Selected recent heavy flavor results from ATLAS and CMS

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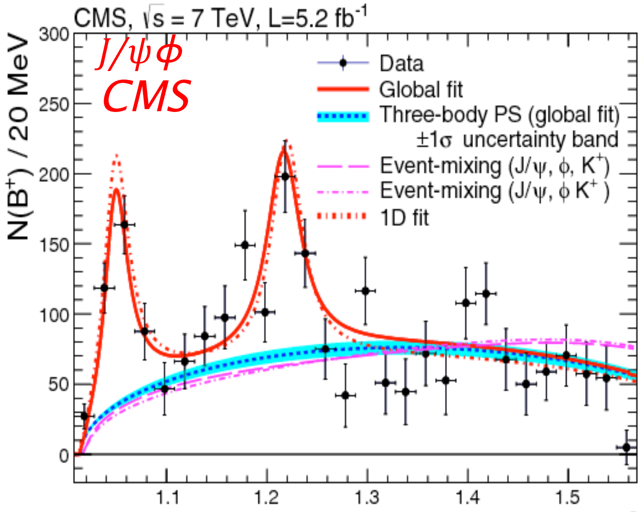
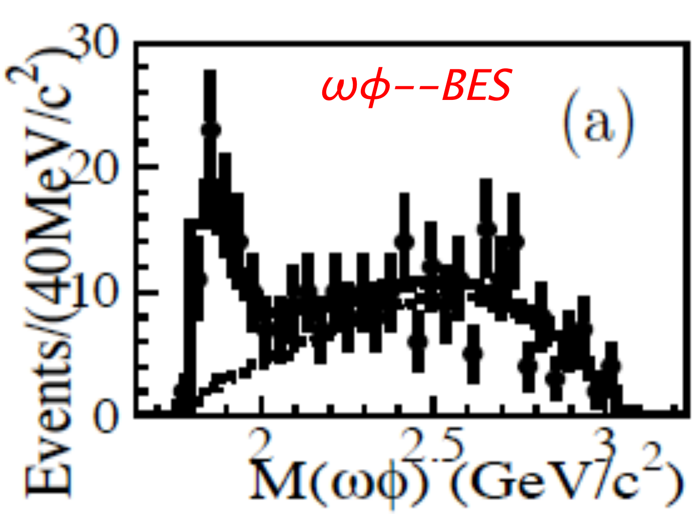
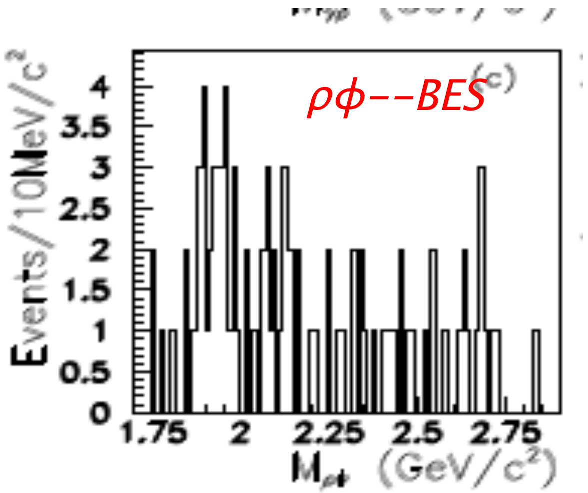
Topic I—studies of $J/\psi J/\psi$ system at CMS & ATLAS

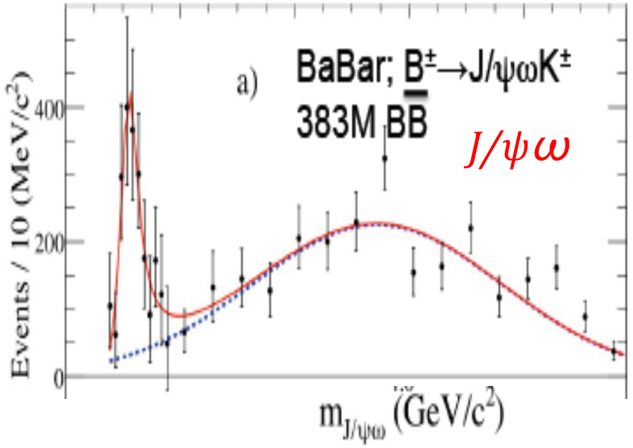
Near Threshold puzzle

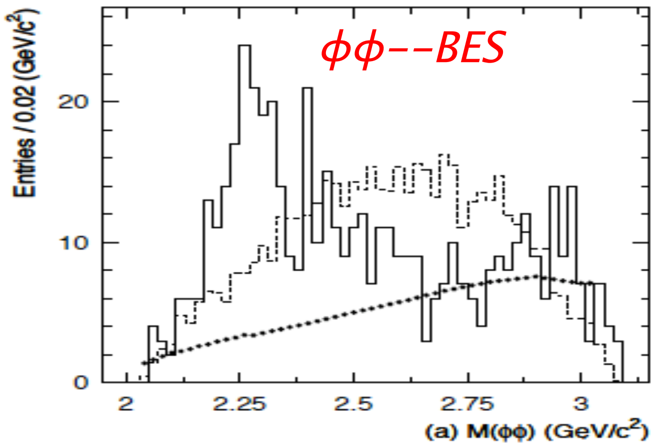


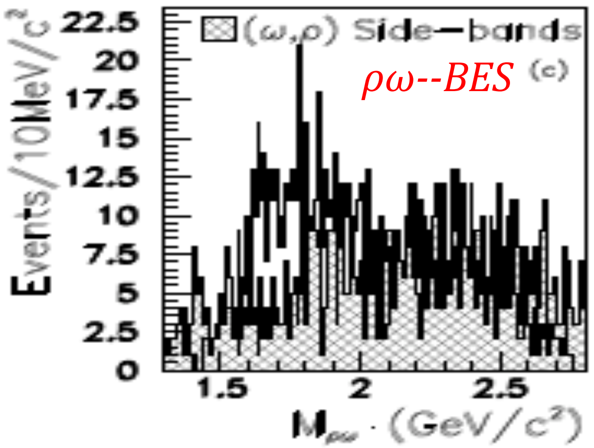




PRD 77, 012001(2008)







Clean vector-vector (VV) system:

--excesses when both V has no isospin

--not clear when one V has isospin

extend to other VV system, where V is composed of heavy quark?

IJMPA Vol. 28, No. 18 (2013) 1330020

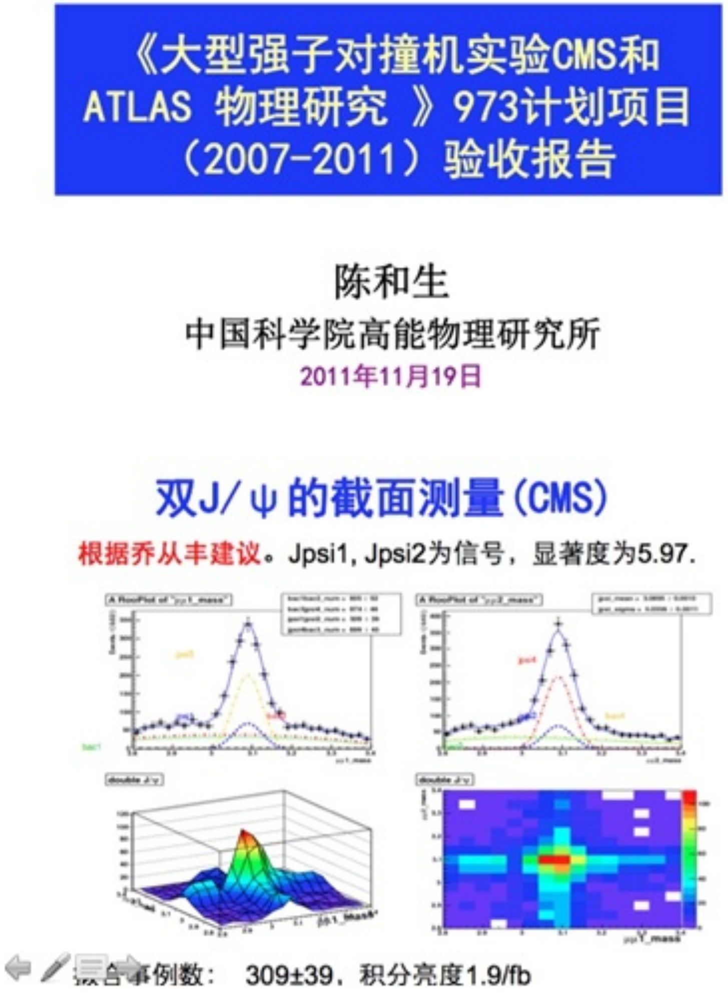
New Domain of Exotics: All-Heavy Tetra-quarks

- First mention of 4c states at 6.2 GeV (1975): Prog. of Theo. Phys. Vol. 54, No. 2

  (Just one year after the discovery of J/ψ)

- First calculation of 4c states (1981): Z. Phys. C 7 (1981) 317

- Many theoretical studies on $(c\bar{c}c\bar{c})$, $(b\bar{b}b\bar{b})$, $(b\bar{b}c\bar{c})$:
  - controversial on existence of bound states below $\eta_b\eta_b$ threshold;
  - consistent on existence of resonant states above $\eta_b\eta_b$ threshold.



- **Jianguo Bian** initialized di-J/ψ cross section analysis

$J/\psi J/\psi$--Data samples & Event selections

- 135 fb^{-1} CMS data taken in 2016, 2017 and 2018 LHC runs

- Blinded signal region: [6.2,7.8] GeV

  based on preliminary investigation on data collected in 2011-2012

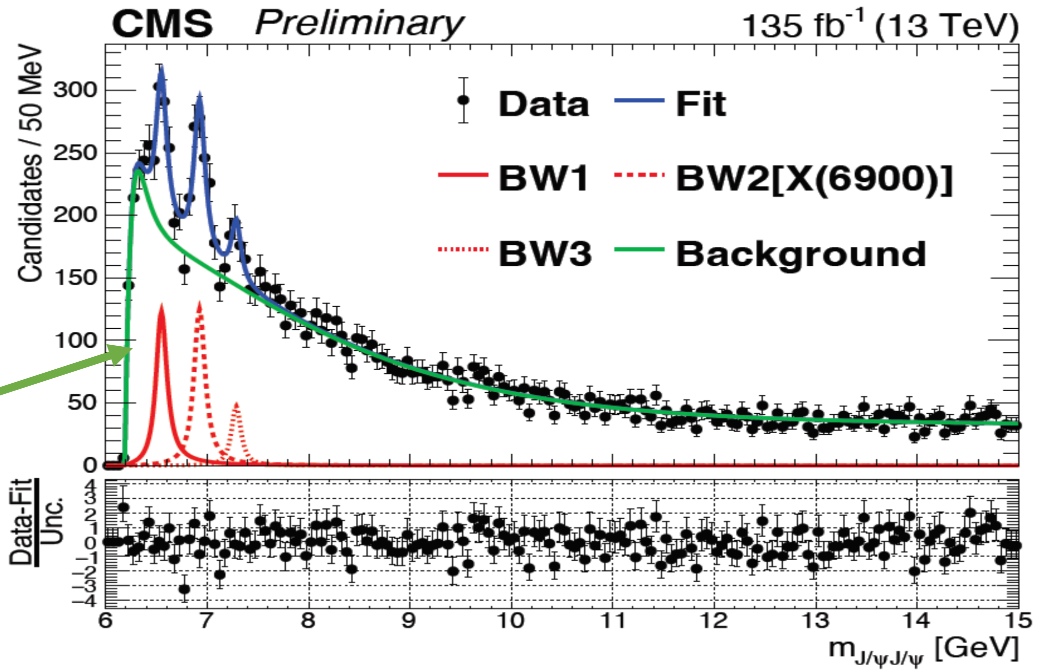
- Main selections:
  - Fire corresponding trigger in each year
  - $p_T(\mu)$>=2.0 GeV; $|\eta(\mu)|$<=2.4; $p_T(\mu)$ (J/ψ) >=3.5 GeV (2017&2018); $p_T(\mu^+\mu^-)$>=3.5 GeV;
  - $m(\mu^+\mu^-)$ in [2.95,3.25] GeV; then constrain $m(\mu^+\mu^-)$ to J/ψ mass
  - 4μ vertex probability >0.005

- Signal and background samples produced by Pythia8, JHUGen, HELAC-Onia…

CMS background (BW0 + NRSPS + DPS)

$\chi^2\ prob = 79\%$
[6.2,15] GeV

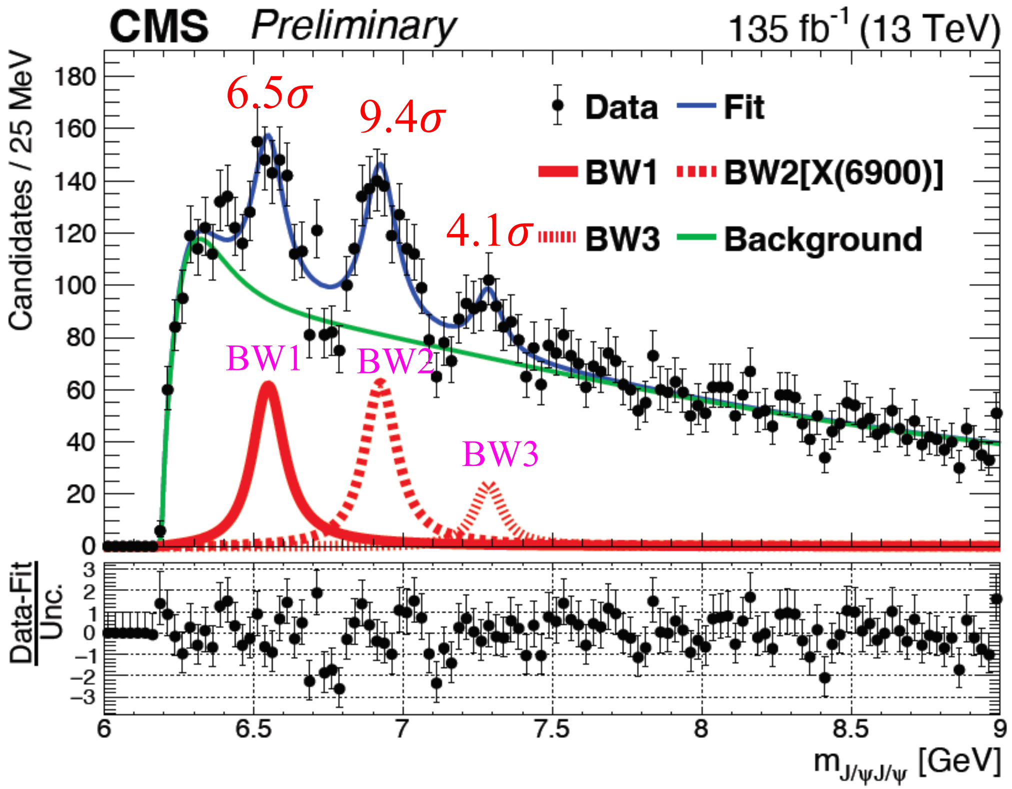
CMS background (BW0 + NRSPS + DPS)



- Most significant structure in first step is a BW at threshold, BW0--what is its meaning?
- Treat BW0 as part of background due to:
    - Inadequacy of our NRSPS model at threshold though one floating parameter?
    - BW0 parameters very sensitive to other model assumptions
    - A region populated by feed-down from possible higher mass states
    - Possible coupled-channel interactions, pomeron exchange processes…
- NRSPS+NRDPS+BW0 as our background

Final CMS model: 3 BWs + Background (null)

χ^2 Prob. = 1%
[6.2,7.8] GeV



Statistical significance based on:

2 ln(L_0/L_{max})

	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	6552 ± 10	6927± 9	7287± 19
Γ	124± 29	122± 22	95± 46
N	474± 113	492± 75	156± 56

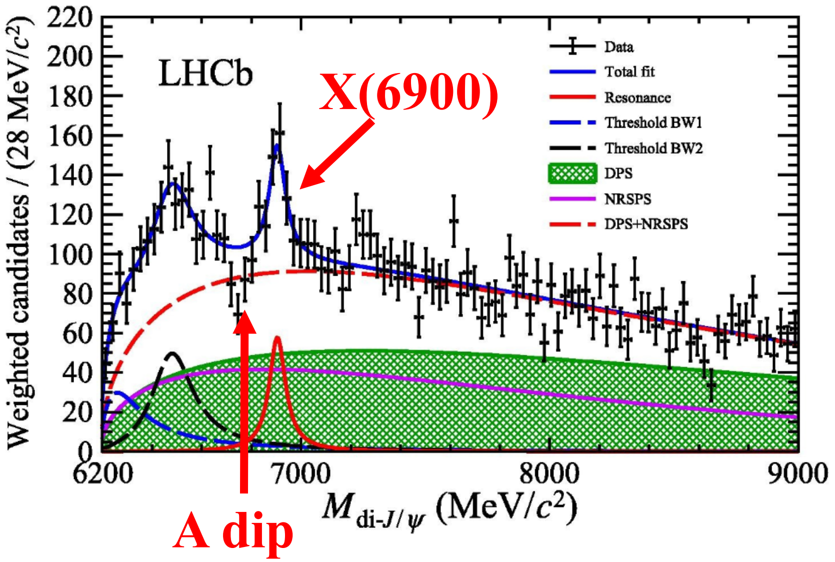
- BW2[X(6900)] (>9.4σ) – confirmation
- Observation of BW1 (>5.7σ)
- Evidence for BW3 (>4.1σ)

Statistical significance only

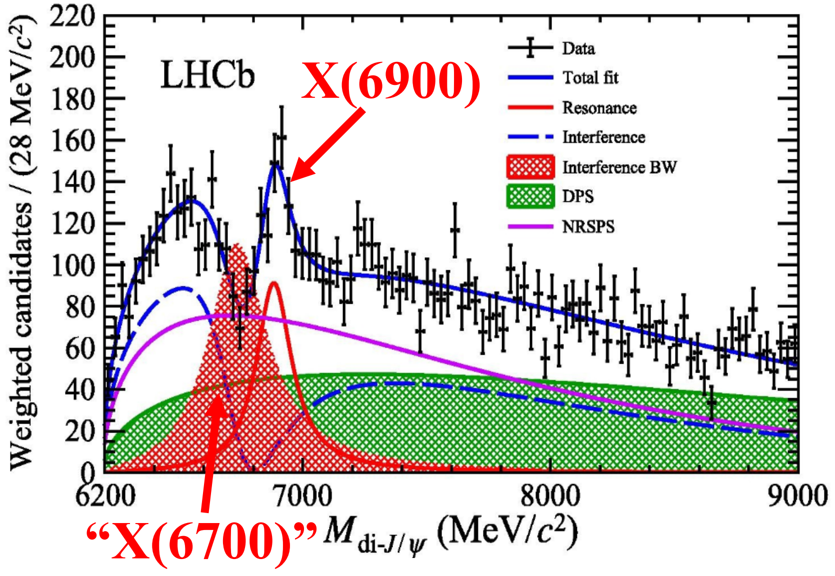
X(6900) reported by LHCb (Liupan An & Yanxi Zhang)

- In 2020, LHCb reported X(6900) state in J/ψJ/ψ final state, Sci.Bull.65 (2020) 23
- Tried two different models
  - Model I: background+2 auxiliary BWs+ X(6900) ⟶ poor description of 'dip' around 6.7 GeV
  - Model II: a "virtual" X(6700) to interfere with NRSPS background to account for dip
- LHCb agnostic on which one is to be preferred
- What happens if fit CMS data using LHCb models?

Model I



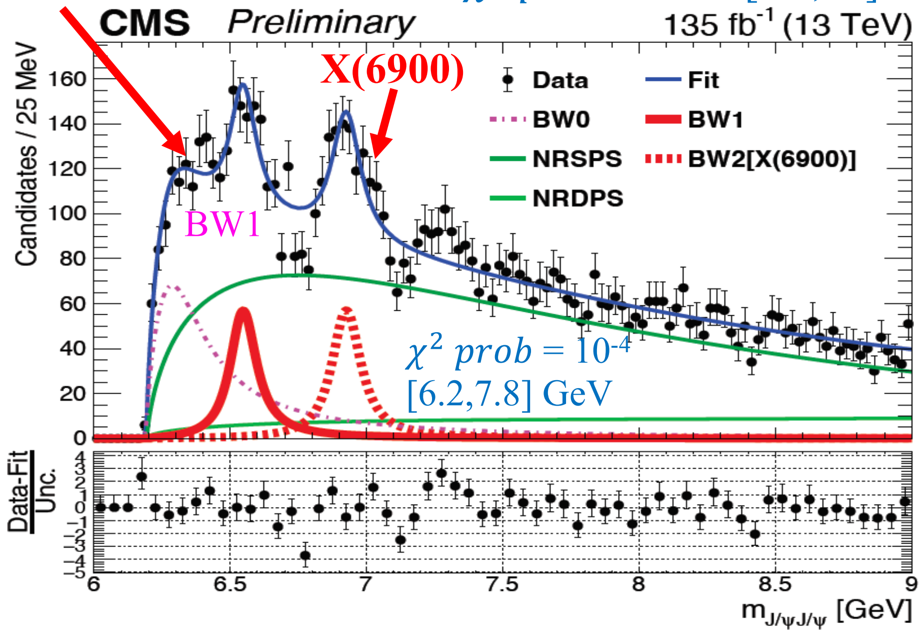
Model II

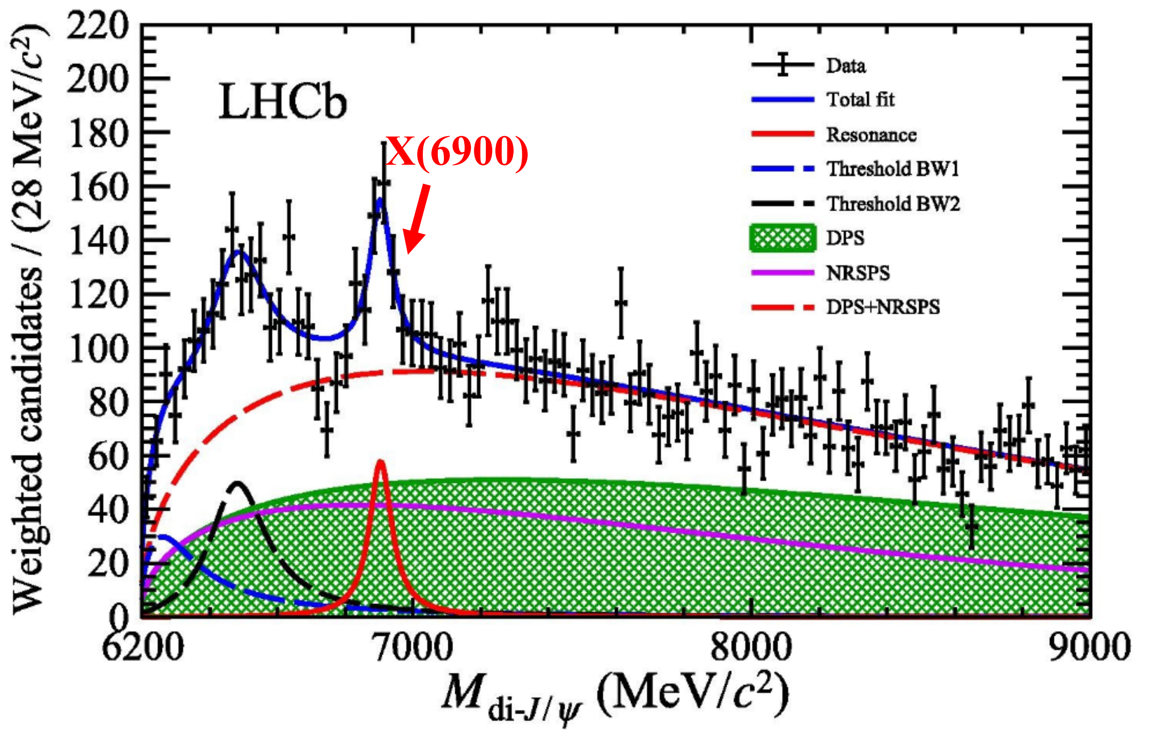


Fit with LHCb model I--background+2 auxiliary BWs+ X(6900)

A shoulder

χ^2 *prob* = 51% [6.2,15] GeV





Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

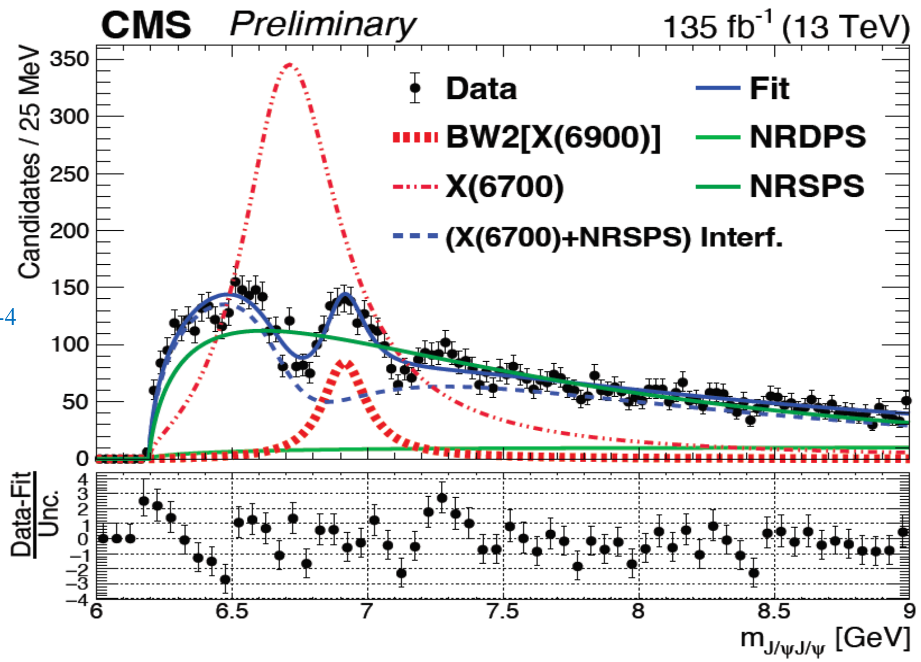
X(6900) parameters are in good agreement with LHCb
LHCb did not give parameters for another 2 BWs

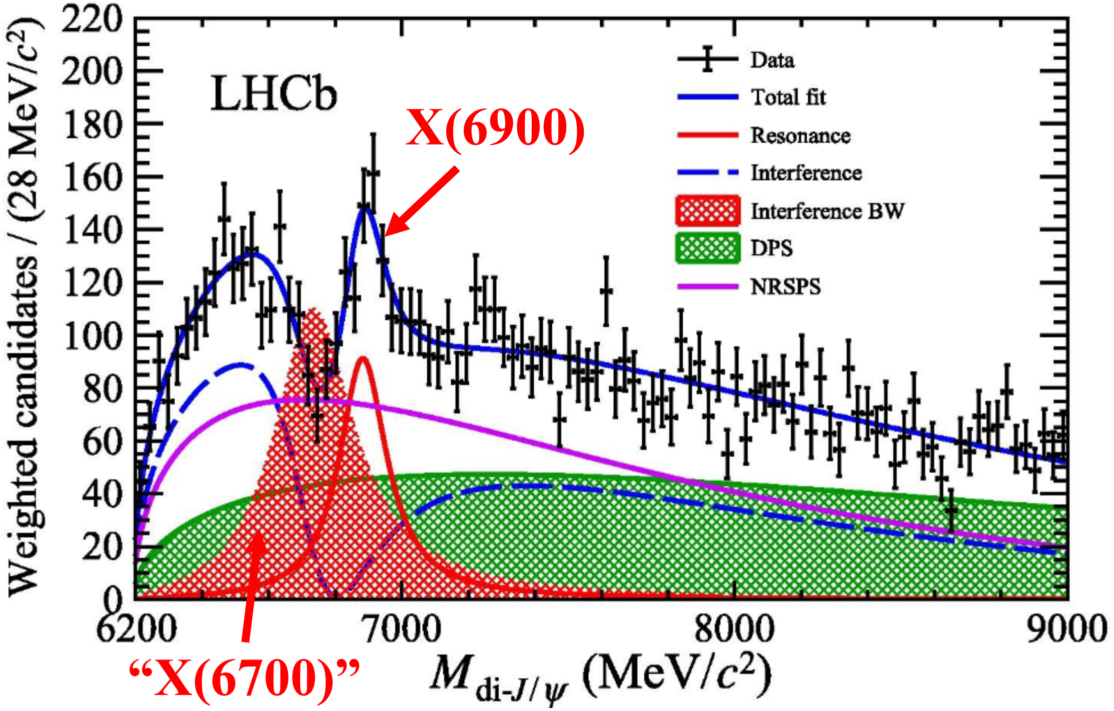
- CMS Data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct
- *Does not describe well dips*

- CMS vs LHCb comparisons:
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4 \approx$ 8X (muon acceptance due to pseudo-rapidity range)
  - Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
  - Similar number of final events
  - 2X yield @CMS for X(6900)

Fit with LHCb model II—DPS+X(6900)+“X(6700)” interferes with NRSPS

χ^2 *prob* = 10^{-4}
[6.2,7.8] GeV





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CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

All CMS fits presented are not very good:
...other interference scenarios are under study in CMS

- X(6900) parameters are consistent
- CMS obtained larger amplitude and natural width for BW1
- CMS's X(6600) is 'eaten' –does not describe X6600 and below
- Does not describe X(7200) region

CMS $J/\psi J/\psi$ result

CMS found 3 significant structures using 135 fb^{-1} 13 TeV data

M[BW1] = 6552 $\pm$ 10 $\pm$ 12 MeV	Γ[BW1] = 124 $\pm$ 29 $\pm$ 34 MeV	>5.7**σ**
M[BW2] = 6927 $\pm$ 9 $\pm$ 5 MeV	Γ[BW2] = 122 $\pm$ 22 $\pm$ 19 MeV	>9.4**σ**
M[BW3] = 7287 $\pm$ 19 $\pm$ 5 MeV	Γ[BW3] = 95 $\pm$ 46 $\pm$ 20 MeV	>4.1**σ**

- BW2 consistent with X(6900) reported by LHCb
- CMS found two new structures, provisionally named as X(6600), X(7200)
- A family of structures which are candidates for all-charm tetra-quarks!

- Dips in the data show possible interference effects --- Under study
- More data/knowledge needed to understand nature of near threshold region

- ***All-heavy quark exotic structures offer system easier to understand***
- ***A new window to understand strong interaction***

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-003/index.html

CMS has good sensitivity to all-muon final states in this mass region

Observation of Di-charmonium excess in the four-muon final state at ATLAS

Using. $\mathcal{L} = 139\ \mathrm{fb}^{-1}$ of 13 TeV of ATLAS Run-2 data collected in 2015 to 2018

Search in the 4μ final state through the di-J/ψ and $J/\psi + \psi(2S)$ channels

di-$\psi(2S) \rightarrow 4\mu$ statistically not accessible with Run-2 data

Signal simulated with JHU: TQ mass = 6.9 GeV, width = 0.1 GeV, spin = 0

Background processes (simulated with Pythia8):

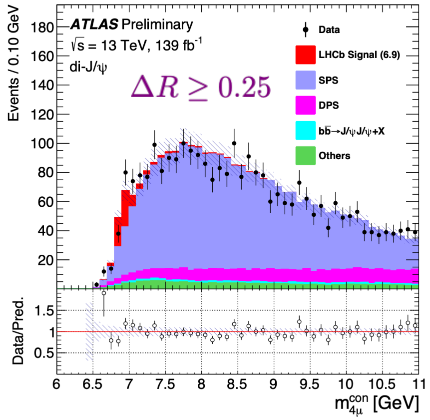
prompt di-J/ψ: Single Parton Scattering (SPS) and Double Parton Scattering (DPS)

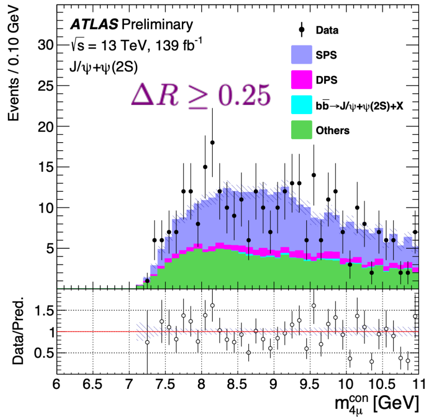
non prompt di-J/ψ: $b\bar{b} \rightarrow J/\psi J/\psi$

"Others" background: single (prompt or non prompt) charmonium plus fake muons, non-peaking background containing no real charmonium candidates

(CRs defined in sidebands and by requiring one charmonium containing a non muon track)

SPS mass shape validated Usin. $\Delta R \geq 0.25$ CR





Event selection and signal and control regions:

Signal region	SPS/DPS control region	non-prompt region
Di-muon or tri-muon triggers, Opposite charged muons from the same J/ψ or $\psi(2S)$ vertex, Loose muon ID, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons $m_{J/\psi} \in \{2.94, 3.25\}$ GeV, or $m_{\psi(2S)} \in \{3.56, 3.80\}$ GeV, Loose vertex cuts $\chi^2_{4\mu}/N < 40$ and $\chi^2_{\text{di-}\mu}/N < 100$,		
Vertex $\chi^2_{4\mu}/N < 3$, $L_{xy}^{4\mu} < 0.2$ mm, $\lvert L_{xy}^{\text{di-}\mu}\rvert < 0.3$ mm,		Vertex $\chi^2_{4\mu}/N > 6$, $\lvert L_{xy}^{\text{di-}\mu}\rvert > 0.4$ mm
$m_{4\mu} < 7.5$ GeV, $\Delta R < 0.25$ between charmonia	7.5 GeV$< m_{4\mu} < 12.0$ GeV (SPS) 14.0 GeV$< m_{4\mu} < 25.0$ GeV (DPS)	

N = 5

w.r.t primary vertex closest in z

Observation of Di-charmonium excess in the four-muon final state at ATLAS

Fit Models

Unbinned maximum likelihood fits on the four-muon mass spectra < 11 GeV, no ΔR cut

fit signal region $\Delta R < 0.25$, fit control region $\Delta R \geq 0.25$, with transfer factors for background yields from MC or data driven methods

The signal probability density function (PDF) consists of several interfering S-wave Breit-Wigner resonances, convoluted with a mass resolution function

$$f_s(x) = \left| \sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i} \right|^2 \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\alpha)$$

no interference with NRSPS (LHCb model)

di-J/ψ channel:

models with different numbers of resonances (2 or 3) are compared in terms of χ^2 or toy MC distributions

$J/\psi + \psi(2\mathrm{S})$ channel:

Model A: same resonances as in di-J/ψ, plus a 4th standalone resonance

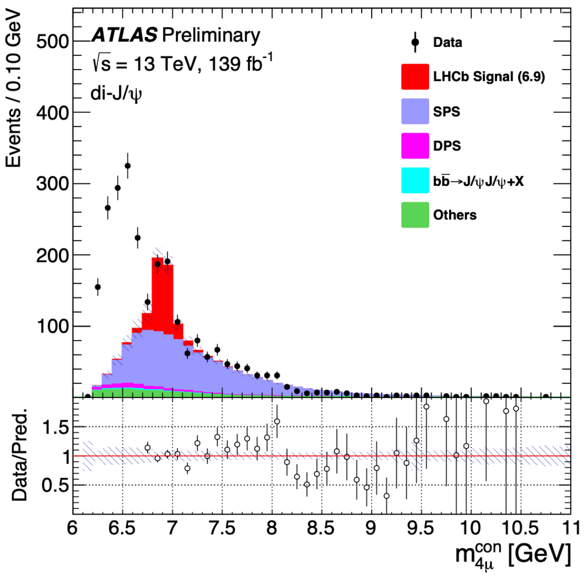
$$f_s(x) = \left(\left| \sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i} \right|^2 + \left| \frac{z_3}{x^2 - m_3^2 + i m_3 \Gamma_3} \right|^2 \right) \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x} \right)^2} \otimes R(\alpha)$$

Model B: a single resonance

Observation of Di-charmonium excess in the four-muon final state at ATLAS

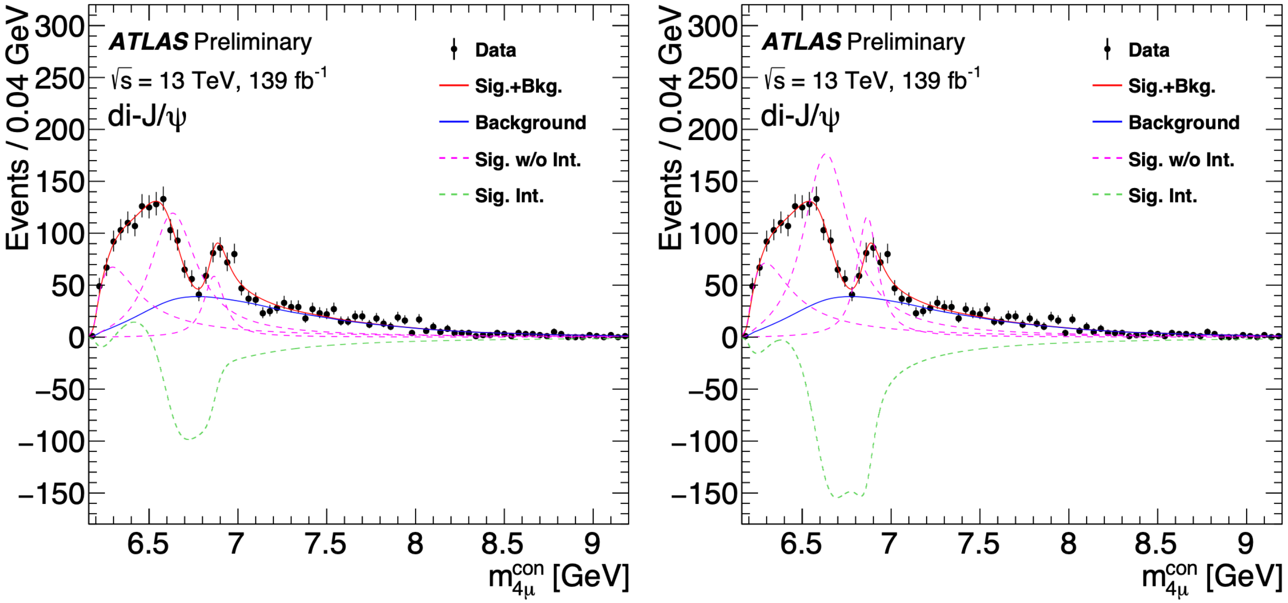
Results in di-J/ψ channel

4μ mass distribution from data and background predictions before fit



feed-down from $J/\psi + \psi(2S)$ or higher di-charmonium resonances not included

fitted mass in SR, 3-resonance fit (2 out of 4 degenerate solutions for z_i)



Fitted masses and widths

(GeV)	m_0	Γ_0	m_1	Γ_1
di-J/ψ	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2	—	
consistent with LHCb	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	

significance of third resonance: 10σ

using LHCb Model I values for 3rd resonance gives similar results

LHCb Model II fit (interference with NRSPS) disfavoured based on fit quality

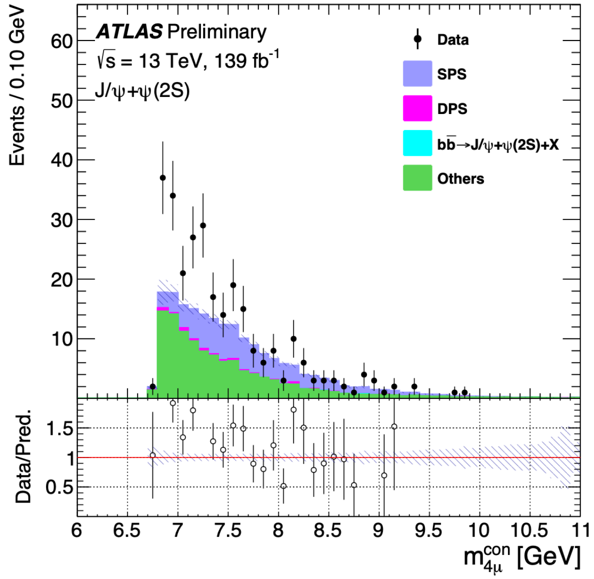
70% worse fit quality for 2-resonance fit

6.9 GeV resonance confirmed, best fit with 3 interfering resonances, other explanations possible

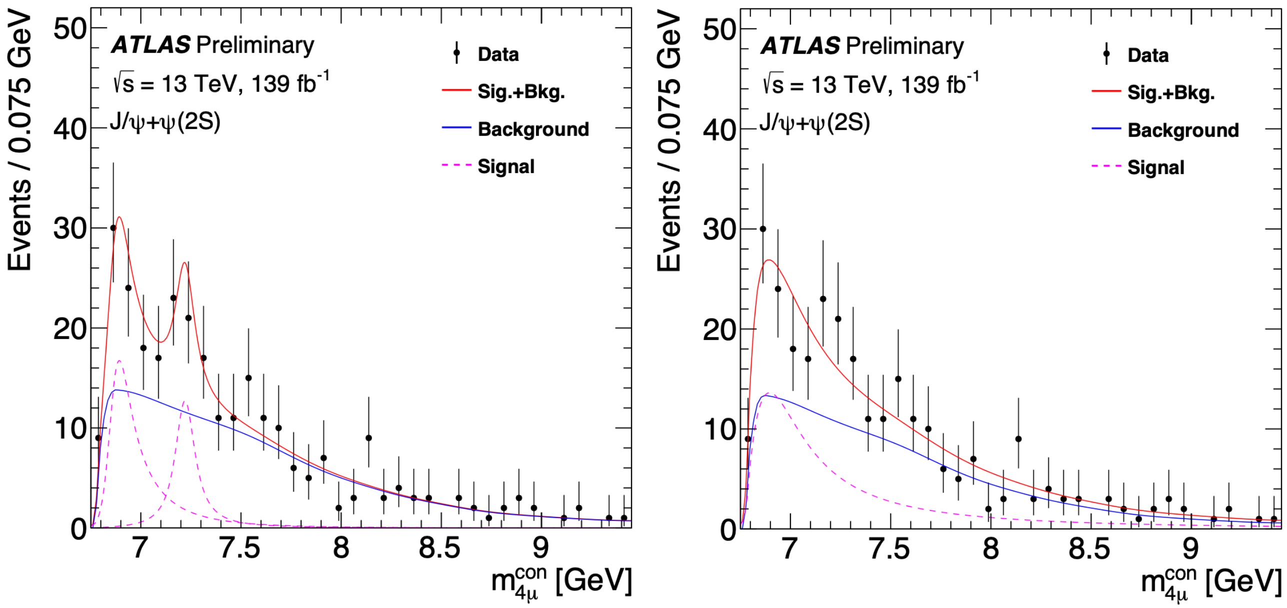
Observation of Di-charmonium excess in the four-muon final state at ATLAS

Results In $J/\psi + \psi(2S)$ channel

4μ mass distribution from data and background predictions before fit



fitted mass in SR (Model A and Model B)



significance Model A: 4.6σ

second resonance (7.2 GeV): 3.2σ

(hint for a 7.2 GeV resonance in LHCb data)

significance Model B: 4.3σ

Fitted masses and widths

(GeV)		m_3	Γ_3
J/ψ+$\psi(2S)$	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$

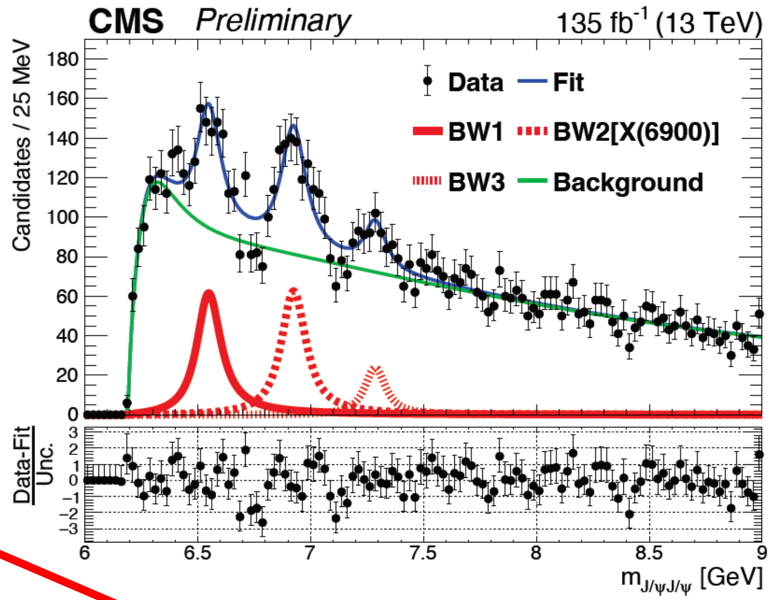
Evidence for an enhancement at 6.9 GeV and a resonance at 7.2 GeV, other explanations possible

What are they—an accident?

arXiv:2108.04017 **[hep-ph]**

TABLE 4: The mass-spectra of S and P-wave tetraquark T_{4c}, generated from our model. M_{th} [49] is threshold mass of two mesons. (Units are in MeV)

$N^{2S+1}L_J$	J^{PC}	$\langle K.E.\rangle$	$E^{(0)}$	$\langle V_C^{(0)}\rangle$	$\langle V_L^{(0)}\rangle$	$\langle V_{SS}^{(1)}\rangle$	$\langle V_{LS}^{(1)}\rangle$	$\langle V_T^{(1)}\rangle$	$V^{(1)}(r)$	M_f	$\mathbf{M_{th}}$ [49]	Threshold
1^1P_1	1^{--}	363.9	320.3	-366.7	337.5	-14.4	0	0	-2.6	6553	-	-
1^3P_0	0^{-+}	356.7	320.2	-366.7	337.5	-7.2	-56.9	-43.1	-2.6	6460	6398.1	$\eta_c(1S)\chi_{c0}(1P)$
1^3P_1	1^{-+}	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554	6494.1	$\eta_c(1S)\chi_{c1}(1P)$
1^3P_2	2^{-+}	356.6	320.2	-366.7	337.5	-7.2	28.4	-2.1	-2.4	6587	6539.6	$\eta_c(1S)\chi_{c2}(1P)$
1^5P_1	1^{--}	342.4	320.4	-366.7	337.5	7.2	-85.3	-30.2	-2.7	6459	6508.8	$\eta_c(1S)h_{c1}(1P)$
1^5P_2	2^{--}	342.2	320.2	-366.7	337.5	7.2	-28.4	30.2	-2.5	6577	6607.6	$J/\psi(1S)\chi_{c1}(1P)$
1^5P_3	3^{--}	342.3	320.3	-366.7	337.5	7.2	56.9	-8.6	-2.5	6623	6653.1	$J/\psi(1S)\chi_{c2}(1P)$
2^1P_1	1^{--}	414.7	688.7	-263.4	548.6	-11.2	0	0	-1.6	6925	-	-
2^3P_0	0^{-+}	410.0	689.6	-263.4	548.6	-5.6	-46.2	-34.5	-1.7	6851	-	-
2^3P_1	1^{-+}	410.0	689.6	-263.4	548.6	-5.6	-23.1	17.2	-1.6	6926	-	-
2^3P_2	2^{-+}	410.0	689.6	-263.4	548.7	-5.6	23.1	-3.4	-1.7	6951	-	-
2^5P_1	1^{--}	398.7	689.5	-263.4	548.6	-5.6	-69.3	-24.2	-1.7	6849	-	-
2^5P_2	2^{--}	398.7	689.5	-263.4	548.6	5.6	-23.1	24.2	-1.5	6944	-	-
2^5P_3	3^{--}	398.8	689.7	-263.4	548.6	5.6	46.2	-6.9	-1.6	6982	-	-
3^1P_1	1^{--}	479.8	982.2	-215.5	727.8	-9.3	0	0	-1.1	7221	-	-
3^3P_0	0^{-+}	475.2	982.7	-215.5	727.7	-4.6	-41.9	-31.0	-1.2	7153	-	-
3^3P_1	1^{-+}	475.1	982.6	-215.5	727.7	-4.6	-20.9	15.5	-1.2	7220	-	-
3^3P_2	2^{-+}	475.1	982.6	-215.5	727.8	-4.6	20.9	-3.1	-1.0	7243	-	-
3^5P_1	1^{--}	465.9	982.8	-215.5	727.7	4.6	-62.8	-21.7	-1.2	7150	-	-
3^5P_2	2^{--}	465.7	982.6	-215.5	727.8	-4.6	-20.9	21.7	-1.1	7236	-	-
3^5P_3	3^{--}	465.8	982.6	-215.5	727.8	4.6	41.9	-6.2	-1.1	7271	-	-



M[BW1] = 6552 ± 10 ± 12 MeV
M[BW2] = 6927 ± 9 ± 5 MeV
M[BW3] = 7287 ± 19 ± 5 MeV

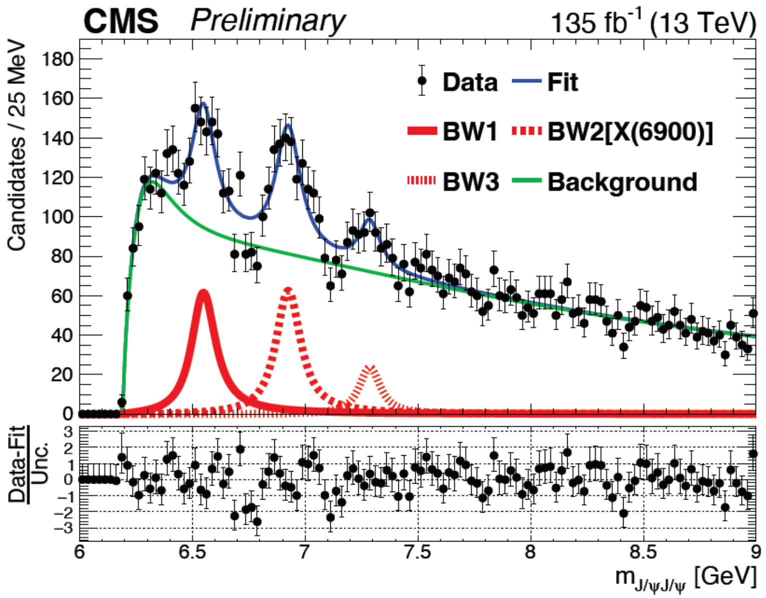
- Radial excited p-wave states like J/ψ series?
- *J^{PC}=1^{-+} ?   An exotic quantum number!*
- Next important step: measure J^{PC}

What are they?

Nucl. Phys. B 966 (2021) 115393

Table 1. Predictions of the masses (MeV) of S-wave fully heavy $T_{4Q}(nS)$ tetraquarks. Only 0^{++} and 2^{++} are considered for $T_{bc\bar{b}\bar{c}}$. The uncertainty is from the coupling constant $\alpha_s = 0.35 \pm 0.05$.

$T_{4Q}(nS)$ states	J^P	Mass($n=1$)	Mass($n=2$)	Mass($n=3$)	Mass($n=4$)
$T_{cc\bar{c}\bar{c}}$	0^{++}	6055^{+69}_{-74}	6555^{+36}_{-37}	6883^{+27}_{-27}	7154^{+22}_{-22}
	2^{++}	6090^{+62}_{-66}	6566^{+34}_{-35}	6890^{+27}_{-26}	7160^{+21}_{-22}
$T'_{cc\bar{c}\bar{c}}$	0^{++}	5984^{+64}_{-67}	6468^{+35}_{-35}	6795^{+26}_{-26}	7066^{+21}_{-22}
$T_{bc\bar{b}\bar{c}}$	0^{++}	12387^{+109}_{-120}	12911^{+48}_{-51}	13200^{+35}_{-36}	13429^{+29}_{-30}
	2^{++}	12401^{+117}_{-106}	12914^{+49}_{-49}	13202^{+35}_{-36}	13430^{+29}_{-29}
$T'_{bc\bar{b}\bar{c}}$	0^{++}	12300^{+106}_{-117}	12816^{+48}_{-50}	13104^{+35}_{-35}	13333^{+29}_{-29}
$T_{bb\bar{b}\bar{b}}$	0^{++}	18475^{+151}_{-169}	19073^{+59}_{-63}	19353^{+42}_{-42}	19566^{+33}_{-35}
	2^{++}	18483^{+149}_{-168}	19075^{+59}_{-62}	19355^{+41}_{-43}	19567^{+33}_{-35}
$T'_{bb\bar{b}\bar{b}}$	0^{++}	18383^{+149}_{-167}	18976^{+59}_{-62}	19256^{+43}_{-42}	19468^{+34}_{-34}



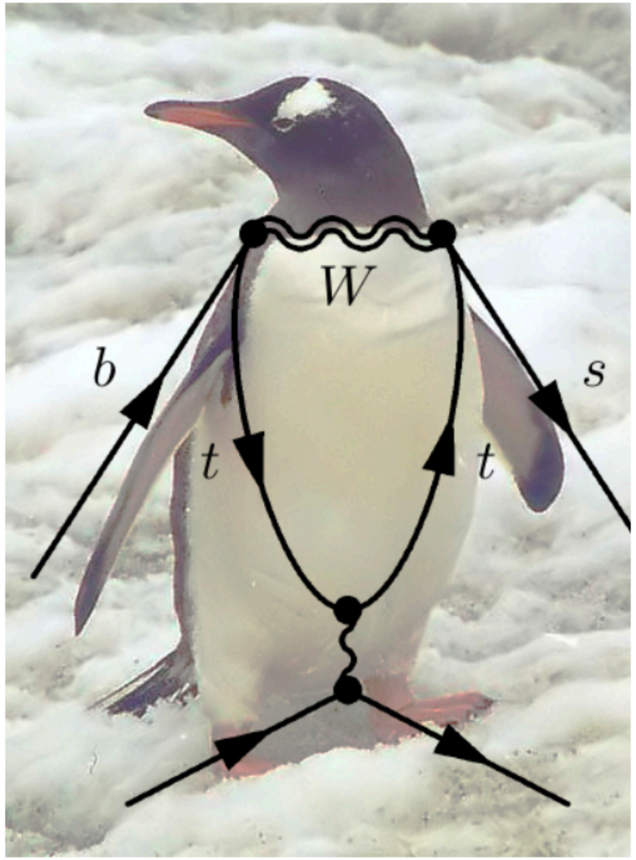
M[BW1] = 6552 ± 10 ± 12 MeV
M[BW2] = 6927 ± 9 ± 5 MeV
M[BW3] = 7287 ± 19 ± 5 MeV

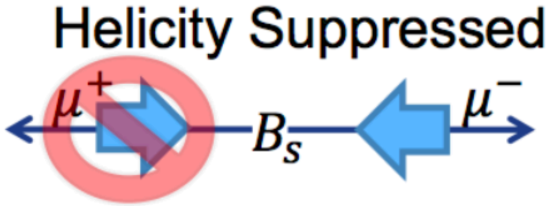
- Radial excited S-wave states?
- *$J^{PC}=0^{++}$ or 2^{++}?*
- **Next important step: measure J^{PC}**

- *Other possibilities exist! i.e. threshold effect…*

Topic II—$B_S \rightarrow \mu^+ \mu^-$ at CMS

$B_s \rightarrow \mu\,\mu$ at CMS

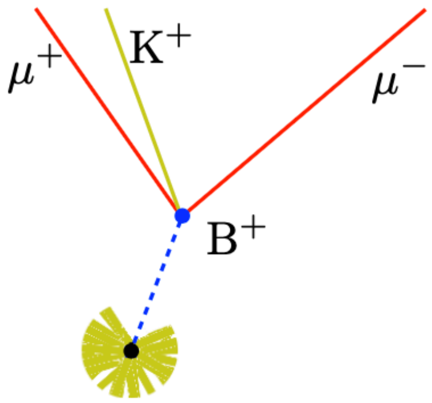




- Rare $b \rightarrow s\ell\ell$ process in SM (10^{-9})
  - Sensitive to New Physics effects
- Theoretically clean
  - non perturbative contributions are in $B_{(s)}$ decay constant
    - well known from Lattice QCD
- Anomalies in rare B decays
  - 3.1σ LFU violation in R(K)
  - 2-3σ discrepancies in branching fraction and angular observables

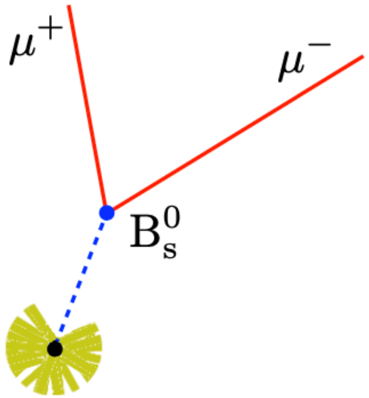
Dominant Contributions

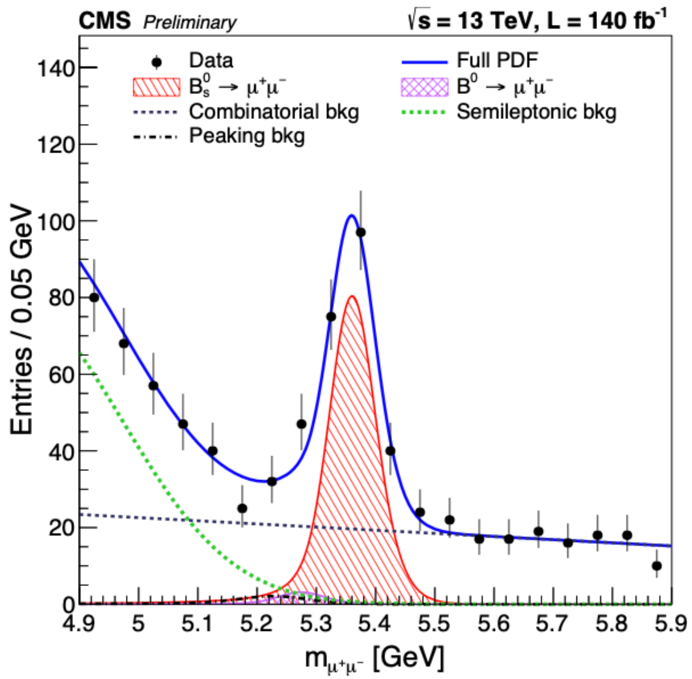
3-body and partial decays



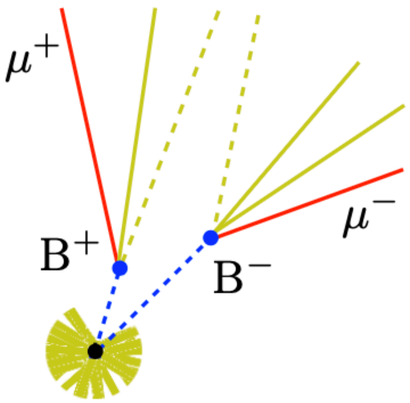
Muons from the same B hadron

Signal $B_s \rightarrow \mu\mu$



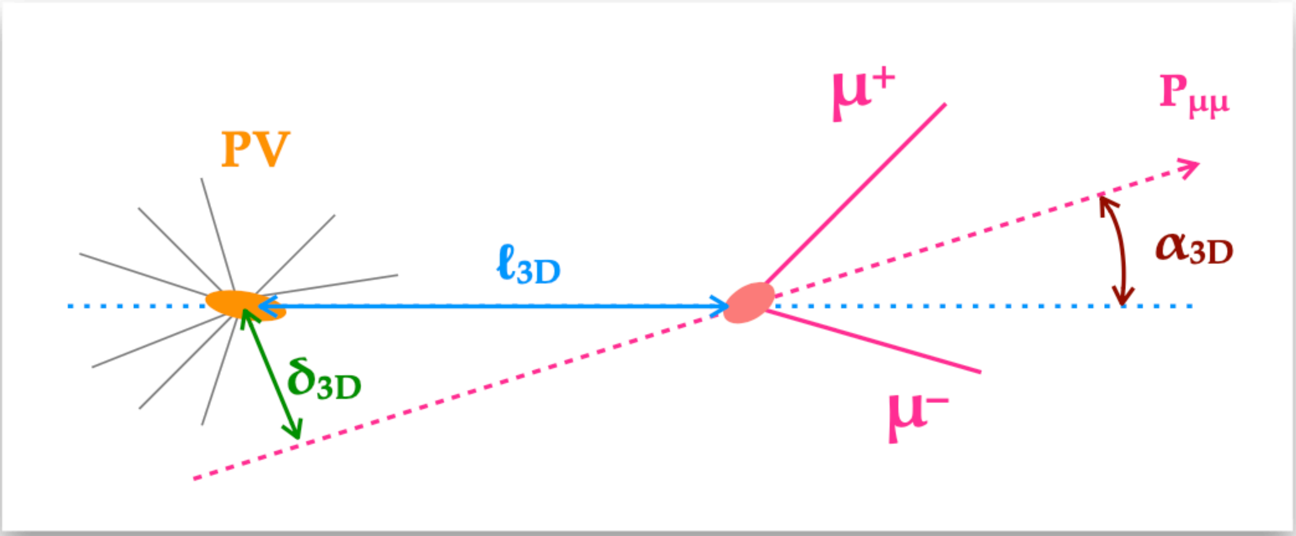


Combinatorial Background



Muons originate from different B hadrons

Multivariate Analysis

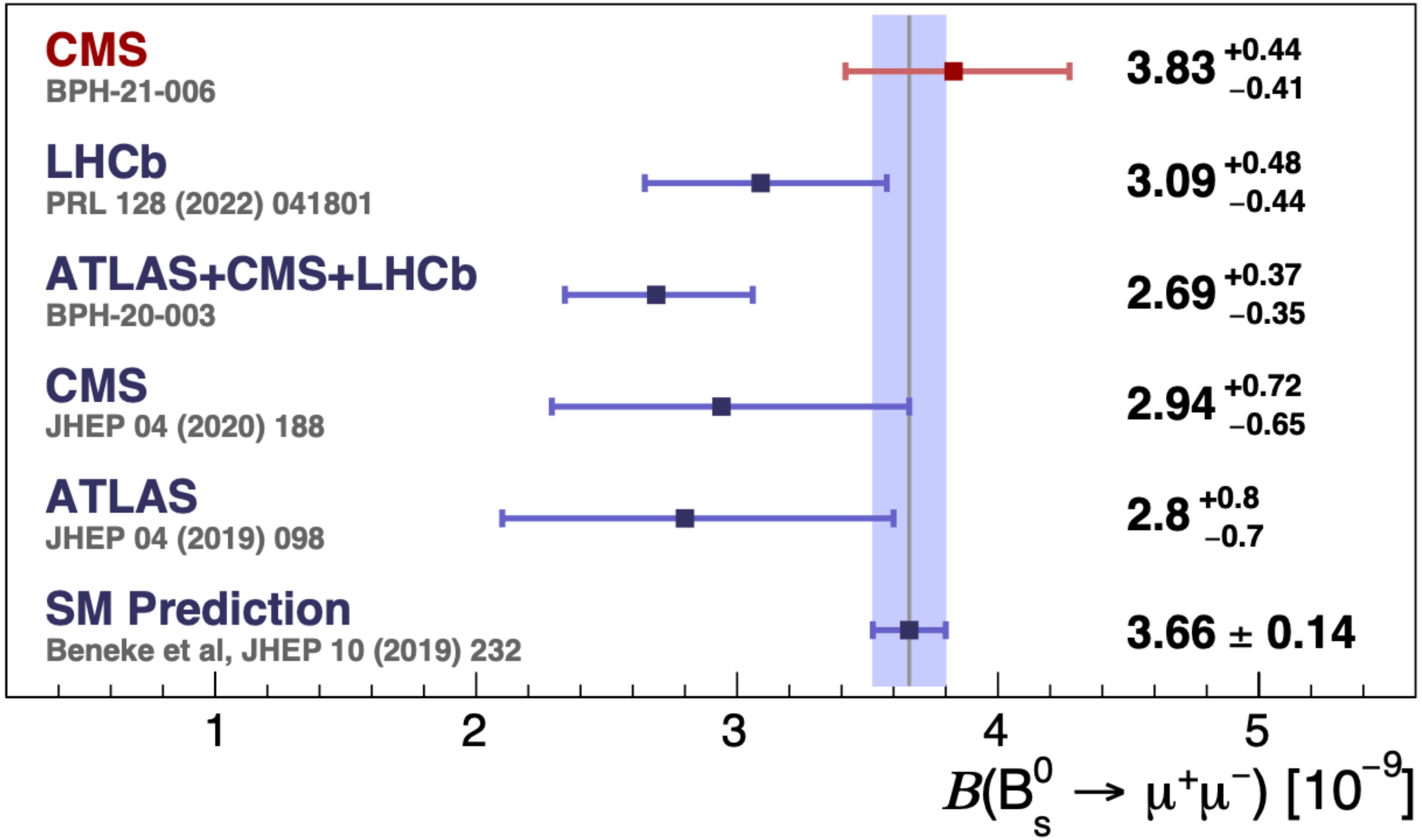


- New multivariate analysis (MVA_B) used to suppress the dominant backgrounds
  - Trained with signal MC and mass sideband data with the XGBoost package (advanced gradient boosting algorithm)
- Most discriminating variables
  - Pointing angles: α_{2D}, α_{3D}
  - Impact parameter and its significance: δ_{3D}, $\delta_{3D}/\sigma(\delta_{3D})$
  - Flight length and its significance: $\ell_{3D}/\sigma(\ell_{3D})$
  - Isolation for B candidate and muons
  - Dimuon vertex quality

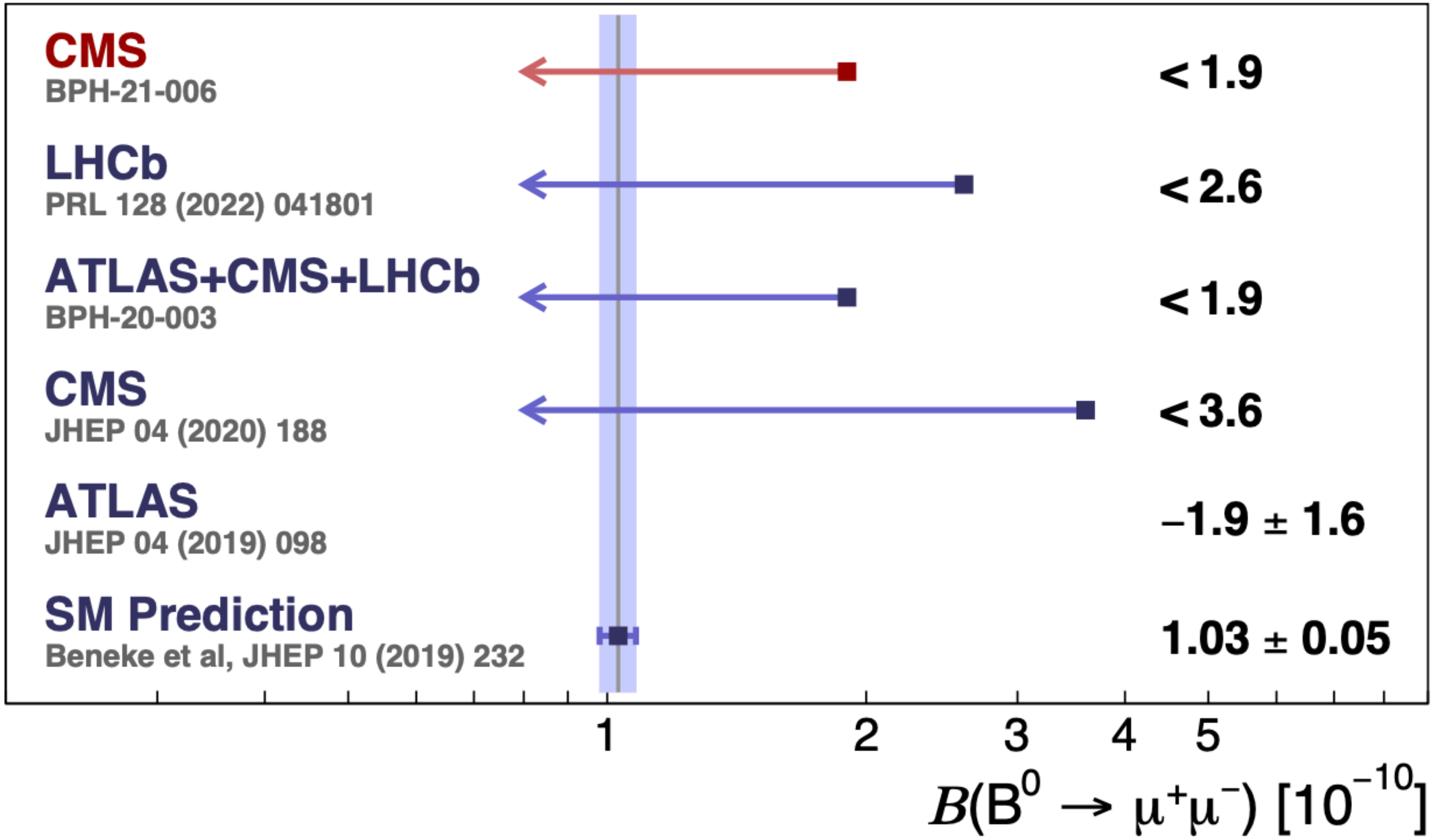
$B_s \rightarrow \mu\,\mu$ BF Result

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

Alternative using Bs→J/ψϕ: $\mathcal{B}(\mathrm{B}_s^0 \to \mu^+\mu^-) = \left[3.95^{+0.39}_{-0.37}\,(\mathrm{stat})\,^{+0.27}_{-0.22}\,(\mathrm{syst})\,^{+0.21}_{-0.19}\,(\mathrm{BF})\right] \times 10^{-9}$



$B^0 \to \mu\,\mu$ BF Result



Summary of CMS $B_{(S)}$ -> μ μ

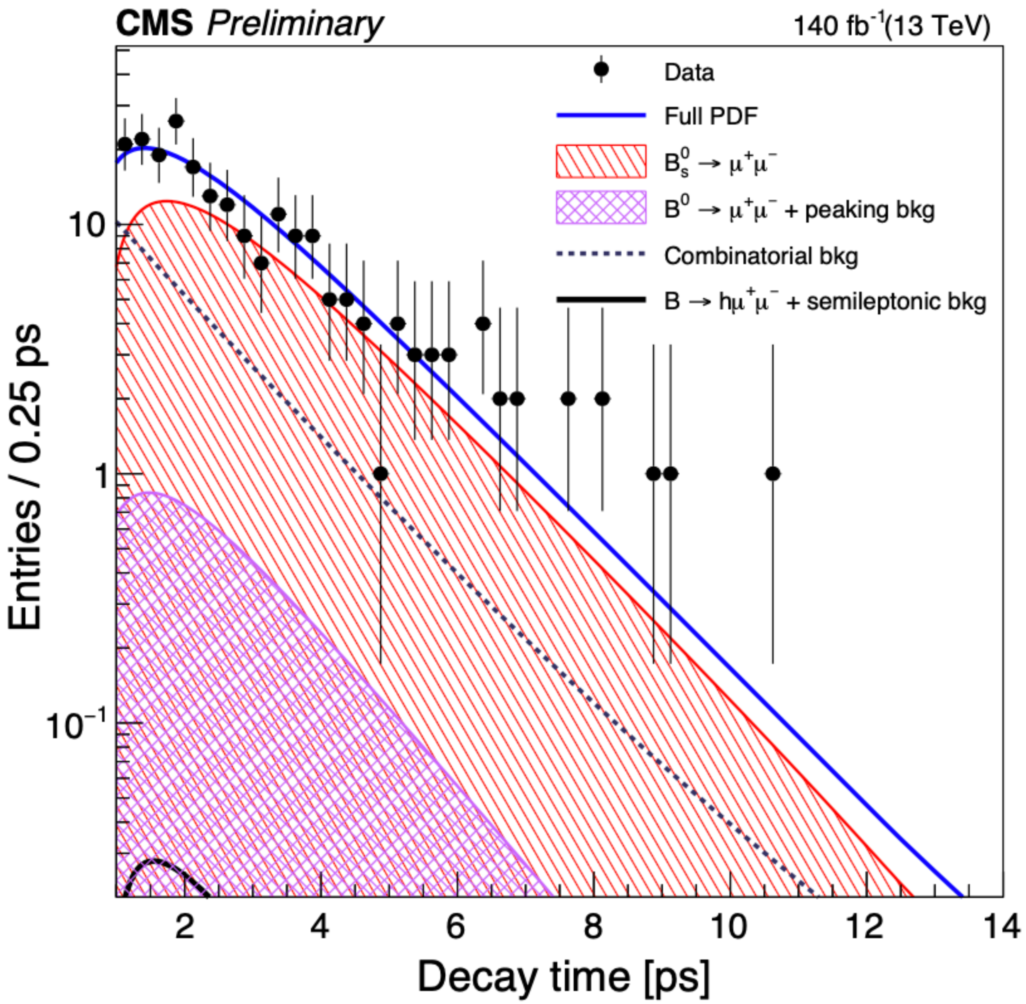
- Studies of rare $B_{(s)} \to \mu^+\mu^-$ decays provides a unique tool to explore and understand rare B decay anomalies
  - Theoretically clean
  - Sensitive to the same processes
- CMS finalized analysis of 140 fb^{-1} data collected during LHC Run-2
  - All results are consistent with SM predictions
- Relative uncertainty on $BF(B_s \to \mu^+\mu^-)$ has been reduced to 11%
  - The best single measurement to date
- Statistical uncertainty dominates
  - Good perspectives for further improvements with upcoming Run-3 data

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/ BPH-21-006/index.html

Stay tuned!

Backup

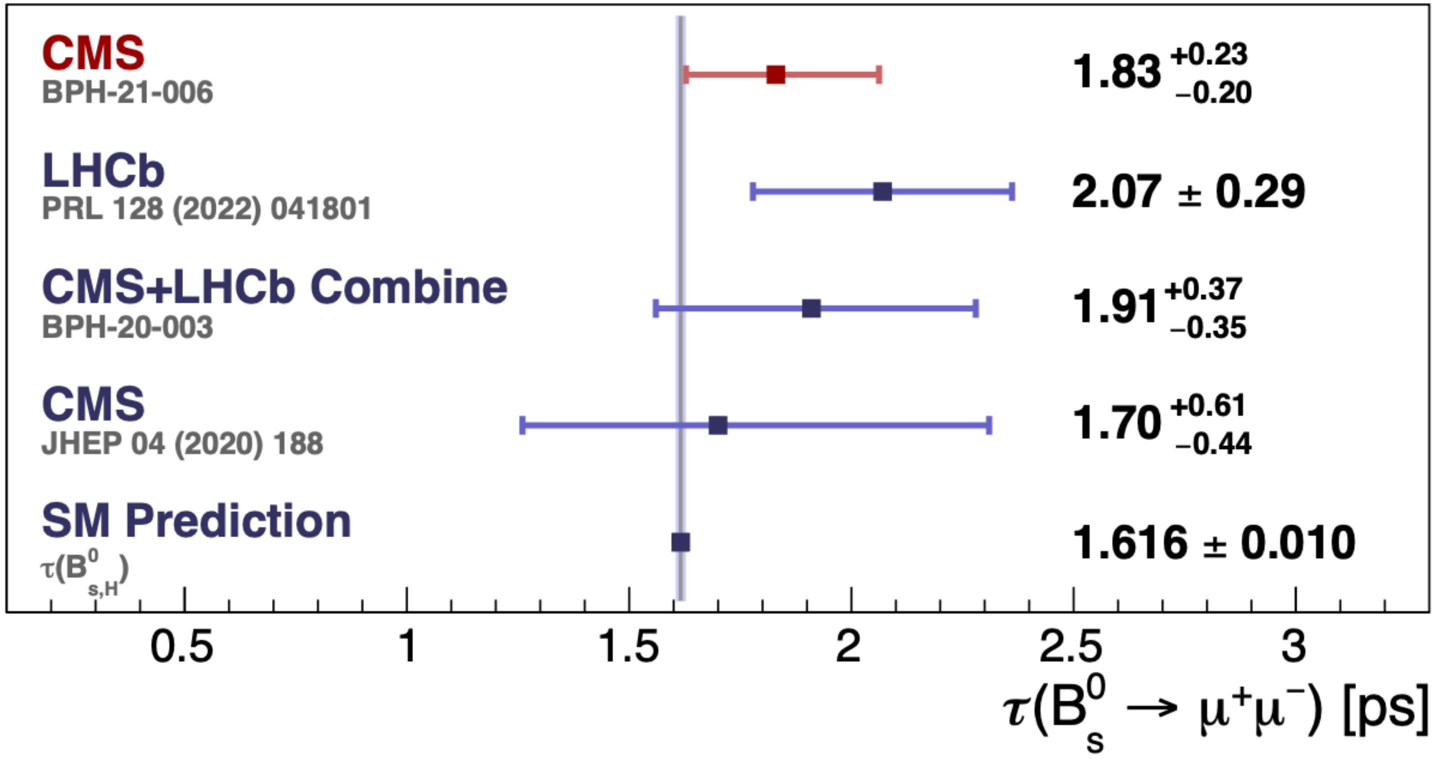
Effective Lifetime Measurement



- In the absence of CP violation only the heavy Bs state decays into dimuon
  - Different composition of states may be allowed by New Physics.
- Efficiency correction
  - Decay time efficiency derived from MC
  - Corrected by $B^+ \to J/\psi K^+$ data to mitigate the bias from tight MVA_B requirement.
    - The residual bias and the difference between $B_s \to \mu\mu$ and $B^+ \to J/\psi K^+$ are considered as a systematic uncertainty.

$B^0 \rightarrow \mu\,\mu$ BF Result

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



Summary of systematic uncertainties and CMS result

Table 2: Systematic uncertainties on masses and widths, in MeV.

Source	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta\Gamma_{BW1}$	$\Delta\Gamma_{BW2}$	$\Delta\Gamma_{BW3}$
signal shape	3	4	3	14	7	7
NRDPS	1	< 1	< 1	3	3	4
NRSPS	3	1	1	18	15	17
feeddown shape	11	1	1	25	8	6
momentum scaling	1	3	4	-	-	-
resolution	< 1	< 1	< 1	< 1	< 1	1
efficiency	< 1	< 1	< 1	1	< 1	1
combinatorial background	< 1	< 1	< 1	2	3	3
total	12	5	5	34	19	20

- Investigated effects of systematics on local significance by a profiling procedure
  a discrete set of individual alternative signal and background hypotheses tested in minimization
  - Significant change: BW1 significance changed from 6.5σ to >5.7σ
  - No relative significance changes for BW2 and BW3

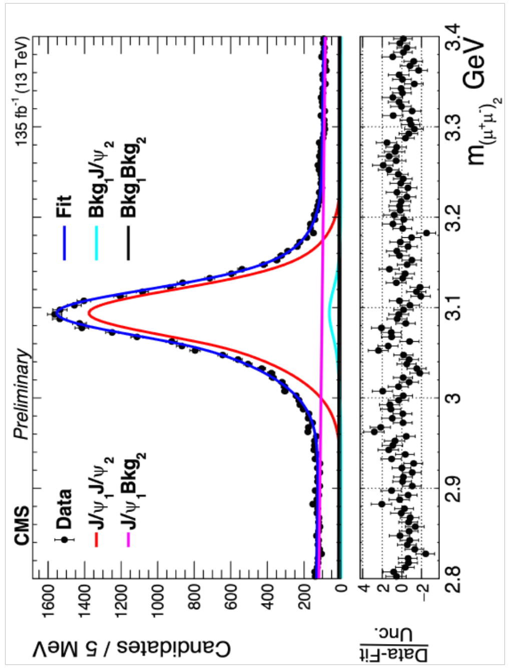
M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV	>5.7σ
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV	>9.4σ
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV	>4.1σ

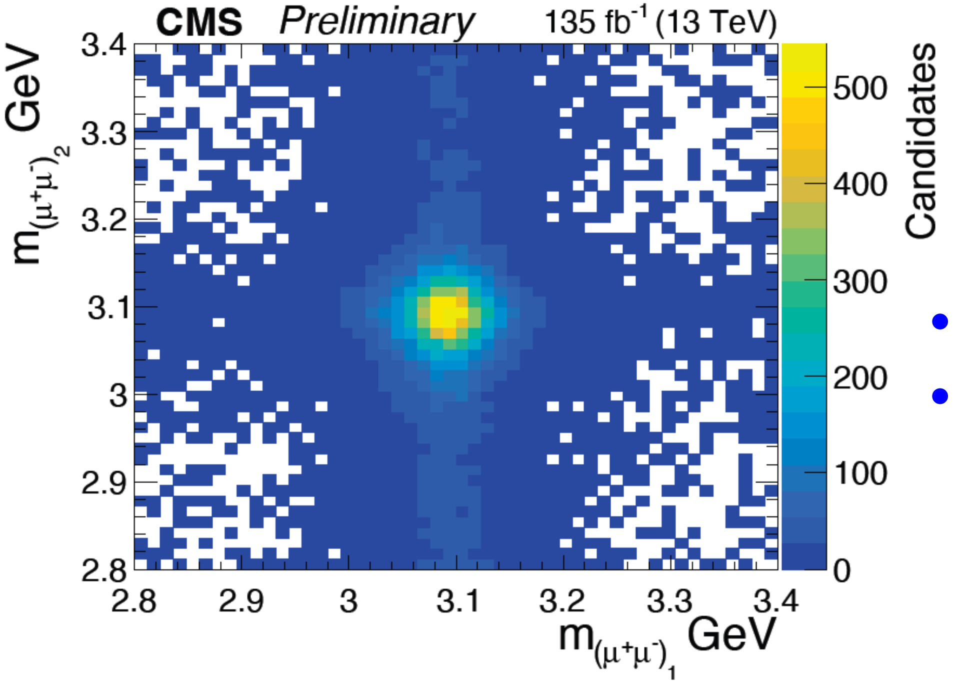
consistent →

X(6900) [LHCb]
(somewhat different fit model)

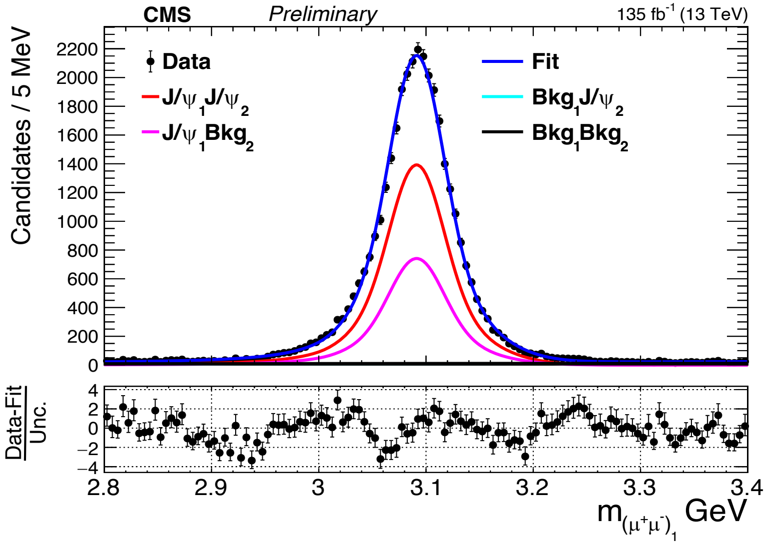
M[BW2]=6905±11±7 MeV
Γ[BW2] =80±19±33 MeV

J/ψ signal





- Remove by J/ψ mass related cuts
- Clean J/ψ signal as seen



- ~15000 J/ψ pairs after final selection (m(J/ψ J/ψ <15 GeV)

- ~9000 J/ψ pairs after final selection (m(J/ψ J/ψ <9 GeV)

Steps to identify structures in $J/\psi J/\psi$ mass spectrum

- Null-hypothesis (initial baseline model): NRSPS+NRDPS
- Add potential structures to baseline model
  - Add most prominent structure to baseline model
  - Calculate its local significance
  - Keep in baseline only if $> 3\sigma$ significance
  - Repeat until no more $> 3\sigma$ structures

NRSPS—Non-Resonant Single Parton Scattering

NRDPS—Non-Resonant Double Parton Scattering

Local significance: standard likelihood ratio method

$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)}, \text{ where } \Gamma(m) = \Gamma_0 \frac{q m_0}{q_0 m},$$

Relativistic S-wave Breit-Wigner (BW) for each structure convolved with resolution function

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Significances including systematics

- To include systematics, alternative resonance/background shapes applied in the fit:
- Calculate signal- and null-hypothesis NLL_{syst} including systematic using:

$$NLL_{syst-sig} = \mathrm{Min}\{NLL_{nom-sig}, NLL_{alt-i-sig} + 0.5 + 0.5 \cdot \Delta dof\}$$

  - $NLL_{nom-sig}$ means the NLL of nominal 'signal hypothesis' fit.
  - $NLL_{alt-i-sig}$ means the NLL of i-th alternative fit of 'signal hypothesis'
  - Δdof means the additional free parameters comparing to the nominal 'signal hypothesis' fit.
- $NLL_{syst-null} = \mathrm{Min}\{NLL_{nom-null}, NLL_{alt-j-null} + 0.5 + 0.5 \cdot \Delta dof\}$
- Significance including systematics as usual from $NLL_{syst-null} - NLL_{syst-sig}$

	Significance with syst.
BW1	5.7σ
BW2	*no sensible changes*
BW3	*no sensible changes*

Final CMS model: 3 BWs + Backgrounds+ BW0