Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO

# Recent CMS results on exotic hadrons

## HADRON 2021

### 19th International Conference on Hadron Spectroscopy and Structure

### in memoriam Simon Eidelman


Samet Lezki

On Behalf of the CMS Collaboration

# Recent CMS results on exotic hadrons

★ Study of the $B^+ \to J/\psi \bar{\Lambda} p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV;
*JHEP* 12 (2019) 100

★ Measurement of the $\Upsilon$(1S) pair production cross section and search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV;
PLB 808 (2020) 135578

★ Observation of the $B_s^0 \to X(3872)\phi$ decay; PRL 125 (2020) 15, 152001

★ Evidence for $\chi_{c1}$(3872) in PbPb collisions and studies of its prompt production at $\sqrt{s_{NN}} = 5.02$ TeV; arXiv:2102.13048; Submitted to *Phys. Rev. Lett.*

# Study of the $B^+ \to J/\psi \bar{\Lambda} p$ decay

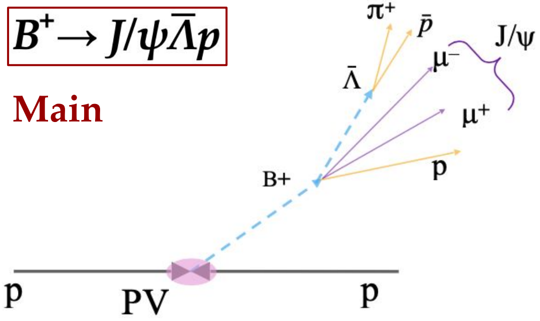
# Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay - Motivation & Topology

- $B^- \to J/\psi\Lambda\bar{p}$ decay was observed with low statistic by Belle in 2005 [PRD 72 (2005) 051105].
  [the first observation of B-meson decay into baryons and a charmonium state.]

- Studies of the intermediate inv. Mass spectra in 3-body decays of B-mesons & $\Lambda_b$ baryon of the $J/\psi p$ system [PRL 115 (2019) 072001, **pentaquark** state by LHCb in $\Lambda_b^0 \to J/\psi K^- p$] and of charmonium+baryon systems make this kind of decays quite interesting.

**$B^+ \to J/\psi\bar{\Lambda}p$**

**Main**



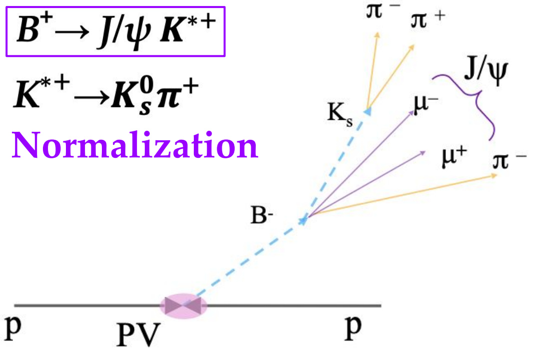

**Reconstruction strategy:** **Main**

- ➔ Kinematic fit of p and $\pi$ tracks to the $\Lambda$ vertex (by constraint to $\Lambda$ mass)
- ➔ Kinematic fit of $\mu^+$,$\mu^-$,p and $\Lambda$ to the common B vertex(by constraint of the $M(\mu^+\mu^-)$ to the $J/\psi$ mass.
- ➔ The best PV selected by the minimal 3D pointing angle of the B momenta.

**$B^+ \to J/\psi K^{*+}$**

**$K^{*+} \to K^0_s \pi^+$**

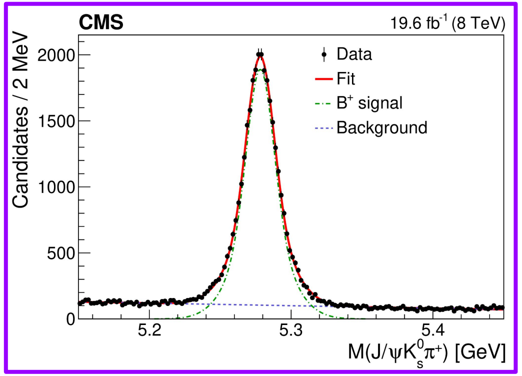
**Normalization**




**The reconstruction strategy is the same as the main channel.** The decay $B^+ \to J/\psi K^{*+}$ is chosen as the normalization channel:

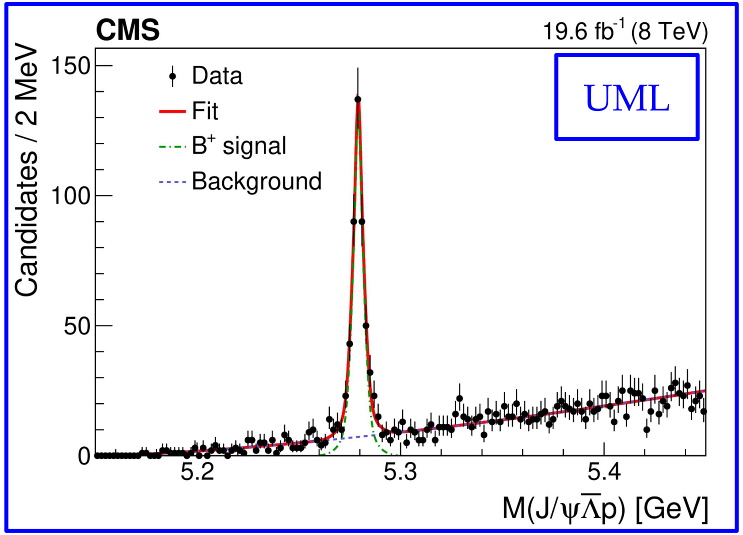
- ➔ Similar decay topology
- ➔ Measured with high precision

**Normalization**



# Study of the $B^{+} \to J/\psi\bar{\Lambda}p$ decay - Signal extraction

★ **Lack of the hadron identification:** → proton mass assigned to the highest $p_T$ tracks
→ $K_s^0$ veto applied for cleaning the $\Lambda$ sample by contamination




➔ **Unbinned Maximum-Likelihood fit**

➔ **Signal**: Three Gaussian with a floating common mean and overall normalization (widths and relative normalization from MC)

➔ **Background**: Polynomial $(x - x_0)^{\alpha}$ threshold
$x_0 = M_{PDG}(\Lambda) + M_{PDG}(p) + M_{PDG}(J/\psi)$

★ **More details about selection criteria, efficiency calculation and systematic evaluation can be found at [*JHEP* 12 (2019) 100].**

# Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay - Branching Fraction calculation

$$\frac{\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} =$$

$$= \frac{N(B^+ \to J/\psi\bar{\Lambda}p)\mathcal{B}(K^{*+} \to K^0_S\pi^+)\mathcal{B}(K^0_S \to \pi^+\pi^-)\epsilon(B^+ \to J/\psi K^{*+})}{N(B^+ \to J/\psi K^{*+})\mathcal{B}(\bar{\Lambda} \to \bar{p}\pi^+)\epsilon(B^+ \to J/\psi\bar{\Lambda}p)}$$

$$\frac{\mathcal{B}[B^+ \to J/\psi\bar{\Lambda}p]}{\mathcal{B}[B^+ \to J/\psi K^{*+}]} = [1.054 \pm 0.057(\text{stat}) \pm 0.035(\text{syst}) \pm 0.011(\mathcal{B})] \times 10^{-2}$$

and using $\mathcal{B}[B^+ \to J/\psi K^{*+}] = [1.43 \pm 0.08] \times 10^{-3}$

$$\mathcal{B}[B^+ \to J/\psi\bar{\Lambda}p] = [15.1 \pm 0.8(stat) \pm 0.5(syst) \pm 0.9(\mathcal{B})] \times 10^{-6}$$

PDG mean value of $\mathcal{B}[B^+ \to J/\psi\bar{\Lambda}p] = [11.8 \pm 3.1] \times 10^{-6}$

The latest Belle measurement $\mathcal{B}[B^+ \to J/\psi\bar{\Lambda}p] = [11.7 \pm 2.8^{+1.8}_{-2.3}] \times 10^{-6}$

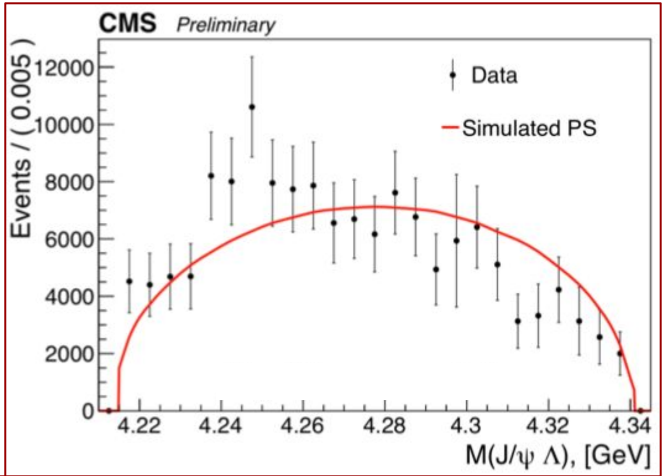
**The most precise measurement to date and consistent with Belle**

# Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay - Study of invariant masses

- Thanks to the large signal yield, CMS tried to perform a search for new exotic multiquark states in the **efficiency-corrected** two-body intermediate systems of the three-body decay.

  - Background subtraction is performed using The ***sPlot*** technique with the invariant mass **M[ $J/\psi\bar{\Lambda}p$]** as the **discriminating variable**

**The background subtracted distributions are compared with pure three-body PS shapes:**

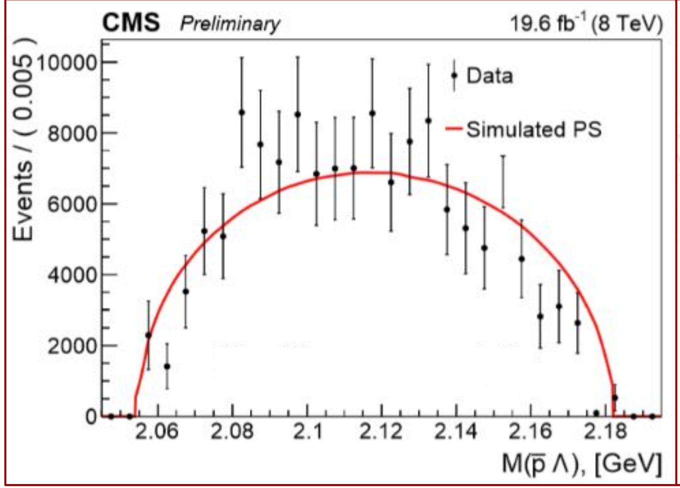


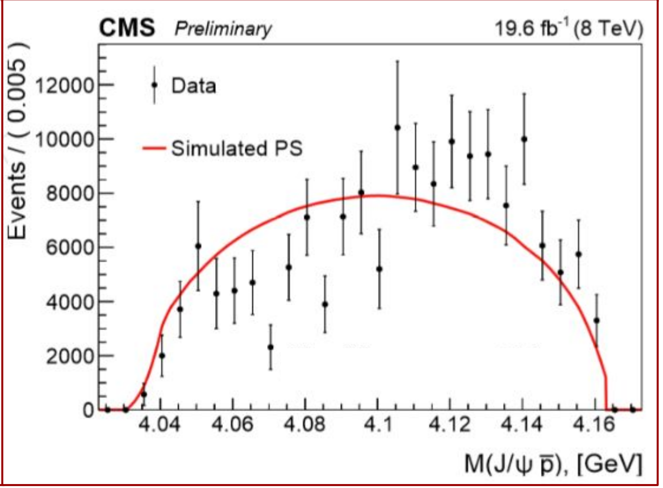

They are inconsistent with the pure three-body PS hypothesis with a significance more than:

→ $5.5\sigma$ for $J/\psi\bar{\Lambda}$

→ $6.1\sigma$ for $J/\psi p$

→ $3.4\sigma$ for $\bar{\Lambda}p$



# Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay - Model independent method

- This method has been first introduced by BaBar [PRD 79 (2009) 112001, PRD 85 (2012) 052003] and later used by LHCb [PRD 92 (2015) 112009, PRL 117 (2016) 082002].

| Resonance | Mass (MeV) | Natural width (MeV) | $J^P$ |
|---|---|---|---|
| $K_4^*(2045)^+$ | $2045 \pm 9$ | $198 \pm 30$ | $4^+$ |
| $K_2^*(2250)^+$ | $2247 \pm 17$ | $180 \pm 30$ | $2^-$ |
| $K_3^*(2320)^+$ | $2324 \pm 24$ | $150 \pm 30$ | $3^+$ |

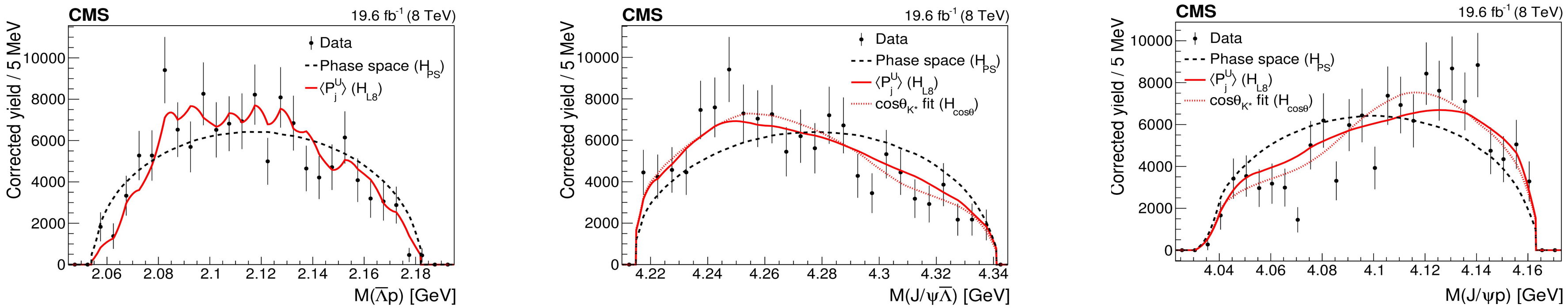
There are at least three known **$K^{*+}$ resonances** that can decay to $\bar{\Lambda}p$. This method has been used to properly account for possible contributions(due to their reflections) onto the other two intermediate two-body invariant mass spectra.

In each efficiency-corrected M[$\bar{\Lambda}p$] bin, the cos($\vartheta_{K^*}$) distribution can be expressed as the expansion in terms of Legendre polynomial;

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{j=0}^{l_{max}} \langle P_j^U \rangle P_j(\cos\theta_{K^*})$$

**$l_{max} = 2J$;**
**cos($\vartheta_{K^*}$) = the helicity angle of $K^{*+}$ in the $\bar{\Lambda}p$ system**

- The simulation-based reweighting according to the observed angular structure in the $\bar{\Lambda}p$ system shows that the description of the distributions of the invariant masses M[$J/\psi\bar{\Lambda}$] & M[$J/\psi p$] is much improved after accounting for the angular and invariant mass characterizing the $\bar{\Lambda}p$ system.
  The incompatibility of the data with reweighted PS distribution is quantified by using a likelihood ratio method and results to vary from $1.3\sigma$ to $2.8\sigma$(for $J/\psi p$) and $2.7\sigma$(for $J/\psi\bar{\Lambda}$).



# Search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$

# The search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ - Introduction

- Quarkonium pair production at LHC:
  - **Single-parton scattering** (SPS): dominant→strongly correlated→small |Δy|
  - **Double-parton scattering** (DPS): difficult to calculate→ less correlated→ large |Δy|

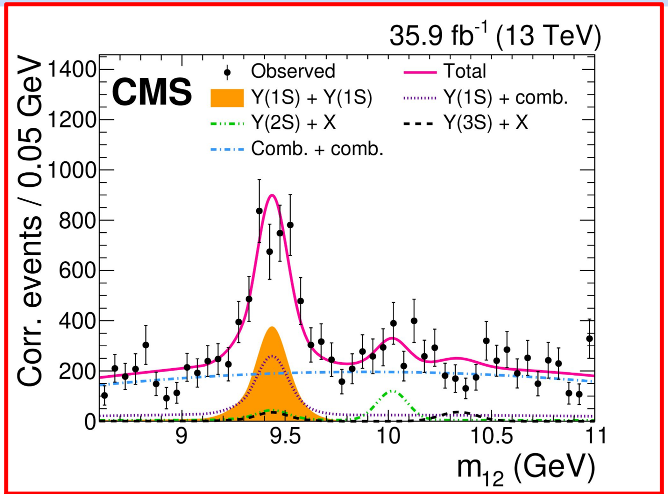
- Models for **tetraquark** bound states or generic resonances predicts that their **masses should be close** to **twice the $\Upsilon$(1S) mass**.

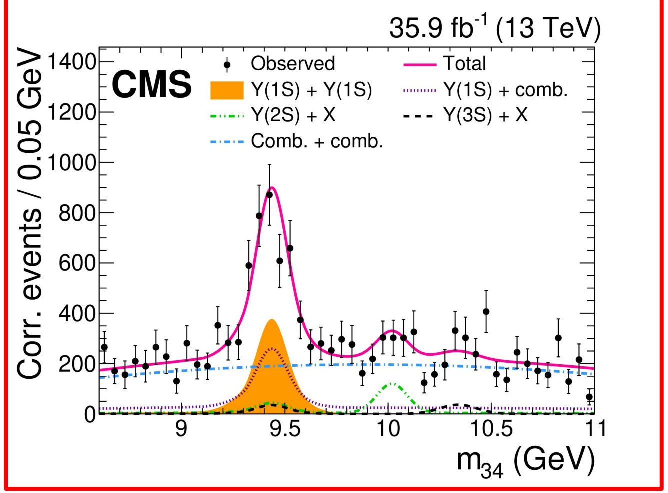
- CMS performed a tetraquark $(bb\bar{b}\bar{b})$ search in $\Upsilon(1S)\mu^+\mu^-$ final states using 2016 data at $\sqrt{s}$ = 13 TeV corresponding to 35.9 $fb^{-1}$.

**Base strategy**:
- ➔ Searched a resonance in $\Upsilon(1S)\mu^+\mu^-$ final states where $\Upsilon$(1S) decay to $\mu^+\mu^-$
- ➔ $p_T[\mu] > 2.5$ GeV, $P_{vtx}[4\mu] > 5\%$ and $M[\mu^+\mu^-] \in [M_{Y(1S)}-2\sigma, M_{Y(1S)}+2\sigma]$
- ➔ $4\mu$ paired in $\Upsilon$ states and second $\mu^+\mu^-$ rejected if compatible with J/$\psi$.

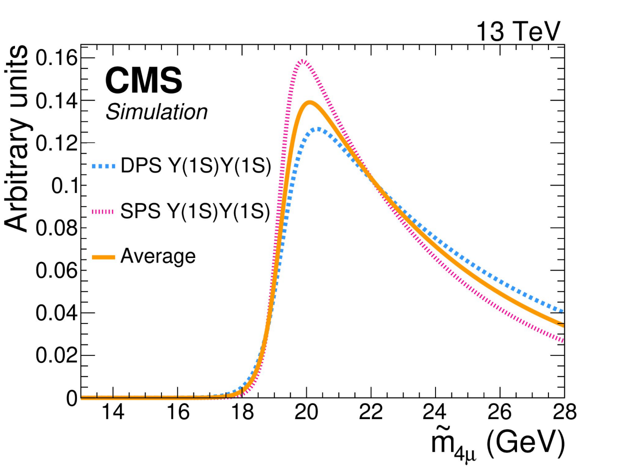
**$\Upsilon$(1S)$\Upsilon$(1S) mass distribution**:
- ➔ $m_{12}$(top) and $m_{34}$(bottom) projections and the results of the 2D fit to the muon pair invariant masses.
- ➔ Each event is corrected for acceptance and efficiency using MC.
- ➔ Signal model: Double-Crystal Ball
- ➔ Background model: Gaussian for $\Upsilon$(2S,3S) and 2nd order Chebychev polynomial for the combinatorics.

PLB 808 (2020) 135578



# The search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ - Double $\Upsilon$ production as BKG source




Mass difference:

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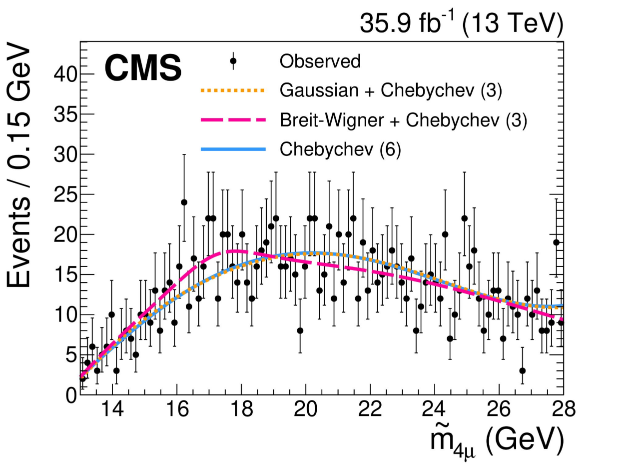
$$\tilde{m}_{4\mu} = m_{4\mu} - m_{\mu\mu} + m_{\Upsilon(1S)}$$

has been used to improve the mass resolution (the improvement ~50%).

➔ $M[\mu^+\mu^-] \in [M_{Y(1S)}-2\sigma, M_{Y(1S)}+2\sigma]$: $N[\Upsilon\Upsilon] = 74 \pm 13$

➔ The shape of the $\Upsilon(1S)$ pair contribution in the $\Upsilon(1S)\mu^+\mu^-$ spectrum is estimated from MC: Sigmoid × falling exponential with $f_{DPS}$(DPS-to-inclusive fraction) from fiducial cross section measurement.




Background shape parameterization is defined using events with low $4\mu$ vertex fit probability:

➔ $P_{vtx}[4\mu] \in [10^{-10}, 10^{-3}]$

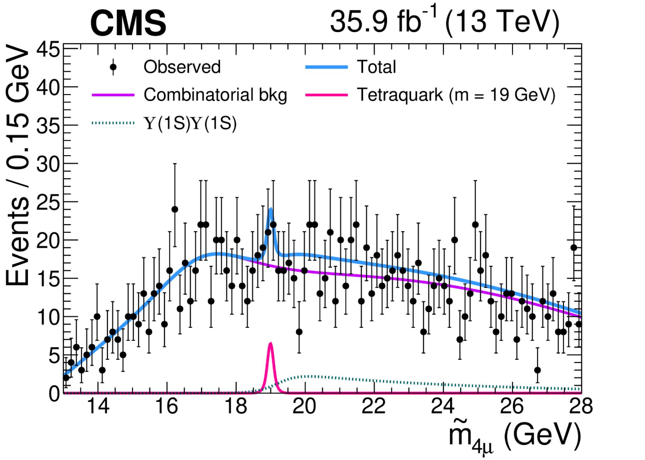
Distribution of the combinatorial background has been fitted using different fit models:

➔ Gaussian + 3rd order Chebychev polynomial

➔ Breit-Wigner + 3rd order Chebychev polynomial

➔ 6th order Chebychev polynomial

# The search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ - An example signal at 19 GeV & Upper Limit

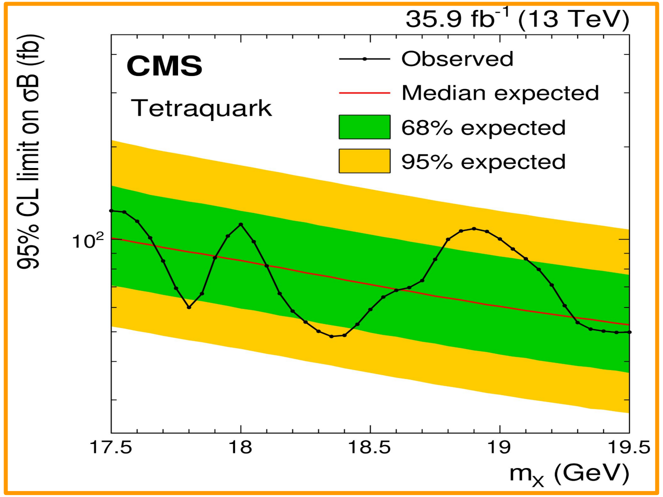



An example signal for the tetraquark model with a mass of 19 GeV is fitted:

➔ Signal model: Double-Gaussian

➔ $\Upsilon(1S)$ pair production is a background to the resonance search

➔ Significance: ~1$\sigma$




➔ The fiducial cross section for $\Upsilon(1S)$ pair where $|y[\Upsilon(1S)]| < 2.0$ at $\sqrt{s} = 13$ TeV is measured at CMS with 35.9 fb$^{-1}$ data.

➔ Observed upper limit at 95% CL is set on the production cross section and branching fraction: $\sigma_{pp\to X}\times B[X\to\Upsilon(1S)\mu^+\mu^-\to 4\mu]$

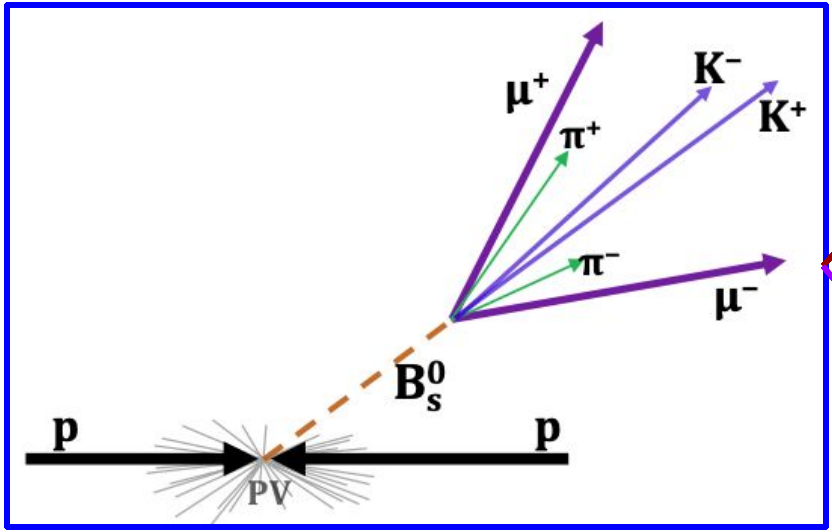
➔ No significant excess is observed near $\Upsilon(1S)\Upsilon(1S)$ mass in [17.5, 19.5] GeV.

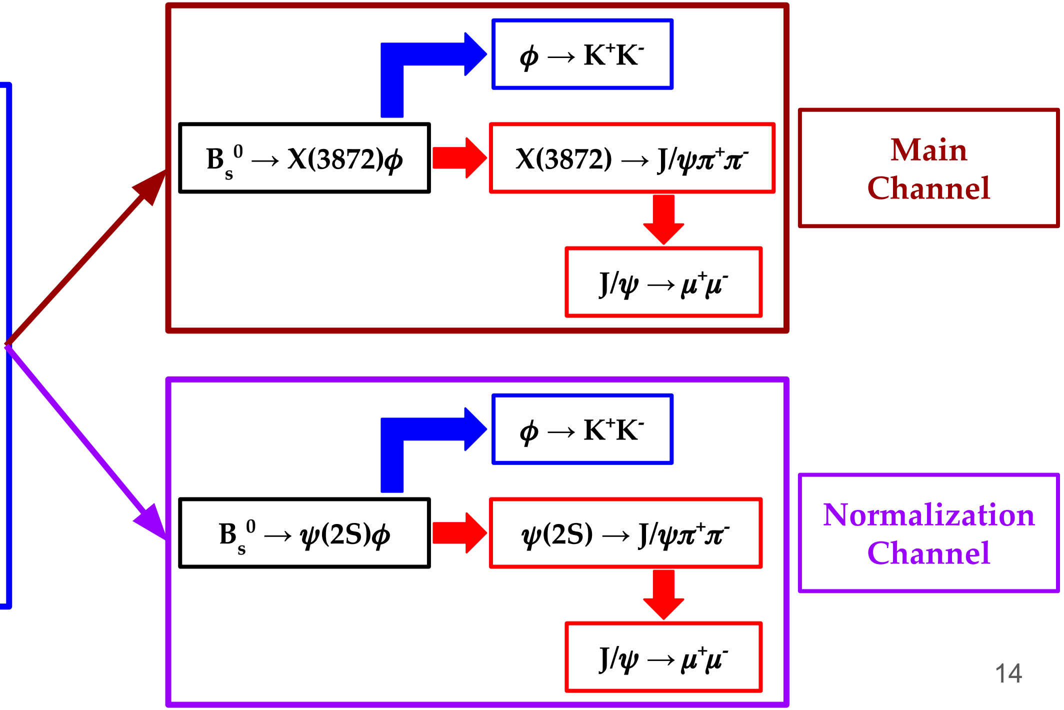
➔ Upper Limits are also set for scalar, pseudoscalar and spin-2 states. More details: PLB 808 (2020) 135578 & Backup

# Observation of the $B_s^0 \rightarrow X(3872)\phi$ decay

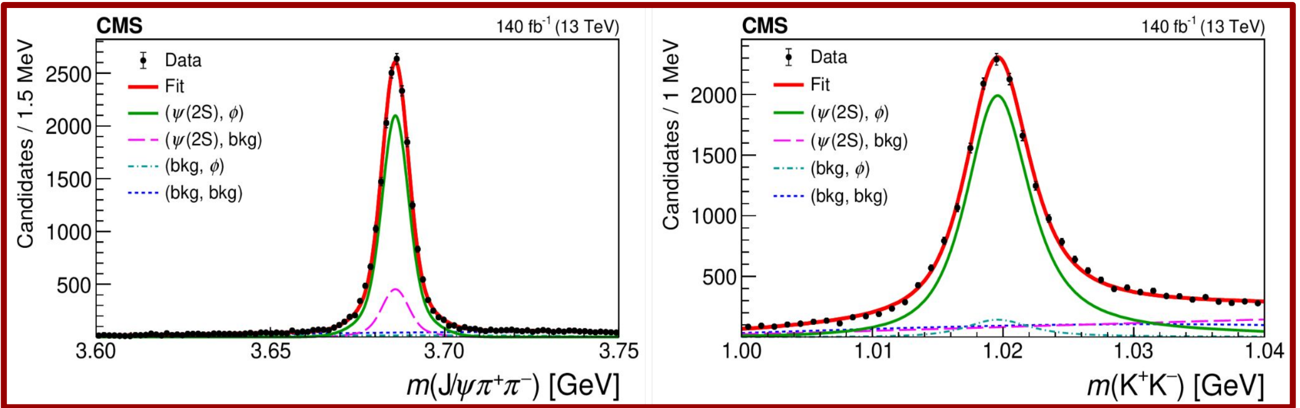
# Observation of the $B_s^0 \to X(3872)\phi$ decay - Introduction & Topology

- X(3872) was observed in 2003 by Belle with a mass very near to $m(D^0D^{*0})$ threshold, $\Gamma < 1.2$ MeV and $J^{PC}=1^{++}$
- But still we don't know if it is a molecule, a tetraquark or a conventional charmonium state $\chi_{c1}(3872)$ !!!
- X(3872) was never observed in $B_s^0$ decays, only promptly in pp, non-prompt from $B^0$, $B^+$, $\Lambda_b^0$ and prompt and non-prompt in PbPb collisions.



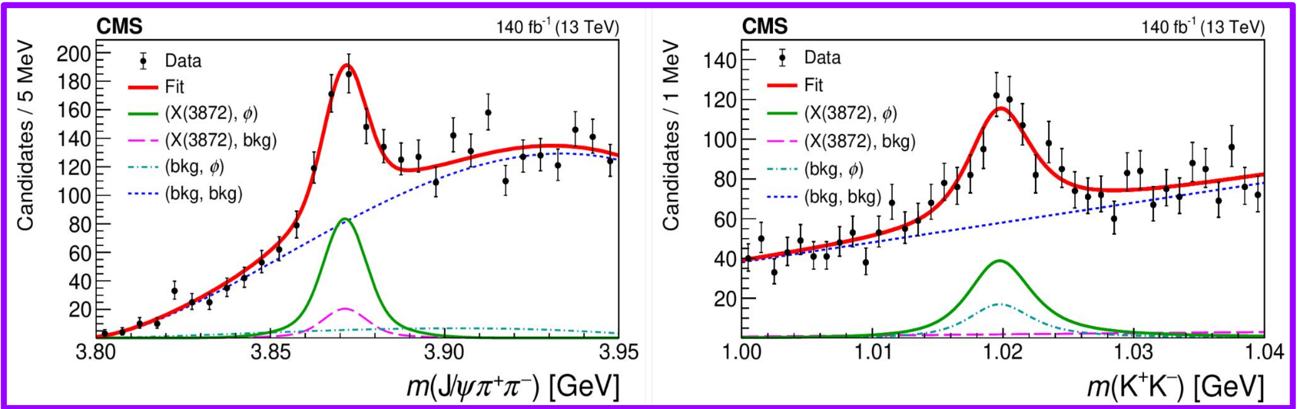



# Observation of the $B_s^0 \to X(3872)\phi$ decay - Normalization & Observation




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

PRL 125 (2020) 15, 152001




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

Left: A 2D fit to $m(J/\psi\pi^+\pi^-)$ in the $\psi(2S)$ mas window

Right: A 2D fit to m(KK) in the $\phi$ mass window.

**$N[B_s^0] = 15359 \pm 171$**

Left: A 2D fit to $m(J/\psi\pi^+\pi^-)$ in the X(3872) mas window

Right: A 2D fit to m(KK) in the $\phi$ mass window.

**$N[B_s^0] = 299 \pm 39$**

First observation with significance > $6\sigma$

The BR ratio R is calculated correcting the yields with the relative efficiencies. See next slide!

# Observation of the $B_s^0 \to X(3872)\phi$ decay - *R*; Calculations & Comparison

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

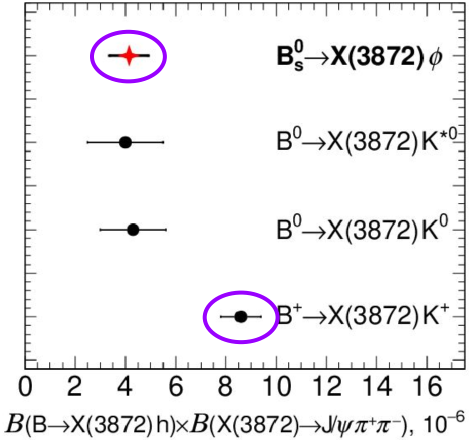
= **[2.21 ± 0.29(stat) ± 0.17(syst)]%**

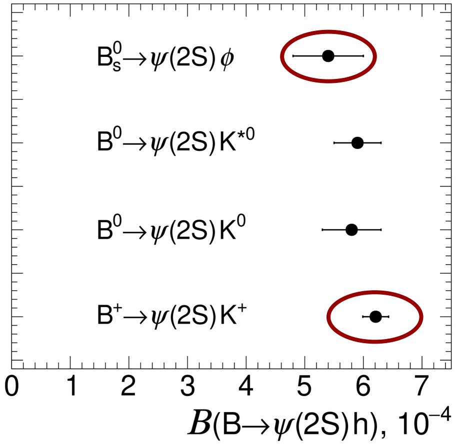
Later it has been confirmed by LHCb, JHEP 02 (2021) 024:
*R* = [2.42 ± 0.23(stat) ± 0.07(syst)]%

$$\mathcal{B}(B_s^0 \to X(3872)\phi)\,\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) = (4.14 \pm 0.54\,(\text{stat}) \pm 0.32\,(\text{syst}) \pm 0.46\,(\mathcal{B})) \times 10^{-6}$$

It is consistent with analogous $B^0$ decay, but two times smaller than $B^+$:

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



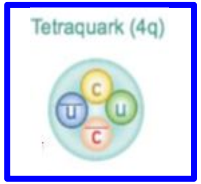

Significantly lower than the corresponding $\psi$ (2S) decay:

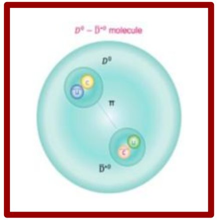
$$\frac{\mathcal{B}(B_s^0 \to \psi(2S)\phi)}{\mathcal{B}(B^+ \to \psi(2S)K^+)} = 0.87 \pm 0.10$$

In PRD 102 (2020) 034017, this results is interpreted as favouring the **compact tetraquark hypothesis** of the **X(3872) state.**

# Evidence for $\chi_{c1}(3872)$ in PbPb collisions

# Evidence for $\chi_{c1}$(3872) in PbPb collisions - Introduction




❖ The study of X(3872) production rate in HI collisions, with reference to a standard charmonium [$\psi$(2S)], may help to separate a **compact tetraquark configuration** (r ≲ 1fm) from a **large sized configuration of a molecular state** (r ~10fm).

➔ In relativistic HI collisions the formation of QGP (an extended volume of deconfined quarks & gluons) could enhance the production of X(3872) state through the quark coalescence mechanism which depends on the spatial configuration of exotic state.

➢ Relevant parameter is the ratio of hadron yields calculated in the coalescence model to those in the statistical hadronization model.

[It assumes the produced matter being in thermodynamic equilibrium
& **is known to describe the yields of hadrons in HI collisions very well**]

➢ Longer distances between (anti-)quarks could also lead to **higher** X(3872) **dissociation rate** similar to suppression mechanism of quarkonia in HI collisions.

**Its much larger size makes the molecule easier to be produced but also to be destroyed than 4q**

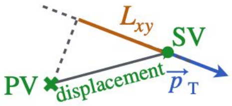
➔ The common Interaction Model [arXiv:2006.15044] seems to reproduce the recent LHCb study of X(3872) prompt production as a function of final state particle multiplicity [*PRL* 126 (2021) 9, 092001]

# Evidence for $\chi_{c1}(3872)$ in PbPb collisions - Signals in B-enriched & inclusive samples

**In B-enriched data sample:**

(non-prompt part, i.e. from B decays, it is produced **outside the QGP**)

$$l_{xy} = \frac{L_{xy} \cdot m}{|\vec{p}_T|}$$



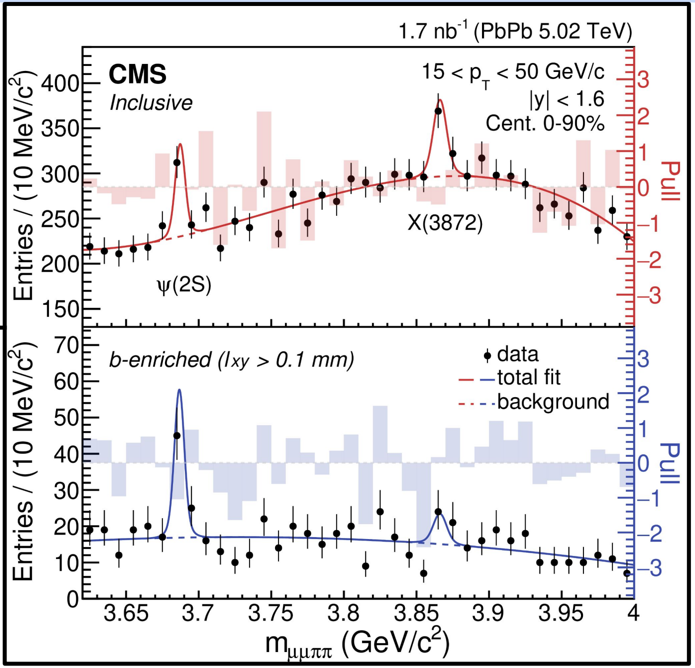

★ **Non-prompt $\psi$(2S) is clearly visible**

**In inclusive data sample:**

(interested in prompt part produced **inside the QGP**)

★ **First evidence of inclusive X(3872) production in HI collisions [statistical significance ~4.2$\sigma$]**

★ **A clear $\psi$(2S) signal to same final state is also visible**




**To gain more insights, the prompt X(3872) to $\psi$(2S) ratio:** arXiv:2102.13048

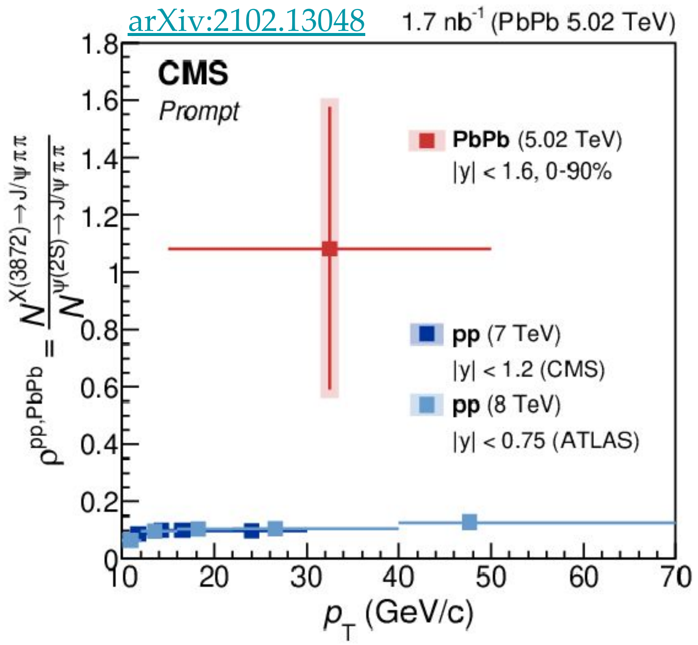
$$\rho^i = \frac{N_i^{X(3872)\to J/\psi\,\pi\pi}}{N_i^{\psi(2S)\to J/\psi\,\pi\pi}} \quad N^{i\to J/\psi\pi\pi} = N^i_{\rm raw} f^i_{\rm prompt} / (\alpha\, \epsilon_{\rm reco}\, \epsilon_{\rm sel})^i \quad f_{\rm prompt} = 1 - \frac{N_{\rm b\text{-}enr} / f^{\rm b\text{-}enr}_{\rm nonprompt}}{N_{\rm incl}}$$

$$f^{\rm b\text{-}enr}_{\rm nonprompt} = N_{\rm nonprompt}(l_{xy} > 0.1\,{\rm mm}) / N_{\rm nonprompt}$$

## Evidence for $\chi_{c1}$(3872) in PbPb collisions - Ratio of prompt X(3872) & $\psi$(2S) yields

- The **ratio** of **corrected** yields of prompt X(3872) to prompt $\psi$(2S), times their branching fractions into $J/\psi\pi^+\pi^-$:

[arXiv:2102.13048](https://arxiv.org/abs/2102.13048)




The ratios in pp and PbPb collisions are connected to the nuclear modification factors $R_{AA}^{X(3872)}$ and $R_{AA}^{\psi(2S)}$: **The meson yield ratio in nucleus-nucleus and pp interactions normalized by the number of inelastic nucleon-nucleon collisions.**

$$\rho^{PbPb} = \rho^{pp}\frac{R_{AA}^{X(3872)}}{R_{AA}^{\psi(2S)}}$$

**= 1.08 ± 0.49(stat) ± 0.52(syst)**

**[to be compared with typical values of 0.1 for pp collisions]**

- The **ratio measurement** is affected by several sources of sizeable systematic uncertainty, **see backup**.

# Summary

★ For the study of $B^+ \to J/\psi\bar{\Lambda}p$, the model-independent approach is used, which accounts for the contribution from known $K_\Gamma^{*+}$ (J=2,3,4) resonances with spins 4 decaying to the $\bar{\Lambda}p$ system improves the agreement significantly, decreasing the incompatibility with data to less than $3\sigma$ in both the $J/\psi p$ & $J/\psi\bar{\Lambda}$ invariant mass spectra. [*JHEP* 12 (2019) 100]

★ No significant excess has been observed in $\Upsilon(1S)\mu^+\mu^-$ mass spectrum, consistent with a narrow resonance, in the M[X] ∈ [16.5, 27.0] GeV. To be performed with full Run-II data. [PLB 808 (2020) 135578]

★ A new decay mode $B_s^0 \to X(3872)\phi$ has been observed. Production of the X(3872) in B decays supports its unconventional nature. [PRL 125 (2020) 15, 152001]

★ The first evidence of X(3872) production in HI collisions has been observed.
The $\varrho[N^{X(3872)}/N^{\psi(2S)}]_{prompt} \times BR[\psi(2S)/X(3872)]$ into $J/\psi\pi^+\pi^-$ needs more statistics but still provides a unique experimental input to theory community. [arXiv:2102.13048]

CMS has important role to take part in the sector of both conventional and exotic hadron spectroscopy with a few well thought and configured contribution (in which the possible triggers & the characteristics - either features or limitations - of the detector allows to be competitive).

New exciting results are expected with the exploitation of the full Run-II (Run-III) data sample…

# Backup

# Study of the $B^+ \to J/\psi \bar{\Lambda} p$ decay - Systematic Uncertainties

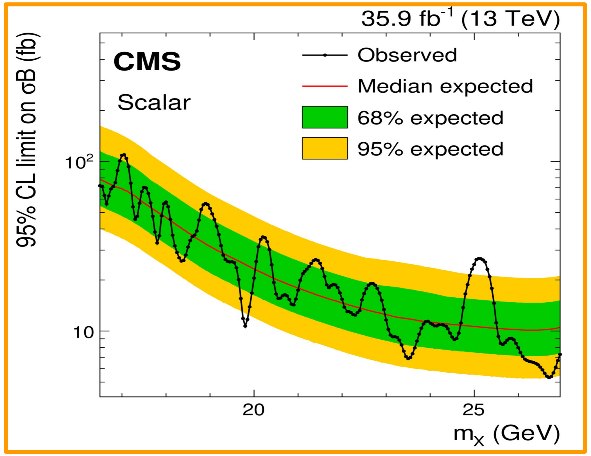
| Source | Relative uncertainty (%) |
|---|---|
| Discrepancy between data and simulation | 2.2 |
| Background model in the $M(J/\psi\overline{\Lambda}p)$ distribution | 1.1 |
| Background model in the $M(J/\psi K^0_S\pi^+)$ distribution | 0.1 |
| Background model in the $M(K^0_S\pi^+)$ distribution | 1.2 |
| Signal model in the $M(J/\psi\overline{\Lambda}p)$ distribution | 0.9 |
| Signal model in the $M(J/\psi K^0_S\pi^+)$ distribution | 0.6 |
| Simulated sample event count | 1.7 |
| Total systematic uncertainty | 3.3 |

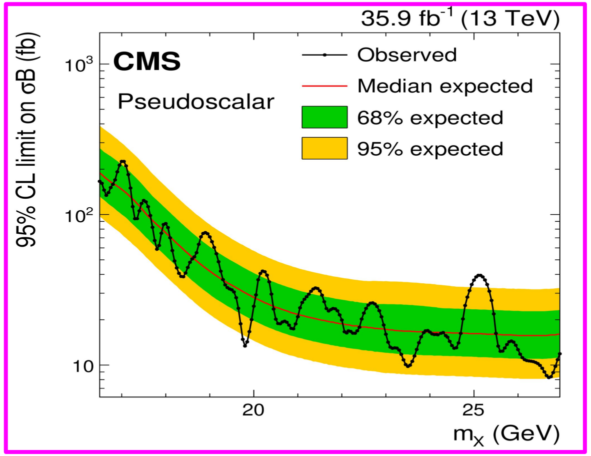
# The search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ - Systematic Uncertainties

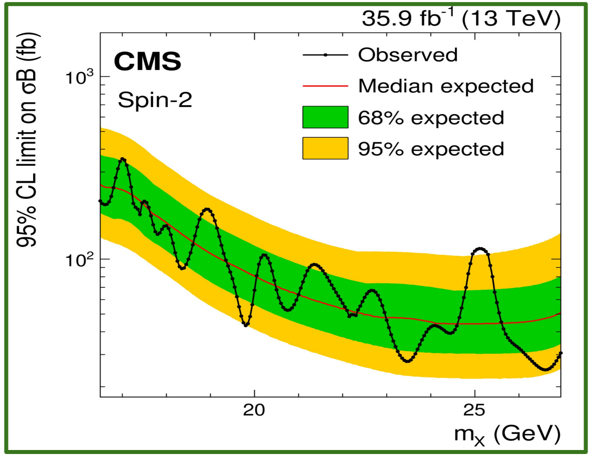
| Uncertainty source | Uncertainty (%) | Impact on $\sigma_{fid}$ (pb) |
|---|---|---|
| Integrated luminosity | 2.5 | 2.0 |
| Muon identification | 2.0 | 1.6 |
| Trigger | 6.0 | 4.7 |
| Vertex probability | 1.0 | 0.8 |
| $\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$ | 4.0 | 3.2 |
| Signal and background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

# The search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ - Scalar & Pseudoscalar & Spin-2

- The results of a search for a light narrow resonance, **such as a bound state beyond-the-standard model**, does not show any significant narrow excess of candidates above the background expectation.
- This generic search in the extended mass window is probed using JHUGEN models.
- Upper Limits on the product of the production cross-section of a resonance and the BF to a final state of 4 muons via an intermediate $\Upsilon(1S)$ are set @95% CL (using the modified frequentist construction $CL_s$ in the asymptotic approximation).
- The largest excess is observed @ 25.1GeV with a local statistical significance of 2.4$\sigma$.
- ULs range between 5 ÷ 380fb depending on the mass and signal model chosen (scalar, pseudoscalar, spin-2):



# Observation of the $B_s^0 \to X(3872)\phi$ decay - Systematic Uncertainties

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

# Evidence for $\chi_{c1}(3872)$ in PbPb collisions - Systematic Uncertainties

| | $N(\psi(2S))$ | $N(\chi_{c1}(3872))$ | $N(\chi_{c1}(3872))/N(\psi(2S))$ |
|---|---|---|---|
| Yield Extraction | 4.6% | 4.8% | 8.0% |
| Acceptance | 2.6% | 0.7% | 2.7% |
| Efficiency | 27.1% | 45.5% | 40.3% |
| $p_{\mathrm{T}}$ Shape | 12.4% | 2.9% | 12.8% |
| TnP | 4.3% | 4.0% | 0.3% |
| Prompt Fraction | 14.8% | 7.9% | 8.1% |
| Total | 39.7% | 48.1% | 48.3% |

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