Recent results of exotic hadron studies at CMS

清華大學
Tsinghua University
Zhen Hu

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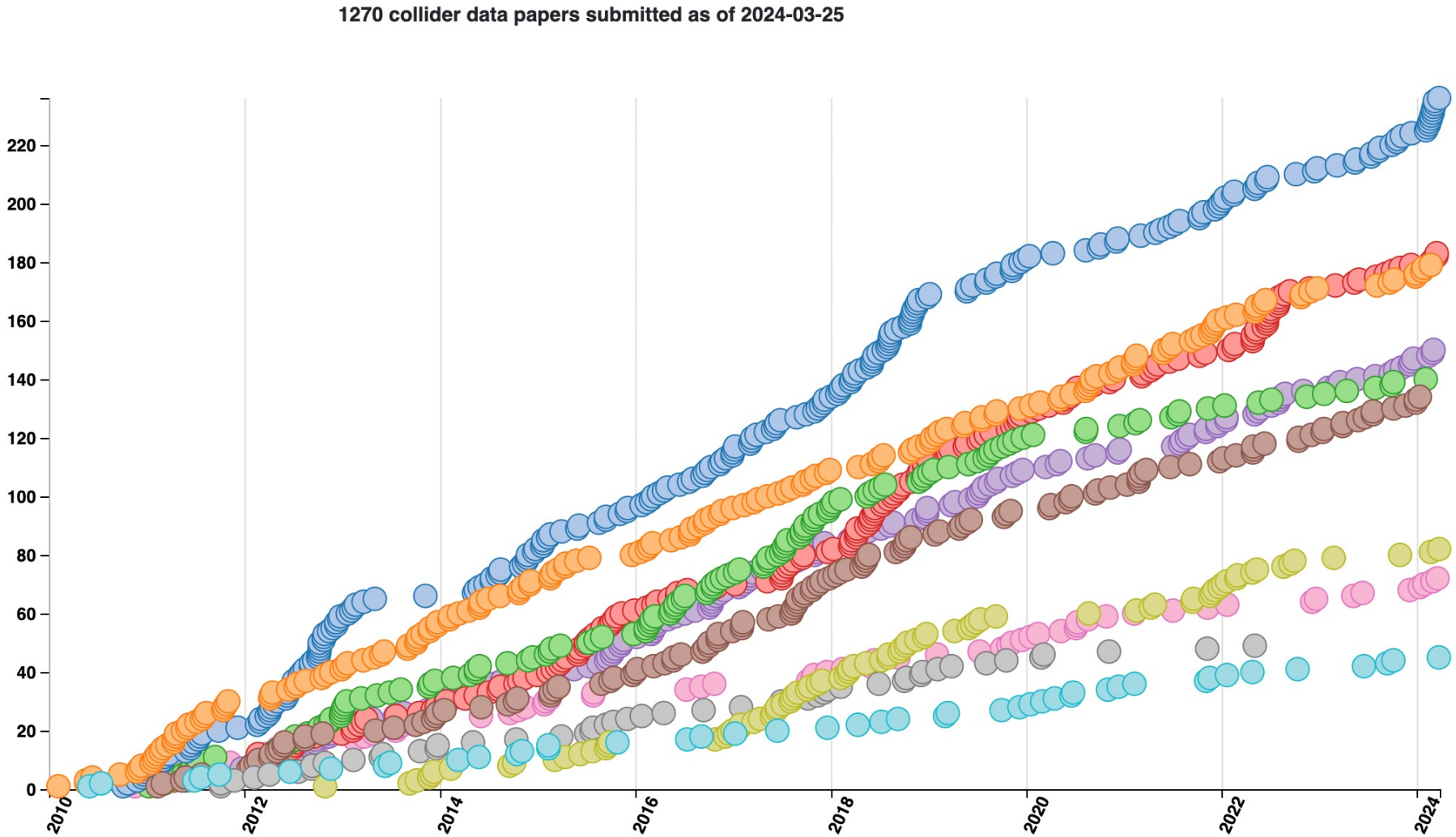
The **Large Hadron Collider** (**LHC**) at CERN is the world's largest particle collider. It lies in a tunnel 27 kilometres in circumference and as deep as 175 metres beneath the France–Switzerland border near Geneva.

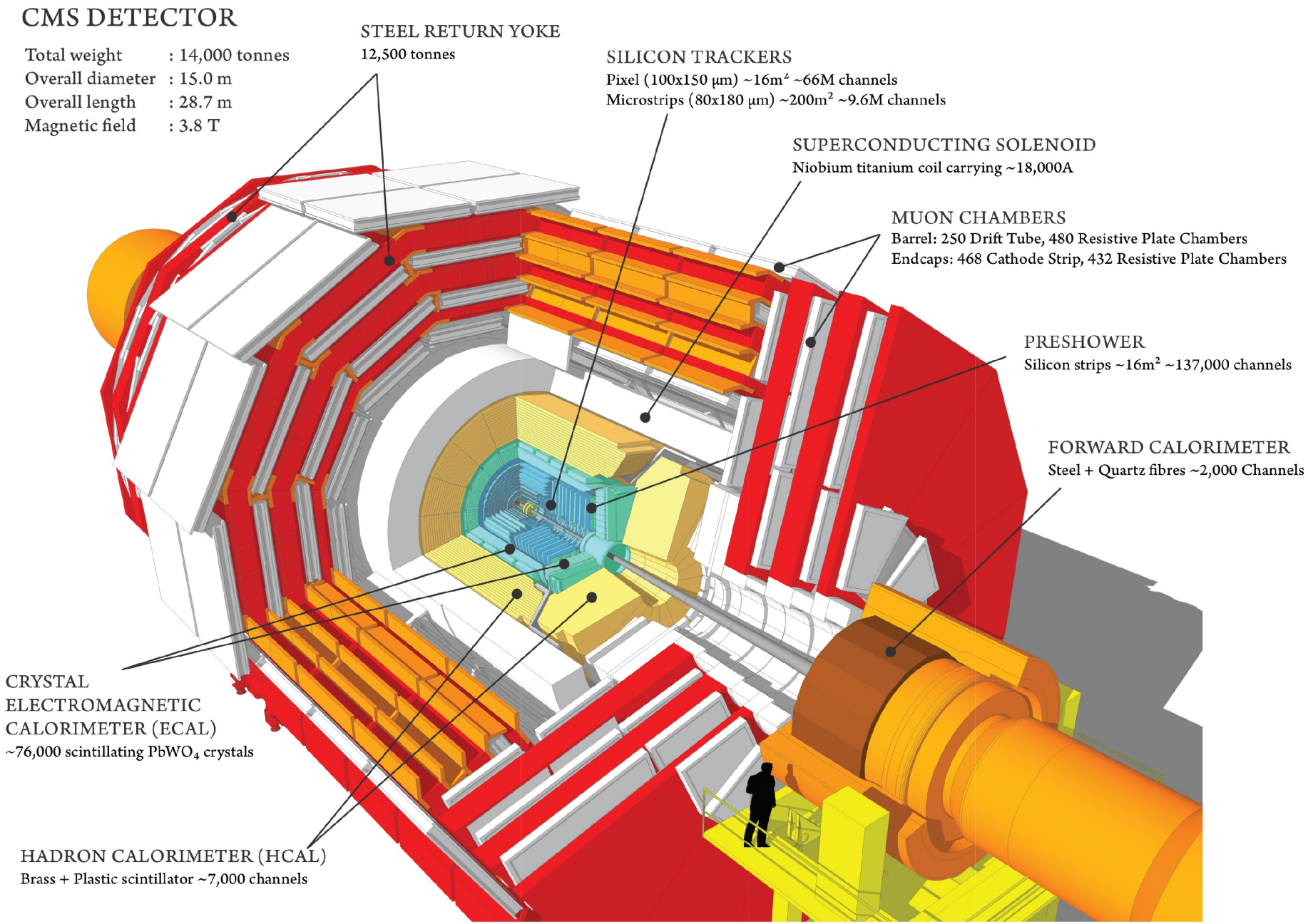
CMS Publications vs time

Show all | Total | Exotica | Standard Model | Supersymmetry | Higgs | Top | Heavy Ions

B and Quarkonia | Forward and Soft QCD | Beyond 2 Generations | Detector Performance



CMS Detector

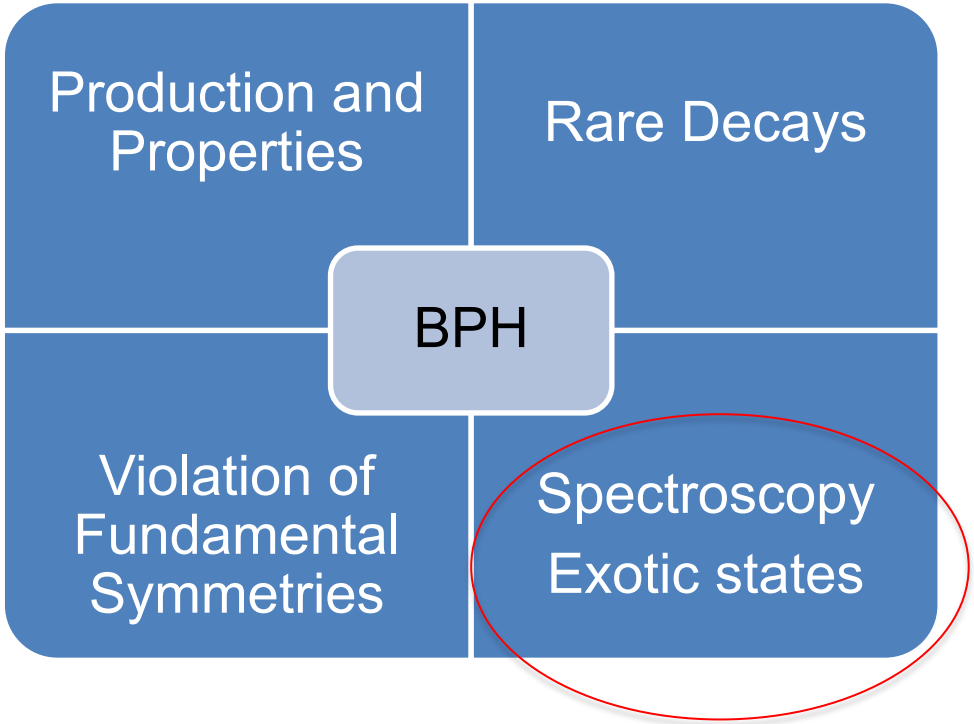


CMS BPH Group

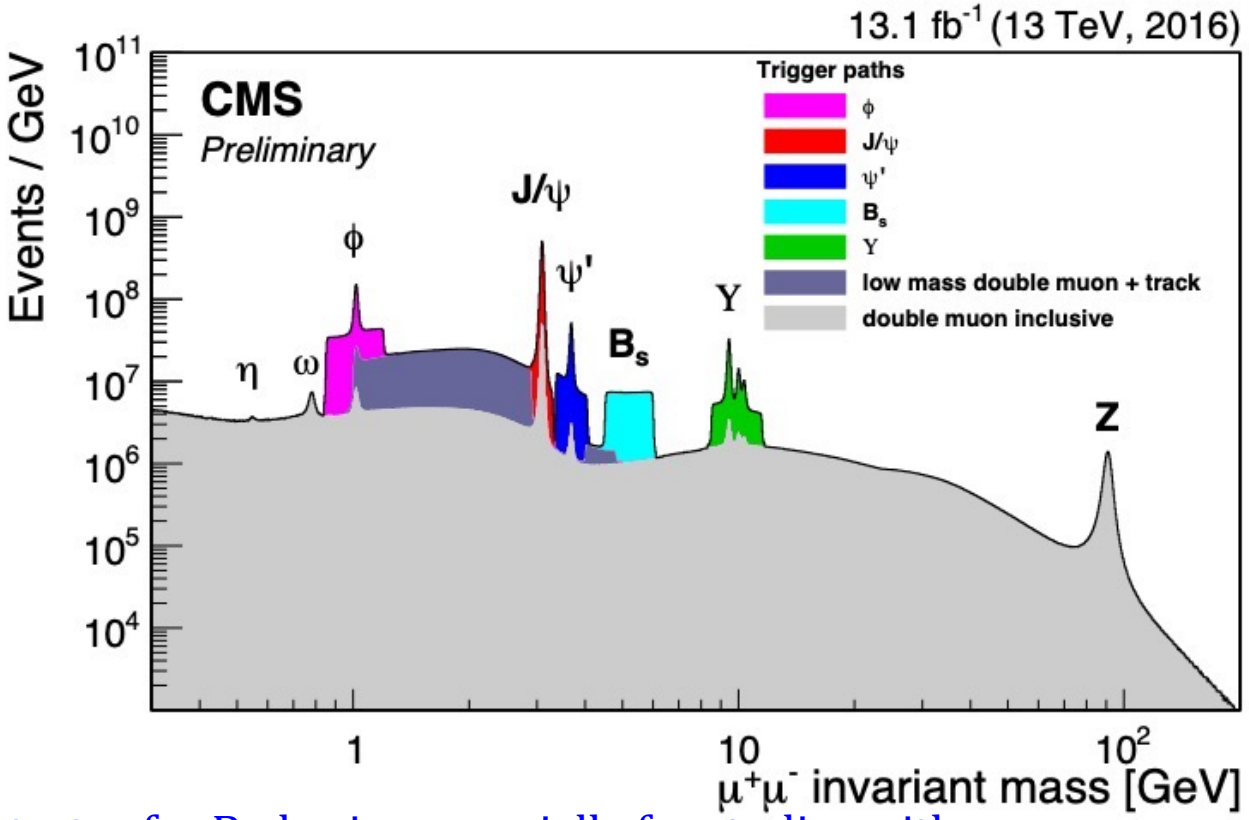
Home page: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

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

- Quarkonium Production
  - Bottomium States
  - Charmonium States
- B and BB Production
  - Inclusive Measurements
  - B^0 and B^+ Production
  - B_s^0 Production
  - B_c^+ Production
- B Meson Decays
  - $B \to K^{(*)}\mu^+\mu^-$
  - $B_s^0 \to \mu^+\mu^-$
- CP Violation
- Baryons
- Spectroscopy, Exotic States



CMS dimuon & trigger



Excellent detector for B physics, especially for studies with muons

- Muon system
  - High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ
- Silicon Tracking detector, B=3.8T
  - $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution
- Special triggers for different analyses at increasing Inst. Lumi.
  - μ p_T, ($\mu\mu$) p_T, ($\mu\mu$) mass, ($\mu\mu$) vertex, and additional μ

CMS exotic hadron results

- X(3872) studies
  - Measurement of X(3872) to $J/\psi\pi^+\pi^-$ (2013)
  - Observation of $B_s^0 \to X(3872)\phi$ (2020)
  - Evidence of X(3872) in PbPb collisions (2022)

- Observations of new structures
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- Searches without showing significance structures
  - Upper limit for $X(5568)^\pm \to B_s^0\pi^\pm$ (2020)
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  - Observation of $\Lambda_b^0 \to J/\psi\,\Xi^-K^+$ (2024)

X(3872) in heavy-ion collisions

- The inner structure of X(3872) affects its production in HIC

Tetraquark

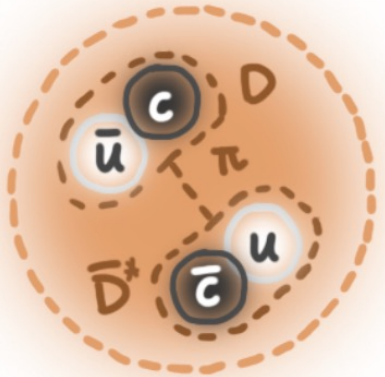
Tightly bound
Small radius

$r_{4q} \approx r_{c\bar{c}} \approx 0.3\,\text{fm}$

Compact four quark state

Hadron molecule

Loosely bound
Large radius

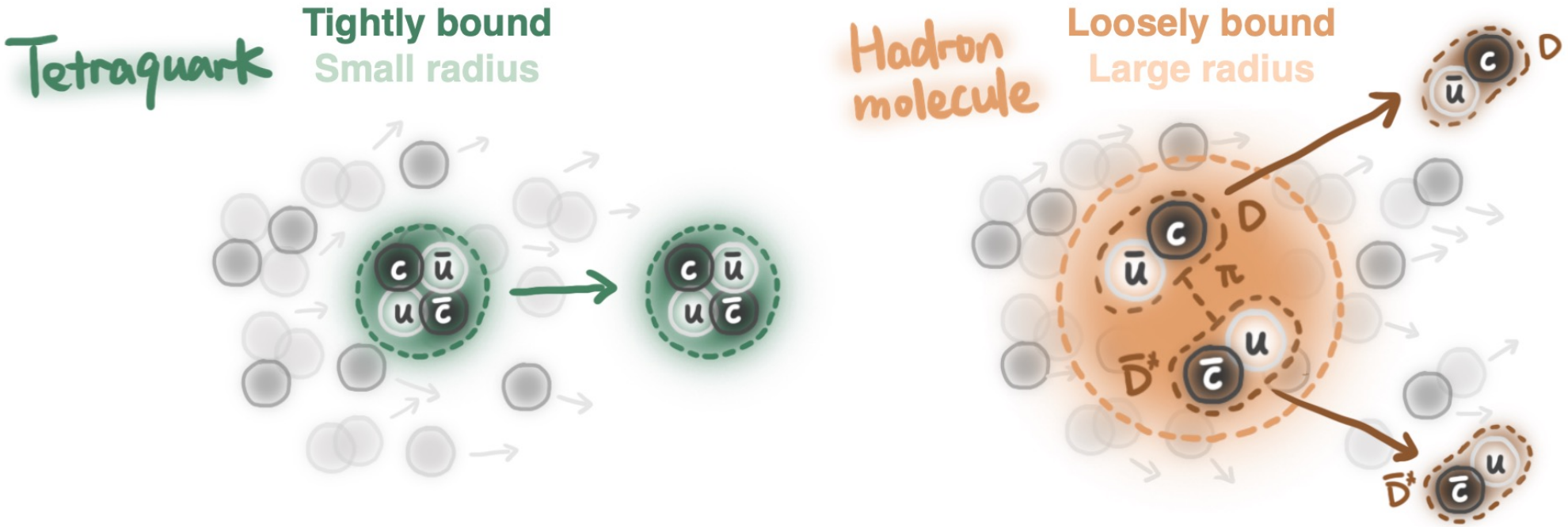


r_{mol} as large as 5 fm

D-D̄* hadron molecule

X(3872) in heavy-ion collisions

- Breakup by comoving particles ➜ Suppress X(3872)



X(3872) in heavy-ion collisions

- Coalescence with particles in QGP ➜ Enhance X(3872)

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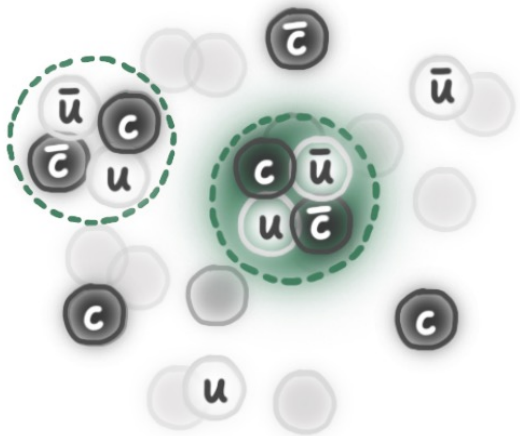

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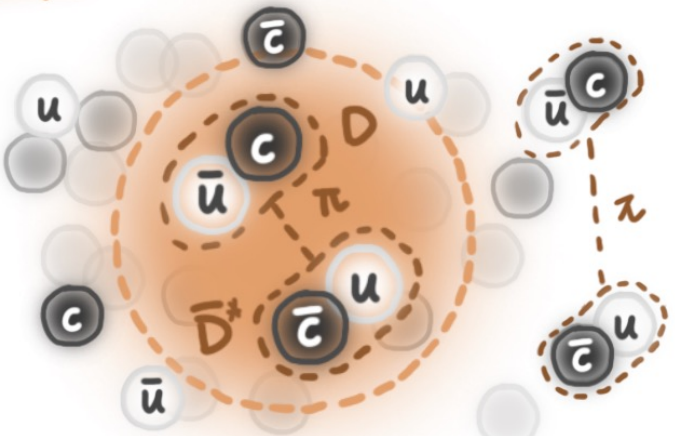
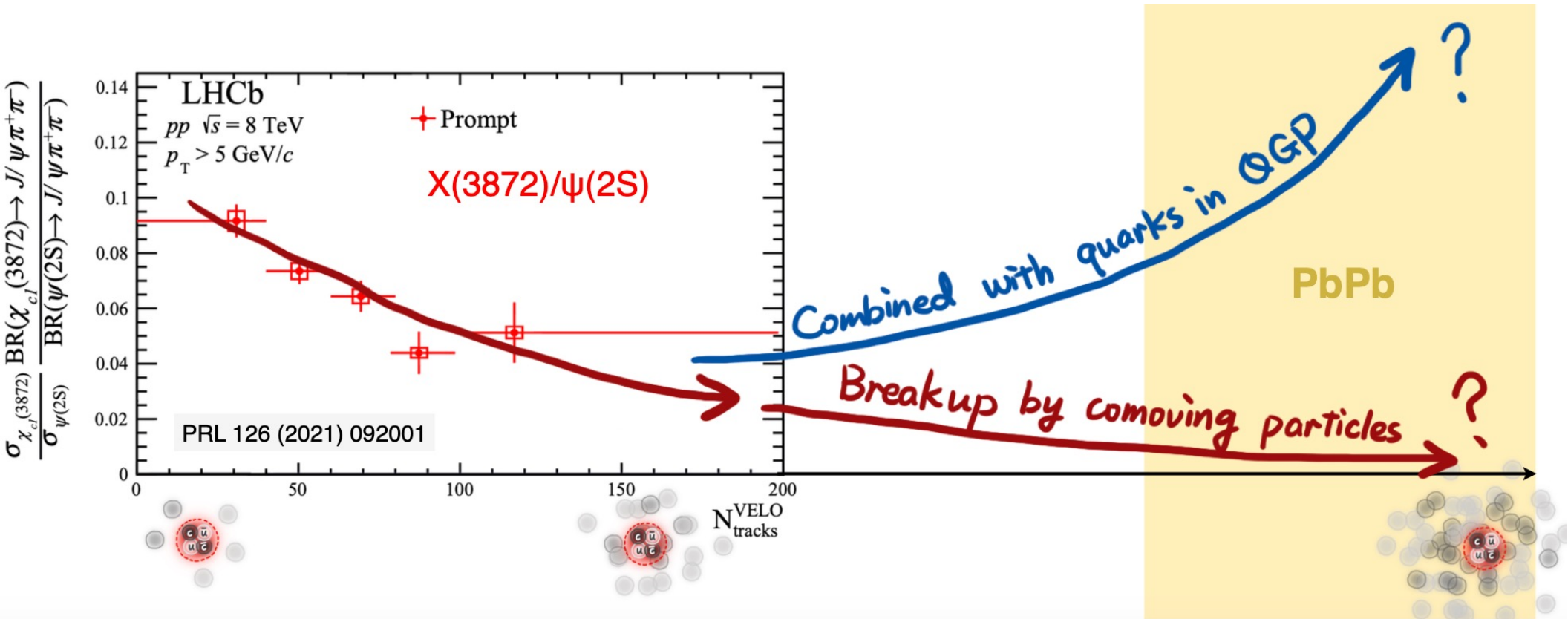


X(3872) in heavy-ion collisions

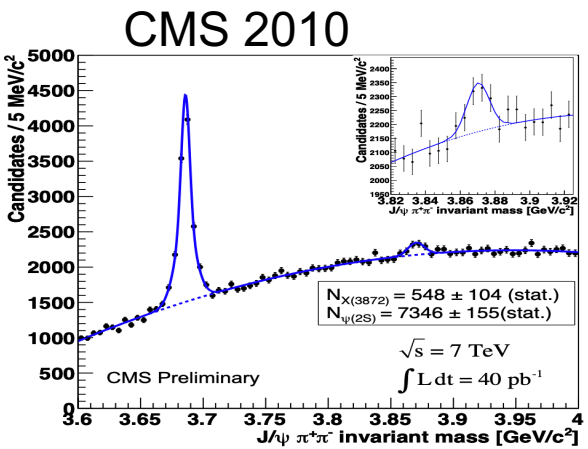
- Coalescence with particles in QGP → Enhance X(3872)
- Breakup by comoving particles → Suppress X(3872)

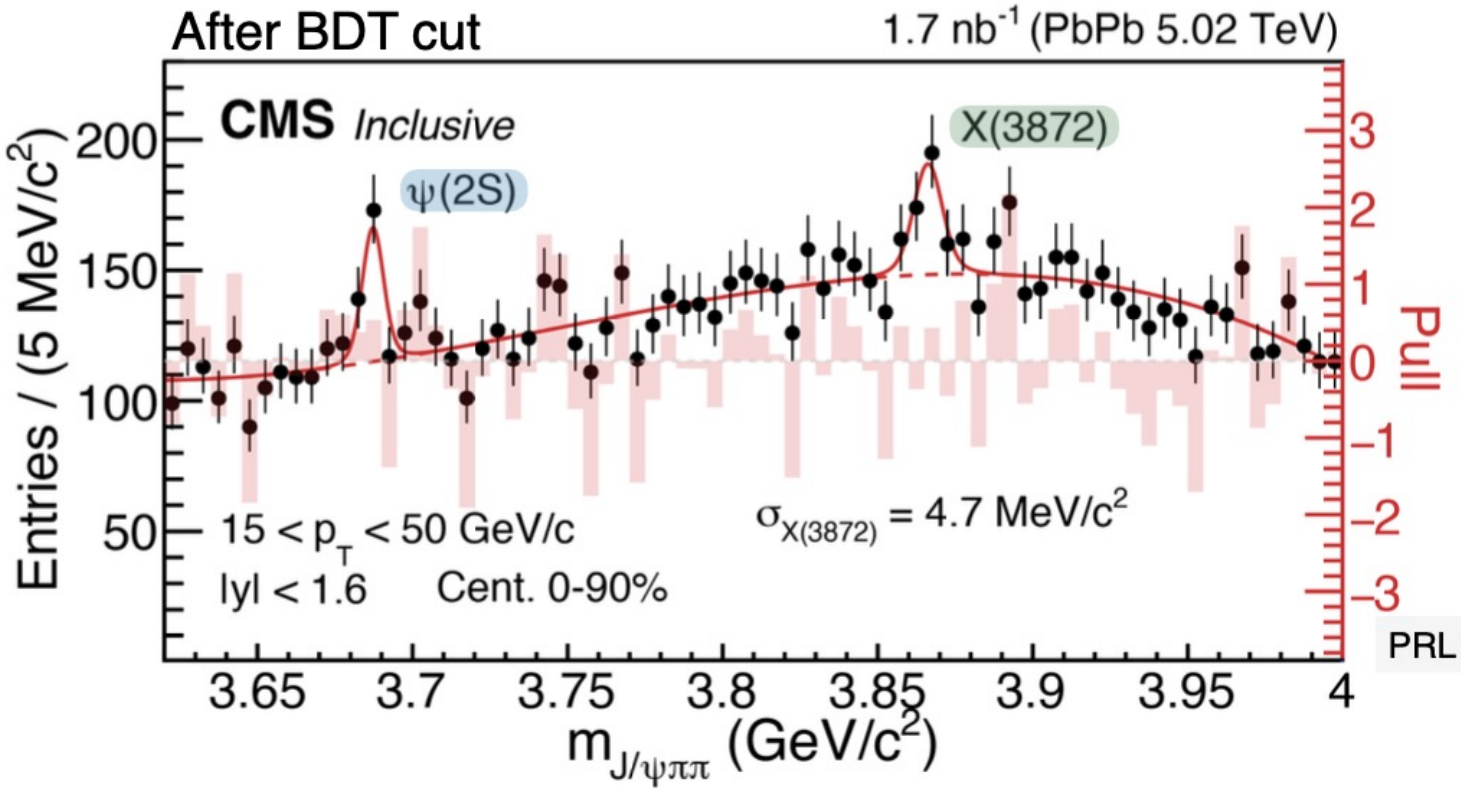


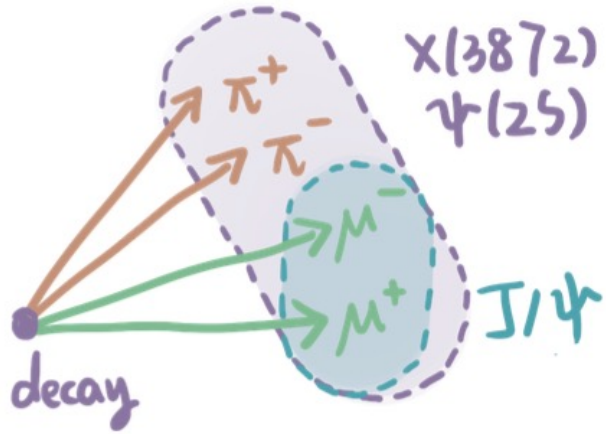
Destroyed by comoving particles due to smaller binding energy than ψ(2S)?

X(3872) in heavy-ion collisions

- First evidence of X(3872) production in heavy ion collisions
- Statistical significance ~ 4.2 σ



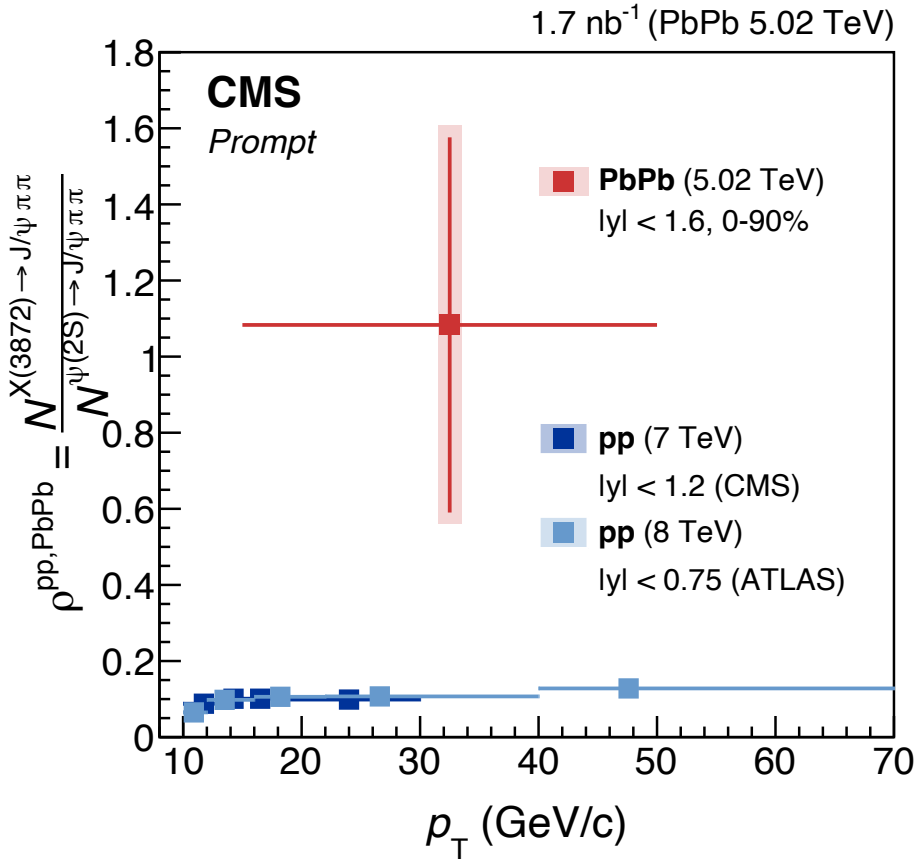




PRL 128 (2022) 032001

X(3872) in heavy-ion collisions

X(3872)/ψ(2S) Ratio in PbPb



- X(3872) to ψ(2S) ratio

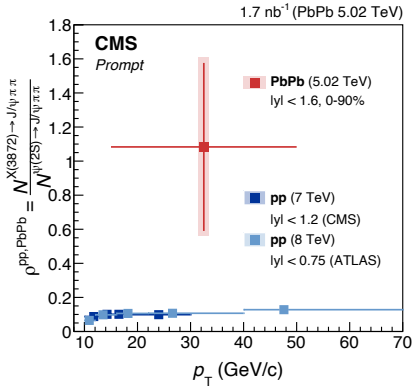
ρ_{PbPb} = 1.08 ± 0.49 (stat.) ± 0.52 (syst.)

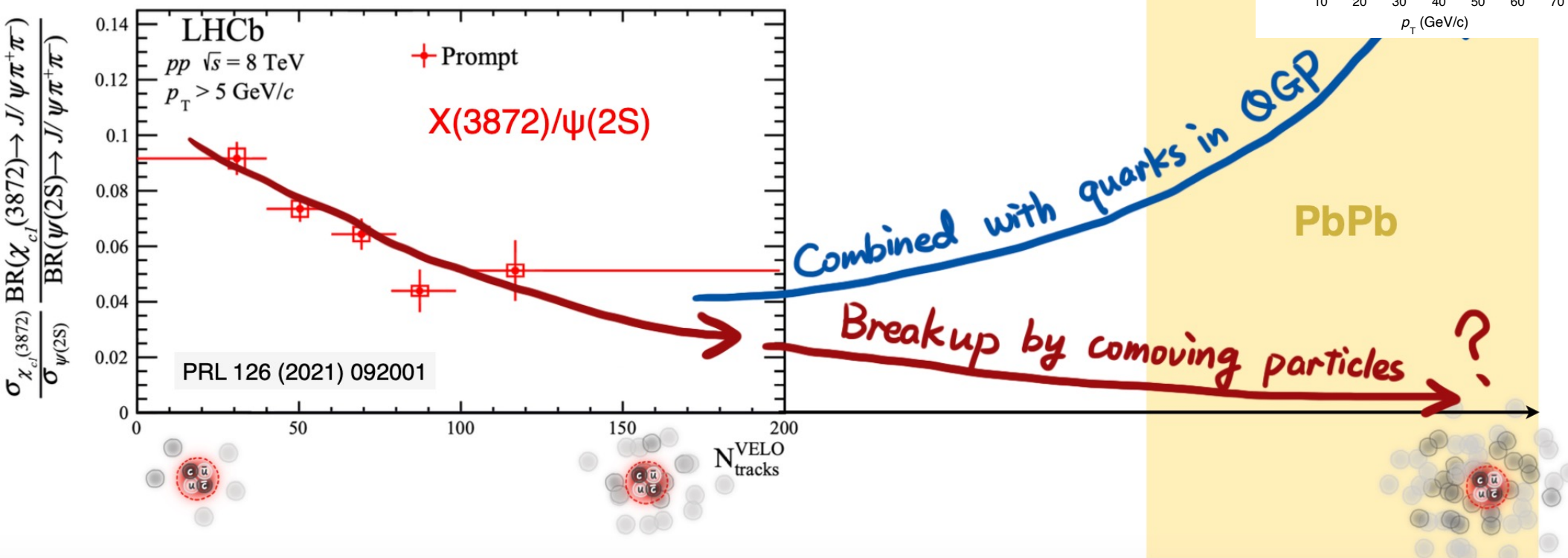
- Indication of ρ enhancement in PbPb w.r.t to pp
- Better precision needed to draw conclusion

X(3872) in heavy-ion collisions

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

$\rho_{PbPb} = 1.08 \pm 0.49\ (stat.) \pm 0.52\ (syst.)$





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New domain of exotics: all-heavy tetra-quarks

- First mention of 4c states at 6.2 GeV (1975)
  - Just one year after the discovery of J/ψ

We expect at least three exotic mesons with hidden charm, $c\bar{c}(p\bar{p}-n\bar{n})$ [between 3.7~4.1 GeV], $c\bar{c}\lambda\bar{\lambda}$ [~4.1 GeV] and $c\bar{c}c\bar{c}$ [~6.2 GeV], to which we refer

Progress of Theoretical Physics, Vol. 54, No. 2, August 1975

A Possible Model for New Resonances

——*Exotics and Hidden Charm*——

Yoichi IWASAKI

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received January 20, 1975)

- First calculation of 4c states (1981): Z. Phys. C 7 (1981) 317

$(cc)_{\underline{3}}* - (\bar{c}\bar{c})_{\underline{3}}$

L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.55
	1	$0^{-+}, 1^{-+}, 2^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}$	
2	0	2^{++}	6.78
	1	$1^{+-}, 2^{+-}, 3^{+-}$	
	2	$0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}$	
3	0	3^{--}	6.98
	1	$2^{-+}, 3^{-+}, 4^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

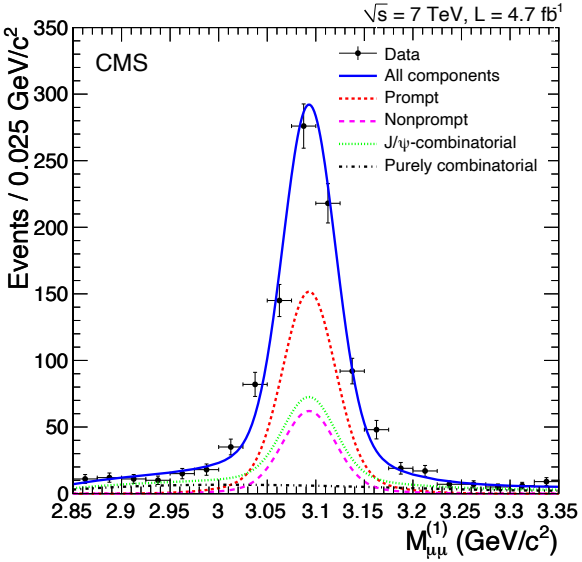
$(cc)_{\underline{6}} - (\bar{c}\bar{c})_{\underline{6}}*$

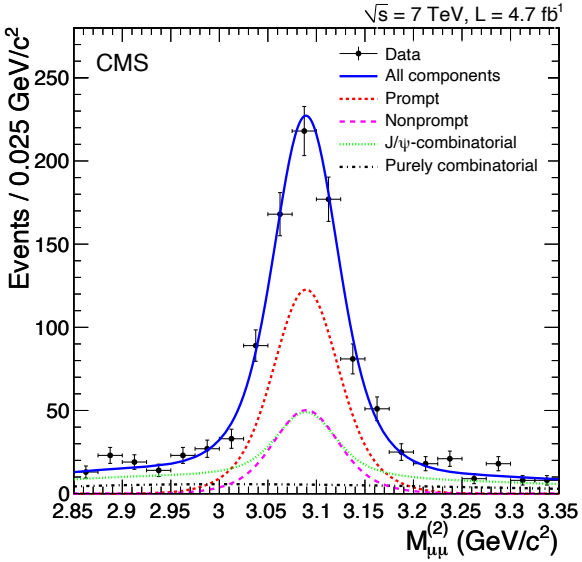
L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.82
2	0	2^{++}	7.15
3	0	3^{--}	7.41

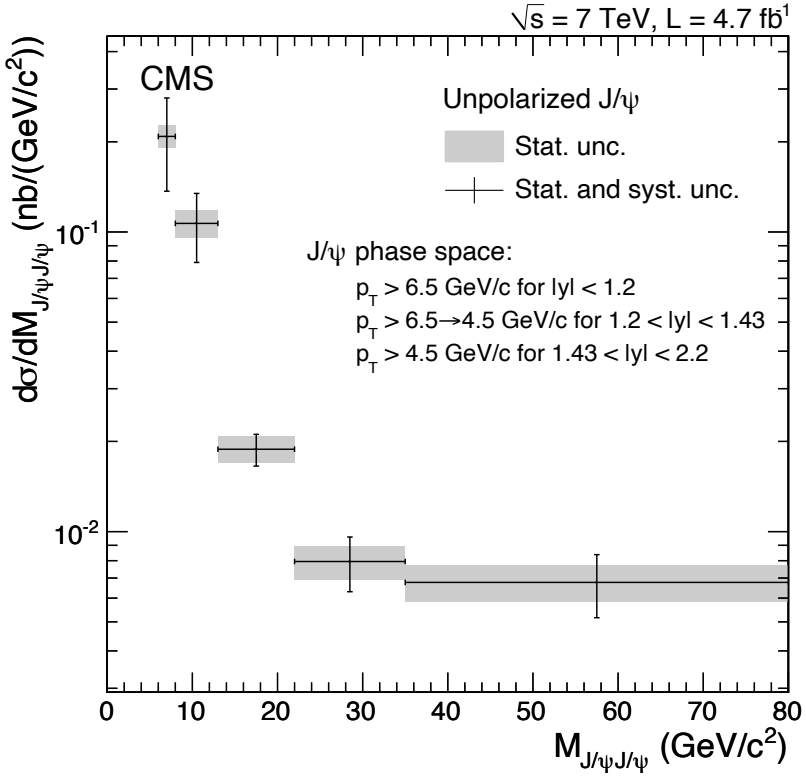
- A different exotic system compared to exotics with light quarks

J/ψJ/ψ cross section at 7 TeV

J. High Energy Phys. 09 (2014) 094







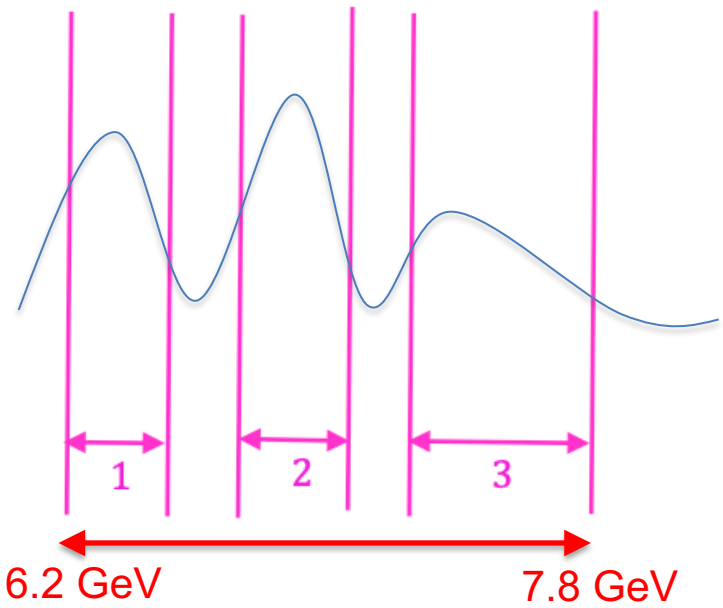
Total cross section, assuming unpolarized prompt J/ψJ/ψ pair production
1.49 ± 0.07 (stat.) ± 0.13 (syst.) nb

Different assumptions about the J/ψJ/ψ polarization imply modifications to the cross section ranging from -31% to +27%.

J/ψJ/ψ blind mass window for 13 TeV

We saw hints at Run I data (7 TeV & 8 TeV)
Proposed three signal regions for Run II data

Signal: $X \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$



Blinded mass windows for Run II:

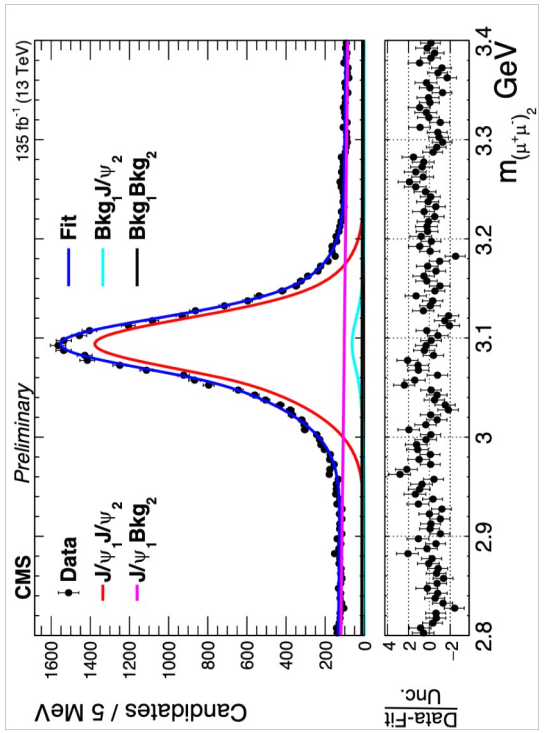
1. [6.3,6.6] GeV
2. [6.8,7.1] GeV
3. [7.2,7.8] GeV
   (for potential wide structure)

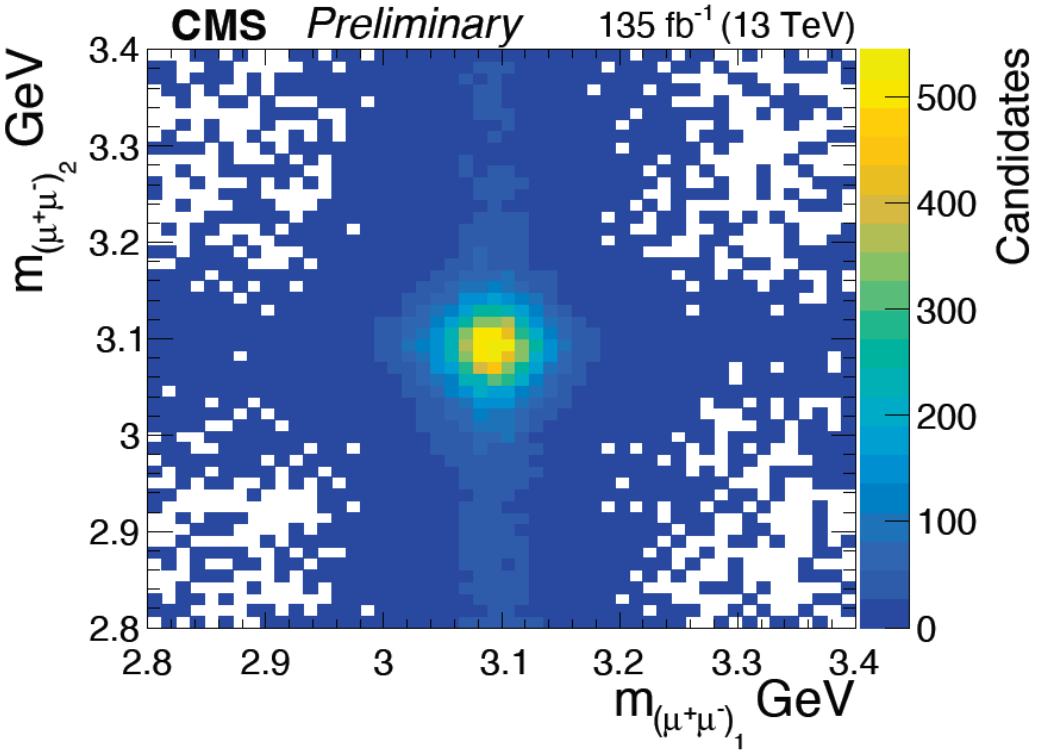
These mass windows will be windows for LEE for potential structures

Run I data will be ignored for significance calculation

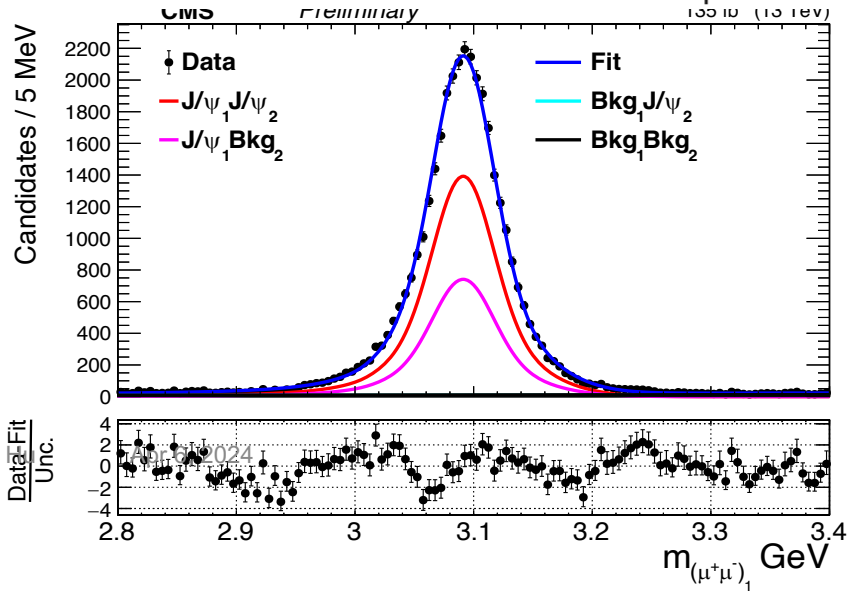
CMS eventually decide to blind the whole region: [6.2, 7.8] GeV after LHCb released their result (13 TeV, 2020)

J/ψJ/ψ candidates at 13 TeV

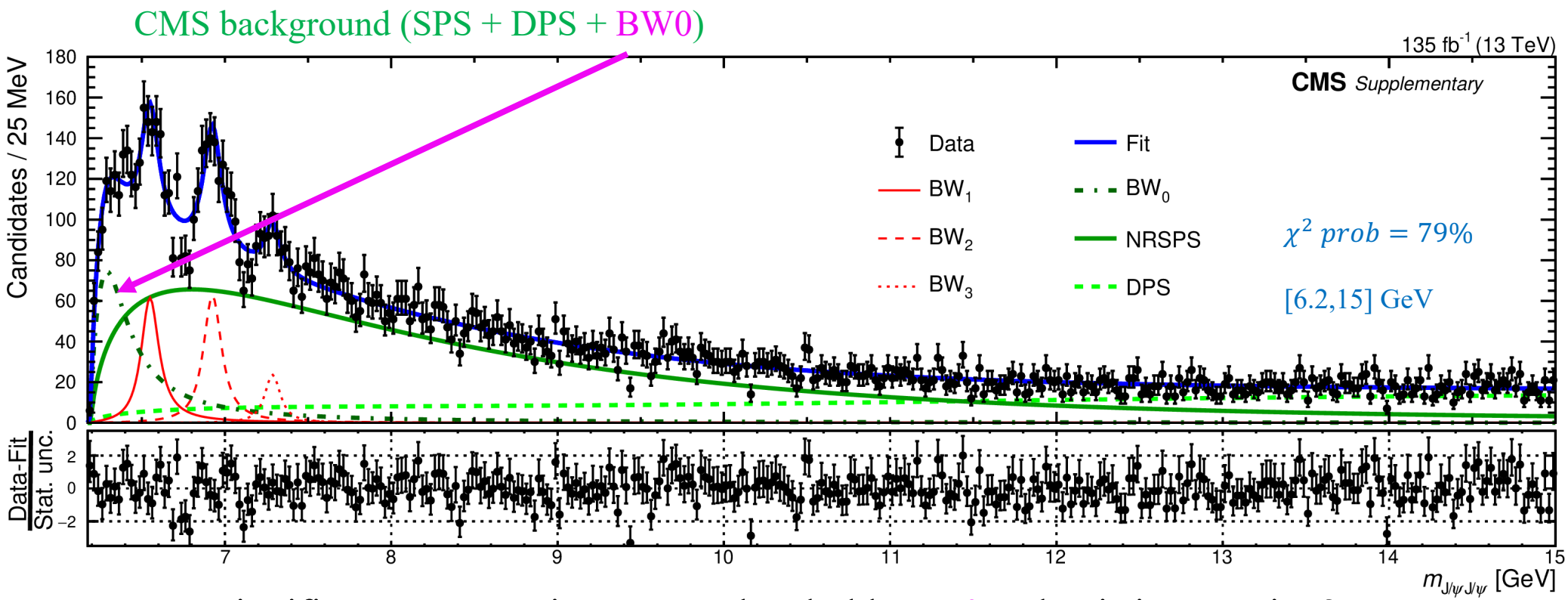




- CMS data: 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs
- J/ψ mass and vertex related cuts removed
- Clean J/ψ signals are seen

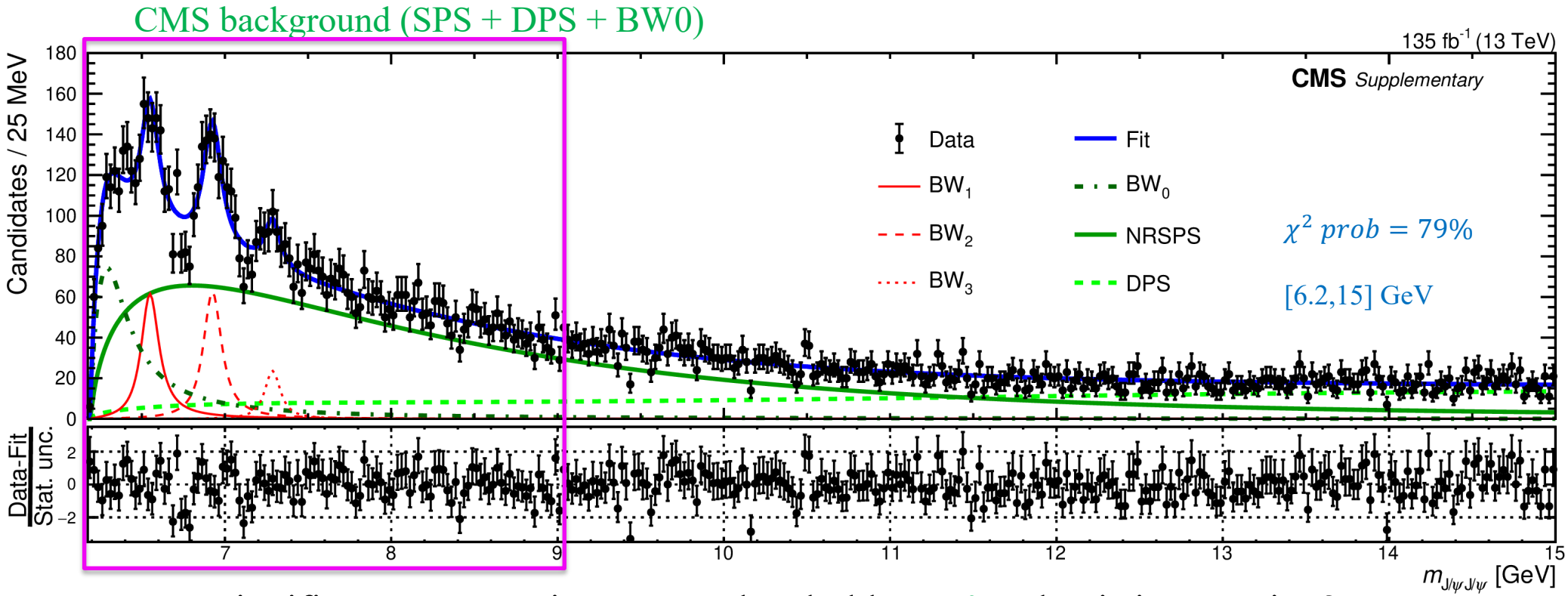


CMS background (SPS + DPS + BW0)



- Most significant structure is a BW at threshold, BW0--what is its meaning?
- Treat BW0 as part of background due to:
  - BW0 parameters very sensitive to SPS and DPS model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…

CMS background (SPS + DPS + BW0)



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  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…
- SPS+DPS+BW0 as our background

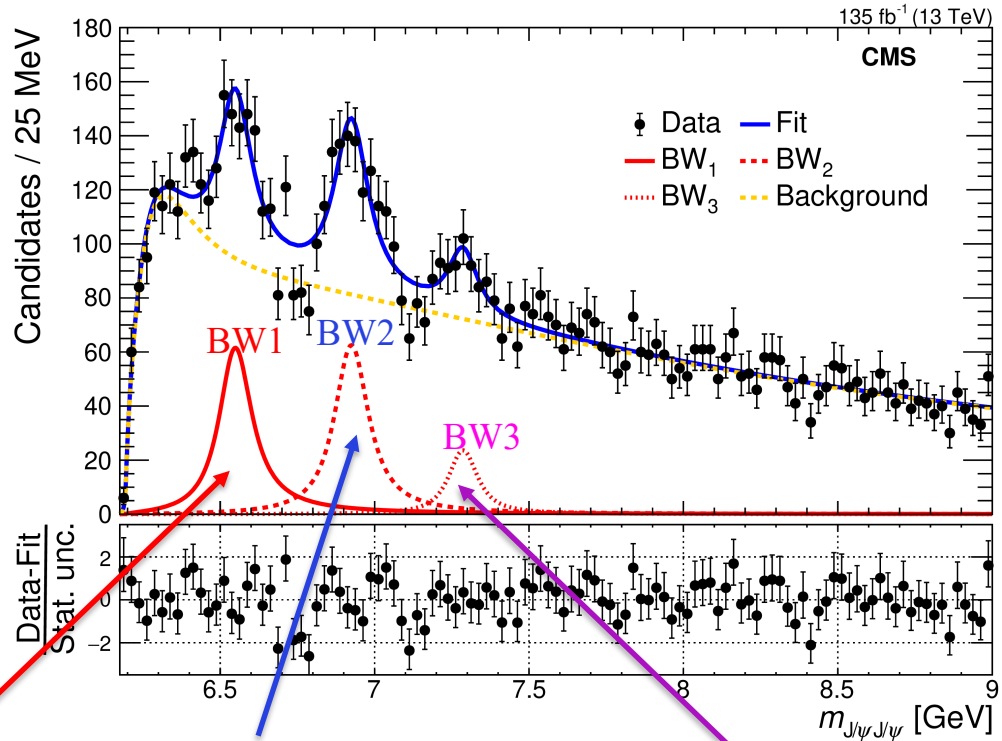
CMS J/ψJ/ψ model: 3 BWs + Background

χ^2 Prob. = 1%

[6.2,7.8] GeV

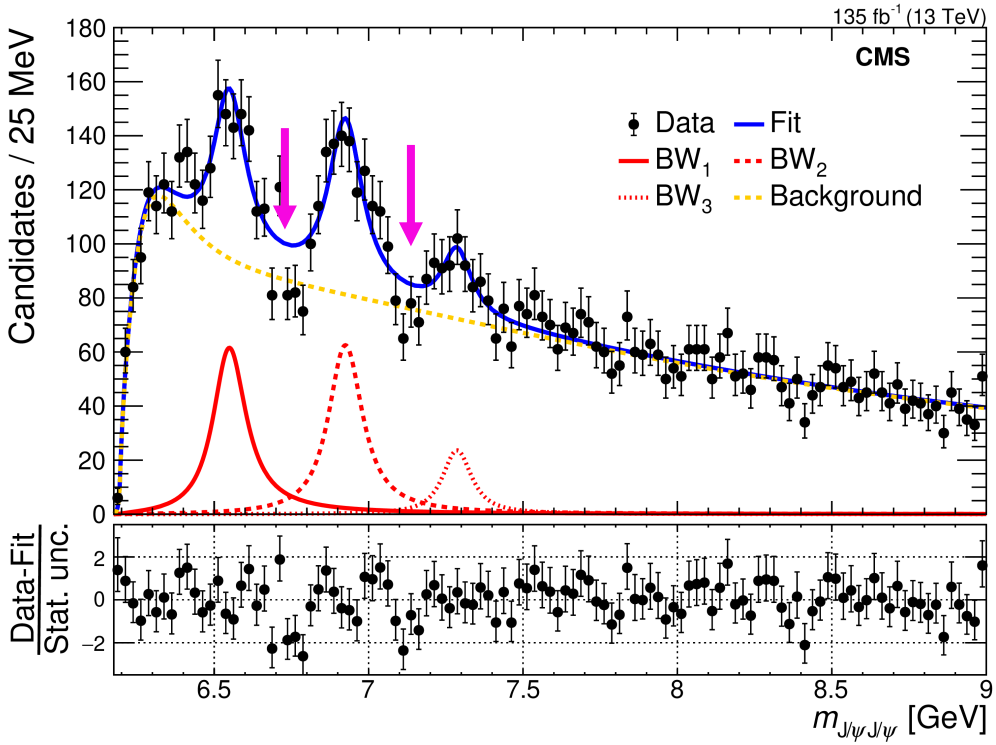
Statistical significance based on:

$2\ \ln(L_0/L_{max})$



	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287\ ^{+20}_{-18} \pm 5$
Γ	$124\ ^{+32}_{-26} \pm 33$	$122\ ^{+24}_{-21} \pm 18$	$95\ ^{+59}_{-40} \pm 19$
N	$470\ ^{+120}_{-110}$	$492\ ^{+78}_{-73}$	$156\ ^{+64}_{-51}$
σ(stat.)	6.5	9.4	4.1
σ(stat. + syst.)	5.7	9.4	4.1
	Observation	Confirmation of X(6900) from LHCb	Evidence

The dips



- Possibility #1:
  - Interference among structures?

- Possibility #2:
  - Multiple fine structures to reproduce the dips?
  - Mentioned in PAS

- More secrets to dig out
- We explored possibility #1 in detail

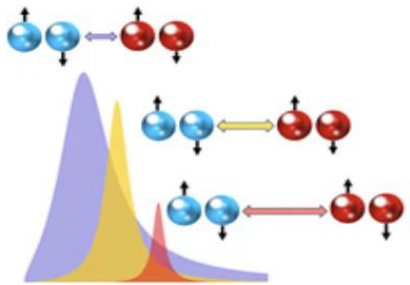
CMS J/ψJ/ψ interference fit

Editors' Suggestion

New Structures in the $J/\psi J/\psi$ Mass Spectrum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

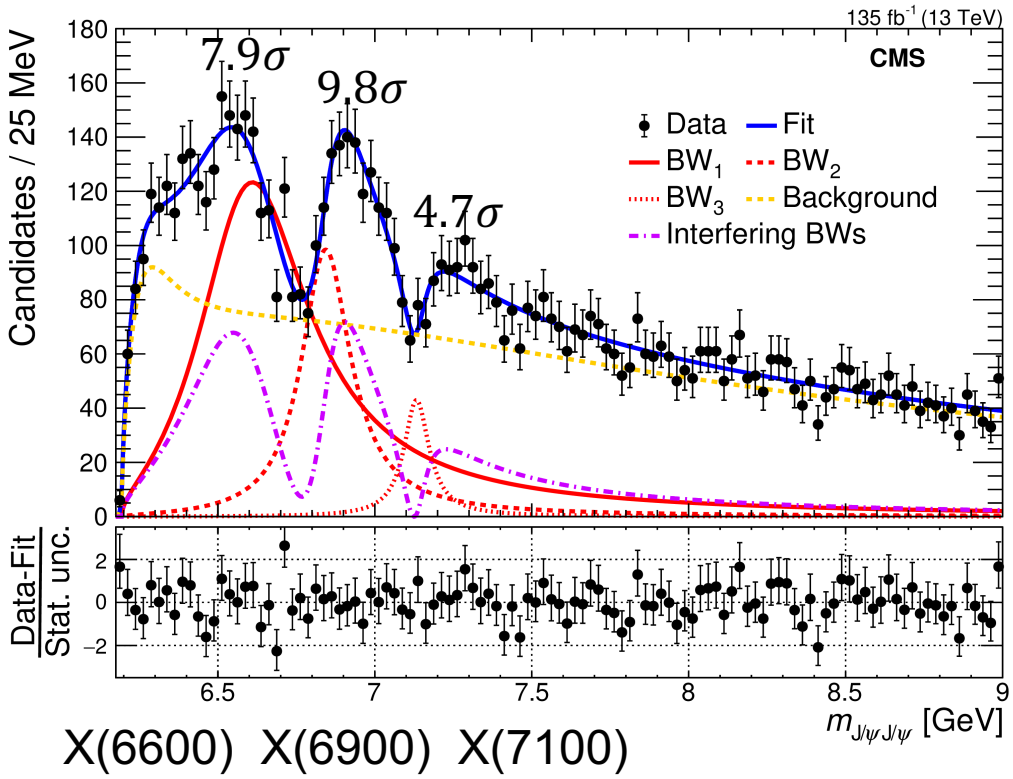
A. Hayrapetyan *et al.* (CMS Collaboration)

Phys. Rev. Lett. **132**, 111901 (2024) – Published 15 March 2024



Three structures, $X(6900)$ and two new ones around 6.64 and 7.13 GeV, are seen in the $J/\psi J/\psi$ mass spectrum that are consistent with being part of a family of radial excitations.

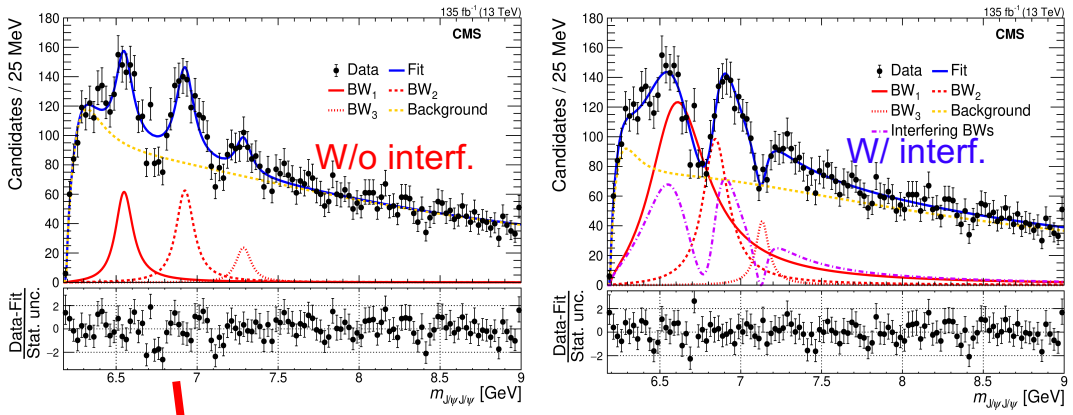
Show Abstract +



- Fit with interf. among BW1, BW2, and BW3 describes data well
- Measured mass and width in the interference fit

		BW_1	BW_2	BW_3
Interference	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}

Comparison with some theoretical calculations



1^1P_1	1^{--}	363.9	320.3	-366.7	337.5	-14.4	0	0	-2.6	6553	-	-
1^3P_0	0^{-+}	356.7	320.2	-366.7	337.5	-7.2	-56.9	-43.1	-2.6	6460	6398.1	$\eta_c(1S)\chi_{c0}(1P)$
1^3P_1	1^{-+}	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554	6494.1	$\eta_c(1S)\chi_{c1}(1P)$
1^3P_2	2^{-+}	356.6	320.2	-366.7	337.5	-7.2	28.4	-2.1	-2.4	6587	6539.6	$\eta_c(1S)\chi_{c2}(1P)$
1^5P_1	1^{--}	342.4	320.4	-366.7	337.5	7.2	-85.3	-30.2	-2.7	6459	6508.8	$\eta_c(1S)h_{c1}(1P)$
1^5P_2	2^{--}	342.2	320.2	-366.7	337.5	7.2	-28.4	30.2	-2.5	6577	6607.6	$J/\psi(1S)\chi_{c1}(1P)$
1^5P_3	3^{--}	342.3	320.3	-366.7	337.5	7.2	56.9	-8.6	-2.5	6623	6653.1	$J/\psi(1S)\chi_{c2}(1P)$
2^1P_1	1^{--}	414.7	688.7	-263.4	548.6	-11.2	0	0	-1.6	6925	-	-
2^3P_0	0^{-+}	410.0	689.6	-263.4	548.6	-5.6	-46.2	-34.5	-1.7	6851	-	-
2^3P_1	1^{-+}	410.0	689.6	-263.4	548.6	-5.6	-23.1	17.2	-1.6	6926	-	-
2^3P_2	2^{-+}	410.0	689.6	-263.4	548.7	-5.6	23.1	-3.4	-1.7	6951	-	-
2^5P_1	1^{--}	398.7	689.5	-263.4	548.6	-5.6	-69.3	-24.2	-1.7	6845	-	-
2^5P_2	2^{--}	398.7	689.5	-263.4	548.6	5.6	-23.1	24.2	-1.5	6944	-	-
2^5P_3	3^{--}	398.8	689.7	-263.4	548.6	5.6	46.2	-6.9	-1.6	6982	-	-
3^1P_1	1^{--}	479.8	982.2	-215.5	727.8	-9.3	0	0	-1.1	7221	-	-
3^3P_0	0^{-+}	475.2	982.7	-215.5	727.7	-4.6	-41.9	-31.0	-1.2	7153	-	-
3^3P_1	1^{-+}	475.1	982.6	-215.5	727.7	-4.6	-20.9	15.5	-1.2	7220	-	-
3^3P_2	2^{-+}	475.1	982.6	-215.5	727.8	-4.6	20.9	-3.1	-1.0	7243	-	-
3^5P_1	1^{--}	465.9	982.8	-215.5	727.7	4.6	-62.8	-21.7	-1.2	7150	-	-
3^5P_2	2^{--}	465.7	982.6	-215.5	727.8	-4.6	-20.9	21.7	-1.1	7236	-	-
3^5P_3	3^{--}	465.8	982.6	-215.5	727.8	4.6	41.9	-6.2	-1.1	7271	-	-

arXiv:2108.04017 **[hep-ph]**

P-wave

M[BW1] = 6552 ± 10 ± 12 MeV

M[BW2] = 6927 ± 9 ± 5 MeV

M[BW3] = 7287 ± 19 ± 5 MeV

Table 1. Predictions of the masses (MeV) of S-wave fully heavy $T_{4Q}(nS)$ tetraquarks. Only 0^{++} and 2^{++} are considered for $T_{bc\bar{b}\bar{c}}$. The uncertainty is from the coupling constant $\alpha_s = 0.35 \pm 0.05$.

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$T_{4Q}(nS)$ states	J^P	Mass(n=1)	Mass(n=2)	Mass(n=3)	Mass(n=4)
$T_{cc\bar{c}\bar{c}}$	0^{++}	6055^{+69}_{-74}	6555^{+36}_{-37}	6883^{+27}_{-27}	7154^{+22}_{-22}
	2^{++}	6090^{+62}_{-66}	6588^{+34}_{-35}	6920^{+27}_{-26}	7160^{+22}_{-22}
$T'_{cc\bar{c}\bar{c}}$	0^{++}	5984^{+64}_{-67}	6468^{+26}_{-26}	6795^{+26}_{-26}	7066^{+21}_{-22}
$T_{bc\bar{b}\bar{c}}$	0^{++}	12387^{+109}_{-120}	12911^{+33}_{-33}	13200^{+35}_{-36}	13429^{+29}_{-30}
	2^{++}	12401^{+117}_{-106}	12914^{+45}_{-49}	13202^{+35}_{-36}	13430^{+29}_{-29}
$T'_{bc\bar{b}\bar{c}}$	0^{++}	12300^{+106}_{-117}	12816^{+48}_{-50}	13104^{+35}_{-35}	13333^{+29}_{-29}
$T_{bb\bar{b}\bar{b}}$	0^{++}	18475^{+151}_{-169}	19073^{+59}_{-63}	19353^{+42}_{-42}	19566^{+33}_{-35}
	2^{++}	18483^{+149}_{-168}	19075^{+59}_{-62}	19355^{+41}_{-43}	19567^{+33}_{-35}
$T'_{bb\bar{b}\bar{b}}$	0^{++}	18383^{+149}_{-167}	18976^{+59}_{-62}	19256^{+43}_{-42}	19468^{+34}_{-34}

S-wave

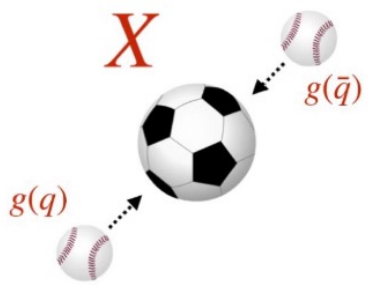
M[BW1] = 6638 ± 10 ± 12 MeV

M[BW2] = 6847 ± 9 ± 5 MeV

M[BW3] = 7134 ± 19 ± 5 MeV

- Radial excited p-wave states (like J/ψ series)?
- Or Radial excited S-wave states?
- Theoretical situation difficulty & confusing
  - Important next step: measure J^{PC} to clarify

Spin Parity Analysis (on going)

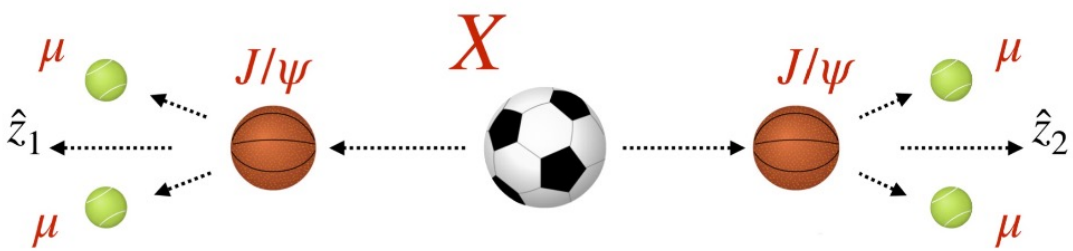


Polarization in production

- Spin-0: $gg \to X$
- Spin-1: $q\bar{q} \to X$ produce $J_z = \pm 1$
- Spin-2:

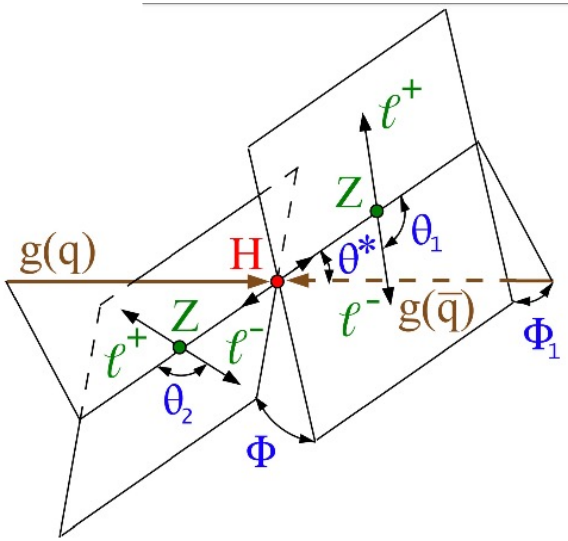
  $gg \to X$ produce $J_z = 0, \pm 2$, minimal coupling: $J_z = \pm 2$

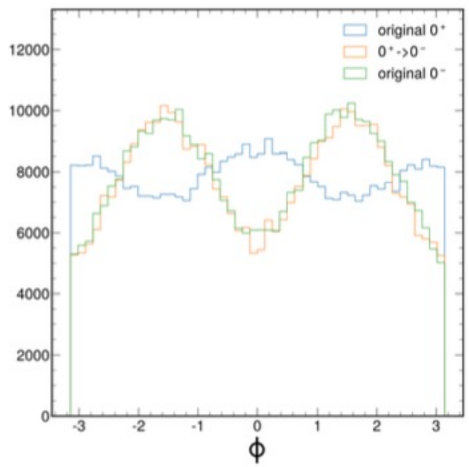
  $q\bar{q} \to X$ produce $J_z = \pm 1$

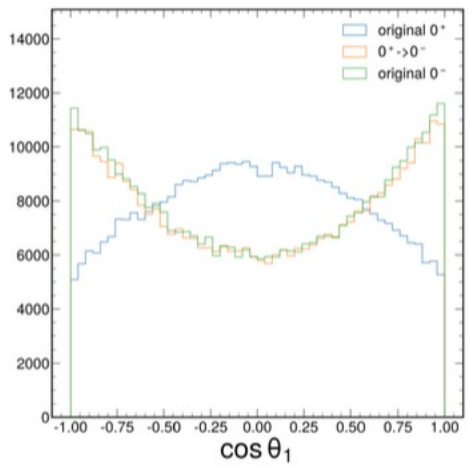


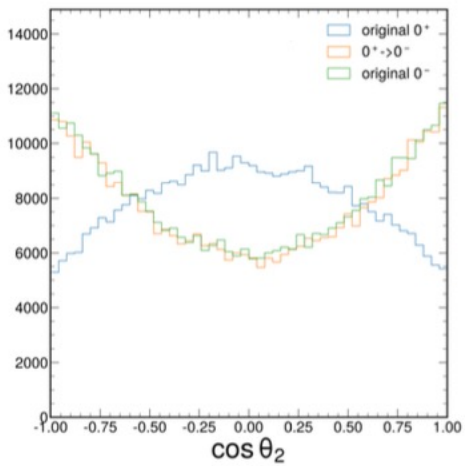
Polarization in decay

- Spin-0: 0^+, 0^-
- Spin-1: 1^-, 1^+
- Spin-2: 2^+, 2^-







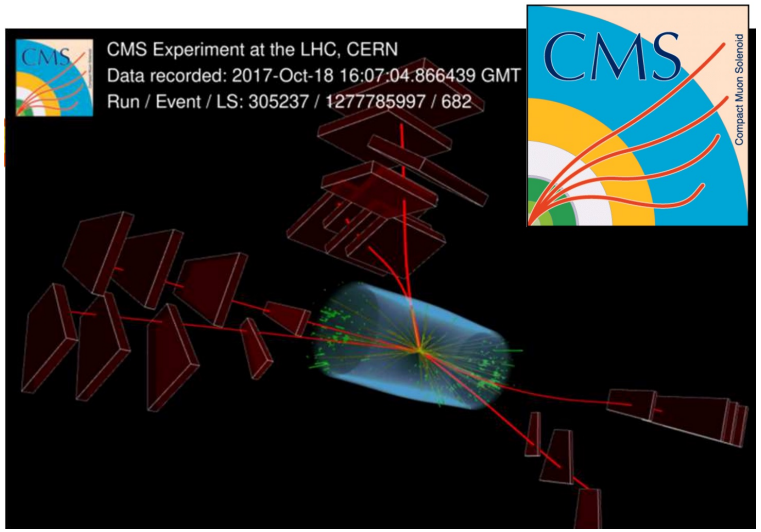


Observation of triple J/ψ

Signal yield: $5^{+2.6}_{-1.9}$events

Significance > 5σ

σ(pp→J/ψJ/ψJ/ψX)
= 272 +141−104 (stat) ± 17 (syst) fb



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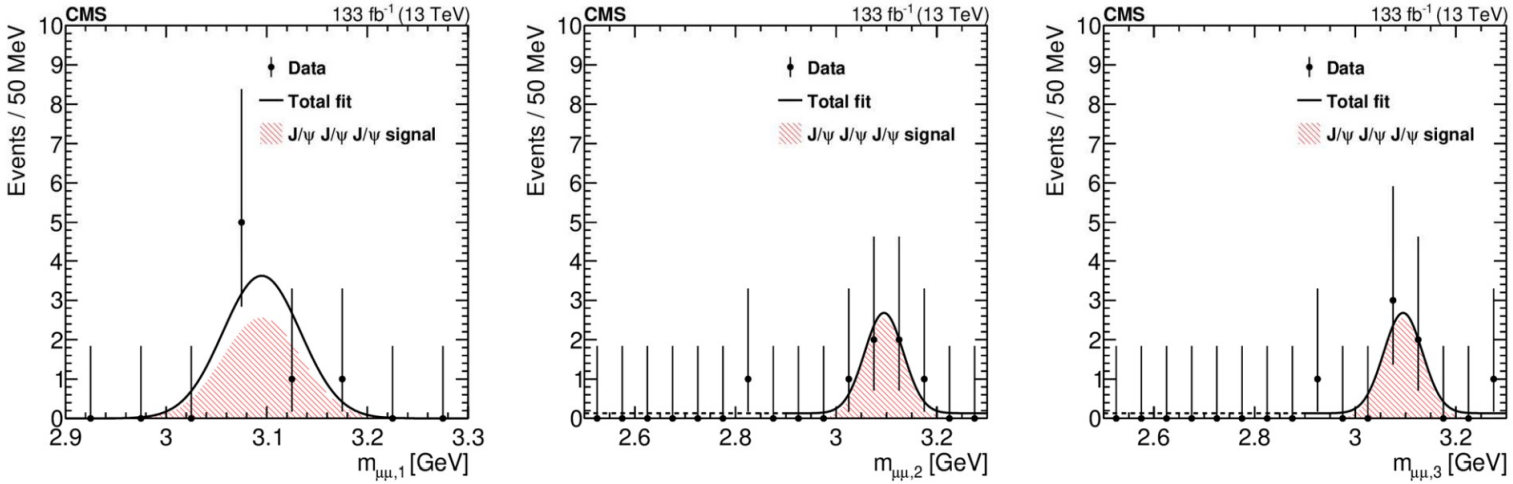


"6c" search in future?

CMS exotic hadron results

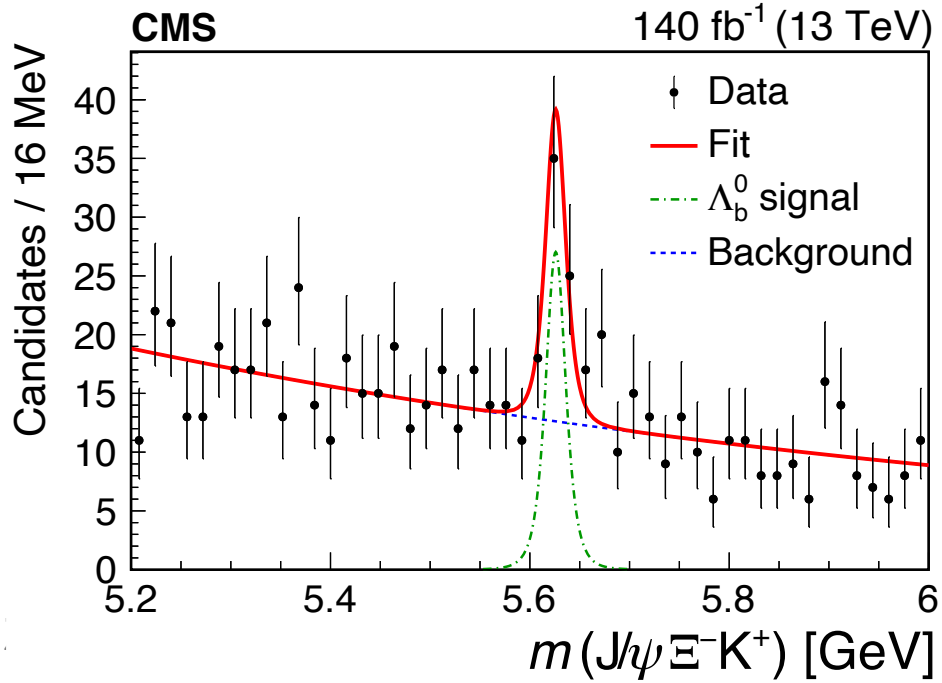
- X(3872) studies
  - Measurement of X(3872) to $J/\psi\pi^+\pi^-$ (2013)
  - Observation of $B_s^0 \to X(3872)\phi$ (2020)
  - Evidence of X(3872) in PbPb collisions (2022)

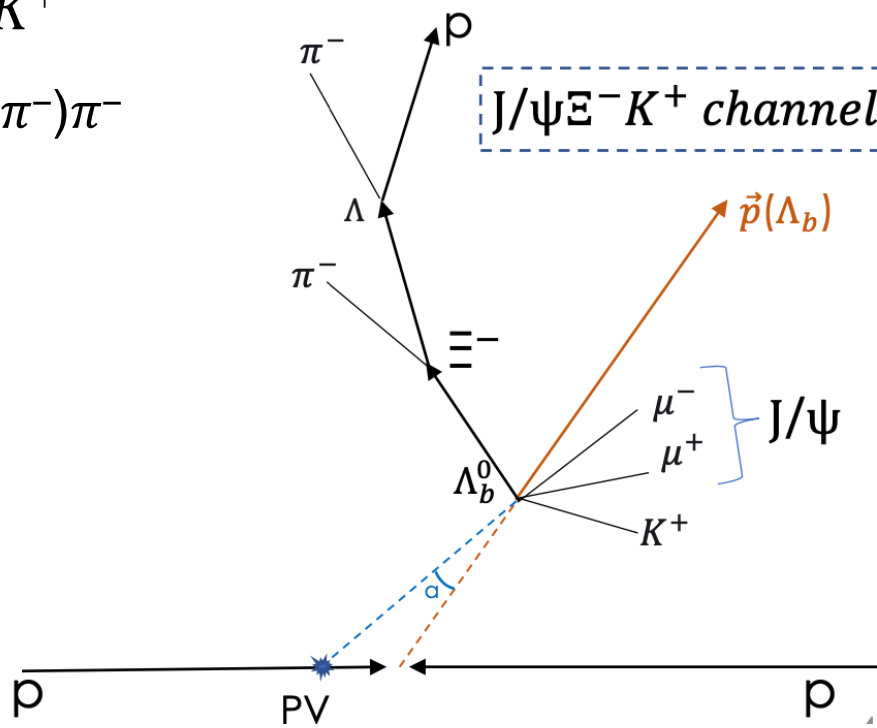
- Observations of new structures
  - Observation of new structure in $J/\psi\phi$ from $B^\pm \to J/\psi\phi K^\pm$ (2014)
  - Observation of new structure in $J/\psi\, J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (2023)

- Searches without showing significance structures
  - Upper limit for $X(5568)^\pm \to B_s^0\pi^\pm$ (2020)
  - Observation of $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ (2022)
  - Observation of $\Lambda_b^0 \to J/\psi\Xi^-K^+$ (2024)

Observation of $\Lambda_b \to J/\psi\, \Xi^- K^+$

- Multi-body decays of b-hadrons may proceed through exotic intermediate resonances
  - E. g. pentaquark $J/\psi\, p$ structure in $\Lambda_b \to J/\psi\, p\, K^-$ observed by LHCb
  - $\Lambda_b \to J/\psi\, \Xi^- K^+$ final state can unveil yet-unobserved (e. g. doubly-strange) pentaquarks
- First-time observation of $\Lambda_b \to J/\psi\, \Xi^- K^+$
  - In final states with $J/\psi \to \mu\mu$, $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$
  - $\mathbf{5.8}\ \boldsymbol{\sigma}$ significance





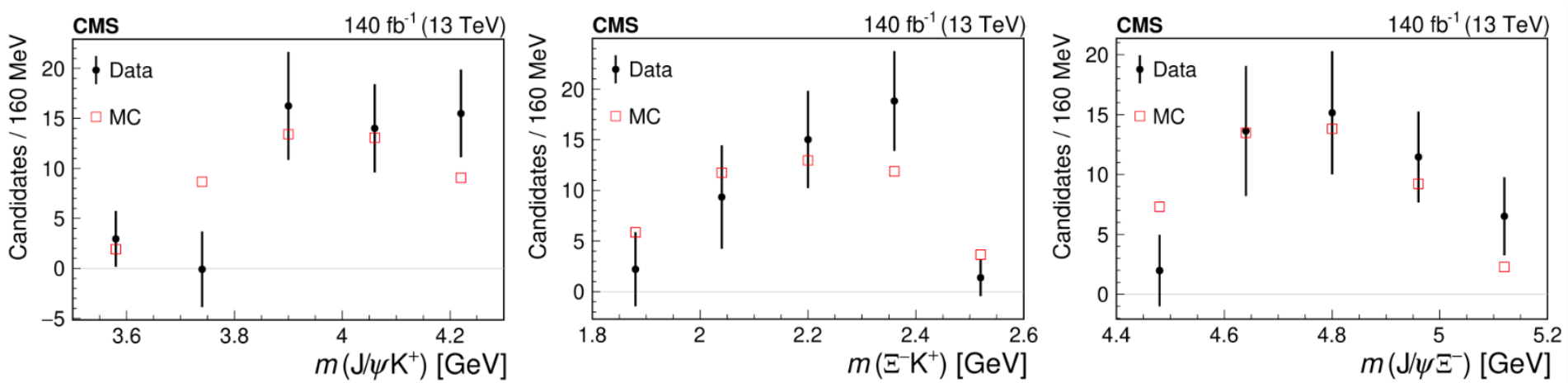
Observation of $\Lambda_b \to J/\psi\,\Xi^-K^+$

- $\Lambda_b \to J/\psi\,\Xi^-K^+$ branching fraction ratio measurement
  - Large systematics cancellation in the measured ratio R
  - Result dominated by low signal statistics

$$R = \frac{B(\Lambda_b \to J/\psi\,\Xi^-K^+)}{B(\Lambda_b \to \psi(2S)\Lambda)} = \frac{N_{signal}}{N_{ref.}} \times \frac{\epsilon_{signal}}{\epsilon_{ref.}} \times \frac{B(\psi(2S) \to J/\psi\,\pi^-\pi^+)}{B(\Xi^- \to \Lambda\pi^-)}$$

$$= [\mathbf{3.38 \pm 1.02\ (stat.) \pm 0.61 (syst.) \pm 0.03\ (B)}]\ \%$$

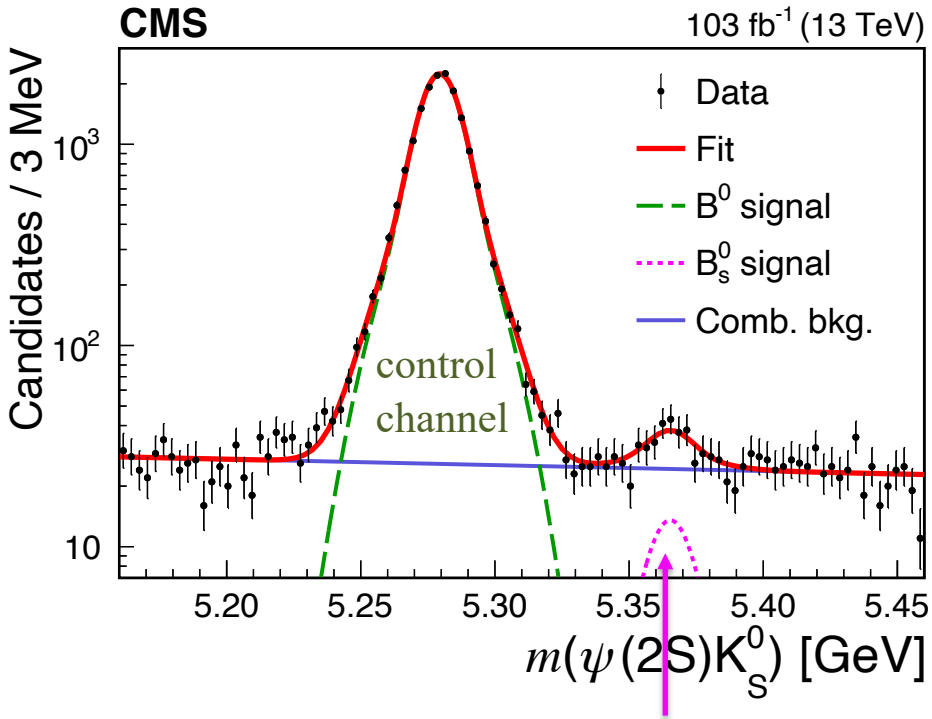
- Search for intermediate resonances



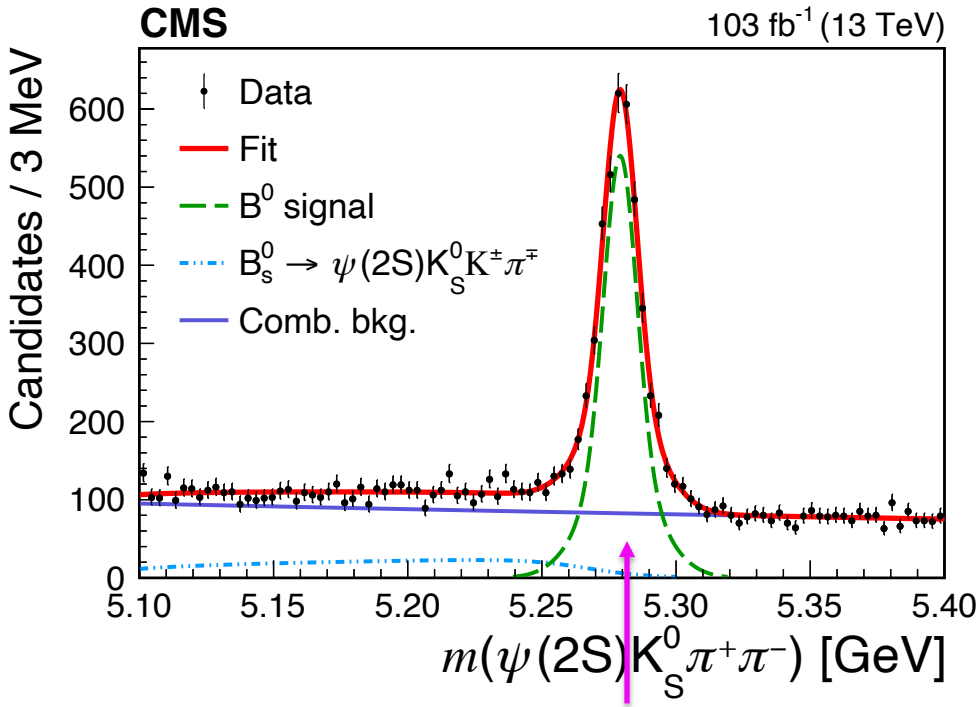
No evidence of resonant structures at this signal statistics

Observation of $B^0 \to \psi(2S) K_0^S \pi^+ \pi^-$

- 103 fb^{-1} @ 13 TeV pp collision data



Significance 5.2σ !
First observation of
$B_s^0 \to \psi(2S) K_S^0$!



Significance > 30
First observation

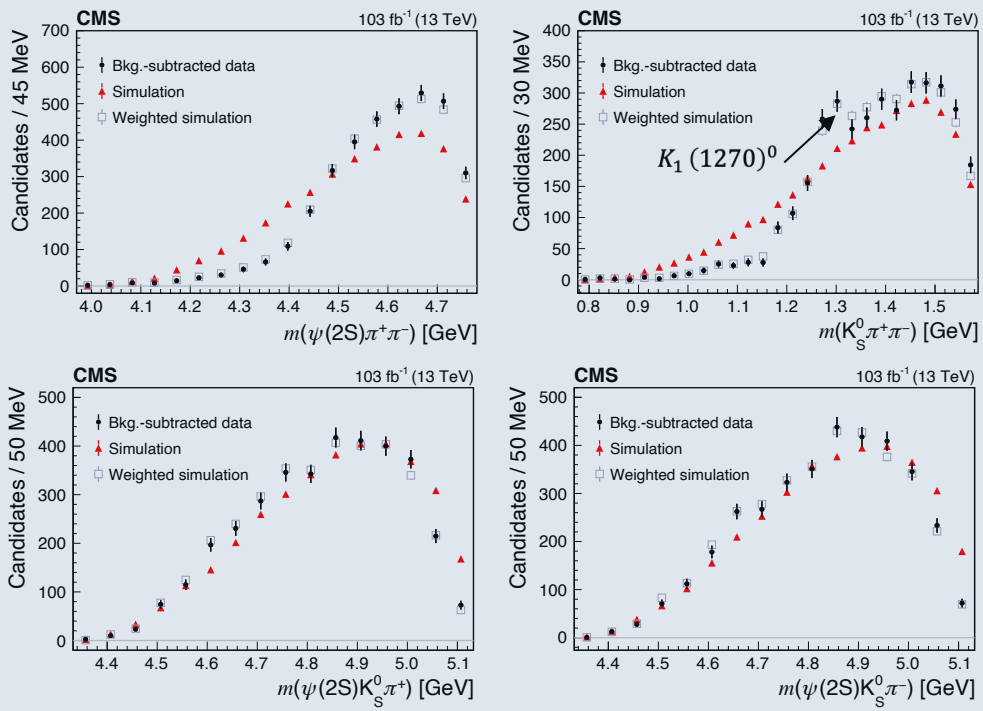
$$\mathcal{B}(B^0 \to \psi(2S) K_S^0 \pi^+ \pi^-)/\mathcal{B}(B^0 \to \psi(2S) K_S^0) = 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst}),$$

$$\mathcal{B}(\bar{B}_s^0 \to \psi(2S) K_S^0)/\mathcal{B}(B^0 \to \psi(2S) K_S^0) = (3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2}$$

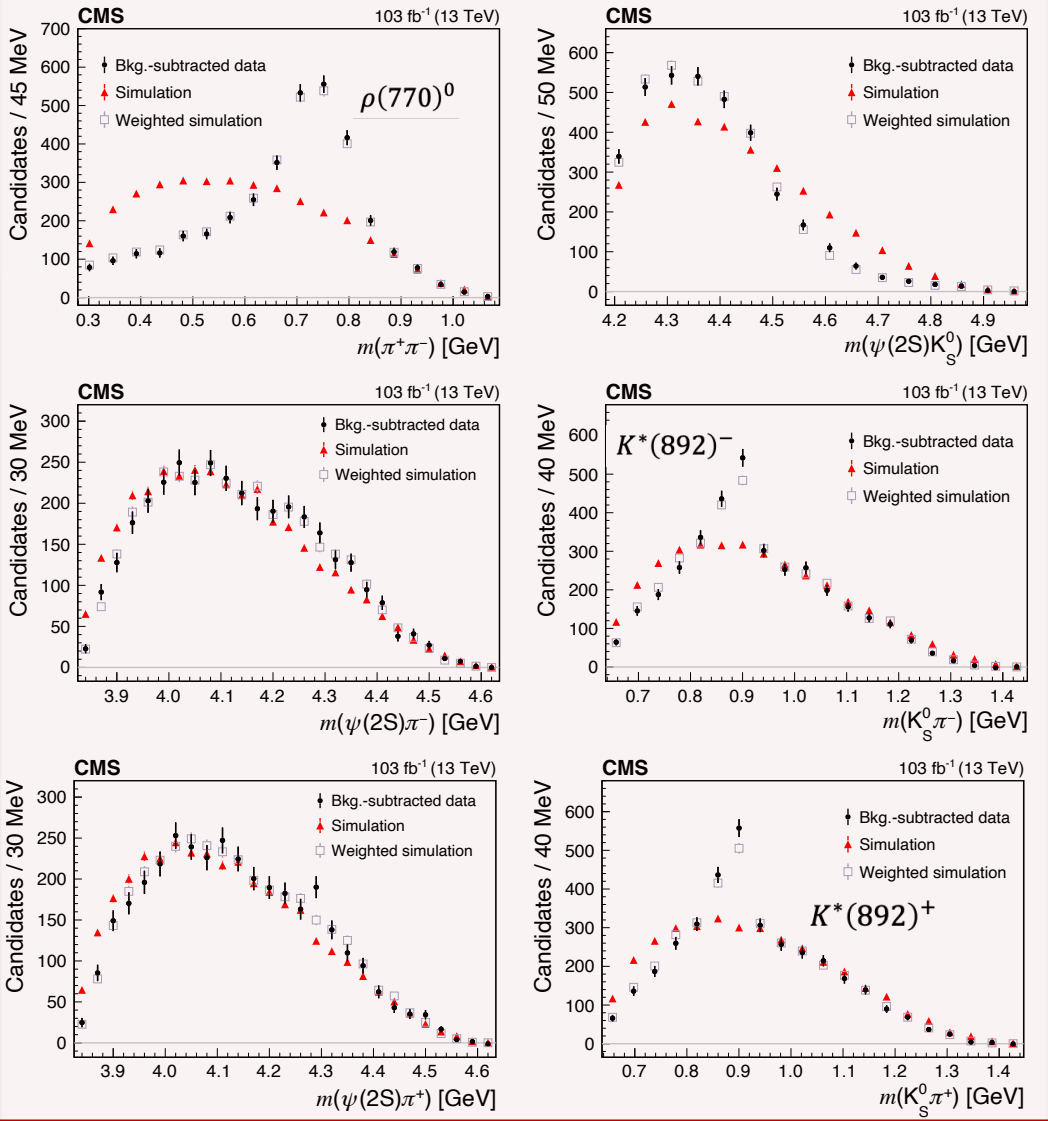
Observation of $B^0 \to \psi(2S) K_0^S \pi^+ \pi^-$

- No evidence of new resonant structures at this signal statistics

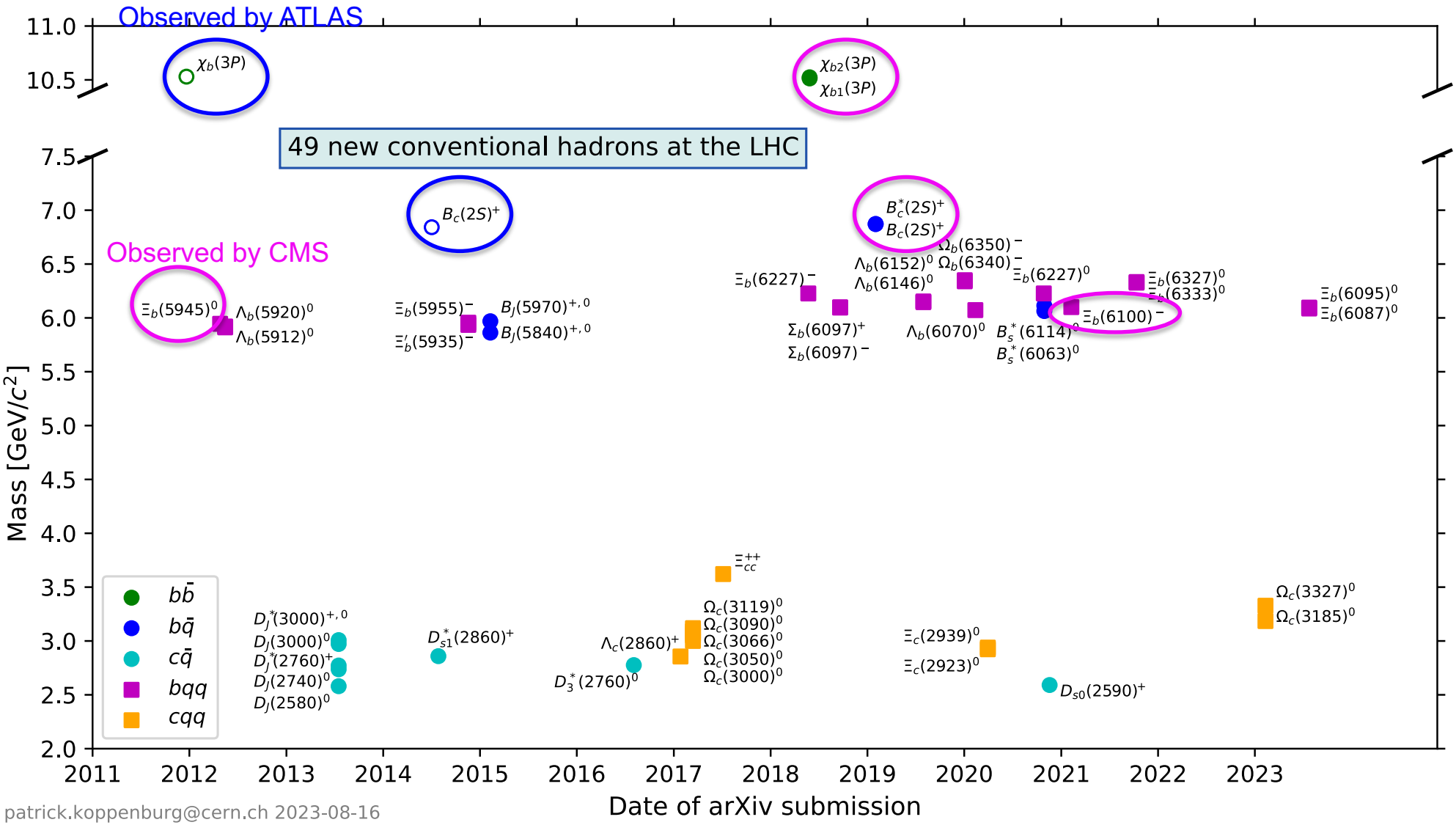
3-body intermediate invariant masses



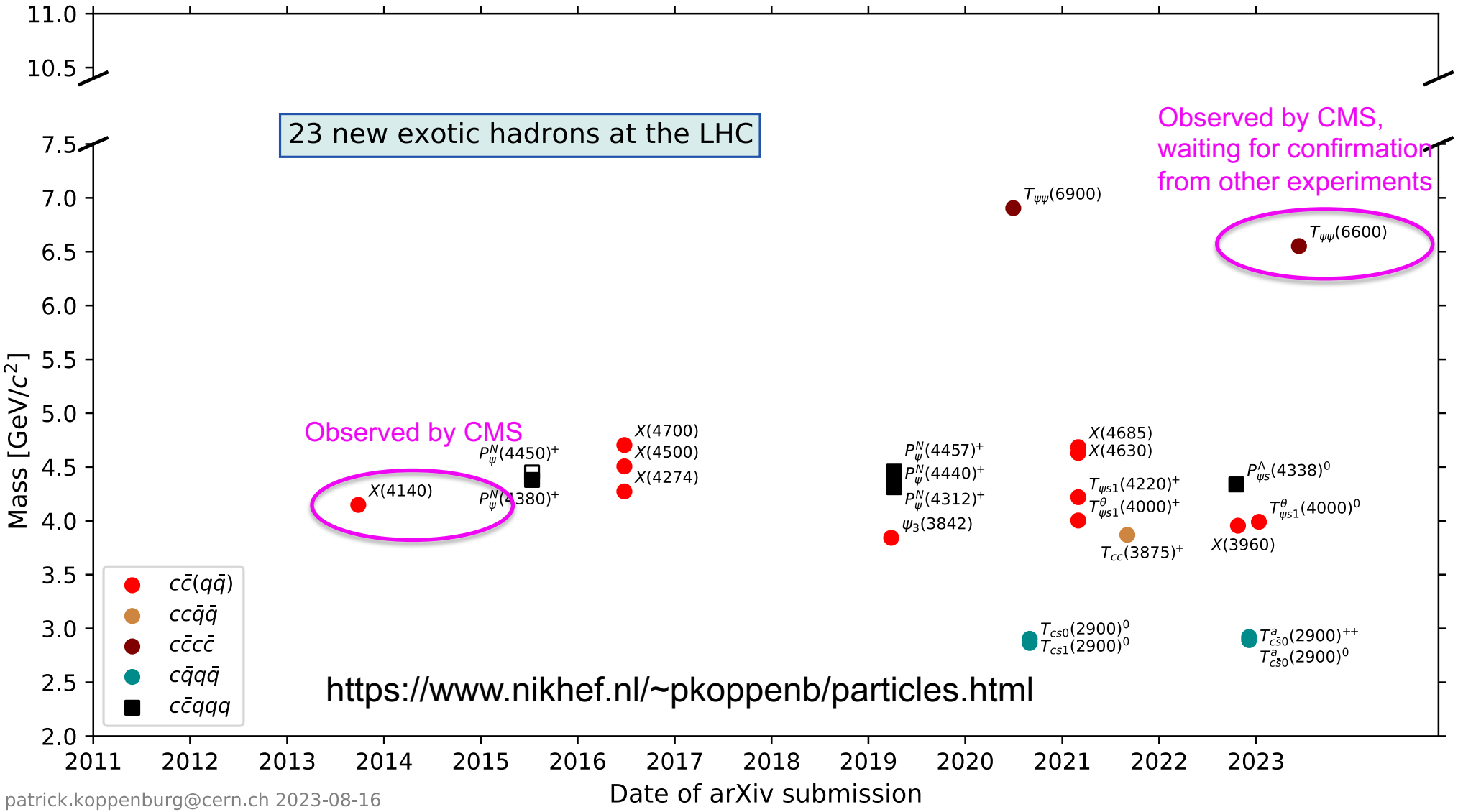
2-body intermediate invariant masses



New conventional hadrons at LHC

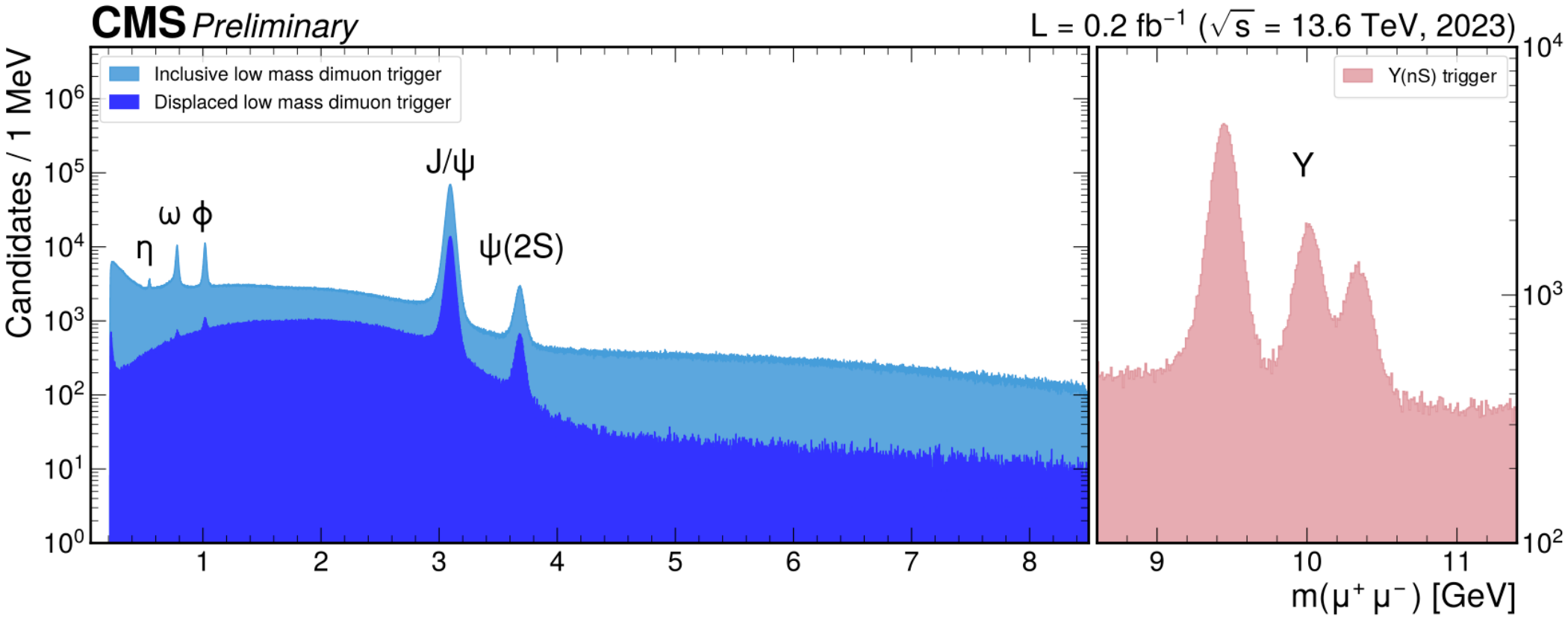


New exotic hadrons at LHC



Outlook

New trigger in Run-3 !



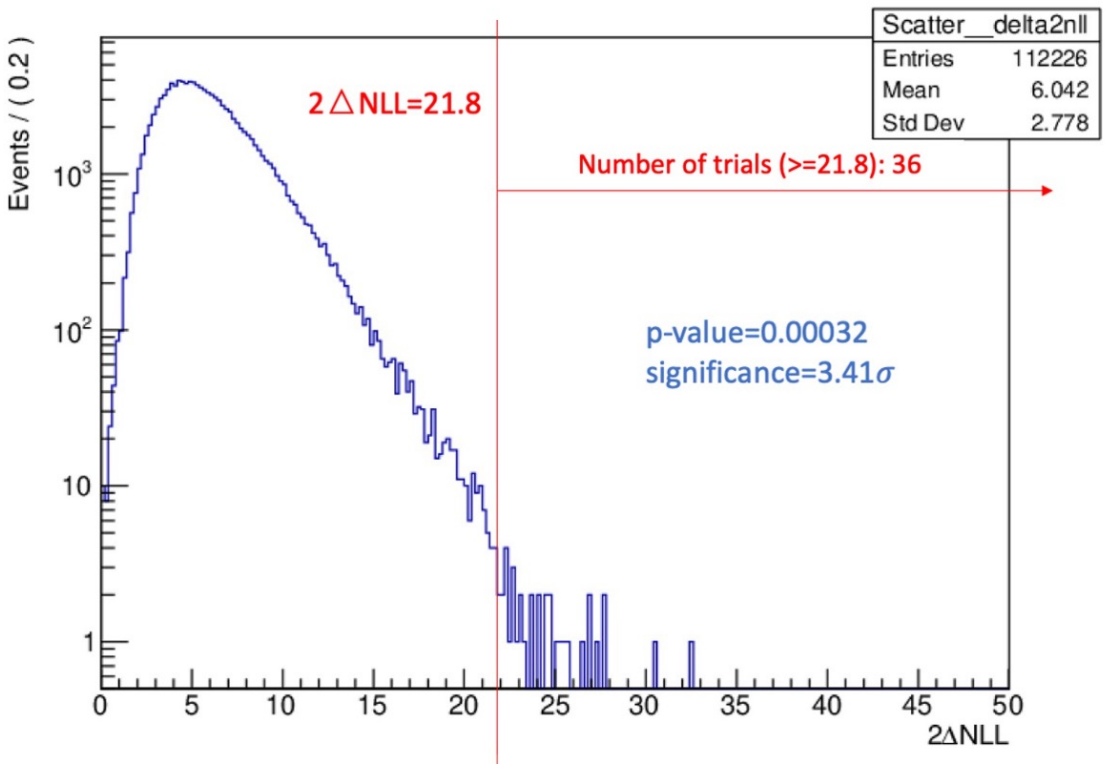
Thank you!

Backup

Global significance of BW3

- Generating Toys using background PDFs
- Find the most significant fluctuation in each trial
- Count trials with a fluctuation equal or bigger than data

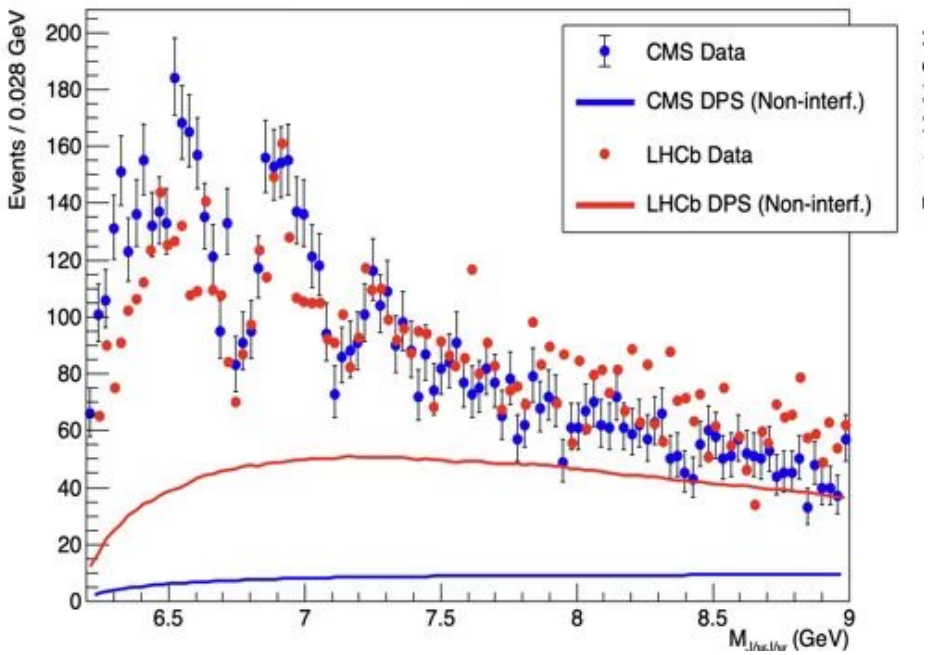
Search mass window: 7.05-7.8 GeV
Search width window: 50-260 MeV
Phase space: unconstrained



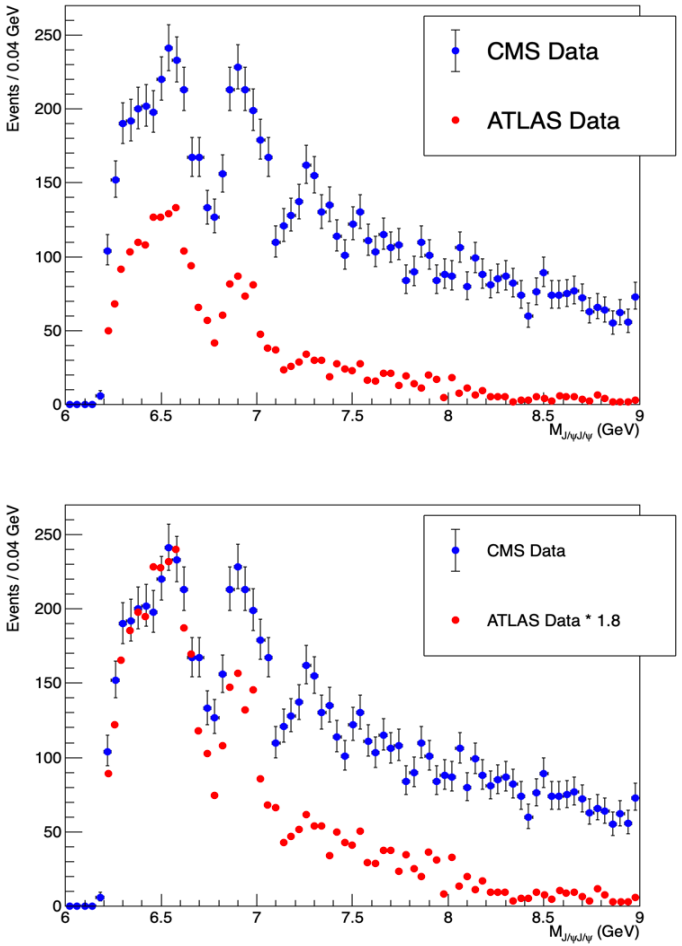
Global significance of BW3: **3.4σ**

ATLAS-CMS-LHCb data comparison

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



- Comparing with LHCb, CMS has:
  - 135/(3+6) ≈ 15X int. lum.
  - $(5/3)^4$ ≈ 8X muon acceptance
  - Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
  - Similar number of final events, but much less DPS
  - 2X yield @CMS for X(6900)



- Comparing with CMS, ATLAS has:
  - 1/3 –1/2 of CMS data (trigger?)
  - dR cut—remove high mass events