

LHCb results and perspectives

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On behalf of the LHCb collaboration

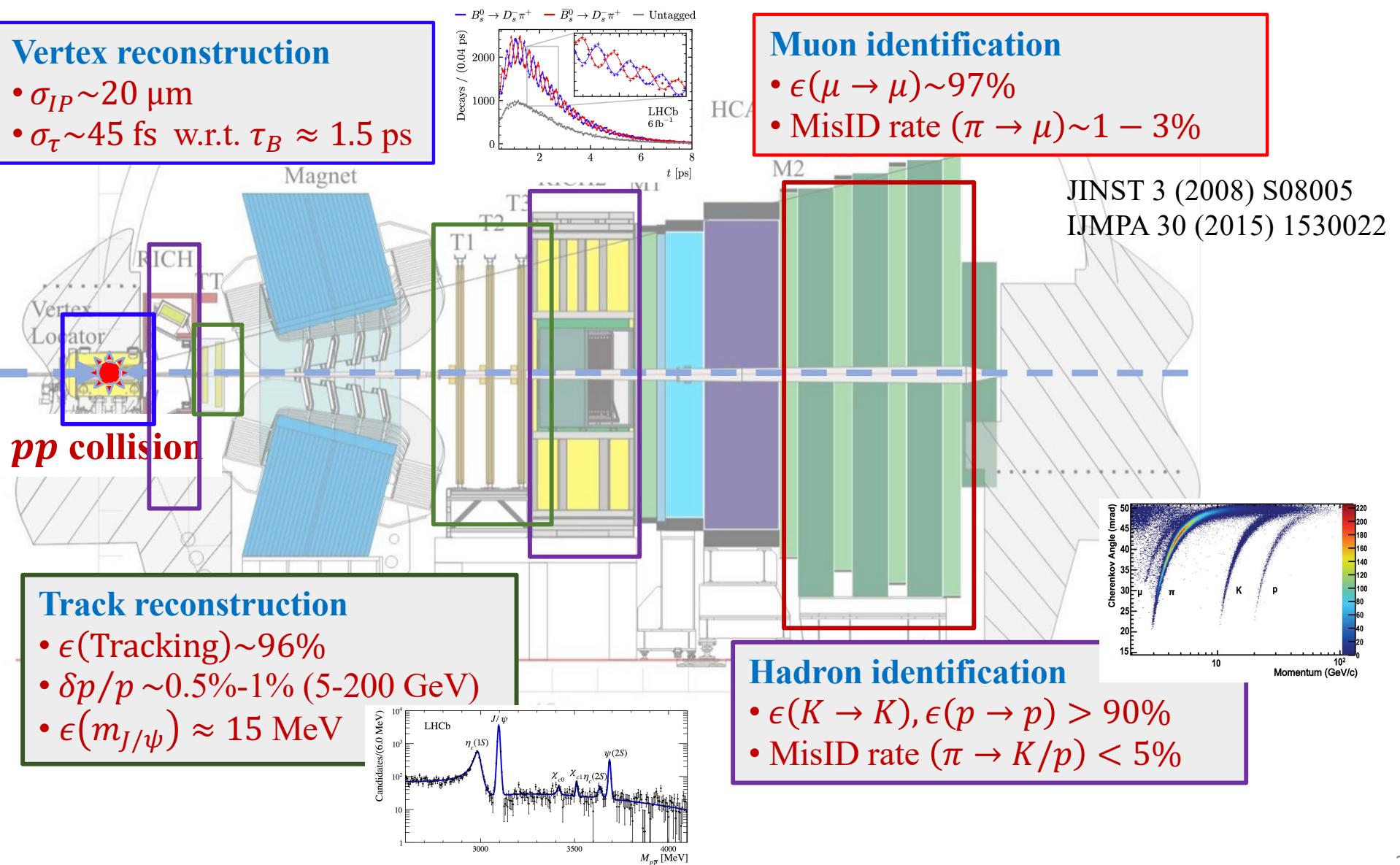


22/Nov/2021

Workshop on “Double charm tetraquark and other exotics”, Lyon, France

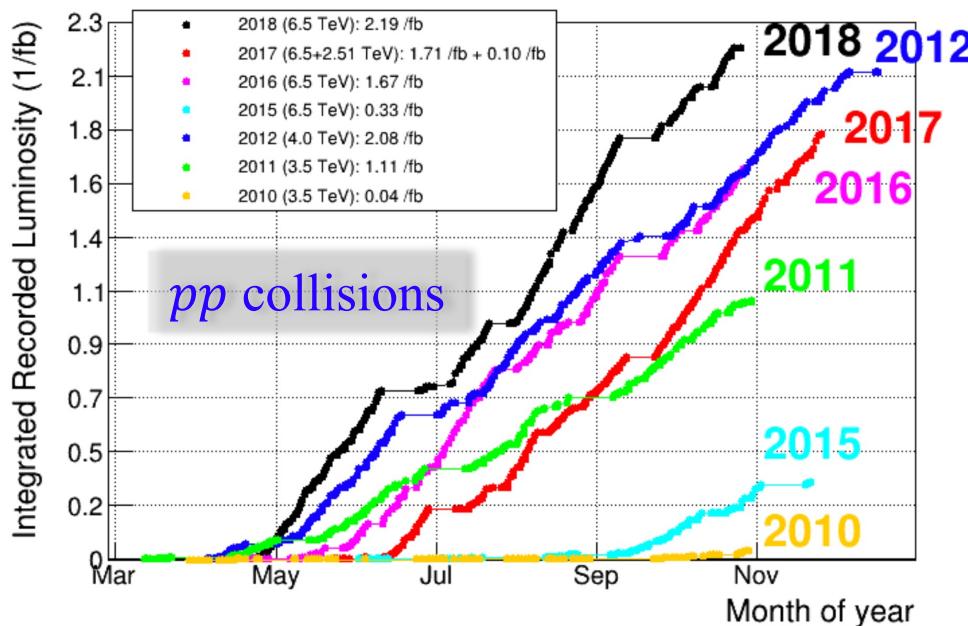
The LHCb experiment

- Dedicated for heavy flavor, reaching $p_T \sim 0$



LHCb data till now

- Run I: $\int \mathcal{L} = 3 \text{ fb}^{-1}$ at 7 or 8 TeV
- Run II: $\int \mathcal{L} = 6 \text{ fb}^{-1}$ at 13 TeV



All possible states are produced

$$\sigma(pp \rightarrow c\bar{c}X, \text{LHCb, 13 TeV}) \approx 2.3 \text{ mb}$$

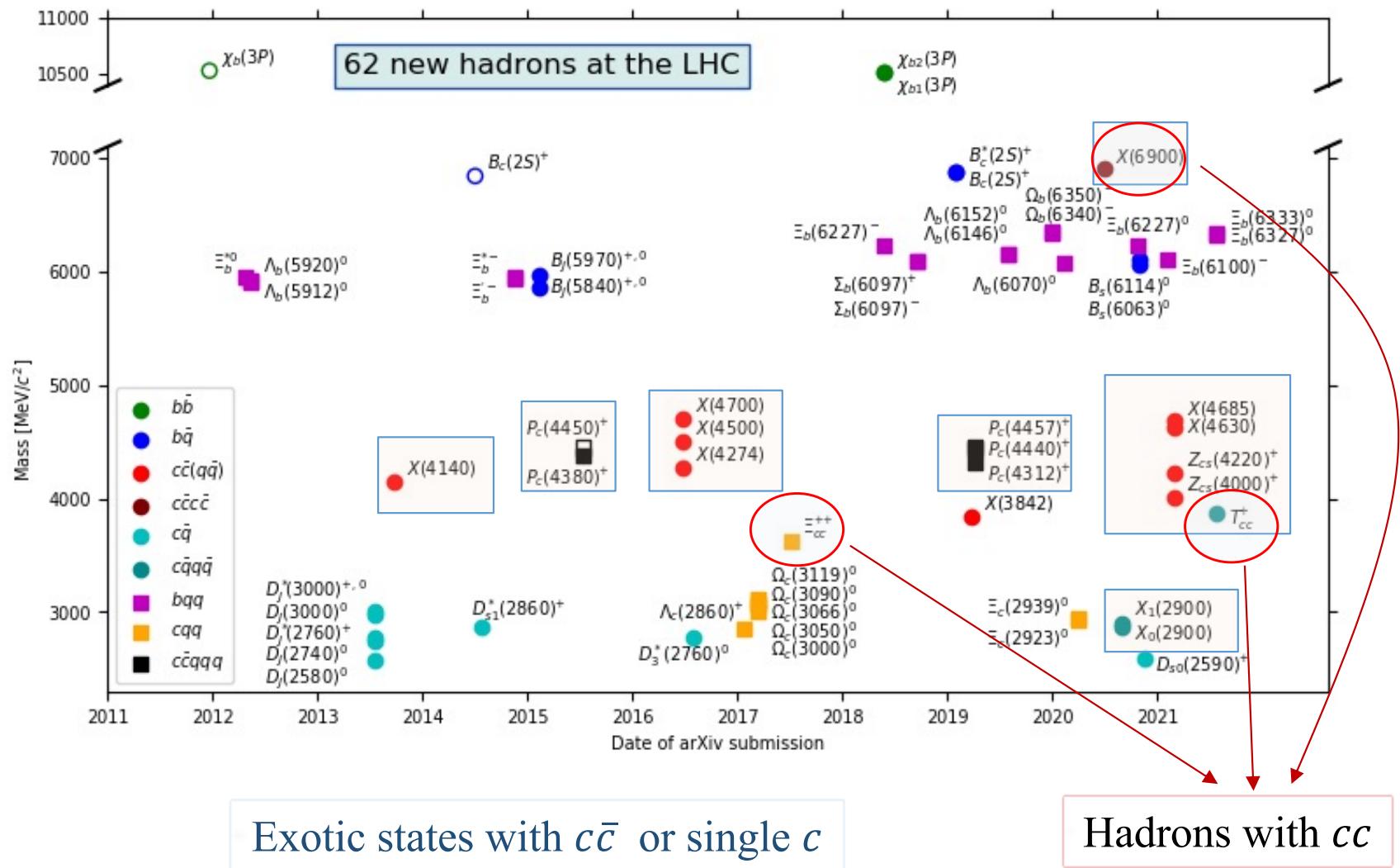
$$D^0 : D^+ : D_s^+ : \Lambda_c^+ : \Xi_{cc} \dots$$

$$\sigma(pp \rightarrow b\bar{b}X, \text{LHCb, 13 TeV}) \approx 0.14 \text{ mb}$$

$$B^+ : B^0 : B_s^0 : \Lambda_b^0 \dots$$

JHEP 05 (2017) 074
PRL 118 (2017) 052002

New hadron states at LHC(b)

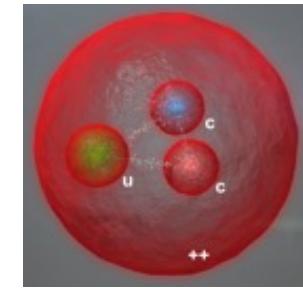
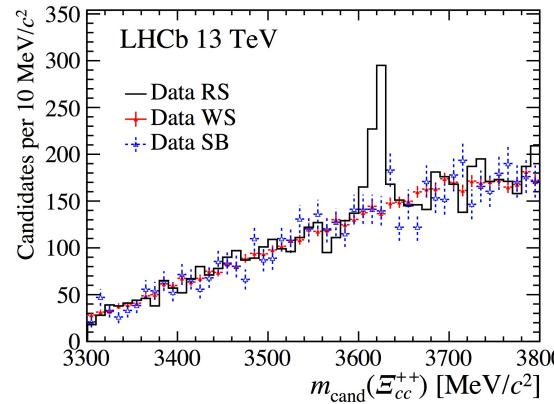
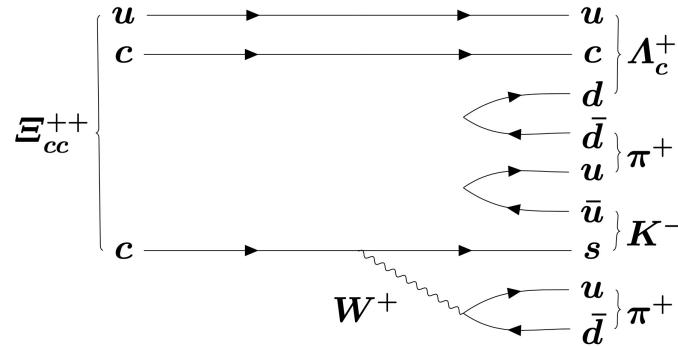


$\Xi_{cc}^{++}(ccu)$

- Observed in the “discovery” channel $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

CPC42 (2018) 051001

PRL119 (2017) 112001



- Production CPC44 (2020) 022001

$$\frac{\sigma(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = (2.22 \pm 0.40) \times 10^{-4} \text{ for } p_T > 4 \text{ GeV}$$

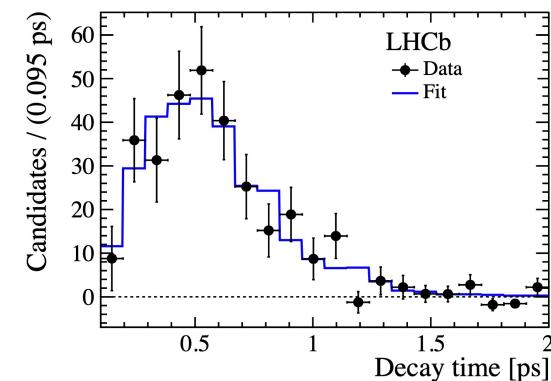
- Lifetime PRL121 (2018) 052002

$$\tau_{\Xi_{cc}^{++}} = 0.256^{+0.024}_{-0.022} \pm 0.014 \text{ ps}$$

$$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} \sim \tau_{\Xi_{cc}^{++}} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$$

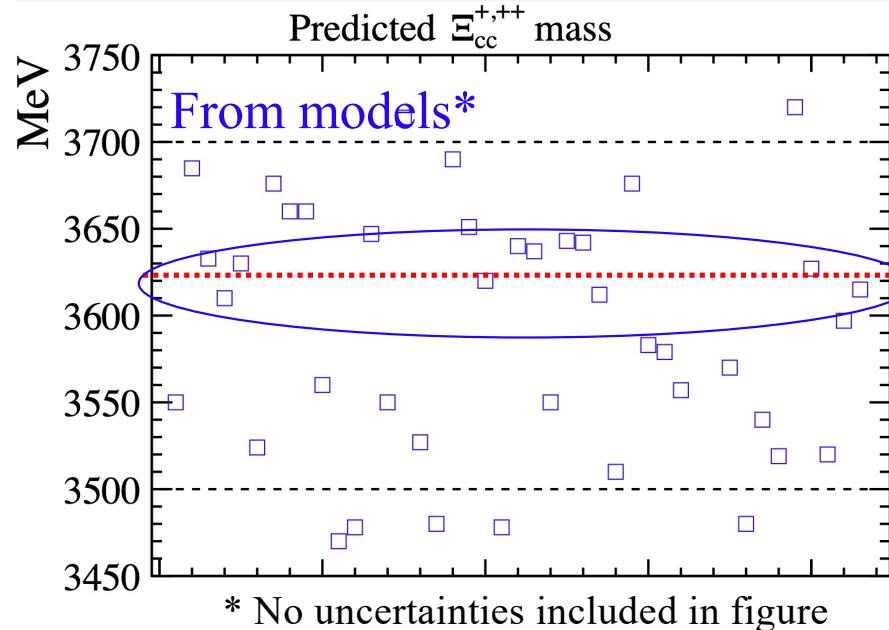
- Mass JHEP 02 (2020) 049

$$m_{\Xi_{cc}^{++}} = 3621.55 \pm 0.23 \pm 0.30 \text{ MeV}/c^2$$

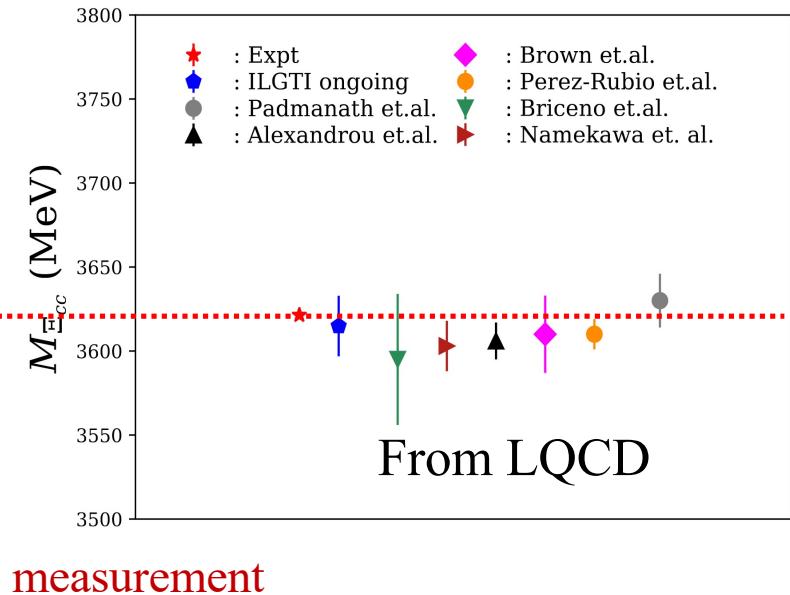


Understanding the mass

- Before LHCb discovery



M. Padmanath (LHCb implication 2017)



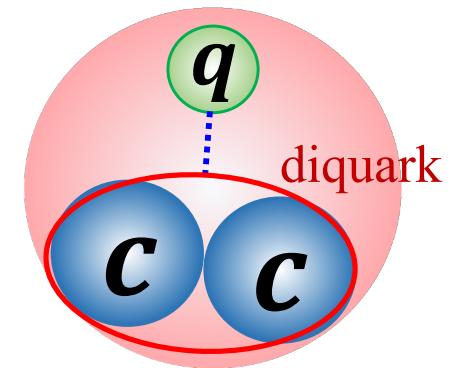
LHCb measurement

- A deep binding between $cc \rightarrow$ the diquark picture

$$V_{cc} \approx \frac{1}{2} V_{c\bar{c}} \approx -130 \text{ MeV}$$

- A compact structure serving as color source, ccq spectrum similar to $\bar{Q}q$, not difficult to calculate
- Potential model for cc in analogy to quarkonia

Question: can we observe cc ρ -mode excitation?



Pro.Theor.Phys. 82 (1989) 760

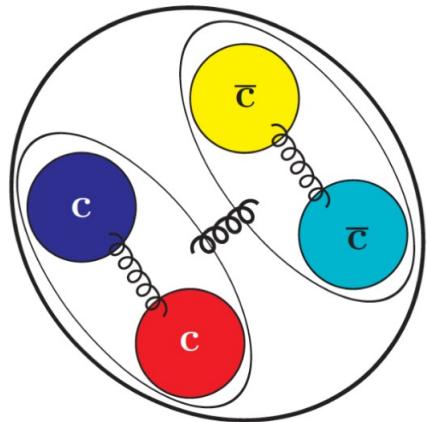
PRD 66 (2002) 014008

PRD 90 (2014) 094007

...

Fully heavy $QQ\bar{Q}\bar{Q}$ states

$QQ\bar{Q}\bar{Q}$ states exist using a qualitative argument from QQ diquark



Studies back to 1970s, focusing on low-lying state

PRL 36 (1976) 1266
Z.Phys.C7 (1981) 317
PRD 25 (1982) 2370

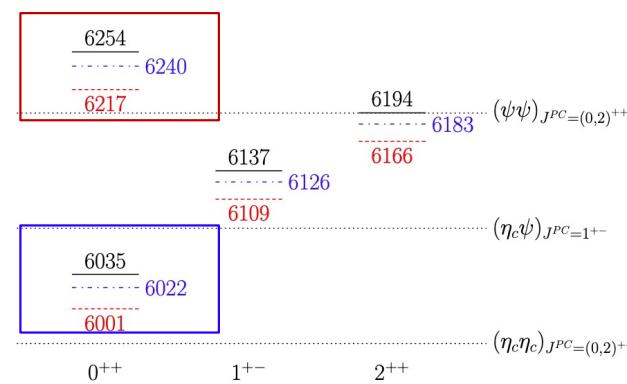
Many advance calculations, mostly use QQ diquark,
but don't agree on:

- Are they bound?
- How many states?
- What are there masses

PRL 36 (1976) 1266
Z.Phys.C7 (1981) 317
PRD86 (2012) 034004
PRD97 (2017) 094015
PRD95 (2015) 034001
PRD95 (2017) 054019
PLB773 (2017) 01647

...

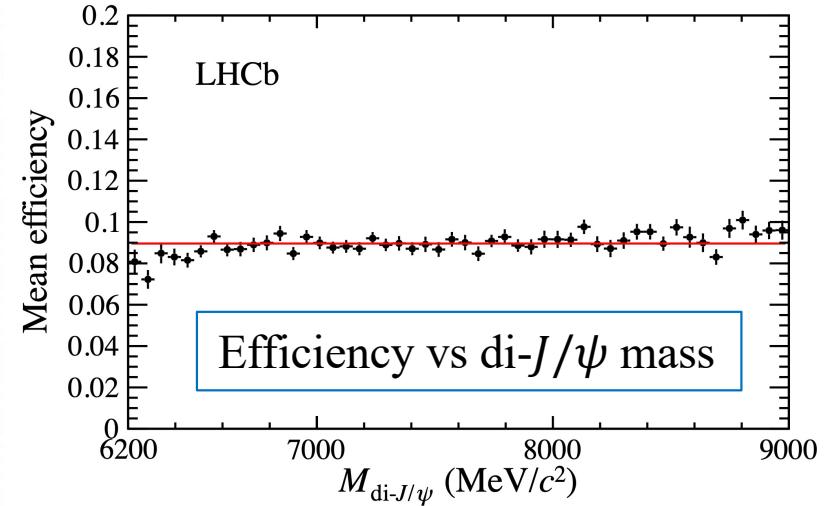
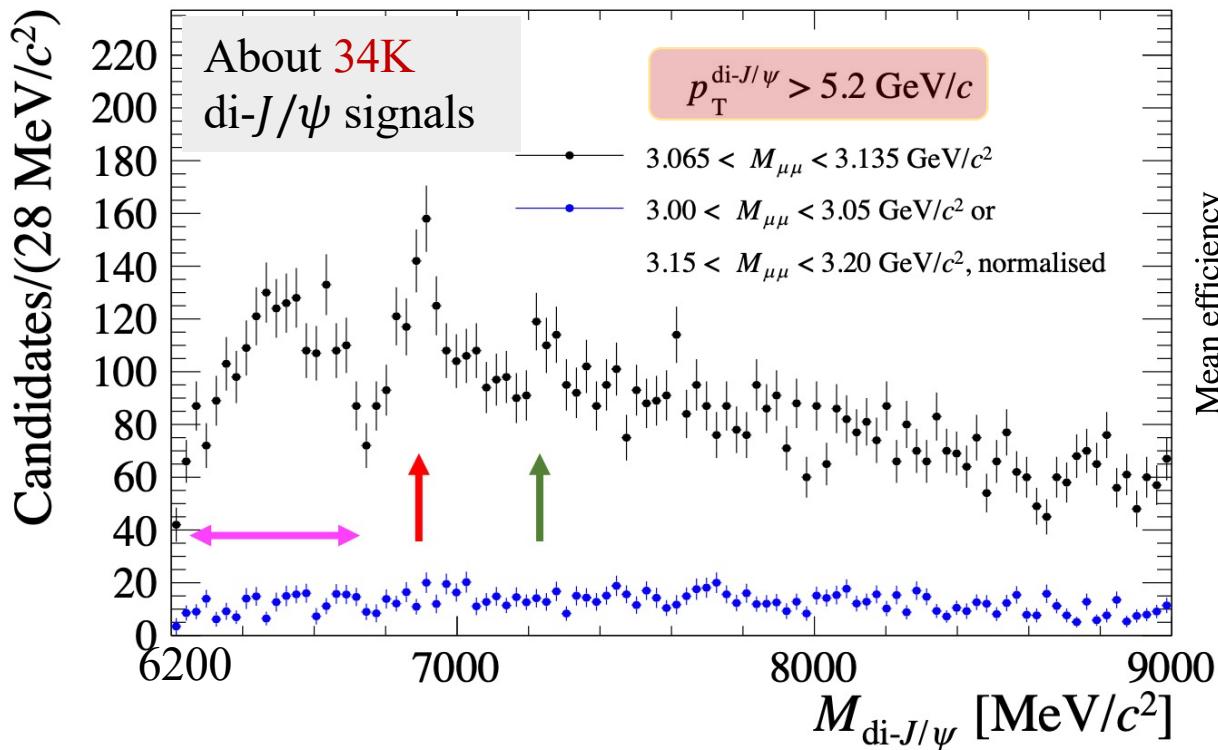
J^{PC}	Currents	$m_{ccc\bar{c}}$ (GeV)
0^{++}	$J_1^{0^{++}}$	6.44 ± 0.15
	$J_2^{0^{++}}$	6.46 ± 0.16
1^{+-}	$J_{3\alpha}^{1^{+-}}$	6.51 ± 0.15
2^{++}	$J_{4\alpha\beta}^{2^{++}}$	6.51 ± 0.15



(b) $cc\bar{c}\bar{c}$

Di- J/ψ invariant mass at LHCb

Science Bulletin 65 (2020) 1983



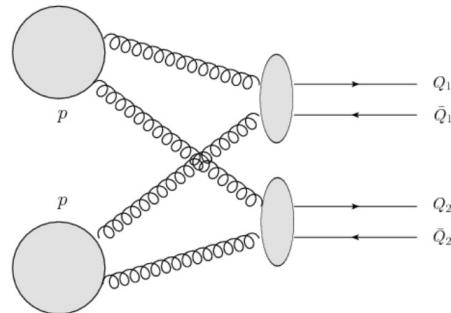
- Broad structure at $6.2 - 6.8 \text{ GeV}$ close to di- J/ψ mass threshold
- Narrow peak at 6.9 GeV
- Hint of another structure at 7.2 GeV
- Structure not present in J/ψ background sample
- Not caused by detection effect: only marginal variation of efficiency

Di- J/ψ production

Two components: SPS and DPS

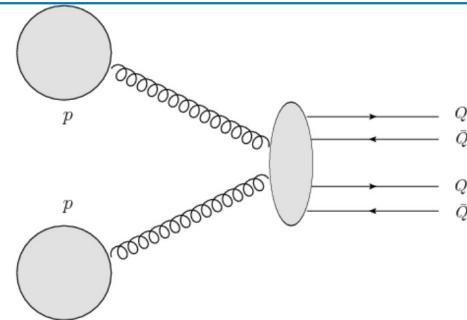
PLB751 (2015)479
PRD94 (2016) 05407

Double Parton Scattering (DPS)



Smooth di- J/ψ continuum

Single Parton Scattering (SPS)



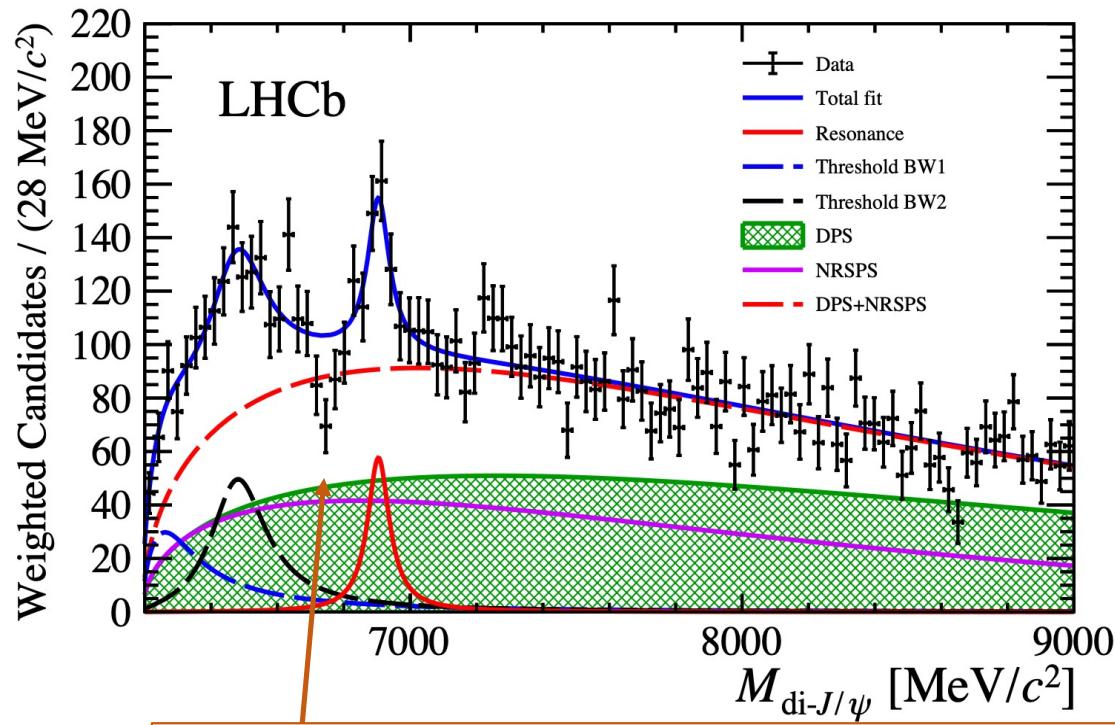
Both smooth continuum and resonant $cc\bar{c}\bar{c}$ structures.
Averagely larger di- J/ψ p_T than in DPS

Di- J/ψ mass spectrum for continuum:

- DPS: constructed from single J/ψ kinematics
- SPS: empirical function $\Phi_2(m) \times e^{c \cdot m}$

Di- J/ψ mass modeling (I)

- SPS and DPS continua
- Breit-Wigner (BW) functions for peaking structures
 - Threshold structure (6.2 – 6.8 GeV): two BWs, **significance > 6 σ**
 - Structure at 6.9 GeV: single BW, **significance > 5 σ**
 - Hint at 7.2 GeV: **significance < 1 σ**



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

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

Science Bulletin 65 (2020) 1983

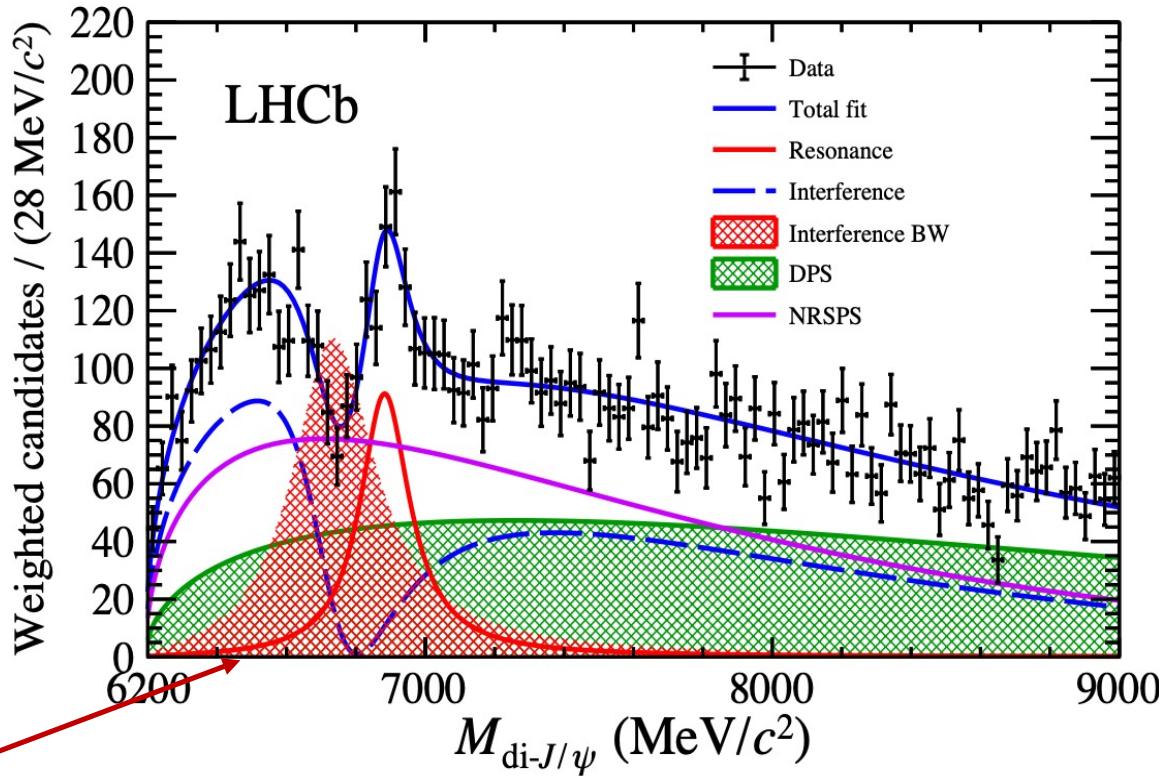
Di- J/ψ mass modeling (II)

- A wide BW interfering with SPS, a second BW for 6.9 GeV peak
 - Fit quality improve from $P(\chi^2) = 4.6\%$ to 15.5%
 - Caveat: too simple, SPS assumed to have J^P of the wide BW

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

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

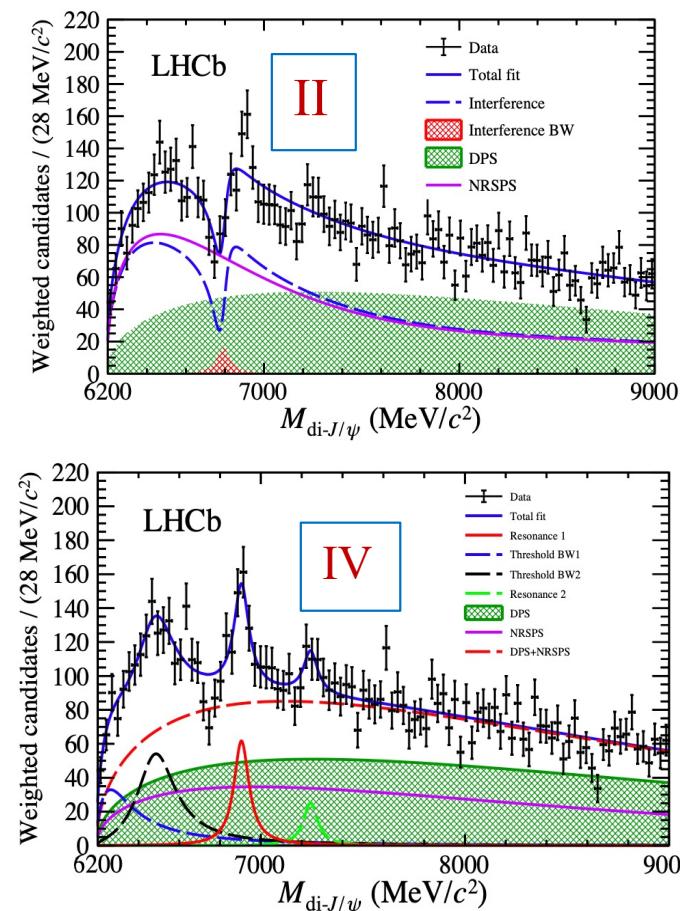
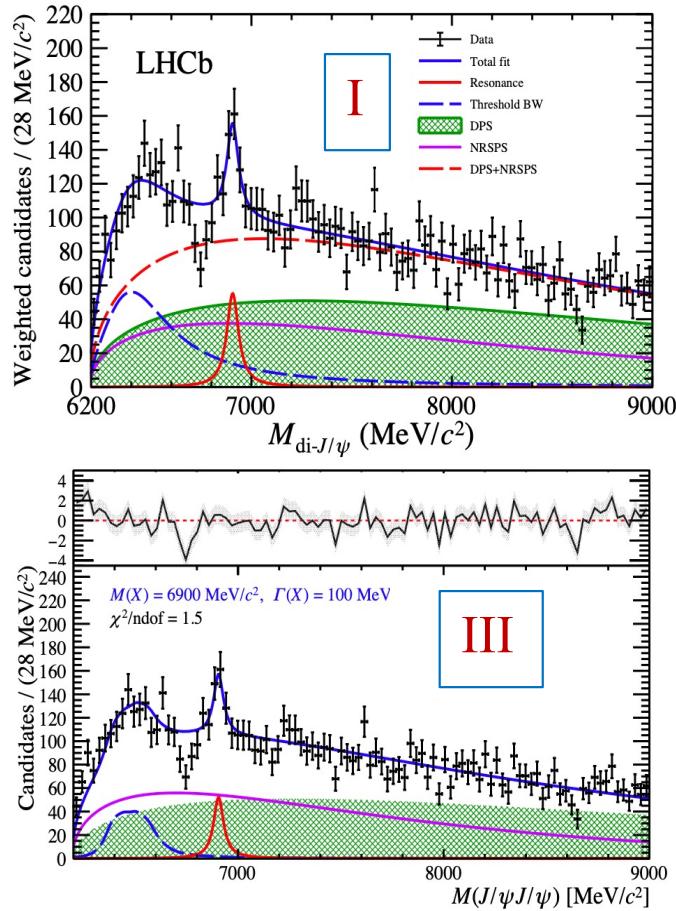
Science Bulletin 65 (2020) 1983



Other models

- I. One BW for threshold structure + X(6900), w/o interference, $P(\chi^2) = 1.2\%$
- II. Only one BW, interfering with SPS, $P(\chi^2) = 2.8\%$
- III. Threshold structure due to feed-down decays of excited charmonia (e.g. $\chi_c J/\psi$)
- IV. Including a component for 7.2 GeV peak

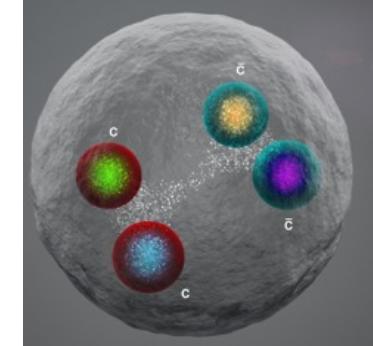
Science Bulletin 65 (2020) 1983



Fits summary and structure

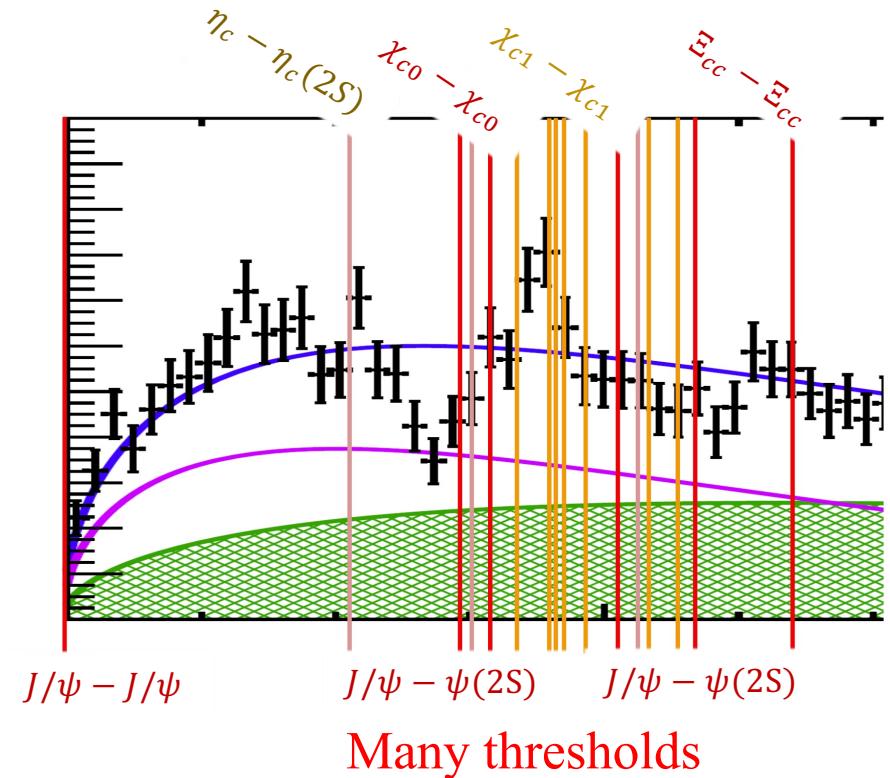
- Structure at threshold: one BW, two BWs or feed-down from excited states
 - Interference between a BW and SPS preferred
- Structure at 6.9 GeV: **consistent with a BW**
- $X(6900)$ production (no-interference hypothesis):

$$R \equiv \frac{\sigma_X \times \mathcal{B}[X \rightarrow J/\psi J/\psi]}{\sigma_{J/\psi J/\psi}} = [1.1 \pm 0.4 \pm 0.3]\%$$



- Interpretation of structures
 - $X(6900)$ may be P- or 2S-wave state
 - Broad structure at threshold in region of low lying states ($0^{++}, 1^{+-} \dots$)
 - Coupled channel rescattering?

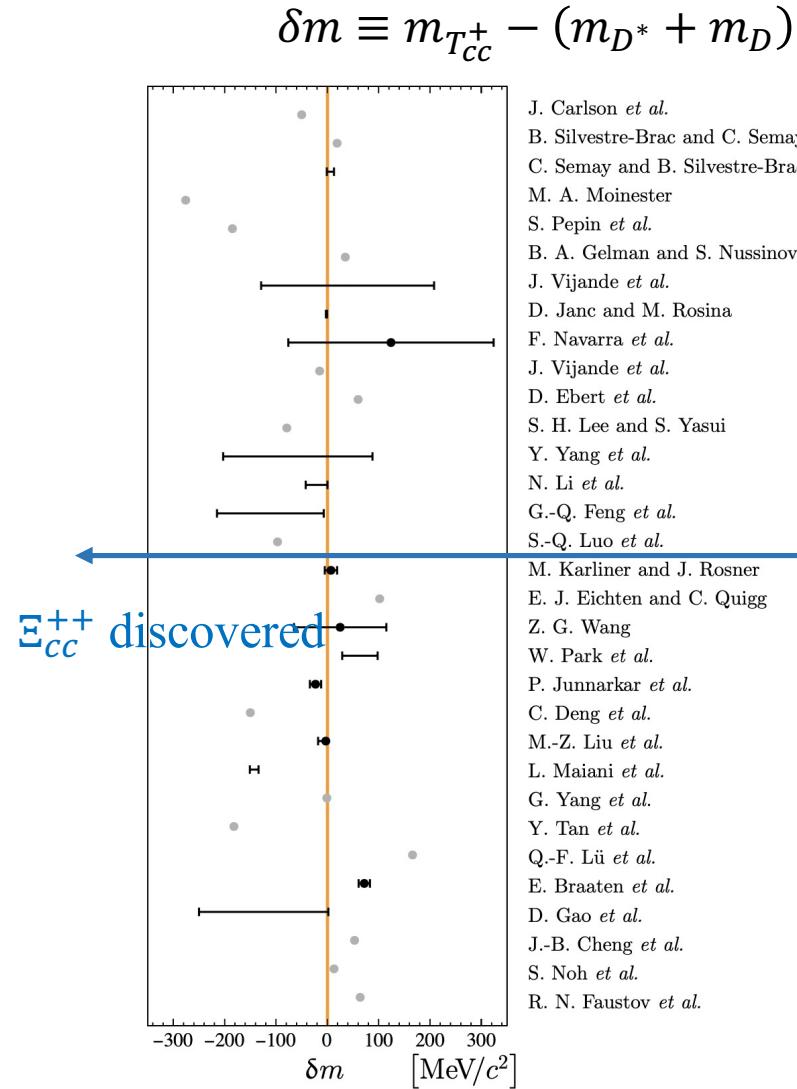
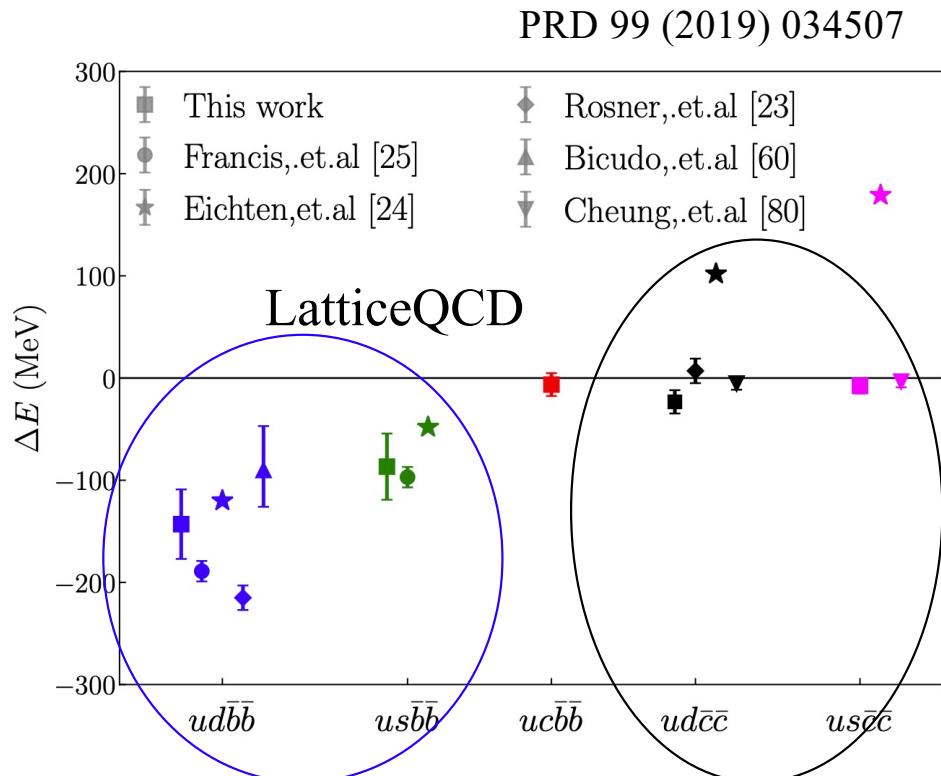
[PRL102 (2009) 114039, PRD102 (2020) 114030, PRD102 (2020) 074003, EPJC80 (2020) 871, PRD102 (2020) 114039, arXiv2006.13756, 2009.08376, PRL 126 (2021) 132001, PRD 103 (2021) 014001, PRD 104 (2021) 014018, PRD 103 (2021) 05163...]



Doubly charmed tetraquark

In heavy quark limit $m_Q \rightarrow \infty$, $QQ\bar{q}\bar{q}'$ states tightly bound and stable against strong decays

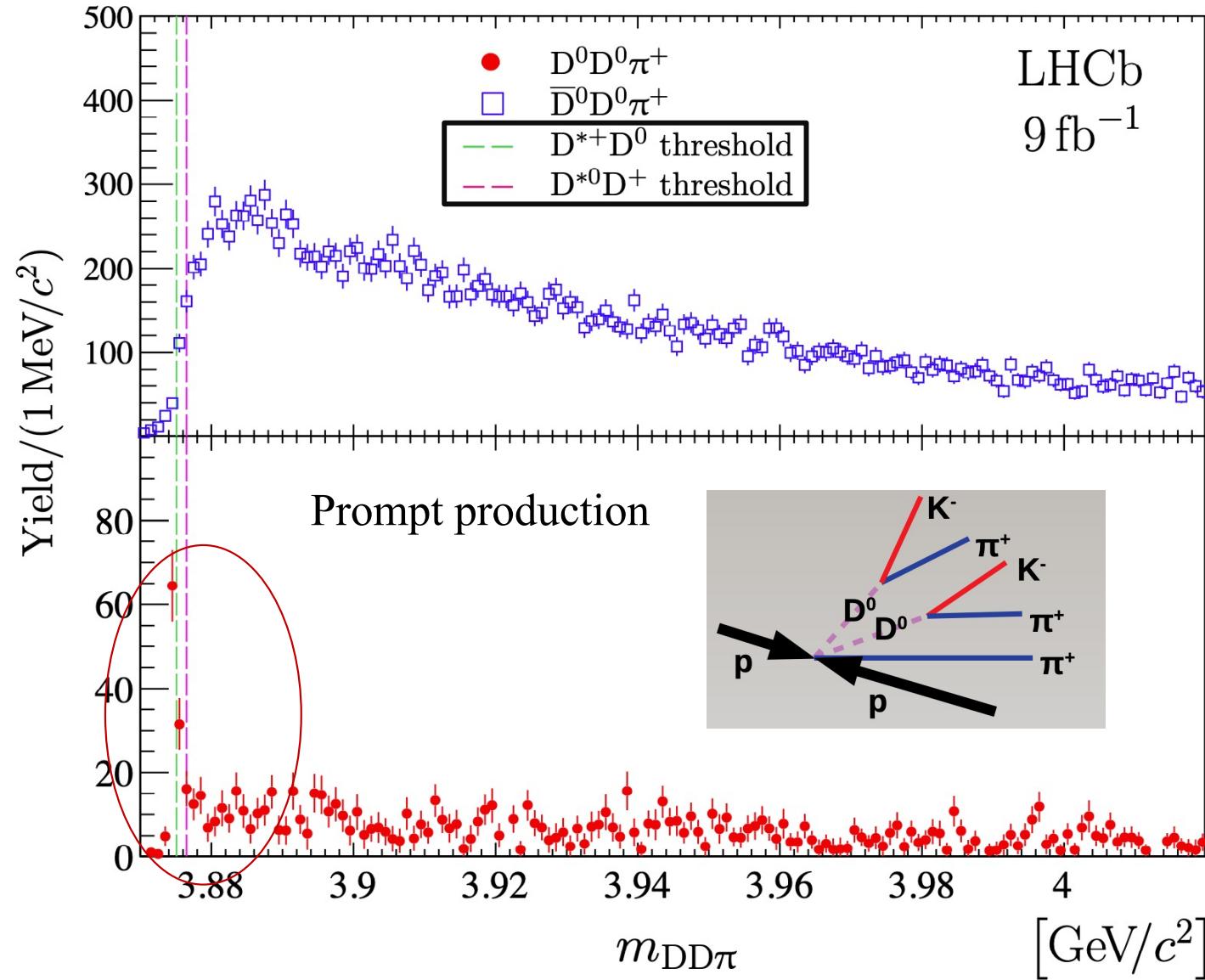
- True for $bb\bar{q}\bar{q}'$ according to models and Lattice QCD, but not conclusive for $cc\bar{q}\bar{q}'$, $bc\bar{q}\bar{q}$
- Studies boosted by discovery of Ξ_{cc}^{++}



Observation of T_{cc}^+ at LHCb



Narrow structure observed in $D^0 D^0 \pi^+$ mass spectrum, close to $D^{*+} D^0$ threshold with minimal quark contents $cc\bar{u}\bar{d}$. Structure not present in $\bar{D}^0 D^0 \pi^+$ final state

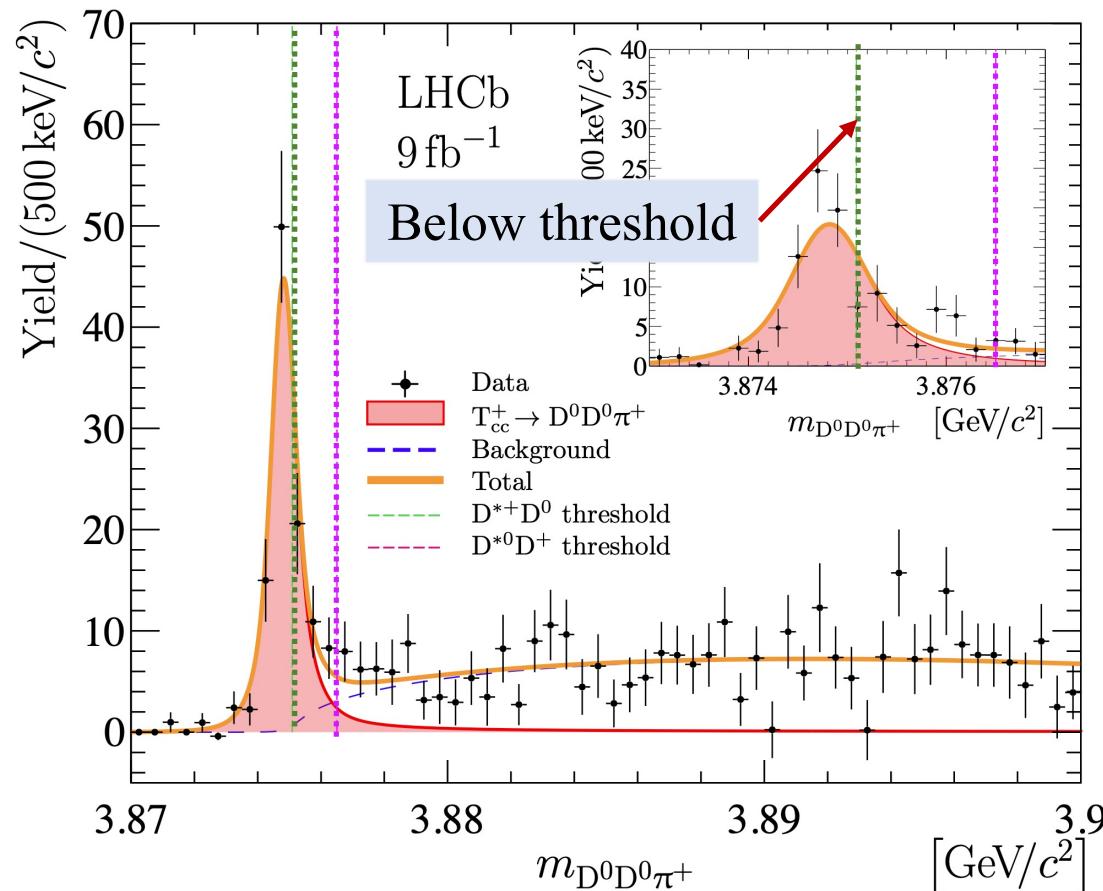


Fit with Breit-Wigner function

- Lowest $cc\bar{u}\bar{d}$ state has $s_{cc} = 1, s_{\bar{u}\bar{d}} = 0, l = 0$, so that $J^P = 1^+$
Prog.Part.Nucl.Phys.107 (2019) 237
- Data modelled with sum of a P-wave relativistic BW plus 2-body phase space

$$\delta m_{\text{BW}} = -273 \pm 61 \pm 5^{+11}_{-14} \text{ keV, negative by } 4.3\sigma$$

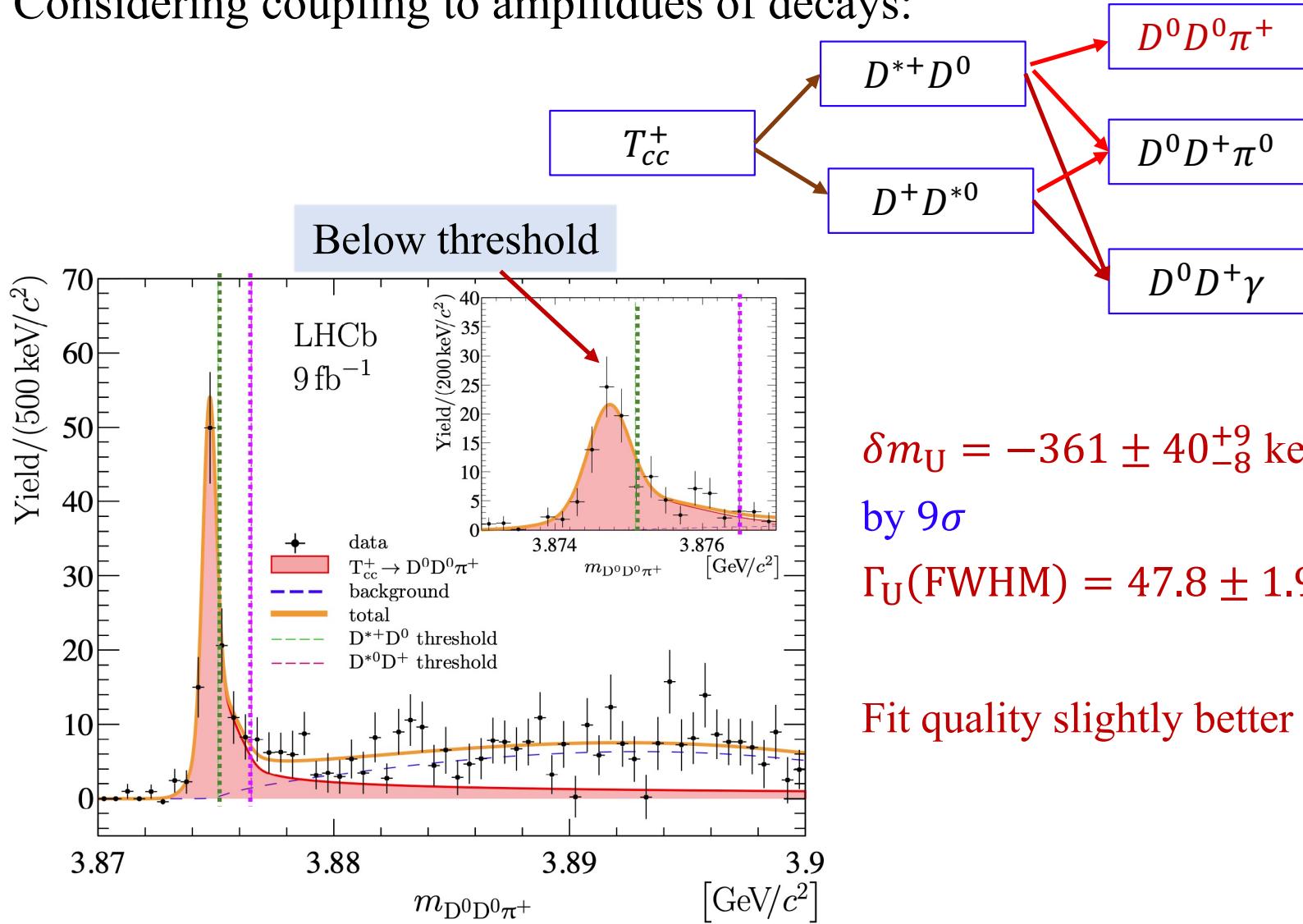
$$\Gamma_{\text{BW}} = 410 \pm 165 \pm 43^{+18}_{-38} \text{ keV, not a weak decay}$$



Advance modeling of signal line shape

- Unitarized 3-body Breit-Wigner for T_{cc}^+
- Considering coupling to amplitudes of decays:

arXiv:2019.01038
arXiv:2019.01056



$$\delta m_U = -361 \pm 40^{+9}_{-8} \text{ keV, negative}$$

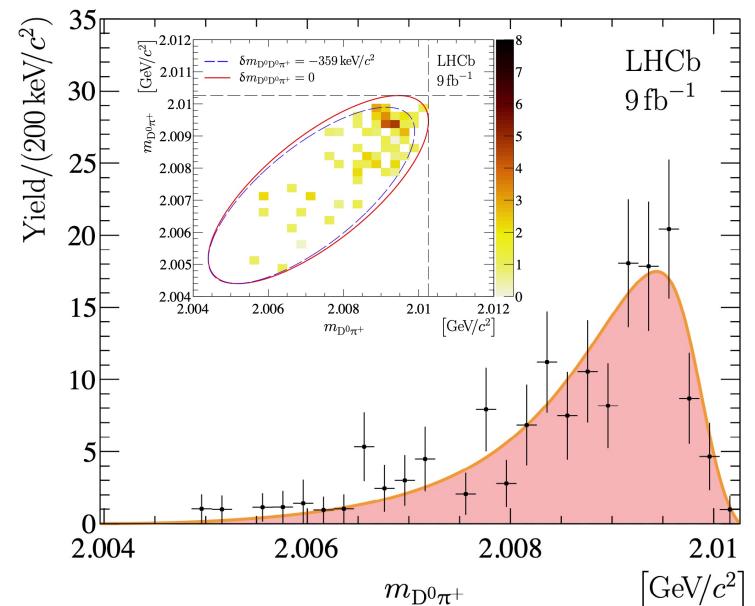
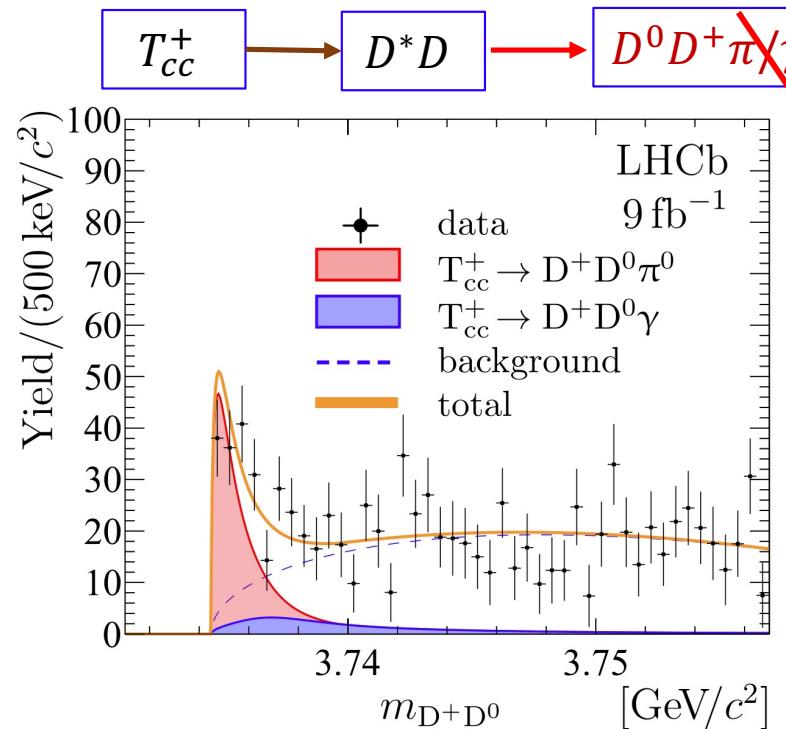
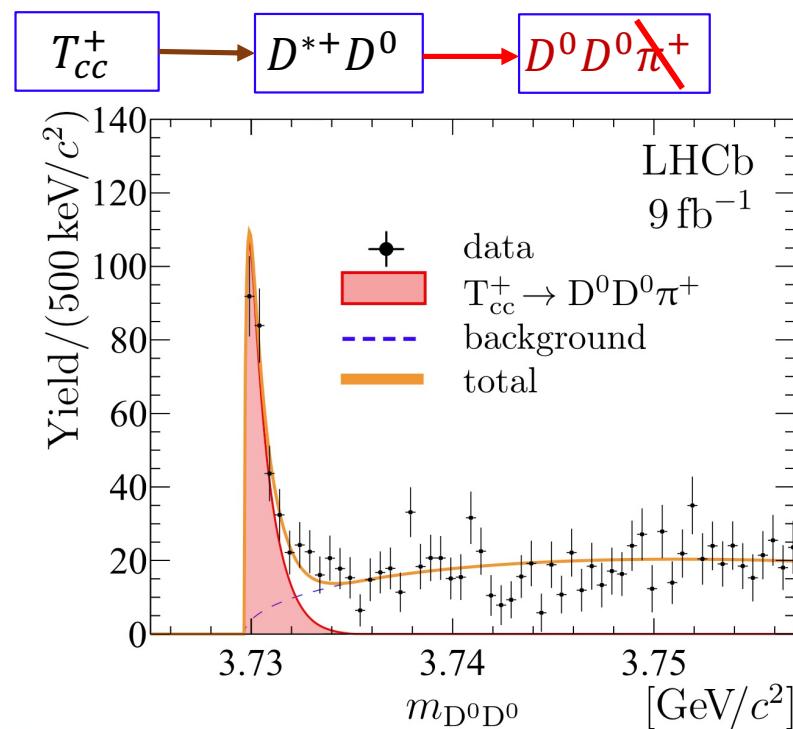
by 9σ

$$\Gamma_U(\text{FWHM}) = 47.8 \pm 1.9 \text{ keV}$$

Fit quality slightly better than BW

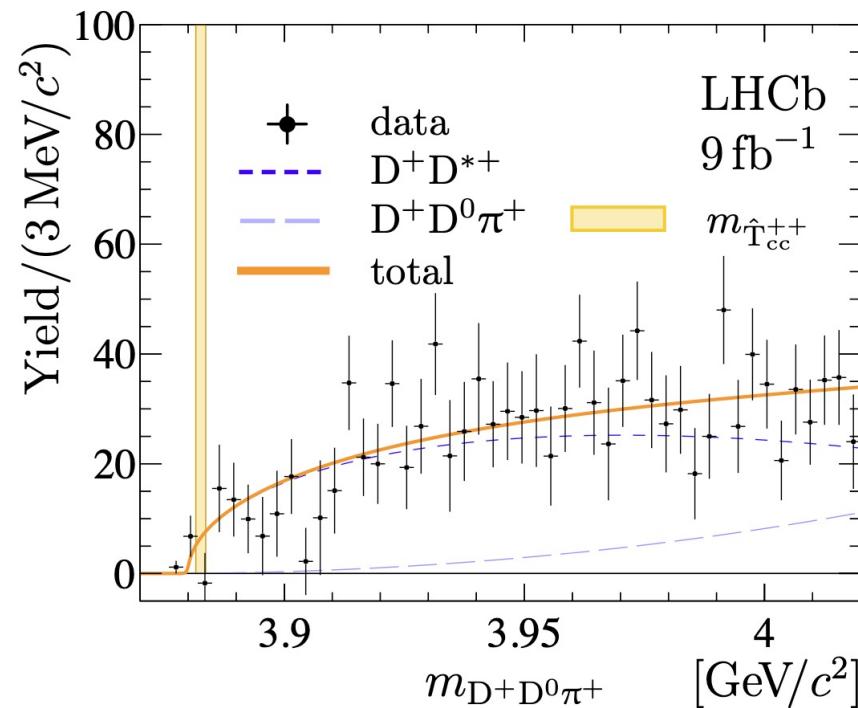
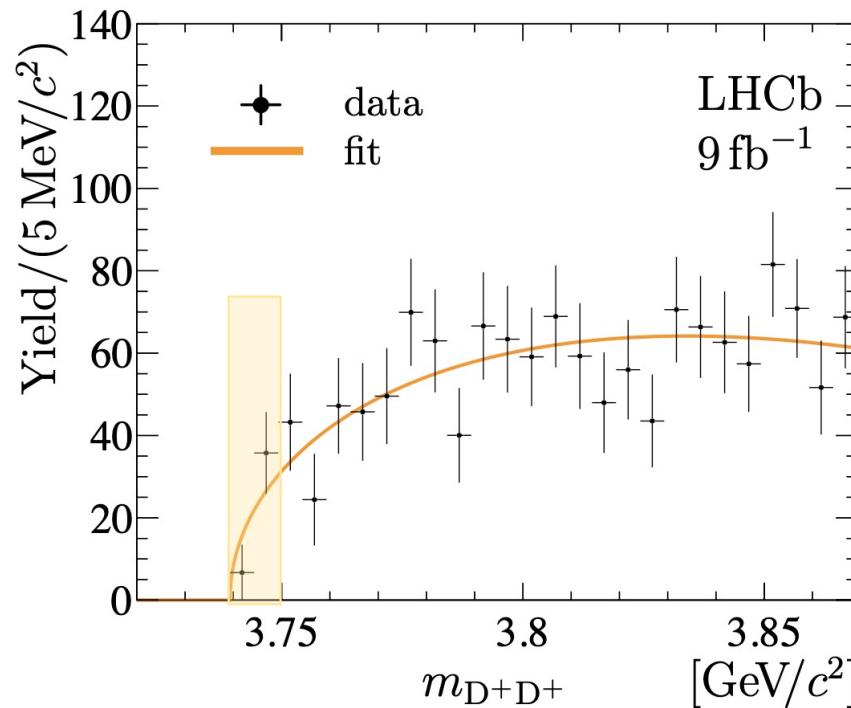
Intermediate offshell D^{*+}

- **$m_{D^0\pi^+}$ distribution:** data and unitarized model agree with each other, suggesting true D^{*+} contribution
- **$m_{D^0D^{0,+}}$ in $D^0D^{0,+}$ samples:** receive contribution from partially reconstructed $T_{cc}^+ \rightarrow D^{*+}D^0$ decays, yields and shapes in unitarized model agree with data



The isospin partner?

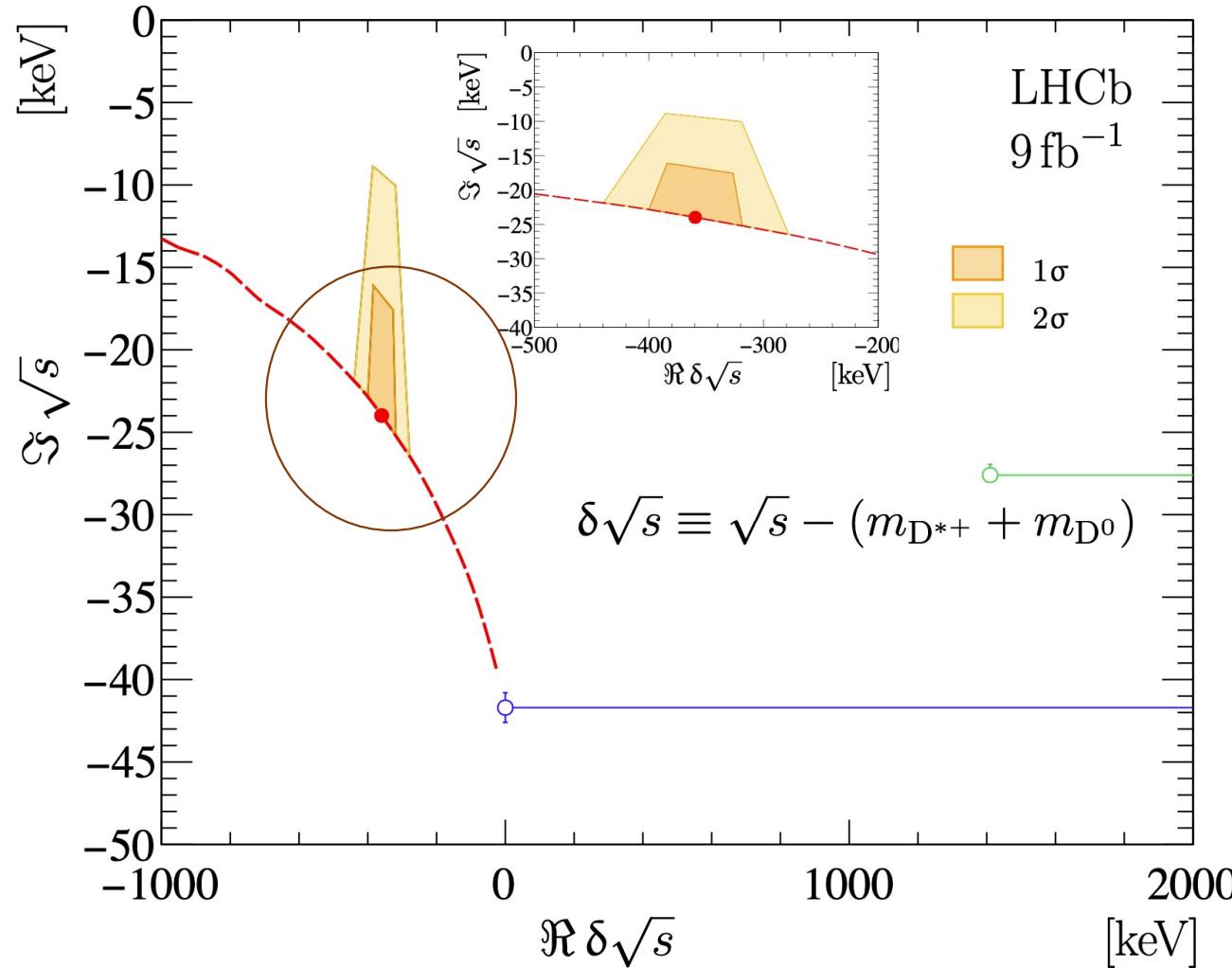
- T_{cc}^+ may be an isoscalar or zero-component of isotriplet:
 $\hat{T}_{cc}^{++}(cc\bar{d}\bar{d})$, $\hat{T}_{cc}^+(cc\bar{u}\bar{d})$, $\hat{T}_{cc}^0(cc\bar{u}\bar{u})$
- Consistency between T_{cc}^+ and D^0D^0 , D^0D^+ mass spectrum, no hint of \hat{T}_{cc}^{++} and \hat{T}_{cc}^0 in isotriplet. T_{cc}^+ consistent with isoscalar
- No evidence \hat{T}_{cc}^{++} structure in D^+D^+ or $D^+D^0\pi^+$ spectrum
 ➤ Too wide? Production late too low? Well below threshold? Unbound?



Amplitude pole and scattering length

$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}$ keV, $\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14}$ keV, close to peak mass and FWHM

Scattering length: $a = [-(7.16 \pm 0.51) + i (1.85 \pm 0.28)]$ fm, **attraction force**

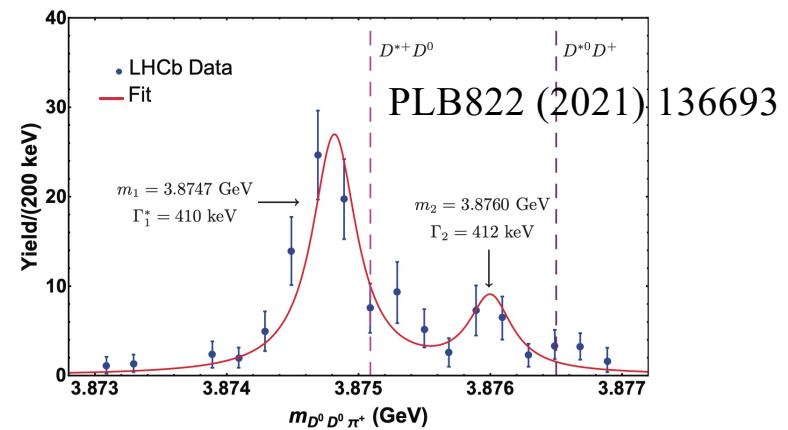


Detailed studies in
[arXiv:2110.07484](https://arxiv.org/abs/2110.07484)
[arXiv:2108.06002](https://arxiv.org/abs/2108.06002)

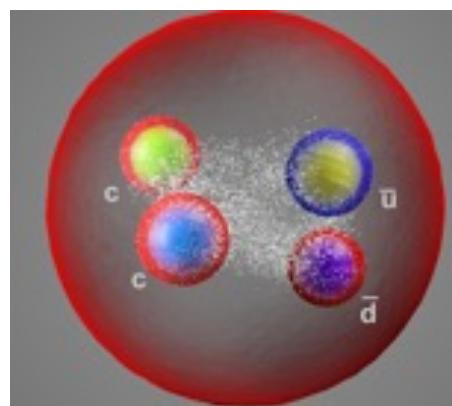
The true structure

- Compact tetraquark $cc\bar{u}\bar{d}$: long anticipated, mass and J^P consistent
- But also consistent with loosely bound $D^{*+}D^0$ molecule: $D^{*+}D^0$ S-wave, mass close to threshold, dynamics, fewer state...
 - A second state of $D^{*0}D^+$?

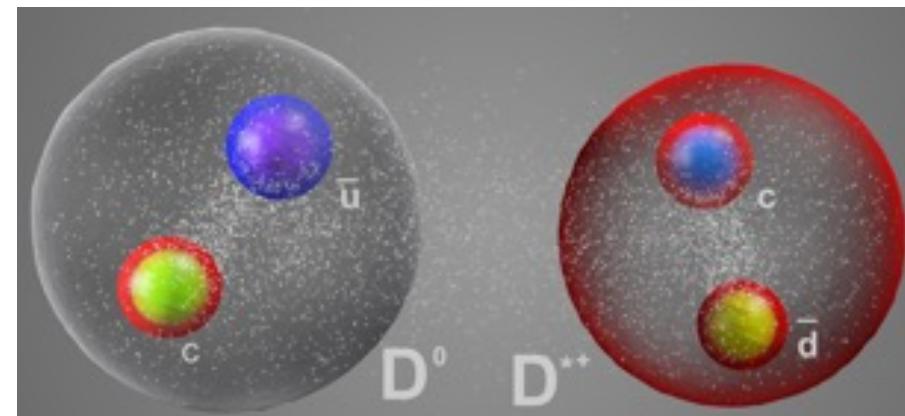
PLB822 (2021) 136693, arXiv:2110.02944
Chin.Phys.Lett.38(2021) 092001
arXiv:2110.15270, arXiv:2111.01081,
arXiv:2110.07484,arXiv:2110.13765,
arXiv:2109.02531,arXiv:2109.02828



Compact



Molecule



Summary and prospects

- Observations of: $ccq \rightarrow cc\bar{c}\bar{c} \rightarrow cc\bar{q}\bar{q}$
- Do we understand more about cc binding?
- Prospects

➤ Analyses with current data

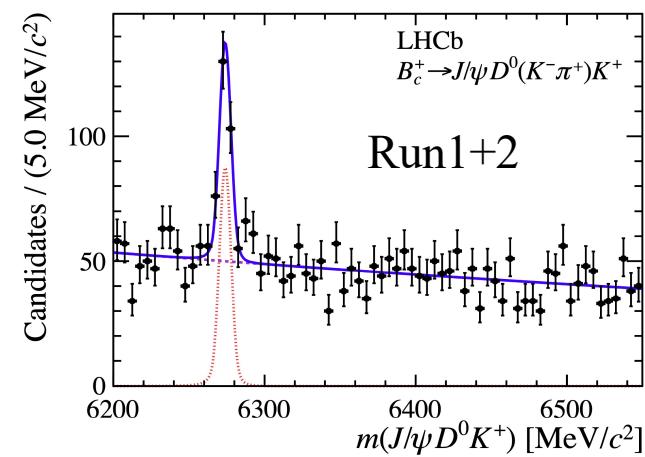
Fully heavy: $J/\psi + Q\bar{Q}$; Doubly charmed tetraquark: $\Sigma_c^{(*)} D^{(*)} \dots$; Triple charm: $J/\psi D$;
 Hidden charm tetraquark: $\Sigma_c^{(*)} \bar{D}^{(*)} \dots$

➤ Upgrade

- 7× data by 2030, 14× for hadronic
- Allow to search for T_{cc} and T_{ccc} in B_c^+ decays
- Sensitivity for Ξ_{bc} and T_{bc} states

Decay mode	arXiv:1808.08865	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \rightarrow X(3872)(\rightarrow J/\psi \pi^+ \pi^-) K^+$		14k	30k	180k
$B^+ \rightarrow X(3872)(\rightarrow \psi(2S)\gamma) K^+$		500	1k	7k
$B^0 \rightarrow \psi(2S) K^- \pi^+$		340k	700k	4M
$B_c^+ \rightarrow D_s^+ D^0 \bar{D}^0$		10	20	100
$\Lambda_b^0 \rightarrow J/\psi p K^-$		340k	700k	4M
$\Xi_b^- \rightarrow J/\psi \Lambda K^-$		4k	10k	55k
$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$		7k	15k	90k
$\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+$		50	100	600

LHC		LH-LHC	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}
Upgrade I	Upgrade Ib	Upgrade II	$> 300 \text{ fb}^{-1} (?)$



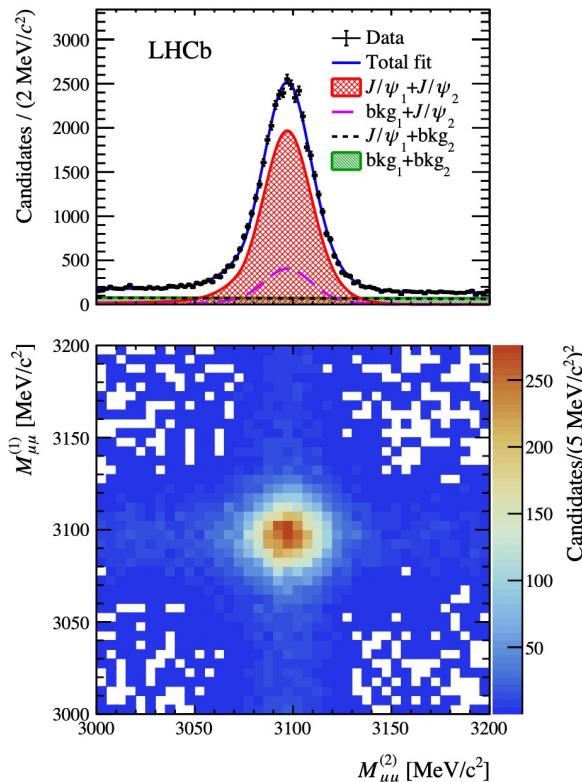
Backup slides

Di- J/ψ sample at LHCb

- Full Run1 and Run2 data

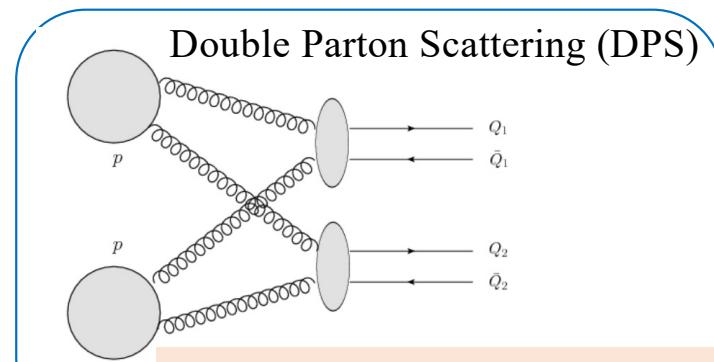
About 34K
di- J/ψ signals

Science Bulletin 65 (2020) 1983

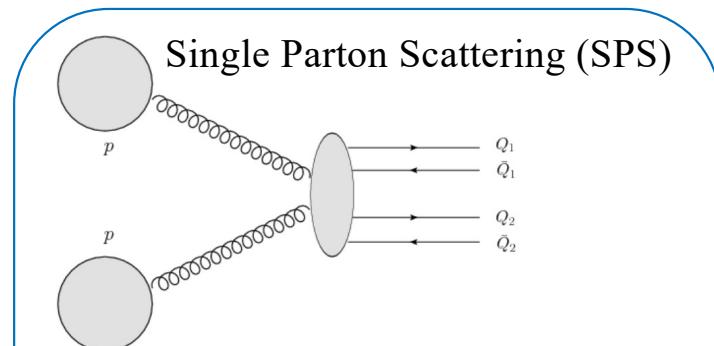


Two production processes

JHEP 06 (2017) 047



Smooth di- J/ψ continuum



Both smooth continuum and
resonant $cc\bar{c}\bar{c}$ structures.
Averagely larger p_T than DPS

Exotics

Table 1: Tetra- and pentaquark candidates and their plausible valence quark content.

States	Quark content
$X_0(2900)$, $X_1(2900)$ [32, 33]	$\bar{c}dus$
$\chi_{c1}(3872)$ [8]	$c\bar{c}q\bar{q}$
$Z_c(3900)$ [34–38], $Z_c(4020)$ [39, 40], $Z_c(4050)$ [41], $X(4100)$ [42], $Z_c(4200)$ [43], $Z_c(4430)$ [44–47], $R_{c0}(4240)$ [46]	$c\bar{c}ud$
$Z_{cs}(3985)$ [48], $Z_{cs}(4000)$, $Z_{cs}(4220)$ [49]	$c\bar{c}u\bar{s}$
$\chi_{c1}(4140)$ [50–53], $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ [53], $X(4630)$, $X(4685)$ [49], $X(4740)$ [54]	$c\bar{c}s\bar{s}$
$X(6900)$ [25]	$c\bar{c}cc\bar{c}$
$Z_b(10610)$, $Z_b(10650)$ [55]	$b\bar{b}ud\bar{d}$
$P_c(4312)$ [56], $P_c(4380)$ [57], $P_c(4440)$, $P_c(4457)$ [56], $P_c(4357)$ [58]	$c\bar{c}uud$
$P_{cs}(4459)$ [59]	$c\bar{c}uds$

Tetraquarks

Surveying candidates



observed (>1 group)

no deep binding

observed (1 group)

not confirmed (>1 group)

channel	deeply bound
$J^P = 1^+$	$bb\bar{u}\bar{d}$ $bc\bar{u}\bar{d}$ $bb\bar{l}\bar{s}$ $bc\bar{l}\bar{s}$ $bs\bar{u}\bar{d}$ $cs\bar{u}\bar{d}$ $bb\bar{u}\bar{c}$ $bb\bar{s}\bar{c}$ $cc\bar{u}\bar{d}$ $cc\bar{l}\bar{s}$ $bb\bar{b}\bar{b}$
$J^P = 0^+$	$bb\bar{u}\bar{u}$ $cc\bar{u}\bar{u}$ $bb\bar{u}\bar{d}$ $bc\bar{u}\bar{d}$ $bb\bar{l}\bar{s}$ $bc\bar{l}\bar{s}$ $bb\bar{s}\bar{s}$ $cc\bar{s}\bar{s}$ $bs\bar{u}\bar{d}$ $cs\bar{u}\bar{d}$ $bb\bar{u}\bar{c}$ $bb\bar{s}\bar{c}$ $bb\bar{c}\bar{c}$ $cc\bar{u}\bar{d}$ $bb\bar{b}\bar{b}$

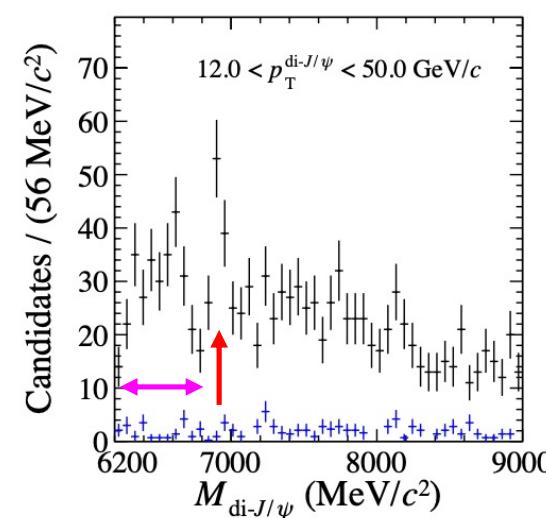
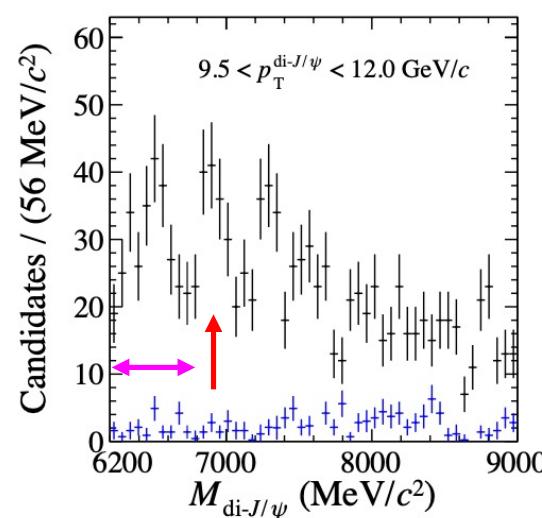
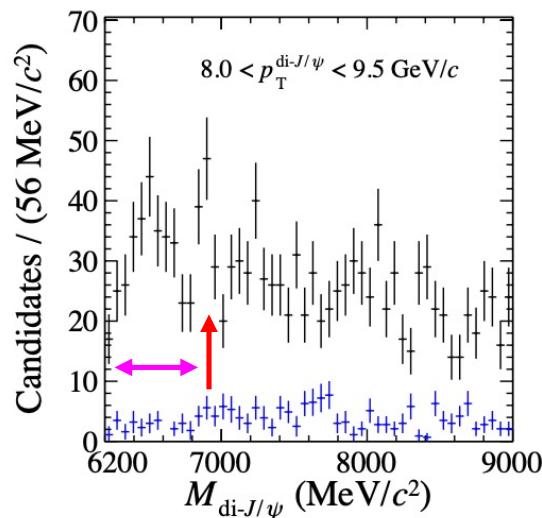
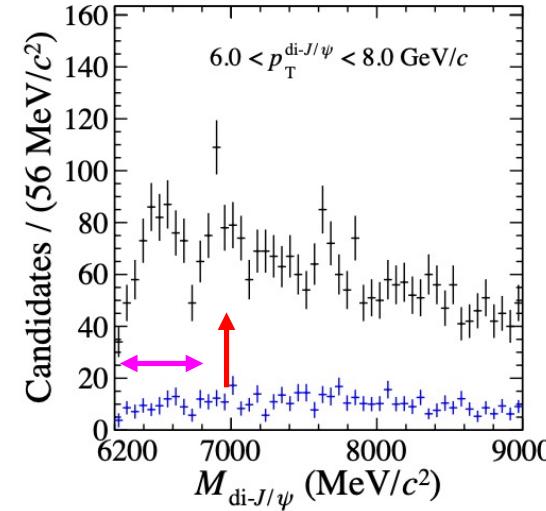
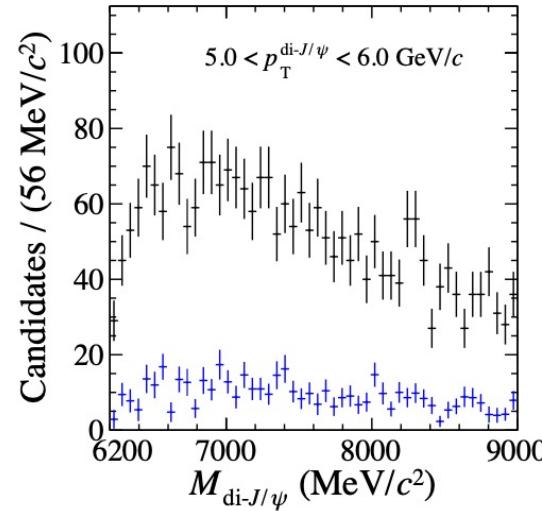
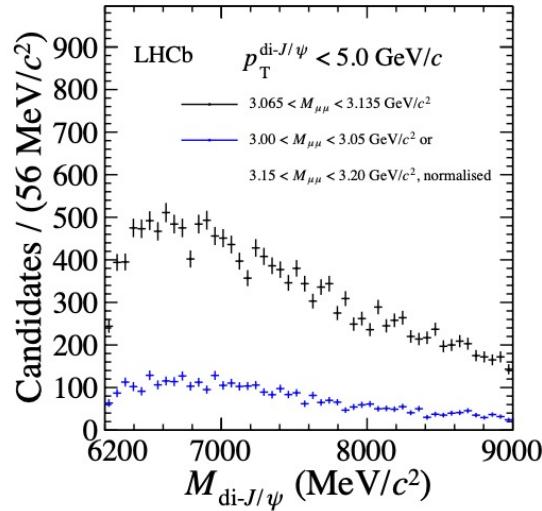
$X(6900)$ signal stability



- Combinatorial backgrounds show smooth J/ψ -pair mass distribution
- Structures are stable with respect to different data-taking periods
- Residual backgrounds with multiple use of muon track produce no such structure
- Residual contamination from b -hadron decays has a smooth distribution
- Variation of detection efficiency with respect to mass is marginal
- Contribution from partially reconstructed $\gamma \rightarrow J/\psi X$ decays is expected to be negligibly small

Di- J/ψ invariant mass (II)

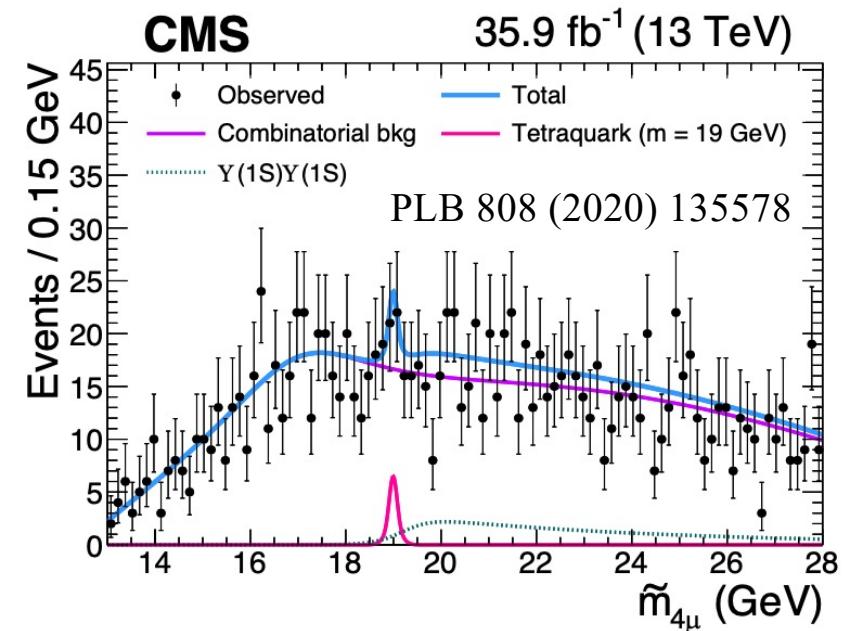
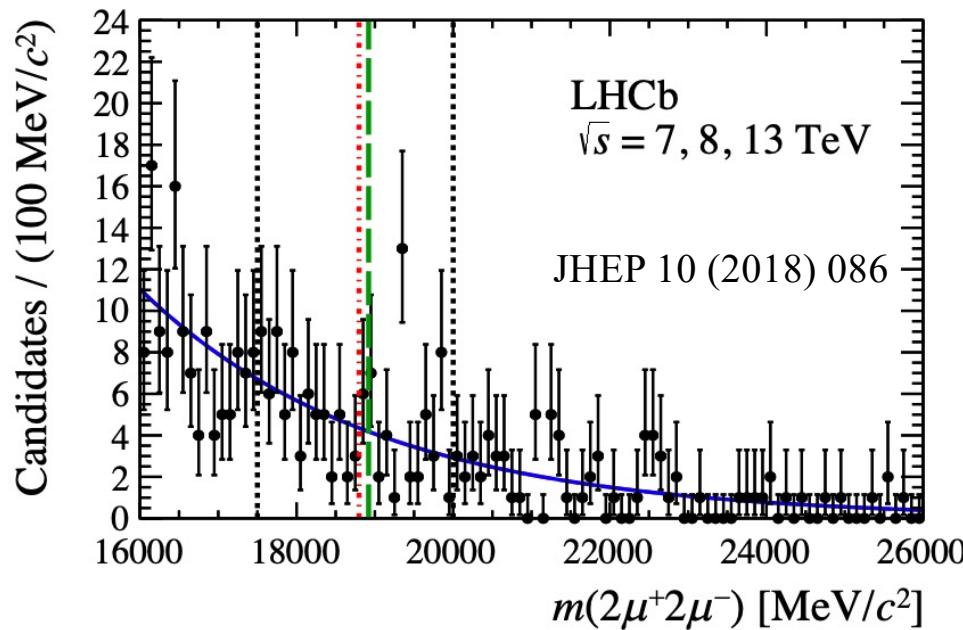
- Same structures in all high di- J/ψ p_T bins, evidence increasing with p_T



The bottom partner

- 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. Eager to see full data analysis at CMS/ATLAS

□ LHCb inconsistent with SELEX

$$\Delta \Xi_{cc} = m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^+)_{\text{SELEX}} = 103 \pm 2 \text{ MeV}$$

Inconsistent with being isospin partners !

$0 < \Delta \Xi_{cc} \lesssim 2 \text{ MeV}$ by models and LQCD

□ Ξ_c^+ direct search with full LHCb data

Local signif. of 3.1σ at $3620 \text{ MeV}/c^2$

$$\frac{\sigma(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} < 0.6 \text{ (95\%)}$$

for $m = 3620 \text{ MeV}/c^2$ and $\tau = 80 \text{ fs}$

Very small τ or $\text{Br}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)$

