4μ light and heavy resonances at CMS

LHCP 2023, 24 May
2023 Belgrade, Serbia

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*on behalf of the **CMS Collaboration***

Work is supported by MEPhI program “Priority2030”

Outline

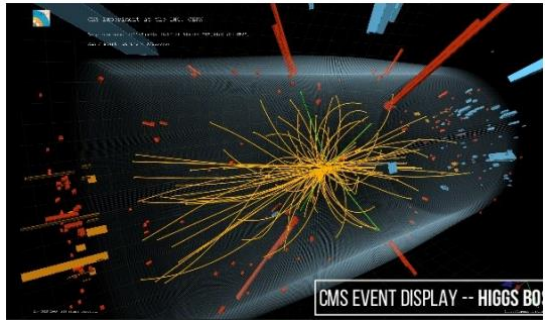
CMS collaboration has several recent results on spectroscopy:

- Observation of $\Xi_b(6100)^-$ baryon
- Observation of $\Lambda_b^0 \to J/\psi\, \Xi^-\, K^+$ decay (**NEW**)
- Observation of $B^0 \to \psi(2S)\, K_S^0 \pi^+\pi^-$ and $B_s^0 \to \psi(2S)\, K_S^0$ decays

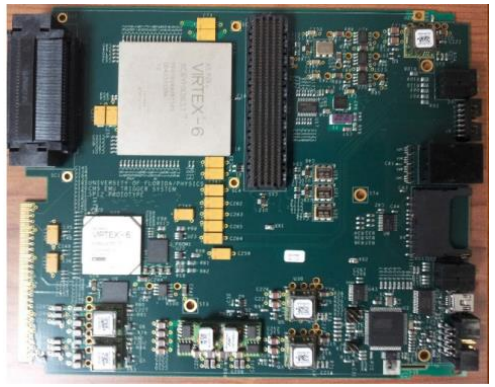
Covered in a talk by Maksim on Friday + a poster yesterday

- **Observation of $\eta \to 4\mu$ decay**
- **Near-threshold resonances decaying to $J/\psi\, J/\psi$**

CMS trigger & readout system



LHC collisions ~40 MHz



L1 trigger
~100 kHz (hard limit)
3.2 µs/evt (hard limit)

We can record more, but trading off either the event size OR the prompt reconstruction

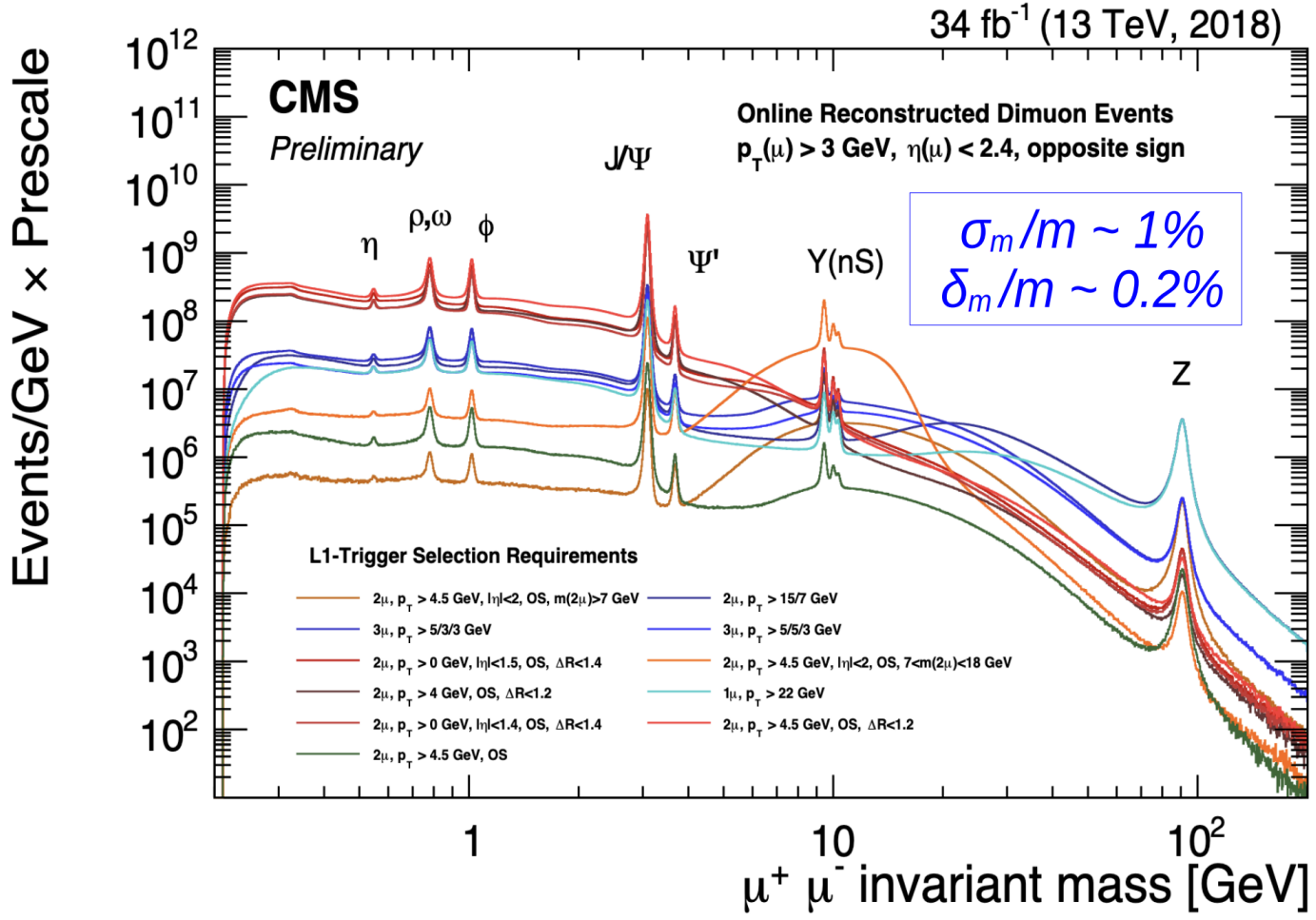
High-Level Trigger, HLT
~0.5 s/evt (hard limit)
1.5 kHz (soft limit)

GRID

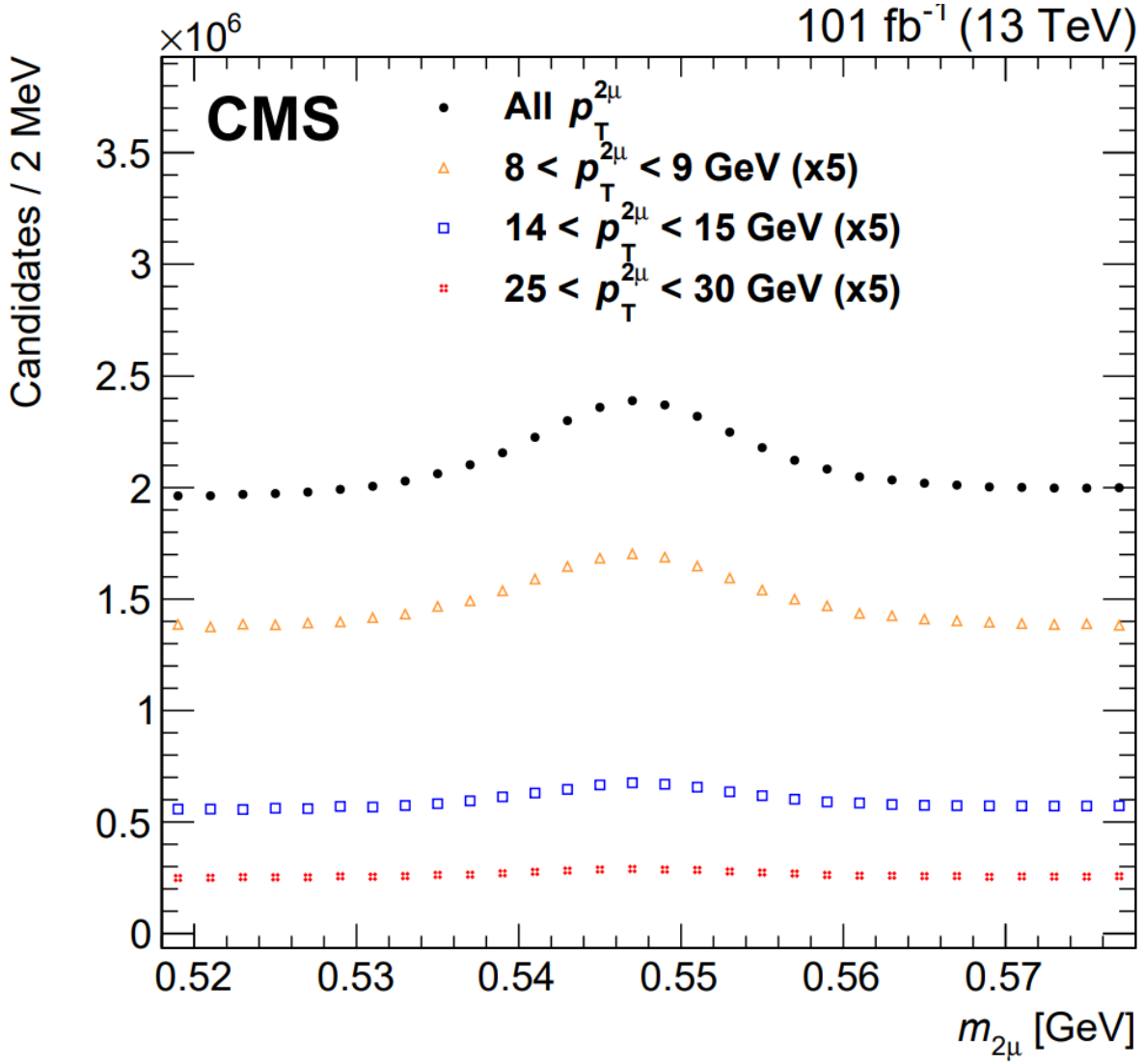
Dimuon scouting data

L1 path	p_T [GeV]	$\|\eta\|$	ΔR	$m_{2\mu}$ [GeV]	Charge	Fraction
#1	>4.0 (4.5)	–	<1.2	–	OS	90%
#2	–	< 1.5	< 1.4	–	OS	48%
#3	>15, >7	–	–	–	–	46%
#4	>4.5	< 2.0	–	7–18	OS	9%

- After L1, events are typically further filtered by the HLT
  - → ~1 MB / event, O(100 Hz) for muons
- For the ***scouting stream (2017 and 2018)***, only minimal requirements are applied after the HLT reconstruction
- Very limited high-level event information is saved
  - **→ 4-8 kB / event, O(2-5 kHz) for muons**



$\eta \to \mu^+\mu^-$ in scouting data



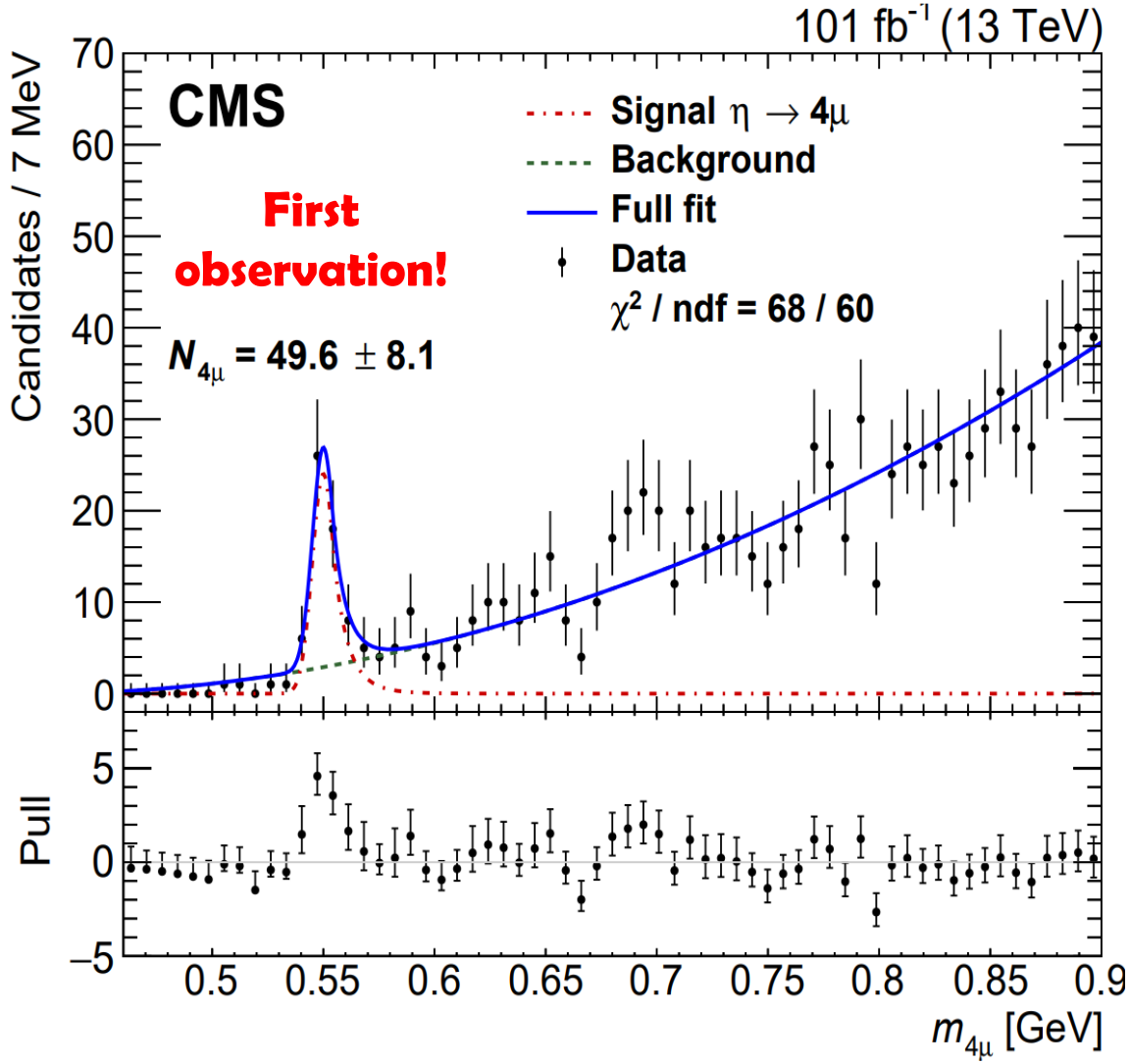
- Around **4.5 x 10^6** signal $\eta \to \mu^+\mu^-$ events in the scouting data!
- $\mathcal{B}(\eta \to \mu^+\mu^-) \sim 6 \times 10^{-6}$!

→ ~**10^{12} η** produced in "CMS acceptance"
(even more after correcting for efficiency)

$\eta \to \mu^+\mu^-$ signal is used to calibrate η meson production vs. p_T and y in MC

BPH-22-003, arXiv:2305.04904

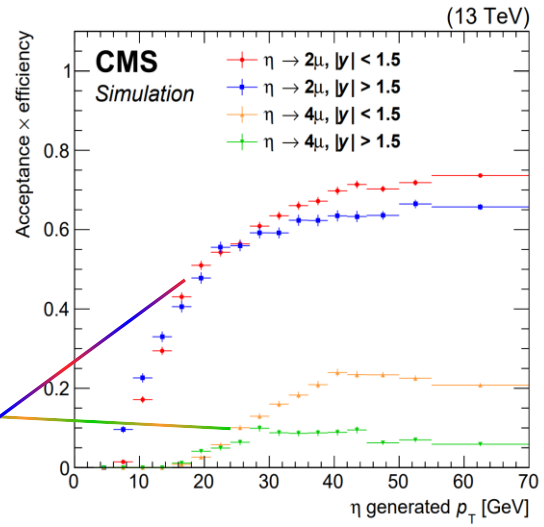
$\eta \to \mu^+\mu^-\mu^+\mu^-$ observation



- A clear narrow peak of ~50 events, near the kinematic threshold
- Fit with Crystall-Ball + threshold $(m_{4\mu} - 4m_{\mu})^{\beta}$
- **Significance > 5σ**
- Several misreconstructed decays were shown to not be able to produce such a peak

$\mathcal{B}$ measured relative to $\eta \to \mu^+\mu^-$ using $\mathbf{A} \times \boldsymbol{\varepsilon}$ ratio $^{4\mu}/_{2\mu}$ map vs. p_T and y:

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$

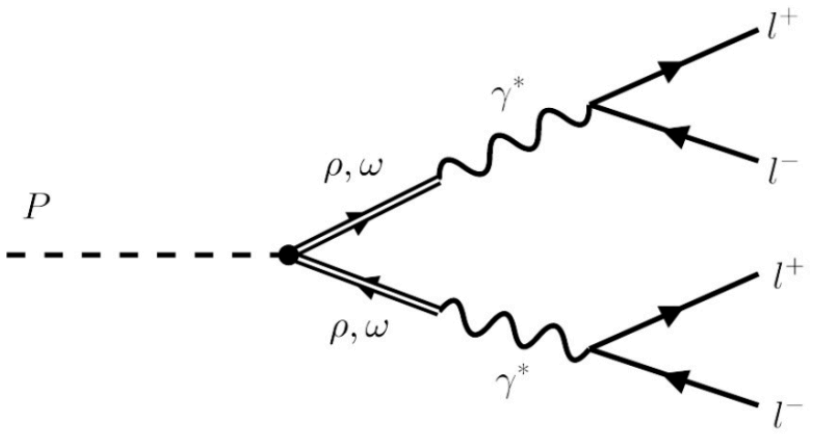


i,j = p_T, y ranges

[BPH-22-003](), [arXiv:2305.04904]()

$\eta \to \mu^+\mu^-\mu^+\mu^-$

BPH-22-003, arXiv:2305.04904



Fully-leptonic decays of pseudoscalar mesons η and η':

- Allow precision tests of the SM
- Impact the knowledge of hadronic correction $(g\text{-}2)_\mu$

So far, the following modes have been observed:

$\eta \to \mu^+\mu^-$ (SERPUKHOV-134, 1980), $\eta \to e^+e^-e^+e^-$ (KLOE-2, 2011), $\eta' \to e^+e^-e^+e^-$ (BESIII, 2022)

We present the first observation of $\eta \to \mu^+\mu^-\mu^+\mu^-$, and measurements

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.86 \pm 0.14\,(\text{stat}) \pm 0.12\,(\text{syst})) \times 10^{-3}$$

$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B}_{2\mu})) \times 10^{-9}$$

In agreement with SM prediction: $3.98 \pm 0.15 \cdot 10^{-9}$ [*Chin.Phys.C 42 (2018) 2, 023109*]

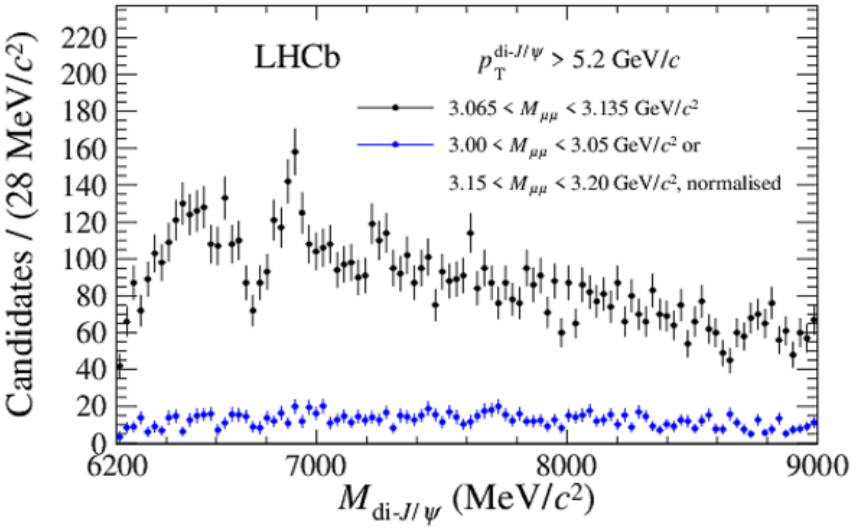
Tetraquark candidates decaying to J/ψ pairs

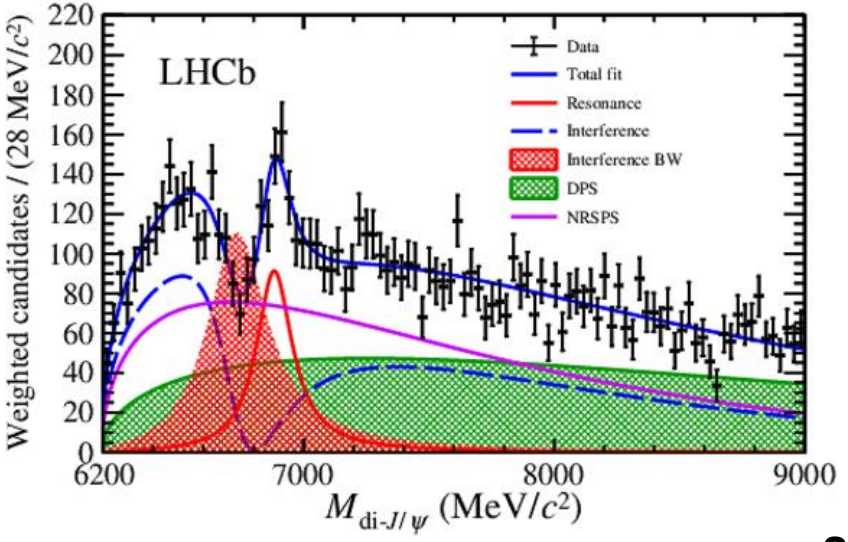
- In 2020, LHCb collaboration reported observation of significant structure close to J/ψ J/ψ mass threshold
- Run1 + Run2 data were used (9fb^{-1})
- A fit model without interference was not able to describe the dip at 6800 MeV
- Assuming interference between NRSPS & X(6900), satisfactory description was achieved
- Structure at the very threshold (significant!) not understood, described by a sum of two BW
- X(6900) peak significance > 5σ

Decays into J/ψ J/ψ suggest fully-charm tetraquark nature of the state!

$T_{c\bar{c}c\bar{c}}$, $T_{\psi\psi}$

Sci.Bull. 65 (2020) 23, 1983





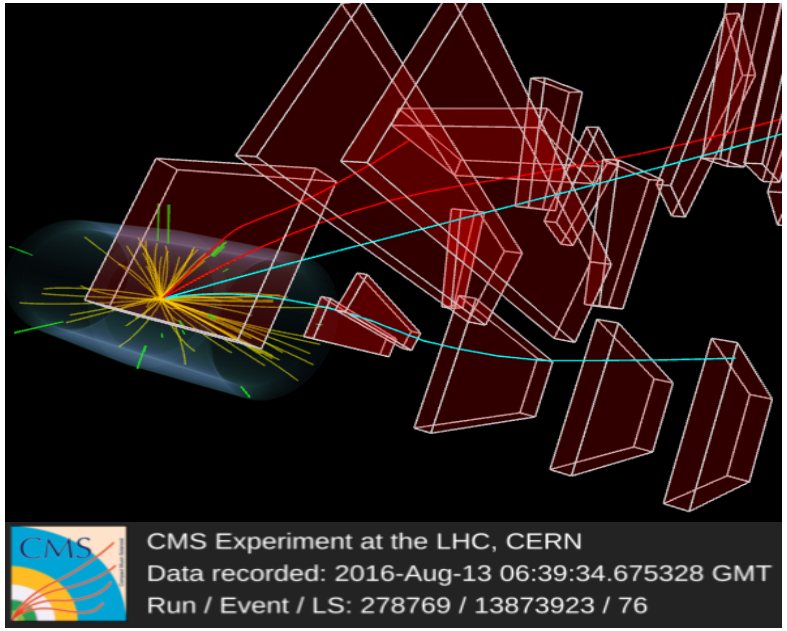
CMS selection of J/ψ pairs

Run-2 (13 TeV) pp collision data
J/ψ+μ trigger
$p_T(\mu) > 2$ GeV
$p_T(J/\psi) > 3.5$ GeV,
$2.95 < M(\mu^+\mu^-) < 3.25$ GeV
good $\mu^+\mu^-$ vertex fit
good $\mu^+\mu^-$ vertex fit with J/ψ mass constraint
good $\mu^+\mu^-\mu^+\mu^-$ vertex fit
In case of multiple candidates:

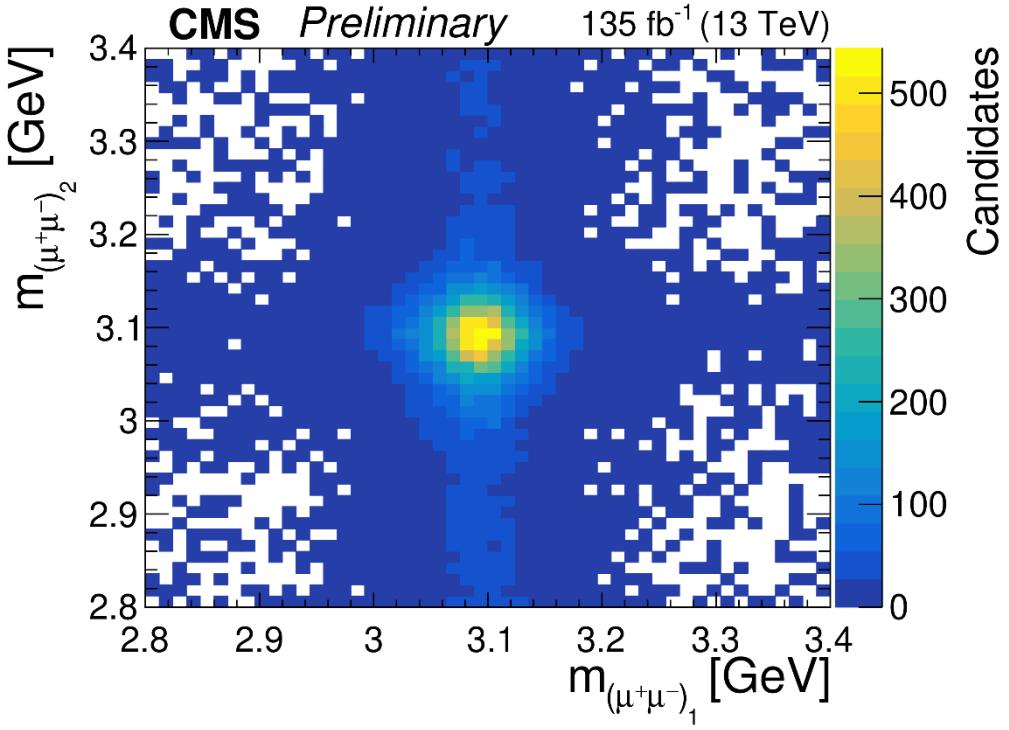
- From same 4 muons: select the one with smaller
  $[(m_{\mu\mu1}-M_{J/\psi})/\sigma_1]^2 + [(m_{\mu\mu2}-M_{J/\psi})/\sigma_2]^2$
- From different muons: leave

Simulated MC samples:

- ✓ non-resonant SPS
- ✓ non-resonant DPS
- ✓ Signal samples X→J/ψ J/ψ with different mass
- ✓ Samples for feed-down studies $X\to[c\bar{c}]_1[c\bar{c}]_2\to J/\psi\, J/\psi$



CMS-PAS-BPH-21-003



$J/\psi\, J/\psi$ mass spectrum fit

CMS-PAS-BPH-21-003

To better constrain SPS & DPS backgrounds, the spectrum is fit up to 15 GeV (see backup). Here shown only m < 9 GeV

NRSPS and NRDPS components: MC-driven shapes

$\chi^{\alpha} \bullet \exp(-\chi^{\beta}/\gamma) \bullet \mathrm{Pol}_2(\chi)$, where $\chi = m_{J/\psi J/\psi} - 2M(J/\psi)$

Threshold enhancement: ad-hoc Breit-Wigner

Signals: Relativistic Breit-Wigner functions

Mass resolution ~few MeV negligible compared to structure width

3 significant structures observed!

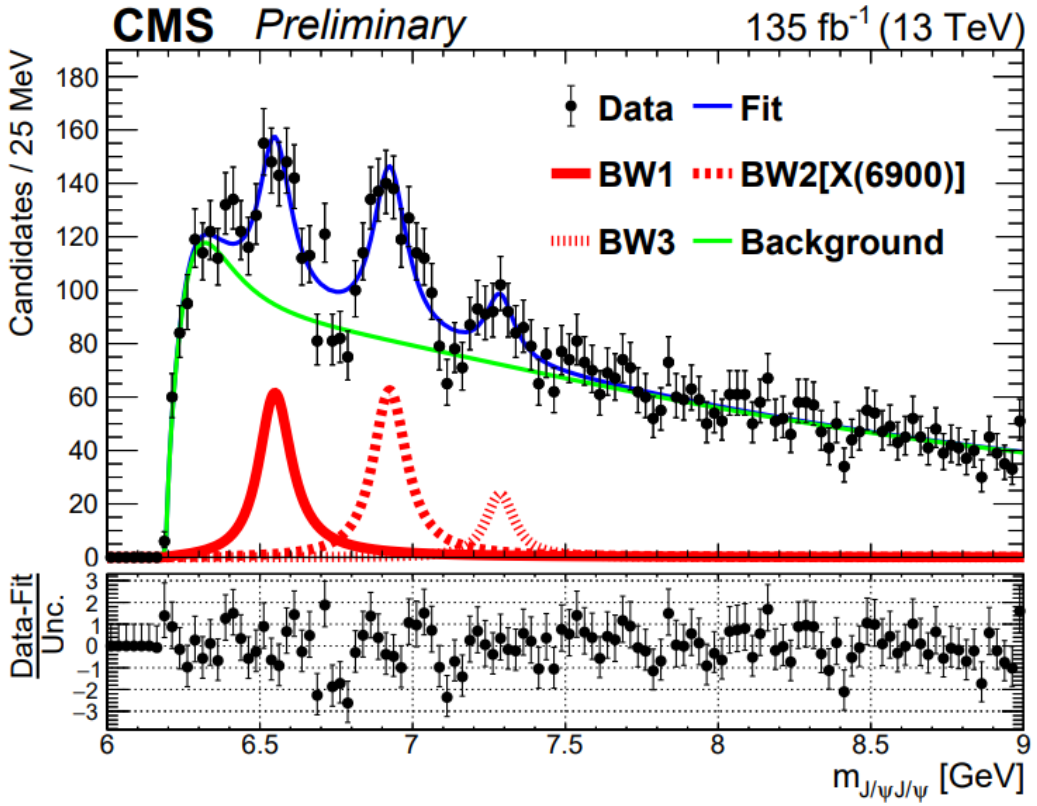
X(6600): 6.5σ observation

X(6900): 9.4σ confirmation

X(7300): 4.1σ evidence

Systematic uncertainties:

- Signal shapes
- Background shapes
- Including feed-downs $X \to [c\bar{c}]_1[c\bar{c}]_2 \to J/\psi\, J/\psi$
- Momentum scale
- Mass resolution, efficiency correction



	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

The dips between peaks are not well-described…

Comparison CMS vs LHCb vs ATLAS

arxiv.org/abs/2304.08962

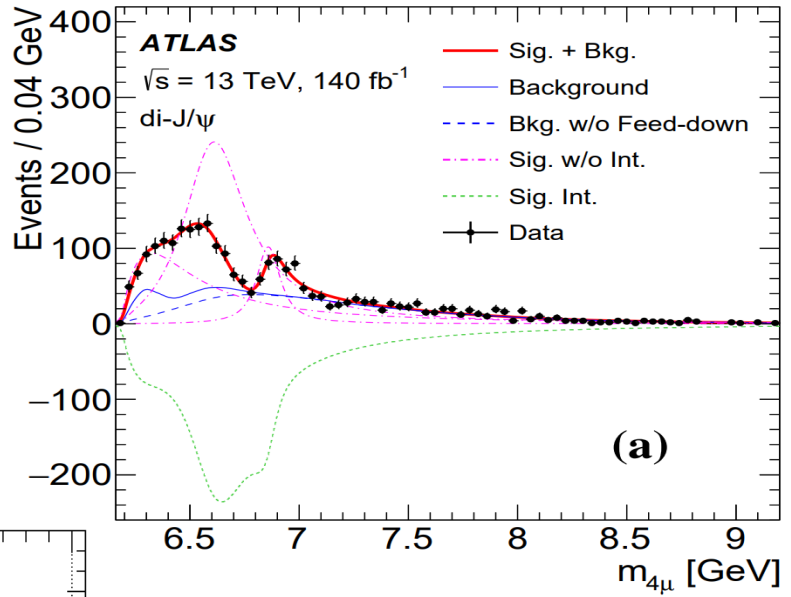
ATLAS investigated not only J/ψ J/ψ, but also $\psi(2S)$ J/ψ mass spectrum
Several structures are "seen", two models with interference are applied
But only **X(6900)** structure is above 5σ → **confirmation**

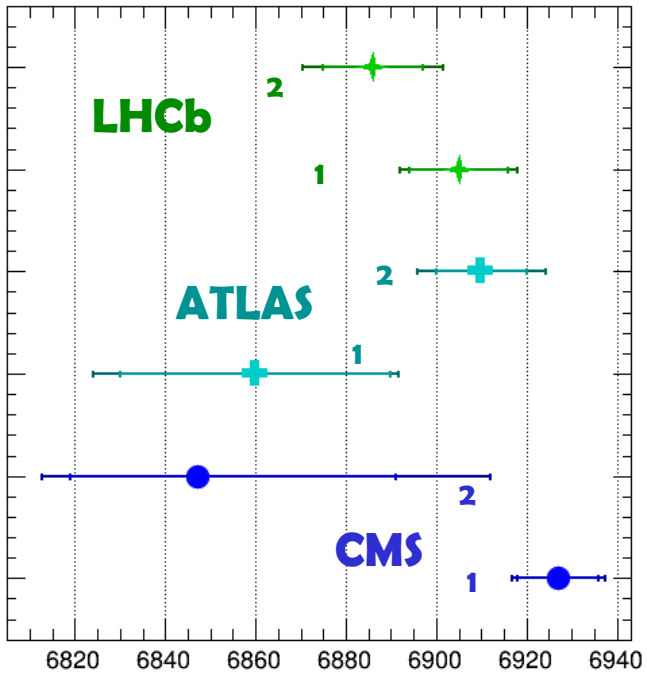
Comparison of X(6900) mass in MeV:

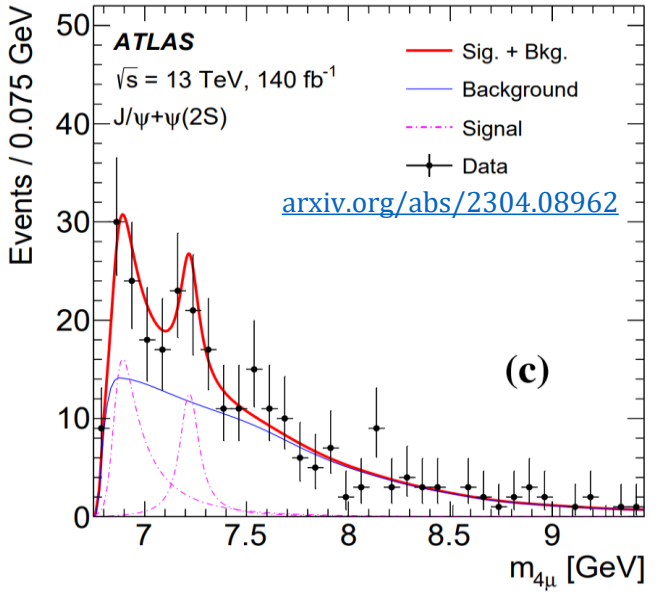
Model	LHCb	ATLAS	CMS
1	6905±11±7	$6860 \pm 30^{+10}_{-20}$	6927±9±5
2	6886±11±11	6910±10±10	$6847^{+44}_{-28}{}^{+48}_{-20}$

(see next slide)

Models are different between experiments! (see backup)
Not exactly "apples-to-apples" comparison,
but the masses still agree with each other.







$J/\psi\,J/\psi$ mass spectrum fit with interference

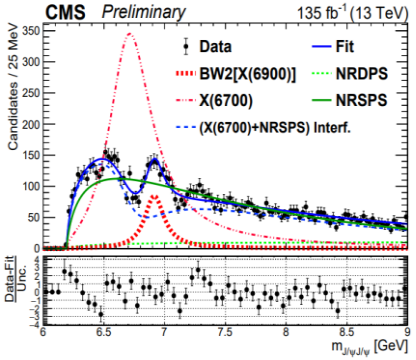
LHCb interference model does not provide a good description of CMS data

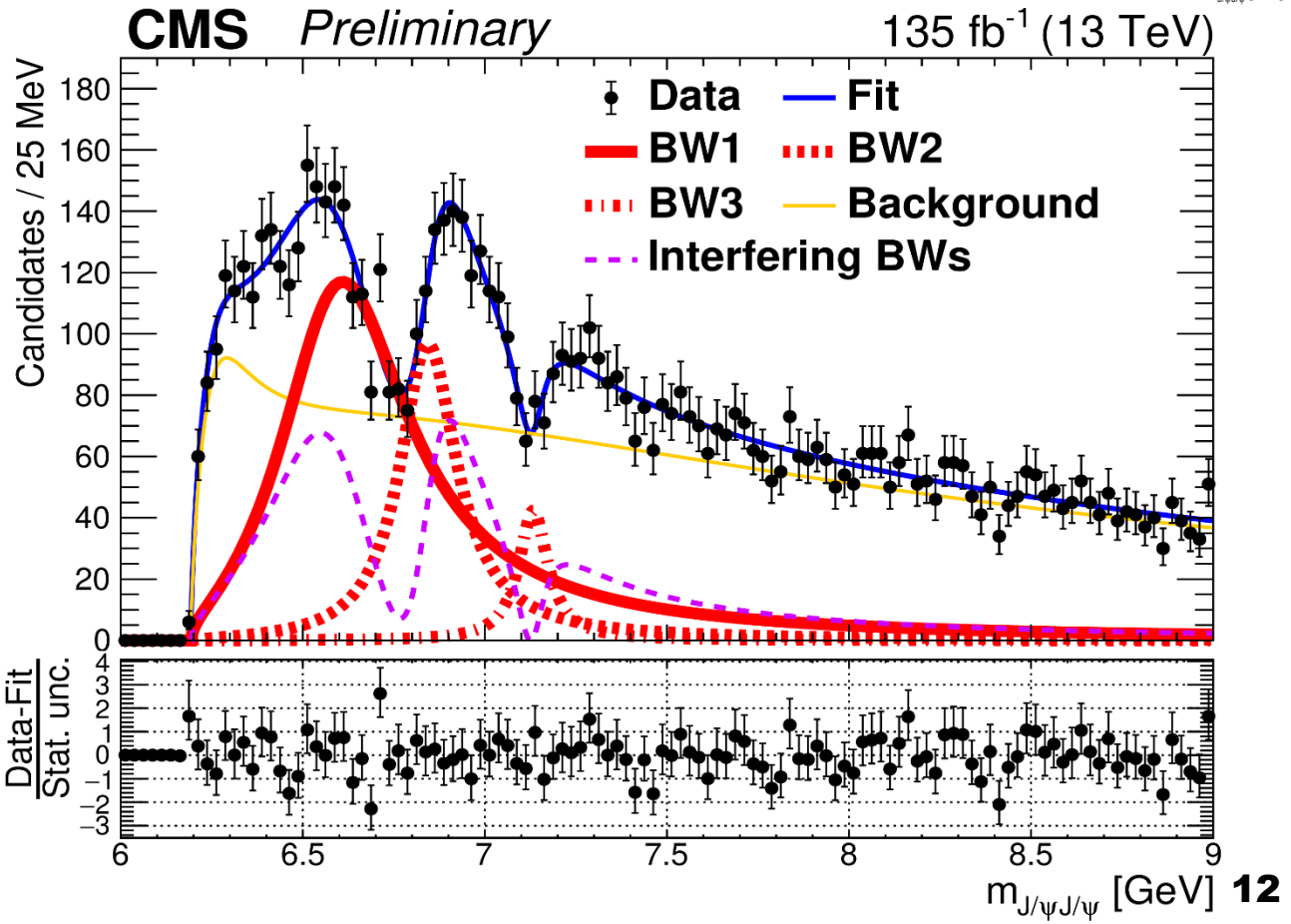
A model with 3 interfering resonances significantly improves the fit quality, both dips are now described

Masses and widths are shifted w.r.t. the non-interference fit

X(6900) parameters in agreement with ATLAS & LHCb

Other interpretations of the observed structures are also possible





[CMS-PAS-BPH-21-003]

	BW1	BW2	BW3
m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
Γ [MeV]	$444^{+226+109}_{-199-235}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

Summary

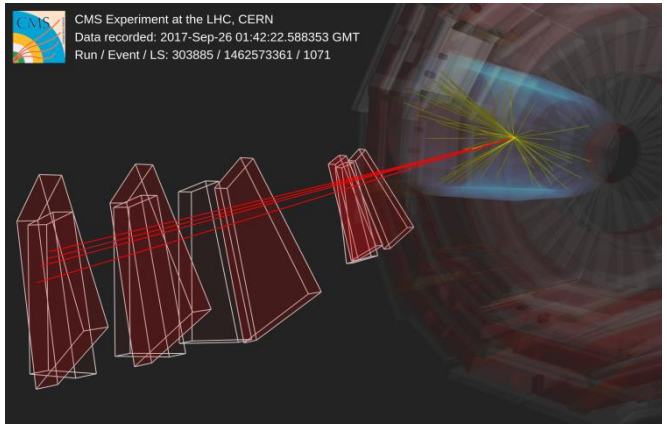
- CMS is a perfect experiment for multi-muon signatures!
- Using high-rate *scouting* triggers, we observe $\eta \to \mu^+\mu^-\mu^+\mu^-$ decay
  - the measured $\mathcal{B}$ consistent with SM

- The study of M(J/ψ J/ψ) distribution near threshold results in:
  - Confirmation of X(6900)
  - First observation of X(6600)
  - First evidence for X(7300)
  - Interference model describes the data better than non-interference one
  - Run-3 data will allow more detailed studies of these tetraquark-like structures

Thank you!

BACKUP

More links

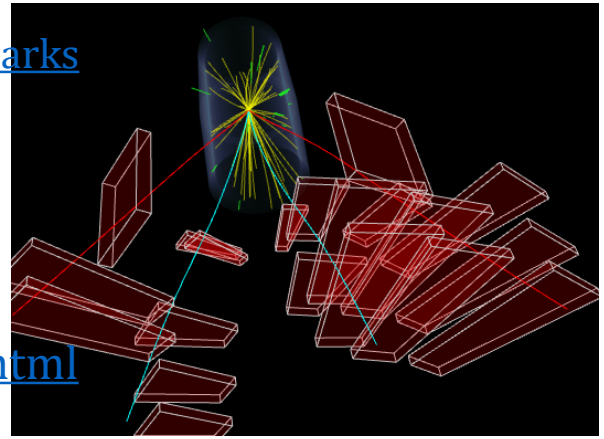


$\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$

- https://arxiv.org/abs/2305.04904
- https://doi.org/10.17182/hepdata.140340
- https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH-22-003/index.html
- https://cms.cern/news/what-eta-meson-does-when-no-ones-looking

$T_{\psi\psi}$ (?) $\rightarrow J/\psi\, J/\psi$

- https://cms.cern/news/cms-observes-potential-family-tetra-quark-states-composed-only-charm-quarks
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-003/index.html



CMS B-physics preliminary results

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH/index.html

CMS B-physics results

http://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html

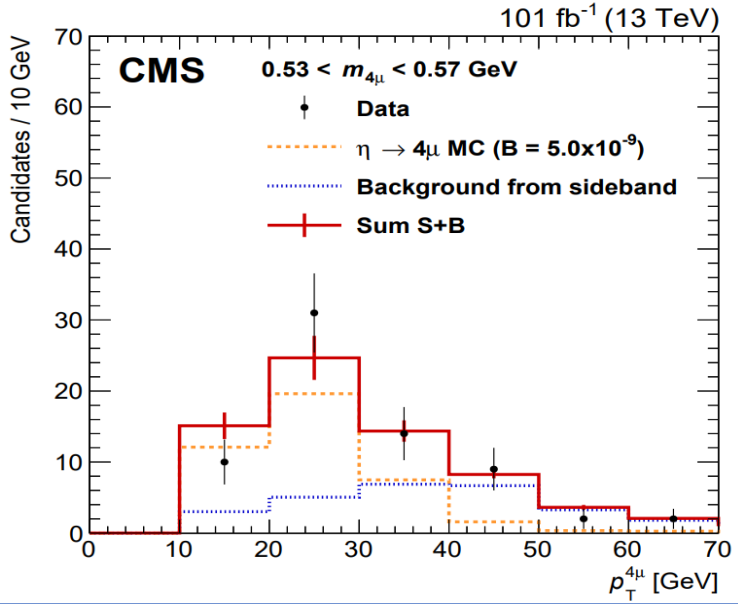
$\eta \to \mu^+\mu^-\mu^+\mu^-$ predictions and backgrounds

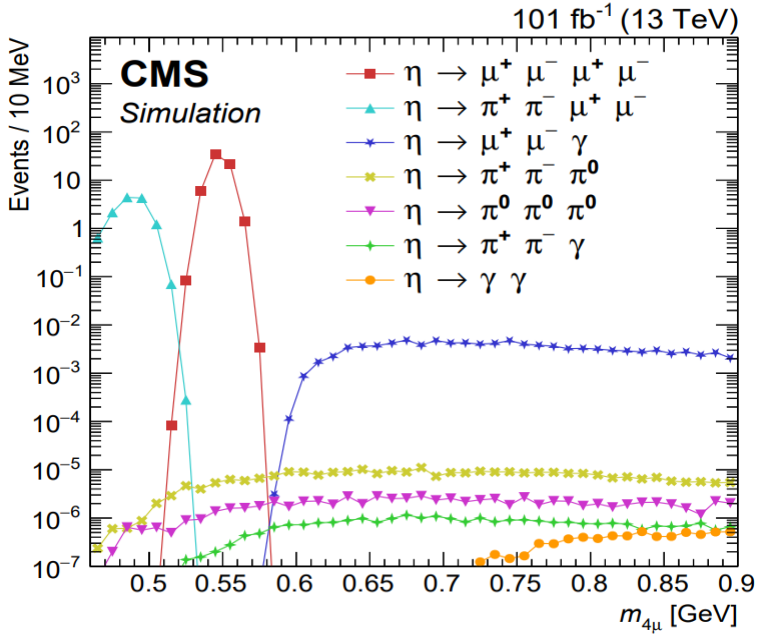
Table 8. Central final branching ratio predictions as a combined weighted average of the results presented. Errors are symmetrised. n_σ stands for the number of standard deviations the measured results are from our predictions.

decay	this work	experimental value [1]	n_σ
$\pi^0 \to e^+e^-\gamma$	$1.169(1)\,\%$	$1.174(35)\,\%$	0.15
$\eta \to e^+e^-\gamma$	$6.61(50) \times 10^{-3}$	$6.90(40) \times 10^{-3}$	0.45
$\eta \to \mu^+\mu^-\gamma$	$3.26(46) \times 10^{-4}$	$3.1(4) \times 10^{-4}$	0.26
$\eta' \to e^+e^-\gamma$	$4.38(32) \times 10^{-4}$	$4.69(20)(23) \times 10^{-4}$	0.70
$\eta' \to \mu^+\mu^-\gamma$	$0.75(6) \times 10^{-4}$	$1.08(27) \times 10^{-4}$	1.19
$\pi^0 \to e^+e^-e^+e^-$	$3.36689(5) \times 10^{-5}$	$3.34(16) \times 10^{-5}$	0.17
$\eta \to e^+e^-e^+e^-$	$2.71(2) \times 10^{-5}$	$2.4(2)(1) \times 10^{-5}$	1.38
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$3.98(15) \times 10^{-9}$	$< 3.6 \times 10^{-4}$	
$\eta \to e^+e^-\mu^+\mu^-$	$2.39(7) \times 10^{-6}$	$< 1.6 \times 10^{-4}$	
$\eta' \to e^+e^-e^+e^-$	$2.10(45) \times 10^{-6}$	notseen	
$\eta' \to \mu^+\mu^-\mu^+\mu^-$	$1.69(36) \times 10^{-8}$	not seen	
$\eta' \to e^+e^-\mu^+\mu^-$	$6.39(91) \times 10^{-7}$	not seen	

[Chin.Phys.C 42 (2018) 2, 023109]

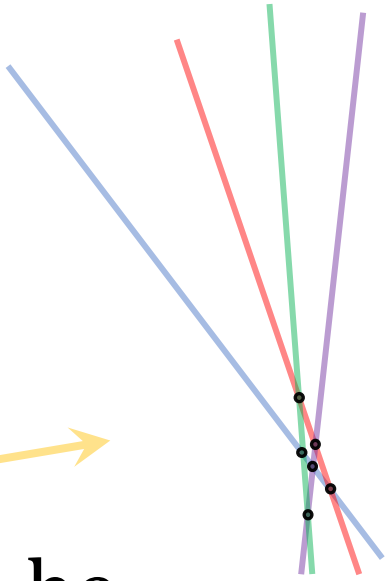
p_T spectrum consistent with [MC prediction calibrated with $\eta \to \mu^+\mu^-$] + bkg





Gen-level MC shows that misreconstructed decays have significantly different shape in $m(4\mu)$

$\eta \to \mu^+\mu^-\mu^+\mu^-$ selection



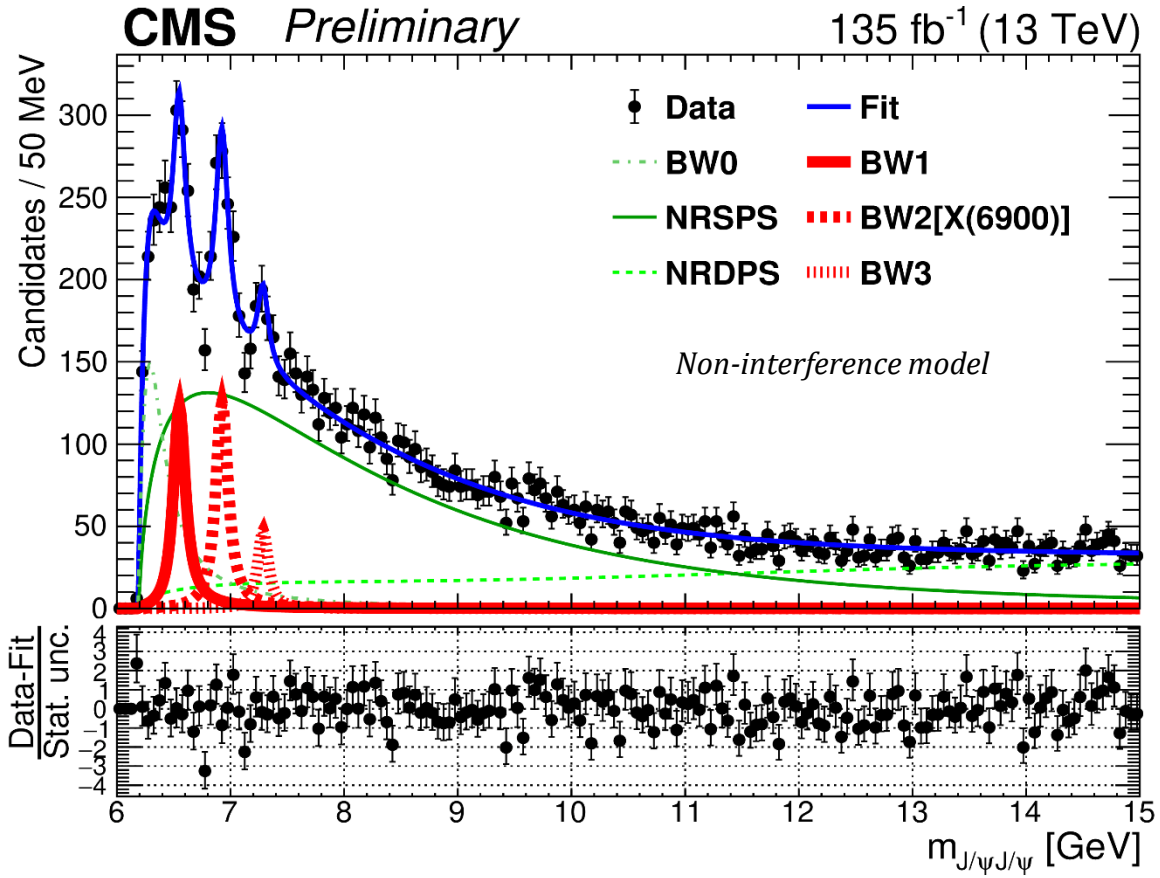
$p_T(\mu)$>3 GeV

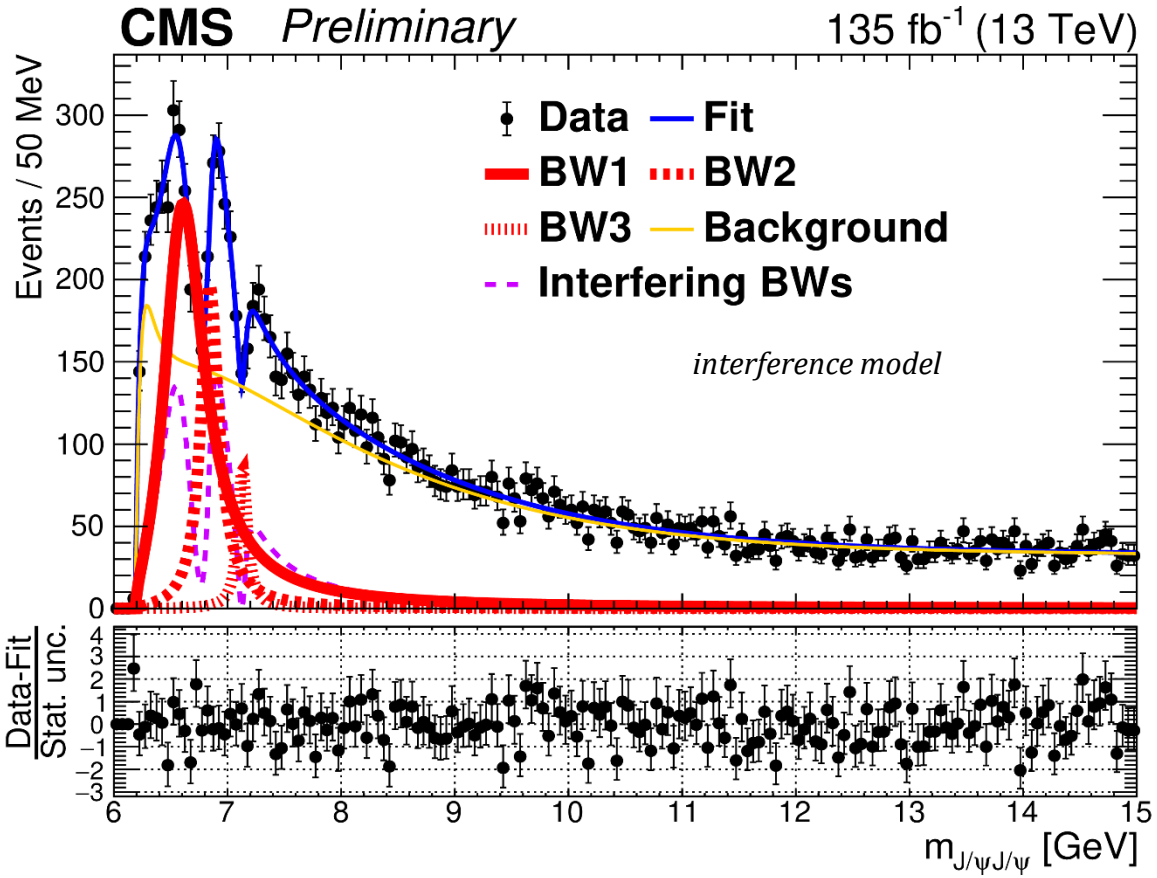
Each of the 6 possible dimuon vertices should be reconstructed and they all should be compatible in position

$\mu_1\mu_2$ $\mu_1\mu_3$ $\mu_1\mu_4$ $\mu_2\mu_3$ $\mu_2\mu_4$ $\mu_3\mu_4$

A *"feature"* of scouting data: we can't fit vertices offline, as muon hits/tracks are not saved but HLT tries to fit and save every ***dimuon***

$J/\psi\, J/\psi$ mass spectrum up to 15 GeV





BKG shapes: $\boldsymbol{\chi^{\alpha} \cdot \exp(-\chi^{\beta}/\gamma) \cdot \mathrm{Pol}_2(\chi)}$, where $\chi = m_{J/\psi J/\psi} - 2M(J/\psi)$

SPS: α floating; β, γ, Pol2 parameters fixed to MC.

DPS: α=0.5, β=1; γ and Pol2 parameters fixed to MC

Comparison CMS vs LHCb vs ATLAS

3 interfering BW

3 non-interfering BW

4 non-interfering BW

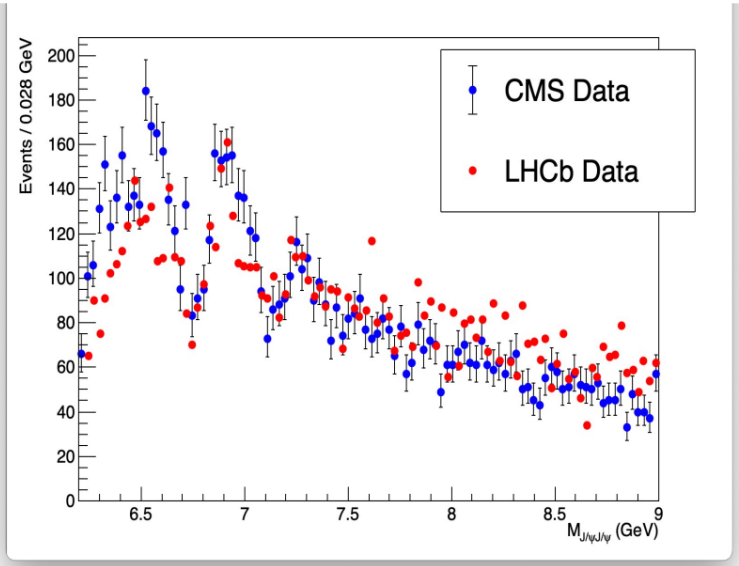
Model	LHCb	ATLAS	CMS
1	$6905 \pm 11 \pm 7$	$6860 \pm 30^{+10}_{-20}$	$6927 \pm 9 \pm 5$
2	$6886 \pm 11 \pm 11$	$6910 \pm 10 \pm 10$	$6847^{+44\ +48}_{-28\ -20}$

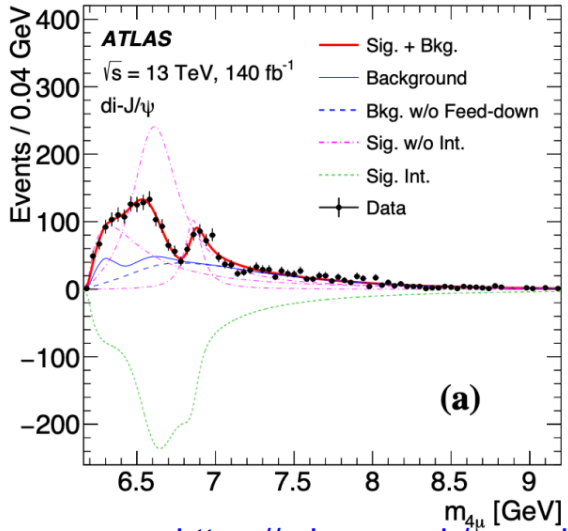
BW + [3 interfering BW]

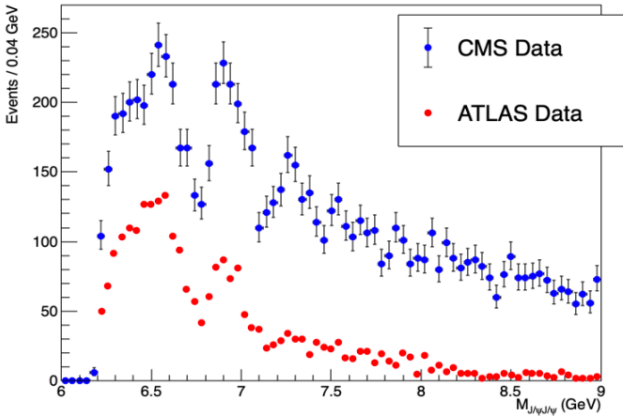
BW + [BW interfering with SPS]

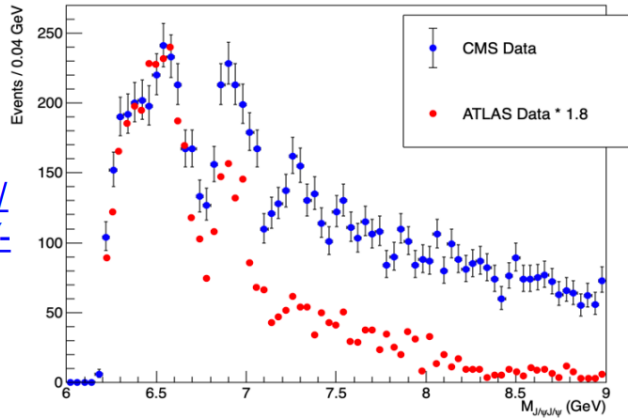
J/ψ J/ψ mass spectrum comparison

Comparison plots in this page are not made by CMS
（taken from https://indico.cern.ch/event/1158681/contributions/5162594/ ）









- CMS vs LHCb comparisons:
  - Similar number of final events, but much less DPS
  - 2X yield @CMS for X(6900)

https://cds.cern.ch/record/2856327/files/ANA-BPHY-2022-01-PAPER.pdf

- CMS vs ATLAS comparisons:
  - ATLAS is 1/3 –1/2 of CMS data (trigger?)
  - ATLAS used dR cut—remove high mass events
  - ATLAS has slightly worse resolution