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Production studies of double Bottomonia at CMS

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Outline

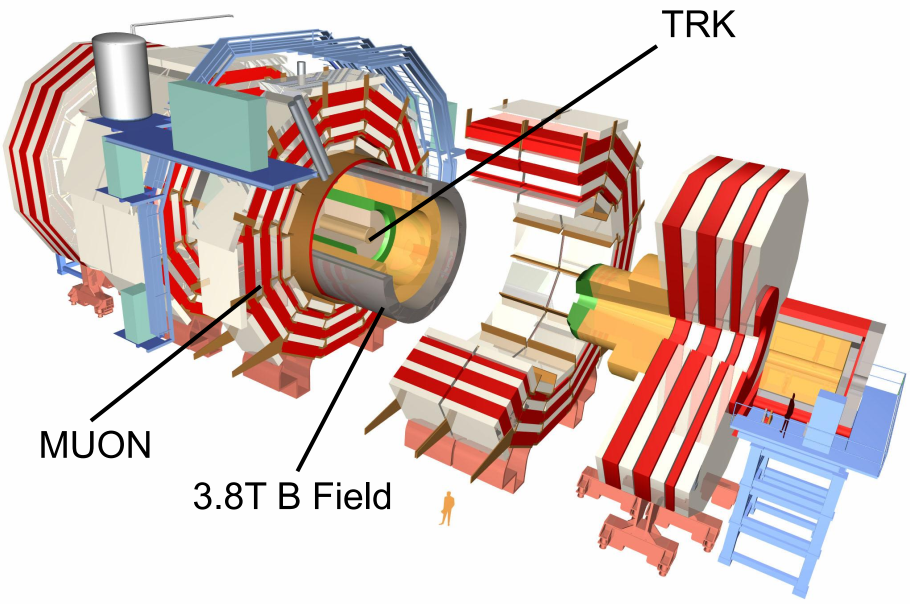
1. Motivation: the quarkonium production
2. CMS detector
3. Recent CMS measurements (CMS-BPH-18-002 - Phys. Lett. B 808 (2020) 135578):
    - **Υ**(1S) pair production cross section and search for resonances decaying to **Υ**(1S) $\mu^+\mu^-$
4. Conclusions

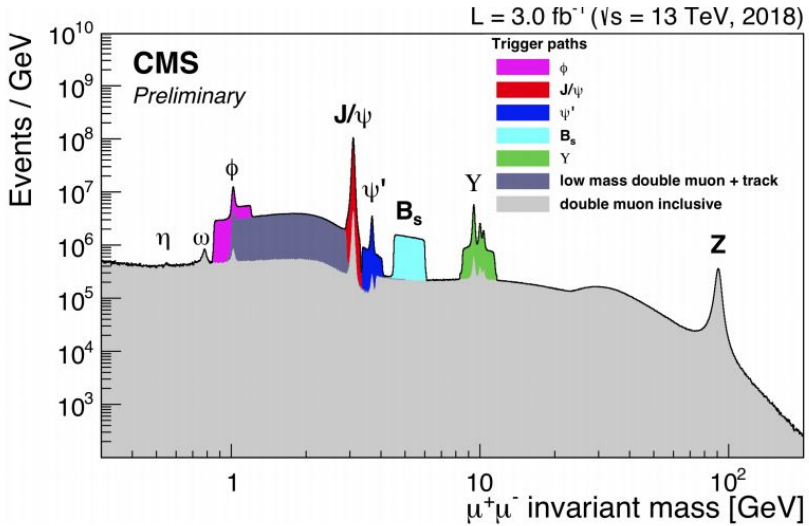
Motivation

- Quarkonium pair production is an important probe of both perturbative and nonperturbative processes in QCD
- Insight into particle production at LHC:
  - Single-parton scattering (SPS): dominant → strongly correlated → small $|\Delta y|$
  - Double-parton scattering (DPS): difficult to calculate → less correlated → large $|\Delta y|$
- Potential ground for discovery for tetraquark bound state or generic resonances with masses close to twice the **Υ**(1S) meson mass.

CMS detector and Muon trigger

- The Muon system, the Silicon Tracker and the Magnetic Field system allow the measurement of muon pairs over a wide range of η and p_T.
- A flexible trigger system accommodates Higgs physics, SUSY searches, and even quarkonium.





CMS-BPH-18-002
Phys. Lett. B 808 (2020) 135578

Υ(1S) pair production cross section and search for resonances decaying to **Υ**(1S) $\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV

Yields extraction

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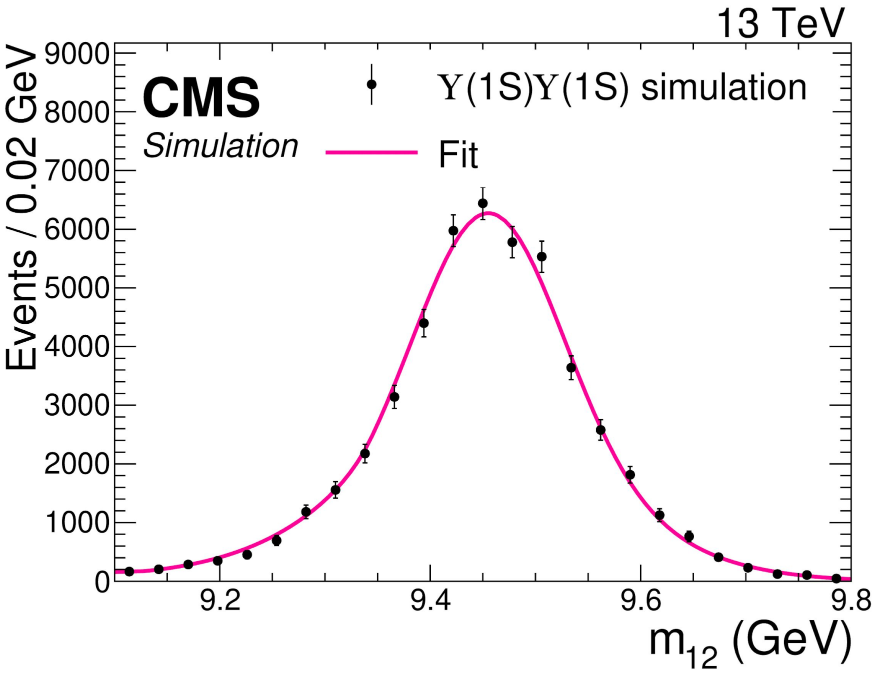
- Unbinned two-dimensional maximum likelihood fit to invariant mass distributions of two OS muon pairs
  - Signal: sum of two Crystal Ball functions
  - The contribution from **Υ**(2S) and **Υ**(3S) modeled with Gaussian function
  - The combinatorial background are modeled with 2[nd] Chebychev polynomials
- Yields are corrected for the four muons efficiency and acceptance



Projection of the 2D fit (line) to the m_{12} invariant mass distribution (points) for the SPS **Υ**(1S)**Υ**(1S) simulation. The vertical bars on the points show the statistical uncertainty only.

Measurement of the fiducial cross-section

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Assuming unpolarized **Υ**(1S) meson:

$$\sigma_{fid} = 79 \pm 11(stat) \pm 6(syst) \pm 3(\mathcal{B})\ pb$$

$$\sigma_{fid} = \frac{N^{corr}}{\mathcal{L}\mathcal{B}^2}$$

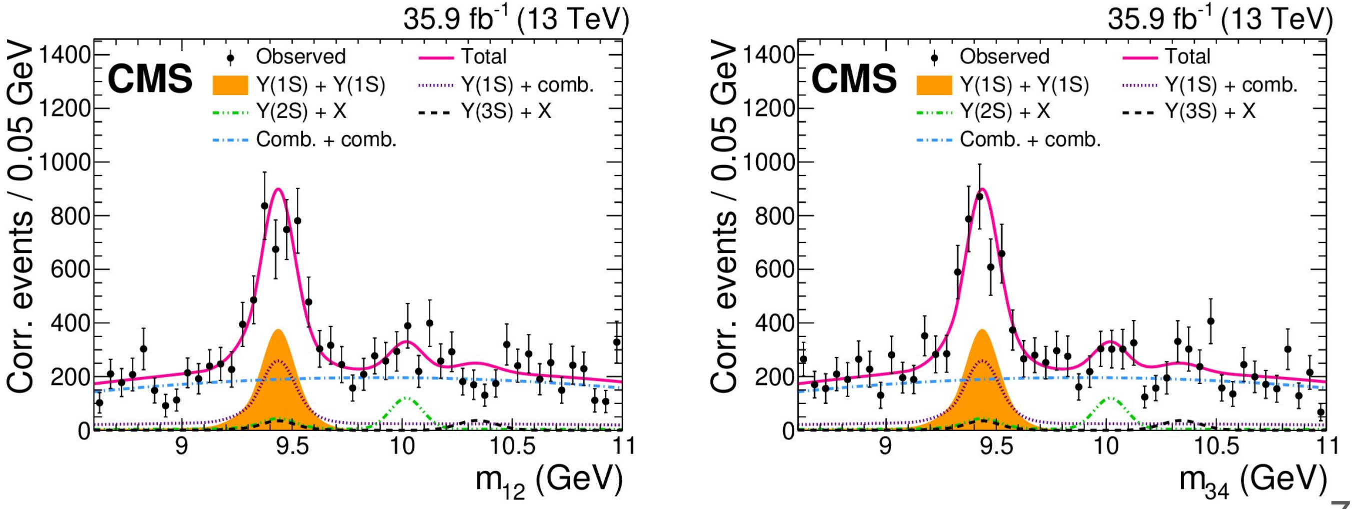
$$\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = (2.48 \pm 0.05)\%$$

Previous CMS measurement, in the same fiducial region at 8 TeV (JHEP05 (2017) 013)

$$\sigma_{fid} = 69 \pm 13(stat) \pm 7(syst) \pm 3(\mathcal{B})\ pb$$

Backgrounds:

- **Υ**(2S)+**Υ**(2S)
- **Υ**(3S)+**Υ**(3S)
- **Υ**(2S)+**Υ**(1S)
- **Υ**(3S)+**Υ**(1S)
- **Υ**(1S)+Combinatorial bkg
- **Υ**(2S)+Combinatorial bkg
- **Υ**(3S)+Combinatorial bkg
- Combinatorial bkg + Combinatorial bkg



Effect of the polarization

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- Quarkonia polarizations are measured from angular distributions of μμ decays
- The polarization of the **Υ**(1S) states affects the angular distributions of the leptons produced in the **Υ**(1S)→**μ⁺μ⁻** decays through the following formula:

$$\frac{d^2N}{d\cos\theta d\phi} \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi)$$

Where θ and ϕ are the polar and azimuthal angles, respectively, of the positively charged muon with respect to the the z axis of the polarization frame.

λ_θ	-1.0	-0.5	-0.3	-0.1	$+0.1$	$+0.3$	$+0.5$	$+1.0$
$\Delta\sigma_{\text{fid}}$	-60%	-22%	-12%	-3.7%	$+3.4\%$	$+9.4\%$	$+14\%$	$+25\%$

Measurement of the DPS-to-inclusive fraction: Methodology

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DPS production ⇒ large |**Δ**y(**Υ**(1S),**Υ**(1S))|, largely uncorrelated, and large $m_{\Upsilon(1S)\Upsilon(1S)}$

- The distributions of **Δ**ϕ(**Υ**(1S),**Υ**(1S)), **Δ**R(**Υ**(1S),**Υ**(1S)) and p_T(**Υ**(1S),**Υ**(1S)) also differ for the SPS and DPS, but large theoretical uncertainties.
- Methodology to extract the fraction:

First σ_{fid} is measured in 5 bins of |**Δ**y(**Υ**(1S),**Υ**(1S))| and 5 bins of $m_{\Upsilon(1S)\Upsilon(1S)}$ → Then it is compared to the expected distribution of SPS and DPS → The fraction is measured with a binned maximum likelihood fit of these 2 simulated distribution to the measured σ_{fid} is measured in 5 bins of |**Δ**y(**Υ**(1S),**Υ**(1S))| and 5 bins of $m_{\Upsilon(1S)\Upsilon(1S)}$

Measurement of the DPS-to-inclusive fraction: Results

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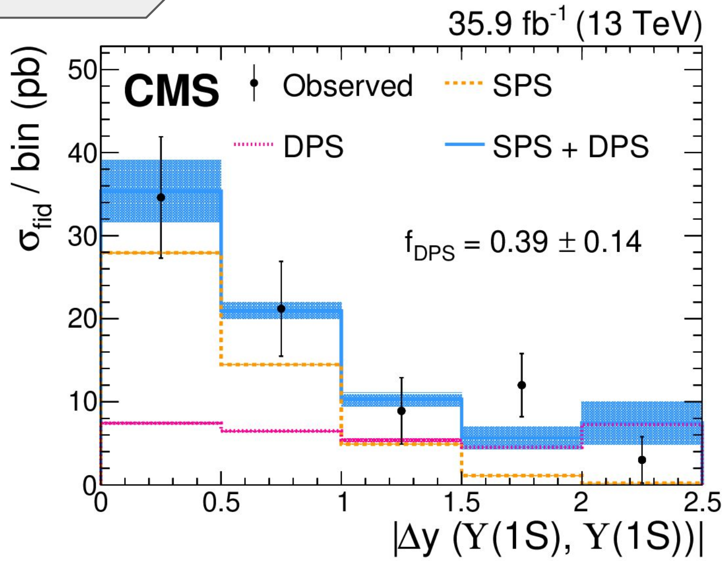
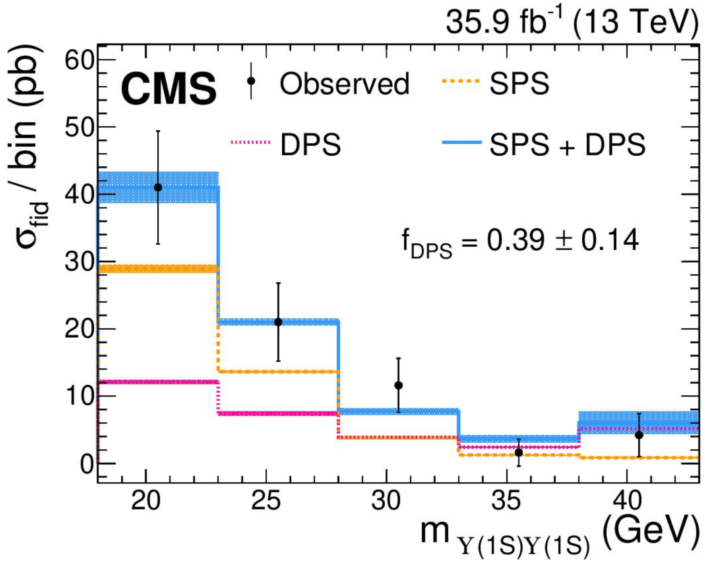
This measurement is performed for the first time at CMS!

$$f_{DPS} = \frac{\sigma_{fid}^{DPS}}{\sigma_{fid}^{SPS} + \sigma_{fid}^{DPS}} = \begin{cases} (39 \pm 14)\% & using \; |\Delta y(\Upsilon(1S), \Upsilon(1S))| \\ (27 \pm 22)\% & using \; m_{\Upsilon(1S),\Upsilon(1S)} \end{cases}$$





Search for resonances: Methodology

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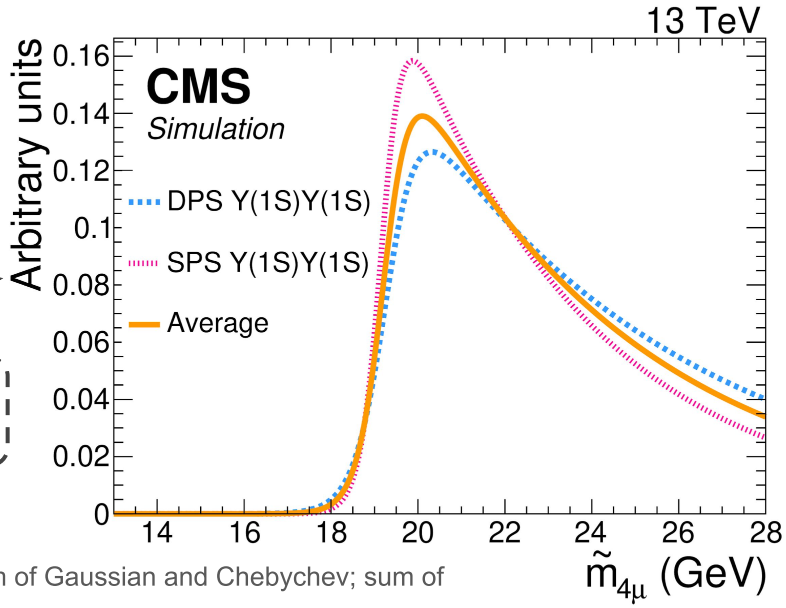
- Using the mass-difference observable $\tilde{m}_{4\mu} = m_{4\mu} - m_{\mu\mu} + m_{\Upsilon(1S)}$ which has a resolution about 50% better than $m_{4\mu}$ for signal events, and are similar for the combinatorial background
- Yields extraction: unbinned maximum-likelihood fit to the spectrum
  - Signal: sum of two Gaussian
  - Background:
    - Simulated **Υ**(1S)**Υ**(1S) process: product of sigmoid and exponential function
    - Combinatorial background is obtained in the fit from data in the signal region: smooth function (Chebychev pol. various orders; sum of Gaussian and Chebychev; sum of Breit-Wigner and Chebychev)



Search for resonances: tetraquark

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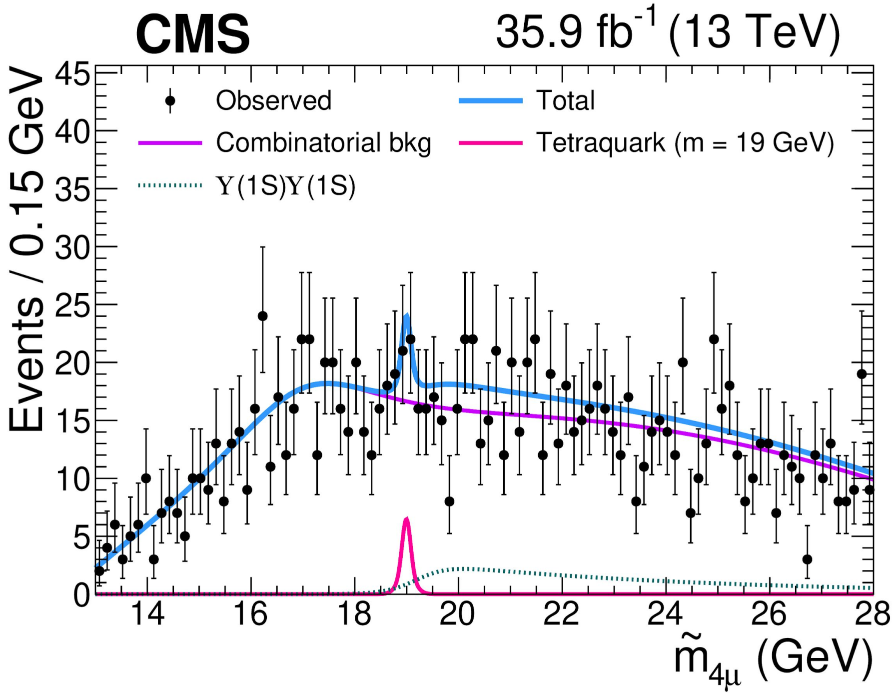
- A example signal for tetraquark model with mass of 19 GeV, which has a significance of about 1**σ**

Υ(1S) pair production is a background to the resonance search



Search for resonances: Results

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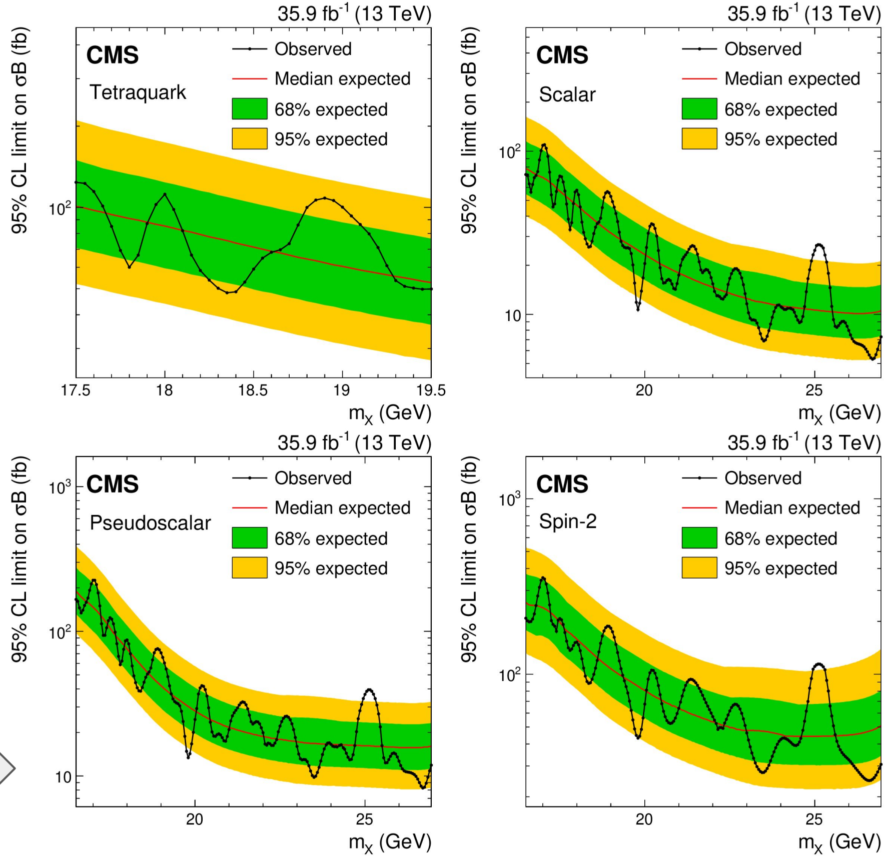
Tetraquarks with masses between 17.5 GeV and 19.5 GeV
Generic narrow resonance with mass around 16.5 GeV and 27 GeV

Observed upper limits 95% CL on the product of the cross section and branching fraction for a tetraquark (upper left), scalar (upper right), pseudoscalar (lower left), and spin-2 (lower right) states.



The largest excess is observed for a resonance mass of 25.1 GeV, and has a local significance of 2.4**σ** for the scalar signal hypothesis

Summary

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- The fiducial cross section for **Υ**(1S) in the fiducial region where both **Υ**(1S) mesons have an absolute rapidity below 2.0 at $\sqrt{s}$ = 13 TeV is measured at CMS with 2016 data (35.9 fb^{-1}).
  - The result are presented assuming that the **Υ**(1S) mesons are produced unpolarized, and also the effect of the polarization was showed.
- The contribution of DPS to the total inclusive **Υ**(1S) pair production cross section is determined for the first time.
- The results of a search are also presented for a light narrow resonance, such as tetraquark or a bound state BSM, decaying to a **Υ**(1S) and a pair of opposite-sign muons.
  - No excess of events compatible with a signal is observed

Conclusions

- CMS has produced several new results in the field of quarkonium production and polarization.

- Thanks for listening!

Backup Slides

Systematic uncertainties in the **Υ**(1S) pair production

Table 1: Systematic uncertainties considered in the Υ(1S) pair production cross section measurement. The last column gives the associated absolute uncertainty in the measurement of σ_{fid}.

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
$\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-)$	4.0	3.2
Signal and background models	1.2	1.0
Method closure	1.5	1.2
Total	8.1	6.4