第二届LHCb前沿物理研讨会

Tetraquarks at LHCb

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List of public analyses

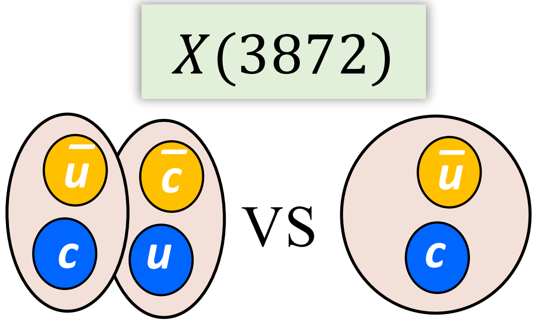
1. Analysis of $B^+ \to D^+D^-K^+$, $X_{0,1}(2900) \to D^-K^+$, arXiv:2009.00025, 2009.00026
2. Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays, $X(4740) \to J/\psi\phi$, arXiv:2011.01867
3. Multiplicity-dependent $\chi_{c1}(3872)/\psi(2S)$ production, $\chi_{c1}(3872)/\psi(2S)$, arXiv:2009.06619
4. Observation of structure in J/ψ-pair mass spectrum, $X(6900) \to J/\psi J/\psi$, arXiv:2006.16957
5. $\psi_2(3823)$ and $\chi_{c1}(3872)$ in $B^+ \to (J/\psi\pi^+\pi^-)K^+$, $\psi_2(3823) + \chi_{c1}(3872)$, arXiv:2005.13422
6. Study of $\chi_{c1}(3872)$ lineshape, $\chi_{c1}(3872)$, arXiv:2005.13419
7. Observation of $\Lambda_b^0 \to \chi_c(3872)pK^-$ decay, $\chi_{c1}(3872)$, arXiv:1907.00954
8. Spectroscopy in prompt $D\overline{D}$ final state, $X(3843), \chi_{c2}(3930)$ ..., arXiv:1903.12240
9. Model-independent study of exotics in $B^0 \to J/\psi K^+\pi^-$, $Z_c(4200), Z_c(4600)$, arXiv:1901.05745
10. Evidence of exotic in $B^0 \to \eta_c(1S)K^+\pi^-$, $Z_c(4100)^+$, arXiv:1809.07416
11. Beautiful tetraquarks in $\Upsilon\mu^+\mu^-$ final state, $X_{bb\bar{b}\bar{b}}$, arXiv:1806.09707
12. AmAn of $B^+ \to J/\psi\phi K^+$, $X(4140), X(4274), X(4500), X(4700)$, arXiv:1606.07898, 1606.07895
13. Confirmation of $Z_c(4430)^+$, $Z_c(4430)^+$, arXiv:1510.01951, 1404.1903
14. Measurement quantum numbers of $X(3872)$, $J^{PC} = 1^{++}$, arXiv:1504.06339, 1302.6269
15. Evidence of $X(3872) \to \psi(2S)\gamma$, arXiv:1404.0275
16. Prompt production of $X(3872)$, arXiv:1112.5310

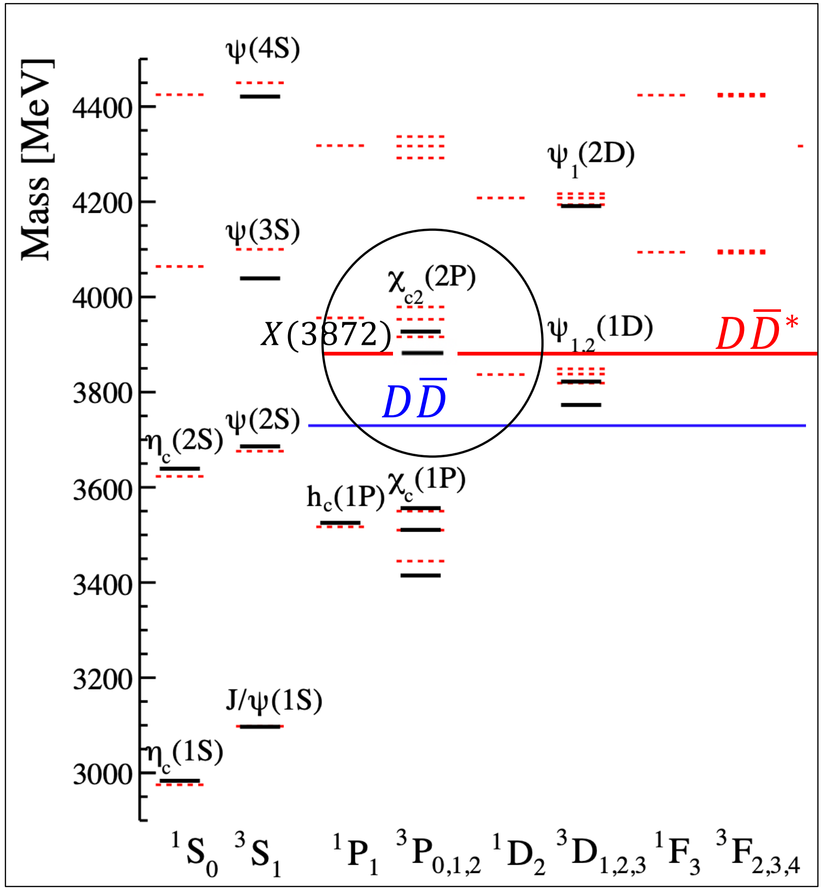
Refs. L1-L16

Observation Evidence Null

Exotic or not: $X(3872)$?

Refs. L8/14





$J^{PC} = 1^{++}$ determined with $B^+ \to (J/\psi\rho)_X K^+$

$\chi_{c1}(2P)$?

Nearby states of $\chi_{c0,2}(2P)$ candidates:

- $X(3860)$, observed in $e^+e^- \to J/\psi(D\bar{D})$
- $X_{0/2}(3915)$, observed in $D\bar{D}, J/\psi\omega$
- $X(3940)$, observed in $e^+e^- \to J/\psi(D\bar{D}^*)$

PRD100(2019)094003, Rev.Mod.Phys.90 (2018)015003, Rev.Mod.Phys.90 (2018)015004, Phys.Rept.639 (2016) 1

Mass and Width of $X(3872)$

Refs. L5/6

$m_{X(3872)} = 3871.64 \pm 0.06 \pm 0.01$ MeV

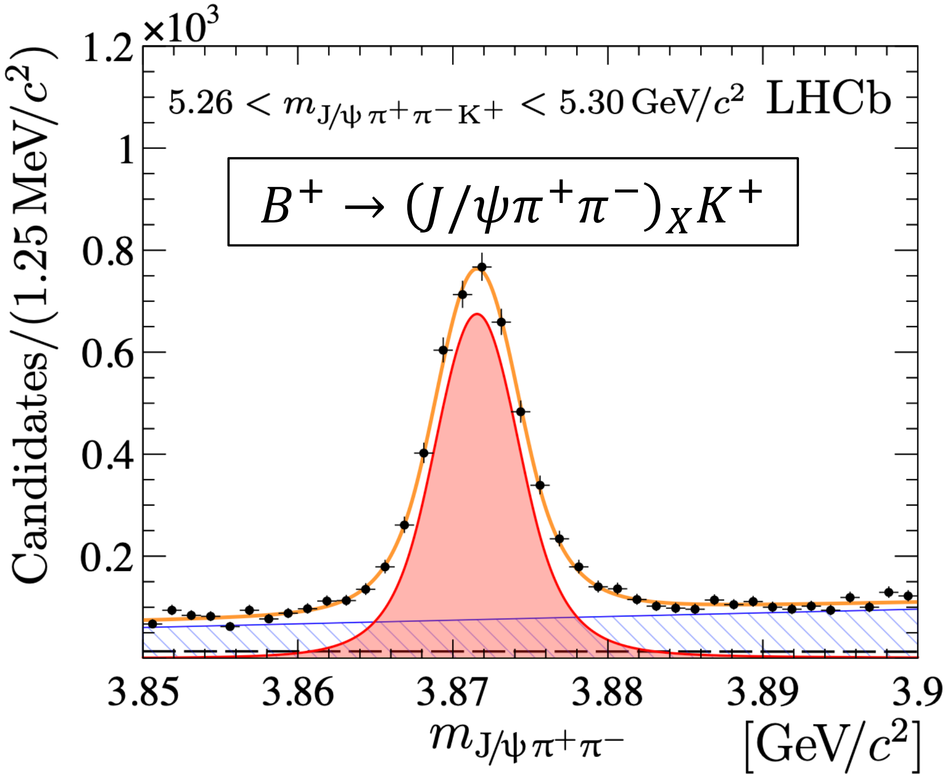
$m_{D^0\bar{D}^{*}} - m_{X(3872)} = 0.07 \pm 0.12(\delta m_K)$ MeV

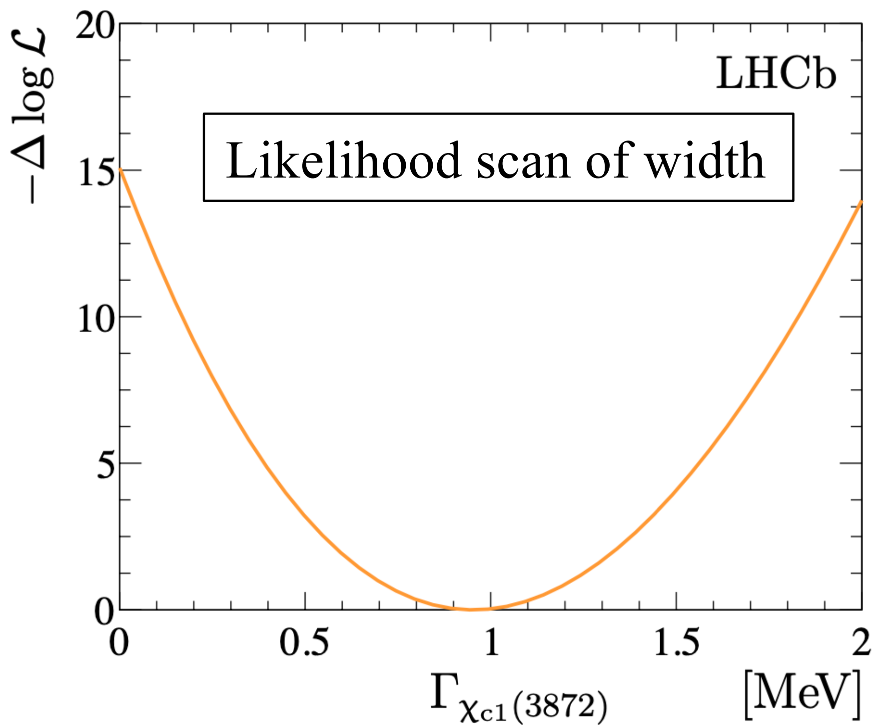
$\Gamma_{X(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21$ MeV

Not zero by 5.5σ

- Fit assuming S-wave Breit-Wigner
- Experimental resolution ≈ 2.4 MeV

Consistent with study using inclusive $b \to X(3872)$ decays





$X(3872)$ Flatte parameterization

Ref. L6

Lineshape distorted due to coupling to threshold: $X(3872) \to DD^*$

$k = \sqrt{2\mu E}$

Flatte lineshape: PRD76(2007)034007

$$\frac{dR(J/\psi\pi^+\pi^-)}{dE} \propto \frac{\Gamma_\rho(E)}{|D(E)|^2}$$

$$D(E) = E - E_f + \frac{i}{2}[g(k_1 + k_2) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0]$$

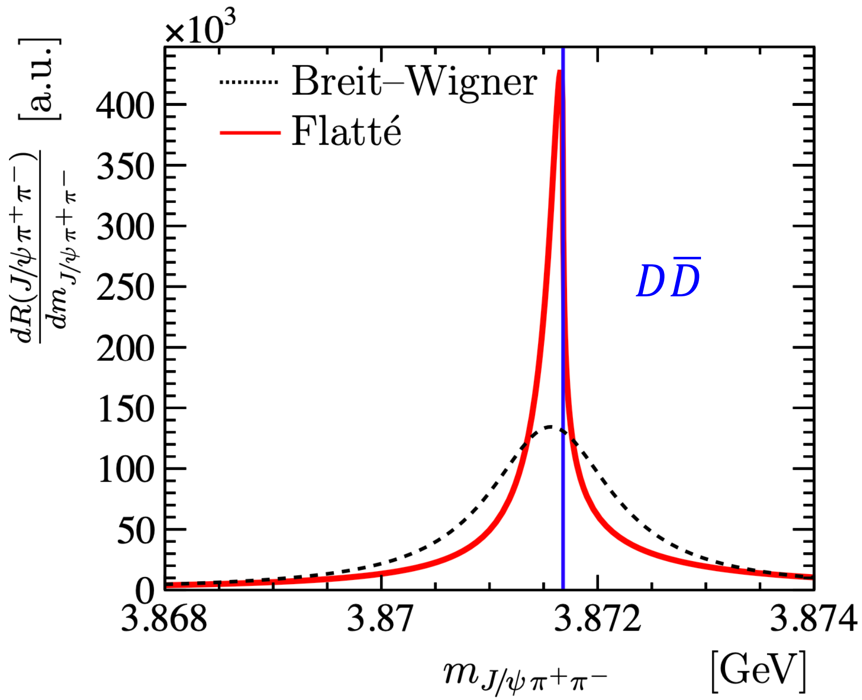
k_1: $D^0 D^{*0}$; k_2: $D^+ D^{*-}$; $\Gamma_\rho(E)$: $J/\psi\rho$; $\Gamma_\omega(E)$: $J/\psi\omega$; Γ_0: Others

$$E \equiv m_{J/\psi\pi^+\pi^-} - (m_{D^0} + m_{D^{*0}})$$

$$E_f = m_0 - (m_{D^0} + m_{D^{*0}})$$

Free parameters: $E_f, g, g_\rho, g_\omega, \Gamma_0$

Constrained using measured BFs



Mode [MeV]	Mean [MeV]	FWHM [MeV]
$3871.69^{+0.00+0.05}_{-0.04-0.13}$	$3871.66^{+0.07+0.11}_{-0.06-0.13}$	$0.22^{+0.06+0.25}_{-0.08-0.17}$

$m_{D^0\bar{D}^*} - m_{X(3872)} = 0.01 \pm 0.14$ MeV

Pole structure of $|D(E)|^2$ studied (syst. limited):
- ✓ resonances wrt $J/\psi\pi^+\pi^-$ channel
- ✓ quasi-bound for DD^*, quasi-virtual not excluded, pole positions prefer a large molecule component

$X(3872)$ decay&production

Ref. L2/7/15/16

$$\frac{B[X(3872)\to\psi(2S)\gamma]}{B[X(3872)\to J/\psi(1S)\gamma]} = 2.46 \pm 0.64 \pm 0.29$$

Not very consistent with BESIII

For comparison: $B[\chi_{b1}(2P) \to \Upsilon(2S)\gamma]/B[\chi_{b1}(2P) \to \Upsilon(1S)\gamma] = 2.0 \pm 0.3$

Prompt production: $\frac{\sigma[pp\to X(3872)X]}{\sigma[pp\to\psi(2S)X]} = \frac{(2.6\pm0.9)\times10^{-2}}{B(X(3872)\to J/\psi\pi^+\pi^-))}$ $\approx 0.6 \pm 0.3$

Λ_b^0 decay : $\frac{B[\Lambda_b^0\to X(3872)pK^-]}{B[\Lambda_b^0\to\psi(2S)pK^-]} = (5.4 \pm 1.1)\times10^{-2}/(\frac{B[X(3872)\to J/\psi\pi^+\pi^-]}{B[\psi(2S)\to J/\psi\pi^+\pi^-]})$ $\approx 0.4 \pm 0.2$

B_s^0 decay : $\frac{B[B_s^0\to X(3872)\phi]}{B[B_s^0\to\psi(2S)\phi]} = (2.42 \pm 0.24)\times10^{-2}/(\frac{B[X(3872)\to J/\psi\pi^+\pi^-]}{B[\psi(2S)\to J/\psi\pi^+\pi^-]})$ $\approx 0.2 \pm 0.1$

PRD100(2019)094003

Parameter index	Decay mode	Branching fraction
1	$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
2	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(52.4^{+25.3}_{-14.3})\%$
3	$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
4	$X(3872) \to \gamma\psi(3686)$	$(2.4^{+1.3}_{-0.8})\%$

$$\frac{\Gamma_{\chi_{c1}(2P)}}{\Gamma_{\chi_{c1}(1P)}} \sim \frac{B(\chi_{c1}(1P) \to J/\psi\gamma)}{B(\chi_{c1}(2P) \to \psi(2S)\gamma)} \sim 15$$

For comparison:

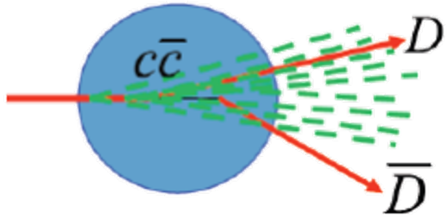
- $\sigma[\chi_{c1}(1P)]/\sigma(J/\psi)\sim0.4$ (prompt)
- $\frac{B(B^+\to\chi_{c1}(1P)K^+)}{B(B^+\to J/\psi K^+)} \approx 0.49$
- $\frac{B(B^+\to\chi_{c1}(1P)K^0\pi^+)}{B(B^+\to J/\psi K^0\pi^+)} \approx 0.51$
- $\frac{B(B^+\to\chi_{c1}(1P)K^{*+})}{B(B^+\to J/\psi K^{*+})} \approx 0.20$

…

$X(3872)$ in "nuclear" environment

Ref. L3

Broken due to FSI with co-moving particles (comover model)



Rate depends on two parameters: **binding energy, size**

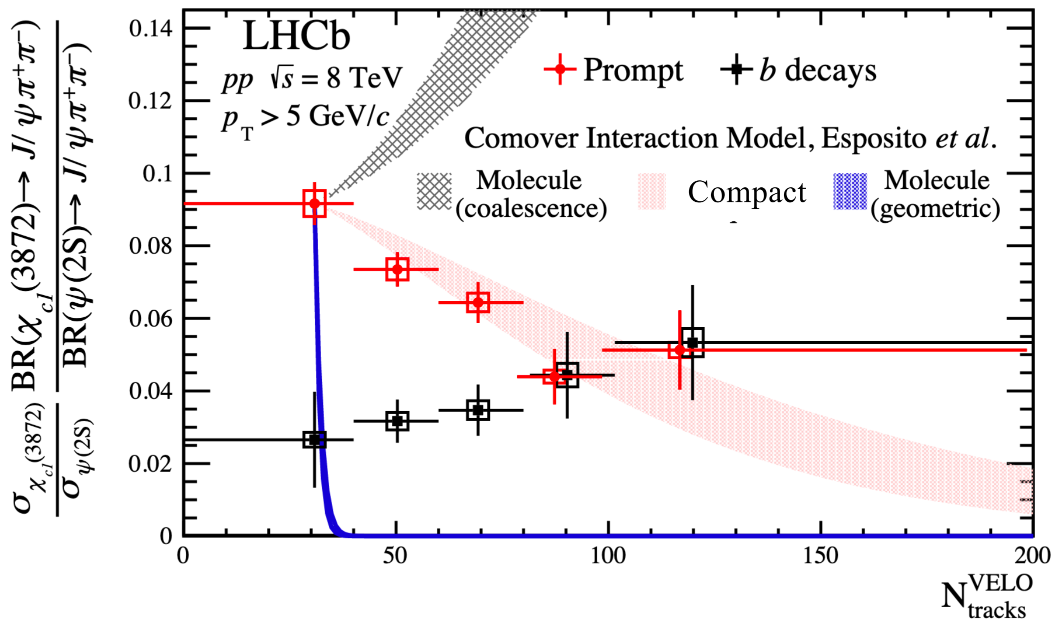
Explained $\psi(2S)/J/\psi$, $\Upsilon(nS)/\Upsilon(1S)$ production ratios in pPb data

arXiv:2006.15044

	$E_{\mathcal{Q}}^{\text{thr}}$	$r_{\mathcal{Q}}$	$\sigma_{\mathcal{Q}}^{\text{geo}}$	$\langle v\sigma\rangle_{\mathcal{Q}}$
$\psi(2S)$	50 MeV	0.45 fm	6.36 mb	5.15 ± 0.84 mb
$X(3872)$ compact	116 keV	0.65 fm	13.3 mb	11.61 ± 1.69 mb
$X(3872)$ molecule	116 keV	6.6 fm	1368 mb	1197 ± 171 mb

$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\text{geo}} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{\text{thr}}}{E_c}\right)^n \right\rangle$$

$$E_{\mathcal{Q}}^{\text{thr}} = m_{DD^{(*)}} - m$$



- Breakup rate too small compared to expectation in **molecule** picture
- Consistent with a **compact** state

$\mathrm{N}_{\text{tracks}}(data) = \mathrm{N}_{\text{tracks}}(model)$?

b-decay vs prompt

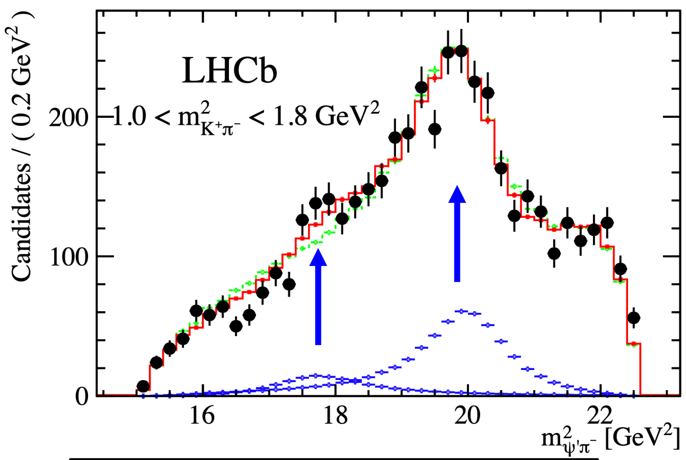
$X(3872)$ the only one (?) observed in e^+e^-, b-decay and prompt pp collisions

Production mechanism?
Internal structure?
Difficulties to identify wide states in prompt hadron collisions?

Z_c^+ in beauty decays:

$Z_c(4430)^-, 1^+$
$Z_c(4200)^-, 0^-$

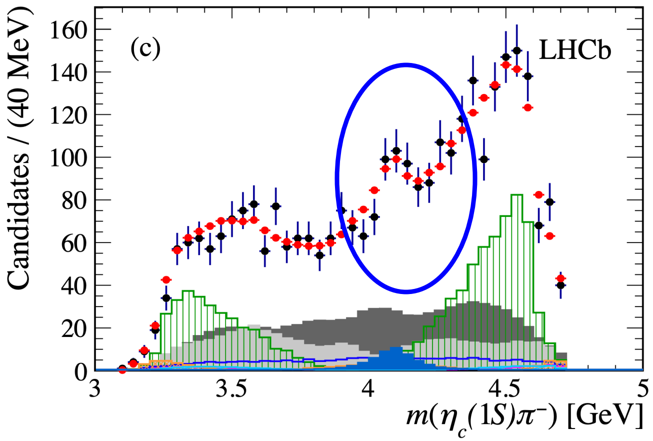
Ref. L13



$B^0 \to \psi(2S)K^+\pi^-$

Ref. L10

$Z_c(4200)^-, 0^+$ or 1^-

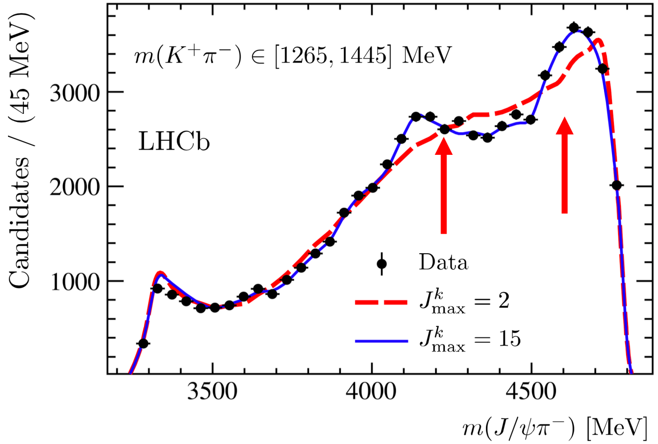


$B^0 \to \eta_c K^+\pi^-$

Ref. L9

Model independent method

$Z_c(4200)^-, Z_c(4600)^-$



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

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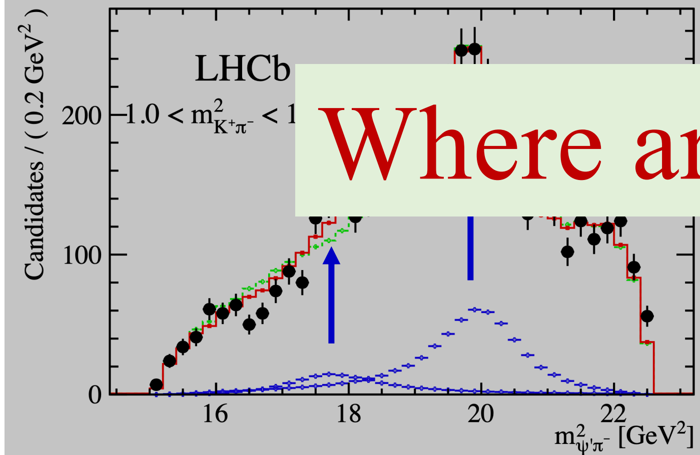
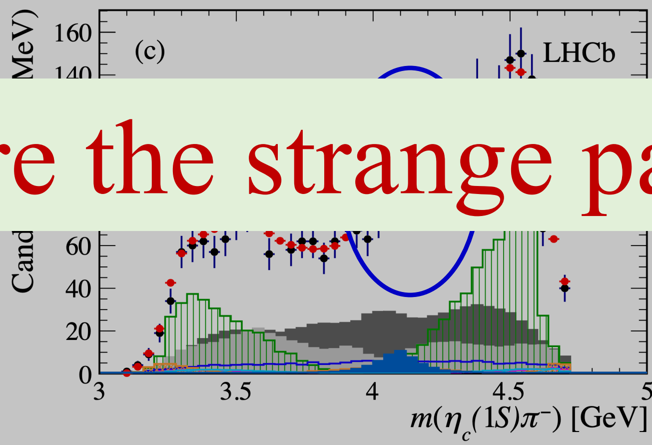
Ref. L13



$B^0 \to \psi(2S)K^+\pi^-$

Ref. L10

$Z_c(4200)^-, 0^+$ or 1^-



$B^0 \to \eta_c K^+\pi^-$

Ref. L9

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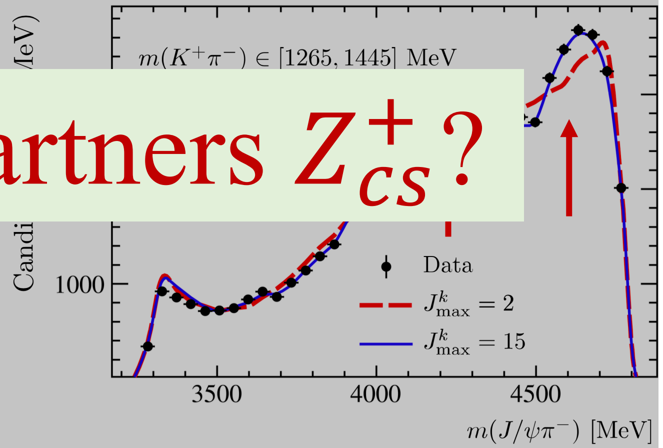


$B^0 \to J/\psi K^+\pi^-$

Where are the strange partners Z_{cs}^+?

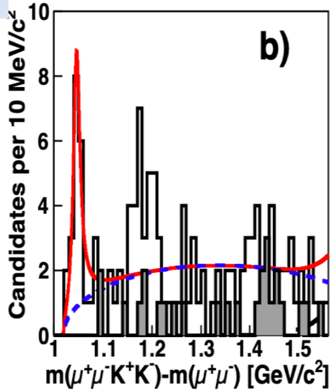
Tetraquark in $J/\psi\phi$ system

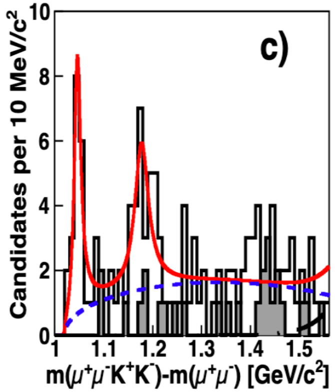
$X \to J/\psi\phi$ first seen by CDF, confirmed by CMS

- Observation of $X(4140)$
- Evidence of $X(4274)$
- 1D analysis

PRL102(2009)242002
Mod.Phys.Lett.A32(2017)26
PLB734(2014)261

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

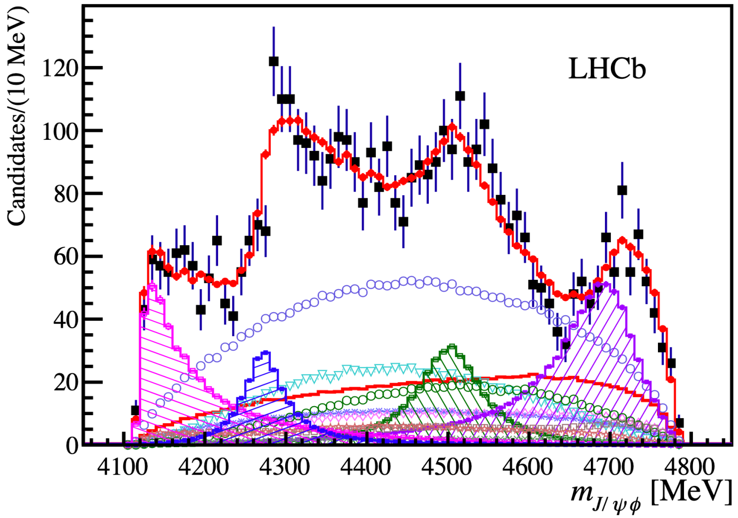




LHCb amplitude analysis, observed four states

- All much wider
- Only Run I data

States	J^{PC}	Mass/MeV	Width/MeV
$X(4140)$	1^{++}	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$
$X(4274)$	1^{++}	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$
$X(4500)$	0^{++}	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
$X(4700)$	0^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

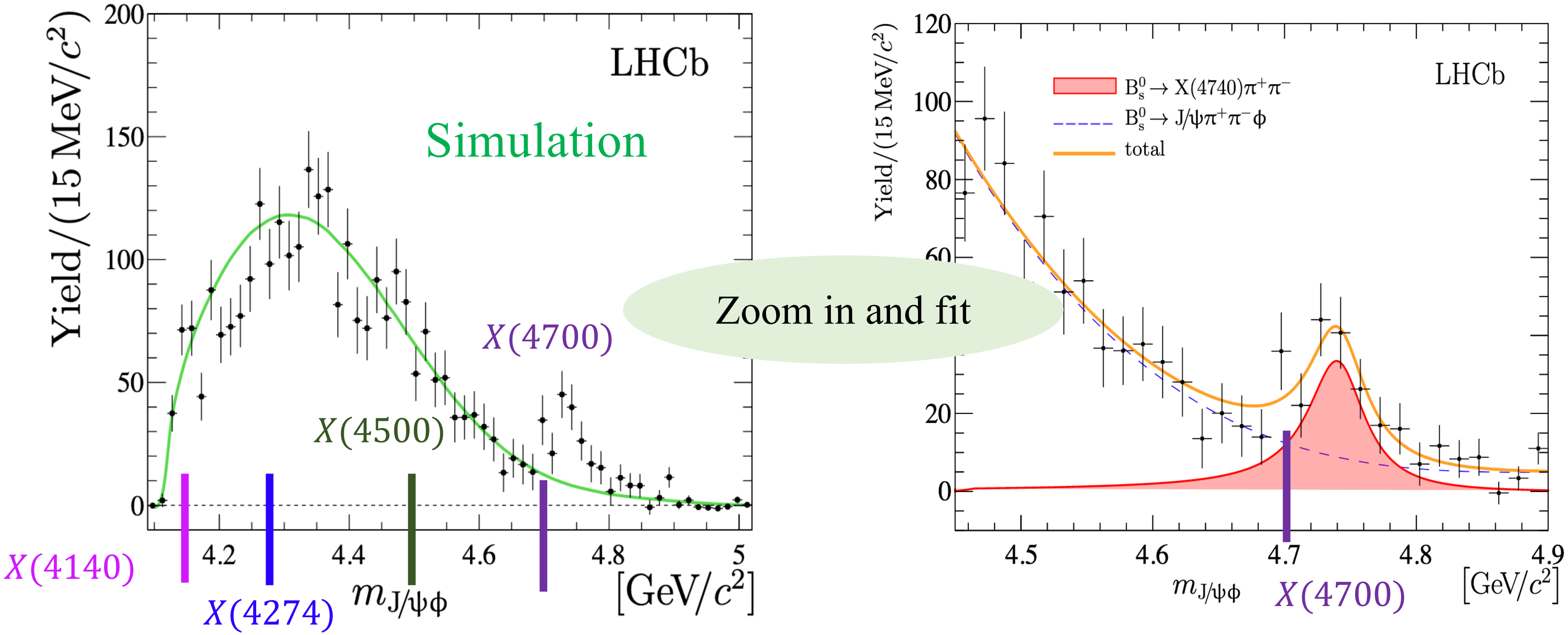


Ref. L9

“New” $X(4740)$ structure

Ref. L2

A $J/\psi\phi$ structure in $B_s^0 \to J/\psi\phi\pi^+\pi^-$ decay



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:

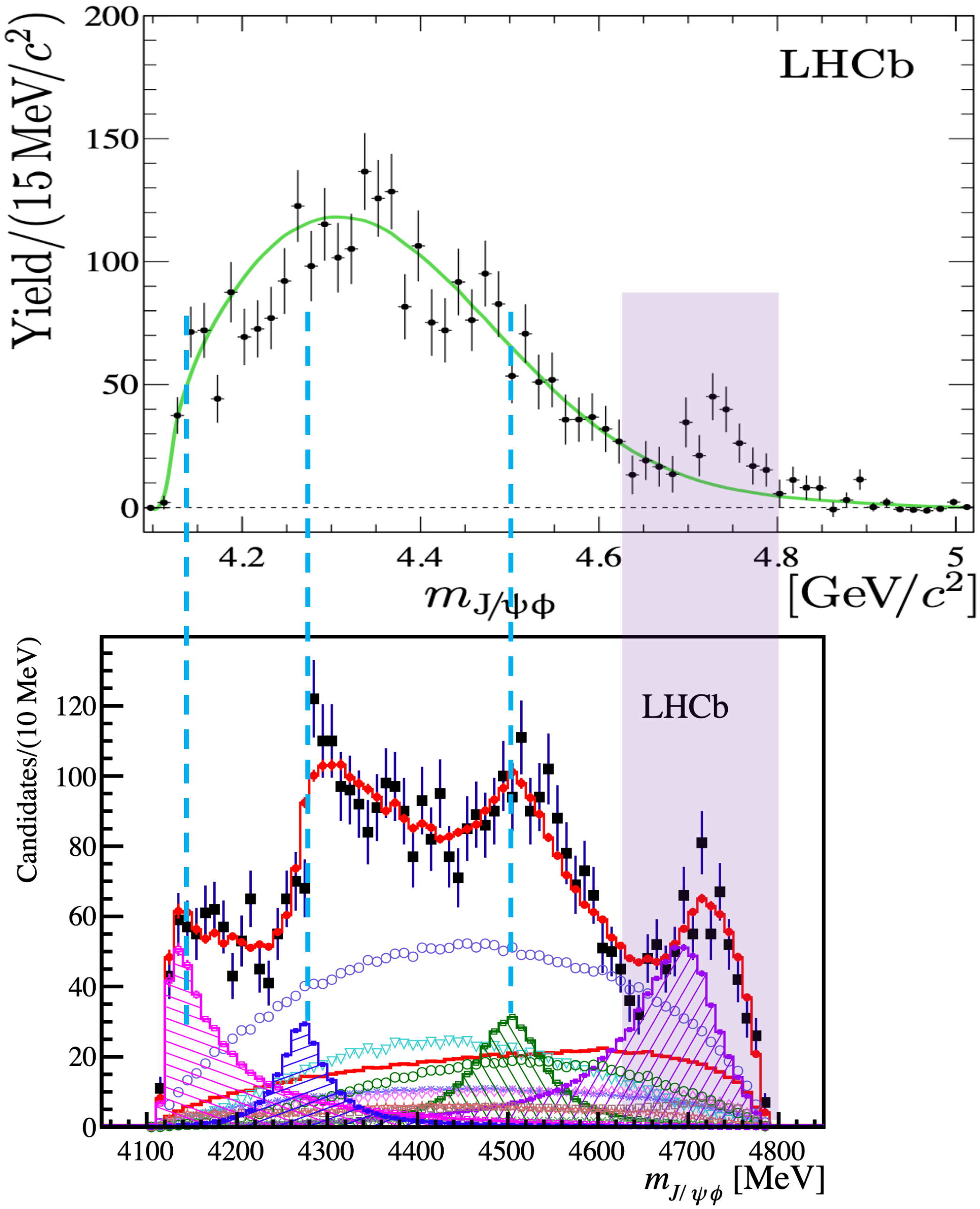
- Shape of underlying non-X
- Alternative P-wave or D-wave BW
- Inteference $\mathcal{F}_S(m_{J/\psi\phi}) \propto \left|\mathcal{A}(m_{J/\psi\phi}) + b(m_{J/\psi\phi})\,e^{i\varphi}\right|^2$

Maybe not new

Ref. L2

- 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



Molecular vs tetraquark

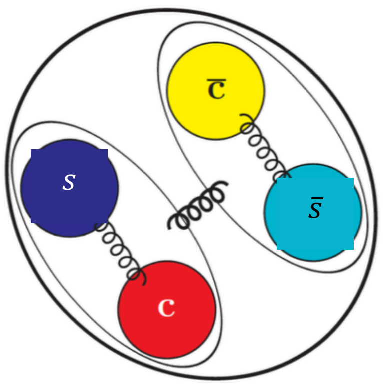
Difficult to interpretation as molecular states

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

60 MeV away

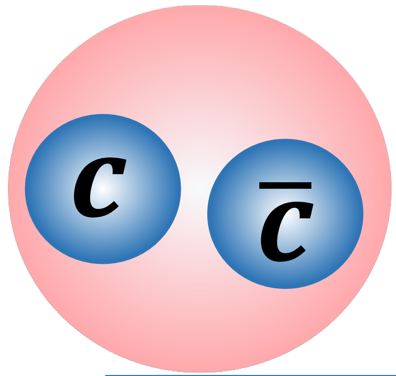
$P = -$ for S-wave

$X(4274), X(4500)$, 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

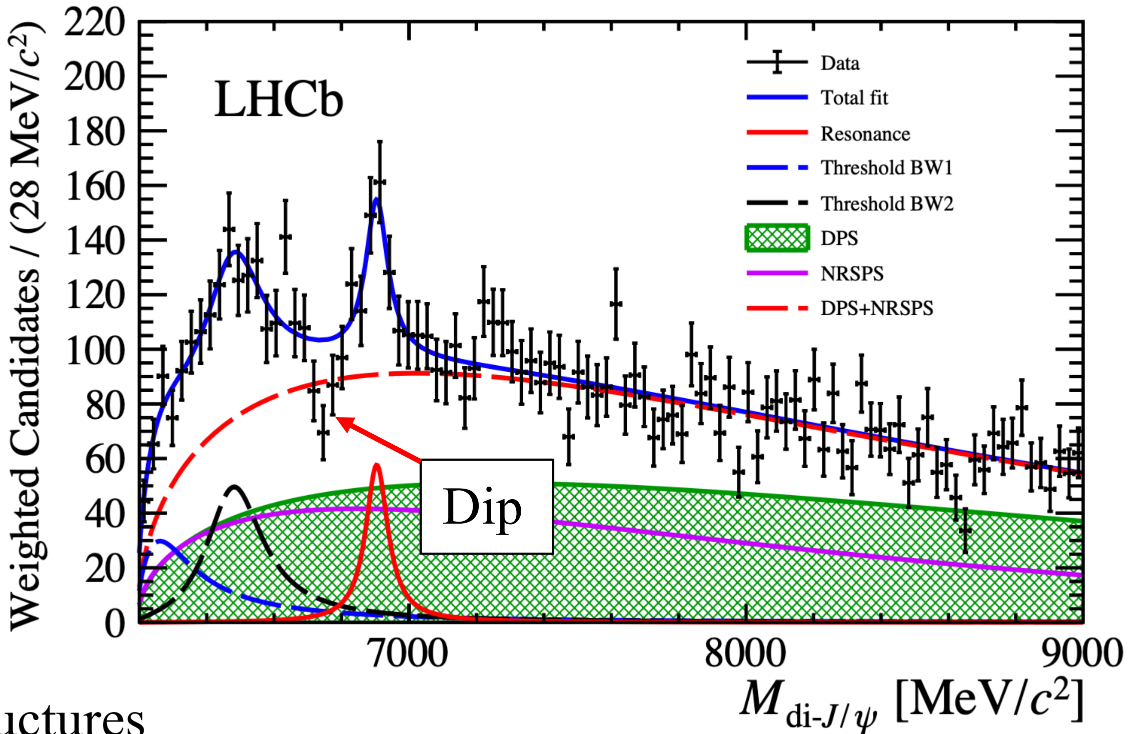
Decay in $J/\psi\omega$, DD^*?

Full-charm tetraquark candidate

Ref. L4

Di-J/ψ mass spectrum

- $J/\psi \to \mu^+\mu^-$
- All data, 34K signal pairs



Spectrum modelling:

- Smooth function for non-resonant production
- Breit-Wigner (BW) for peaking structures
  - ✓Broad structure (2 BWs): $> 5\sigma$
  - ✓Structure at 6.9 GeV/c^2 (1 BW): $> 5\sigma$
  - ✓7.2 GeV/c^2 structure: $< 1\sigma$

$$m[X(6900)] = 6905 \pm 11 \pm 7 \text{ MeV}$$

$$\Gamma[X(6900)] = 80 \pm 19 \pm 33 \text{ MeV}$$

$$\frac{\sigma[pp\to(X\to J/\psi J/\psi)]}{\sigma(pp\to J/\psi J/\psi)} = (1.1 \pm 0.5)\%$$

Other scenario possible: $J/\psi\chi_c$ feeddown…

$$\sigma(pp \to J/\psi J/\psi) = 15.2 \pm 1.3 \text{ nb}$$

Difficulty to model the dip at 6.8 GeV !

JHEP 06 (2017) 047

Full-charm tetraquark candidate

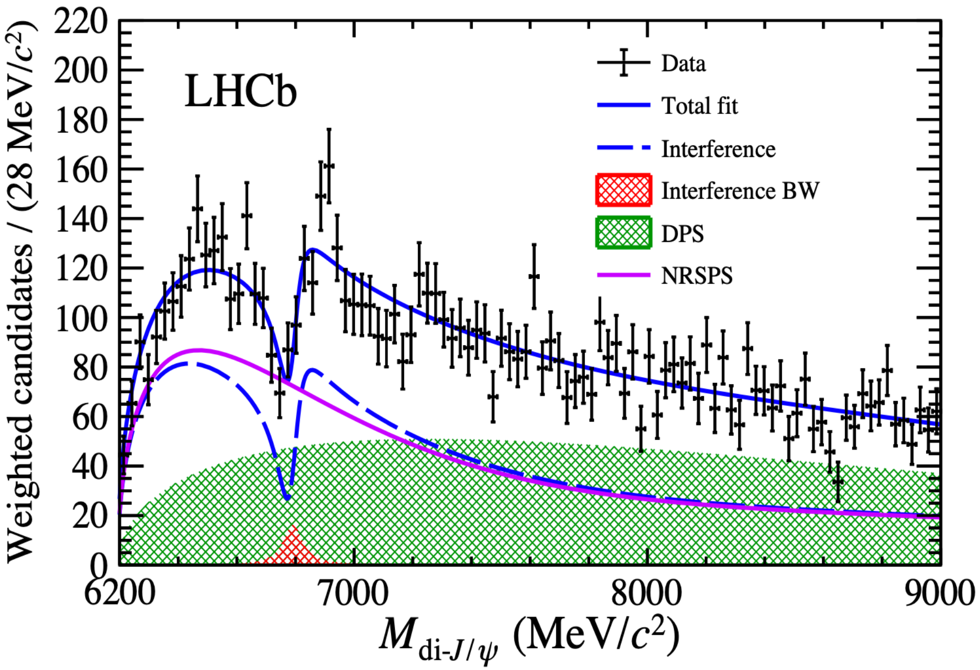
Ref. L4

Interference to describe dip at 6.8 GeV

Two separate choices of possible compositions

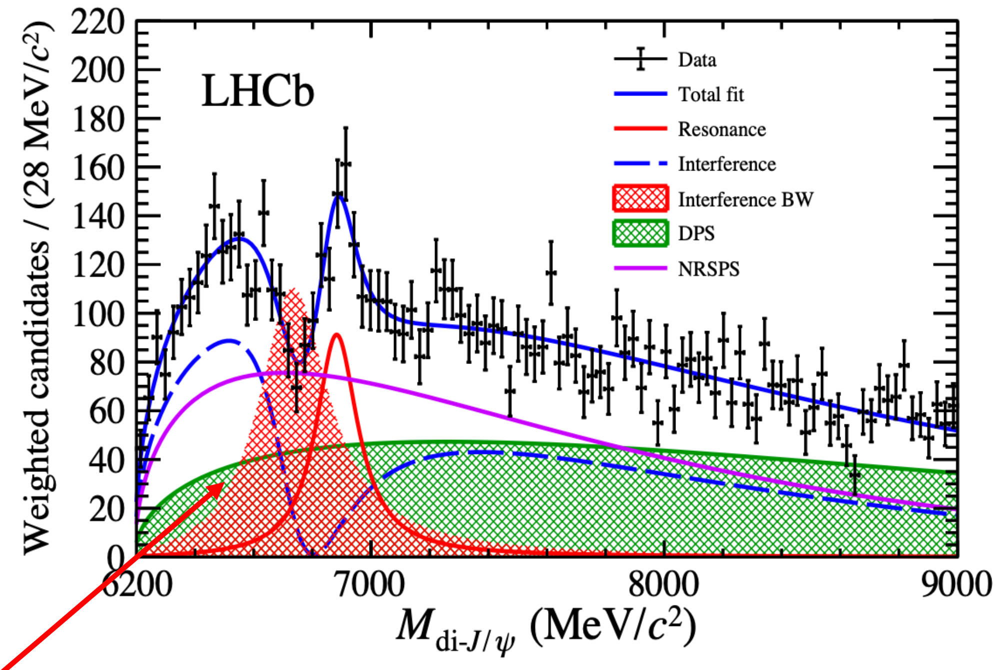
I

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



II

(Non-resonant + BW1) + BW2,
$P_{\chi^2} = 15.5\%$



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

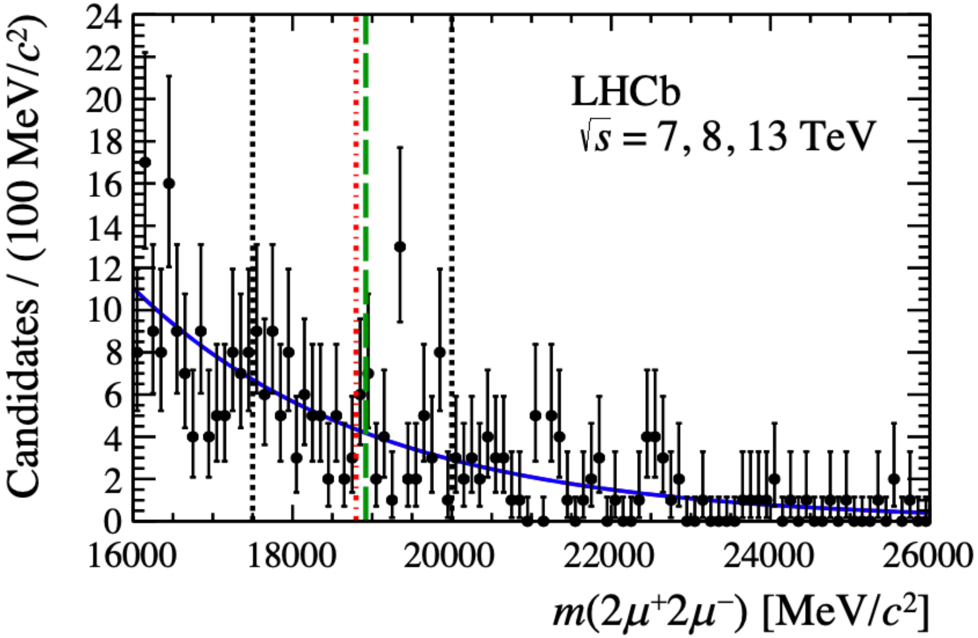
$m[X(6900)] = 6886 \pm 11 \pm 11\ \text{MeV}$
$\Gamma[X(6900)] = 168 \pm 33 \pm 69\ \text{MeV}$

Other quarkonium pairs

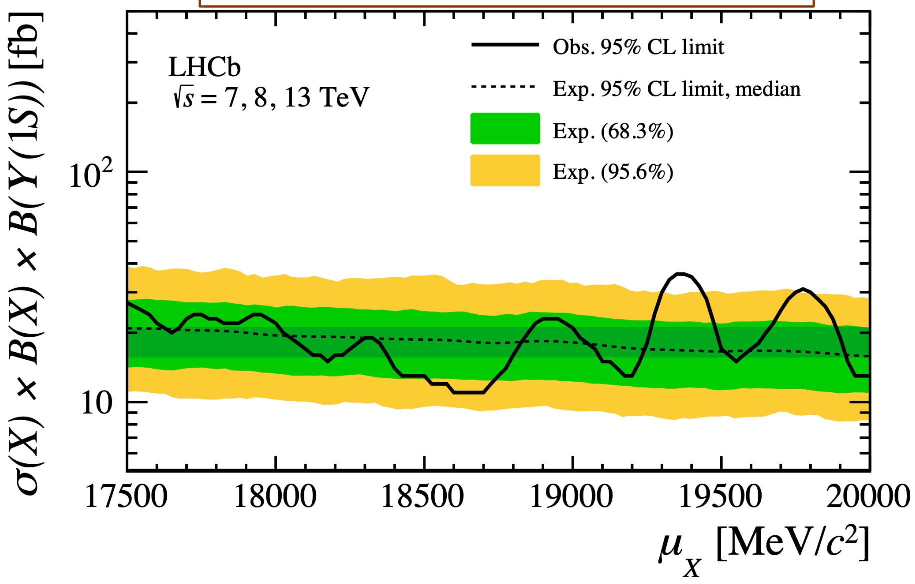
Ref. L11

$T_{bb\bar{b}\bar{b}}$ searched in $\Upsilon\mu^+\mu^-$, including di-Υ candidates, 6.3 fb^{-1} data

- No obvious di-Υ signals at LHCb
- $\sigma <\sim 20$ fb at 95%



Upper limit on production



$\psi(2S)J/\psi, J/\psi\Upsilon$ being studied, signals ~1% of di-J/ψ

- Smaller production and $\mu^+\mu^-$ decay rate
- A few signal counts?

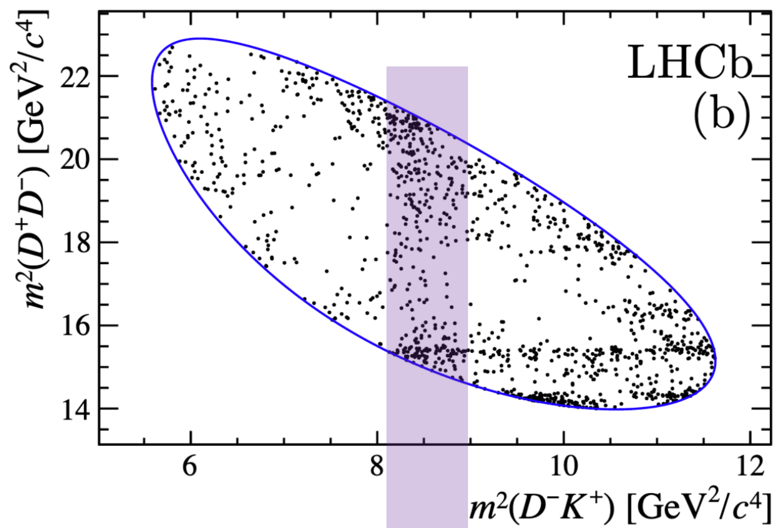
Structures in $B^+ \to D^+ D^- K^+$

Ref. L1

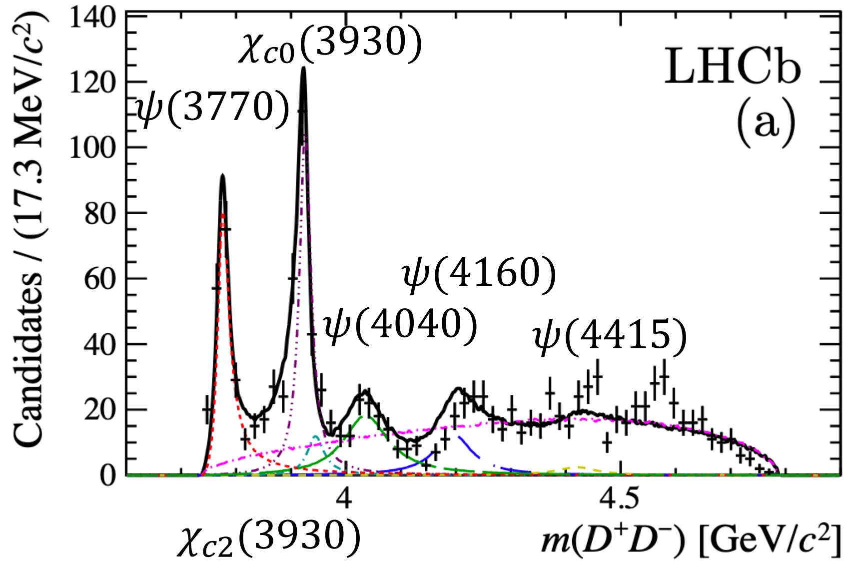
$D^- K^+ (\bar{c}\bar{s}ud)$ structure observed in $B^+ \to D^+ D^- K^+$ decays

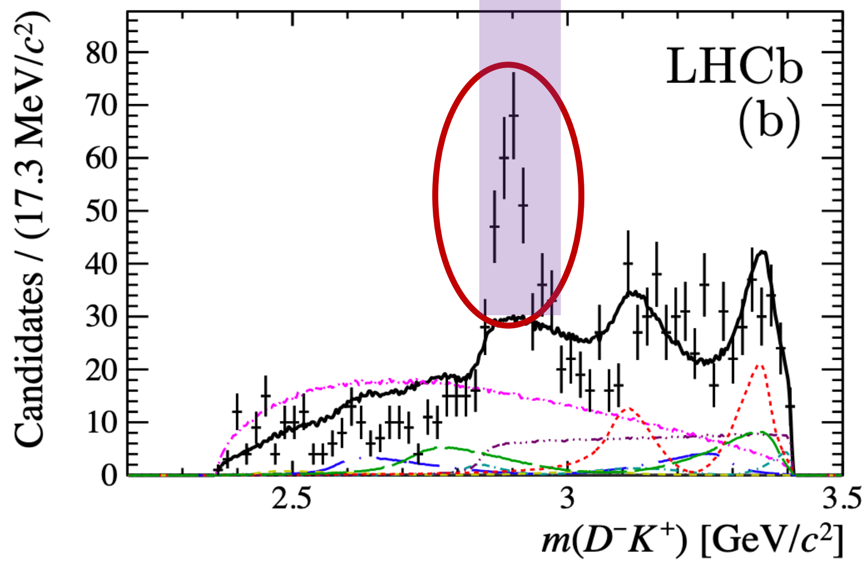
Only charmonia expected for conventional hadrons: $0^{++}, 1^{--}, 2^{++}$

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



Structure not due to charmonia reflections



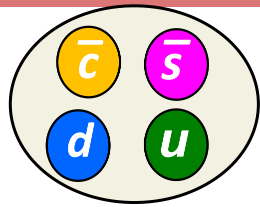


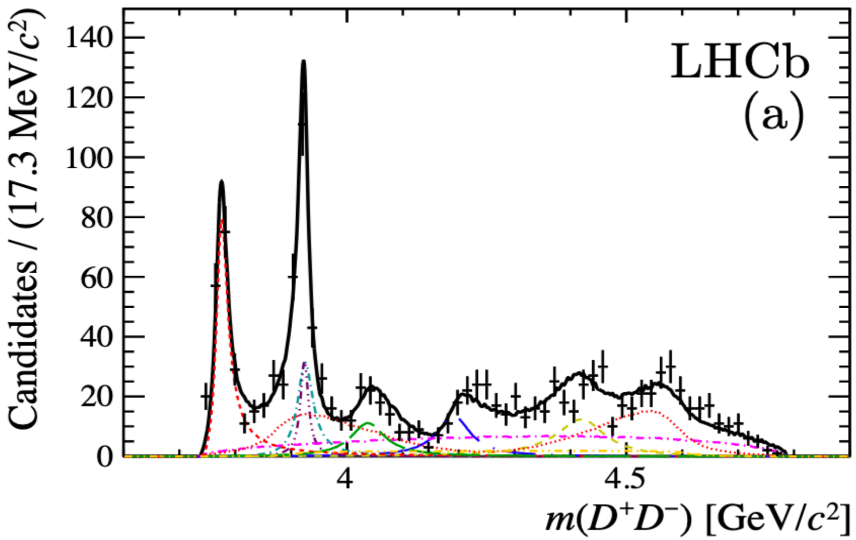
Open charm tetraquark candidates

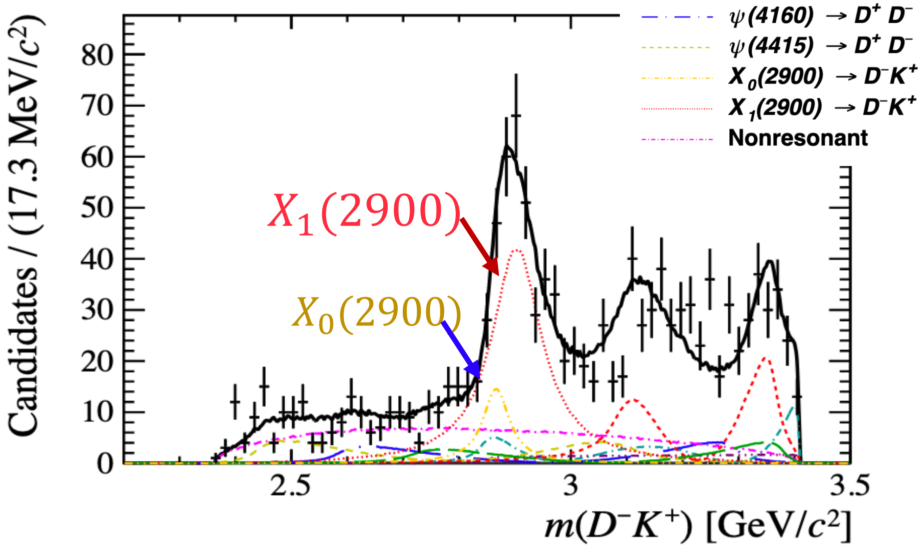
Ref. L1

Good fit with two $X \to D^- K^+$ structures: $0^+, 1^-$

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







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!

In total 22 $B \to \bar{D}^{(*)} D^{(*)} K^{0/+}$ modes and $B_s \to \bar{D}^{(*)} D^{(*)} KK$, $B \to D_s^+ \bar{D} \pi^{+/-} \ldots$

Some related by isospin. Allow to study similar states, with 100-10K signals

PLB 704 (2011) 559

Summary

- Extensive studies of $X(3872)$, **settled**?
- Charged $Z_c(c\bar{c}u\bar{d})$ in b decays, **how many; strange partners; production**
- Many $X(c\bar{c}s\bar{s}) \to J/\psi\phi$ states, **possible excited $c\bar{c}$ states?**
- Fully heavy states $X_{QQ\bar{Q}\bar{Q}}$, **full spectrum?**
- Open charm tetraquark $csu\bar{d}$: **many more to be studied**

Tetraquarks | Molecule | Cusps | ….

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日益深入的理论研究与
有限的实验能力的矛盾

Thank you for your attention

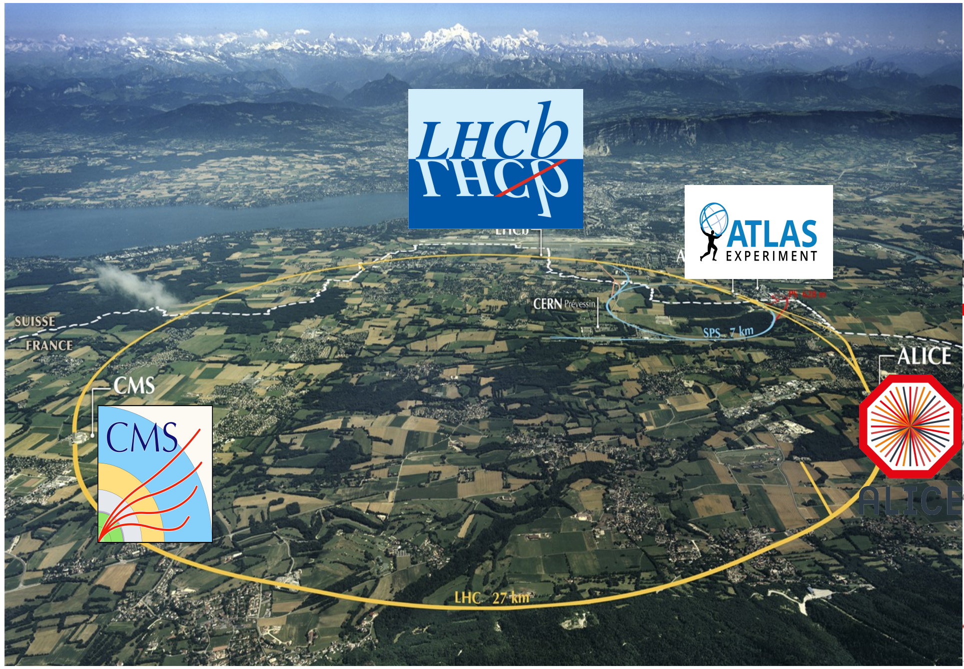
Backups

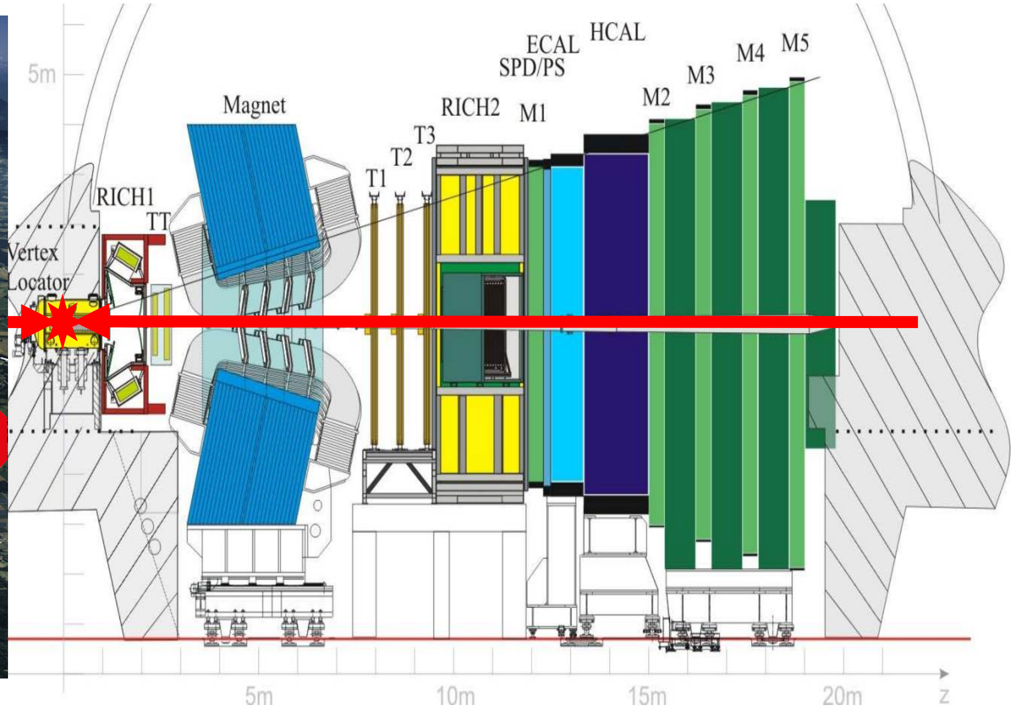
LHCb experiment

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



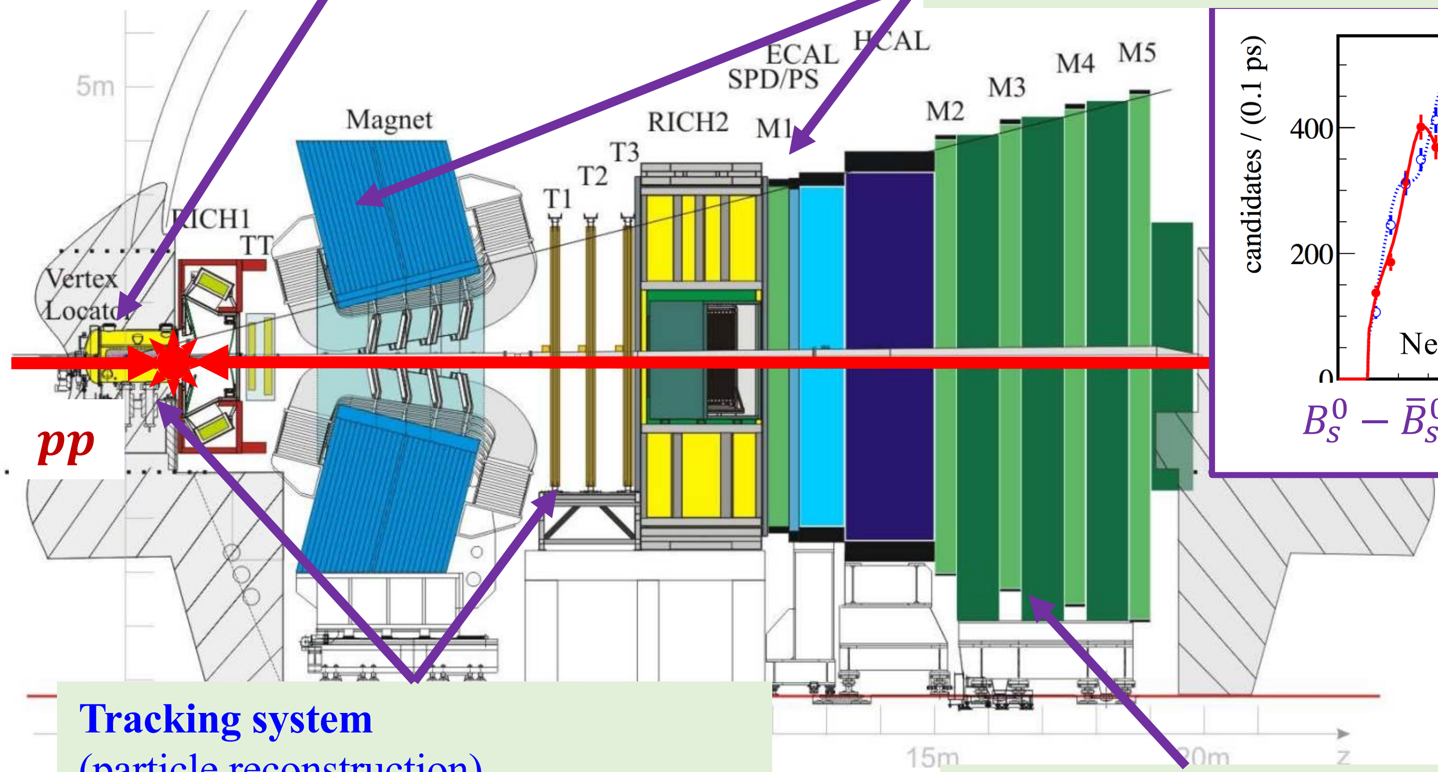


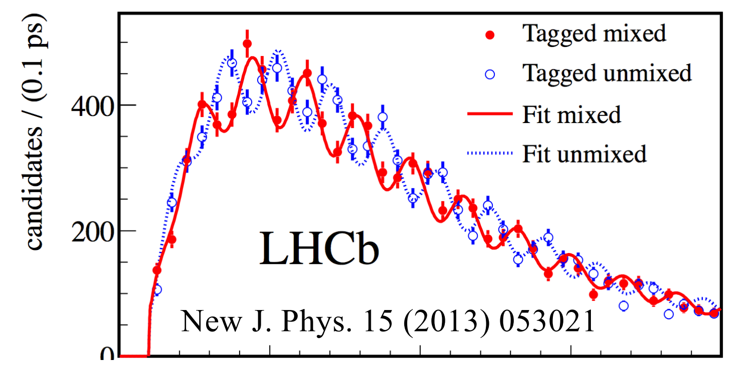
LHCb detector

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

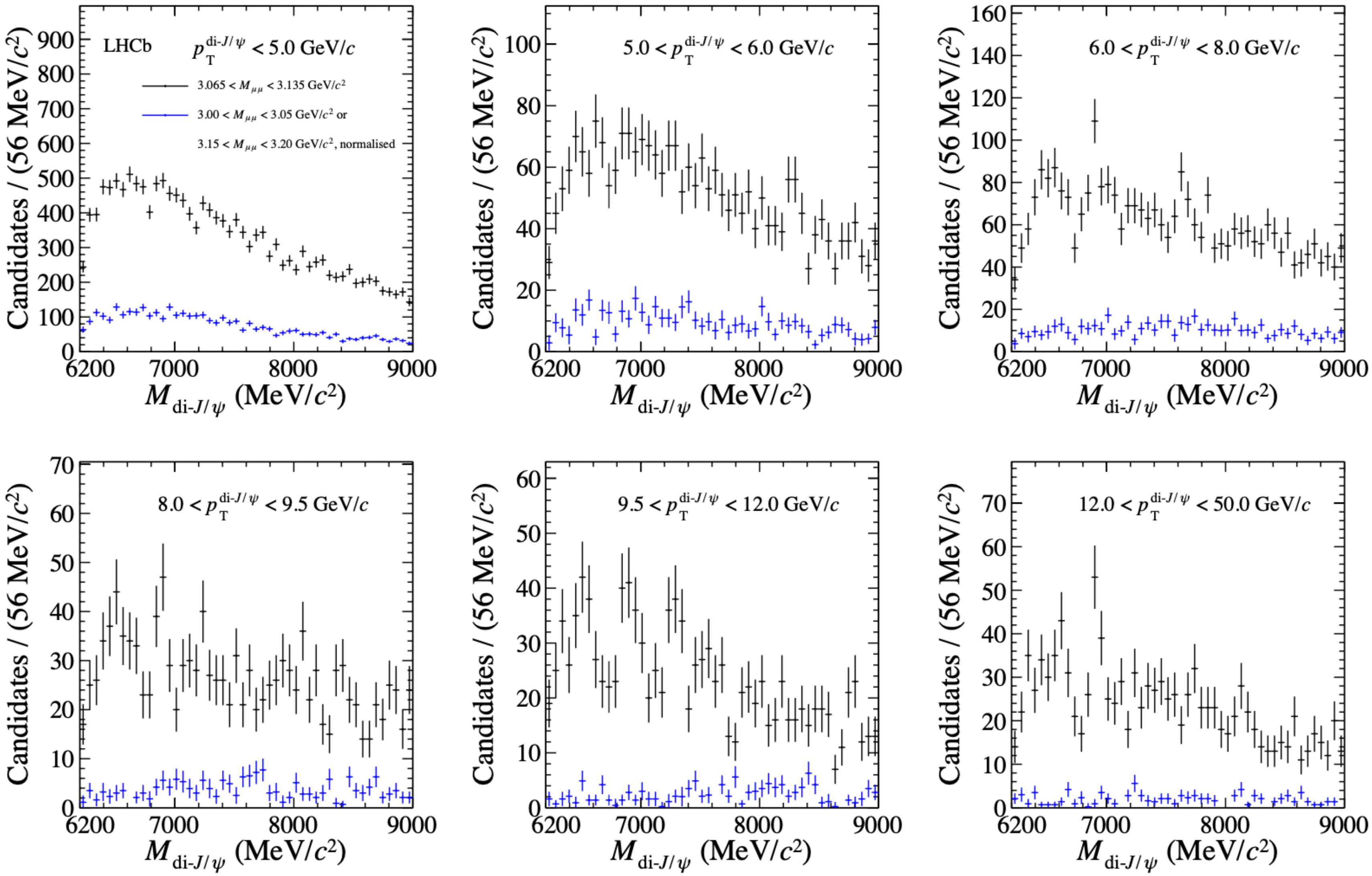
Tracking system
(particle reconstruction)
- ϵ(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV

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

Di-J/ψ invariant mass

- Same structures presented in high p_T bins

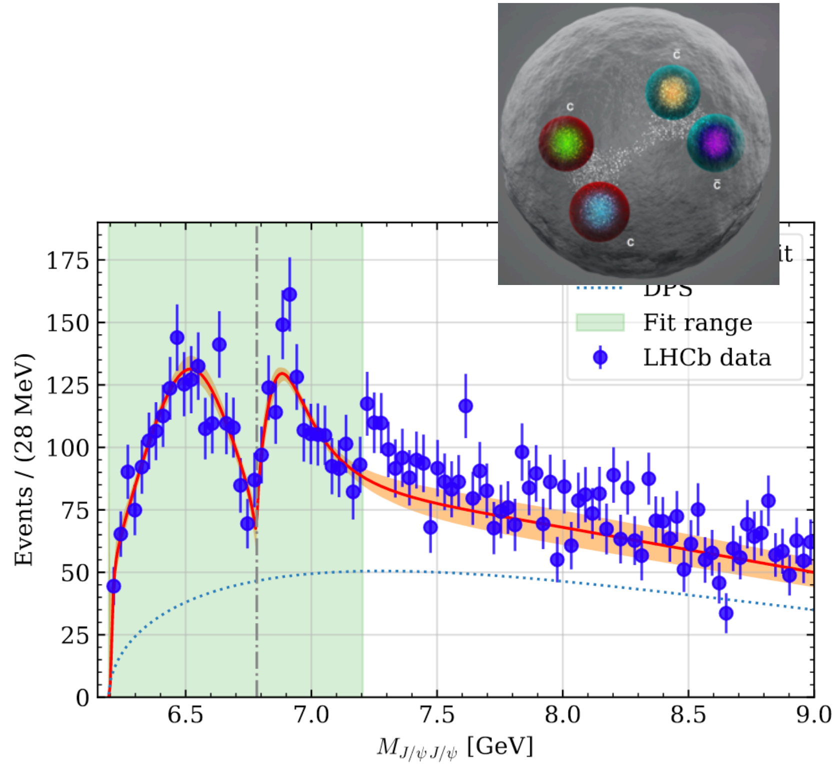
arXiv:2006.16957



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 ($\psi\psi, \psi'\psi$…)

$B^+ \to D^+ D^- K^+$ distribution