Exotic hadrons at hadronic machines

I. Yeletskikh
on behalf of the ATLAS, LHCb, CMS, D0, CDF and GlueX Collaborations

- **Results on Pentaquarks spectrum;**
- **Study of di-J/ψ production and 4μ resonances;**
- **Exotic (tetraquark) states decaying into $J/\psi\pi^+$, $J/\psi K^+$ and $J/\psi\varphi$;**
- **Exotica in the D^+K^- spectrum: open charm tetraquark;**
- **Searches for $X(5568)$ state;**

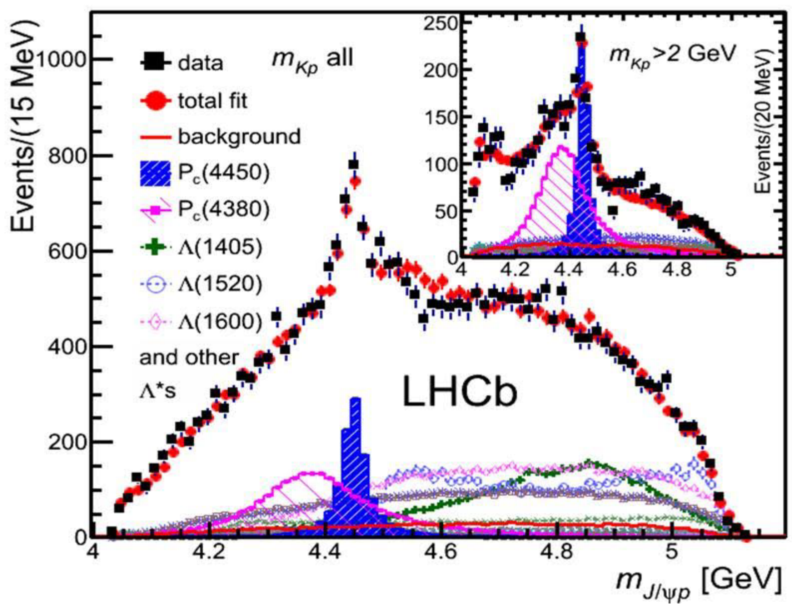
Results on Pentaquark spectrum

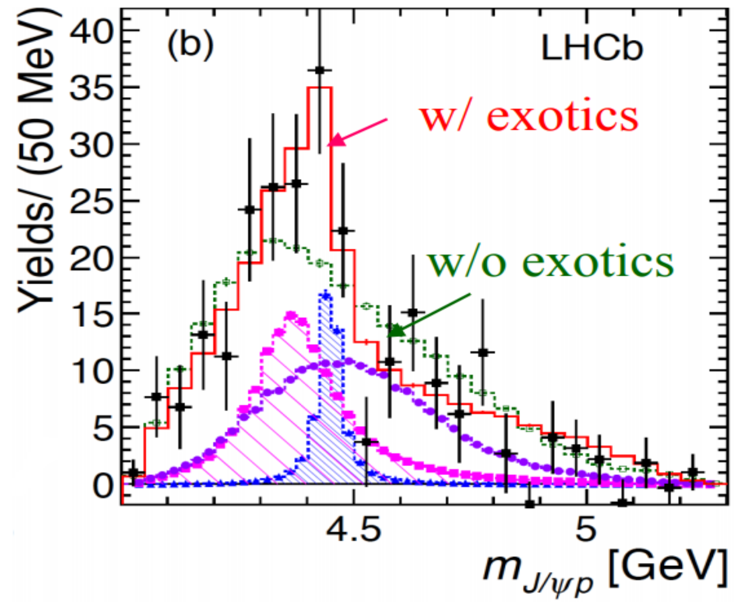
- New charmonium pentaquark states from LHCb, ATLAS;
  - 2015 LHCb discovery: exotic signals in $\Lambda_b \rightarrow J/\psi pK$ decays;
  - 2019 update (LHCb Run II results);
  - ATLAS Run I results;
  - Pentaquarks in Tevatron data;
  - Photoproduction channel;
- Pentaquark with strangeness;
- Theoretical highlights, perspectives and plans;

Pentaquark results from LHCb

- In 2015 LHCb experiment discovered exotic contributions to $\Lambda_b \to J/\psi pK$ decays (26K Λ_b candidates analyzed);
- Two signals in M($J/\psi p$) spectrum was consistent with pentaquark states P_c(4380) and P_c(4450);
- Significance of the two signals observed to be 9σ and 12σ respectively;

Phys. Rev. Lett. 115, 072001





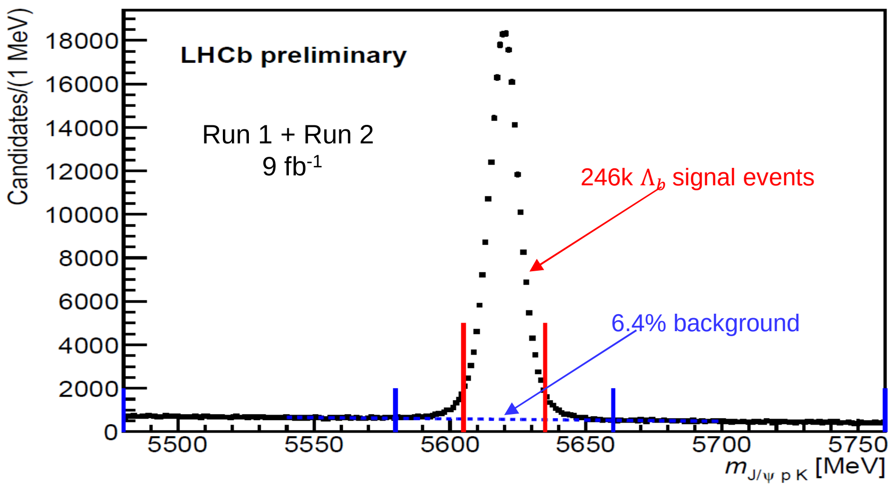
Phys. Rev. Lett. 117, 082003

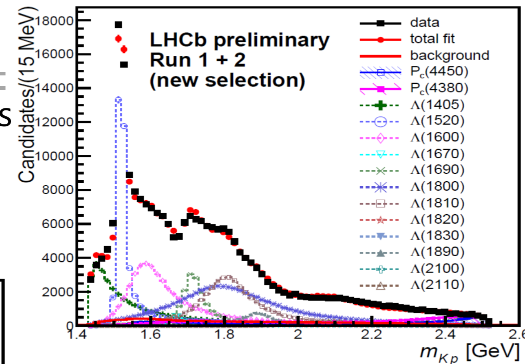
- Later the evidence for exotic contribution was also seen in $\Lambda_b \to J/\psi, p, \pi$ decays;
  - Significance of two pentaquark signals + Z_c(4200) tetraquark signal is 3.1σ;
  - Significance of two pentaquark signals without Z_c(4200) is 3.3σ;

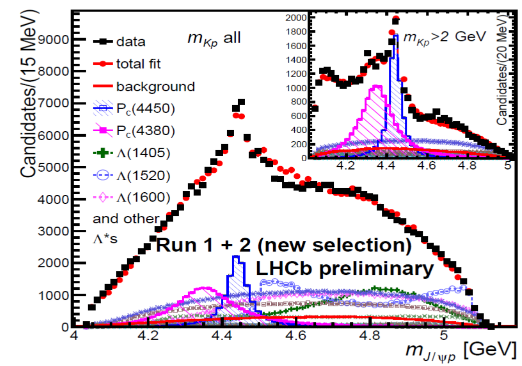
LHCb pentaquarks in Run II data

Run II provides ~9x statistics of Run I for $\Lambda_b \to J/\psi pK$ decays (246K candidates).

Phys. Rev. Lett. 122 (2019) 222001



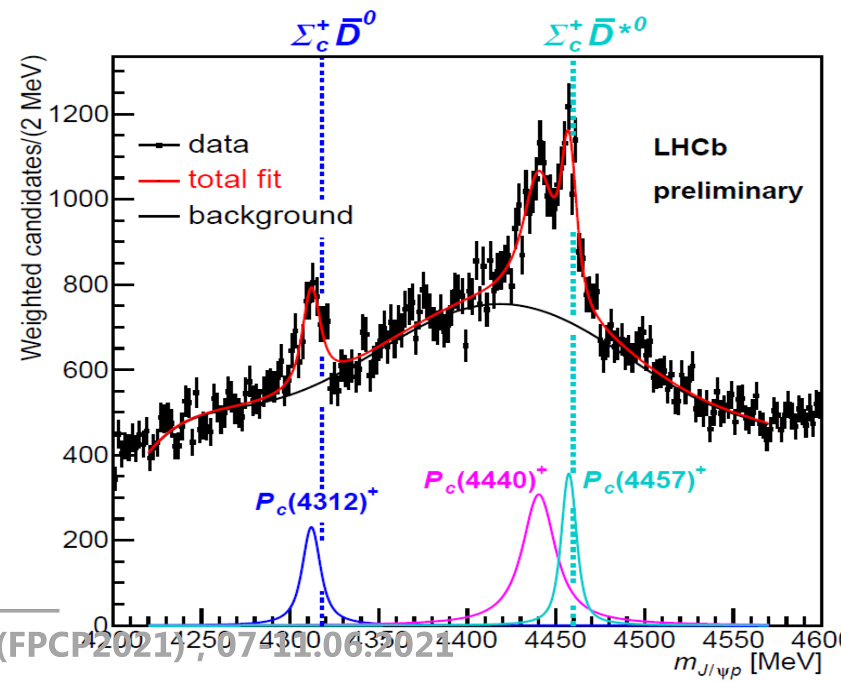


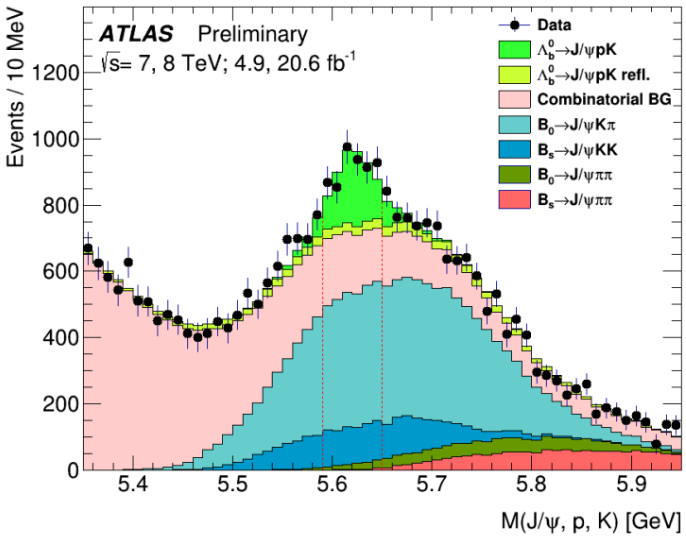


New state $P_c(4312)$ (width ~10 MeV) and 7.4σ significance has been discovered.

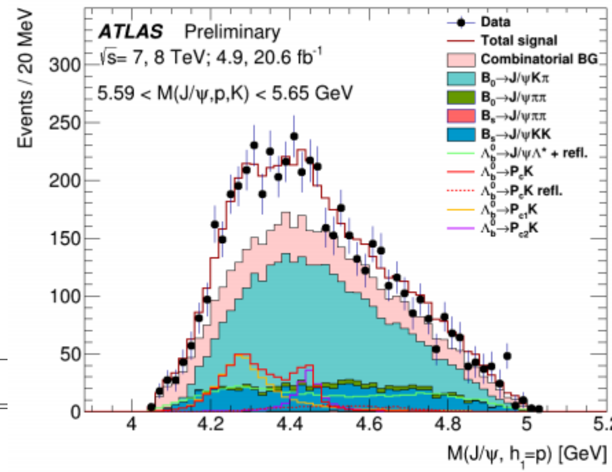
State $P_c(4450)$ revealed its substructure: two states $P_c(4457)$, $P_c(4440)$ (widths 6.4 и 21 MeV respectively) and 5.4σ significance w.r.t. to single state hypothesis;

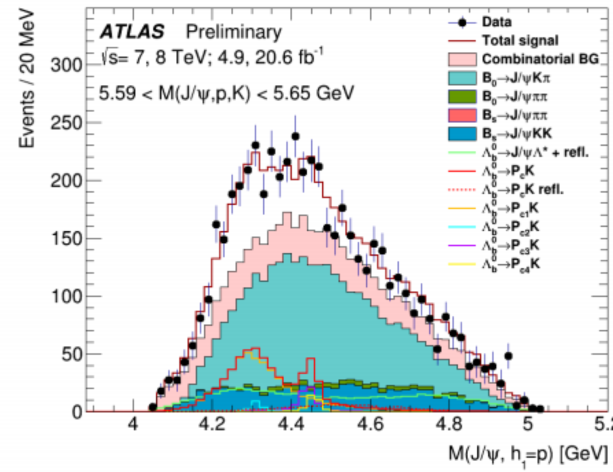
Analysis methods were not sensitive to the wide $P_c(4380)$ state.





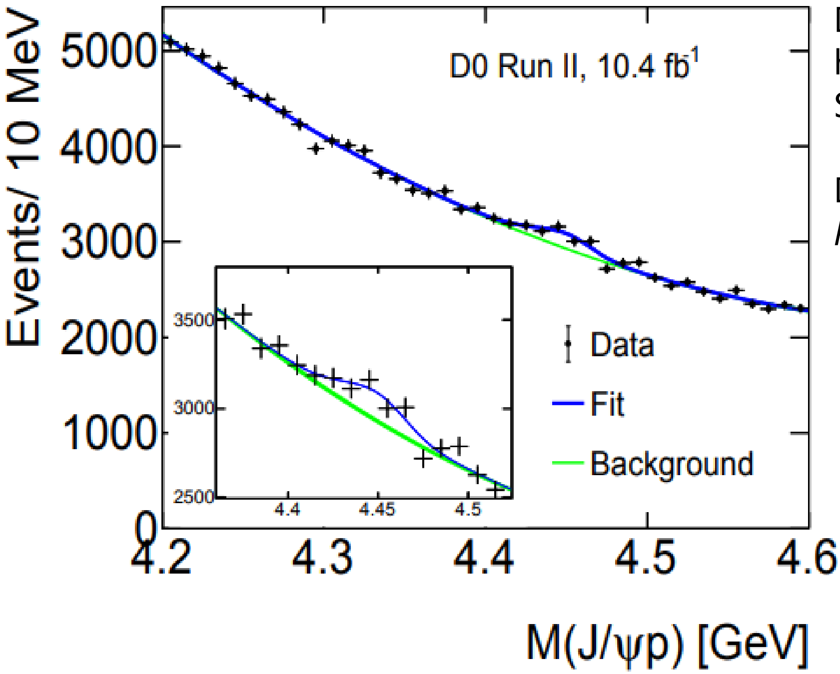
With ATLAS Run I data the amplitude analysis of ~1K of $\Lambda_b \to J/\psi pK$ has been performed; signal area is contaminated by physical and combinatorial background





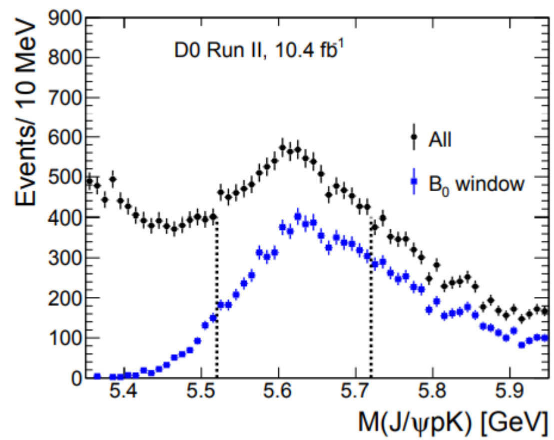
Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat) $^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat) $^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat) $^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV

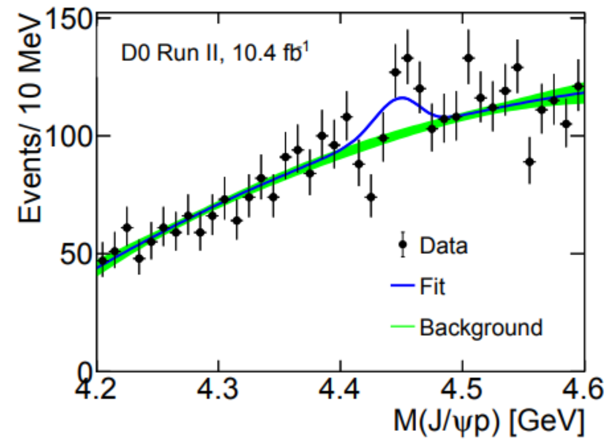
Parameters of pentaquarks are consistent with those measured by LHCb; 4 P_c hypothesis is also consistent with ATLAS data;
'No-pentaquarks' hypothesis describes data poorly (p-value=$9.1 \cdot 10^{-3}$)
Run II studies are ongoing;



D0 experiment performed analysis of the inclusive M(*J/ψp*) spectrum. Signal has been observed consistent with LHCb parameters for pentaquarks. Significance of the signal is 3.7σ and yield is 830±206 events;

D0 data are not sensitive to $P_c(4312)$ state and to separation of $P_c(4440)$ and $P_c(4457)$.

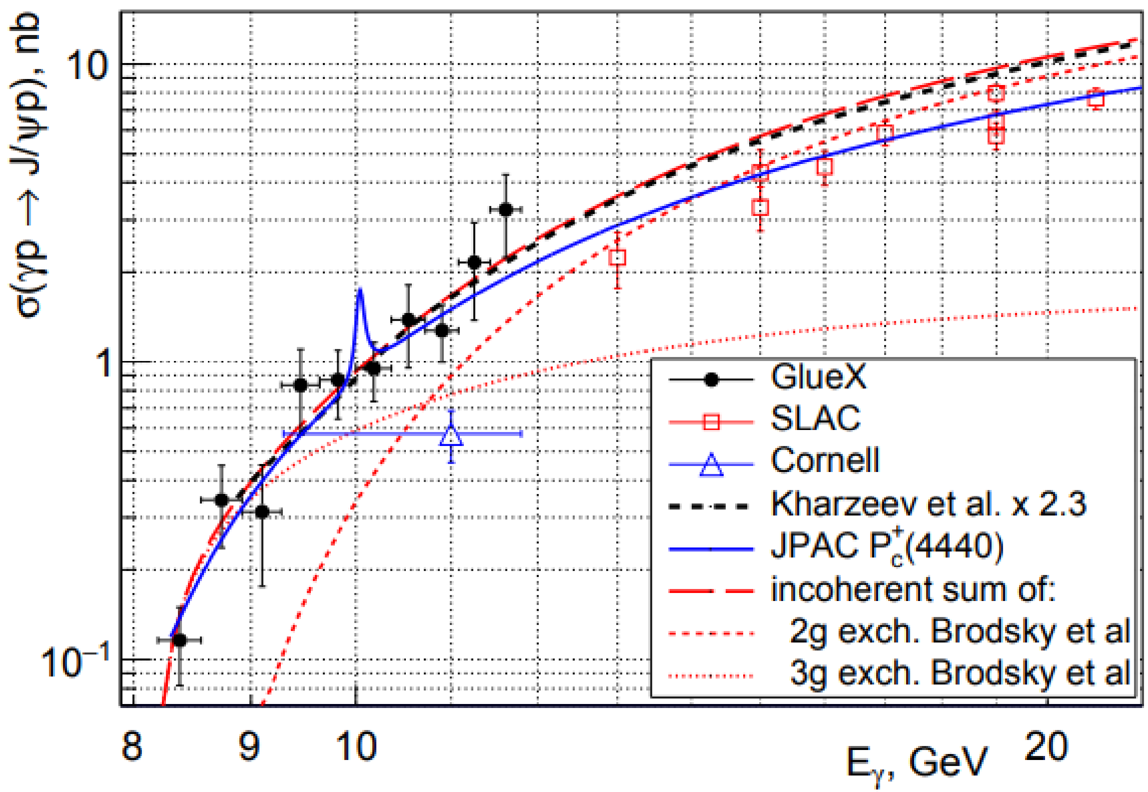


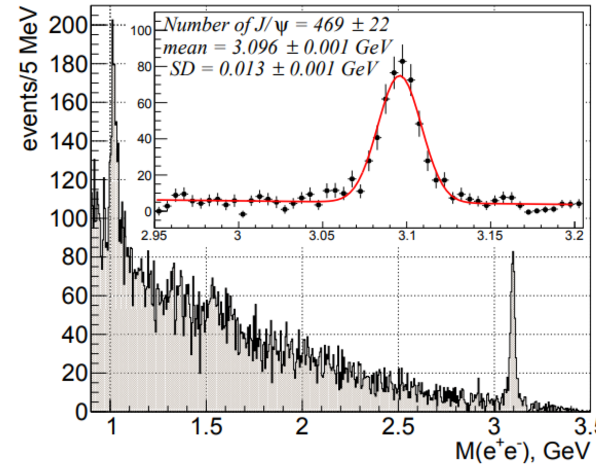


Interestingly, requiring events into Λ_b mass window decreases significance to 2.3σ and yield to 82±37 events (right plot).
This implies that most of pentaquarks are produced not from Λ_b decays;

Phys.Rev.Lett. 123 (2019) 7, 072001

Photoproduction channel *γp*→X →*J/ψp* has been studied at GlueX experiment.



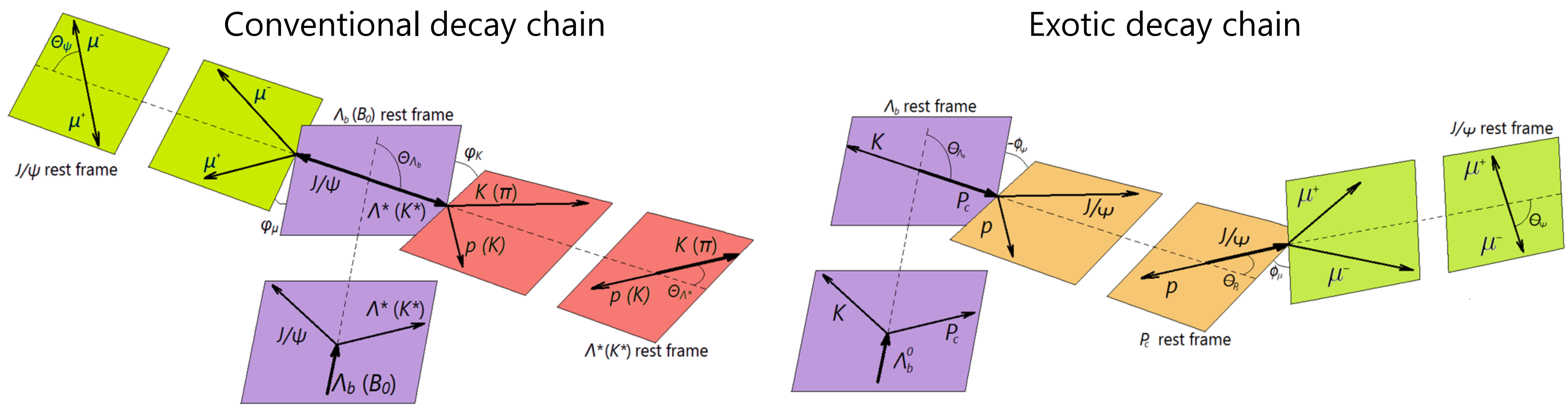


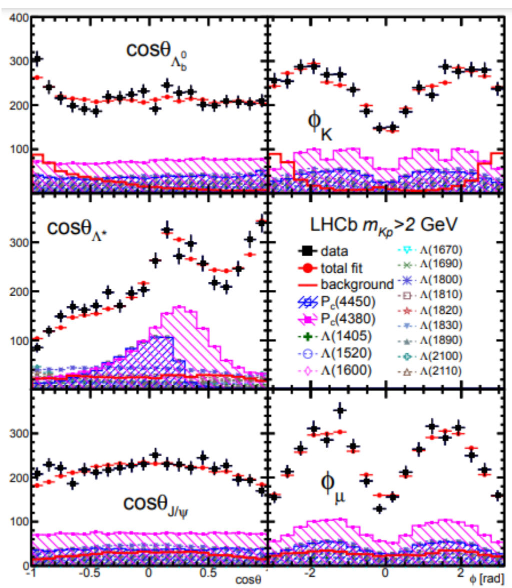
469 ± 22 *J/ψ* candidates produced.

Limits at the 90% C.L. are set for the cross section times branching ratio for the known pentaquark states:

4.6 nb for $P_c(4312)$
1.8 nb for $P_c(4440)$
3.9 nb for $P_c(4457)$

$\Lambda_b \to J/\psi,p,K$ decays simulation

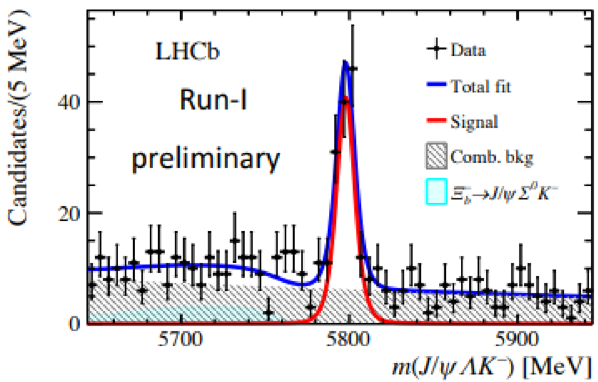


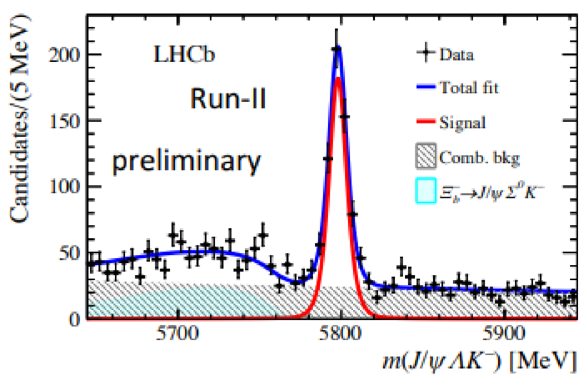


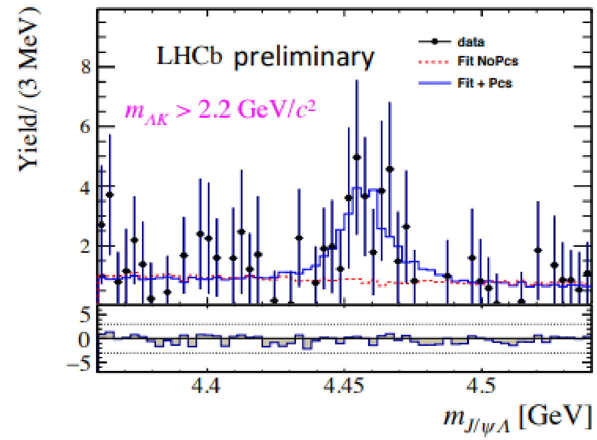
- Decay kinematics suggest that exotic contributions can reveal themselves not only via mass spectrum but in the angular distributions as well (ref. plot from LHCb pentaquark 2015 paper (left));
- Amplitude analysis approaches usually operate multi-dimensional (masses, angles) fits to extract decay parameters and parameters of the exotic states with higher precision;
- For the wide states (like P_c(4380)) amplitude analysis is the only option, since in this case complex effects like interference between different amplitudes can be accounted for;

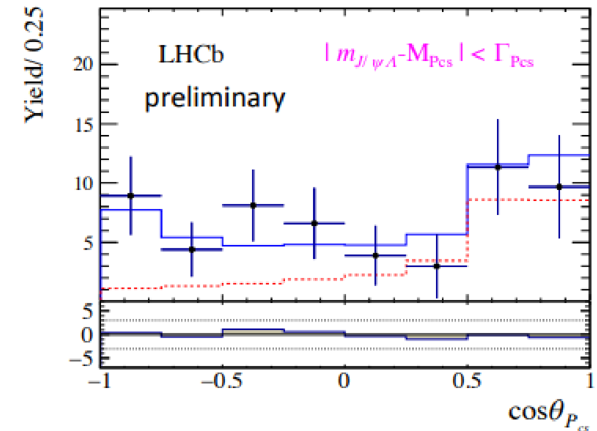
arXiv:2012.10380

$\Xi_b^- \to J/\psi K^- \Lambda$









State	M_0 [MeV]	Γ[MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$

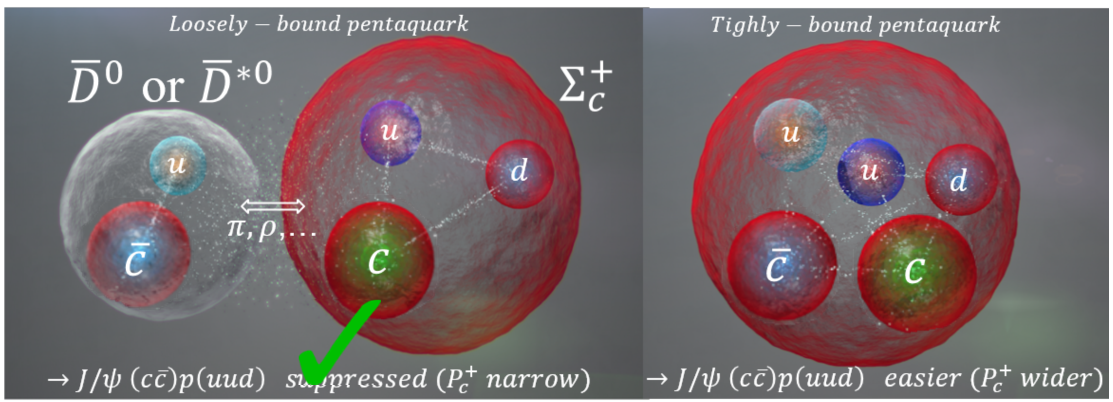
P_{cs} mass 19MeV below the $\Xi_c^0 \bar{D}^{*0}$ threshold. Statistic not enough for J^P determination.

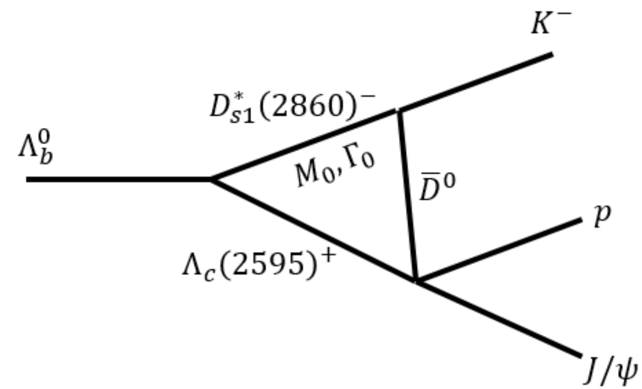
Run-I + Run-II data: ~1750 signals, purity ~80%

3.1σ significance when syst. uncertainty considered

Pentaquarks: theoretical highlights…

- $P_c(4312)$, $P_c(4440)$, $P_c(4457)$, $P_{cs}(4459)$ are narrow states close to baryon-meson decay thresholds;
- Several theoretical models applicable: compact pentaquarks, hadro-charmonium states, triangular singularities, ΣD 'molecular' bound states, etc.
- Branching ratios between different decay channels are the observables that are most sensitive to internal structure of these states;
- Thus, new measurements needed: other decay modes, spin-parity measurements, precise decay constants measurements, discovery of other states in exotics spectrum;
- Naïve QCD predicts electrically neutral P_c partners, pentaquarks with strangeness (seems to be discovered), etc.



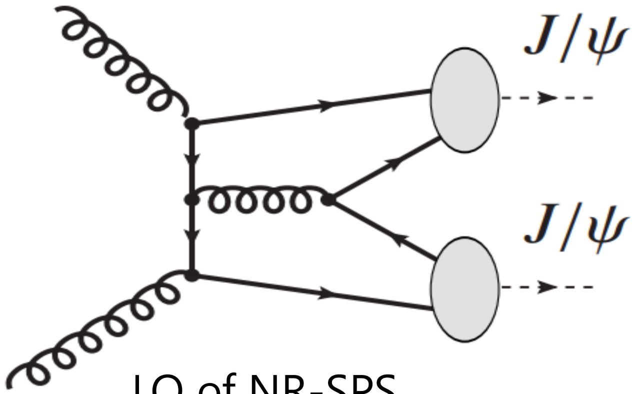


- Experimental studies are ongoing;

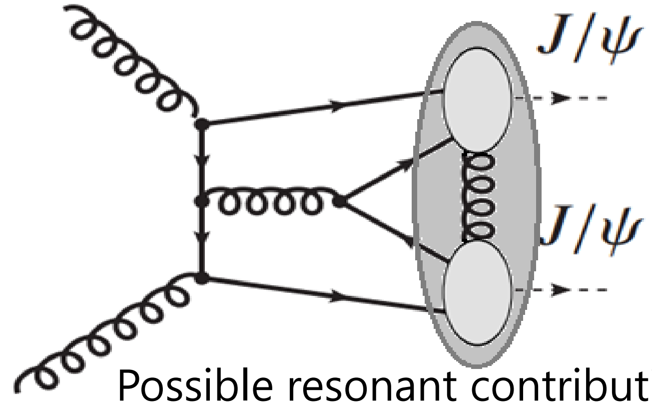
Study of di-J/ψ production and 4μ resonances

- LHCb discovery in the 4μ invariant mass spectrum
  - Exotic double-charmonium state?

J/ψ pair production



LO of NR-SPS

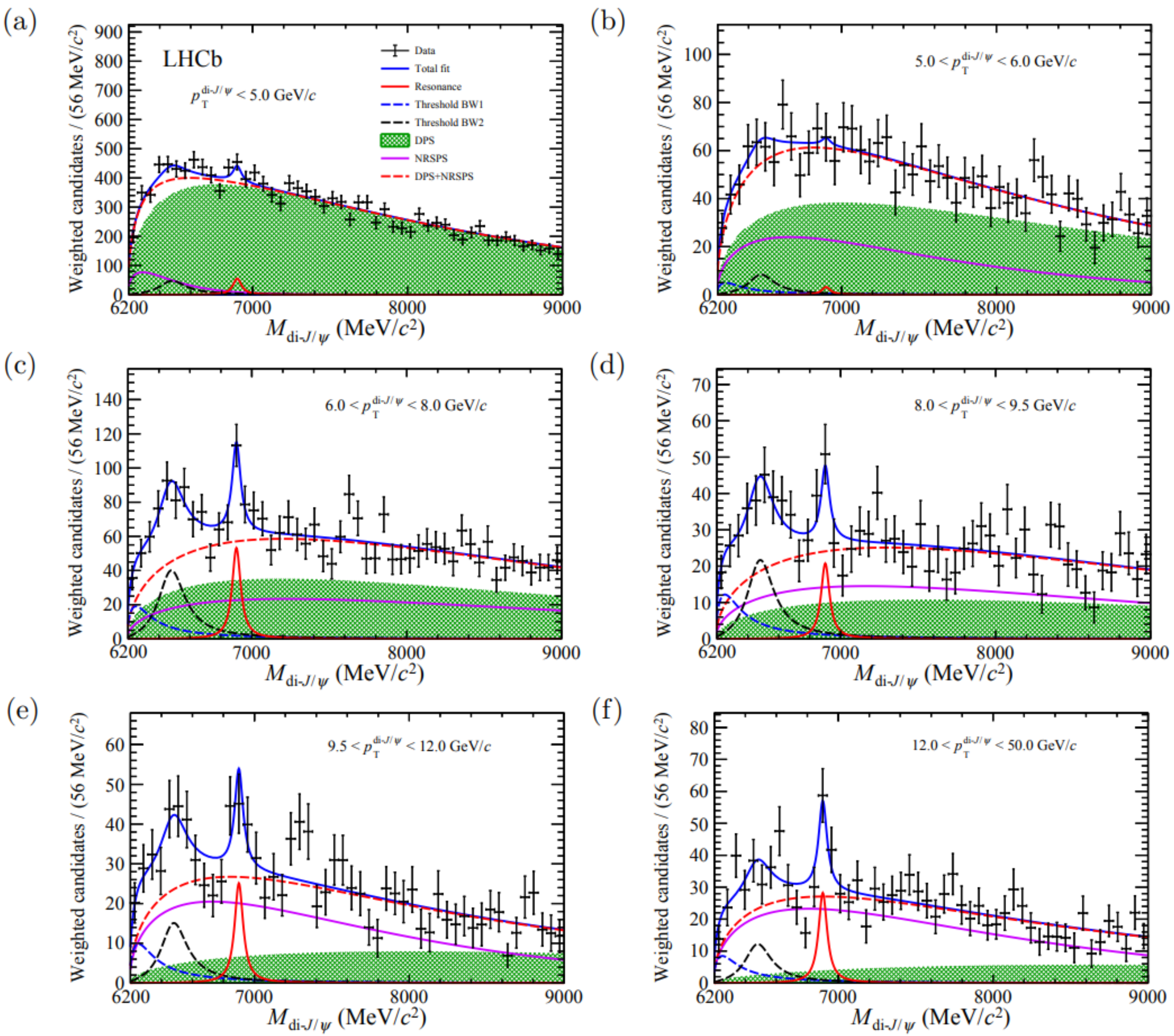


Possible resonant contribution

+ higher order processes with, e.g., additional light jets or c-jets in the final state

- There are basically two mechanisms of di-*J/ψ* production: SPS (Single Parton Scattering) and DPS (Double Parton scattering);
- Possible resonant production is (very likely) related to SPS mechanism (see diagrams);
- Interference effects are expected between NR-SPS and signal, thus, in case spin-parity measurement of the possible resonance, one needs to sum up amplitudes for these processes coherently;
- Threshold effects are expected near the di-*J/ψ* threshold and interfere with NR-SPS background;
- DPS (similar to combinatorial bkg) and can be well modeled using, e.g., event mixing approach;

J/ψ pair spectrum in LHCb data



https://cds.cern.ch/record/2722544/files/2006.16957.pdf?version=2

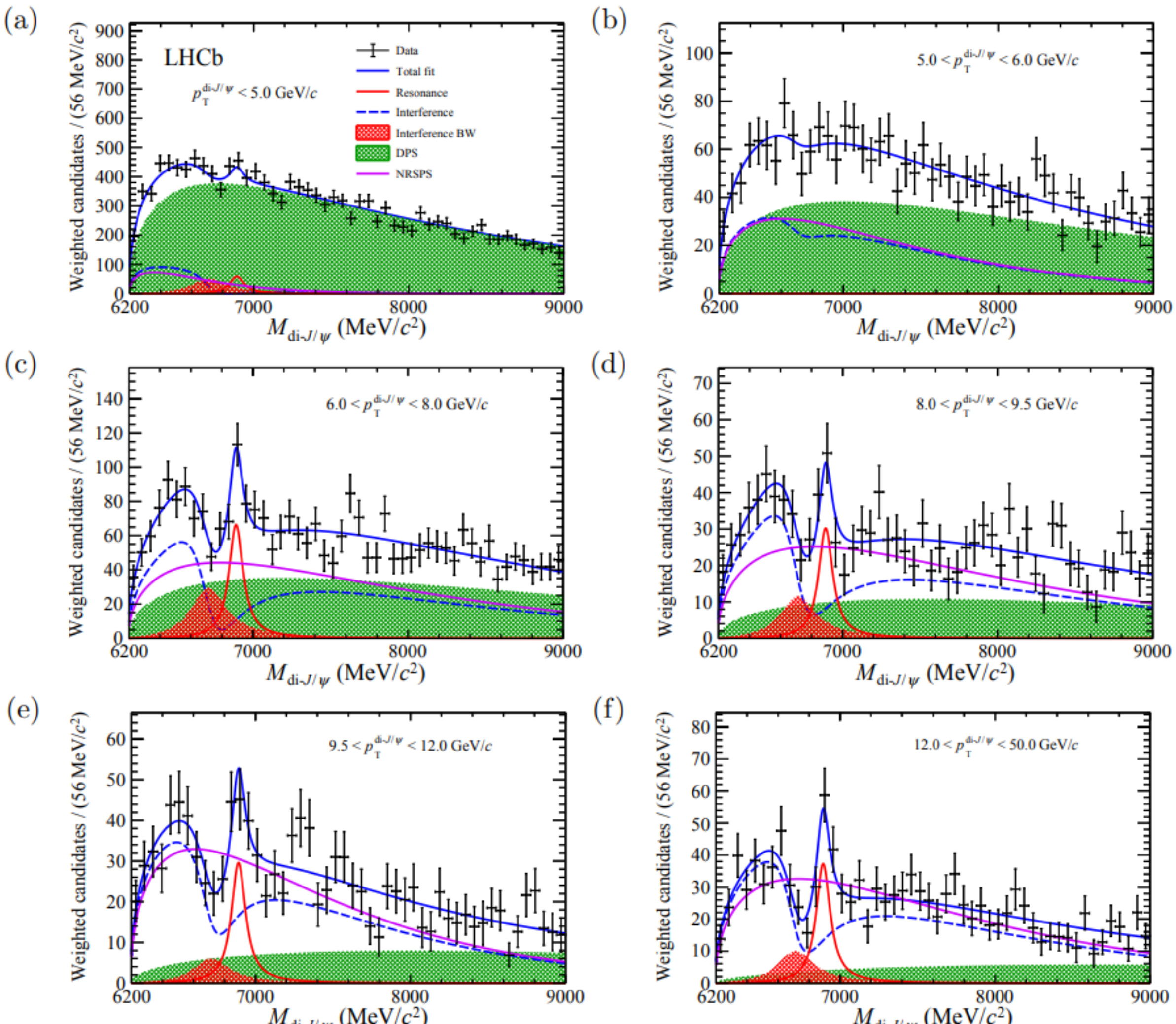
Invariant mass spectra of di-J/ψ candidates in bins of p_T di-J/ψ and overlaid results of fits.

No interference effect are accounted for in the model.

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

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

J/ψ pair spectrum in LHCb data



https://cds.cern.ch/record/2722544/files/2006.16957.pdf?version=2

Invariant mass spectra of di-J/ψ candidates in bins of p_T di-J/ψ and overlaid results of fits. Interference effect are included between threshold effects and NRSPS process.

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

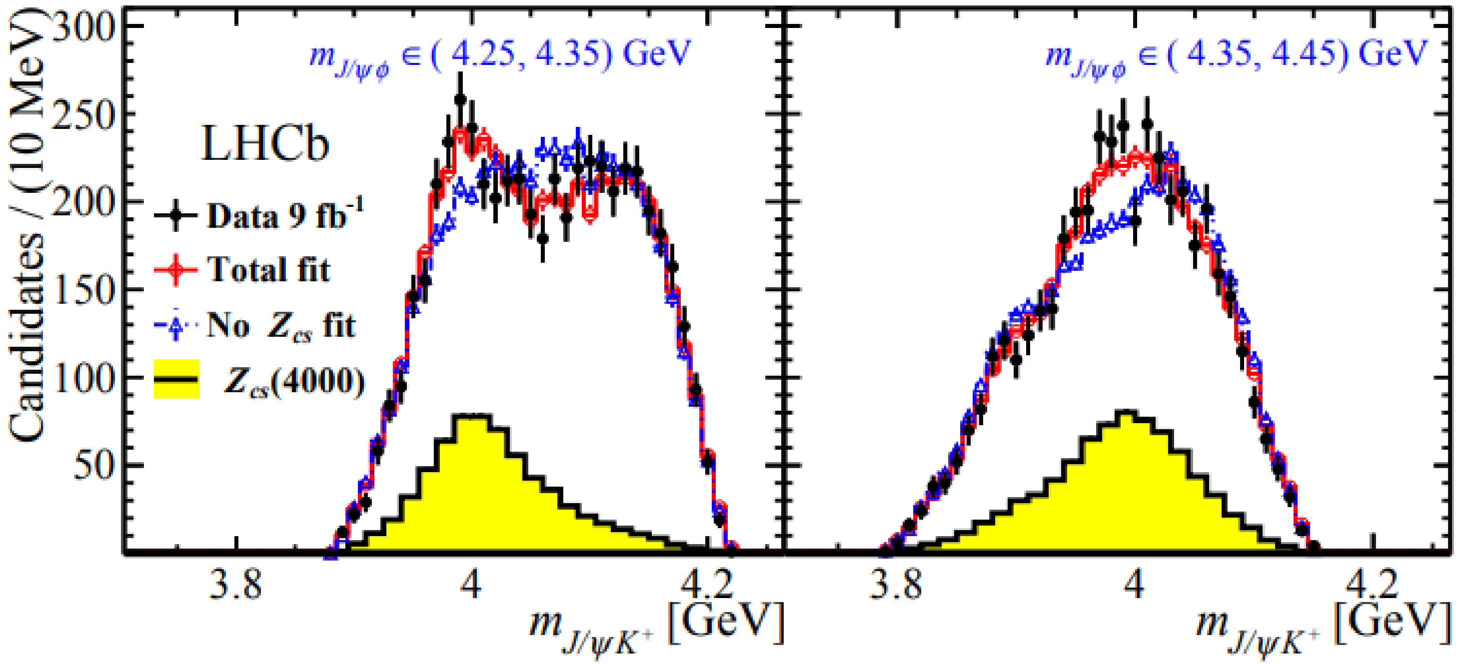
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}.$$

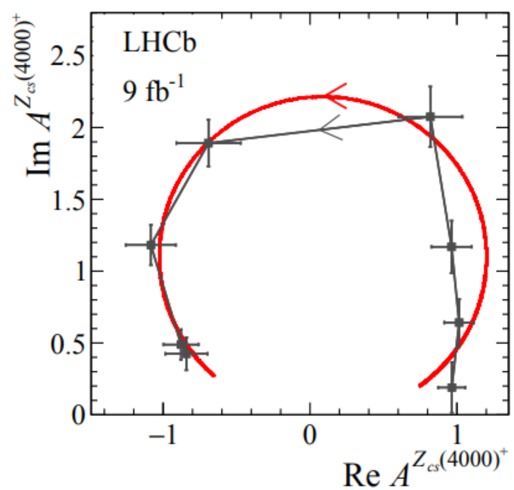
Exotic states decaying into $J/\psi\pi^+$, $J/\psi K^+$ and $J/\psi\varphi$

- Z_{cs} states in $J/\psi K^+$ final states;
- X states in $J/\psi\varphi$ final states
- Z_c states in $J/\psi\pi^+$ states;

New states in $B^+ \to J/\psi K^+ \varphi$ decays

- LHCb performed amplitude analysis of ~24K candidates of $B^+ \to J/\psi K^+ \varphi$ decays;
- Several exotic contributions to these decays have been observed;
- $Z_{cs}^+(4000)$ state is observed with significance 15σ. $M=4003\pm6^{+4}_{-14}$, $\Gamma=131\pm15\pm26$;

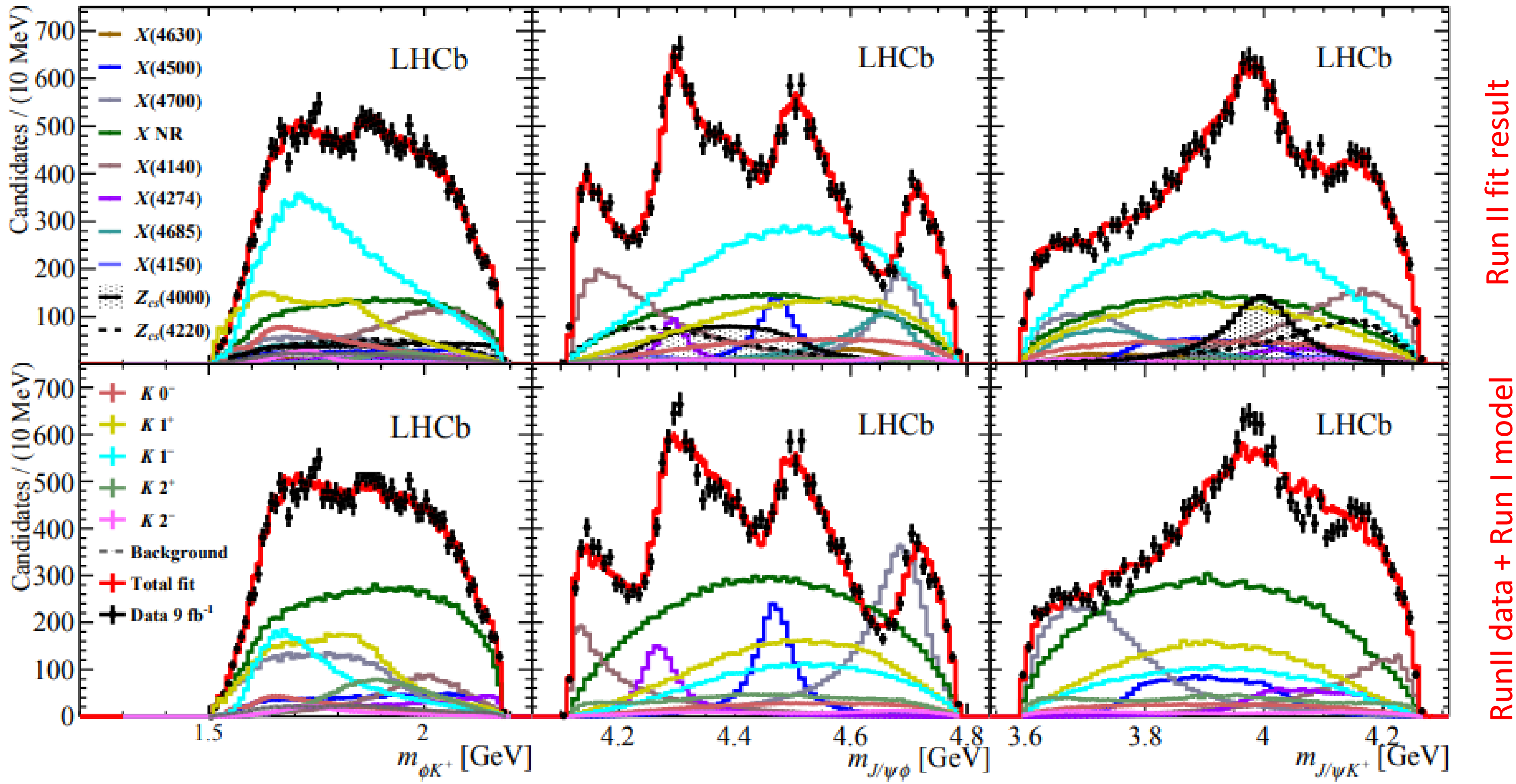




- Observed properties of $Z_{cs}^+(4000)$ are consistent with the resonant nature of this state;
- Spi-parity preferred is 1^+;

New states in $B^+ \to J/\psi K^+ \varphi$ decays

- $Z_{cs}^{+}(4220)$ (1^+) state is observed with significance 5.9σ. $M=4216\pm24^{+43}_{-30}$, $\Gamma=233\pm52^{+97}_{-73}$;



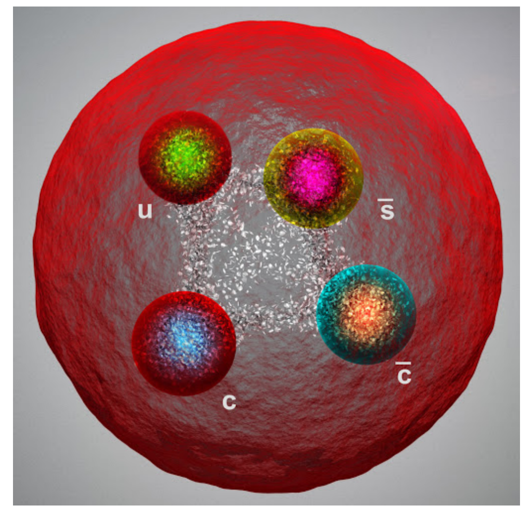
New states in $B^+ \to J/\psi K^+ \varphi$ decays

arXiv:2103.01803

Contribution		Significance [$\times\sigma$]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
	All $K(1^+)$				$25 \pm 4^{+6}_{-15}$
2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10^{+16}_{-46}$	$149 \pm 41^{+231}_{-23}$	
2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37^{+124}_{-48}$	$276 \pm 50^{+319}_{-159}$	
1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3^{+3}_{-11}$
	All $K(2^-)$				$2.1 \pm 0.4^{+2.0}_{-1.1}$
1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
	All $K(1^-)$				$50 \pm 4^{+10}_{-19}$
1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2^{+35}_{-8}$
2^3S_1	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5^{+11}_{-17}$
	$K(2^+)$				
2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22^{+194}_{-31}$	$318 \pm 82^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
	$K(0^-)$				
2^1S_0	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2^{+1.0}_{-3.8}$
	$X(2^-)$				
	$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
	$X(1^-)$				
	$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
	All $X(0^+)$				$20 \pm 5^{+14}_{-7}$
	$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
	$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
	$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
	All $X(1^+)$				$26 \pm 3^{+8}_{-10}$
	$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
	$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
	$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
	All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
	$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
	$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

- In addition to exotic conributions to $J/\psi\varphi$ spectrum reported in 2017, two new states $X(4630)$ and $X(4685)$ are observed (ref. table).

- All (charged and neutral)states observed are relatively wide (Γ~100-200 MeV), the question about their structure is to be addressed; these could be candidates for compact tetraquarks;

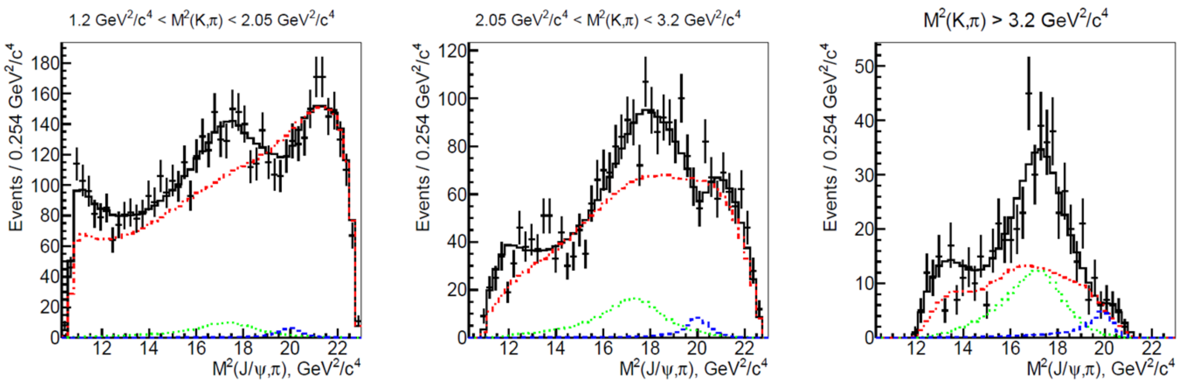


Phys. Rev. Lett. 118 (2017) 022003
Phys. Rev. D **95** (2017) 01202

Z_c(4200) was discovered by BELLE collaboration with a significanceof 6.2σ in 2014. An amplitude analysis was performed to determine the parameters of this state:

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4318 ± 48	4315 ± 40	4196^{+31}_{-29}	4209 ± 14	4203 ± 24
Width, MeV	720 ± 254	220 ± 80	370 ± 70	64 ± 18	121 ± 53
Significance (Wilks)	3.9σ	2.3σ	8.2σ	3.9σ	1.9σ

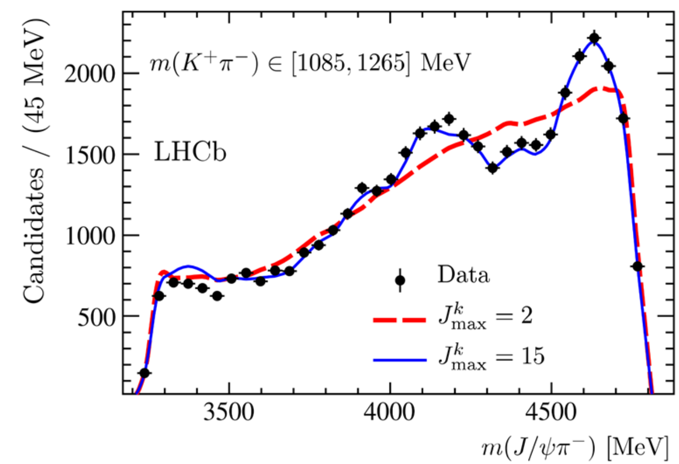
$$M = 4196^{+31+17}_{-29-13}\ \text{MeV}$$
$$\Gamma = 370^{+70+70}_{-70-132}\text{MeV}$$



10.1103/PhysRevD.90.112009

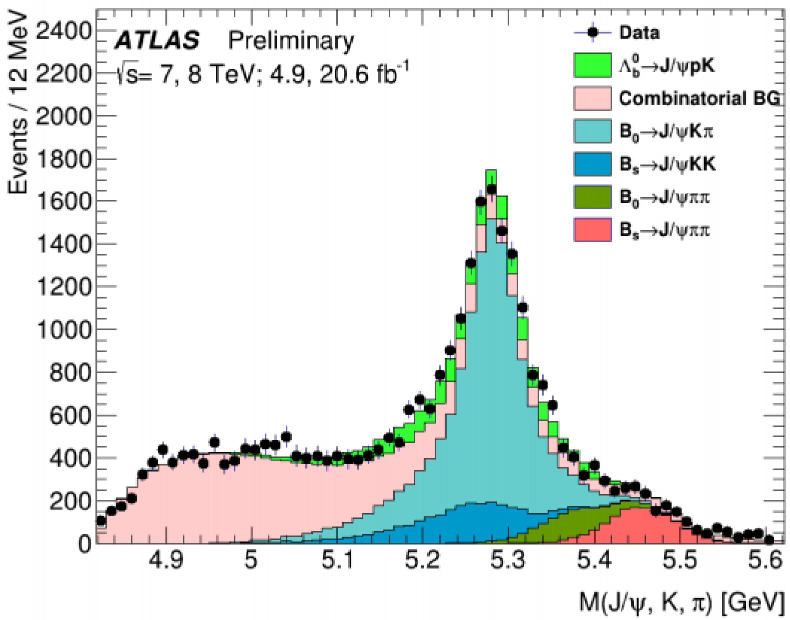
In 2008 BaBar collaboration performed model independent analysis of **B⁰→ J/ψKπ** decays to study Z_c(4430) state. No evidence of Z_c(4200) existence was found; ATLAS Run I studies gave hint on presence of Z_c contribution to B-meson decays;

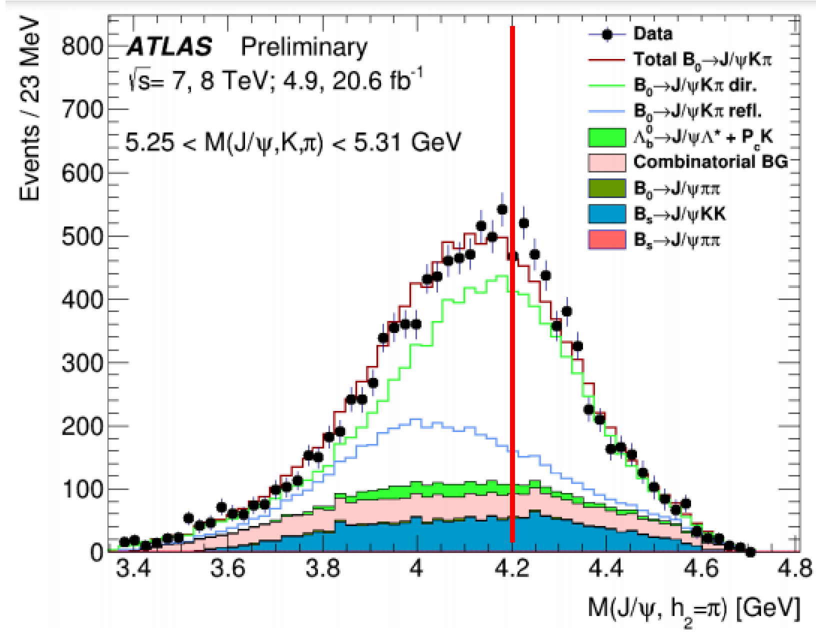
In 2019 LHCb collaboration performed model independent analysis of **B⁰→ J/ψKπ** decays. They discovered an exotic structure near the mass m(J/ψπ) = 4200 MeV.



Phys. Rev. Lett. 122, 152002 (2019)

ATLAS analyzed ~10K $B^0 \to J/\psi K\pi$ decays with Run I data w.r.t. properties of intermediate states. Data description without exotic contributions is not satisfatory (right plot) and demonstrates hint on $Z_c^+(4200)$ contribution.





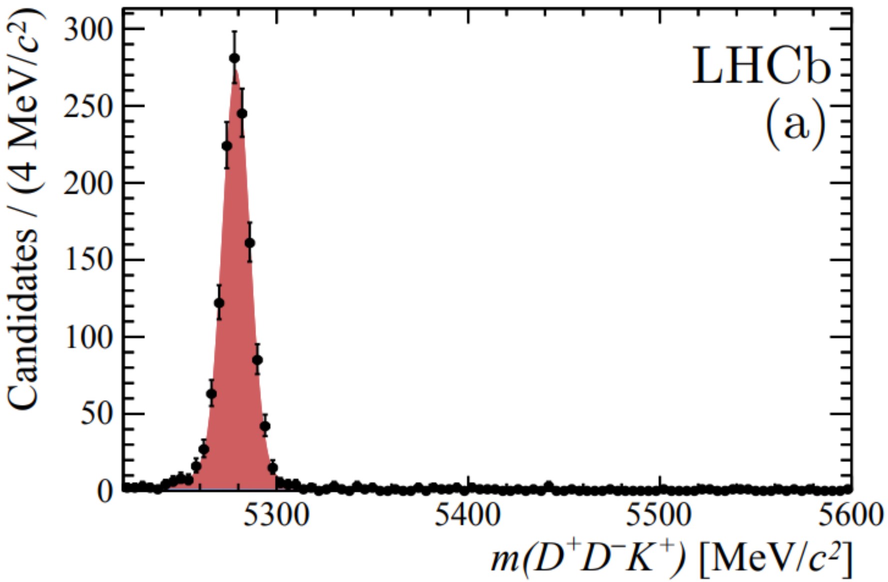
- $Z_c(4200)$ is also one of the exotic candidates with large (~300-400MeV) decay width, implying specific internal structure of this state;
- Many theoretical works are dedicated to the physics of this state:
  - Eur.Phys.J. C75 (2015) 8, 358; -- Z_c as tetraquark state;
  - PHYSICAL REVIEW D 98, 094028 (2018); -- Z_c as hadro-charmonium;
  - PhysRevD.100.051502; -- Z_c as triangular singularity;
  - Int. J. Mod. Phys. A30 (2015) 1550168 -- Z_c as DD^* molecular state;

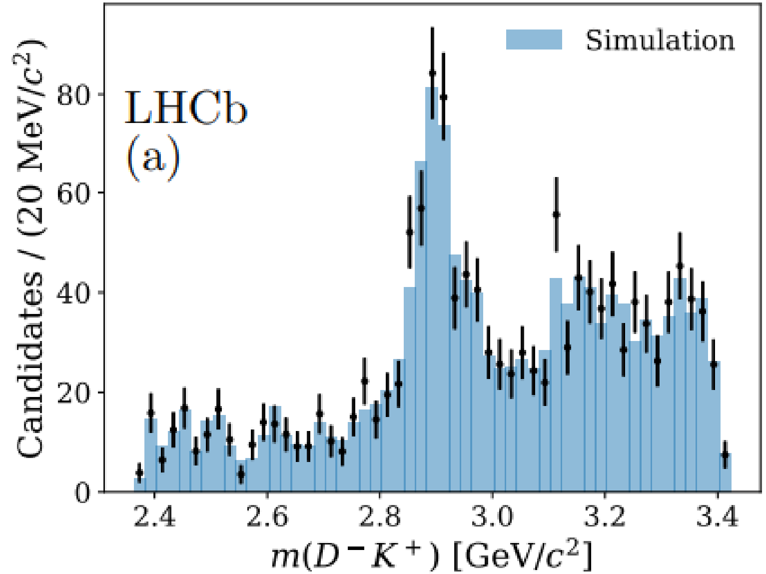
Exotica in the D^+K^- spectrum: open charm tetraquark

Exotica in the D^+K^- spectrum: open charm tetraquark

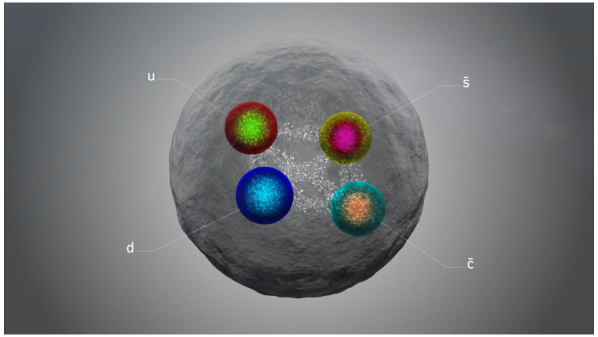
arXiv:2009.00025

LHCb analyzed 1260 candidates of $B^+ \to D^+D^-K^+$ decays.
Model independent analysis showed evidence for the exotic contribution to the D^+K^- spectrum.





The estimated significance of the signal is 3.7σ and its mass is around 2.9GeV.
This discrepancy could be explained by a new, manifestly exotic, charm-strange resonance.

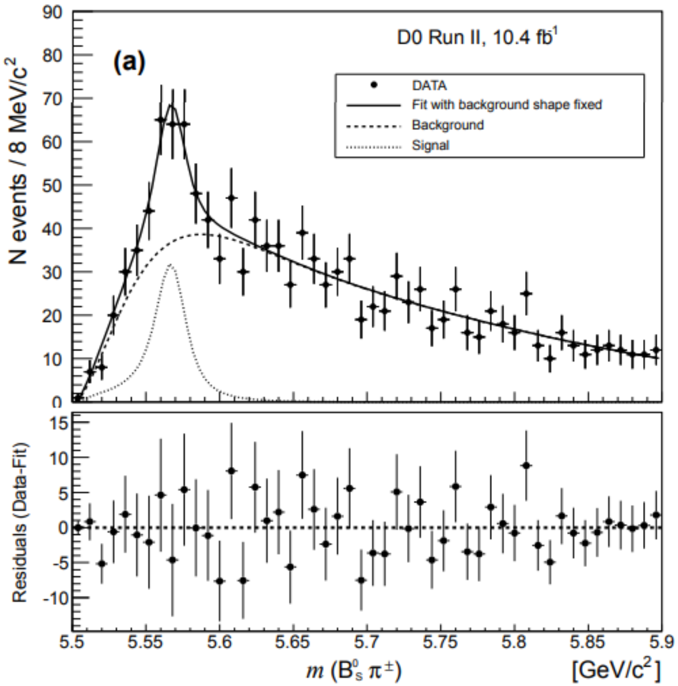


Searches for $X(5568)$ decaying into $B_s\pi^{\pm}$

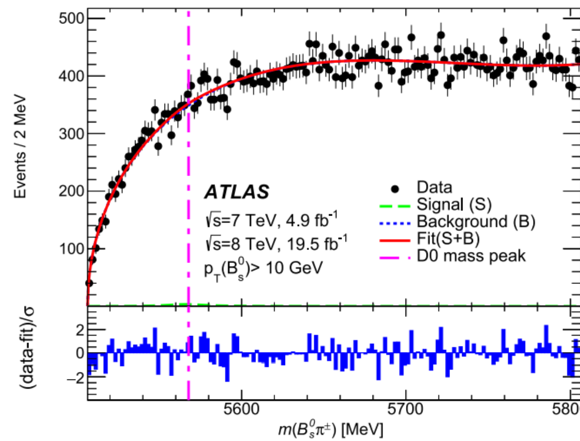
Study of $X(5568)$ state in $B_s\pi^\pm$ decays

D0 experiment claimed evidence for the $X(5568)$ state decaying into $B_s\pi^\pm$, naturally interpreted as *bsud* tetraquark candidate.

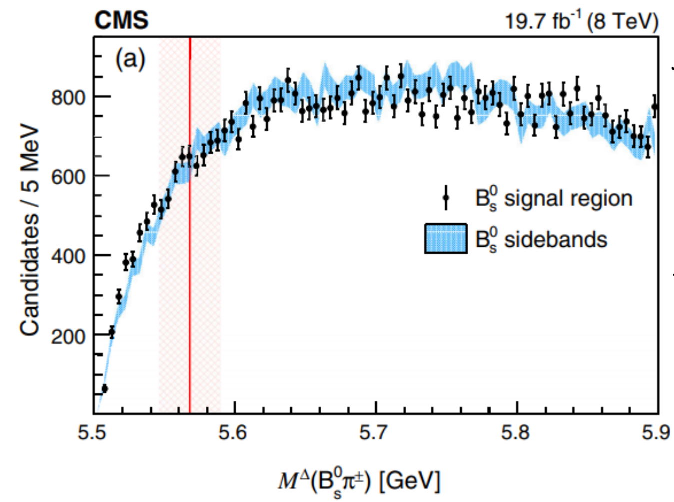
Phys. Rev. Lett., 117, 022003



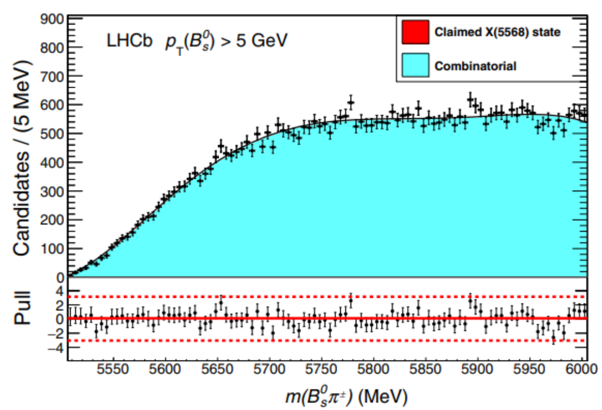
Other experiments performed analyses to search for this state:



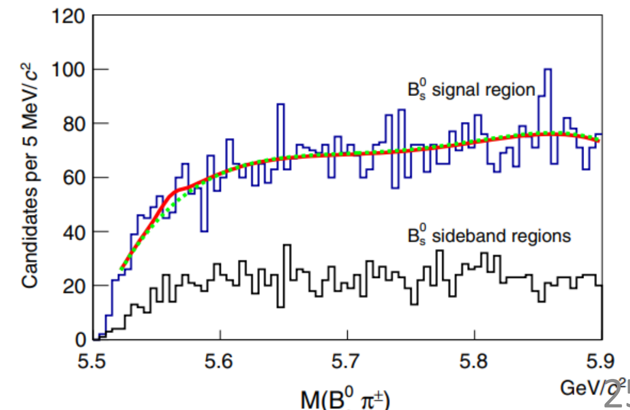
Phys. Rev. Lett. **120**, 202007



Phys. Rev. Lett. **120**, 202005



Phys. Rev. Lett. **117**, 152003



Phys. Rev. Lett. **120**, 202006

None of other experiments observed significant signal in the corresponding mass region…

Conclusions

- Exotic hadronic states represent a field of new physics within the Standard Model;
- Many of the states have been expected in theoretical studies, many have unexpected properties;
- There is a wide set of theoretical models within QCD that describe physics of pentaquark and tetraquark states, new experimental studies are needed to provide constraints for these models;
- Experimental efforts are focused on discoveries of new states, precise measurements of the observable properties for the exotic candidates, observations of new decay channels, etc.
- Experimental techniques allow studying wide resonances with exotic structure, providing precise backgrounds estimations, accounting for complex interference effects, performing multi-dimentional kinematic analysis, etc. This provides vast amount of information for the theory…

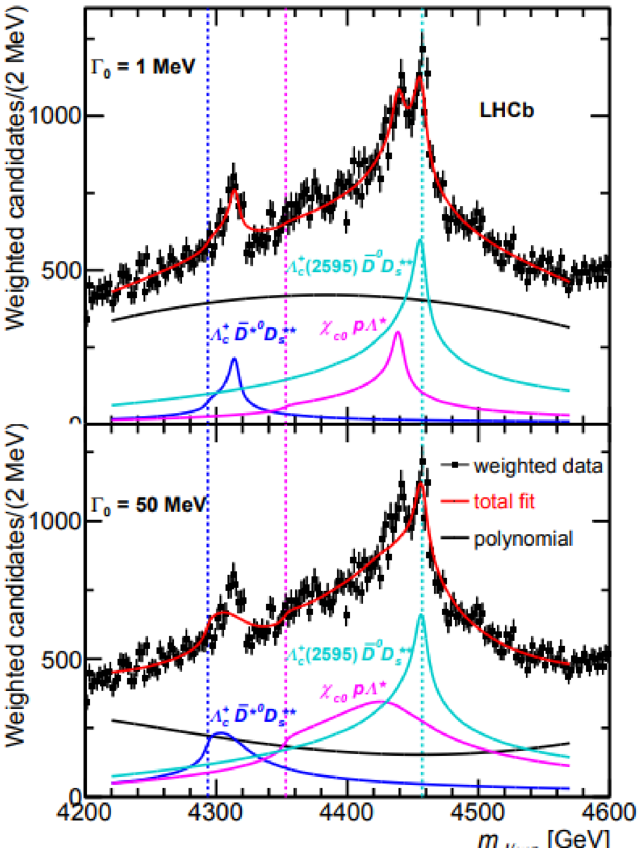
Thanks for your attention!

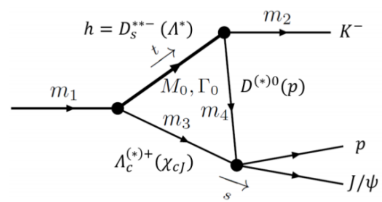
BACKUP

LHCb pentaquarks in Run II data

State	M [MeV]	Γ [MeV]	(95% C.L.)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Phys. Rev. Lett. 122 (2019) 222001





Left: fit using only triangular (rescattering) diagrams contributions

Right: different fits of signal area with 3 or 4 prntaquarks