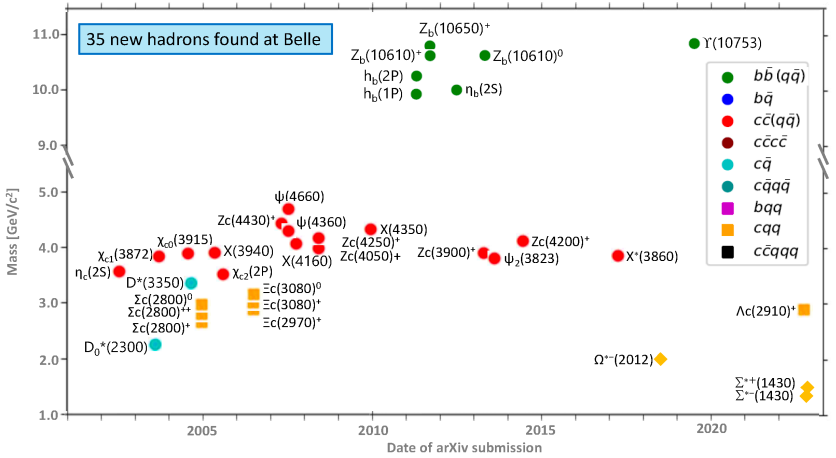
Hadron Spectroscopy

Kai Yi
Nanjing Normal University
ICFA Seminar 2026
Tomaya, Japan · November 4, 2026

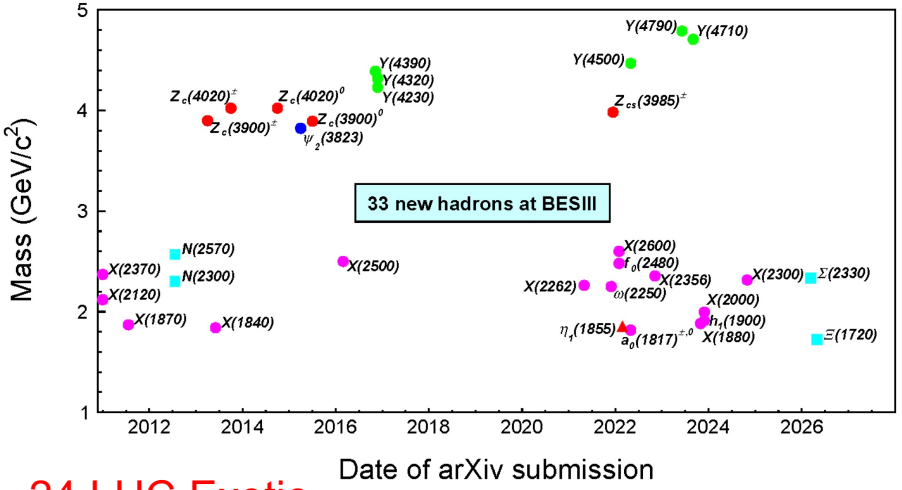


New particle Zoo

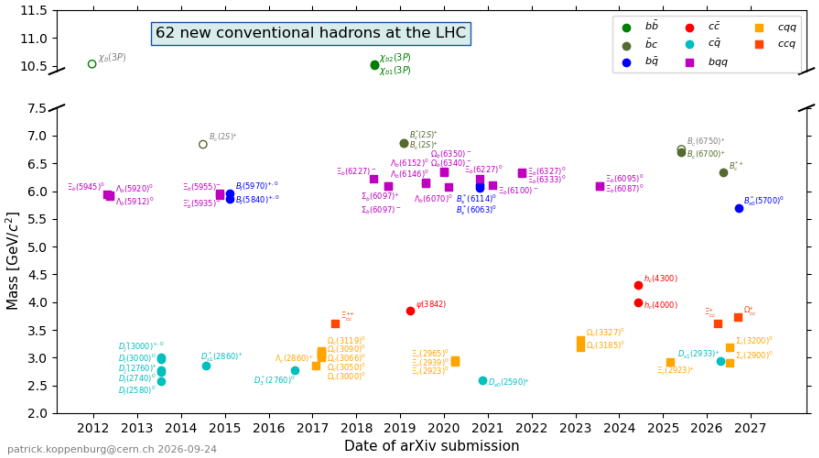
35 Belle hadrons



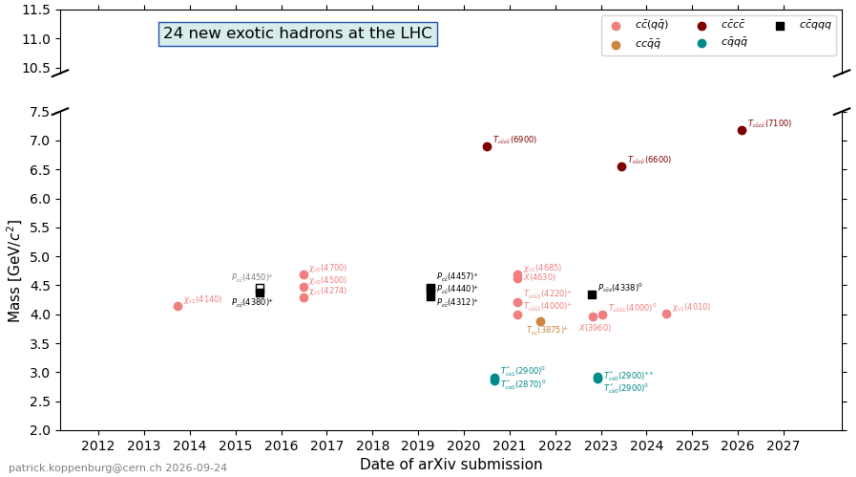
33 BESIII hadrons



62 LHC conventional



24 LHC Exotic

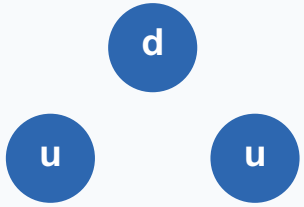


Traditional Hadrons & The Top Quark Exception

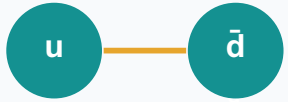
Physics Letters 8, 214 (1964)

Hadron Confinement

Quarks form color-neutral hadrons: baryons (qqq) and mesons (qq̄).



p = uud



$\pi^+ = u\,\bar{d}$

5 Active Flavors

Up, down, strange, charm and bottom form observable hadrons.

Up · Down · Strange · Charm · Bottom

Forms Hadrons Successfully

Top Quark Exception

Top quarks decay before hadronization can occur.

?

Top Decay: ~5×10^{-25} s

Hadronization: ~10^{-23} s

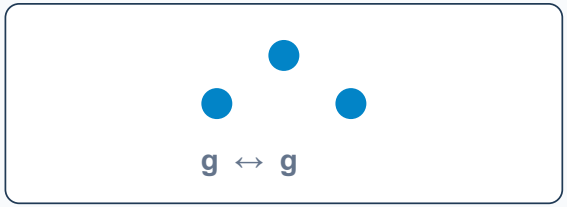
No traditional hadrons formed

Exotic hadrons

Bound states beyond conventional quark–antiquark and three-quark hadrons

GLUONIC

GLUEBALLS



Bound states dominated by gluons, enabled by the self-interaction of QCD.

Fritzsch & Minkowski (1975)
Nuovo Cimento A 30, 393

EXOTIC $\bar{Q}Q$

MULTIQUARKS



Four-quark and five-quark configurations extend beyond the simplest meson and baryon valence pictures.

R. L. Jaffe (1977)
Phys. Rev. D 15, 267

$t\bar{t}$

TOPONIUM



A top–antitop dynamic proposed in 1980’s

J. H. Kühn (1985)
CERN-TH.4151/85

Schematic configurations • Not to scale

Sources: DOI 10.1007/BF02730295 | 10.1103/PhysRevD.15.267 | CERN-TH.4151/85

Outline for recent experimental progress

Conventional and near-threshold hadrons

- BESIII, Belle II, LHCb and ATLAS/CMS

Exotic hadrons and QCD threshold dynamics

- Glueball candidates at BESIII
- All-charm structures at ATLAS, CMS and LHCb
- Toponium at ATLAS and CMS

Overall summary

Recent progress in hadron spectroscopy

BESIII

X(3872) and Tcc(4020)

Coupled-channel Analysis of $\chi_{c1}(3872)$

- Line shape crucial to understand nature of $\chi_{c1}(3872)$
- Advantages at BESIII:
  - Simultaneous access to $\pi\pi J/\psi$ and $D^0\bar{D}^{*0} \to D^0\bar{D}^0\pi^0$
  - Very good mass resolutions:
    $\pi^+\pi^- J/\psi$ ~ 2 MeV; $D^0\bar{D}^0\pi^0$ ~ 0.8 MeV

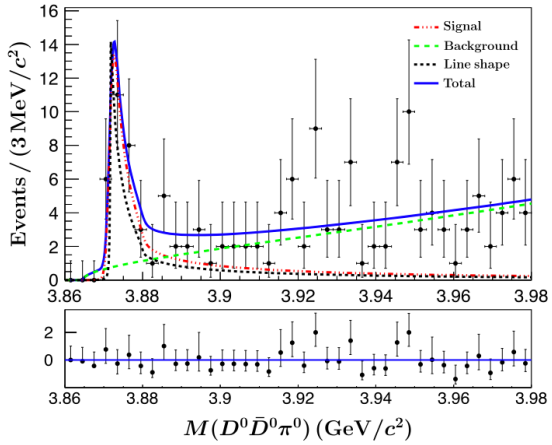
- Use framework developed by Hanhart et al.
  PRD 81, 094028 (2010)

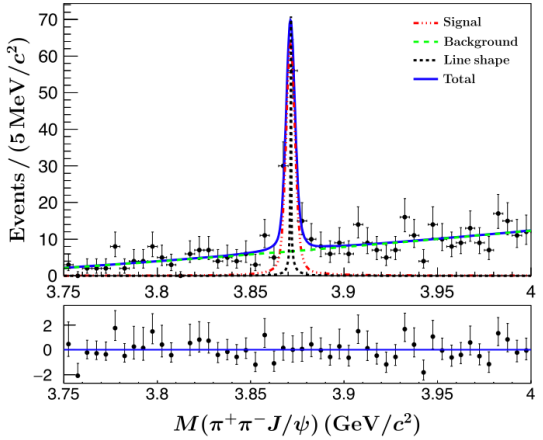
$$\frac{d\mathrm{B}(D^0\bar{D}^0\pi^0)}{dE} = \boldsymbol{B}\frac{1}{2\pi} \times \frac{g * k_{\mathrm{eff}}(E)}{|D(E)|^2} \times \mathrm{Br}(D^{*0} \to D^0\pi^0)$$

$$\frac{d\mathrm{B}(\pi^+\pi^- J/\psi)}{dE} = \boldsymbol{B}\frac{1}{2\pi} \times \frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}$$

$$D(E) = E - E_X + \frac{1}{2}g * \left(\kappa_{\mathrm{eff}}(E) + ik_{\mathrm{eff}}(E) + \kappa^c_{\mathrm{eff}}(E) + ik^c_{\mathrm{eff}}(E)\right) + \frac{i}{2}\Gamma_0$$

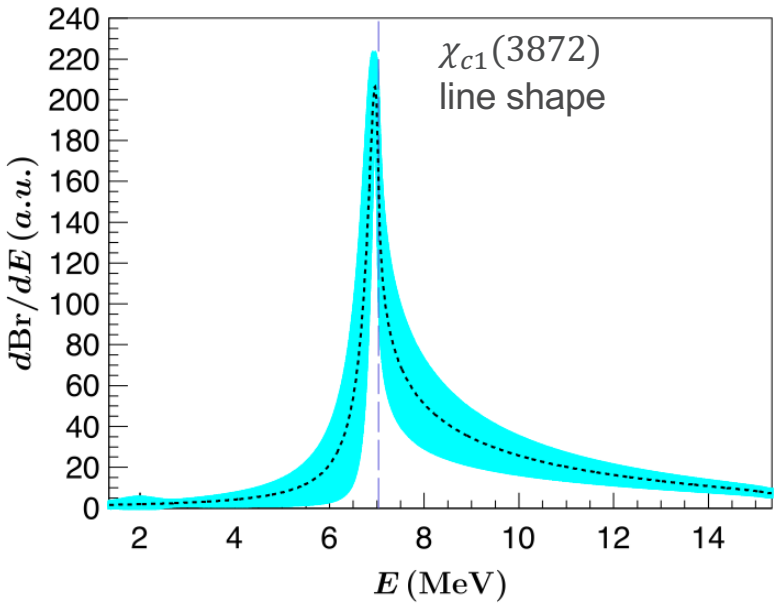
PRL132, 151903 (2024)





Coupled-channel Analysis of $\chi_{c1}(3872)$

PRL132, 151903 (2024)

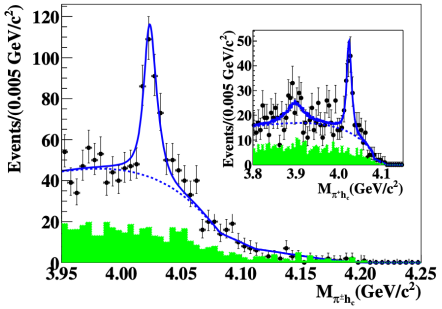


- Fit results:
  - $\Gamma_0 = (2.67 \pm 1.77^{+8.01}_{-0.82})$ MeV
  - $M_X = \left(3871.63 \pm 0.13^{+0.06}_{-0.05}\right)$ MeV

Parameters	BESIII	LHCb
g	$0.16 \pm 0.010^{+1.12}_{-0.11}$	$0.108 \pm 0.003^{+0.005}_{-0.006}$
Re[EI] (MeV)	$7.04 \pm 0.15^{+0.07}_{-0.08}$	7.10
Im[EI] (MeV)	$-0.19 \pm 0.08^{+0.14}_{-0.19}$	-0.13
$\Gamma[\pi^+\pi^- J/\psi]/\Gamma[D^0\bar{D}^{*0}]$	$0.05 \pm 0.01^{+0.01}_{-0.02}$	0.11 ± 0.03
FWHM (MeV)	$0.44^{+0.13+0.38}_{-0.35-0.25}$	$0.22^{+0.06+0.25}_{-0.08-0.17}$
Z	0.18	0.15 (0.33)

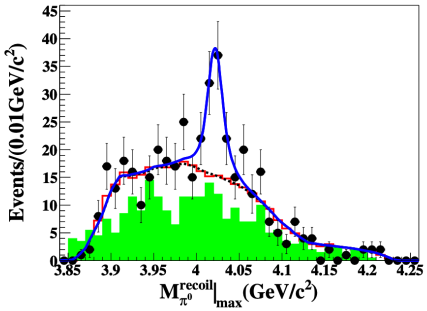
Compositeness hints at large molecular component

Multi-channel Analysis of $T_{c\bar{c}}(4020)$



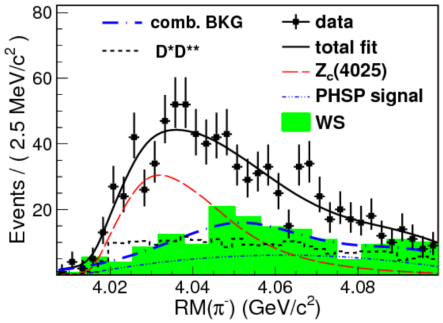
$\pi^{\pm}(\pi^{-}h_c)^{\mp}$

PRL111, 242001 (2013)



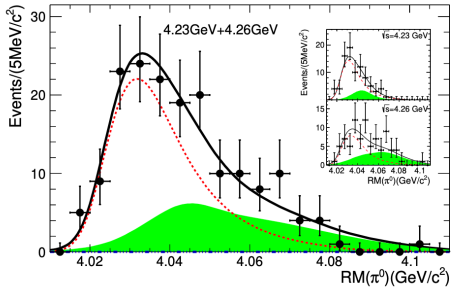
$\pi^0(\pi^0 h_c)$

PRL113, 212002 (2014)



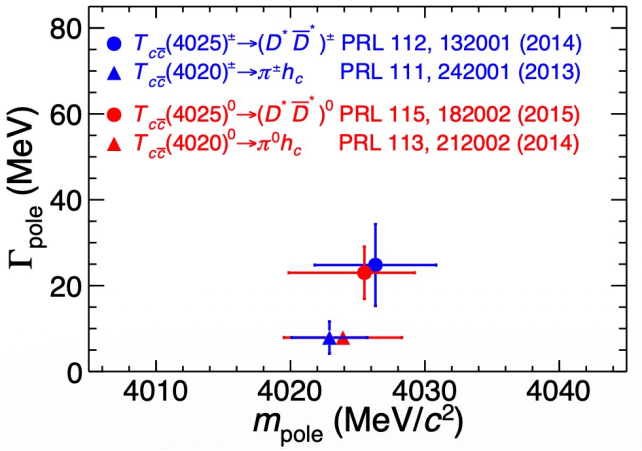
$\pi^{\pm}(D^*\bar{D}^*)^{\mp}$

PRL112, 132001 (2014)



$\pi^0(D^*\bar{D}^*)^0$

PRL115, 182002 (2015)

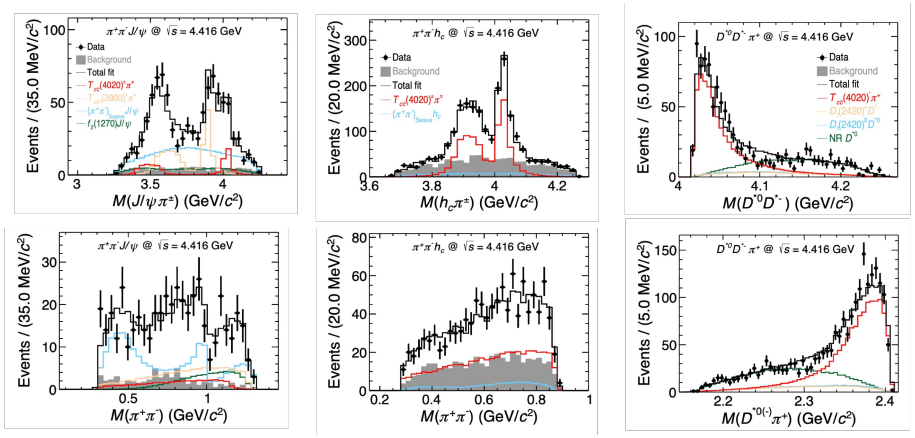


- Mass consistent in open and hidden charm modes but width in hidden charm mode smaller
- Spin and parity not yet determined
  ⇒ multi-channel joint PWA: $D^*\bar{D}^*, \pi h_c, \pi J/\psi$

Multi-channel Analysis of $T_{c\bar{c}}(4020)$

- Use 1.6 /fb data sample at 4.400 and 4.416 GeV

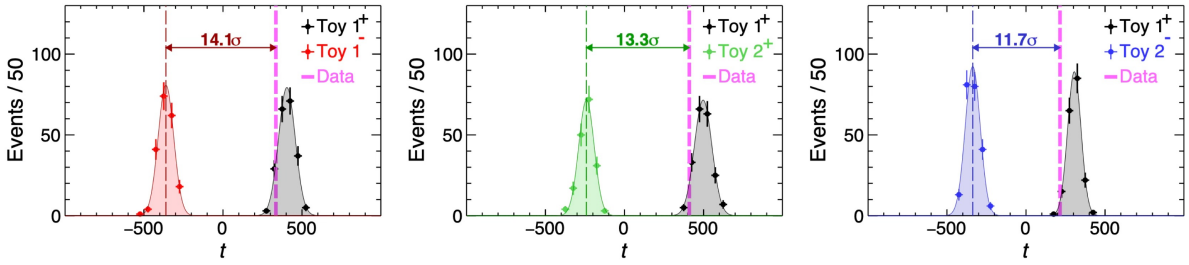
arXiv:2603.05564



$$\frac{B[Z_c(4020) \to \pi J/\psi]}{B[Z_c(4020) \to D^{*0}\bar{D}^{*-}]} = (3.6 \pm 0.6 \pm 1.6) \times 10^{-3}$$

$$\frac{B[Z_c(4020) \to \pi h_c]}{B[Z_c(4020) \to D^{*0}\bar{D}^{*-}]} = (8.9 \pm 1.3 \pm 2.3) \times 10^{-2}$$

J^P of $Z_c(4020)$ determined to be 1^+ with significance > 10σ



Belle II

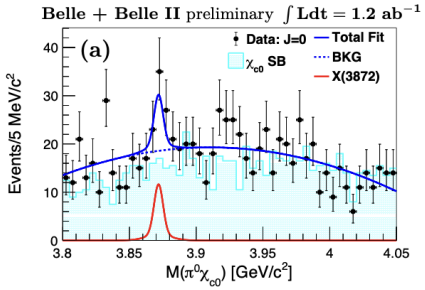
New decays of X(3872) and $\mathbf{D_{s0}^{*}(2317)^{+}}$

New result for $X(3872) \to \pi^0\chi_{cJ}(1P)$

[arXiv:2606.24578, submitted to PRL]

- The pionic transitions $X(3872) \to \pi^0\chi_{cJ}(1P)$ sensitive to its internal structure [PRD 77, 014013 (2008)].
  - Expected ratio $\Gamma_0:\Gamma_1:\Gamma_2 =$ 0:2.7:1 (charmonium 2^3P_1) $or =$ 2.88:0.97:1 (tetra-quark/molecule)
- $\pi^0\chi_{c0,c2}$ No hints [PRD 105, 072009 (2022)]; $\pi^0\chi_{c1}$ BES yes [PRL 122, 202001 (2019)]; Belle no [PRD 99, 111101 (2019)].

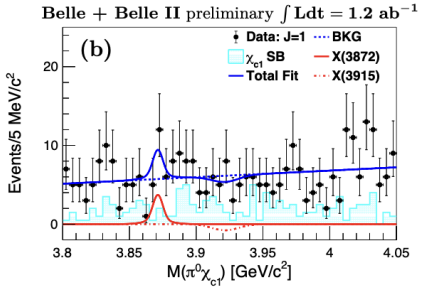
$\pi^0\chi_{c0}$



First evidence of $X(3872) \to \pi^0\chi_{c0}$: 23.7±8.1 events, 3.4σ

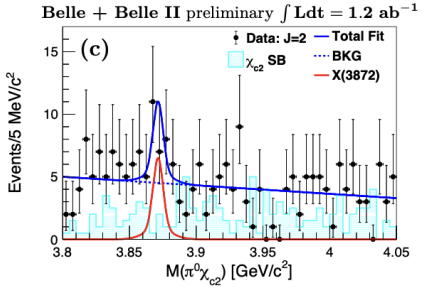
$\Gamma_0/\Gamma_{\pi\pi J/\psi} = 2.3 \pm 0.8 \pm 0.4$, $\Gamma_1/\Gamma_{\pi\pi J/\psi} = 0.3 \pm 0.2 \pm 0.1$, $\Gamma_2/\Gamma_{\pi\pi J/\psi} = 1.0 \pm 0.4 \pm 0.2$

$\pi^0\chi_{c1}$



$\Gamma_1/\Gamma_{\pi\pi J/\psi} < 0.9$, $\Gamma_2/\Gamma_{\pi\pi J/\psi} < 1.8$ $\quad \Gamma_0/\Gamma_1 > 2.6$, $\quad \Gamma_0/\Gamma_2 > 1.3$. $\quad$ @90%

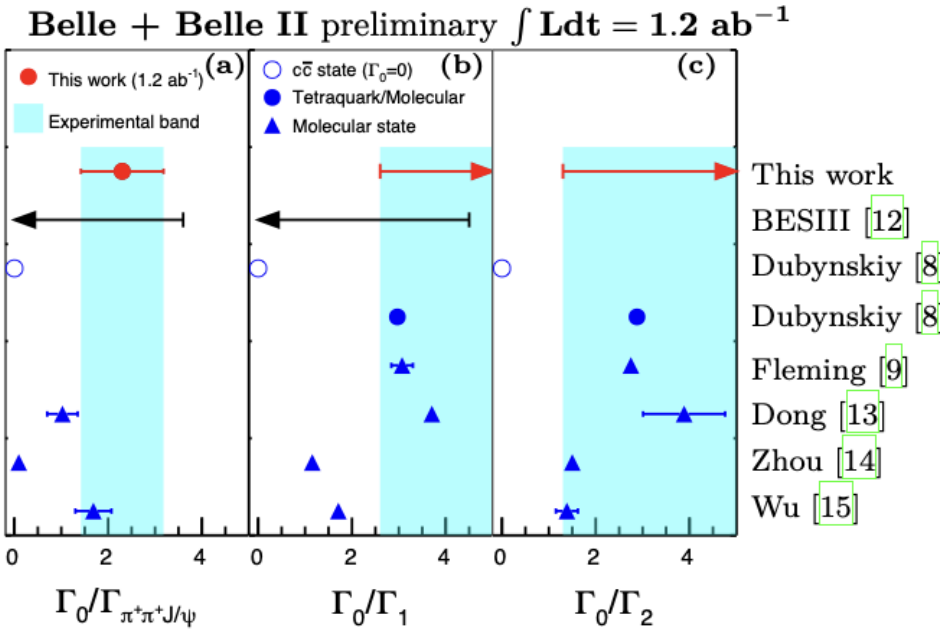
$\pi^0\chi_{c2}$



$\mathcal{B}(X(3872) \to \pi^0\chi_{c0}) = (9.9 \pm 4.8)\%$,

New result for $X(3872) \to \pi^0 \chi_{cJ}(1P)$

[arXiv:2606.24578]



- A comparison on (a) $\Gamma_0/\Gamma_{\pi^+\pi^- J/\psi}$, (b) Γ_0/Γ_1, (c) Γ_0/Γ_2

- **Disfavors a pure charmonium interpretation**
  - $\Gamma(X(3872) \to \pi^0 \chi_{c0})$ should be zero as $\chi_{c1}(2P)$

- **Consistent with most of molecular scenario**

- Absolute BF of $X(3872) \to \pi^0 \chi_{c0}$ at $(9.9 \pm 4.8)\%$ the largest hidden charm decay mode up to date

[8] Phys. Rev. D 77, 014013 (2008)
[9] Phys. Rev. D 78, 094019 (2008)
[12] Phys. Rev. D 105, 072009 (2022)
[13] Phys. Rev. D 79, 094013 (2009)
[14] Phys. Rev. D 100, 094025 (2019)
[15] Eur. Phys. J. C 81, 193 (2021)

First observation of $D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma$

PRL 136, 241901 (2026)

The $D_{s0}^{*}(2317)^{+} \to D_{s}^{+}\pi^{0}$ was first observed by BaBar in 2003 [PRL 90, 242001 (2003)].

$D_{s0}^{*}(2317)^{\pm}$ **DECAY MODES**

$D_{s0}^{*}(2317)^{-}$ modes are charge conjugates of modes below.

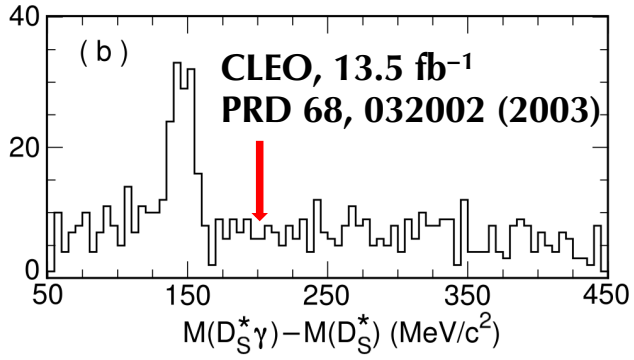
Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D_s^+\pi^0$	(100^{+0}_{-20}) %		298
Γ_2	$D_s^+\gamma$	<5 %	CL=90%	323
Γ_3	$D_s^*(2112)^+\gamma$	<6 %	CL=90%	
Γ_4	$D_s^+\gamma\gamma$	<18 %	CL=95%	323
Γ_5	$D_s^*(2112)^+\pi^0$	<11 %	CL=90%	
Γ_6	$D_s^+\pi^+\pi^-$	$< 4 \times 10^{-3}$	CL=90%	194
Γ_7	$D_s^+\pi^0\pi^0$	not seen		205

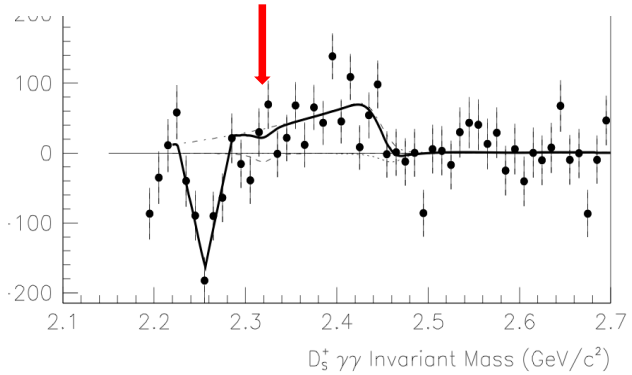
Mass << lowest $c\bar{s}$ meson with $J^P = 0^+$

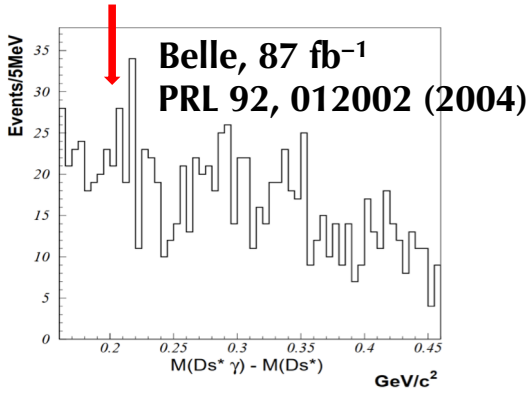
- molecular states
- quark-antiquark configurations
- tetraquark structures
- mixed states

Different BFs from different models.

$D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma$ searched by CLEO, Belle, and BaBar



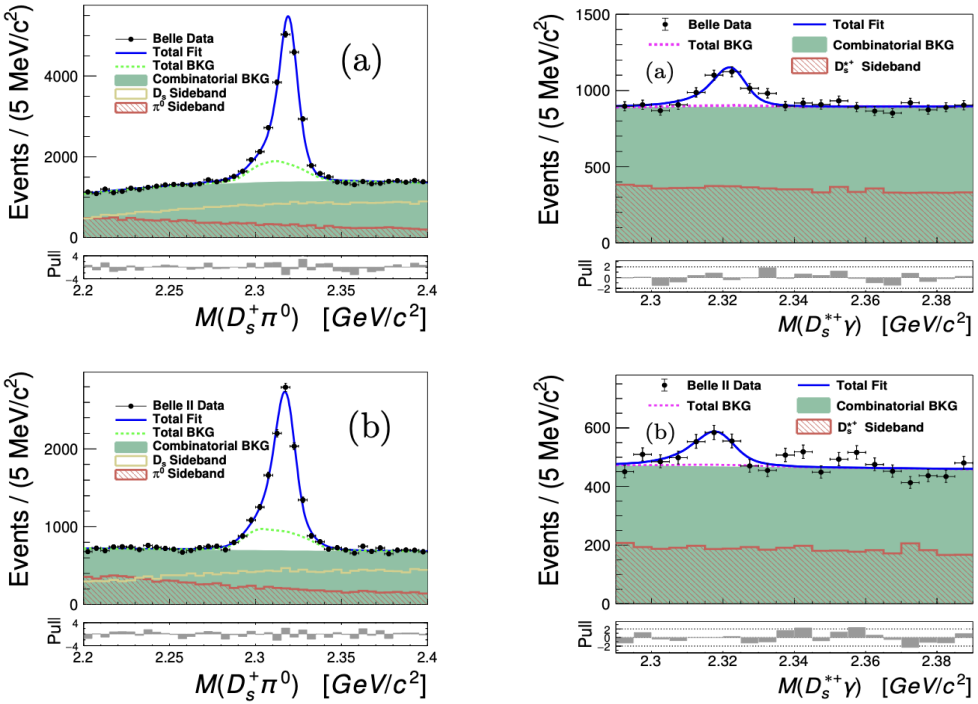




First observation of $D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma$

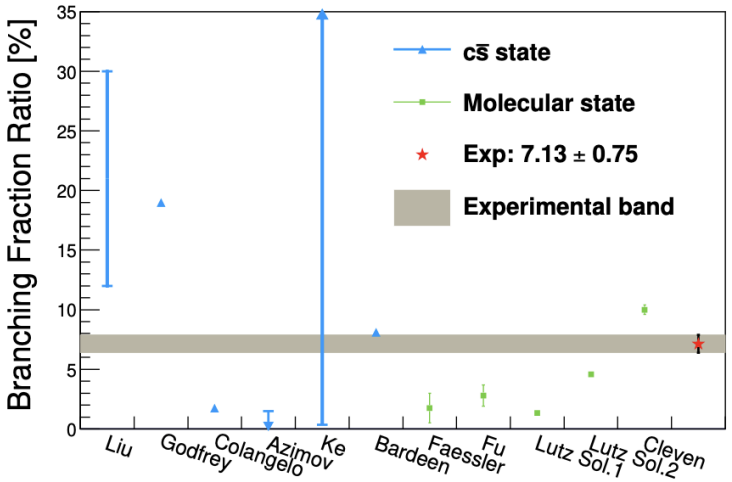
PRL 136, 241901 (2026)

- **Target:** $D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma$
- **Control channel:** $D_{s0}^{*}(2317)^{+} \to D_{s}^{+}\pi^{0}$
- **Using all Belle data (983 fb^{-1}) and Belle II data (427 fb^{-1})**



$$\mathcal{R} = \frac{\mathcal{B}(D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma)}{\mathcal{B}(D_{s0}^{*}(2317)^{+} \to D_{s}^{+}\pi^{0})}$$

$$= [7.14 \pm 0.70(\text{stat.}) \pm 0.23(\text{syst.})]\%$$



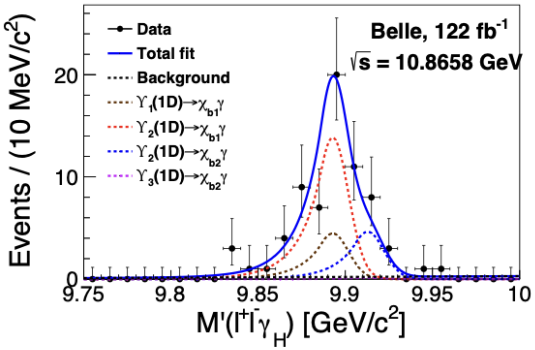
Lean for molecule

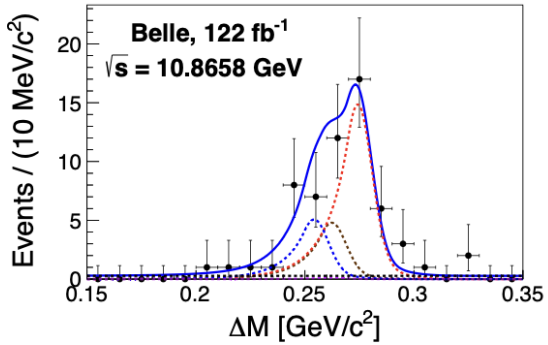
First evidences for $\Upsilon_1(1D)$ and $\Upsilon_3(1D)$

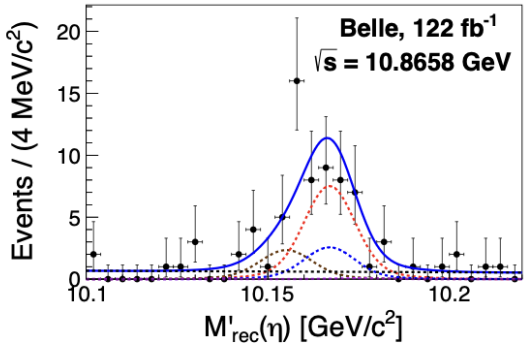
$\Upsilon_J(1D) \to \chi_{b1,b2}\gamma_L$, $\chi_{b1,b2} \to \Upsilon(1S)\gamma_H$, $\Upsilon(1S) \to \ell^+\ell^-$

Three-dimensional fit results

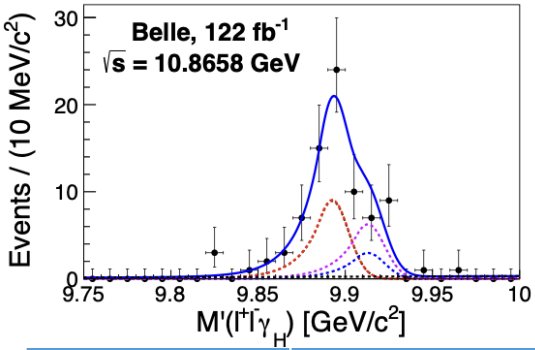
$e^+e^- \to \Upsilon_J(1D)\eta$

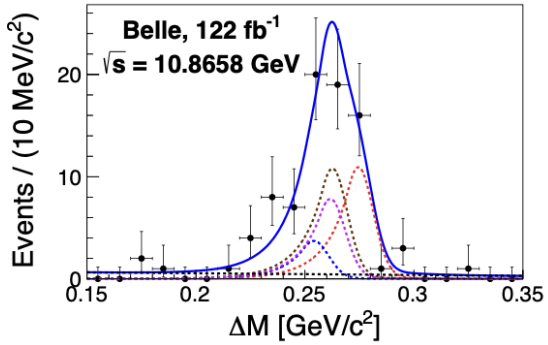


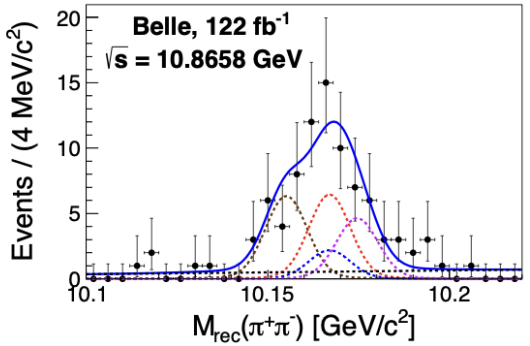




$e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$ $\quad \Delta M = M(\ell^+\ell^-\gamma_H\gamma_L) - M(\ell^+\ell^-\gamma_H)$







$\Upsilon_2(1D)$ mass
(10167.0±1.0±0.2) MeV/c^2
Δm_{21} = $m(\Upsilon_2(1D)) - m(\Upsilon_1(1D))$
(11.8±1.5±0.4) MeV/c^2
Δm_{32} = $m(\Upsilon_3(1D)) - m(\Upsilon_2(1D))$
(7.6±2.4±0.6) MeV/c^2

Channel	N^{sig} ($e^+e^- \to \Upsilon_J(1D)\eta$)	N^{sig} ($e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$)	$\Sigma_{stat.}$ ($\Sigma_{syst.}$)
$\Upsilon_1(1D) \to \chi_{b1}\gamma$	12.2±6.3	24.7±6.5	5.1σ (4.8σ)
$\Upsilon_2(1D) \to \chi_{b1}\gamma$	37.8±8.0	25.0±6.7	>10σ (>10σ)
$\Upsilon_2(1D) \to \chi_{b2}\gamma$	12.9±6.0	8.5±4.2	
$\Upsilon_3(1D) \to \chi_{b2}\gamma$	0.3±2.8	17.9±6.7	3.1σ (3.0σ)

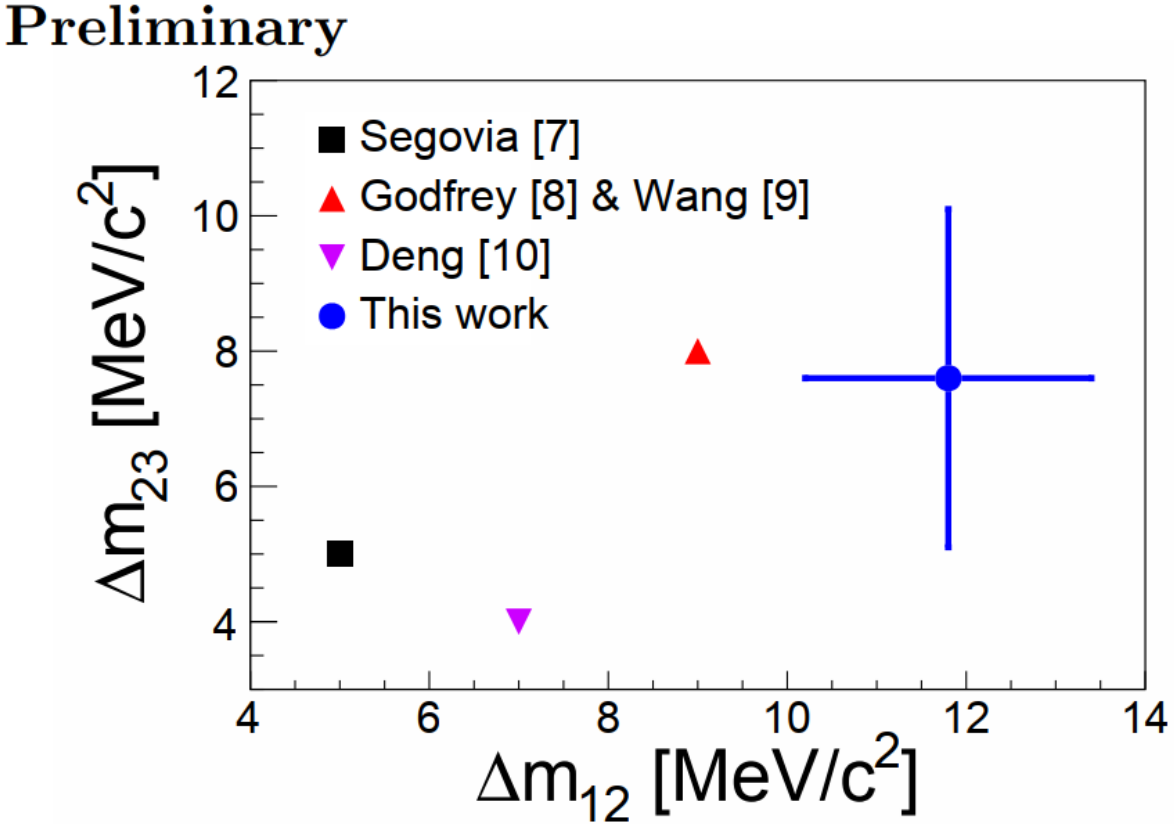
From the fit:

$$\frac{\mathcal{B}(\Upsilon_2(1D)\to\chi_{b2}\gamma)}{\mathcal{B}(\Upsilon_2(1D)\to\chi_{b1}\gamma)} = 0.66\pm0.27\pm0.15$$

Consistent with the prediction of ≈0.3 in PRD 92, 054034 (2015).

The comparison of mass splittings Δm_{12} and Δm_{23} with different theoretical predictions

[arXiv:2607.04369, accepted by PRL]



Segovia [7]: nonrelativistic constituent quark model [PRD 93, 074027 (2016)]

Godfrey [8]: relativistic quark model [PRD 92, 054034 (2015)]

Wang [9]: modified relativistic quark model with a screening effect [EPJC 78, 915 (2018)]

Deng [10]: screened potential model [PRD 95, 074002 (2017)]

LHCb

Heavy mesons and charm baryons

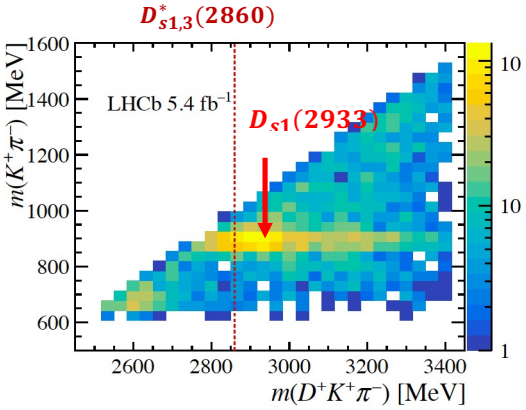
~5X!!! 9 fb^{-1} in Run 1+2 → 37 fb^{-1} including Run 3!

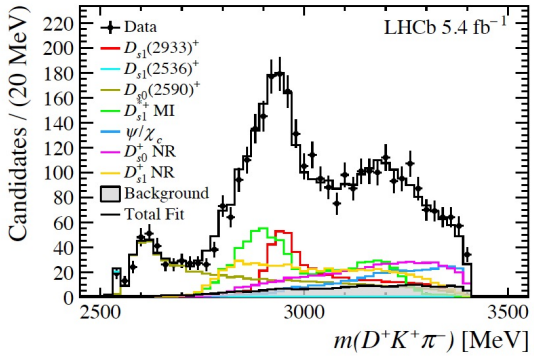
Conventional meson spectroscopy

$D_{s1}(2933)^+$ in $B^0 \to D^+D^-K^+\pi^-$

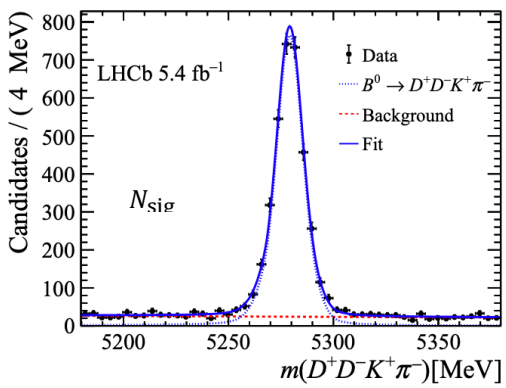
- Amplitude analysis in full phase space
- $D_{s0}(2590)^+$ confirmed
- A new state $D_{s1}(2933)^+$ observed (>10σ)
  - $J^P = 1^+$ determined with > 5σ
  - 1st observation of a radial excitation of P-wave D_s^+ states

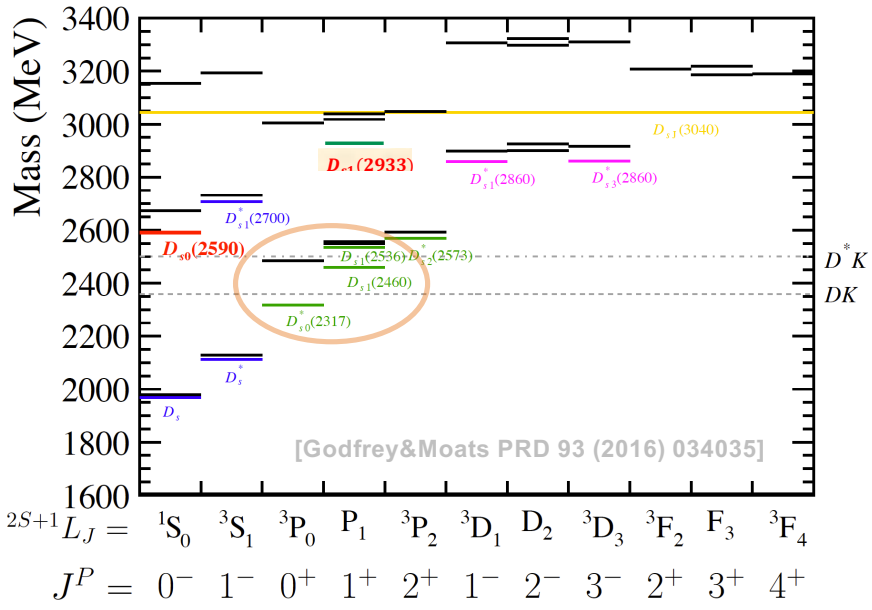
$$m_0 = 2933\,^{+6}_{-5}\,(\text{stat})\,^{+4}_{-3}\,(\text{syst})\,\text{MeV},$$
$$\Gamma_0 = 72\,^{+18}_{-12}\,(\text{stat})\,^{+7}_{-10}\,(\text{syst})\,\text{MeV},$$





[arXiv:2604.21257]

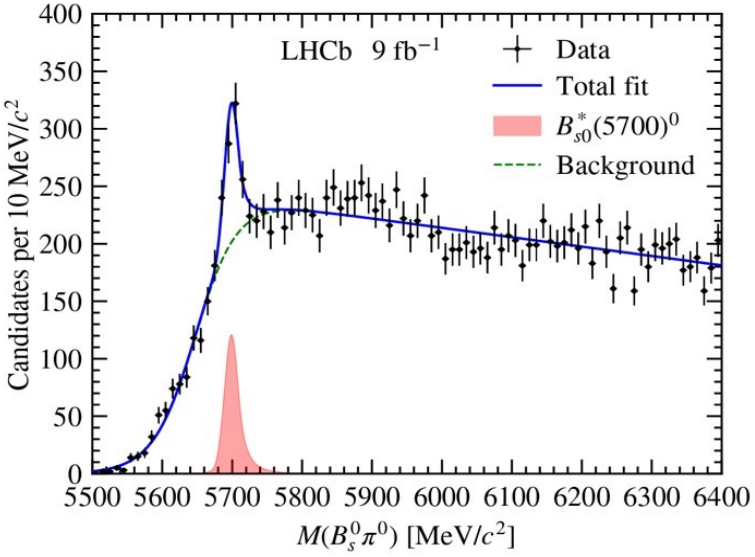


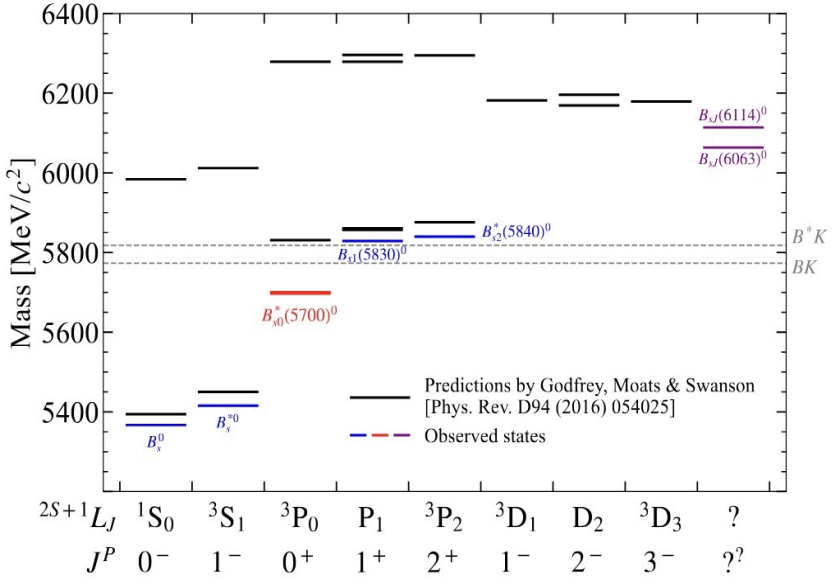


Observation of a narrow $B^*_{s0}(5700)^0$

[LHCb: arXiv:2609.25178]

- Analogous to $D^*_{s0}(2317)^+ \to D_s^+\pi^0$, LHCb observed an unexpectedly light and narrow B_s^{*0} state in $B_s^0\pi^0$ mass distribution



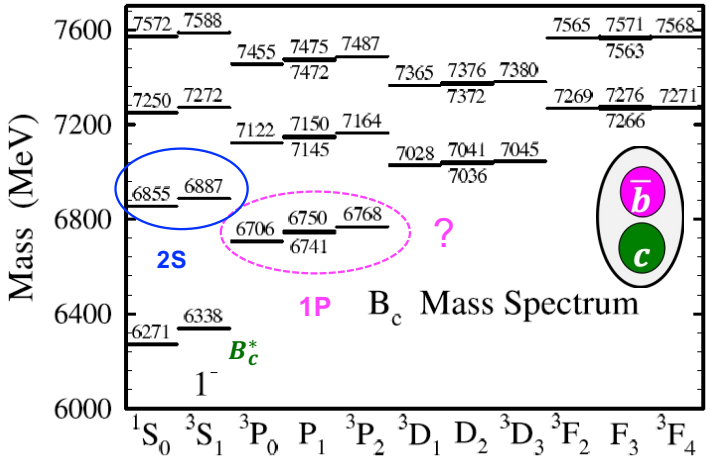


$$m = 5698.9 \pm 1.5 \pm 0.6\ \text{MeV}/c^2$$

$$m\left(B^*_{s0}(5700)\right) - m(B_s^0) = 332.0 \pm 1.5 \pm 0.6\ \text{MeV}/c^2$$
$$m(D^*_{s0}(2317)) - m(D_s^+) = 349.2 \pm 0.7\ \text{MeV}/c^2$$

Orbitally excited B_c^+ states from $B_c^+\gamma$

- B_c^+ spectroscopy is rich, but only few excited states have been observed
  - $B_c(2S)^+$ have been discovered (ATLAS, CMS & LHCb)
  - ATLAS recently observed B_c^{*+}
- Search for $B_c(1P)^+$ states in $B_c^+\gamma$ mass spectrum using run1+2 data
  - using $B_c^+ \to J/\psi(\to \mu^+\mu^-)\pi^+$ decay and calorimeter photon
  - There are four $B_c(1P)^+$ states, but six possible peaks



$\to B_c^+\gamma$: fully reconstructed peak

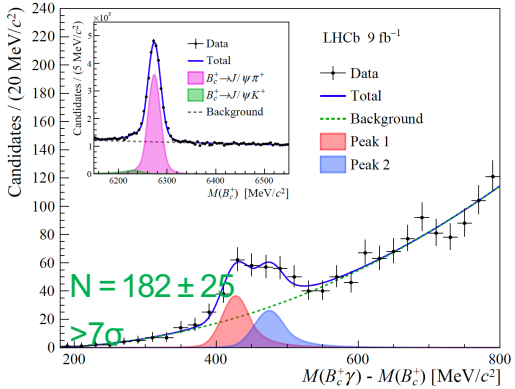
$\to B_c^{*+}\ (\to B_c^+\gamma)\gamma$: partially reconstructed peak, mass shifted downwards by $\delta M = M(B_c^{*+}) - M(B_c^+)$

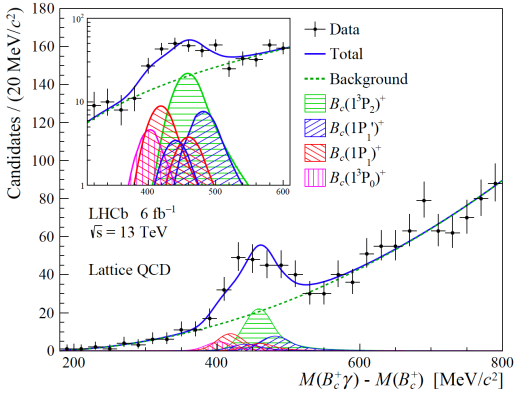
States	1^3P_0	$1P_1$	$1P_1'$	1^3P_2
Decays	$B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^{*+}(\to B_c^+\gamma)\gamma$
#peaks	1	2	2	1

Orbitally excited B_c^+ states from $B_c^+\gamma$

[PRL 135 (2025) 231902]
[PRD 112 (2025) 112003]

- A wide peaking structure is observed within the predicted mass range
  - Good fit with two peaks, with free masses & widths dictated by resolution
  - $M_1 = 6704.8 \pm 5.5 \pm 2.8 \pm 0.3\ \mathrm{MeV}/c^2$
  - $M_2 = 6752.4 \pm 9.5 \pm 3.1 \pm 0.3\ \mathrm{MeV}/c^2$
- Fit data with inputs from various theory predictions
  - Measure relative production cross-section of $B_c(1P)$ states compared to ground-state:
  - $R = 0.20 \pm 0.03 \pm 0.02 \pm 0.03$ ($p_T < 20$ GeV/c and $2 < \eta < 4.5$)





The 1st observation of two orbitally excited B_c^+ states

Single and doubly charmed baryons

Σ_c^{**} in $B^- \to \Lambda_c^+ \bar{p} \pi^-$

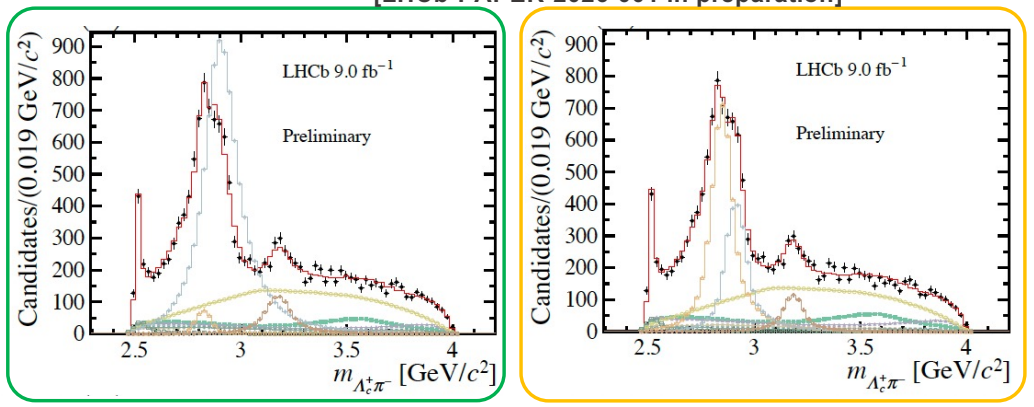
- A new peak seen at 3200 MeV
- Large statistics show the 2846 peak is overlap of two resonances, $\Sigma_c(2800)^0$ and $\Sigma_c(2900)^0$ but two fit solutions called group A and B
- Observation of new states: $\Sigma_c(2900)^0$ and $\Sigma_c(3200)^0$
  - $\Sigma_c(2800)^0$ at BaBar resolved into $\Sigma_c(2800)^0$ and $\Sigma_c(2900)^0$

$$\mathcal{R}(\Sigma_c^{**0}) \equiv \frac{\mathrm{FF}[B^- \to \Sigma_c^{**0}(\to \Lambda_c^+ \pi^-)\bar{p}]}{\mathrm{FF}[B^- \to \Sigma_c(2455)^0(\to \Lambda_c^+ \pi^-)\bar{p}]};$$

- Possible interpretation:
  - $\Sigma_c(2800)^0$: 1P or 2S
  - $\Sigma_c(2900)^0$: 2S or 1P

J^P (A)	J^P (B)
$(3/2)^+$	$(1/2)^-$
$(1/2)^-$	$(3/2)^+$
$(3/2)^-$	$(3/2)^-$

[LHCb-PAPER-2026-001 in preparation]

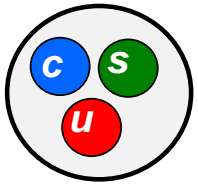


Parameter	Group A	Group B
$m_{\Sigma_c(2800)^0}$ [GeV/c^2]	$2.8192 \pm 0.0060 \pm 0.0020$	$2.8483 \pm 0.0037 \pm 0.0055$
$\Gamma_{\Sigma_c(2800)^0}$ [GeV]	$0.0326 \pm 0.0068 \pm 0.0080$	$0.0990 \pm 0.0072 \pm 0.0209$
$m_{\Sigma_c(2900)^0}$ [GeV/c^2]	$2.9077 \pm 0.0048 \pm 0.0087$	$2.9143 \pm 0.0032 \pm 0.0081$
$\Gamma_{\Sigma_c(2900)^0}$ [GeV]	$0.1754 \pm 0.0082 \pm 0.0225$	$0.0921 \pm 0.0061 \pm 0.0234$
$m_{\Sigma_c(3200)^0}$ [GeV/c^2]	$3.1859 \pm 0.0059 \pm 0.0144$	$3.1898 \pm 0.0054 \pm 0.0107$
$\Gamma_{\Sigma_c(3200)^0}$ [GeV]	$0.1331 \pm 0.0176 \pm 0.0267$	$0.1001 \pm 0.0154 \pm 0.0323$
$\mathcal{R}(\Sigma_c(2800)^0)$	$0.09 \pm 0.02 \pm 0.05$	$0.86 \pm 0.07 \pm 0.42$
$\mathcal{R}(\Sigma_c(2900)^0)$	$1.68 \pm 0.07 \pm 0.29$	$0.50 \pm 0.04 \pm 0.19$
$\mathcal{R}(\Sigma_c(3200)^0)$	$0.21 \pm 0.03 \pm 0.05$	$0.17 \pm 0.03 \pm 0.05$
$\mathcal{R}(\Sigma_c(2520)^0)$	$0.09 \pm 0.01 \pm 0.02$	$0.11 \pm 0.01 \pm 0.03$
$\mathcal{R}((\Lambda_c^+\pi^-)_{\mathrm{NR\,S-wave}})$	$2.19 \pm 0.14 \pm 0.22$	$2.23 \pm 0.11 \pm 0.30$

Ξ_c^{**+} states at 2.9-3.1 GeV

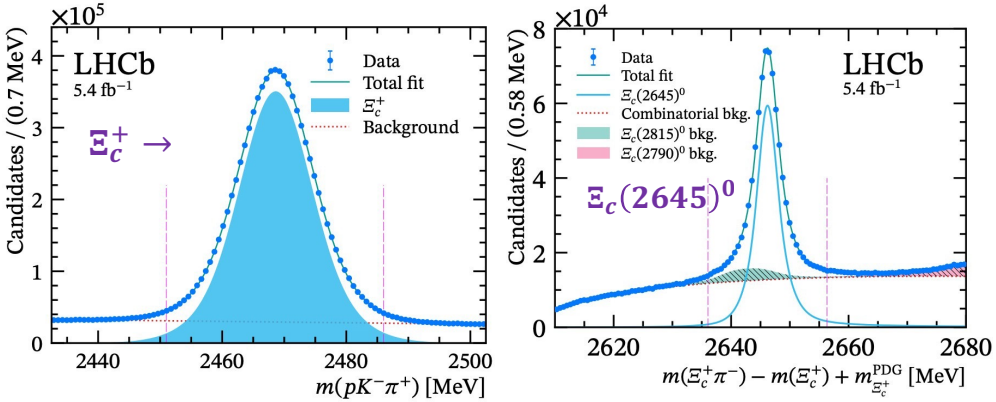
[PRL 132 (2025) 161901]

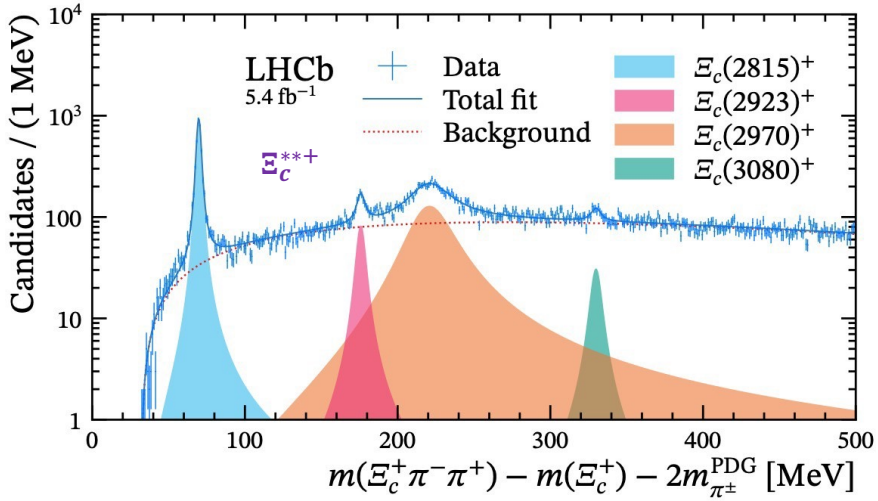
Search with $\Xi_c(2645)^0\pi^+ \to \Xi_c^+\pi^-\pi^+$



- Four peaks with high significance
- $\Xi_c(2923)^+$ observed for 1st time (isospin partner known)
- $\Xi_c(3080)^+$ seen in this decay mode for 1st time
- $\Xi_c(2970)^+$ with ~30 MeV width – confirms different to $\Lambda_c K\pi$ peak
- Precise measurements:

$$m[\Xi_c(2815)^+] = 2816.65 \pm 0.03 \pm 0.03 \pm 0.23\,\text{MeV},$$
$$\Gamma[\Xi_c(2815)^+] = 2.07 \pm 0.08 \pm 0.12\,\text{MeV},$$
$$m[\Xi_c(2923)^+] = 2922.8 \pm 0.3 \pm 0.5 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(2923)^+] = 5.3 \pm 0.9 \pm 1.4\,\text{MeV},$$
$$m[\Xi_c(2970)^+] = 2968.6 \pm 0.5 \pm 0.5 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(2970)^+] = 31.7 \pm 1.7 \pm 1.9\,\text{MeV},$$
$$m[\Xi_c(3080)^+] = 3076.8 \pm 0.7 \pm 1.3 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(3080)^+] = 6.8 \pm 2.3 \pm 0.9\,\text{MeV},$$





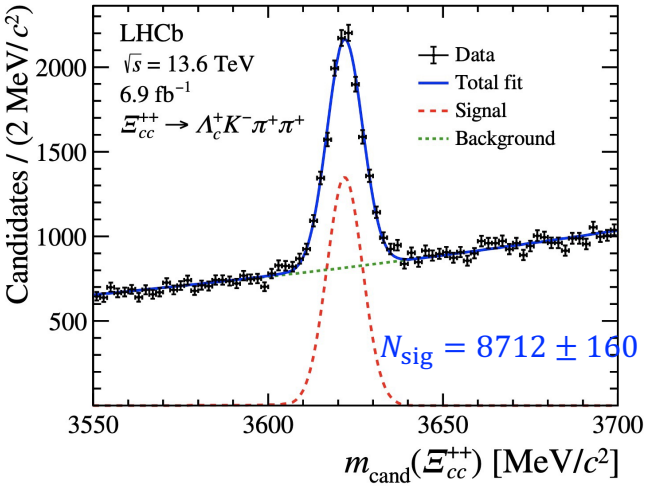
Observation of Ξ_{cc}^{+}

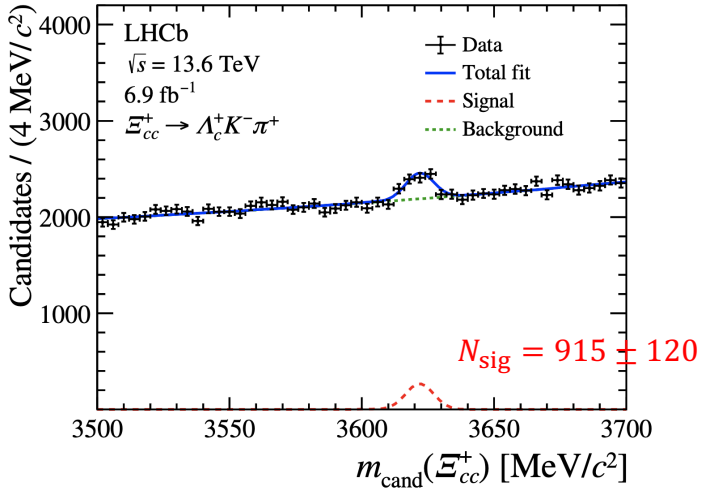
[PRL 137 (2026) 021902]

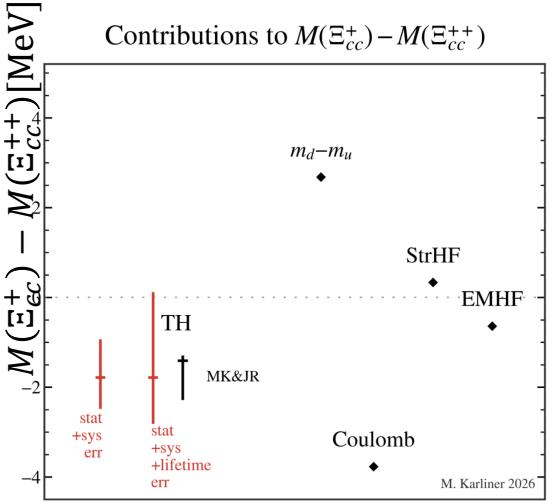
- $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ decay mode is used with LHCb 2024 data (6.9 fb^{-1})
  - A clear peak observed with local significance > 7s, consistent with LHCb previous searches
  - Ξ_{cc}^{++} yield per fb^{-1} = 1262 (285) at 2024 (Run2) data ⟹ improved by a factor of 4

[PRD 96 (2017) 3, 033004]

$$m(\Xi_{cc}^{+}) = 3619.97 \pm 0.83\,(\text{stat}) \pm 0.26\,(\text{syst})\,{}^{+1.90}_{-1.30}(\tau)\ \text{MeV}/c^2$$
$$m(\Xi_{cc}^{+}) - m(\Xi_{cc}^{++}) = -1.77 \pm 0.84\,(\text{stat}) \pm 0.15\,(\text{syst})\,{}^{+1.90}_{-1.30}(\tau)\ \text{MeV}/c^2$$



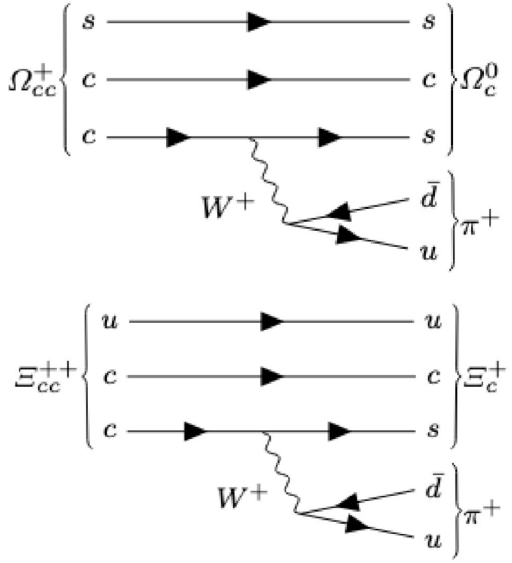




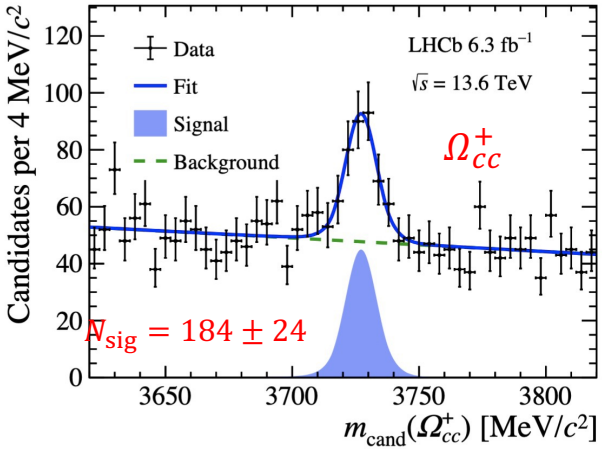
Observation of Ω_{cc}^{+}

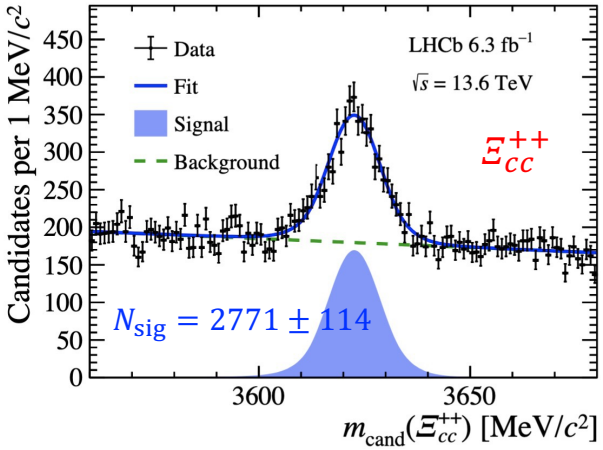
[arXiv: 2609.21921]

- $\Omega_{cc}^{+} \to \Omega_c^0 \pi^+, \Omega_c^0 \to pK^-K^-\pi^+$ decay is used with 2024 (6.3 fb^{-1}) data
- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+, \Xi_c^+ \to pK^-\pi^+$ decay as control mode
- A clear peak observed with global significance 8.7s
- The peak remains significant after a tight requirement on the decay time t > 170 fs, indicating weakly-decaying nature



$$m(\Omega_{cc}^{+}) = 3725.9 \pm 1.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.4(\tau) \pm 0.6(\text{ext})\ \text{MeV}/c^2$$
$$m(\Omega_{cc}^{+}) - m(\Xi_{cc}^{++}) = 104.3 \pm 1.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.4(\tau) \pm 0.5(\text{ext})\ \text{MeV}/c^2$$





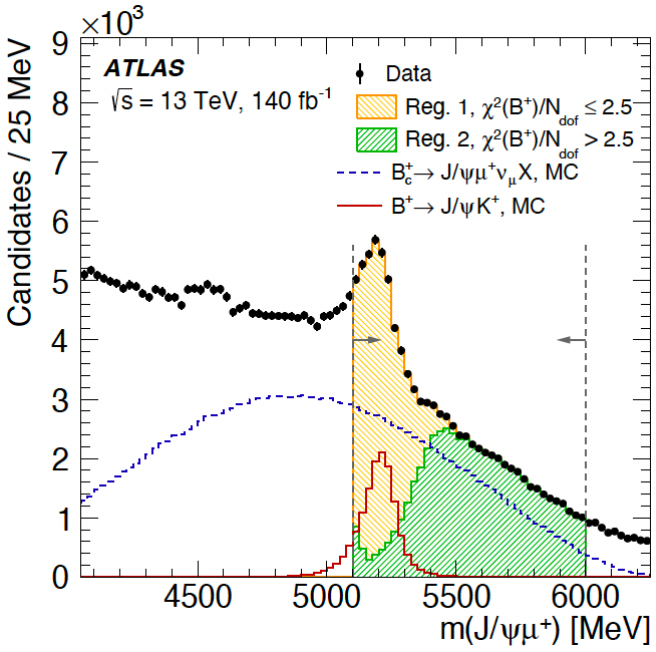
Precise measurements of the lifetime and production are underway with the full LHCb Run 3 data

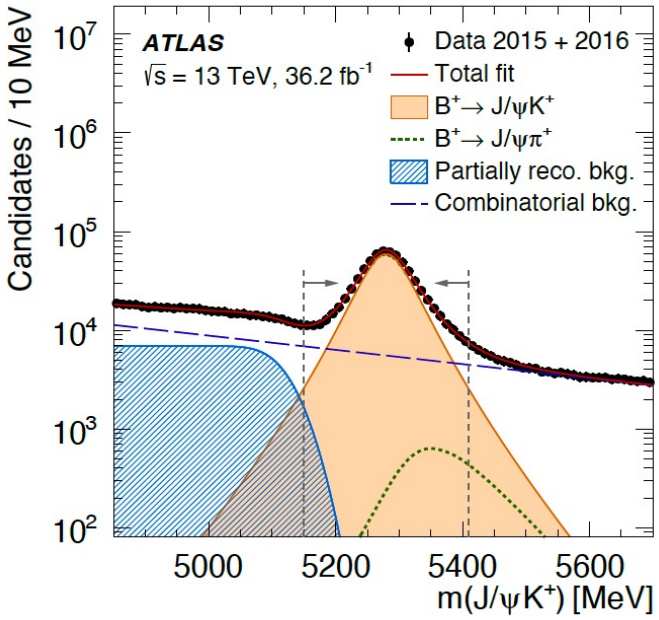
ATLAS/CMS

B_c^{*+} and state(s) in Yϕ final state

B_c^{*+} meson analysis

[PRL 137 (2026) 141901]





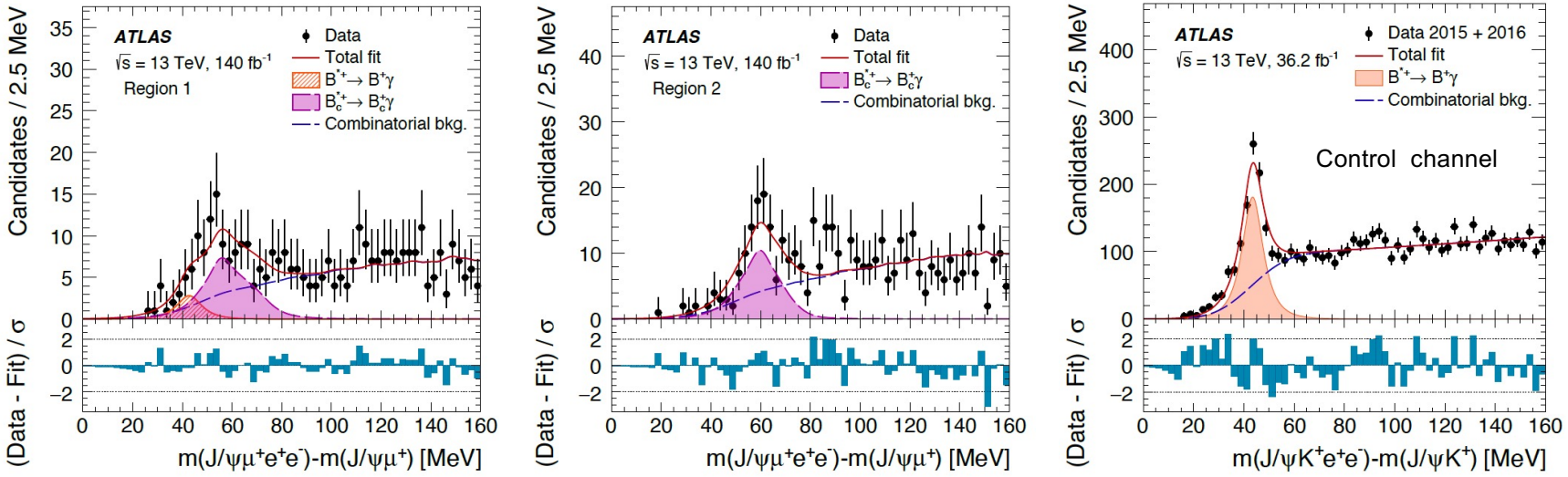
$B_c^+ \to J/\psi(\to \mu^+\mu^-)\mu^+\nu_\mu X$

~20 times larger than

$B_c^+ \to J/\psi\pi^+$

- Only B_c^+ candidates with $5.1 < m(J/\psi\mu^+) < 6.0\,\text{GeV}$ is kept (left plot)
- Fitted with kaon mass with B^+ mass constraint (right) to suppress $B^+ \to J/\psi K^+$. Define region 1 ($\chi^2(B^+)/N \leq 2.5$) and region 2 ($\chi^2(B^+)/N > 2.5$)

Excited B_c^{*+} mass fit result

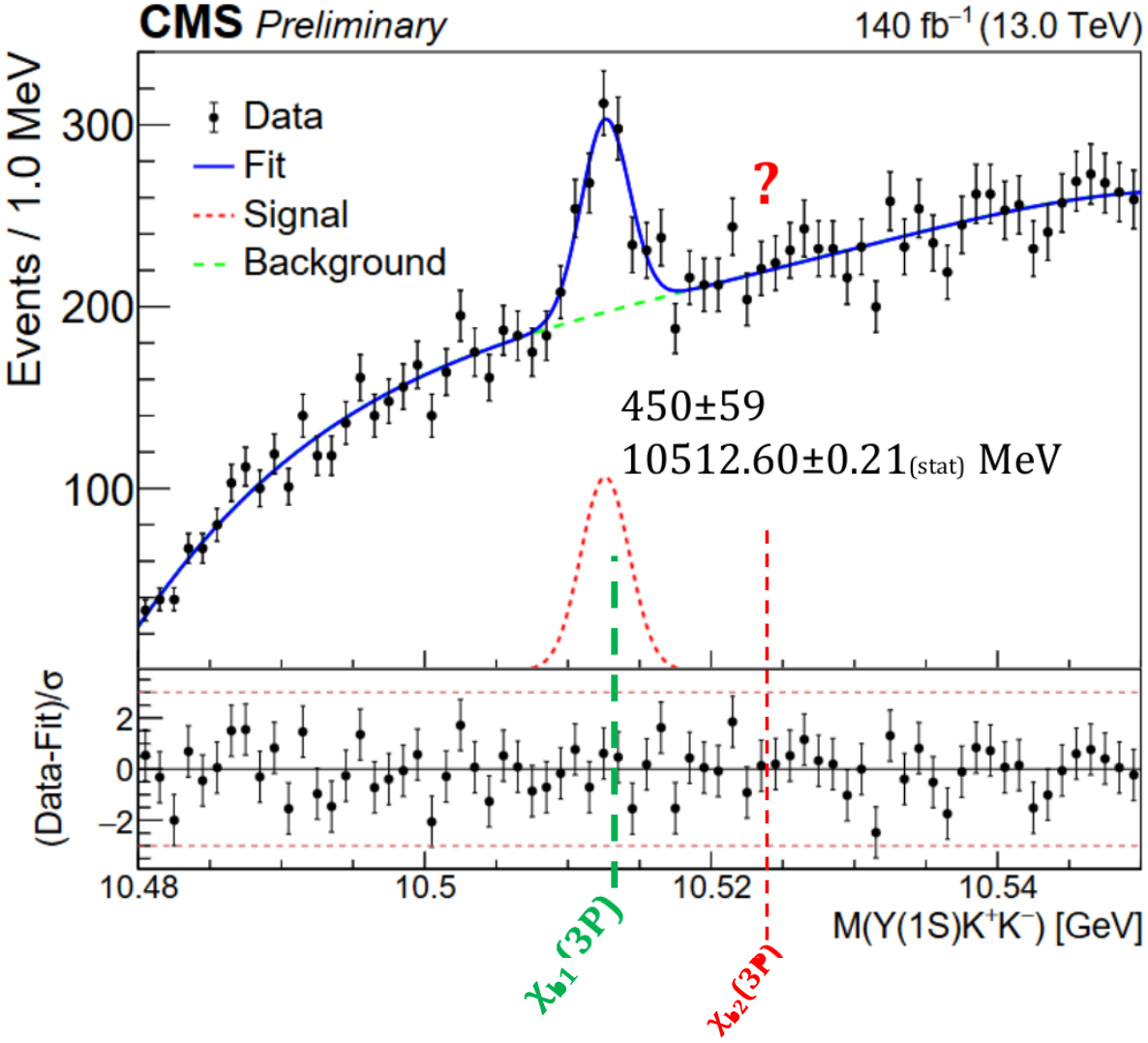


- Though converted photon only ~0.4%, 169±19 B_c^{*+} signal events in region 1&2 together
- B^{*+} is suppressed relative to B_c^{*+} in region 1 (softer photon) and absent in region 2.
- Simultaneous fit to $\Delta m_{B_c^{*+}}$ for both regions (left & middle)
  Significance exceeds 8σ – first observation of the the lightest excitation B_c^{*+} !

$$m(B_c^{*+}) = 6339.0 \pm 1.4\ (\text{stat.})^{+1.0}_{-1.4}\ (\text{syst.}) \pm 0.3(m_{B_c^+})\ \text{MeV}$$

CMS-PAS-BPH-25-009

CMS Run-2 search for Yϕ state



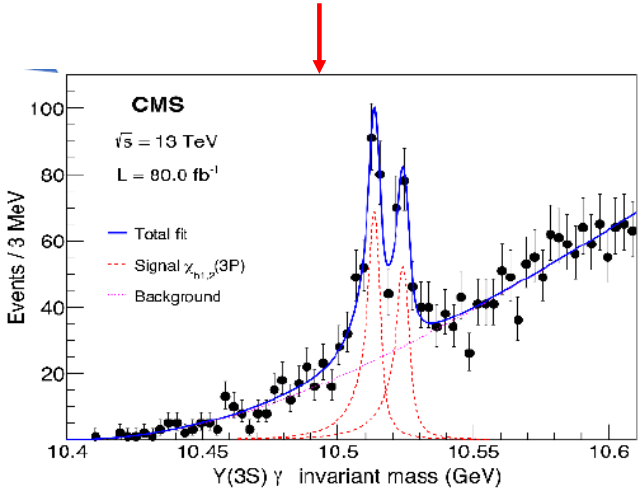
A narrow peak is observed! ~detector resolution

Significance ~ 10 s.d.

Mass consistent with $\chi_{b1}(3P)$ within 1.5 σ

no visible expected $\chi_{b2}(3P)$

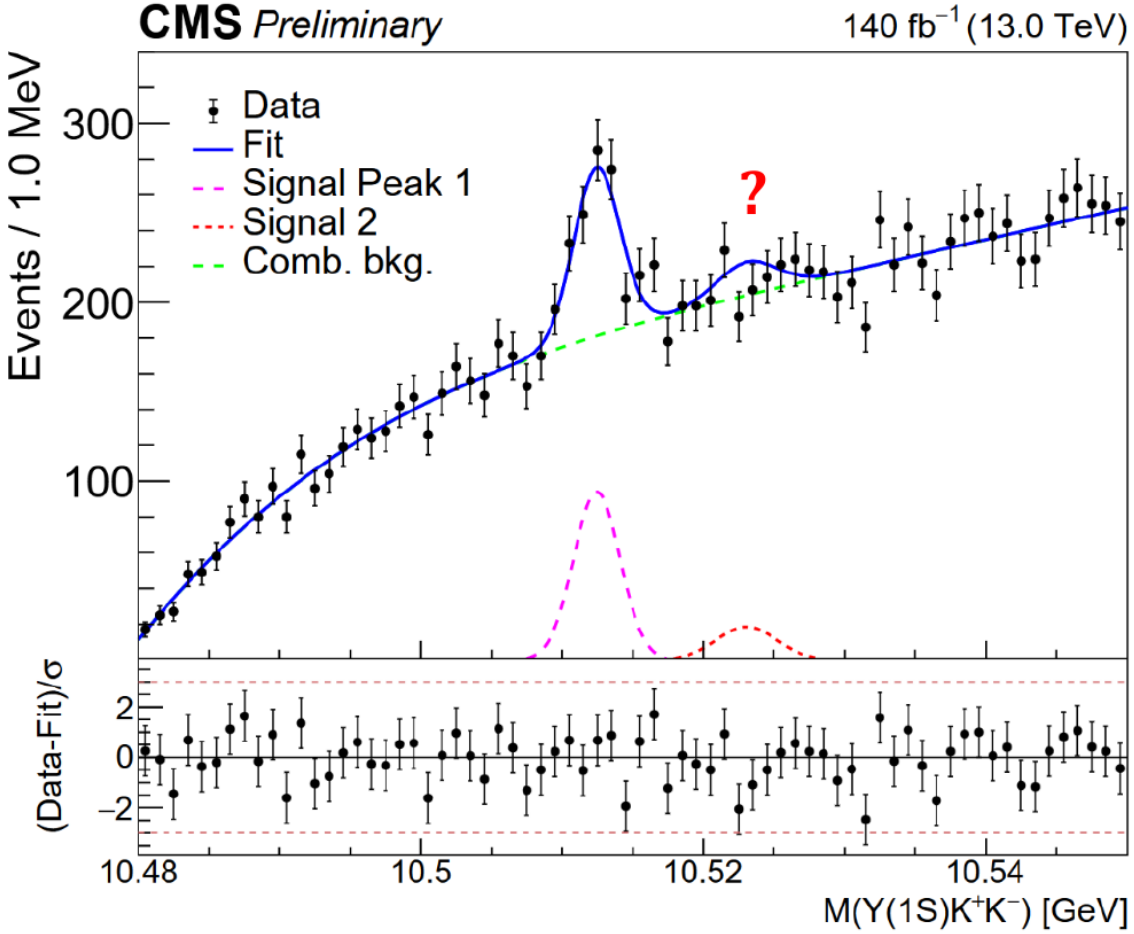
Similar yield to Y(3S)γ



Phys. Rev. Lett. 121 (2018) 092002

CMS-PAS-BPH-25-009

CMS Run-2 search for Yϕ state



$\chi_{b2}(3P)$ yield = 49±48 if included

Null $\chi_{b2}(3P)$ may indicate exotic components, i.e., cs tetraquark?

Measured mass: 10 512.60 ± 0.21(stat) ± 0.20(syst) ± 0.11 MeV

Specially selected “exotic" hadrons

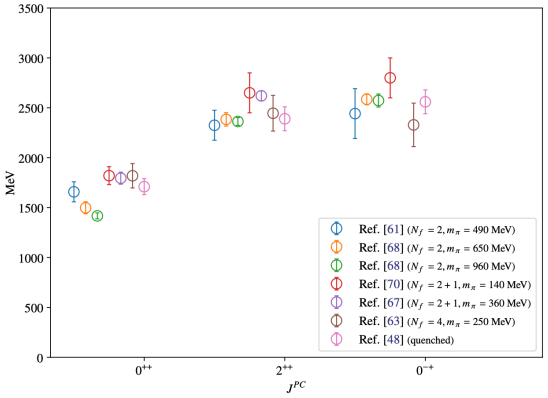
Recent experimental progress

BESIII

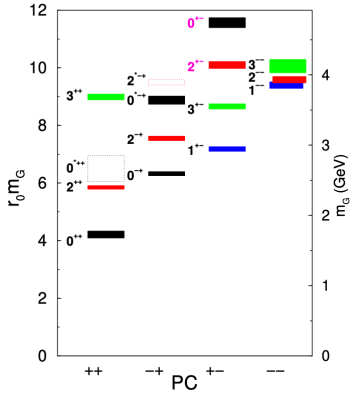
Glueball searches

The Search for Glueballs

- Long-standing question: can we identify states without valence quarks?
- Lattice QCD predictions for low-lying glueballs:



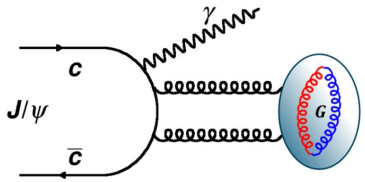
arXiv:2305.04869



PRD60, 034509 (1999)

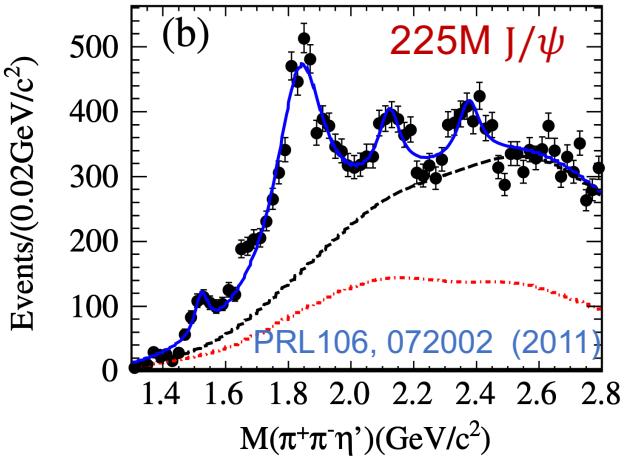
- Predicted mass of 0^{-+} glueball: ~2.3 – 2.6 GeV
- Small number of expected pseudoscalars in the quark model provide a clean environment

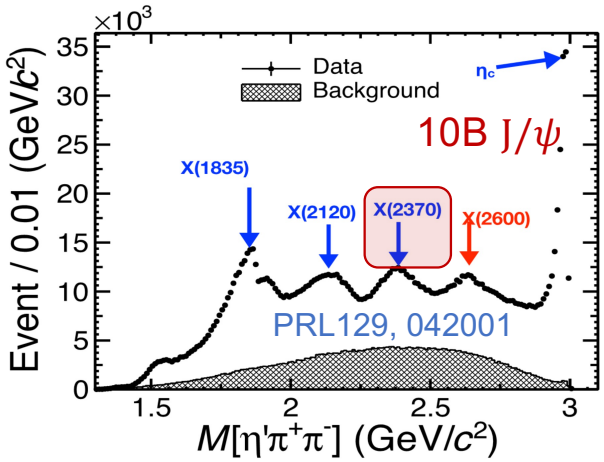
- Search in gluon-rich environments, such as J/ψ radiative decays



- Decay pattern should be rather incompatible with expectations from $SU(3)_F$

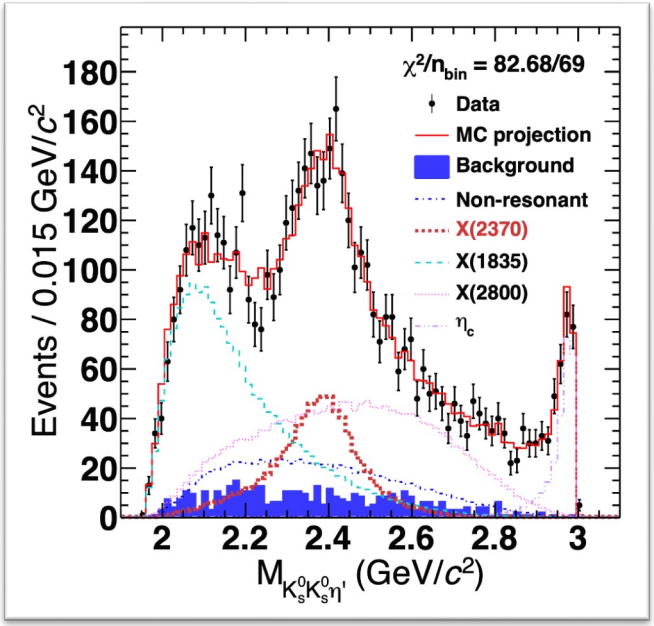
$J/\psi \to \gamma\pi^+\pi^-\eta'$





- Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$, mass consistent 0^{-+} glueball
- Also seen in $J/\psi \to \gamma K\bar{K}\eta'$ [EPJC80, 746 (2020)]

PRL132,181901 (2024)



- New in $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ [PRL132. 181901 (2024)]
  - C parity and exchange symmetry forbid $\pi^0 K_S^0 K_S^0 \eta'$ ⇒ low background level
  - Restrict $K_S^0 K_S^0$ to $f_0(980)$ and perform PWA
  - J^{PC} determined to be 0^{-+}

Lightest 0^{-+} Glueball as Dominant Constituent of X(2370)

arXiv:2607.20366

The lightest 0-+ glueball is the dominant constituent of the X(2370)

- **These properties are fully consistent with the expected signatures of glueball**
- **Other interpretations hardly explain all of them simultaneously; alternatives remain**

High production rate Narrow partial widths

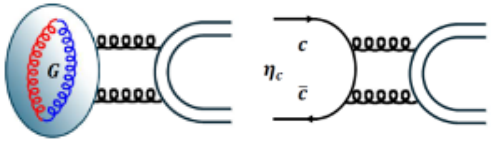
Decay channel	$\mathcal{B}$ $(\times 10^{-4})$
$J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\pi$	$3.25 \pm 0.25^{+0.73}_{-0.75}$
$J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta$	$3.2 \pm 0.1^{+0.9}_{-1.0}$
$J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta'$	$1.94 \pm 0.04^{+0.33}_{-0.88}$
$J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\eta'$	$0.39 \pm 0.05 \pm 0.10$

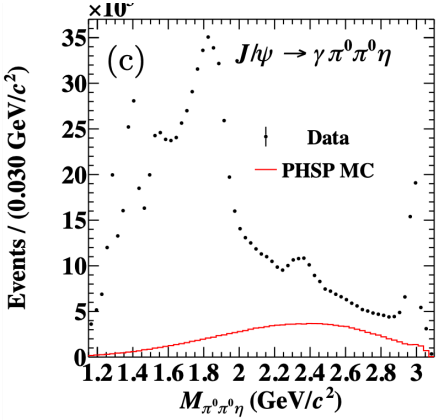
- $K\bar{K}\eta'$: $f_0(980)\eta'$ ...
- $\pi\pi\eta'$: $f_0(980)\eta'$, $f_0(500)\eta'$ ...
- $\pi\pi\eta$: $a_0(980)\pi^0 f_0(500)\eta, f_0(1500)\eta f_0(1710)\eta$ ...
- $K\bar{K}\pi$: $K_0^*(1430)\bar{K}$, $K_0^*(800)\bar{K}$, $a_0(980)\pi^0$ ...

$$B(J/\psi \to \gamma X(2370)) > 1\times10^{-3}$$

Partial width of each two-body decay ~MeV

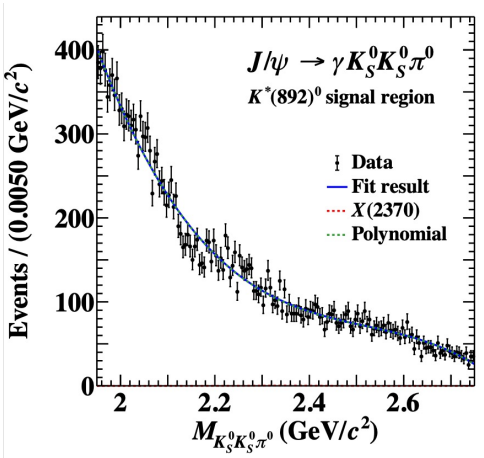
η_c–like decay pattern





Five "golden" decay modes

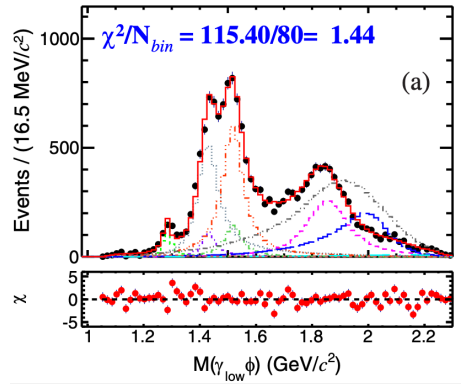
flavor-singlet property



$B[X(2370) \to K^*(892)\overline{K}] < 1.6\%@90\%C.L.$

Suppression of K*(892)K

$q\bar{q}$ suppression



Resonance R	$J/\psi \to \gamma R \to \gamma\gamma\omega$ $(\times10^{-6})$ [29]	$J/\psi \to \gamma R \to \gamma\gamma\phi$ $(\times10^{-6})$ [30]
$\eta(1405)$	$3.54 \pm 0.20^{+0.65}_{-0.24}$	$3.57 \pm 0.18^{+0.59}_{-0.61}$
$X(1835)$	< 0.11	$3.37 \pm 0.19^{+0.78}_{-1.10}$
$X(2370)$	< 0.04	< 0.11

Suppression of $\gamma\omega$,$\gamma\phi$

All-charm tetraquarks

ATLAS, CMS and LHCb

All-charm spectroscopy: Run 2

Sci.Bull. 65 (2020) 23, 1983-1993

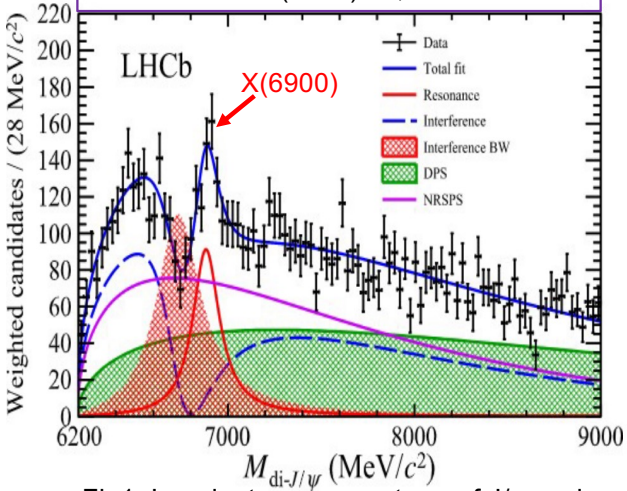


Fig1: Invariant mass spectrum of J/ψ -pair candidates using model II.

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

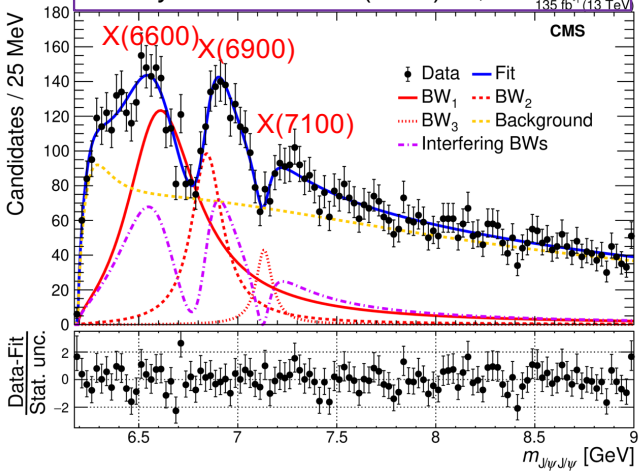


Fig2: The J/ψJ/ψ invariant mass spectrum in the range up to 9 GeV, with fits consisting of three signal functions.

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

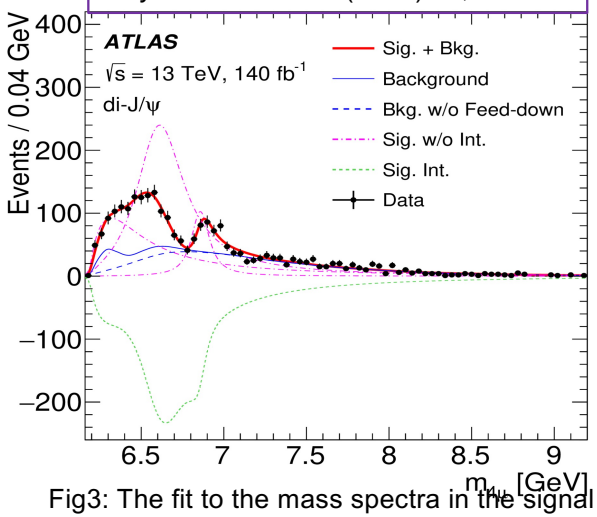
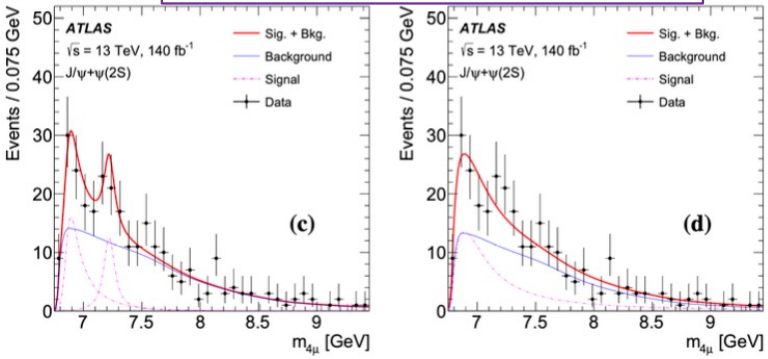


Fig3: The fit to the mass spectra in the signal regions in the di-J/ψ with model A.

- Three structures seen in J/ψJ/ψ spectrum—by LHCb, ATLAS & CMS
- X6900 is well established, CMS claimed two more structures
- All three experiments used interference to explain the dips
- ATLAS also explored J/ψ ψ(2S) decay mode

Phys.Rev.Lett. 131, 151902



Status of $J/\psi\psi(2S)$ channel before CMS result

- ATLAS 2023 result for $J/\psi\psi(2S) \rightarrow 4\mu$

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

4.7σ for X(6900) in Model α

3.0σ for the stand-alone resonance

- ATLAS new result (2025) $J/\psi\psi(2S) \rightarrow 4\mu + 2\pi$

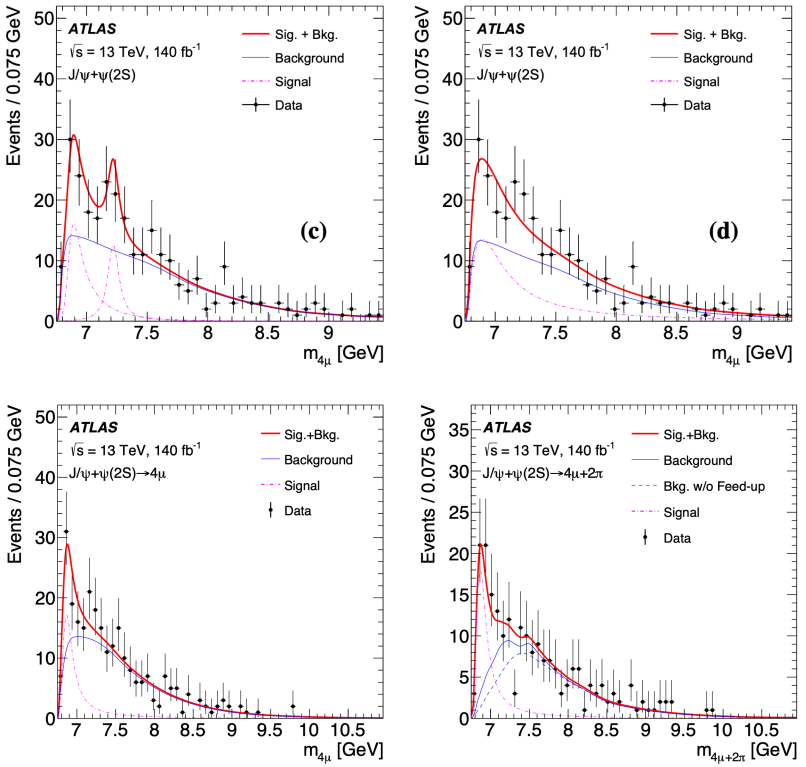
  Phys.Rev.D 113 (2026) 11, 112015

Simultaneous fit of 2 channels:
J/ψψ(2S) [4μ and 4μ+2π]

8.9σ for X(6900) in J/$\psi\psi$(2S) with 4μ and 4μ+2π final state

Set a upper limit for X(7200)

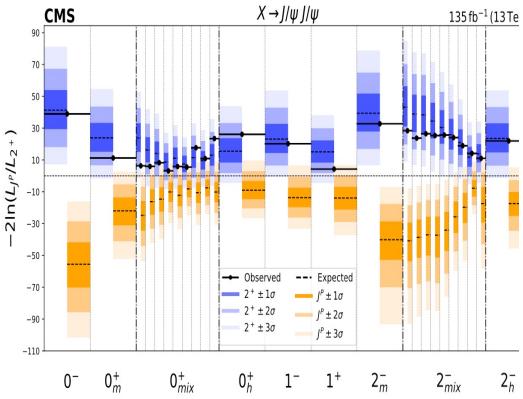
X(7200) / X(6900) = 0.12 ± 0.11
(UL < 0.41, 95% CL)



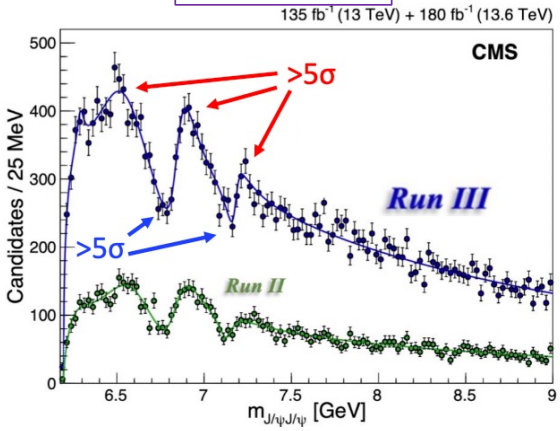
	model A	model B	model C
m / GeV	$6.860 \pm 0.023 \pm 0.010$	$6.902 \pm 0.008 \pm 0.010$	$6.884 \pm 0.017^{+0.058}_{-0.005}$
Γ / GeV	$0.082 \pm 0.032 \pm 0.015$	$0.183 \pm 0.025 \pm 0.007$	$0.178 \pm 0.054^{+0.176}_{-0.024}$
R	$1.08 \pm 0.20^{+0.40}_{-0.09}$	$0.93 \pm 0.17 \pm 0.11$	—

All-charm spectroscopy: Run 3 establish & Run 2 spin parity

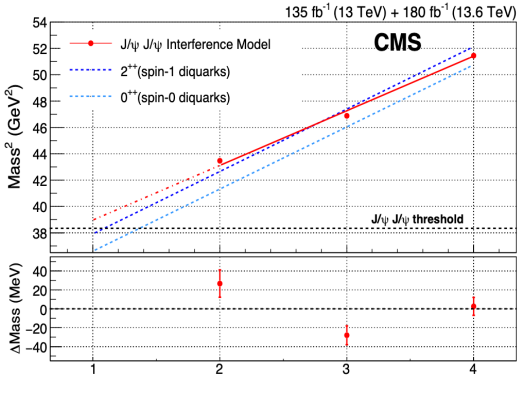
BPH-24-002



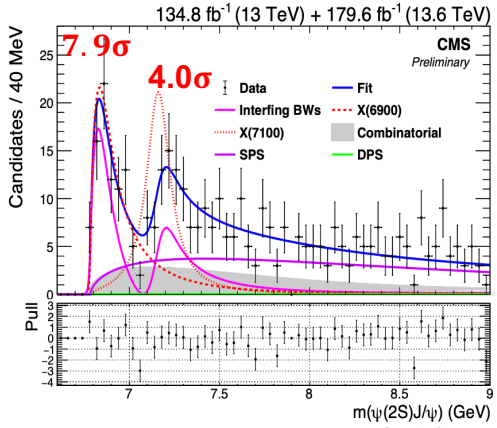
BPH-24-003



BPH-24-003

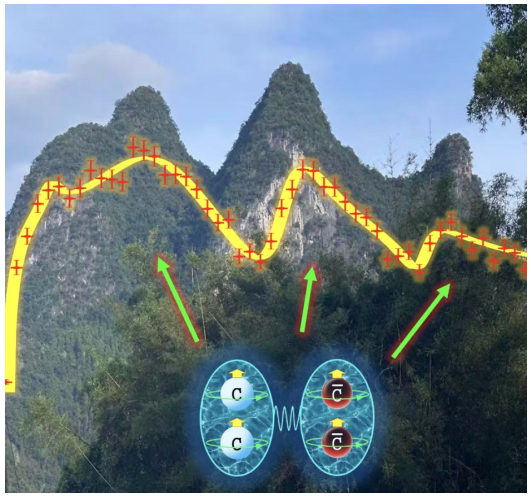


BPH-22-004



- $J^{PC} = 2^{++}$ is favored for all X states assuming same spin parity for all 3 states
- Each structure and interference among them well established (>>5σ)
- Masses fit well on a Regge trajectory
  supporting radial tetraquark interpretation, with other possibilities

- CMS has also extended $J/\psi\psi(2S)$ channel
  observation of X6600 and evidence of X7100, 2.5σ interference hinted



Connections among $J/\psi J/\psi$, $\phi\phi$ and $J/\psi\phi$?

$J/\psi J/\psi$ system

Same flavor ~ 2^+

$\phi\phi$ system

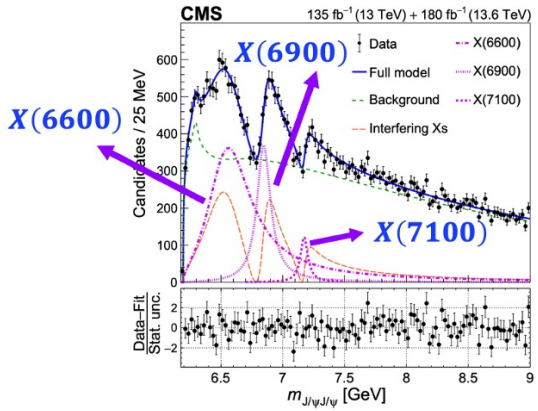
BESIII $J/\psi \to \phi\phi\gamma$

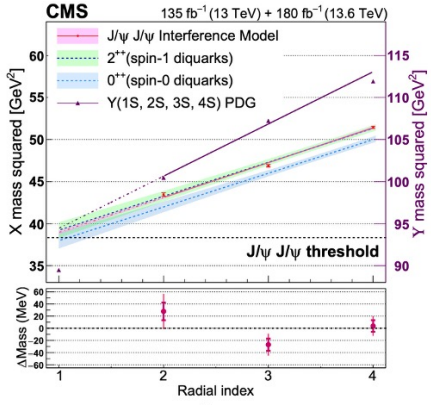
Same flavor ~ 2^+

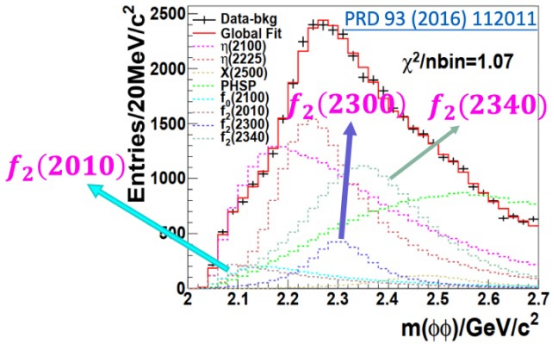
$J/\psi\phi$ system

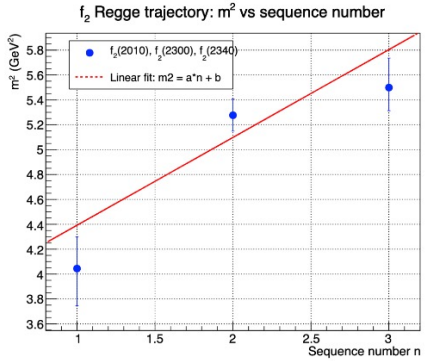
LHCb $B \to J/\psi\phi$K

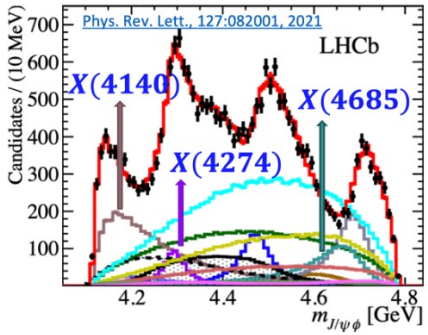
Different flavor ~ 1^+

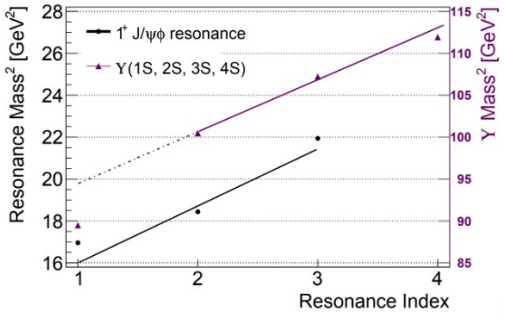










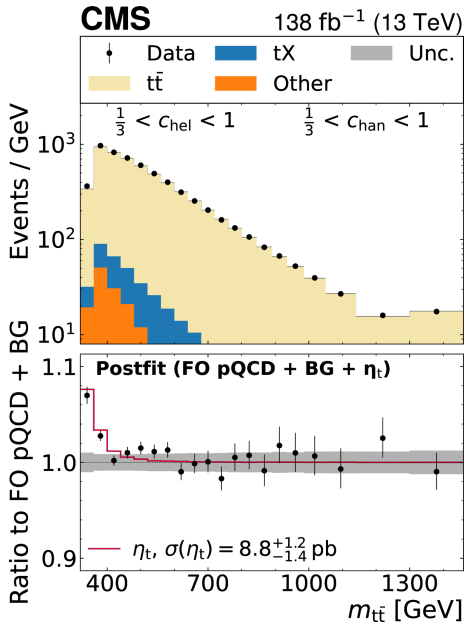


The top–antitop threshold dynamics

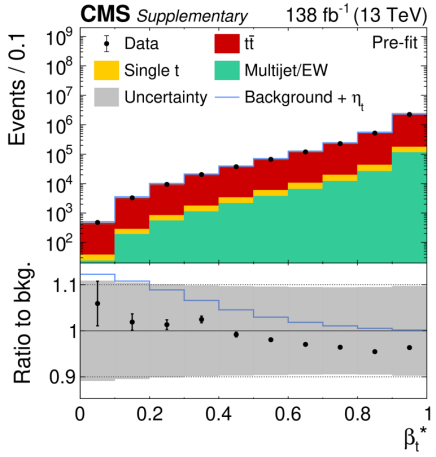
ATLAS and CMS

CMS: threshold excess in two decay channels

13 TeV pp collisions · 138 fb⁻¹ · model-dependent η_t interpretation



Dilepton: m(t $\bar{t}$), high c_{hel} & c_{han}
Post-fit; red: fitted η_t



Single-lepton: β^*_t, all categories
Pre-fit; blue: baseline + η_t

First observation: dilepton

A spin-0 resonance search found an excess near the threshold, correlated with lepton angles.

8.8 +1.2/−1.4 pb · >5σ observed

Independent single-lepton + jets

Fit β^*_t and two spin observables in four reconstruction / b-tag categories.

5.1 ± 0.9 pb · 6.1σ observed

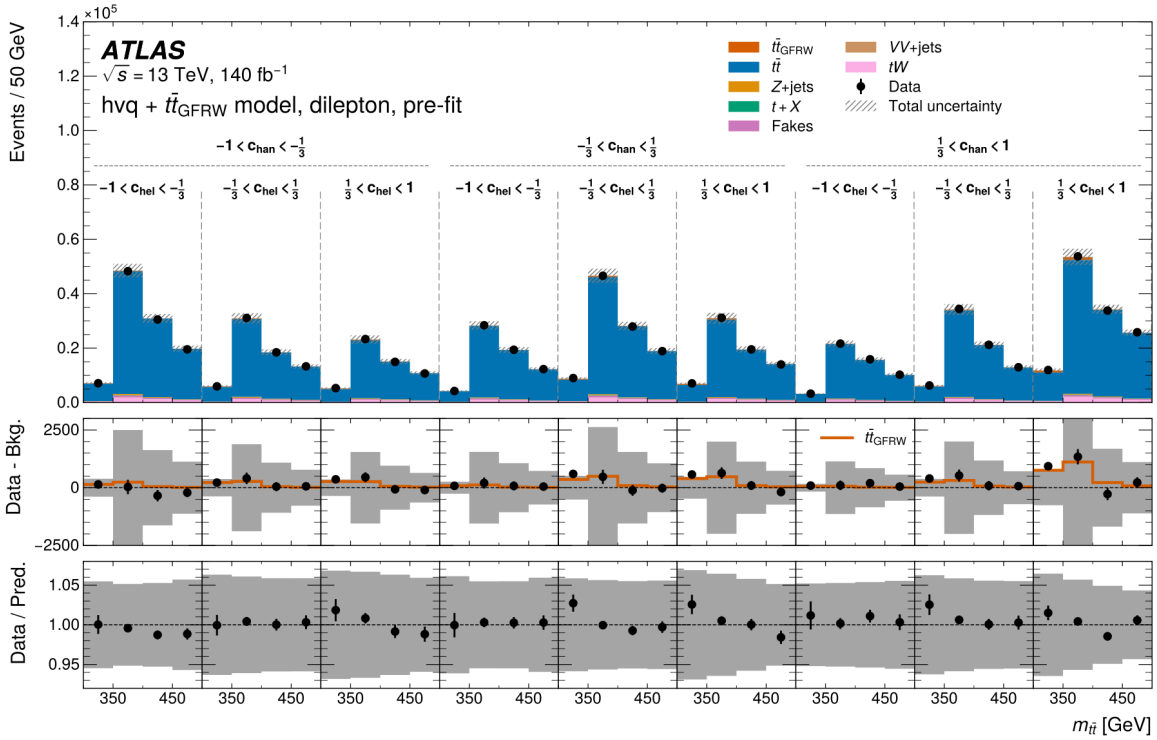
Both compare data with a fixed-order QCD baseline; quoted cross sections use a simplified η_t template.

CMS Collaboration, Rep. Prog. Phys. 88 (2025) 087801, arXiv:2503.22382, Fig. 1c.

CMS Collaboration, arXiv:2608.19546 (2026), Additional Fig. 5.

ATLAS: independent confirmation in dileptons

13 TeV pp collisions · 140 fb⁻¹ · nine spin-sensitive regions



Pre-fit m(t t̄) in nine c_{hel} × c_{han} regions

What the plot shows

Low-mass excess is strongest in bins with large spin-angle values. Orange shows the NRQCD contribution added to the baseline.

Selection and fit

Opposite-sign e/μ pair, ≥2 jets, ≥1 b-tag. Fit four mass bins in each angular region; include control regions for backgrounds.

Published result

9.3 +1.4/−1.3 pb

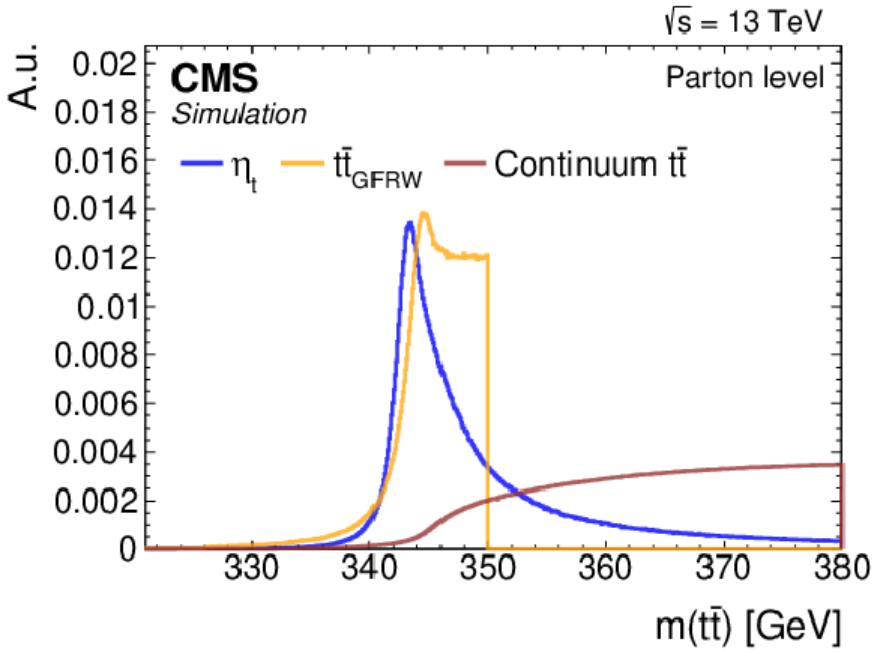
>8σ observed (6σ expected) against the stated pQCD-only baseline.

Green's-function NRQCD model; its fitted normalization is model-dependent.

ATLAS Collaboration, Rep. Prog. Phys. 89 (2026) 057801, arXiv:2601.11780, Fig. 3.

Possible interpretations of the threshold enhancement

A QCD quasi-bound contribution is plausible; the underlying dynamics need further tests



Parton-level templates, each normalized to unit area
GFRW cutoff at 350 GeV is a model choice

QCD threshold dynamics

Attractive color-singlet $t\bar{t}$ interactions can produce a short-lived $^1S_0$ quasi-bound enhancement. The finite top width smears individual levels.

Different descriptions of the same region

CMS uses a simplified pseudoscalar η_t template; ATLAS uses a Green's-function-reweighted model. Their shapes and fitted normalizations differ.

Alternative hypothesis and discrimination

A new pseudoscalar could contribute and interfere with the continuum. Test lineshapes, spin and rates across channels with improved QCD predictions.

Current mass resolution does not resolve an isolated bound-state peak.

CMS TOP-25-002 Fig. 1a; ATLAS arXiv:2601.11780; Djouadi et al., arXiv:2412.15138.

Summary: Hadron Spectroscopy

- **A rapid expanding spectrum--from glueballs to top-quark threshold dynamics**
  Significant progress from Belle-II, BESIII, ATLAS, CMS, LHCb (5X data)
  …Glueball, all charm tetraquark, top-antitop threshold dynamics…

- **Hadron spectroscopy moving beyond peak counting**
  From identifying peaks to understanding their nature

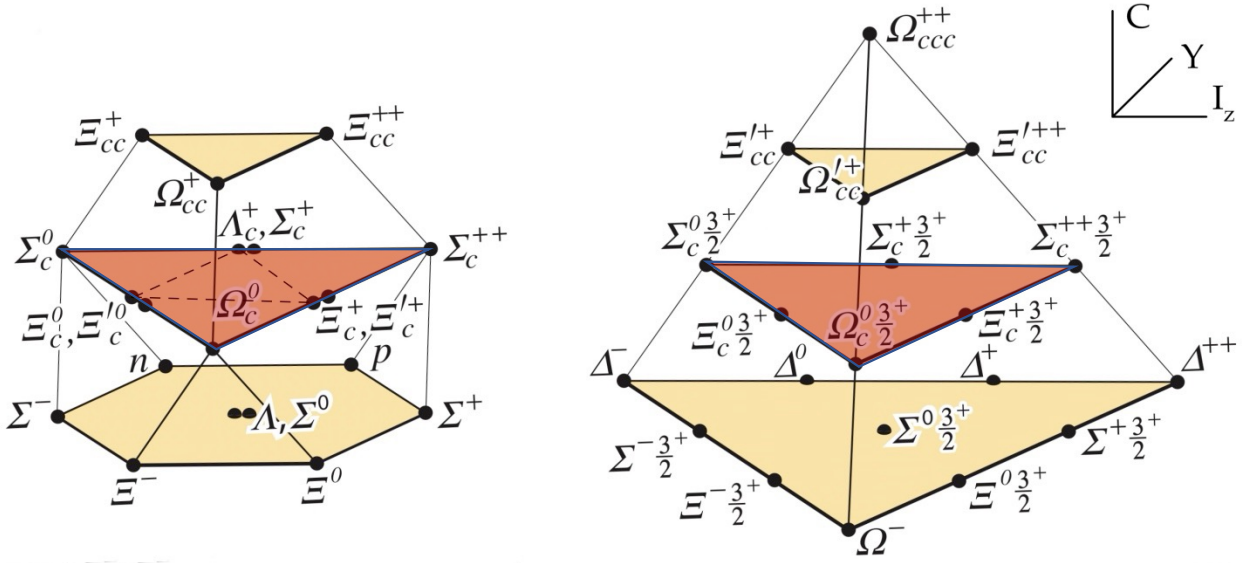
- **Complementary from different experiments**
  X(3872), $\mathbf{D_{s0}^{*}(2317)^{+}}$ & $\boldsymbol{B_{s0}^{*}(5700)^{0}}$**, all charm tetra-quark,…**

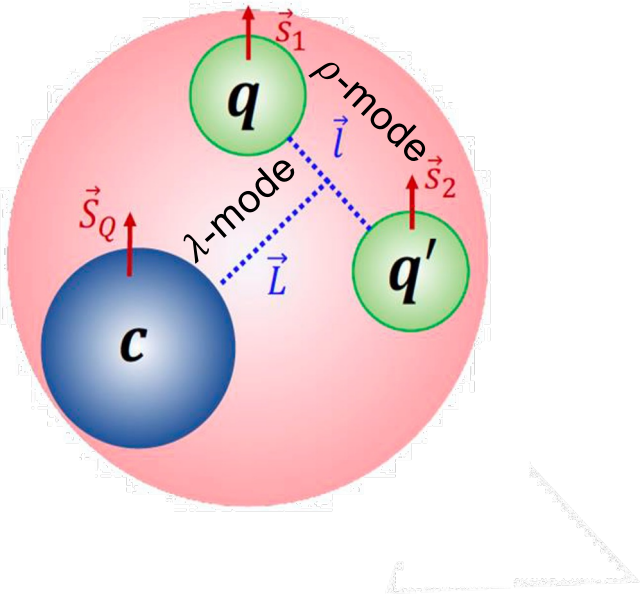
New era of precision hadron spectroscopy!

Backup

Charm baryon spectrum

- Nice platform for nonperturbative QCD
  - Heavy + light diquark
  - λ + ρ mode excitation





Σ_c^{**} in $B^- \to \Lambda_c^+ \bar{p} \pi^-$

- $\Sigma_c^0(cdd)$ experimental status limited
  - $\Sigma_c(2455)^0$, $\Sigma_c(2520)^0$ well established
  - Mass of $\Sigma_c(2800)^0$ in tension

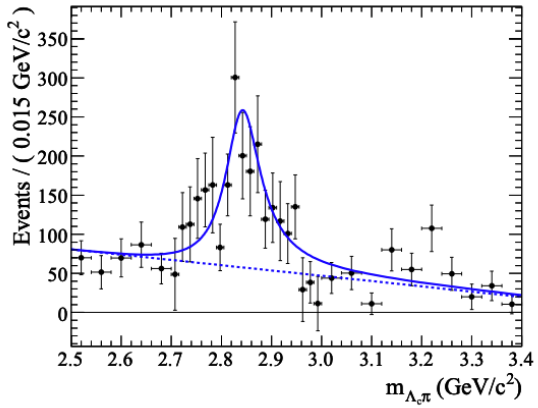
BaBar: $2846 \pm 8 \pm 10$ MeV PRD 78 (2008) 112003

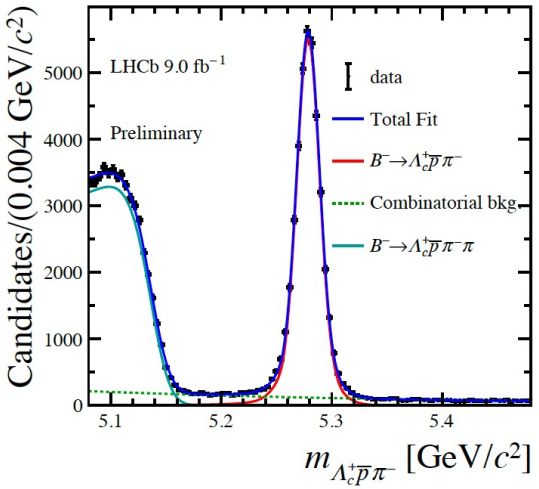
Belle: $2801.9^{+3.2+2.1}_{-3.1-6.0}$ MeV PRL 94 (2005) 122002

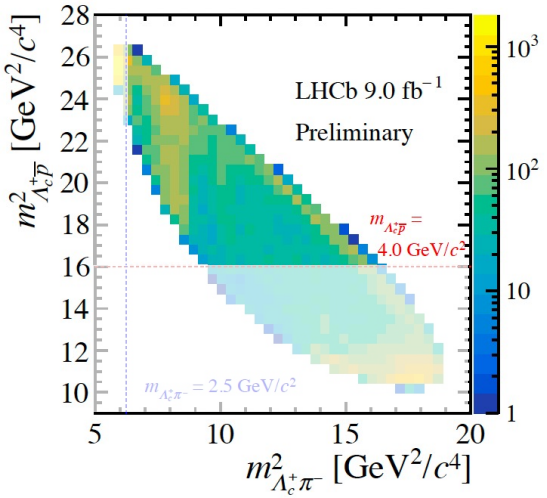
  - Babar used the same final state, observed peak at 2846 MeV

- LHCb performed amplitude analysis in search for excited $\Sigma_c^{**0} \to \Lambda_c^+ \pi^-$
  - $\Sigma_c(2455)^0$ studied separately
  - Region with threshold enhancement vetoed
  - Resonance includes $\Sigma_c \to \Lambda_c^+ \pi^-$ and $\overline{\Delta}^{--} \to \bar{p}\pi^-$ excitations

[LHCb-PAPER-2026-001 in preparation]

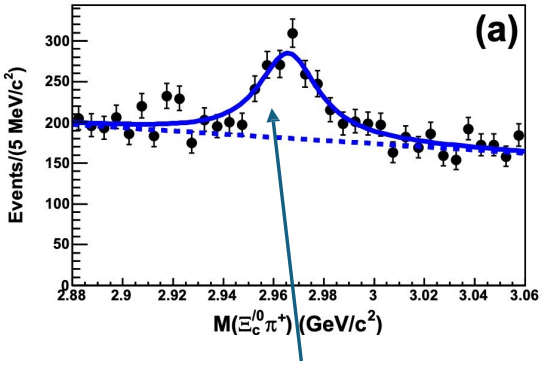




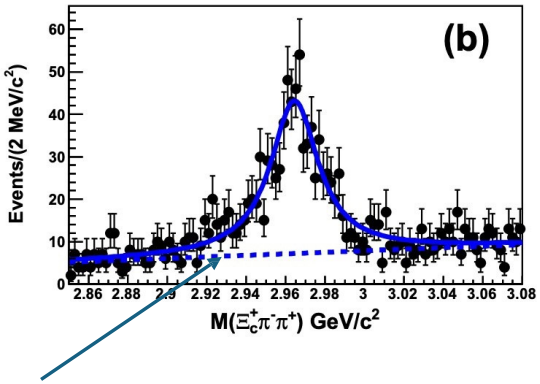


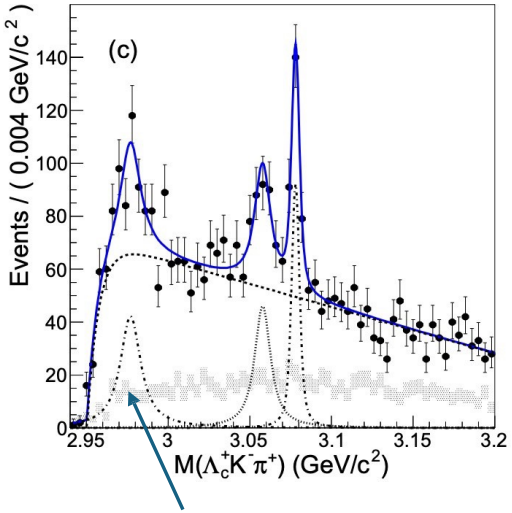
Ξ_c baryons

- Charmed baryons exhibit rich spectrum of excited states
- Over 100 $\Xi_c(csu, csd)$ states expected in mass range 2.8 – 3.8 GeV
  - Many experimental results, many puzzles remain
  - e.g. "$\Xi_c(2970)^+$" could be multiple different states
  - ⇒ Need more measurements, more decay modes, more precision

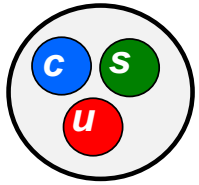


Ξc(2970)+ → Ξc′⁰π+ / Ξc+π−π+
m = 2966.0 ± 0.9 MeV, Γ = 28.1 ± 3.8 MeV
Belle, PRD 94, 052011 (2016)



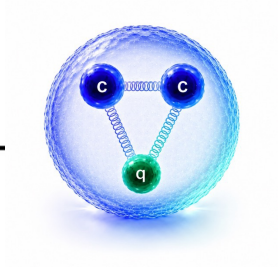


"Ξc(2970)+" → ΛcKπ
m = 2974.9 ± 2.6 MeV
Γ = 14.8 ± 4.8 MeV
Belle, PRD 89, 052003 (2013)
arXiv:1312.1026



Doubly charmed baryons

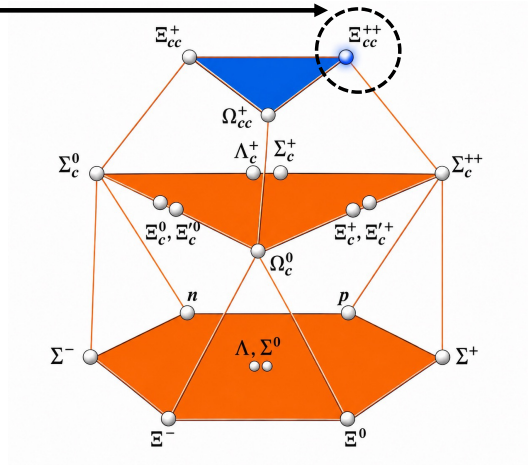
- From the SU(4)$_f$ multiplets, three weakly decaying doubly charmed baryons are expected

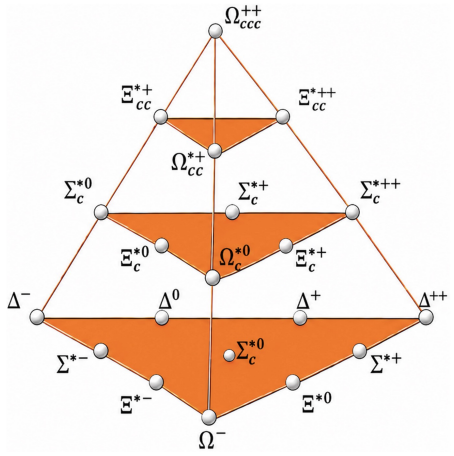


[JHEP 07 (2003) 061]
[PRD 102 (2020) 054513]
[PRD 83 (2020) 034026]

Mass	$m(\Xi_{cc}^{++}) \sim m(\Xi_{cc}^{+}) \sim m(\Omega_{cc}^{+}) - 100$ MeV
Lifetime	$\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) \sim 150\,\text{fs} > \tau(\Xi_{cc}^{+})$
Production	$\sigma(\Xi_{cc}^{++}) \sim \sigma(\Xi_{cc}^{+}) \sim 3 \cdot \sigma(\Omega_{cc}^{+})$ and $\sigma(H_{cc})/\sigma(H_c) \sim \mathcal{O}(10^{-4})$

LHCb Run 1+2 established the Ξ_{cc}^{++} baryon successfully, while searches for Ξ_{cc}^{+} and Ω_{cc}^{+} remained inconclusive…

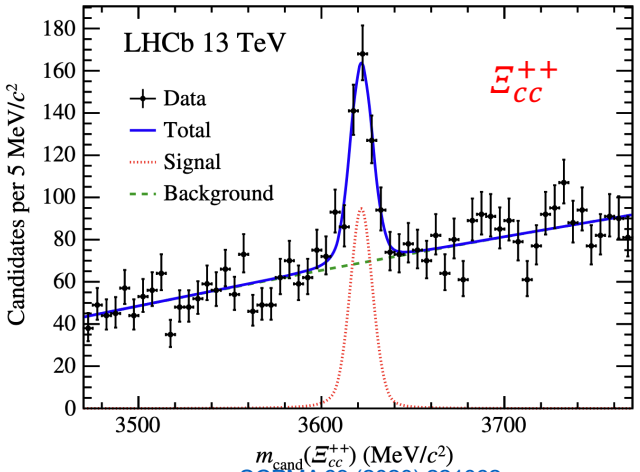




Experimental status before LHCb Run 3

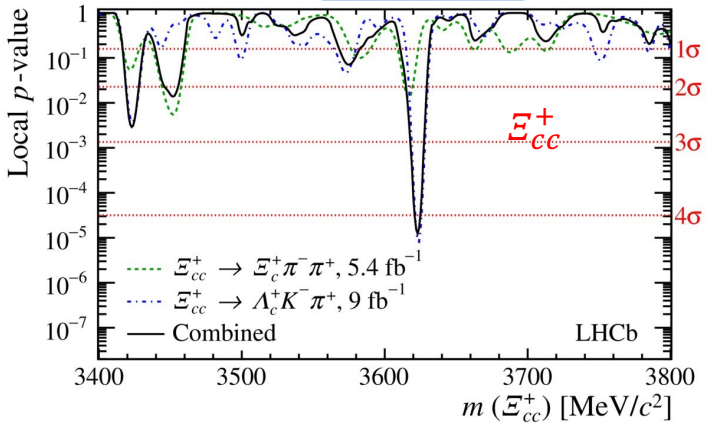
- [SELEX] First experimental claim on Ξ_{cc}^{+} and Ξ_{cc}^{++}
  - $m(\Xi_{cc}^{+}/\Xi_{cc}^{++}) = 3520/3460$ MeV, $\tau(\Xi_{cc}^{+}) < 33$ fs at 90% CL
  - Not confirmed by other experiments
- [LHCb] Observation of the Ξ_{cc}^{++}
  - Ξ_{cc}^{++} first observed in $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and confirmed in $\Xi_{cc}^{+} \to \Xi_c^+ \pi^+$
  - $m(\Xi_{cc}^{++}) = 3622$ MeV and $\tau(\Xi_{cc}^{++}) = 256$ fs
- [LHCb] Searched for Ξ_{cc}^{+} in $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+ / \Xi_c^+ \pi^- \pi^+$ and Ω_{cc}^{+} in $\Omega_{cc}^{+} \to \Xi_c^+ K^- \pi^+$
  - No significant signal is observed

PRL 119 (2017) 112001

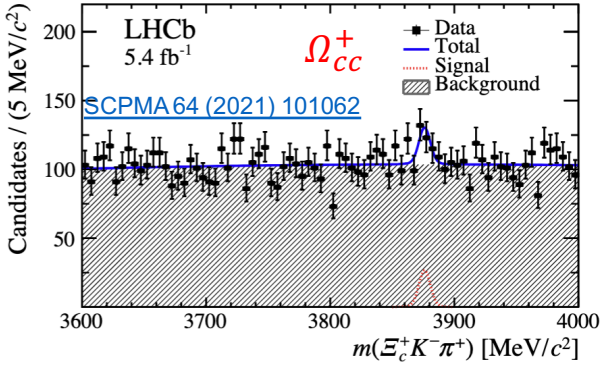


SCPMA 63 (2020) 221062

JHEP 12 (2021) 107



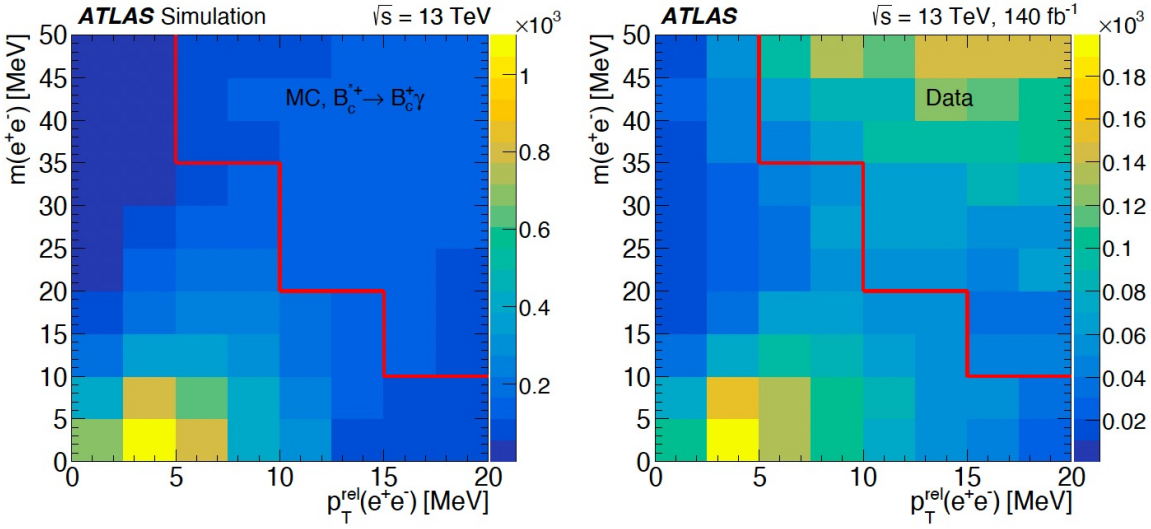
SCPMA 64 (2021) 101062



Excited B_c^{*+} meson search

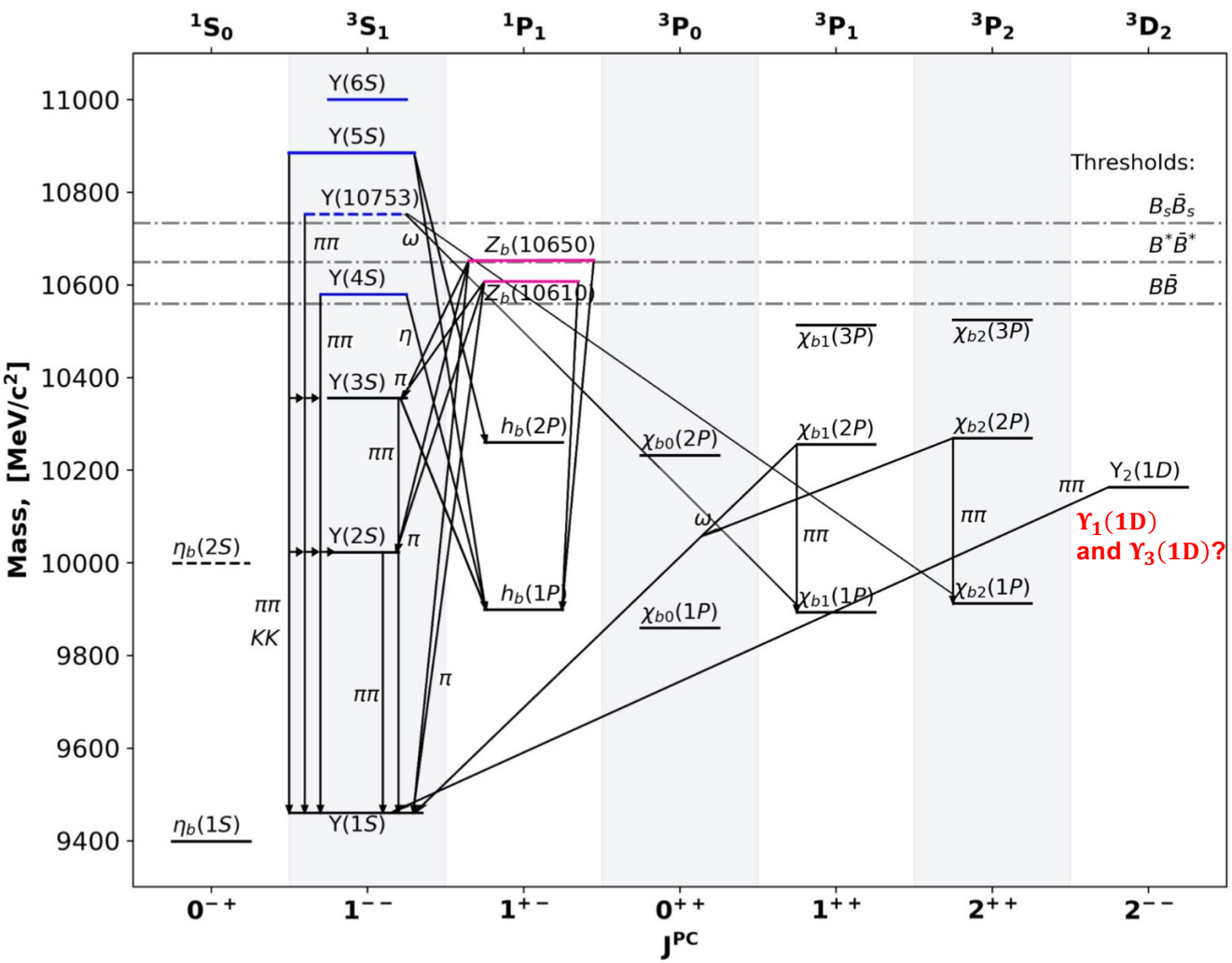
[PRL 137 (2026) 141901]

- Besides the known excited B_c states – radial excitations of $B_c(2S)^+$, $B_c^*(2S)^+$, and the P-wave state $B_c(1P)^+$ – the lightest excited state B_c^{*+} is predicted by Lattice and QCD potential models, but has never been observed due to the very soft photon in its decay. Two techniques to tackle it
  - ✓ The BR of $B_c^+ \to J/\psi(\to \mu^+\mu^-)\mu^+\nu_\mu X$ is ~20 times larger thar $B_c^+ \to J/\psi\pi^+$
  - ✓ The soft photon turns into two soft e^+e^- tracks in tracking material – use special tracking down to 0.1 GeV in p_T (default is 0.5 GeV) to reconstruct the soft converted photon



- To suppress fake converted photons, 2D cut on e^+e^- momentum transverse to line between PV and e^+e^- vertex, and on the e^+e^- mass, is applied
- Signal events tend to have lower values of these quantities while backgrounds have harder distributions

Bottomonium



- **Conventional bottomonium**
- **Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)**
- **Exotic charged states (Z_b^+)**

Only one D-wave $\Upsilon_2(1D)$ observed

Υ(10753) was first observed in $\pi^+\pi^-\Upsilon(nS)$ final states using Belle scan data [JHEP 10, 220 (2019)]

Υ(10753) widely interpreted as conventional bottomonium, tetraquark, or hybrid states

Belle II collected 19.8 fb^{-1} at $\sqrt{s}$ around 10.75 GeV to study

$e^+e^- \to \Upsilon_J(1D)\eta$ and $e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$

[arXiv:2607.04369, accepted by PRL]

Motivation

- ×Up to now, only one D-wave bottomonium state, $\Upsilon_2(1D)$, was observed by CLEO and BaBar [PRD 70, 032001 (2004), PRD 82, 111102 (2010)]. The mass of $\Upsilon_2(1D)$ is (10163.7±1.4) MeV/c^2.
- Belle studied $e^+e^- \to \Upsilon_J(1D)\eta$ and $e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$ at $\sqrt{s}$ = 10.866 GeV in the recoil mass spectra of η and $\pi^+\pi^-$ [EPJC 78, 633 (2018), PRL 108, 032001 (2012)].

- The $\Upsilon_J(1D)$ mass have been predicted by theory. However there are no reported experimental results in the mass differences among $\Upsilon_1(1D)$, $\Upsilon_2(1D)$, and $\Upsilon_3(1D)$.

References	$\Upsilon_1(1D)$ mass (MeV/c^2)	$\Upsilon_2(1D)$ mass (MeV/c^2)	$\Upsilon_3(1D)$ mass (MeV/c^2)
PRD 93, 074027 (2016)	10117	10122	10127
PRD 92, 054034 (2015)	10138	10147	10155
PRD 95, 074002 (2017)	10146	10153	10157
EPJC 78, 915 (2018)	10153	10162	10170

- Within the hadronic loop mechanism, the branching fractions for $\Upsilon(10860,11020) \to \Upsilon_J(1D)\eta$ and $\Upsilon(10860) \to \Upsilon_J(1D)\pi^+\pi^-$ range in magnitude from 10^{-4} to 10^{-3} [PRD 94, 094039 (2016), PRD 97, 094018 (2018), PRD 102, 114037 (2020)].

Dataset used in this work:

$\sqrt{s}$ (MeV)	$\mathcal{L}$ (fb^{-1})
10731.3	0.946
10771.2	0.955
10829.5	1.697
10848.9	0.989
10857.4	0.988
10865.8	122.0
10877.8	0.978
10882.8	1.848
10888.9	0.990
10898.3	2.408
10907.3	0.980
10928.7	1.149
10957.5	0.969
10975.3	0.999
10990.4	0.985
11003.9	0.976
11014.8	0.771
11018.5	0.859
11020.8	0.982

Born cross sections and branching fractions at $\sqrt{s}$ = 10.866 GeV

$$\sigma^{(1)}_{\rm Born} = \sigma_{\rm Born}(e^+e^- \to \Upsilon_J(1D)\eta)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma) = \frac{N^{\rm sig}\,|1-\Pi|^2}{\mathcal{L}\sum_{i=1}^{2}\varepsilon_i\mathcal{B}_i^{\rm int}\,(1+\delta_{\rm ISR})}$$

$$\mathcal{B}^{(1)}_{\Upsilon(10860)} = \mathcal{B}(\Upsilon(10860) \to \Upsilon_J(1D)\eta)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma) = \frac{N^{\rm sig}}{N_{\Upsilon(10860)}\sum_{i=1}^{2}\varepsilon_i\mathcal{B}_i^{\rm int}}$$

$$\sigma^{(2)}_{\rm Born} = \sigma_{\rm Born}(e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma) = \frac{N^{\rm sig}\,|1-\Pi|^2}{\mathcal{L}\,\varepsilon\,\mathcal{B}^{\rm int}\,(1+\delta_{\rm ISR})}$$

$$\mathcal{B}^{(2)}_{\Upsilon(10860)} = \mathcal{B}(\Upsilon(10860) \to \Upsilon_J(1D)\pi^+\pi^-)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma) = \frac{N^{\rm sig}}{N_{\Upsilon(10860)}\,\varepsilon\,\mathcal{B}^{\rm int}}$$

Channel	$\varepsilon_{\eta\to\gamma\gamma,\eta\to\pi^+\pi^-\pi^0}$	$N^{\rm sig}$	$\mathcal{B}^{(1)}_{\Upsilon(10860)}(\times10^{-3})$	$\sigma^{(1)}_{\rm Born}$(pb)
$e^+e^- \to \Upsilon_1(1D)\eta,\ \Upsilon_1(1D) \to \chi_{b1}\gamma$	0.102, 0.041	12.2 ± 6.3	$0.34 \pm 0.18 \pm 0.06$	$0.17 \pm 0.09 \pm 0.03$
$e^+e^- \to \Upsilon_2(1D)\eta,\ \Upsilon_2(1D) \to \chi_{b1}\gamma$	0.103, 0.042	37.8 ± 8.0	$1.05 \pm 0.22 \pm 0.12$	$0.52 \pm 0.11 \pm 0.06$
$e^+e^- \to \Upsilon_2(1D)\eta,\ \Upsilon_2(1D) \to \chi_{b2}\gamma$	0.103, 0.042	12.9 ± 6.0	$0.70 \pm 0.33 \pm 0.18$	$0.34 \pm 0.17 \pm 0.09$
$e^+e^- \to \Upsilon_3(1D)\eta,\ \Upsilon_3(1D) \to \chi_{b2}\gamma$	0.104, 0.043	0.3 ± 2.8	$0.02 \pm 0.15 \pm 0.02$	$0.01 \pm 0.07 \pm 0.01$
Channel	$\varepsilon_{\pi^+\pi^-}$	$N^{\rm sig}$	$\mathcal{B}^{(2)}_{\Upsilon(10860)}(\times10^{-3})$	$\sigma^{(2)}_{\rm Born}$(pb)
$e^+e^- \to \Upsilon_1(1D)\pi^+\pi^-,\ \Upsilon_1(1D) \to \chi_{b1}\gamma$	0.177	24.7 ± 6.5	$0.19 \pm 0.05 \pm 0.03$	$0.09 \pm 0.02 \pm 0.01$
$e^+e^- \to \Upsilon_2(1D)\pi^+\pi^-,\ \Upsilon_2(1D) \to \chi_{b1}\gamma$	0.180	25.0 ± 6.7	$0.19 \pm 0.06 \pm 0.03$	$0.09 \pm 0.03 \pm 0.01$
$e^+e^- \to \Upsilon_2(1D)\pi^+\pi^-,\ \Upsilon_2(1D) \to \chi_{b2}\gamma$	0.181	8.5 ± 4.2	$0.13 \pm 0.06 \pm 0.04$	$0.06 \pm 0.03 \pm 0.02$
$e^+e^- \to \Upsilon_3(1D)\pi^+\pi^-,\ \Upsilon_3(1D) \to \chi_{b2}\gamma$	0.182	17.9 ± 6.7	$0.27 \pm 0.09 \pm 0.03$	$0.13 \pm 0.05 \pm 0.02$

Here, i = 1 represents $\eta \to \gamma\gamma$; and i = 2 represents $\eta \to \pi^+\pi^-\pi^0$.

- **To calculate the radiative correction factor, we assume the dressed cross section measured in this work.**
- **$N_{\Upsilon(10860)} = \mathcal{L}\sigma(e^+e^- \to b\bar{b})$ = (4.2±0.2)×10^7 [PRL 113, 142001 (2014)]**

The dressed cross sections as a function of C.M. energy:

We combine the $\Upsilon_1(1D)$, $\Upsilon_2(1D)$, and $\Upsilon_3(1D)$ states due to significant cross feeds among them.

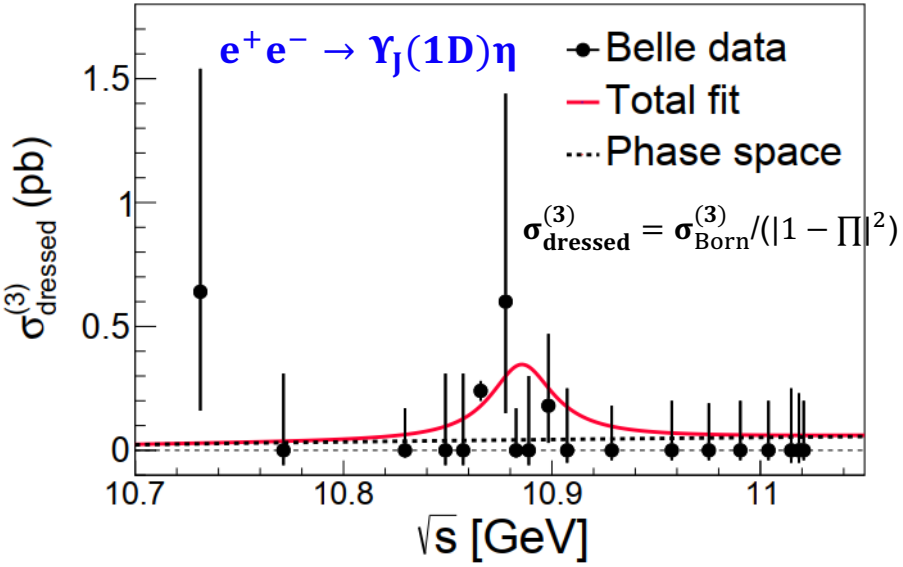
The fit function as below

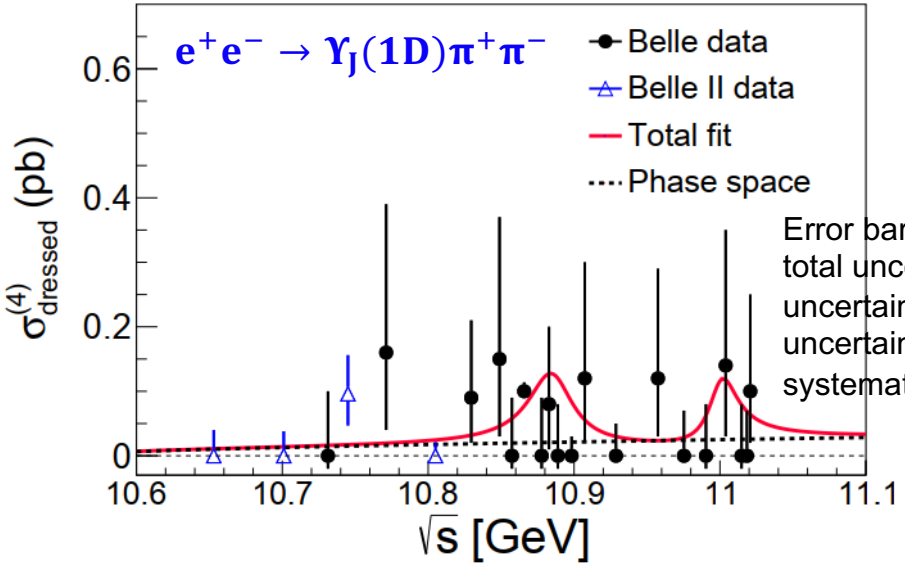
$$\sigma^{(3)}_{\rm Born} = \sigma_{\rm Born}(e^+e^- \to \Upsilon_J(1D)\eta)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma)\,\mathcal{B}(\chi_{b1,b2} \to \Upsilon(1S)\gamma)$$

$$\sigma^{(4)}_{\rm Born} = \sigma_{\rm Born}(e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma)\,\mathcal{B}(\chi_{b1,b2} \to \Upsilon(1S)\gamma)$$

$$\Big|\sum_{i=1}^{2}\frac{\sqrt{12\pi\Gamma_{ee,i}\mathcal{B}_i\Gamma_i}}{s-M_i^2-iM_i\Gamma_i}\sqrt{\frac{\Phi(\sqrt{s})}{\Phi(M_i)}}e^{i\phi}\Big|^2 + c_{\rm NR}\Phi(\sqrt{s})$$

2 BWs + phase-space





Error bars represent the total uncorrelated uncertainties (statistical uncertainty + additive systematic uncertainty).

- The dots show the dressed cross sections measured in this work.
- The triangles show the dressed cross sections for $e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$ at Belle II [JHEP 06 (2026) 278].

The signal significances of fit outputs are less than 3σ, the upper limits at 90% C.L. are also given in square brackets.

$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \Upsilon_J(1D)\eta)\mathcal{B}_f$	$(0.091 \pm 0.039 \pm 0.016)$ $[<0.14]$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \Upsilon_J(1D)\eta)\mathcal{B}_f$	$(0.000 \pm 0.018 \pm 0.005)$ $[<0.04]$
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \Upsilon_J(1D)\pi^+\pi^-)\mathcal{B}_f$	$(0.034 \pm 0.013 \pm 0.006)$ $[<0.06]$
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \Upsilon_J(1D)\pi^+\pi^-)\mathcal{B}_f$	$(0.020 \pm 0.016 \pm 0.005)$ $[<0.05]$

$\mathcal{B}_f = \mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma)\mathcal{B}(\chi_{b1,b2} \to \Upsilon(1S)\gamma)$