XXXI Cracow EPIPHANY Conference

on the recent LHC results

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Heavy flavour results from CMS

CMS detector and BPH

Essentials of CMS BPH (b and Quarkonia) reco:

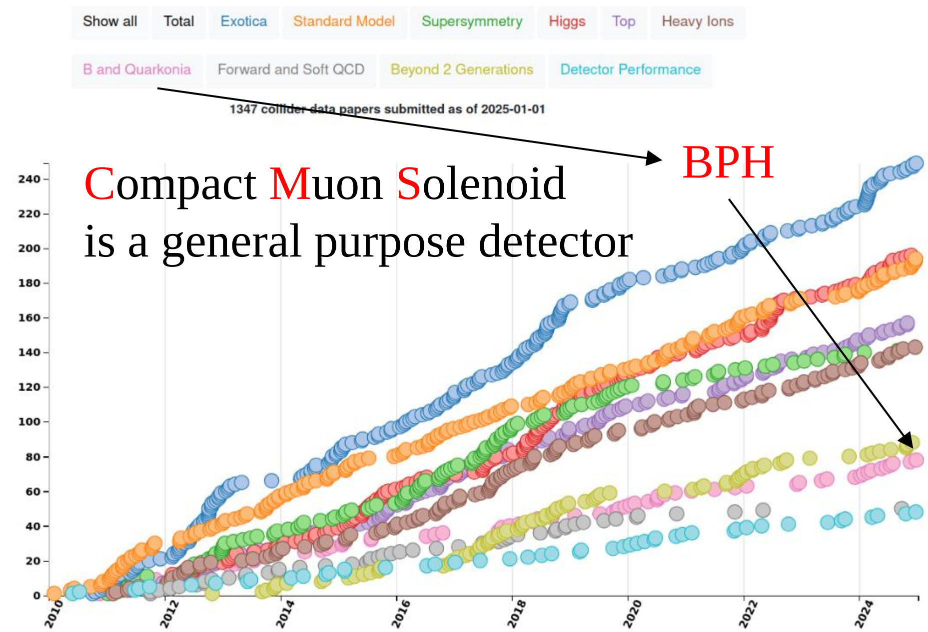
Tracker:
- vertex resolution down to 15μm
  typically tip (2016) 25-90μm, (2017+) 20-75μm
- for central muons above 99% tracking eff.

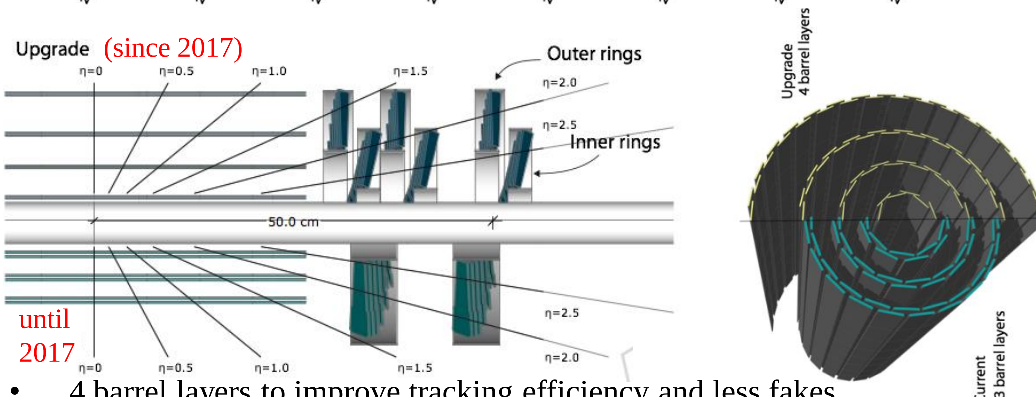
Muon system:
- identification of track, high-purity muon ID
  (fake rate ~10^{-3}).
- provide muon trigger
- initial momentum assignment

Muon reconstruction (Tracker+Muon syst):
- combines "tracker" and "muon system" data
  $\sigma_{p_T}/p_T \sim 1\%$ in barrel (3% in endcaps).
- dimuon mass resolution (η dependent)
  $\sigma_M/M \sim 0.6\text{-}1.5\% \rightarrow \sigma_{J/\psi} \approx 20 - 70$ MeV

Since 2017 new Pixel Detector.
- first layer closer to beam pipe (3.9cm)
- 4 layers to improve:
  purity, low p_T reach, precision

Compact Muon Solenoid
is a general purpose detector



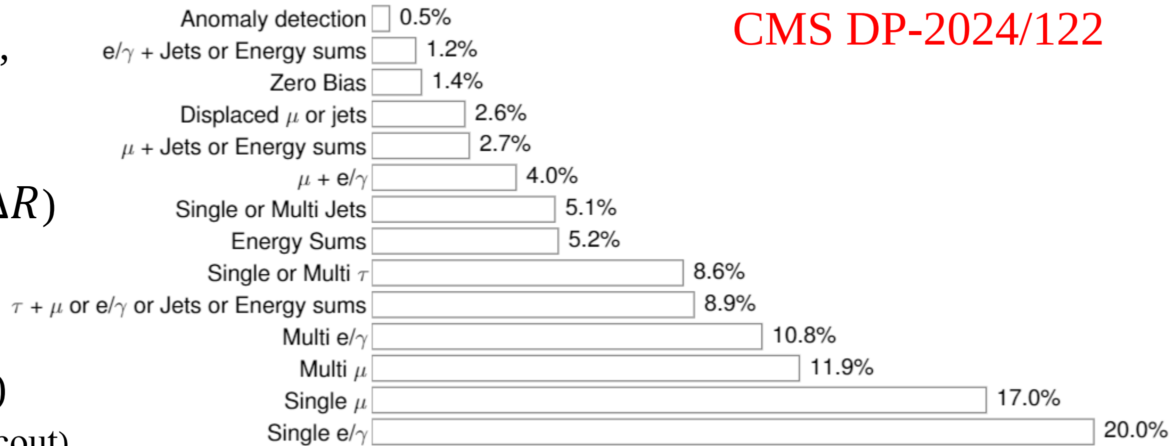


- 4 barrel layers to improve tracking efficiency and less fakes
- Less material and better radial distribution
- New readout chip recovers inefficiency at high pile up
- Can tolerate L=2×10^{34}cm^{-2}s^{-1}, 100 PU, integrated luminosity of 500fb^{-1}

CMS-TDR-011
CERN-LHCC-2012-016

Dimuon triggers (for b,c-physics)

CMS DP-2024/122



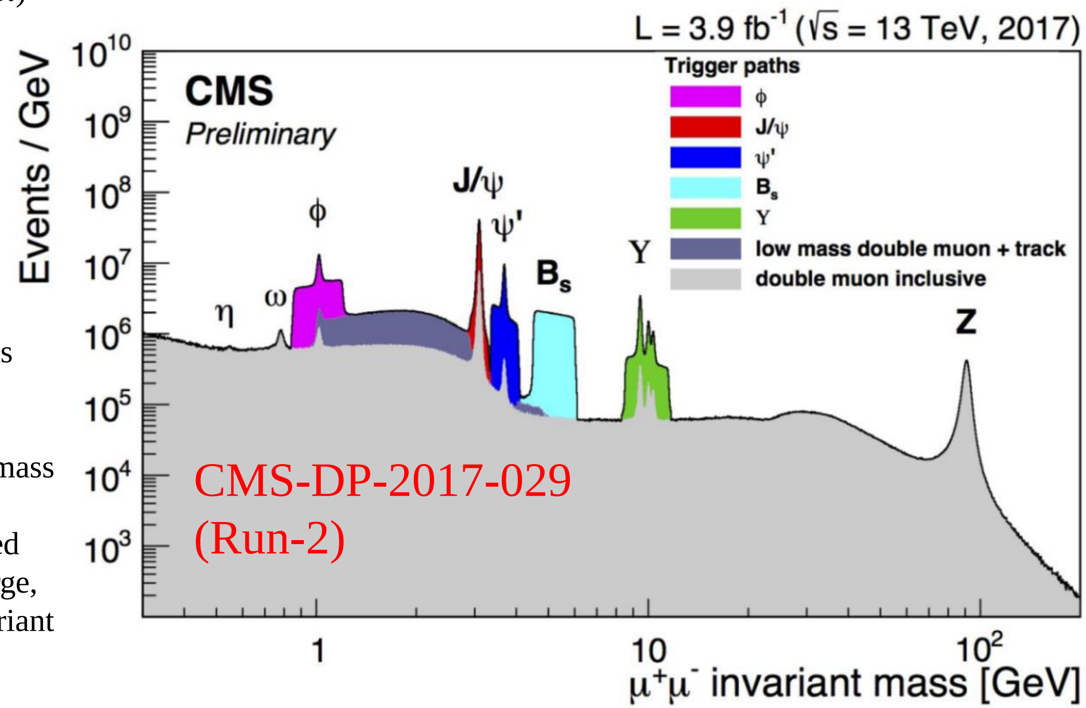
Level-1 (calo+muon, dedicated hardware), rate 100kHz→112kHz: typical di-muon inclusive L1 thresholds:

$4\text{ GeV}+3^{RUN3}/4^{RUN2}\text{GeV } (+\text{OS}+\Delta R)$

CMS bandwith@L1
~13kHz for flavor physics (multi μ).

HLT (all detectors, C++ at computer farm)
rate ~1kHz→2kHz (reg),5kHz(park), 27kHz(scout)

- Combined reconstruction in Muon System and Inner tracker
- Dedicated low mass dimuon mass triggers enabled at HLT (impr. Run3).
- b-physics data (mostly) in parking stream



1) The light gray continuous distribution represents events collected with inclusive dimuon triggers with high p_T thresholds.
2) The dark gray band is collected by a trigger with low-mass non-resonant dimuon plus a track.
3) The other colored spectra are acquired using specialized triggers which require a pair of muons with opposite charge, a vertex-fit probability > 0.5%, and specific dimuon invariant mass and p_T regions.

Selection of recent results

78	BPH-23-004	Evidence for CP violation and measurement of CP-violating parameters in $B_s^0 \to J/\psi\,\phi(1020)$ decays in pp collisions at $\sqrt{s} = 13$ TeV	Submitted to PRL	26 December 2024
77	BPH-21-002	Angular analysis of the $B^0 \to K^*(892)^0\mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	18 November 2024
76	BPH-22-012	Test of lepton flavor universality in semileptonic B_c^+ meson decays in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to PRL	1 August 2024
75	BPH-22-001	Measurement of the $B_s^0 \to J/\psi K_S^0$ effective lifetime from proton-proton collisions at $\sqrt{s} = 13$ TeV	JHEP 10 (2024) 247	2024-10-31
74	BPH-22-009	Measurement of the polarizations of prompt and non-prompt J/ψ and $\psi(2S)$ mesons produced in pp collisions at $\sqrt{s} = 13$ TeV	PLB 858 (2024) 139044	2024-10-01
73	BPH-23-005	Search for CP violation in $D^0 \to K_S^0K_S^0$ decays in proton-proton collisions at $\sqrt{s} = 13$ TeV	EPJC 84 (2024) 1264	2024-12-06
72	BPH-22-006	Observation of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV	PRD 109 (2024) L111101	2024-06-06

CMS-PAS-BPH-23-001	Measurement of the ratio of the $B_c^+ \to J/\psi\tau^+\nu_\tau$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$ branching fractions using three-prong τ lepton decays in proton-proton collisions at $\sqrt{s} = 13$ TeV		29 August 2024
CMS-PAS-BPH-23-008	Search for rare charm decays into two muons (Run3)		28 July 2024
CMS-PAS-BPH-22-007	Measurement of double-differential and total charm-production cross sections at 7 TeV		23 July 2024

65	BPH-21-006	Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV	PLB 842 (2023) 137955	2023-05-12

Recent CPV results
$(B_s \to J/\psi\phi,\, D^0 \to K_s K_S)$

CP violation in CKM matrix

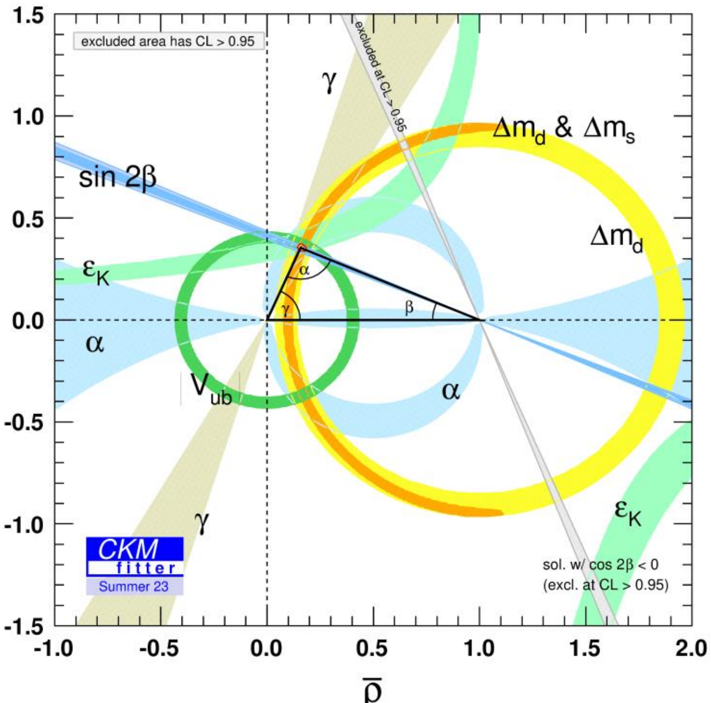
Wolfenstein parametrization of CKM matrix

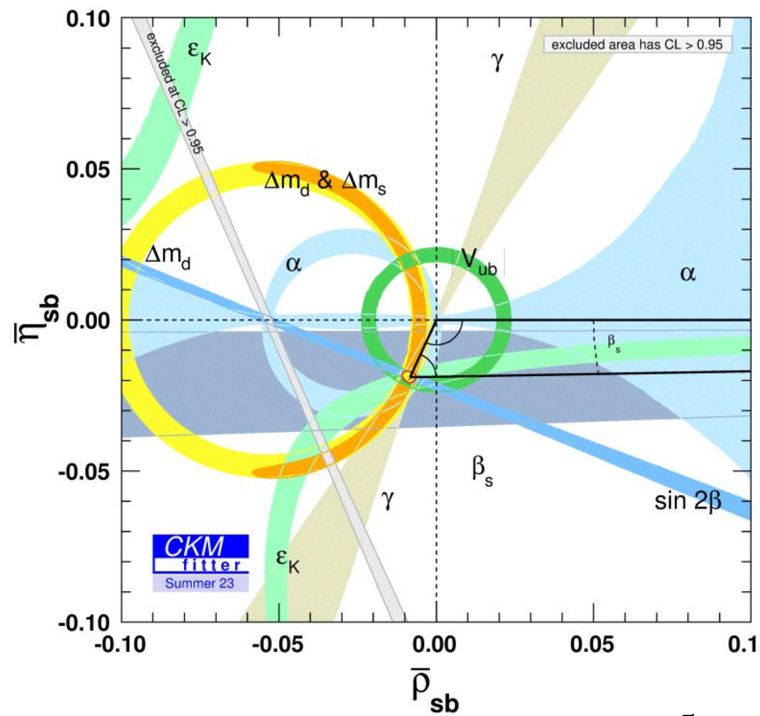
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix} + O(\lambda^4)$$

The unitarity condition $V^\dagger V = VV^\dagger = 1$ implies (among other relations):

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \qquad V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0$$

'big unitarity triangle'





'B_s unitarity triangle'

$(V_{ik}V_{kl}V_{il}^*V_{kj}^*) = J\ \sum_{mn}\ \varepsilon_{ikm}\varepsilon_{jln}$. J-Jarlskog invariant (all u. triangles, $|J| = 2 * area \approx 3 \cdot 10^{-5}$)

CPV in $B_s \to f_{CP} = J/\psi\phi$

The $B-\bar{B}$ states can oscillate due to box diagrams, common description – state mixing.

One can identify L-light and H-heavy mass eigenstates:

$$|B_{(s)L,H}\rangle = p\,|B^0_{(s)}\rangle \pm q\,|\bar{B}_{(s)}{}^0\rangle$$

where, for $B_q - \overline{B_q}$ system ($q = d, s$):

$$\frac{q}{p} \approx \frac{V^*_{tb}V_{tq}}{V_{tb}V^*_{tq}} \qquad \text{here } \left|\frac{q}{p}\right| \approx 1$$

In the case when both $B_{(s)}$ and $\bar{B}^0_{(s)}$ may decay to the same CP eigenstate f_{CP} (η_f - CP eigenvalue) and only single weak phase contributes $b \to c + \bar{c}s$:

$$\frac{\bar{A}}{A} \equiv \frac{A\left(\overline{B_{(s)}}^0 \to f_{CP}\right)}{A\left(B_{(s)}{}^0 \to f_{CP}\right)} = \eta_f \frac{V^*_{cs}V_{cb}}{V_{cs}V^*_{cb}} \qquad \text{here } \left|\frac{\bar{A}}{A}\right| \approx 1$$

Finally, since it is possible:

$$B_{(s)}{}^0 \to f_{CP} \;\text{ and }\; B_{(s)}{}^0 \to \overline{B_{(s)}}^0 \to f_{CP}$$

The decay width of initially produced $B^0/\bar{B}^0$:

$$a_{CP} = \frac{\Gamma\left(B_{(s)}{}^0(t)\to f_{CP}\right) - \Gamma\left(\overline{B_{(s)}}^0(t)\to f_{CP}\right)}{\Gamma\left(B_{(s)}{}^0(t)\to f_{CP}\right) + \Gamma\left(\overline{B_{(s)}}^0(t)\to f_{CP}\right)} \propto \eta_f \mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}}{A}\right)\sin(\Delta m\, t)$$

λ_{CP}

CPV in mixing: $\left|\frac{q}{p}\right| \neq 1$

$$\Gamma(M \to \bar{M}) \neq \Gamma(\bar{M} \to M)$$

CPV in decay: $\left|\frac{\mathcal{A}_{\bar{M}\to\bar{f}}}{\mathcal{A}_{M\to f}}\right| \neq 1$

$$\Gamma(M \to f) \neq \Gamma(\bar{M} \to \bar{f})$$

interference $\mathrm{Im}\left(\frac{q}{p}\cdot\frac{\mathcal{A}_{\bar{M}\to f}}{\mathcal{A}_{M\to f}}\right) \neq 0$

(interplay between mixing and decay)

$$\Gamma(M \to f) \neq \Gamma(\bar{M} \to f)$$

$B_s \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$

CMS-BPH-23-004

The $B_s \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$ is one of "golden channels" to study CP violation.

- in good approximation there is only single weak phase contributing to decay - penguin diagram contributions are minor

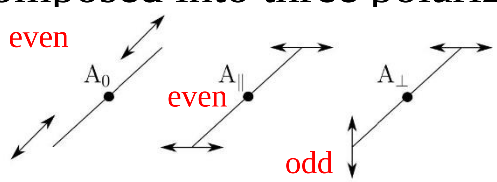
96.5 fb^{-1} (2017,2018)

- the final state can be reconstructed with high signal to background ratio (measurable final signature, intermediate object mass constraint on J/ψ, (ϕ-broad));
- clear signature for triggering: $J/\psi \to \mu^+\mu^-$, note: third muons – a tagger. [two triggers: $J/\psi \to \mu^+\mu^-$ with tagging μ or displaced $J/\psi \to \mu^+\mu^- + \phi \to K^+K^-$ vertex.]

Difficulty: Final state is a mixture of CP-even and CP-odd states.

- Spin-0 pseudoscalar B_s decays into spin-1 vector mesons J/ψ and $\phi(1020)$
- Decay amplitude decomposed into three polarization states (different CP):

A_0 (longitudinal),
$A_\parallel$ (parallel),
$A_\perp$ (perpendicular),

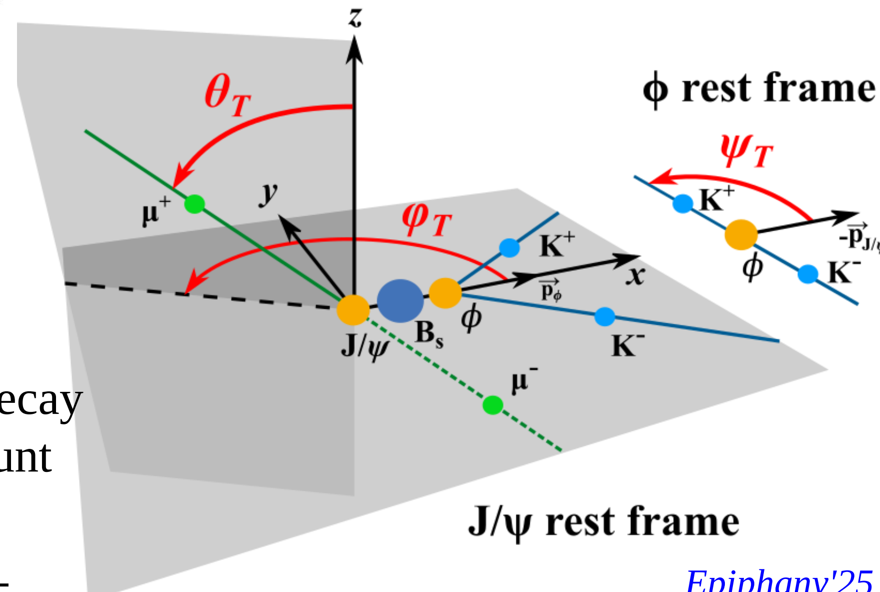


Time dependent and flavour tagged angular analysis to disentangle CP final states.

Three angles $\Theta = (\theta_T, \psi_T, \varphi_T)$,

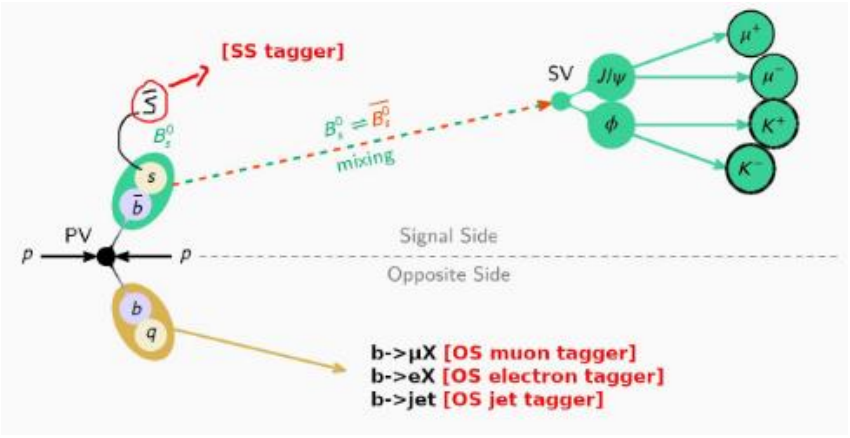
(transversity method: Dighe,Dunietz,Fleischer Eur.Phys.J C6(1999)647).

Contributions A_S ("S-wave") from non-resonant decay $B_s \to \mu^+\mu^-K^+K^-$, $B_s \to J/\psi f_0(980)$ taken into account



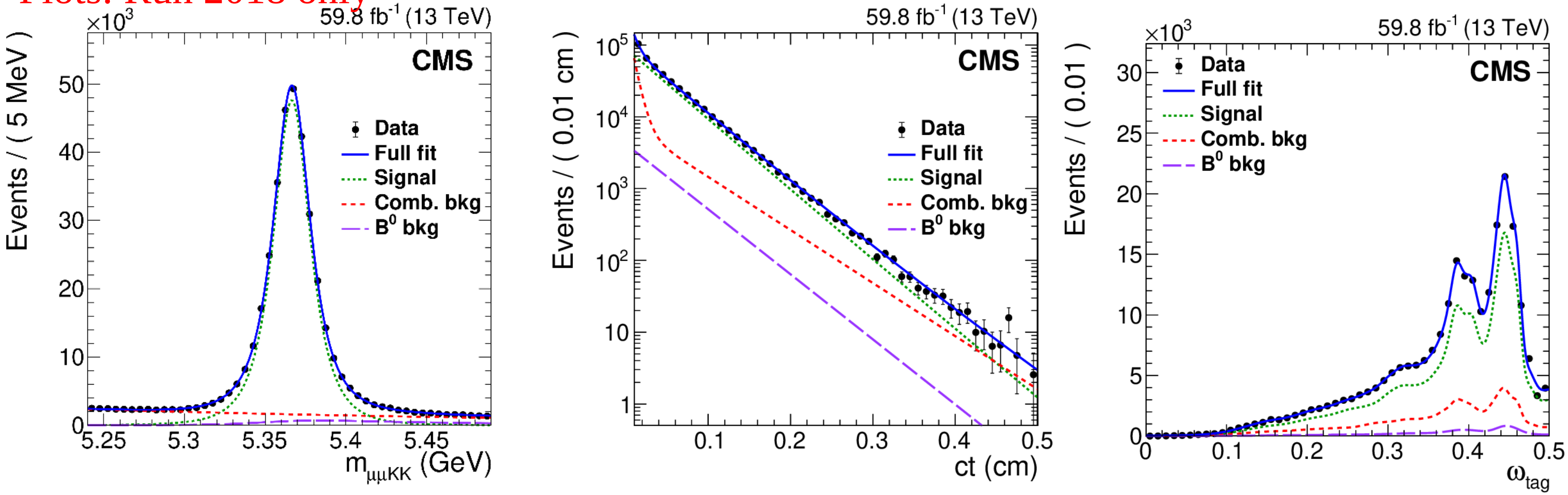
$B_s \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$

- Recent Improvement: inclusive flavour tagging framework with Machine Learning techniques: OS muon, OS electron, OS jet, SS particle. Tagging calibrated with of $B^+ \to J/\psi K^+$, validated with $J/\psi\ \ K^*(892)^0 \to \mu^+\mu^-K^+\pi^-$



- another key factor: excellent time resolution to handle fast $B_s^0 \leftrightarrow \overline{B_s}^0$ oscillations

Plots: Run 2018 only



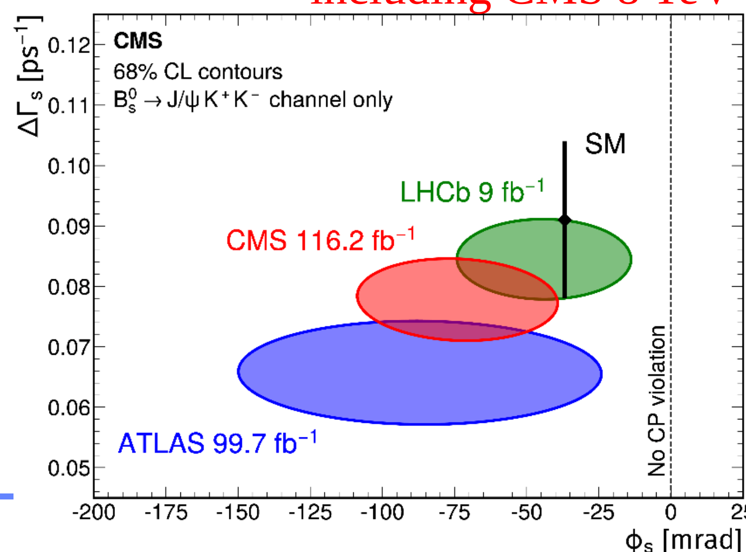
$B_s \to J/\psi\ \phi(1020)$ results: measurement of ϕ_s and $\Delta\Gamma_s$ and Δm_s

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

- $\phi_s = -2\beta_s$ in agreement with SM and WA: $\phi_s^{SM} = -37 \pm 1$ mrad, $\phi_s^{WA} = -49 \pm 19$ mrad
- $\Delta\Gamma_s^{SM} = 0.091 \pm 0.013\ ps^{-1}$ $\Delta\Gamma_s^{WA} = 0.084 \pm 0.005\ ps^{-1}$
- $\Gamma_s^{WA} = 0.6573 \pm 0.0023\ ps^{-1}$
- $\Delta m_s^{SM} = 18.77 \pm 0.86 ps^{-1}$, Δm_s^{WA} : $17.765 \pm 0.006 ps^{-1}$,
- $\lvert\lambda\rvert = \lvert \frac{q}{p}\frac{\bar{A}}{A}\rvert$ consistent with no direct CPV

including CMS 8 TeV

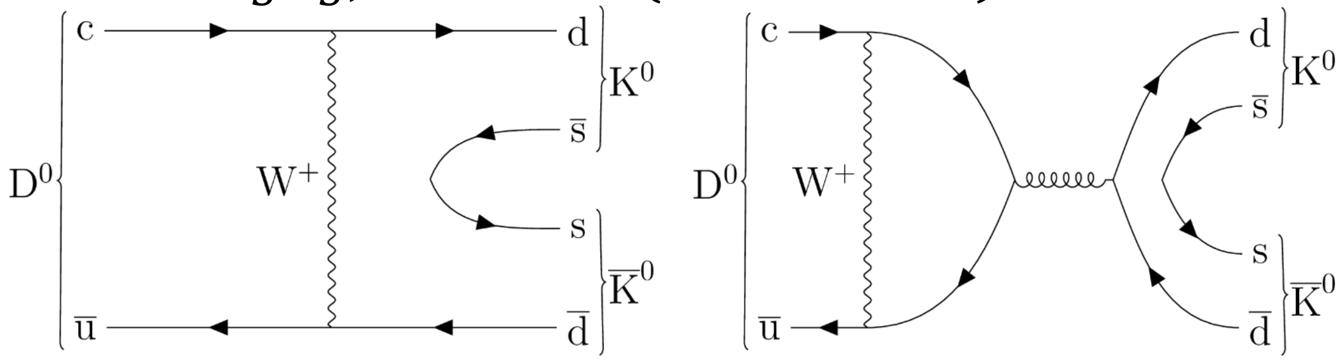
CMS: First evidence of CP violation in this channel (previously Δm_s and $\lvert\lambda\rvert$) by CMS



Search for CP violation in $D^0 \to K_S K_S$

Eur. Phys. J. C 84 (2024) 1264
41.6 fb^{-1} (2018)

- In contrast to K, B systems CP violation in charm mesons suppressed by Glashow–Iliopoulos–Maiani mechanism → search for new physics
- CP violation in $D^0 \to K^+K^-$ and $\pi^+\pi^-$ observed by LHCb
- CMS: $D^0 \to K_S K_S$, small BR $(1.41 \pm 0.05) \times 10^{-4}$



- Goal: $A_{CP} = \frac{\Gamma(D^0 \to K_S K_S) - \Gamma(\bar{D}^0 \to K_S K_S)}{\Gamma(D^0 \to K_S K_S) + \Gamma(\bar{D}^0 \to K_S K_S)}$, LHCb, Belle: $(-1.9 \pm 1.1)\%$.

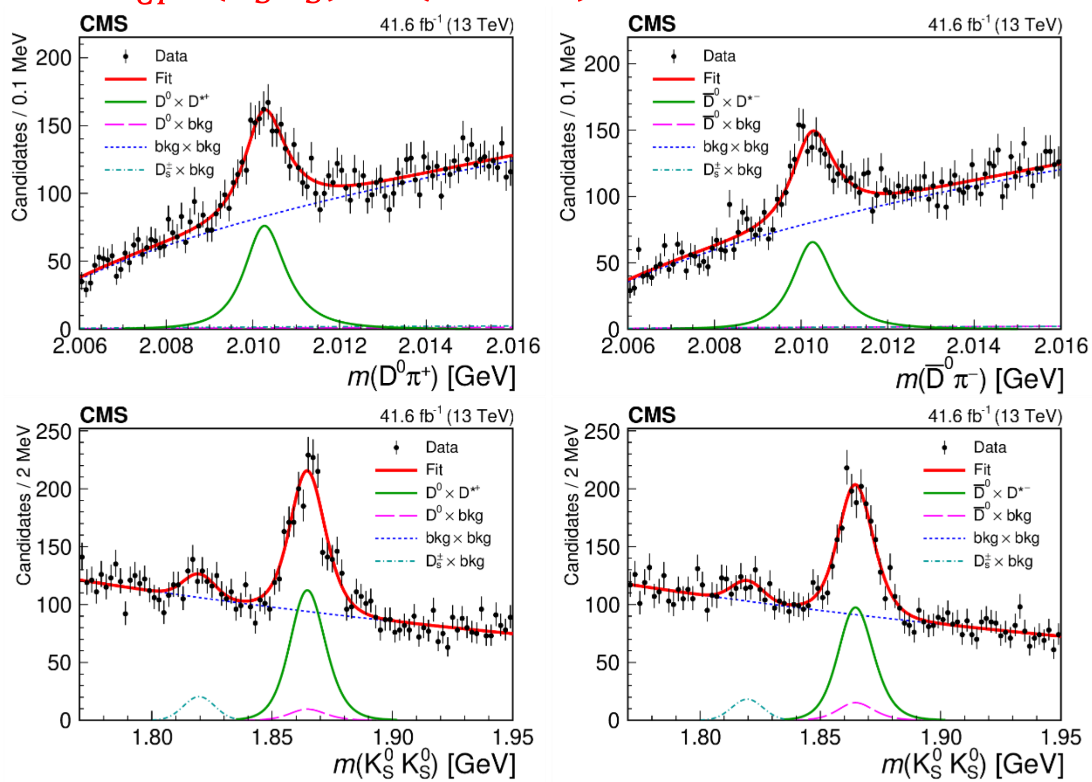
Search for CP violation in $D^0 \to K_s K_S$

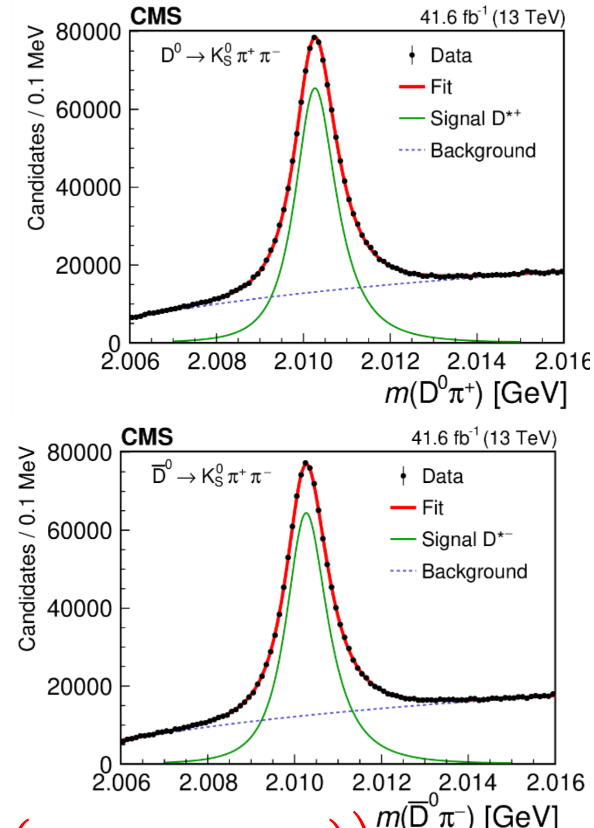
- fully hadronic final state – trigger: single-muon intended for $b \to c\mu X$ or $c \to s\mu X, c$ from cascade decays, with transverse-impact parameter. Trigger thresholds varying with instantaneous luminosity+levelling. Rely on parking datasets, 1.2×10^{10} events in 41.6 fb^{-1}
- flavour of D^0meson from $D^{*+} \to D^0\pi^+$ decays (pion ch. tags $D^0/\overline{D}^0$).
- We measure CP asymmetry difference ΔA_{CP} between signal channel ($D^0 \to K_S K_S$) and reference non-CPV ($D^0 \to K_S\pi^+\pi^-$), measured prev. to be consistent with 0.
- Several components contribute to asymmetry: $A_{CP} \approx A_{CP}^{raw} - A_{CP}^{pro} - A_{CP}^{det}$
- $A_{CP}^{raw} = \frac{\mathrm{N}(D^{*+}\to D^0\pi^+)-\mathrm{N}(D^{*-}\to \overline{D}^0\pi^-)}{\mathrm{N}(D^{*+}\to D^0\pi^+)-\mathrm{N}(D^{*-}\to \overline{D}^0\pi^-)}$
- A_{CP}^{pro}- production effects, A_{CP}^{det}- detector effects cancels out while measuring A_{CP} for signal and reference channel.
- $\Delta A_{CP} = A_{CP}(K_S K_S) - A_{CP}(K_S\pi^+\pi^-)$= $A_{CP}^{raw}(K_S K_S) - A_{CP}^{raw}(K_S\pi^+\pi^-)$

Search for CP violation in $D^0 \rightarrow K_S K_S$

measured raw asymmetry
$A_{CP}^{raw}(K_S K_S) = (7.1 \pm 3)\%$

measured raw asymmetry
$A_{CP}^{raw}(K_S \pi^+ \pi^-) = (0.78 \pm 0.1)\%$





CMS result $A_{CP}(K_S K_S) = \left(6.2 \pm 3.0(stat) \pm 0.2(syst) \pm 0.8\left(A_{CP}^{WA}(K_S \pi^+ \pi^-)\right)\right)\%$

- consistent with no CP violation.
- first CMS CPV result in charm sector, main uncertainty due to statistics → improvements

Highlights of other recent results

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

140 fb^{-1} (2016-2018)

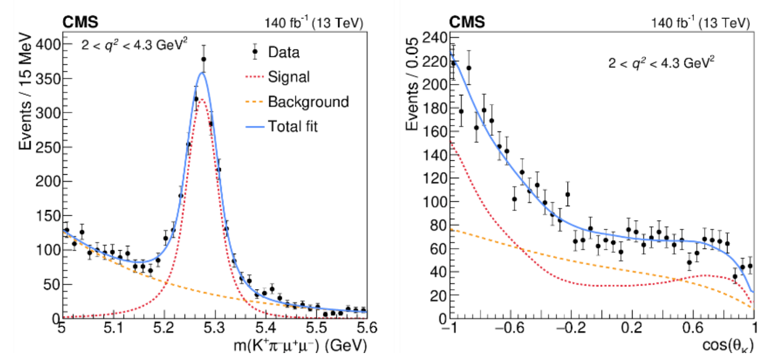
CMS-BPH-21-002

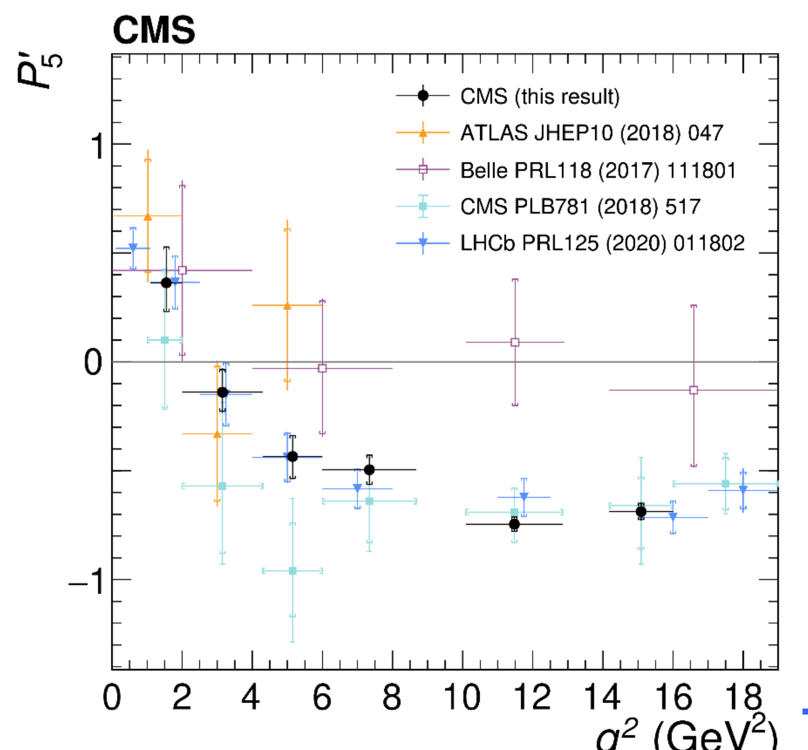
- purpose: measure a set of observables in angular analysis, already measured by CMS (Run1) & others
- $b \to sll$ loop FCNC SM BR $O(10^{-6})$
- Angular parameters for $\frac{d^4N}{dq^2 d\cos\theta_K d\cos\theta_l\, d\cos\phi}$ from 4D fit (dep. q^2) to mass and angular distributions $(\theta_l, \theta_K, \phi)$ [small differences in definitions wrt LHCb]:

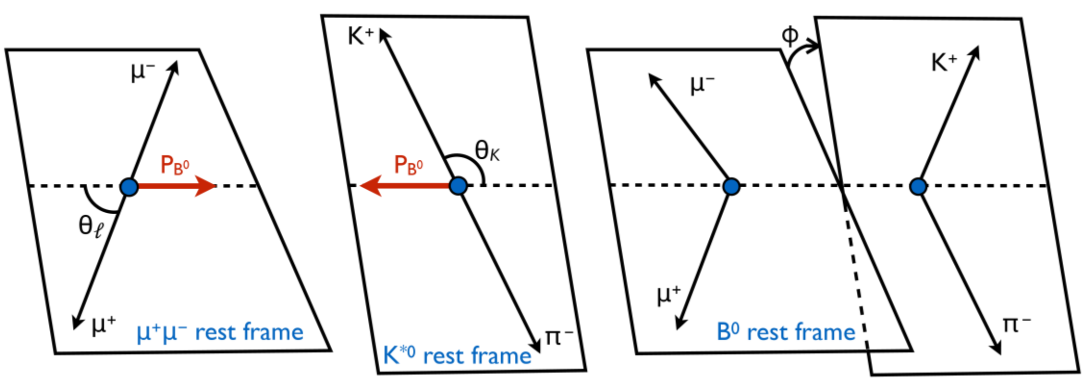
$$F_L, P_1, P_2, P'_4, P'_5, P'_8$$

[JHEP 01 (2009)019, JHEP01 (2013) 048, JHEP05(2013)137]

- result: some tensions in q^2 below J/ψ for P_2 and P'_5, good agreement with LHCb results.
- results among most precise exp. measurements







test of $b \to cl\nu$ LFU with $R_{J/\Psi}$

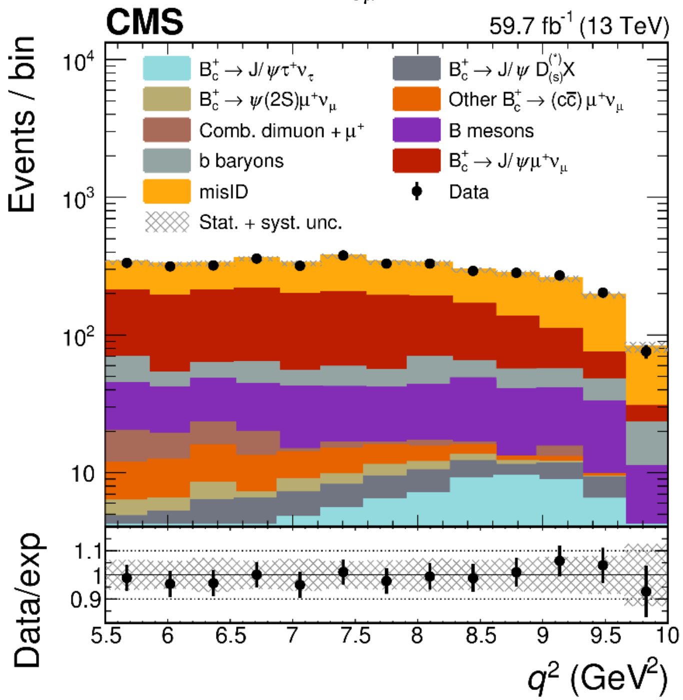
$$R_{J/\psi} = \frac{BR(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{BR(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$ with $J/\psi \to \mu^+\mu^-$,

SM expectation $R = 0.2582 \pm 0.0038$,

- muonic τ decays $\tau^+ \to \mu^+ \nu_\mu \overline{\nu_\tau}$

$(q^2 = (p_{B_c^+} - p_{J/\psi})^2, p_{B_c^+} = \frac{m_{B_c^+}}{m_{3\mu}^{vis}} p_{3\mu}^{vis}; 3DIP/\sigma, L_{xy}/\sigma)$

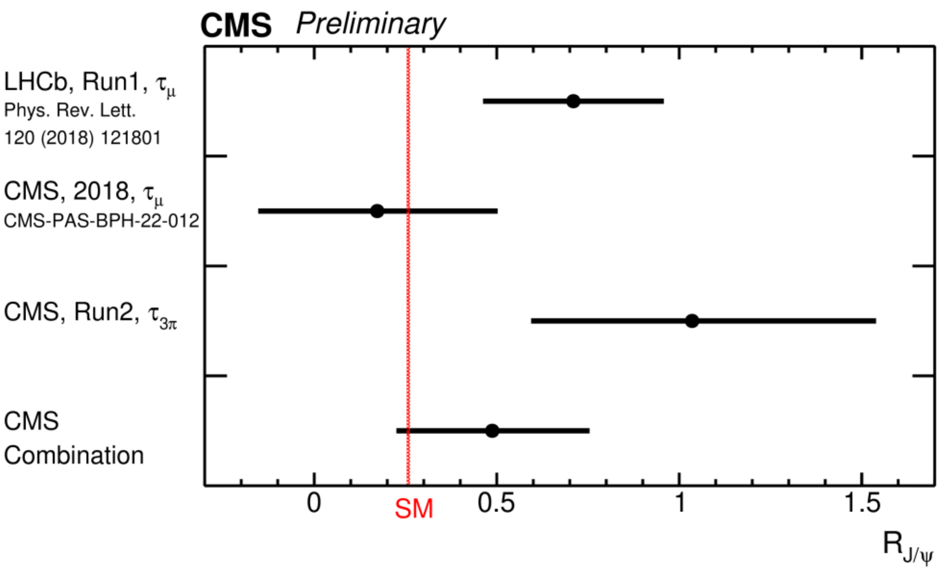
CMS BPH-22-012
$59.7\ fb^{-1}$ (2018)



- $R_{J/\psi} = 0.17 \pm 0.33$
  $[0.17^{+0.18}_{-0.17}(stat)^{+0.21}_{-0.22}(syst)^{+0.19}_{-0.18}(theo)]$

- 3 prong τ dcays $\tau^+ \to \pi^+\pi^-\pi^+(+\pi^0)\overline{\nu_\tau}$
- $R_{J/\psi} = 1.04^{+0.50}_{-0.44}$

$138\ fb^{-1}$ (2016-2018)
CMS PAS BPH-23-001



CMS combined:
$R_{J/\psi} = 0.49 \pm 0.25\ (stat) \pm 0.09\ (syst)$

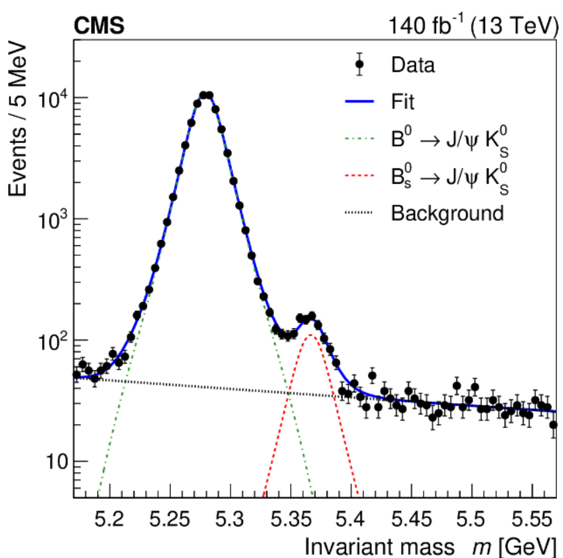
$B_s \to J/\psi K_S$ effective lifetime

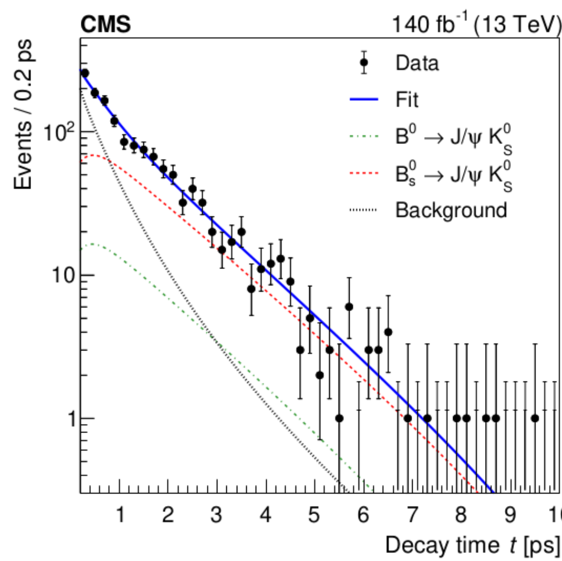
- B_s^0 propagates as B_H or B_L mass eigenstates with different lifetimes $\Delta\Gamma \approx 0.08$ ps related to $B \to J/\psi K_S$, but penguin diagrams no more Cabibbo suppressed
- $J\psi \to \mu^+\mu^-, K_S \to \pi^+\pi^-$, effectively measure B_H, CP-odd.

JHEP 10 (2024) 247

- effective lifetime: $\tau(J/\psi K_S) = \frac{\int t[\Gamma\left(B_s^0(t)\to J/\psi K_S\right)+\Gamma\left(\overline{B_s}^0(t)\to J/\psi K_S\right)]\mathrm{d}t}{\int [\Gamma\left(B_s^0(t)\to J/\psi K_S\right)+\Gamma\left(\overline{B_s}^0(t)\to J/\psi K_S\right)]\mathrm{d}t}$
- 2D Unbinned maximum likelihood fit to mass and lifetime, $t = m\frac{\vec{L}_{xy}\cdot\vec{p}_T^B}{\left(\vec{p}_T^B\right)^2}$

140 fb^{-1}
2016-2018





$m(J/\psi K_S)$
5.34-5.42 GeV

SM: $1.62 \pm 0.02\ ps$

- Result: $\tau(J/\psi K_S) = 1.59 \pm 0.07\ (stat) \pm 0.03\ (syst)$ ps; most precise measurement to date

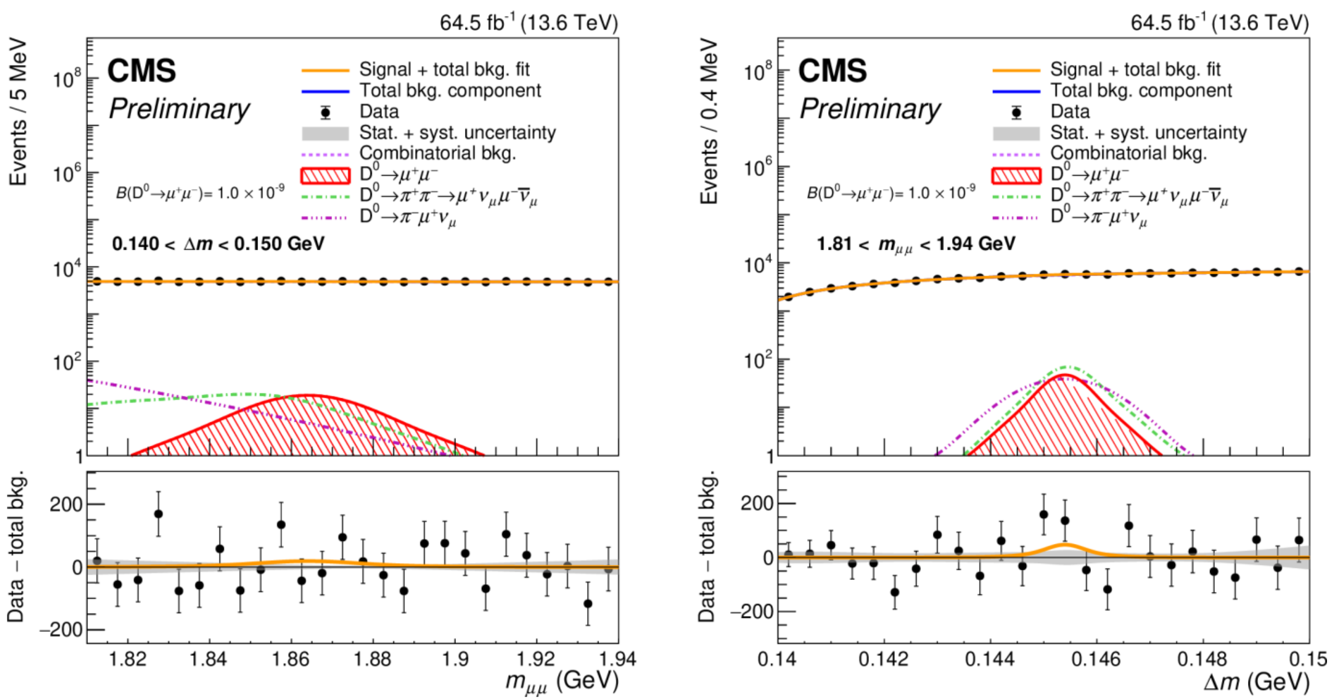
search for rare charm decays: $D^0 \to \mu^+\mu^-$

CMS PAS BPH-23-008

- very rate FCNC expected SM $BR \sim 3 \times 10^{-13}$; any NP may introduce large enhance
- Run-3 analysis, exploring new low-mass double muon trigger

64.5 fb^{-1}
2022-2023

- main background combinatorial; use $D^*(2010)^+ \to D^0\pi^+$ decays. Normalization: $D^0 \to \pi^+\pi^-$.



$\Delta m = m(D^{*+}) - m(D^0)$

- Result: no significant excess of events above background, $BR(D^0 \to \mu^+\mu^-) < 2.6 \times 10^{-9}$ (95% CL); most sensitive measurement to date

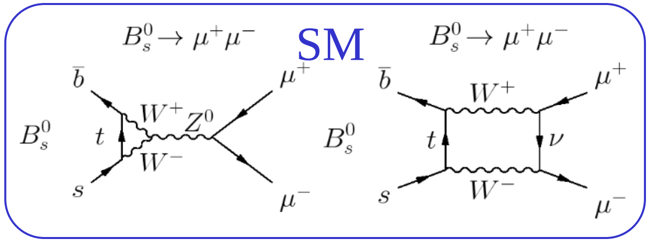
rare $B_s/B_d \to \mu^+\mu^-$ decays

- two of CMS flagship channels, Phys. Lett. B 842 (2023) 137955

JHEP04 (2020) 188
Nature 522 (2015) 68
Phys.Rev.Lett. 111(2013) 101804

- In the SM the tree-level diagrams do not contribute to FCNC, but can occur by box and penguin diagrams.

  Helicity suppressed by $\left(\frac{m_\mu}{m_B}\right)^2$, CKM suppressed $|V_{ts,td}|^2$



- Rare $B^0_{(s)} \to \mu^+\mu^-$ decays are ideal place to look for NP.

- SM predictions [Czaja, Misiak 2407.03810 see also Beneke et al JHEP 10 (2019) 232, Bobeth et al. Phys.Rev.Lett. 112 (2014) 101801]
  $BR(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.64 \pm 0.12)\cdot 10^{-9}$ $BR(B^0 \to \mu^+\mu^-)_{\rm SM} = (9.71 \pm 0.33)\cdot 10^{-11}$

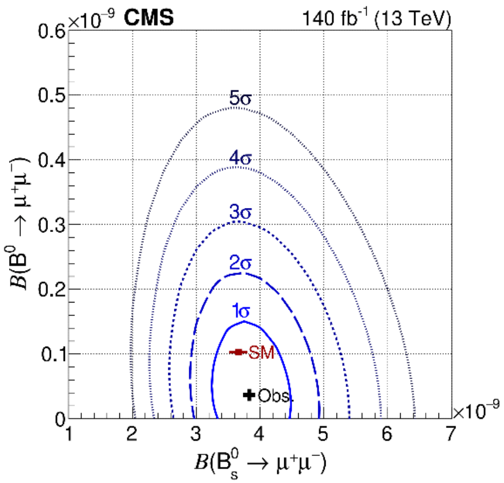
CMS result (2022):

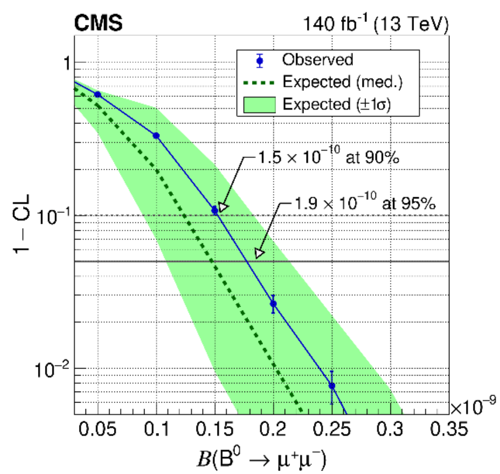
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\text{stat})\ ^{+0.19}_{-0.16}\ (\text{syst})\ ^{+0.14}_{-0.13}\ (f_s/f_u)\right] \times 10^{-9},$$

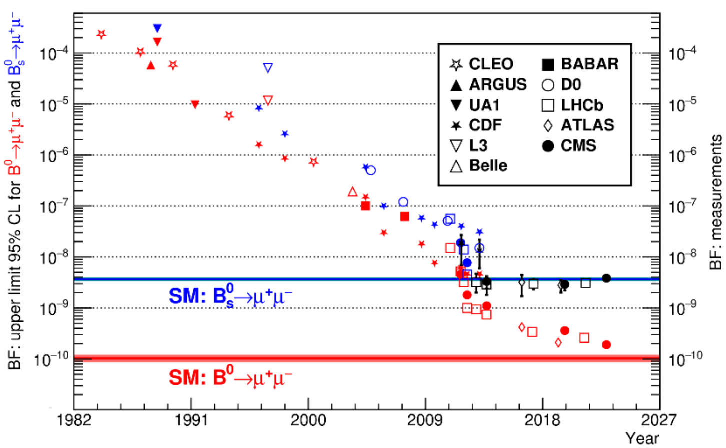
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\ (\text{stat})\ ^{+0.08}_{-0.09}\ (\text{syst})\right] \times 10^{-10}.$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.5 \times 10^{-10} \text{ at 90\% CL},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at 95\% CL},$$







Summary

- CMS is well suited for precise heavy flavour analyses.
- Several recent results overviewed:
  - CMS has updated measurement of CPV "golden channel" $B_s \to J/\psi\phi(1020)$
  - first CMS search for CP violation in charm
  - precise angular measurement in $B^0 \to K^{*0}\mu^+\mu^-$
  - most precise limit for $D^0 \to \mu^+\mu^-$ decay set
  - test of $b \to cl\nu$ lepton flavour universality with $R_{J/\Psi}$
  - effective $B_s \to J/\psi K_S$ lifetime measured
  - rare "flagship" decay $B_s \to \mu^+\mu^-$ measured by CMS, limits set for $B \to \mu^+\mu^-$
- no inconsistency with SM found so far
- many other interesting results like available.
  CMS B Physics and Quarkonia (BPH) results