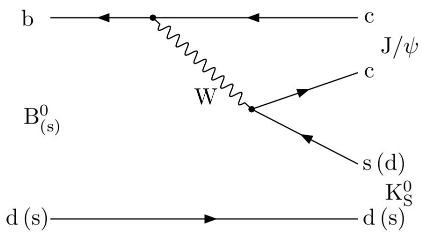
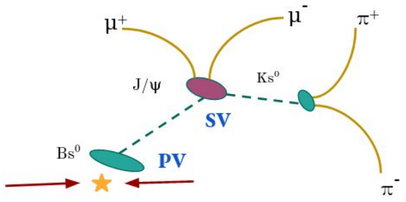
Highlights in heavy-flavour physics from the CMS experiment

Priyanka Sadangi, Kai Yi
On behalf of CMS Collaboration

Measurement of $B_s^0 \rightarrow J/\Psi K_S^0$ effective lifetime

- ★ Decay probability of any particle defined as, $P \propto e^{-t/\tau}$
  τ = lifetime of the particle, t = decay time of the particle.
- ★ An effective lifetime for a B_s^0 decay channel is obtained by fitting a single exponential function to decay time.
- ★ LHCb lifetime results : 1.75 ± 0.12 (stat) ± 0.07 (syst) ps
  Journal : Nuclear Physics, Section B 873 (2013)
- ★ SM expected results : 1.619 ± 0.019 ps





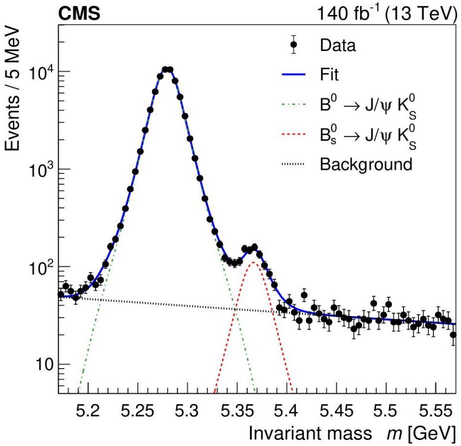
- ★ Signal decay - $B_s^0 \rightarrow J/\Psi K_s^0$ $(1.92 \pm 0.14 \times 10^{-5})$
- ★ Control channel - $B^0 \rightarrow J/\Psi K_s^0$
- ★ Related through interchanging all d quarks with s quarks.

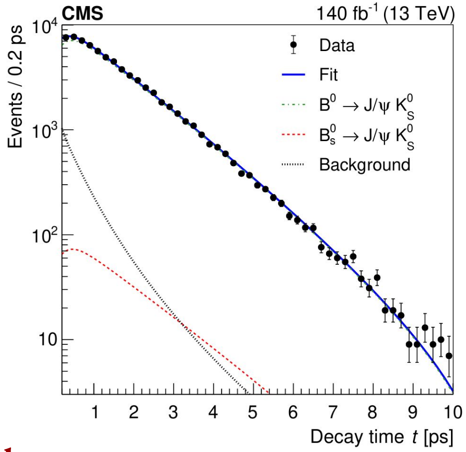
Decay time is defined as, $$t = \frac{L_{xy} M_{B_s^0}}{p_T}$$

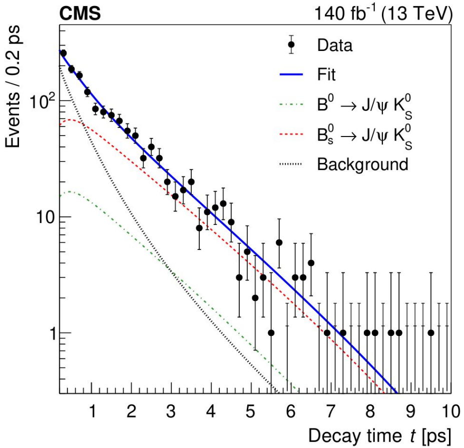
M_B is the mass of the B candidate. (Reconstructed mass), Lxy is the length difference between the PV and SV in transverse plane.

The effective lifetime is obtained by performing 2D UML fit to the $J/\psi K_s^0$ invariant mass and the decay time.

Measurement of $B_s^0 \rightarrow J/\Psi K_S^0$ effective lifetime







Results

Parameters	Values (ps)
B^0 lifetime	1.521 ± 0.007
B_s^0 lifetime	1.59 ± 0.07

Consistent with PDG (1.519 ± 0.004 ps)

- ★ SM expected results : 1.619 ± 0.019 ps
- ★ The measured effective lifetime from the simultaneous fit,
  $\tau B_s^0 \rightarrow J/\Psi K_s^0 = 1.59 \pm 0.07\ (\text{stat}) \pm 0.03\ (\text{syst})$ ps.
- ★ The result is in agreement with the standard model prediction and ~50% smaller uncertainty compared to previous result.

Published - JHEP10(2024)247

CP violation measurement in $D^0 \rightarrow K_S^0 K_S^0$ decays

★ Up-quark CPV: largely unexplored, SM highly suppressed (GIM) [PRL 122 (2019) 211803]

★ $D^0 \rightarrow K_S^0 K_S^0$: CPV up to O(1%) possible → sensitive to BSM [PRD 92 (2015) 054036]

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

$$A_{CP}(K_S^0 K_S^0) = (6.2 \pm 3.0 \pm 0.2 \pm 0.8)\%,$$

★ Uncertainties: statistical, systematic, and from $A_{CP}(K_S^0\pi^+\pi^-)$ measurement.

★ Consistent with no CPV within 2.0σ; agrees with LHCb (−3.1±1.3)% (2.7σ) and Belle (0.0±1.5)% (1.8σ).

★ First CMS search for CP violation in the charm sector.

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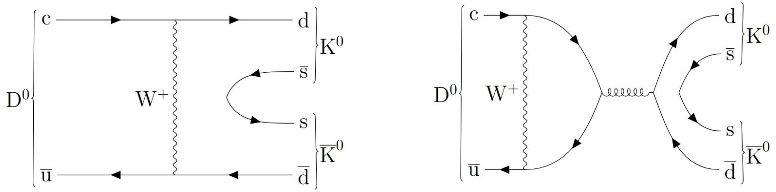
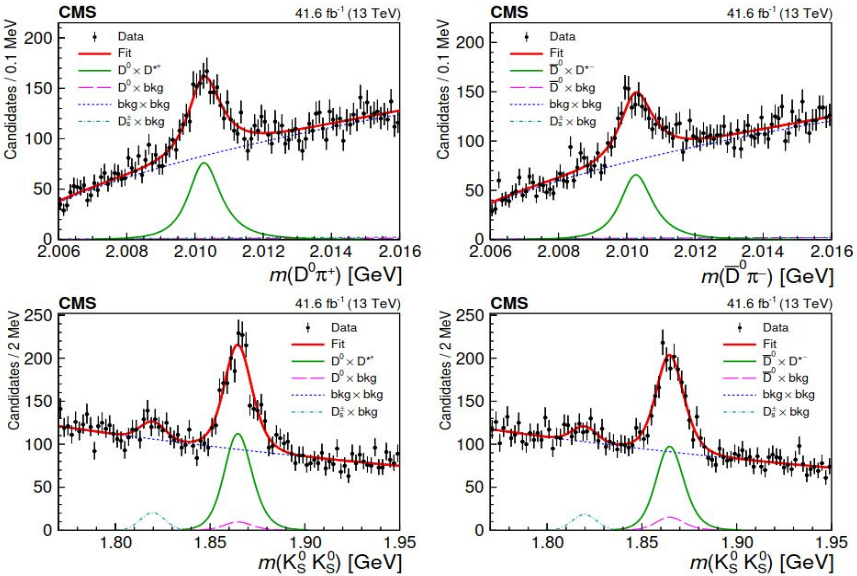
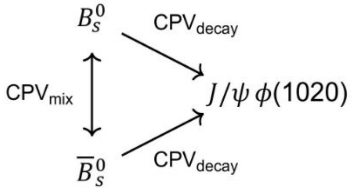




Measurement of CP-violating parameters in $B_s^0 \to J/\psi\phi$

- ★ B_s^0 meson decays probe time-dependent CP violation from the interference between direct decay and flavor mixing.
- ★ Precise Standard Model (SM) prediction:
  $\phi_s \approx -2\beta_s \approx -37 \pm 1$ mrad, derived from CKM matrix fits ([CKMfitter, UTfit])
- ★ Sensitive probe for New Physics (NP): Any deviation may indicate contributions from beyond-SM particles in B_s^0 mixing loops.



$$\Gamma\left(B^0_{S\,(\rightsquigarrow \bar{B}^0_S)} \to f\right)(t) \overset{?}{\neq} \Gamma\left(\bar{B}^0_{S\,(\rightsquigarrow B^0_S)} \to f\right)(t)$$

Previous ϕ_s Measurements

- ★ CMS 8 TeV data: $\phi_s = -75 \pm 97$ mrad — consistent with SM expectation ([PLB 757 (2016) 97]).
- ★ Global fits: SM expectations have ~20x smaller uncertainties than current experimental measurements, highlighting the need for more precision.

Motivation for This Analysis

- ★ Largest tagged signal sample to date: Equivalent to ~27,500 $B_s^0 \to J/\psi\phi$ events from 13 TeV data (96.5 fb^{-1}).
- ★ Novel ML-based tagging: Uses both same- and opposite-side tagging (OS and SS) for significantly improved tagging power.

Objective: Achieve improved precision on ϕ_s and search for NP-induced CP violation

Measurement of CP-violating parameters in $B_s^0 \to J/\psi\phi$

The physics parameters are extracted with **unbinned multidimensional extended maximum-likelihood (UML) fit**

- *Physics parameters*: ϕ_s, $|\lambda|$, $\Delta\Gamma_s$, Γ_s, Δm_s, $|A_0|^2$, $|A_\perp|^2$, $|A_S|^2$, $\delta_{//}$, $\delta_\perp$, $\delta_{S\perp}$
- *Observables*: m_{Bs}, t, σ_t, $\cos\theta_T$, $\cos\psi_T$, ϕ_T, ω_{tag}

Fit model

Analytical decay rate
Time resolution (extracted from prompt background)
Angular efficiency (extracted from MC)
Time efficiency (from $B^0 \to J/\psi\ K^*$ events in data)

$$\frac{P(t,\sigma_t,\Theta,\xi_{tag},\omega_{tag},m\,|\,\alpha)}{\epsilon(t)} = \left[\Gamma(t,\Theta,\xi_{tag},\omega_{tag}\,|\,\alpha)\otimes G(t\,|\,\sigma_t)\right]\cdot\epsilon(\Theta)\cdot P(\sigma_t)P(m)P(\omega_{tag})+P_{bkg}(\ldots)$$

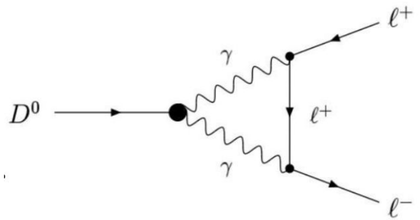
Fit results

Parameter	Fit value	Stat. unc.	Syst. unc.
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
$\lvert\lambda\rvert$	1.011	± 0.014	± 0.012
$\lvert A_0\rvert^2$	0.5300	$^{+0.0016}_{-0.0014}$	± 0.0044
$\lvert A_\perp\rvert^2$	0.2409	± 0.0021	± 0.0030
$\lvert A_S\rvert^2$	0.0067	± 0.0033	± 0.0009
$\delta_\parallel$ [rad]	3.145	± 0.089	± 0.025
$\delta_\perp$ [rad]	2.931	± 0.089	± 0.050
$\delta_{S\perp}$ [rad]	0.48	± 0.15	± 0.05

- ★ Measured CP phase: $\phi_s = -73 \pm 23_{(stat)} \pm 7_{(syst)}$ mrad
- ★ Combined with Run 1: $\phi_s = -74 \pm 23$ mrad
- ★ Evidence of CP violation at 3.2σ.
- ★ Compatibility: Consistent with SM, constraints space for new physics models.
- ★ First CMS measurement at 13 TeV using combined flavor tagging.
  - Strengthens world average precision on ϕ_s.
  - Paves way for Run 3 and HL-LHC improvements.

Submitted to - PRL

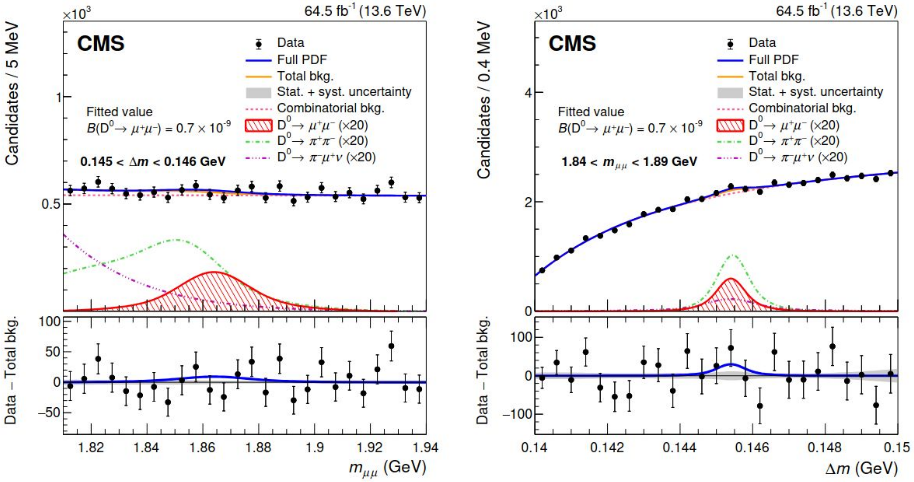
Search for the rare decay $D^0 \to \mu^+\mu^-$



- ★ Rare decays of hadrons is one of the most promising place to look for new physics beyond SM.
- ★ FCNC processes, forbidden at tree level, as they are highly sensitive to new physics effects.
- ★ $D^0 \to \mu^+\mu^-$ is one such process (very clean) and the goal is to measure its branching fraction.
- ★ SM Prediction: $BF(D^0 \to \mu^+\mu^-) \sim 3 \times 10^{-13}$ [PRD.66.014009]
- ★ Most stringent experimental search $BF < 3.5 \times 10^{-9}$ at 95% CL from LHCb, [PRL.131.041804]
- ★ CMS searches for this using 64.5 fb^{-1} data during 2022-2023.
- ★ search for $D^0 \to \mu^+\mu^-$ in cascade $D^{*+} \to D^0\pi^+$
  - ○ Background control: extra soft pion suppresses background by orders of magnitude.
- ★ Signal extraction: 2D unbinned fit to $m(D^0 \to \mu^+\mu^-)$ and $\Delta m \equiv m(D^{*+}) - m(D^0)$.
- ★ Normalization: use $D^0 \to \pi^+\pi^-$ (kinematically similar) to cancel efficiencies and reduce systematics.
- ★ No significant excess over background expectation is found

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

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

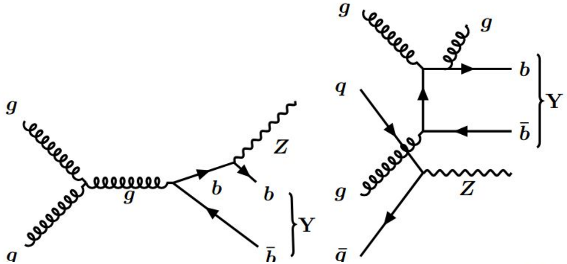


Significant improvement compared to previous result.

Submitted to - PRL

Search for the production of an upsilon (nS) meson in association with a Z boson

- ★ Associated production of a heavy quarkonium (ϒ) and an electroweak boson (Z) provides a unique test of perturbative QCD and quarkonium production models.
- ★ Sensitive to both Single Parton Scattering (SPS) and Double Parton Scattering (DPS) contributions.
- ★ Dataset: pp collisions at $\sqrt{s}$ = 13 TeV, integrated luminosity 138 fb^{-1} (2016–2018 CMS data).



- ★ Fit strategy: 2D UML fit to $m_{\mu\mu}$(ϒ) and $m_{\mu\mu}$(Z) to extract yields.
  - ○ 34.6 ± 9.0 (Z + ϒ(1S))
- ★ First observation (5.3 σ) of Z+ϒ production
- ★ Fiducial cross section ratio:

$$R_{(Z+\Upsilon(1S))} = (21.1 \pm 5.5_{stat} \pm 0.6_{syst}) \times 10^{-3}$$

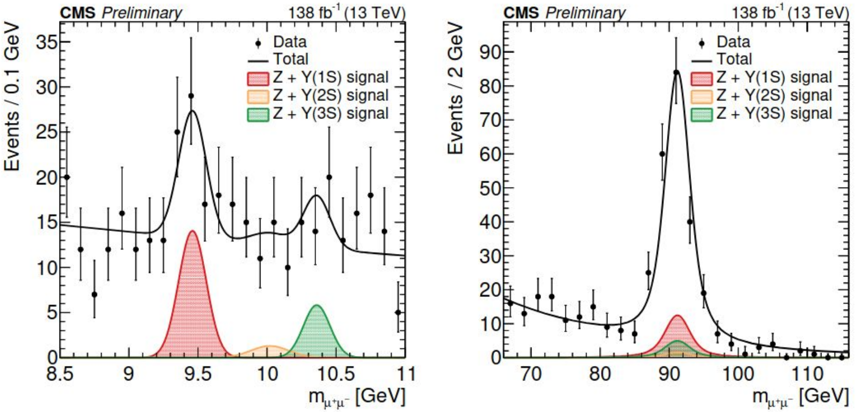
- ★ DPS cross section ratio:

$$R_{(Z+\Upsilon(1S))}(DPS) = (20.2 \pm 7.5_{stat} \pm 0.6_{syst}) \times 10^{-3}$$

- ★ Effective DPS cross section:

$$\sigma_{\text{eff}} = 13.0^{+7.8}_{-3.5}\ \text{mb}$$

consistent with double-quarkonium results in pp and p$\bar{p}$ collisions.



- ★ First differential σ_{eff} measurement in bins of ϒ(1S) p_T and Z boson p_T, probing parton spatial distributions in the proton. [Plots in backup]

Will be Submitted to - PRL

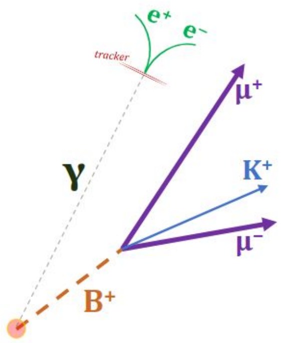
First exclusive reconstruction of the B^{*+}, B^{*0}, and Bs^{*0} mesons and precise measurement of their masses

- Hyperfine splittings (mass differences between excited and ground-state B mesons) are key benchmarks for testing heavy-quark dynamics and QCD models.
- Previous approaches: (a) LEP: Averaged flavor-blind transitions. (b) LHCb, CLEO, Belle: Indirect inference of mass differences with limited precision.
- $m(B^{*+})-m(B^{+})$: LHCb measured from difference between $B_{s2}{}^{*}(5840)^0 \to B^{*+}K^-$ and $(5840)^0 \to B^+K^-$ peak positions.
- $m(B^{*+})-m(B^{*0})$: CMS measured from difference between $B_{s1}(5830)^0 \to B^{*0}K_S{}^0$ and peak positions CMS.
- At B-factories previous measurements via $\Upsilon(5S)$ decays:
  - $\Upsilon(5S)\to B_s{}^0\overline{B}_s{}^0$, $\Upsilon(5S)\to B_s{}^{*0}\overline{B}_s{}^0$, $\Upsilon(5S)\to B_s{}^0\overline{B}_s{}^{*0}$, $\Upsilon(5S)\to B_s{}^{*0}\overline{B}_s{}^{*0}$
- Results were not in good agreement (PDG scale factor: 2.9).
- Central value larger than for B^+ and B^0 mesons.
- CMS Analysis Strategy: Trigger: Use all available triggers — no trigger requirement.
- Reconstruction: $B^+\to\psi K^+$, $B^0\to\psi K^*(892)^0[K^+\pi^-]$, $B_s{}^0\to\psi\phi[K^+K^-]$, J/ψ or $\psi(2S)\to\mu^+\mu^-$
- Photon conversion:
  - Detect $\gamma\to e^+e^-$, Refit e^+e^- tracks with m=0 constraint, Fit $B\gamma$ vertex, then refit to PV for improved mass resolution.

B_s^* MASS

From mass difference below and the B_s^0 mass.

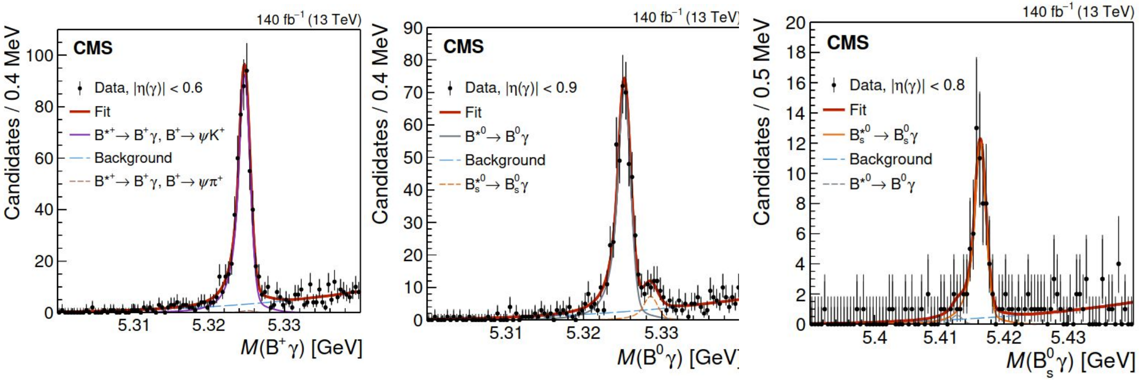
VALUE (MeV)		DOCUMENT ID		TECN
$5415.4^{+1.8}_{-1.5}$	OUR FIT Error includes scale factor of 2.9.			
5415.8 ± 1.5	OUR AVERAGE Error includes scale factor of 2.6.			
$5416.4 \pm 0.4 \pm 0.5$		LOUVOT	2009	BELL
$5411.7 \pm 1.6 \pm 0.6$		[1] AQUINES	2006	CLEO



First exclusive reconstruction of the B^{*+}, B^{*0}, and Bs^{*0} mesons and precise measurement of their masses

	Parameter	Value	PDG 2024 [MeV]
1	$\Delta m(B^{*+}) \equiv m(B^{*+}) - m(B^{+})$	$45.277 \pm 0.039 \pm 0.027$ MeV	45.34 ± 0.20
2	$\Delta m(B^{*0}) \equiv m(B^{*0}) - m(B^{0})$	$45.471 \pm 0.056 \pm 0.028$ MeV	45.34 ± 0.20
3	$\Delta m(B_s^{*0}) \equiv m(B_s^{*0}) - m(B_s^{0})$	$49.407 \pm 0.132 \pm 0.041$ MeV	48.5 ± 1.4
4	$m(B^{*+})$	$5324.69 \pm 0.04 \pm 0.03 \pm 0.07$ MeV	
5	$m(B^{*0})$	$5325.19 \pm 0.06 \pm 0.03 \pm 0.08$ MeV	
6	$m(B_s^{*0})$	$5416.34 \pm 0.13 \pm 0.04 \pm 0.10$ MeV	
7	$m(B^{*0}) - m(B^{*+})$	$0.50 \pm 0.07 \pm 0.01 \pm 0.05$ MeV	
8	$m(B_s^{*0}) - m(B^{*+})$	$91.66 \pm 0.14 \pm 0.03 \pm 0.12$ MeV	
9	$m(B_s^{*0}) - m(B^{*0})$	$91.15 \pm 0.14 \pm 0.03 \pm 0.12$ MeV	
10	$m(B_s^{*0}) - \frac{1}{2}\left[m(B^{*0}) + m(B^{*+})\right]$	$91.40 \pm 0.13 \pm 0.03 \pm 0.12$ MeV	
11	$\Delta m(B^{*0}) - \Delta m(B^{*+})$	$0.19 \pm 0.07 \pm 0.01$ MeV	
12	$\Delta m(B_s^{*0}) - \Delta m(B^{*+})$	$4.13 \pm 0.14 \pm 0.03$ MeV	
13	$\Delta m(B_s^{*0}) - \Delta m(B^{*0})$	$3.94 \pm 0.14 \pm 0.03$ MeV	
14	$\Delta m(B_s^{*0}) - \frac{1}{2}\left[\Delta m(B^{*0}) + \Delta m(B^{*+})\right]$	$4.03 \pm 0.13 \pm 0.03$ MeV	
15	$\Delta m(B^{*0}) / \Delta m(B^{*+})$	$1.0043 \pm 0.0015 \pm 0.0002$	
16	$\Delta m(B_s^{*0}) / \Delta m(B^{*+})$	$1.0912 \pm 0.0031 \pm 0.0007$	
17	$\Delta m(B_s^{*0}) / \Delta m(B^{*0})$	$1.0866 \pm 0.0031 \pm 0.0007$	
18	$2\,\Delta m(B_s^{*0}) / \left[\Delta m(B^{*+}) + \Delta m(B^{*0})\right]$	$1.0889 \pm 0.0030 \pm 0.0007$	

Simultaneous fit in the 7 categories with different η regions. The mass distributions of the $B^{+}\gamma$, $B^{0}\gamma$, and $B_s^{0}\gamma$ candidates for the 3 categories with the best invariant mass resolution, the rest 4 in backup.



- ★ 3 states reconstructed fully exclusively for the 1st time.
- ★ Precision order of magnitude better than PDG.
- ★ Systematics much smaller than stat. uncertainty.

Submitted to - PRL

Summary

★ The CMS Heavy-Flavor Physics group has delivered several important recent results across CP violation studies, rare decay searches, quarkonium production, and heavy-meson spectroscopy, continually pushing for better precision and broader coverage in the sector.

★ This presentation showcases a selection of recent and impactful results from the CMS Heavy-Flavor Physics program.

★ Overall Impact:
CMS's precision tracking, muon identification, and flexible triggering allow it to deliver flavor physics results competitive with dedicated experiments, making it a central player in the global heavy-flavor program.

Stay tuned with CMS for new results!

Backup

CP violation measurement in $D^0 \to K_S^0 K_S^0$ decays

CP Asymmetry Extraction

- Method: 2D maximum-likelihood fit on $m(D^{*+})$ and $m(D^0)$
- Simultaneous fit to D^{*+} and D^{*-} samples; yields free
- Selections: $m(\pi^+\pi^-)$ within PDG ±20 MeV
    - $m(K_S K_S)$ in [1.7, 2.0] GeV
    - Displacement $>9\sigma$ (xyz), $>2\sigma$ (xy)
- Bkg suppression: fit alternative topologies, vertex prob. cuts

Search for the production of an upsilon (nS) meson in association with a Z boson

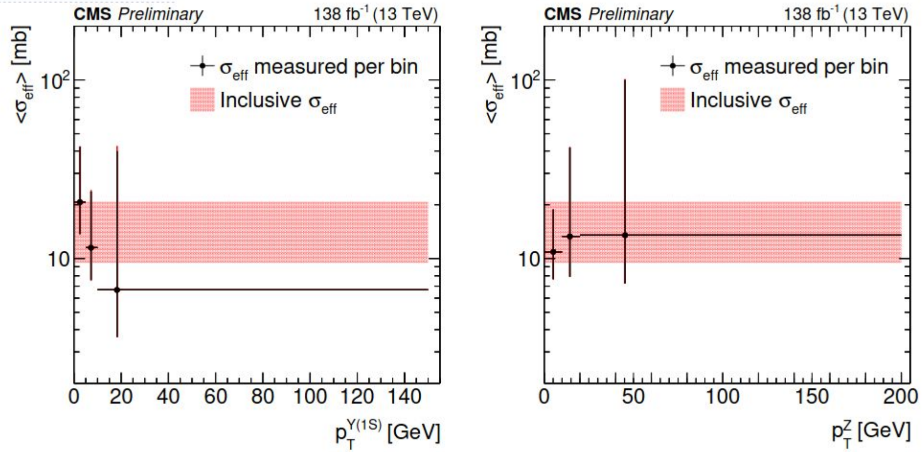
	$Z\to \mu^+\mu^- + \Upsilon(1S) \to \mu^+\mu^-$	$Z \to \mu^+\mu^-\mu^+\mu^-$
All muons	$\lvert\eta\rvert \leq 2.4$	
p_T [GeV]	$30, > 15 \ > 3, 3$	$> 20, > 10, > 5, 5$

$$\frac{\sigma(pp \to Z+\Upsilon(1S)) \times \mathcal{B}(Z\to\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)}{\sigma(pp \to Z) \times \mathcal{B}(Z\to\mu^+\mu^-\mu^+\mu^-)} = \left(\frac{N^{SPS}_{Z+\Upsilon(1S)}}{\epsilon^{SPS}_{Z+\Upsilon(1S)}} + \frac{N^{DPS}_{Z+\Upsilon(1S)}}{\epsilon^{DPS}_{Z+\Upsilon(1S)}}\right) \frac{\epsilon_{Z\to\mu^+\mu^-\mu^+\mu}}{N_{Z\to\mu^+\mu^-\mu^+\mu}} = [21.1 \pm 5.5\,(\text{stat}) \pm 0.6\,(\text{syst})] \times 10^{-3}$$

Cross section ratio for DPS component $[20.2 \pm 7.5\,(\text{stat}) \pm 0.6\,(\text{syst})] \times 10^{-3}$

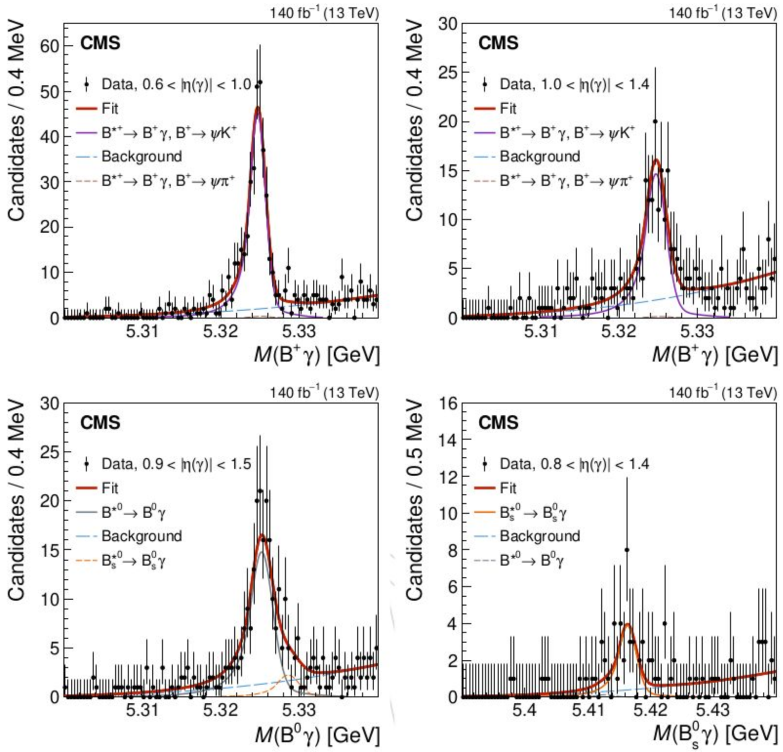
$$\sigma_{\text{eff}} = \frac{\sigma(\Upsilon(1S))}{\mathcal{R}^{DPS}_{Z+\Upsilon(1S)}} \frac{\mathcal{B}(Z\to\mu^+\mu^-)\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)}{\mathcal{B}(Z\to\mu^+\mu^-\mu^+\mu^-)} \frac{A_{Z+\Upsilon(1S)}}{A_Z}$$

$$= 13.0^{+7.8}_{-3.5}\,\text{mb}$$

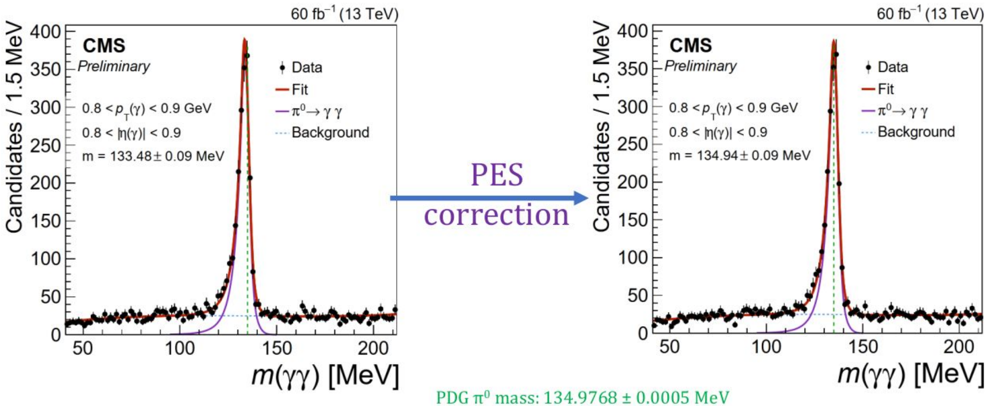


First exclusive reconstruction of the B^{*+}, B^{*0}, and Bs^{*0} mesons and precise measurement of their masses

The rest 4 categories with different η regions



Photon energy scale calibration with π^0



PDG π^0 mass: 134.9768 ± 0.0005 MeV

Photon energy from conversions is underestimated out of the box, developed a dedicated correction