Anomalies and Precisions : Latest CMS B-physics highlights

Alibordi Muhammad

On behalf of the
CMS collaboration

XXX Crakow EPIPHANY Conference
on Precision Physics at High Energy Colliders

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Content to be delivered

1. Current status of CMS
2. Anomaly and precision of CMS B-physics in the context of larger aspect of physics
3. Analysis :
   - Spectroscopy

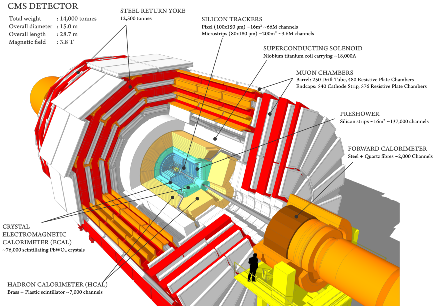
     $\eta \to \mu^+\mu^-\mu^+\mu^-$ - Phys. Rev. Lett. 131 (2023) 091903 : (NEW)
     $B_s^0 \to \mu^+\mu^-$ properties - Phys. Lett. B 842 (2023) 137955
   - Lepton flavor violation

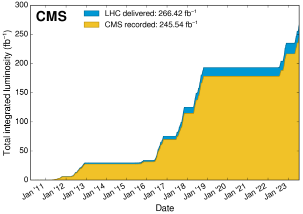
     $\tau \to 3\mu$ - arXiv:2312.02371[hep-ex] : (NEW)
     $R(J/\psi) : B_c^+ \to J/\psi\tau^+\nu_\tau$ - CMS-PAS-BPH-22-012 : (NEW)
     $R(K) : B^\pm \to K^\pm\ell^+\ell^-$ - CMS-PAS-BPH-22-005 : (NEW)
   - Studies of discrete symmetries

     $\phi_s : B_s^0 \to J/\psi\phi(1020)$ - Phys. Lett. B 816 (2021) 136188
     $A_{FB}, F_L : B^+ \to K^{*+}\mu^+\mu^-$ - JHEP 04 (2021) 124
4. Summary and take away lesson

Current status of CMS and B-Physics

- We had $L_{int} = pp : 29.89\,\text{fb}^{-1}$ in 2023
- Total $L_{int} = pp : 245.54\,\text{fb}^{-1}$
- Flagship analysis : CP asymmetry, LFV, rare B decays ($B_s^0 \to \mu\mu$)
- For more challenging aspects : Phase-2 TDR





(CMS-Lumi)

In this talk:
Doubly Dalitz decay, flavor changing neutral current

- $\eta \to \mu^+\mu^-\mu^+\mu^-$, $B_s^0 \to \mu^+\mu^-$

Accidental symmetry : LFUV : BABAR,Belle,Belle-II, LHCb combined departure in $R(D^*) \sim 3.3\sigma$ wrt SM

- $\tau \to 3\mu$, $B_c^+ \to J/\psi\tau^+\nu_\tau$, $B^\pm \to K^\pm\ell^+\ell^-$

Matter-antimatter asymmetry : CP asymmetry

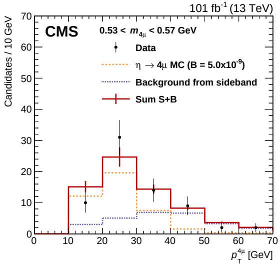
- $B_s^0 \to J/\psi\phi(1020)$, $B^+ \to K^{*+}\mu^+\mu^-$

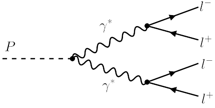
- Spectroscopy

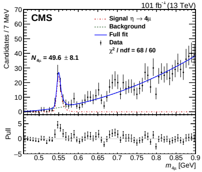
  $\eta \to \mu^+\mu^-\mu^+\mu^-$ - Phys. Rev. Lett. 131 (2023) 091903 : NEW
  $B_s^0 \to \mu^+\mu^-$ properties - Phys. Lett. B 842 (2023) 137955

$\eta \to \mu^+\mu^-\mu^+\mu^-$

- Double Dalitz decay of η is the precision test of SM and sensitive to the BSM
- $\gamma - \eta$ interaction contributes to the hadronic LBL component of a_μ
- pp collision data : 101 fb^{-1}
- $\eta \to 4\mu$ mass window : 0.53-0.57 GeV, normalization channel $\eta \to 2\mu$







First measurement of the rare doubly Dalitz decay of $\eta \to 4\mu$

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{ij} N^{ij}_{2\mu} \frac{A^{ij}_{4\mu}}{A^{ij}_{2\mu}}}$$

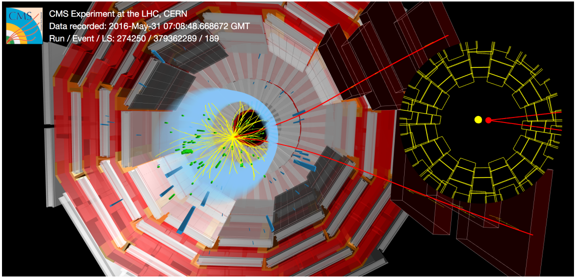
i, j : bin numbers , 32 bins in p_T in the range of $7 - 70$ GeV

$$\boxed{\mathcal{B}(\eta \to 4\mu) = [5.0 \pm 0.8(\text{stat}) \pm 0.7(\text{syst}) \pm 0.7(\mathcal{B}_{2\mu})] \times 10^{-9}}$$

$B_s^0 \to \mu^+\mu^-$

1. Data : $\sqrt{s} = (2016 - 2018) 13$ TeV.
2. Integrated luminosity : $\mathcal{L}_{\text{int}} = 140\,\text{fb}^{-1}$

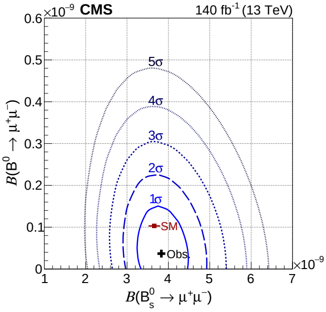
$B_s^0 \to \mu^+\mu^-$ event display
two - μ's are originating from the decay vertex



1. Normalization and control channel : $B^+ \to J/\psi K^+$, $B_s^0 \to J/\psi\phi$
2. Background : Combinatorial, rare B decays with two muons : $B \to h\mu\mu$, $h \in (\pi, K, p)$, rare B decays with two hadron : $B \to h'h'$

$\mathrm{B_s^0} \to \mu^+\mu^-$

1. HLT : Di-μ : $4.8(4.5) < m_{\mu^+\mu^-} < 6.0$ GeV Run-I(Run-II)
2. $d_{ca} < 0.5\,\text{cm},\; P(\chi^2/dof) > 0.5\%$



Branching fraction :

$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \frac{N_s}{N_{\mathbf{obs}}^{B^+}} \frac{f_u}{f_s} \frac{\epsilon_{\mathbf{tot}}^{B^+}}{\epsilon_{\mathbf{tot}}} \mathcal{B}(\mathrm{B^+} \to \mathrm{J}/\psi \mathrm{K^+}) \mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-); \quad \mathrm{B^0} : \frac{f_d}{f_u}$$

Result :

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

$\mathrm{B}_\mathrm{s}^0 \to \mu^+\mu^-$

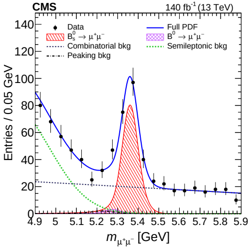
PDF for lifetime determination (2DUML):

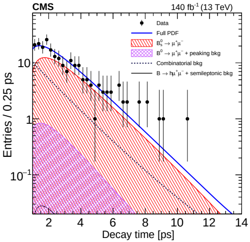
$$
\begin{aligned}
\mathcal{P}(m_{\mu^+\mu^-}, t; \sigma_t) = {} & N_{\textbf{sig}} P_{\textbf{sig}}(m_{\mu^+\mu^-}) T_{\textbf{sig}}(t; \sigma_t) \epsilon_{\textbf{sig}}(t) \\
& + N_{\textbf{peak}} P_{\textbf{peak}}(m_{\mu^+\mu^-}) T_{\textbf{peak}}(t; \sigma_t) \epsilon_{\textbf{peak}}(t) \\
& + N_{\textbf{semi}} P_{\textbf{semi}}(m_{\mu^+\mu^-}) T_{\textbf{semi}}(t; \sigma_t) \epsilon_{\textbf{semi}}(t) \\
& + N_{\textbf{comb}} P_{\textbf{comb}}(m_{\mu^+\mu^-}) T_{\textbf{comb}}(t; \sigma_t)
\end{aligned}
$$

Determined lifetime value

$$
\tau_{\mu^+\mu^-} = [1.83^{+\mathbf{0.23}}_{-\mathbf{0.20}}(\text{stat})^{\mathbf{0.04}}_{\mathbf{0.04}}(\text{syst})]\,\mathrm{ps}
$$

A complimentary 1DUML is performed using sWeight toward unfolding the $\tau_{\mu^+\mu^-}$ which is consistent with the 2DUML.

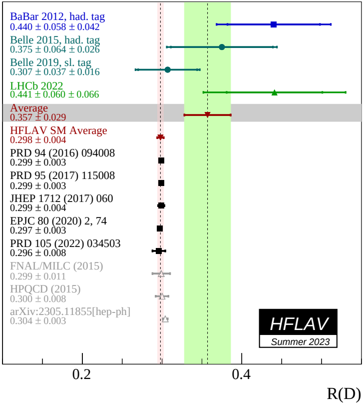




- Lepton flavour violation

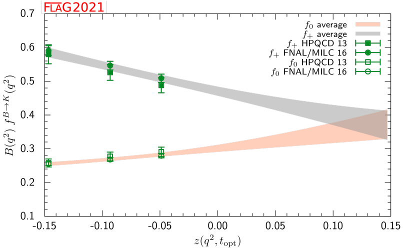
  $\tau \to 3\mu$ - CMS-PAS-BPH-22-012 : NEW
  $R(J/\psi)$: $B_c^+ \to J/\psi\tau^+\nu_\tau$ - CMS-PAS-BPH-22-012 : NEW
  $R(K)$: $B^\pm \to K^\pm\ell^+\ell^-$ - CMS-PAS-BPH-22-005 : NEW

Lepton flavour universality violation



- Lattice QCD results : form factor $(B \to K)$extrapolation is residing far from exact $SU(3)$ symmetry : extra momentum contribution in the matrix elements through the form factors

1. Origin of the deviation : indicates violation of the Lepton flavor universality, a symmetry in the gauge sector and an accidental near-symmetry of the Yukawa sector of the standard model by which all leptons couple with the same strength
2. $B_c^+ \to J/\psi \tau^+ \nu_\tau$, $B^\pm \to K^\pm \ell^+ \ell^-$: the unknown QCD corrections enters through the matrix elements of the decays in terms of the form factors (QCD review , PDG)
3. Lattice, Lepto-quarks model in the non-perturbative and perturbative limits of QCD has tried to incorporate additional couplings by considering additional particle or lattice corrections



$\tau \to 3\mu$ - introduction

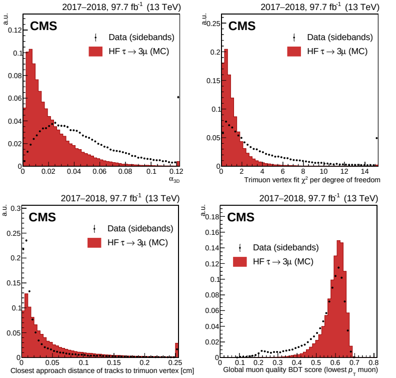
- In SM (sourced by neutrino transition in loops) $\mathcal{B} \sim \mathcal{O}(10^{-55})$
- BSM scenarios : $\mathcal{B} \sim \mathcal{O}(10^{-10})$, attainable at current LHC energy
- Data : 2017+2018 (new), Combined with 2016 results
- $\tau \to 3\mu$: two category search : HF : $D_s^+ \to \tau^+\nu_\tau$, $B^+/B^0 \to \tau + X$, W boson : $W^+ \to \tau^+\nu_\tau$
- Branching fraction from event yield :

$$N_{3\mu(\mathrm{D})} = N_{\mu\mu\pi} \frac{\mathcal{B}(\mathrm{D_s^+} \to \tau^+\nu_\tau)}{\mathcal{B}(\mathrm{D_s^+} \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(\mathrm{D})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{D})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\,\mathrm{trig}}_{3\mu(\mathrm{D})}}{\epsilon^{2\mu\,\mathrm{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu)$$

$$N_{3\mu(\mathrm{B})} = N_{\mu\mu\pi}\, f \frac{\mathcal{B}(\mathrm{B} \to \tau + \mathrm{X})}{\mathcal{B}(\mathrm{B} \to \mathrm{D_s^+} + \mathrm{X})\mathcal{B}(\mathrm{D_s^+} \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(\mathrm{B})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{B})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\,\mathrm{trig}}_{3\mu(\mathrm{B})}}{\epsilon^{2\mu\,\mathrm{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu)$$

$$N_{3\mu(\mathrm{W})} = \mathcal{L}\,\sigma(\mathrm{pp} \to \mathrm{W} + \mathrm{X})\,\mathcal{B}(\mathrm{W} \to \tau\nu_\tau)\,\mathcal{A}_{3\mu(\mathrm{W})}\,\epsilon_{3\mu(\mathrm{W})}\,\mathcal{B}(\tau \to 3\mu)$$

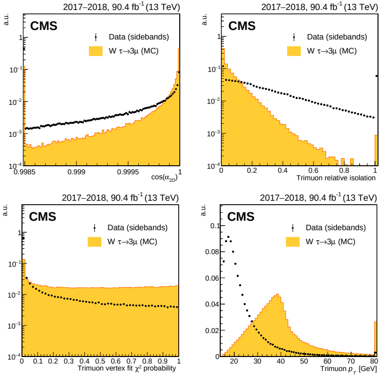
$\tau \to 3\mu$ - discriminators with highest power



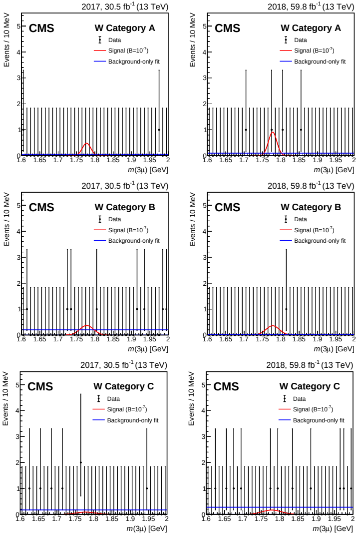
- DCA to the 3μ vertex of all other tracks ($p_T > 1\text{GeV}$)
- muon reconstruction quality BDT score of the lowest p_T muon of the triplet

Best discriminators :

- α_{3D} : 3D angle between $\vec{p}_{3\mu}$ and the vector from the beamline to three particle common vertex
- χ^2/DOF of the 3μ vertex fit

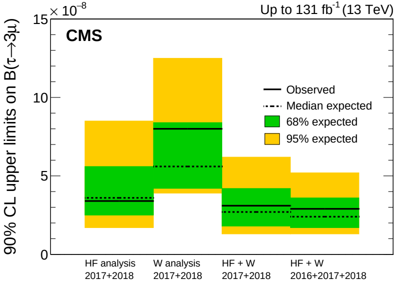


$\tau \to 3\mu$ - result



Three mass resolution categories : background-only fit

- $A : \sigma_m = 12$ MeV, $\sigma_m/m < 0.07\%$
- $B : \sigma_m = 19$ MeV, $0.07 < \sigma_m/m < 1.05\%$
- $C : \sigma_m = 25$ MeV, $\sigma_m/m > 1.05\%$



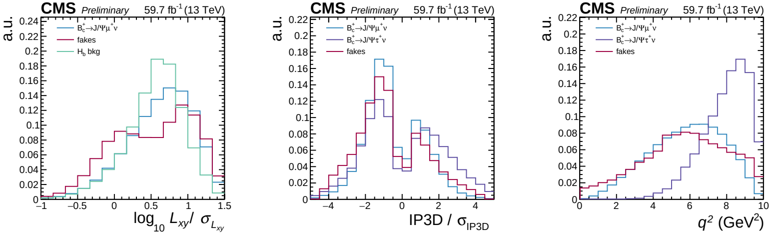
2017+2018 data is combined with 2016 data : $L_{int} = 131\ fb^{-1}$, the observed(expected) upper limit on $\mathcal{B}(\tau \to 3\mu)$

- $CL - 90\% : 2.9(2.4) \times 10^{-8}$
- $CL - 95\% : 3.6(3.0) \times 10^{-8}$

$R(J/\psi) : B_c^+ \to J/\psi \tau^+ \nu_\tau$

- $R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$, $J/\psi \to \mu^+\mu^-$, $\tau^+ \to \mu^+ \nu_\mu \nu_\tau$
- L1 trigger : events with 3 muons , leading μ : $p_T > 5$ GeV, sub-leading μ : $p_T > 3$ GeV, no p_T requirement for sub-sub-leading muon
- 2 muons from the common vertex of J/ψ and muon ($\mu^+\mu^-\mu^+$) not originating from J/ψ vertex referred as 3rd muon
- Offline selections : HLT : $J/\psi + \mu$, $d_{xy} < 0.05$ cm, $d_0 < 0.2$ cm, $\mathcal{P}(B_c^+(3^{rd}\ \mu)\text{vertex}) > 0.01\%$,
- $m_{B_c^+} < 10$ GeV, $p_T^{\mu 1} > 6$ GeV, $p_T^{\mu 2, \mu 3} > 4$ GeV
- Discriminator between $\mu \& \tau$ channel :
  $q^2 = (p_{B_c^+} - p_{J/\psi})^2$, $p_{B_c^+} = m_{B_c^+} / m_{3\mu}^{vis} \cdot p_{3\mu}^{vis}$, $IP3D/\sigma_{IP3D}$, $L_{xy}/\sigma_{L_{xy}}$

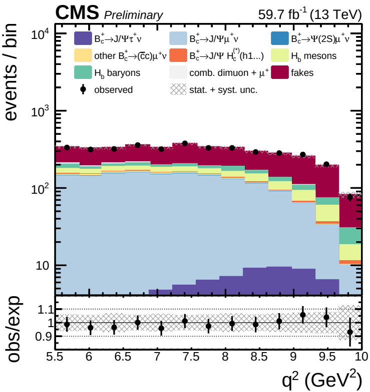
π , K : misidentified as μ : fakes, $\text{H}_b \to J/\psi(\mu^+\mu^-) + \mu^+$

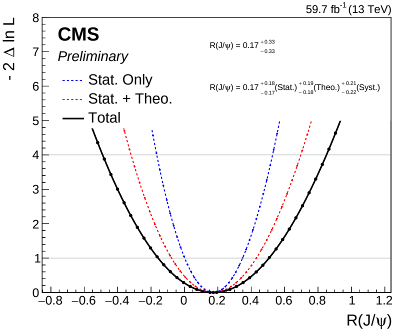


$R(J/\psi) : B_c^+ \to J/\psi \tau^+ \nu_\tau$

Physics comparison with data in q^2 discriminator

$R(J/\psi) = 0.17^{0.18}_{-0.17}(\text{stat})^{+0.21}_{-0.22}(\text{syst})^{0.19}_{-0.18}(\text{theo})$



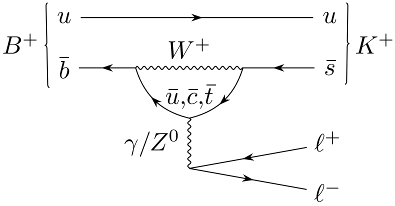


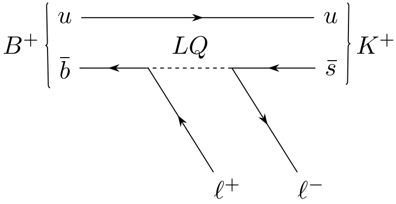
$m(3\mu) < m_{B_c^+}$, $q^2 > 5.5\ \text{GeV}^2$, $IP3D/\sigma_{IP3D} > 2$

Within 0.3σ with value predicted by SM and 1.3σ with the value measured by LHCb

This result will certainly help the theory to be more tuned

$R(K) : B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$





- In order to avoid systematics in the low momentum region double ratio method is approached
- $R(K)(q^{\mathbf{2}}) = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)(q^{\mathbf{2}})}{\mathcal{B}(B^+ \to J/\psi(\mu^+\mu^-)K^+)} / \frac{\mathcal{B}(B^+ \to K^+e^+e^-)(q^{\mathbf{2}})}{\mathcal{B}(B^+ \to J/\psi(e^+e^-)K^+)}$
- The analysis exploits the usage of B-Parking (POS-EPS-2019-139) data collected with a delayed trigger
- L1 : $\mu_{trig} : p_t > 9\,\text{GeV}, IP_{xy}/\sigma_{xy} > 6,\ \mu_{\mathbf{2}} : p_t > 2\,\text{GeV},$ $\Delta z(\mu_{trig}, K^+) < 1\,\text{cm},\ \Delta z(\mu_{trig}, \mu_{\mathbf{2}}) < 1\,\text{cm}$
- Offline selections : HLT : $p_T(K^+) > 1\,\text{GeV}, p_T(B^+) > 3\,\text{GeV},\ L_{xy}/\sigma_{L_{xy}} > 1,\ P_{B^+\mathbf{vextex}} > 10^{-\mathbf{5}},$
- $\cos\alpha_{\mathbf{3}D}(B^+) > 0.9,\ 5.0 < m_{B^+} < 5.6\,\text{GeV}$

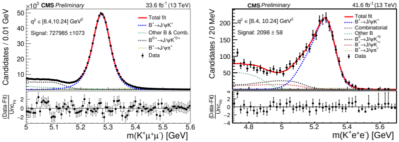
$R(K) : B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$

Yield in three different resonance bin, for electrons a dedicated low momentum algorithm (LP) was in application, for *details please visit our physics summary*

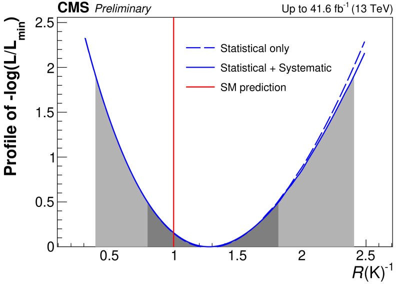
Channel	q^2 range	Yield
$B^+ \to K^+\mu^+\mu^-$	1.1–6.0 GeV^2	1267 ± 55
$B^+ \to J/\psi(\mu^+\mu^-)K^+$	8.41–10.24 GeV^2	$728\,000 \pm 1100$
$B^+ \to \psi(2S)(\mu^+\mu^-)K^+$	12.60–14.44 GeV^2	$68\,300 \pm 500$

Channel	q^2 range	PF-PF yield	PF-LP yield
$B^+ \to K^+e^+e^-$ (low-q^2)	1.1–6.0 GeV^2	17.9 ± 7.2	3.0 ± 5.9
$B^+ \to J/\psi(e^+e^-)K^+$	8.41–10.24 GeV^2	4857 ± 84	2098 ± 58
$B^+ \to \psi(2S)(e^+e^-)K^+$	12.60–14.44 GeV^2	320 ± 20	94 ± 11

Mass yield signals : signal and background sums the total *pdf* of the fit.



Likelihood function from the fit profiled as a function of $R(K)^{-1}$



In the $1.1 < q^2 < 6.0\,\mathrm{GeV}^2$

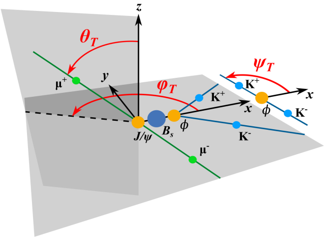
1. $R(K) = 0.78^{+0.47}_{-0.23}$
2. $\mathcal{B}(K^{\pm}\mu^{+}\mu^{-}) = (12.42 \pm 0.68) \times 10^{-8}$
3. This measurement is limited by the statistical precision of the electron channel
4. The inclusive branching fraction in the same q^2 range is consistent with and has a comparable precision to the present world average value

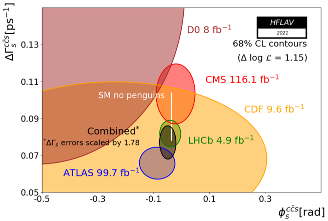
- Studies of discrete symmetries

  $\phi_s : B_s^0 \to J/\psi\phi(1020)$ - Phys. Lett. B 816 (2021) 136188
  $A_{FB}, F_L : B^+ \to K^{*+}\mu^+\mu^-$ - JHEP 04 (2021) 124

$B_s^0 \to J/\psi\phi$ introduction

- HFLAV includes: current CMS result $\Rightarrow$
- Flavour tagged time dependent angular analysis
- We measure $\phi_s \simeq -2\beta_s$
- A robust model also open the plethora of measuring : Γ_s, $\Delta\Gamma_s$, $|\lambda|$, Δm_s
- $$p_s = f\left(\sqrt{\frac{P_{tag}S}{2}}\sqrt{\frac{S}{S+B}}\,e^{-\frac{\sigma_{ct}^2\Delta m_s^2}{2}}\right)$$





1. P-Wave: $B_s^0 \to J/\psi\phi$
   1.1 A_0 : $L = 0$, CP-even.
   1.2 $A_\perp$: $L = 1$, CP-odd.
   1.3 $A_\parallel$: $L = 2$, CP-even.
2. S-Wave: Non resonant $B_s^0 \to J/\psi\, K^+K^-$, and $B_s^0 \to J/\psi\, f_0(\to K^+K^-)$
   2.1 A_S : $L = 0$, CP-even.
3. Transversity basis : θ_T, ϕ_T, ψ_T
4. Reconstruction: kinematic fit - J/ψ, fit four tracks to PV using Kalman vertex fitter, save best B_s candidate with highest vertex fit probability.
5. Physics selections : Optimization - `GA`.

$\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ Decay Rate

$$\frac{d^4\Gamma(B_s^0(t))}{d\Theta dt} = \widetilde{\mathcal{F}}(\Theta, ct, \alpha) = \sum_{i=1}^{10} \mathcal{O}_i(\alpha, t) \cdot g_i(\Theta) \tag{1}$$

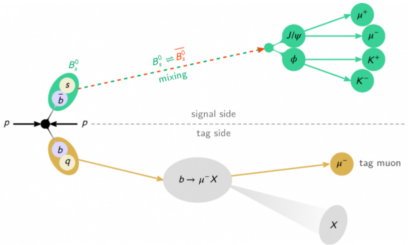
$$\mathcal{O}_i = N_i e^{-\Gamma_s t} \left[a_i \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_i \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_i \xi(1-2\omega)\cos(\Delta m_s t) + d_i \xi(1-2\omega)\sin(\Delta m_s t)\right] \tag{2}$$

i	$g_i(\theta_T, \psi_T, \varphi_T)$	N_i	a_i	b_i	c_i	d_i
1	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert\lvert A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad S = -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \qquad D = -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2} \tag{3}$$

C is sensitive to direct CPV and S is sensitive to small ϕ_s

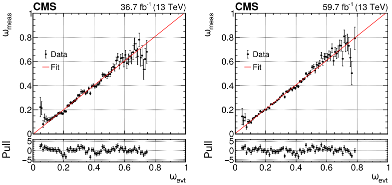
Flavour tagging



1. b quarks are produced in $b\bar{b}$ pairs.
2. Additional muon is used to Tag the flavour of $\mathrm{B_s^0}$, via $b \to \mu X$ decays of the other b
3. OS-muon tagger, tagging variable : μ^Q
   $\mu^- \to os : b \to$ signal : $\bar{b}$
   $\mu^+ \to os : \bar{b} \to$ signal : b
4. Developed : simulated $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$,
   Calibrated : self tagged $\mathrm{B^\pm} \to \mathrm{J}/\psi\mathrm{K^\pm}$.

Figures of merit :

1. $\epsilon_{\mathrm{tag}} = N_{\mathrm{tag}}/N_{\mathrm{total}}$: tagging efficiency.
2. $\omega_{\mathrm{tag}} = N_{\mathrm{tag,wrong}}/N_{\mathrm{tag}}$: per-event mistag probability evaluated with a DNN.
3. $P_{\mathrm{tag}} = \epsilon_{\mathrm{tag}}(1 - 2\omega_{\mathrm{tag}})^2$: tagging power.
4. $\mathrm{f}_{dnn} = 1 - \omega_{\mathrm{evt}}$.



Dataset	$\epsilon_{\mathrm{tag}}(\%)$	$\omega_{\mathrm{tag}}(\%)$	$P_{\mathrm{tag}}(\%)$
2017	$(45.7 \pm 0.1)\,\%$	$(27.1 \pm 0.1)\,\%$	$(9.6 \pm 0.1)\,\%$
2018	$(50.9 \pm 0.1)\,\%$	$(27.3 \pm 0.1)\,\%$	$(10.5 \pm 0.1)\,\%$

Final Results

ϕ_s and $\Delta\Gamma_s$ are consistent with SM prediction (arXiv:1102.4274).

$$\boxed{\phi_s = -11 \pm 50\,(\mathrm{stat}) \pm 10\,(\mathrm{syst})\,\mathrm{mrad},\ \Delta\Gamma_s = 0.114 \pm 0.014\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst})\,\mathrm{ps}^{-1}}$$

Γ_s and Δm_s are consistent with world average values (PhysRevD.98.030001).

$$\boxed{\Gamma_s = 0.6531 \pm 0.0042\,(\mathrm{stat}) \pm 0.0026\,(\mathrm{syst})\,\mathrm{ps}^{-1},\ \Delta m_s = 17.51 \pm^{+0.10}_{-0.09}\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\,\hbar\mathrm{ps}^{-1}}$$

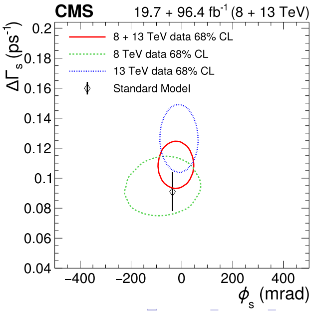
Further combined with $\sqrt{s} = 8\,\mathrm{TeV}$ result (PLB2016.03.046)

$$\boxed{\phi_s = -21 \pm 44\,(\mathrm{stat}) \pm 10\,(\mathrm{syst})\,\mathrm{mrad},\ \Delta\Gamma_s = 0.1032 \pm 0.0095\,(\mathrm{stat}) \pm 0.0048\,(\mathrm{syst})\,\mathrm{ps}^{-1}}$$

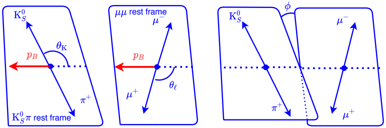
1. $|\lambda|$ is consistent with no direct CP violation.

$$\boxed{|\lambda| = 0.972 \pm 0.026(\mathrm{stat}) \pm 0.003(\mathrm{syst})}$$

2. First time CMS measures $|\lambda|$ and Δm_s.
3. A precise measurement with all taggers and with a $J/\psi - TrkTrk$ trigger is in the pipeline.



A_{FB}, F_L : $B^+ \to K^{*+}\mu^+\mu^-$ - introduction



- Measurement of forward-backward asymmetry (A_{FB}), and longitudinal polarization (F_L)
- This result is based on the 8TeV data with $L_{int} = 20\,\text{fb}^{-1}$
- Angular analysis with two angles : θ_K, & θ_l
- Two oppositely charged muon : $p_T > 3.5$ GeV, &$|\eta| < 2.2$ fitted to a common vertex with $\chi^2(\mathcal{P}_{vtx}) < 10\%$
- $\cos\alpha < 0.9$, $p_T^{\mu^+\mu^-} > 6.9$ GeV
- Offline signal reconstructed with a $K^{*+}(\to K_s^0\pi^+)$ and the two muons already selected
- $4.8 < m_{K_s^0\pi^+\mu^+\mu^-} < 5.8$ GeV

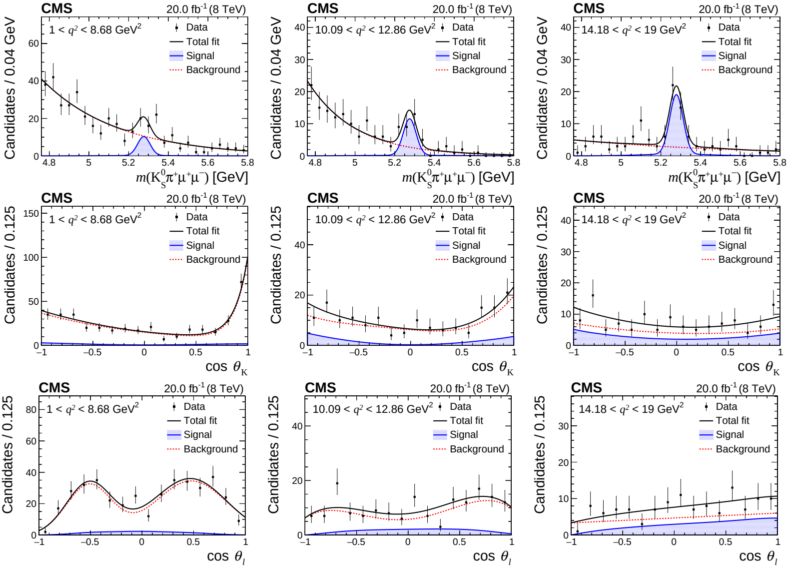
decay distribution as function of q^2:

$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_K\, d\cos\theta_\ell\, dq^2} = \frac{9}{16}\left\{\frac{2}{3}\left[F_S + 2A_S\cos\theta_K\right](1-\cos^2\theta_\ell)\right.$$
$$+\ (1-F_S)\left[2F_L\cos^2\theta_K\,(1-\cos^2\theta_\ell)\right.$$
$$+\ \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)(1+\cos^2\theta_\ell)$$
$$\left.\left.+\ \frac{4}{3}A_{FB}\left(1-\cos^2\theta_K\right)\cos\theta_\ell\right]\right\}.$$

fit model : signal + background

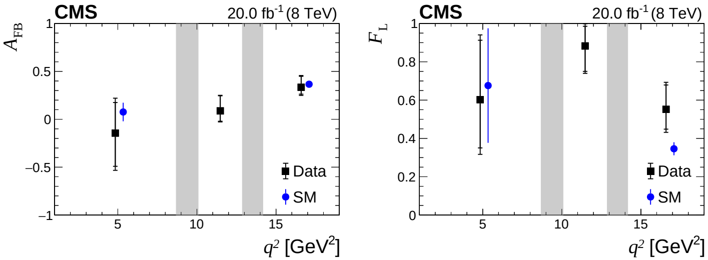
$$\text{pdf}(m,\cos\theta_K,\cos\theta_\ell) = Y_S\, S^m(m)\, S^a(\cos\theta_K,\cos\theta_\ell)\,\epsilon(\cos\theta_K,\cos\theta_\ell)$$
$$+\,Y_B\, B^m(m)\, B^{\theta_K}(\cos\theta_K)\, B^{\theta_\ell}(\cos\theta_\ell).$$

$A_{FB}, F_L : B^+ \to K^{*+}\mu^+\mu^-$ - final fit



$A_{FB}, F_L : B^+ \to K^{*+}\mu^+\mu^-$ - results

The results are shown with black square which comprises both statistical and total uncertainties and a comparison with SM is also shown in the plot advocates about the consistency with SM



q^2 (GeV^2)	Y_S	A_{FB}	F_L
$1 - 8.68$	22.1 ± 8.1	$-0.14\,^{+0.32}_{-0.35} \pm 0.17$	$0.60\,^{+0.31}_{-0.25} \pm 0.13$
$10.09 - 12.86$	25.9 ± 6.3	$0.09\,^{+0.16}_{-0.11} \pm 0.04$	$0.88\,^{+0.10}_{-0.13} \pm 0.05$
$14.18 - 19$	45.1 ± 8.0	$0.33\,^{+0.11}_{-0.07} \pm 0.05$	$0.55\,^{+0.13}_{-0.10} \pm 0.06$

- The vertical shaded regions corresponds to the regions dominated by $B^+ \to K^{*+}J/\psi$ and $B^+ \to K^{*+}\psi(2S)$ decays
- These are the first results from this exclusive decay mode and are in agreement with a standard model prediction

Summary

- We have presented the results of some of the flagship analyses of CMS B-Physics Analysis Group (BPAG)
- These results are competitive with results of dedicated b-factories, such as Belle or LHCb
- These are the results with highest precision what CMS could achieved with Run-I and Run-II data
- Many new exciting ideas are being materializing now in terms of analyses, tagging algorithm, and trigger lines
- Our experience with systematic uncertainties reflects that CMS was in great condition in the last Runs (Run-I & Run-II) and CMS is ready to unfold various unknown features of flavour physics in the upcoming Run-III.

Back-up

Maximum likelihood fit

Event PDF :

$$P = \frac{N_{\mathrm{sig}}}{N_{\mathrm{tot}}} P_{\mathrm{sig}} + \frac{N_{\mathrm{bkg}}}{N_{\mathrm{tot}}} P_{\mathrm{bkg}}$$

Negative log likelihood :

$$-\ln \mathcal{L} = -\sum_{i=0}^{N_{\mathrm{evt}}} \ln P_i + N_{\mathrm{tot}} - N_{\mathrm{evt}} \ln N_{\mathrm{tot}}$$

$$\begin{aligned}
P_{\mathrm{sgn}} &= \epsilon(ct)\,\epsilon(\Theta)\,[\widetilde{\mathcal{F}}(\Theta, ct, \alpha) \otimes G(ct, \sigma_{ct})]\, P_{\mathrm{sgn}}(\mathrm{m}_{B_s^0})\, P_{\mathrm{sgn}}(\sigma_{ct})\, P(\xi)_{\mathrm{sgn}}\,, \\
P_{\mathrm{comb}} &= P_{\mathrm{comb}}(\cos\theta_T, \phi_T)\, P_{\mathrm{comb}}(\cos\psi_T)\, P_{\mathrm{comb}}(ct)\, P_{\mathrm{comb}}(\mathrm{m}_{B_s^0})\, P_{\mathrm{comb}}(\sigma_{ct})\, P(\xi)_{\mathrm{comb}}\,, \\
P_{\mathrm{peak}} &= P_{\mathrm{peak}}(\cos\theta_T, \phi_T)\, P_{\mathrm{peak}}(\cos\psi_T)\, P_{\mathrm{peak}}(ct)\, P_{\mathrm{peak}}(\mathrm{m}_{B_s^0})\, P_{\mathrm{peak}}(\sigma_{ct})\, P(\xi)_{\mathrm{peak}}\,,
\end{aligned} \tag{4}$$

1. $\epsilon(ct)\,\epsilon(\Theta)$: Efficiency.
2. $\widetilde{\mathcal{F}}(\Theta, ct, \alpha)$: Decay distribution.
3. $G(ct, \sigma_{ct})$: Gaussian resolution.

1. $P(\mathrm{m}_{B_s^0})$: Mass PDFs.
2. $P(\sigma_{ct})$: Decay time uncertainty PDFs.
3. $P(\xi)$: Tag distribution.

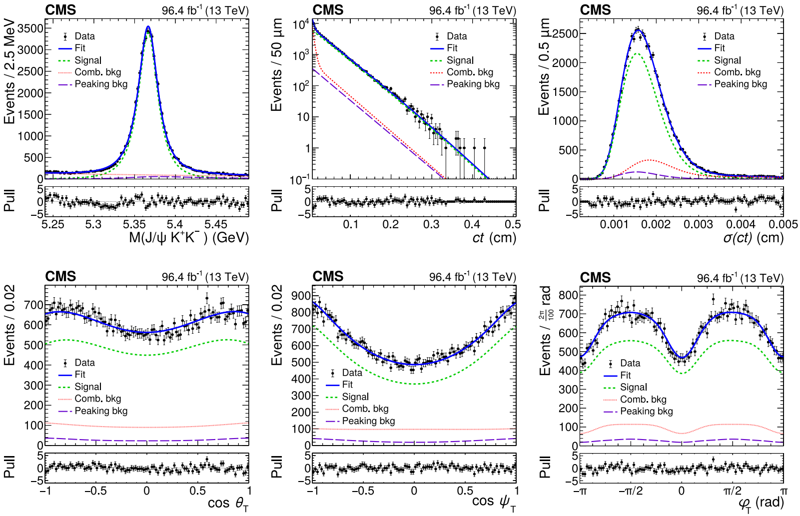
Decay time and angular background :

$$\boxed{P(\cos\theta_T, \phi_T),\ P(\cos\psi_T),\ P(ct)}$$

The peaking background P_{peak} is originated from the decay $\mathrm{B_d^0} \to \mathrm{J}/\psi\,\mathrm{K}^{*0} \to \mu^+\mu^-\,\mathrm{K}^+\pi^-$ where the pion is misidentified as a kaon.

One dimensional Data fit projections

One dimensional projection of multidimensional unbined extended maximum likelihood fit.



B_s^0-$\overline{B}_s^0$ mixing

1. Direct CPV :

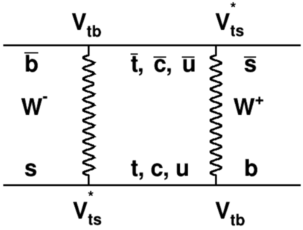
$$P(B_s^0 \to f) \neq P(\overline{B}_s^0 \to \bar{f})$$

2. Indirect CPV in mixing :

$$P(B_s^0 \to \overline{B}_s^0) \neq P(\overline{B}_s^0 \to B_s^0)$$

3. CPV in Interference :

$$P(B_s^0 \to f_{cp}) \neq P(B_s^0 \to \overline{B}_s^0 \to \bar{f}_{cp})$$



$$|B_{L,H}\rangle = p\,|B_s^0\rangle \pm q\,|\overline{B}_s^0\rangle, \quad |p|^2 + |q|^2 = 1$$

Time dependent CPV

$$\begin{aligned} a_{cp} &\propto \Gamma(\overline{B}_s^0 \to f_{cp}) - \Gamma(B_s^0 \to f_{cp}) \\ &\propto \eta_f \sin(\phi_s) \sin(\Delta m_s t) \end{aligned} \quad (5)$$

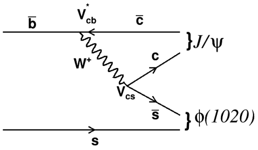
$$m_s = \frac{M_L + M_H}{2}, \quad \Delta m_s = M_H - M_L$$

$$\Gamma_s = \frac{\Gamma_H + \Gamma_L}{2}, \quad \Delta\Gamma_s = \Gamma_L - \Gamma_H$$

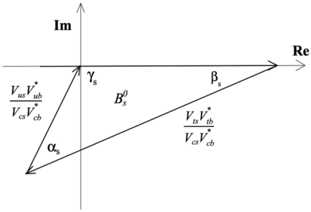
CPV : B_s^0 meson

The very definition of the convention independent parameter $\lambda_{\rm cp}$ specific for the $\mathrm{B}_s^0 \to \mathrm{J}/\psi\phi \to \mu^+\mu^-\mathrm{K}^+\mathrm{K}^-$ decay can be defined by combining the mixing and tree level $b \to c\bar{c}s$ transition,

$$\begin{aligned}\lambda_{\rm cp} &= \left(\frac{p}{q}\right)_{B_s^0} \frac{\bar{A}_{J/\psi\phi}}{A_{J/\psi\phi}} \\ &= \mathcal{E}_{\rm cp}\left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right) \\ &= \mathcal{E}_{\rm cp}\frac{e^{-i\beta_s}}{(e^{-i\beta_s})^*} \\ &= \mathcal{E}_{\rm cp} e^{-2i\beta_s}\end{aligned} \tag{6}$$



$$\boxed{\mathrm{B}_s^0 : V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$$



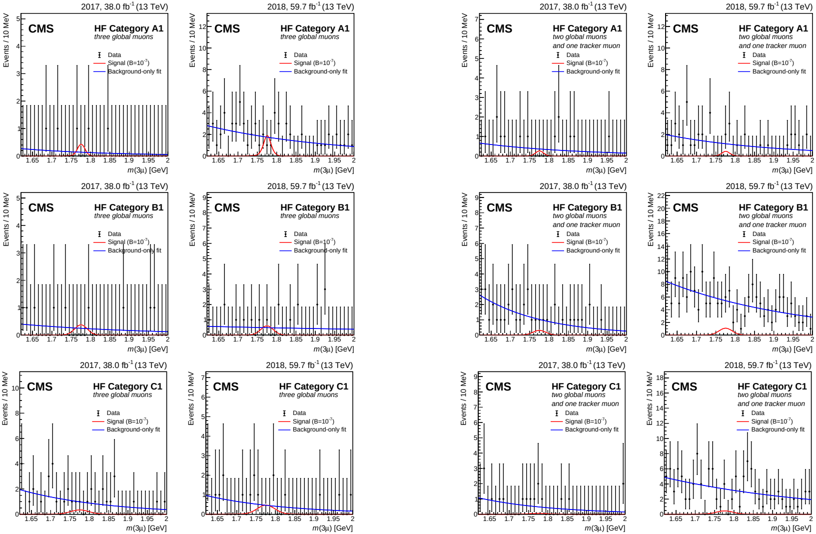
B_s^0 interference case :

$$\boxed{arg(\lambda_{\rm cp}) = -2\beta_s \simeq \phi_s}$$

$\lambda_{\rm cp}$: conditions

1. $|\bar{A}/A| \neq 1 \to$ direct CPV
2. $|q/p| \neq 1 \to$ indirect CPV
3. $\mathrm{Im}(\lambda) \to$ interference CPV

$\tau \to 3\mu$



2017, 38.0 fb-1 (13 TeV)
2018, 59.7 fb-1 (13 TeV)
CMS
HF Category A1
three global muons
two global muons
and one tracker muon
HF Category B1
HF Category C1
Data
Signal (B=10-7)
Background-only fit
Events / 10 MeV
m(3μ) [GeV]

Systematic uncertainty - $\mathrm{B_s^0}$ meson

	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [$\hbar$ ps^{-1}]	$\lvert\lambda\rvert$	Γ_s [ps^{-1}]	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$\lvert A_S\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]
Statistical uncertainty	50	0.014	0.10	0.026	0.0042	0.0047	0.0063	0.0077	0.12	0.16	0.083
Model bias	7.9	0.0019	–	0.0035	0.0005	0.0002	0.0012	0.001	0.020	0.016	0.006
Model assumptions	–	–	–	0.0046	0.0003	–	0.0013	0.001	0.017	0.019	0.011
Angular efficiency	3.8	0.0006	0.007	0.0057	0.0002	0.0008	0.0010	0.002	0.006	0.015	0.015
Proper decay length efficiency	0.3	0.0062	0.001	0.0002	0.0022	0.0014	0.0023	0.001	0.001	0.002	0.002
Proper decay length resolution	3.5	0.0009	0.021	0.0015	0.0006	0.0007	0.0009	0.007	0.006	0.025	0.022
Data/simulation difference	0.6	0.0008	0.004	0.0003	0.0003	0.0044	0.0029	0.007	0.007	0.007	0.028
Flavor tagging	0.5	$<10^{-4}$	0.006	0.0002	$<10^{-4}$	0.0003	$<10^{-4}$	$<10^{-3}$	0.001	0.007	0.001
Sig./bkg. ω_{evt} difference	3.0	–	–	–	0.0005	–	0.0008	–	–	–	0.006
Peaking background	0.3	0.0008	0.011	$<10^{-4}$	0.0002	0.0005	0.0002	0.003	0.005	0.007	0.011
S-*P* wave interference	–	0.0010	0.019	–	0.0005	0.0005	–	0.013	–	0.019	0.019
$P(\sigma_{ct})$ uncertainty	$<10^{-1}$	0.0019	0.028	0.0004	0.0008	0.0006	0.0008	0.001	0.001	0.002	0.005
Total systematic uncertainty	10.0	0.0070	0.032	0.0083	0.0026	0.0049	0.0045	0.016	0.028	0.045	0.048

1. ϕ_s : Model bias an angular efficiency.
2. $\Delta\Gamma_s$ and Γ_s : lifetime efficiency.
3. $\Delta \mathrm{m_s}$: Lifetime resolution, SP- wave interference and peaking background.

4. $\lvert\lambda\rvert$: Angular efficiency and and model assumption.

$B_s^0 \to \mu^+\mu^-$ Effective lifetime

The effective lifetime : $B_s^0 \to \mu^+\mu^-$

$$\tau_{\mu^+\mu^-} = \frac{\int_0^\infty t[\Gamma(B_s^0 \to \mu^+\mu^-) + \Gamma(\overline{B}_s^0 \to \mu^+\mu^-)]dt}{\int_0^\infty [\Gamma(B_s^0 \to \mu^+\mu^-) + \Gamma(\overline{B}_s^0 \to \mu^+\mu^-)]dt}$$

and t is the proper decay time of the B_s^0 meson Relation : $\tau_{\mu^+\mu^-} \leftrightarrow \tau_{B_s^0}$

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1 - y_s^2}\left(\frac{1 + 2\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} y_s}\right); \quad y_s = \frac{\tau_{B_s^0}\Delta\Gamma_s}{2}$$

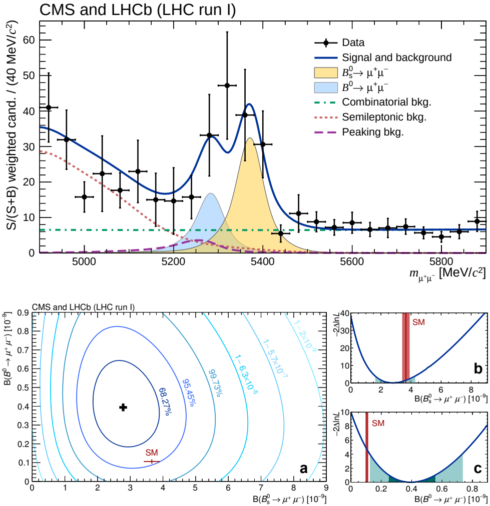
Where,

$$\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} \equiv -\frac{2\mathcal{R}(\lambda)}{1 + |\lambda|^2}, \quad \lambda \equiv \frac{q\overline{A}_{\mu^+\mu^-}}{pA_{\mu^+\mu^-}}$$

$$A_{\mu^+\mu^-} : |\psi_{B_s^0}\rangle \to |\psi_{\mu^+\mu^-}\rangle$$

CMS & LHCb combination $\mathrm{B_s^0} \to \mu^+\mu^-$

Weighted distribution di-muon invariant mass and the likelihood contours in the $\mathcal{B}(\mathrm{B_d^0} \to \mu^+\mu^-)$ versus $\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-)$ plane



Reference - Nature 522 (2015) 68