# XYZ at LHCb

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on behalf of the LHCb collaboration

**PHIPSI19**
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**Novosibirsk, Russia**

# Outline

- Overview on exotic hadrons
- The LHCb detector
- Recent results
  - Search for beautiful tetraquarks in the $\Upsilon(1S)\mu^+\mu^-$ invariant-mass spectrum
  - Evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ decays
  - Model-independent observation of exotic contributions to $B^0 \to J/\psi K^+\pi^-$ decays
- Summary

# Exotic hadrons

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

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

- Quark model was postulated by M. Gell-Mann and G. Zweig in 1964
  Phys.Lett. 8 (1964) 214, CERN-TH-412

- Conventional mesons $q\bar{q}$ and baryons $qqq$
- Exotic hadrons — beyond conventional
- Could be various multiquark states, hadron molecules, glueballs, hybrids…

- First charmonium-like state seen by Belle in 2003 PRL 91 (2003) 262001

VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

**Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays**

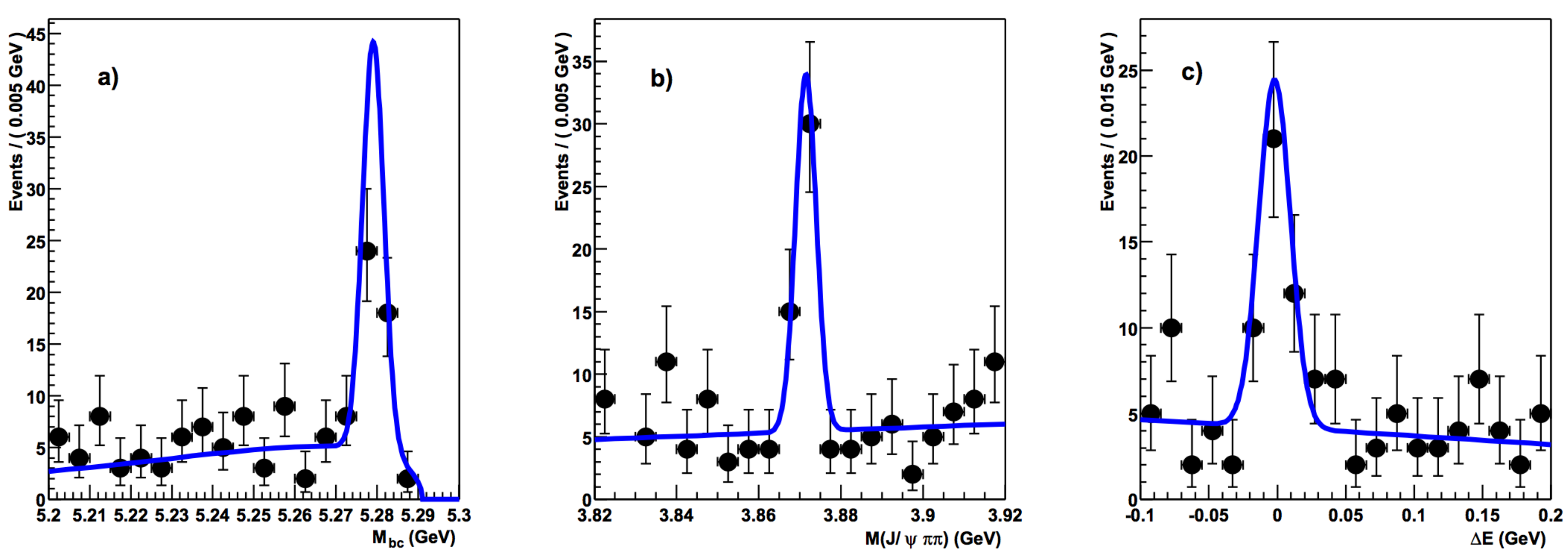



FIG. 2: Signal-band projections of (a) $M_{\rm bc}$, (b) $M_{\pi^+\pi^- J/\psi}$ and (c) $\Delta E$ for the $X(3872) \to \pi^+\pi^- J/\psi$ signal region with the results of the unbinned fit superimposed.

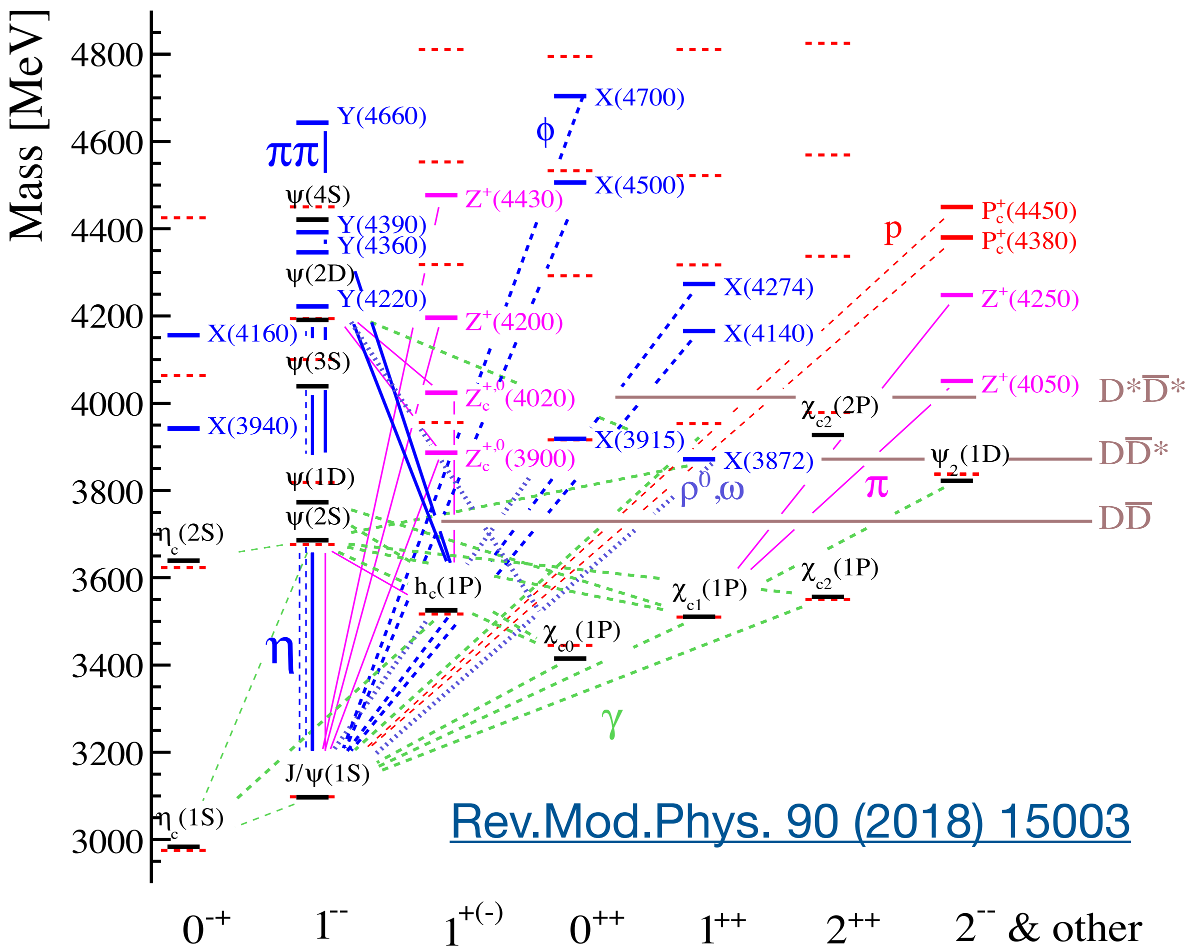
- $B^{\pm} \to$ X(3872)$K^{\pm}$
  X(3872) $\to J/\psi\pi^{+}\pi^{-}$

- Even after 15 years nature of this state is still under discussion

- Since then more than 20 new exotics states were found

# Exotic hadrons

## Charmonium-like states




Rev.Mod.Phys. 90 (2018) 15003

## Commonly used nomenclature

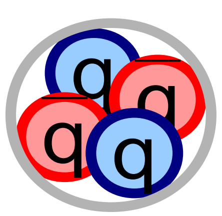
**X** — neutral, first seen in B-decays, positive parity

**Y** — neutral, first seen the Initial State Radiation (ISR) processes, negative parity

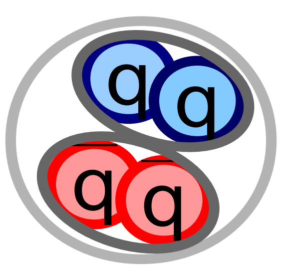
**Z** — charged (and their isospin partners)

**P** — pentaquarks

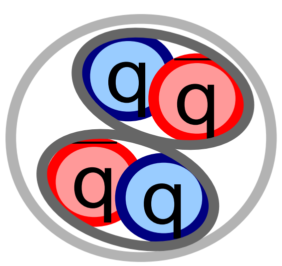
## Many theoretical interpretations in discussion



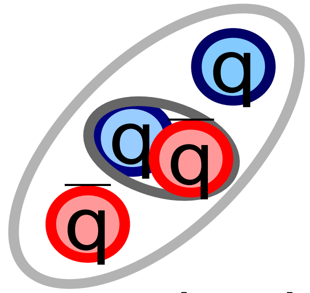
Tightly bound tetraquarks



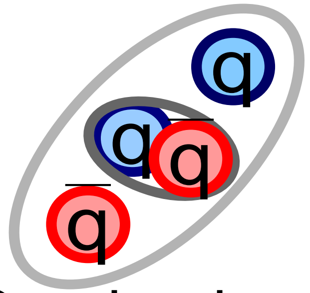
Diquarkonium



Meson molecules



Hadroquarkonium



Quarkonium adjoint meson

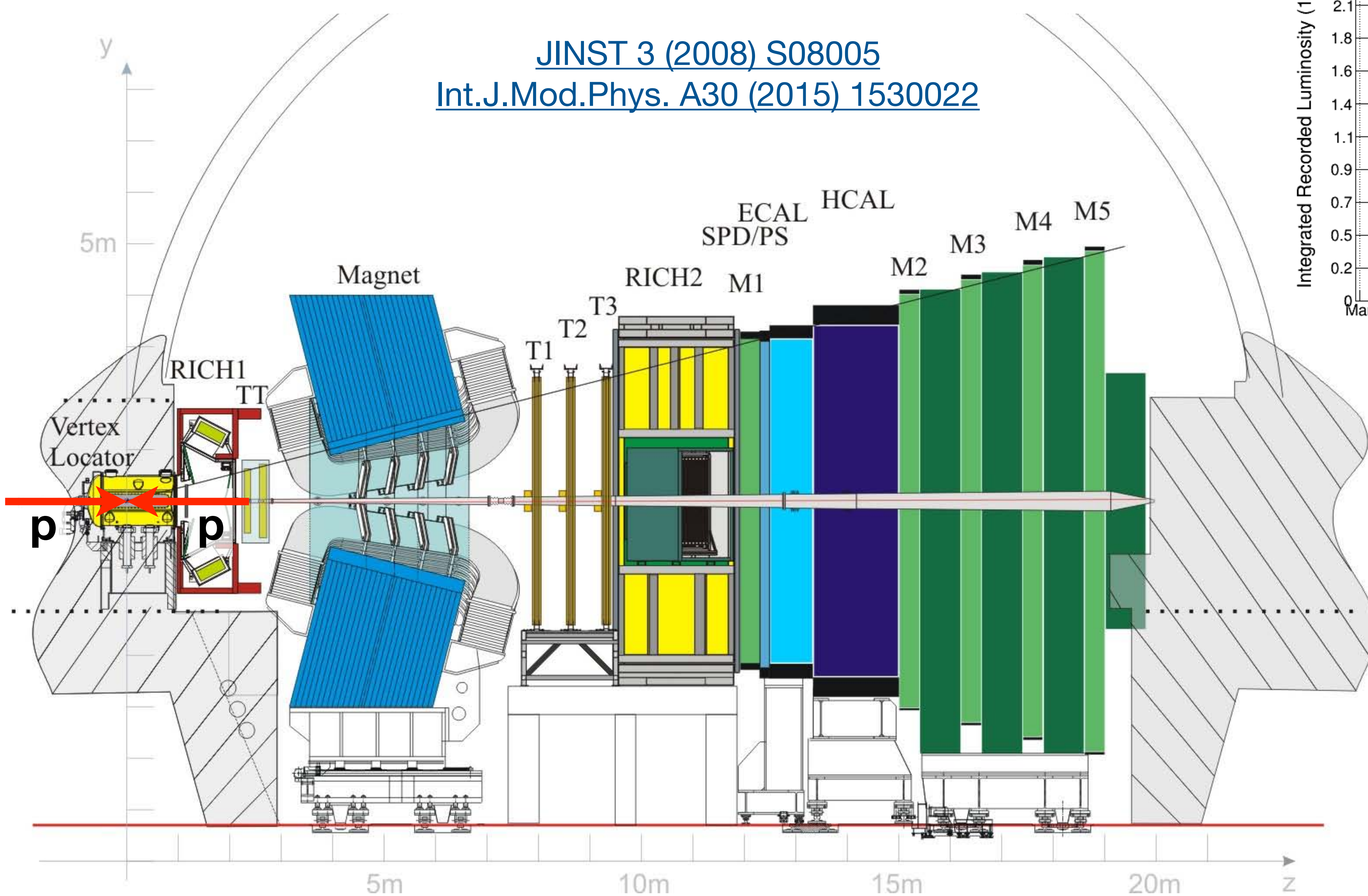
Further search for new exotic hadrons and determine their properties

# The LHCb detector

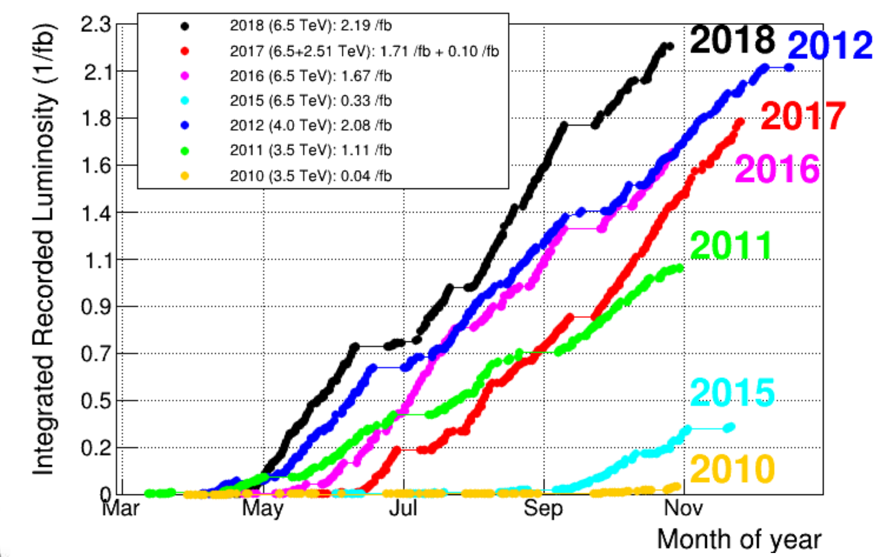
Details are given in the talk by Pavel Krokovny

- **VELO**: **impact parameter** resolution $(15 + 29/p_T[\mathrm{GeV}/c])\ \mu\mathrm{m}$, **decay time** resolution ~45 fs
- **Tracking stations, Magnet**: **momentum** resolution $\Delta p/p = 0.4\,\%$ at $5\ \mathrm{GeV}/c$, $1.0\,\%$ at $200\ \mathrm{GeV}/c$
- **PID efficiency**: for $e^-$ ~90% with 5% $e\to h$ misID, for **K** ~95% with 5% $\pi\to$K misID, for **μ** ~97% with 1-3% $\pi\to\mu$ misID
- **Calorimetric system**: **ECAL** resolution $\sim 1\%\oplus 9\%/\sqrt{E[\mathrm{GeV}]}$ , **HCAL** resolution $\sim 9\%\oplus 69\%/\sqrt{E[\mathrm{GeV}]}$
- **Trigger efficiency:** ~90% for **dimuon**, ~30% for multibody **hadronic**

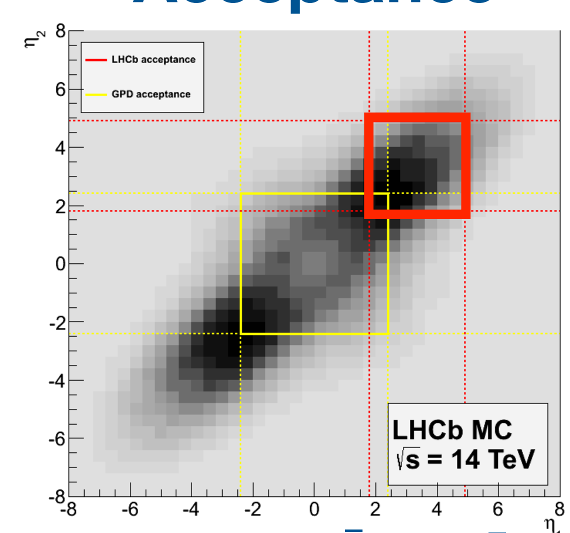
JINST 3 (2008) S08005
Int.J.Mod.Phys. A30 (2015) 1530022




LHCb integrated recorded luminosity in pp 2010-2018




## Acceptance




~40% of $b\bar{b}$ and $c\bar{c}$

$B^0 : \Lambda_b^0 : B_s^0 \sim 4 : 2 : 1$

JHEP08 (2014) 143

# Search for exotics with LHCb

## Exotic hadrons studies at LHCb

- in weak b-hadron decays:
  low combinatorial background
  low signal yield
- in prompt pp-production:
  large combinatorial background
  access to a high mass region

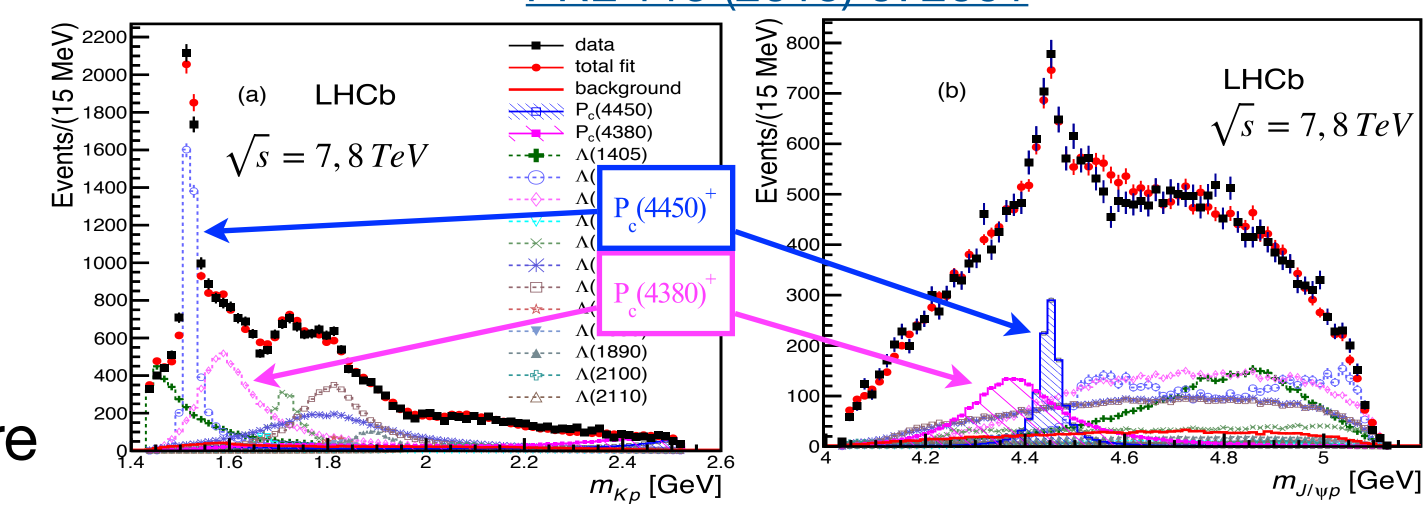
## Tools

- angular distributions, Dalitz and Argand plots
- amplitude analysis, model independent approach

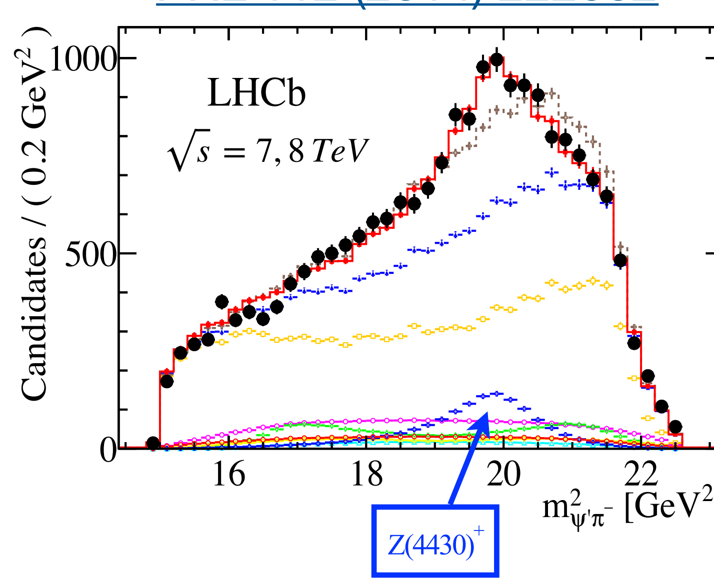
## Highlights from LHCb

- X(3872)
  - production studies EPJ C72 (2012) 1972
  - $J^{PC}$ determination PRL 110 (2013) 222001
  - observation of radiative decays Nucl.Phys. B886 (2013) 665
- $Z(4430)^+$ confirmation of resonance nature PRL 112 (2014) 222002, PRD 92 (2015) 112009
- $P_c(4380)^+$ and $P_c(4450)^+$ observation PRL 115 (2015) 072001, PRL 117 (2016) 082002
- Four resonance states in $J/\psi\phi$-system in $B^+ \to J/\psi\phi K^+$, including confirmation of X(4140) and X(4274) PRL 118 (2017) 022003, PRD 95 (2017) 012002

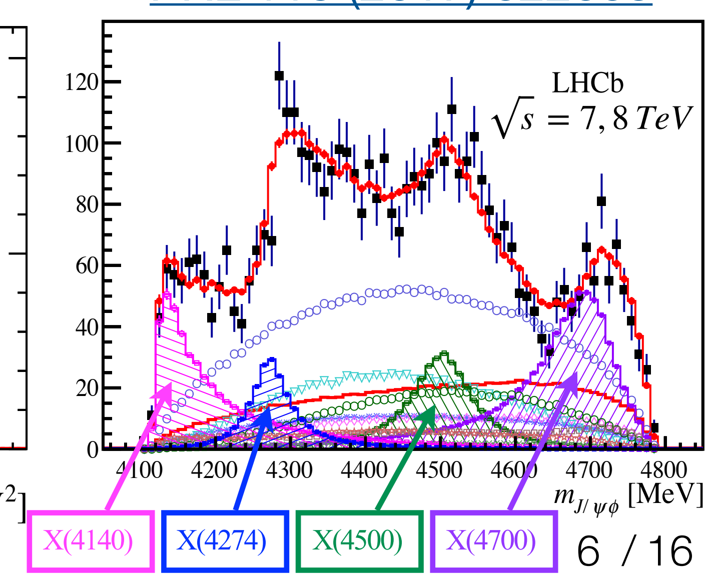
PRL 115 (2015) 072001




PRL 112 (2014) 222002




PRL 118 (2017) 022003

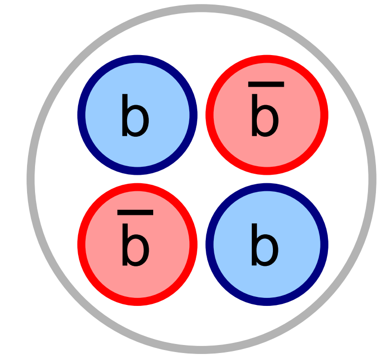


# Search for beautiful tetraquarks

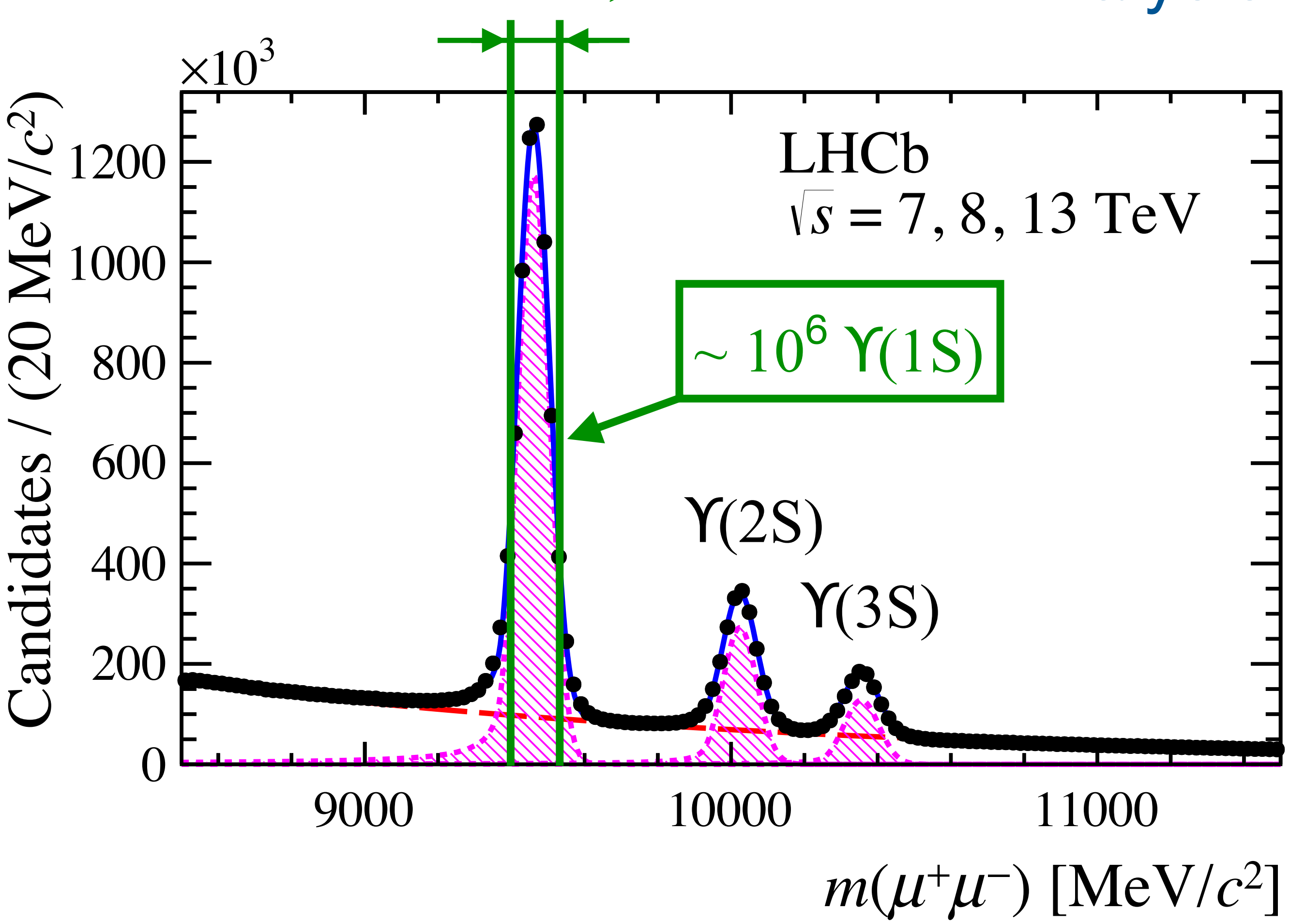
JHEP 10 (2018) 086

## Motivation

- No hadron containing more than two heavy quarks has been observed so far
- Theoretical predictions for $X_{b\bar{b}b\bar{b}}$:
  - Mass within $[18.4;\, 18.8]\ \mathrm{GeV}/c^2$
  - Mass typically below $\eta_b\eta_b$ threshold, therefore decay to $\Upsilon l^+ l^- (l = e, \mu)$
  - Cross-section $\sigma(pp \to X_{b\bar{b}b\bar{b}}) \times Br(X_{b\bar{b}b\bar{b}} \to 2l^+ 2l^-) \sim 1\,\mathrm{fb}$ FERMILAB-PUB-17-395-T
- Lattice QCD calculations do not find any evidence of this state



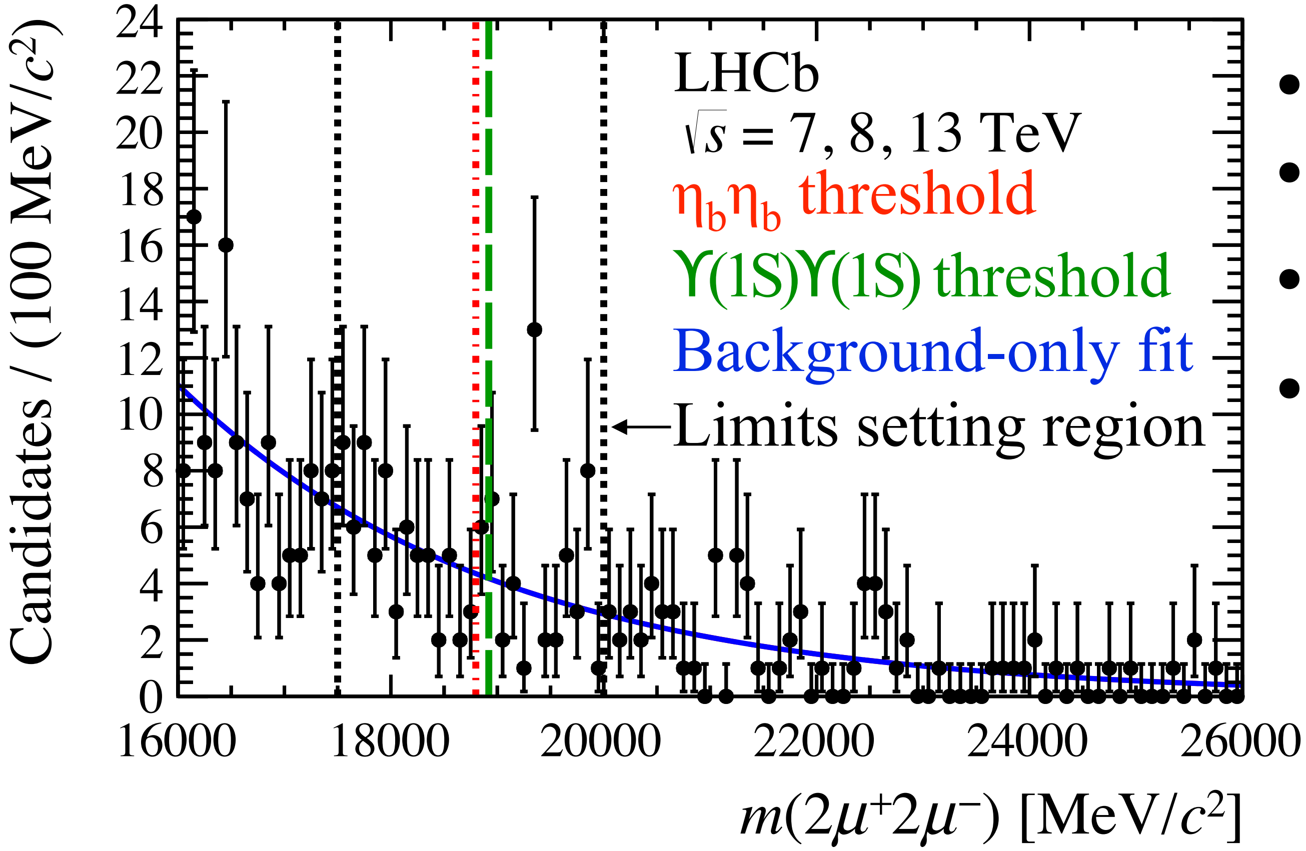

## Analysis strategy




- Search in $\Upsilon(1S)[\to \mu^+\mu^-]\mu^+\mu^-$ spectra
- Normalization decay: $\Upsilon(1S) \to \mu^+\mu^-$
- Data of $6.3\,\mathrm{fb}^{-1}$ collected in
  - 2011@7TeV,
  - 2012@8TeV,
  - 2015-2017@13TeV

# Search for beautiful tetraquarks

JHEP 10 (2018) 086



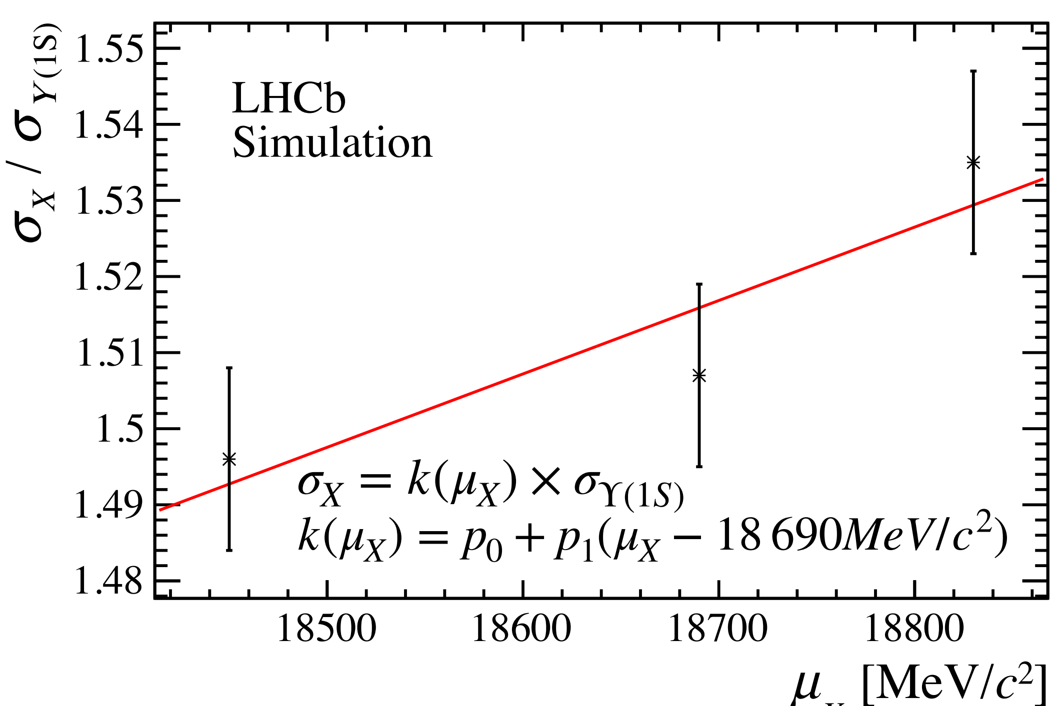

- Cut-based selection
- J/ψ mass veto: $m(\mu^+\mu^-) \notin [3050; 3150]$ MeV/$c^2$
- $X_{b\bar{b}b\bar{b}}$ searched in mass range [17.5; 20] GeV/$c^2$
- Fiducial region: $p_T(\mu^\pm) < 30$ GeV/c, $2.0 < y < 4.5$

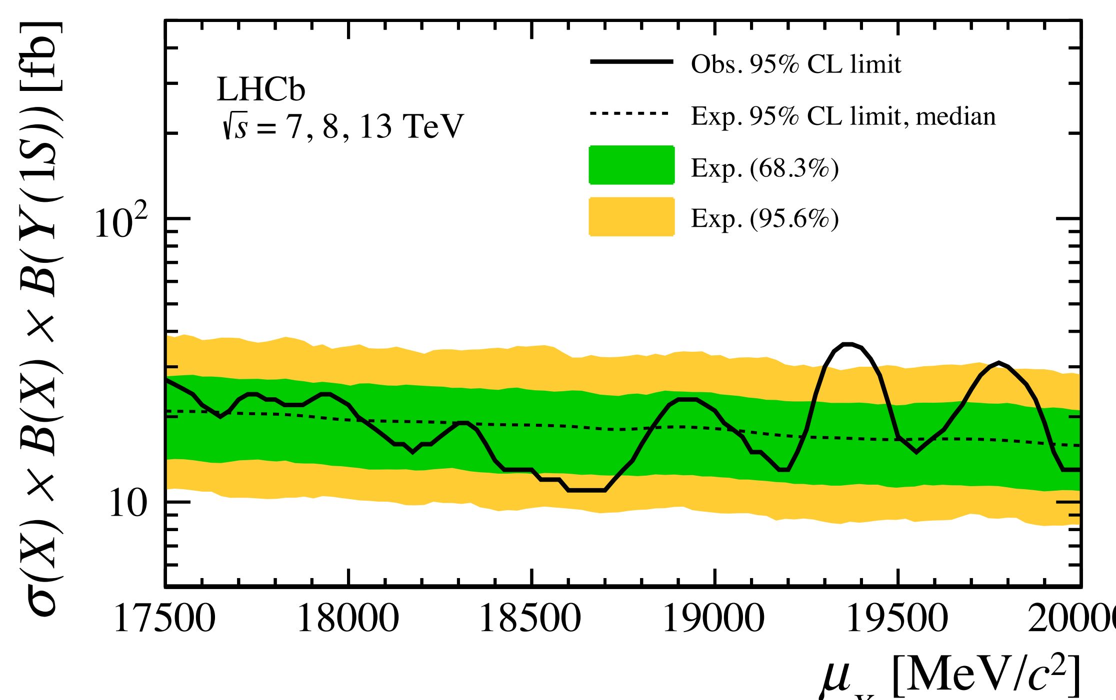
No significant excess is seen in data, therefore upper limit is set for:

$$S = \sigma(pp \to X) \times Br(X \to \Upsilon(1S)\mu^+\mu^-) \times \times Br(\Upsilon(1S) \to \mu^+\mu^-)$$

- $\sigma(X_{b\bar{b}b\bar{b}}) \sim$ 60-70 MeV/$c^2$, multiplied by a scaling factor taken from simulation

- Likelihood profile as a function of S is integrated to determine upper limits



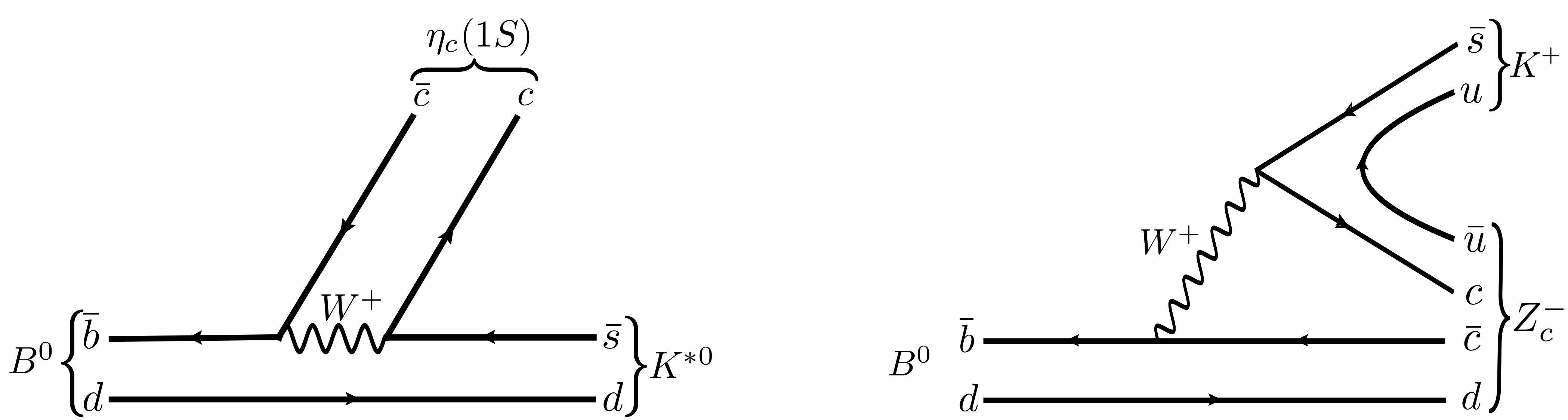
# $\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$ decays

Eur.Phys.J. C78 (2018) 1019

## Motivation

- Important input for understanding nature of exotic hadrons, in particular of $Z_c(3900)^-$ state discovered in $J/\psi\pi^-$ system by BESIII PRL 111 (2013) 242001
  - $Z_c(3900)^-$ as analogue of quarkonium hybrids $\to \eta_c\pi^-$ resonance $J^P = 0^+, 1^-, 2^+$ (based on lattice QCD) PRL 111 (2013) 162003
  - $Z_c(3900)^-$ as hadrocharmonium $\to \eta_c\pi^-$ resonance $m = 3800$ MeV/$c^2$ PRD 87 (2013) 091501
- Diquark model $\to \eta_c\pi^-$ resonance below the open-charm threshold $J^P = 0^+$ PRD 71 (2005) 014028

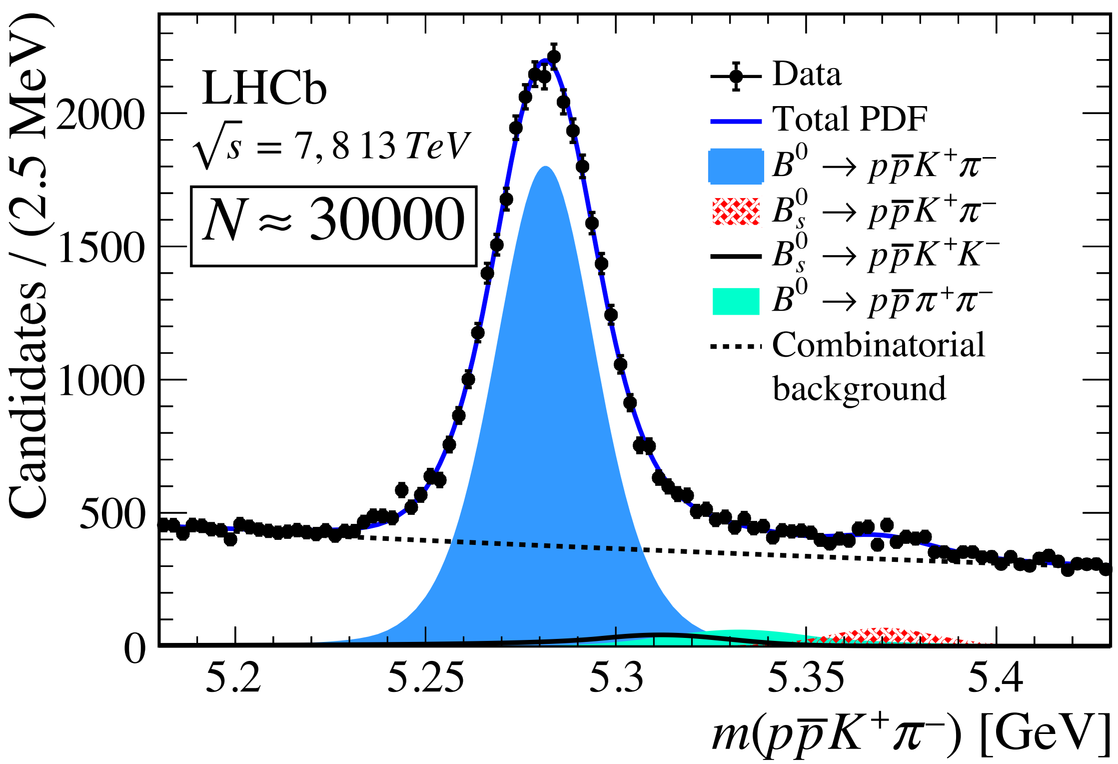
### therefore, search for an $\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$ decays

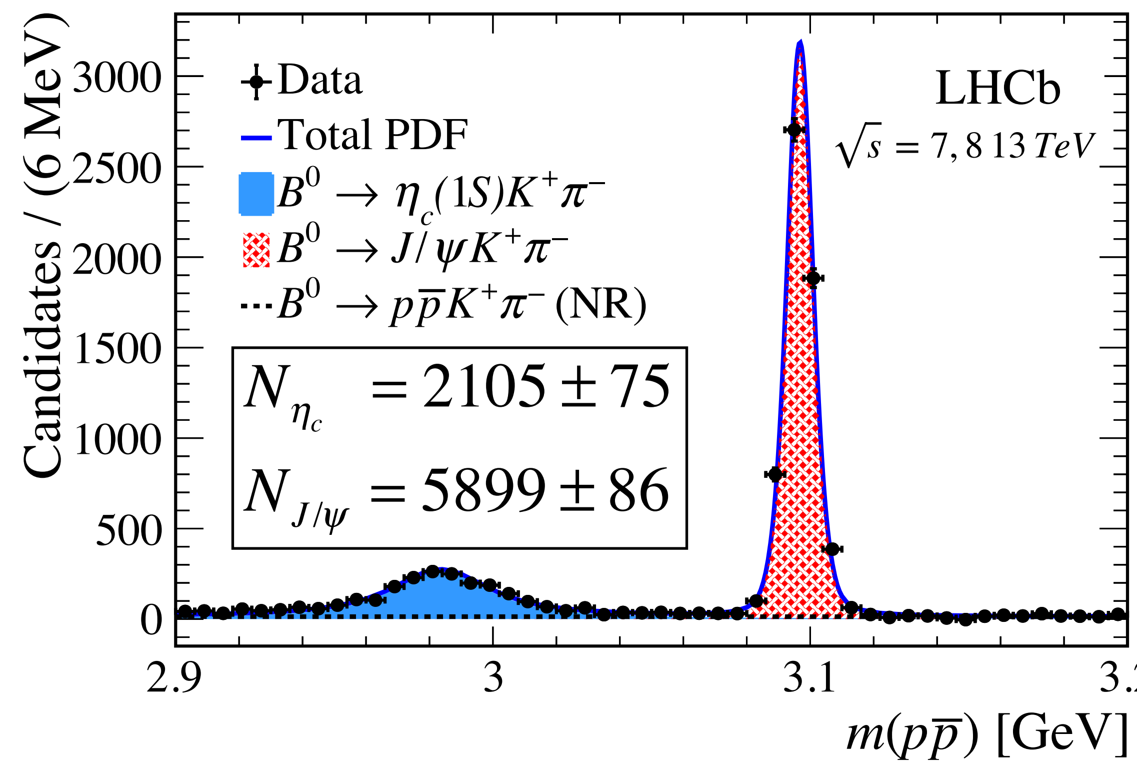


# $\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$ decays

Eur.Phys.J. C78 (2018) 1019

$B^0 \to p\bar{p}K^+\pi^-$ — *sPlot* → $B^0 \to c\bar{c}[\to p\bar{p}]K^+\pi^-$




- Reconstruction using $\eta_c \to p\bar{p}$ mode
- Normalization decay: $B^0 \to J/\psi[\to p\bar{p}]K^+\pi^-$
- Reconstruction and selection efficiencies largely cancel in the ratio

- Data of $4.7\text{fb}^{-1}$ collected in
  - 2011@7TeV,
  - 2012@8TeV,
  - 2016@13TeV

## Branching fraction

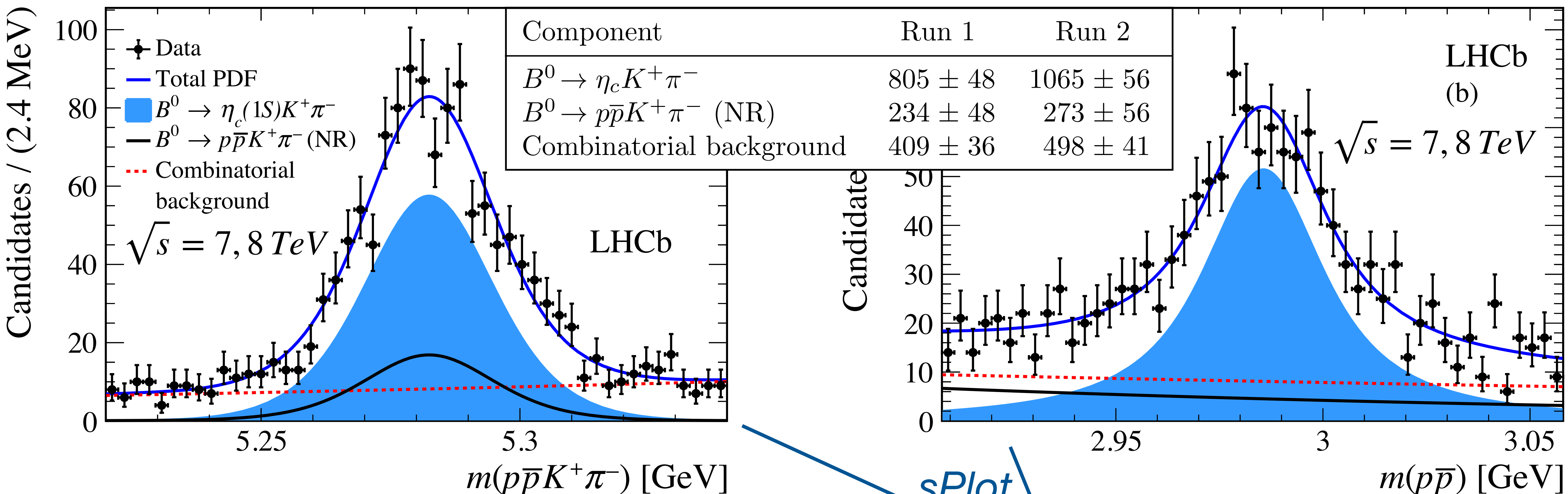
$$\mathcal{B}(B^0 \to \eta_c K^+\pi^-) = (5.73 \pm 0.24\,(stat) \pm 0.13\,(syst) \pm 0.66) \times 10^{-4}$$

Dominant uncertainty from external branching fractions

# $\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$ decays

Eur.Phys.J. C78 (2018) 1019

## 2D fit $m(p\bar{p}K^+\pi^-)$-$m(p\bar{p})$ for Run-I and Run-II

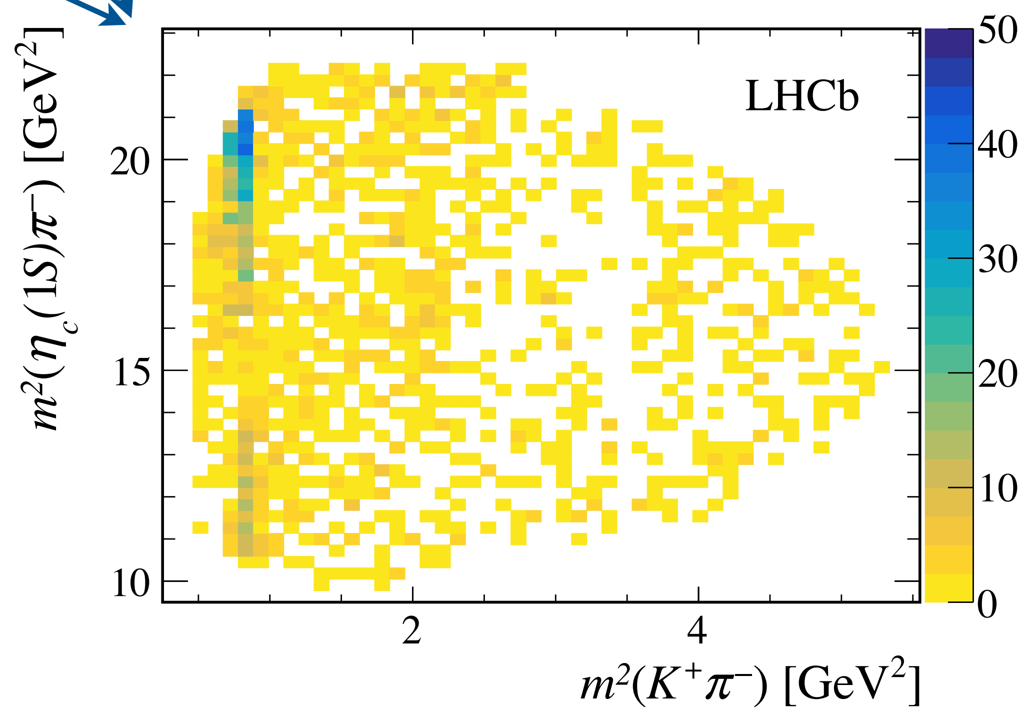



| Component | Run 1 | Run 2 |
|---|---|---|
| $B^0 \to \eta_c K^+\pi^-$ | $805 \pm 48$ | $1065 \pm 56$ |
| $B^0 \to p\bar{p}K^+\pi^-$ (NR) | $234 \pm 48$ | $273 \pm 56$ |
| Combinatorial background | $409 \pm 36$ | $498 \pm 41$ |

sPlot

## Dalitz plot analysis

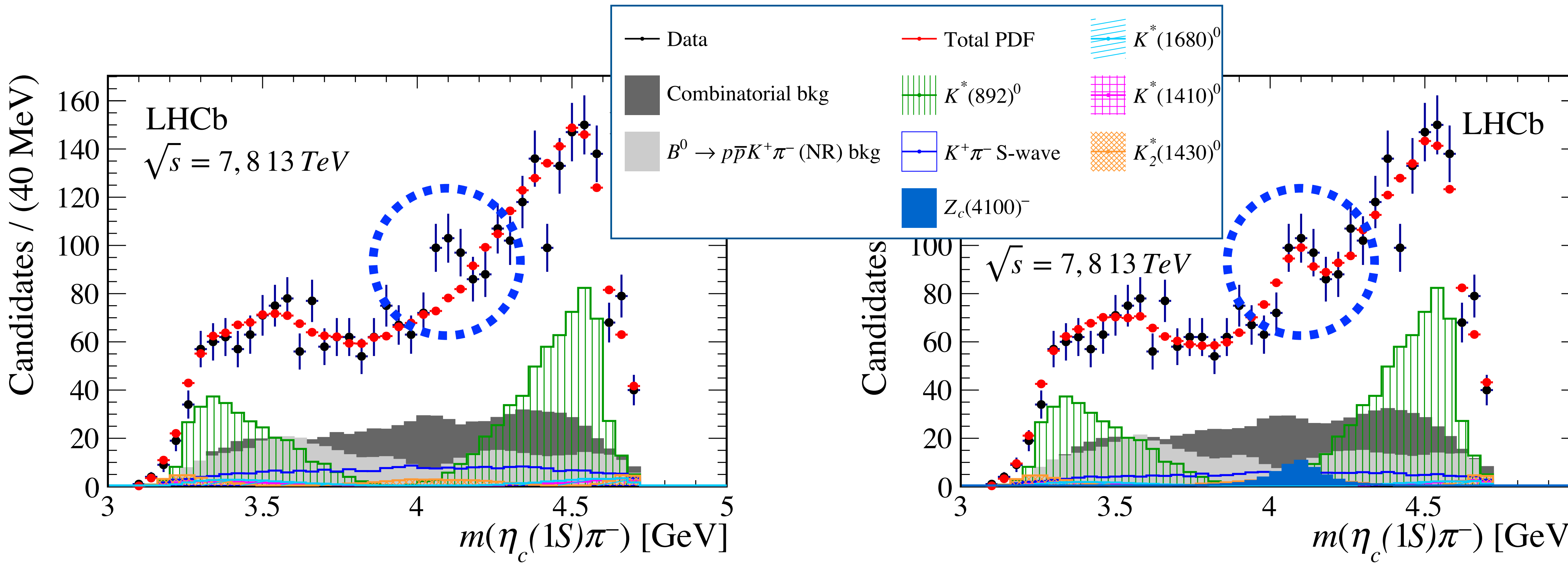
- Fit model: signal + non-resonant + combinatorial
- Decay amplitude: sum of resonant $K^+\pi^-$ + non-resonant processes
- Six $K^{*0}$ resonances give significant contributions
- Exotic $Z_c(4100)^- \to \eta_c\pi^-$ contribution added to improve the fit



# $\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$ decays

Eur.Phys.J. C78 (2018) 1019

$K^+\pi^-$ only contributions — $K^+\pi^-$ and $\eta_c\pi^-$ contributions




- Good description is achieved by adding an exotic $Z_c(4100)^- \to \eta_c\pi^-$ component
- Evidence for exotic $Z_c(4100)^-$ resonance ($3.4\sigma$ significance considering systematics)
- Both $J^P = 0^+$ and $J^P = 1^-$ are consistent with the data
- $M = 4096 \pm 20^{+18}_{-22}\ \mathrm{MeV/c^2}$, $\Gamma = 152 \pm 58^{+60}_{-35}\ \mathrm{MeV}$
- Quasi-two-body branching fraction:

$$\mathcal{B}(B^0 \to Z_c(4100)^- K^+,\ Z_c(4100)^- \to \eta_c\pi^+) = (1.89 \pm 0.64\ ^{+0.73}_{-0.67}) \times 10^{-5}$$

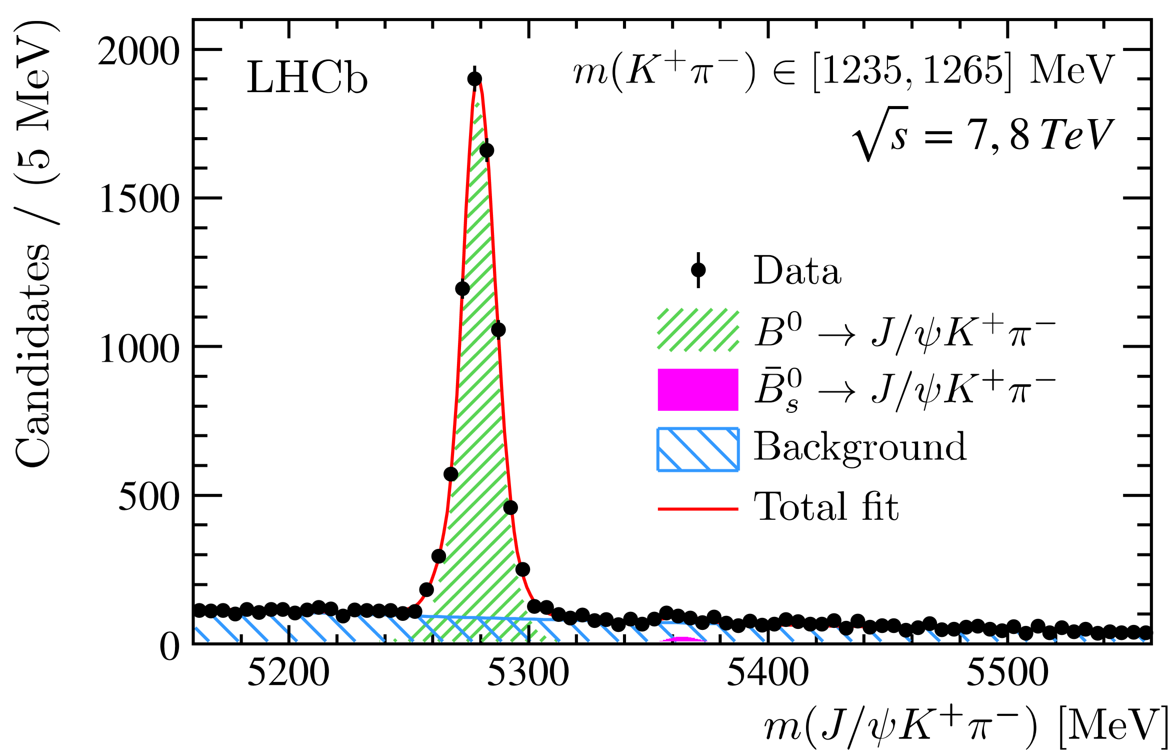
# Exotic contributions to $B^0 \to J/\psi K^+\pi^-$

Submitted to PRL
arXiv:1901.05745

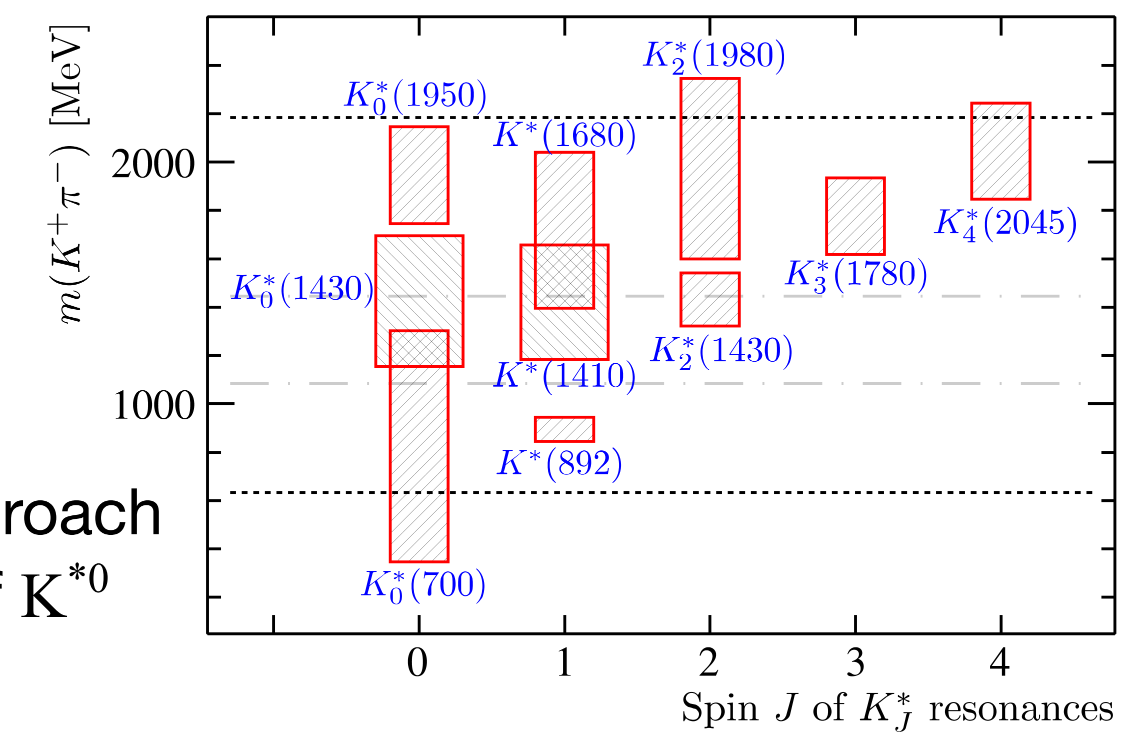
## Motivation

- $Z_c(4430)^-$ state discovered by Belle in $Z_c(4430)^- \to \psi(2S)\pi^-$ PRL 100 (2008) 142001
  - not confirmed by BaBar PRD 79 (2009) 112001
  - confirmed by LHCb PRL 112 (2014) 222002
- $Z_c(4430)^- \to J/\psi\pi^-$ not yet confirmed
  - Belle find evidence for $Z_c(4430)^- \to J/\psi\pi^-$ in $B^0 \to J/\psi K^+\pi^-$, and also observed a new state $Z_c(4200)^- \to J/\psi\pi^-$ PRD 90 (2014) 112009

## Analysis strategy




- Large statistics of ~$5\times10^5$ events allow independent fits in bins over $m(K^+\pi^-)$
- Purity > 90% in all $m(K^+\pi^-)$ bins

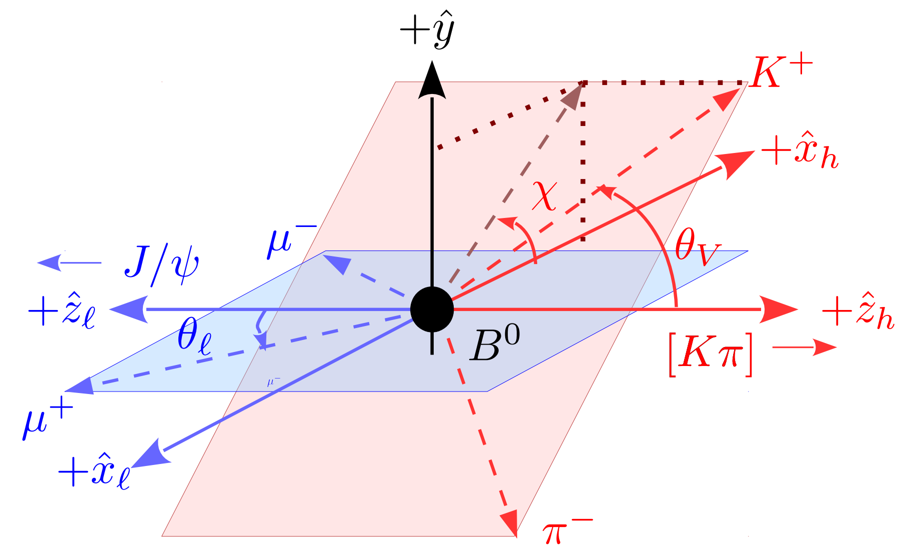



- Poor knowledge of the conventional $K^{*0}$ spectrum
- To bypass the problem the model-independent approach only requiring knowledge of the $J_{max}$ (highest spin of $K^{*0}$ contributions) is used

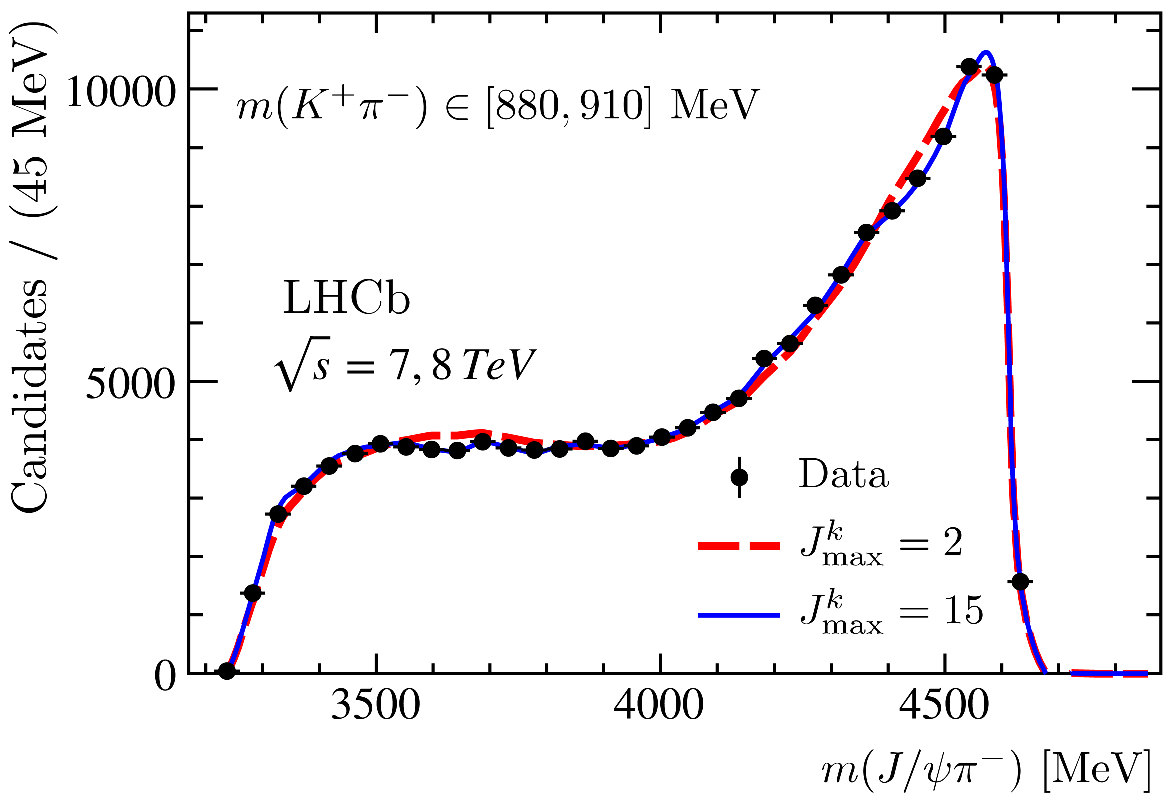
# Exotic contributions to $B^0 \to J/\psi K^+\pi^-$

Submitted to PRL
arXiv:1901.05745

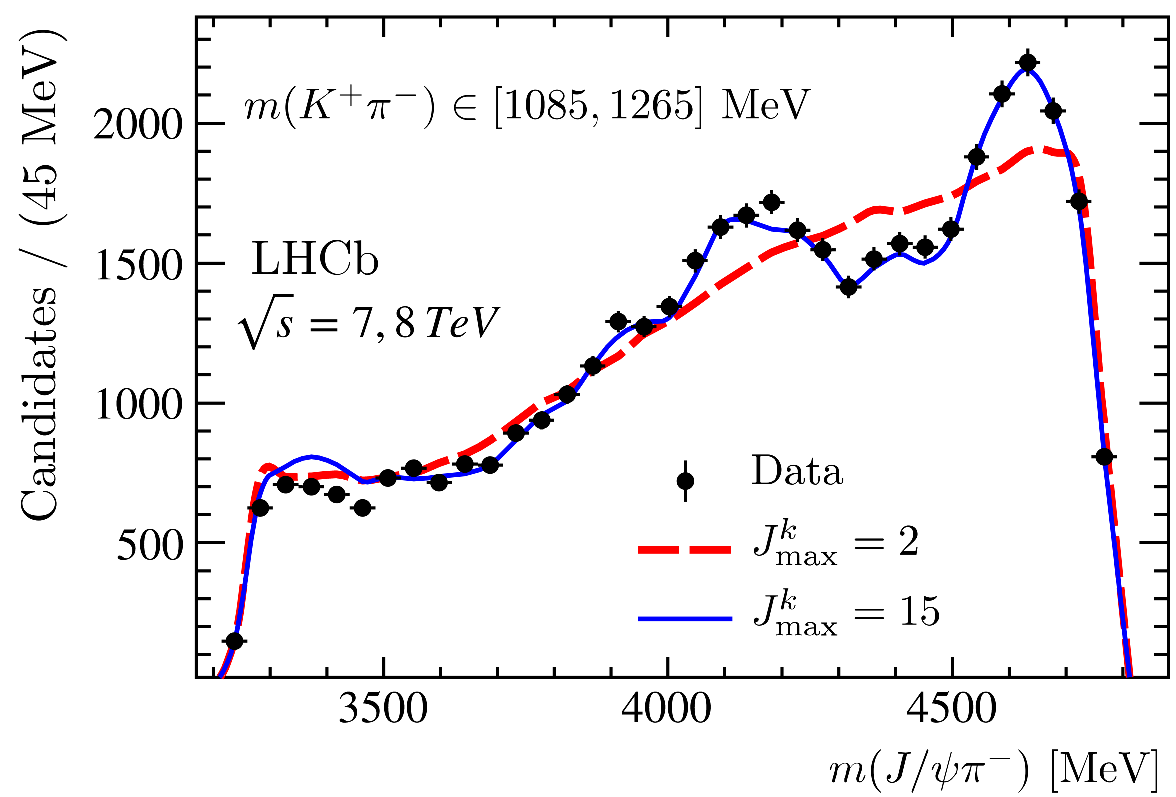
- Kinematic variables: $m(K^+\pi^-)$, $\chi$, $\theta_l$, $\theta_V$
- 3D angular fits in bins of $m(K^+\pi^-)$
- Fit model includes only $K^{*0}$ contributions with allowed J up to $J_{max}$
- Fine $m(K^+\pi^-)$ binning: conclusion is independent of $K^{*0}$ line shapes




## Region dominated by the $K^*(892)^0$




## Outside $K^*(892)^0$ region

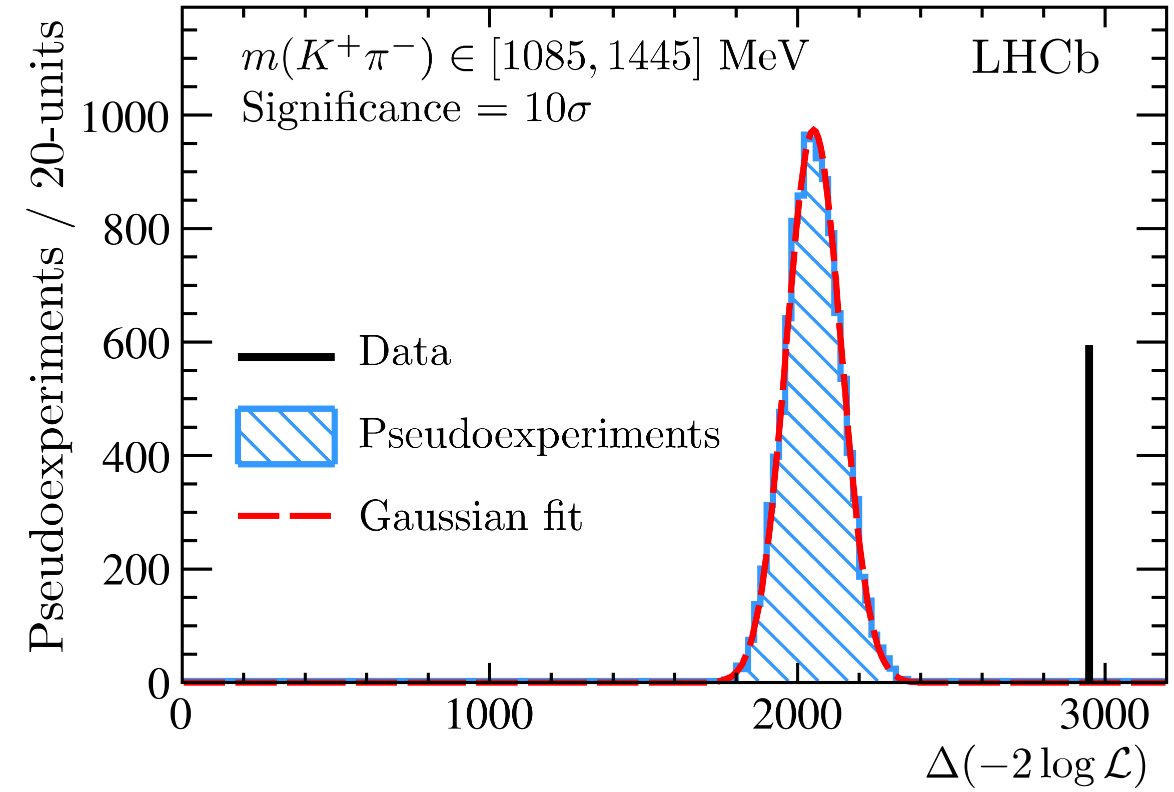



- Need unphysical $J_{max}$=15 to describe data.

Observation of exotic contributions in a model-independent way

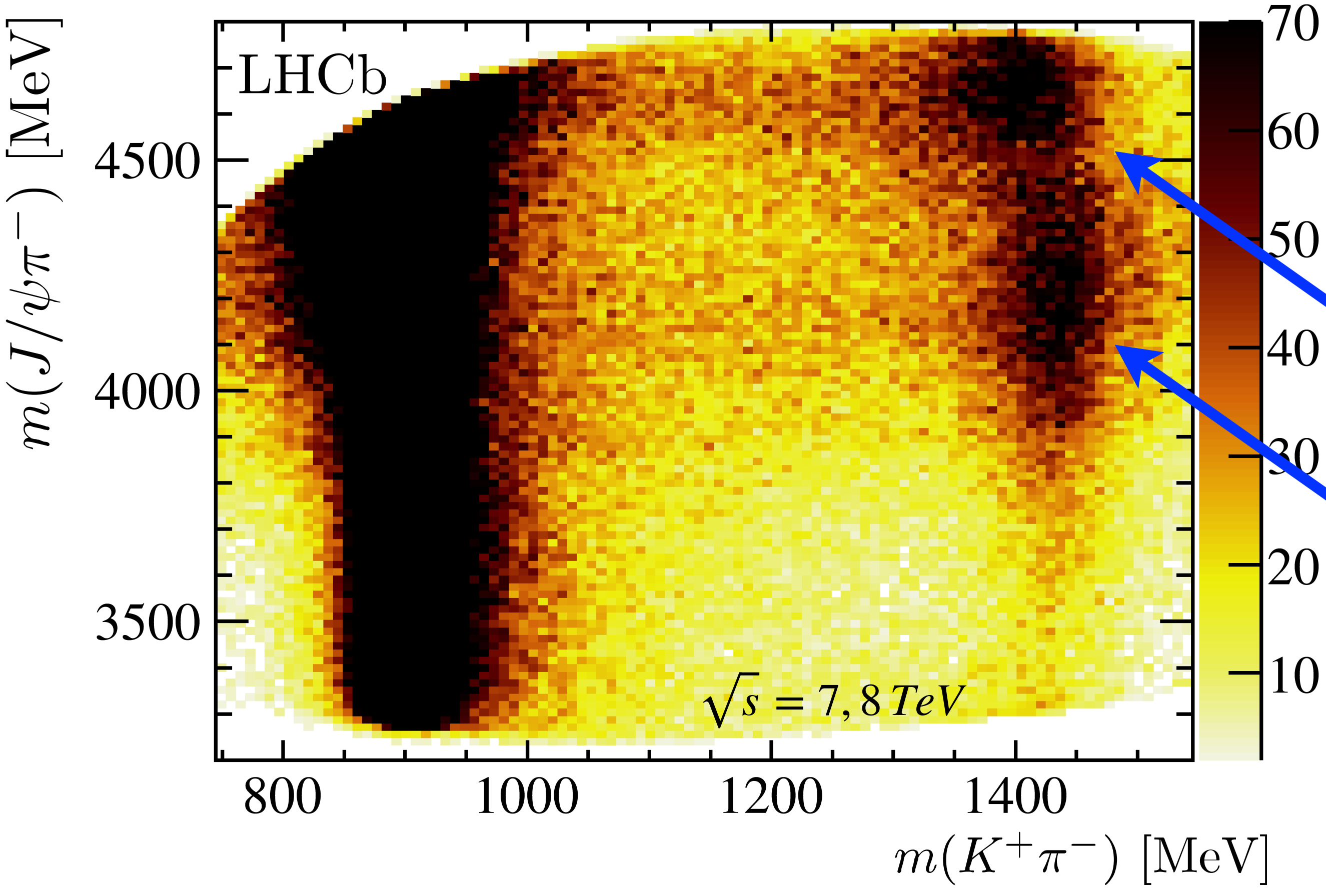
# Exotic contributions to $B^0 \to J/\psi K^+\pi^-$

Submitted to PRL
arXiv:1901.05745




- The likelihood ratio test demonstrates that data reject $K^{*0}$ only hypothesis with $10\sigma$ significance

## Dalitz plot for background-subtracted data




- Some structure at $m(J/\psi\pi^-) \approx 4600$ MeV/$c^2$
- Indications of the $Z(4200)^-$ seen by Belle

The nature of the non-$K^{*0}$ contributions can be investigated with a future amplitude analysis

# Conclusion

- The LHCb experiment provides a significant contribution to the knowledge of exotic hadron spectroscopy:
  - Search for beautiful tetraquarks $X_{b\bar{b}b\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$, upper limit is set
  - Evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ decays
  - Model-independent observation of exotic contributions to $B^0 \to J/\psi K^+\pi^-$ decays
- The analyses presented are based on only part of Run-II data
- Looking forward for new results from analyses of $9\ \mathrm{fb}^{-1}$ of full Run-I and Run-II data sample!

For the recent charm and charmonium results from LHCb see further talks by Ivan Belyaev and Alexey Dzyuba