粒子物理前沿卓越创新中心第八次会议

Recent results of hadron spectroscopy at LHCb

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Contents

- Introduction and LHCb
- Conventional hadrons
  - ➢ Observation of new excited Ξ_c^0 states

    [PRL 124 (2020) 222001]
  - ➢ Observation of a new excited D_s^+ state

    [LHCb-PAPER-2020-034, arXiv:2011.09112]
- Exotic hadrons
  - ➢ Full charmed tetraquark candidate $X_{cc\bar{c}\bar{c}}(6900)$

    [arXiv:2006.16957, Science Bulletin 65 (2020) 1983]
  - ➢ Evidence of a pentaquark state with strangeness $P_{cs}(4459)^0$

    [LHCb-PAPER-2020-039]

The strong interaction

- Strong interaction and QCD less known than EW in the Standard Model

  Knowledge of QCD is fundamental and critical in precision SM tests

Contributions to muon g-2

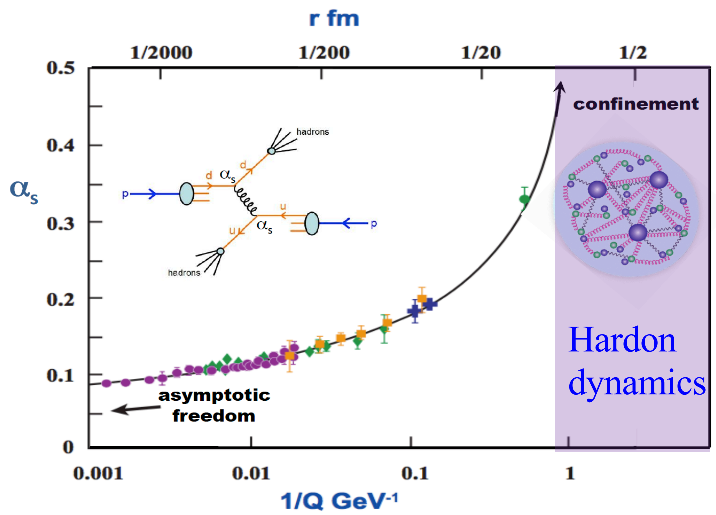
arXiv:1311.2198

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

QCD贡献

QCD uncertainty

实验: $a_\mu^{E821} = (116\,592\,089 \pm 63) \times 10^{-11}$

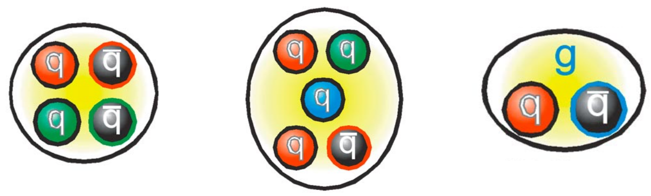


- Hadron spectroscopy: opportunities to study non-perturbative QCD

- Exotic hadrons/multiple quark interactions may reveal new dynamics

  QCD → Effective theory

Exotics



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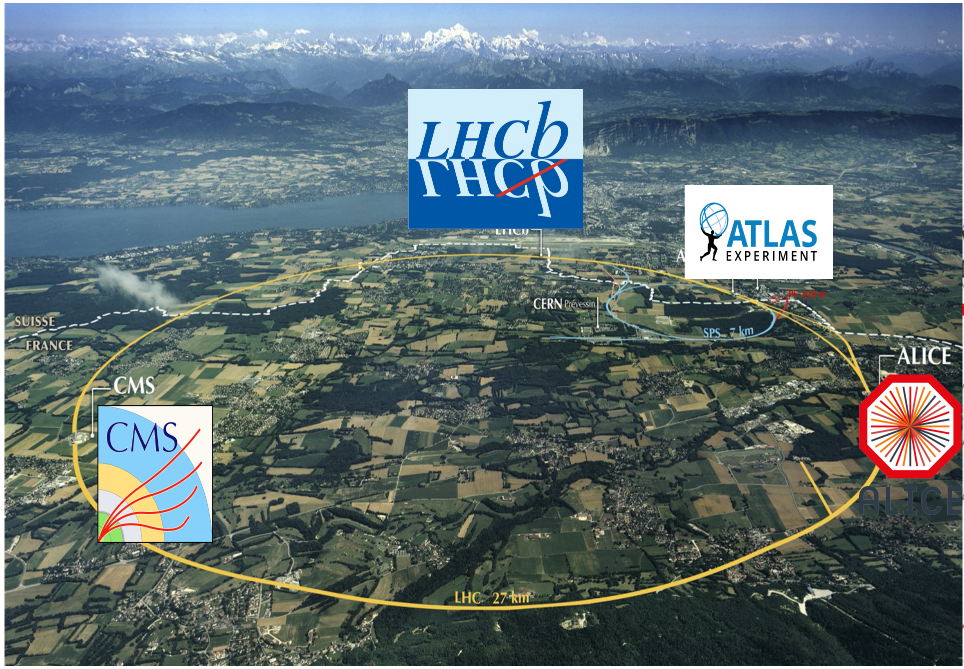
tetraquark ? pentaquark ? hybrid ?

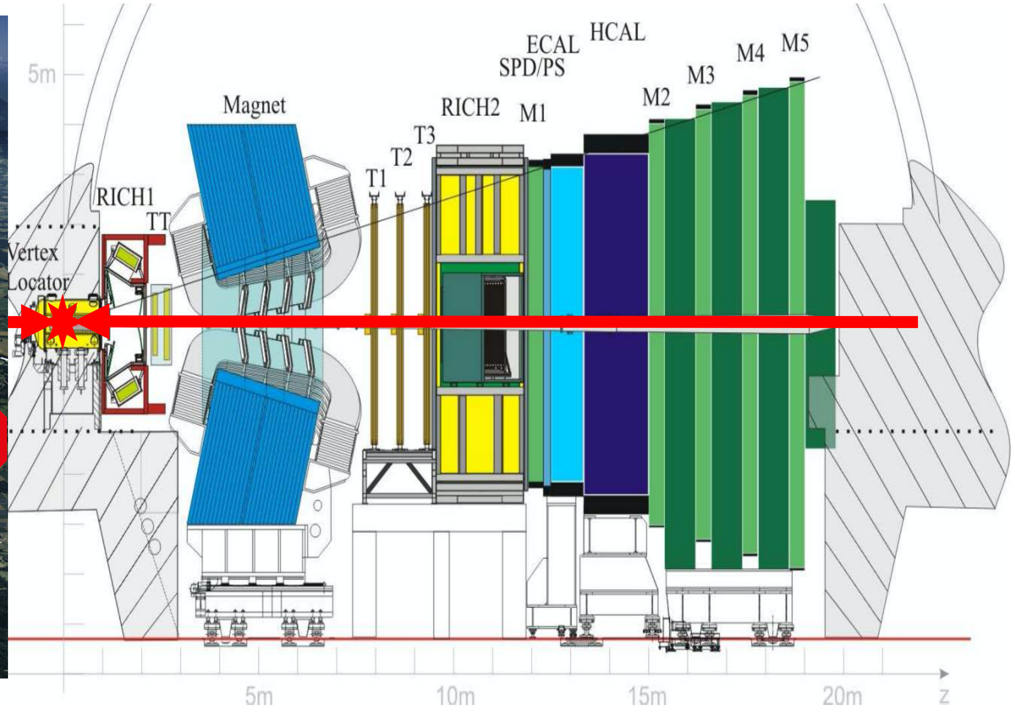
LHCb experiment

One of the four large experiments at CERN
Aiming for precision measurements in b, c flavor sectors
Forward acceptance: $2 < \eta < 5$

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

Large Hadron Collider Experiments



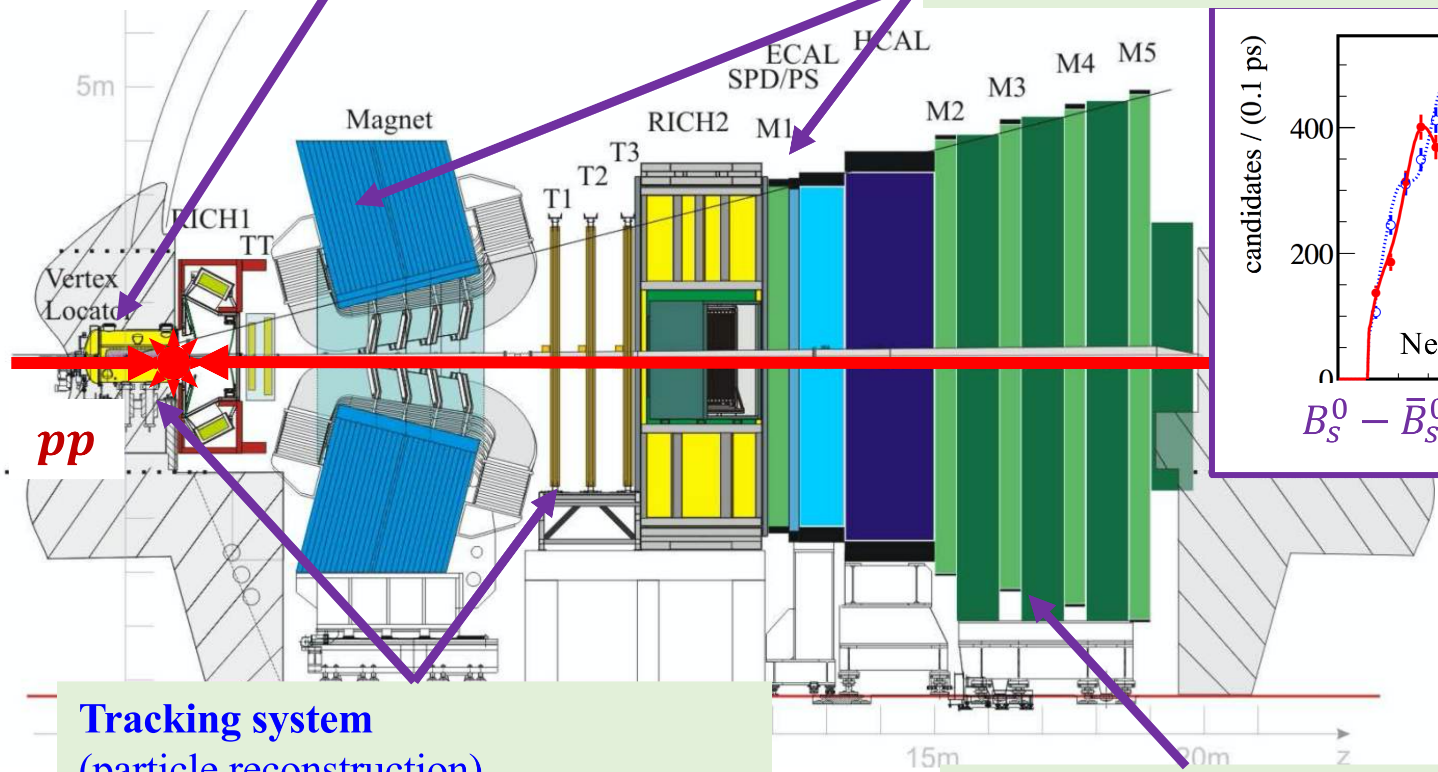


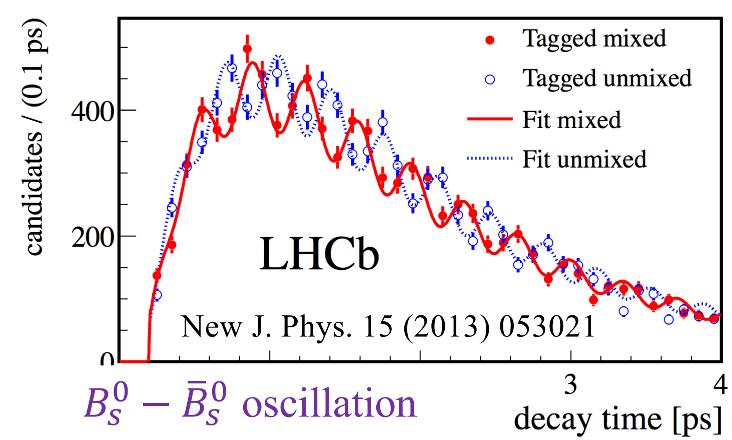
LHCb detector

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

Vertex Locator (vertex reconstruction)
- Impact parameter resolution: 20μm
- Decay time resolution: 45 fs (τ_B~1.5 ps)

RICH detectors
($K/\pi/p$ separation <100 GeV)
- $\epsilon(K \to K)$~95%
- Mis-ID $\epsilon(\pi \to K)$~5%



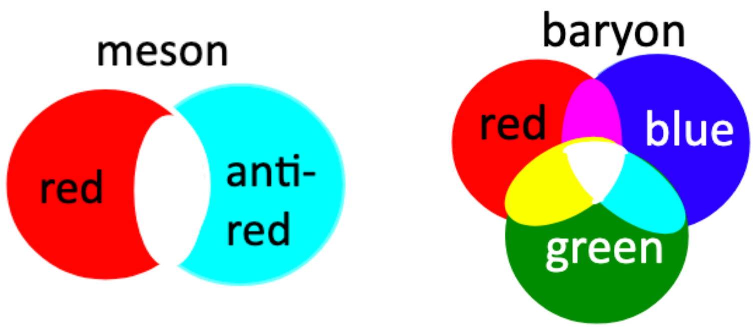


$B_s^0 - \bar{B}_s^0$ oscillation

Tracking system
(particle reconstruction)
- ϵ(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV

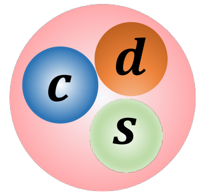
Muon system
(μ identification)
- $\epsilon(\mu \to \mu)$~97%
- Mis-ID $\epsilon(\mu \to \mu)$~$1-3\%$

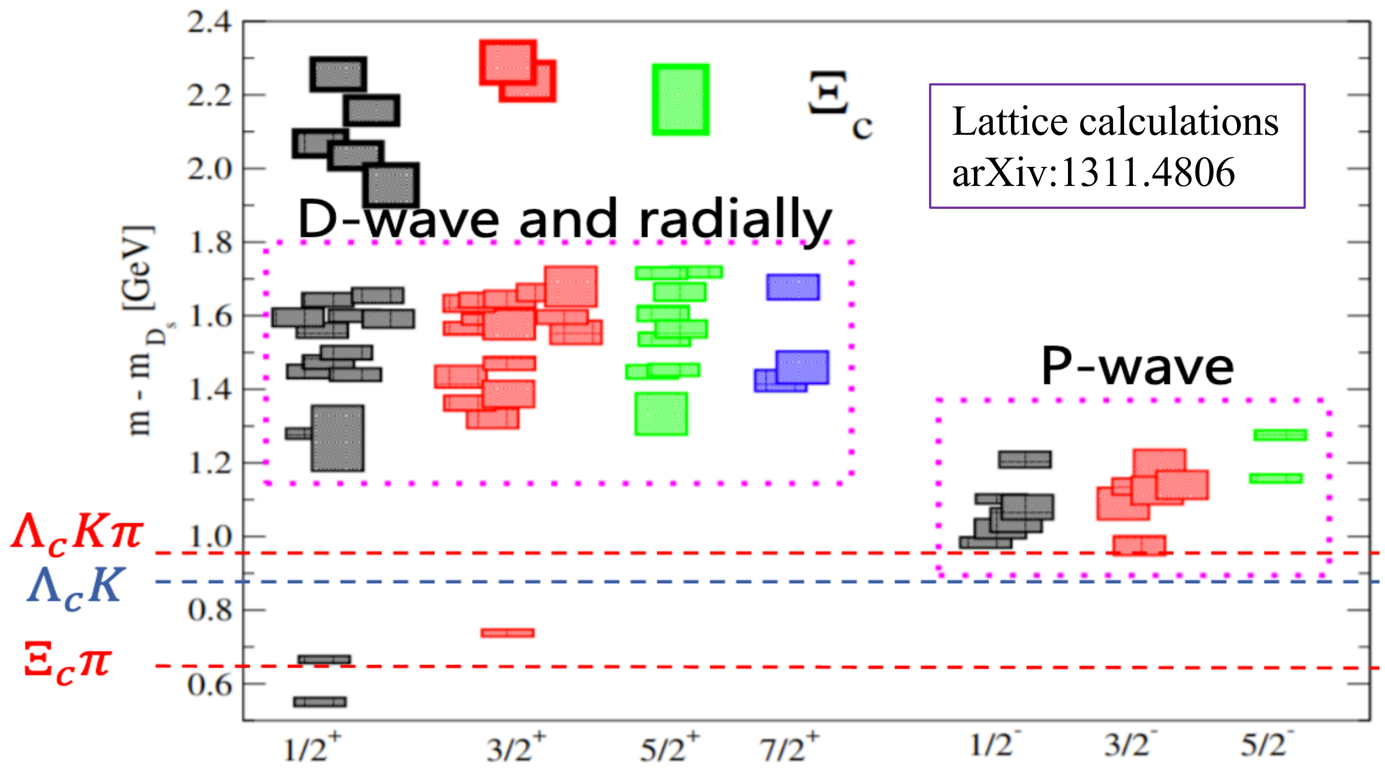
Conventional hadrons



Exicited Ξ_c states

- Rich excited Ξ_c spectroscopy, only about 10 states identified
- All states possible in prompt *pp* collisions





Known Ξ_c in PDG

Ξ_c^+

Ξ_c^0

$\Xi_c'^+$

$\Xi_c'^0$

$\Xi_c(2645)$

$\Xi_c(2790)$

$\Xi_c(2815)$

$\Xi_c(2930)$

$\Xi_c(2970)$
was $\Xi_c(2980)$

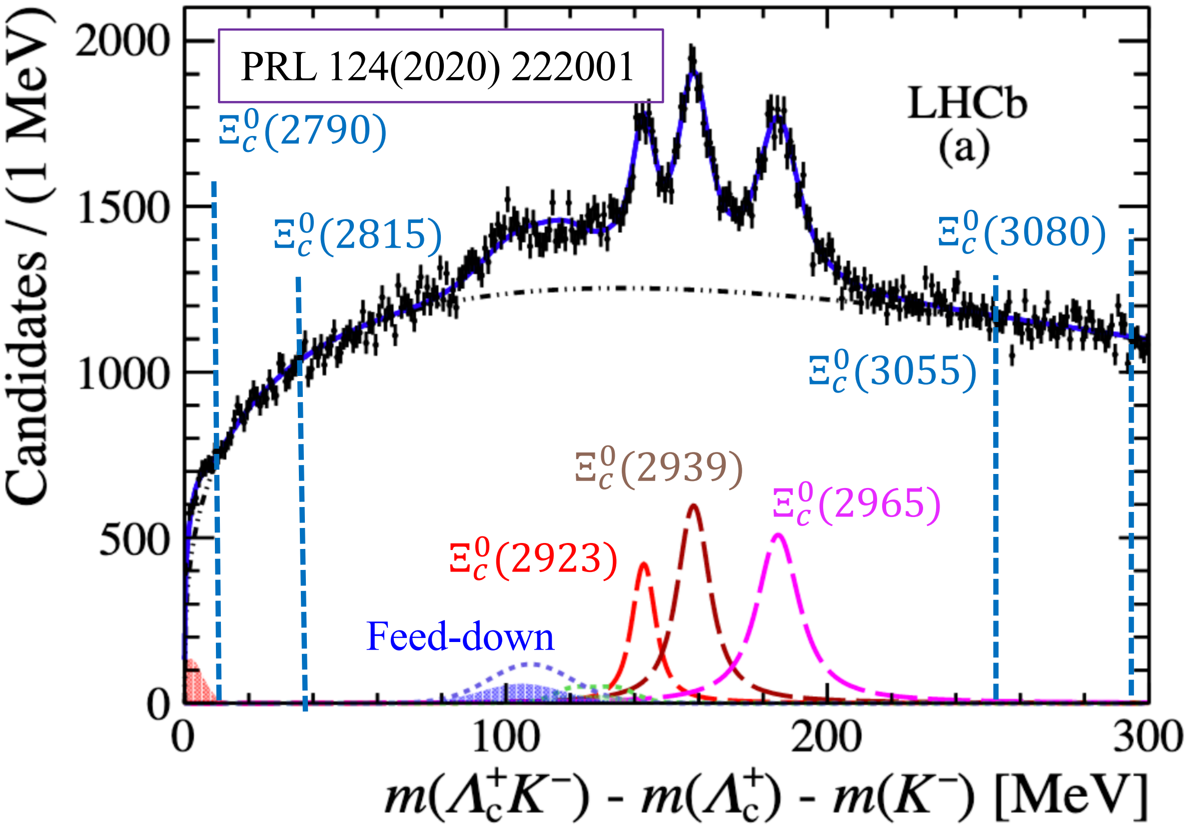
$\Xi_c(3055)$

$\Xi_c(3080)$

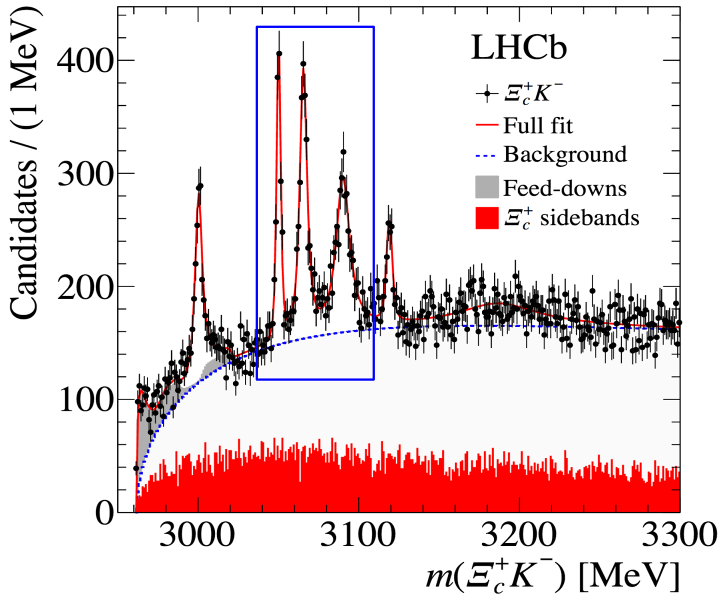
$\Xi_c(3123)$

Observation of new Ξ_c^{**0} states

- Mass spectrum of $\Xi_c^{**0} \to \Lambda_c^+ K^-$ at LHCb, three new states observed
  - ➢ $\Xi_c^0(2923)$, $\Xi_c^0(2939)$: previously seen in $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ decay as a $\boldsymbol{\Xi_c^0(2930)}$
  - ➢ $\Xi_c^0(2965)$: mass close to $\boldsymbol{\Xi_c^0(2970)}$ observed in $\Lambda_c^+ K\pi$ decay, but not the same
- Higher states seen by feed-down, other known states not obvious,

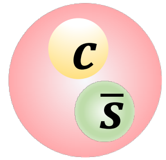


Compared to $\Xi_c^+ K^-$ spectrum



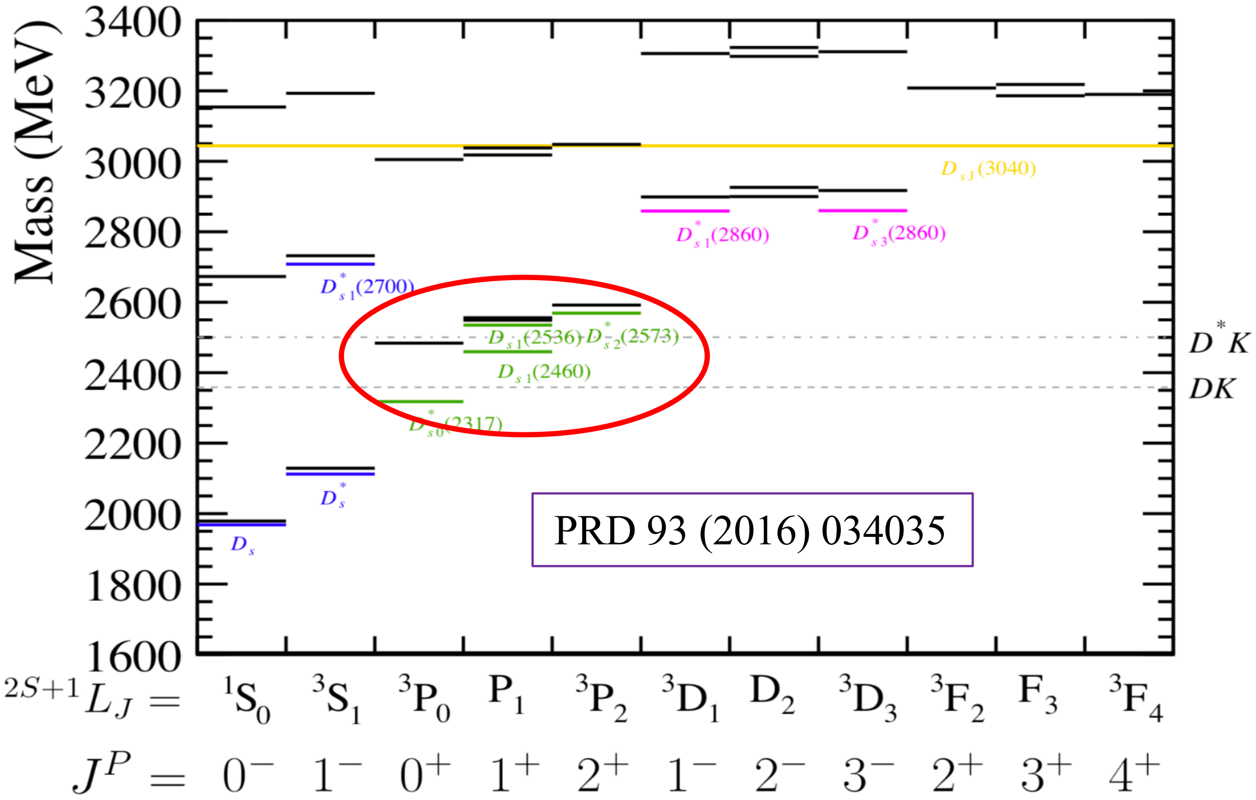
PRL 118 (2017) 182001

Excited D_s^+



- Spectrum known better than baryons
- But still hard to establish SU(3) for D_s^{**+}, D^{**}
  - ➢ Large discrepancy with predicted masses
  - ➢ $D_{s0}^*(2317)^+$, $D_{s1}^*(2460)^+$ as $D^{(*)}K$ molecular?
- Matching of complete spectrum is important
  - ➢ Beauty decay clean environment, allowing to measure J^{PC}

PLB641(2006)278
PRD82(2010)054022
PRD89(2014)014026
…

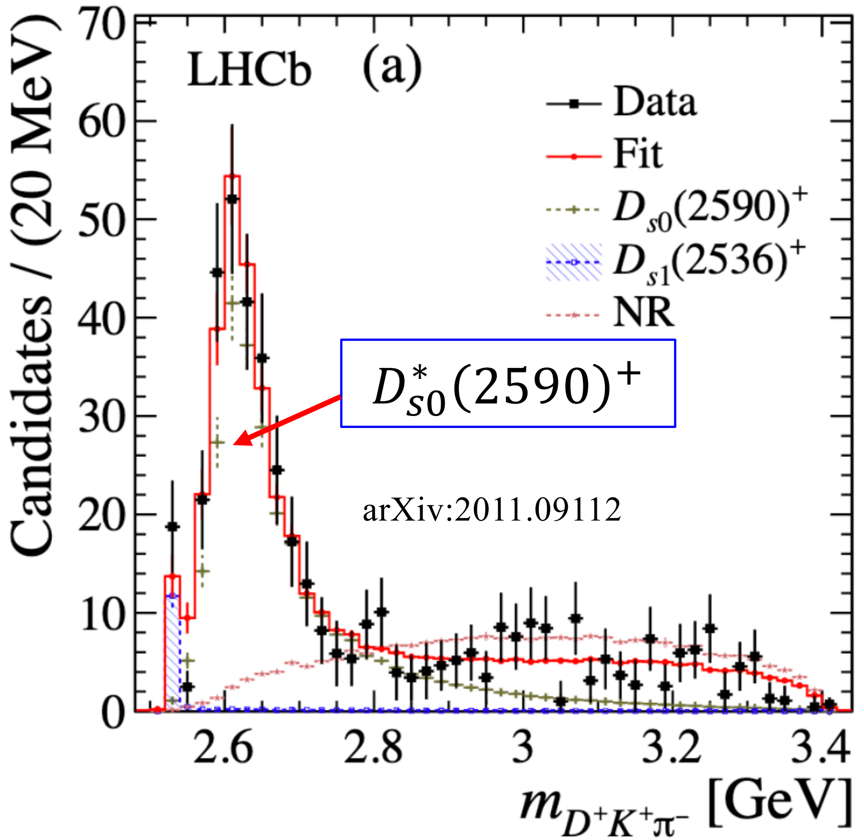


Observation of new excited D_s^+

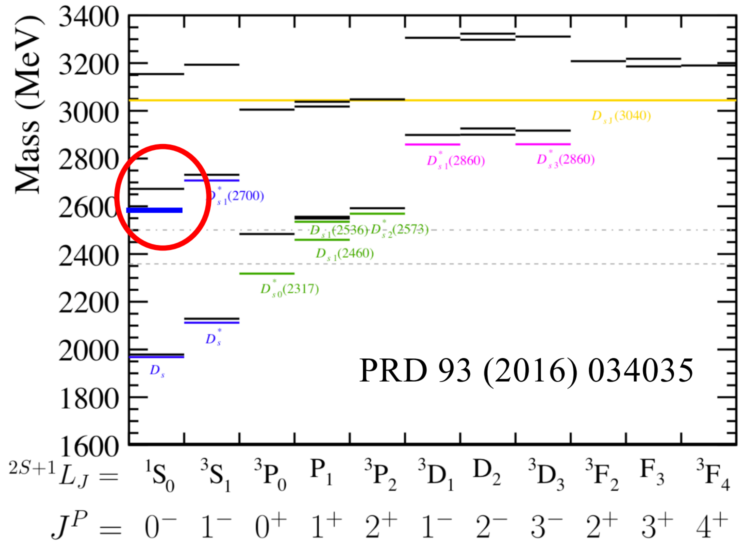
- Looking for excited D_s^+ in $D^+K^+\pi^-$ final states, in $B^0 \to D^-D^+K^+\pi^-$ decays
- Significant structure at $m_{D^+K^+\pi^-} \approx 2.6$ GeV
- Amplitude fit for $m_{K^+\pi^-} < 0.75$ GeV region, dominated by $K_0^*(700)^0$ s-wave

  $J^P = 0^-$ preferred, $1^+, 2^-$ rejected by >15σ

  $m_R = 2591 \pm 6 \pm 7$ MeV, $\Gamma_R = 89 \pm 16 \pm 12$ MeV

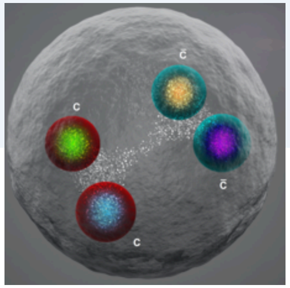


Consistent with the $D_s(2^1S_0)^+$ state.
Width is compatible with prediction, but mass 80 MeV lower !



Exotic hadrons

Fully charmed state $T_{cc\bar{c}\bar{c}}$



- Existence of $T_{cc\bar{c}\bar{c}}$ predicted early since charm discovery

  Y. Iwasaki, *Is a state $c\bar{c}c\bar{c}$ found at 6.0 GeV?*, Phys. Rev. Lett. **36** (1976) 1266.

  K.-T. Chao, *The (cc) - ($\bar{c}\bar{c}$) (diquark-antidiquark) states in e^+e^- annihilation*, Z. Phys C **7** (1981) 317.

- Recent calculations: many possible $T_{cc\bar{c}\bar{c}}$, mostly $m_{T_{cc\bar{c}\bar{c}}} \in [5.8, 7.4]$ GeV/c^2
  - ➢ Decaying into $J/\psi J/\psi$ directly or via feed-down when $m_{T_{cc\bar{c}\bar{c}}} > 2m_{J/\psi}$

J^{PC}	$cc\bar{c}\bar{c}$ $N[(S_D, S_{\bar{D}})S, L]J$	E^{th} [MeV]
0^{++}	1[(1, 1)0, 0]0	5883
0^{++}	2[(1, 1)0, 0]0	6573
0^{++}	1[(1, 1)2, 2]0	6835
0^{++}	3[(1, 1)0, 0]0	6948
0^{++}	2[(1, 1)2, 2]0	7133
0^{++}	3[(1, 1)2, 2]0	7387
1^{+-}	1[(1, 1)1, 0]1	6120
1^{+-}	2[(1, 1)1, 0]1	6669
1^{+-}	1[(1, 1)1, 2]1	6829
1^{+-}	3[(1, 1)1, 0]1	7016
1^{+-}	2[(1, 1)1, 2]1	7128
1^{+-}	3[(1, 1)1, 2]1	7382
1^{--}	1[(1, 1)0, 1]1	6580
1^{--}	1[(1, 1)2, 1]1	6584
1^{--}	2[(1, 1)0, 1]1	6940
1^{--}	2[(1, 1)2, 1]1	6943
1^{--}	3[(1, 1)0, 1]1	7226
1^{--}	3[(1, 1)2, 1]1	7229
0^{-+}	1[(1, 1)1, 1]0	6596
0^{-+}	2[(1, 1)1, 1]0	6953
0^{-+}	3[(1, 1)1, 1]0	7236
1^{++}	1[(1, 1)2, 2]1	6832
1^{++}	2[(1, 1)2, 2]1	7130
1^{++}	3[(1, 1)2, 2]1	7384
2^{++}	1[(1, 1)2, 0]2	6246
2^{++}	1[(1, 1)2, 2]2	6827
2^{++}	1[(1, 1)0, 2]2	6827
2^{++}	2[(1, 1)2, 0]2	6739
2^{++}	3[(1, 1)2, 0]2	7071
2^{++}	[illegible]	[illegible]
2^{++}	[illegible]	[illegible]
2^{++}	[illegible]	[illegible]
2^{++}	3[(1, 1)0, 2]2	7380

arXiv:1911.00960

J^{PC}	m_{X_c}(GeV)
0^{++}	6.44 ± 0.15
	6.59 ± 0.17
	6.47 ± 0.16
	6.46 ± 0.16
	6.82 ± 0.18
0^{-+}	6.84 ± 0.18
	6.85 ± 0.18
0^{--}	6.84 ± 0.18
1^{++}	6.40 ± 0.19
	6.34 ± 0.19
1^{+-}	6.37 ± 0.18
	6.51 ± 0.15
1^{-+}	6.84 ± 0.18
	6.88 ± 0.18
1^{--}	6.84 ± 0.18
	6.83 ± 0.18
2^{++}	6.51 ± 0.15
	6.37 ± 0.19

PLB 773 (2017) 247

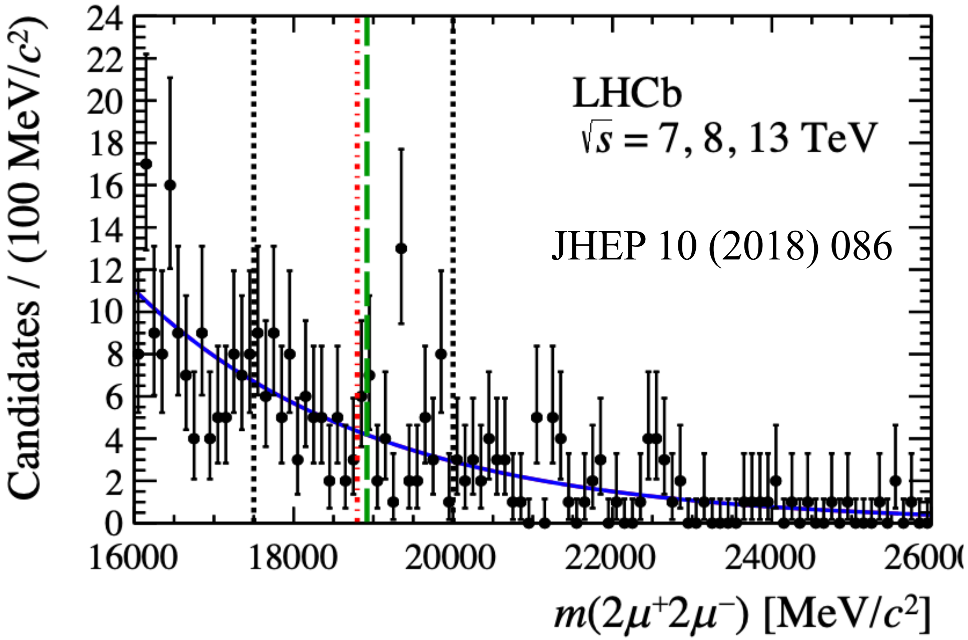
J^{PC}	S-wave	P-wave
0^{++}	$\eta_c(1S)\eta_c(1S)$, $J/\psi J/\psi$	$\eta_c(1S)\chi_{c1}(1P)$, $J/\psi h_c(1P)$
0^{-+}	$\eta_c(1S)\chi_{c0}(1P)$, $J/\psi h_c(1P)$	$J/\psi J/\psi$
0^{--}	$J/\psi\chi_{c1}(1P)$	$J/\psi\eta_c(1S)$
1^{++}	–	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$, $\eta_c(1S)\chi_{c0}(1P)$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

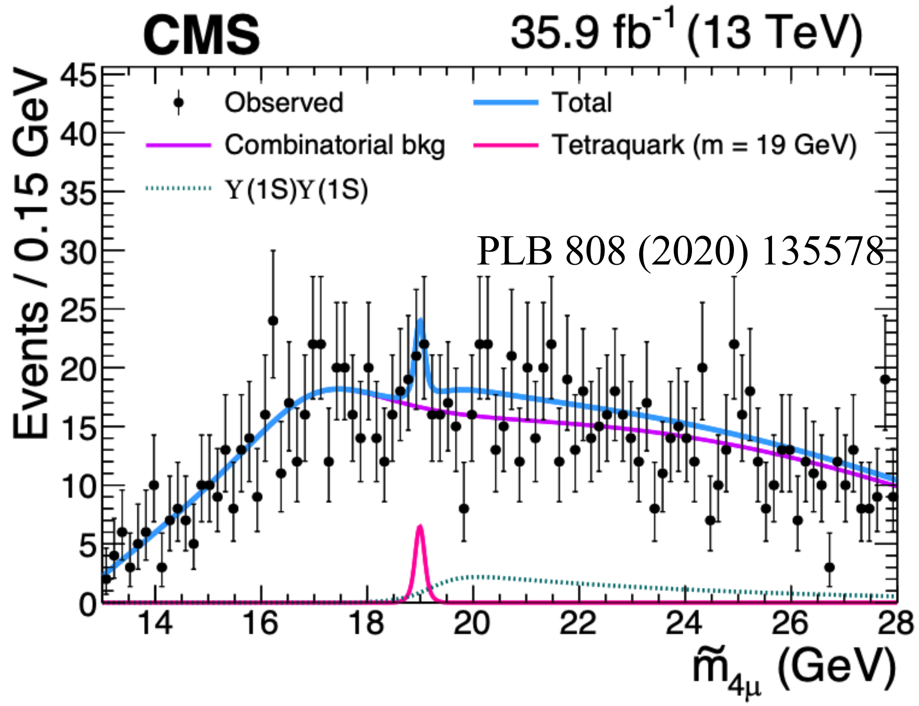
The bottom partner: $T_{bb\bar{b}\bar{b}}$

- Searched for in $\Upsilon\mu^+\mu^-$ final state by LHCb and CMS

LHCb: 6.3 fb^{-1} CMS: 35.9 fb^{-1}

No obvious signals, low production rate ?

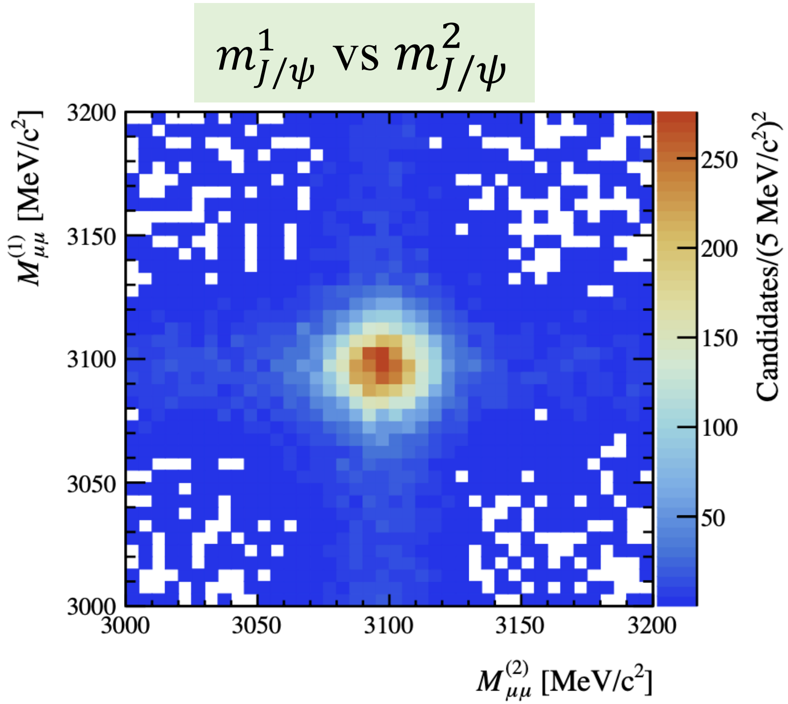


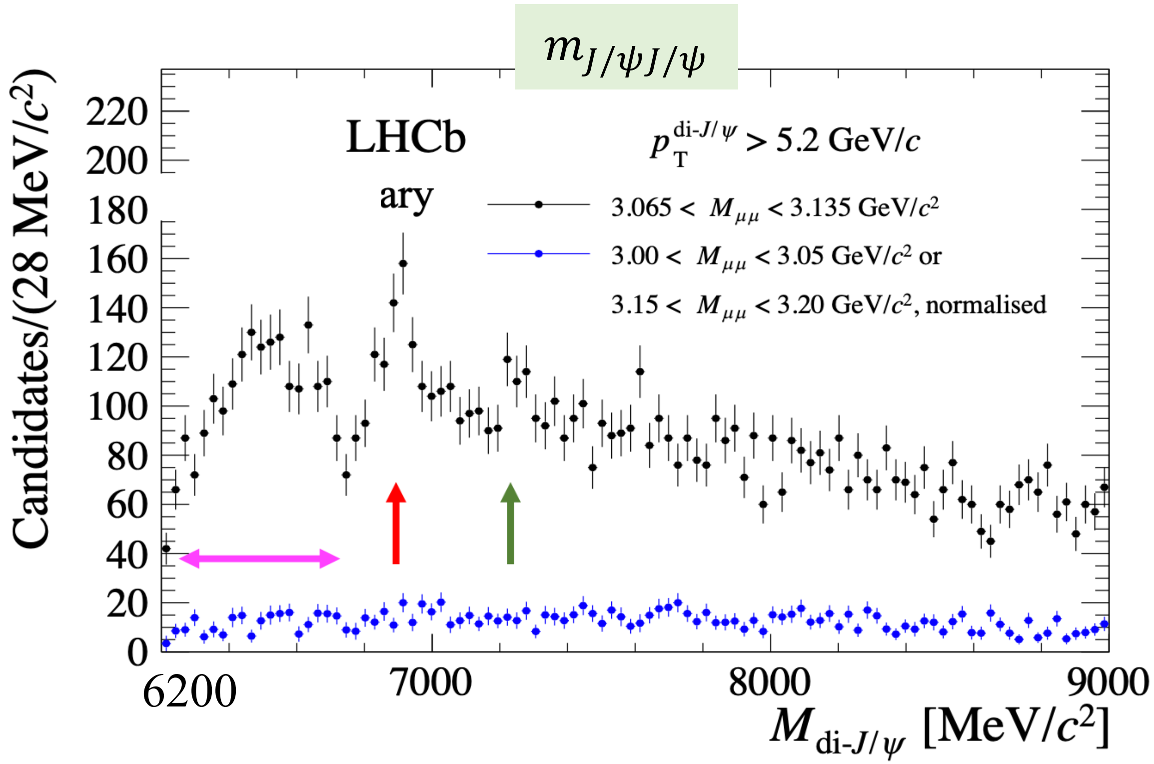


Di-J/ψ production

- Full LHCb data, about 34K di-J/ψ signals

arXiv:2006.16957
Science Bulletin 65 (2020) 1983



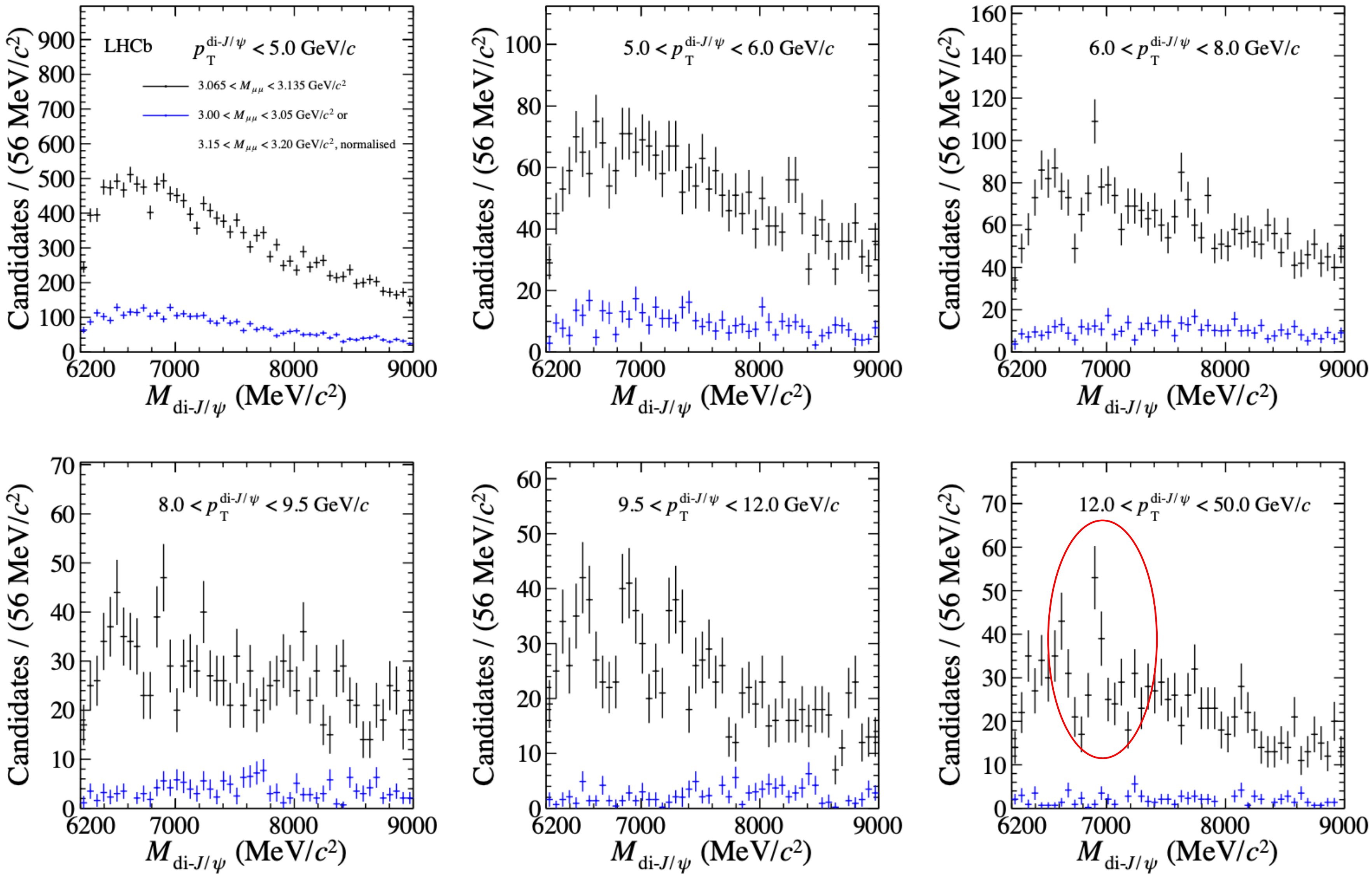


- Broad structure at 6.2-6.8 GeV/c^2, close to Di-J/ψ mass threshold
- Narrow peak at 6.9 GeV/c^2
- Hint of another structure at 7.2 GeV/c^2
- No obvious structure in J/ψ background sample

Non-peaking hypothesis rejected at 6σ !

Di-J/ψ invariant mass

- Same structures presented in all high $p_T(J/\psi J/\psi)$ bins



Di-J/ψ mass modeling (I)

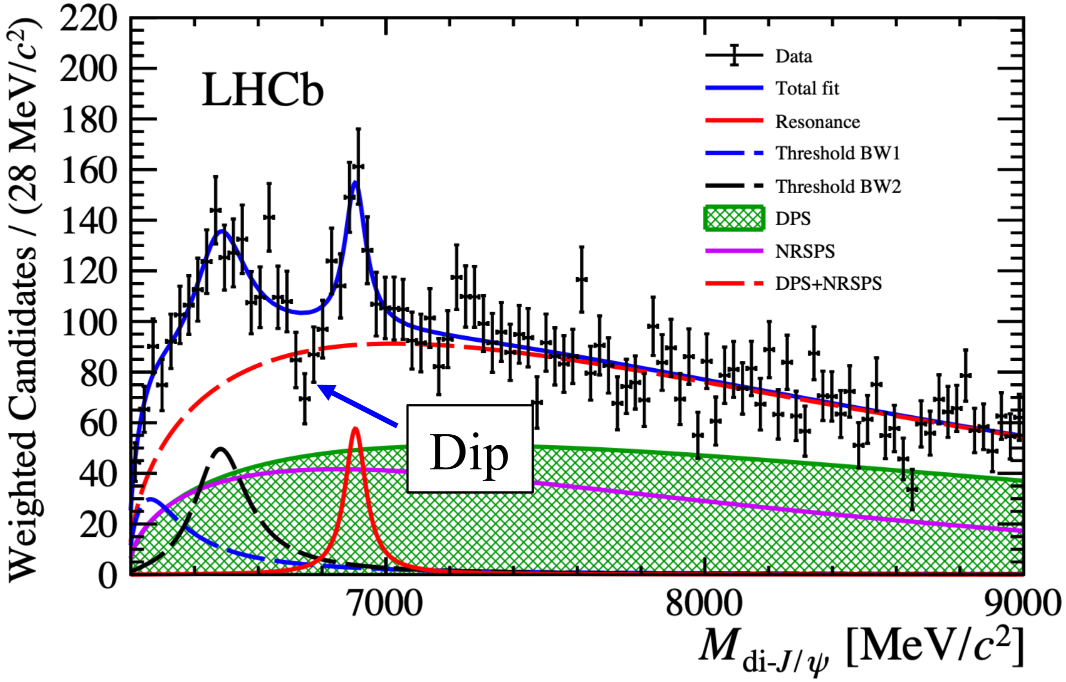
- Smooth function for non-resonant production
- Breit-Wigner (BW) for peaking structures

- Individual significances:
  - ✓ Broad structure: $> 5\sigma$
  - ✓ Structure at 6.9 GeV/c^2 : $> 5\sigma$
  - ✓ 7.2 GeV/c^2 structure: $< 1\sigma$
- Threshold structure complicated

  Two BWs versus one BW:

  $P(\chi^2_{ndf})$: 1.2% → 4.6%

  Need more states?



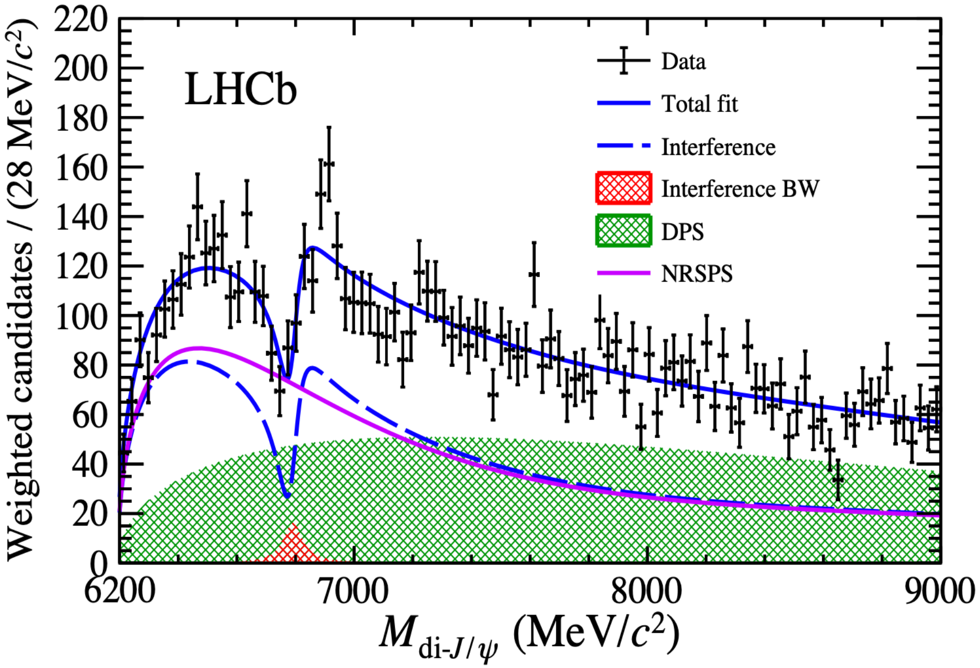
$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV}$$

Difficulty to model the dip at 6.8 GeV !

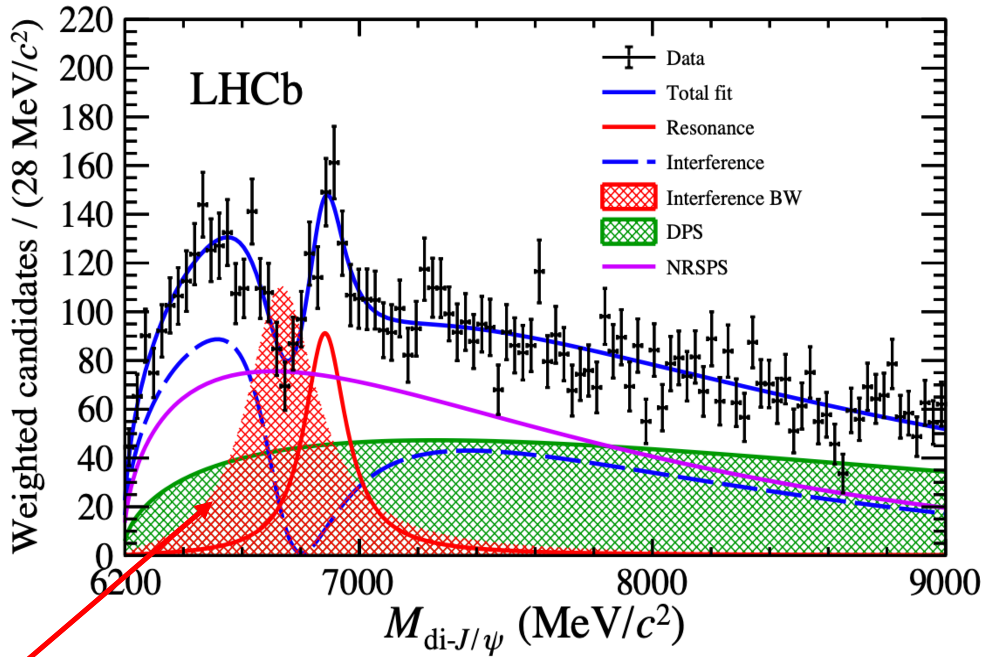
Di-J/ψ mass modeling (II)

- Interferences to describe dip at 6.8 GeV
- Two separate choices of possible compositions

Non-resonant + one BW, $P_{\chi^2} = 2.8\%$



Non-resonant + two BWs, $P_{\chi^2} = 15.5\%$



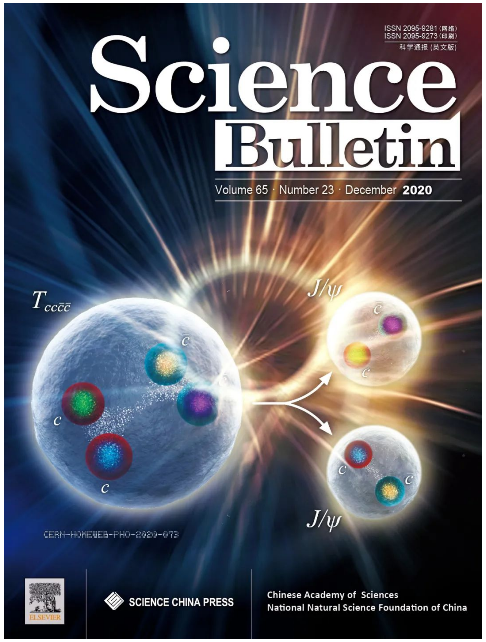
$m = 6741\ \text{MeV}/c^2$
$\Gamma = 288\ \text{MeV}/c^2$

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

Different from Model I

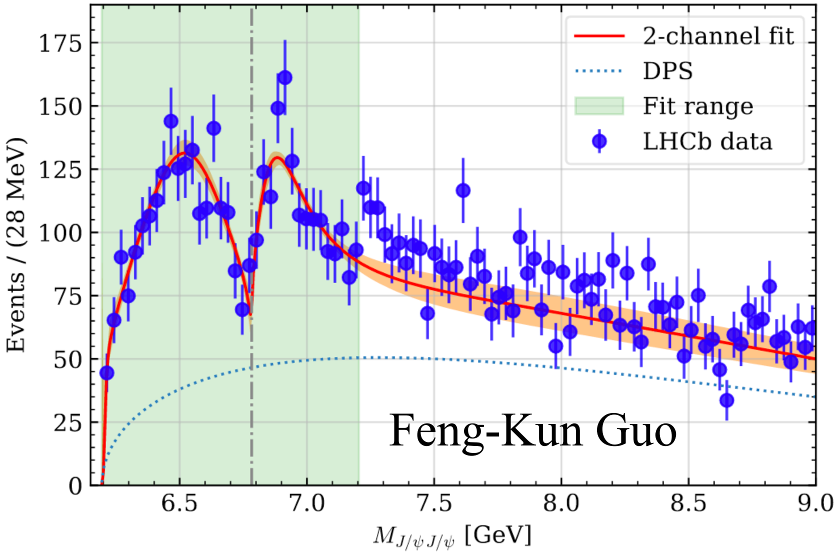
Interpretations

- Candidates of four-charm-quark states
- But difficult to understand all structures
  - ➢ Relative narrow peak at 6.9 GeV, a BW resonance $X(6900)$. Parameters depends on interference effect
  - ➢ Brow structure at threshold: one BW, multiple BWs or feed-downs. More information (J^P etc.) needed
  - ➢ Interference is possible and fits better, but not significant enough yet
- Other similar states: $J/\psi\ \psi',\ J/\psi\Upsilon, ss\bar{s}\bar{s}\ \ldots$

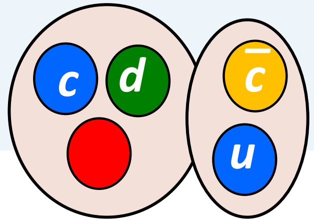


Internal structure: naturally tetraquark, but also explained with coupled channels ($\psi\psi, \psi'\psi\ldots$)

arXiv:2009.07795, arXiv: 2011.00978, arXiv: 2011.11374, arXiv: 2011.04346 …



Pentaquark states



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

  Narrow and close to thresholds of $\Lambda_c^+ \bar{D}^{*0}, \Sigma_c \bar{D}^{(*)}$, supports a molecule picture

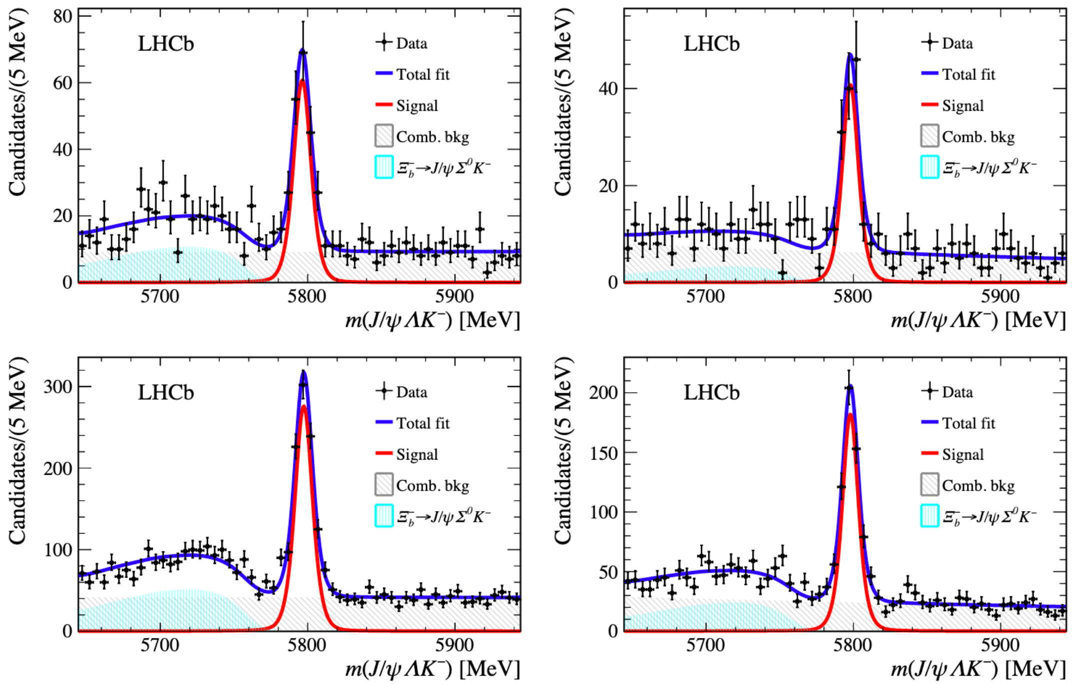
- Existence of $P_{cs}^+(c\bar{c}sud) \to J/\psi\Lambda$ predicted, possibly produced in $\Xi_b^- \to J/\psi \Lambda K^-$
- Triangle singularity may also be present in $\Xi_b^- \to J/\psi \Lambda K^-$

PRL 105 (2010) 232001,
PRC 93(2016) 064203,
PRD 93(2016)094009
Symmetry 12 (2020) 10
…

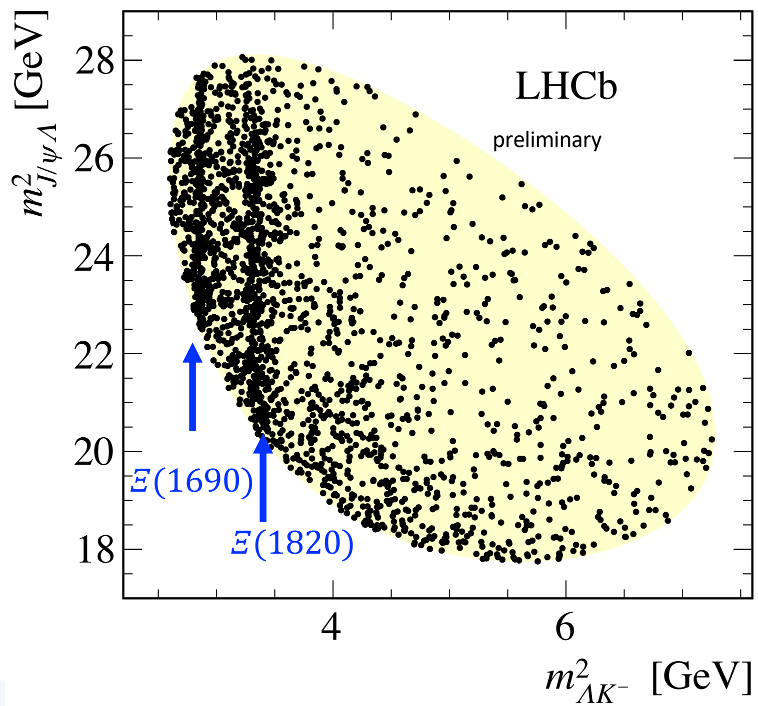
$\Xi_b^- \to J/\psi \Lambda K^-$ by LHCb

LHCb-PAPER-2020-039

About 1800 signal decays



Two large $\Xi^{**} \to \Lambda K^-$ contributions

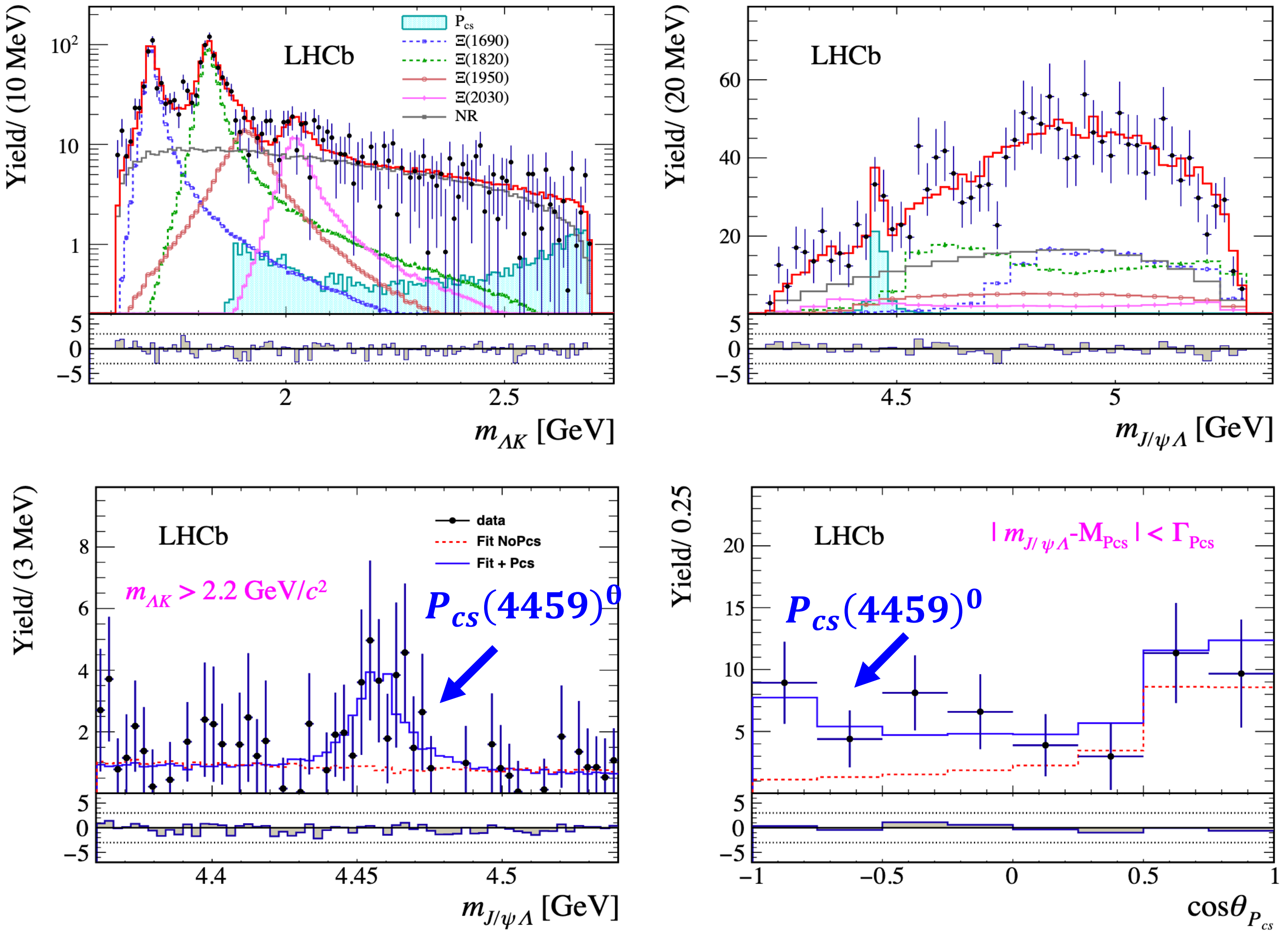


$\Xi_b^- \to J/\psi \Lambda K^-$ amplitude fit

LHCb-PAPER-2020-039

- Only a few components needed, statistics limited
- Evidence of a $J/\psi\Lambda$ structure, $P_{cs}(4459)^0$, with a significance of $> 3.1\sigma$

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



A $c\bar{c}uds$ state?

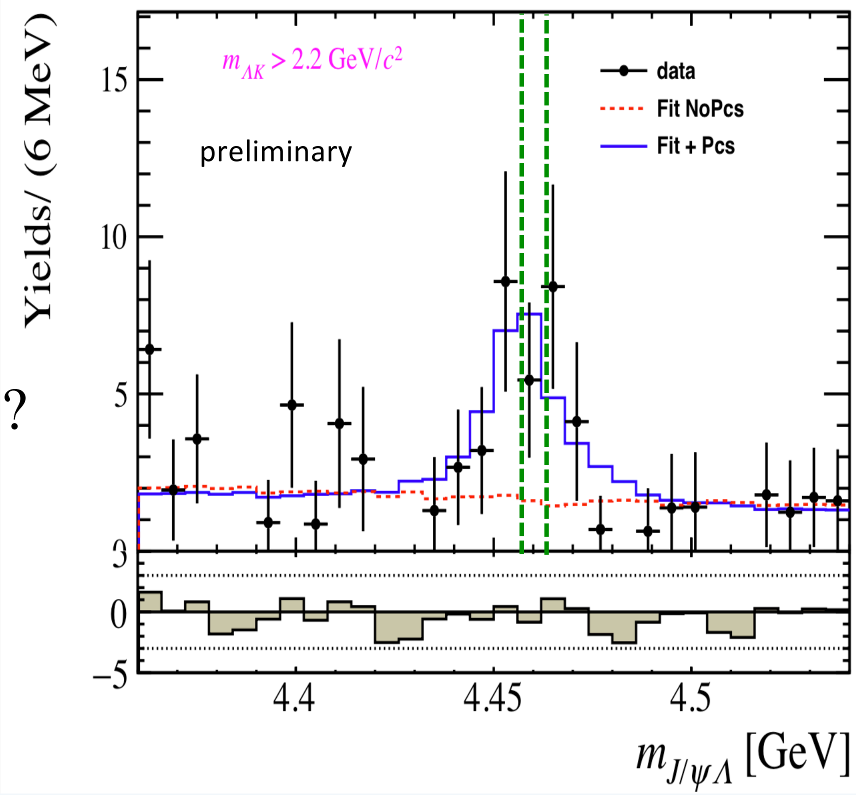
LHCb-PAPER-2020-039

- Molecular states built from $\Xi_c\bar{D}, \Xi_c'\bar{D}, \Xi_c^*\bar{D}, \Xi_c\bar{D}^*, \Xi_c'\bar{D}^*, \Xi_c^*\bar{D}^* \ldots$

PRD101(2020)034018

System	$[\Xi_c'\bar{D}]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]^{\sharp}_{\frac{5}{2}}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-18.5^{+6.4}_{-6.8}$	$-15.6^{+6.4}_{-7.2}$	$-2.0^{+1.8}_{-3.3}$	$-7.5^{+4.2}_{-5.3}$	$-17.0^{+6.7}_{-7.5}$	$-8.0^{+4.5}_{-5.6}$	$-0.7^{+0.7}_{-2.2}$	$-13.3^{+2.8}_{-3.0}$	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4423.7^{+6.4}_{-6.8}$	$4568.7^{+6.4}_{-7.2}$	$4582.3^{+1.8}_{-3.3}$	$4502.9^{+4.2}_{-5.3}$	$4635.4^{+6.7}_{-7.5}$	$4644.4^{+4.5}_{-5.6}$	$4651.7^{+0.7}_{-2.2}$	$4319.4^{+2.8}_{-3.0}$	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

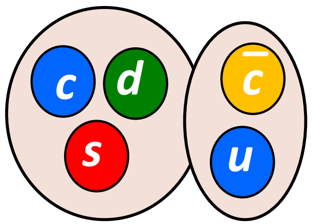
Two nearby states



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

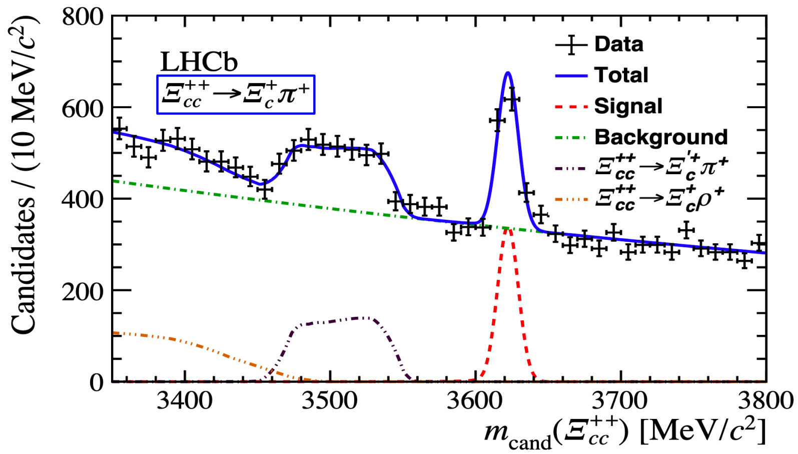
  More data needed to resolve

- Other states, confirmation in other decays?
  - ➢ LHCb Run3

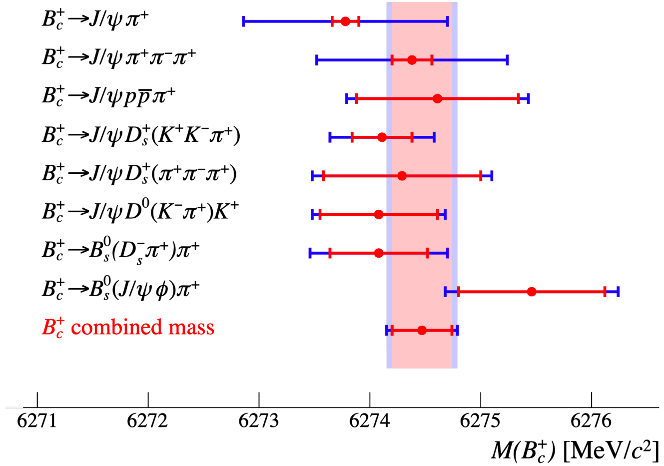


Other results

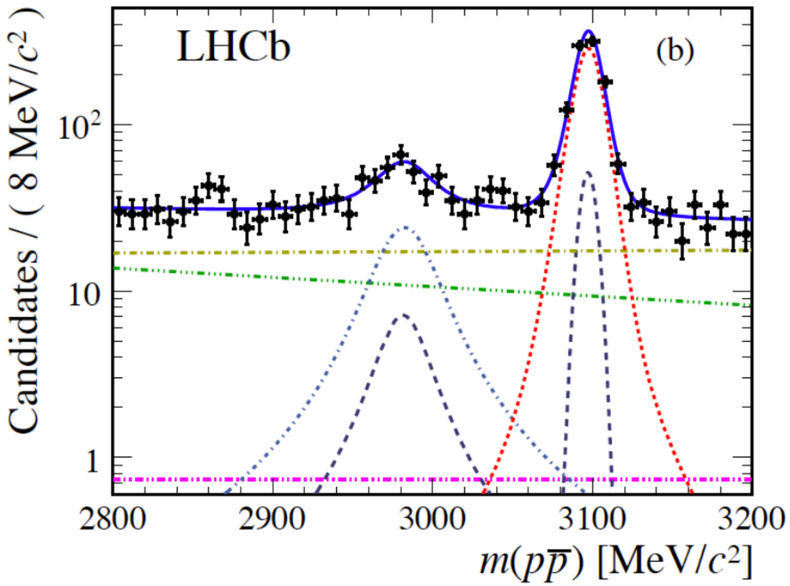
Precise measurement of Ξ_{cc}^{++} mass



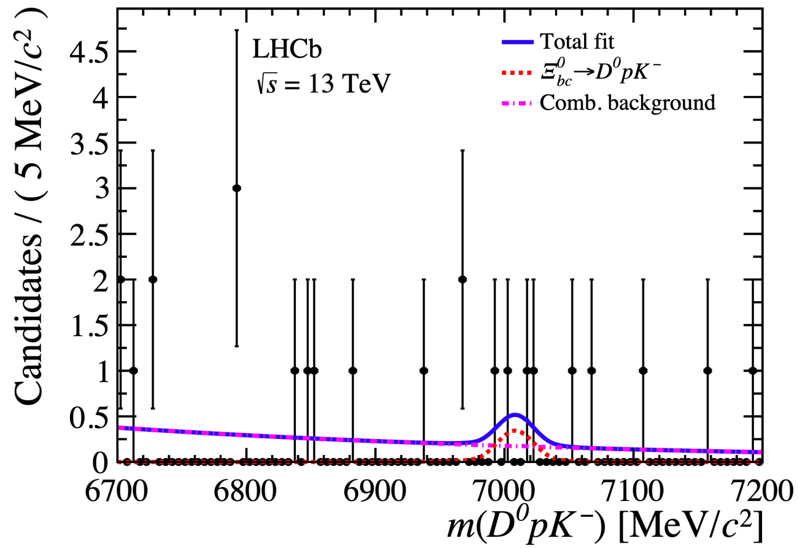
Precise measurement of B_c^+ mass



First observation of $\Lambda_b^0 \to \eta_c p K^-$ decay

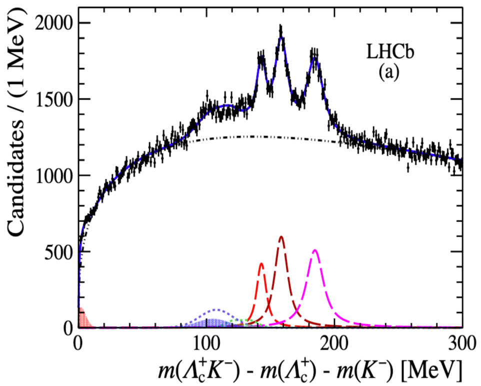


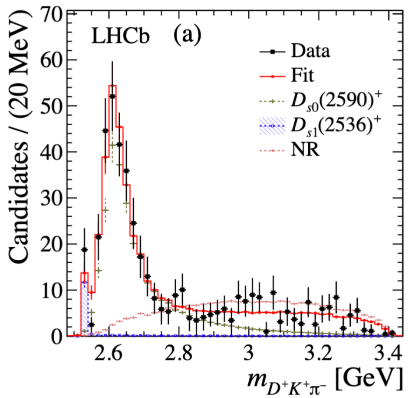
Search for doubly heavy $\Xi_{bc}^0 \to D^0 p K^-$

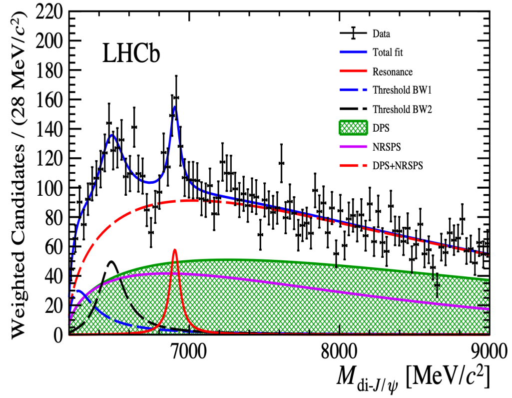


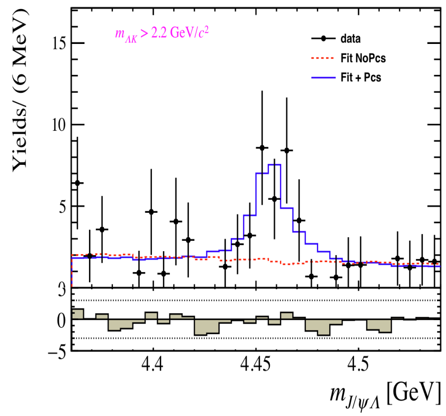
Summary

- New results on heavy hadron spectroscopy at LHCb
  - **Three new excited Ξ_c^0 states**
  - **New excited D_s^+ state (2^1S_0)**
  - **Fully charmed tetraquark candidates $X_{cc\bar{c}\bar{c}}(6900)$**
  - **Evidence of pentaquark with strangeness $P_{cs}(4459)^0$**







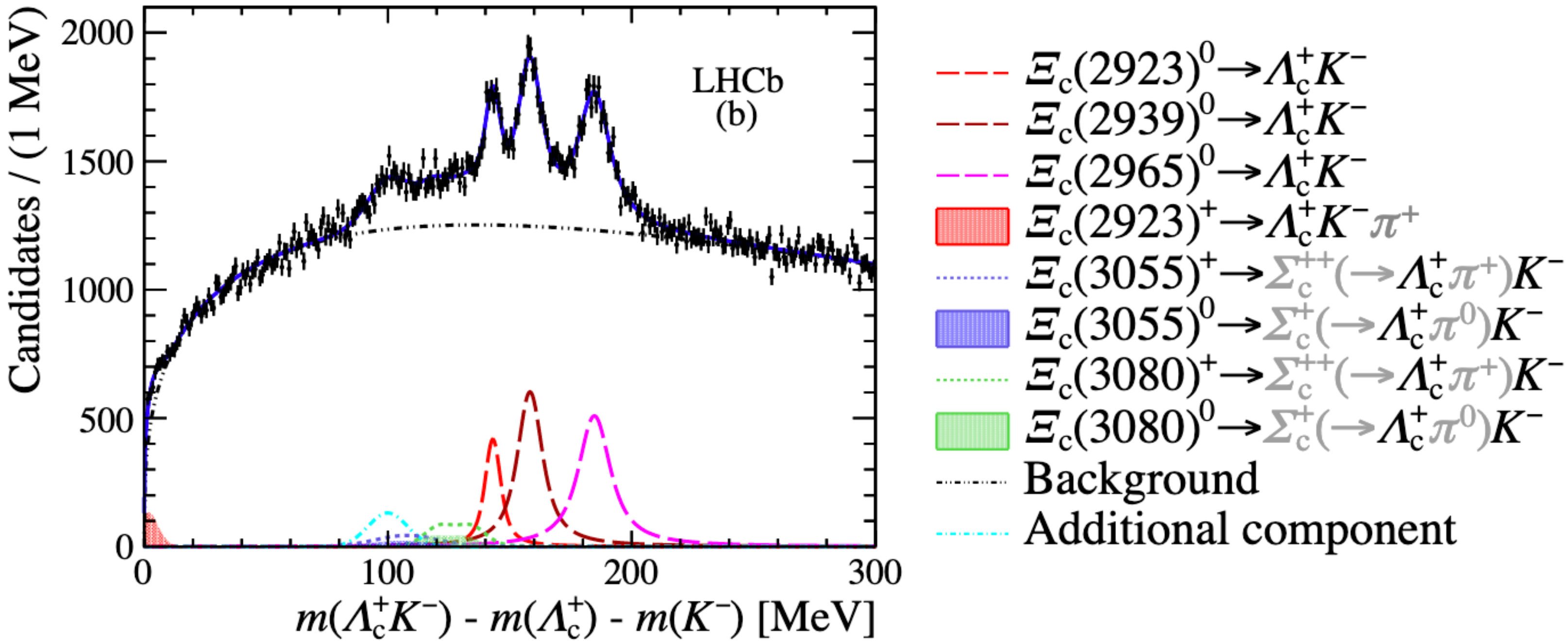


Contributions led by Chinese institutes in LHCb

Thank you for your attention

Backups

Observation of Ξ_c^{*0} states



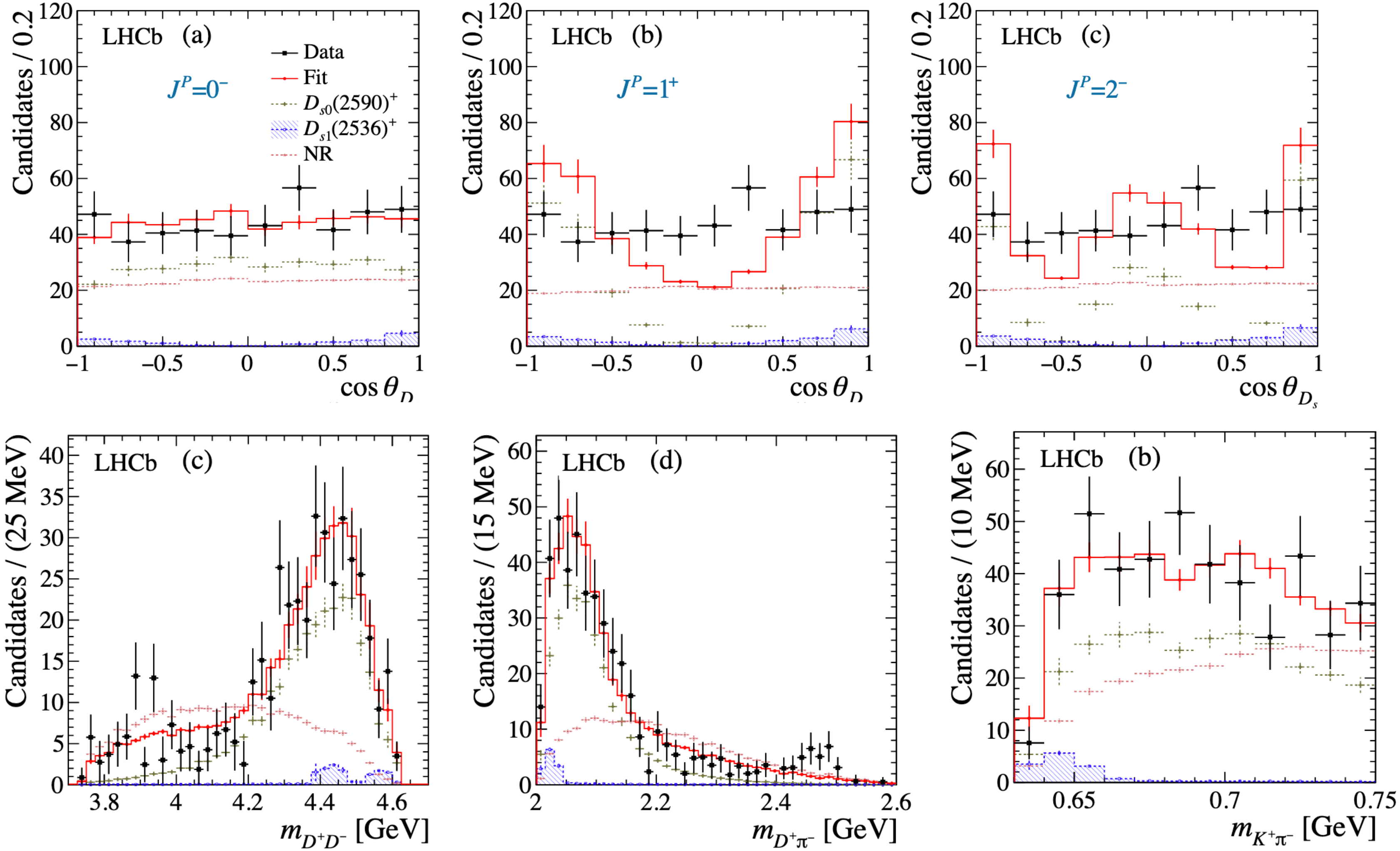
$$m(\Xi_c(2923)^0) = 2923.04 \pm 0.25 \pm 0.20 \pm 0.14\text{MeV}, \Gamma(\Xi_c(2923)^0) = 7.1 \pm 0.8 \pm 1.8\text{MeV},$$

$$m(\Xi_c(2939)^0) = 2938.55 \pm 0.21 \pm 0.17 \pm 0.14\text{MeV}, \Gamma(\Xi_c(2939)^0) = 10.2 \pm 0.8 \pm 1.1\text{MeV}$$

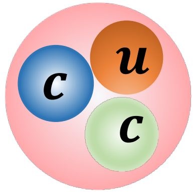
$$m(\Xi_c(2965)^0) = 2964.88 \pm 0.26 \pm 0.14 \pm 0.14\text{MeV}, \Gamma(\Xi_c(2965)^0) = 14.1 \pm 0.9 \pm 1.3\text{MeV}$$

$$\begin{aligned} m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) \simeq m(\Xi_c(2923)^0) - m(\Sigma_c(2800)^0) &\simeq 125\text{ MeV}, \\ m(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) &\simeq 125\text{ MeV}, \\ m(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) &\simeq 125\text{ MeV}. \end{aligned}$$

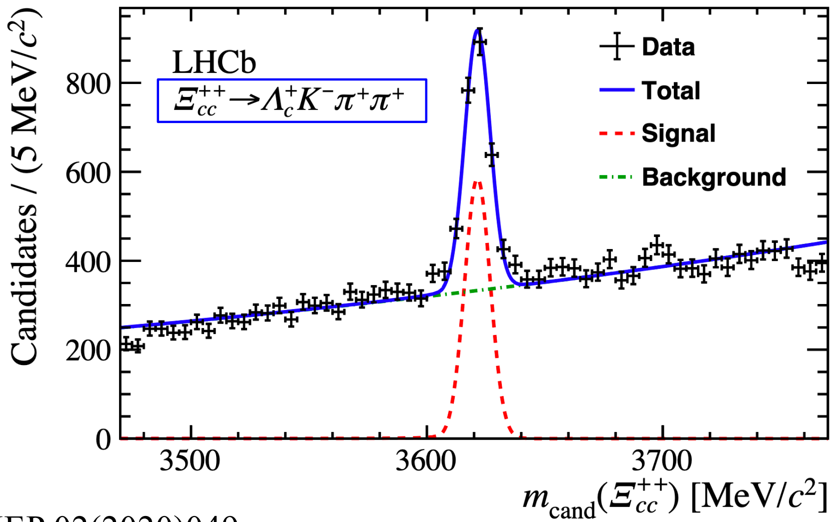
Observation of new D_s^{*+} states

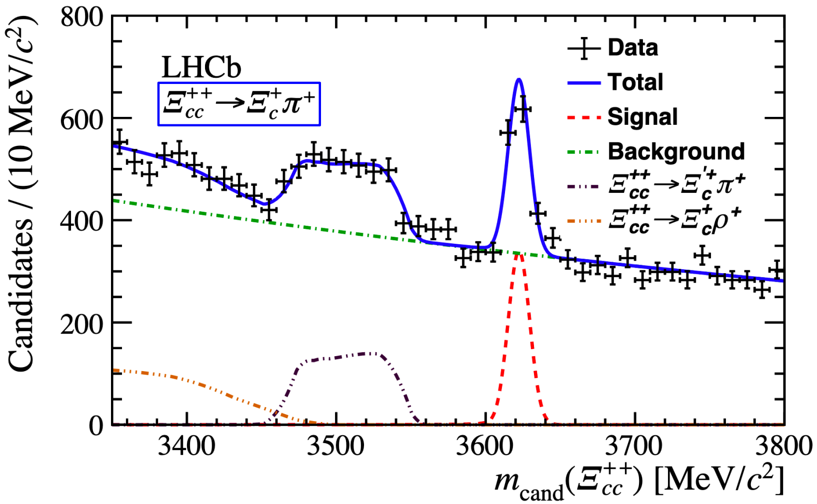


Precision Ξ_{cc}^{++} mass



- Ξ_{cc}^{++} the only established doubly charmed baryon by experiment
  - Observed in $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ decays
  - Weak decay: $\tau = 0.256^{+0.024}_{-0.022} \pm 0.014$ ps
  - Mass: $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.80$ MeV, consistent with models and LQCD
- $m(\Xi_{cc}^{++})$ updated using almost full Run II data, combining both known modes





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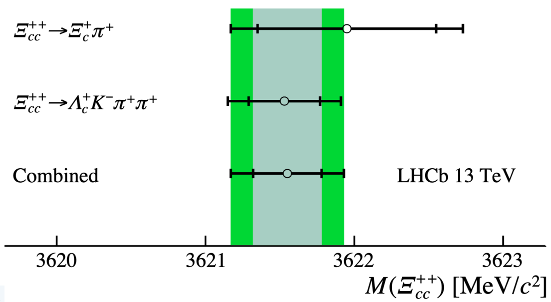
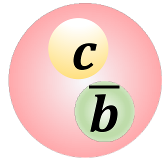


$$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30 \text{ MeV}$$

Precision B_c^+ mass measurement

- B_c^+ has unique properties
  - ➢ Consists of two different heavy quarks
  - ➢ Excited spectroscopy similar to heavy quarkonia
  - ➢ Production and decay properties distinct from quarkonia



A special system to test QCD and effective models

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- Mass measured combining almost all decay modes, mostly observed by LHCb

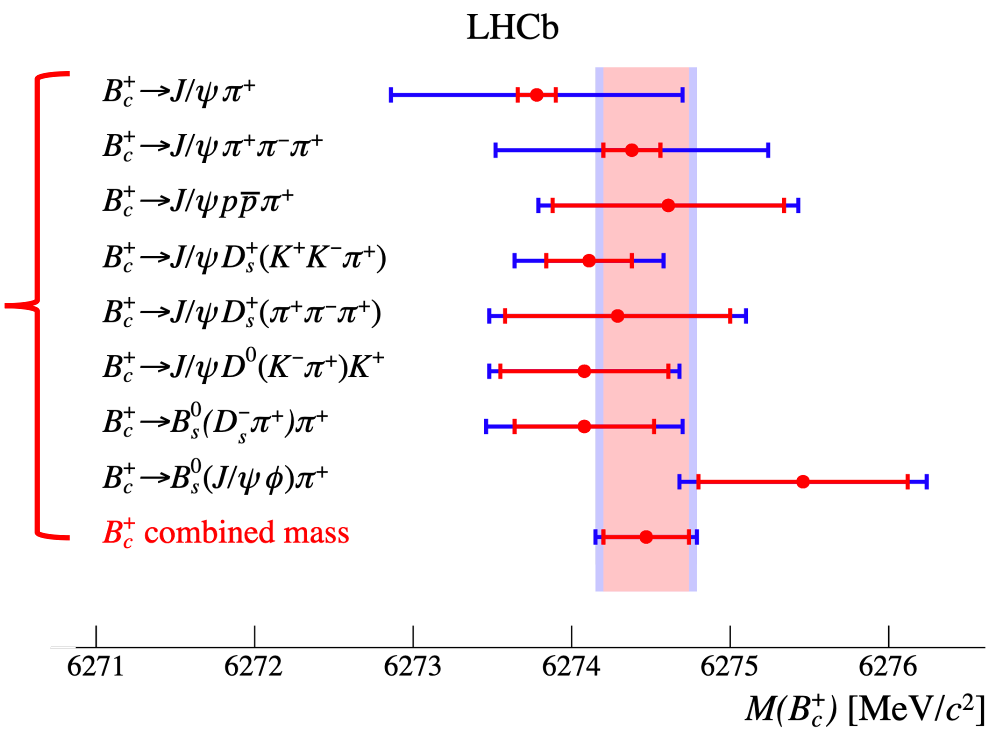
Competing between statistical and systematic uncertainties

$m(B_c^+) = 6274.47 \pm 0.32$ MeV

Compared with:

PDG: 6274.9 ± 0.8 MeV

LQCD: $6278 \pm 6 \pm 4$ MeV



How to interpret data

1. There are nontrivial structures
2. But difficult to understand all structures
   - ✓ Peak at 6.9 GeV relatively isolated, well modeled by a BW X(6900)
   - ✓ Structure at threshold: one BW, multiple BWs or feed-downs
   - ✓ Interference is possible and fits better, but not significant enough yet
3. Statistics could help, LHCb needs Run3. But CMS and ATLAS have many more data
4. Theory inputs?
   - ✓ Production arXiv:2009.08450 …
   - ✓ Structure arXiv:2009.07795 …
   - ✓ Spectrum arXiv:2006.14445 …
   - ✓ Spin-parity arXiv:2007.05501 …
5. Other decay may also help

   $J/\psi\, \psi',\ J/\psi \Upsilon, ss\bar{s}\bar{s}$ …