Search for exotic resonances with the CMS experiment

Leonardo Lunerti† on behalf of CMS Collaboration

†*Università and INFN Bologna*

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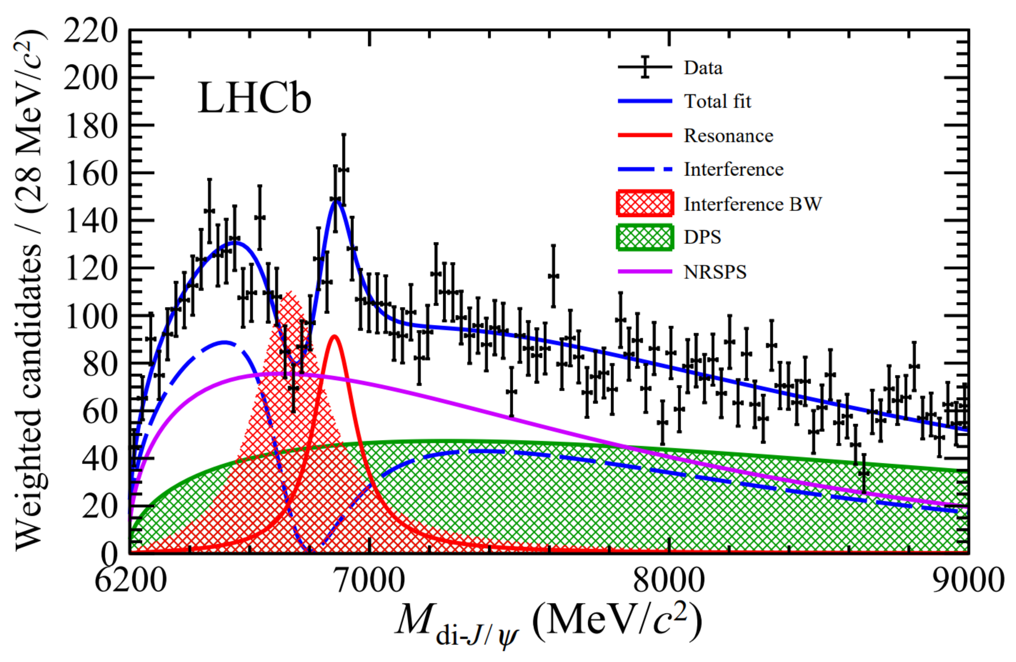
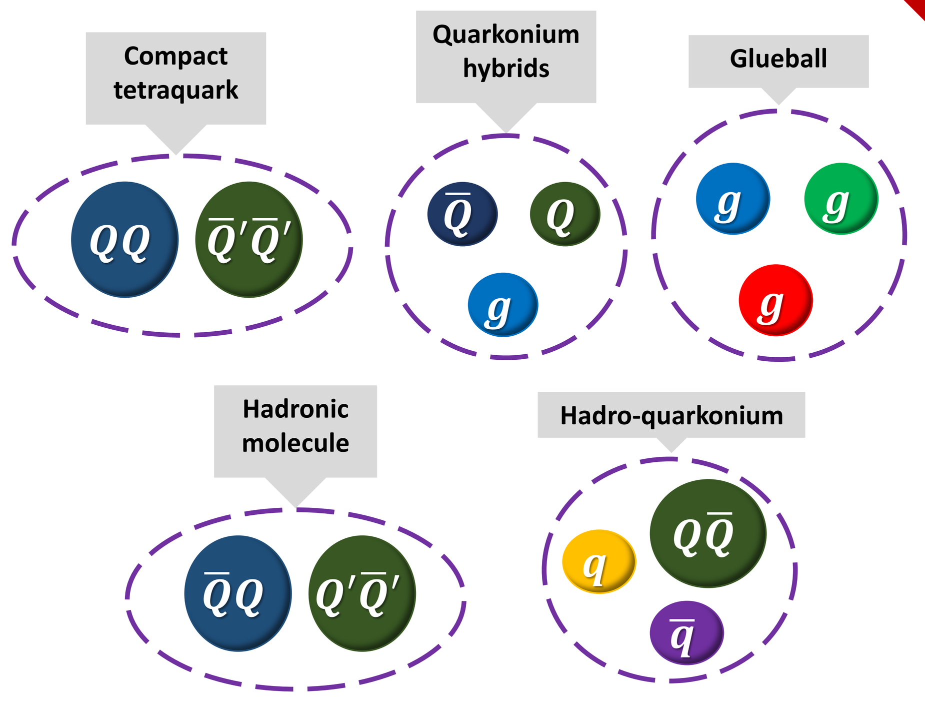
Introduction 1



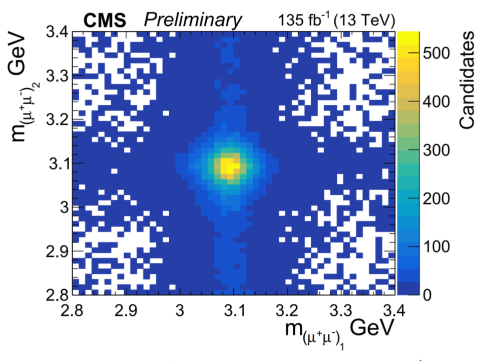
- Many doubly-heavy **tetraquarks** and several **pentaquarks candidates** are **known**: their **theoretical interpretation remain contested.**
- **Standard model QCD** allows the existence of **more complex structures other than mesons and baryons**, such as **four- or five-quarks hadrons** (tetraquarks or pentaquarks) states and states with **active gluonic degrees of freedom** (hybrids) and even **gluon-only states** (glueballs) [1].
- **Beyond standard model interpretations** of the observed **exotic hadrons** states are avaliable [2,3].

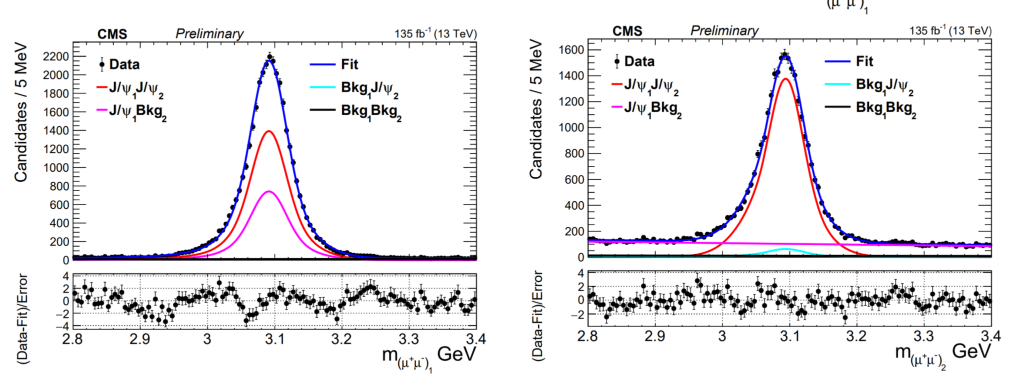


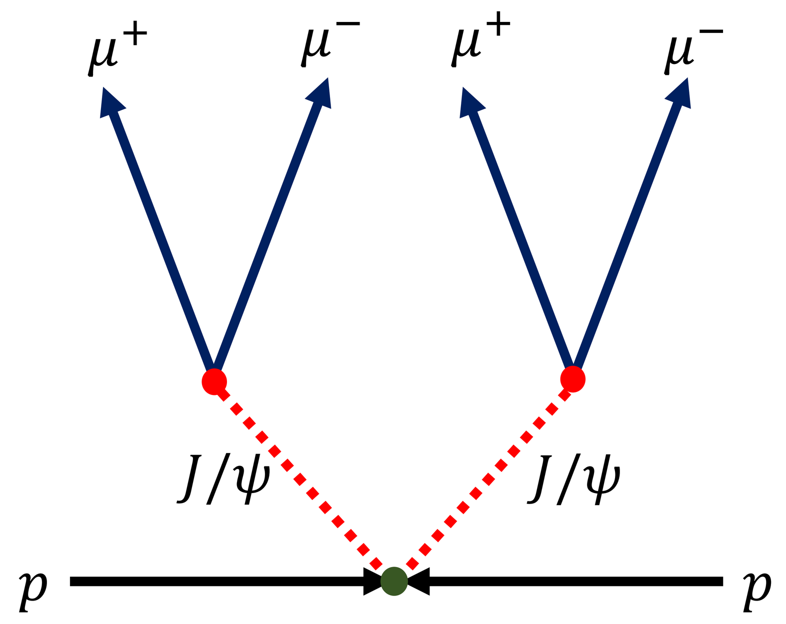
- In 2020 **LHCb Collaboration observed a peak in the $J/\psi\, J/\psi$ invariant mass spectrum**, designated as $X(6900)$ which has been interpreted as an all-charm tetraquark [4].
- LHCb's mass spectrum shows a **broad excess of events**, just above the kinematic threshold, that **background models do not account for**
- The $X(6900)$ peak is compelling but **a proper understanding of the $J/\psi\, J/\psi$ mass spectrum remains uncertain**.
- The same measurement performed by **CMS** could profit of a **higher sensitivity** since the resonance has been shown to be produced at **higher p_T**.

Trigger event selection 2

Selection optimization
- Fixed prior to look at $m(J/\psi\, J/\psi) < 7.8$ GeV region
- Based on past CMS analyses [6]
- Cross check performed maximizing Punzi figure of merit using signal meson + data-determined backgrounds yielded similar selection







Two-level **trigger** system requiring a μ **candidate + $\mu^+\mu^-$ pair**

2016 (36.3 fb^{-1})
- $|\eta(\mu)| < 2.5$
- $\mu^+\mu^-$ closest approach < 0.5 cm
- $\mu^+\mu^-$ χ^2 vertex fit probability $< 0.5\%$

2017-2018 (98.6 fb^{-1})
- Same 2016 criteria
- $2.95 < m(\mu^+\mu^-) < 3.25$ GeV
- $p_T(\mu^\pm) > 3.5$ GeV

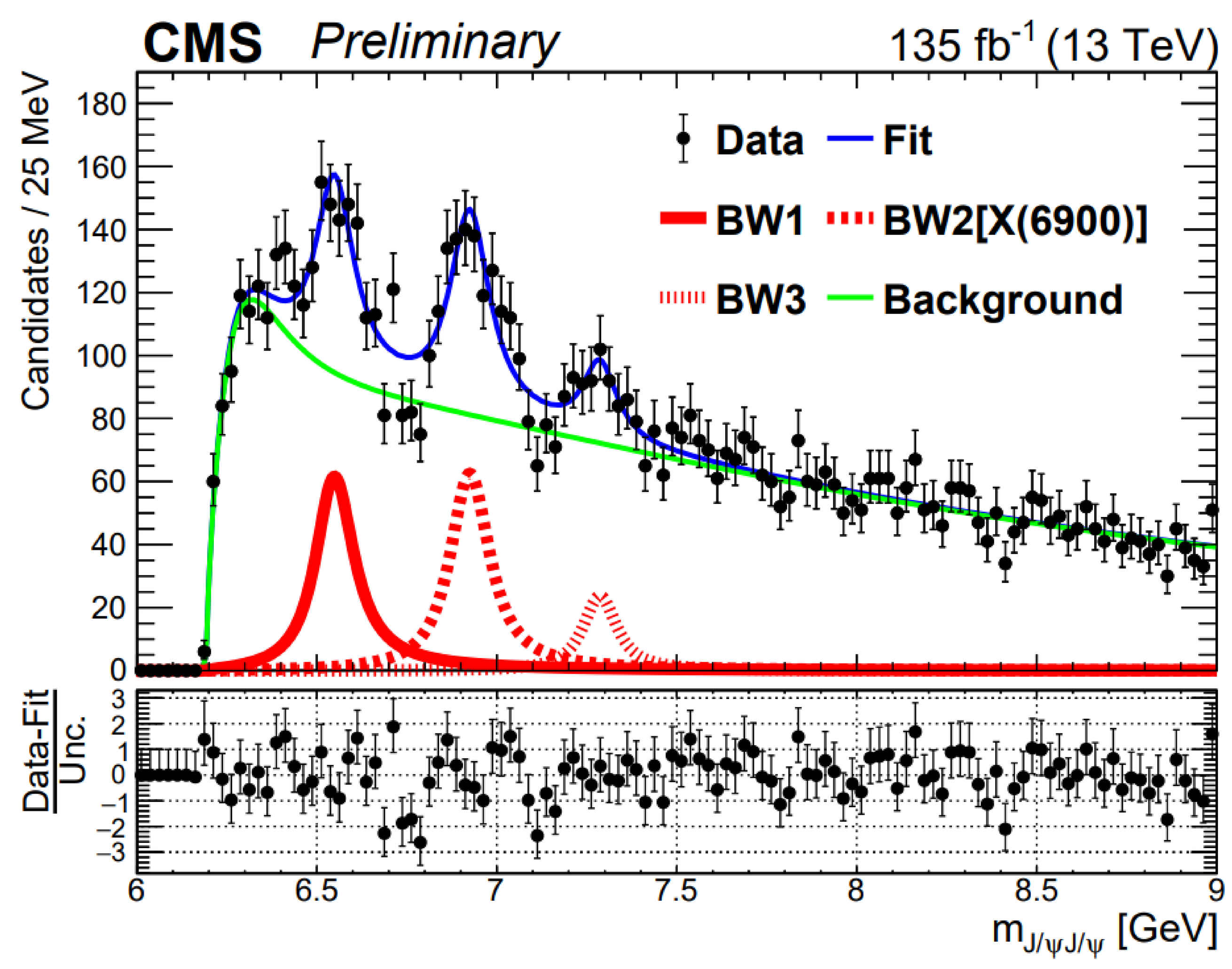
Offline selection

Muons
- Pass *soft identification* [5]
- $p_T(\mu) > 2$ GeV and $|\eta(\mu)| < 2.4$

J/ψ vertex
- $p_T(\mu^+\mu^-) > 3.5$ GeV
- Vertex fit probability > 0.5%
- $m(\mu^+\mu^-)$ constrained to $m^{\text{PDG}}_{J/\psi}$

$J/\psi\, J/\psi$ vertex
- $\mu^+\mu^-\mu^+\mu^-$ vertex fit probability > 0.5%
- $J/\psi\, J/\psi$ vertex fit probability >0.1%
- Best muon permutation based on mass-uncertainty-weighted distance in the 2D $m(\mu^+\mu^-) - m_{J/\psi}$ plane

Fit strategy 3



Background shapes based on MC simulations:
- **Nonresonant single-parton scattering** (NRSPS)

$$f_{SPS}(x, x_0, \alpha, p_1, p_2, p_3) =$$
$$= (x - x_0)^\alpha \times \left(1 - \left(\frac{1}{(15 - x_0)^2} - \frac{p_1}{10}\right)(15 - x)^2\right)$$
$$\times \exp\left(-\frac{(x - x_0)^{p_3}}{2p_2^{p_3}}\right)$$

where $x_0 = 2M_{J/\psi}$

- **Nonresonant double-parton scattering** (NRDPS)

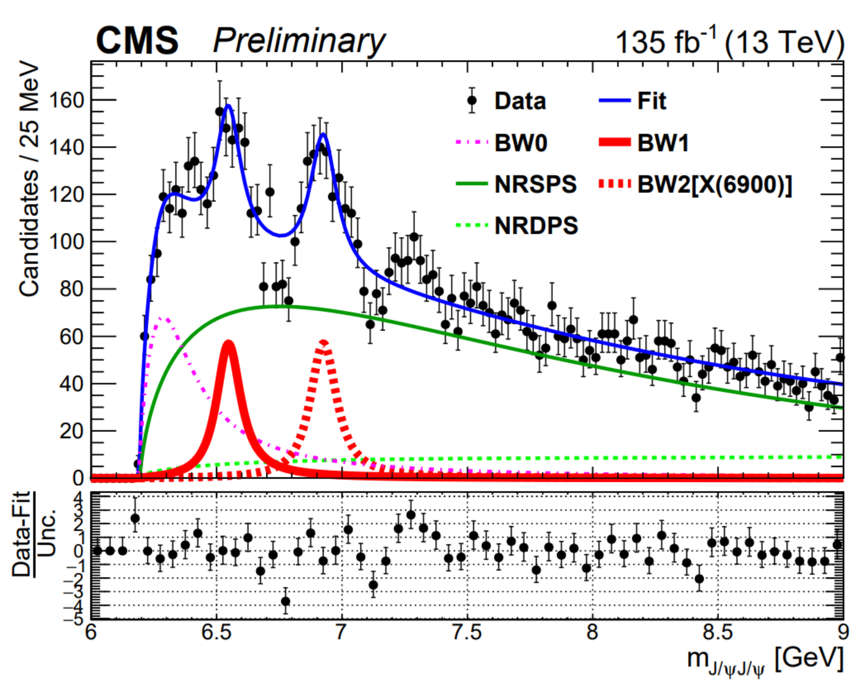
$$f_{DPS}(x) = \sqrt{x_t} \times \exp(-\alpha x_t) \times (p_0 + p_1 x_t + p_2 x_t^2)$$

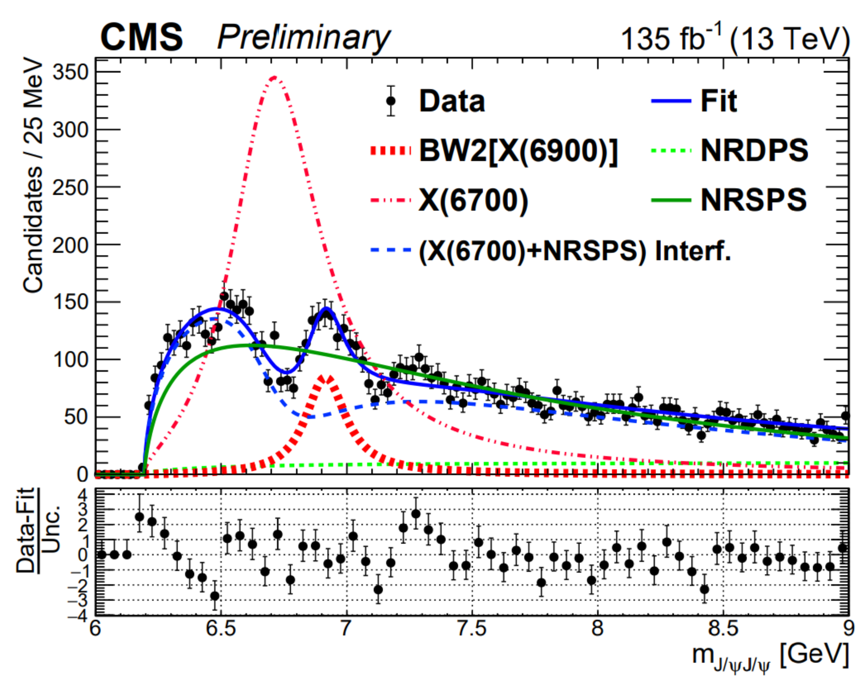
where $x_t = x - x_0$ and $x_0 = 2M_{J/\psi}$

Fit model building:
- Perform a sequence of fits adding new features until a reasonable description of data is obtained
- Starting from NRSPS+NRDPS+BW0 model
- New features are added one at the time if their local significance exceeds 3 standard deviations
- Repeat until no additional structures above 3 standard deviations are found

Signal shapes are relativistic **Breit-Wigner** functions convolved with **Gaussian resolution functions** (BW):
- **BW0** → threshold enhancement
- **BW1** → structure at ≃ 6600 MeV
- **BW2** → $X(6900)$
- **BW3** → structure at ≃ 7200 MeV

CMS data with LHCb fit models 4





Model I:
- Background modeled using NRSPS+NRDPS shapes
- Signal modeled using 3 Breit-Wigner functions: BW0 and BW1 to model $X(6300)$ and $X(6500)$ structures and BW2 to model $X(6900)$ resonance

Results:
- $M[\text{BW2}] = 6927 \pm 10$ MeV; $\Gamma[\text{BW2}] = 117 \pm 24$ MeV → consistent with LHCb
- Fit probability $\chi^2 = 1.2 \times 10^{-4}$ for mass region below 7.5 GeV: the model fails to describe the dip at 6750 MeV and the structure at 7200 MeV.
- The fit fails in describing the data as reported also by LHCb.

Model II:
- Background modeled using NRSPS+NRDPS shapes
- Signal modeled using a Breit-Wigner to model the $X(6900)$ resonance and a Breit-Wigner + interference term to model the dip at 6700 MeV.

Results:
- Better description of the dip at 6700 MeV and fit results compatible with LHCb
- Fit probability $\chi^2 = 0.84 \times 10^{-4}$ for mass region below 7.5 GeV: the region around 6550 MeV is now poorly described.
- The discrepancies around peak/dip structure at 7200 MeV also contribute to a poor fit result.

Summary 5

The $J/\psi\, J/\psi$ **mass spectrum** has been analyzed using **pp collision at $\sqrt{s} = 13$ TeV recorded by the CMS experiment** in the 2016-2018 data-taking period corresponding to **an integrated luminosity of 135 fb^{-1}**

Three resonance-like structures exceeding 3 standard deviations have been observed

	Mass (MeV)	Width (MeV)	Local significance
BW1	$6552 \pm 10 \pm 12$	$124 \pm 29 \pm 34$	$> 5.7\,\sigma$
BW2	$6927 \pm 9 \pm 5$	$122 \pm 22 \pm 19$	$> 9.4\,\sigma$
BW3	$7287 \pm 19 \pm 5$	$95 \pm 46 \pm 20$	$> 4.1\,\sigma$

The fit model provides a good description of the data, however:
- Fit probability $\chi^2 = 0.01$ for mass region below 7.5 GeV → the **model does not account for** the **dips** around **6750 and 7150 MeV**
- Models **incorporating interference** are an important class to explore
- **Including more resonances** in the fit to account for the dips in non-interference models is also forseen

Bibliography 6

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[6] CMS Collaboration, "Measurement of Prompt J/ψ Pair Production in pp Collisions at √s = 7 TeV", *JHEP* **09** (2014) 094, doi:10.1007/JHEP09(2014)094, arXiv:1406.0484.

leonardo.lunerti@cern.ch