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Rencontres du Vietnam, Flavour Physics Conference 2022

# Heavy Flavour Physics at the LHC

Speaker:
Vincenzo Mastrapasqua
on behalf of the LHC Collaboration

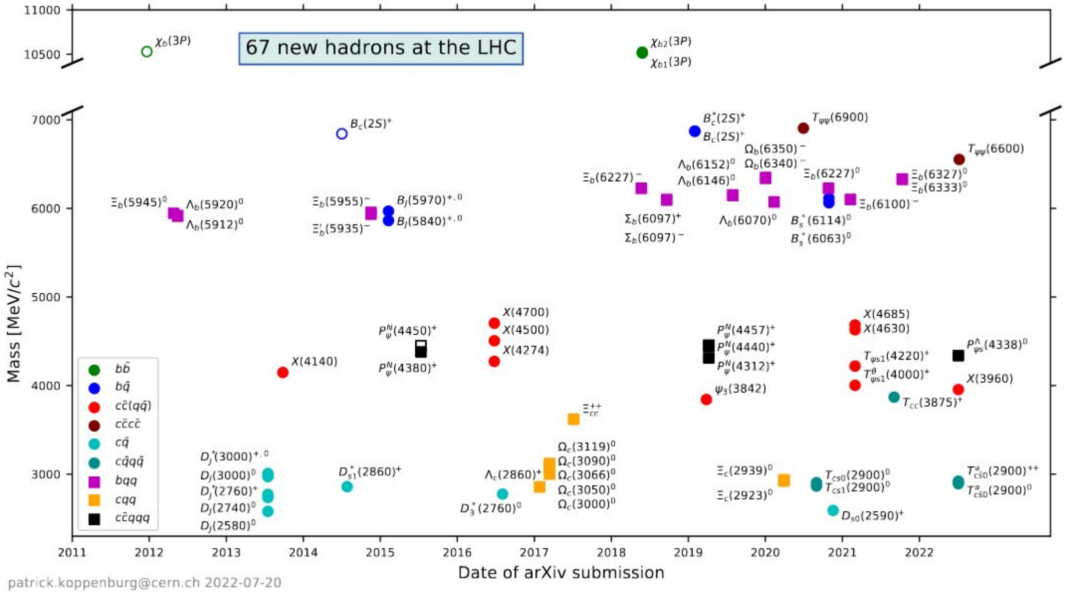
Università degli Studi di Bari “Aldo Moro”
Istituto Nazionale di Fisica Nucleare - Sez. Bari
CMS Collaboration

# Heavy Flavour Physics at the LHC

LHC provides high luminosity for heavy flavour physics processes

**Heavy flavor production cross section several order of magnitudes greater than at e-e colliders,**

but the hadron collisions environment is characterized by **complex initial state and high background**



patrick.koppenburg@cern.ch 2022-07-20

**67 new hadrons** discovered at LHC since its start!

LHCb-FIGURE-2021-001, 2022 updated

LHCb proposes a **new naming scheme** to navigate through this growing particle zoo

arXiv:2206.15233

# Selected recent results at LHC

A selection of recent results from the LHC Collaboration is here presented

- **Heavy Flavour exotic spectroscopy**:
  - Observation of a di-charmonium resonance X(6900)
    - LHCb: Sci.Bull. 65 (2020), 23
    - CMS: CMS-PAS-BPH-21-003
    - ATLAS: ATLAS-CONF-2022-040
  - $T^{a}_{c\bar{s}0}(2900)^{++/0}$ in B → $\bar{D}D_s^+\pi$ decay — LHCb-PAPER-2022-026 and LHCb-PAPER-2022-027
  - X(3960) candidate in $B^+ \to D_s^+ D_s^- K^+$ — LHCb-PAPER-2022-018 and LHCb-PAPER-2022-019
  - J/ψΛ resonance in $B^- \to J/\psi\Lambda\bar{p}$ decay — LHCb-PAPER-2022-031

  (in preparation)

- **Heavy Flavour production and conventional spectroscopy**:
  - $B_c \to J/\psi D_s^{(*)}$ decays — ATLAS: JHEP 08 (2022) 087
  - $\chi_{c1}(3872)$ production in pp / pPb / PbPb — LHCb: LHCb-CONF-2022-001 CMS: PRL 128 (2022) 032001
  - Simultaneous triple J/ψ production — CMS: https://arxiv.org/abs/2111.05370 (submitted to Nature Physics)

# Heavy Flavour exotic spectroscopy

# X(6900) at LHCb in 2020

$J/\psi J/\psi$ ( ➔ $4\mu$) spectrum studied at LHCb using 9 $fb^{-1}$ of pp collisions at $\sqrt{s}$ = 7, 8, 13 TeV

Sci.Bull. 65 (2020), 23

Two structures are reported:

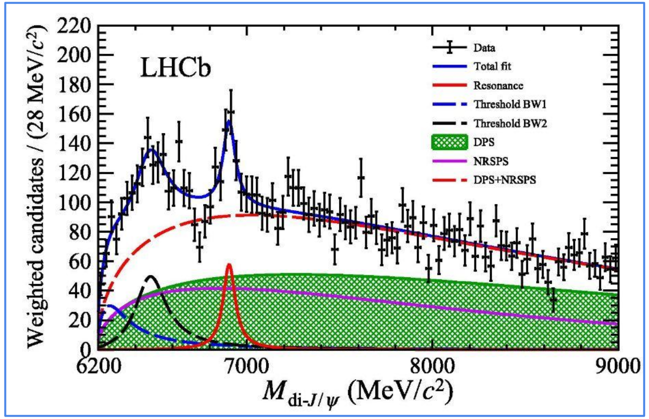
- **A narrow resonance, X(6900)**, renamed $T_{\psi\psi}(6900)$
- A broad structure near the di-$J/\psi$ mass threshold

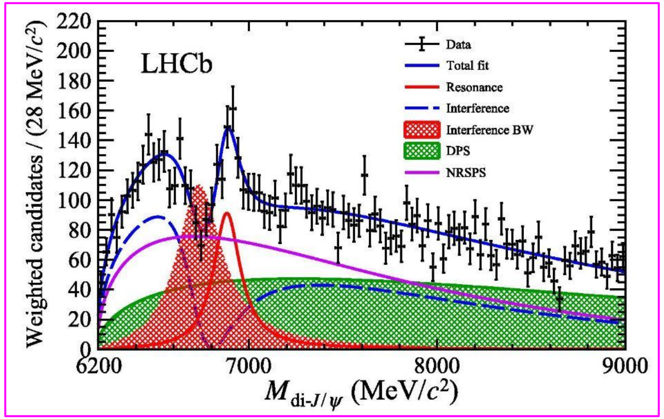
Background contribution for $J/\psi$ pair production:

- Non-Resonant Single Parton Scattering (NRSPS)
- Non-Resonant Double Parton Scattering (DPS)

**Two signal + background fit models are considered**:

- **Model 1 (top)** - poor description of the "dip" at 6.7 GeV
  - background
  - Breit-Wigner for X(6900)
  - two auxiliary Breit-Wigner (near threshold)
- **Model 2 (bottom)**
  - a "virtual" X(6700) to interfere with NRSPS is added



# X(6900) at CMS in 2022

J/ψJ/ψ ( ➔ 4μ) spectrum studied at CMS using 135 $fb^{-1}$ of pp collisions at $\sqrt{s}$ = 13 TeV (2016-2018) CMS-PAS-BPH-21-003

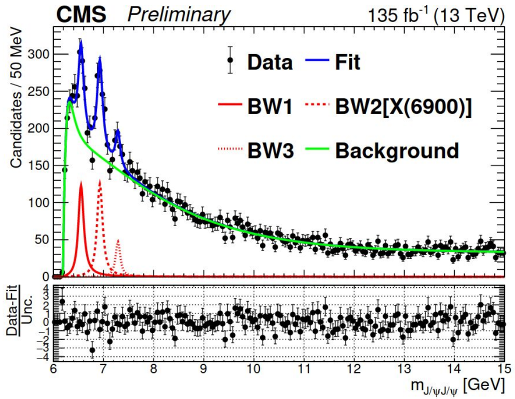
**Event selection and reconstruction**:

- **3-μ trigger**: $\mu^+\mu^-$ from J/ψ + third muon (on muons from J/ψ: $p_T(\mu^+\mu^-)$ > 3.5 GeV in 2017-2018)
- **blinded signal region m(J/ψJ/ψ) in [6.2, 7.8] GeV** (from preliminary investigation on 2011-2012 data)
- $p_T(\mu)$ > 2.0 GeV; $|\eta(\mu)| < 2.4$; loose muon identification
- $m(\mu^+\mu^-)$ in [2.95, 3.25] GeV; $p_T(\mu^+\mu^-)$ > 3.5 GeV $P_{vtx}(\mu^+\mu^-)$ > 0.5%
- common vertex fit: $P_{vtx}(4\mu)$ > 0.5%
- Arbitration of multiple candidates:
  - Select best combination of same 4μ (from MC: 0.2%)
  - Keep all candidates arising from more than four muons (from MC: 0.2%)

$$\chi^2_m = \left(\frac{m_1(\mu^+\mu^-)-M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-)-M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

**Background model**:

- **NRSPS**: threshold function * pol2 * exponential
- **NRDPS**: threshold function * pol2 * exponential
- **BW0**: Relativistic Breit-Wigner near J/ψJ/ψ threshold
  - inadequacy of NRSPS near threshold
  - feed-down of partially reconstructed higher mass states
  - possible coupled-channel interactions, pomeron-exchange processes, etc.




$\chi^2$-Prob = 79% in [6.2, 15] GeV

# X(6900) at CMS in 2022

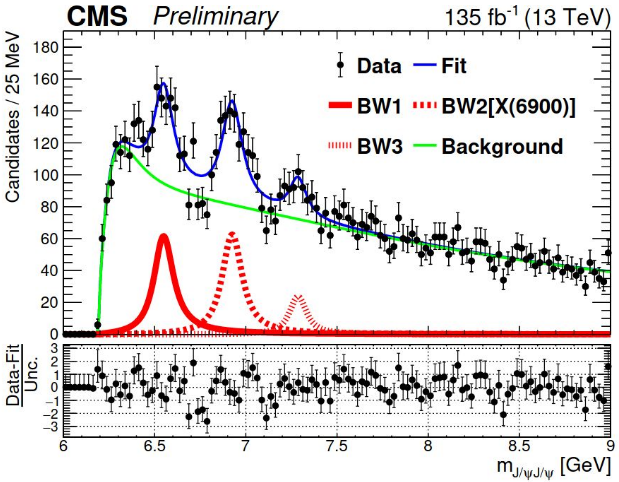
## CMS signal + background model

Three Relativistic Breit-Wigner ($J^P = 0^+$) are considered

| | Mass (MeV) | Width (MeV) | Local stat. signif. |
|---|---|---|---|
| BW1 | 6552 ± 10 ± 12 | 124 ± 29 ± 34 | > 5.7σ |
| BW2 | 6927 ± 9 ± 5 | 122 ± 22 ± 19 | > 9.4σ |
| BW3 | 7287 ± 19 ± 5 | 95 ± 46 ± 20 | > 4.1σ |

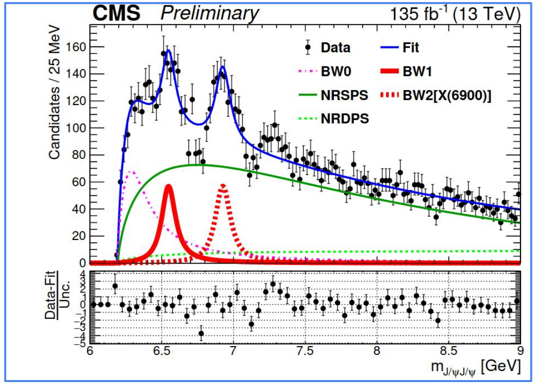
first error is statistic, second is systematic error

X(6900) confirmed at CMS
Values consistent with LHCb

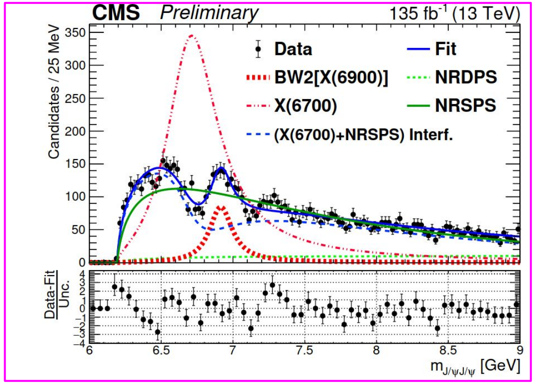



## LHCb signal models + CMS background

- **Model 1:**
  - X(6900) parameters in agreement
  - but dip at 6.7 not well described
- **Model 2:**
  - Larger X(6700) amplitude
  - X(7300) region not well described




$\chi^2$-Prob = $10^{-4}$ in [6.2, 7.8] GeV




$\chi^2$-Prob = $10^{-4}$ in [6.2, 7.8] GeV

# X(6900) at ATLAS in 2022

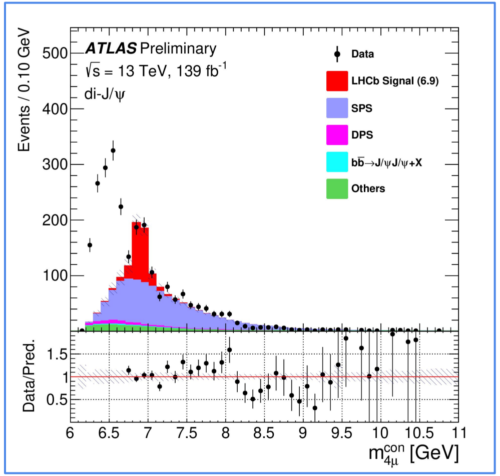
J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 139 fb$^{-1}$ of pp at √s = 13 TeV ATLAS-CONF-2022-040

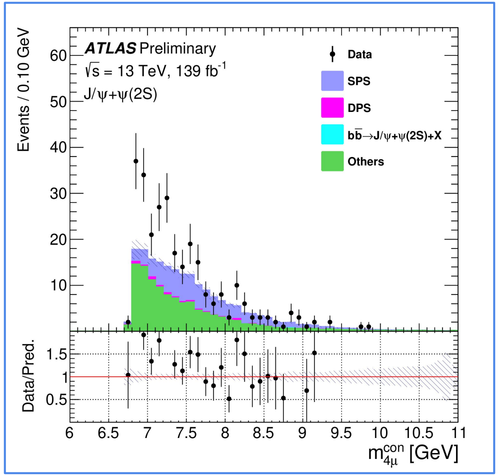
Prompt (SPS, DPS) and non-prompt ( $b\bar{b} \to J/\psi J/\psi$ ) background contributions are considered

**Event selection, reconstruction and definition of signal and control regions** →

| Signal region | SPS/DPS control region | non-prompt region |
|---|---|---|
| Di-muon or tri-muon triggers, Opposite charged muons from the same $J/\psi$ or $\psi(2S)$ vertex, Loose muon ID, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in \{2.94, 3.25\}$ GeV, or $m_{\psi(2S)} \in \{3.56, 3.80\}$ GeV, Loose vertex cuts $\chi^2_{4\mu}/N < 40$ and $\chi^2_{\text{di-}\mu}/N < 100$, | | |
| Vertex $\chi^2_{4\mu}/N < 3$, $L^{4\mu}_{xy} < 0.2$ mm, $\lvert L^{\text{di-}\mu}_{xy}\rvert < 0.3$ mm, | | Vertex $\chi^2_{4\mu}/N > 6$, $\lvert L^{\text{di-}\mu}_{xy}\rvert > 0.4$ mm |
| $m_{4\mu} < 7.5$ GeV, $\Delta R < 0.25$ between charmonia | 7.5 GeV $< m_{4\mu} < 12.0$ GeV (SPS) 14.0 GeV $< m_{4\mu} < 25.0$ GeV (DPS) | |

**4μ mass data vs background predictions before fit for J/ψJ/ψ and J/ψ+ψ(2S)**




Feed-down from higher mass states not included

**Signal model: interfering BWs ⊗ resolution**

- J/ψJ/ψ: 2/3 interfering BW
- J/ψ+ψ(2S):
  - A: 3 interfering BW + 4$^{th}$ resonance
  - B: single resonance

# X(6900) at ATLAS in 2022

**J/ψJ/ψ: best fit obtained with 3 interfering BWs**, 70% worse fit quality for 2-resonance fit

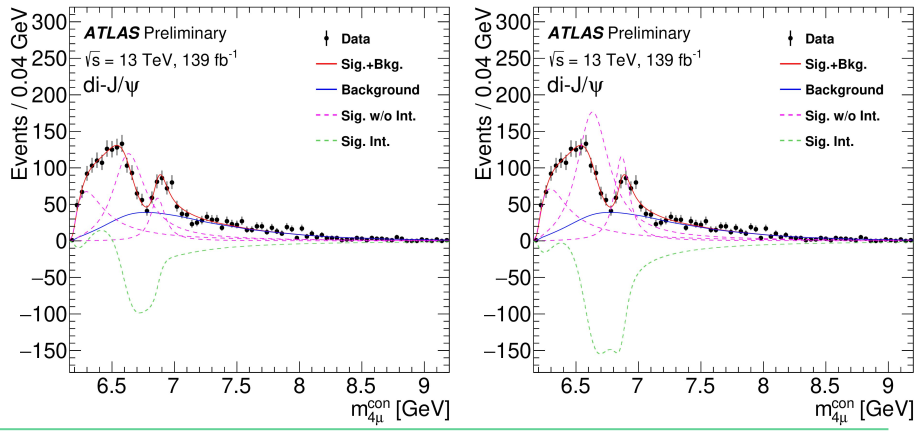
**6.9 GeV resonance confirmed**, consistent with LHCb

$$m = 6.87 \pm 0.03^{+0.06}_{-0.01} GeV$$

$$\Gamma = 0.12 \pm 0.04^{+0.03}_{-0.01} GeV$$

Similar results using LHCb Model 1 as signal model, Model 2 disfavoured by fit quality

fitted mass in SR, 3-resonance fit (2 out of 4 degenerate fit results)

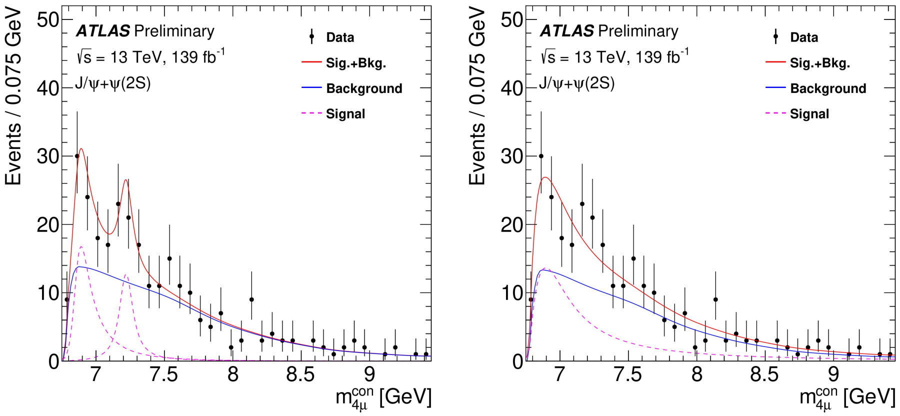



**Fit on J/ψψ(2S) mass spectrum**, significance:

- Model A: 4.6σ
  - X(7200): 3.2σ
- Model B: 4.3σ

**Evidence for an enhancement at 6.9 GeV and 7.2 GeV, but other explanations are possible**

fitted mass in SR, Model A (left) and Model B (right)



# Observation of tetraquarks in $B \to \bar{D} D_s^+ \pi$

LHCb-PAPER-2022-026

LHCb-PAPER-2022-027

Two decay channels reconstructed at LHCb using 9 $fb^{-1}$ of pp collisions (Run 1 + Run 2)

- 3751 $B^+ \to D^- D_s^+ \pi^+$ cands (purity: 95.2%)
- 4008 $B^0 \to \bar{D}^0 D_s^+ \pi^-$ cands (purity: 90.7%)

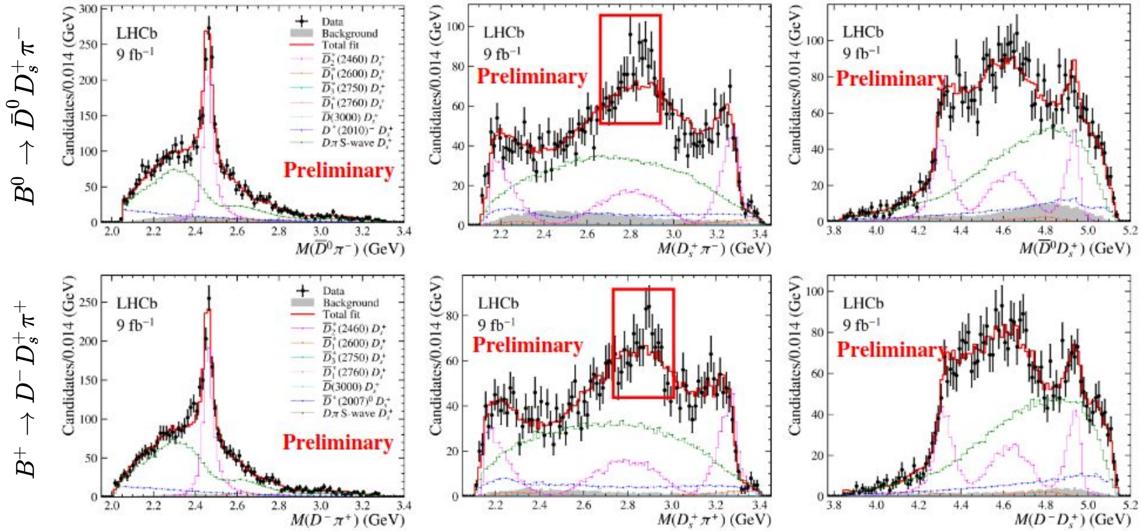
Amplitudes for intermediate resonances derived from helicity formalism

Approximate isospin symmetry ➔ parameters shared between channels

Amplitude analysis - UML Fit:

**Fit with only D** resonances does not describe well data**, even if more D** are added

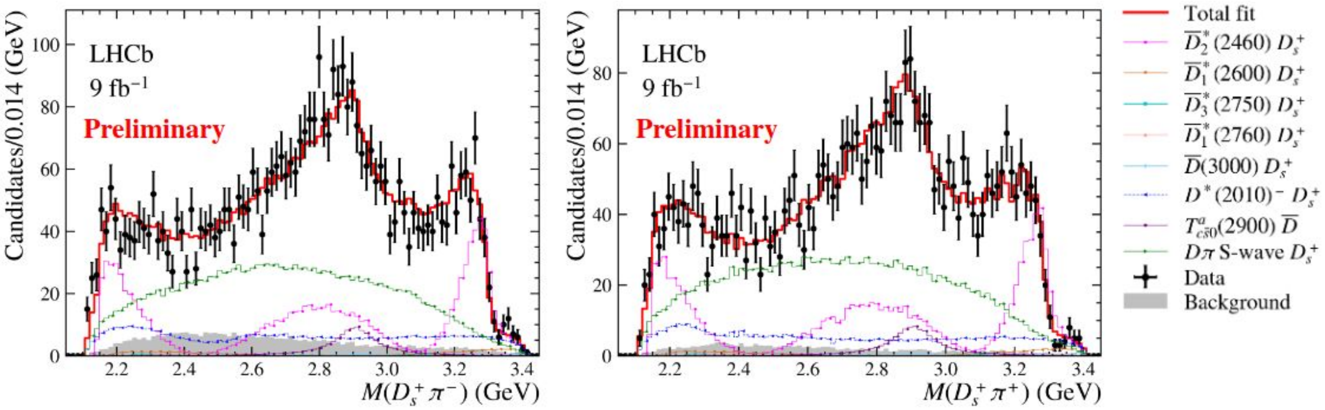
**Contribution from $D_s\pi$ is added**



# Observation of tetraquarks in $B \to \bar{D} D_s^+ \pi$

**Fit with additional $D_s^+\pi^\pm$ resonance**, named $T^a_{c\bar{s}0}(2900)^{++/0}$

$B^0 \to \bar{D}^0 D_s^+ \pi^-$ $B^+ \to D^- D_s^+ \pi^+$




**$M(D_s\pi)$ well described adding a $J^P = 0^+$ resonance in each channel (significance > 9σ)**

$J^P = 0^+$ favoured over other spin-parity assignment by over 7.5σ

**Resonances' parameters** measured: M = 2.908 ± 0.011 ± 0.020 GeV Γ = 0.136 ± 0.023 ± 0.011 GeV

First tetraquarks composed of $[c\bar{s}u\bar{d}]$, $[c\bar{s}\bar{u}d]$: **ongoing search for isospin partner $T^a_{c\bar{s}0}(2900)^+ \to D_s^+\pi^0$**

# Observation of tetraquarks in $B^+ \to D_s^+ D_s^- K^+$

LHCb-PAPER-2022-018

LHCb-PAPER-2022-019

360 $B^+ \to D_s^+ D_s^- K^+$ cands reconstructed at LHCb using 9 fb$^{-1}$ of pp collisions (Run 1 + Run 2)

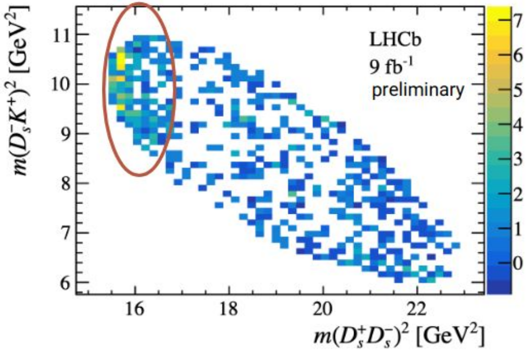
**Near-threshold enhancement observed in m($D_s^+D_s^-$)**

Amplitudes derived from helicity formalism

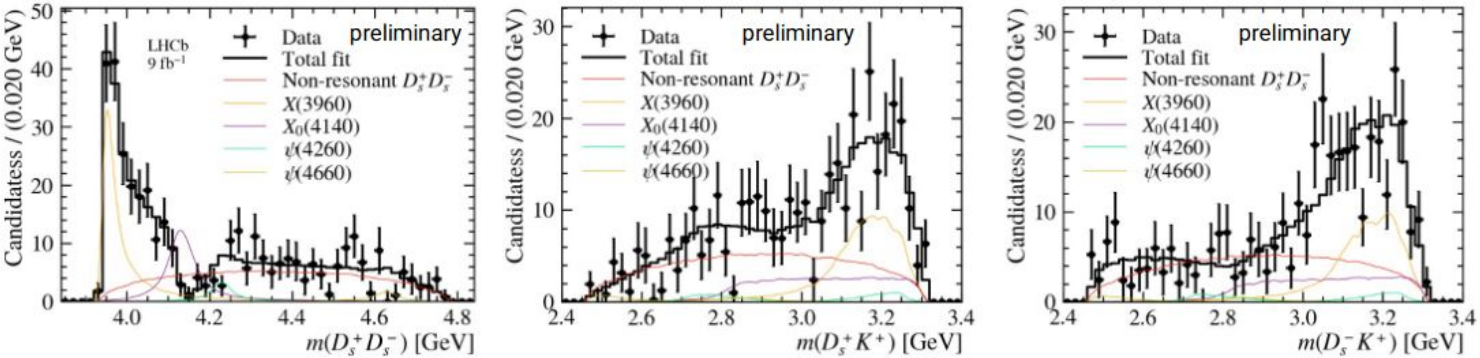
UML fit on background-subtracted data

**Baseline model well describes data**:

- $0^{++}$: X(3960), $X_0$(4140), non-resonant
- $1^{--}$: ψ(4260), ψ(4660)




**X(3960) describes near-threshold peak**
**Interference with $X_0$(4140) accounts for the dip**



# Observation of tetraquarks in $B^+ \to D_s^+ D_s^- K^+$

Fit results

| Component | $J^{PC}$ | $M_0$ [MeV] | $\Gamma_0$ [MeV] | $\mathcal{F}$ [%] | $\mathcal{S}$ [$\sigma$] |
|---|---|---|---|---|---|
| $X(3960)$ | $0^{++}$ | $3955 \pm 6 \pm 12$ | $48 \pm 17 \pm 10$ | $24.2 \pm 7.6 \pm 7.9$ | 12.6 (14.3) |
| $X_0(4140)$ | $0^{++}$ | $4133 \pm 7 \pm 11$ | $69 \pm 17 \pm 7$ | $17.7 \pm 4.9 \pm 7.7$ | 3.7 (3.9) |
| $\psi(4260)$ | $1^{--}$ | 4230 | 55 | $3.7 \pm 0.4 \pm 3.0$ | 3.1 (3.3) |
| $\psi(4660)$ | $1^{--}$ | 4633 | 64 | $2.2 \pm 0.2 \pm 0.5$ | 2.9 (3.2) |
| NR | $S$-wave | - | - | $46.6 \pm 13.3 \pm 11.3$ | 3.1 (3.4) |

First uncertainty is statistical, and second systematic

**Assuming that X(3960) is that same particle as $\chi_0(3930)$** (OK within 3σ), **the following ratio is evaluated**:

$$\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^+)} = \frac{\mathcal{B}(B^+ \to D^+ D^- K^-)\, FF^X_{D^+ D^- K^+}}{\mathcal{B}(B^+ \to D_s^+ D_s^- K^-)\, FF^X_{D^+ D^- K^+}} = 0.29 \pm 0.09\,(stat) \pm 0.10\,(syst) \pm 0.08\,(ext)$$

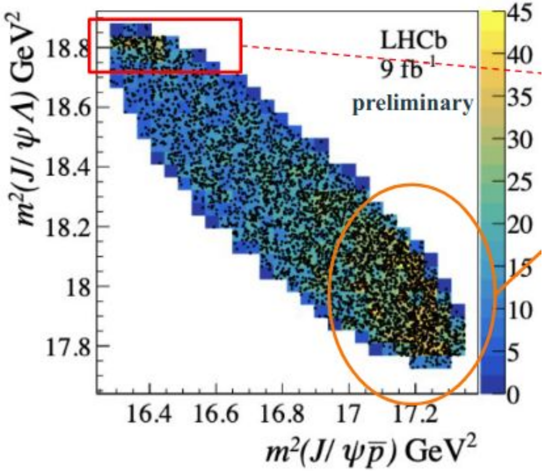
Conventional charmonia prevalently decay into $D^{(*)}\bar{D}^{(*)}$

**Ratio smaller than 1 implies the exotic nature of the state**

- Precision measurements on X(3960) and $\chi_0(3930)$ needed to understand if they are the same particle
- X(3960) / $\chi_0(3930)$ / $\chi_0(3915)$ ➔ J/ψω decays could give further information on the exotic nature

# Observation of J/ψΛ resonance in $B^- \to J/\psi\Lambda\bar{p}$

Decay studied at CMS (19.8 $fb^{-1}$, 8 TeV): inconsistent with flat phase space
JHEP 12 (2019) 100



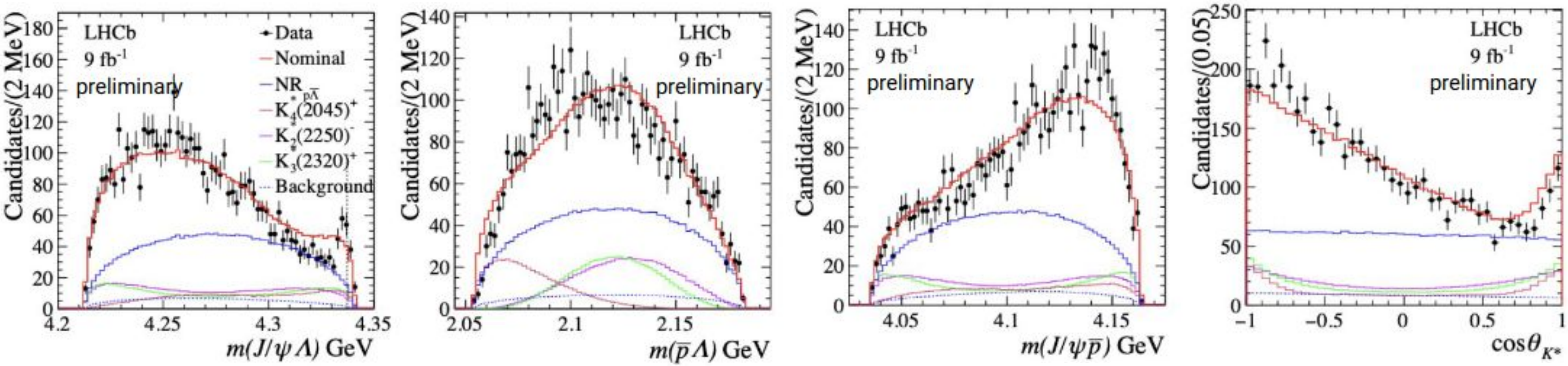

Analysis on full LHCb dataset: 9 $fb^{-1}$ of pp collisions (Run 1 + Run 2)
LHCb-PAPER-2022-031

4600 $B^-$ cands collected with a displaced J/ψ ➜ μμ trigger (purity: 93%)

**Narrow structure in J/ψΛ, activity in J/ψp̄**

Full amplitude analysis (6D) to investigate possible reflections from $K^*_{2,3,4}$

**K*-only model cannot describe data** ($\chi^2$/ndf = 123/33)



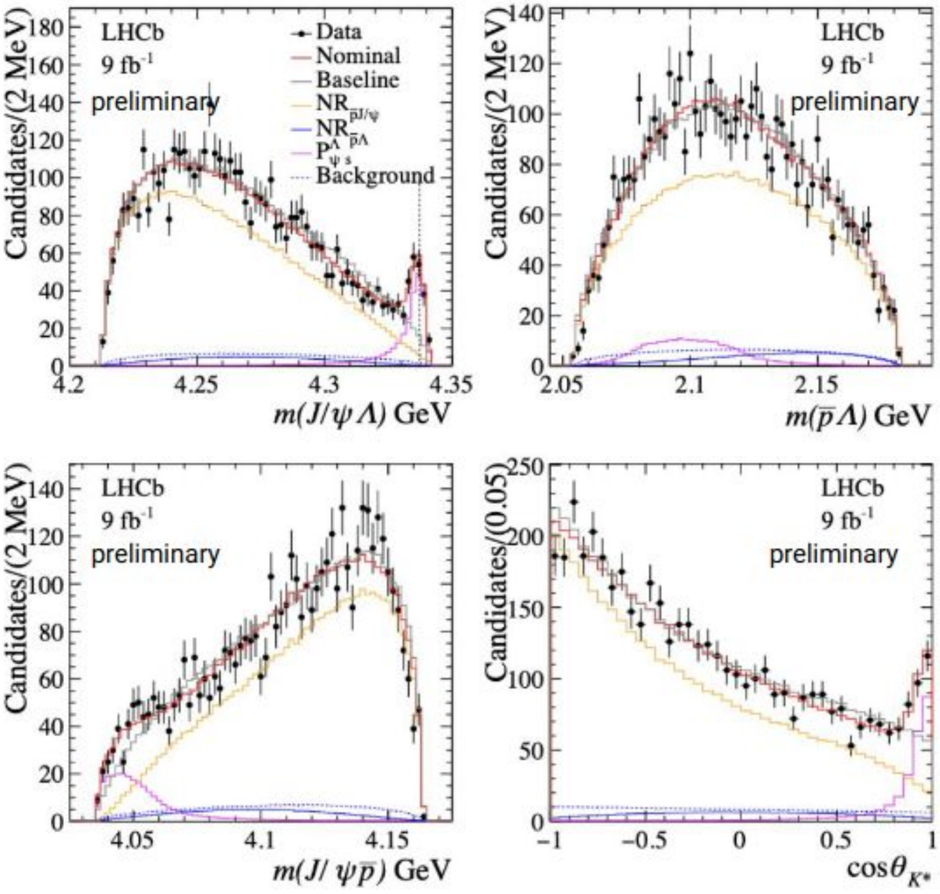
# Observation of J/ψΛ resonance in $B^- \to J/\psi\Lambda\bar{p}$

Goodness-of-fit test: $\chi^2_{max}$ of 1D projections

- **Baseline model:**
  - NR($\bar{p}\Lambda$) + NR($\bar{p}J/\psi$)
  - $\chi^2$/ndf = 121/39
- **Model with J/ψΛ:**
  - NR($\bar{p}\Lambda$) + NR($\bar{p}J/\psi$) + $P^{\Lambda}_{\psi s}(J/\psi\Lambda)$
  - $\chi^2$/ndf = 55.3/39 p = 4.4%

**Fit results:**

- $m(P^{\Lambda}_{\psi s})$ = 4338.2 ± 0.7 MeV
- $\Gamma(P^{\Lambda}_{\psi s})$ = 7.0 ± 1.2 MeV
- $f(P^{\Lambda}_{\psi s})$ = 12.5 ± 0.7 %
- Favoured spin J = ½
- Parity P = -1 favoured
- $J^P = ½^+$ rejected at 90% CL
- significance > 10σ (from Wilks' theorem)



# Heavy Flavour production and non-exotic spectroscopy

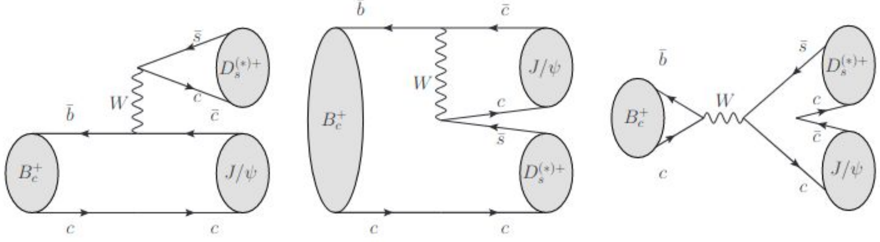
# Study of $B_c \to J/\psi D_s^{(*)}$ decays

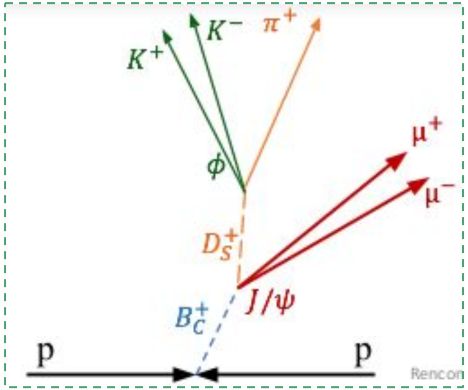
The $B_c$ decays are reconstructed at ATLAS using 139 $fb^{-1}$ of pp collisions (Run 2) JHEP 08 (2022) 087

Pseudoscalar meson decaying into two vector states described with **three helicity amplitudes**: **$A_{++}$, $A_{--}$** (transverse polarizations), **and $A_{00}$** (longitudinal polarization)

- **Decays' reconstruction:**
  - $J/\psi \to \mu^+\mu^-$
  - $D_s^+ \to \phi(\to K^+K^-)\pi^+$
  - $D_s^* \to D_s\pi^0/\gamma$ (soft, not reco'd)
- **Fiducial region:**
  - $p_T(B_c) > 15$ GeV
  - $|\eta(B_c)| < 2.0$
- **Reference decay:**
  - $B_c^+ \to J/\psi\pi^+$

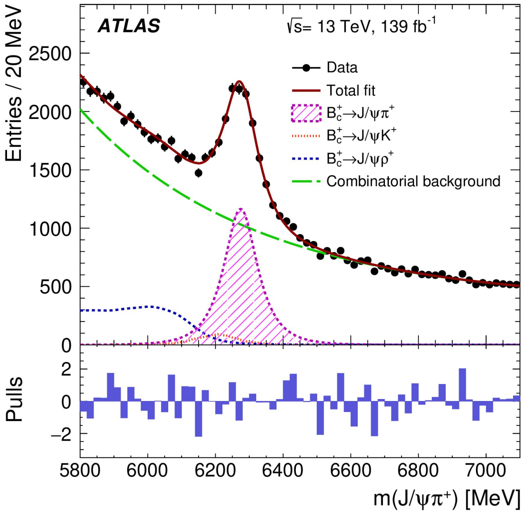
Feynman diagrams for $B_c \to J/\psi D_s$ decays




Signal yield for reference decay:

$$N(B_c^+ \to J/\psi\pi^+) = 8440^{+550}_{-470}$$



# Study of $B_c \to J/\psi D_s^{(*)}$ decays

**2D UML fit** in $m(J/\psi D_s)$ and $J/\psi$ helicity angle $\cos(\theta'(\mu^+))$

- $N(B_c \to J/\psi D_s^+) = 241 \pm 28$ (stat.)
- $N(B_c \to J/\psi D_s^*) = 424 \pm 46$ (stat.)

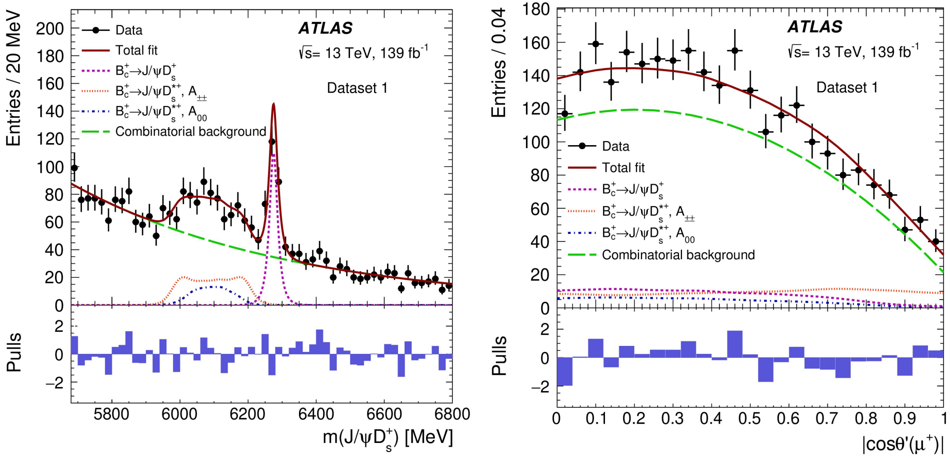
From fit: ratios of branching fractions $R(D_s^{*+}/\pi)$, $R(D_s^+/\pi)$, $R(D_s^{*+}/D_s^+)$ and the transverse polarization fraction $\Gamma_{\pm\pm}/\Gamma_{00}$

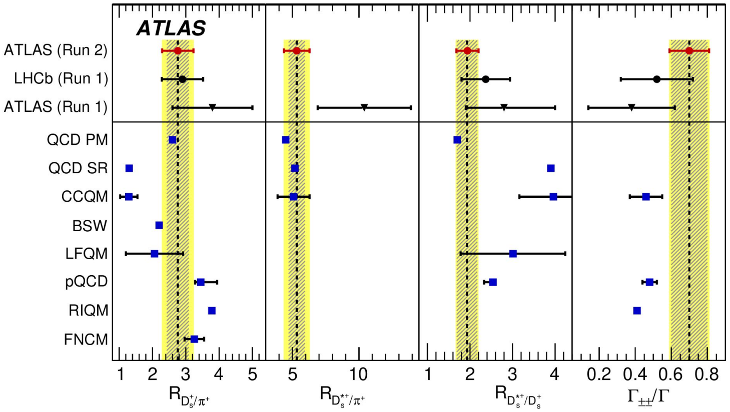
**Measurements in agreement with previous ones, with improved precision**

$R(D_s^{*+}/\pi)$ well described by predictions

Other predictions consistently deviate from data

$\Gamma_{\pm\pm}/\Gamma_{00}$ in agreement with naive ⅔ spin counting



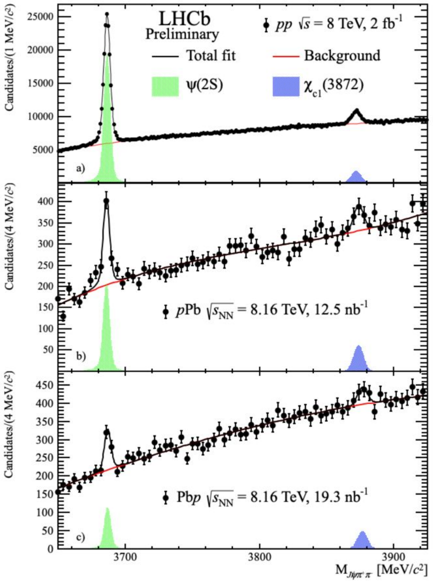



# X(3872) production in different collision systems

**X(3872)** [aka $\chi_{c1}$(3872)] does not fit $c\bar{c}$ spectrum: **narrow state above $D\bar{D}$ threshold**

**LHCb**: first measurement of $\chi_{c1}$(3872) in pPb
LHCb-CONF-2022-001

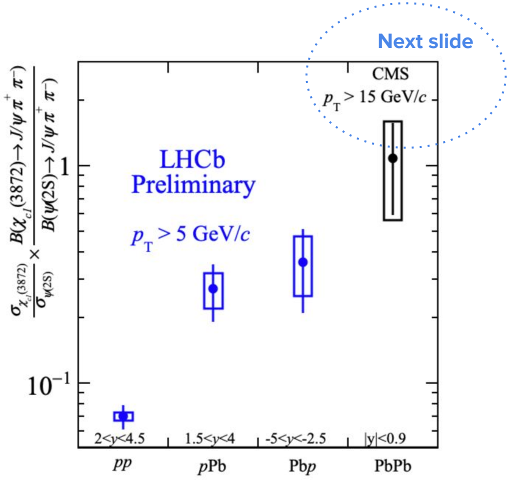
$\chi_{c1}$(3872) and ψ(2S) - as reference - reconstructed in $J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$ final state




Pseudo decay-time to select prompt component:

$t_z = (z_{decay} - z_{PV})\, M / p_z$

| System | Rapidity | Energy | Luminosity |
|---|---|---|---|
| $pp$ | $2 < y < 4.5$ | 8 TeV | $2\,\mathrm{fb}^{-1}$ |
| $p$Pb | $1.5 < y_{cm} < 4$ | 8.16 TeV | $12.5\,\mathrm{nb}^{-1}$ |
| Pb$p$ | $-5 < y_{cm} < -2.5$ | 8.16 TeV | $19.3\,\mathrm{nb}^{-1}$ |




Initial state-effect are largely cancelled in the ratio

The ratio increases with the system size, different from the decreasing trend as multiplicity observed in pp [PRL 126 (2021) 092001]

Hint that coalescence effect dominates $\chi_{c1}$(3872) production in pPb?

# X(3872) production in different collision systems

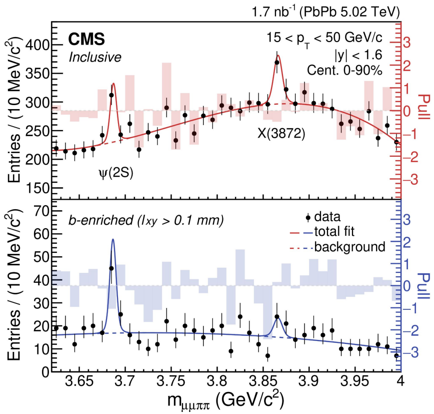
First evidence using 1.7 $nb^{-1}$ of PbPb collisions data (2018) at CMS at $\sqrt{s_{NN}}$ = 5.02 TeV per nucleon pair PRL 128 (2022) 032001

kinematical range: $15 < p_T < 50$ GeV/c, $|y| < 1.6$

**UML fit to extract signal yields for ψ(2S) and X(3872)**

Final state: $J/\psi(\rightarrow \mu^+\mu^-)\,\pi^+\pi^-$

**Significance for inclusive X(3872): 4.2σ**

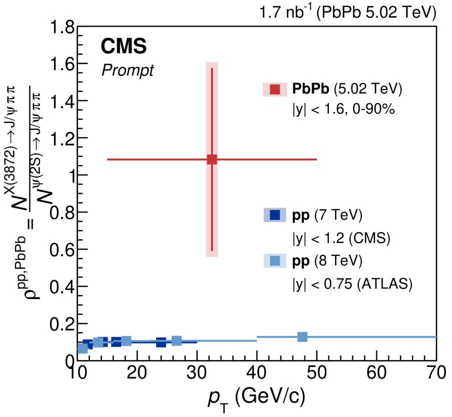



Prompt fraction estimated with MC studies

Yields corrected by acceptance and overall efficiency

**Ratio of corrected yields for prompt production in PbPb collisions $\rho^{pp}$ :**

- **compatible with 1** (within 1σ)
- **compatible with $\rho^{pp} \approx 0.1$** (within 2σ)




Much larger data sample expected in Run-3 at LHC in order to improve the measurement and understand the internal structure of X(3872) and the differences of its production mechanism w.r.t. ψ(2S)

# Simultaneous production of three J/ψ mesons

N-parton scattering: simultaneous hard interaction of N partons

$$\sigma_{\mathrm{DPS}}^{\mathrm{pp}\to\psi_1\psi_2+\mathrm{X}} = \left(\frac{\mathrm{m}}{2}\right)\frac{\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_1+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_2+\mathrm{X}}}{\sigma_{\mathrm{eff,DPS}}}$$

$\psi_1 \neq \psi_2$: m = 1
$\psi_1 = \psi_2$: m = 2

**Triple J/ψ production is a probe for Triple Parton Scattering** (TPS)

$$\sigma_{\mathrm{TPS}}^{\mathrm{pp}\to\psi_1\psi_2\psi_3+\mathrm{X}} = \left(\frac{\mathrm{m}}{3!}\right)\frac{\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_1+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_2+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_3+\mathrm{X}}}{\sigma_{\mathrm{eff,TPS}}^2}$$

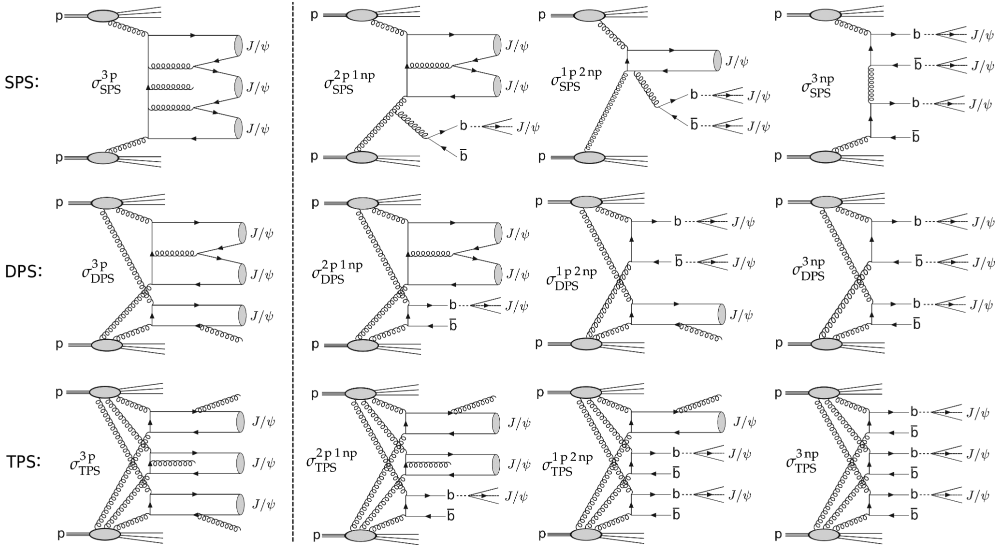
Simplest theoretical approach: uncorrelated partons

$$\sigma_{eff,TPS} = \kappa\,\sigma_{eff,DPS} \qquad \kappa = 0.82 \pm 0.11$$

from PRL 118 (2017) 122001

**3-J/ψ Production via both prompt and non-prompt contributions**

Pure prompt production: Nonprompt contributions:




Effective xsec $\sigma_{\mathrm{eff,DPS}}$: pp transverse overlap
From simulation it is expected $\sigma_{\mathrm{eff,DPS}} \approx$ 20-30 mb

Previous measurements:

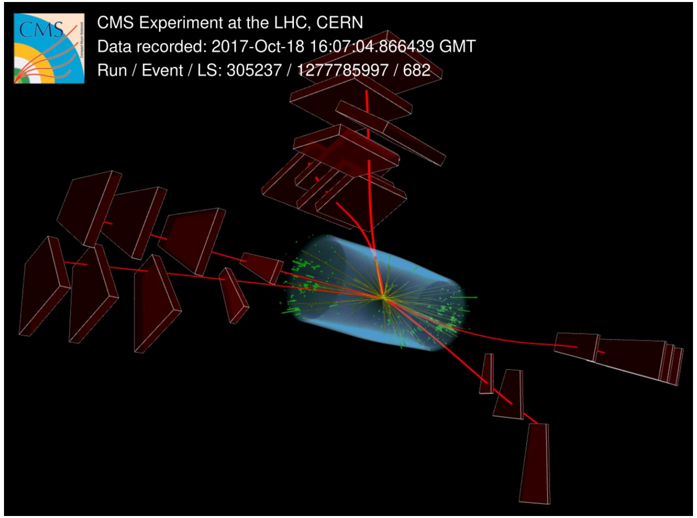
- ≈ 3-10 mb from di-quarkonia final states
- ≈ 10-20 mb from jets, photons, EW bosons

Disagreement due to parton correlation, different contribution from quarks/gluons, poor control of SPS contribution

# Simultaneous triple-J/ψ production at CMS

First observation at CMS using 133 $fb^{-1}$ of pp collisions at 13 TeV

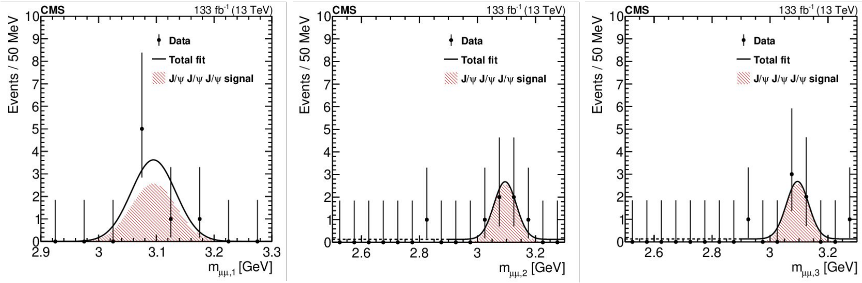
https://arxiv.org/abs/2111.05370




**Event selection**:

- J/ψ+μ trigger
- PV chosen as highest $\sum p_T^2$
- event with six muons (3 OS pairs)
- three μ-pairs with
  - opposite sign
  - $m(\mu^+\mu^-)$ in [2.9, 3.3] GeV
  - good common vertex
  - compatible with PV (can be non-prompt)

**Very clean signature - Six 3-J/ψ events passing selection**




Signal yield extraction → N = 5.0 ± 2.0
dimuon BR = (5.961 ± 0.033)% (PDG)

Trigger eff.: 0.84 ± 0.034 (MC)
ID*reco eff. 0.78 ± 0.01 (data driven)

$$\sigma(pp \to 3J/\psi) = \frac{N}{\varepsilon_{trig}\,\varepsilon_{id}\,\varepsilon_{reco}\,\mathcal{L}\,[\mathcal{B}(J/\psi \to \mu\mu)]^3} = 272^{+141}_{-104}(stat) \pm 17(syst)\ fb$$

# Simultaneous triple-J/ψ production at CMS

**Theoretical total 3-J/ψ cross section expressed as sum of contributions from SPS, DPS and TPS**

Each process has contribution from both prompt and non-prompt production

DPS and TPS contributions as product of SPS terms

Using SPS cross-sections from generators:

$$\sigma_{eff,DPS} = 2.7^{+1.4}_{-1.0}(exp)^{+1.5}_{-1.0}(theo)\,mb$$

**SPS, DPS and TPS contributions**:

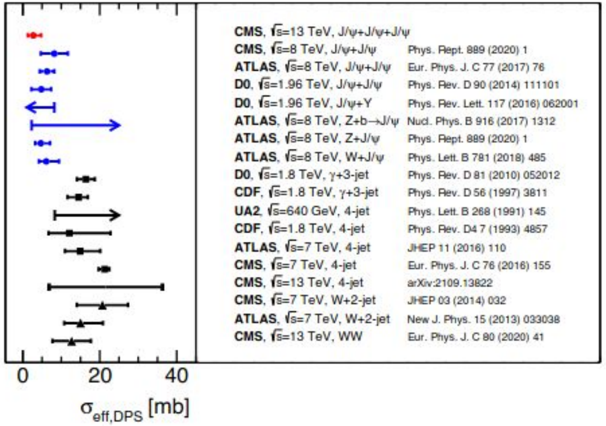
$f_{SPS}$ = 6% **$f_{DPS}$ = 74%** **$f_{TPS}$ = 20%**

$\sigma_{eff,DPS}$ value consistent with other measurement from di-quarkonium production, but not with extractions from processes with jets, photons and W bosons (probably because of contributions from EW sector)

$$\begin{aligned}\sigma^{3J/\psi}_{tot} &= \sigma^{3J/\psi}_{SPS} + \sigma^{3J/\psi}_{DPS} + \sigma^{3J/\psi}_{TPS} \\ &= \left(\sigma^{3p}_{SPS} + \sigma^{2p1np}_{SPS} + \sigma^{1p2np}_{SPS} + \sigma^{3np}_{SPS}\right) \\ &\quad + \left(\sigma^{3p}_{DPS} + \sigma^{2p1np}_{DPS} + \sigma^{1p2np}_{DPS} + \sigma^{3np}_{DPS}\right) + \left(\sigma^{3p}_{TPS} + \sigma^{2p1np}_{TPS} + \sigma^{1p2np}_{TPS} + \sigma^{3np}_{TPS}\right)\end{aligned}$$

$$\sigma^{3J/\psi}_{DPS} = \frac{\mathrm{m}_1\left(\sigma^{2p}_{SPS}\sigma^{1p}_{SPS} + \sigma^{2p}_{SPS}\sigma^{1np}_{SPS} + \sigma^{1p}_{SPS}\sigma^{1p1np}_{SPS} + \sigma^{1p1np}_{SPS}\sigma^{1np}_{SPS} + \sigma^{1p}_{SPS}\sigma^{2np}_{SPS} + \sigma^{2np}_{SPS}\sigma^{1np}_{SPS}\right)}{\sigma_{eff,DPS}},$$

$$\sigma^{3J/\psi}_{TPS} = \frac{\mathrm{m}_3\left(\left(\sigma^{1p}_{SPS}\right)^3 + \left(\sigma^{1np}_{SPS}\right)^3\right) + \mathrm{m}_2\left(\left(\sigma^{1p}_{SPS}\right)^2\sigma^{1np}_{SPS} + \sigma^{1p}_{SPS}\left(\sigma^{1np}_{SPS}\right)^2\right)}{\sigma^2_{eff,TPS}},$$



# Conclusions

- A **selection of recent results in B-Physics production and spectroscopy from the LHC Collaboration** is presented
- **67 new hadrons have been discovered at LHC since its start** and the particle zoo is constantly growing
- **Different experiments at the LHC observe independently new particles** and can confirm each others' results
- Further understanding of QCD is possible thanks to **precise measurement of physics parameters in different collisions environments**

# THANKS FOR YOUR ATTENTION

contacts:
vincenzo.mastrapasqua@ba.infn.it
vincenzo.mastrapasqua@cern.ch