

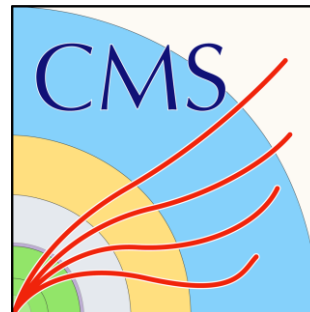
# Hadronization Fractions and Exotic Heavy Flavor at CMS

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Phenomenology 2023 Symposium - Pittsburgh

<https://indico.cern.ch/event/1218225/>

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# Outline

- Bottom quark hadronization fractions at hadron colliders
  - Measurements of hadronization fractions
  - Observations from LHC-b
  - Recent CMS measurements
    - $J/\psi$  final states
    - Hadronic final states
- Exotic heavy flavor production
  - Observation of X(6900)
  - $J/\psi J/\psi$  mass spectrum at CMS
  - Resonance fits
- Triple  $J/\psi$  production
  - Measurement of  $\sigma_{\text{eff,DPS}}$

# Bottom Quark Hadronization Fractions

- Number of weakly decaying B hadrons reconstructed in an exclusive final state:

$$N_X = \sigma_b \cdot A \cdot f_q \cdot \mathcal{B}(B_q \rightarrow X) \cdot \epsilon_X$$

- Measured branching fractions (eg, for  $B_s^0$ ):

$$\mathcal{B}(B_s^0 \rightarrow X) = \frac{N_X}{\sigma_b \cdot A \cdot f_s \cdot \epsilon_X}$$

- Ratio of branching fractions (eg,  $B \rightarrow \mu^+ \mu^-$ ):

$$\frac{\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_d^0 \rightarrow \mu^+ \mu^-)} = \frac{N_{B_s \rightarrow \mu^+ \mu^-}}{N_{B_d \rightarrow \mu^+ \mu^-}} \cdot \frac{f_d}{f_s}$$

- Need to know hadronization fractions for precision measurements at hadron colliders

# Bottom Quark Hadronization Fractions

- Assumed to be independent of environment,  $p_T(B)$ ...

$$f_u + f_d + f_s + f_{\text{baryon}} = 1$$

- Measured at LEP ( $\sqrt{s} = M_Z$ ) and the Tevatron

Quantity		Z decays	Tevatron
$B^+$ or $B^0$ fraction	$f_u = f_d$	$0.407 \pm 0.007$	$0.344 \pm 0.021$
$B_s^0$ fraction	$f_s$	$0.101 \pm 0.008$	$0.115 \pm 0.013$
$b$ -baryon fraction	$f_{\text{baryon}}$	$0.085 \pm 0.011$	$0.198 \pm 0.046$
$B_s^0/B^0$ ratio	$f_s/f_d$	$0.249 \pm 0.023$	$0.334 \pm 0.040$

$\sim 2 \sigma$

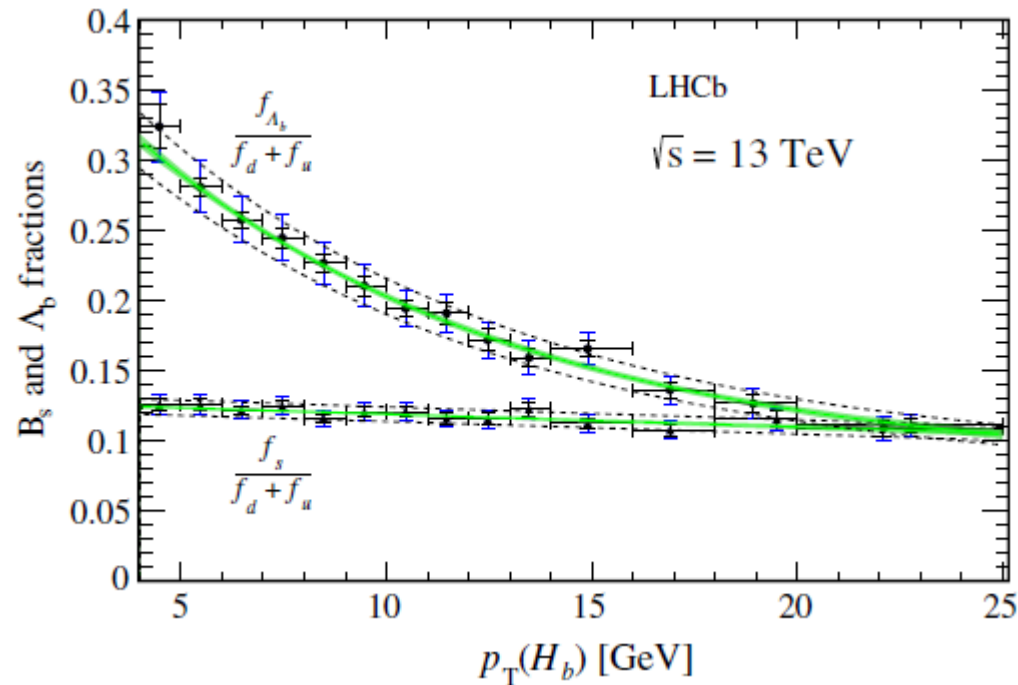
- Environmental influence is potentially an important systematic effect
  - Could limit precision  $B_s$  branching fraction measurements

# Environmental Influence on Hadronization Fractions

- LHC-b observed significant  $p_T(\Lambda_b)$  dependence
  - Weaker but significant dependence on  $p_T(B_s)$

Inclusive semi-leptonic decays:

$$H_b \rightarrow H_c X \mu^- \bar{\nu}_\mu$$



$$\frac{f_s}{f_u + f_d}(p_T) = A[p_1 + p_2 \times (p_T - \langle p_T \rangle)]$$

$$p_2 = (-0.91 \pm 0.25) \times 10^{-3} \text{ GeV}^{-1}$$

Phys. Rev. D 100, 031102(R)

# New CMS Measurement of $f_s/f_u$

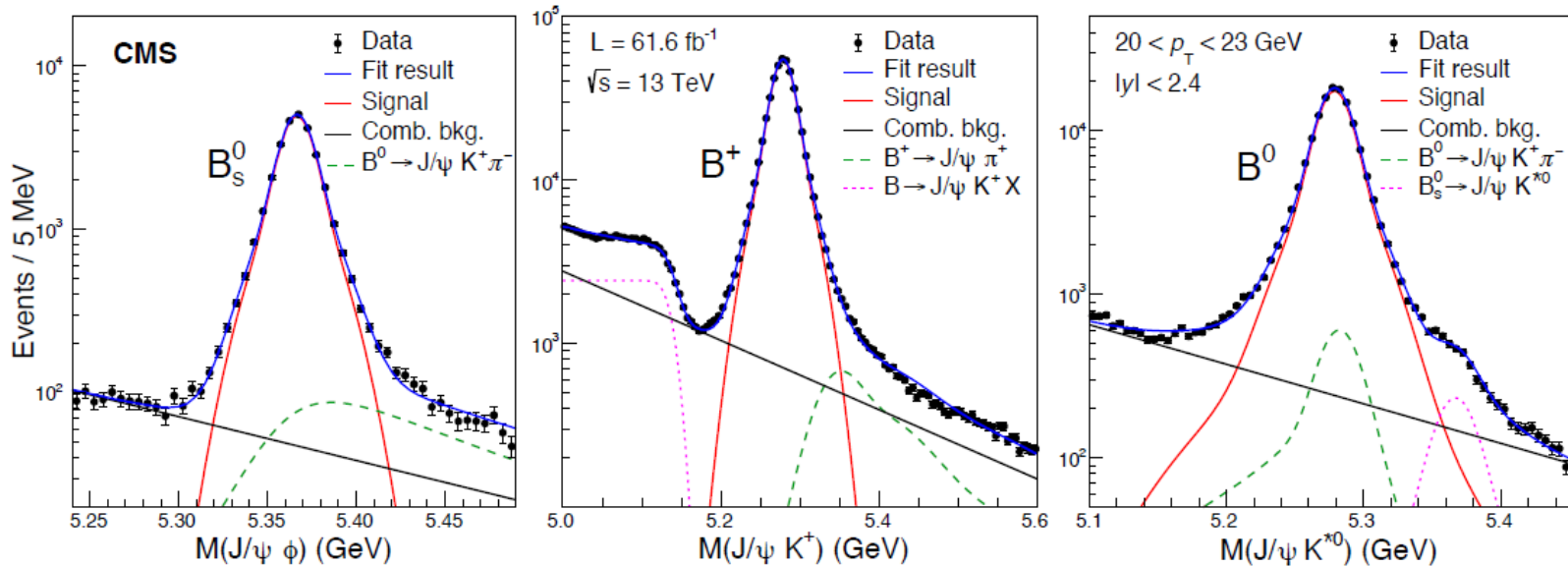
- $pp$  collisions at  $\sqrt{s} = 13$  TeV,  $61.6 \text{ fb}^{-1}$  collected in 2018
- Di-muon + track trigger:
  - $p_T(\mu^\pm) > 4 \text{ GeV}$ ,  $|\eta| < 2.5$ ,  $m(\mu^+\mu^-)$  within  $2.9 - 3.3 \text{ GeV}$
  - $p_T(track) > 1.2 \text{ GeV}$ ,  $|\eta| < 2.4$
  - Displaced vertex requirement
- Offline reconstruction:
  - $B^+ \rightarrow J/\psi K^+$
  - $B^0 \rightarrow J/\psi K^{*0}, K^{*0} \rightarrow K^-\pi^+$
  - $B_s^0 \rightarrow J/\psi \phi, \phi \rightarrow K^+K^-$

Vertex fit quality cuts  
 $12 < p_T(B) < 70 \text{ GeV}$   
 $|y| < 2.4$

arXiv:2212.02309

# New CMS Measurement of $f_s/f_u$

Example:  $20 < p_T < 23$  GeV



- Determined from fit:
  - Shape of combinatorial background
  - Shape of  $B^+ \rightarrow J/\psi K^+ X$  component
- Constrained from Monte Carlo:
  - Cabibbo suppressed decay fraction
  - Swapped kaon/pion mass assignments

# New CMS Measurement of $f_s/f_u$

- In principle,

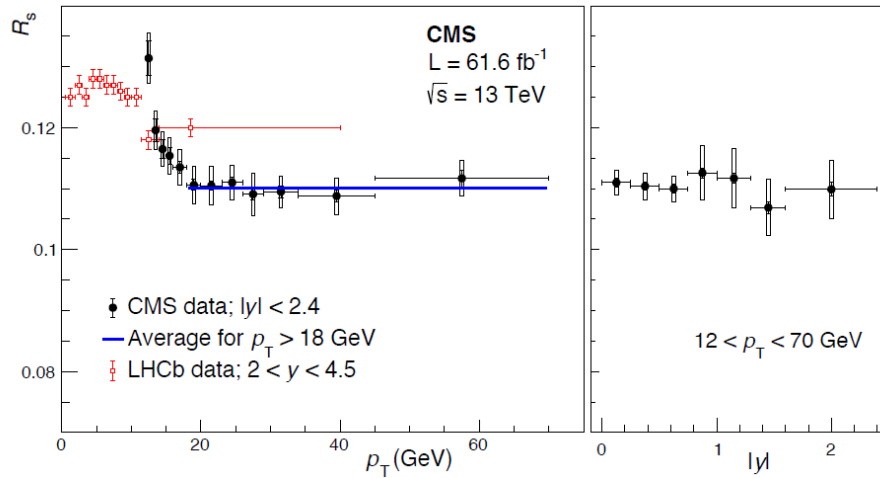
$$\frac{f_s}{f_u} = \frac{N_{B_s}}{N_{B^+}} \cdot \frac{\epsilon_{B^+}}{\epsilon_{B_s}} \cdot \frac{\mathcal{B}(B^+ \rightarrow J/\psi K^+)}{\mathcal{B}(B_s \rightarrow J/\psi \phi) \mathcal{B}(\phi \rightarrow K^+ K^-)}$$

- Most branching fractions are measured precisely
- But  $\mathcal{B}(B_s \rightarrow J/\psi \phi)$  is dominated by an LHC-b analysis that measures the  $p_T$  dependence of  $f_s/f_d$ 
  - Phys. Rev. D 104, 032005 (August 2021)

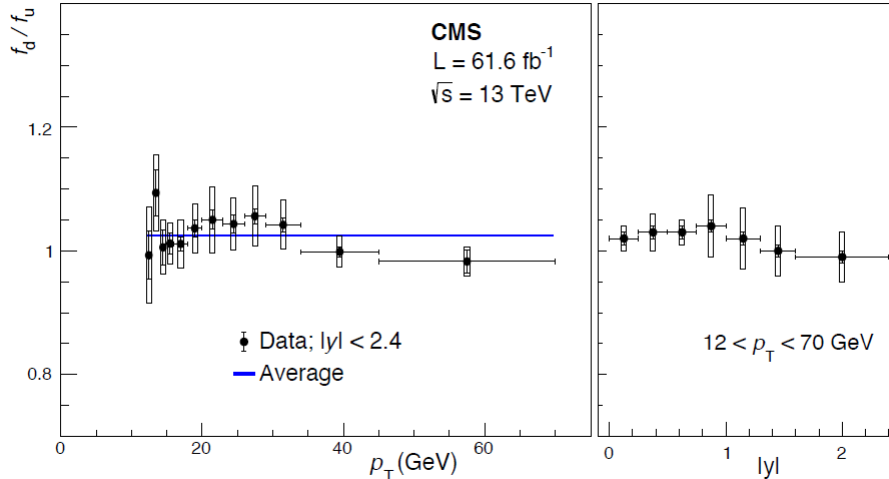
- CMS chooses to report measurements of

$$\mathcal{R}_d = \frac{f_d}{f_u} \cdot \frac{\mathcal{B}(B^0 \rightarrow J/\psi K^{*0}) \mathcal{B}(K^{*0} \rightarrow K^- \pi^+)}{\mathcal{B}(B^+ \rightarrow J/\psi K^+)}$$
$$\mathcal{R}_s = \frac{f_s}{f_u} \cdot \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi) \mathcal{B}(\phi \rightarrow K^+ K^-)}{\mathcal{B}(B^+ \rightarrow J/\psi K^+)}$$

# New CMS Measurement of $f_s/f_u$



- Matches LHC-b result at low  $p_T$
- No significant dependence on rapidity



- Branching fractions for  $B^0$  and  $B^+$  are known precisely
- Compatible with unity  
 $f_d/f_u = 1.015 \pm 0.051$

- $\mathcal{R}_s = 0.1102 \pm 0.0027$  for  $p_T > 18$  GeV

# Alternative CMS Analysis of $f_s/f_u$

- The ratio  $f_s/f_u$  could be determined if branching fractions were known precisely

- Reliable theoretical prediction for the ratio

$$\frac{\mathcal{B}(B_S^0 \rightarrow D_S^+ \pi^-)}{\mathcal{B}(B^0 \rightarrow D^- h^+)} \sim \frac{\tau_{B_S}}{\tau_{B_d}} \left| \frac{V_{ud}}{V_{us}} \right|^2 \left( \frac{f_\pi}{f_K} \right)^2 \left[ \frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)} \right]^2 \left| \frac{a_1(D_S \pi)}{a_1(D_d K)} \right|^2$$

Phys. Rev. D **82**, 034038 (2010)

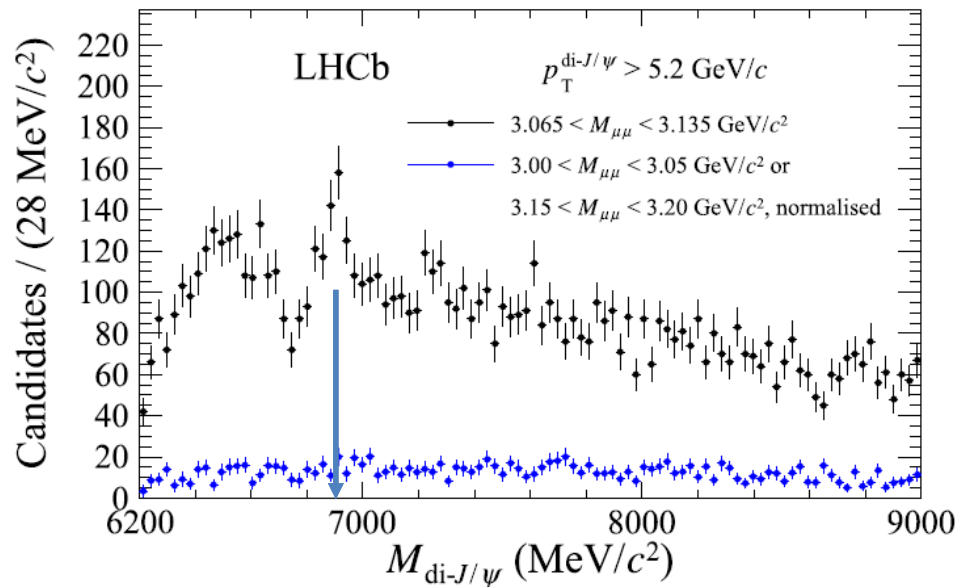
- Motivates reconstructing these decays in  $pp$  collisions
- The challenge is collecting these using a suitable trigger

## B Parking at CMS

- Single muon trigger:
  - Minimum  $p_T$  requirement
  - Minimum signed impact parameter significance
  - Thresholds and pre-scales adjusted based on instantaneous luminosity to level the trigger rate
  - High level trigger rate  $< 5$  kHz
- 10 billion events saved to tape and reconstructed when computing resources become available
- Opposite side jets provide an unbiased sample of b-decays
  - 60-90% purity estimated by reconstructing  $B \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$
- *Now possible to reconstruct fully hadronic B decays*

# Exotic Heavy Flavor Decaying to $J/\psi J/\psi$

- In 2020, LHCb reported observation of X(6900) in the  $J/\psi J/\psi$  mass spectrum



Sci. Bull. 65 (2020) 1983

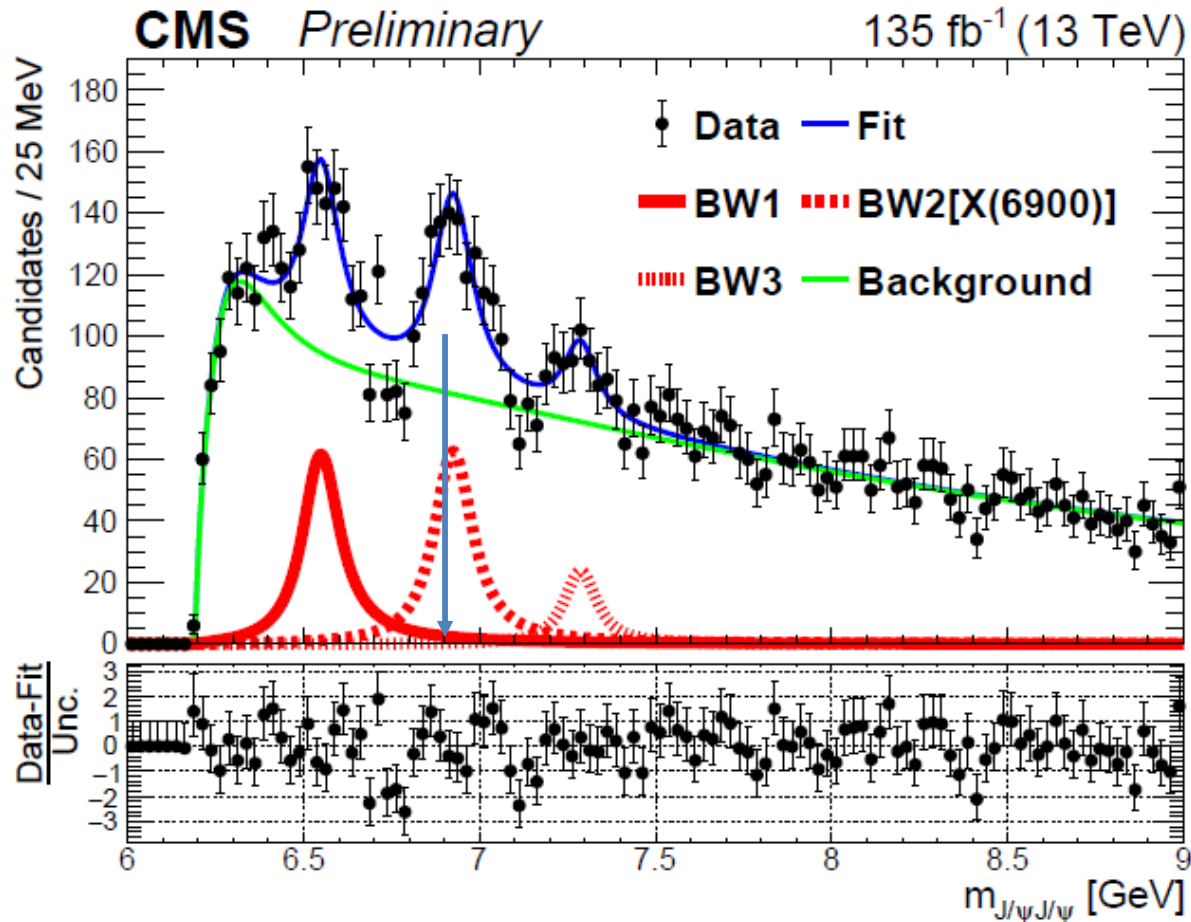
- The nature of the state remains unclear
- Description of the line shape is challenging
  - Multiple resonances near threshold?
  - Interference?

# Reconstruction of $J/\psi J/\psi$ at CMS

- Data sample:
  - $135 \text{ fb}^{-1}$  (2016 – 2018),  $\sqrt{s} = 13 \text{ TeV}$
- Level 1 trigger:
  - Three muon candidates
  - Opposite charge pair with  $p_T^{(1)} > 5 \text{ GeV}$ ,  $p_T^{(2)} > 3 \text{ GeV}$ ,  $m < 9 \text{ GeV}$
- High Level Trigger:
  - $|\eta(\mu)| < 2.5$
  - $\mu^+ \mu^-$  pair from a common vertex with  $2.95 < m < 3.25 \text{ GeV}$
- Offline selection:
  - Four muons with  $p_T > 2 \text{ GeV}$ ,  $|\eta| < 2.4$
  - $p_T(\mu^+ \mu^-) > 3.5 \text{ GeV}$ ,  $2.95 < m < 3.25 \text{ GeV}$
  - Mass constrained fit to a common vertex

CMS BPH-21-003

# Reconstruction of $J/\psi J/\psi$ at CMS



- Observes X(6900) resonance and other structures

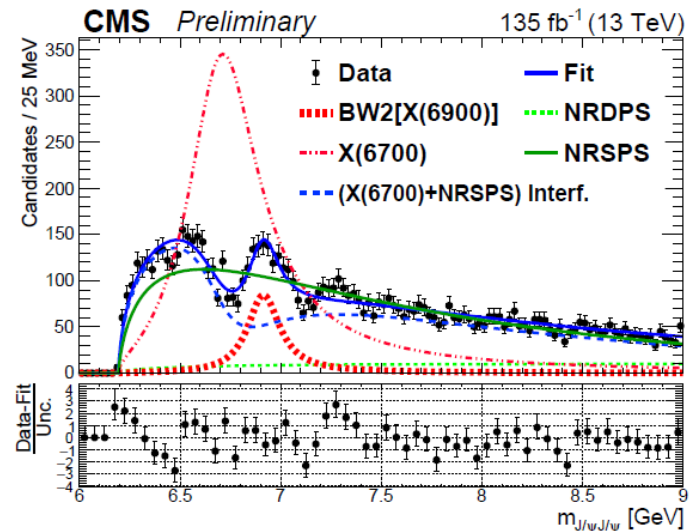
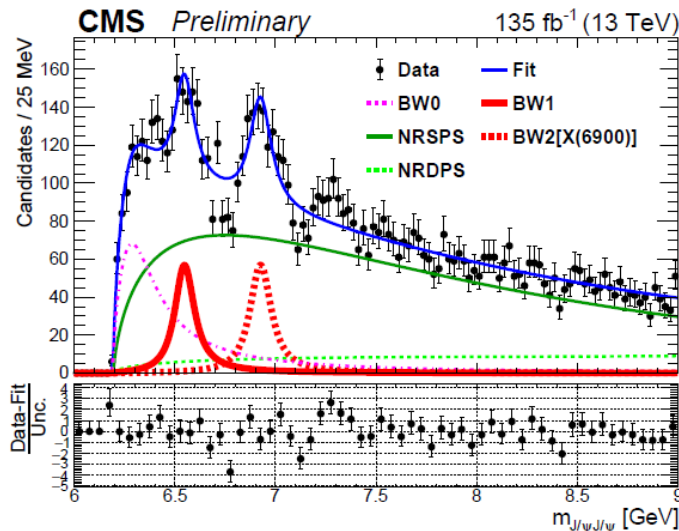
# Description of Resonant $J/\psi J/\psi$ Structures

- Background description:
  - Non-resonant single/double parton scattering (PYTHIA)
    - Dominates at low/high mass
  - Feed down from other excited states (HELAC-ONIA, CASCADE)
  - Parametrized by empirical functions
    - Threshold + polynomial + exponential
- Signal description:
  - Relativistic Breit-Wigner convoluted with resolution function

	BW1	BW2	BW3
$m$ (MeV)	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
$\Gamma$ (MeV)	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
$N$	$474 \pm 113$	$492 \pm 75$	$156 \pm 56$
Significance	$6.5\sigma$	$9.4\sigma$	$4.1\sigma$

# Resonance Fit Models

- LHCb considered alternative signal models
  - Threshold enhancement modeled by additional Breit-Wigner functions
  - Dip at 6700 MeV modeled by a Breit-Wigner and destructive interference with NRSPS background

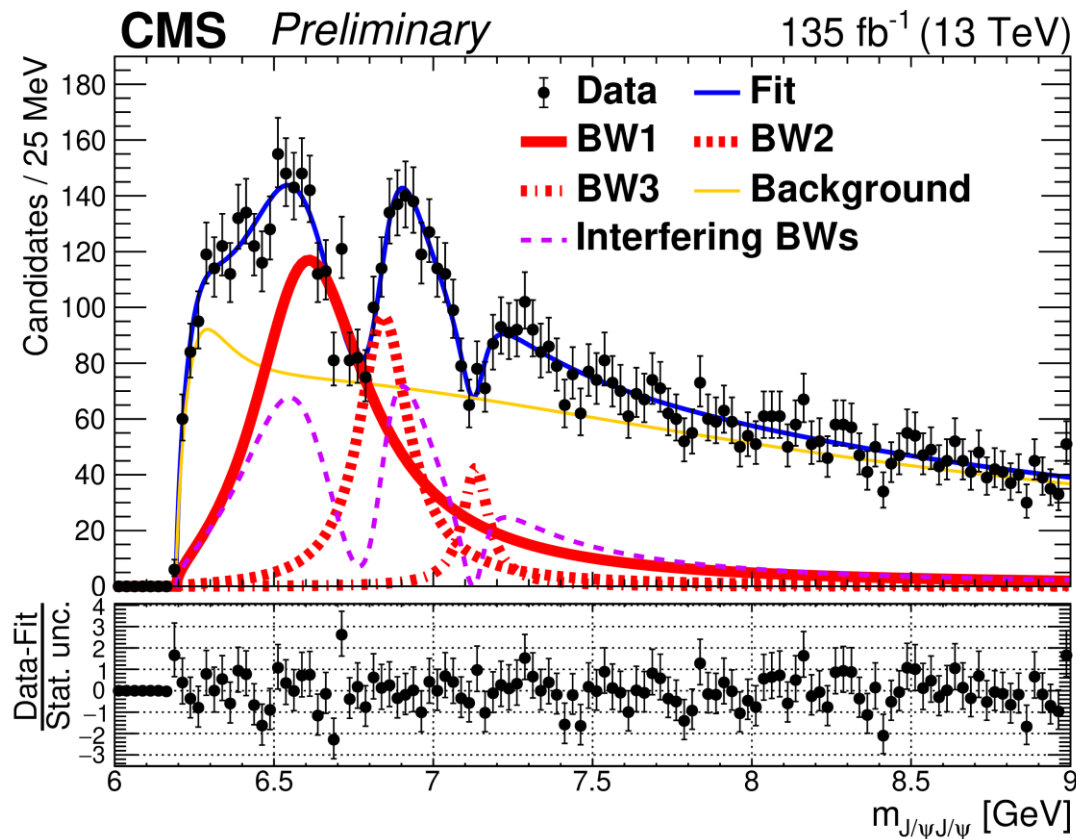


- CMS observes generally poor fit quality

# Resonance Fit Models

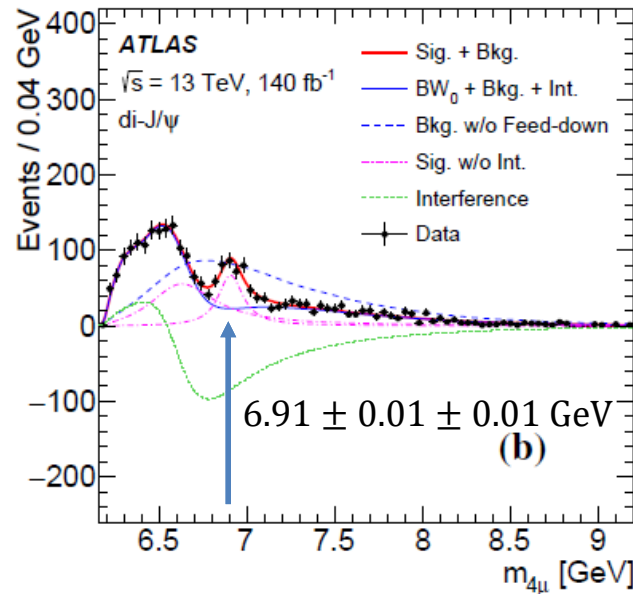
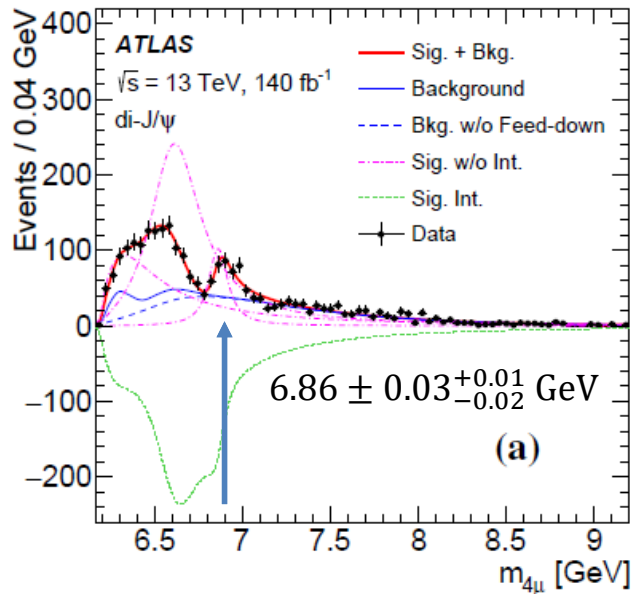
- CMS observes good description using interfering Breit-Wigner signal functions:

$$f(x) \sim \left| r_1 e^{i\phi_1} BW_1(x) + BW_2(x) + r_3 e^{i\phi_3} BW_3(x) \right|^2$$



# Recent Results from ATLAS

- Background model:
  - Single Parton Scattering constrained by  $\Delta R > 0.25$  control region
  - Non-prompt  $J/\psi$  background constrained by  $\chi_{4\mu}^2$  or  $L_{xy}^{di-\mu}$  control regions
  - Feed-down from  $J/\psi$   $\psi(2S)$  decays
- Signal models:
  - Sig A: Three interfering Breit-Wigner functions
  - Sig B: Two Breit-Wigner functions, one interferes with SPS background

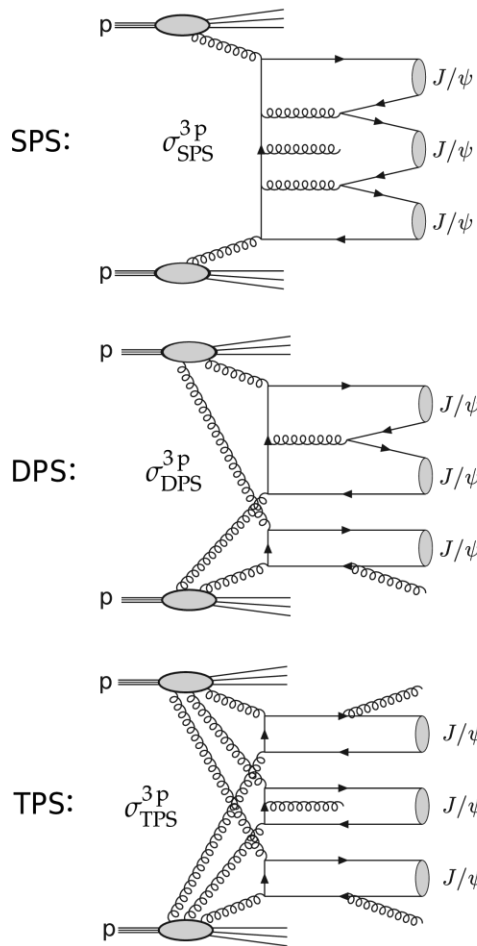


[arXiv:2304.08962](https://arxiv.org/abs/2304.08962)

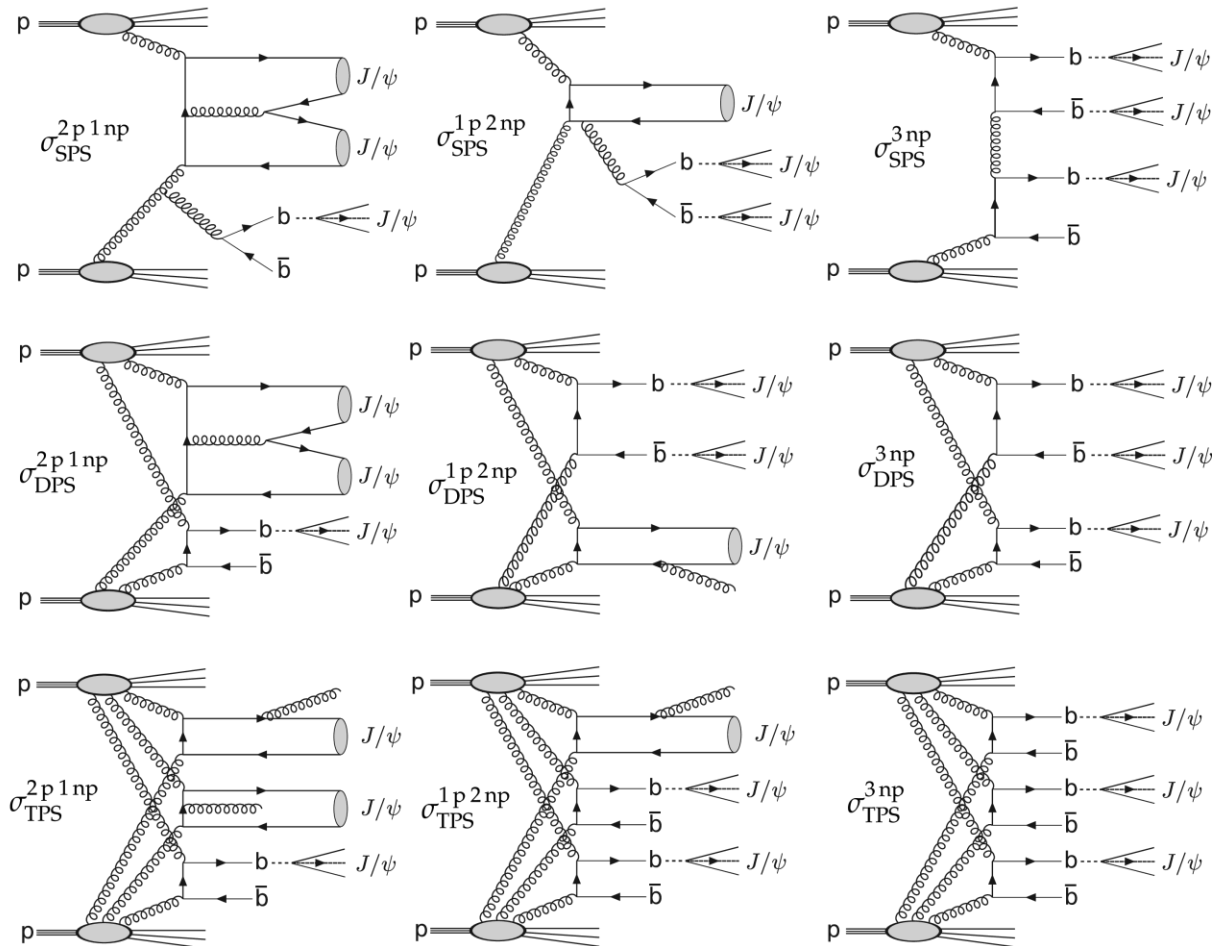
# Triple $J/\psi$ Production at CMS

BPH-21-004 / [arXiv:2111.05370](https://arxiv.org/abs/2111.05370)

Pure prompt production:



Nonprompt contributions:



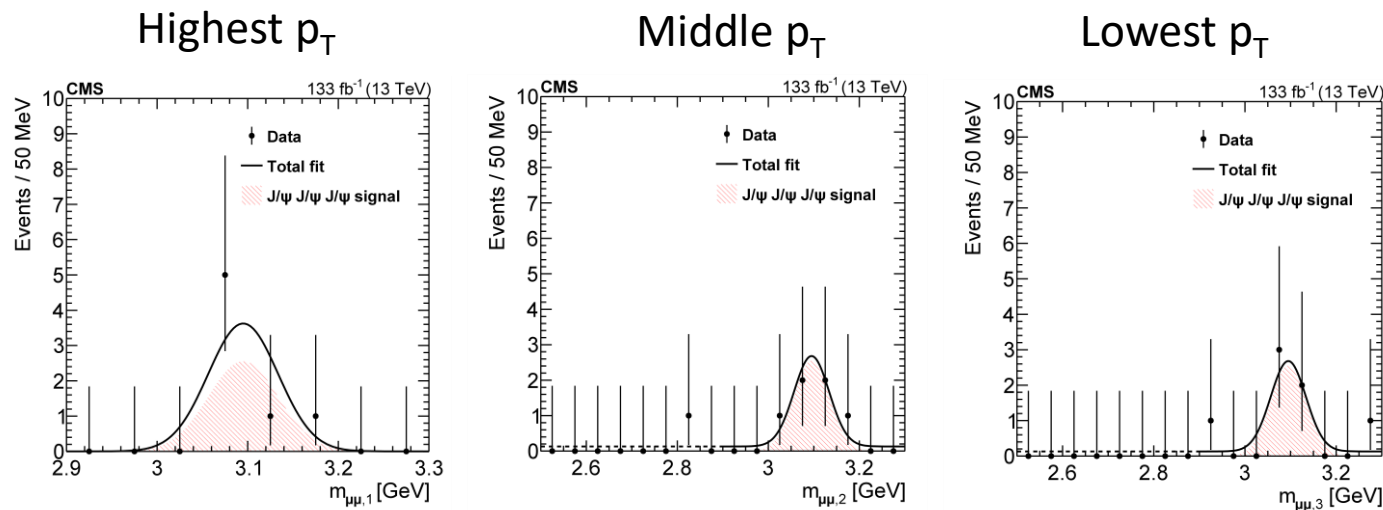
# Triple $J/\psi$ Production at CMS

- Assumption:

$$\sigma_{\text{DPS}}^{pp \rightarrow \psi_1 \psi_2 + X} = \left(\frac{m}{2}\right) \frac{\sigma_{\text{SPS}}^{pp \rightarrow \psi_1 + X} \sigma_{\text{SPS}}^{pp \rightarrow \psi_2 + X}}{\sigma_{\text{eff,DPS}}}$$
$$\sigma_{\text{TPS}}^{pp \rightarrow \psi_1 \psi_2 \psi_3 + X} = \left(\frac{m}{3!}\right) \frac{\sigma_{\text{SPS}}^{pp \rightarrow \psi_1 + X} \sigma_{\text{SPS}}^{pp \rightarrow \psi_2 + X} \sigma_{\text{SPS}}^{pp \rightarrow \psi_3 + X}}{\sigma_{\text{eff,TPS}}^2}$$
$$\sigma_{\text{eff,DPS}} = (0.82 \pm 0.11) \sigma_{\text{eff,TPS}}$$

- Prompt and non-prompt SPS cross sections calculated using HELAC-ONIA and MADGRAPH5 aMC@NLO
- Measurement of triple- $J/\psi$  cross section provides a new measurement of  $\sigma_{\text{eff,DPS}}$ .

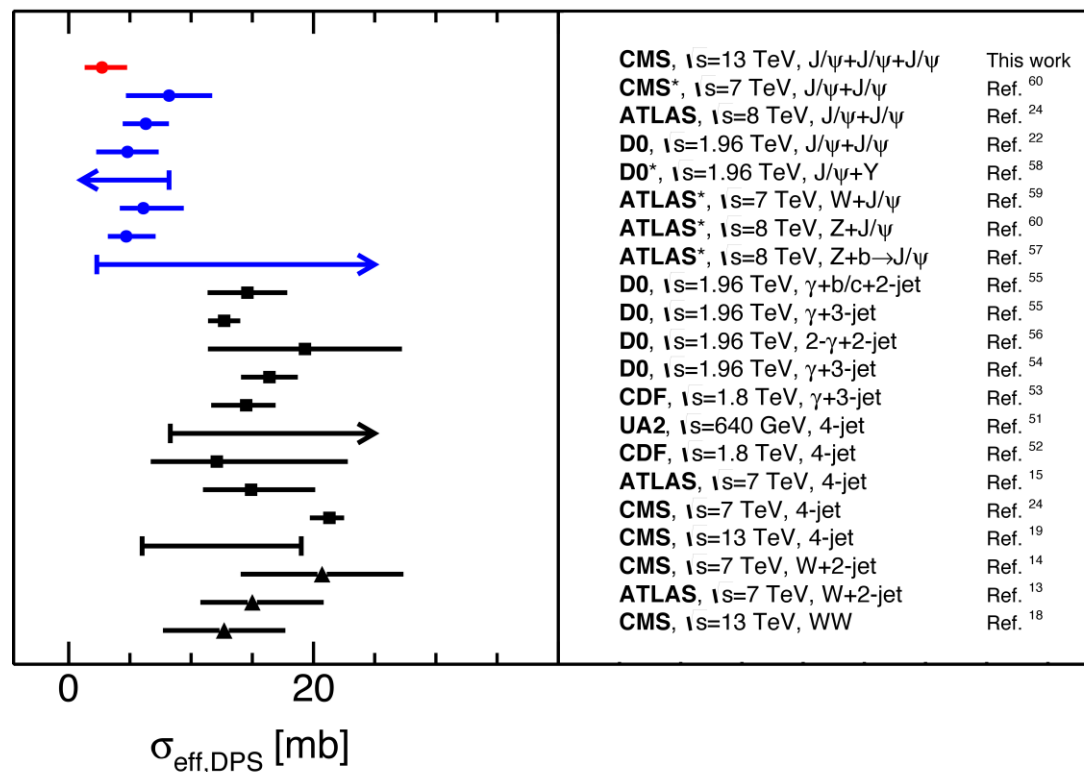
# Triple $J/\psi$ Production at CMS



$$N_{sig}^{3J/\psi} = 5.0^{+2.6}_{-1.9}$$

$$\sigma_{\text{eff,DPS}} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo}) \text{ mb}$$

# Triple $J/\psi$ Production at CMS



Smaller values of  $\sigma_{\text{eff,DPS}}$  for quarkonia compared to harder processes suggest  $x$  dependence

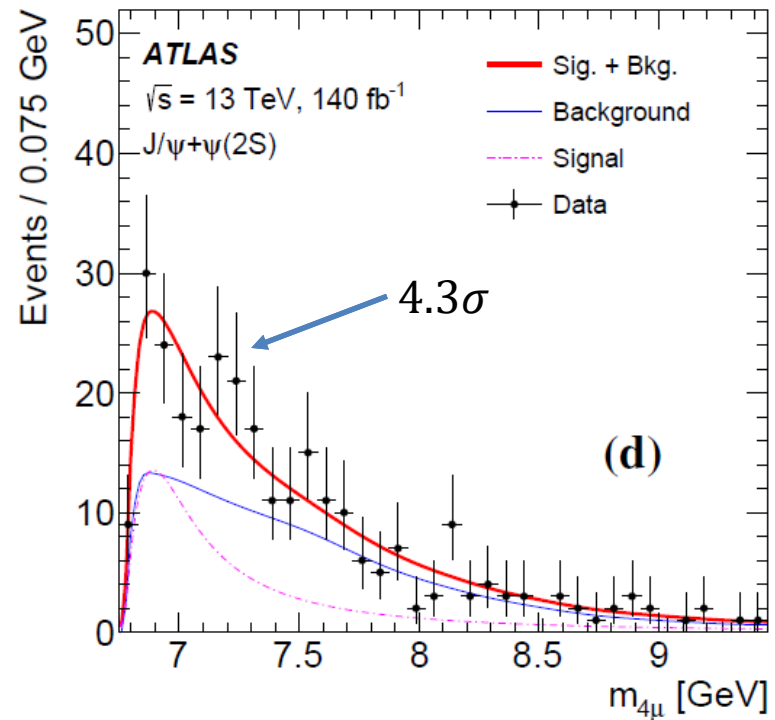
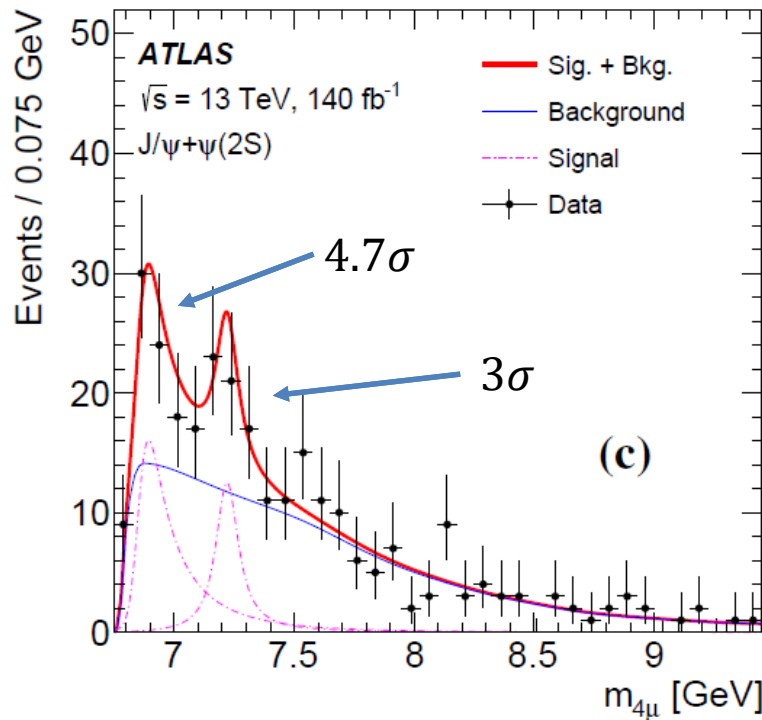
# Summary

- Bottom quark hadronization fractions
  - CMS observes  $p_T$  dependence in  $f_s/f_u$  in agreement with LHCb
  - No variation with rapidity observed
  - Measures  $f_d/f_u$  compatible with unity as is typically assumed
  - Reduced dependence on unknown branching fractions may be possible with fully hadronic B decays
- Exotic charm states decaying to  $J/\psi J/\psi$ 
  - CMS confirms resonance parameters of X(6900) state
    - Also observed by ATLAS
  - Observation of additional resonances X(6600) and X(7300)
  - Resonance parameters appear to be stable
  - Spectrum is described well by interfering Breit-Wigner functions
- Triple  $J/\psi$  Production
  - New measurement of  $\sigma_{\text{eff,DPS}}$  in low  $x$  process

# Backup Material

# Recent Results from ATLAS

- The X(6900) is above the  $J/\psi \psi(2S)$  threshold
- Signal near threshold includes all resonances observed in  $J/\psi J/\psi$  final state



# Triple $J/\psi$ Production at CMS

## Calculated SPS cross sections

SPS single- $J/\psi$ production		SPS double- $J/\psi$ production			SPS triple- $J/\psi$ production			
HO(DATA)	MG5NLO+PY8	HO(NLO*)	HO(LO)+PY8	MG5NLO+PY8	HO(LO)	HO(LO)+PY8	HO(LO)+PY8	MG5NLO+PY8
$\sigma_{\text{SPS}}^{1\text{p}}$	$\sigma_{\text{SPS}}^{1\text{np}}$	$\sigma_{\text{SPS}}^{2\text{p}}$	$\sigma_{\text{SPS}}^{1\text{p}1\text{np}}$	$\sigma_{\text{SPS}}^{2\text{np}}$	$\sigma_{\text{SPS}}^{3\text{p}}$	$\sigma_{\text{SPS}}^{2\text{p}1\text{np}}$	$\sigma_{\text{SPS}}^{1\text{p}2\text{np}}$	$\sigma_{\text{SPS}}^{3\text{np}}$
$570 \pm 57 \text{ nb}$	$600^{+130}_{-220} \text{ nb}$	$40^{+80}_{-26} \text{ pb}$	$24^{+35}_{-16} \text{ fb}$	$430^{+95}_{-130} \text{ pb}$	$< 5 \text{ ab}$	$5.2^{+9.6}_{-3.3} \text{ fb}$	$14^{+17}_{-8} \text{ ab}$	$12 \pm 4 \text{ fb}$

## Expected contributions to $N_{\text{tot}}^{3J/\psi}$

Process:	3 prompt	2 prompt+1 nonprompt	1 prompt+2 nonprompt	3 nonprompt	Total
$\sigma_{\text{SPS}}^{3J/\psi} \text{ (fb)}$	$< 0.005$	5.7	0.014	12	18
$N_{\text{SPS}}^{3J/\psi}$	0.0	0.10	0.0	0.22	0.32
$\sigma_{\text{DPS}}^{3J/\psi} \text{ (fb)}$	8.4	8.9	90	95	202
$N_{\text{DPS}}^{3J/\psi}$	0.15	0.16	1.65	1.75	3.7
$\sigma_{\text{TPS}}^{3J/\psi} \text{ (fb)}$	6.1	19.4	20.4	7.2	53
$N_{\text{TPS}}^{3J/\psi}$	0.11	0.36	0.38	0.13	1.0
$\sigma_{\text{tot}}^{3J/\psi} \text{ (fb)}$	15	34	110	114	272
$N_{\text{tot}}^{3J/\psi}$	0.3	0.6	2.0	2.1	5.0

# Acknowledgements

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