



Search for CP violation in charm sector at the CMS experiment

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Agenda

- **Introduction**
- **Data sample**
- **ACP in MC**
- **Fits to data**
- **Systematics uncertainties**
- **Results**
- **Further improvements**

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**

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

Indirect CPV in **mixing**

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

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

CPV in decay+mixing **interference**

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

- We will focus on the search for **direct CPV in charm!**

Introduction to the analysis

- 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 $D^0 \rightarrow K_S^0 K_S^0$ to be as large as $O(1\%) \leftarrow$ more significant than in many other D^0 decay channels
- [Latest experimental calculation by LHCb](#) [PRD104(2021)031102]:

$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\% \leftarrow \text{no CPV}$$
- Many systematic uncertainties in A_{CP} cancel if measured via ΔA_{CP} :

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

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

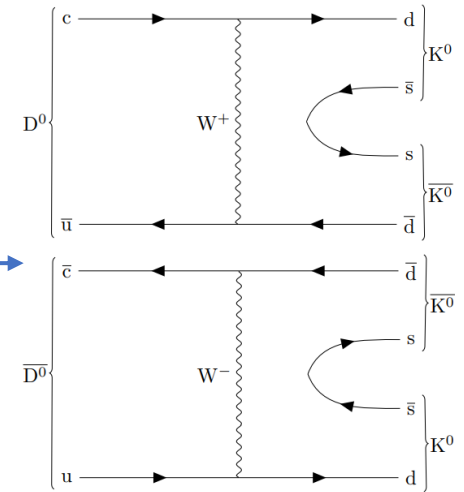
$$A_{\text{prod}} = \frac{\sigma_{pp \rightarrow D^{*+} X} - \sigma_{pp \rightarrow D^{*-} X}}{\sigma_{pp \rightarrow D^{*+} X} + \sigma_{pp \rightarrow D^{*-} X}}$$

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

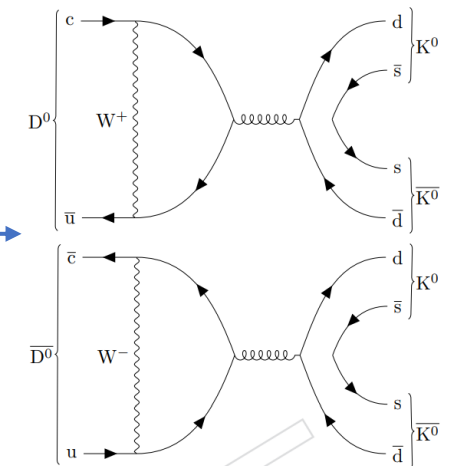
- $\Delta A_{CP} = A_{CP}^{\text{raw}}(D^0 \rightarrow K_S^0 K_S^0) - A_{CP}^{\text{raw}}(D^0 \rightarrow K_S^0 \pi^+ \pi^-)$
 - Reference channel is very similar in kinematics and topology $\rightarrow A_{\text{prod}}$ and A_{det} **cancel out**.
- The **flavor is tagged** by $D^{*\pm} \rightarrow D^0(\bar{D}^0)\pi^\pm$

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

Exchange diagram $\rightarrow$

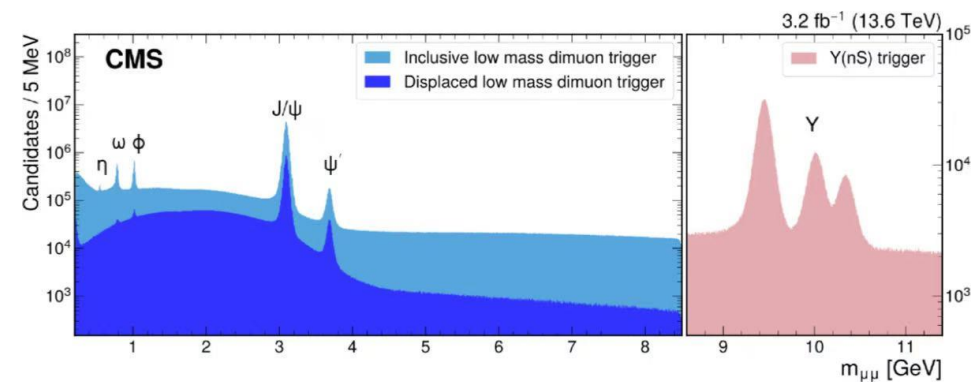
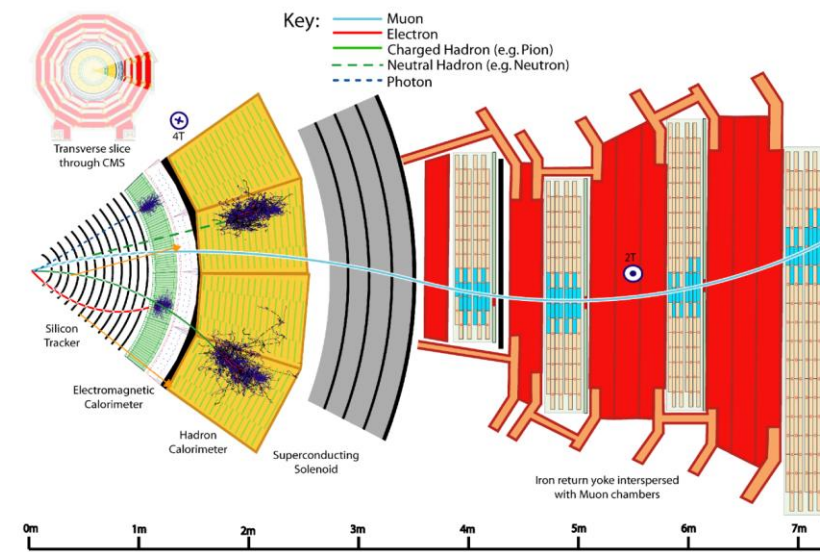


PA diagram $\rightarrow$



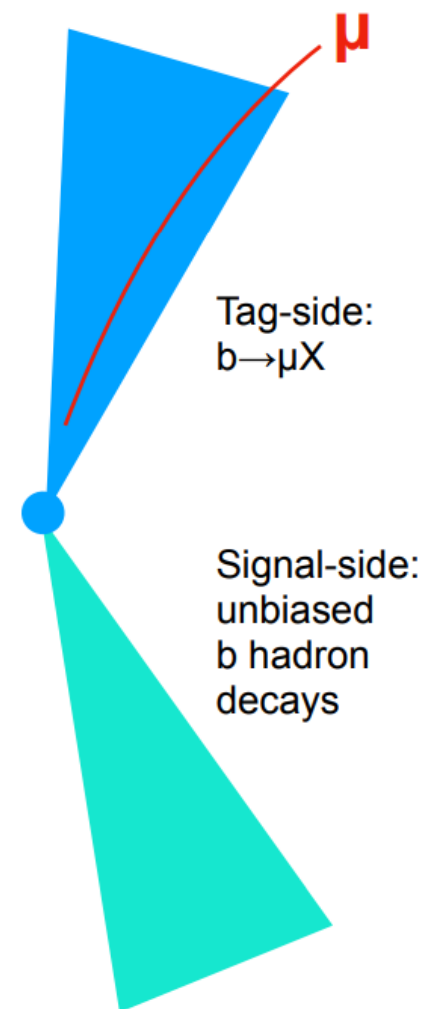
Challenges for charm CP violation measurement

- CMS can perform studies in the scope of Heavy Flavor Physics
 - Excellent tracking system able to reconstruct vertices with high decay time resolution (e.g., $\sigma_t \sim 65$ fs for $B_S^0 \rightarrow J/\psi \phi$) up to $|\eta| < 2.5$
 - Complementary to LHCb ($2 < |\eta| < 5$)
 - Enormous amount of data collected
 - $\sim 7.5 \cdot 10^{13}$ bb pairs produced at Point 5 during Run 2 (geometric acceptance not considered)
- Some **CMS** flavor physics **highlights** from recent years:
 - [B_S → μ⁺ μ⁻ \(world's most precise\)](#) [PLB842(2023)137955]
 - [η → μ⁺ μ⁻ μ⁺ μ⁻ observation](#) [PRL131(2023)091903]
 - [Triple J/ψ production observation](#) [Nat.Phys.19(2023)338]
 - [Observation of Ξ_b\(6100\)⁻ → Ξ_b⁻ π⁺ π⁻](#) [PRL126(2021)252003]
 - [Observation of X\(6900\) → J/ψ J/ψ](#) [PRL132(2024)111901]
- Our golden mode — dimuon final states! (e.g. $J/\psi \rightarrow \mu^+ \mu^-$)
- **BUT:** D⁰ mainly decays to the **fully-hadronic final states!**
 - New revamped **trigger strategy** is required
 - Collection of unbiased D⁰ events should be implemented



Bparking miniAOD 2018 data set

- A dedicated data set corresponding to the integral $L = 41 \text{ fb}^{-1}$ 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($\sim 75\text{-}80\%$) of the events in dataset come from beauty semi-leptonic decays $b \rightarrow \mu X$
- Almost every time $b \rightarrow \mu c \nu X$
- The muon p_T cut at trigger level: $7\text{-}12 \text{ GeV} \Rightarrow D$ 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 $p_T \Rightarrow$ it is perfect for CPV search



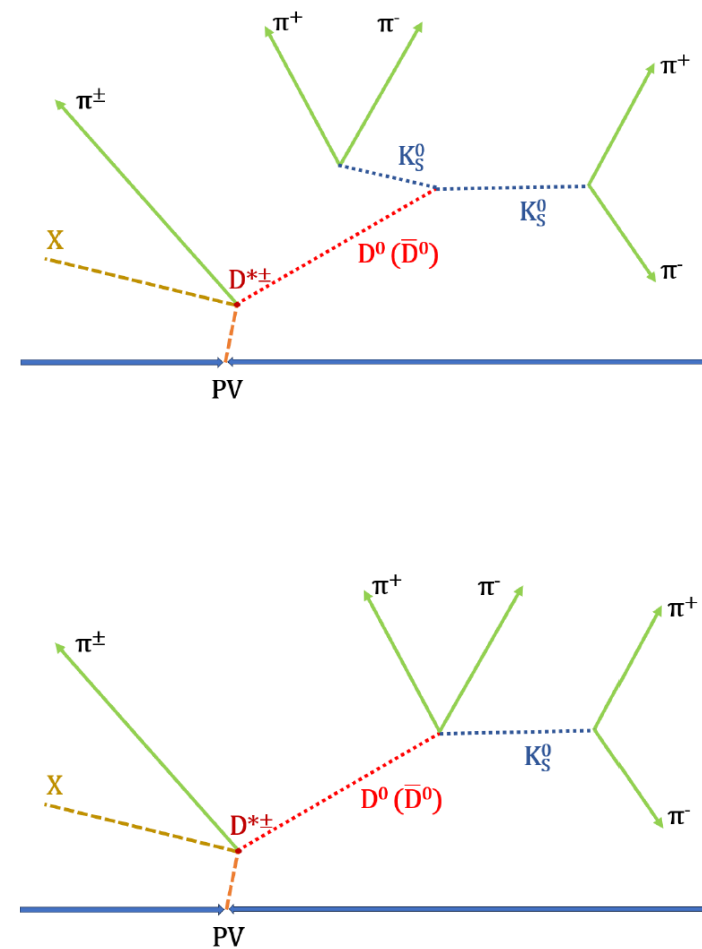
Event selection in data and MC

Data:

- $K_S^0 \pi \pi$ (normalization channel) and $K_S^0 K_S^0$ (signal channel) channels have almost identical kinematics and topology $\Rightarrow$ the reconstruction efficiencies asymmetries cancel in the measured difference of differences ΔA_{CP}
- K_S^0 reconstructed from $\pi \pi$ fitted to the vertex with PDG mass constraint
- D^0 momentum points to PV
- D^0 is the result of $K_S^0 K_S^0$ or $K_S^0 \pi \pi$ vertex fit
- $D^{*\pm}$ is the result of $D^0 \pi^\pm$ vertex fit
- Selection criteria were optimized for improving accuracy of signal extraction in $D^0 \rightarrow K_S^0 K_S^0$

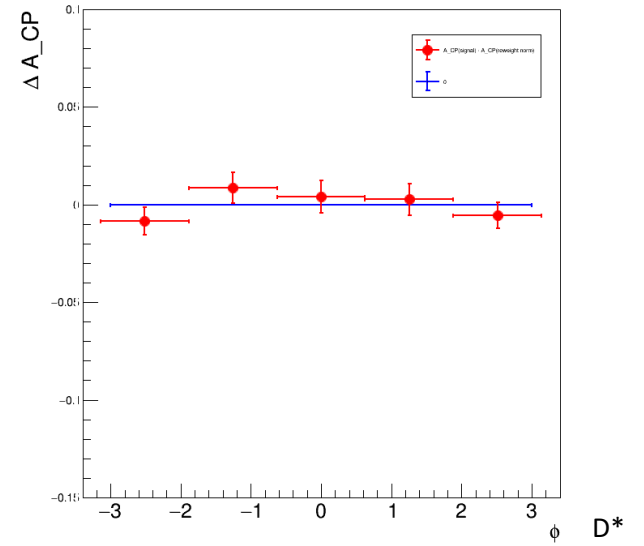
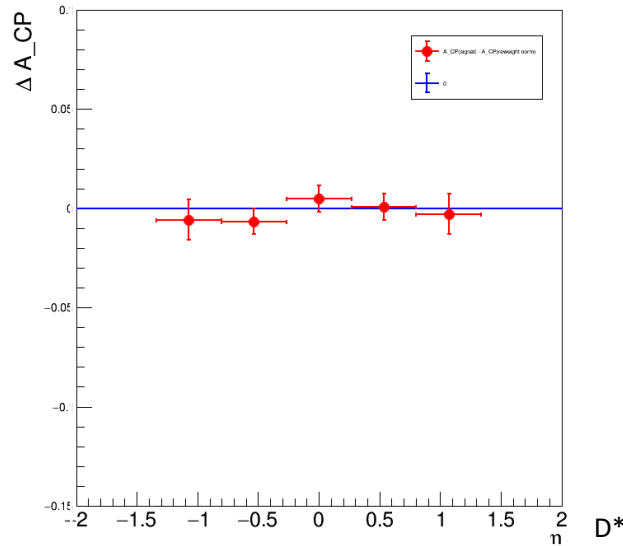
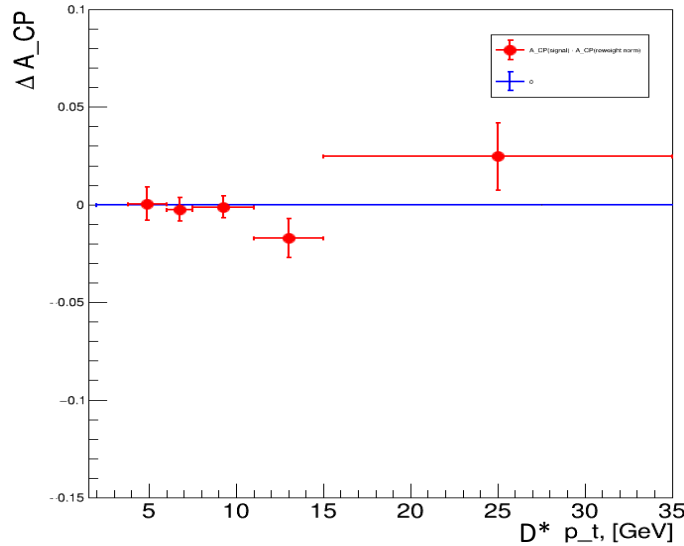
MC:

- Generated with PYTHIA 8.230 and processed with GEANT-4 to include CMS detector simulation particularities



ΔA_{CP}^{raw} in MC

$$\Delta A_{CP} = A_{CP}^2 - A_{CP}^1 = A_{CP}^{raw2} - A_{CP}^{raw1}$$



ΔA_{CP}^{raw} in whole MC sample: $(0.126 \pm 0.336)\%$

Perfect agreement with 0!

Possible p_T , η or ϕ dependence in individual channel cancels out in ΔA_{CP} – as expected!

Signals and A_{CP}^{raw} in $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

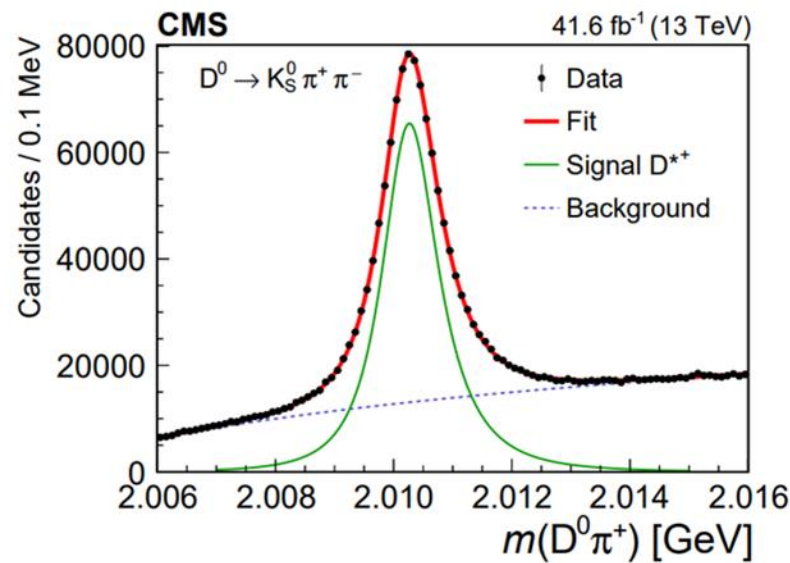
Fits of “+” and “-” are simultaneous:
all parameters of their pdfs are shared;
only yields are floating

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

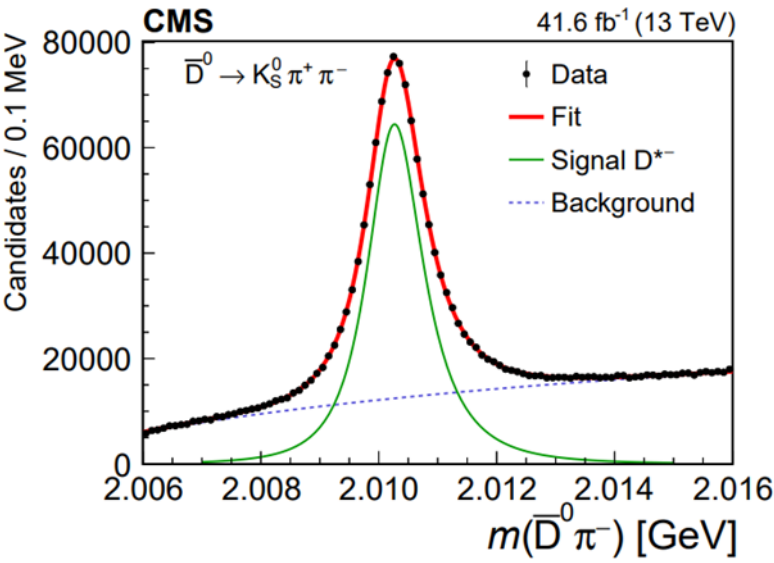
Signal pdf: *Johnson function*
Background pdf: *Threshold function • Pol₁*

Charge of pion	N	χ^2 with 100 bins
π^+	944817 ± 3489	78
π^-	930148 ± 3395	93

Fit to D^{*+} candidates



Fit to D^{*-} candidates



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

$A_{CP}^{raw}(D^0 \rightarrow K_S^0 \pi^+ \pi^-) = (0.78 \pm 0.10)\%$

Signals and A_{CP}^{raw} in $D^0 \rightarrow K_S^0 K_S^0$

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

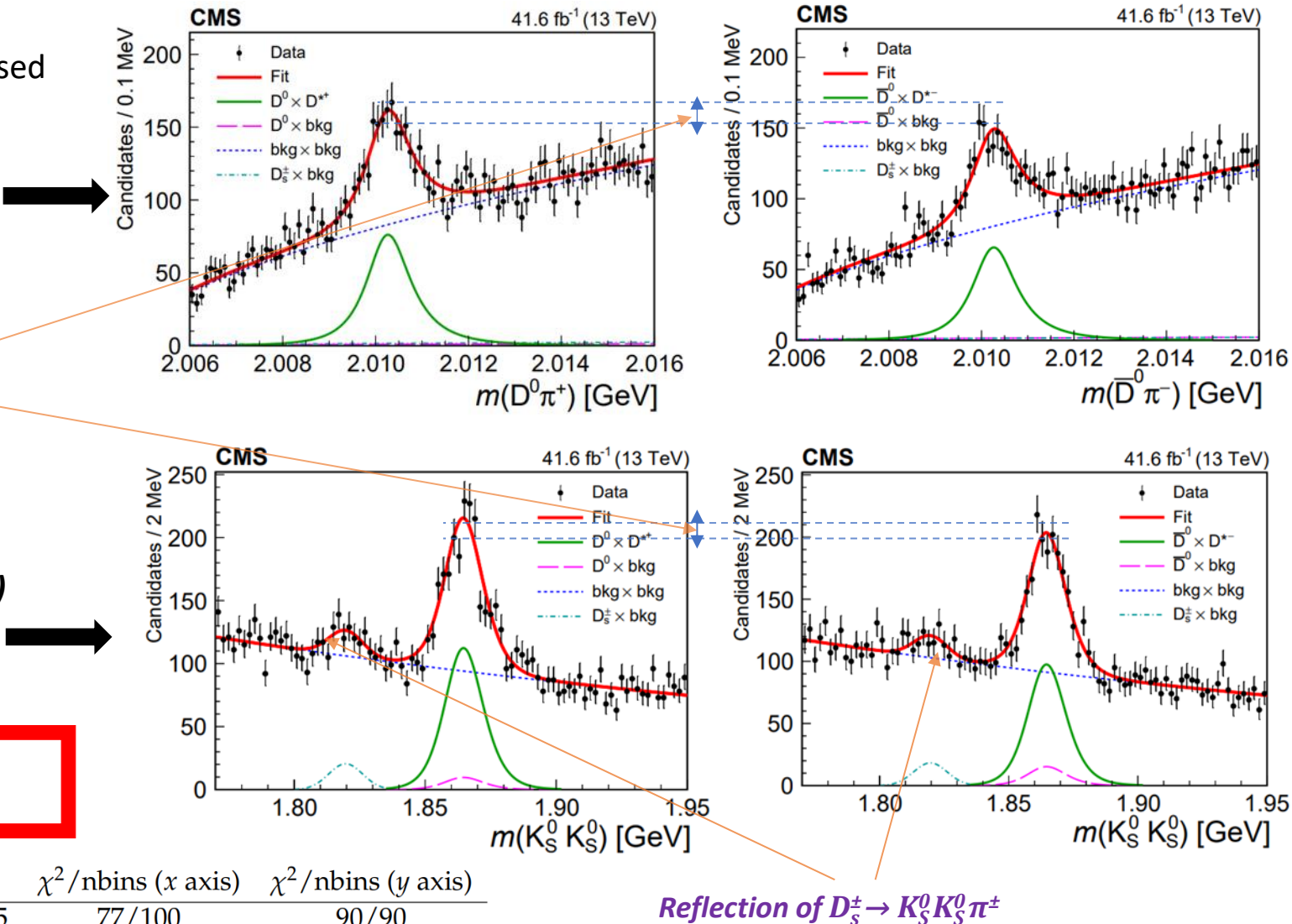
Projections on $x^+ = m(D\pi^+)$ and $x^- = m(D\pi^-)$ axes of 2d-fit

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

Projections on $y^+ = m(K_S^0 K_S^0)$ and $y^- = m(K_S^0 K_S^0)$ axes of 2d-fit

$$A_{CP}^{raw}(D^0 \rightarrow K_S^0 K_S^0) = (7.065 \pm 3.022)\%$$

Charge of pion	$N_{sig \cdot sig}$	$N_{sig \cdot bgd}$	$N_{bgd \cdot bgd}$	$N_{Ds \cdot bgd}$	$\chi^2/nbins$ (x axis)	$\chi^2/nbins$ (y axis)
π^+	1095 ± 46	94 ± 52	8653 ± 115	165 ± 45	77/100	90/90
π^-	951 ± 44	149 ± 52	8397 ± 115	144 ± 46	93/100	62/90



Sources of systematical uncertainties

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

Systematics is much smaller than statistics: 0.2% vs. 3%

Results

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

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

- Using **RUN 2 2018 b-parking dataset** with a lot of charm hadrons produced in semileptonic b decays
- The resulting $\Delta A_{CP}^{\text{raw}}$:

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

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

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

- 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)%] , **but is worse in precision ~ 2 times!**  **Improvement is required!**

Further improvement

- The final result for [the first charm CP violation measurement on CMS](#):

$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (6.2 \pm 3.1)\%$$

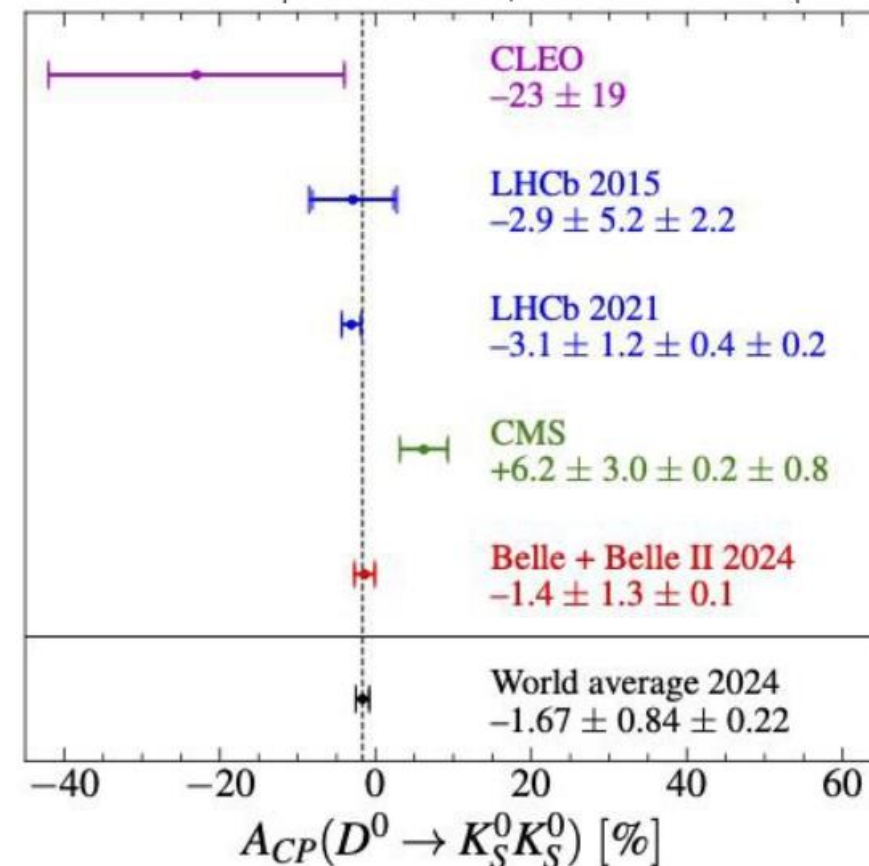
- Though this result is in agreement with [previous measurements](#), it has worse precision (compared with [the LHCb results](#) and [the Belle II results](#)):

$(6.2 \pm 3.1)\%$ vs. $(-3.1 \pm 1.3)\%$ or $(-1.4 \pm 1.3)\%$

~2 times worse precision!

- The CMS experiment is working on the improvement of the precision:
 - Adding RUN3 data, collected with similar parking triggers on single muon
 - Adding the data of semileptonic D^0 origin $B \rightarrow \mu^\mp D^0(\bar{D}^0) \bar{\nu}_\mu(\nu_\mu) X$

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



Summary

- The **first CMS measurement of CP violation in charm** is performed:

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

- Though initially **not optimized** for such searches, **CMS is able to perform studies of CP violation in charm**:
 - New Parking single muon triggers allow to collect unbiased charm events and exploit fully-hadronic final states
- The results of CMS **are compatible** with B-factories and LHCb
- The CMS will extend its charm CP violation program with:
 - ❑ New RUN 3 data
 - ❑ New tagging techniques (involving $B \rightarrow \mu^\mp D^0(\bar{D}^0) \bar{\nu}_\mu(\nu_\mu) X$ decays)
 - ❑ New decays for the search

Thank you!