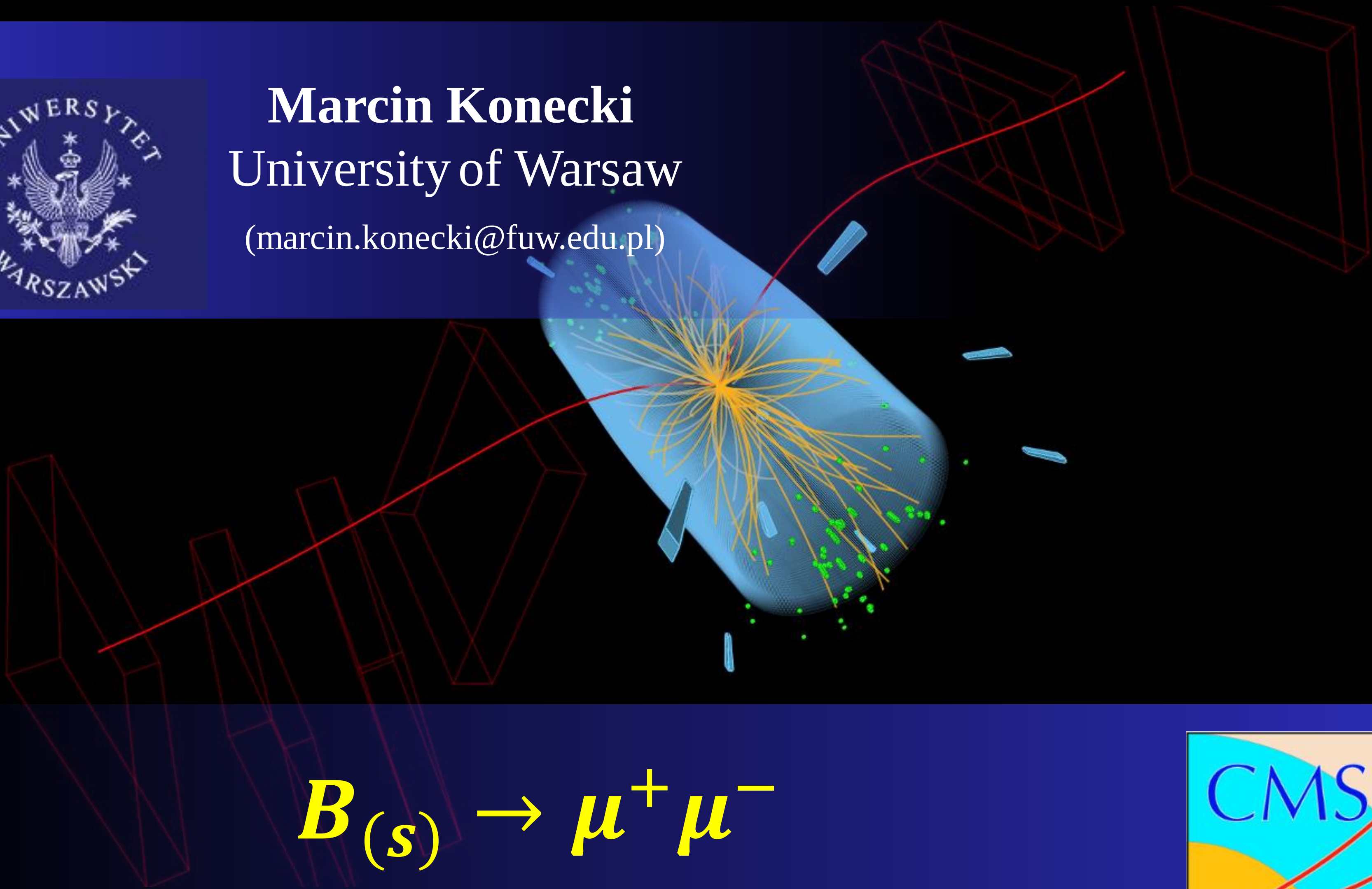
Standard Model and Beyond

5^{th} Symposium of the Division for Physics of Fundamental Interactions
of the Polish Physical Society
21-23 October 2022, Katowice

Marcin Konecki
University of Warsaw
(marcin.konecki@fuw.edu.pl)



$B_{(s)} \to \mu^+ \mu^-$ and other B-meson decays at CMS

CMS

The design goals of CMS:

1. A very good and redundant muon system
2. The best possible ECAL consistent with 1)
3. A high quality central tracking to achieve 1) and 2)
4. A financially affordable detector

CMS Technical Proposal
CERN/LHCC 94-38

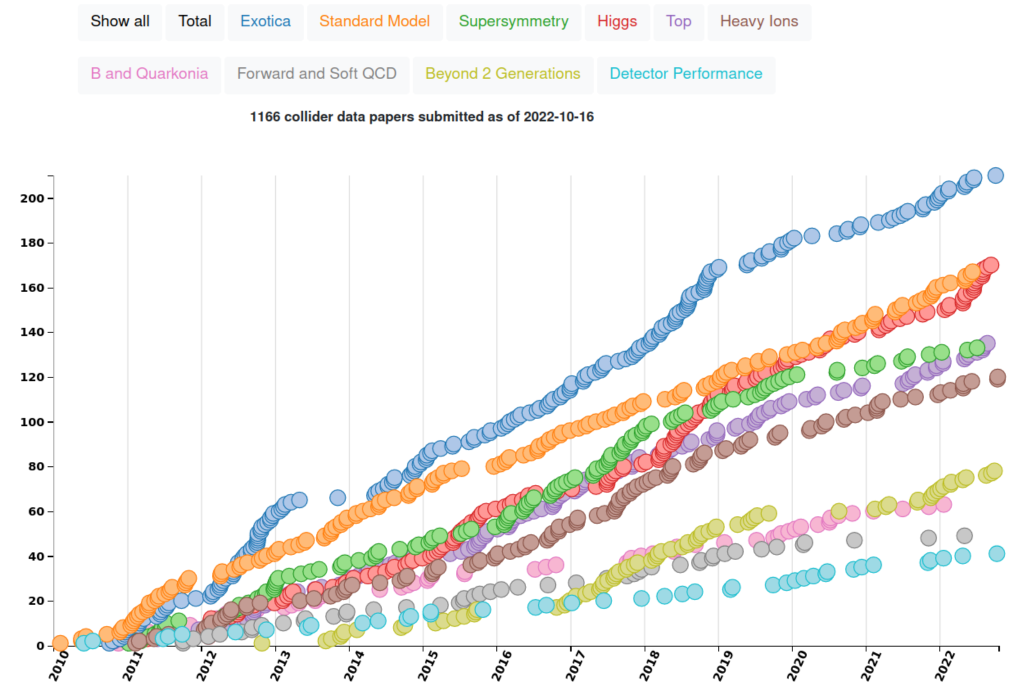
-3.8T solenoid 13m long, 6m diameter
- high eta HCAL coverage
-Silicon based inner tracking system supplementing all types of reconstr.

Powerful reconstruction of:

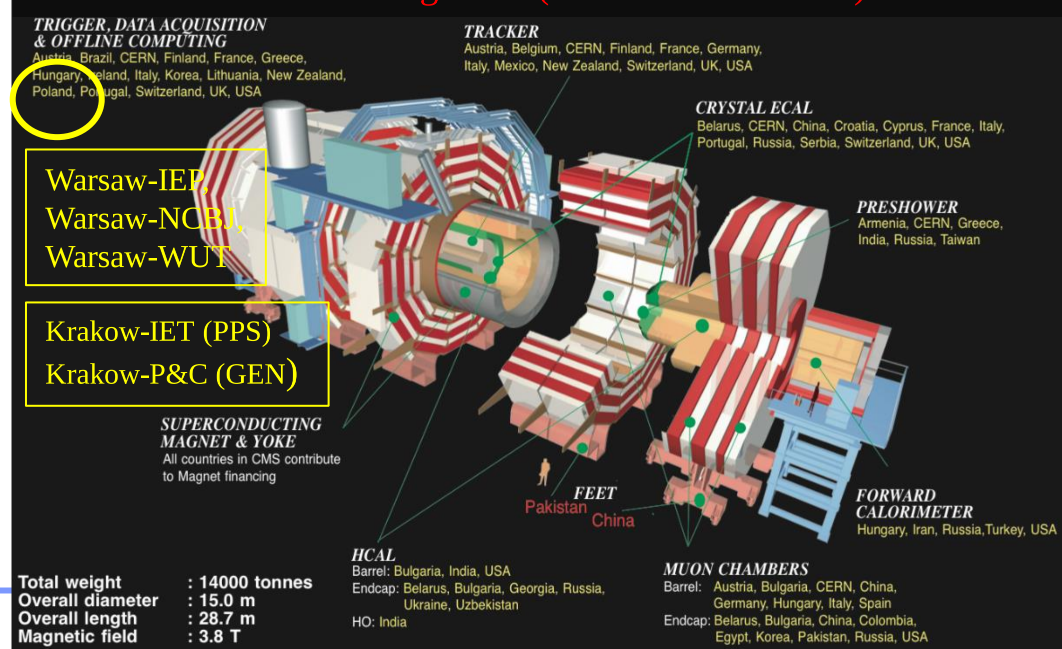
μ, e/γ, τ-jets, jets, MET

(+tracks, vertices)

CMS is a general-purpose experiment



54 Countries, 239 Institutes, 5000+members (~2100 authors)
~3000 scientists and engineers (+1000 PhD students)



B – physics with CMS – an update

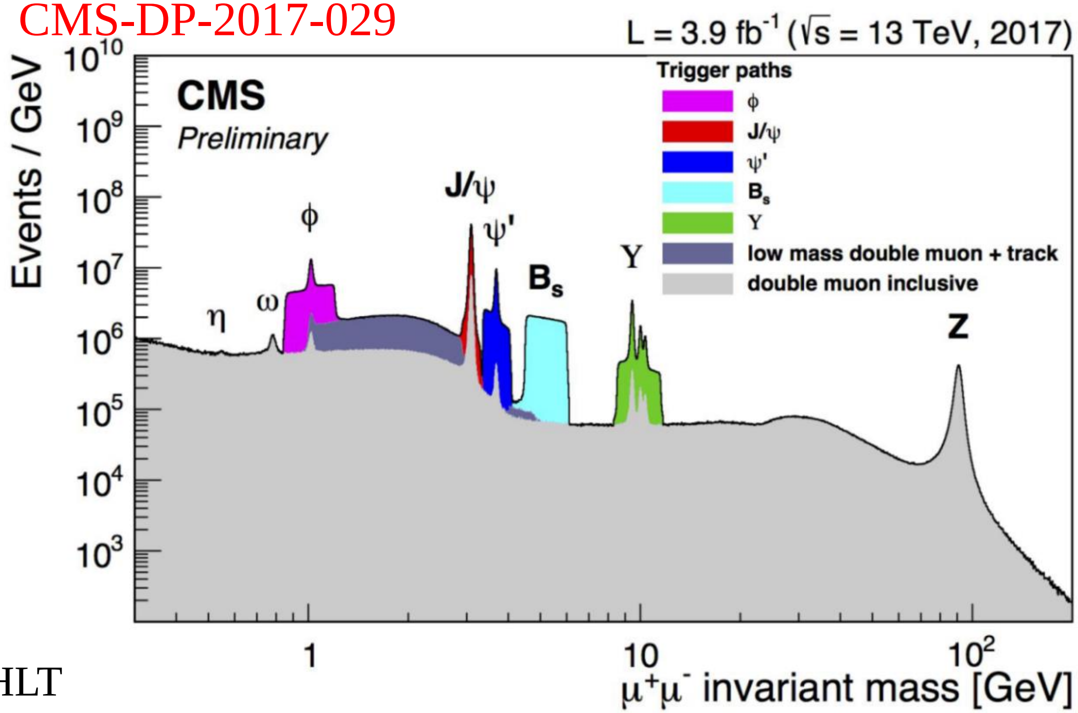
	CMS-PAS-BPH-21-006	Measurement of $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu\mu$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV	July 2022

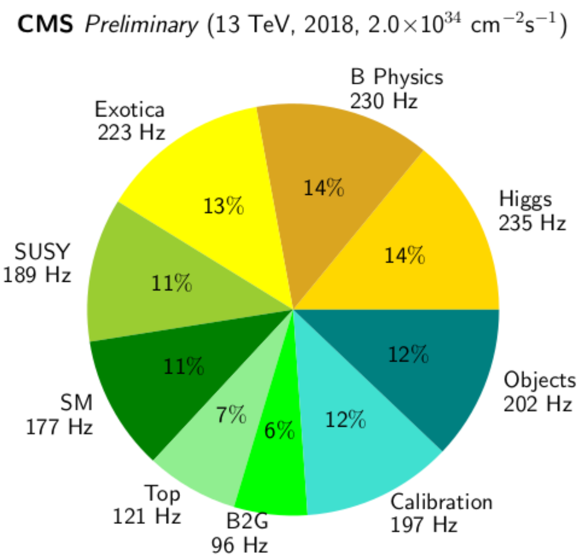
63	BPH-18-004	Observation of $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_S^0$ decays	EPJC 82 (2022) 499
62	BPH-21-004	Observation of triple J/ψ meson production in proton-proton collisions at $\sqrt{s} = 13$ TeV	Accepted by NP
61	BPH-18-003	Measurement of prompt open-charm production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV	JHEP 11 (2021) 225
60	BPH-20-004	Observation of a new excited beauty strange baryon decaying to $\Xi_b^-\pi^+\pi^-$	PRL 126 (2021) 252003
59	BPH-15-009	Angular analysis of the decay $B^+ \to K^*(892)^+\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV	JHEP 04 (2021) 124
58	BPH-19-001	Measurement of $B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV	PRD 102 (2020) 092007
57	BPH-17-004	Search for the lepton flavor violating decay $\tau \to 3\mu$ in proton-proton collisions at $\sqrt{s} = 13$ TeV	JHEP 01 (2021) 163
56	BPH-14-009	Investigation into the event-activity dependence of Υ(nS) relative production in proton-proton collisions at $\sqrt{s} = 7$ TeV	JHEP 11 (2020) 001
55	BPH-20-001	Measurement of the CP-violating phase ϕ_s in the $B_s^0 \to J/\psi\,\phi(1020) \to \mu^+\mu^-K^+K^-$ channel in proton-proton collisions at $\sqrt{s} = 13$ TeV	PLB 816 (2021) 136188
54	BPH-17-005	Observation of the $B_s^0 \to X(3872)\phi$ decay	PRL 125 (2020) 152001

49	BPH-16-004	Measurement of properties of $B_s^0 \to \mu^+\mu^-$ decays and search forf $B^0 \to \mu^+\mu^-$ with the CMS experiment	JHEP 04 (2020) 188
46	BPH-18-007	Observation of two excited B_c^+ states and measurement of the B_c^+(2S) mass in pp collisions at $\sqrt{s} = 13$ TeV	PRL 122 (2019) 132001

Dimuon triggers (for b-physics)

CMS-DP-2017-029





HLT

Dimuon mass distribution collected with various dimuon triggers:

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.

Level-1:

Typical di-muon inclusive L1 thresholds: 2012: 10+0GeV, Run2: 12+5GeV→15+7, 8+8GeV, **4+4+OS+Δ*R***

~10% of CMS bandwith@L1 (10kHz) for flavor physics.

CMS detector and b-physics

Essentials of CMS muon reconstruction:

Tracker:

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

Muon system:

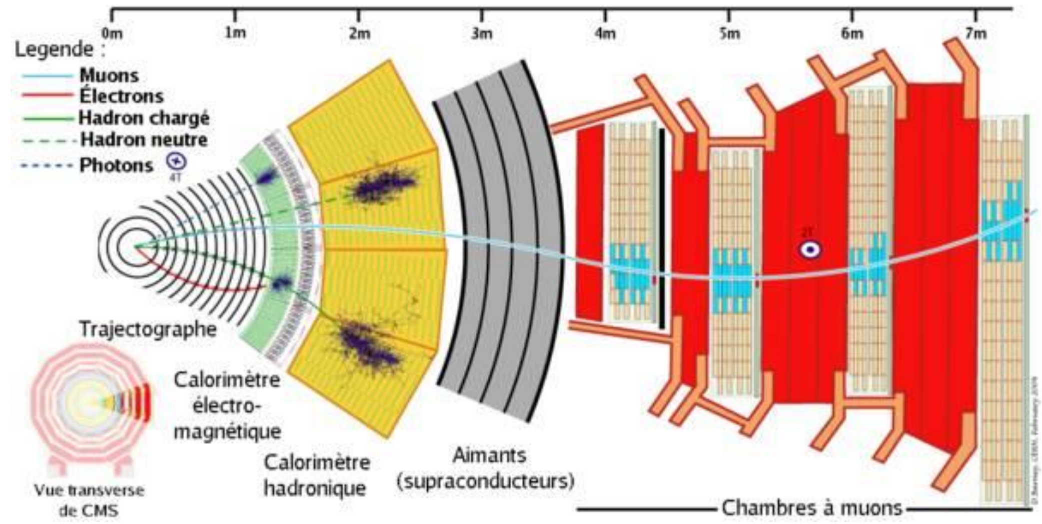
- identification of track, high-purity muon ID (fake rate ~10^{-3}).
- provide muon trigger
- initial momentum assignment

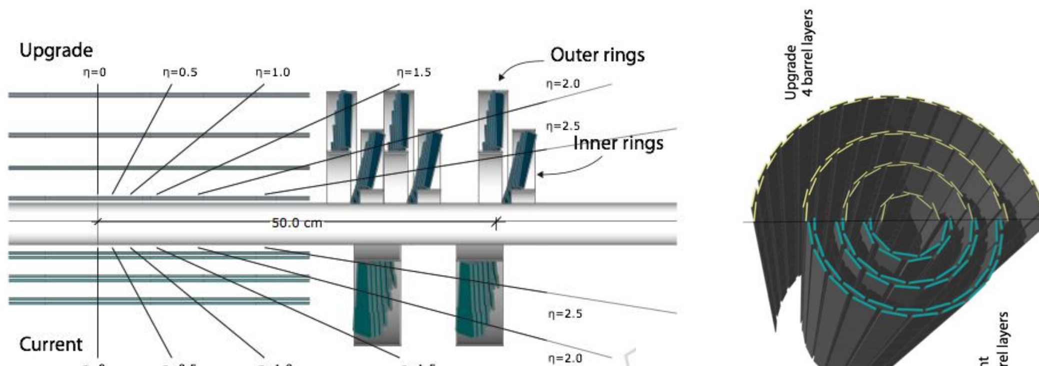
Muon reconstruction (Tracker+Muon syst):

- 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





- 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

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

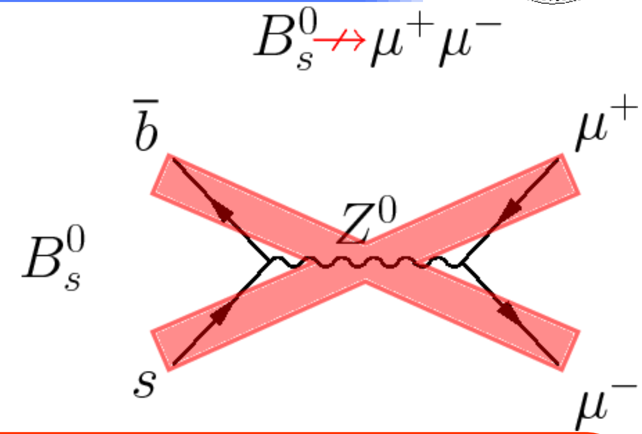
CMS PAS BPH-21-006
CMS PAS BPH-20-003
JHEP04 (2020) 188
Nature 522 (2015) 68
Phys.Rev.Lett. 111(2013) 101804

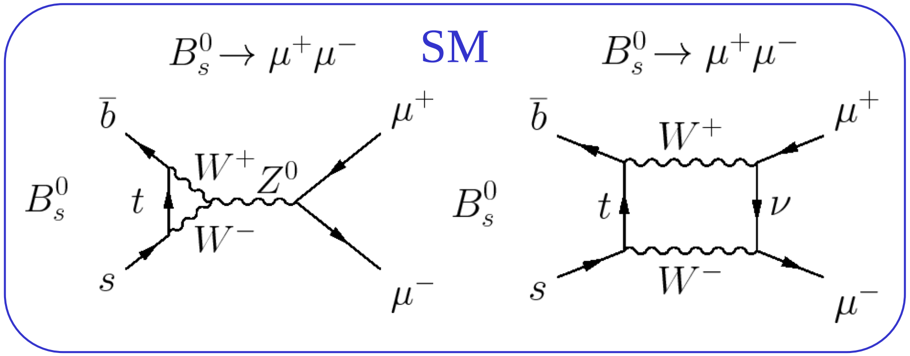
$B^0_{(s)} \to \mu^+\mu^-$: motivation

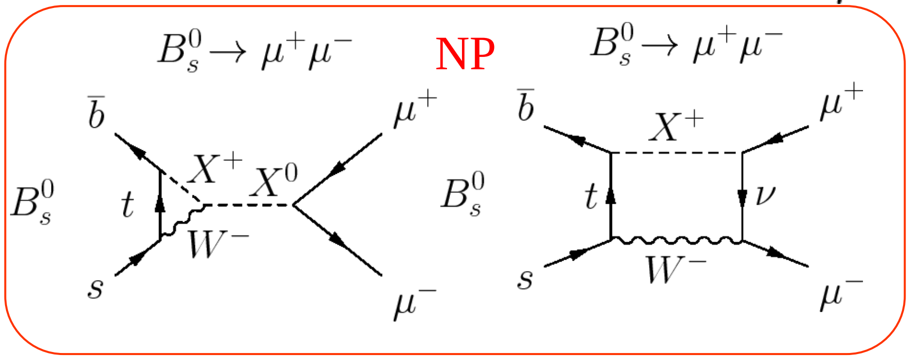
In the SM the tree-level diagrams do not contribute to FCNC, but can occur by box and penguin diagrams.

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 [Beneke et al, JHEP 10 (2019) 232]:

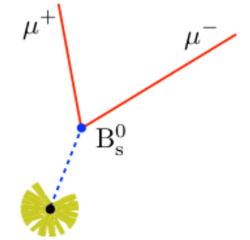
$$BR(B^0_s \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.14) \cdot 10^{-9}$$
$$BR(B^0 \to \mu^+\mu^-)_{SM} = (1.03 \pm 0.05) \cdot 10^{-10}$$

BSM: ex. NP scenarios in extended Higgs sector may enhance or suppress decay predictions. The precise measurements of BR may constraint BSM models.

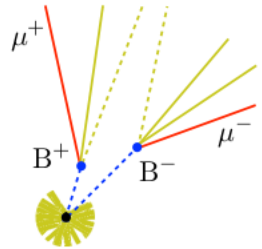
$B^0_{(s)} \rightarrow \mu^+\mu^-$: analysis

Search for $B \rightarrow \mu\mu$ around B^0 and B^0_s masses.

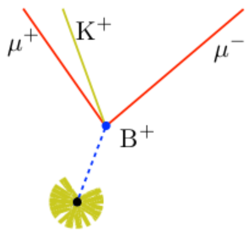
- Example of blind CMS analysis (5.15 – 5.50 GeV hidden wrt analysis region 4.9 – 5.9 GeV).



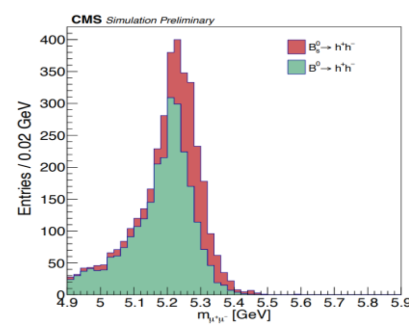
- Clear signal: two muons from one displaced vertex – common vertex fit.
  $\mu\mu$ momentum aligned along flight direction
  peaking invariant mass $M_{B^0}, M_{B^0_s}$

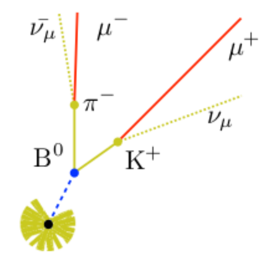


- Background sources:
  - combinatorial dimuon background where muons originate from two different heavy quarks
  - partially reconstructed semileptonic decays where both muons originate from the same B meson
    non peaking: $B \rightarrow h\mu\nu, B \rightarrow h\mu\mu, \Lambda_b \rightarrow p\mu\nu$
  - from two hadrons misidentified as muons (rare decays) - v. small with tight identification of muons with developed MVA_μ.
    peaking: $B \rightarrow hh'$ (ex. $B^0 \rightarrow K^+\pi^-$, $B^0_s \rightarrow K^+K^-$).
    Misidentification probability measured from data using
    $K^0_S \rightarrow \pi^+\pi^-$, $\phi \rightarrow K^+K^-$ and $\Lambda \rightarrow p\pi^-$ (negl.)
    Good agreement with simulation, main source K, π decays



Multivariate analysis with MVA_B discriminator combining multiple discriminating observables for non peaking bkgd.
Finally unbinned maximum likelihood (UML) fits to extract results





$B^0_{(s)} \to \mu^+\mu^-$: analysis

- Normalization channel $B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+$ to minimize uncertainties of $b\bar{b}$ production

$$BR(B^0_s \to \mu^+\mu^-) = BR(B^+ \to J/\psi K^+) \frac{N^{obs}(B^0_s \to \mu^+\mu^-)}{N^{obs}(B^+ \to J/\psi K^+)} \cdot \frac{\epsilon(B^+ \to J/\psi K^+)}{\epsilon(B^0_s \to \mu^+\mu^-)} \cdot \frac{f_u}{f_s}$$

$$BR(B^0 \to \mu^+\mu^-) = BR(B^+ \to J/\psi K^+) \frac{N^{obs}(B^0 \to \mu^+\mu^-)}{N^{obs}(B^+ \to J/\psi K^+)} \cdot \frac{\epsilon(B^+ \to J/\psi K^+)}{\epsilon(B^0 \to \mu^+\mu^-)} \cdot \frac{f_u}{f_d}$$

- Alternative: $B^0_s \to J/\psi\phi(1020) \to \mu^+\mu^- K^+ K^-$

$$BR(B^0_s \to \mu^+\mu^-) = BR(B^0_s \to J/\psi\phi) \frac{N^{obs}(B^0_s \to \mu^+\mu^-)}{N^{obs}(B^0_s \to J/\psi\phi)} \cdot \frac{\epsilon(B^0_s \to J/\psi\phi)}{\epsilon(B^0_s \to \mu^+\mu^-)}$$

- The $\frac{f_u}{f_s}$ - B^+/B^0_s fragmentation ratio and $BR(B^0_s \to J/\psi\phi)$, $BR(B^+ \to J/\psi K^+)$ are external inputs from LHCb and PDG.

- Most systematic uncertainties cancel in the ratio

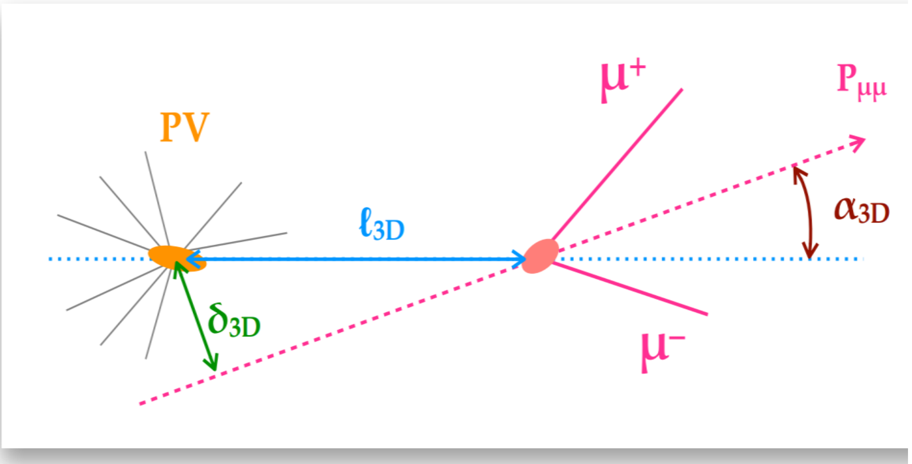
Event selection

- Previously: Run-I data (25/fb) and Run-II (2016, 36/fb)
- Now use 140 fb^{-1} of Run-II data
  2016a (20.0 fb^{-1}), 2016b (16.6 fb^{-1}), 2017 (42.0 fb^{-1}), 2018 (61.3 fb^{-1})
- Level-1: 2 opposite sign muons,
  $p_T(\mu) \geq 4\text{GeV}, |\eta| < 1.5$
- HLT: high-quality dimuon SV,
  mass around B or J/ψ.
- Offline selection → (table)

OFFLINE selection	$B \to \mu^+\mu^-$	$B^+ \to J/\psi K^+$	$B_s^0 \to J/\psi\phi$
B candidate mass [GeV]	[4.90, 5.90]	[4.90, 5.90]	[4.90, 5.90]
Blinding window [GeV]	[5.15, 5.50]		
$p_{T\mu}$ [GeV]	> 4	> 4	> 4
$\|\eta_\mu\|$	< 1.4	< 1.4	< 1.4
3D SV displacement significance	> 6	> 4	> 4
$p_{T\mu\mu}$ [GeV]	> 5	> 7	> 7
$\mu\mu$ SV probability	> 0.025	> 0.1	> 0.1
$\mu\mu$ invariant mass [GeV]	[4.9, 5.9]	[2.9, 3.3]	[2.9, 3.3]
Kaon p_T [GeV]		> 1	> 1
Mass-constrained fit probability		> 0.025	> 0.025
2D $\mu\mu$ pointing angle [rad]		< 0.4	< 0.4
ϕ candidate mass [GeV]			[1.01, 1.03]

Key MVA_B input variables:

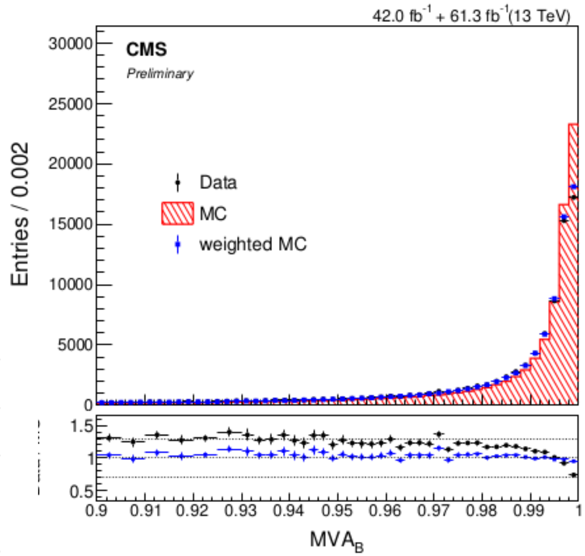
- 2D and 3D Pointing angles α
- 3D impact parameter δ and δ/σ
- Flight length l_{3D}, its significance l_{3D}/σ
- Isolation of B candidates and muons
- dimuon vertex quality



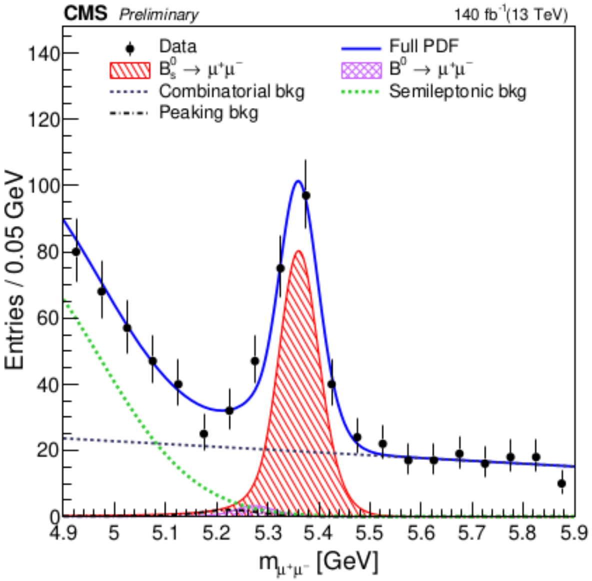
Multivariate analysis

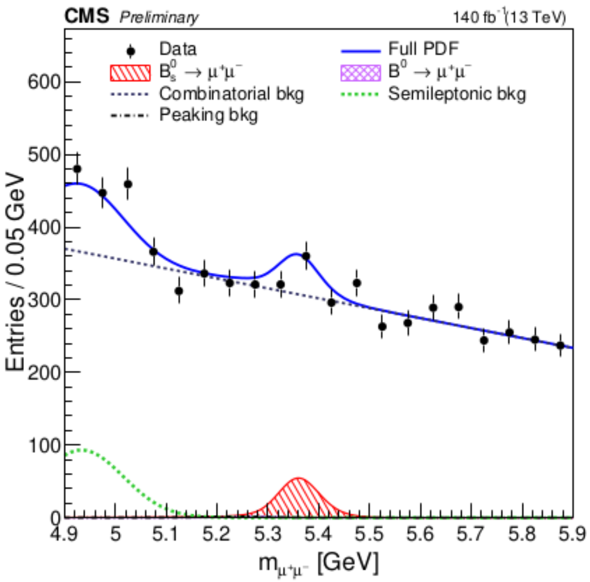
- MVA_B trained with XGBoost library.
- Training on mixture of:
  - simulated signal $B \to \mu\mu$ events and
  - data background events selected using the sidebands of the dimuon mass (outside of blinding window) . Aim – combinatorial and partially reconstr. bkd. Events split into training and testing (2:1). 3 classifiers trained separately to classify all data (event number modulo 3).
- MVA mismodeling can be a serious source of systematics
  Control sample from $B^+ \to J/\psi K^+$ with tuned selection to match $B \to \mu\mu$ kinematics.
  - correct input: $\mu\mu K$ observables, ignore K in isolation
  - soft kaon $p_T(K) < 1.5$ GeV,
  - scaled flight lengths significance
- Efficiency corrections for $B \to \mu\mu$ decays, reweight MC based on XGBoost classifier trained on difference data-MC in $B^+ \to J/\psi K^+$
- Loose region: $MVA_B > 0.9$; Tight region: $MVA_B > 0.99$

Method	Loose MVA_B selection			Tight MVA_B selection		
	2016	2017	2018	2016	2017	2018
Ratio	1.011 ± 0.013	0.939 ± 0.007	0.903 ± 0.008	1.058 ± 0.019	0.891 ± 0.008	0.885 ± 0.010
XGBoost	0.991 ± 0.008	0.949 ± 0.003	0.917 ± 0.002	1.008 ± 0.011	0.905 ± 0.004	0.908 ± 0.002



$B_{(s)} \to \mu^+\mu^-$ branching fraction fit





Unbinned 2D maximum likelihood (UML) fits with dimuon inv. mass and uncertainty

Events are categorized based on:

- η of the most forward muon: [0.0,0.7] or [0.7,1.4]
- dataset: 2016-2018 divided in 4 periods
- Signal purity based on MVA: loose [0.90,0.99] or tight [0.99,1.0]

Use $f_s/f_u = 0.231 \pm 0.008$ based on p_T dependent results from LHCb PRD 104 (2021) 032005

Effect	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$
Trigger efficiency	2 – 4%	
Pileup	1%	
Vertex quality requirement	1%	
MVA_B correction	2–3%	
Tracking efficiency (per kaon)	2.3%	
$B^+ \to J/\psi K^+$ shape uncertainty	1%	
Fit bias	2.2%	4.5%
f_s/f_u- ratio of the B meson production fractions	3.5%	-

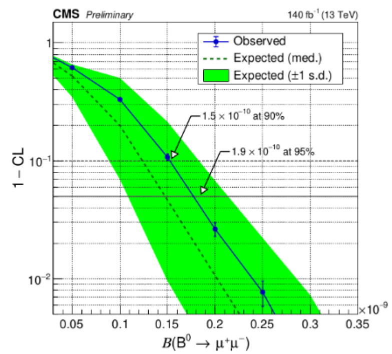
$B_{(s)} \rightarrow \mu^+\mu^-$ BR fit result

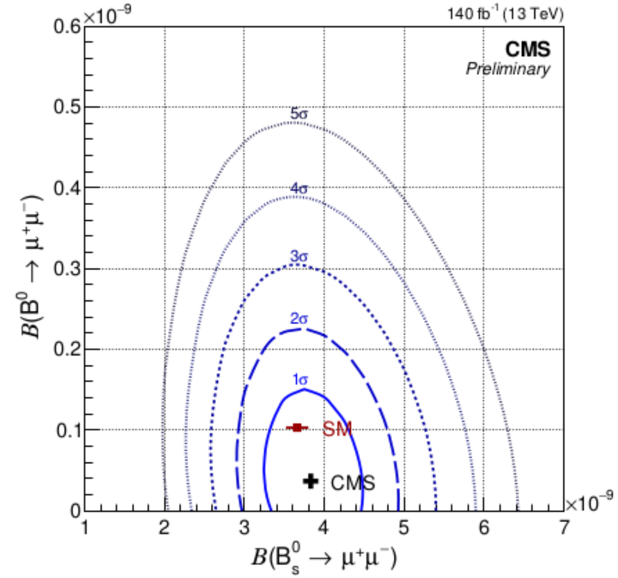
$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\text{stat})\ ^{+0.19}_{-0.16}\ (\text{syst})\ ^{+0.14}_{-0.13}\ (f_s/f_u)\right] \times 10^{-9},$$

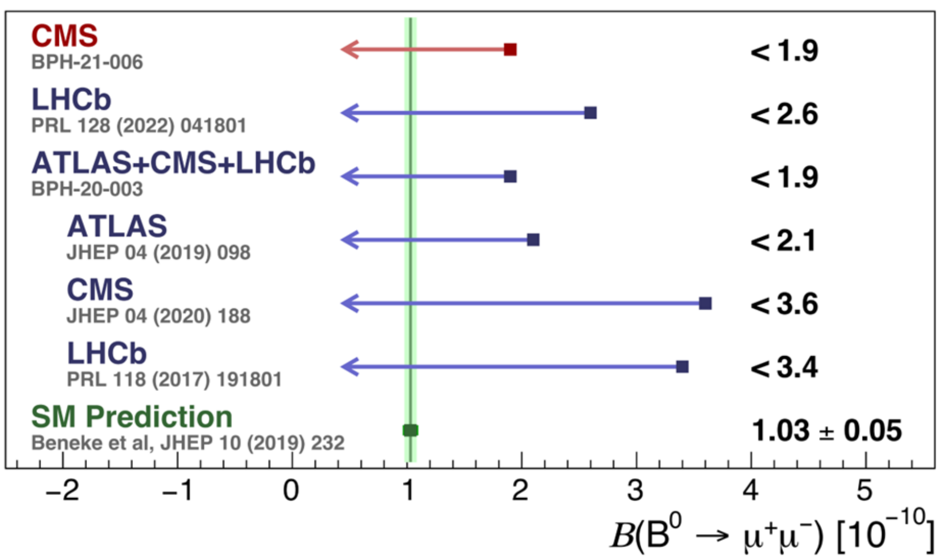
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\ (\text{stat})\ ^{+0.08}_{-0.09}\ (\text{syst})\right] \times 10^{-10}.$$

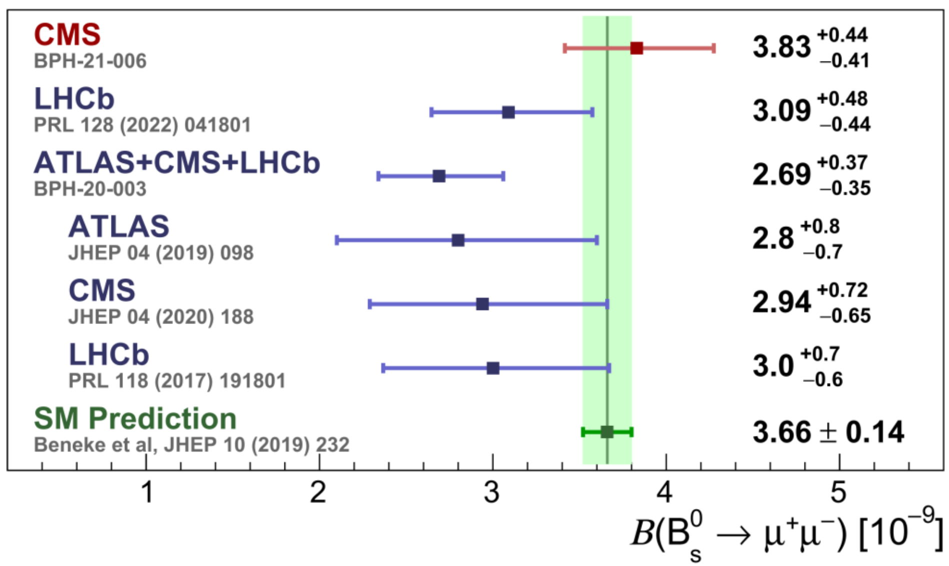
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-10} \text{ at } 90\% \text{ CL},$$

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





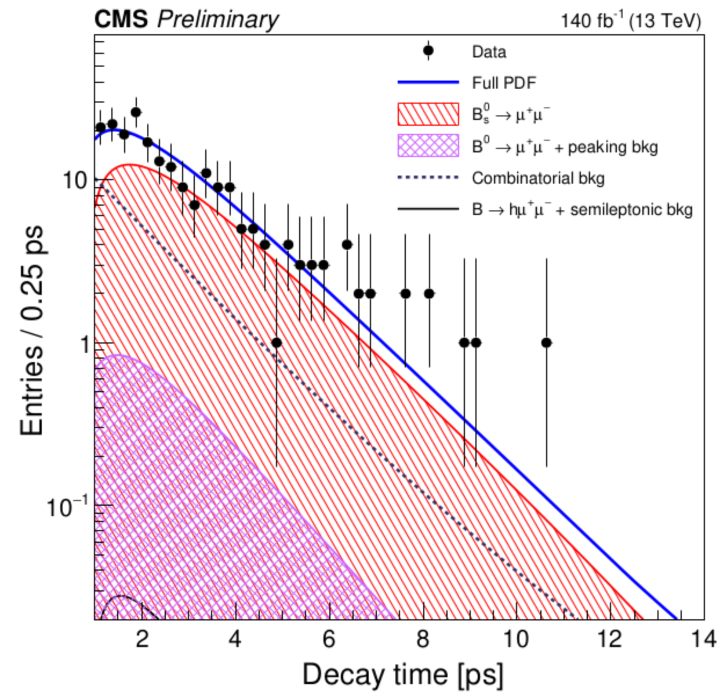


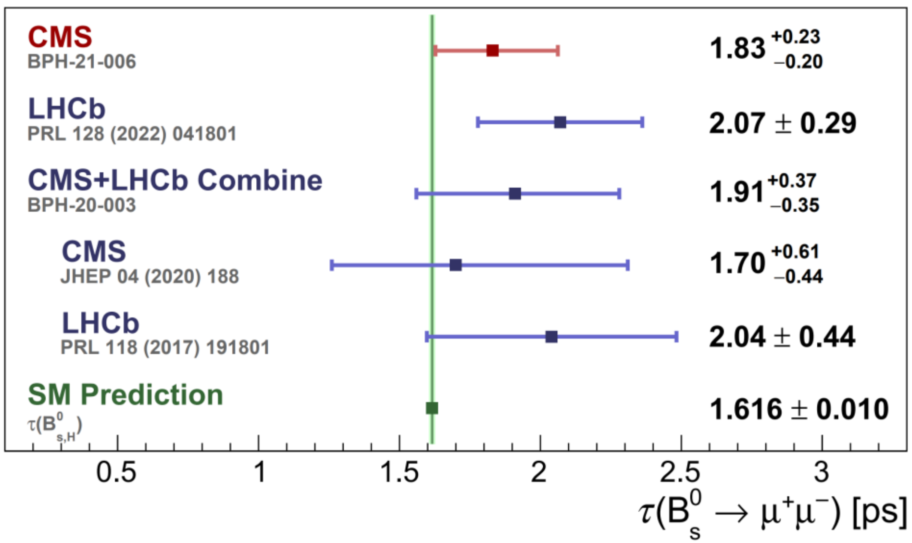


$B_s \to \mu^+\mu^-$ effective lifetime

Unbinned maximum likelihood fit to dimuon invariant mass, lifetime and its uncertainty

$$\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\ \text{ps}$$





Note: $\mu^+\mu^-$ is CP-odd, only $B_{s,H} \to \mu^+\mu^-$

Effect	2016a	2016b	2017	2018
Efficiency modeling		0.01		
Lifetime dependence		0.01		
Decay time distribution mismodeling	0.10	0.06	0.02	0.02
Lifetime fit bias	0.04	0.04	0.05	0.04
Total	0.11	0.07	0.05	0.04

(selection of) other B-meson decays

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

Phys. Lett. B 816 (2021) 136188 previous, Run-1 result: Phys.Lett.B 757 (2016) 97

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
- 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.

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 $\phi(1020)$
- CP eigenvalue of final states depends on the orbital momentum: $\eta_f = (-1)^l$
- Decay amplitude decomposed into tree polarization states:

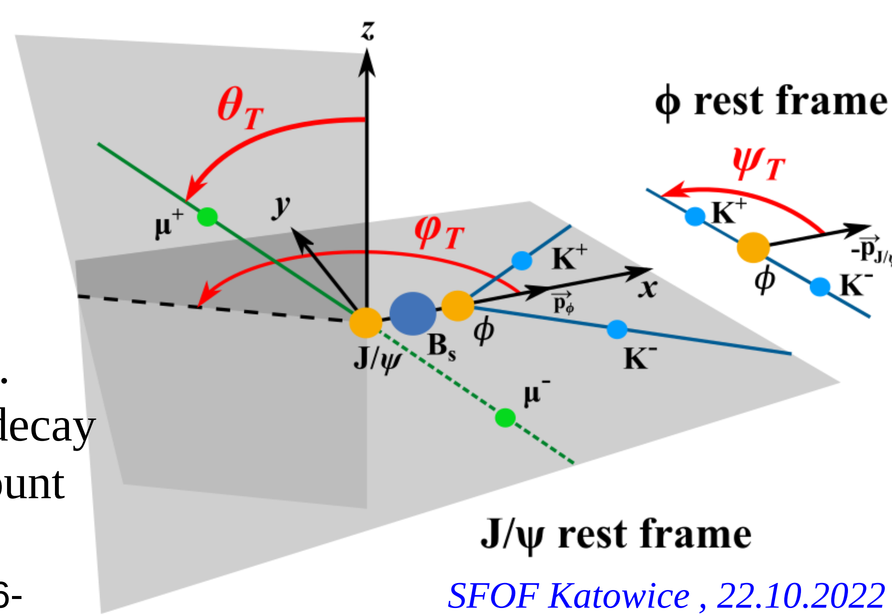
  A_0 (longitudinal), $l = 0 \to$ CP even
  $A_\perp$ (perpendicular), $l = 1 \to$ CP odd
  $A_\parallel$ (parallel), $l = 1 \to$ CP even

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).

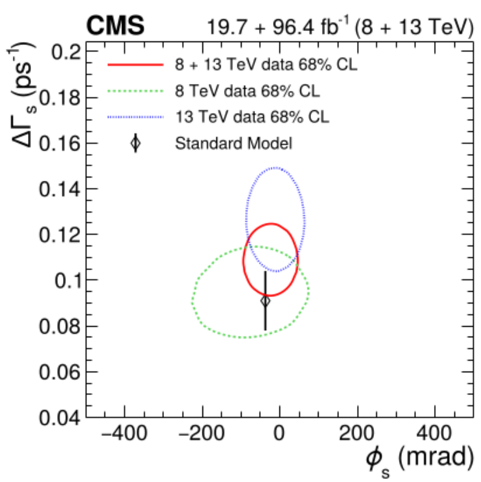
Contributions A_S ("S-wave") from non-resonant decay $B_s \to \mu^+\mu^-K^+K^-$, $B_s \to J/\psi f_0(980)$ taken into account



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

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0026
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0049
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0045
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.05
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

- ϕ_s and $\Delta\Gamma_s$ in agreement with SM: $\phi_s^{SM} = -36.82^{+0.86}_{-0.60}$ mrad, $\Delta\Gamma_s^{SM} = 0.091 \pm 0.013\ ps^{-1}$
- Γ_s consistent with world average: $\Gamma_s^{WA} = 0.6600 \pm 0.0016\ ps^{-1}$
- Δm_s consistent with SM pred.: $18.77 \pm 0.86 ps^{-1}$, slight tension with world average ($17.749 \pm 0.020 ps^{-1}$),
- $|\lambda|$ - consistent with no direct CVP
- First measurement of Δm_s and $|\lambda|$ by CMS



Combined results:

$$\phi_s = -21 \pm 44\ \text{(stat)} \pm 10\ \text{(syst) mrad}$$

$$\Delta\Gamma_s = 0.1032 \pm 0.0095 \pm 0.0048\ \text{ps}^{-1}$$

in agreement with SM predictions

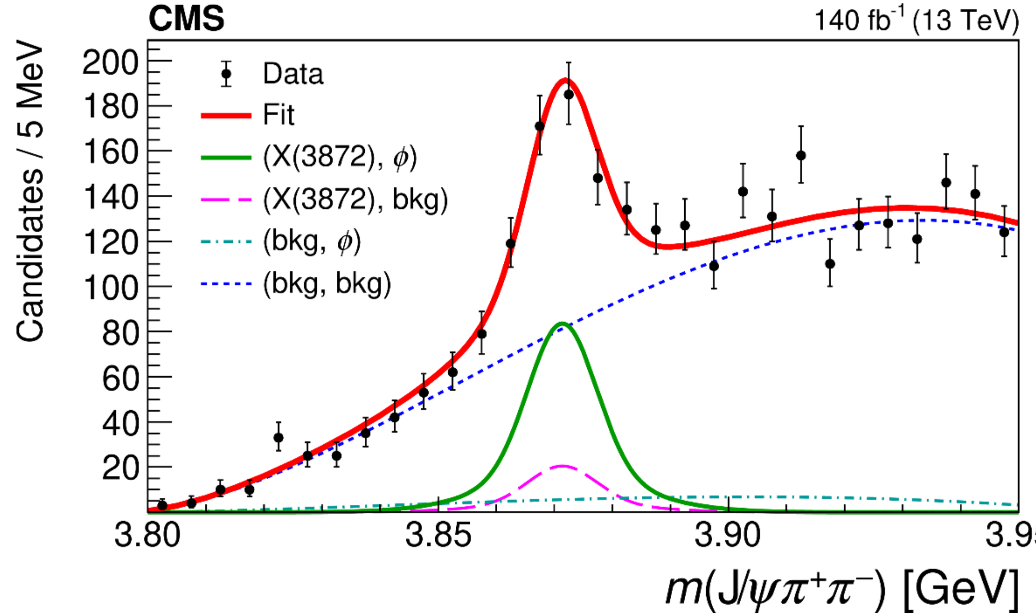
$B_s^0 \to X(3872)\phi$ PRL 125 (2020) 152001

- Discovery of $X(3872)$ by Belle in 2003 opened a new era of exotic quarkonium-like spectroscopy
- $X(3872)$ - narrow state above $D\bar{D}$ threshold
- The nature of $X(3872)$ still unexplained (tetraquark/mesonic molecule/…), some properties already established (ex. $J^{PC} = 1^{++}$).
- Additional information can be extracted by comparing various $BR[B \to X(3872)h]$ for different B mesons.
- similar decay topology – cancelation of some systematic effects

$$R \equiv \frac{\mathcal{B}[B_s^0 \to X(3872)\phi]\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[B_s^0 \to \psi(2S)\phi]\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]} = \frac{N[B_s^0 \to X(3872)\phi]}{N[B_s^0 \to \psi(2S)\phi]} \frac{\epsilon_{B_s^0 \to \psi(2S)\phi}}{\epsilon_{B_s^0 \to X(3872)\phi}}$$

with $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$

$B_s^0 \to X(3872)\phi$



reconstruction:

- dimuon (J/ψ) trigger
- kinematic vertex fit with of 2 muons and 4 tracks with constraint on $m_{J/\psi}^{PDG}$
- mass windows ($J/\psi, \phi, X, \psi(2S), B_s^0$).
- MC-base optimalisation of selection, efficiencies

ML fits to $\psi(2S)\phi$ and $X(3872)\phi$.

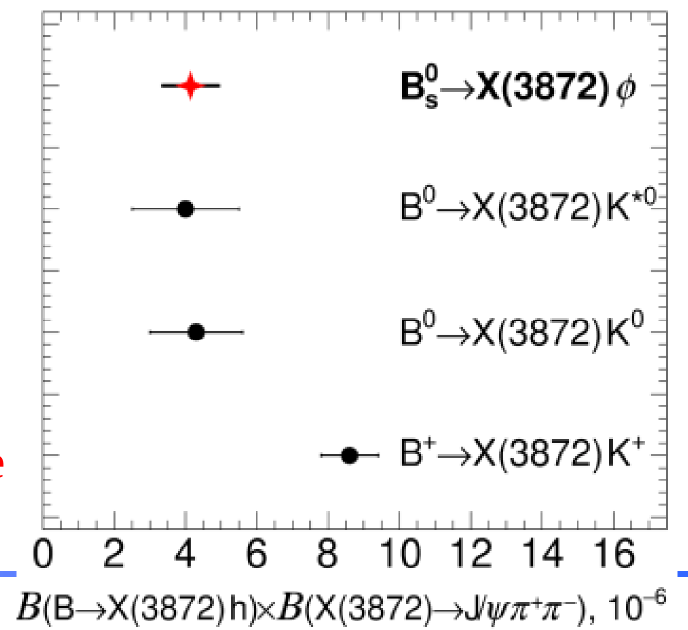
m_X left free in the fit (right value found).

$B_s \to X(3872)\phi$ – significance over 6σ.

$$R = [2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst})]\%.$$

Note: $\frac{BR[B_s^0 \to X(3872)\phi]}{BR[B^+ \to X(3872)K^+]} = 0.482 \pm 0.063 \pm 0.037 \pm 0.070$

wrt $\frac{BR[B_s^0 \to \psi(2S)\phi]}{BR[B^+ \to \psi(2S)K^+]} = 0.87 \pm 0.10$



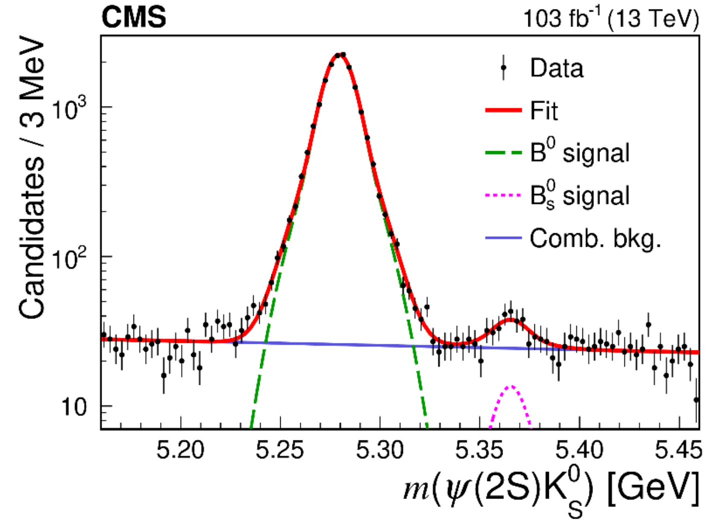
Can be explained in the tetraquark model of the $X(3872)$ state

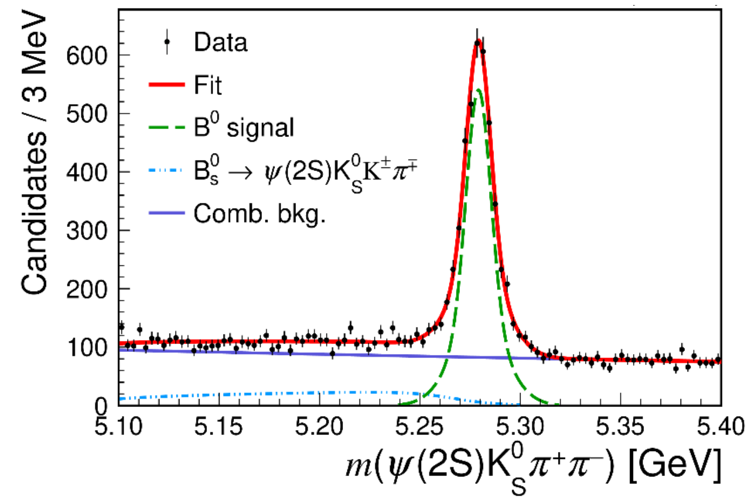
Evidence for $X(3872)$ in $Pb - Pb$ by CMS: Phys. Rev. Lett. 128, 032001

$B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_s^0$

EPJC82 (2022) 449 arXiv:2201.09131

- motivation: several exotic states reported in last two decades, nature of most of them unclear. Decays of B mesons to charmonium resonances well suited to study flavour sector of the SM and open a window to new physics. Interest from CPV.
- data: Run-2 (2017-18, $103 fb^{-1}$)
  - dimuon trigger, PV and VTX(K_s)
  - shape of $B_s^0 \to \psi(2S)K_s^0K^\pm\pi^\mp$ from MC
  - poor description of intermediates mass distribution but no evidence for narrow exotic structures
- significance of observation:
  $B_s^0 \to \psi(2S)K_s^0$: 5.2σ
  $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$: over 30σ
- BR ratios:





$$\frac{\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} = \frac{f_d}{f_s}\frac{\epsilon(B^0 \to \psi(2S)K_S^0)}{\epsilon(B_s^0 \to \psi(2S)K_S^0)}\frac{N(B_s^0 \to \psi(2S)K_S^0)}{N(B^0 \to \psi(2S)K_S^0)} = (3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2},$$

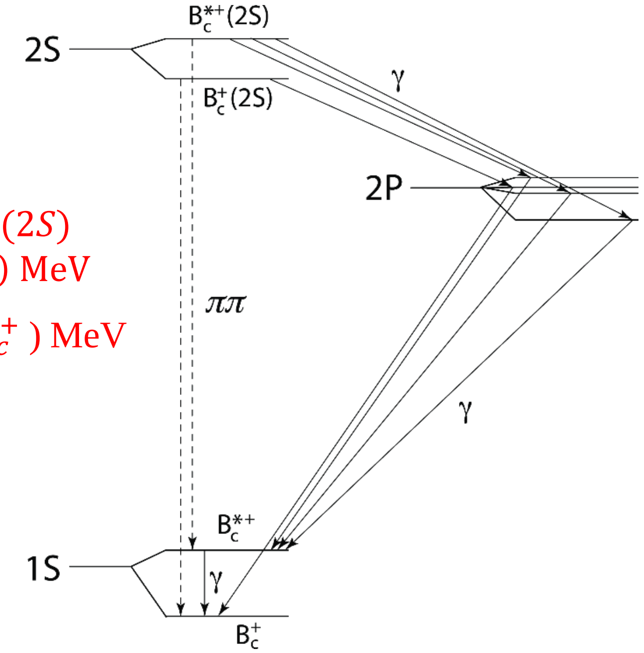
$$\frac{\mathcal{B}(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} = \frac{\epsilon(B^0 \to \psi(2S)K_S^0)}{\epsilon(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)}\frac{N(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)}{N(B^0 \to \psi(2S)K_S^0)} = 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst}).$$

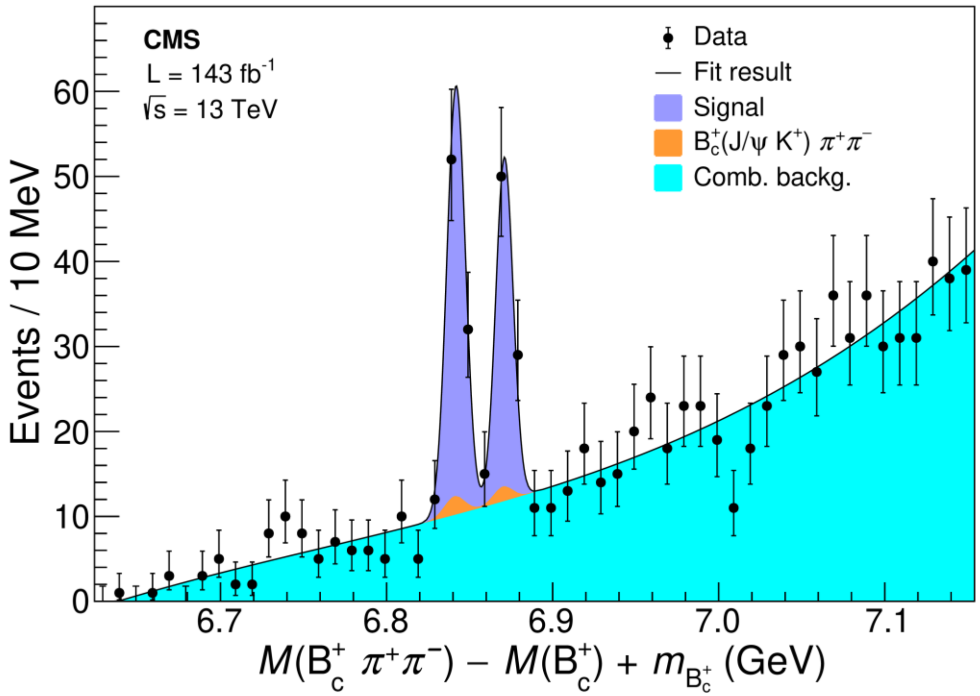
$B_c^+(2S)$ and $B_c^{+*}(2S)$ PRL 122 (2019) 132001, PRD 102 (2020) 092007

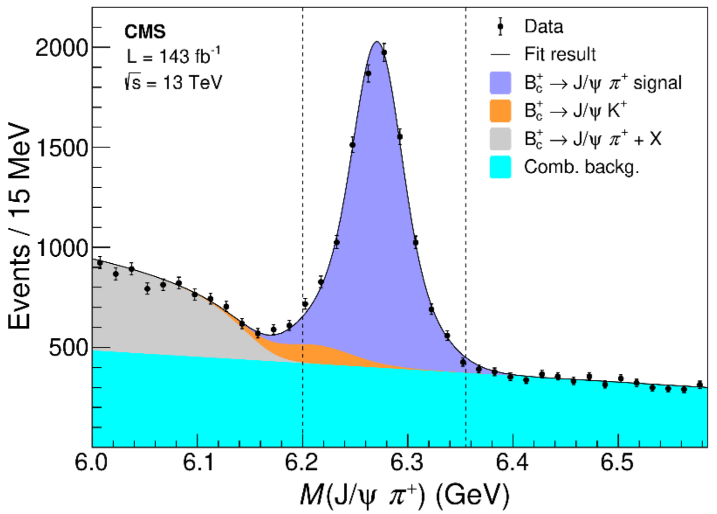
B_c family relatively difficult for production,
(ground state discovered by CDF, 1998). B_c family expected to be very populated.

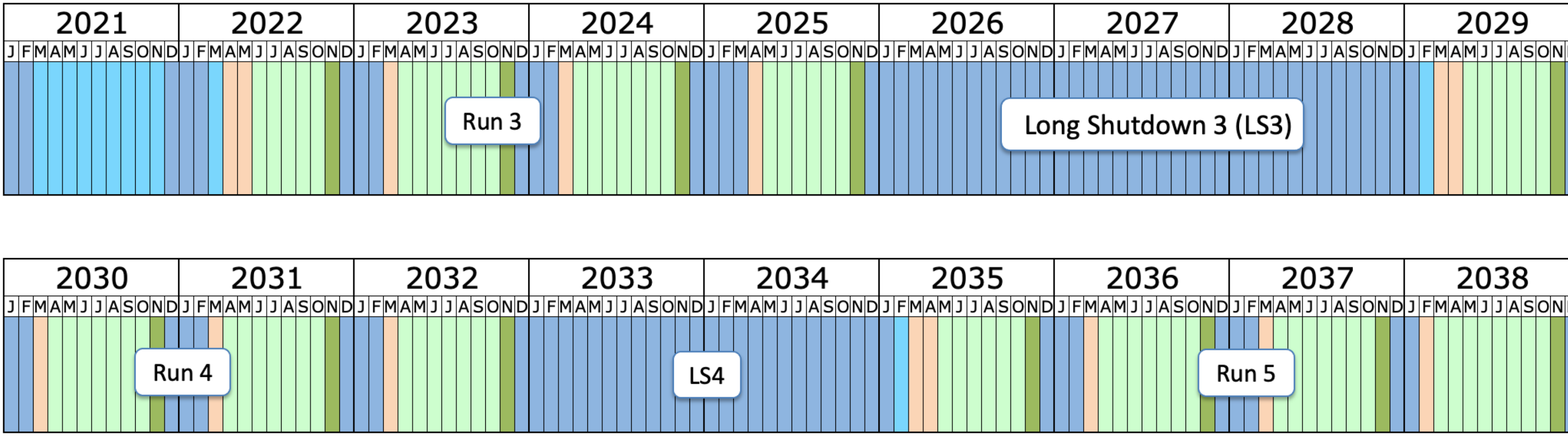
CMS (Run 2, 2015-2018):

- The observation of well-resolved signals consistent with the $B_c^+(2S)$ and B_c^{*+} $(2S)$ hyperfine partner states: 6.5 σ, separation $\Delta M = 29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV
- The first measurement of $B_c^+(2S)$ mass: 6871.0 ± 1.2(stat) ± 0.8(syst) ± 0.8(B_c^+) MeV
- The measurement cross section ratios: $B_c^+(2S)$ to B_c^+, $B_c^{*+}(2S)$ to B_c^+ and $B_c^{*+}(2S)$ to $B_c^+(2S)$









Last updated: January 2022