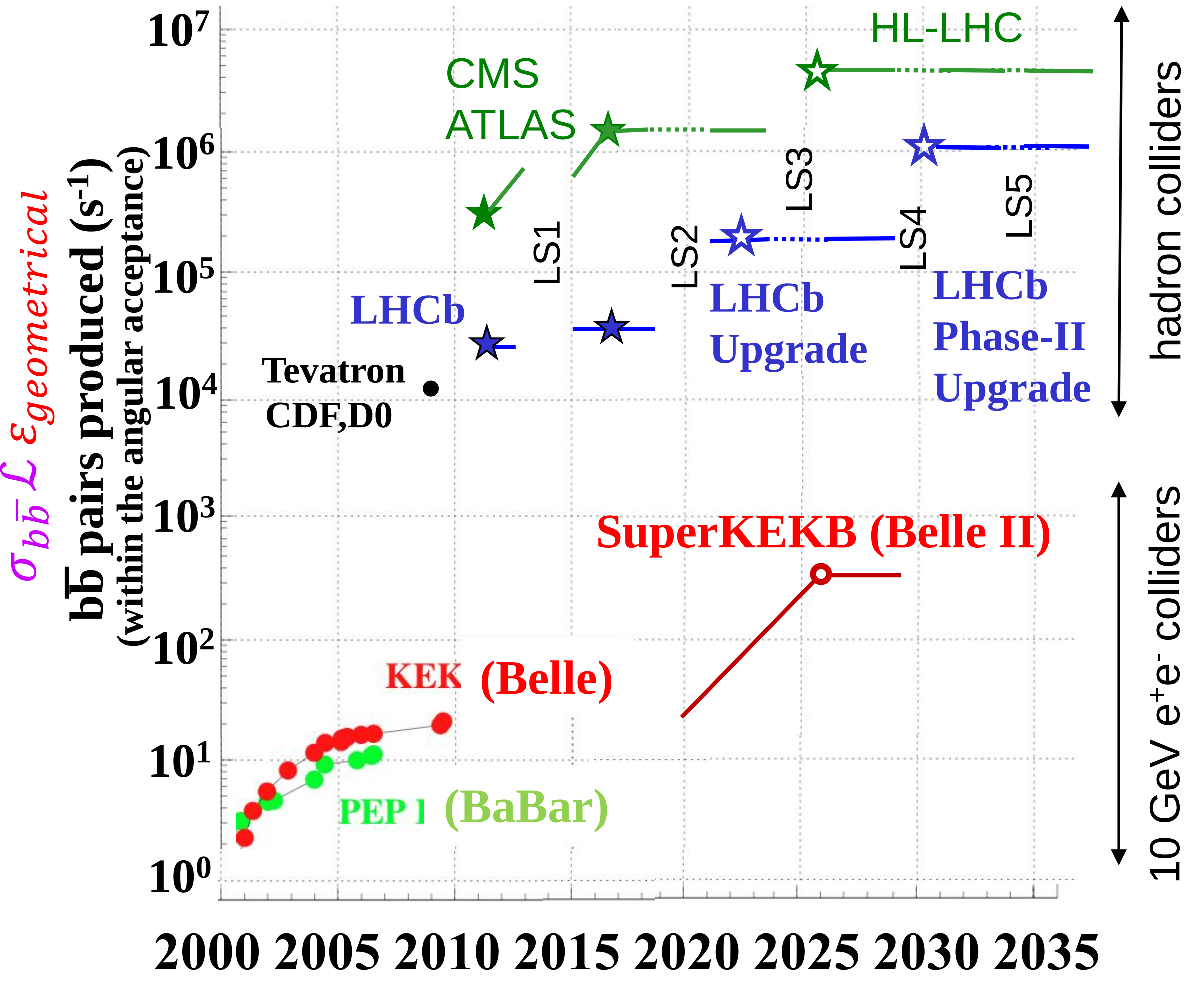
Heavy flavor hadron spectroscopy prospects at LHCb

Tomasz Skwarnicki
Syracuse University

(a few highlights rather than comprehensive review)

EF06: QCD and strong interactions: Hadronic structure and forward QCD
Working group meeting June 24, 2020

Colliders and $b\bar{b}$ rates



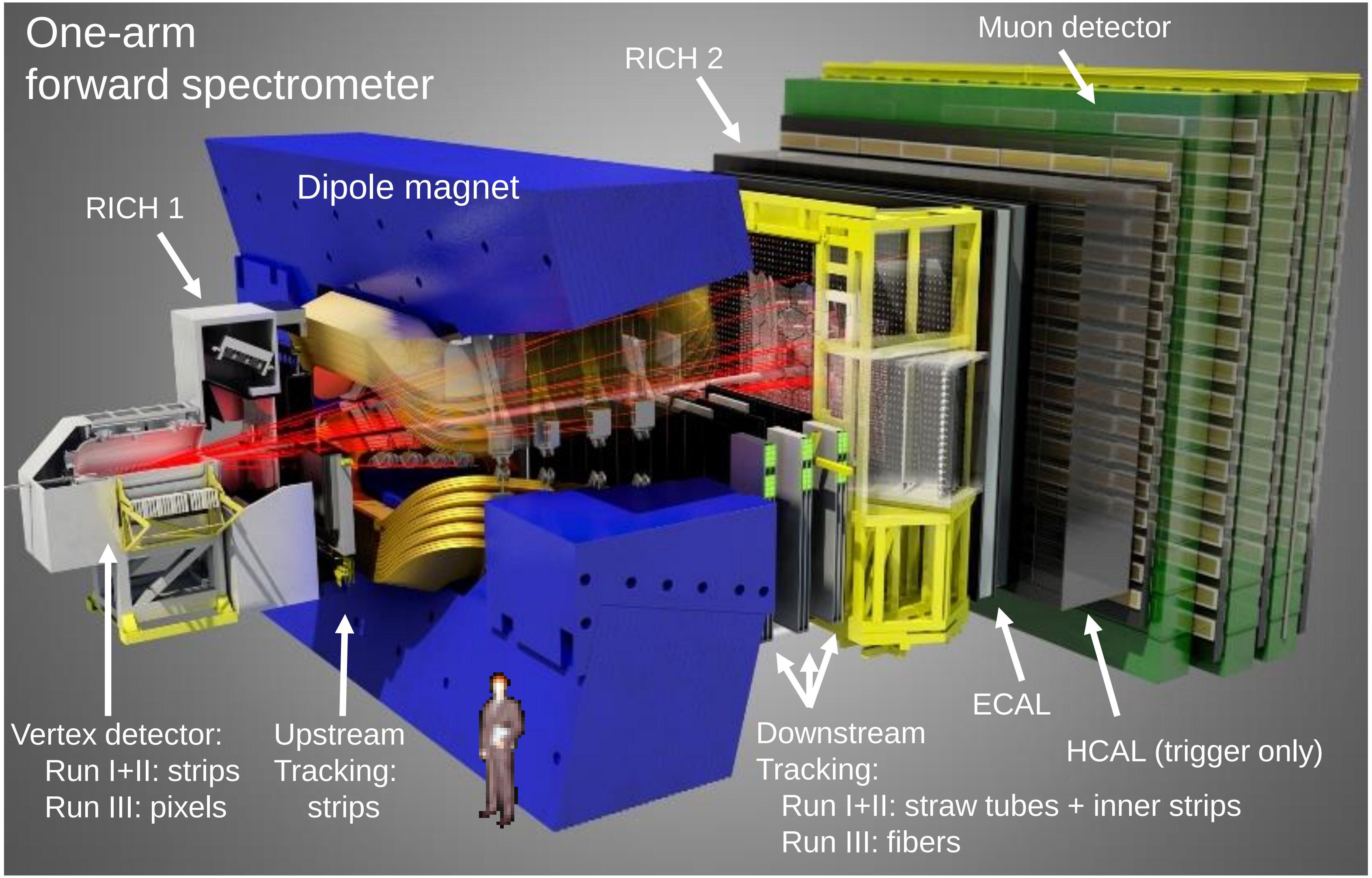
$\int \mathcal{L}\, dt$ now

CDF 10 fb^{-1} , D0 8 fb^{-1}

	Run I	Run II	Run III	Run IV	Run V+VI
LHCb	3 fb^{-1}	6 fb^{-1}	50 fb^{-1}		300 fb^{-1}
ATLAS,CMS	25 fb^{-1}	450 fb^{-1}		3000 fb^{-1}	

- Tremendous **rate potential** at **hadron colliders**
  - background cross-sections are also large
    - **triggering** is the major challenge
    - hadron identification (π/K/p) helps bkg suppression
  - physics reach determined by **detector capabilities** not by the machine
    - LHCb runs at diluted instantenous luminosity
    - LHCb upgrades are detector rather than machine upgrades
- Collect all b-hadron species at the same time
  - **Spectroscopy of b-baryons and of B_c states** which are out of reach of the 10 GeV e^+e^- factories, in addition to **B, B_s spectroscopy**
- Charm rates a factor of 10 higher than beauty rates:
  - Prompt production as well as in b-quark decays (the latter gives smaller backgrounds).
  - Also central-region production, heavy ion runs
  - **Spectroscopy of charmed baryons and mesons**
  - **Doubly-charmed states!** Doubly-beautiful states in the future?

LHCb detector



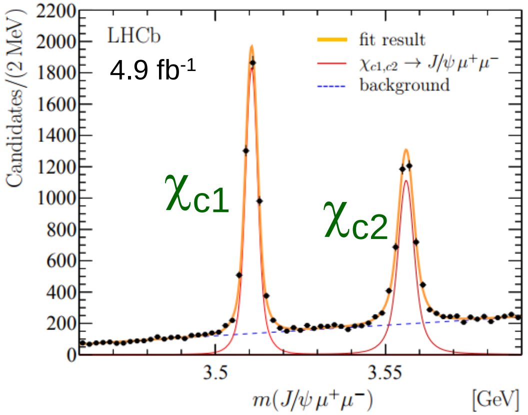
- LHCb Upgrade (in progress, Run III+IV):
  - Fully software trigger at 40 MHz; luminosity $4\times10^{32} \rightarrow 2\times10^{33}$ $cm^{-2}s^{-1}$; 9 → 50 fb^{-1}
  - Finer segmentation of tracking detectors to deal with 5 times higher pile-up (1.5 → 7.6 visible interactions per crossing)
- LHCb Upgrade Phase II (~2030, Run V+VI):
  - Further luminosity upgrade; → 1-2 $\times10^{34}$ $cm^{-2}s^{-1}$; → 300 fb^{-1}
  - Need timing in tracking detectors and finer segmentation to deal with ~40 visible interactions per crossing

- First hadron-collider experiment optimized to heavy flavor physics:
  - Entire trigger bandwidth dedicated to it
  - Main mission is search for BSM physics in CP violation and in rare decays of beauty and charm hadrons
  - The same detector features make it also optimal for heavy flavor hadron spectroscopy
- Forward spectrometer:
  - Similar b,c cross-section as for the central detectors, but in much smaller detection volume:
    - Factor of 10 cheaper than ATLAS/CMS
    - Less electronic channels, smaller event size, more affordable large trigger bandwidth to tape (Run II: 12 kHz, Run III >20 kHz)
    - Can detect lower p_T muons
    - Space for RICH detectors
- Good hadron ID (missing in central detectors)
- Some disadvantages relative to Belle II:
  - Limited γ/π^0 detection. Will get worse in Run III. Major ECAL upgrade in the future?
  - Lower absolute tracking efficiency
  - Often made up by higher production rates
- Trigger on muons and displaced vertices:
  - Run I+II: hardware L0 trigger 40 MHz→1 MHz readout to HLT
  - Run III: 40 MHz readout to HLT (allows increase of instantaneous luminosity)

Conventional charmonium spectroscopy

LHCb-PAPER-2017-036, PRL 119 (2017) 221801

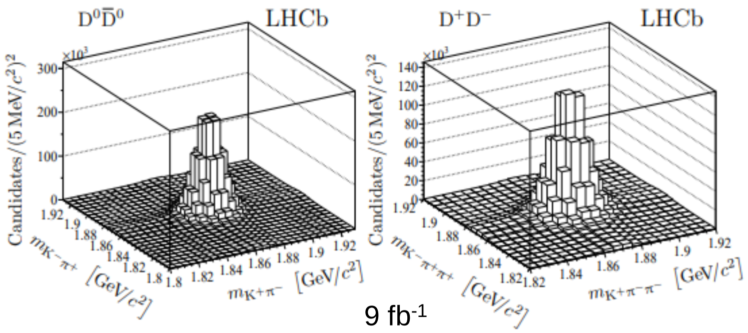
$\chi_{c1,2} \to \mu^+\mu^- J/\psi,\ J/\psi \to \mu^+\mu^-$



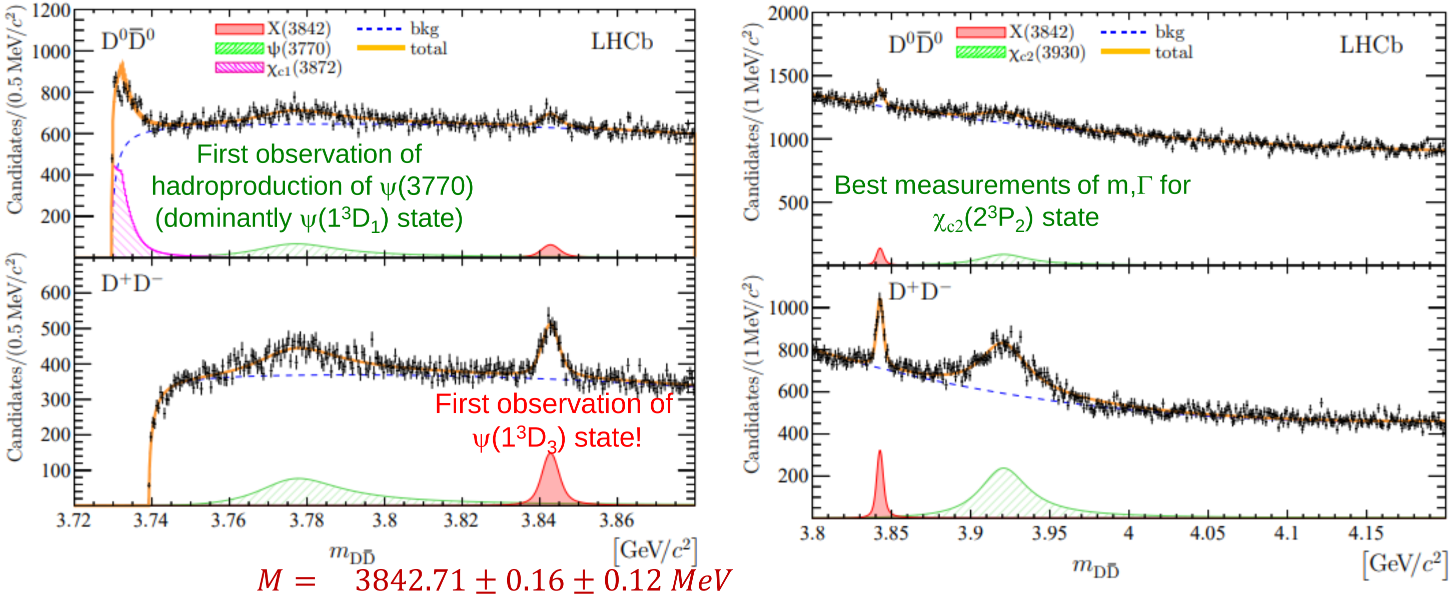
The best world measurements of masses and widths of $\chi_{c1,2}$

Detection of di-muon transition instead of γ transition, a very promising method for high statistics data samples in LHCb Upgrades I and II: $\mu^+\mu^- J/\psi$, $\pi^+\pi^-(\mu^+\mu^- J/\psi)$, $\mu^+\mu^-\Upsilon$, $\mu^+\mu^- B_c$, …

LHCb-PAPER-2019-005, JHEP 1907 (2019) 035



Purely hadronic final states!

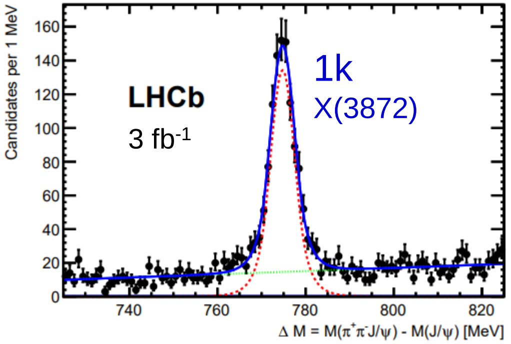


$$M = 3842.71 \pm 0.16 \pm 0.12\ MeV$$
$$\Gamma = 2.79 \pm 0.51 \pm 0.35\ MeV$$

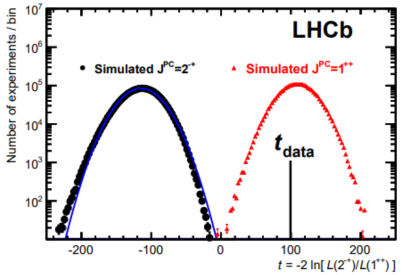
Expect a lot of interesting results in the future from studies of heavy meson-meson pairs (also heavy baryon-baryon pairs e.g. $\Lambda_c^+\Lambda_c^-$)

Exotic charmonium spectroscopy: X(3872)

LHCb-PAPER-2013-001, PRL 110 (2013) 222001; 1 fb^{-1}
LHCb-PAPER-2015-015, PR D92 (2015) 011102; 3 fb^{-1}

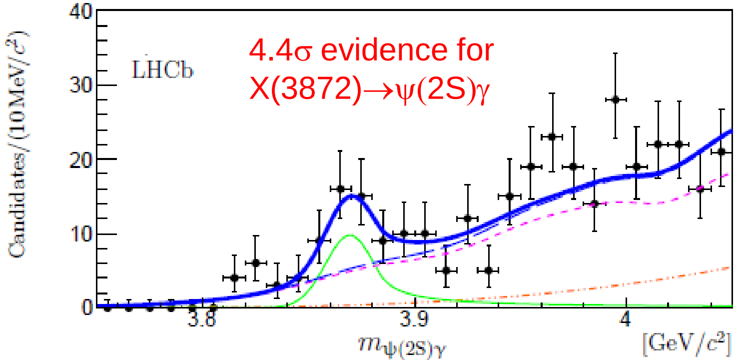


$B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\, \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$



From angular correlations determine X(3872) J^{PC} to be 1^{++}

LHCb-PAPER-2014-008, NP B886 (2014) 665 110 (2013) 222001; 3 fb^{-1}



$B^+ \to X(3872)K^+$, $X(3872) \to \psi(2S)\gamma$, $\psi(2S) \to \mu^+\mu^-$

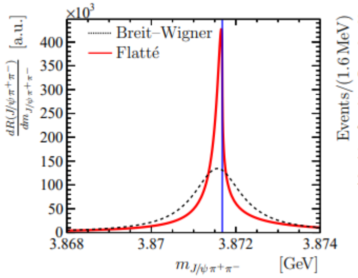
γ detected in ECAL

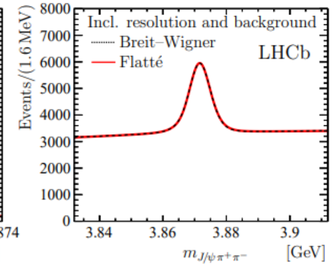
Value of $BR(X(3872)\to\psi(2S)\gamma)/BR(X(3872)\to J/\psi\gamma)$ important for X(3872) interpretations
Not well determined and presently controversial

LHCb-PAPER-2020-008,
arXiv:2005.13419
3 fb^{-1}

$H_b \to X(3872)\ldots$, $X(3872) \to J/\psi\, \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$

- Breit-Wigner fit
  $m_{X(3872)} - m_{\psi(2S)} = 185.598 \pm 0.067 \pm 0.068\,\text{MeV}$
  $m_{X(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010\,\text{MeV}$
  $\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10\,\text{MeV}$ previously UL only
  $\delta E = m_{D^0} + m_{\bar{D}^{*0}} - m_{X(3872)} = 0.01 \pm 0.14\,\text{MeV}$
- Flatté lineshape accounts for the opening up of $\bar{D}^0 D^{*0}$ threshold
- Flattè fit:
  Mode $= 3871.69^{+0.00+0.05}_{-0.04-0.13}$ MeV (in agreement wit the mean of the BW lineshape)
  FWHM $= 0.22^{+0.06+0.25}_{-0.08-0.17}$
- FWHM $\ll \Gamma_{BW}$: importance of a physically well-motivated lineshape parameterization





Future: coupled-channel analysis of the X(3872) lineshape including $D\bar{D}^*$ channel

(crude projections by T.S.)

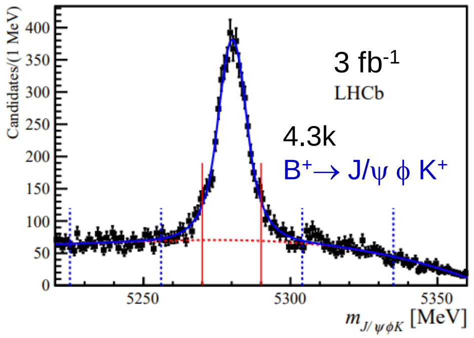
	LHCb U. Phase I		LHCb U. Phase II		Belle II	
Decay mode	3 fb^{-1}	9 fb^{-1}	50 fb^{-1}	300 fb^{-1}	0.7 ab^{-1}	50 ab^{-1}
$B^+ \to K^+X(3872)$ $(\to J/\psi\pi^+\pi^-)$	1k	6k	33k	200k	0.17k	11k
$B^+ \to K^+X(3872)$ $(\to \psi(2S)\gamma)$	36	0.2k	*1k*	7k		2k
$B^+ \to K^+X(3872)$ $(\to J/\psi(1S)\gamma)$	0.6k	2.7k	*15k*	90k	36	2k

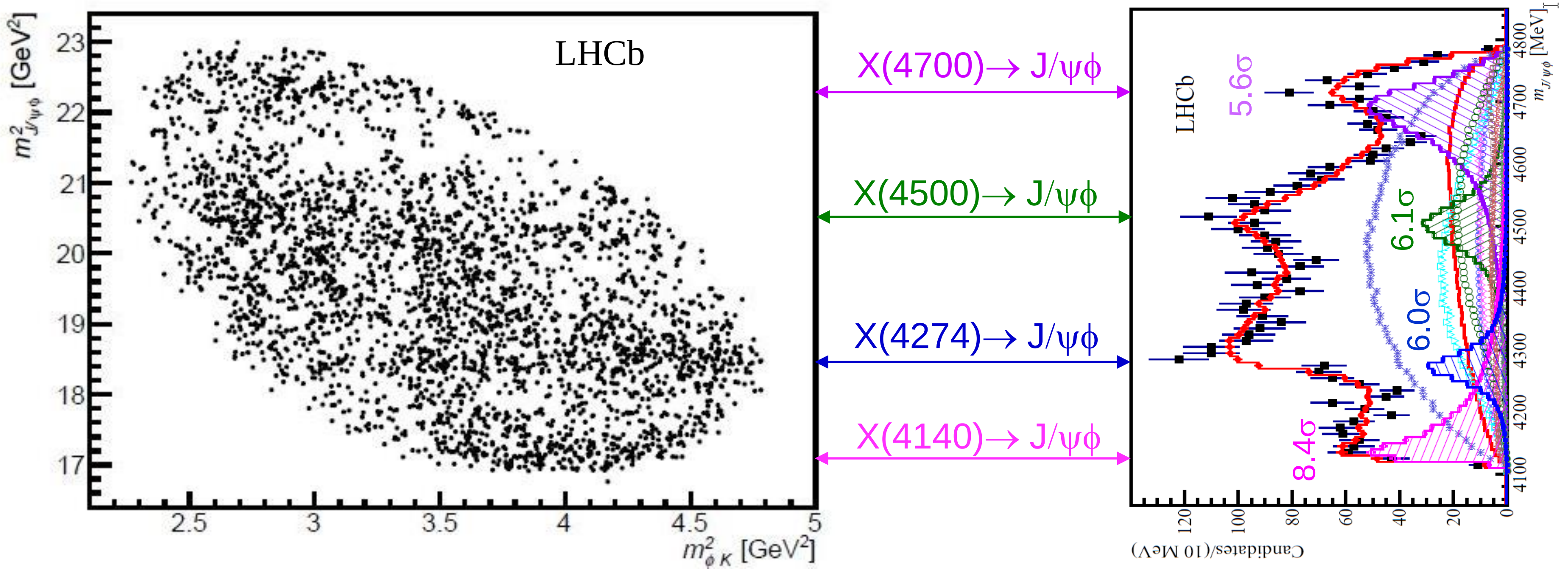
Exotic charmonium spectroscopy: ψϕ, ψπ$^{\pm}$ states

Example:

LHCb-PAPER-2016-018,-019
PRL118, 022003 (2017)
PRD95, 012002 (2017)

$B^+ \to J/\psi\ \phi\ K^+$,
$\phi \to K^+K^-$, $J/\psi \to \mu^+\mu^-$





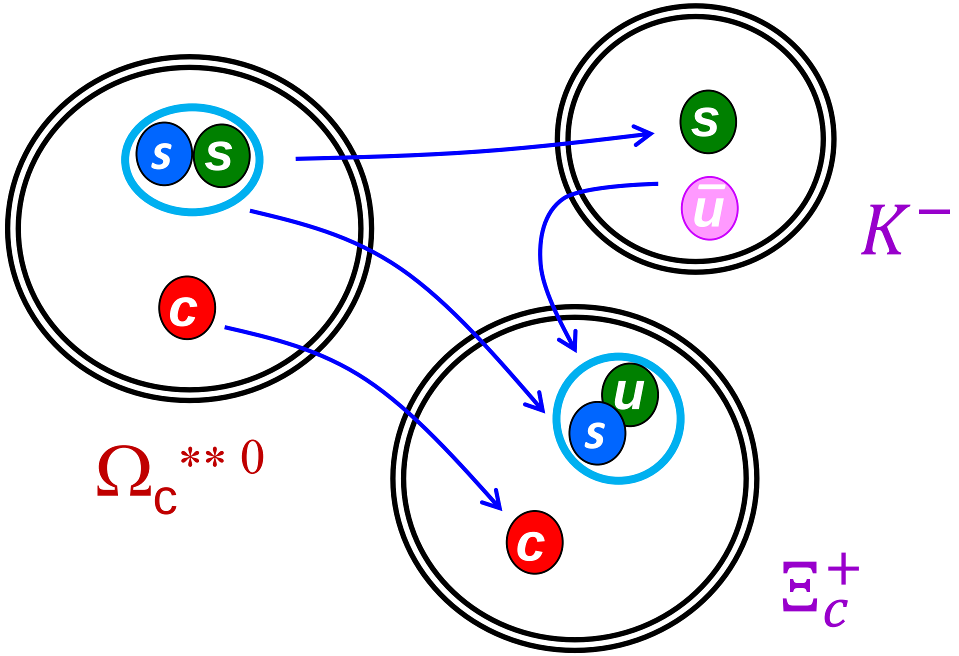
X(4140) was previously observed by CDF,CMS,D0. Hints of X(4274) in CDF data.

- Many puzzling structures observed in $B \to X\ K, X \to$ J/ψϕ, J/ψπ$^{\pm}$,ψ(2S)π$^{\pm}$,…
- Conventional kaon excitations contribute to the same *B* decay modes
- Amplitude analyses with larger statistics will help shed more light into their nature

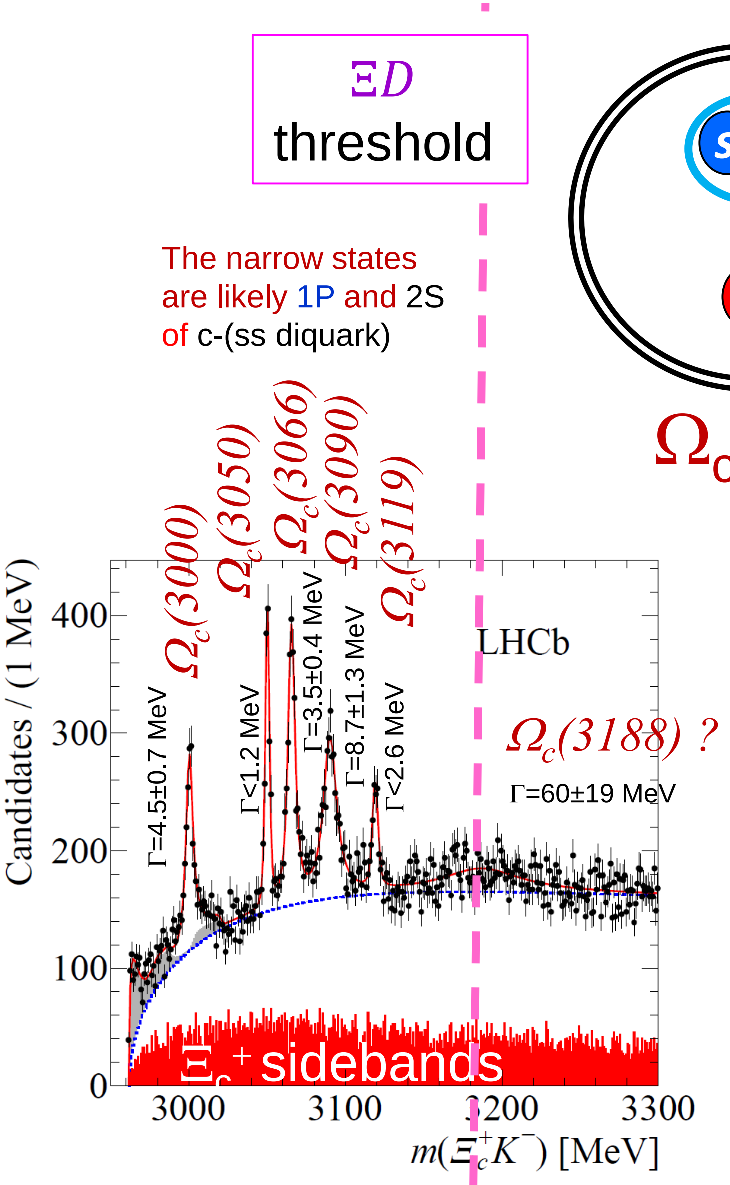
Conventional heavy baryons

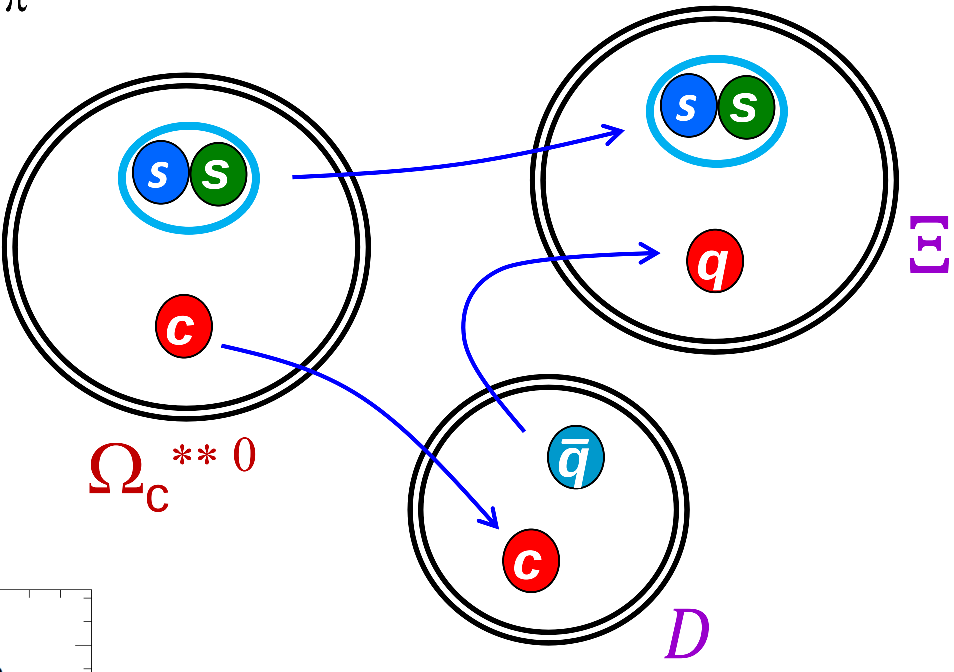
- A lots of new states are being discovered. Many contain nice evidence for diquark substructure e.g.

LHCb-PAPER-2017-002, PRL 118 (2017) 182001; 3.3 fb^{-1} $\Omega_c^{**0} \rightarrow \Xi_c^+ K^-$, $\Xi_c^+ \rightarrow p K^- \pi^+$



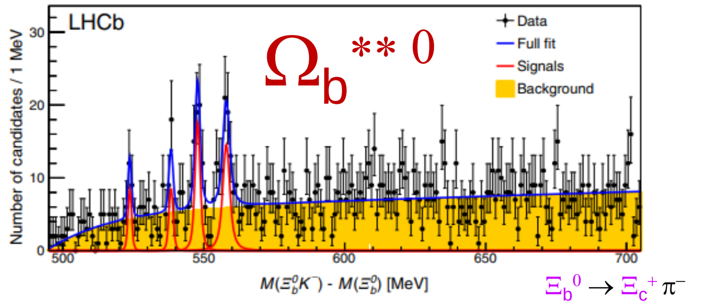
OZI allowed but rips the diquark apart
– suppressed (narrow states)





the diquark survives
– fast fall apart (wide states)

LHCb-PAPER-2019-042, PRL 124 (2020) 082002; 9 fb^{-1}



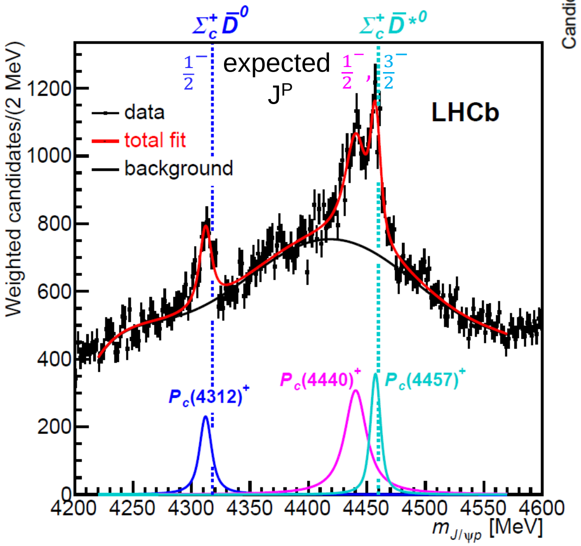
Future:

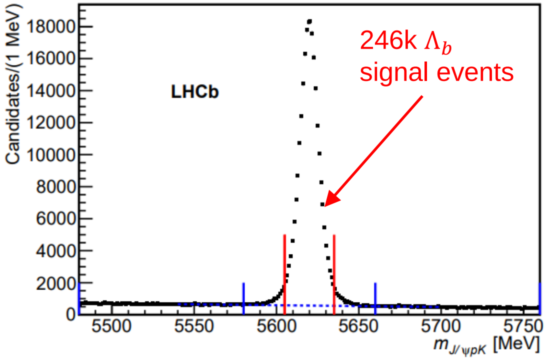
Many more charm and beauty baryons to discover
Study different decay modes of known baryons

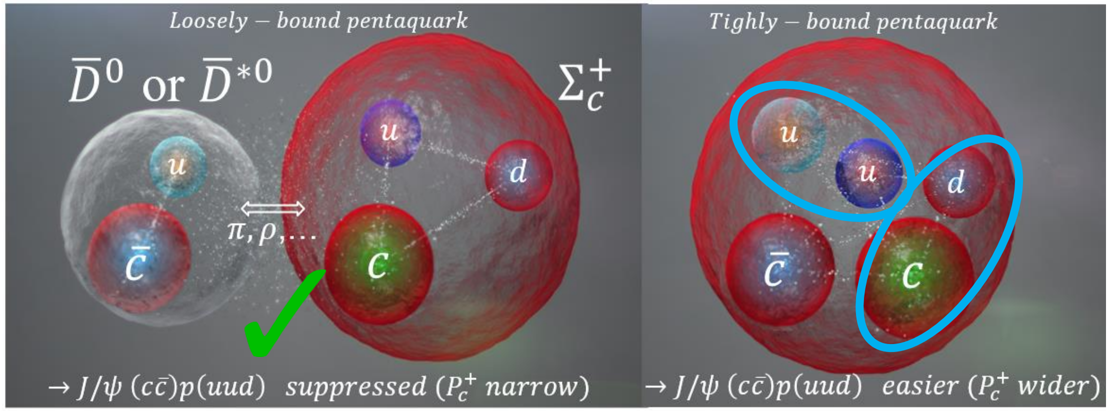
Exotic heavy baryons: pentaquarks

LHCb-PAPER-2015-029, PRL 115 (2015) 072001; 3 fb^{-1}
LHCb-PAPER-2019-014, PRL 122 (2019) 222001; 9 fb^{-1}

$\Lambda_b^0 \to P_c^+ K^-$,
$P_c^+ \to J/\psi p$,
$J/\psi \to \mu^+\mu^-$





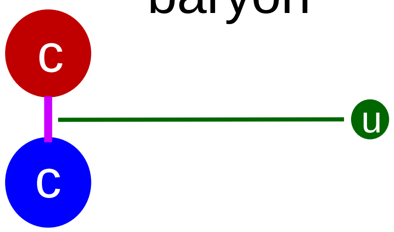


Masses expected near $\bar{D}^{(*)}\Sigma_c^+$ thresholds

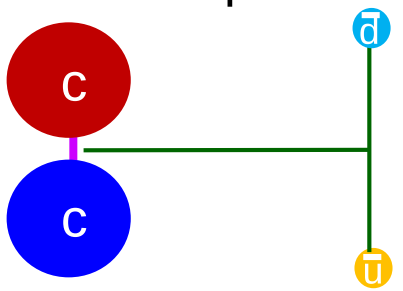
- First undisputed observation of pentaquark states
  - The latest results seem to favor loosely-bound meson-baryon substructure ($\bar{D}^{(*)}\Sigma_c^+$), but much more work is needed to establish their internal dynamics
- Some of future work:
  - J^P determination from data
  - $\bar{D}^{(*)}\Sigma_c^{+*}$ states also expected and should be relatively narrow
  - Are there also wide P_c^+ states as the 2015 amplitude analysis suggested?
  - Are these states also produced in Cabibbo suppressed process: $\Lambda_b^0 \to P_c^+ \pi^-$?
  - Decays to open charm particles?
  - Isospin partners?
  - Strange partners e.g. $P_{cs}^+ \to J/\psi\Lambda$?

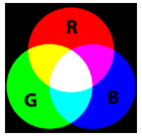
Doubly flavored baryons and tetraquarks

baryon

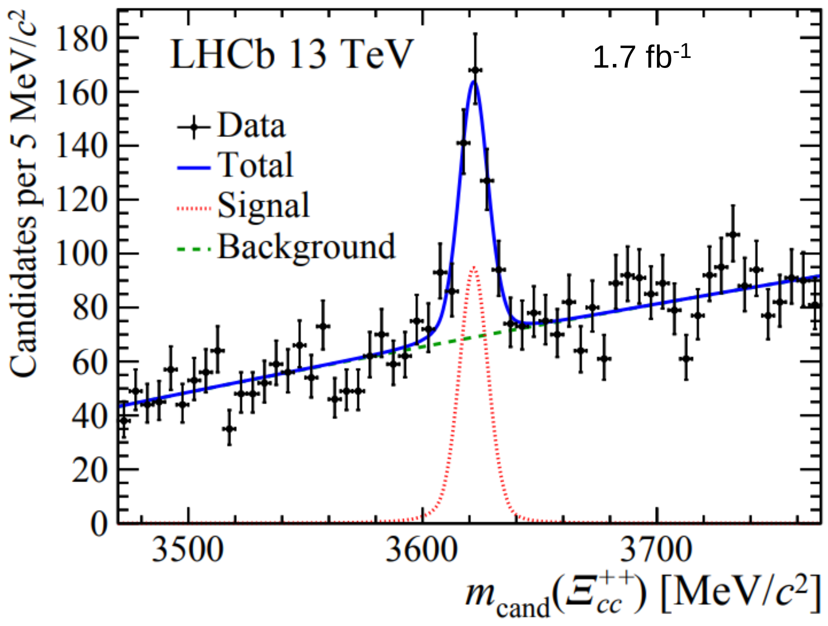


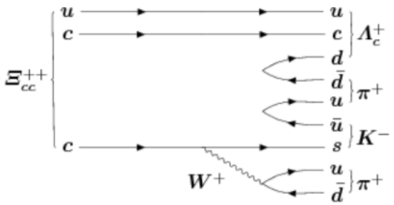
tetraquark





LHCb-PAPER-2017-018, LHCb PRL 119 (2017) 112001





$\Lambda_c^+ \to pK^-\pi^+$

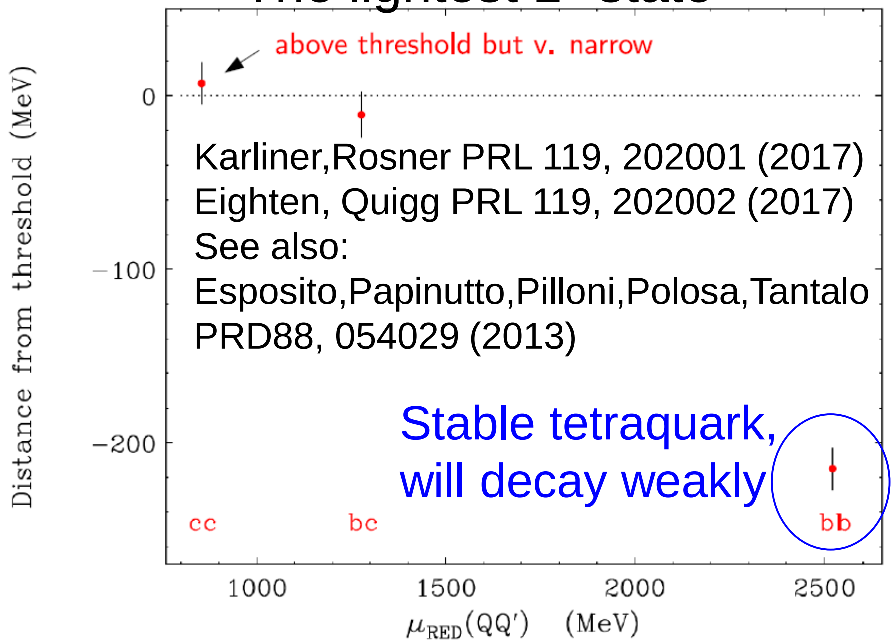
the same toolkit

Karliner,Rosner PRD90,094007 (2014)

State	Quark content	$M(J=1/2)$	$M(J=3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621 ± 1 55

The lightest 1^+ state



Karliner,Rosner PRL 119, 202001 (2017)
Eighten, Quigg PRL 119, 202002 (2017)
See also:
Esposito,Papinutto,Pilloni,Polosa,Tantalo PRD88, 054029 (2013)

Stable tetraquark, will decay weakly

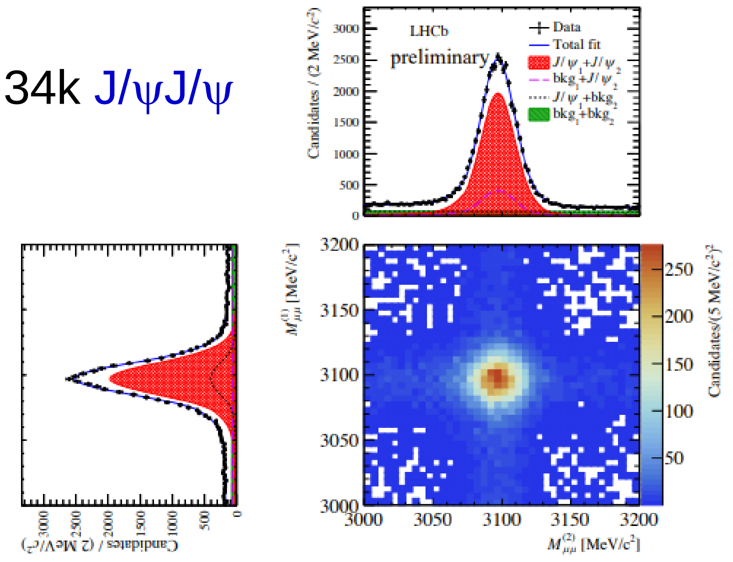
Consistent results predicted by LQCD: Francis,Hudspith,Lewis,Maltman PRL 1118,142001 (2017)

Future searches for such states above or below the $(Q\bar{q})(Q\bar{q})$ threshold will be very exciting

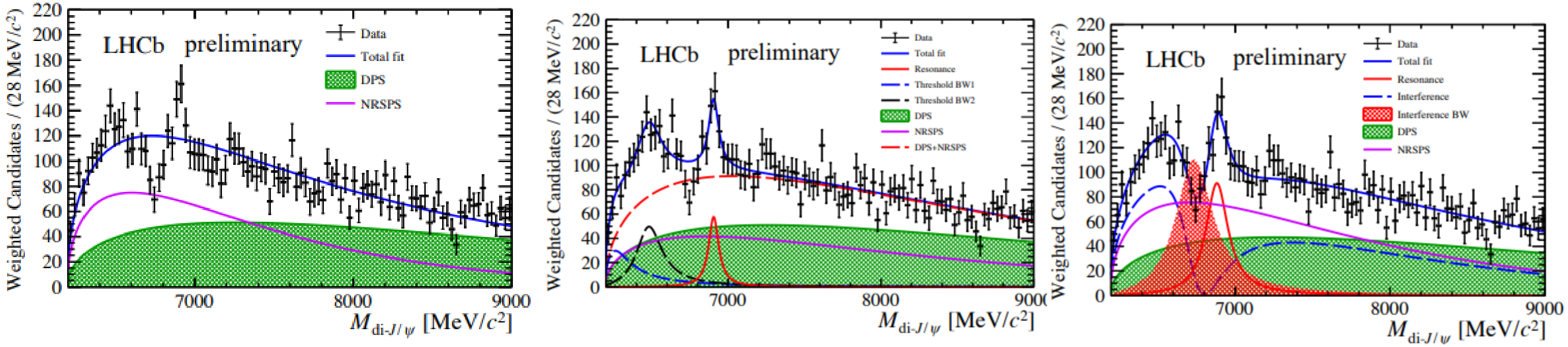
Doubly hidden-charm tetraquark?

LHCb-PAPER-2020-011 in preparation
Preliminary results shown at CERN seminar
Liupan An, June 16, 2020, 9 fb^{-1}

34k $J/\psi J/\psi$



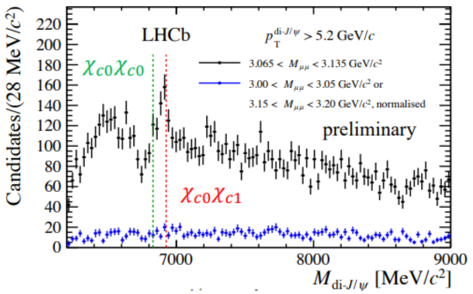
$T_{c\bar{c}c\bar{c}} \to J/\psi J/\psi \to (\mu^+\mu^-)(\mu^+\mu^-)$



Structure	Significance	
	$p_T^{\text{di-}J/\psi}$-threshold	$p_T^{\text{di-}J/\psi}$-binned
Any structure beyond NRSPS+DPS	$3.4\,\sigma$	$6.0\,\sigma$
threshold structure+6.9 GeV/c^2 peak	$6.4\,\sigma$	$6.9\,\sigma$
threshold structure	$6.0\,\sigma$	$6.5\,\sigma$
6.9 GeV/c^2 peak	$5.1\,\sigma$	$5.4\,\sigma$

preliminary

- Very significant structure in $J/\psi J/\psi$ mass is observed
- Interpretation is not clear:
  - one or more interfering resonances (diquark substructure?)
  - possible effects due to nearby $\chi_{c0}\chi_{c0,1}$ thresholds



This discovery opens a new chapter in heavy flavor hadron spectroscopy to be written by future measurements

Summary

- LHC offers enormous rates of heavy quarks via hadronic production cross-sections and large instantaneous luminosity
- Good place to study hadron spectroscopy with heavy quarks, including multi-quark exotics
- LHCb is well suited for such studies, thanks to hadron ID and large trigger bandwidth devoted to heavy flavors
  - Several ground-breaking discoveries ($J/\psi p$ pentaquarks, doubly-charmed baryons, very recently $J/\psi J/\psi$ states)
- Near and farther future upgrades of the LHCb detector to take better advantage of the opportunity offered by the LHC