Heavy flavour spectroscopy at LHCb (including exotic states)

UNIVERSITÀ DEGLI STUDI DI MILANO

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on behalf of the LHCb collaboration

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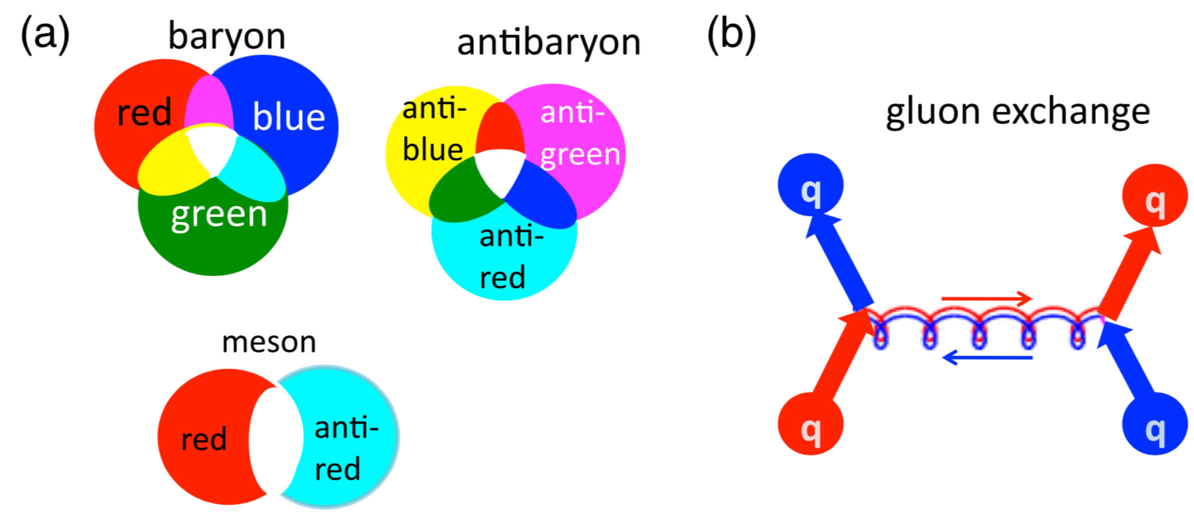
Outline

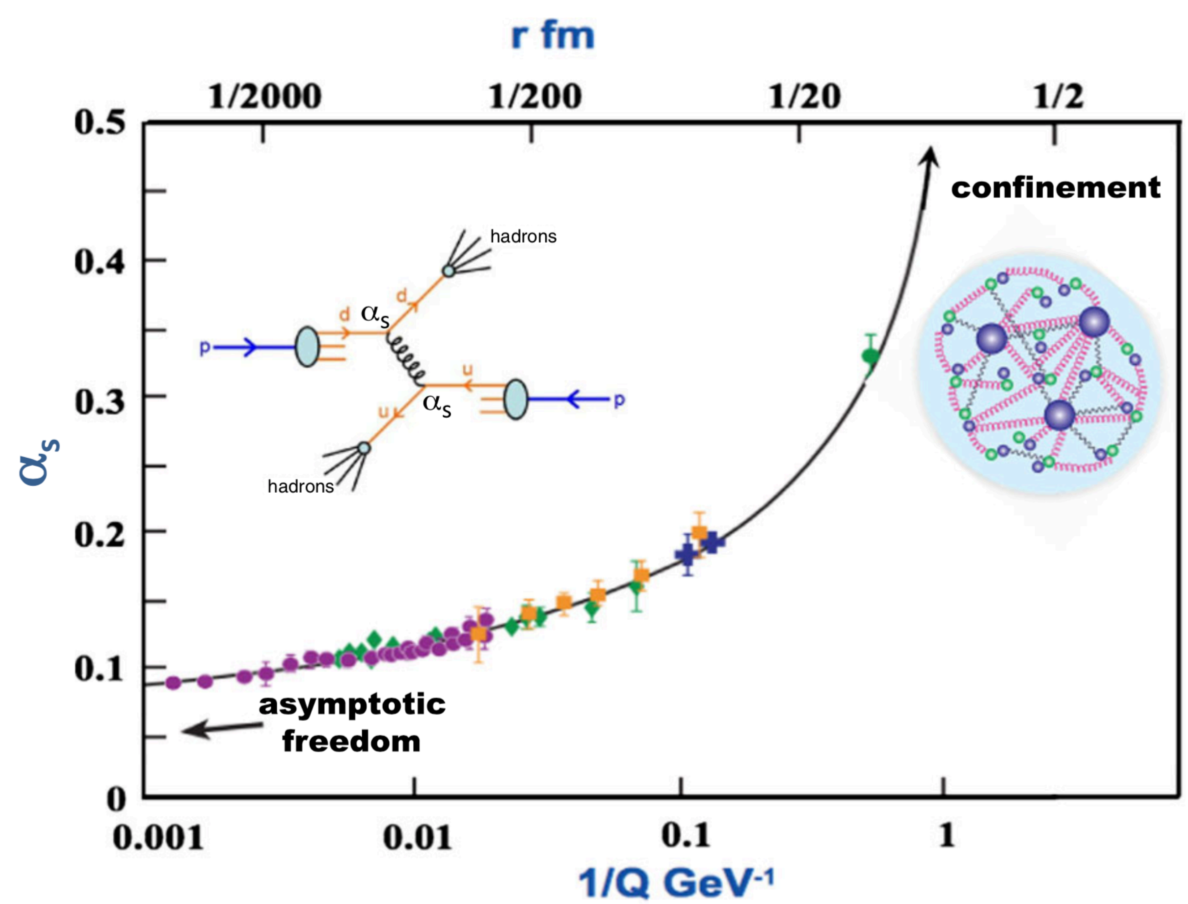
- Introduction
- LHCb experiment
- Recent results
  - Evidence for $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ decays LHCb-PAPER-2018-034, arXiv:1809.07416
  - Observation of two new resonances in $\Lambda_b\pi^\pm$ systems LHCb-PAPER-2018-032, arXiv:1809.07752
  - Search for beautiful tetraquarks in $\Upsilon(1S)\mu^+\mu^-$ invariant-mass spectrum LHCb-PAPER-2018-027, JHEP 10 (2018) 086
- Summary

Introduction

Rev. Mod. Phys. 90, 15003 (2018)

- Quantum chromodynamics (QCD) describes interactions of quarks and gluons. Accepted theory of strong interactions
- Quark and gluon composition of observed hadrons in experiments is very complex: “QCD dilemma”
- Understanding QCD (long-distance) is also very important for improving sensitivity in new physics searches, e.g. flavour physics, muon *g-2*

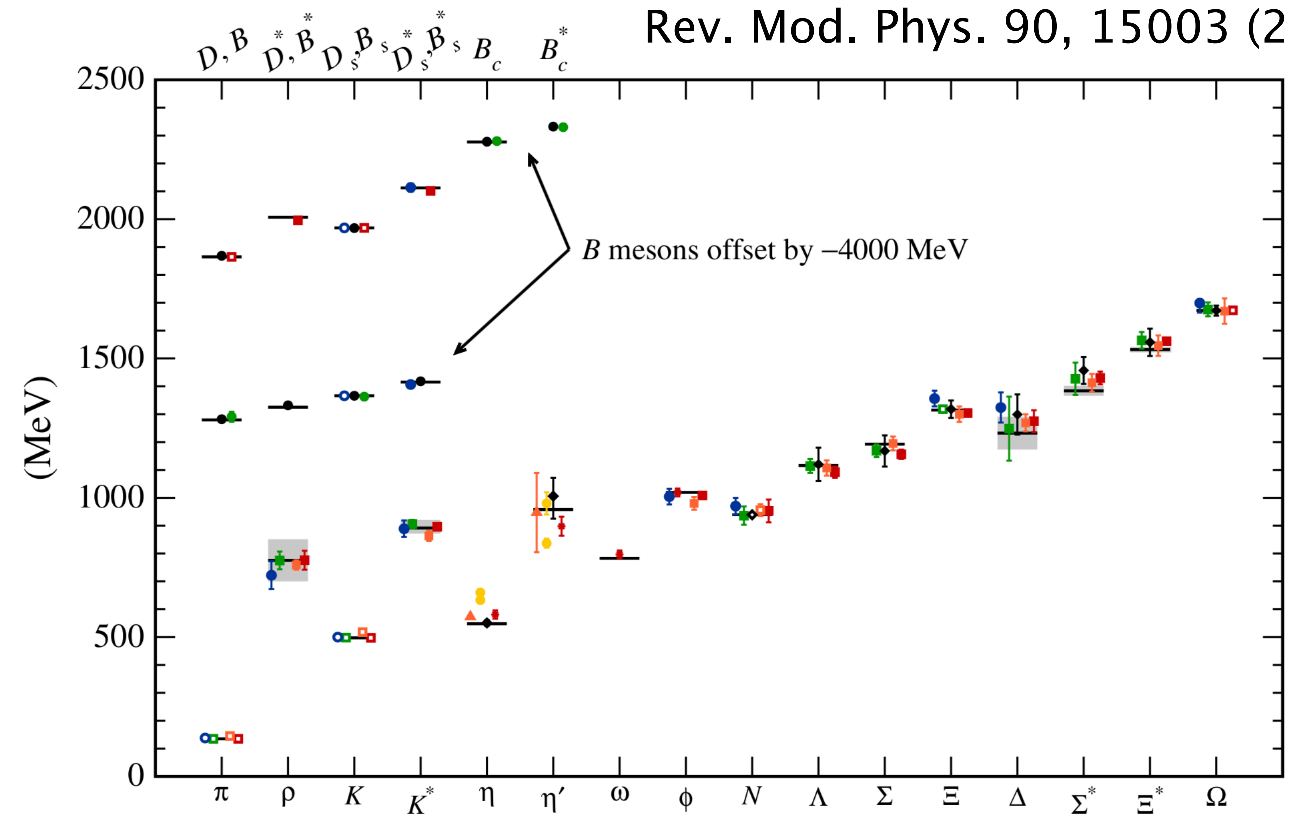


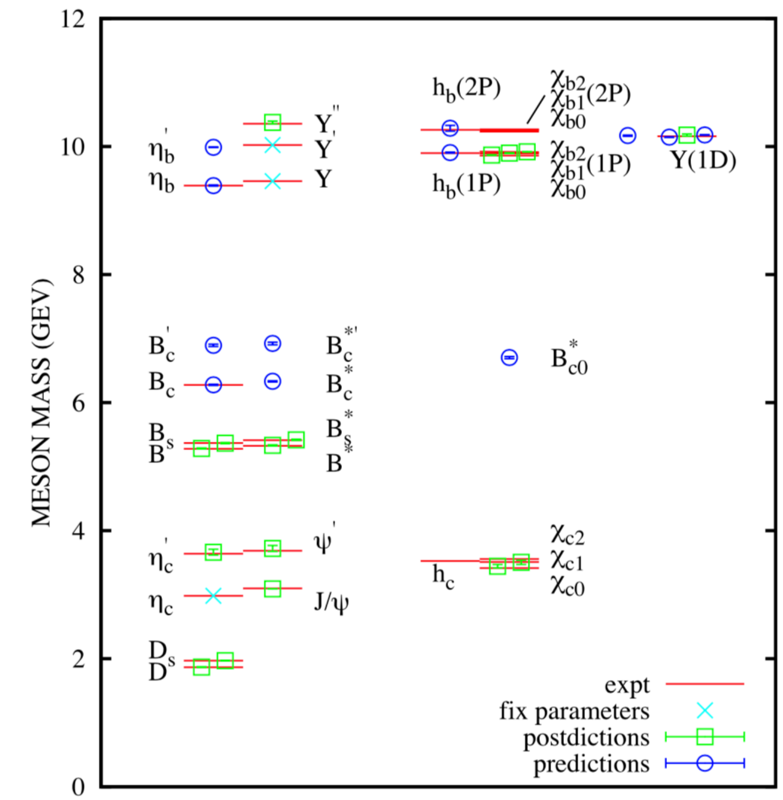


Quark Model

- A goal of QCD is to predict the spectrum of strongly-interacting particles
- Phenomenological models developed to overcome limitations of lattice QCD (LQCD) calculations
- Hadron spectroscopy provide important anchor points for both LQCD calculations and phenomenological models

Rev. Mod. Phys. 90, 15003 (2018)

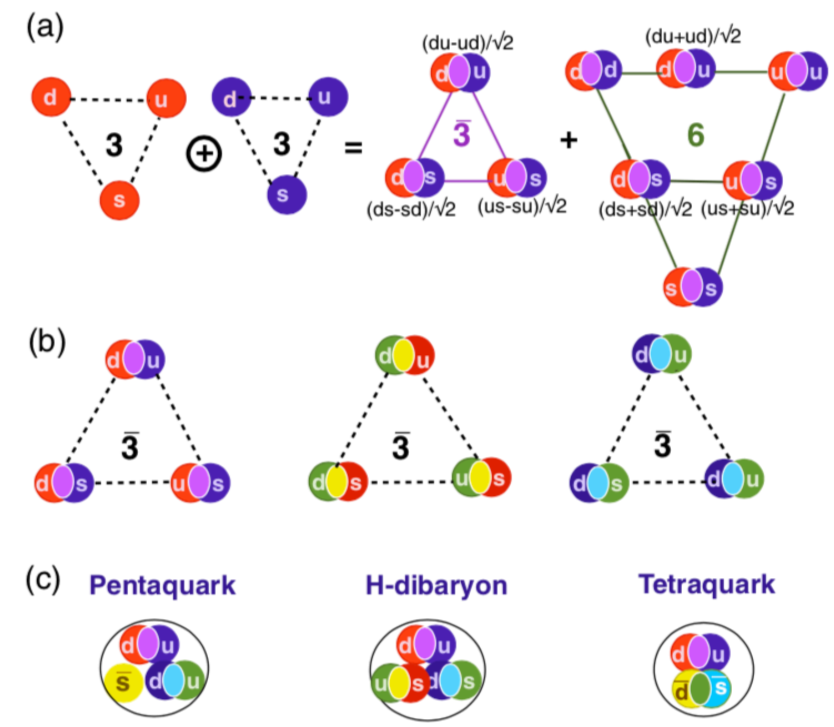


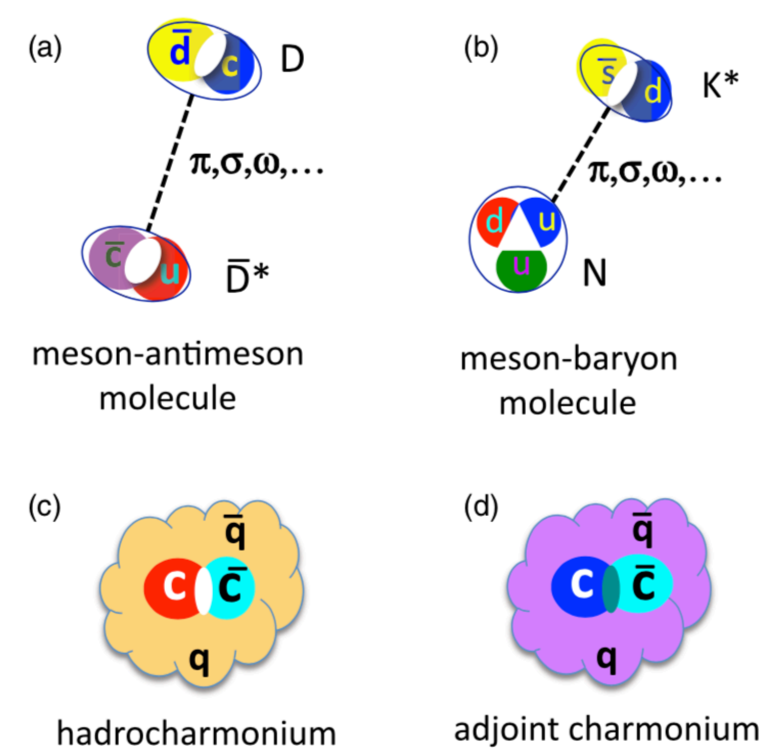


Nonstandard (“exotic”) hadrons

- Identify patterns in hadron spectroscopy beyond (qqq) baryons and (q$\bar{q}$) mesons to help development of theoretical models
- Pentaquark baryons and tetraquark mesons already mentioned in original Gell-Mann, Zweig formulation of quark model (1964)
- Different models proposed for quark composition and binding mechanisms of “exotic” states

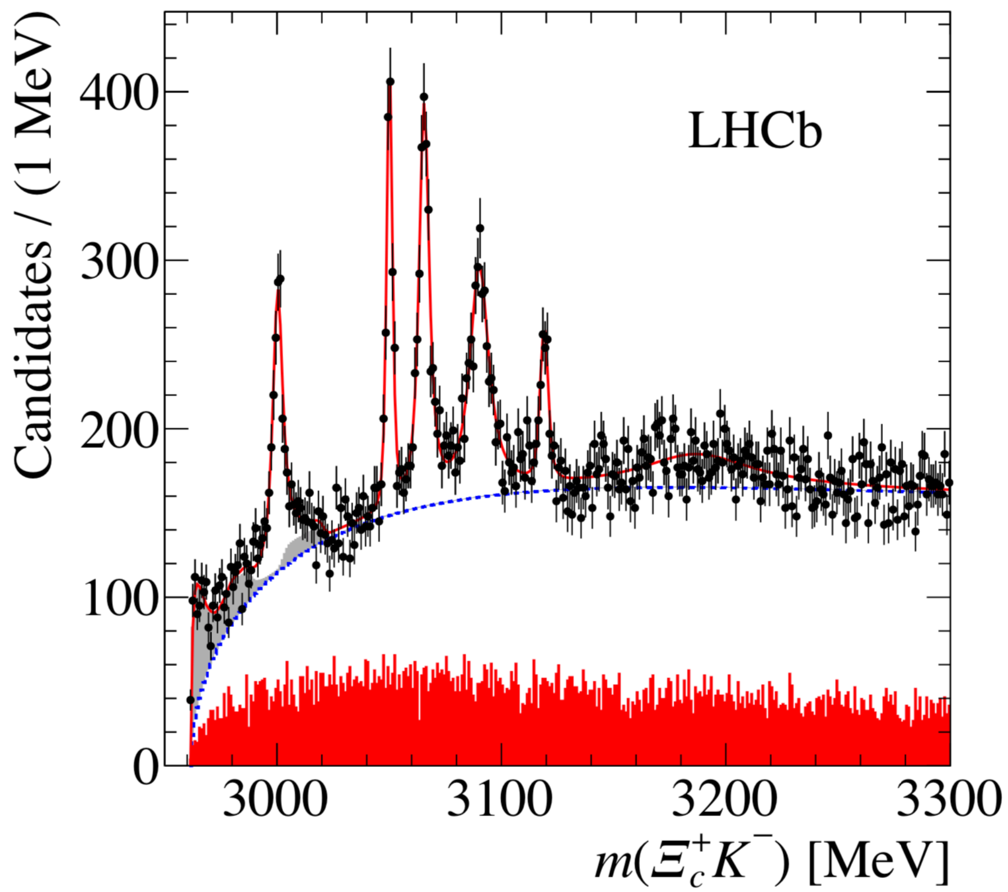
Rev. Mod. Phys. 90, 15003 (2018)



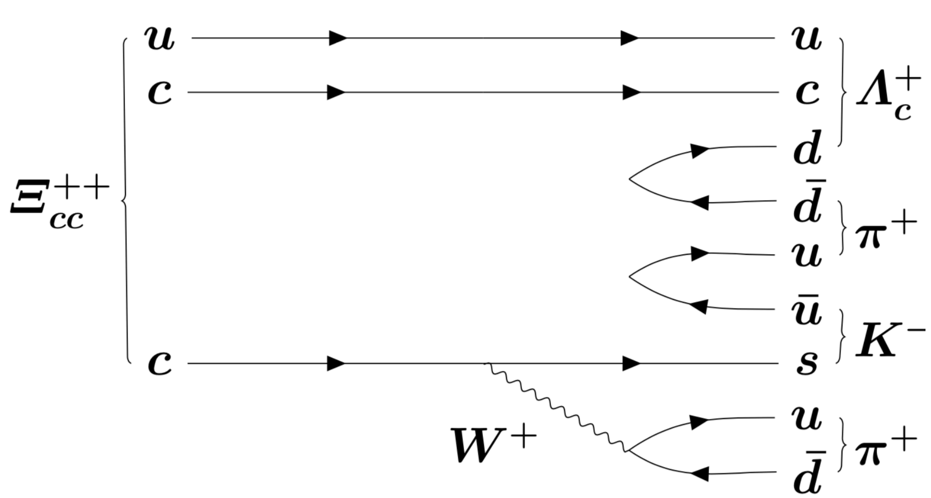


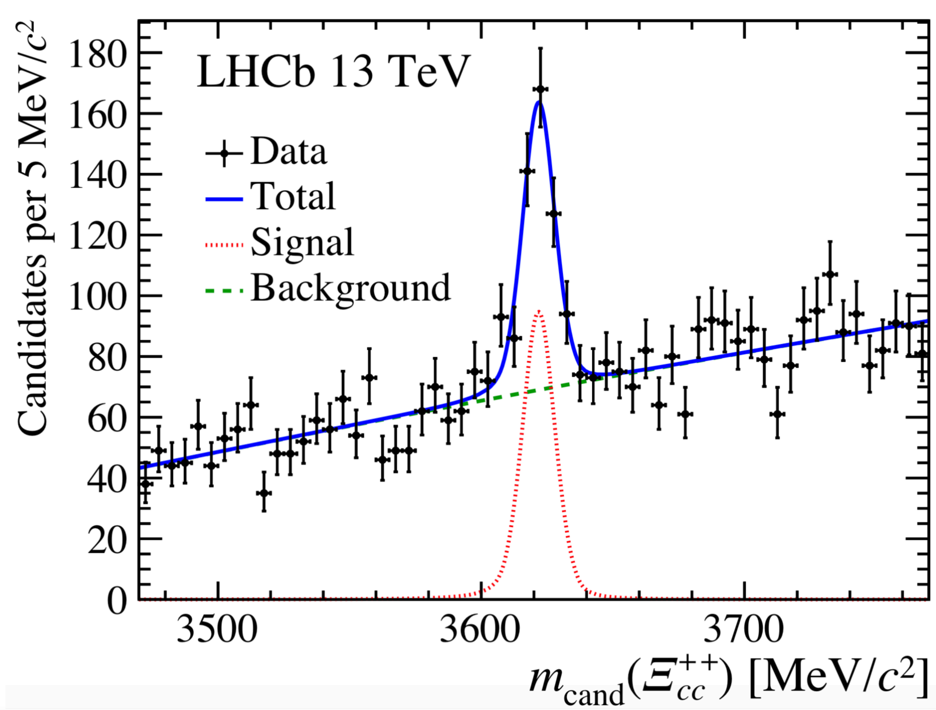
New "standard" hadrons at LHCb

- Discovery of five narrow excited Ω_c^0 states
  Phys. Rev. Lett. 118, 182001 (2017)



- Discovery of doubly charmed baryon Ξ_{cc}^{++}
  Phys. Rev. Lett. 119, 112001 (2017)
  - Observed also in $\Xi_c^+\pi^+$ final state
    Phys. Rev. Lett. 121, 162002 (2018)

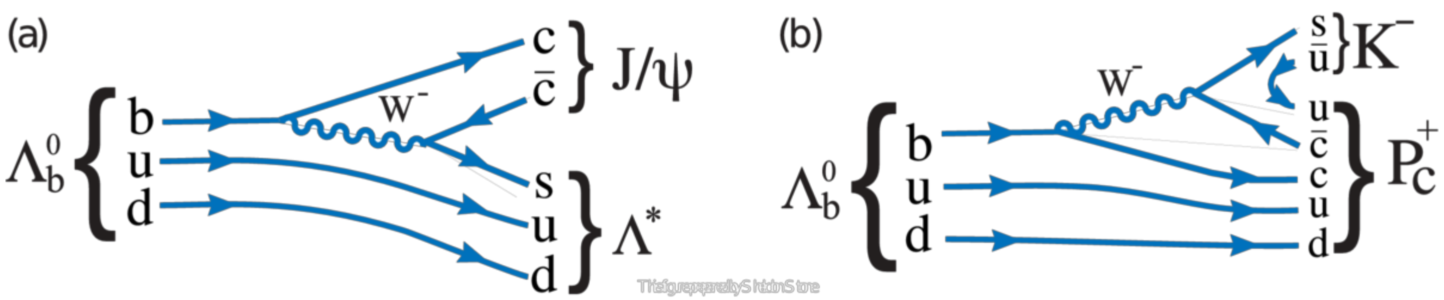


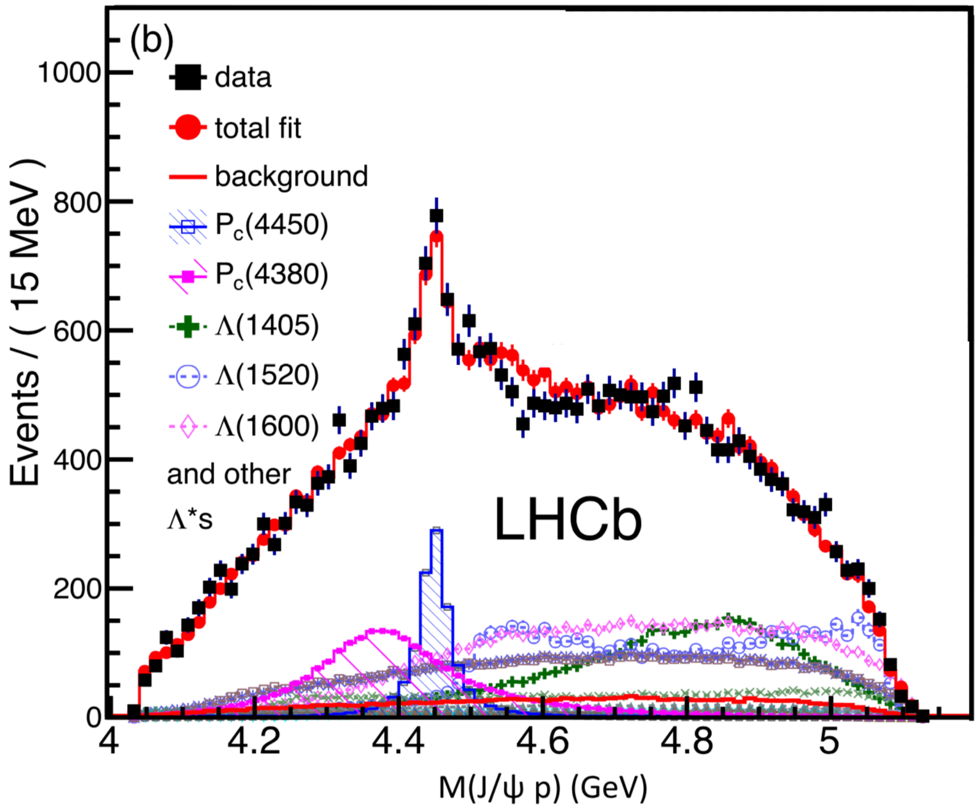


New “exotic” hadrons at LHCb

- New pentaquark candidates in J/Ψ p system

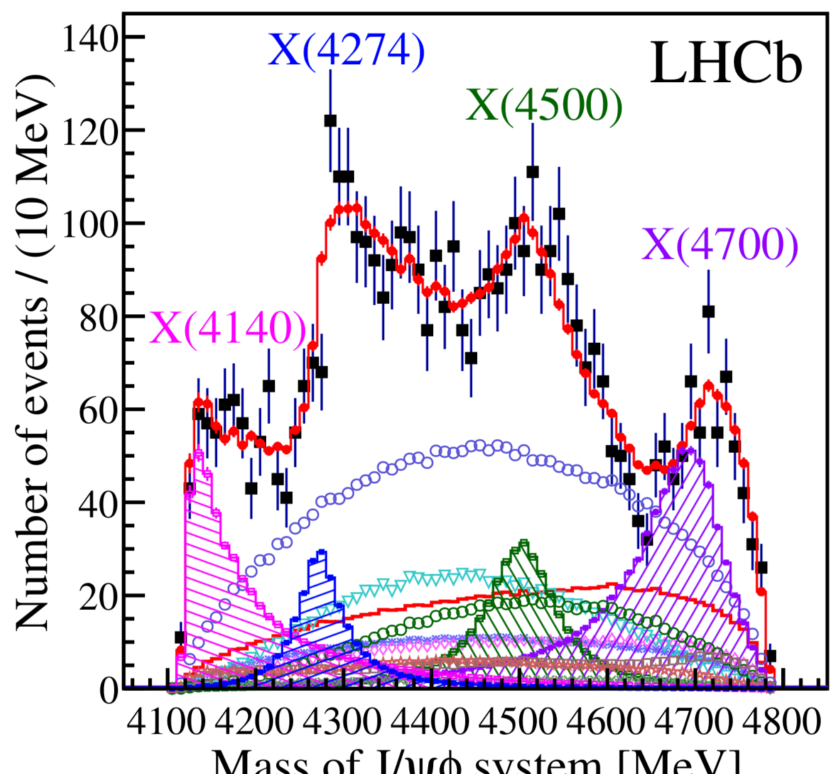
  Phys. Rev. Lett. 115, 072001 (2015)





- New tetraquark candidates in J/Ψϕ system
  - binding mechanism could involve tightly binding tetra quarks or $D_s^+D_s^{*-}$ pairs

  Phys. Rev. Lett. 118, 022003 (2017)

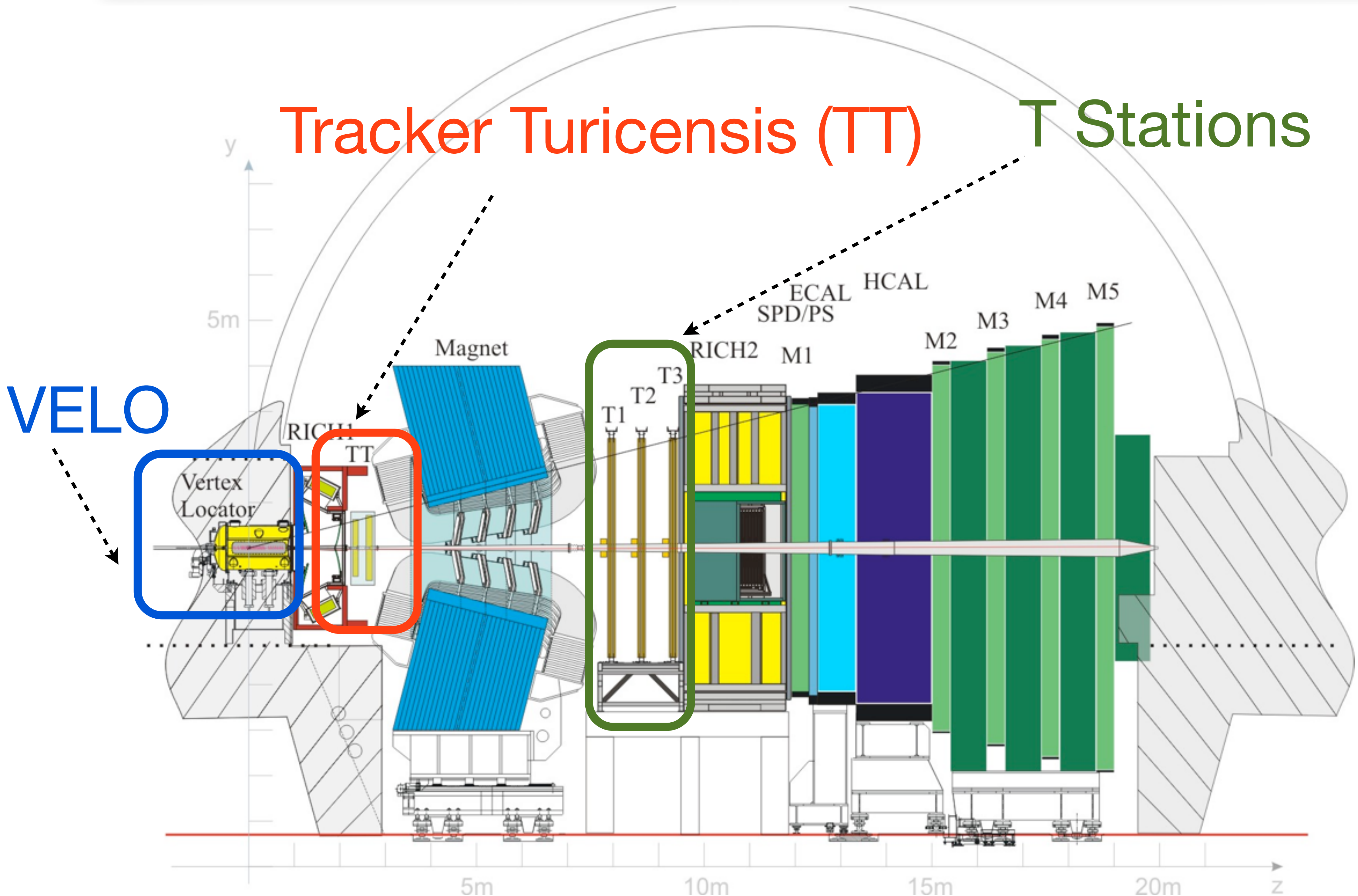


LHCb experiment

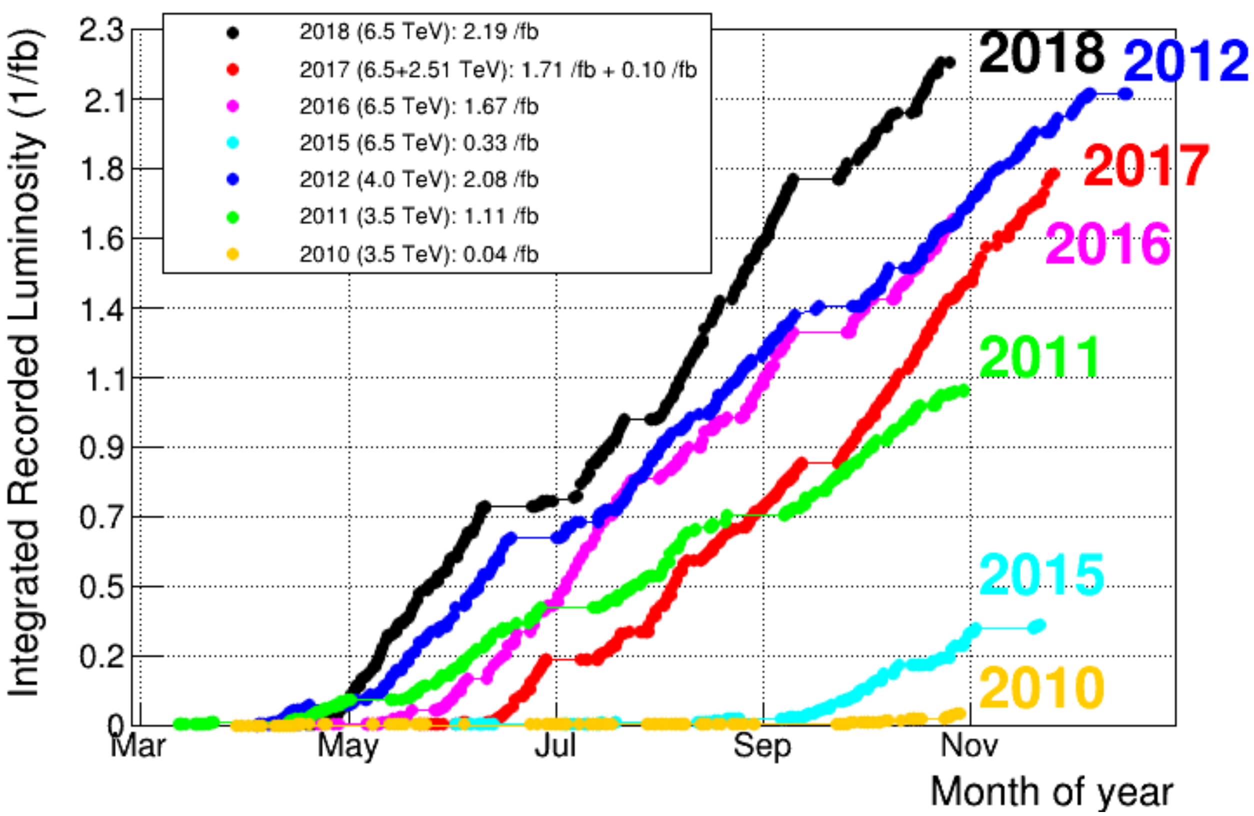
LHCb physics program

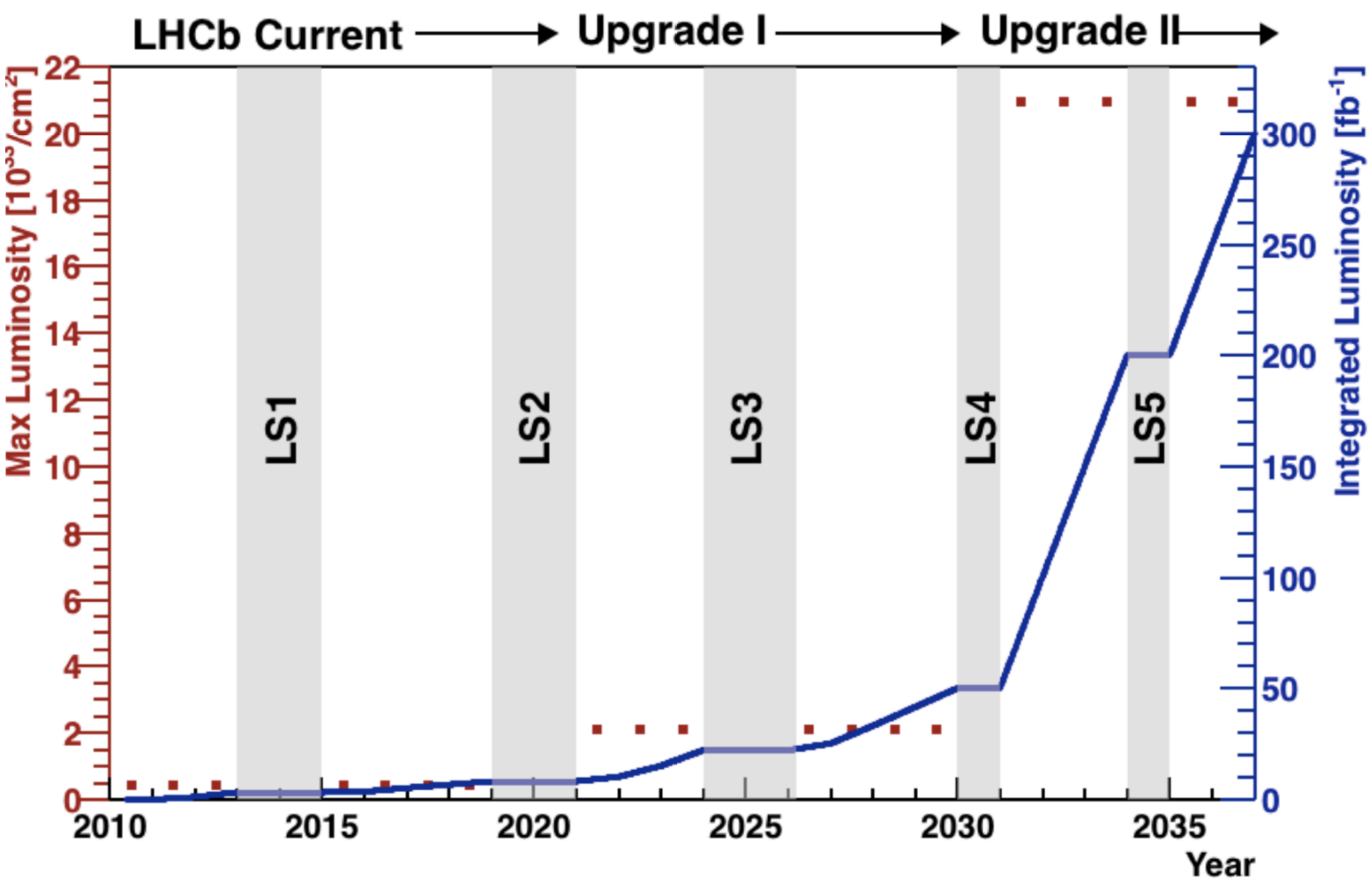
CKM and *CP* violation	sin2β, γ, ϕ_s, $\lvert V_{ub}/V_{cb}\rvert$, CPV in B^0, B_s^0, D^0, b-baryons… See D. Hills' talk
Rare decays	$B_{(s)}^0 \to \mu^+\mu^-$, $b \to s\mu^+\mu^-$, $b \to se^+e^-$, $\Sigma^+ \to p\mu^+\mu^-$,…See K. Mueller's talk
Spectroscopy	**Tetraquarks, Pentaquarks, Ξ_{cc}^{++}, Ω_c^*, Ξ_b^{-*},…**
Electroweak QCD, Exotica	Z^0, W^+, top, Dark photons, Long-lived particles,..
Ion, Fixed-target	Heavy ions, p-Gas, nuclear effects,… See G. Graziani's talk

LHCb detector at CERN



LHCb data sample and plans





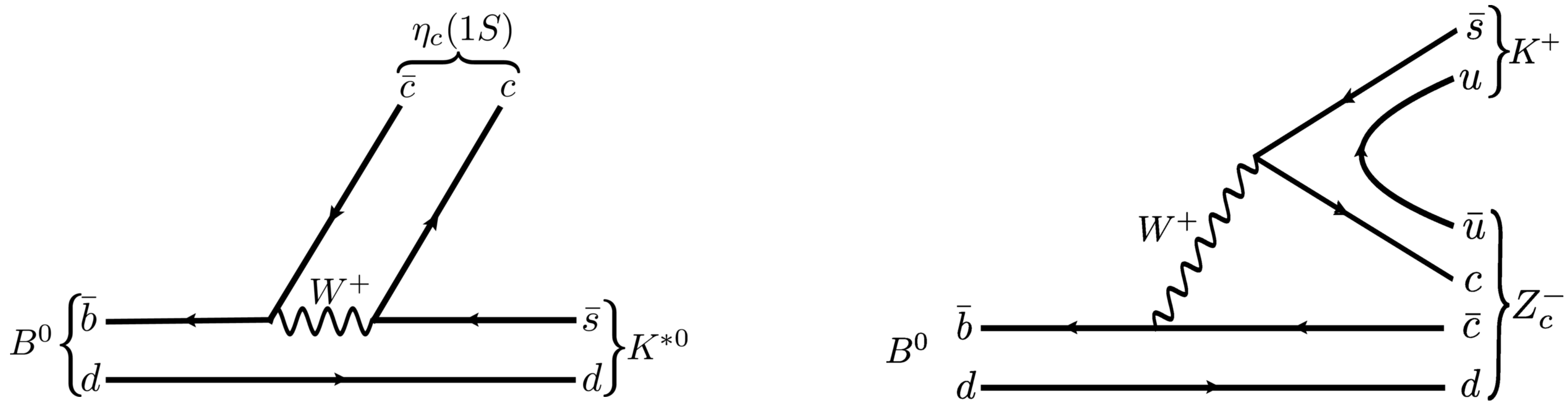
- Collected >9 fb^{-1} in 2010-2018. Major detector upgrade during LS2 (Upgrade I- 2020). Aim at 50 fb^{-1} before 2030
- Major detector upgrade during LS4 (Upgrade II - 2030). Aim at >300 fb^{-1} after 2030 - ….

See O. Steinkamp's talk

Recent results

Evidence for $\eta_c(1S)\pi^-$ resonance

Search for $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ decays

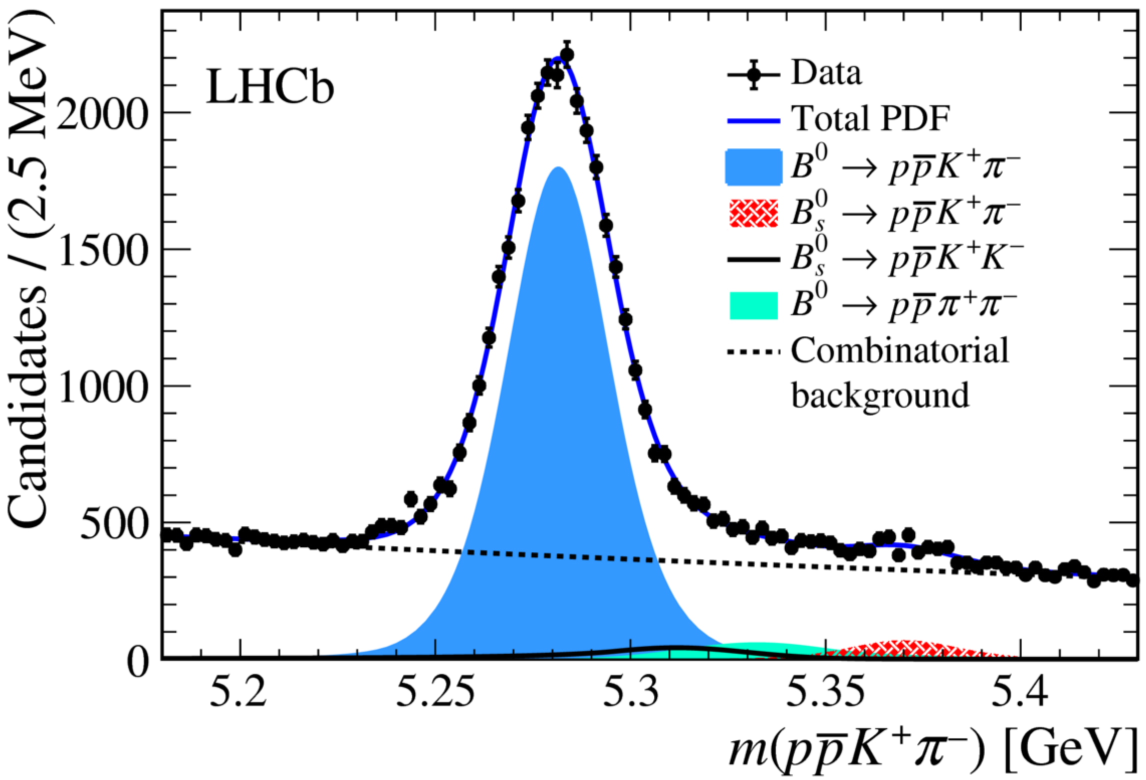


- Important input for understanding nature of exotic hadrons, in particular of $Z_c(3900)^-$ state ($J/\Psi\ \pi^-$ system) discovered by BESIII
  - hadrocharmonium model ⇒ $\eta_c(1S)\pi^-$ resonant state m= 3800 MeV
  - quarkonium hybrid model ⇒ $\eta_c(1S)\pi^-$ resonant state $J^P=0^+, 1^-, 2^+$ m= 4025, 3770, 4045 MeV
  - diquark model ⇒ $\eta_c(1S)\pi^-$ resonant state $J^P=0^+$ and m<3770 MeV

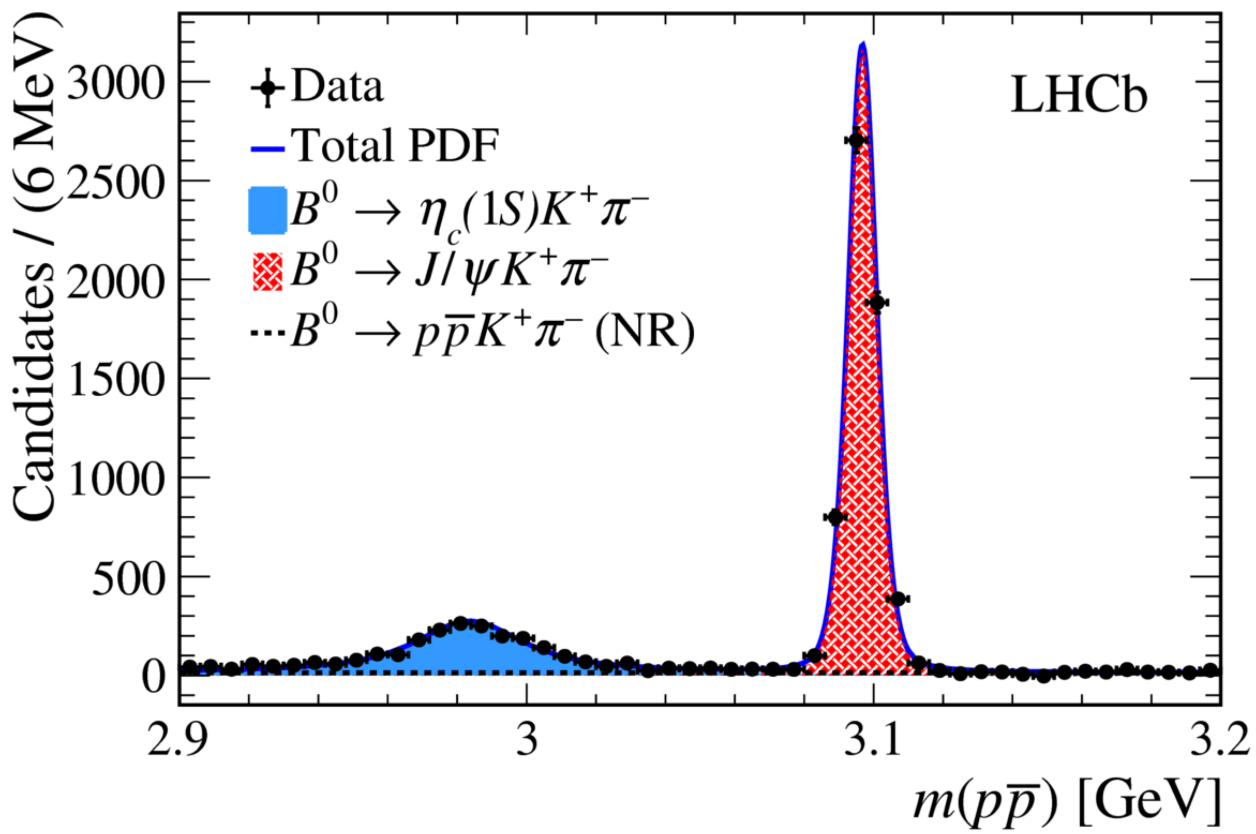
Signal yields

2011-2016 data - 4.7 fb^{-1}

30.000 $B^0 \to p\bar{p}K^+\pi^-$ decays



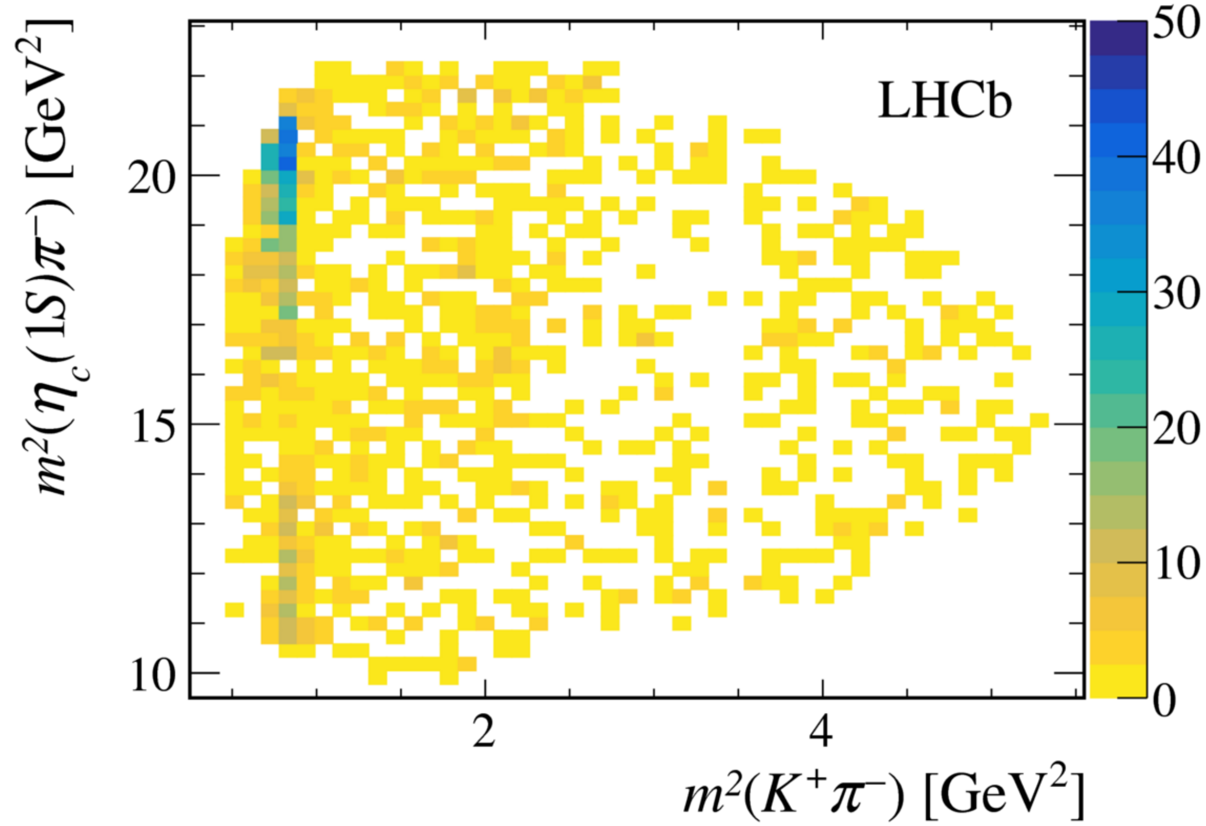
2.100 $B^0 \to \eta_c(1S)K^+\pi^-$ decays



- PID from RICH detectors is crucial for signal selection
- Reconstruct $\eta_c(1S) \to p\bar{p}$ decay mode
- Use $B^0 \to p\bar{p}K^+\pi^-$ decays as control sample and $B^0 \to J/\Psi K^+\pi^-$ ($J/\Psi \to p\bar{p}$) as normalisation mode for BR measurement

Amplitude analysis of $B^0 \to \eta_c(1S)K^+\pi^-$ decays

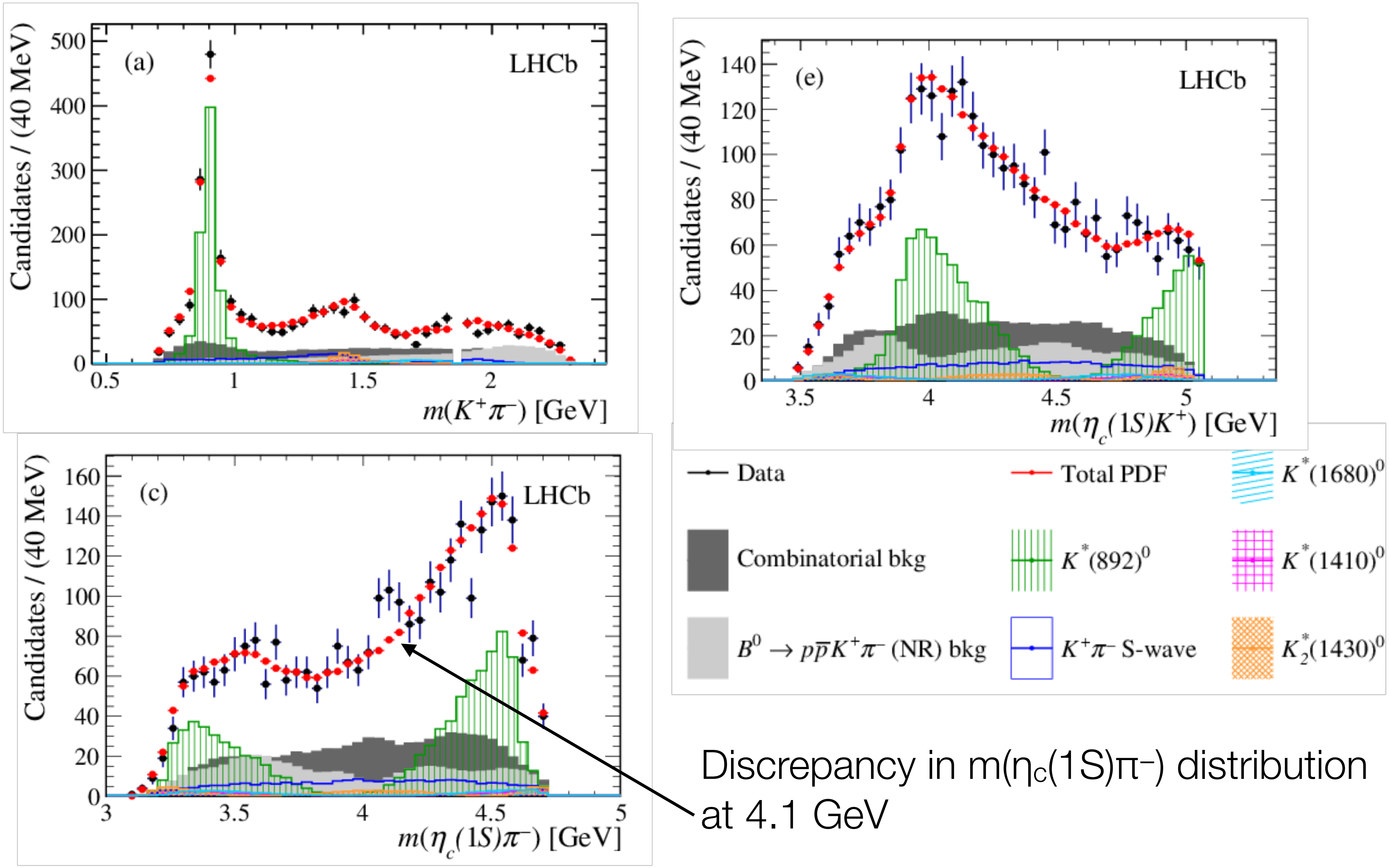
- Study Dalitz plot of 3 pseudoscalar final state particles: $m^2(K^-\pi^+)$, $m^2(\eta_c\pi^-)$
- η_c natural width $\Gamma \sim 32$ MeV taken into account
- Isobar model to describe the decay amplitude: coherent sum of resonant $K^-\pi^+$ and non-resonant processes
- $K^-\pi^+$ S-wave with LASS model
- Exotic $Z_c^- \to \eta_c\pi^-$ contribution added to improve the fit to data



$K^-\pi^+$ resonant contributions

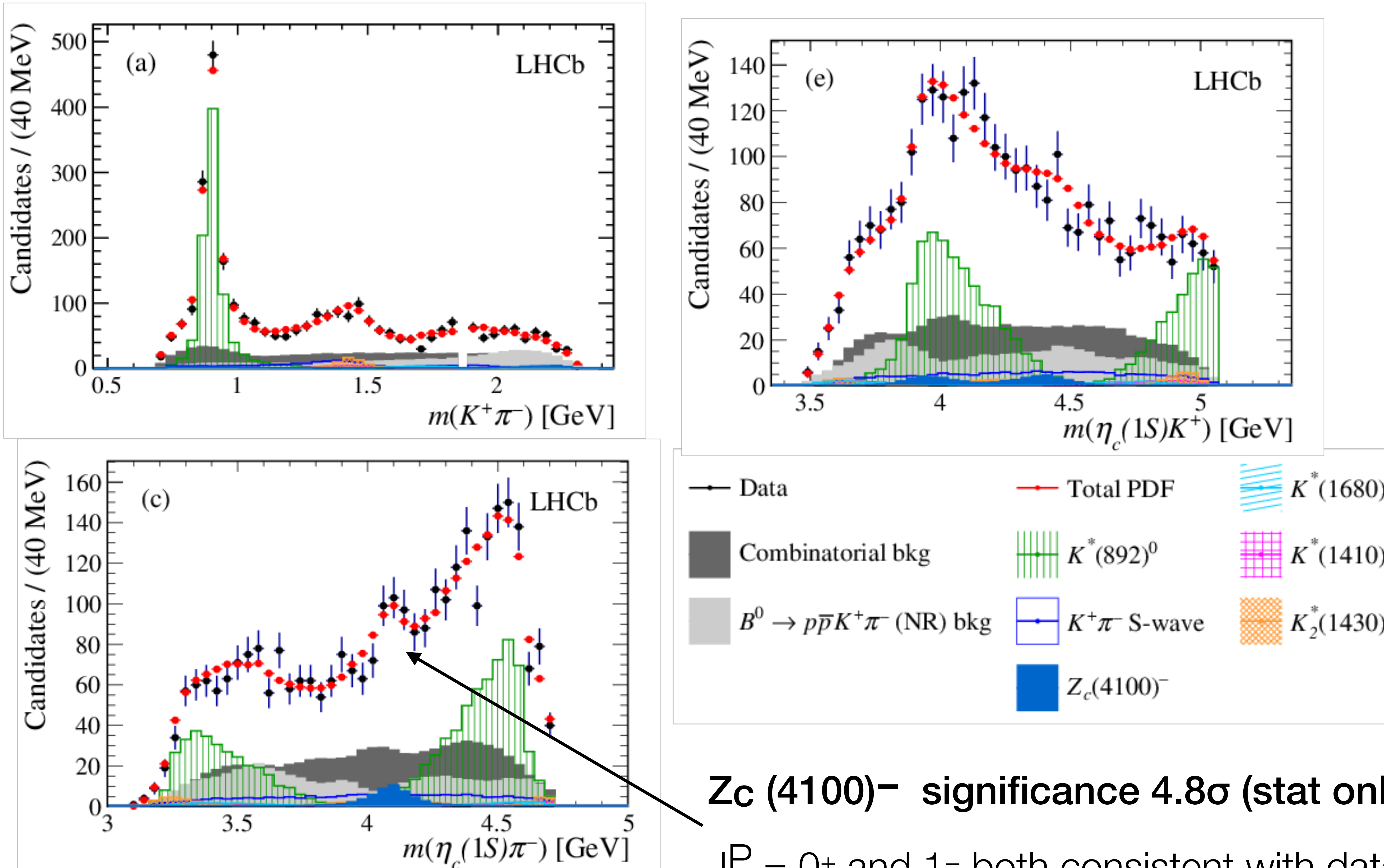
Resonance	Mass [MeV]	Width [MeV]	J^P	Model
$K^*(892)^0$	895.55 ± 0.20	47.3 ± 0.5	1^-	RBW
$K^*(1410)^0$	1414 ± 15	232 ± 21	1^-	RBW
$K_0^*(1430)^0$	1425 ± 50	270 ± 80	0^+	LASS
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+	RBW
$K^*(1680)^0$	1717 ± 27	322 ± 110	1^-	RBW
$K_0^*(1950)^0$	1945 ± 22	201 ± 90	0^+	RBW

Model with only $K^-\pi^+$ contributions



Discrepancy in $m(\eta_c(1S)\pi^-)$ distribution at 4.1 GeV

Model with $K^-\pi^+$ and $\eta_c(1S)\pi^+$ contributions



Z_c (4100)$^-$ significance 4.8σ (stat only)

J^P = 0^+ and 1^- both consistent with data

$B^0 \to \eta_c(1S) K^+ \pi^-$ results

LHCb-PAPER-2018-034, arXiv:1809.07416
submitted to EPJC

- BR measurement $\mathcal{B}(B^0 \to \eta_c K^+ \pi^-) = (5.73 \pm 0.24 \pm 0.13 \pm 0.66) \times 10^{-4}$
  - dominant error from external branching fractions
- Amplitude model results

Amplitude	Fit fraction (%)	Branching fraction (10^{-5})
$B^0 \to \eta_c K^*(892)^0$	$51.4 \pm 1.9\ ^{+1.7}_{-4.8}$	$29.5 \pm 1.6 \pm 0.6\ ^{+1.0}_{-2.8} \pm 3.4$
$B^0 \to \eta_c K^*(1410)^0$	$2.1 \pm 1.1\ ^{+1.1}_{-1.1}$	$1.20 \pm 0.63 \pm 0.02 \pm 0.63 \pm 0.14$
$B^0 \to \eta_c K^+\pi^-$ (NR)	$10.3 \pm 1.4\ ^{+1.0}_{-1.2}$	$5.90 \pm 0.84 \pm 0.11\ ^{+0.57}_{-0.69} \pm 0.68$
$B^0 \to \eta_c K_0^*(1430)^0$	$25.3 \pm 3.5\ ^{+3.5}_{-2.8}$	$14.50 \pm 2.10 \pm 0.28\ ^{+2.01}_{-1.60} \pm 1.67$
$B^0 \to \eta_c K_2^*(1430)^0$	$4.1 \pm 1.5\ ^{+1.0}_{-1.6}$	$2.35 \pm 0.87 \pm 0.05\ ^{+0.57}_{-0.92} \pm 0.27$
$B^0 \to \eta_c K^*(1680)^0$	$2.2 \pm 2.0\ ^{+1.5}_{-1.7}$	$1.26 \pm 1.15 \pm 0.02\ ^{+0.86}_{-0.97} \pm 0.15$
$B^0 \to \eta_c K_0^*(1950)^0$	$3.8 \pm 1.8\ ^{+1.4}_{-2.5}$	$2.18 \pm 1.04 \pm 0.04\ ^{+0.80}_{-1.43} \pm 0.25$
$B^0 \to Z_c(4100)^- K^+$	$3.3 \pm 1.1\ ^{+1.2}_{-1.1}$	$1.89 \pm 0.64 \pm 0.04\ ^{+0.69}_{-0.63} \pm 0.22$

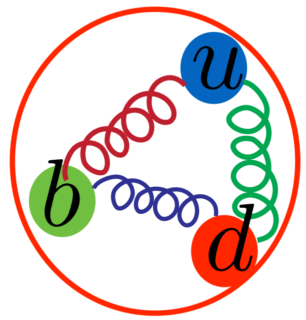
- Evidence of exotic $Z_c^+(4100)$ resonance (3.4σ including sys errors). Mass and width measured as:

$$m_{Z_c^-} = 4096 \pm 20\ ^{+18}_{-22}\ \mathrm{MeV} \qquad \Gamma_{Z_c^-} = 152 \pm 58\ ^{+60}_{-35}\ \mathrm{MeV}$$

Beautiful baryons

- Bottom baryons are composed of a *b* quark and two lighter quarks (*bqq'*)

$$\Lambda_b^0 = (udb)$$

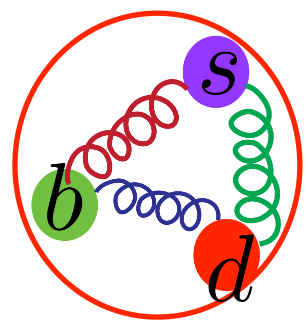


not observed

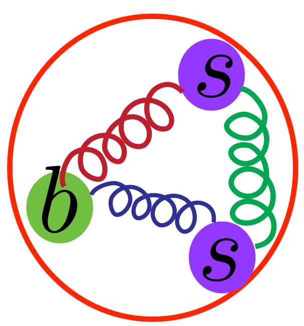
$$\Sigma_b^0 = (udb)$$

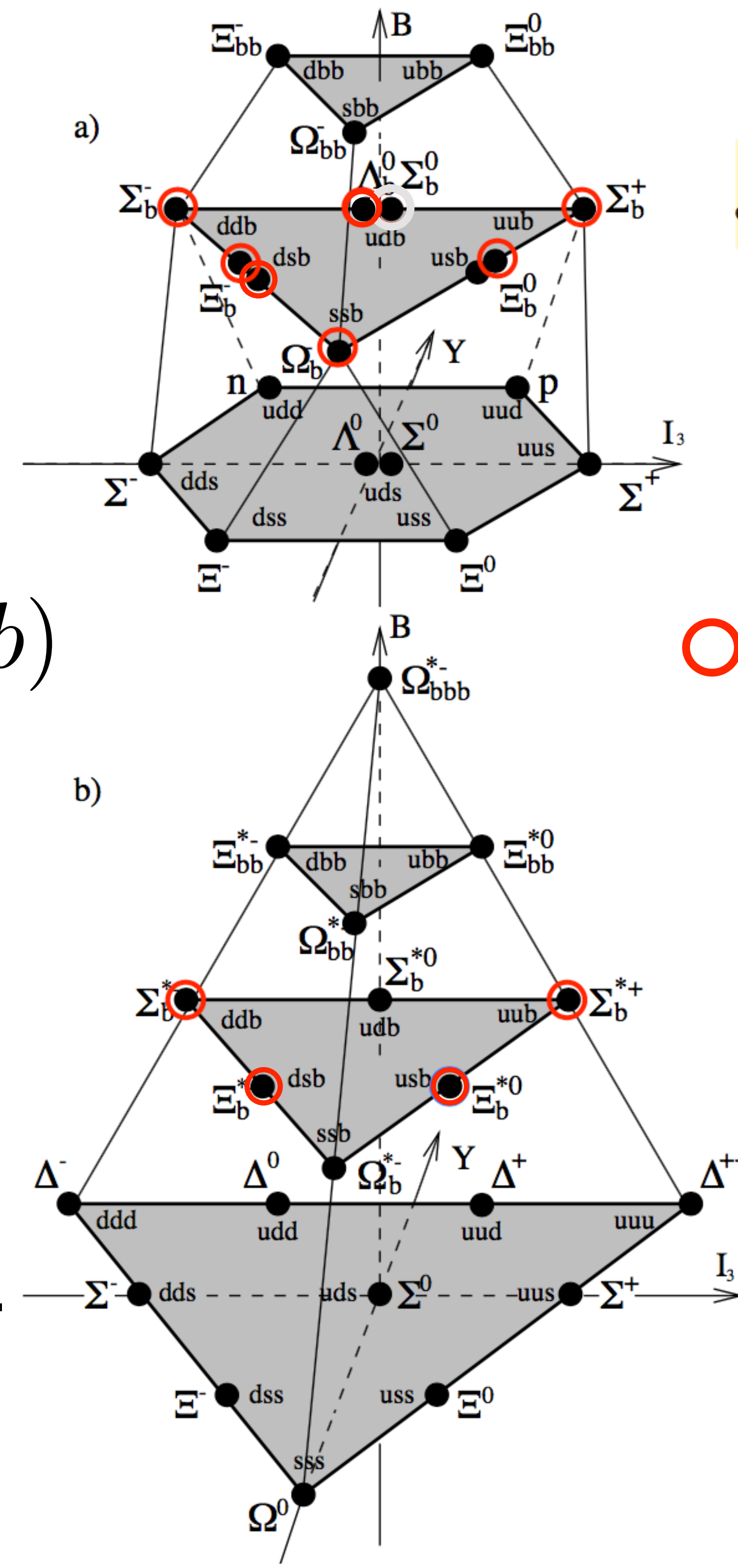
$$\Sigma_b^+ = (uub) \quad \Sigma_b^- = (ddb)$$

$$\Xi_b^0 = (usb) \quad \Xi_b^- = (dsb)$$



$$\Omega_b^- = (ssb)$$





$$\mathbf{J^P} = \frac{1}{2}^+$$

observed

$$\mathbf{J^P} = \frac{3}{2}^+$$

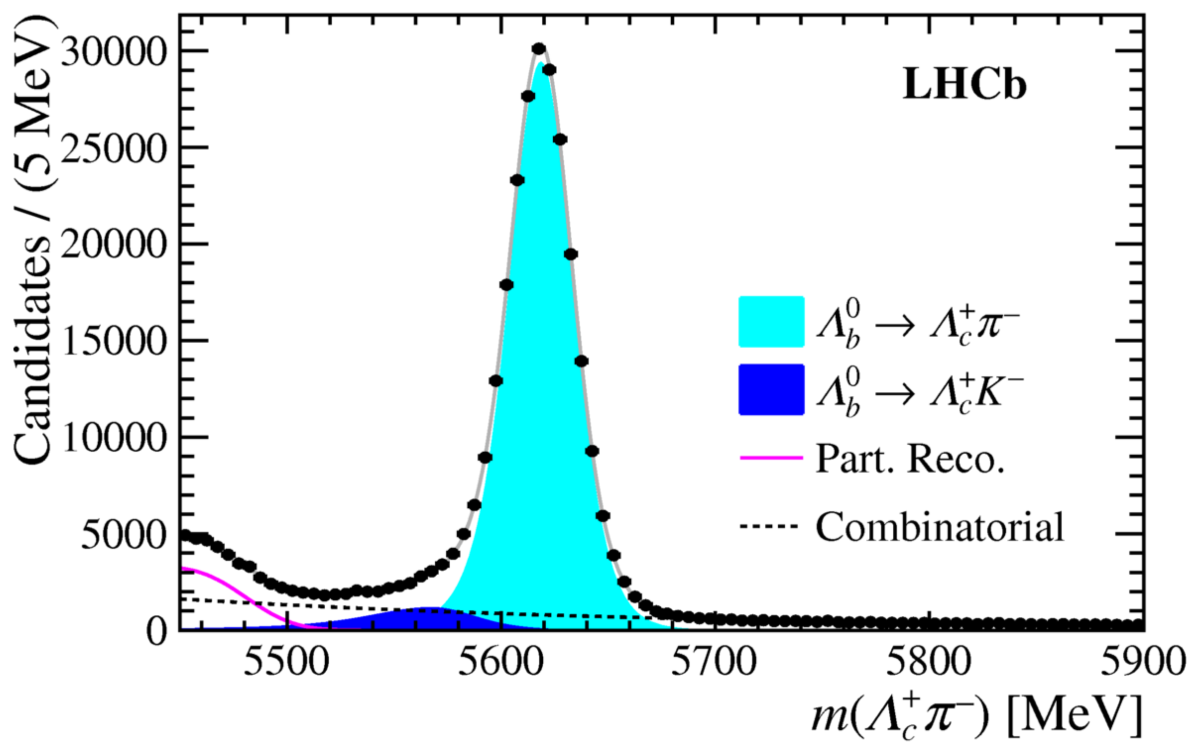
- Few excited bottom baryons observed so far. Their study is relevant for understanding the dynamics of constituent quarks

Observation of two resonances in $\Lambda_b\pi^\pm$ systems

LHCb-PAPER-2018-032, arXiv:1809.07752
accepted by PRL

- Use copious sample of $\Lambda_b \to \Lambda_c^+\pi^-$, $\Lambda_c^+ \to pK^-\pi^+$
- Λ_b candidates within ±50 MeV of mass peak are combined with a prompt pion
- $\Lambda_b\pi^-$ and $\Lambda_b\pi^+$ combinations are then studied

$\Lambda_b \to \Lambda_c^+\pi^-$ sample, 230k evt

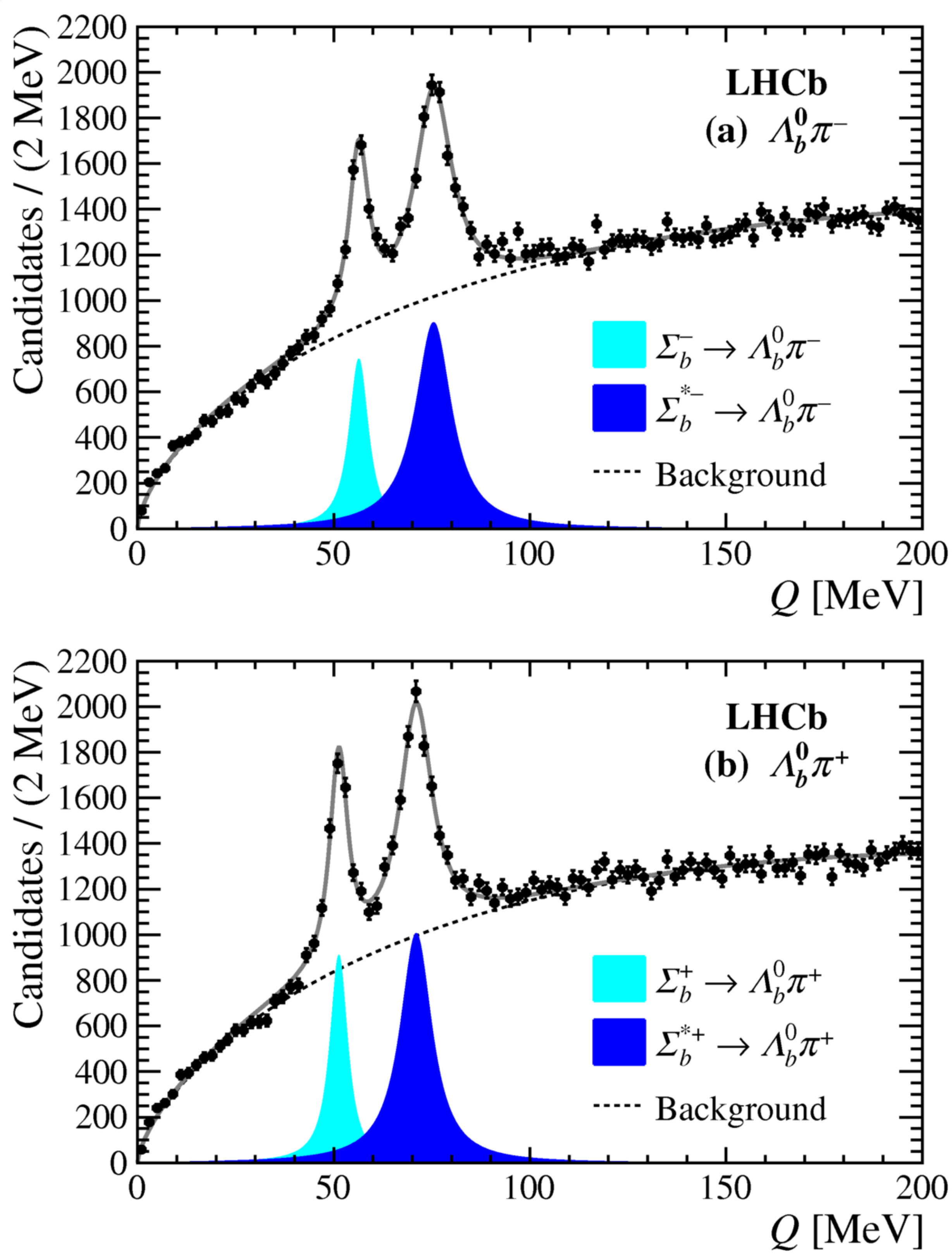


2011-2012 data - 3.0 fb^{-1}

Observation of two resonances in $\Lambda_b\pi^{\pm}$ systems

- Fit the Q-value distributions $Q=m(\Lambda_b\pi^{\pm})-m(\Lambda_b)-m(\pi^{\pm})$
- The $\Sigma_b^{\pm}$, $\Sigma_b^{*\pm}$ signals are obvious
- Precise measurements of masses and widths

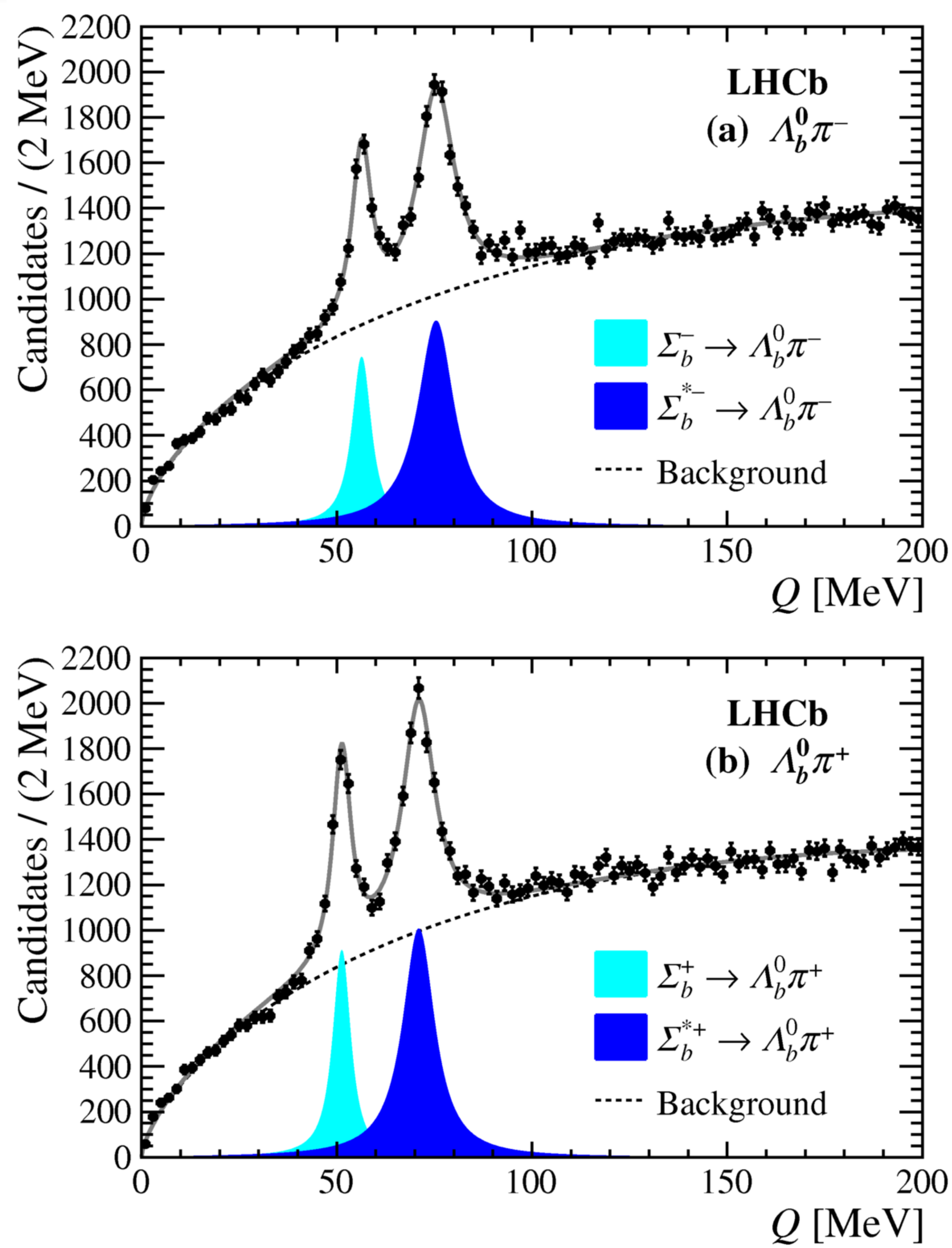
State	Q_0 [MeV]	Γ [MeV]	Yield
Σ_b^-	56.45 ± 0.14	5.33 ± 0.42	3270 ± 180
Σ_b^{*-}	75.54 ± 0.17	10.68 ± 0.60	7460 ± 300
Σ_b^+	51.36 ± 0.11	4.83 ± 0.31	3670 ± 160
Σ_b^{*+}	71.09 ± 0.14	9.34 ± 0.47	7350 ± 260



Observation of two resonances in $\Lambda_b\pi^{\pm}$ systems

- Fit the Q-value distributions $Q = m(\Lambda_b\pi^{\pm}) - m(\Lambda_b) - m(\pi^{\pm})$
- The $\Sigma_b^{\pm}$, $\Sigma_b^{*\pm}$ signals are obvious
- Precise measurements of masses and widths

Quantity	Value [MeV]
$m(\Sigma_b^-)$	$5815.64 \pm 0.14 \pm 0.24$
$m(\Sigma_b^{*-})$	$5834.73 \pm 0.17 \pm 0.25$
$m(\Sigma_b^+)$	$5810.55 \pm 0.11 \pm 0.23$
$m(\Sigma_b^{*+})$	$5830.28 \pm 0.14 \pm 0.24$
$\Gamma(\Sigma_b^-)$	$5.33 \pm 0.42 \pm 0.37$
$\Gamma(\Sigma_b^{*-})$	$10.68 \pm 0.60 \pm 0.33$
$\Gamma(\Sigma_b^+)$	$4.83 \pm 0.31 \pm 0.37$
$\Gamma(\Sigma_b^{*+})$	$9.34 \pm 0.47 \pm 0.26$



Observation of two resonances in $\Lambda_b\pi^{\pm}$ systems

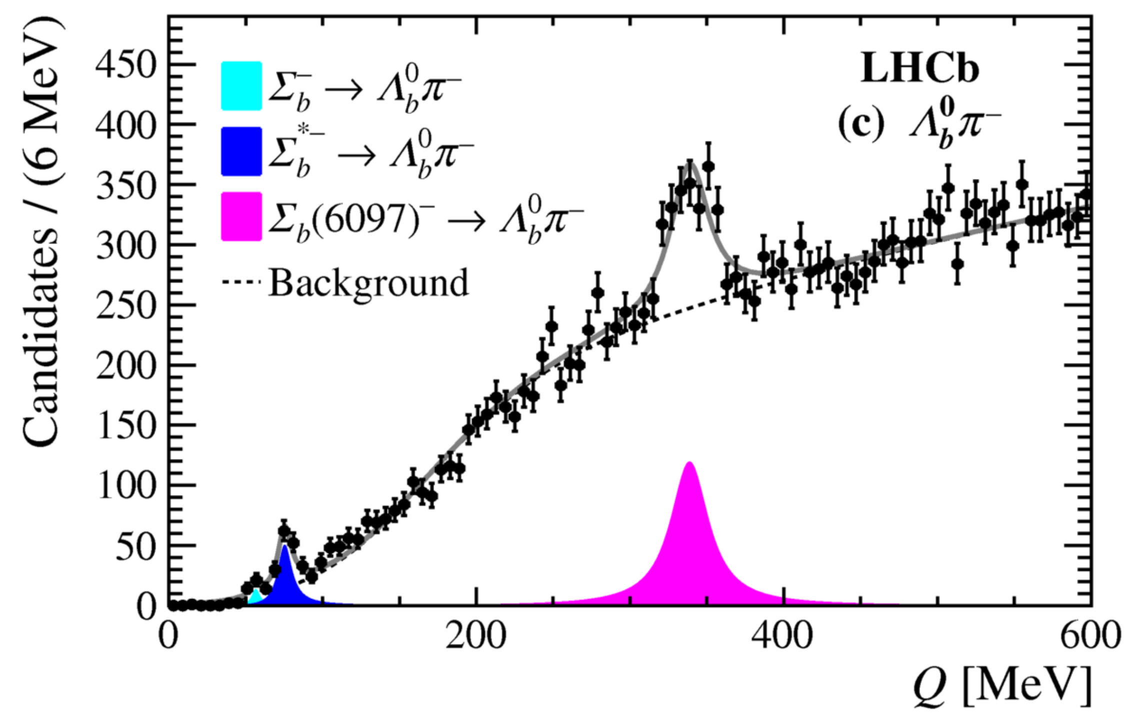
- Observation of two new states $\Sigma_b(6097)^-$ and $\Sigma_b(6097)^+$
- Local statistical significance of 12.7σ and 12.6σ
- Mass and widths measured as

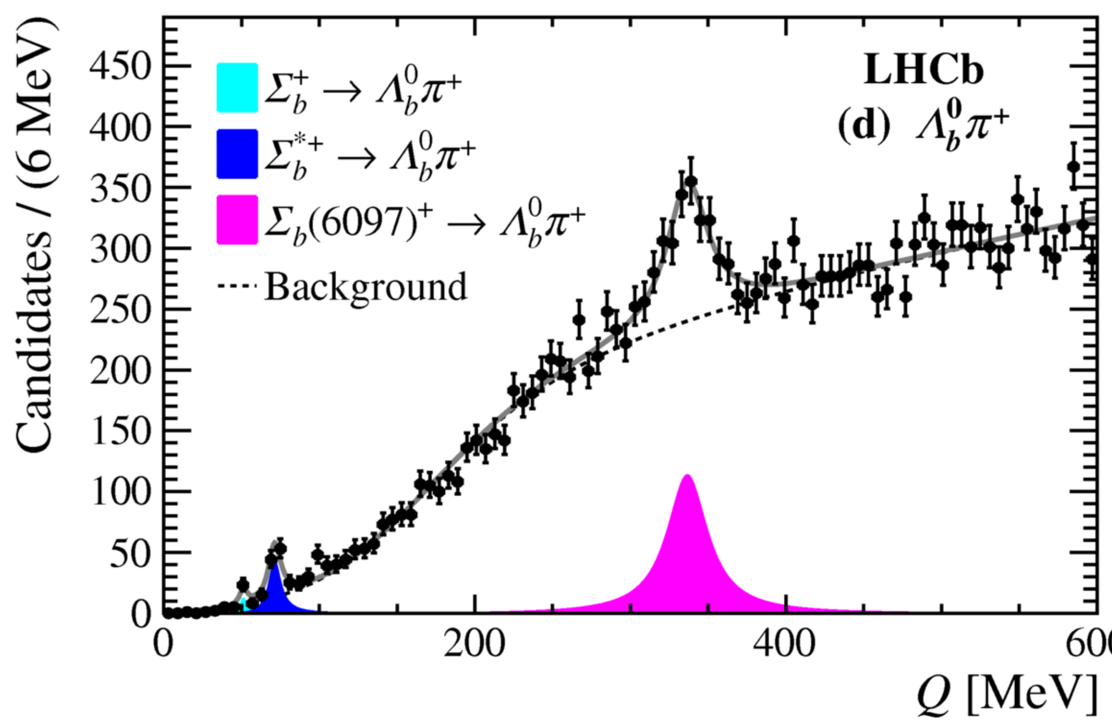
Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$

- In the heavy-quark limit, five $\Sigma_b(1P)$ states are expected. New observed structures compatible with 1P excitations

LHCb-PAPER-2018-032, arXiv:1809.07752

2011-2012 data - 3.0 fb^{-1}



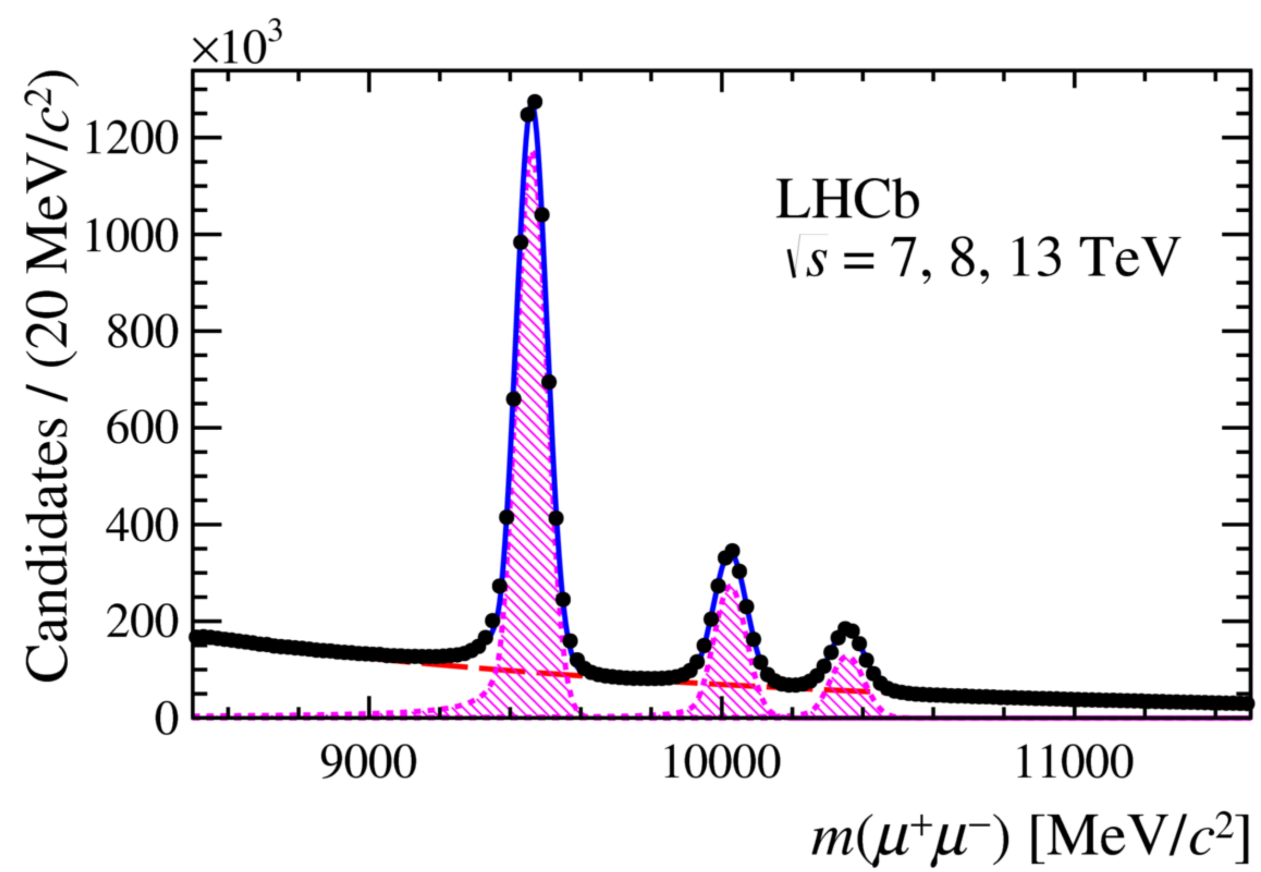


Search for beautiful tetraquarks

2011-2017 data - 6.3 fb^{-1}

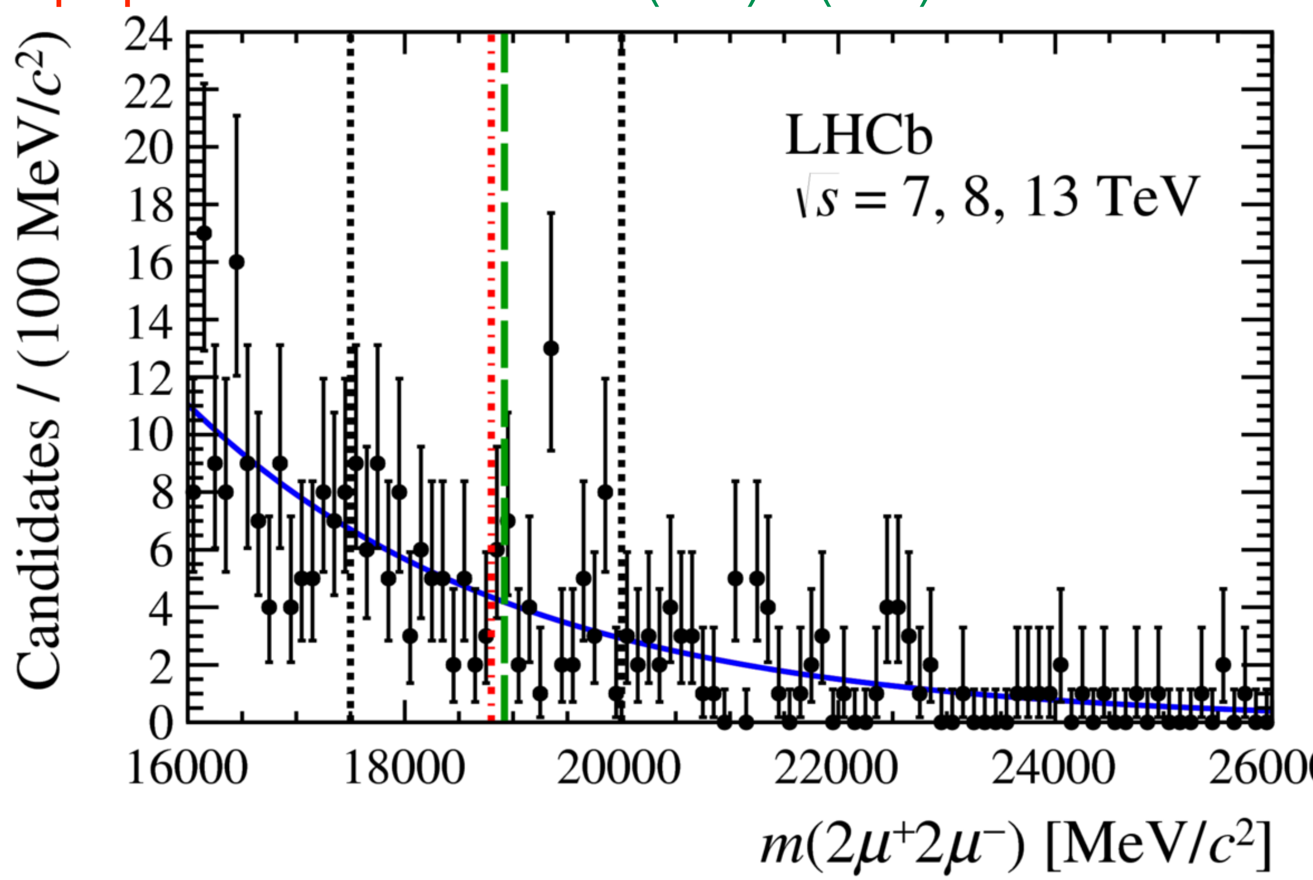
- Predictions for $X(b\bar{b}b\bar{b})$ tetraquark in the mass region [18.4-18.8] GeV below $\eta_b\eta_b$ threshold
- Predicted cross-section $X(b\bar{b}b\bar{b}) \to 2\mu^+2\mu^-$ of $\mathcal{O}$(1 fb)
- Search for $X(b\bar{b}b\bar{b})$ in the $\Upsilon(1S)\mu^+\mu^-$ invariant mass distribution

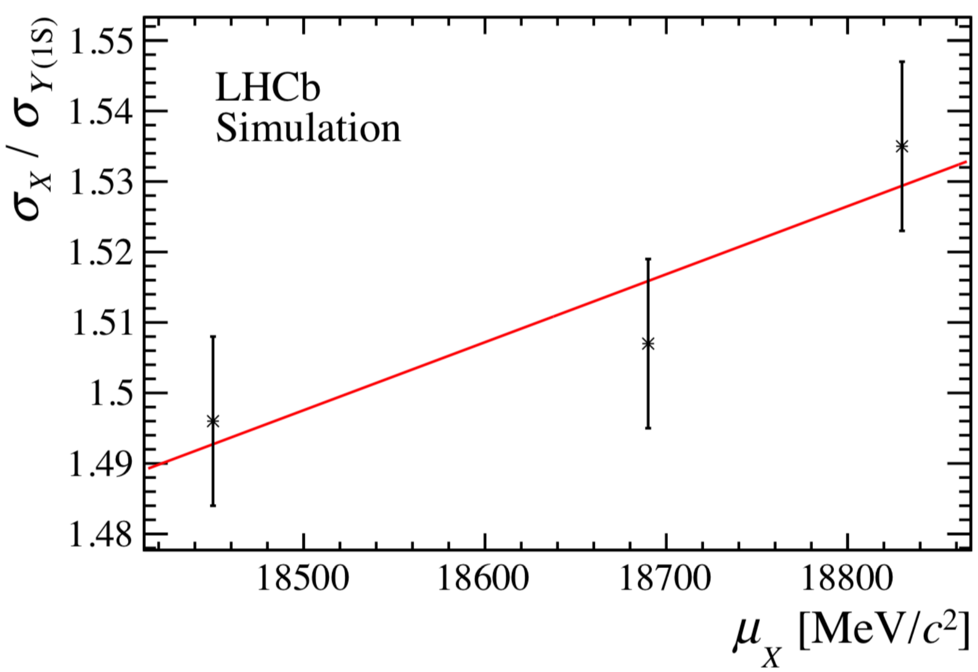
Distribution of $m(\mu^+\mu^-)$: clear $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ signals



Analysis strategy

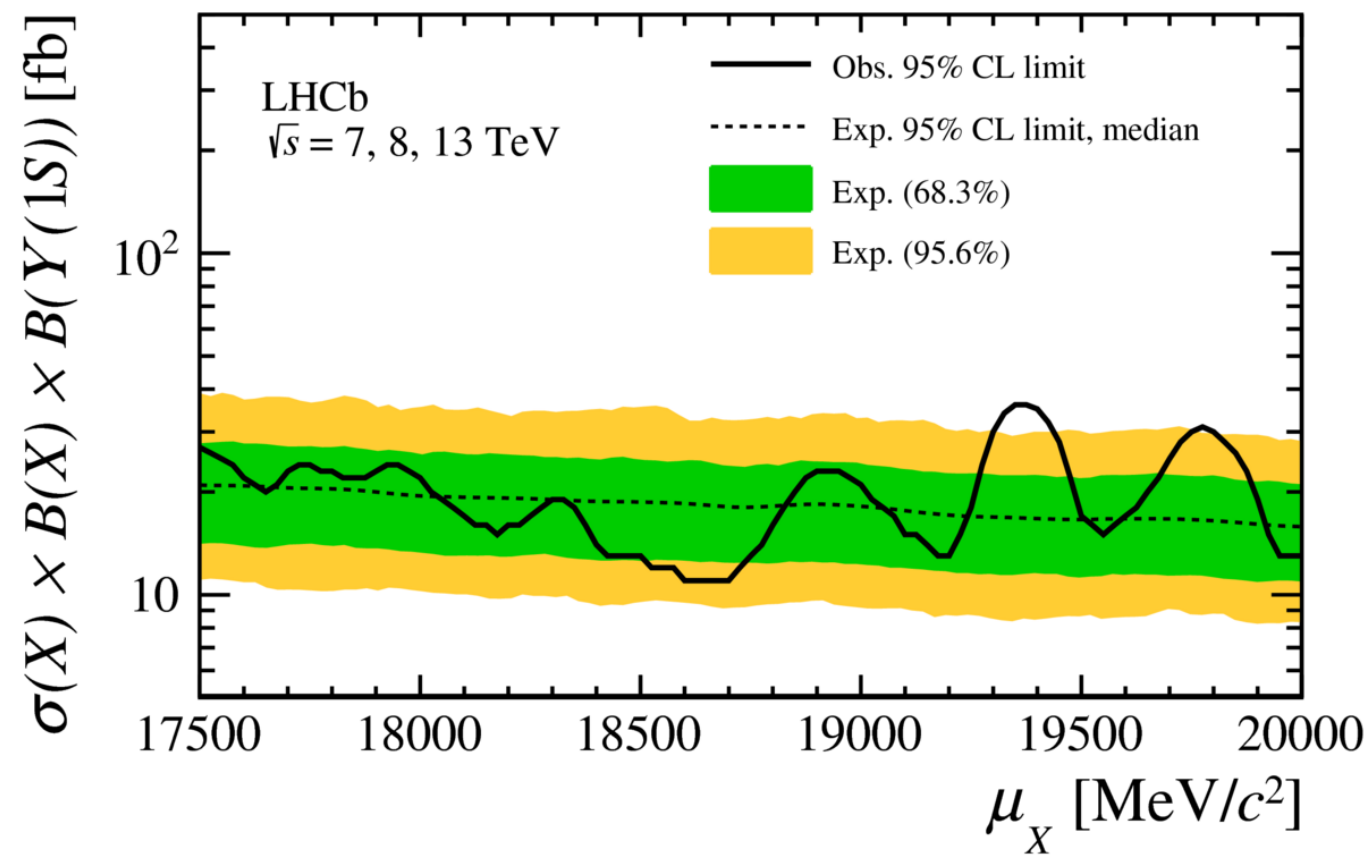
- Retain Υ(1S) candidates is 2.5σ window for $m(2\mu^+2\mu^-)$ fits
- X(b<u>b</u>b<u>b</u>) searched in the mass window [17.5-20] GeV
- Muon candidates with $p \in [8,500]$GeV, $p_T > 1$GeV
- Υ(1S)→ $\mu^+\mu^-$ used as normalisation mode for cross-section measurement
- Typical X mass resolution in the range of [60-70] MeV. Scaling factor wrt Υ(1S) mass resolution from simulated data





Upper limits on X($b\bar{b}b\bar{b}$) production

LHCb-PAPER-2018-027, JHEP 10 (2018) 086



- No significant excess in X mass range [17.5-20] GeV
- Limits on X production cross-section are statistically dominated
- Set upper limits on S:

$$S \equiv \sigma(pp \to X) \times \mathcal{B}(X \to \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$$

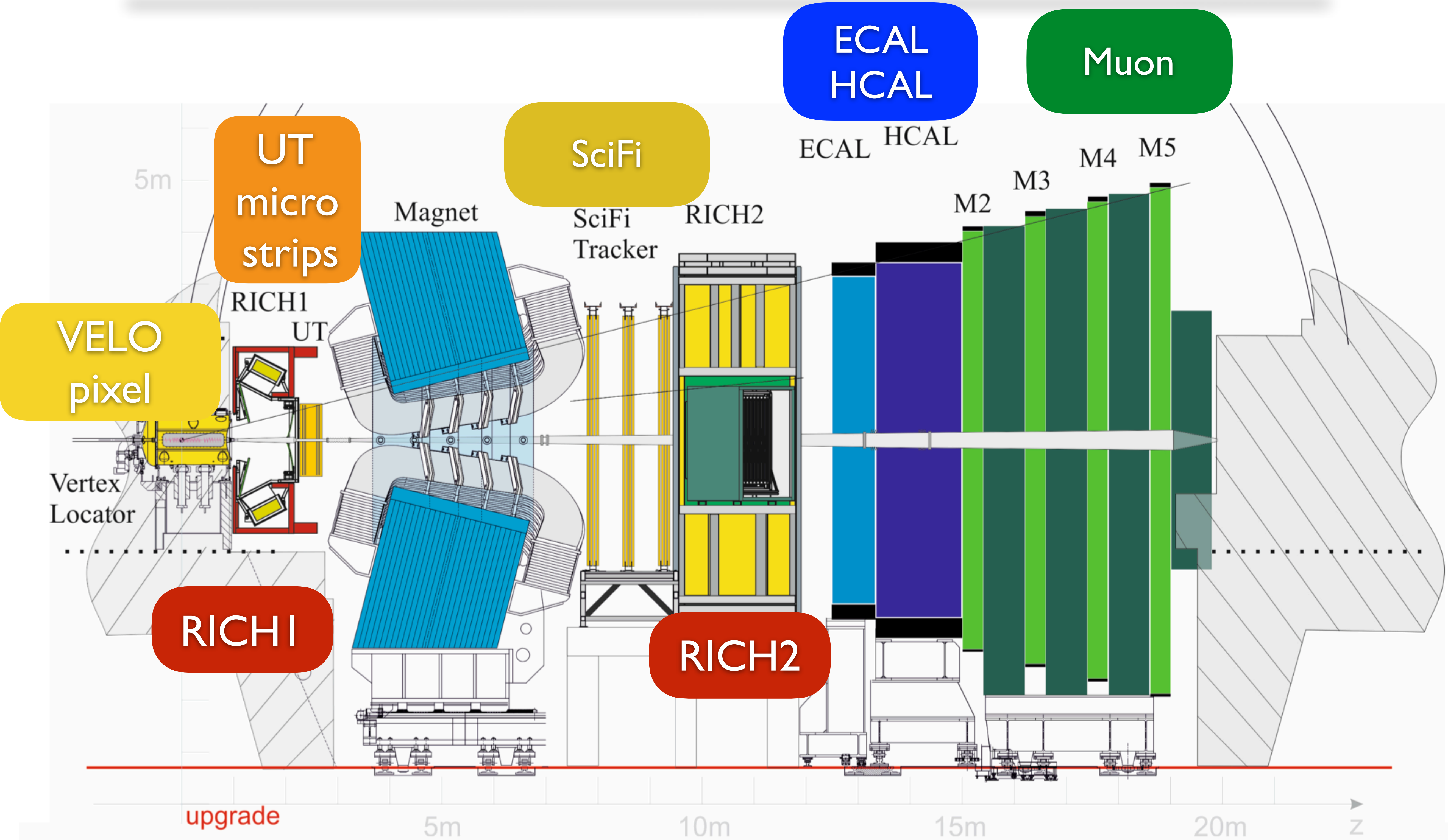
- Upper limits on X production cross-section $\mathcal{O}$(10 fb)

Summary

- LHCb keeps producing interesting results in heavy flavour spectroscopy, also discovering new exotic states
  - Evidence for new tetraquark candidate $Z_c^+(4100) \to \eta_c\pi^-$ in $B^0 \to \eta_c(1S)K^+\pi^-$ decays
  - Observation of two new resonances in $\Lambda_b\pi^\pm$ systems: $\Sigma_b(6097)^-$ and $\Sigma_b(6097)^+$ states
  - Upper limit on production cross-section for $X(b\underline{b}b\underline{b})$ tetraquark set at $\mathcal{O}(10\ \text{fb})$

Backup slides

LHCb Upgrade detector



- Major detector upgrade during Long Shutdown 2 (LS2) in 2020