Heavy flavor spectroscopy studies at CMS

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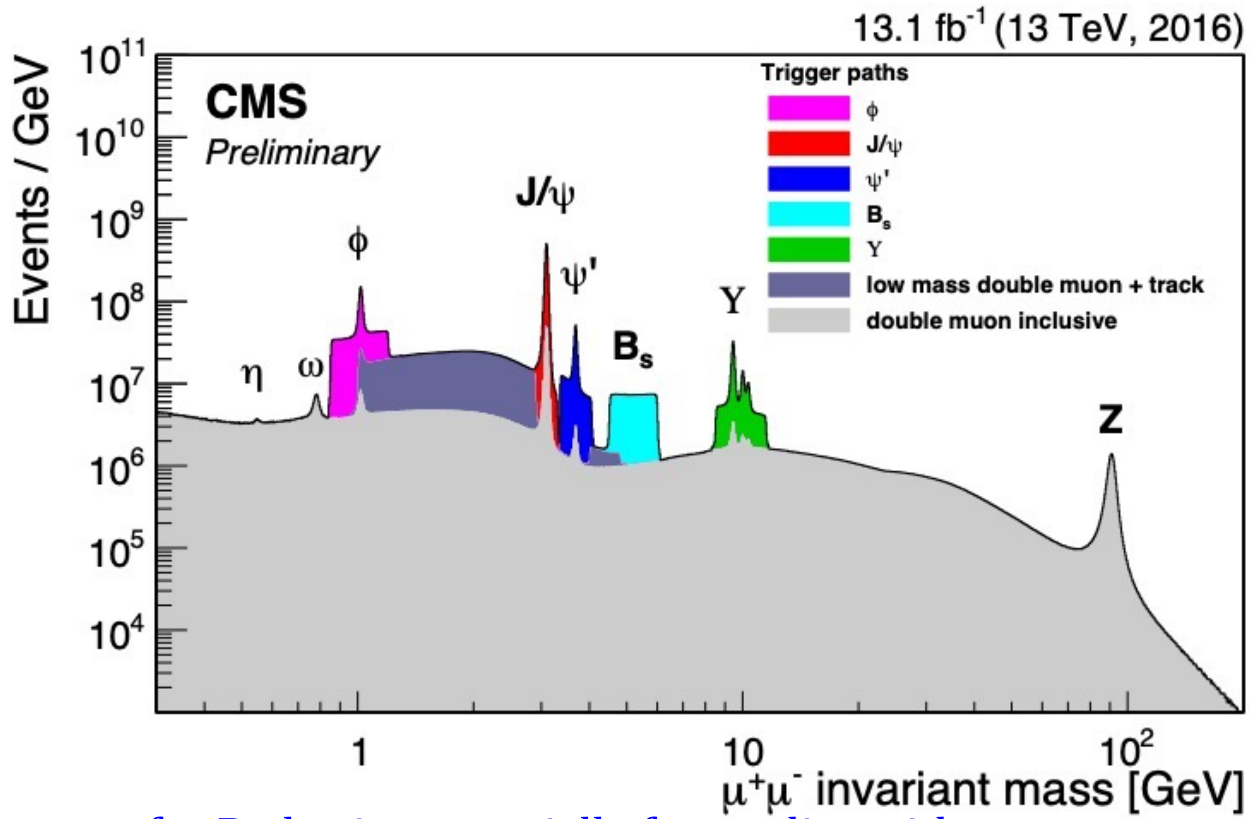
On behalf of the CMS Collaboration

GHP2025

Marth 14, 2025

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

Heavy flavor spectroscopy studies at CMS

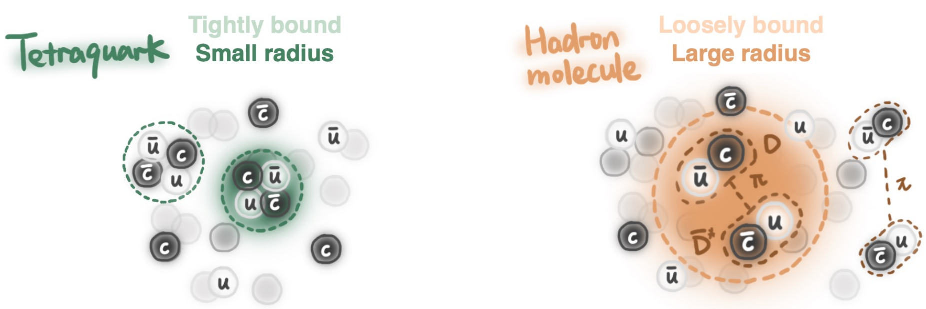
- X(3872) studies
  - Measurement of X(3872) to $J/\psi\pi^+\pi^-$ (2013) *JHEP 04 (2013) 154*
  - Observation of $B_s^0 \to X(3872)\phi$ (2020) *PRL 125 (2020) 152001*
  - Evidence of X(3872) in PbPb collisions (2022) *PRL 128 (2022) 032001*

- Observations of new exotic hadrons
  - Observation of X(4140) in $J/\psi\phi$ from $B^\pm \to J/\psi\phi K^\pm$ (2014) *MPLA 32 (2017) 1750139*
  - Observation of new structure in $J/\psi\, J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (2024) *PRL 132 (2024) 111901*

- Observations of new decay channels (after 2022 only)
  - Observation of $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ (2022) *EPJC 82 (2022) 499*
  - Observation of $\Lambda_b^0 \to J/\psi\,\Xi^-K^+$ (2024) *EPJC 84 (2024) 1062*
  - Observation of $\Xi_b^- \to \psi(2S)\Xi^-$ (2024) *PRD 110 (2024) 012002*

X(3872) in heavy-ion collisions

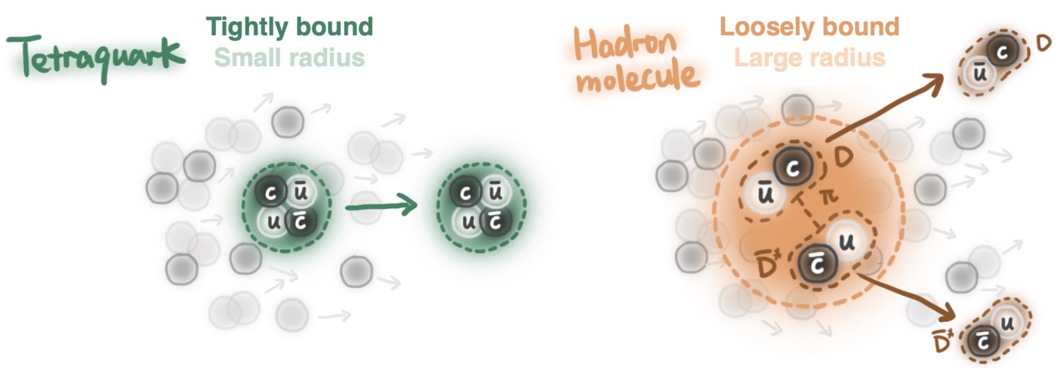
- Coalescence with particles in QGP ➜ Enhance X(3872)



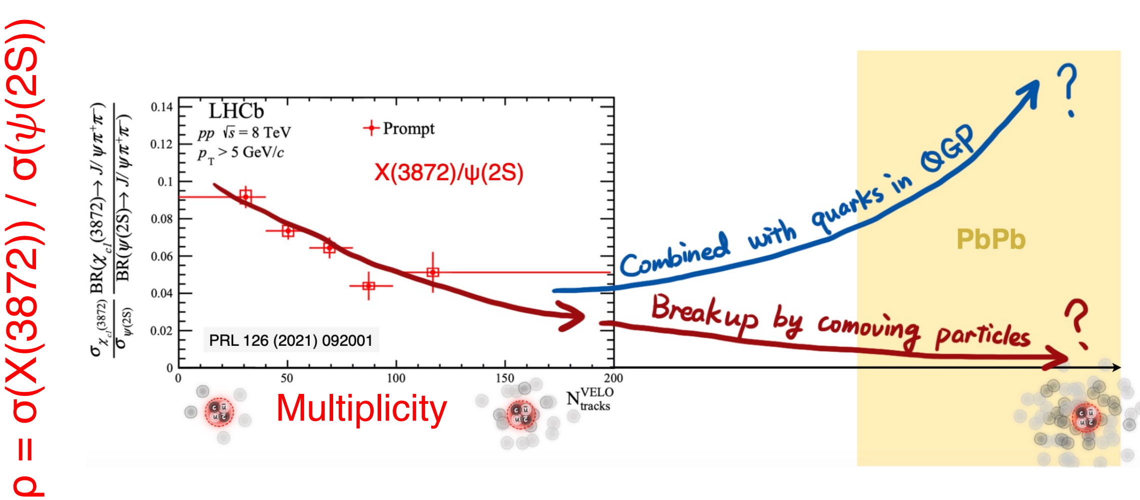
X(3872) inner structure:

Compact, molecule

- Breakup by co-moving particles ➜ Suppress X(3872)



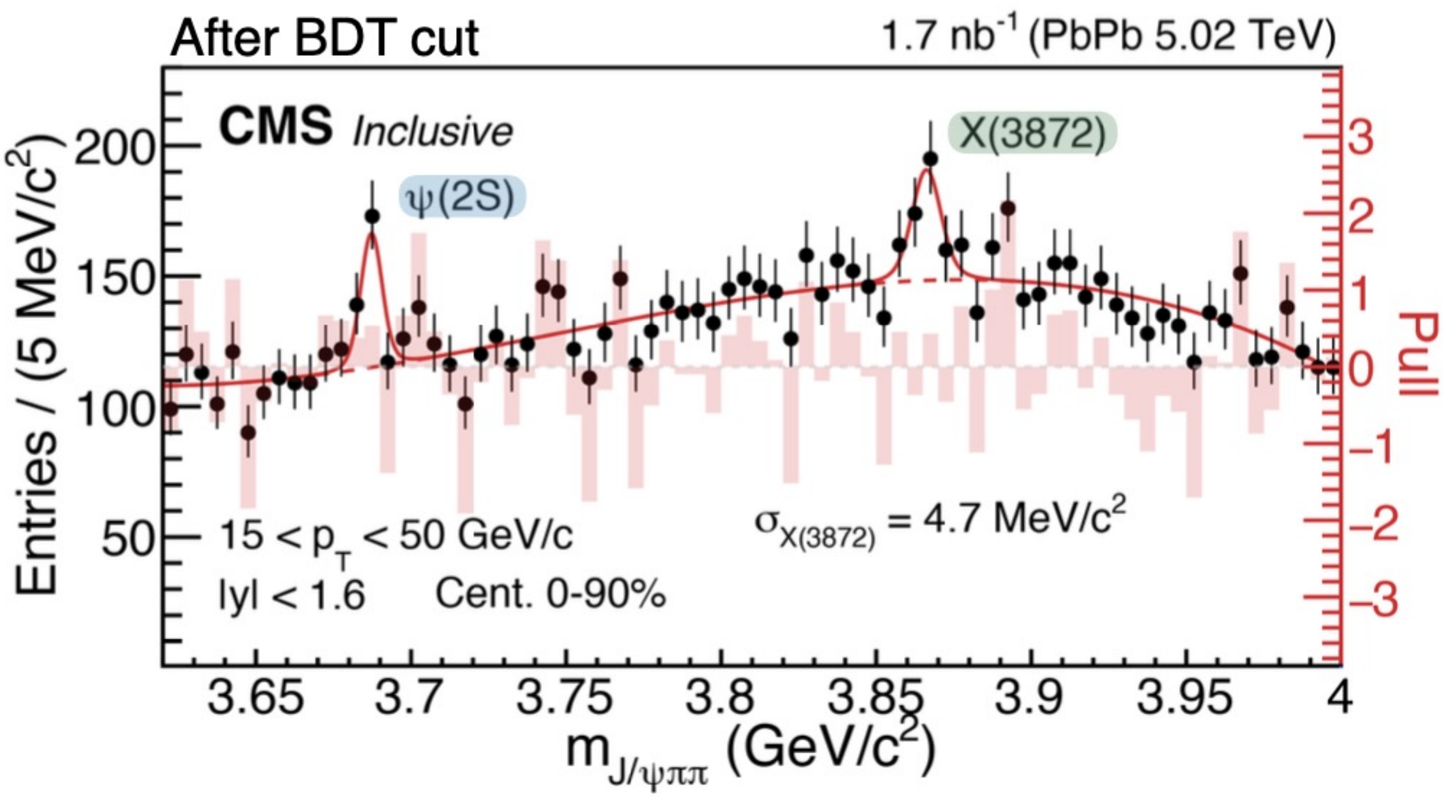
affects production in HI



What to expect in HI?

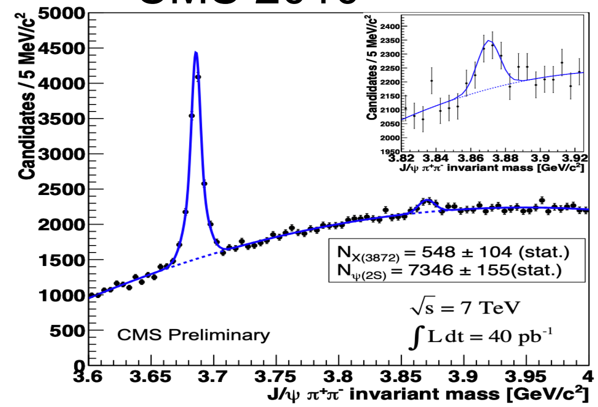
X(3872) in heavy-ion collisions

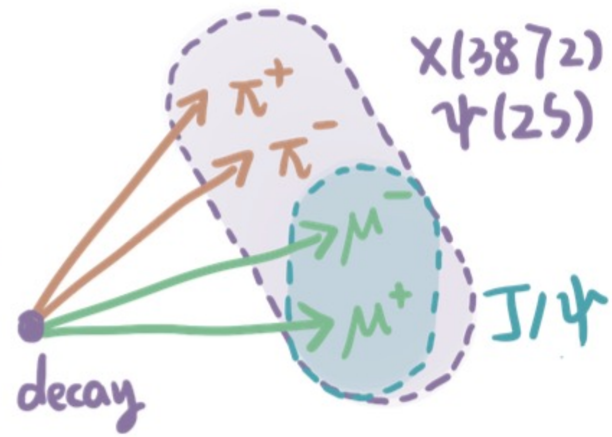
- First evidence of X(3872) production in HI
- Statistical significance ~ 4.2 σ



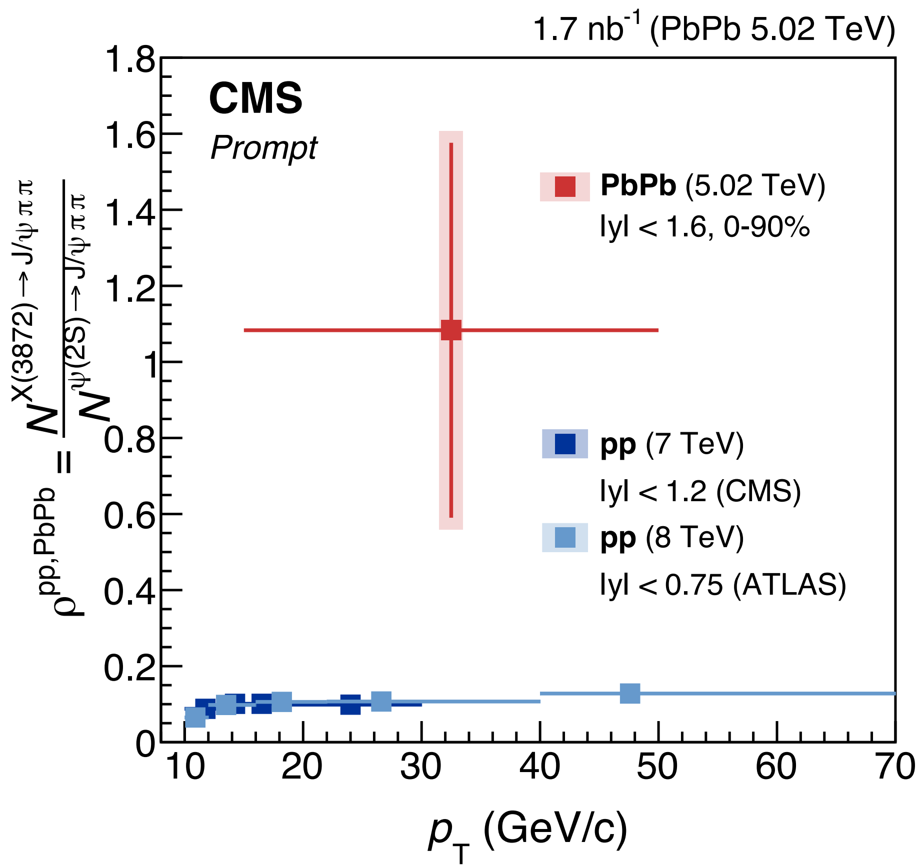
PRL 128 (2022) 032001

CMS 2010





X(3872)/ψ(2S) Ratio in PbPb



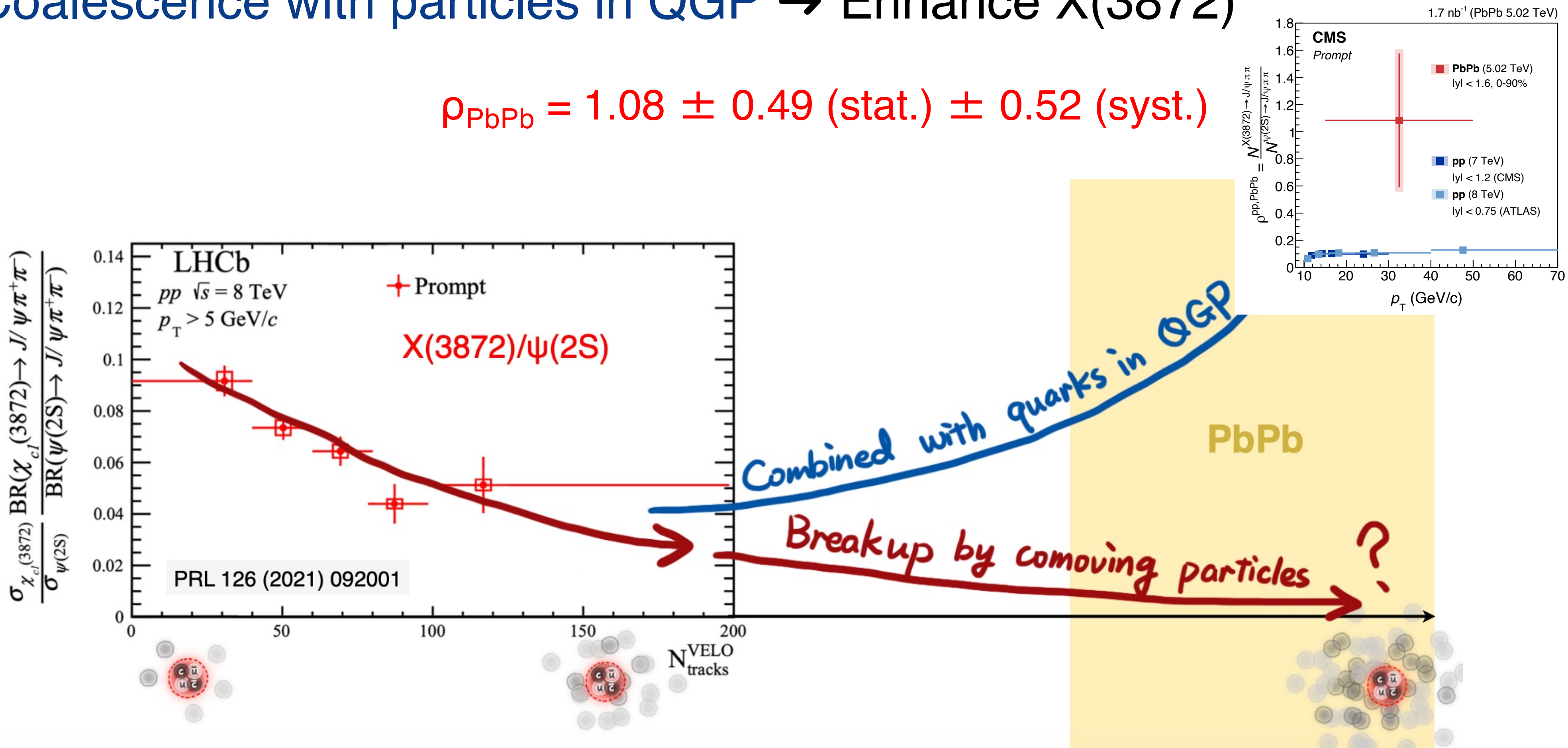
PRL 128 (2022) 3, 032001

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

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



Molecule indication? Still debatable

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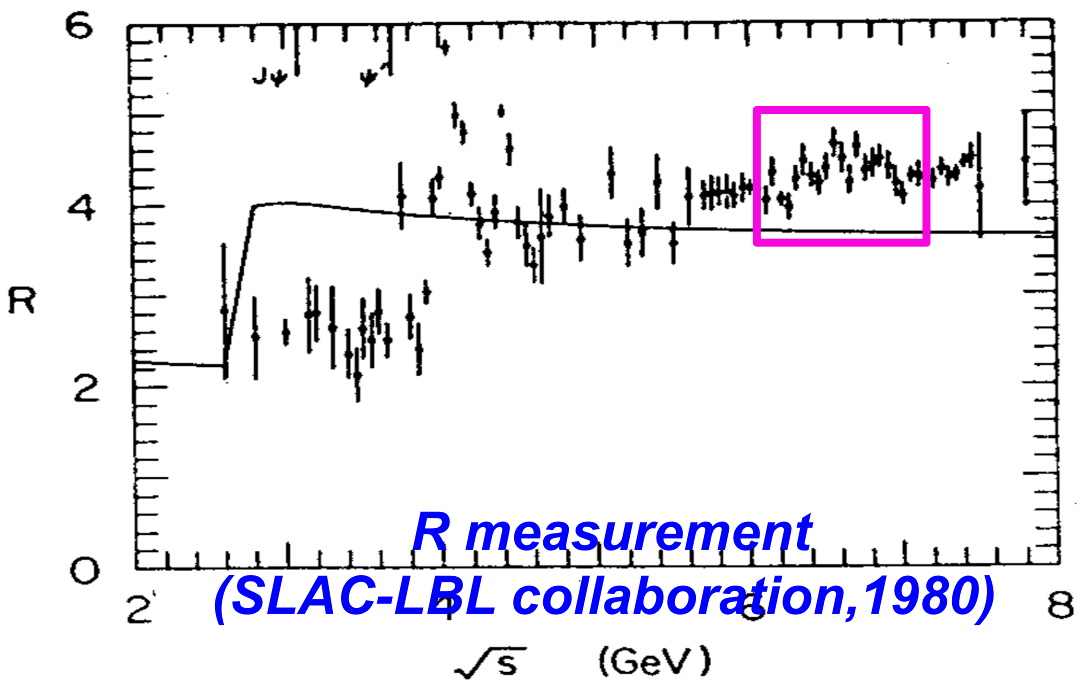
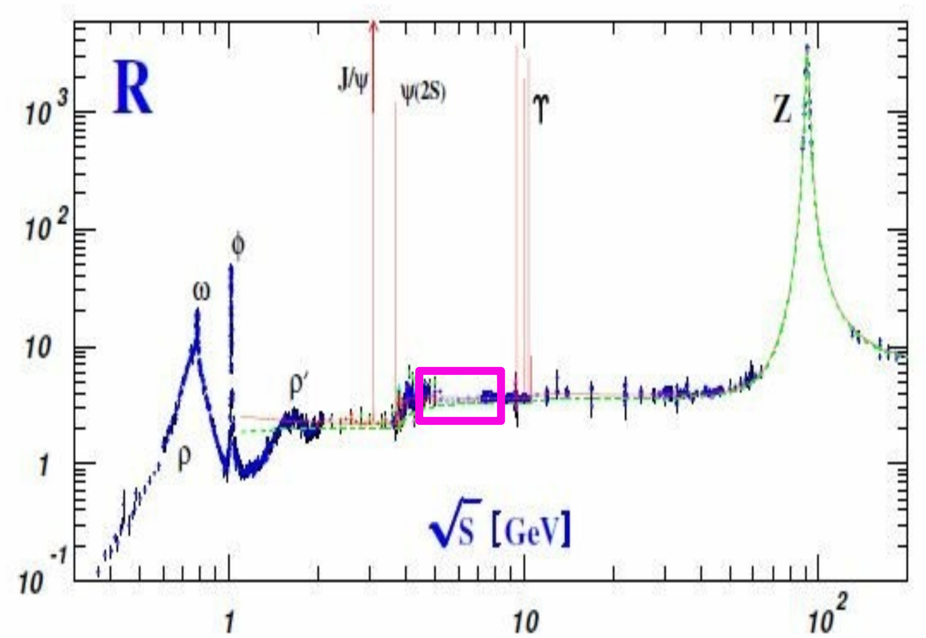
New domain of exotics: all-heavy tetra-quarks

- First mention of 4c states at 6.2 GeV (1975):
  Y. Iwasaki, Prog. of Theo. Phys. Vol. 54, No. 2



R measurement
(SLAC-LBL collaboration,1980)



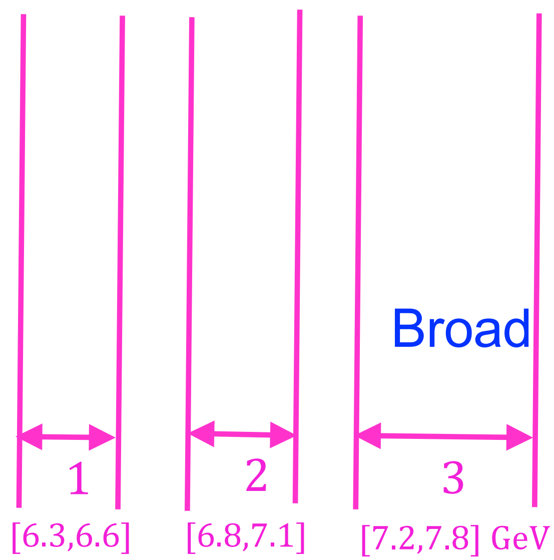
- Inspired by 1980 R curve, first calculation of 4c states (1981):
  K.-T. Chao, Z. Phys. C 7 (1981) 317

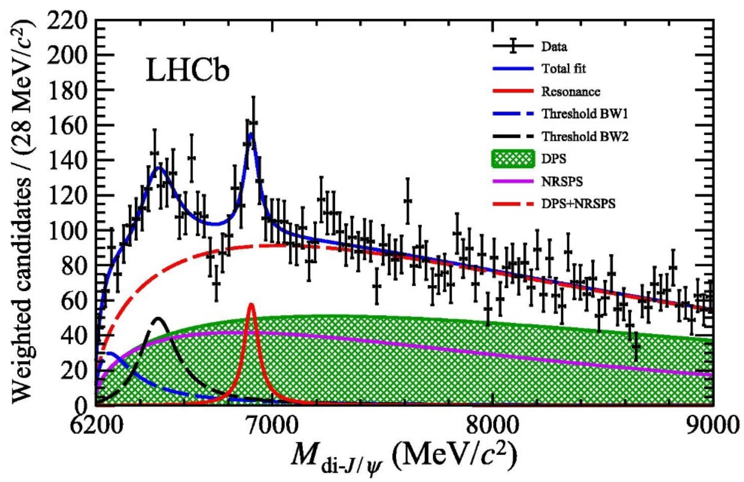
J/ψJ/ψ blind mass window for 13 TeV

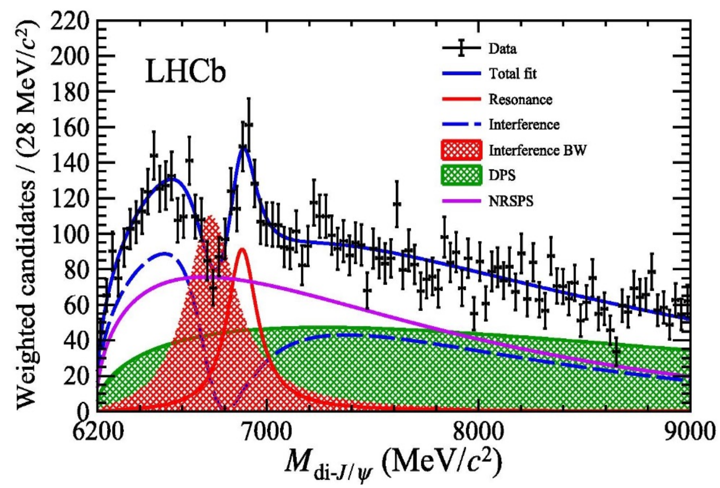
Designed 3 signal regions based on Run I hints

LHCb first got X(6900) out of the door! Congrats !

Sci.Bull.65 (2020) 23

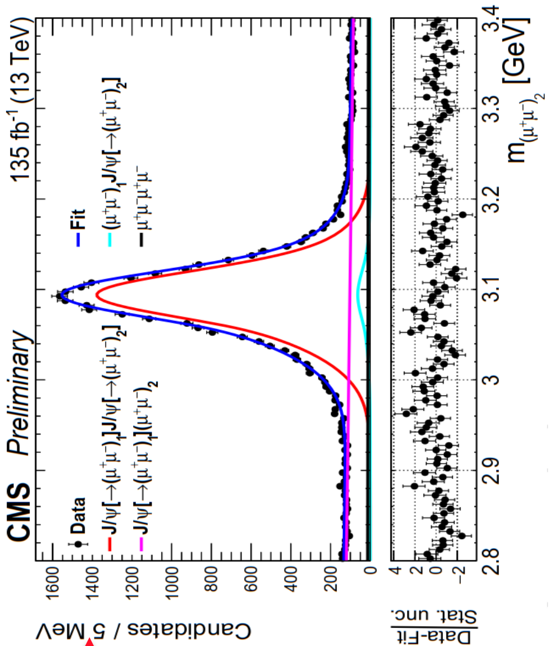


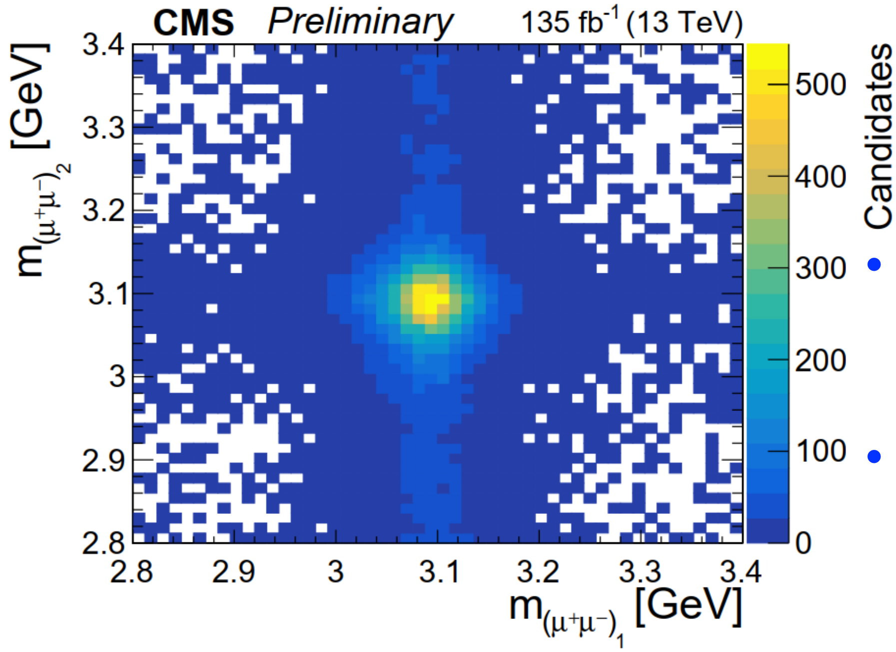




CMS merged 3 regions into one: [6.2, 7.8] GeV after LHCb's X(6900)

J/ψJ/ψ candidates at 13 TeV



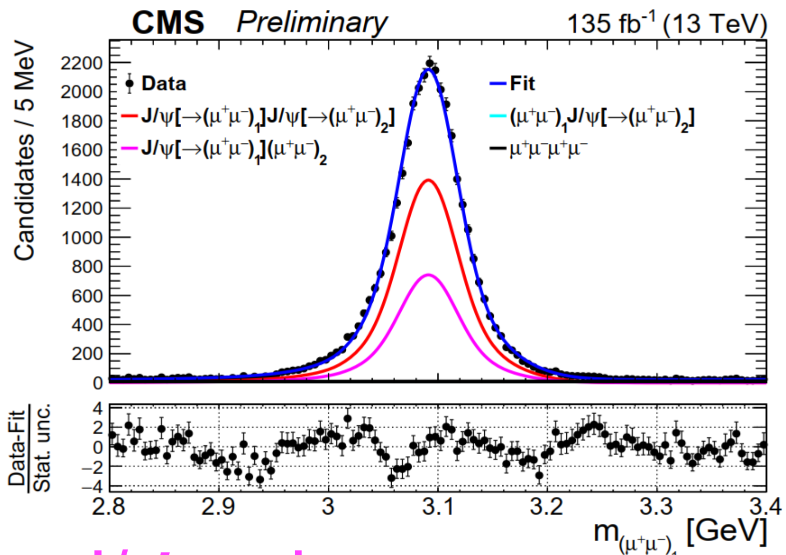


- ~15000 J/ψ pairs after (m(J/ψ J/ψ) <15 GeV)
- ~9000 J/ψ pairs (m(J/ψ J/ψ) <9 GeV)

Low p_T

J/ψ

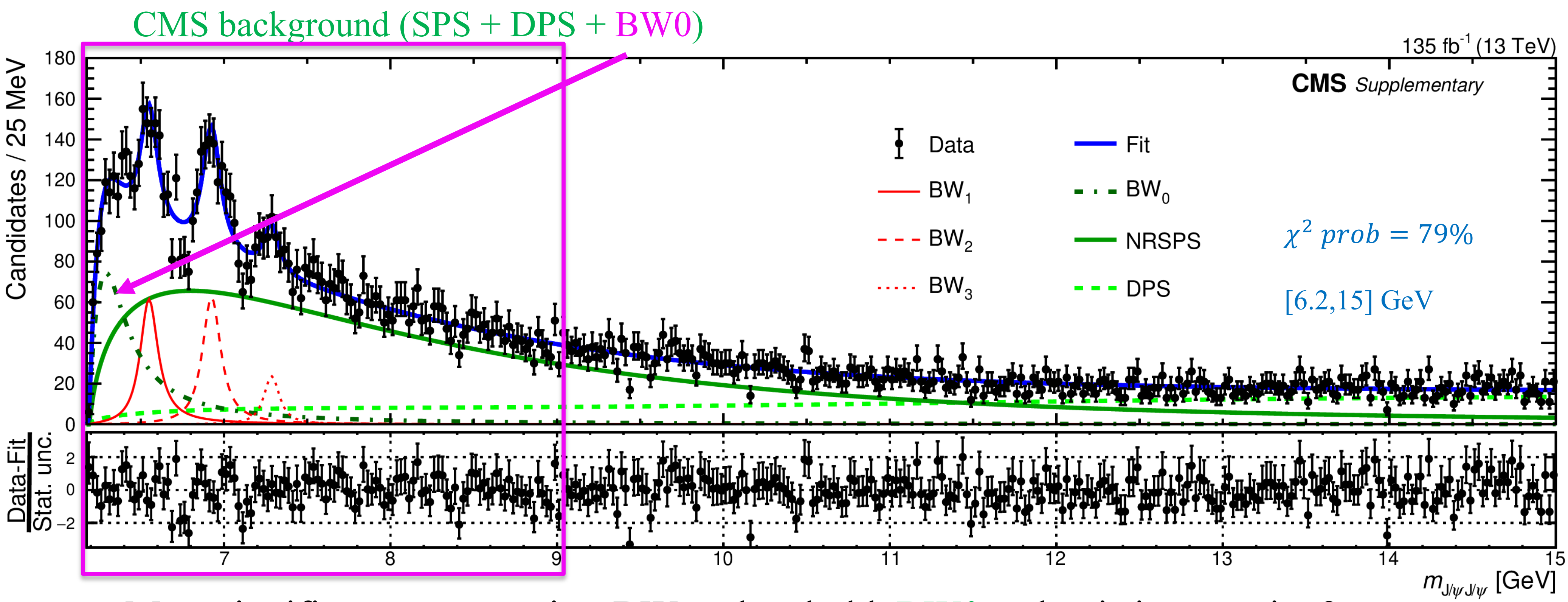
High p_T



PRL 132 (2024) 111901

Large high p_T clean J/ψ pairs

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…
- SPS+DPS+BW0 as our background

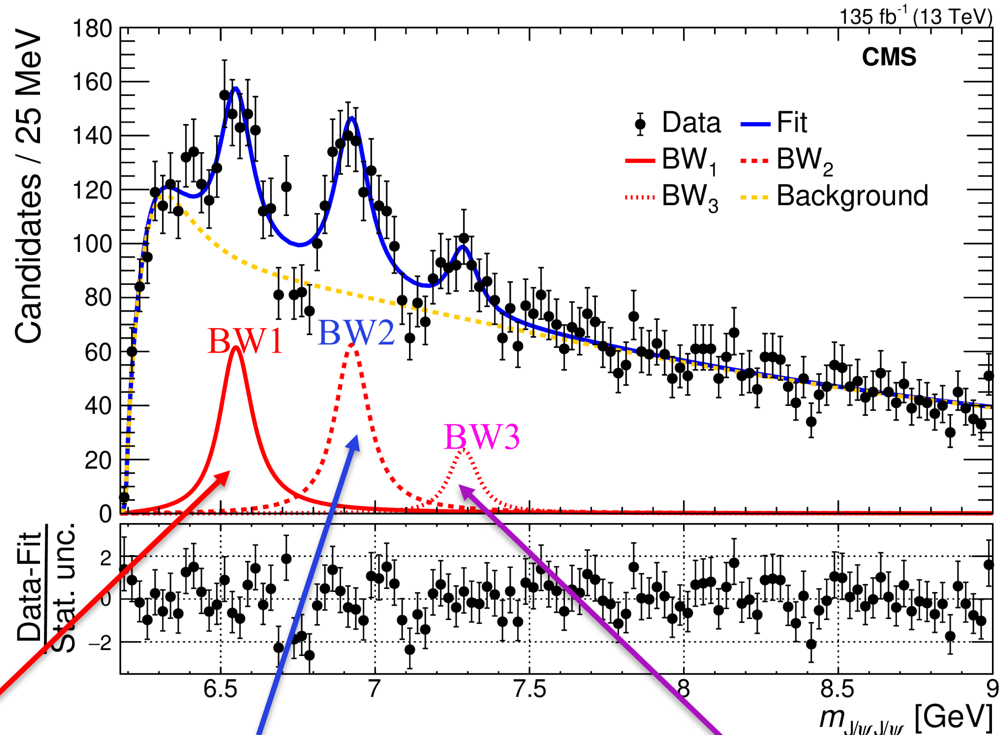
CMS J/ψJ/ψ model: 3 BWs + Background

PRL 132 (2024) 111901

χ^2 Prob. = 1%

[6.2,7.8] GeV

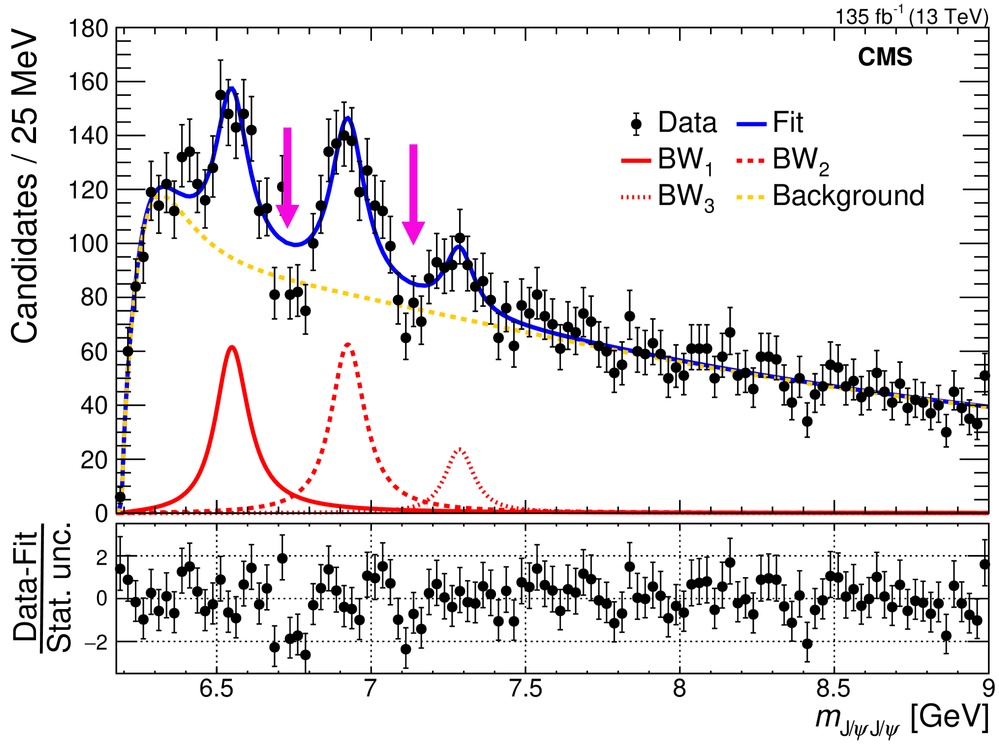
Statistical significance based on:
$2\ln(L_0/L_{max})$



	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

PRL 132 (2024) 111901



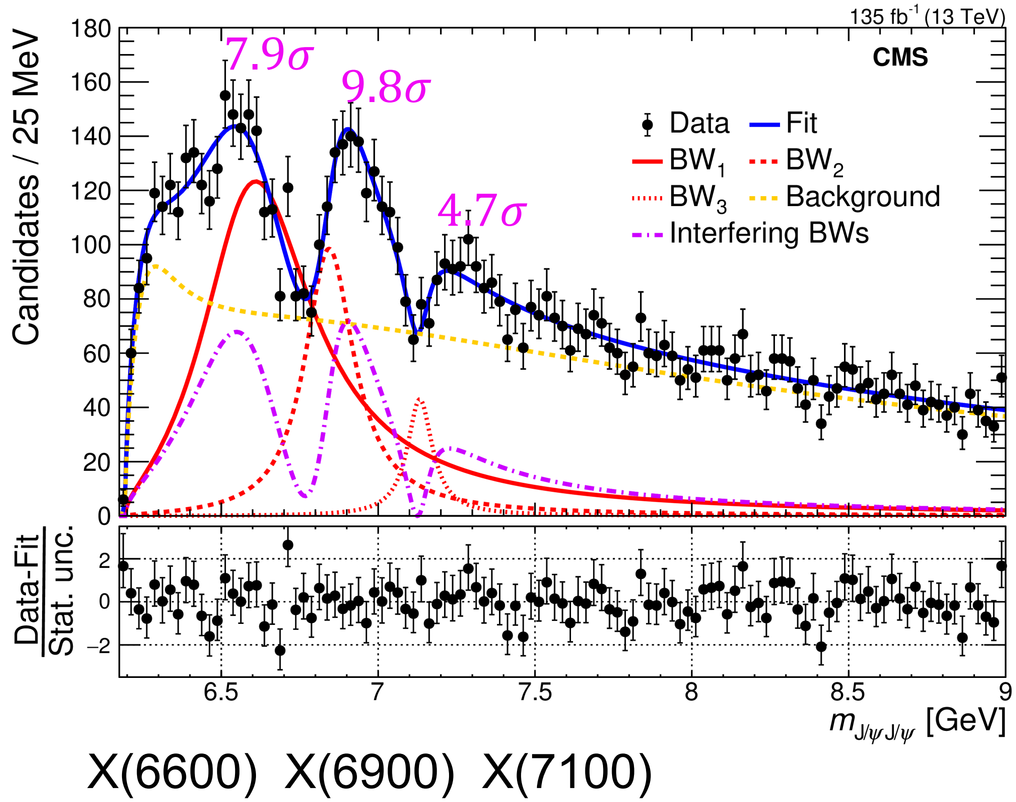
- ➢ Possibility #1:
- Interference among structures?

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

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

CMS J/ψJ/ψ interference fit

PRL 132 (2024) 111901



- 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 theoretical calculations

Nucl. Phys. B 966 (2021) 115393 *S-wave*

$T_{4Q}(nS)$ 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}	6566^{+34}_{-35}	6890^{+27}_{-26}	7160^{+21}_{-22}

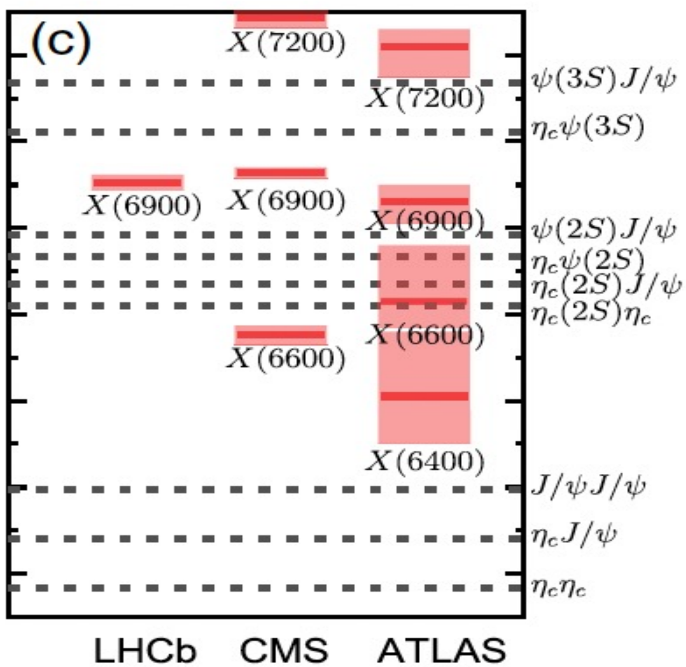
M[BW1] = 6638^{+43+16}_{-38-31} MeV

M[BW2] = 6847^{+44+48}_{-28-20} MeV

M[BW3] = 7134^{+48+41}_{-25-15} MeV

Ground states
Missing n=1

- Radial excited states?
- measure J^{PC} to clarify



- PRD 109 (2024) 054034 (2024) new theoretical result
- More explanations?

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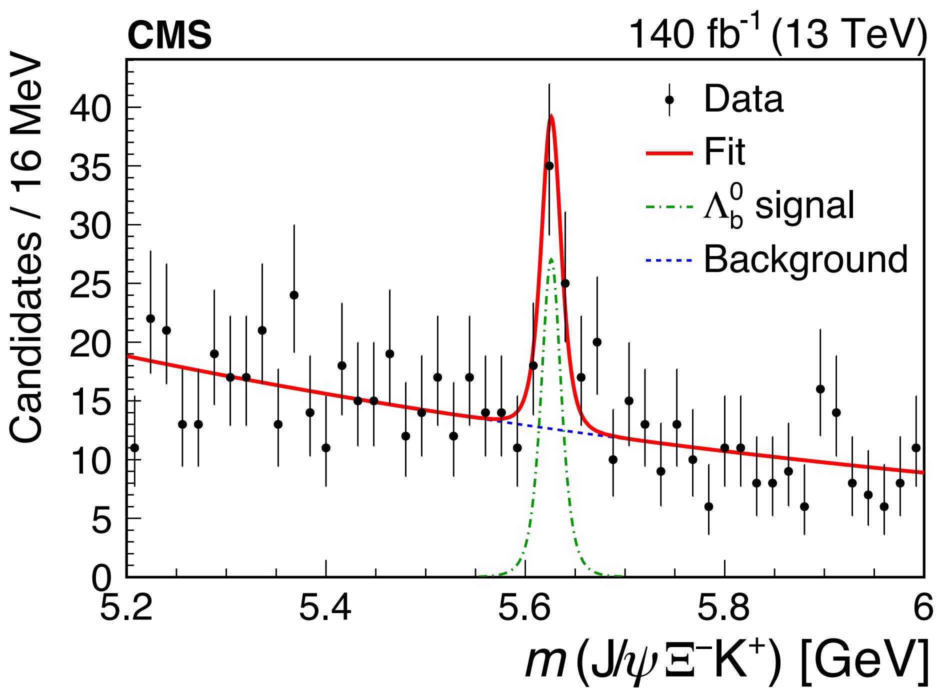
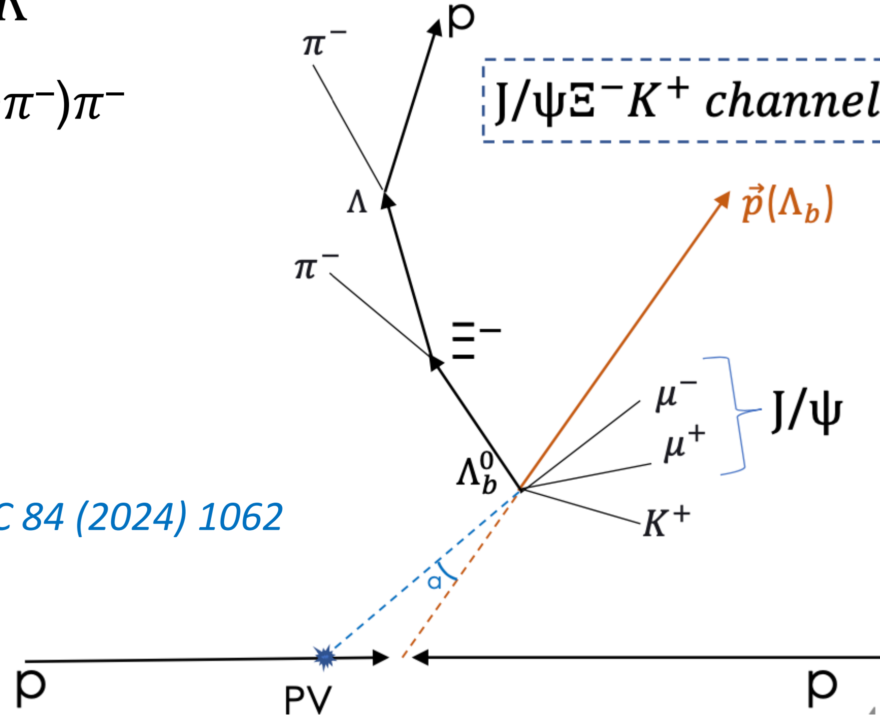
- Observations of new decay channels (after 2022 only)
  - Observation of $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ (2022), $B_s^0 \to \psi(2S)K_S^0$
  - Observation of $\Lambda_b^0 \to J/\psi\,\Xi^-K^+$ (2024)
  - Observation of $\Xi_b^- \to \psi(2S)\Xi^-$ (2024)

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 $J/\psi \to \mu\mu$, $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$
  - **5.8σ** significance





EPJC 84 (2024) 1062

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

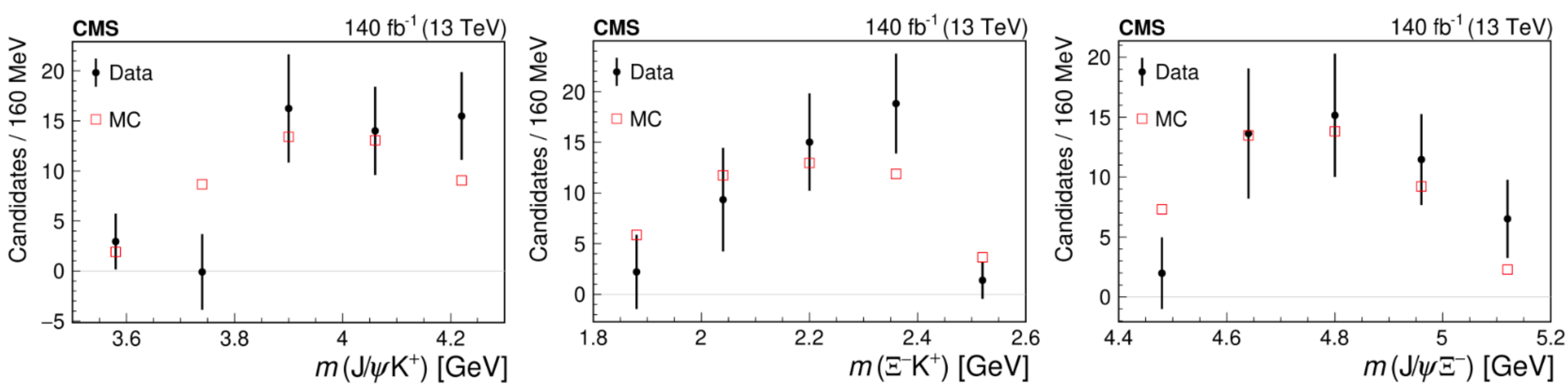
- $\Lambda_b \to J/\psi\, \Xi^- K^+$ branching fraction ratio measurement
  - Large systematics cancellation in the measured ratio R
  - Result dominated by low signal statistics

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

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

- Search for intermediate resonances

EPJC 84 (2024) 1062

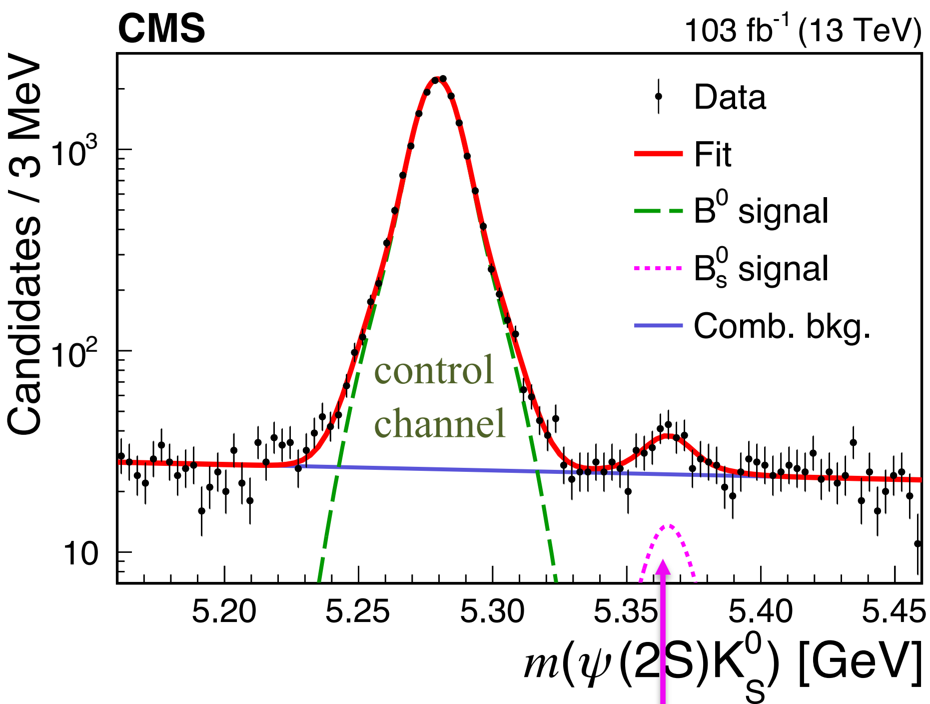


No evidence of resonant structures at this signal statistics

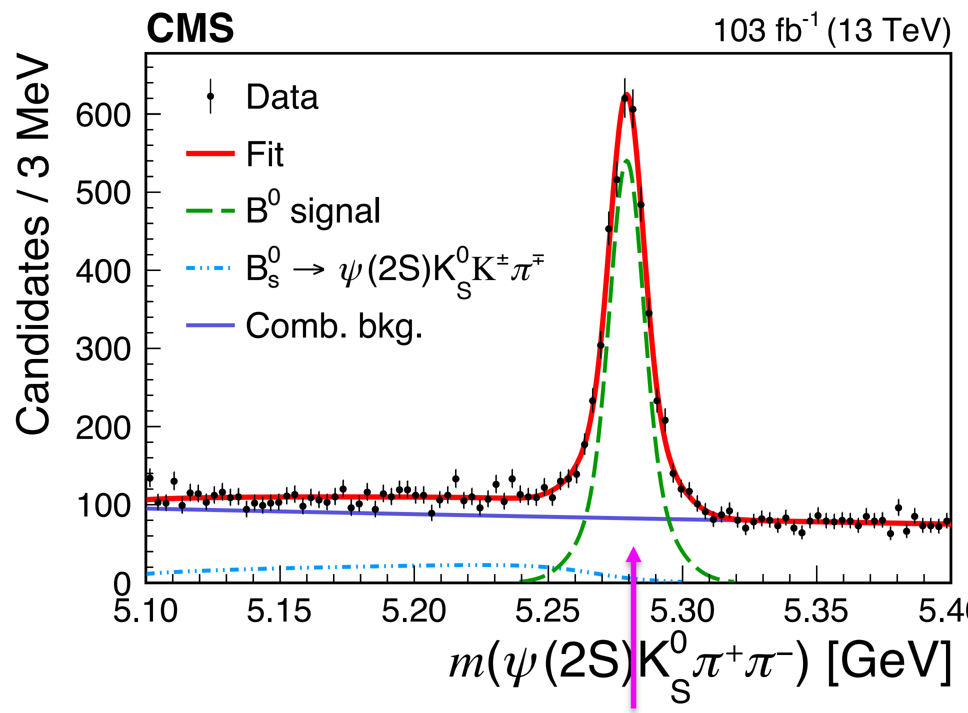
Observation of $B^0 \to \psi(2S) K_S^0 \pi^+ \pi^-$

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

EPJC 82 (2022) 499



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



Significance > 30
First observation

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

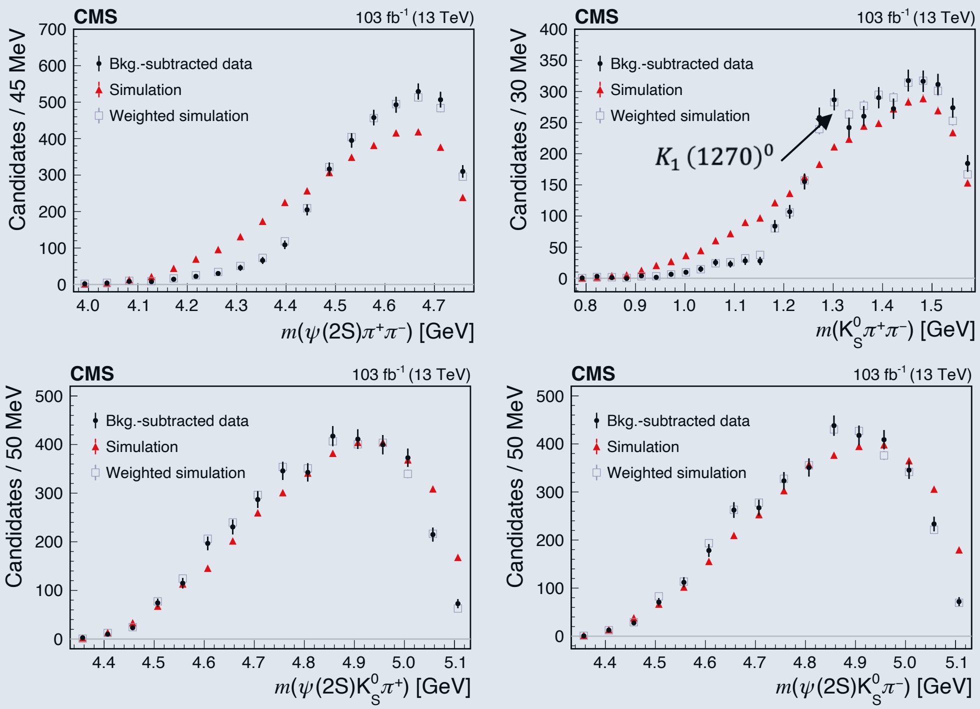
$$\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)/\mathcal{B}(B^0 \to \psi(2S)K_S^0) = (3.33 \pm 0.69\ (\text{stat}) \pm 0.11\ (\text{syst}) \pm 0.34\ (f_s/f_d)) \times 10^{-2}$$

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

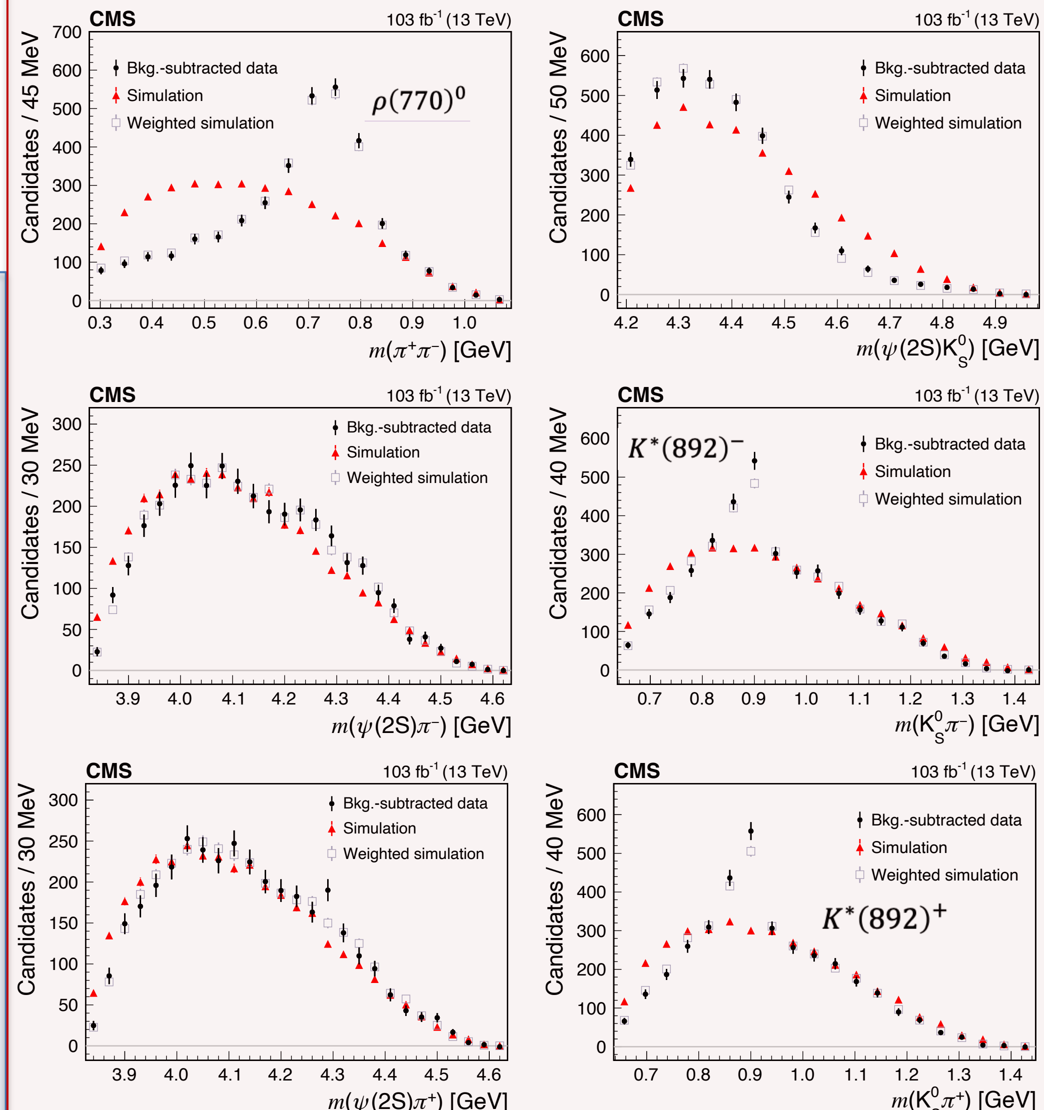
EPJC 82 (2022) 499

- No evidence of new resonant structures at this signal statistics

3-body intermediate invariant masses



2-body intermediate invariant masses

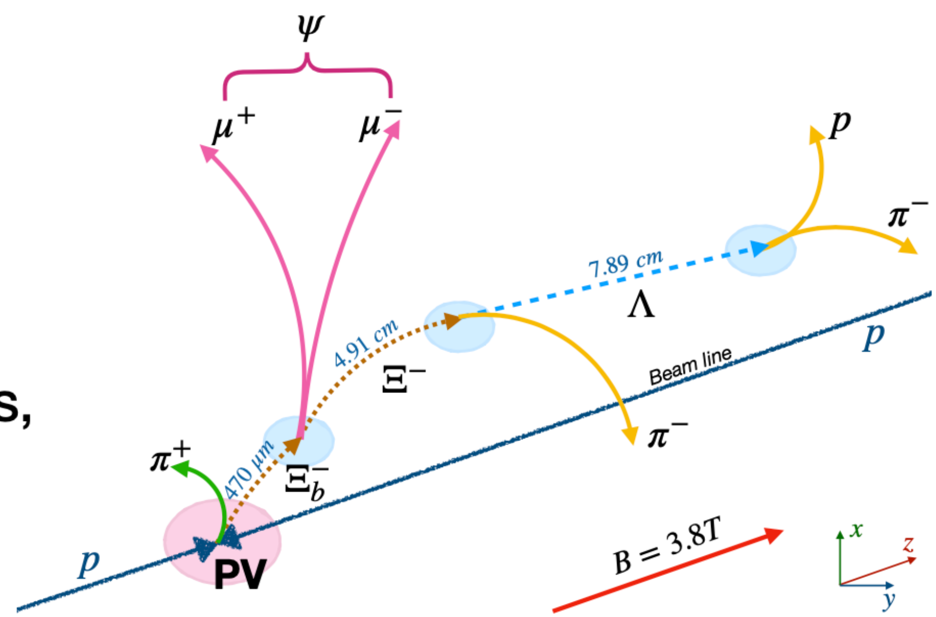


$\Xi_b \rightarrow \psi(2S)\Xi$ observation and Ξ_b^{*0} studies

Increasing data statistics @LHC allows **exploration of ground and excited Ξ_b states**

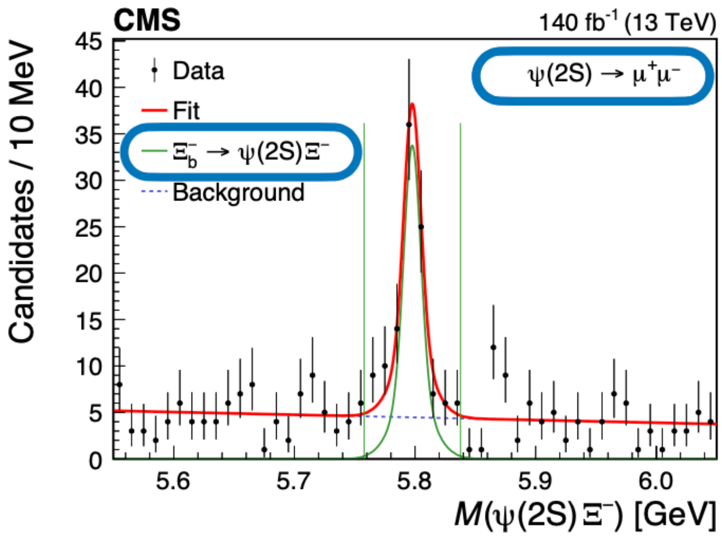
- Weak ground Ξ_b decays: possible intermediate resonances or CP violation
- Measurements of both ground and excited (Ξ_b^*) state properties constrain heavy quark EFT → **better understanding of quark dynamics and hadronization**

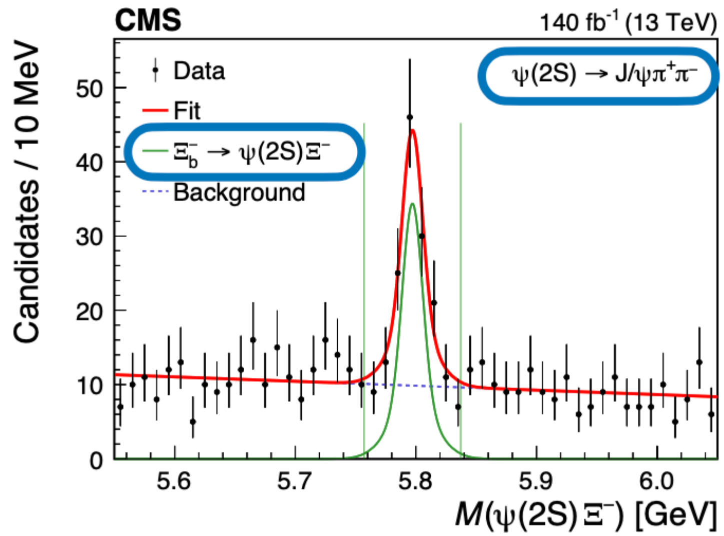
- Full Run2 140 fb^{-1}
- Ξ_b^- reconstructed via: $\Xi_b^- \rightarrow J/\psi\Xi^-$, $\Xi_b^- \rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\Xi^-$, $\Xi_b^- \rightarrow \psi(2S)(\rightarrow \mu\mu)\Xi^-$, $\Xi_b^- \rightarrow J/\psi\Lambda\ K^-$ with $J/\psi \rightarrow \mu\mu$ and $\Xi^- \rightarrow \Lambda\ (p\pi)\pi^-$
- Ξ_b^{*0} from fitting Ξ_b^- virtual track and π^+ from PV
- **rich topology:** leverage vertex refit, long Ξ and Λ lifetime, mass constraints, mass differences



$\Xi_b \to \psi(2S)\Xi$ observation and Ξ_b^{*0} studies

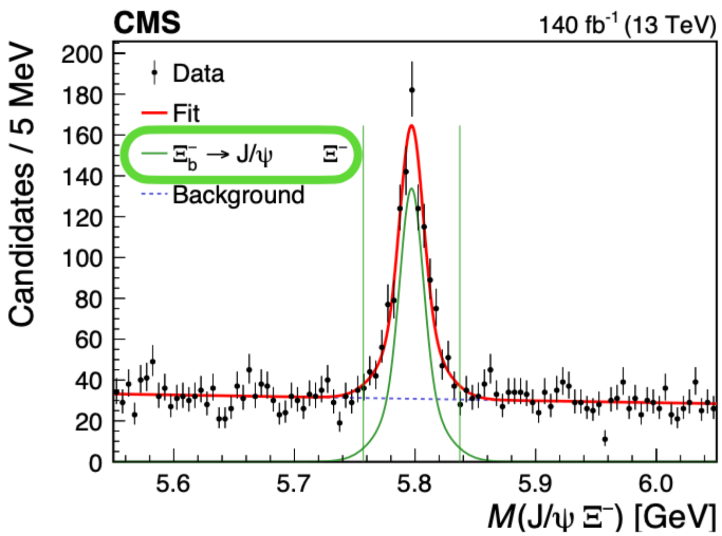
- First observation of $\Xi_b \to \psi(2S)\Xi$





PRD 110 (2024) 012002

obs. > 5σ



Decay channel	N	$m^{fit}_{\Xi_b^-}$ (MeV)	σ_{eff} (MeV)
$\Xi_b^- \to J/\psi\Xi^-$	846 ± 40	5797.1 ± 0.6	16.3 ± 1.0
$\Xi_b^- \to J/\psi\Lambda K^-$	920 ± 98	5798.8 ± 0.9	11.9 ± 1.5
$\Xi_b^- \to J/\psi\Sigma^0 K^-$	880 ± 170	—	—
$\Xi_b^- \to \psi(2S)\Xi^-$ (with $\psi(2S) \to \mu^+\mu^-$)	74 ± 11	5797.7 ± 1.4	11.1 ± 2.0
$\Xi_b^- \to \psi(2S)\Xi^-$ (with $\psi(2S) \to J/\psi\pi^+\pi^-$)	90 ± 14	5797.2 ± 1.7	13.1 ± 2.8

$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.84\,^{+0.21}_{-0.19}\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.02\,(\mathcal{B})$$

$\Xi_b \rightarrow \psi(2S)\Xi$ observation and Ξ_b^{*0} studies

- Novel measurements of b-baryon properties

PRD 110 (2024) 012002

Properties of Ξ_b^{*0}

- Using $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$ with multiple Ξ_b^- decays ($\psi(2S)\Xi^-, J/\psi\,\Xi^-, J/\psi\,\Lambda K^-, J/\psi\,\Sigma^0 K^-$)
- Ξ_b^{*0} mass and decay width extracted in a fit to $\Delta M = M(\Xi_b^- \pi^+) - M(\Xi_b^-) - m_{\pi^+}^{PDG}$

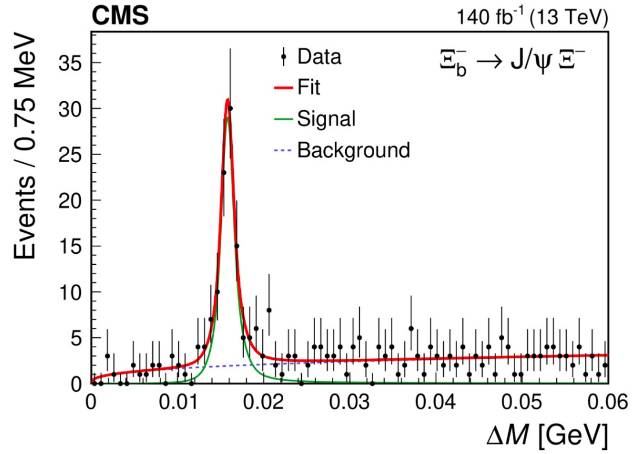
→ **Improved mass resolution** wrt. $M(\Xi_b^- \pi^+)$

$$m_{\Xi_b^{*0}} = 5952.4 \pm 0.1(\text{stat} + \text{syst}) \pm 0.6(m_{\Xi_b^-})\ \text{MeV}$$
$$\Gamma_{\Xi_b^{*0}} = 0.87^{+0.22}_{-0.20}(\text{stat}) \pm 0.16(\text{syst})\ \text{MeV}$$

Latest LHCb result $m_0 \quad 5952.37 \pm 0.02 \pm 0.01 \pm 0.6\ (\Xi_b^-)$

$$\Gamma(\Xi_b^{*0}) = 0.87 \pm 0.06 \pm 0.05\,\text{MeV}$$

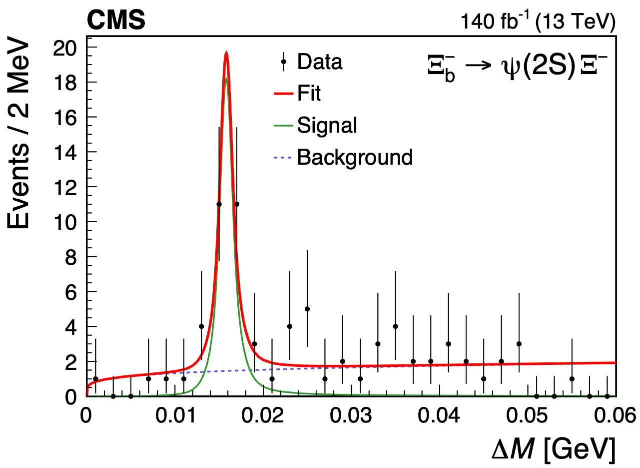
(Phys. Rev. Lett. 131 (2023) 171901)



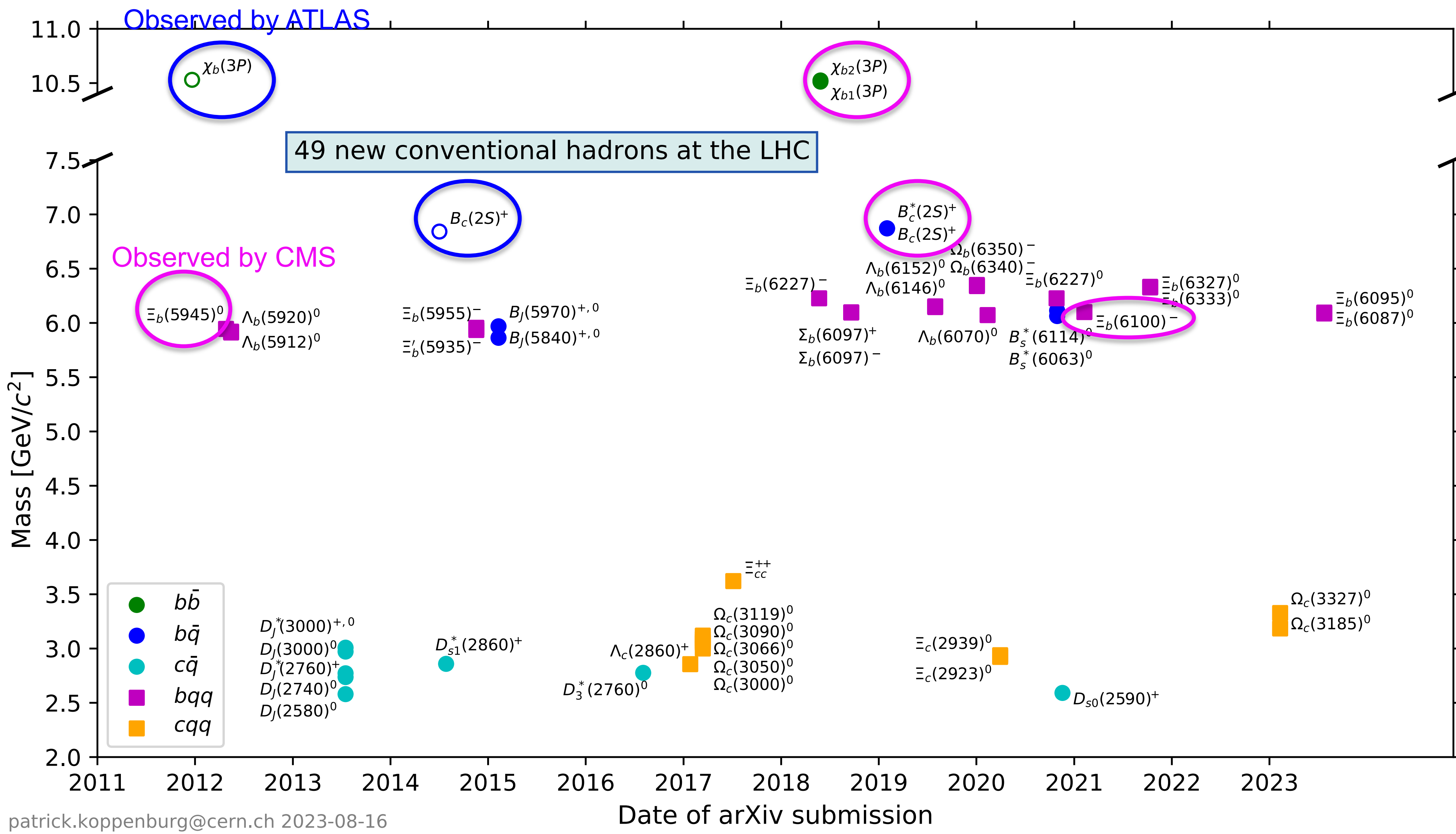
- Ξ_b^{*0} and Ξ_b^- **production cross-section ratio** (in tight fidual region)

$$\frac{\sigma(pp \rightarrow \Xi_b^{*0} X) B(\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+)}{\sigma(pp \rightarrow \Xi_b^- X)} = 0.23 \pm 0.04\ (\text{stat}) \pm 0.02\ (\text{syst})$$

→ $\sim 1/4$ of Ξ_b^- are produced in $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$

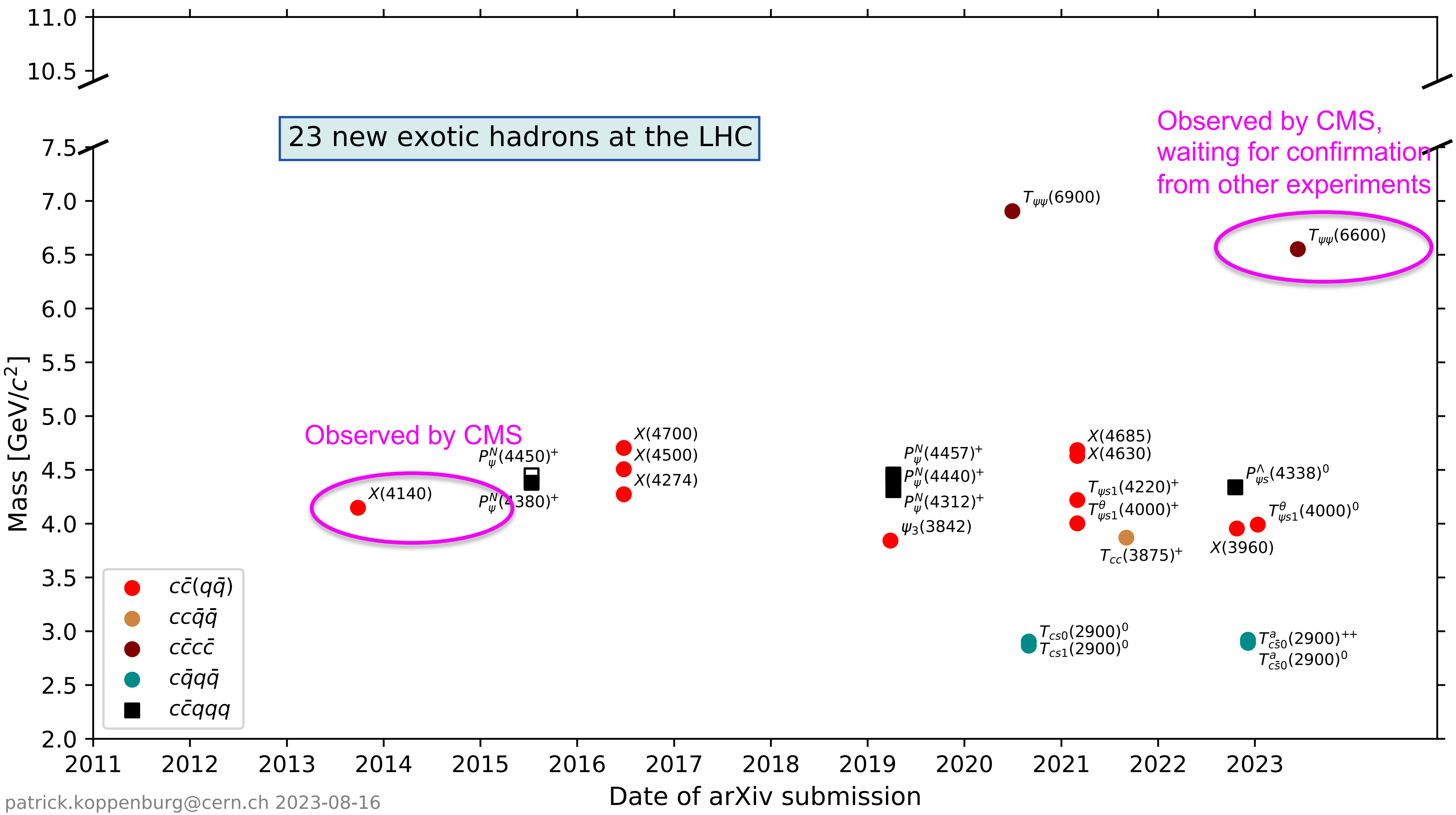


New conventional hadrons at LHC



https://www.nikhef.nl/~pkoppenb/particles.html

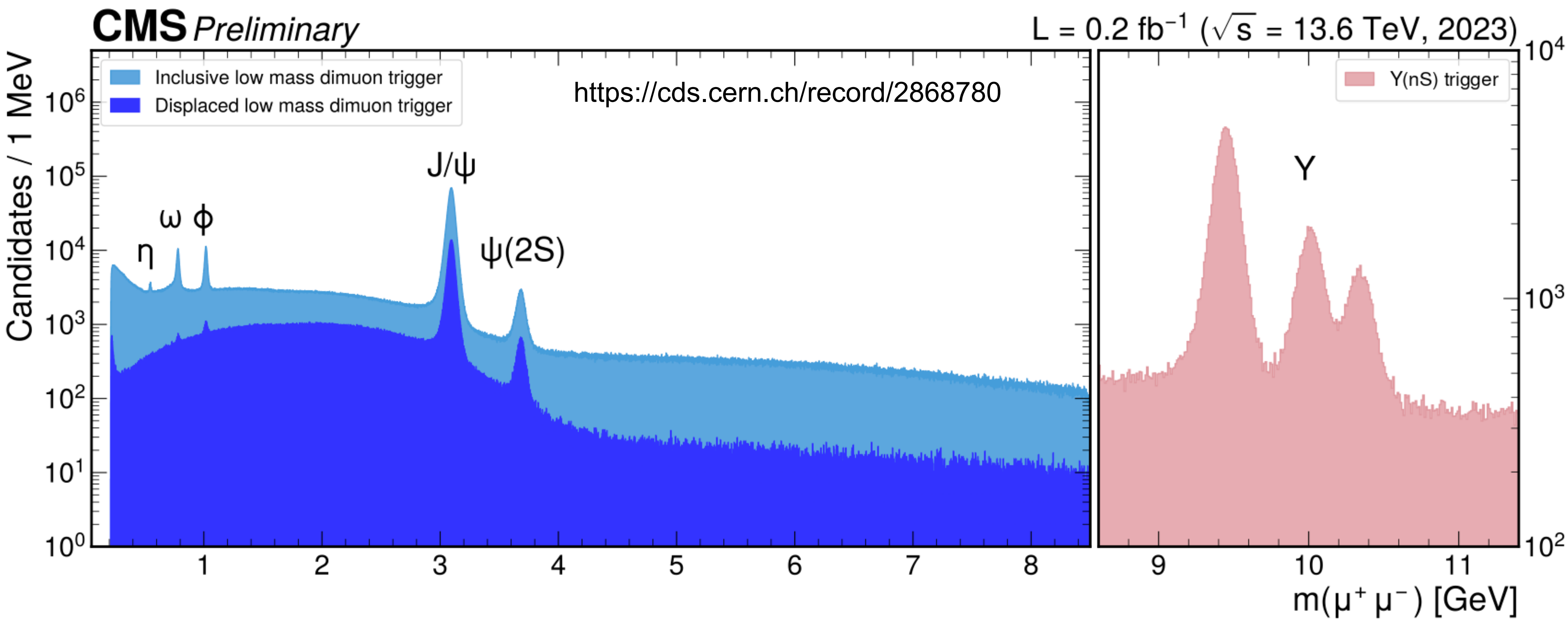
New exotic hadrons at LHC



https://www.nikhef.nl/~pkoppenb/particles.html

Outlook

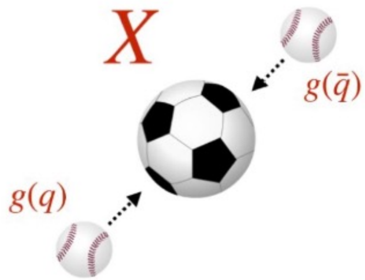
New triggers in Run-3 !



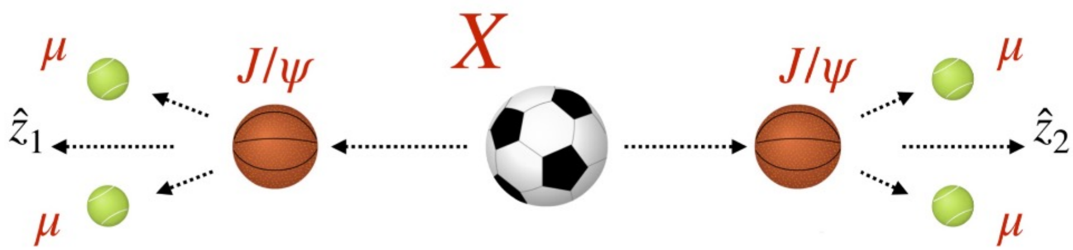
Thank you!

Backup

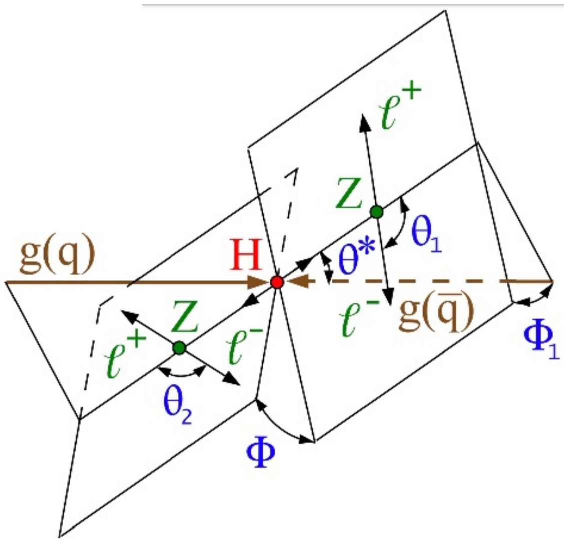
Spin Parity Analysis (on going)

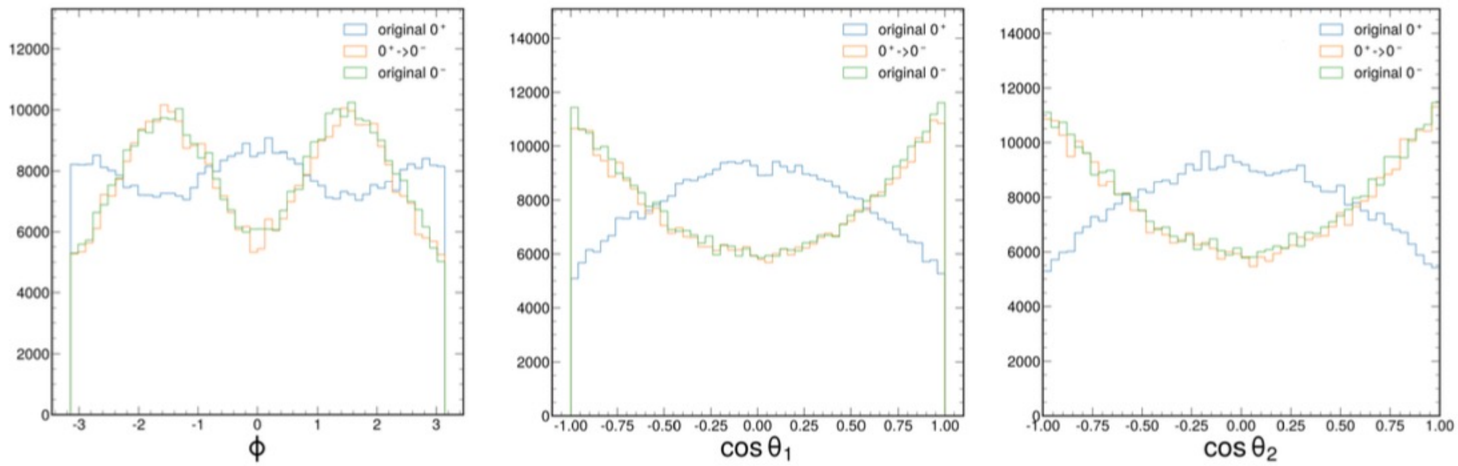


Polarization in production
- Spin-0: $gg \to X$
- Spin-1: $q\bar{q} \to X$ produce $J_z = \pm 1$
- Spin-2:
  - $gg \to X$ produce $J_z = 0, \pm 2$, minimal coupling: $J_z = \pm 2$
  - $q\bar{q} \to X$ produce $J_z = \pm 1$



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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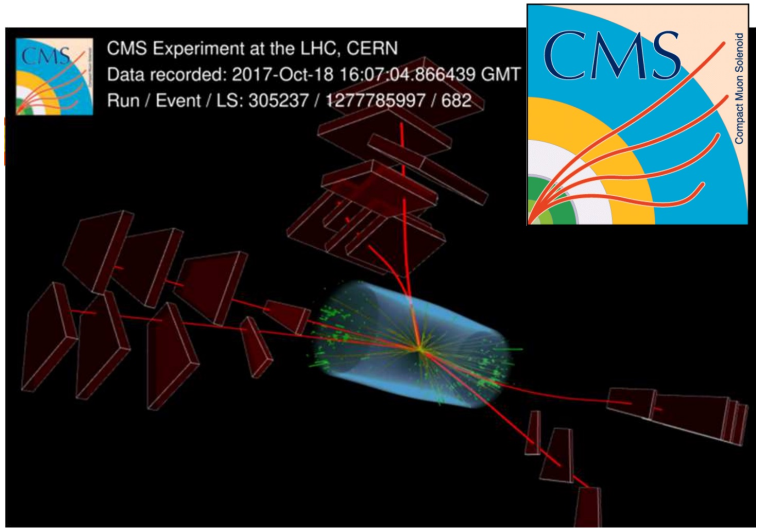
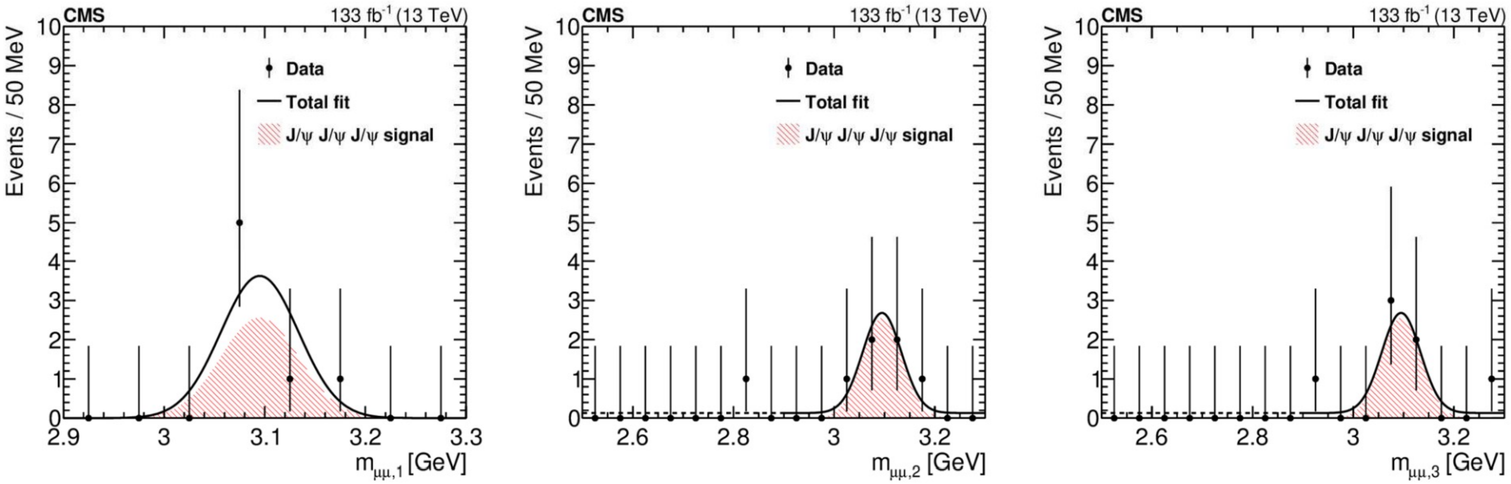
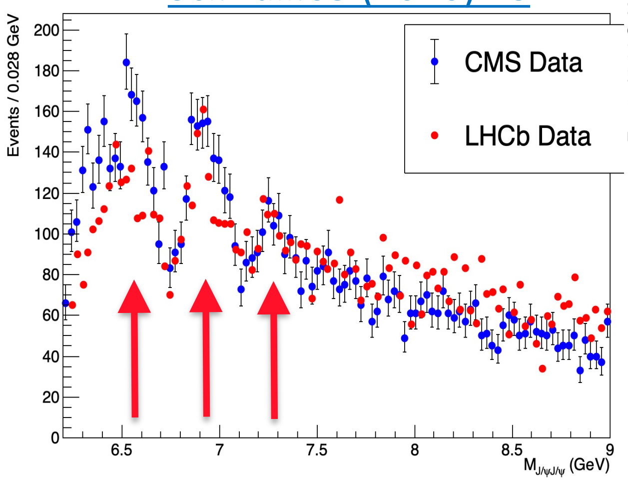


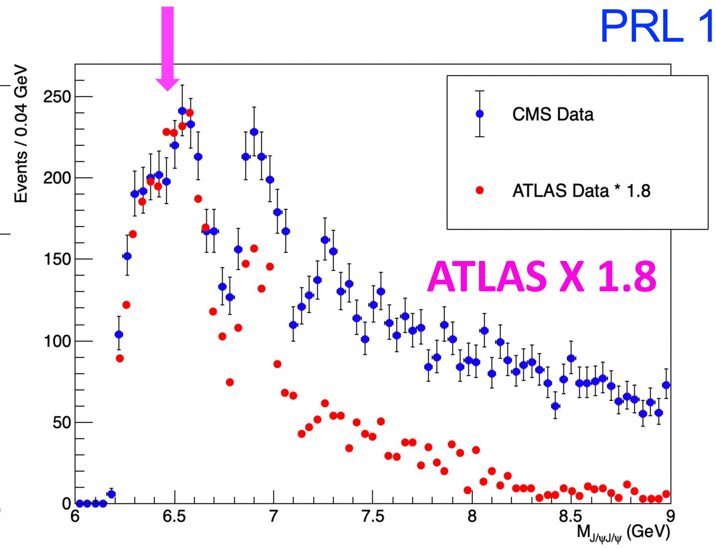


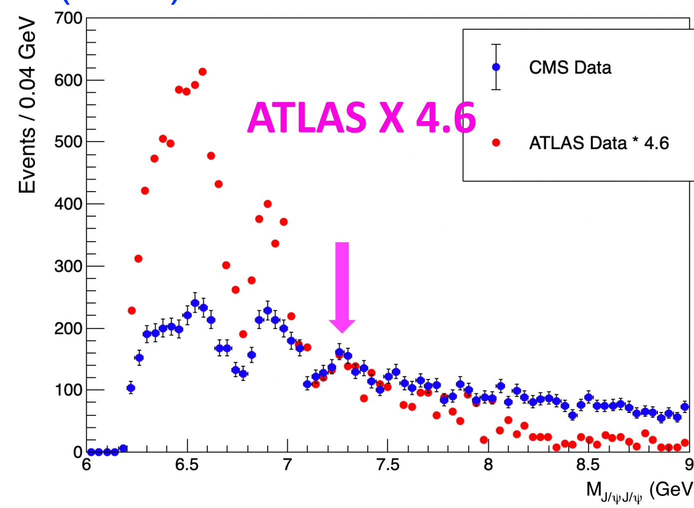
"6c" search in future?

Comparison with LHCb & ATLAS

Sci.Bull.65 (2020) 23 | PRL 131 (2023) 151902





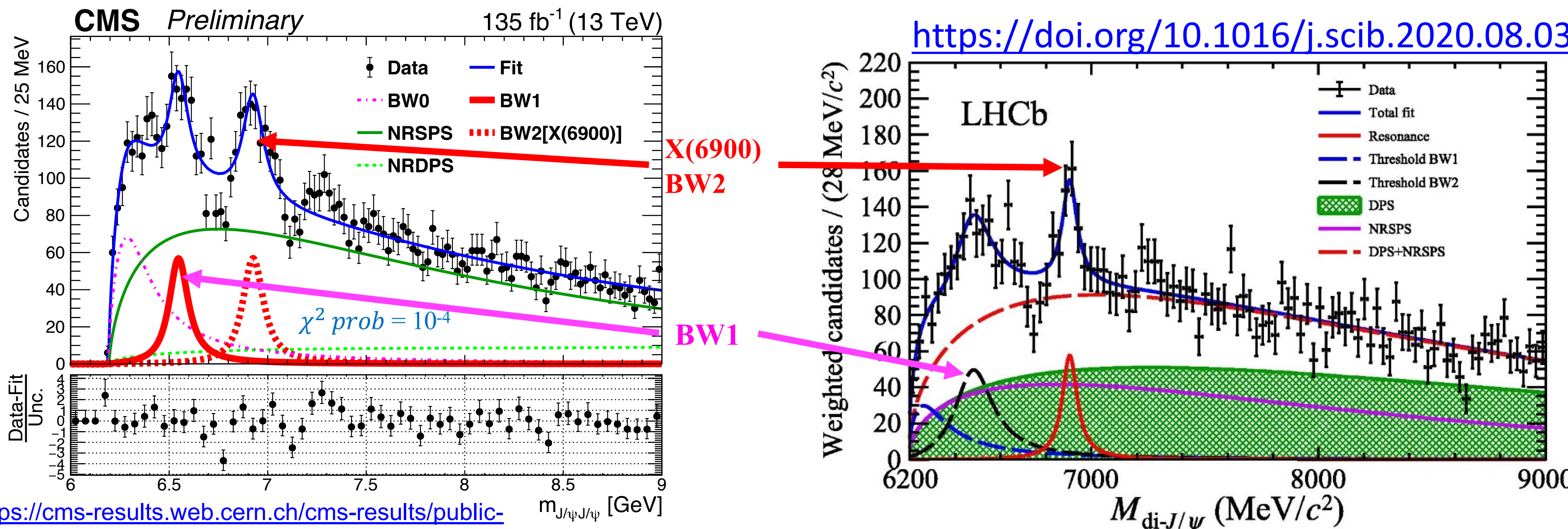


- Consistent shape for X(6900) for 3 experiments
- Consistent shape for X(7100) for 3 experiments after scaling
- Consistent shape for X(6600) for CMS and ATLAS after scaling

  Hard to say between CMS/ATLAS and LHCb

Fit CMS data with LHCb model I : 2 auxiliary BWs + X(6900) + bkg

https://doi.org/10.1016/j.scib.2020.08.032



https://cms-results.web.cern.ch/cms-results/public-results/superseded/BPH-21-003/index.html

Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

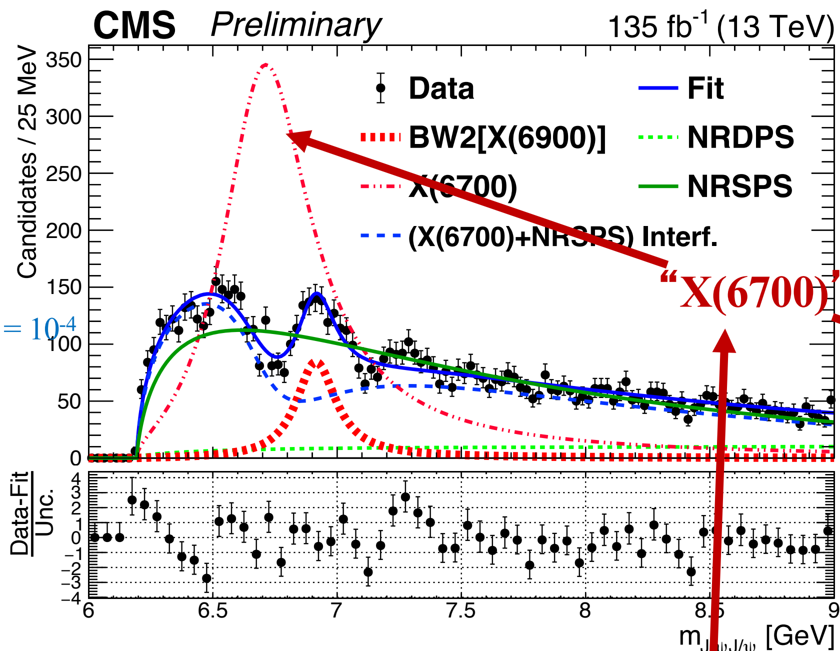
BW2 are in good agreement with LHCb X(6900)

- LHCb did not give parameters for BW1
    - CMS has a shoulder before BW1
    - helps make BW1 distinct
- ***Does not describe 2 dips well***

CMS and LHCb Fit Comparison - 2

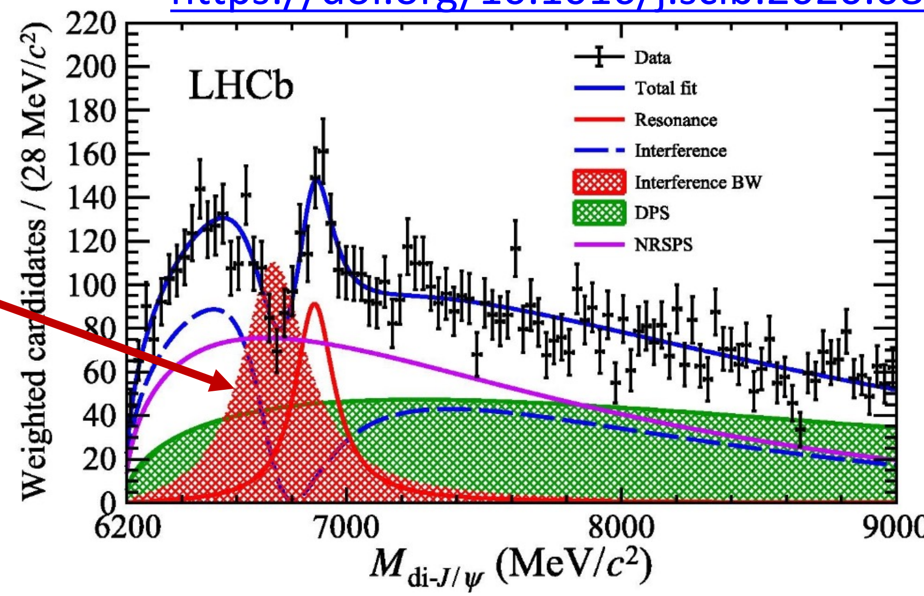
Fit CMS data with LHCb model II : “X(6700)” interferes with NRSPS + X(6900) + Bkg

https://doi.org/10.1016/j.scib.2020.08.032



χ^2 *prob* = 10^{-4}

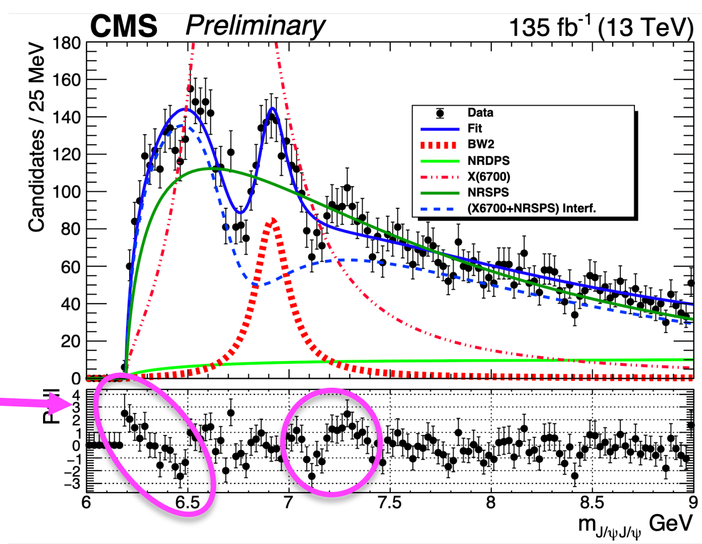
“X(6700)”



https://cms-results.web.cern.ch/cms-results/public-results/superseded/BPH-21-003/index.html

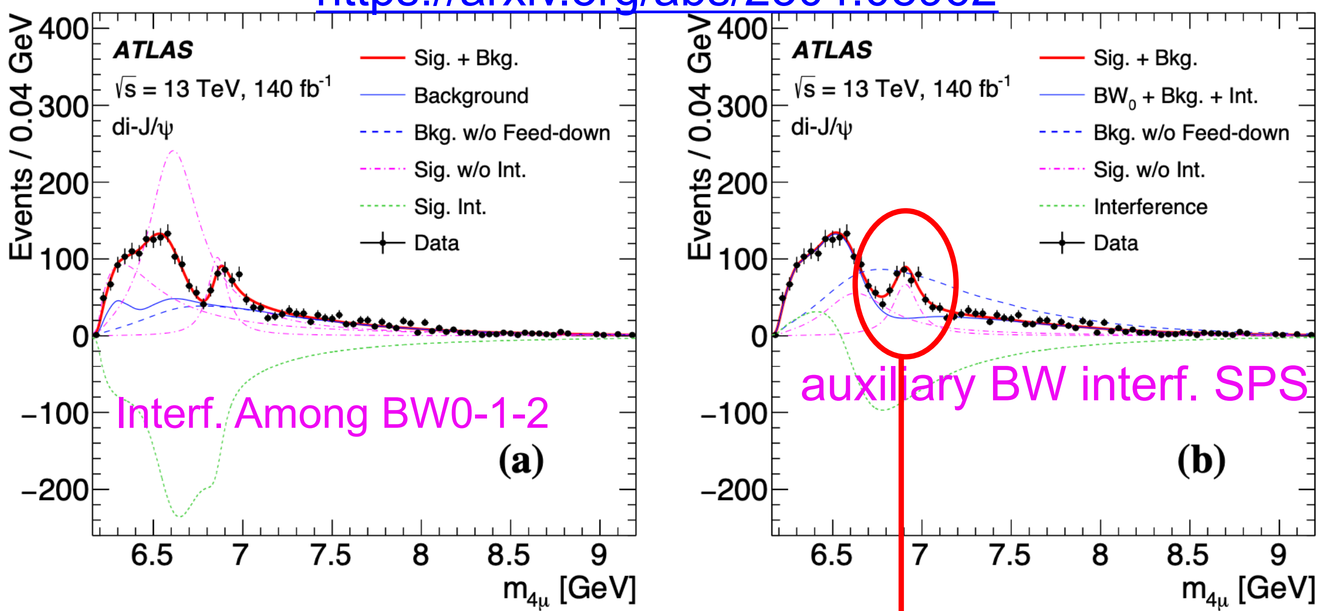
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model II	6741 ± 6	288 ± 16	6886 ± 11 ± 11	168 ± 33 ± 69
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

- CMS obtained larger amplitude and wider width for X(6700)
- Does not describe X(6600) and below
- Does not describe X(7200) region



CMS and ATLAS Fit Comparison

https://arxiv.org/abs/2304.08962



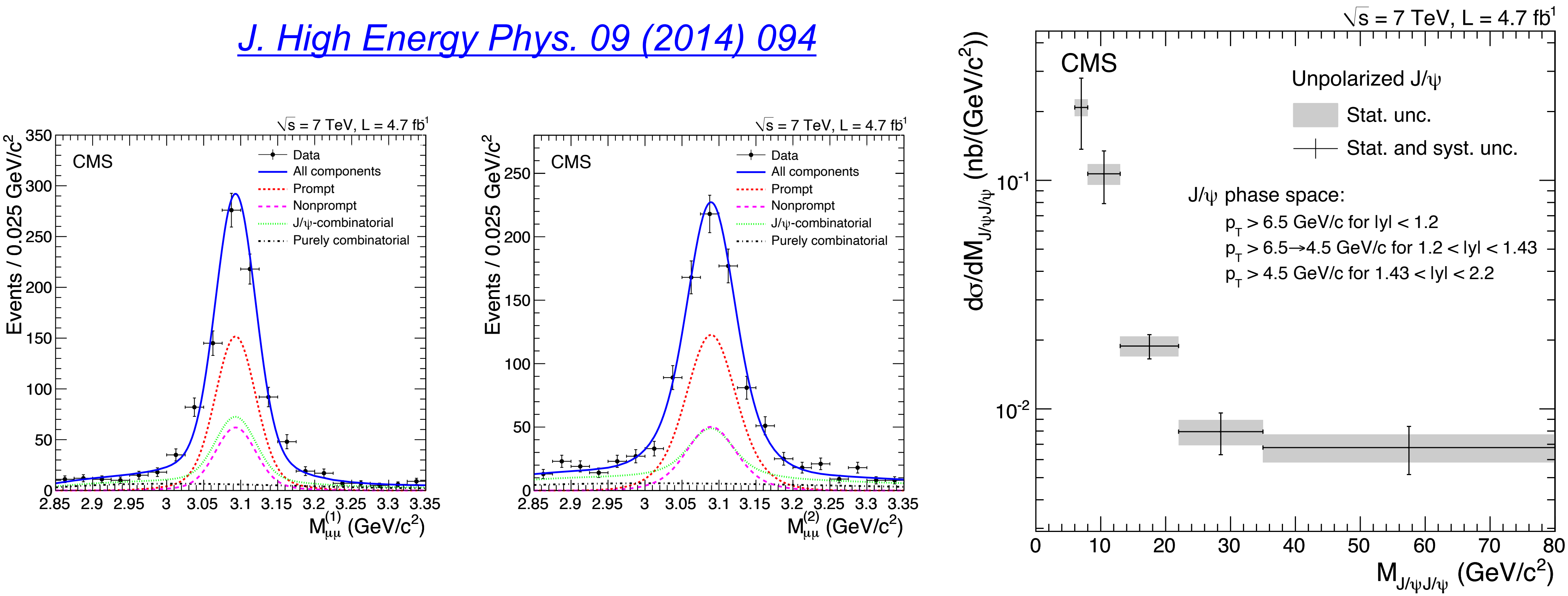
di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

X(6900) > 5σ

- ATLAS model A: analogous to LHCb model I, but 2 auxiliary BWs interfere with X(6900)
- ATLAS Model B: analogous to LHCb model II, one auxiliary BW interferes with NRSPS
- Both models describe the data well
  - the broad structure at the lower mass could result from other physical effects, such as the feed-down
- The 3rd peak mass is consistent with the LHCb observed X(6900), with significance > 5σ

J/ψJ/ψ cross section at 7 TeV

[J. High Energy Phys. 09 (2014) 094]()

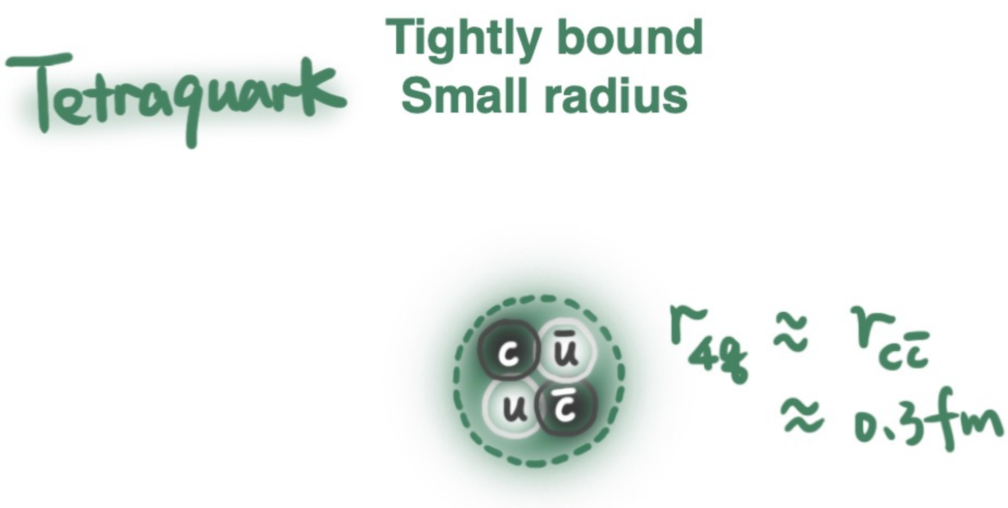


Total cross section, assuming unpolarized prompt J/ψJ/ψ pair production
1.49 ± 0.07 (stat.) ± 0.13 (syst.) nb

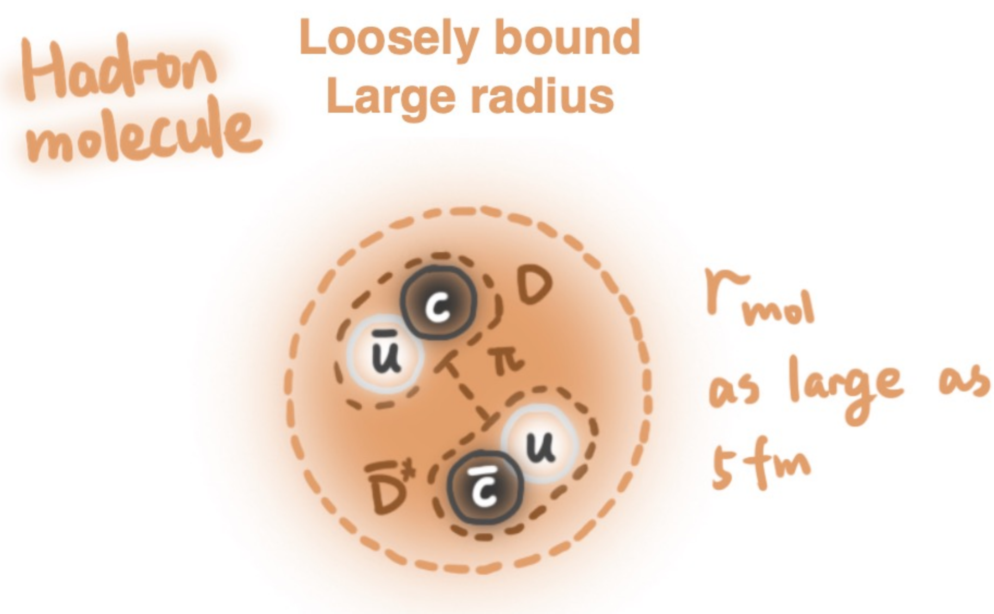
Different assumptions about the J/ψJ/ψ polarization imply modifications to the cross section ranging from -31% to +27%.

X(3872) in heavy-ion collisions

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



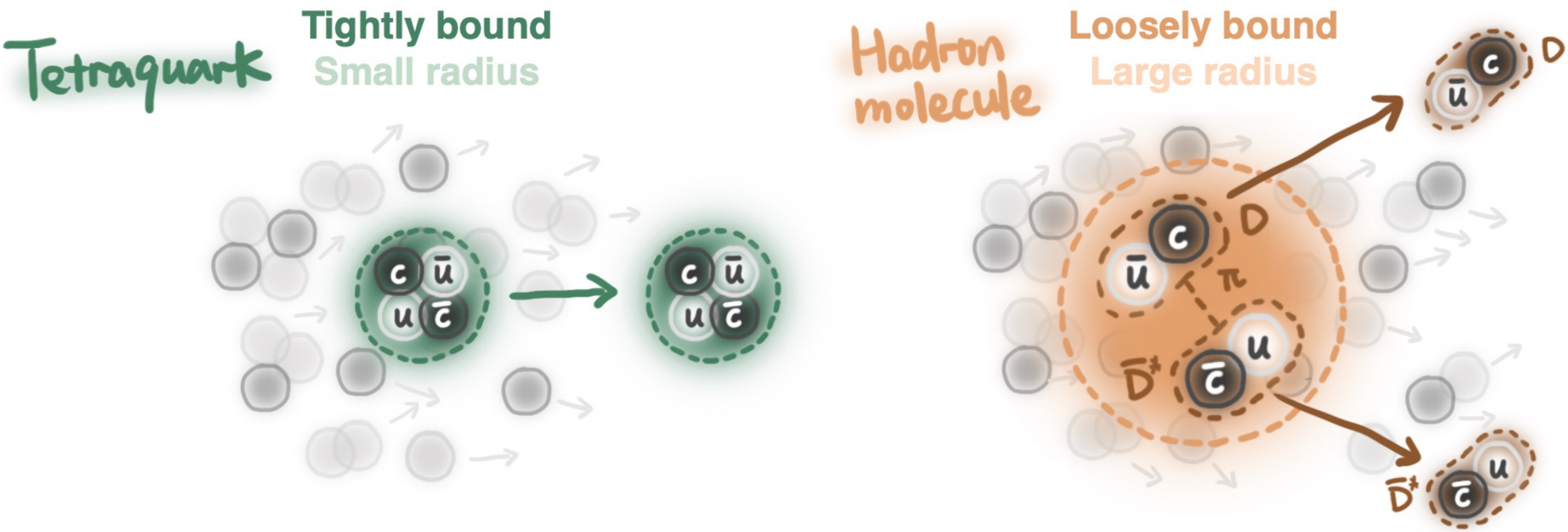
Compact four quark state



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)