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CP violation measurement in charm meson decays at the CMS experimentriment

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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

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

Indirect CPV in mixing

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

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

CPV in decay+mixing interference

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

- 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

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

- Theoretical SM calculations [PRD92(2015)054036] predict CPV in $D^0 \to K_S^0 K_S^0$ to be as large as *O(1%)* ← more significant then in in many other D^0 decay channels
- Latest experimental calculation by LHCb [PRD104(2021)031102]:

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

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

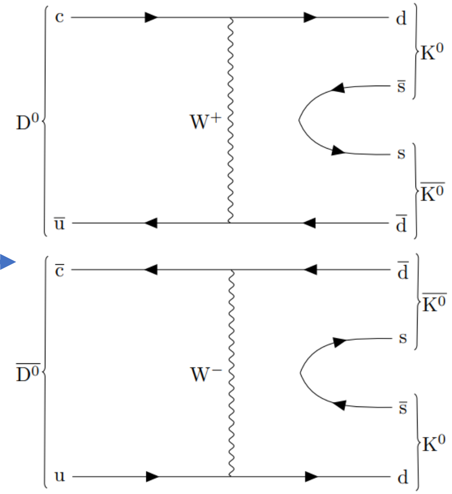
$$A_{CP} = \boxed{A_{raw}} - \boxed{A_{prod}} - \boxed{A_{det}}$$

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

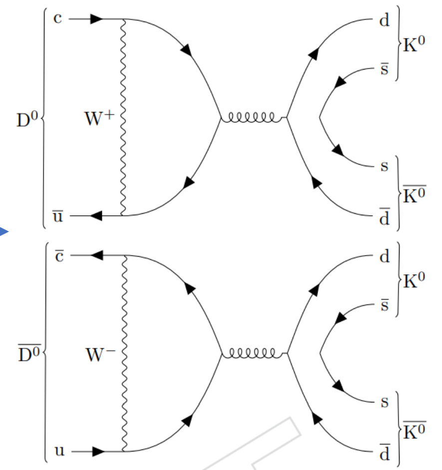
$$A_{prod} = \frac{\sigma_{pp \to D^{*+}X} - \sigma_{pp \to D^{*-}X}}{\sigma_{pp \to D^{*+}X} + \sigma_{pp \to D^{*-}X}}$$

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

Exchange diagram



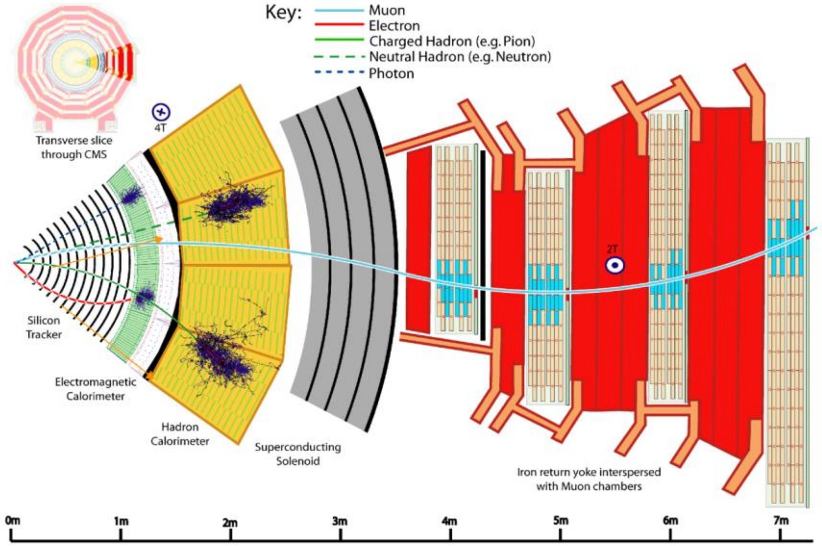
PA diagram



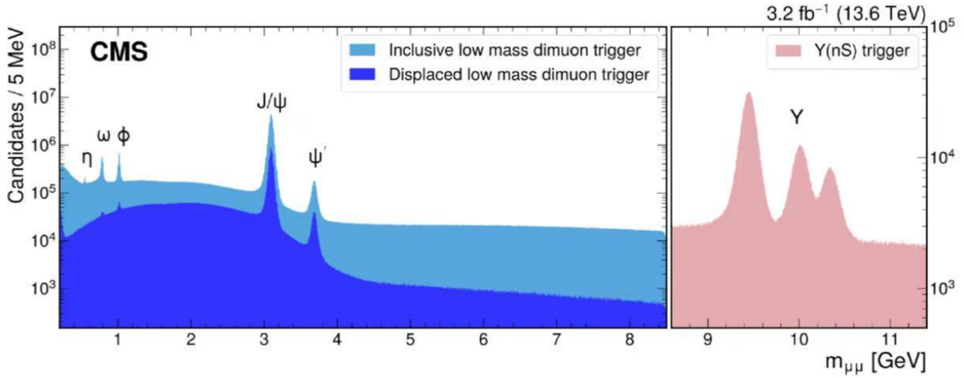
- **$\Delta A_{CP} = A_{CP}^{raw}(D^0 \to K_S^0 K_S^0) - A_{CP}^{raw}(D^0 \to K_S^0 \pi^+\pi^-)$**
  - Reference channel is very similar in kinematics and topology → A_{prod} and A_{det} cancel out.
- The **flavor is tagged** by **$D^{*\pm} \to D^0 (\bar{D}^0)\pi^\pm$**

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., σt ~ 65 fs for $B_s^0 \rightarrow J/\psi\ \varphi$) up to $|\eta| < 2.5$
    - Complementary to LHCb ($2 < |\eta| < 5$)
  - Enormous amount of data collected
    - ~ $7.5 \cdot 10^{13}$ bb pairs produced at Point 5 during Run 2 (geometric acceptance not considered)

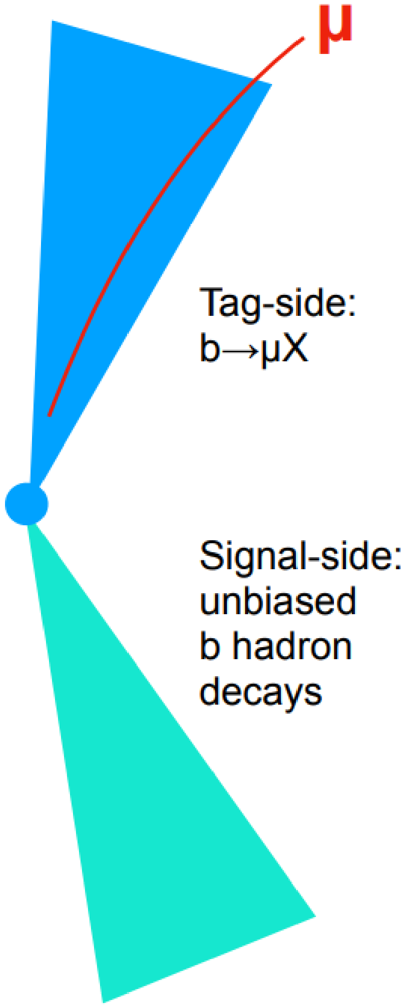


- Some **CMS** flavor physics **highlights** from recent years:
  - $B_S \rightarrow \mu^+ \mu^-$ (world's most precise) [PLB842(2023)137955]
  - $\eta \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ observation [PRL131(2023)091903]
  - Triple J/ψ production observation [Nat.Phys.19(2023)338]
  - Observation of $\Xi_b(6100)^- \rightarrow \Xi_b^- \pi^+\pi^-$ [PRL126(2021)252003]
  - Observation of X (6900) $\rightarrow J/\psi\ J/\psi$ [PRL132(2024)111901]
- Our golden mode — dimuon final states! (e.g. $J/\psi \rightarrow \mu^+ \mu^-$)
- **BUT:** D^0 mainly decays to the ***fully-hadronic final states***!
  - ➢ New revamped **trigger strategy** is required
  - ➢ Collection of unbiased D^0 events should be implemented



Bparking miniAOD 2018 data set

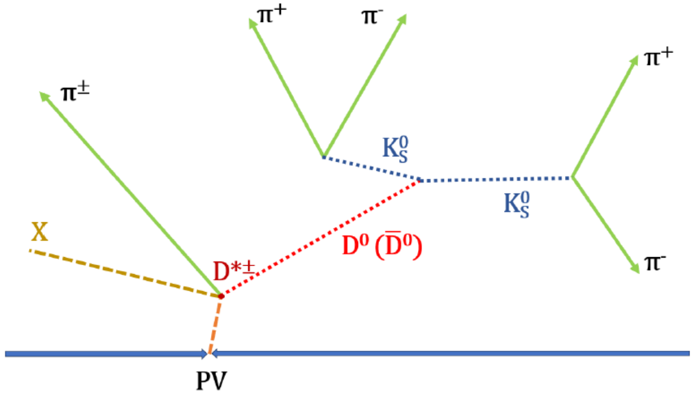
- A dedicated data set corresponding to the integral $L = 41$ fb^{-1} is used
- A set of single muon triggers with different thresholds on muon p_T and impact parameter are used
- Due to these thresholds, most(~ 75-80%) of the events in dataset come from beauty semi-leptonic decays $b \to \mu X$
- Almost 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



Event selection in data and MC

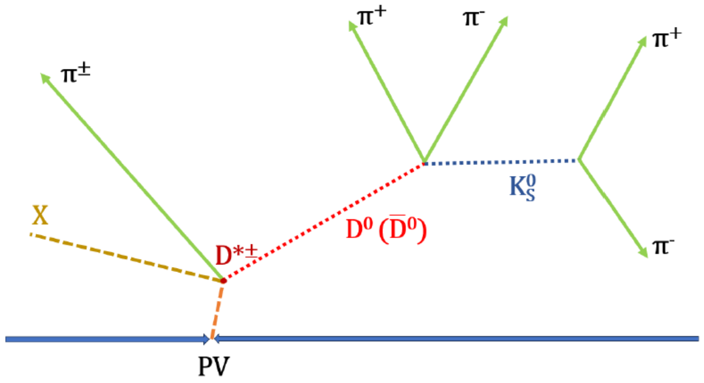
Data:

- $\mathbf{K_S^0\pi\pi}$ **(normalization channel)** and $\mathbf{K_S^0K_S^0}$ **(signal channel)** channels have almost identical kinematics and topology => the reconstruction efficiencies asymmetries cancel in the measured difference of differences ΔA_{CP}
- K_S^0 reconstructed from ππ 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^0ππ 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 $D^0 \rightarrow K_S^0 K_S^0$



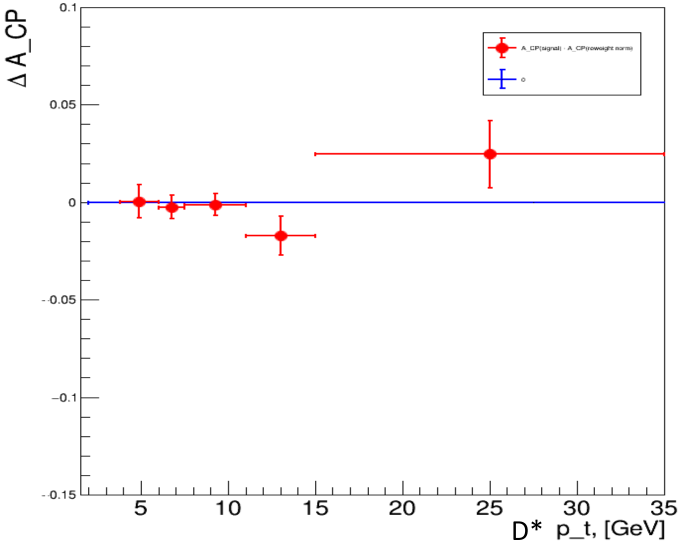
MC:

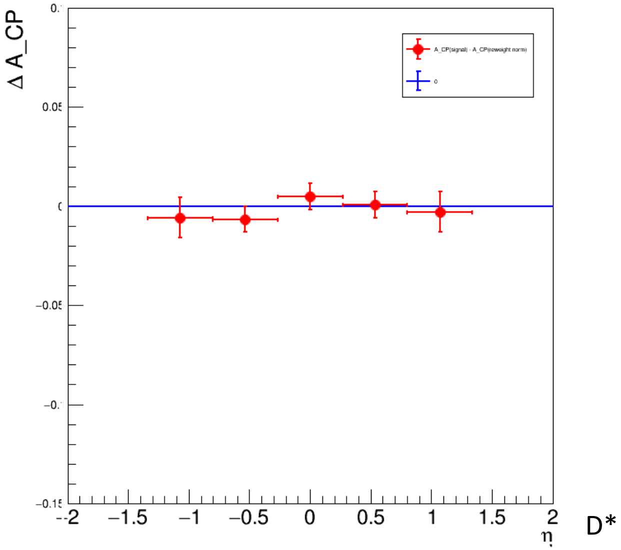
- Generated with PYTHIA 8.230 and processed with GEANT-4 to include CMS detector simulation particularities

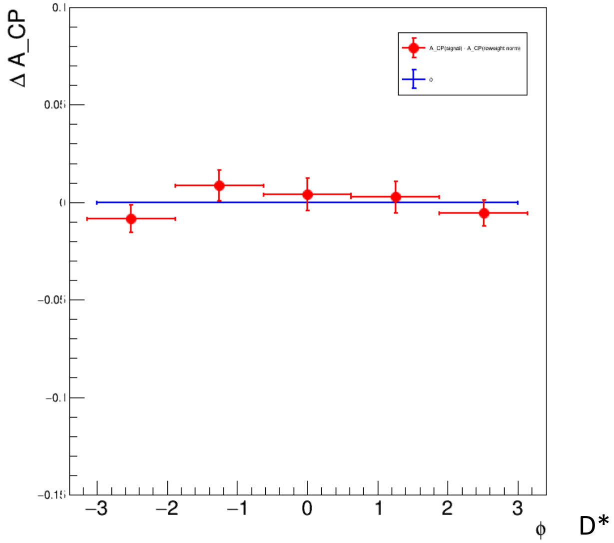


ΔA_{CP}^{raw} in MC

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







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 $D^0 \to K_S^0\pi^+\pi^-$

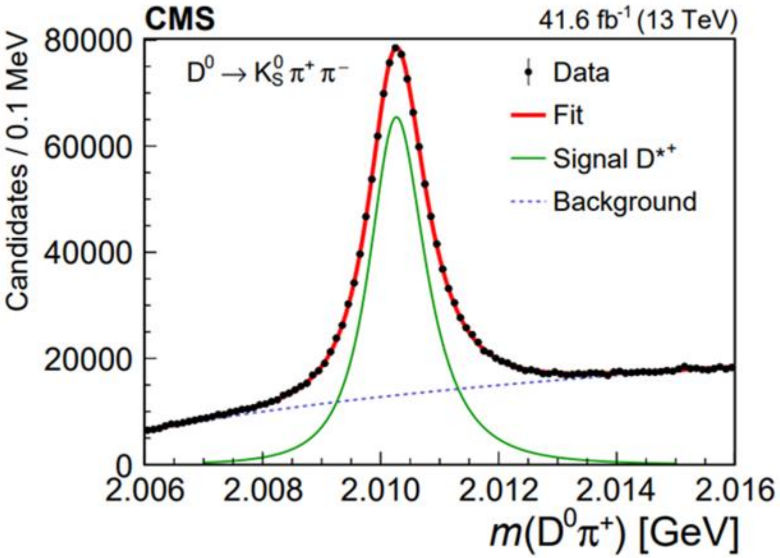
Fits of "+" and "–" are simultaneous:
all parameters of their pdfs are shared;
only yields are floating

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

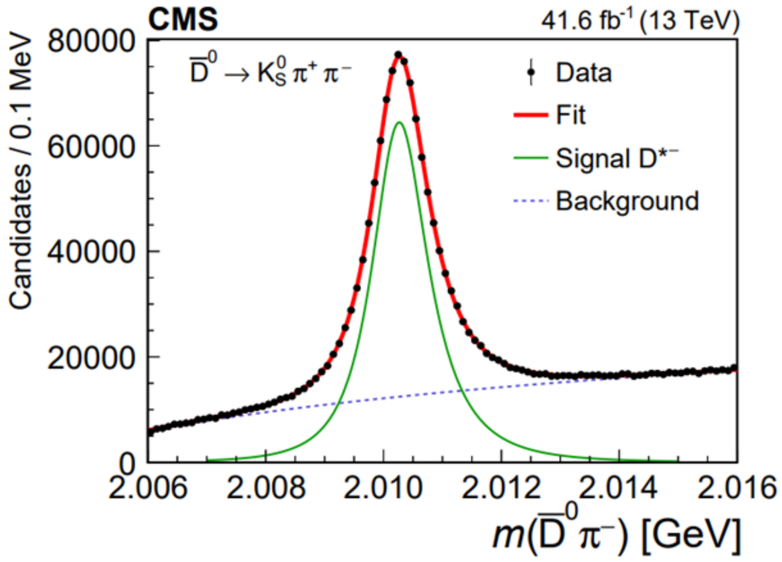
Signal pdf: *Johnson function*
Background pdf: *Threshold function• Pol_1*

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



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

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

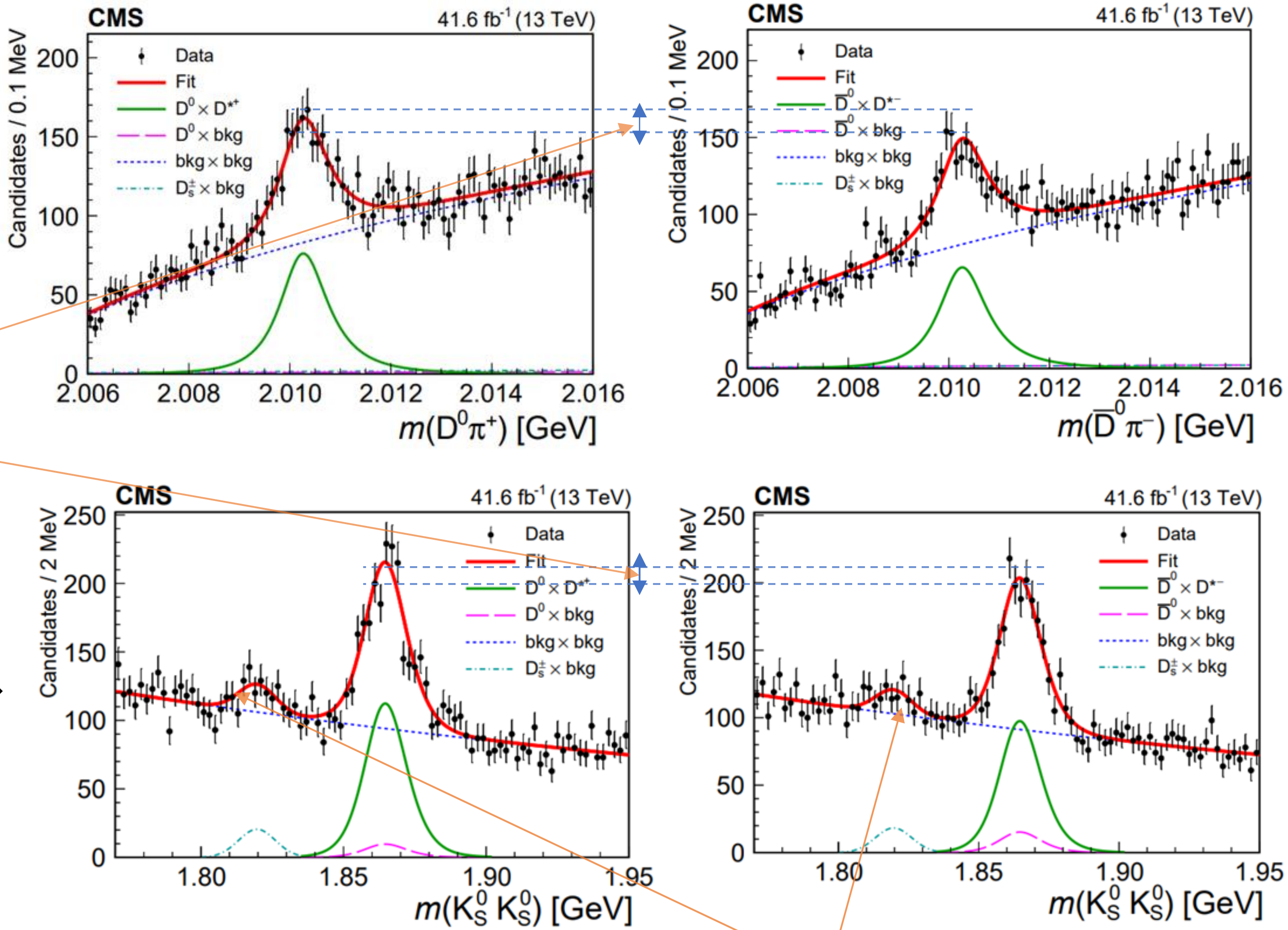
Signals and A_{CP}^{raw} in $D^0 \to K_S^0 K_S^0$

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



Reflection of $D_s^\pm \to K_S^0 K_S^0 \pi^\pm$

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

Charge of pion	$N_{sig\cdot sig}$	$N_{sig\cdot bgd}$	$N_{bgd\cdot bgd}$	$N_{Ds\cdot bgd}$	χ^2/nbins (x axis)	χ^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

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Sources of systematical 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

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

Results

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

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

- Using **RUN 2 2018 b-parking dataset** with a lot of charm hadrons produced in semileptonic b decays

- The resulting ΔA_{CP}^{raw}:

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

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

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

- The result is consistent with **no CPV in $D^0 \to K_S^0 K_S^0$** 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***:

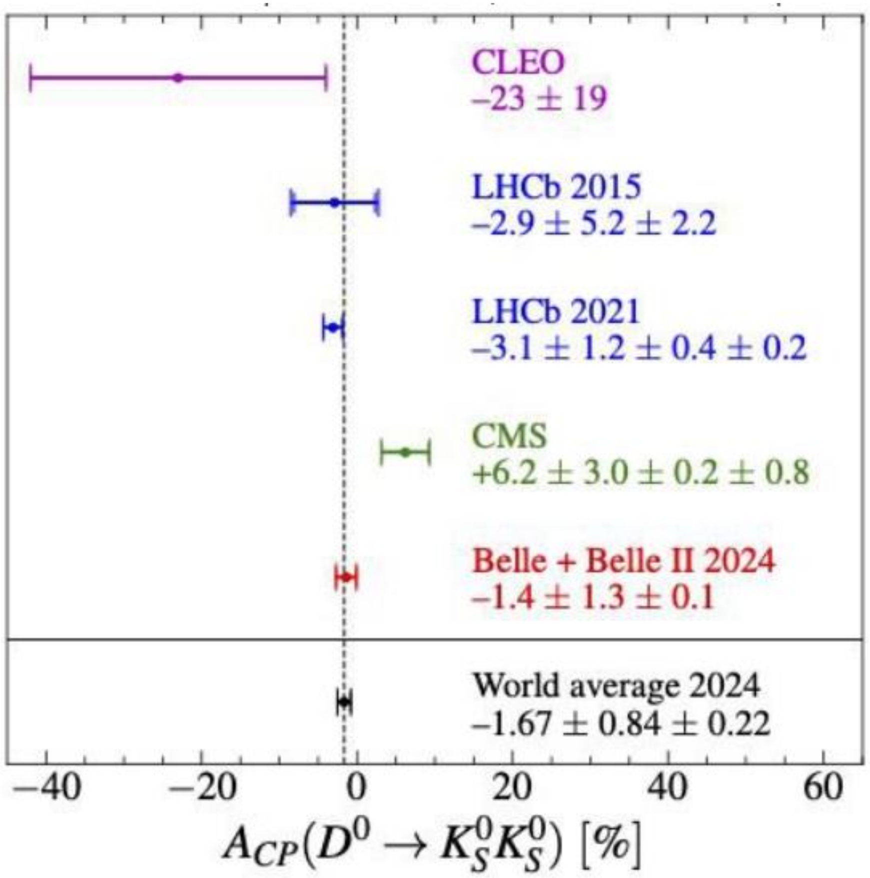
$$A_{CP}(f) \equiv \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\bar{D}^0 \to f\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\bar{D}^0 \to f\right)}$$

$$\boxed{A_{CP}(D^0 \to K^0_S K^0_S) = (6.2 \pm 3.1)\%}$$

- 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 ± 3.1)% vs. **(-3.1 ± 1.3)%** or **(-1.4 ± 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 $\mathbf{B \to \mu^{\mp} D^0(\bar{D}^0)\, \overline{\nu_\mu}\, (\nu_\mu)\, X}$

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** $\rightarrow \mu^{\mp}\, D^0(\overline{D}^0)\ \overline{\upsilon_\mu}\ (\upsilon_\mu)$ **X** decays)
  - ❑ New decays for the search

Thank you!

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