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Recent CMS results on CP violation and rare decays

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Agenda

- **Introduction**
- **CP violation:**
  - **Direct CPV in charm ($D^0 \rightarrow K^0_S K^0_S$)**
  - **Evidence for mixing induced CPV in B^0_s → J/ψ φ(1020)**
- **Rare decays:**
  - **Observation of J/ψ → $\mu^+\mu^-\mu^+\mu^-$**
  - **Search for $D^0 \rightarrow \mu^+\mu^-$**
- **Summary**

Motivation for CPV and rare decays searches

- The **SM** perfectly describes particle physics, but has a number of unsolved problems:
  - **Baryon asymmetry of the Universe (BAU)**
  - **Tree-level Flavour changing neutral current**
  - **Existence of extra fermions and bosons**
  - **Etc…**
- Above mentioned new physics signatures can be tested via **CP violation measurements** and **rare decay searches**
- 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*
- Rare decays are predicted to have low branching in the SM
  - ➢ Enhancement signifies ***new physics presence*** (FCNC, extra fermions and bosons, tetraquarks, pentaquarks, R-parity violating supersymmetry, etc.)
- We present the most recent CMS measurements of CPV in $\mathbf{D^0 \rightarrow K^0_S K^0_S}$ and $\mathbf{B^0_s \rightarrow J/\psi\ \varphi(1020)}$

and searches for rare $\mathbf{J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-}$ and $\mathbf{D^0 \rightarrow \mu^+\mu^-}$ decays

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

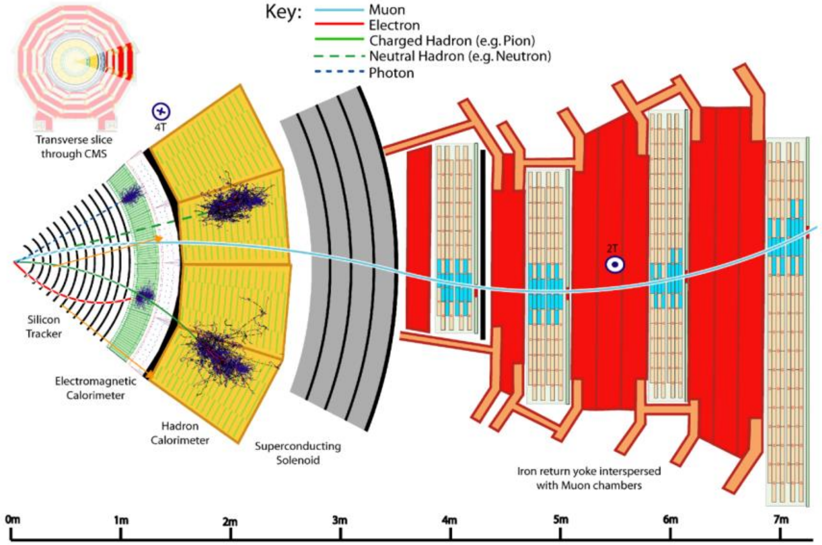
  - Complementary to LHCb (2 < |η| < 5)

\+ Enormous amount of data collected

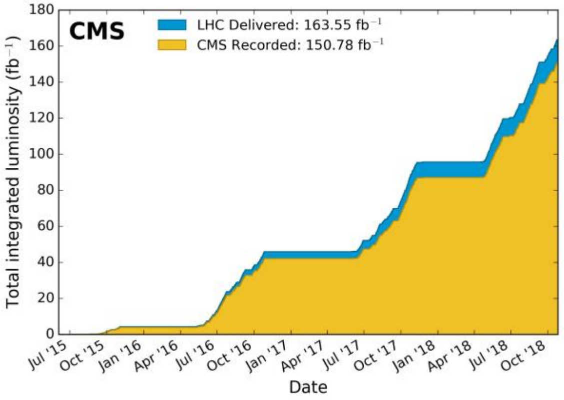
  - ~ 7.5 · 10^{13} bb pairs produced at Point 5 during Run 2 (geometric acceptance not considered)

– High pile up NPV ~ 40 (in Run 2)

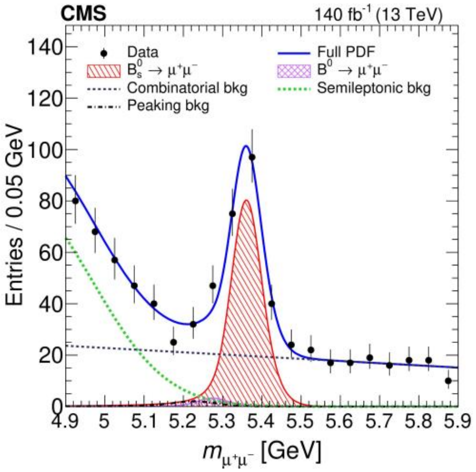
– No reliable hadronic particle identification available



CMS luminosity in Run-2



B_s ➜ $\mu^+\mu^-$



Search for CP violation in $D^0 \rightarrow K^0_S K^0_S$

EPJC84(2024)1264

$A_{CP}(D^0 \rightarrow K^0_S K^0_S)$

- 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 $D^0 \rightarrow K^0_S K^0_S$ to be as large as *O(1%)* ← more significant than in many other D^0 decay channels
- The **flavor is tagged** by **$D^{*\pm} \rightarrow D^0 (\bar{D}^0)\pi^\pm$**
- Many systematic uncertainties in A_{CP} cancel if measured via ΔA_{CP}:

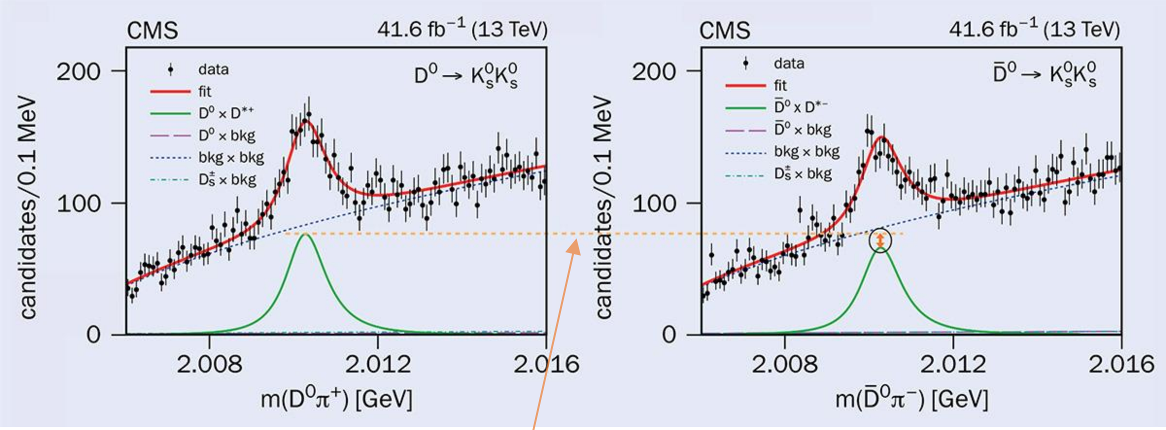
$$A_{CP} = \boxed{A_{raw}} - \boxed{A_{prod}} - \boxed{A_{det}}$$

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

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

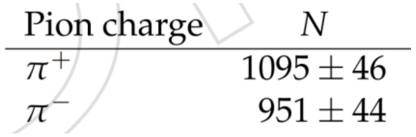
$$A_{det} \approx \frac{\epsilon_{\pi^+} - \epsilon_{\pi^-}}{\epsilon_{\pi^+} + \epsilon_{\pi^-}}$$

Fit to data in $K^0_S K^0_S$ channel



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

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



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

$$\boxed{A_{CP}(D^0 \rightarrow K^0_S K^0_S) = (6.2 \pm 3.0 \pm 0.2 \pm 0.8)\%}$$ ← **no CPV**

The first CMS study of CP violation in the charm sector!
Further works on charm CPV measurements are *in progress*!

EPJC84(2024)1264

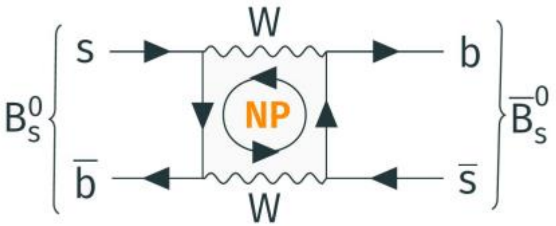
Evidence for time-dependent CP violation in B_s^0 mesons

arxiv.org/abs/2412.19952

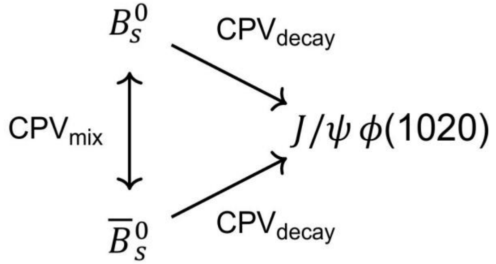
Submitted to PRL

Motivation: CPV in interference

- 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



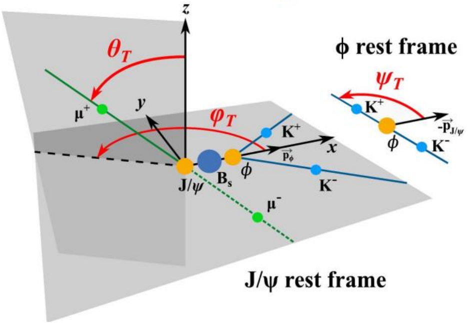
- This analysis presents measurement of time-dependent CPV in B_s^0 via the golden mode $\mathbf{B_s^0} \rightarrow$ **J/ψ φ(1020) → μ⁺ μ⁻ K⁺ K⁻**
- The study performs time-dependent **angular analysis** to separate the CP eigenstates ("transversity basis" used) and **flavor analysis** to resolve the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



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

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

Transversity basis



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

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

Deep neural networks (DNN) for tagging!

arxiv.org/abs/2412.19952

Flavor tagging technique

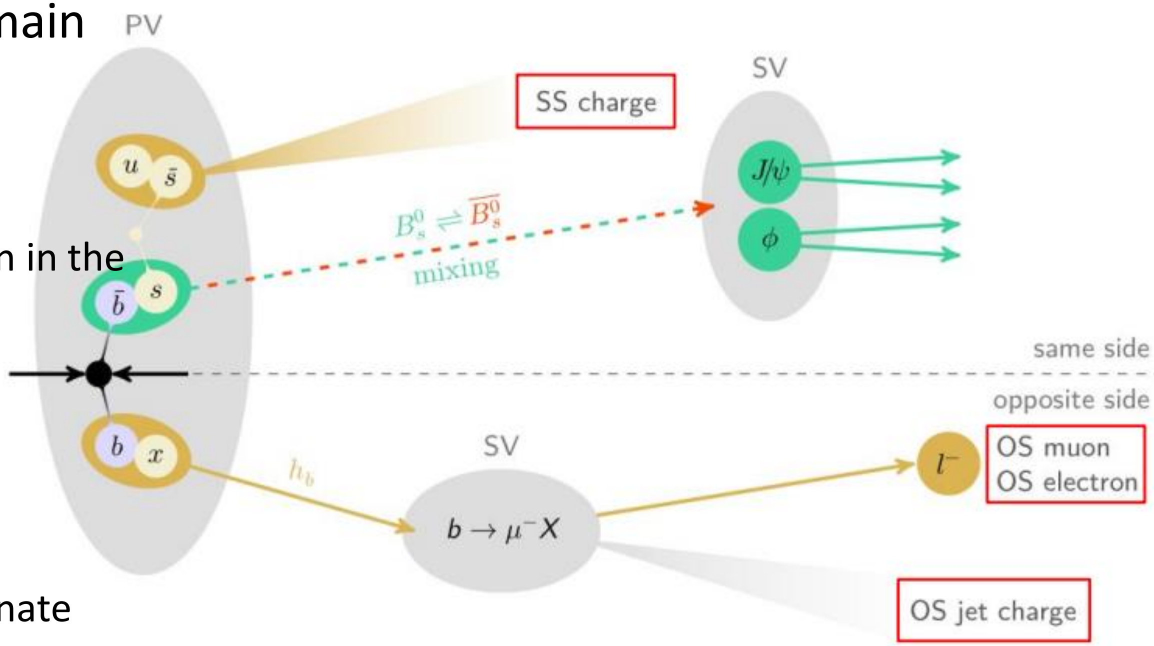
- Four **DNN-based algorithms** are used, divided into two main categories:
  - ❑ **Same side (SS):** exploits the B_s^0 fragmentation
    1. SS tagger: leverages charge asymmetries in the B_s^0 fragmentation
  - ❑ **Opposite side (OS):** exploits decay products of the other B hadron in the event
    1. OS muon: leverages b ➔ $\mu^- X$ 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 is used to discriminate correct-tag vs wrong-tag; Lepton charge ➔ ξ_{tag}; DNN score ➔ ω_{tag}

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

  2. Charge-based taggers (OS jet, SS): DNN is used to discriminate B_s^0 vs $\bar{B}_s{}^0$; DNN score ➔ Prob(B_s) ➔ ξ_{tag} ; ω_{tag}

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

Schematic representation of a generic event



Useful definitions

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

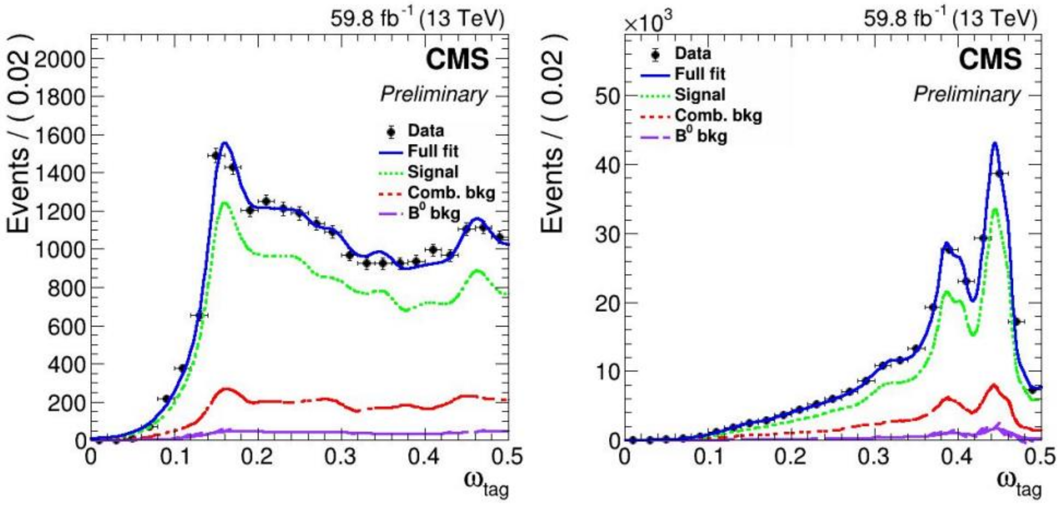
$$\epsilon_{tag} = \frac{N_{tag}}{N_{tot}}, \quad \omega_{tag} = \frac{N_{mistag}}{N_{tag}}, \quad \mathcal{D}_{tag} = 1 - 2\omega_{tag}, \quad P_{tag} = \epsilon_{tag}\mathcal{D}_{tag}^2$$

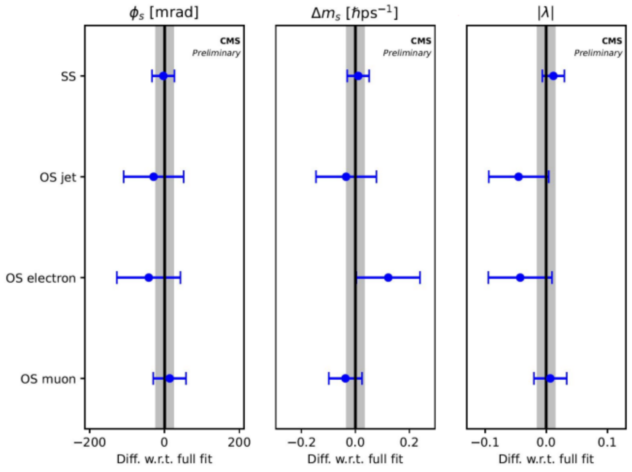
The algorithms are optimized and trained in simulated events and calibrated in data with self-tagging B^+ ➔ $J/\psi K^+$ decays

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 $N_{Bs} \cdot P_{tag}$ ($490k \cdot 5.6\% \approx 27.5k$) 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

arxiv.org/abs/2412.19952

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:**

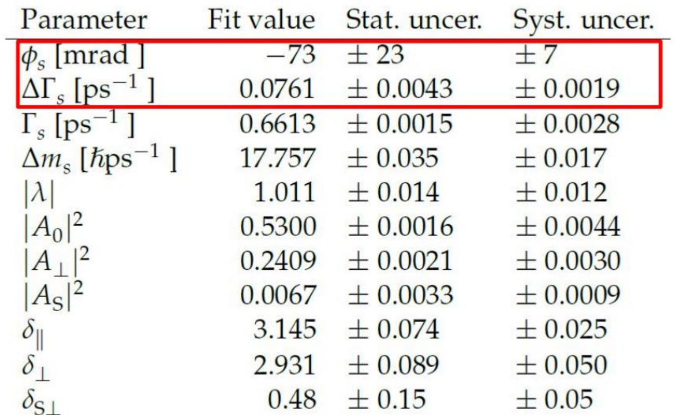
$$\Gamma_s^{WA} = 0.6573 \pm 0.0023 \text{ ps}^{-1} \qquad \Delta m_s^{WA} = 17.765 \pm 0.006\ \hbar\text{ps}^{-1}$$

- **|λ|** is **consistent** with **no direct CPV** (|λ| = 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]$^{-1}$

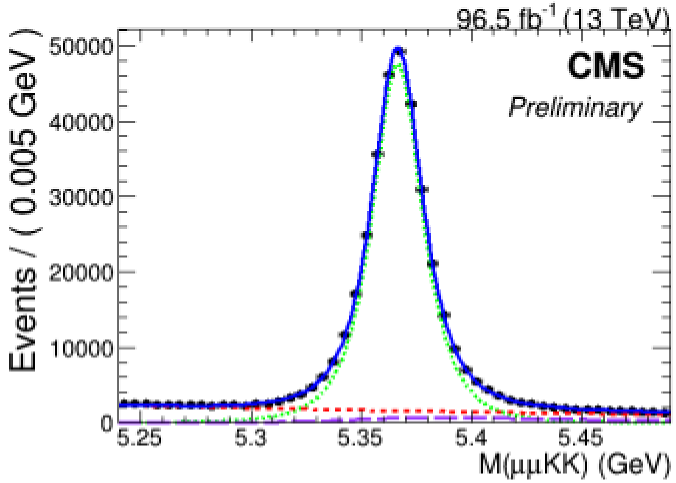
First evidence of CPV in $B_s^0 \to J/\psi\, K^+ K^-$ decays **(3.2 σ)!**

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
$\|\lambda\|$	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

Fit projection on the input observable of inv. mass M($\mu^+\mu^-K^+K^-$), the 2018 data.



arxiv.org/abs/2412.19952

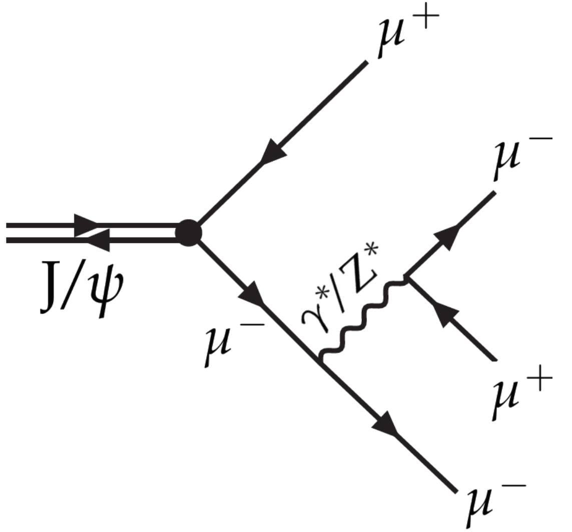
Observation of J/ψ → $\mu^+\mu^-\mu^+\mu^-$

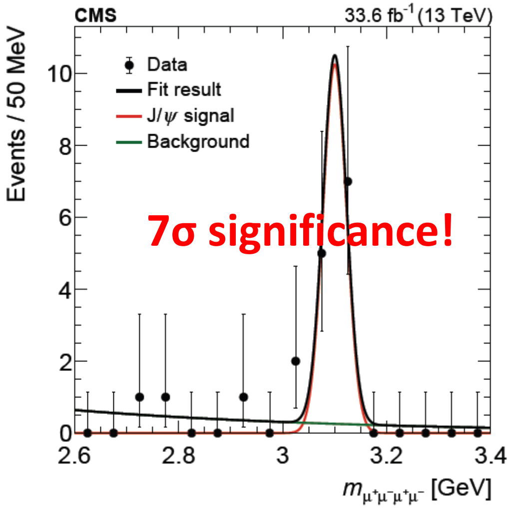
PRD109(2024)L111101

First observation of $J/\psi \to \mu^+ \mu^- \mu^+ \mu^-$

- Multileptonic decays is a clear signature at hadron collider experiment
- In the **SM** decays $\mathbf{J/\psi \to l^+ l^- l^+ l^-}$ occur via $\mathbf{l \to l\, \gamma^*/Z^*}$ (see Figure on the right)
  - **New physics** scenarios may replace $\mathbf{\gamma^*}$ and $\mathbf{Z^*}$ and enhance the process [PLB791(2019)130, JHEP03(2014)105, PRD90(2014)035027]
- Previous studies by BESIII:
  - ❖ Observation of $\mathbf{J/\psi \to e^+ e^- e^+ e^-}$ and $\mathbf{J/\psi \to e^+ e^- \mu^+ \mu^-}$ [PRD109(2024)052006]
  - ❖ Upper limit established on $\mathbf{J/\psi \to \mu^+ \mu^- \mu^+ \mu^-}$ **BF**: 1.6×10^{-6} [PRD109(2024)052006] at 90% CL
- The branching fraction, relative to $\mathbf{J/\psi \to \mu^+ \mu^-}$ is measured

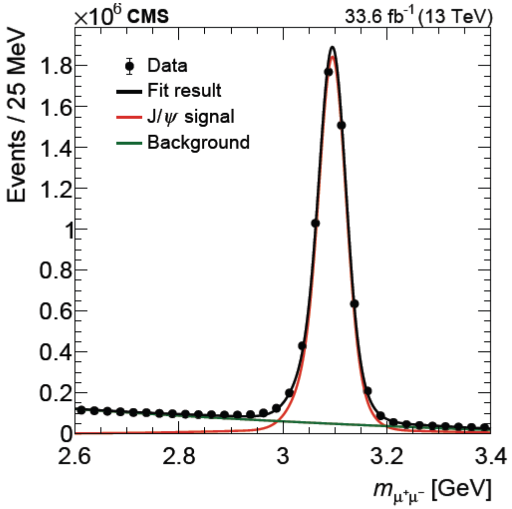
Leading-order Feynmann diagram representing the $\mathbf{J/\psi \to \mu^+ \mu^- \mu^+ \mu^-}$





7σ significance!

4 muon distribution



dimuon distribution

Branching ratio is computed via:

$$\frac{\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-)} = \frac{N(\mathrm{J}/\psi \to \mu^+\mu^-\mu^+\mu^-)}{N(\mathrm{J}/\psi \to \mu^+\mu^-)} \Big/ \frac{\epsilon_{\mathrm{J}/\psi \to \mu^+\mu^-\mu^+\mu^-}}{\epsilon_{\mathrm{J}/\psi \to \mu^+\mu^-}}$$

Branching ratio value:

$$\boxed{\frac{\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-)} = [16.9^{+5.5}_{-4.6}\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst})] \times 10^{-6}}$$

Using world-average B($\mathbf{J/\psi \to \mu^+ \mu^-}$):

$$\boxed{\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-\mu^+\mu^-) = [10.1^{+3.3}_{-2.7}\,(\mathrm{stat}) \pm 0.4\,(\mathrm{syst})] \times 10^{-7}}$$

Consistent with SM!

PRD109(2024)L111101

Search for the rare decay $D^0 \rightarrow \mu^+\mu^-$

arxiv.org/abs/2506.06152

Submitted to PRL

Motivation for $D^0 \to \mu^+ \mu^-$ search

- **$D^0 \to \mu^+ \mu^-$** decay involves SM-suppressed **FCNC** of **c → u** type, which is not well-studied
- The SM BF estimation:
  - ❑ **B ($D^0 \to \mu^+ \mu^-$)** = 3 x 10^{-13} [PRD66(2002)014009]
  - ❑ **New physics** models (leptoquarks, R-parity, violating SUSY extra fermions or gauge bosons) may enhance the BF up to the level of the LHC accessibility [PRD79(2009)017502]
- Previous measurement by LHCb:
  - ❖ Upper limit established on **BF**: 3.1 (3.5) x 10^{-9} [PRL131(2023)041804] at 90 (95)% CL

Event selection for the analysis

- The CMS analyses utilizes new samples of RUN3 2022 && 2023 with novel inclusive dimuon trigger!
- D^0 is required to origin from **$D^{*\pm} \to D^0\pi^\pm$**
  - Pion improves vertex constraints and reduces the background by two orders
- The BF is calculated with respect to the BF of **$D^0 \to \pi^+\pi^-$**

Reduces the uncertainties
Related to D production*

$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) = \mathcal{B}(\mathrm{D}^0 \to \pi^+\pi^-)\frac{N_{\mathrm{D}^0\to\mu\mu}}{N_{\mathrm{D}^0\to\pi\pi}}\frac{\varepsilon_{\mathrm{D}^0\to\pi\pi}}{\varepsilon_{\mathrm{D}^0\to\mu\mu}}$$

- BDT discriminator is applied to give the most stringent expected limit on **B ($D^0 \to \mu^+ \mu^-$)**

arxiv.org/abs/2506.06152

Fits to data

2D UML fit of ($\Delta m = M(D\pi^{\pm}) - M(D)$) vs $M(D)$ are applied

Signal pdf: *Two (three) Gaussian function for M_D (Δm) with common means*

Backgrounds from D^0 decays: *Two (three) Gaussian function for M_D (Δm) with common means*

Combinatorial Background pdf: *Exponential function in M_D and modified for Δm:*

$$\left(1 - e^{-\frac{\Delta m - m_\pi}{C}}\right)\left(\frac{\Delta m}{m_\pi}\right)^{A} + B\left(\frac{\Delta m}{m_\pi} - 1\right)$$

Signal yield in $\mathbf{D^0 \to \pi^+\pi^-}$: **195 ± 17**

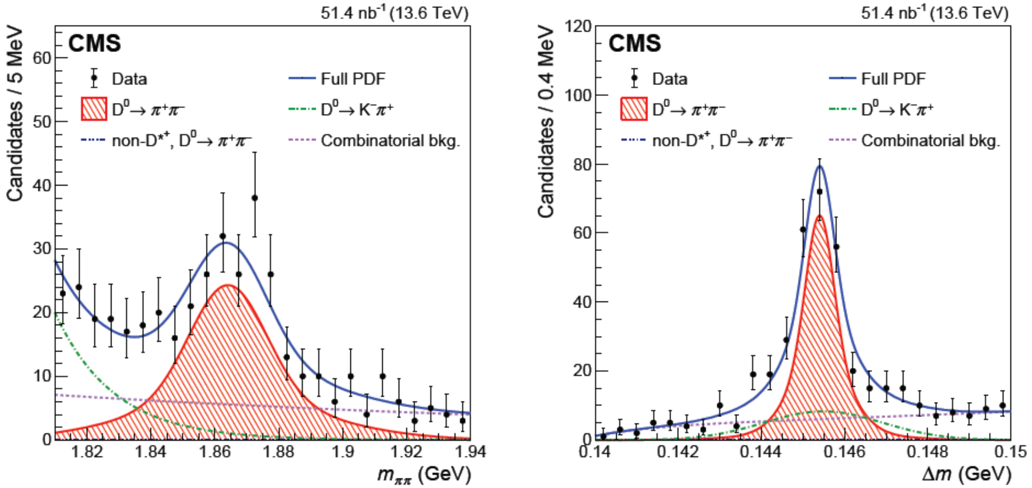
Signal yield in $\mathbf{D^0 \to \mu^+\mu^-}$: **100 ± 120** ← *No signal found! Observed significance is 0.8 s.d.*

Upper limit is set using the asymptotic CL_s method:

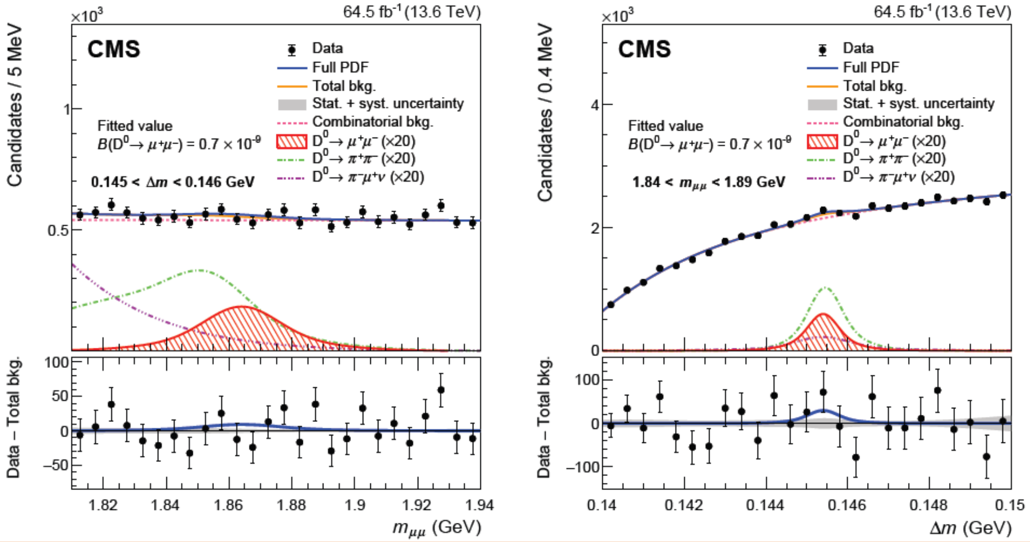
B ($\mathbf{D^0 \to \mu^+\mu^-}$) < 2.1 (2.4) x 10^{-9} at 90 (95%) CL

The most sensitive to date and provides a significant improvement since previous LHCb measurement [PRL131(2023)041804]

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



Fit to data in $D^0 \to \mu^+\mu^-$ channel



arxiv.org/abs/2506.06152

Summary

- We present 2 recent CMS results on the CP violation and 2 results on the rare decays searches:
  - Search for direct CP violation in $D^0 \rightarrow K_S^0 K_S^0$:
    - First CMS measurement of CP violation in charm: $A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (6.2 \pm 3.0\ (\text{stat}) \pm 0.2\ (\text{syst}) \pm 0.8\ (A_{CP}(D^0 \rightarrow K_S^0 \pi^+\pi^-)))\%$
  - Measurement of the time-dependent CP violation in $B_s^0 \rightarrow J/\psi\ \varphi$
    - First evidence of CP violation in $B_s^0 \rightarrow J/\psi\ K^+ K^-$: $\varphi_s = -74 \pm 23$ mrad
  - First observation of $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
    - Branching fraction: $B(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-) = (10.1 \pm^{3.3}_{2.7}\ (\text{stat}) \pm 0.4\ (\text{syst})) \times 10^{-6}$
  - Search for the rare decay $D^0 \rightarrow \mu^+ \mu^-$
    - Limit on the Branching fraction: $B(D^0 \rightarrow \mu^+ \mu^-) < 2.4 \times 10^{-9}$ at 95% CL
- 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 make the results of CMS in flavor physics compatible with B-factories
- New data of 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!

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СИНТЕЗ