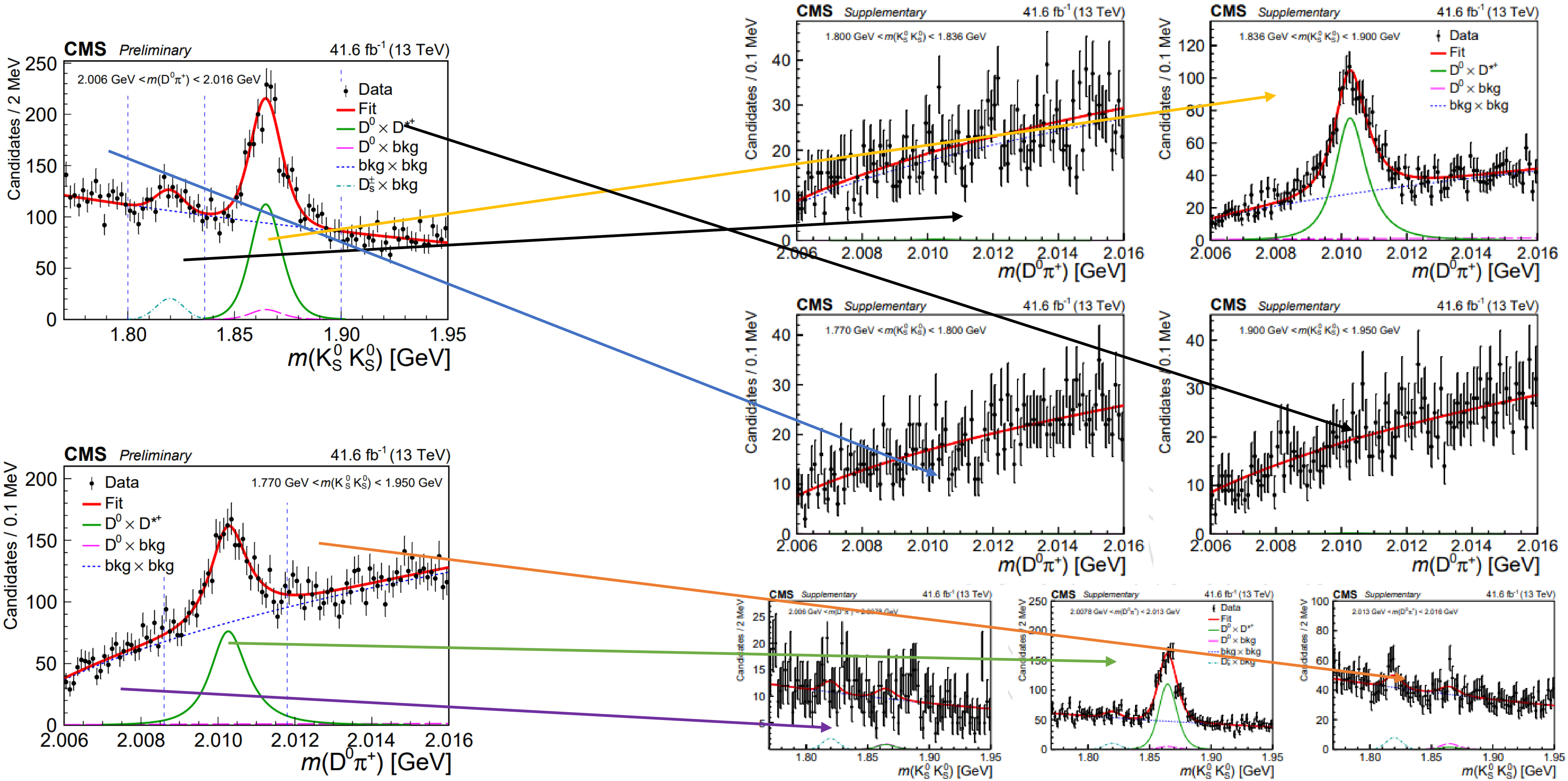
Source	Values (ps)
Deviation in control channel lifetime	0.002
Limited MC statistics	0.006
Efficiency modeling	0.002
Signal and background mass model	0.022
Background decay time model	0.014
Mass shape variation	0.007
Different fit strategy	0.006
Total	0.028

Systematic uncertainties in the time-dependent CPV ($B_s^0 \rightarrow J/\psi\ \varphi$):

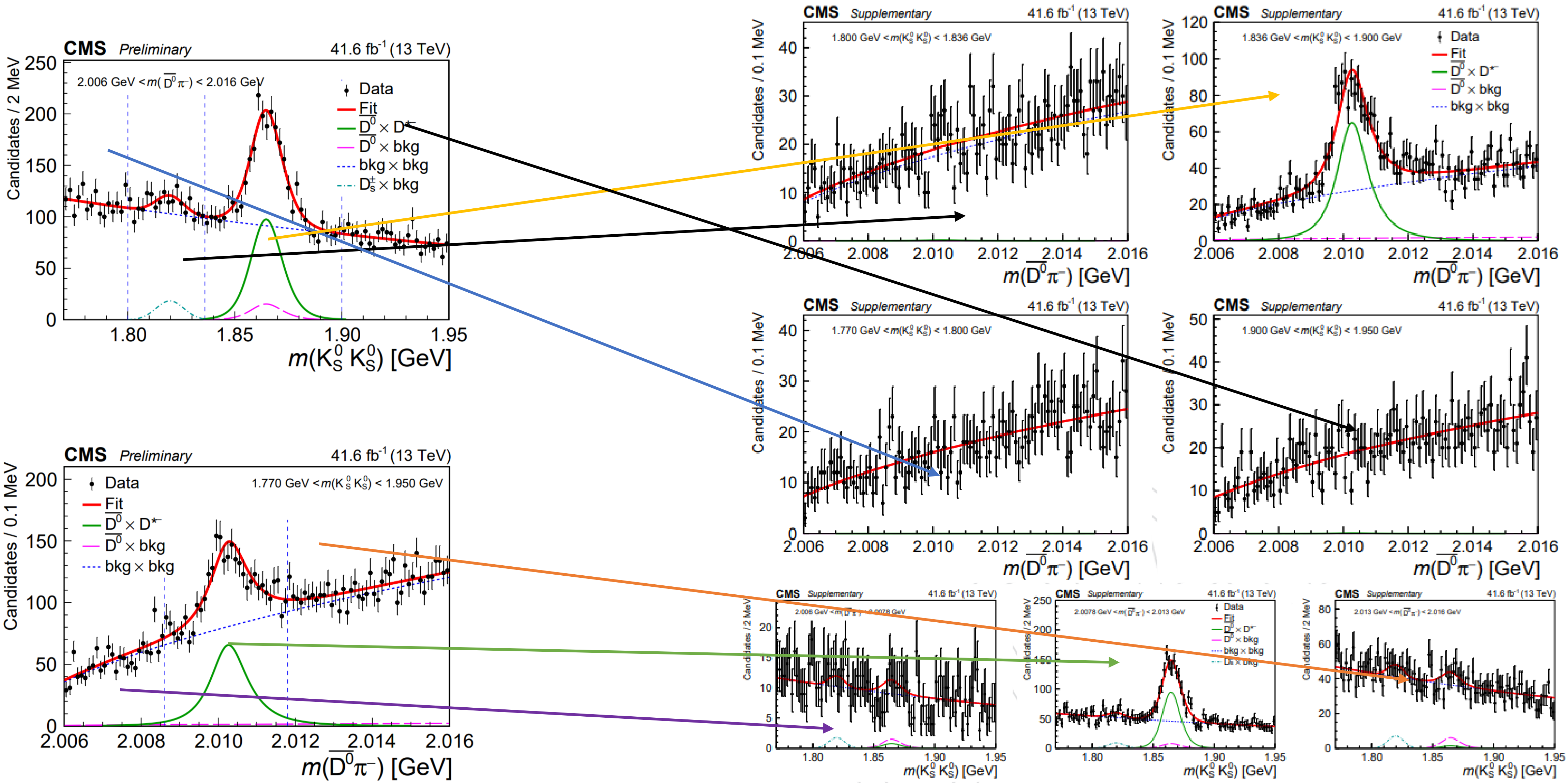


	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	Δm_s [$\hbar$ps^{-1}]	$\lvert\lambda\rvert$	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$\lvert A_S\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]
Statistical uncertainty	23	0.0043	0.0015	0.035	0.014	0.0016	0.0021	0.0033	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

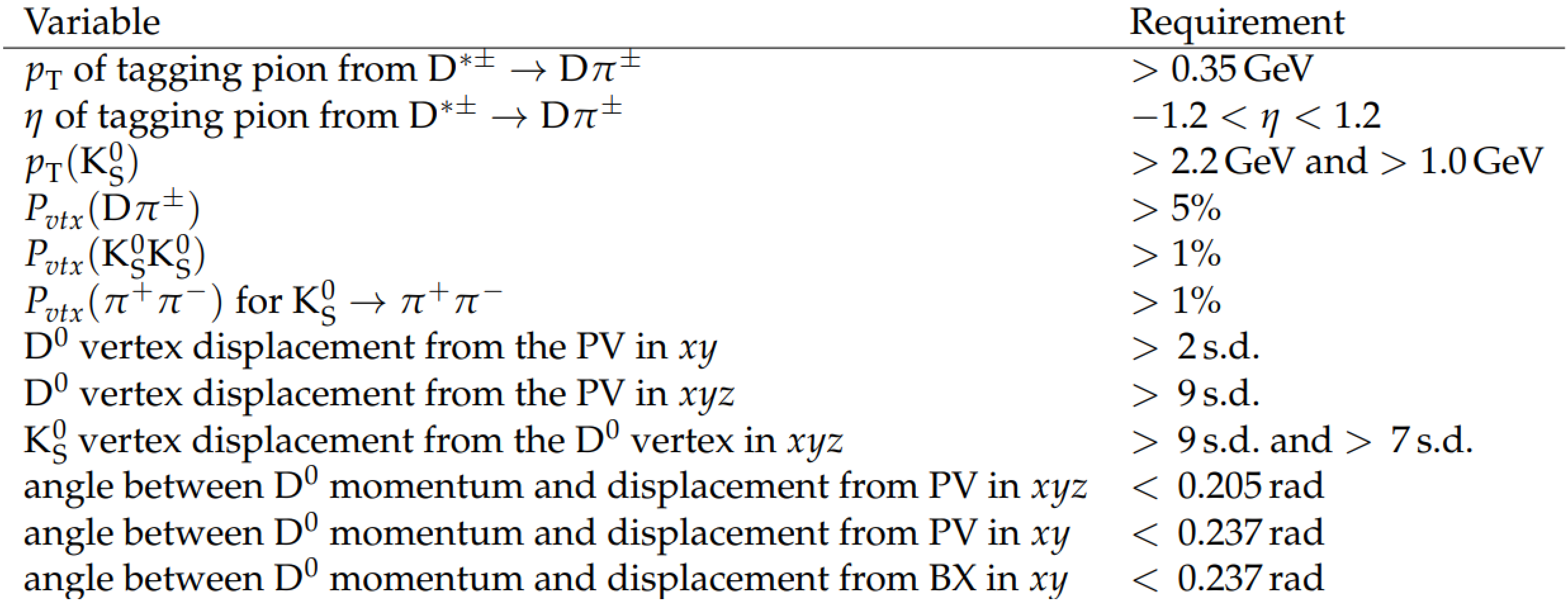
CPV($D^0 \to K^0_S K^0_S$): projections of 2D-fit to D^0 candidates



CPV($D^0 \to K^0_S K^0_S$): projections of 2D-fit to $\overline{D^0}$ candidates



CPV($D^0 \to K^0_S\, K^0_S$): final selections



Variable	Requirement
p_T of tagging pion from $D^{*\pm} \to D\pi^\pm$	$> 0.35\,\text{GeV}$
η of tagging pion from $D^{*\pm} \to D\pi^\pm$	$-1.2 < \eta < 1.2$
$p_T(K^0_S)$	$> 2.2\,\text{GeV}$ and $> 1.0\,\text{GeV}$
$P_{vtx}(D\pi^\pm)$	$> 5\%$
$P_{vtx}(K^0_S K^0_S)$	$> 1\%$
$P_{vtx}(\pi^+\pi^-)$ 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

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Lifetime measurement: signal efficiency

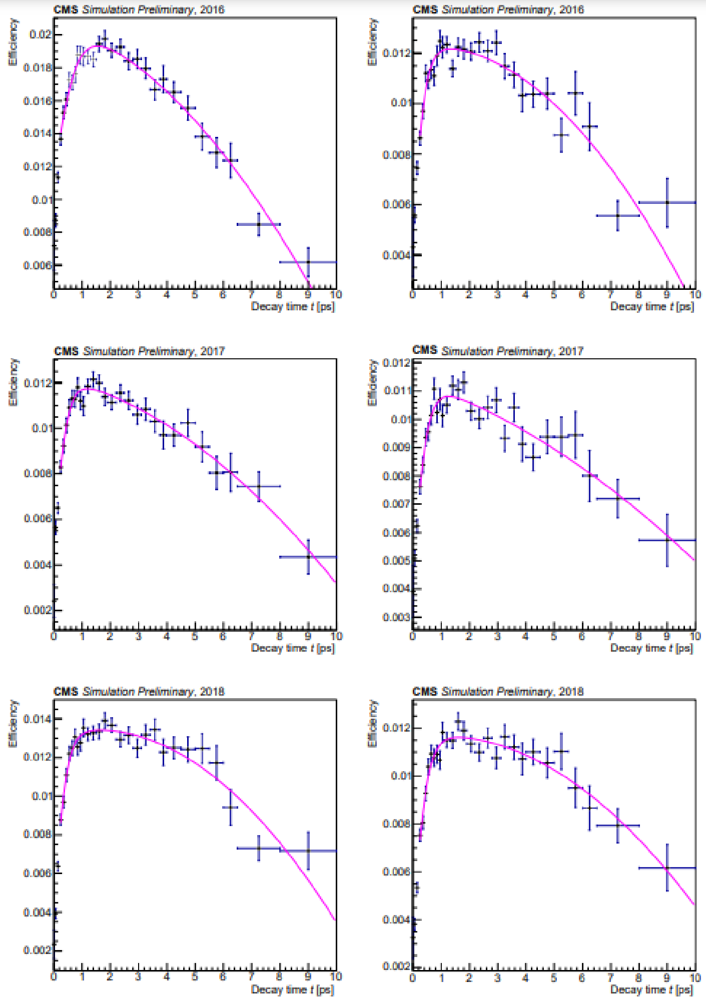

Figure 4: The signal efficiency as a function of the decay time for the $B^0 \to J/\psi K^0_S$ (left) and $B^0_s \to J/\psi K^0_S$ (right) decays from simulation for each of the three data-taking years. The vertical bars indicate the statistical uncertainty, and the horizontal bars give the bin width. The curves show the projections of the fit to the simulated event samples.

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Lifetime measurement: projections of 2D plot by years

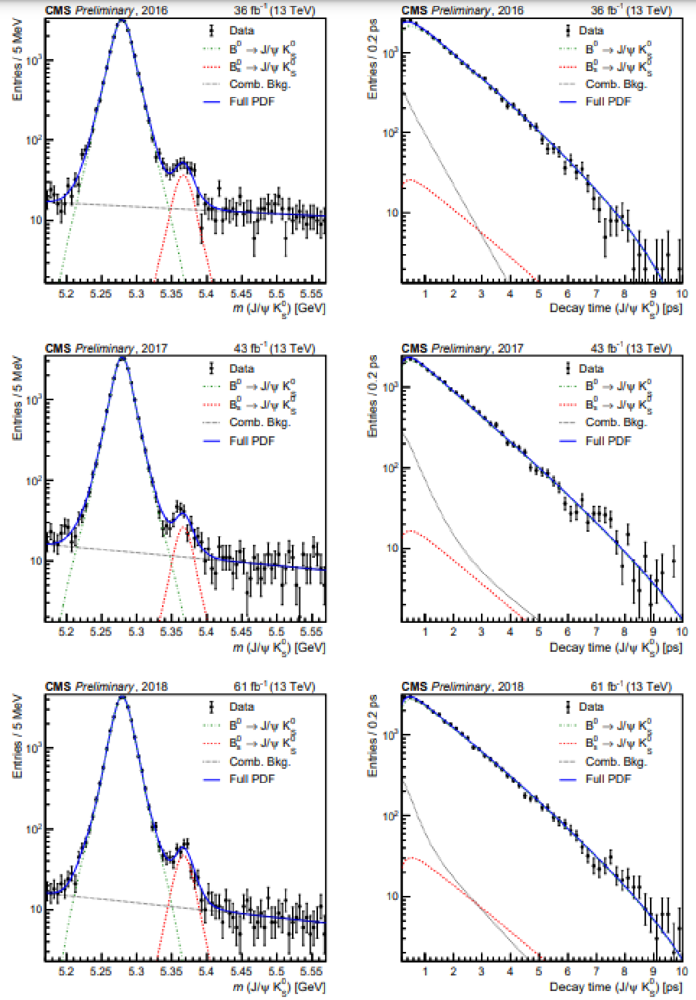

Figure 5: Distributions of the $J/\psi K^0_S$ invariant mass (left) and decay time (right) from data (points), along with the projections from the 2D UML fit for each year of data taking. The vertical bars on the data points indicate the statistical uncertainty. The dashed, dotted-dashed, dotted and solid lines represent the signal, control channel, combinational background, and total fit contributions respectively.

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Lifetime measurement: projections in subranges

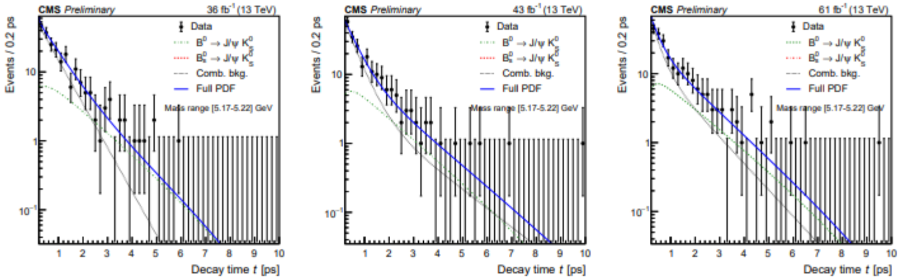

Figure 6: The 2D UML fit projection on the decay time axis for mass range $5.17 < m < 5.22$ GeV for 2016, 2017 and 2018 respectively.

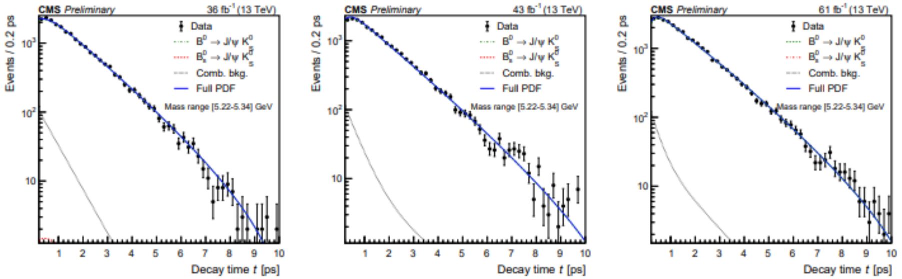

Figure 7: The 2D UML fit projection on the decay time axis for mass range $5.22 < m < 5.34$ GeV for 2016, 2017 and 2018 respectively.

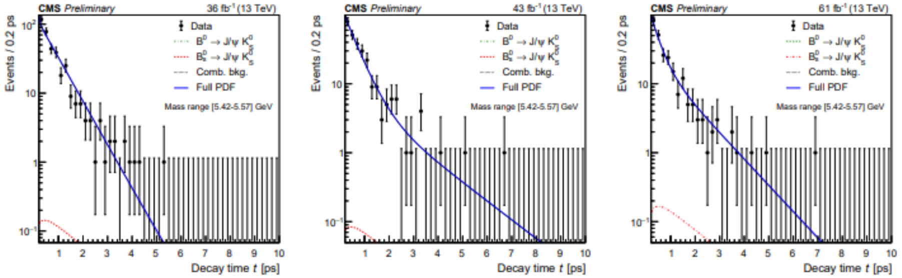

Figure 8: The 2D UML fit projection on the decay time axis for mass range $5.42 < m < 5.57$ GeV for 2016, 2017 and 2018 respectively.

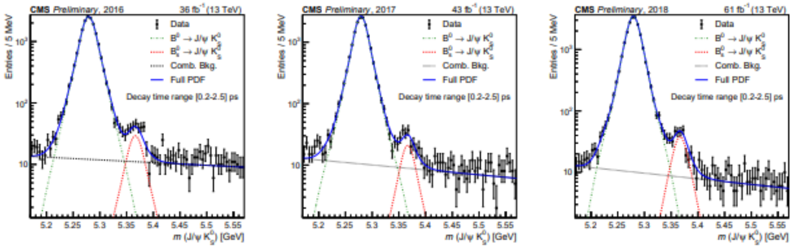

Figure 9: The 2D UML fit projection plots on the mass axis for decay time range $0.2 < t < 2.5$ ps for 2016, 2017 and 2018 respectively.

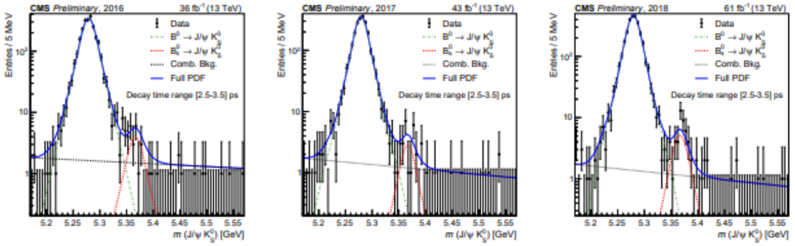

Figure 10: The 2D UML fit projection plots on the mass axis for decay time range $2.5 < t < 3.5$ ps for 2016, 2017 and 2018 respectively.

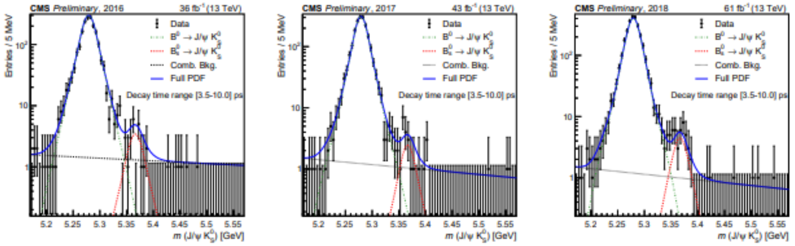

Figure 11: The 2D UML fit projection plots on the mass axis for decay time range $3.5 < t < 10$ ps for 2016, 2017 and 2018 respectively.

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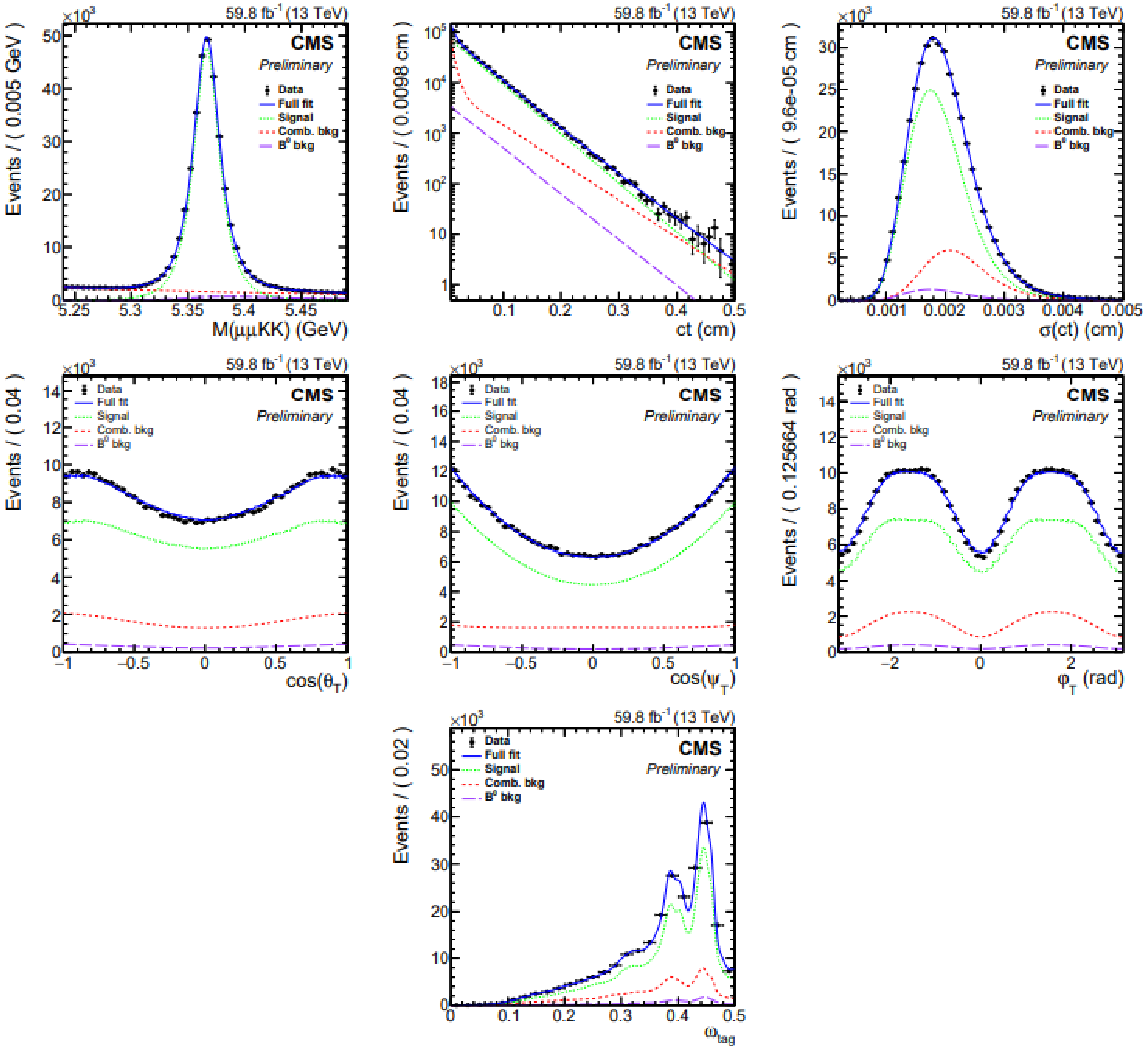
time-dependent CPV ($B_s^0 \to J/\psi\ \phi$): The distributions for the input observables for the standard trigger category



Projections of the fit on input observables, 2018 data

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