B-Physics measurements with CMS and ATLAS data

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Outline

- Fragmentation fraction ratio
- Rare double-Dalitz decay of $\eta \rightarrow 4\mu$
- Study of di-charmonium spectrum
- Study of $B_c^+ \rightarrow J/\psi\ D_s^{(*)+}$ decay

Ratio of fragmentation fractions (f_s/f_u, f_d/f_u) with CMS data

- The fragmentation fractions: f_u, f_d, and f_s -> probability of b-quark to hadronize to B-mesons or b-baryons such as B^+ (f_u), B_d^0(f_d), B_s^0 (f_s), Λ_b(udb) etc.

- Since in the fragmentation process, the color force fields create quark-antiquark pairs that combine with a bottom quark (bq, bq_1q_2) to create B-meson or b-baryon, it can not be reliably calculated by perturbative QCD, so must be determined empirically.

- Very useful when measuring branching fraction of B_s^0 (e.g., $B_s^0 \to \mu^+\mu^-$) relative to other B-mesons (most often use B^0 or B^+ to cancel the effect of b-hadron production cross section, integrated luminosity and other systematic uncertainties).

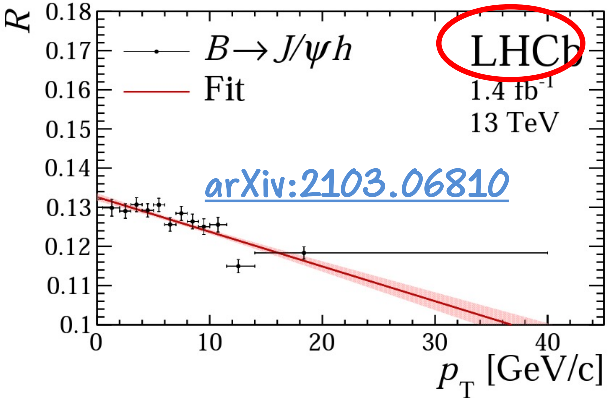
- However, f_u/f_s is one of the major uncertainties for measurement of branching fraction of $B_s^0 \to \mu^+\mu^-$:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B_s^0 \to \mu^+\mu^-}} \frac{f_u}{f_s}$$

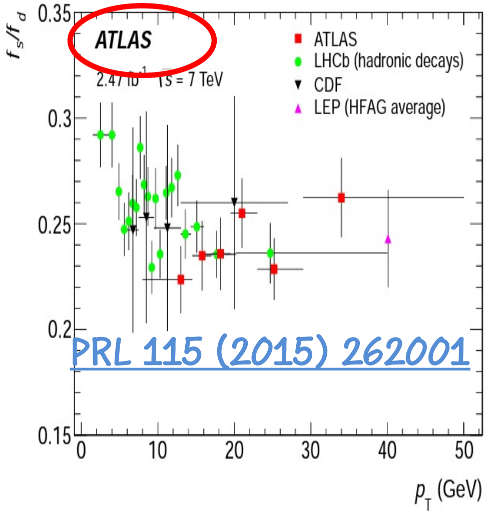
- So, precise measurement of fragmentation ratio is important. However, the ratio depends on kinematic variables such as transverse momentum, and pseudo-rapidity of the b-hadron.

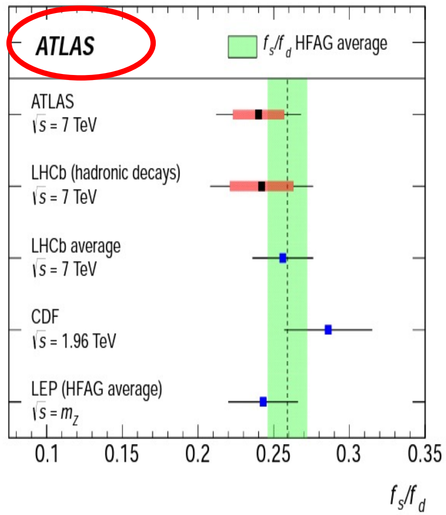
Previous results on fragmentation fraction ratio

- LHCb and ATLAS have measured these parameters: LHCb has seen P_T dependence whereas ATLAS didn't observe such P_T dependency (although measured in different P_T range).



$$\frac{f_s}{f_u} = \frac{n_{\rm corr}(B_s^0 \to J/\psi\phi)}{n_{\rm corr}(B^+ \to J/\psi K^+)} \frac{\mathcal{B}(B^+ \to J/\psi K^+)}{\mathcal{B}(B_s^0 \to J/\psi\phi)\mathcal{B}(\phi \to K^+K^-)} = \frac{\mathcal{R}}{\mathcal{F}_R}$$





- CMS measures R_s (f_s/f_u) and f_d/f_u using the decays $B_s^0 \to J/\psi\ (\mu^+\mu^-)\ \phi\ (K^+K^-)$, $B^+ \to J/\psi\ (\mu^+\mu^-)K^+$ .and $B^0 \to J/\psi\ K^{*0}(K^-\pi^+)$. To be precise CMS measures

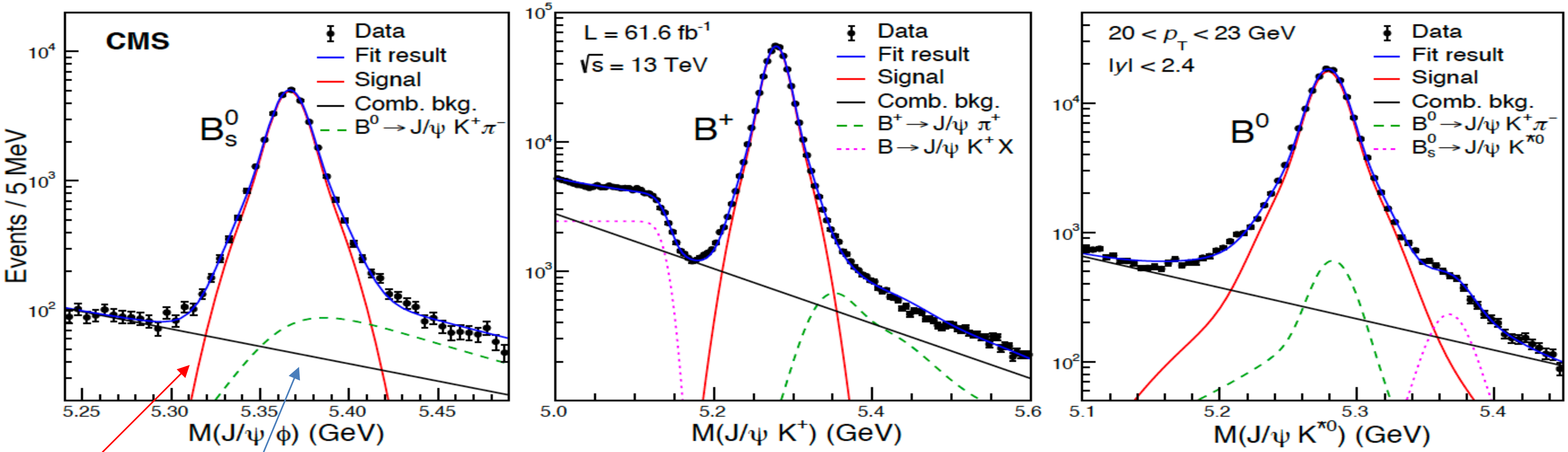
$$\mathcal{R}_s = (N_{B_s^0}/\epsilon_{B_s^0})\,/\,(N_{B^+}/\epsilon_{B^+}) = f_s/f_u\ \frac{\mathcal{B}(B_s^0 \to J/\psi\,\phi)\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(B^+ \to J/\psi\,K^+)}$$

$$\mathcal{R}_d = \frac{N_{B^0}}{\epsilon_{B^0}} \Big/ \frac{N_{B^+}}{\epsilon_{B^+}} = f_d/f_u\ \frac{\mathcal{B}(B^0 \to J/\psi\,K^{*0})\mathcal{B}(K^{*0} \to \pi^-K^+)}{\mathcal{B}(B^+ \to J/\psi\,K^+)}$$

- In the ratio J/ψ branching fraction cancels out. We measure R_s (instead of f_s/f_u) as available measurement of $B_s^0 \to J/\psi\phi$ branching fraction and of f_s are correlated.

- CMS uses 61.6 fb^{-1} data collected during 2018 with COM energy 13TeV.

Signal yields for B_s^0, B^+, and B^0

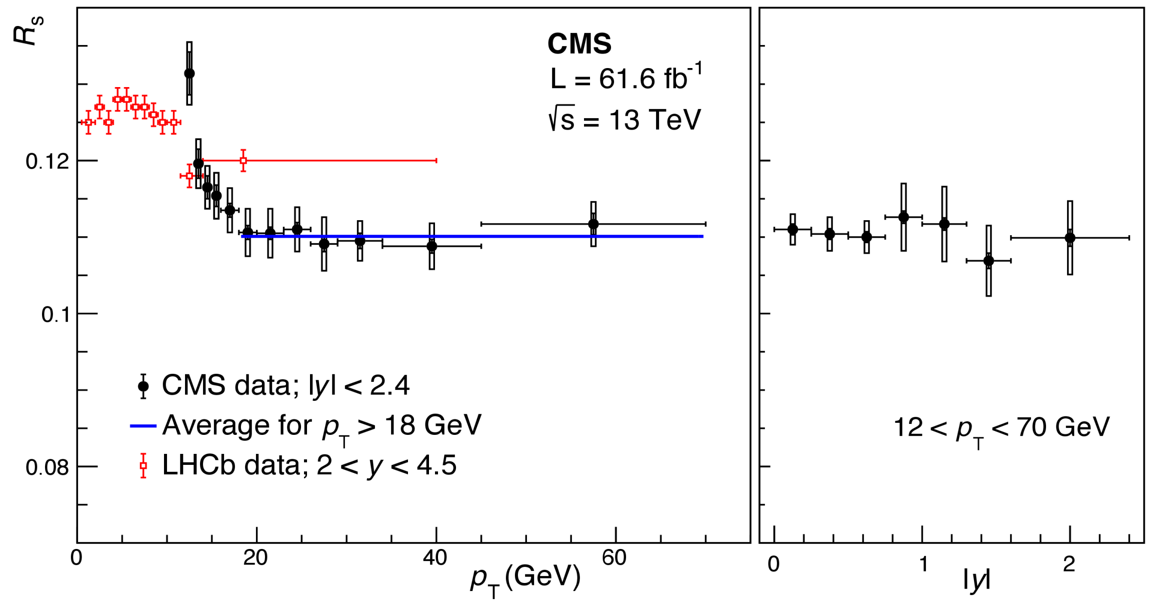


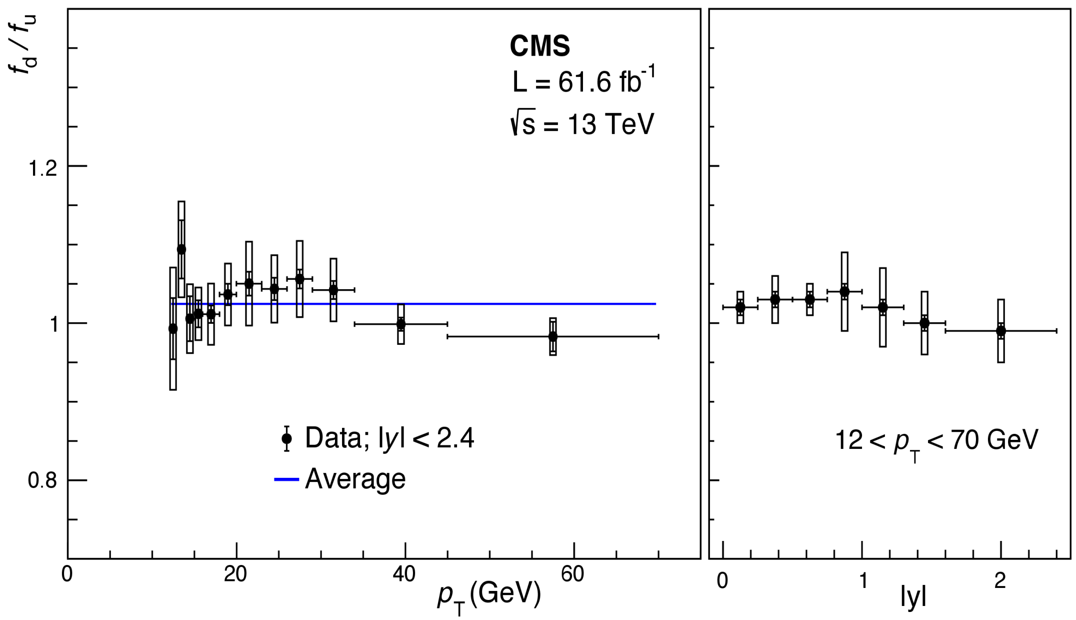
- Signal pdf: Double Gaussian with common mean, independent widths
- Combinatorial background: Exponential
- The other peaking/non-peaking background normalizations/pdfs are either fixed/floated depending on kind of background and information available, e.g.:

- $B^0 \to J/\psi K^+\pi^-$ (where pion can be misidentified as kaon) is Johnson function, with normalization fixed w.r.t signal yield.
- $B \to J/\psi K^+X$ is error function with free shape parameters
- $B^+ \to J/\psi\pi^+$, triple gaussian, normalization fixed to signal yield and scaled by BF ratios
- $B^0 \to J/\psi K^+\pi^-$,shape and relative normalization w.r.t. unswapped fixed from MC.
- $B_s \to J/\psi K^{*0}$ shape fixed from MC, normalization fixed to signal yield.

R_s and f_d/f_u results with CMS data

- The measured R_s does not show any |y| dependence, although there is clear dependence on P_T at low P_T followed by flat shape in high P_T.
- Similar dependency observed by LHCb.
- Averaging the P_T>18 GeV, the value of $Rs= 0.1102 \pm 0.0027$

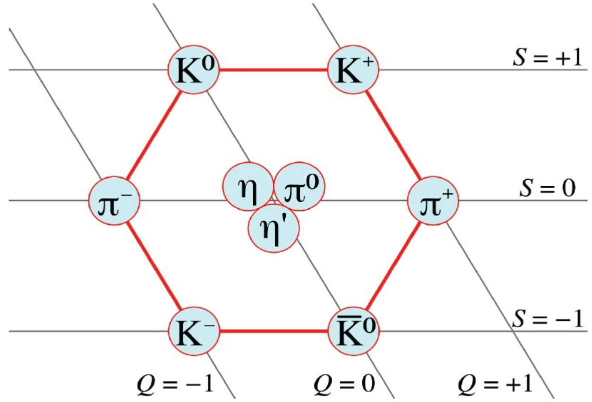




arXiv:2212.02309 (submitted to PRL)

- The ratio f_d/f_u shows no dependency on either P_T or |y|.
- The average over all P_T points given the value: 1.015 ± 0.051. This is consistent with unity as expected from strong isospin symmetry.
- This result will be crucial in the measurement $B_s^0 \to \mu^+\mu^-$ in future.

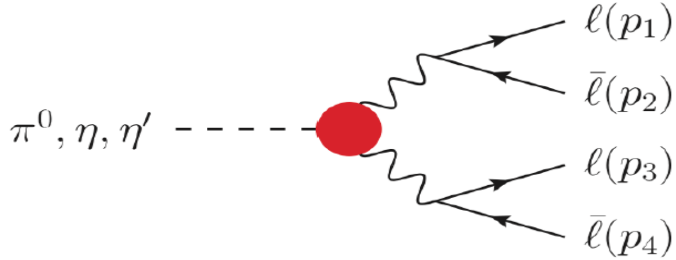
The rare decay of η –> μ⁺μ⁻μ⁺μ⁻ with CMS Data



- Neutral Meson – Pseudoscalar, like π^0, with Strangeness(S)=0 and Charge (Q)=1. $J^{PC}= 0^{-+}$
- Mixture of light quark states:

$$\eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

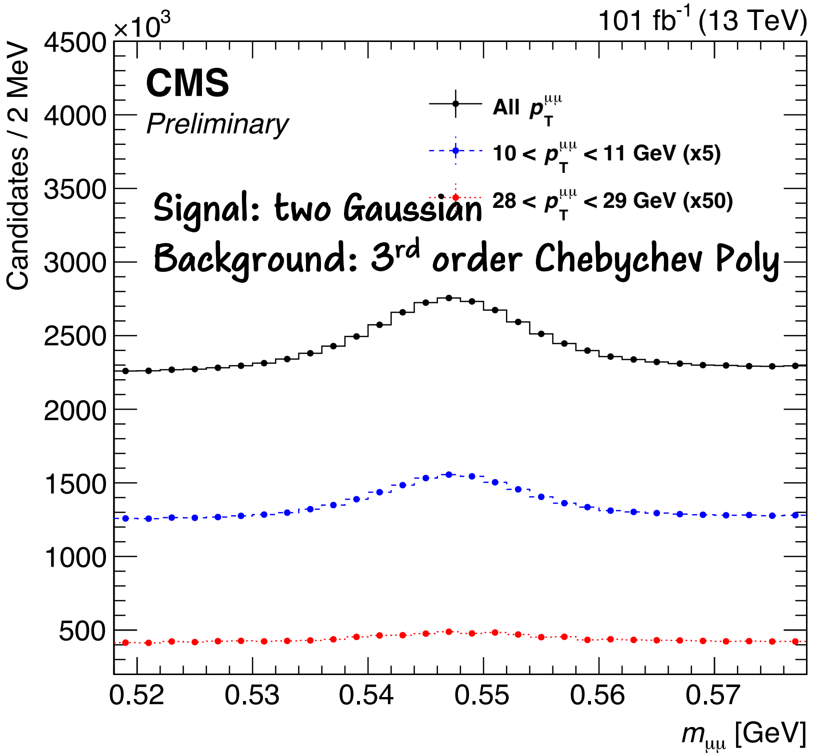
- Mass: 547.9MeV, Width= 0.0013MeV

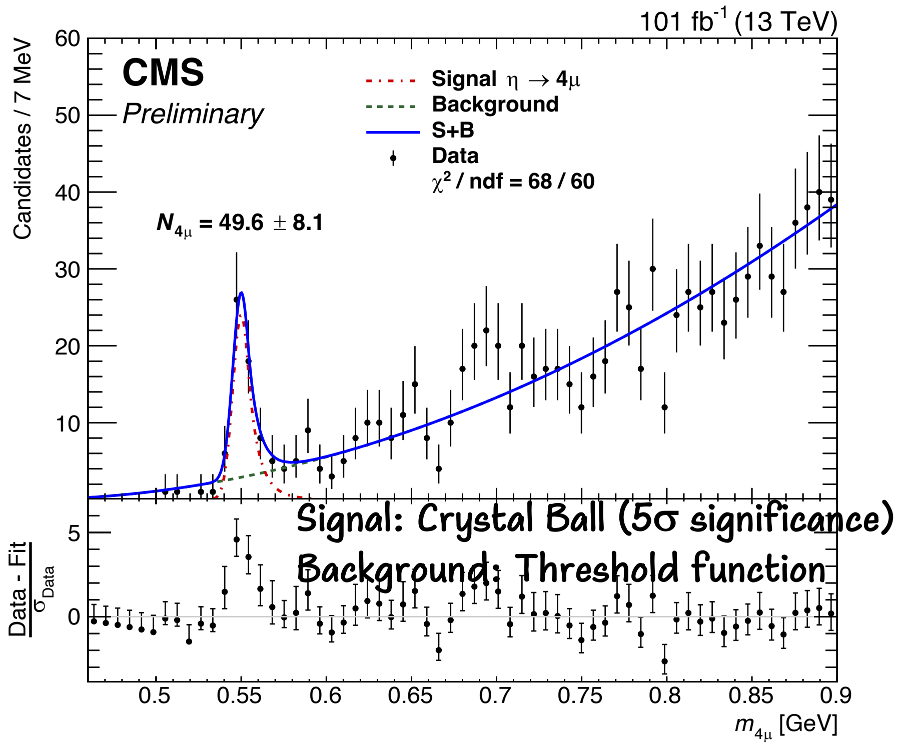


- η decays to 4 leptons through radiative double Dalitz decays where two virtual photons internally convert to leptons pairs.
- No Hadrons among decay products -> Matrix element directly sensitive to the η meson transition form factor.
- The knowledge of η meson coupling to the virtual photons is important for calculation of anomalous magnetic moment of muon.
- Study of this process provide a sensitive probe to new Physics, e.g., dark photons, light Higgs scalars, axion-like particles which is complementary to detect new particles below GeV mass scale.

Analysis strategy

- CMS uses 13 TeV data (101 fb^{-1}) collected during 2017 and 2018.
- Use $\eta \to \mu^+\mu^-$ [where $B(\eta \to \mu^+\mu^-) = (5.8 \pm 0.8) \times 10^{-6}$] as the reference channel.
- Dedicated set of high-rate triggers are developed to improve the efficiency at low mass [low P_T muon threshold and keeps only limited information(<10kB)/event].
- Two/Four muons to come from same vertex. About 4.5M $\eta \to 2\mu$ signals and ~50 $\eta \to 4\mu$ signal events found.





Branching fraction measurement for η–>4μ

BF of η–>4μ

#of 4μ signal yield

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$

Acceptance x Efficiency for 4μ events

BF of η–>2μ

Acceptance x Efficiency for 2μ events

#of 2μ signal yield

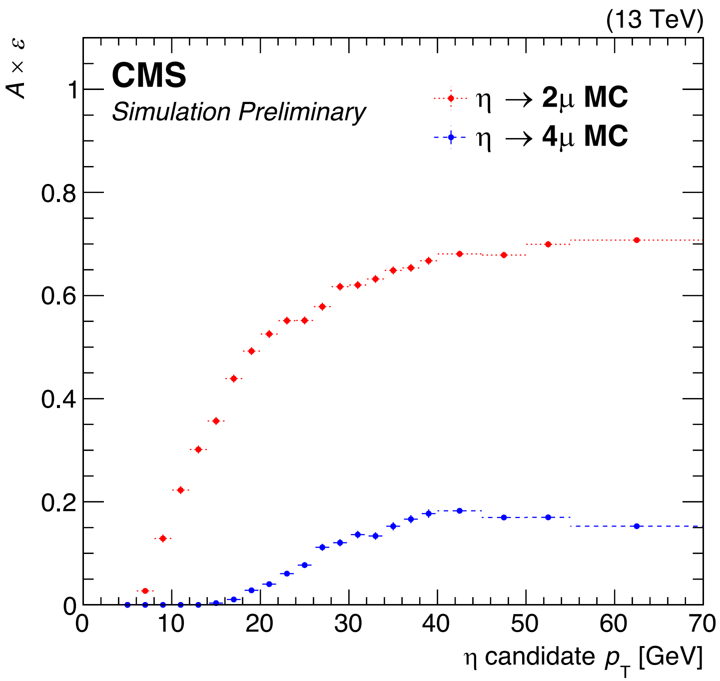
Here ***i*** and ***j*** runs over the P_T and pseudo-rapidity of η mesons

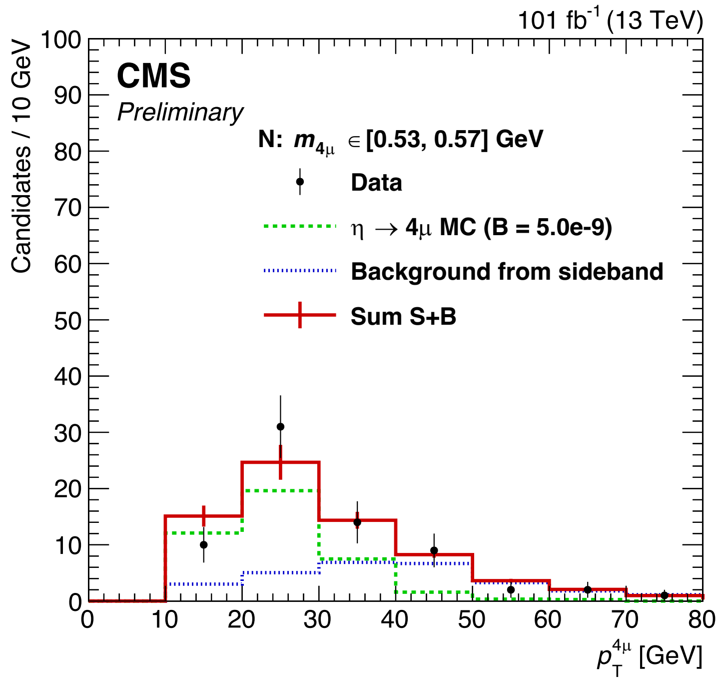
- Using the signal yields and acceptance values, we get $\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.9 \pm 0.1\,(\text{stat}) \pm 0.1\,(\text{syst})) \times 10^{-3}$
- However, using the world average value of BF of η–>2μ, $\mathcal{B}(\eta \to 2\mu) = (5.8 \pm 0.8) \times 10^{-6}$

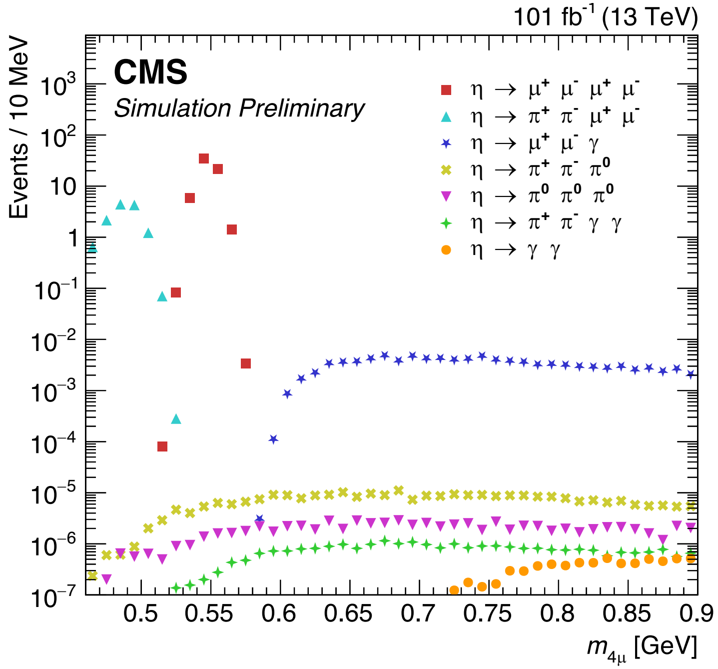
$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B})) \times 10^{-9}.$$

- The expected theoretical value of η to 4μ decay is (3.98 ± 0.15) x 10^{-9} .
- The observed central value 25% more than prediction, however consistent given large error.

η–> 4μ result with CMS data







- Main Source of syst shown below: (Several sources already cancels out in the ratio)

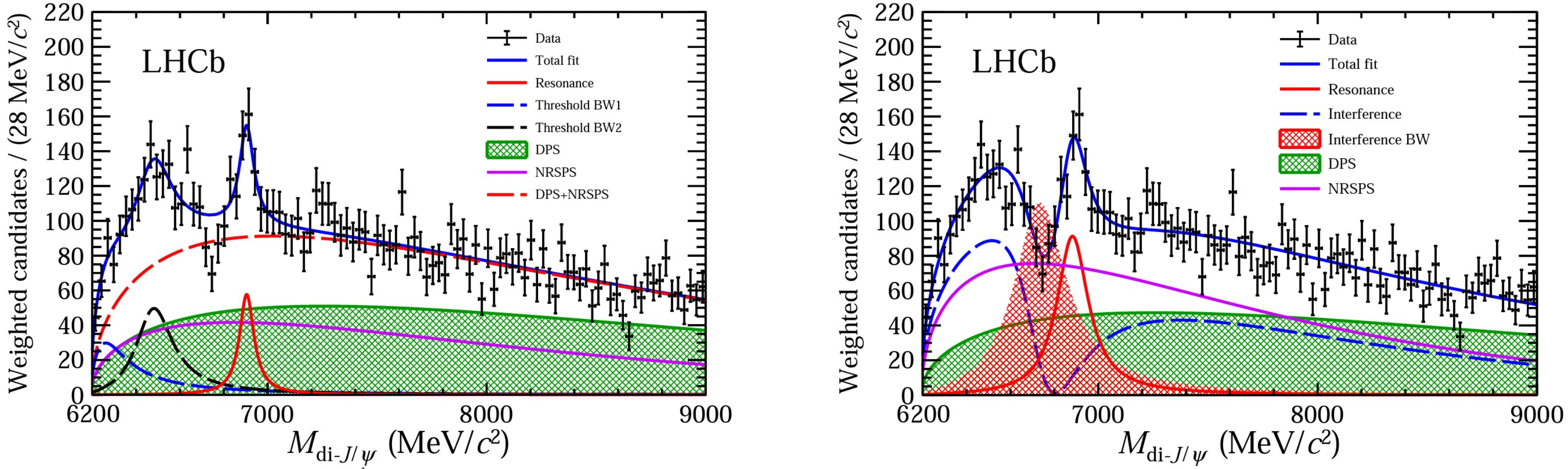
Track P_T threshold	9%
Trigger P_T threshold	8.4%
Efficiency plateau	3.2%
Fit signal model, $N_{4\mu}$	3.4%
Fir background model, $N_{4\mu}$	4.2%
Fit signal and bkg model, $N_{2\mu}$	3.8%
Total Syst Uncertainty	14.3%

- This is first observation of the double Dalitz decay η–>4μ with high-rate muon trigger.
- It is very important to measure the reference channel precisely.

CMS-PAS-BPH-22-003

Di-charmonium excess in 4μ final state

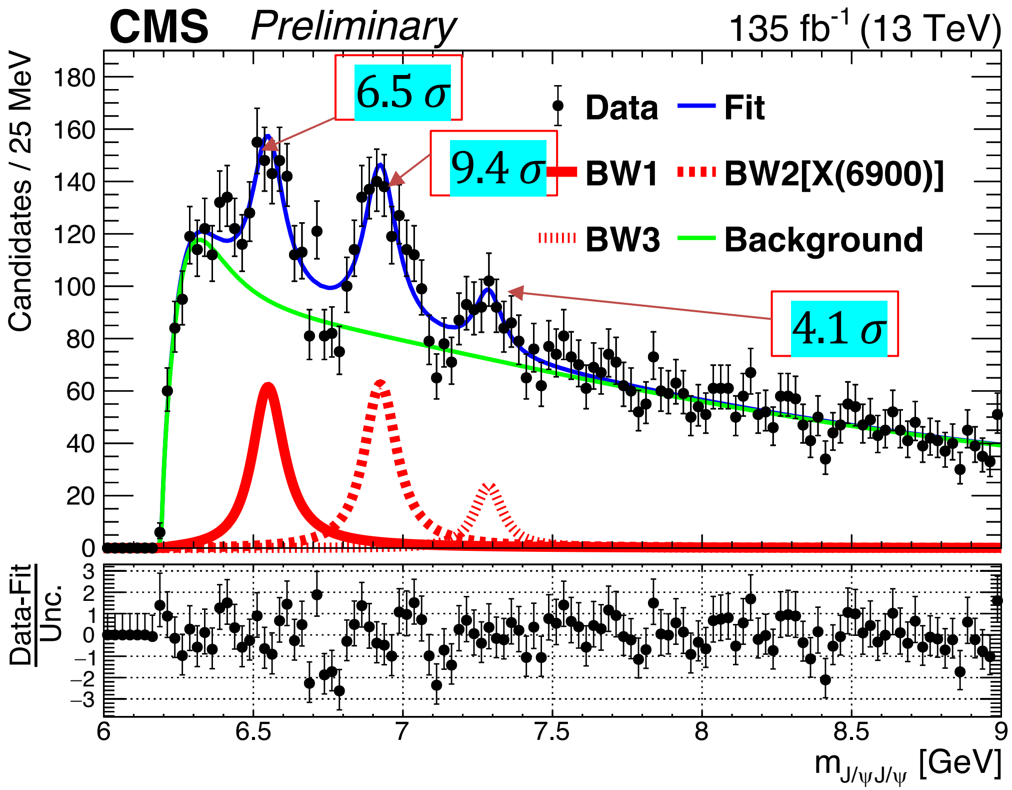
- Apart from conventional mesons(two quark states) and baryons(three quark states) many tetraquarks and several pentaquarks candidates are observed in experiment but their theoretical interpretation remain contested.
- The first experimental evidence for exotic hadron was $\chi_{c1}(3872)$ observed by Belle Collaboration in 2003 [PRL 91 (2003) 262001].
- In 2020, LHCb reported evidence of narrow resonance in di-J/ψ (-> 4μ) spectrum, at around 6.9 GeV, which can be interpreted as tetraquark consisting of four charm quarks.



Science Bulletin 65 (2020) 1983

LHCb model I: no interference	LHCb model II: with interference
$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$ $\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV}$	$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$ $\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}$

di-J/ψ spectrum without interference model using CMS data



Fit model building:

- Sequential fit starting from background-only hypothesis to increasingly complex ones.
- Add new features if their local significance exceeds 3 standard deviations.

Signal shapes are relativistic S-wave Breit-Wigner functions convolved with double Gaussian resolution functions (BW):

- BW_1 -> structure at ≃ 6600 MeV
- BW_2 -> $X(6900)$
- BW_3 -> structure at ≃ 7200 MeV

Background shapes based on MC simulations:

- **Non-resonant single-parton scattering** (NRSPS)

$$f_{SPS}(x, x_0, \alpha, p_1, p_2, p_3) = (x - x_0)^{\alpha} \times \left(1 - \left(\frac{1}{(15 - x_0)^2} - \frac{p_1}{10}\right)(15 - x)^2\right) \times \exp\left(-\frac{(x - x_0)^{p_3}}{2p_2^{p_3}}\right)$$

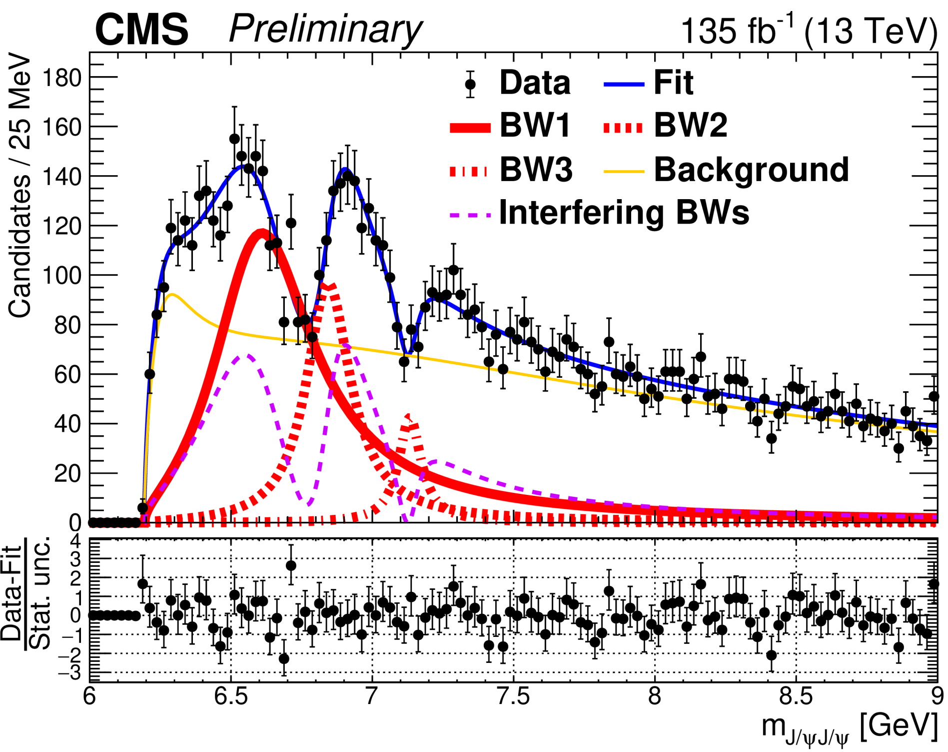
where $x_t = x - x_0$ and $x_0 = 2M_{J/\psi}$

- **Non-resonant double-parton scattering** (NRDPS):

$$f_{DPS}(x) = \sqrt{x_t} \times \exp(-a x_t) \times (p_0 + p_1 x_t + p_2 x_t^2) \quad \text{where } x_0 = 2M_{J/\psi}$$

di-J/ψ spectrum with interference model using CMS data

		BW$_1$	BW$_2$	BW$_3$
Non interference	m[MeV]	6552 ± 10 ± 12	6927 ± 9 ± 4	7287± 19 ± 5
	Γ[MeV]	124 ± 29 ± 34	122 ± 22 ± 19	95 ± 46 ± 20
	N	474 ± 113	492 ± 75	156 ± 56
Interference	m[MeV]	$6638^{+43}_{-38}\,^{+16}_{-31}$	$6847^{+44}_{-28}\,^{+48}_{-20}$	$7134^{+48}_{-25}\,^{+41}_{-15}$
	Γ[MeV]	$444^{+226}_{-199}\,^{+109}_{-235}$	$191^{+66}_{-49}\,^{+25}_{-17}$	$97^{+40}_{-29}\,^{+29}_{-26}$

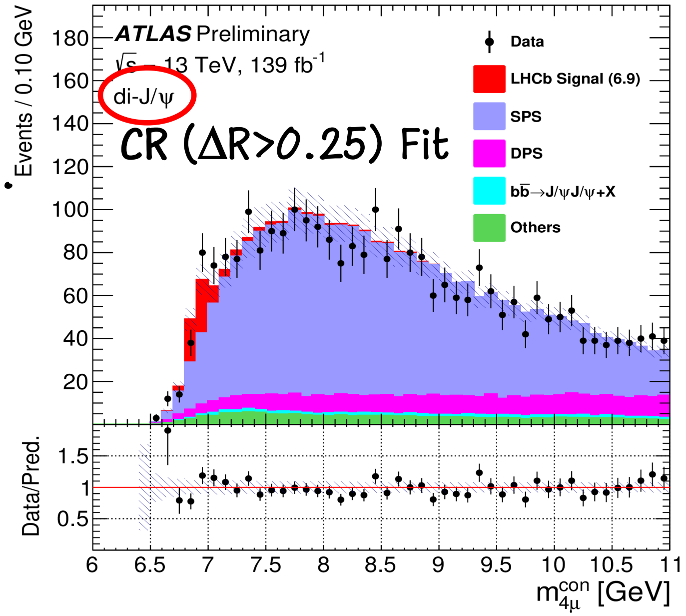


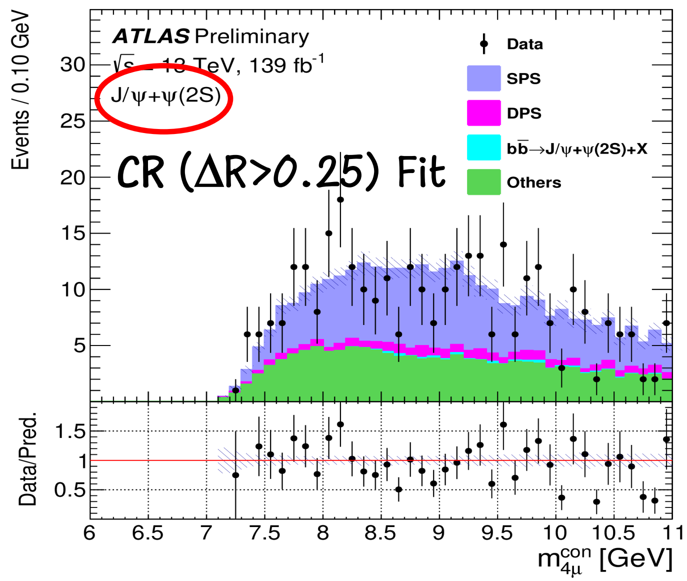
- The non-interference model doesn't account for dip around 6750 and 7150 MeV
- The fit to the mode with three interference leads to shifts in masses of three components.
- Fitting our data with LHCb models give poor fit probabilities although BW parameters are similar.
- Theoretical calculation suggests these structures be identified as part of a family of radial excited P-wave states, whose masses are calculated to be 6554, 6926 and 7220 MeV.

CMS-PAS-BPH-21-003

Di-charmonium study with ATLAS data

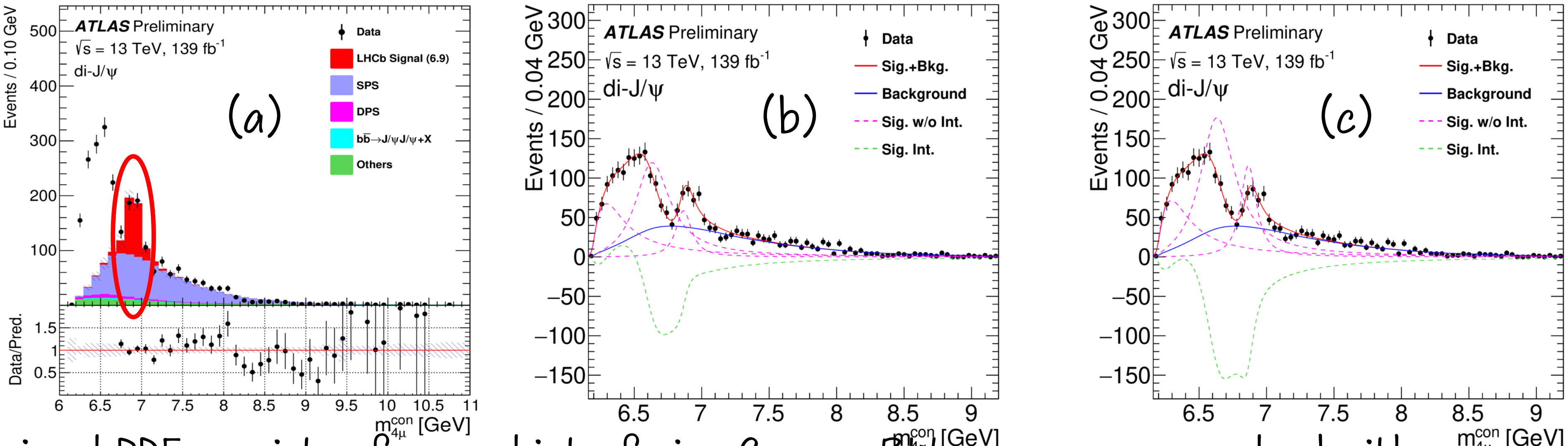
- ATLAS uses 13 TeV Run2 data (139 fb^{-1}) collected during 2015 – 2018.
- Search 4μ final state through di-J/ψ and J/ψ +ψ(2S) mode.
- Signal: TQ -> J/ψ + J/ψ (or ψ(2S)) -> 4μ.
- Background processes:
  - (i)prompt di-J/ψ: SPS and DPS
  - (ii) non-prompt di-J/ψ: bb -> J/ψ + J/ψ + X
  - (iii) Ohers: Single charmonium + fake muons, non-peaking without any real charmonium





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)	

Fit to di-J/ψ mass spectrum



- The signal PDF consists of several interfering S-wave BW resonances convolved with mass resol.
- The number of resonances changed from 1 to 2 or 3, and compared with the χ^2 values of fit.

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

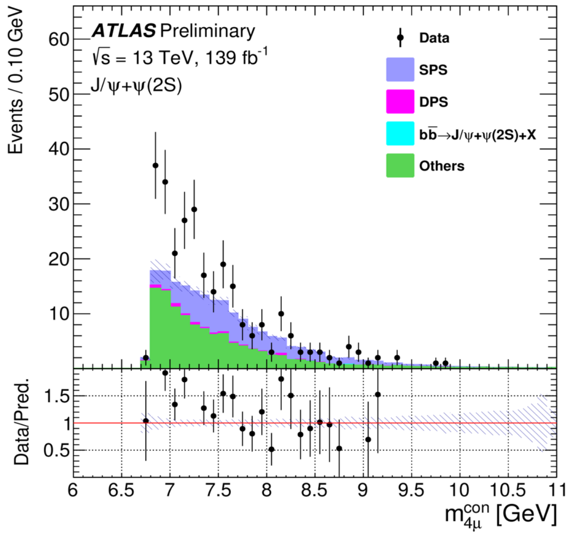
(GeV)	m_0	Γ_0	m_1	Γ_1
di-J/ψ	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2	—	
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	

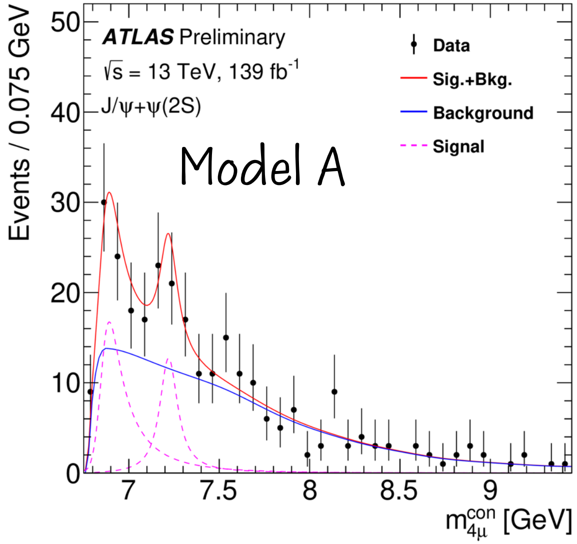
m_i (Γ_i) : masses (widths) of resonances
z_i: represents amplitude
R(α): resolution function
The function under square root: phase space

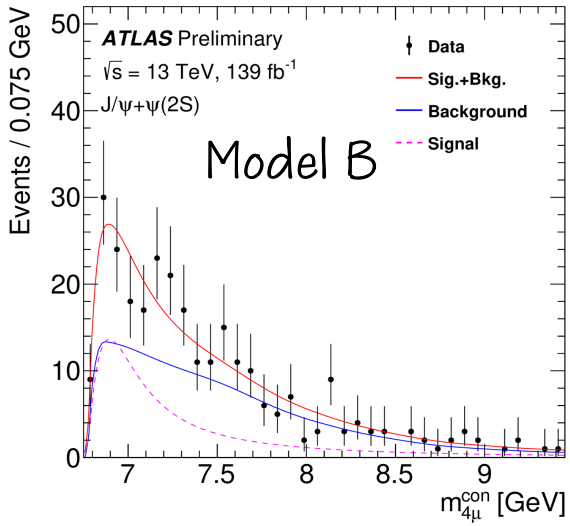
(b) and (c) fitted with 3 resonances but with different resonances magnitudes and interferences.

- The resonance at around 6.9GeV is consistent with LHCb and has 10σ significance.
- LHCb Model-II is disfavored due to worse fit quality (worse χ^2/NDF).

Fit to J/ψ + ψ(2S) mass spectrum







ATLAS-CONF-2022-040

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

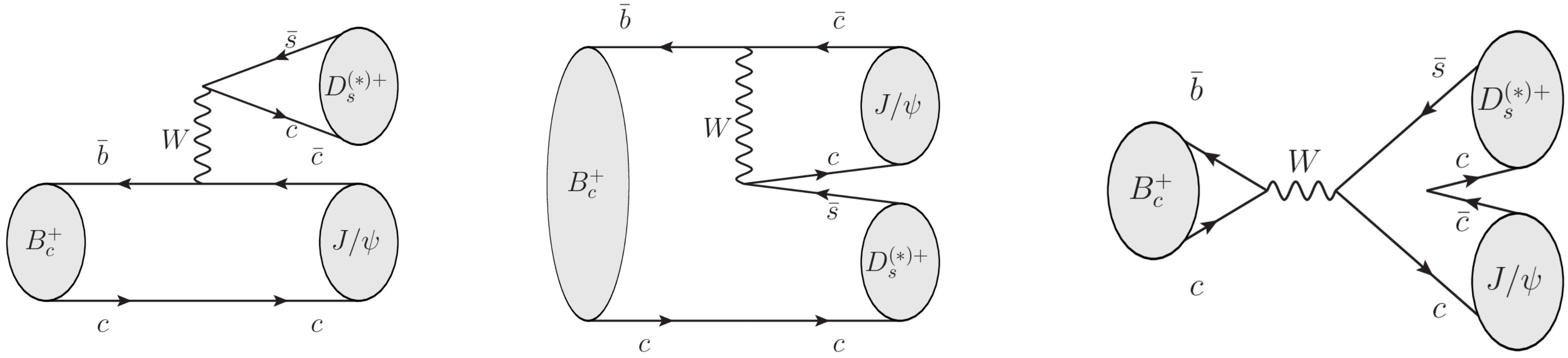
(GeV)		m_3	Γ_3	
J/ψ+ψ(2S)	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$	—
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$	—

- Model A: Same as di-J/ψ case + 4th standalone resonance (first 3 resonance fixed from di-J/ψ)
- Model B: Single resonance (without z_0,z_1 and z_2 terms in above equation).

- Signal significance from the best fit for Model A(B) are 4.6σ(4.3σ).
- In the fit Model A, the significance of second resonance found at 7.2 GeV is 3.2σ. Such structure at 7.2 GeV was seen by LHCb in di-J/ψ spectrum.
- We need more data to confirm this as multiple non-interfering resonances, reflection effects, threshold enhancements etc, can not be ruled out completely.

The decay $B_c^+ \to J/\psi\ D_s^{(*)+}$ using ATLAS data

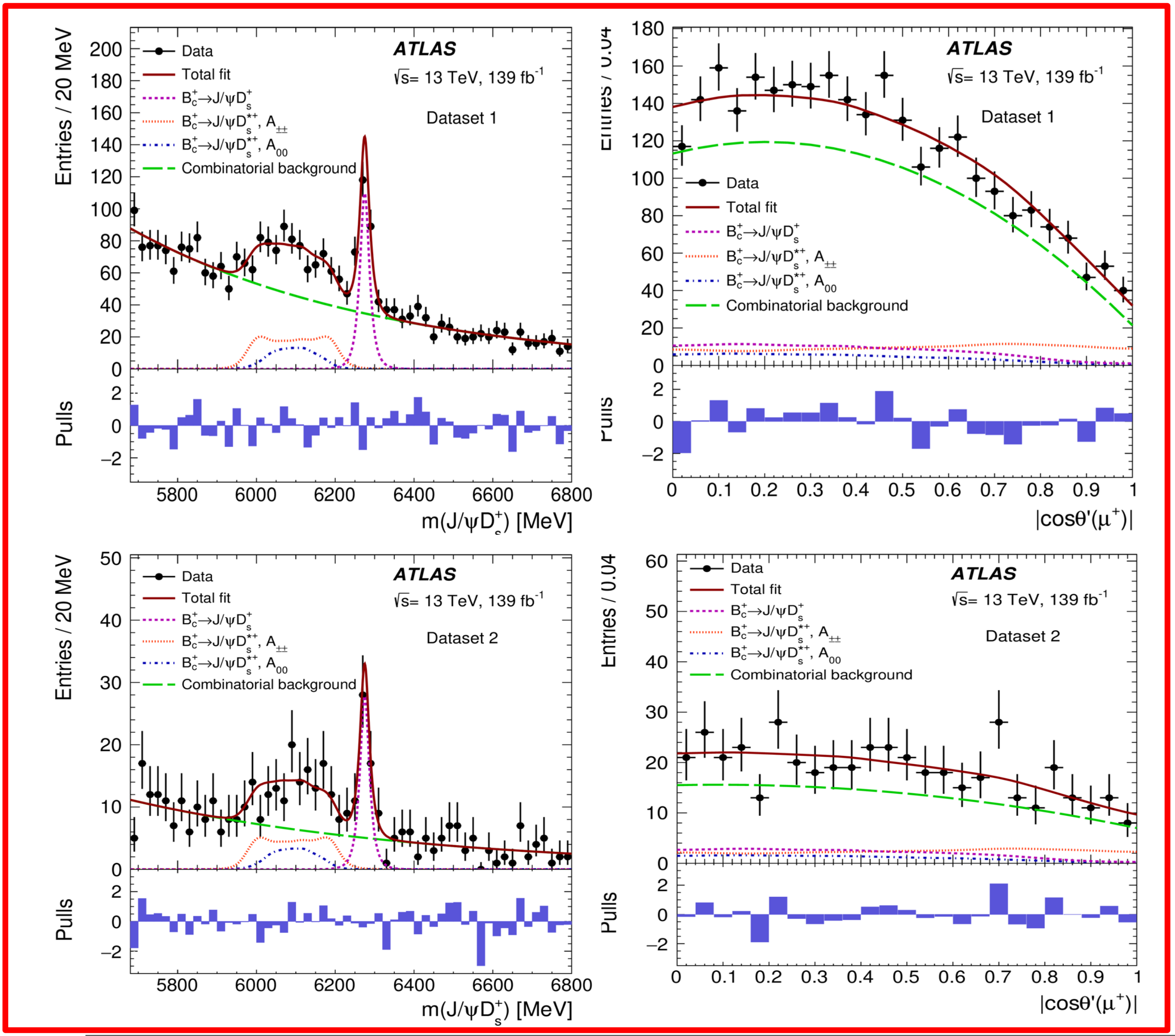
- Being the only weakly decaying meson consisting of two heavy quarks, B_c^+ provides unique testing ground for different theoretical approaches that describe its production and decays.
- B_c^+ decays can occur through a weak transition of either heavy quarks or weak annihilation.
- B_c^+ decay to J/ψ final state involves a b-quark transition with c-quark being spectator and annihilation diagram.
- ATLAS studied decay of $B_c^+ \to J/\psi\ D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ where $J/\psi \to \mu^+\mu^-$, $D_s^{*+} \to D_s^+\pi^0$, $D_s^+ \to \phi\ (K^+K^-)\ \pi^+$



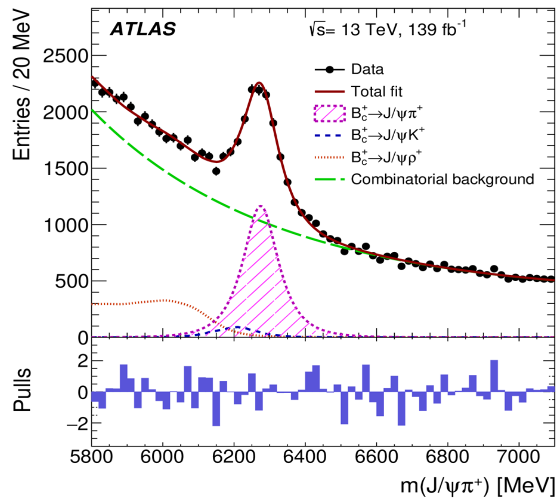
- The branching fractions are measured with respect to a reference channel $B_c^+ \to J/\psi\ \pi^+$ as well as $BF(B_c^+ \to J/\psi\ D_s^{*+}) / BF(B_c^+ \to J/\psi\ D_s^+)$.
- The decay of $J/\psi D_s^{*+}$ (Pseudo-scalar -> two vector states) is described by three helicity amplitudes -> Measure their relative contributions , e.g. $A_{\pm\pm}$

Results for $B_c^+ \to J/\psi\, D_s^{(*)+}$ decay with ATLAS data

- The two non-overlapping datasets corresponding to two different triggers used for the analysis.
- An extended UML fit to $m(J/\psi D_s^{(*)+})$ and $|\cos\theta'(\mu^+)|$ is performed together to extract signal yields, as well as the transverse polarization fractions in $B_c^+ \to J/\psi\, D_s^{*+}$ decay.



- The branching fraction of $B_c^+ \to J/\psi\, D_s^+$ or $B_c^+ \to J/\psi\, D_s^{*+}$ with respect to $B_c^+ \to J/\psi\, \pi^+$ ($R_{D_s^+/\pi^+}$ or $R_{D_s^{*+}/\pi^+}$) uses dataset 1 whereas $R_{D_s^{*+}/D_s^+}$ uses dataset 2.
- $\theta'(\mu^+)$: helicity angle, defined in the rest frame of the muon pair (angle between μ^+ and D_s^+ momenta).



Results and theory comparisons

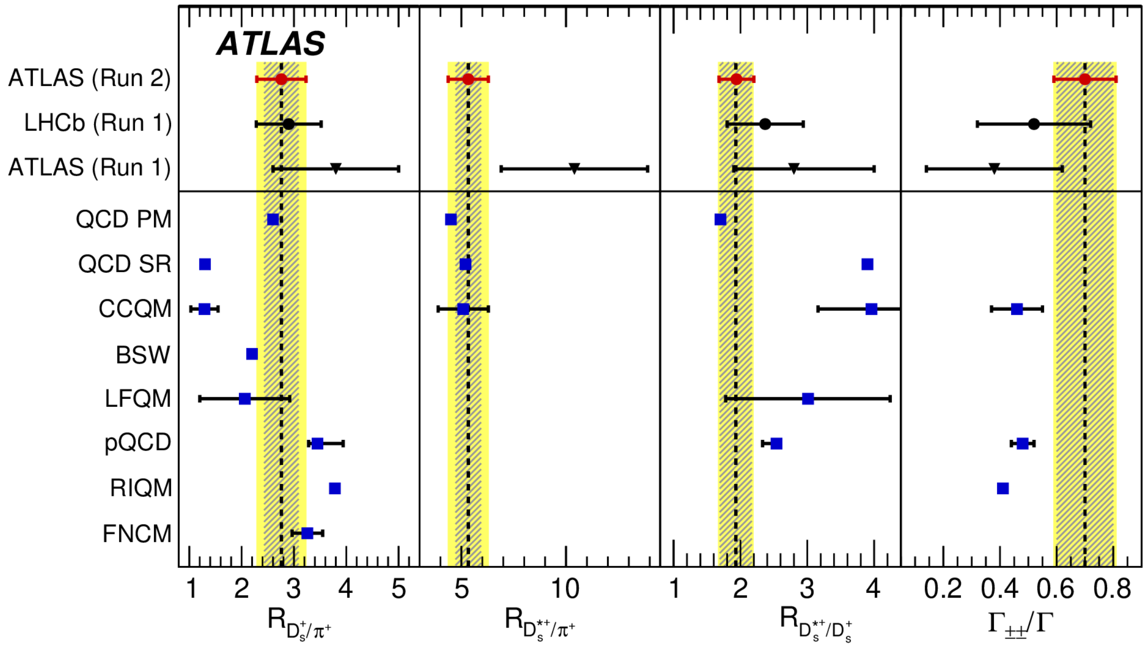
$$R_{D_s^+/\pi^+} = 2.76 \pm 0.33 \pm 0.29 \pm 0.16$$

$$R_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61 \pm 0.67 \pm 0.32$$

$$R_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24 \pm 0.09$$

$$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10 \pm 0.04$$

arXiv: 2203.01808 (JHEP 08, 2022(087))



Parameter	Value
$m_{B_c^+}$ [MeV]	6274.8 ± 1.4
$\sigma_{B_c^+}$ [MeV]	11.5 ± 1.5
$r_{D_s^{*+}/D_s^+}$	1.76 ± 0.22
$f_{\pm\pm}$	0.70 ± 0.10
$N^{\mathrm{DS1}}_{B_c^+\to J/\psi D_s^+}$	193 ± 20
$N^{\mathrm{DS2}}_{B_c^+\to J/\psi D_s^+}$	49 ± 10
$N^{\mathrm{DS1}}_{B_c^+\to J/\psi D_s^{*+}}$	338 ± 32
$N^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^+}$	241 ± 28
$N^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^{*+}}$	424 ± 46

Parameter	Value
$m_{B_c^+}$ [MeV]	6274.5 ± 1.5
$\sigma_{B_c^+}$ [MeV]	47.5 ± 2.5
$N_{B_c^+\to J/\psi\pi^+}$	8440^{+550}_{-470}

- All the results are consistent with earlier measurements by ATLAS and LHCb, although with better precision now.
- Various measured quantities are compared with data the QCD relativistic potential model calculation agrees well with the three ratios of BFs.

Summary and discussions

- CMS and ATLAS pursues broad spectrum of B-physics measurements.
- The precision measurements of fragmentation fraction would be crucial input for the $B_s^0 \to \mu^+\mu^-$ branching fraction.
- The first observation of double Dalitz rare decay of $\eta \to 4\mu$ is reported.
- Di-charmonium mass spectrum was studied by CMS and ATLAS. The detailed interpretation of the structures (whether they are four charm tetra quark states) are yet to be confirmed.
- The decay of B_c^+ meson to $J/\psi D_S^{(*)+}$ is reported and compared with different theoretical calculations.
- More results on Run2, as well as Run3 data (with COM energy of 13.6 TeV) coming soon.