Recent HF and CPV results from the CMS experiment

清華大學
Tsinghua University

Zhen Hu
on behalf of the CMS collaboration

Oct 25, 2025

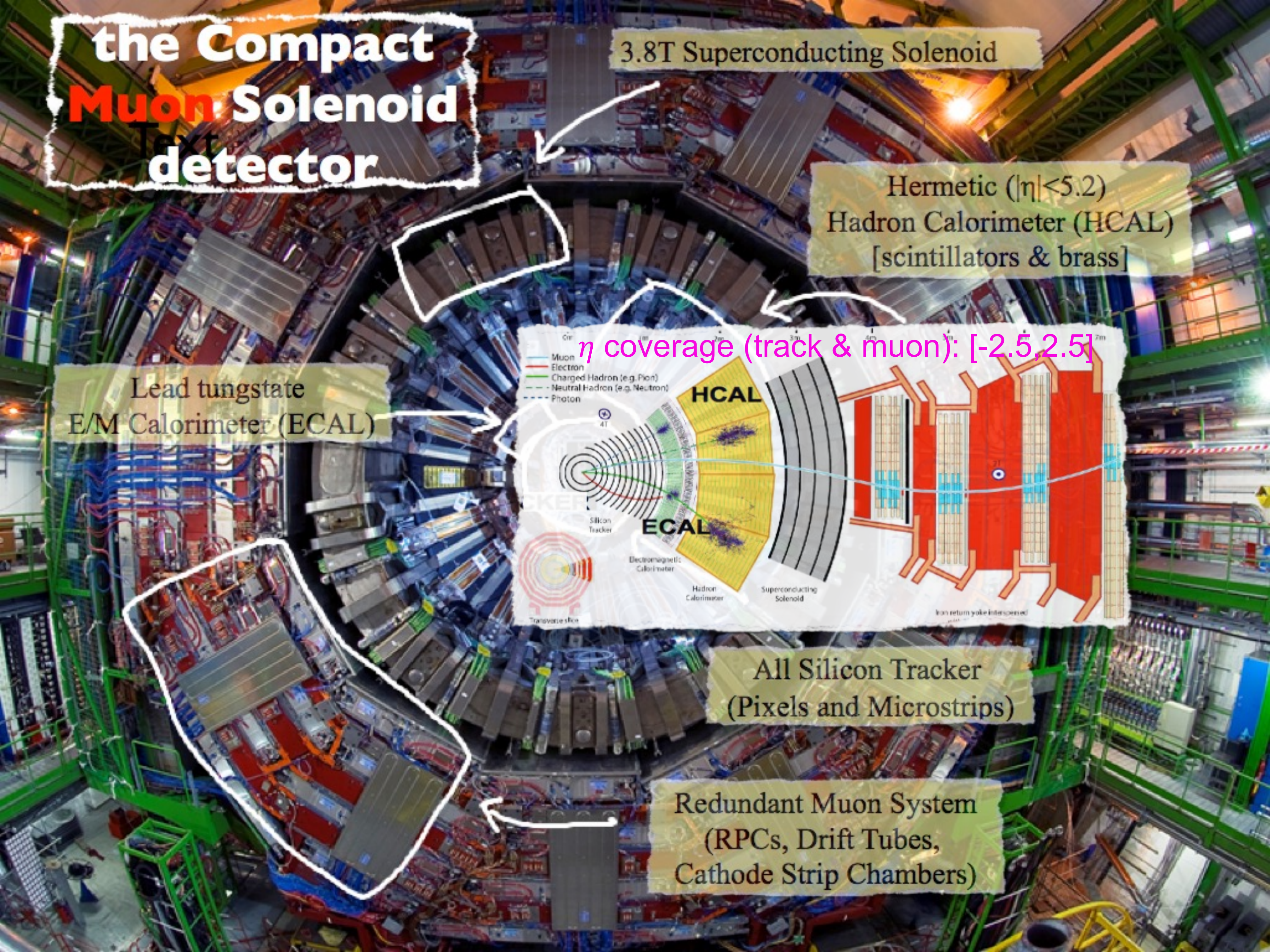
The **Large Hadron Collider** (**LHC**) at CERN is the world's largest particle collider. It lies in a tunnel 27 kilometres in circumference and as deep as 175 metres beneath the France–Switzerland border near Geneva.

CMS B Physics Group

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

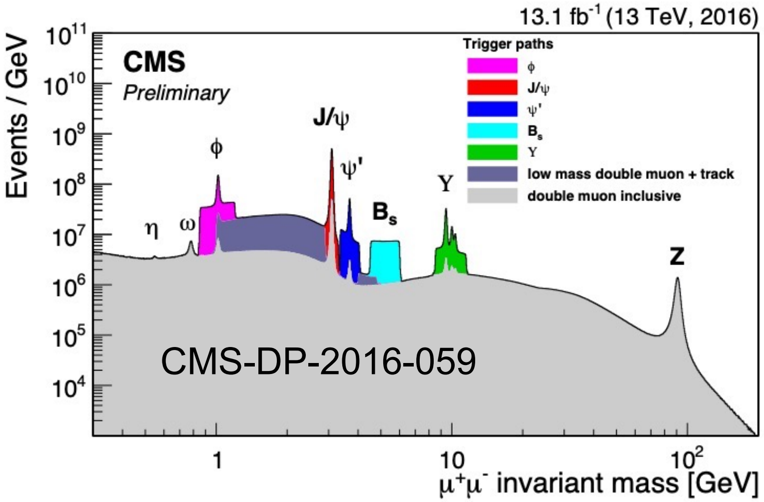
- Quarkonium Production
  - Bottomium States
  - Charmonium States
- B and BB Production
  - Inclusive Measurements
  - B^0 and B^+ Production
  - B_s^0 Production
  - B_c^+ Production
- B Meson Decays
  - $B \to K^{(*)}\mu^+\mu^-$
  - $B_s^0 \to \mu^+\mu^-$
- CP Violation
- Baryons
- Spectroscopy, Exotic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

Production and Properties	Rare Decays
BPH	
Violation of Fundamental Symmetries	Spectroscopy Exotic states



the Compact Muon Solenoid detector
Text
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
η coverage (track & muon): [-2.5,2.5]
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
HCAL
ECAL
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Transverse slice
Lead tungstate
E/M Calorimeter (ECAL)
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

CMS trigger & dimuon spectrum

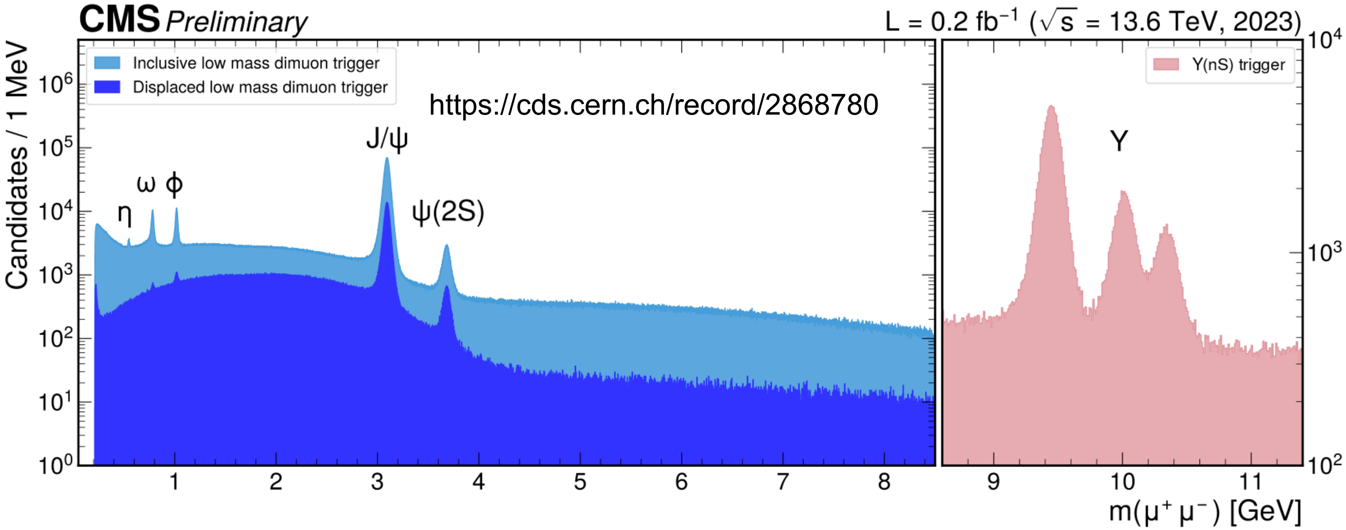


Excellent detector for studies with muons

- 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
  - μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ



Significant acceptance improvement in Run-3!

Recent HF and CPV results

- Spectroscopy of exotic hadrons
  - Observation of X(6600) and X(7100) in $\mathrm{J}/\psi\,\mathrm{J}/\psi$
    Observation of X(6900) in $\mathrm{J}/\psi\,\psi(2S)$ (4/2025, submit to Sci. Adv.)
  - Spin-parity measurement of the tetraquark family X(6600),X(6900),X(7100) (4/2025, accepted by Nature)

- Conventional hadrons
  - CMS: First full reconstruction of B* mesons (5/2025, submitted to PRL)
  - Full angular analysis of $\mathrm{B}^0 \to \mathrm{K}^*(892)^0\mu^+\mu^-$ (3/2025, published in PLB)

- CP violations
  - Search for CPV through $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ (2024, published in EPJC)
  - Measurement of CPV through $B^0_s \to \mathrm{J}/\psi\,\phi(1020)$ (2024, submitted to PRL)

New domain of exotics: all-heavy tetra-quarks

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

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

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

A Possible Model for New Resonances

——Exotics and Hidden Charm——

Yoichi IWASAKI

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received January 20, 1975)

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

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

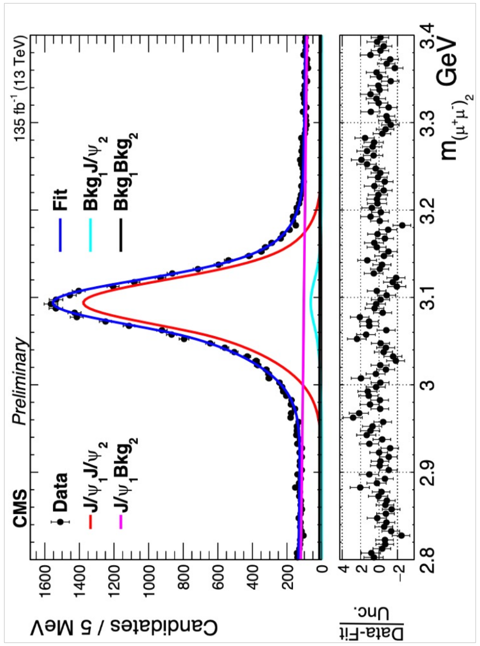
$(cc)_{\underline{3}^*} - (\overline{cc})_{\underline{3}}$

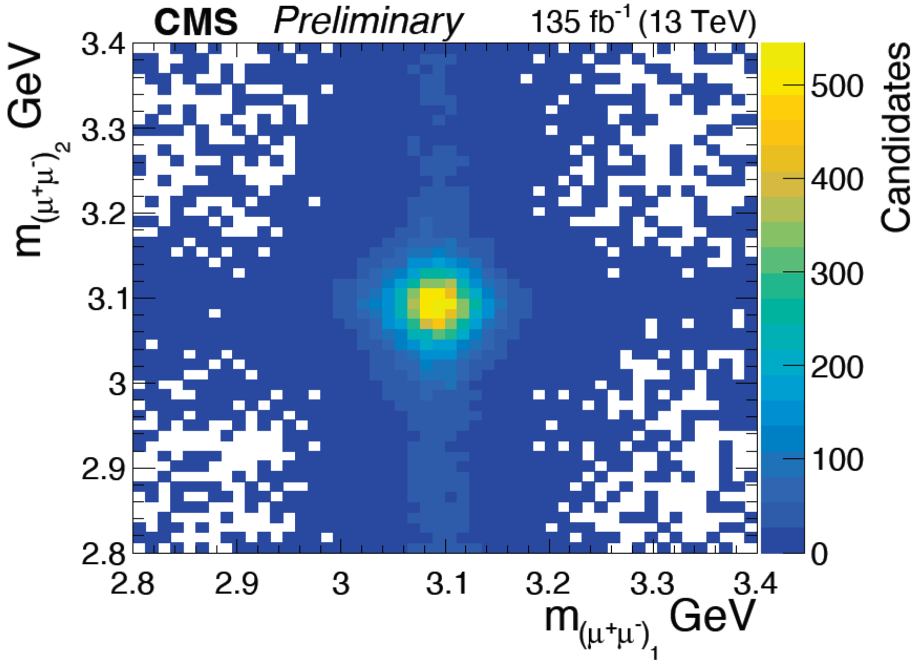
$(cc)_{\underline{6}} - (\overline{cc})_{\underline{6}^*}$

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

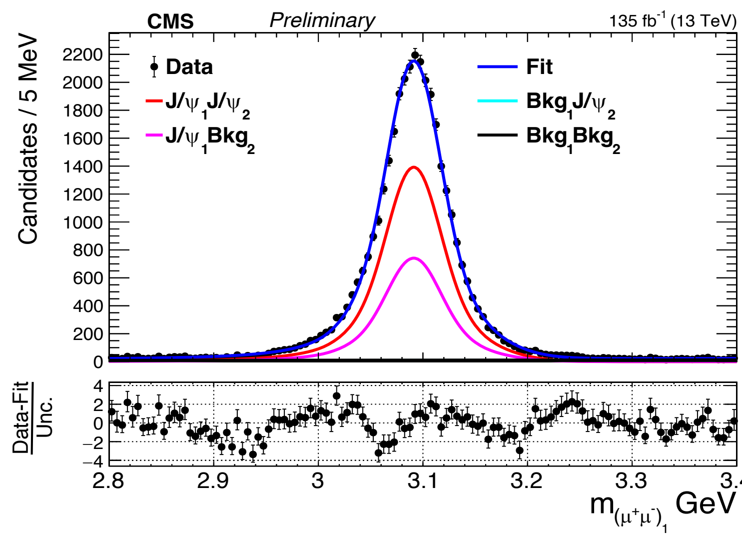
- A different system compared to exotics with light quarks

CMS J/ψJ/ψ candidates at 13 TeV





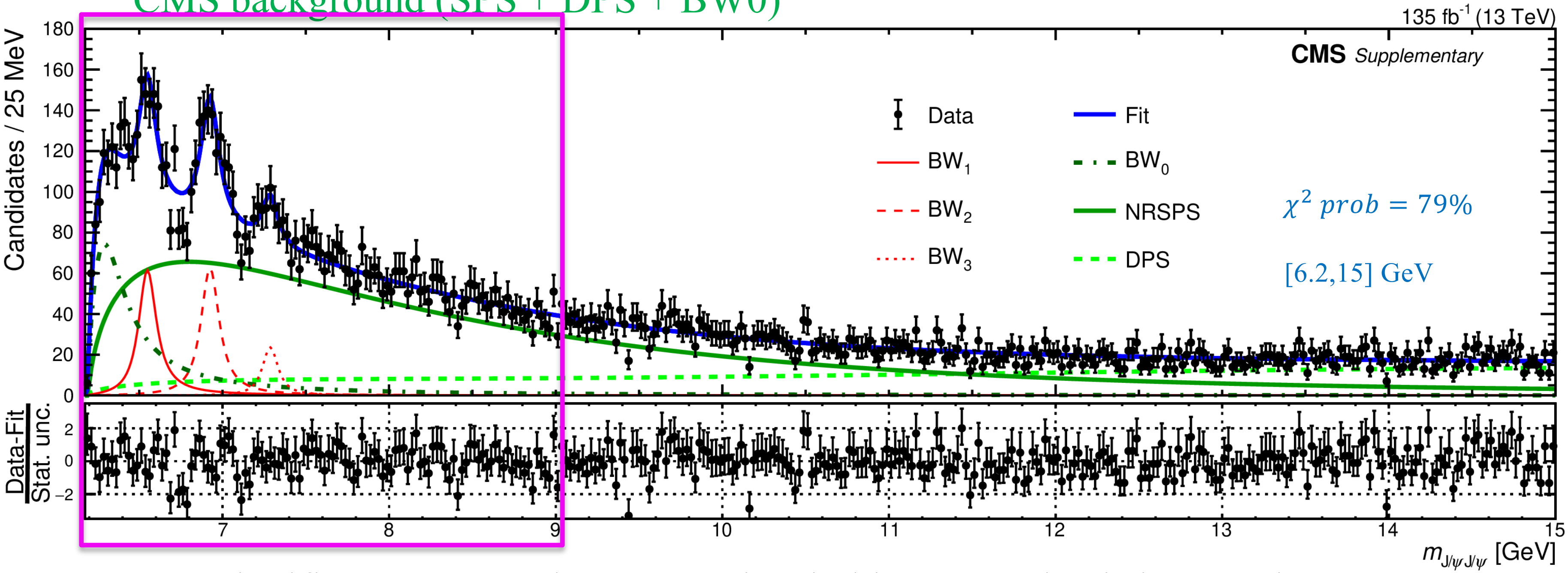
- J/ψJ/ψ from CMS:
  - 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs
  - Clean J/ψJ/ψ signals are seen
  - J/ψ mass and vertex related cuts removed



CMS background (SPS + DPS + BW0)

PRL 132 (2024) 111901

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

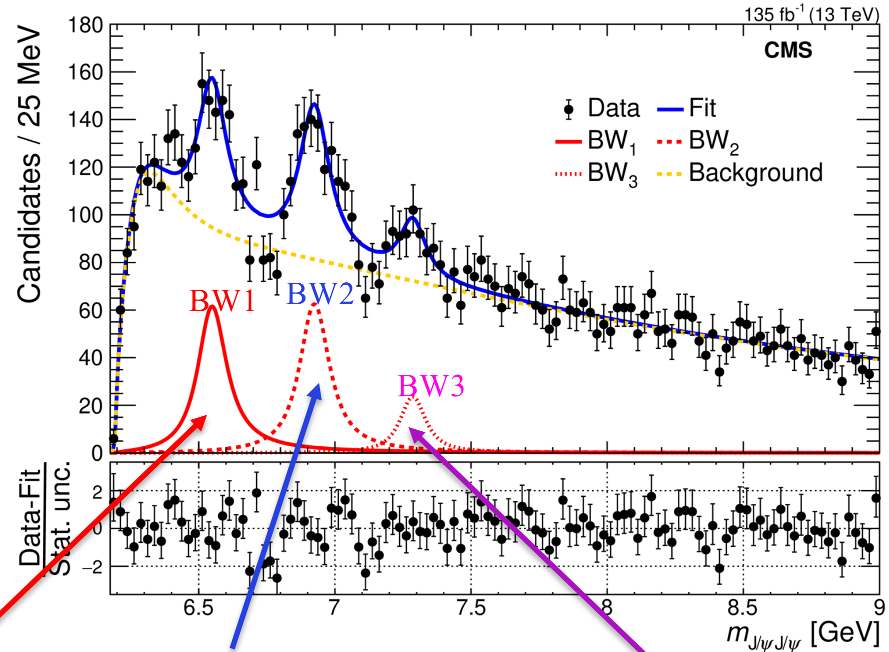
CMS J/ψJ/ψ fit: 3 BWs + Background

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
	First Observation	Confirmation of X(6900) from LHCb	Evidence

CMS J/ψJ/ψ interference fit

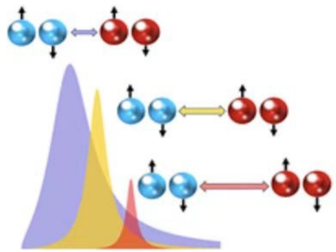
PRL 132 (2024) 111901

Editors' Suggestion

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

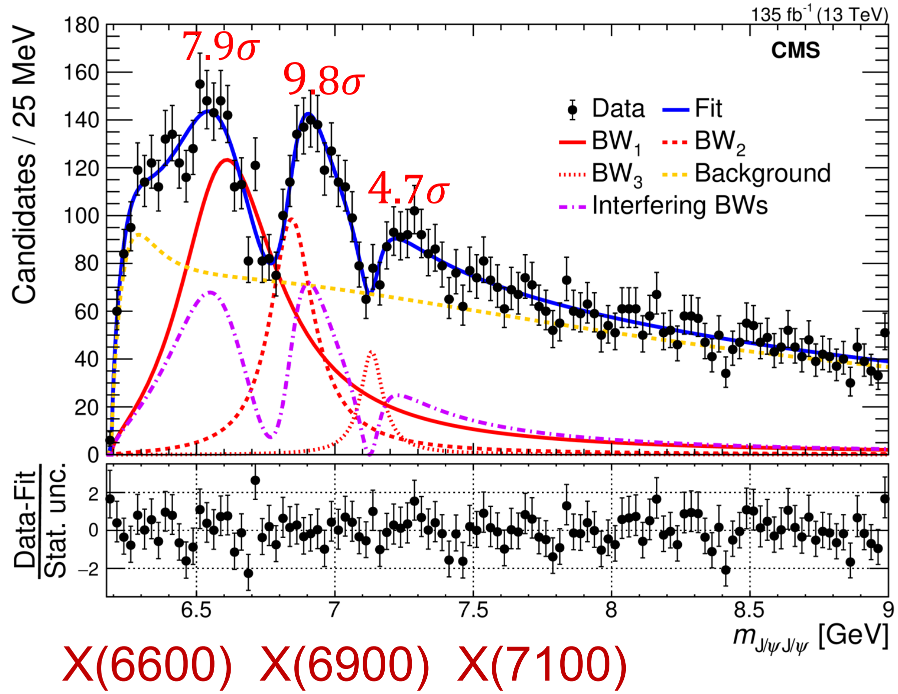
A. Hayrapetyan *et al.* (CMS Collaboration)

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



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

Show Abstract +

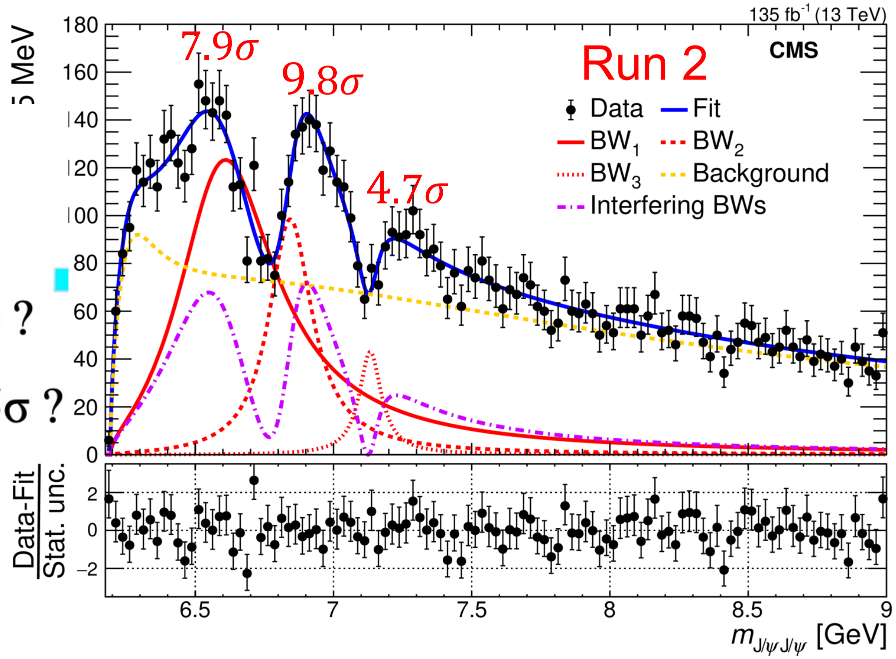


- Fit with interf. among BW1, BW2, and BW3 describes data well
- Measured mass and width in the interference fit

		BW_1	BW_2	BW_3
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

CMS J/ψJ/ψ Run 3 ?

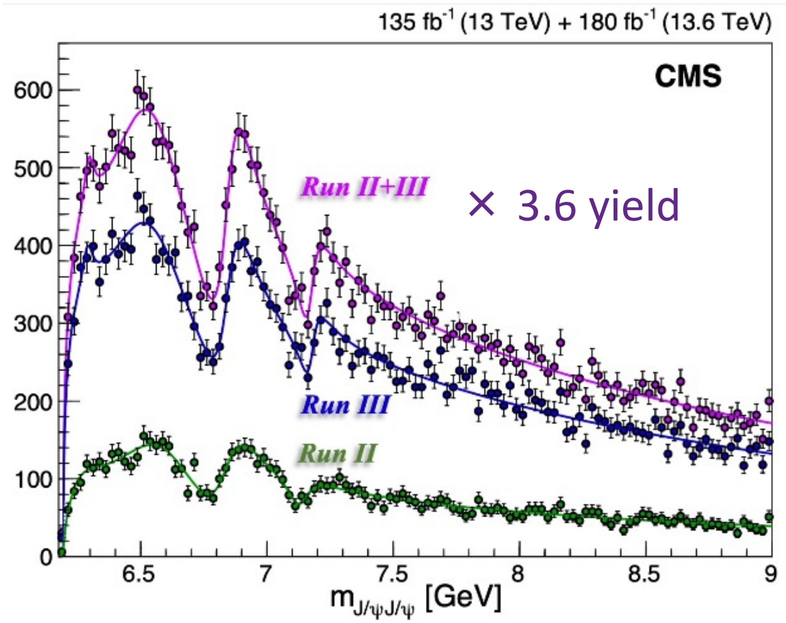
- **X(7100)**: 4.7σ & Interference < 4σ
- Significance of **ALL** states over 5σ ?
- Significance of **interference** over 5σ ?

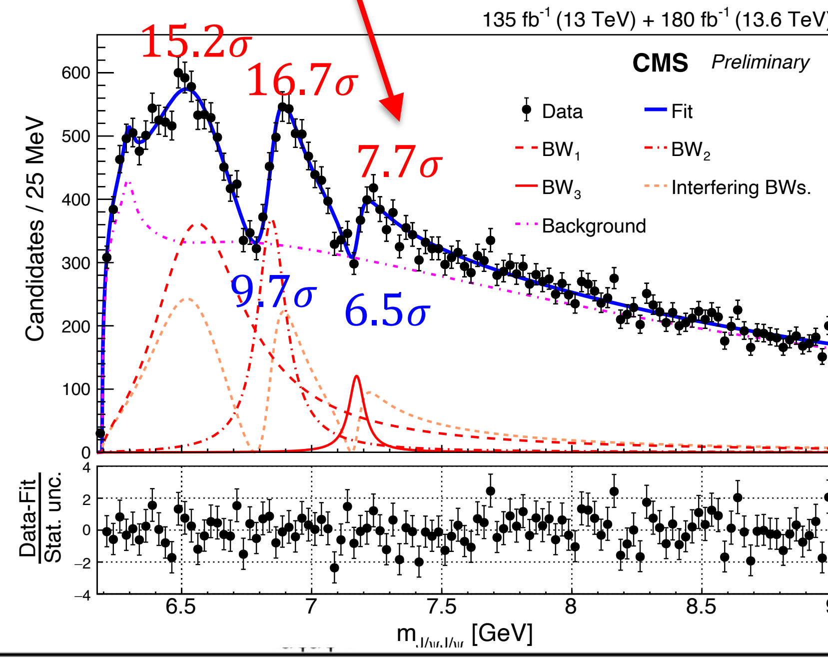


- Data samples [315 fb^{-1}]
  - Run II: 135 fb^{-1} data taken in 2016, 2017 and 2018
  - Run III: 180 fb^{-1} data taken in 2022, 2023 and 2024
  - J/ψJ/ψ events：3.6 * Run II

CMS J/ψJ/ψ fit – Run 2+3

First observation of X(7100) CMS-PAS-BPH-24-003



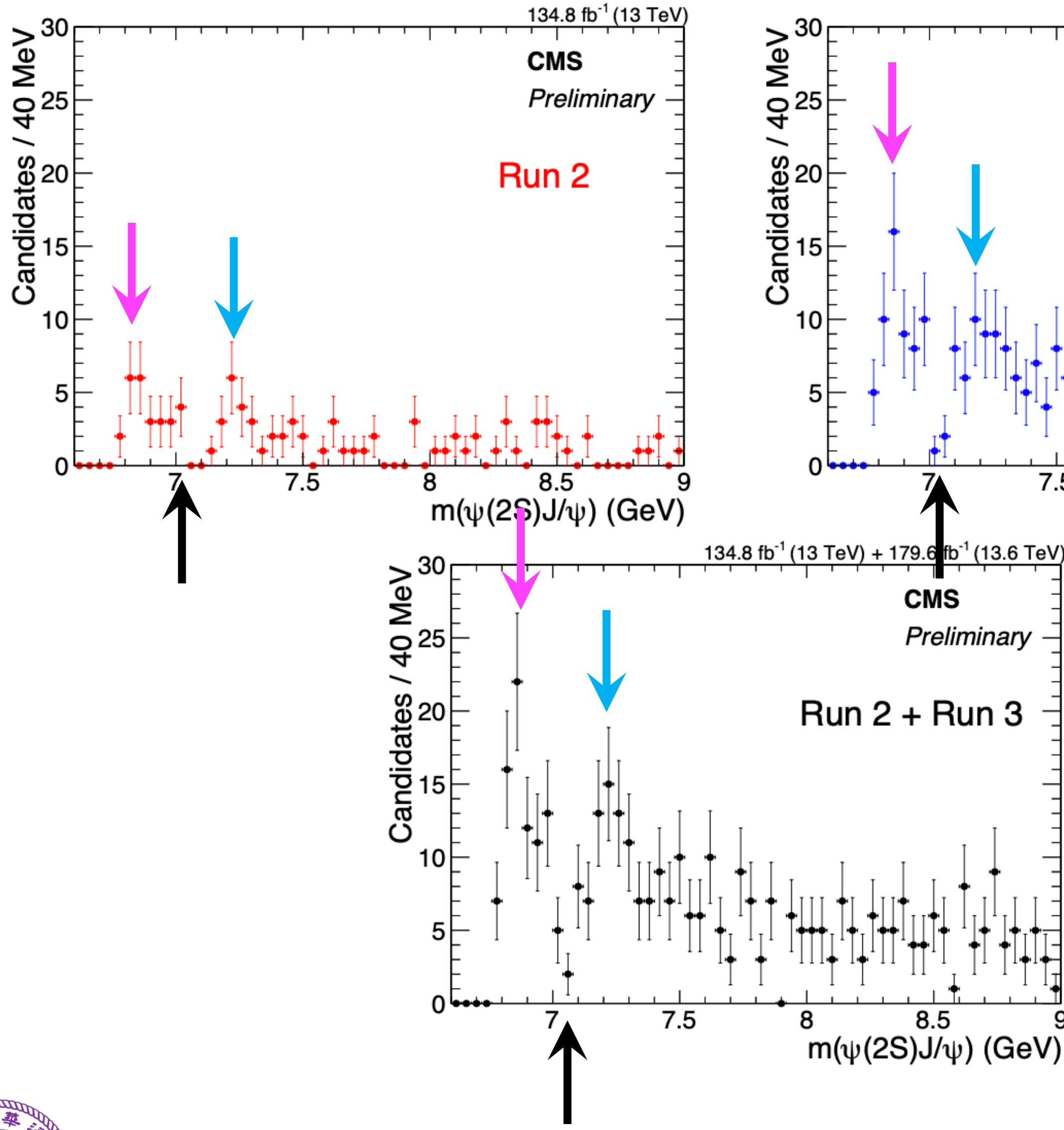


	BW1	BW2	BW3	Interf BW1-BW2	Interf BW2-BW3	Interf BW1-BW2-BW3
Significance (σ)	15.2	16.7	7.7	9.7	6.5	9.9

First observation of interferene

		BW$_1$	BW$_2$	BW$_3$
Interference	m (MeV)	$6593\ ^{+15}_{-14} \pm 25$	$6847\ ^{+10}_{-10} \pm 15$	$7173\ ^{+9}_{-10} \pm 13$
(Run 2+Run 3)	Γ (MeV)	$446\ ^{+66}_{-54} \pm 87$	$135\ ^{+16}_{-14} \pm 14$	$73\ ^{+18}_{-15} \pm 10$
Interference	m (MeV)	$6638\ ^{+43+16}_{-38-31}$	$6847\ ^{+44+48}_{-28-20}$	$7134\ ^{+48+41}_{-25-15}$
(Run 2 [12])	Γ (MeV)	$440\ ^{+230+110}_{-200-240}$	$191\ ^{+66+25}_{-49-17}$	$97\ ^{+40+29}_{-29-26}$

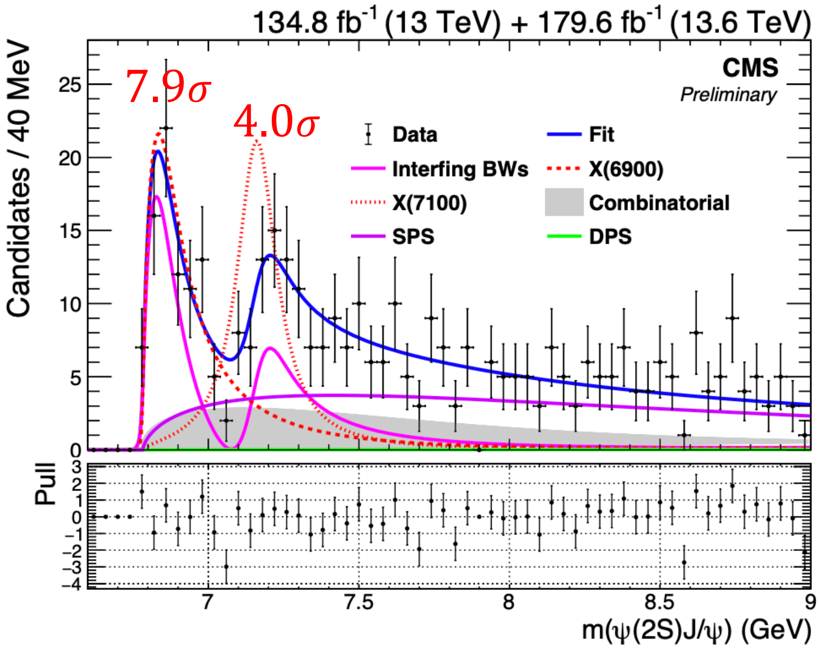
CMS ψ(2S)J/ψ mass Run 2+3



CMS-PAS-BPH-22-004

- X(6900) is obvious
- X(7100) is visible
- Signal dominated by Run3

CMS ψ(2S)J/ψ fit Run 2+3



First observation of X(6900) → ψ(2S)J/ψ

Evidence of X(7100) → ψ(2S)J/ψ

CMS-PAS-BPH-22-004

Submit to Sci. 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]	$J/\psi J/\psi$	Interference	m (MeV)	$6593^{+15}_{-14} \pm 25$	$6847^{+10}_{-10} \pm 15$	$7173^{+9}_{-10} \pm 13$
		(Run 2+Run 3)	Γ (MeV)	$446^{+66}_{-54} \pm 87$	$135^{+16}_{-14} \pm 14$	$73^{+18}_{-15} \pm 10$
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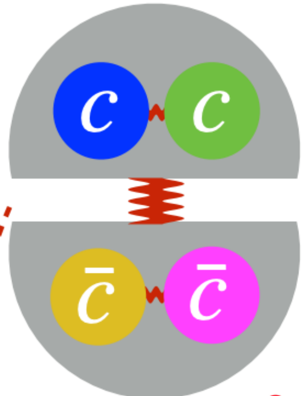
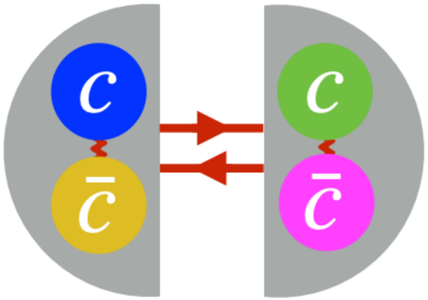
4c States Spin Parity



- Fundamental study of matter at quark level…
  — unique all-heavy tetraquark states



- Quantum numbers $J^{PC} = ?$
  directly related to structure:

- Tightly-bound tetraquark:

(cc) or $(\bar{c}\bar{c})$ identical ⇒ color anti-triplet (bg-gb,..) $L = 0$, axial vector $S_{1,2} = 1$

$(cc) + (\bar{c}\bar{c})$ ⇒ $L = 0\ (\mathrm{n}S):\ S = 0, 2\ \Rightarrow J^P = 0^+, 2^+$ ← most likely for a tetraquark

$L = 1\ (\mathrm{n}P):\ S = 1\ \Rightarrow\ J^P = 0^-, 1^-, 2^-$ ← less likely

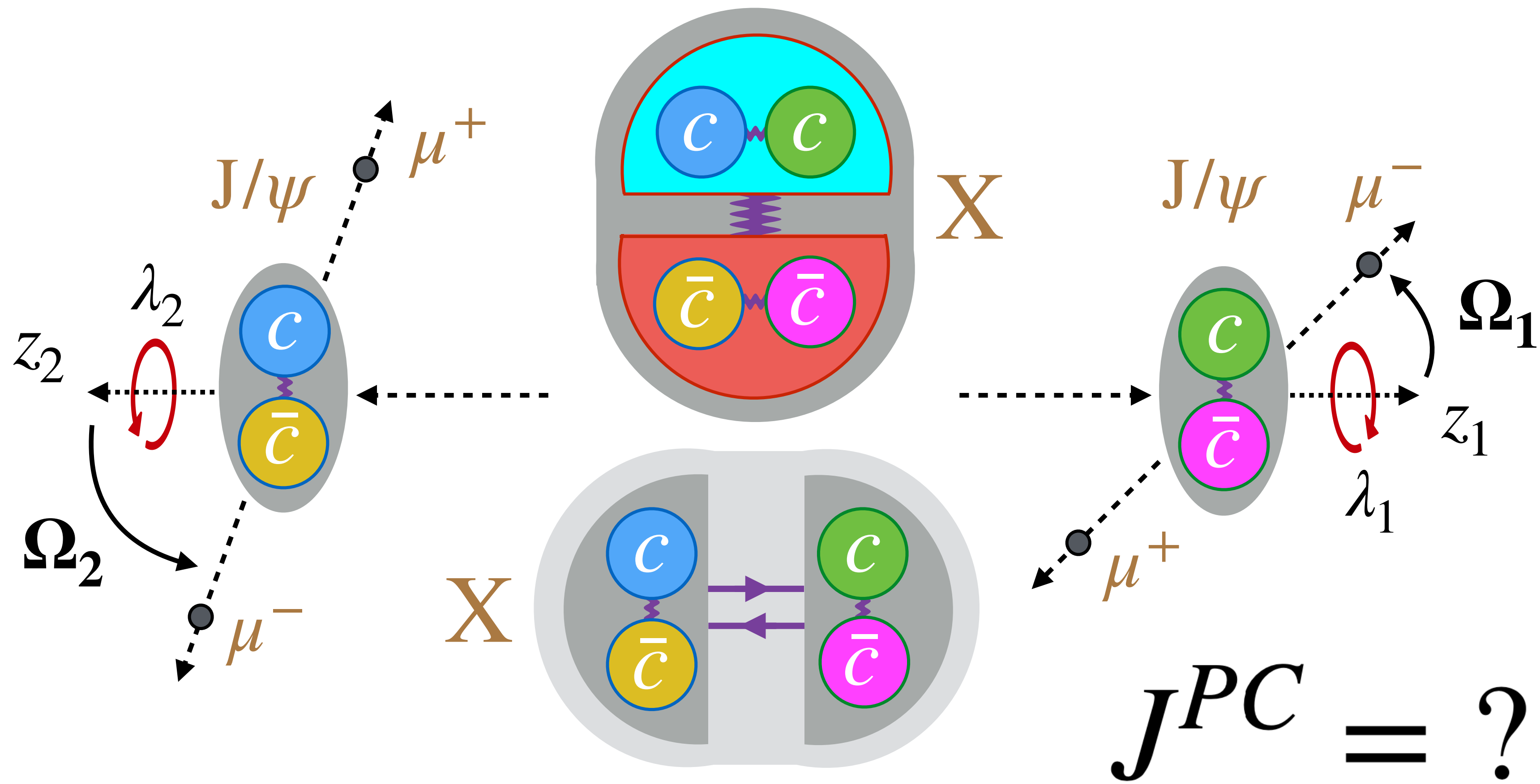
$n = 1,2,3,4,..$ $\quad L = 2\ (\mathrm{n}D):\ S = 0\ \Rightarrow\ J^P = 2^+$

unlikely → 1^+

$S = 2\ \Rightarrow\ J^P = 0^+, 1^+, 2^+, 3^+, 4^+\ \ \ldots$

- Molecular: less restrictions (e.g. meson $S_{1,2} = 0,1$): recall $J^P = 1^+$

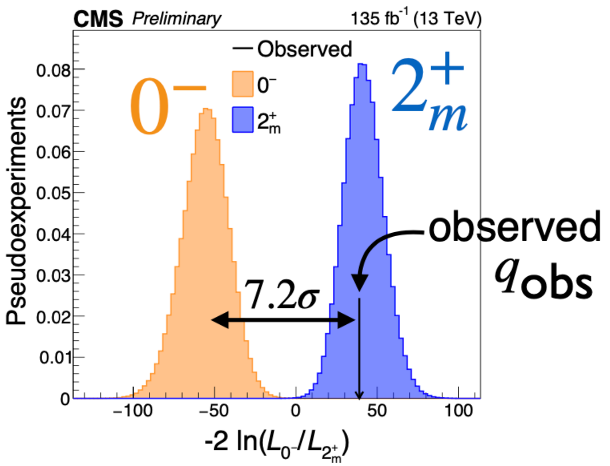
CMS Angular Analysis

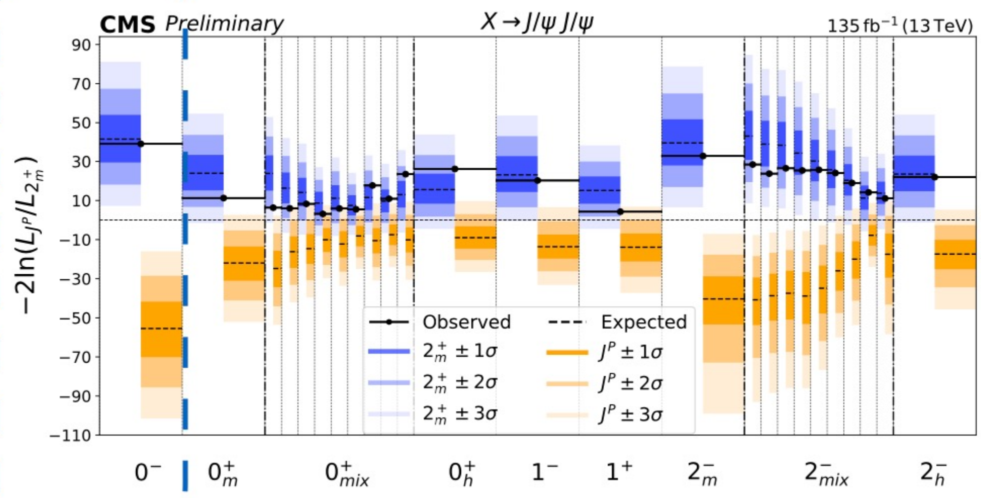


$J^{PC} = ?$

CMS Statistical Analysis of J^{PC}

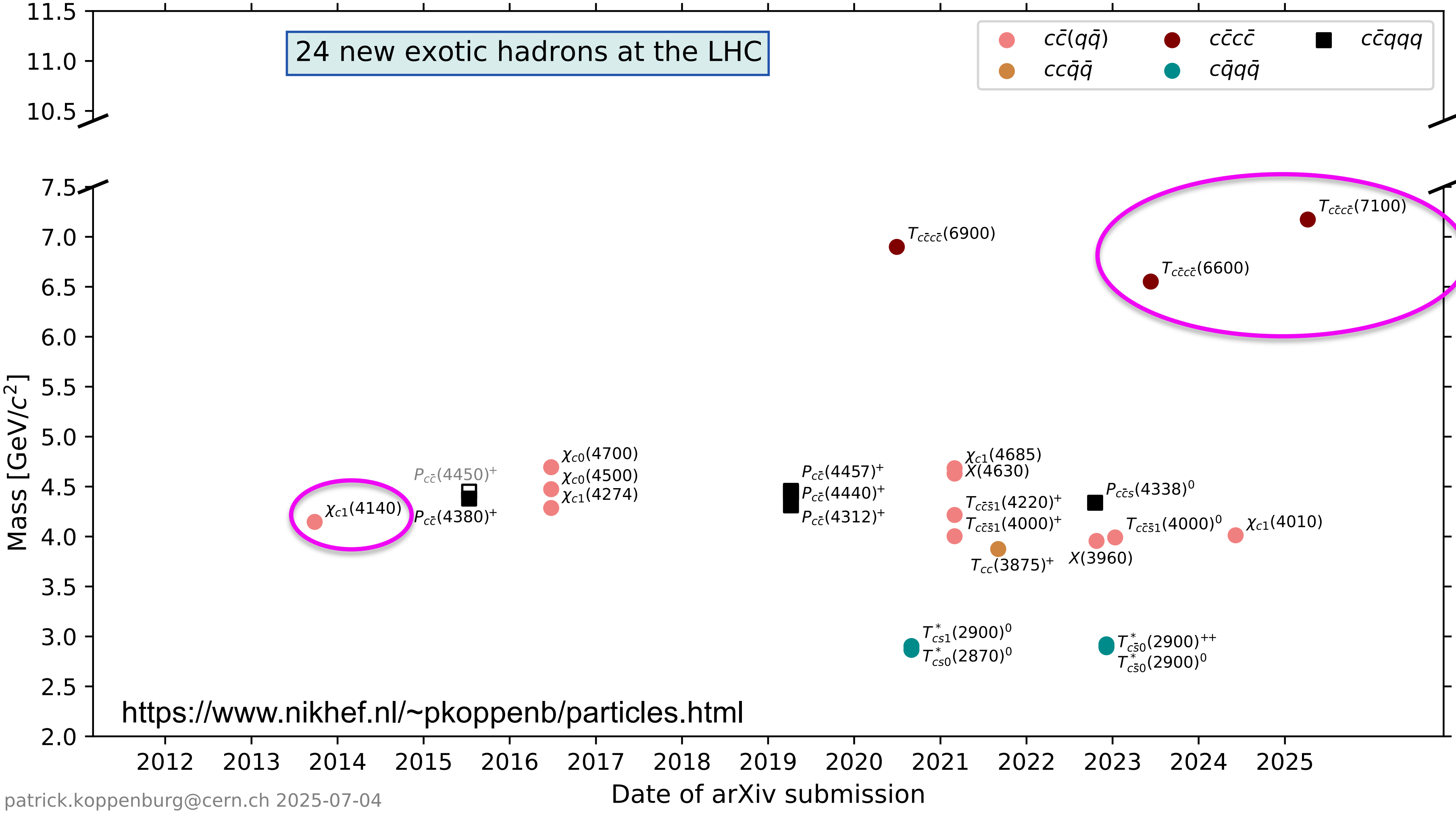
CMS-PAS-BPH-24-002, arXiv:2506.07944, accepted by Nature





- 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

Summary: new exotic hadrons at LHC



More details in Yilin Zhou's talk 8:50 tomorrow

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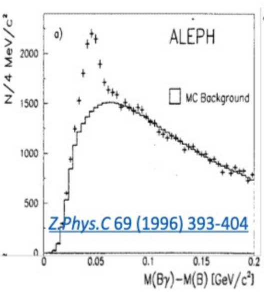
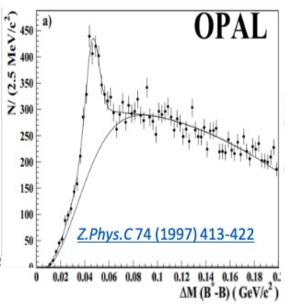
- CP violations
  - Search for CPV through $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ (2024, published in EPJC)
  - Measurement of CPV through $B^0_s \to \mathrm{J}/\psi\,\phi(1020)$ (2024, submitted to PRL)

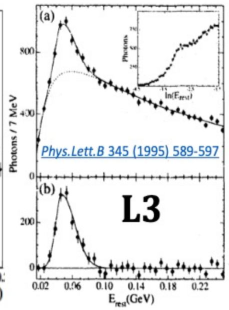
History of B* meson studies

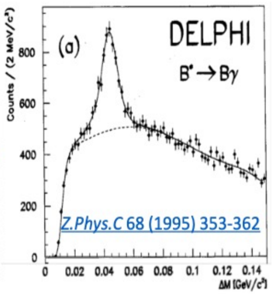
LEP experiments L3, DELPHI, OPAL, ALEPH
using $Z \to b\bar{b}$ process, inclusively reconstruct B meson as **b-jet**
combine **b-jet** with a converted photon (calibrated via π^0)

Measure **averaged between B^{*+}, B^{*0}, and B_s^{*0}** mass difference
***m*(B*)−*m*(B)**









Assumes $\Delta m = m(B^{*0})-m(B^0)=m(B^{*+})-m(B^+)$
for D mesons such Δm are different by 1.5 MeV!

$m_{B^*}-m_B$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN
45.21 ± 0.21 OUR FIT				
45.42 ± 0.26 OUR AVERAGE includes data from $m_{B^*}-m_B$				
46.2 ±0.3 ±0.8		1 ACKERSTAFF	1997M	OPAL
45.3 ±0.35 ±0.87	4227	1 BUSKULIC	1996D	ALEP
45.5 ±0.3 ±0.8		1 ABREU	1995R	DLPH
46.3 ±1.9	1378	1 ACCIARRI	1995B	L3

28+ year-old measurements!

Mass differences also measured via P-wave B_s^0 states

$m(B^{*+})-m(B^+)$ measured by LHCb using the difference between $B^*_{s2}(5840)^0 \to B^{*+}K^-$ and $B^*_{s2}(5840)^0 \to B^+K^-$ peak positions

$m(B^{*+})-m(B^{*0})$ was measured by CMS (BPH-16-003) via the difference between $B_{s1}(5830)^0 \to B^{*0}K^0_S$ and $B_{s1}(5830)^0 \to B^{*+}K^-$ peak positions

PDG still has a single "entry" for B^{*+} and B^{*0}!

- $B^{\pm}$ 1/2(0⁻)
- B^0 1/2(0⁻)
- $B^{\pm}/B^0$ ADMIXTURE
- $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE
- V_{cb} and V_{ub} CKM Matrix Elements
- B^* 1/2(1⁻)
- $B_1(5721)$ 1/2(1⁺)

B^* MASS	5324.71 ± 0.21 MeV
$m_{B^*}-m_B$	45.21 ± 0.21 MeV
$m_{B^{*+}}-m_{B^+}$	45.37 ± 0.21 MeV
$\lvert(m_{B^{*+}}-m_{B^+})-(m_{B^{*0}}-m_{B^0})\rvert$	< 6 MeV CL=95.0%
$m_{B^{*0}}-m_{B^{*+}}$	0.91 ± 0.26 MeV

Main challenge: very low-energy photons emitted in B*→Bγ

Do we have enough data in CMS to exclusively reconstruct B^{*+}, B^{*0}, and B_s^{*0} mesons via J/ψ modes and provide separate measurements of the respective Δm?

$B_s{}^{*0}$ measurements at B-factories

B_s^{*0} mass difference w.r.t. B_s^0 was previously measured at B-factories via the energy spectrum of reconstructed B_s^0 mesons assumed to be produced in Υ(5S) decays:

- $\Upsilon(5S) \to B_s^0 \overline{B}_s^0$
- $\Upsilon(5S) \to B_s^{*0} \overline{B}_s^0$
- $\Upsilon(5S) \to B_s^0 \overline{B}_s^{*0}$
- $\Upsilon(5S) \to B_s^{*0} \overline{B}_s^{*0}$

However, the results were not in a good agreement with each other (PDG scale factor 2.9)

Central value of the mass difference is larger in comparison to B^+ & B^0

$m_{B_s^*} - m_{B_s}$

VALUE (MeV)		DOCUMENT ID		TECN	COMMENT
$48.5^{+1.8}_{-1.5}$	OUR FIT Error includes scale factor of 2.9.				
46.1 ± 1.5	OUR AVERAGE				
$45.7 \pm 1.7 \pm 0.7$		[1] AQUINES	2006	CLEO	$e^+ e^- \to \Upsilon(5S)$
47.0 ± 2.6		[2] LEE-FRANZINI	1990	CSB2	$e^+ e^- \to \Upsilon(5S)$

B_s^* MASS

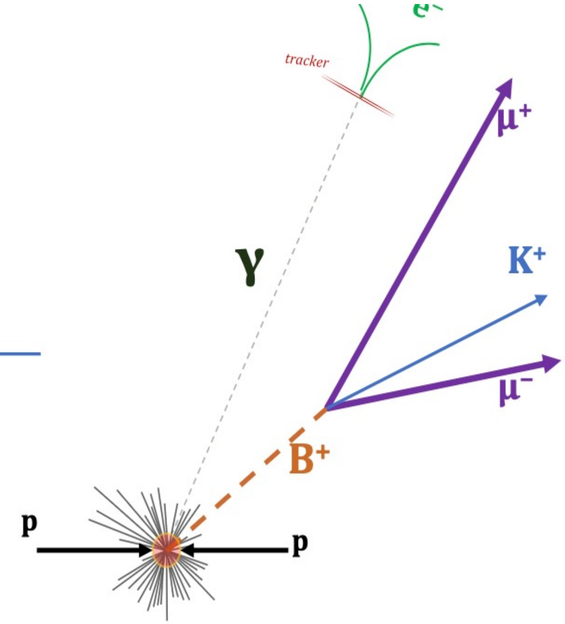
From mass difference below and the B_s^0 mass.

VALUE (MeV)		DOCUMENT ID		TECN
$5415.4^{+1.8}_{-1.5}$	OUR FIT Error includes scale factor of 2.9.			
5415.8 ± 1.5	OUR AVERAGE Error includes scale factor of 2.6.			
$5416.4 \pm 0.4 \pm 0.5$		LOUVOT	2009	BELL
$5411.7 \pm 1.6 \pm 0.6$		[1] AQUINES	2006	CLEO

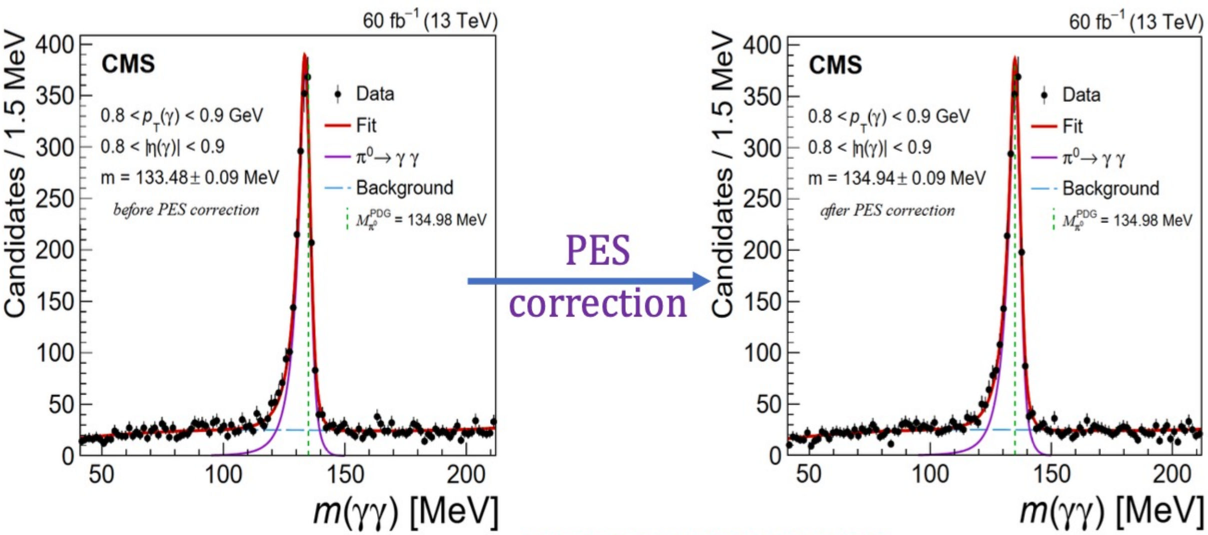
Do we have enough data in CMS to exclusively reconstruct B^{*+}, B^{*0}, and B_s^{*0} mesons via J/ψ modes and provide separate measurements of the respective Δm?

[CMS-BPH-24-011](), [arXiv:2508.05820]()

- No selection of a single trigger, use all
- Standard reconstruction of charmonium decays
  - $B^+ \to \psi K^+$, $B^0 \to \psi K^*(892)^0$ $[K^+\pi^-]$, $B_s^0 \to \psi \varphi$ $[K^+K^-]$, J/ψ or $\psi(2S)$ $\to \mu^+\mu^-$
- Add a **photon conversion**, refit e^+e^- tracks with m=0 constraint, Fit Bγ vertex
- Refit Bγ into PV to improve the mass resolution



Photon energy scale calibration with π^0



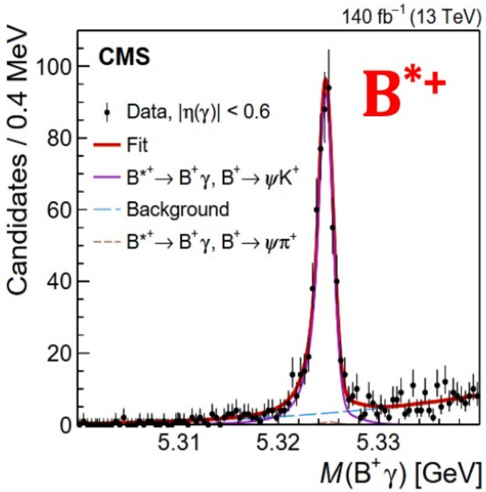
PDG π^0 mass: 134.9768 ± 0.0005 MeV

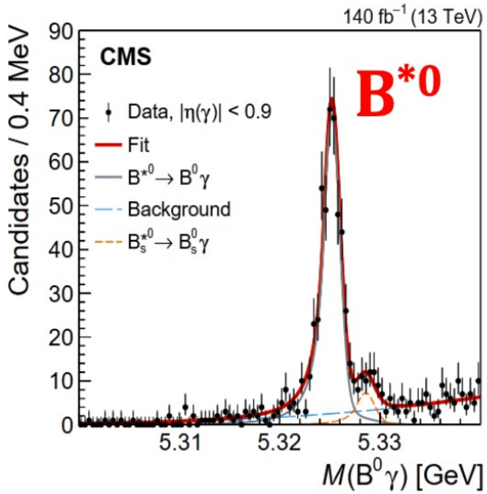
Photon energy from conversions is underestimated out of the box, developed a dedicated correction

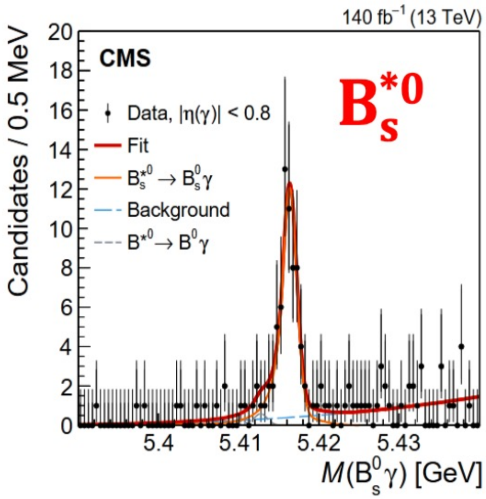
$\pi^0 \to \gamma\gamma$ signal from two conversions, in a number of p_T and η ranges,

B* signals in CMS Run 2 data

CMS-BPH-24-011, arXiv:2508.05820







Simultaneous fit in the 7 categories

Most sensitive 3 are shown here, the other 4 in backup

Signals are described by DCB shapes fixed to MC
except a common (for all) resolution scaling factor

Mass differences are shared (within B flavour)

$B^+ \to J/\psi\pi^+$ fixed shape and relative normalization

$B^{*0} \Leftrightarrow B_s^{*0}$ cross-feed: shifted signal shapes, for B^{*0} fixed relative normalization

Bkg: $(m-m^0)^\beta$ with common β

3 states reconstructed fully exclusively for the 1st time

Precision order of magnitude better than PDG

Systematics much smaller than stat. uncertainty

$M(X\gamma) = m(X\gamma) - m(X) + M^{PDG}(X)$

CMS B* mass results

CMS-BPH-24-011, arXiv:2508.05820

	Parameter	Value
1	$\Delta m(\mathrm{B}^{*+}) \equiv m(\mathrm{B}^{*+}) - m(\mathrm{B}^{+})$	$45.277 \pm 0.039 \pm 0.027$ MeV
2	$\Delta m(\mathrm{B}^{*0}) \equiv m(\mathrm{B}^{*0}) - m(\mathrm{B}^{0})$	$45.471 \pm 0.056 \pm 0.028$ MeV
3	$\Delta m(\mathrm{B}_s^{*0}) \equiv m(\mathrm{B}_s^{*0}) - m(\mathrm{B}_s^{0})$	$49.407 \pm 0.132 \pm 0.041$ MeV
4	$m(\mathrm{B}^{*+})$	$5324.69 \pm 0.04 \pm 0.03 \pm 0.07$ MeV
5	$m(\mathrm{B}^{*0})$	$5325.19 \pm 0.06 \pm 0.03 \pm 0.08$ MeV
6	$m(\mathrm{B}_s^{*0})$	$5416.34 \pm 0.13 \pm 0.04 \pm 0.10$ MeV
7	$m(\mathrm{B}^{*0}) - m(\mathrm{B}^{*+})$	$0.50 \pm 0.07 \pm 0.01 \pm 0.05$ MeV
8	$m(\mathrm{B}_s^{*0}) - m(\mathrm{B}^{*+})$	$91.66 \pm 0.14 \pm 0.03 \pm 0.12$ MeV
9	$m(\mathrm{B}_s^{*0}) - m(\mathrm{B}^{*0})$	$91.15 \pm 0.14 \pm 0.03 \pm 0.12$ MeV
10	$m(\mathrm{B}_s^{*0}) - \frac{1}{2}\left[m(\mathrm{B}^{*0}) + m(\mathrm{B}^{*+})\right]$	$91.40 \pm 0.13 \pm 0.03 \pm 0.12$ MeV
11	$\Delta m(\mathrm{B}^{*0}) - \Delta m(\mathrm{B}^{*+})$	$0.19 \pm 0.07 \pm 0.01$ MeV
12	$\Delta m(\mathrm{B}_s^{*0}) - \Delta m(\mathrm{B}^{*+})$	$4.13 \pm 0.14 \pm 0.03$ MeV
13	$\Delta m(\mathrm{B}_s^{*0}) - \Delta m(\mathrm{B}^{*0})$	$3.94 \pm 0.14 \pm 0.03$ MeV
14	$\Delta m(\mathrm{B}_s^{*0}) - \frac{1}{2}\left[\Delta m(\mathrm{B}^{*0}) + \Delta m(\mathrm{B}^{*+})\right]$	$4.03 \pm 0.13 \pm 0.03$ MeV
15	$\Delta m(\mathrm{B}^{*0}) / \Delta m(\mathrm{B}^{*+})$	$1.0043 \pm 0.0015 \pm 0.0002$
16	$\Delta m(\mathrm{B}_s^{*0}) / \Delta m(\mathrm{B}^{*+})$	$1.0912 \pm 0.0031 \pm 0.0007$
17	$\Delta m(\mathrm{B}_s^{*0}) / \Delta m(\mathrm{B}^{*0})$	$1.0866 \pm 0.0031 \pm 0.0007$
18	$2\,\Delta m(\mathrm{B}_s^{*0}) / \left[\Delta m(\mathrm{B}^{*+}) + \Delta m(\mathrm{B}^{*0})\right]$	$1.0889 \pm 0.0030 \pm 0.0007$

PDG 2024 [MeV]

45.34 ± 0.20
45.34 ± 0.20
48.5 ± 1.4

Main result: hyperfine splittings in B system
Order of magnitude precision improvement!

Adding PDG B masses

"B* mass" 5324.75±0.20 MeV
B_s^{*0} mass 5415.4±1.4 MeV

Mass differences between vector states

In agreement, 3 times more precise

CMS-BPH-16-003

$M_{\mathrm{B}^{*0}} - M_{\mathrm{B}^{*+}} = 0.91 \pm 0.24 \pm 0.09 \pm 0.02$ MeV

first measurements

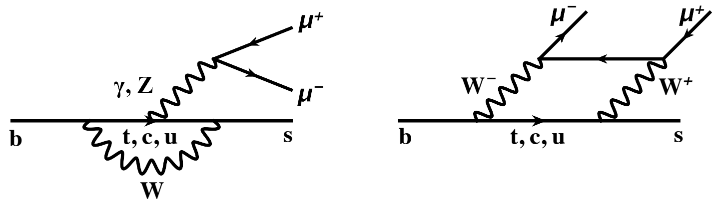
Differences between hyperfine splittings: ***first measurements***

Ratios between hyperfine splittings: ***first measurements***

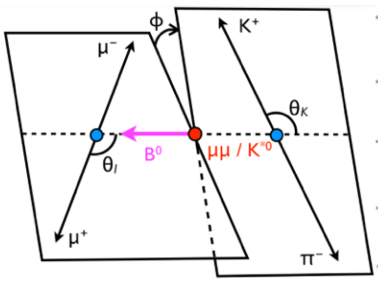
Submitted to PRL

Full angular analysis of $B^0 \to K^{*0}\mu\mu$

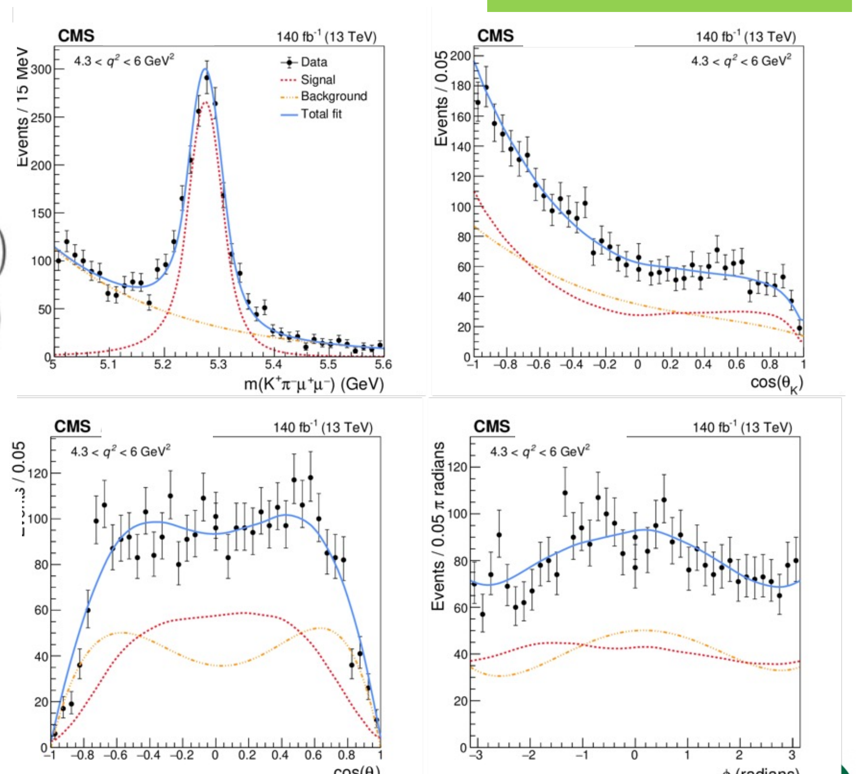
golden indirect probes of NP



CMS-BPH-21-002
PLB 864 (2025) 139406



$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\,d\cos\theta_l\,d\cos\theta_K\,d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + \boxed{F_L}\cos^2\theta_K$$
$$+\left(\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\right)\cos 2\theta_l$$
$$+\frac{1}{2}\boxed{P_1}(1-F_L)\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+\sqrt{(1-F_L)F_L}\left(\frac{1}{2}\boxed{P_4'}\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{P_5'}\sin 2\theta_K\sin\theta_l\cos\phi\right)$$
$$-\sqrt{(1-F_L)F_L}\left(\boxed{P_6'}\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}\boxed{P_8'}\sin 2\theta_K\sin 2\theta_l\sin\phi\right)$$
$$+2\boxed{P_2}(1-F_L)\sin^2\theta_K\cos\theta_l - \boxed{P_3}(1-F_L)\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big],$$



$$\mathrm{pdf}(m,\cos\theta_K,\cos\theta_l,\phi) = Y_S\Big[S^C(m)\,S^a(\cos\theta_K,\cos\theta_l,\phi)\,\epsilon^C(\cos\theta_K,\cos\theta_l,\phi)$$
$$+R\cdot S^M(m)\,S^a(-\cos\theta_K,-\cos\theta_l,-\phi)\,\epsilon^M(\cos\theta_K,\cos\theta_l,\phi)\Big]$$
$$+Y_B\,B^m(m)\,B^a(\cos\theta_K,\cos\theta_l,\phi)$$

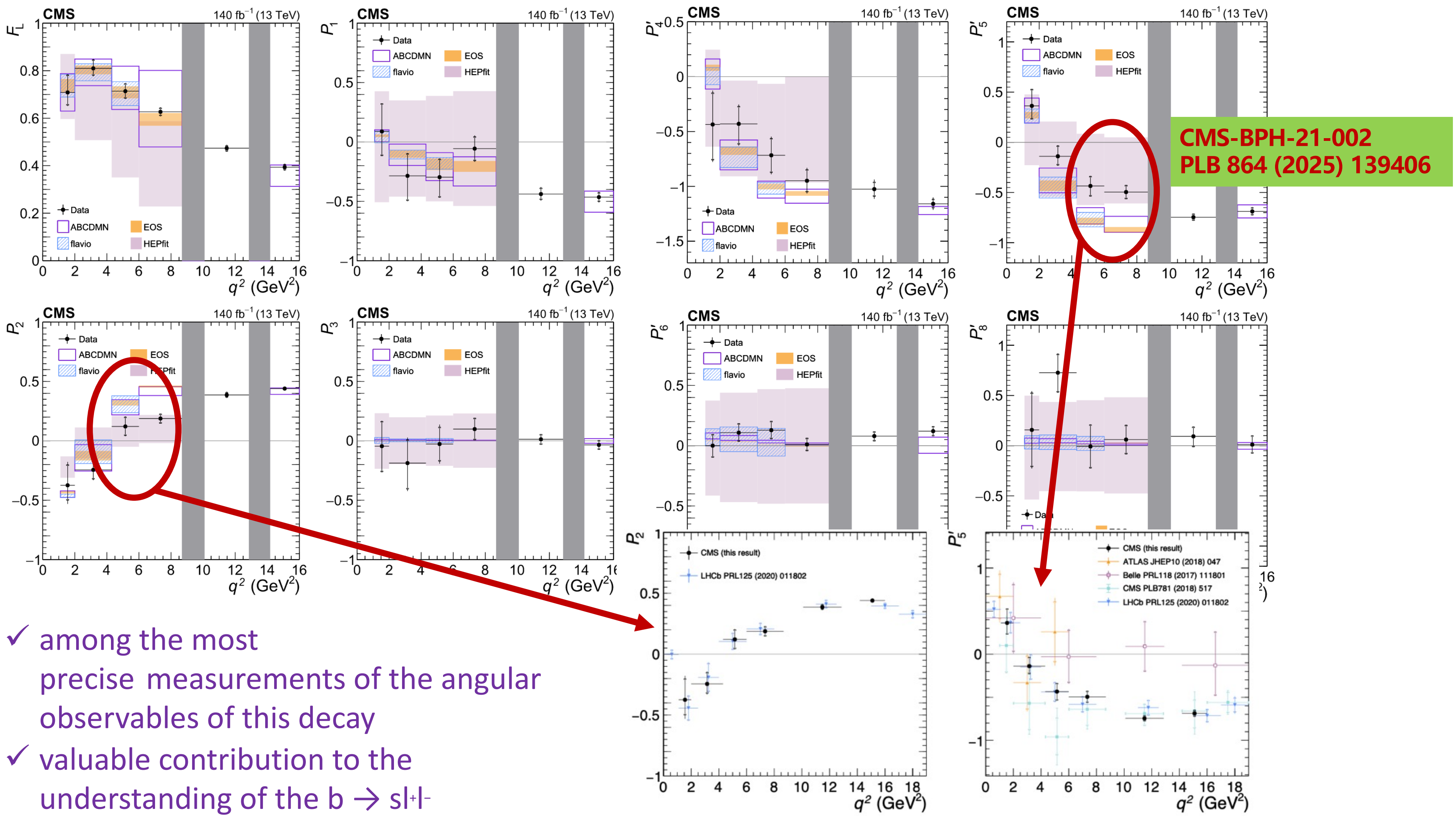
Angular rate

Signal and bkg mass shapes

KDE efficiency

Bkg angular shape

Full angular analysis of $B^0 \to K^{*0}\mu\mu$



- ✓ among the most precise measurements of the angular observables of this decay
- ✓ valuable contribution to the understanding of the $b \to sl^+l^-$

Recent HF and CPV results

- Spectroscopy of exotic hadrons
  - Observation of X(6600) and X(7100) in $\mathrm{J}/\psi\,\mathrm{J}/\psi$
    Observation of X(6900) in $\mathrm{J}/\psi\,\psi(2S)$ (4/2025, submit to Sci. Adv.)
  - Spin-parity measurement of the tetraquark family X(6600),X(6900),X(7100) (4/2025, accepted by Nature)

- Conventional hadrons
  - CMS: First full reconstruction of B* mesons (5/2025, submitted to PRL)
  - Full angular analysis of $\mathrm{B}^0 \to \mathrm{K}^*(892)^0\mu^+\mu^-$ (3/2025, published in PLB)

- CP violations
  - Search for CPV through $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ (2024, published in EPJC)
  - Measurement of CPV through $B^0_s \to \mathrm{J}/\psi\,\phi(1020)$ (2024, submitted to PRL)

Search for CPV in $D^0 \to K_s^0 K_s^0$

- CPV in up-quark (heavily suppressed) not as well studied as in down-quark

First observation by LHCb $A_{CP}(D^0 \to KK) - A_{CP}(D^0 \to \pi\pi) = (-15.4 \pm 2.9) \times 10^{-4}$

Belle $A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\,\%$

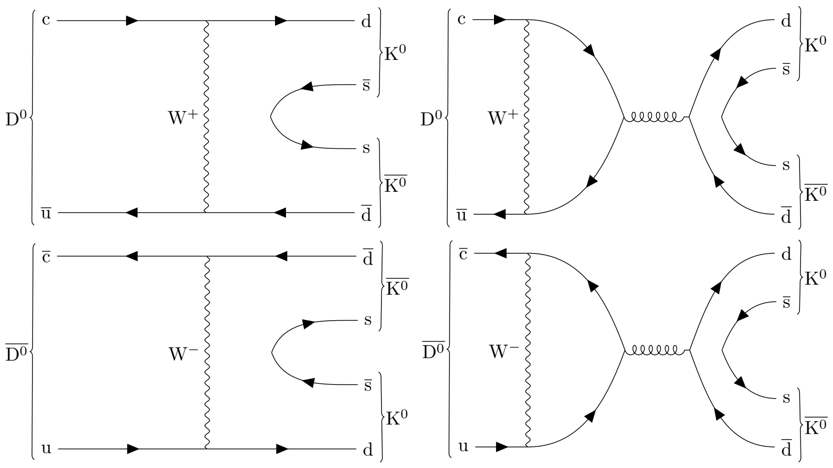
LHCb $A_{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\,\%$ PRL122(2019)211803

The current world average for the time-integrated CP asymmetry is $A_{CP}(K_S^0 K_S^0) = -1.9 \pm 1.1\,\%$ [19], which is dominated by results from the LHCb [25] and Belle [26] Collaborations.

- First CPV measurement in charm sector at CMS
  - 2018 data, 41.6 fb^{-1} BParking dataset
  - contains O(10^{10}) semileptonic B decays

$$A_{CP} = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$$

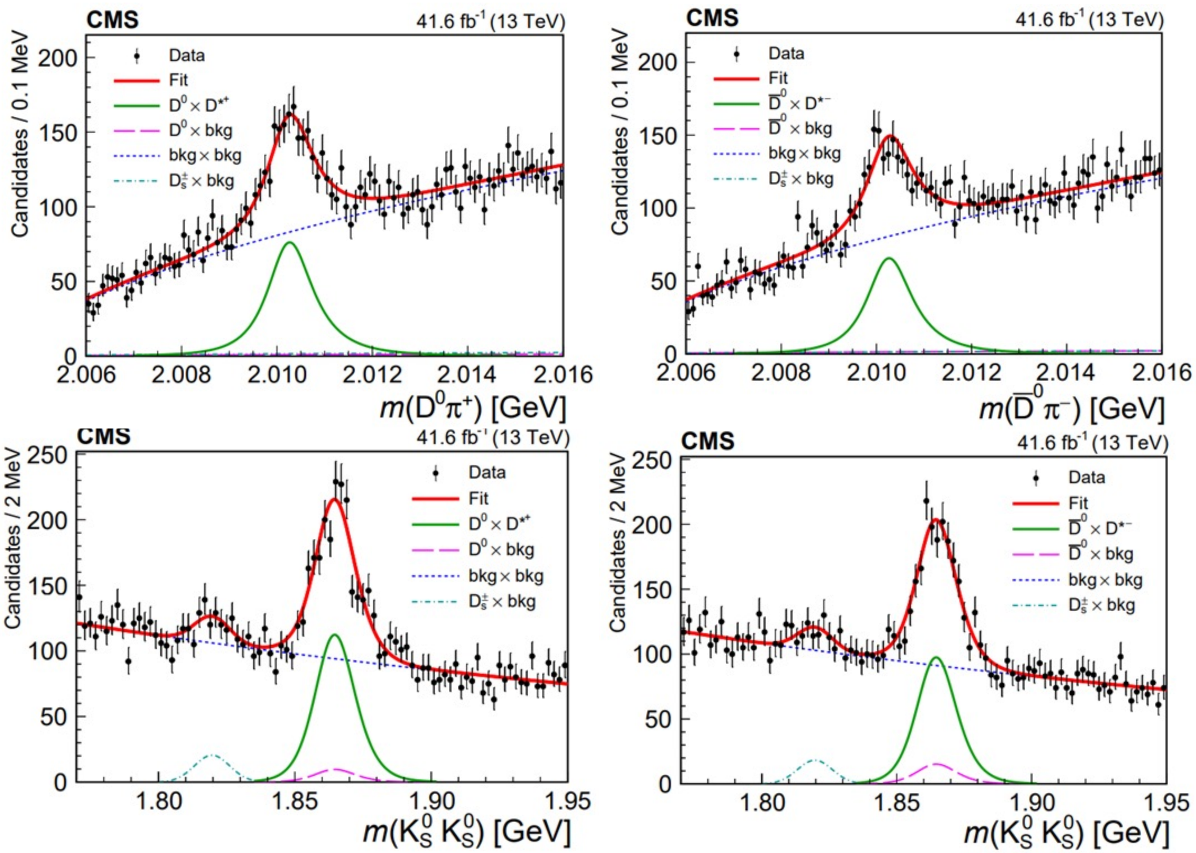
$$A_{CP} = A_{CP}^{\text{raw}} - A_{CP}^{\text{pro}} - A_{CP}^{\text{det}}$$



Search for CPV in $D^0 \to K_s^0 K_s^0$

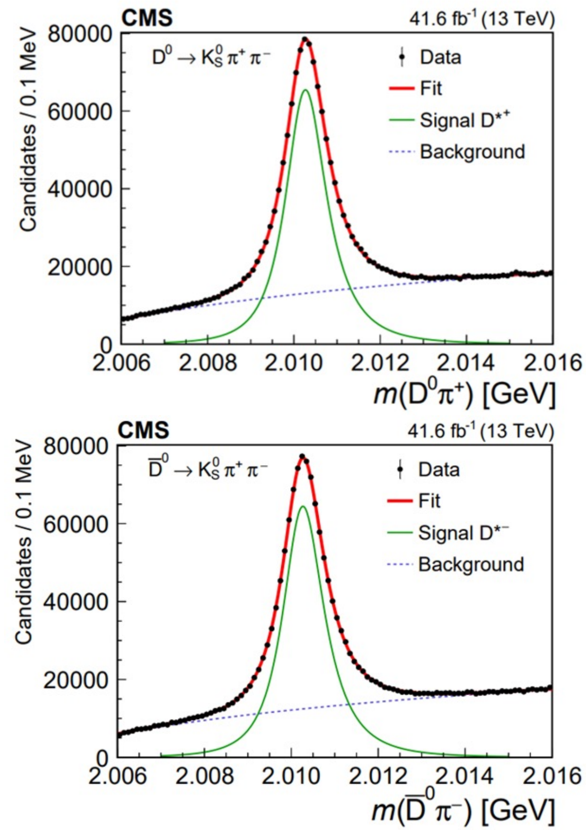
$A_{CP}^{raw}(\mathrm{K_S^0K_S^0}) = (7.1 \pm 3)\,\%$

Pion charge	N	χ^2 (x axis)	χ^2 (y axis)
π^+	1095 ± 46	77	90
π^-	951 ± 44	93	62



$A_{CP}^{raw}(\mathrm{K_S^0}\pi\pi) = (0.78 \pm 0.10)\,\%$

Charge of pion	N	χ^2 with 100 bins
π^+	944817 ± 3489	78
π^-	930148 ± 3395	93



$$A_{CP} = A_{CP}^{raw}(\mathrm{K_S^0K_S^0}) - A_{CP}^{raw}(\mathrm{K_S^0}\pi\pi) - A_{CP}(\mathrm{K_S^0}\pi\pi)$$

Search for CPV in $D^0 \to K_s^0 K_s^0$

$$\Delta A_{CP} \equiv A_{CP}(\mathrm{K_S^0 K_S^0}) - A_{CP}(\mathrm{K_S^0}\pi^+\pi^-) = 6.3 \pm 3.0\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst})\,\%.$$

$$A_{CP}(\mathrm{K_S^0 K_S^0}) = 6.2 \pm 3.0\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}) \pm 0.8(A_{CP}(\mathrm{K_S^0}\pi^+\pi^-))\,\%$$

Source	Uncertainty, %
$m(\mathrm{D}\pi^\pm)$ signal model	0.10
$m(\mathrm{D}\pi^\pm)$ background model	0.02
$m(\mathrm{K_S^0 K_S^0})$ signal model	0.04
$m(\mathrm{K_S^0 K_S^0})$ background model	0.02
$m(\mathrm{K_S^0 K_S^0})$ fit range	0.04
Reweighting	0.09
ΔA_{CP} in MC	0.13
Total	0.20

- Compatible with no CPV at 2σ, with LHCb at 2.7σ, with Belle at 1.8σ
- Statistically limited， systematic primarily from fit models
- Paves the way for future more accurate measurements
- More details in Vladimir’s talk at 14:20 this afternoon

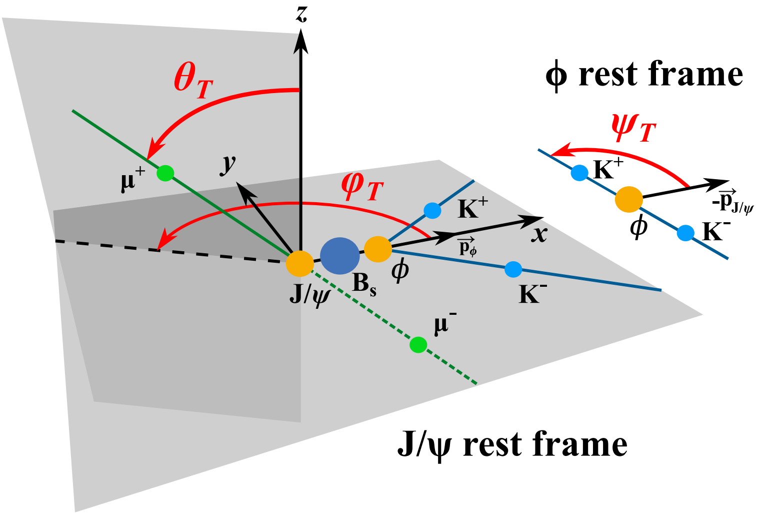
EPJC84(2024)1264

CPV in $B_s^0 \to J/\psi\,\phi(1020)$ decays

- 2017 + 2018 dataset, 13 TeV, 96.5 fb^{-1} (~ 491000 signal events)
  - passing $J/\psi + \mu$ or $J/\psi + \phi$ trigger
  - $J/\psi \to \mu\mu$, $\phi \to KK$
- Time-and flavour-dependent angular analysis, 7D UML fit

$$m, ct, \sigma_{ct}, \omega_{tag}, \cos\theta_{\mathrm{T}}, \cos\psi_{\mathrm{T}}, \varphi_{\mathrm{T}}$$

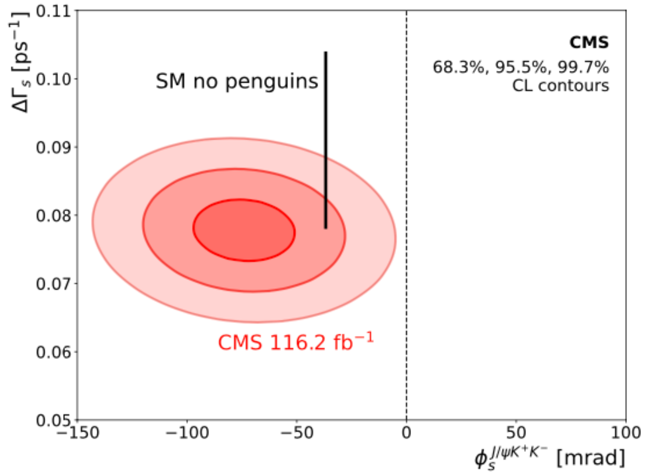
- **angular analysis**: to separate CP eigenstates
  angular efficiencies
- **flavour tagging**: to infer $\mathrm{B_s^0}/\bar{\mathrm{B}}_s^0$ flavour at production
  tagging decision and mistag probability
- **time analysis**: to model flavour oscillations
  time efficiency and resolution



CPV in $B_s^0 \to J/\psi\,\phi(1020)$ decays

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-73	± 23	± 7
$\Delta\Gamma_s$ [ps^{-1}]	0.0761	$\pm$ 0.0043	$\pm$ 0.0019
Γ_s [ps^{-1}]	0.6613	$\pm$ 0.0015	$\pm$ 0.0028
Δm_s [$\hbar$ps^{-1}]	17.757	$\pm$ 0.035	$\pm$ 0.017
$\lvert\lambda\rvert$	1.011	$\pm$ 0.014	$\pm$ 0.012
$\lvert A_0\rvert^2$	0.5300	$\pm$ 0.0016	$\pm$ 0.0044
$\lvert A_\perp\rvert^2$	0.2409	$\pm$ 0.0021	$\pm$ 0.0030
$\lvert A_S\rvert^2$	0.0067	$\pm$ 0.0033	$\pm$ 0.0009
$\delta_\parallel$	3.145	$\pm$ 0.074	$\pm$ 0.025
$\delta_\perp$	2.931	$\pm$ 0.089	$\pm$ 0.050
$\delta_{S\perp}$	0.48	$\pm$ 0.15	$\pm$ 0.05

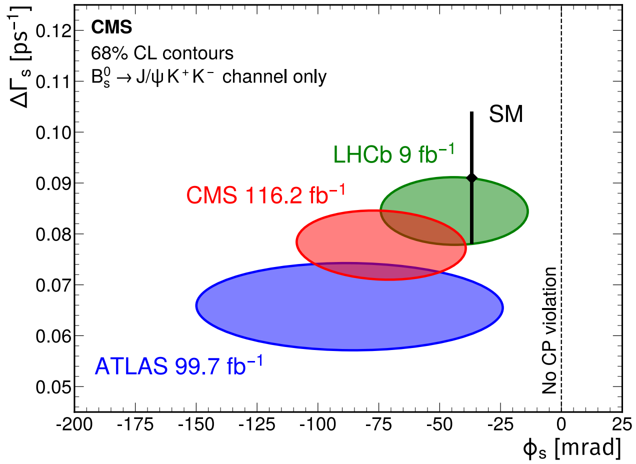
combined with 8 TeV analysis



3.2 σ evidence of CP violation in $B_s^0 \to J/\psi\phi$ decays

results in agreement with SM and other experiments

still statistically limited, competitive with other measurements



Comparable in precision to the world's most precise single measurement by LHCb

arXiv:2412.19952 , Submitted to PRL

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  - Measurement of CPV through $B^0_s \to \mathrm{J}/\psi\,\phi(1020)$ (2024, submitted to PRL)

Quarkonium measurements

- First Upsilon cross-section measurements with Run 3 data
  - Extended to **higher pT**: up to 200 GeV
  - At **higher** collision energy: 13.6 TeV
  - Close collaboration with theorists from China: Yanqing Ma, Yu Feng, Hongfei Zhang, Zhiguo He, …
  - Results to be shown in the QWG conference next month

- Experimental Review of the Quarkonium Physics at the LHC

  Symmetry **2025**, *17*(9), 1521;

  https://doi.org/10.3390/sym17091521

  Published in the Special Issue:

  Symmetry in Hadron Physics (Jialun Ping)

Summary

- CMS paint a full picture of fully-charm tetraquarks:
  - Measured masses of 3 resonances with full Run2+3 data
  - Measurement of spin-parity reveal their $J^{PC} = 2^{++}$
- CMS fully exclusively reconstruct, for the first time, B^{*+}, B^{*0}, and B_s^{*0} signals
  - Order of magnitude precision improvement in the Δm values!
  - 18 various measurements, including differences and ratios, are provided for completeness
- The first CMS measurement of CP violation in charm is performed
- Full angular analysis of $\boldsymbol{B^0 \to K^{*0} \mu\mu}$
- Stay tuned for more results including those with much larger Run 3 dataset!

Thank you!