21st International Conference on B-Physics
at Frontier Machines, July 3rd, 2023

SPECTROSCOPY & PRODUCTION OF DI-ONIA STATES @CMS

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On Behalf of the CMS Collaboration

HADRON SPECTROSCOPY: AN INTRODUCTION

- A **RENAISSANCE** since the discovery of X(3872) in 2003!
- >70 new conventional & exotic states have been discovered.
  - Exotic states are not yet fully explained by theoretical models!
- Experimental studies and explorations are crucial to examine the nature of these states and extend our understanding of QCD.
- With the **excellent tracking & muon identification**, CMS is contributing too!

Today's Outline

Observation of new structure in the J/ψ mass spectrum in pp collisions at 13 TeV

Ref.
CMS arXiv:2306.07164, submitted to PRL

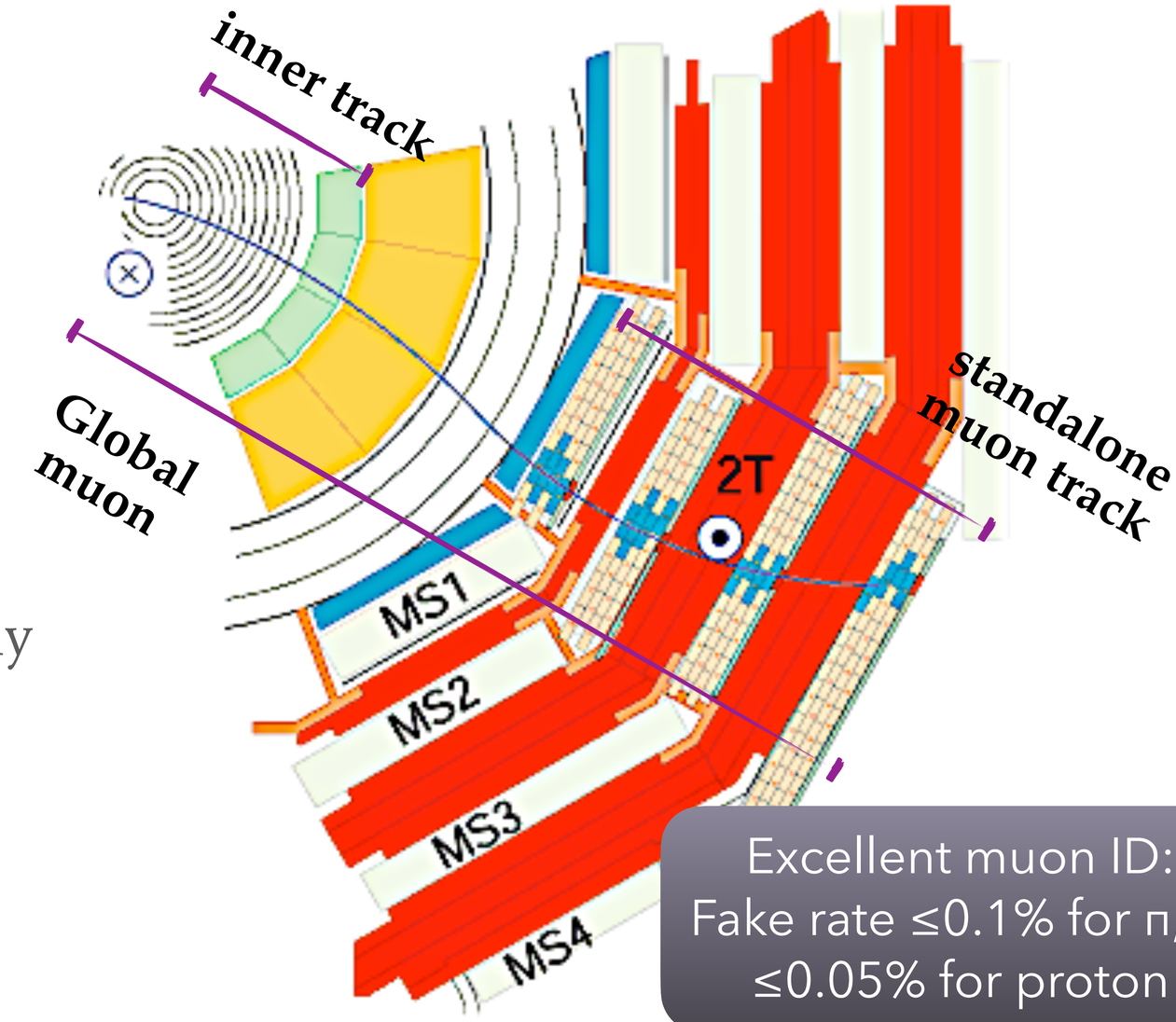
Measurement of the Υ(1S) pair production cross section and search for resonances decaying to Υ(1S)$\mu^+\mu^-$

Ref.
CMS PLB 808 (2020) 135578

CMS MUON RECONSTRUCTION

As muon in the name of the detector,
CMS does have an excellent muon system!

- **CMS muon system**:
  - 3 different devices, with a large coverage up to $|\eta|<2.4$.
  - Good dimuon mass resolution: ~0.6-1.5% (depending on $|y|$).
- **Reconstruction algorithms**:
  - **Standalone muon**: reconstructed in muon system only
  - **Global muon**: standalone muon ⇒ inner track
  - **Tracker muon**: inner track ⇒ muon system

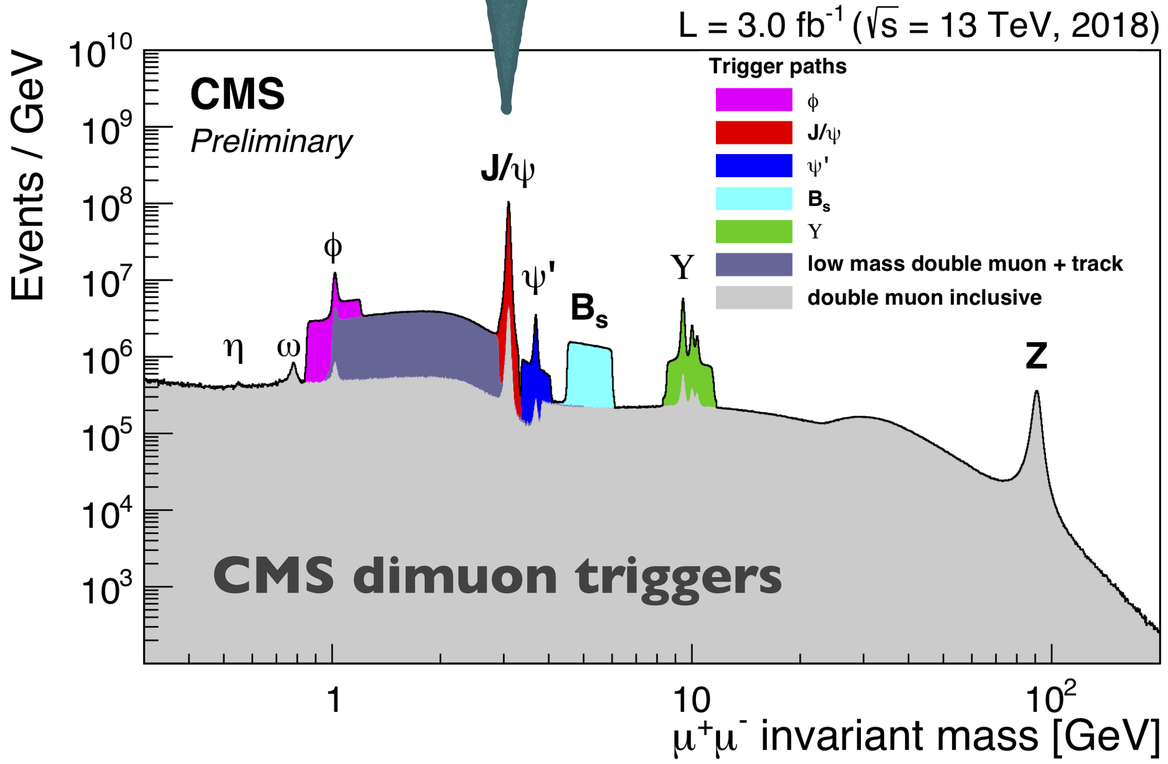


Excellent muon ID:
Fake rate ≤0.1% for π,K;
≤0.05% for proton

CMS HEAVY FLAVOR TRIGGERS

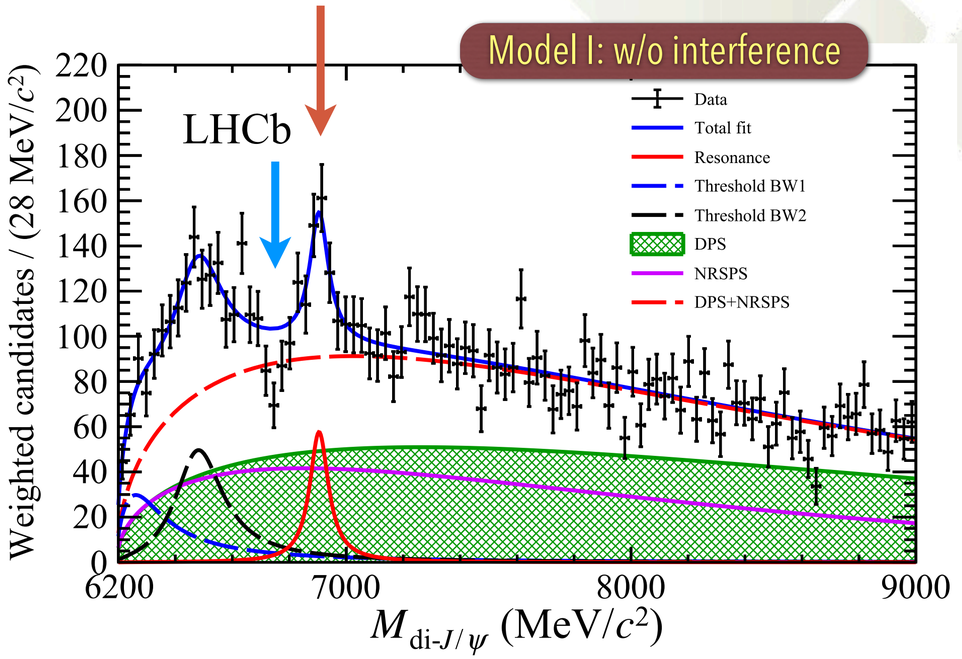
- **CMS trigger system**:
  - Fast hardware trigger (L1) @ 100 kHz
  - Software trigger with full tracking & vertex reconstruction (HLT) @ 1.5 kHz.
  - Specific triggers were developed for various analyses, e.g. J/ψ+μ trigger.
  - Trigger requirements tightened with increased luminosity.
  - ~15% of bandwidth is given to flavor physics; "scouting" & "parking" streams for extended capabilities.

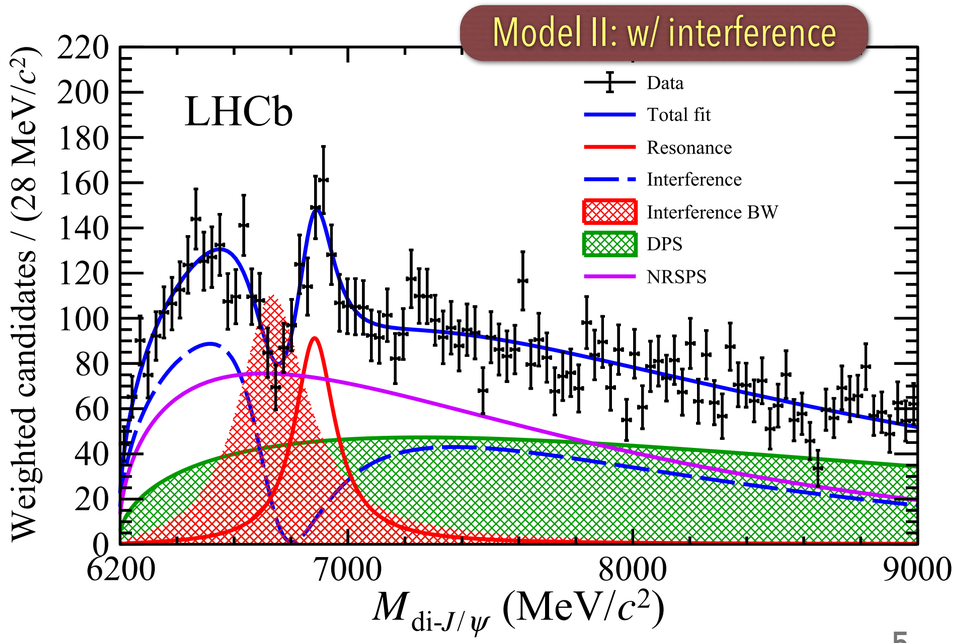
The flavor physics analyses rely on displaced/non-displaced quarkonia (J/ψ, ψ' & Υ), B(s), non-resonant dimuon triggers.



STRUCTURES IN THE J/ΨJ/Ψ MASS SPECTRUM

- In 2020 LHCb observed a significant structure **near J/ψ J/ψ mass threshold**.
- **A narrow structure at 6.9 GeV was found** ⇒ X(6900), suggesting a **very-charming cc̄cc̄ state**!
  - Fitting model without interference cannot describe the **dip around 6.8 GeV**;
  - With interference between non-resonant single-parton scattering (NRSPS) & X(6900), resulting a satisfactory description.
  - The structure at the threshold, as modeled by a sum of 2 BW, is not yet understood.





LHCb Science Bulletin 65 (2020) 1983

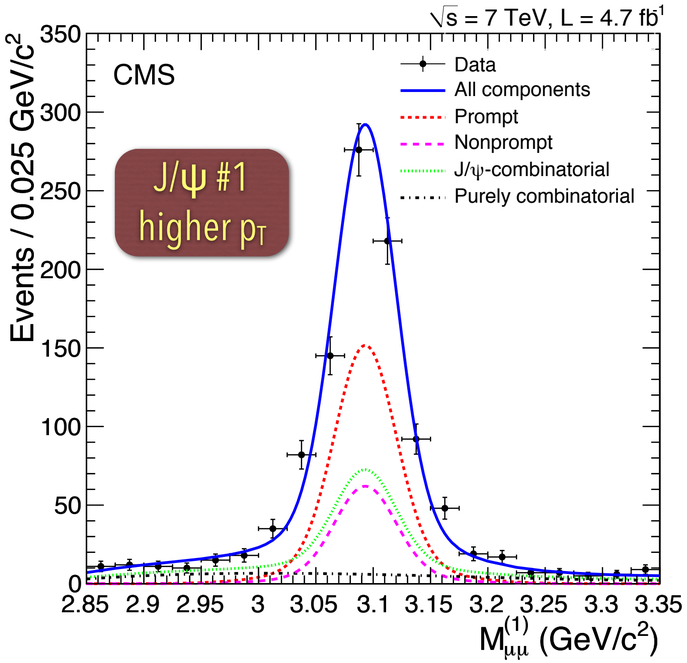
J/ΨJ/Ψ PROD CROSS SECTIONS

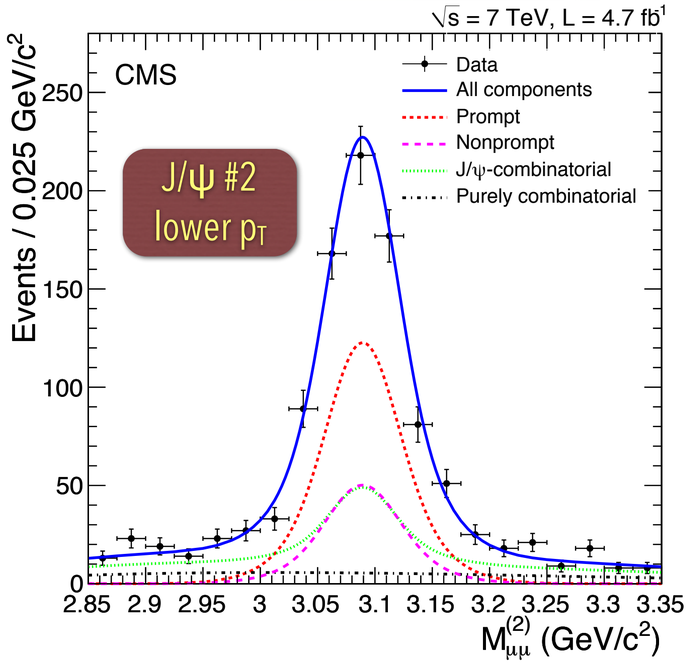
- CMS has already measured double J/ψ production cross sections in **total** and **differentially** with 7 TeV data.
- Covers a phase-space at higher p_T and central y (*complementary to LHCb coverage!*).

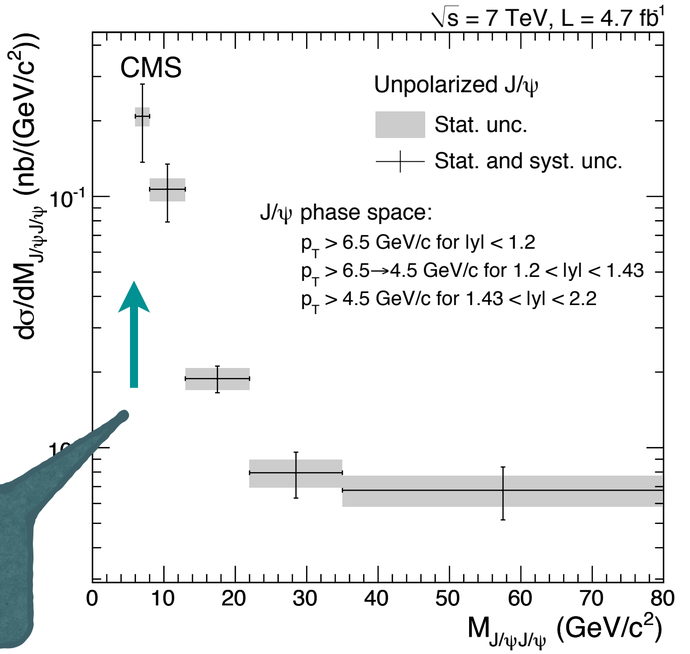
CMS JHEP 09 (2014) 094

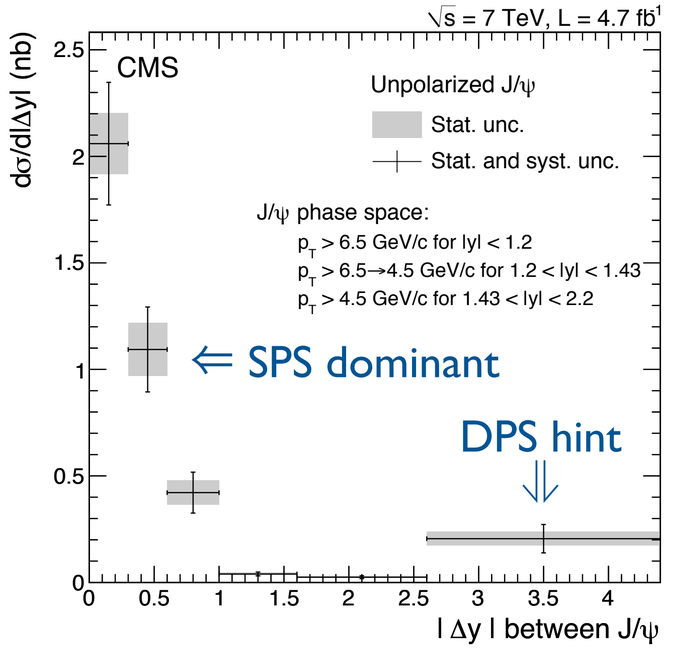
Total cross section @ 7 TeV:
$\sigma_{tot} = 1.49 \pm 0.07\ (stat) \pm 0.13\ (syst)$ nb

Not yet enough to study the structure; need statistics!





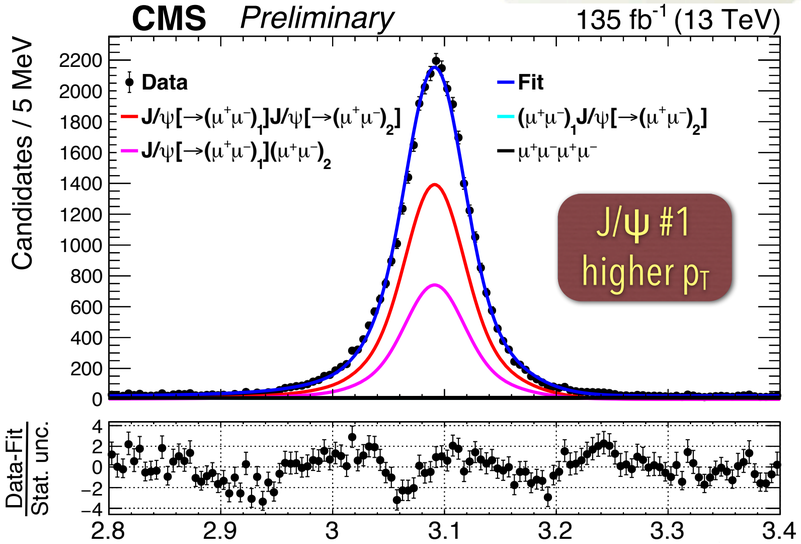




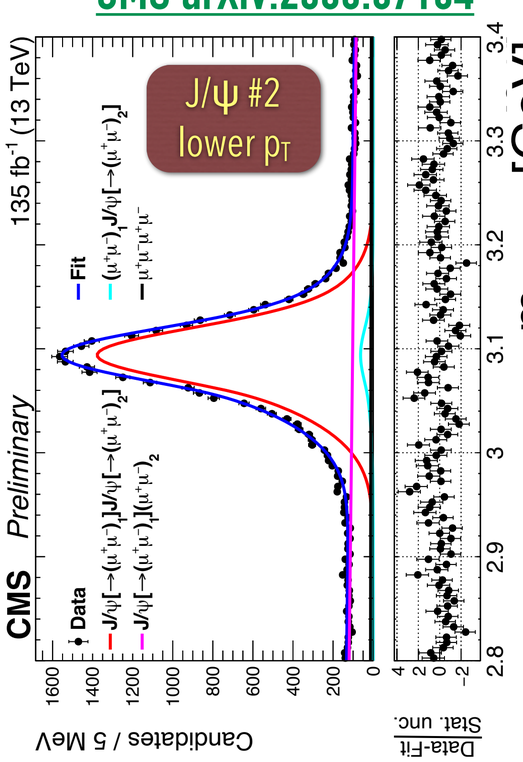
MORE J/ΨJ/Ψ EVENTS AT 13 TEV

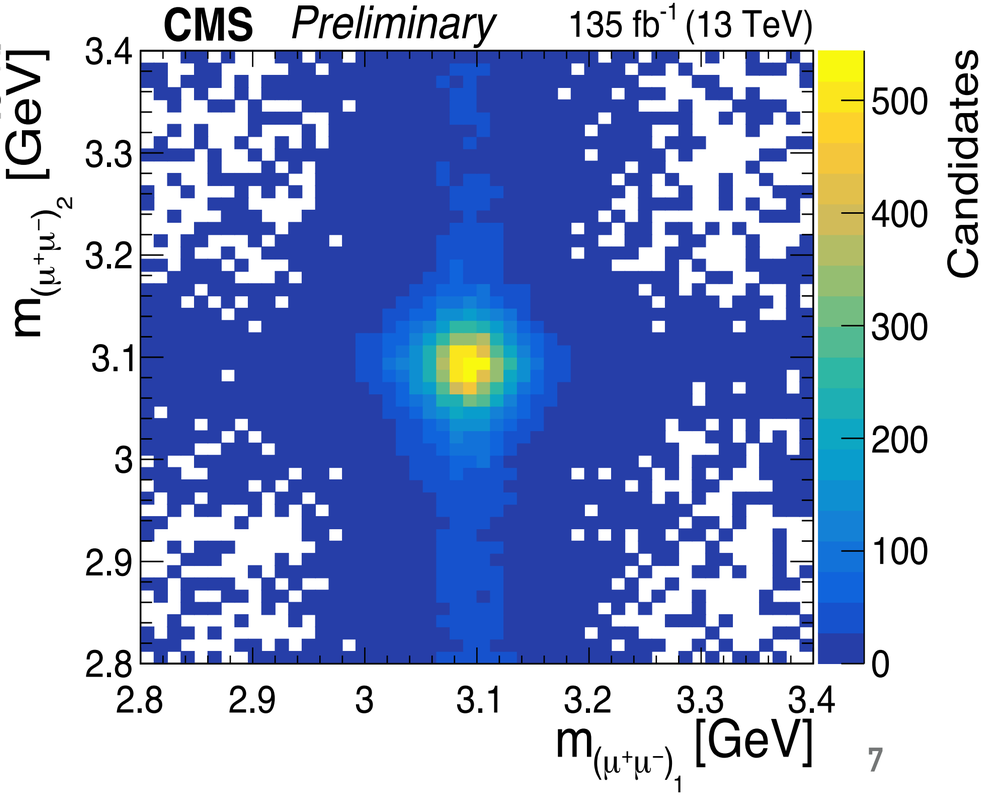
- **CMS analyzed 135 fb^{-1} of 13 TeV data recorded during LHC Run-2.**
- Trigger: **3μ with a J/ψ mass window**.
- Selection and reconstruction:
  - $p_T(\mu) > 2$ GeV, $|\eta(\mu)| < 2.4$; $p_T(J/\psi) > 3.5$ GeV;
  - 2μ & 4μ vertex fits; J/ψ mass constraint applied;
  - Resolving 4μ multiple combination by minimizing $(\Delta m_1/\sigma_{m_1})^2 + (\Delta m_2/\sigma_{m_2})^2$.

Very clear J/ψ J/ψ signals!



CMS arXiv:2306.07164





EXAMINATION OF J/ΨJ/Ψ MASS SPECTRUM

NRSPS: non-resonant single parton scattering
DPS: (non-resonant) double parton scattering

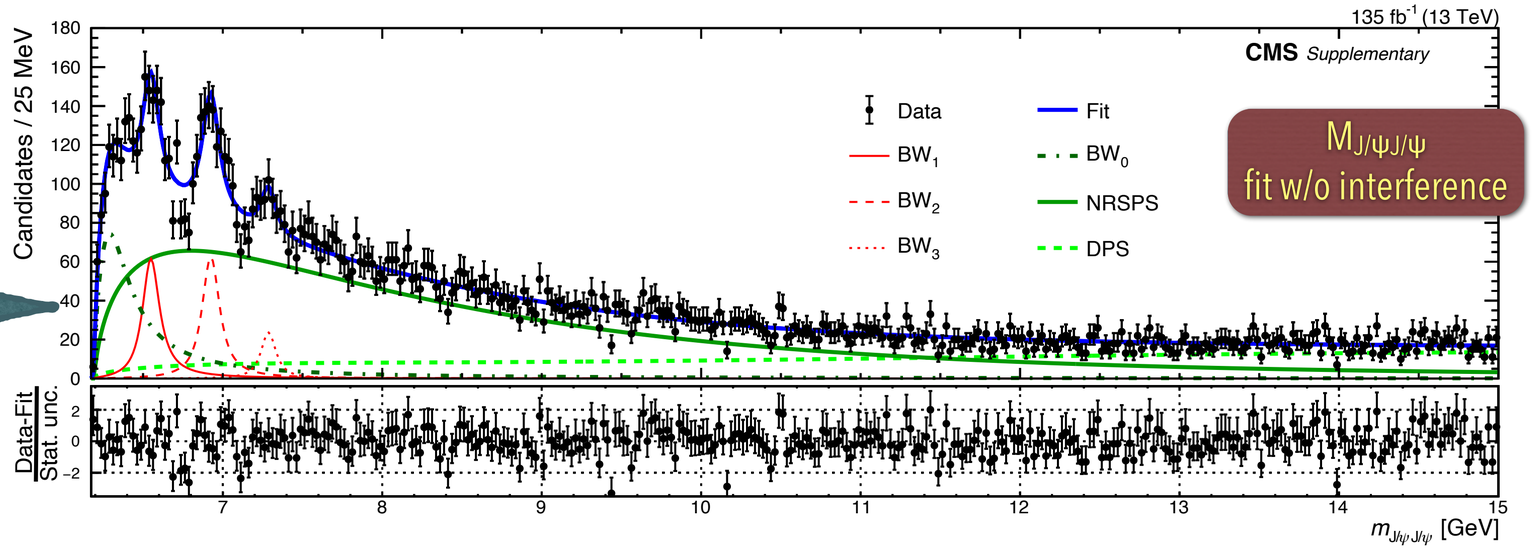
- The starting point: null model — **NRSPS + DPS**
- Add potential structure(s)/peak(s) step-by-step:
  - Add new structure/peak and calculate the corresponding local significance;
  - Keep the new model if and only if the significance >3σ;
  - Repeat until no more >3σ structures.

To better constrain SPS & DPS backgrounds, fit up to 15 GeV!

Bkg. model: **NRSPS+DPS+BW_0**

BW_0: BW at threshold, treated as background due to:

- ➡ BW_0 parameters very sensitive to NRSPS and DPS models;
- ➡ A region with feed-down from possible higher mass states;



CMS BASELINE MODEL: FITTED PARAMETERS

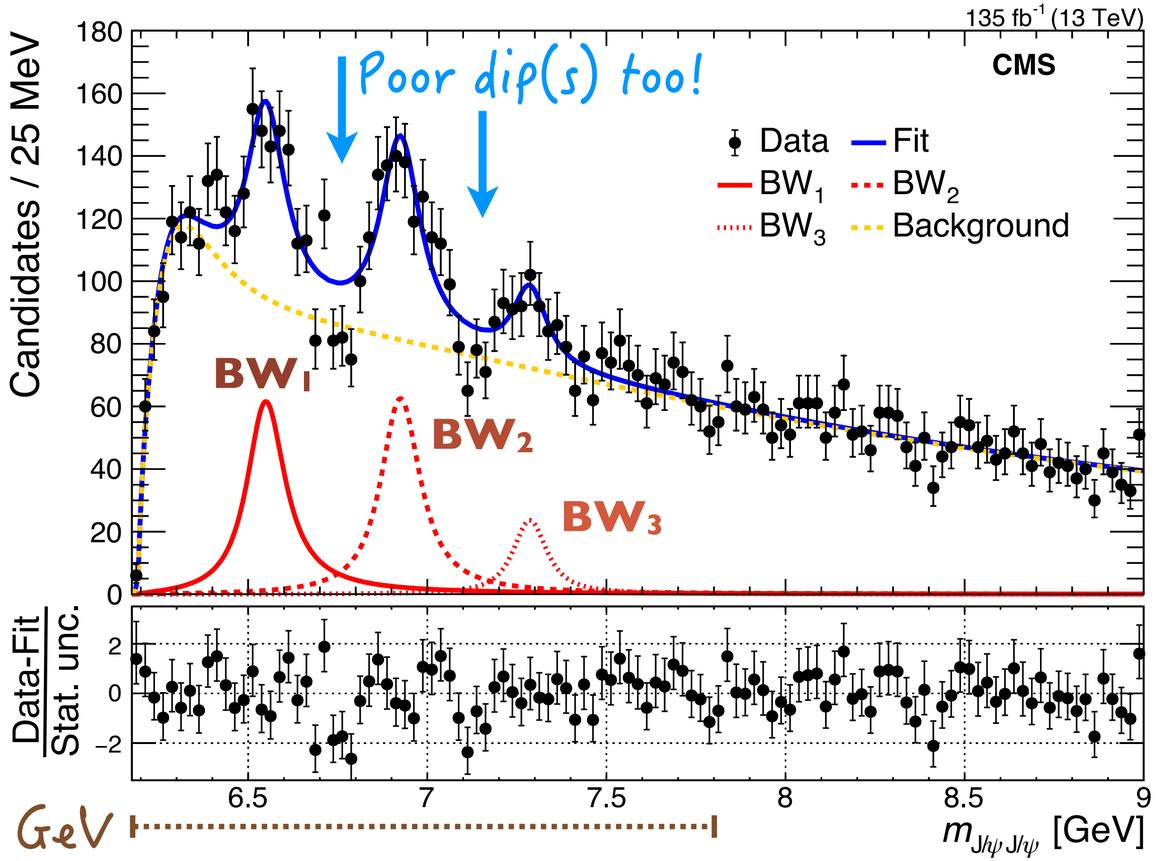
- **CMS baseline model** = **background(NRSPS+DPS+BW_0)** + **BW_1** + **BW_2** + **BW_3**
- Model the signal structures by relativistic BW, convolved with resolution functions.
- No correction of acceptance & trigger/selection efficiencies ⇒ systematics.

	BW_1	BW_2	BW_3
m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
signif.(*stat.*)	6.5σ	9.4σ	4.1σ
(*stat.+syst.*)	5.7σ	9.4σ	4.1σ

Observation!

Confirmed LHCb X(6900)

Evidence!



χ2 prob = 9% up to 7.8 GeV

CMS arXiv:2306.07164

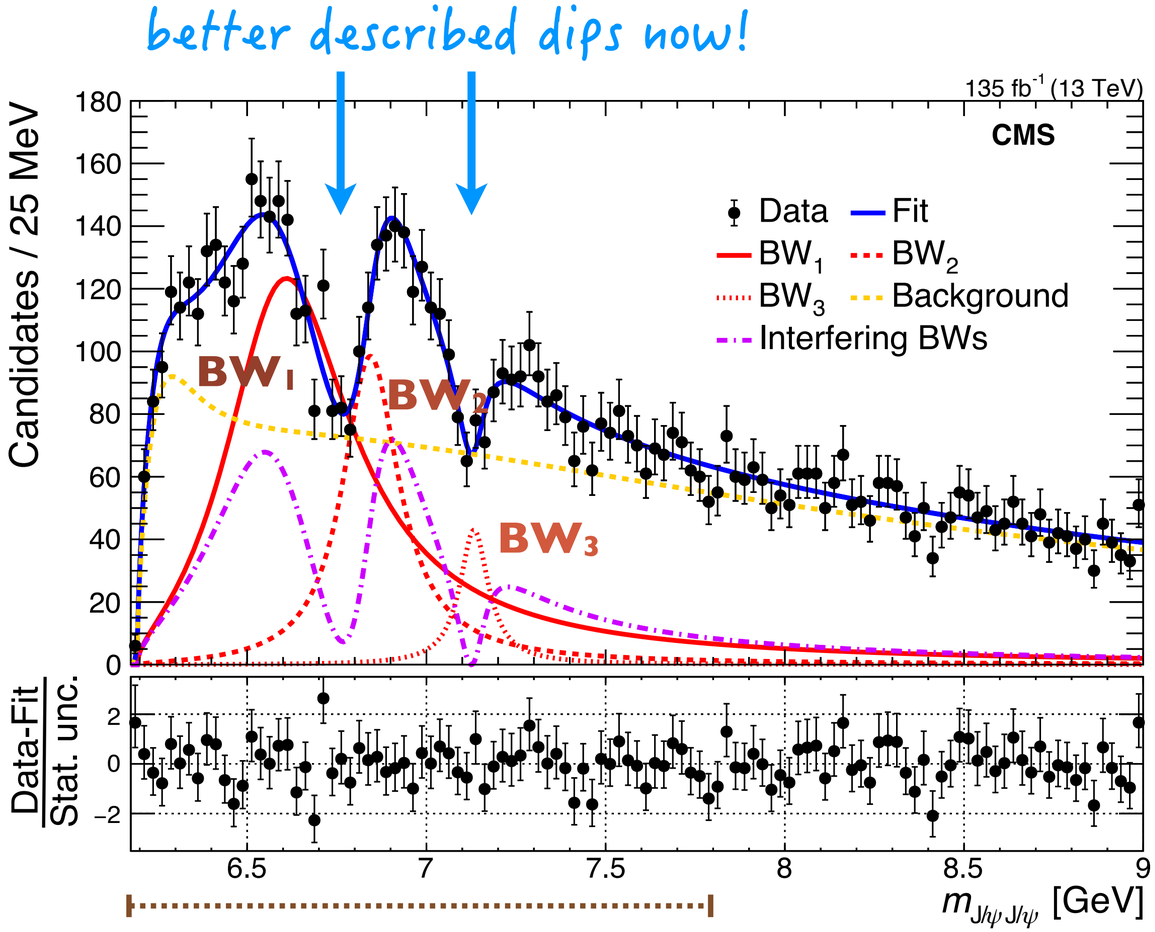
CMS MODEL WITH INTERFERENCE

- Interference among various combinations of BWs have been tested;
- Our pick-up — **three-way interfered $BW_1/BW_2/BW_3$**:

$$p \propto |r_1 \exp(i\phi_1)\mathrm{BW}_1 + \mathrm{BW}_2 + r_3 \exp(i\phi_3)\mathrm{BW}_3|^2$$

- This model **significantly improves the fit quality**, both dips are now described.
- Masses and widths of BWs are shifted w.r.t. the non-interference fit:

	BW_1	BW_2	BW_3
m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}



CMS arXiv:2306.07164

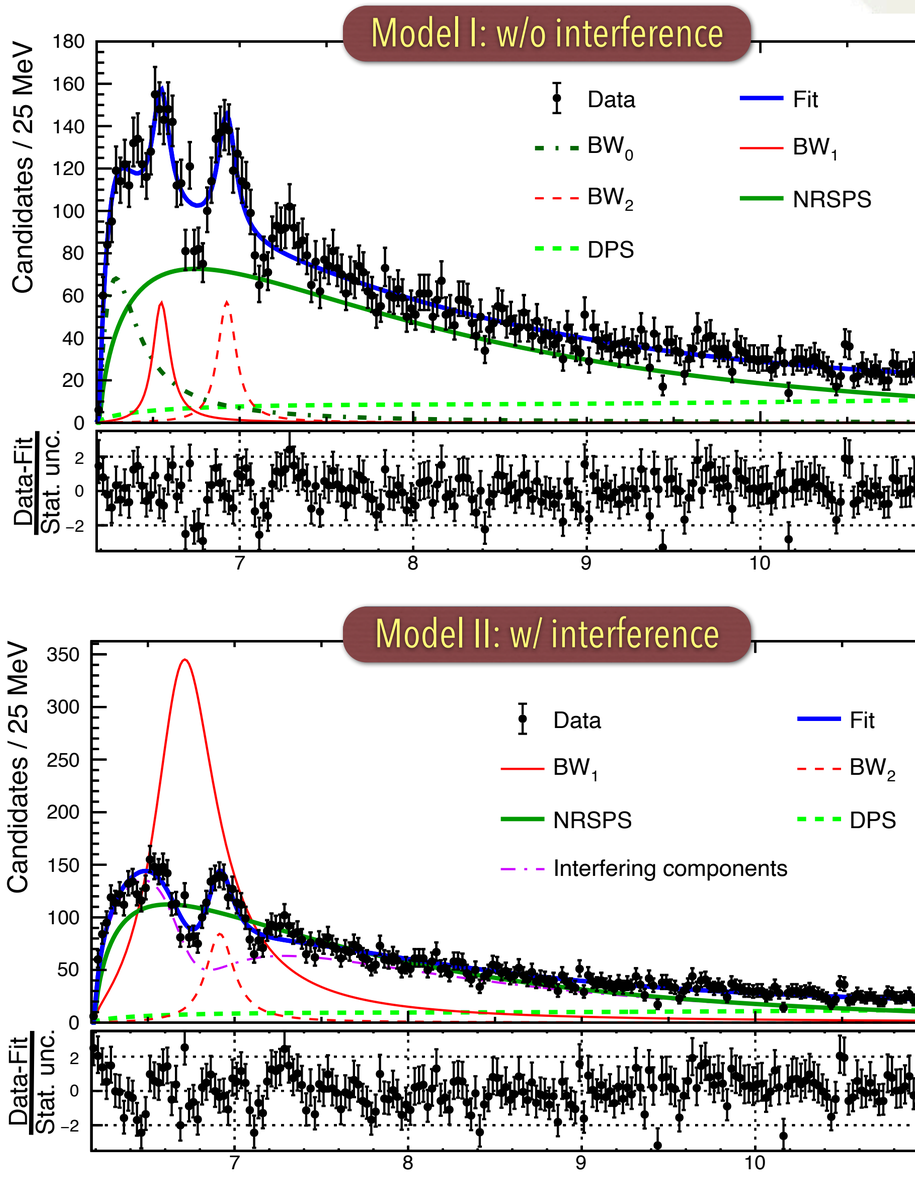
ALTERNATIVE FITS WITH LHCB MODELS

- In order to make a direct comparison to the results from LHCb, we also used LHCb models (I and II) to fit the CMS data.

		M_{BW1}	Γ_{BW1}	$M_{X(6900)}$	$\Gamma_{X(6900)}$
Model I	LHCb			6905±13	80±38
	CMS	6550±10	112±27	6927±10	117±24
Model II	LHCb	6741±6	288±16	6886±16	168±76
	CMS	6736±38	439±65	6918±10	187±40

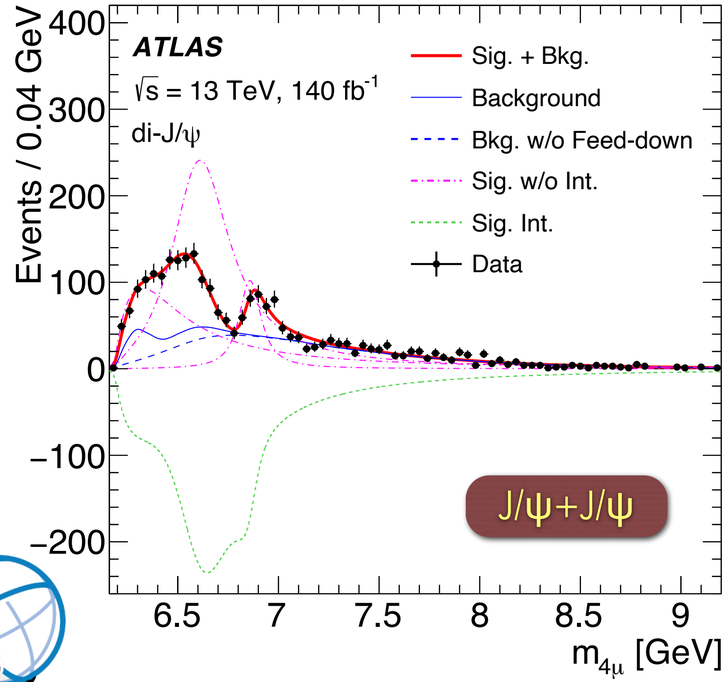
  - Fit with model I (*w/o interference*) shows a good agreement of X(6900) parameters;
  - CMS finds wider BW_1 from the fit with model II (*w/ interference*).

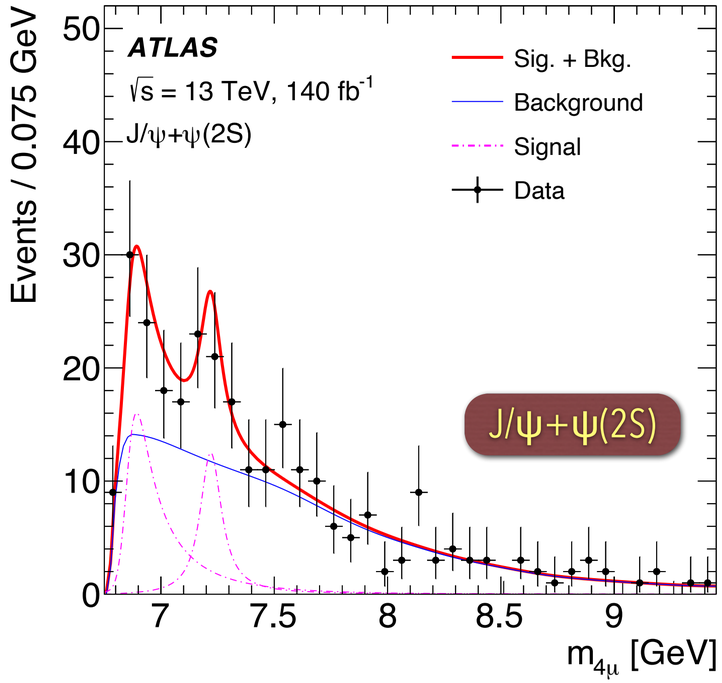
...but both fits have rather poor χ^2 prob (0.9% and 0.8%)



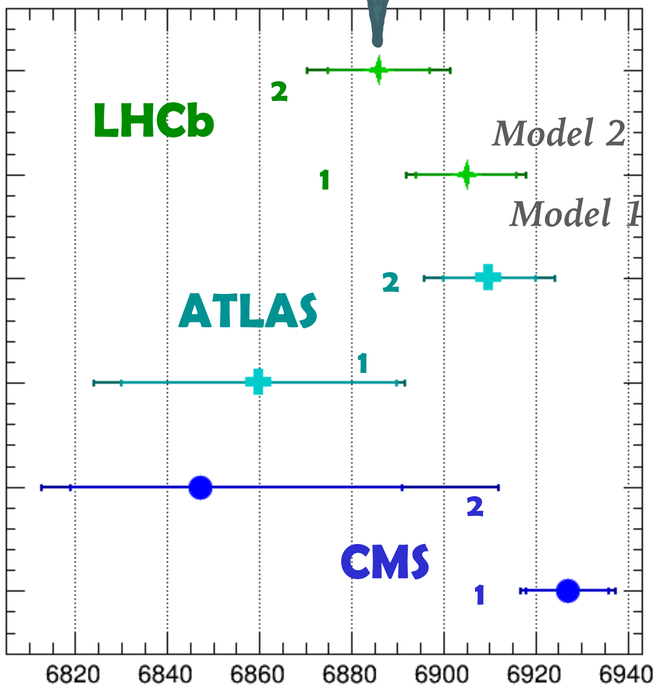
INVESTIGATION BY ATLAS

- ATLAS investigated **J/ψ J/ψ and ψ(2S) J/ψ** mass spectra:
  - Structures have been seen, two models with interference are introduced in the fits;
  - **X(6900) is significant (>5σ) ⇒ triple confirmation!**



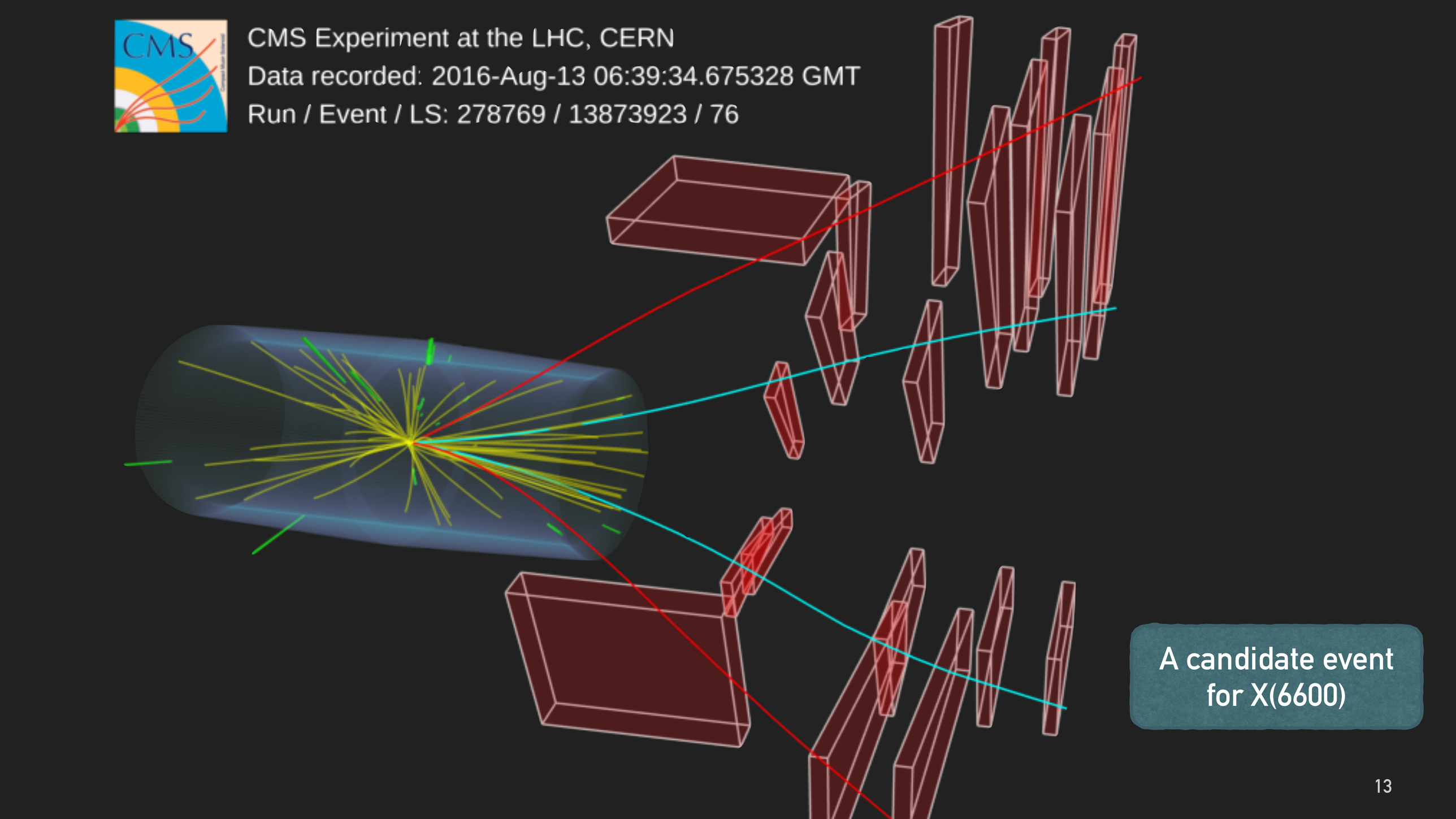


Fitting models are different among 3 experiments / Not an apple-to-apple comparison!
However the X(6900) masses still (more-or-less) agree…



(S. Polikarpov @ LHCP)

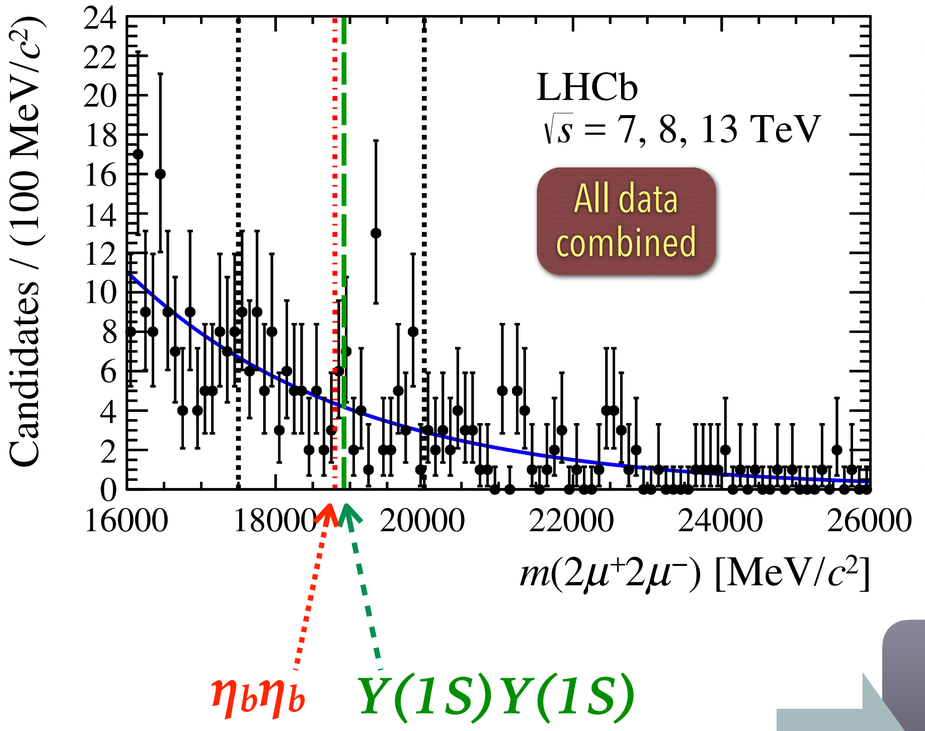
ATLAS, arXiv:2304.08962, Submitted to PRL

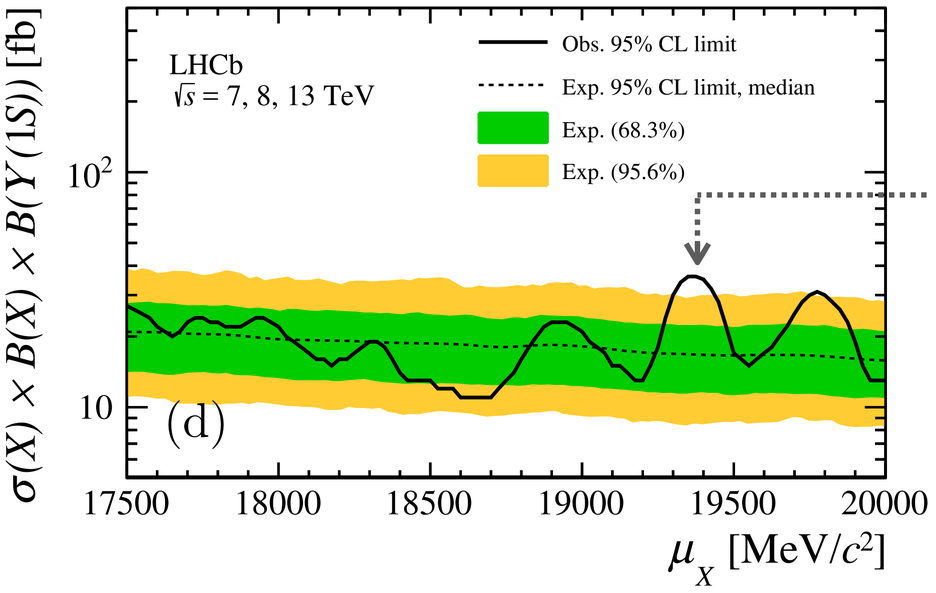


A candidate event for X(6600)

FROM "FULL CHARM" TO "FULL BEAUTY"

- Heavy bottom tetraquarks [$bb\bar{b}\bar{b}$ states] are predicted by theoretical models too!
- Look for **narrow resonances in $\Upsilon(1S)\mu^+\mu^-$, around b-quark mass × 4.**
- LHCb searched for such a signal without finding a hint (yet):





maximal local signif. = 2.5σ @ 19.35 GeV

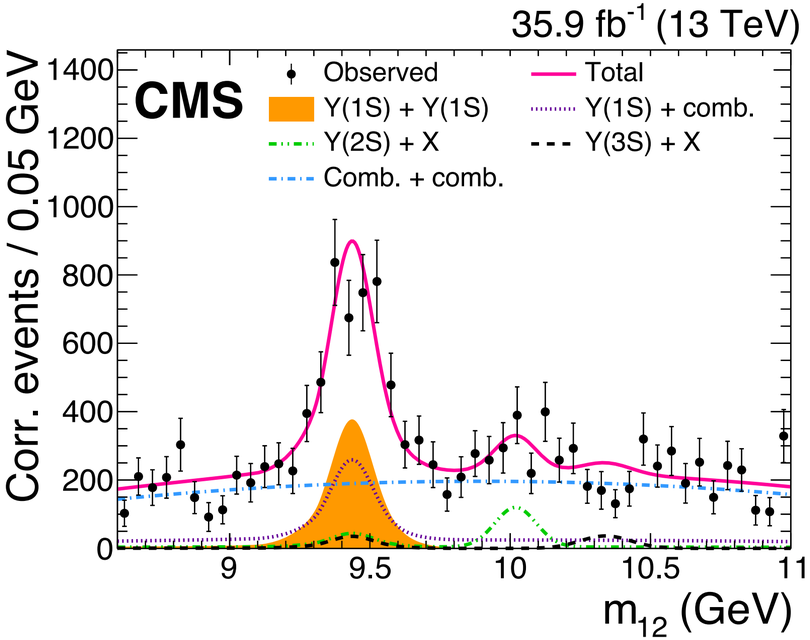
CMS can probe for a different kinematic region!
Perform a generic search of narrow resonances in $\Upsilon(1S)\mu^+\mu^-$ in an extended mass window 16.5–27 GeV.

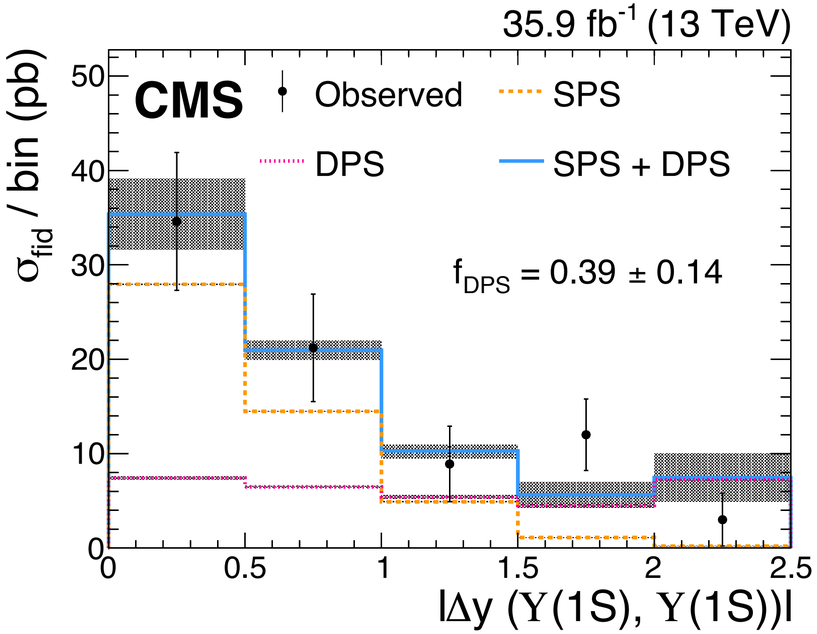
LHCb JHEP 10 (2018) 086

MEASUREMENT OF Υ(1S) PAIR PRODUCTIONS

- Υ(1S) pair production is the standard reference for the tetraquark bound state or generic narrow resonance searches, with the target mass close to Υ(1S) mass×2.
- CMS analysis with **35.9 fb^{-1} recorded in 2016**:
  - **Final state of 4μ paired in Υ states**, $J/\psi \to \mu^+\mu^-$ candidate vetoed.
  - 4μ vertex fit, $p_T(\mu) > 2.5$ GeV
  - Fiducial region: $|y(\Upsilon(1S))| < 2.0$
  - Events are then corrected by efficiency and acceptance derived from MC.

Measure **DPS-to-inclusive fraction** too!





CMS PLB 808 (2020) 135578

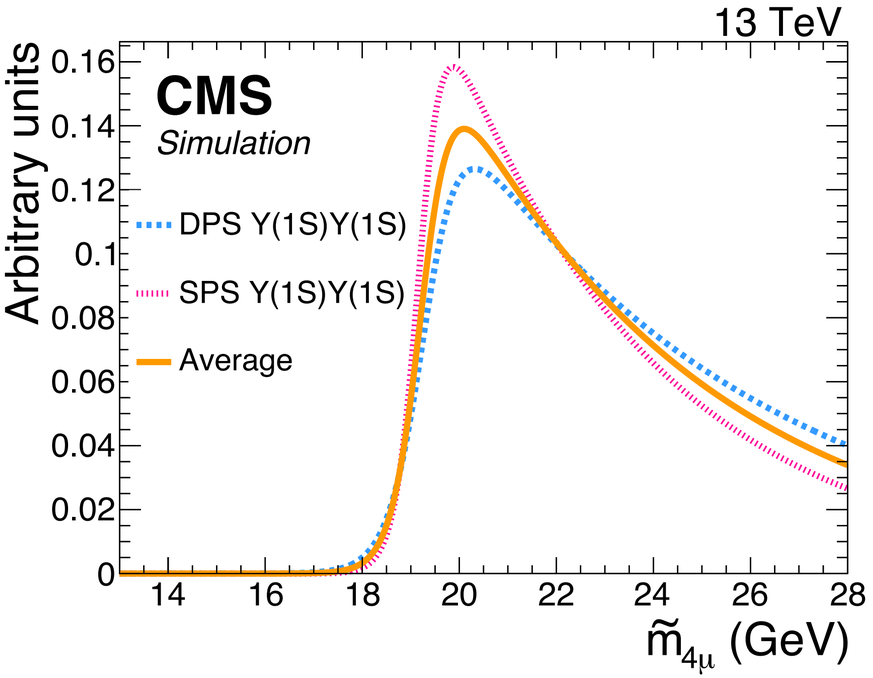
Fiducial cross section @ 13 TeV:
σ_{fid} = 79 ± 11 (stat) ± 6 (syst) ± 3 (BF) pb

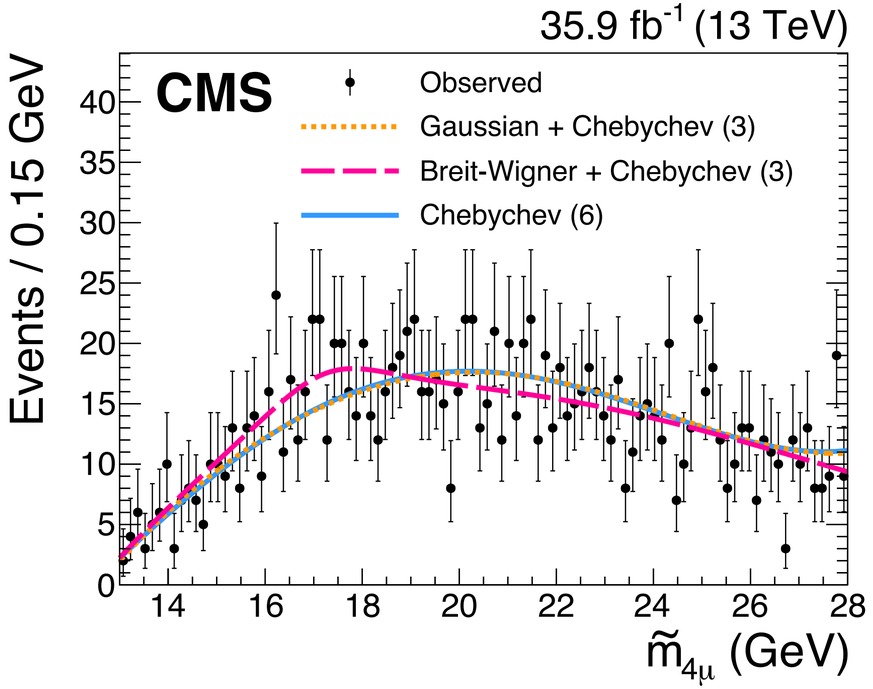
EXAMINATION OF Y(1S)μ⁺μ⁻ MASS SPECTRUM

- **Mass difference** is introduced to improve the mass resolution (*~50% better in resolution*):

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

- $m_{\mu\mu} \in [m_{\Upsilon(1S)} - 2\sigma, m_{\Upsilon(1S)} + 2\sigma]$
- Background components:
  - **Υ(1S)Υ(1S)**: from simulation, nominal model is an average between the DPS and SPS templates;
  - **Combinatorial**: fit to data with sets of several generic functions.
    - Verified using a control region where the vertex fit x^2 probability of the 4μ is in the range of $[10^{-10}, 10^{-3}]$.

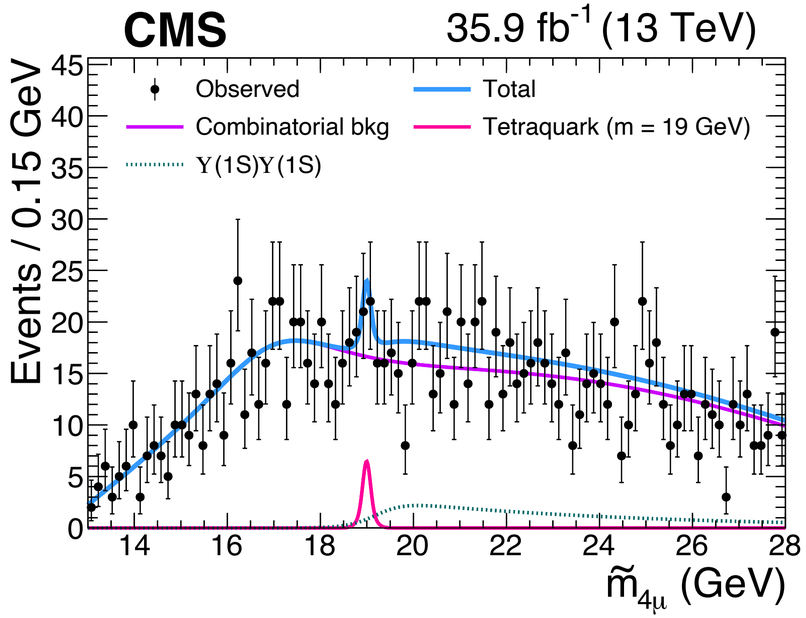


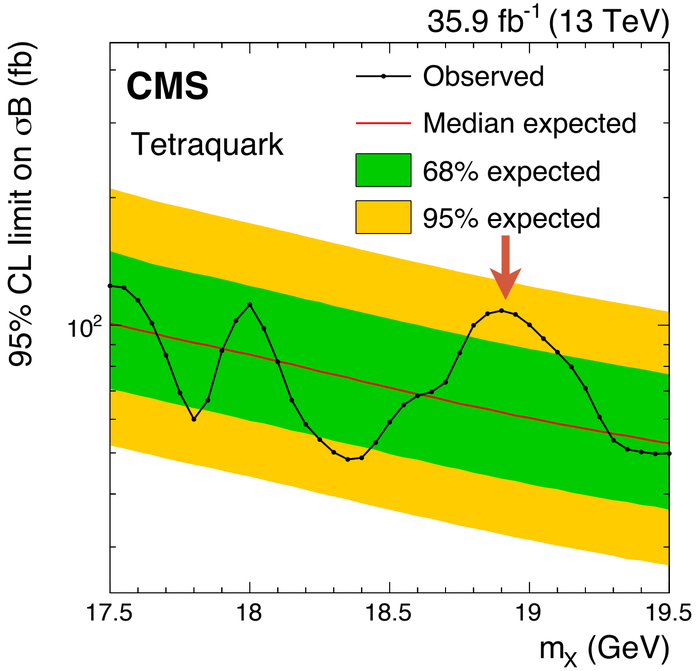


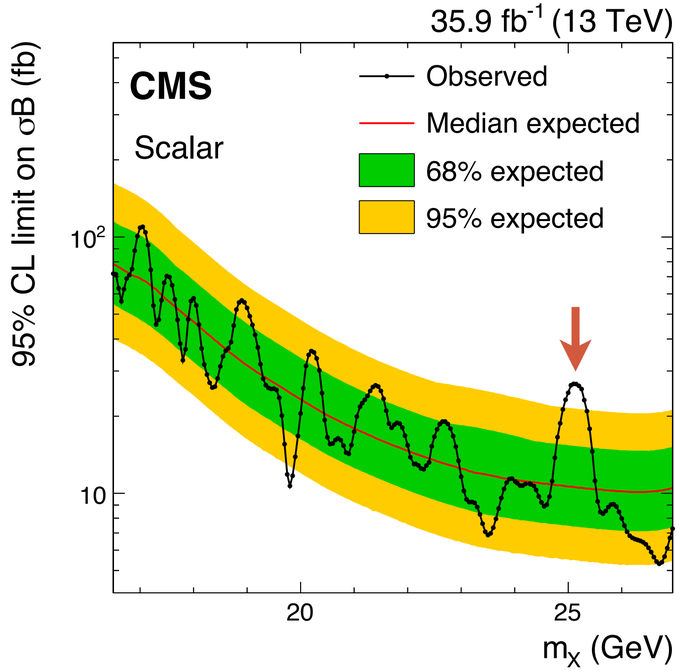
SEARCH FOR Υ(1S)μ⁺μ⁻ RESONANCE

CMS PLB 808 (2020) 135578

- Scanning over Υ(1S)μ⁺μ⁻ mass spectrum, **no significant narrow excess** of events is observed above the background expectation.



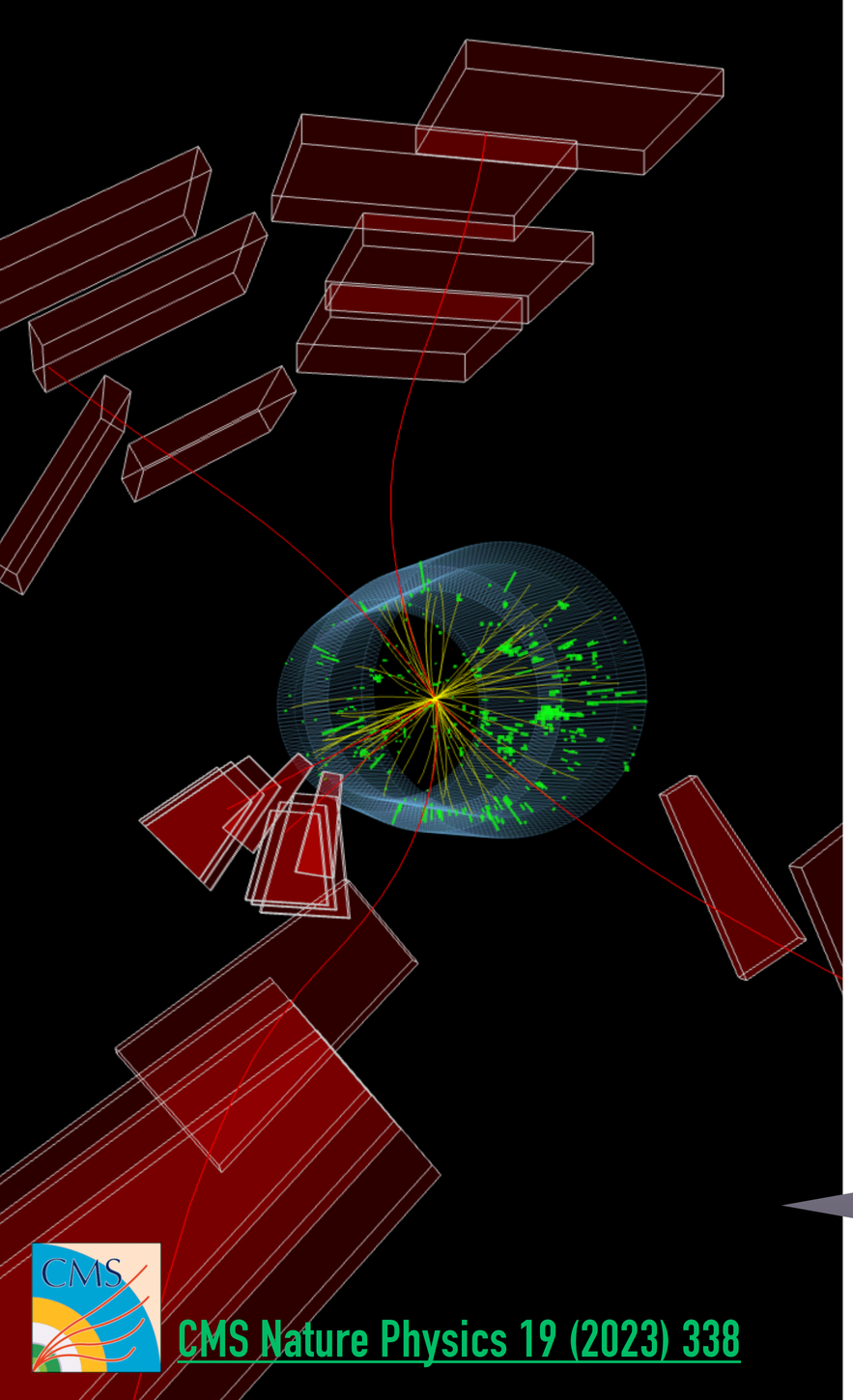




Limits are also set for pseudoscalar and spin-2 models.

An example signal is shown for the tetraquark model with a mass of 19 GeV, which has a significance of about 1σ.

Largest excess at 25.1 GeV w/ a local significance of 2.4σ for the scalar signal hypothesis.



SUMMARY

- Thanks to the great muon performance and dynamic trigger configurations, CMS play a key role in exotic hadron spectroscopy searches too!
- **CMS found 3 significant structures in J/ψ J/ψ mass spectrum, as full-charm tetra-quark candidates:**
  - **X(6900) consists with LHCb and ATLAS results.**
  - Two new structures X(6600) and X(7300) seen for the first time.
- **No excess of narrow resonance observed in Υ(1S)μ⁺μ⁻ mass spectrum between 16.5–27.0 GeV.**

First observation of triple J/ψ production too!
$N = 5.0^{+2.6}_{-1.9}$ (~1 bkg), significance > 5σ.
Future potential "6 charm" state?

CMS Nature Physics 19 (2023) 338


BACKUP