Recent CMS Results on Exotic Hadron States

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on behalf of the CMS collaboration

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Contents

1. $X(3872)$ production (arxiv:2005.04764, accepted by PRL)
   - *First observation* of $B_s^0 \to X(3872)\phi$
   - measurement of

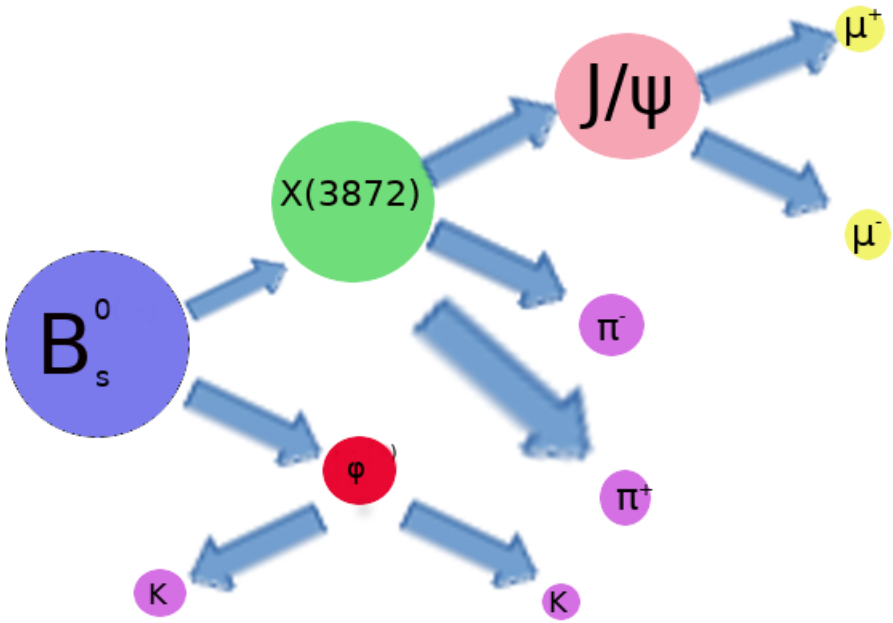
$$R = \frac{\mathcal{B}(B_s^0 \to X(3872)\phi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

2. $\Upsilon(1S)\mu^+\mu^-$ production (PLB 808 (2020) 135578)
   - measurement of $\Upsilon(1S)\Upsilon(1S)$ cross section at $|y_\mu| < 2.0$
   - determination of double-parton scattering contribution
   - search for exotic states in $\Upsilon(1S)\mu^+\mu^-$ invariant mass distribution

- Observed by Belle collaboration in 2003 in B^+ decays to $J/\psi\pi^+\pi^-$
- Mass coincides with $D^{*0}D^0$ threshold, $\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10$ MeV
- $J^{PC} = 1^{++}$
- Decays to open charm dominantly
- Branching fractions to $J/\psi\rho$ and $J/\psi\omega$ comparable, isospin violation

Many theoretical models proposed, none of them explains completely all properties of $X(3872)$

- $\sqrt{s} = 13$ TeV
- integrated luminosity 140 fb^{-1}
- 2016-2018 years



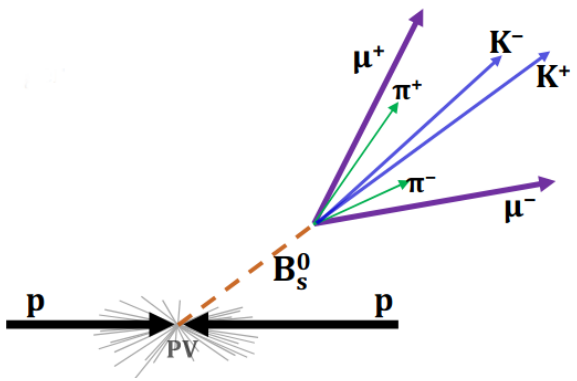
Normalization channel: $B_s^0 \to \psi(2S)\phi$

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

Event selection

- 2μ forming J/ψ and matching trigger requirements
- 4 high-purity tracks, kaon $p_T > 2.2$ GeV (major) and > 1.5 GeV (minor), pion $p_T > 0.7$ GeV
- vertex fit with J/ψ mass constraint, $> 7\%$ probability
- cosine of 2D B_s^0 pointing angle to primary vertex > 0.999
- B_s^0 2D detach significance $> 15\sigma$

- $p_T(B_s^0) > 10$ GeV
- π/K mass assignment:
  $m_{J/\psi\pi^+\pi^-}$ in [3.60..3.95] GeV
  $m_{K^+K^-}$ in [1.00..1.04] GeV
  $m_{J/\psi\pi^+\pi^-K^+K^-}$ in [5.32..5.42] GeV
  If >1 combination passes,
  candidate is rejected

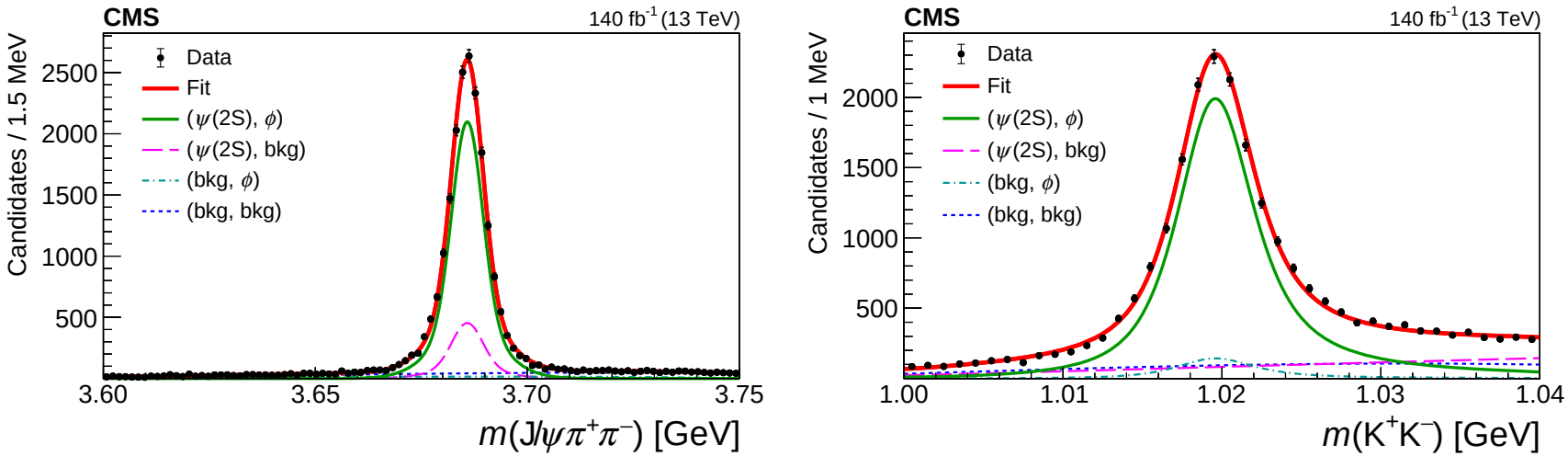


$m_{\pi^+\pi^-} > 0.45$ GeV for $\psi(2S)$ decay, > 0.7 GeV for $X(3872)$ decay

2D maximun-likelihood fit

- $\psi(2S)$ sig: double Gaussian with common mean
- $\psi(2S)$ bg: $(y - y_0)^\beta \cdot Pol_1(y), y_0 = m_{J/\psi} + 0.45$
- ϕ sig: Breit-Wigner convolved with double Gaussian
- ϕ bg: $(x - x_0)^\alpha \cdot Pol_1(x), x_0 = 2m_K$

$B_s^0 \to \psi(2S)\phi$



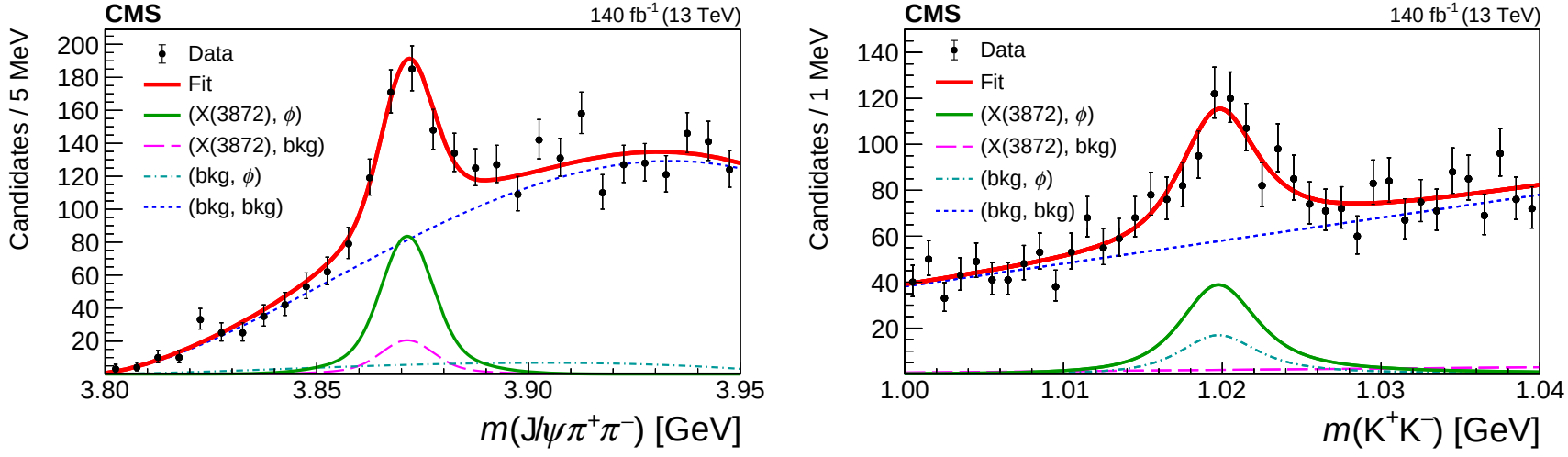
$N_{evt} = 15359 \pm 171$

2D maximun-likelihood fit

The same fit model as for $\psi(2S)$, ratio of widths of $J/\psi\pi^+\pi^-$

Gaussians fixed from $\psi(2S)$, scaling parameter is free

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

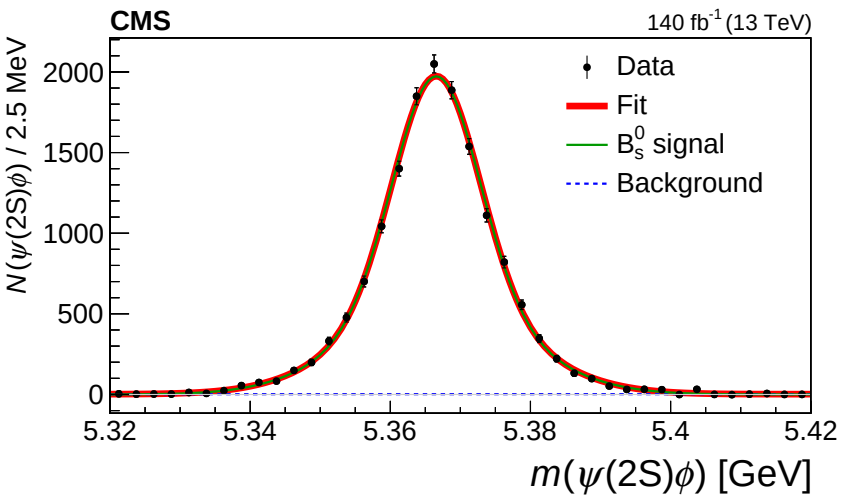


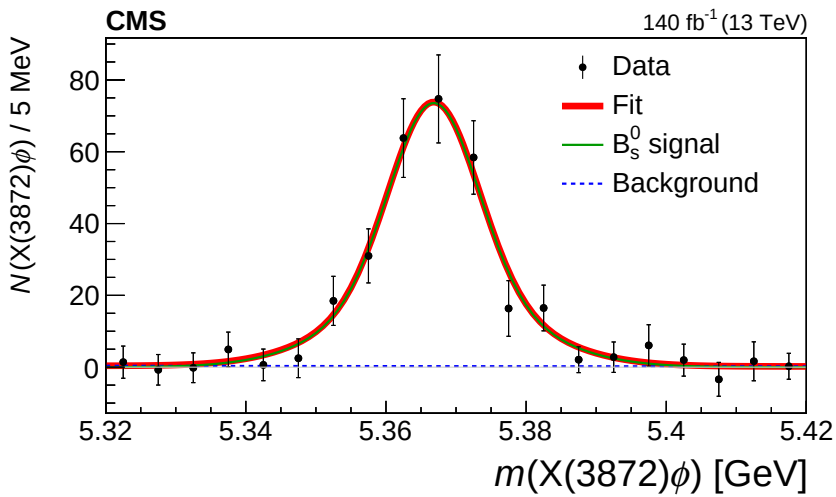
$$N_{sig} = 299 \pm 39$$

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

B_s^0 mass distribution

- $m_{J/\psi\pi^+\pi^-K^+K^-} - m_{J/\psi\pi^+\pi^-} + m_X$ studied: improve resolution, remove correlation between $m_{J/\psi\pi^+\pi^-K^+K^-}$ and $m_{J/\psi\pi^+\pi^-}$
- sPlot from $m_{J/\psi\pi^+\pi^-}$: $m_{K^+K^-}$ 2D invariant mass distribution
- double Gaussian (signal) + exponential function (background)





Source	Uncertainty (%)
$m(\mathrm{K}^+\mathrm{K}^-)$ signal model	< 0.1
$m(\mathrm{K}^+\mathrm{K}^-)$ background model	2.5
$m(\mathrm{J}/\psi\,\pi^+\pi^-)$ signal model	5.3
$m(\mathrm{J}/\psi\,\pi^+\pi^-)$ background model	4.3
Non-B_s^0 background	1.2
Simulated sample size	2.2
Total	7.7

$$R = \frac{\mathcal{B}(B_s^0 \to X(3872)\phi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = \frac{N_X}{N_\psi} \times \frac{\varepsilon_\psi}{\varepsilon_X}$$

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

$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 0.482 \pm 0.063(\text{stat.}) \pm 0.037(\text{syst.}) \pm 0.070(\text{Br}),$$

about twice lower than for $\psi(2S)$

Indicats $X(3872)$ is not a pure charmonium state

Motivation:

- Search for new exotic states (e.g. $bb\bar{b}\bar{b}$ tetraquarks) (performed by LHCb, now mass and acceptance area is extended)

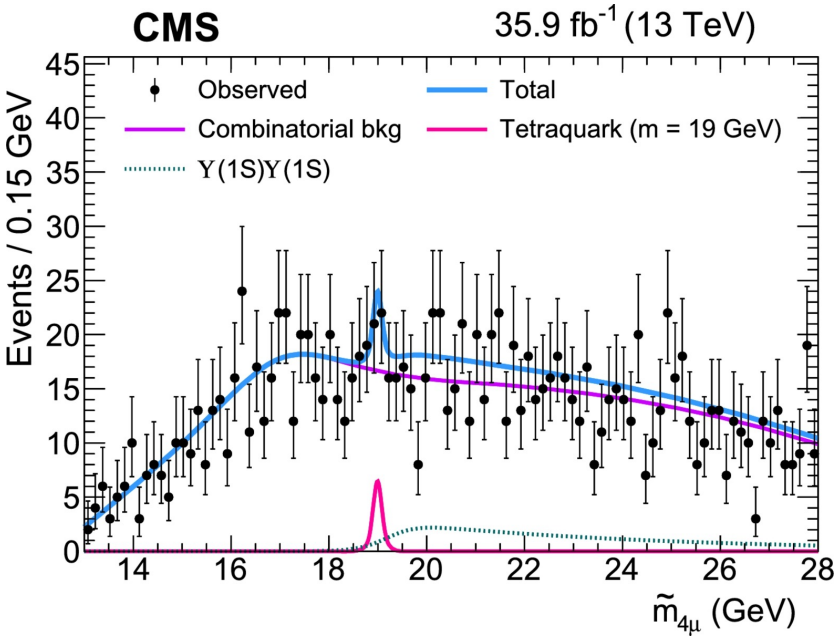
Statistics: Run II data 2016 (35.9 fb^{-1})

Selection criteria established using simulation for different hypotheses for resonances

- 4μ separated from each other, $|y| < 2.0$, at least three matching with trigger objects
- $\mu^+\mu^-$ mass consistent with $\Upsilon(1S)$, the other pair inconsistent with J/ψ
- vertex fit probability $> 0.5\%$

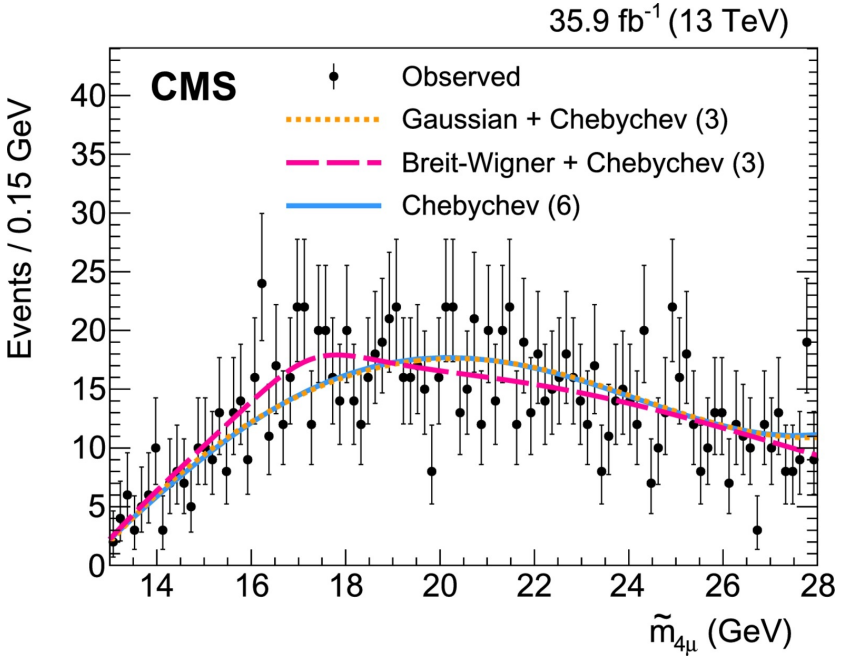
$$\tilde{m_{4\mu}} = m_{4\mu} - m_{\mu^+\mu^-} + m_{\Upsilon(1S)}$$

Signal region



vertex fit probability $> 0.5\%$

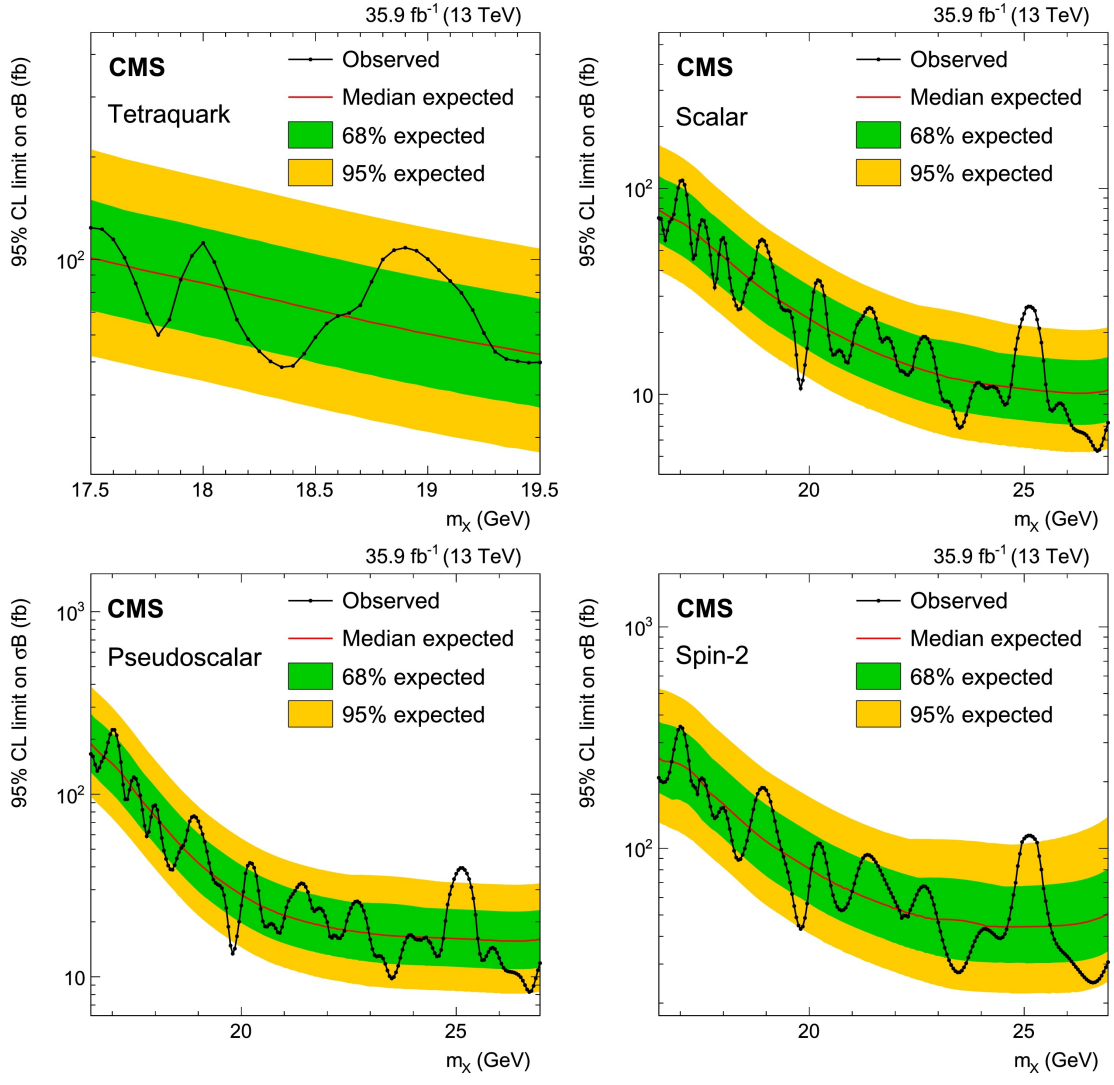
Control region



vertex fit probability
$10^{-10} \ldots 10^{-3}$

Example of signal with 1σ significance

$\Upsilon(1S)\mu^+\mu^-$ production
Upper limits on cross section



2.4σ local statistical significance at 25.1 GeV for scalar resonance

Results

- *First observation* of $B_s^0 \to X(3872)\phi$
- Measurement of branching ratio

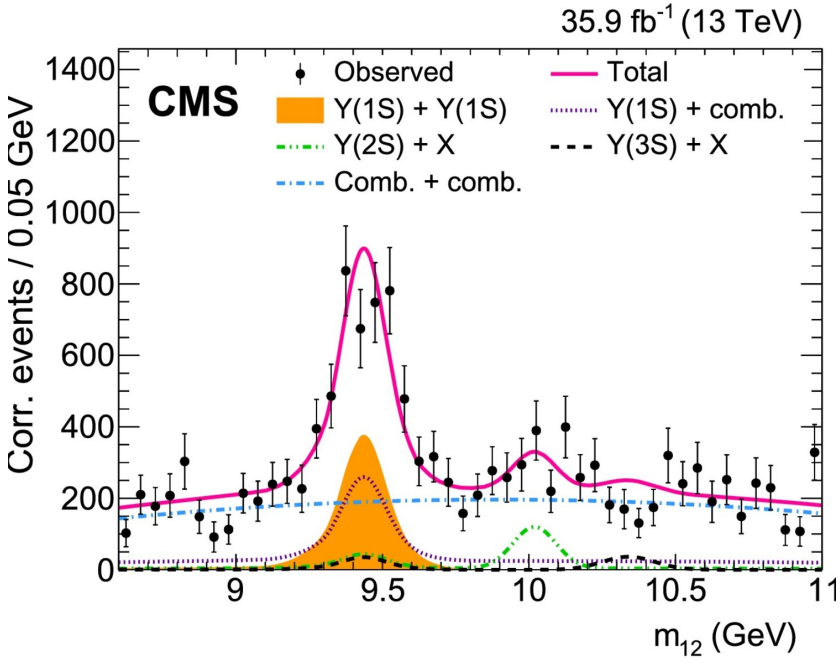
$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} =$$

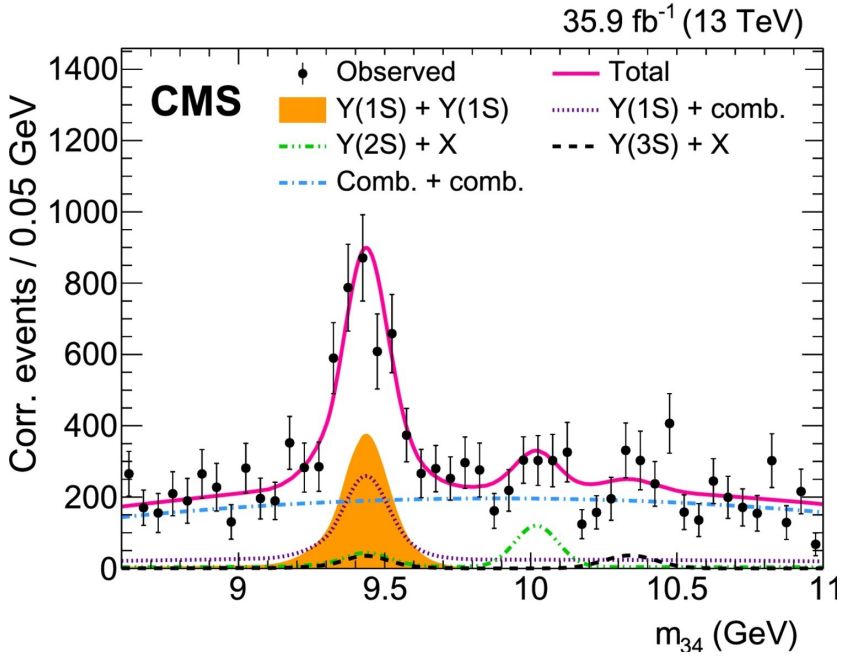
$$= (2.21 \pm 0.29 \pm 0.17)\%$$

- No new signals in $\Upsilon(1S)\mu^+\mu^-$ state are observed

Backup slides
$\Upsilon(1S)\Upsilon(1S)$ *production cross section*

$$\sigma = \frac{N^{\text{corr}}}{\mathcal{L}\mathcal{B}^2(\Upsilon(1S)\mu^+\mu^-)},$$



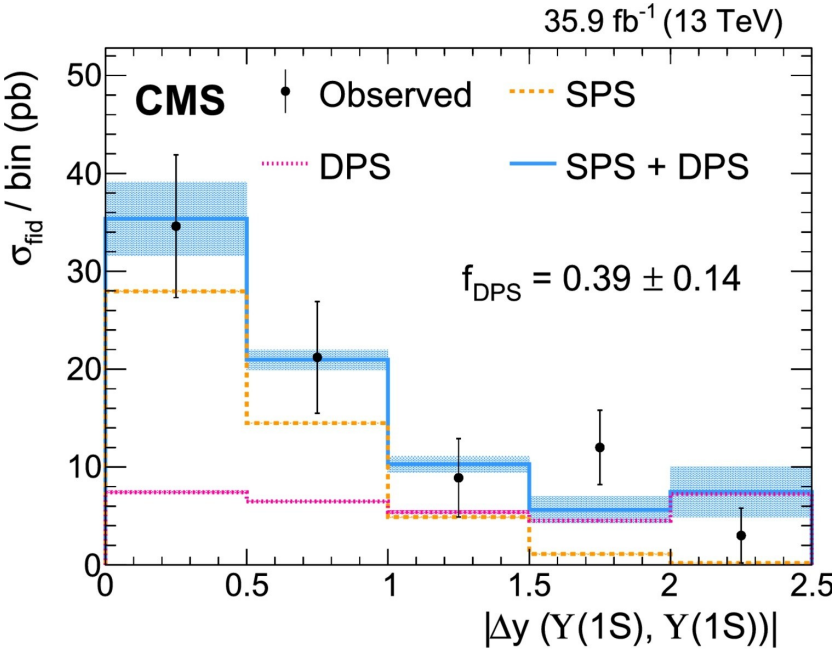


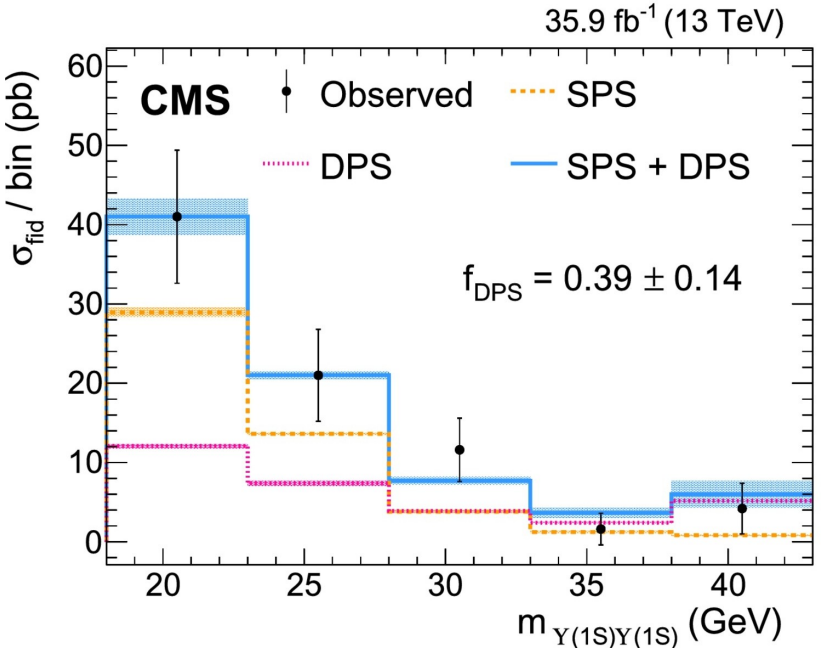
$$N_{sig} = 111 \pm 16,$$

$$\sigma = 79 \pm 11 \pm 6 \pm 3 \text{ pb}.$$

Uncertainty source	Uncertainty (%)	Impact on σ_{fid} (pb)
Integrated luminosity	2.5	2.0
Muon identification	2.0	1.6
Trigger	6.0	4.7
Vertex probability	1.0	0.8
$\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$	4.0	3.2
Signal and background models	1.2	1.0
Method closure	1.5	1.2
Total	8.1	6.4

Backup slides
Double-parton scattering fraction determination





Double-parton scattering fraction $f = (39 \pm 14)\%$