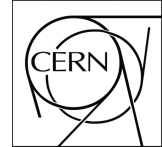




第八届全国重味物理与量子色动力学研讨会



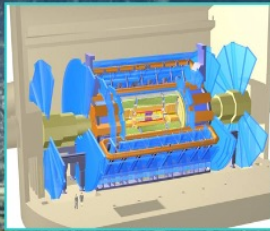
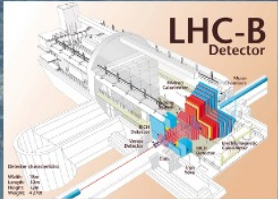
CMS实验上的B物理研究进展

清华大学

Tsinghua University

胡震





ATLAS

LHCb

CERN Meyrin

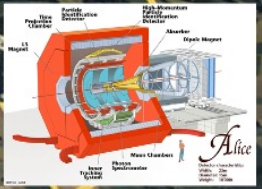
CERN Prévessin

SPS 7 km

ALICE



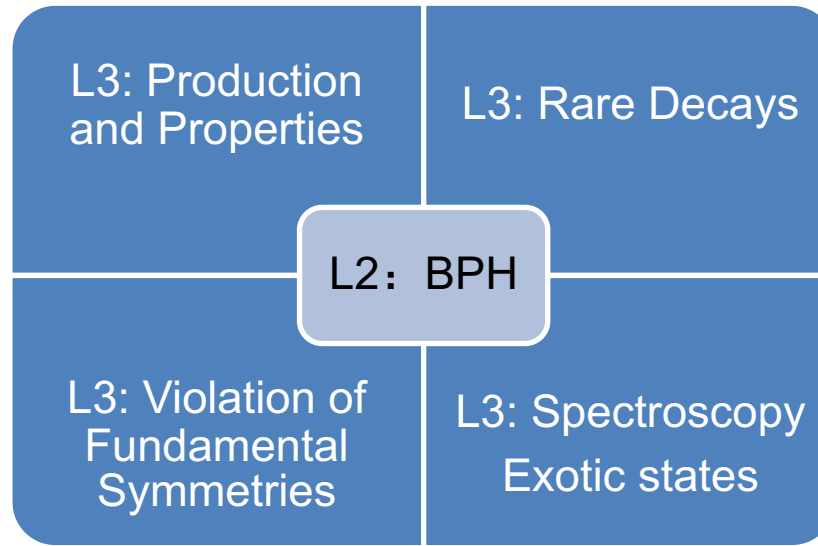
The **Large Hadron Collider (LHC)** at CERN is the world's largest particle collider. It lies in a tunnel 27 kilometres in circumference and as deep as 175 metres beneath the France–Switzerland border near Geneva.



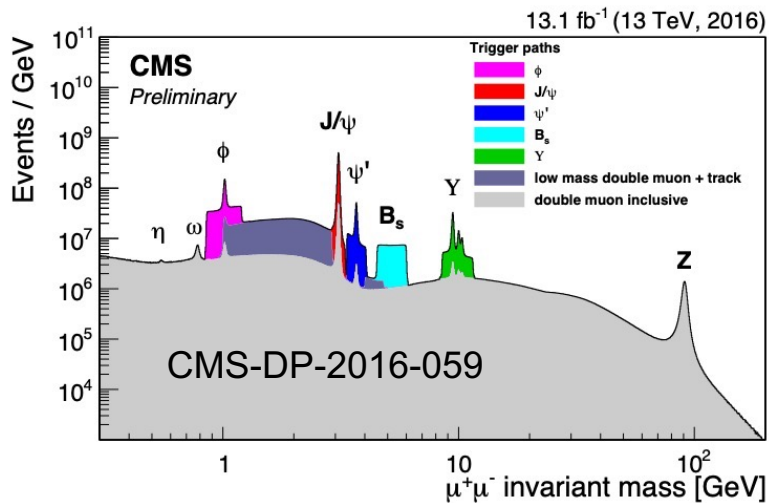
LHC 27 km



87 publications: <https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html>



- L2 Convener short list: 易凯 (南师)
- L3 Convener: 胡震 (清华), 王张奇尔 (浙大), 王晰宁 (清华)
 - BPH conference contact: 王徽 (南师)
 - BPH MC contact: 周漪林 (复旦), 弗拉基米尔 (清华)
 - BPH trigger contact: 赵一扬 (清华)

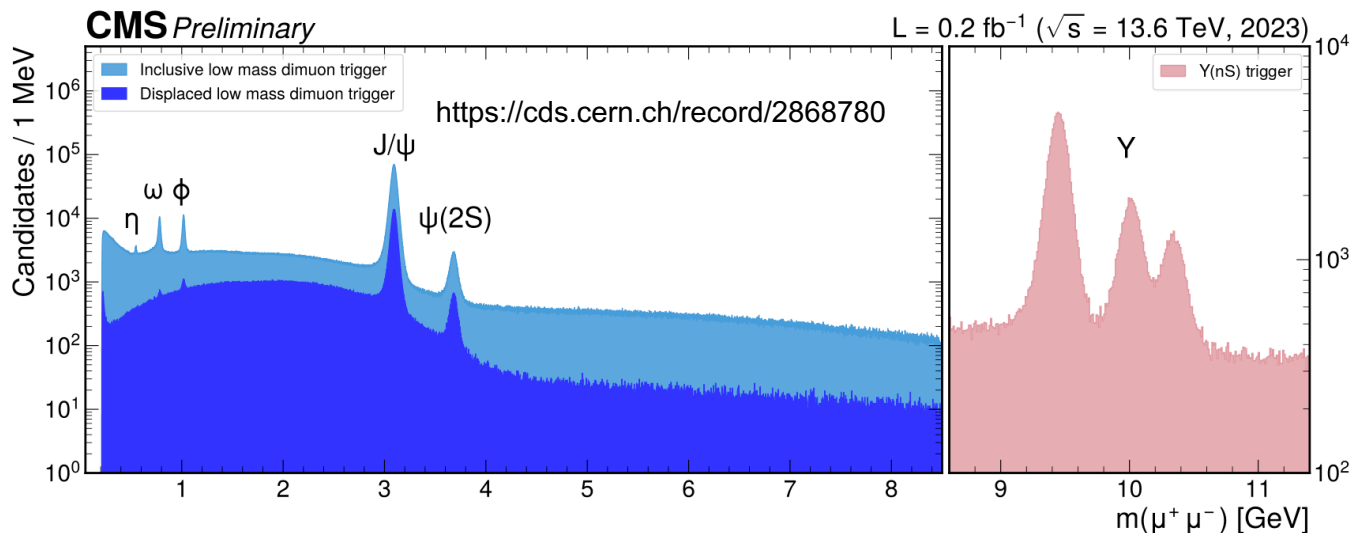


Excellent detector for studies with muons

- 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



Majority of analyses rely on dimuon triggers

- Special triggers for different analyses
 - μp_T , $(\mu\mu) p_T$, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ



Significant acceptance improvement in Run-3!




- Production & properties

-  – $Y(nS)$ cross section measurements at 13.6 TeV (submitted to JHEP)
-  – Full angular analysis of $B^0 \rightarrow K^{*0}\mu\mu$ (PLB)
- Differential \mathcal{B} measurement and angular analysis of $B_s^0 \rightarrow \phi\mu\mu$

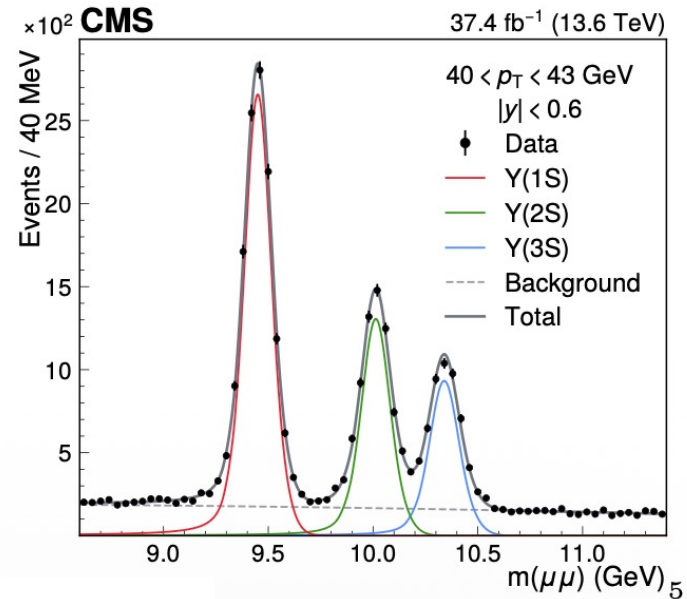
- Search for new rare decays

- Observation of $\eta \rightarrow \mu^+\mu^-e^+e^-$
- Search for $B_s^0 (B^0) \rightarrow 4\mu$
- Search for $\tau \rightarrow 3\mu$

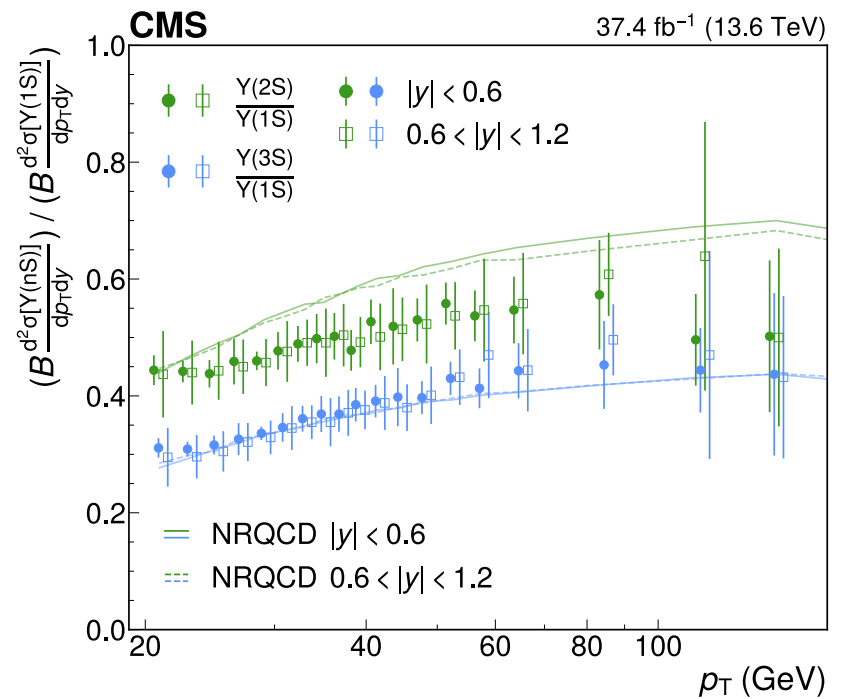
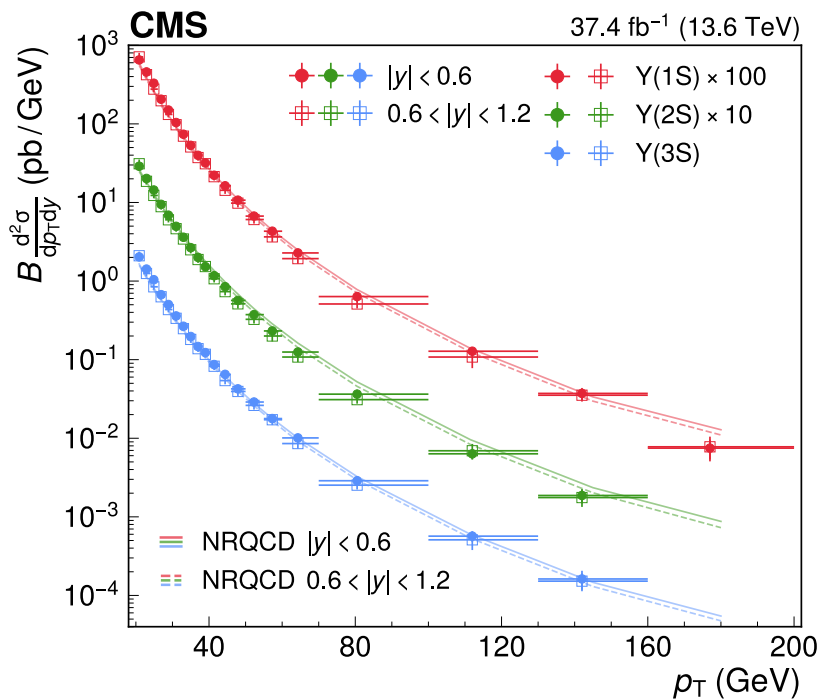
- Spectroscopy

-  – Observation of $X(6600)$ and $X(7100)$ in $J/\psi J/\psi \rightarrow 4\mu$
-  – Observation of $X(6900) \rightarrow J/\psi \psi(2S) \rightarrow 4\mu$ (submitted to Sci. Adv.)
-  – J^{PC} measurement of the tetraquark family $X(6600), X(6900), X(7100)$ (Nature)

- Measurement of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production cross sections at $\sqrt{s} = 13.6$ TeV
- Important input to global fits to derive inclusive quarkonium production
- Analysis done with 2022 data (37.4 fb^{-1})
 - ▶ $\Upsilon(nS) \rightarrow \mu^+ \mu^- \Rightarrow$ dimuon triggers
- The cross sections are measured differentially in p_T , in the range 20–200 GeV
 - ▶ First time this measurement is extended to 200 GeV
 - ▶ Two rapidity categories are considered: $|y| < 0.6$ and $0.6 < |y| < 1.2$
- Cross sections measured using
 - ▶ Signal yields extracted from a fit to the dimuon invariant mass spectrum
 - ▶ Efficiencies measured in data ($\Upsilon(nS)$ assumed to be produced unpolarised)
- Feed-down contributions from heavier $b\bar{b}$ states are included



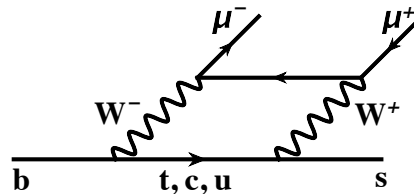
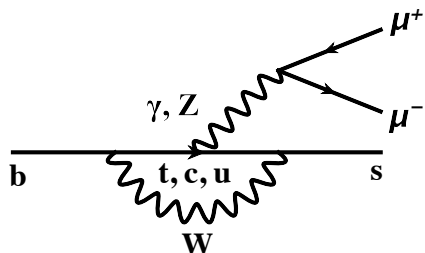
- Reasonably good agreement with non-relativistic QCD (NRQCD) predictions
- CMS文章引用了中国理论家的计算:
Y. Feng, B. Gong, C.-H. Chang, and J.-X. Wang [Chin. Phys. C 45 \(2021\) 013117](https://doi.org/10.1088/1674-7580/45/01/013117)



Experimental Review of the Quarkonium Physics at the LHC

Symmetry **2025**, 17(9), 1521 <https://doi.org/10.3390/sym17091521>

Golden indirect probes of NP



$$\frac{1}{d\Gamma/dq^2 dq^2 d\cos\theta_l d\cos\theta_K d\phi} \frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right.$$

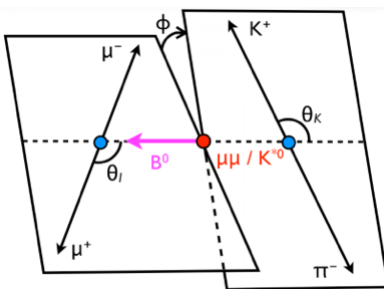
$$+ \left(\frac{1}{4}(1 - F_L) \sin^2 \theta_K - F_L \cos^2 \theta_K \right) \cos 2\theta_l$$

$$+ \frac{1}{2} P_1 (1 - F_L) \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi$$

$$+ \sqrt{(1 - F_L) F_L} \left(\frac{1}{2} P_4' \sin 2\theta_K \sin 2\theta_l \cos \phi + P_5' \sin 2\theta_K \sin \theta_l \cos \phi \right)$$

$$- \sqrt{(1 - F_L) F_L} \left(P_6' \sin 2\theta_K \sin \theta_l \sin \phi - \frac{1}{2} P_8' \sin 2\theta_K \sin 2\theta_l \sin \phi \right)$$

$$+ 2 P_2 (1 - F_L) \sin^2 \theta_K \cos \theta_l - P_3 (1 - F_L) \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \Big]$$



Angular rate

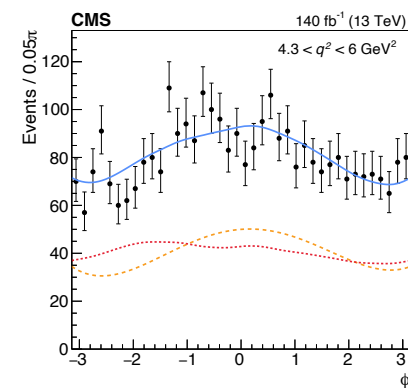
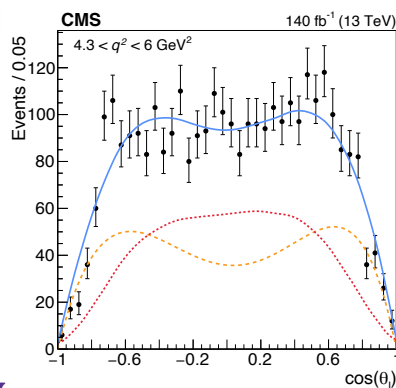
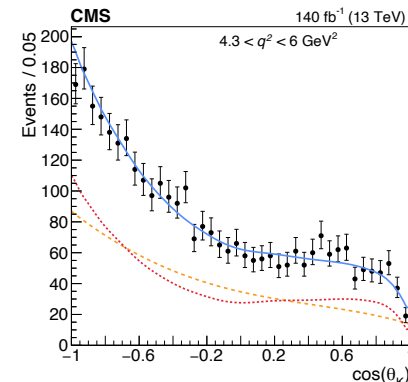
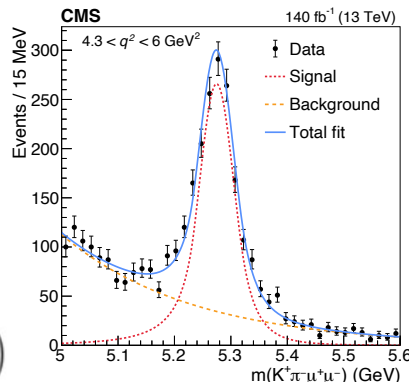
$$\text{pdf}(m, \cos \theta_K, \cos \theta_l, \phi) = Y_S \left[S^C(m) S^a(\cos \theta_K, \cos \theta_l, \phi) \epsilon^C(\cos \theta_K, \cos \theta_l, \phi) \right.$$

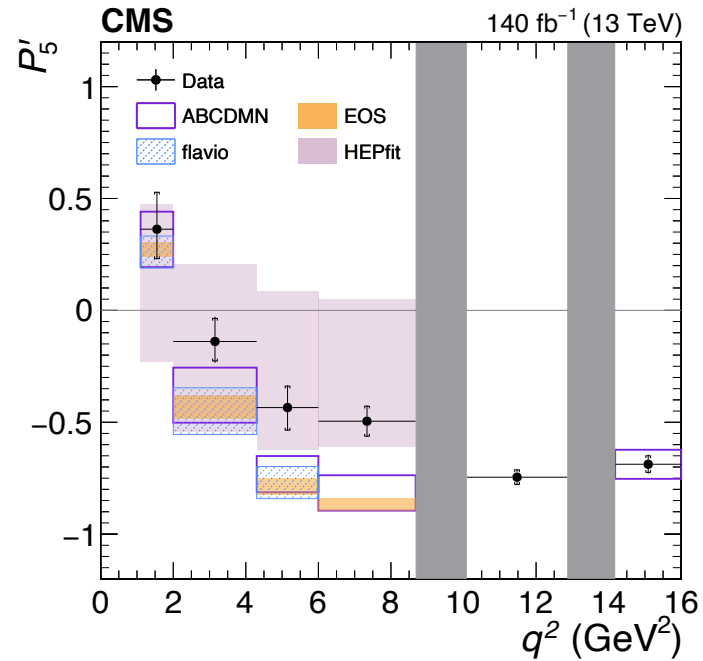
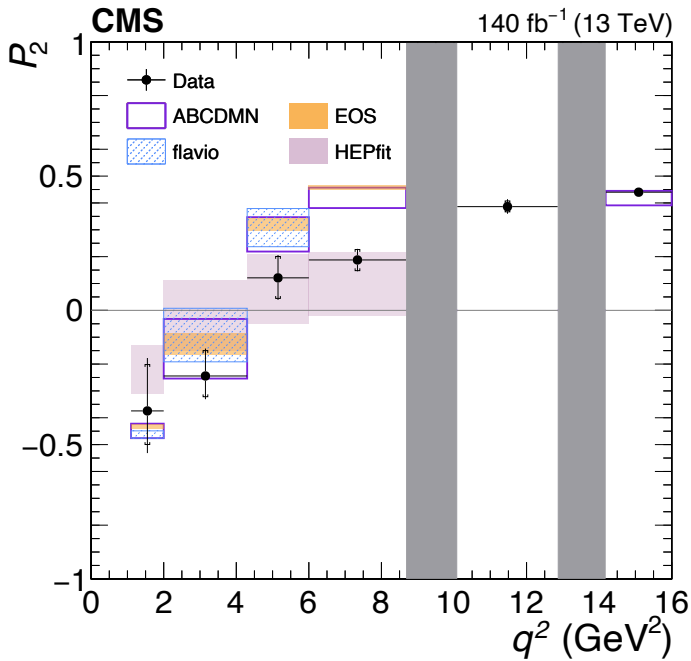
$$+ R \cdot S^M(m) S^a(-\cos \theta_K, -\cos \theta_l, -\phi) \epsilon^M(\cos \theta_K, \cos \theta_l, \phi) \Big]$$

$$+ Y_B B^m(m) B^a(\cos \theta_K, \cos \theta_l, \phi) \quad \text{KDE efficiency}$$

Signal and bkg mass shapes

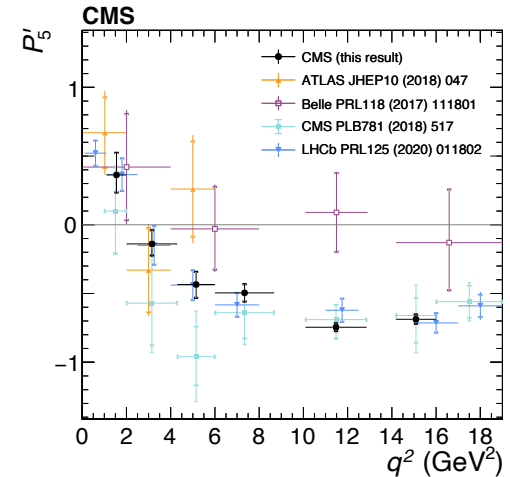
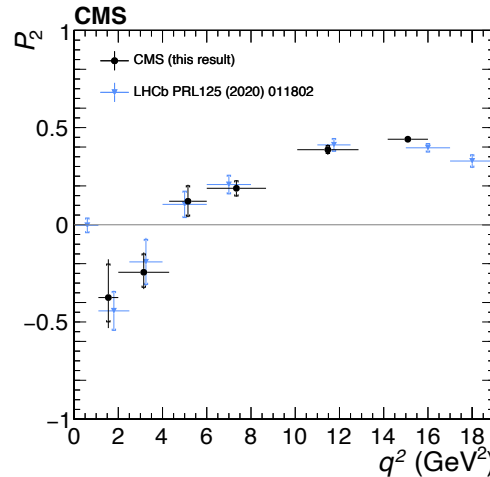
Bkg angular shape



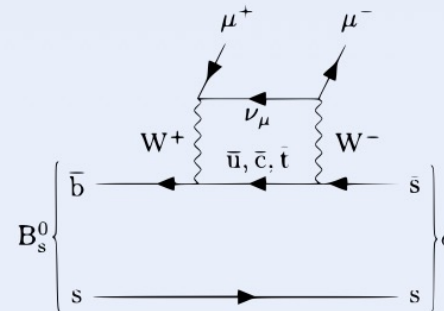


✓ Among the most precise measurements of the angular observables of this decay

✓ Valuable contribution to the understanding of the $b \rightarrow sll$

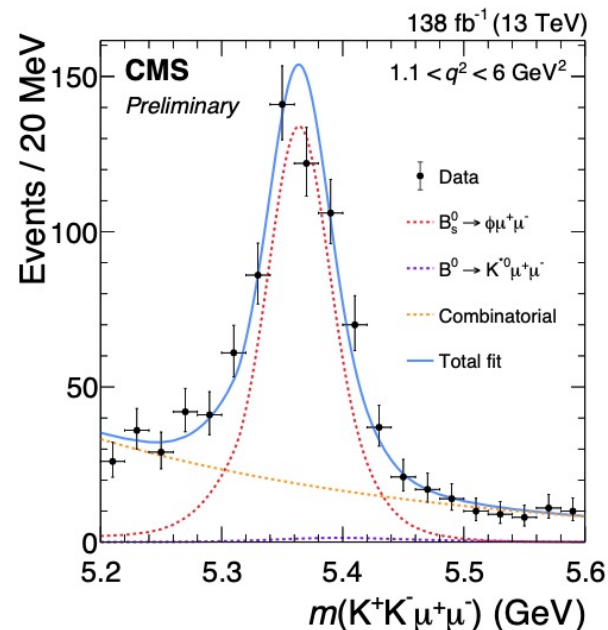


- Differential \mathcal{B} measurement and angular analysis of $B_s^0 \rightarrow \phi \mu^+ \mu^-$ decays
 - ▶ First study of these decays at CMS
- Sensitive probe for new physics
- Analysis performed using Run 2 data (138 fb^{-1})

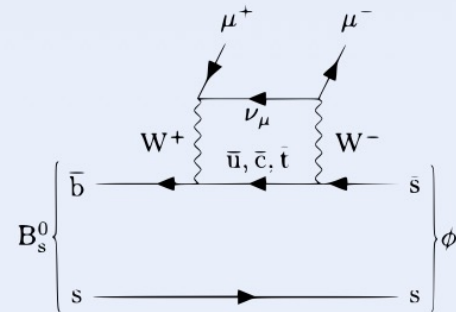


1. Differential \mathcal{B} measurement

- \mathcal{B} measured in bins of the squared dimuon invariant mass $1.1 < q^2 < 19 \text{ GeV}^2$
- Normalisation to $B_s^0 \rightarrow \phi J/\psi(\mu^+ \mu^-)$ process
 - ▶ Similar kinematics \Rightarrow strong suppression of systematic uncertainties
- Signal and normalisation yields extracted from a fit to the data
- Peaking background from $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays

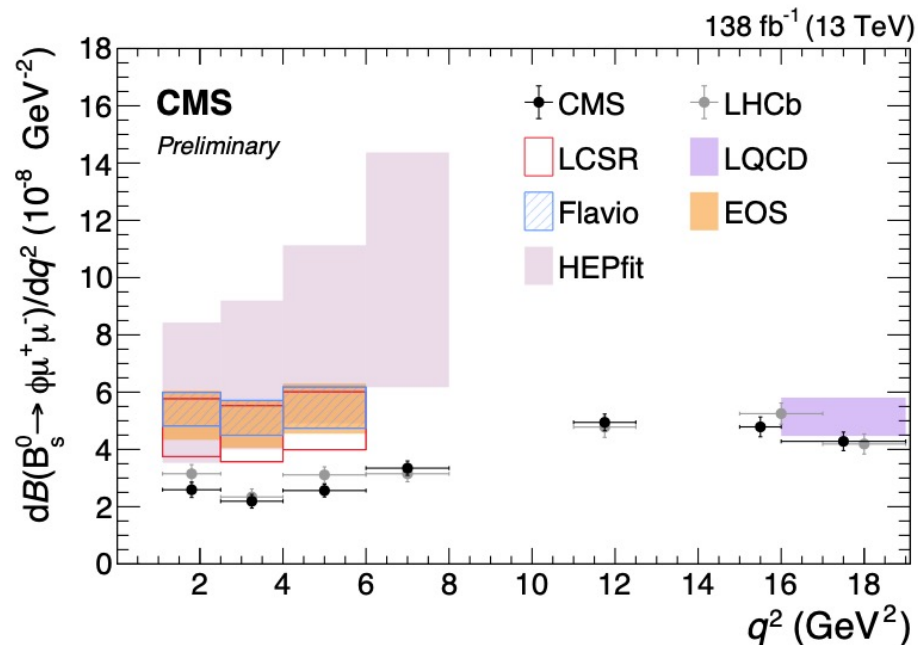


- Differential \mathcal{B} measurement and angular analysis of $B_s^0 \rightarrow \phi \mu^+ \mu^-$ decays
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1. Differential \mathcal{B} measurement

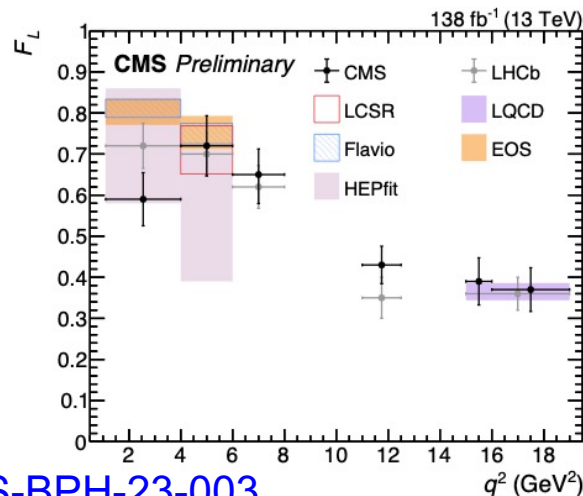
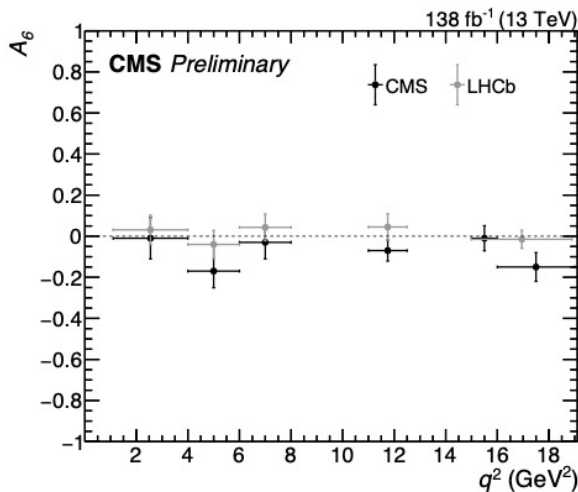
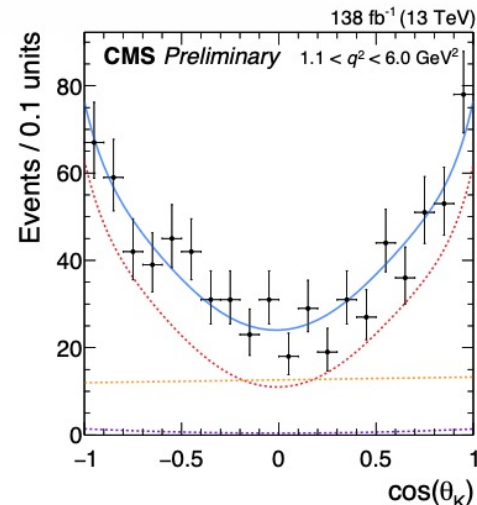
- Measurement is limited by statistical uncertainties
- 2σ compatibility with the latest LHCb results
- Up to 4.2σ tension with the various theory predictions



[CMS-PAS-BPH-23-003](#)

2. Angular analysis

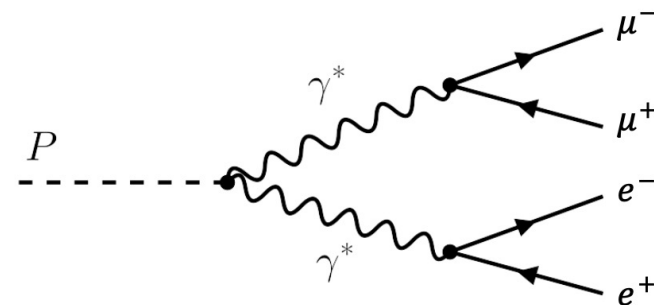
- Goal is to measure CP-asymmetry (A_6) and the fraction of longitudinal polarisation of the ϕ -meson (F_L)
- Measurement performed in bins of q^2 from a simultaneous fit to $m(B_s^0)$, $\cos\theta_K$, and $\cos\theta_\ell$
 - ▶ Angular decay rate integrated over Φ
- Results are in good agreement with LHCb measurement
- Good compatibility with theoretical predictions



[CMS-PAS-BPH-23-003](#)

- Production & properties
 - $Y(nS)$ cross section measurements at 13.6 TeV
 - Full angular analysis of $B^0 \rightarrow K^{*0} \mu \mu$
 - Differential \mathcal{B} measurement and angular analysis of $B_s^0 \rightarrow \phi \mu \mu$
- Search for new rare decays
 - Observation of $\eta \rightarrow \mu^+ \mu^- e^+ e^-$
 - Search for $B_s^0 (B^0) \rightarrow 4\mu$
 - Search for $\tau \rightarrow 3\mu$
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 - Observation of $X(6900) \rightarrow J/\psi \psi(2S) \rightarrow 4\mu$
 - JPC measurement of the tetraquark family $X(6600), X(6900), X(7100)$

- Double-Dalitz decay used as test of the SM
 - Contribute to light-by-light hadronic component of the muon anomalous magnetic moment
 - Sensitive to new physics [Rep. Prog. Phys. 86 016201]
- Latest (2008) experimental result
 - $BR < 1.6 \times 10^{-4}$ [Phys. Rev. D 77, 032004]
 - CELSIUS/WASA Collaboration
- CMS
 - Run 3 data collected in 2022 from new inclusive di-muon trigger (38 fb^{-1})
 - Measure BR of $\eta \rightarrow \mu\mu ee$ wrt a normalization channel $\eta \rightarrow \mu\mu\gamma$



$$(3.1 \pm 0.4) \times 10^{-4}$$

$$\frac{\mathcal{B}_{2\mu 2e}}{\mathcal{B}_{2\mu\gamma}} = \frac{N_{2\mu 2e}}{N_{2\mu\gamma}} \frac{\epsilon_{2\mu\gamma}}{\epsilon_{2\mu 2e}}$$

From MC simulations

- A peak in the invariant mass of the $2\mu 2e$ is observed

Statistical significance $> 5\sigma$

$$\frac{\mathcal{B}_{2\mu 2e}}{\mathcal{B}_{2\mu\gamma}} = (6.9 \pm 0.9(\text{stat}) \pm 1.8(\text{syst})) \times 10^{-3}$$

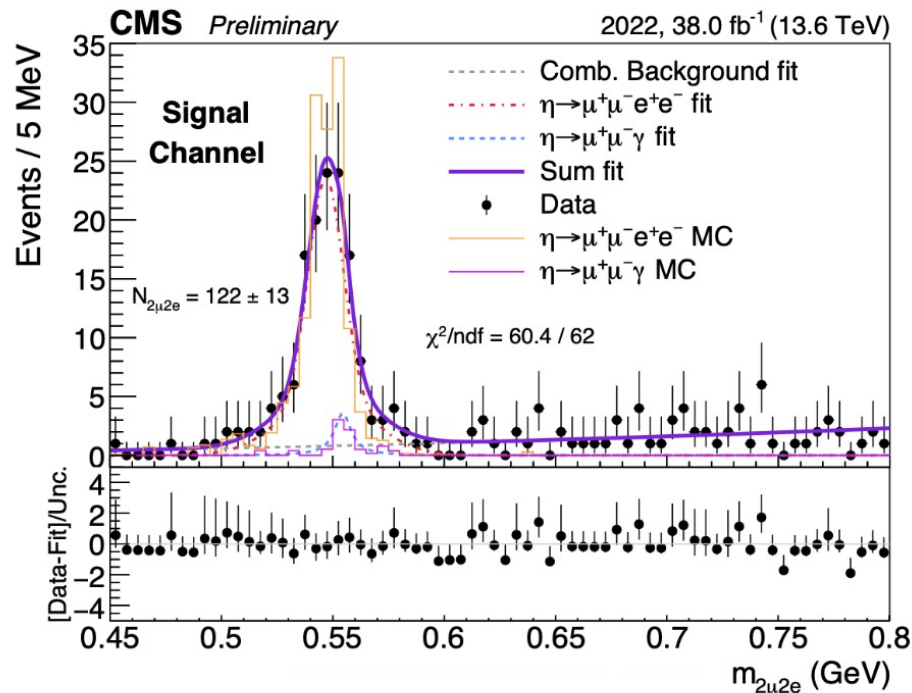
$$\mathcal{B}(\eta \rightarrow 2\mu 2e) = (2.1 \pm 0.7) \times 10^{-6}$$

$$0.3(\text{stat}) \pm 0.6(\text{syst}) \pm 0.3(\mathcal{B}_{2\mu})$$

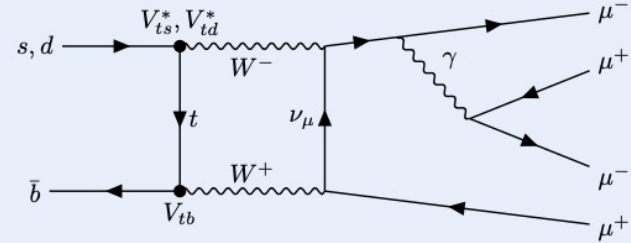
Compatible with the expected value of the SM:

$$\mathcal{B}(\eta \rightarrow 2\mu 2e) \sim 2.3 \times 10^{-6}$$

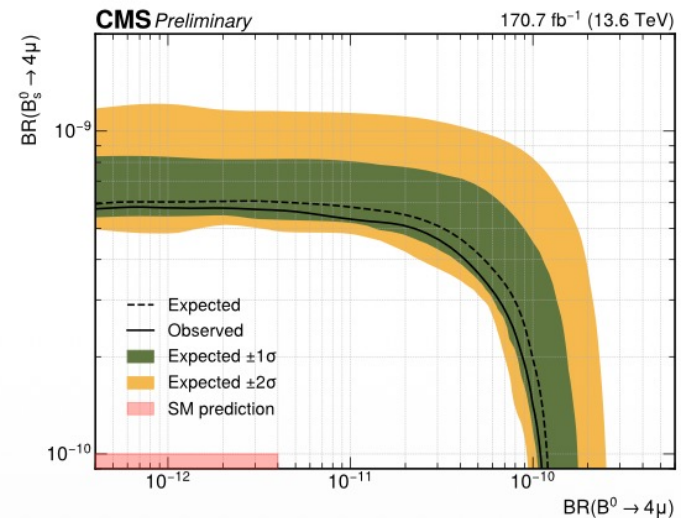
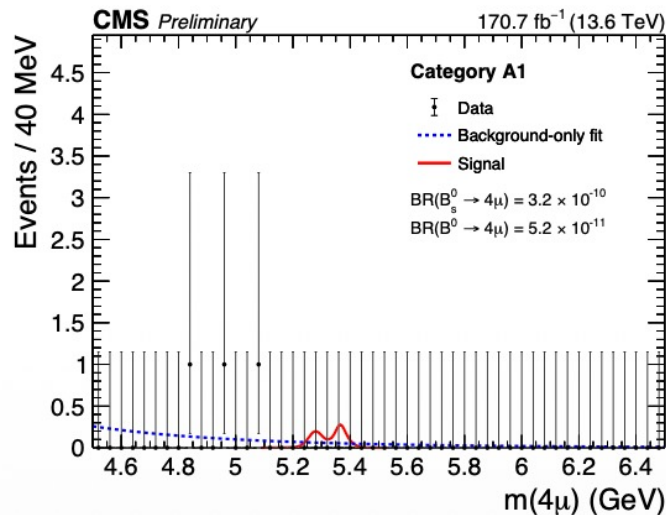
[\[Chinese Phys. C 42 \(2018\) 023109\]](#)



- Search for B_s^0 (B^0) $\rightarrow \mu^+ \mu^- \mu^+ \mu^-$ (flavour-changing neutral currents) decays
- Sensitive probe for new physics (useful input for effective field theories)



- Analysis of 2022–2024 data recorded with B-parking dimuon triggers
- No excess over background observed
- Observed limits: $\mathcal{B}(B_s^0 \rightarrow 4\mu) < 5.7 \times 10^{-10}$ and $\mathcal{B}(B^0 \rightarrow 4\mu) < 1.3 \times 10^{-10}$
 - ▶ Improvement of $\sim 30\%$ over previous best limits
- First limits in 2D plane are provided



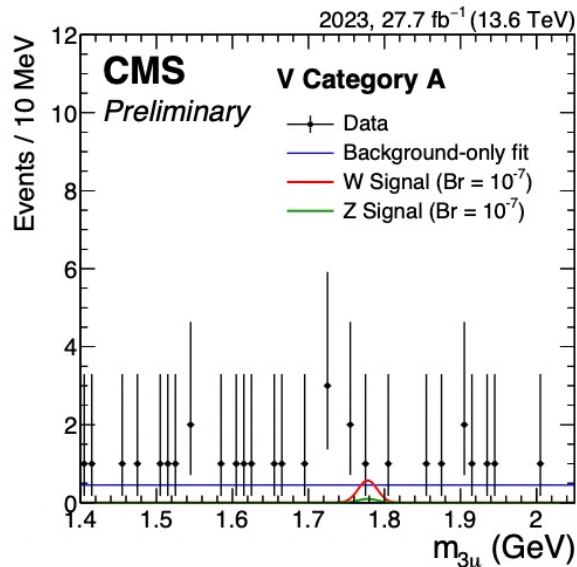
The SM allows charged LFVs through neutrino oscillation, but with vanishing BRs

$$\mathcal{B}(\tau \rightarrow 3\mu) \sim \mathcal{O}(10^{-55}) \text{ [Eur. Phys. J. C (2020) 80:438]}$$

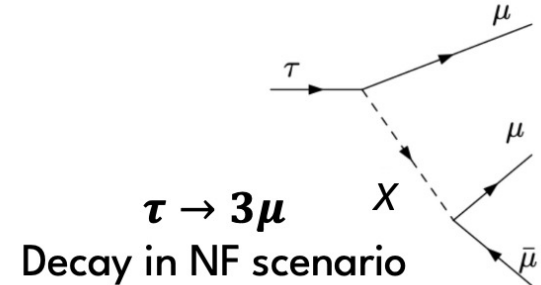
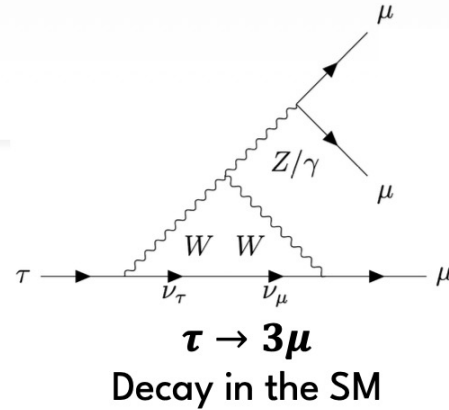
Extensions to the SM predict a much higher BRs

$$\text{Expected values: } \mathcal{B}(\tau \rightarrow 3\mu) \sim \mathcal{O}(10^{-10} - 10^{-8}) \text{ [JHEP10(2018)148]}$$

- Run 3 (2022+23) data (62 fb^{-1})
- W/Z and heavy flavour production channels



$$\mathcal{B}(\tau \rightarrow 3\mu) < 6.7 \times 10^{-8} \text{ (90\% CL)}$$



Year	Collab.	Process	Exp. UL *	Obs. UL *
2010	Belle	$ee \rightarrow \tau\tau$	-	2.1
2010	BaBar	$ee \rightarrow \tau\tau$	4.0	3.3
2024	CMS	B/D and W	2.4	2.9
2024	Belle II	$ee \rightarrow \tau\tau$	1.8	1.9
2026	LHCb	$D/B \rightarrow \tau X$	2.0	1.9
2026	ATLAS	B/D and W	7.5	8.7

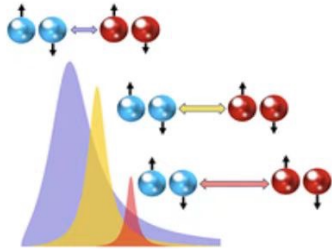
* $\times 10^{-8}$ @ 90% C.L.

- Production & properties
 - $Y(nS)$ cross section measurements at 13.6 TeV
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 - Differential \mathcal{B} measurement and angular analysis of $B_s^0 \rightarrow \phi \mu \mu$
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Editors' Suggestion

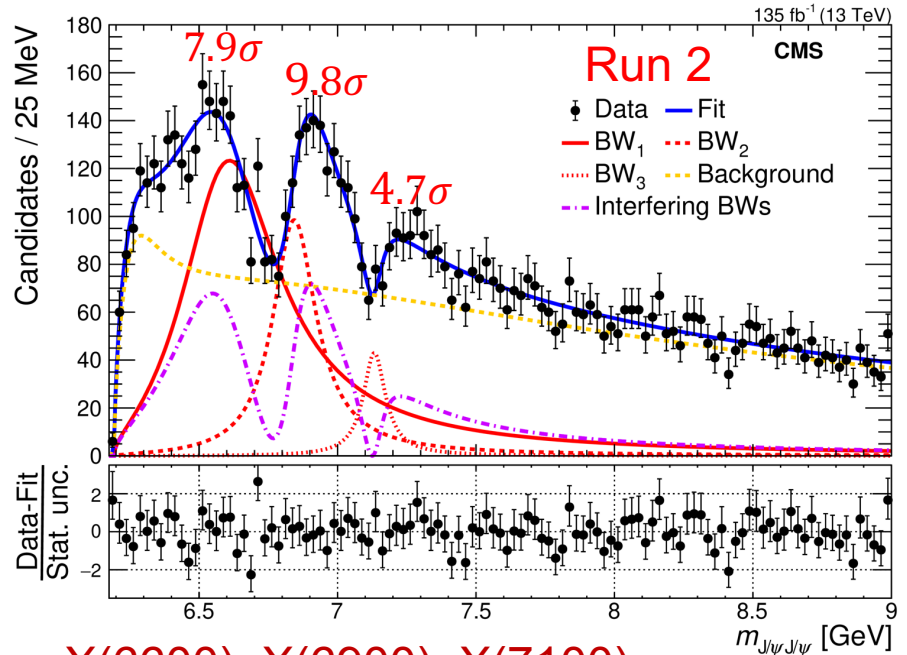
New Structures in the $J/\psi J/\psi$ Mass Spectrum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

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.

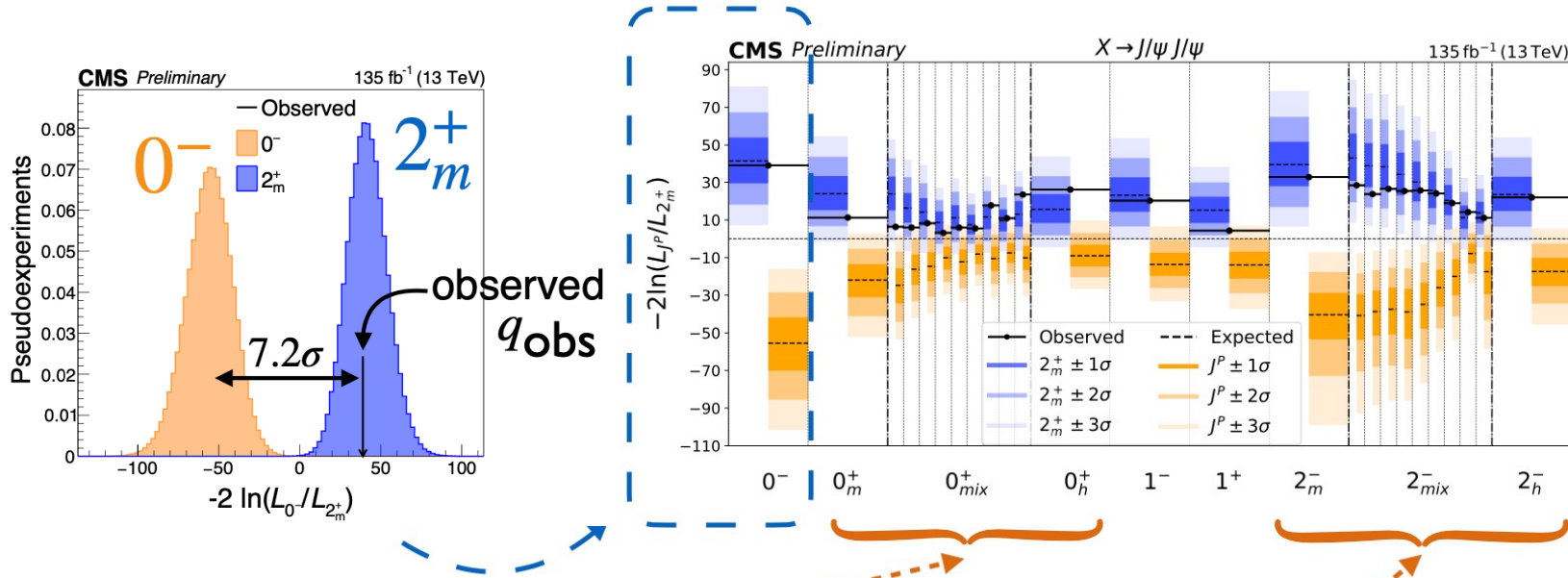
[Show Abstract](#) +



X(6600) X(6900) X(7100)

- 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}

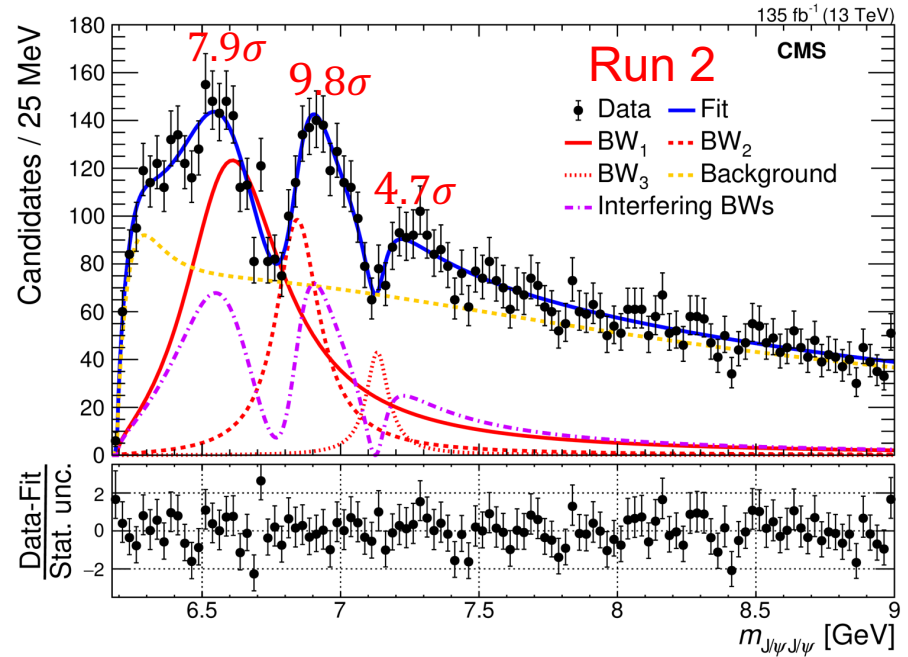


- Scan mixture of two 0^{++} amplitudes (11 steps)
 - constructive interference most conservative
- Scan mixture of two 2^{--} amplitudes (11 steps)
 - no interference (different spin projections)

• Data are consistent with a 2^{++} model, inconsistent with others

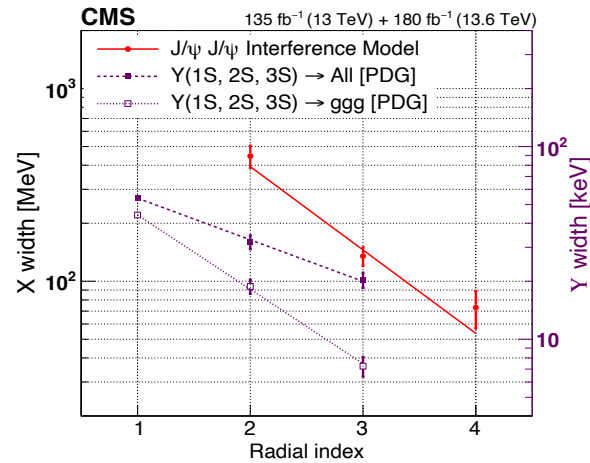
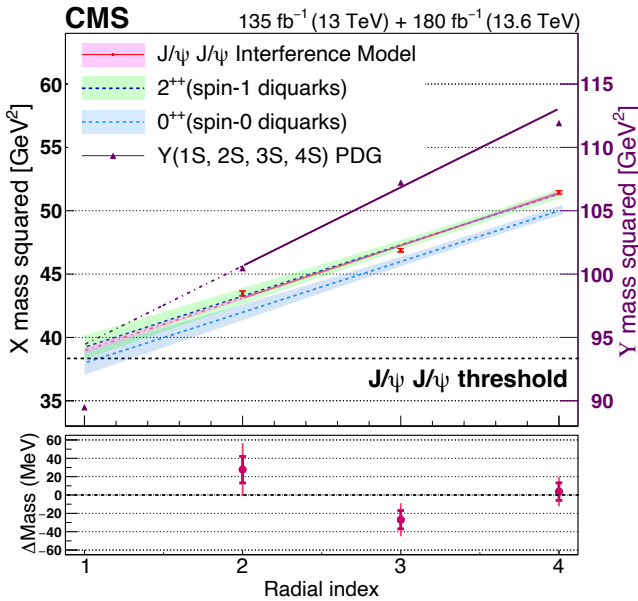
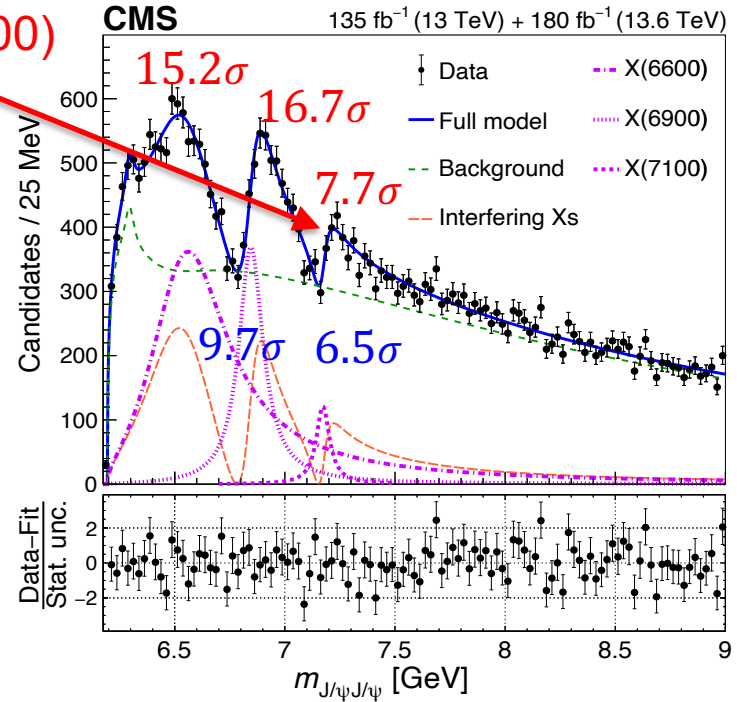
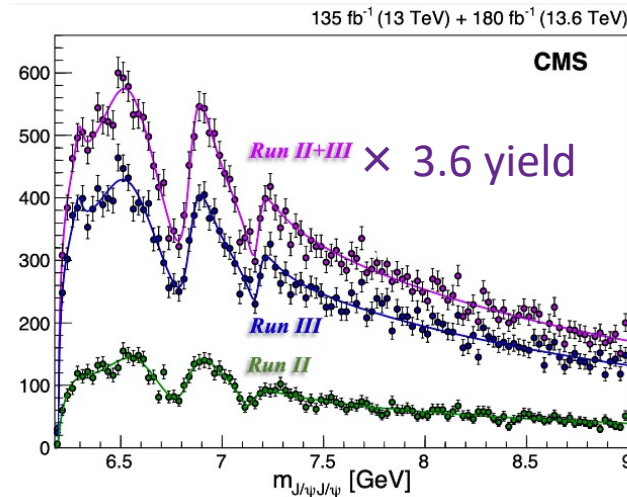
More details in 张敬庆's talk 14:20 tomorrow

- **X(7100)**: 4.7σ & Interference $< 4\sigma$
- Significance of **ALL** states over 5σ ?
- Significance of **interference** over 5σ ?



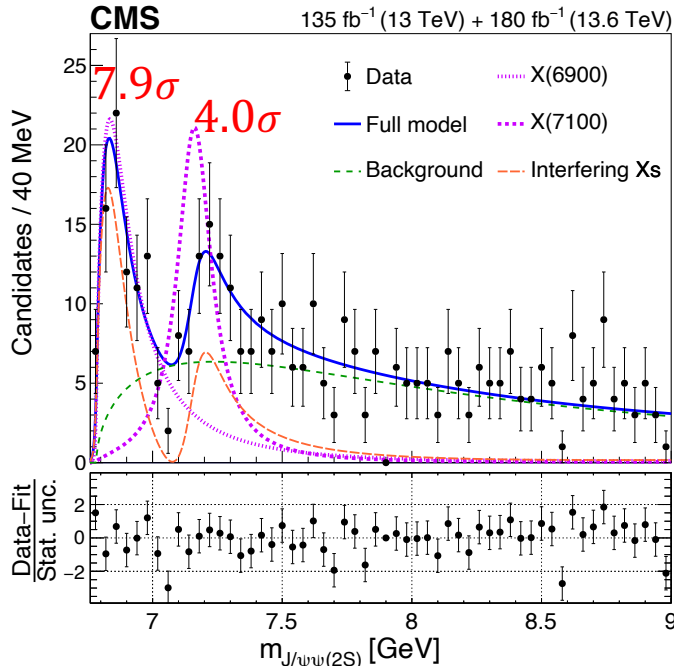
- **Data samples [315 fb⁻¹]**
 - Run II: 135 fb⁻¹ data taken in 2016, 2017 and 2018
 - Run III: 180 fb⁻¹ data taken in 2022, 2023 and 2024
 - J/ψJ/ψ events: 3.6 * Run II

First observation of X(7100)





Observation of $X(6900) \rightarrow \psi(2S)J/\psi$



First observation of
 $X(6900) \rightarrow \psi(2S)J/\psi \rightarrow 4\mu$

Evidence of $X(7100) \rightarrow \psi(2S)J/\psi$

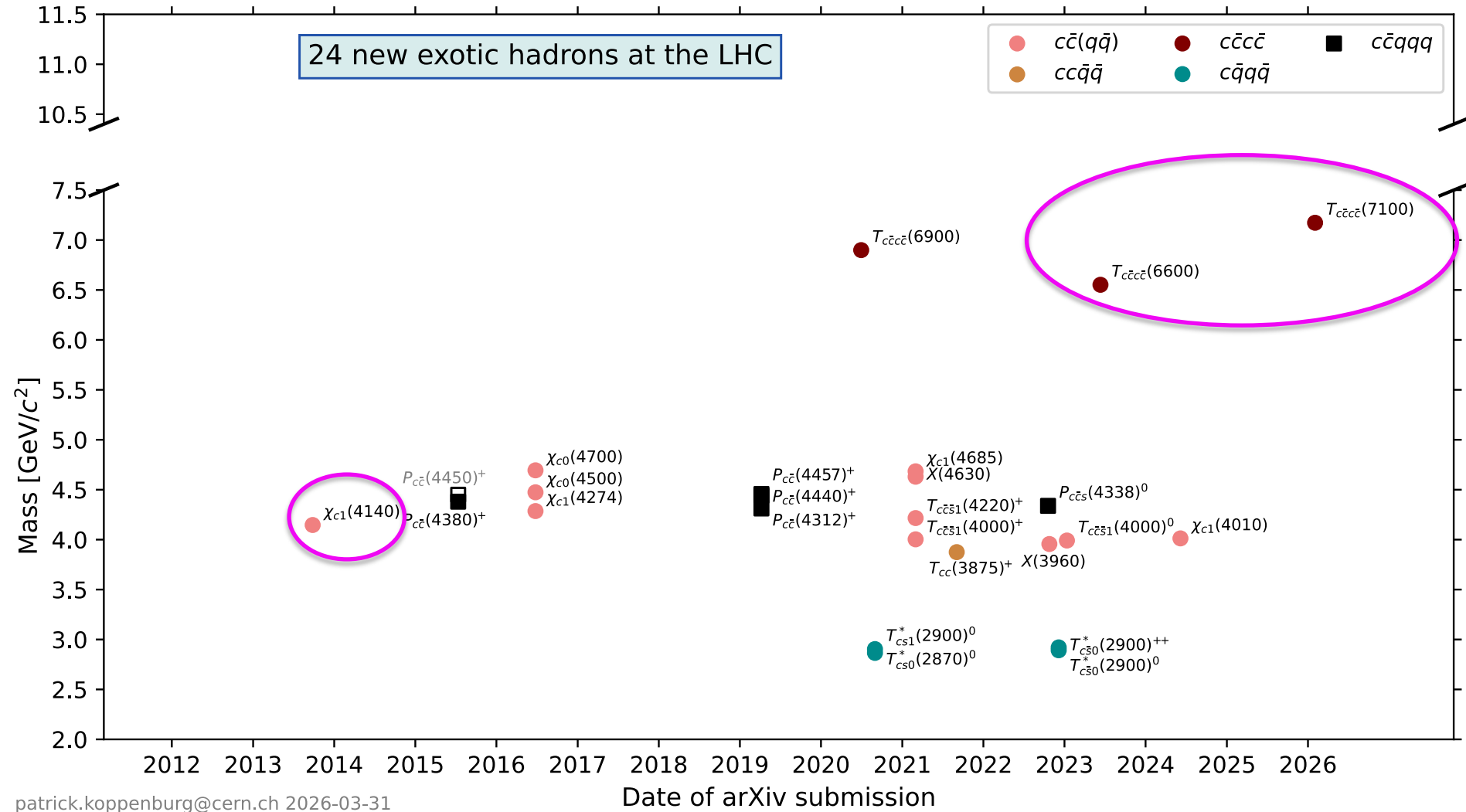
[Submitted to Science Adv.](#)

Fit	Sample	Interf.		X(6600)	X(6900)	X(7100)
f_{i23}	J/ $\psi\psi(2S)$	BW ₂ , BW ₃	m :	—	$6876^{+46+110}_{-29-110}$	7169^{+26+74}_{-52-70}
			Γ :	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
f_{JJ} [1]	J/ ψ J/ ψ	Interference (Run 2+Run 3)	m (MeV)	$6593^{+15}_{-14} \pm 25$	$6847^{+10}_{-10} \pm 15$	$7173^{+9}_{-10} \pm 13$
			Γ (MeV)	$446^{+66}_{-54} \pm 87$	$135^{+16}_{-14} \pm 14$	$73^{+18}_{-15} \pm 10$
		Interference (Run 2 [12])	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}

More details in 周漪林's talk 10:45 Monday

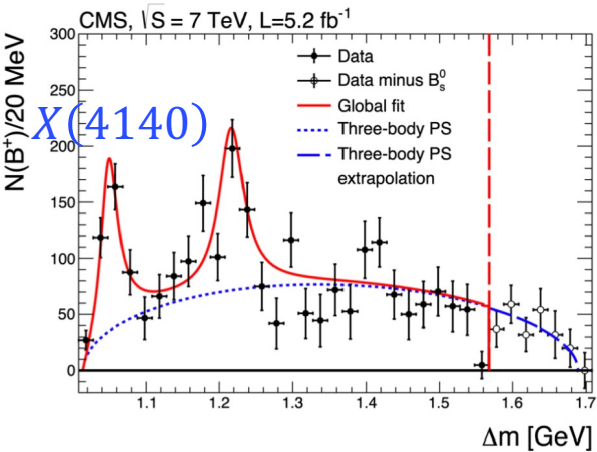
[arXiv:2602.02252](https://arxiv.org/abs/2602.02252)





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

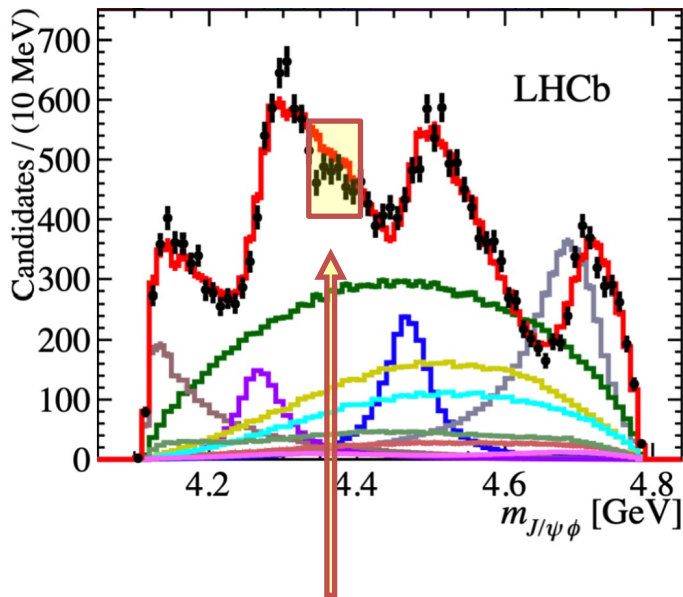
- 10 new $J/\psi\phi$ and $J/\psi K$ structures have been claimed in $B \rightarrow J/\psi\phi K$ decays by LHCb
- Not confirmed by other experiments apart from $X(4140)$ and $X(4274)$
- Width of $X(4140)$ by LHCb is inconsistent with previous measurements



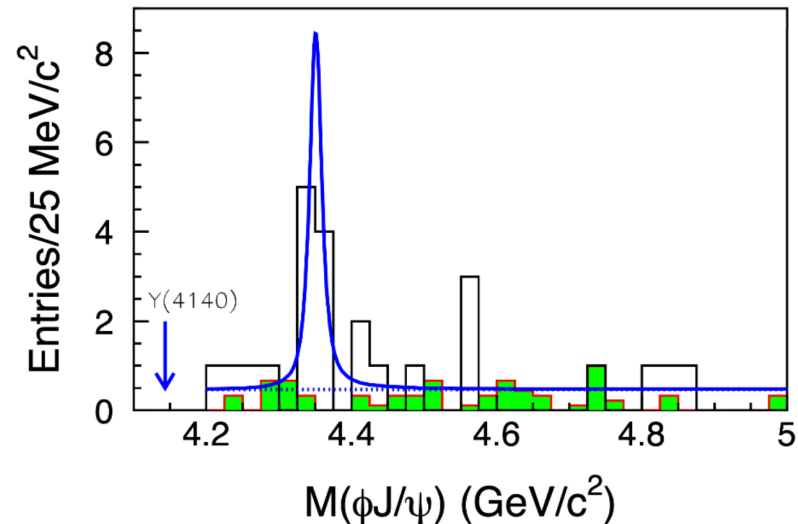
[Phys. Lett. B, 734:261, 2014](#)

Year	Experiment	Luminosity [fb ⁻¹]	Process/Yield $B \rightarrow J/\psi\phi K$	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	$\gamma\gamma \rightarrow J/\psi\phi$	$X(4350)$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$		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		$e^+e^- \rightarrow \gamma J/\psi\phi$	-	-	-		-
2015	DØ	10.4	$p\bar{p} \rightarrow J/\psi\phi + \text{anything}$	$X(4140)$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$		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
				$X(4274)$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-31}$	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	$pp \rightarrow J/\psi\phi + \text{anything}$	$X(4274)$	$4298 \pm 6 \pm 9$	$92^{+22}_{-18} \pm 57$		4.1
				$X(4500)$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$65^{+20}_{-16} \pm 32$		6.1

[Chin. Phys. Lett. 2025 42\(12\): 120202](#)



[Phys. Rev. Lett., 104:112004, 2010](#)



- **Notable shoulder** between 4.32 and 4.39 GeV in the $J/\psi\phi$ mass spectrum
- **Remind:** 2010, Belle, $\gamma\gamma \rightarrow J/\psi\phi$, **Evidence of $X(4350)$** , 3.2σ
- Several tetraquarks have been predicted around 4.3 GeV
- Potential resonance around 4.35 GeV
 - CMS has higher sensitivity in the low-mass region, doing amplitude analysis for $B \rightarrow J/\psi\phi K$ with comparable statistic

More details in 周泓键's talk 11:00 Monday

- Production & properties
 - First quarkonium measurements at 13.6 TeV
 - Full angular analysis of $B^0 \rightarrow K^{*0}\mu\mu$ and $B_s^0 \rightarrow \phi\mu\mu$
- Rare decays
 - First observation of $\eta \rightarrow \mu^+\mu^-e^+e^-$
- Spectroscopy
 - CMS paint a full picture of fully-charm tetraquarks
 - Measurement of spin-parity reveal their $J^{PC} = 2^{++}$
- Stay tuned for more results with much larger Run 3 dataset
- Chinese teams playing leading roles for CMS BPH

Thank you!