CP violation studies at CMS

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On behalf of the CMS Collaboration

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Outline

Introduction

CPV in $D^0 \to K_S^0 K_S^0$

$B_s^0 \to J/\psi K_S^0$ effective lifetime

Conclusion

Introduction

CPV – one of the Sakharov's necessary conditions for a Baryon asymmetry of the Universe generating

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

1. Direct CPV in decays $\Gamma(P \to f) \neq \Gamma(\bar{P} \to \bar{f})$
2. Indirect CPV in oscillations
3. Interference: CPV in decays + oscillations

We present the results of recent CMS measurements of

1. Direct CPV in charm
2. Lifetime measurement of the B_s^0 decay to CP-odd state (useful for better understanding of CPV in mixing)

CPV in $D^0 \to K_S^0 K_S^0$

arXiv:2405.11606

Introduction

In contrast to strangeness and beauty, CPV is suppressed in charm

Theoretical SM calculations[1] predict CPV in $D^0 \to K_S^0 K_S^0$ to be as large as O(1%) ← more significant then in many other D0 decay channels

Latest experimental calculation by LHCb[2]

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

This work is the first CPV in charm sector at CMS

Measurement strategy

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

$$A_{CP} \simeq A_{CP}^{raw} - A_{CP}^{production} - A_{CP}^{detector}$$

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

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

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

Flavor tagging: $D^{*\pm} \to D^0\left(\overline{D^0}\right)\pi^\pm$

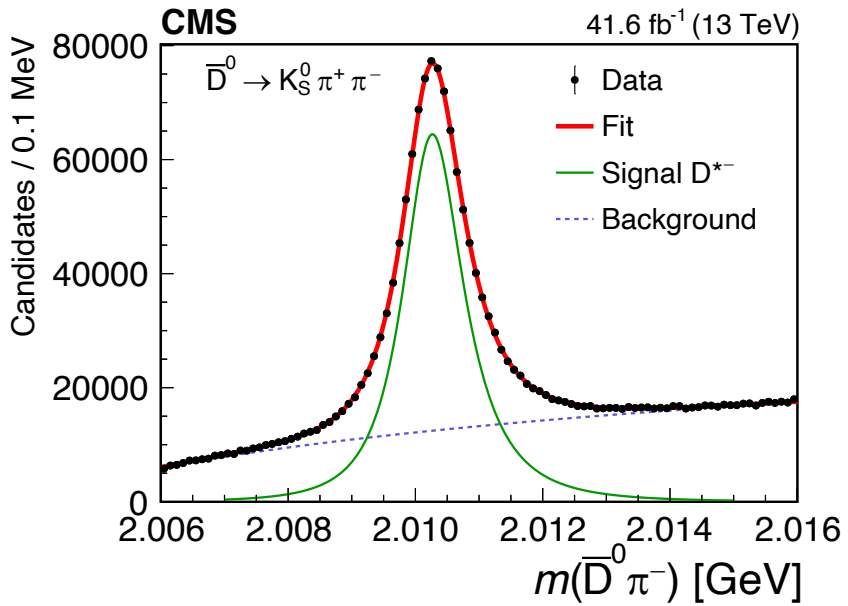
Signal events extraction

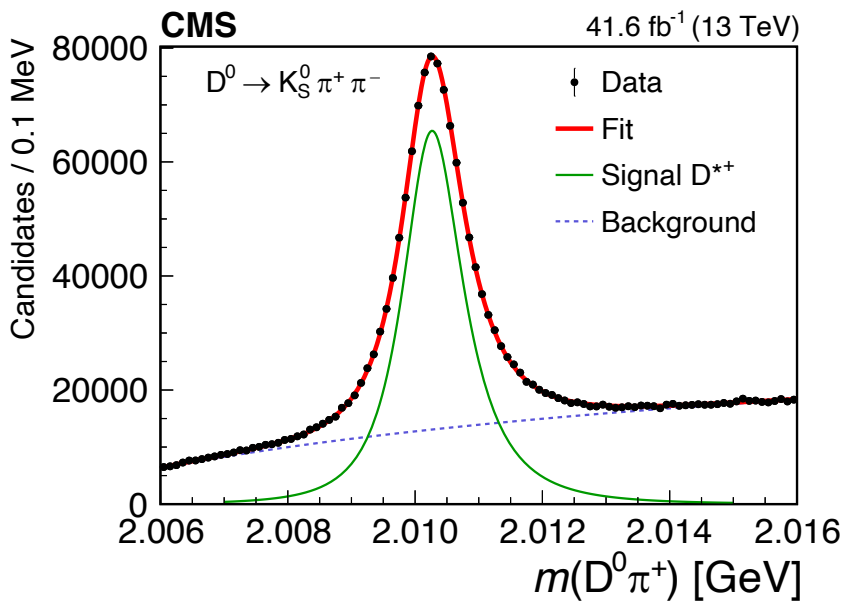
Signal events were selected using cut-based method

Fits of “+” and “–” are simultaneous: all parameters are shared, yields are floating

1D UML fit of $\left(M(D\pi^{\pm}) - M(D) + M_D^{PDG}\right)$ is performed

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



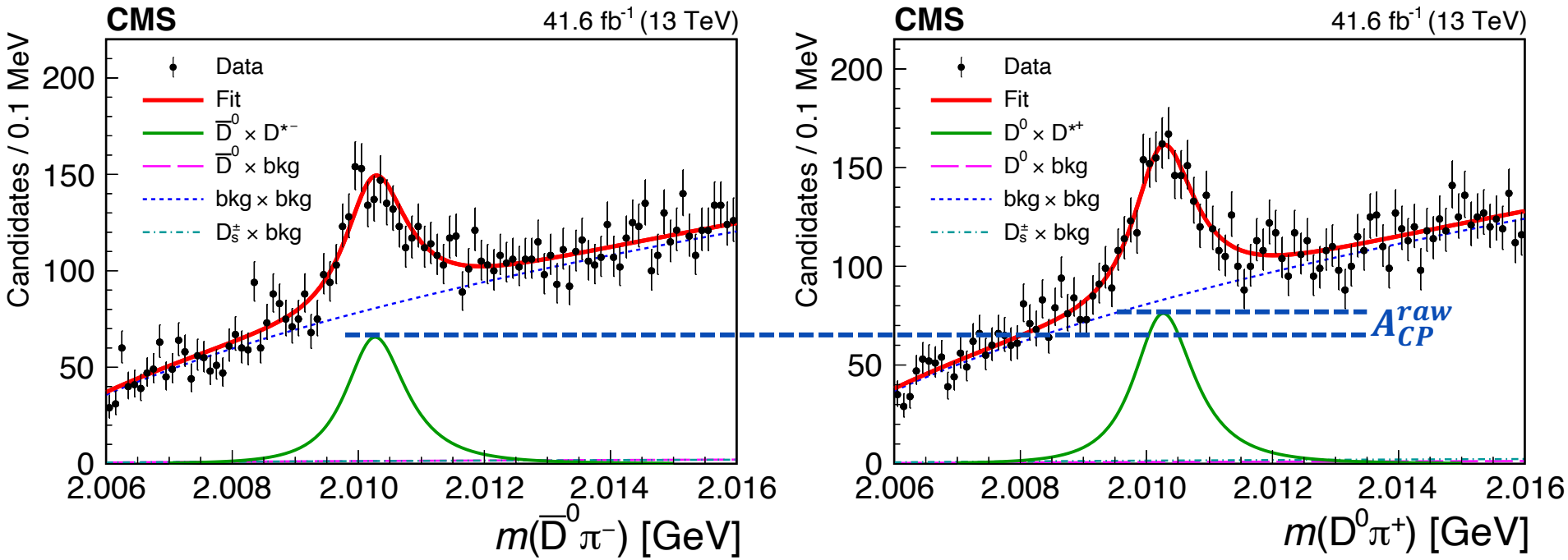


Signal events extraction

Fits of “+” and “–” are simultaneous: all parameters are shared, yields are floating

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

Resulting $A_{CP}^{raw}\left(K_S^0 K_S^0\right) = (7.1 \pm 3.0)\%$



Measurement

$A_{CP}^{raw}\left(K_S^0 K_S^0\right)$ *is measured*

$$A_{CP}^{raw}\left(K_S^0 K_S^0\right) = (7.1 \pm 3.0)\%$$

ΔA_{CP}^{raw} is calculated using following expression

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

After all ΔA_{CP}^{raw} *is measured*

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

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

$$A_{CP}\left(\mathrm{D}^0 \to K_S^0 K_S^0\right) = \left(6.2 \pm 3.0(stat) \pm 0.2(syst) \pm 0.8\left(A_{CP}^{PDG}\right)\right)\%$$

Results

The first measurement of CP-violation in charm in CMS

$$A_{CP}\left(\mathrm{D}^0 \to K_S^0 K_S^0\right) = \left(6.2 \pm 3.0(stat) \pm 0.2(syst) \pm 0.8\left(A_{CP}^{PDG}\right)\right)\%$$

The result is consistent with no CPV in $D^0 \to K_S^0 K_S^0$ at 2.0σ

The value is consistent with LHCb[2] results at the level of 2.7σ

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

and with Belle[3] measurement at the level of 1.8σ

$$(6.2 \pm 3.1)\% \; vs. \; (0.0 \pm 1.5)\%$$

$B_s^0 \to J/\psi K_S^0$ effective lifetime

arXiv:2407.13441

Introduction and motivation

This analysis presents a measurement of the B_s^0 effective lifetime τ in the CP-odd final state $J/\psi K_S^0$ with the CMS Run 2 dataset.

As soon as $J/\psi K_S^0$ is CP-odd state, neglecting CPV in B_s mixing $\tau\left(B_s^0 \to J/\psi K_S^0\right)$ is $\tau\left(B_{s,H}\right)$

This allows us to accurately measure the B_s^0 heavy-state lifetime, which is useful for understanding the mixing in B_s^0 mesons

Measurement strategy

The proper decay time t of the B meson candidate is determined using

$$\tau = m \frac{\vec{L}_{xy} \cdot \vec{p}_T^B}{(\vec{p}_T^B)^2}$$

$\vec{L}_{xy}$ is the vector in the transverse plane from the beamline to the B meson candidate fitted decay vertex

$\vec{p}_T^B$ - transverse momentum of the B candidate

m - invariant mass of the B candidate

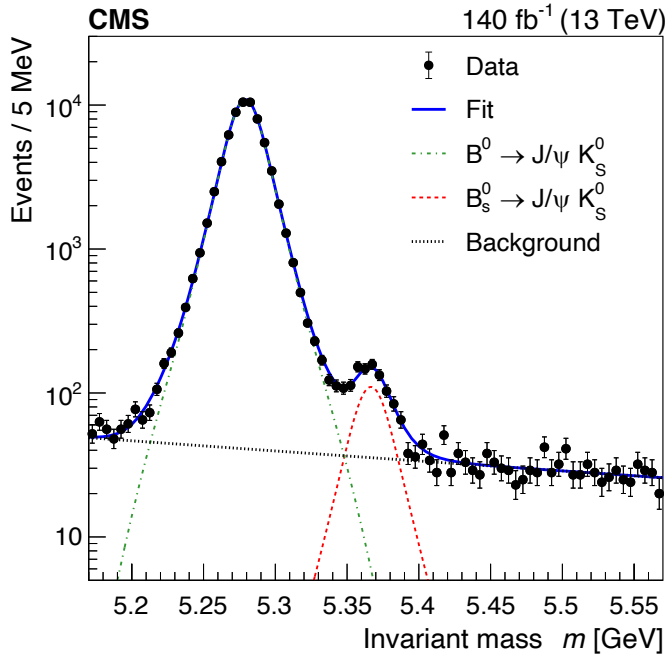
$B^0 \to J/\psi K_S^0$ - control channel for various bias tests and validations

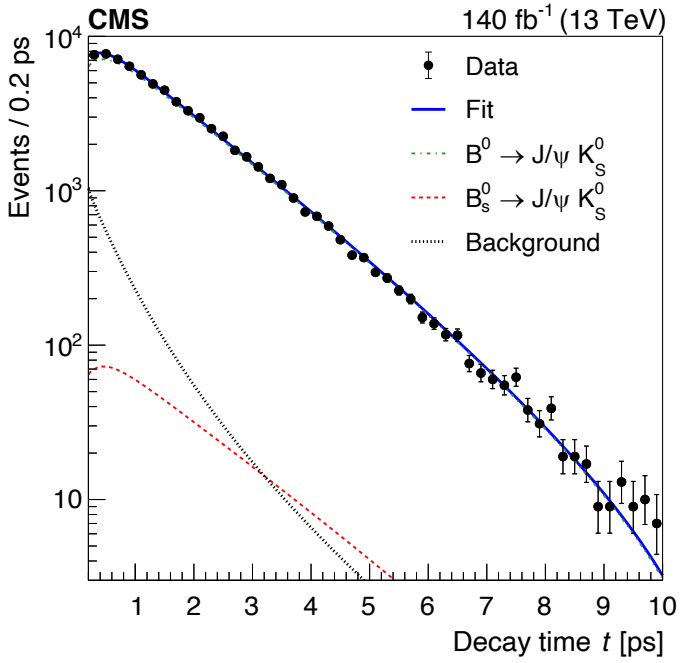
Signal events extraction

Preprocessing: cut-based + BDT trained with 8 discriminating variables

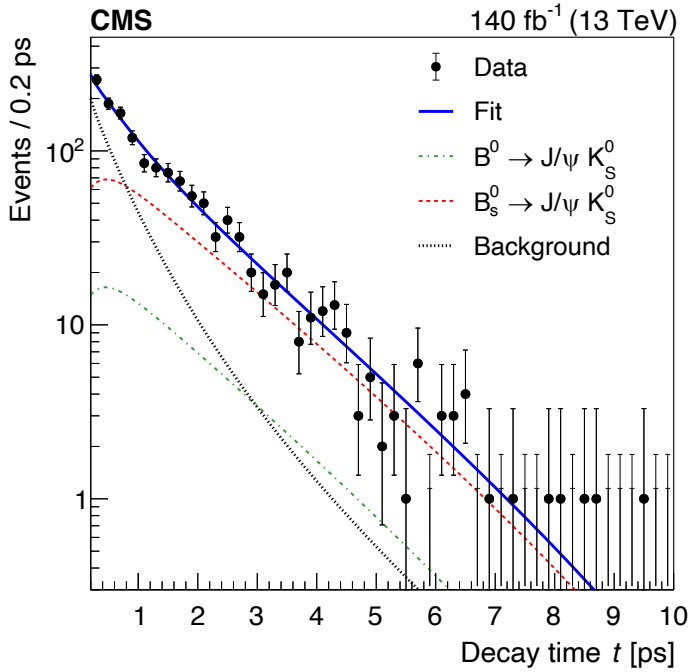
2D UML fit to the $\mathrm{m}(J/\psi K_S^0)$ and proper decay time

Both B_s^0 and B^0 are fitted





B_s^0 signal region



Results

Using the latest measurements and assuming the SM:

$$\tau^{SM}\left(B_s^0 \to J/\psi\, K_S^0\right) = 1.62 \pm 0.02\, ps$$

Available measurement from LHCb[4]:

$$\tau^{LHCb}\left(B_s^0 \to J/\psi K_S^0\right) = 1.75 \pm 0.14\, ps$$

The control channel 's effective lifetime is found to be in good agreement with the world-average value.

The measurement of B_s effective lifetime:

$$\tau(B_s^0 \to J/\psi K_S^0) = 1.59 \pm 0.07\,(stat) \pm 0.03\,(syst)\, ps$$

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**

Conclusion

We present two recent CMS results on the CP violation and lifetime measurements:

- First CMS measurement of CP violation in charm
- The most precise measurement of effective lifetime of the $B_s^0 \to J\psi K_S^0$

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

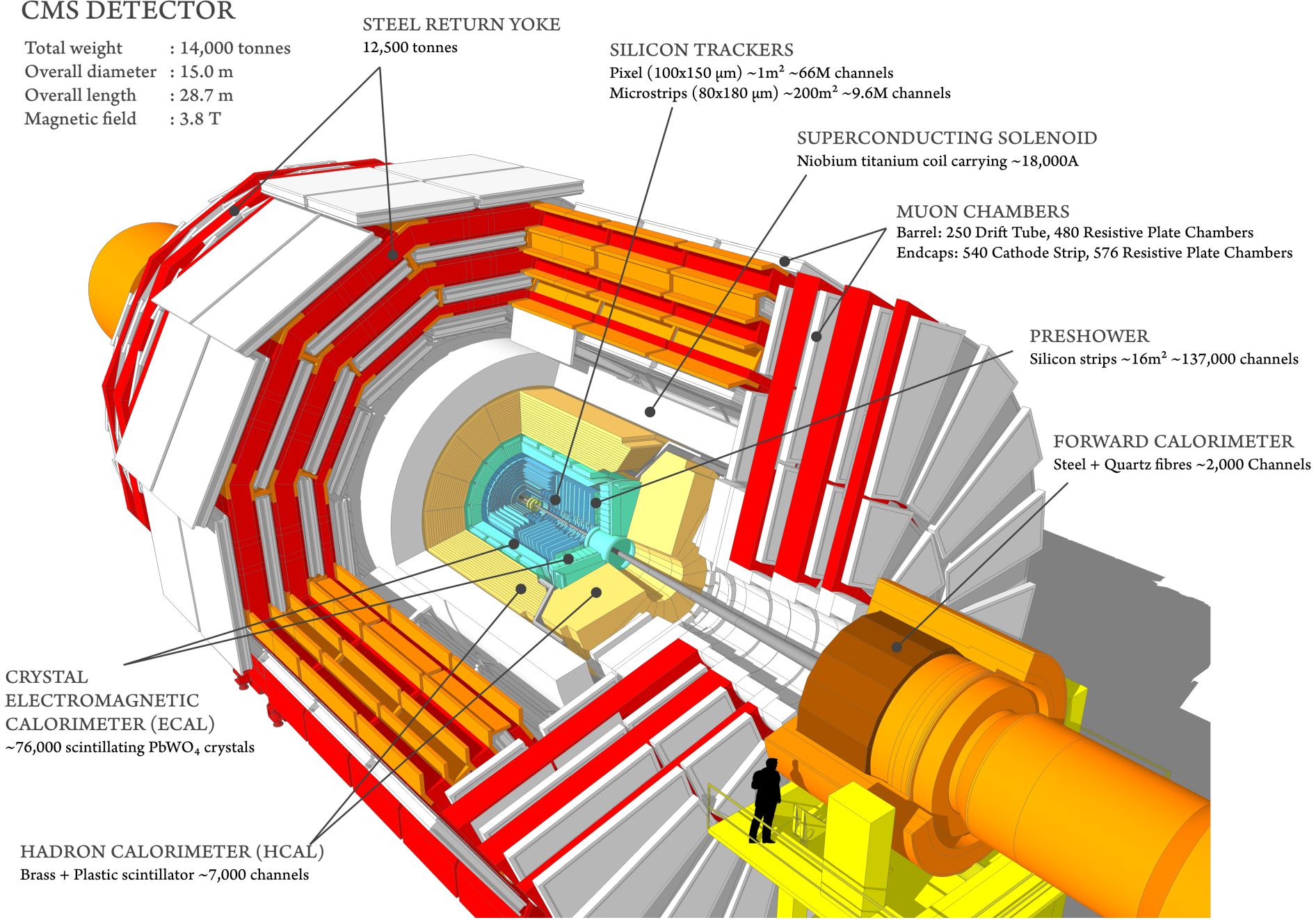
Run 3 will provide unique opportunities thanks of a revamped trigger strategy, which will lead to the collection of an unprecedented amount of data suitable for flavor physics studies

Thank you!

References

1. PRD92(2015)054036
2. PRL122(2019)211803
3. PRL119(2017)171801
4. Nucl.Phys.B(2013)873

Backup


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~1m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

B-parking dataset

A dedicated data set corresponding to the integral $L = 41\ fb^{-1}$ is used

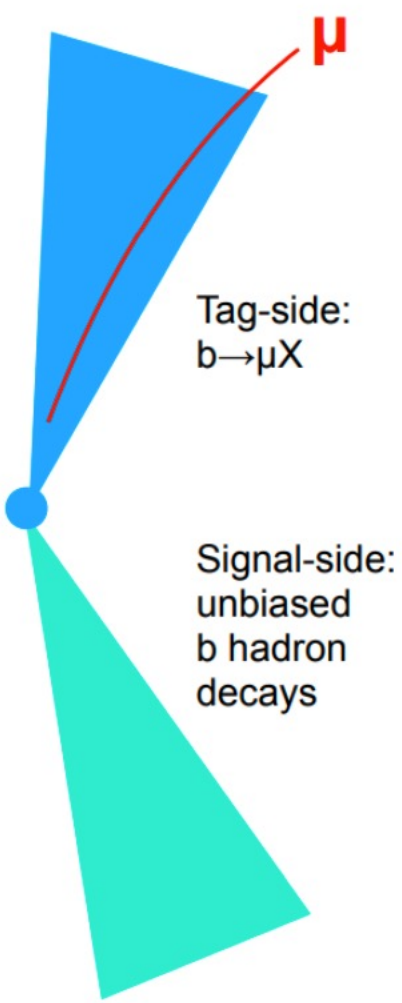
A set of single muon triggers with different thresholds on p_T^{μ} and impact parameter are used

Due to these thresholds, most (~75-80%) 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 p_T^{μ} 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



Selection in $D^0 \to K_S^0 K_S^0$

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

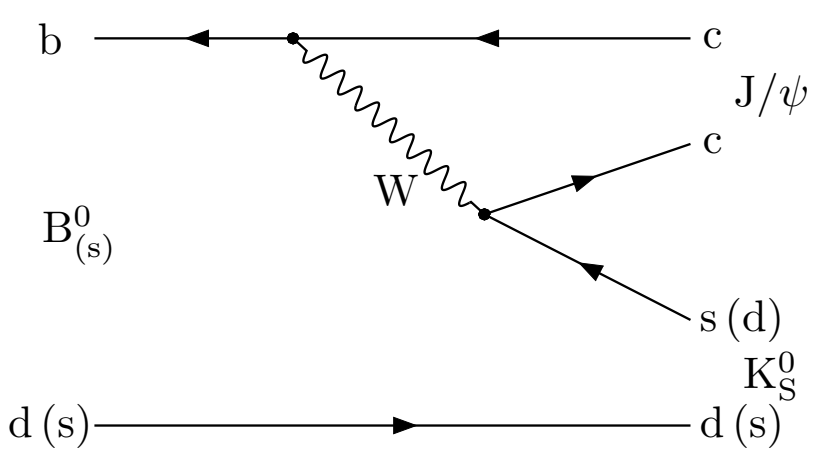
Proper decay time

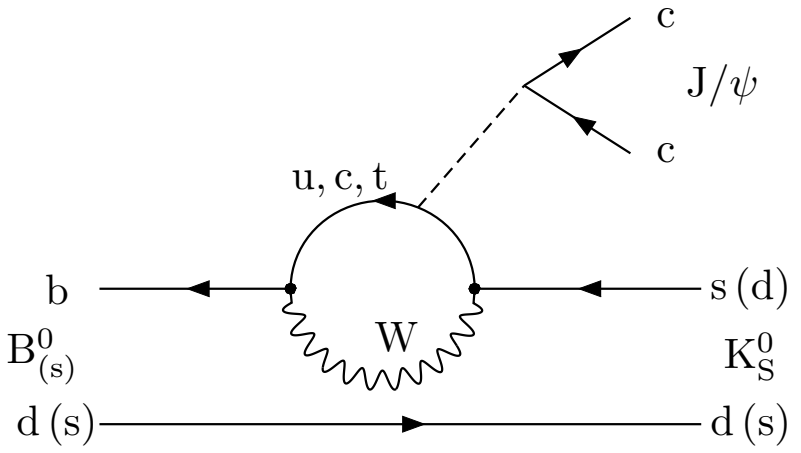
$$\tau(J\psi K_S^0) \equiv \frac{\int_0^\infty t \cdot \left(\Gamma_{B_s^0 \to J\psi K_S^0} + \Gamma_{\overline{B_s^0} \to J\psi K_S^0}\right) dt}{\int_0^\infty \left(\Gamma_{B_s^0 \to J\psi K_S^0} + \Gamma_{\overline{B_s^0} \to J\psi K_S^0}\right) dt}$$

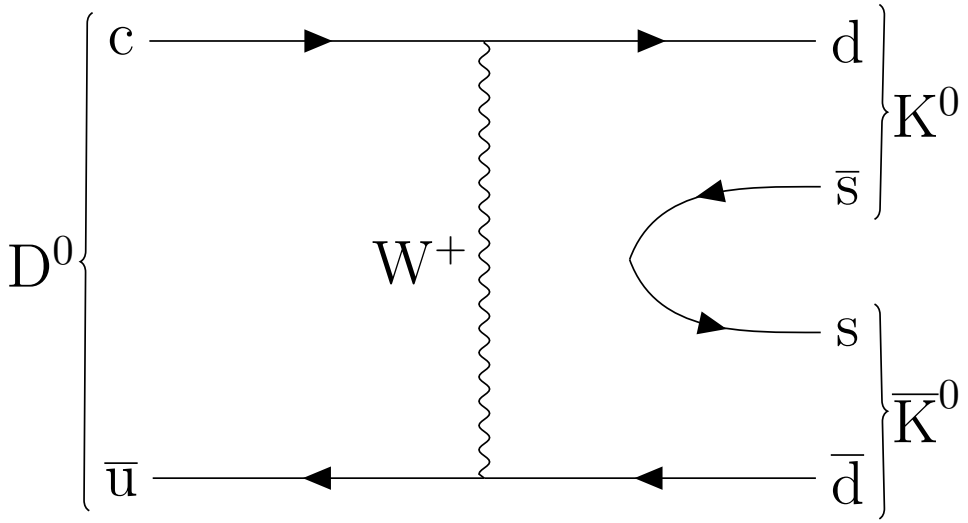
$$= \frac{\tau_{B_s^0}}{1 - y_s^2}\left(\frac{1 + 2A_{\Delta\Gamma} y_s + y_s^2}{1 + A_{\Delta\Gamma} y_s}\right),$$

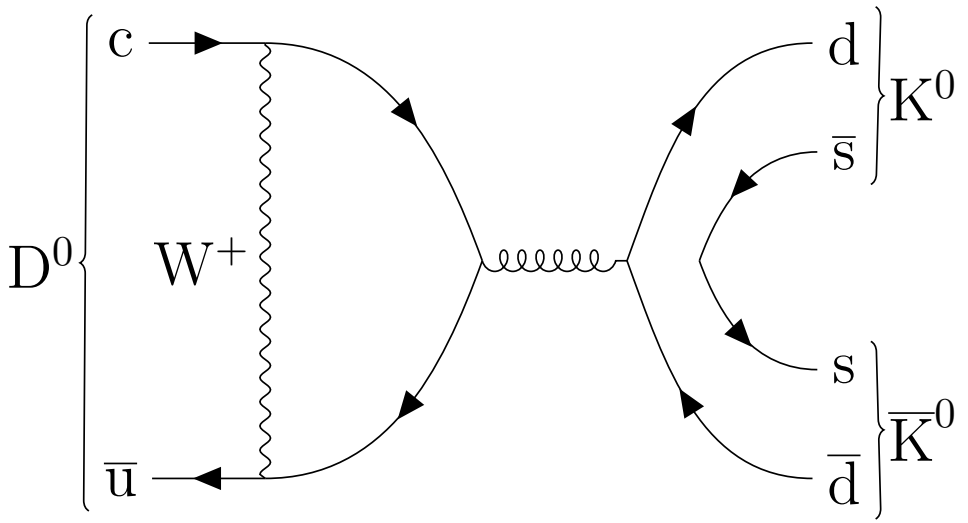
Where $y_s = \tau_{B_s^0}\Delta\Gamma/2$ – normalized decay width difference

Feynman diagrams



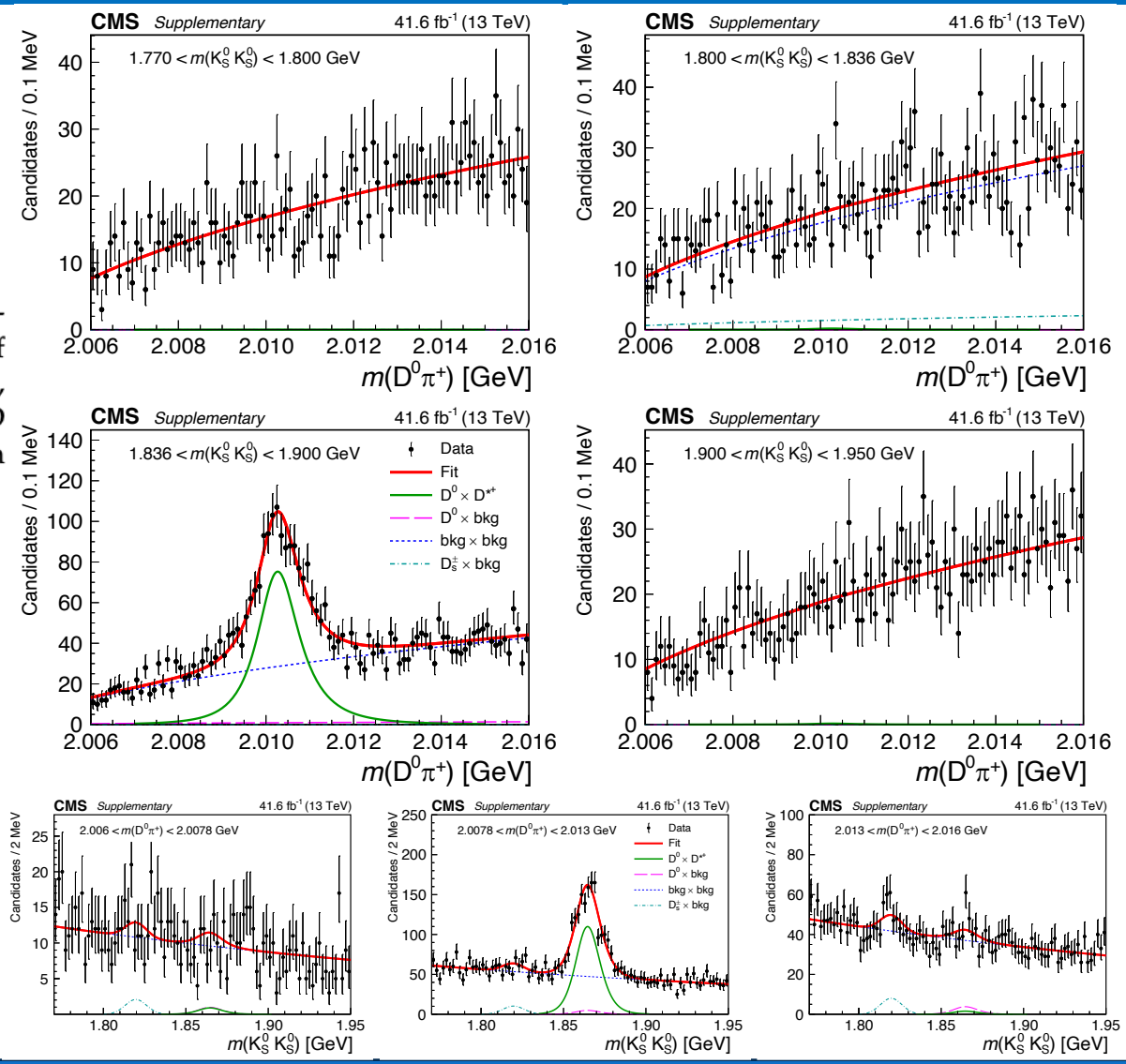






Fit

Figure A.1: Results of the 2D fit to the $m(D\pi^{\pm}) \times m(K^0_S K^0_S)$ for the signal channel, D^{*+} candidates. Upper and middle rows show 1D projections of the 2D fit on $m(D^0\pi^+)$ in ranges of $m(K^0_S K^0_S)$: left sideband (upper left), region of $D_s^{\pm} \to K^0_S K^0_S \pi^{\pm}$ contamination (upper right), signal region of $K^0_S K^0_S$ (middle left), and right sideband (middle right). Lower row shows 1D projections of the 2D fit on $m(K^0_S K^0_S)$ in ranges of $m(D^0\pi^+)$: left sideband (left), signal region of $D^0\pi^+$ (center), and right sideband (right).



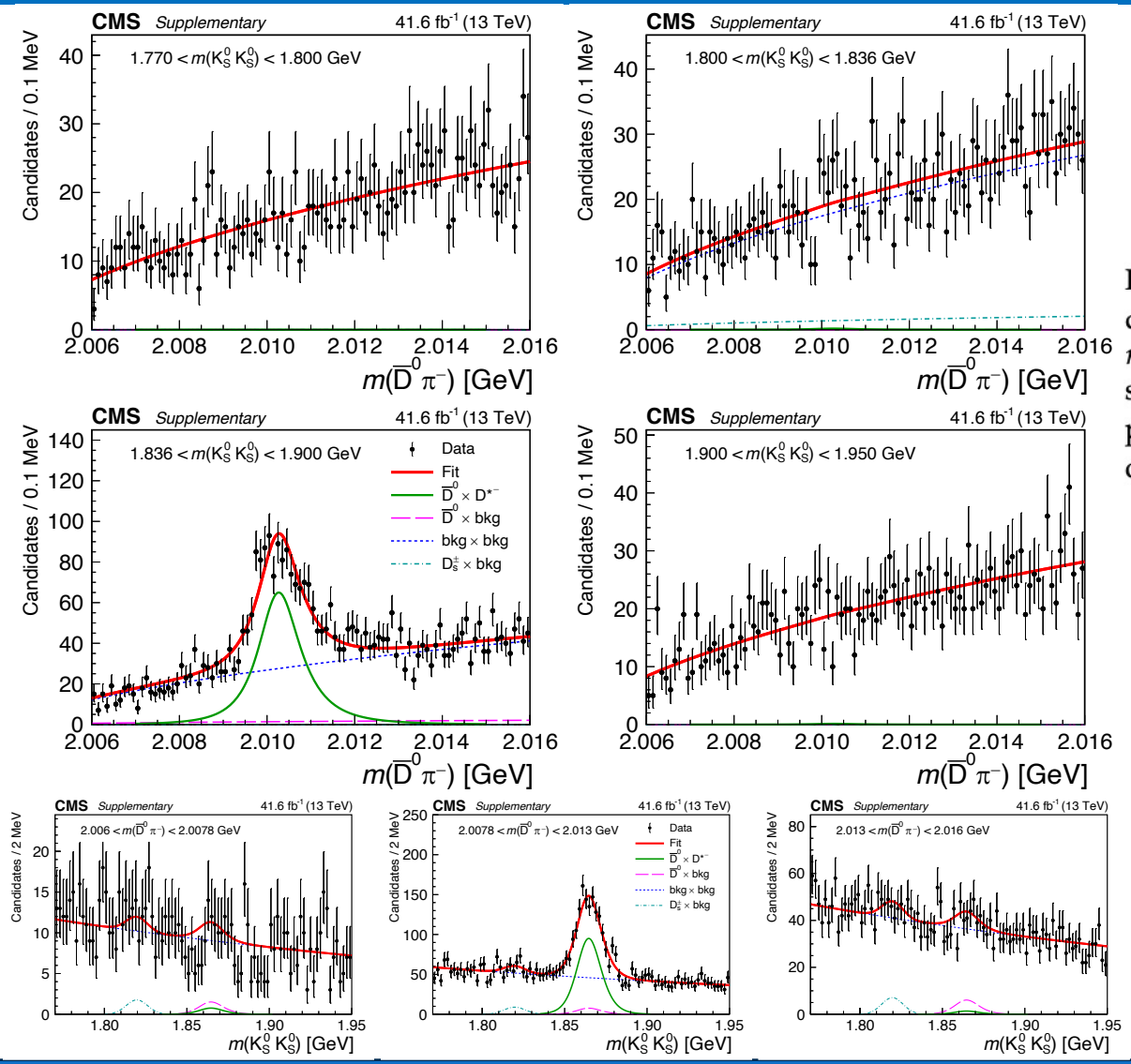
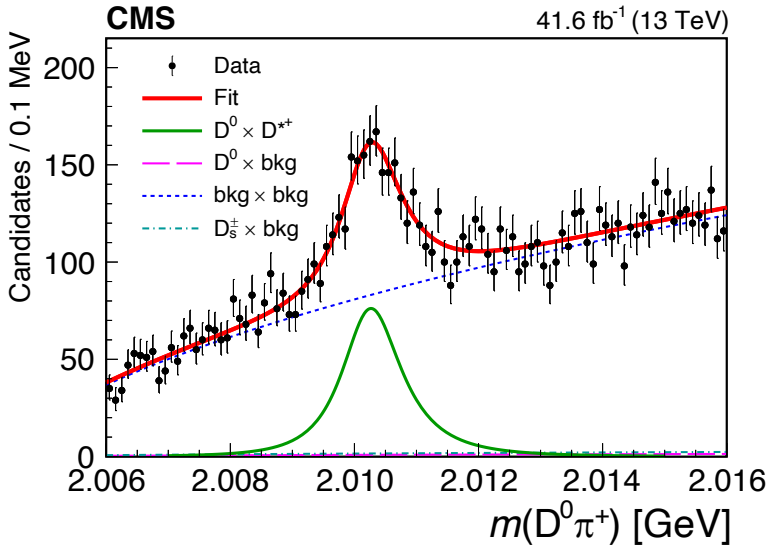


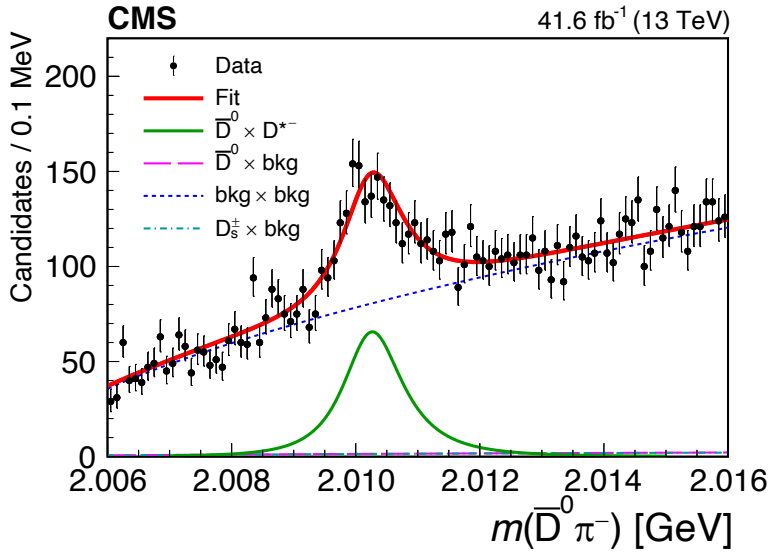
Figure A.2: Results of the 2D fit to the $m(\mathrm{D}\pi^{\pm}) \times m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ for the signal channel, D^{*-} candidates. Upper and middle rows show 1D projections of the 2D fit on $m(\overline{\mathrm{D}}^0\pi^-)$ in ranges of $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$: left sideband (upper left), region of $\mathrm{D}^{\pm}_\mathrm{s} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}\pi^{\pm}$ contamination (upper right), signal region of $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ (middle left), and right sideband (middle right). Lower row shows 1D projections of the 2D fit on $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ in ranges of $m(\overline{\mathrm{D}}^0\pi^-)$: left sideband (left), signal region of $\overline{\mathrm{D}}^0\pi^-$ (center), and right sideband (right).

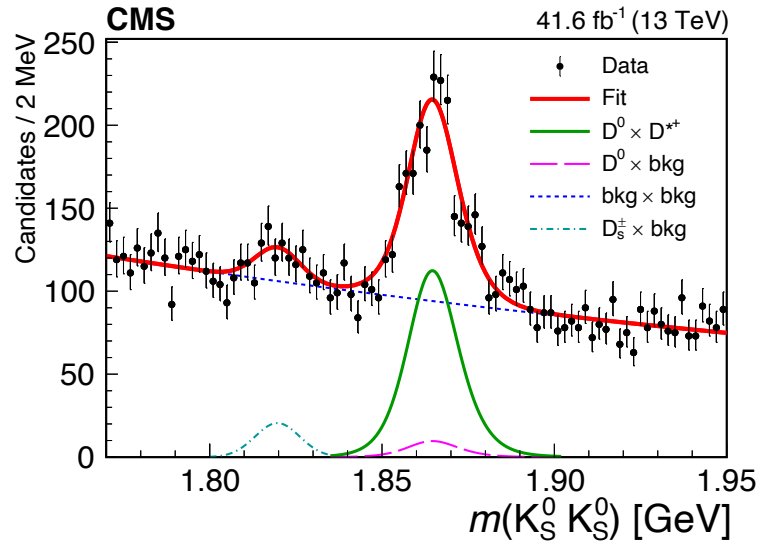
Fit projections

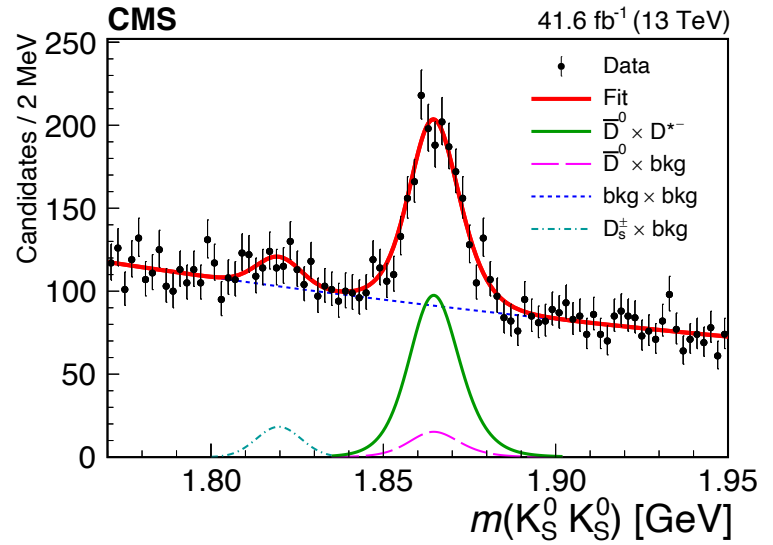
The invariant mass distributions for D^{*+} candidates (left) and D^{*-} candidates (right), with the $m(D\pi^+)$ distributions in the upper row and the $m\left(K_S^0 K_S^0\right)$ distributions in the lower row.

Projections of the simultaneous 2D fit are also shown









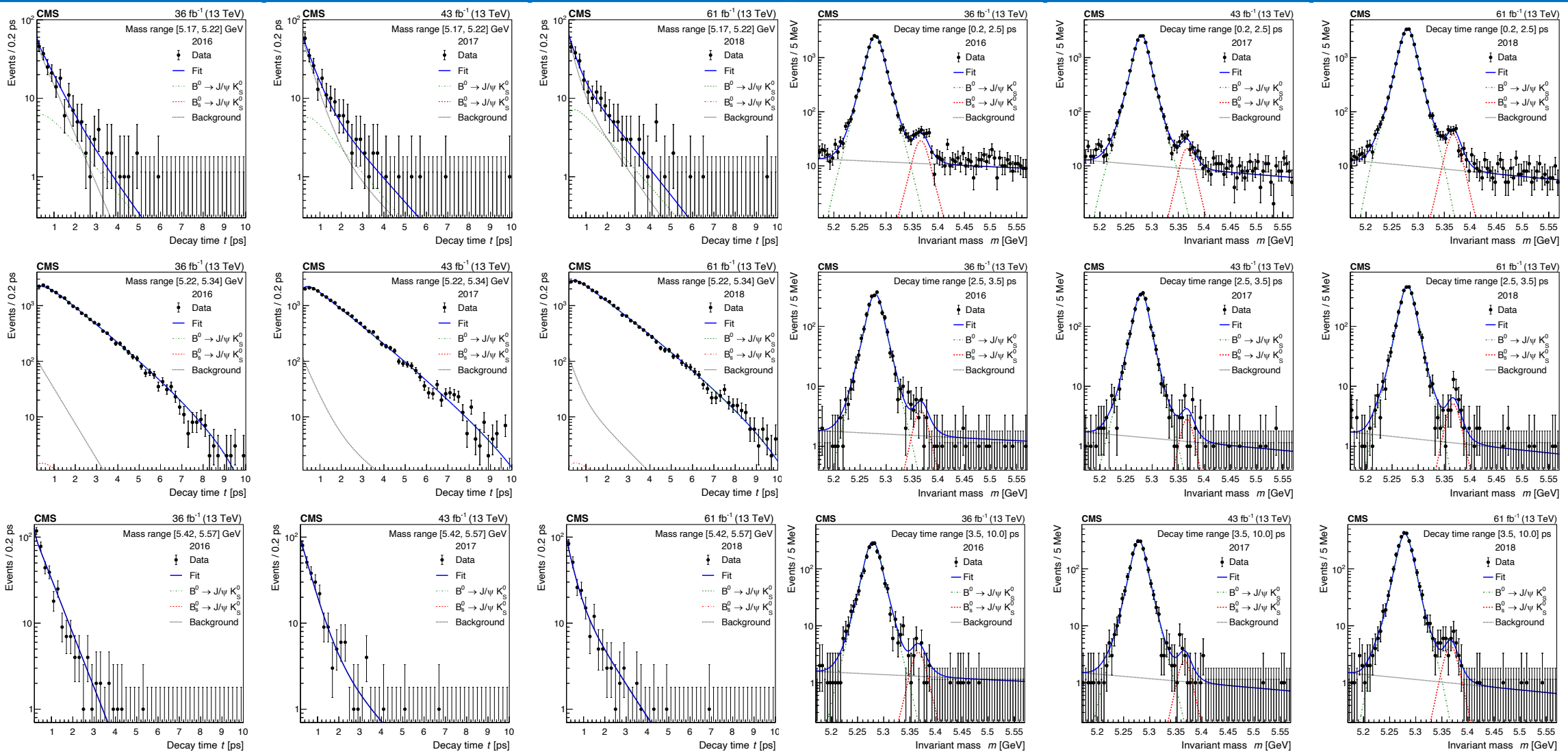
Source	Uncertainty (%)
$m(\mathrm{D}\pi^{\pm})$ signal model	0.10
$m(\mathrm{D}\pi^{\pm})$ background model	0.02
$m(\mathrm{K^0_S K^0_S})$ signal model	0.04
$m(\mathrm{K^0_S K^0_S})$ background model	0.02
$m(\mathrm{K^0_S K^0_S})$ fit range	0.06
Reweighting	0.09
Total	0.16

Variable	Requirement
$\lvert\eta\rvert$ of the tagging pion from $\mathrm{D}^{*\pm} \to \mathrm{D}\pi^{\pm}$	<1.2
p_{T} of the tagging pion from $\mathrm{D}^{*\pm} \to \mathrm{D}\pi^{\pm}$	>0.35 GeV
$p_{\mathrm{T}}(\mathrm{K^0_S})$	>2.2 and >1.0 GeV
$\mathrm{K^0_S}$ vertex displacement significance from the D^0 vertex in xyz	>7 and >9
D^0 vertex displacement significance from the PV in xy	>2
D^0 vertex displacement significance from the PV in xyz	>9
$P_{\mathrm{vtx}}(\mathrm{D}\pi^{\pm})$	>5%
$P_{\mathrm{vtx}}(\mathrm{K^0_S K^0_S})$	>1%
$P_{\mathrm{vtx}}(\pi^+\pi^-)$ for $\mathrm{K^0_S} \to \pi^+\pi^-$	>1%
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 beamline in xy	<0.237 rad

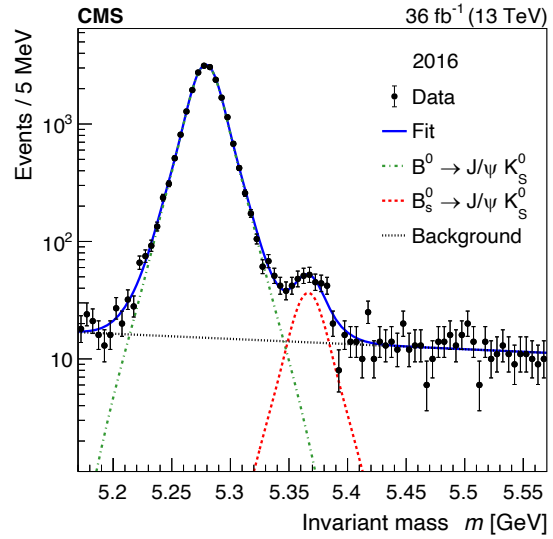
Decay	N	χ^2 (x axis)	χ^2 (y axis)
$\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$	1095 ± 46	77	90
$\mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-$	951 ± 44	93	62

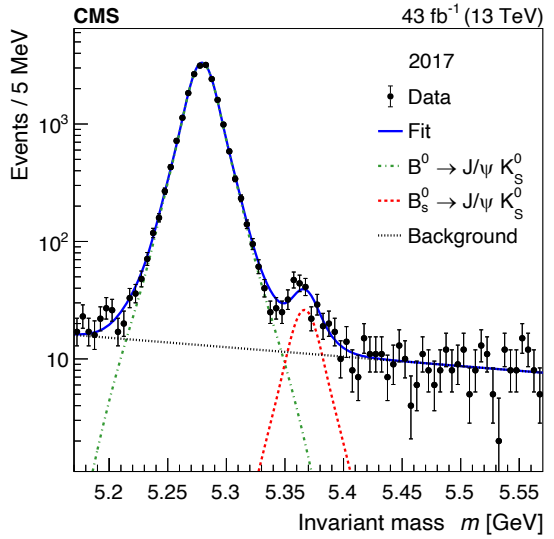
Decay	N	χ^2 with 100 bins
$\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$	$944\,800 \pm 3\,500$	78
$\mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-$	$930\,150 \pm 3\,400$	93

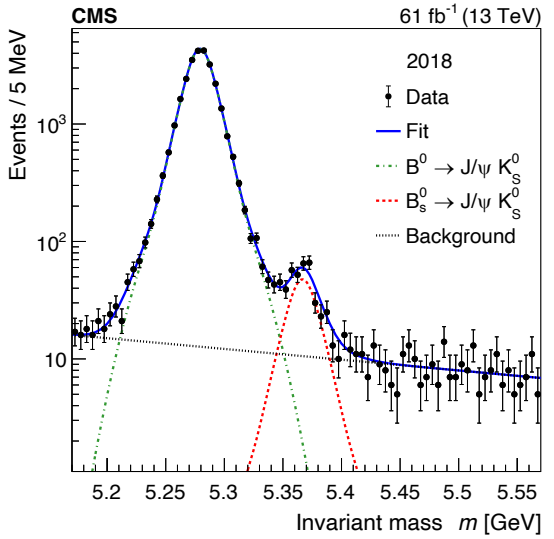
Subrange projection plots

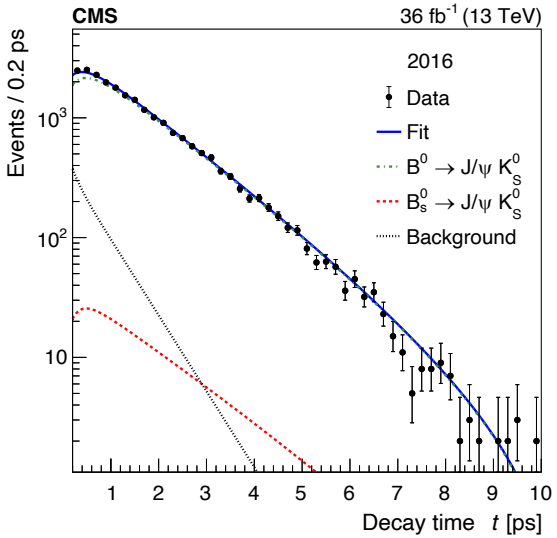


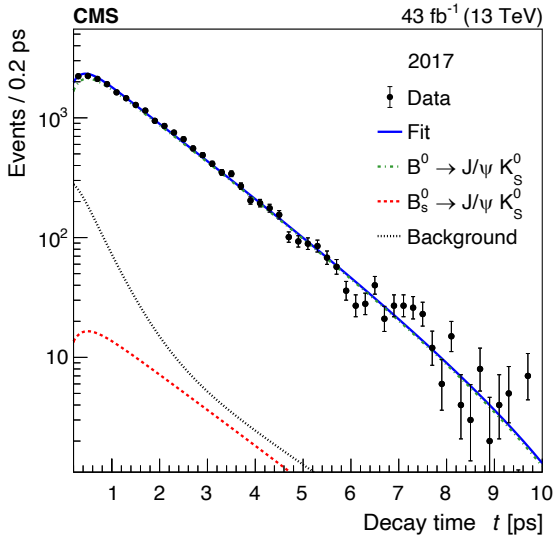
Projection plots from the 2D UML fits

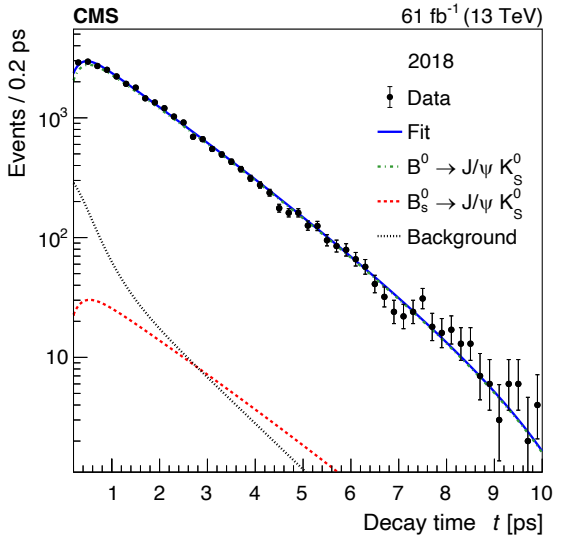












Systematics

Source	Value (ps)
Limited MC event count	0.006
Efficiency modeling	0.002
Signal and background invariant mass model	0.022
Background decay time model	0.014
Invariant mass shape variation	0.004
Different fit strategy	0.006
Deviation in control channel lifetime	0.004
Total	0.028