Recent results from CMS on exotica

4th Workshop on Anti-Matter, Hyper-Matter and Exotica Production at the LHC

EMMI 2023 @ Bologna

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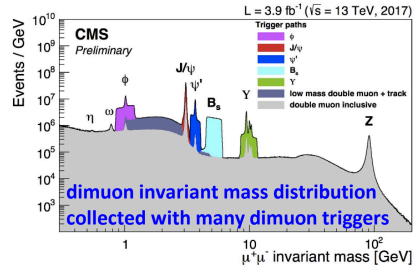
Introduction

- **CMS is providing significant contributions to beauty and quarkonium sectors,** mainly using final states containing muon pairs (due to trigger constraints).



  - This is possible thanks to the combination of :
    - **excellent tracking & high-purity muon identification performances**,
    - **a flexible trigger system** essential to collect data @ increasing luminosity & pile-up,
    - the large production cross-sections for heavy flavoured particles in *pp* collisions [LHC is a "quarkonium factory"; prompt production + from B decays (charmonia only)]

- **Selected relevant results integrate and/or complement the LHCb results !**

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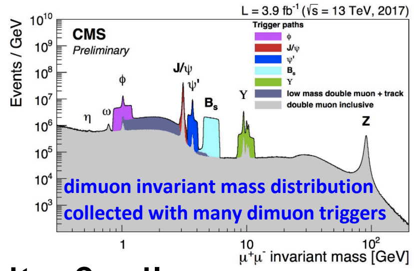

- **Selected relevant results integrate and/or complement the LHCb results !**
  - A complete review of **CMS results in conventional and exotic hadron spectroscopy** (WP for Snowmass2021) can be found here : arXiv:2204.06667

    Many results in conventional [$(\bar{b}c)$,$(\bar{b}b)$,$(\bar{b}s)$,(udb),(dsb) systems] & exotic spectroscopy

    $B_c^{(*)+}(2S)$ $\chi_{b(1,2)}(3P)$ $B^{0*}_{s(1,2)}$ Λ_b^{0**} Ξ_b^{**-}

  - Pointers to all CMS Heavy Flavour results can be found here: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

CMS results in exotic hadron spectroscopy / outline

- **First observation of the decay $B_s^0 \to X(3872)\phi$**
- **First evidence of $X(3872)$ production in PbPb collisions**
- **Search for resonances in the $J/\psi\, J/\psi$ final state**

PRL 125 (2020) 152001

PRL 128 (2022) 032001

CMS-PAS-BPH-21-003

https://cds.cern.ch/record/2815336/files/BPH-21-003-pas.pdf

- I will focus here only on these enough recent **exotic meson spectroscopy** results
- Other previous results:

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- Other previous results:
  - $X(3872)$ **production properties** in pp collisions — JHEP 04 (2013) 154
  - Search for the beauty partner of $X(3872)$ in the $\Upsilon(1S)\,\pi^+\pi^-$ spectrum — PLB 727 (2013) 57
  - **Peaking structures** in the $J/\psi\,\phi$ mass spectrum in the $B^+ \to J/\psi\,\phi K^+$ decay — PLB 734 (2014) 261
  - Search and Upper Limits for the $X(5568)$ in the $B_s^0\pi^+$ — PRL 120 (2018) 202005
  - Search for **pentaquark states** in the $J/\psi\, p$, $J/\psi\,\bar{\Lambda}$ final states ($B^+ \to J/\psi\,\bar{\Lambda}p$) — JHEP 12 (2019) 100
  - Search for narrow heavy bottom tetraquark decaying to $\Upsilon(1S)\,\mu^+\mu^-$ — PLB 808 (2020) 135578
  - Look for possible narrow exotic structures in 2-body mass spectra for the …
    … newly observed decays $\Lambda_b^0 \to J/\psi\,\Lambda\phi$ — PLB 802 (2020) 135203
    $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ — EPJC 82 (2022) 499

Production & decays @ CMS - I

- **Two main production processes of charmonia (& charmonium-like) states @ Hadron Colliders :**

  - **Prompt (inclusive):** $pp(p\overline{p}) \to (c\overline{c}) + X$
  - ***b-jets* (exclusive B-decays):** $B \to (c\overline{c}) + X$

  ***di-muons* are used as trigger signatures (+ tracks for displaced topologies)**

NOTE: bottomonium explored by triggering on prompt *di-muons* around the S-wave states ($Y(nS)$, $n = 1,2,3$)

- **Establishing XYZ existence with both production mechanisms would be ideal, but …**

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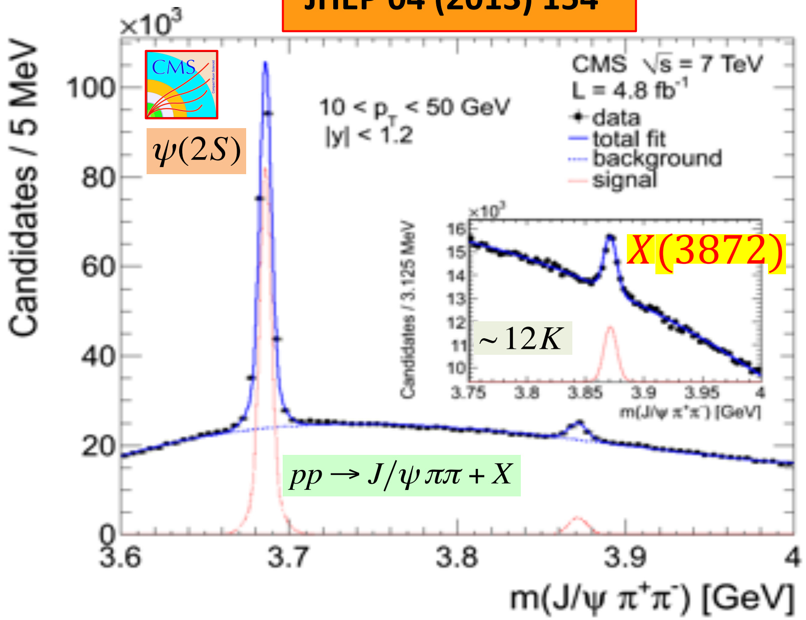
JHEP 04 (2013) 154



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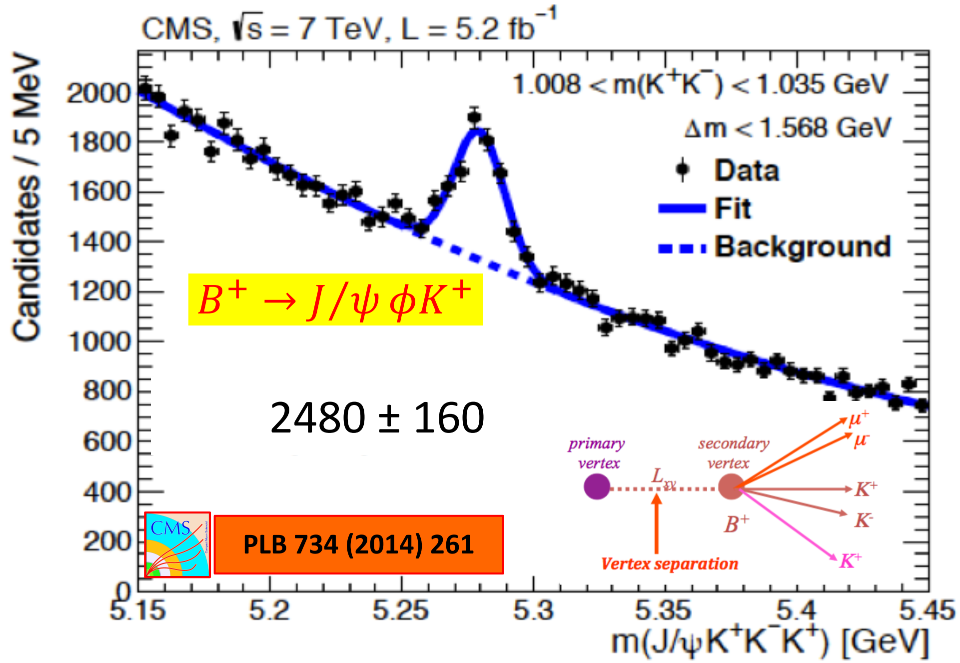

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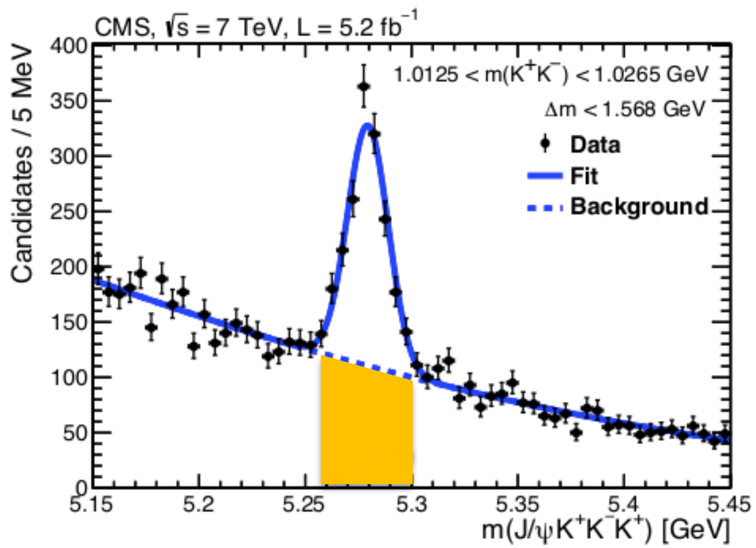
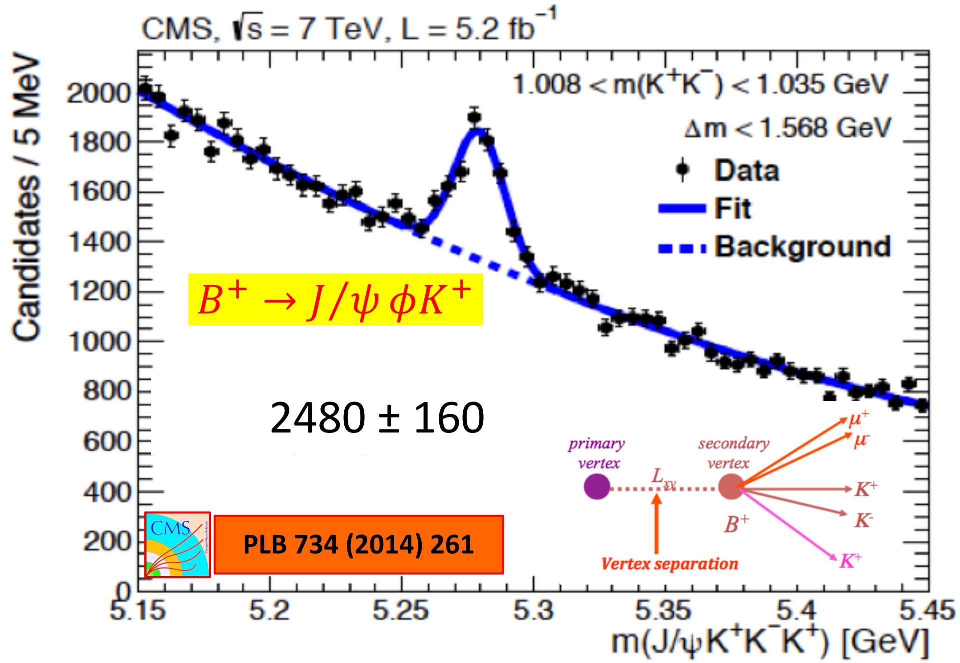


[tighter requirements]

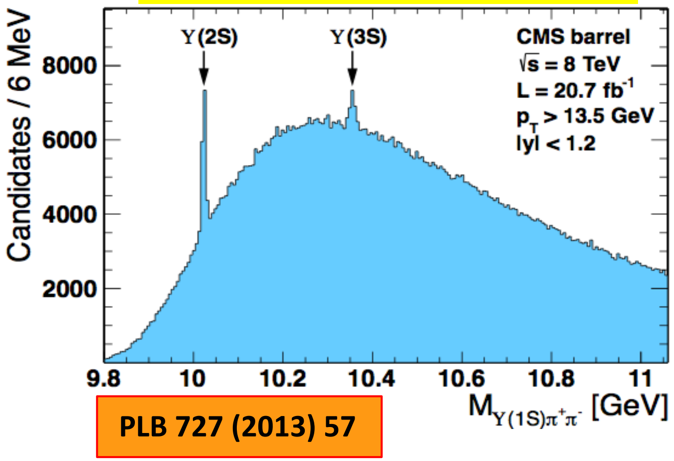


Production & decays @ CMS - II

- **Typical decay processes (suitable when lacking *Hadron Identification* capabilities):**
  - **Hadronic transitions** to a lighter $c\bar{c}$ meson through the emission of light hadrons $[\pi, \pi\pi, K_S^0, \phi, \Lambda, \dots]$
    - suitable for triggering on dimuon objects (J/ψ , $\psi(2S)$ - both prompt/displaced - also, **non-resonant dimuons** sharing a common vertex)

… in the different topologies: prompt, …

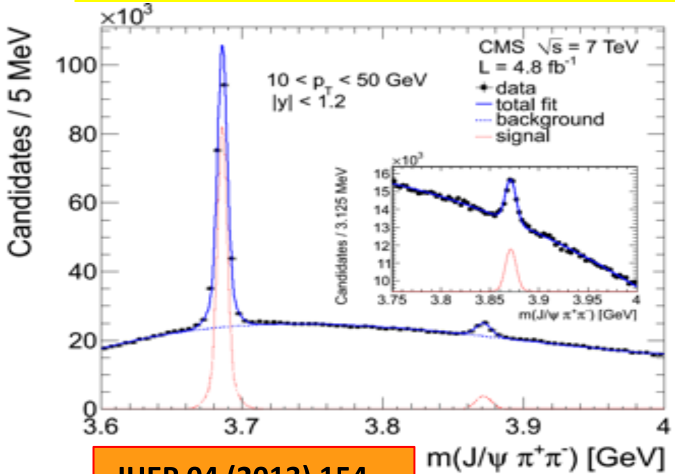
$\Upsilon(2S,3S) \to \Upsilon(1S)\,\pi^+\pi^-$



PLB 727 (2013) 57

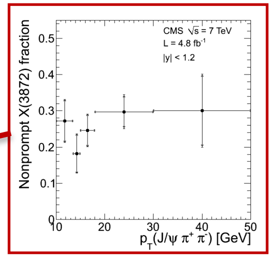
(only prompt)

$\psi(2S), X(3872) \to \psi(1S)\,\pi^+\pi^-$



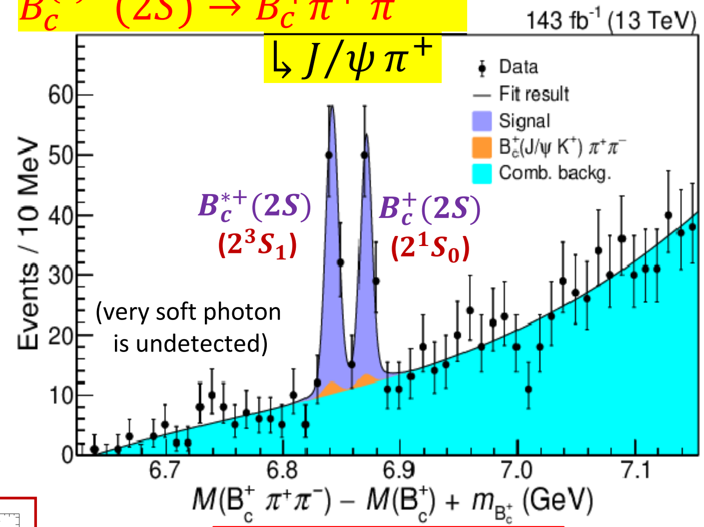
JHEP 04 (2013) 154

(inclusive = **prompt** + + non-prompt)



$B_c^{(*)+}(2S) \to B_c^+\pi^+\pi^-$

$\hookrightarrow J/\psi\,\pi^+$



PRL 122 (2019) 132001

(displaced B_c + **prompt di-pion**)

Production & decays @ CMS - II

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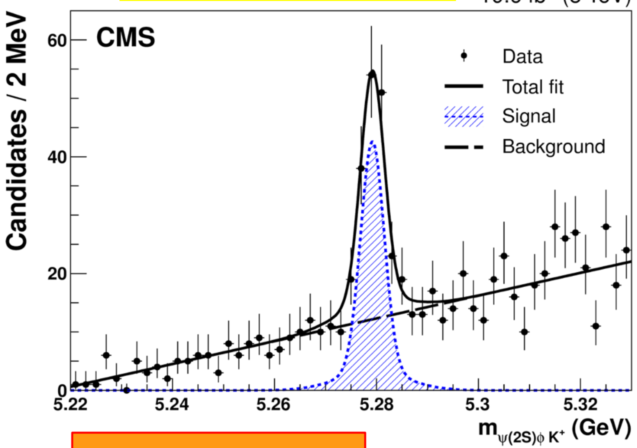
… in the different topologies: **prompt, non-prompt, …**

(first observation)

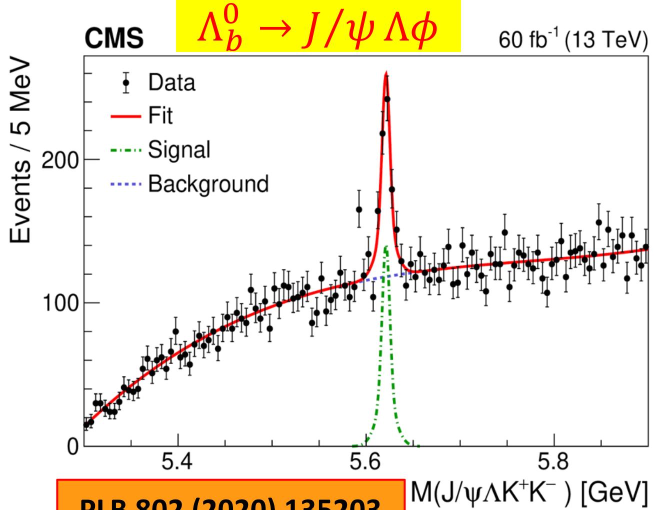
$B^+ \to \psi(2S)\phi K^+$



PLB 764 (2017) 66

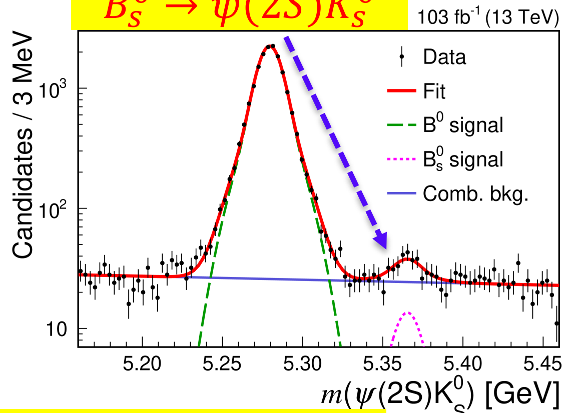
(first observation)

$\Lambda_b^0 \to J/\psi\,\Lambda\phi$

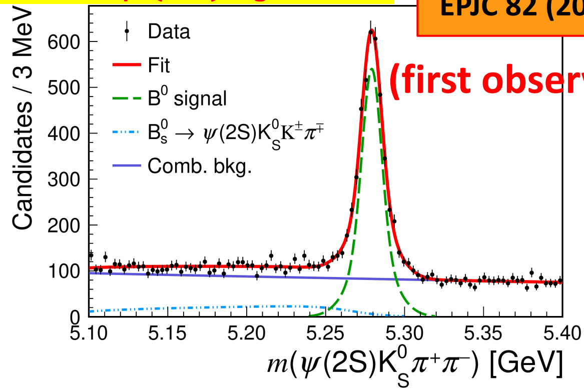


PLB 802 (2020) 135203

$B_S^0 \to \psi(2S)K_S^0$



$B^0 \to \psi(2S)K_S^0\pi^+\pi^-$



EPJC 82 (2022) 499

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Production & decays @ CMS - II

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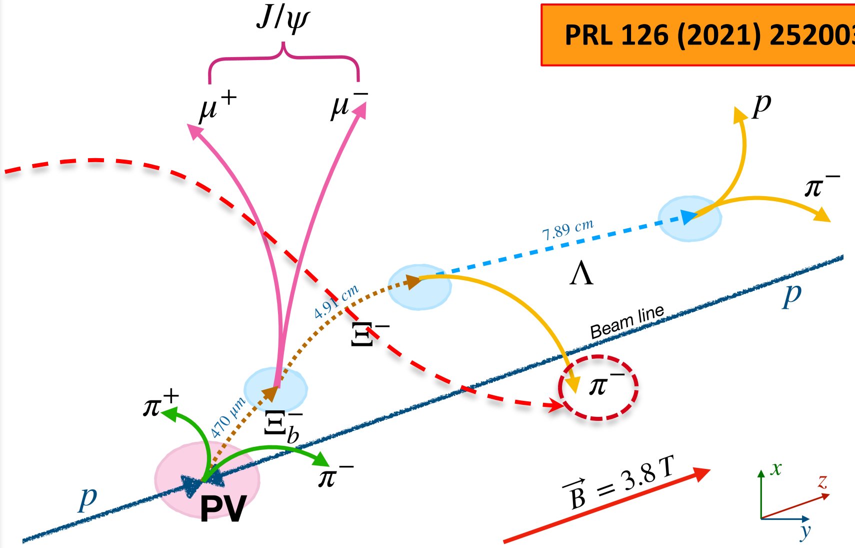
… in the different topologies: **prompt, non-prompt,** "long-lived" (baryonic decay chains)

Good efficiency for low-p_T tracks,
both **prompt** and more or less **displaced** from the PV.
The **displaced tracks** are crucial for the reconstruction of

- the $K_S^0 \to \pi^+\pi^-$,
- the self-flavour tagging $\Lambda^0 \to p\pi^-$ decays
- the $\Xi^- \to \Lambda^0 \pi^-$ decays (these π^- are very soft & displaced)

Decay chain from $\Xi_b^{**}(6100)^- \to \Xi_b^- \pi^+ \pi^-$

PRL 126 (2021) 252003



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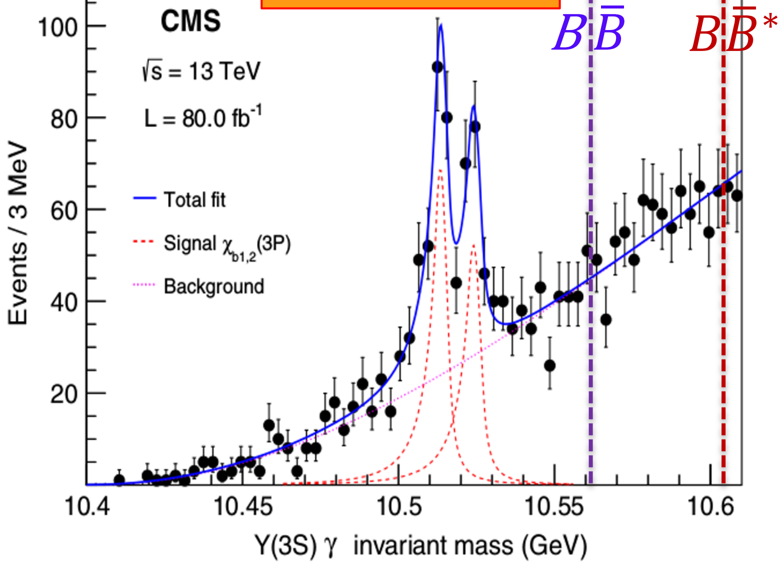
  … in the different topologies: **prompt, non-prompt, "long-lived"** (baryonic decay chains**)**

- **Electromagnetic transitions** to a lighter $c\bar{c}$ meson through the emission of a γ
  - using **photons *converted in the tracker material*** (reco issue: *low efficiency* & for $E_\gamma > 400 MeV$)

PRL 121 (2018) 092002



- $\Delta m_{21} = (10.60 \pm 0.64 \pm 0.17) MeV$
- $\chi_{bJ}(3P)$ mass resolution $\cong 2.2\ MeV$

(first observation of resolved doublet)

There have been earlier measurements related to the $\chi_{bJ}(3P)$ mass by ATLAS, LHCb & D0, but without being able to distinguish between the candidates $(J = 1, 2)$ of the $\chi_{bJ}(3P)$ multiplet

First observation of the decay $B_s^0 \to X(3872)\phi$

PRL 125 (2020) 152001

$\sqrt{s} = 13TeV$

$\mathcal{L} = 140fb^{-1}$

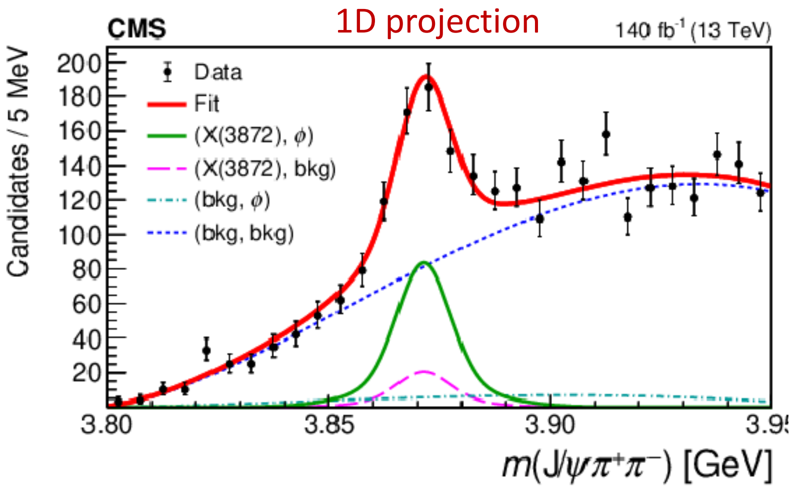
(Run-II)

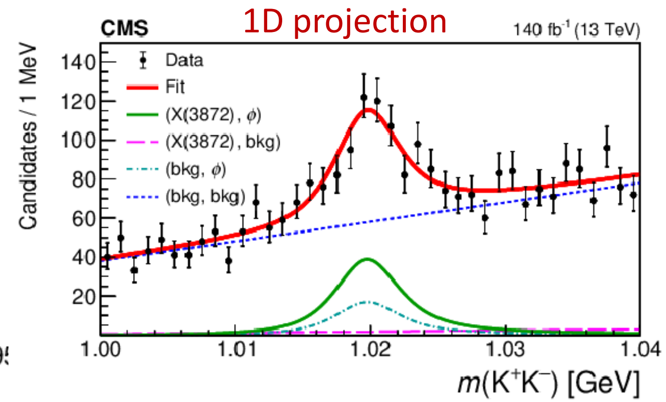
Observation of the new decay mode $B_s^0 \to X(3872)\phi$

CMS recently observed a new decay mode involving the $X(3872)$ reconstructed by $X(3872) \to J/\psi\,\pi^+\pi^-$

The signal of $B_s^0 \to X(3872)\phi$ is extracted with reference to the control channel $B_s^0 \to \psi(2S)\phi$ (having the same decay topology and similar kinematics) **used as normalization channel for the BF measurement** (many systematic uncertainties cancel out in the ratio) [see next slide]

- **Signal yield determined from a simultaneous 2D fit** of the distributions … $m(J/\psi\,\pi^+\pi^-)$, $m(K^+K^-)$
  - $N(B_s^0 \to X(3872)\phi) = 299 \pm 39$
  - **Stat. significance > 6σ (systematics included)**





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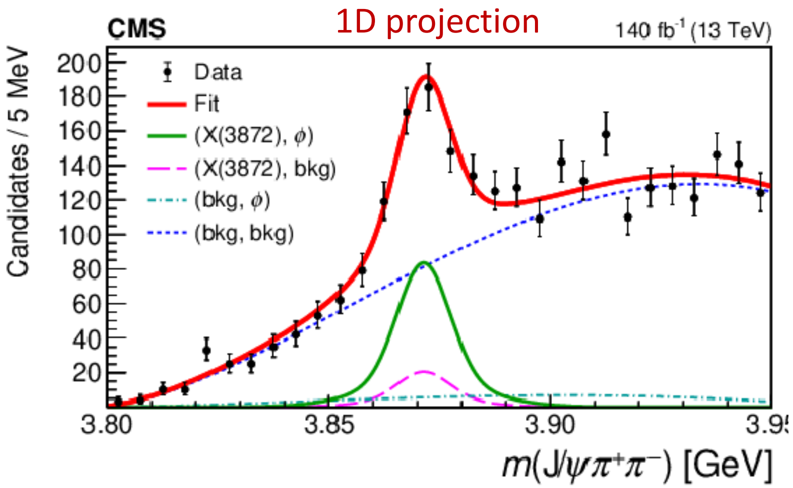
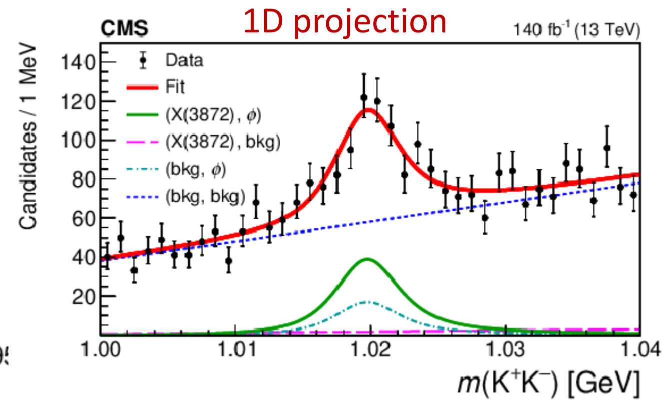
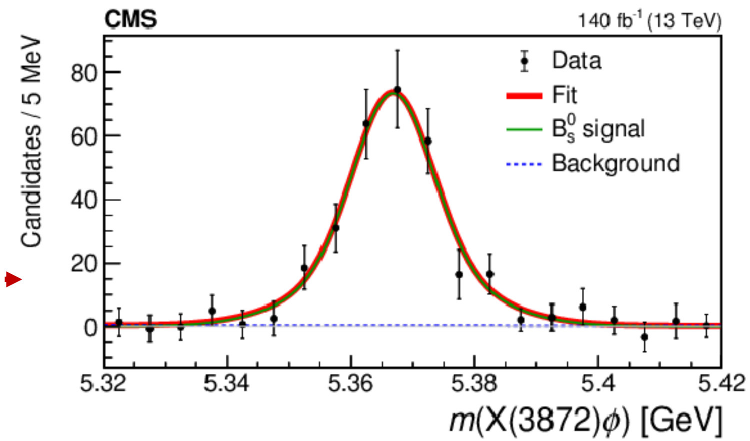




- **Evaluation of the residual non-B_s^0 background** [non-B_s^0 production of $X(3872)\phi$] **by using the non-resonant** bkg-subtracted $m(X(3872)\phi)$ **obtained by means of the *sPlot* technique.** **This bkg contribution is 1.7% (**0.5% for $\psi(2S)\phi$ **).**



Branching fraction (ratios)

Product of branching fractions for $B_s^0 \to X(3872)\phi$ measured relative to $B_s^0 \to \psi(2S)\phi$:

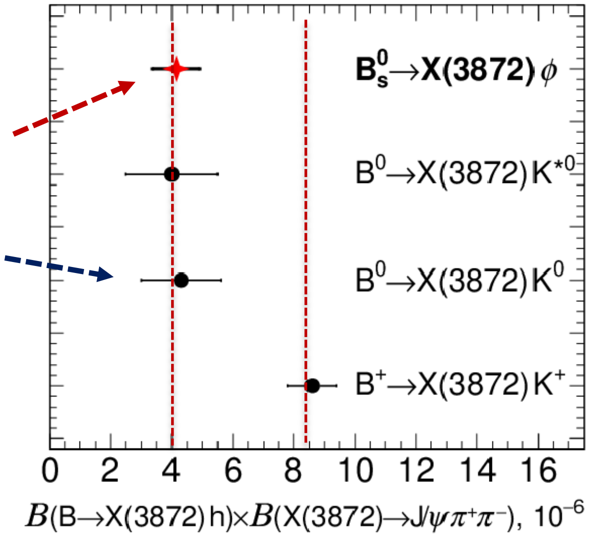
$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi)} \times \frac{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst}))\%$$

(confirmed later by LHCb [JHEP02 (2021)024]: $(2.42 \pm 0.23(\text{stat}) \pm 0.07(\text{syst}))\%$)

Branching fraction consistent with that of $B^0 \to X(3872)K^{(*)0}$:

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

$$\mathcal{B}(B^0 \to X(3872)K^0)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.3 \pm 1.3)\times 10^{-6}$$



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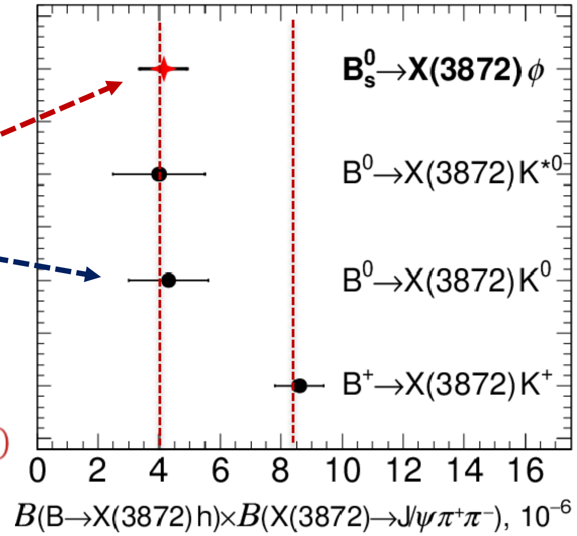
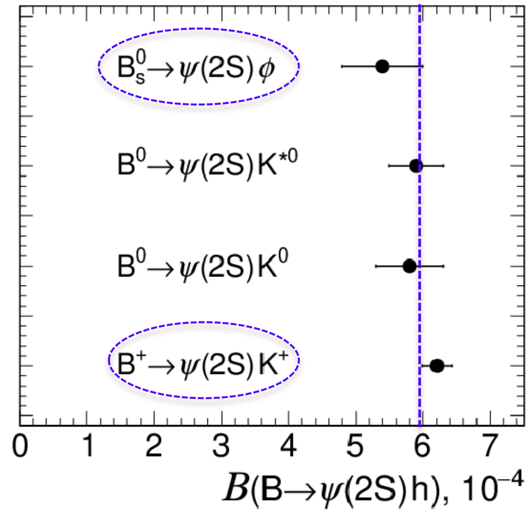


Significant difference in branching fraction ratio (neutral-to-charged) compared to $\psi(2S)$ modes:

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

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



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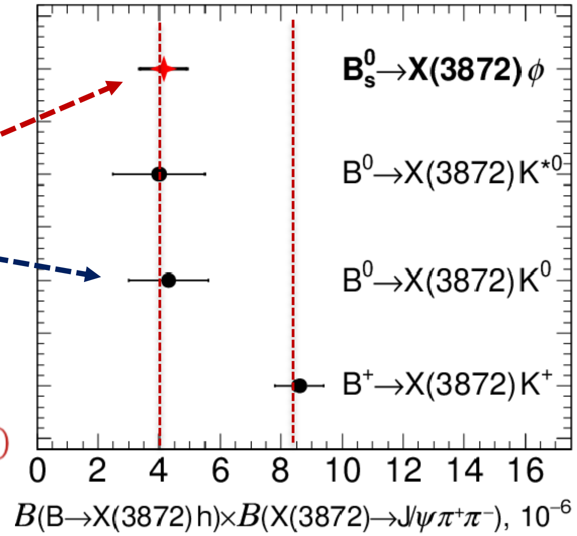

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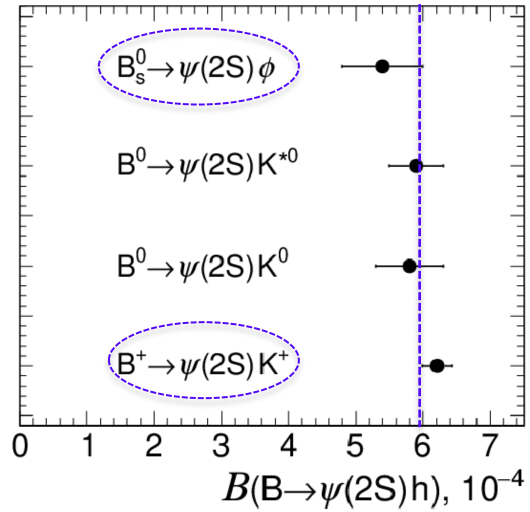
- **This suggests a difference in the production dynamics of the *exotic* $X(3872)$ in B^0 & B_s^0 decays compared to B^+ with respect to the *standard* $\psi(2S)$**

- **This observation may help in the comprehension of the nature of $X(3872)$**
  - **in the tetraquark (diquark-based) scenario this is explained by the fact that the amplitude for the charged decay gets 2 contributions of the same order instead of 1** [Maiani *et al.*, PRD 102 (2020) 034017]



First evidence of $X(3872)$ in PbPb collisions

PRL 128 (2022) 032001

$\sqrt{s_{NN}} = 5.02 TeV$

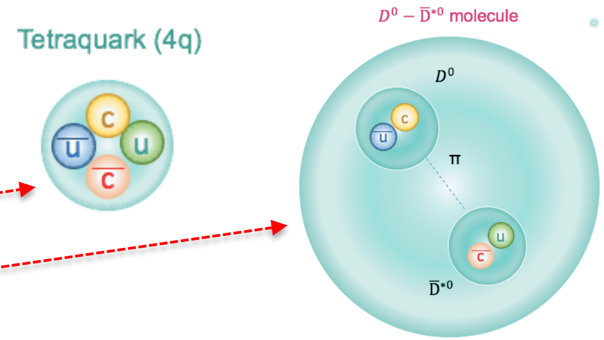
(c.o.m. energy per nucleon pair)

$\mathcal{L} = 1.7 nb^{-1}$

(End of Run-II / 2018)

Can we learn more about X(3872) nature using HI collisions ?

- **The study of X(3872) production rate in HI collisions, with reference to a standard charmonium (ψ(2S)), may help to separate a compact tetraquark configuration (radius ≲*1fm*) from a large-sized configuration of a molecular state (radius ∼*10fm*)**



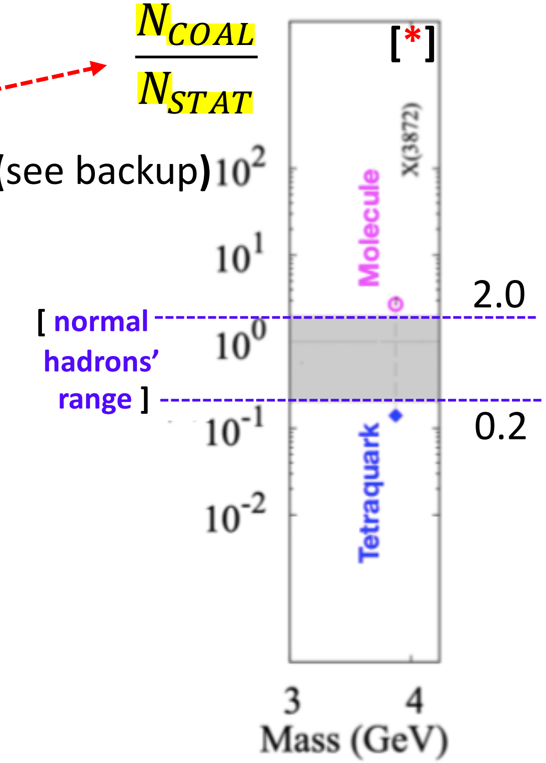
- **In relativistic HI collisions the formation of QGP** (an extended volume of deconfined quarks & gluons) **could enhance the production of the X(3872) state through the quark coalescence mechanism which depends on the spatial configuration (size) of the exotic state !**

  - 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 thermodynamical equilibrium **& is known to describe the yields of hadrons in HI collisions very well]**

  -

$\frac{N_{COAL}}{N_{STAT}}$ (see backup)



[*] PRL 106 (2011) 212001

Can we learn more about X(3872) nature using HI collisions ?

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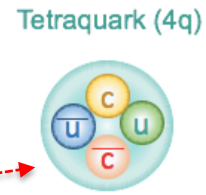

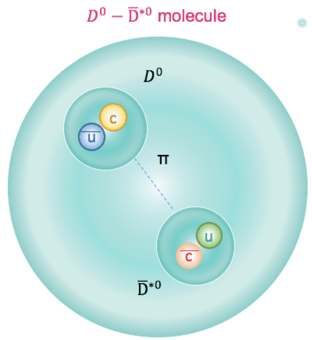

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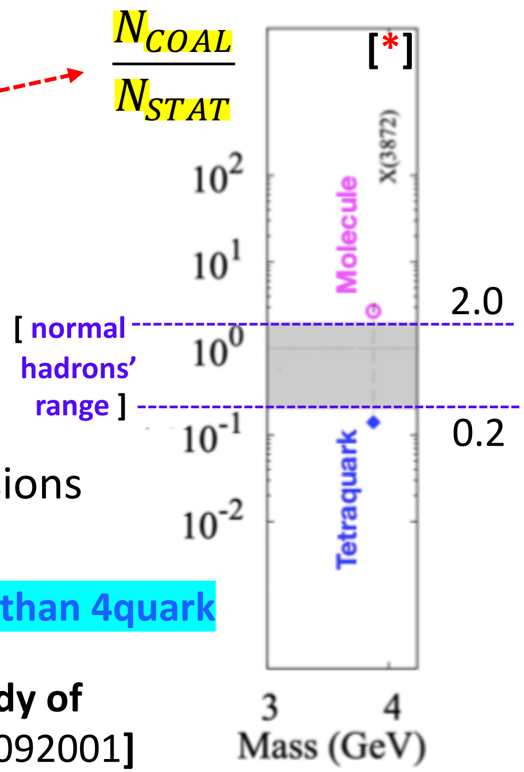
  - Relevant parameter is the **ratio of hadron yields** calculated in the coalescence model to those in the **statistical hadronization model**

    [it assumes the produced matter being in thermodynamical 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



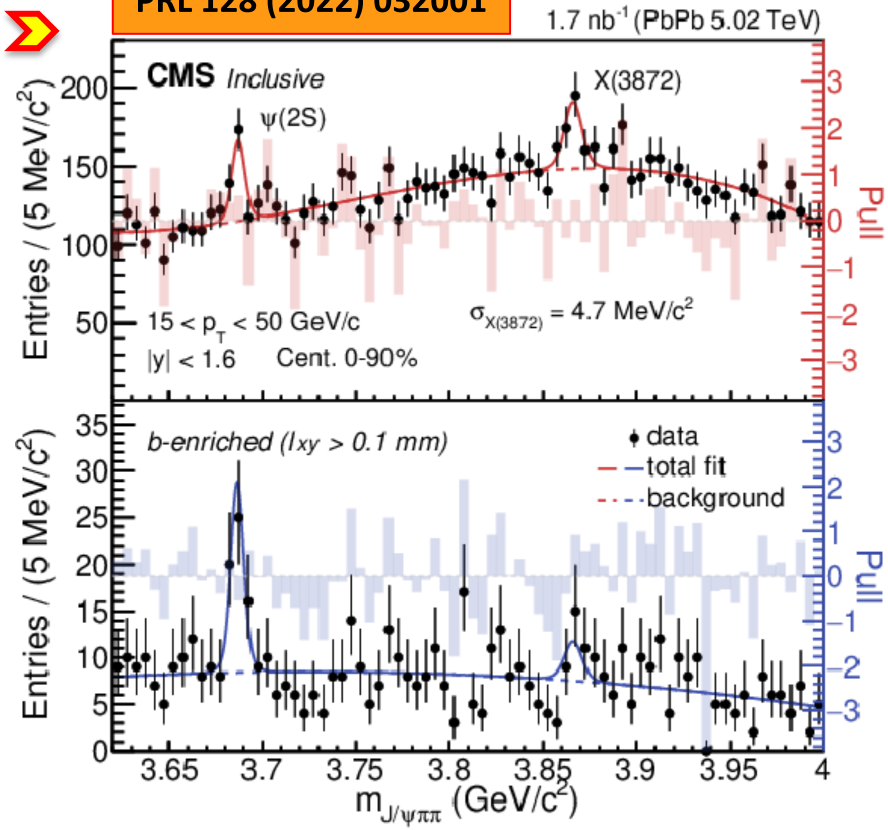
Its much larger size makes the molecule easier to be produced but also to be destroyed than 4quark

- **The *Comover Interaction Model* [**EPJ C81 (2021) 669**] seems to reproduce the LHCb study of X(3872) prompt prod. as a function of final state particle multiplicity [**PRL 126 (2021) 092001**]**

[*] **PRL 106 (2011)** 212001

Signals in B-enriched & inclusive samples ($J/\psi\,\pi^+\pi^-$ final state)

PRL 128 (2022) 032001



In *inclusive* data sample :

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

- **Clearly visible $X(3872)$ & $\psi(2S)$ signals to same final state**

In B-enriched data sample :

(non-prompt part, i.e., from B decays: $\ell_{xy} = \frac{L_{xy} \cdot m_{PDG}}{|\vec{p}_T|} > 0.1$ mm
it is produced outside the QGP)

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

first evidence of inclusive $X(3872)$ production in HI collisions [statistical significance **~4.2σ]**

- **To gain more insights we need to quantify the prompt $X(3872)$ to $\psi(2S)$ ratio** (next slide)

$$R = \frac{N^X_{corr}}{N^\psi_{corr}} \quad , \quad N^i_{corr} = \frac{N^i_{raw} \cdot f^i_{prompt}}{(\alpha \cdot \varepsilon_{tot})^i}$$

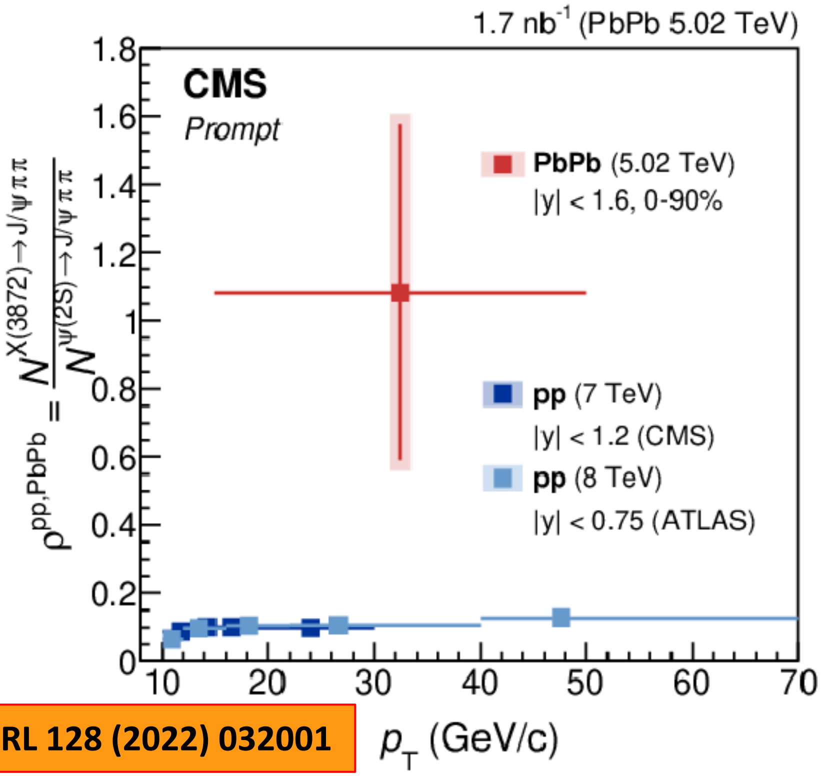
$$1 - \frac{N_{B-enr}/f^{non-prompt}_{B-enr}}{N_{incl}}$$

[see backup]

Ratio of corrected prompt $X(3872)$ & $\psi(2S)$ yields

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

$$R = \frac{N^X_{corr}}{N^{\psi(2S)}_{corr}}$$



PRL 128 (2022) 032001

Note: stat.err.=bars & syst.err.=boxes (not added!)

$R(PbPb) = 1.08 \pm 0.49(stat.) \pm 0.52(syst.)$

… to be compared with …

$R(pp) \sim 0.1$ (both ATLAS & CMS)

- The ratio measurement is affected by several sources of sizeable systematic uncertainty
- More statistic is needed to get a conclusive result

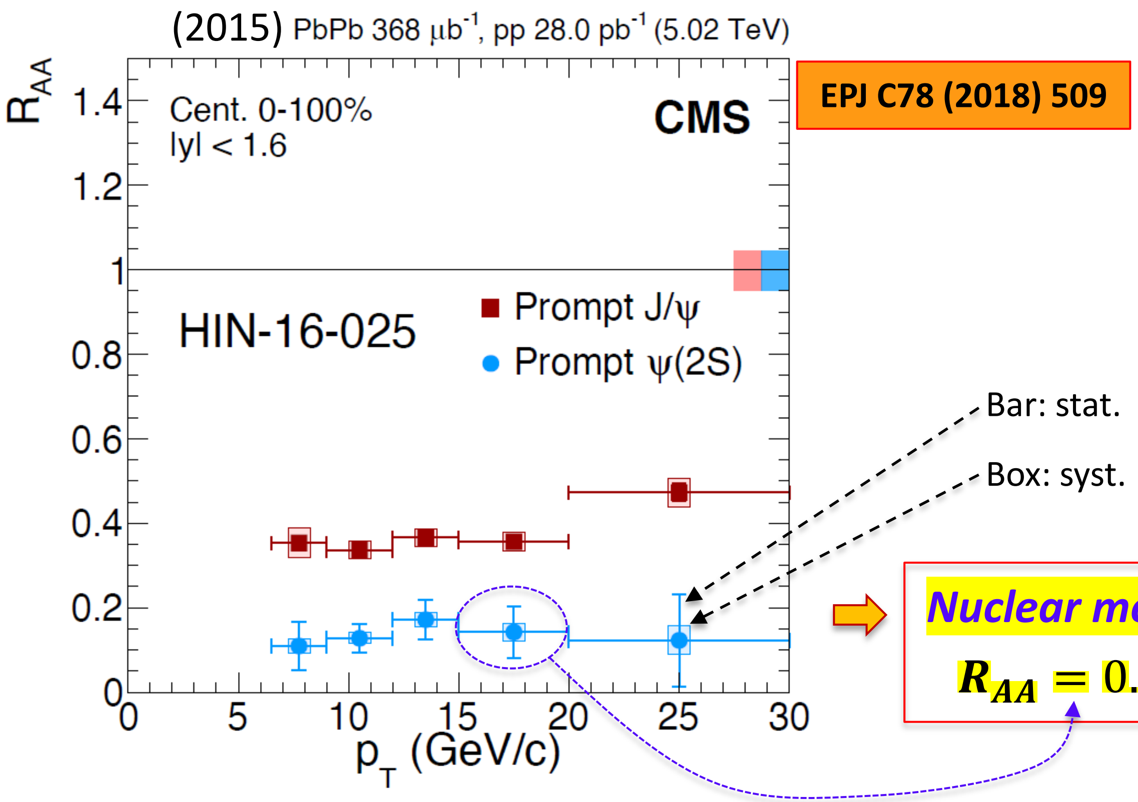
S-wave Charmonia nuclear modification factors in PbPb

- This ratio measurement - considered alone - may hint that …

… the $X(3872)$ is less suppressed than $\psi(2S)$.

While we have no idea about the *nuclear modification factor* of the $X(3872)$,

CMS has already reported a significant suppression of $\psi(2S)$ in PbPb collisions :



EPJ C78 (2018) 509

***Nuclear modification factor* of prompt $\psi(2S)$:**

$$R_{AA} = 0.142 \pm 0.061(stat.) \pm 0.020(syst.)$$

Plans for prompt X(3872) in HI

- For the observation of inclusive X(3872) production: the expected integrated luminosity of PbPb in Run-3 is 4-5nb^{-1} (was 6nb^{-1} originally but 2022 PbPb Run was cancelled); a stat. significance > **6σ** is expected.

- For the $\mathbf{X-to-\psi(2S)}$ ratio, $\boldsymbol{R(PbPb)}$, for X(3872) prompt production, the statistical uncertainty can be suppressed by a factor ~1.5 and the systematics can be improved since the largest uncertainty comes from the difference between data and MC (by weighting MC to data).
Nevertheless, the enhancement cannot be enough to clearly separate $\boldsymbol{R(PbPb)}$ from $\boldsymbol{R(pp)}$.

- For this reason, we are thinking to move to different observables that do not use $\boldsymbol{\psi}$(2S) as a reference; not only $\boldsymbol{\psi}$(2S) is suppressed in PbPb but it is also not well modelled by theories.

  One possibility could be to measure the Nuclear Modification Factor (R_{AA}) of the X(3872),
  Namely the ratio between the yields in PbPb and pp.
  It might be hard using a low-PU reference pp dataset, …
  … but it might be also possible to extrapolate to 5TeV from 7TeV, 13TeV and 14TeV.

  For R_{AA} of X(3872) the uncertainty from branching ratio is cancelled out,
  thus facilitating the comparison to theoretical calculations.

Observation of new structures in the $J/\psi\, J/\psi$ mass spectrum $(T_{cc\bar{c}\bar{c}} \rightarrow J/\psi\, J/\psi \rightarrow 4\mu)$

CMS-PAS-BPH-21-003 $\sqrt{s} = 13 TeV$ $\mathcal{L} = 135 fb^{-1}$

(Run-II)

https://cds.cern.ch/record/2815336/files/BPH-21-003-pas.pdf (PAS)

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-003/index.html (Preliminary Plots)

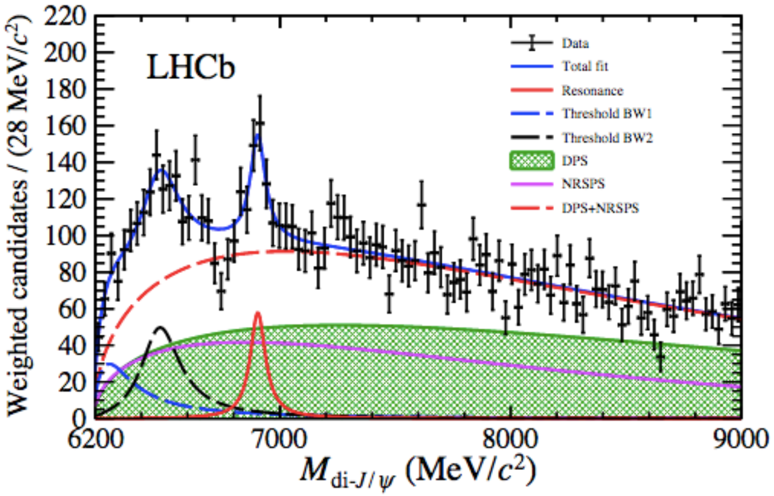
For comparison: Science Bulletin 65 (2020) 1983

https://cds.cern.ch/record/2815676/files/ATLAS-CONF-2022-040.pdf **ATLAS-CONF-2022-040**

LHCb models for the $J/\psi\, J/\psi$ mass spectrum

- In 2020 LHCb observed a peak in the $J/\psi\, J/\psi$ **mass spectrum, the $X(6900)$**, which was considered with great interest as a **possible *all-charm tetraquark*** **(**even if also alternative interpretations have been advocated**).** LHCb **reported two alternative fit models:**

- **Model-I :**



3 B.-W.s: - 1 for the signal peak $X(6900)$

- other 2 auxiliary "threshold" B.-W.s for the initial raise and first "bump"

NRSPS+DPS shapes for the background

- **Model-II :**

LHCb models for the fit of $J/\psi J/\psi$ mass spectrum

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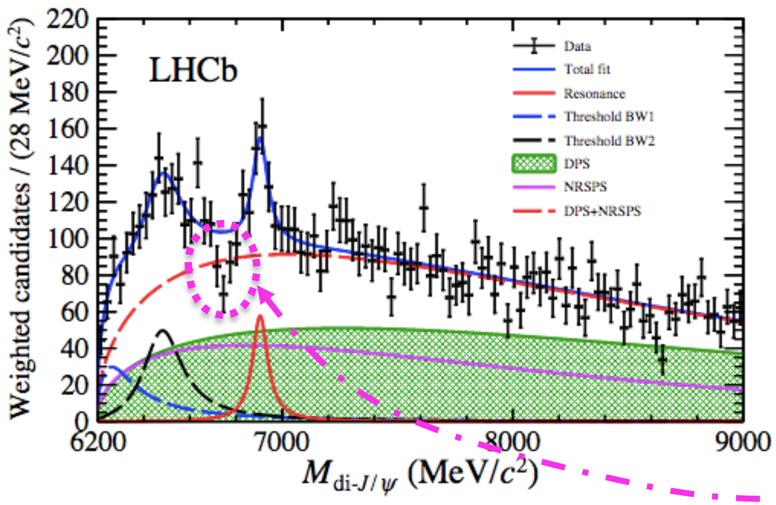

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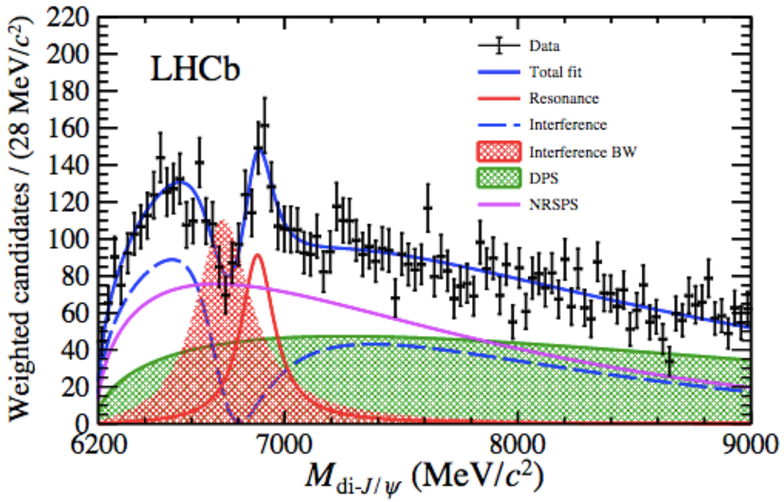


It poorly describes the dip, suggesting to try a destructive interference of a "virtual" B.-W. with the NRSPS bkg. component, while getting rid of the "threshold B.-W.s".

Masses & **natural widths** for the $X(6900)$ result to be compatible in the two models. LHCb is agnostic on which one is to prefer.

CMS baseline model to fit the $J/\psi\, J/\psi$ mass spectrum - I

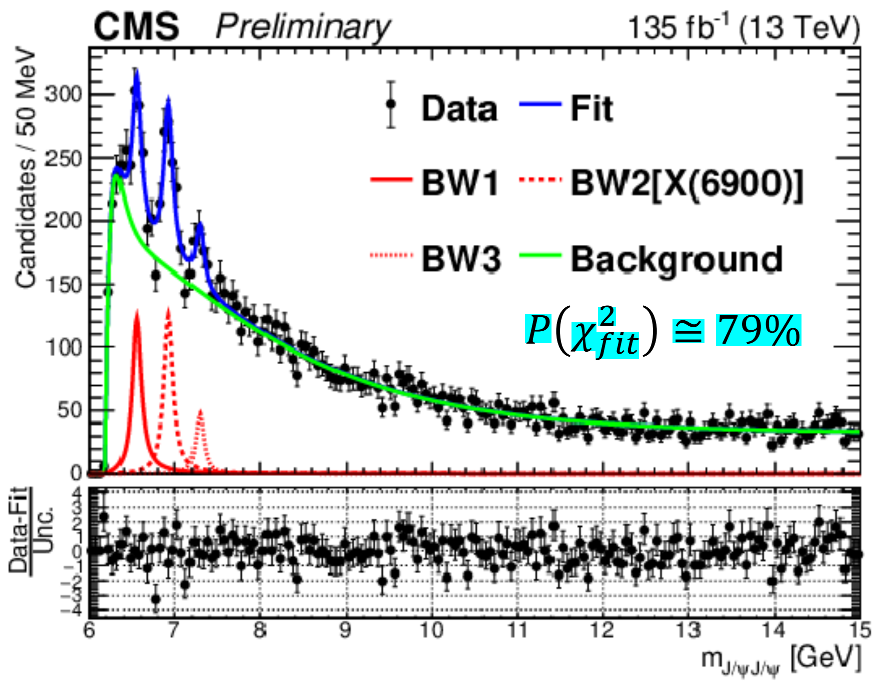
After **event selection** (4μs in final state; see backup) a **baseline model** to fit the **di-J/ψ** spectrum is built with a **minimal** number of potential structures **added to the null-hypothesis** (bkg-only) by adding - @ each subsequent step - the *most prominent* structure & keeping it in the baseline… if local statistical significance $> 3\sigma$ (standard likelihood ratio method). This is repeated until no more structures can be added.

The specific followed sequence is:

1) Initial null-hypothesis model : **NRSPS + NRDPS**

- from Pythia8 distributions, parametrized by:

$$\text{SPS: } threshold\ func. * poly2 * exponential$$
$$\text{DPS: } sqrt * poly2 * exponential$$



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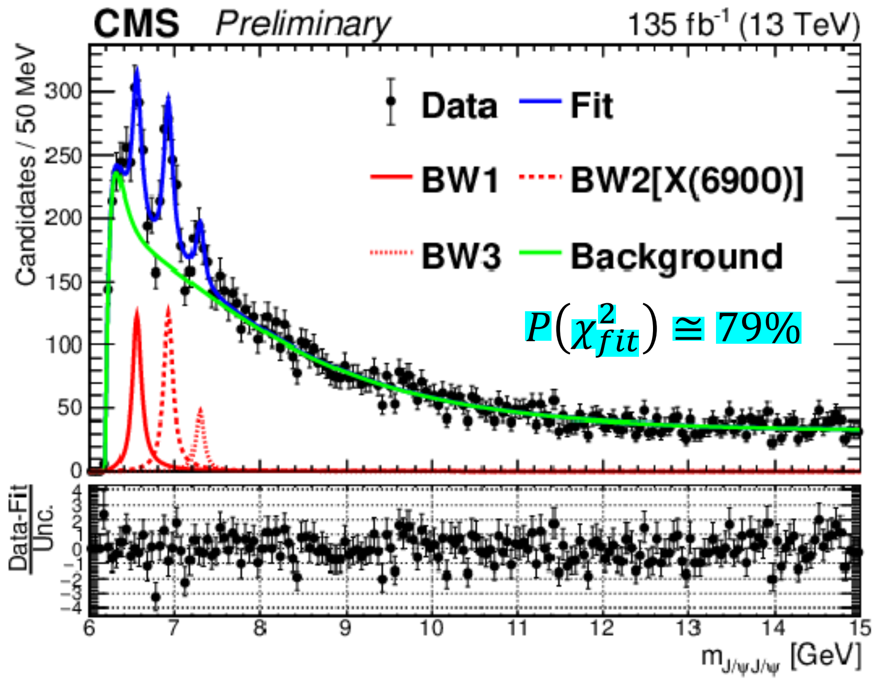
$$\text{SPS: } threshold\ func. * poly2 * exponential$$
$$\text{DPS: } sqrt * poly2 * exponential$$

2) Add the most significant structure (@ threshold) modelled empirically (*ad hoc*) by a B.-W. and consider it as part of the background (**BW0**) since:

- this region is populated by feed-down from possible higher mass states (checked @MC)
- this region could be affected by possible coupled-channel interactions, final state rescattering, etc …
- the NRSPS model shaped via a unique floating parameter: it turns out to be inadequate to shape the threshold region



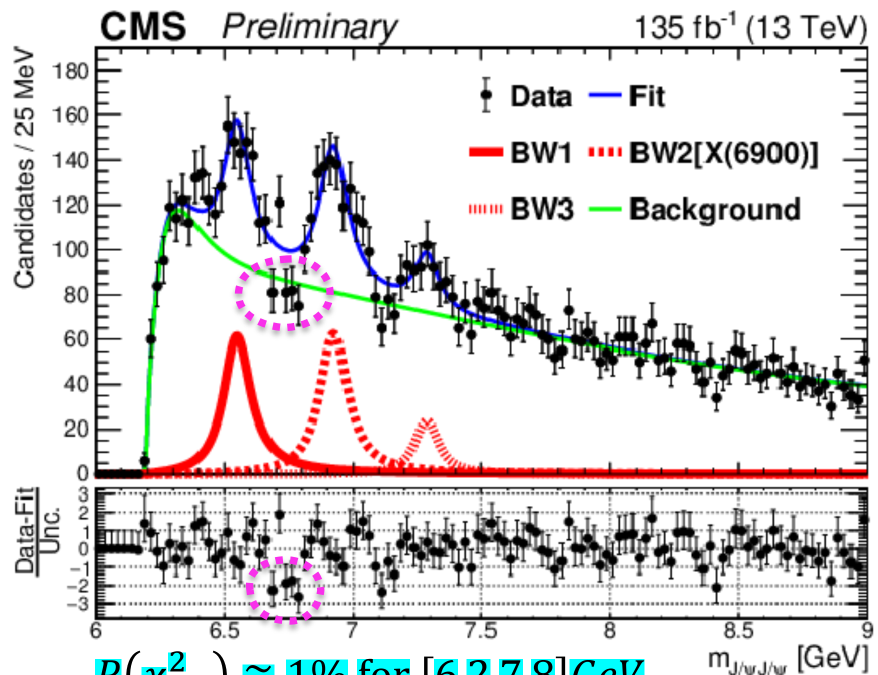
Bkg-hypothesis model : **BW0 + NRSPS + NRDPS**

Note: BW0 parameters very sensitive to the additional part of the model

CMS baseline model to fit the $J/\psi J/\psi$ mass spectrum - II

Now, we model structures beyond bkg-hypothesis by using relativistic B.-W. functions (with $\mathrm{L} = 0$) …

- convolved with double-Gaussian resolution functions
- <u>not</u> modified by acceptance & trigger/selection efficiencies
  (varying very slowly in the search region: consider as systematics)



$P(\chi^2_{fit}) \cong 1\%$ for $[6.2, 7.8]\, GeV$

3) Add B.-W. @ $\approx 6900 MeV$:

BW2 ($> \mathbf{9.4\sigma}$) ⇨ **CONFIRMATION of $X(6900)$**

4) Add B.-W. @ $\approx 6550 MeV$: **BW1** ($> \mathbf{6.5\sigma}$)

⇨ **OBSERVATION of $X(6600)$**

5) Add B.-W. @ $\approx 7300 MeV$: **BW3** ($> \mathbf{4.1\sigma}$) ⇨ **EVIDENCE for $X(7300)$**

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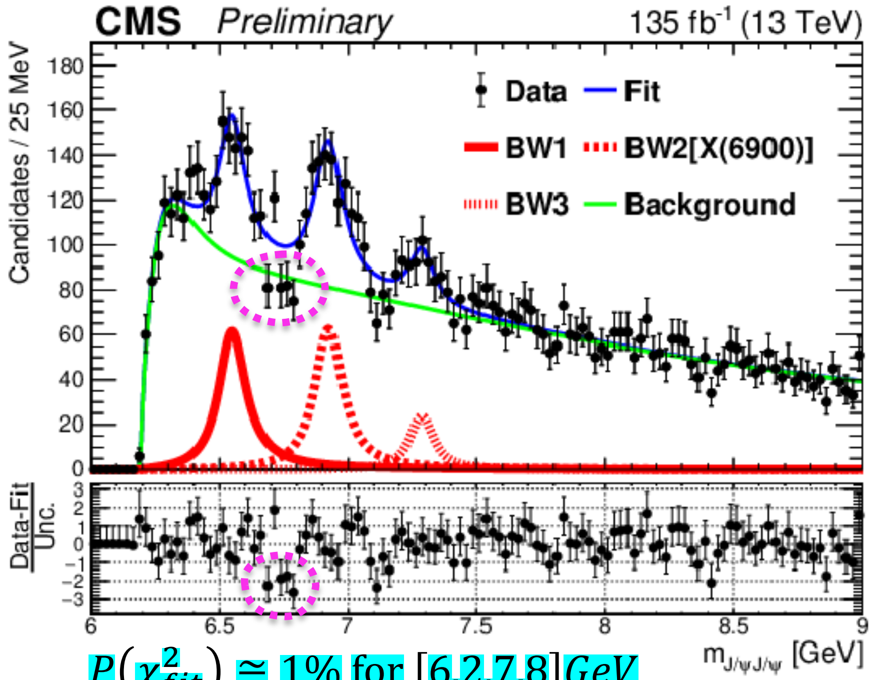

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⇨ **OBSERVATION of $X(6600)$**

5) Add B.-W. @ $\approx 7300 MeV$: **BW3** ($> 4.1\sigma$) ⇨ **EVIDENCE for $X(7300)$**

Fit results including also the systematic uncertainties:

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

Table 2: Systematic uncertainties on masses and widths, in MeV.

Source	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta\Gamma_{BW1}$	$\Delta\Gamma_{BW2}$	$\Delta\Gamma_{BW3}$
signal shape	3	4	3	14	7	7
NRDPS	1	<1	<1	3	3	4
NRSPS	3	1	1	18	15	17
momentum scaling	1	3	4	-	-	-
mass resolution	<1	<1	<1	<1	<1	1
combinatorial background	<1	<1	<1	2	3	3
efficiency	<1	<1	<1	1	<1	1
feeddown shape	11	1	1	25	8	6
total	12	5	5	34	19	20

(CASCADE, HELAC-ONIA)

(Pythia8, JHUGen)

Agreement with LHCb (Model-I / non-interf.)

$m(6900)$	$\Gamma(6900)$
$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$

Application of LHCb fit models to the $J/\psi J/\psi$ mass spectrum - I

- **CMS baseline fit provides** $X(6900)$ parameters **in agreement** with **LHCb non-interference fit (Model-I)**.

In order to remove potential model-dependencies in a comparison between results, …
we also apply - to our data - the two LHCb main models, but using CMS-specific background shapes.
(NRSPS + NRDPS)

Compare with Model-I :

- Apply 2 auxiliary B.-W.s + $X(6900)$ + CMS Bkg. model

Note: 1) CMS data show a ***shoulder*** that helps make BW1 more distinct

2) the main dip remains undescribed as well as the dip/peak $\approx 7.2-7.3GeV$

- Overall g.o.f : 2) the dip remains undescribed

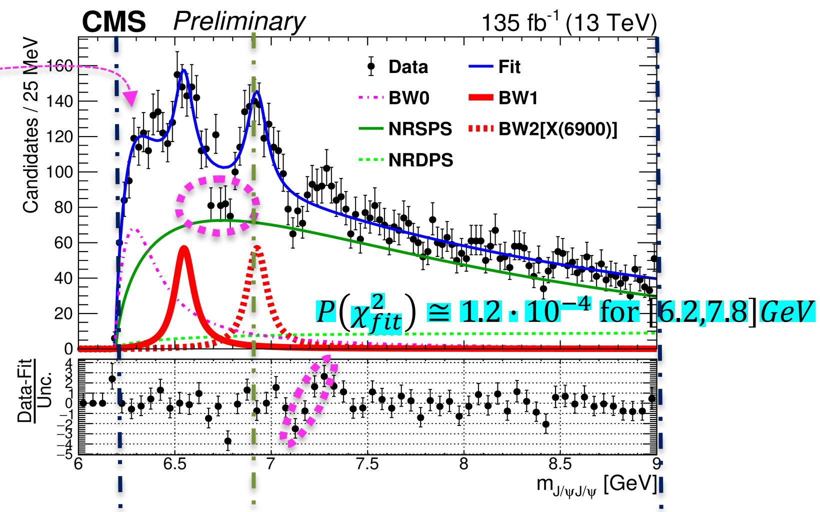
$P(\chi^2_{fit}) \cong 0.51$ for $[6.2,15]GeV$

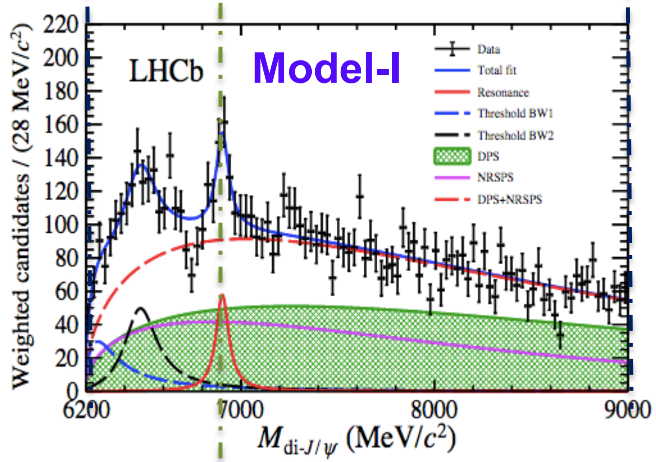
$P(\chi^2_{fit}) \cong 1.2 \cdot 10^{-4}$ for $[6.2,7.8]GeV$

⇨ **worse fit than CMS baseline fit model**

- $X(6900)$ parameters still in good agreement :

Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24



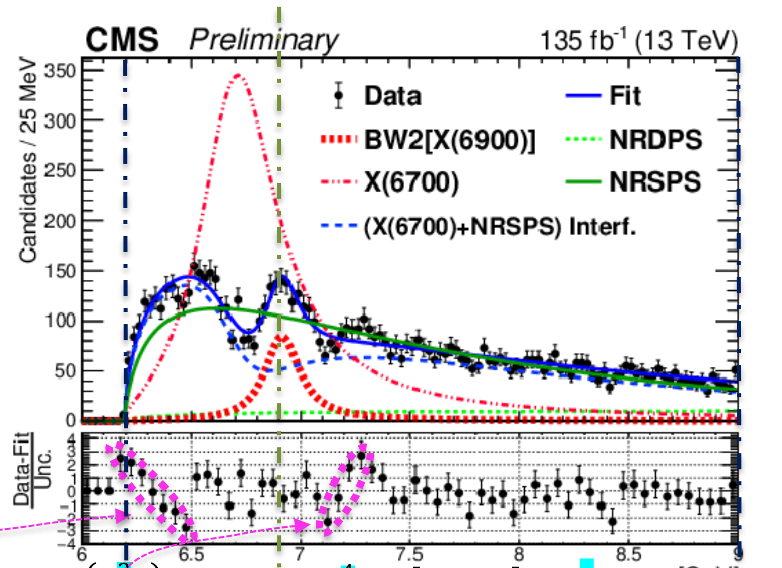


Compare with Model-II :

- Apply an **interference** between a **"virtual"** $X(6700)$ & CMS NRSPS + $X(6900)$ + CMS NRDPS

$(439 \pm 65)MeV$!

Note: 1) CMS data show **larger** amplitude & width for $X(6700)$
2) CMS's $X(6600)$ is "eaten" by this interference



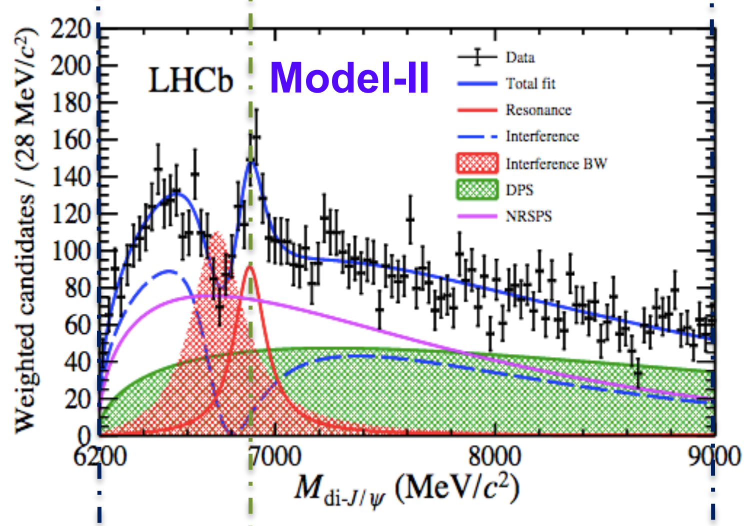
$P(\chi^2_{fit}) \cong 0.84 \cdot 10^{-4}$ for $[6.2, 7.8]\,GeV$

- Overall g.o.f : the fit remains poor:

$$P(\chi^2_{fit}) \cong 0.84 \cdot 10^{-4} \text{ for } [6.2, 7.8]\,GeV$$

⇨ **worse fit than CMS baseline fit model**

⇨ **worse fit than LHCb fit Model- I**
(region $\approx 6550\,MeV$ poorly described; same for $\approx 7200\,MeV$)
[unlike Model-II that better describes LHCb data]



- $X(6900)$ parameters still consistent :

[$X(6700) \equiv BW1$]

Exp.	Fit	m(BW1)	Γ(BW1)	$m(6900)$	$\Gamma(6900)$
LHCb	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

Find the comparison with ATLAS **di-J/ψ** spectrum in the backup!

CMS preliminary result on $J/\psi\, J/\psi$ spectrum & work-in-progress

- CMS di-J/ψ spectrum hints a possible rich pattern of 3 structures (candidates to be all-charm tetraquarks):

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
St.Sig. (systematic effects included)	$> 5.7\sigma$	$> 9.4\sigma$	$> 4.1\sigma$
	OBSERVATION of $X(6600)$	CONFIRMATION of $X(6900)$	EVIDENCE for $X(7300)$

... under the assumption of no interference between signal components and between signal & background

- All CMS fits presented are not very good/satisfactory and ...
  ... **other interference scenarios/models are currently under study to describe the dip(s)** (that hint possible interference effects). This is mandatory to have out a paper.
  The near-threshold region needs also to be better understood (more data may be needed).

- The measurement of the production Xsections (in a fiducial region) is in our plans as well.

- CMS has good sensitivity to all-muon final states (see also the **triple-J/ψ** result), thus it is worthy to explore $J/\psi\, \psi(2S)$ and **di-$\psi(2S)$** spectra. [NATURE Physics 304 (2023) 1]
  Run-3 will be certainly useful to afford more or enough statistics.

Perspectives & Plans

- Run-3 (2022-25) has started - the plan is to approx. double the statistics collected in first 2 Runs.
  - Rethought tracking/vertexing needs - especially @ low p_T - for the mini-AOD data format (AOD will be only on tape)
  - Refined/improved trigger strategy for B-Physics and Quarkonia (in Run-3 harsher experimental conditions)
  - The data that are going to be collected in Run-3 can certainly help to achieve very interesting new and updated results, integrating and/or complementing LHCb results (pp) and ALICE (HI collisions), … … in spite of huge backgrounds, trigger constraints, particle identification limitations.

  By the way … the physics potentiality of data already collected (Run-2) is far from being fully explored (currently several analyses are still ongoing).

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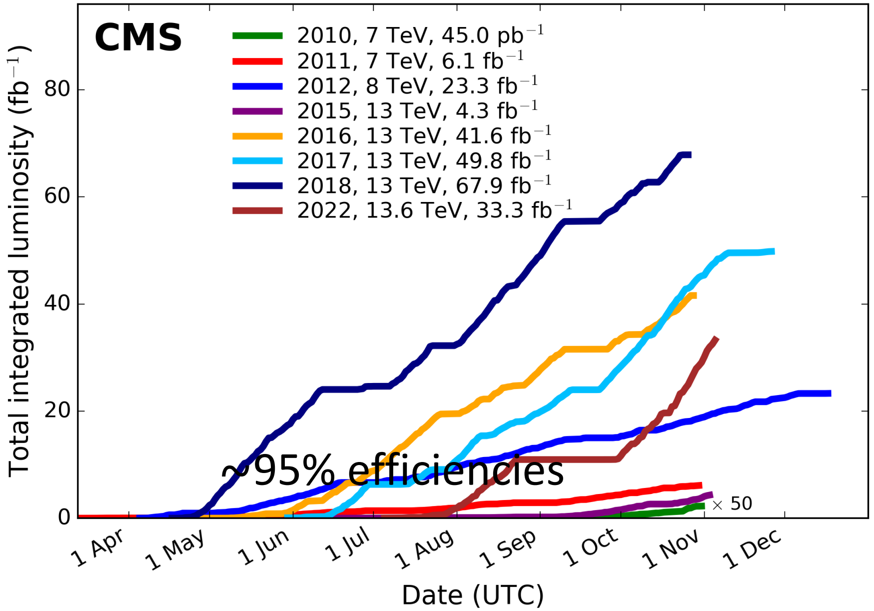
  By the way … the physics potentiality of data already collected (Run-2) is far from being fully explored (currently several analyses are still ongoing).

- Analysis efforts will be oriented where the specific strengths of the CMS detector and reconstruction algorithms make us competitive, both in exotics searches and in the extraction of signals of rare spectroscopic transitions.
  - Double-charmonia(bottomonia) measurements & searches can be carried out at the same(better) sensitivity compared to LHCb, thanks to **large muons' acceptance**.
  - Radiative spectroscopic transitions thanks to **precise photon conversions.**
  - Beauty hadrons rare decays (observations, Branching Fractions) thanks to the **good efficiency for low-p_T tracks**, both **prompt** and **displaced** from the Primary Vertex; especially exploting **signatures with K_S^0, Λ^0 and ϕ reconstructed mesons** to fight the overwhelming backgrounds due to huge track multiplicity.
  - QCD exotics in **HI collisions** (X(3872), …), hardly doable at ALICE.

Backup & additional material

Run-1 & -2 + Run-3 data taking

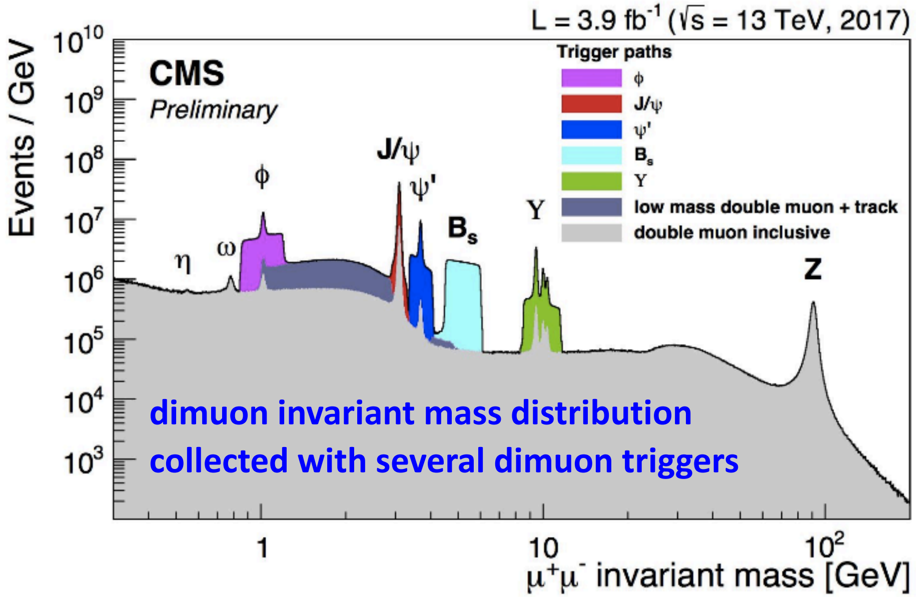
- The LHC Run-II was characterized by excellent LHC & CMS performances :

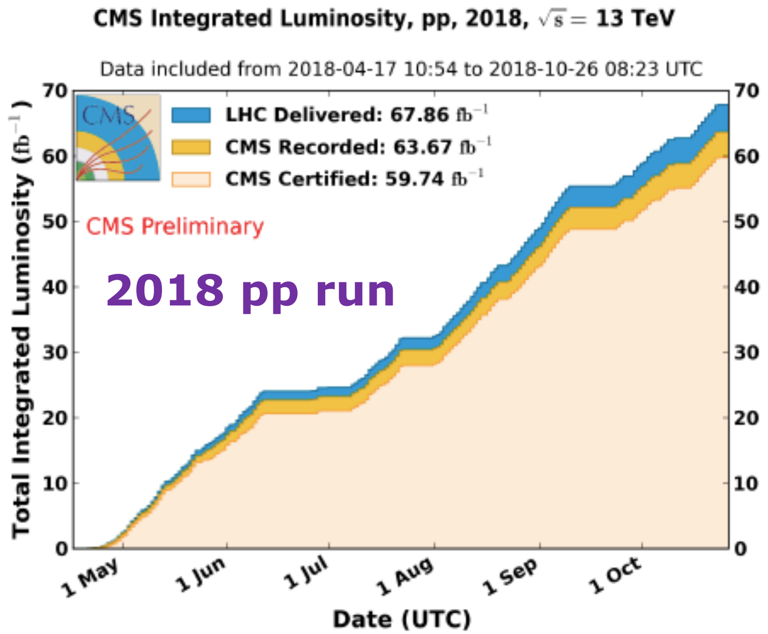


Data samples

	$L_{int} \approx$
Run-I	
$\sqrt{s} = 7TeV$ 2011	**5**
$\sqrt{s} = 8TeV$ 2012	**20**
Run-II	
$\sqrt{s} = 13TeV$ 2015	**4**
2016	**38**
2017	**45**
2018	**60**

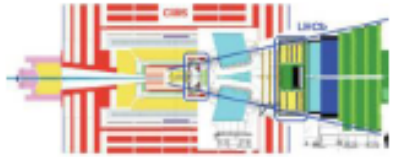
Used for the results discussed here





X(3872) @ CMS : prompt production Xsection

Exploiting the previous measurements, the ***prompt production xsection*** for the *X(3872)* is measured as a function of p_T @ central rapidities (complementary to LHCb):



$$\sigma^{\text{prompt}}_{X(3872)} \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{1-f^B_{X(3872)}}{1-f^B_{\psi(2S)}} \cdot R \cdot \left(\sigma^{\text{prompt}}_{\psi(2S)} \cdot \mathcal{B}(\psi(2S)\to\mu^+\mu^-)\right) \cdot \frac{\mathcal{B}(\psi(2S)\to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S)\to\mu^+\mu^-)}$$

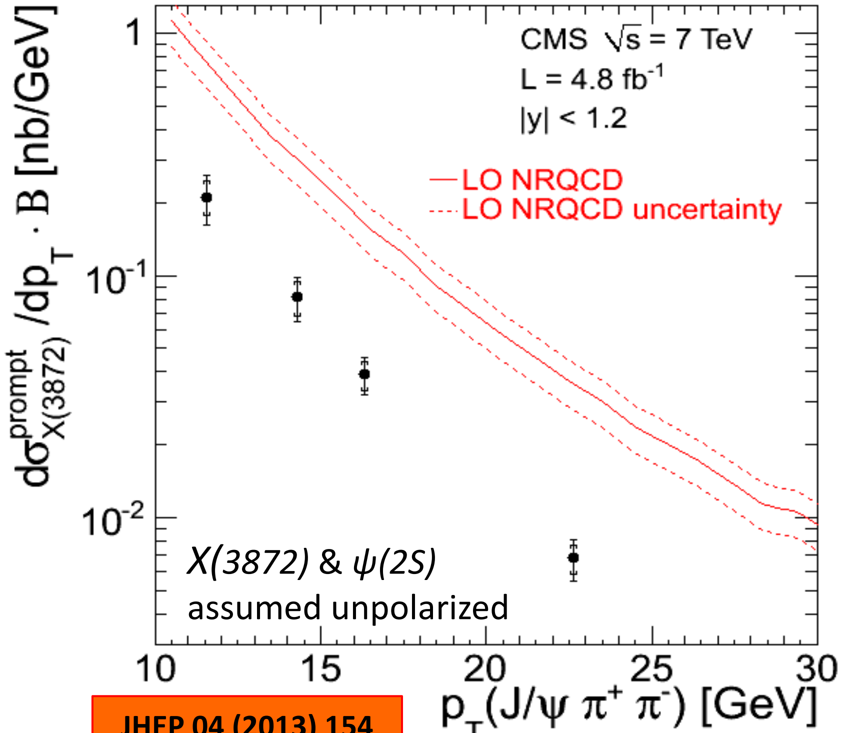
non-prompt fraction

Cross sections ratio

measured by CMS in JHEP02 (2012) 011

from PDG

$$R \equiv \frac{\sigma(pp\to X(3872)+\text{anything})\cdot B(X(3872)\to J/\psi\pi^+\pi^-)}{\sigma(pp\to\psi(2S)+\text{anything})\cdot B(\psi(2S)\to J/\psi\pi^+\pi^-)} = \frac{N_{X(3872)}\cdot A_{\psi(2S)}\cdot\varepsilon_{\psi(2S)}}{N_{\psi(2S)}\cdot A_{X(3872)}\cdot\varepsilon_{X(3872)}}$$



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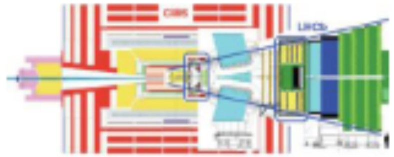
- Results are compared with a theoretical prediction based on **NRQCD factorization @ LO approach by Artoisenet & Brateen** [PhysRevD.81.114018] with calculations normalized using Tevatron results, modified by the authors to match CMS phase-space
- The shape is reasonably well described by the theory while the predicted cross section is overestimated by over 3σ ![the same happens with LHCb data @ low p_T]
- Integrating over p_T (10-30*GeV*) [and |y|<1.2] get the integrated cross section times the branching fraction:

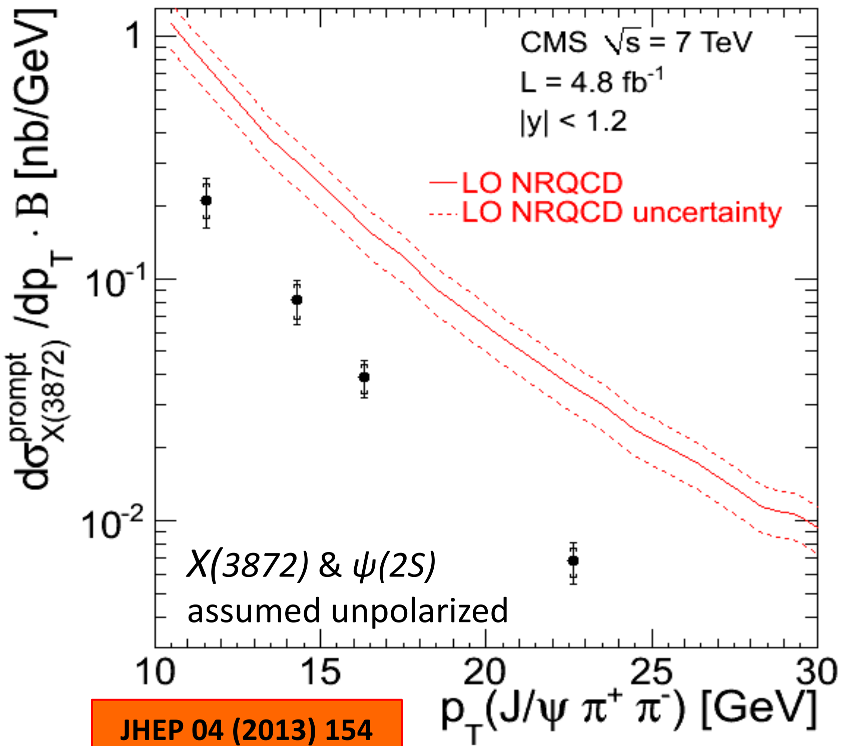
$$\sigma^{prompt}_{X(3872)} \times B\left(X(3872) \to J/\psi\ \pi^+\pi^-\right) \cong (1.06 \pm 0.11 \pm 0.15) nb$$



- Exploiting the previous measurements, the ***prompt production xsection*** for the *X(3872)* is measured as a function of p_T @ central rapidities (complementary to LHCb):

$$\sigma^{\text{prompt}}_{X(3872)} \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{1 - f^B_{X(3872)}}{1 - f^B_{\psi(2S)}} \cdot R \cdot \left(\sigma^{\text{prompt}}_{\psi(2S)} \cdot \mathcal{B}(\psi(2S) \to \mu^+\mu^-)\right) \cdot \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$$

non-prompt fraction | Cross sections ratio | measured by CMS in JHEP02 (2012) 011 | from PDG



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- Predictions by Artoisenet & Brateen assume, within an S-wave molecular model, the relative momentum of the mesons being bound by an upper limit of 400*MeV* which is quite high for a loosely bound molecule, but they assume it is possible as a result of rescattering effects.

- On the other hand, an upper limit lower of one order of magnitude would imply lower prompt production rates of few orders of magnitude **[Bignamini et al., PRL 103 32009) 162001]**

X(3872) : experimental results & interpretations

- **One crucial aspect is the possibility to discriminate experimentally between …**
  compact multiquark configuration ($c\bar{c}u\bar{u}$) & loosely bound hadronic molecule (by proximity to $D\bar{D}^{0*}$ threshold)

[conventional charmonium ($\chi_{c1}(2P)$ for $J^{PC}=1^{++}$) has been ruled out by the mass value & the fact should be a pure isoscalar state]

- ***X(3872)* would be a large and fragile molecule with a miniscule binding energy (~100 *KeV*)**

$$E_{binding}^{X(3872)} \cong m(D^0 D^{*0}) - m(X) = 2m(D^0) + \Delta m(D^{*0} - D^0) - m(X) = (0.09 \pm 0.28) MeV$$

… that leads to a radius of ~*10 fm* (~5 times as large as the deuteron) !

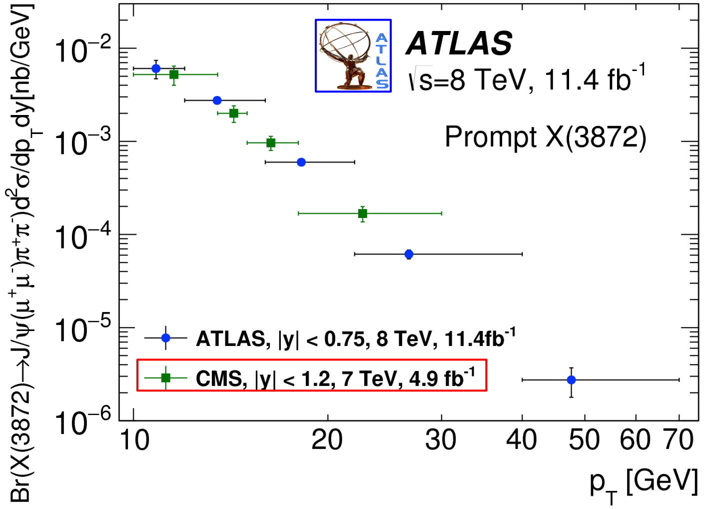
- **The previous CMS measurement is not supporting an S-wave molecular interpretation**
- **Pure molecular model** (Swanson *et al.*) **not supported by the LHCb measurement of the radiative $X(3872) \to \psi(2S)\gamma$ sub-decay in the $B^+ \to X(3872)K^+$ decays**
- **Significant *L* would hint a molecular structure; however …**
  ***D*-wave fraction in $X(3872) \to J/\psi\ \rho^0$, for $J^{PC}=1^{++}$, results to be consistent with 0 [LHCb PRD 92 (2015) 011102]**

- Alternatively, to the compact tetraquark option, a possible interpretation for the $X(3872)$ is a **mixture of a charmonium state $\chi_{c1}(2\,^3P_1)$ & an S-wave molecule $\bar{D}^0 D^{*0}$.**

- **Results on $X(3872)$ production from ATLAS** have been compared with the latter model [next slide]

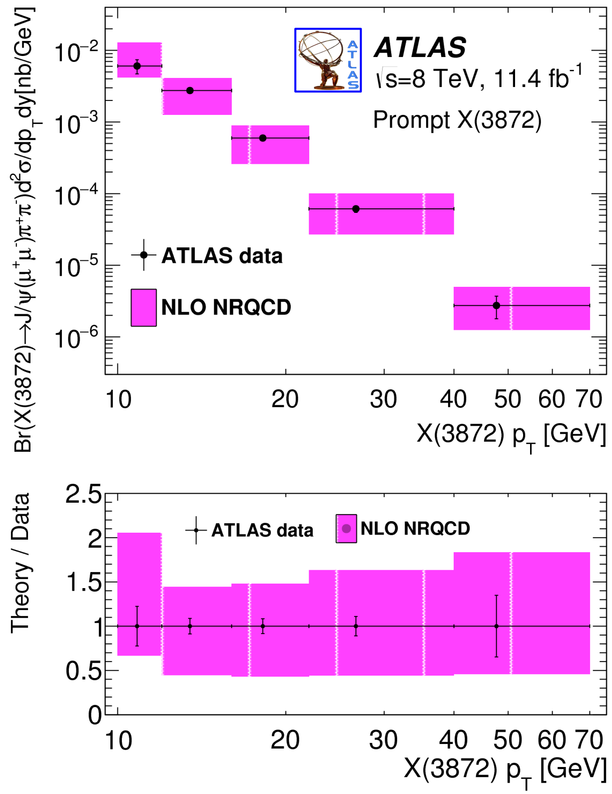
Comparison with a mixed molecule-charmonium state

- **Comparison of ATLAS with CMS results shows consistency.**
  Beware that:
  - ATLAS points positioned @ the mean p_T of the weighted signal events
  - CMS points positioned @ the mean p_T of the theoretical predictions



- **Measured prompt production xsection (times BFs), as a function of p_T, is compared to NLO NRQCD predictions assuming the** $X(3872)$ **modelled as a mixture of** $\chi_{c1}(2P)$ **& a** $\bar{D}^0 D^{*0}$ **molecular state** by Meng *et al.* [PRD96 (2017) 074014].

The first would play crucial role in the short-distance production, while the second would be mainly in charge of the hadronic decays of $X(3872)$ into $DD\pi$, $DD\gamma$ as well as $J/\psi\,\rho$, $J/\psi\,\omega$.

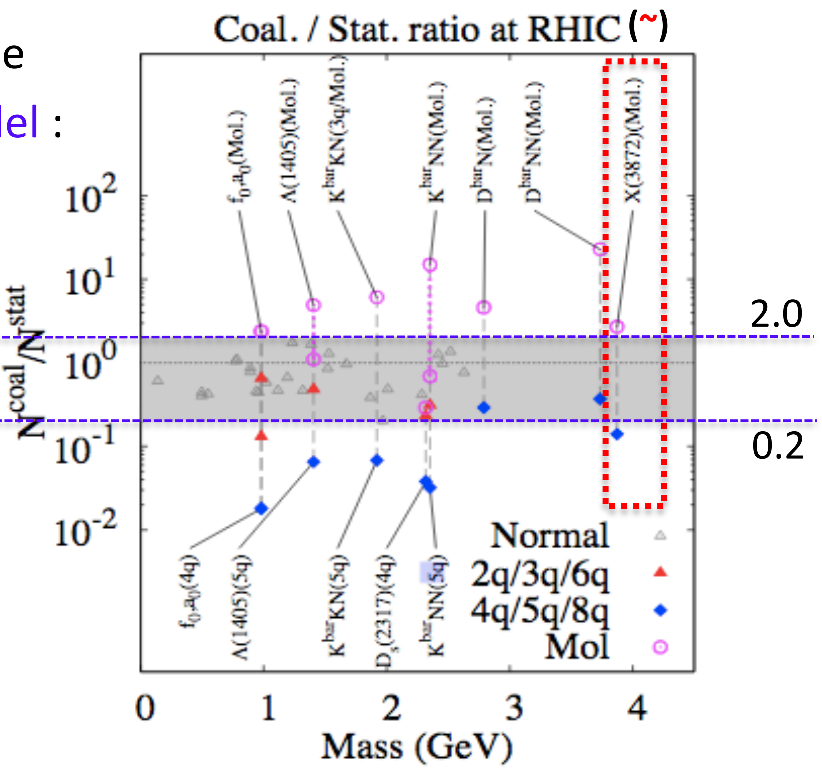


Can we learn more about X(3872) nature using HI collisions?

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

$$\frac{N_{COAL}}{N_{STAT}}$$

Range of ratios for normal hadrons (2quarks/3quarks) & for crypto-exotic hadrons with usual 2q/3q configs



The yield of a hadron in relativistic HI collisions reflects its structure !

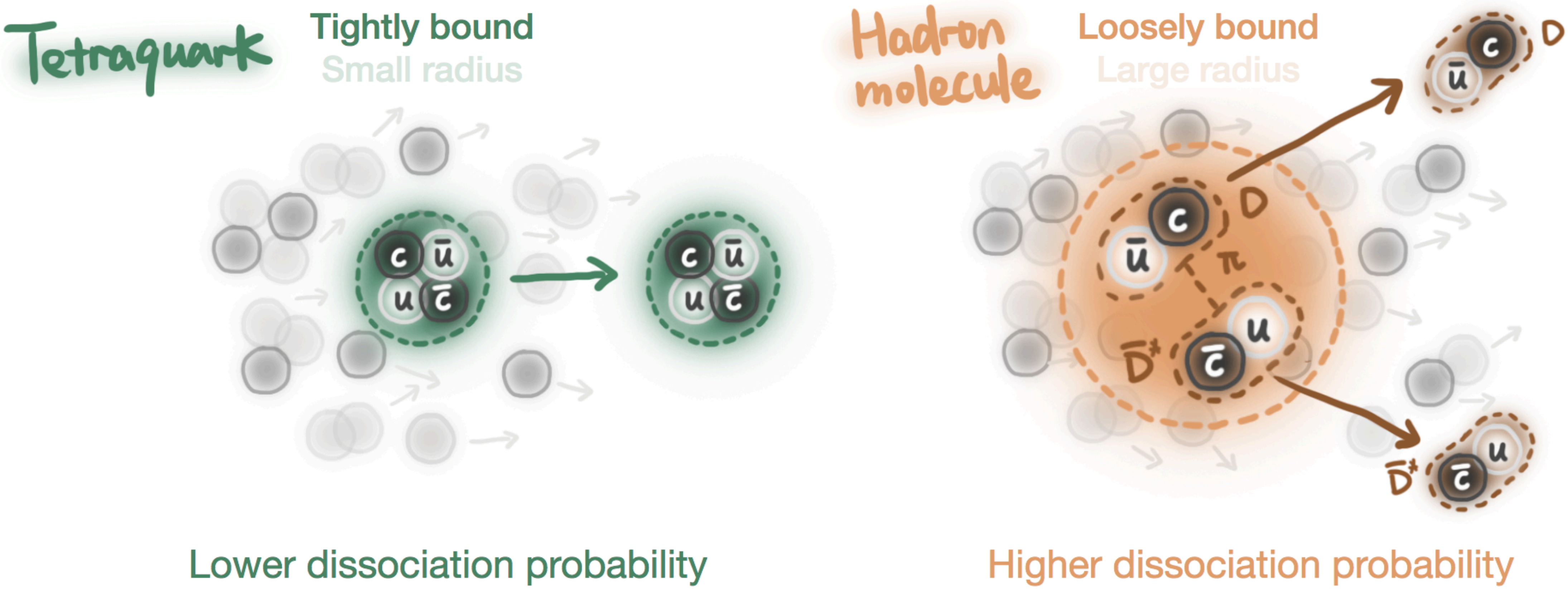
(~) Note: Also holds for LHC: freezout conditions similar to those @RHIC

How an X(3872) behaves in a high color density environment?

Depends on its nature....

- Breakup by comoving particles ➜ Suppress X(3872)

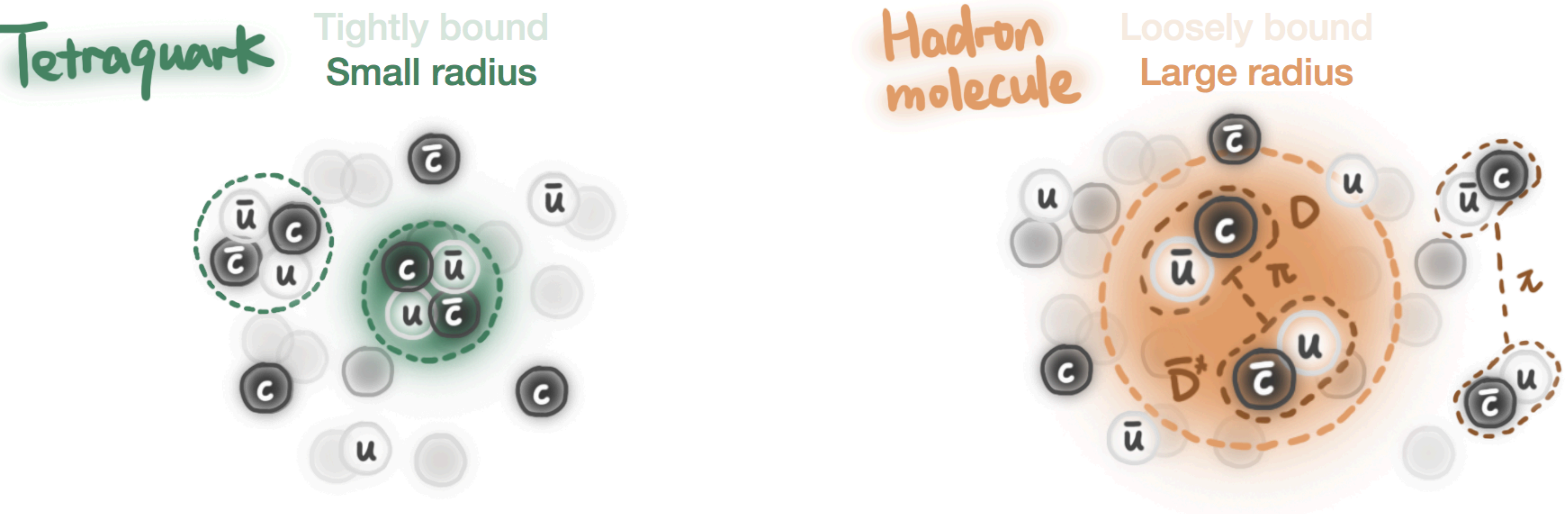
➡ Reflect the nature of X(3872)



How an X(3872) behaves in a high color density environment?

Depends on its nature….

- Breakup by comoving particles ➜ Suppress X(3872)
- Coalescence with diffusing particles ➜ Enhance X(3872)

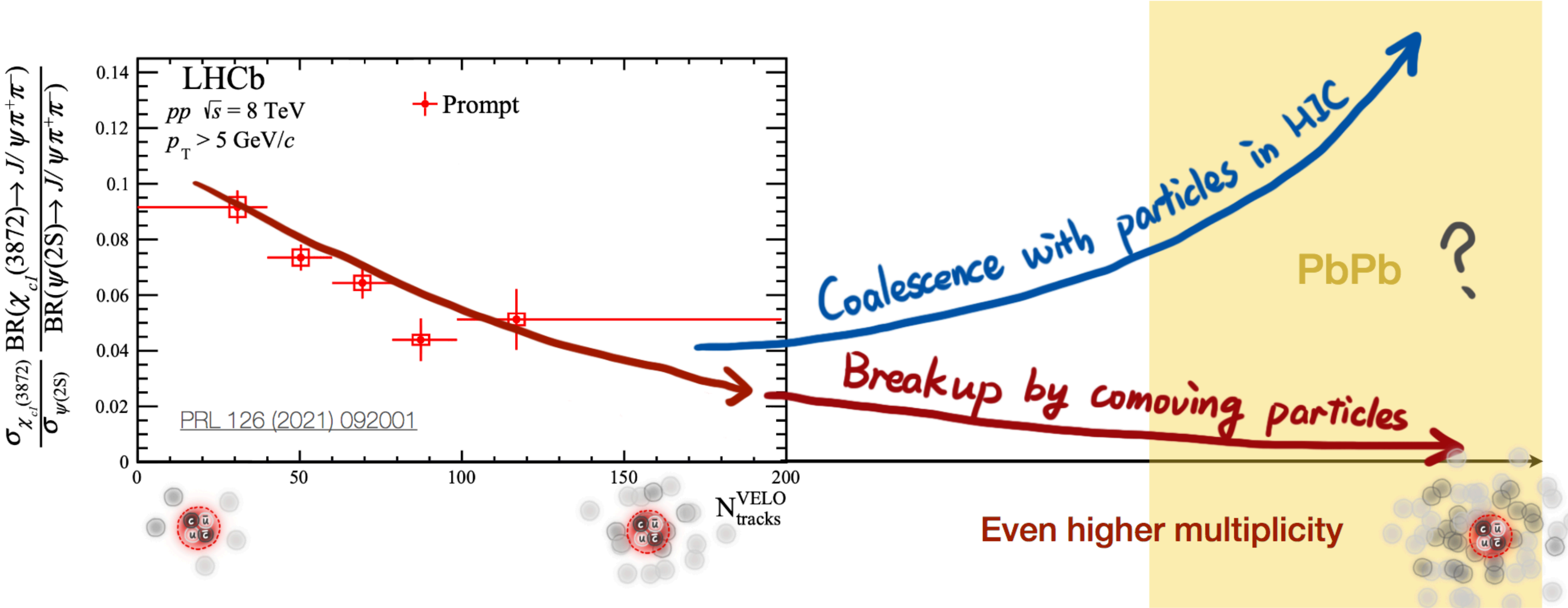


Coalescence probability depends on X(3872) inner structure and particle distribution

How an X(3872) behaves in a high color density environment?

Depends on its nature....

- Breakup by comoving particles ➜ Suppress X(3872)
- Coalescence with diffusing particles ➜ Enhance X(3872)

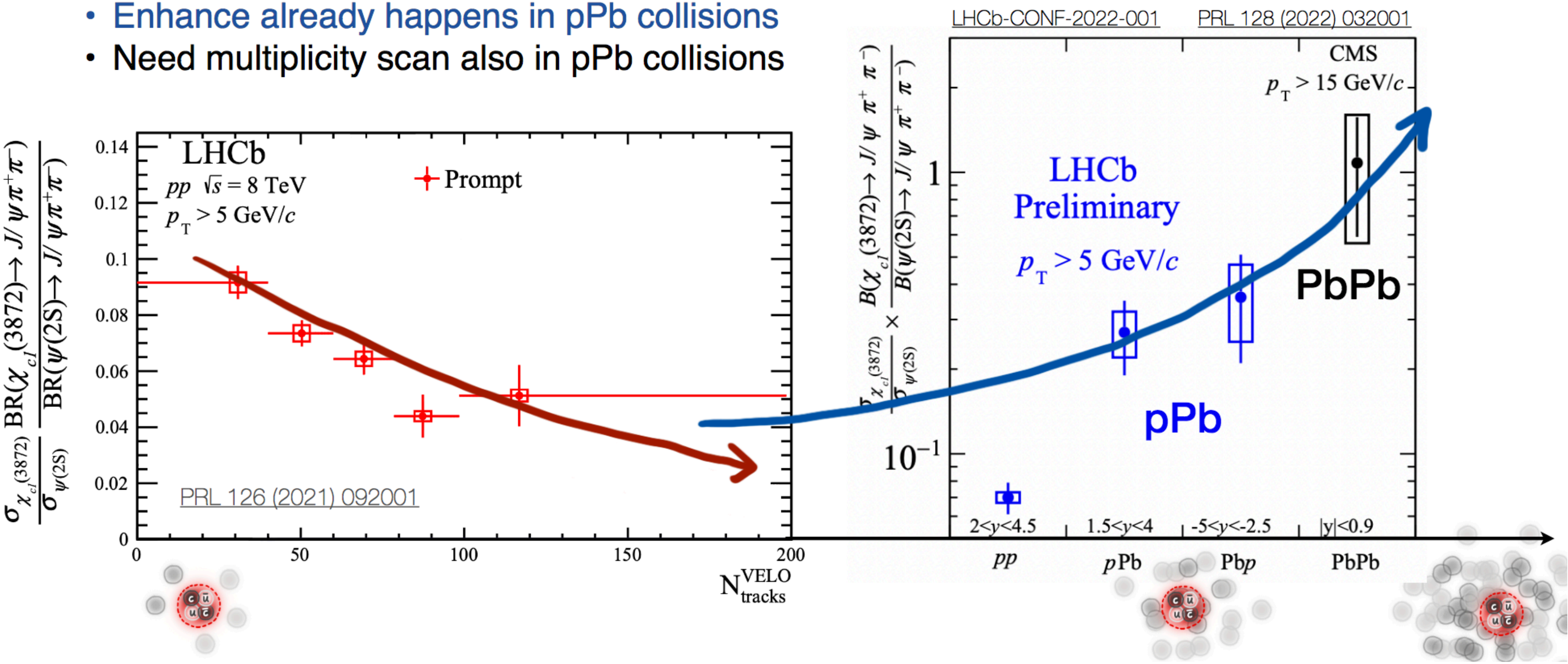


(courtesy of CMS colleague J.Wang)

How an X(3872) behaves in a high color density environment?

Depends on its nature….

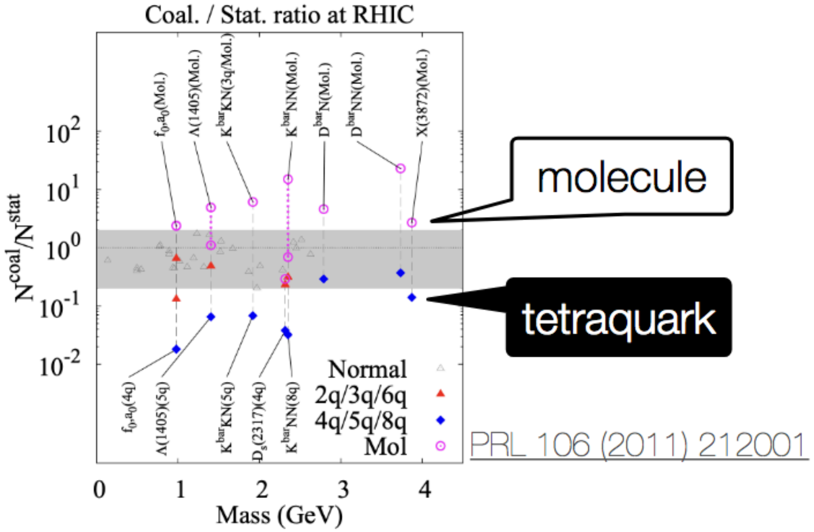
- Enhance already happens in pPb collisions
- Need multiplicity scan also in pPb collisions

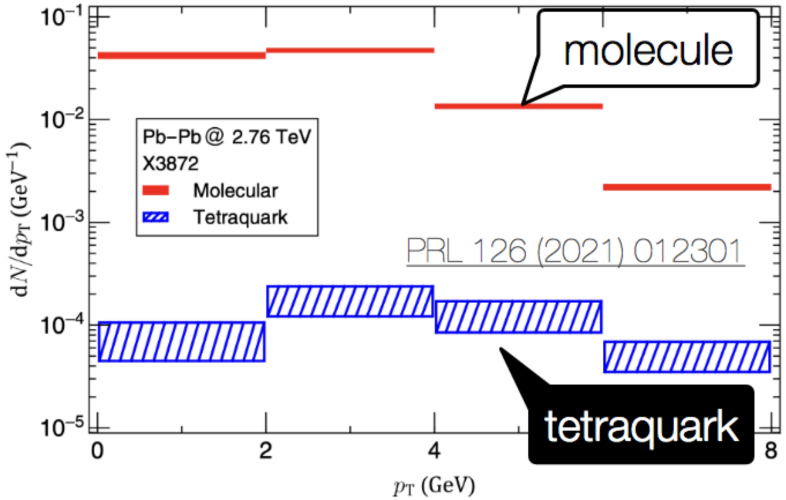


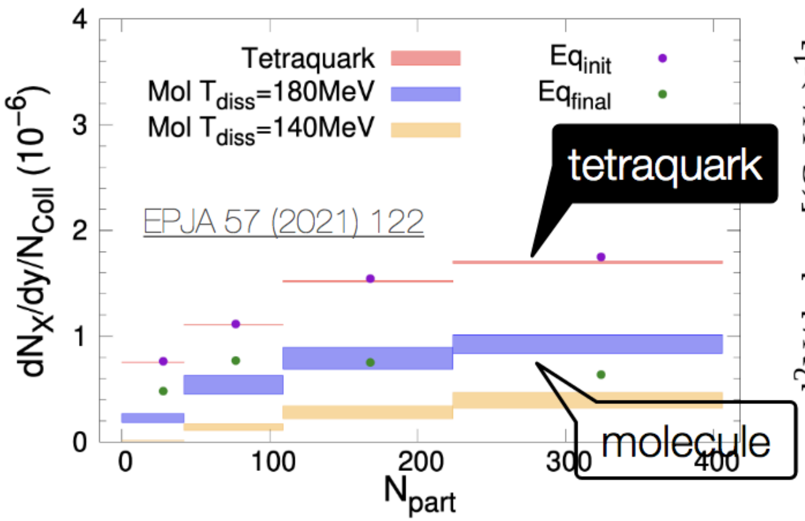
(courtesy of CMS colleague J.Wang)

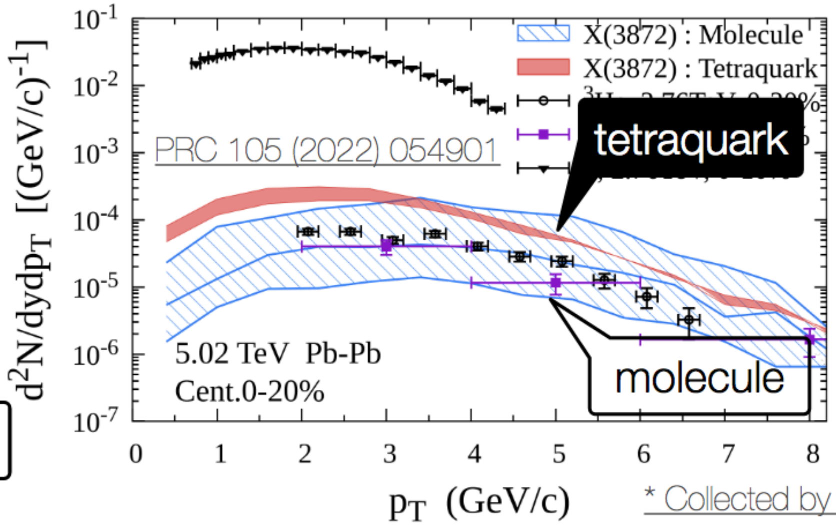
How an X(3872) behaves in a high color density environment?

What the theory says?









* Collected by J. Zhao

- Many theoretical efforts!
- Divergence in theoretical calculations
- Different recombination and dissociation implementation

(courtesy of CMS colleague J.Wang)

Corrected prompt X(3872) & $\psi(2S)$ yields

- The ratio of corrected yields of prompt X(3872) to prompt $\psi(2S)$ is defined as: $R = \frac{N_{corr}^{X}}{N_{corr}^{\psi}}$ $\psi(2S)$

  - prompt yields are corrected for efficiency and acceptance from ...

    ... a PYTHIA MC embedded in HYDJET PbPb background

$$N_{corr}^{i} = \frac{N_{raw}^{i} \cdot f_{prompt}^{i}}{(\alpha \cdot \varepsilon_{tot})^{i}}$$

  - prompt fractions are calculated from the # of candidates of the inclusive signal (from nominal fit) and # of candidates in the B-enriched sample (from the fit to the signal after applying $\ell_{xy} > 0.1mm$):

$$f_{prompt}^{(i)} = 1 - \frac{N_{B-enr} / f_{B-enr}^{non-prompt}}{N_{incl}}$$

with the latter to be corrected for the non-prompt candidates with $\ell_{xy} < 0.1mm$:

$$f_{B-enr}^{non-prompt} = \frac{N^{non-prompt}(\ell_{xy} < 0.1mm)}{N^{non-prompt}}$$ (obtained from MC)

CMS selection of $J/\psi\, J/\psi$ candidates - I

Trigger requirements

	2016	2017-18
L1	at least 3 μ	at least 3 μ
		leading μ : $p_T > 5.0 GeV$; sub-leading μ : $p_T > 3.0 GeV$ (*)
		at least one pair of OS μs : $m < 9.0 GeV$
HLT	each μ : $\lvert\eta(\mu)\rvert < 2.5$; at least one pair of OS μs : $2.95 < m < 3.25 GeV$, $P(\mathrm{vtx}) > 0.5\%$	each μ : $\lvert\eta(\mu)\rvert < 2.5$; at least one pair of OS μs : $2.95 < m < 3.25 GeV$, $P(\mathrm{vtx}) > 0.5\%$
		each μ forming the "triggering" pair (J/ψ) : $p_T(\mu) > 3.5 GeV$

Offline selection

2016	2017-18
HLT bit fired	HLT bit fired
each μ : SOFT-ID, $p_T(\mu) > 2.0 GeV$, $\lvert\eta(\mu)\rvert < 2.4$	each μ : SOFT-ID, $p_T(\mu) > 2.0 GeV$, $\lvert\eta(\mu)\rvert < 2.4$
$J/\psi\, J/\psi$ candidates are built (can be more than 1/event): for each J/ψ : $2.95 < m < 3.25 GeV$, $P(\mathrm{vtx}) > 0.5\%$, kin−fit : $P(J/\psi) > 0.1\%$, $p_T(J/\psi) > 3.5 GeV$	$J/\psi\, J/\psi$ candidates are built (can be more than 1/event): for each J/ψ : $2.95 < m < 3.25 GeV$, $P(\mathrm{vtx}) > 0.5\%$, kin−fit : $P(J/\psi) > 0.1\%$, $p_T(J/\psi) > 3.5 GeV$
4μ vertex fit : $P(4\mu - \mathrm{vtx}) > 0.5\%$, kinematic fit : $P(J/\psi\, J/\psi - \mathrm{fit}) > 0.1\%$	4μ vertex fit : $P(4\mu - \mathrm{vtx}) > 0.5\%$, kinematic fit : $P(J/\psi\, J/\psi - \mathrm{fit}) > 0.1\%$
	at least 2 OS μs (forming a J/ψ) : $p_T(\mu) > 3.5 GeV$
Best candidate selected if 2 $J/\psi\, J/\psi$ candidates are formed with the same 4μ (~ 0.2% of the cases); both conserved if they have at least 1 different μ (~ 0.2% of the cases)	Best candidate selected if 2 $J/\psi\, J/\psi$ candidates are formed with the same 4μ (~ 0.2% of the cases); both conserved if they have at least 1 different μ (~ 0.2% of the cases)

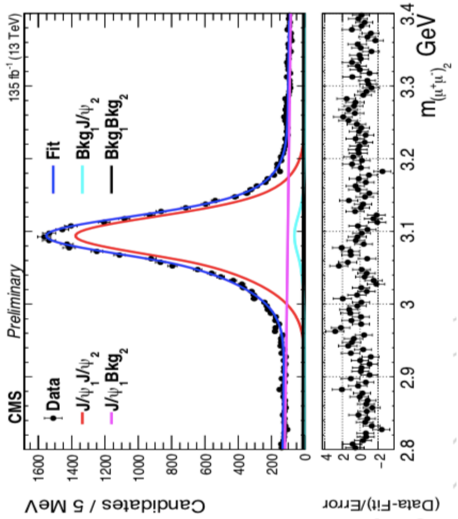
Overall kinematic phase-space selected: - for 2016: $p_T(\mu) > 2.0 GeV$, $\lvert\eta(\mu)\rvert < 2.4$, $p_T(J/\psi) > 3.5 GeV$

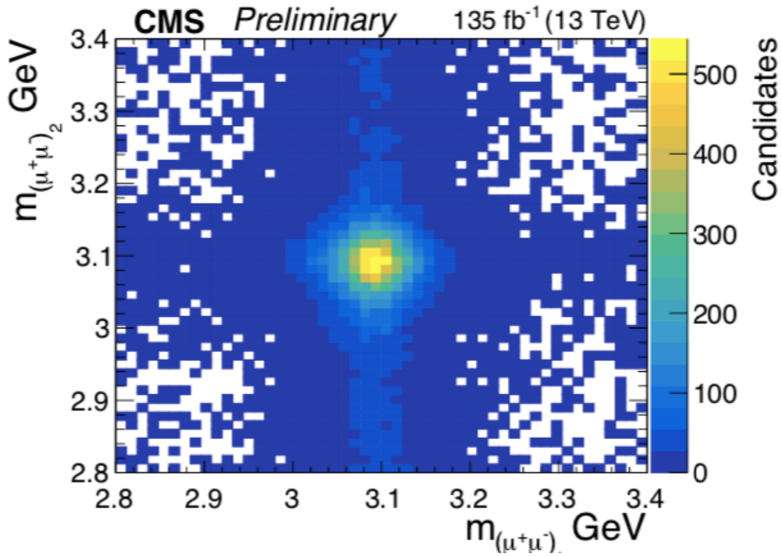
- for 2017-18: in addition: *at least* two OS μs with $p_T(\mu) > 3.5 GeV$

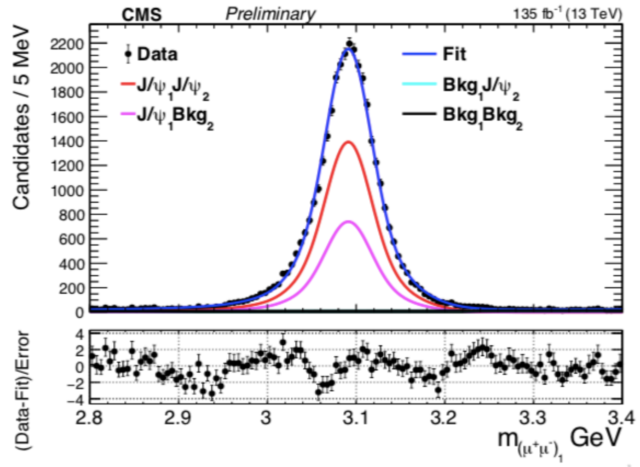
(*) These L1 requirements do not have relevant effect offline (on reconstructed efficiency and spectrum)

- The sample has $14{,}049$ ($8{,}651$) $J/\psi\, J/\psi$ signal pairs for $m(J/\psi\, J/\psi) < 15.0(9.0) GeV$.

  The 4-muons mass resolution ranges from $\sim 10 MeV$ (@ $6.5 GeV$) to $\sim 18 MeV$(@ $7.3 GeV$).







- The offline selection in the previous slide was determined in an unbiased and model independent way: selection criteria were fixed before looking at the data in the signal region $m(J/\psi\, J/\psi) < 7.8 GeV$ and relied also on loose requirements aligned with past experience in double-J/ψ analysis. This approach is possible thanks to the high purity of the J/ψ signal.

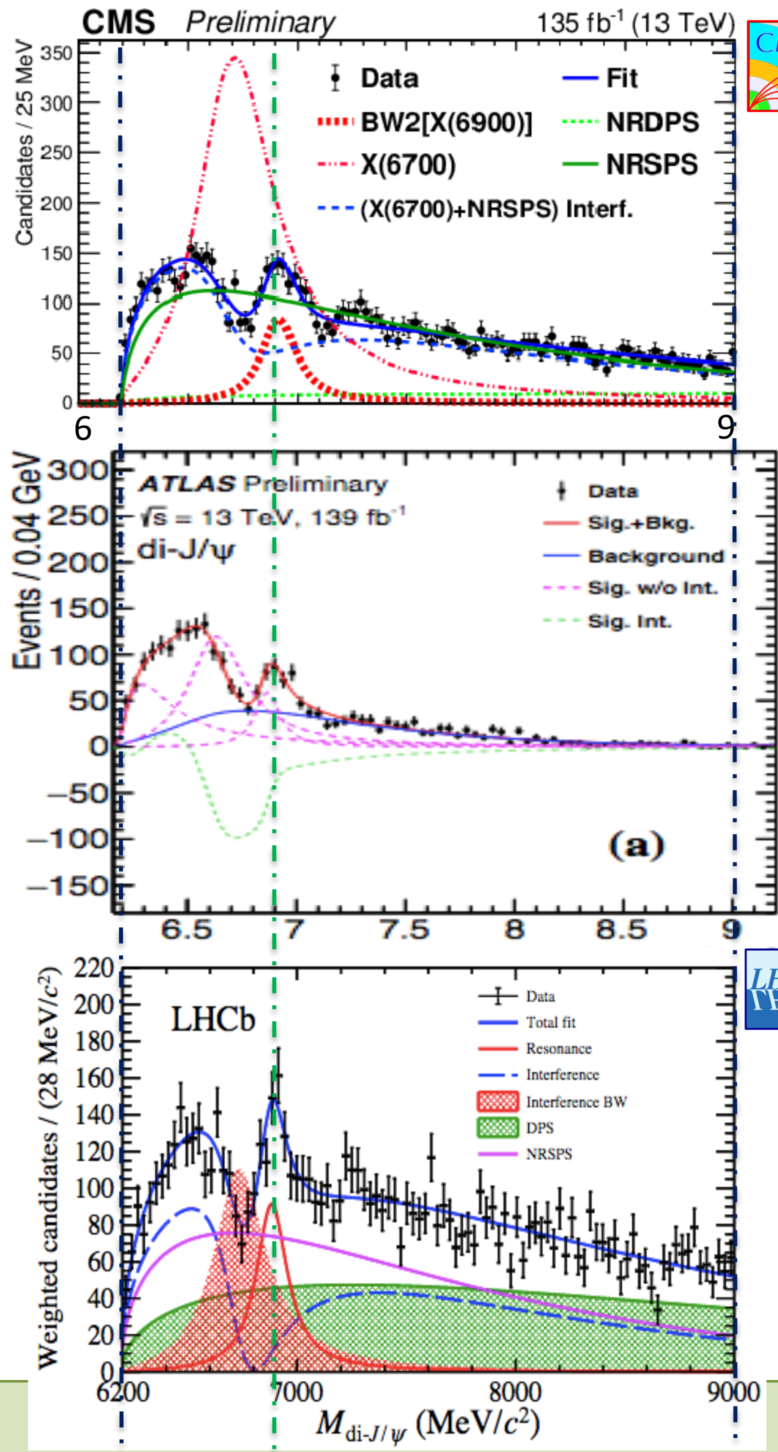
  As a cross-check, an optimization was afterwords performed by simulating a $9 GeV\ 0^+$ signal meson and using backgrounds from data, yielding to a selection very similar to the original one.

Comparison of interference fit results on $J/\psi\, J/\psi$ spectrum by ATLAS, CMS & LHCb

- ATLAS model considers 3 B.-W.s and their possible interference to describe the dip @ $\approx 6800 MeV$ together with the large initial shoulder. This interference is different from that in LHCb's Model-II, thus the shown comparison is not fully meaningful.

  Different binnings and vertical scales do not help the comparison of the data points.

- Note: CMS & LHCb seem to have a similar number of $X(6900)$ candidates. Evidently there is a compensation among different major factors:
  - integrated luminosity : 135/9 ~ **15X**
  - muon acceptance (pseudorapidity): $(5/3)^4$ ~ **8X**
  - muon kinematical cuts (reco efficiency): $p_T > 0.6 GeV$ (LHCb) vs. (CMS) $p_T > 3.5\ or\ 2.0 GeV$



LHCb Model-II

Model-II

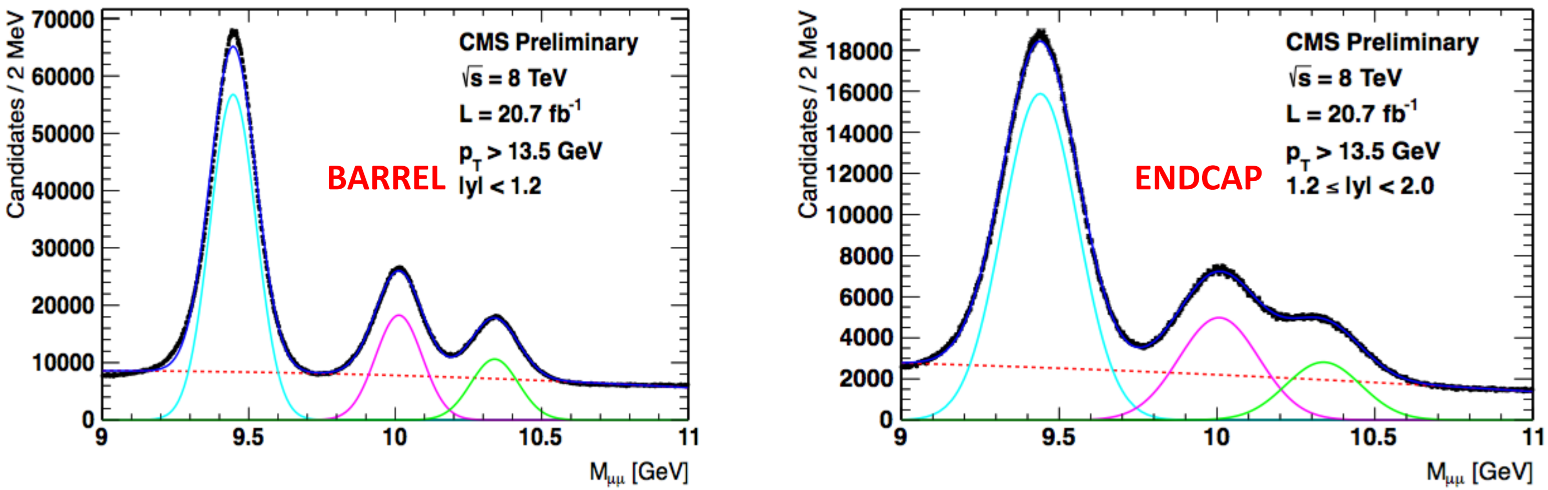
Search for X_b - I

- **Heavy Quark symmetry suggests an X_b as 'bottomonium counterpart' of $X(3872)$.**
  Molecular model suggests to search close to $B\overline{B}^{(*)}$ threshold ($m \cong 10.562(604) GeV$);
  [model dependent prediction for a $B\overline{B}^{(*)}$ molecule by Swanson (2004)**]**

  looked for $X_b \to \Upsilon(1S)\,\pi^+\pi^-$ decay seemingly analogous to $X(3872) \to J/\psi\,\pi^+\pi^-$

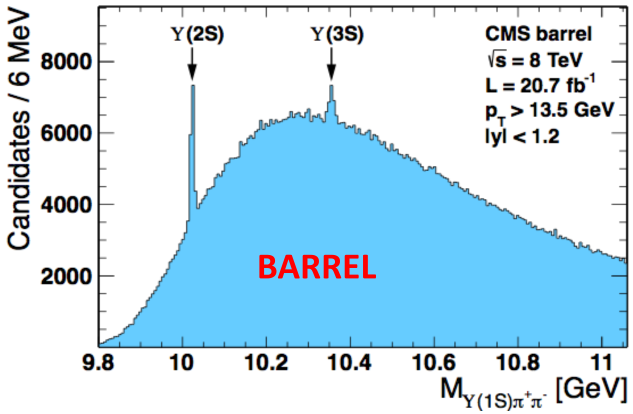
- **Analysis strategy:** search for a peak - other than known $\Upsilon(2S), \Upsilon(2S)$ - in the $\Upsilon(1S)\,\pi^+\pi^-$ spectrum within 10-11GeV
  [expecting **narrow width** & possibly **sizable BF** similarly to X(3872)]

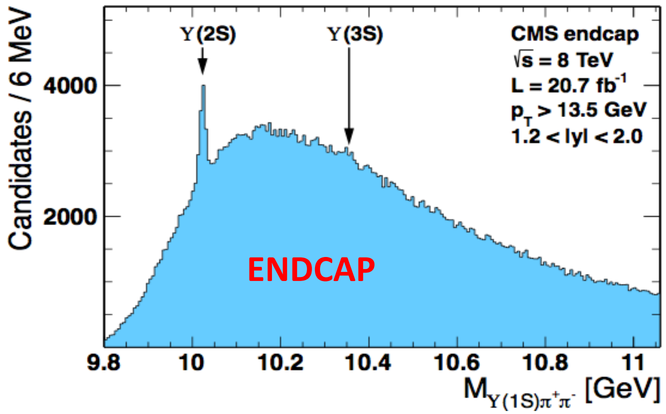
- **collected (pp@$8TeV$) large sample of $\Upsilon(nS) \to \mu^+\mu^-$ [better mass resolution and lower bkg in the barrel]:**



Search for X_b - II

- X_b cands are reconstructed by associating two oppositely selected charged tracks to the $\Upsilon(1S)$ cand.; the $\Upsilon(1S)\ \pi^+\pi^-$ spectrum is studied in the kinematic region $p_T > 13.5 GeV,\ |y| < 2.0$:





- Selection criteria optimized by using a genetic algorithm that maximized the expected significance of the signal in the mass region near the $\Upsilon(2S)$.
  The statistical significance of the signal is expected to be $> 5\sigma$ if the following ratio that represents the X_b BF times the production Xsection relative to the $\Upsilon(2S)$ …

$$R \equiv \frac{\sigma\left(pp \to X_b\right)}{\sigma\left(pp \to \Upsilon(2S)\right)} \cdot \frac{BF\left(X_b \to \Upsilon(1S)\pi^+\pi^-\right)}{BF\left(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-\right)}$$

… is > 6.56% [analogous to that of X(3872) relative to the $\Upsilon(2S)$].

For each mass point of a mass scan (by 10*MeV*-sized steps), the mass spectrum is fitted (gaussian signal with width fixed to values from the simulation & 3rd order polynomial bkg**) and *R* is evaluated as ...**

observed YIELDS

$$R = \frac{N^{obs}_{X_b}}{N^{obs}_{\Upsilon(2S)}} \cdot \frac{\varepsilon_{\Upsilon(2S)}}{\varepsilon_{X_b}}$$

overall EFFICIENCIES estimated from SIMULATION

Assumptions in simulation:

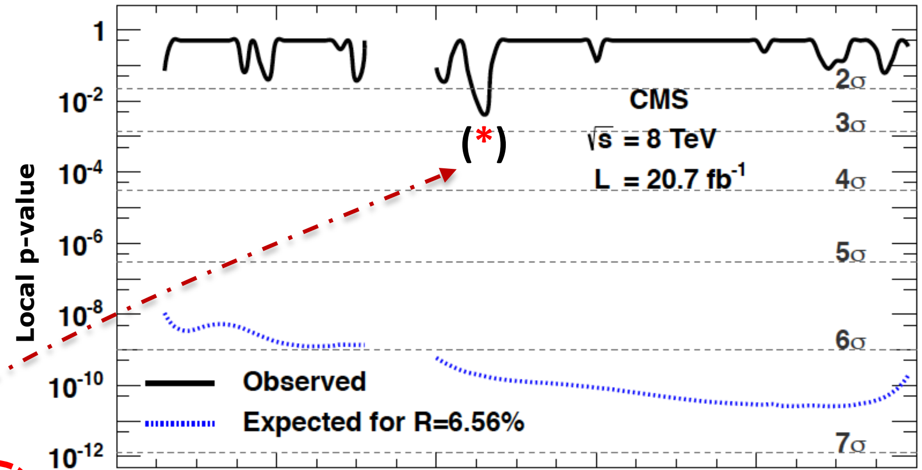
- **same production mechanism for *Y(2S)* and X_b**
- **same dipion mass distribution for *Y(2S)* and X_b**
- ***Y(2S)* and X_b assumed both unpolarized**

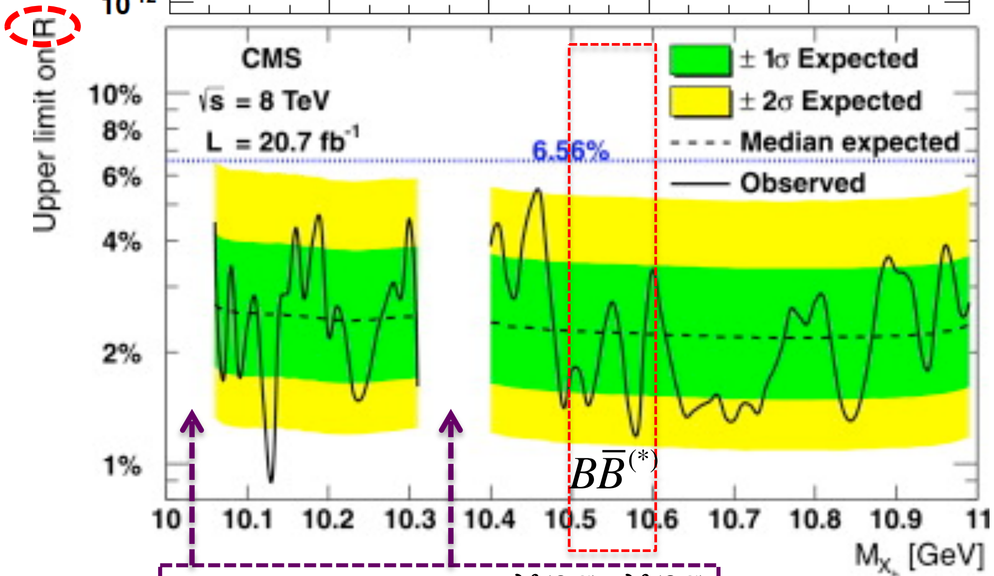
...and a local *p-value* is calculated

(asymptotic approach & barrel/endcap combination)

[(*) : smallest *p-value* = 0.004 $\Rightarrow 2.8\sigma \xrightarrow{LEE} 0.8\sigma$]

NO significant excess observed





95% CL upper limits set on the ratio *R* :

observed UL range: 0.9% to 5.4%

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- According to Karliner&Rosner [PRD91 (2015) 014014], **the analogy with $X \to J/\psi\ \pi^+\pi^-$ is misguided for this particular decay channel**: $X_b \to \Upsilon(1S)\ \pi^+\pi^-$ **should be forbidden by G-parity conservation :**

  - **For the $X(3872)$ the *I*-conserving decay $X \to J/\psi\omega$ was kinematically suppressed, thus equally likely than the *I*-violating $X \to J/\psi\rho^0$:**

$$\frac{B(X \to J/\psi(\pi^+\pi^-\pi^0))}{B(X \to J/\psi(\pi^+\pi^-))} = 1.0 \pm 0.4 \pm 0.3$$

($\pi^+\pi^-\pi^0$: ω^0; $\pi^+\pi^-$: ρ^0)

  - **In the beauty sector Isospin should be well conserved & $X_b \to \Upsilon(1S)\omega$ allowed (preferred if it exists) !**

- **Thus, the search strategy for X_b should include the reconstruction of these decays with 1 or 2 photons:**

$$X_b \xrightarrow{(*)} \Upsilon(1S)\omega(\to \pi^+\pi^-\pi^0), \quad \pi^0 \to 2\gamma$$
$$X_b \to \chi_b(1P)\pi^+\pi^-, \quad \chi_b(1P) \to \Upsilon(1S)\gamma$$
$$X_b \to \Upsilon(3S)\gamma$$

(*) No significant signal found by Belle in *Y(5S)* decays [PRL113, 142001 (2014)]

- **NOT easy task for CMS & ATLAS :**

  Reconstruction of SOFT photons by conversions into the tracker …

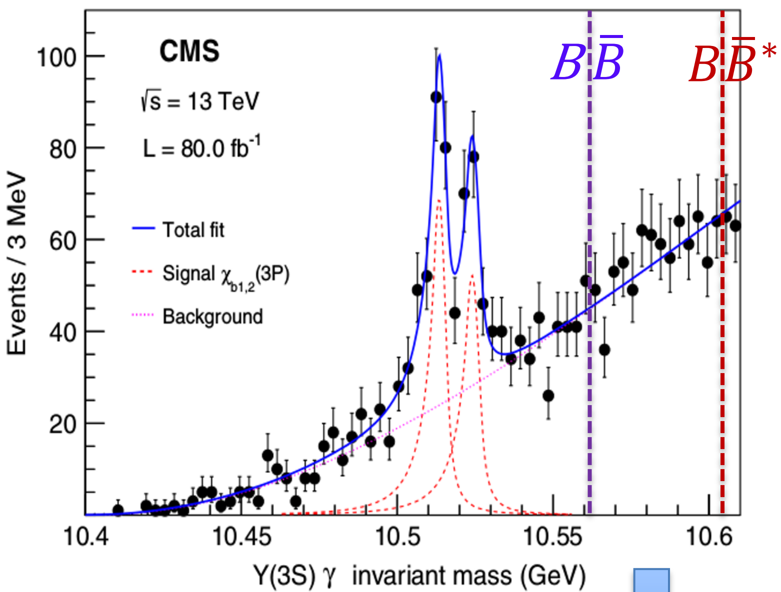
  - … provides enough mass resolution to resolve the two peaks
  - **… BUT conversion efficiency is LOW !**

- **Makes sense to use full Run-2 dataset !**

Is the hypothetical X_b seen decaying radiatively ?

The bottomonium *analogs* of the $\chi_{c1}(2P)$ and $X(3872)$ states …
would be the … $\chi_{b1}(3P)$ **and** X_b (the latter suggested by Heavy Quark symmetry)

Confirming that the $\chi_{b1}(3P)$ is well below the open-beauty threshold would suggest differences w.r.t. the charmonium: $\chi_{c1}(2P)$ is expected to be approximately 100MeV above the $D\bar{D}$ threshold



Among the possibilities…
- the single peak seen by LHCb could have been the X_b or a mixture of the $\chi_{b1}(3P)$ and the possible X_b state (Karliner & Rosner [PRD91 (2015) 014014] ; in analogy with the $X(3872)$ interpreted as a mixture of $\chi_{c1}(2P)$ & $D^0\bar{D}^{*0}$ molecule),
- it could simply be the conventional (unresolved) $\chi_{bJ=1,2}(3P)$ and in this case a hypothetical X_b might exist at higher masses close to the $B\bar{B}^{(*)}$ thresholds.

At the level of the current statistics no hint of the hypothetical X_b that might exist close to the $B\bar{B}^{(*)}$ thresholds [radiatively decaying as $X_b \to \Upsilon(3S)\gamma$]

This measurement strongly disfavours the breaking of the conventional pattern of splittings in the doublet and supports the standard hierarchy (*J=2* heavier than *J=1*) i.e. the proximity of open-beauty threshold have no relevant influence on the splitting

Introduction to searches in the $\Upsilon(1S)\mu^+\mu^-$ final state

- CMS released a measurement of the $\Upsilon(1S)$ pair production Xsection @ $\sqrt{s} = 13TeV$

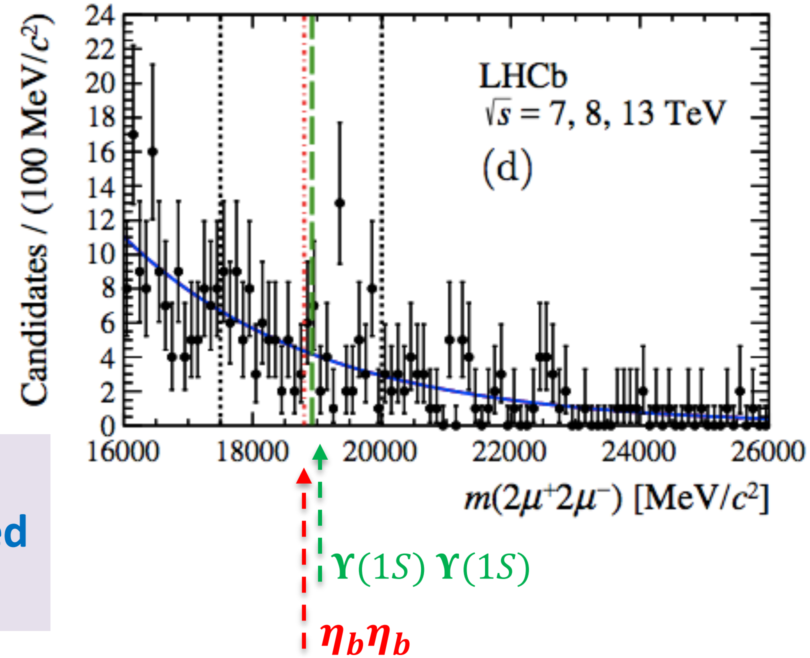
This process serves as a standard reference in a search for narrow resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ since the final state is the same and the event selection is similar.

The existence of an heavy bottom tetraquark [$bb\overline{b}\overline{b}$] predicted by few theoretical models (*) [below twice the η_b mass] is searched in a mass window between $17.5 \div 19.5$ GeV (namely around 4 times the mass of the bottom quark), within the $\Upsilon(1S)\mu^+\mu^-$ final state.

- LHCb searched for such tetraquarks without finding any hint of a signal [JHEP 10 (2018) 086]

- This new analysis probes a kinematical region not accessible at LHCb. CMS has also a very competitive acceptance for muons from $\Upsilon(1S)$ decays.

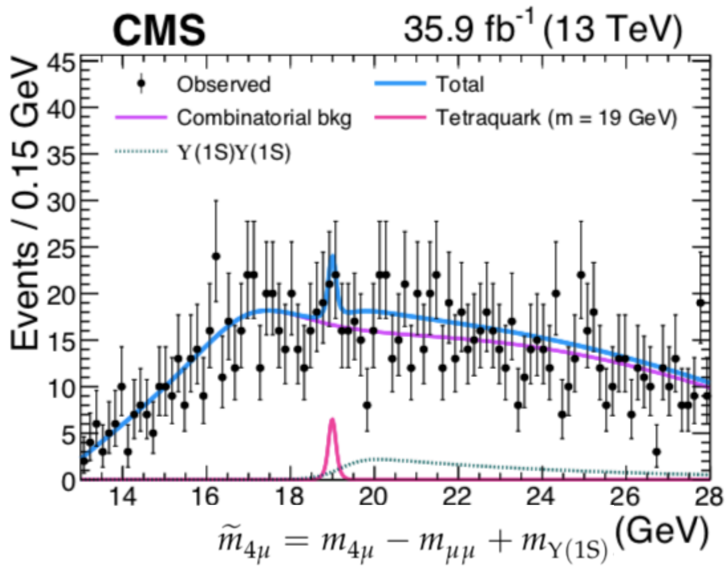
Moreover … a generic search for narrow resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ was performed in an extended mass window $16.5 \div 27$GeV .



(*) Y.Chen *et al.*, PLB 705 (2013) 93 ; A.V. Berezhnoy *et al.*, PRD 86 (2012) 034004

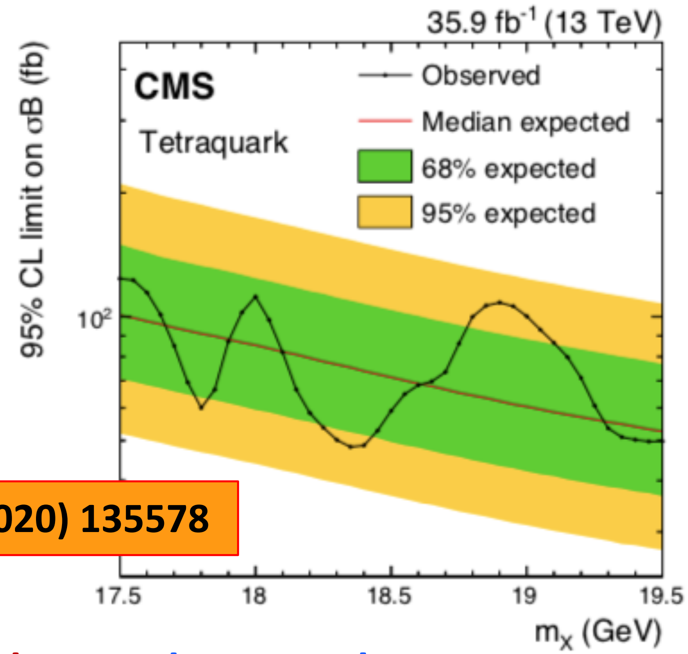
Search for a $bb\bar{b}\bar{b}$ tetraquark state

- **No significant narrow excess of candidates is observed above the background expectation.**



An example of 4quark signal at 19GeV is shown
This mass window is probed using the bottomonium model.
In UML fits the signal has FWHM ~200MeV for a 18GeV resonance.

Upper limits on the product of the production Xsection of a resonance & the BF to the final state of 4 muons via an intermediate $\Upsilon(1S)$, $\sigma(T_{bb\bar{b}\bar{b}})\times\mathcal{B}(T_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu^+\mu^-)$, are set @95% CL (using the modified frequentist construction CL_s in the asymptotic approx.**).**



Using the number of $\Upsilon(1S)\Upsilon(1S)$ events observed in data as a reference, a resonance with a mass at ~19GeV and having a similar production Xsection **(*)** and BF to 4 muons as the $\Upsilon(1S)\Upsilon(1S)$ production, would produce ~100 candidates in our data sample (given the similarity between the kinematic distributions of both processes).

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(*) $[79 \pm 11(stat) \pm 6(syst) \pm 3(BF)]pb$ for $|y| < 2.0$

- **A further search for a light narrow resonance, such as a BSM bound state, does not show any significant narrow excess of candidates above the background expectation** (see backup)**.**

Perspectives & Plans for Phase-2

What is planned for Phase-2/HL-LHC (Run-4, …)? **[** focusing on this kind of Physics … **]**

- the **availability of tracking information at Level-1 trigger** will be crucial to retain the full physics potential when pile up conditions expected (<PU>~140-200) will hold.

- the **new additional timing layer** (**M**ip **T**iming **D**etector) will allow:
  - **some hadronic PID capabilities for the softer** ($p_T < 2\text{GeV}$) **charged track**
  - an upgrade of the 3D vertex fit to a 4D one, thus allowing **precision timing for charged hadrons & converted photons** and - consequently - **an effective pile up mitigation**.

- even more **careful** ***dedicated trigger strategy*** will be needed