Observation of new $X \to J/\psi\phi$ and $Z_{cs}^{+} \to J/\psi K^{+}$ states in $B^{+} \to J/\psi\phi K^{+}$

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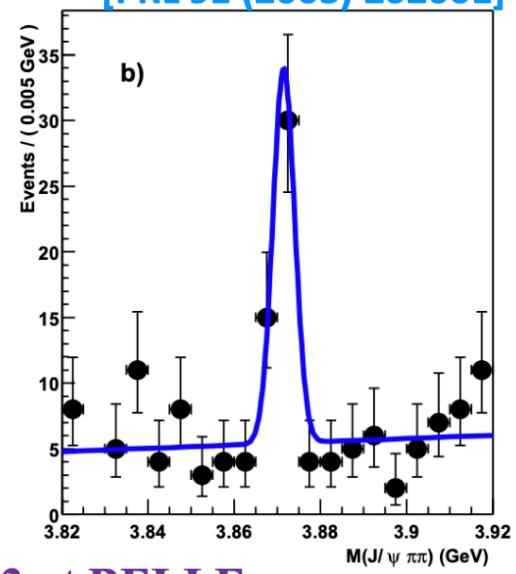
Exotic states

S0031-9163(64)92001-3

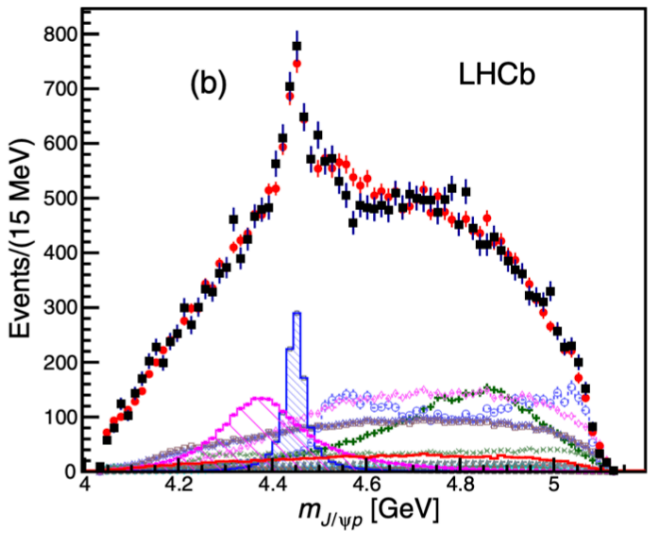
- Existence of exotic states predicted when quark model was proposed
- First tetraquark candidate observed at BELLE in 2003, first pentaquark candidates at LHCb in 2015

[PRL 91 (2003) 262001]



2003 at BELLE

[PRL 115 (2015) 072001]



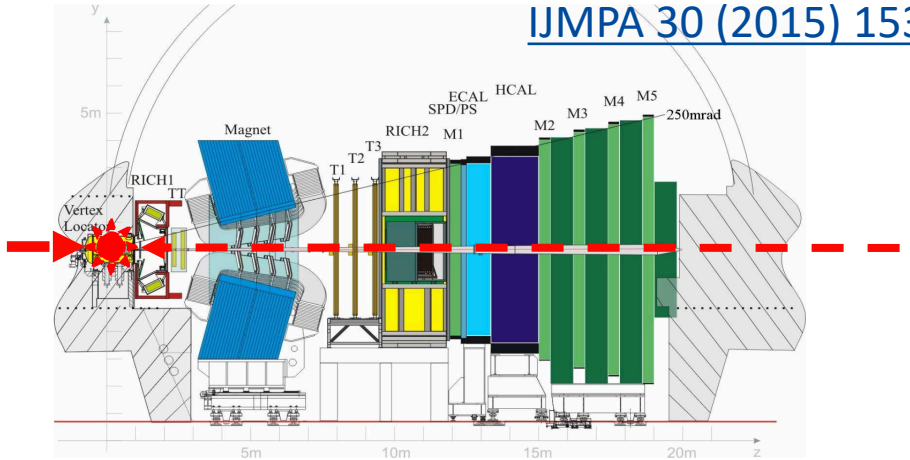
2015 at LHCb

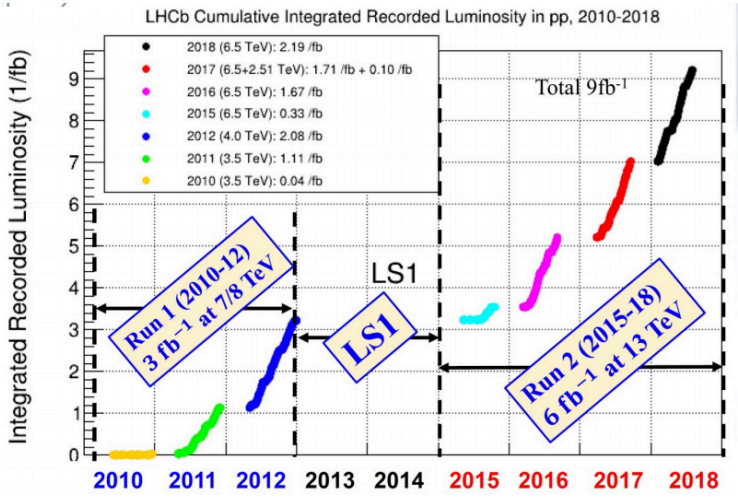
- Study of exotic states can help to probe the dynamics of low-energy non-perturbative QCD

The LHCb detector

- A single-arm forward spectrometer covering $2 < \eta < 5$
- Designed for heavy flavour physics
- Suitable for spectroscopy study
  - Very precise vertex resolution ➔ detect heavy flavor decay vertices
    - ✓ $\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
  - Powerful particle identification ➔ separate protons/kaons/pions/muons

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

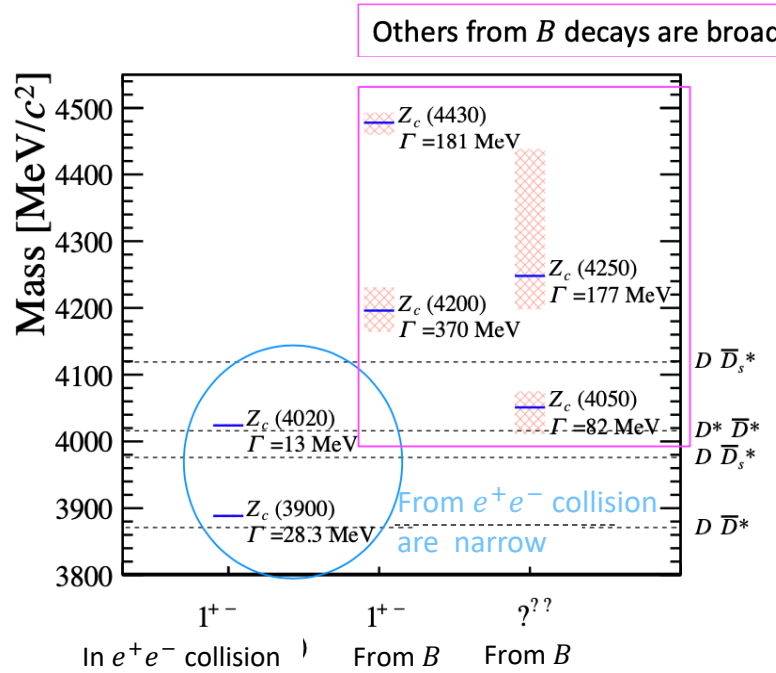




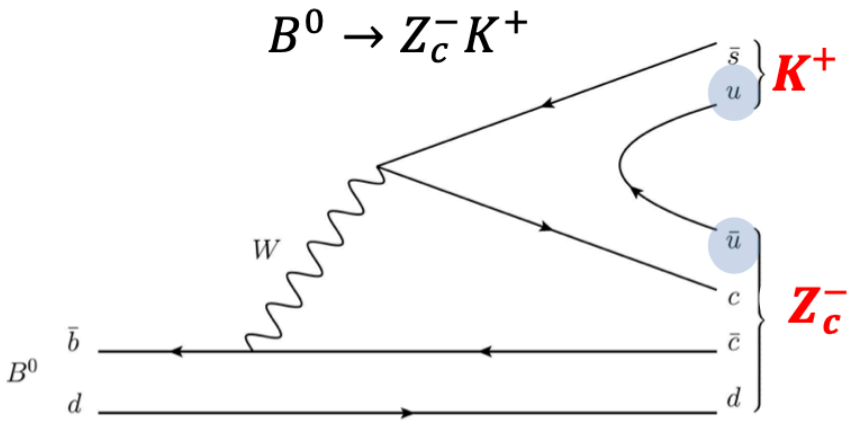
Search for Z_{cs} $(c\bar{c}u\bar{s})$

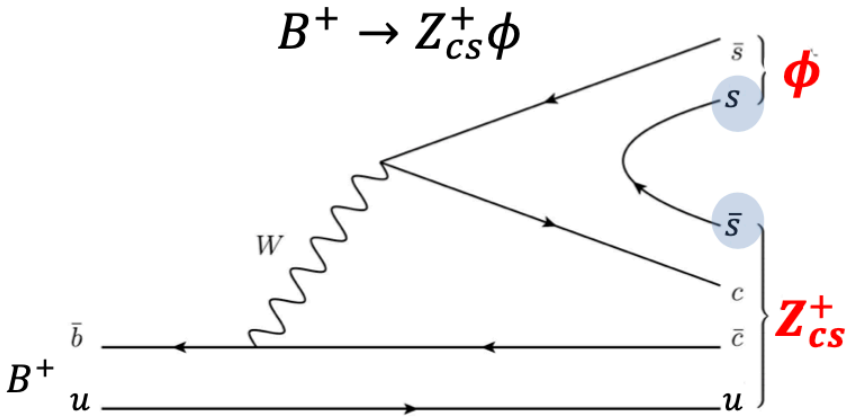
- Several Z_c^- states were observed in e^+e^- collision or B decays
  - Natural to search for the SU(3) partner of Z_c

- Similar Feynman diagrams in $B^0 \to Z_c^- K^+$ and $B^+ \to Z_{cs}^+ \phi$



PLB 798 (2019) 135022

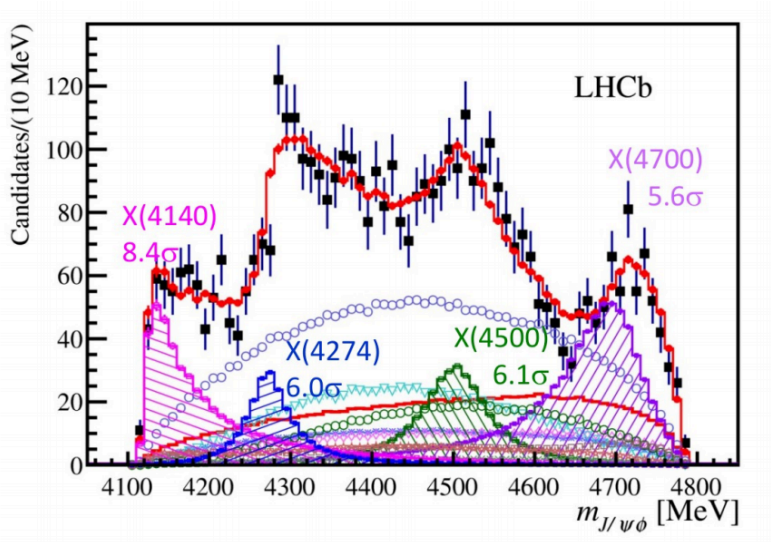


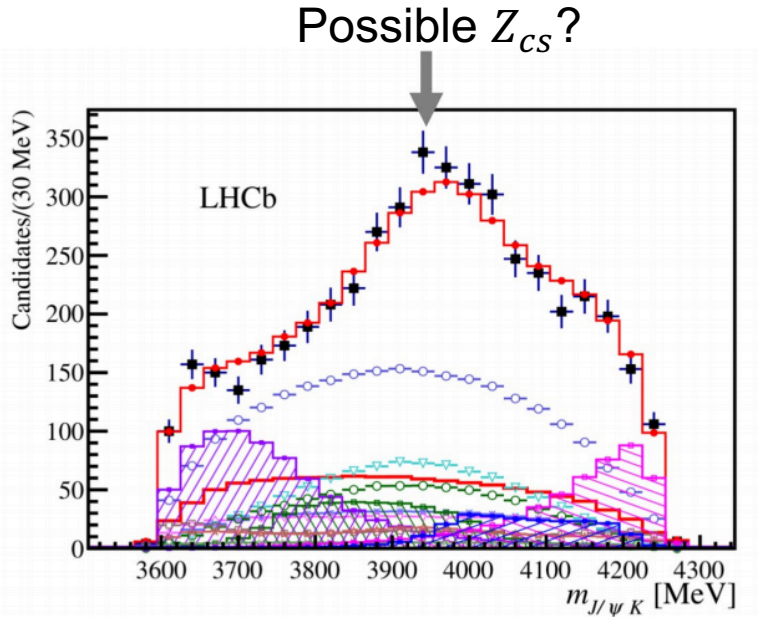


$B^+ \to J/\psi\phi K^+$ with Run1 data

PRL 118, 022003 (2017)

- A 6D amplitude analysis (AmAn) was performed to search for $X \to J/\psi\phi$ $(c\bar{c}s\bar{s})$ and $Z_{cs}^+ \to J/\psi K^+$ $(c\bar{c}u\bar{s})$
- Four X states observed
  - $X(4140),\ X(4274),\ X(4500),\ X(4700)$
- Z_{cs} not observed
  - But a hint in $m(J/\psi K)$ around 4000 MeV

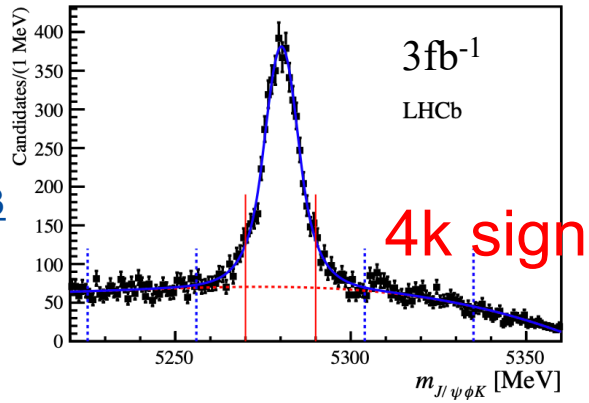




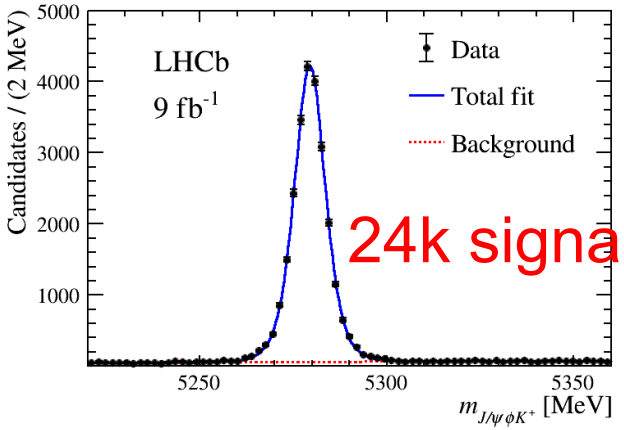
Update with full Run1 + Run2 data

- Better selection criteria
  - Much higher purity; background fraction ~4%, a factor of 6 smaller
  - 6× larger signal yield

PRL. 118 (2017) 022003



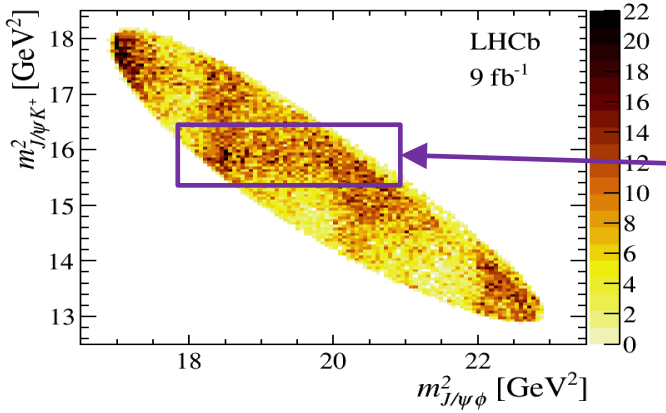
4k signals



24k signals

PhysRevLett.127.082001

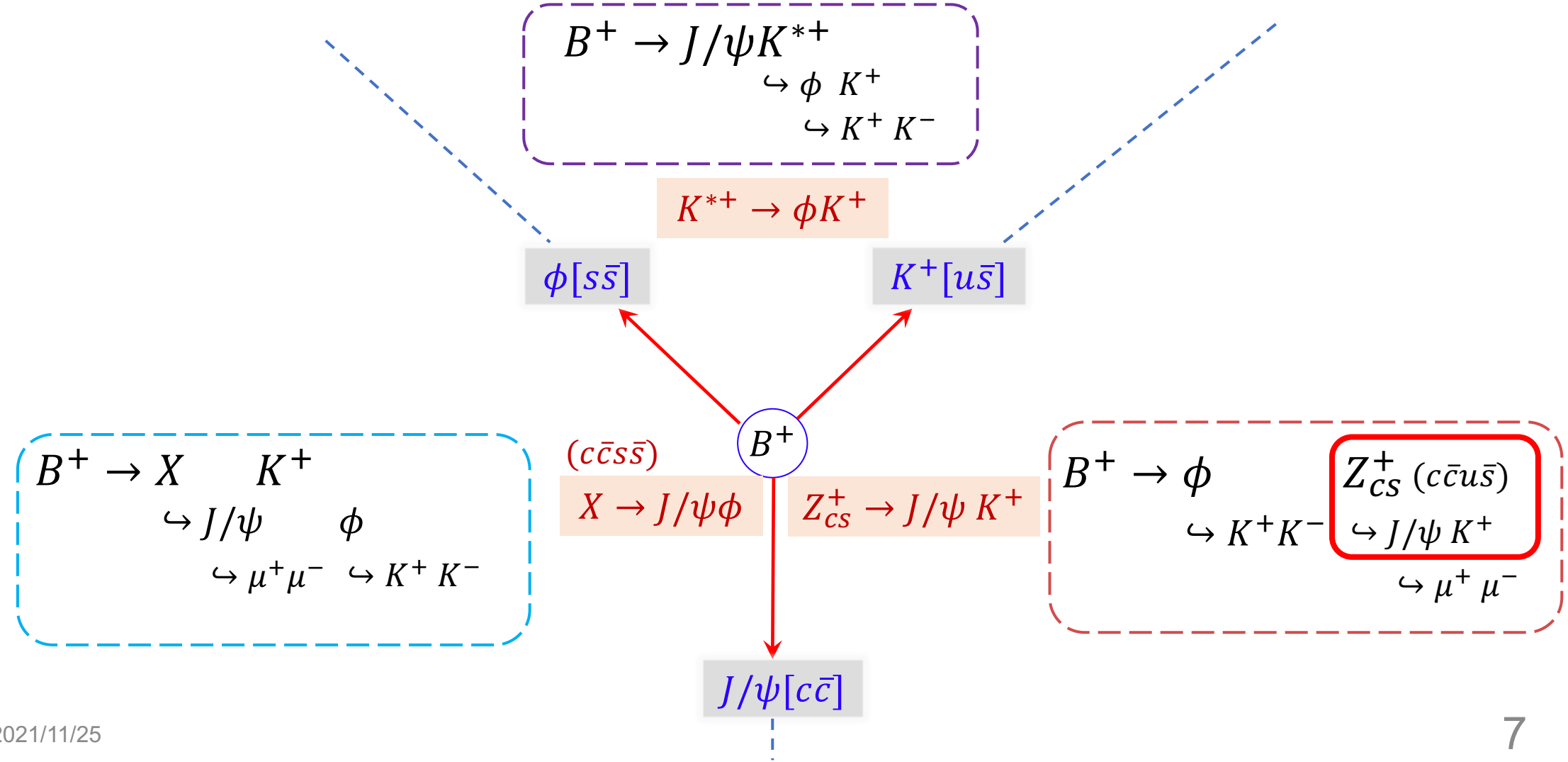
- Dalitz plot



Hint of Z_{cs}^+

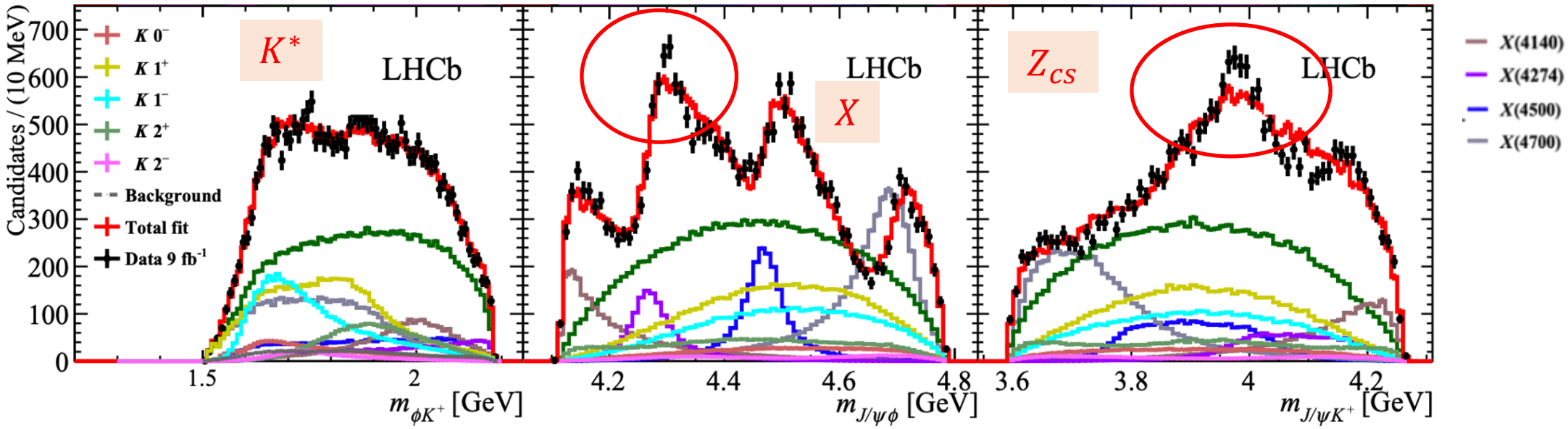
Resonant contributions

- Three different decay paths



Amplitude fit (Run1 model)

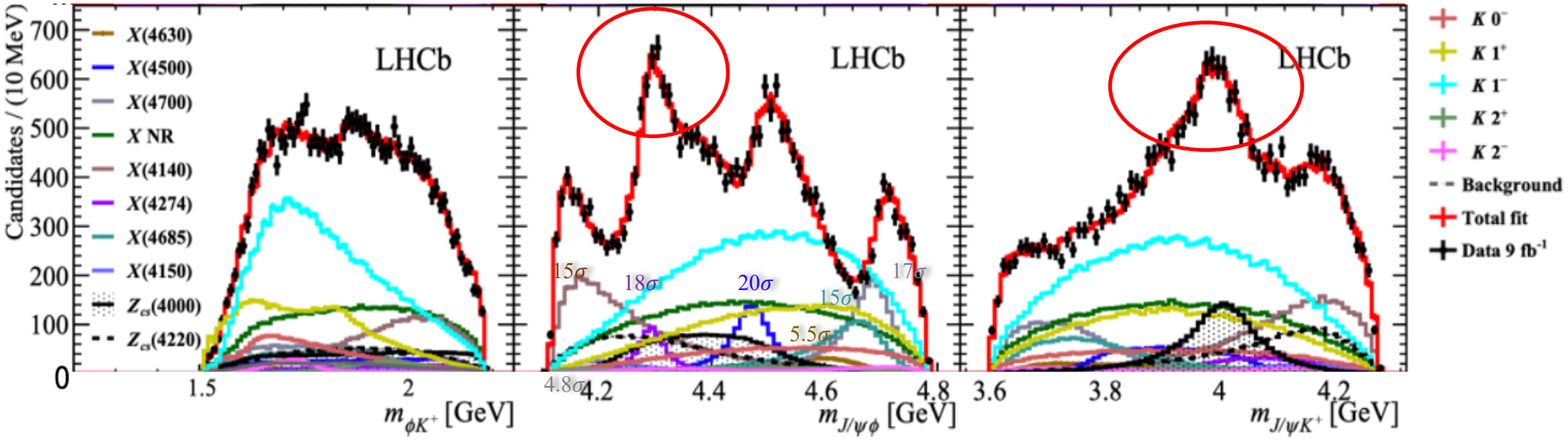
- Start from using Run1 model
  - 9 K^* states + 4 X states
  - cannot well describe the data



- Limited improvement by only adding more K^* states

Amplitude fit (updated model)

- Adding exotic states
  - With largest imporvement of fit quality: $Z_{cs}(4000)$, $X(4685)$
  - Other significant structures: $X(4630)$, $Z_{cs}(4220)$, $X(4150)$
- Much better description



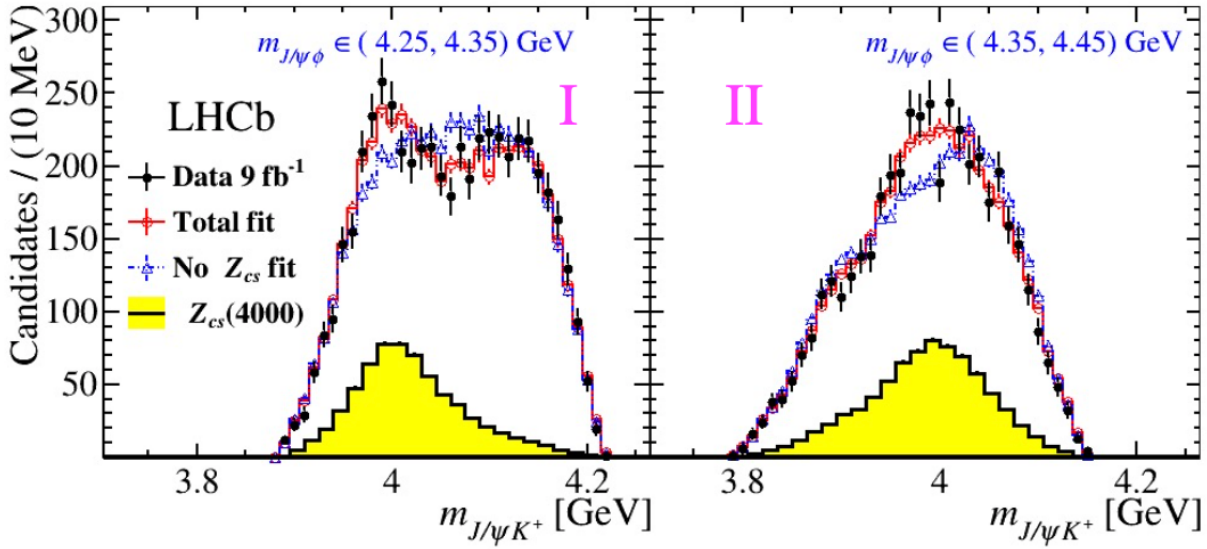
Fit results

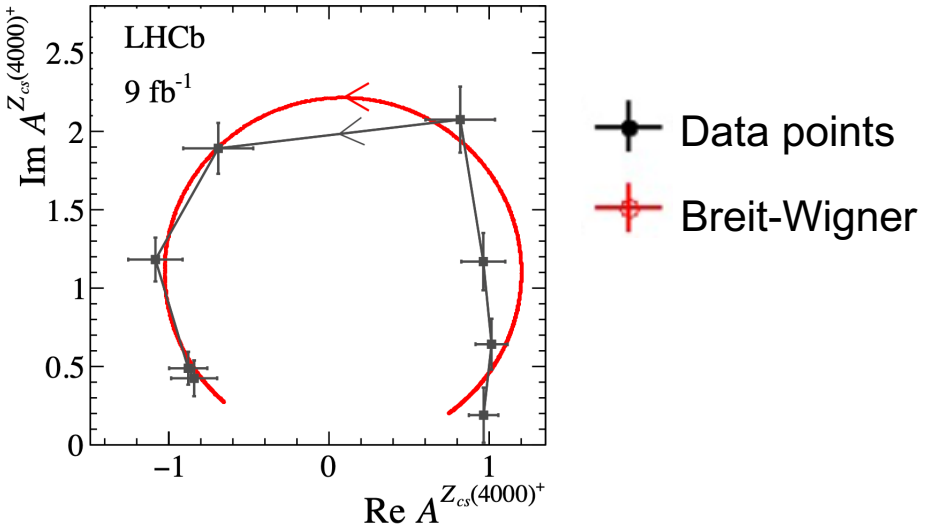
Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]
$X(4140)$	13	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$
$X(4274)$	18	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$
$X(4500)$	20	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$
$X(4700)$	17	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$
$X(4685)$	15	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$
$X(4630)$	5.5	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$
$X(4150)$	4.8	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$
$Z_{cs}(4000)$	15	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$
$Z_{cs}(4220)$	5.9	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$

- The four X states in Run 1 analysis confirmed
- $X(4630)$ and $X(4685)$ observed
- $Z_{cs}(4000)$ and $Z_{cs}(4220)$ observed

Z_{cs}^{+} results

- The J^P of $Z_{cs}(4000)^+$ determined as 1^+, the J^P of $Z_{cs}(4220)^+$ is 1^+ or 1^-
- $Z_{cs}(4000)^+$ can be clearly viewed in slices of $m(J/\psi\phi)$





- The Argand plot indicates the resonant character of $Z_{cs}(4000)^+$

Comparison to BESIII's $Z_{cs}(3985)$

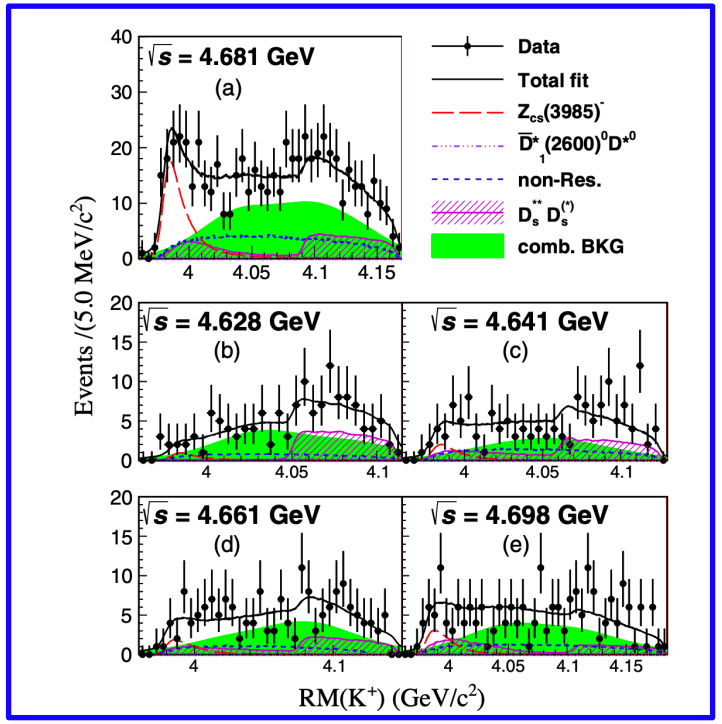
- BESIII observed a narrow Z_{cs} in $D_s D^* + D D_s^*$ mass distribution

$$m_{\text{pole}}[Z_{cs}(3985)^-] = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \text{MeV}/c^2,$$
$$\Gamma_{\text{pole}}[Z_{cs}(3985)^-] = (12.8^{+5.3}_{-4.4} \pm 3.0)\ \text{MeV}.$$

- Tests performed:
  - Mass and width of $Z_{cs}(4000)$ fixed to BESIII's result ➔ $-2\ln\mathcal{L}$ is worse by 160 units
  - Adding additional $Z_{cs}(3985)$ doesn't improve the fit

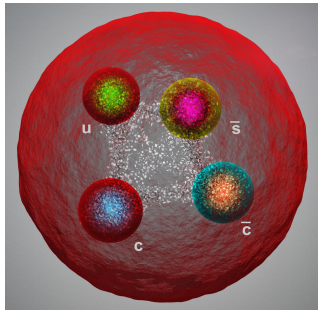
- No evidence that $Z_{cs}(3985)$ and $Z_{cs}(4000)$ are the same state

BESIII

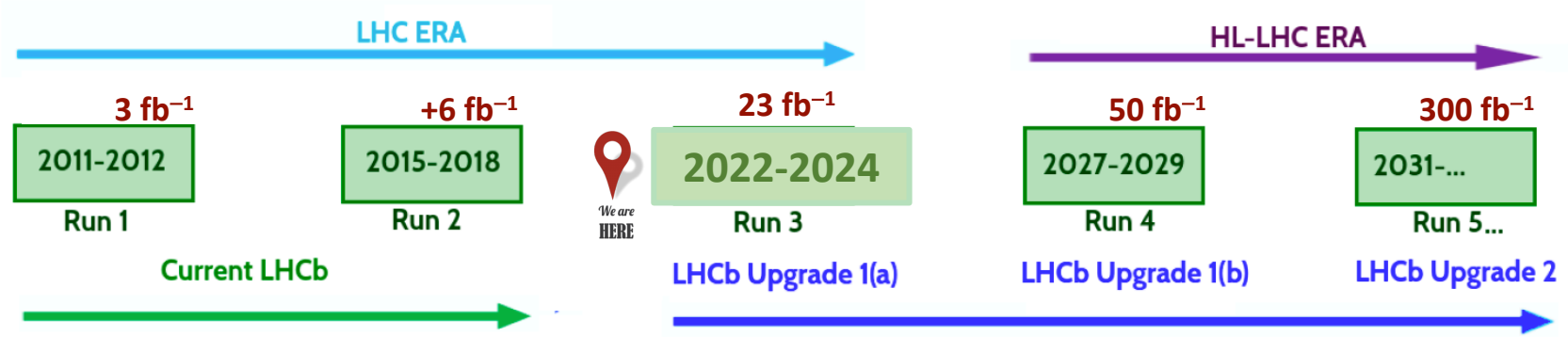


PRL 126 (2021) 102001

Summary and outlook



- Four new exotic states are observed in $B^+ \to J/\psi\phi K^+$ channel
  - $Z_{cs}(4000),\ Z_{cs}(4420), X(4630),\ X(4685)$
- LHCb upgrade



- Expect to 7x more data by 2029 than current, half of these by 2023
- Could have another 6x increase from Upgrade II
- Open new opportunities for discovery of more exotic states

Thank you for your attention !