Exotic hadrons at CMS

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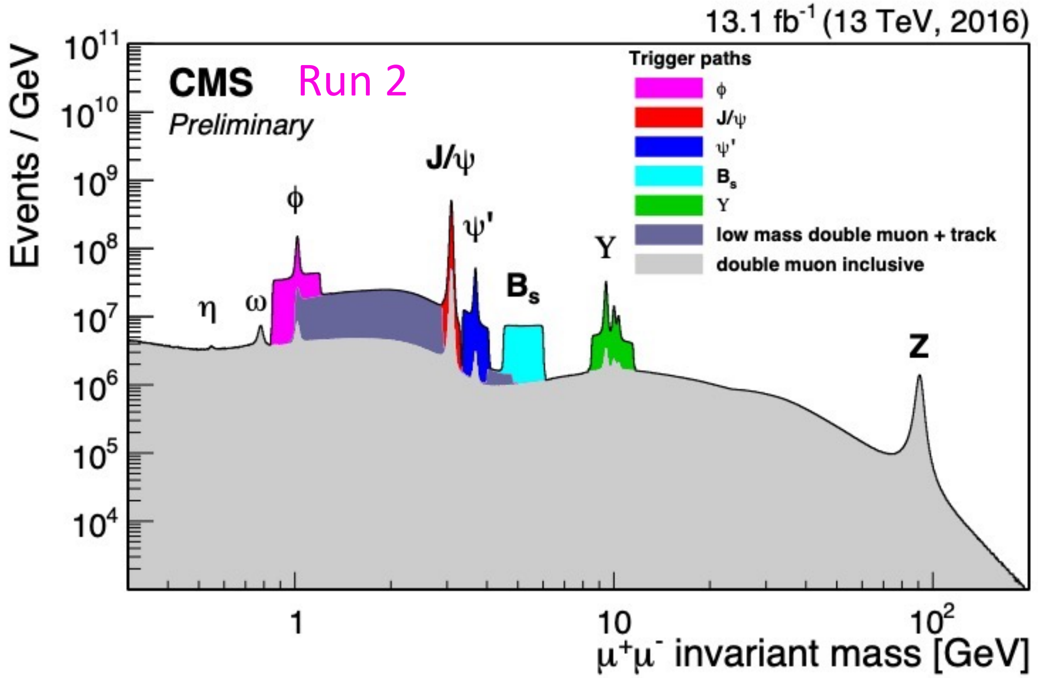
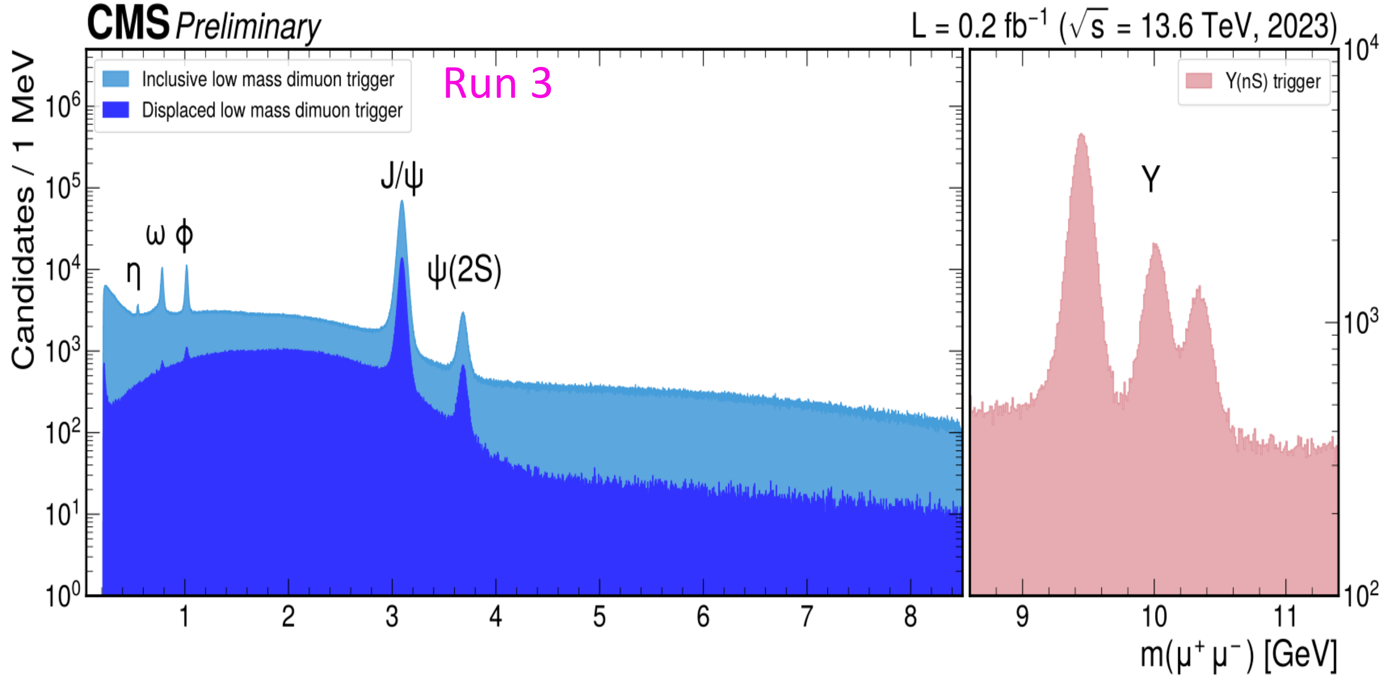
第八届强子谱和强子结构研讨会

CMS dimuon & trigger





❖Excellent detector for B physics, especially for studies with muons

- Muon system
  - High-purity muon ID, Dm/m~0.6% for J/ψ
- Silicon Tracking detector, B=3.8T
  - Dp_T/p_T~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

❖Run 3 improvement for trigger:

- Added dimuon trigger @parked data
- [4,3] GeV trigger & [2,2] trigger

Outline

- ❖X(3872) @CMS
- ❖Y(4140) @CMS
- ❖All-charm tetra-quark @CMS
- ❖Summary

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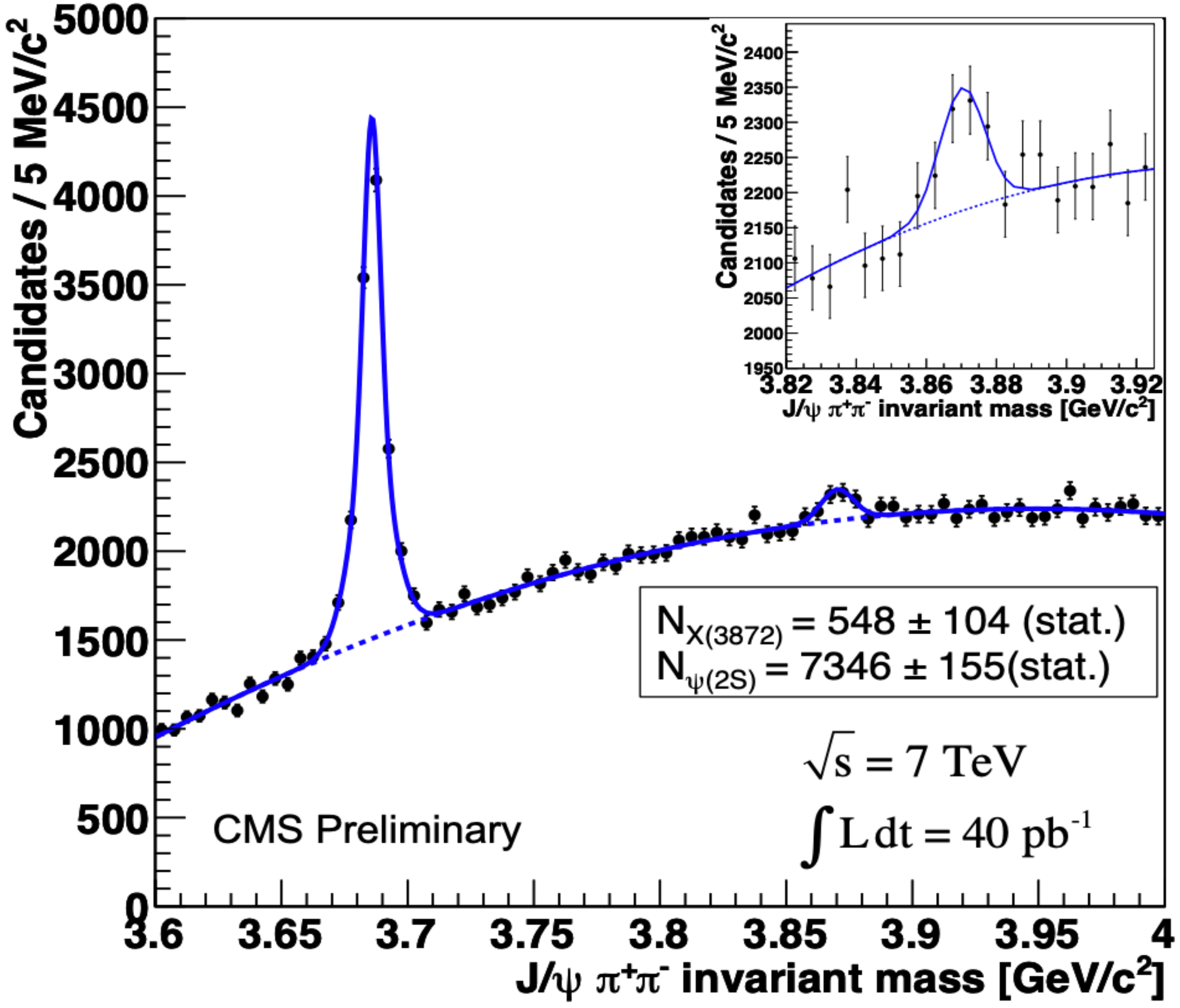
X(3872) at CMS—2010



$$R = \frac{\sigma(pp \to X(3872) + \text{anything}) \times BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything}) \times BR(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

$$R = 0.087 \pm 0.017(stat.) \pm 0.009(syst.)$$

The first LHC experiment re-discovered X(3872), CMS PAS BPH-10-018

X(3872) at CMS—2011

Fit:
Unbinned maximum likelihood fit.
J/ψ mass fixed to the PDG value.

Fit results:

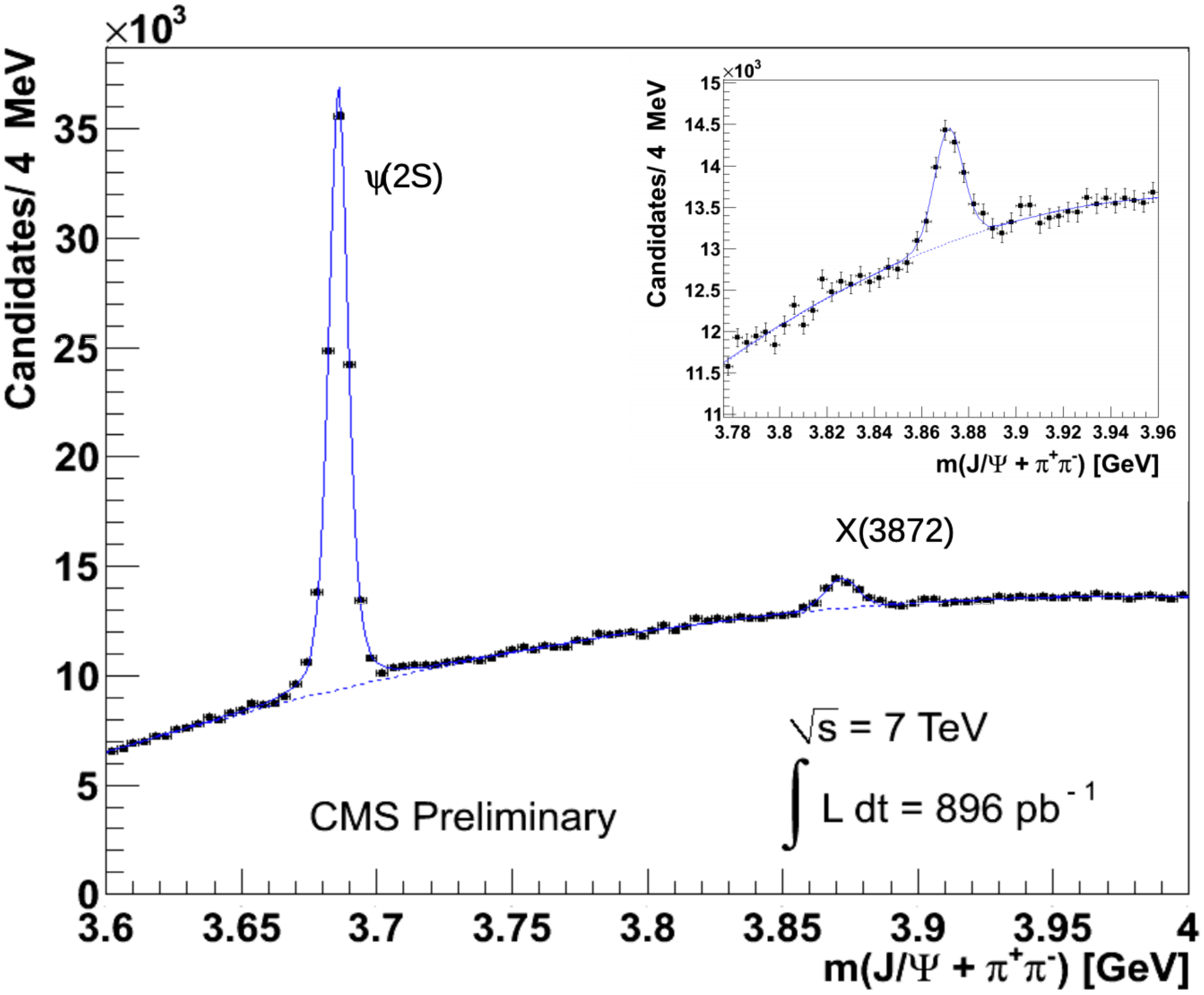
ψ(2S) Voigtian:
μ = 3685.90 ± 0.02 MeV
σ = 3.2 ± 0.1 MeV
γ = 0.00283 ± 0.00005
N = 72594 ± 518

X(3872) Gaussian:
μ = 3871.5 ± 0.5 MeV
σ = 6.1 ± 0.4 MeV
N = 5303 ± 341

Chebychev Polynomial:
c1 = 0.321 ± 0.002
c2 = -0.091 ± 0.002

χ^2/ndf = 0.99

PDG mass values:
ψ(2S) = 3686.09 ± 0.04 MeV
X(3872) = 3871.57 ± 0.25 MeV



The first LHC experiment re-discovered X(3872), CMS DP 2011/009

X(3872) at CMS—2013

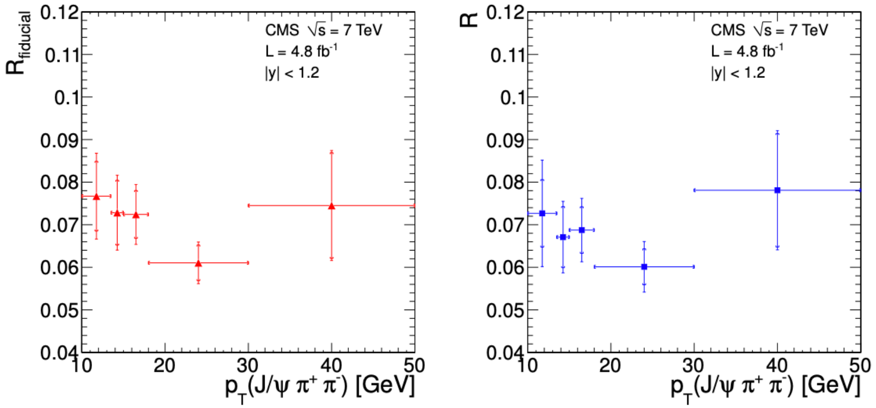
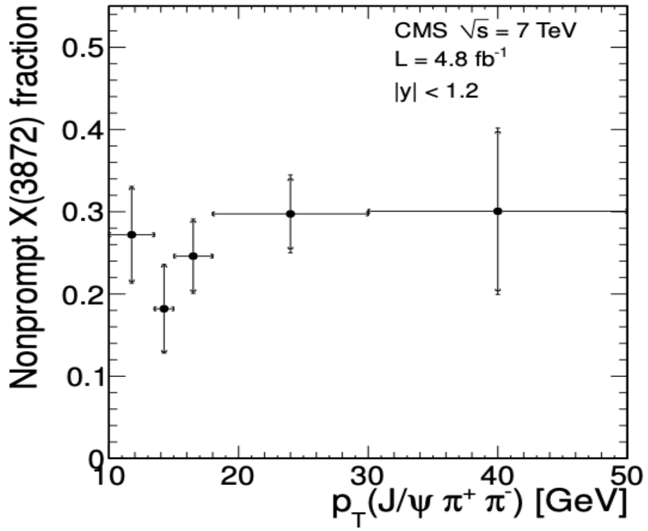
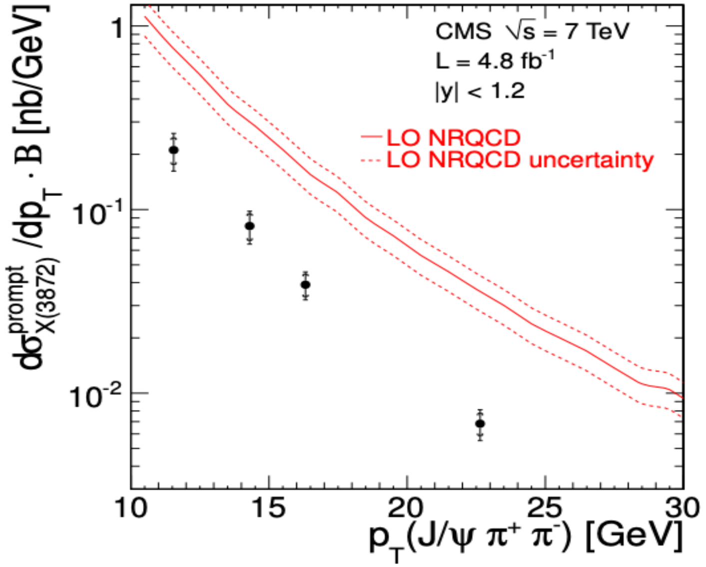
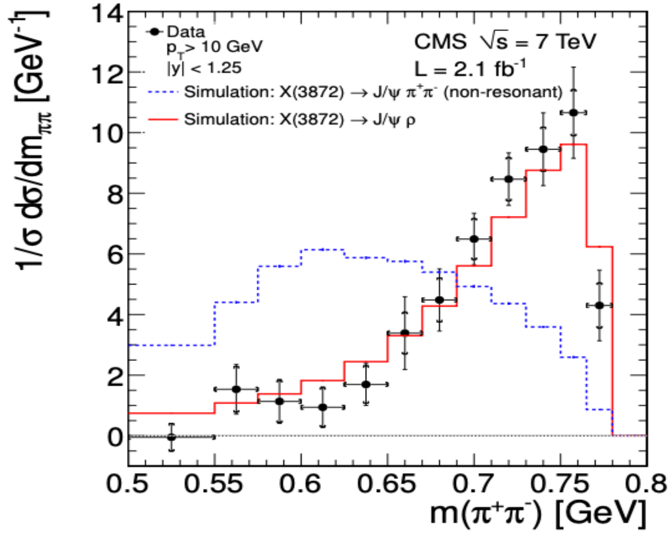


Figure 3. Ratios of the X(3872) and $\psi(2S)$ cross sections times branching fractions, without (R_{fiducial}, left) and with (R, right) acceptance corrections for the muon and pion pairs, as a function of p_T. The inner error bars indicate the statistical uncertainty and the outer error bars represent the total uncertainty. The data points are placed at the centre of each p_T bin.

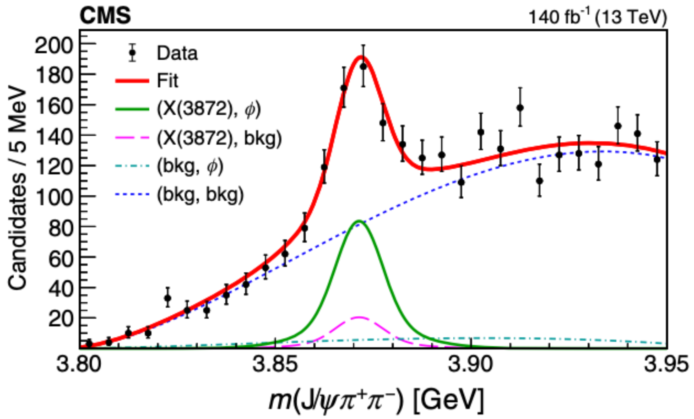


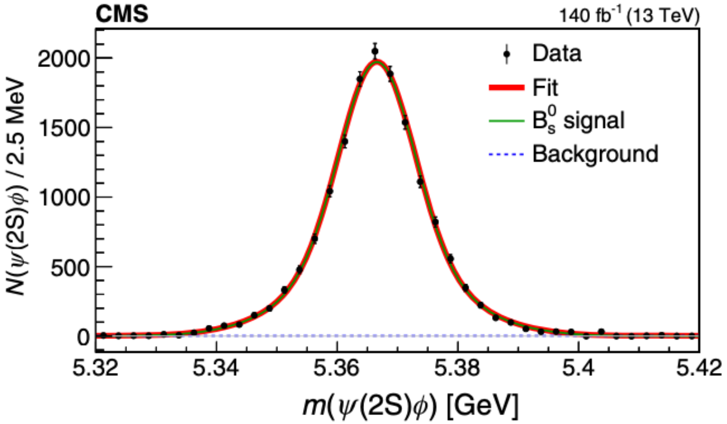


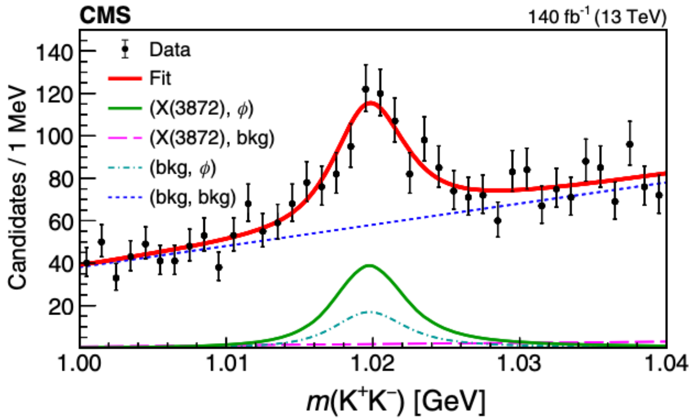


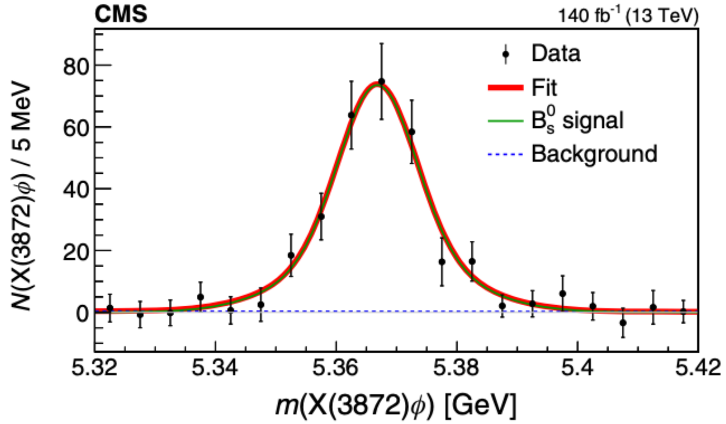
Detailed measurements, JHEP 04 (2013) 154

X(3872) at CMS $B_s \to X(3872)\phi$—2020









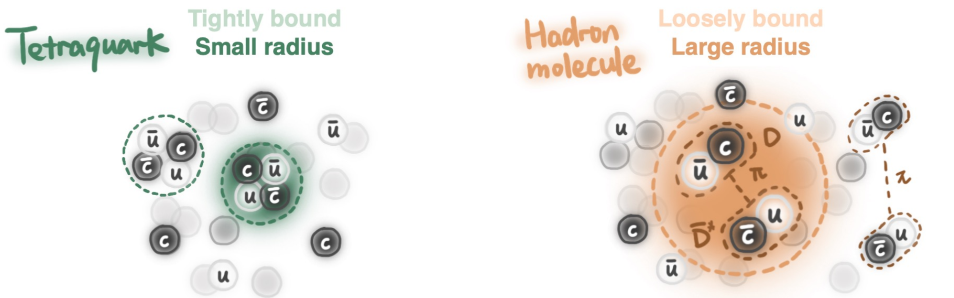
$$R \equiv \frac{\mathcal{B}[B_s^0 \to X(3872)\phi]\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[B_s^0 \to \psi(2S)\phi]\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]}$$
$$= \frac{N[B_s^0 \to X(3872)\phi]}{N[B_s^0 \to \psi(2S)\phi]}\frac{\epsilon_{B_s^0 \to \psi(2S)\phi}}{\epsilon_{B_s^0 \to X(3872)\phi}}.$$

$$R = [2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst})]\%.$$

$B_s \to X(3872)\phi$, PRL 125 152001 (2020)

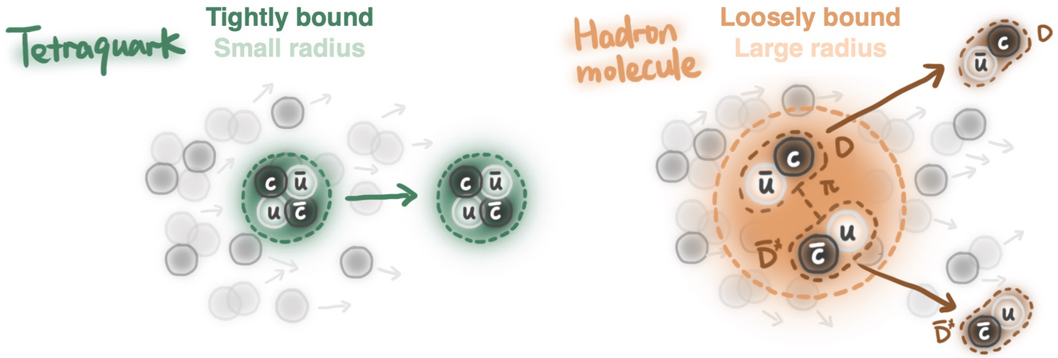
X(3872) in High color density envir.

❖ **Coalescence with diffusing constituent particles in QGP** → Enhance X(3872)



$r_{4q} \approx r_{c\bar{c}} \approx 0.3\ fm$ $\quad$ r_{mol} *as large as* $5\ fm$

❖ **Breakup by co-moving particles** → Suppress X(3872)



Lower dissociation prob. $\quad$ Higher dissociation prob.

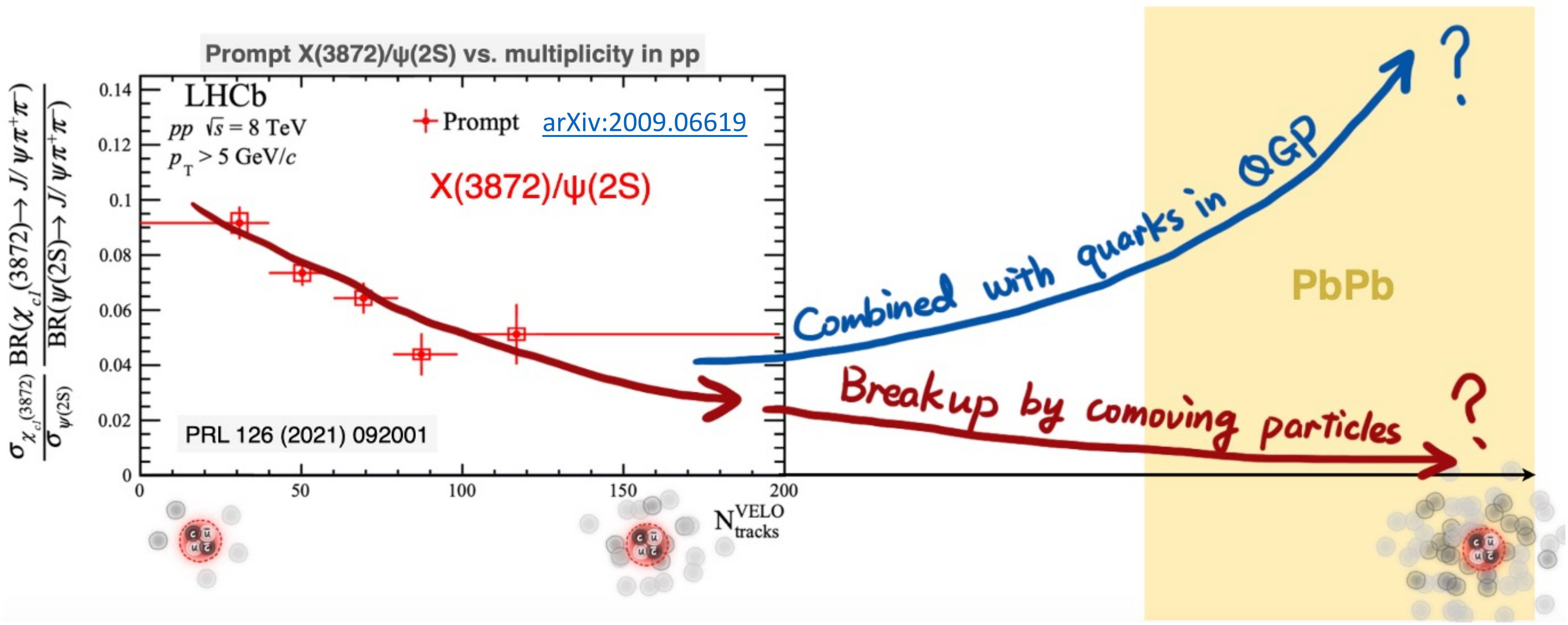
- ❑ Molecule easier to be produced and destroyed than tetraquark ($r_{4q} \ll r_{mol}$)
- ❑ Recreation probability depends on **particle density distribution** and **X(3872) size**

🔎 Production in heavy ion collisions: **Reveal the inner structure of X(3872)**

X(3872) in High-multiplicity pp collisions

❖ The ratio of X3872 to ψ (2S) cross-section **decrease with multiplicity** from LHCb **in pp collisions**

What to expect in HI?



X(3872) in Heavy-ion collisions @ CMS

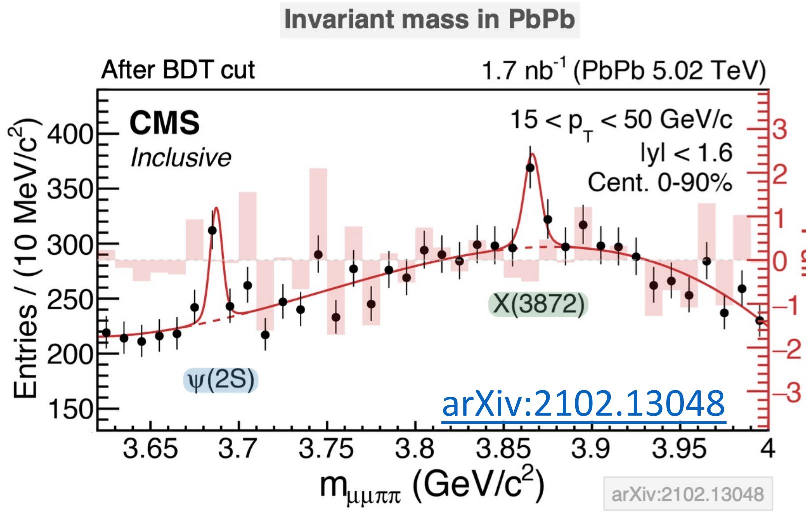
❖ **First evidence of X(3872) in heavy ion collisions!**

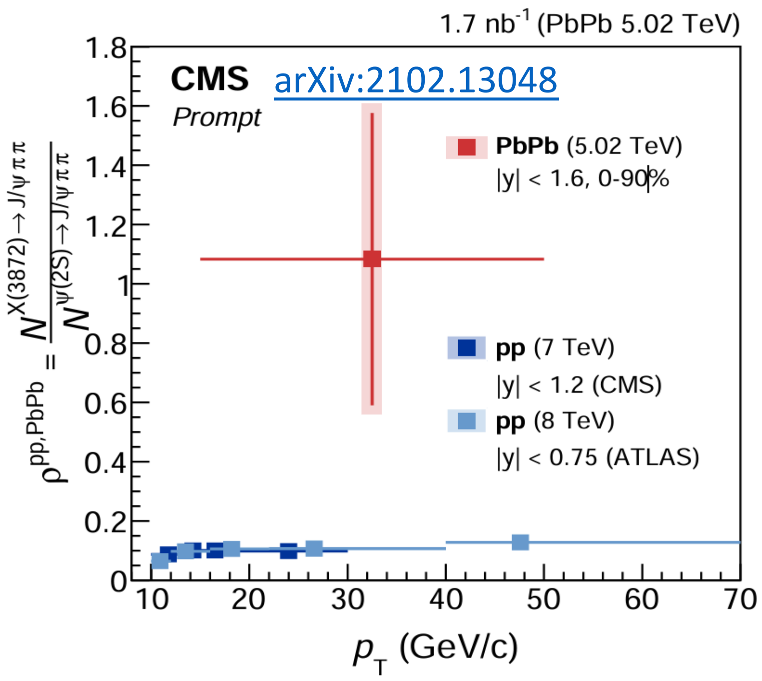
Statistical significance ~ 4.2σ

❖ **X(3872)/ψ(2S) Ratio in PbPb**

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

Indication of ρ enhancement in PbPb collisions

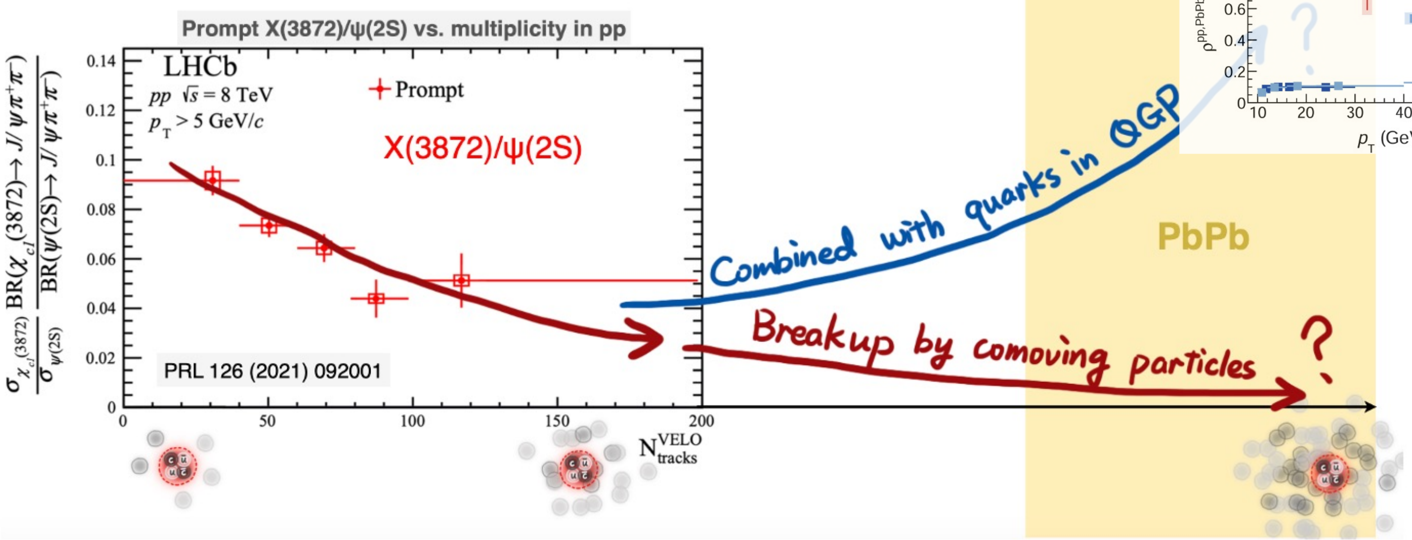


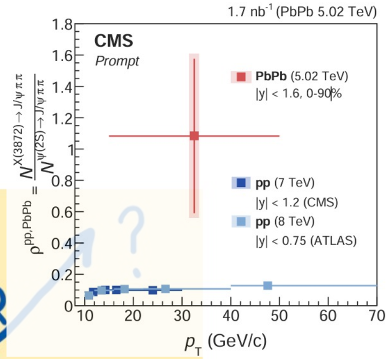


Molecule indication?

Still debatable

Coalescence seems to play important role in PbPb





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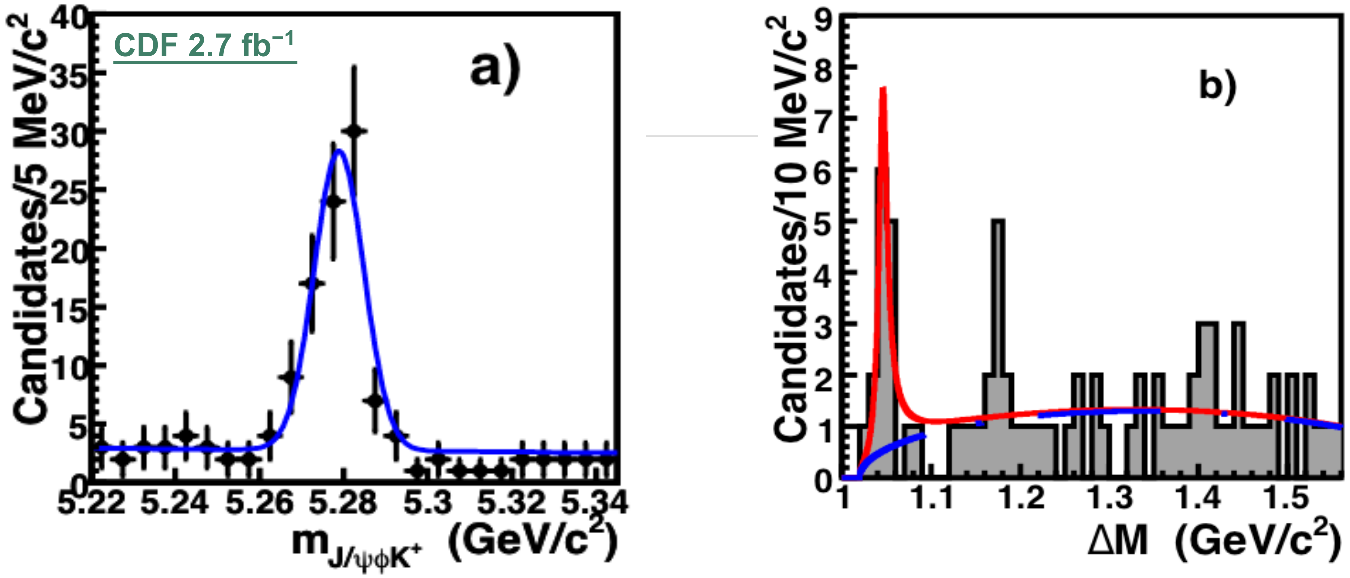
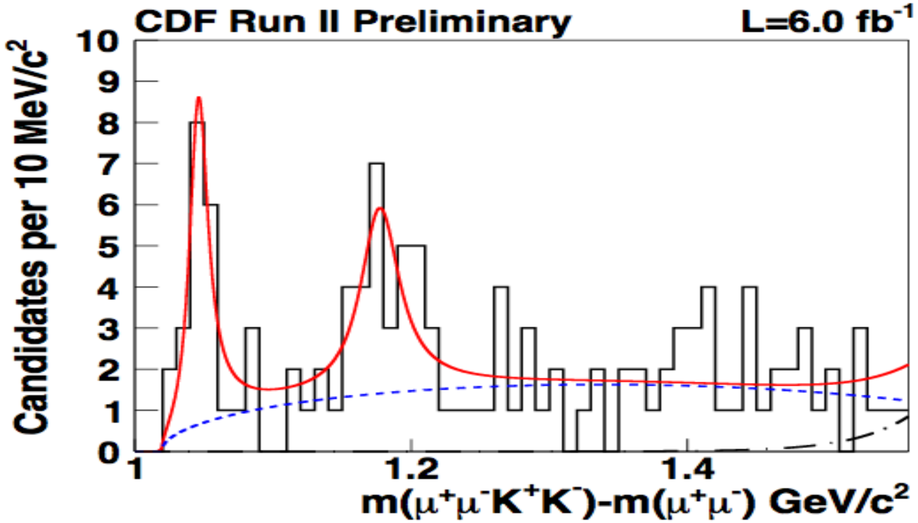
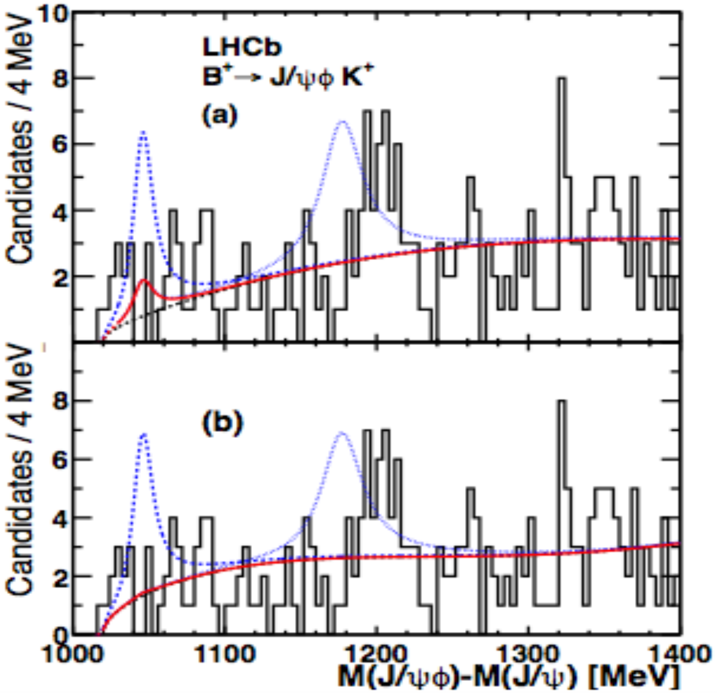
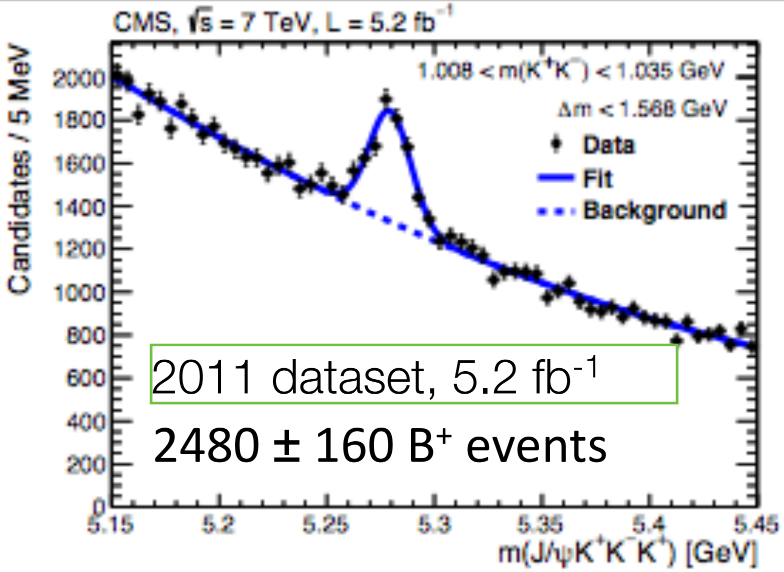
Results from CMS (2011-2014)

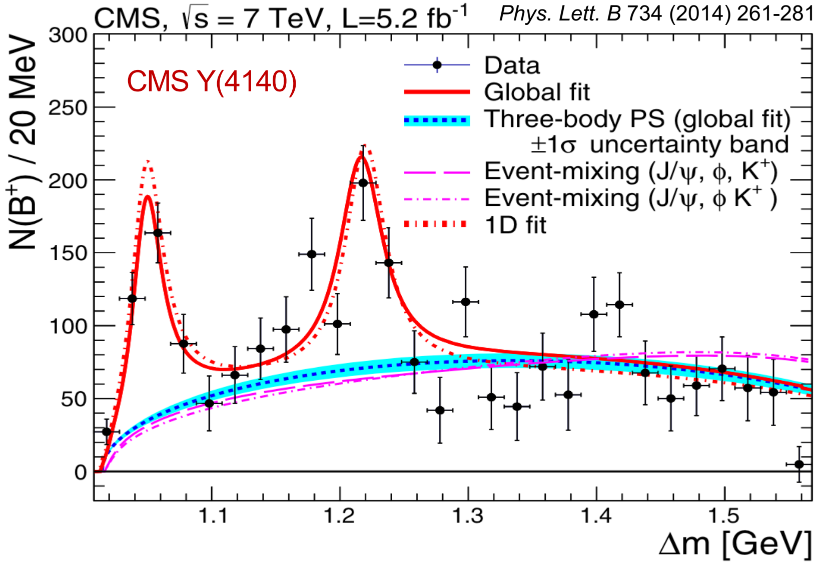
Phys.Rev.Lett. 102 (2009) 242002











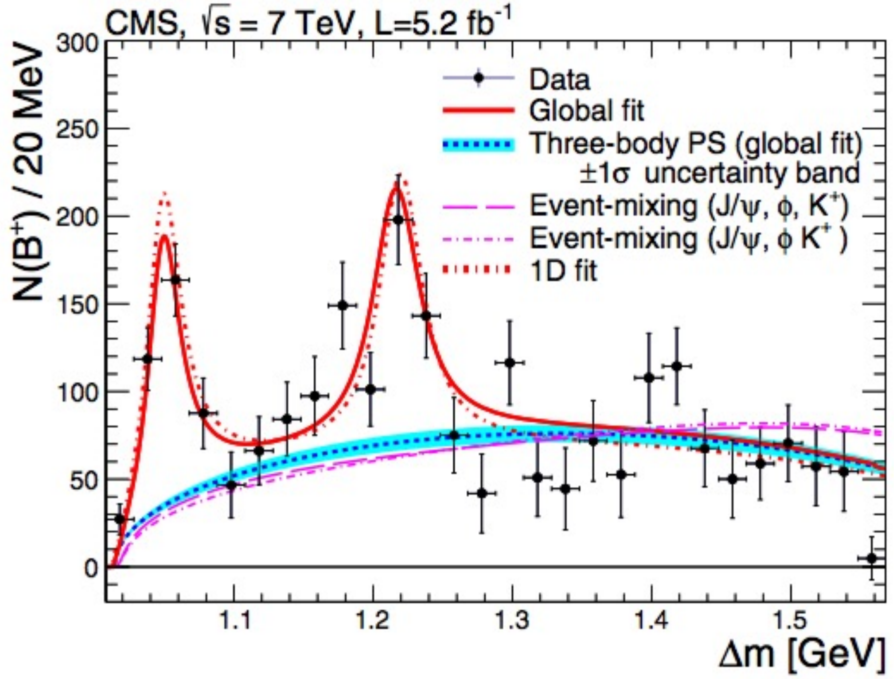
Results from CMS (2011-2014)

❖ Investigating the $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$

- exclude Δm >1.568 GeV region to avoid bkg from $B_s \rightarrow \psi(2S)\varphi \rightarrow J/\psi\pi^+\pi^-\varphi$ decays

❖ Δm spectrum obtained by:

- dividing the dataset in 20MeV Δm bins
- extracting the number of B signal in each Δm bin by fitting the $J/\psi\varphi K$ spectrum



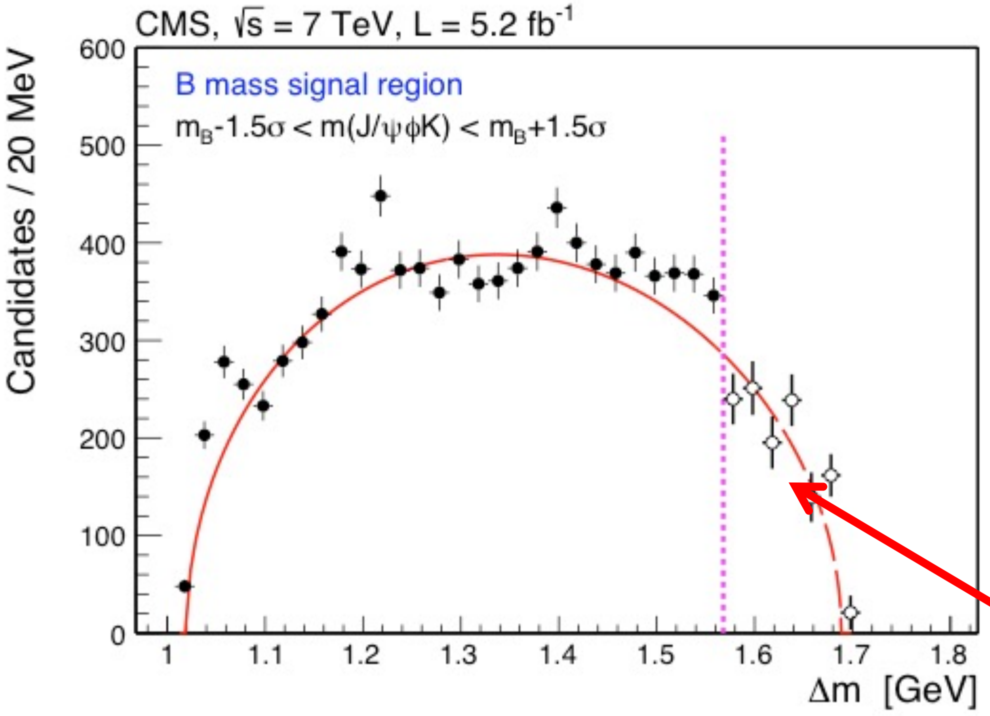
Yield	Mass (MeV)	Γ (MeV)
310 ± 70	$4148.0 \pm 2.4(stat) \pm 6.3(\text{syst})$	$28^{+15}_{-11}(stat) \pm 19(syst)$
418 ± 170	$4313.8 \pm 5.3(stat) \pm 7.3(\text{syst})$	$38^{+30}_{-15}(stat) \pm 16(syst)$

➢ CMS confirmed Y(4140) with a significance >5 standard deviations,

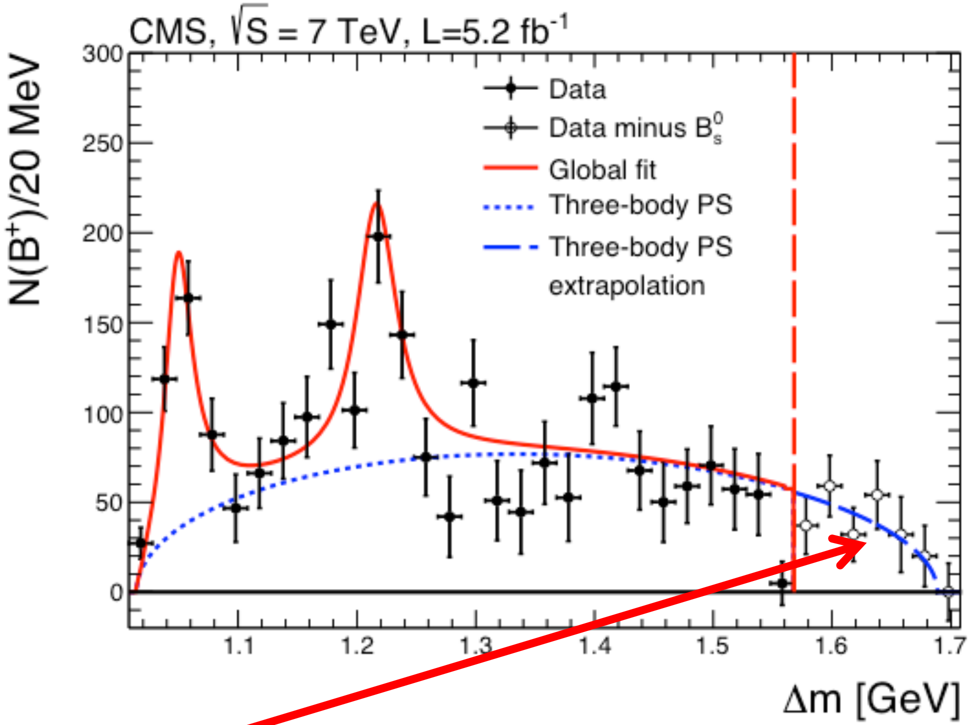
and saw evidence for a second structure in the same mass spectrum

Results from CMS (2011-2014)

- The Δm spectrum after subtracting B^0_s contribution but including non-B evens, within 1.5σ *(σ = 9.3MeV) of the B mass*



- The extension of the Δm spectrum, after subtracting non-B background, to the full phase space



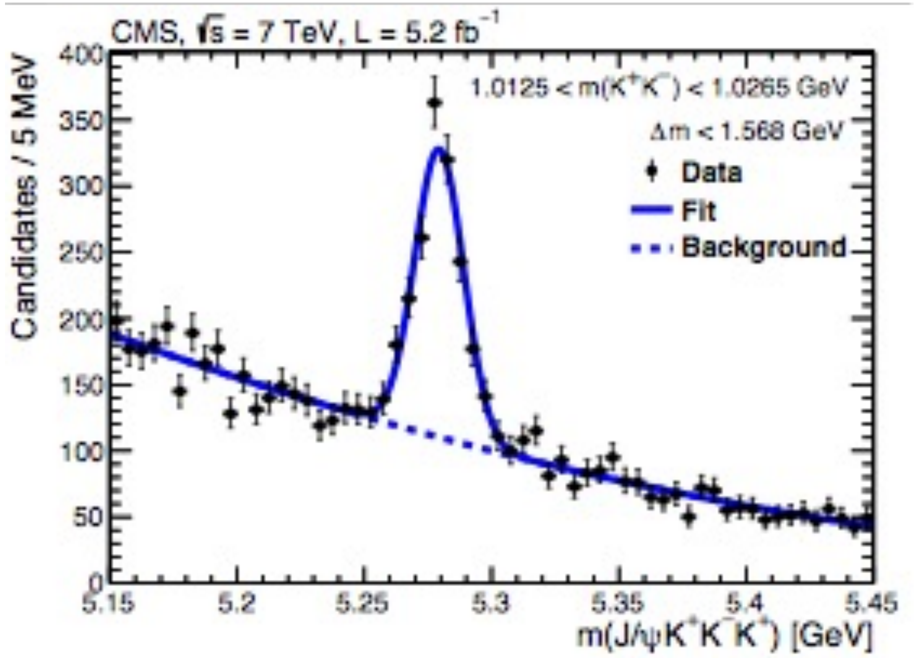
The events in pervious cutoff region are consistent with phase space

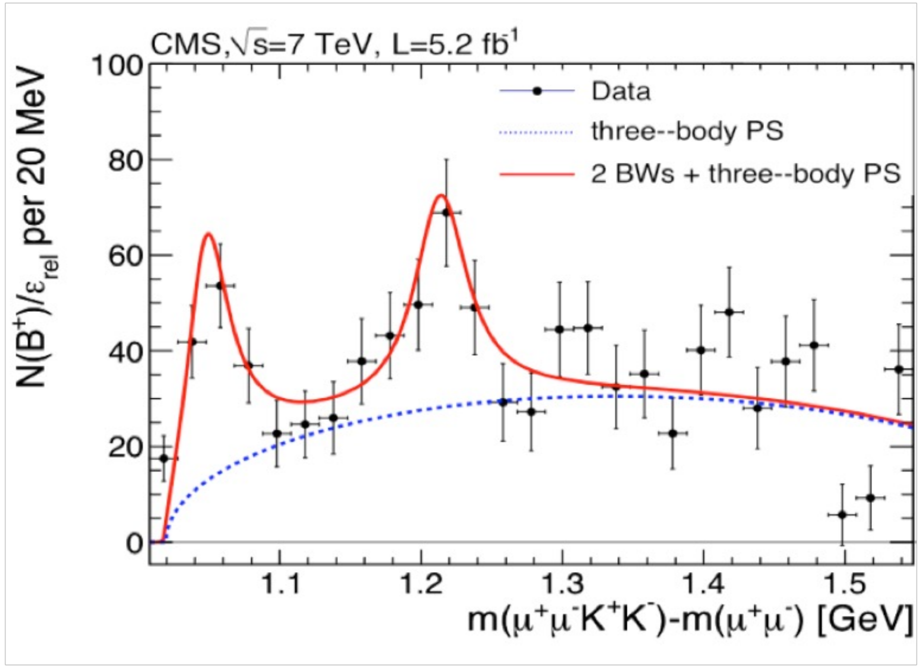
PLB 734 261 (2014)

Results from CMS (2011-2014)

Additional requirements:

- kaon p_T > 1.5 GeV
- B^+ vertex CL > 10%
- B^+ vertex detachment: >7X from beamspot
- m(K+K-) within 7 MeV of φ mass





Solid structures appear in clean B sample.

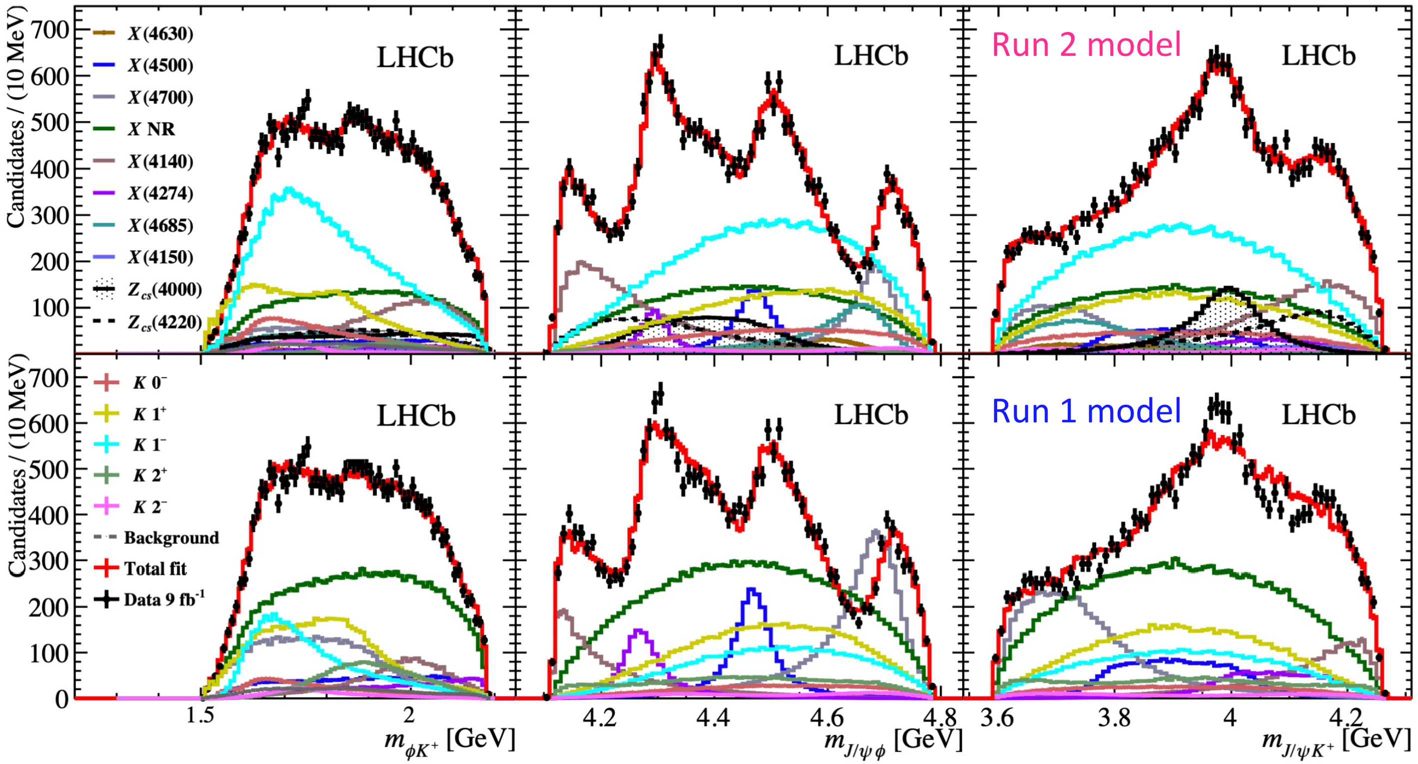
40% of default B signal, 10X less non-B background

➢ Reasonable to try amplitude analysis

Y(4140) at LHCb

❖ Run1 + Run2 data, $B^+ \to J/\psi\phi K^+$

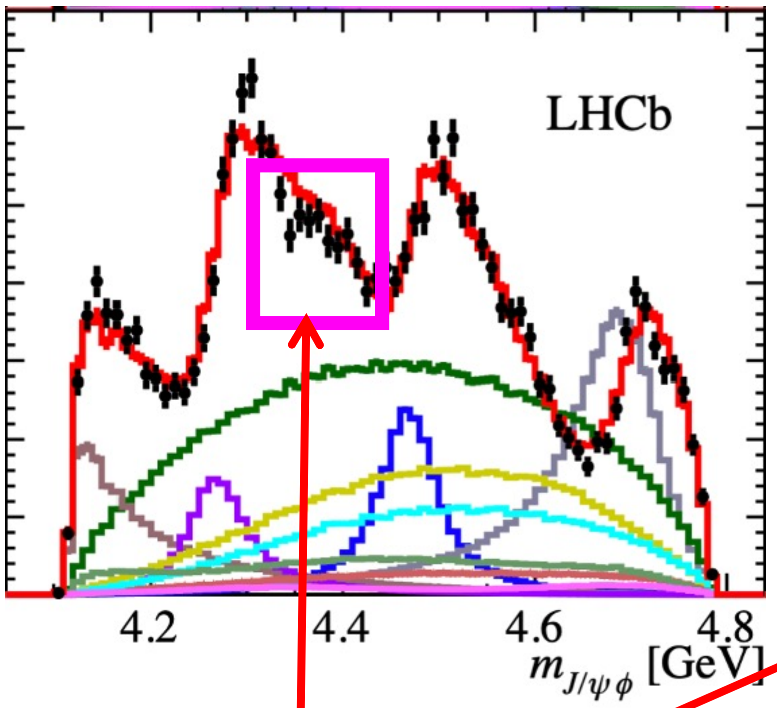
Phys. Rev. Lett. 118, 022003 (2017)
Phys. Rev. Lett. 127, 082001 (2021)

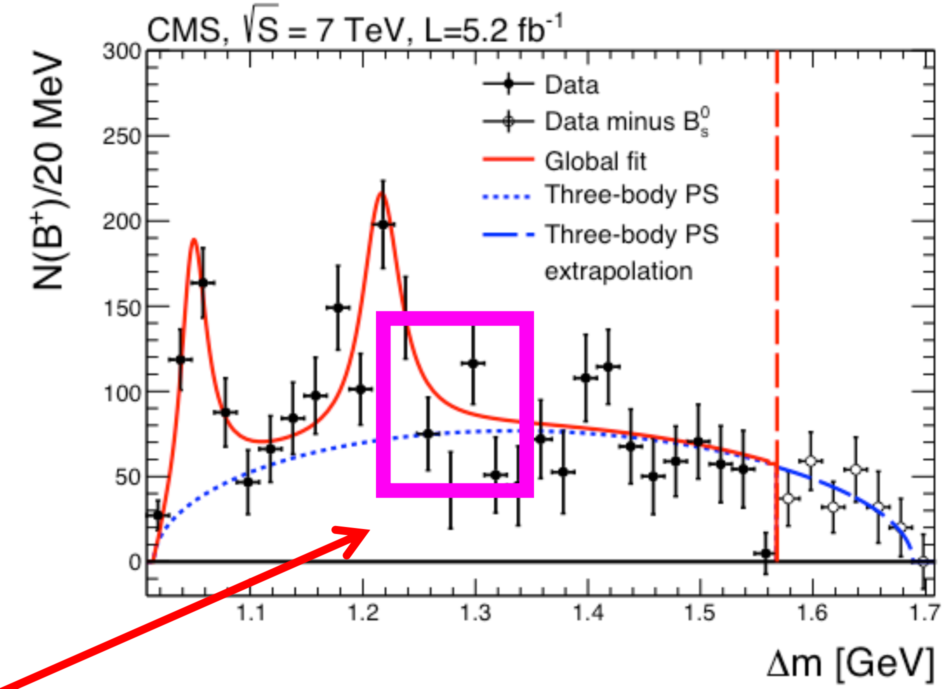


J^P	Contribution		Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
1^+	$2^1\mathrm{P}_1$	$K(1^+)$	4.5 (4.5)	$1861 \pm 10\,^{+16}_{-46}$	$149 \pm 41\,^{+231}_{-23}$	
	$2^3\mathrm{P}_1$	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37\,^{+124}_{-48}$	$276 \pm 50\,^{+319}_{-159}$	
	$1^3\mathrm{P}_1$	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3\,^{+3}_{-11}$
2^-	$1^1\mathrm{D}_2$	$K_2(1770)$	7.9 (8.0)	1773	186	
	$1^3\mathrm{D}_2$	$K_2(1820)$	5.8 (5.8)	1816	276	
1^-	$1^3\mathrm{D}_1$	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2\,^{+35}_{-8}$
	$2^3\mathrm{S}_1$	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5\,^{+11}_{-17}$
2^-	$2^3\mathrm{P}_2$	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22\,^{+194}_{-31}$	$318 \pm 82\,^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
0^-	$2^1\mathrm{S}_0$	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2\,^{+1.0}_{-3.8}$
2^-		$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
1^-		$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
0^+		$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
		$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
		$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
1^+		$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
		$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
		$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
1^+		$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
		$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

- For $B^+ \to J/\psi\phi K^+$, LHCb claim
  - 7 structures in $J/\psi\phi$: $X(4140), X(4274), X(4500), X(4700)$, $X(4150), X(4630), X(4685)$
  - 2 structures in $J/\psi K^+$: $Z_{cs}(4000), Z_{cs}(4220)$
- **No confirmation** by other experiments yet except for $X(4140)$ and $X(4274)$
- Larger width of $X(4140)$ measured by LHCb: $162 \pm 21^{+24}_{-49}$ MeV

Revisit Y(4140)



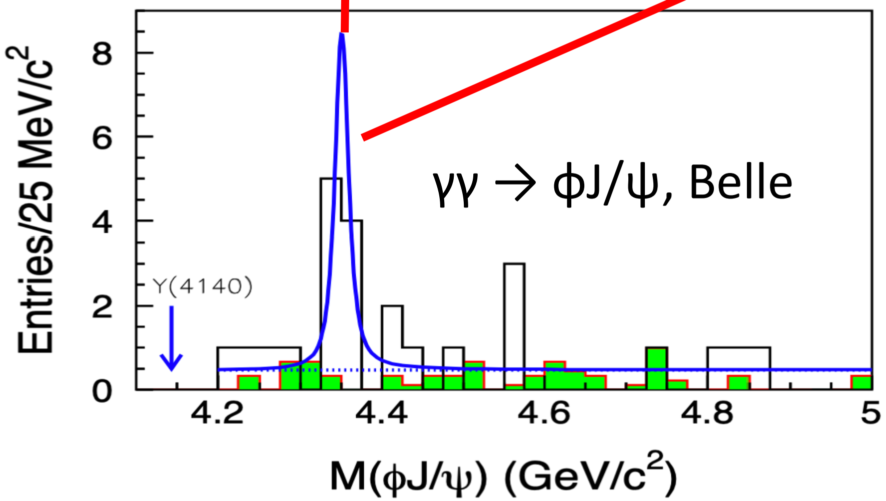


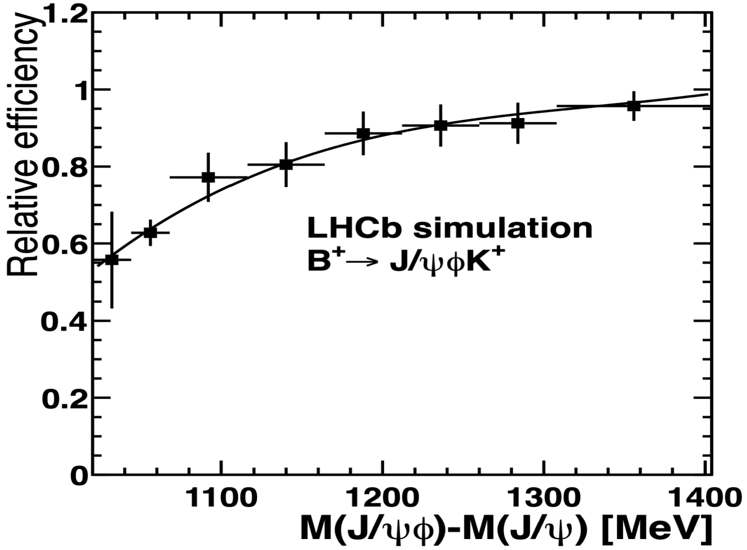
A structure at ~4.35 GeV?

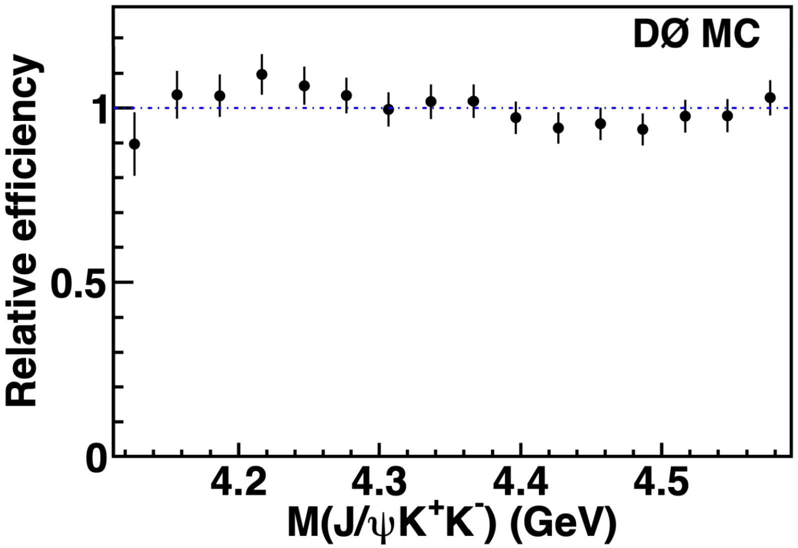
Suppressed at B decay if high spin

Collaborating with Liming Zhang

CMS amplitutde analysis







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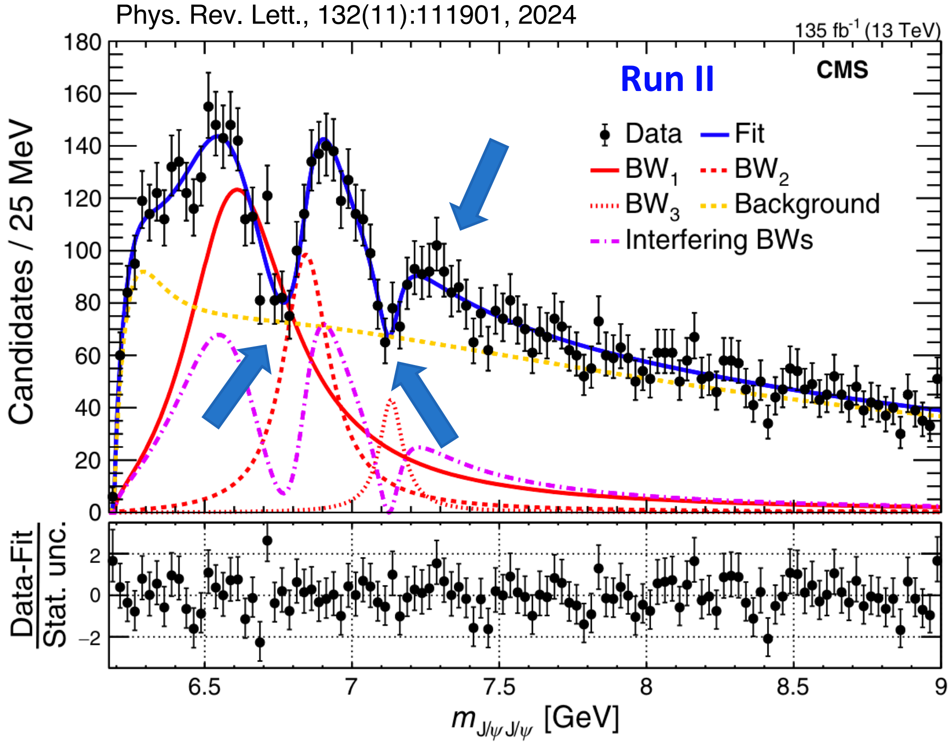
All-charm tetraquarks at CMS—2024

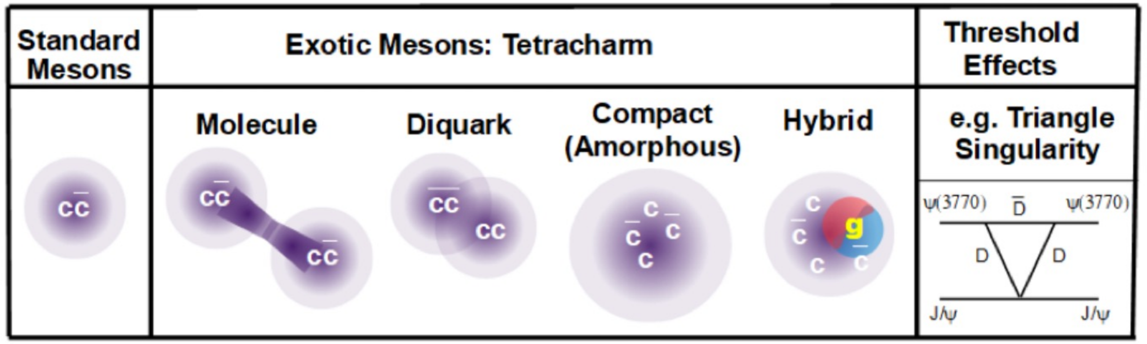


- **Run 2 result:**
  - **X(7100)**: 4.7σ
  - **Interference** < 4σ
- **With 3.6X statistics:**
  - ❑ ***ALL states*** over 5σ ?
  - ❑ ***Interferences*** over 5σ ?

> ➢ **Imply same J^{PC} quantum numbers**
>
> ➢ **> 200 MeV mass splittings ==> Radial excitations ?**

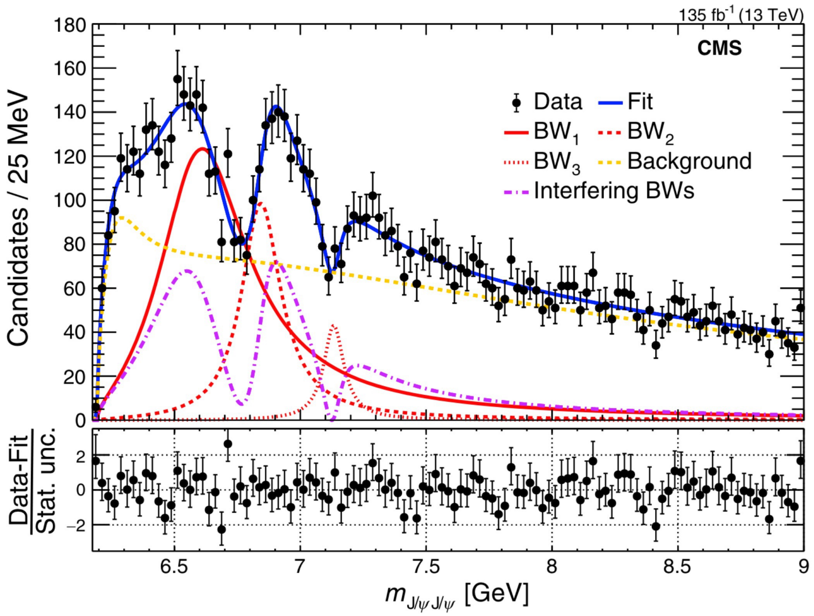
A family of all-charm tetraquarks with same J^{PC} ?

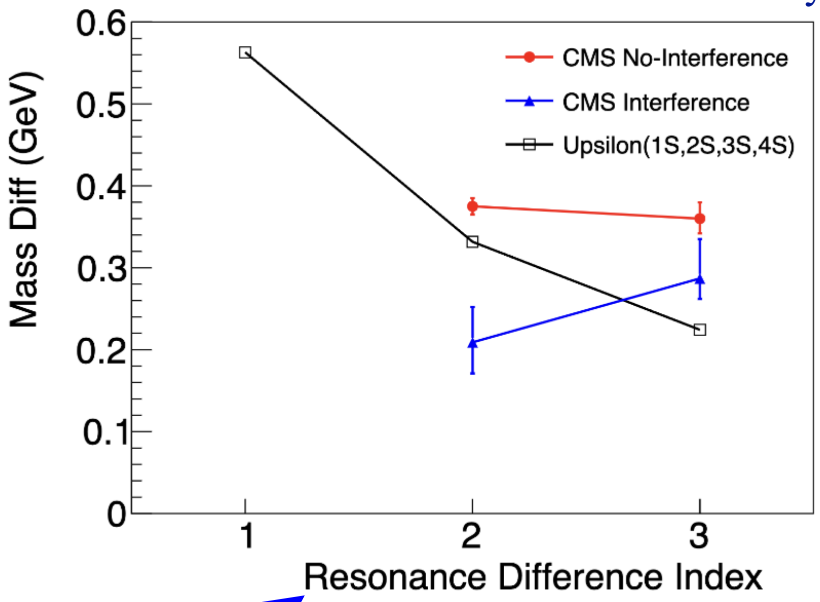
- **Models of potential quark configurations for J/ψJ/ψ mesons**
  - Meson-meson "molecule" ($c\bar{c}$- $c\bar{c}$)
  - pair of diquarks (cc-$\bar{c}\bar{c}$)
  - hybrid
  - artifact of dicharmonia production thresholds
  - ……

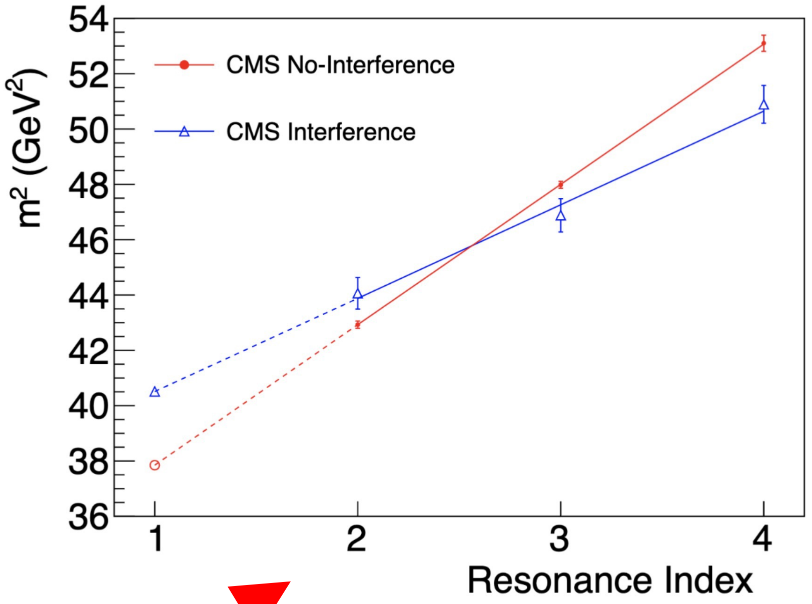


All-charm tetraquarks at CMS—2024

Chinese Phys. Lett. 41 111201





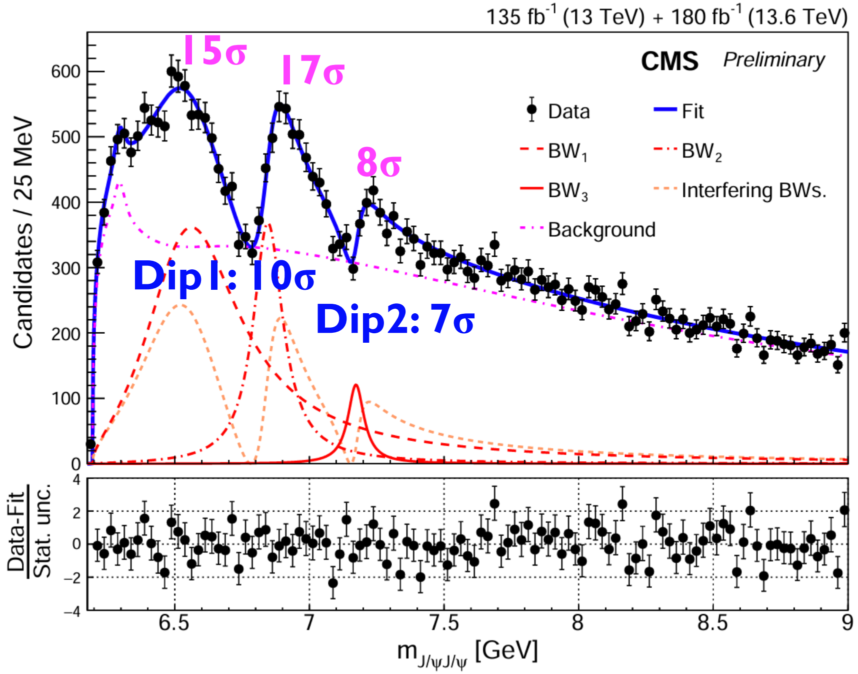


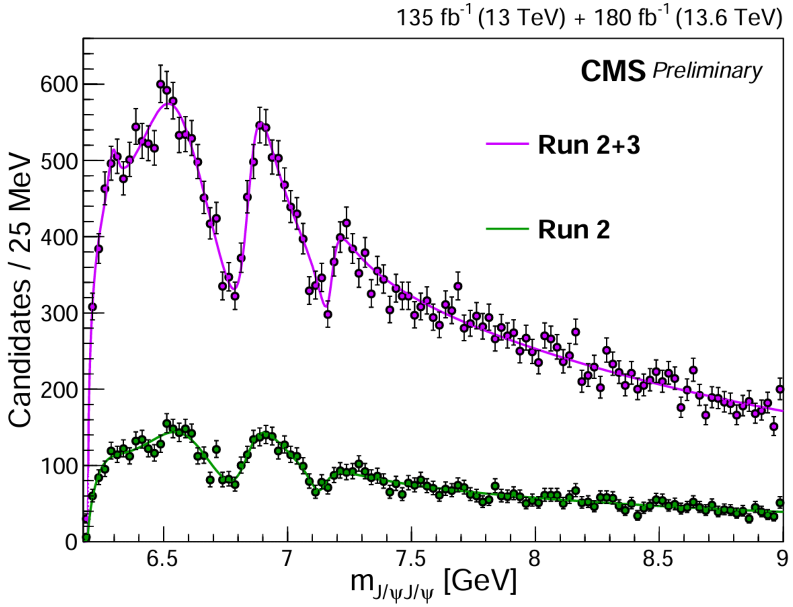
- Mass splitting of triplet similar to Υ family
- Mass quuare of triplet align with quatun number（Regge trajectory）
- Inteference among triplet indicates they have same J^{PC}

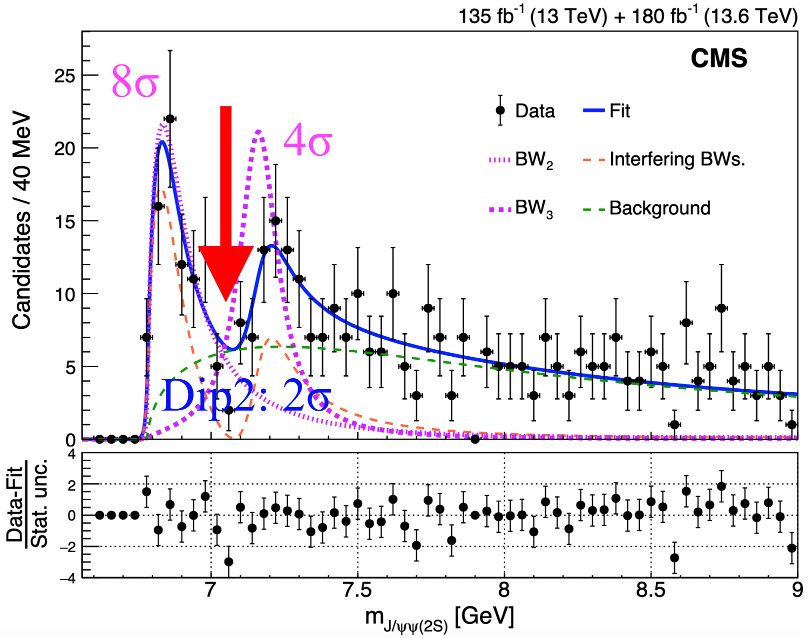
➢ Need large statistics, different decay channels, properties measurement!

All-charm tetraquarks at CMS—2025

❖ Interference model with Run II + III:

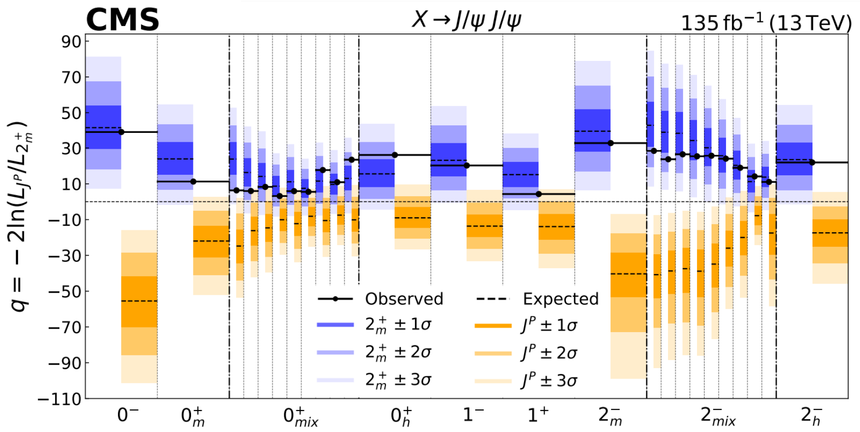






- All state and dips well above **5σ**
- Quantum **interference** among structures validated
- Data favor $J^{PC} = 2^{++}$

- **Seems favor spin 1 diquark model**



Family of all-charm tetraquarks with same J^{PC}

offers new perspectives on interpretation for exotics !

Summary

❖ CMS has contributed to the following:

- X(3872) @CMS
- Y(4140) @CMS
- All-charm tetra-quark @CMS

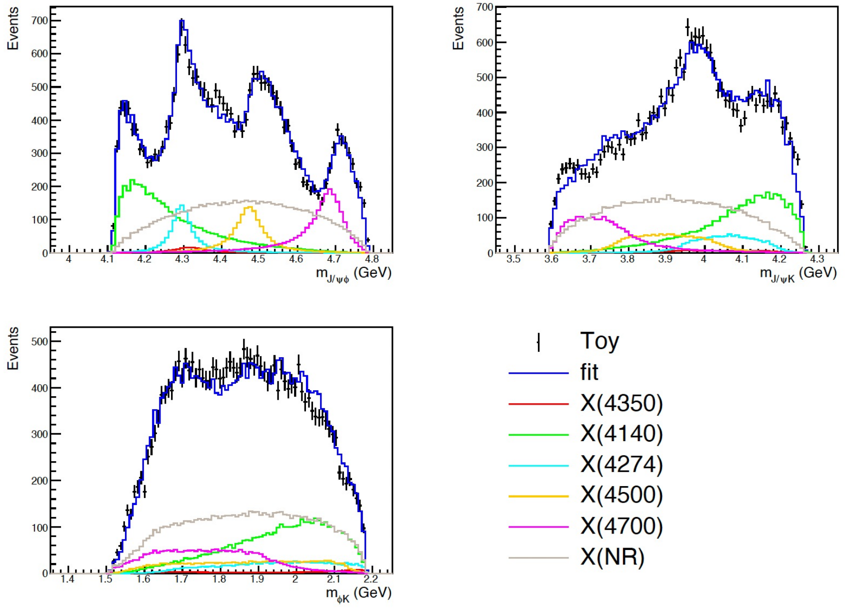
❖ CMS is going to contribute more !

Backup

Revisit Y(4140)

Table 5: The significance of $X(4350)$ for each spin-parity hypothesis. We consider the $X(4350)$'s mass values of 4320, 4340 and 4360 MeV, each tested with width values of 50 and 100 MeV. The components $X(4150)$, $X(4630)$, and $X(4685)$ are removed from the fit model. The significance $[\sigma]$ is approximated as $\sqrt{-2\Delta \ln L}$ when considering the degree of freedom is 1.

J^P	$M = 4320$ MeV, $\Gamma = 50$ MeV	$M = 4340$ MeV, $\Gamma = 50$ MeV	$M = 4360$ MeV, $\Gamma = 50$ MeV	$M = 4320$ MeV, $\Gamma = 100$ MeV	$M = 4340$ MeV, $\Gamma = 100$ MeV	$M = 4360$ MeV, $\Gamma = 100$ MeV
0^+	3.5	3.3	2.6	3.4	3.3	3.1
0^-	4.8	5.3	5.5	6.2	6.4	6.5
2^+	4.7	4.4	4.3	5.8	5.5	5.4
2^-	8.6	7.3	6.9	11.9	10.8	10.1
1^+	5.7	5.5	6.0	7.1	7.3	7.7
1^-	6.2	7.3	8.0	7.8	8.8	9.6



Toy data mimic LHCb data

Figure 17: The $J/\psi\phi$, ϕK and $J/\psi K$ mass distributions along with the fit models are shown for the most significance case (2^-) in Table 5.