Hadron Spectroscopy and Exotic Searches at LHCb

Elisabetta Spadaro Norella
on behalf of LHCb collaboration

LFC19
Trento, 10/09

Outline

- Introduction
- LHCb experiment
- Highlights on exotic searches at LHCb
- The ‘pentaquark’ case
    - New results on $\Lambda_b \to J/\psi p K$
    - study of $B^0_{(s)} \to J/\psi p \bar{p}$ decay

Elisabetta Spadaro Norella
LFC19

Quark model

SCHEMATIC MODEL OF BARYONS AND MESONS *

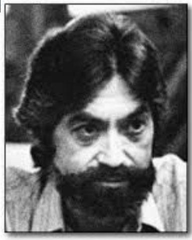
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowes

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva



general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

- Multiquark hadrons are called exotics:
  - ‘tetraquark’ with 4 quarks
  - ‘pentaquarks’ with 5 quarks
- Many exotic searches in the light-quarks sector without success:
  - too many broad overlapping states
  - Relativistic treatment of *u, d, s* quark components

→ 30 exotics states seen in heavy-quark sector

Heavy-quarkonia spectra

[S. L. Olsen, T. Skwarnicki, and D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003]

- Charmonium (cc-bar) and bottonium (bb-bar) spectra can be described by a semi-relativistic phenomenological potential (effective Cornell pot.)

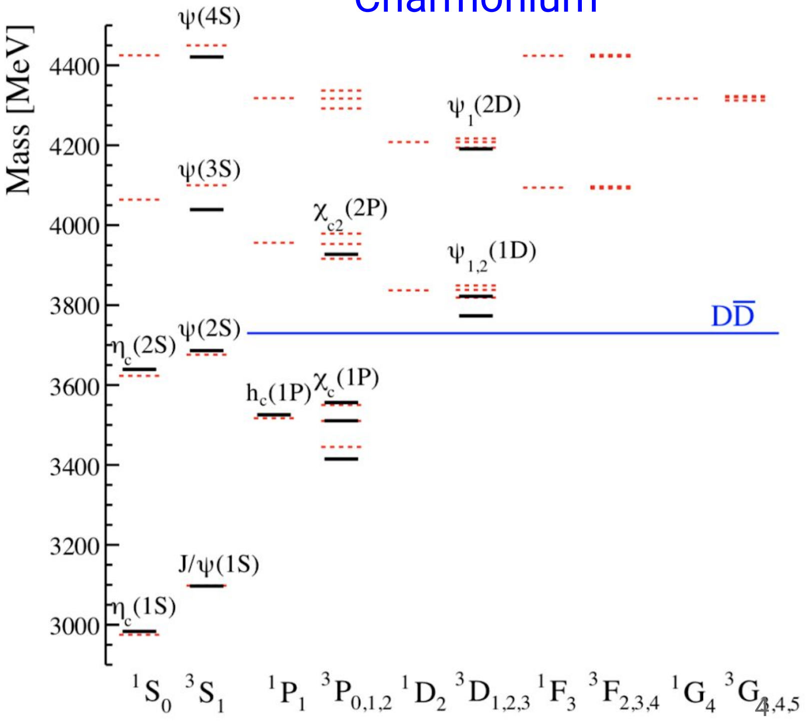
$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + \sigma r + \delta(1/r^2)$$

  - short-distance color potential
  - long distance confinement term
  - spin-spin, spin-orbit corrections

Good place to search for **exotics**:

- Few missing states below open-charm (bottom) threshold
- narrow and non overlapping states

Charmonium

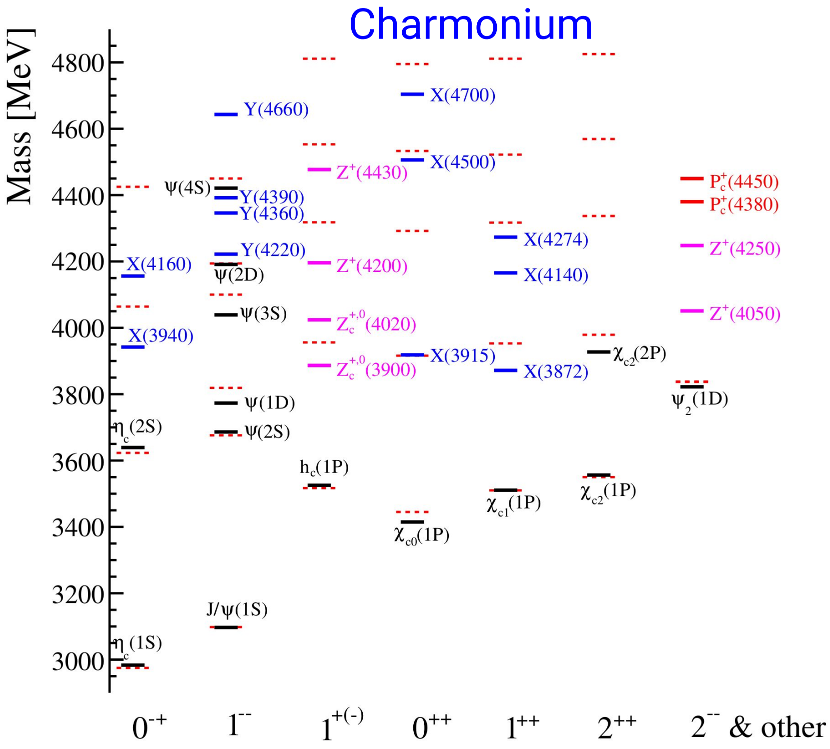


Elisabetta Spadaro Norella

Heavy-quarkonia spectra

- Exotics states classify as
  - $qq\bar{q}\bar{q}$: X, Y (neutral), Z^+ (charged, $J^{PC}=1^{--}$)
  - $qqqq\bar{q}$: P^+_c
- composed by cc-bar because they decay to charmonia
- not standard hadrons because do not overlap with predicted levels
- too much narrow to be above open charm threshold
  - example of X(3872): first exotic measured by Belle (2003)

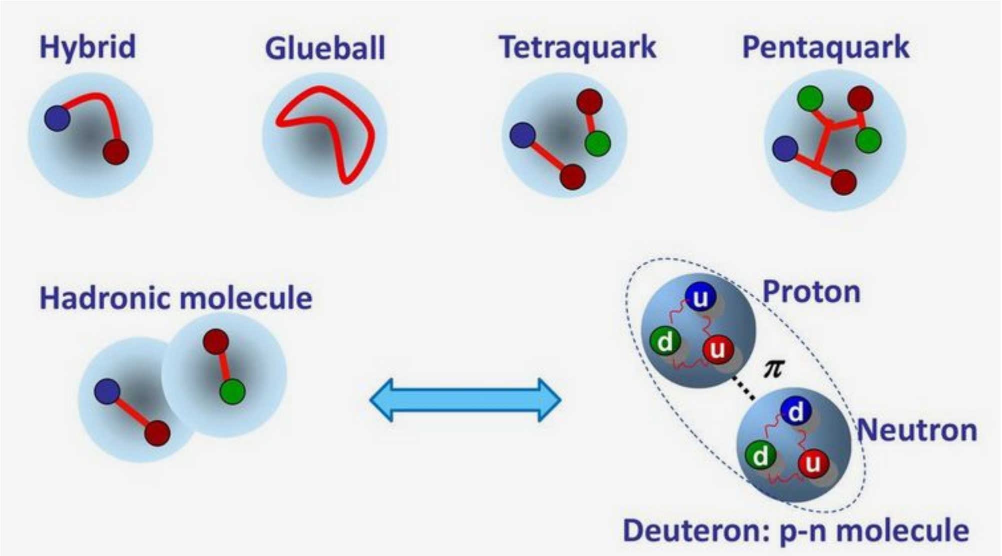
→ **more complex internal structures**



Multiquark models

Not clear picture, a lot of different models:

- tight tetra or pentaquarks
- molecules of meson-meson, meson-baryon
- hybrid-meson
- ...
- or rescattering effects → triangle diagrams

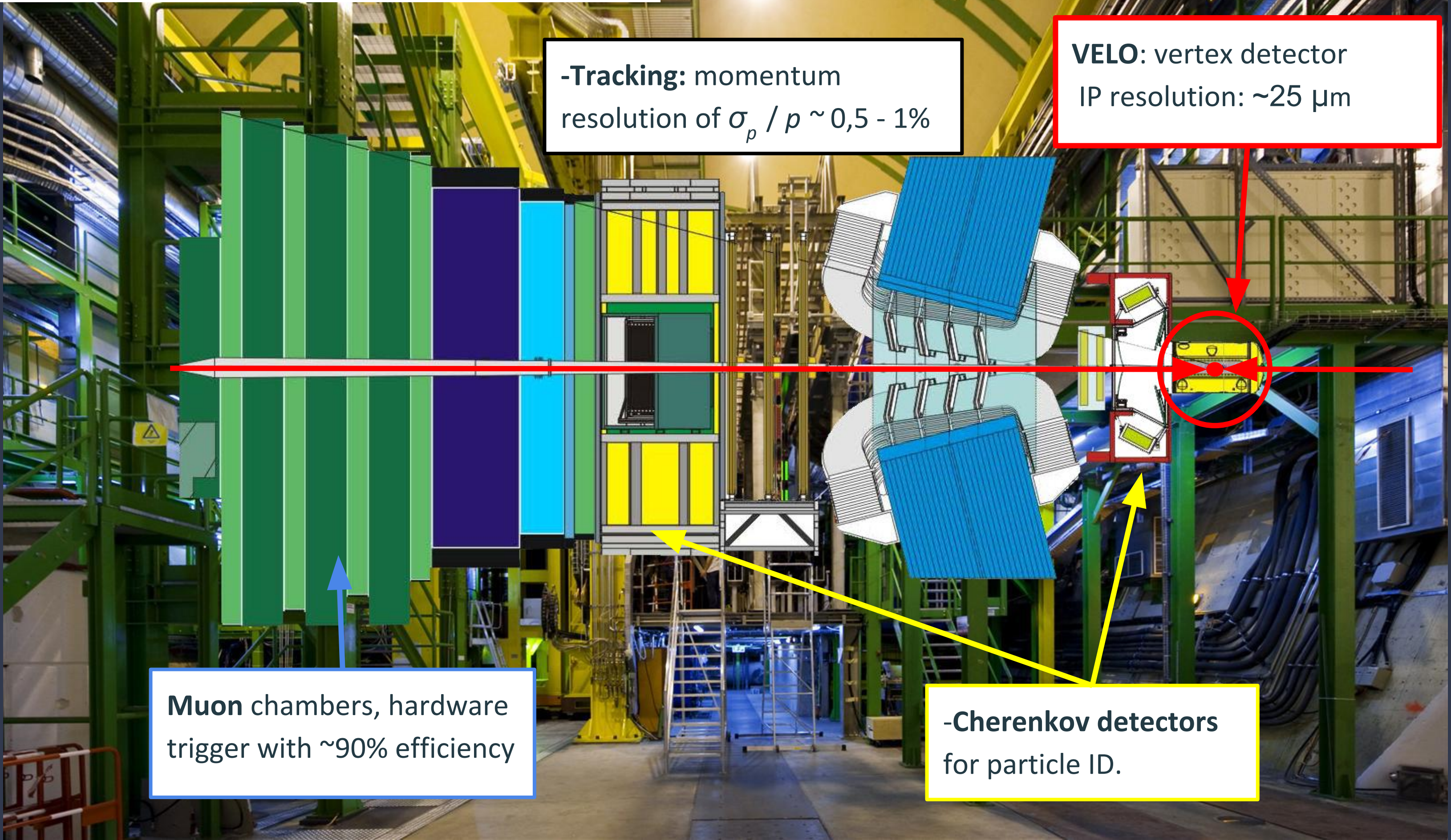


What is the role of LHCb in this framework?

The LHCb experiment

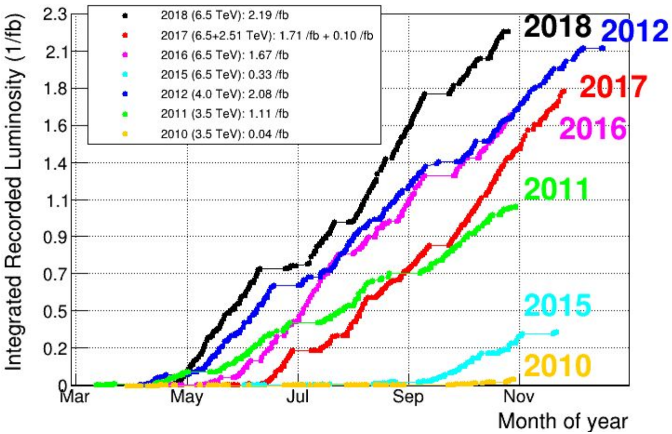
Forward single arm spectrometer 2< η <5

JINST 3 (2008) S08005



LHCb: state of art at √s

- Run 1: ~ 3 fb^{-1} of pp collisions at s = 7-8 TeV
- Run 2: ~ 6 fb^{-1} of pp collisions at s = 13 TeV
- <u>Goal for Run3 and Run4</u>: 50 fb^{-1}



By design: CP violation and b, c-physics

- > 10^4 × larger b production rate than the B factories @ Υ(4S)
- Access to all b-hadrons: B^+, B^0, B_s, B^+_c, b-baryons

⇒ Excellent results not only in CP violation and rare decays but also in LFU, **exotic and conventional spectroscopy,** EW and QCD physics ….

Highlights on exotic searches at LHCb

'Tetraquark' candidates:

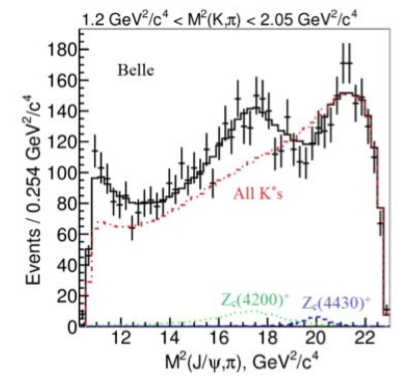
- Confirmation of the $Z_c(4430)^+$
- Neutral exotics in $B^+ \rightarrow J/\psi\phi K^+$ decays

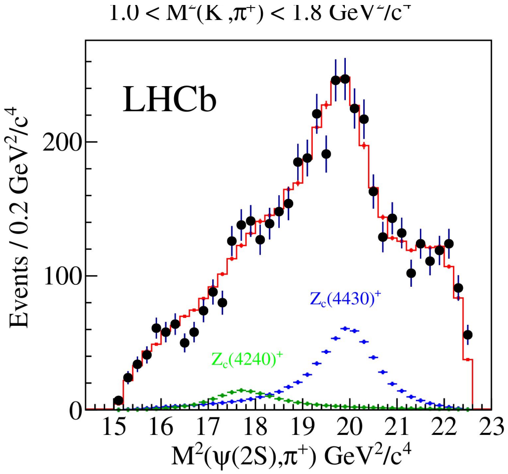
'Pentaquark' candidates:

- $\Lambda_b \rightarrow J/\psi p K^+$ decays: old and new results
- New searches with $B^0_{(s)} \rightarrow J/\psi p\bar{p}$ decay

$Z_c(4430)^+$ state in $B^0 \to \psi(2S) K^+ \pi^-$ decays

- **Belle** first observation of $Z_c(c\bar{c}u\bar{d})$: $J^P = 1^+$ at 3.4σ level [Phys. Rev. Lett. 100, 142001]
- **BABAR** didn't find a significant deviation from $K^+\pi^-$ reflections
- **LHCb** results consistent with Belle (13.9σ) with 3 fb^{-1}
  - Amplitude analysis: simultaneous fit in kinematic variables to extract parameters like quantum numbers [Phys. Rev. Lett. 112 (2014) 222002]
  - Model-independent analysis: without any modelling of the resonance lineshapes demonstrates that the peaks aren't $K^+\pi^-$ reflections [Phys. Rev. D92 (2015) 112009]





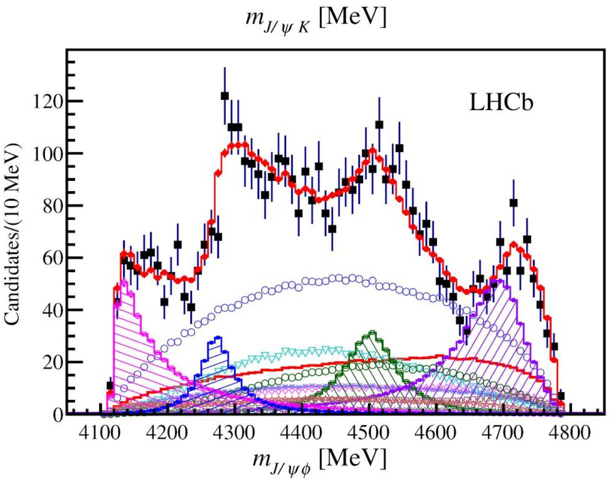
Neutral exotics in $B^+ \rightarrow J/\psi \phi K^+$ decays

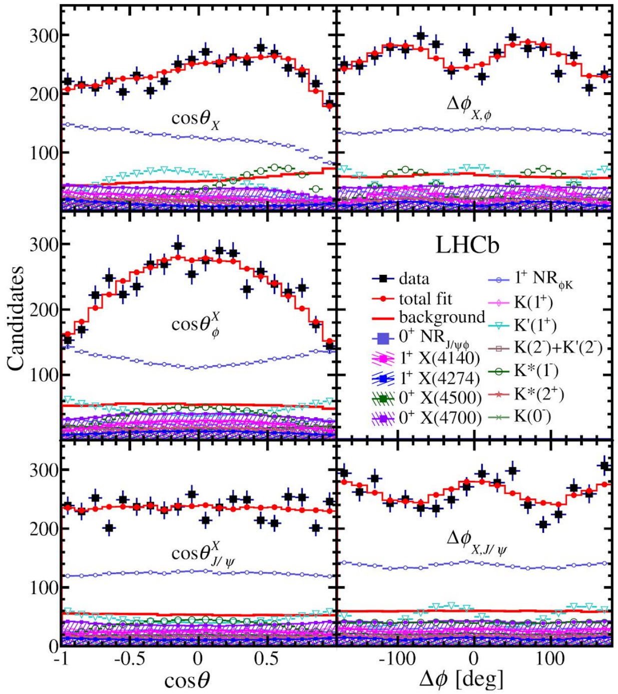
[Phys. Rev. Lett. 118 (2016) 022003], [Phys. Rev. D95 (2016) 012002]

- Analysis with 3 fb^{-1}
- Only $K^* \rightarrow \phi K^+$ cannot describe the $J/\psi\phi$ invariant mass
- Confirmation of 2 states: X(4140), X(4274)
- 2 new observed states: X(4500), X(4700) with > 5σ

Interpretations:

- X(4140) with larger width and $J^{PC} = 1^{++}$.
- Molecular model with 0^{++} or 2^{++} $D^+_s D^{*-}_s$ states is ruled out [Phys. Lett. B 678, 186.]





Pentaquark candidates

$\Lambda_b \to J/\psi pK$ decays: Run 1 results

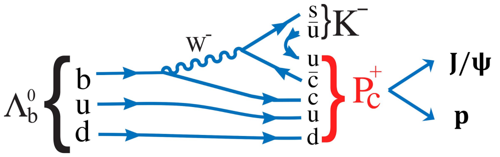
[PRL 115, 072001 (2015)]

LHCb observed pentaquark candidates in 2015 after 50 years of searches

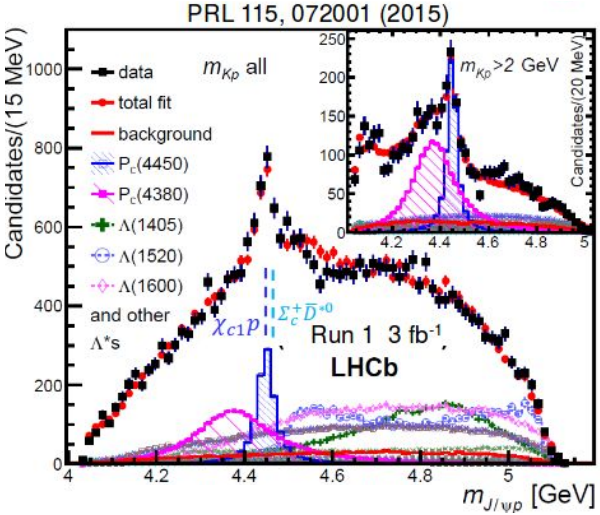
2 states with 6D amplitude analysis:

- $P_c(4450)$ → clearly visible
- $P_c(4380)$ → broader, in order to fit data

Consistent with pentaquarks with minimal quark content of uudcc'



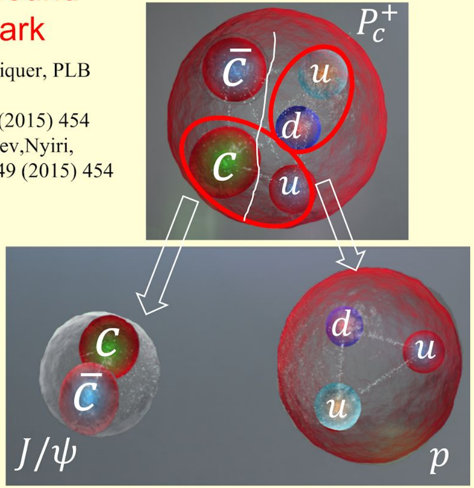
$P_c(4450)^+$	$M =$	$4450 \pm 2 \pm 3$ MeV
	$\Gamma =$	$39 \pm 5 \pm 19$ MeV
	$F.F. =$	$4.1 \pm 0.5 \pm 1.1$ %
$P_c(4380)^+$	$M =$	$4380 \pm 8 \pm 29$ MeV
	$\Gamma =$	$205 \pm 18 \pm 86$ MeV
	$F.F. =$	$8.4 \pm 0.7 \pm 4.2$ %



Interpretations

Tightly-bound pentaquark

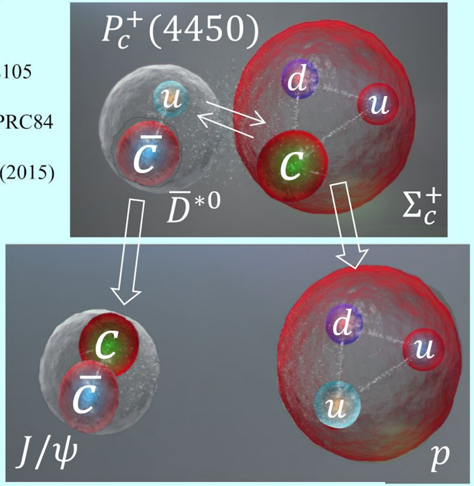
Maiani,Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich,Matveev,Nyiri, Sarantsev PLB 749 (2015) 454
and others



$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$

Loosely-bound pentaquark

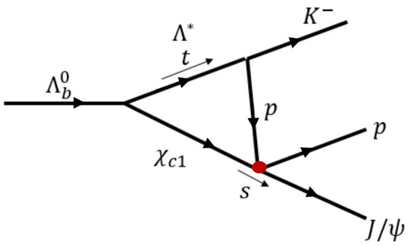
Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PRC84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others



$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim\text{few MeV}$

Triangle diagram

Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others



- Tightly bound states
- Large widths in principle
- Many states expected in isospin multiplets

- Low binding energy, narrow states
- Only S-wave, few states predicted
- Independently decaying components

$P_c(4450)^+ = \chi_{c1}p$ threshold?

Elisabetta Spadaro Norella

$\Lambda_b \rightarrow J/\psi pK$ Run1 + Run2 analysis

[PRL 122, 222001 (2019)]

9 times statistics of 2015 analysis (~9 fb^{-1}) → 246k events

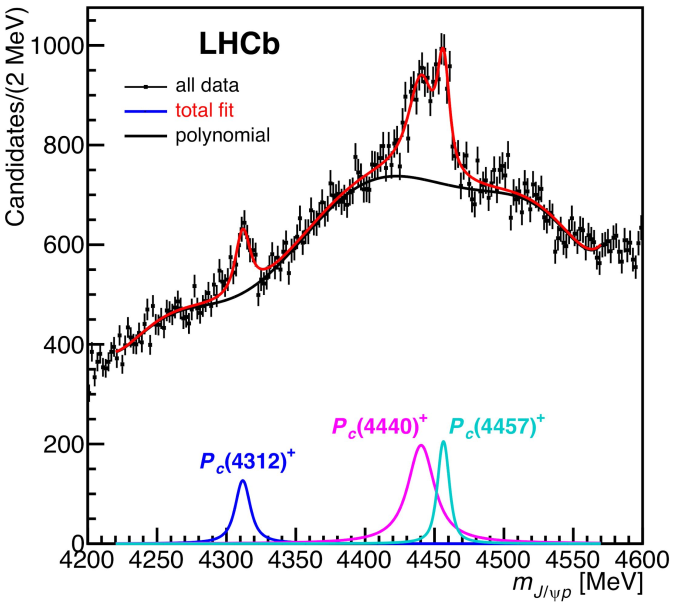
Fit to $m_{J/\psi p}$ invariant-mass distribution (full amplitude analysis in preparation)

Three narrow peaks clearly visible but a lot of background

- New $P_c(4312)^+$ → 7.3σ
- Peak at 4450 MeV resolved in 2 narrower peaks → 5.4σ
- No sensitive to broad $P_c(4380)^+$

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

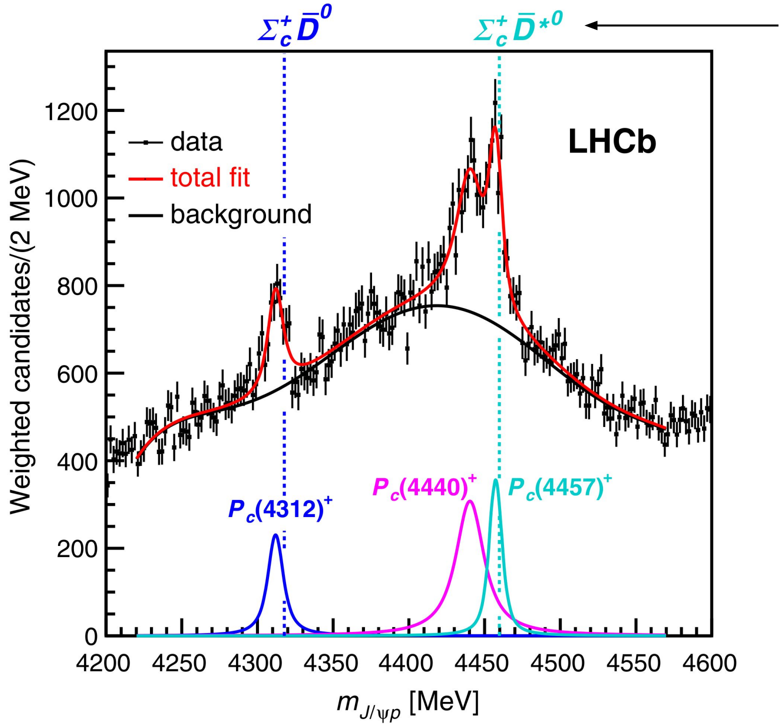
high-order polynomial



Molecular system?

[PRL 122, 222001 (2019)]

Near threshold masses and narrow resonances favor the hypothesis of molecules of baryon-meson



Only **below** this molecule threshold

Two molecules: $\Sigma_c^+ D^0$, $\Sigma_c^+ D^{*0}$
→ 2 states with different spin

BUT the 1D fit cannot exclude other models

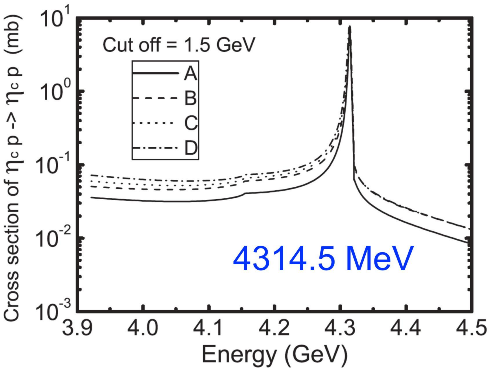
- need an amplitude analysis for J^P quantum numbers
- find isospin partners

Previous predictions

Several theoretical predictions for molecular models before 2015 are in agreement with LHCb results

- Predicted three states with energy very closed to what is observed
- Also for M~4314 MeV

PR C85 044002 (2012)



$M_{\text{LHCb}} = 4311.9 \pm 0.7^{+6.8}_{-0.6}$ MeV

PR C85 044002 (2012)

		$\Sigma_c D^0$		$\Sigma_c D^{*0}$	
$J^P = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650	-	-	-	-
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	$4318.964 - 0.362i$	1.826	$4459.513 - 0.417i$	2.667
	1500	$4314.531 - 1.448i$	6.259	$4454.088 - 1.662i$	8.092
	2000	$4301.115 - 5.835i$	19.68	$4438.277 - 7.115i$	23.90
$J^P = \frac{3}{2}^-$					
	650	-	-	-	-
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	-	-	$4459.507 - 0.420i$	2.673
	1500	-	-	$4454.057 - 1.681i$	8.123
	2000	-	-	$4438.039 - 7.268i$	23.14

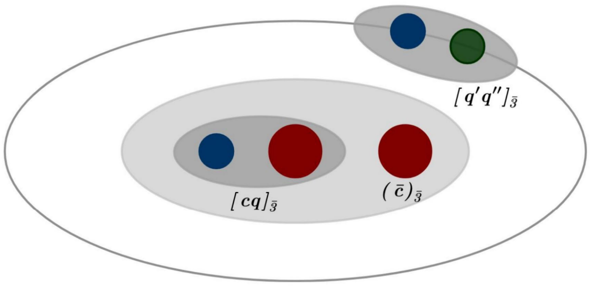
Λ : cut off on exchanged meson mass
$\Delta E = E_{\text{thr}} - M$: "binding energy"

Tight Pentaquark

Ali et al, PLB 793, 365 (2019);
Ali et al, 1907.06507 predicts more states with $(ud)_{S=1}$

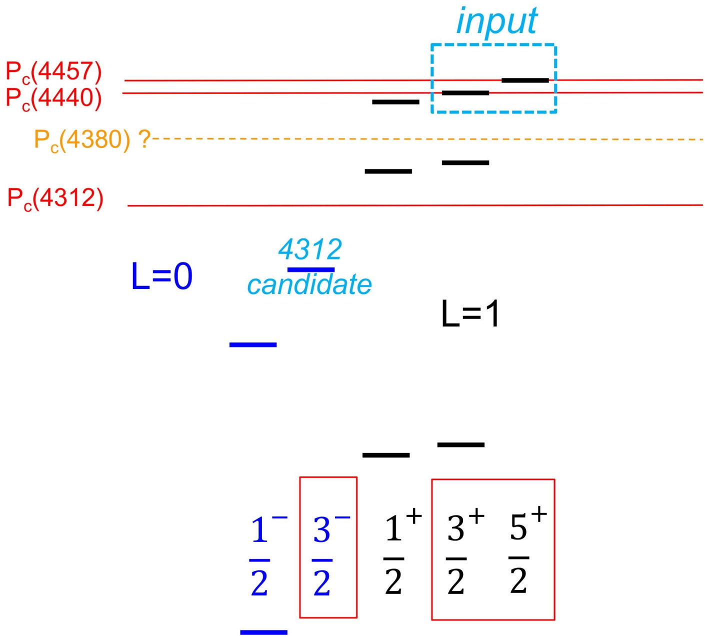
Tight-pentaquark models:

- very rich spectra
- Predict a lot of different J^{PC} for the observed P_c states



$$((uc)_{S=0,1}(ud)_{S=0}\bar{c}_{S=1/2})_{L=0}$$

$$((uc)_{S=0,1}(ud)_{S=0}\bar{c}_{S=1/2})_{L=1}$$

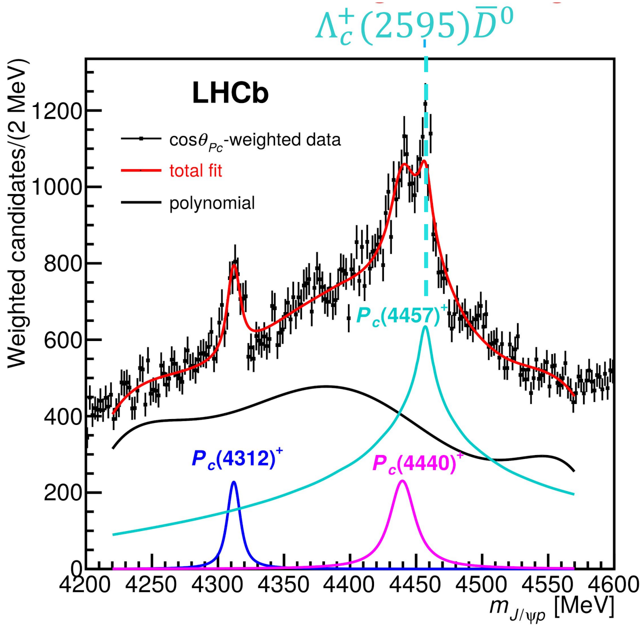


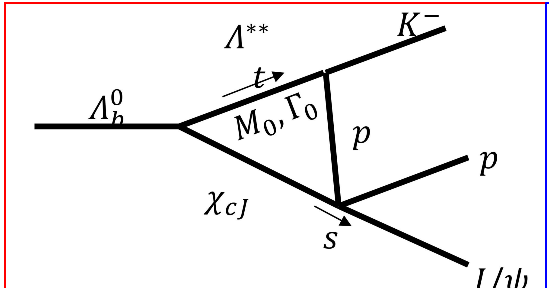
Elisabetta Spadaro Norella

Triangle diagrams?

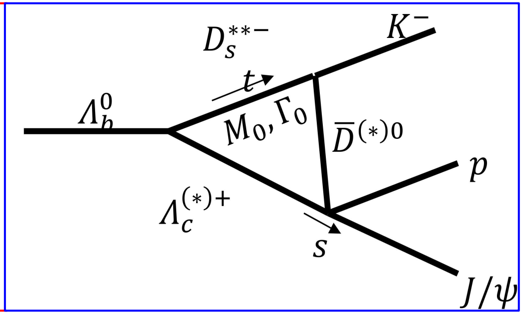
[PRL 122, 222001 (2019)]

Can produce peaking structure at or above mass threshold, but not below





Guo *et al,* PRD 92 (2015) 071502 and others



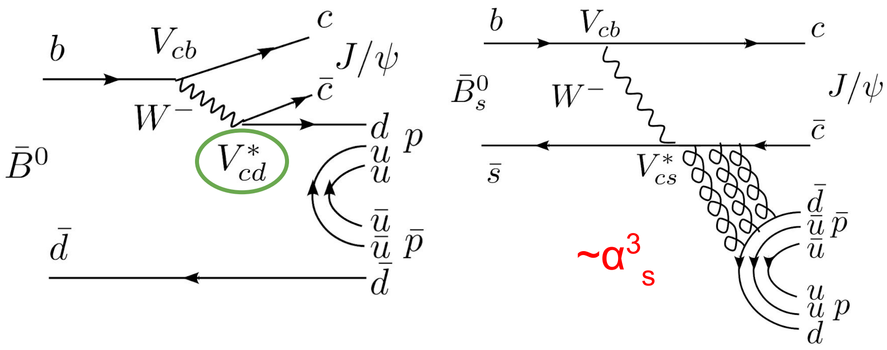
- $P_c(4312)^+$ and $P_c(4440)^+$ too far from threshold
- $P_c(4457)^+$: at the threshold of $\Lambda^+_c D^0$
- BUT to reproduce reasonable width for $D_{s1}^*(2860)$, the fit is not as good as with BW

New exotic searches

New exotic analysis: $B^0_{(s)} \to J/\psi p\bar{p}$ decay

[Phys. Rev. Lett. 122, 191804]

- Candidate for pentaquark searches in $J/\psi p$ and $J/\psi \bar{p}$ and for glueball in pp system
- Both processes are suppressed due to Cabibbo and OZI suppression



Elisabetta Spadaro Norella

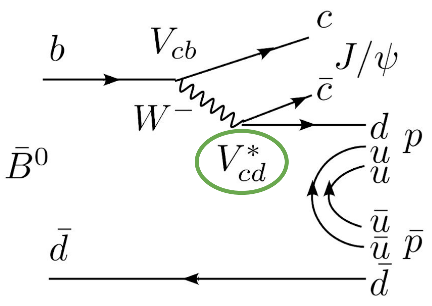
New exotic analysis: $B^0_{(s)} \to J/\psi p\bar{p}$ decay

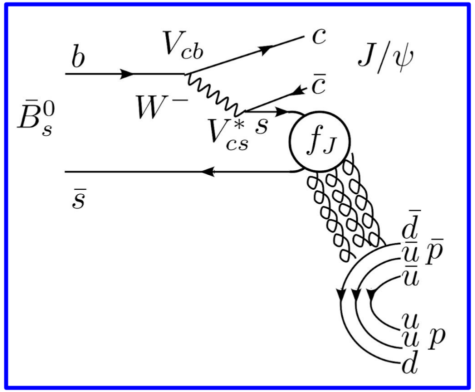
[Phys. Rev. Lett. 122, 191804]

- Candidate for pentaquark searches in $J/\psi p$ and $J/\psi\bar{p}$ and for glueball in pp system

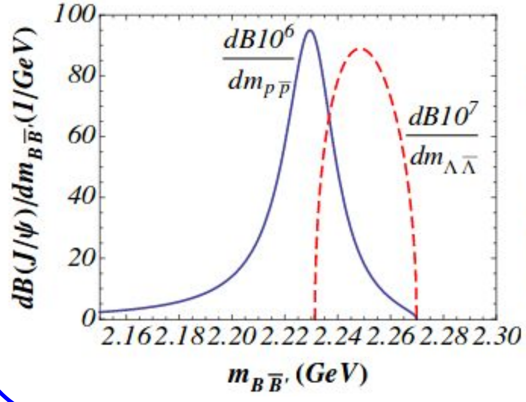
- Both processes are suppressed due to Cabibbo and OZI suppression

Eur. Phys. J. C75 (2015), no. 3 101





Resonant state $f_j(2220) \to p\bar{p}$, peak at 2.2 GeV



- Limit on BR of B_s with no resonant structure:

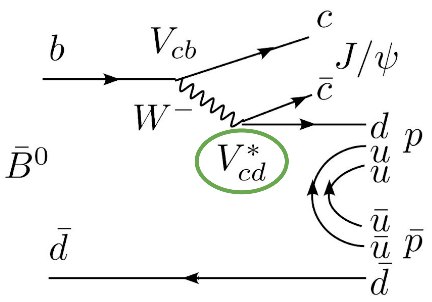
$$\mathcal{B}(\bar{B}^0_s \to J/\psi p\bar{p}) \leq 10^{-9}$$

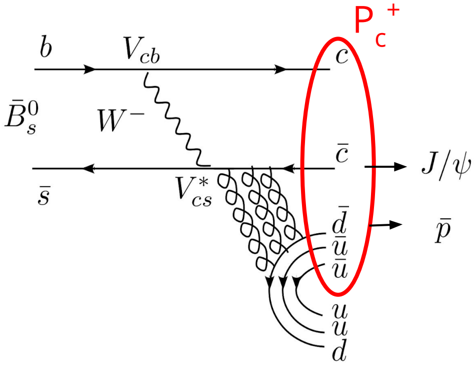
Elisabetta Spadaro Norella

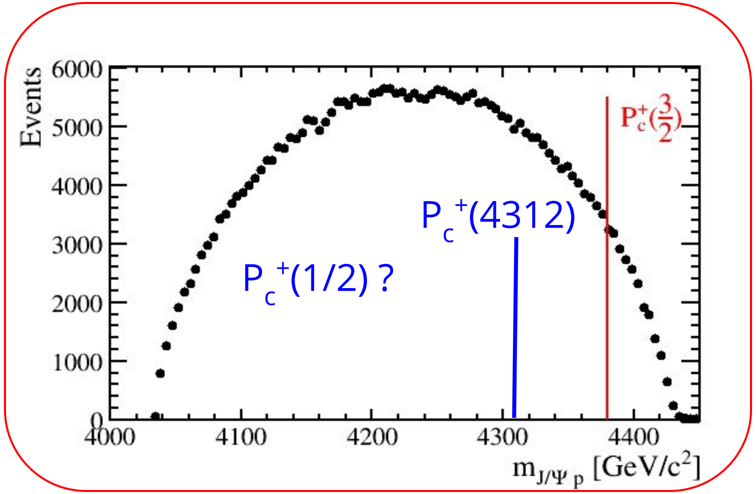
New exotic analysis: $B^0_{(s)} \to J/\psi p\bar{p}$ decay

[Phys. Rev. Lett. 122, 191804]

- Candidate for pentaquark searches in $J/\psi p$ and $J/\psi \bar{p}$ and for glueball in $p\bar{p}$ system
- Both processes are suppressed due to Cabibbo and OZI suppression



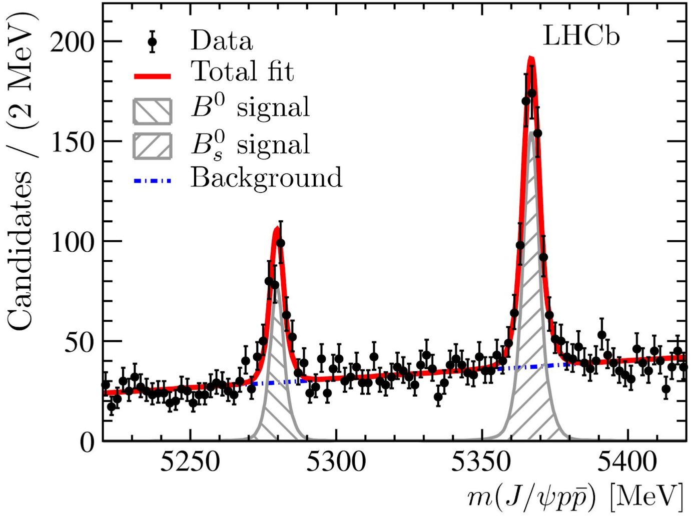




New exotic analysis: $B^0_{(s)} \to J/\psi p\bar{p}$ decay

[Phys. Rev. Lett. 122, 191804]

First observation of $B^0_{(s)} \to J/\psi p\bar{p}$ decays with 2011-2016 data (5.2 fb^{-1})



Mode	Yield
$B^0 \to J/\psi p\bar{p}$	256 ± 22
$B^0_s \to J/\psi p\bar{p}$	609 ± 31

$$\mathcal{B}(B^0 \to J/\psi p\bar{p}) = (4.51 \pm 0.40\,(\text{stat}) \pm 0.44\,(\text{syst})) \times 10^{-7},$$
$$\mathcal{B}(B^0_s \to J/\psi p\bar{p}) = (3.58 \pm 0.19\,(\text{stat}) \pm 0.33\,(\text{syst})) \times 10^{-6},$$

- BR of B_s: 2 order of magnitude higher than expected
- Best single measurement of B_s and B^0 masses

$m(B_s)$ = 5366.85 ± 0.19 ± 0.13 MeV
$m(B_d)$ = 5279.74 ± 0.30 ± 0.10 MeV

Amplitude analysis is ongoing with data till 2018 → around twice the statistics

Conclusions

- Exotics searches very active both in experimental and theoretical side → a lot of models: how can we experimentally distinguish between them?
- A lot of interesting results from LHCb, in addition to the ones already mentioned
  - Observation of the $\Lambda^0_b \to \chi_{c1}(3872)pK^-$ decay JHEP, arXiv:1907.00954 (2019)
  - Evidence of $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$, EPJ. C78 1019(2018)
  - Observation of Exotic Contributions to $B^0 \to J/\psi K^+\pi^-$, PRL 122 152002(2019)
  - Beautiful tetraquarks in the $\Upsilon(1S)\mu^+\mu^-$ invariant mass spectrum, JHEP 10 086(2018)
  - A search for weakly decaying b-flavored pentaquarks, PRD 97, 032010 (2017)
- Excellent long term prospects for exotic searches at LHCb

Elisabetta Spadaro Norella

Long term prospects

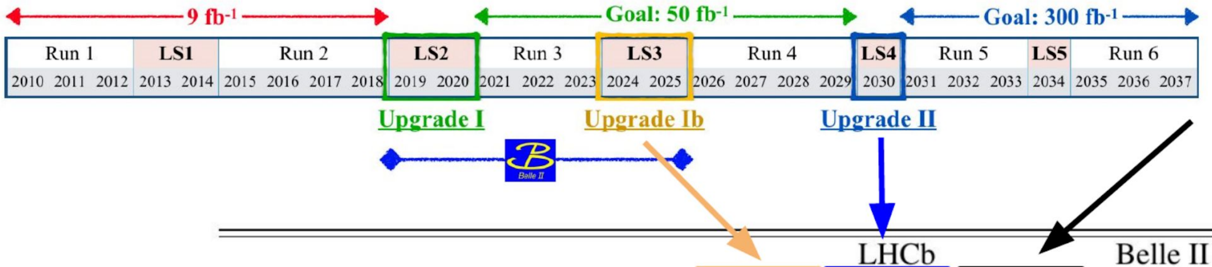
Study X(3872) lineshape

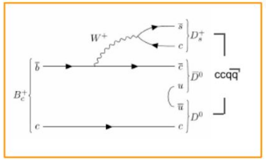
Study charged exotic mesons $Z(4430)^+$

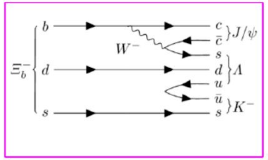
Exotic charm states - doubly charm tetraquark

P_c observation channel

Search for hidden-charm pentaquark with strangeness - 1st observation with ~300 events (PLB 772 265 (2017))







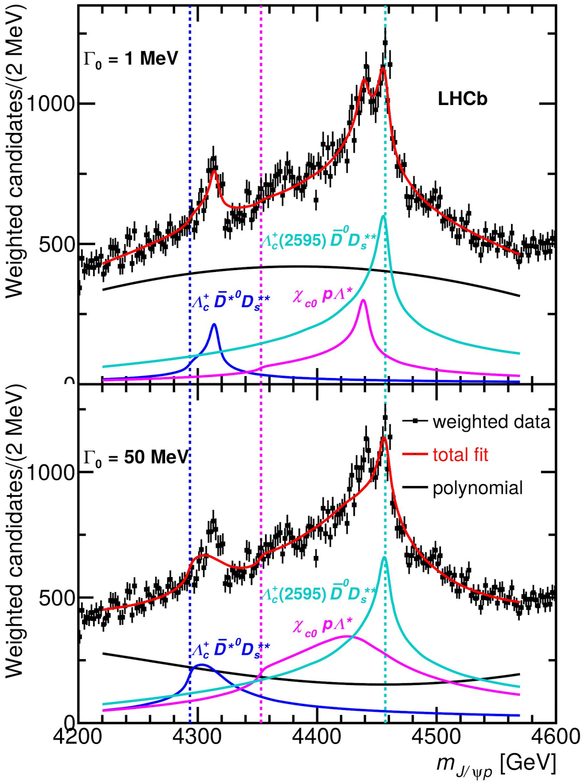
Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}	Belle II 50 ab^{-1}
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \bar{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi p K^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k	< 6k
$\Xi_{bc}^+ \to J/\psi \Xi_c^+$	50	100	600	—

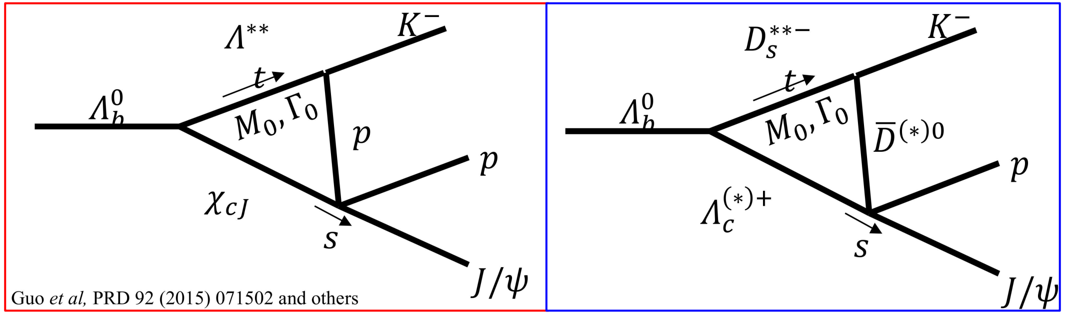
CERN-LHCC-2018-027
arXiv:1808.08865

Thank you for the attention!

BACKUP SLIDES

Triangle diagrams

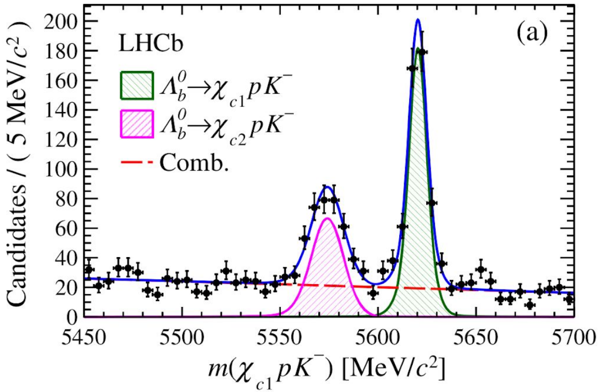




- First fit with small widths ~ 1 MeV → unrealistic value
- Second fit with more plausible widths not performing well

$P_c(4450)^+$ decaying to $\chi_{c1}p$
Rev. Lett. 119, 062001 (2017)

An observation of $P_c(4450)^+$ decaying in the $\chi_{c1}p$ final state (and not $\chi_{c0,\,c2}p$) would confirm exotic nature of the resonance



First observation of the decays $\Lambda_b^0 \to \chi_{c1} p K^-$ and $\Lambda_b^0 \to \chi_{c2} p K^-$

- First investigation, with limited statistics (3 fb^{-1}, full LHCb Run 1)
- $\text{N}(\Lambda_b^0 \to \chi_{c1} p K^-) = 453 \pm 25$
- Not enough to analyse the $\chi_{c1}p$ mass spectrum, will be updated with Run 2 data
- First measurement of the branching fractions relative to $\Lambda_b^0 \to J/\psi p K^-$
- $\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$
- $\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$