强子物理在线论坛

Hadron Physics Online Forum (HAPOF)

LHCb实验奇特强子态研究最新进展

张艳席

北京大学

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Contents

- Introduction
- Hidden charm, hidden strange exotic $cs\bar{c}\bar{s}$ in $J/\psi\phi$ system

  [arXiv:2011.01867]
- First open charm tetraquark candidates $\bar{c}\bar{s}ud$ in D^-K^+ system

  [arXiv:2009.00025, 2009.00026]
- First fully charmed tetraquark candidates $cc\bar{c}\bar{c}$ in di-J/ψ system

  [arXiv:2006.16957, Science Bulletin 65 (2020) 1983]
- First evidence of hidden charm pentaquark with strangeness candidate $c\bar{c}sud$ in $\Xi_b^- \to J/\psi\Lambda K^-$ decays

  [LHCb-PAPER-2020-039]

Apiologies if your work is not acknowledged!

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

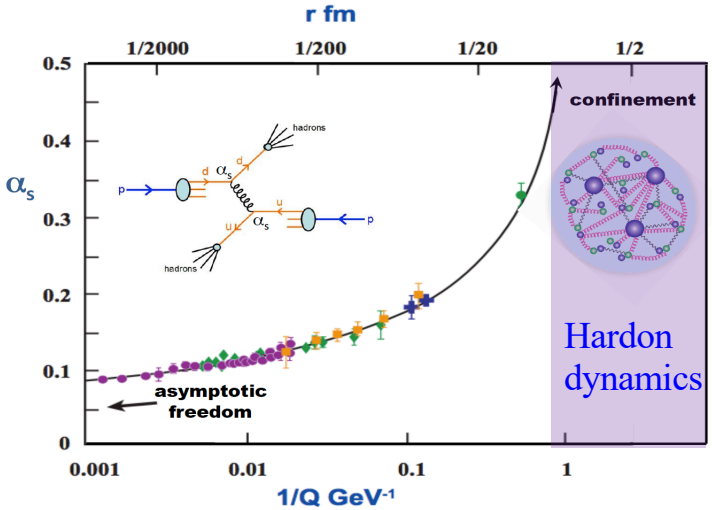
Contributions to muon g-2 — arXiv:1311.2198

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

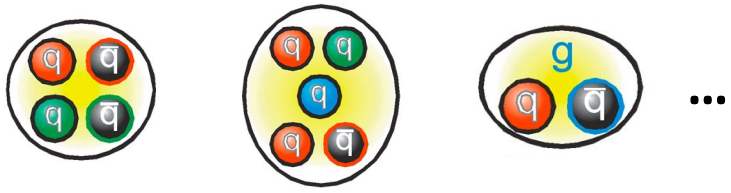


- Hadron spectroscopy: opportunities to study non-perturbative QCD

- Exotic hadrons/multiple quark interactions may reveal new dynamics

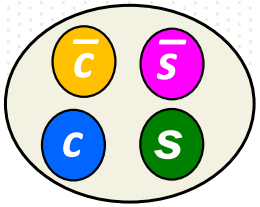
  QCD → Effective theory

Exotics



tetraquark ? pentaquark ? hybrid ? ...

Tetraquark candidate in $J/\psi\phi$ system



[arXiv:2011.01867]

Tetraquarks in $J/\psi\phi$ systems

- $X \to J/\psi\phi$ first seen by CDF, 2 narrow states in 1D analysis of $B^+ \to J/\psi\phi K^+$ decay
  - Observation of $X(4140)$
  - Evidence of $X(4274)$

PRL102(2009)242002
Mod.Phys.Lett.A32(2017)26

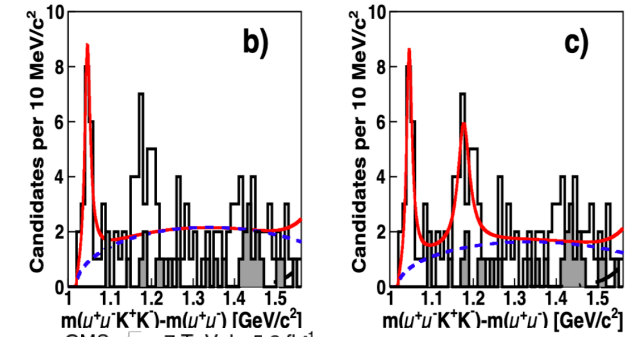
$c\bar{c}s\bar{s}$ quark contents

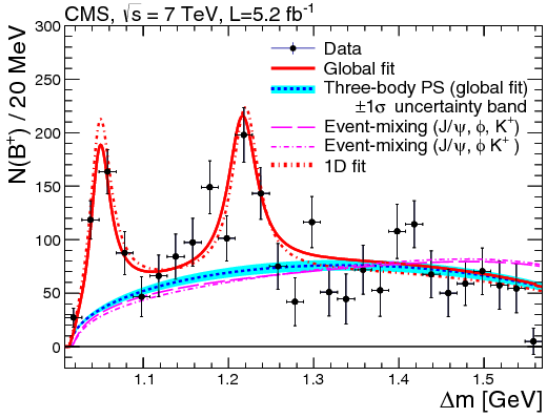
- Both structures confirmed by CMS
  - Mass and width consistent with CDF

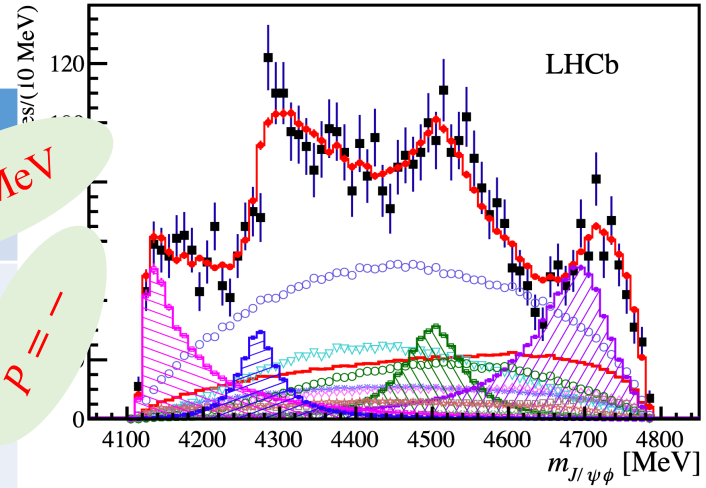
PLB734(2014)261

- Four states by LHCb with amplitude analysis
  - All much wider !

PRD95(2017)012002
PRL118(2017)022003





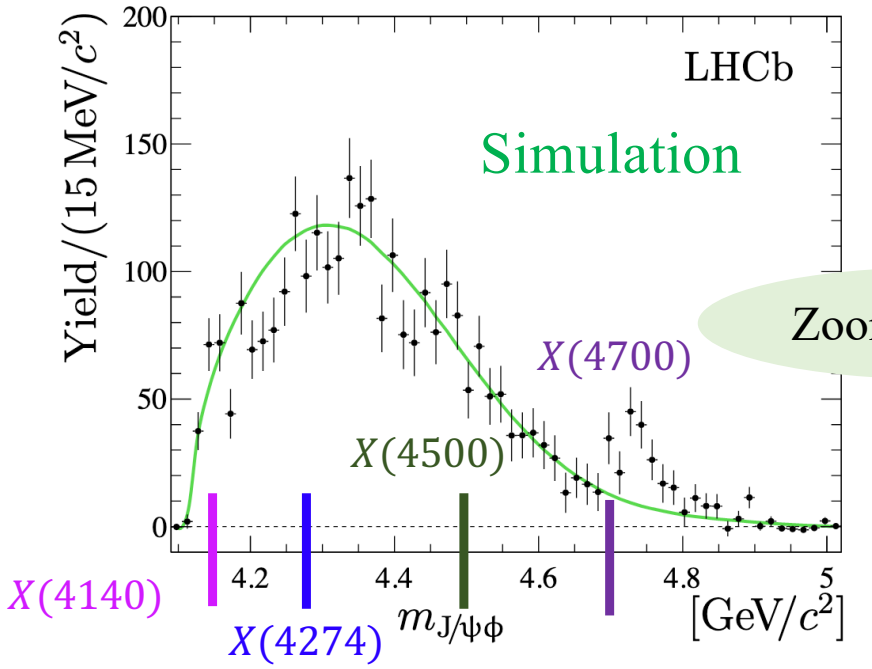


States	J^{PC}	Mass/MeV	Width/MeV	Nearest thresholds
$X(4140)$	1^{++}	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$D_s^+ \bar{D}_s^{*-}$: 4080
$X(4274)$	1^{++}	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	$D_s^+ D_{s0}^*(2317)^-$: 4286
$X(4500)$	0^{++}	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$D_s^+ D_{s1}^*(2536)^-$: 4503
$X(4700)$	0^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$D_s^{*+} \bar{D}_{s2}^*(2573)^-$: 4681

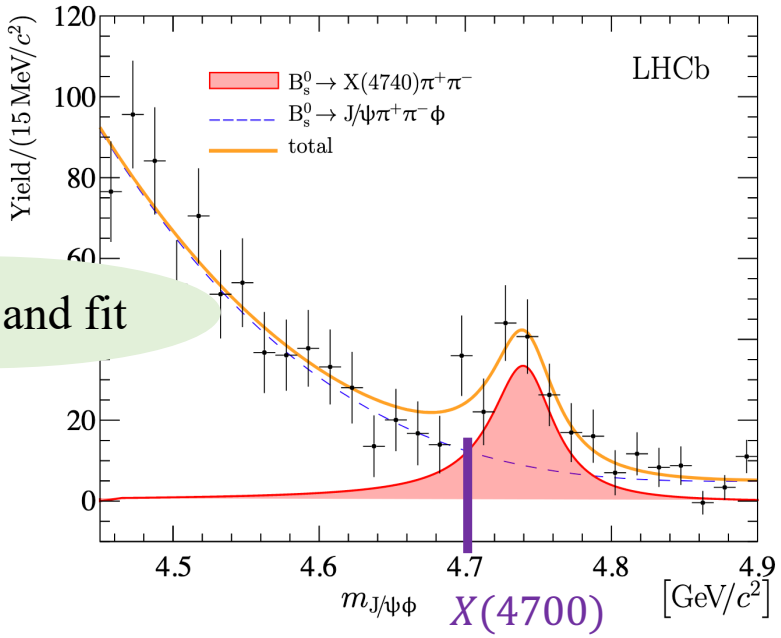
New $X(4740)$ structure

arXiv:2011.01867

- A $J/\psi\phi$ structure in $B_s^0 \to J/\psi\phi\pi^+\pi^-$ decay
  - Only present for K^+K^- consistent with ϕ
  - Checked reflections of $X(3872)$, $\psi(2S) \to J/\psi\pi^+\pi^-$, or $\phi^* \to \phi\pi^+\pi^-$



Zoom in and fit



- 1D fit using S-wave Breit-Wigner

$$m_{X(4740)} = 4741 \pm 6 \pm 6 \text{ MeV}$$
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11 \text{ MeV}$$

Systematic uncertainties:

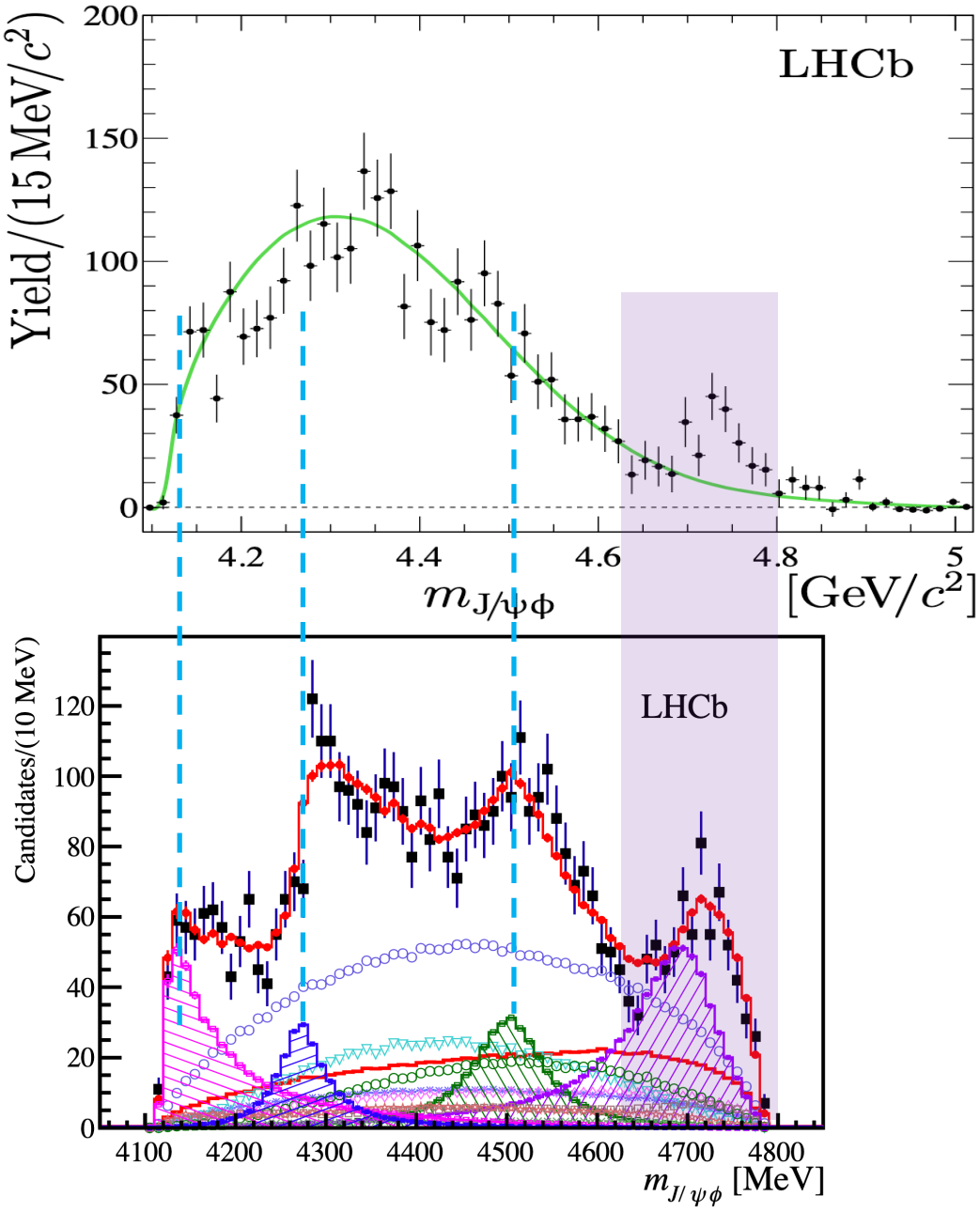
- Shape of underlying non-X
- Alternative P-wave or D-wave BW
- Inteference $\mathcal{F}_S\left(m_{J/\psi\phi}\right) \propto \left|\mathcal{A}\left(m_{J/\psi\phi}\right) + b\left(m_{J/\psi\phi}\right) e^{i\varphi}\right|^2$

New $X(4740)$ structure

arXiv:2011.01867

- Could be the $X(4700)$ in $B^+ \to J/\psi\phi K^+$ decay
- Amplitude fit needed to resolve

Contribution relatively larger than other X states

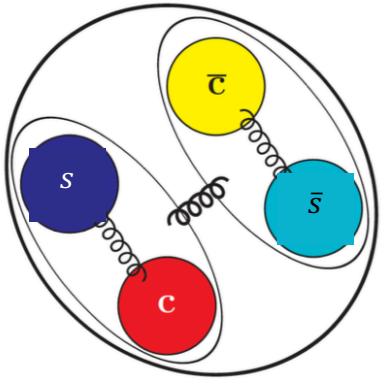


Interpretation

- Difficult for $D_s^{(**)+}D_s^{(**)-}$ molecular states: closest S-wave pairs have 0^-

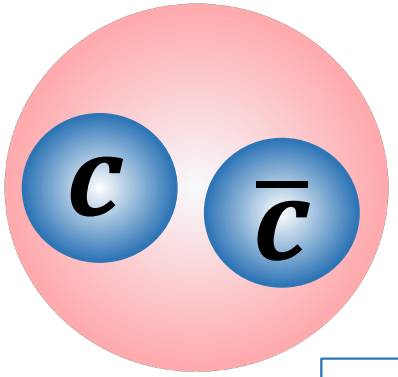
CPC41(2017)053105

$X(4274), X(4500), X(4700)$ tightly bound $cs\bar{c}\bar{s}$ states. But $X(4140)$ difficult



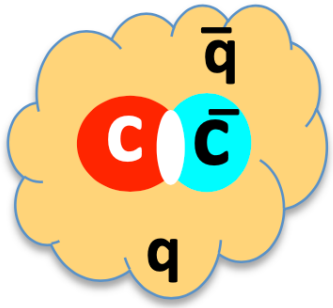
PRD101(2020)054039
PRD99(2019)094032
EPJC79(2020)72
PRD94(2016)074007
EPJC77(2017)160

$X(4140)$: $c\bar{c}$ state $\chi_{c1}(3P)$?
$X(4274)$: $c\bar{c}$ state $\chi_{c1}(3P)$?



EPJC80(2020)626
EPJC80(2020)464
EPJC77(2017)174
PRD94(2016)074007
PLB766(2017)174

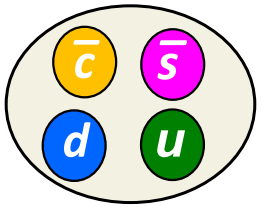
Decay in $J/\psi\omega$?



$X(4274)$ as $\psi'\phi$ hadrocharmonium, but not others

EPJC99(2019)045206

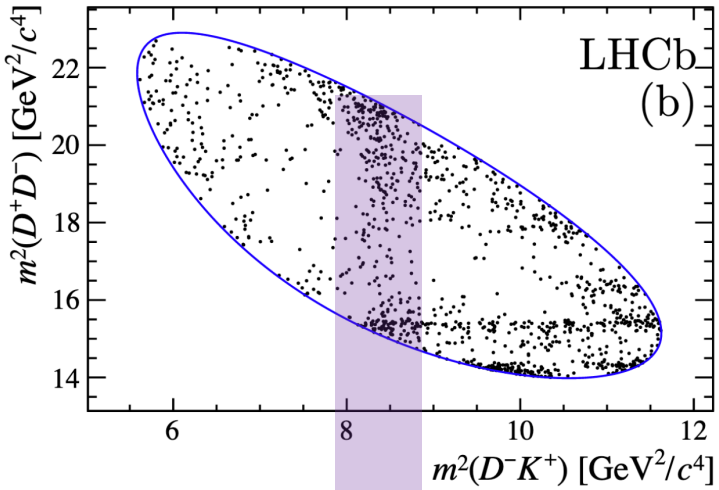
$D^- K^+ (\bar{c}\bar{s}ud)$ tetraquark candidates



[arXiv:2009.00025, 2009.00026]

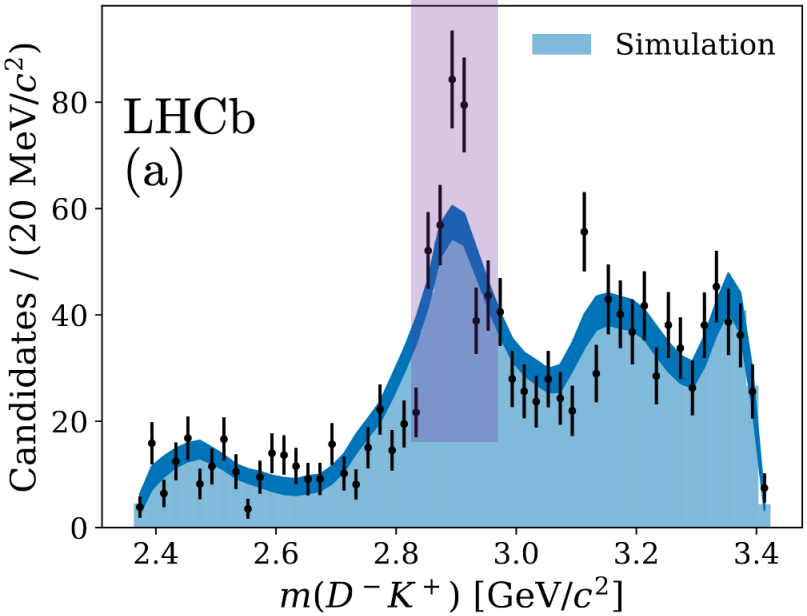
Observation of $D^-K^+(\bar{c}\bar{s}ud)$ structure

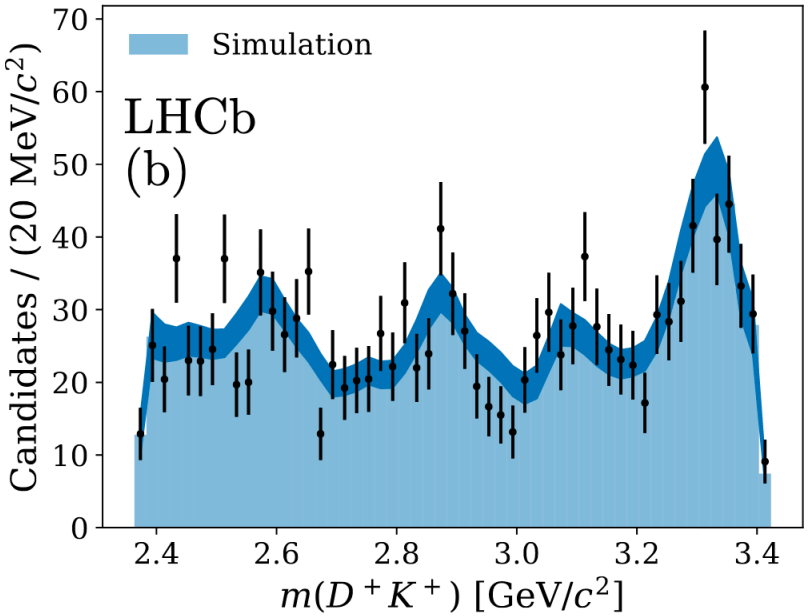
- $B^+ \to D^+D^-K^+$ decays: only charmonia expected for conventional hadrons



Model independent studies arXiv:2009.00025

- Moments extracted from $m(D^+D^-)$
- Can't be described by $[c\bar{c}]$ up to $J_{max} = 2$, rejected with a significance of 3.9σ
- Prominent discrepancy at $m(D^-K^+) \sim 2.9$ GeV





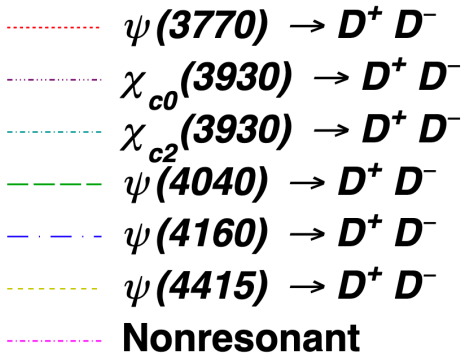
Observation of $D^-K^+(\bar{c}\bar{s}ud)$ structure

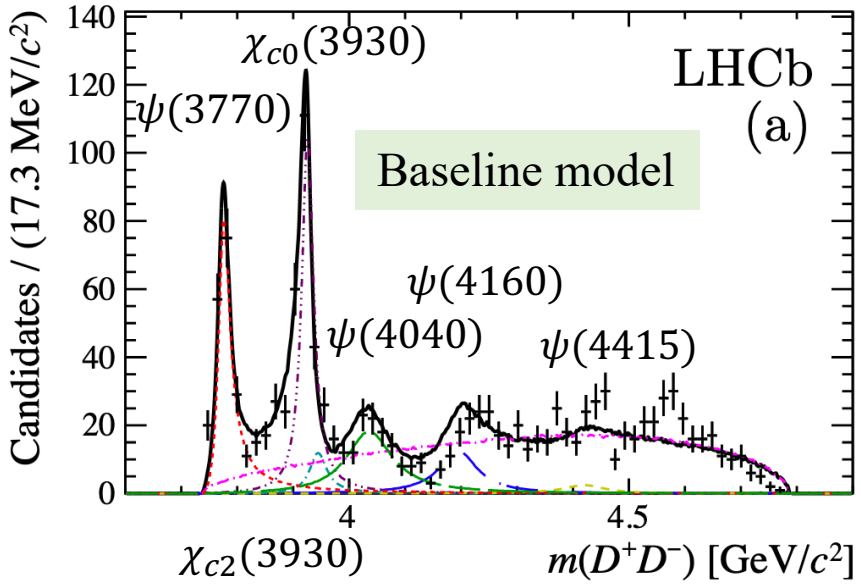
- Amplitude analysis

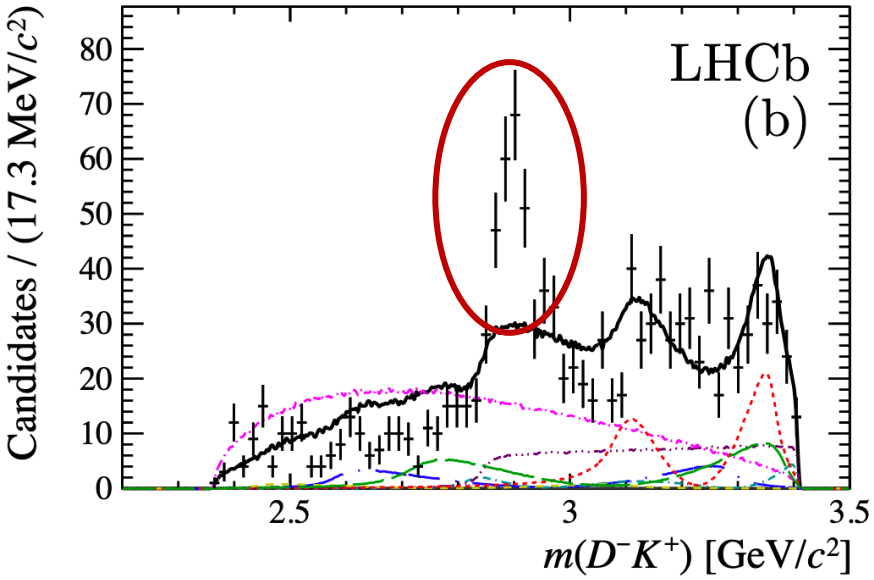
arXiv:2009.00026

- For $c\bar{c} \to D^+D^-$, $\mathrm{P} = \mathrm{C} = (-)^J$: $J^{\mathrm{PC}} = 0^{++}(\chi_{c0}), 1^{--}(\psi), 2^{++}(\chi_{c2})\ldots$

Partial wave (J^{PC})	Resonance	Mass (MeV/c^2)	Width (MeV)
S wave (0^{++})	$\chi_{c0}(3860)$	3862 ± 43	201 ± 145
	$X(3915)$	3918.4 ± 1.9	20 ± 5
P wave (1^{--})	$\psi(3770)$	3778.1 ± 0.9	27.2 ± 1.0
	$\psi(4040)$	4039 ± 1	80 ± 10
	$\psi(4160)$	4191 ± 5	70 ± 10
	$\psi(4260)$	4230 ± 8	55 ± 19
	$\psi(4415)$	4421 ± 4	62 ± 20
D wave (2^{++})	$\chi_{c2}(3930)$	3921.9 ± 0.6	36.6 ± 2.1
F wave (3^{--})	$X(3842)$	3842.71 ± 0.20	2.79 ± 0.62







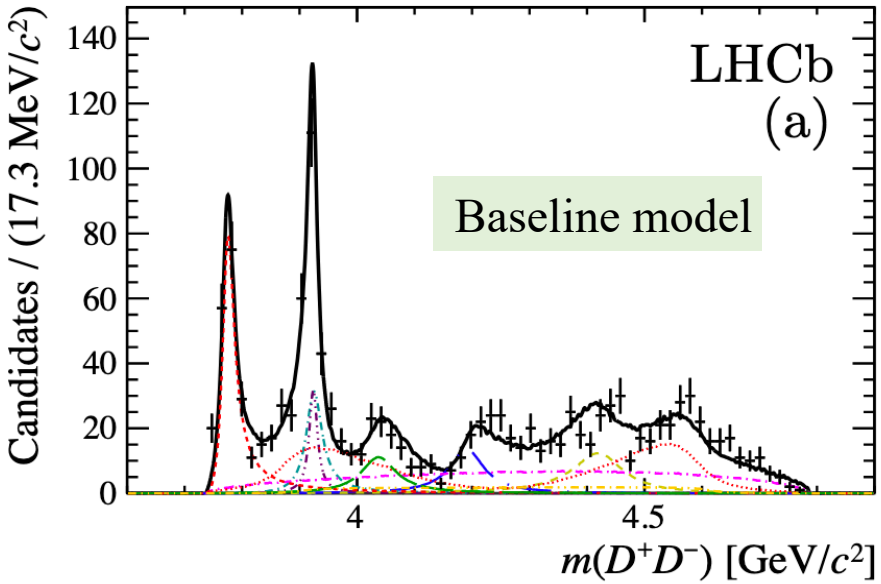
Reflections difficult to generate this "narrow" structure

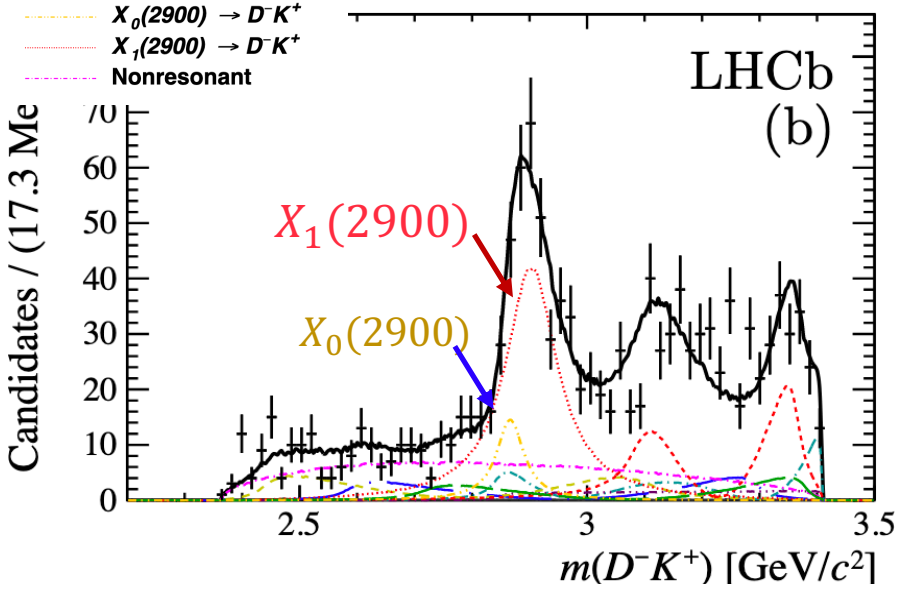
Observation of $D^-K^+(\bar{c}\bar{s}ud)$ structure

- Adding two D^-K^+ structures: $0^+, 1^-$

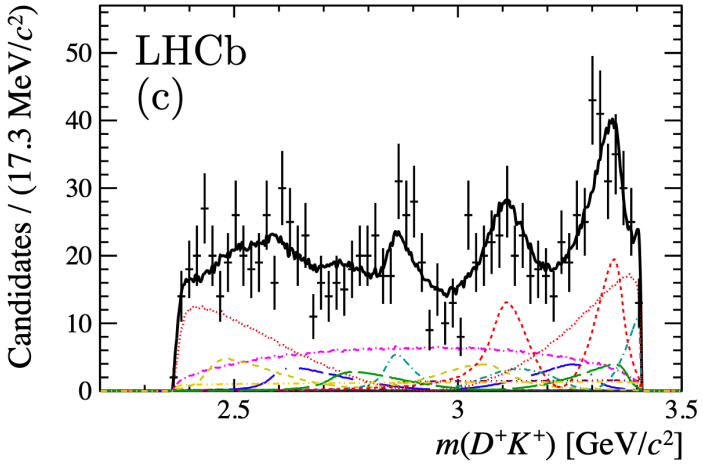
  Note: no $D^+K^+[cu\bar{s}\bar{d}]$ structure needed

arXiv:2009.00026





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

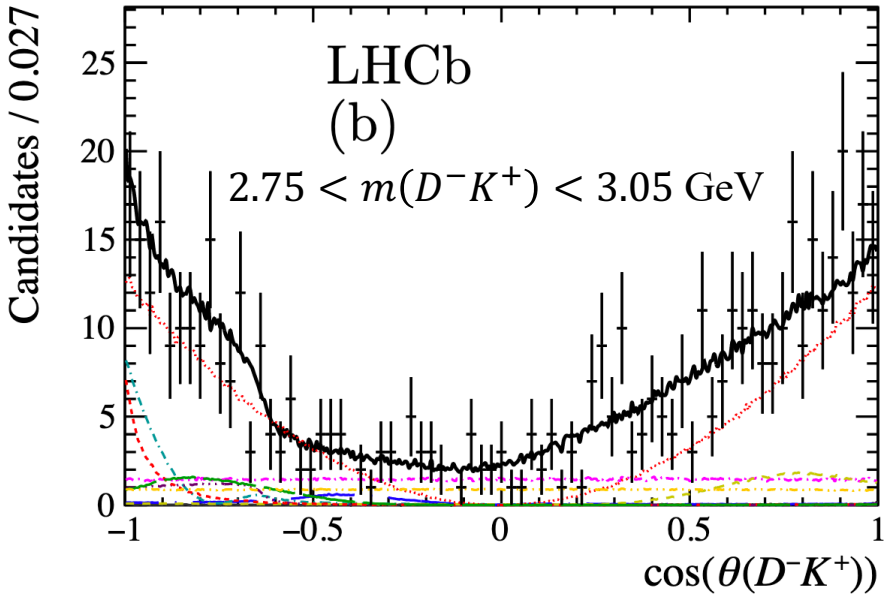


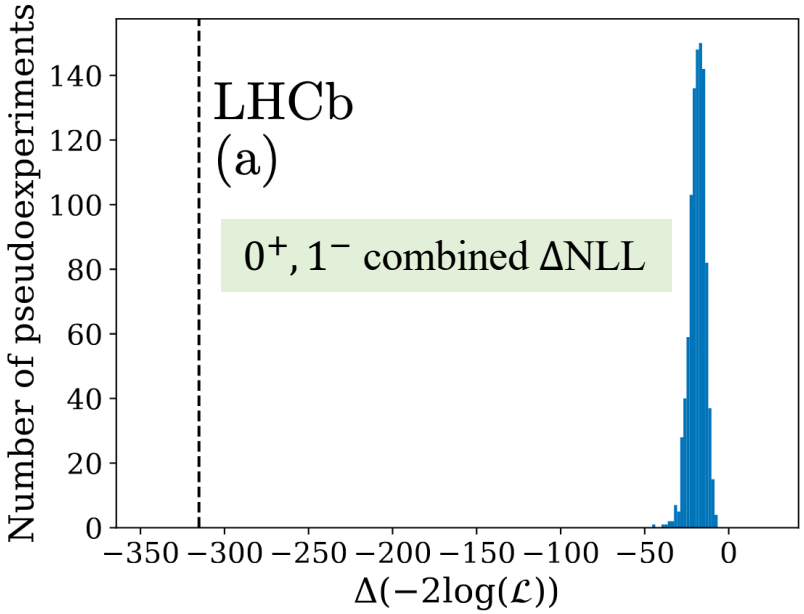
Quite large contribution!

Observation of $D^-K^+(\bar{c}\bar{s}ud)$ structure

arXiv:2009.00026

- $0^+$and 1^- states needed to describe $\cos(D^-K^+)$ distribution





- Preference over other models

X states	No X	$X_0 + X_1$	X_0	X_1	X_2	$X_1 + X_2$
Δ2NLL	–	−316	−218	−230	−162	−308
$\Delta\chi^2$	–	−203	−113	−172	−136	−197

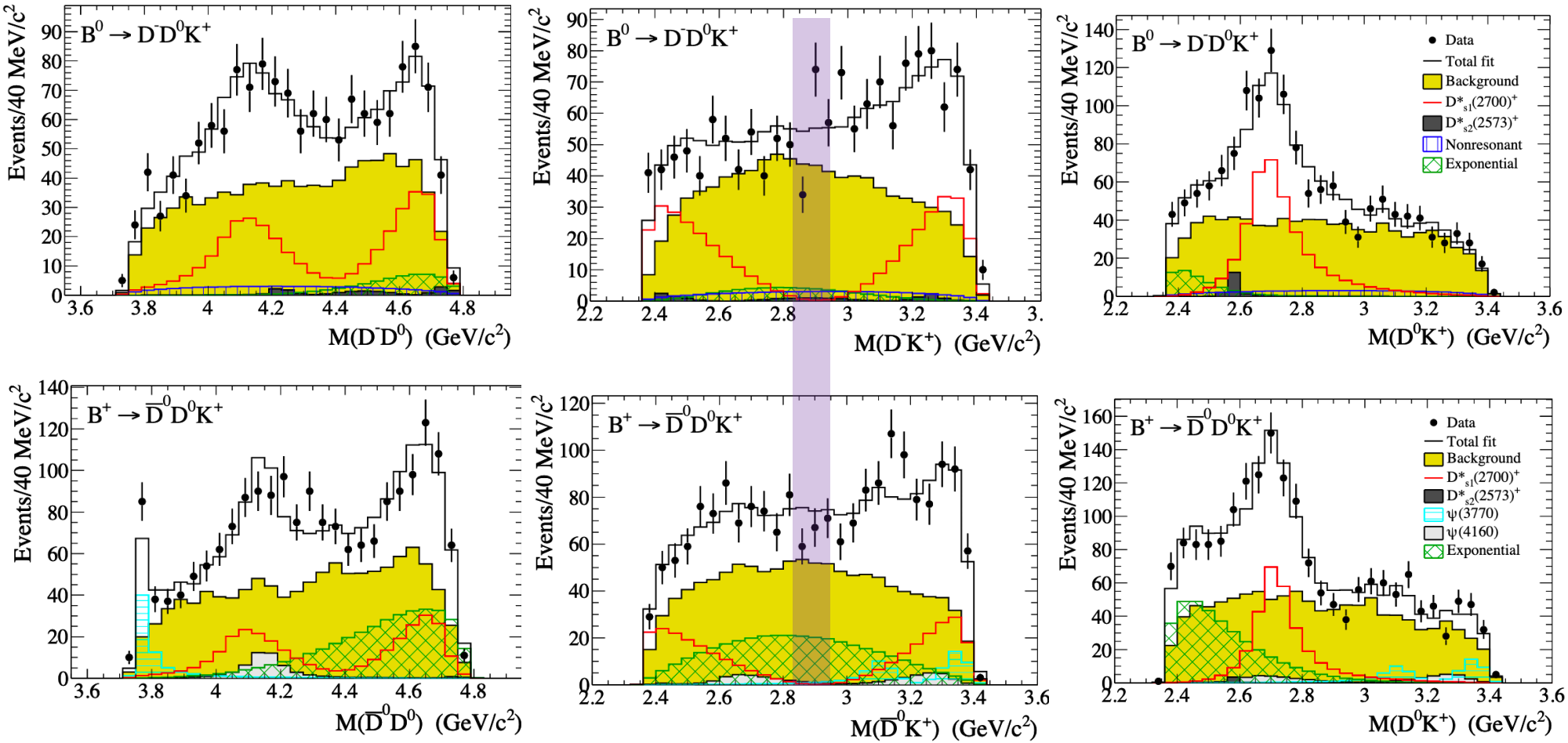
$X_1 + X_2$ only slightly worse than $X_1 + X_0$

Overlooked before?

PRD91(2015)052002

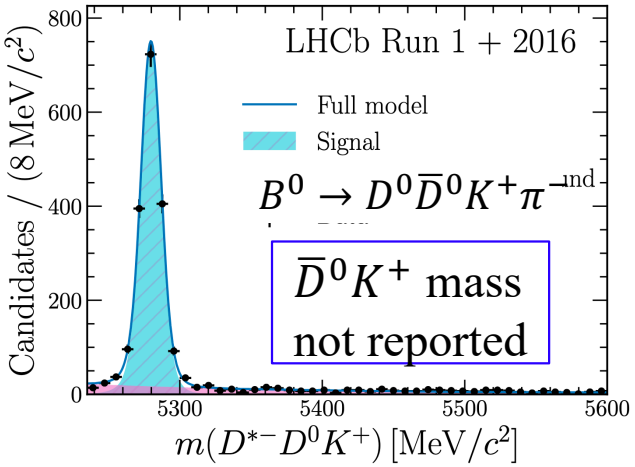
- DK structure not obvious in $B^0 \to D^- D^0 K^+$, $B^+ \to \overline{D}^0 D^0 K^+$ by Babar

  Buried in the background?

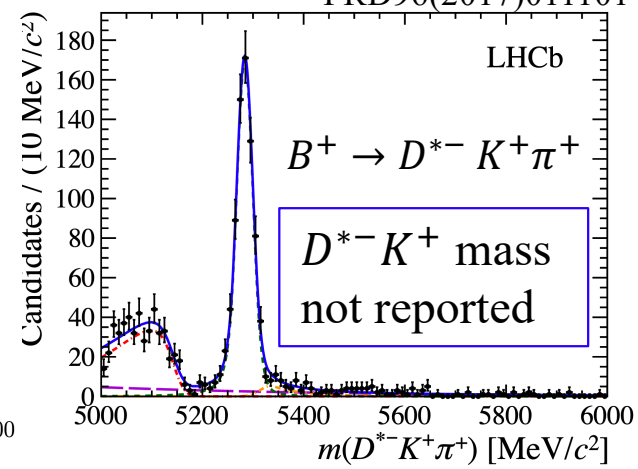


Overlooked before?

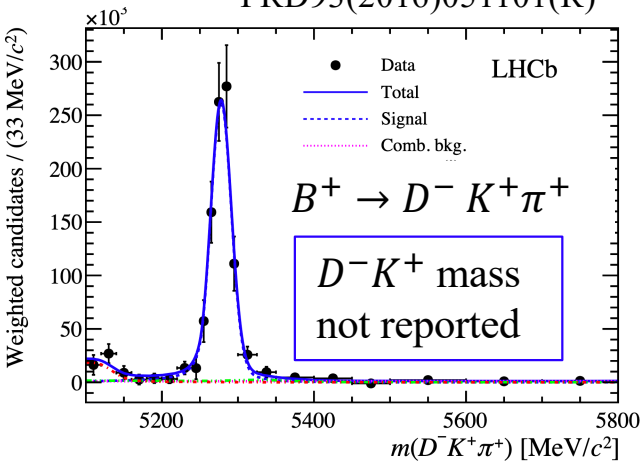
PRD102(2020)051102



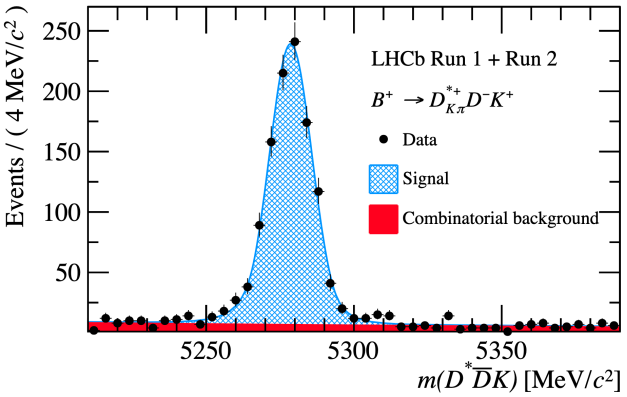
PRD96(2017)011101



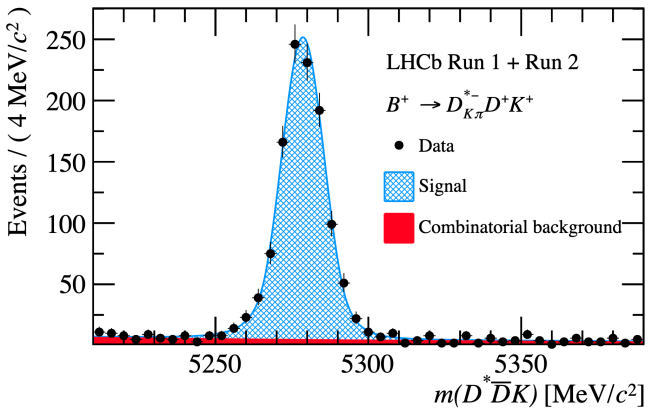
PRD93(2016)051101(R)



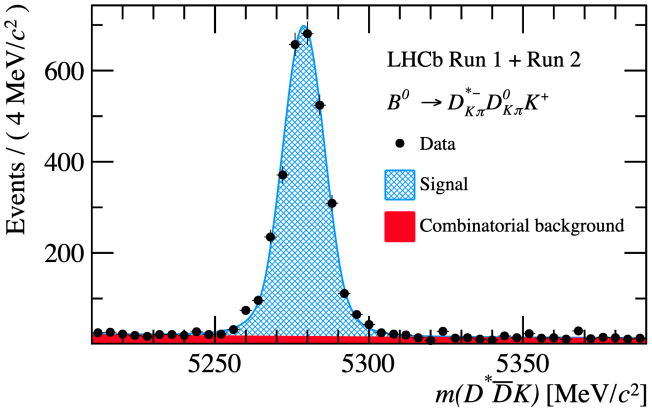
$B^+ \to D^{*+}D^-K^+$



$B^+ \to D^{*-}D^+K^+$



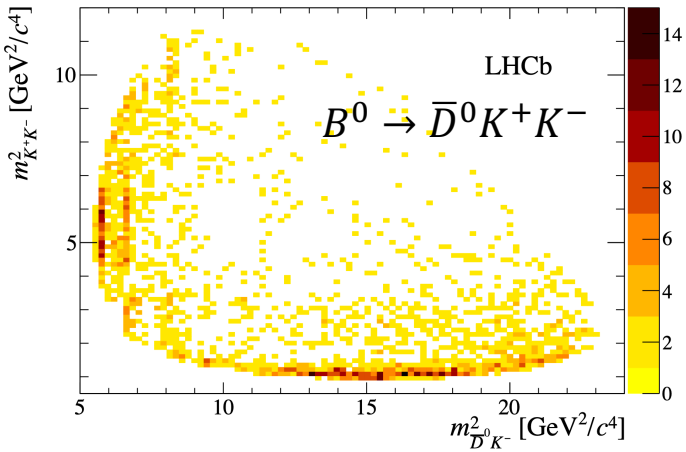
$B^0 \to D^{*-}D^0K^+$

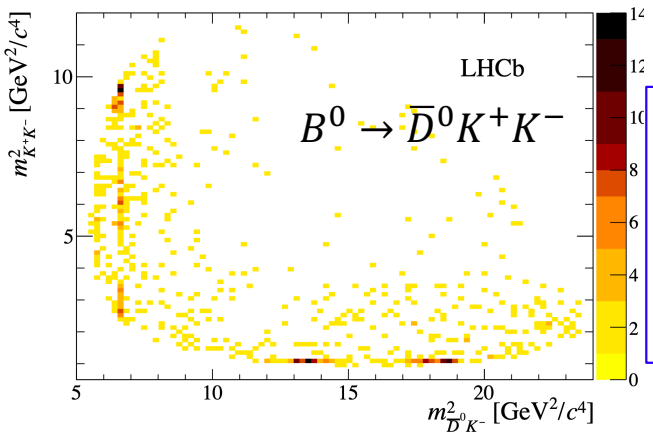


arXiv:2005.10264

$D^-K^+, D^{*-}K^+$ mass not reported

Overlooked before?



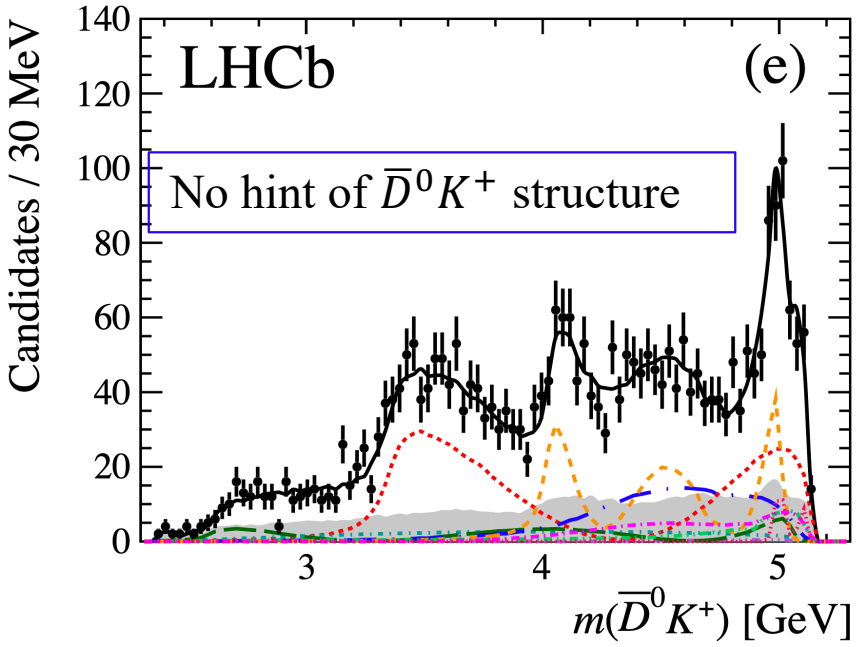


PRD98(2018)072006

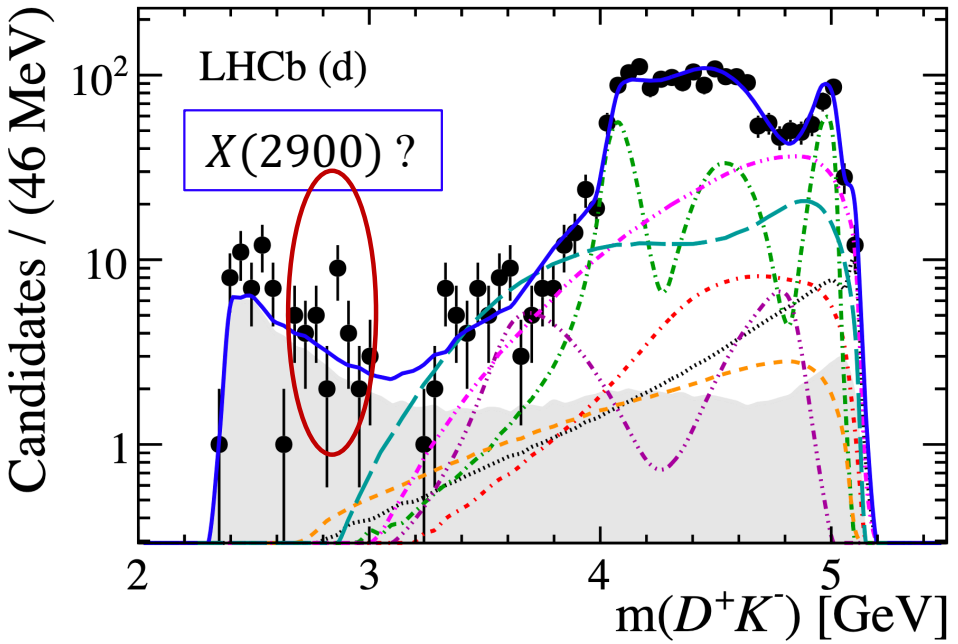
$B^0_{(s)} \to \overline{D}^0 K^+ K^-$

- D_s^{**-} contributions
- No hint of $\overline{D}^0 K^+$ structure

$B^0 \to \overline{D}^0 K^+ \pi^-$ PRD92(2015)012012



$B^- \to D^+ K^- \pi^-$ PRD91(2015)0920022



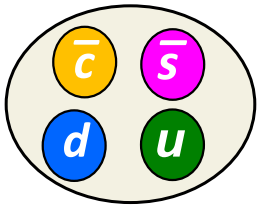
Interpretations

- $\bar{c}\bar{s}ud$ tetraquark
- Two thresholds: $D^*K^*(0^+)$ and $D_1K(1^-)$, possible cusp or DK molecular

	Pros	Cons
Tightly bound tetraquark	$I(J^p) = 0(0^+)$ candidate	Missing low-lying 0^+ and other states Missing $I = 1$ states and spin partners P-wave state $X_1(2900)$ difficult to explain
Molecule	Close thresholds, matching parities	Decay widths, spin/isospin parterners

arXiv:2010.09395, 2010.04045, 2009.14538, 2008.07959, 2008.07833, 2008.07516, 2008.07145, 2008.07348 …

Experimental studies: many possibilities

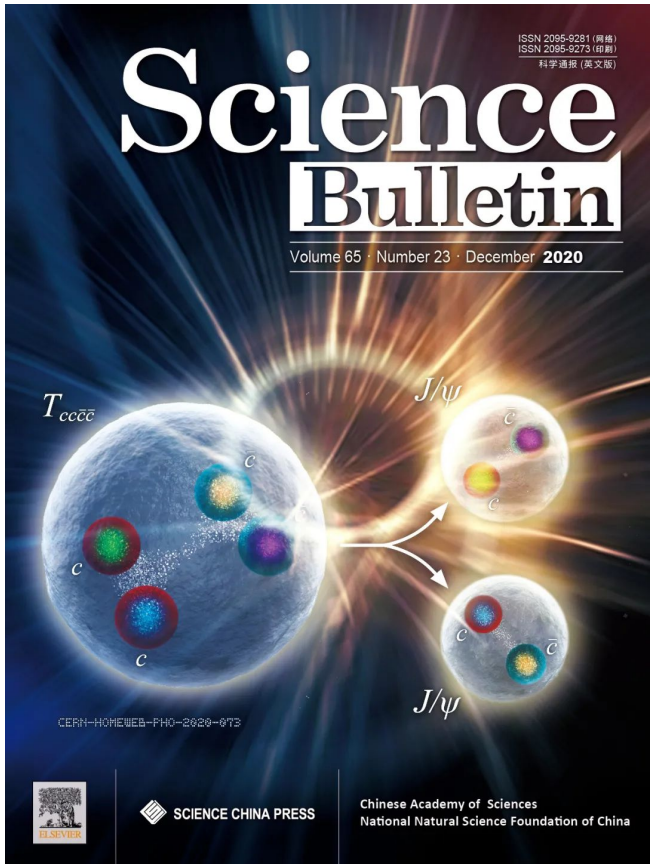


- Its isospin and partners $\bar{c}\bar{s}qq$
- $1^+, 2^+$ … states
- Production modes: $B \to D_{(s)}^{(*)+/-/0} X$)
- Decay modes: $X \to D^-K^0, D^{*-}K^+, D^-K^{*+}, \bar{D}^*K^0 \ldots$

A cook book?

Distinguishing interpretations
arXiv:2009.05352, 2009.01182

Fully charmed states at LHCb



$T_{cc\bar{c}\bar{c}}$ not new

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.

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J. Wu *et al.*, *Heavy-flavored tetraquark states with the $QQ\bar{Q}\bar{Q}$ configuration*, Phys. Rev. **D97** (2018) 094015, arXiv:1605.01134.

M.-S. Liu, Q.-F. L, X.-H. Zhong, and Q. Zhao, *All-heavy tetraquarks*, Phys. Rev. **D100** (2019) 016006, arXiv:1901.02564.

G.-J. Wang, L. Meng, and S.-L. Zhu, *Spectrum of the fully-heavy tetraquark state $QQ\bar{Q}'\bar{Q}'$*, Phys. Rev. D **100** (2019) 096013, arXiv:1907.05177.

M. A. Bedolla, J. Ferretti, C. D. Roberts, and E. Santopinto, *Spectrum of fully-heavy tetraquarks from a diquark+antidiquark perspective*, arXiv:1911.00960.

X. Chen, *Fully-charm tetraquarks: $cc\bar{c}\bar{c}$*, arXiv:2001.06755.

Masses and decays

- Many $T_{cc\bar{c}\bar{c}}$ states, $m \in [5.8, 7.4]$ GeV/c^2, mostly below 7 GeV
- Some decays have two J/ψ mesons

$cc\bar{c}\bar{c}$		
J^{PC}	$N[(S_D, S_{\bar{D}})S, L]J$	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^{++}		
2^{++}	arXiv:1911.00960	
2^{++}		
2^{++}	$3[(1,1)0,2]2$	7380

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

Directly or via feed-down

$m > 6.2$ GeV/c^2

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

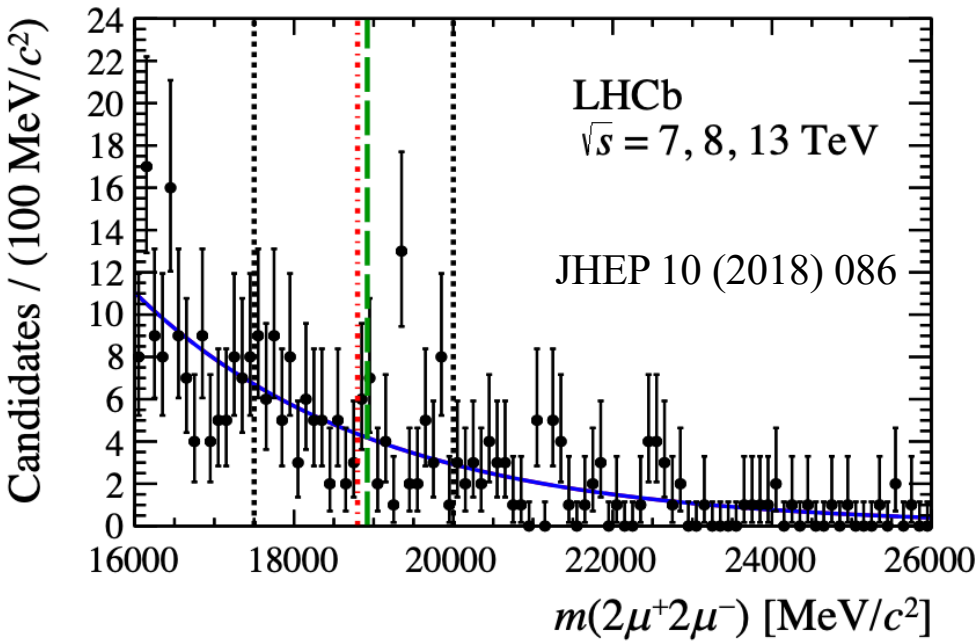
PLB 773 (2017) 247

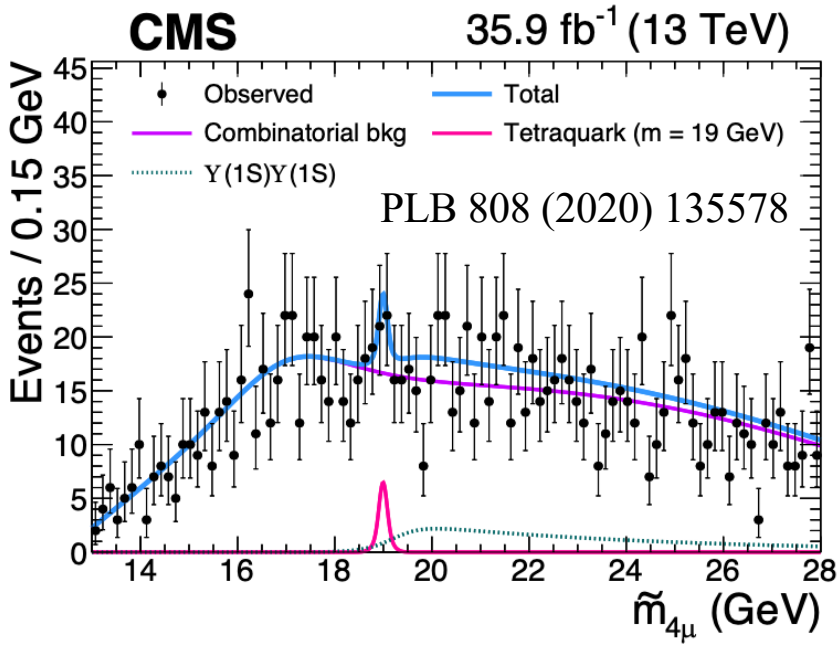
The bottom partner: $T_{bb\bar{b}\bar{b}}$

- 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



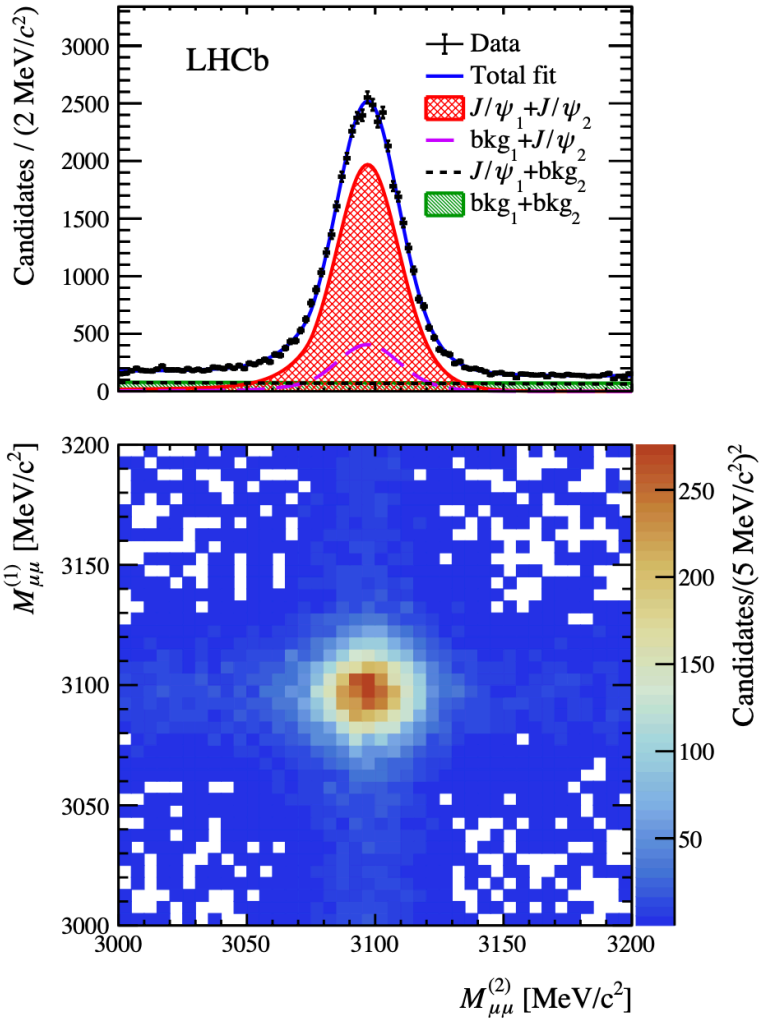


Di-J/ψ production

arXiv:2006.16957
Science Bulletin 65 (2020) 1983

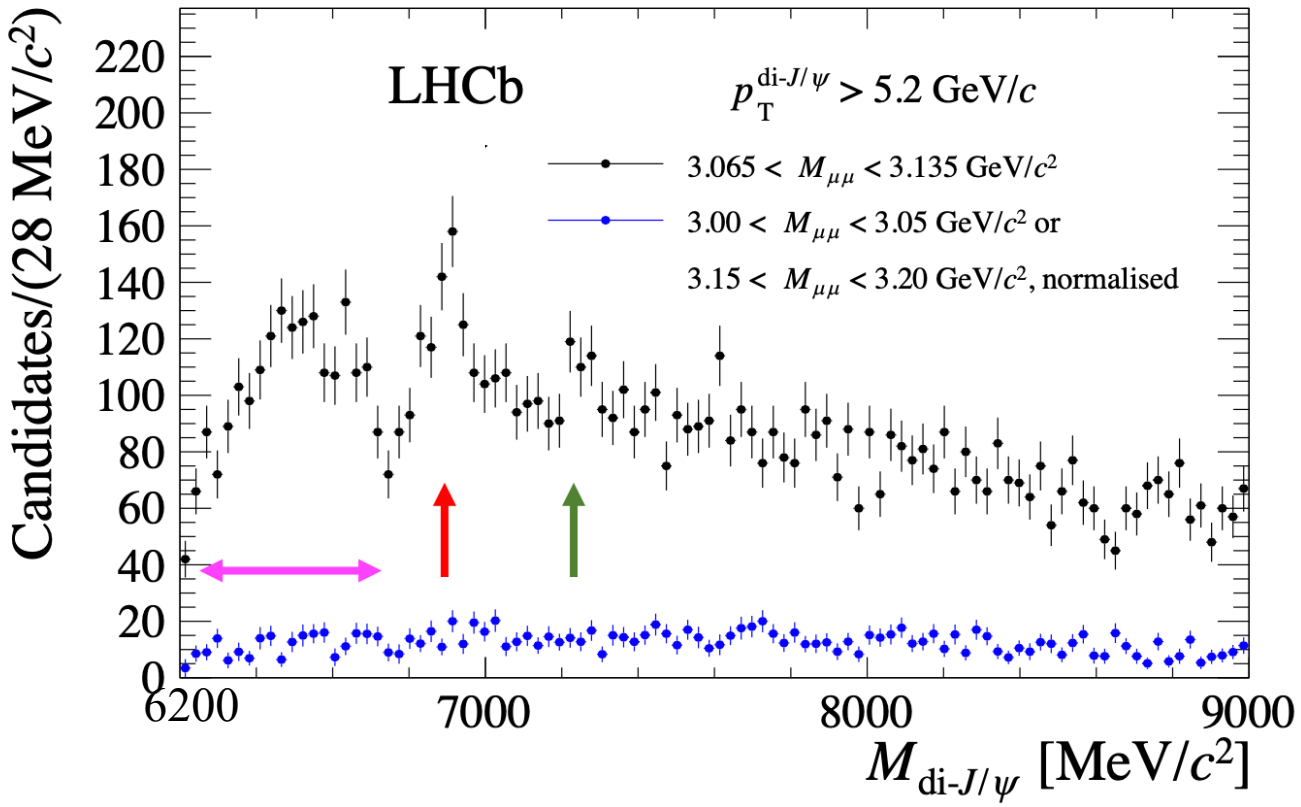
- Full LHCb data

About 34000 J/ψ signals in total



Di-J/ψ invariant mass

arXiv:2006.16957



- Broad structure at 6.2-6.8 GeV/c^2 close to above Di-J/ψ mass threshold
- Narrow peak at 6.9 GeV/c^2
- Hint of another structure at 7.2 GeV/c^2

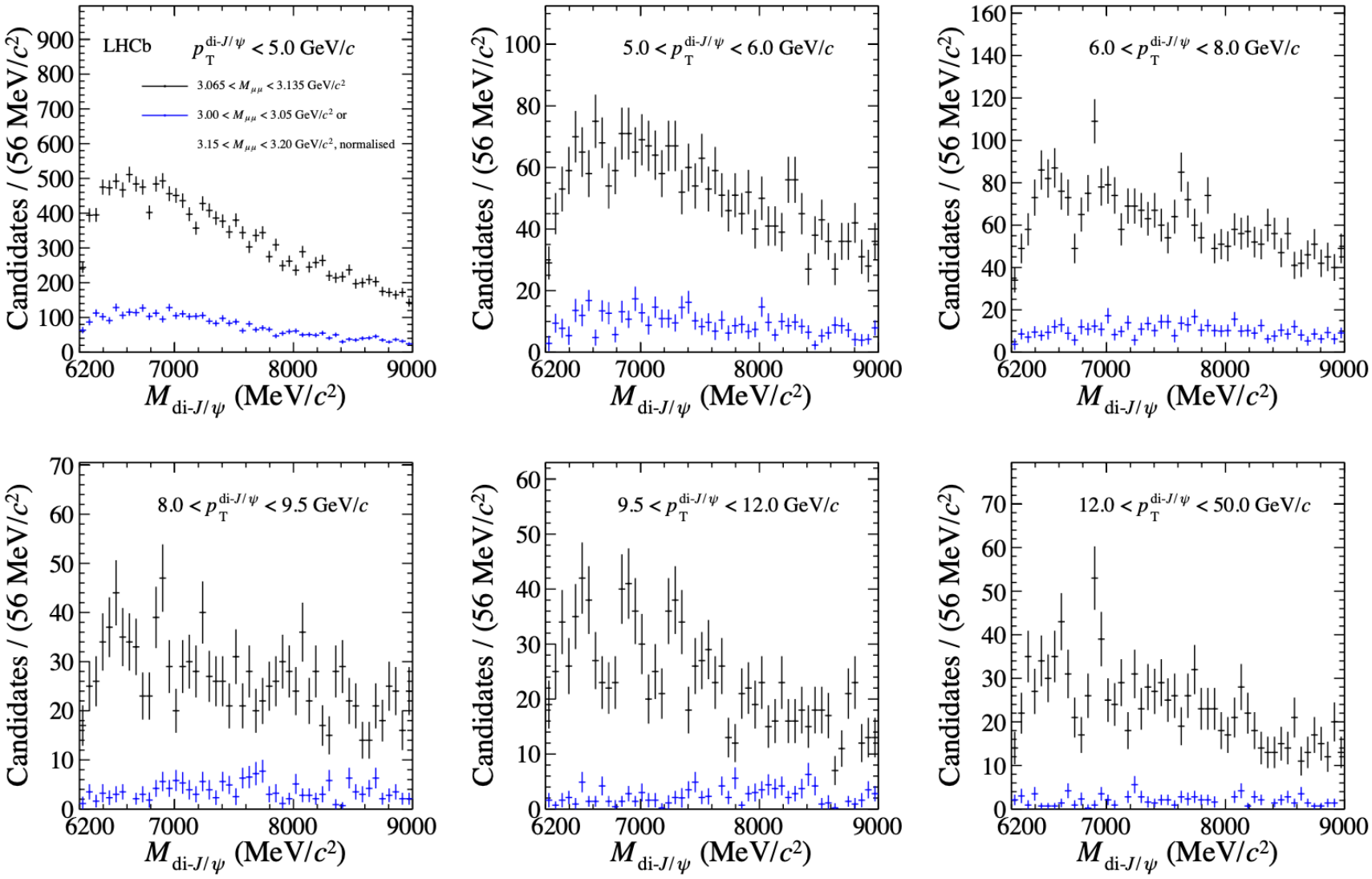
Not present in J/ψ background sample

Non-peaking hypothesis rejected at global significance of 6σ !

Di-J/ψ invariant mass

- Same structures presented in high p_T bins

arXiv:2006.16957

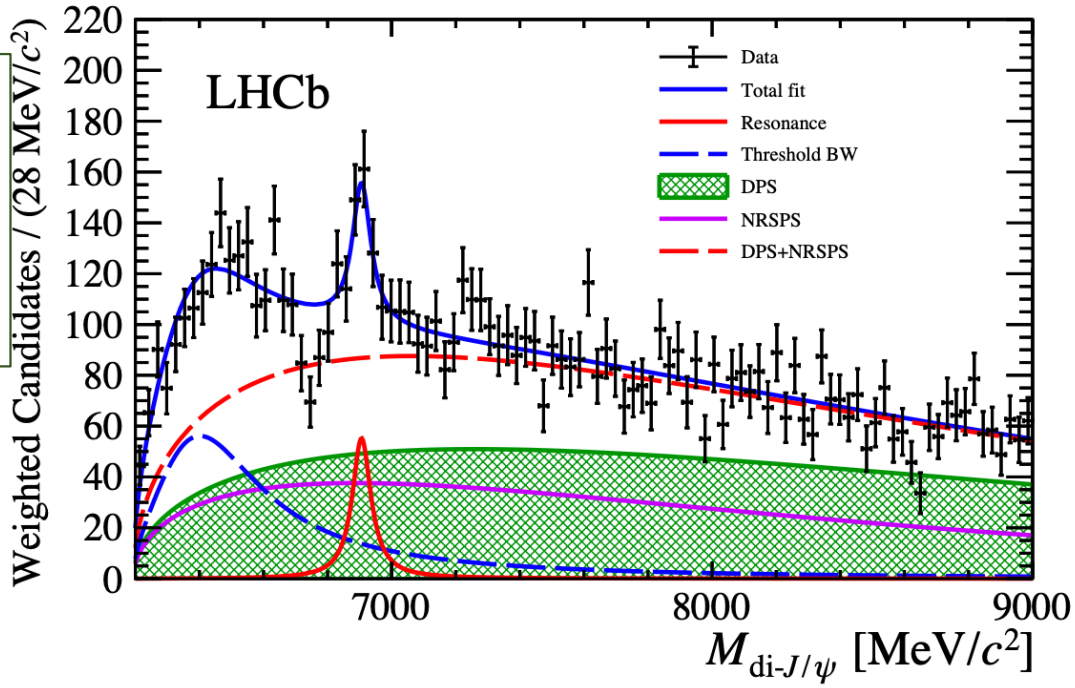


Di-J/ψ mass modeling (I)

arXiv:2006.16957

- 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: $< 1\sigma$



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- Individual significances:
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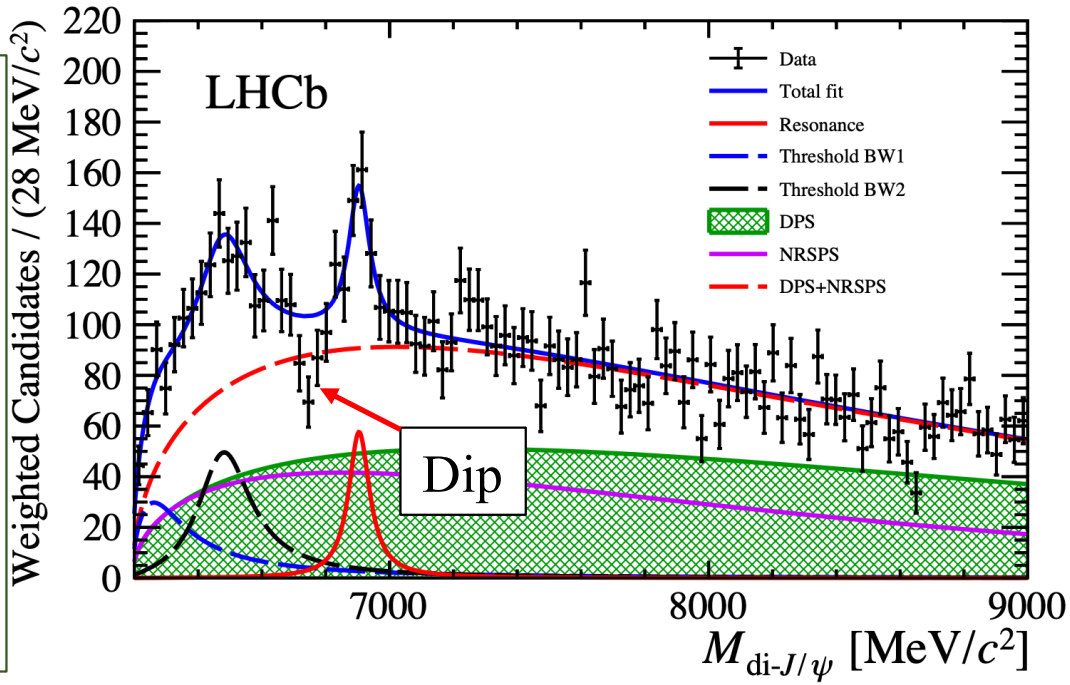
  - ✓Structure at 6.9 GeV/c^2 : $> 5\sigma$
  - ✓7.2 GeV/c^2 structure: $< 1\sigma$
- Improvement with two BWs for the broad structure than one $P(\chi^2_{ndf})$: 1.2% → 4.6%

More states?



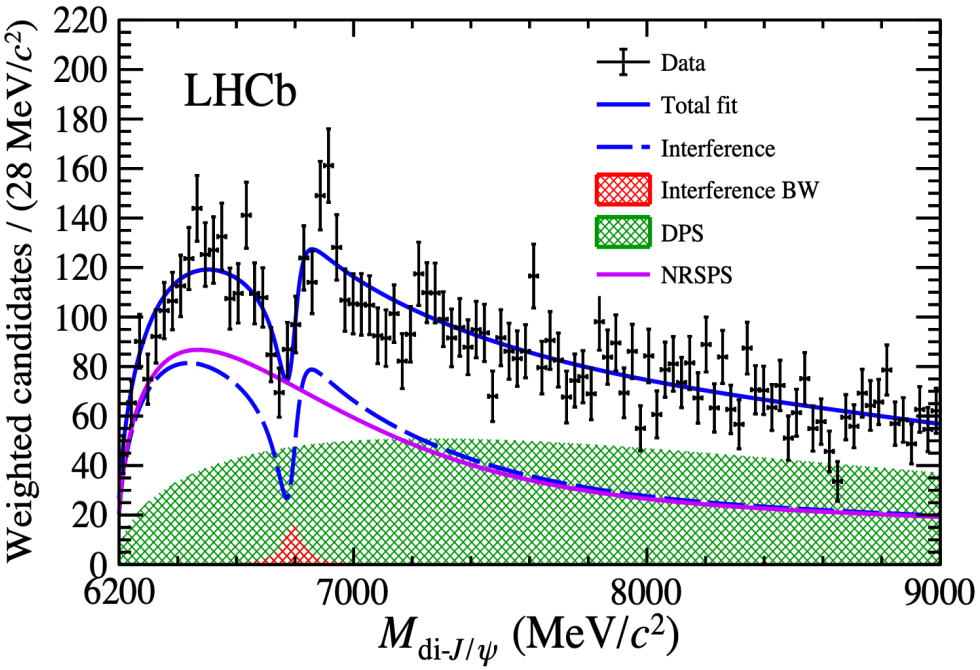
$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV}$$

Difficulty to model the dip at 6.8 GeV !

Di-J/ψ mass modeling (II)

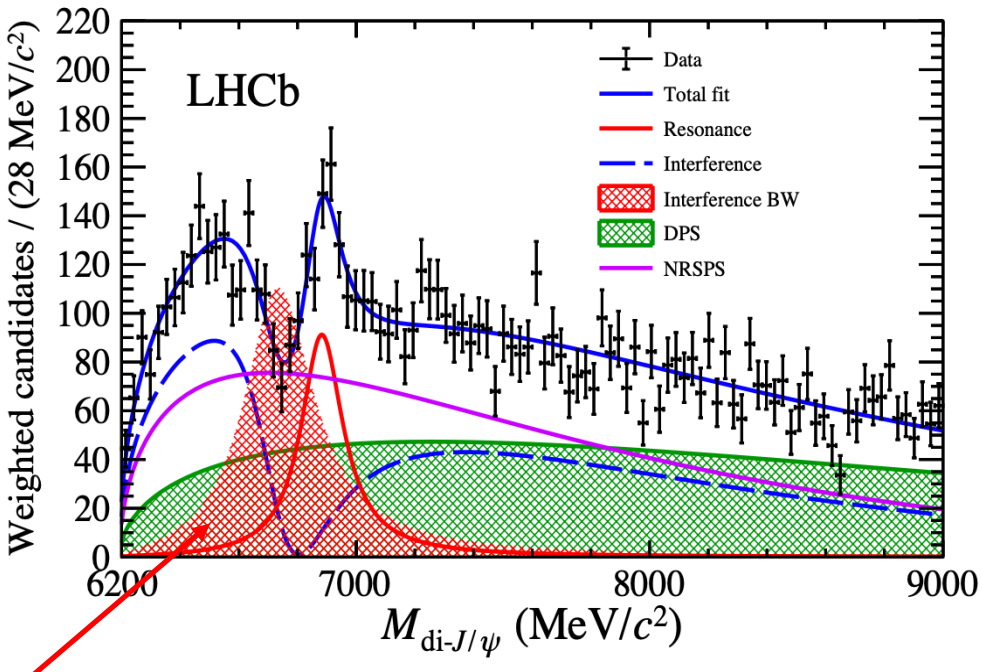
❑ Interferences

A BW interfering with non-resonant ($P = 2.8\%$)



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

A BW for X(6900) plus a second BW interfering with non-resonant ($P = 15.5\%$)



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

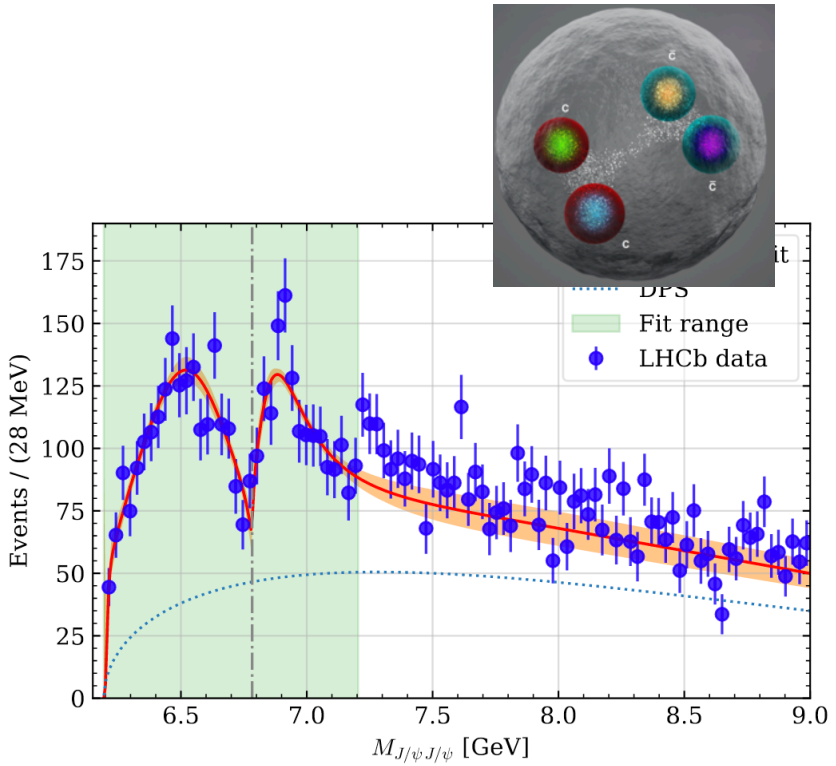
Very different from Model I

How to interpret data

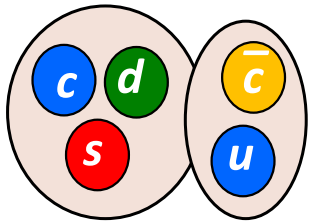
1. There are nontrivial structures
2. But difficult to understand all structures
   - ✓ Peak at 6.9 GeV relatively isolated, well modeled by a BW X(6900)
   - ✓ Structure at threshold: one BW, multiple BWs or feed-downs
   - ✓ Interference is possible and fits better, but not significant enough yet
3. 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

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

Structure: naturally tetraquark but also explained with coupled channels ($\psi\psi, \psi'\psi$…)



First evidence of $P_{cs}^{+}(c\bar{c}sud)$ candidate in $J/\psi\Lambda$



Pentaquark states

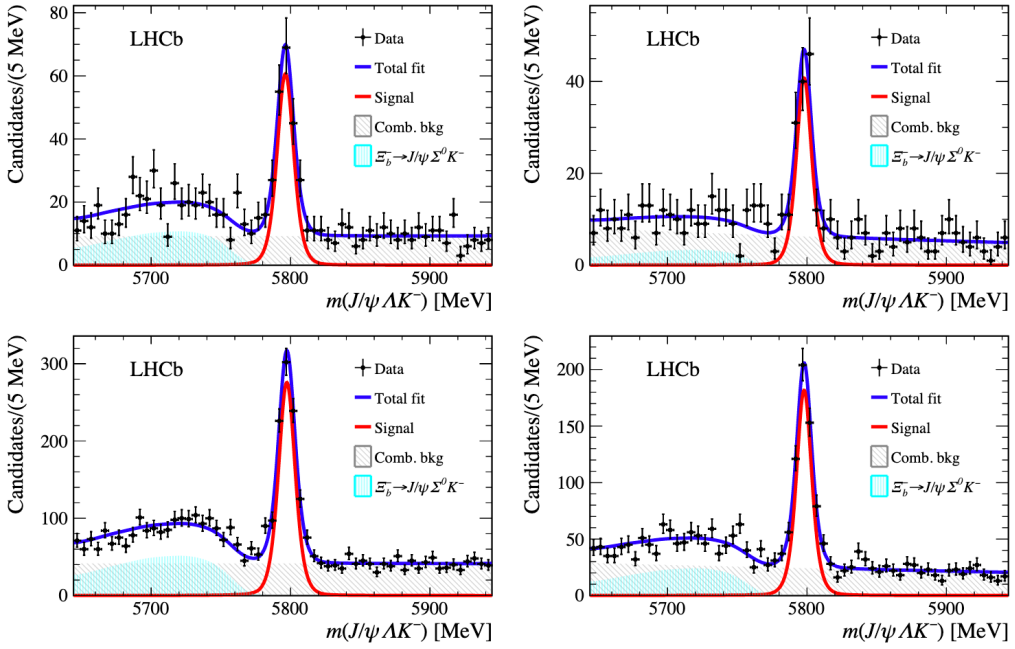
LHCb-PAPER-2020-039

- Pentaquark states observed in $J/\psi p$ system in $\Lambda_b^0 \to J/\psi p K^-$ decays
  Narrow and close to thresholds of $\Lambda_c^+ \overline{D}^{*0}, \Sigma_c \overline{D}^{(*)}$ supports molecule picture
- Existence of $J/\psi\Lambda$ states predicted, possibly produced in $\Xi_b^- \to J/\psi\Lambda K^-$
- Triangle singularity may be present in $\Xi_b^- \to J/\psi\Lambda K^-$

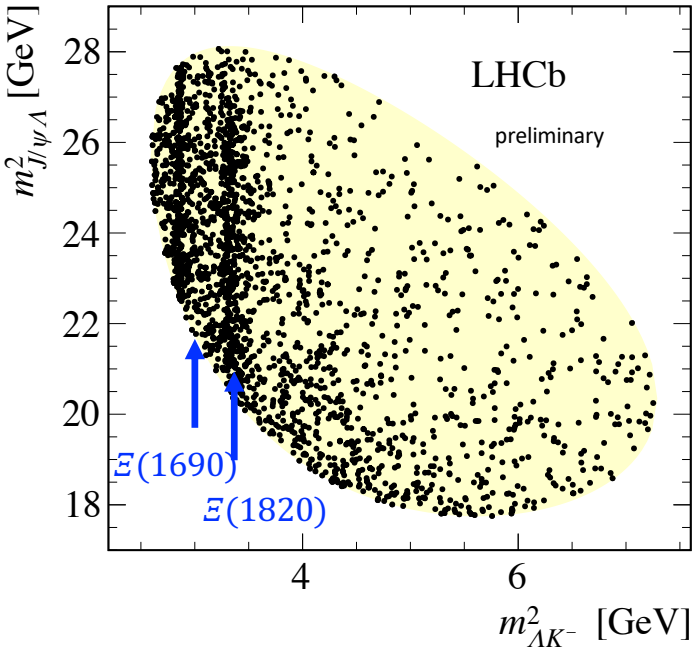
PRL 105 (2010) 232001,
PRC 93(2016) 064203,
PRD 93(2016)094009
Symmetry 12 (2020) 10
…

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

About 1800 signal decays



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

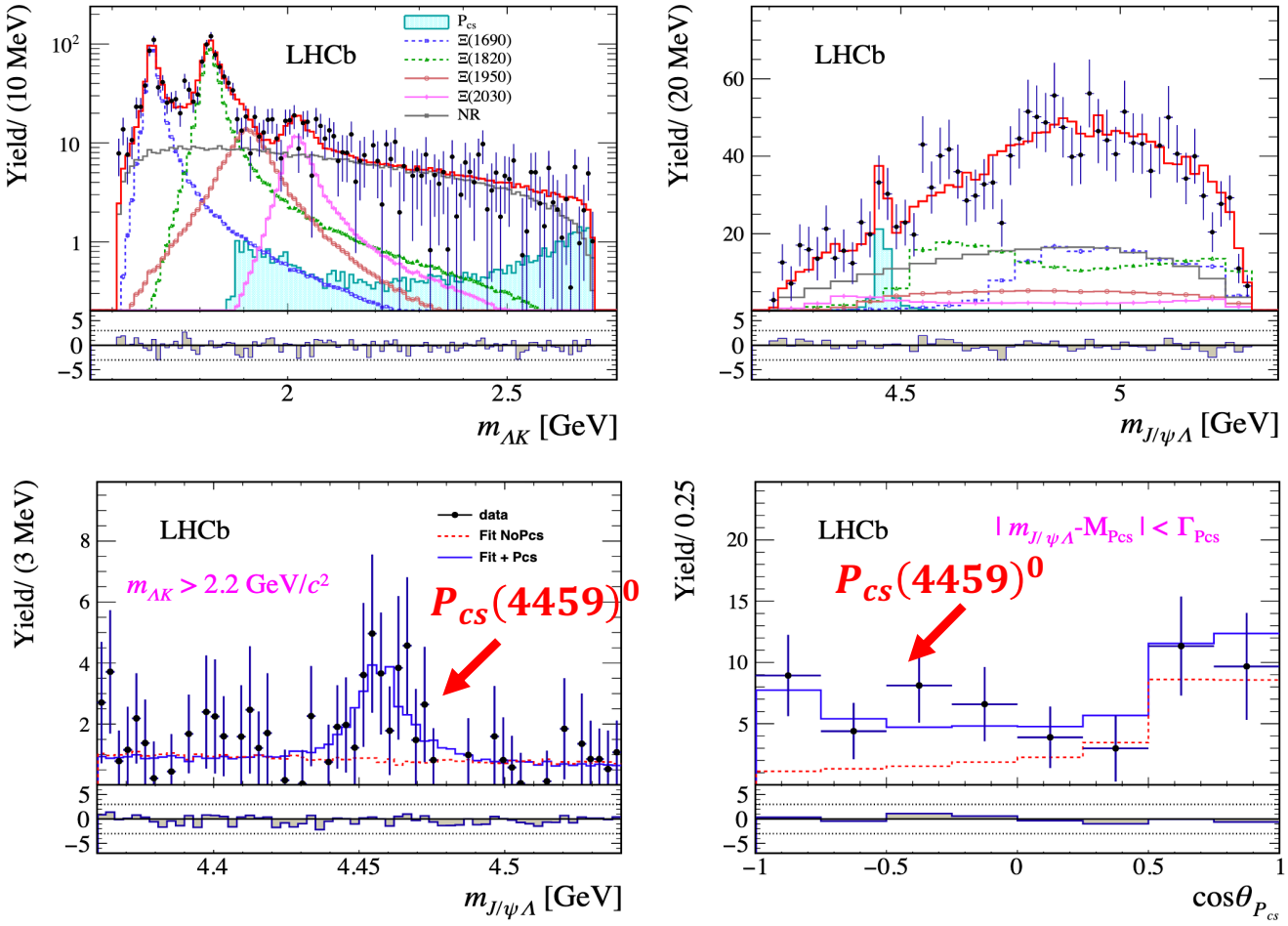


$\Xi_b^- \to J/\psi \Lambda K^-$ amplitude fit

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 $> 3.1\sigma$

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



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

LHCb-PAPER-2020-039

- Molecular states built from $\Xi_c\bar{D}, \Xi_c'\bar{D}, \Xi_c^*\bar{D}, \Xi_c\bar{D}^*, \Xi_c'\bar{D}^*, \Xi_c^*\bar{D}^* \ldots$
  - Isospin-isospin interactions, vanish for $\bar{D}\Lambda_c^+$, $\bar{D}_s^*\Lambda_c^+$ $D_s^{*-}\Sigma_c^+$ … PRD101(2020)034018

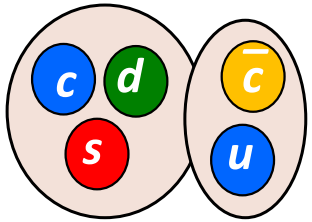
System	$[\Xi_c'\bar{D}]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{5}{2}}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$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

  - $J/\psi\Lambda, \bar{D}\Lambda_c^+ \ldots$ also exist in other models

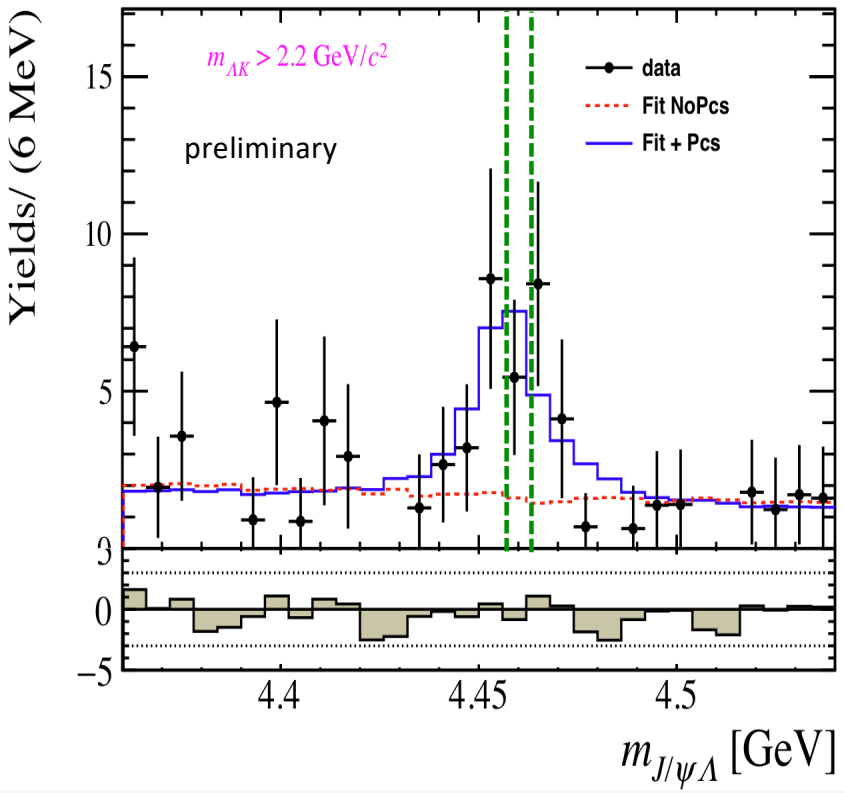
- $P_{cs}(4459)^0$ mass close to $\Xi_c\bar{D}^*$ threshold, two $I = 0$ states with $\frac{1}{2}^-$ or $\frac{3}{2}^-$

  More data needed to resolve

- Confirmation by other states, decays

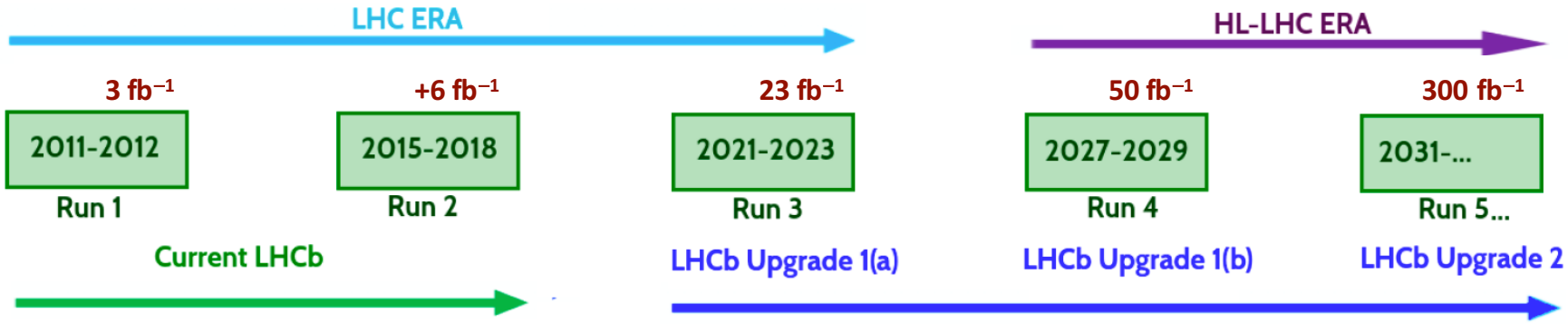


Two nearby states



Prospects

[arXiv:1808.08865]



Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi p K^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi \Xi_c^+$	50	100	600

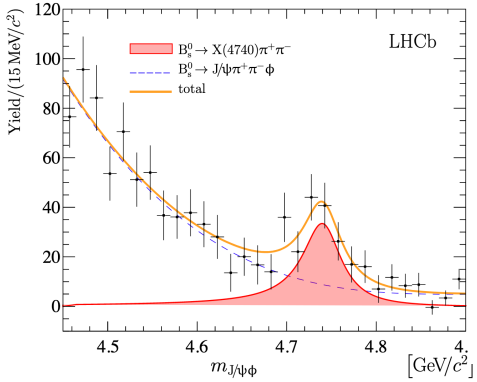
Luminosity + trigger

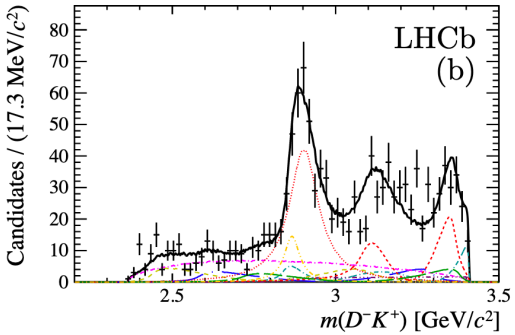
Any good thing is possible

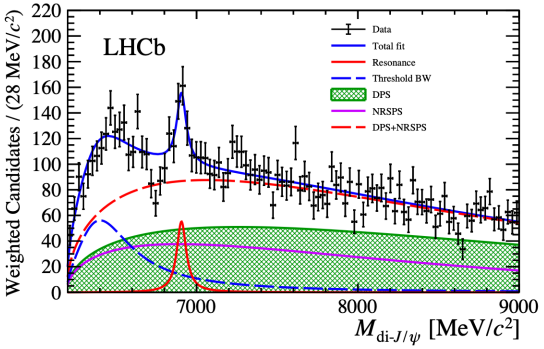
Summary

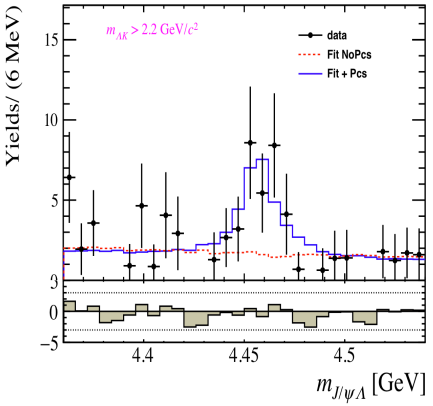
- Recent progress on exotic hadron spectroscopy by LHCb
  - ➢ **$cs\bar{c}\bar{s}$ structure in $J/\psi\phi$ system**
  - ➢ **Open charm tetraquark candidates $\bar{c}\bar{s}ud$ in D^-K^+ system**
  - ➢ **Fully charmed tetraquark candidates $cc\bar{c}\bar{c}$ in di-J/ψ system**
  - ➢ **Hidden charm strange pentaquark candidate $c\bar{c}uds$ in $J/\psi\Lambda$ system**

New fields in experimental studies, more to be measured/understood !









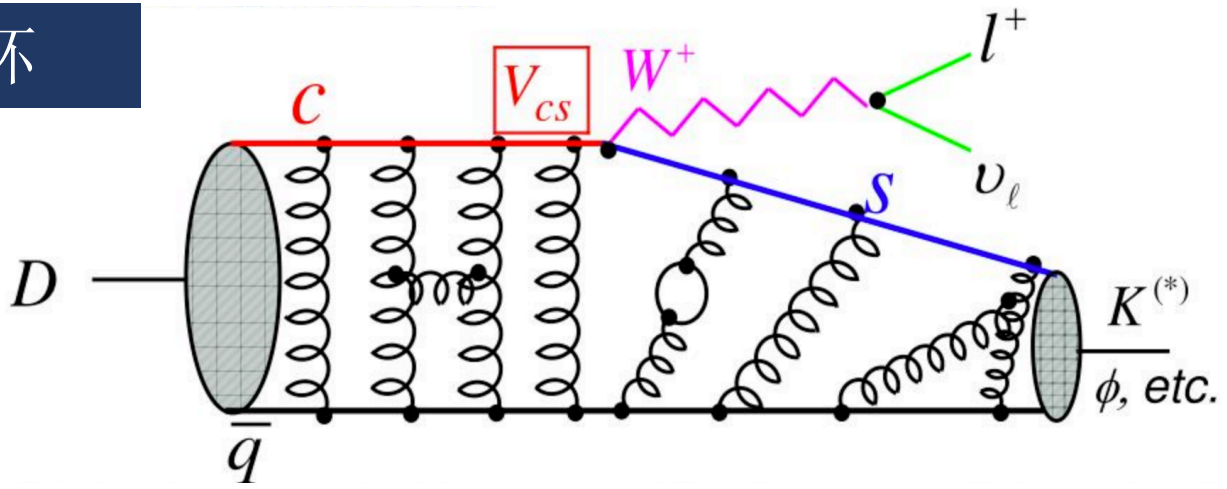
Thank you for your attention

Backups

非微扰QCD

- 是精确检验标准模型需要控制的本底

例子1: CP 破坏



例子2：g-2

arXiv:1311.2198

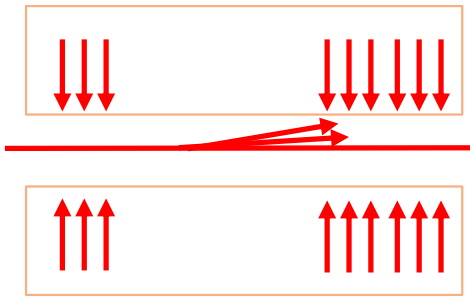
标准模型计算
g-2的误差源

	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

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

LHCb detector



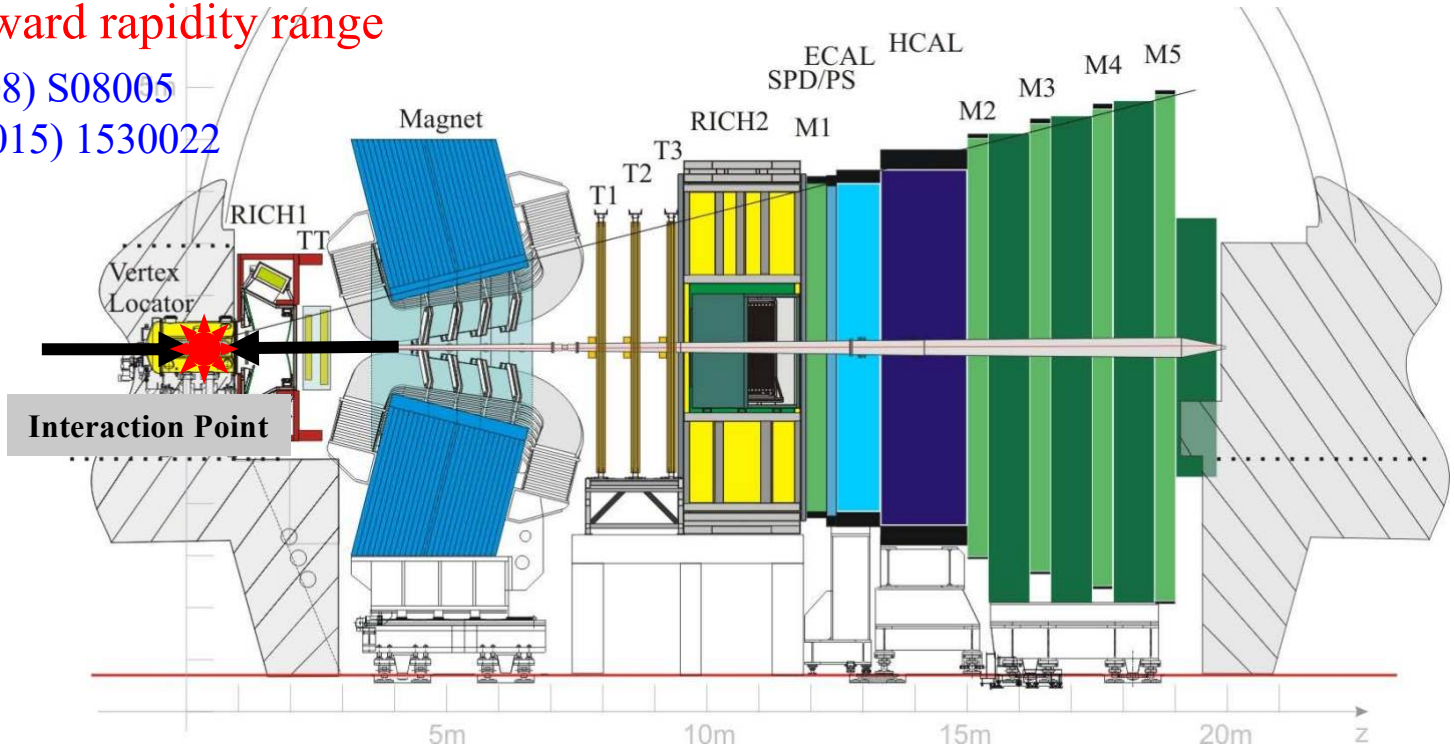
Aiming for precision measurements in b, c sectors

→ but becoming a General Purpose Detector

→ in forward rapidity range

JINST 3 (2008) S08005

IJMPA 30 (2015) 1530022



Excellent vertex and IP, decay time resolution:

- $\sigma(\text{IP}) \approx 20$ μm for high-p_{T} tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- \pi^+$ decays

Very good momentum resolution:

- $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0,200)$ GeV
- $\sigma(m_B) \approx 24$ MeV for two-body decays

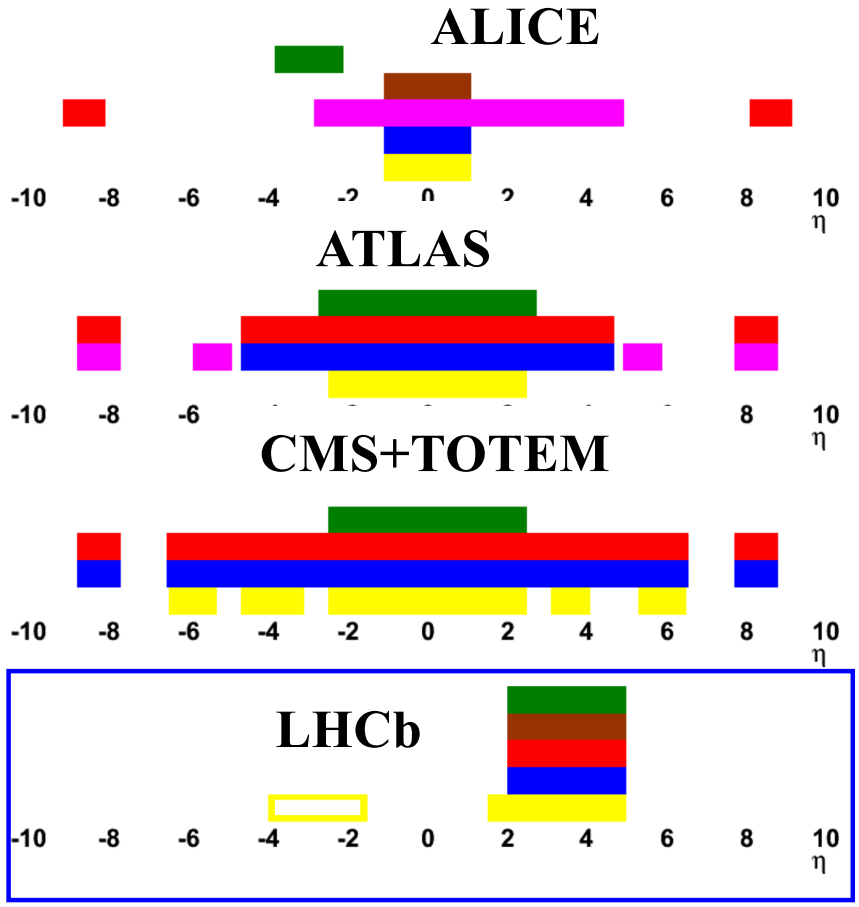
Hadron and Muon identification

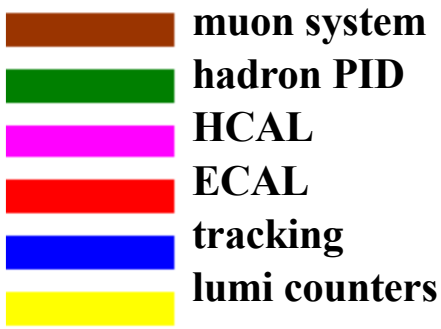
- $\epsilon_{K\to\text{K}} \approx 95\%$ for $\epsilon_{\pi\to\text{K}} \approx 5\%$ up to 100 GeV
- $\epsilon_{\mu\to\mu} \approx 97\%$ for $\epsilon_{\pi\to\mu} \approx 1 - 3\%$

Data good for analyses

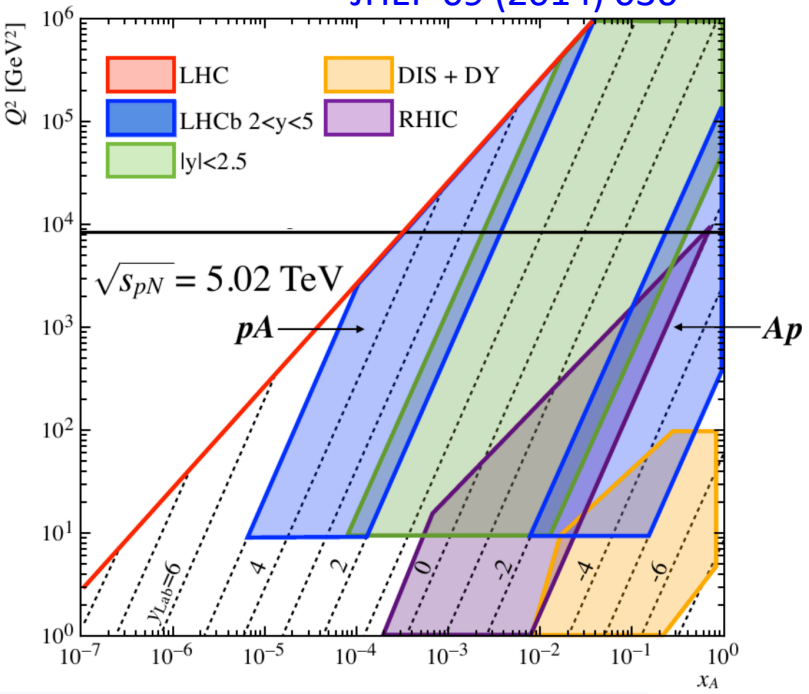
- $> 99\%$

LHCb experiment





JHEP 09 (2014) 030



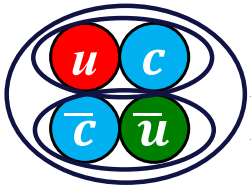
LHCb fully instrumented in the forward region $(2 < \eta < 5)$

- Heavy ion studies in a unique kinematic area: low p_T, large y, very small or large x
- Complementary to other LHC experiments

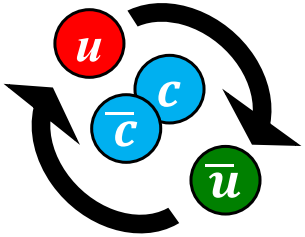
$X(3872)$

- Interpretation of X(3872) structure

Compact tetraquark/pentaquark



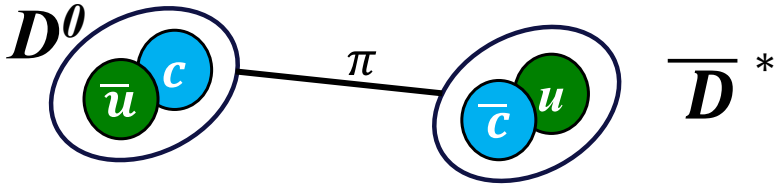
Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules

PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



Mixtures of exotic +conventional states

$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

- "Binding" energies E_b for disassociation $(2m_D - m_H)$

$D\bar{D}^*$ Molecule

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027

J. Phys. G 32 (3) 2006