Experimental overview on heavy spectroscopy

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Outline

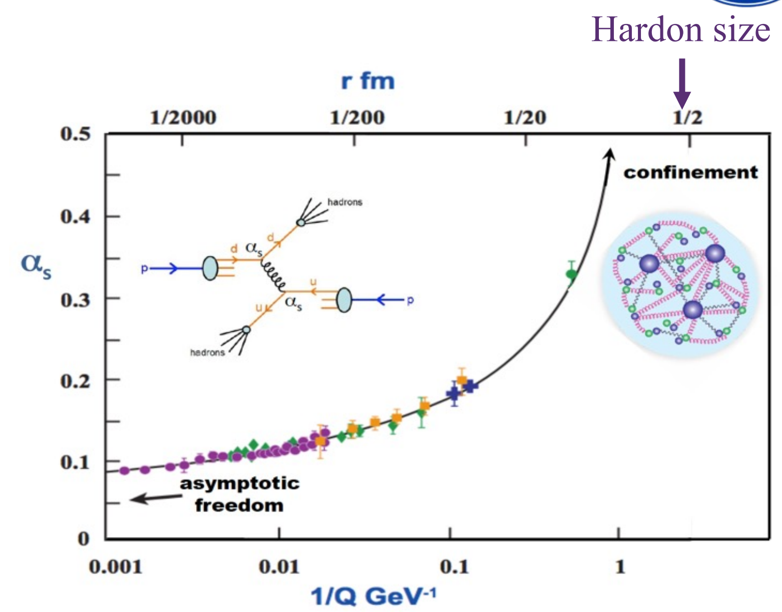
- ➢ Introduction
- ➢ Heavy hadron spectroscopy: conventional and exotic
  - ✓ Heavy meson
  - ✓ Heavy baryon
- ➢ Summary

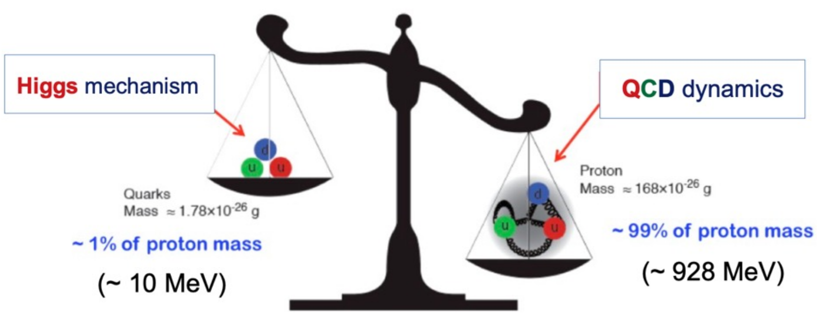
PDG:	2001	2021
$D_{(s)J}$	10	27
$B_{(s)J}$	4	12
$c\bar{c}-\text{like}$	13	40
$b\bar{b}-\text{like}$	12	16
$c-\text{baryons}$	8	27
$b-\text{baryons}$	0	23

I apologize for not covering all the experiments results.

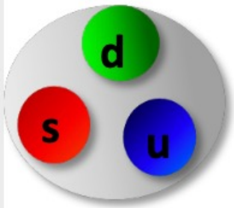
Introduction

- Quarks and gluons not isolated in nature.
  - Formation of colorless bound states: "**Hadrons**"
  - **1-fm scale** size of hadrons?
- Hadron spectroscopy provides opportunities to study QCD in the non-perturbative region
  - Extensive and precise spectroscopy combined with a thorough theoretical analysis, will add substantially to our knowledge of QCD
- Complex exotic hadrons can reveal new or hidden aspects of the dynamics of strong interactions
  - Predicted in quark model
  - Recent results show strong evidence for their existence





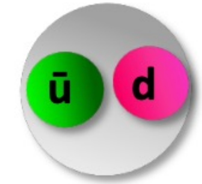
Different types of hadrons to be explored



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

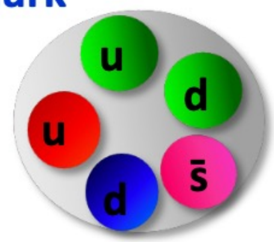


π=ūd

Other possible combinations of quarks and gluons :

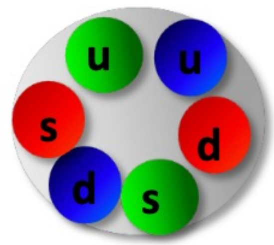
Pentaquark

S= +1 Baryon



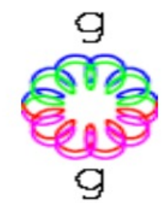
H di-Baryon

Tightly bound 6 quark state



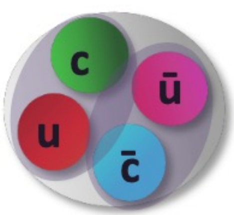
Glueball

Color-singlet multi-gluon bound state



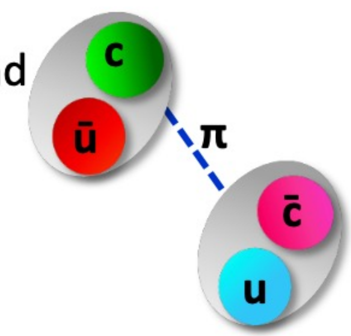
Tetraquark

Tightly bound diquark & anti-diquark

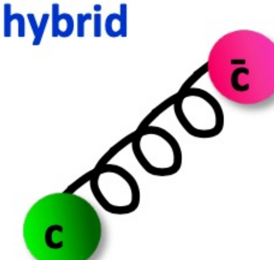


Molecule

loosely bound meson-antimeson "molecule"



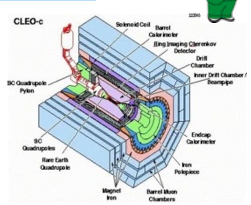
qq̄ -gluon hybrid mesons



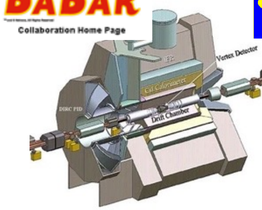
Main contributors worldwide

- **e^+e^- collider**

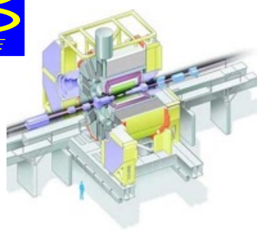
CLEO-c



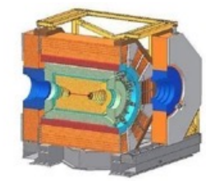
BABAR



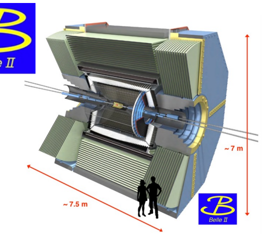
BELLE



BESIII

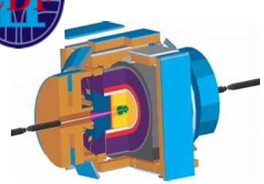


Belle II

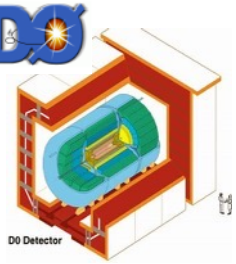


- **Hadron collider**

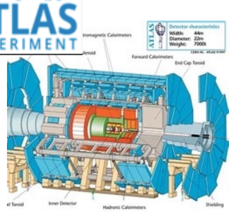
CDF



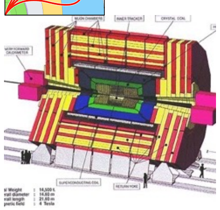
DØ



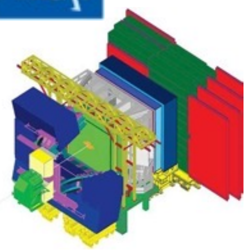
ATLAS EXPERIMENT



CMS



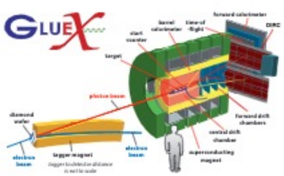
LHCb



- **Fixed-target experiments**

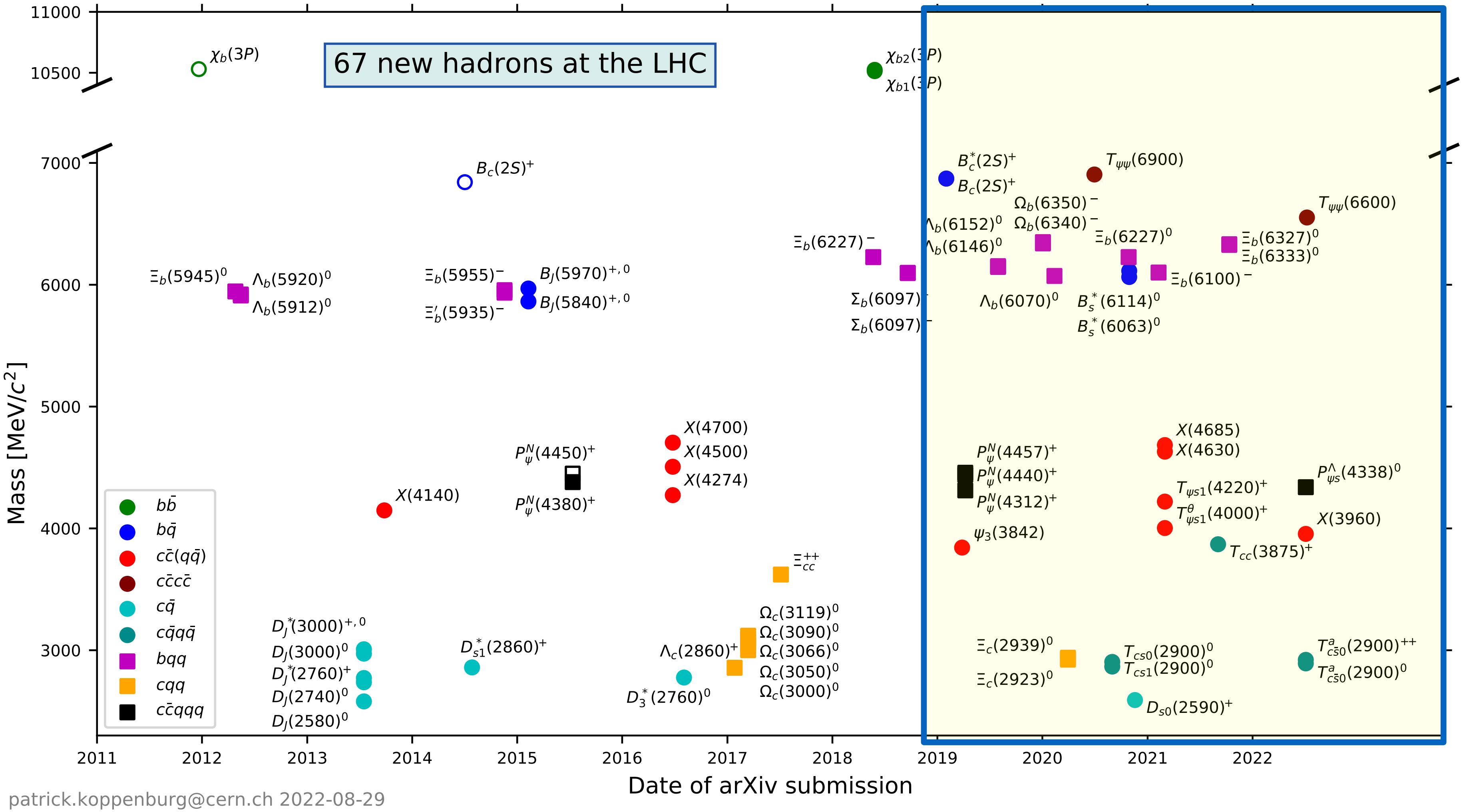
COMPASS

GlueX



Heavy hadron Spectroscopy

an example: LHC as a Large Hadron Discovery Factory

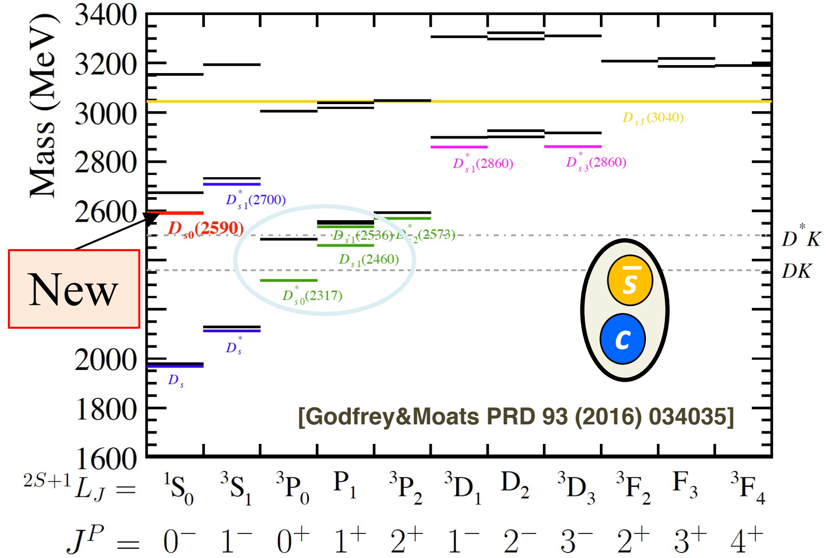


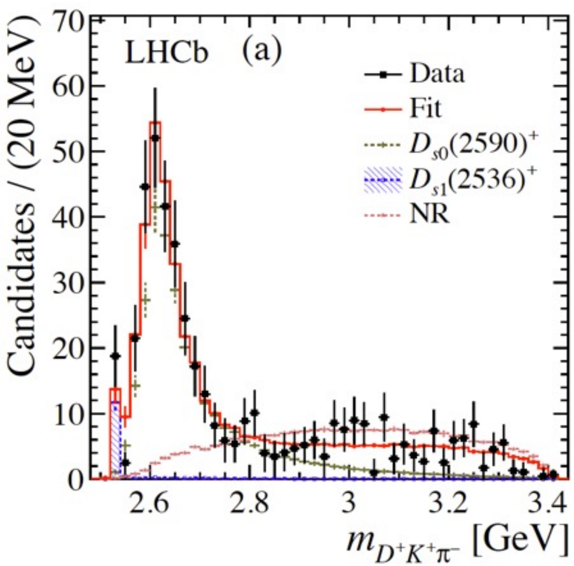
Heavy mesons

A new state $D_s^+(2590)$ from $B^0 \to D^+D^-K^+\pi^-$

PRL126, 122002 (2021)

- Big puzzle: $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ have much smaller masses than the predictions
- Additional experimental input is helpful
- Use $B^0 \to D^+D^-K^+\pi^-$ decay with 5.4 fb^{-1} of RUN2 at LHCb
  - $m(K^+\pi^-) < 0.75$ GeV consistent with S-wave $K^+\pi^-$
- $D^+K^+\pi^-$ invariance mass shows a strong peak





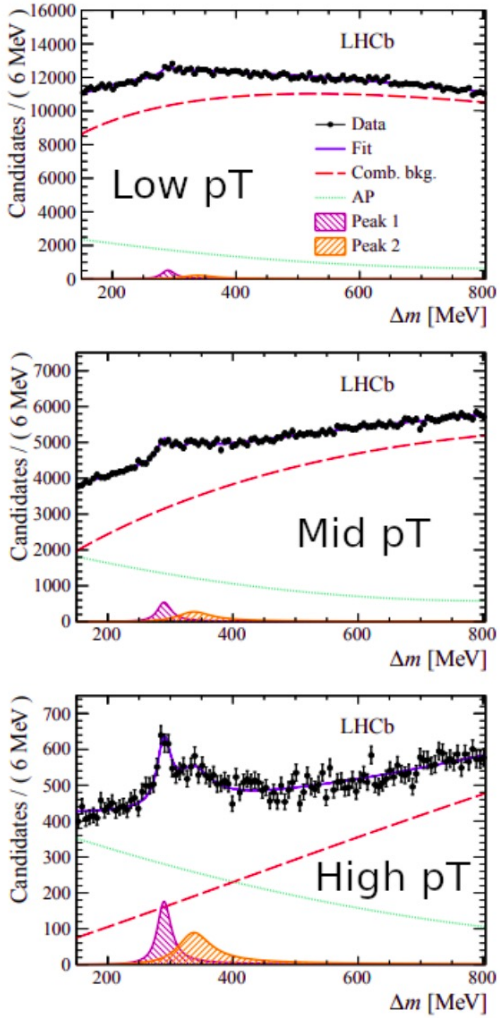
- Amplitude fit is performed

State	Pole Mass [MeV]	Pole Width [MeV]	J^P
$D_{s0}(2590)^+$	$2591 \pm 6 \pm 7$	$89 \pm 16 \pm 12$	0^-

- Strong candidate for $D_s(2^1S_0)$

Observation of new excited B_s^0 states

EPJC 81, 601 (2021)

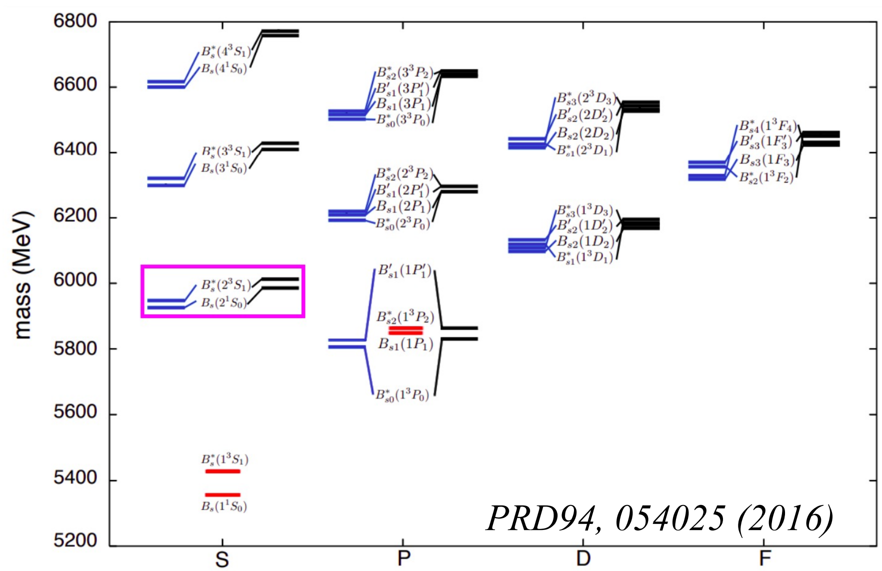


- $\Delta m = m(B^+K^-) - M_{B^+} - M_{K^-}$

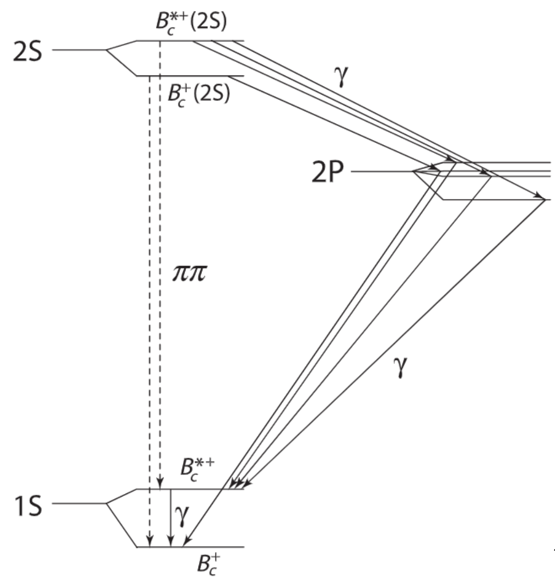
- The B_s^0 excitation spectrum is mostly unexplored
- A structure is observed in the $B^{\pm}K^{\mp}$ mass spectrum with 9 fb^{-1} RUN 1+2 data.
- Well described with a two-resonance model

$$m_1 = 6063.5 \pm 1.2\,(\text{stat}) \pm 0.8\,(\text{syst})\,\text{MeV},$$
$$\Gamma_1 = 26 \pm 4\,(\text{stat}) \pm 4\,(\text{syst})\,\text{MeV},$$
$$m_2 = 6114 \pm 3\,(\text{stat}) \pm 5\,(\text{syst})\,\text{MeV},$$
$$\Gamma_2 = 66 \pm 18\,(\text{stat}) \pm 21\,(\text{syst})\,\text{MeV}.$$

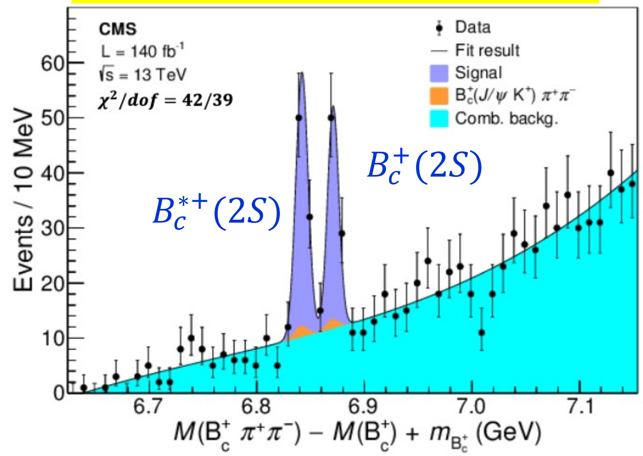
Their assignments in the spectrum is not yet conclusive



Observation of two excited Bc mesons



CMS, PRL122,132001 (2019)



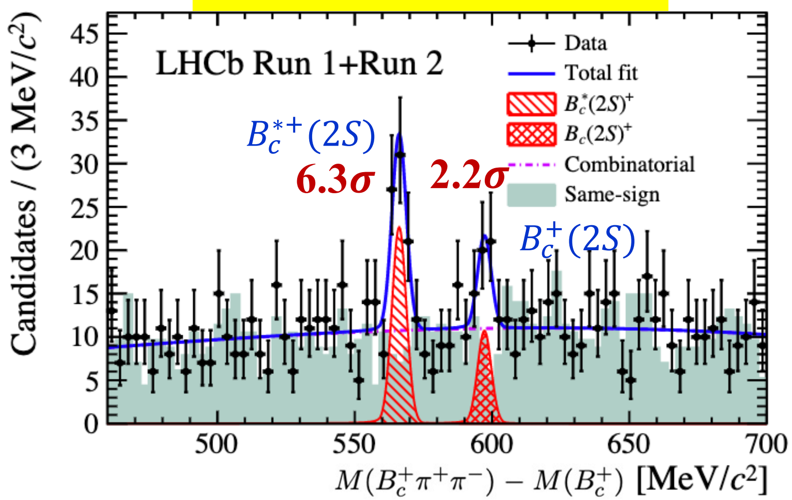
two peaks significance >5σ

$B_c^{*+}(2S)$ peak shifted down by the mass difference of B_c^{+*} and B_c^{+}

peak position difference
$\Delta M = 29.1 \pm 1.5 \pm 0.7$ MeV
(lower than truth of mass difference)

$$M(B_c(2S)^+) = \mathbf{6871.0 \pm 1.2\,(stat) \pm 0.8\,(syst) \pm 0.8\,(B_c^+) MeV}$$

LHCb 122, 232001 (2019)



$$M(B_c^*(2S)^+)_{rec} = M(B_c^*(2S)^+) - [M(B_c^{+*}) - M(B_c^+)]$$
$$6841.2 \pm 0.6\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst}) \pm 0.8\,(B_c^+)\ \mathrm{MeV}/c^2,$$

$$M(B_c(2S)^+) =$$
$$6872.1 \pm 1.3\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst}) \pm 0.8\,(B_c^+)\ \mathrm{MeV}/c^2.$$

peak position difference
$\Delta M = 31.0 \pm 1.4 \pm 0.0$ MeV

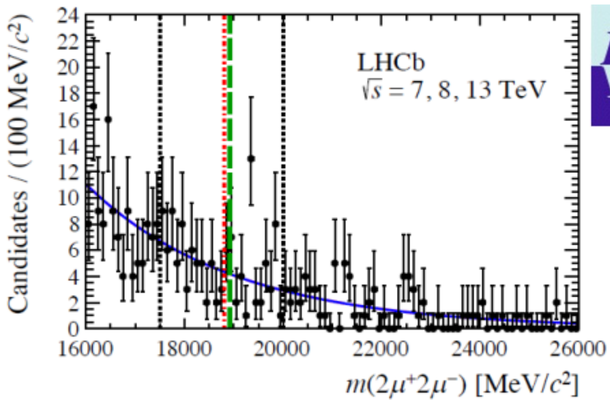
Hidden-flavor exotic hadrons

Study on fully heavy tetraquark state

- Existence of $T_{Q_1Q_2\bar{Q}_3\bar{Q}_4}$ states ($Q_i = c$ or b) is expected by many QCD models
- $T_{bb\bar{b}\bar{b}}$ was searched for at LHCb and CMS, but not observed

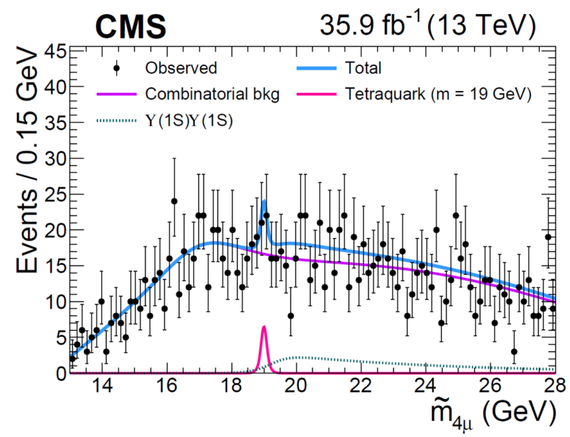
$T_{bb\bar{b}\bar{b}}$ searches at LHCb [JHEP 10, 086 (2018)]

- 6.3 fb^{-1} at 7, 8 and 13 TeV
- Explored the mass region 17.5 – 20.0 GeV/c^2
- No significant signal



$T_{bb\bar{b}\bar{b}}$ searches at CMS [PLB808, 135578(2020)]

- 35.9 fb^{-1} at 13 TeV
- Explored the mass region 17.5 – 19.5 GeV/c^2
- No significant signal



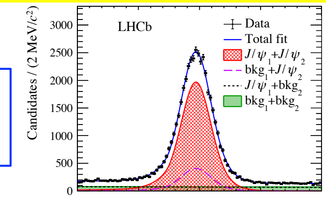
- $T_{cc\bar{c}\bar{c}}$ states predicted to have $M \in [5.8, 7.4]$ GeV/c, away from known quarkonia and quarkonium-like exotic states

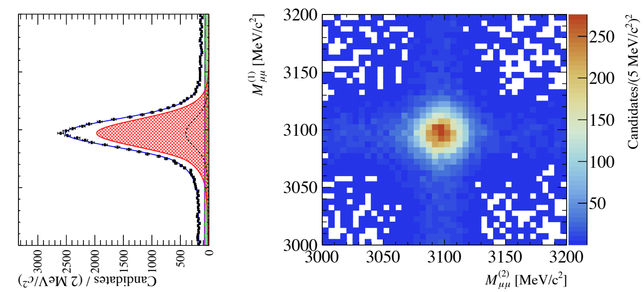
Observation of fully charmed tetraquark state X(6900) [$cc\bar{c}\bar{c}$]

Science Bulletin 23, 1983 (2020)

- Double $J/\psi(\rightarrow \mu^+\mu^-)$ combinations in Run 1+2 data
- The J/ψ-pair invariant mass spectrum is inconsistent with non-resonant SPS- and DPS-only hypothesis by more than 5σ in the $[6.2, 7.4]$ GeV/c^2 mass region
- Assuming X(6900) is a resonance with Breit-Wigner lineshape

$\boldsymbol{N(J/\psi}$ **pair**$) =$ $\boldsymbol{(33.57 \pm 0.23)\times 10^3}$





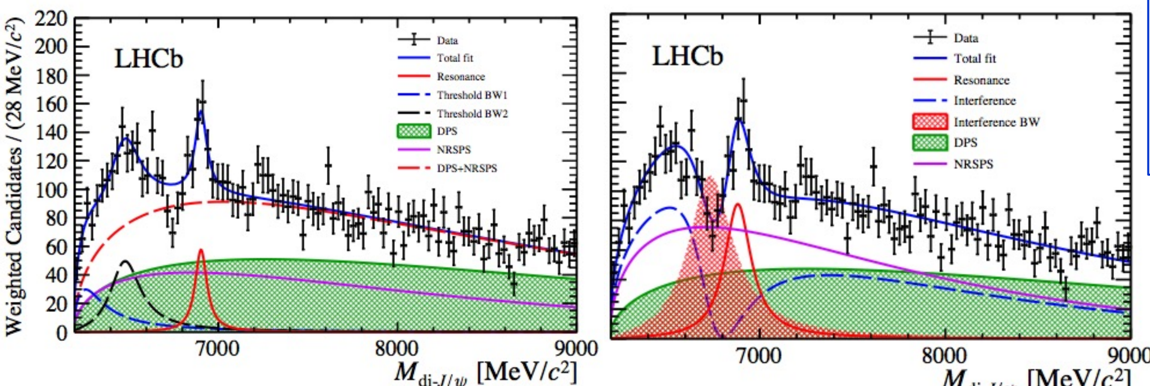
- ✓ Model I: Based on no-interference fit (worse fitting quality)

$$M[\mathrm{X(6900)}] = 6905 \pm 11(\mathrm{stat}) \pm 7(\mathrm{syst})\ \mathrm{MeV}/c^2$$
$$\Gamma[\mathrm{X(6900)}] = 80 \pm 19(\mathrm{stat}) \pm 33(\mathrm{syst})\ \mathrm{MeV}/c^2$$

- ✓ Model II: Based on the simple model with interference (better fitting quality)

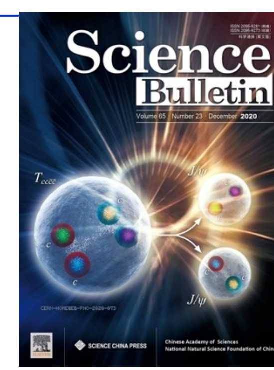
$$M[\mathrm{X(6900)}] = 6886 \pm 11(\mathrm{stat}) \pm 11(\mathrm{syst})\ \mathrm{MeV}/c^2$$
$$\Gamma[\mathrm{X(6900)}] = 168 \pm 33(\mathrm{stat}) \pm 69(\mathrm{syst})\ \mathrm{MeV}/c^2$$

consistent with predicted $T_{cc\bar{c}\bar{c}}$ states

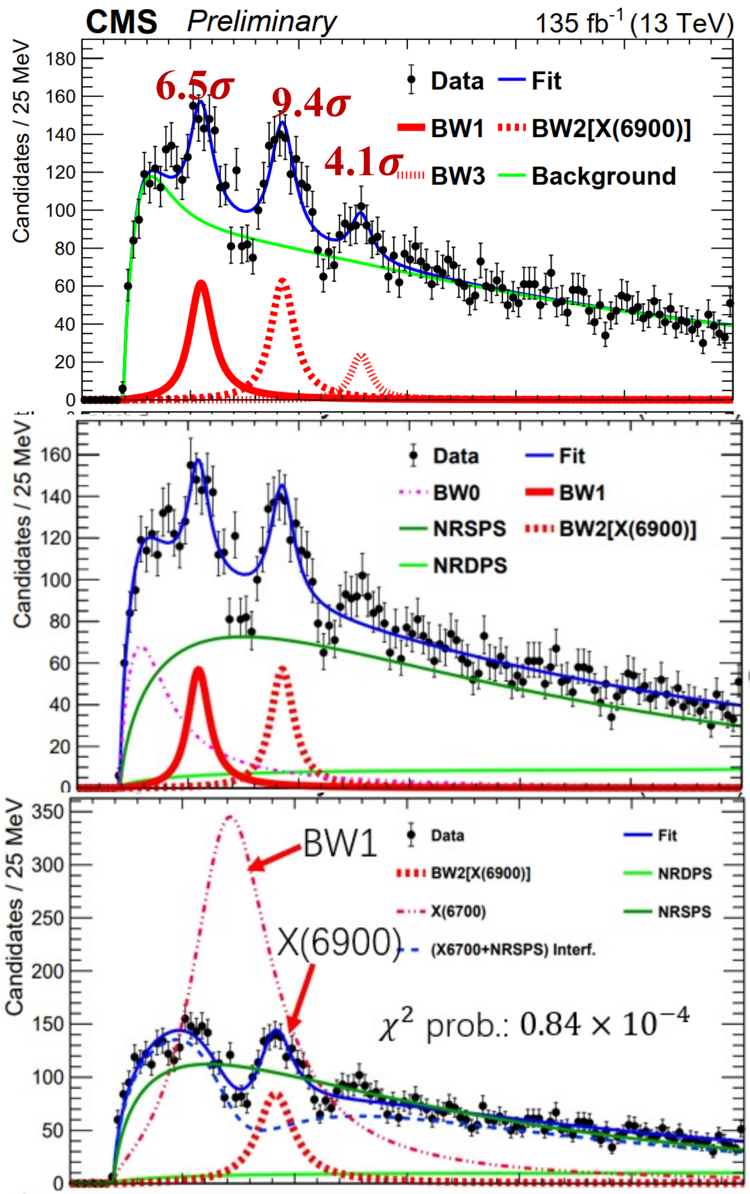


The lower broader structure:

- feed-down from heavier quarkonia, e.g. $T_{cc\bar{c}\bar{c}} \rightarrow \chi_c(\rightarrow J/\psi\gamma) + J/\psi$
- near-threshold kinematic rescattering effects



Observations of fully charmed tetraquark state X(6600) [$cc\bar{c}\bar{c}$]



- CMS finds two new structures X(6600) and X(7200)
- BW2 consistent with X(6900)

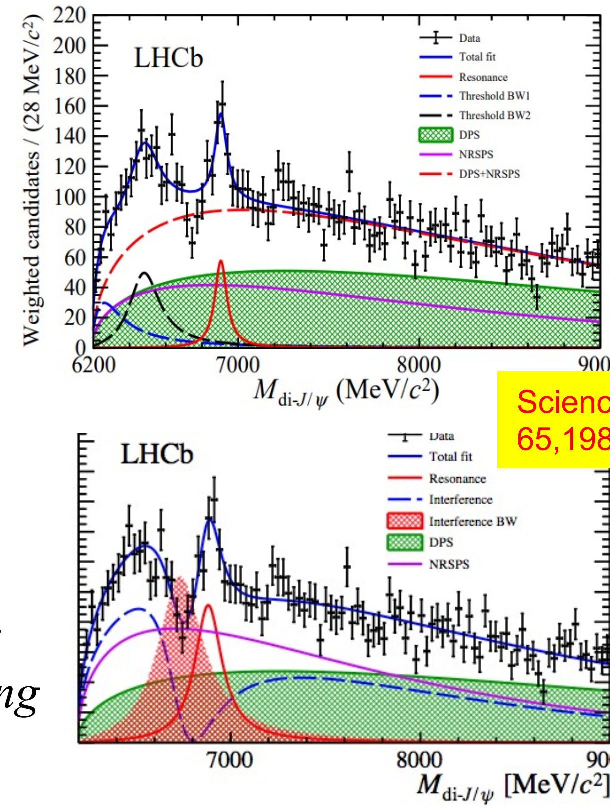
M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV

⟺

dips are not well described

⟺

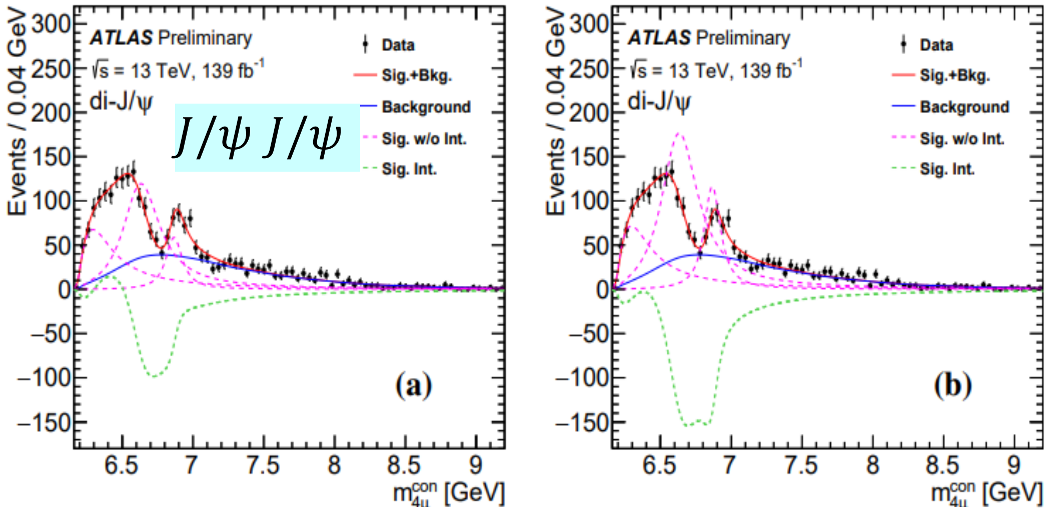
more interference studies are ongoing



Science Bulletin 65,1983 (2020)

ATLAS confirmations of X(6900)

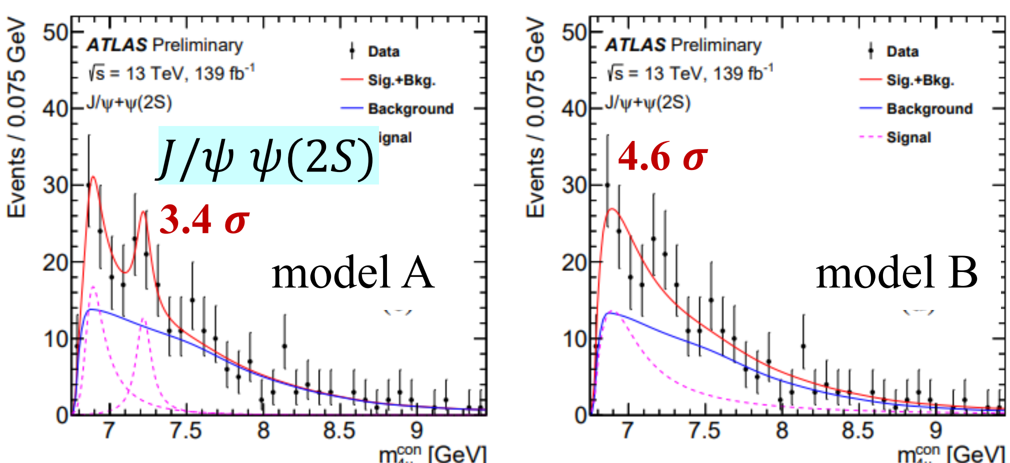
ATLAS-CONF-2022-040



3BW fits

(GeV)		m_0	Γ_0	m_1	Γ_1
di-J/ψ		$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
		m_2	Γ_2	—	
		$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	

- The **3rd peak** mass is consistent with the LHCb observed X(6900), with significance of **10σ**
- The broad structure at the lower mass could from other physical effects, e.g. feed-down from higher di-charmonium resonances



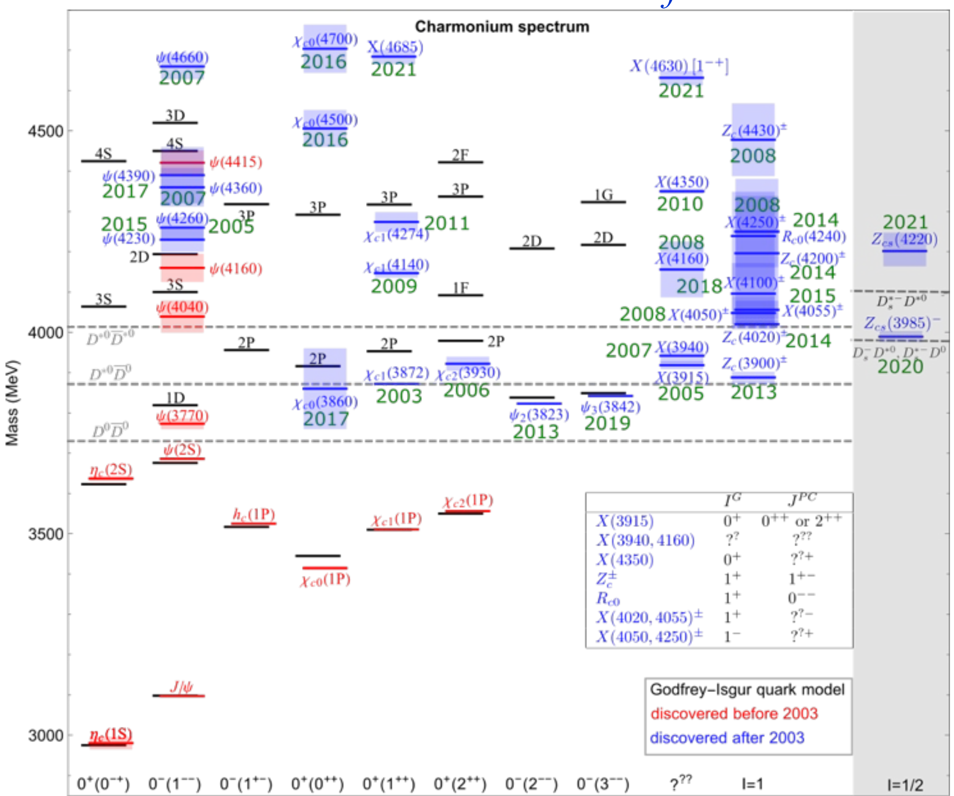
(GeV)		m_3	Γ_3
J/ψ+$\psi(2S)$	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$

- 1st peak could be related to X(6900): **4.6 σ**
- 2nd peak could be related to X(7200): **3.4 σ**

Heavy quarkonium(-like) sector

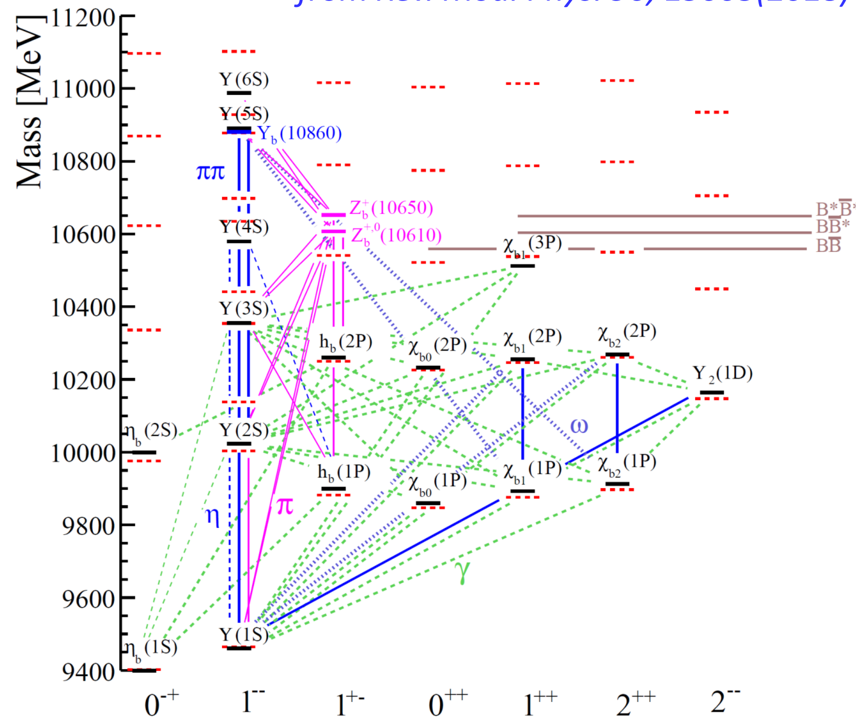
Charmonium-like($c\bar{c}$) spectrum

from F-K. Guo



Bottomonium-like ($b\bar{b}$) spectrum

from Rev. Mod. Phys. 90, 15003(2018)



What have we learnt about $X(3872)$

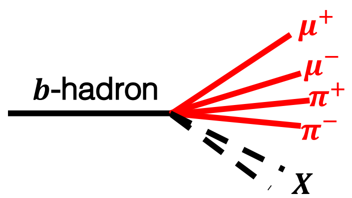
- $X(3872)$ nature is still uncertain, although many studies are performed since 2003
  - **$J^{PC} = 1^{++}$**
  - **Mass = 3871.69 ± 0.17 MeV**
  - **Width < 1.2 MeV** @90% CL

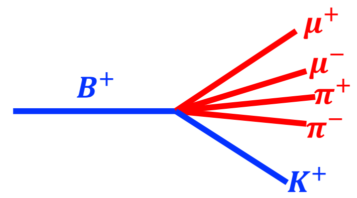
  $\delta E = (m_{D^{*0}} + m_{D^0}) - m_{X(3872)} = \mathbf{0.01 \pm 0.20}$ **MeV**
- Production
  - In e^+e^- collision, see strong connection of Y(4260) resonance decays [BESIII, PRL 112. 092001 (2014); 122, 202001 (2019)]
  - In b-hadron decays: B, Bs, Λ_b, …
  - Prompt production in $pp/p\bar{p}$ and heavy ion collision
- What is it?
  - **Loosely $D^0\bar{D}^{0*}$ bound state?**
  - **Mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{0*}$?**
- Important to fully explore its production and decay properties

Mode			Fraction (Γ_i/Γ)
Γ_1		e^+e^-	$< 2.8 \times 10^{-6}$
Γ_2		$\pi^+\pi^- J/\psi(1S)$	$(3.8 \pm 1.2)\%$
Γ_3		$\pi^+\pi^-\pi^0 J/\psi(1S)$	not seen
Γ_4		$\omega\eta_c(1S)$	$< 33\%$
Γ_5	★	$\omega J/\psi(1S)$	$(4.3 \pm 2.1)\%$
Γ_6		$\phi\phi$	not seen
Γ_7		$D^0\bar{D}^0\pi^0$	$(49^{+18}_{-20})\%$
Γ_8	★	$\bar{D}^{*0}D^0$	$(37 \pm 9)\%$
Γ_9		$\gamma\gamma$	$< 11\%$
Γ_{10}		$D^0\bar{D}^0$	$< 29\%$
Γ_{11}		D^+D^-	$< 19\%$
Γ_{12}		$\pi^0\chi_{c2}$	$< 4\%$
Γ_{13}	★	$\pi^0\chi_{c1}$	$(3.4 \pm 1.6)\%$
Γ_{14}		$\pi^0\chi_{c0}$	$< 70\%$
Γ_{15}		$\pi^+\pi^-\eta_c(1S)$	$< 14\%$
Γ_{16}		$\pi^+\pi^-\chi_{c1}$	$< 7 \times 10^{-3}$
Γ_{17}		$p\bar{p}$	$< 2.4 \times 10^{-5}$
Radiative decays			
Γ_{18}		γD^+D^-	$< 4\%$
Γ_{19}		$\gamma\bar{D}^0D^0$	$< 6\%$
Γ_{20}	★	$\gamma J/\psi$	$(8 \pm 4) \times 10^{-3}$
Γ_{21}		$\gamma\chi_{c1}$	$< 9 \times 10^{-3}$
Γ_{22}		$\gamma\chi_{c2}$	$< 3.2\%$
Γ_{23}	★	$\gamma\psi(2S)$	$(4.5 \pm 2.0)\%$

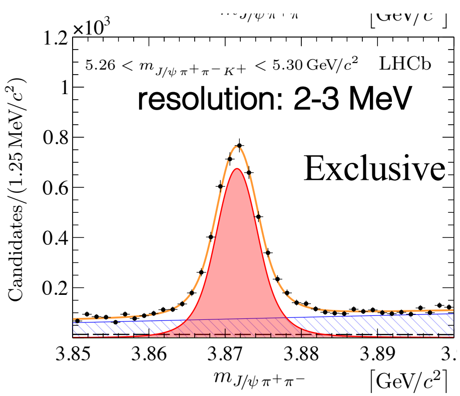
$X(3872)$ lineshape

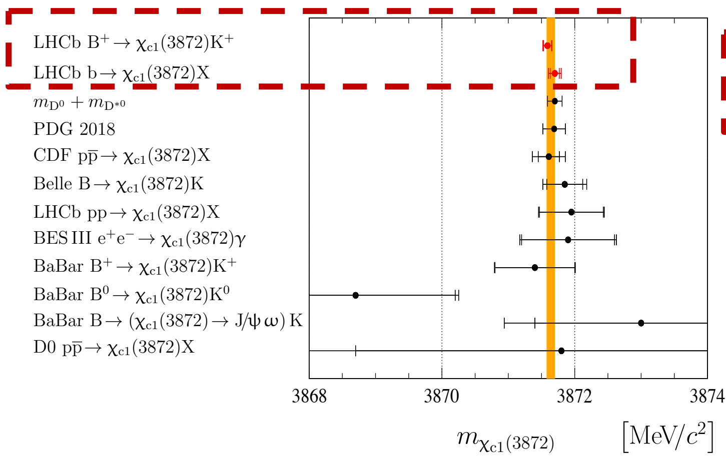
- Two measurements using $X(3872) \to J/\psi\pi^+\pi^-$ related to $\psi(2S)$
  - **Inclusive** $b \to X(3872)$ + anything: ~15.6k signals (more bkg) [PRD 102, 092005 (2020)]
  - **Exclusive** $B^+ \to X(3872)K^+$: ~4.2k signals (less bkg) [JHEP 08, 123 (2020)]

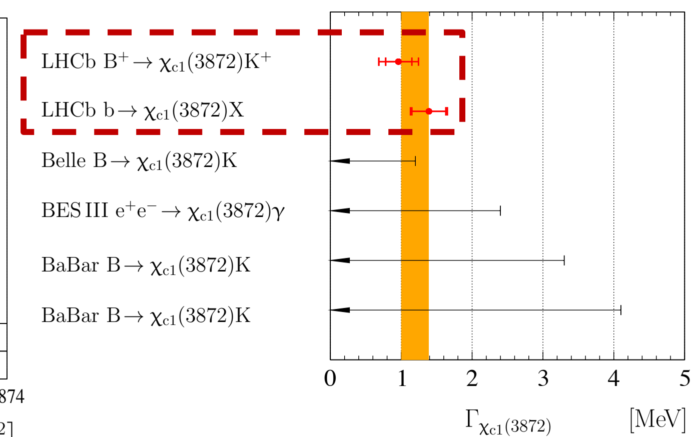




- ✓ baseline model: Breit-Wigner(BW) Fit
- ✓ Flatté function also investigated







- The opening up of $D^0\bar{D}^{*0}$ threshold distorts the BW lineshape
- First determination of non-zero width
- A better parametrization of the lineshape is needed.

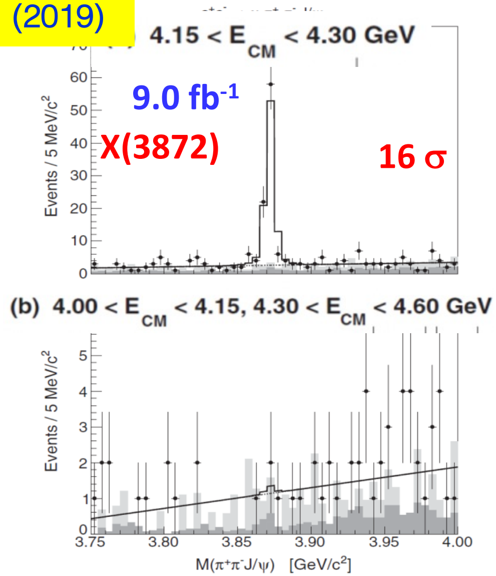
➢ LHCb average

- ✓ $M_{\mathrm{BW}} = 3871.64 \pm 0.06 \pm 0.01\ \mathrm{MeV}/c^2$; $\Gamma_{\mathrm{BW}} = 1.19 \pm 0.19\ \mathrm{MeV}/c^2$
- ✓ $\delta E = M(D^0) + M(\bar{D}^{*0}) - M(\chi_{c1}(3872)) = 0.07 \pm 0.12\ \mathrm{MeV}/c^2$

$X(3872)$ production (1)

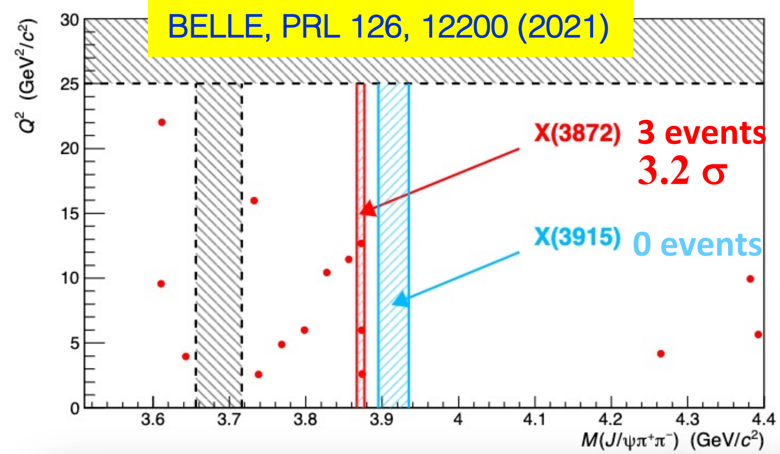
- Radiative production in $e^+e^- \to \gamma\, X(3872)$

BESIII, PRL122, 202001 (2019)



- From two-photon process: evidence of $\gamma\gamma^* \to X(3872) \to \pi^+\pi^- J/\psi$

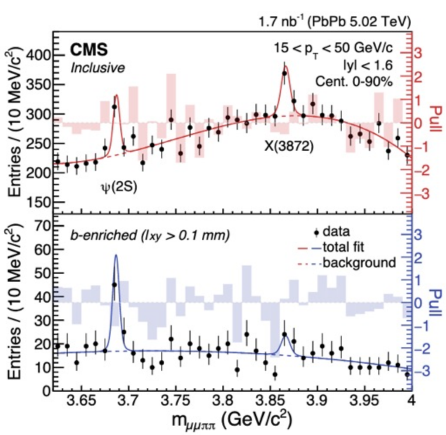
BELLE, PRL 126, 12200 (2021)

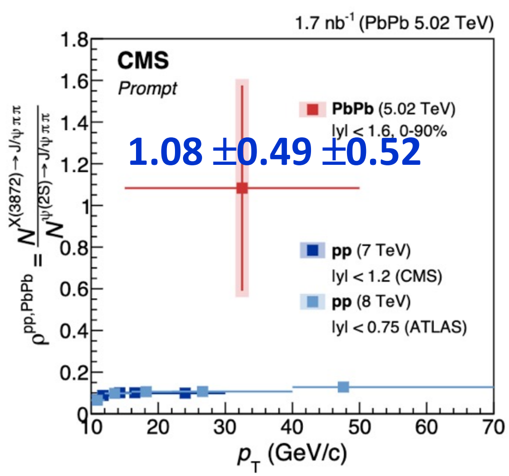


$$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X \to J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8}\ (\text{stat.}) \pm 0.7\ (\text{syst.})\ \text{eV}$$

- Evidence in heavy ion collision: P_bP_b collision at $\sqrt{S_{NN}} = 5.02$ TeV per nucleon pair

CMS, PRL128, 032001 (2022)



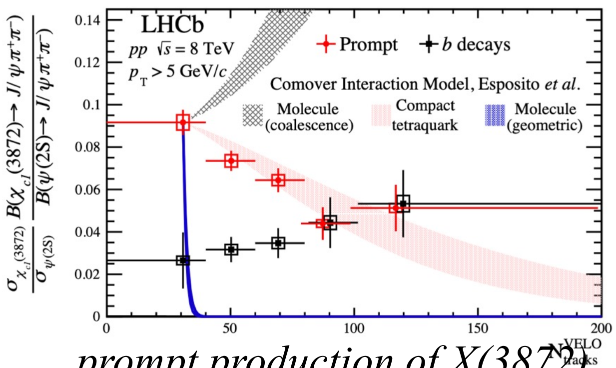


An indication of large R in P_bP_b collisions with respect to the pp collisions.

$X(3872)$ production (2)

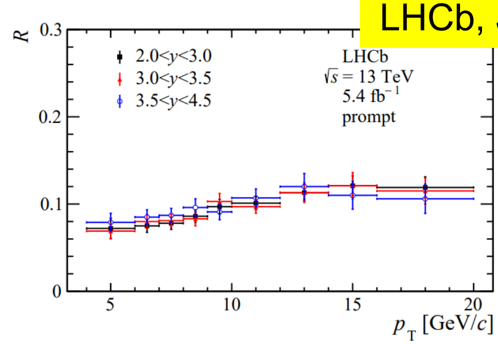
- Observation of prompt X(3872) relative to $\psi(2S)$ in pp collisions

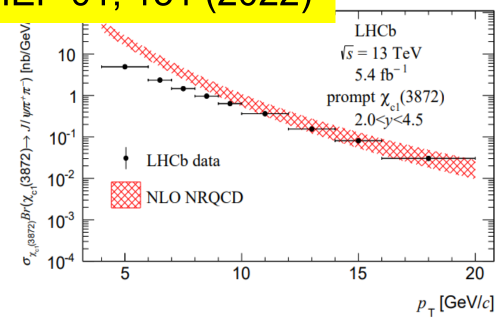
LHCb, PRL126, 092001 (2021)



prompt production of X(3872) suppressed relative to prompt ψ(2S) production as multiplicity increases.

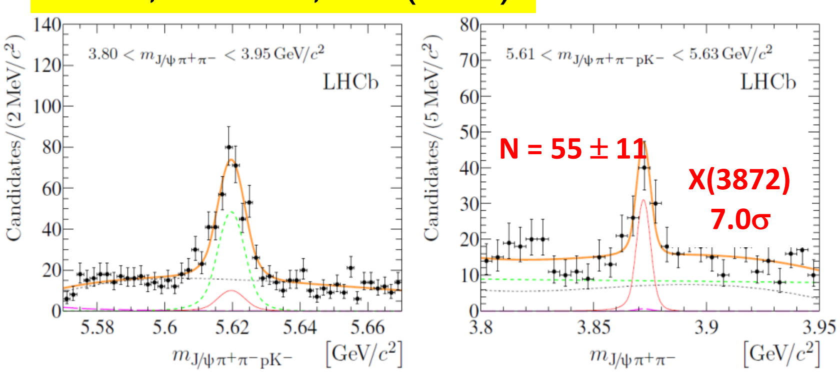
LHCb, JHEP 01, 131 (2022)





- From Λ_b^0 decays: $\Lambda_b^0 \to pK^- X(3872)$

LHCb, JHEP 09, 028 (2019)

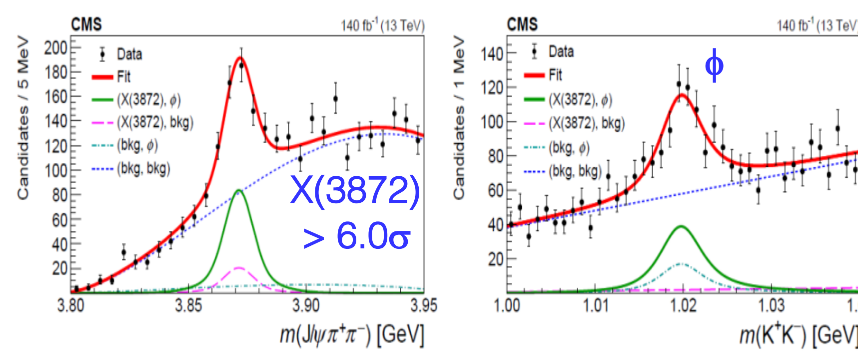


half of pK^- from $\Lambda(1520)$

- From B_s decays:

  $B_s \to X(3872)\,\phi$ at CMS and LHCb

CMS, PRL125, 152001 (2020)



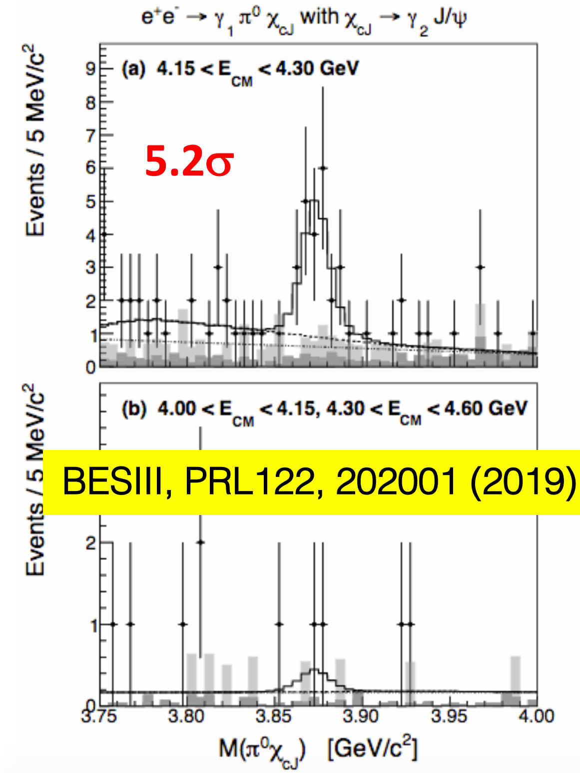
$$\frac{Br(B_s^0 \to X(3872)\phi)}{Br(B^+ \to X(3872)K^+)} = 0.482 \pm 0.063 \pm 0.037 \pm 0.070\ (Br)$$

about two times smaller than the ratio for $\psi(2S)$

Also observe $B_s \to X(3872)\,K^+K^-$ at LHCb (in later slides)

More X(3872) decay information

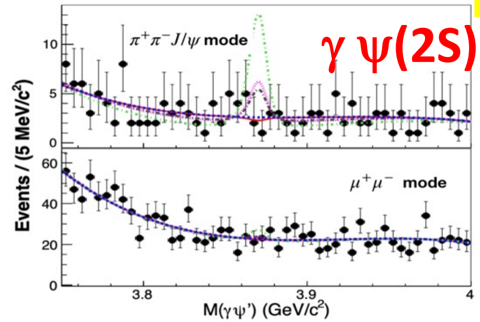
- Observation of X(3872) $\rightarrow \pi^0 \chi_{c1}$

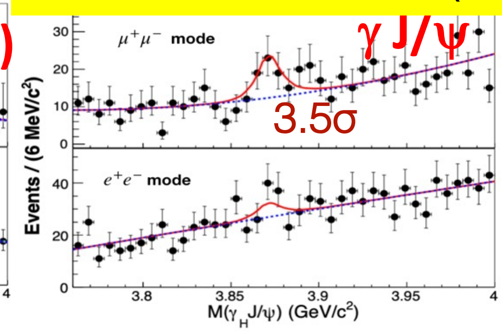


BESIII, PRL122, 202001 (2019)

- Transition of $X(3872) \rightarrow \gamma J/\psi$, $\gamma\psi(2S)$

BESIII, PRL 124, 242001 (2020)





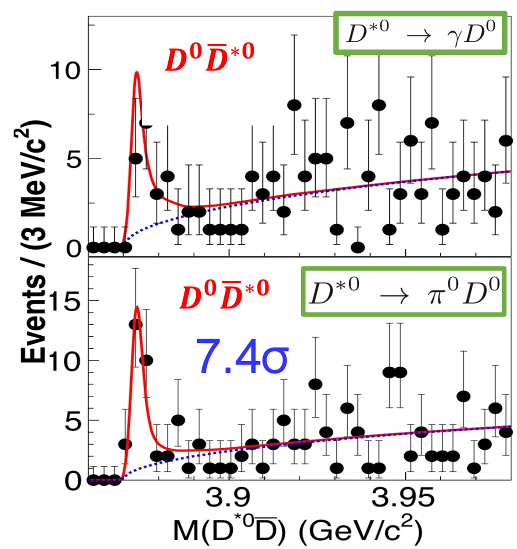
$$R = \frac{BF(X(3872) \to \gamma\psi(2S))}{BF(X(3872) \to \gamma J/\psi)} < 0.59 \text{ at 90\% C.L.}$$, agrees with Belle(<2.1), while challenges Babar(3.4±1.1) and LHCb results (2.46± 0.70)

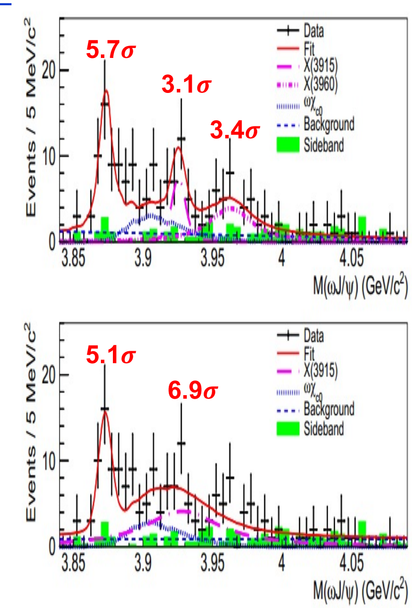
- Observation of X(3872) → ωJ/ψ

BESIII, PRL 122, 232002 (2019)

- Observation of X(3872) $\rightarrow D^0\bar{D}^{*0}$

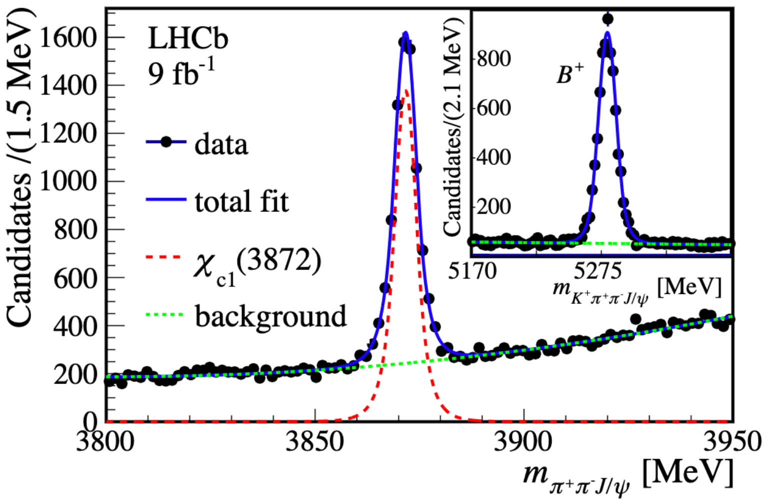
BESIII, PRL 124, 242001 (2020)



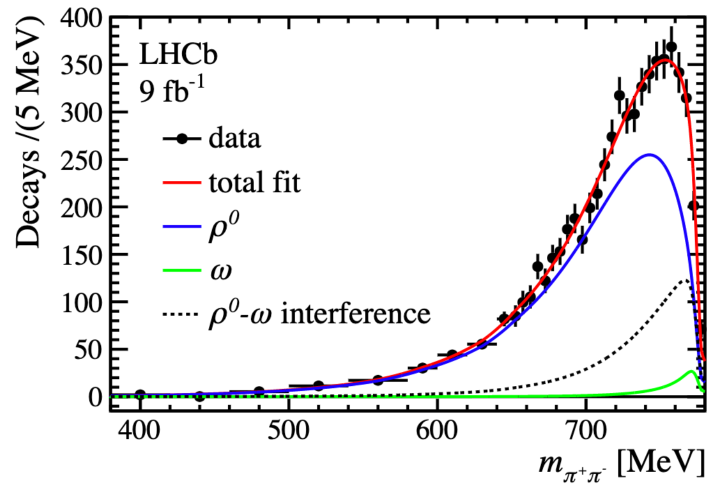


Observation of sizeable ω contribution in $X(3872) \to \pi^+\pi^- J/\psi$

arXiv:2204.12597



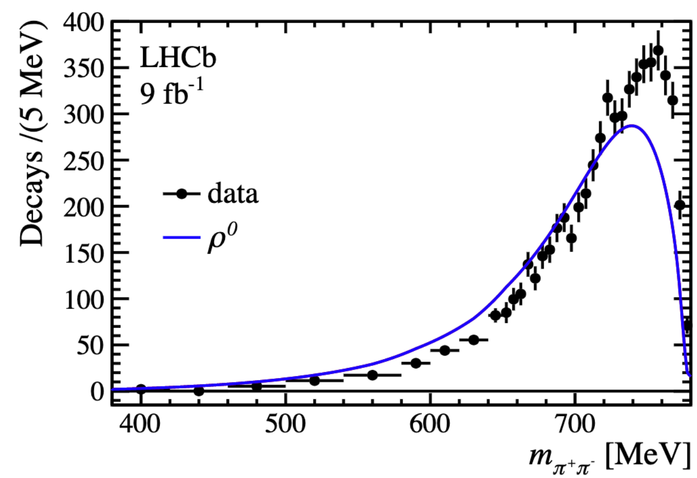
$B^+ \to K^+ X(3872)$ studied with RUN 1+2 data



$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = \sqrt{\frac{\mathcal{B}(\omega\to\pi^+\pi^-)}{\mathcal{R}^{0\,\prime}_{\omega/\rho}}} = 0.29 \pm 0.04.$$

$$\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = \sqrt{\frac{\mathcal{B}(\psi(2S)\to\pi^0 J/\psi)}{\mathcal{B}(\psi(2S)\to\eta J/\psi)}\,\frac{p_\eta{}^3}{p_{\pi^0}{}^3}} = 0.045 \pm 0.001$$

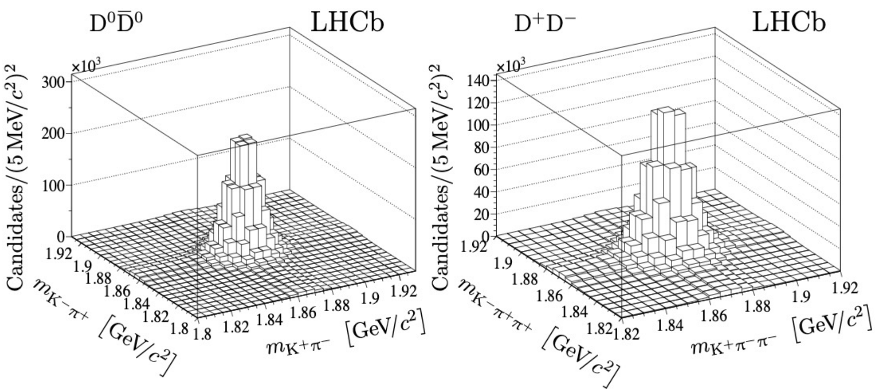
The isospin violating ρ^0 contribution, quantified for the first time with proper subtraction of the ω contribution, is an order of magnitude too large for X(3872) to be a pure charmonium state.

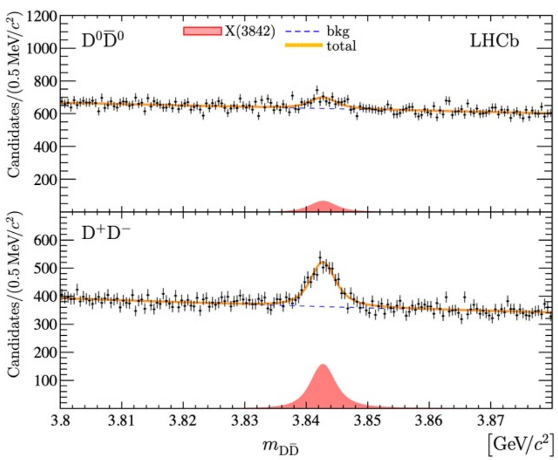


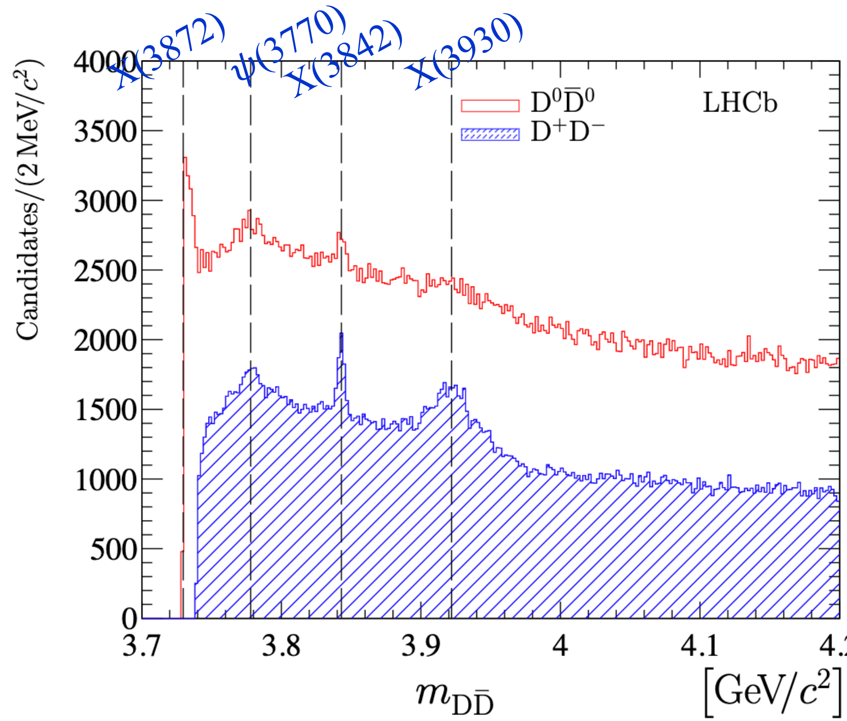
Observation of the X(3842)

JHEP07, 035(2019)

With Run 1+2 data, pairs of D mesons from prompt production







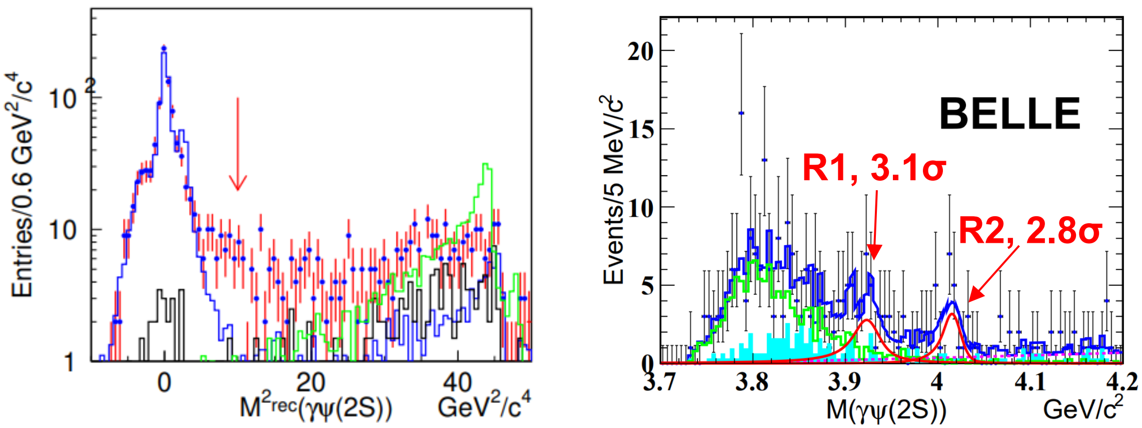
- Very narrow state due to suppression of the F-wave centrifugal barrier factor
- strong candidate of the missing $\psi_3(1^3D_3)$ charmonium state with $J^P = 3^{--}$

$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\text{MeV}/c^2\,,$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\text{MeV}\,,$$

X states in $\gamma\gamma \to \gamma\psi(2S)$

PRD 105, 112011 (2022)

- P-wave triplets near 3.9 GeV/c² remains puzzle, where $X(3930)$, as a good candidate of $\chi_{c2}(2P)$, has a hyperfine splitting of 12 MeV/c² between $\chi_{c2}(2P)$ and $X(3915)$



Resonant parameters	$J=0$	$J=2$
M_{R_1}	$3922.4 \pm 6.5 \pm 2.0$	
Γ_{R_1}	$22 \pm 17 \pm 4$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$9.8 \pm 3.6 \pm 1.2$	$2.0 \pm 0.7 \pm 0.2$
M_{R_2}	$4014.3 \pm 4.0 \pm 1.5$	
Γ_{R_2}	$4 \pm 11 \pm 6$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$6.2 \pm 2.2 \pm 0.8$	$1.2 \pm 0.4 \pm 0.2$

- Both 0^{++} and 2^{++} can be produced in two-photon collisions and decay to $\gamma\psi(2S)$ via E1 transition.
- Evidence for the structure R_1 near 3.92 GeV/c², which may be $X(3915)$ and $\chi_{c2}(3930)$
- R_2 matches none of the known states (mass agrees with HQSS-predicted 2^{++} partner of $X(3872)$, but width conflicts)

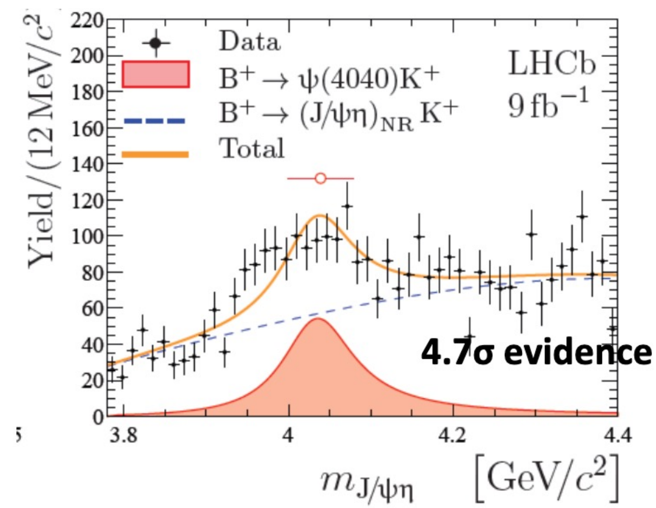
Charmonium(-like) states in $B^+ \to K^+ \eta J/\psi$

JHEP 22, 046 (2020)

- With RUN 1+2 LHCb data, evidence is found for $\psi_2(3823) \to \eta J/\psi$ and $\psi(4040) \to \eta J/\psi$

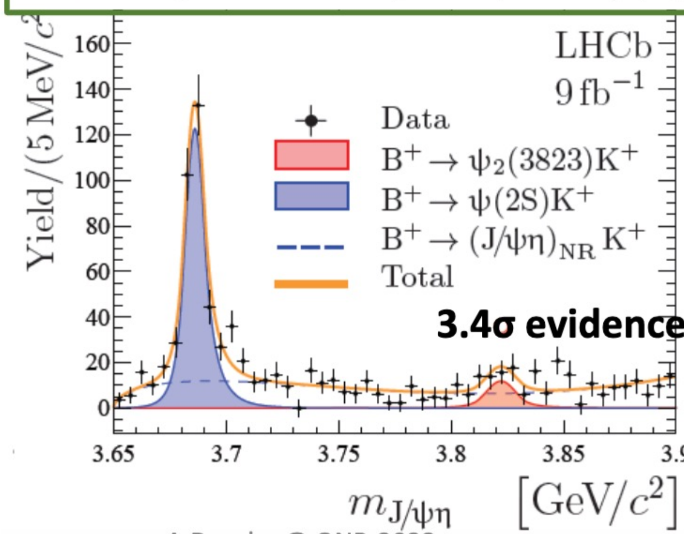
$$F_{\psi_2(3823)} = \left(5.95\,^{+3.38}_{-2.55}\right) \times 10^{-2},$$
$$F_{\psi(4040)} = (40.6 \pm 11.2) \times 10^{-2}.$$

- Searches for the known XYZ states and provides UL on BF in $B^+ \to K^+ X$



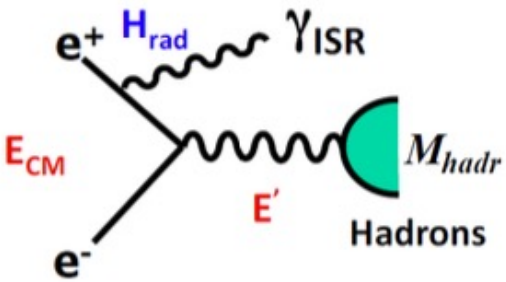
$$F_X \equiv \frac{\mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to J/\psi\eta)}{\mathcal{B}(B^+ \to \psi(2S)K^+) \times \mathcal{B}(\psi(2S) \to J/\psi\eta)},$$

$$B_X \equiv \mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to J/\psi\eta)$$

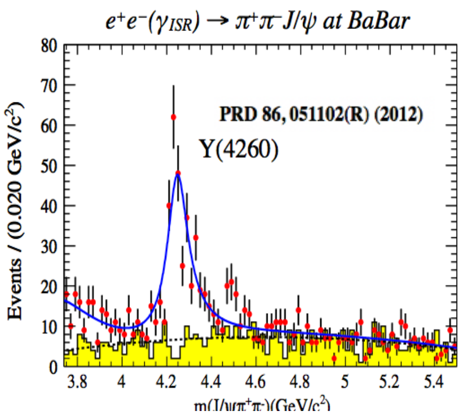


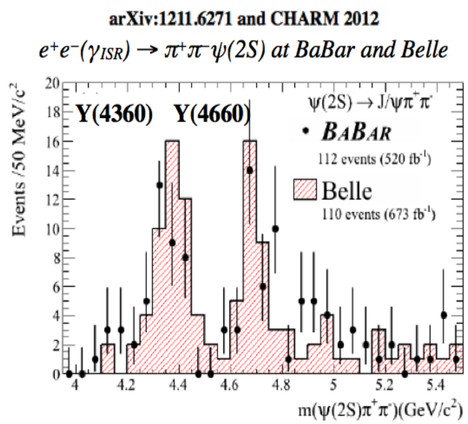
	Upper limit at 90% CL	
	F_X $[10^{-2}]$	B_X $[10^{-7}]$
ψ(3770)	2.2	4.6
ψ_3(3842)	2.9	6.1
ψ(4160)	4.2	8.7
ψ(4415)	4.6	9.6
R(3760)	2.0	4.1
R(3790)	3.2	6.7
$Z_c(3900)^0$	2.1	4.3
ψ(4230)	1.9	3.9
ψ(4360)	6.0	12.4
ψ(4390)	11.6	24.1
$Z_c(4430)^0$	6.1	12.7
X'_C	1.9	3.9

The Y states



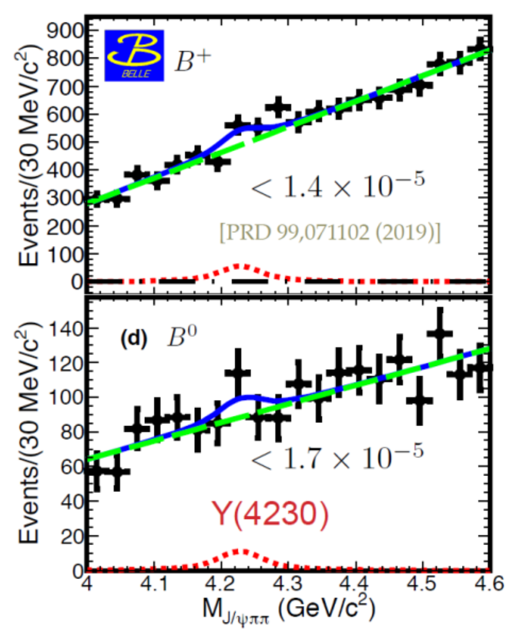
Y states: charmonium-like states with $J^{PC}=1^{--}$; Observed in direct e+e- annihilation or initial state radiation (ISR).



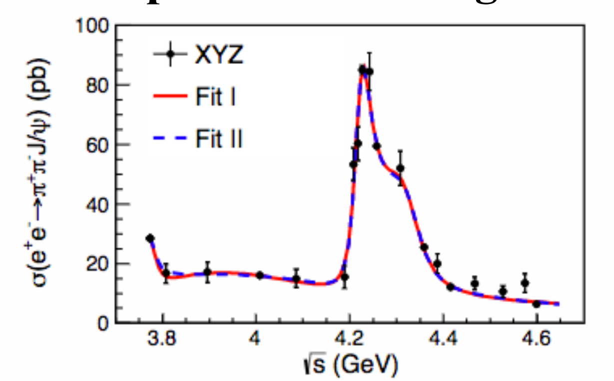


- **While not seen yet in B decays**

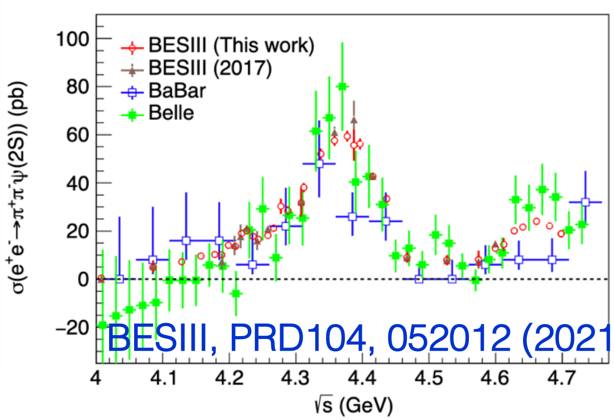
$B^{\pm,0} \to K^{\pm,0}\pi^+\pi^- J/\psi$



- **Improved knowledges from BESIII**

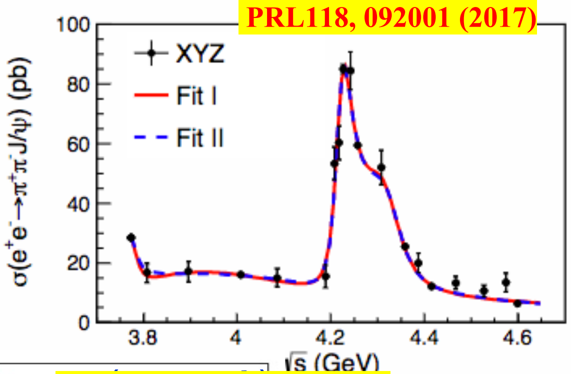


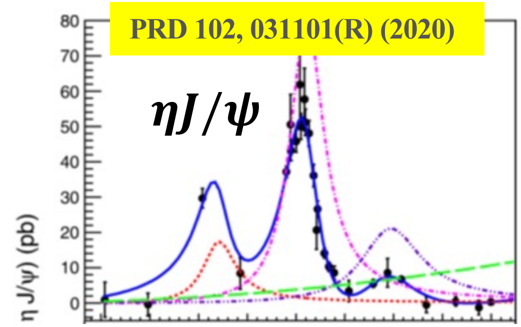
BESIII, PRL118, 092001 (2017)

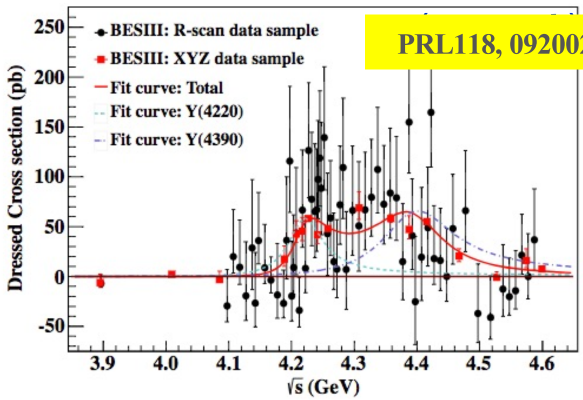


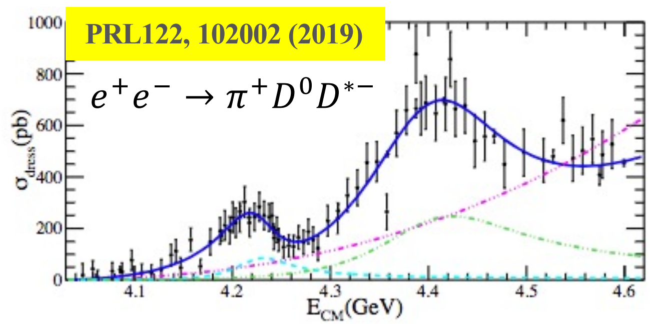
BESIII, PRD104, 052012 (2021)

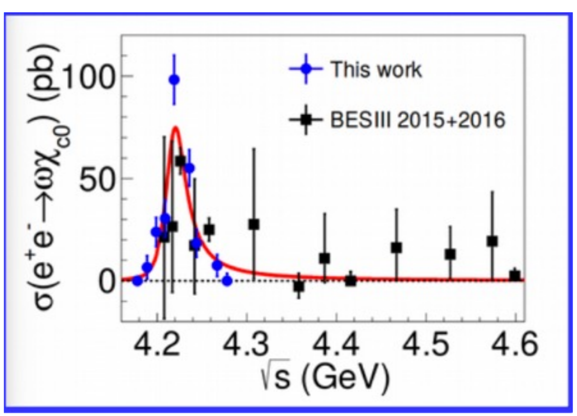
Y(4260) ➔ Y(4230) and new Y's

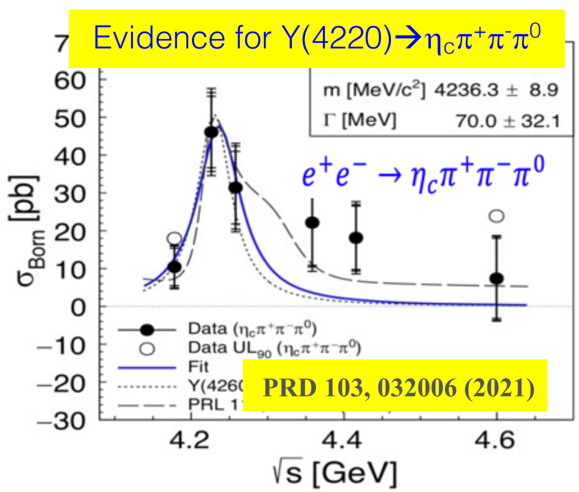




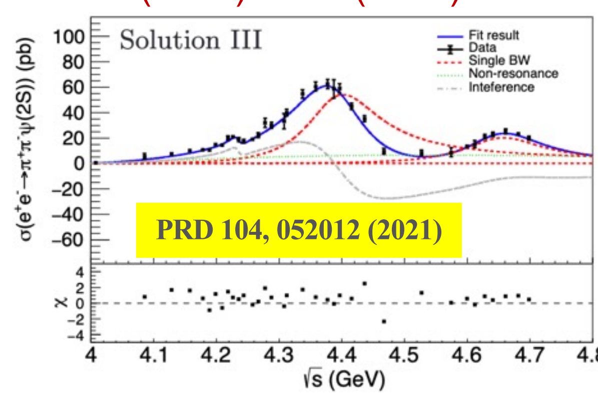




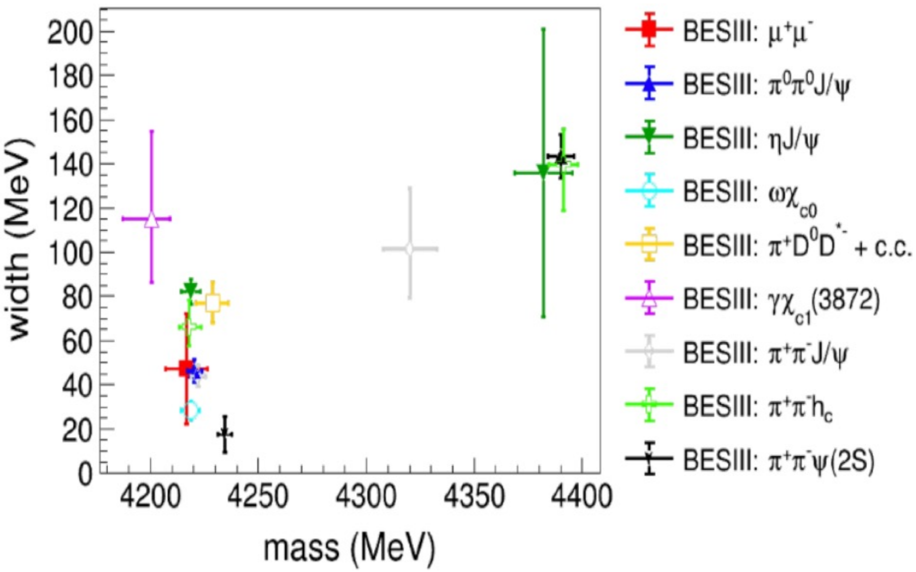


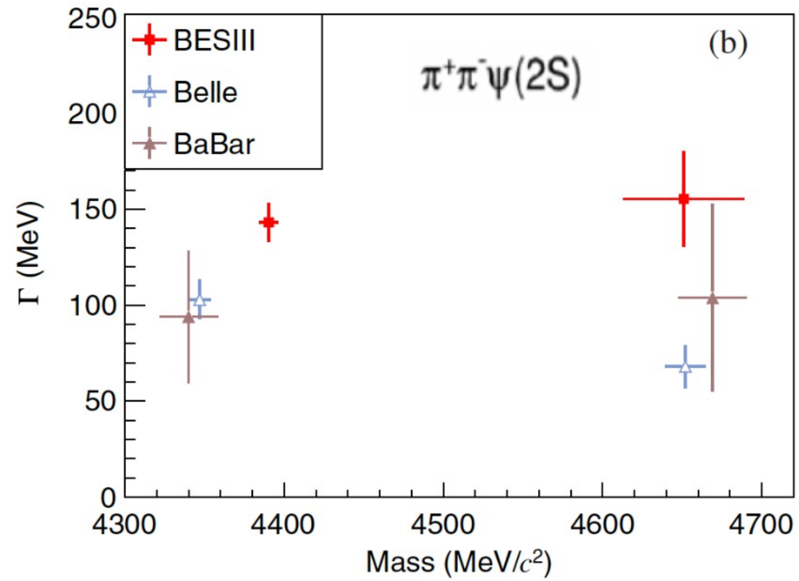


confirmed Y(4220), Y(4390) and Y(4660)



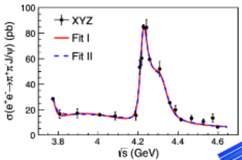
Y(4230), Y(43XX) and Y(4660)



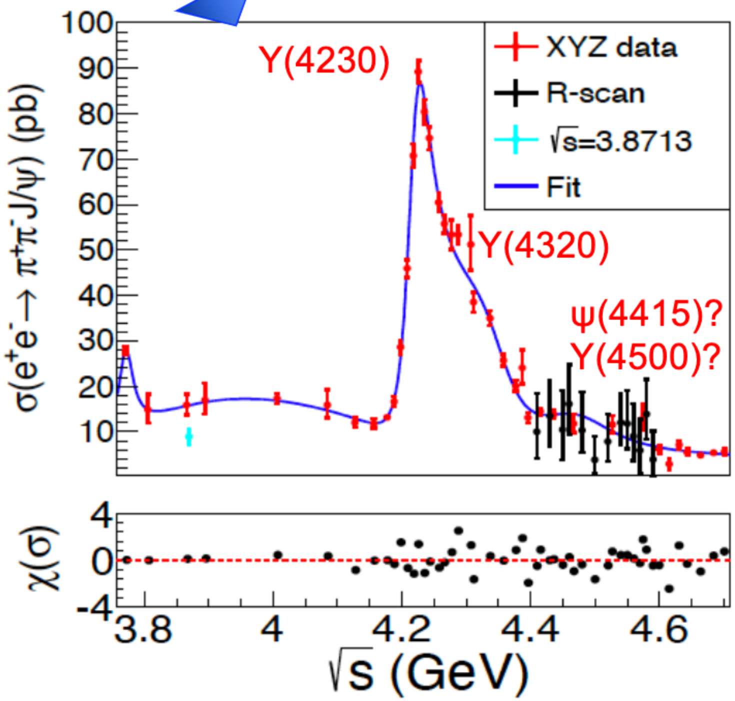


Cross sections of $e^+e^- \to \pi^+\pi^- J/\psi$

arXiv:2206.08554



Higher statistics, higher precision, higher energies, better fit



- ✓ Y(4230) and Y(4320) observed with > 10σ
- ✓ Structure around 4 GeV better fit by a BW (before exp)
- ✓ Evidence ~3σ of a structure at higher energies ψ(4415)? The new Y(4500)?
- ✓ By including the high energy state in the fit, the Y(4320) parameters change

$M_{Y(4230)} = 4221.4 \pm 1.5 \pm 2.0$ MeV/c^2

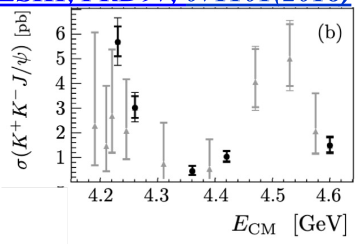
$\Gamma_{Y(4230)} = 41.8 \pm 2.9 \pm 2.7$ MeV

$M_{Y(4320)} = 4298 \pm 12 \pm 26$ MeV/c^2

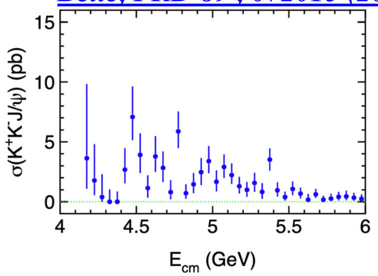
$\Gamma_{Y(4320)} = 127 \pm 17 \pm 10$ MeV

Cross sections of $e^+e^- \to K^+K^-J/\psi$

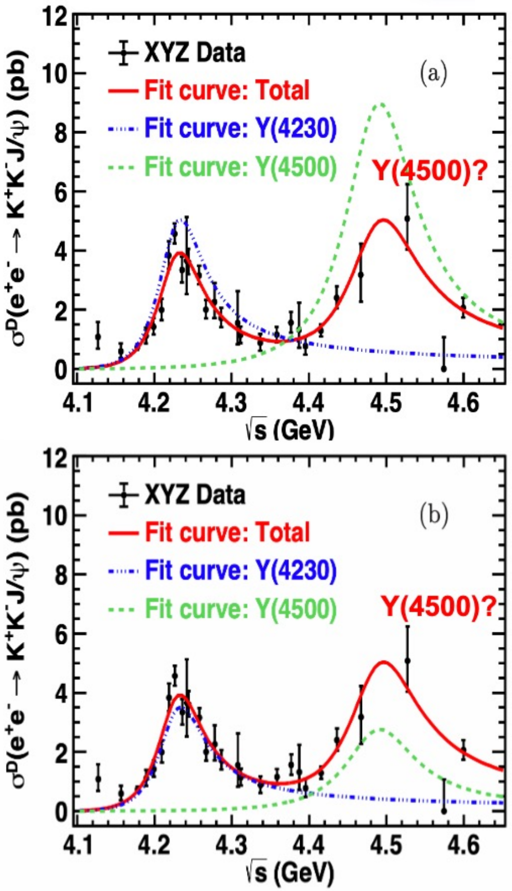
BESIII, PRD97, 071101(2018)



Belle, PRD 89 , 072015 (2014)



arXiv:2204.07800



Investigating the strange content inside Y(4230)

✓ First observation of Y(4230) → K^+K^-J/ψ peak

$$0.02 < \frac{\mathcal{B}(Y(4230) \to K^+K^-J/\psi)}{\mathcal{B}(Y(4230) \to \pi^+\pi^-J/\psi)} < 0.26$$

✓ Resonance Y(4500) > 5σ, consistent with the predictions of:

- 5S-4D mixing scheme (PRD99,114003 (2019))
- heavy-antiheavy hadronic molecules model (ProgrPhys41,65(2021))
- Lattice QCD result for a $(cs\bar{c}\bar{s})$ state (PRD73,094510 (2006))

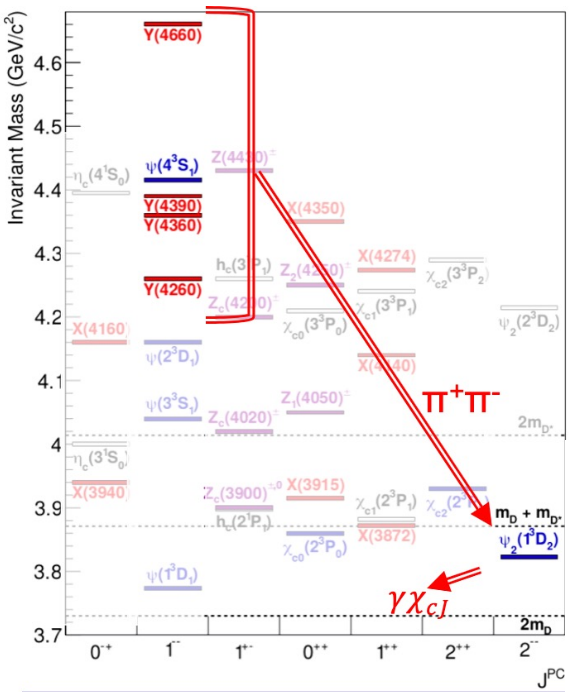
	Parameters	Solution I	Solution II
$Y(4230)$	M(MeV)	$4225.3 \pm 2.3 \pm 21.5$	
	Γ_{tot}(MeV)	$72.9 \pm 6.1 \pm 30.8$	
	$\Gamma_{ee}\mathcal{B}$(eV)	$0.42 \pm 0.04 \pm 0.15$	$0.29 \pm 0.02 \pm 0.10$
$Y(4500)$	M(MeV)	$4484.7 \pm 13.3 \pm 24.1$	
	Γ_{tot}(MeV)	$111.1 \pm 30.1 \pm 15.2$	
	$\Gamma_{ee}\mathcal{B}$(eV)	$1.35 \pm 0.14 \pm 0.06$	$0.41 \pm 0.08 \pm 0.13$
phase angle	φ(rad)	$1.72 \pm 0.09 \pm 0.52$	$5.49 \pm 0.35 \pm 0.58$

arXiv:2204.07800 submitted to PRL

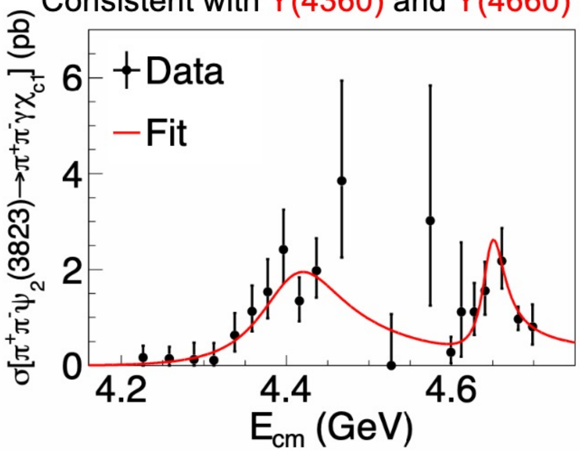
Cross sections of $e^+e^- \to \pi^+\pi^-\psi(3823)$

arXiv:2203.05815

first observation of vector Y states
decaying to D-wave charmonium state

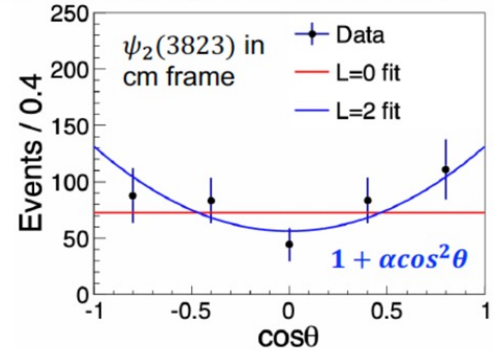


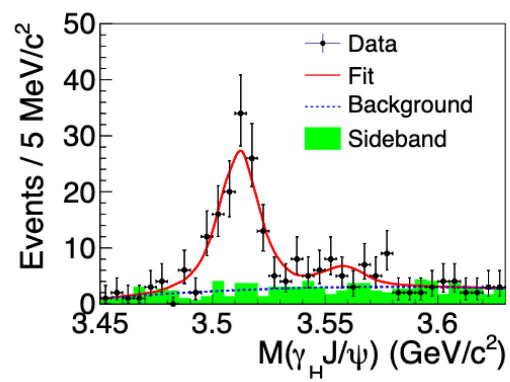
Consistent with Y(4360) and Y(4660)



S-wave $\pi^+\pi^-$, *such as* $f_0(500)$

$L = 2$ slightly favored over $L = 0$





Parameters	Solution I	Solution II
$M[R_1]$	$4406.9 \pm 17.2 \pm 4.5$	
$\Gamma_{\rm tot}[R_1]$	$128.1 \pm 37.2 \pm 2.3$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_1}\mathcal{B}_2$	$0.36 \pm 0.10 \pm 0.03$	$0.30 \pm 0.09 \pm 0.03$
$M[R_2]$	$4647.9 \pm 8.6 \pm 0.8$	
$\Gamma_{\rm tot}[R_2]$	$33.1 \pm 18.6 \pm 4.1$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_2}\mathcal{B}_2$	$0.24 \pm 0.07 \pm 0.02$	$0.06 \pm 0.03 \pm 0.01$
ϕ	$267.1 \pm 16.2 \pm 3.2$	$-324.8 \pm 43.0 \pm 5.7$

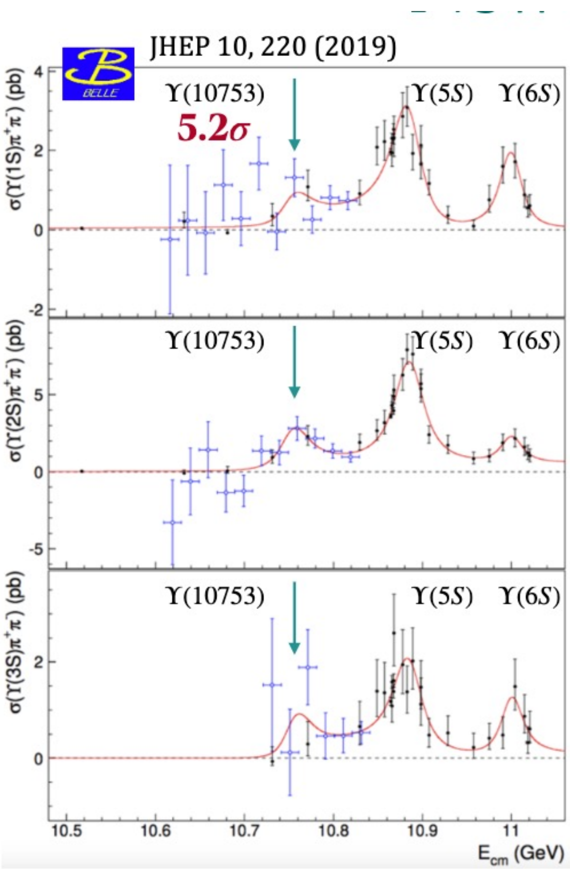
Most precise measurement

mass and width of $\psi_2(3823)$:
$m = 3823.12 \pm 0.43 \pm 0.13$ MeV/c^2
$\Gamma < 2.9$ MeV (at 90% CL)

- consistent with Y(4360) and Y(4660)

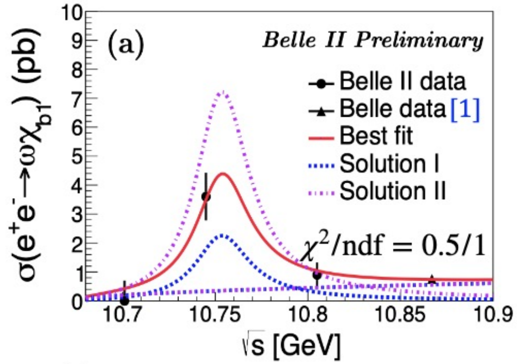
$$\frac{\mathcal{B}[\psi_2(3823)\to\gamma\chi_{c2}]}{\mathcal{B}[\psi_2(3823)\to\gamma\chi_{c1}]} = 0.33 \pm 0.12 (< 0.51))$$

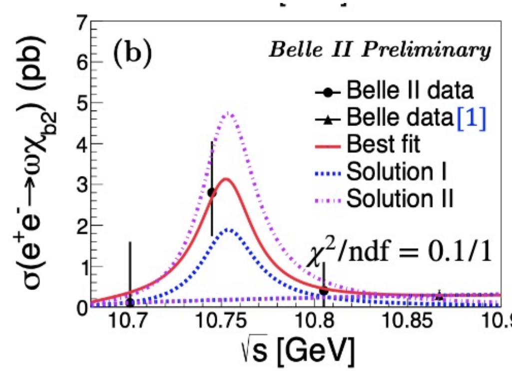
Studies on $\Upsilon(10753)$



	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5 ^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9 ^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$

- Belle observed $\Upsilon(10753)$ in $e^+e^- \to \pi^+\pi^-\Upsilon(\mathrm{nS})$
- Considered as conventional bottomonium or exotic hadron
- Expected to decay into $\omega\chi_{bJ}$ with BF of 10^{-3} if mixing of 4S and 3D bottomonium states.





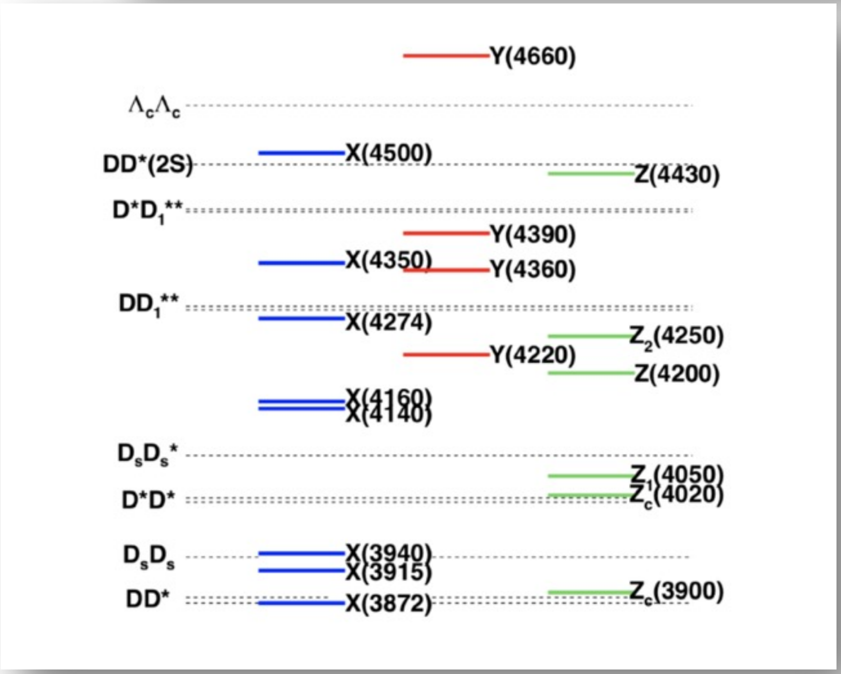
- Belle II observed peak cross sections of $e^+e^- \to \omega\chi_{bJ}$ at $\Upsilon(10753)$, while no obvious peak at $\Upsilon(10860)$
  - $\frac{\Gamma_{ee}\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b1})}{\Gamma_{ee}\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b2})} \sim 1.0$ agrees with the expectation for NRQCD
  - $\frac{\Gamma_{ee}\mathcal{B}(\omega\chi_{b1/2})}{\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(2S))^{[2]}} \sim 1.5$ for $\Upsilon(10753)$ and ~ 0.1 for $\Upsilon(10860)$

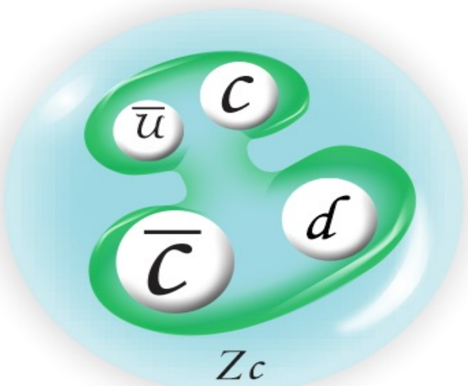
implying hadro-bottomonium interpretation of $\Upsilon(10753)$

The Zc states [$c\bar{c}u\bar{d}$]

from S. L. Olsen, arXiv:1511.01589, arXiv:1812.10947

$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [49], Belle [50]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [69]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [51]
				$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII [52]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [53], BaBar [66]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [62]
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [53], BaBar [66]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle [54, 56, 57], LHCb [58]
				$B \to K + (J\psi\,\pi^+)$	Belle [62]

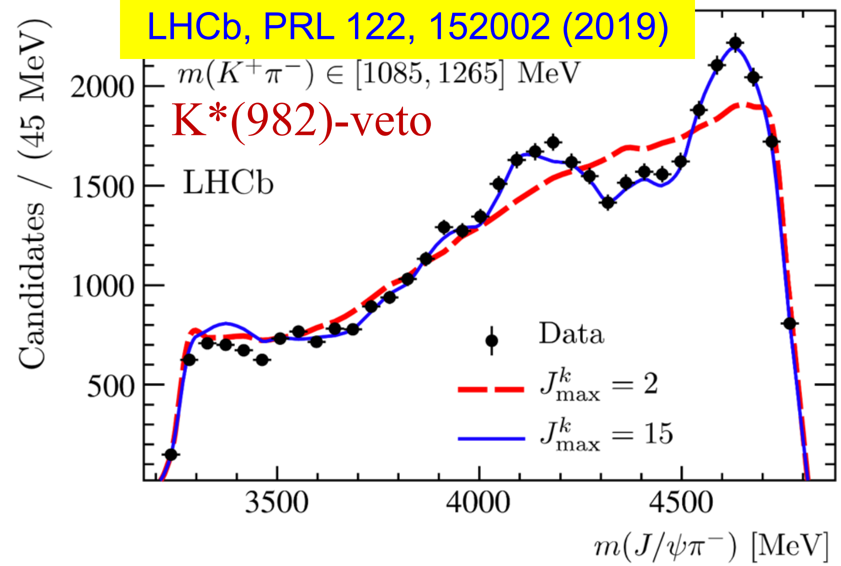


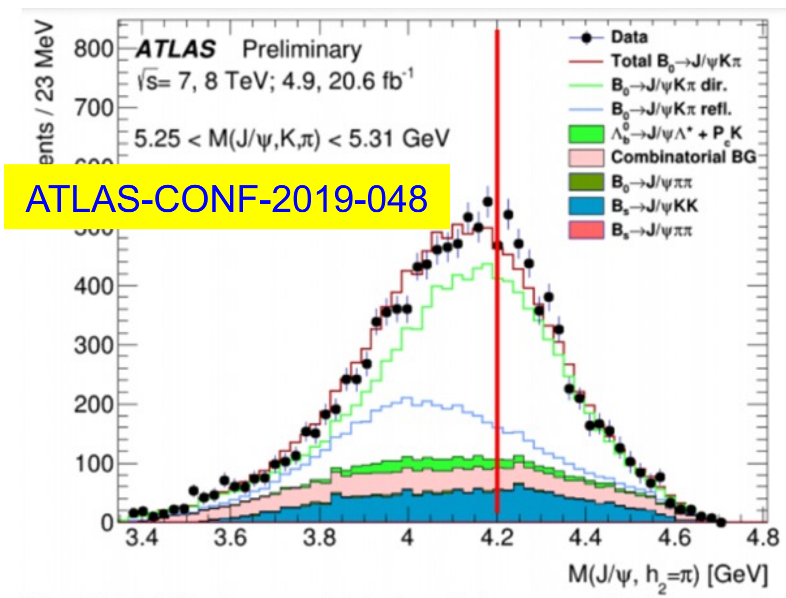


Most of them are close to the mass thresholds of charmed meson pairs

Confirmed exotic contribution in $B^0 \to J/\psi K^+\pi^-$

- Amplitude analysis of $B^0 \to J/\psi K^+\pi^-$ at LHCb using RUN1 data
- Data inconsistent with K*-only contributions by 10 σ
- New Zc components needed around 4200 MeV and 4600 MeV



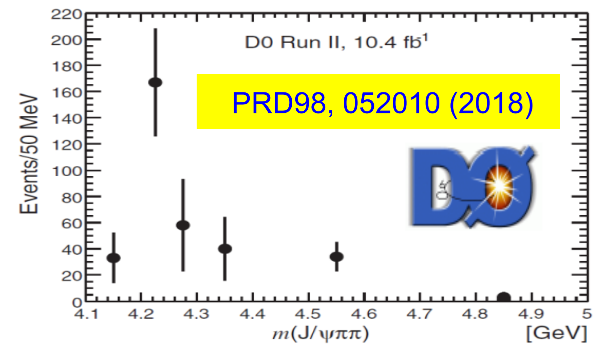


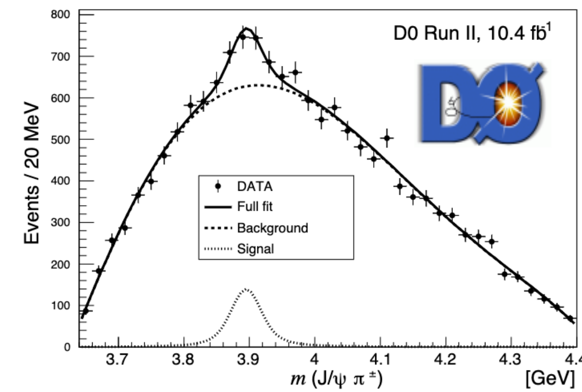
- ATLAS studied ~10K $B^0 \to J/\psi K^+\pi^-$ using RUN1 data
- Hint of Zc(4200) contribution, as data description w/o exotic contributions is not satisfactory

Zc(3900): correlated with the Y(4260)

- D0 presented evidence for the charged Zc(3900) decaying to J/ψπ in semi-inclusive weak decays of *b*-flavored hadrons.
- The signal is correlated with a parent $J/\psi\pi^+\pi^-$ system in the invariant mass range 4.2–4.7 GeV, that would include the exotic structure Y(4260)

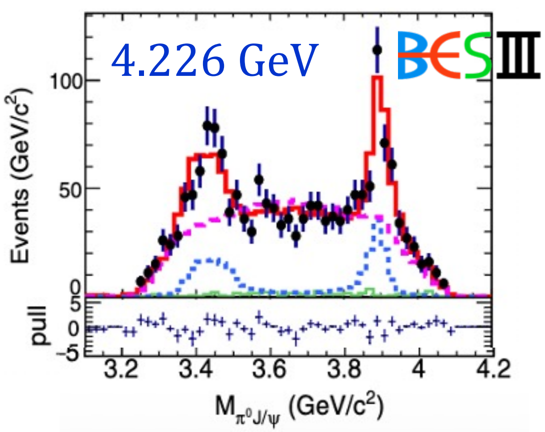
$H_b \to \pi^+\pi^- J/\psi$ + anything

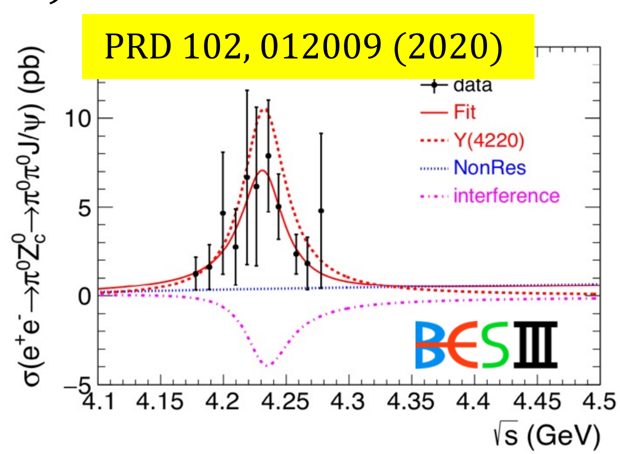




Amplitude analysis of $e^+e^-\to\pi^0Z_c(3900)^0$ at BESIII

- Simultaneous PWA fit of $e^+e^-\to\pi^0\pi^0 J/\psi$ to the four energy points between 4.226 GeV and 4.258 GeV
- The spin-parity of $Z_c(3900)^0$ determined to be 1^+

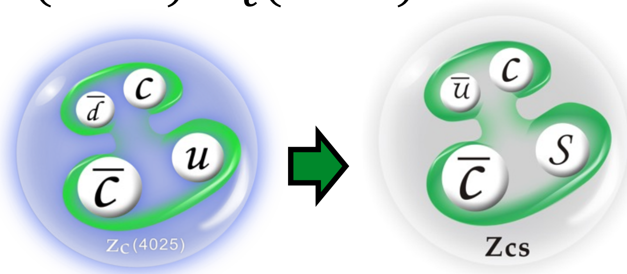




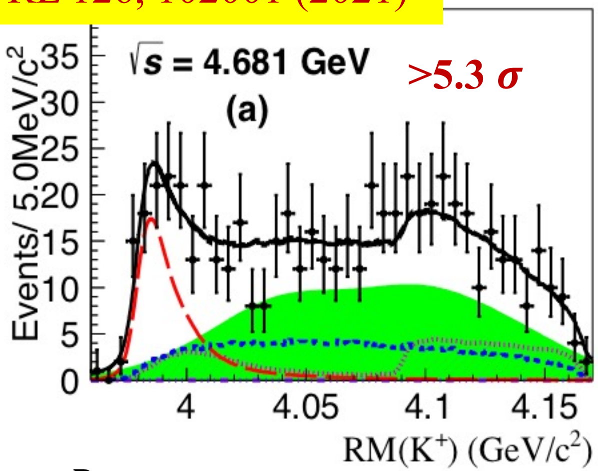
- Compatible with the Y(4220) line shape
- Indication of correlation between the production of the Y(4220) and Zc(3900)

Zcs: SU(3) partner of Zc state

- **Important to look for Z_{cs}, the SU(3) partners of $X(3872)$/ $Z_c(3900)$**
- BESIII analyzes the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ with 3.7fb^{-1} data at energies between 4.628 and 4.698GeV



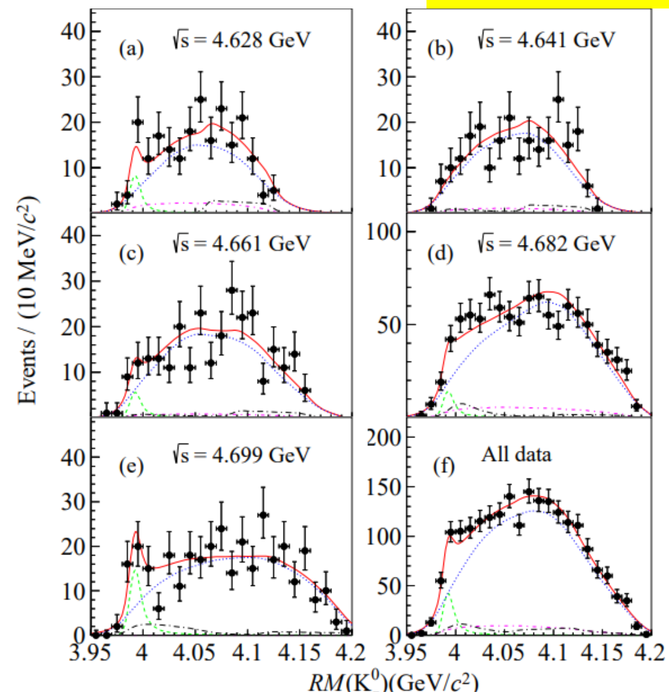
PRL 126, 102001 (2021)



- A fit of $J^P=1^+$ S-wave Breit-Wigner with mass dependent width returns:

	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

$e^+e^- \to K_S^0(D_s^- D^{*+} + D_s^{*-} D^+)$ arXiv:2204.13703

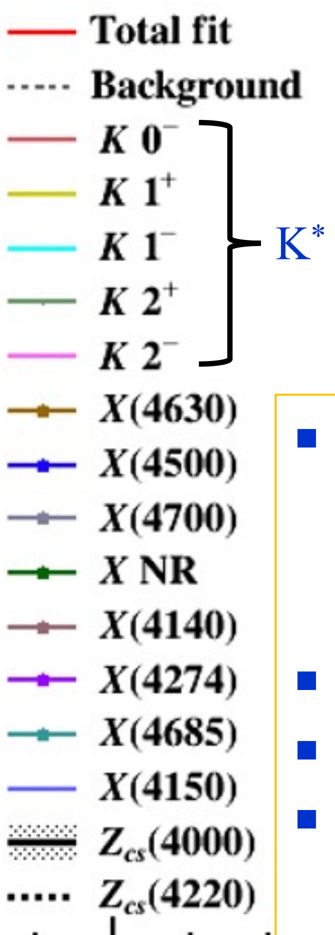


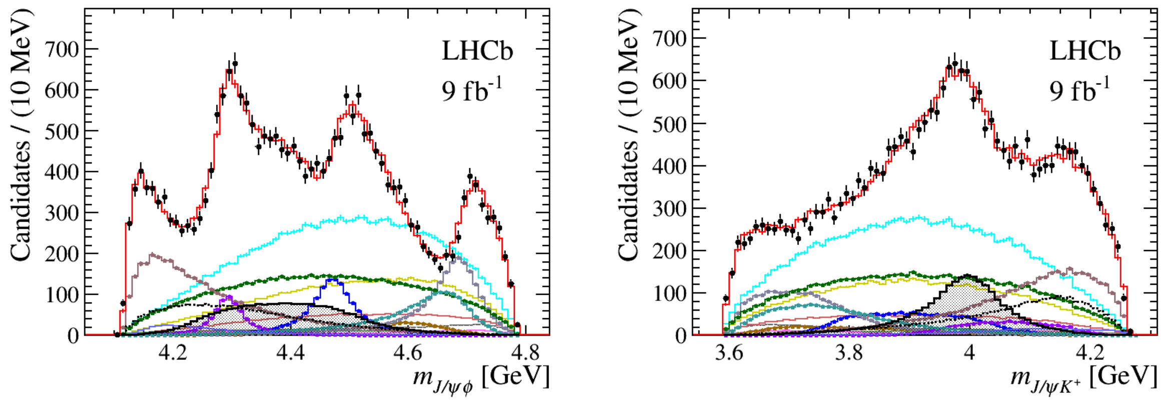
First candidate of the hidden-charm tetraquark with strangeness, and isospin triplet confirmed!

Amplitude analysis of $B^+ \to J/\psi \phi K^+$

- With Run 1 $B^+ \to J/\psi \phi K^+$ data, LHCb performed 1st amplitude fit and observed $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ ➔ $[c\bar{c}s\bar{s}]$ tetraquark ?
- **LHCb RUN 1+2**: 24K signals, about 6× larger than RUN 1

PRL127, 082001 (2021)





- New states:
  $Z_{cs}(4000)$, $X(4685)$ > 15σ
  $Z_{cs}(4220)$, $X(4630)$ > 5σ
  $X(4150)$ < 5σ
- $Z_{cs}(4000)$ & $X(4685)$: 1^+
- $Z_{cs}(4220)$ can be 1^+ or 1^-
- Confirmed states:
  $X(4140)$, $X(4274)$,
  $X(4500)$, $X(4700)$

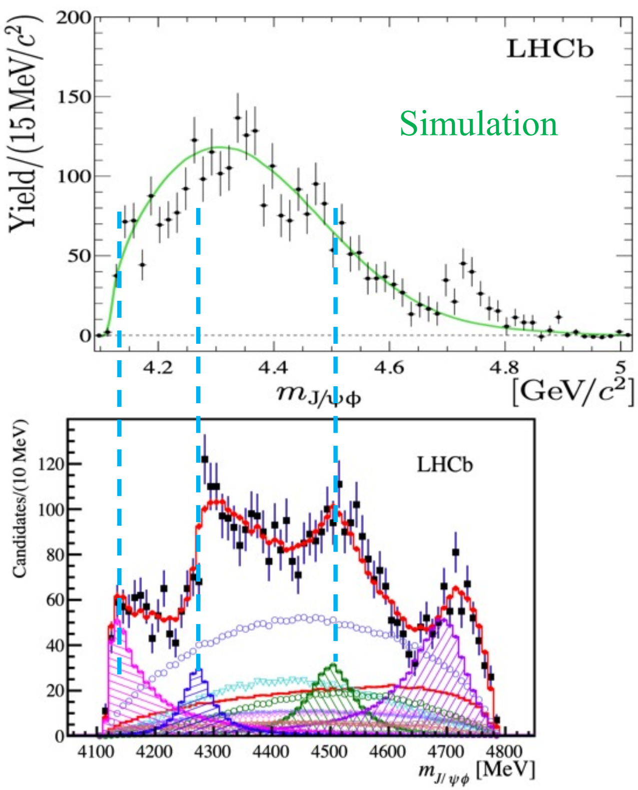
Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$	Syst. included(Stat.)			
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5\,^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3\,^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5\,^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

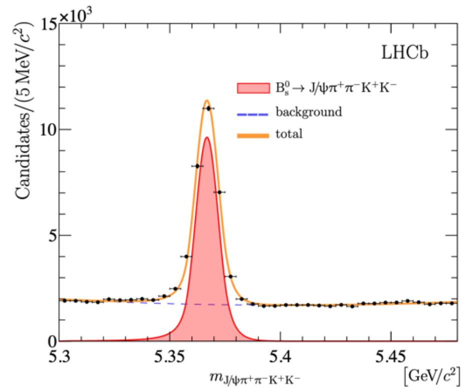
$X(4740)$ structure with $[c\bar{c}s\bar{s}]$

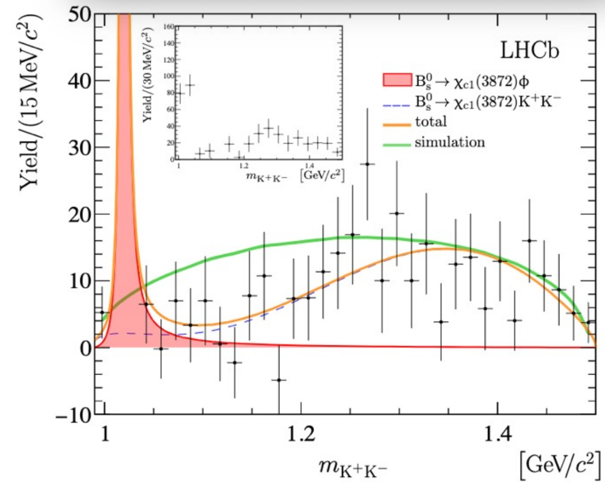
JHEP02, 024 (2021)

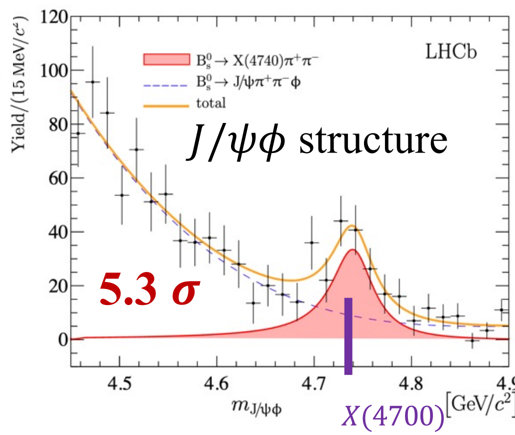
- Study of $B_S^0 \to J/\psi\pi^+\pi^-K^+K^-$ using LHCb RUN 1+2 data: 26.5K signals
- Observations of $B_S^0 \to X(3872)K^+K^-$ and $X(3872)\phi$

$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2},$$
$$\mathcal{R}_{K^+K^-} = 1.57 \pm 0.32 \pm 0.12,$$









1D fit using S-wave Breit-Wigner

$m_{X(4740)} = 4741 \pm 6 \pm 6$ MeV

$\Gamma_{X(4740)} = 53 \pm 15 \pm 11$ MeV

Systematic uncertainties:

- Shape of underlying non-X
- Alternative P-wave or D-wave BW
- Inteference $\mathcal{F}_S(m_{J/\psi\phi}) \propto |\mathcal{A}(m_{J/\psi\phi}) + b(m_{J/\psi\phi})e^{i\varphi}|^2$

$X(4740)$: could be the $X(4700)$ in $B^+ \to J/\psi\phi K^+$

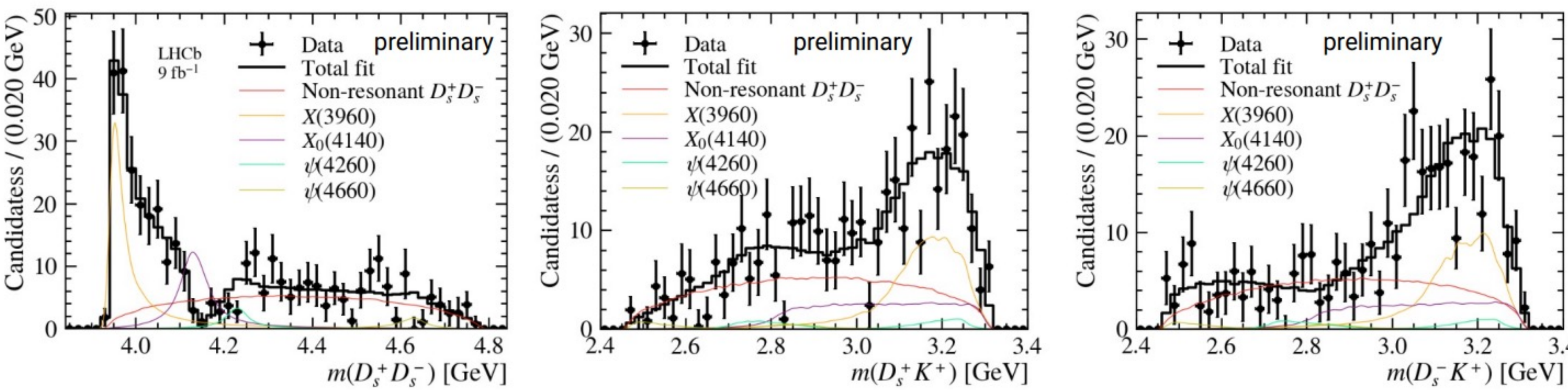
New $[c\bar{c}s\bar{s}]$ state in $D_s^+ D_s^-$

LHCb-PAPER-2022-018
LHCb-PAPER-2022-019

- Study of $B^+ \to D_s^+ D_s^- K^+$ with 9 fb^{-1} at LHCb,
- Near threshold structure $X(3960)$ **12σ**, $J^P = 0^{++}$
- X(4140) accounts for the dip around 4.14 GeV
- If $X(3960)$ and $\chi_{c0}(3930)$ the same particle, they could be exotic $[c\bar{c}s\bar{s}]$.

$$\frac{\mathcal{B}(X \to D^+ D^-)}{\mathcal{B}(X \to D_s^+ D_s^-)} \sim 0.29$$

	Mass (MeV/c^2)	Width (MeV/c^2)	J^{PC}
$\chi_{c0}(3930)$	3921.7 ± 1.8	18.8 ± 3.5	0^{++}

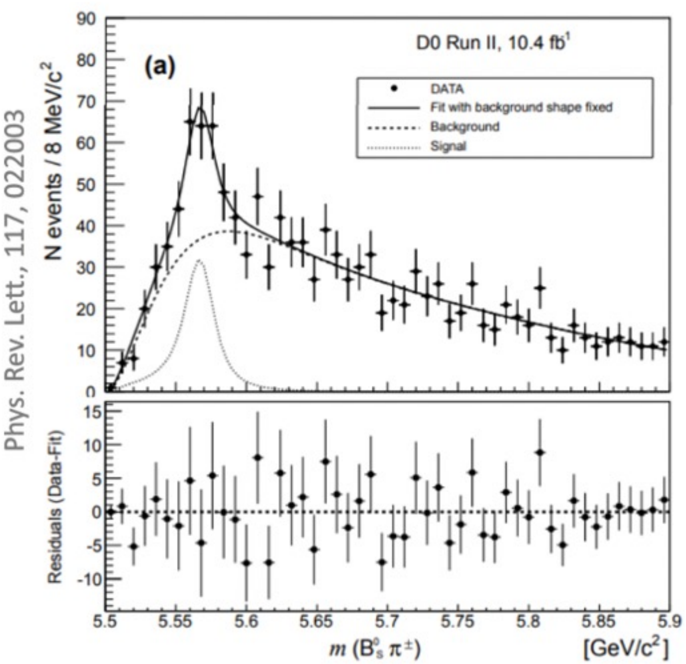


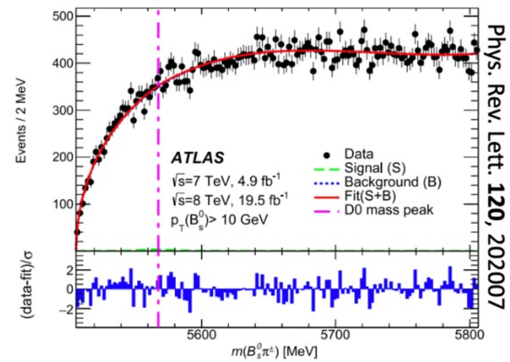
Component	J^{PC}	M_0 [MeV]	Γ_0 [MeV]	$\mathcal{F}$ [%]	$\mathcal{S}$ [σ]
$X(3960)$	0^{++}	$3955 \pm 6 \pm 12$	$48 \pm 17 \pm 10$	$24.2 \pm 7.6 \pm 7.9$	12.6 (14.3)
$X_0(4140)$	0^{++}	$4133 \pm 7 \pm 11$	$69 \pm 17 \pm 7$	$17.7 \pm 4.9 \pm 7.7$	3.7 (3.9)
$\psi(4260)$	1^{--}	4230	55	$3.7 \pm 0.4 \pm 3.0$	3.1 (3.3)
$\psi(4660)$	1^{--}	4633	64	$2.2 \pm 0.2 \pm 0.5$	2.9 (3.2)
NR	S-wave	-	-	$46.6 \pm 13.3 \pm 11.3$	3.1 (3.4)

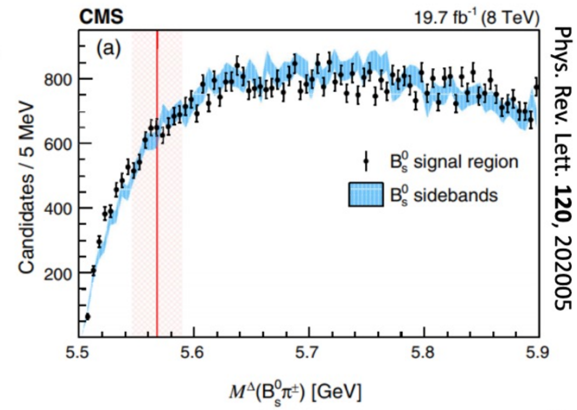
Open-flavor exotic mesons

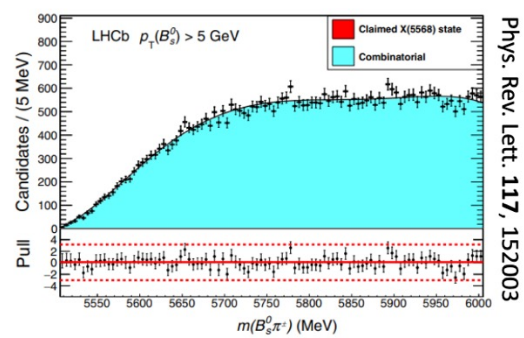
Study on X(5568) in $B_s\pi^+$

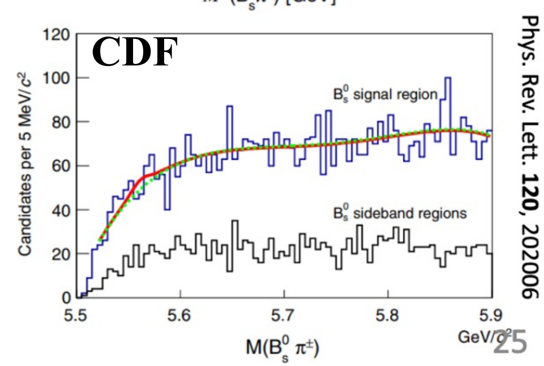
- D0 claimed evidence for the X(5568) in decaying to $\boldsymbol{B_s\pi^+}$, interpreted as tetraquark state [***bsud***]
- But not seen in other experiments







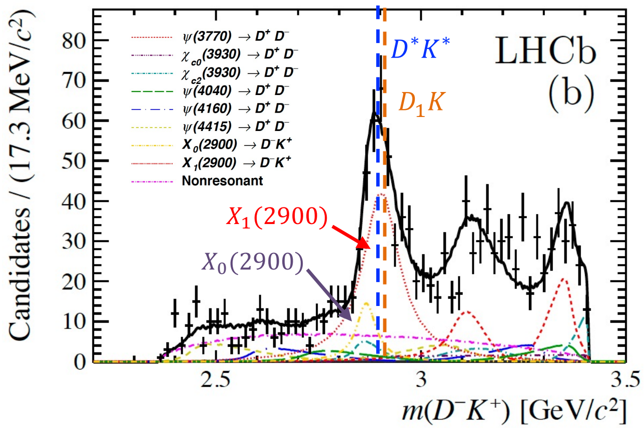


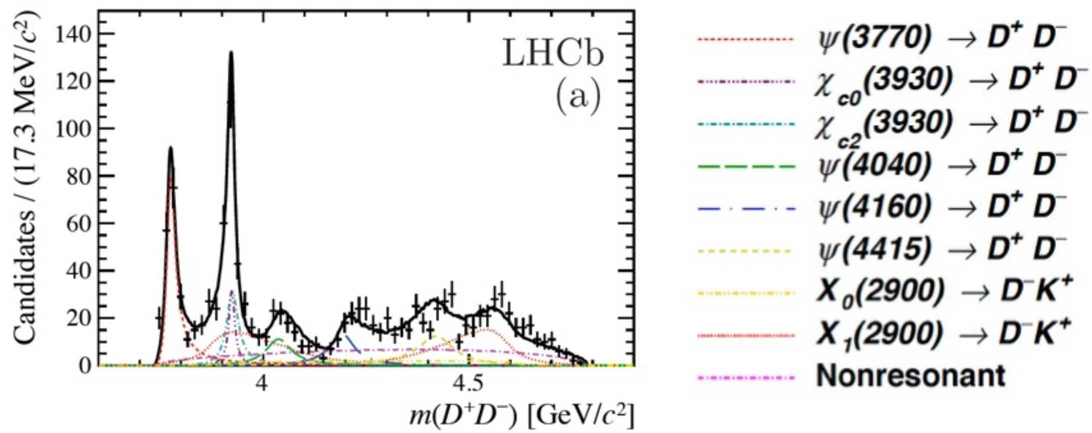


Observation of open-charm exotic state X(2900) [$\bar{c}\bar{s}ud$]

PRL125, 242001 (2020)
PRD102, 112003 (2020)

- $B^+ \to D^+D^-K^+$ decays with RUN 1+2 data
  - Ideal channel to search for the open-charm tetraquark
  - Contributions: no Fav D_{sJ}^+, Sup charmonium, Fav open-charm tetraquark(?)
- Observation of two D^-K^+ states (BW) at ~2.9 GeV, $J^P=0^+, 1^-$



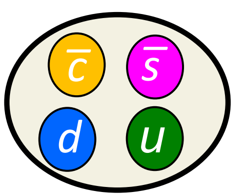


- Need more intricate theoretical studies
  - Very close to D^*K^*, D_1K thresholds. Rescattering ?

Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$

States	Mass/MeV	Width/MeV	Fraction/%
$X_0(2900)$	$2866 \pm 7 \pm 2$	$57 \pm 12 \pm 4$	$5.6 \pm 1.4 \pm 0.5$
$X_1(2900)$	$2904 \pm 5 \pm 1$	$110 \pm 11 \pm 4$	$30.6 \pm 2.4 \pm 2.1$

Quite large contribution!

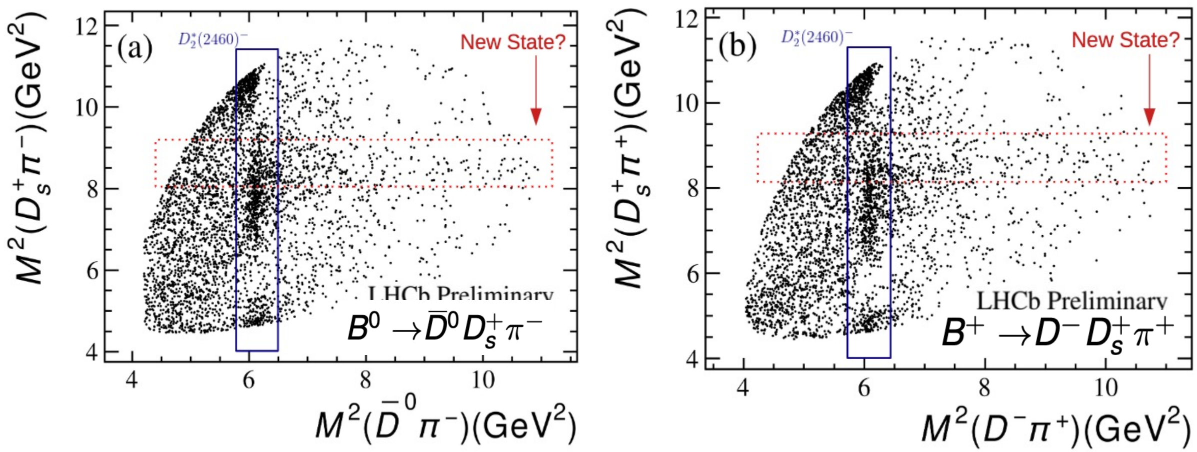


Candidates for the 1st open-charm tetraquarks (four different flavors)!

Observation of a doubly charged tetraquark $T_{c\bar{s}0}(2900)^{++}$ [$c\bar{s}u\bar{d}$] and its neutral partner $T_{c\bar{s}0}(2900)^{0}$ [$c\bar{s}\bar{u}d$]

LHCb-PAPER-2022-026
LHCb-PAPER-2022-027

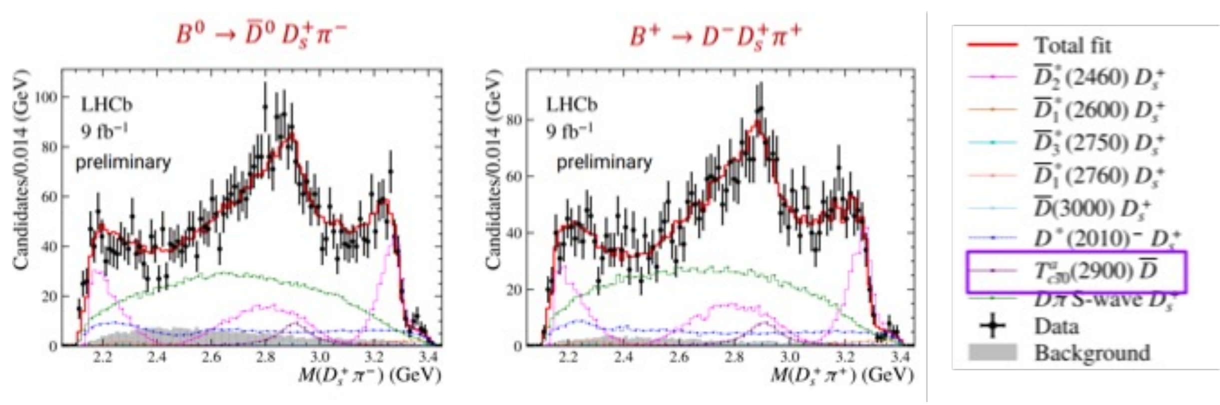
- First simultaneous amplitude analysis of $B^+ \to D\ \ D_s^+\pi^+$ & $B^0 \to \bar{D}^0 D_s^+\pi^+$ with RUN 1+2 9 fb^{-1} data



- $D_s\pi$ mass spectra well described by adding $J^P = 0^+$ (> **7.5 σ**) $T^a_{c\bar{s}0}(2900)$ > **9 σ**

$$M = 2.908 \pm 0.011 \pm 0.020\,\mathrm{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\mathrm{GeV}$$

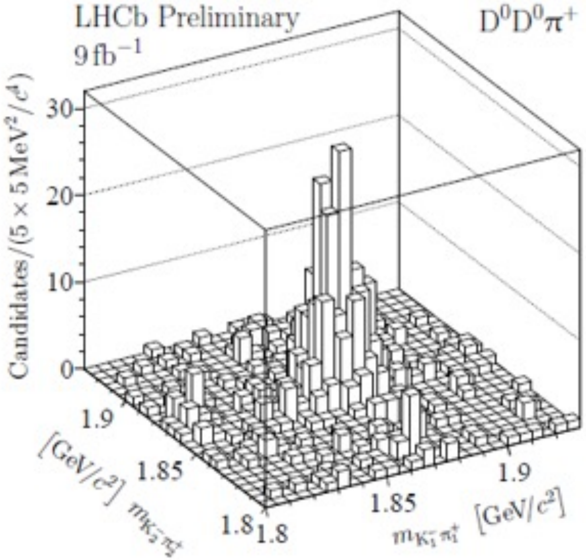
- Separate resonance fits:
  - $T^{a0}_{c\bar{s}}$: $m = 2892 \pm 14 \pm 15\,\mathrm{MeV}$, $\Gamma = 119 \pm 26 \pm 12\,\mathrm{MeV}$;
  - $T^{a++}_{c\bar{s}}$: $m = 2921 \pm 17 \pm 19\,\mathrm{MeV}$, $\Gamma = 137 \pm 32 \pm 14\,\mathrm{MeV}$

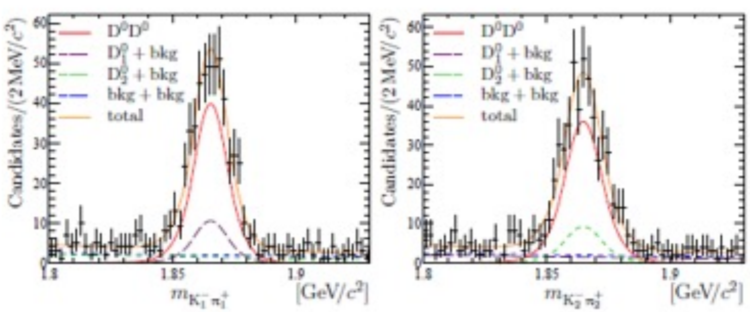


Observation of doubly-charm tetraquark state T_{cc}^{+} $[cc\bar{u}\bar{d}]$

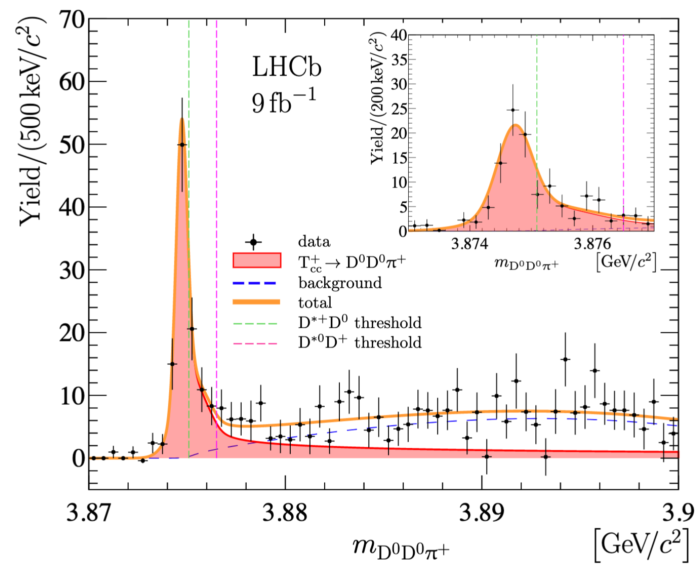
Full Run 1+2 data

arXiv:2109.01038
Nature Comm.13, 3351 (2022)



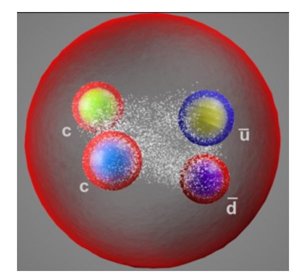


Fit with relativistic *P*-wave **BW** function



$$\delta m \equiv m_{T_{cc}^{+}} - (m_{D^{*+}} + m_{D^0})$$

$T_{cc}^{+} \to D^0 D^0 \pi^+$ $\delta m_{BW} = -273 \pm 61 \pm 5^{+11}_{-14}\ \mathrm{keV}/c^2, \Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38}\ \mathrm{keV}$



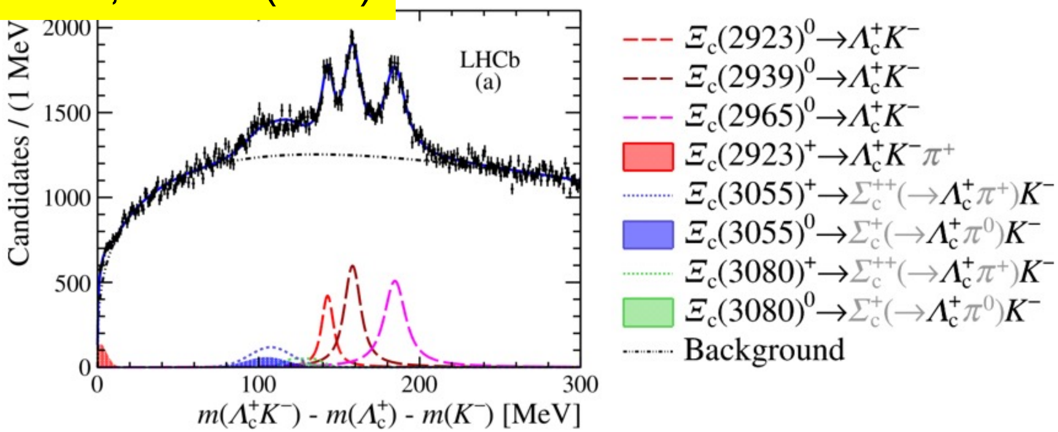
- consistent with expectation for ground isoscalar $T_{cc}^{+}(cc\bar{u}\bar{d})$ state with $J^P = 1^+$

Heavy baryons

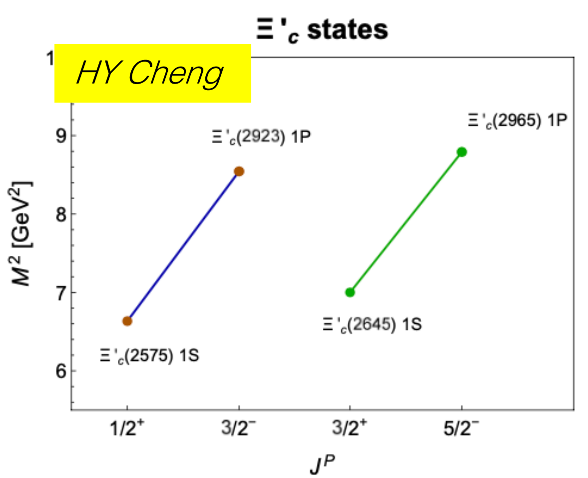
Observation of new Ξc baryons

- Three excited Ξ_c^0 are observed in decaying into $\Lambda_c^+ K^-$
- Using LHCb RUN 2 data at 13 TeV

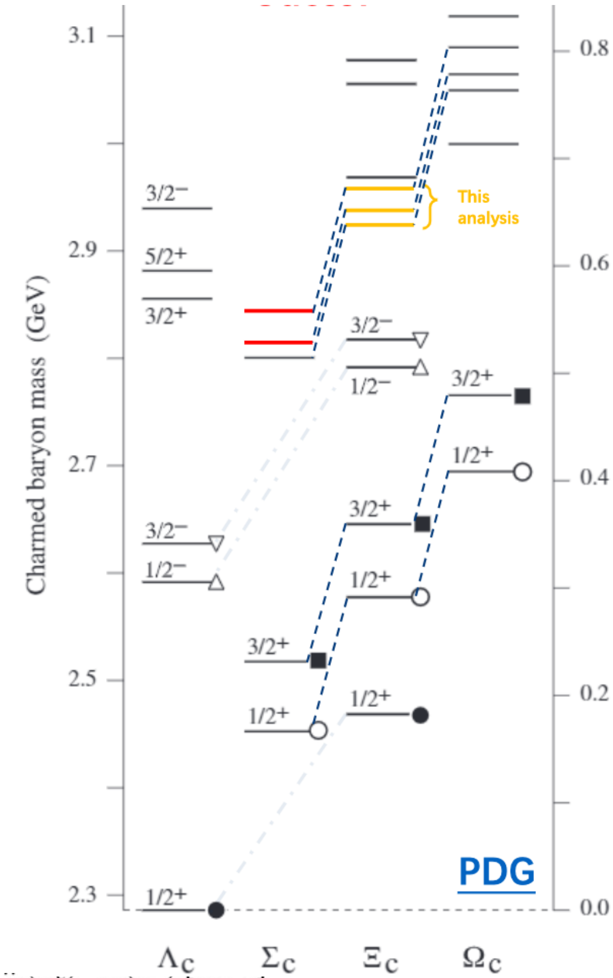
PRL124, 222001 (2020)



HY Cheng



Genuine property of these states are not fully understood yet.



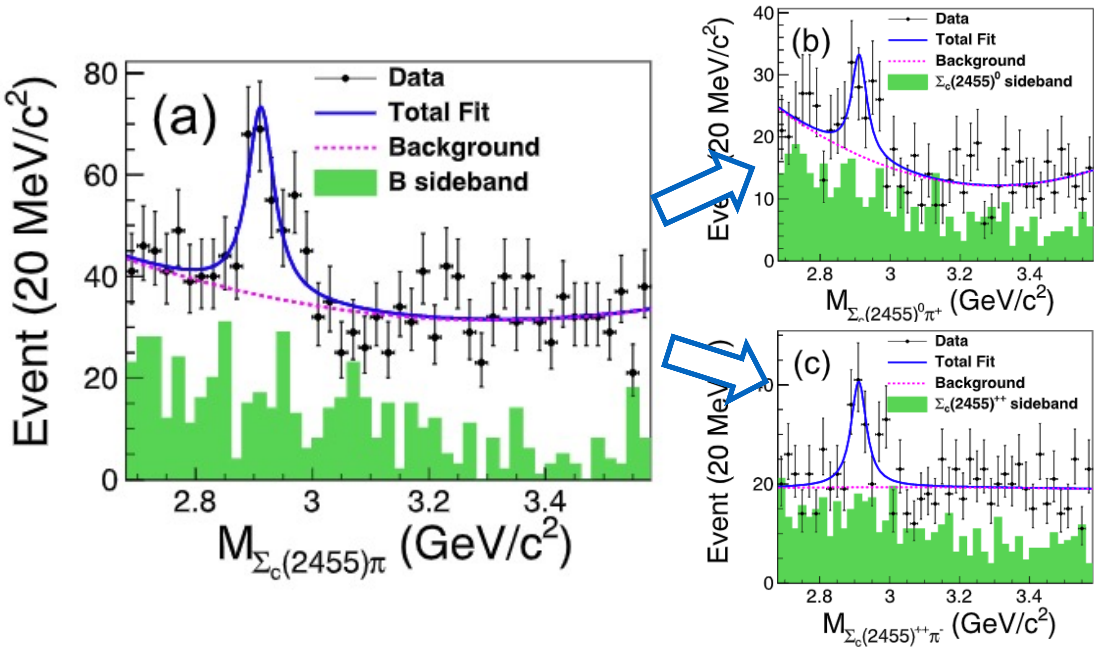
Resonance	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

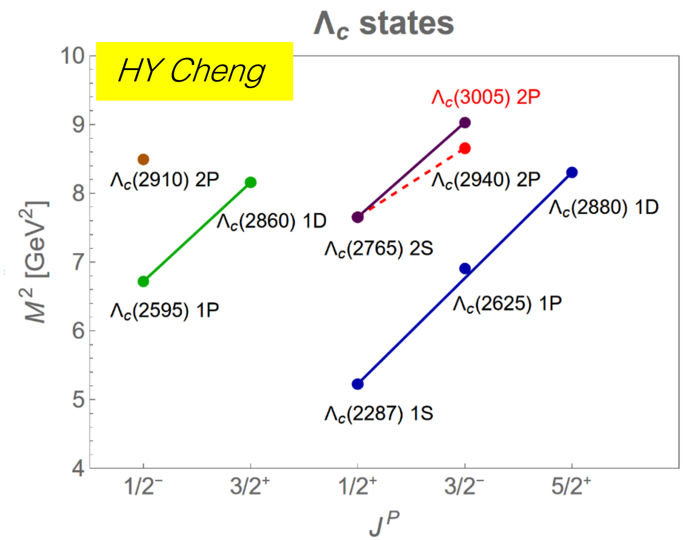
Stat. Sys. input

Evidence of new excited charmed baryon Λ_c^*

arXiv: 2206.08822

- Study on $\bar{B}^0 \to \Sigma_c\ (2455)^{0,++}\pi^{\pm}\bar{p}$ with Belle data
- Combined fit to $\Sigma_c\ (2455)^{0,++}\pi^{\pm}$ mass spectra





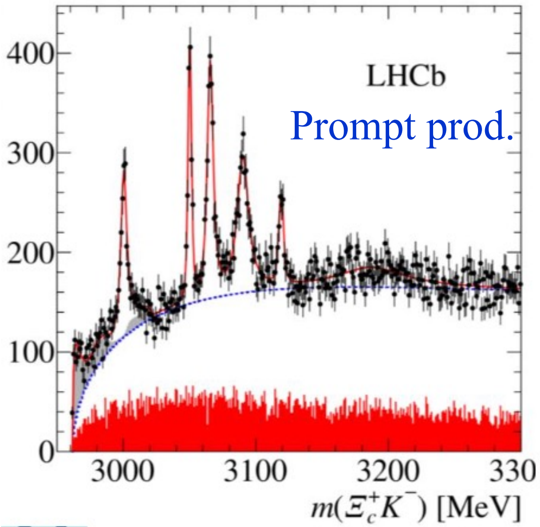
State	Mass (MeV/c^2)	Width (MeV)
$\Lambda_c(2880)^+$	2881.63 ± 0.24	$5.6^{+0.8}_{-0.6}$
$\Lambda_c(2940)^+$	$2939.6^{+1.3}_{-1.5}$	20^{+6}_{-5}
$\Lambda_c(2910)^+$ (this analysis)	$2913.8 \pm 5.6 \pm 3.8$	$51.8 \pm 20.0 \pm 18.8$

a good candidate for $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$ [arXiv:2207.03022]

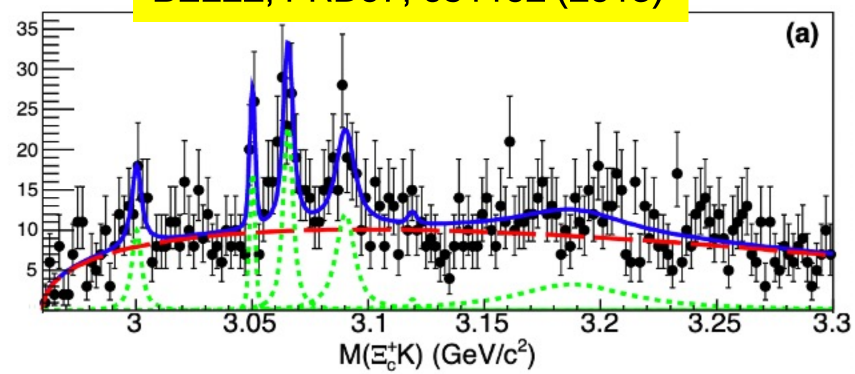
significance with 4.2 σ after considering possible $\Lambda_c(2880)$ and $\Lambda_c(2940)$ contributions

Confirmation of the excited Ω_c states

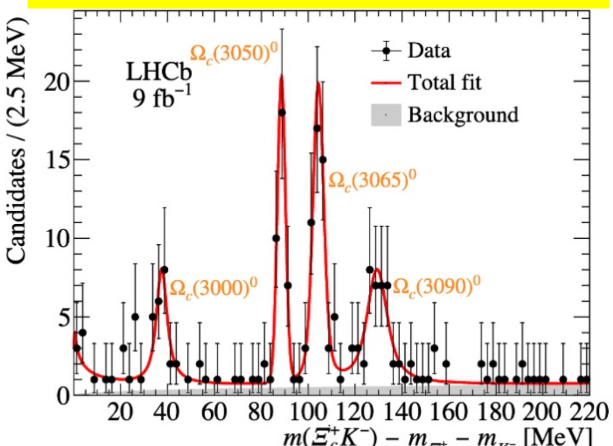
LHCb, PRL118, 182001 (2017)



BELLE, PRD97, 051102 (2018)



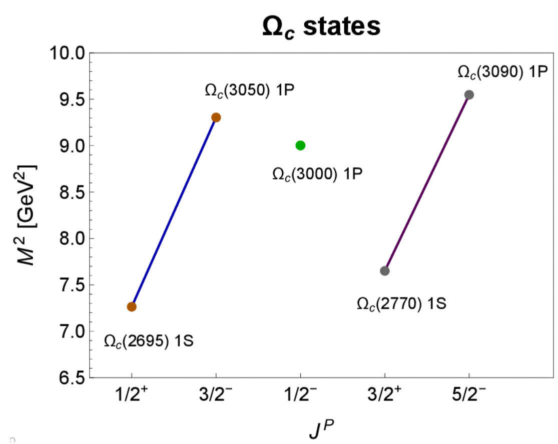
LHCb, PRD 104, L091102 (2021)



$N(\Omega_b^- \to \Xi_c^+ K^- \pi^-) = 240 \pm 17$

	Prompt		b-decays	
Resonance	Mass [MeV]	Γ [MeV]	Mass [MeV]	Γ [MeV]
$\Omega_c(3000)^0$	3000.4 ± 0.2 ± 0.1	4.5 ± 0.6 ± 0.3	2999.2 ± 0.9 ± 0.9	4.8 ± 2.1 ± 2.5
$\Omega_c(3050)^0$	3050.2 ± 0.1 ± 0.1	0.8 ± 0.2 ± 0.1	3050.1 ± 0.3 ± 0.2	< 1.6 @ 95% CL
$\Omega_c(3065)^0$	3065.6 ± 0.1 ± 0.3	3.5 ± 0.4 ± 0.2	3065.9 ± 0.4 ± 0.4	1.7 ± 1.0 ± 0.5
$\Omega_c(3090)^0$	3090.2 ± 0.3 ± 0.5	8.7 ± 1.0 ± 0.8	3091.0 ± 1.1 ± 1.0	7.4 ± 3.1 ± 2.8

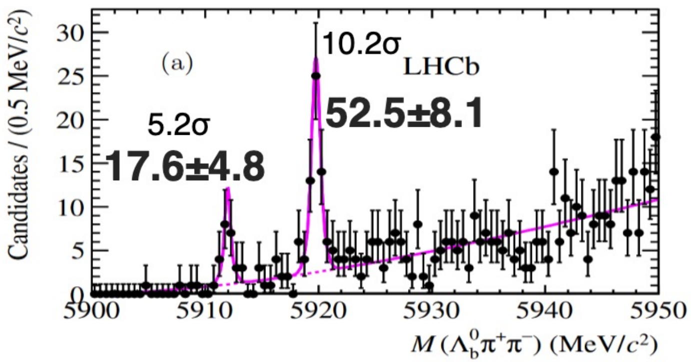
four of the five observed states are confirmed in b-baryon decays and e^+e^- collisions



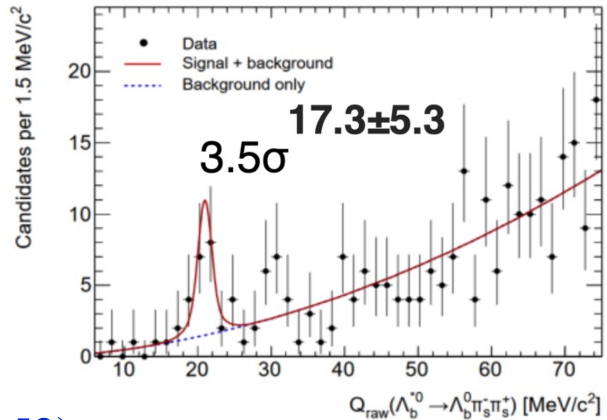
New excited Λ_b^* states in $\Lambda_b\pi^+\pi^-$ (1)

- Λ_b(5912) & Λ_b(5920) were observed at LHCb and later Λ_b(5920) confirmed by CDF

LHCb, PRL109,172003 (2012)



CDF, PRD88, 071101(2013)

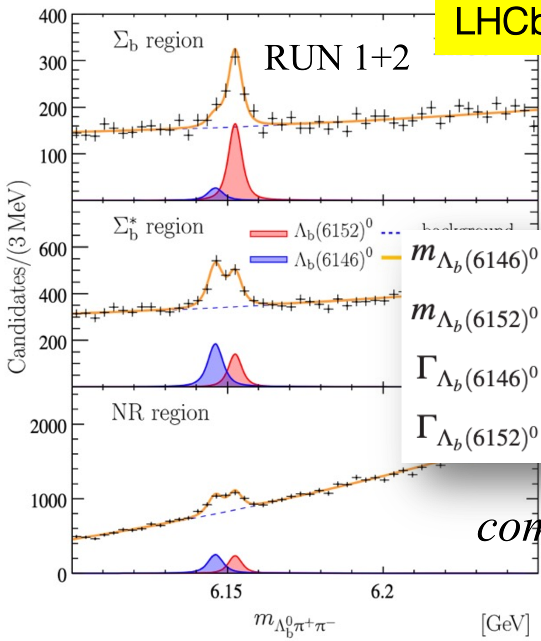


likely they are doublet of $\Lambda_b(1P)$

Near kinematic threshold

- Observation of Λ_b(6146) & Λ_b(6152)

LHCb, PRL123,152001 (2019)

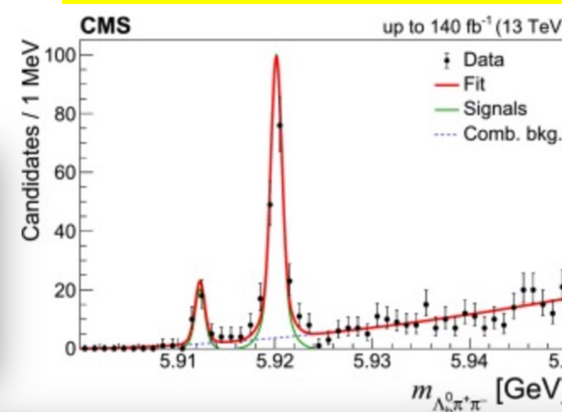


$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\ \text{MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\ \text{MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3\ \text{MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3\ \text{MeV},$$

compatible with $\Lambda_b(1D)$

- Confirmation of Λ_b(5912) & Λ_b(5920)

CMS, PLB803, 135345(2020)

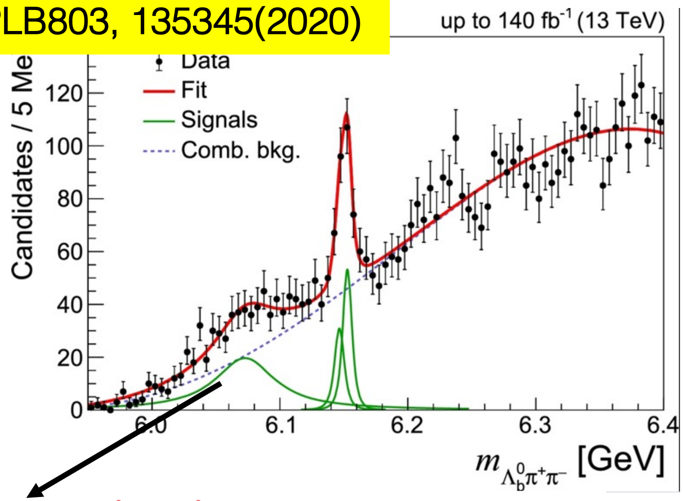


$$M(\Lambda_b^0(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17\ \text{MeV},$$
$$M(\Lambda_b^0(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17\ \text{MeV},$$

New excited Λ_b^* states in $\Lambda_b\pi^+\pi^-$ (2)

- Confirmation of the doublet of $\Lambda_b(6146)$ & $\Lambda_b(6152)$

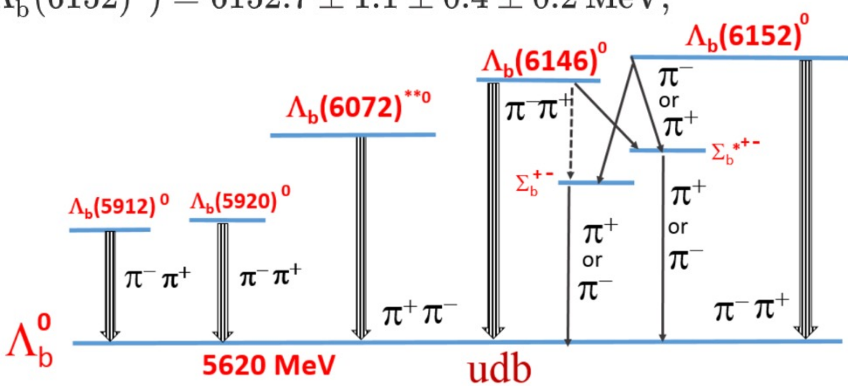
CMS, PLB803, 135345(2020)



Evidence for a new broad resonance,
M = 6075 ± 5 (stat) MeV and Γ = 55 ±11 (stat) MeV

could be an overlap of some close/partially reconstructed states

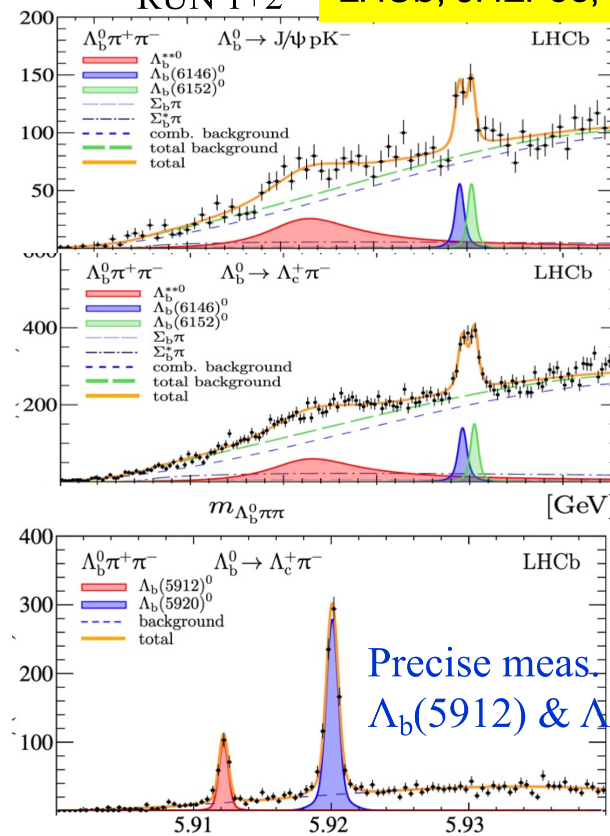
$$M(\Lambda_b^0(6146)^0) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2\,\text{MeV},$$
$$M(\Lambda_b^0(6152)^0) = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2\,\text{MeV},$$



- Observation of the broad resonance

RUN 1+2

LHCb, JHEP06, 136(2020)



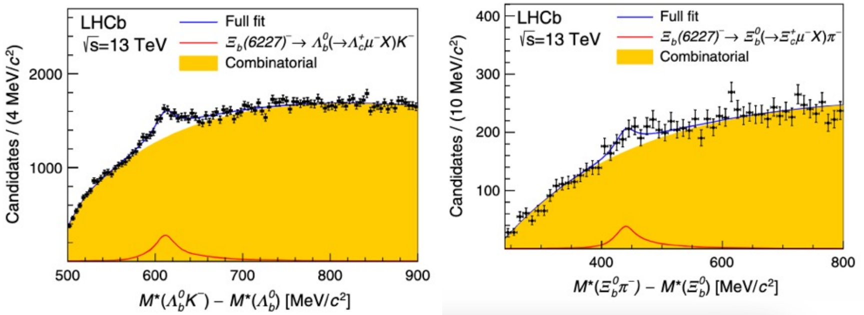
Precise meas. of $\Lambda_b(5912)$ & $\Lambda_b(5920)$

$$m_{\Lambda_b^{**0}} = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2\,\text{MeV} \quad \boldsymbol{\Lambda_b(2S)?}$$
$$\Gamma_{\Lambda_b^{**0}} = 72 \pm 11 \pm 2\,\text{MeV}$$
$$m_{\Lambda_b(5912)^0} = 5912.21 \pm 0.03 \pm 0.01 \pm 0.21\,\text{MeV},$$
$$m_{\Lambda_b(5920)^0} = 5920.11 \pm 0.02 \pm 0.01 \pm 0.21\,\text{MeV},$$
$$\Gamma_{\Lambda_b(5912)^0} < 0.25\,(0.28)\,\text{MeV},$$
$$\Gamma_{\Lambda_b(5920)^0} < 0.19\,(0.20)\,\text{MeV},$$

Observation of new excited Ξ_b states

$\Xi_b(6227)^- \rightarrow \Lambda_b K^-, \Xi_b^0 \pi^-$

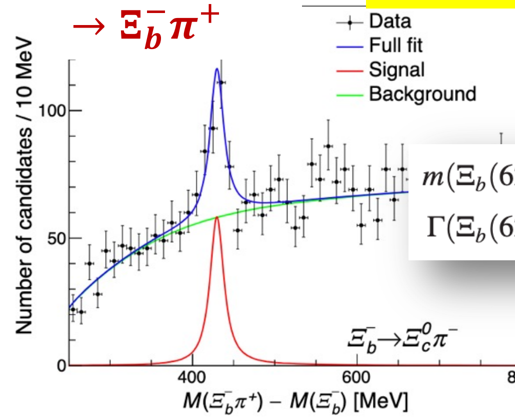
LHCb, PRL121, 072002(2018)



$$\Gamma_{\Xi_b(6227)^-} = 18.1 \pm 5.4(\text{stat}) \pm 1.8(\text{syst})\ \text{MeV}/c^2,$$
$$m_{\Xi_b(6227)^-} = 6226.9 \pm 2.0(\text{stat}) \pm 0.3(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV}/c^2,$$

$\Xi_b(6227)^0 \rightarrow \Xi_b^- \pi^+$

LHCb, PRD 103, 012004 (2021)

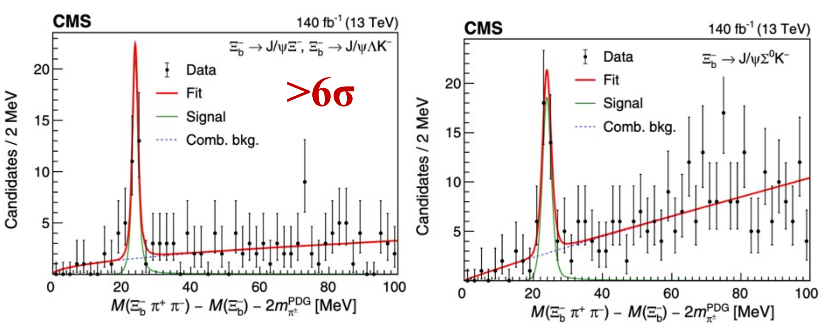


$$m(\Xi_b(6227)^0) = 6227.1^{+1.4}_{-1.5} \pm 0.5\ \text{MeV},$$
$$\Gamma(\Xi_b(6227)^0) = 18.6^{+5.0}_{-4.1} \pm 1.4\ \text{MeV},$$

$\Xi_b(6227)$: consistent with a $\Xi_b(1P)$ state

$\Xi_b(6100)^- \rightarrow \Xi_b^- \pi^+ \pi^-$

CMS, PRL126,252003 (2021)

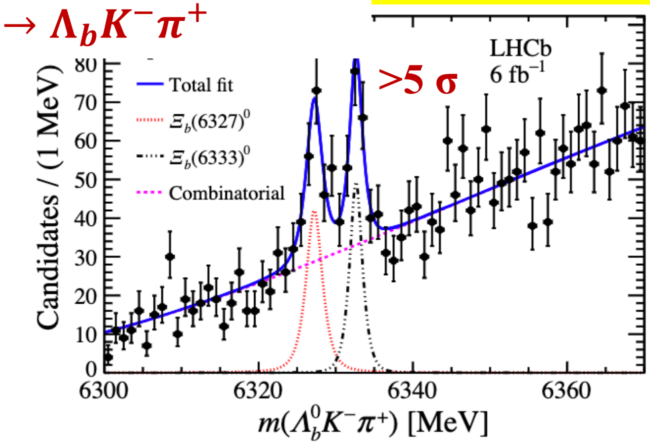


$M = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6$ MeV

$\Gamma < 1.9$ MeV at 95% CL

$\Xi_b(6327)^0$ & $\Xi_b(6333)^0 \rightarrow \Lambda_b K^- \pi^+$

LHCb, PRL128, 162001 (2022)

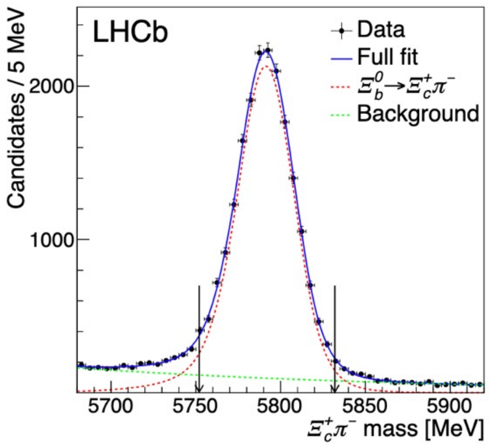


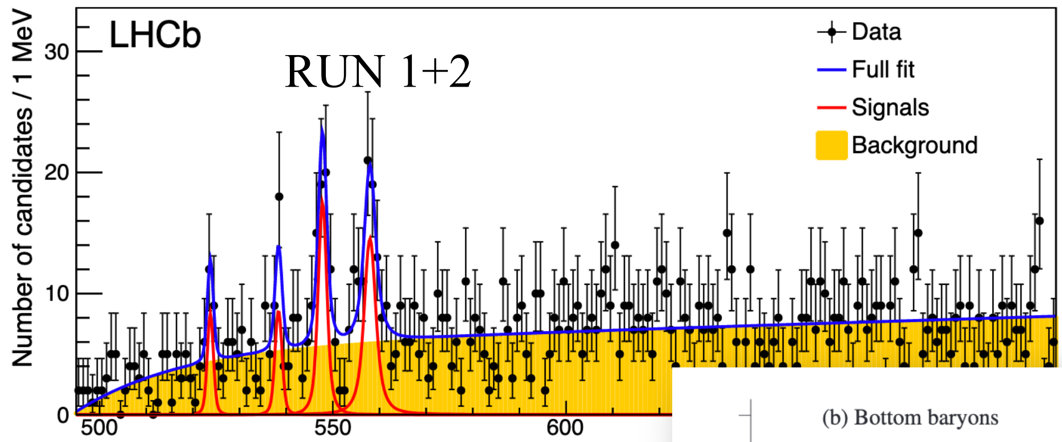
$$m[\Xi_b(6327)^0] = 6327.28^{+0.23}_{-0.21} \pm 0.12 \pm 0.24\ \text{MeV},$$
$$m[\Xi_b(6333)^0] = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22\ \text{MeV},$$

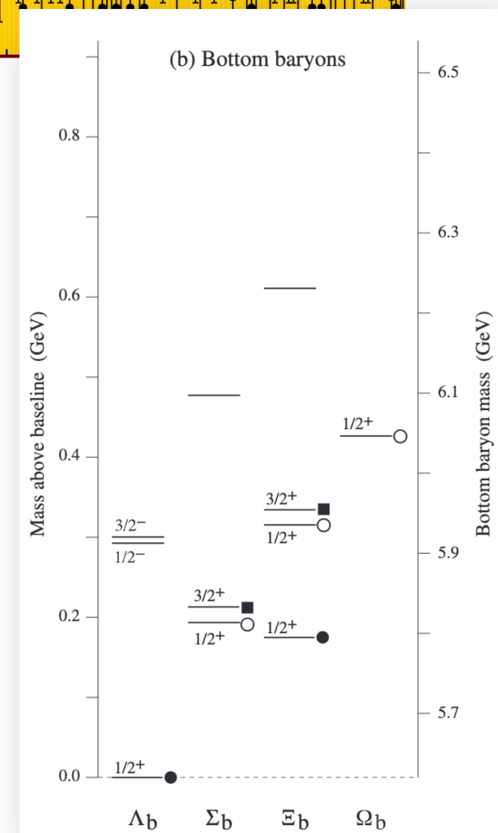
consistent with the 1D excited Ξ_b doublets.

Observation of new excited Ω_b states

PRL124, 082002 (2020)



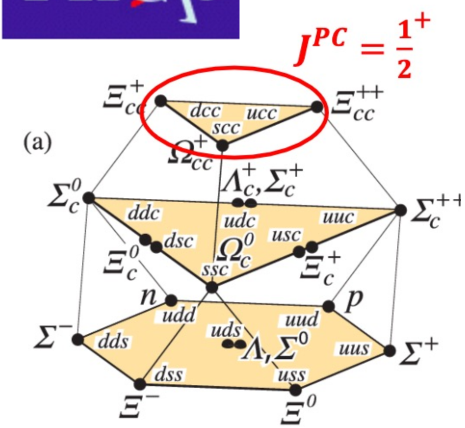


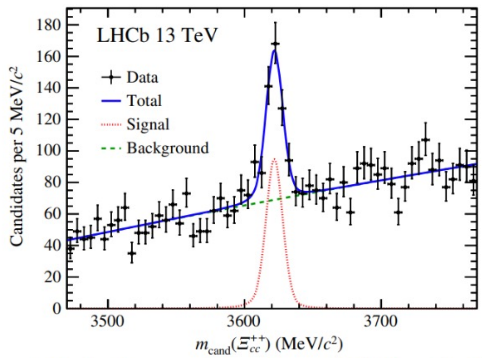


	Mass [MeV]	Width [MeV]	Significances [σ]	
			Local	Global
$\Omega_b(6316)^-$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	$< 2.8\ (4.2)$	3.6	2.1
$\Omega_b(6330)^-$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	$< 3.1\ (4.7)$	3.7	2.6
$\Omega_b(6340)^-$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	$< 1.5\ (1.8)$	7.2	6.7
$\Omega_b(6350)^-$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	$< 2.8\ (3.2)$ $1.4^{+1.0}_{-0.8} \pm 0.1$	7.0	6.2

observation

Observation of $\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+$





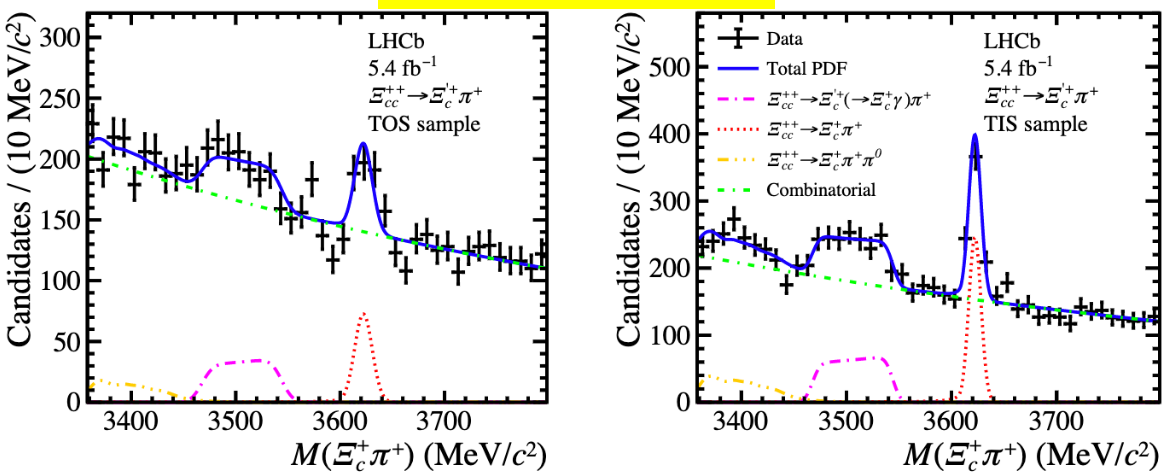
First observation in $m(\Lambda_c^+ K^- \pi^+ \pi^+)$

PRL 119 (2017) 112001

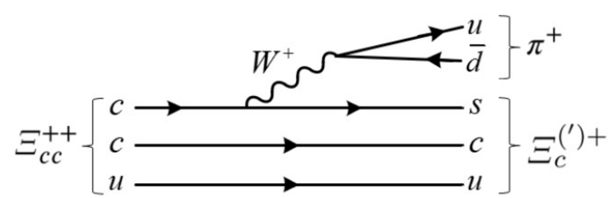
A lot of Ξ_{cc}^{++} study done by LHCb:

- Mass: $m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30$ MeV/c^2 (Stat. Sys.) — JHEP 02 (2020) 049
- Lifetime: $\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022} \pm 0.014$ ps — PRL 121 (2018) 052002
- Production: $\frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = 2.22 \pm 0.27 \pm 0.29$ — CPC44 (2020) 022001
- Branching fraction
  - $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$: $\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)} = 0.035 \pm 0.009 \pm 0.003$ — PRL 121 (2018) 162002
  - $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$: $\frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} < 1.7$ — JHEP 10 (2019) 124

JHEP 05, 038 (2022)



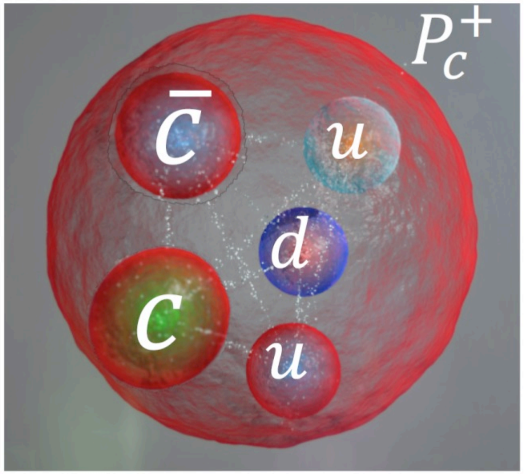
RUN 2 LHCb data @13TeV



Third Ξ_{cc}^{++} decay channel is observed!

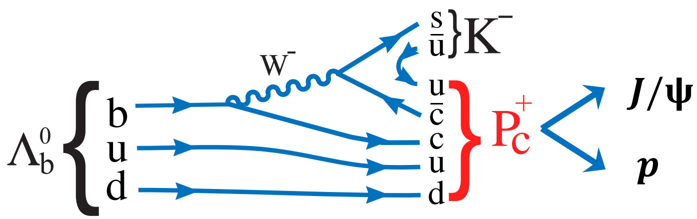
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+} \pi^+)} = 1.41 \pm 0.17 \pm 0.10$$

Pentaquark states



Pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$ decays

- Pentaquarks [$c\bar{c}uud$] were first observed in 2015 by LHCb in $\Lambda_b^0 \to J/\psi p K^-$ decays

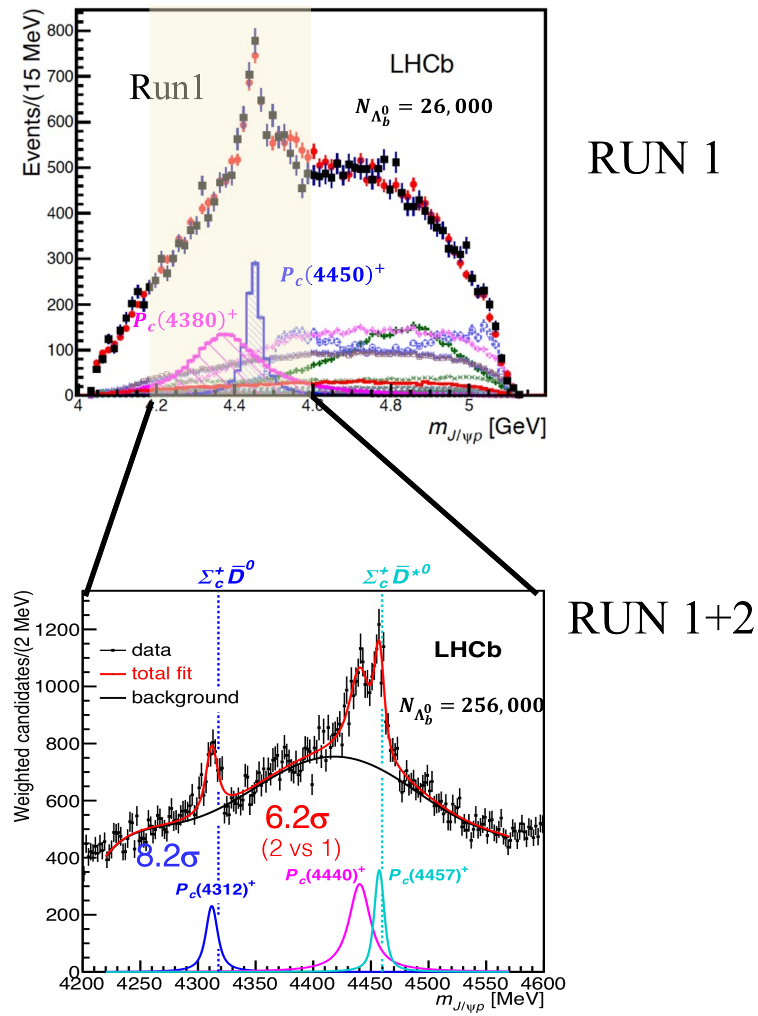


- New pentaquark and fine structure were discovered in 2019 with x10 signals
  - Three narrow pentaquarks just below $\Sigma_c^+ D^{(*)0}$ thresholds, favors molecular picture

State	M [MeV]	Γ [MeV] (95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$ (< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$ (< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$ (< 20)

- A lot of open questions:
  - J^P, more decay modes,…?
  - SU(3) partners, hidden-bottom pentaquarks?

PRL115, 072001(2015)



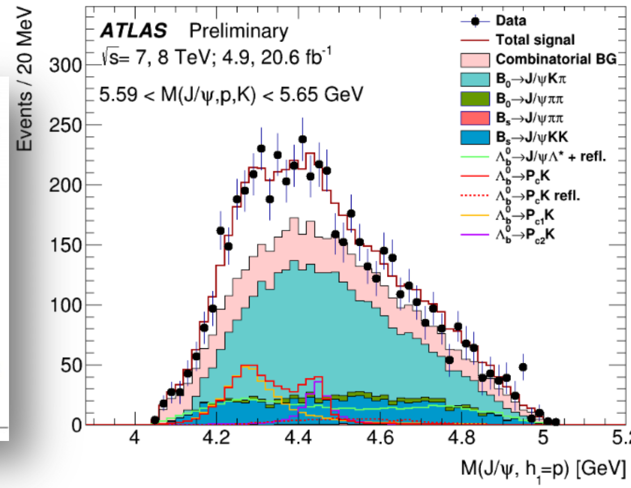
PRL122, 222001(2019)

Pc confirmations in *b* decays at ATLAS and D0

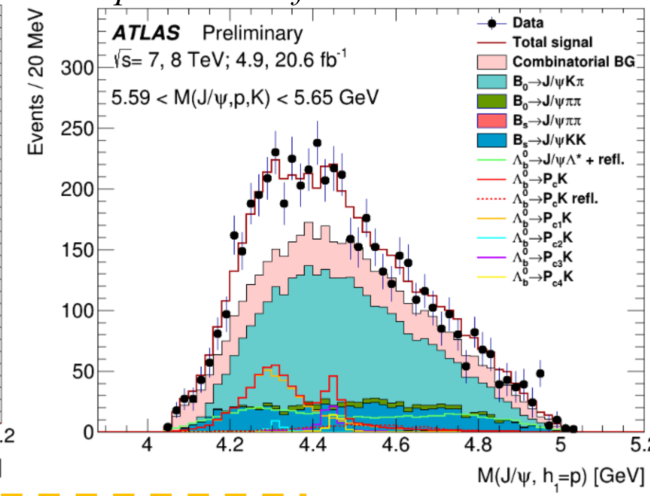
- ATLAS studied ~1K $\Lambda_b^0 \to J/\psi p K^-$ using RUN1 data — ATLAS-CONF-2019-048
- **Pc states are needed to describe data**: two Pc's fit (left) and four Pc's fit (right)

Fitted Pc parameters consistent with LHCb's

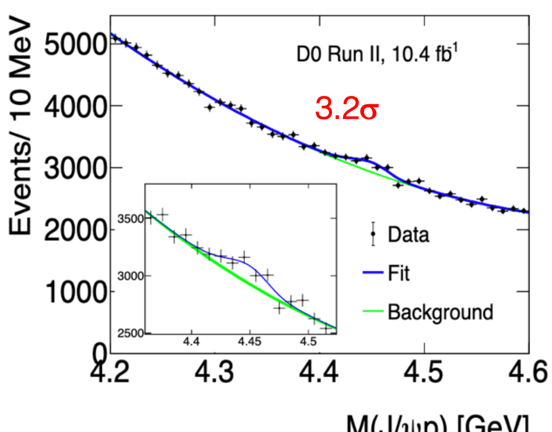
Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	$140^{+77}_{-50}(\text{stat})^{+41}_{-33}(\text{syst})$ MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	$4449^{+20}_{-29}(\text{stat})^{+18}_{-10}(\text{syst})$ MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	$51^{+59}_{-48}(\text{stat})^{+14}_{-46}(\text{syst})$ MeV	$39 \pm 5 \pm 19$ MeV

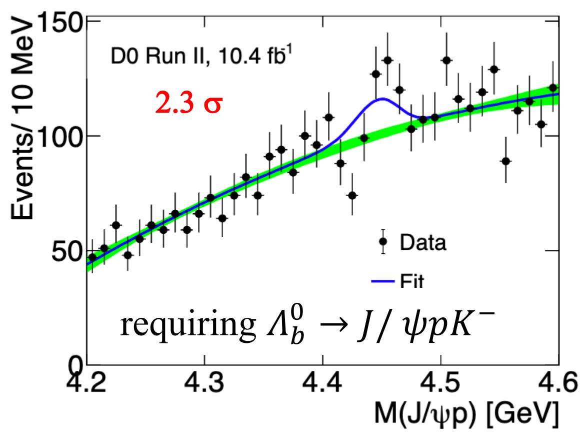


Pc parameters fixed to LHCb's results



- **D0 studied $J/\psi p$ in *b*-decays with displaced vertex** — D0, arXiv:1910.11767
- **A sum of Pc(4440) and Pc(4457) confirmed in b-decays:** **major contributions from b SL decays**



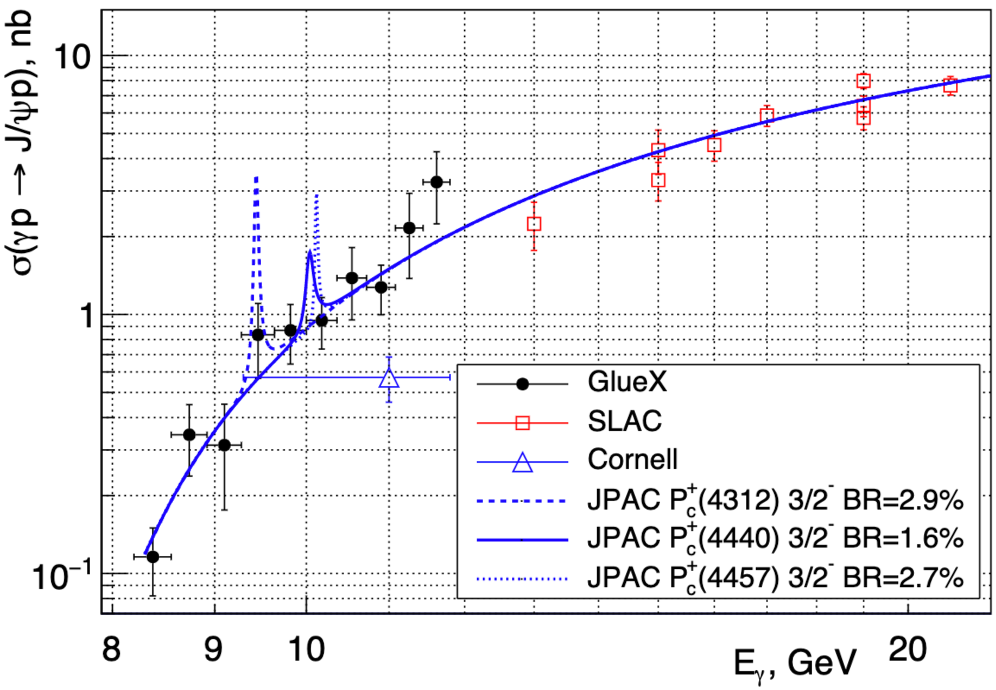


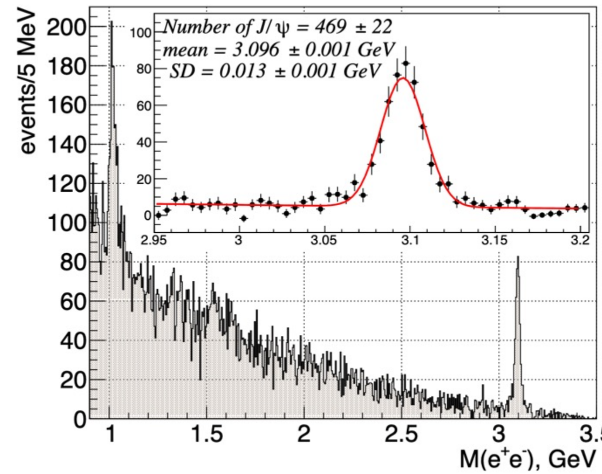
- **Pc(4312) is not evident**
- **No Pc states seen in prompt production**

Pentaquark photoproduction at GlueX

PRL123, 072001 (2019)

- Photoproduction: $\gamma p \to P_c \to J/\psi p$ studied with GlueX data in 2016 and 2017
- Combined data from SLAC and Cornell





Model-dependent upper limits at the 90% C.L. are et for cross section times branching fraction for the Pc states:

4.6 nb for $P_c(4312)$
1.8 nb for $P_c(4440)$
3.9 nb for $P_c(4457)$

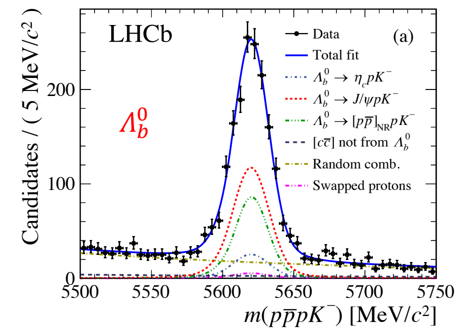
The results do not exclude the molecular model, but are an order of magnitude lower than the predictions in the hadrocharmonium scenario.

Search for Pc in $\Lambda_b^0 \to \eta_c p K^-$

PRD102, 112012 (2020)

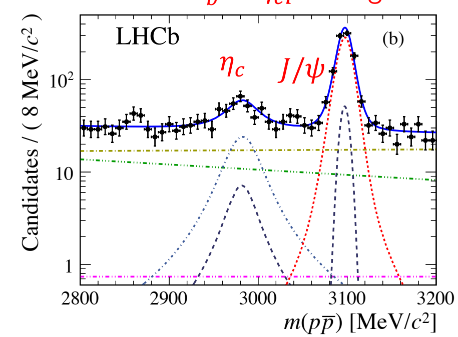
- Same quark contents as $\Lambda_b^0 \to J/\psi p K^-$
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule,
  $R(P_c(4312)^+) = \frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)}$ ~3 is predicted

  [PRD 100, 034020 (2019); 100, 074007 (2019); 102, 036012 (2020)]



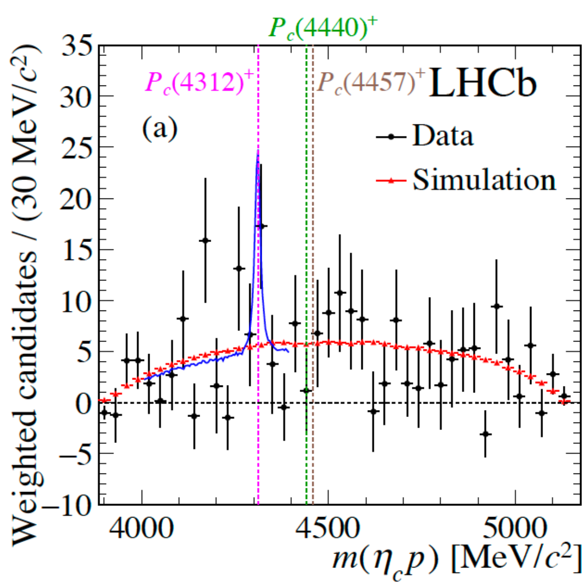
- LHCb run2 data (5.5 fb^{-1}): η_c reconstructed using $\eta_c \to p\bar{p}$
- Study background-subtracted $\eta_c p$ mass spectrum

~170 $\Lambda_b^0 \to \eta_c p K^-$ signals



No significant $P_c(4312)^+$ contribution (~2σ)

$R(P_c(4312)^+) < 0.24$ @ 95% C.L.
(Uncertainty is too large to give any conclusion yet)



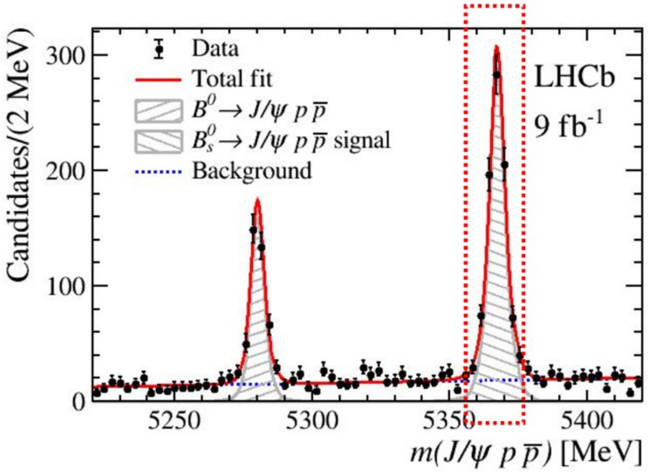
Pc state in $B_s^0 \to J/\psi p\bar{p}$

PRL 128, 062001 (2022)

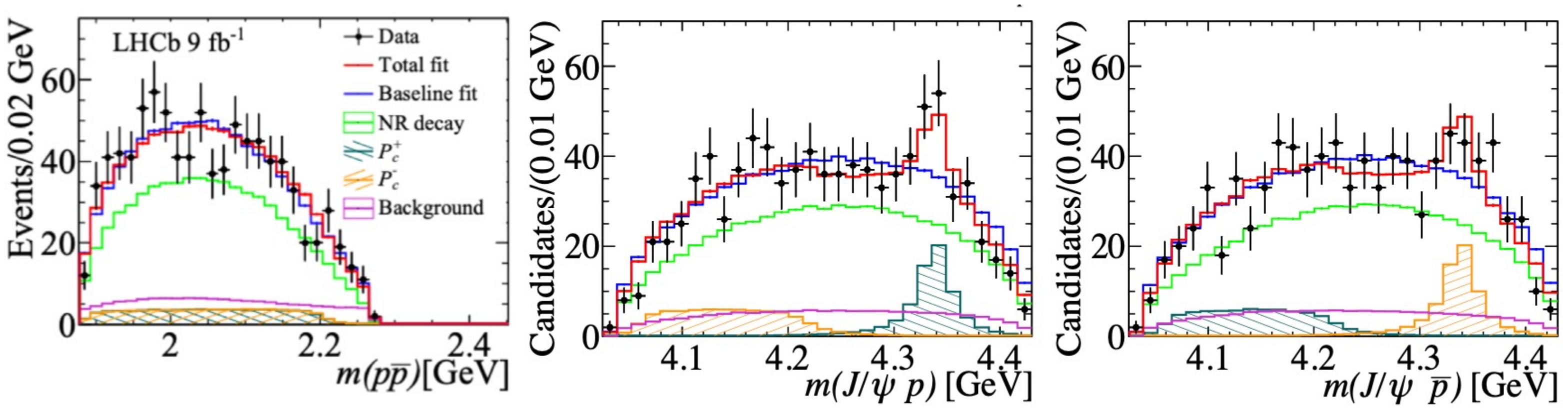
- RUN 1+2 data, untagged *B* decay, with CP conservation, ~800 signals
- 4D amplitude analysis implemented
- Evidence for a new pentaquark-like state Pc:

$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\ \text{MeV}$$

$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV}$$



- 3.1~3.7σ for $(\frac{1}{2}^{\pm}, \frac{3}{2}^{\pm})$ hypothesis; statistics not sufficient for determining the spin-parity

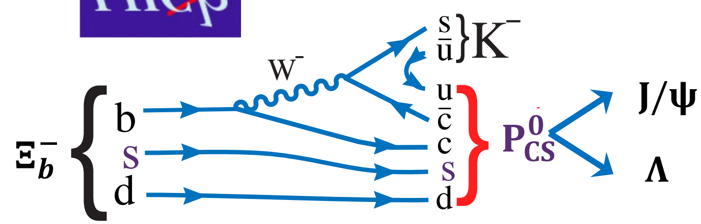


- No evidence for $P_c(4312)$, glueball $f_J(2220)$, $p\bar{p}$ enhancement

Evidence for the hidden-charm strange pentaquark

Sci. Bull. 66, 1278(2021)

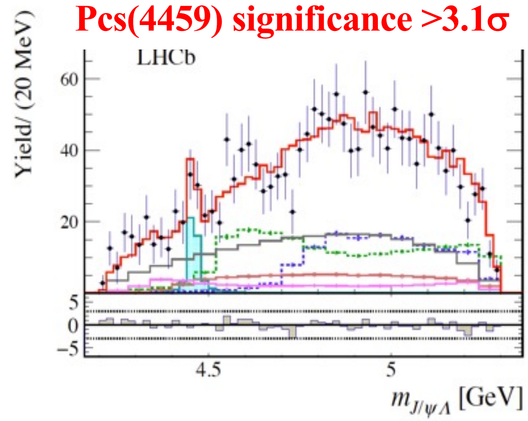
- Aim to search for P_{cs}, a SU(3) partner of P_c state
- RUN 1+2 data: detect ~1750 $\Xi_b^- \to J/\psi \Lambda K^-$ signals
- 6D amplitude analysis is performed
- Statistics not enough for J^P determination



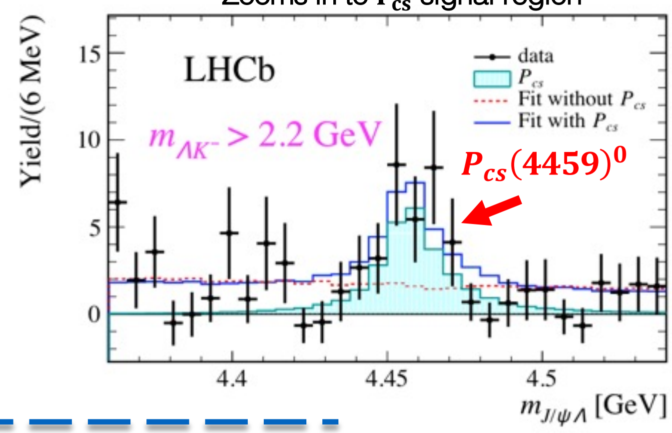
$m(P_{cs}^0) = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV

$\Gamma(P_{cs}^0) = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

Pcs(4459) significance >3.1σ



Zooms in to P_{cs} signal region

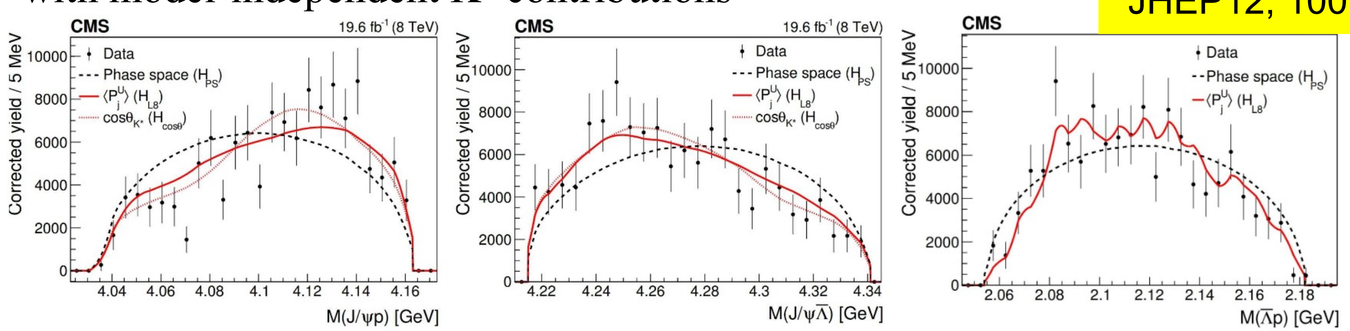


- $P_{cs}(4459)^0$ mass close to $\Xi_c \bar{D}^*$ threshold, two $I = 0$ states with $\frac{1}{2}^-$ or $\frac{3}{2}^-$

  More data needed to resolve

- $B^- \to J/\psi \Lambda \bar{p}$ decays with 19.6 fb^{-1} CMS data
- It finds that data is inconsistent with purely phase space distributions, but consistent with model-independent K* contributions

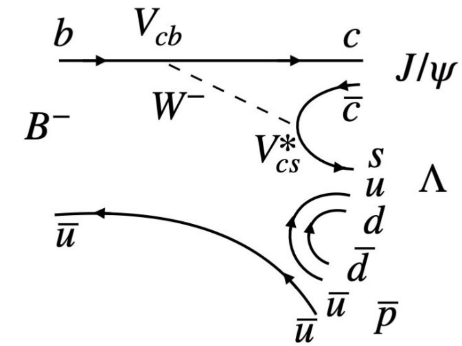
JHEP12, 100(2019)



Observation of the hidden-charm strange pentaquark

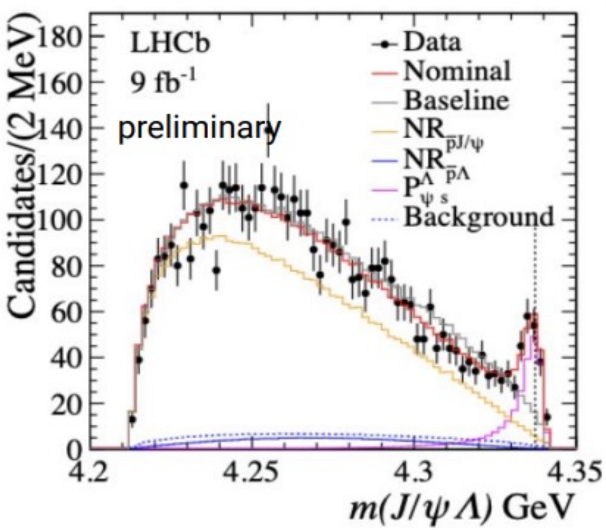
LHCb-PAPER-2022-031

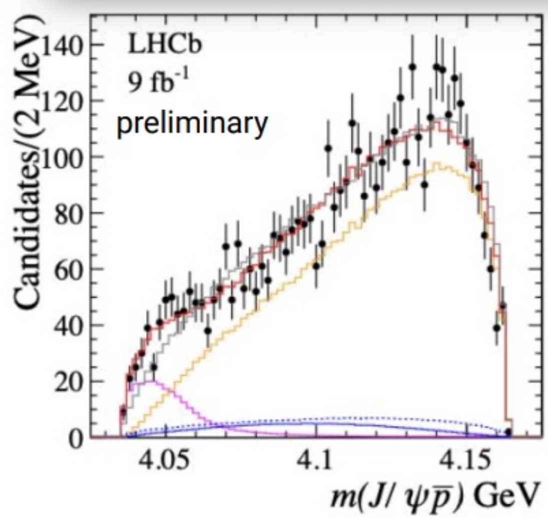
- narrow structure in $J/\psi\Lambda$ in $B^- \to J/\psi\Lambda\bar{p}$ decays, with 9 fb^{-1} LHCb data
- amplitude analysis is performed
- $P^{\Lambda}_{\psi s}(4338) \to J/\psi\Lambda$ observed with significance larger than 10σ
- $J^P = \frac{1}{2}^-$ preferred and close to $\Xi_c^+ D^-$ threshold
  - 0.8 MeV above $\Xi_c^+ D^-$;
  - 2.9 MeV above $\Xi_c^0 \bar{D}^0$

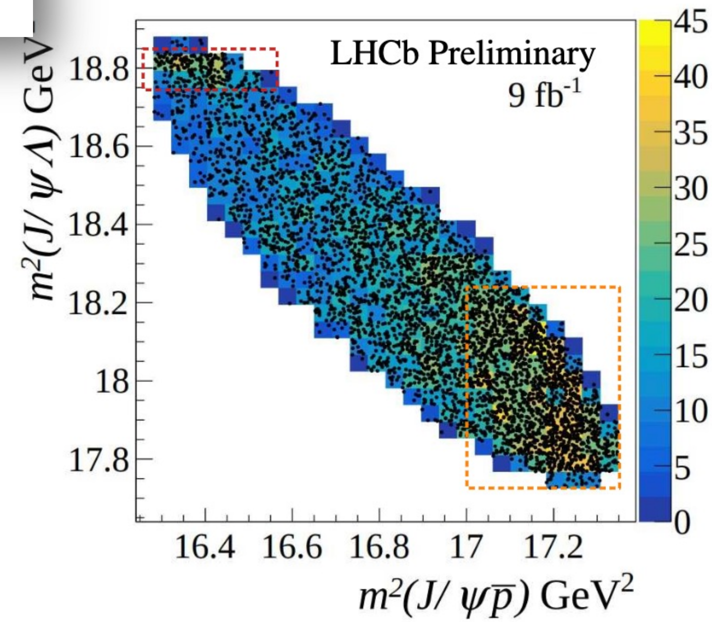


$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\text{MeV}$$

$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\,\text{MeV}$$







Summary

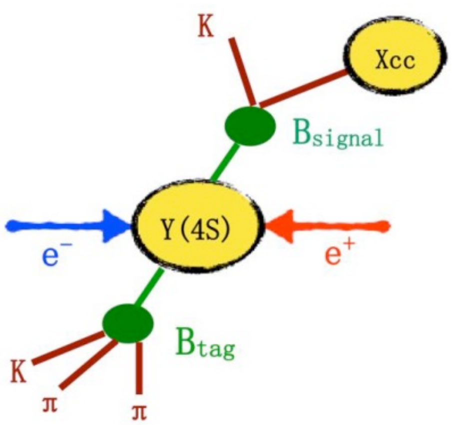
- An exciting period of finding new (heavy) hadrons
- Many new hadrons are observed at different experiments
  - trend of over-populated singly-charm and singly-bottom baryon states: some could be exotic candidates?
  - further understanding of X/Y/Z ($c\bar{c}q\bar{q}$) states: a new member **Y(4500)**
  - hidden-charm tetraquark states:
    Zcs(3985), Zcs(4000) and Zcs(4220) [$c\bar{c}u\bar{s}$];
    X(6900), X(6600) [$c\bar{c}c\bar{c}$];
    X(4630), X(4685), X(4740), X(3960) [$c\bar{c}s\bar{s}$];
  - singly charmed tetraquark states:
    X(2900) [$\bar{c}\bar{s}ud$]; $T_{c\bar{s}0}(2900)^{++}$ [$c\bar{s}u\bar{d}$]; $T_{c\bar{s}0}(2900)^{0}$ [$c\bar{s}\bar{u}d$]
  - doubly charmed tetraquark state: T_{cc}^{+} [$cc\bar{u}\bar{d}$]
  - observation/evidence of new pentaquark states: **Pc(4312), Pc(4440), Pc(4457)** and Pc(4337) [$c\bar{c}uud$]; P_{cs}**(4338)**, P_{cs}(4459) [$c\bar{c}uds$]
- More data are desired for marginal evidence or observation, determination of spin-parity
  - new results based on higher statistics data can be expected

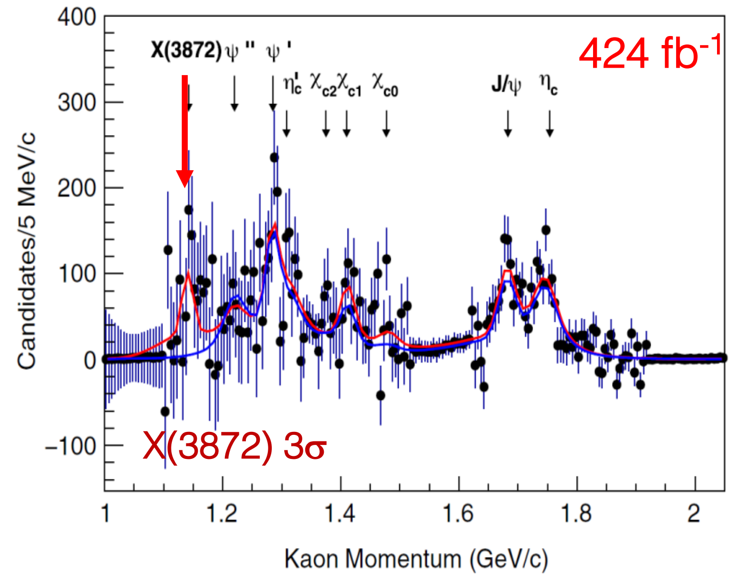
Thank you!

谢谢！

$X(3872)$ absolute decay rate

- Determination of the absolute branching fraction for $B^{\pm} \to X(3872)K^{\pm}$ leads to the absolute branching fraction of $X(3872) \to \pi^{+}\pi^{-}J/\psi$
  ➔ nature of X(3872)





Measure K momentum spectrum in B rest frame.

BaBar: PRL 124, 152001 (2020)

BF$(B^{+} \to X(3872)\,K^{+})$ **=(2.1 ±0.6±0.3)× 10⁻⁴**

By using the measured product BF: (8.6 ±0.8)× 10⁻⁶ (from PDG)

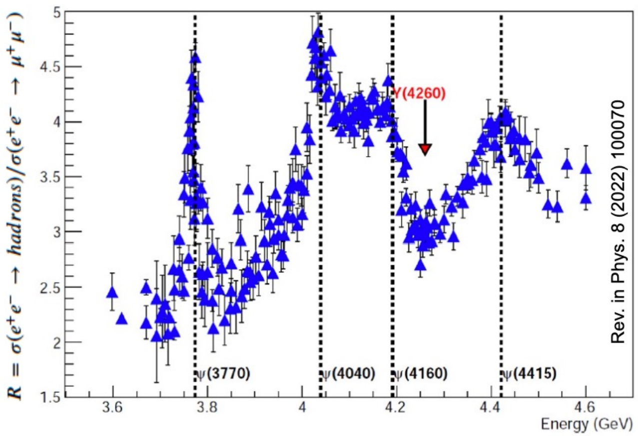
➔ BF($X(3872) \to \pi^{+}\pi^{-}J/\psi$) = (4.1±1.3) %

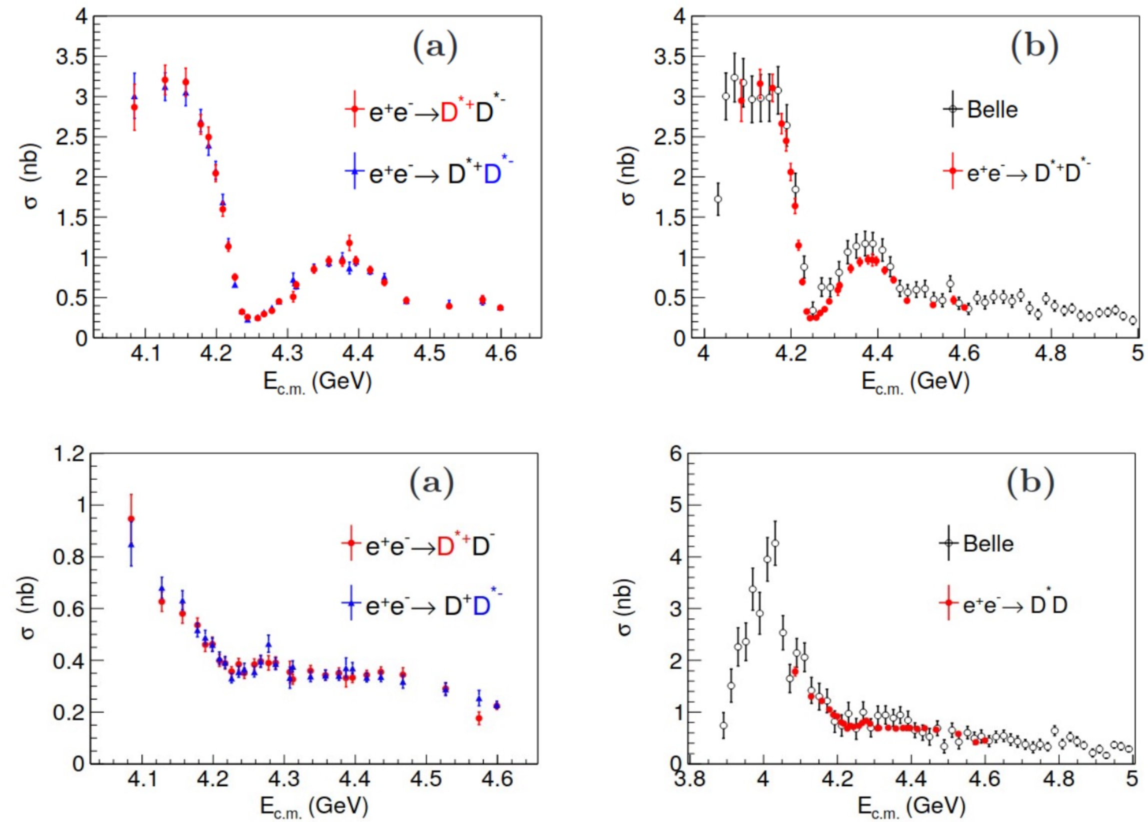
Support X(3872) a molecular hypothesis.

Open charm cross sections

- essential to fully understand the XYZ states
- Important input for coupled-channel analysis

JHEP2022, 55 (2022)





- Good agreement with existing measurements, with best precisions
- Structure at 4.39 GeV in D^*D^*?