Exotic spectroscopy at LHCb

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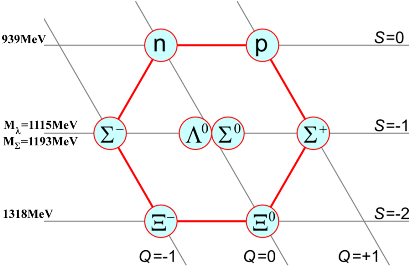
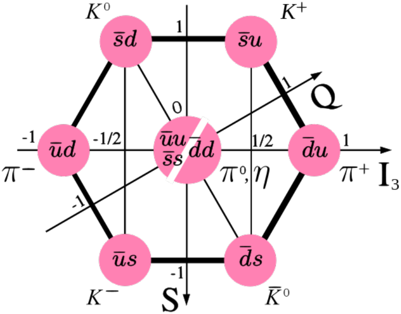
Outline

- exotic states overview
- summary of LHCb results on exotic states
- model independent analysis of $\Lambda_b \to J/\psi p K^-$ decays
- study of $B_s \pi^-$ system

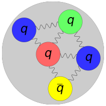
Quark model and exotic states

- bound states of quarks to form mesons and baryons first proposed by Gell-Mann and Zweig in 1964 to explain *explosion* of discovered particles





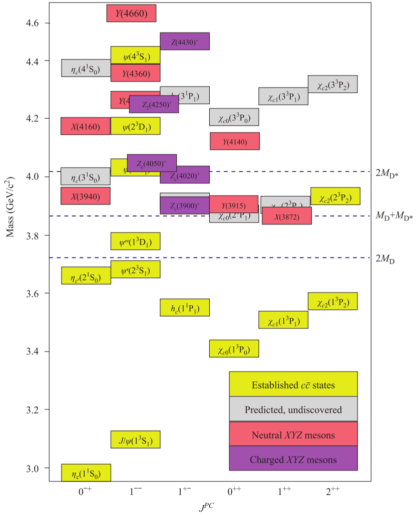
- other possible states composed by 4 or 5 quarks *not a priori excluded*



no evidences for almost 40 years ⇒ **Exotic states**

Exotic states: first observations

- since 2003 many different exotic (**XYZ**) candidates have been seen in $c\bar{c}$ and $b\bar{b}$ spectra at B and c factories
- they don't fit to conventional quarkonia states well predicted by QCD-motivated potential models
- their production and structure is still not clear
- $\Rightarrow$ **they need experimental and theoretical studies**



[arXiv:1411.7738v1]

Summary of LHCb results on exotic states

- search for $X(5568)^- \to B_s\pi^-$ **[LHCb-CONF-2016-004]**
- observation of pentaquarks in $\Lambda_b \to J/\psi pK^-$
  - moments analysis **[arXiv:1604.05708v1]** **NEW!**
  - amplitude analysis **[PRL 115 (2015) 072001]**
- $Z(4430)^-$ confirmation in $B_d \to \psi(2S)K^+\pi^-$
  - moments analysis **[PRD 92 (2015) 112009]**
  - amplitude analysis **[PRL 112 (2014) 222002]**
- $X(3872)$ studies
  - quantum numbers measurement $\Rightarrow J^{PC} = 1^{++}$ **[PRD 92 011102(R) (2015)], [PRL 110 222001 (2013)]**
  - measurement of $\mathcal{B}(X(3872) \to \psi(2S)\gamma)/\mathcal{B}(X(3872) \to J/\psi\gamma))$ **[Nucl.Phys.B 886 (2014) 665-680]**
  - mass measurement **[JHEP 06 (2013) 065]**
  - search for new decays **[EPJC (2013) 73:2462]**
  - production **[EPJC (2012) 72:1972]**

Model independent evidence for $J/\psi p$ contributions in $\Lambda_b \to J/\psi p K^-$ decays

Motivations

$\Lambda_b \to J/\psi pK^-$ amplitude analysis $\Rightarrow P_c^+$ states at 15 σ but:

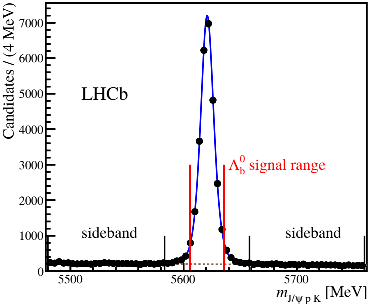
- Λ^* spectroscopy is a complex problem also from the experimental point of view
- high density of predicted states, probably with large widths, would make it difficult to identify them experimentally
- nonresonant contributions with non-trivial K^-p mass dependence may also be present

$\Rightarrow$ **inspect $\Lambda_b \to J/\psi pK^-$ data with a model independent approach with respect to K^-p contributions**

[arXiv:1604.05708v1]

Model independent analysis of $\Lambda_b \to J/\psi p K^-$ decays

- same selection criteria of amplitude analysis
- $\sim$ 27000 events, pure sample with 5.4% of combinatorial background within $\pm 2\sigma$ ($\sigma = 7.5\,\mathrm{MeV/c^2}$) of peak
- background subtraction weight w

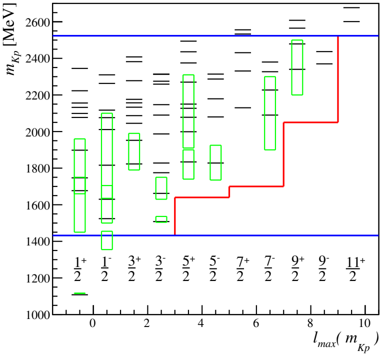


- 6D efficiency parametrization $\epsilon = \epsilon(m_{Kp}, cos(\theta_{\Lambda^*}), \Omega_a)$
- assess level of consistency of data with $\Lambda_b \to \Lambda^*(\to pK^-)J/\psi$ hypothesis (H_0), with minimal assumptions about the spin and lineshape of Λ^* contributions

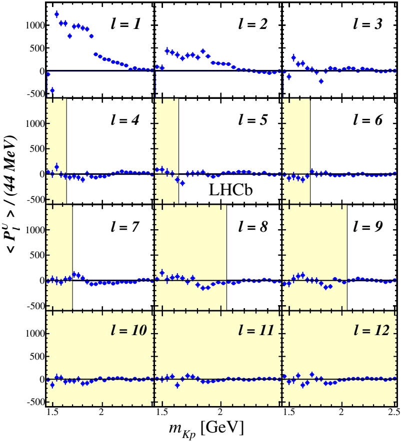
[arXiv:1604.05708v1]

Decay description through $(m_{Kp}, cos\theta_{\Lambda^*})$

- $$\frac{dN}{dcos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(cos\theta_{\Lambda^*})$$
- under the H_0 hypothesis
  $l_{max} = 2J_{max} \Rightarrow l_{max}(m_{Kp})$



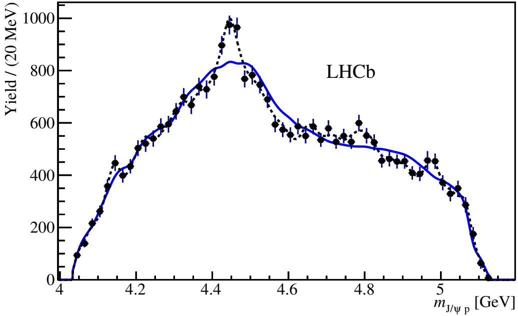
- $$\langle P_l^U \rangle^k = \sum_{i=1}^{N^k} \frac{w_i}{\epsilon_i} P_l(cos\theta^i_{\Lambda^*})$$



[arXiv:1604.05708v1]

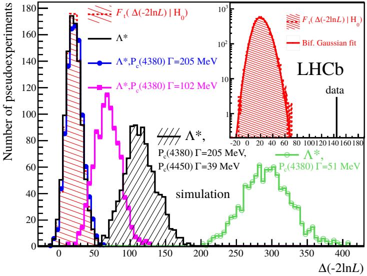
Projection onto $m_{J/\psi p}$

- per-event weight $\mathcal{F}(m_{Kp}, cos\theta_{\Lambda^*}|H_0) = \mathcal{F}(m_{Kp}|H_0)\mathcal{F}(cos\theta_{\Lambda^*}|H_0, m_{Kp})$
- $\mathcal{F}(m_{Kp}|H_0)$ from m_{Kp} histogram interpolation
- $\mathcal{F}(cos\theta_{\Lambda^*}|H_0, m_{Kp})$ from Legendre polynomials expansion
- generate events uniformly in $(m_{Kp}, cos\theta_{\Lambda^*})$ and weight with $\mathcal{F}(m_{Kp}, cos\theta_{\Lambda^*}|H_0)$



[arXiv:1604.05708v1]

Results of the model independent approach



- hypothesis test through likelihood ratio
- H_1 used $l \leq l_{large}$ where $l_{large} = 31$ is sufficient to fully describe $m_{J/\psi p}$ spectrum
- test the significance of $l_{max}(m_{Kp}) \leq l \leq l_{large}$ moments which cannot be induced via $\Lambda_b \to J/\psi\Lambda^*$ decays

demonstrates at more than 9 σ that $\Lambda_b \to J/\psi p K^-$ decays cannot be described with $K^- p$ contributions alone

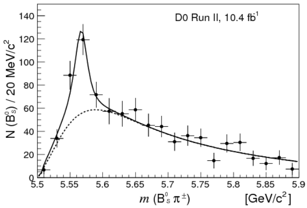
[arXiv:1604.05708v1]

Search for structure in the $B_s\pi^{\pm}$ spectrum

Motivations

- recently the D0 collaboration claimed the observation of a new tetraquark at 5.1 σ
- $X(5568)^- \to B_s\pi^-$, $B_s \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$
- the proposed quark content is $\bar{b}s\bar{u}d$ $\Rightarrow$ its mass would be dominated by one constituent quark $\Rightarrow$ **important hint to understand exotics bound mechanism**

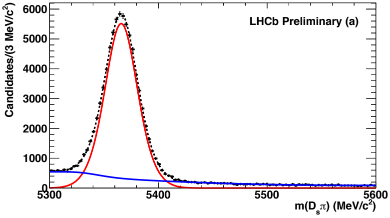
- $M = 5567.8 \pm 2.9(stat)^{+0.9}_{-1.9}(syst)\ \mathrm{MeV/c^2}$
- $\Gamma = 21.9 \pm 6.4(stat)^{+5.0}_{-2.5}(syst)\ \mathrm{MeV/c^2}$
- B_s coming from $X^-(5568)$:
  $\rho = (8.6 \pm 1.9 \pm 1.4)\%$

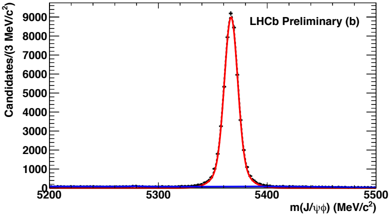


[arXiv:1602.07588v2]

LHCb data sample and selection of the candidates

- data sample corresponding to $3\,\mathrm{fb}^{-1}$ of pp collision data at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$
- B_s candidates selected in $B_s \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ as by D0, but also in $B_s \to D_s^-(\to K^+K^-\pi^-)\pi^+$
- well known selection criteria, since have been used in studies for B^+K^-, $B^+\pi^-$ and $B_d\pi^+$ (cross-check channel)



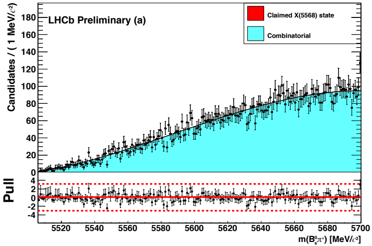


- **sample $\sim$ 20 times larger** than that available to the D0 collaboration

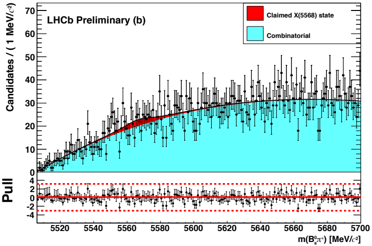
[LHCb-CONF-2016-004]

Fit to the Q-value distributions and results

- spectra are presented in term of $Q := M(B_s\pi) - M(B_s) - M(\pi)$
- signal shape is an S-wave Breit-Wigner with mass and width parameters fixed to those obtained by D0 ($Q_{X(5568)} = 61.4\,\mathrm{MeV/c^2}$)



$B_s\ p_T > 5\,\mathrm{GeV/c}$



$B_s\ p_T > 10\,\mathrm{GeV/c}$, D0-like

- the fit has a p-value of 34.0% and **no significant $X(5568)^-$ yield**
- $\rho_X^{LHCb}(B_s\ p_T > 5\,\mathrm{GeV/c}) < 0.009\ (0.010)$ @ 90 (95) % CL
- $\rho_X^{LHCb}(B_s\ p_T > 10\,\mathrm{GeV/c}) < 0.016\ (0.018)$ @ 90 (95) % CL

[LHCb-CONF-2016-004]

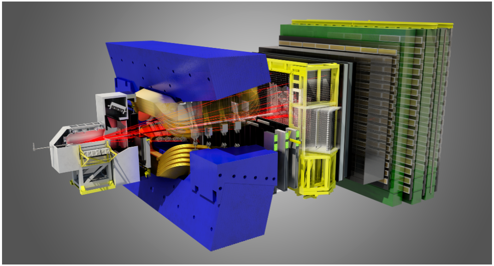
Conclusions

- $\Lambda_b \to J/\psi p K^-$ model independent analysis strongly supports the pentaquark states introduced in the model of the amplitude analysis
- no visible $X(5568)^-$ signal at LHCb
- several results obtained by LHCb with Run1 data
- looking forward to Run2 to obtain further exciting results!

Thanks and stay tuned!

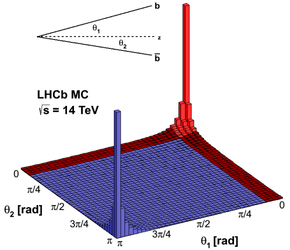
Extra slides

The LHCb detector



- **precise primary and secondary vertex reconstruction**: 20 μm for high-p_T tracks
- **excellent momentum resolution**: $\Delta p/p = 0.5\%$ at low momentum to 1.0 % at 200 GeV/c
- **very good separation of charged π, K and p** and **excellent muon identification** over the $2 < p < 100$ GeV/c range

- **$2 < \eta < 5$** range: $\sim$ 25% of $b\bar{b}$ pairs inside LHCb acceptance



- $\mathcal{L} = 3\,\text{fb}^{-1}$ in 2011+2012 data taking $\Rightarrow$ **$\sim 10^{12}$ $b\bar{b}$ pairs**
- data taking restarted in 2015: at the end of 2016 we expect to **double the statistics**