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

WIFAI 2025


**Gabriele Romolini**

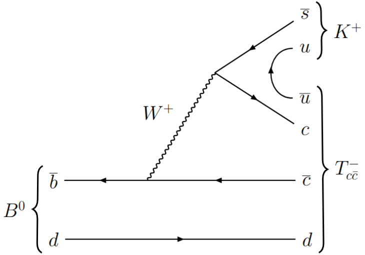
November 12, 2025

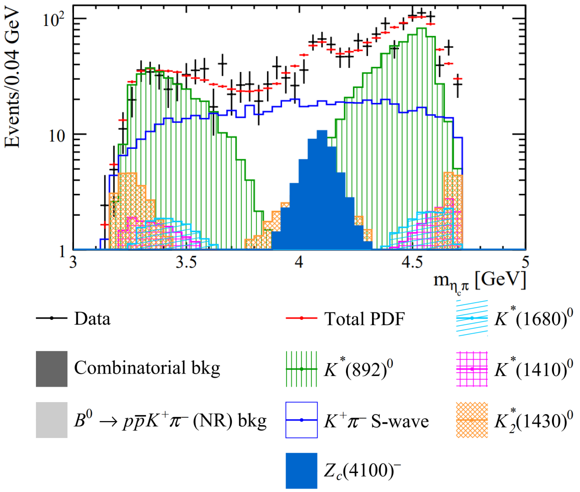
Università di Ferrara e INFN sezione di Ferrara

# Introduction

# The $B^0 \to \eta_c(1S) K^+ \pi^-$ decays at LHCb

- Evidence found by LHCb with Run1 and 2016 data in the $\eta_c(1S)\pi^-$ **[EPJC 78 (2018) 1019]**
- Several theoretical studies investigate its nature
- Now using full Run1 and Run2 dataset $\sim 9\ \text{fb}^{-1}$



# Candidates selection

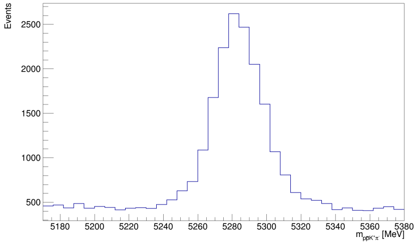
# Preselection and MVA

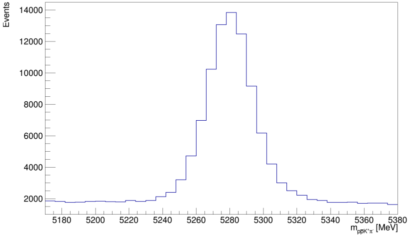
Loose preselection on $B^0 \to p\bar{p}K^+\pi^-$

- ▷ Track quality
- ▷ Particles momentum
- ▷ Vertex quality

Trained BDT using MC and data sideband

- ▷ Using $B^0$ and $p/\bar{p}$ properties
- ▷ Separate BDT for Run1 and Run2
- ▷ Using PID for Run2 in the BDT
- ▷ Loose PID cut for Run1

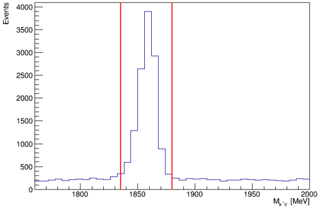


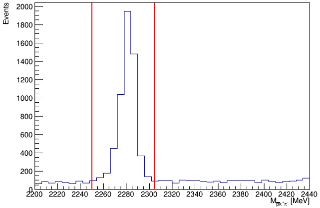



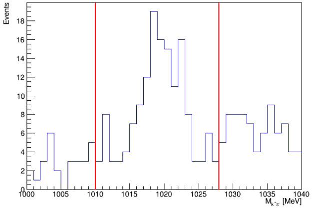
# Other vetoes

Vetoed other sources of background

- $\Lambda_c^+ \rightarrow pK^-\pi^+ \rightarrow 2240 < m_{\bar{p}K^+\pi^-} < 2305$ MeV
- $D^0 \rightarrow K^-\pi^+ \rightarrow 1835 < m_{K^+\pi^-} < 1880$ MeV
- $\phi \rightarrow K^+K^- \rightarrow 1010 < m_{K\pi_{\rightarrow K}} < 1028$ MeV
- Duplicate tracks and multiple candidates



# $B^0$ and $\eta_c(1S)$ selection

# Fit strategy

One dimensional fit performed for studies and checks

- Optimise fit range
- Check shape distribution $\rightarrow$ Fixed from MC
- Performed on $m_{p\bar{p}K^+\pi^-}$ and $m_{p\bar{p}}$ on various ranges
- $B^0$: Hypatia function
- $\eta_c(1S)$: Relativistic Breit-Wigner $*$ Crystall ball

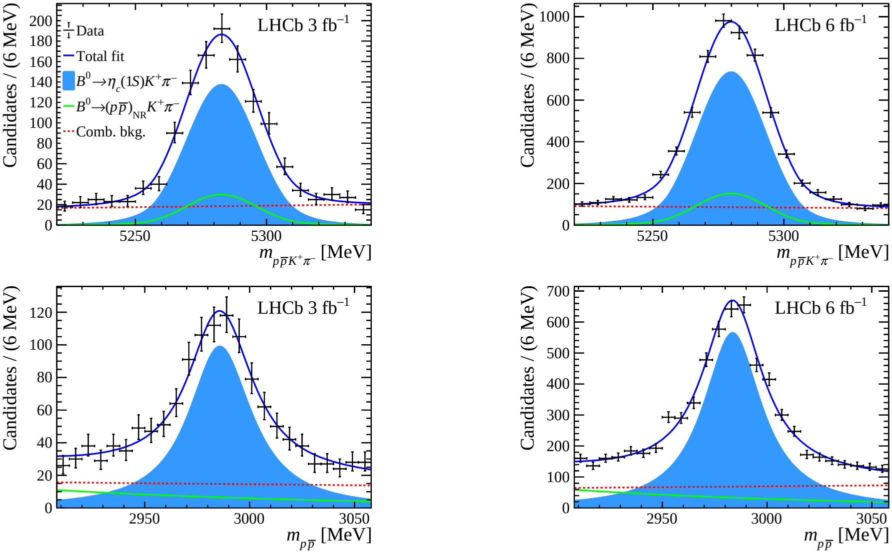
Two dimensional fit performed to extract signal and background components

- $5220 < m_{p\bar{p}K^+\pi^-} < 5340$ MeV, $2908 < m_{p\bar{p}} < 3058$ MeV
- Signal component: $B^0 \times \eta_c(1S)$
- Non-resonant (NR) component: $B^0 \times \exp$
- Combinatorial component: $\exp \times \exp$
- Used to compute SWeights of each component

# Fit results

Run1

Run2



# Branching fraction measurement

# Branching fraction measurement

Update $\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-)$ to also measure $\mathcal{B}(B^0 \to \eta_c(1S)K^\star(\to K^+\pi^-))$

- Normalisation channel $B^0 \to J/\psi K^+\pi^-$ extracted with the same strategy of $B^0 \to \eta_c(1S)K^+\pi^-$, $3072 < m_{p\bar{p}} < 3122$ MeV
- Efficiencies calculated using reweighted MC
- Separately for Run1 and Run2

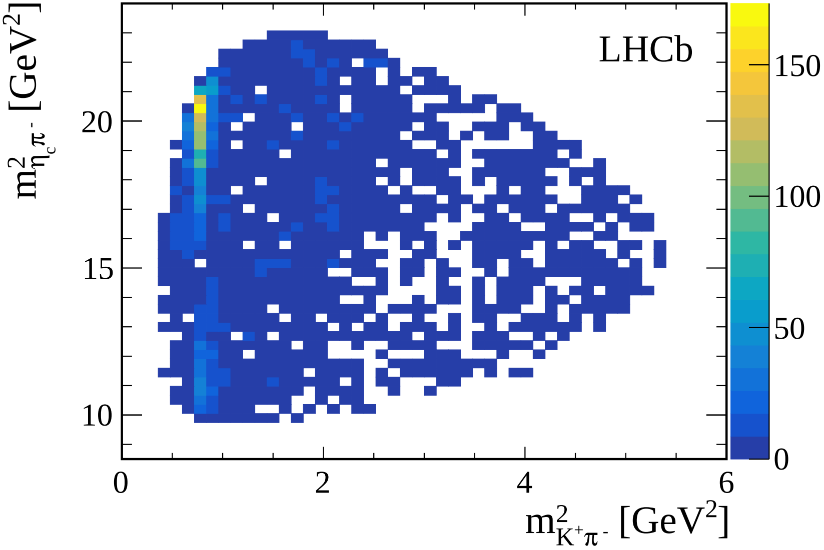
$$\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = \mathcal{B}(B^0 \to J/\psi K^+\pi^-)\frac{\mathcal{B}(J/\psi \to p\bar{p})}{\mathcal{B}(\eta_c(1S) \to p\bar{p})}\frac{N_{\eta_c}}{N_{J/\psi}}\frac{\epsilon_{J/\psi}}{\epsilon_{\eta_c}}$$

Weighted sum of Run1 and Run2 result:

$$\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = (5.82 \pm 0.20_{\text{stat}} \pm 0.23_{\text{syst}} \pm 0.55_{\text{ext}}) \times 10^{-4}$$

# Dalitz plot analysis

# Dalitz plot from signal events



# Amplitude fit model

`Laura++` package used to perform the amplitude fit

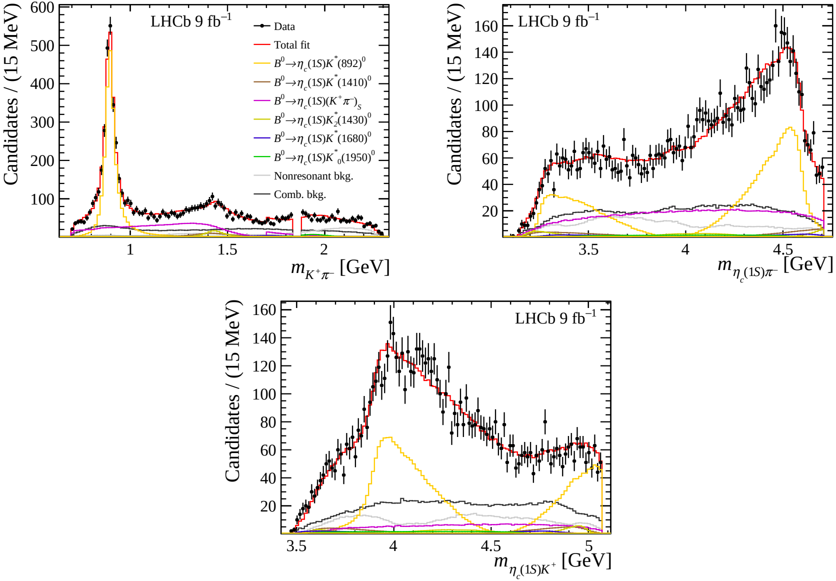
- Changes applied to take into account the natural width of $\eta_c(1S)$
- Signal efficiency calculated from MC taking into account the full selection
- Bkg contribution extracted from two-dimensional fit
- Baseline model with only conventional contributions
  - Considered only significant contributions
  - $K^*(892)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$, $K^*(1950)$
- All resonances parametrised with relativistic Breit-Wigner except $K_0^*(1430)$
  - $K_0^*(1430)$: LASS function, floating scattering length and the effective range

# Baseline model results

- Multiple fit to ensure global minimum is reached
- Optimised LASS cutoff
- Mass and width of $K_0^*(1430)$ gaussian constrained to PDG values
- Other $K^*$ fixed to PDG values

| | $K^*(892)$ | $K^*(1410)$ | LASS | $K_2^*(1430)$ | $K^*(1680)$ | $K_0^*(1950)$ |
|---|---|---|---|---|---|---|
| $K^*(892)^0$ | $49.3 \pm 1.2^{+3.8}_{-3.4}\%$ | $-2.1 \pm 1.8^{+3.1}_{-3.3}\%$ | 0.0 | 0.0 | $0.8 \pm 1.2^{+3.7}_{-4.5}\%$ | 0.0 |
| $K^*(1410)^0$ | | $4.5 \pm 1.4^{+3.2}_{-3.1}\%$ | 0.0 | 0.0 | $-3.2 \pm 1.5^{+6.5}_{-2.3}\%$ | 0.0 |
| LASS | | | $35.6 \pm 5.5^{+5.7}_{-4.5}\%$ | 0.0 | 0.0 | $7.0 \pm 10.3^{+7.9}_{-8.6}\%$ |
| $K_2^*(1430)^0$ | | | | $3.7 \pm 0.9^{+1.3}_{-2.0}\%$ | 0.0 | 0.0 |
| $K^*(1680)^0$ | | | | | $2.1 \pm 0.9^{+1.3}_{-1.7}\%$ | 0.0 |
| $K_0^*(1950)^0$ | | | | | | $2.4 \pm 0.5^{+2.7}_{-2.4}\%$ |

# Baseline model projections

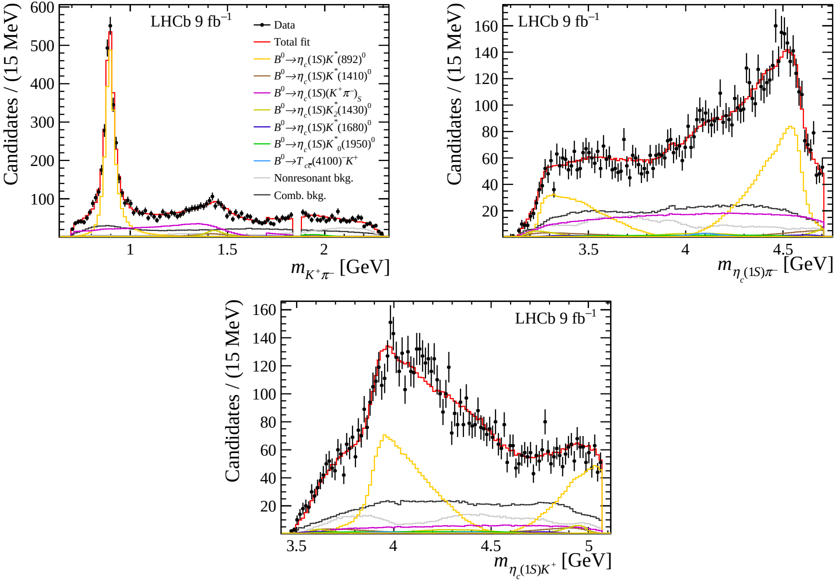


# Extended model

- Added $\eta_c(1S)\pi^-$ component, $J^P = 1^-$ best data description
  - $m_{T^-_{\bar{c}c}} = 4067 \pm 13$ MeV, $\Gamma_{T^-_{\bar{c}c}} = 506 \pm 166$ MeV
- Multiple fit to ensure global minimum is reached
- Same strategy for $K^*$ masses and widths

| | $K^*(892)$ | $K^*(1410)$ | LASS | $K^*_2(1430)$ | $K^*(1680)$ | $K^*_0(1950)$ | $T^-_{\bar{c}c}$ |
|---|---|---|---|---|---|---|---|
| $K^*(892)^0$ | $49.1 \pm 1.3^{+2.5}_{-3.4}\%$ | $-1.4 \pm 1.1^{+10.0}_{-5.1}\%$ | 0 | 0 | $0.3 \pm 0.9^{+3.0}_{-2.8}\%$ | 0 | $1.1 \pm 0.7^{+1.2}_{-1.5}\%$ |
| $K^*(1410)^0$ | | $3.9 \pm 0.9^{+5.1}_{-2.6}\%$ | 0 | 0 | $-2.6 \pm 1.2^{+7.7}_{-2.3}\%$ | 0 | $-0.7 \pm 0.3^{+0.9}_{-0.6}\%$ |
| LASS | | | $31.6 \pm 5.0^{+7.2}_{-5.7}\%$ | 0 | 0 | $5.1 \pm 5.7^{+29.1}_{-29.6}\%$ | $3.4 \pm 1.6^{+1.9}_{-2.1}\%$ |
| $K^*_2(1430)^0$ | | | | $4.0 \pm 0.9^{+1.5}_{-2.6}\%$ | 0 | 0 | $0.1 \pm 0.2^{+0.4}_{-0.3}\%$ |
| $K^*(1680)^0$ | | | | | $1.5 \pm 0.9^{+2.1}_{-2.2}\%$ | 0 | $0.5 \pm 0.3^{+0.3}_{-1.4}\%$ |
| $K^*_0(1950)^0$ | | | | | | $2.2 \pm 0.7^{+8.4}_{-8.5}\%$ | $0.7 \pm 0.3^{+0.6}_{-1.4}\%$ |
| $T^-_{\bar{c}c}$ | | | | | | | $1.1 \pm 0.5^{+1.0}_{-1.1}\%$ |

# Extended model projections



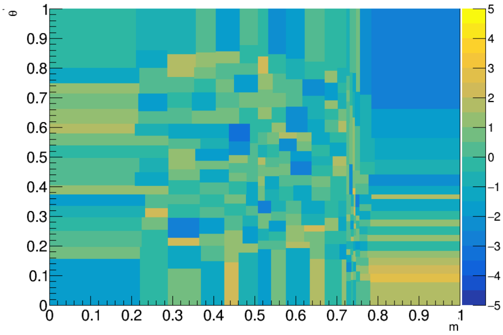
# Goodness of fit and significance

Goodness of fit estimated with various method

- ▷ 2D pull plot from toy generated based on the model
- ▷ Unnormalised Legendre moments

Significance of $T_{c\bar{c}} \to \eta_c(1S)\pi^-$ calculated using Wilks' theorem

- ▷ Significance found for $T_{c\bar{c}}$ with $J^P = 1^-$ is $3.6\sigma$
- ▷ Including systematics the significance is measured to be $2.5\sigma$ $\to$ No evidence



# Conclusions

# Results

This results supersede the LHCb analysis [**EPJC 78 (2018) 1019**]

- $T_{\bar{c}c}^{-}$ candidate not significant once systematics are taken into account
- $\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = (5.82 \pm 0.20 \pm 0.23 \pm 0.55) \times 10^{-4}$
- Updated $\mathcal{B}(B^0 \to \eta_c(1S)K^\star(\to K^+\pi^-))$

| Decay | Branching ratio $(10^{-5})$ |
|---|---|
| $B^0 \to \eta_c(1S)K^*(892)(\to K^+\pi^-)$ | $28.69 \pm 1.21 \pm 1.13^{+2.21}_{-1.98} \pm 2.71$ |
| $B^0 \to \eta_c(1S)K^*(1410)(\to K^+\pi^-)$ | $2.62 \pm 0.82 \pm 0.10^{+1.86}_{-1.80} \pm 0.25$ |
| $B^0 \to \eta_c(1S)K_0^*(1430)(\to K^+\pi^-)$ | $17.92 \pm 2.80 \pm 0.71^{+3.26}_{-2.56} \pm 1.69$ |
| $B^0 \to \eta_c(1S)K^+\pi^-$ (S-Wave) | $8.96 \pm 1.42 \pm 0.35^{+1.63}_{-1.28} \pm 0.84$ |
| $B^0 \to \eta_c(1S)K_2^*(1430)(\to K^+\pi^-)$ | $2.15 \pm 0.53 \pm 0.08^{+0.76}_{-1.16} \pm 0.20$ |
| $B^0 \to \eta_c(1S)K^*(1680)(\to K^+\pi^-)$ | $1.22 \pm 0.52 \pm 0.05^{+0.76}_{-0.99} \pm 0.12$ |
| $B^0 \to \eta_c(1S)K_0^*(1950)(\to K^+\pi^-)$ | $1.40 \pm 2.56 \pm 0.06^{+1.57}_{-1.40} \pm 0.13$ |

This analysis is currently submitted to EPJC and on arXiv

THANKS FOR YOUR ATTENTION

# Run1 + 2016 comparison

Previous analysis:

Spin 0

$$m_{T^-_{\bar{c}c}} = 4059 \pm 30 \text{ MeV},$$
$$\Gamma_{T^-_{\bar{c}c}} = 163 \pm 67 \text{ MeV}$$
$$FF = 3.5 \pm 1.6$$

Spin 1

$$m_{T^-_{\bar{c}c}} = 4096 \pm 20 \text{ MeV},$$
$$\Gamma_{T^-_{\bar{c}c}} = 152 \pm 58 \text{ MeV}$$
$$FF = 3.3 \pm 1.1$$

Current analysis:

Spin 0

$$m_{T^-_{\bar{c}c}} = 4090 \pm 14 \text{ MeV},$$
$$\Gamma_{T^-_{\bar{c}c}} = 178 \pm 60 \text{ MeV}$$
$$FF = 3.1 \pm 1.0$$

Spin 1

$$m_{T^-_{\bar{c}c}} = 4096 \pm 21 MeV,$$
$$\Gamma_{T^-_{\bar{c}c}} = 394 \pm 173 MeV$$
$$FF = 3.6 \pm 1.2$$

# Extended model with $J^P = 1^-$