Experimental overview on hadron spectroscopy

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Outline

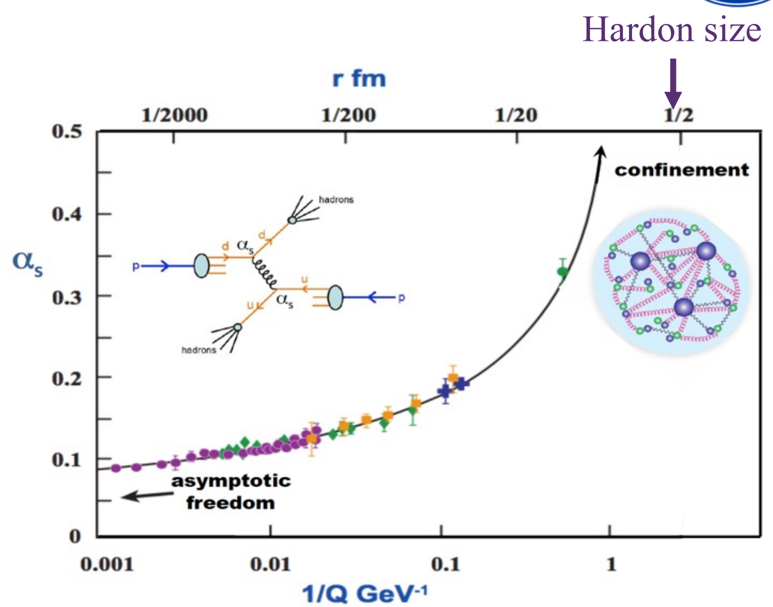
- Introduction
- Hadron spectroscopy: conventional and exotic
  - ✓ Light (exotic) hadron
  - ✓ Heavy meson
  - ✓ Heavy baryon
- Summary

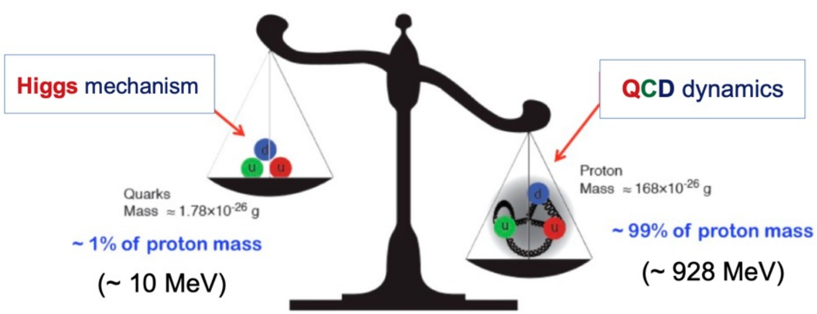
PDG:	2001	2021
$D_{(s)J}$	10	27
$B_{(s)J}$	4	12
$c\bar{c}-\text{like}$	13	40
$b\bar{b}-\text{like}$	12	16
$c-\text{baryons}$	8	27
$b-\text{baryons}$	0	23

I apologize for not covering all the experiments results.

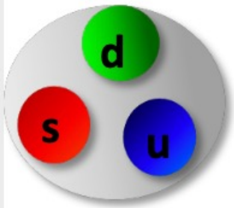
Introduction

- 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





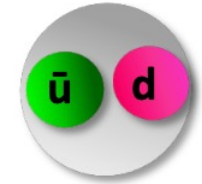
Different types of hadrons to be explored



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

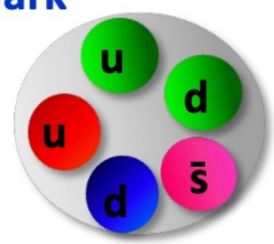


π=ūd

Other possible combinations of quarks and gluons :

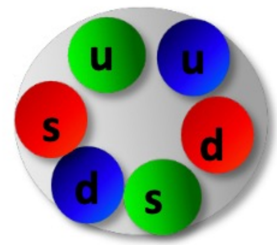
Pentaquark

S= +1 Baryon



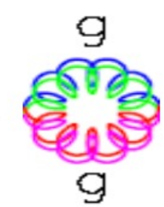
H di-Baryon

Tightly bound 6 quark state



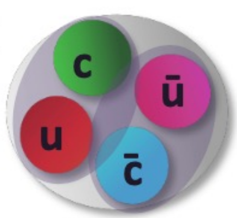
Glueball

Color-singlet multi-gluon bound state



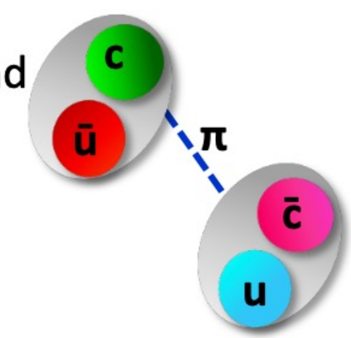
Tetraquark

Tightly bound diquark & anti-diquark

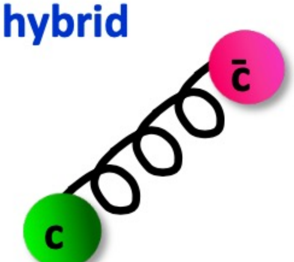


Molecule

loosely bound meson-antimeson "molecule"



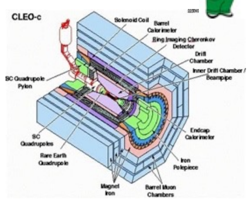
qq̄ -gluon hybrid mesons

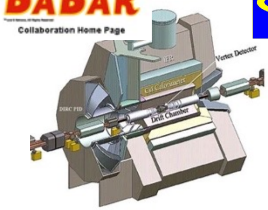


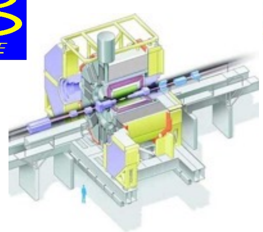
Main contributors worldwide

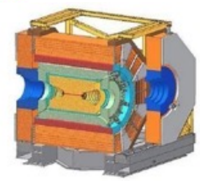
- **e$^+$e$^-$ collider**

CLEO-c

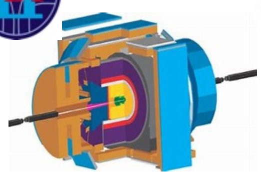


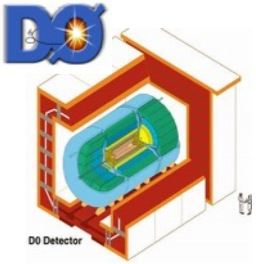


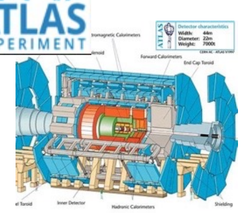


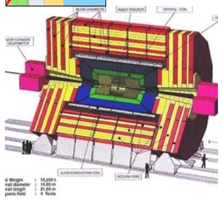


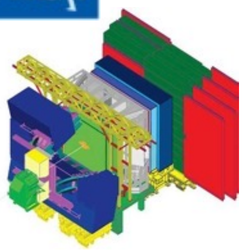
- **Hadron collider**





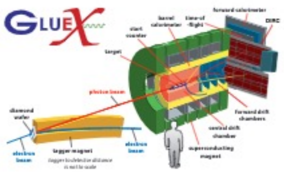




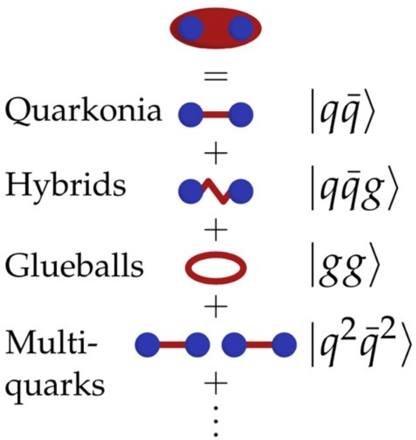


- **Fixed-target experiments**

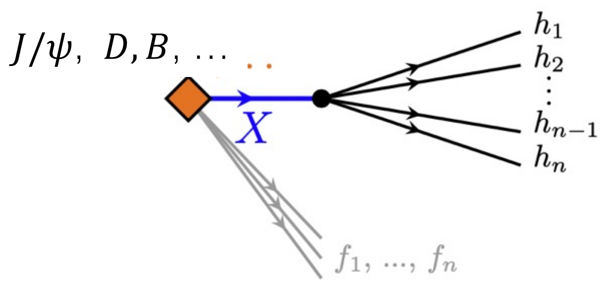
COMPASS



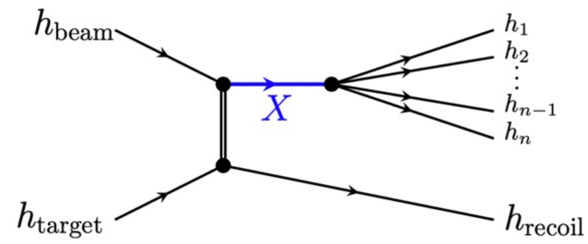
Light hadron spectroscopy

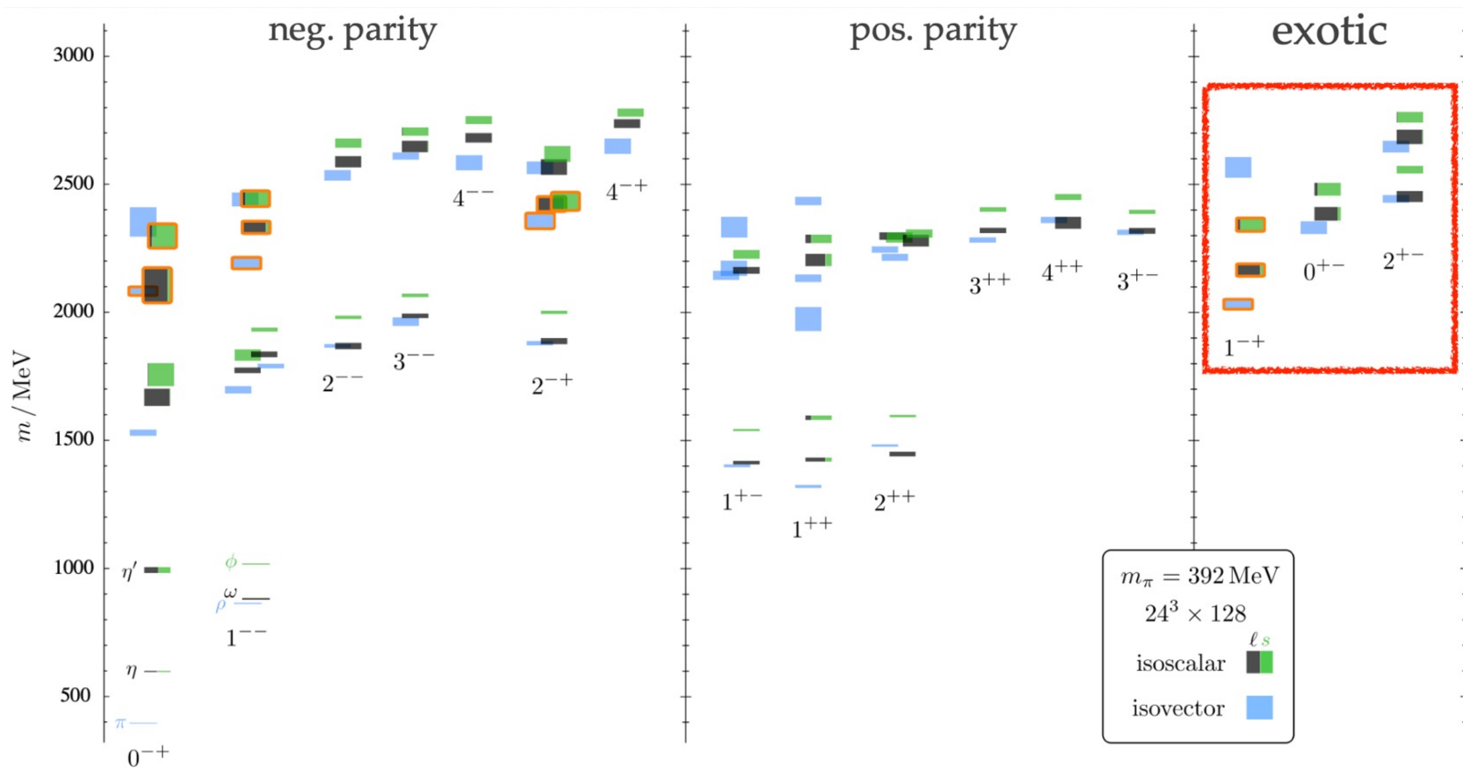


BESIII, LHCb, Belle (II) …



GlueX, Compass, …

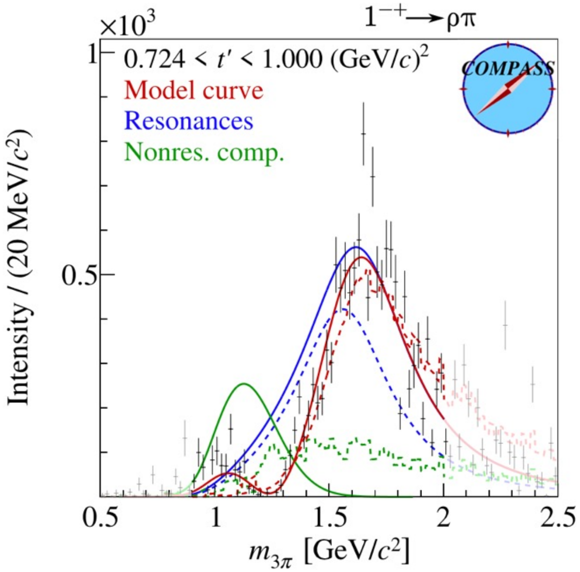




π_1 states of spin-exotic quantum number

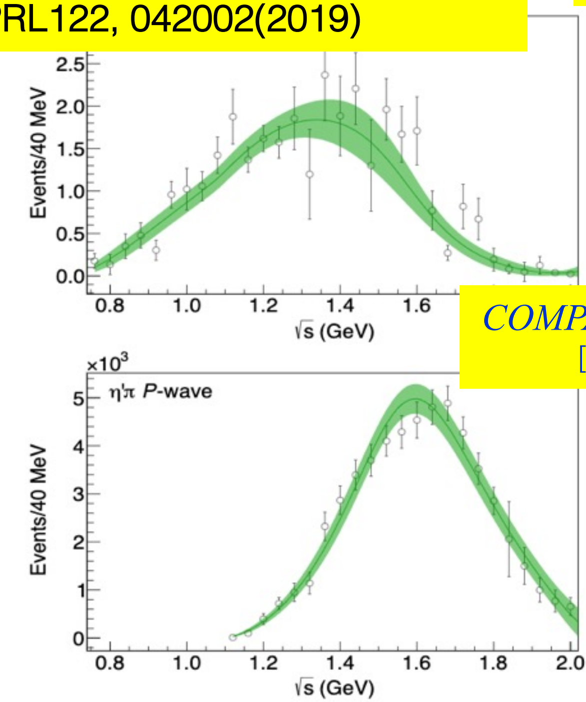
- Experimental evidence for a 1^{-+}: ➔ can not be a quarkonium state
  - $\pi_1(1400)$: GAMS, VES, E852, CBAR, COMPASS
  - $\pi_1(1600)$: VES, E852, COMPASS

PRD98, 092003(2018)

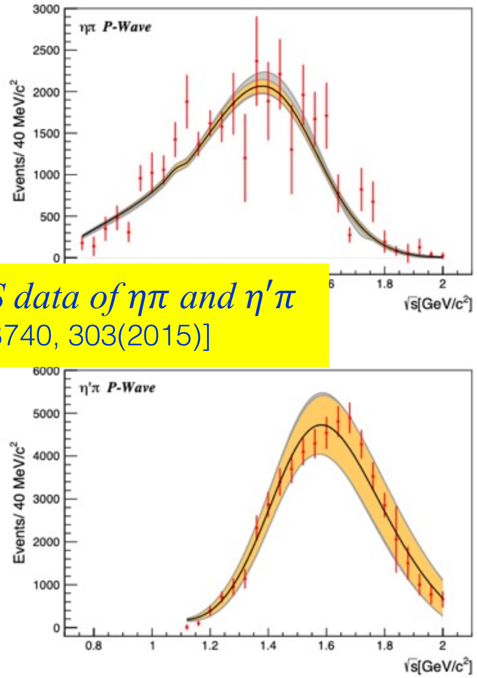


Evidence for $\pi_1(1600) \to \rho\pi$

JPAC fit:
PRL122, 042002(2019)



Another combined fit
Kopf et al, EPJC81, 1056 (2021)



COMPASS data of $\eta\pi$ and $\eta'\pi$
[PLB740, 303(2015)]

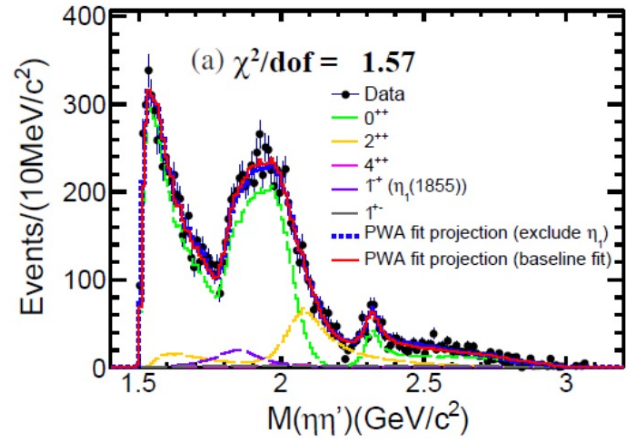
- Only $\pi_1(1600)$ is required, while $\pi_1(1400)$ is in question
- Larger dataset in COMPASS and GlueX are under studies

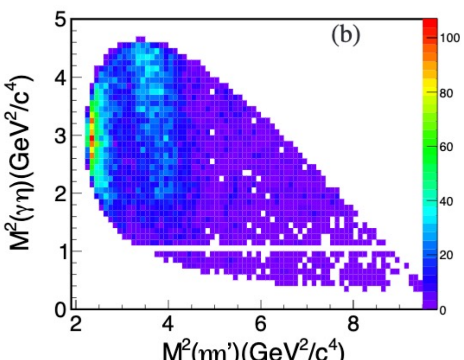
$\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$

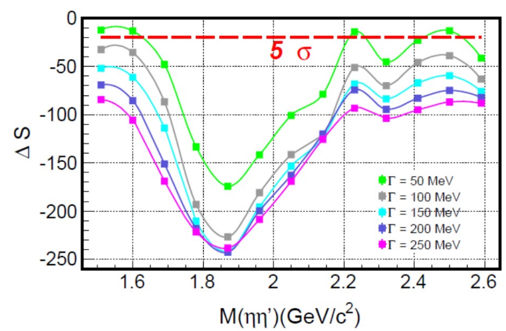
- PWA of $J/\psi \to \gamma\eta\eta', \eta' \to \gamma\pi^+\pi^-, \pi^+\pi^-\eta$ using 10B J/ψ decays data

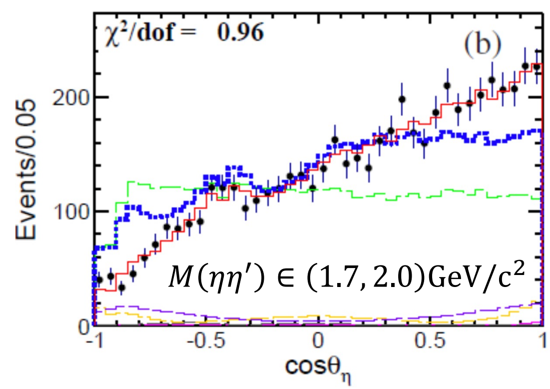
BESIII, arXiv:2202.00621, 2202.00623

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	1992	442	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	2314	144	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	-	-	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	2011	202	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ







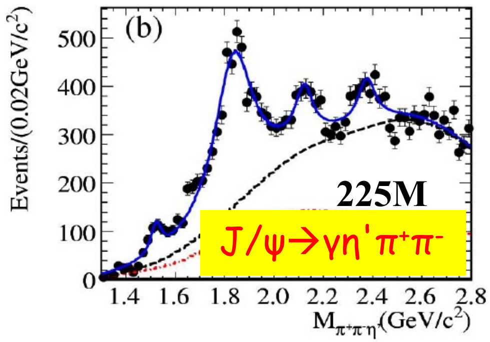


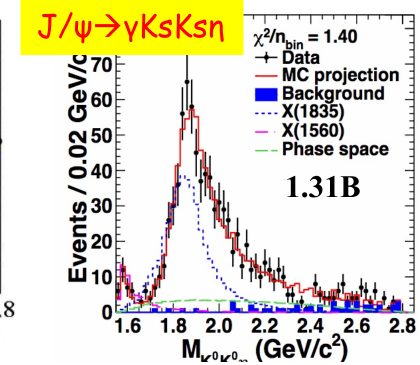
- An isoscalar 1^{-+}, $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ ($>19\sigma$)

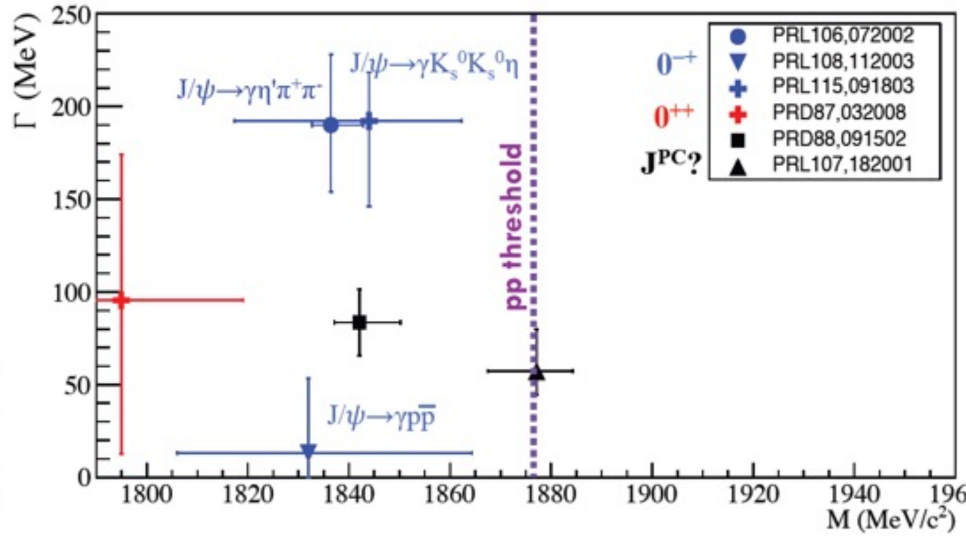
$$M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV}/c^2, \Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV}/c^2$$

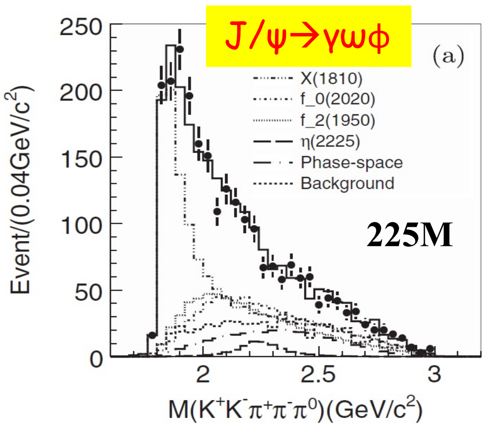
$$B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = \left(2.70 \pm 0.41^{+0.16}_{-0.35}\right) \times 10^{-6}$$

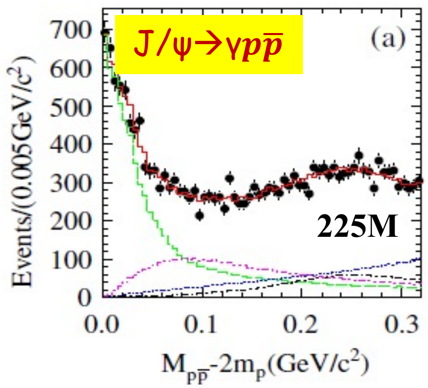
X($p\bar{p}$)/X(18??) from J/ψ radiative decays





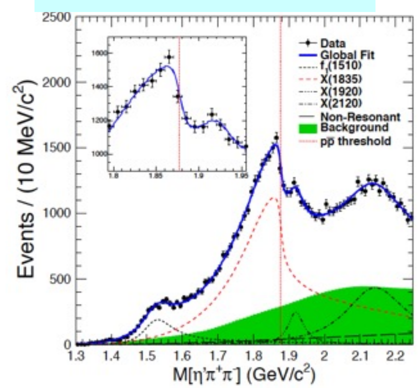






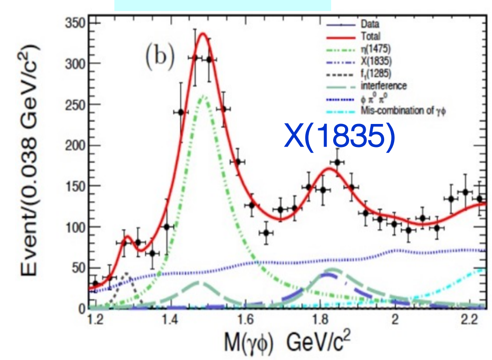
PRL117, 042002 (2016)

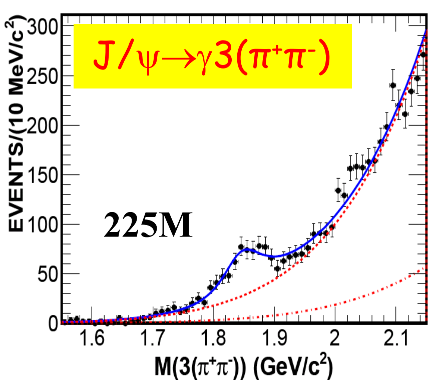
$J/\psi \to \gamma\eta'\pi^+\pi^-$

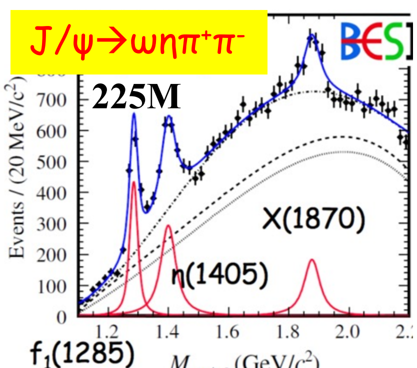


PRD97, 051101(R)(2018)

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



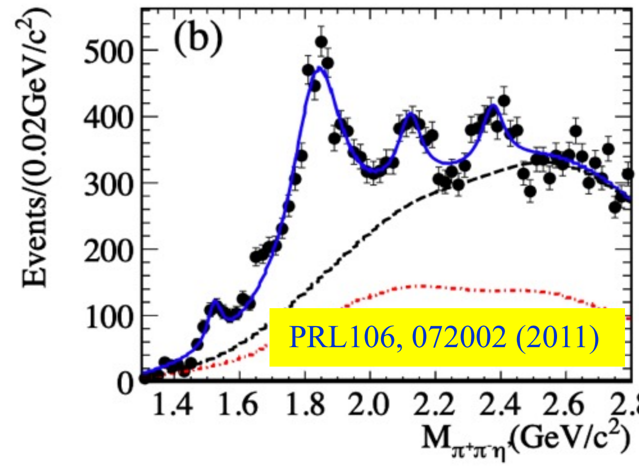




Are they the same state? It is crucial to understand their connections.

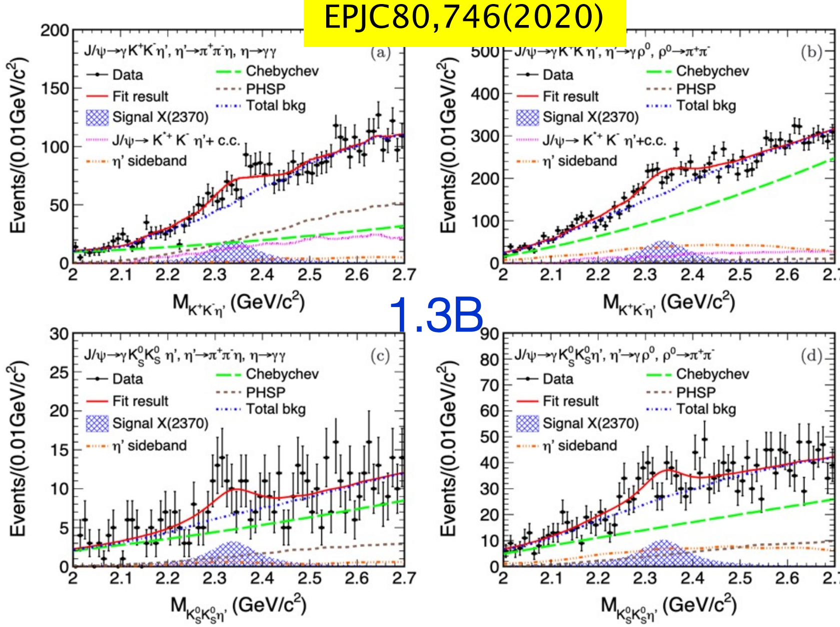
The X(2120) and X(2370)

- Observed in $J/\psi \to \gamma \eta' \pi^+ \pi^-$ at BESIII [PRL106, 072002 (2011)][PRL117, 042002(2016)]
- Candidates of glueball states
- Combined analysis of $J/\psi \to \gamma K^+ K^- \eta'$ and $\gamma K_S K_S \eta'$
- Search for X(2370) in $J/\psi \to \gamma \eta \eta \eta'$

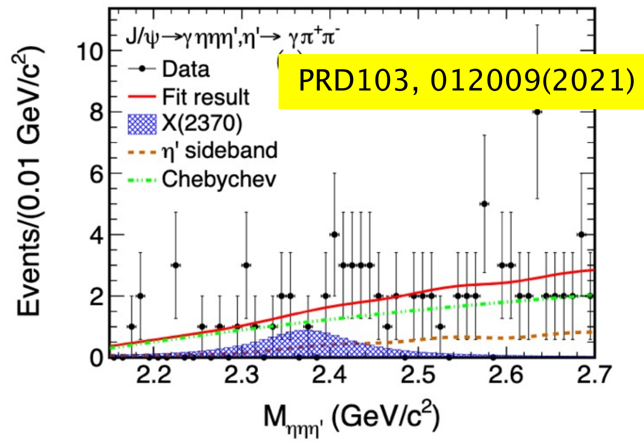


PRL106, 072002 (2011)

EPJC80,746(2020)



1.3B



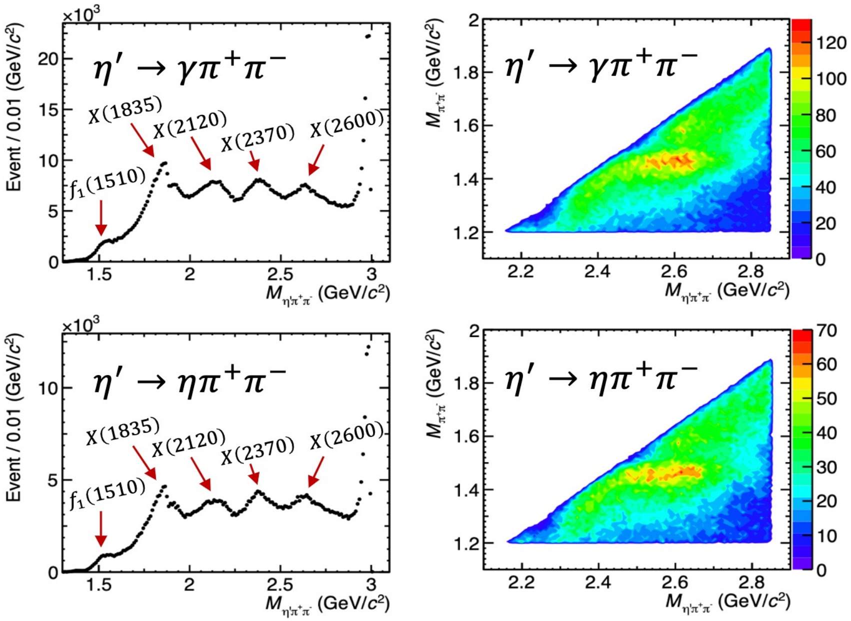
PRD103, 012009(2021)

$$M_{X(2370)} = 2341.6 \pm 6.5(\text{stat.}) \pm 5.7(\text{syst.})\ \text{MeV}/c^2,$$
$$\Gamma_{X(2370)} = 117 \pm 10(\text{stat.}) \pm 8(\text{syst.})\ \text{MeV},$$

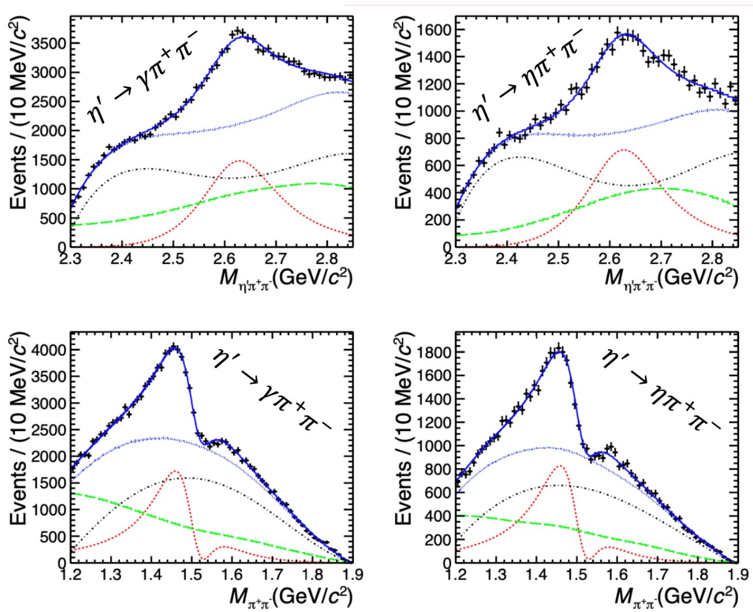
- Observation of $X(2370) \to K\bar{K}\eta'$ with stat. significance of 8.3σ
- No evidence of $X(2120) \to K\bar{K}\eta'$
- No evidence of $X(2370) \to K\bar{K}\eta'$

$\gamma\eta'\pi^+\pi^-$ from 10B J/ψ decays

BESIII, arXiv: 2201.10796



- Observation of new structure X(2600)
- Correlation with M($\pi^+\pi^-$)~1.5GeV
- Assume $J/\psi \to \gamma f_0(1500) X(2600)$, $\gamma f_2'(1525) X(2600)$ and interference in $\pi^+\pi^-$ spectrum



Case	$f_0(1500)$	$X(2600)$
Mass (MeV/c^2)	$1498.0 \pm 4.5^{+4.0}_{-15.2}$	$2617.8 \pm 2.1^{+18.2}_{-1.9}$
Width (MeV)	$166 \pm 10^{+13}_{-26}$	$200 \pm 8^{+20}_{-17}$

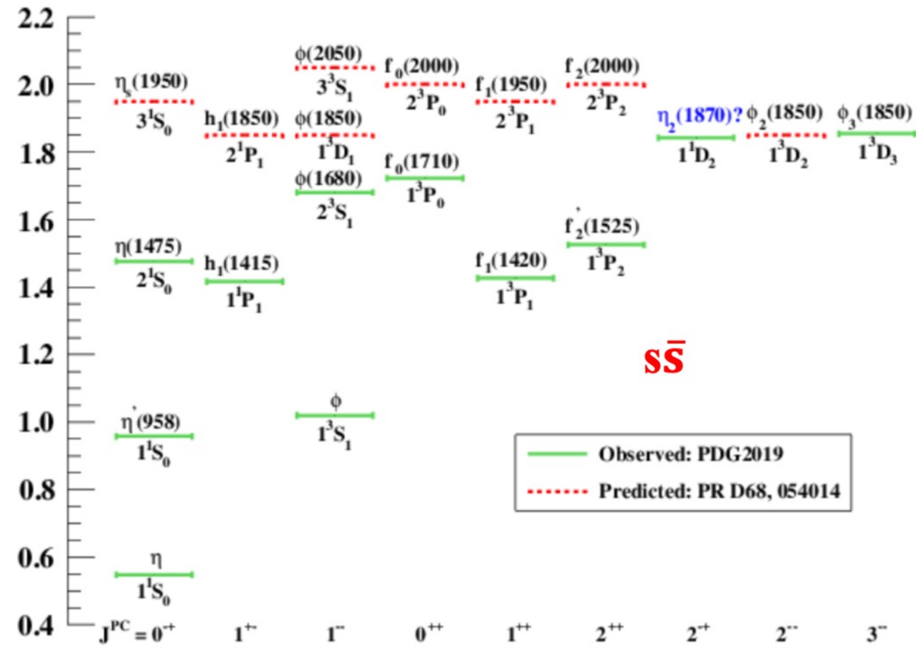
Case	$f_0(1500)$	$f_2'(1525)$
Events	26917 ± 1069	19094 ± 759
Efficiency	19%	15%
BF ($\times 10^{-5}$)	$3.39 \pm 0.18^{+0.91}_{-0.66}$	$2.43 \pm 0.13^{+0.31}_{-1.11}$

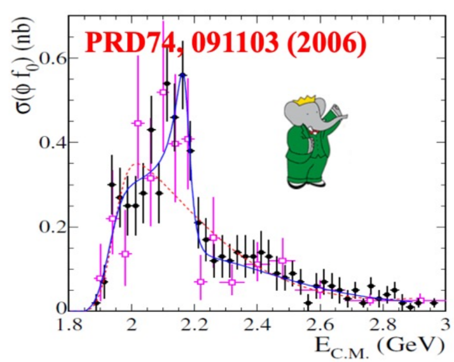
Studies on the $\phi(2170)$/Y(2175)

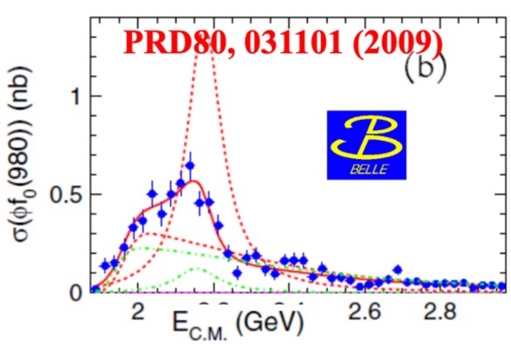
- A strangenium(-like) state: Y-particle with strange quark

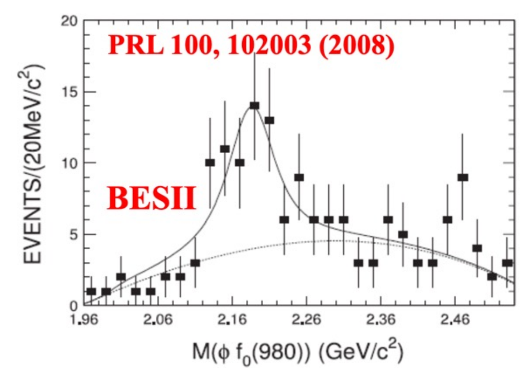
➤ **Theorists explain $\phi(2170)$ as**

- ✓ $s\bar{s}g$ hybrid
- ✓ 2^3D_1 or 3^3S_1 $s\bar{s}$
- ✓ tetraquark
- ✓ Molecular state $\Lambda\bar{\Lambda}$
- ✓ $\phi f_0(980)$ resonance with FSI
- ✓ Three body system ϕKK

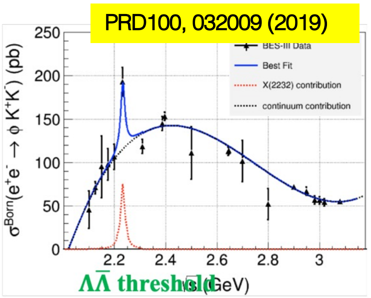


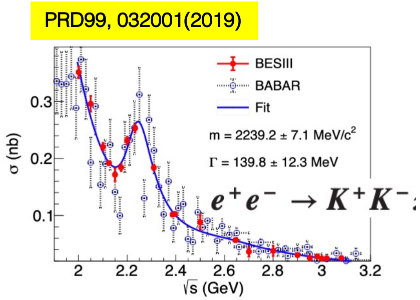


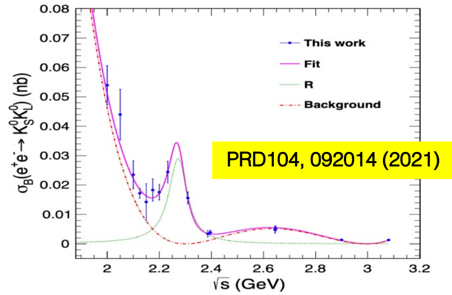


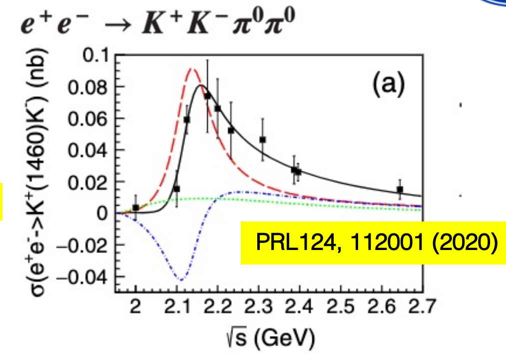


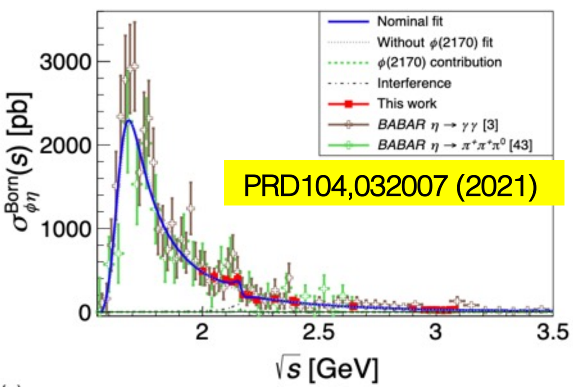
More results on the $\phi(2170)/Y(2175)$

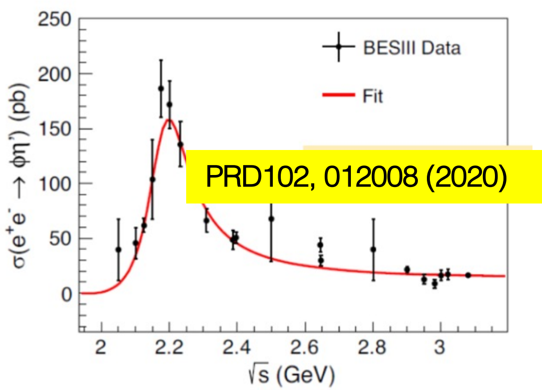


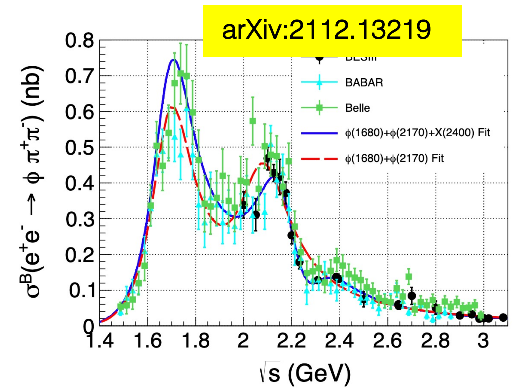


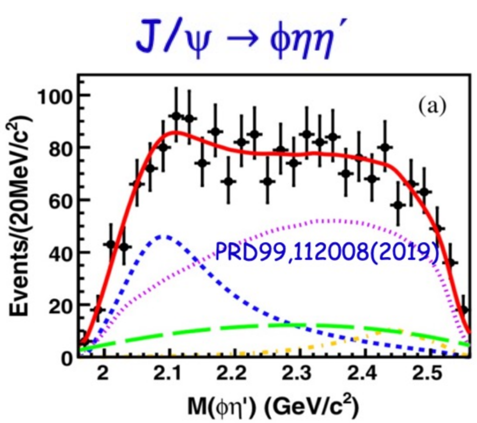


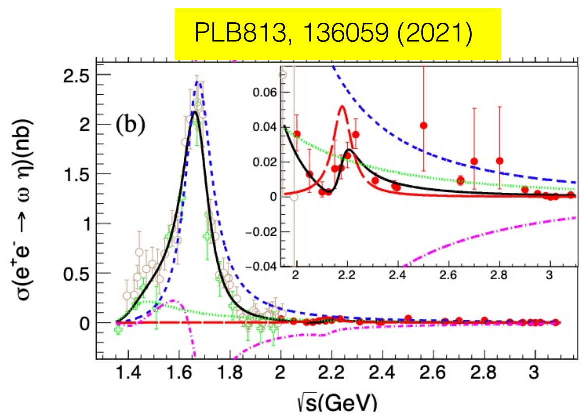


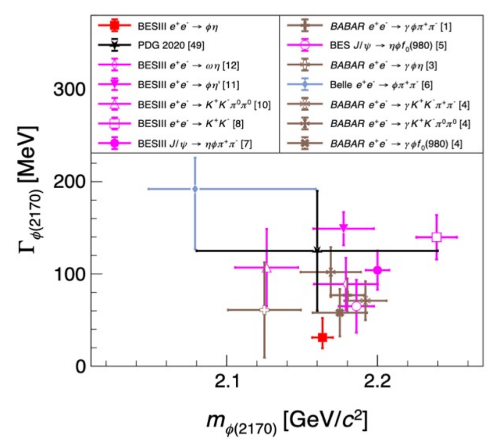










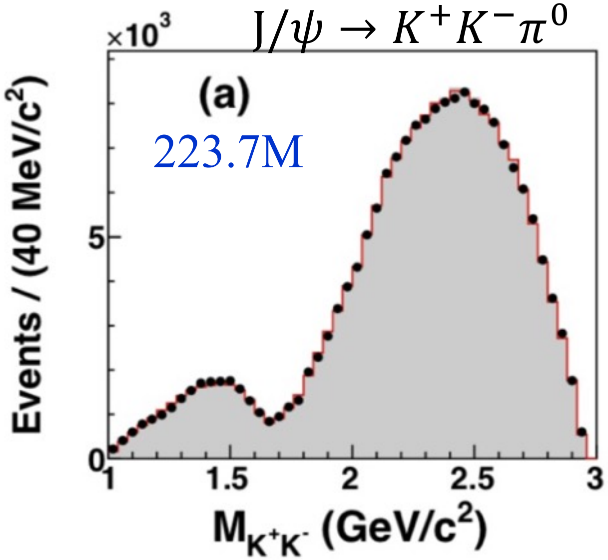


$\phi(2170)/Y(2175)$ is still a mystery

Strangenium and strange-mesons in $J/\psi \to K^+K^-\pi^0$ and $\psi(3686) \to K^+K^-\eta$

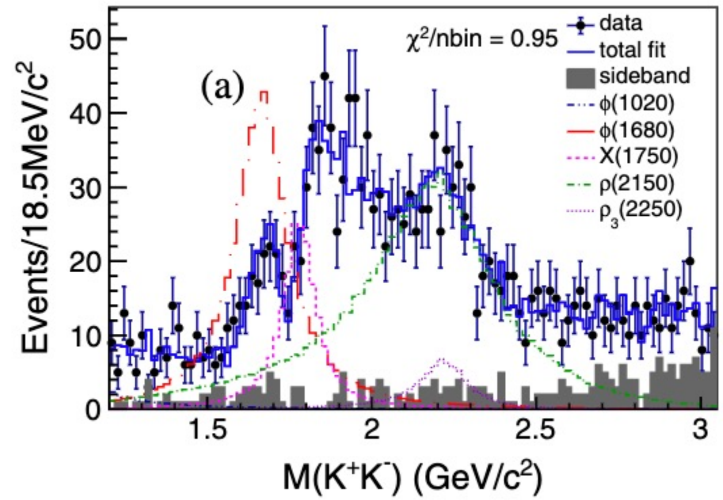
PRD100, 032004 (2019)

$J/\psi \to K^+K^-\pi^0$



PRD101, 032008 (2020)

448M $\psi(3686)$ decays

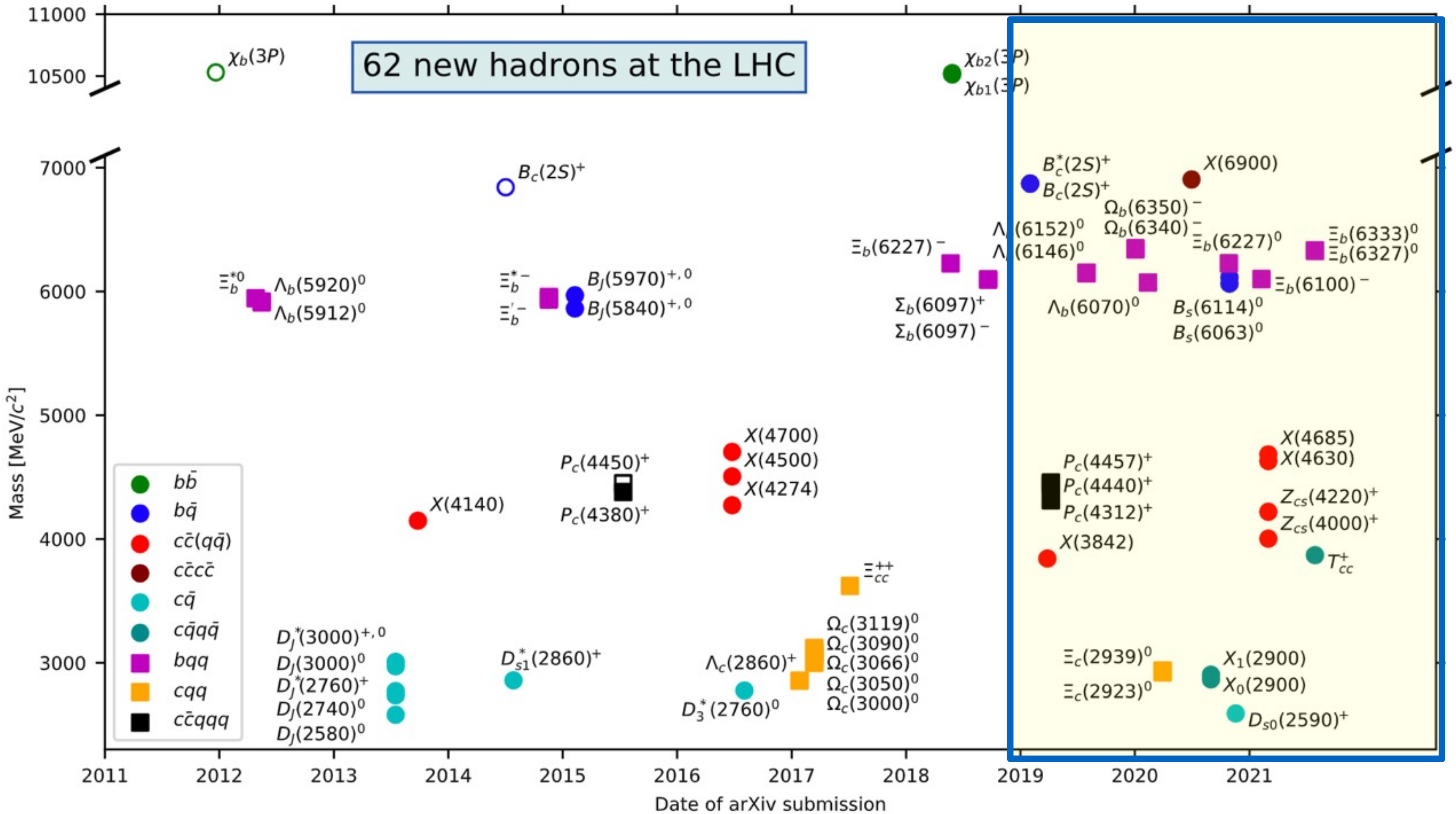


- First observations of $K_2^*(1980)$ and $K_4^*(2045)$ in J/ψ decays
- Two broad K^+K^- 1^{--} structures are observed: possible from $\omega(1650)$ and $\rho(2150)$

- Dip around 1.75 GeV requires another 1^{--} resonance X(1750) to introduce interference with $\phi(1680)$: could be $\rho(1700)$ or X(1750) (photoproduction at FOCUS)
- Broad K^+K^- structure around 2.2 GeV: contributions from $\rho(2150)$ and/or $\rho_3(2250)$ resonances

Heavy hadron Spectroscopy

an example: LHC as a Large Hadron Discovery Factory

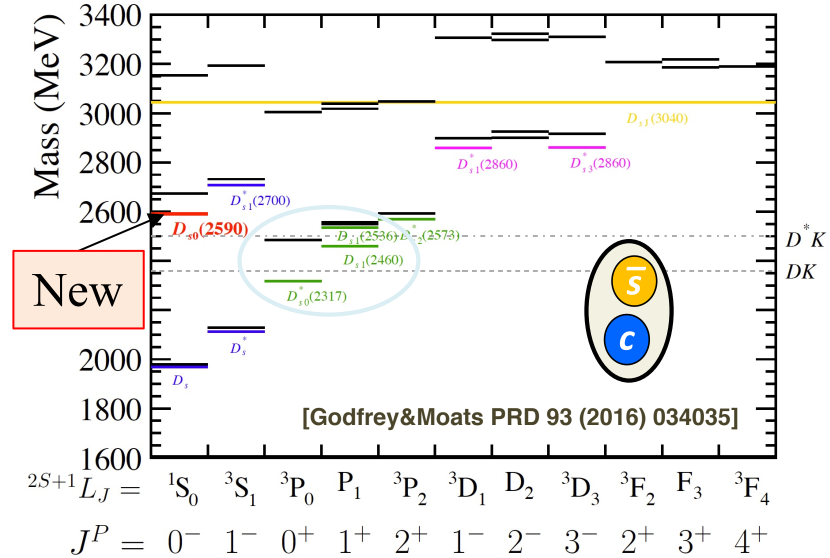


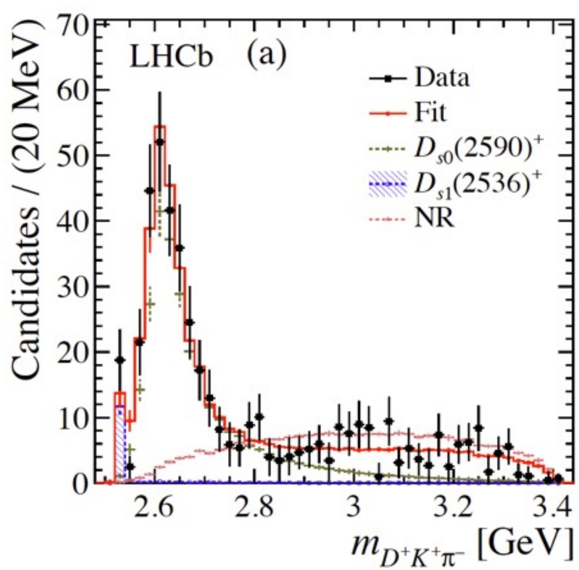
Heavy mesons

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



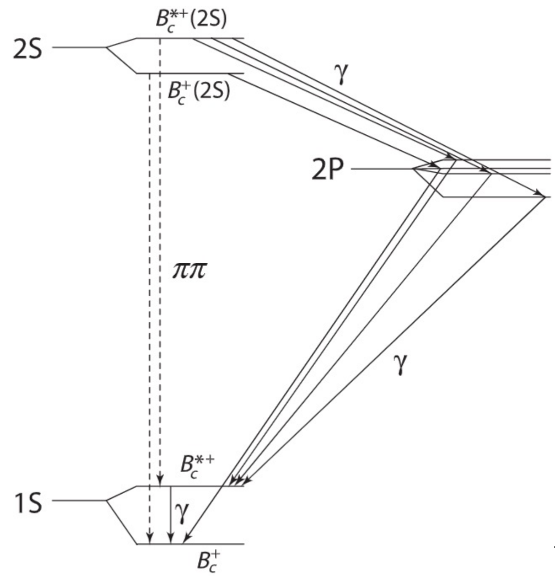


- Amplitude fit is performed

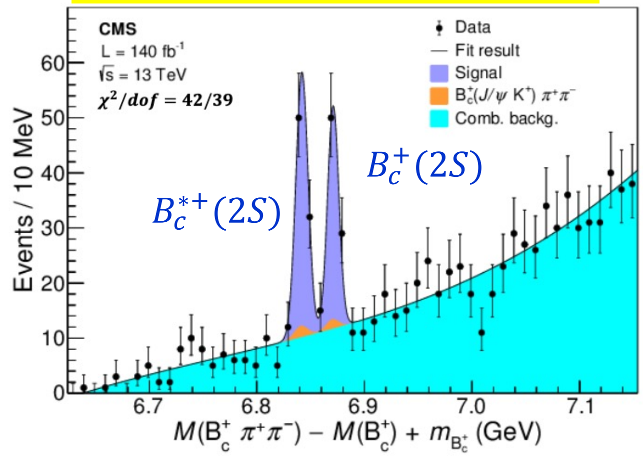
State	Pole Mass [MeV]	Pole Width [MeV]	J^P
$D_{s0}(2590)^+$	$2591 \pm 6 \pm 7$	$89 \pm 16 \pm 12$	0^-

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

Observation of two excited Bc mesons



CMS, PRL122,132001 (2019)



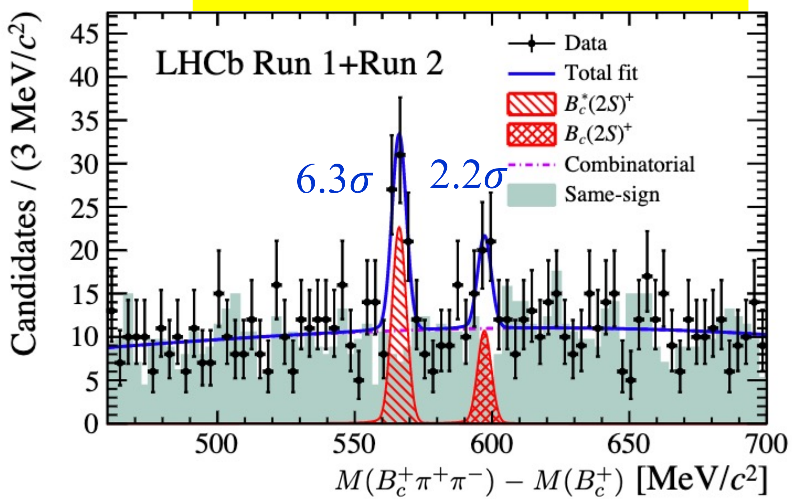
two peaks significance >5σ

$B_c^{*+}(2S)$ 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)

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

LHCb, PRL122, 232001 (2019)



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

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

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

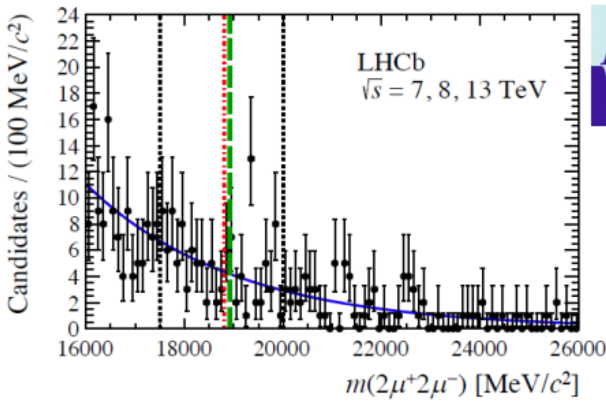
Hidden-charm tetraquark states

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

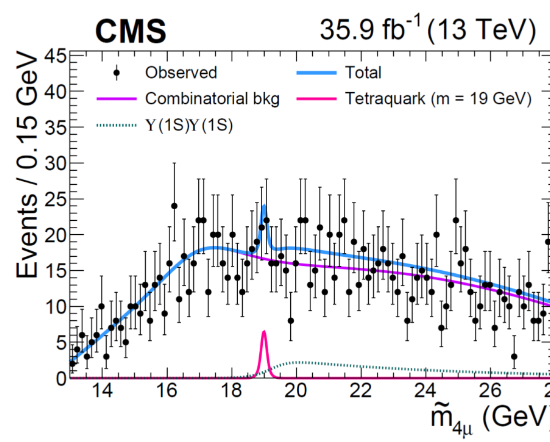
$T_{bb\bar{b}\bar{b}}$ searches at LHCb [JHEP 10, 086 (2018)]

- 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 [PLB 808, 135578(2020)]

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



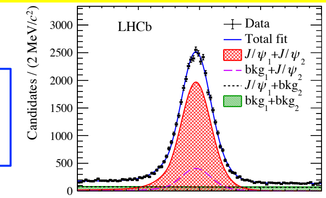
- ❖ $T_{cc\bar{c}\bar{c}}$ states predicted to have $M \in [5.8, 7.4]$ GeV$/c$, away from known quarkonia and quarkonium-like exotic states

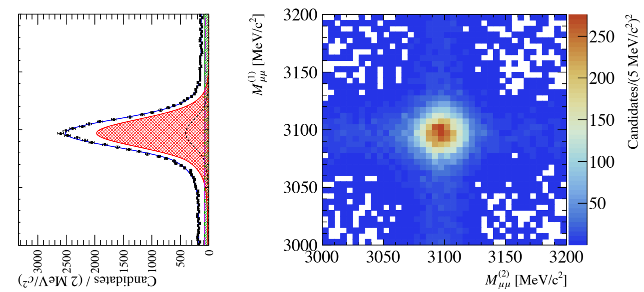
Observation of fully charmed tetraquark state X(6900) [$cc\bar{c}\bar{c}$]

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

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





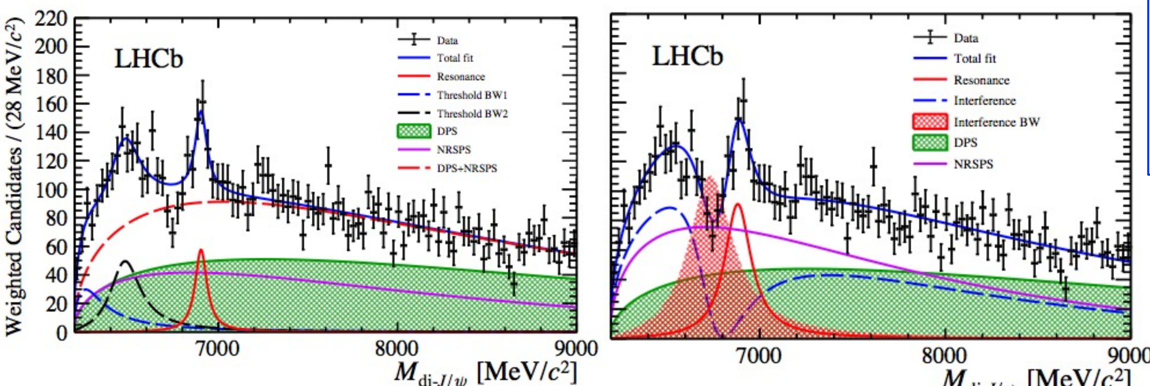
- ✓ Model I: Based on no-interference fit (worse fitting quality)

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

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

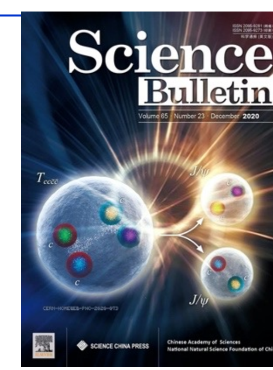
$$M[\text{X(6900)}] = 6886 \pm 11(\text{stat}) \pm 11(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma[\text{X(6900)}] = 168 \pm 33(\text{stat}) \pm 69(\text{syst})\ \text{MeV}/c^2$$

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



The lower broader structure:

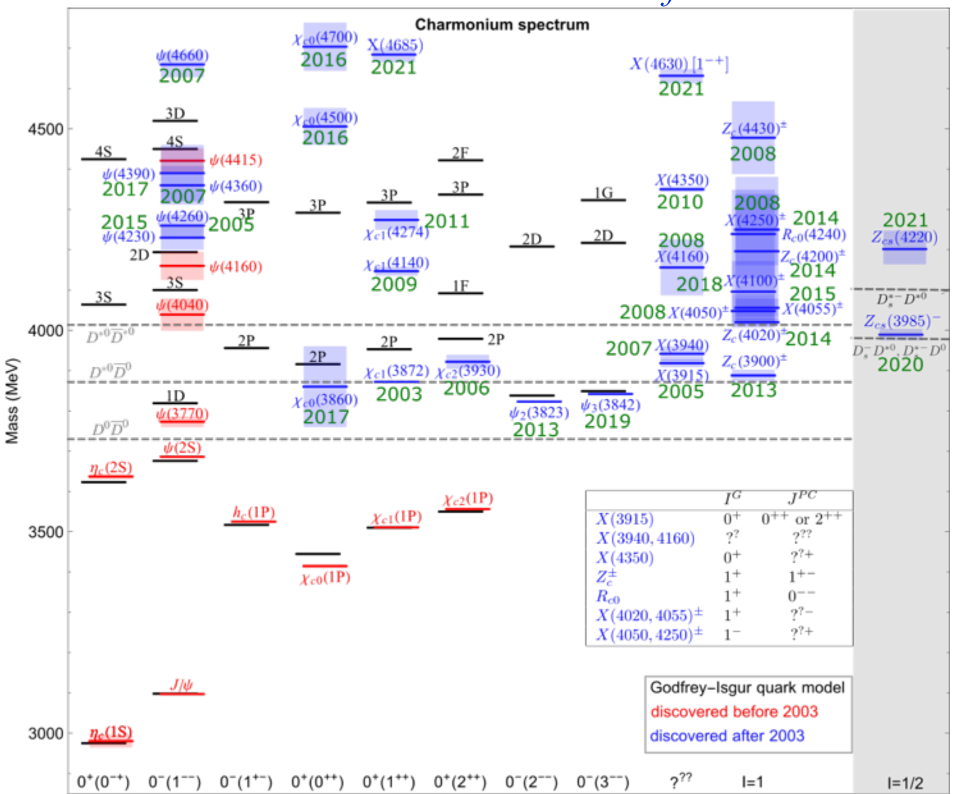
- feed-down from heavier quarkonia, e.g. $T_{cc\bar{c}\bar{c}} \rightarrow \chi_c(\rightarrow J/\psi\gamma) + J/\psi$
- near-threshold kinematic rescattering effects



Heavy quarkonium(-like) sector

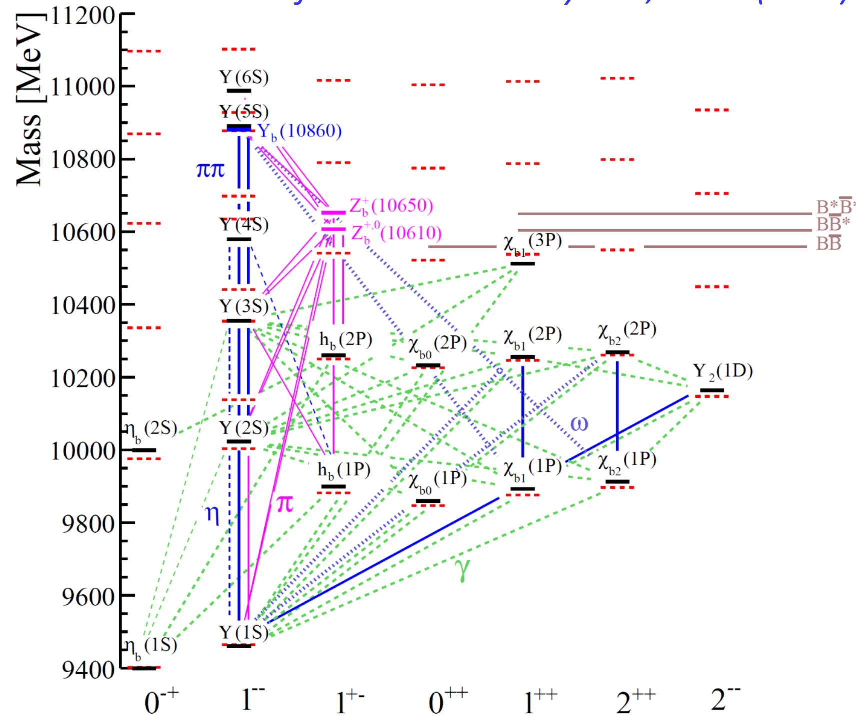
Charmonium-like($c\bar{c}$) spectrum

from F-K. Guo



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

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



What have we learnt about $X(3872)$

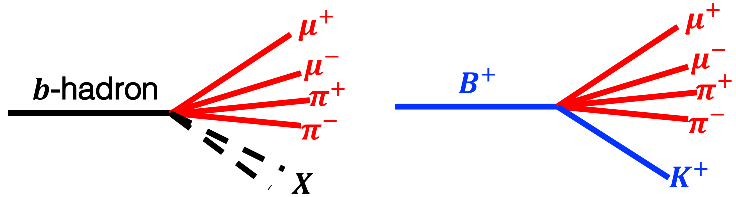
- $X(3872)$ nature is still uncertain, although many studies are performed since 2003
  - **$J^{PC} = 1^{++}$**
  - **Mass = 3871.69 ± 0.17 MeV**
  - **Width < 1.2 MeV** @90% CL

  $\boldsymbol{\delta E = (m_{D^{*0}} + m_{D^0}) - m_{X(3872)} = 0.01 \pm 0.20}$ **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

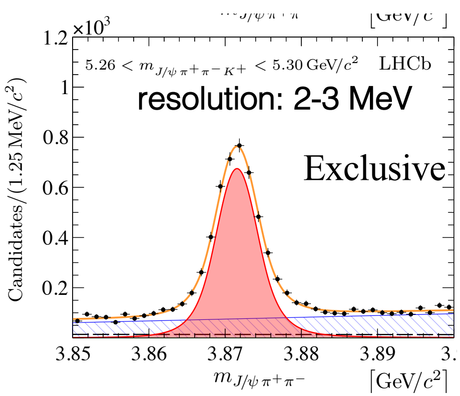
Mode			Fraction (Γ_i/Γ)
Γ_1		e^+e^-	$< 2.8 \times 10^{-6}$
Γ_2		$\pi^+\pi^- J/\psi(1S)$	$(3.8 \pm 1.2)\%$
Γ_3		$\pi^+\pi^-\pi^0 J/\psi(1S)$	not seen
Γ_4		$\omega\eta_c(1S)$	$< 33\%$
Γ_5	★	$\omega J/\psi(1S)$	$(4.3 \pm 2.1)\%$
Γ_6		$\phi\phi$	not seen
Γ_7		$D^0\bar{D}^0\pi^0$	$(49^{+18}_{-20})\%$
Γ_8	★	$\bar{D}^{*0}D^0$	$(37 \pm 9)\%$
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}	★	$\gamma\psi(2S)$	$(4.5 \pm 2.0)\%$

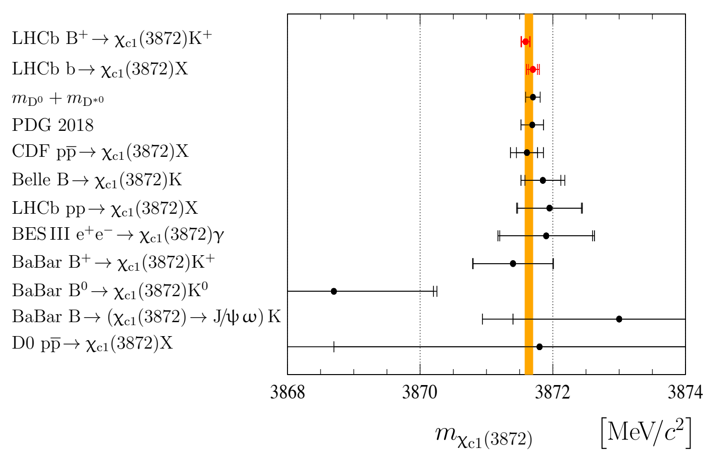
$X(3872)$ lineshape

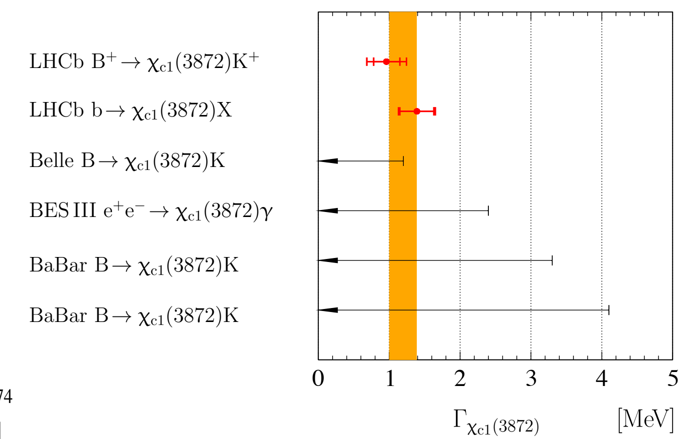
- Two measurements using $X(3872) \to J/\psi\pi^+\pi^-$ related to $\psi(2S)$
  - **Inclusive** $b \to X(3872)$ + anything: ~15.6k signals (more bkg) [PRD 102, 092005 (2020)]
  - **Exclusive** $B^+ \to X(3872)K^+$: ~4.2 signalsk (less bkg) [JHEP 08, 123 (2020)]



✓ Baseline: Breit-Wigner(BW) Fit;
✓ Flatté function also investigated;





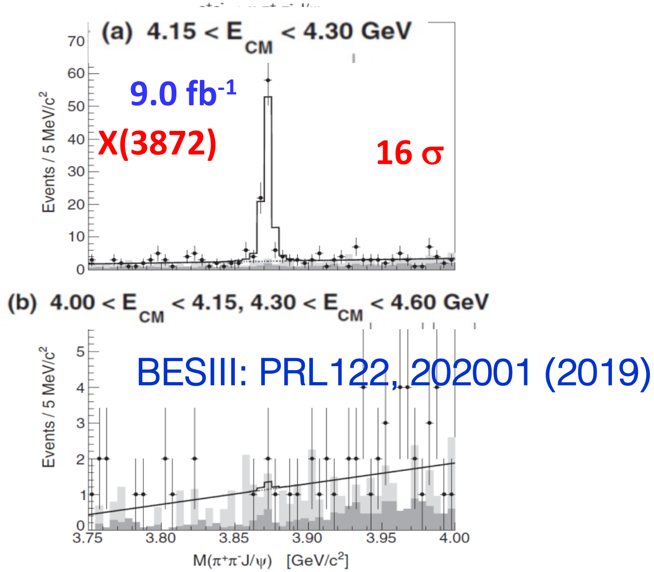


- The opening up of $\boldsymbol{D^0\bar{D}^{*0}}$ threshold distorts the BW lineshape
- First determination of non-zero width
- A better parametrization of the lineshape is needed.

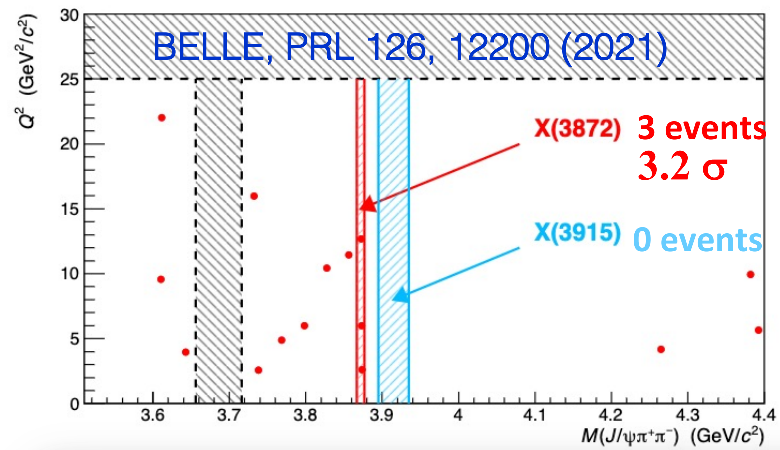
➢ LHCb average
- ✓ $M_{\mathrm{BW}} = 3871.64 \pm 0.06 \pm 0.01\ \mathrm{MeV}/c^2$; $\Gamma_{\mathrm{BW}} = 1.19 \pm 0.19\ \mathrm{MeV}/c^2$
- ✓ $\delta E = M(D^0) + M(\bar{D}^{*0}) - M(\chi_{c1}(3872)) = 0.07 \pm 0.12\ \mathrm{MeV}/c^2$

$X(3872)$ Production (1)

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



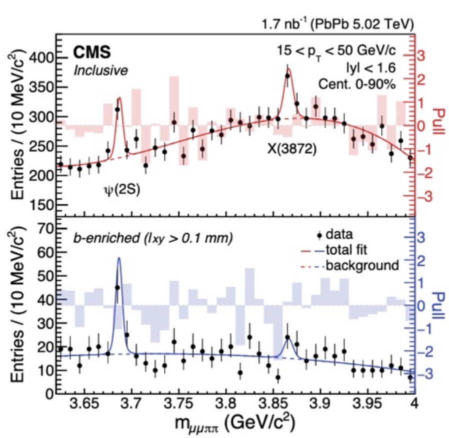
- From two-photon process: evidence of $\gamma\gamma^* \to X(3872) \to \pi^+\pi^- J/\psi$

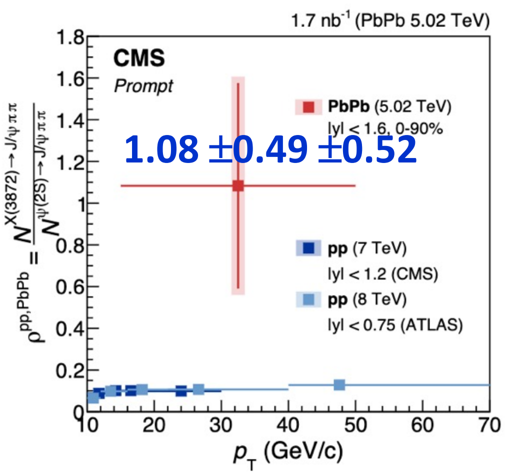


$$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X \to J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8}\ (\text{stat.}) \pm 0.7\ (\text{syst.})\ \text{eV}$$

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

CMS, PRL128, 032001 (2022)



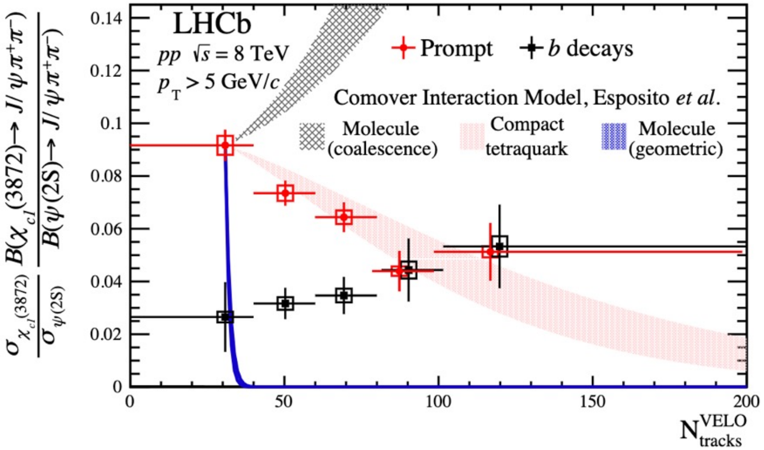


An indication of large R in P_bP_b collisions with respect to the pp collisions.

$X(3872)$ Production (2)

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

LHCb, PRL126, 092001 (2021)

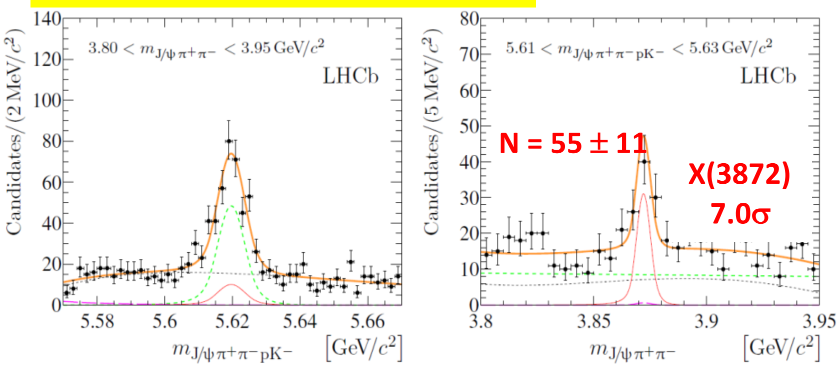


✓ prompt production of X(3872) suppressed relative to prompt ψ(2S) production as multiplicity increases.

✓ an important ingredient to obtain a full understanding of the nature of X(3872)

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

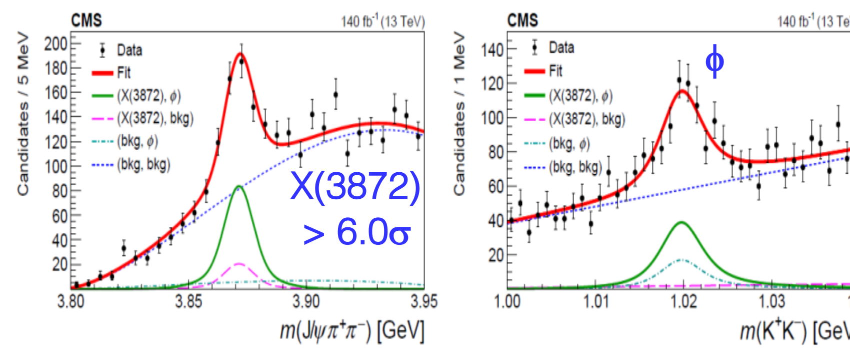
LHCb, JHEP 09, 028 (2019)



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

- From B_s decays: $B_s \to X(3872)\,\phi$ at CMS and LHCb

CMS, PRL125, 152001 (2020)



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

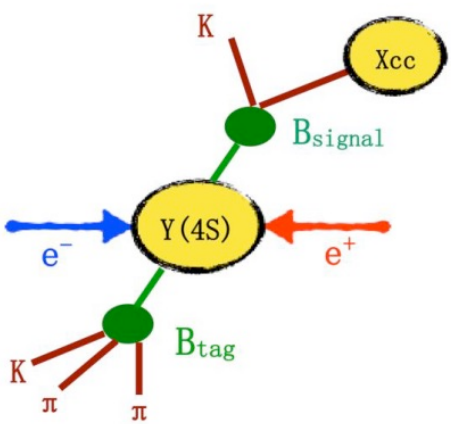
about two times smaller than the ratio for $\psi(2S)$

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

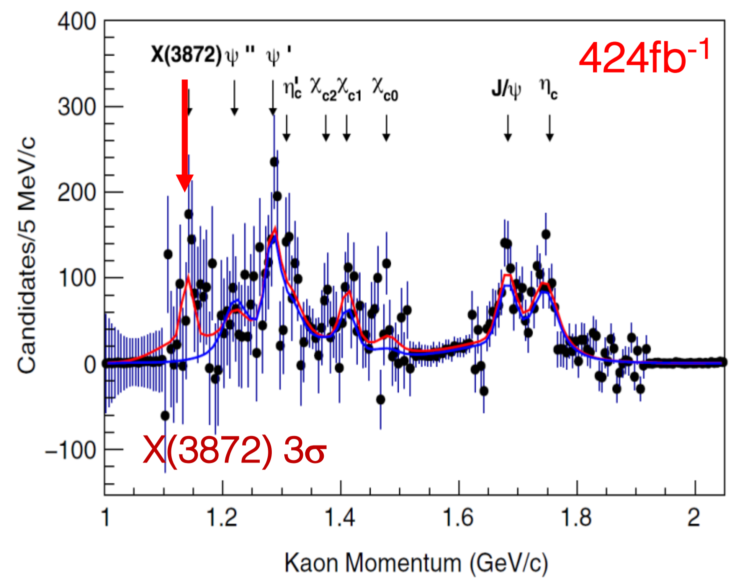
$X(3872)$ absolute decay rate

- 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)

$BF(B^+ \to X(3872)\,K^+) = (2.1 \pm 0.6 \pm 0.3) \times 10^{-4}$

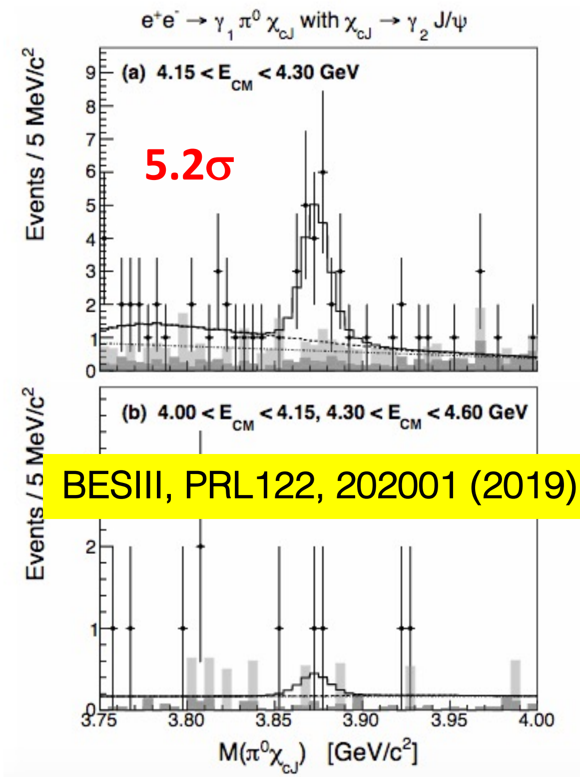
By using the measured product BF: $(8.6 \pm 0.8) \times 10^{-6}$ (from PDG)

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

Support X(3872) a molecular hypothesis.

More X(3872) decay information

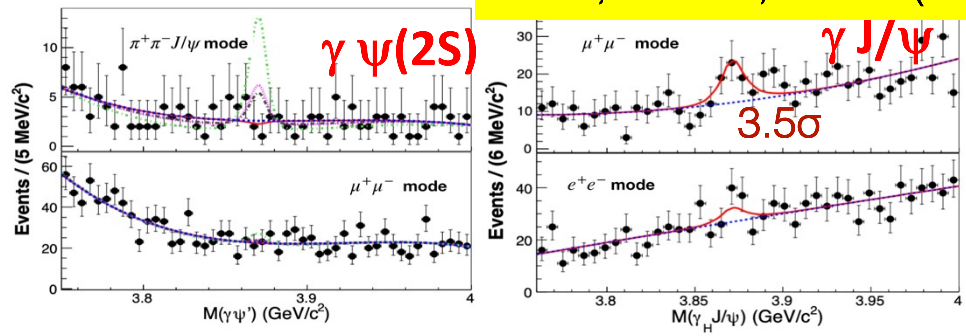
- Observation of X(3872) $\rightarrow \pi^0 \chi_{c1}$



BESIII, PRL122, 202001 (2019)

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

BESIII, PRL 124, 242001 (2020)



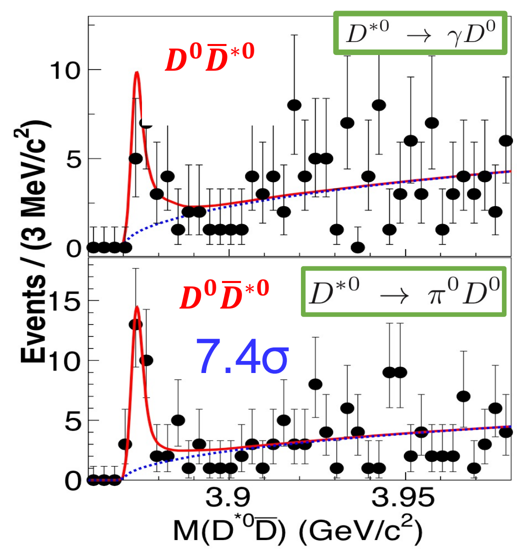
$$R = \frac{BF(X(3872) \rightarrow \gamma\psi(2S))}{BF(X(3872) \rightarrow \gamma J/\psi)} < 0.59 \text{ at 90\% C.L.}$$, agrees with Belle(<2.1), while challenges Babar(3.4±1.1) and LHCb results (2.46± 0.70)

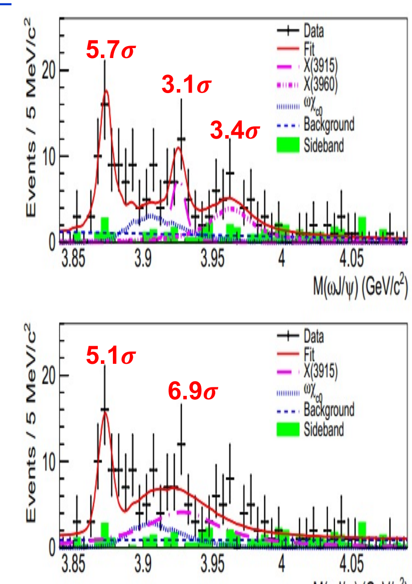
- Observation of X(3872) → ωJ/ψ

BESIII, PRL 122, 232002 (2019)

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

BESIII, PRL 124, 242001 (2020)



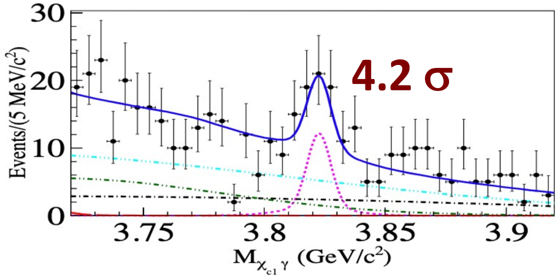


X(3823): good candidate for $\psi(1^3D_2)$

$B \to \chi_{c1}\gamma K$

$e^+e^- \to \pi\pi\psi_2(3823)$:

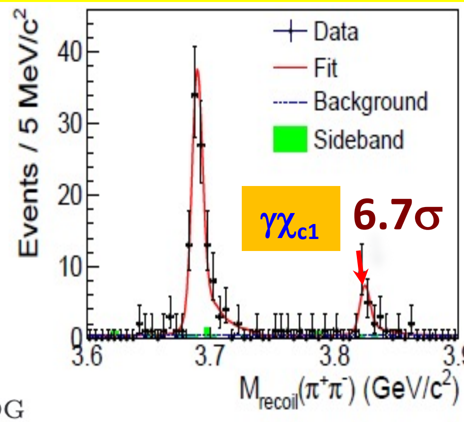
Belle: PRL 111, 032001 (2013)



First evidence!

$$M_{X(3823)} = M^{\text{meas}}_{X(3823)} - M^{\text{meas}}_{\psi'} + M^{\text{PDG}}_{\psi'}$$
$$= 3823.1 \pm 1.8 \pm 0.7 \text{ MeV.}$$

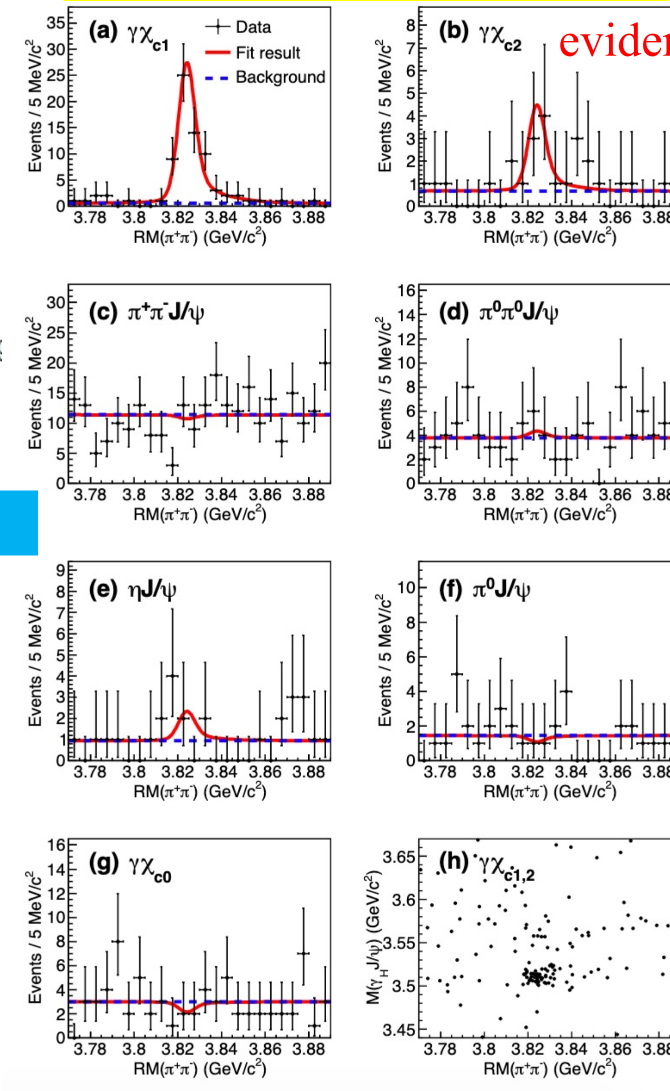
BESIII, PRL91, 112015 (2015)



Observation!

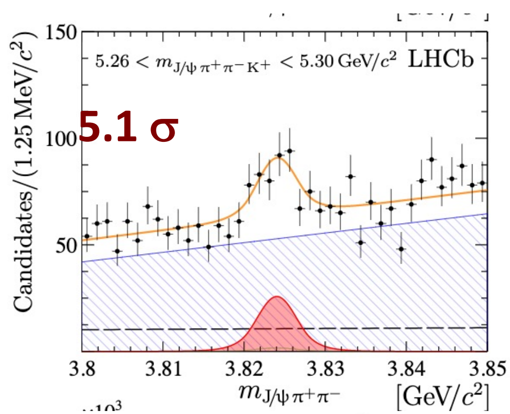
Fit: M=3821.7±1.3±0.7 MeV

BESIII, PRD103, L091102 (2021)



LHCb: JHEP 08, 123 (2020)

$$B^+ \to (\psi_2(3823) \to J/\psi\,\pi^+\pi^-)\,K^+$$

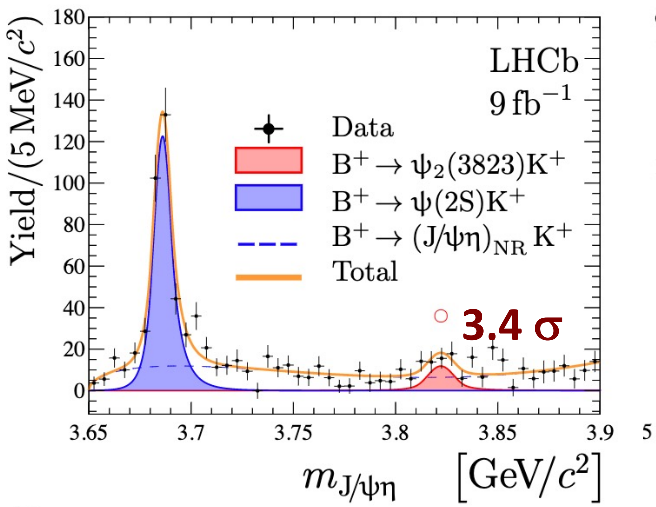


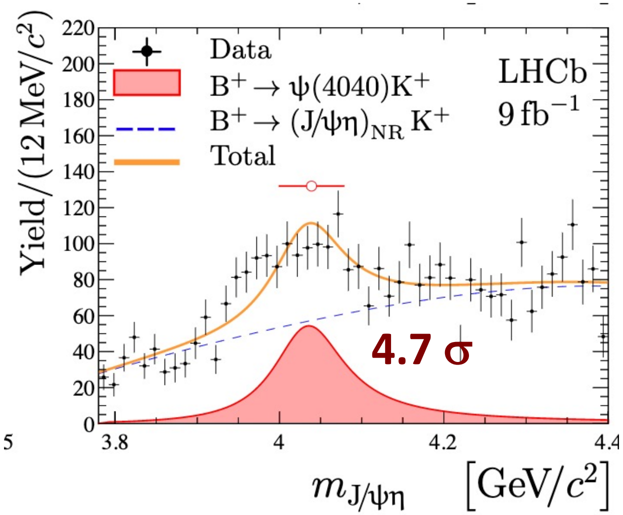
$$m_{\psi_2(3823)} = 3824.08 \pm 0.53 \pm 0.14 \pm 0.01 \text{ MeV}/c^2,$$
$$\Gamma_{\psi_2(3823)} < 5.2\,(6.6) \text{ MeV}.$$

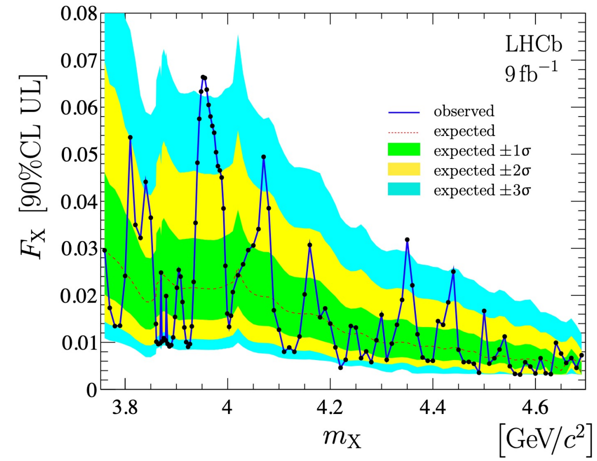
X(3823) in $B^+ \to K^+ \eta J/\psi$

LHCb: arXiv:2202.04045

Search for charmonia and charmonia-like exotics decaying into $\eta J/\psi$







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

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

$$F_{\psi_2(3823)} = \left(5.95\,^{+3.38}_{-2.55}\right) \times 10^{-2},$$

$$F_{\psi(4040)} = (40.6 \pm 11.2) \times 10^{-2}$$

$$\frac{\mathcal{B}(\psi_2(3823) \to J/\psi\eta)}{\mathcal{B}(\psi_2(3823) \to J/\psi\pi^+\pi^-)} = 4.4\,^{+2.5}_{-1.9} \pm 0.9$$

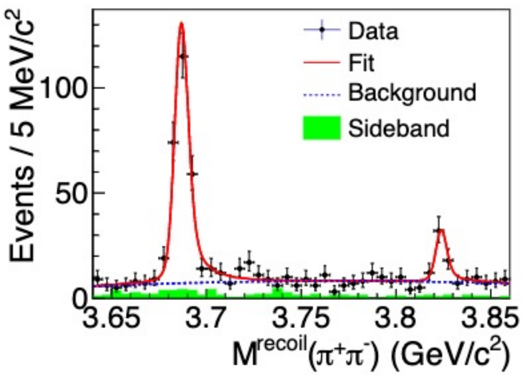
$$B_{\psi_2(3823)} = \left(1.25\,^{+0.71}_{-0.53} \pm 0.04\right) \times 10^{-6},$$

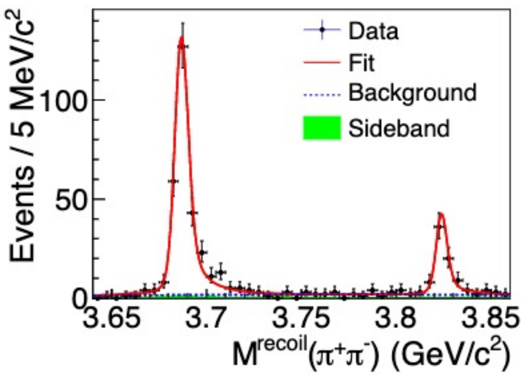
$$B_{\psi(4040)} = (8.53 \pm 2.35 \pm 0.30) \times 10^{-6}$$

X(3823): precision studies

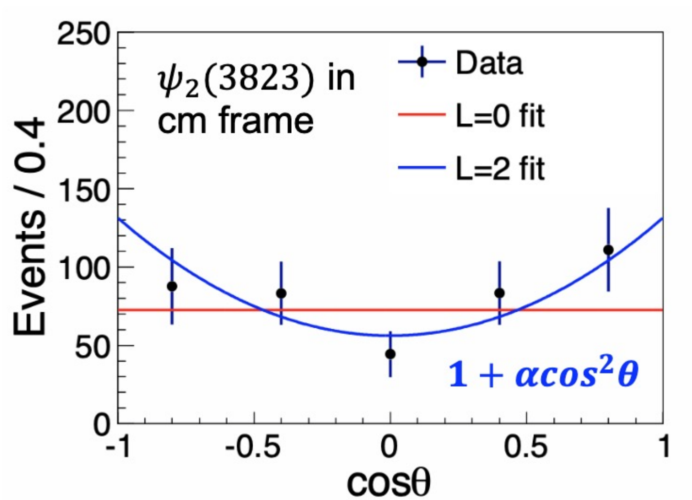
Precision studies of $e^+e^- \to \pi^+\pi^- X(3823)$ using missing photon technique

BESIII: arXiv:2203.05815

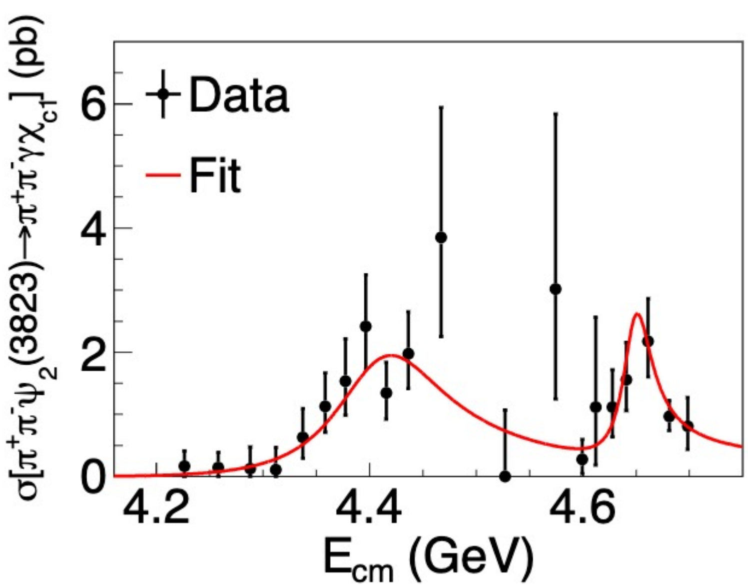




mass and width of $\psi_2(3823)$:
$m = 3823.12 \pm 0.43 \pm 0.13\ \mathrm{MeV}/c^2$
$\Gamma < 2.9\ \mathrm{MeV}$ (at 90% CL)



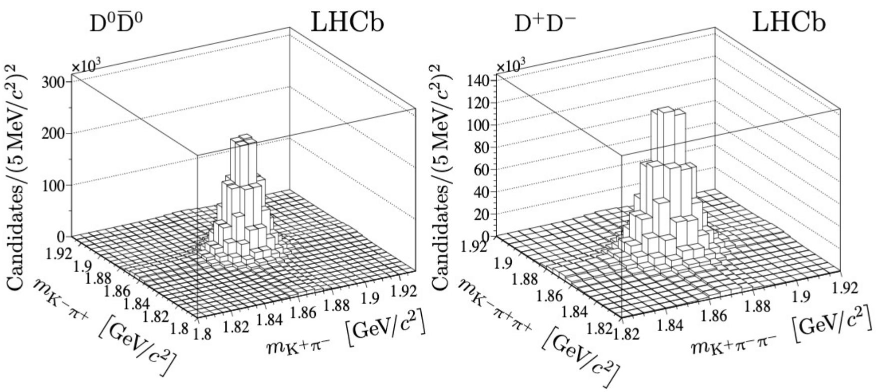
$L = 2$ slightly favored over $L = 0$

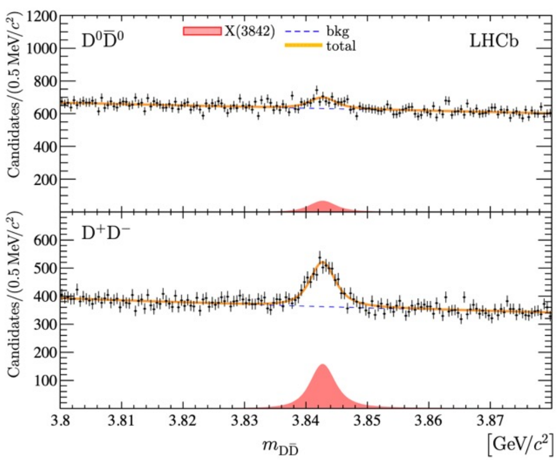


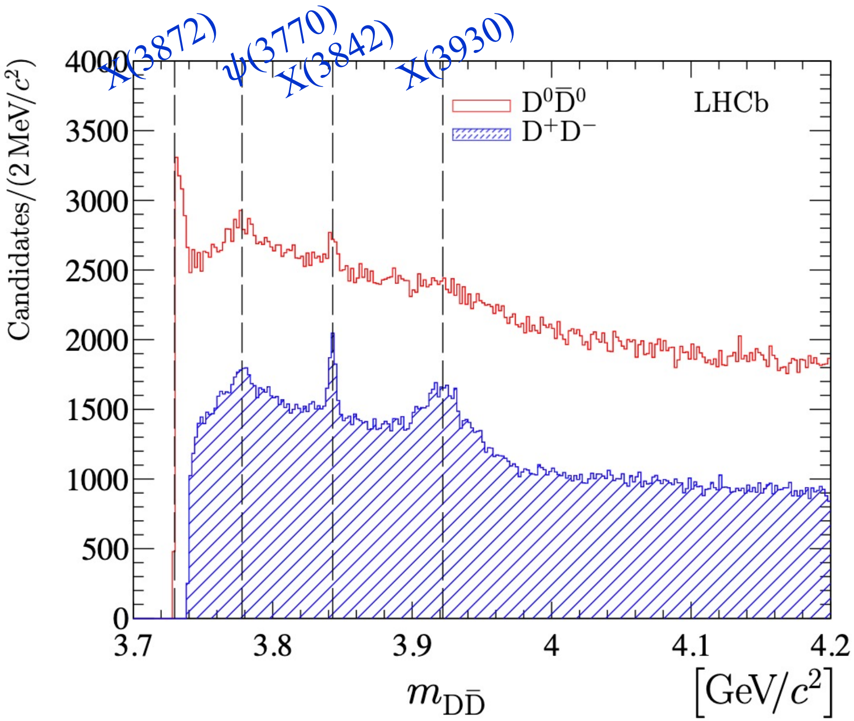
Observation of the X(3842)

JHEP07, 035(2019)

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



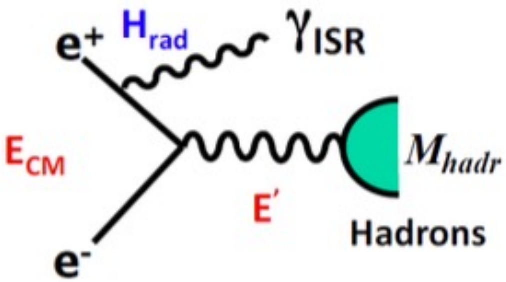




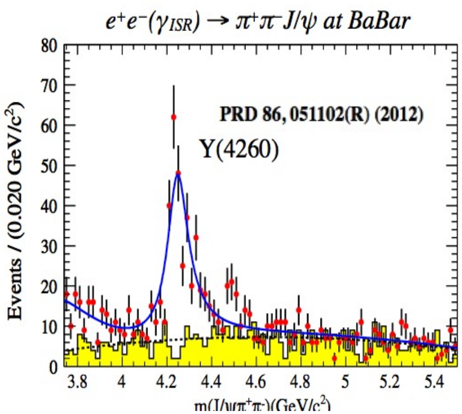
$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV}/c^2\,,$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}\,,$$

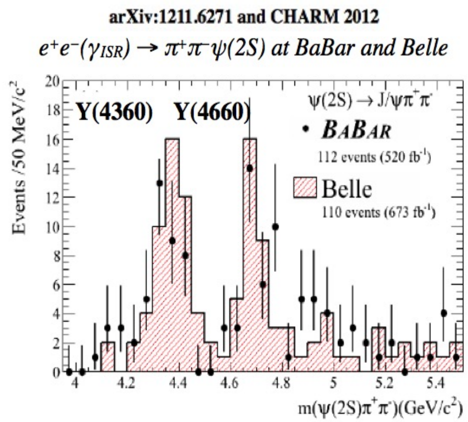
- Very narrow state due to suppression of the F-wave centrifugal barrier factor
- strong candidate of the missing $\psi_3(1^3D_3)$ charmonium state with $J^P = 3^{--}$

The Y states



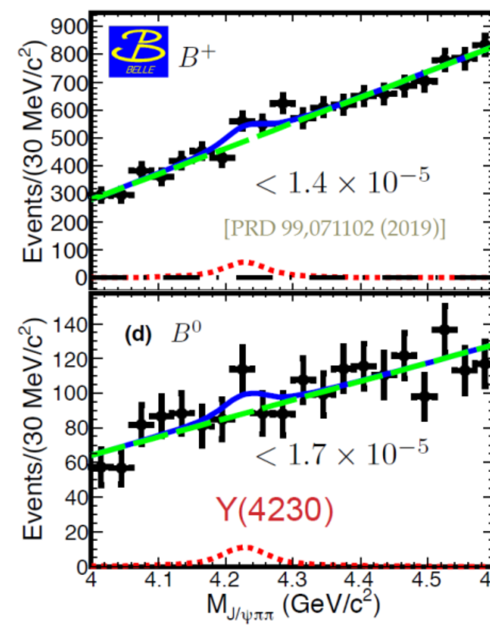
Y states: charmonium-like states with $J^{PC}=1^{--}$;
Observed in direct e+e- annihilation or initial state radiation (ISR).



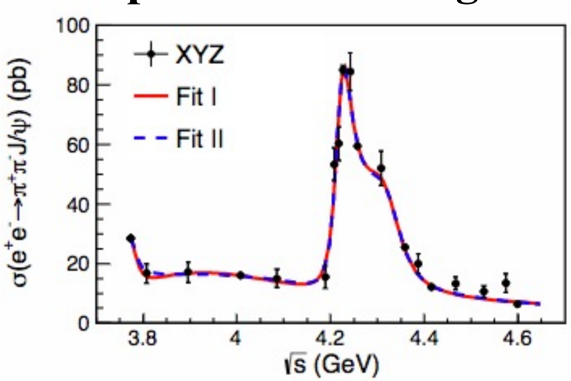


- **While not seen yet in B decays**

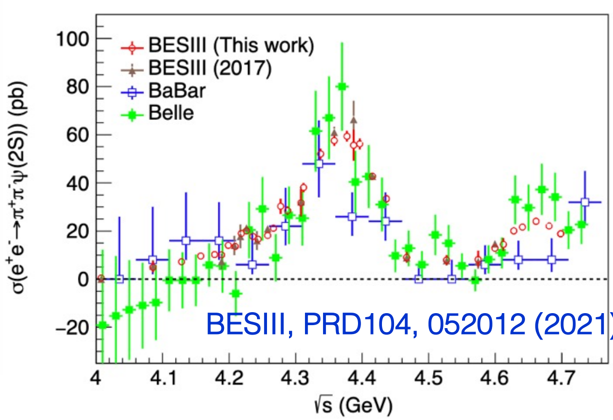
$$B^{\pm,0} \to K^{\pm,0}\pi^+\pi^- J/\psi$$



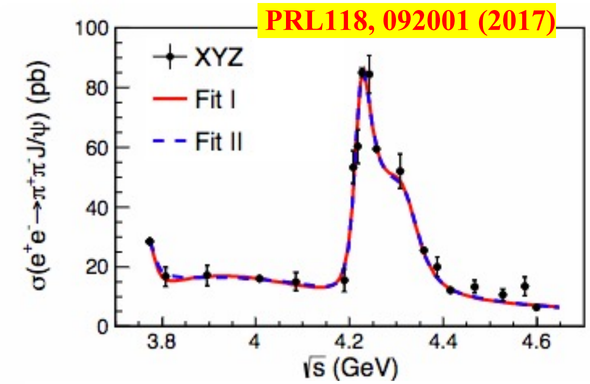
- **Improved knowledges from BESIII**

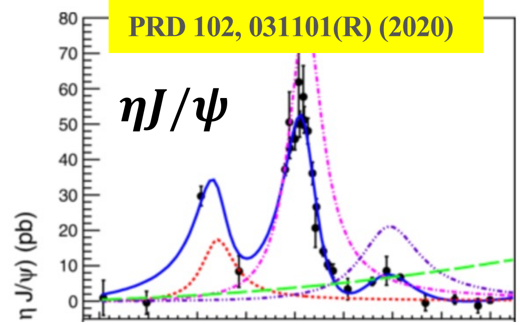


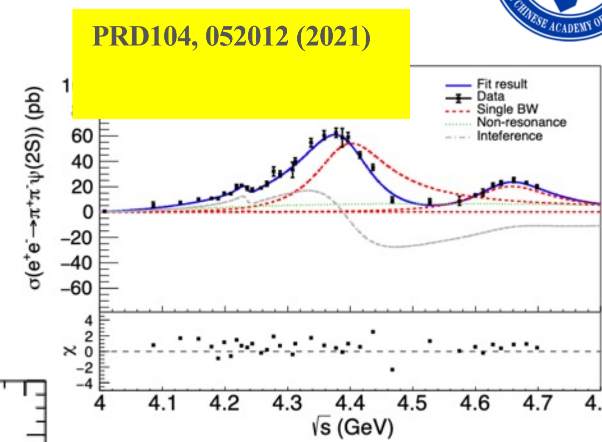
BESIII, PRL118, 092001 (2017)

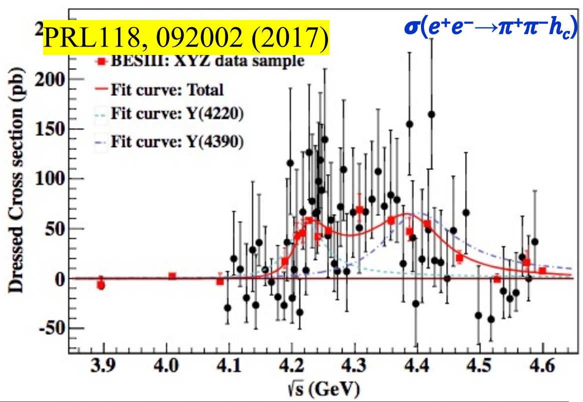


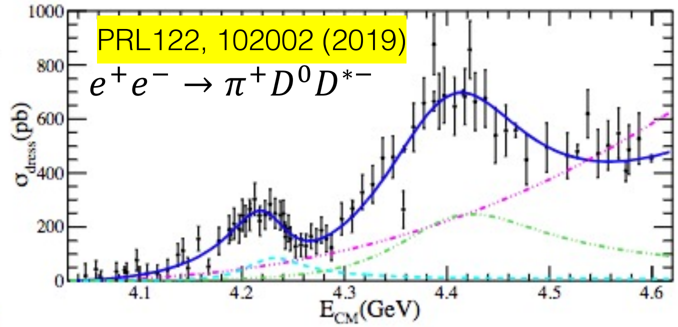
Y(4260) ➔ Y(4220) and new Y's

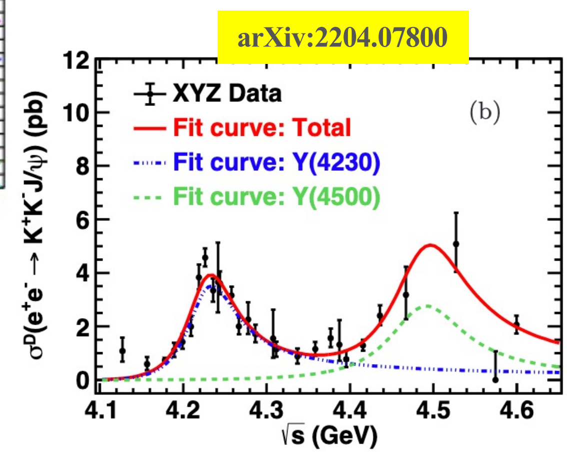


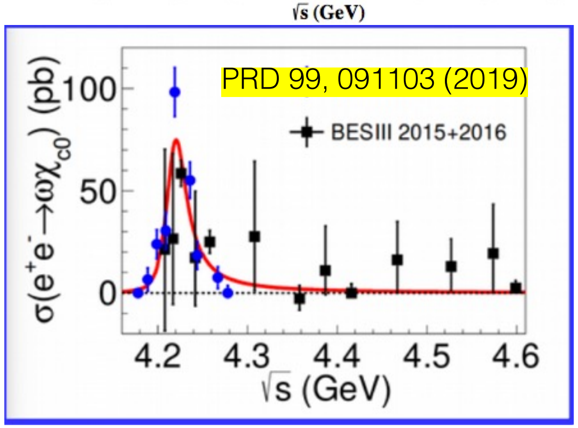


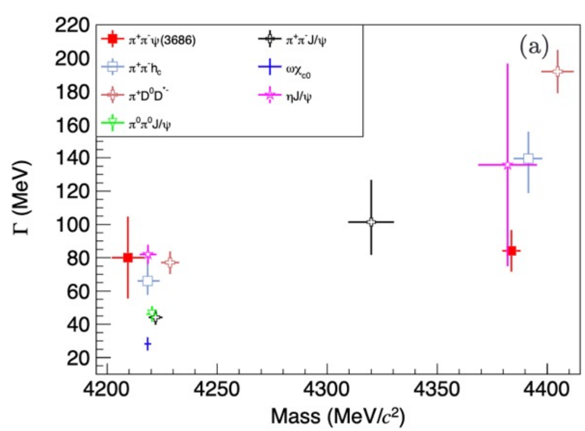












$$0.02 < \frac{\mathcal{B}(Y(4230)\to K^+K^-J/\psi)}{\mathcal{B}(Y(4230)\to \pi^+\pi^-J/\psi)} < 0.26$$

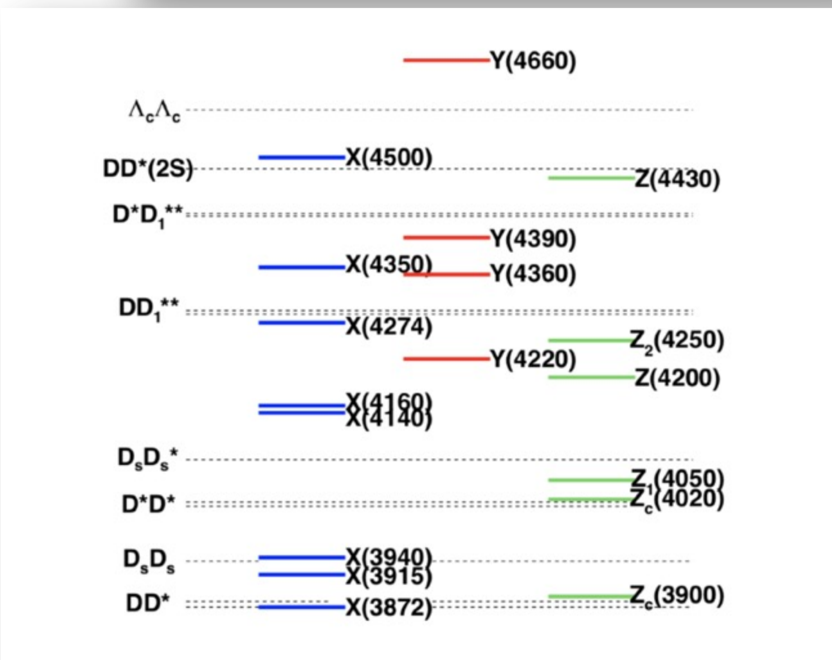
A new state Y(4500) observed

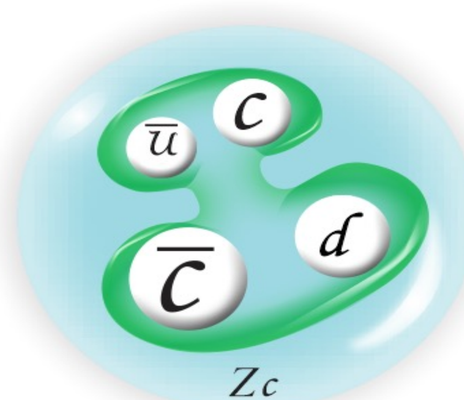
M(MeV)	$4484.7 \pm 13.3 \pm 24.1$
Γ_{tot}(MeV)	$111.1 \pm 30.1 \pm 15.2$

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]

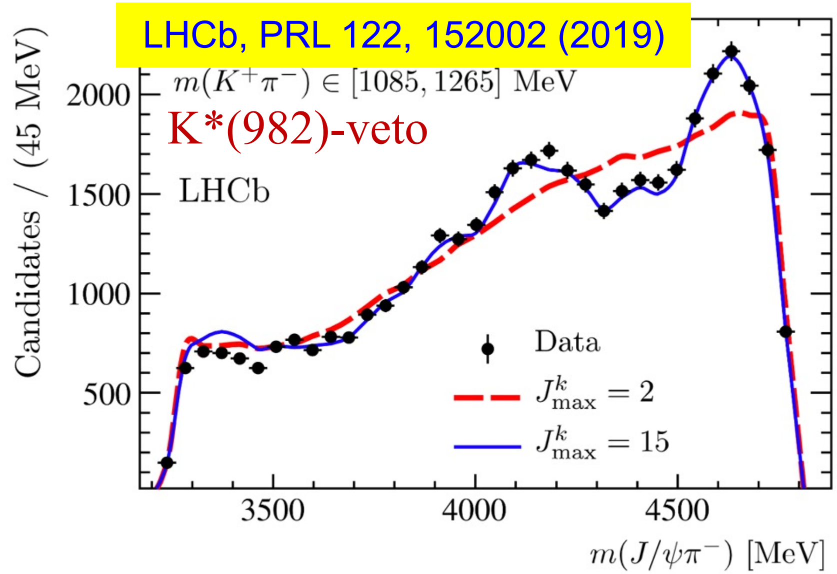


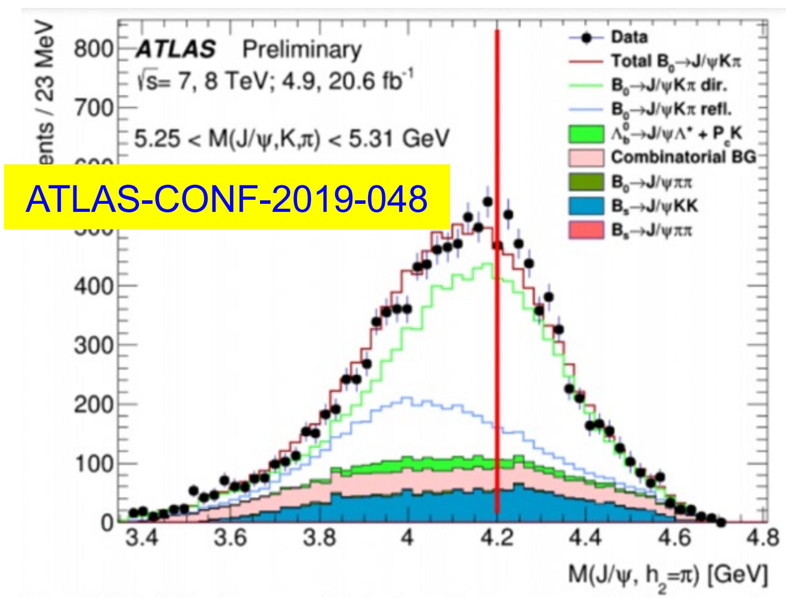


Most of them are close to the mass thresholds of charmed meson pairs

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



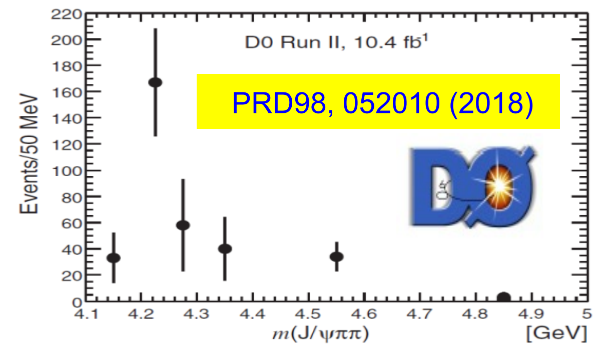


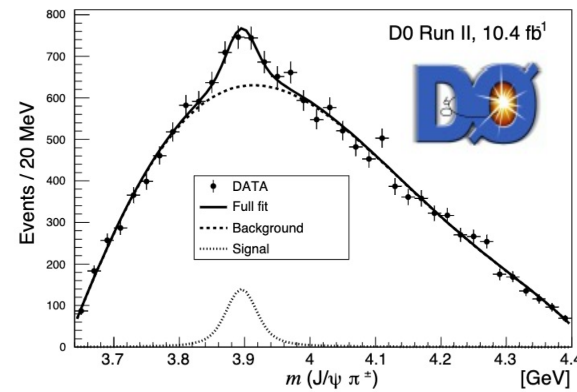
- ATLAS studied ~10K $B^0 \to J/\psi K^+\pi^-$ using RUN1 data
- Hint of Zc(4200) contribution, as data description w/o exotic contributions is not satisfactory

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

- D0 presented evidence for the charged Zc(3900) decaying to $J/\psi\pi$ 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)

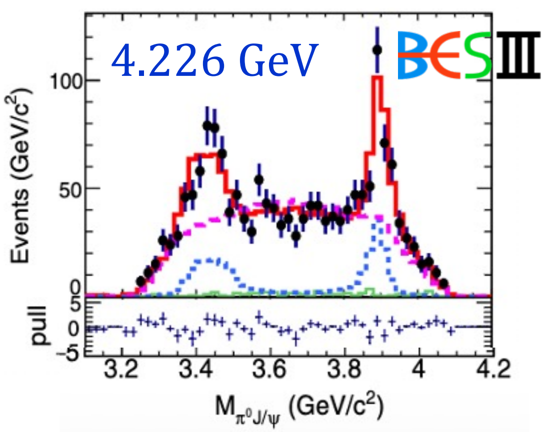
$H_b \to \pi^+\pi^- J/\psi$ + anything



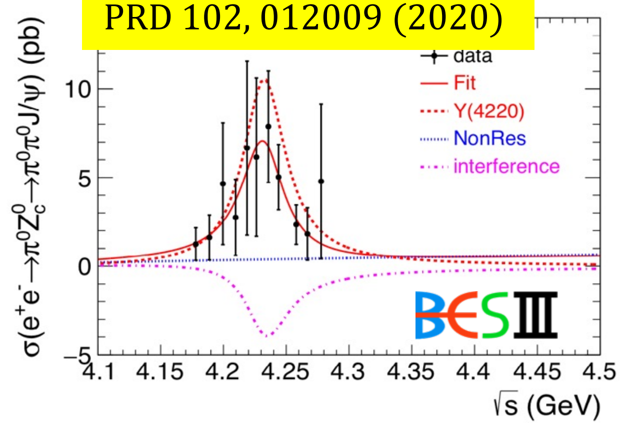


Amplitude analysis of $e^+e^-\to\pi^0 Z_c(3900)^0$ at BESIII

- 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^+



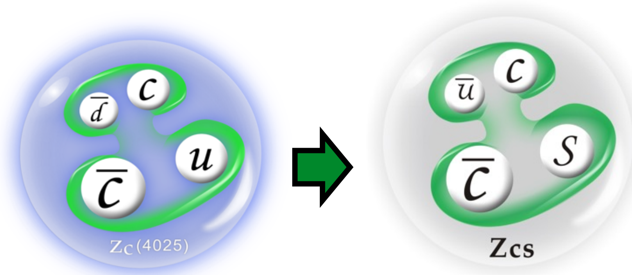
PRD 102, 012009 (2020)



- 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

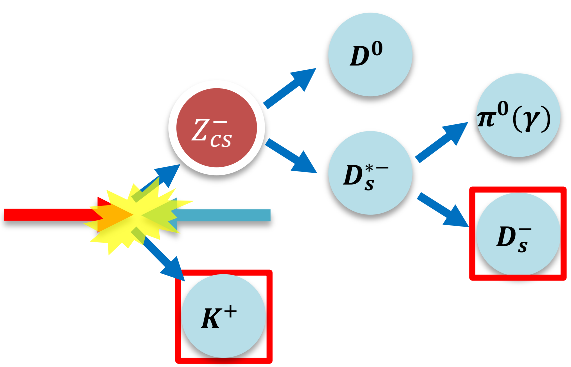
- **Important to look for Z_{cs}, the SU(3) partners of $X(3872)$/ $Z_c(3900)$**
- **It's useful to distinguish different models**
  - Less exchange particles expected the Z_{cs} molecule picture



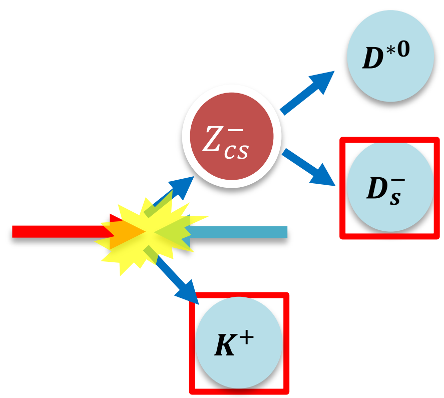
- BESIII analyzes 3.7fb^{-1} data at energies between 4.628 and 4.698GeV
- **Partial reconstruction of K^+ and D_s^-**

PRL 126, 102001 (2021)

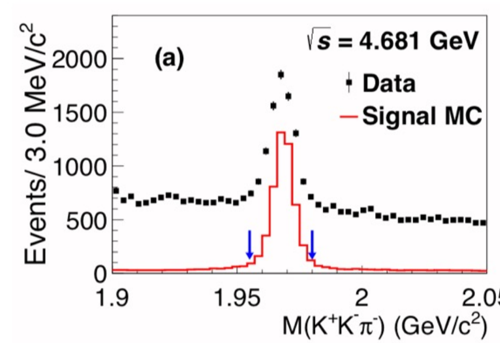
- Signature in the **recoil mass spectrum of $K^+D_s^-$** to identify the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

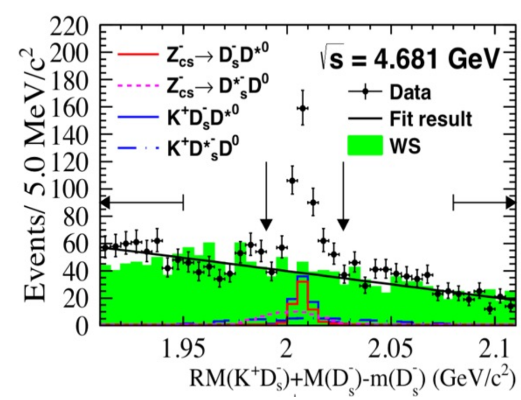


$e^+e^- \to K^+ D_s^{*-} D^0$



$e^+e^- \to K^+ D_s^- D^{*0}$

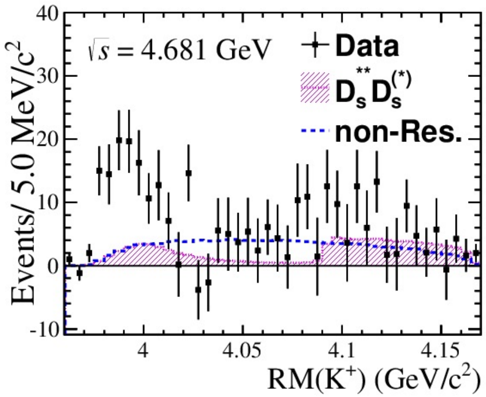


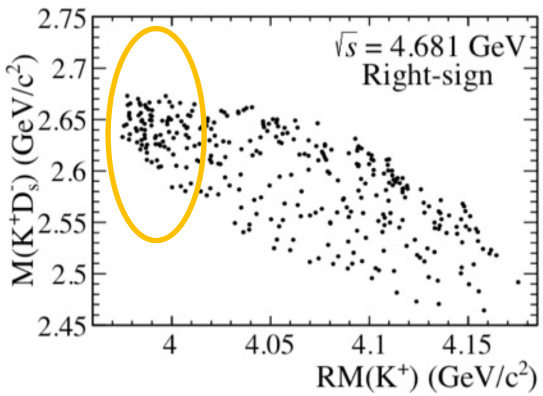


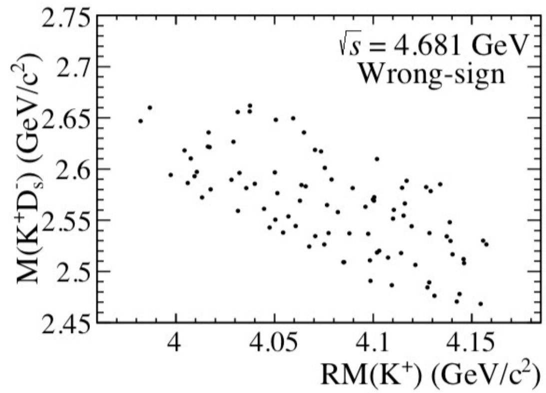
BESIII Observation of the $Z_{cs}(3985)^{\pm}$

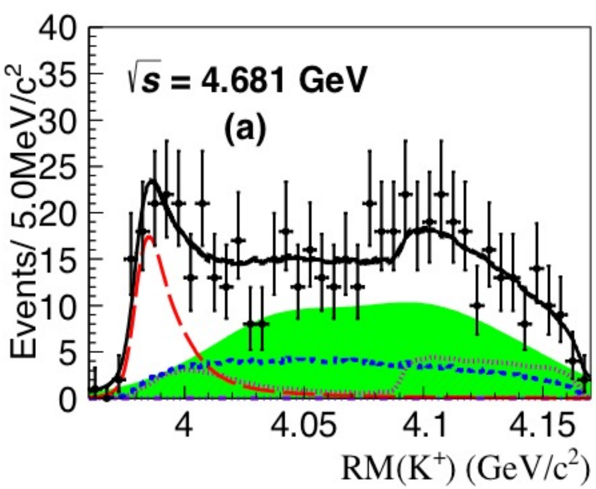
PRL 126, 102001 (2021)

- Data driven background description: wrong Sign (WS) combination of D_s^- and K^-
- Conventional charmed mesons can not describe the enhancement below 4.0 GeV/c^2 at 4.681 GeV









- Assume the structure as a $D_s^- D^{*0}/D_s^{*-} D^0$ resonance, denoting it as the $Z_{cs}(3985)^-$.
- A fit of J^P=1$^+$ S-wave Breit-Wigner with mass dependent width returns:

  $\boldsymbol{m} = 3985.2^{+2.1}_{-2.0} \pm 1.7$ MeV/c^2

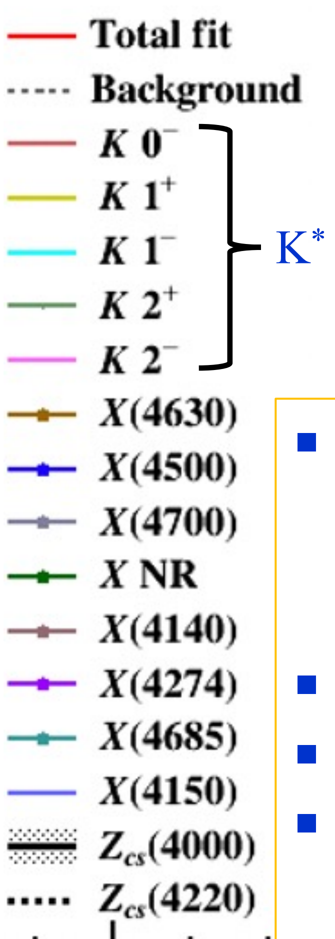
  $\boldsymbol{\Gamma} = 13.8^{+8.1}_{-5.2} \pm 4.9$ MeV
- Global significance: >5.3 $\boldsymbol{\sigma}$

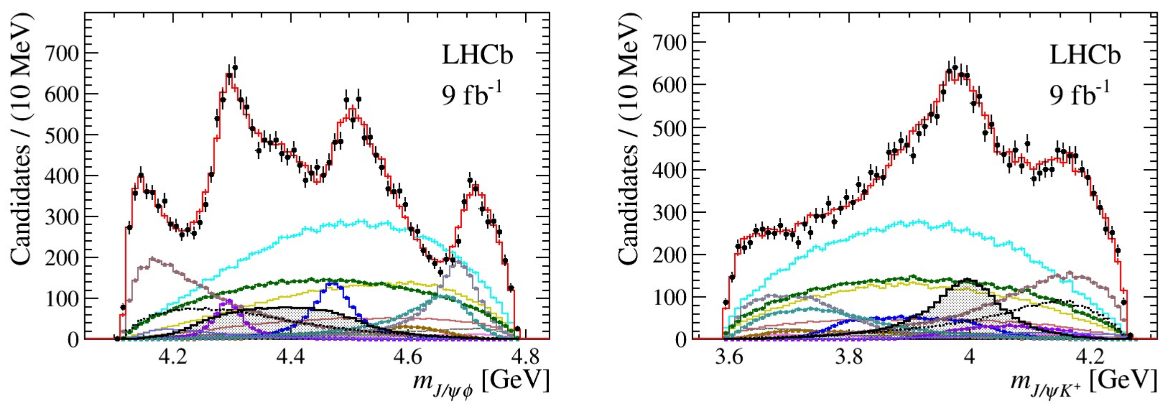
First candidate of the hidden-charm tetraquark with strangeness

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 $X(4700)$ ➔ $[cs\bar{c}\bar{s}]$ 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:
  $X(4140)$, $X(4274)$,
  $X(4500)$, $X(4700)$

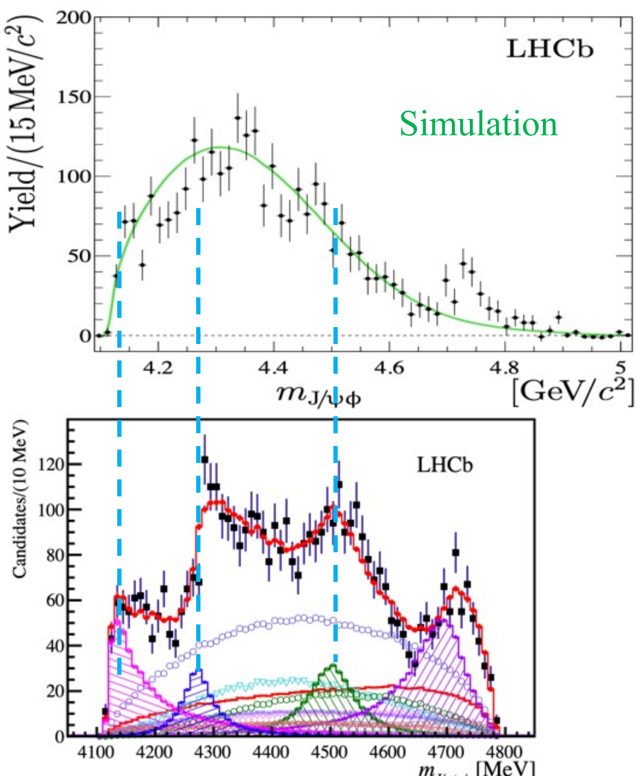
Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$	Syst. included(Stat.)			
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
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)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

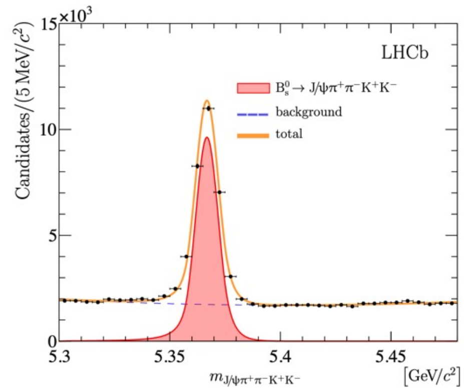
New $X(4740)$ structure

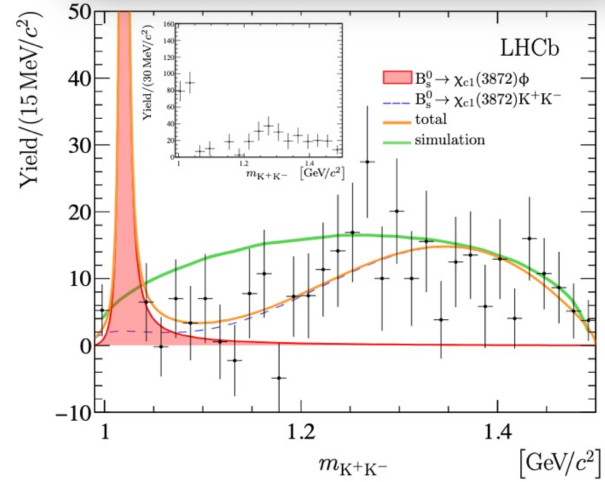
JHEP02, 024 (2021)

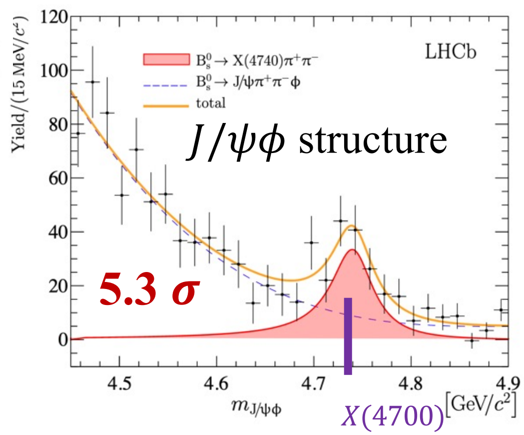
- Study of $B_S^0 \to J/\psi\pi^+\pi^-K^+K^-$ using LHCb RUN 1+2 data: 26.5K signals
- Observations of $B_S^0 \to X(3872)K^+K^-$ and $X(3872)\phi$

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









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:

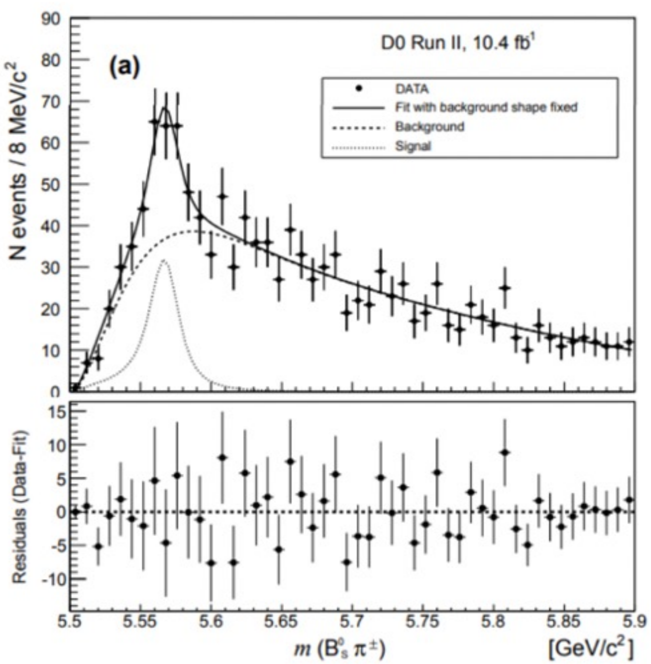
- Shape of underlying non-X
- Alternative P-wave or D-wave BW
- Inteference $\mathcal{F}_S(m_{J/\psi\phi}) \propto |\mathcal{A}(m_{J/\psi\phi}) + b(m_{J/\psi\phi})e^{i\varphi}|^2$

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

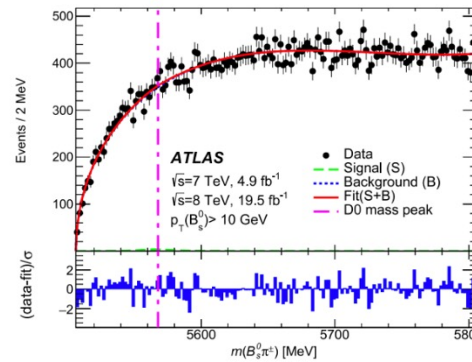
Open-flavor exotic mesons

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

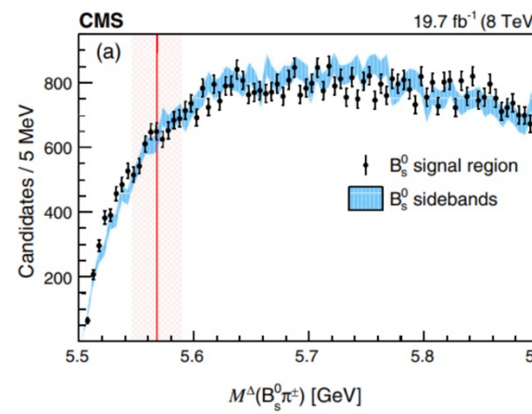
- D0 claimed evidence for the X(5568) in decaying to $B_s\pi^+$, interpreted as tetraquark state [***bsud***]
- But not seen in other experiments



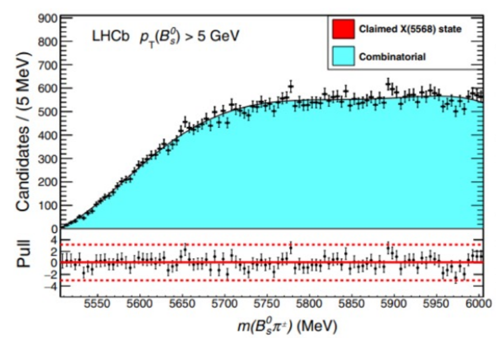
Phys. Rev. Lett., 117, 022003



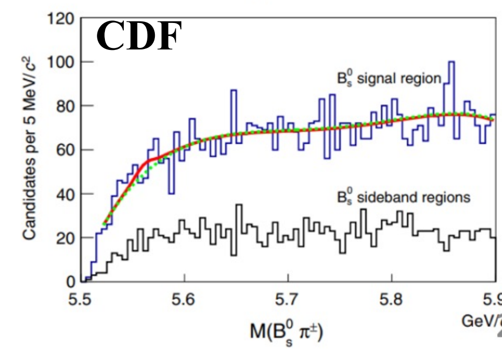
Phys. Rev. Lett. 120, 202007



Phys. Rev. Lett. 120, 202005



Phys. Rev. Lett. 117, 152003

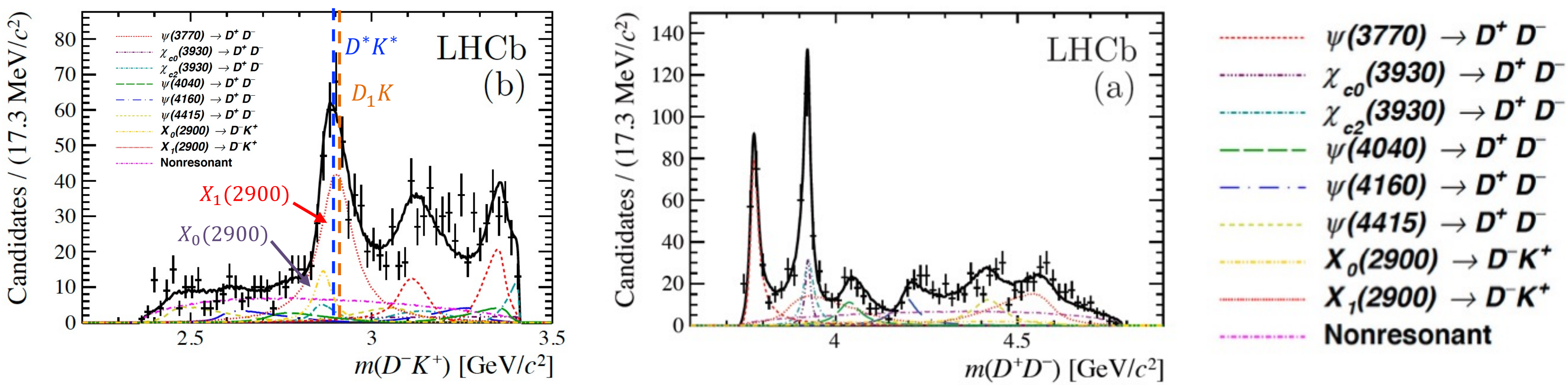


Phys. Rev. Lett. 120, 202006

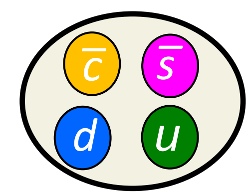
Observation of open-charm exotic state X(2900) [$\bar{c}\bar{s}ud$]

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 ?



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

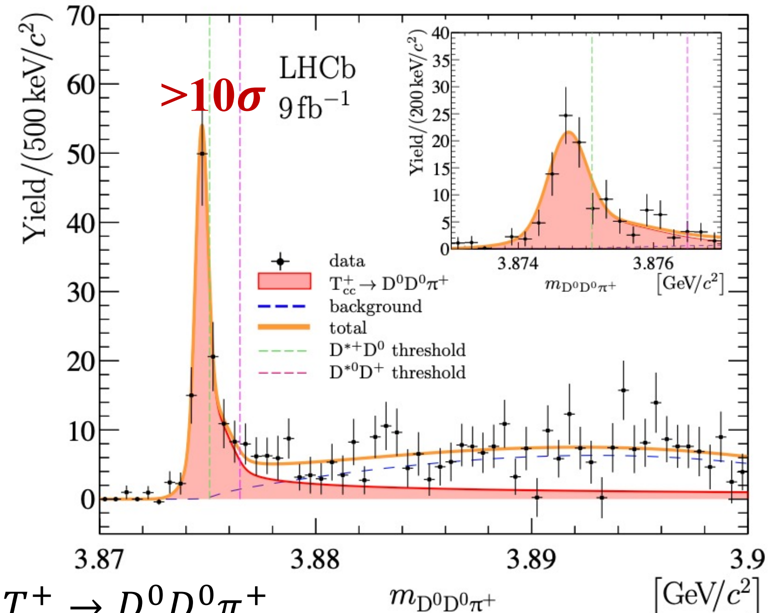
Quite large contribution!

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

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

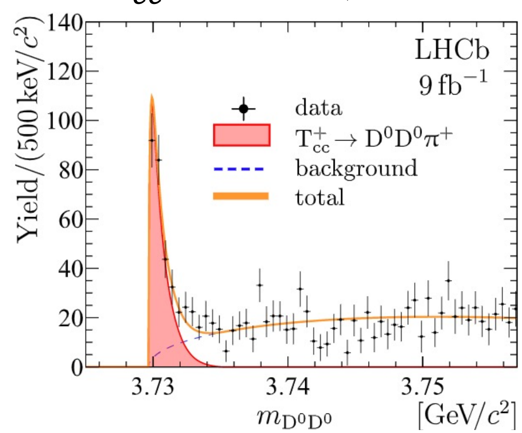
Full Run 1+2 data

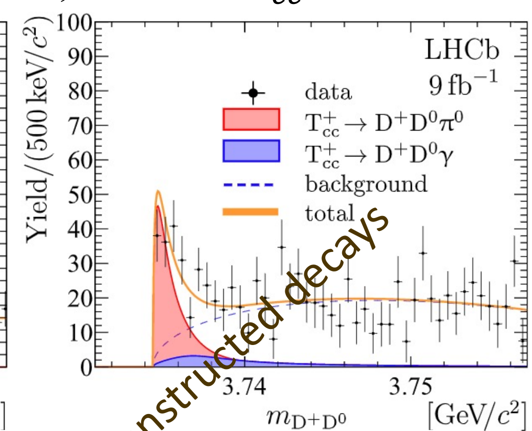
LHCb arXiv: 2109.01038; 2109.01056

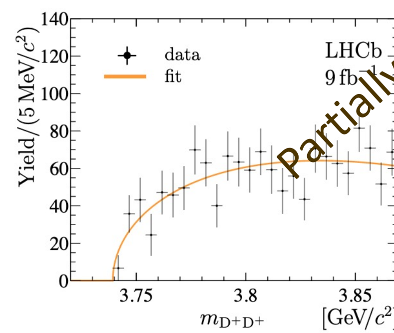


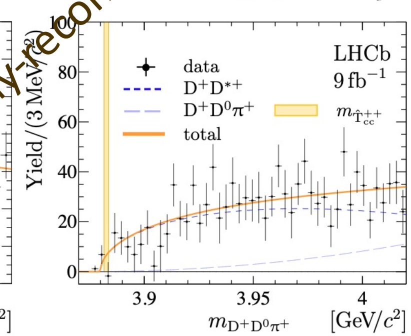
$T_{cc}^{+} \to D^0 D^0 \pi^+$

$T_{cc}^{+} \to D^0 D^{*+}, D^{*0} D^{+}$ seen, while not $T_{cc}^{++} \to D^{*+} D^{+}$









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

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

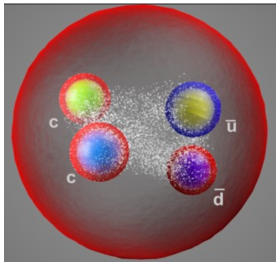
$$\delta m_{BW} = -273 \pm 61 \pm 5^{+11}_{-14}\ \mathrm{keV}/c^2,$$

$$\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38}\ \mathrm{keV}$$

- off-shell $T_{cc}^{+} \to DD^{*}$ decays
- different lineshape model tested

$$\delta m_{U} = -359 \pm 40^{+9}_{-6}\ \mathrm{keV}/c^2$$

no sensitivity on width



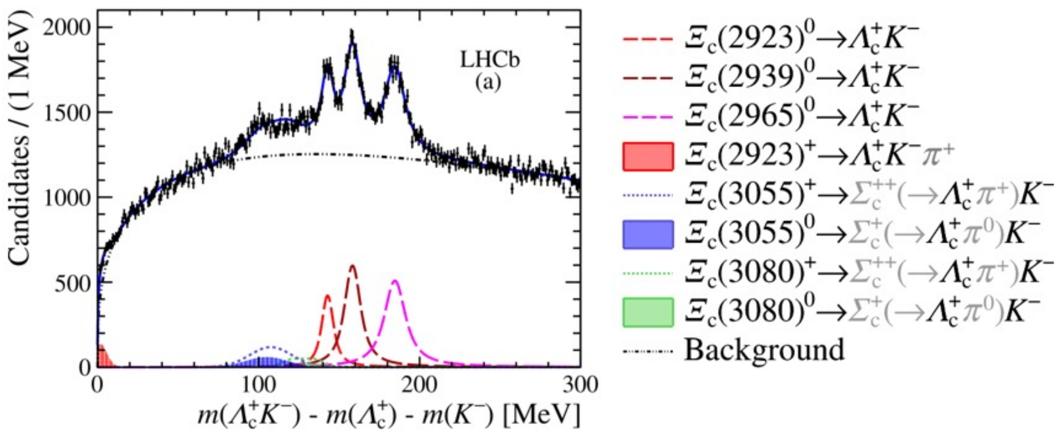
➢consistent with expectation for ground isoscalar $T_{cc}^{+}(cc\bar{u}\bar{d})$ state with $J^P = 1^+$

Heavy baryons

Observation of new Ξc baryons

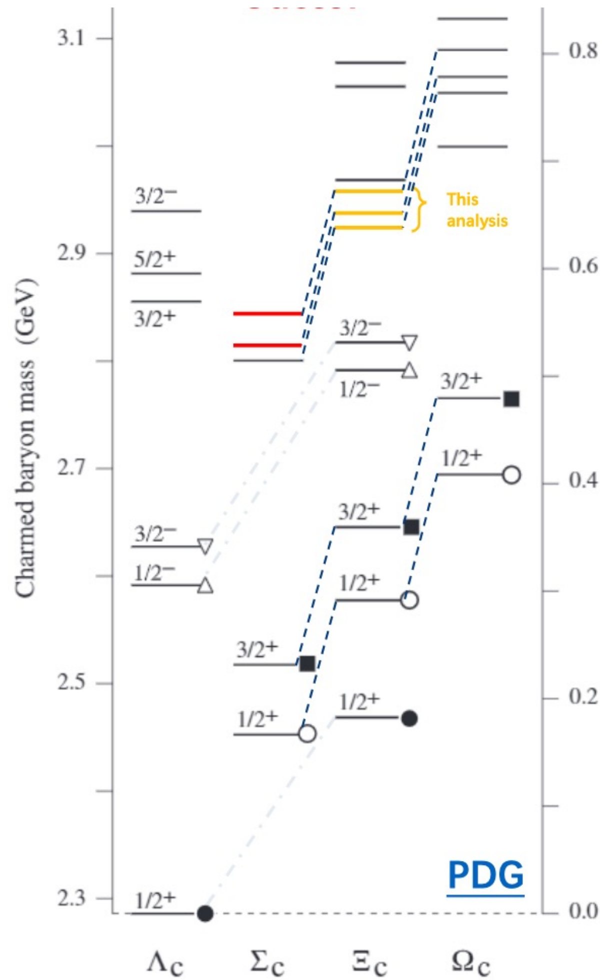
PRL124, 200197 (2020)

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



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

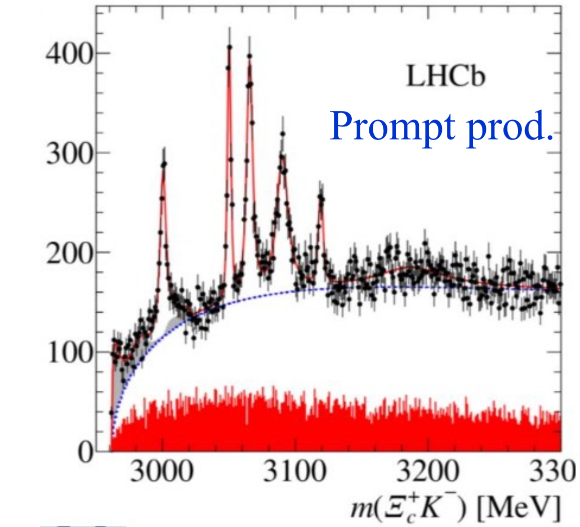
Stat. Sys. input



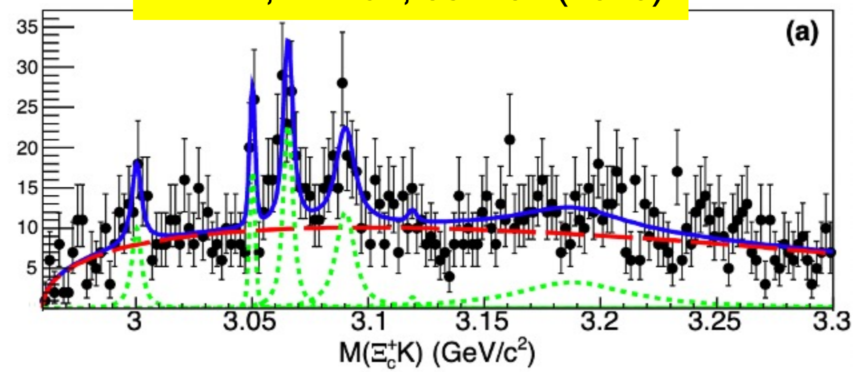
Genuine property of these states are not fully understood yet.

Confirmation of the excited Ω_c states

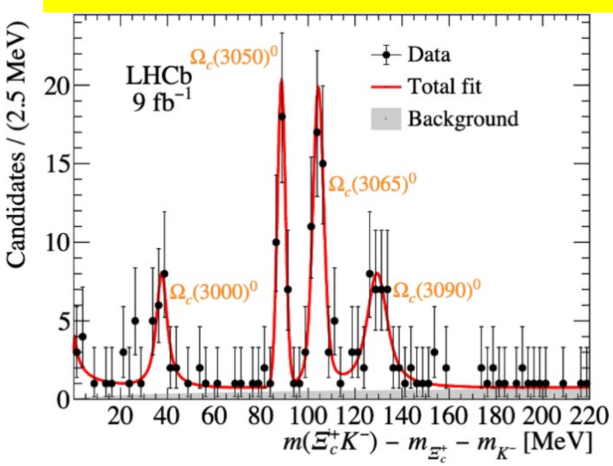
LHCb, PRL118, 182001 (2017)



BELLE, PRD97, 051102 (2018)



LHCb, PRD104, L091102(2021)



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

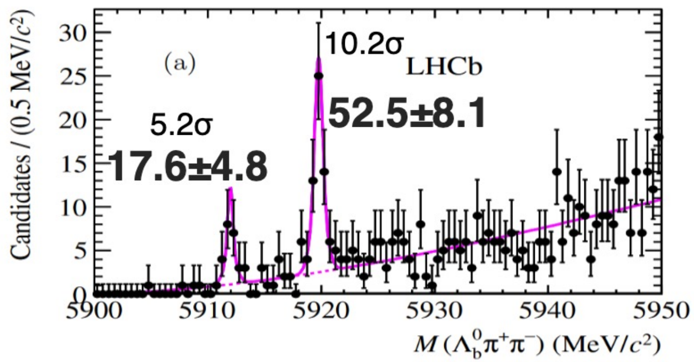
	Prompt		b-decays	
Resonance	Mass [MeV]	Γ [MeV]	Mass [MeV]	Γ [MeV]
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1$	$4.5 \pm 0.6 \pm 0.3$	$2999.2 \pm 0.9 \pm 0.9$	$4.8 \pm 2.1 \pm 2.5$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1$	$0.8 \pm 0.2 \pm 0.1$	$3050.1 \pm 0.3 \pm 0.2$	< 1.6 @ 95% CL
$\Omega_c(3065)^0$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

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)

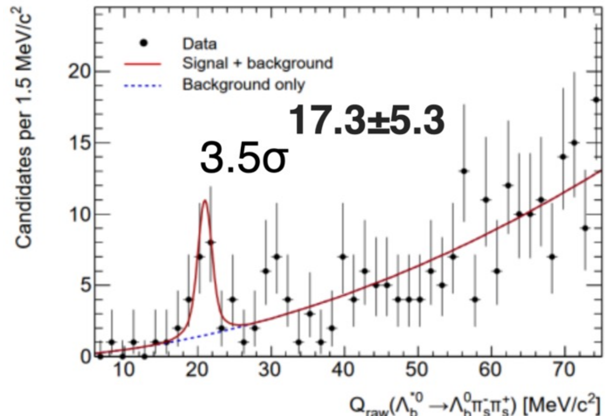
- $\Lambda_b(5912)$ & $\Lambda_b(5920)$ were observed at LHCb and later $\Lambda_b(5920)$ confirmed by CDF

LHCb, PRL109,172003 (2012)



Near kinematic threshold

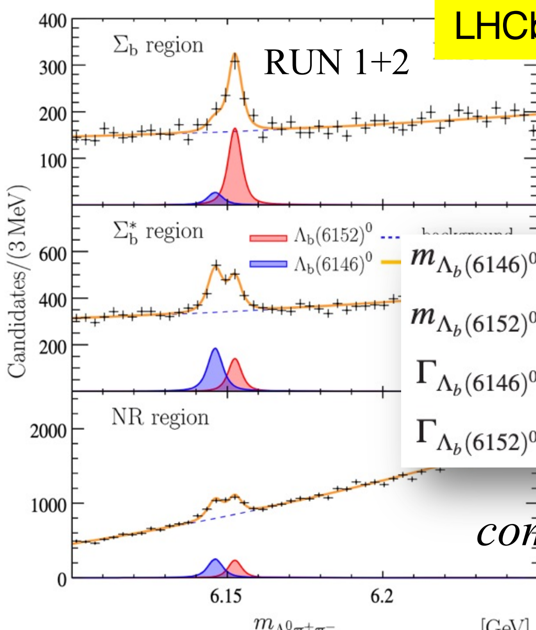
CDF, PRD88, 071101(2013)



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

- Observation of $\Lambda_b(6146)$ & $\Lambda_b(6152)$

LHCb, PRL123,152001 (2019)

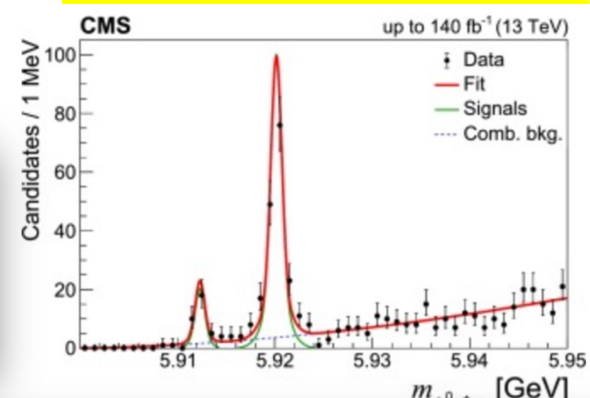


$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3 \text{ MeV},$$

compatible with $\Lambda_b(1D)$

- Confirmation of $\Lambda_b(5912)$ & $\Lambda_b(5920)$

CMS, PLB803, 135345(2020)

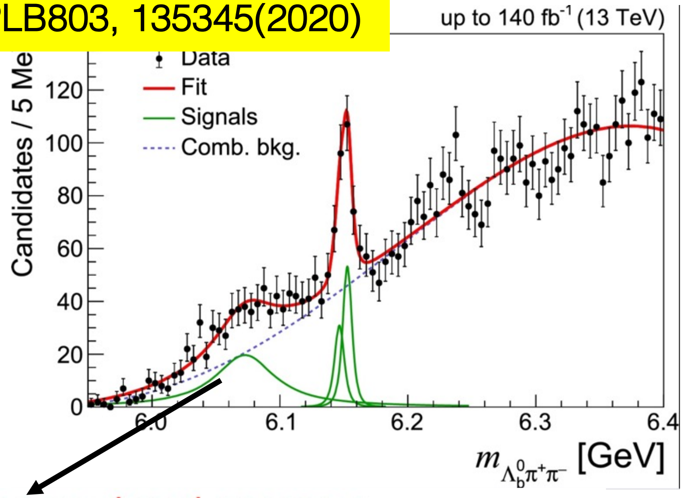


$$M(\Lambda_b^0(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17 \text{ MeV},$$
$$M(\Lambda_b^0(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17 \text{ MeV},$$

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

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

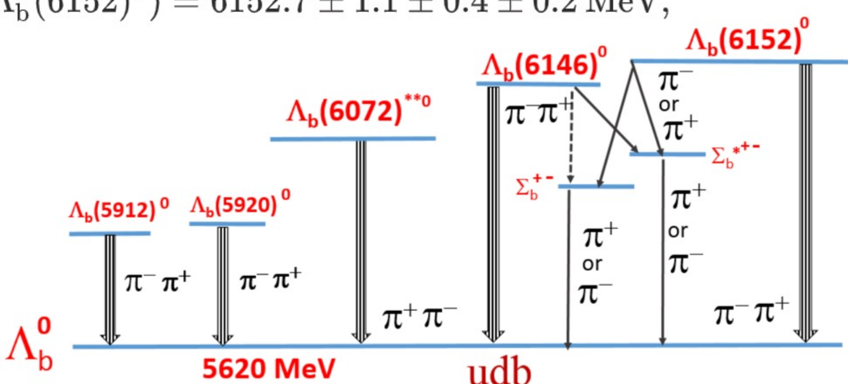
CMS, PLB803, 135345(2020)



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

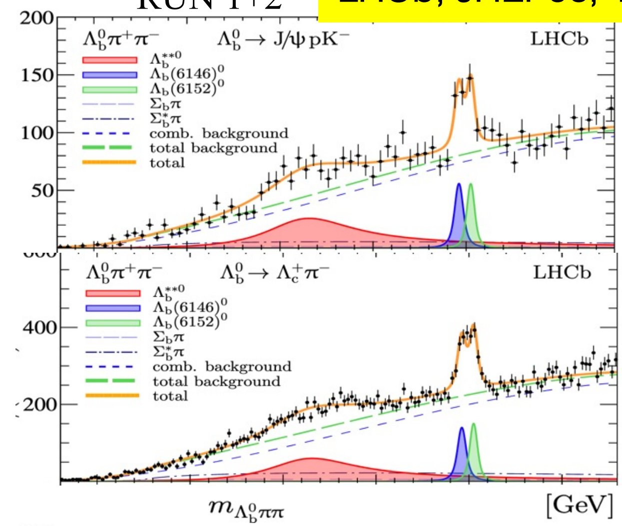
$$M(\Lambda_b^0(6146)^0) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2\,\text{MeV},$$
$$M(\Lambda_b^0(6152)^0) = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2\,\text{MeV},$$

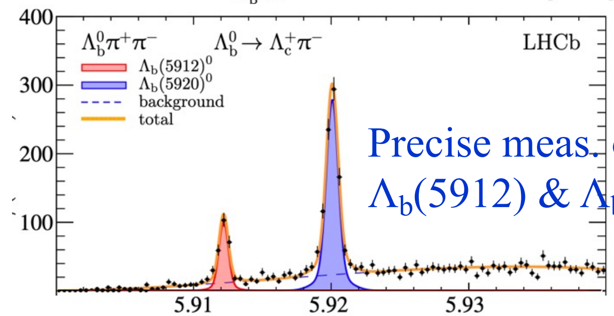


- Observation of the broad resonance

LHCb, JHEP06, 136(2020)

RUN 1+2





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

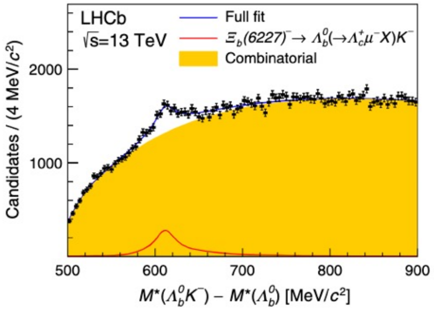
$$m_{\Lambda_b^{**0}} = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2\,\text{MeV}$$ $\boldsymbol{\Lambda_b(2S)}$?

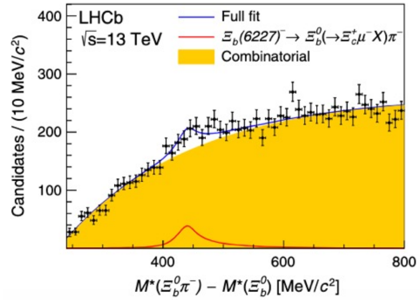
$$\Gamma_{\Lambda_b^{**0}} = 72 \pm 11 \pm 2\ \text{MeV}$$
$$m_{\Lambda_b(5912)^0} = 5912.21 \pm 0.03 \pm 0.01 \pm 0.21\,\text{MeV},$$
$$m_{\Lambda_b(5920)^0} = 5920.11 \pm 0.02 \pm 0.01 \pm 0.21\,\text{MeV},$$
$$\Gamma_{\Lambda_b(5912)^0} < 0.25\,(0.28)\,\text{MeV},$$
$$\Gamma_{\Lambda_b(5920)^0} <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

Observation of new excited Ξ_b states

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

LHCb, PRL121, 072002(2018)

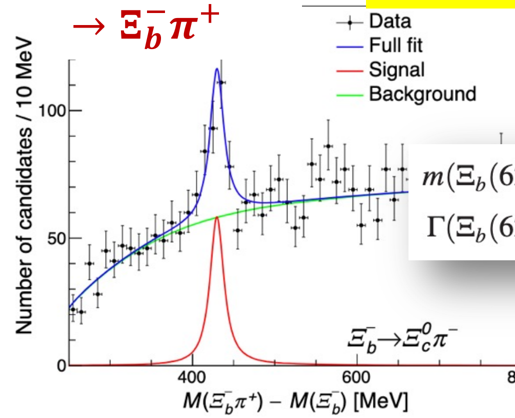




$$\Gamma_{\Xi_b(6227)^-} = 18.1 \pm 5.4(\text{stat}) \pm 1.8(\text{syst})\ \text{MeV}/c^2,$$
$$m_{\Xi_b(6227)^-} = 6226.9 \pm 2.0(\text{stat}) \pm 0.3(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV}/c^2,$$

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

LHCb, PRD 103, 012004 (2021)

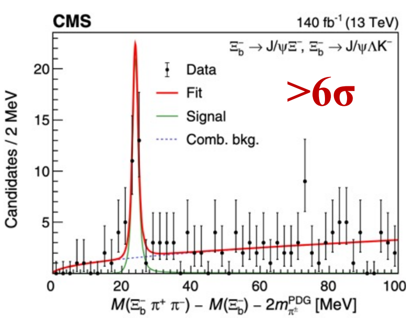


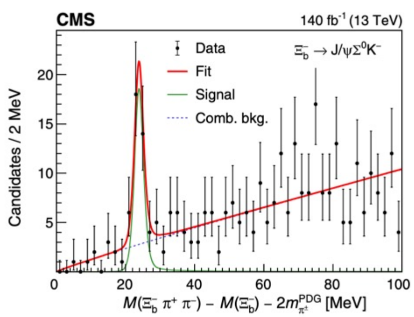
$$m(\Xi_b(6227)^0) = 6227.1^{+1.4}_{-1.5} \pm 0.5\ \text{MeV},$$
$$\Gamma(\Xi_b(6227)^0) = 18.6^{+5.0}_{-4.1} \pm 1.4\ \text{MeV},$$

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

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

CMS, PRL126,252003 (2021)

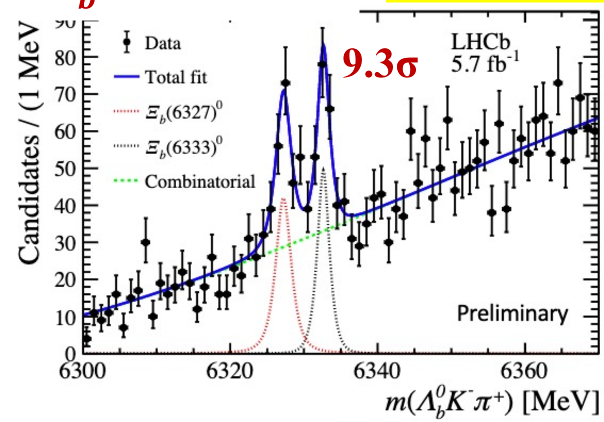




$$M = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6\ \text{MeV}$$
$$\Gamma < 1.9\ \text{MeV at } 95\%\ \text{CL}$$

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

LHCb, arXiv:2110.04497

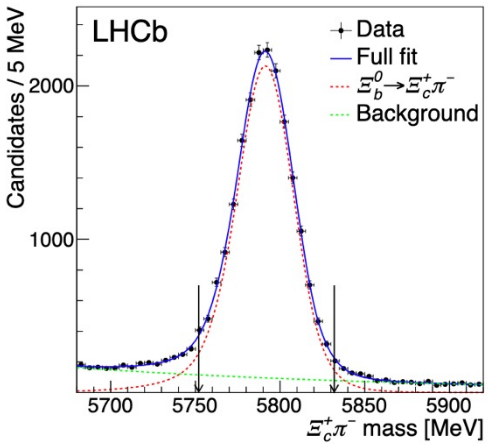


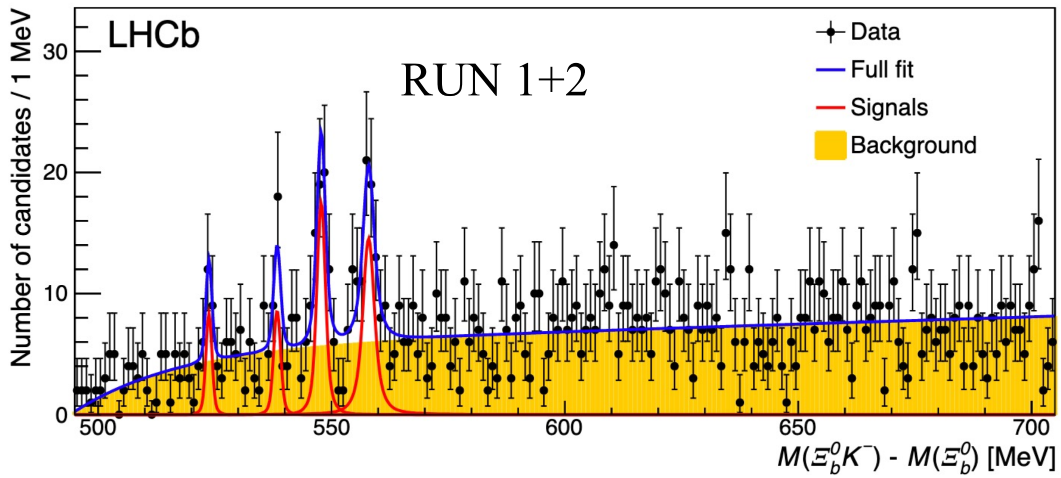
$$m_{\Xi_b(6327)^0} = 6327.26^{+0.23}_{-0.21} \pm 0.08 \pm 0.24\ \text{MeV}$$
$$m_{\Xi_b(6333)^0} = 6332.67^{+0.17}_{-0.18} \pm 0.03 \pm 0.22\ \text{MeV}$$

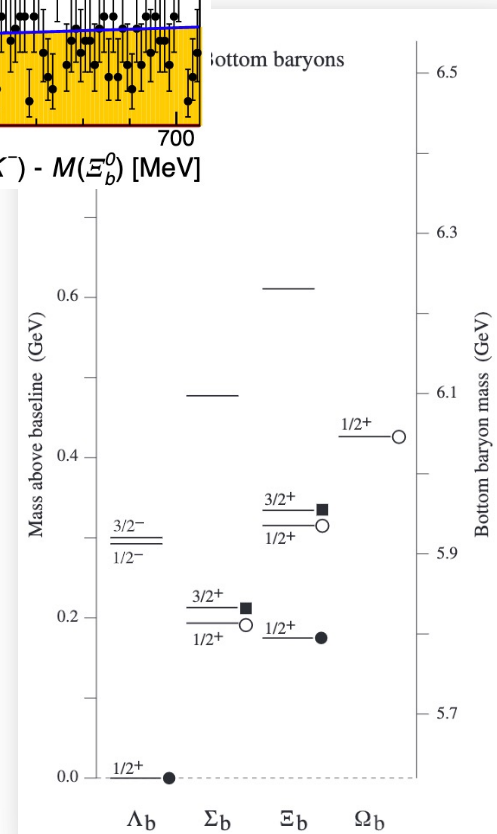
consistent with the 1D excited Ξ_b doublets.

Observation of new excited Ω_b states

PRL124, 082002 (2020)



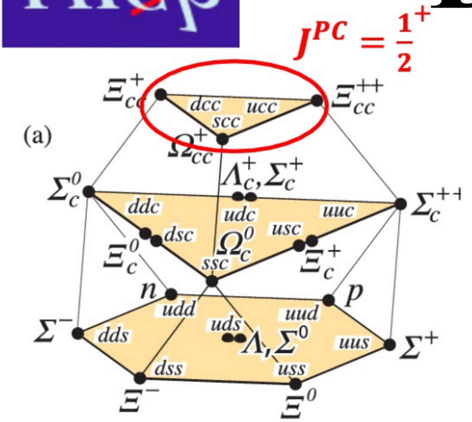


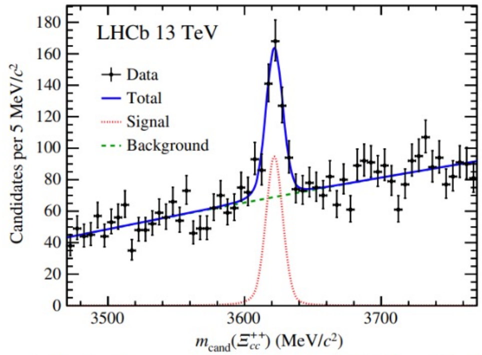


	Mass [MeV]	Width [MeV]	Significances [σ] Local	Global
$\Omega_b(6316)^-$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	$< 2.8\ (4.2)$	3.6	2.1
$\Omega_b(6330)^-$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	$< 3.1\ (4.7)$	3.7	2.6
$\Omega_b(6340)^-$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	$< 1.5\ (1.8)$	7.2	6.7
$\Omega_b(6350)^-$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

observation

Doubly heavy baryons





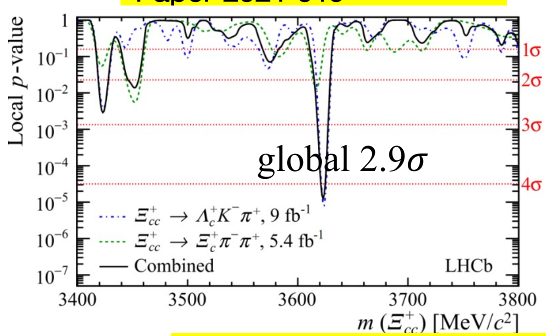
First observation in $m(\Lambda_c^+ K^- \pi^+ \pi^+)$

PRL 119 (2017) 112001

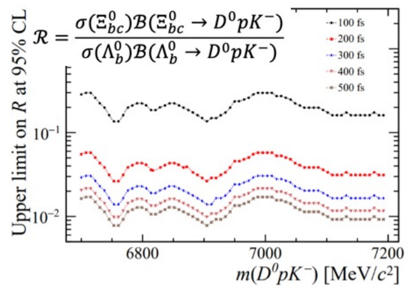
A lot of Ξ_{cc}^{++} study done by LHCb:

- 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
  - $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$: $\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009 \pm 0.003$ 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

Ξ_{cc}^+ SCPMA 63, 221062, (2020) Paper-2021-019

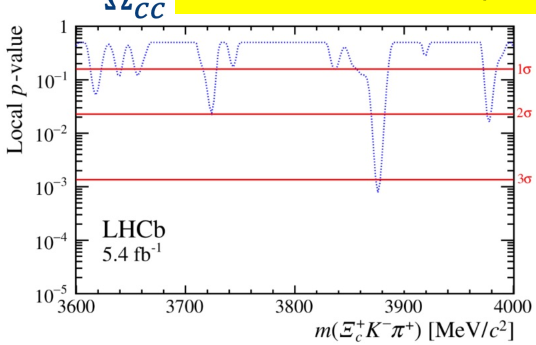


JHEP11, 095(2020)

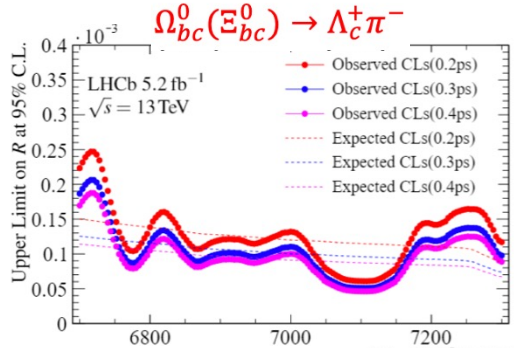


- No evidence of the other doubly charmed baryons yet
- Need RUN 3 data

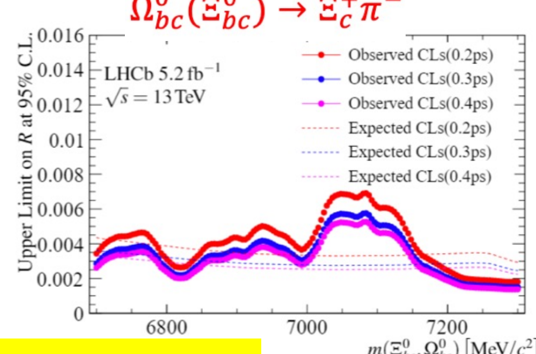
Ω_{cc}^+ SCPMA 64, 101062(2021)



$\Omega_{bc}^0(\Xi_{bc}^0) \to \Lambda_c^+ \pi^-$

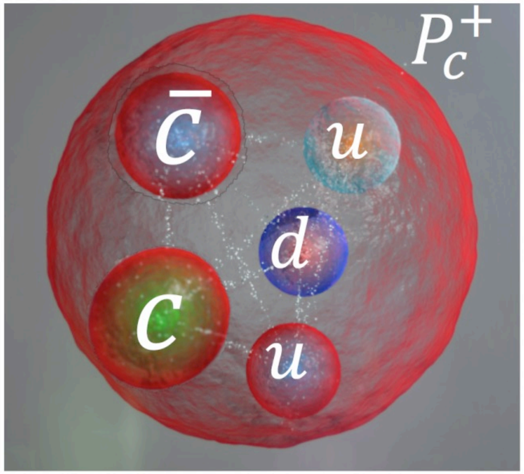


$\Omega_{bc}^0(\Xi_{bc}^0) \to \Xi_c^+ \pi^-$



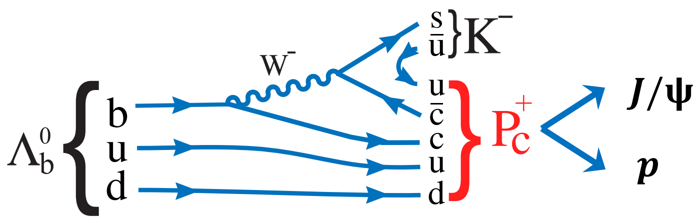
CPC45, 093002 (2021)

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

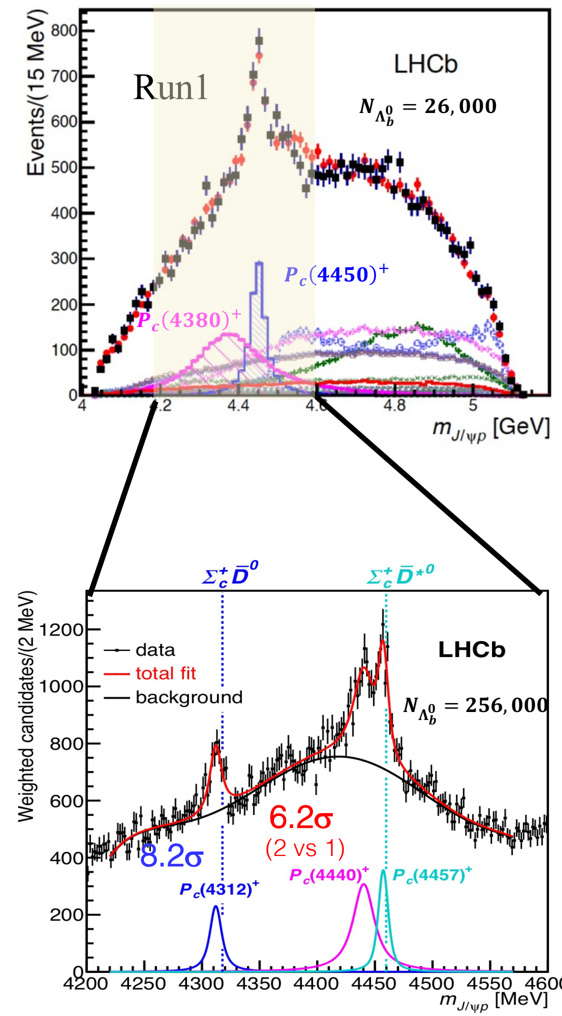


- New pentaquark and fine structure were discovered in 2019 with x10 signals
  - Three narrow pentaquarks just below $\Sigma_c^+ D^{(*)0}$ thresholds, favors molecular picture

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)



RUN 1

RUN 1+2

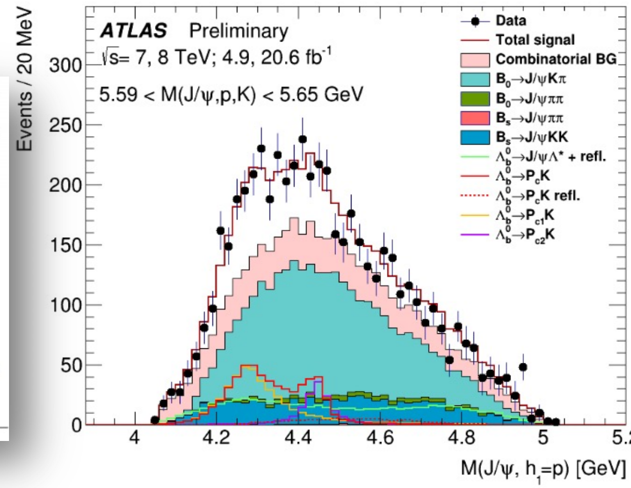
PRL122, 222001(2019)

Pc confirmations in *b* decays at ATLAS and D0

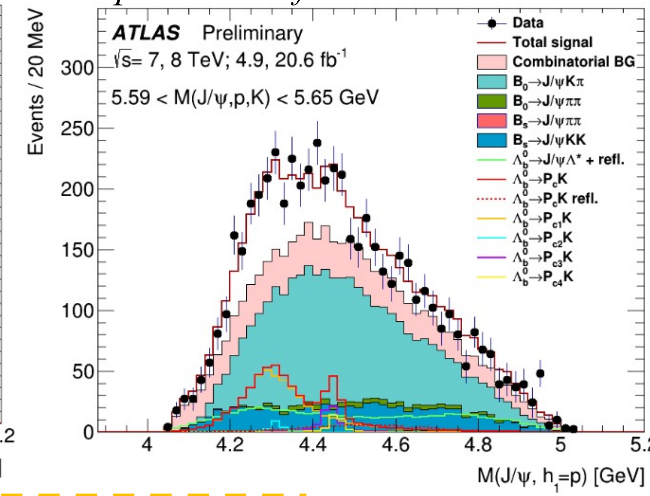
- ATLAS studied ~1K $\Lambda_b^0 \to J/\psi p K^-$ using RUN1 data **ATLAS-CONF-2019-048**
- **Pc states are needed to describe data**: two Pc's fit (left) and four Pc's fit (right)

Fitted Pc parameters consistent with LHCb's

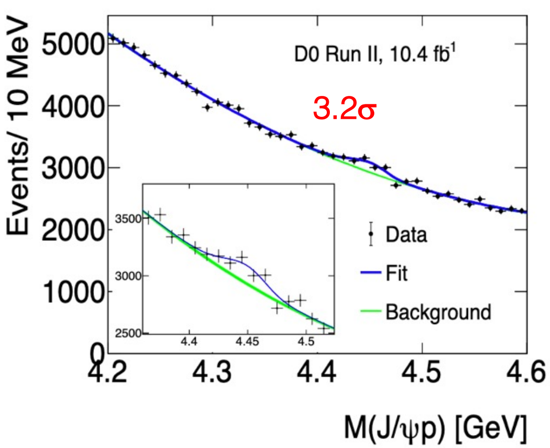
Parameter	Value	LHCb value [5]
$N(P_{c1})$	400^{+130}_{-140}(stat)$^{+110}_{-100}$(syst)	–
$N(P_{c2})$	150^{+170}_{-100}(stat)$^{+50}_{-90}$(syst)	–
$N(P_{c1}+P_{c2})$	540^{+80}_{-70}(stat)$^{+70}_{-80}$(syst)	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}$(stat)$^{+0.2}_{-0.1}$(syst) rad	–
$m(P_{c1})$	4282^{+33}_{-26}(stat)$^{+28}_{-7}$(syst)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

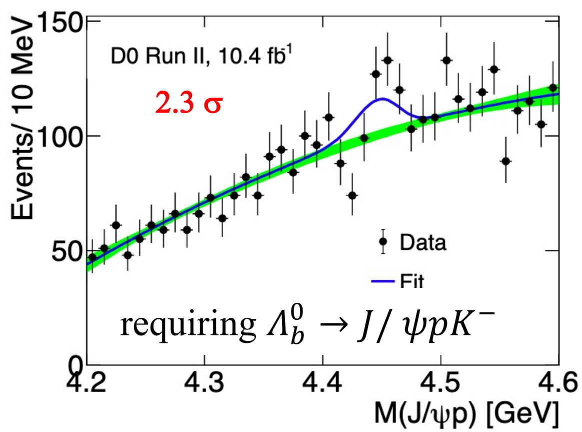


Pc parameters fixed to LHCb's results



- **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**



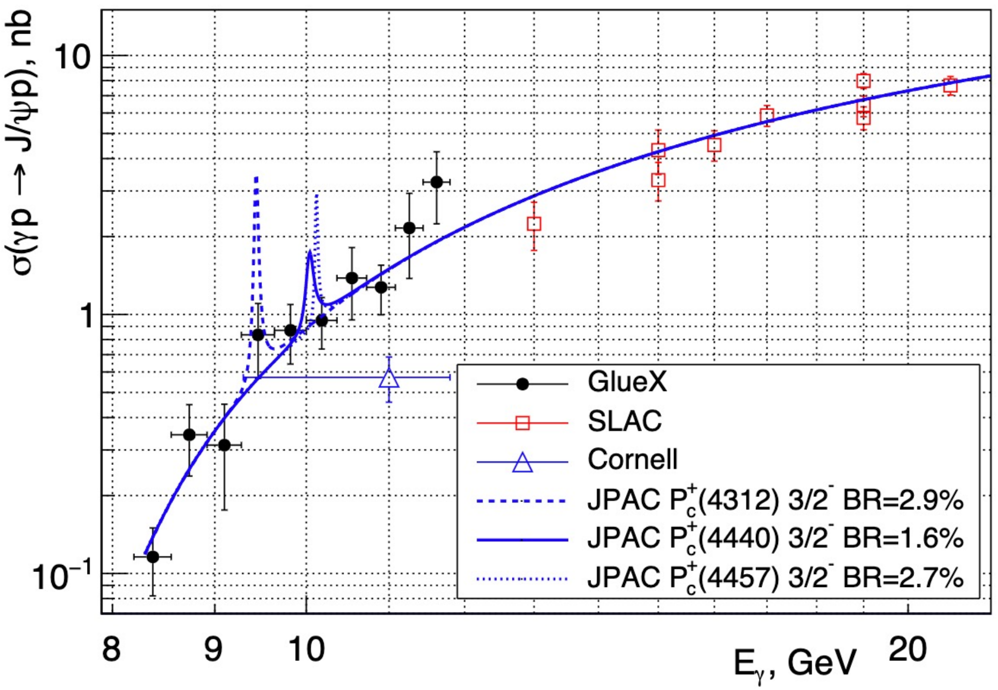


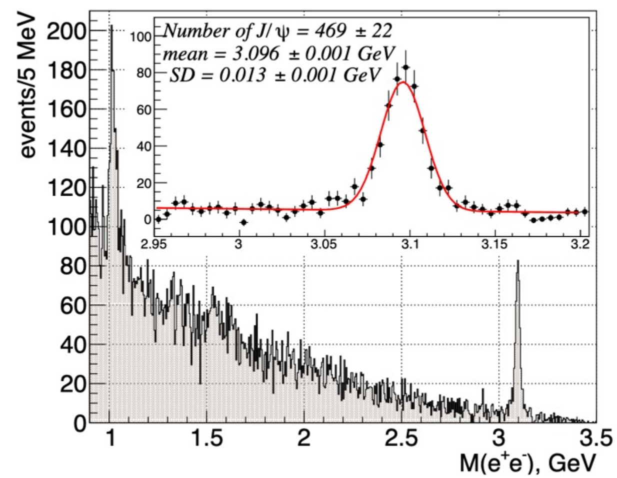
- **Pc(4312) is not evident**
- **No Pc states seen in prompt production**

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.

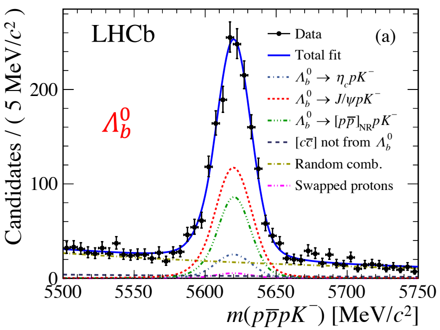
Search for Pc in $\Lambda_b^0 \to \eta_c p K^-$

PRD102, 112012 (2020)

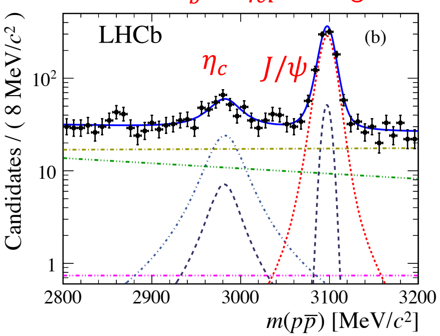
- Same quark contents as $\Lambda_b^0 \to J/\psi p K^-$
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule,
  $R(P_c(4312)^+) = \frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)} \sim 3$ is predicted

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

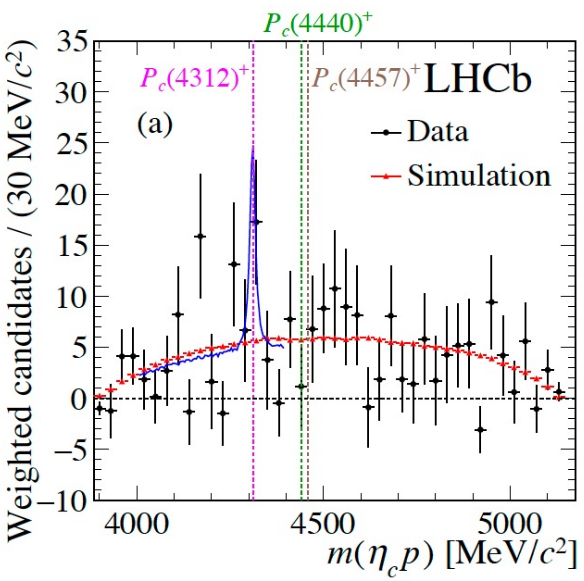
- LHCb run2 data (5.5 fb^{-1}): η_c reconstructed using $\eta_c \to p\bar{p}$
- Study background-subtracted $\eta_c p$ mass spectrum



$\sim$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)

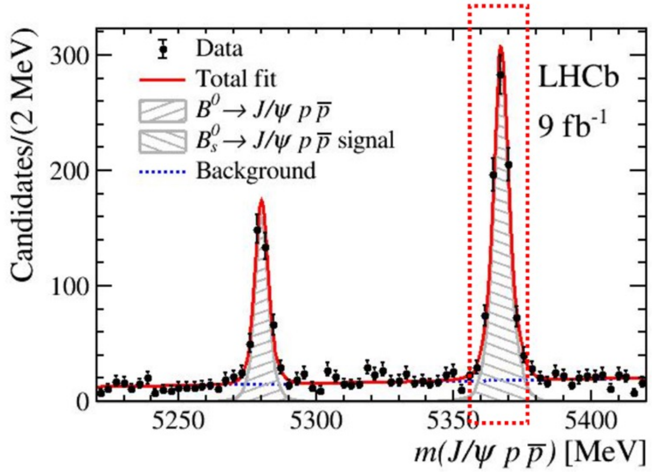
New Pc state in $B_s^0 \to J/\psi p\bar{p}$

PRL 128, 062001 (2022)

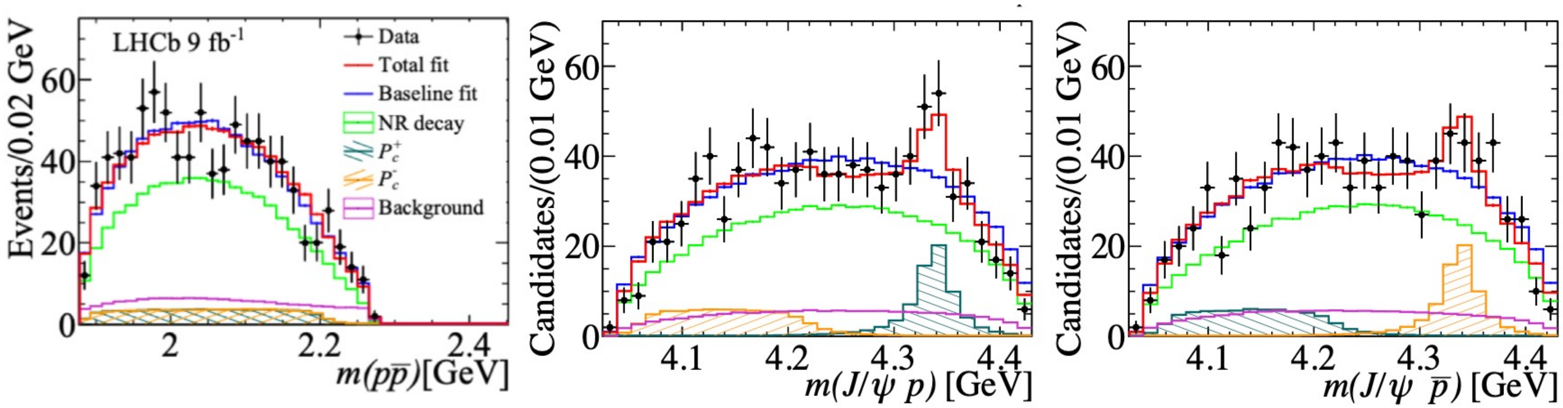
- RUN 1+2 data, untagged *B* decay, with CP conservation, ~800 signals
- 4D amplitude analysis implemented
- Evidence for a new pentaquark-like state Pc:

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

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



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

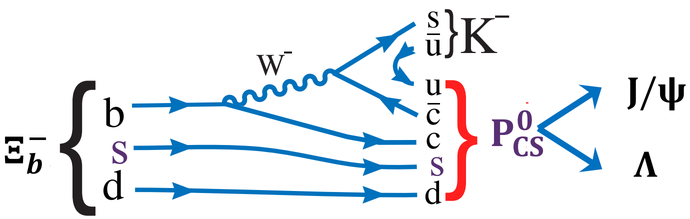


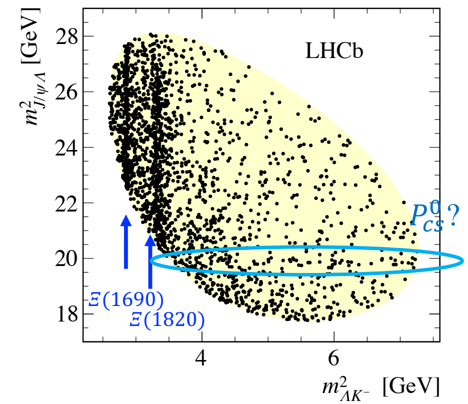
- No evidence for $P_c(4312)$, glueball $f_J(2220)$, $p\bar{p}$ enhancement

Evidence of Pcs in $\Xi_b^- \to J/\psi \Lambda K^-$

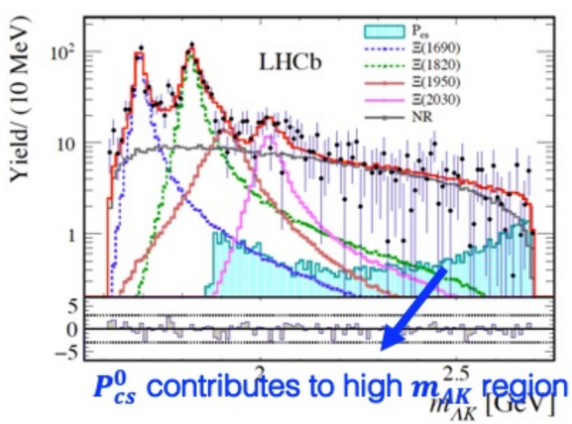
Sci.Bull. 66, 1278(2021)

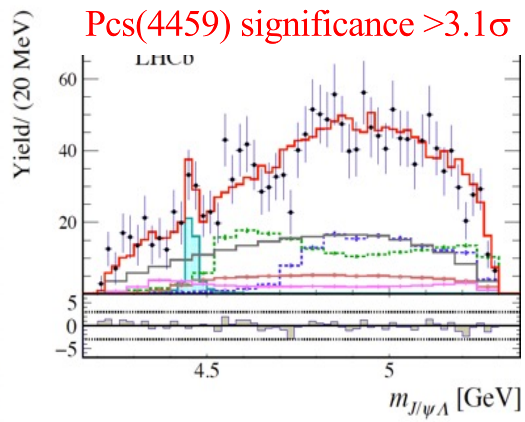
- Aim to search for P_{cs}, a SU(3) partner of P_c state
- RUN 1+2 data: detect ~1750 $\Xi_b^- \to J/\psi \Lambda K^-$ signals

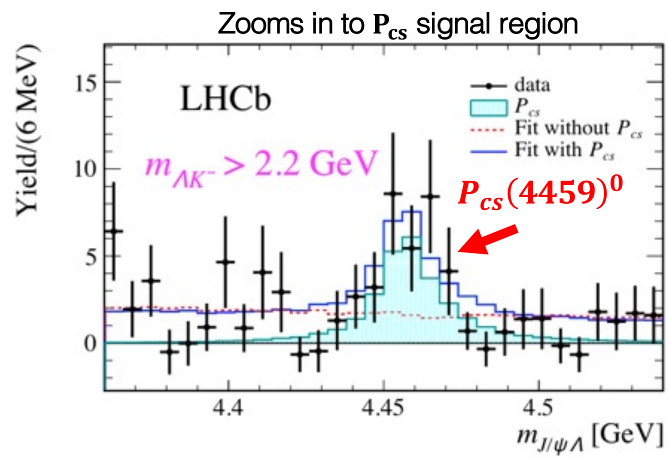




- 6D amplitude analysis is performed







$$m(P_{cs}^0) = 4458.8 \pm 2.9^{+4.7}_{-1.1}\ \text{MeV}, \Gamma(P_{cs}^0) = 17.3 \pm 6.5^{+8.0}_{-5.7}\ \text{MeV}$$

- Statistics not enough for J^P determination
- $P_{cs}(4459)^0$ 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

Summary

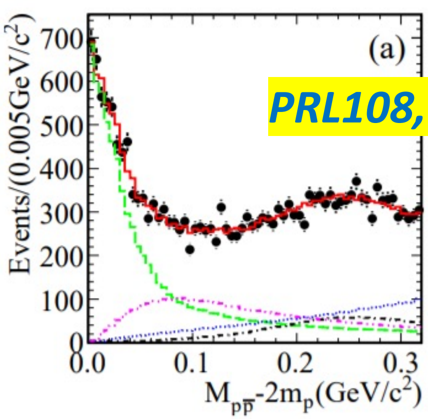
- An exciting period of finding new hadrons during 2019-2022
- Many new hadrons are observed at different experiments
  - new exotic quantum-number hadron: 1^{-+} $\eta_1(1855)$
  - trend of over-populated singly-charm and singly-bottom baryon states: some could be exotic candidates?
  - further understanding of X/Y/Z ($c\bar{c}q\bar{q}$) states
  - new tetraquark states:
    Zcs(3985), Zcs(4000) and Zcs(4226) [$c\bar{c}u\bar{s}$];
    X(6900) [$c\bar{c}c\bar{c}$];
    X(4630), X(685) and $\boldsymbol{X(4740)}$ [$c\bar{c}s\bar{s}$];
    X(2900) [$\bar{c}\bar{s}ud$]; T_{cc}^{+}[$cc\bar{u}\bar{d}$]
  - observation/evidence of new pentaquark states: Pc(4312), Pc(4440), Pc(4457) and Pc(4337) [$c\bar{c}uud$]; $P_{cs}(4459)$ [$c\bar{c}uds$]
- 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($p\bar{p}$)/X(1835) from J/ψ radiative decays

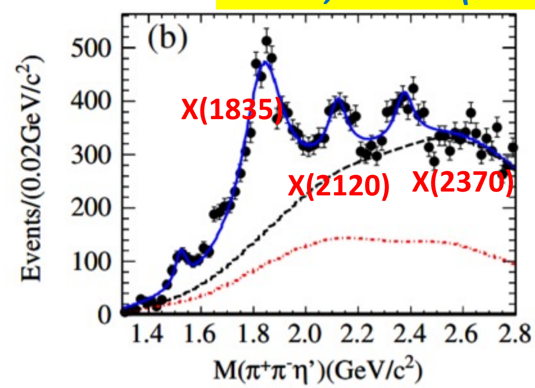
- X($p\bar{p}$)
  - An anomalous strong $p\bar{p}$ threshold enhancement structure which was first observed by BESII in $J/\psi \to \gamma p\bar{p}$
  - BESIII confirmed its existence with much higher significance and PWA (with FSI considered) is performed
    - 0^{-+}
    - Mass = $1836.5^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2
    - Width < 76 MeV/c^2 @ 90% C.L.



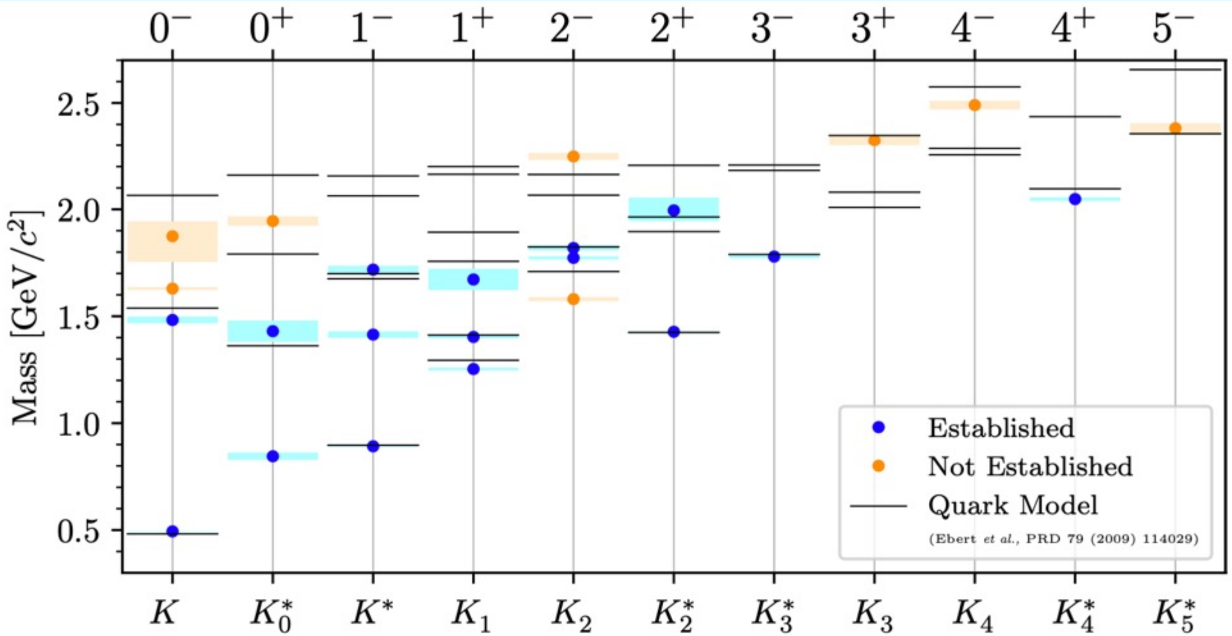
PRL108, 112003 (2012)

- X(1835)
  - First observed by BESII in $J/\psi \to \gamma \eta' \pi^+ \pi^-$
  - BESIII confirmed its existence with much higher significance
    - **Spin-parity is not known**
    - Mass = $1836.5 \pm 3.0^{+5.6}_{-2.1}$ MeV/c^2
    - Width = $190 \pm 9^{+38}_{-36}$ MeV/c^2

PRL106, 072002 (2011)



Are they the same state? A $p\bar{p}$ bound state?
What's the spin-parity of X(1835)?
Why their widths are so different?



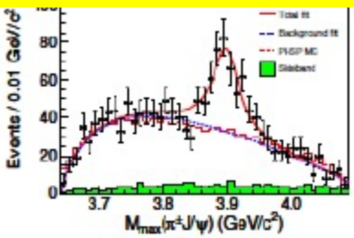
PDG lists 25 strange mesons (2021)

- 16 established states, 9 need further confirmation
- Missing states with respect to quark-model predictions
- Many measurements performed more than 30 years ago

The Zc Family at BESIII

Zc(3900)$^+$

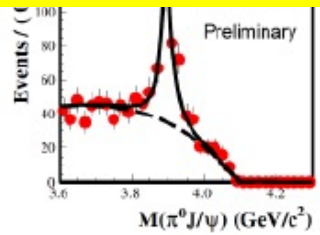
PRL 110, 252001 (2013)



$e^+e^- \to \pi^-\pi^+ J/\psi$

Zc(3900)^0

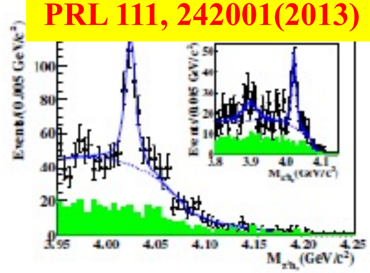
PRL 115, 112003 (2015)



$e^+e^- \to \pi^0\pi^0 J/\psi$

Zc(4020)$^+$

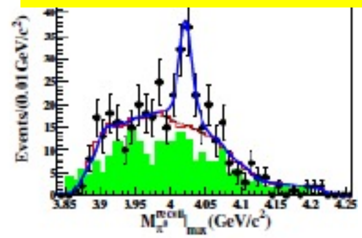
PRL 111, 242001(2013)



$e^+e^- \to \pi^-\pi^+ h_c$

Zc(4020)^0

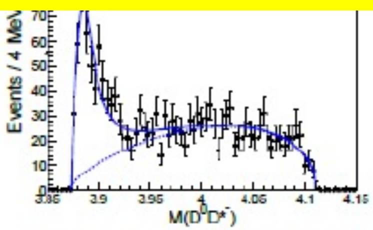
PRL113,212002 (2014)



$e^+e^- \to \pi^0\pi^0 h_c$

Zc(3885)$^+$

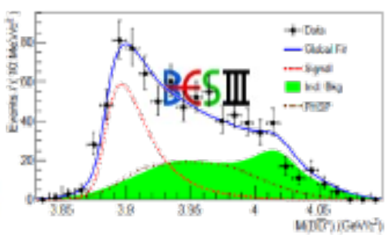
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

Zc(3885)^0

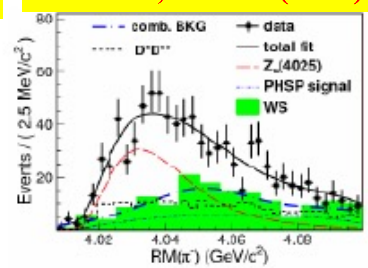
PRL 115, 222002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D})^0$

Zc(4025)$^+$

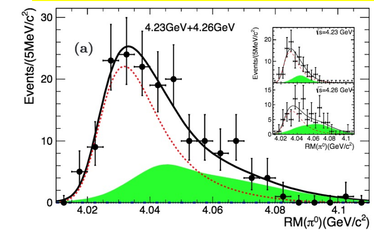
PRL 112, 132001 (2014)



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

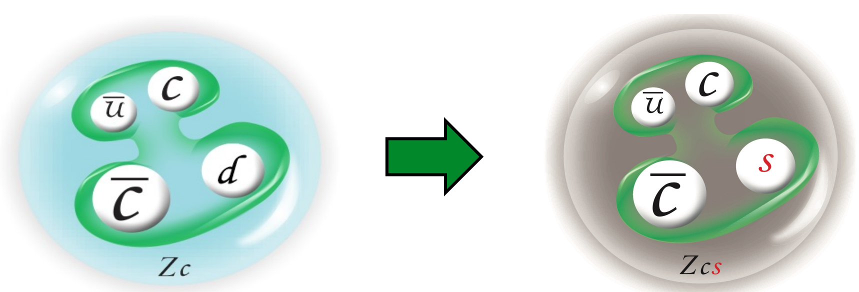
Zc(4025)^0

PRL115, 182002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

Which is the nature of these states?
If exists, there should be SU(3) counter-part Zcs state with strangeness



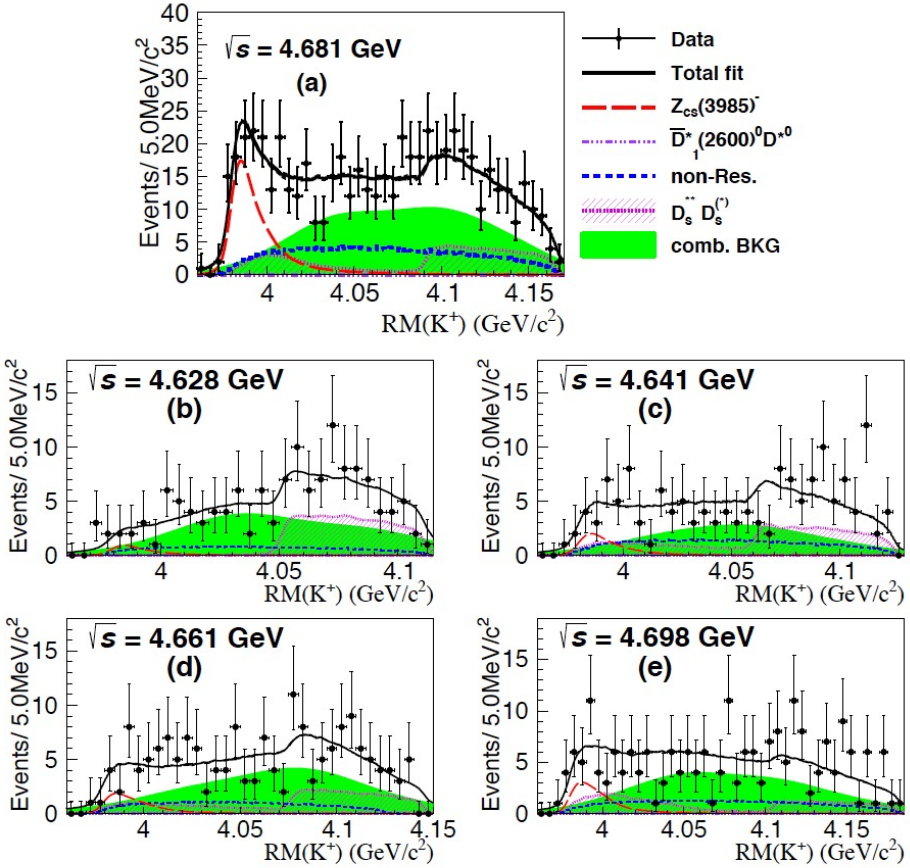
BESIII实验上的Zc家族

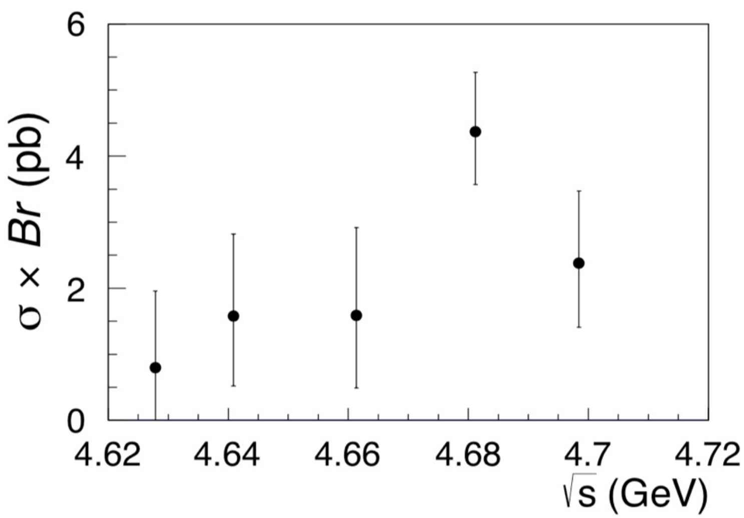
State	Mass (MeV/c²)	Width (MeV)	Decay	Process
$Z_c(3900)^{\pm}$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$\pi^{\pm} J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$ Single D tag	$24.8 \pm 3.3 \pm 11.0$ Single D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$
	$3881.7 \pm 1.6 \pm 2.1$ Double D tag	$26.6 \pm 2.0 \pm 2.3$ Double D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	$(D\bar{D}^*)^0$	$e^+e^- \to (D\bar{D}^*)^0\pi^0$
$Z_c(4020)^{\pm}$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^{\pm} h_c$	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^0\pi^0$

Production cross sections of the $Z_{cs}(3985)^{\pm}$

PRL 126, 102001 (2021)

- Simultaneous fit to the five energy points





- Largest cross sections around 4.681 GeV

The Zcs(3985)$^{\pm}$ and Zc(3900)$^{\pm}$

	1643/pb data @4.681 GeV	525/pb data @4.26 GeV	
	$Z_{cs}(3985)^{\pm}$	$Z_c(3900)^{\pm}$	$Z_c(3885)^{\pm}$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	3899.0±3.6±4.9	3883.9±1.5±4.2
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	46±10±26	24.8±3.3±11.0
$\sigma^{Born} \cdot \mathfrak{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	13.5±2.1±4.8	83.5±6.6±22.0

- close width
- cross section: one-order-of-magnitude less

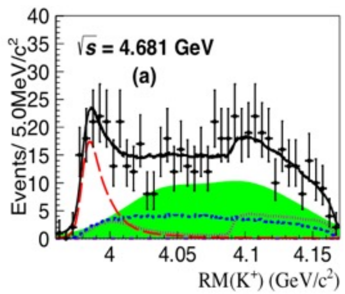
two general comments about charm-tau factory program

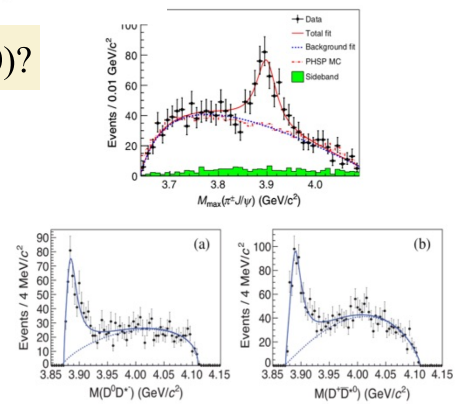
- $J/\psi K^{\pm}$ resonances: $Z_c(3900)$ analogue? $Z_c(3900)^+ = (c\bar{c}u\bar{d})$; $d \to s$: $(c\bar{c}u\bar{s}) \sim D_s\bar{D}^*$ no natural molecular binding, so if discovered, would indicate Tq or a novel mechanism

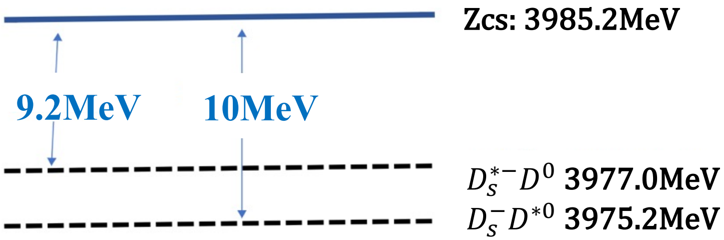
from Marek Karliner in Nov. 2020

~10 MeV above D_sD^*/D_sD thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

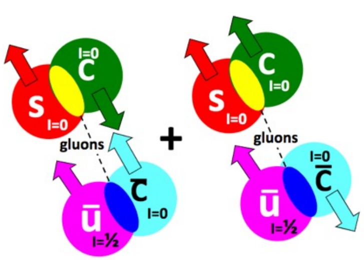
SU(3) partner of Zc(3900)?



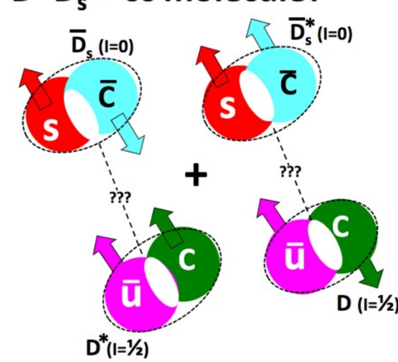




diquark-antidiquark?



D*$\bar{D}_s$ + cc molecule?



$Z_{cs}(3985)$

$K^-Z_{cs}^+$	$\bar{K}^0Z_{cs}^0$	$K^0\bar{Z}_{cs}^0$	$K^+Z_{cs}^-$
1/4	1/4	1/4	1/4

neutral/charged = 1

$Z_c(3900)$

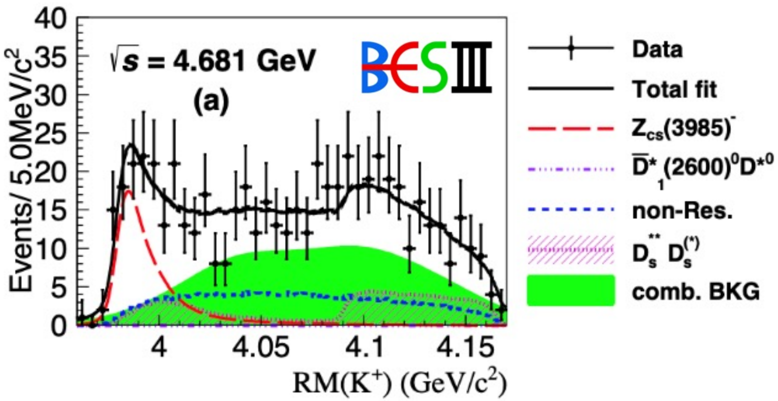
$\pi^-Z_c^+$	$\pi^0Z_c^0$	$\pi^+Z_c^-$
1/3	1/3	1/3

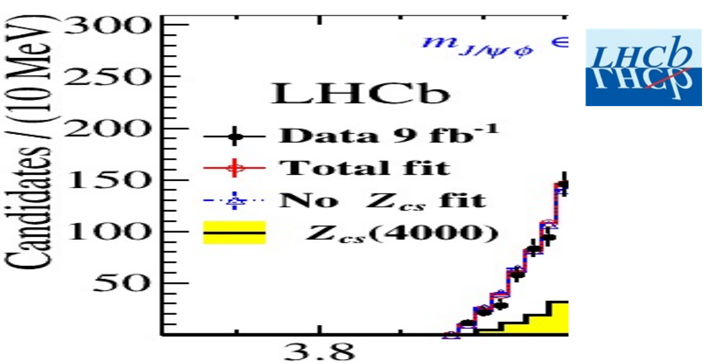
neutral/charged = 1/2

Discussions on the results

$Z_{cs}(3985)$ from e^+e^- annihilations and $Z_{cs}(4000)$ **from B decays**

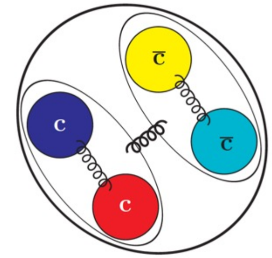
- **their masses** are **close, but widths** are different





Prompt J/ψ pair production

- Using J/ψ pair final states to reconstruct $T_{cc\bar{c}\bar{c}}$
  $J/\psi \to \mu^+\mu^-$ has good trigger efficiency



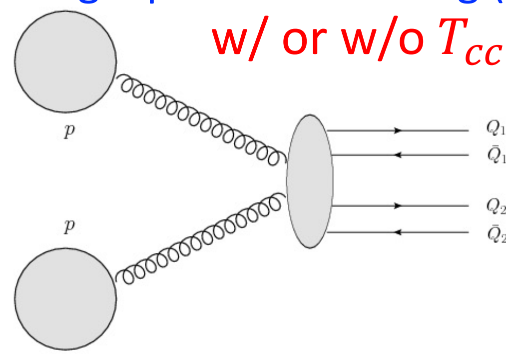
[arXiv: 1803.02522]

J^{PC}	S-wave	P-wave
0^{++}	$\eta_c(1S)\eta_c(1S)$, $J/\psi J/\psi$	$\eta_c(1S)\chi_{c1}(1P)$, $J/\psi h_c(1P)$
0^{-+}	$\eta_c(1S)\chi_{c0}(1P)$, $J/\psi h_c(1P)$	$J/\psi J/\psi$
0^{--}	$J/\psi\chi_{c1}(1P)$	$J/\psi\eta_c(1S)$
1^{++}	–	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$, $\eta_c(1S)\chi_{c0}(1P)$
1^{+-}	$J/\psi\eta_c(1S)$	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$
1^{-+}	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$	–
1^{--}	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$	$J/\psi\eta_c(1S)$

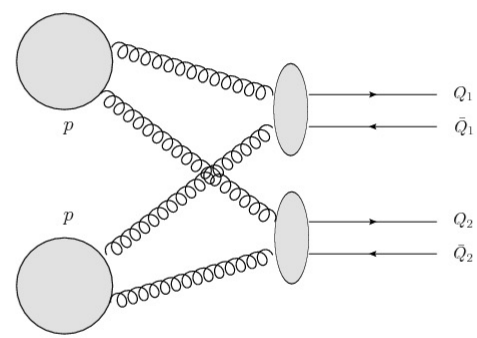
Decays in $2J/\psi$ directly or with feed-down

Single parton scattering (SPS)

w/ or w/o $T_{cc\bar{c}\bar{c}}$



Double parton scatterings (DPS)



- $T_{cc\bar{c}\bar{c}}$ state production via SPS is dominant over DPS
- DPS: dominates high J/ψ pair mass region

The first hint of the signal: $D^0 D^0 \pi^+$ and $D^0 \bar{D}^0 \pi^+$