Experimental road of the $J/\psi\phi$ mass spectrum, current status, and potential

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The 8th National Workshop on Heavy Flavor Physics and Quantum Chromodynamics

Apr 27, 2026

Outline

- ❑ **Review of $J/\psi\phi$ system** Chin. Phys. Lett. 2025 42(12): 120202
- ❑ **Latest results with LHCb amplitude analyses**
- ❑ **Connection with $J/\psi J/\psi$ and $\phi\phi$ systems**
- ❑ **Investigation of high-spin state in $J/\psi\phi$ system**
- ❑ **Summary and prospects**

Review of $J/\psi\phi$ structures

- Experimental reviews of structures in the $J/\psi\phi$ mass spectrum have done in 2013 and 2018
- Substantial progress has been made in studies of $J/\psi\phi$and $J/\psi K$ systems
- Studied across a wide range of facilities:
  - Hadron collider experiments: CDF, CMS, D0, and LHCb
    - Higher production cross sections, allow to access rare decay modes and high-mass regions
  - e^+e^- collider experiments: BaBar, Belle, and BESIII
    - Clean environment and low background levels

Int. J. Mod. Phys. A, 28:1330020, 2013
Int. J. Mod. Phys. A, 33:1850224, 2019

Accelerator	Detectors	Type	$\sqrt{s}$ [GeV]	Running years	Laboratory
Tevatron	CDF DØ	$p\bar{p}$	1800 (Run 1) 1960 (Run 2)	$1992-1996$ $2001-2011$	Fermilab
KEKB	Belle	e^+e^-	10.58 (3.5/8.0)	$1998-2010$	KEK
Super-KEKB	Belle II	e^+e^-	10.58 (4.0/7.0)	$2018-\cdots$	KEK
PEP-II	BaBar	e^+e^-	10.58 (3.1/9.0)	$1999-2008$	SLAC
BEPCII	BESIII	e^+e^-	$2.0-4.95$	$2008-\cdots$	IHEP
LHC	CMS LHCb	pp	>7000 (Run 1) 13000 (Run 2) 13600 (Run 3)	$2009-2013$ $2015-2018$ $2022-\cdots$	CERN

Review of $J/\psi\phi$ structures

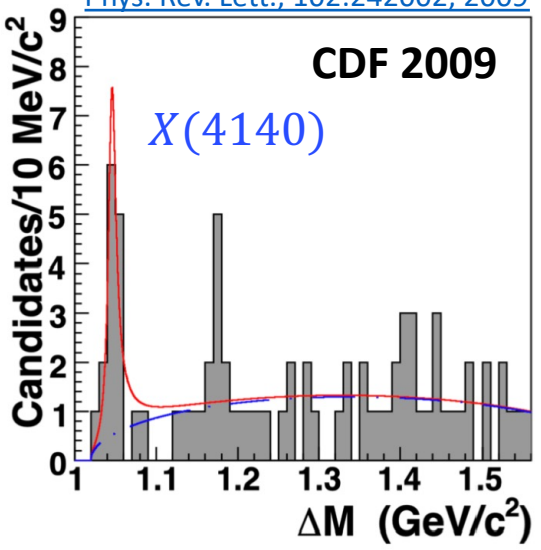
- 2009, CDF, $B^+ \to J/\psi\phi K^+$
  - First report of $X(4140)$, 3.8σ
    - $M = 4143.0 \pm 2.9 \pm 1.2$ MeV; $\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$ MeV
  - Induce great interest in the $J/\psi\phi$ mass spectrum

- 2010, Belle, $\gamma\gamma \to J/\psi\phi$
  - No found $X(4140)$, challenge interpretation of molecular with $J^{PC} = 0^{++}$ or 2^{++}
  - Evidence of $X(4350)$, 3.2σ
    - $M = 4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV; $\Gamma = 13.9^{+18}_{-9} \pm 4$ MeV

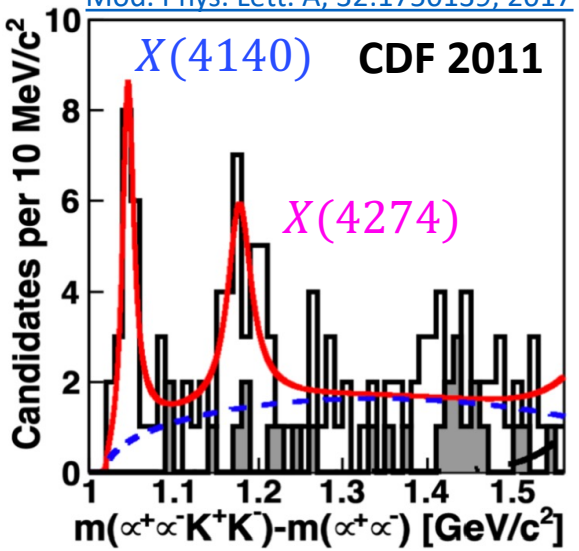
- 2011, CDF, $B^+ \to J/\psi\phi K^+$
  - Confirm $X(4140)$ with > 5σ with larger dataset
    - $M = 4143.4^{+2.9}_{-3.0} \pm 0.6$ MeV; $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV
  - Evidence of $X(4274)$, 3.1σ
    - $M = 4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV; $\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$ MeV

- 2012, LHCb, $B^+ \to J/\psi\phi K^+$ Phys. Rev. D, 85:091103, 2012
  - Not confirmation of $X(4140)$
  - The discrepancy delay the publication of 2011 CDF result which published in 2017 after confirmation by CMS

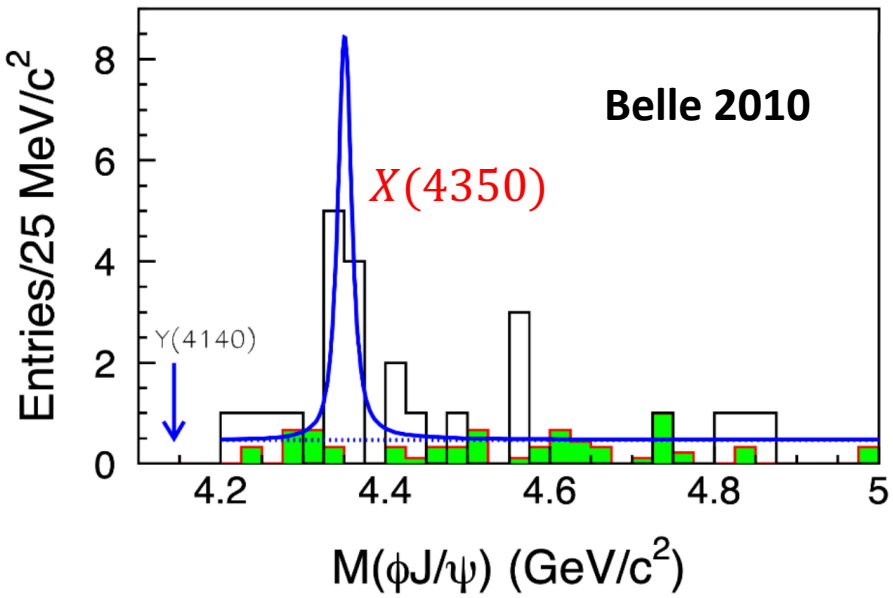
Phys. Rev. Lett., 102:242002, 2009



Mod. Phys. Lett. A, 32:1750139, 2017

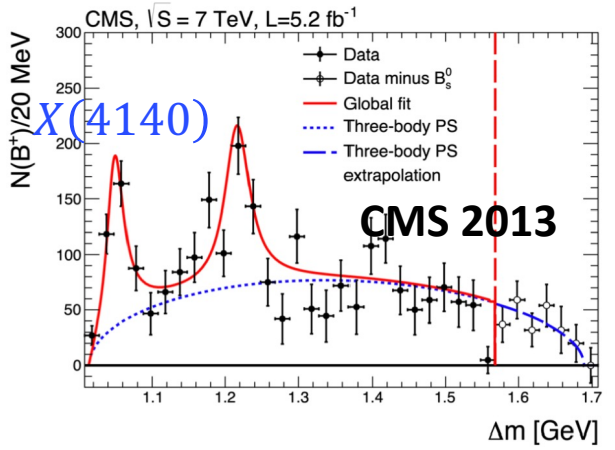


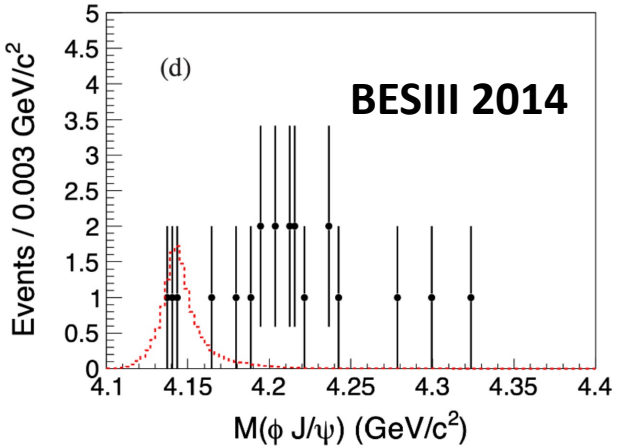
Phys. Rev. Lett., 104:112004, 2010

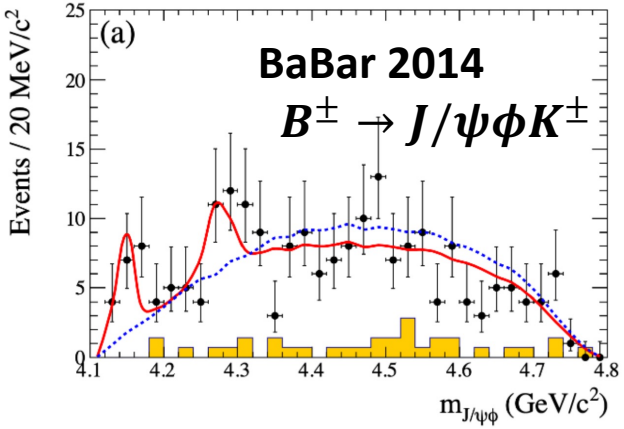


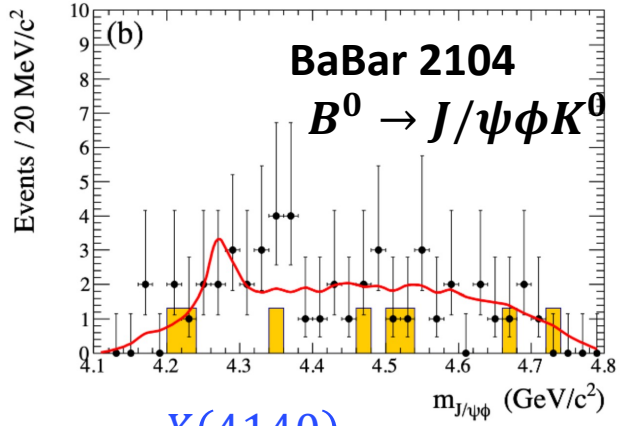
Review of $J/\psi\phi$ structures

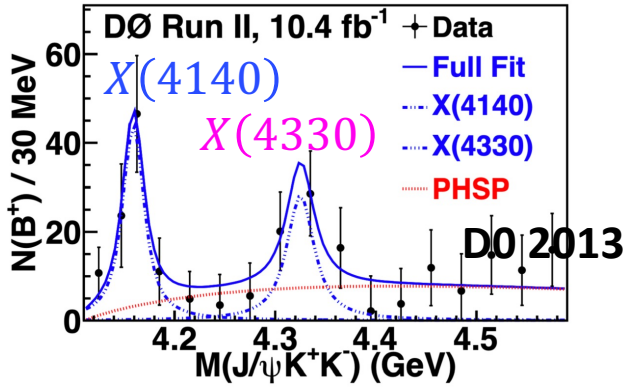
- 2013, CMS, $B^+ \to J/\psi\phi K^+$ Phys. Lett. B, 734:261, 2014
  - Confirm $X(4140)$
    - $M = 4159.0 \pm 4.3 \pm 6.6$ MeV
    - $\Gamma = 19.9 \pm 12.6^{+1.0}_{-8.0}$ MeV
- 2013, D0, $B^+ \to J/\psi\phi K^+$ Phys. Rev. D, 89:012004, 2014
  - Evidence (3.1σ) of a structure consistent with $X(4140)$
    - $M = 4143.0 \pm 2.9 \pm 1.2$ MeV
    - $\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$ MeV
  - Hint of second state at 4328.5±12.0 MeV
- 2014, BESIII, $e^+e^- \to \gamma J/\psi\phi$ at $\sqrt{s}$=4.23, 4.26, and 4.36 GeV
  - No found $J/\psi\phi$ structures Phys. Rev. D, 91:032002, 2015
- 2014, BaBar, $B^{\pm,0} \to J/\psi\phi K^{\pm,0}$ Phys. Rev. D, 91:012003, 2015
  - No found $J/\psi\phi$ structures
- 2015, D0, $pp \to J/\psi\phi$ + *anything* Phys. Rev. Lett., 115:232001, 2015
  - Evidence (4.7σ) of a structure consistent with $X(4140)$
  - $M = 4152.5 \pm 1.7^{+6.2}_{-5.4}$ MeV
  - $\Gamma = 16.3 \pm 5.6 \pm 11.4$ MeV

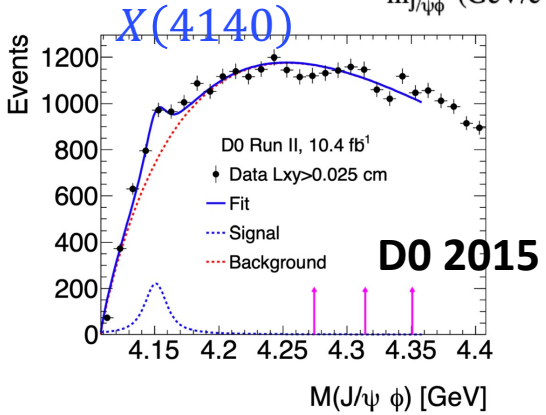








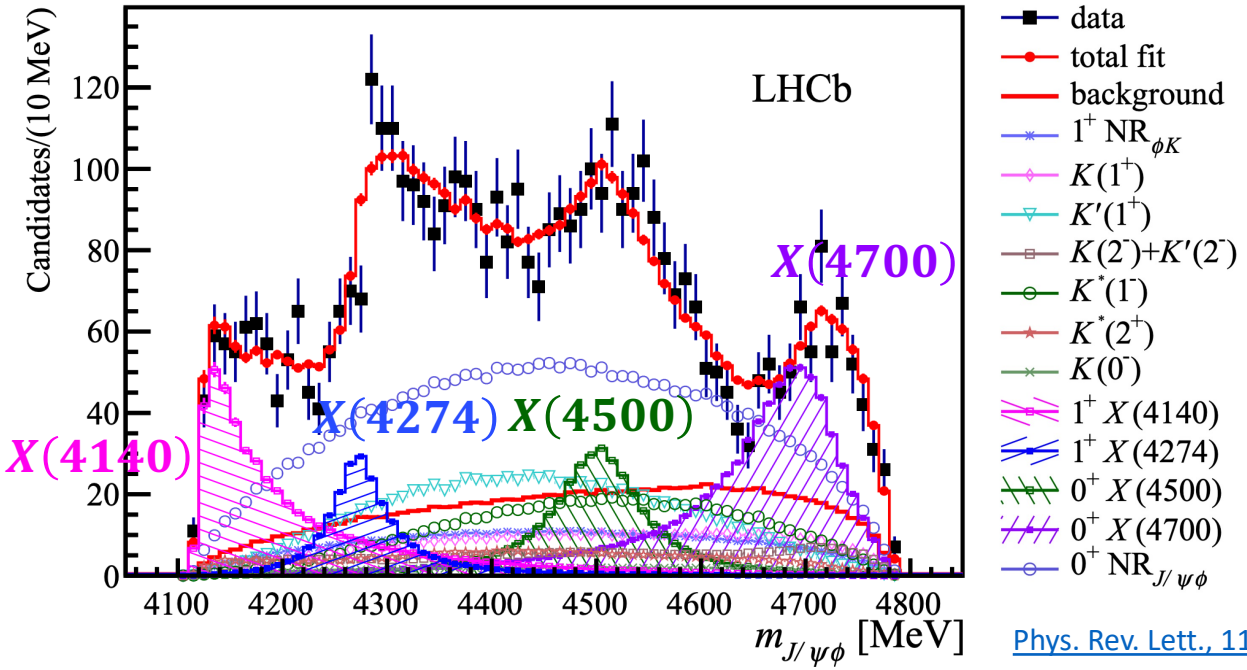




Latest results with LHCb amplitude analyses

- Amplitude fit with multidimensional kinematic information
  - Disentangle overlapping enhancements, determine J^{PC}, account for interference among intermediate states

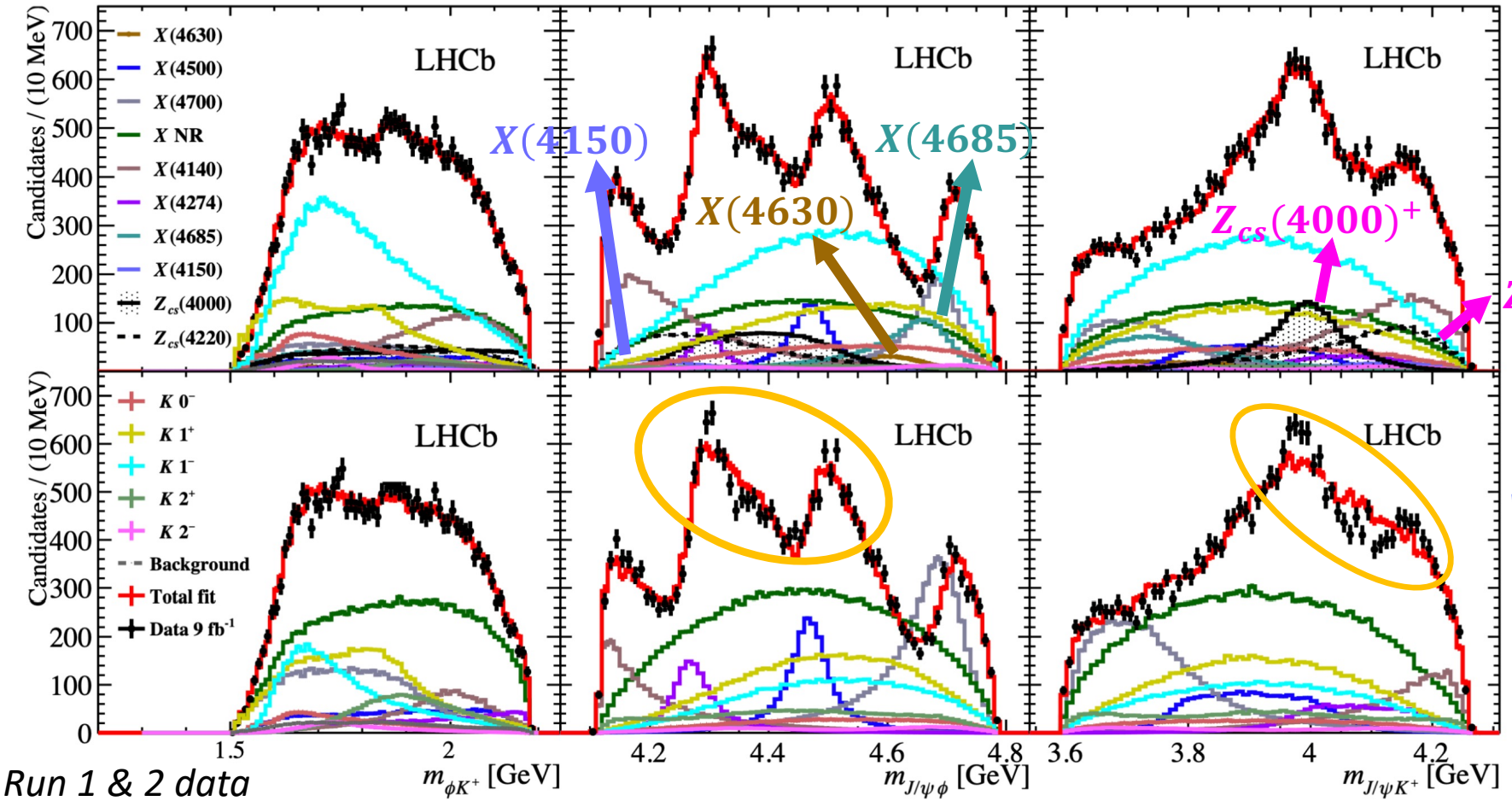
➢ 2016, LHCb, $B^+ \to J/\psi\phi K^+$ with Run 1 data
  - Reestablish $X(4140)$ and $X(4274)$, measured $J^{PC} = 1^{++}$
    - $X(4140)$: $\mathrm{M} = 4146.5 \pm 4.5^{+4.6}_{-2.8}$ MeV; $\Gamma = 83 \pm 21^{+21}_{-14}$ MeV
    - $X(4274)$: $\mathrm{M} = 4273.3 \pm 8.3^{+17.2}_{-3.6}$ MeV; $\Gamma = 56 \pm 11^{+8}_{-11}$ MeV
  - Explore high-mass region with good sensitivity for the first time: $X(4500)$ and $X(4700)$, measured $J^{PC} = 0^{++}$
  - Width of $X(4140)$ much larger than previously determined (vs $\Gamma_{avg} = 17.3^{+6.6}_{-5.3}$ MeV)



Phys. Rev. Lett., 118:022003, 2017

Latest results with LHCb amplitude analyses

- 2021, LHCb, $B^+ \to J/\psi\phi K^+$ with Run 1 and Run 2 data (6x higher statistic vs 2016)
  - Increased statistics required improved fit model
  - New model by adding more component with stat. significance > 5σ
    - $J/\psi\phi$: $X(4150), X(4685), X(4630)$
    - $J/\psi K^+$: $Z_{cs}(4000)^+, Z_{cs}(4220)^+$



with 2021 fit model

with 2016 fit model

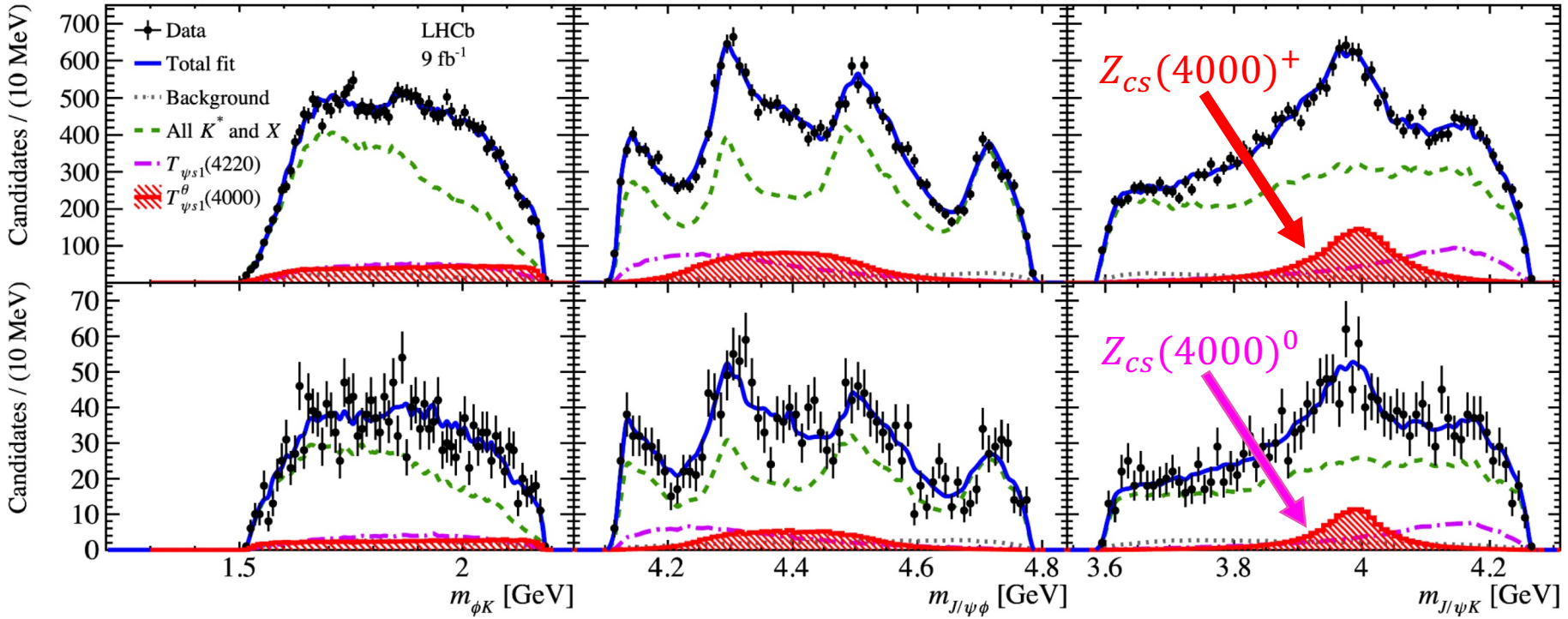
LHCb Run 1 & 2 data

Phys. Rev. Lett., 127:082001, 2021

Latest results with LHCb amplitude analyses

- 2023, LHCb, $B^0 \to J/\psi\phi K_S^0$ with Run 1 and Run 2 data
  - All parameters fixed to 2021 LHCb $B^+ \to J/\psi\phi K^+$ model except for $Z_{cs}(4000)^0$
    - Under assumption of isospin symmetry
  - $J/\psi K_S^0$: $Z_{cs}(4000)^0$ (4σ), possible isospin partner of $Z_{cs}(4000)^+$

Year	Experiment	Luminosity [fb^{-1}]	Process $B \to J/\psi\phi K$	Structure	Mass [MeV]	Width [MeV]	Significance [σ]
2021	LHCb	9	$B^+ \to J/\psi\phi K^+$	$Z_{cs}(4000)^+$	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	15.0
				$Z_{cs}(4220)^+$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	5.9
2023	LHCb	9	$B^0 \to J/\psi\phi K_S^0$	$Z_{cs}(4000)^0$	3991^{+12+9}_{-10-17}	105^{+29+17}_{-25-23}	4.0



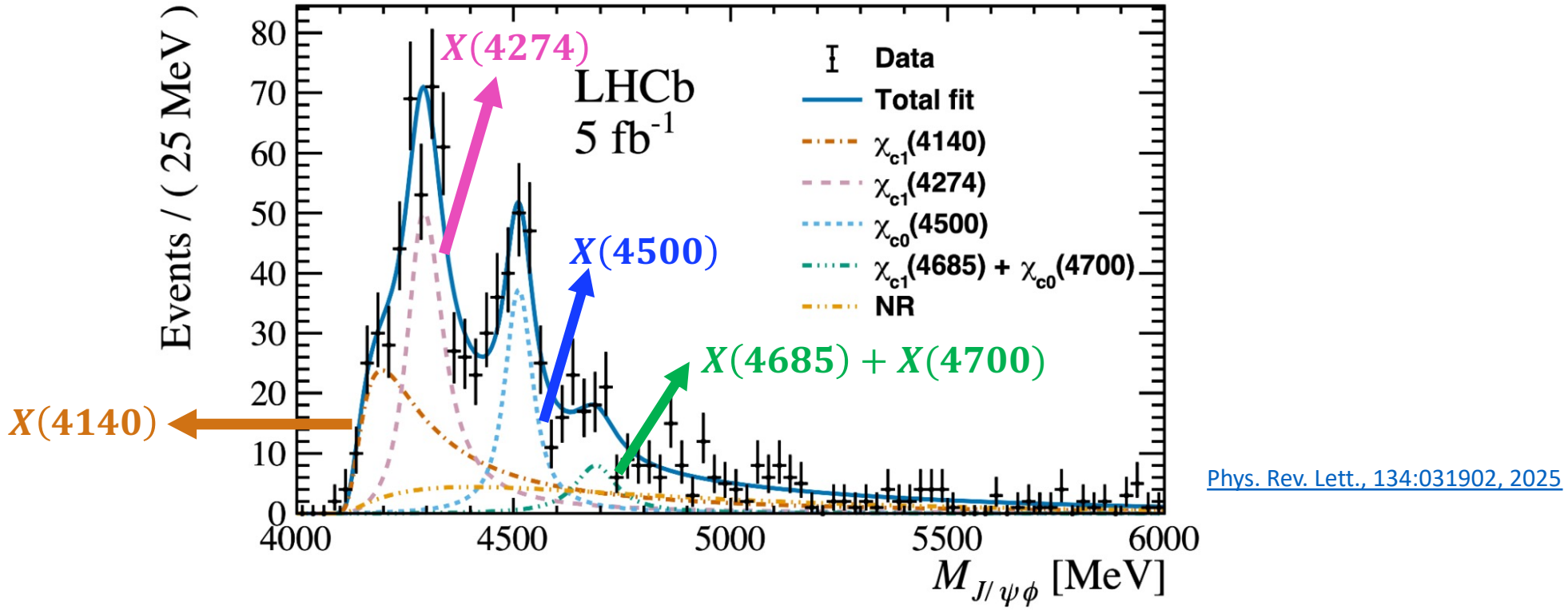
$B^+ \to J/\psi\phi K^+$ *data*

$B^0 \to J/\psi\phi K_S^0$ *data*

Phys. Rev. Lett., 131:131901, 2023

Review of $J/\psi\phi$ structures

- 2024, LHCb, $pp \to J/\psi\phi$ + *anything*
  - First study of $J/\psi\phi$ production in diffractive pp collisions
  - Protons typically remain or dissociate only slightly
  - Low multiplicity, large rapidity gaps devoid of particles
  - Suppressed hadronic activity may enhance the sensitivity to rare produced states
- 5 structures in the fit model: $X(4140)$, $X(4274)$, $X(4500)$, $X(4685)$, and $X(4700)$
- $X(4140)$, $X(4685)$ and (4700) fixed to LHCb 2021 results due to limited statistics
- $X(4274)$ $X(4500)$ consistent with previous results



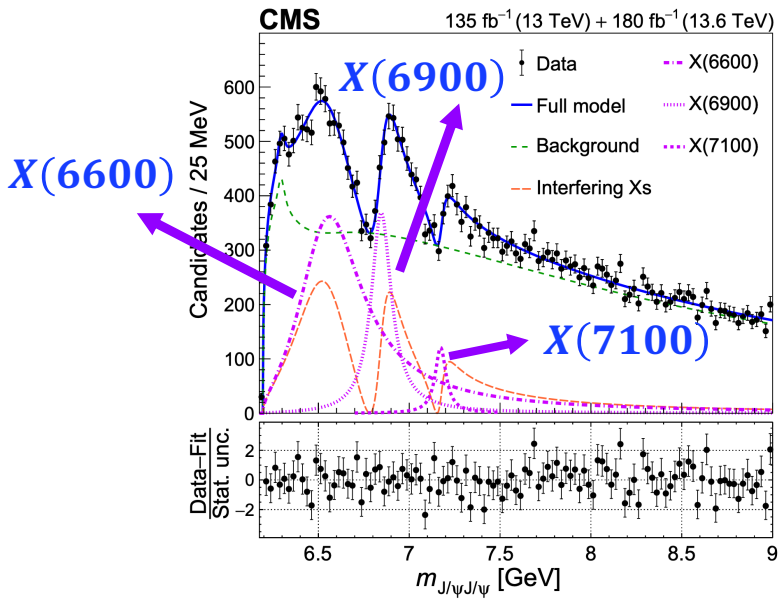
Phys. Rev. Lett., 134:031902, 2025

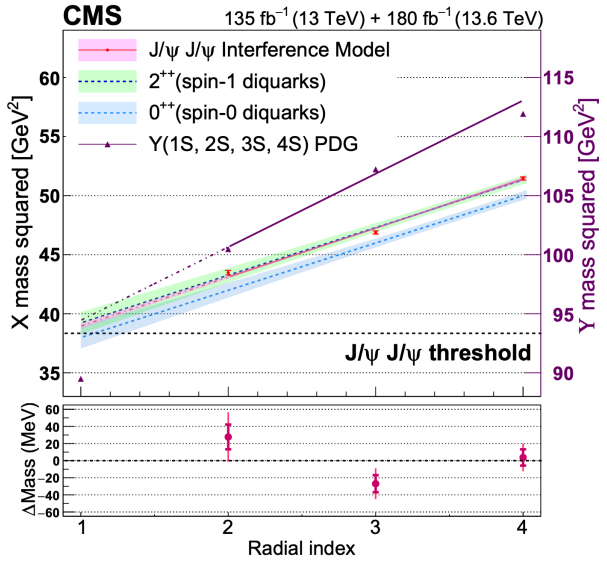
Summary of $J/\psi\phi$ structures

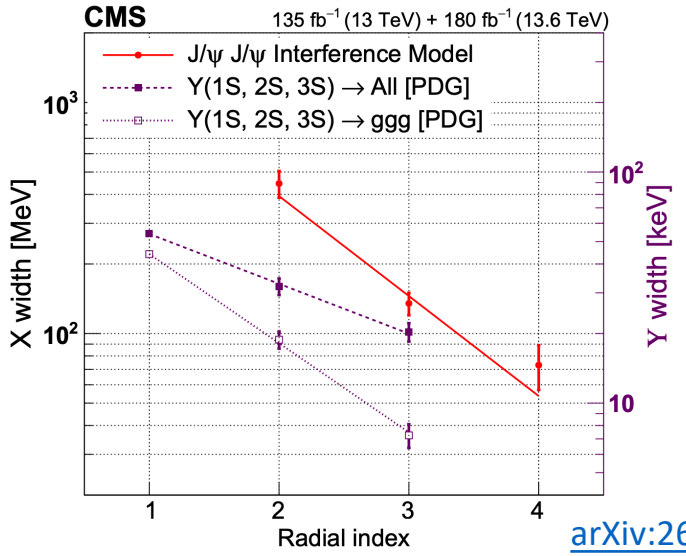
Year	Experiment	Luminosity [fb^{-1}]	Process/Yield $B \to J/\psi\phi K$	Structure	Mass [MeV]	Width [MeV]	J^P	Significance [σ]
2009	CDF	2.7	75 ± 10	$X(4140)$	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$		3.8^*
2010	Belle	825	$\gamma\gamma \to J/\psi\phi$	$X(4350)$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$		3.2
2011	CDF	6.0	115 ± 12	$X(4140)$	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$		$> 5.0^*$
				$X(4274)$	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32.3^{+21.9}_{-15.3} \pm 7.6$		3.1^*
2012	LHCb	0.37	346 ± 20	$X(4140)$	4143.0 (fixed)	15.3 (fixed)		
2013	CMS	5.2	2480 ± 160	$X(4140)$	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$		$> 5.0^*$
2013	DØ	10.4	215 ± 37	$X(4140)$	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$		3.1^*
2014	BaBar	422.5	189 ± 14	$X(4140)$	4143.4 (fixed)	15.3 (fixed)		1.6
2014	BESIII		$e^+e^- \to \gamma J/\psi\phi$	–	–	–		–
2015	DØ	10.4	$p\bar{p} \to J/\psi\phi + \text{anything}$	$X(4140)$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$		4.7
Average				$X(4140)$	4146.8 ± 2.4	$17.3^{+6.6}_{-5.3}$		
2016	LHCb	3	4289 ± 151	$X(4140)$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^+	8.4
				$X(4274)$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^+	6.0^*
				$X(4500)$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^+	6.1^*
				$X(4700)$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^+	5.6^*
2021	LHCb	9	24220 ± 170	$X(4140)$	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	1^+	13
				$X(4150)$	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	2^-	4.8
				$X(4274)$	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	1^+	18
				$X(4500)$	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	0^+	20
				$X(4630)$	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	1^-	5.5
				$X(4685)$	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	1^+	15
				$X(4700)$	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	0^+	17
2024	LHCb	5	$pp \to J/\psi\phi + \text{anything}$	$X(4274)$	$4298 \pm 6 \pm 9$	$92^{+22}_{-18} \pm 57$		4.1
				$X(4500)$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$65^{+20}_{-16} \pm 32$		6.1

- 10 new $J/\psi\phi$ and $J/\psi K$ structures have been claimed in $B \to J/\psi\phi K$ decays by LHCb
- Not confirmed by other experiments apart from $X(4140)$ and $X(4274)$
- Width of $X(4140)$ by LHCb is inconsistent with previous measurements

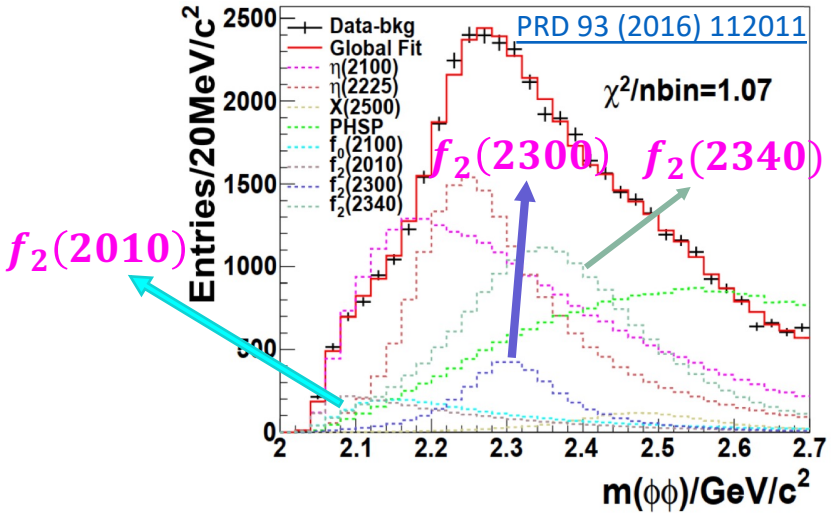
$J/\psi J/\psi$ and $\phi\phi$ systems

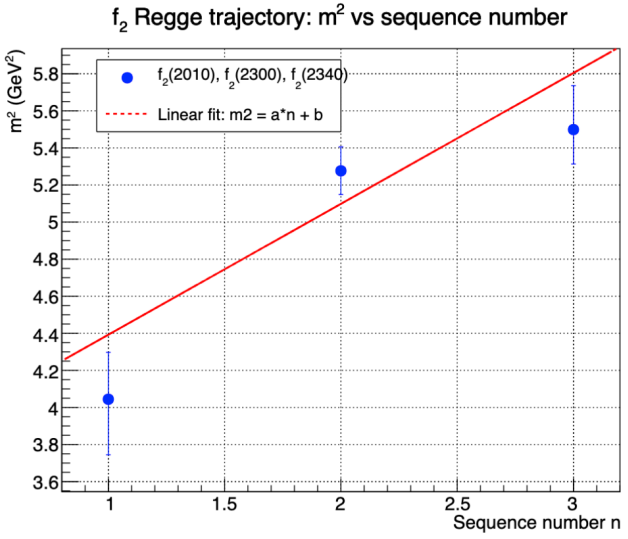


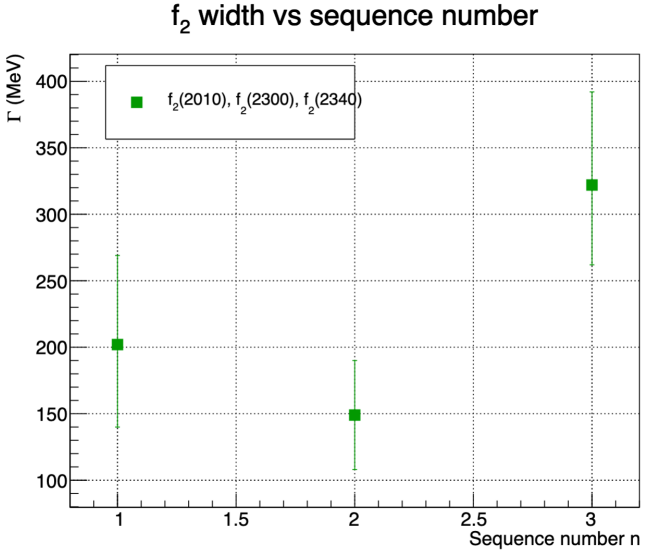




arXiv:2602.02252

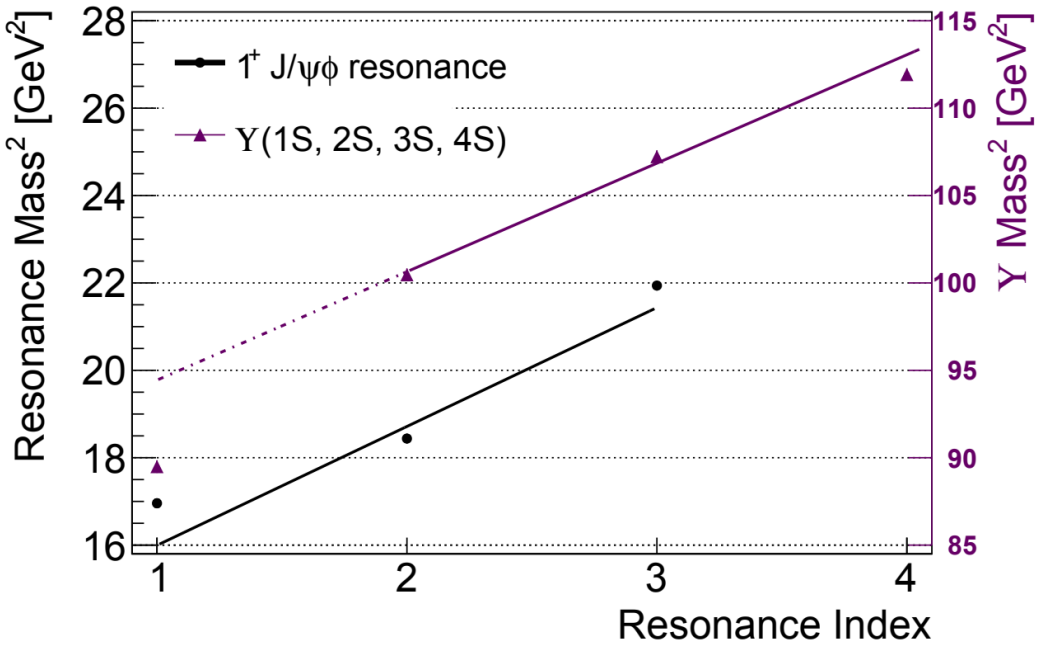


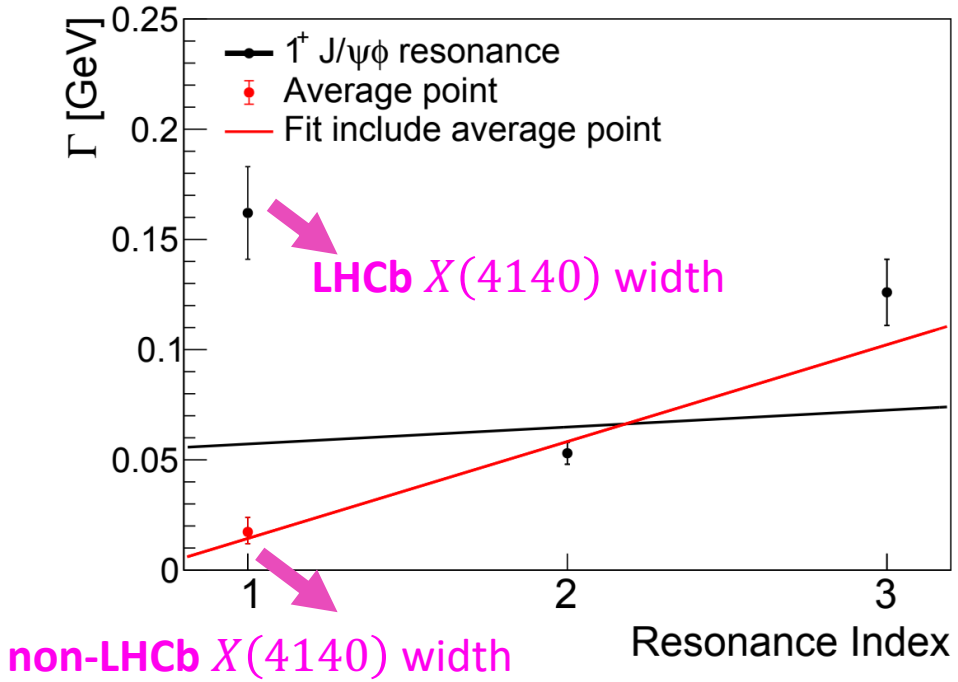




- $J/\psi J/\psi$ system: CMS observed a family of all-charm tetraquark: $X(6600), X(6900), X(7100)$
- $\phi\phi$ systems: partial wave analysis of $J/\psi \to \phi\phi\gamma$ has been performed by BESIII with ~1.3 billion J/ψ events
  - Observe three tensor states $f_2(2010), f_2(2300), f_2(2340)$

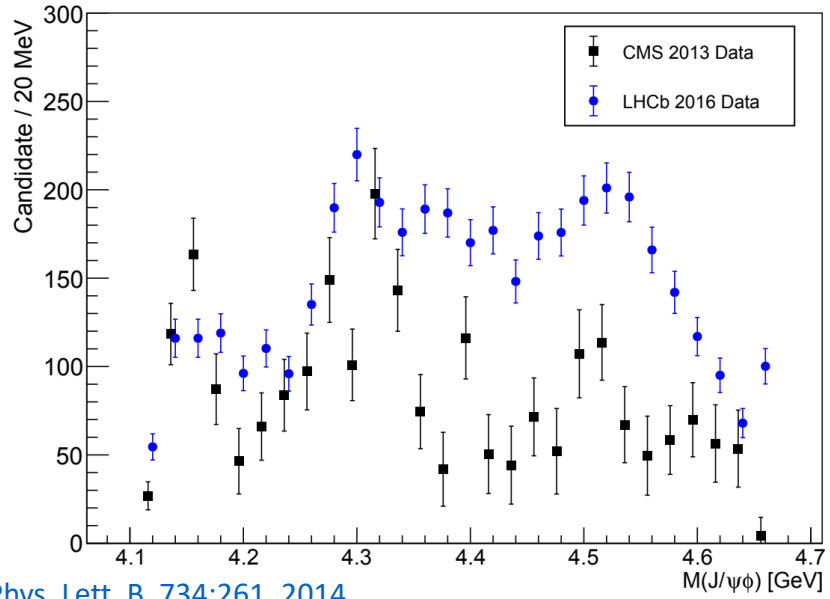
$J/\psi\phi$ system





- Similarities in the $J/\psi\phi$ system
  - Two neutral vector mesons with hidden flavor
  - LHCb studied $B^+ \to J/\psi\phi K^+$
    - Three 1^{++} states decaying to $J/\psi\phi$: $X(4140)$, $X(4274)$, and $X(4685)$
    - The squared masses of these 1^{++} $J/\psi\phi$ resonances algin with Regge-like trajectory
    - Different width trends: non-LHCb $X(4140)$ width vs LHCb $X(4140)$ width

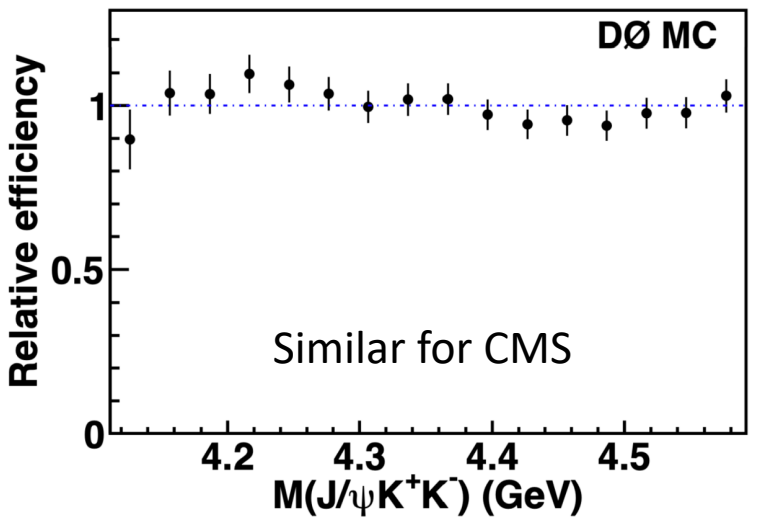
Comparison of $J/\psi\phi$ between CMS and LHCb



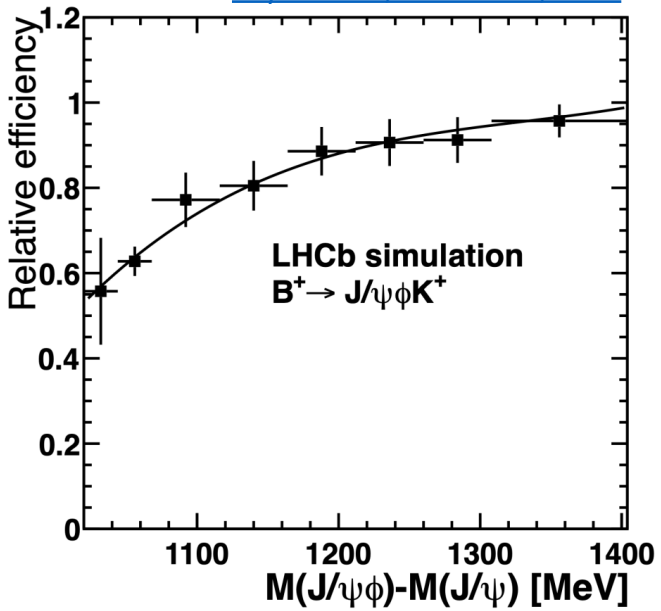
Phys. Lett. B, 734:261, 2014

Phys. Rev. Lett., 118:022003, 2017

Phys. Rev. D, 89:012004, 2014



Phys. Rev. D, 85:091103, 2012

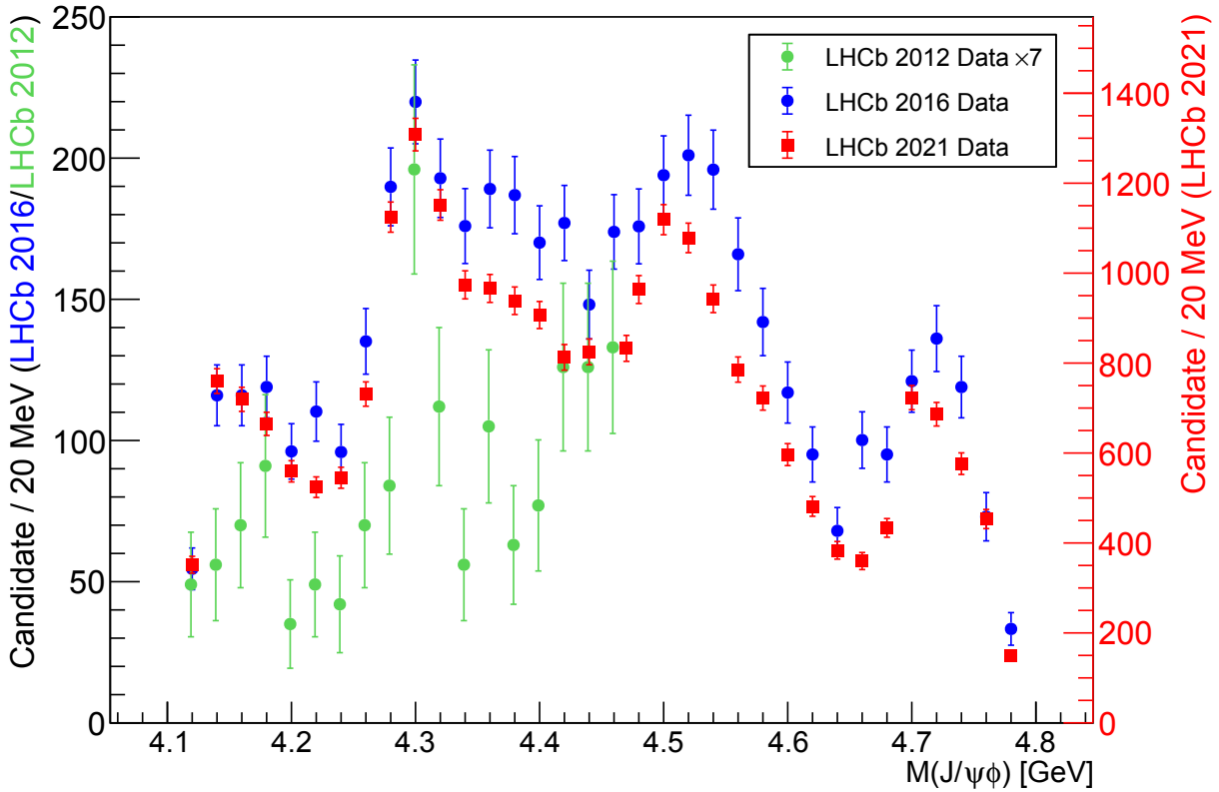


- Limited statistic in other experiments except for CMS and LHCb
- CMS vs LHCb: comparable statistic in low-mass region, lager difference above 4.3 GeV

➢ **Possible reasons for shape inconsistency:**

- Lager background in CMS data
- Different efficiencies:
  - CMS eff. ~20% higher in low-mass threshold than in the high-mass region
  - LHCb eff. > 40% lower near the threshold compared with high-mass region
    - *Higher sensitivity in high-mass region: two additional resonances claimed*
    - *Lower sensitivity in low-mass region: failed to confirm $X(4140)$ and $X(4274)$ with 2012 data*

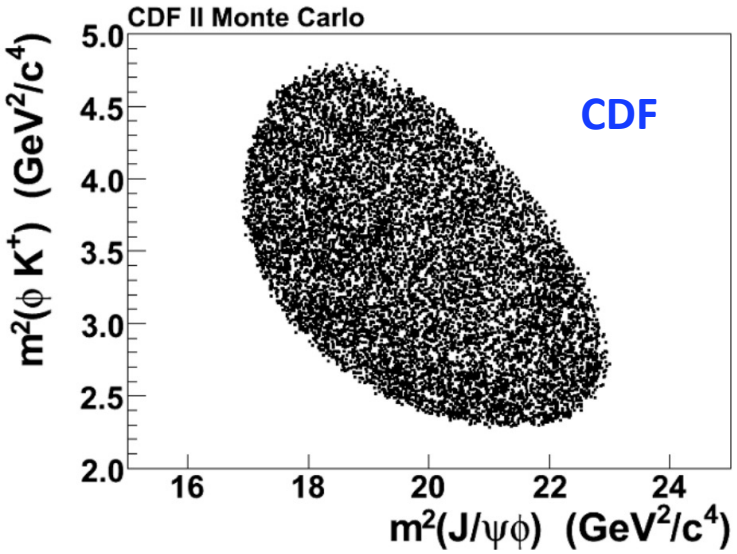
Comparison of LHCb $J/\psi\phi$ from different years

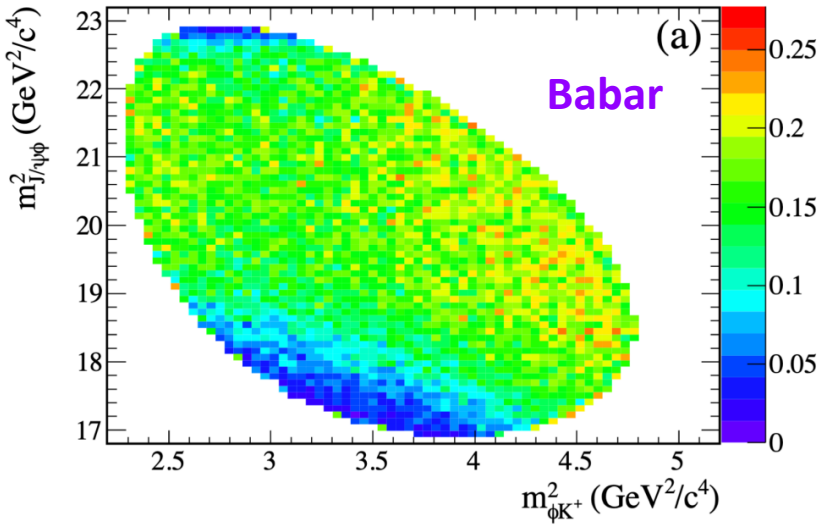


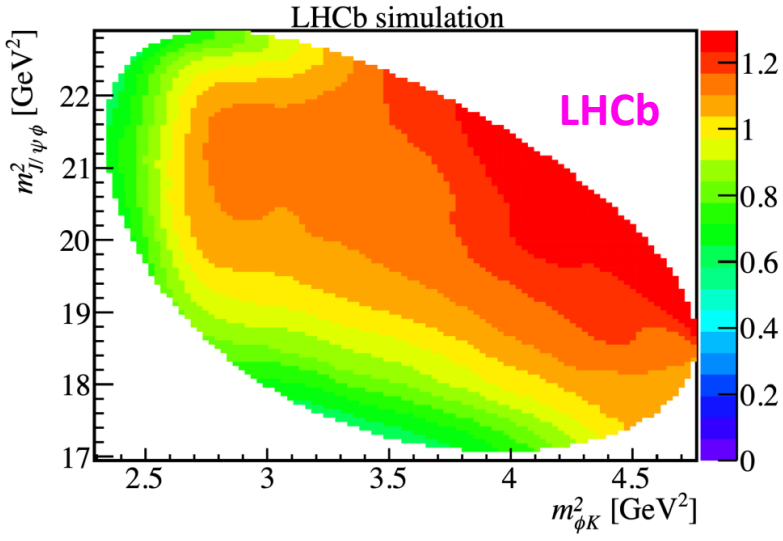
Phys. Rev. D, 85:091103, 2012
Phys. Rev. Lett., 118:022003, 2017
Phys. Rev. Lett., 127:082001, 2021

- Comparison of LHCb $J/\psi\phi$ mass spectrum from 2012, 2016, and 2021
- 2012 data statistically limited, exhibit excess features around 4140 and 4274 MeV after scaling up
- Some inconsistencies across mass spectrum between 2016 and 2021 LHCb data
  - Not expected since there is no apparent change for LHCb tracker
- Possible reasons:
  - Efficiency variations due to different triggers and event selection
  - Statistical fluctuations amplified by the rich resonances

Detector efficiency







- Efficiency maps from different experiments
  - CDF: relatively flat, expected similar for CMS due to comparable detector design
  - BaBar: mostly flat, but drops by ~25% near the low/edge regions of $m^2(J/\psi\phi)$
  - LHCb: large efficiency variation

- Detector configurations help explain these behaviors
  - BaBar/Belle(e^+e^-) reconstruct nearly at-rest B mesons in the transverse plane
    - Near threshold ϕ-decay kaons have little p_T, reduce acceptance at Dalitz edges
  - CDF, D0, CMS: central detector at hadron collider
    - B mesons are highly boosted with near-4π coverage, yielding flatter efficiencies
  - LHCb: forward detector
  - Yield strong longitudinal but modest transverse boosts, producing more pronounced Dalitz variations.

$X(4140)$ measurements

- **Revisit $X(4140)$ measurements**

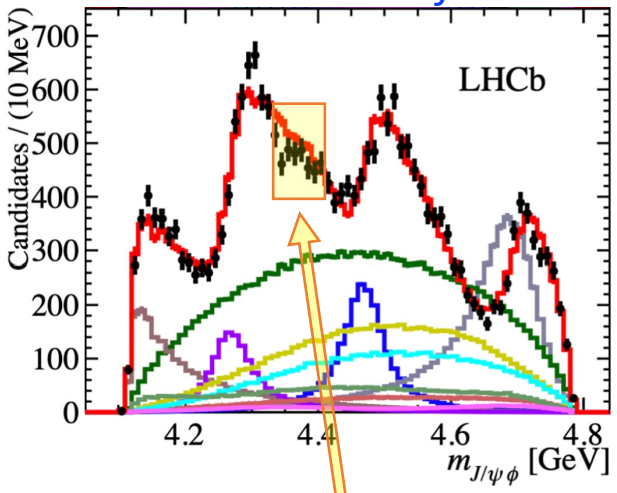
Detector	$M[(X(4140)]$ [MeV]	$\Gamma[X(4140)]$ [MeV]
CDF	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$
CMS	$4148.0 \pm 2.4 \pm 6.3$	$28.0^{+15}_{-11} \pm 19$
DØ 2013	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$
DØ 2015	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$
LHCb 2016 (Run 1 data)	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$
LHCb 2021 (Run 1 and Run 2 data)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$
Average excluding LHCb	4146.6 ± 2.4	$17.3^{+6.6}_{-5.3}$

  - LHCb reports mass consistent with non-LHCb average within 1σ
  - Width differs by more than 2σ

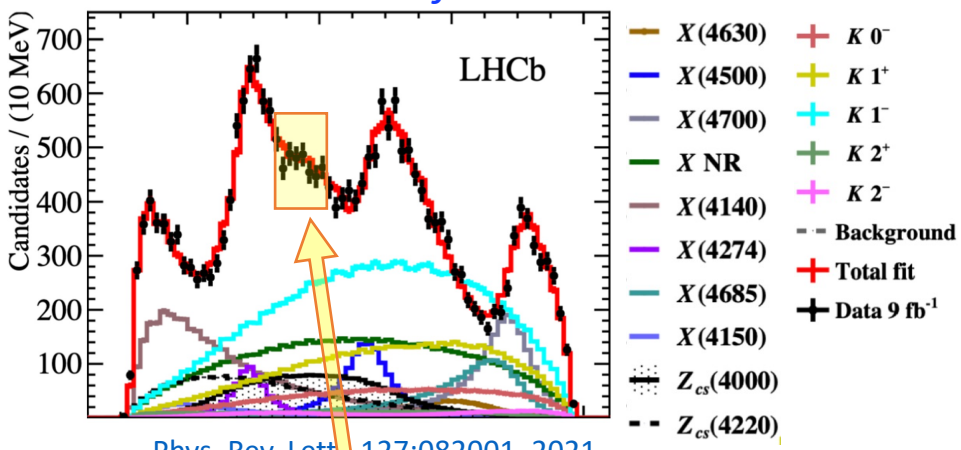
- Imperfect efficiency corrections can bias the extracted resonance parameters
- Complementary measurements with flatter Dalitz-plane efficiency will be essential for cross-checks
  - From ATLAS, Belle II, and CMS …

Potential state around 4.35 GeV

LHCb 2016 fit model

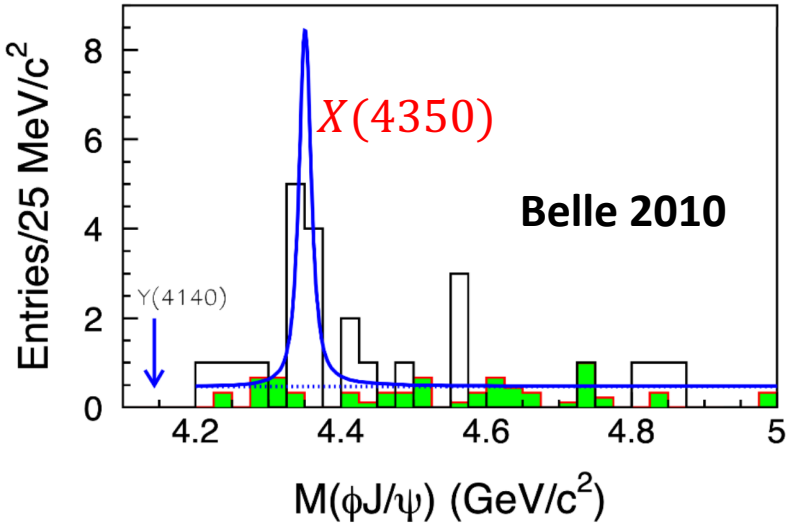


LHCb 2021 fit model



Phys. Rev. Lett., 127:082001, 2021

Phys. Rev. Lett., 104:112004, 2010



- Notable shoulder between 4.32 and 4.39 GeV in the $J/\psi\phi$ mass spectrum
- In updated model, shoulder is described by tails from $X(4274), X(4500)$, other ϕK and $J/\psi K$ resonances
  - Cost of invoking a larger set of states, many of which remain to be confirmed
- **Remind**: 2010, Belle, $\gamma\gamma \to J/\psi\phi$, Evidence of $X(4350)$, 3.2σ, $M = 4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV; $\Gamma = 13.9^{+18}_{-9} \pm 4$ MeV
  - Spin is 0 or 2 according to Landau-Yang theorem
- Several tetraquarks have been predicted around 4.3 GeV Phys. Rev. D, 94:094031, 2016
- Explore alternative descriptions for the shoulder:
  - Potential resonance around 4.35 GeV
    - High spin: production suppression from spin-0 B meson
    - Hybrid: suppressed in B decay

Potential state around 4.35 GeV

- Perform amplitude fit with $X(4350)$ to toy sample (generated based on LHCb 2021 model) Chin. Phys. Lett. 2025 42(12): 120202
  - Scan masses and widths under different J^P for $X(4350)$ and evaluate its significance

- Results

Full-set model

J^P	$M=4320$ $\Gamma=15$	$M=4340$ $\Gamma=15$	$M=4360$ $\Gamma=15$	$M=4320$ $\Gamma=50$	$M=4340$ $\Gamma=50$	$M=4360$ $\Gamma=50$	$M=4320$ $\Gamma=100$	$M=4340$ $\Gamma=100$	$M=4360$ $\Gamma=100$
0^+	2.0	1.4	0.5	2.3	1.9	1.4	2.3	2.1	1.9
0^-	1.5	1.4	1.2	1.4	1.5	1.2	1.2	1.1	1.0
2^+	2.7	3.0	2.2	3.4	3.3	3.0	3.7	3.6	3.4
2^-	1.7	2.3	1.7	2.6	2.3	2.8	3.7	3.4	3.5
1^+	2.4	1.5	2.2	2.0	1.9	2.1	1.7	1.6	1.8
1^-	2.3	2.8	1.8	2.8	2.9	2.7	3.0	3.0	3.1

Reduced-set model

J^P	$M=4320$ $\Gamma=15$	$M=4340$ $\Gamma=15$	$M=4360$ $\Gamma=15$	$M=4320$ $\Gamma=50$	$M=4340$ $\Gamma=50$	$M=4360$ $\Gamma=50$	$M=4320$ $\Gamma=100$	$M=4340$ $\Gamma=100$	$M=4360$ $\Gamma=100$
0^+	3.5	2.6	1.3	3.5	3.3	2.6	3.4	3.3	3.1
0^-	2.0	3.3	3.4	4.8	5.3	5.5	6.2	6.4	6.5
2^+	3.5	3.2	2.8	4.7	4.4	4.3	5.8	5.5	5.4
2^-	4.9	3.5	3.9	8.6	7.3	6.9	11.9	10.8	10.1
1^+	3.7	2.7	4.3	5.7	5.5	6.0	7.1	7.3	7.7
1^-	3.8	5.2	5.3	6.2	7.3	8.0	7.8	8.8	9.6

- Spin-2 hypotheses generally yield higher significances than spin-0
  - *Possibility of potential high-spin $J/\psi\phi$ structure near 4.35 GeV*
- Independent information from other experiments could help to clarify with larger statistics

Summary and prospects

- Review of studies of $J/\psi\phi$ system Chin. Phys. Lett. 2025 42(12): 120202
  - 10 new $J/\psi\phi$ and $J/\psi K$ structures reported by LHCb
  - Squared mass of 1^{++} triplet in the $J/\psi\phi$ system align with Regge trajectory
  - Width of $X(4140)$ by LHCb shows inconsistency with earlier results

- Substantial variation in the efficiency across experiments
- Nonuniform efficiency with imperfect correction can bias measured resonance parameters

- Investigate potential resonance around 4.35 GeV in the $J/\psi\phi$ mass spectrum
  - Other experiments with larger statistics to improve sensitivity

- Near-threshold enhancements in vector-vector systems: $J/\psi\phi, J/\psi J/\psi, \phi\phi, J/\psi\omega, \omega\phi$
  - How about vector-vector structures composed entirely of c and b quarks: $J/\psi\Upsilon$ and $\Upsilon\Upsilon$?

THANKS!

BACKUP

Potential state around 4.35 GeV

➢ Explore potential resonance around 4.35 GeV in the $J/\psi\phi$ mass spectrum

- Generate toy sample based on LHCb 2021 model
  - Reproduce mass and angular distributions for LHCb Run 1 and Run 2 data
- Perform multidimensional amplitude fit on this sample

- Fit setup:
  - Full-set model: Follow LHCb 2021 parameterization, with additional structure near 4.35 GeV [$X(4350)$]
  - Reduced-set model: only includes $X(3450), X(4140), X(4274)$, and two other most significance states $X(4500)$ and $X(4700)$ for $J/\psi\phi$ components (since many not confirmed)

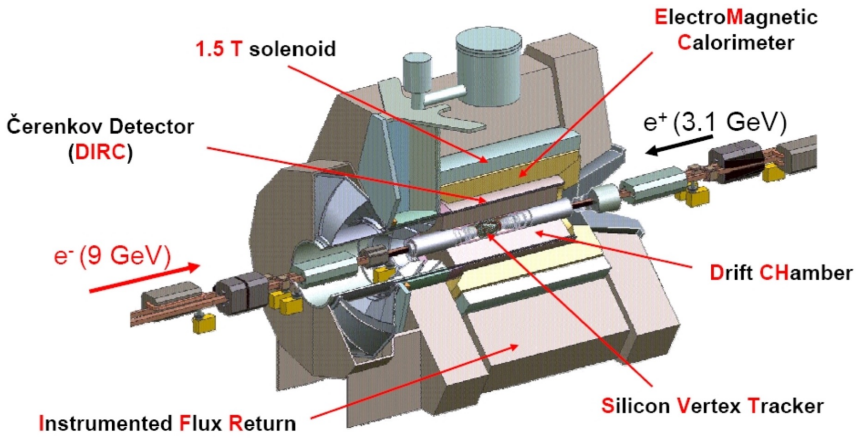
  - Fix parameters related to $J/\psi K$ and ϕK and M and Γ of $J/\psi\phi$ states to LHCb results
    - Reduce computation complexity and potential instability
  - Float amplitudes of $J/\psi\phi$ states

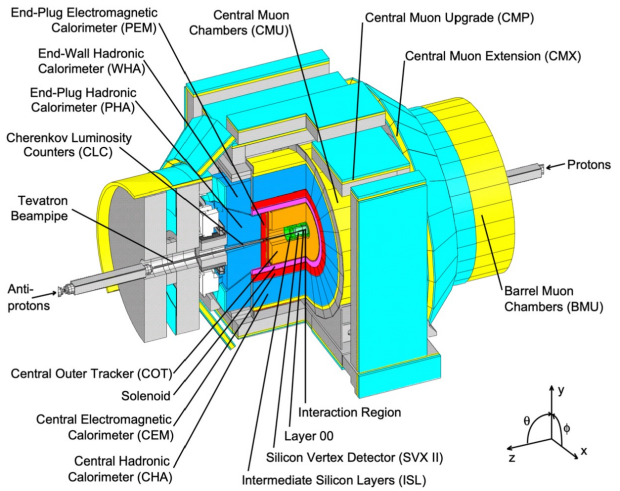
  - Scanned several fixed masses and widths under different J^P for X(4350)
    - Not fixed to Belle measurement due to its limited statistics

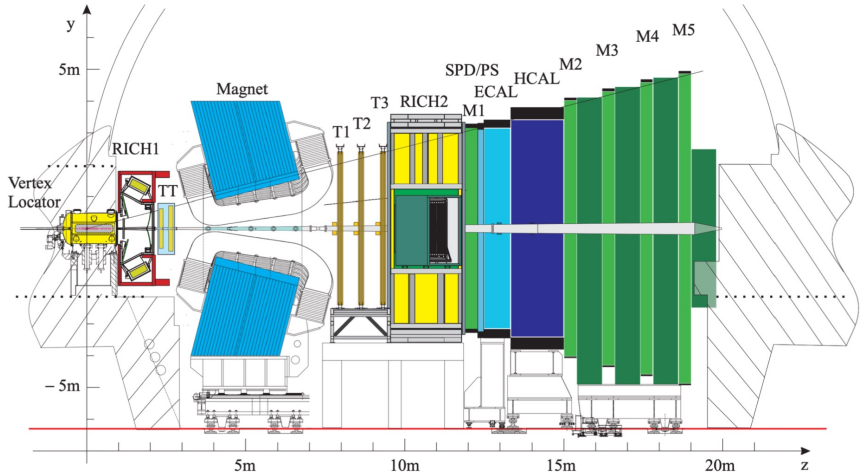
- Significance of $X(4350)$ is calculated from log-likelihood difference between fits with and without $X(4350)$

Detectors

Accelerator	Detectors		Type	$\sqrt{s}$ [GeV]	Running years	Laboratory
Tevatron	CDF	DØ	$p\bar{p}$	1800 (Run 1) 1960 (Run 2)	$1992-1996$ $2001-2011$	Fermilab
KEKB	Belle		e^+e^-	$10.58\ (3.5/8.0)$	$1998-2010$	KEK
Super-KEKB	Belle II		e^+e^-	$10.58\ (4.0/7.0)$	$2018-\cdots$	KEK
PEP-II	BaBar		e^+e^-	$10.58\ (3.1/9.0)$	$1999-2008$	SLAC
BEPCII	BESIII		e^+e^-	$2.0-4.95$	$2008-\cdots$	IHEP
LHC	CMS	LHCb	pp	>7000 (Run 1) 13000 (Run 2) 13600 (Run 3)	$2009-2013$ $2015-2018$ $2022-\cdots$	CERN



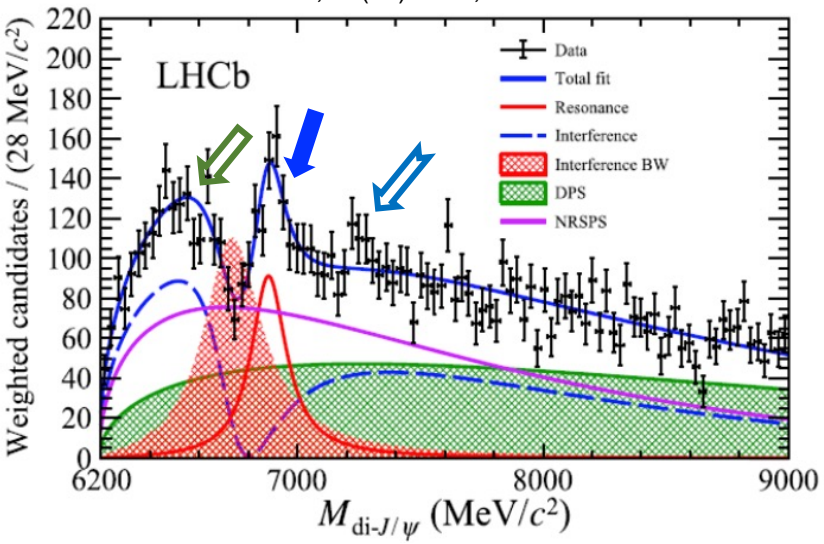




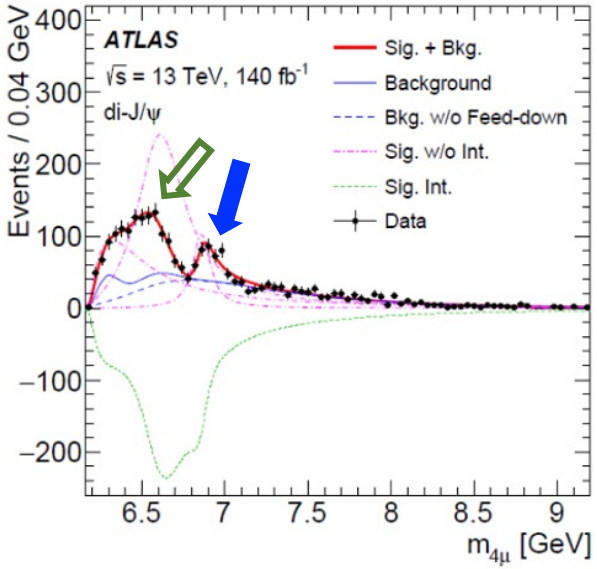
Status of $J/\psi J/\psi$ system

❖ **All-charm Tetraquark on LHC in J/ψJ/ψ channel**

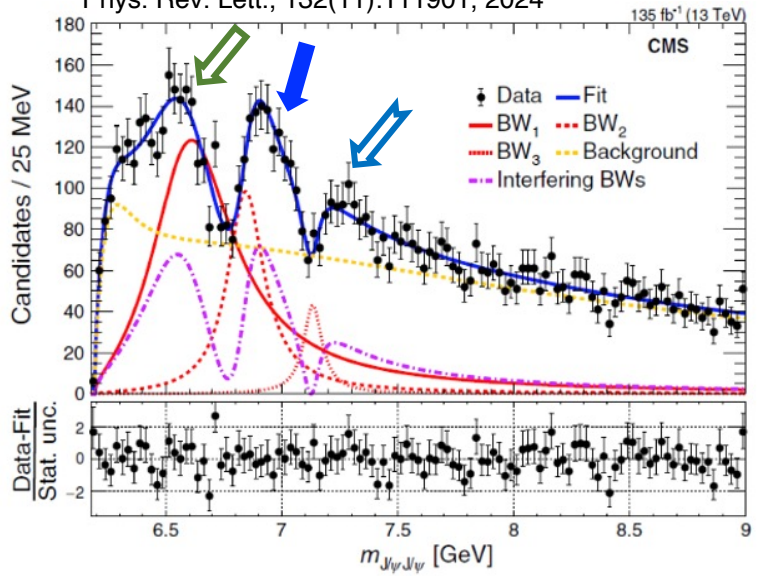
Sci. Bull., 65(23):1983, 2020



Phys. Rev. Lett., 131(15):151902, 2023

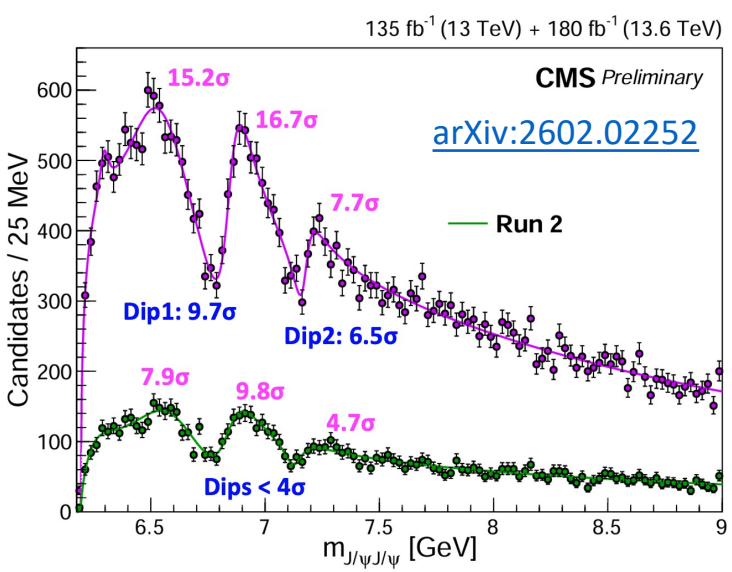


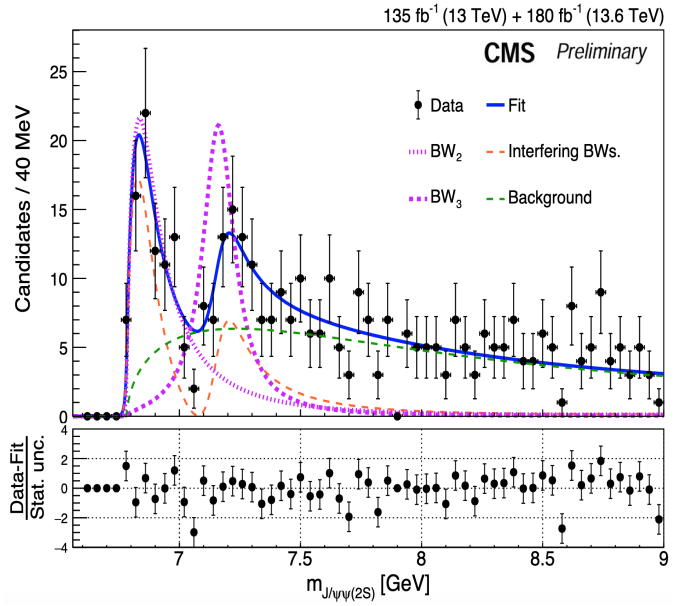
Phys. Rev. Lett., 132(11):111901, 2024



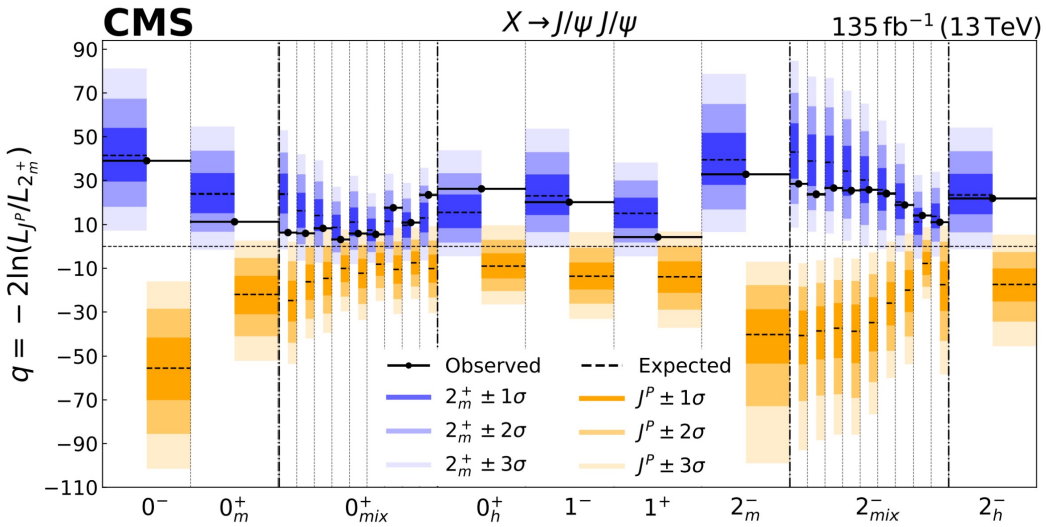
- ❑ **ALL exp observe X(6900) + additional structure** ➢ **Only CMS claimed X(6600) & X(7100)**
  - **Hump @ 6.6 GeV**: Different modeling
  - **Hint @ 7.2 GeV**: LHCb not consider; ATLAS 3σ hint in $J/\psi\psi(2S)$
- ❑ **All exp use interference, but in diff ways**
- ❑ **All exp see a threshold excess. Classified as background**

Status of $J/\psi J/\psi$ system





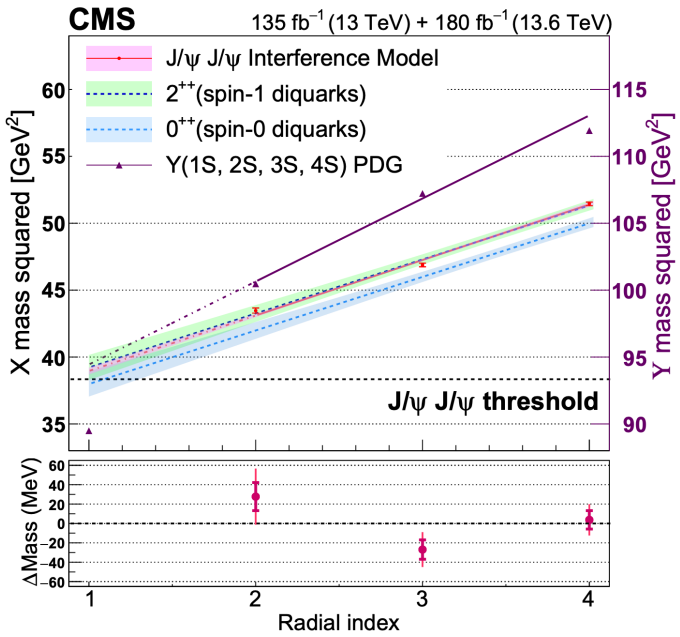
Nature 648 58 (2025)

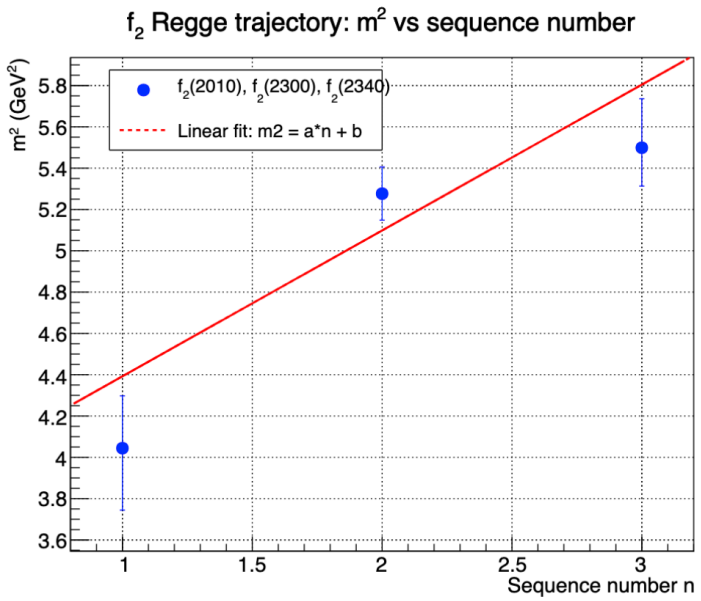


- With 3.6X data, CMS confirm Run 2 results with Run3 data only
- $X(6600)$, $X(6900)$, and $X(7100)$ with significances >> 5σ
- Strong interference among $X(6600)$, $X(6900)$, and $X(7100)$ are observed
  - Imply same J^{PC} quantum numbers
  - First observation of $X(6900)$ and evidence of $X(7100)$ in the $J/\psi\psi(2S)$ channel
- Spin-party measurement of these states at CMS favor $J^{PC} = 2^{++}$
- A family of all-charm tetraquark:
  - > 200 MeV mass splittings among triplet similar to Υ family => Radial excitations
  - Squared masses algin with Regge-like trajectory
  - Width trend similar to Υ family

Similarities between $J/\psi J/\psi$ and $\phi\phi$ systems

arXiv:2602.02252





Component	M [MeV]	Γ [MeV]	J^P
$X(6600)$	$6593^{+15}_{-14} \pm 25$	$446^{+66}_{-54} \pm 87$	2^+
$X(6900)$	$6847 \pm 10 \pm 15$	$135^{+16}_{-14} \pm 14$	2^+
$X(7100)$	$7173^{+9}_{-10} \pm 13$	$73^{+18}_{-15} \pm 10$	2^+

PDG 2025

Component	M [MeV]	Γ [MeV]	J^P
$f_2(2010)$	2011 + 62 - 76	202 + 67 - 62	2^+
$f_2(2300)$	2297 ± 28	149 ± 41	2^+
$f_2(2340)$	2339 + 50 - 40	322 + 70 - 60	2^+

- Similarities between $J/\psi J/\psi$ and $\varphi\varphi$ systems:
  - Three $J^{PC} = 2^{++}$ structures
  - Masses align with Regge-like trajectory
  - Large widths (hundreds of MeV)
  - System with same flavor, restriction in wave function
  - $J/\psi J/\psi$ triplet ($J^{PC} = 2^{++}$):
    consistent with diquark-antidiquark model with spin-1 diquarks and $L = 0$