Experimental status of exotic hadrons

Yanxi ZHANG/张艳席
Peking University

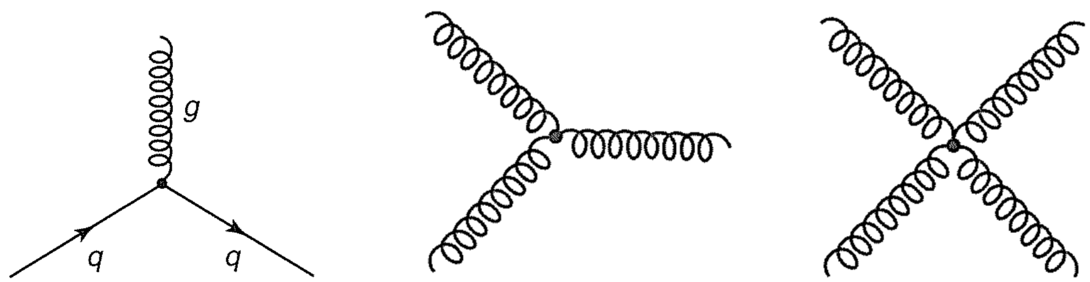
yanxi.zhang@pku.edu.cn

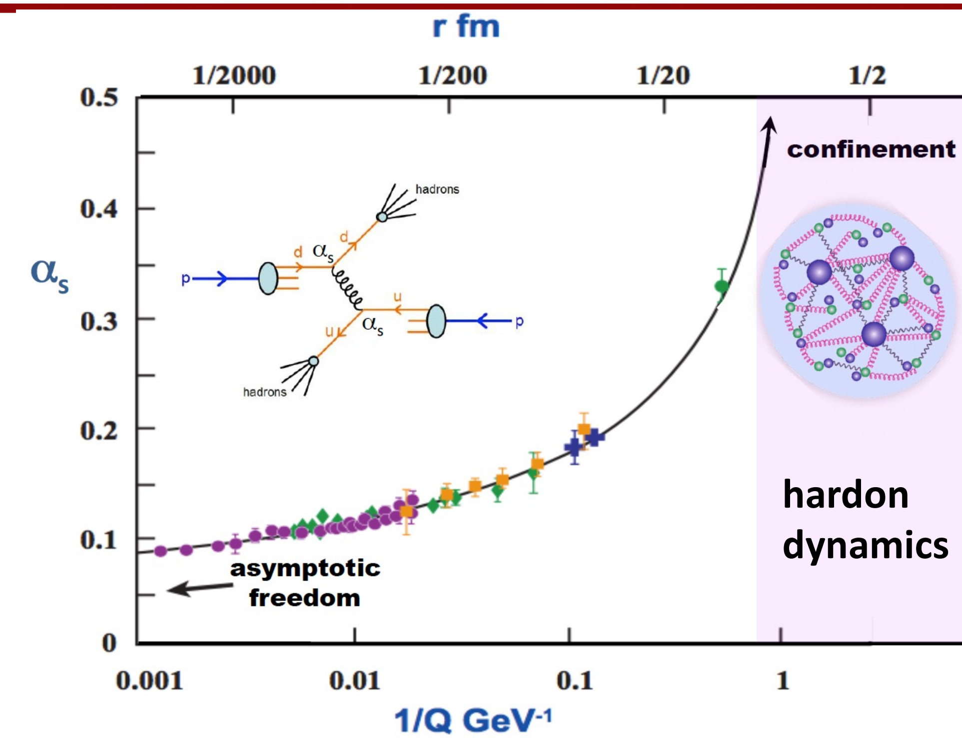
CEPC Workshop on Flavor Physics, New Physics and Detector Technologies

2023/Aug/13 - 18
Fudan University, Shanghai

Understanding QCD

- Rich phenomenon from low to high energy scales



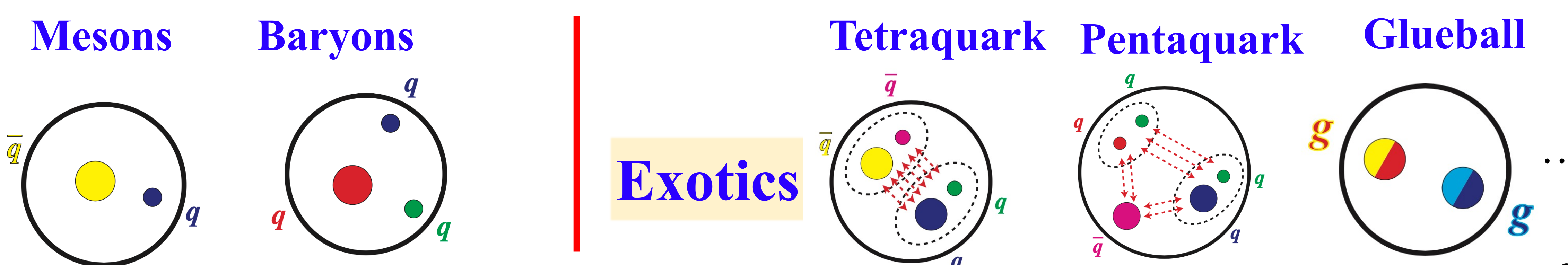


- Difficult for precise calculations, not even "calculable" at low-energy/confinement domain (non perturbative)

Hadron vacuum polarization, flavour anomalies, QGP, QCD in nuclei…

- (Exotic) hadrons: understand low-energy QCD, test models/computational tools

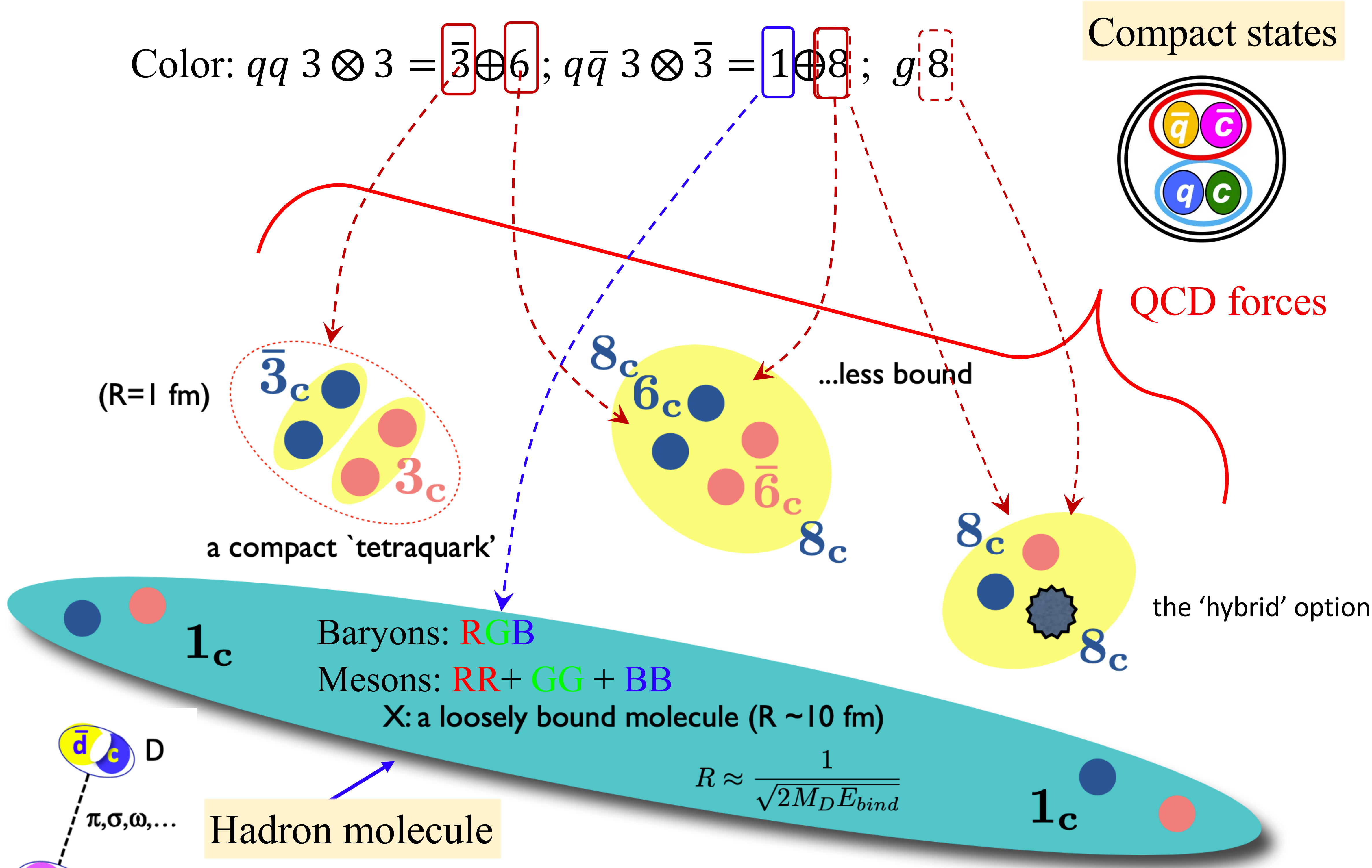
Classification of hadrons (colourless composite objects of quarks/gluons):



Rept.Prog.Phys. 86 (2023) 026201

Color structure in exotic states

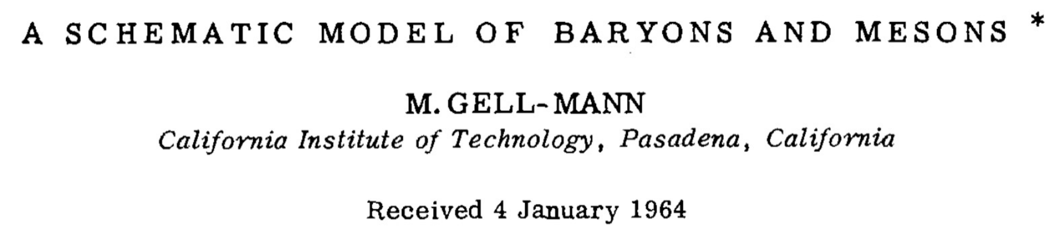
Rev.Mod.Phys. 90 (2018) 015003



Nuclear forces, close to Di-hadron threshold

A brief history of heavy exotic hadrons

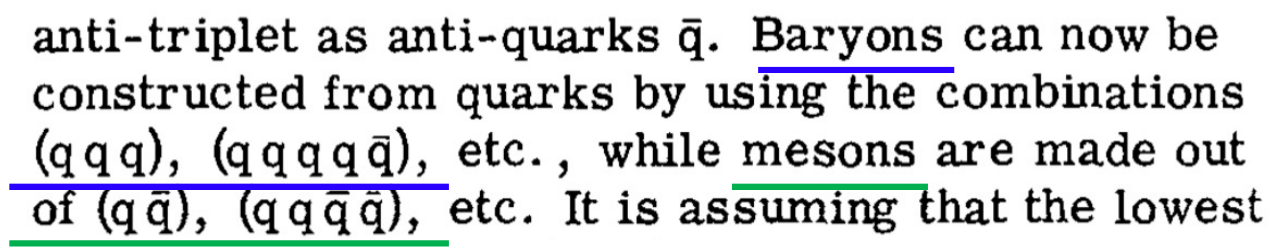
- Predicted in Gell-Mann paper


A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

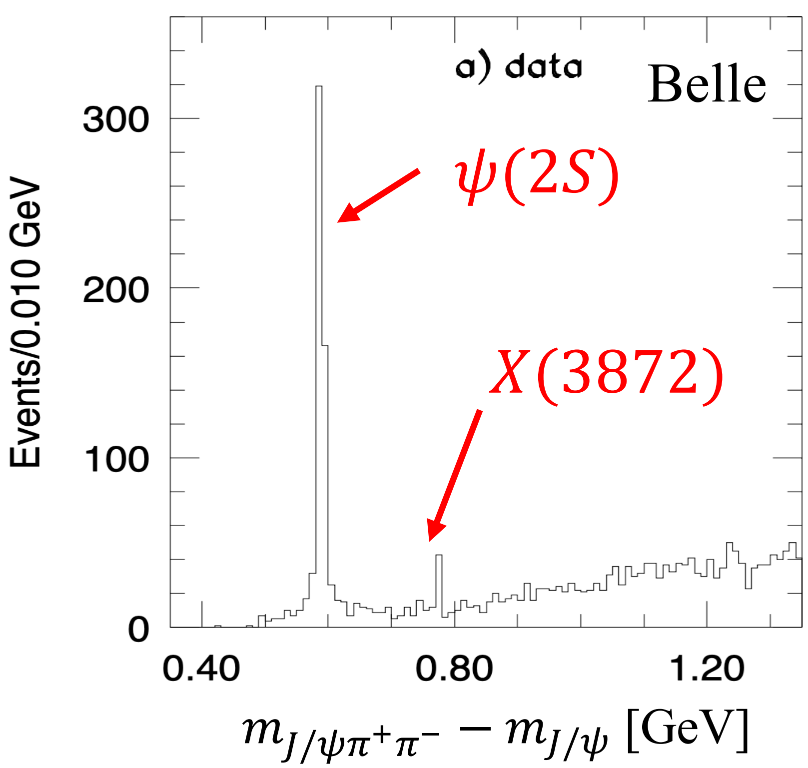
- Difficult to identify light exotic hadrons


anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

- First experimental signature: $X(3872)$ discovered by Belle in 2003

PRL91(2003)262001

e^+e^- machine !



$B^+ \to X(3872)K^+, X(3872) \to J/\psi\pi^+\pi^-$

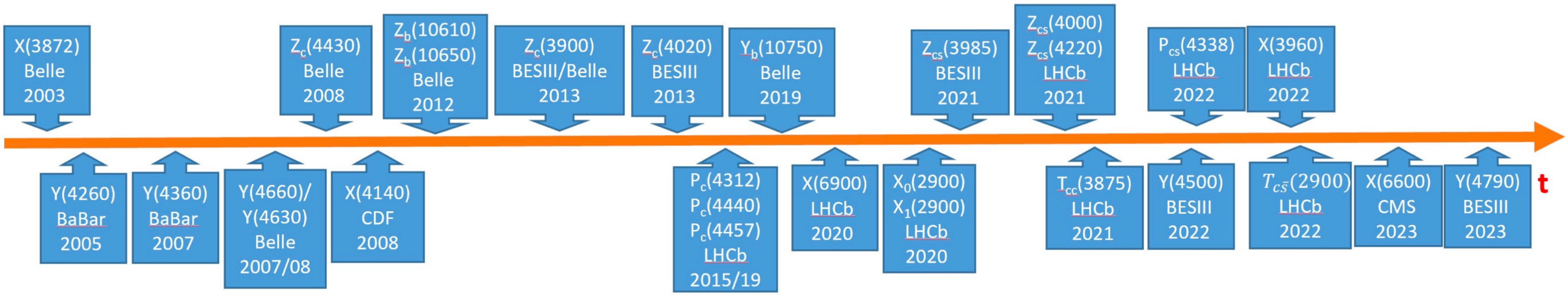
- Mass not fit into $c\bar{c}$ spectrum
- Extremely narrow width
- Close to $D^{*0}\bar{D}^0$ threshold
- Isospin breaking decay …

Likely contains $c\bar{c}u\bar{u}/D^{*0}\bar{D}^0$ component instead of just being a $c\bar{c}$ state

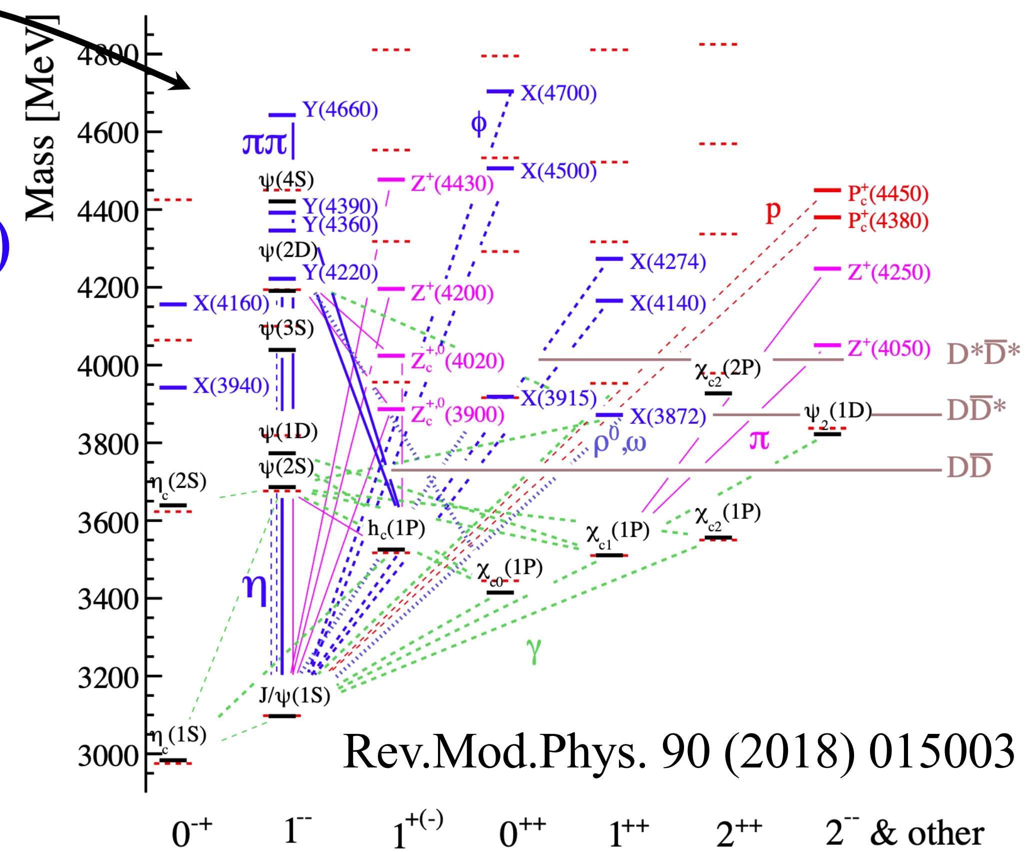
A brief history of heavy exotic hadrons

- Zoo expands within two decades

Stolen from talk by Chang-Zheng Yuan



- ➢ With $c\bar{c}/b\bar{b}$ valence (quarkonium-like)
  - ✓ Neutral and/or vector tetraquarks (XY)
  - ✓ Charged tetraquarks (Z)
  - ✓ Pentaquarks (P_c)
- ➢ With a c quark
- ➢ With cc quarks
- ➢ With two pairs of $c\bar{c}$ quarks

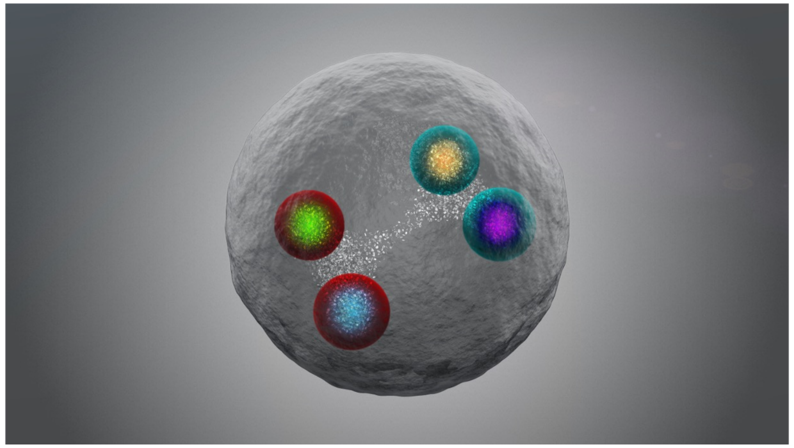


Rev.Mod.Phys. 90 (2018) 015003

Contributed by Belle, BaBar, CDF, BES, LHCb, CMS, ATLAS …

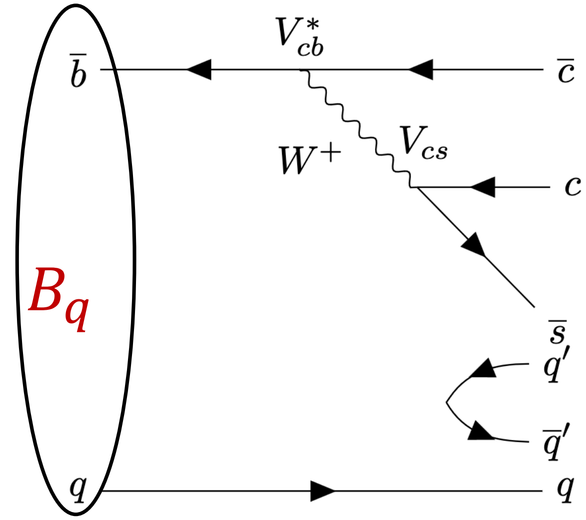
Tetraquarks with $c\bar{c}$ or $b\bar{b}$

$c\bar{c}q\bar{q}$



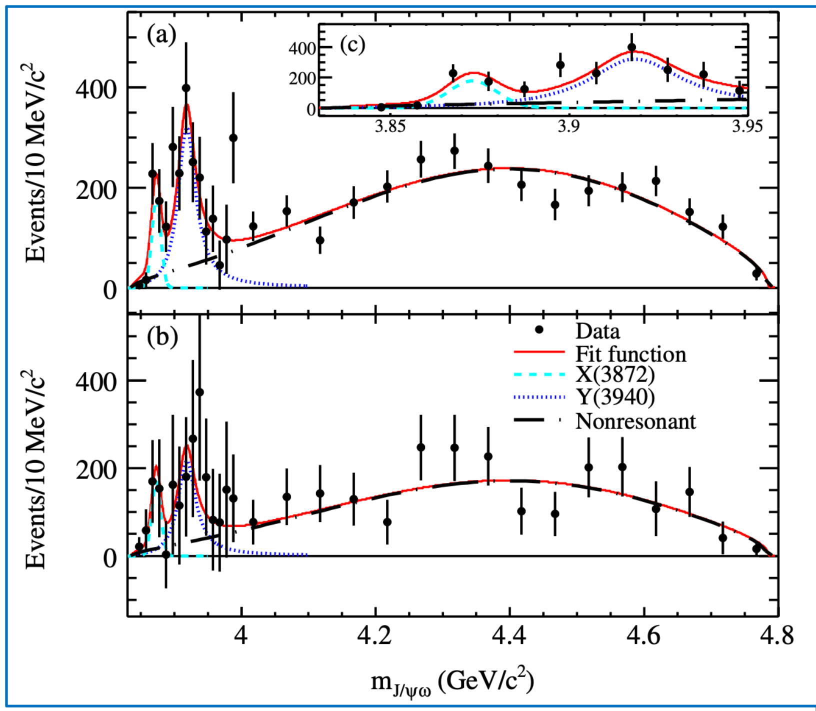
Tetraquarks in B decay

- b-hadron decays provide environment for $c\bar{c}$-exotic hadron production



$B \to X(3872)K, X(3872) \to J/\psi\omega(\pi^+\pi^-)$

$B \to X(3915)K, X(3915) \to J/\psi\omega$

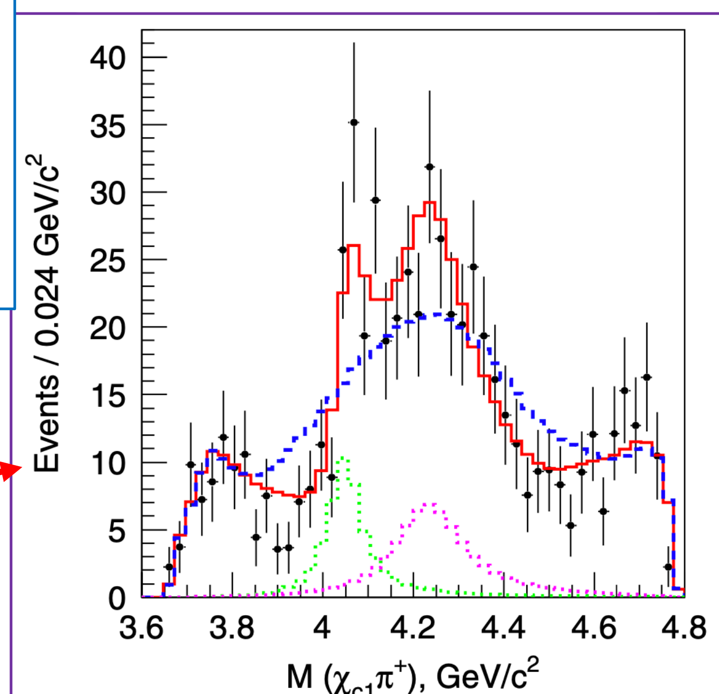


PRD82(2010)011101R

$\bar{B}^0 \to Z_c(4050)^+K^-$

$\bar{B}^0 \to Z_c(4250)^+K^-$

$Z_c^+(c\bar{c}u\bar{d}) \to \chi_{c1}\pi^+$

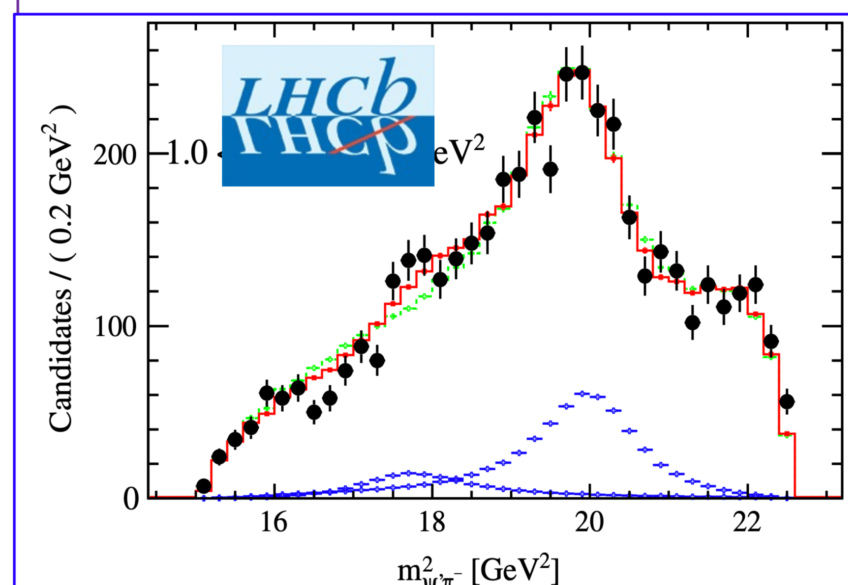


PRD78(2008)072004

$\bar{B}^0 \to Z_c(4430)^+K^-$

$\bar{B}^0 \to Z_c(4200)^+K^-$

$Z_c^+(c\bar{c}u\bar{d}) \to \psi(2S)\pi^+$



PRL112(2014)222002

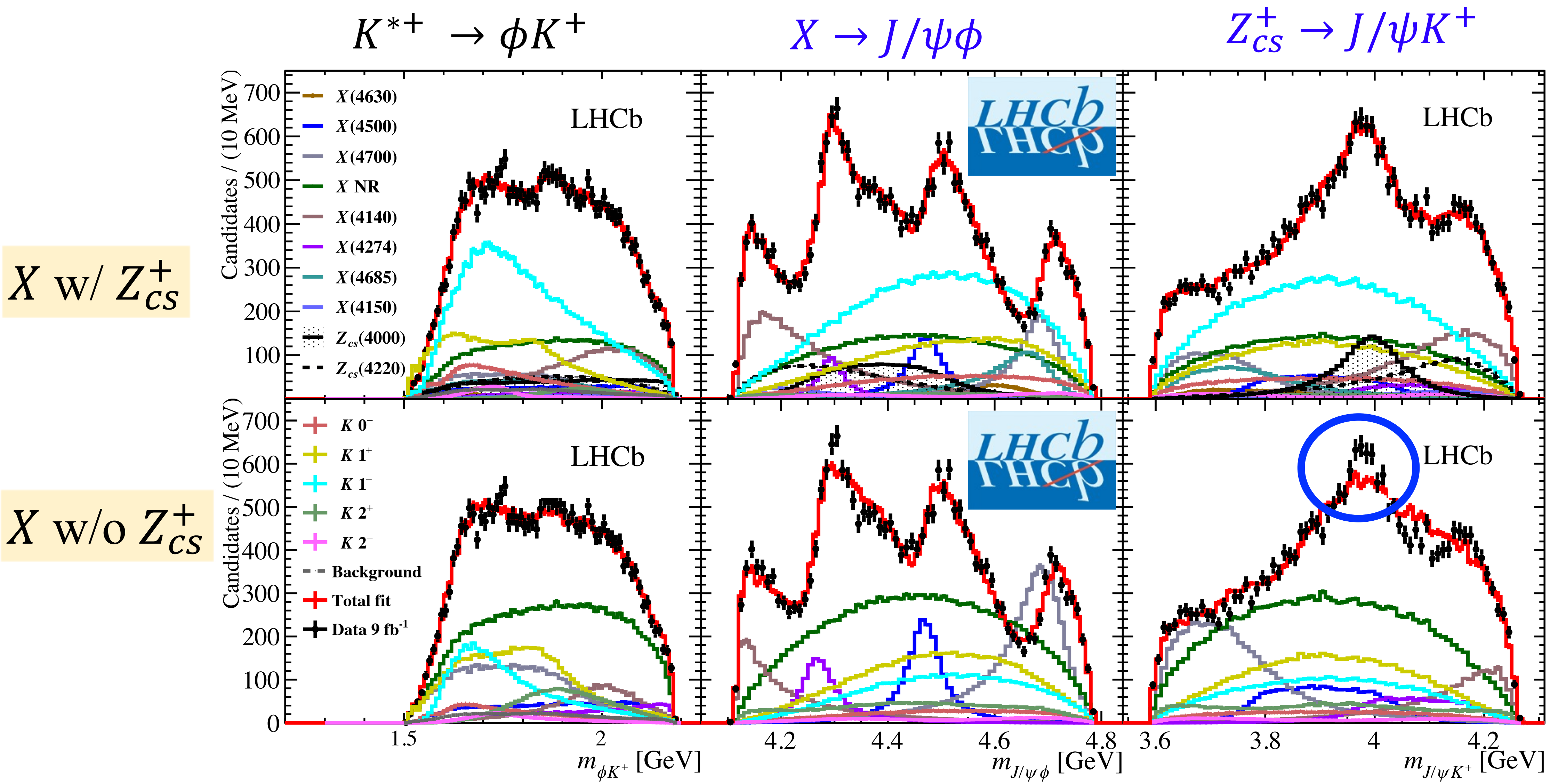
B-factories

Difficult for LHCb for photons

Tetraquark with strangeness in $B^+ \to J/\psi\phi K^+$ decays

PRL127(2021)082001

- Exotic discovered in $B^+ \to J/\psi\phi K^+$ decays
  - Multiple structures in $J/\psi\phi$ spectrum, candidates of $X[c\bar{c}s\bar{s}]$ tetraquarks
  - Two structures in $J/\psi K^+$ spectrum: $Z_{cs}(4000)^+$ and $Z_{cs}(4200)^+$ with $[c\bar{c}u\bar{s}]$



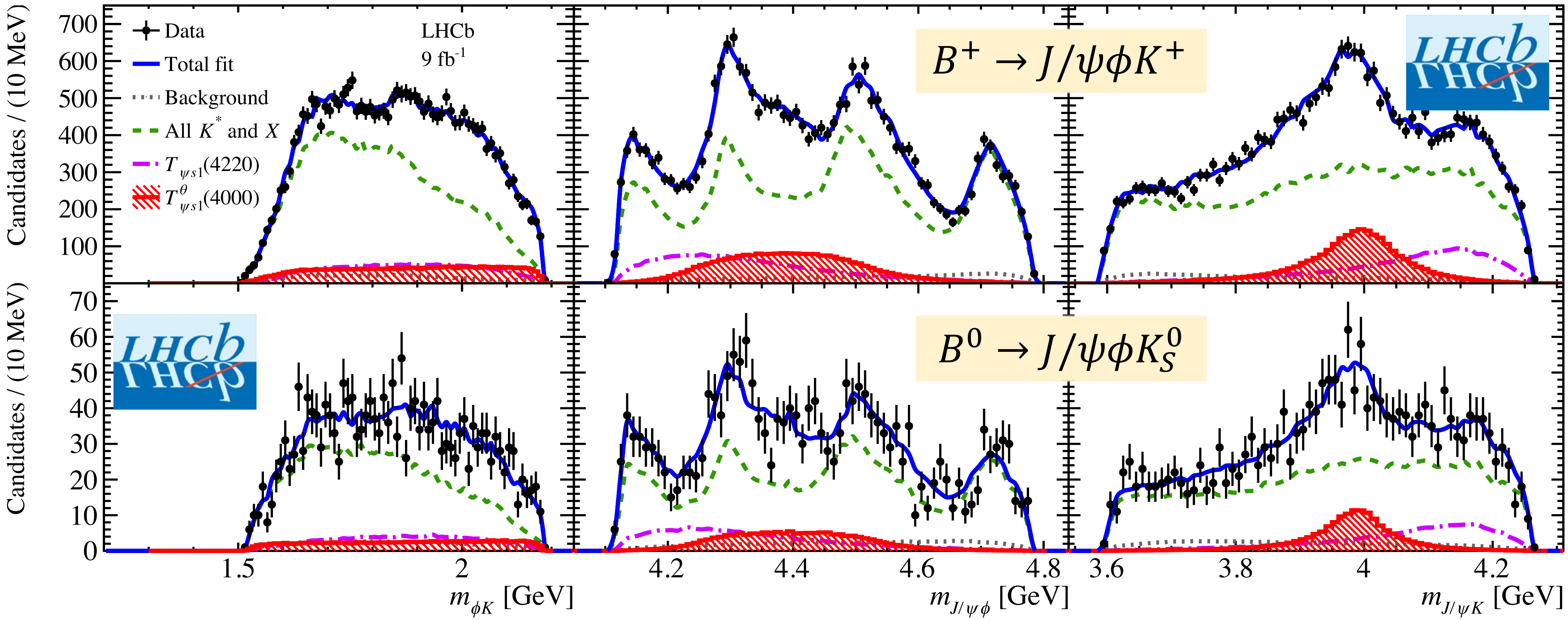
Isospin analysis of $B \to J/\psi\phi K$ decays

LHCb-PAPER-2022-040

- Simultaneous analysis of $B^+ \to J/\psi\phi K^+$ and $B^0 \to J/\psi\phi K_S^0$ decays

Evidence of $Z_{cs}(4000)^0[c\bar{c}d\bar{s}] \to J/\psi K_S^0$, isospin partner of $Z_{cs}(4000)^+$

$$\Delta M_{\text{isospin}} = -12^{+11+6}_{-10-4} \text{ MeV}$$

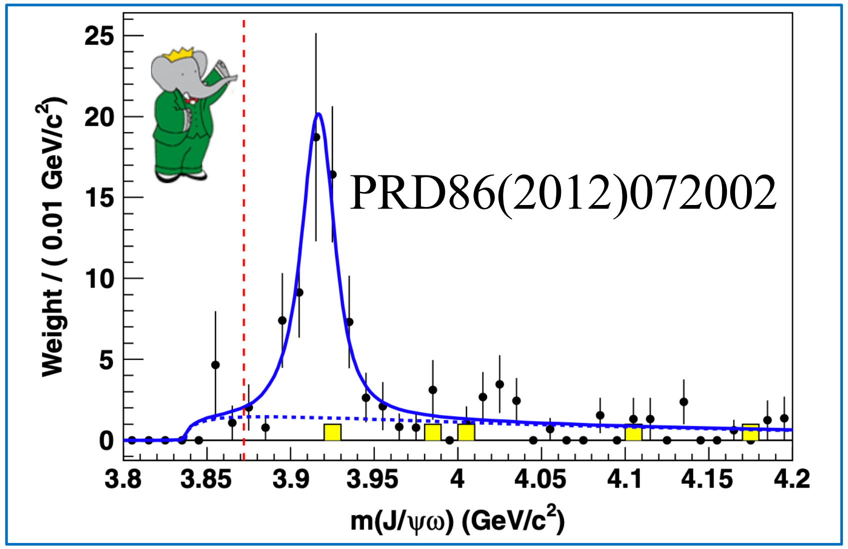


Statistics of $B^0 \to J/\psi\phi K_S^0$ limited by K_S^0 detection

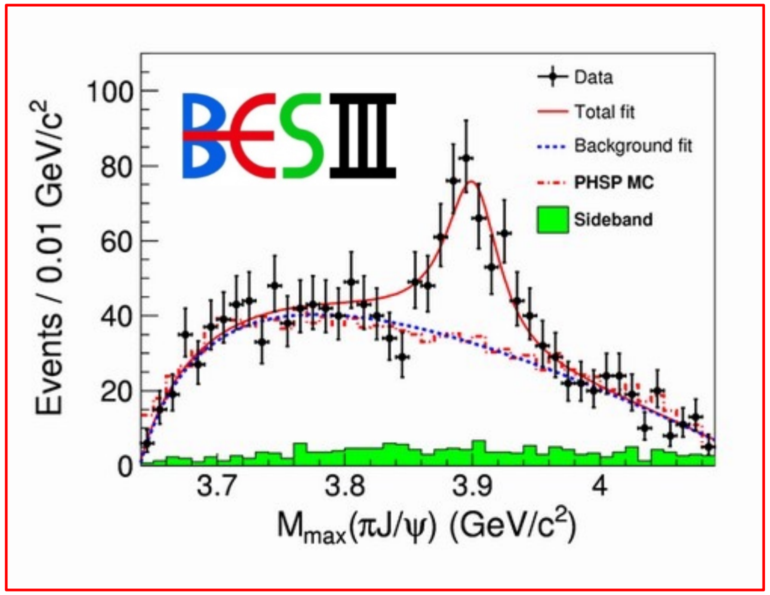
Charmonium like states in e^+e^- production

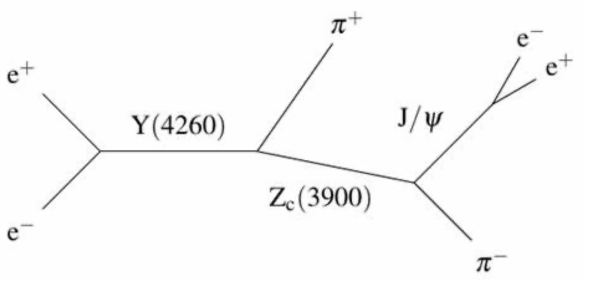
- $e^+e^- \to Y, Zh;\ \gamma\gamma \to X$

$\gamma\gamma \to X(3915)[c\bar{c}q\bar{q}] \to J/\psi\omega$



$e^+e^- \to Z_c(3900)^\pm\pi^\mp, Z_c^+[c\bar{c}u\bar{d}] \to J/\psi\pi^+$

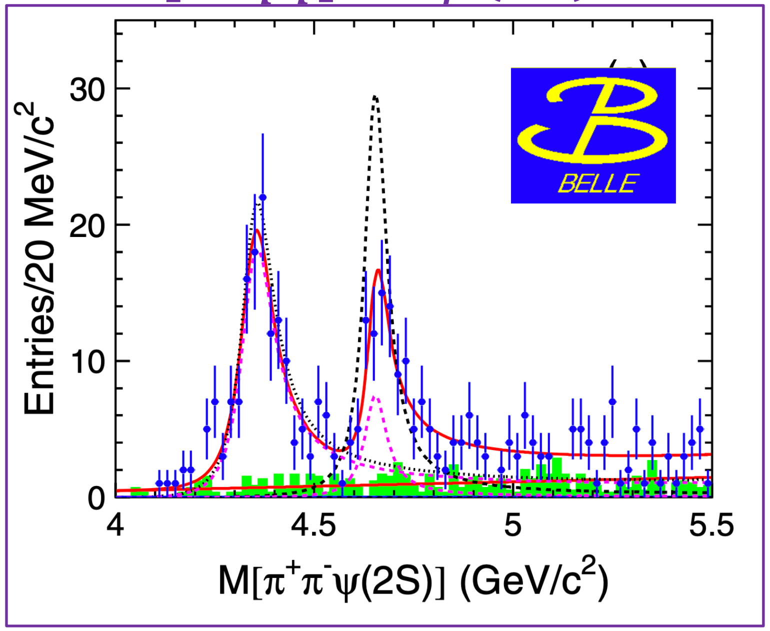




PRL110(2013)252001

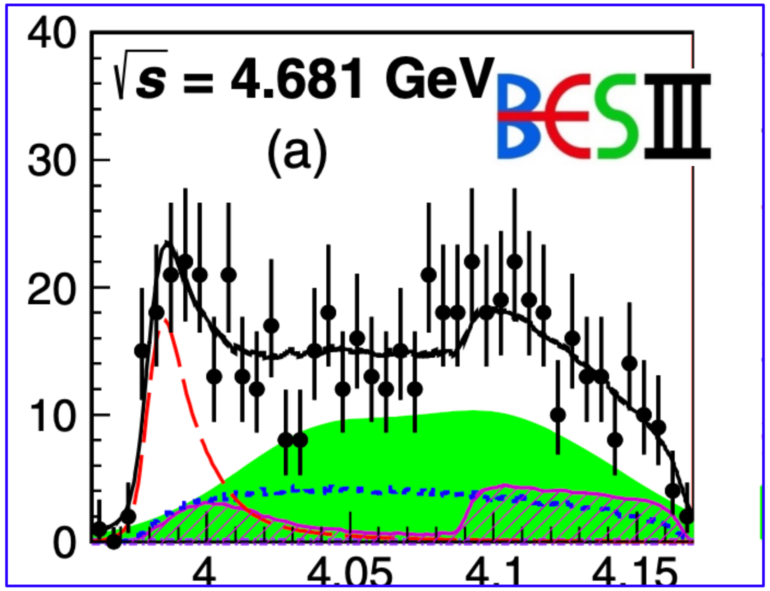
$e^+e^- \to \gamma_{ISR}Y(4360),\ \gamma_{ISR}Y(4660)$

$Y[c\bar{c}q\bar{q}] \to \psi(2S)\pi^+\pi^-$



PRD91(2015)112007

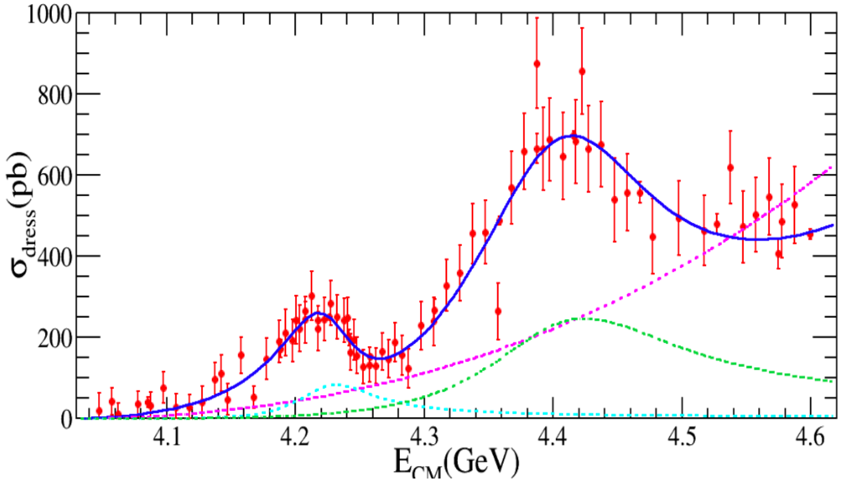
$e^+e^- \to Z_{cs}(3985)^\pm K^\mp, Z_{cs}^+[c\bar{c}u\bar{s}] \to D_s^- D^{*0} + D_s^{*-}D^0$



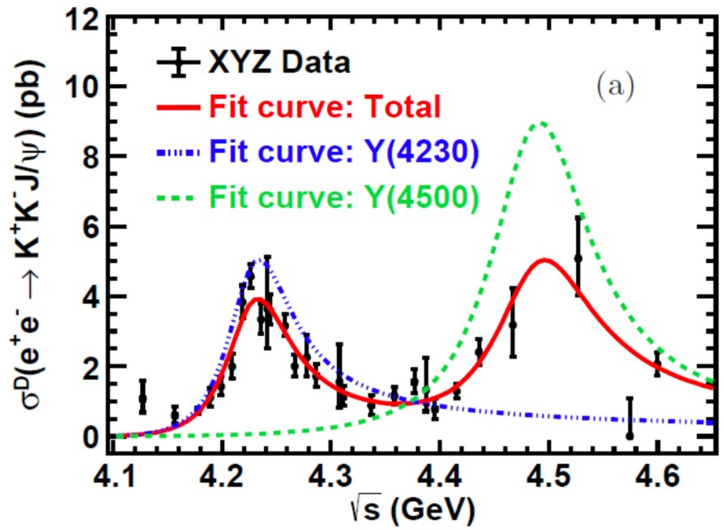
PRL126(2021)102001

Potentials of e^+e^- at BESIII in charm region

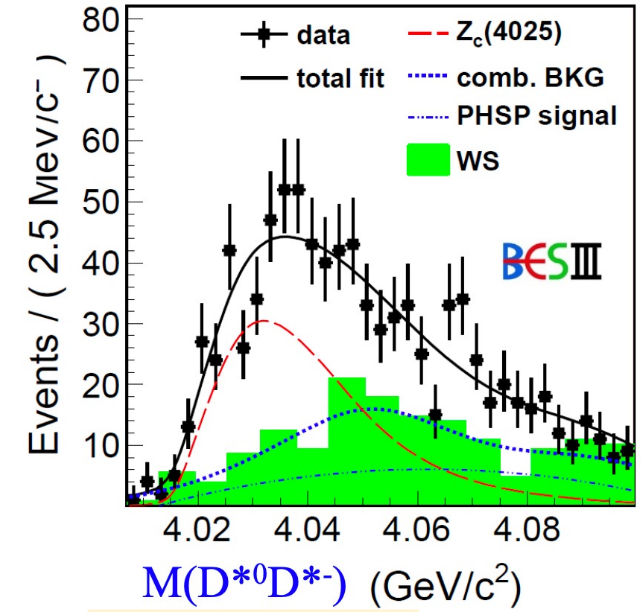
4π acceptance, neutral particle reconstruction, background free…



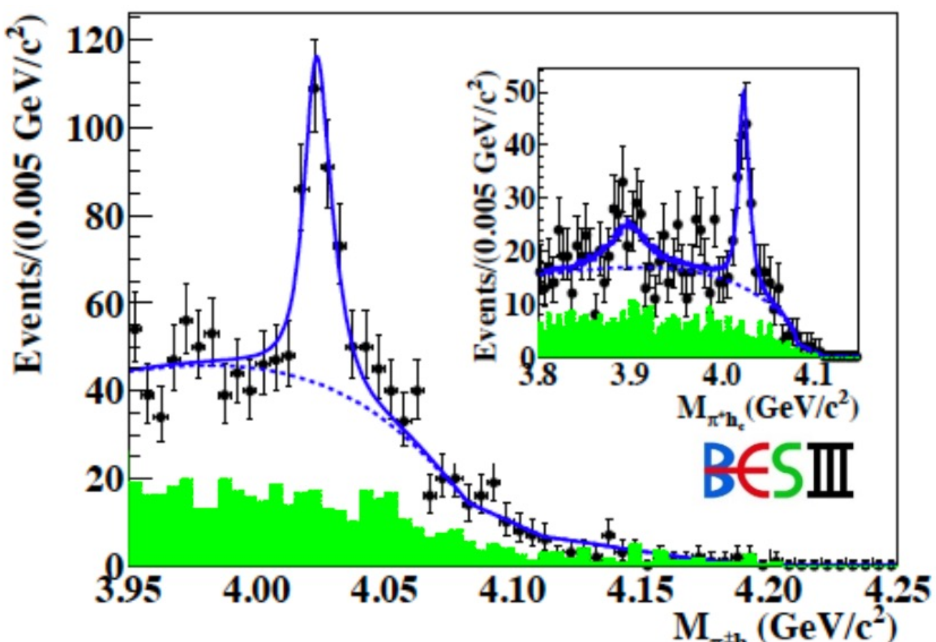
$Y(4230)$



$Y(4500)$



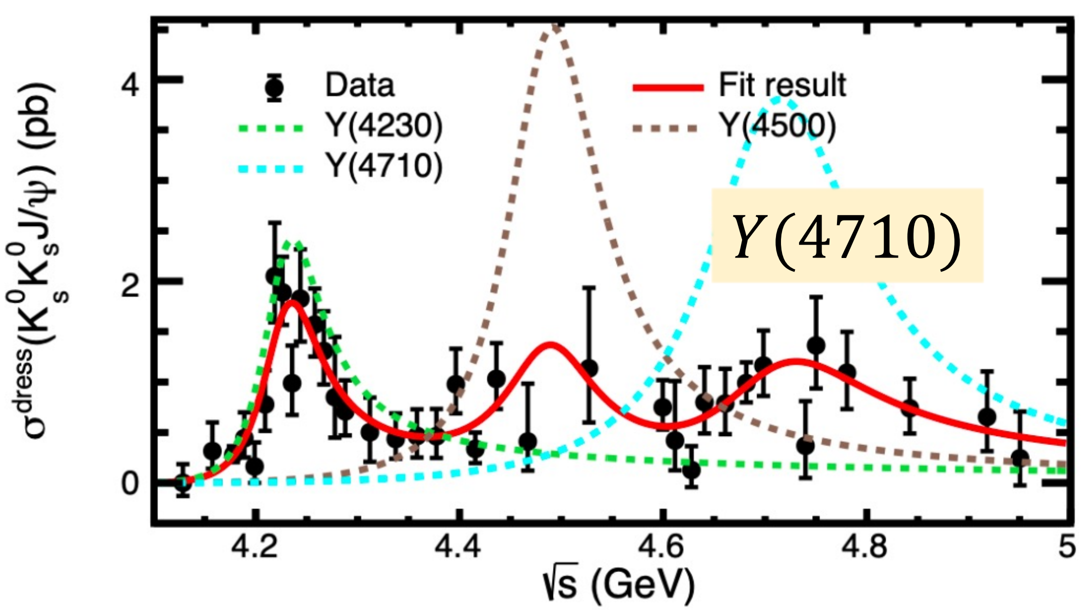
$Z_c(4025)^+$



$Z_c(4020)^+$

PRD107, 092005 (2023)

$e^+e^- \to K_SK_SJ/\psi$



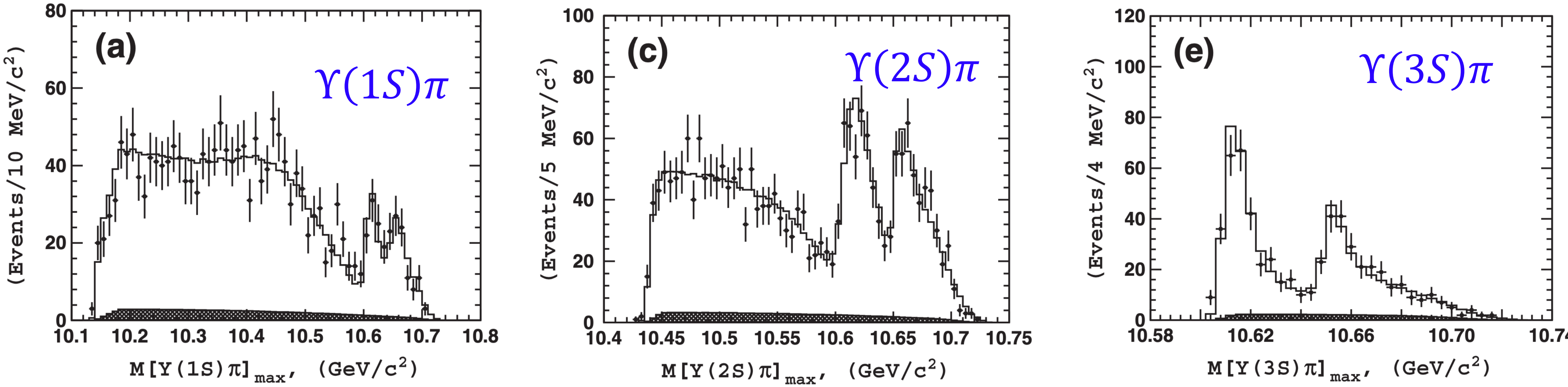
$Y(4710)$

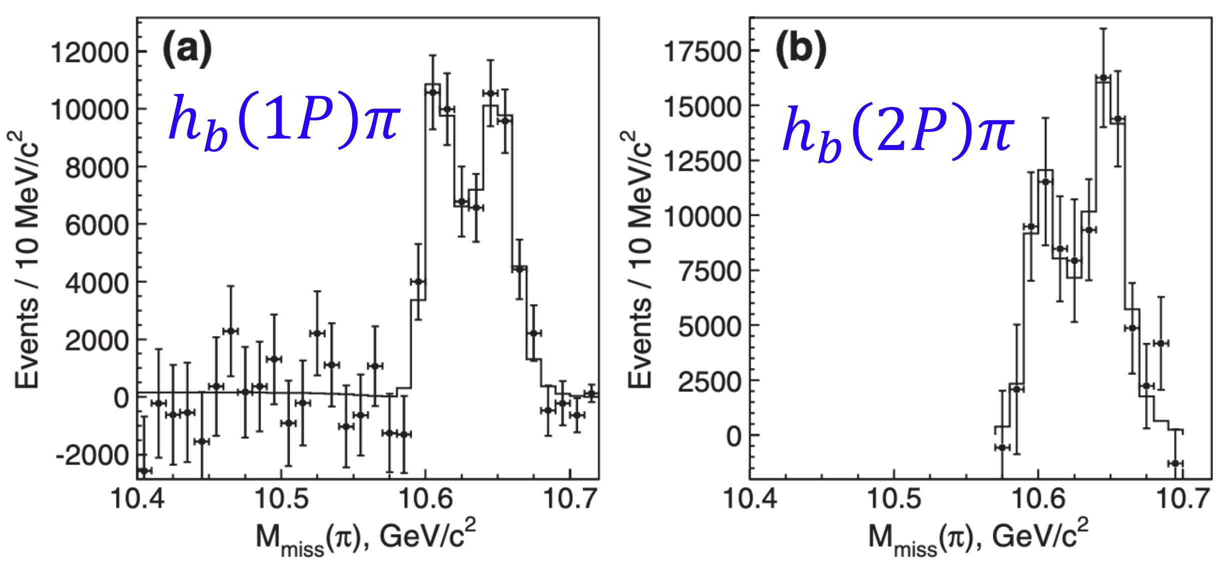
Tetraquark states with $b\bar{b}$

- $e^+e^- \to \Upsilon(10860) \to Z_b(10610)^{\pm}\pi^{\mp}, Z_b(10650)^{\pm}\pi^{\mp}$

  with $Z_b^+[b\bar{b}u\bar{d}] \to \Upsilon(nS)\pi^+,\ h_b(nP)\pi^+$

PRL108(2012)122001

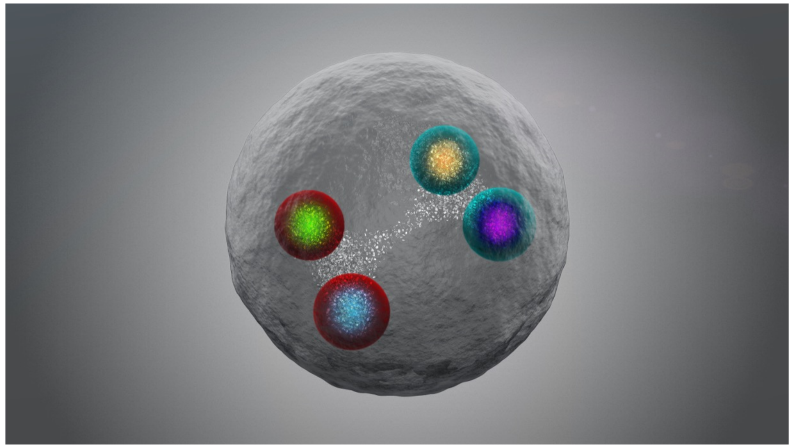




$h_b: S_{b\bar{b}} = 0, L_{b\bar{b}} = 1$

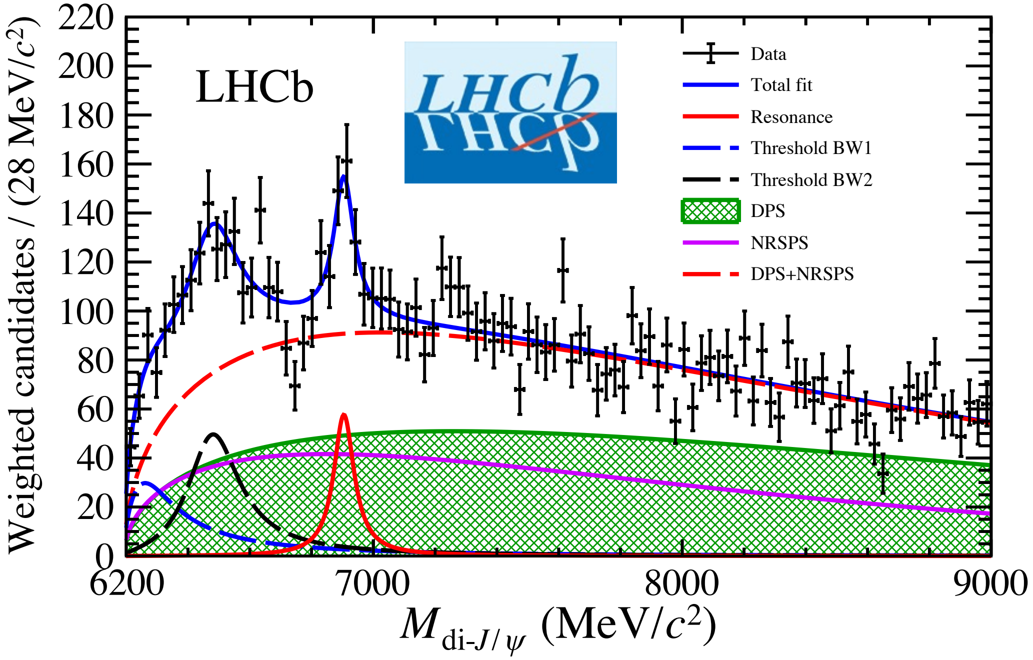
Tetraquarks with two $c\bar{c}$ pairs

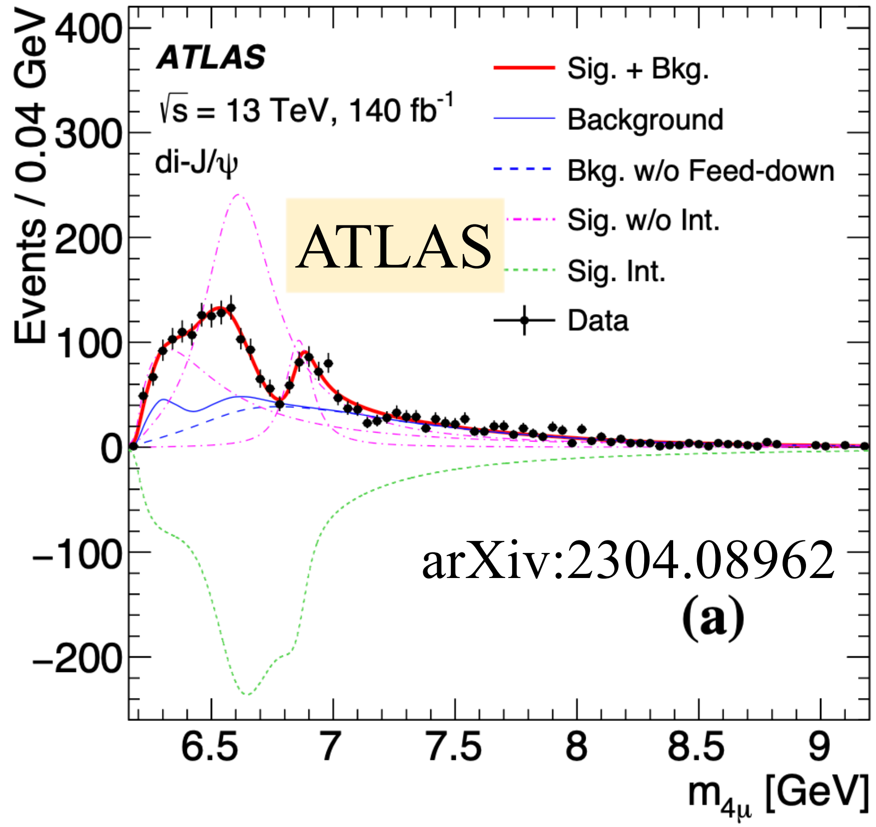
$c\bar{c}c\bar{c}$

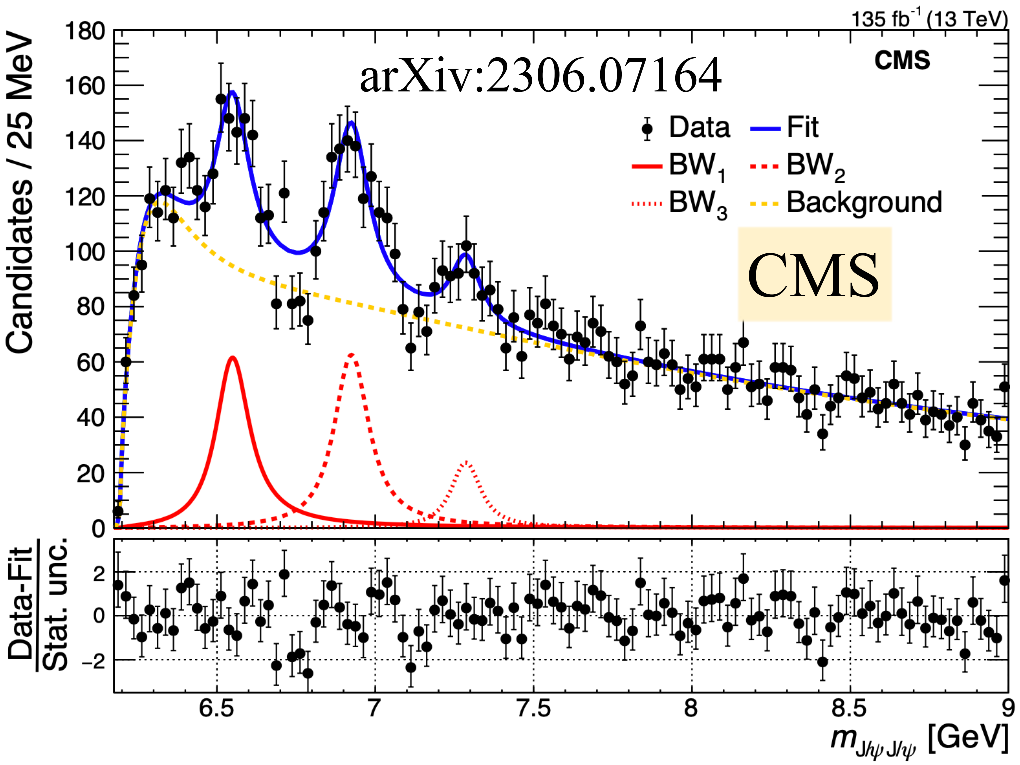


Fully charmed tetraquark in J/ψ-pair spectrum

Science Bulletin 65 (2020) 1983







$X[c\bar{c}c\bar{c}] \rightarrow J/\psi J/\psi$

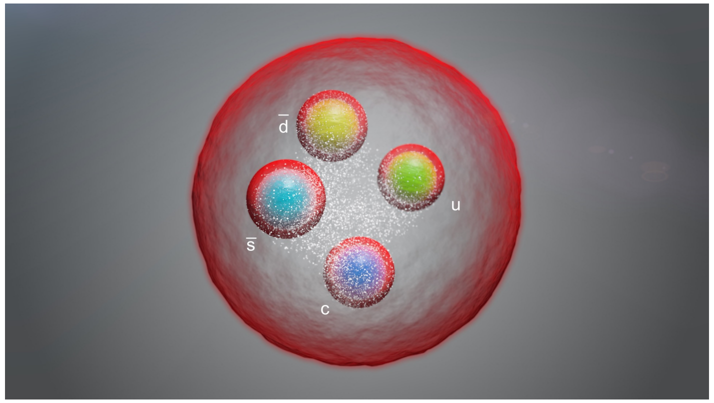
Observation of $X(6900)$ and $X(6550)$

Evidence of $X(7300)$

$\Gamma \sim 100$ MeV

Single (open) charm tetraquarks

$cq\bar{q}\bar{q}$

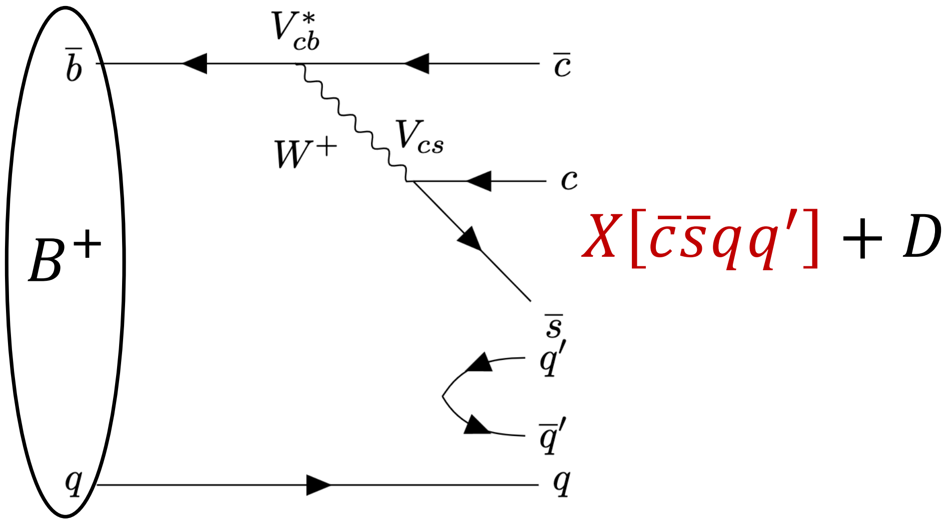


Tetraquarks in $B^+ \to D^+ D^- K^+$

- Structure in $B^+ \to D^+ D^- K^+$ decays:
  $B^+ \to X[\bar{c}\bar{s}ud] D^+$ with $X \to D^- K^+$

  Two states: $X_0(2900)$ and $X_1(2900)$

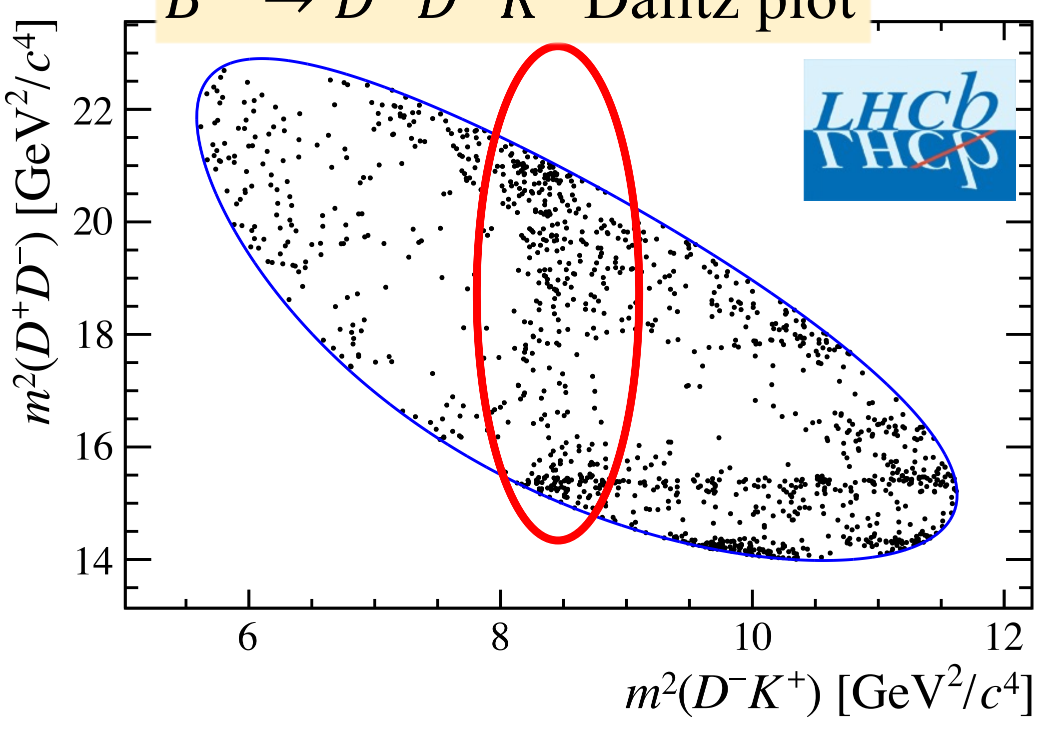
  Same production environment as $c\bar{c}$-tetraquarks



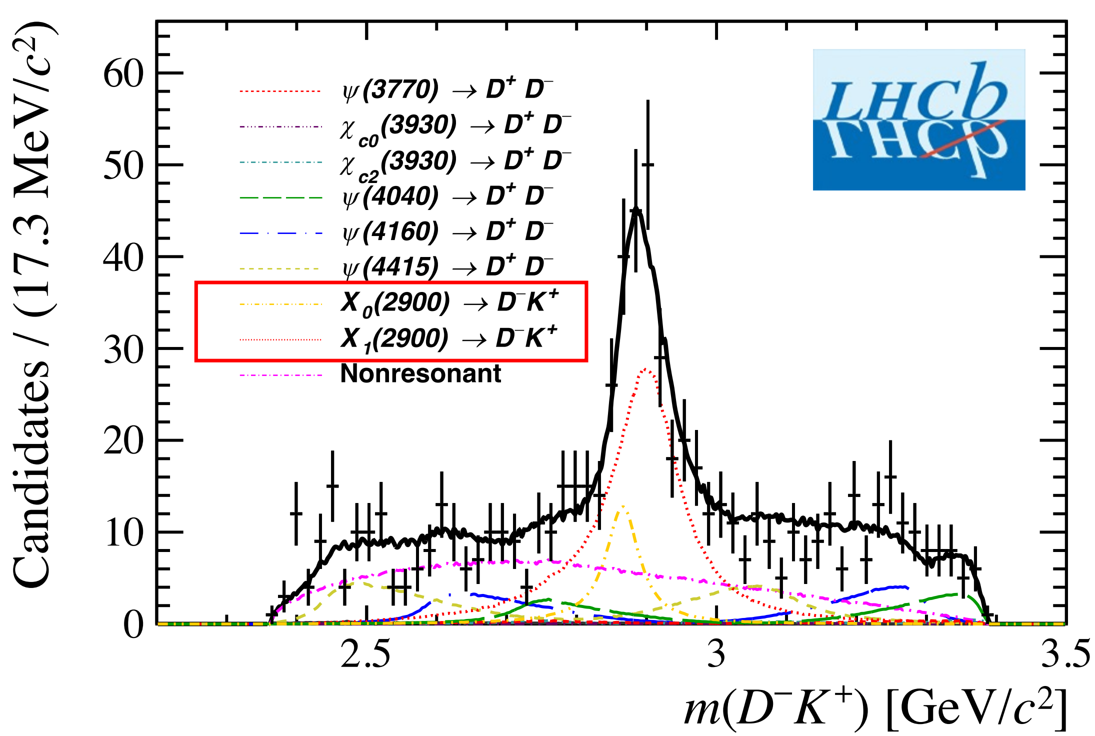
$0^+ \quad X_0(2900): \quad M = 2.866 \pm 0.007 \pm 0.002\,\mathrm{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4\,\mathrm{MeV}$

$1^- \quad X_1(2900): \quad M = 2.904 \pm 0.005 \pm 0.001\,\mathrm{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4\,\mathrm{MeV}$

$B^+ \to D^+ D^- K^+$ Dalitz plot



PRL125(2020)242001

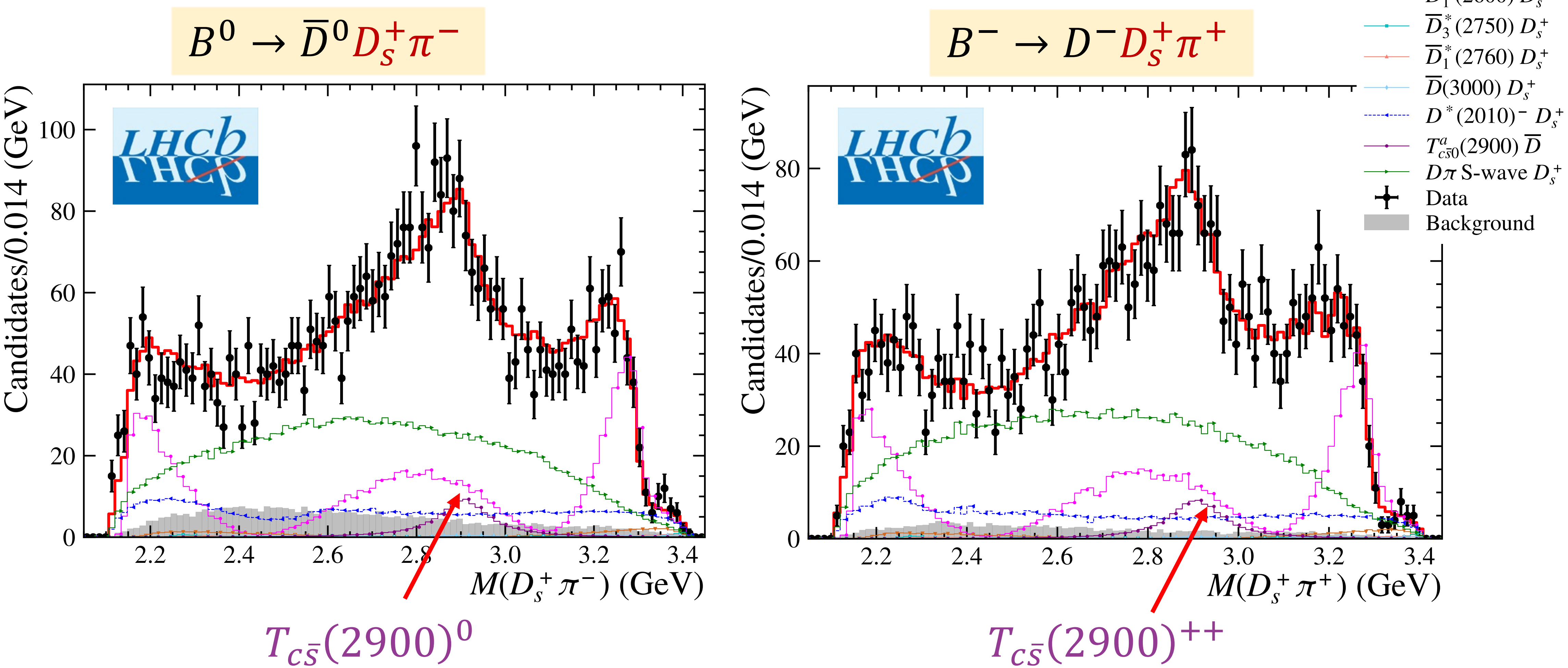


Tetraquarks in $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to \bar{D}^- D_s^+ \pi^+$

- Two isospin patterners: $T_{c\bar{s}}(2900)^0 \to D_s^+ \pi^-$, $T_{c\bar{s}}(2900)^{++} \to D_s^+ \pi^+$

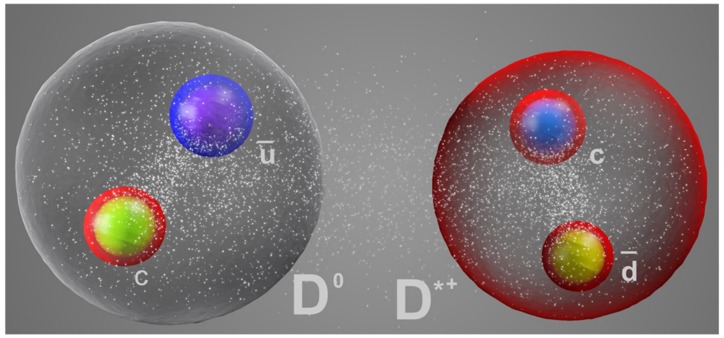
$$M = 2.908 \pm 0.011 \pm 0.020 \text{ GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011 \text{ GeV}$$
$$J^P = 0^+$$

- Quark components: $T_{c\bar{s}}(2900)^0 [cd\bar{s}\bar{u}]$, $T_{c\bar{s}}(2900)^{++} [cu\bar{s}\bar{d}]$



Double (open) charm tetraquark

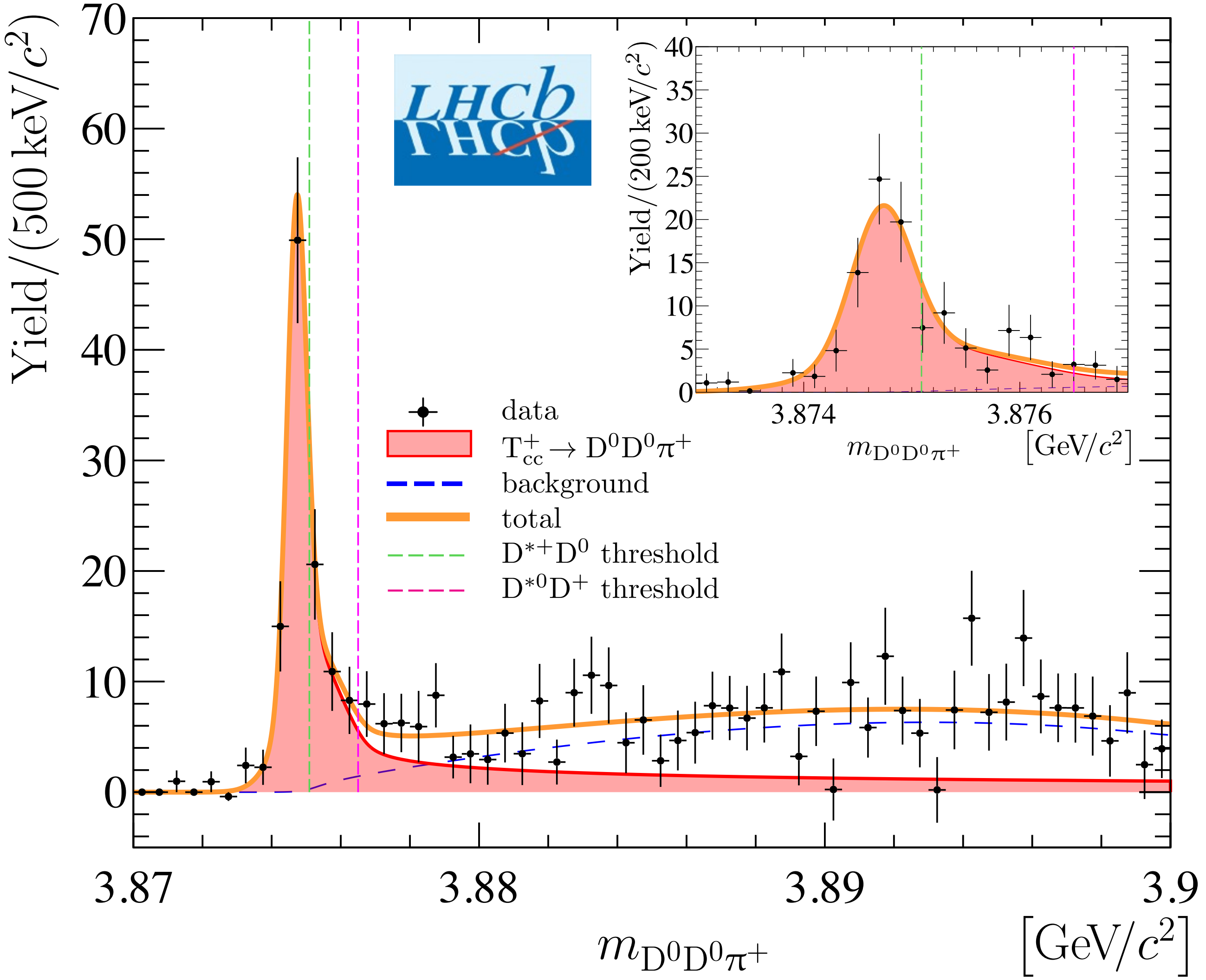
$cc\bar{q}\bar{q}\ (\neq c\bar{c}q\bar{q})$



Observation of T_{cc}^{+} in $D^0 D^0 \pi^+$

[arXiv: 2109.01038] (Nature Physics)
[arXiv: 2109.01056] (Nature Communications)

- $pp \to T_{cc}(3875)^+ \to D^0 D^{*+}$, quark contents $[cc\bar{u}\bar{d}]$
- Mass very close and below $D^0 D^{*+}$ threshold
- Isospin singlet

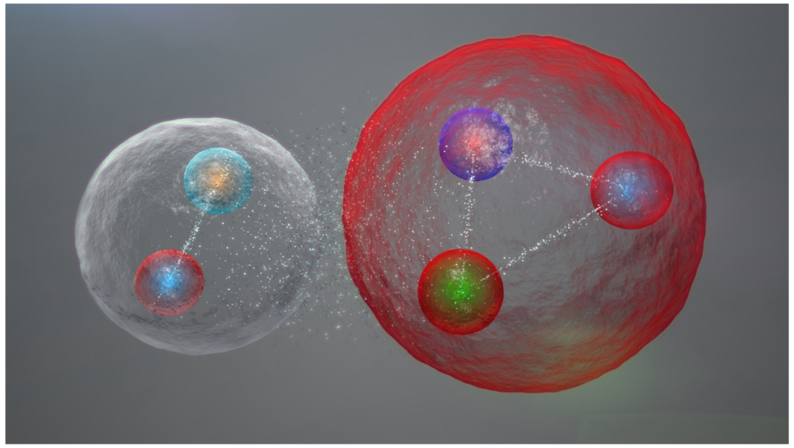


	$\delta\mathfrak{m}$ [keV/c^2]	Γ [keV/c^2]
$\mathfrak{F}^{BW}$	-279 ± 59	409 ± 163
$\mathfrak{F}^{U}$	-361 ± 40	47.8 ± 1.9

$$\delta m = m_{T_{cc}} - m_{D^0} - m_{D^{*+}}$$

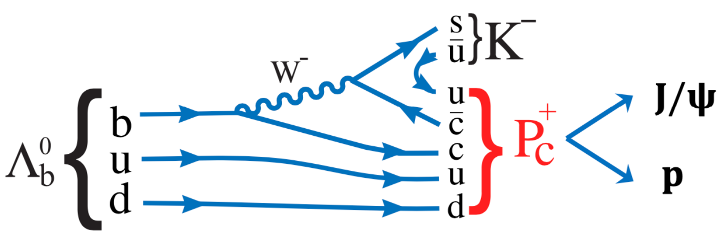
Pentaquarks with $c\bar{c}$

$c\bar{c}qqq$

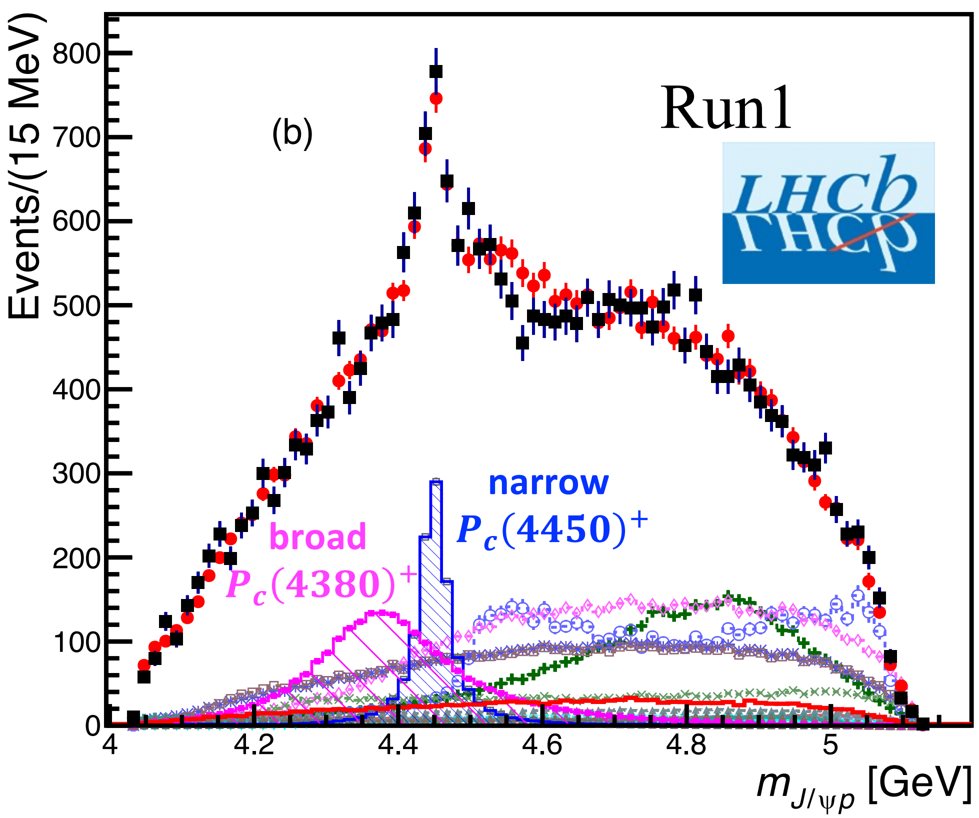


Observation of P_c^+

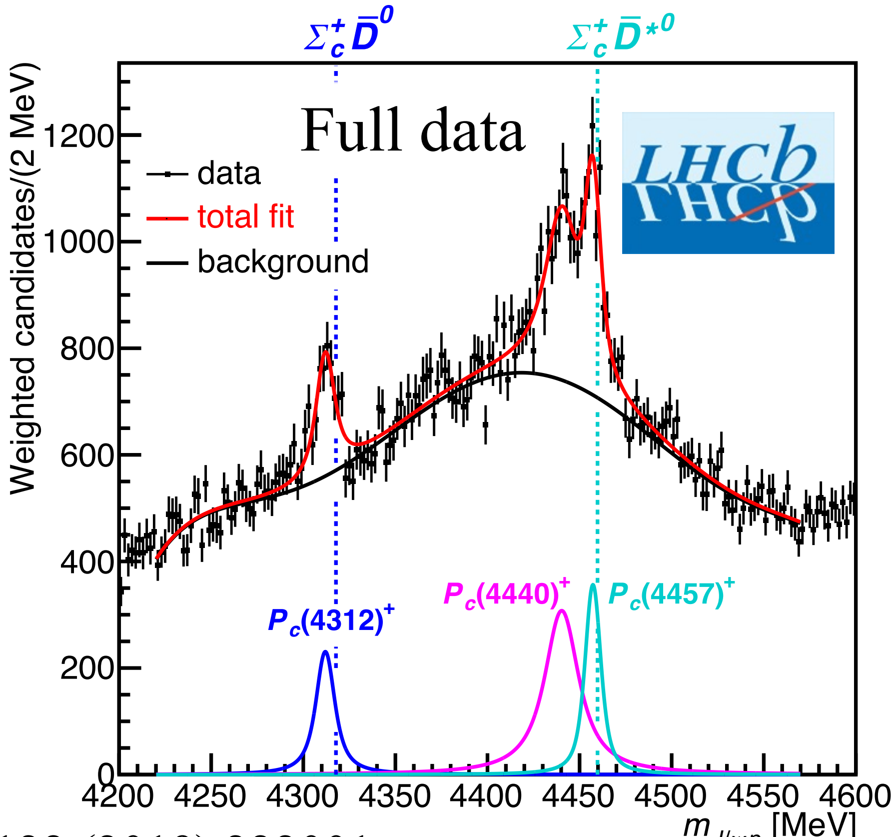
- Structure in Λ_b^0 decays corresponding to $\Lambda_b^0 \to P_c^+ K^-,\ P_c^+ \to J/\psi p$
  - ➢ Run1 data with amplitude analysis: $P_c(4380)^+$, $P_c(4450)^+$
  - ➢ Full data (×9 more) with 1D analysis: $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$
- Minimum quark contents: $P_c^+[c\bar{c}uud]$



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



PRL 115 (2015) 072001



PRL 122 (2019) 222001

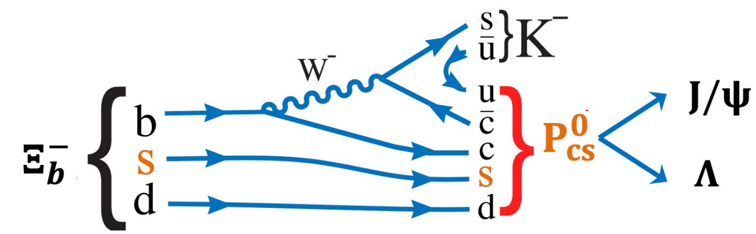
States close to $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ mass thresholds

Evidence of P_{cs}^0 in $\Xi_b^- \to J/\psi \Lambda K^-$ Science Bulletin 66 (2021)1278

- Evidence of structure in $J/\psi\Lambda$ spectrum of $\Xi_b^- \to J/\psi\Lambda K^-$ decay

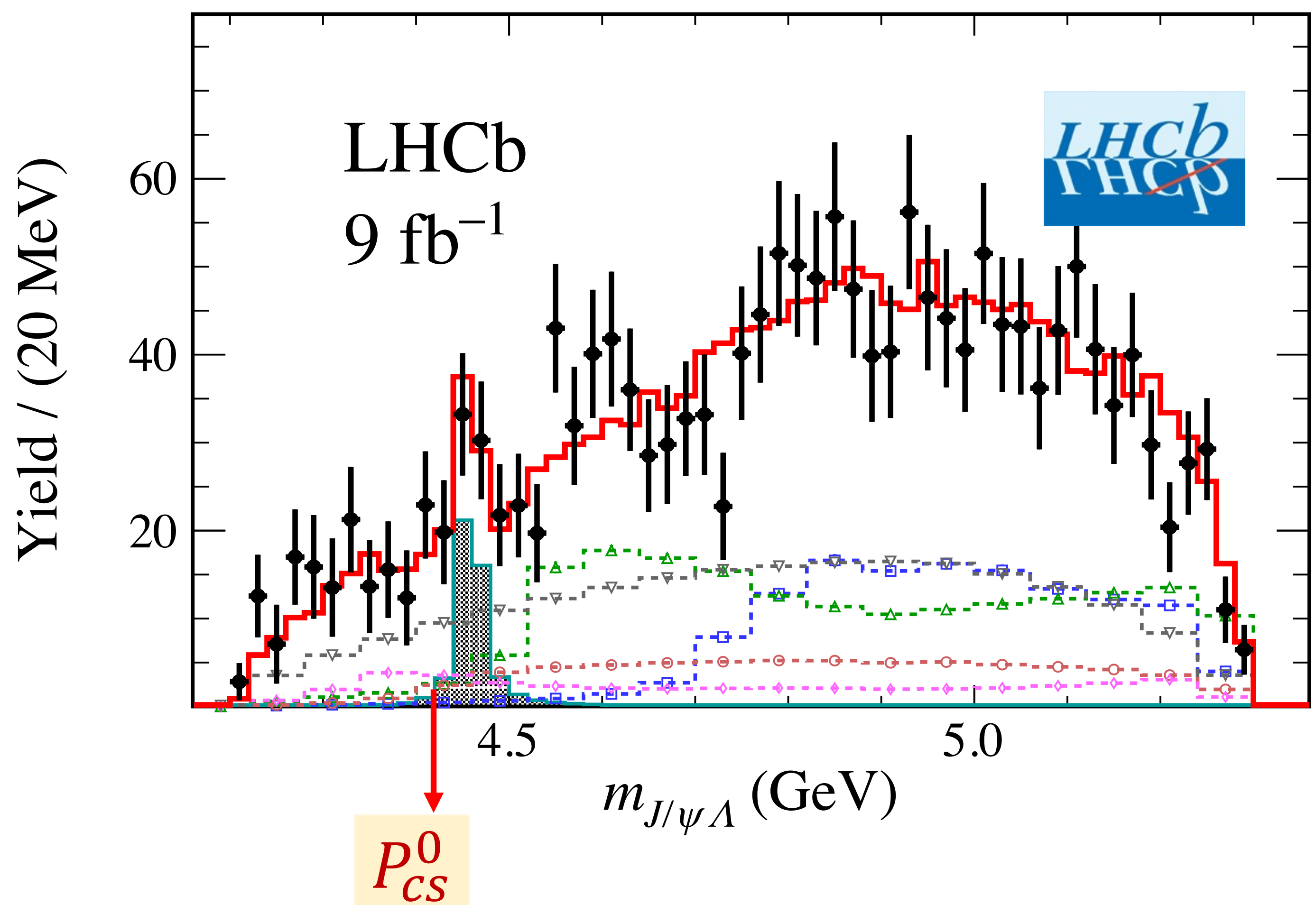
$$\Xi_b^- \to P_{cs}^0 K^-,\ P_{cs}^0 \to J/\psi\Lambda$$

- Minimum quark contents: $P_{cs}^0[c\bar{c}uds]$



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

close to $\Xi_c \bar{D}^*$ mass threshold, where two $c\bar{c}uds$ states are expected

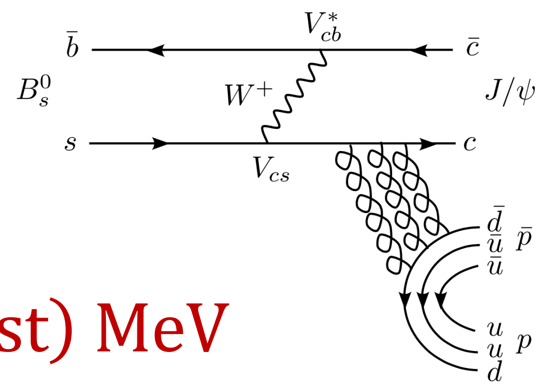


PRD101(2020)034018

P_c^+ state in $B_s^0 \to J/\psi p\bar{p}$ decay

PRL 128 (2022) 062001

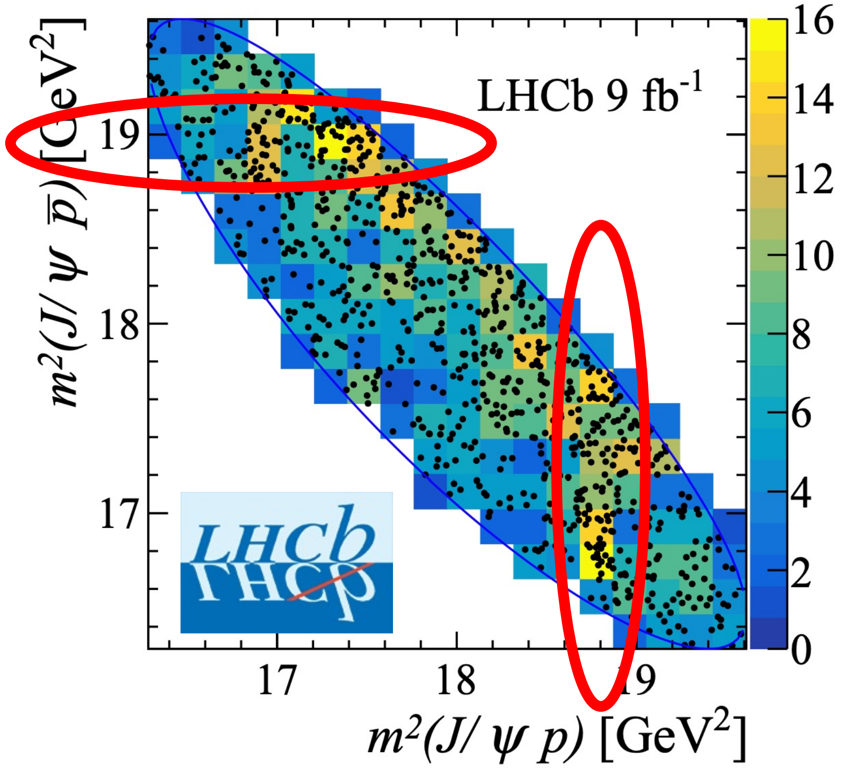
- Evidence of new P_c^+ in B_s^0 decays: $B_s^0 \to P_c^{\pm} p^{\mp}, P_c^+ \to J/\psi p$



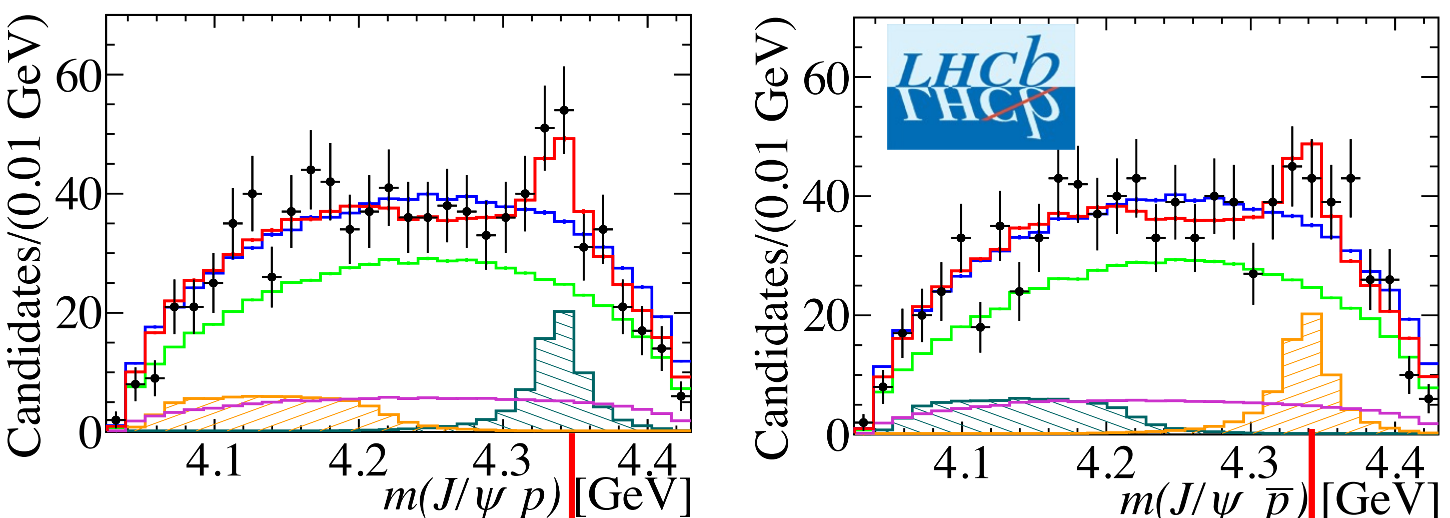
- Preferred $J^P = 1/2^{\pm}, 3/2^{\pm}$

$$M = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\ \text{MeV},\ \Gamma = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV}$$

$B_s^0 \to J/\psi p\bar{p}$ Dalitz plot



Amplitude analysis projection



New P_c structure

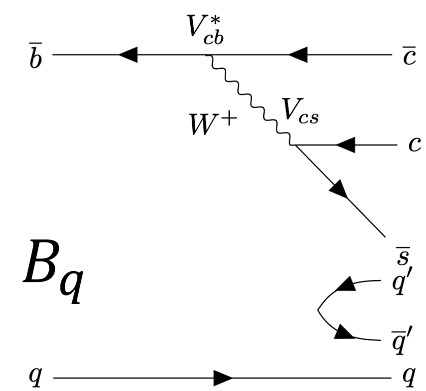
P_{cs}^0 in $B^- \to J/\psi\Lambda\bar{p}$ decays

LHCb-PAPER-2022-031

- Observation of $P_{cs}(4338)^0$ in $B^- \to J/\psi\Lambda\bar{p}$ decays: $B^- \to P_{cs}^0\,\bar{p},\ P_{cs}^0 \to J/\psi\Lambda$

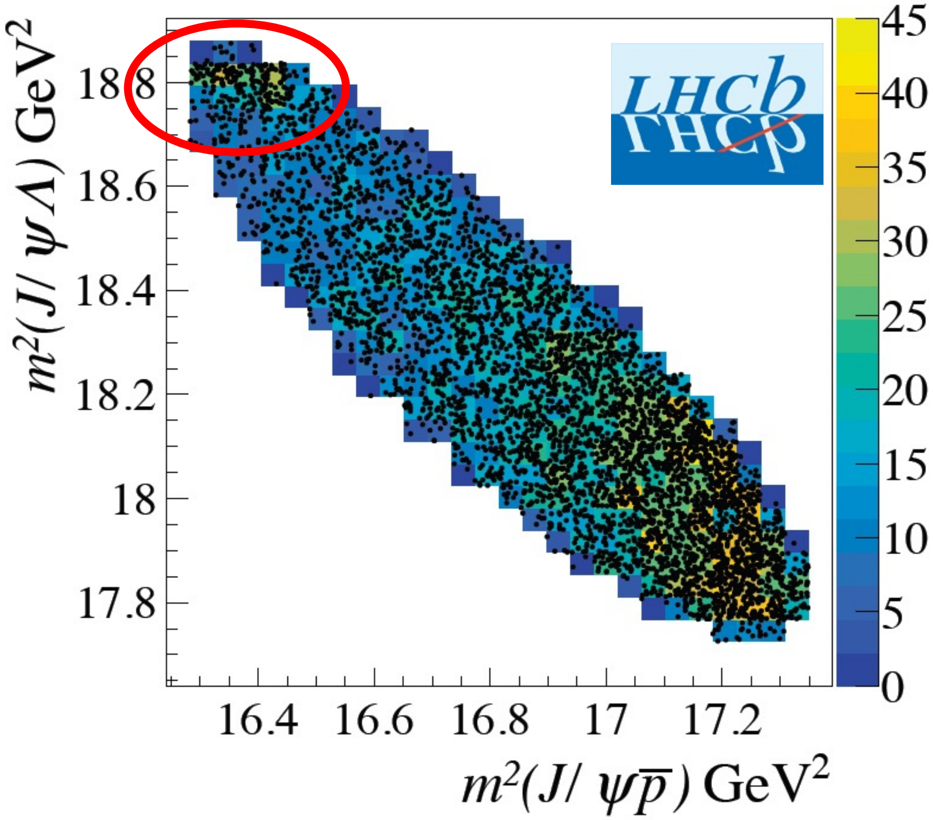
$M = 4338.2 \pm 0.7 \pm 0.4$ MeV, $\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV, $J^P = 1/2^-$ preferred

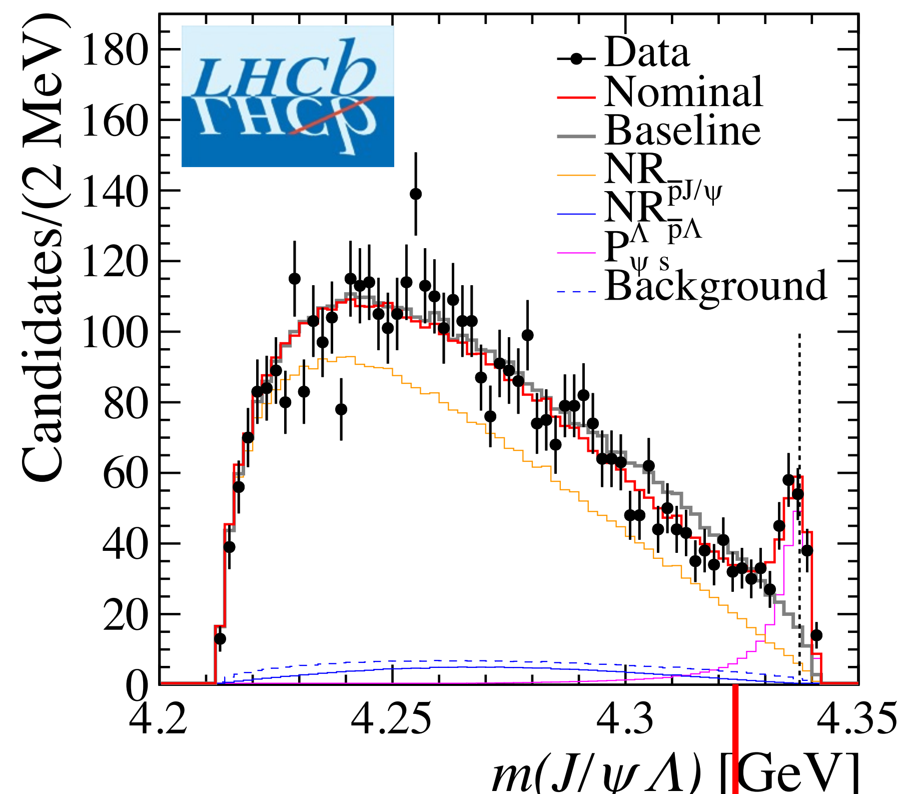
- Close to $\Xi_c^+ D^-$ mass threshold and in S-wave



$[c\bar{c}sqq]$

$B^- \to J/\psi\Lambda\bar{p}$ Dalitz plot



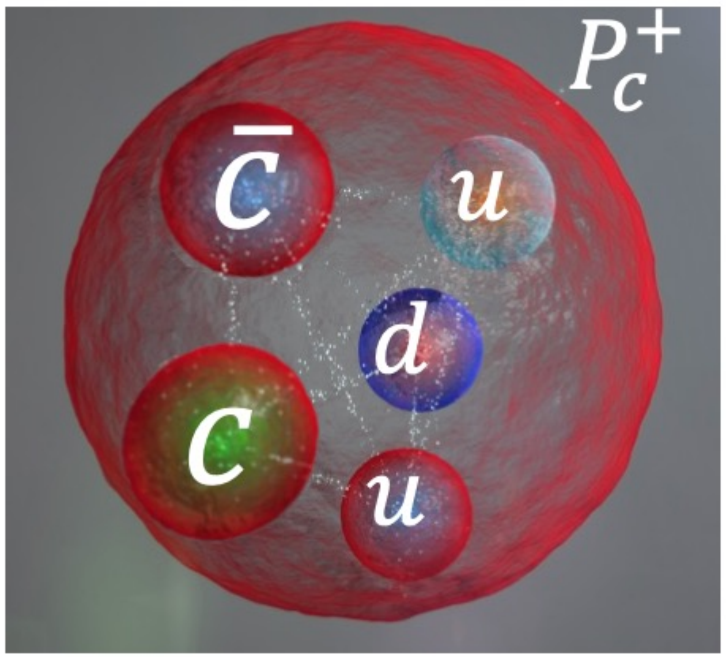


New P_{cs}^0 structure

The puzzle: inner structure

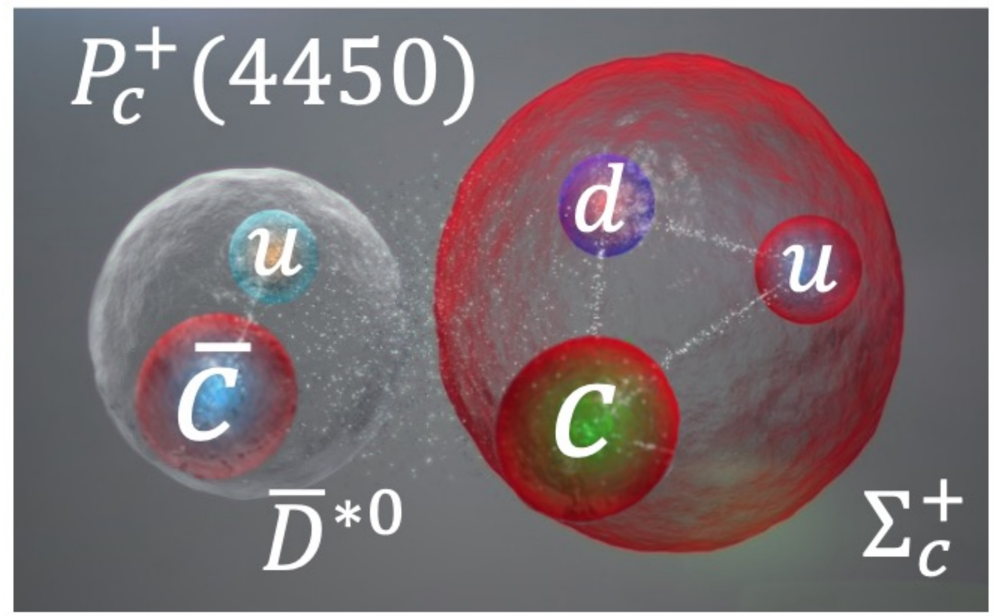
Compact states

Expect many more states than observed



Hadron molecules

Favored by near-threshold states
Some difficult to fit in (non-exotic?)



Where are those compact states? Unstable?

Note: data and model match well for conventional states

Why is LHCb suitable for such studies

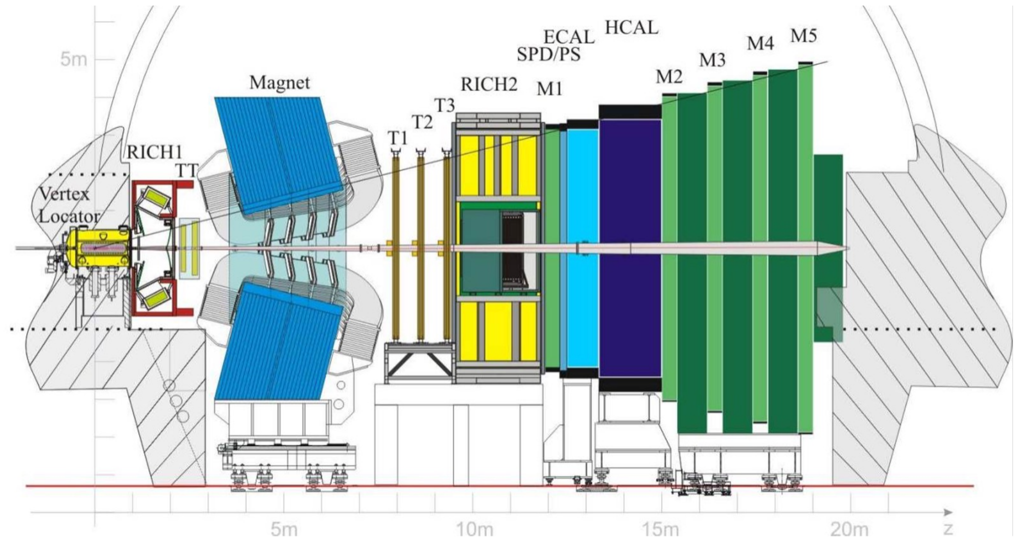
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- LHCb aims for measurements of charm and bottom hadrons

- Large statistics ($pp@\sqrt{s} \sim 10$ TeV)

  $N(b\bar{b}) \sim 10^{-3}b \times 10^{8}b^{-1}/s = 10^{5}/s$

  $N(c\bar{c}) \sim 20 \times N(b\bar{b})$



- All hadron species possible

  $N_{B^+} : N_{B^0} : N_{B_s^0} : N_{\Lambda_b^0} \approx 4:4:1:2$

- Dedicated design for heavy flavor measurement

  Precise vertexing (also benefit from large boost, $\gamma \sim 50$)

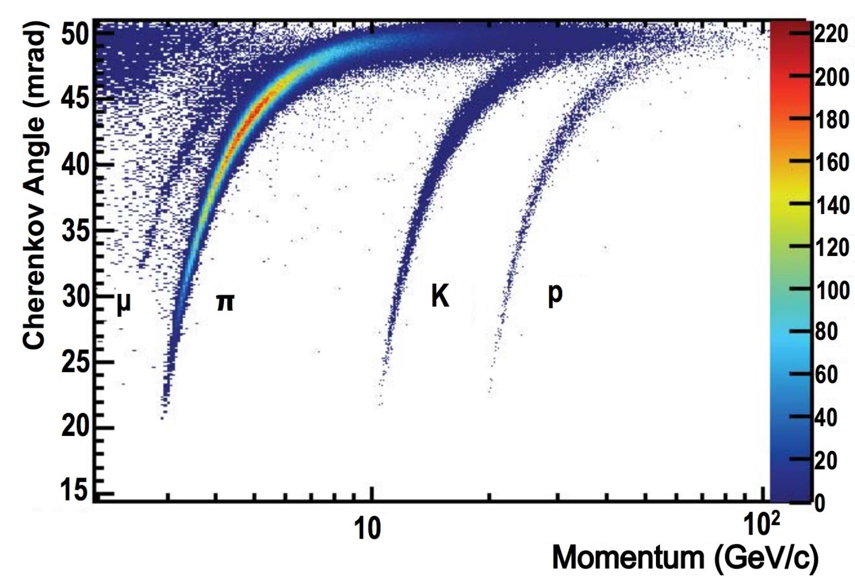
  - $\sigma_{IP} \sim 20$ μm, $\sigma_{\tau} \sim 45$ fs

  High momentum resolution

  - $\delta p/p \sim 0.5\%$-1% (5-200 GeV)
  - $\sigma(m_{J/\psi}) \approx 15$ MeV

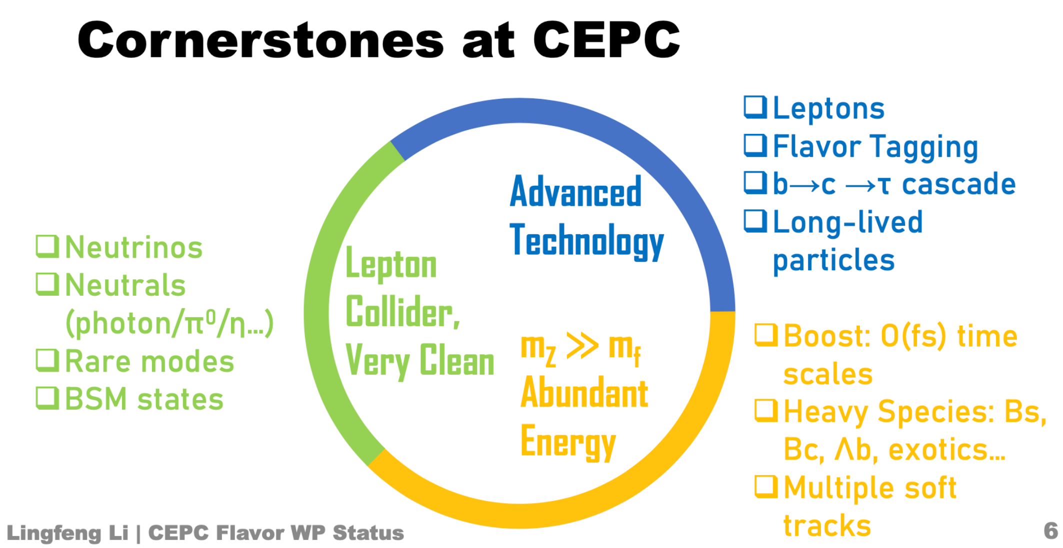
  Powerful particle (hadron) identification

  - $\epsilon(K \to K), \epsilon(p \to p) > 90\%$
  - MisID rate $(\pi \to K/p) < 5\%$



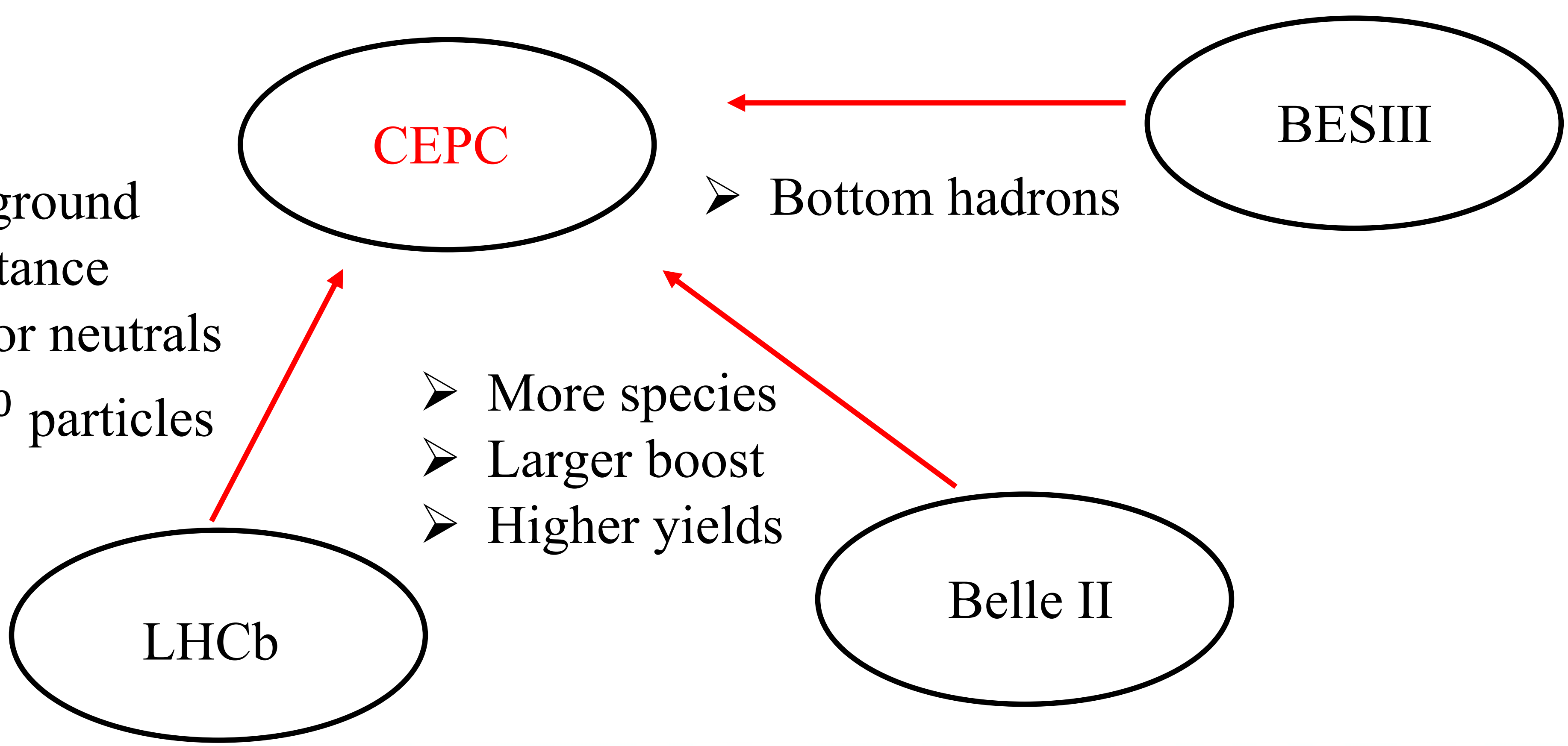
Where CEPC Tera-Z can improve/complement

From slides of Lingfeng Li on Monday



Particle	Belle II	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	1×10^{11}	7.2×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	1×10^{11}
D^0, $\bar{D}^0$			5.2×10^{11}
$D^\pm$			2.2×10^{11}
$D_s^\pm$			8.8×10^{10}
$\Lambda_c^\pm$			5.5×10^{10}
$\tau^\pm$	4.5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)		1.2×10^{11}

Lingfeng Li | CEPC Flavor WP Status 10



- Less background
- Full acceptance
- Efficient for neutrals

  ν, n, γ, V^0 particles

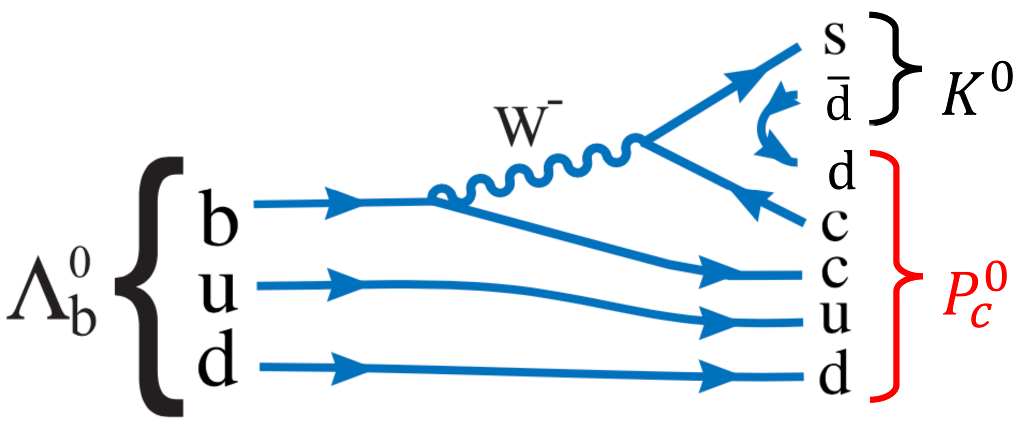
- Bottom hadrons

- More species
- Larger boost
- Higher yields

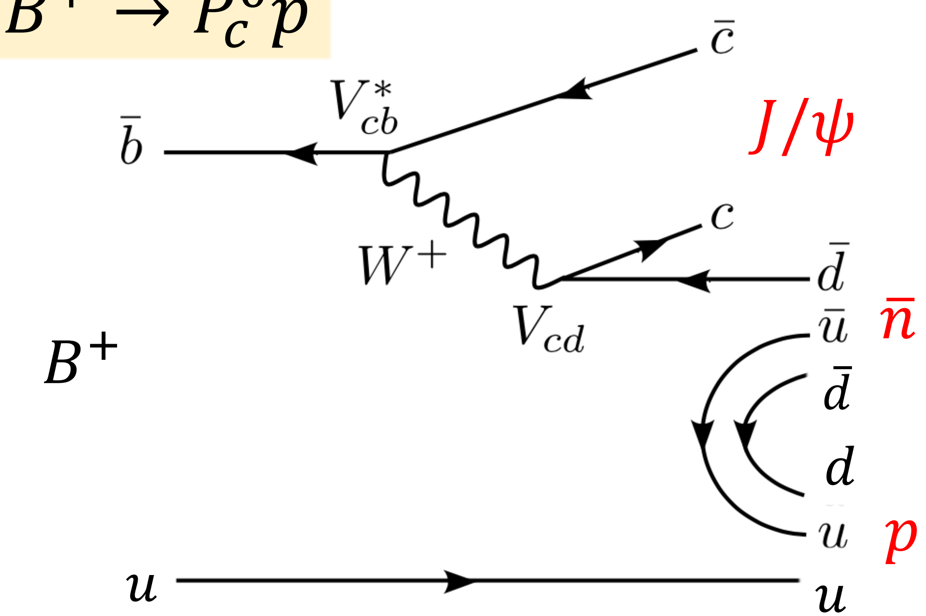
Example 1

- Pentaquark with neutrons (suppose n can be efficiently reconstructed)

$\Lambda_b^0 \to P_c^0 \bar{K}^0,\ P_c^0 \to \psi n$



$B^+ \to \bar{P}_c^0 p$

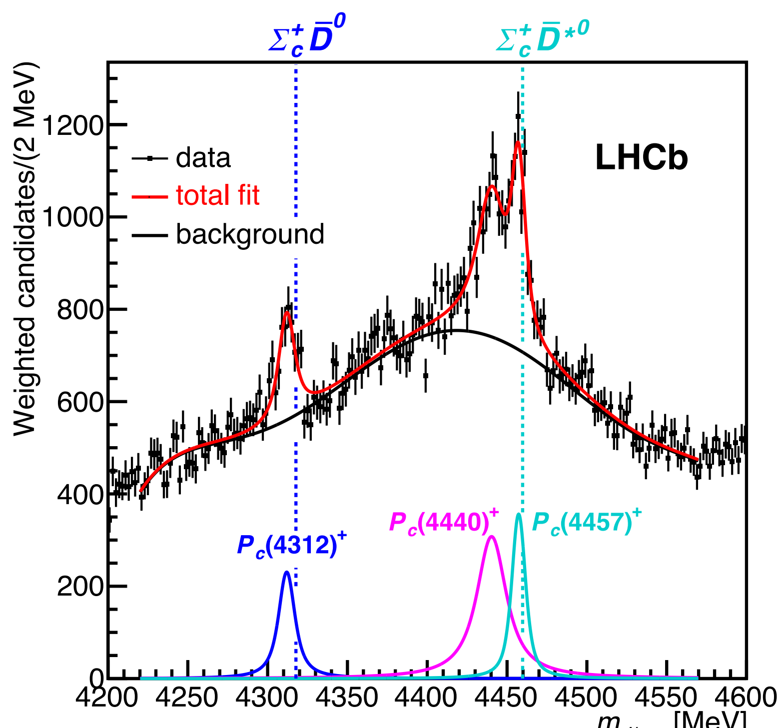


- Pentaquark decays into γ/π^0 final state

$\Lambda_b^0 \to P_c^+ K^-, P_c^+ \to \Sigma_c^+ \bar{D}^{(*)0}, \Lambda_c^+ \bar{D}^{(*)0}, \chi_c p$

$\Lambda_b^0 \to P_c^0 \bar{K}^0, P_c^0 \to \Sigma_c^0 \bar{D}^{(*)0}, \Sigma_c^+ \bar{D}^{(*)-}$

$\Sigma_c^+ \to \Lambda_c^+ \pi^0,\ \ D^{*0} \to D^0 \gamma/\pi^0,\ \ \chi_c \to \psi\gamma$

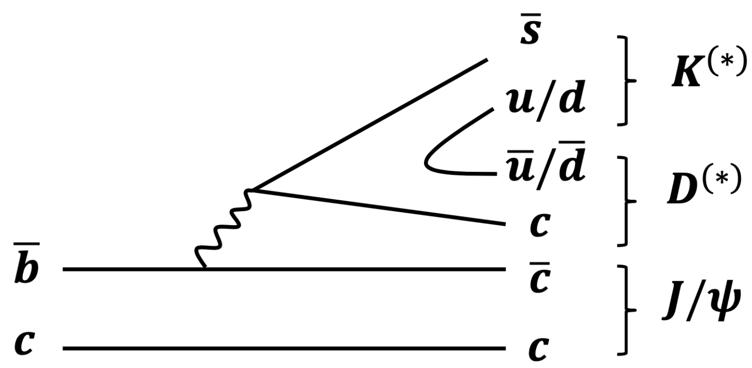


Example2

- Exotic hadrons with multiple heavy quarks

$$Z^0 \to b\bar{b}b\bar{b}X,\quad b\bar{b}c\bar{c}X,\quad c\bar{c}c\bar{c}X$$

$Z^0 \to B_c^+ X,\ B_c^+ \to X(\psi D)K$

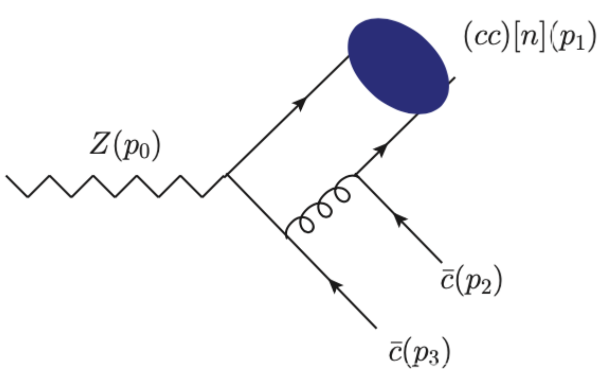


B_c^+ cross-section (pb) at CEPC $\quad N_{B_c^+} \sim 10^9$

States	$\sqrt{s} = m_Z$	$\sqrt{s} = 160$ GeV	$\sqrt{s} = 240$ GeV
B_c	2.58	1.71×10^{-3}	5.34×10^{-4}
B_c^*	3.04	2.05×10^{-3}	6.40×10^{-4}
$B_c(2^1S_0)$	1.54	1.03×10^{-3}	3.20×10^{-4}
$B_c^*(2^3S_1)$	1.82	1.23×10^{-3}	3.83×10^{-4}

[Ze-Yang Zhang et al, EPJC82(2022)246;
Xu-Chang Zheng et al, PRD100(2019)034004]

T_{cc}



$T_{cc\bar{c}\bar{c}},\ T_{bb\bar{b}\bar{b}}$

Other possible final states than di-J/ψ

$$X \to \eta_c J/\psi,\ \chi_c J/\psi \text{ etc.}$$

$$\mathcal{R}_{\Xi_{cc}^+} = \frac{\Gamma(Z \to \Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\Gamma(Z \to \Lambda_c^+)} = 0.85^{+0.10}_{-0.07} \times 10^{-4},$$

$$\mathcal{R}_{\Xi_{cc}^{++}} = \frac{\Gamma(Z \to \Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\Gamma(Z \to \Lambda_c^+)} = 1.70^{+0.20}_{-0.14} \times 10^{-4}$$

Xuan Luo et al, arXiv:2206.05965

$N_{T_{cc}} \sim N_{\Xi_{cc}} \sim 10^6$

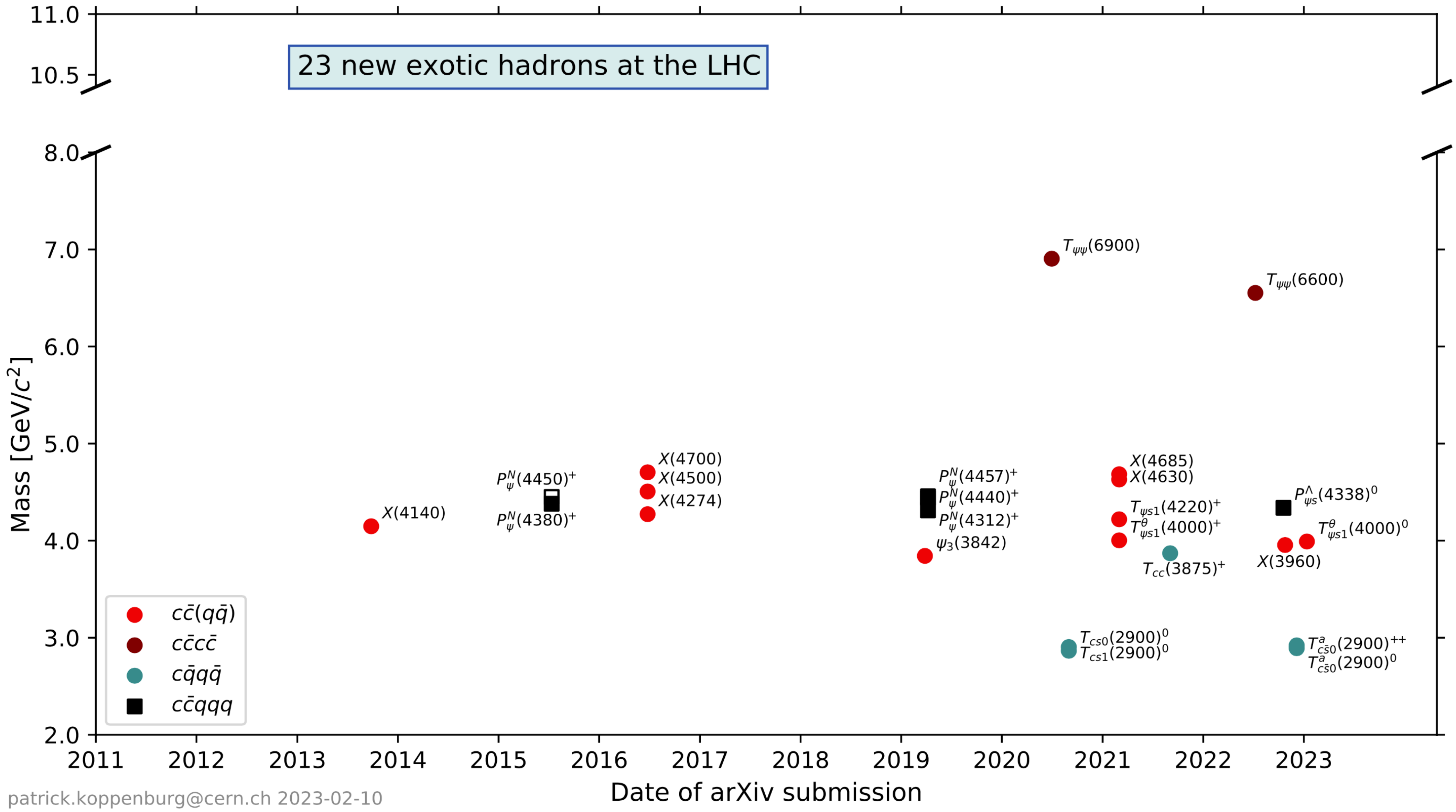
Summary

- Hadrons for the understanding of nonperturbative QCD
- Lots of experimental progresses about heavy exotic hadrons: a new particle zoo
  - $Q\bar{Q}q\bar{q}$: X, Y, Z from e^+e^- and B decays
  - $Q\bar{q}q\bar{q}$: $X(2900), T_{cs}(2900)^{0,++}$ from B decays
  - $QQ\bar{q}\bar{q}$: $T_{cc}(3875)^+$ from pp collisions
  - $Q\bar{Q}Q\bar{Q}$: $X(6900), X(6550)$ from pp collisions
  - $Q\bar{Q}qqq$: $P_c(4312)^+, P_c(4440)^+, P_c(4457)^+, P_{cs}(4338)^0$ from B decays
- More quantitative information on multiple quark hadron dynamics from theory side, but a global and firm conclusion still difficult
- CEPC allows additional opportunities: neutrals, multiple-heavy states…

Thank you for your attention

Backup slides

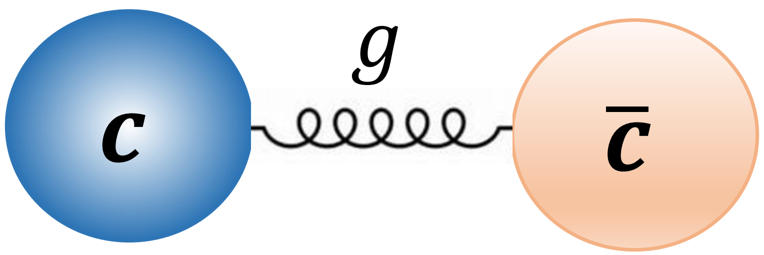
Possible exotic states by LHC



$X(3872)$ as an exotic

$X(3872) \to J/\psi\pi^+\pi^-$, $X(3872)$ contains the $c\bar{c}$ component, like a charmonium

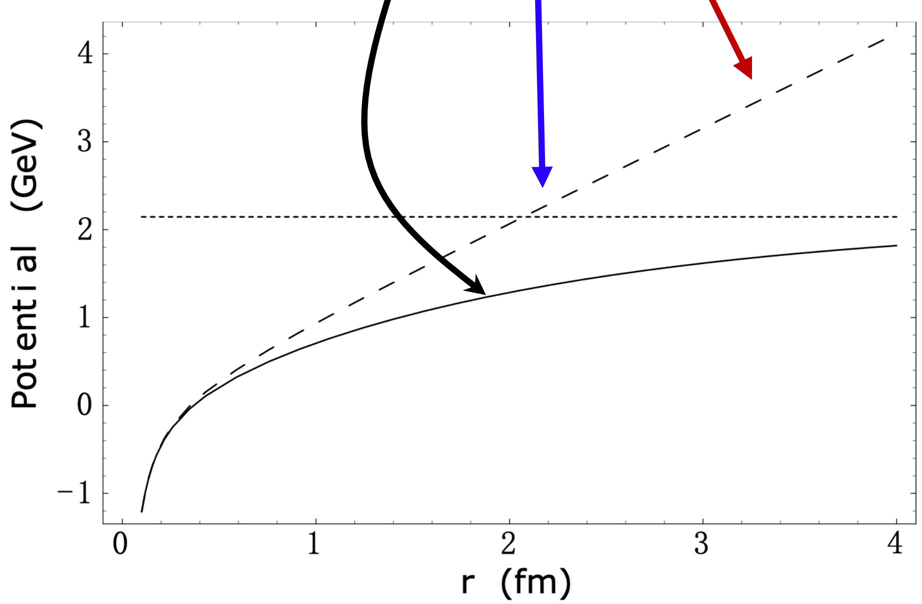
Non-relativistic potential for $\bar{c}c$



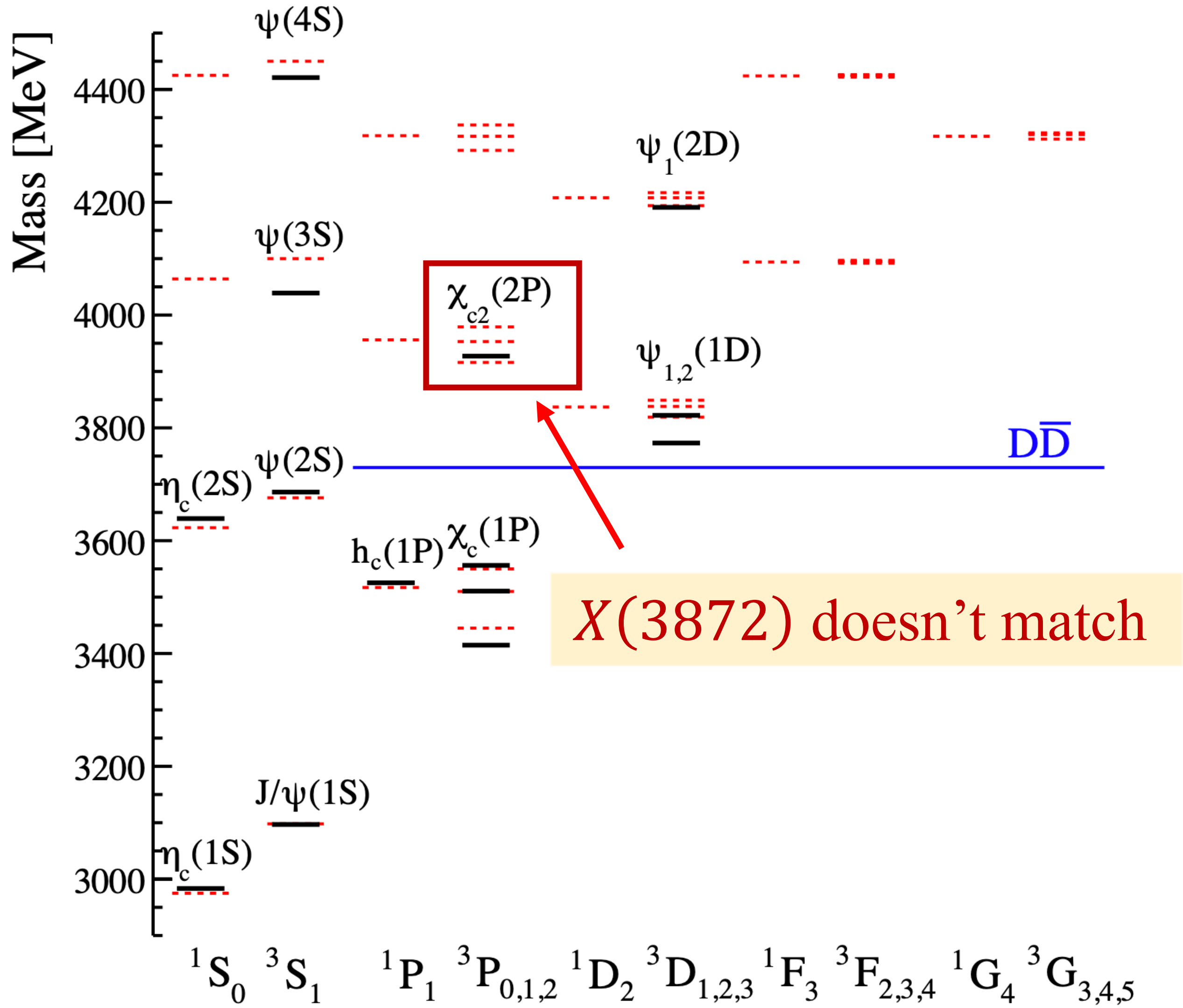
Coulomb

Confinement

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + b\times r$$



Predicted spectrum v.s. experiment



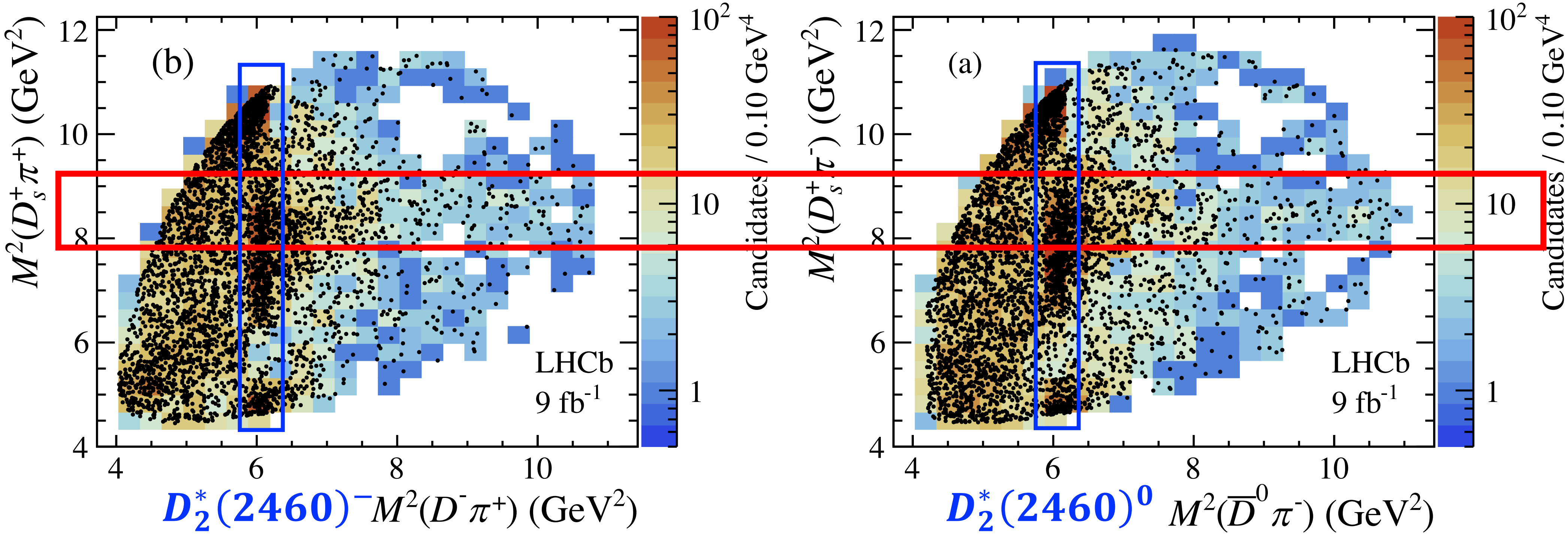
Study of $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

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

- Full 9 fb^{-1} Run1+Run2 LHCb data

  $\Rightarrow$ 4420 $B^0 \to \bar{D}^0 D_s^+ \pi^-$ candidates with signal purity of 90.7%

  3940 $B^+ \to D^- D_s^+ \pi^+$ candidates with signal purity of 95.2%



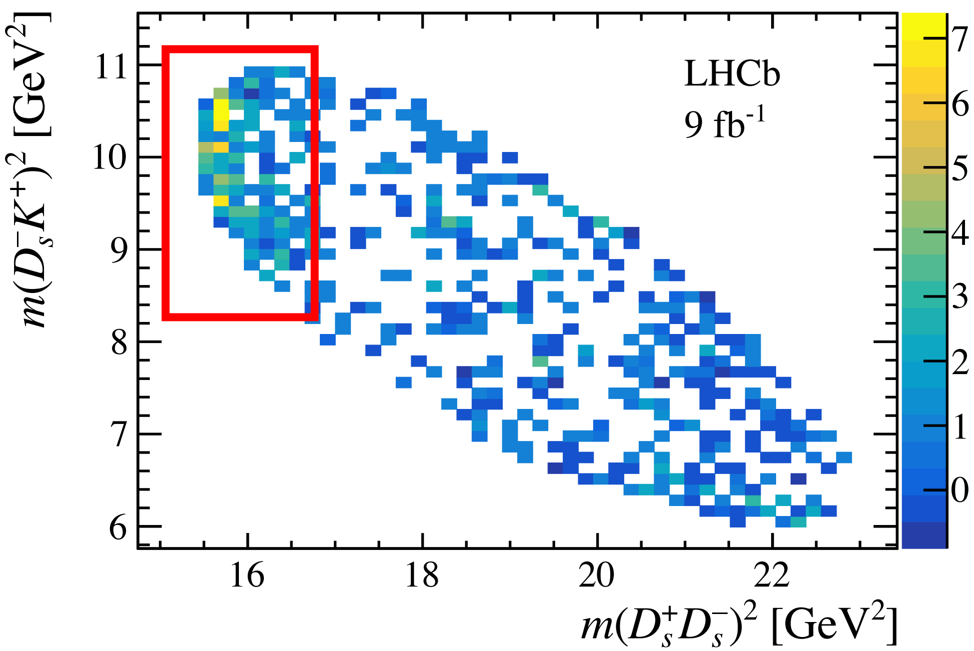
✓Faint horizontal band at $M^2(D_s^+\pi) \approx 8.5\ \text{GeV}^2$ indicating $T_{c\bar{s}}$ candidates

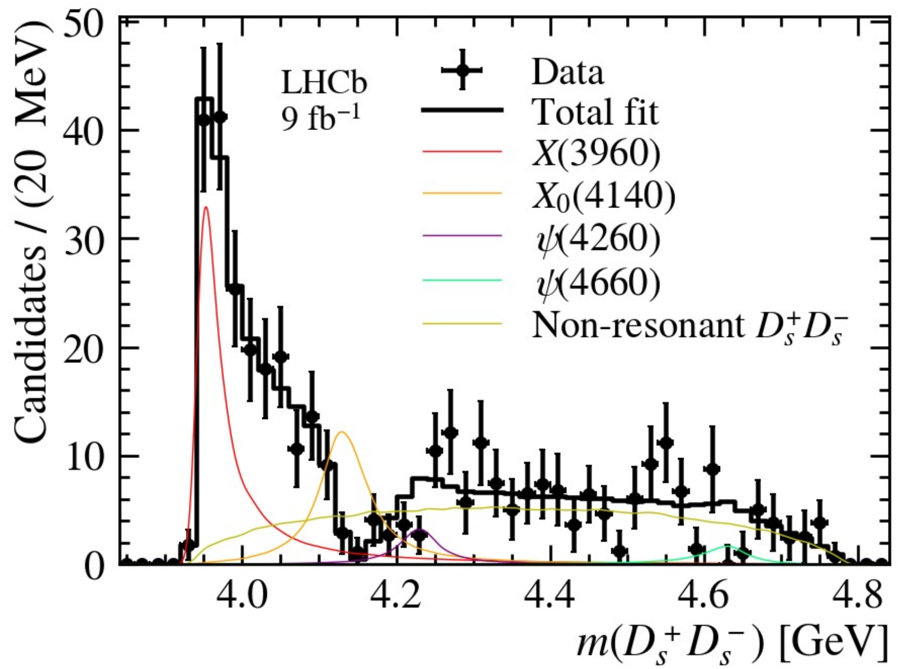
$\Rightarrow$ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

Observation of $X(3960) \to D_s^+ D_s^-$

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

- Threshold enhancement in $B^+ \to D_s^+ D_s^- K^+$, described by $X(3960) \to D_s^+ D_s^-$
  - ➢ $J^{PC} = 0^{++}$ preferred
- Dip at $m(D_s^+ D_s^-) \sim 4.15$ GeV with $X_0(4140)$ or $J/\psi\phi \to D_s^+ D_s^-$ scattering





- $X_0(3930)$ versus $X_0(3960)$

The same state: $\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = 0.29 \pm 0.16$ prefers genuine $s\bar{s}$ content inside X

$B^+ \to J/\psi\phi K^+$ fit parameters

- All states are relatively wide: 50 – 200 MeV

Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	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)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
$\mathrm{NR}_{J/\psi\phi}$	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 $J/\psi\phi$ ($X(4150)$)

New $J/\psi\phi$ ($X(4630)$)

Large width ($X(4140)$)

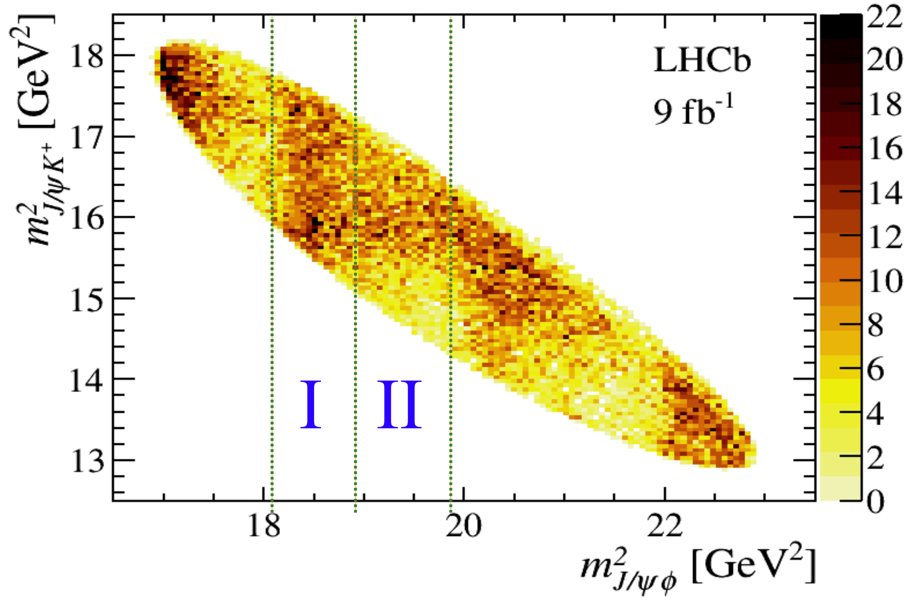
New $J/\psi\phi$ ($X(4685)$)

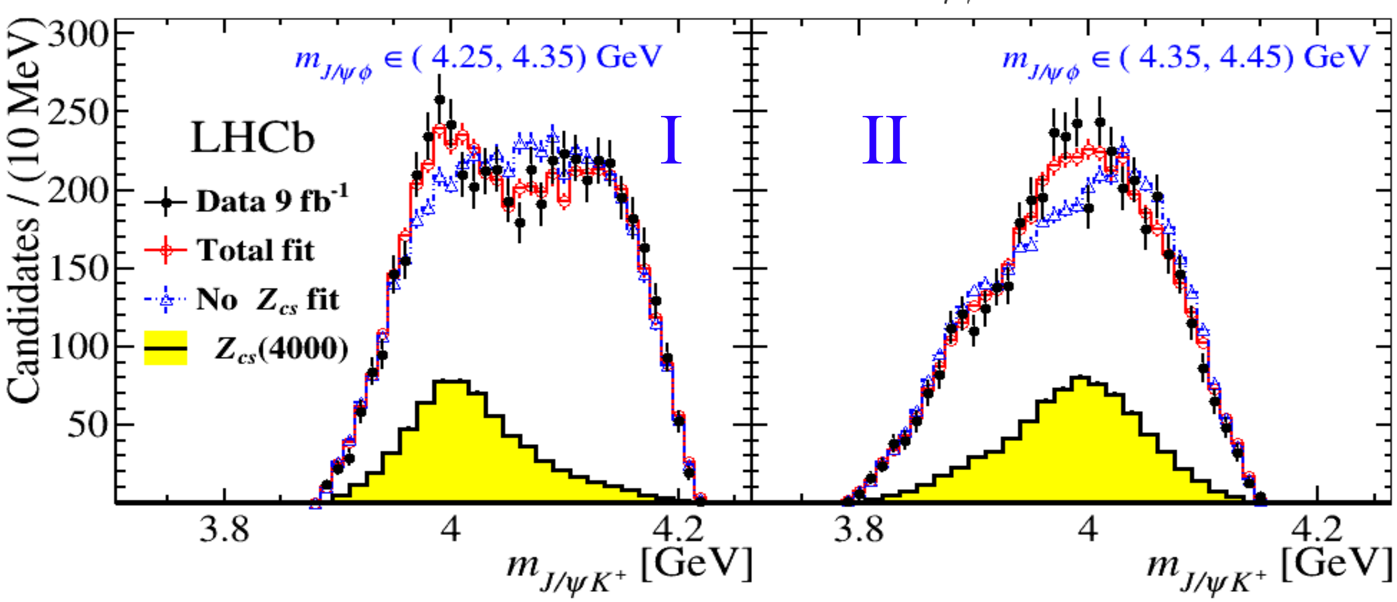
New Z_{cs}^+ states: width inconsistent with $Z_{cs}(3985)^+$ at BESIII. Different state!

Fit projections

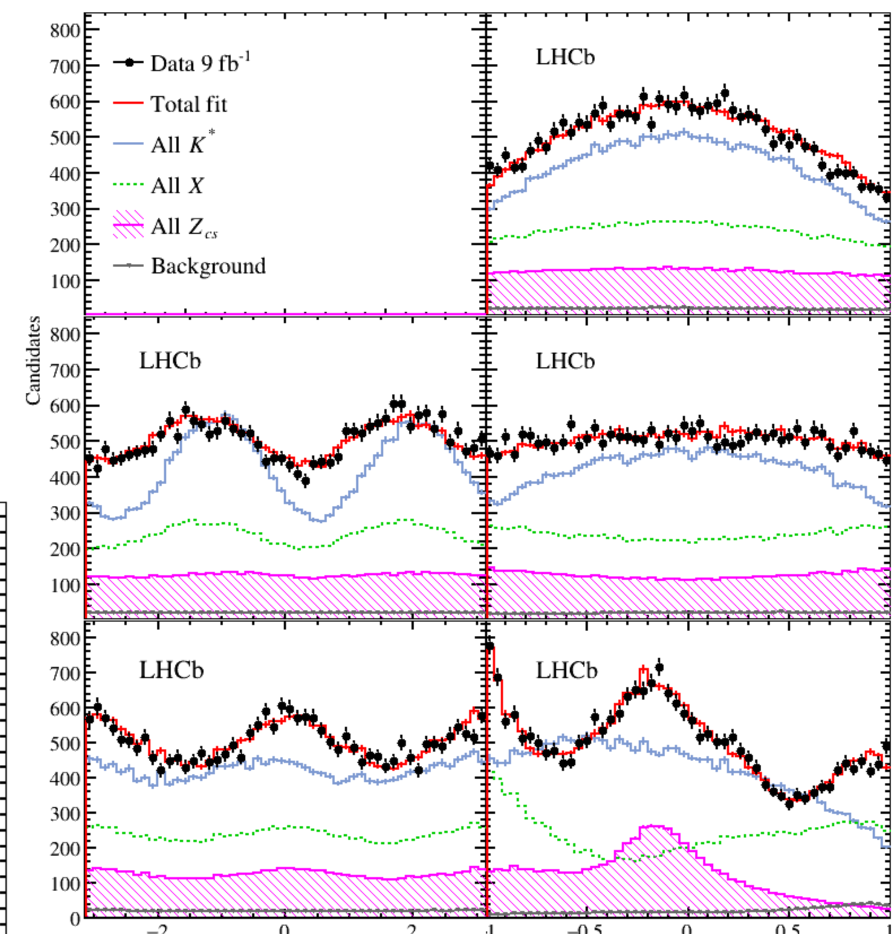
- Z_{cs}^{+} essential to describe data

arXiv:2103.01803





All angular distribution well modelled



Angles in $B^+ \to J/\psi K^*$ chain

J^P analysis

- All X have $C = 1$

$L = 0$ for $J/\psi\phi$ system

Exotic

J^P	$0^{+(+)}$	$0^{-(+)}$	$1^{+(+)}$	$1^{-(+)}$	$2^{+(+)}$	$2^{-(+)}$
$X(4630)$	6.7σ	5.3σ	5.8σ	Prefer	5.9σ	**3.0σ**
$X(4500)$	Prefer	18σ	18σ	18σ	18σ	18σ
$X(4700)$	Prefer	18σ	18σ	18σ	14σ	17σ
$X(4140)$	14σ	15σ	Prefer	14σ	13σ	14σ
$X(4274)$	18σ	18σ	Prefer	18σ	18σ	18σ
$X(4685)$	16σ	16σ	Prefer	15σ	16σ	15σ
$Z_{cs}(4000)$	-	17σ	Prefer	17σ	15σ	16σ
$Z_{cs}(4220)$	-	8.6σ	Prefer	**2.4σ**	4.9σ	5.7σ

Same as $Z_c(4430)^+, Z_c(4200)^+, Z_c(3900)^+$, $L = 0$ for $\psi\pi^+$ system

Interpretations

- Some $X \to J/\psi\phi$ may be $D_s^{(*)}\bar{D}^{(*)}{}_s$ molecular states ?

States	J^{PC}	Mass	Width	Nearest thresholds/MeV	S-wave
$X(4140)$	1^{++}	4118	162	$D_s^+ D_s^{*-}$: 4080	$J^P = 1^+$
$X(4150)$	2^{-+}	4146	135	$D_s^+ D_s^{*-}$: 4080	$J^P = 1^+$
$X(4274)$	1^{++}	4294	53	$D_s^+ D_{s0}^*(2317)^-$: 4286	$J^P = 0^-$
$X(4500)$	0^{++}	4474	77	$D_s^+ D_{s1}^*(2536)^-$: 4503	$J^P = 1^-$
$X(4630)$	1^{-+}	4626	174	$D_s^{*-} D_{s1}^*(2536)^-$: 4636	$J^P = J^-$
$X(4685)$	1^{++}	4684	126	$D_s^{*+} D_{s2}^*(2573)^-$: 4681	$J^P = J^-$
$X(4700)$	0^{++}	4694	87	$D_s^{*+} \bar{D}_{s2}^*(2573)^-$: 4681	$J^P = J^-$

Can't rule out conventional charmonia either, $c\bar{c} \to J/\psi\phi$ not forbidden

- $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$:

May be SU(3) flavor partners of $Z_c(3900)^+$ and $Z_c(4020)^+$, molecular sates, $m_{D*} + m_{D_s} \sim 4$ GeV

arXiv:2011.08725
arXiv:2103.08331