XYZ states at upgraded LHCb

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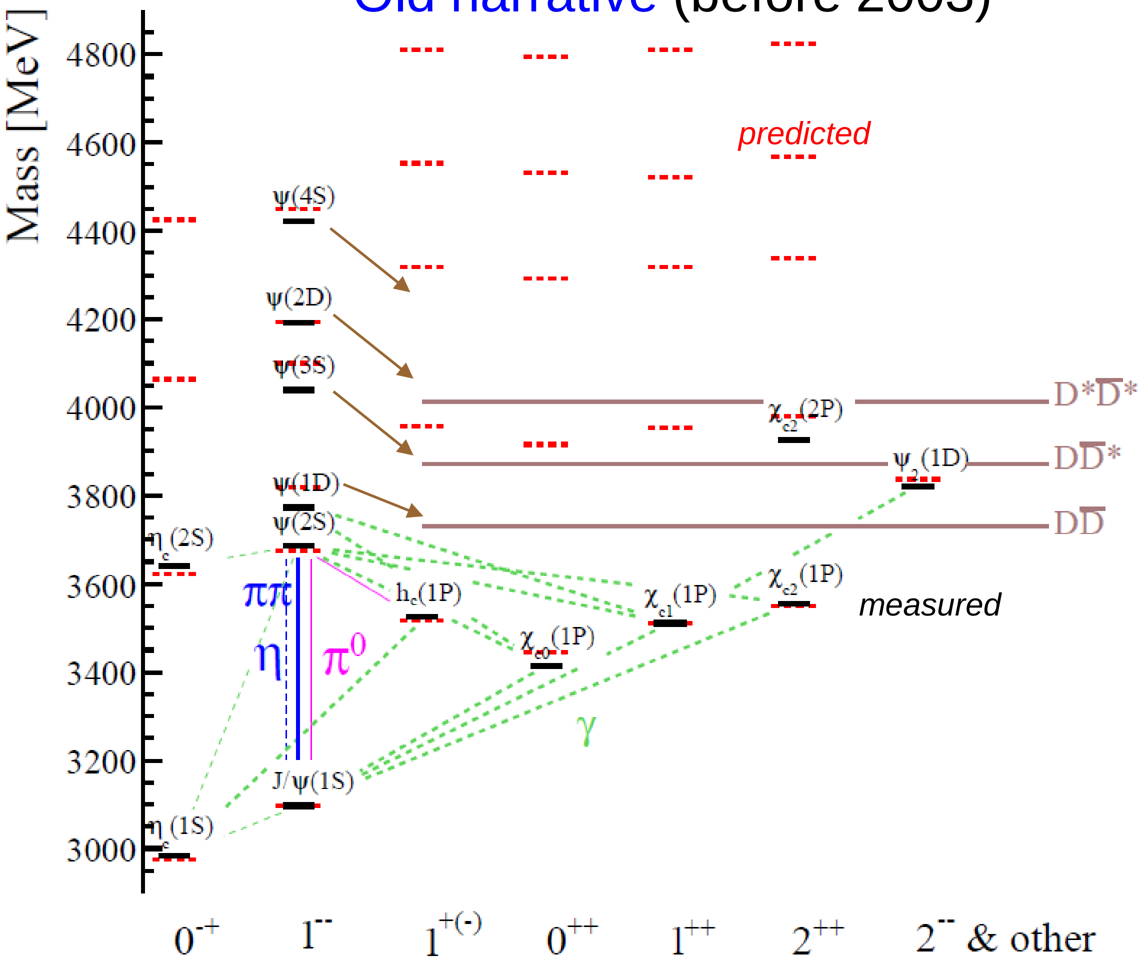
New particle zoo: charmonium above flavor threshold

Above the flavor threshold: More exotic states than $c\bar{c}$ states!

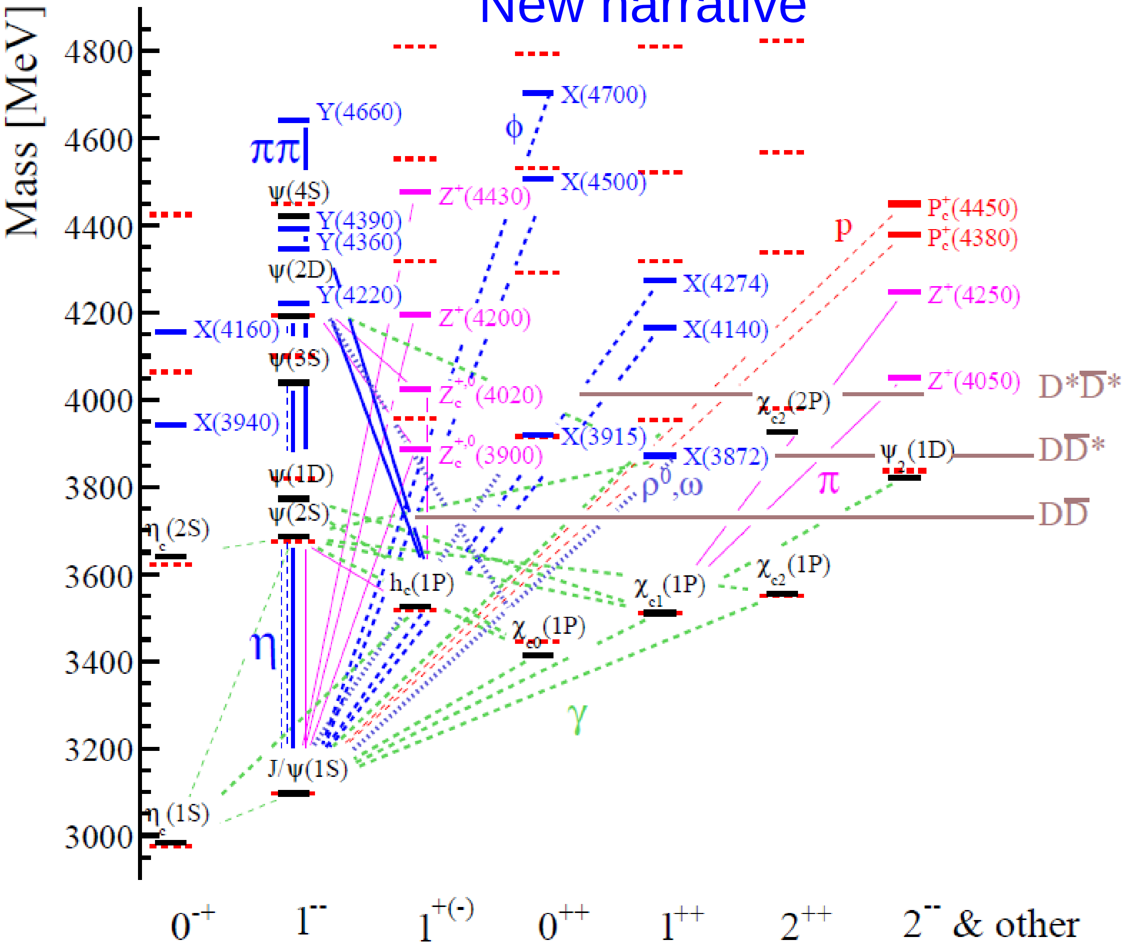
Old narrative (before 2003)



Figures from Olsen,Skwarnicki,Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

Mesons are $(q\bar{q})$ bound states.

New narrative



Mesons are **predominantly** $(q\bar{q})$ bound states below the open flavor threshold. **They are more complex structures above it,** and we have not yet understood them.

All excited light hadrons are above "the open flavor threshold"!

Preface to this talk

It’s Difficult to Make Predictions, Especially About the Future

of the field with poorly understood phenomenology

- The latter makes it a very interesting physics to pursue
- Illustrate future capabilities on a few selected examples

LHCb data samples: present & future

Belle II

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
LHCb Int. Lumi.	$3\ fb^{-1}$ →	$8\ fb^{-1}$	→	$50\ fb^{-1}$	$300\ fb^{-1}$
Inst. Lumi.	$4 \times 10^{32}\ cm^{-2}s^{-1}$		$2 \times 10^{33}\ cm^{-2}s^{-1}$		$2 \times 10^{34}\ cm^{-2}s^{-1}$
$\sqrt{s_{pp}}$	7-8 TeV	13 TeV	14 TeV	14 TeV	14 TeV (27 TeV HE-LHC?)

Limited by LHCb detector ≪ LHC Lumi.

Most of the published analyses (see Anton Poluektov's talk)

Phase I upgrade (under construction)

Overhaul of the detector!

I b

new components

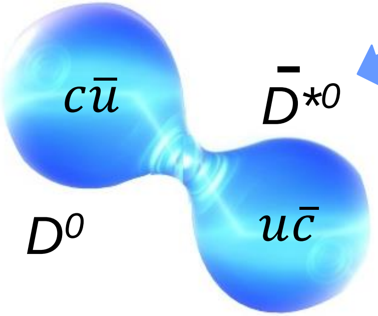
Phase II upgrade (proposed)

Overhaul of the detector!

For details see Alexey Dzyuba's talk this morning!

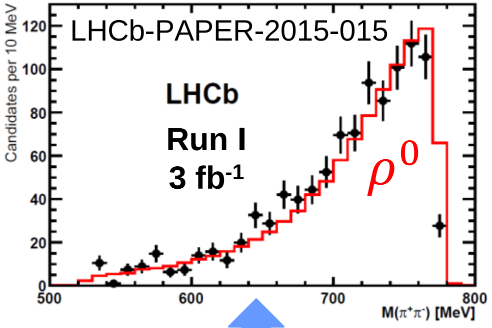
X(3872) is still a puzzle !

Mass near $D^0\bar{D}^{*0}$ threshold !

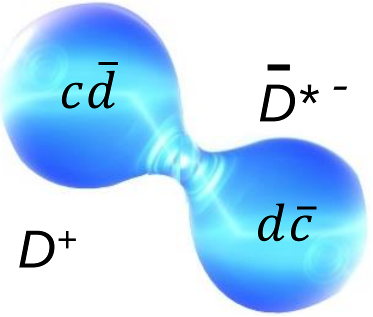


Enhanced isospin violating decays

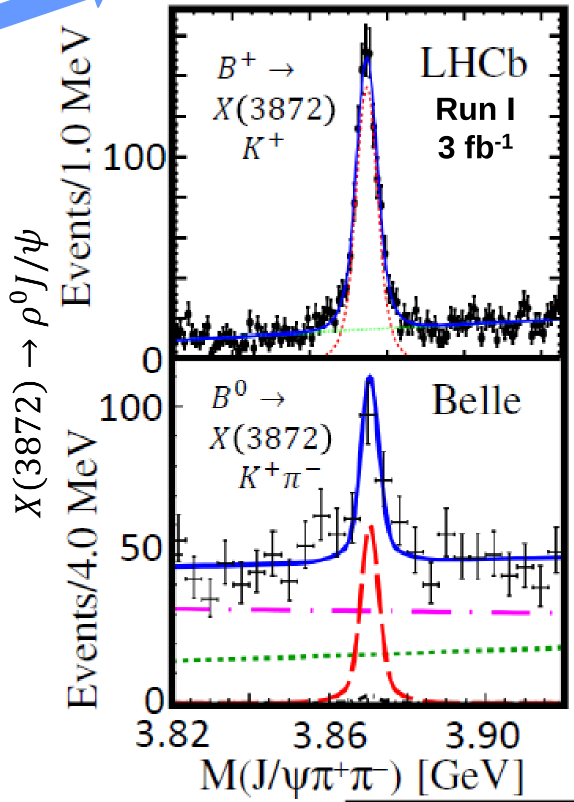
$X(3872) \to \rho^0 J/\psi$

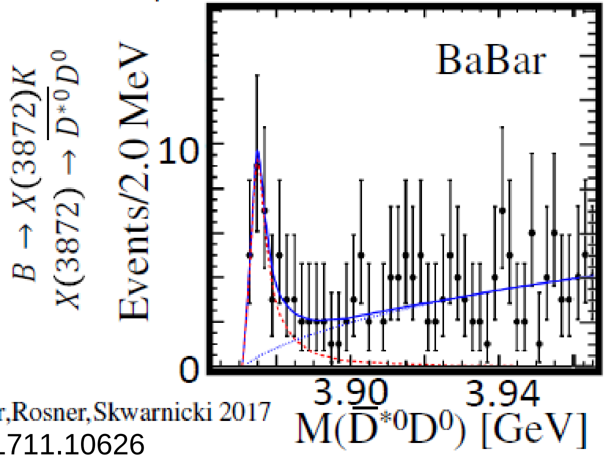


only small admixture of



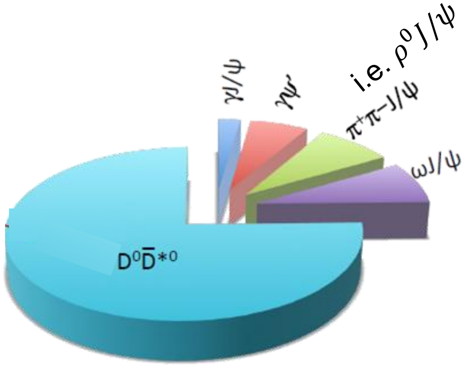
Narrow width in decays to $c\bar{c}$





Karliner,Rosner,Skwarnicki 2017
arXiv:1711.10626

Known decay rates:

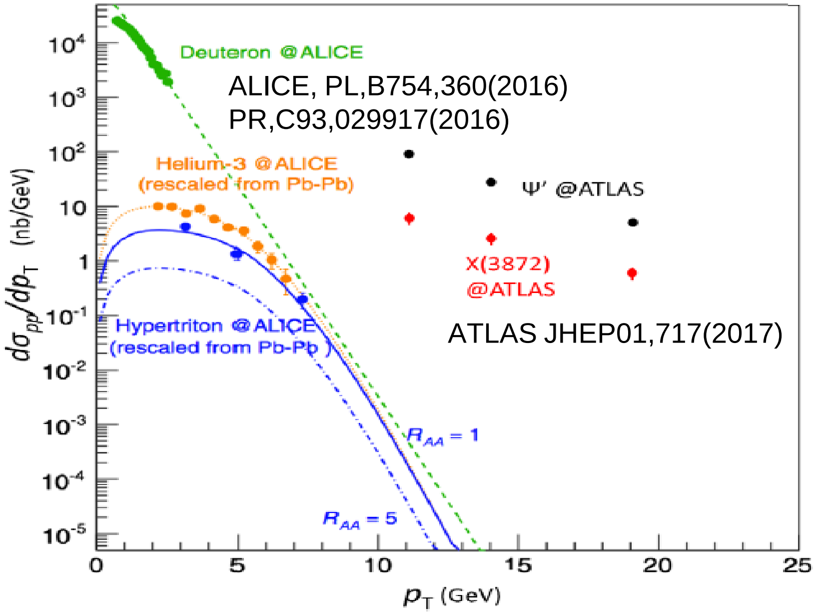


Huge fall-apart mode from the resonance tail above the $D^0\overline{D^{*0}}$ threshold

0^-1^- interacting in S-wave compatible with $J^{PC}=1^{++}$

molecular features

Charmonium-like prompt production rates



A.Esposito et al. PRD92, 034028 (2015)
(ATLAS data inserted by S.Olsen)

Charmonium-like pattern of radiative decays

LHCb $\frac{BR(X(3872)\to\psi(2S)\gamma)}{BR(X(3872)\to J/\psi(1S)\gamma)}$ = 2.48±0.64±0.29 (>0 at 4.4σ)

LHCb-PAPER-2014-008

unlike a molecule

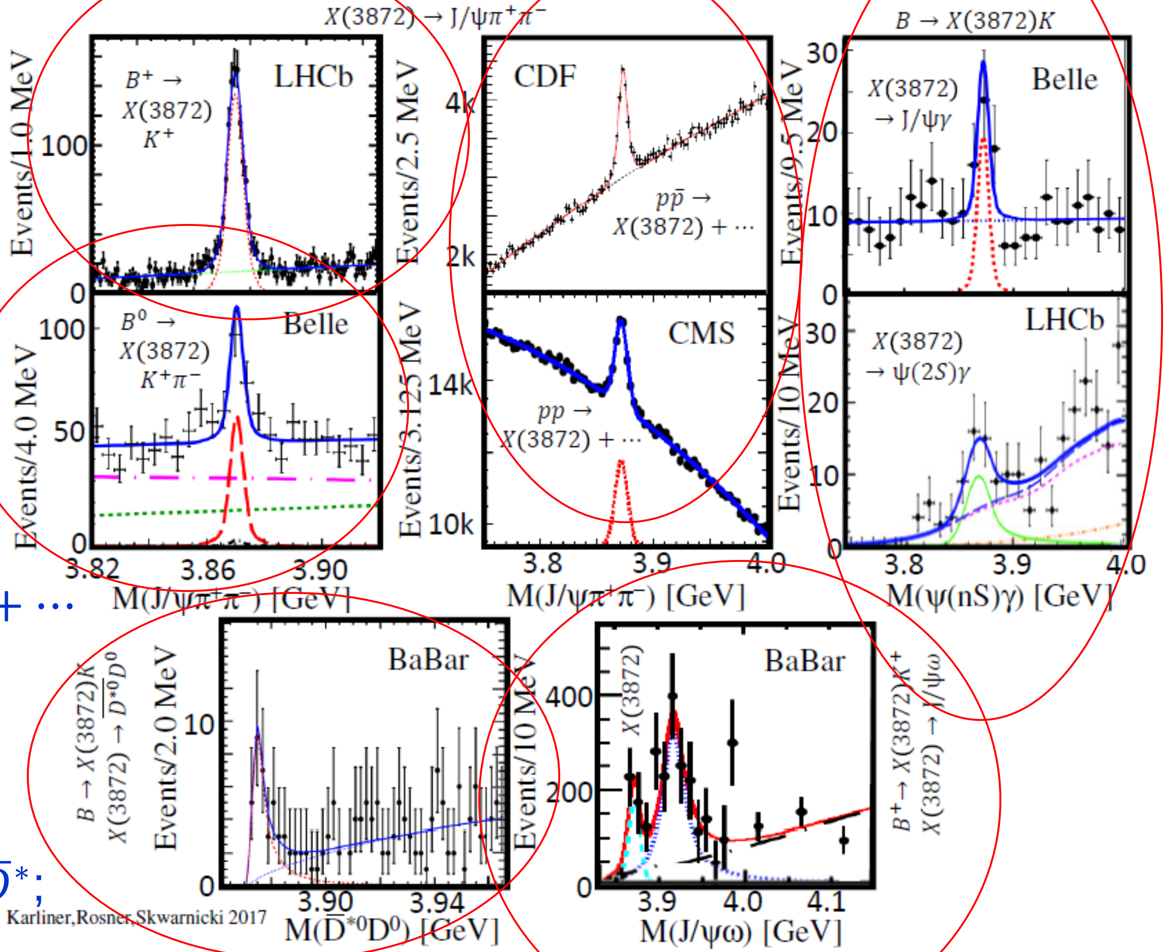
Experimental prospects for X(3872) at LHCb

Mass and natural width of X(3872)

Details of prompt production in forward region at LHC

Improve statistical errors on radiative decays of X(3872)

More production modes $B_s, B_c, \Lambda_b \to X(3872) + \cdots$



Study line shape in $D\bar{D}^*$; coupled-channel line-shape fit

Phase II

Improve statistical errors on X(3872)→ ωJ/ψ (clarify 2nd peak: X(3915))

(crude projections)

	LHCb 3 fb^{-1}	LHCb 8 fb^{-1}	U. Phase I 50 fb^{-1}	U. Phase II 300 fb^{-1}	Belle 0.7 ab^{-1}	Belle II 50 ab^{-1}
Decay mode						
$B^+ \to K^+X(3872)$ $(\to J/\psi\pi^+\pi^-)$	1k	5k	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	2.4k	15k	90k	36	2k

Look for: Phase I-II

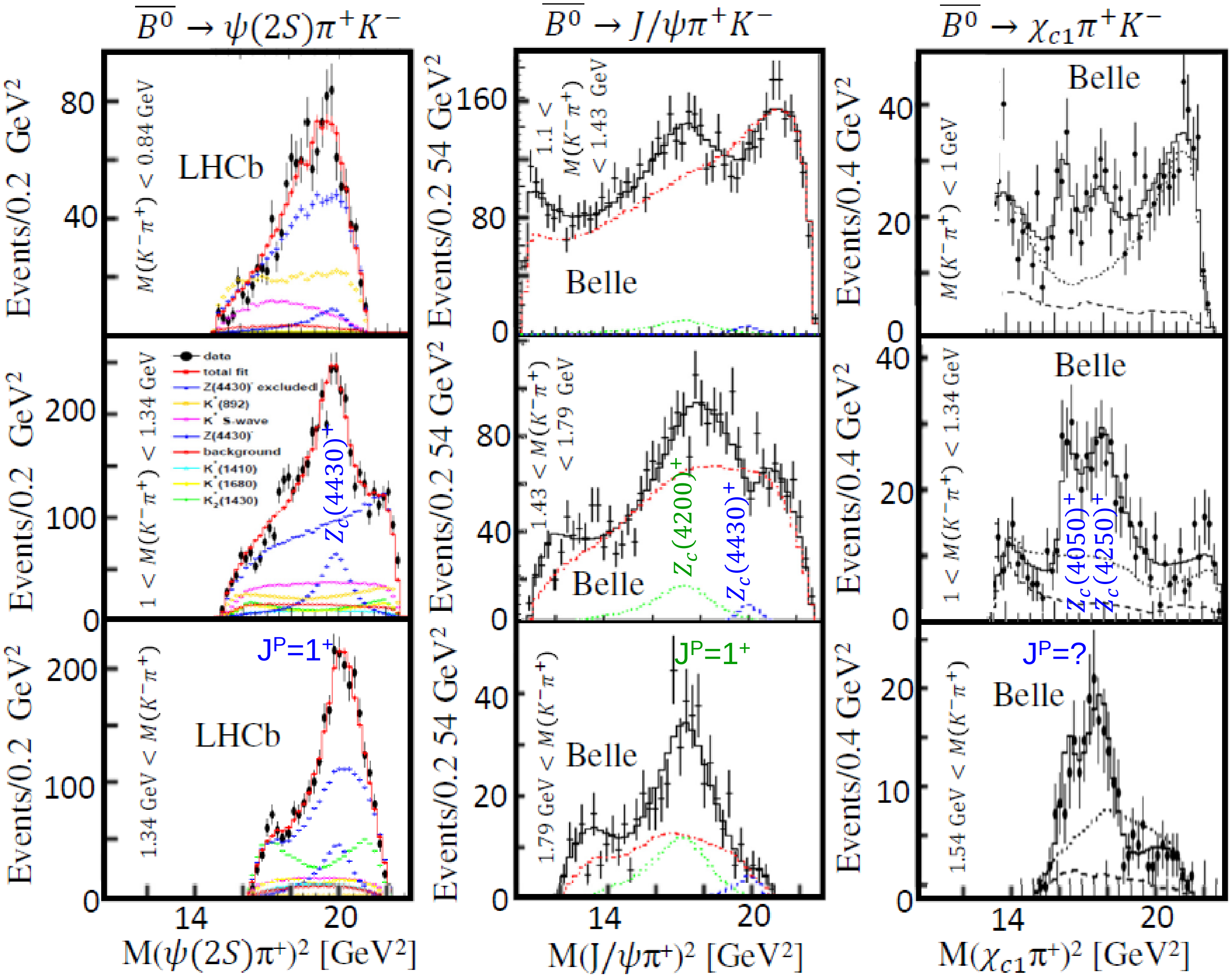
$X(3872) \to \pi^+\pi^-\chi_{c1}(1P)$

since

$\mathrm{BR}(\chi_{b1}(2P) \to \pi^+\pi^-, \pi^0\pi^0\chi_{b1}(1P))$
$=(0.9 \pm 0.1)\%$

Charged charmonium-like states in B decays

Amplitude analyses used to distinguish $\overline{K^{*0}} \to \pi^+ K^-$ and $(c\bar{c})\pi^+$ contributions



$\Gamma_{Z(4430)}$=181±31 MeV

$\Gamma_{Z(4200)}=370^{+100}_{-150}$ MeV

$Z_c(4200)^+$, $Z_c(4050)^+$, $Z_c(4250)^+$ await confirmation (LHCb has enough data to do it already)

$Z_c(3900)^+$ and $Z_c(4020)^+$ observed in $e^+e^- \to \pi^- Z_c^+$, not observed in $B \to K\,Z_c^+$, (and vice versa).

Sensitivity to production mechanism, points to hadron-level interactions.

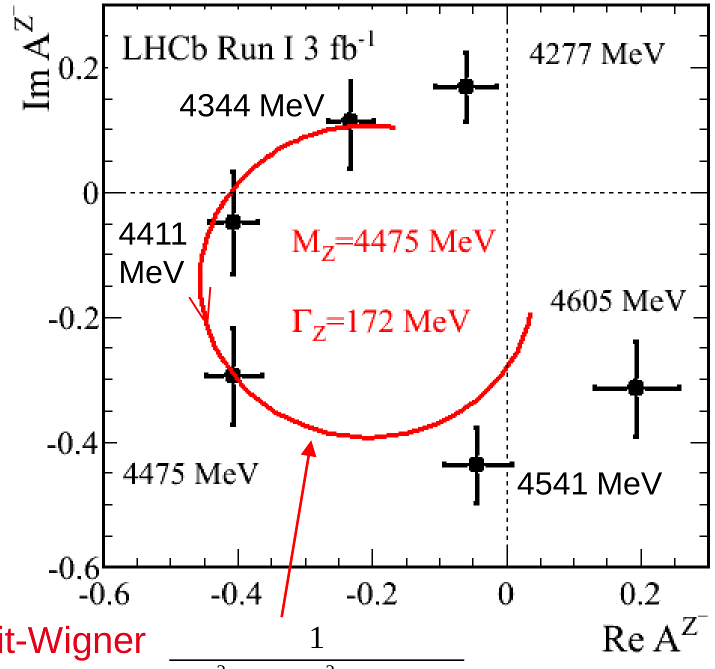
No clear explanations.

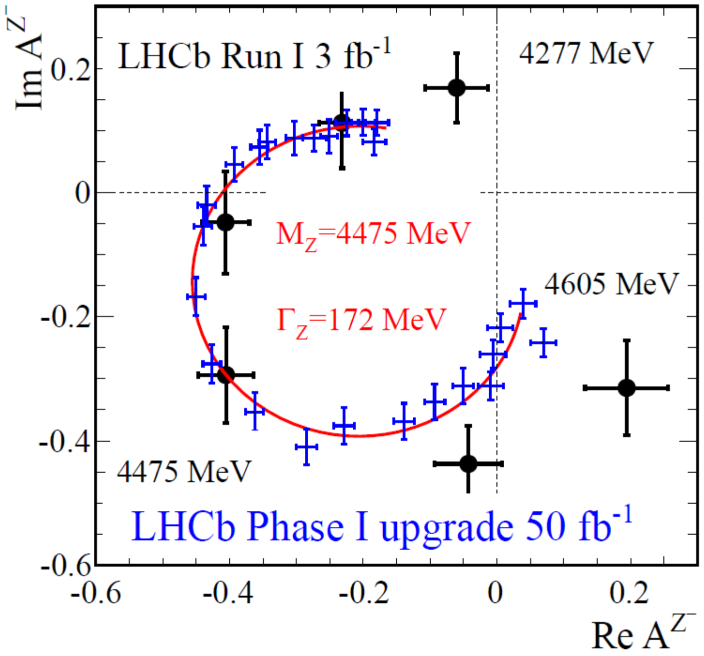
- Too broad to be molecular bound states?
- No tetraquark model can accommodate all of them.
- Rescattering effects?
- Artifacts of complicated amplitude analyses?

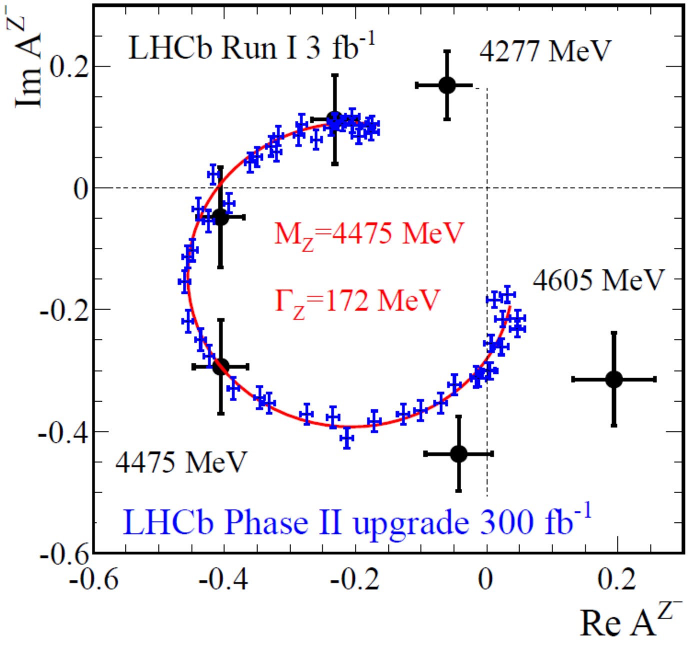
Resonant structure of Z(4430)$^-$?

- Detailed studies of “exotic” amplitudes desired to shed light onto their nature: example Argand diagram of $Z(4430)^- \to \psi(2S)\pi^-$.

LHCb-PAPER-2014-014





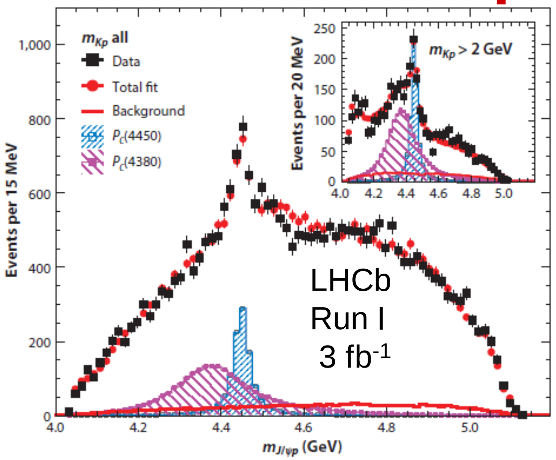


Breit-Wigner amplitude $\dfrac{1}{M_Z^2 - m_{\psi'\pi^+}^2 - i M_Z \Gamma_Z}$

	LHCb		U. Phase I	II	Belle	II
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}	0.7 ab^{-1}	50 ab^{-1}
$B^0 \to \psi(2S)\pi^- K^+$	25k	0.13M	0.8M	5M	2k	0.14M
$B^0 \to J/\psi(1S)\pi^- K^+$	0.4M	1.5M	10M	62M	30k	2M

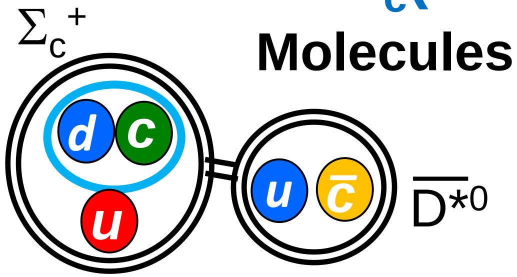
Statistical accuracy will be sufficient to distinguish between resonant poles and cusps. Systematic errors (e.g. K* model dependence) hard to predict.

Interpretations of $P_c(4450)^+$, $P_c(4380)^+$?



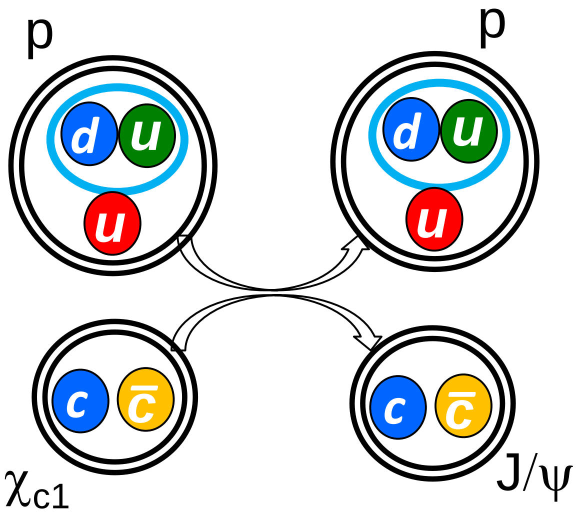
LHCb-PAPER-2015-029

Molecules

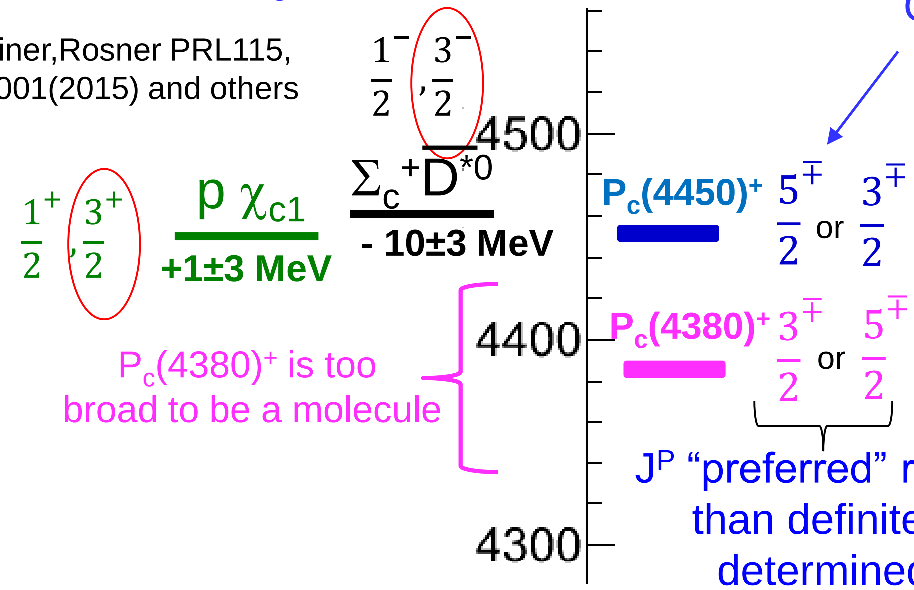


No $\frac{5}{2}^{\pm}$ molecules in this mass range

Karliner,Rosner PRL115, 122001(2015) and others



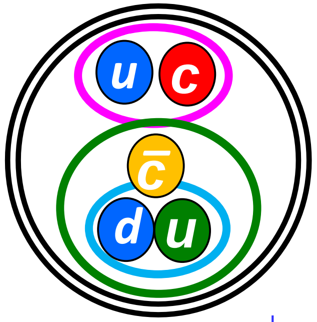
Realistic **rescattering mechanisms (cusps, triangle anomalies)** have the same J^P selection rules as realistic molecular models (must happen in S-wave)



$P_c(4380)^+$ is too broad to be a molecule

J^P "preferred" rather than definitely determined

Tightly-bound penatquark



Can accommodate $\frac{5}{2}^{\pm}$ when at least one diquark in $S=1$ state

Maiani et al PLB749, 289 (2015) and many others

Such mass difference and the opposite parity can be explained by $\Delta L=1$ and $\Delta S=1$

It is crucial to determine J^Ps!

More robust verifications of resonant hypothesis.

Study related channels (see next).

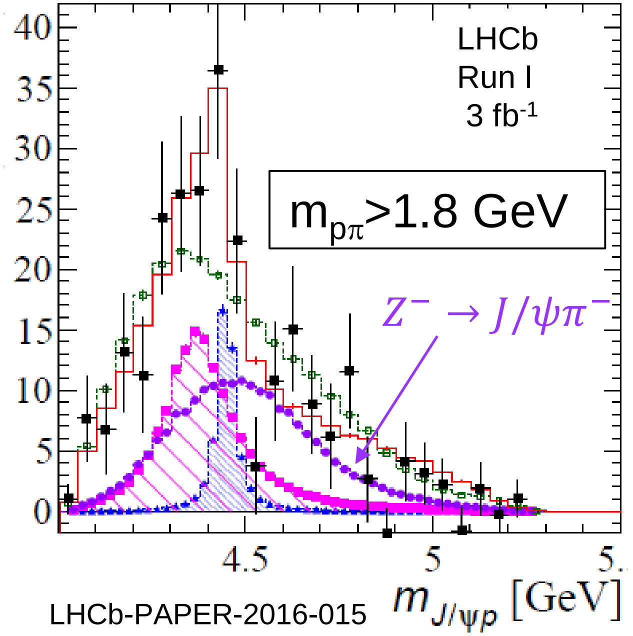
	LHCb		U. Phase I	Phase II
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\Lambda_b \to J/\psi p K^-$	25k	0.13M	0.8M	5M

Other channels related to $P_c(4450)^+$, $P_c(4380)^+$

	LHCb		U. Phase I	Phase II
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\Lambda_b \to J/\psi p K^-$	26k	0.13M	0.8M	5M
$\Lambda_b \to J/\psi p \pi^-$	1.9k	10k	63k	0.4M
$\Lambda_b \to \chi_{c1} p K^-$	0.45k	2.2k	15k	0.1M
$\Lambda_b \to J/\psi p K_s^0 \pi^-$				
$\Lambda_b \to J/\psi p \bar{p}$				
…				

Upgrade statistics will allow for amplitude analyses of sensitivity comparable (much better) than in the discovery paper

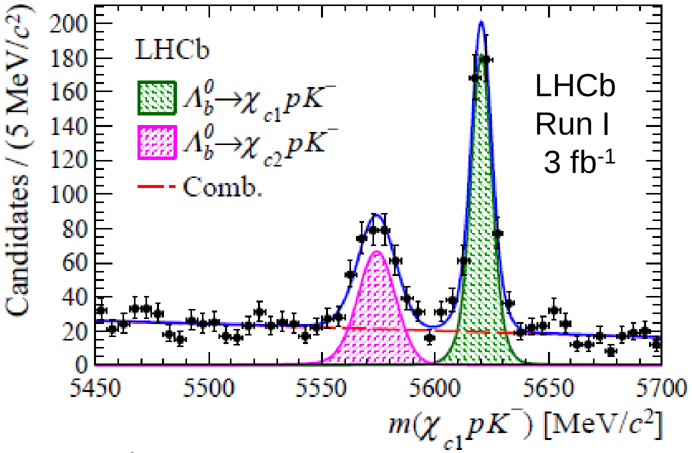
$\Lambda_b \to J/\psi p \pi^-$



LHCb-PAPER-2016-015

Hints of $J/\psi p$ structure; complicated by ambiguities with $Z^- \to J/\psi\pi^-$

A coupled-channel to $J/\psi p$. The $\chi_{c1} p$ mass threshold near $P_c(4450)^+$.



LHCb-PAPER-2017-011

Isospin partners of $P_c(4450)^+$, $P_c(4380)^+$?

- $I_3(J/\psi p) = +\frac{1}{2}$
- Whatever the nature of these states is, $I_3(J/\psi n) = -\frac{1}{2}$ partners should exist. Unfortunately neutrons are not detectable in LHCb.
- However such states can decay to open charm final states

J/ψ n

$\bar{c}cudd$

$\Lambda_b \rightarrow \bar{K}^{*0} + \ldots$ Λ_c^+ $D^{(*)-}$

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

$\bar{K}^{*0} \rightarrow K^-\pi^+$

$D^- \rightarrow K^+\pi^-\pi^-$

$D^{*-} \rightarrow D^0\pi^-, D^0 \rightarrow K^+\pi^-$

- Relative to $J/\psi(\rightarrow \mu^+\mu^-)p$ extra 4 tracks to reconstruct and no dimuon to trigger on (efficiency loss by a factor of ~50).
- Upgrade luminosities are essential to reach sensitivity in these channels

- If $I(J/\psi p) = \frac{3}{2}$ then also

J/ψ p

$\bar{c}cuud$

$\Lambda_b \rightarrow K^- + \ldots$

Σ_c^{++} D^-

$\Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$

Doubly-charged partner (prompt production?)

J/ψ Δ^{++}

$\bar{c}cuuu$

$\Lambda_b \nrightarrow$

Σ_c^{++} $\overline{D^0}$

$\Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$

U-spin partners of $P_c(4450)^+$, $P_c(4380)^+$?

- Strange partners:

$\Lambda \to p\pi^-$

J/ψ Λ

$\bar{c}cuds$

$\Xi_b^- \to K^- + \ldots$ Λ_c^+ D_s^-

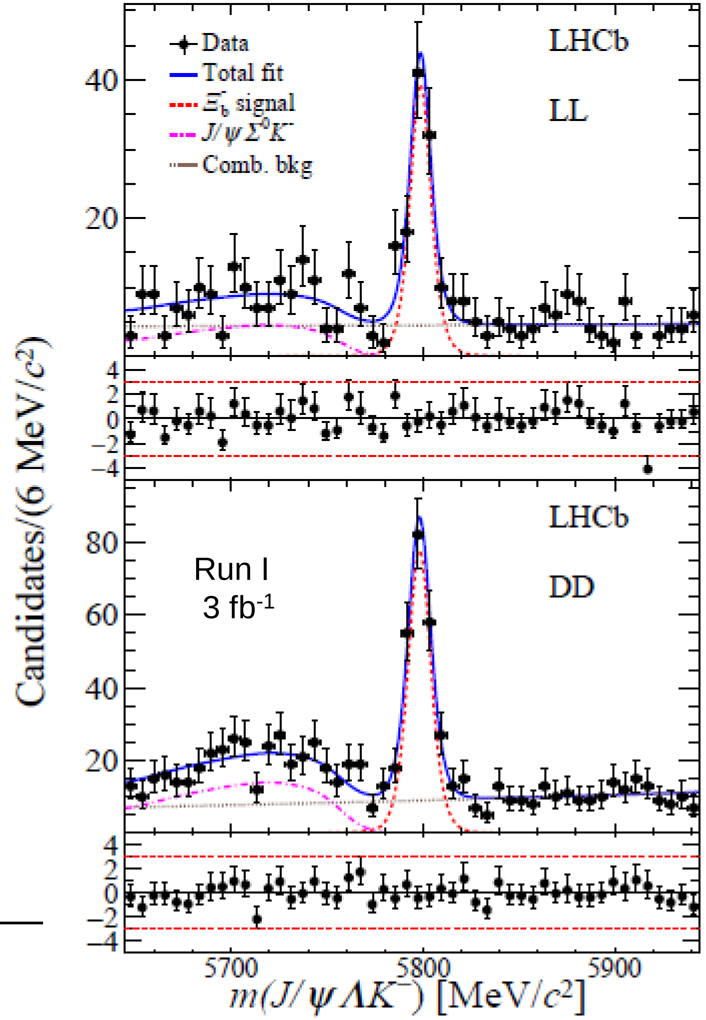
$\Lambda_b \to \phi + \ldots$ $\Lambda_c^+ \to pK^-\pi^+$

$\phi \to K^-K^+$ $D_s^- \to K^+K^-\pi^-$

	LHCb		U. Phase I	U. Phase II
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\Lambda_b \to J/\psi\Lambda\phi$	80	0.4k	3k	16k
$\Xi_b^- \to J/\psi\Lambda K^-$	300	1.6k	10k	60k

This will allow amplitude analyses

[PLB 772 (2017) 265]



LHCb-PAPER-2016-053

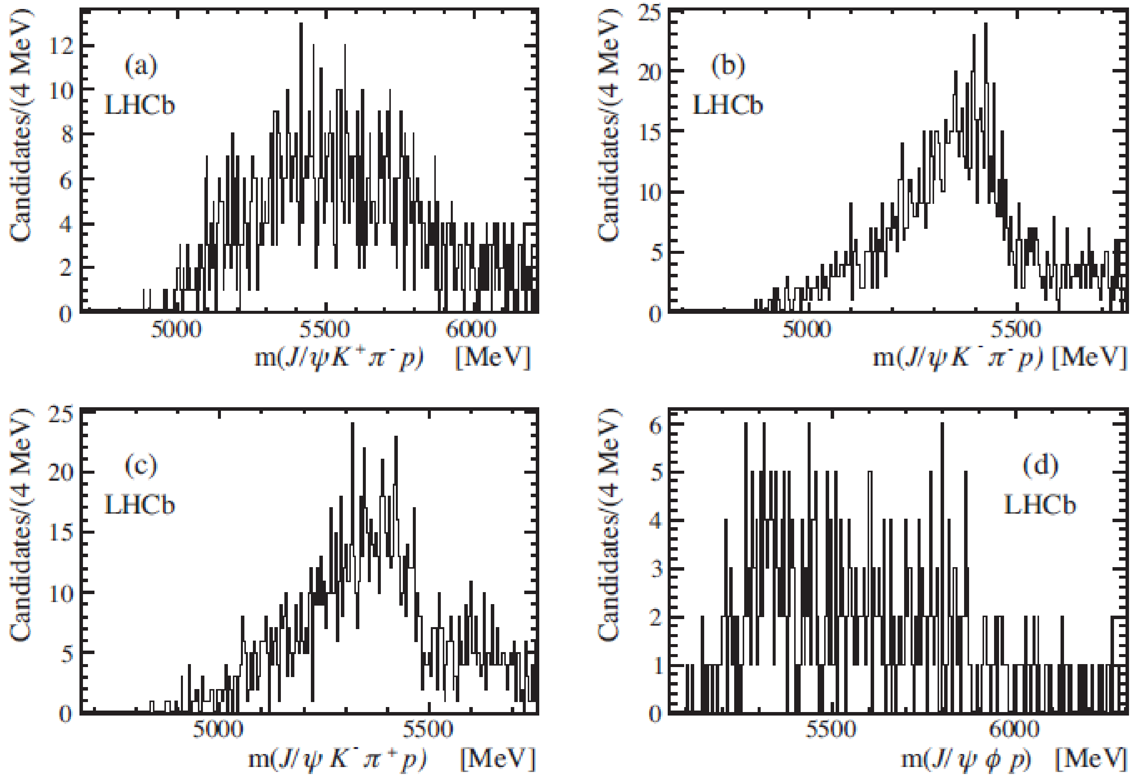
Beautiful analogs of $P_c(4450)^+$,$P_c(4380)^+$?

- Binding of hadrons with beauty quark(s) is "deeper" than with charm quark(s)
- If molecular structures, then masses must be very near relevant baryon-meson thresholds ($\Sigma_b B^*, \Sigma_b^* B$, $\Sigma_b^* B^*$, $\Lambda_b B^*$, $\Lambda_b^* B$)
- Beautiful analogs of the P_c^+ states ($\bar{b}buud$) would decay to easily detectable final state: $\Upsilon(\rightarrow \mu^+\mu^-)p$ (if $\bar{b}busd$ exists in $\Upsilon(\rightarrow \mu^+\mu^-)\Lambda$)
- Unfortunately, can only be searched for in prompt production:
  - Large backgrounds from protons produced in primary pp collision (no secondary vertex formed)
  - If compact pentaquarks then prompt production can be sizeable, but prompt production of the P_c^+ states have not been observed so far

Beautiful $\bar{b}qqqq$ pentaquarks with lifetime

- If binding was large enough, the lightest ones might have masses below the relevant baryon-meson threshold and decay weakly
- A secondary vertex eliminates combinatorial background from the particles produced at the primary vertex
- LHCb has searched for stable $\bar{b}duud$, $\bar{b}suud$, $b\bar{u}udd$, $b\bar{d}uud$ in $J/\psi ph^+h^-$ ($h = K$ or π) in Run I; found no evidence, and set upper limits on their production rate
- Such searches will have a better sensitivity with larger integrated luminosity

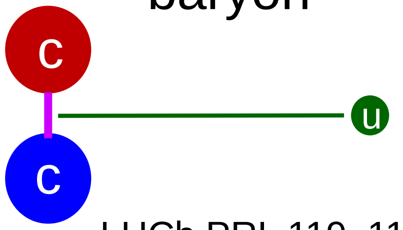
Run I
3 fb^{-1}



LHCb-PAPER-2017-043

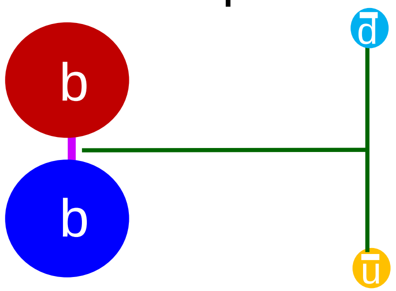
Doubly-flavored tetraquarks

baryon

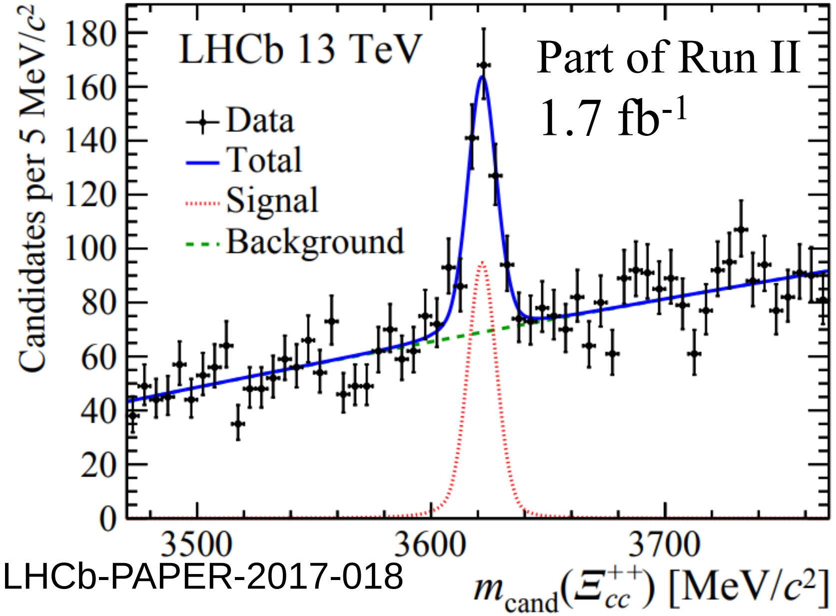


Replace the light quark with light anti-diquark in color triplet configuration

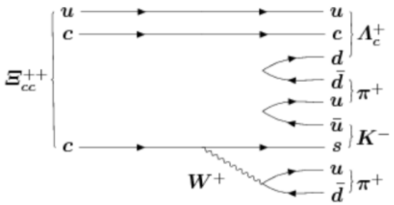
tetraquark



LHCb PRL 119, 112001 (2017)

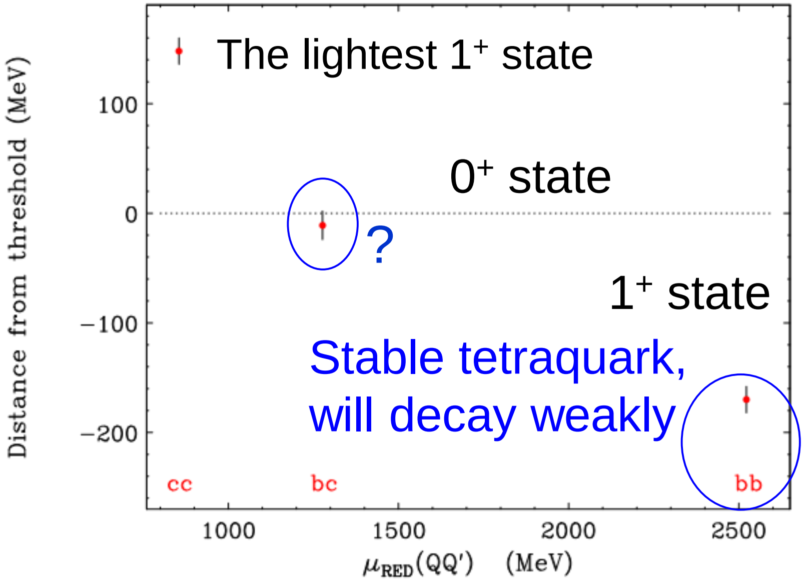


LHCb-PAPER-2017-018



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

the same toolkit



Karliner,Rosner PRL 119, 202001 (2017)

See also:

Eighten, Quigg PRL 119, 202002 (2017);

Esposito,Papinutto,Pilloni,Polosa,Tantalo PRD88, 054029 (2013); and others

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

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	...
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621 ± 1

Detection of stable 1$^+$ $bb[\overline{ud}]$ tratraquark?

- It would have observable lifetime, thus combinatorial background would be under control
- CMS claimed observation of 38 ± 7 $(\Upsilon \to \mu^+\mu^-)(\Upsilon \to \mu^+\mu^-)$ events $(b\bar{b} + b\bar{b})$ in 21 fb^{-1} of 8 TeV data JHEP 1705, 013 (2017).
- Unfortunately bbq baryons have not been detected yet, reflecting low prompt production rates expected for both b quarks to end up in the same hadron, and difficulty in reconstruction of two subsequent weak decays of b quark.
- Dominant decays via $b \to cW^{*-}$ leading to final states $D^0\bar{B}^0\pi^-$, $\boldsymbol{D^+B^-\pi^-}$ $(W^{*-} \to \bar{u}d)$ and $J/\psi K^-\bar{B}^0$, $J/\psi\bar{K}^{(*)0}B^-$, $D^+B^-D_s^-$ $(W^{*-} \to \bar{c}s)$ plus possibly extra pions and heavy mesons in excited states.
- Decay modes with $\bar{B}^0$ or D^0 do not cleanly tag the heavy flavor due to mixing and doubly-Cabibbo suppressed decays of D^0 (causes backgrounds from $b\bar{b}$ production).
- **Inclusive reconstruction efficiencies for $\boldsymbol{B}$ mesons are low at LHCb dues to low branching fractions into low multiplicity final states**
- **Tough prospects even for Phase II upgrade!**
- Look out for detection of bbq baryons as a prelude for any hope for detection of such tertraquarks

Detection of $bc[\overline{ud}]$ tratraquark?

- More favorable prompt production rates. In fact, thousands of B_c^+ $(\bar{b}c)$ have been detected by LHCb already. bcq baryons are expected to be first detected in Phase I, up to a few thousand reconstructed in Phase II.
- Possibly the lightest 0^+ state is stable. The most promising decay modes from $b \to cW^{*-}$: $D^+D^+\pi^-\pi^-$ $(W^{*-} \to \bar{u}d)$, $J/\psi D^+K^-$ $(W^{*-} \to \bar{c}s)$ or $c \to sW^{*-}$: $B^-K^-\pi^+\pi^+$ $(W^{*-} \to \bar{u}d)$. Only one b quark decay to deal with – product branching fractions are more favorable.
- If not stable, then decaying strongly but rather narrow state, just above the $\bar{B}^0D^0$ threshold, with B^-D^+ as the most favorable final state to reconstruct in LHCb.

Detection of $cc[\overline{ud}]$ tratraquark?

- Prompt production of ccq baryon has been already detected!

	LHCb		U. Phase I	II
Decay mode	1.7 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	0.3k	2.2k	14k	90k

- The lightest 1^+ state expected to be above the threshold for electromagnetic decay to $D^0 D^+ \gamma$, thus be very narrow but have no detectable lifetime.
- Not suitable for detection at LHCb, unless its mass is slightly above the threshold for strong decay to $D^+ D^+ \pi^-$. It would be still narrow due to phase space suppression.
- Allowing strange quark in the mix, $cc[\overline{sd}], cc[\overline{us}]$, tetraquark is not as well bound and would be broader. Nevertheless, B_c^+ ($\bar{b}c$) decays, due to $\bar{b} \to \bar{c}W^{*+}$, $W^{*+} \to c\bar{s}$ with $d\bar{d}$ or $u\bar{u}$ popping provides a clean production environment (B_c^+ lifetime!) [see Esposito et al PRD88, 054029 (2013)]. Expect about 100 $B_c^+ \to D_s^+ D^0 \overline{D}^0$ events detected in Phase II.

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:
- Unique gateway to states produced in decays of b-baryons, B_c
- LHCb is well suited for such studies, thanks to hadron ID and large trigger bandwidth devoted to heavy flavors
- Near and farther future upgrades of the LHCb detector to take better advantage of the opportunity offered by the LHC:
  - Precision studies on already observed exotic hadron candidates
  - Hopes for detection of stable or very narrow doubly-flavored tetraquarks
  - Judging from the recent history we should also expect unexpected!