Study of exotic tetraquark states in B-meson decays at the ATLAS experiment

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Introduction

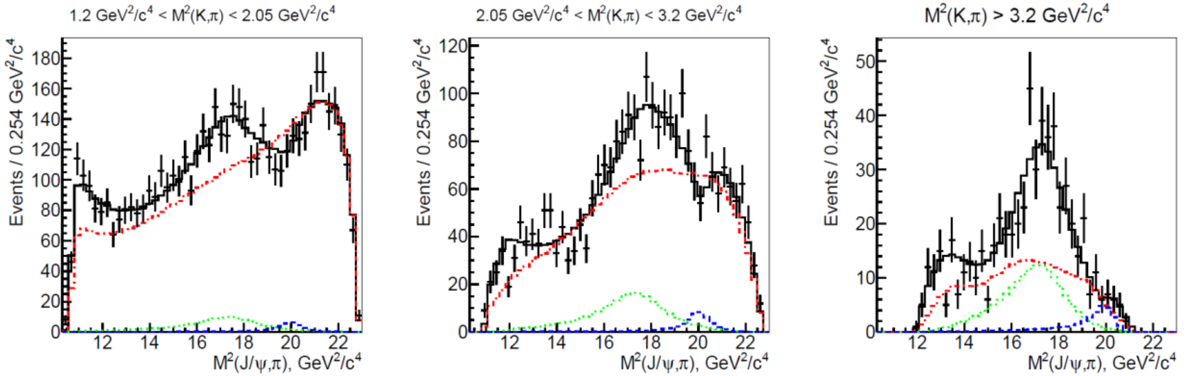
- The quark model of hadrons proposed by Murray Gell-Mann assumes the existence of states with structure beyond standard *qq* and *qqq*-models.

- Z_c(4200) was discovered by BELLE collaboration [1] with a significanceof 6.2σ in 2014. A full amplitude analysis was performed to determine the parameters of this state:

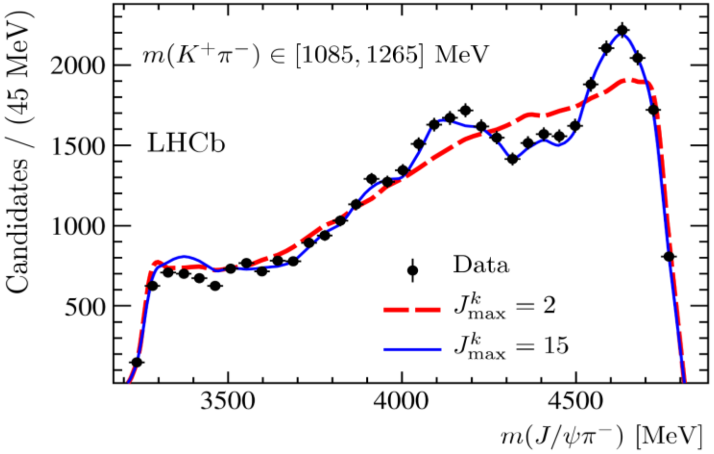
J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4318 ± 48	4315 ± 40	4196^{+31}_{-29}	4209 ± 14	4203 ± 24
Width, MeV	720 ± 254	220 ± 80	370 ± 70	64 ± 18	121 ± 53
Significance (Wilks)	3.9σ	2.3σ	8.2σ	3.9σ	1.9σ

- In 2008 BaBar collaboration performed model independent analysis of $B^0 \to J/\psi K\pi$ decays to study Z_c(4430) state. No evidence of Z_c(4200) existence was found

- In 2019 LHCb collaboration performed model independent analysis of $B^0 \to J/\psi K\pi$ decays [2]. They discovered an exotic structure near the mass m(J/ψπ) = 4200 MeV.



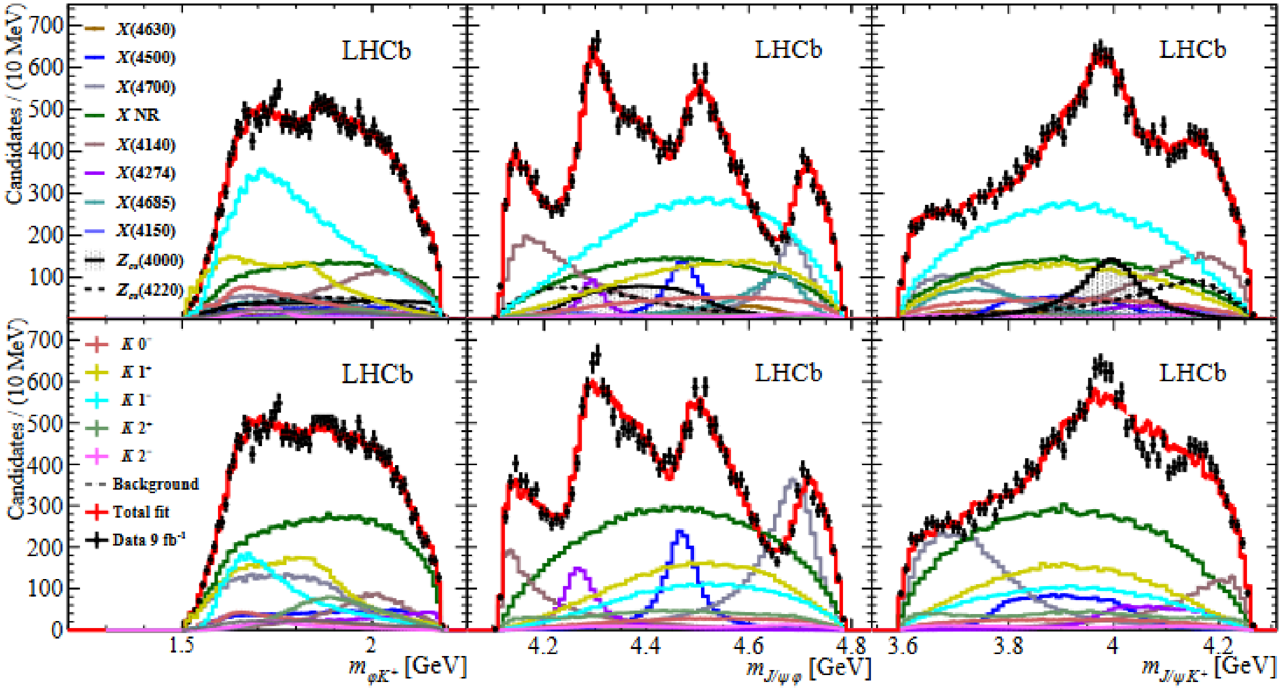
[1] K. Chilikin *et al.* (Belle Collaboration), *Observation of a new charged charmoniumlike state in $\overline{B^0} \to J/\psi K^- \pi^+$ decays*, Phys. Rev. D 90, 112009



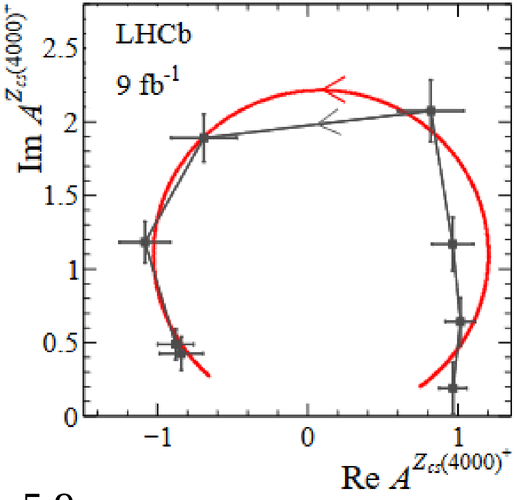
[2] R. Aaij *et al.* (LHCb Collaboration), *Model-Independent Observation of Exotic Contributions to $B^0 \to J/\psi K^+ \pi^-$ Decays*, Phys. Rev. Lett. 122, 152002

Introduction

$Z_{CS}(4000)$ and $Z_{CS}(4220)$ were discovered in $B^+ \to J/\psi\varphi K^+$ by the LHCb collaboration in 2021 [3].



[3] R. Aaij *et al*. (LHCb Collaboration), *Observation of New Resonances Decaying to $J/\psi K^+$ and $J/\psi\phi$*, Phys. Rev. Lett. 127, 082001

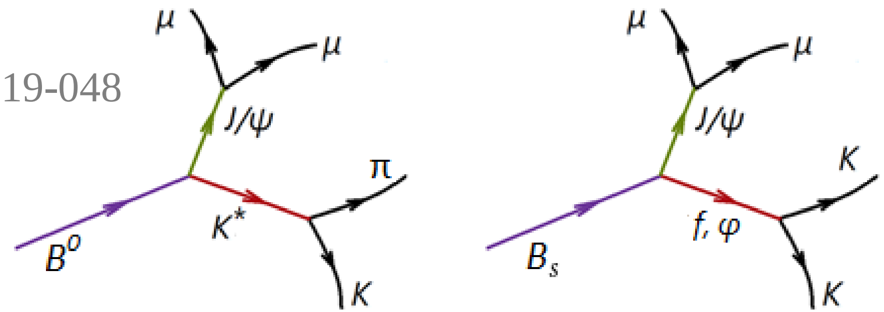


$Z_{CS}(4000)$ significance 15σ:
$M = 4003 \pm 6$ (stat) $^{+4}_{-14}$ (syst) MeV
$\Gamma = 131 \pm 15$ (stat) ± 26 (syst) MeV
$J^P = 1^+$

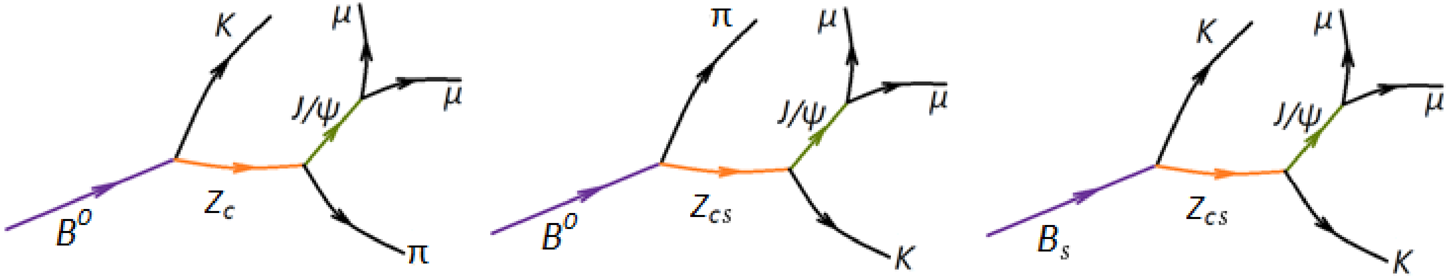
$Z_{CS}(4220)$ significance 5.9σ:
$M = 4216 \pm 24$ (stat) $^{+43}_{-30}$ (syst) MeV
$\Gamma = 233 \pm 52$ (stat) $^{+97}_{-73}$ (syst) MeV
$J^P = 1^+$ or 1^-

Studies of exotic states: Z_c and Z_{cs} in B-meson decays

[4] ATLAS-CONF-2019-048



Conventional decay chains



Exotic decay chains

5 exotic states in $\mathbf{B^0 \to J/\psi K\pi}$

2 exotic states in $\mathbf{B_s \to J/\psi KK}$

- Analysis started as byproduct of Run1 pentaquark study, where *B*-meson decays represent main backgrounds [4]
- The main problem is absence of particle ID. We had to analyze $H_b \to J/\psi h_1 h_2$, where $H_b = \{\Lambda_b, B_d, B_s\}$, $h_1, h_2 = \{p, K, \pi\}$.
- Large width of $Z_c(4200)$ considerably complicates its analysis: very accurate background modelling and account for interference effects are needed. So-called ‘phase-space’ MC (by Pythia8) is used being weighted event-by-event by analytically derived matrix elements. Parameters of these matrix elemets to be defined from fits of MC to data.

Event selection

In this analysis we used the data from the ATLAS experiment at $s^{1/2} = 13$ TeV, full Run2 statistic (140 fb^{-1}). Events consisting of J/ψ (2 muons) and 2 opposite sign hadron tracks were selected.

Selected events include:

- Combinatorial background
- Physical decays:
  - $B^0 \to J/\psi K\pi$ **(matrix el.)**
  - $B^0 \to J/\psi \pi\pi$
  - $B_s \to J/\psi \pi\pi$
  - $B_s \to J/\psi KK$ **(matrix el.)**
  - $\Lambda_b \to J/\psi pK$ **(matrix el.)**
  - $B_s \to J/\psi K\pi$
  - $B^0 \to J/\psi KK$
  - $\Lambda_b \to J/\psi p\pi$

The **fit procedure** is accomplished in **3 iterative** steps (see Appendix3):

- Global fit
- Step2
- SR fit

The main task in optimizing selections is suppressing backgrounds (see Appendix2 for details of cuts optimization):

- p_T muons > 4 GeV, $|\eta|<2.3$
- χ^2/ndof dimuon-vertex < 10
- 2950 MeV < $m(\mu_1\mu_2)$ < 3250 MeV + refit to the PDG J/ψ mass
- L_{xy} (H_b)> 1 mm
- $m(K\pi)$, $m(\pi K)$ > 1550 MeV (to suppress light K* contribution)
- p_T hadrons > 2 GeV
- χ^2/ndof B-vertex < 1.7
- p_T (B-hadron) / p_T (primary vertex) > 0.25
- $m(J/\psi K)$ < 5.1 GeV (to suppress B^+ decays)
- $m(J/\psi K\pi)$, $m(J/\psi \pi K)$ > 4.9 GeV

The following weights have been applied to Monte Carlo events:

- Trigger prescale weights
- *B*-hadron p_T
- Muon reconstruction efficiency

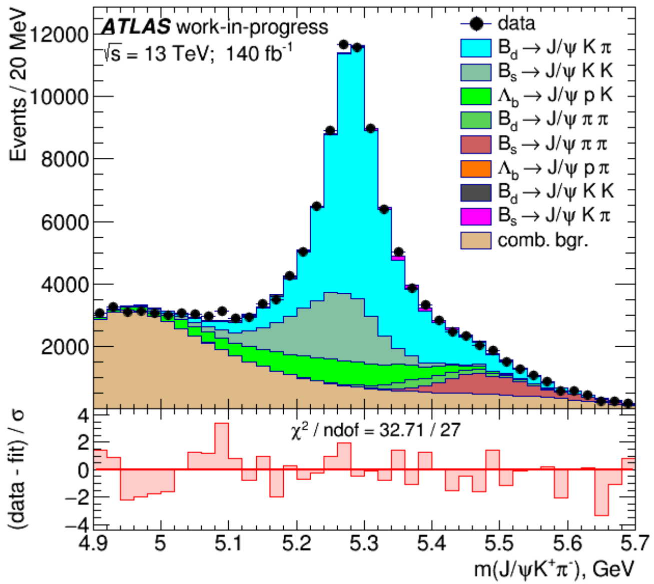
Features of the analysis

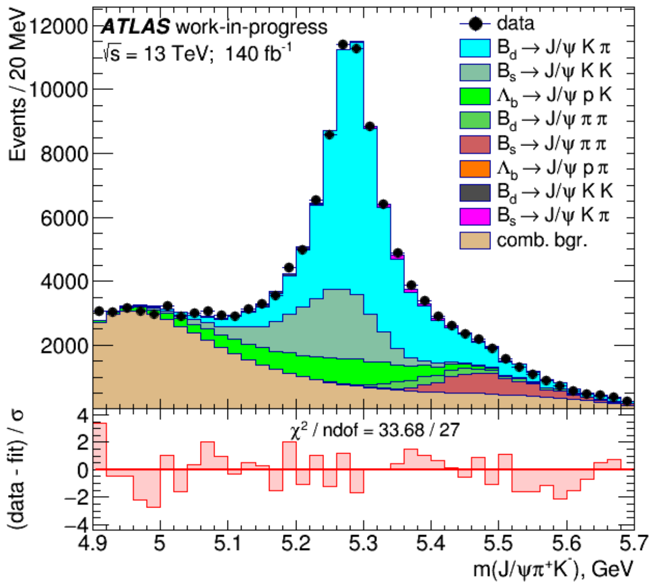
- Amplitude analysis details (https://indico.jinr.ru/event/3154/contributions/17741/) see Appendix1:
  - Parameters of the model (M, Γ, J^P, decay constants) are unknown, therefore, a ready-made MC decay generator cannot be used;
  - On the other hand, the use of Monte Carlo makes it possible to take into account detector effects;
  - MC events at the “detector” level are reweighted by matrix elements calculated taking into account the kinematics of events at the “generator” level.

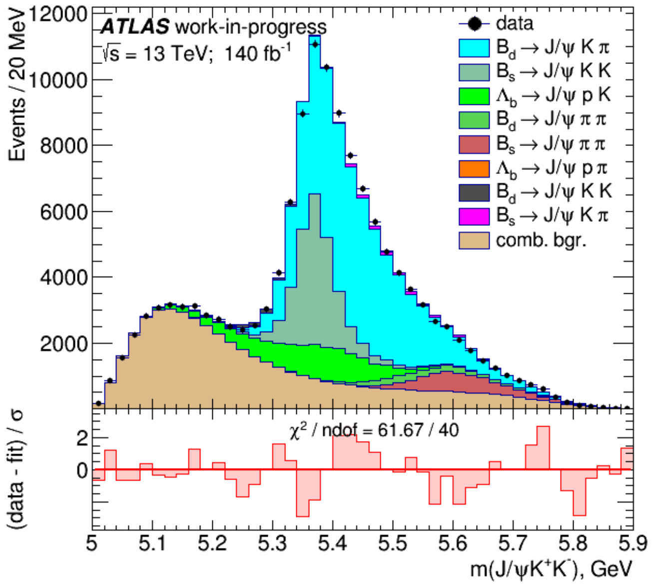
- Evolutionary algorithm for $B^0 \to J/\psi K\pi$ SR shape optimization;

- MC event based pseudo data generator was developed (see Appendix4):
  - Number of dimensions is not limited;
  - Detector effects are naturally accounted for;
  - No need a lot of CPU;
  - Systematic effects can be accounted for;
  - Large enough statistics of background MC is required;

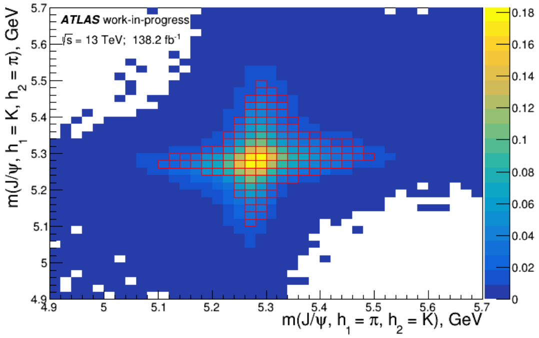
Results of global fit (all states $Z_C(4200)$ $J^P = 2^+$)







$B^0 \to J/\psi K\pi$ SR:



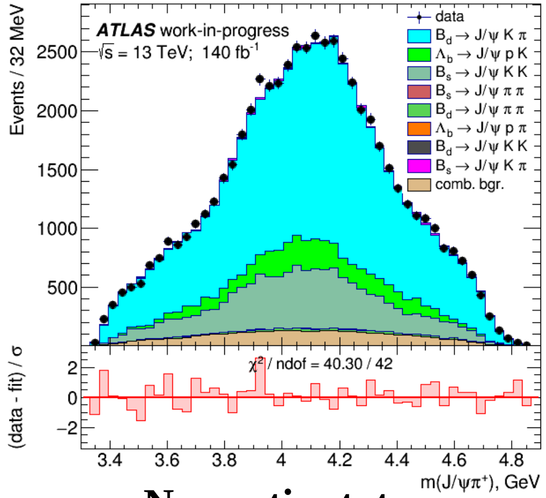
$B_S \to J/\psi KK$ SR:

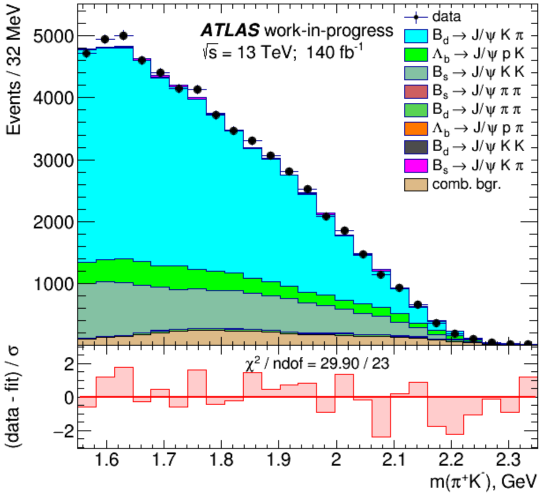
5336 MeV < m(J/ψKK) < 5396 MeV

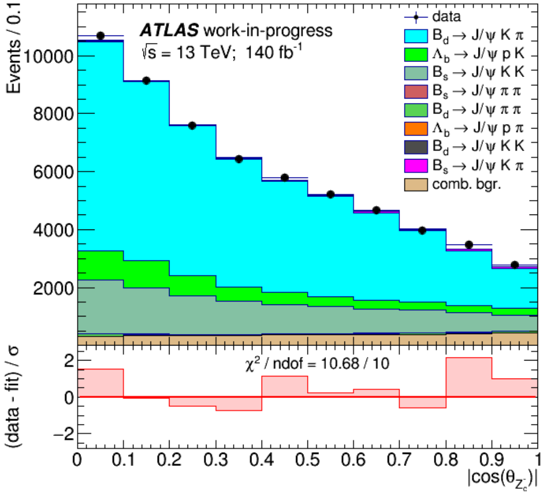
Process	Number of events from the fit	Events in B^0 SR	Events in B_s SR
$B_d^0 \to J/\psi, K, \pi$	52390 ± 490	39090	13360
$\Lambda_b^0 \to J/\psi, p, K$	11980	4940	2920
$B_s^0 \to J/\psi, K, K$	18080^{+380}_{-370}	10700	11420
$B_d^0 \to J/\psi, \pi, \pi$	2200	510	30
$B_s^0 \to J/\psi, \pi, \pi$	5280	84	4
$B^0 \to J/\psi, K, K$	510	37	30
$B_s^0 \to J/\psi, K, \pi$	860	390	28
$\Lambda_b^0 \to J/\psi, p, \pi$	0	0	0

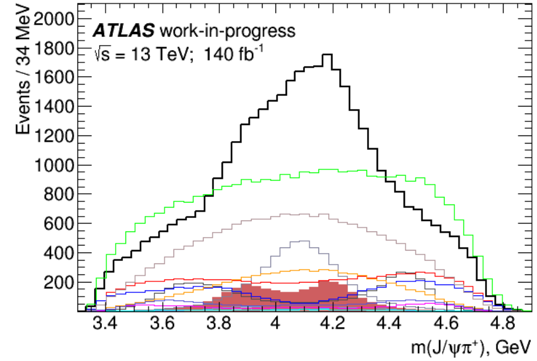
SR of $B^0 \to J/\psi K\pi$ decays

Five exotic states: $Z_c(3900)$, $Z_c(4300)$, $Z_c(4200)$ ($J^P = 2^+$), $Z_{cs}(4000)$, $Z_{cs}(4220)$



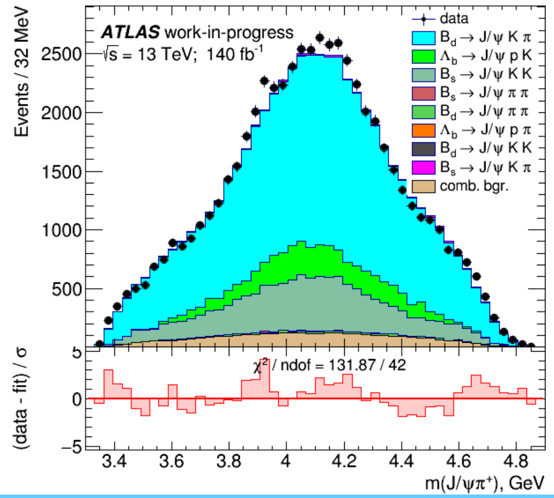


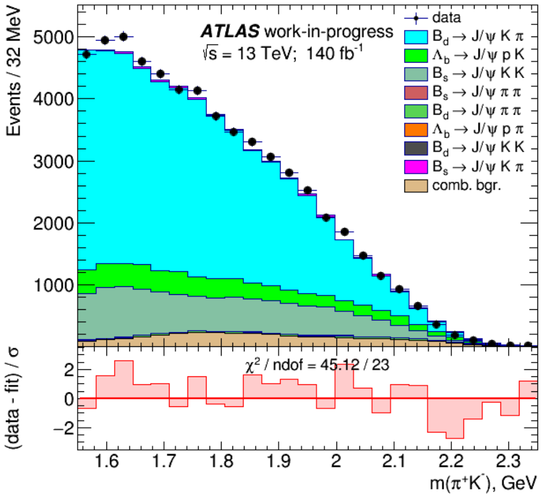


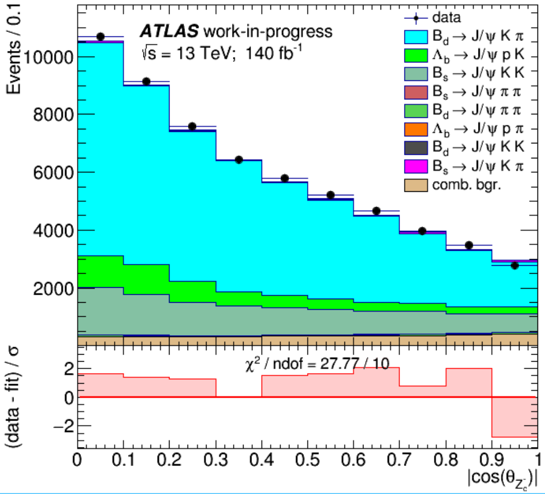


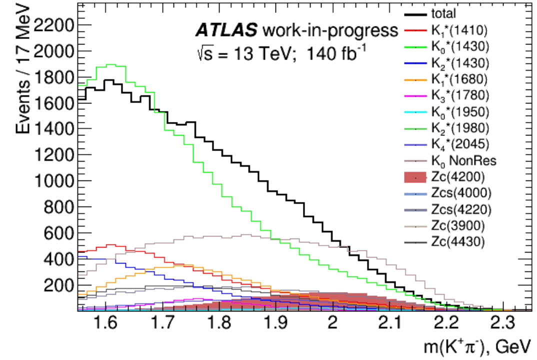
$Z_c(4200)$ mass	$4207^{+13}_{-22}(\text{stat.})^{+8}_{-19}(\text{syst.})$
$Z_c(4200)$ width	$185^{+38}_{-23}(\text{stat.})^{+48}_{-11}(\text{syst.})$

No exotic states



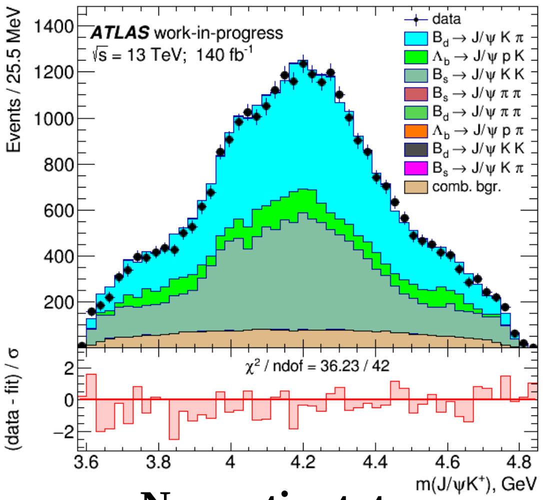


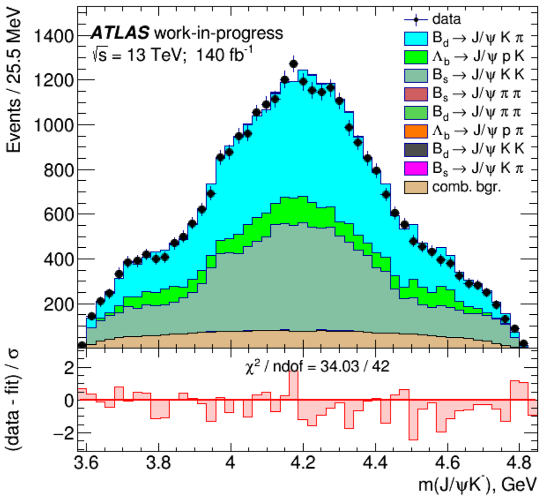


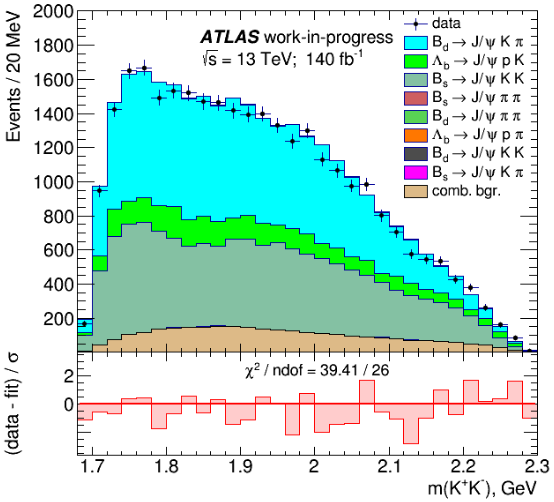


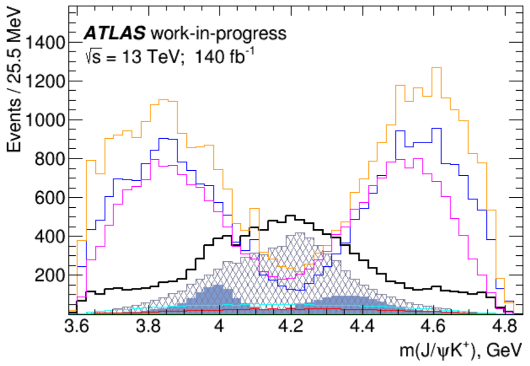
SR of $B_s \to J/\psi KK$ decays

Five exotic states: $Z_c(3900)$, $Z_c(4300)$, $Z_c(4200)$ ($J^P = 2^+$), $Z_{cs}(4000)$, $Z_{cs}(4220)$

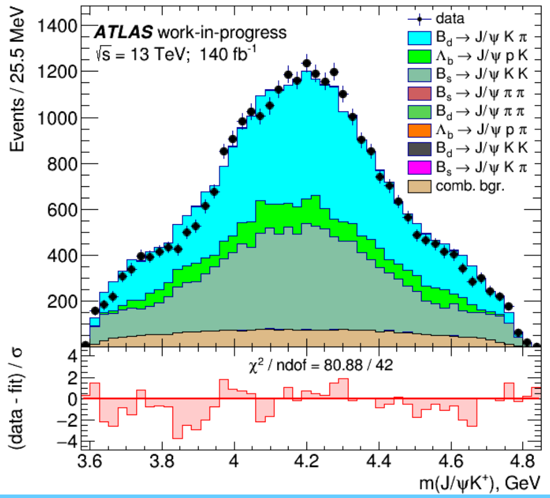


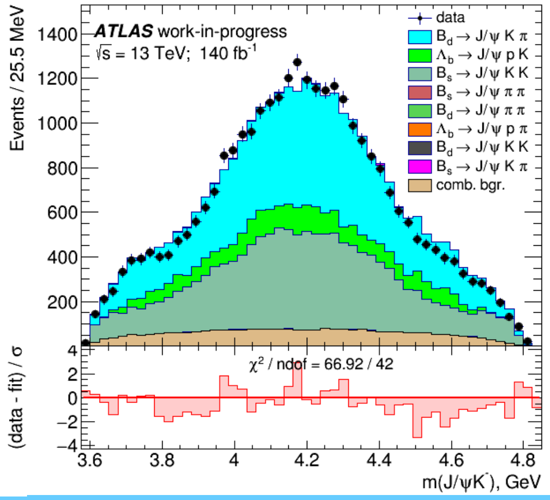


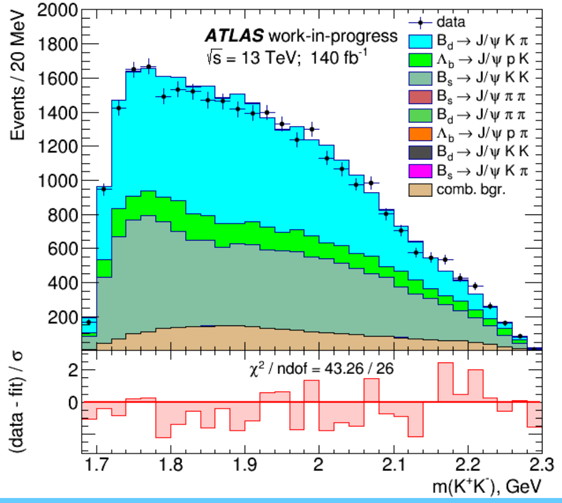




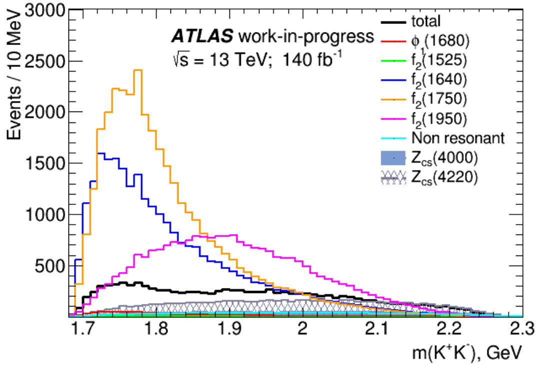
No exotic states







Mass and width of $Z_{cs}(4000)$ and $Z_{cs}(4220)$ are **fixed** to LHCb values



Fit results

Model	$Z_c(4200)$ Mass, MeV Width, MeV	$N_{Z_c(4200)}$	ΔL vs. no exotic	ΔL vs. best model
No exotics	n.a.	n.a.	0.0	-419.4
$Z_c(3900)$, $Z_c(4430)$	n.a.	n.a.	158.6	-260.8
$Z_c(3900)$, $Z_c(4430)$ $Z_{cs}(4000)$, $Z_{cs}(4220)$	n.a.	n.a.	378.3	-41.1
$Z_c(4200)\ 1^+$, $Z_c(3900)$, $Z_c(4430)$	$4187^{+18}_{-19}(\text{stat.})^{+3}_{-7}(\text{syst.})$ $326^{+42}_{-38}(\text{stat.})^{+13}_{-20}(\text{syst.})$	$40090^{+6000}_{-8000}(\text{stat.})^{+3500}_{-4100}(\text{syst.})$	352.1	-67.3

$Z_c(4200)$ J^P	$Z_c(4200)$ mass, MeV width, MeV	$N_{Z_c}(4200)$	ΔL vs. no exotic	model n.d.f. vs. no $Z_c(4200)$	ΔL vs. best
0^-	$4236^{+11}_{-8}(\text{stat.})^{+4}_{-11}(\text{syst.})$ $68^{+11}_{-19}(\text{stat.})^{+58}_{-23}(\text{syst.})$	$570^{+440}_{-62}(\text{syst.})$	390.7	4	-28.7
1^-	$4194^{+27}_{-20}(\text{stat.})^{+3}_{-19}(\text{syst.})$ $107^{+19}_{-34}(\text{stat.})^{+4}_{-56}(\text{syst.})$	$450^{+350}_{-90}(\text{syst.})$	393.7	4	-25.7
1^+	$3984^{+22}_{-13}(\text{stat.})^{+31}_{-7}(\text{syst.})$ $138^{+21}_{-25}(\text{stat.})^{+9}_{-30}(\text{syst.})$	$3110^{+1230}_{-680}(\text{stat.})^{+1810}_{-820}(\text{syst.})$	405.9	6	-13.5
central ⇒ 2^+	$4207^{+13}_{-22}(\text{stat.})^{+8}_{-19}(\text{syst.})$ $185^{+38}_{-23}(\text{stat.})^{+48}_{-11}(\text{syst.})$	$2780^{+1130}_{-530}(\text{stat.})^{+4200}_{-120}(\text{syst.})$	417.7	4	-1.7
2^-	$4212^{+20}_{-13}(\text{stat.})^{+17}_{-1}(\text{syst.})$ $178^{+60}_{-33}(\text{stat.})^{+44}_{-1}(\text{syst.})$	$1870^{+750}_{-330}(\text{stat.})^{+1550}_{-240}(\text{syst.})$	419.4	6	0.0
3^-	$4234^{+31}_{-45}(\text{stat.})^{+10}_{-34}(\text{syst.})$ $247^{+65}_{-70}(\text{stat.})^{+76}_{-26}(\text{syst.})$	$4960^{+1210}_{-1590}(\text{stat.})^{+600}_{-950}(\text{syst.})$	410.2	4	-9.2
3^+	$4220^{+16}_{-14}(\text{stat.})^{+12}_{-4}(\text{syst.})$ $177^{+34}_{-14}(\text{stat.})^{+23}_{-1}(\text{syst.})$	$2100^{+800}_{-430}(\text{stat.})^{+1040}_{-550}(\text{syst.})$	419.4	6	0.0

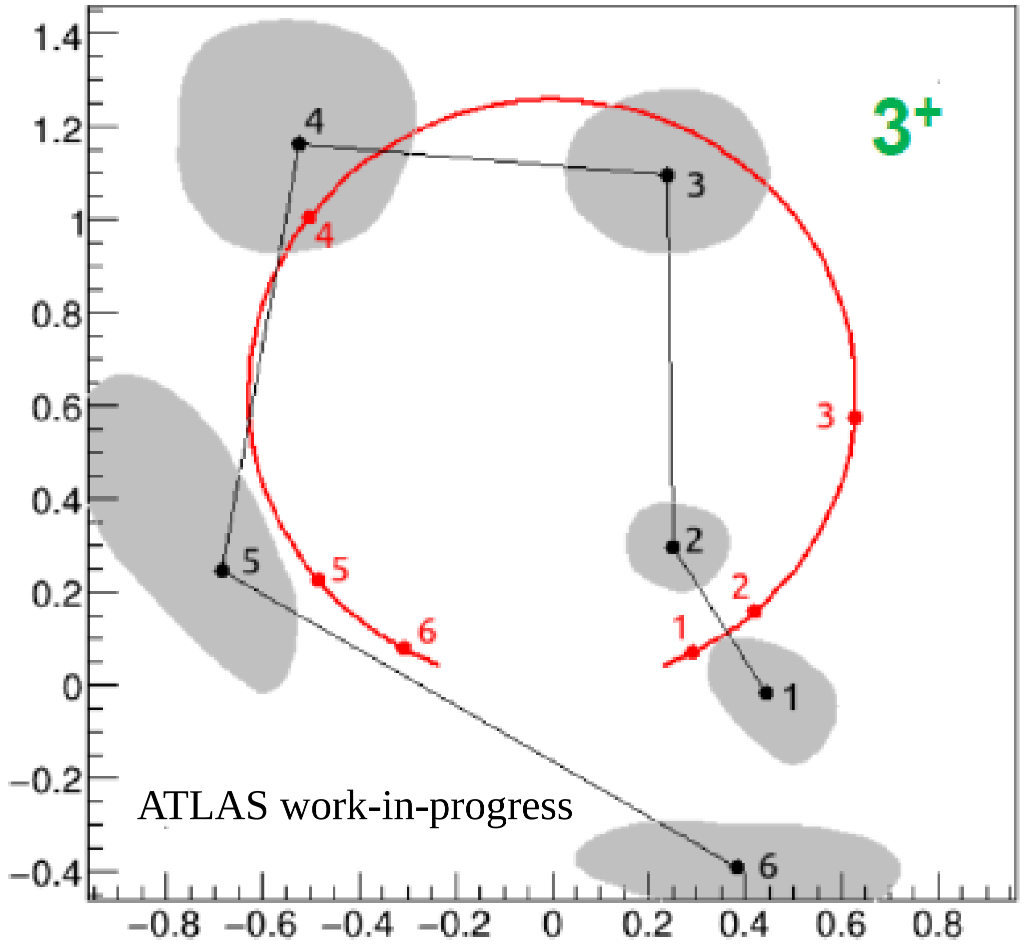
Decay model without exotic components demonstrate poor data/model agreement.
We add different exotic states to examine their effect on data description.

Decay model with 5 exotic states in $B^0 \to J/\psi K\pi$ and 2 exotic states in $B_s \to J/\psi KK$ shows the best data description. Further addition of Z_c/Z_{cs} states has significance less than 1σ (Wilks).

To exclude different spin-parity hypotheses of $Z_c(4200)$ ToyMC approach was used…

Model	ΔL	ΔL with syst.	n.d.f.	Exclusion level
$Z_c(4200)\ 0^-$ vs. $Z_c(4200)\ 2^+$	27.0	11.3 (sys.33)	0	3.17
$Z_c(4200)\ 1^+$ vs. $Z_c(4200)\ 2^+$	11.8	8.8 (sys.34)	-2	2.44
$Z_c(4200)\ 1^-$ vs. $Z_c(4200)\ 2^+$	24.0	14.8 (sys.9)	0	3.02

Argand diagram



To prove resonant behavior of $Z_c(4200)$ Argand diagrams were ploted. For central group of spin-parity hypotheses fit results shows behavior consistent with theoretical predictions. See Appendix5 for more plots.

Systematics study

The most significant sources of systematic uncertainties:

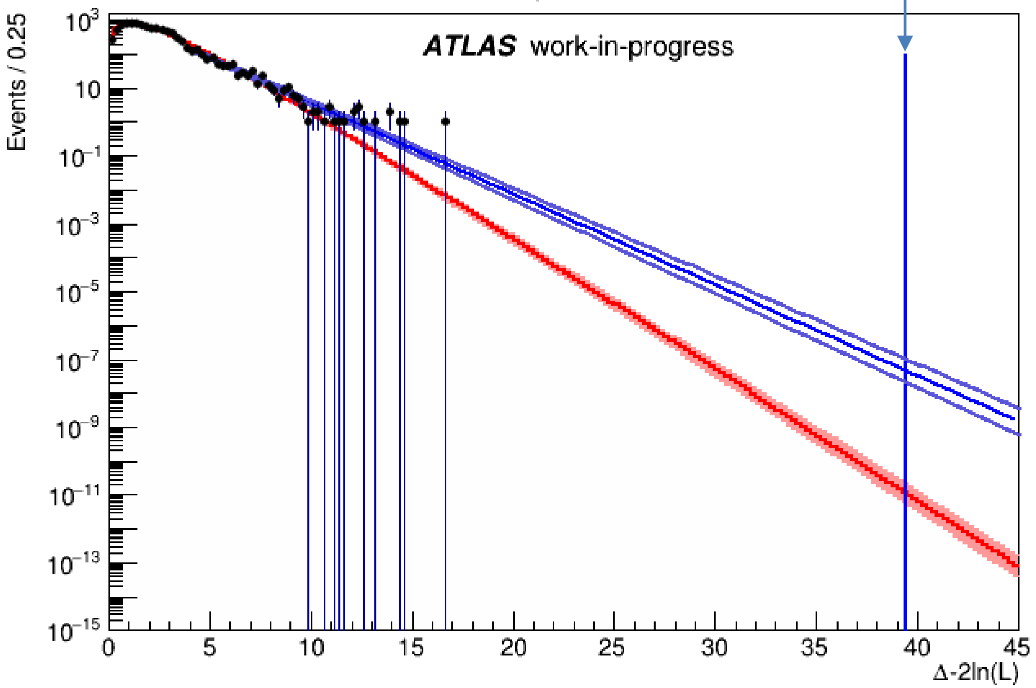
- $\{\delta_0\}$ The uncertainty in the modeling of the $B^0 \to J/\psi K\pi$ decays:
  - uncertainties of the masses and widths of the leading K^* resonances;
  - variation of the matrix element of the non-resonant $K\pi$ component;
- $\{\delta_4\}$ The uncertainty in the modeling of the $B_s \to J/\psi KK$ decays:
  - uncertainties of the masses and widths of the leading f or ϕ resonances;
  - variation of the matrix element of the non-resonant KK component;
- $\{\delta_9\}$ Smearing of the hadron tracks p_T;
- $\{\delta_{10}\}$ Uncertainties in the $Z_{cs}(4000)$ and $Z_{cs}(4220)$ states modeling:
  - $Z_{cs}(4000)$ and $Z_{cs}(4220)$ masses and widths variations;
- $\{\delta_{12}\}$ Variations of the scale-factor d entering the Blatt-Weisskopf factors;

See Appendix6 for full list

Syst. group	$\Delta M_{Z_c(4200)}$ [MeV]	$\Delta\Gamma_{Z_c(4200)}$ [MeV]	$\Delta N_{Z_c(4200)}$
δ_0	$^{+1}_{-7}$	$^{+4}_{-9}$	$^{+310}_{-30}$
δ_1	$^{+0}_{-0}$	$^{+0}_{-0}$	$^{+30}_{-30}$
δ_2	$^{+0}_{-0}$	$^{+0}_{-0}$	$^{+50}_{-50}$
δ_3	$^{+0}_{-0}$	$^{+2}_{-0}$	$^{+0}_{-70}$
δ_4	$^{+2}_{-6}$	$^{+32}_{-1}$	$^{+1600}_{-0}$
δ_5	$^{+0}_{-0}$	$^{+0}_{-0}$	$^{+60}_{-10}$
δ_6	$^{+0}_{-0}$	$^{+0}_{-1}$	$^{+40}_{-70}$
δ_7	$^{+0}_{-0}$	$^{+0}_{-0}$	$^{+10}_{-0}$
δ_8	$^{+0}_{-0}$	$^{+0}_{-0}$	$^{+30}_{-70}$
δ_9	$^{+0}_{-15}$	$^{+9}_{-0}$	$^{+2060}_{-0}$
δ_{10}	$^{+8}_{-6}$	$^{+34}_{-6}$	$^{+2420}_{-0}$
δ_{11}	$^{+0}_{-0}$	$^{+0}_{-0}$	$^{+50}_{-0}$
δ_{12}	$^{+2}_{-4}$	$^{+6}_{-0}$	$^{+30}_{-20}$

Significance of $Z_c(4200)/Z_{cs}$ states estimation

To measure significance of $Z_c(4200)/Z_{cs}$ contribution ToyMC approach was used. Fitting pseudo data is CPU expensive procedure. Thus there is a limit on the possible number of ToyMC experiments. In the case, when the -2ln(L) distribution does not reach the threshold value from data, different analytical extrapolations are used.



$Z_c(4200)$ spin-parity	ΔL	ΔL with syst.	n.d.f.	Sign. toy MC / Toy MC extrap.
2^+	39.4	25.0	4	> 3.7 / 6.60

Significance of the two Z_{cs} states

Model	ΔL	ΔL with syst.	n.d.f.	Significance Toy MC
$Z_c(4200)\ 2^+$, $Z_c(3900)$, $Z_c(4430)$ $Z_{cs}(4000)$, $Z_{cs}(4220)$ vs. $Z_c(4200)\ 1^+$, $Z_c(3900)$, $Z_c(4430)$	65.6	54.1	14	> 3.6

See Appendix7 for -2ln(L) distribution

from fit: **6.8σ**

Summary

- Amplitude analysis of $B^0 \to J/\psi K\pi$ and $B_s \to J/\psi KK$ was performed;
- Results of the analysis show clear evidence of contributions from the exotic states with significance well over 10σ;
- Evidence of $Z_{cs}(4000)$ and $Z_{cs}(4000)$ contribution to both $B^0 \to J/\psi K\pi$ and $B_s \to J/\psi KK$ decays can be claimed at the significance level at least 3.6σ;
- It was shown that five exotic charmonium states $Z_c(3900)$, $Z_c(4300)$, $Z_c(4200)$ and $Z_{cs}(4000)$, $Z_{cs}(4220)$ are needed in the B-meson decay models for full-fledged data description;
- The best models include $Z_c(4200)$ state with spin/parity 2^-, 2^+ and 3^+. Model 2^+ is chosen as the “central” one since it has the highest significance w.r.t. model without $Z_c(4200)$ contribution. 0^- and 1^- spin-parity options are excluded by ATLAS data with exclusion levels over 3σ. $J^P = 1^+$ is also disfavoured by data, however, it’s separated from best model by 2.44σ only. Spin-parity option 3^- cannot be excluded. Some of systematic effects bring quality of this hypothesis close to the quality of the best hypothesis.
- In the absence of Z_{cs} states, the best spin-parity option for $Z_c(4200)$ is 1^+;
- Contribution for $Z_c(4200)$ corresponds to significance 6.6σ derived from the extrapolation of the likelihood ratio distribution;

Thank you for your attention!

Appendix1 Helicity formalism

The problem with using **Spin-orbit** formalism in constructing the decay amplitude is that spin and orbital angular momentum operators of particles are defined in reference frames that are not at rest with respect to one another.

Helicity operator is <u>invariant</u> under both rotations and boosts along momentum direction.

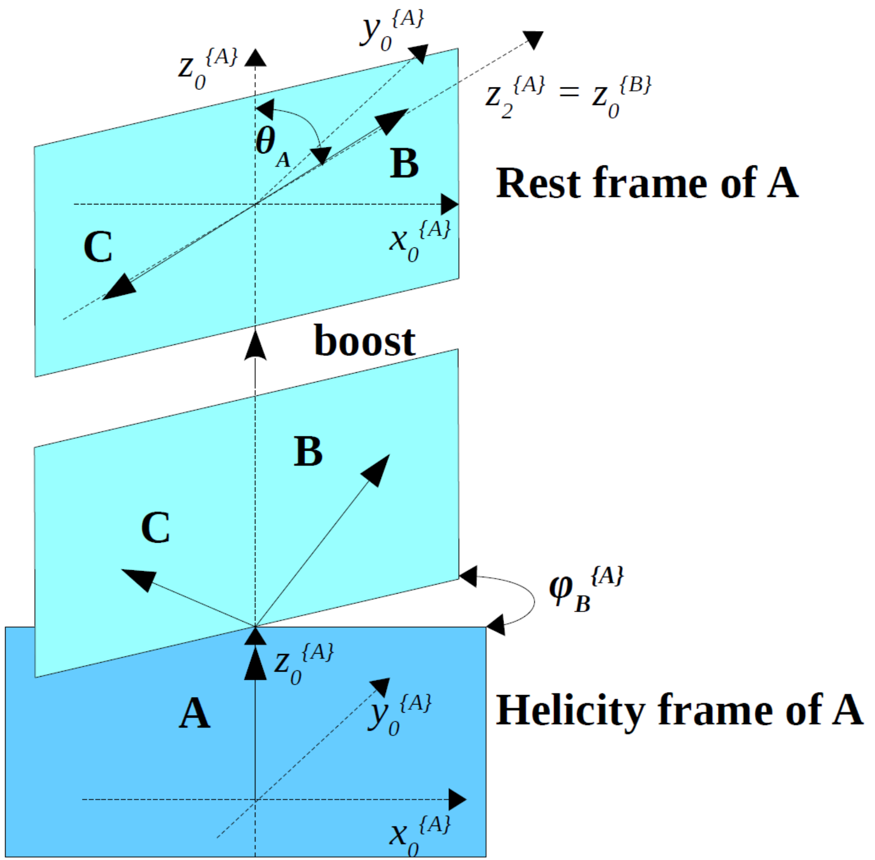
$$Amp_{A\to BC}=H^{A\to BC}_{\lambda_B,\lambda_C}D^{J_A}_{\lambda_A,\lambda_B-\lambda_C}(\phi_B^{\{A\}},\theta_A,0)^*$$

$$D^{J_A}_{\lambda_A,\lambda_B-\lambda_C}(\phi_B^{\{A\}},\theta_A,0)^*=e^{i\lambda_A\phi_B^{\{A\}}}d^{J_A}_{\lambda_A,\lambda_B-\lambda_C}(\theta_A)$$

The behavior of off-shell resonances must be described by the Breit-Wigner term. To describe decays under threshold, Flatté parametrization could be used.

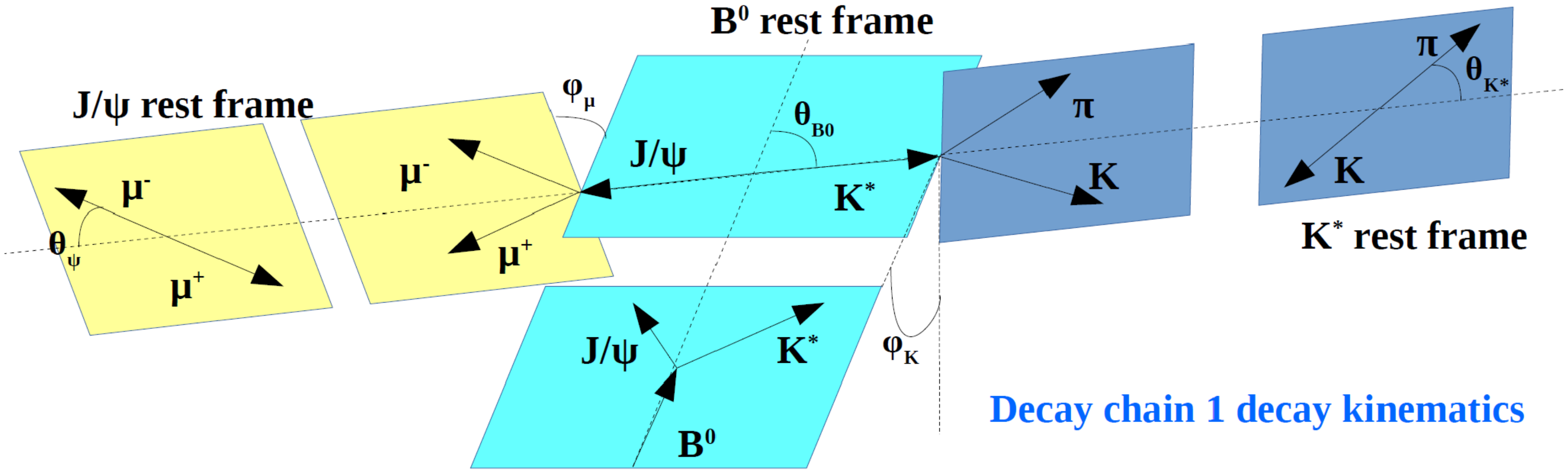
$$BW_R(M_R,m_R,\Gamma_R)=\frac{1}{M_R^2-m_R^2-i\,M_R\,\Gamma(m_R)}$$

$$\Gamma(m_R)=\Gamma_R\left(\frac{p_R}{p_{R0}}\right)^{2L_R+1}\left(\frac{M_R}{m_R}\right)F^2_{L_R}$$



$$\mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C}=\sum_L\sum_S(-1)^{J_B-J_C+L-S+2\lambda_B-2\lambda_C}\sqrt{(2L+1)(2S+1)}B_{LS}\times \begin{pmatrix} J_B & J_C & S\\ \lambda_B & -\lambda_C & \lambda_C-\lambda_B\end{pmatrix}\begin{pmatrix} L & S & J_A\\ 0 & \lambda_B-\lambda_C & \lambda_C-\lambda_B\end{pmatrix}$$

Appendix1 Helicity formalism



Decay chain 1 decay kinematics

For EM or strong decays:

$$\mathcal{H}^{A\to BC}_{-\lambda_B,-\lambda_C} = P_A P_B P_C (-1)^{J_B+J_C-J_A}\mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C};$$

K* decay chain:

$B^0 \rightarrow J/\psi K^*$ (weak decay): $$Amp_{B^0\to J/\psi K^*} = H^{B^0\to J/\psi K^*}_{\lambda_\psi,\lambda_{K^*}} d^0_{0,\lambda_{K^*}-\lambda_\psi}(\theta_{B^0})$$

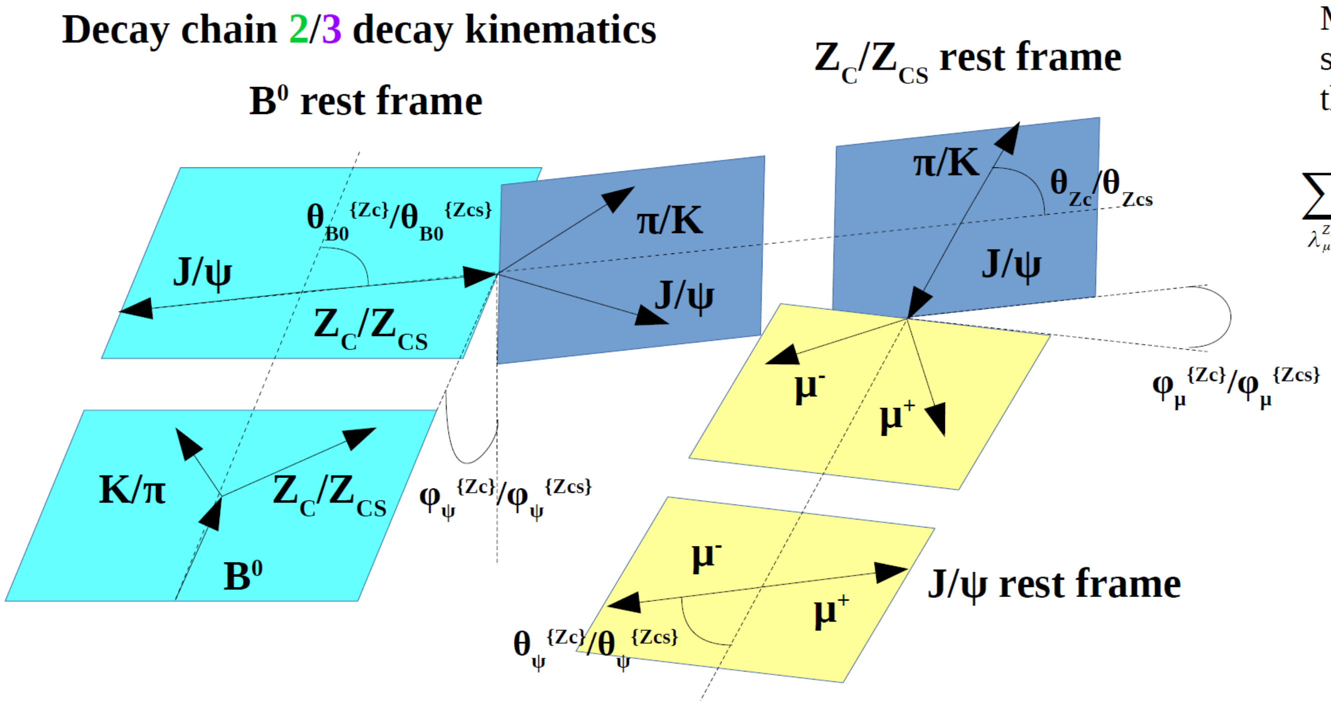
$K^* \rightarrow K\pi$ (strong decay): $$Amp_{K^*\to K\pi} = H^{K^*\to K\pi}_{0,0} e^{i\phi_K\lambda_{K^*}} d^{J_{K^*}}_{\lambda_{K^*},0}(\theta_{K^*}) * R(m(K\pi), L_{B^0}, L_{K^*})$$

$J/\psi \rightarrow \mu\mu$ (electromagnetic decay): $$Amp_{J/\psi\to\mu\mu} = e^{i\phi_{mu}\lambda_\psi} d^0_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi)$$

$$R(m(K\pi), L_{B^0}, L_{K^*}) = \left(\frac{p_{B^0}}{m_{B^0}}\right)^{L_{B^0}} F_{L_{B^0}} BW_{K^*}(M_{K^*}, m(K,\pi), \Gamma_{K^*}) \left(\frac{p_{K^*}}{m(K\pi)}\right)^{L_{K^*}} F_{L_{K^*}}$$

$$Amp_{K^*chain}(m(K,\pi), angles1)_{\Delta\lambda_\mu} = \sum_{\lambda\psi,\lambda K^*}\sum_{K^*states} Amp_{B^0\to J/\psi K^*} Amp_{K^*\to K\pi} Amp_{J/\psi\to\mu\mu}$$

Appendix1 Helicity formalism



Muons are final-state particles, their helicity states in 2, 3 decay chains need to be rotated to the muon helicity states in K* decay chain.

$$\sum_{\lambda_\mu^{Z_c}} D^{J_\mu}_{\lambda_\mu^{Z_c}\lambda_\mu}(\alpha_\mu,0,0)^* = \sum_{\lambda_\mu^{Z_c}} e^{i\lambda_\mu^{Z_c}\alpha_\mu}\delta_{\lambda_\mu^{Z_c}\lambda_\mu} = e^{i\lambda_\mu^{Z_c}\alpha_\mu}$$

$$\alpha_\mu^{Z_C} = atan2((\hat{p}_\mu^{\{\psi\}}\times\hat{x}_1)\hat{x}_2, \hat{x}_1\hat{x}_2),$$

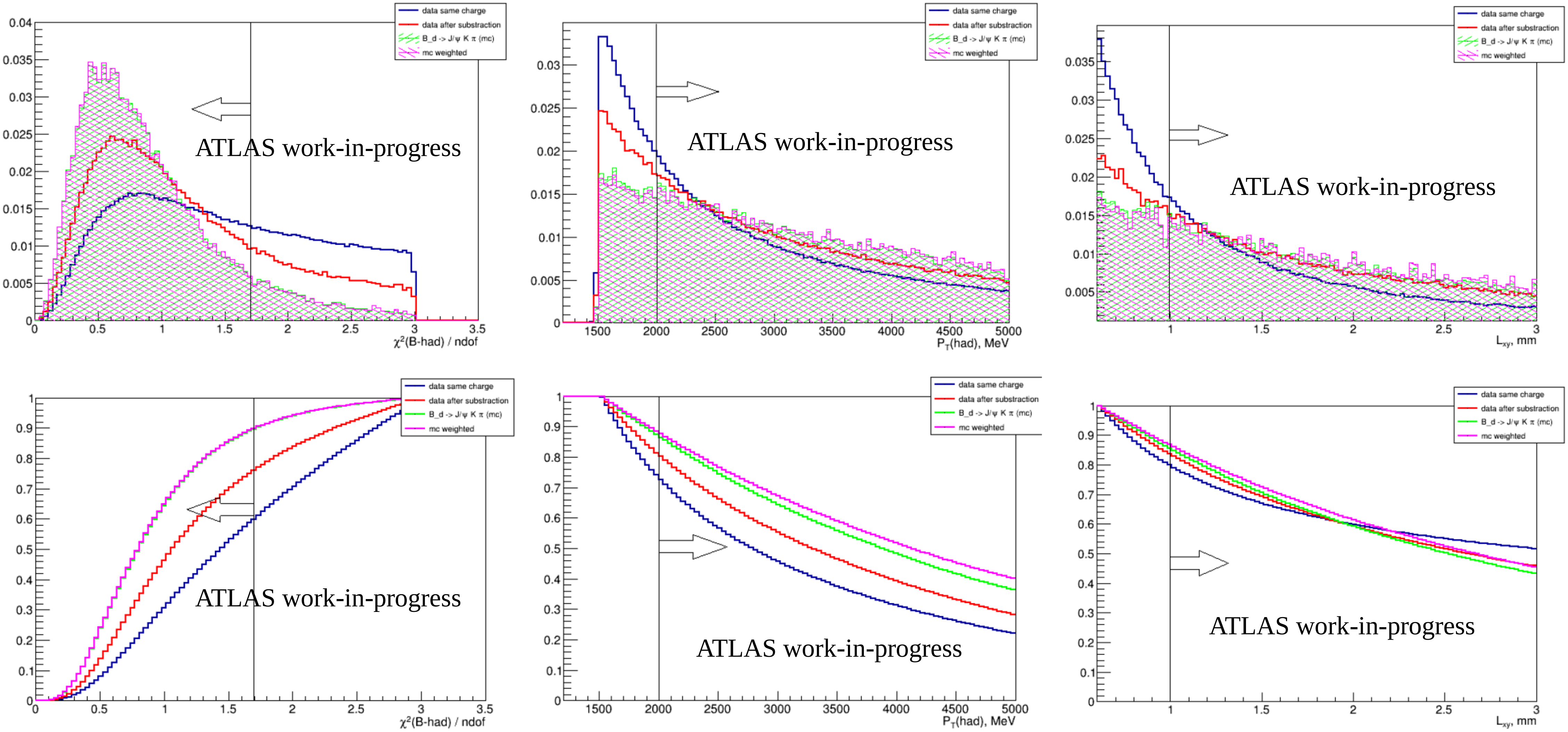
$$\vec{x}_2 = \hat{p}_{K^*}^{\{\psi\}} - (\hat{p}_{K^*}^{\{\psi\}}\hat{p}_\mu^{\{\psi\}})\hat{p}_\mu^{\{\psi\}},$$

$$\vec{x}_1 = \hat{p}_{\pi}^{\{\psi\}} - (\hat{p}_{\pi}^{\{\psi\}}\hat{p}_\mu^{\{\psi\}})\hat{p}_\mu^{\{\psi\}},$$

B^0 decay matrix element:

$$|M^{B^0}|^2 = \sum_{\Delta\lambda_\mu} |Amp_{K^*chain}(m(K,\pi), angles1)_{\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu\alpha_\mu^{Z_c}} Amp_{Z_c chain}(m(J/\psi,\pi), angles2)_{\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu\alpha_\mu^{Z_{cs}}} Amp_{Z_{CS} chain}(m(J/\psi,K), angles3)_{\Delta\lambda_\mu}|^2$$

Appendix2 Selection optimization



Appendix3 Fit Procedure

The fit procedure is accomplished in 3 iterative steps:

- **Step 1 (Global fit):**
  - m(J/ψ, h_1, h_2), where $h_1, h_2 = \{p,K,\pi\}$
  - m(J/ψ, K), m(J/ψ, K), m(pK) in $\Lambda_b \rightarrow J/\psi pK$ SR

N(decays), N(comb bg)
Shape of 4 track comb bg distributions
B_{LS} constants for $\Lambda_b \rightarrow J/\psi pK$ decays

- **Step 2**

  average -2ln(L) for distributions:
  - 2D (m(J/ψ, K^+, π^-), m(J/ψ, π^+, K^-))
  - 1D m(J/ψ, K^+, K^-)

N($B^0 \rightarrow J/\psi K\pi$) error
N($B_S \rightarrow J/\psi KK$) error

- **Step 3 (Signal Region fit):**
  - m(J/ψ, π), m(J/ψ, K), m(K, π), $|\cos(\theta_{Zc})|$, $|\cos(\theta_{Zcs})|$ ($B^0 \rightarrow J/\psi K\pi$ SR)
  - m(J/ψ, K), m(K, K), $|\cos(\theta_{Zcs})|$ ($B_s \rightarrow J/\psi KK$ SR)

B_{LS} constants for $B_S \rightarrow J/\psi KK$ decays
B_{LS} constants for $B^0 \rightarrow J/\psi K\pi$ decays
m(Z_C(4200)), Γ(Z_C(4200))

Appendix4 ToyMC studies

Motivations

- Toy MC (pseudo-data) approach is used to generate pseudo-data based on background model to estimate probability of a signal to be the result of stat.+syst. fluctuation of background.
- Each toy (pseudo-dataset) distribution is fitted by two models and the ΔL is obtained. Number of toys with ΔL larger than that for real data over the total number of toys gives p-value of an observed signal.
- Pseudo-data approach naturally accounts for the correlations between syst. variations!
- In a similar manner pseudo-data allow comparison of different signal models.

- **Generation of toy MC requires P.D.F. of a background model.**

1. Background model is represented by analytic form (e.g., arXiv:1507.03414).
    - In this case we are not limited by number of dimensions
    - Analytic representation of background model is not always possible
    - Detector effects are neglected since (usually) model is estimated on generator level, while fit is performed on reco level.
2. Background model is represented by histogram (set of histograms).
    - Limited to 2D-3D. Several histograms of correlated variables **cannot be used** to represent ND P.D.F.
    - Detector effects are neglected.
3. Model is represented by a set of MC events… common case for complex models…
    - Generation of parametric P.D.F. is possible (e.g., by RooFit) for 3-4 dimensions but takes a lot of CPU. Detector effects are neglected again.

Appendix4 ToyMC studies

Motivations

Model is represented by a set of MC events… can we generate toys without P.D.F. ?

- Each MC event enters model with a certain weight $\boldsymbol{W_i}$. Ratio of this weight to the total event yield represents probability $\boldsymbol{P_i}$ of this event to be observed in real data.
- In our case the weight is a product of an analytic matrix element and a normalization factor.
- To generate toy MC we play random generator on each MC event and include it in pseudo-data with probability $\boldsymbol{P_i}$

- Number of dimensions is not limited.
- Detector effects are naturally accounted for, since for each event we have both generator and reco level information. Generator level information is used to calculate $\boldsymbol{P_i}$, reco-level information is used to perform fits
- No need for a lot of CPU
- Systematic effects are accounted for as variations of $\boldsymbol{W_i}$
- Large enough statistics of background MC is required…

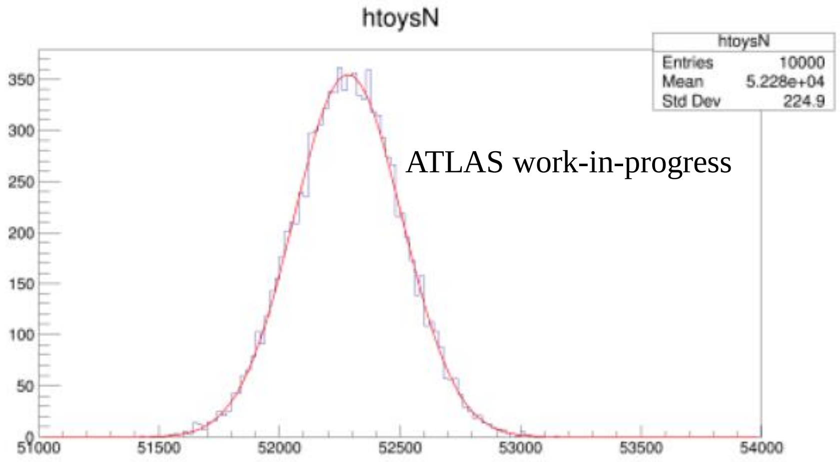
Appendix4 ToyMC studies

Tests and results

Example of generating a 52K pseudo-data events from 300K weighted MC sample.

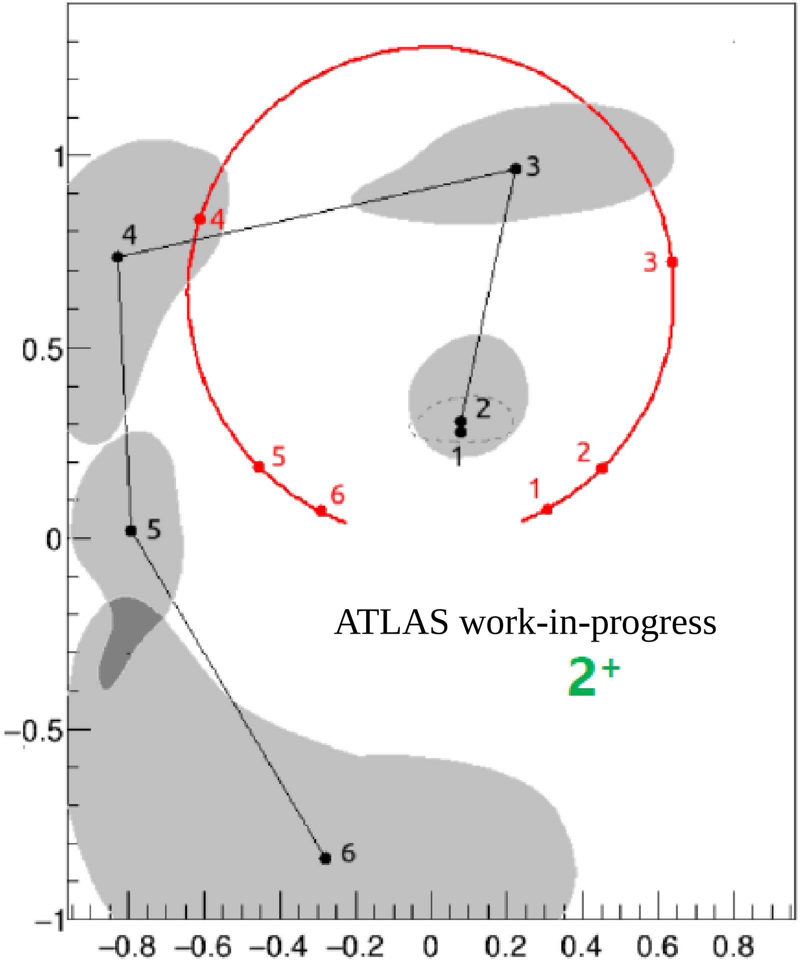
- Average MC weight is 0.16, but some weights are up to ~10.
- We set normalization of total sum of weigths is 52281.5
- After generation – average number of events in set is found to be 52283.3
- Distribution of number of generated events is well described by gaussian with sigma^2 = 50580.0
- It's actually a non-trivial test, since probability of generation is assessed on the event level…
- The following code is used to make decision for each event

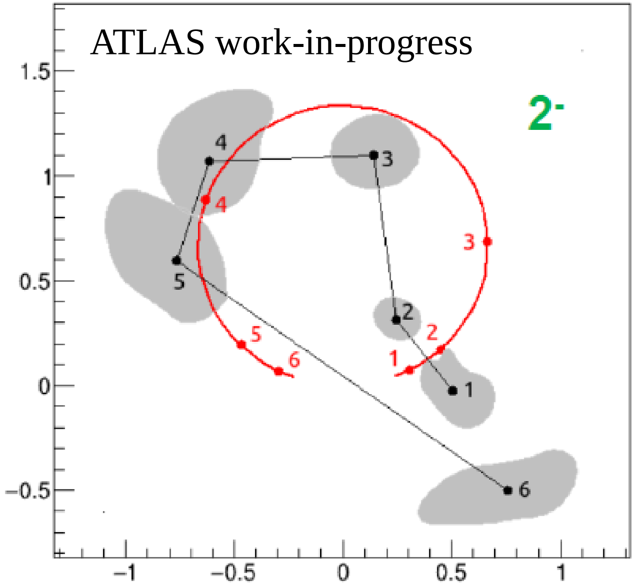
```
std::random_device rd;
std::mt19937 genfnum(rd());
std::uniform_real_distribution<float> rnd01(0.0, 1.0);
float r = rnd01(genfnum);
if( r < weight[i]) <this event is included into pseudo-data set>;
```



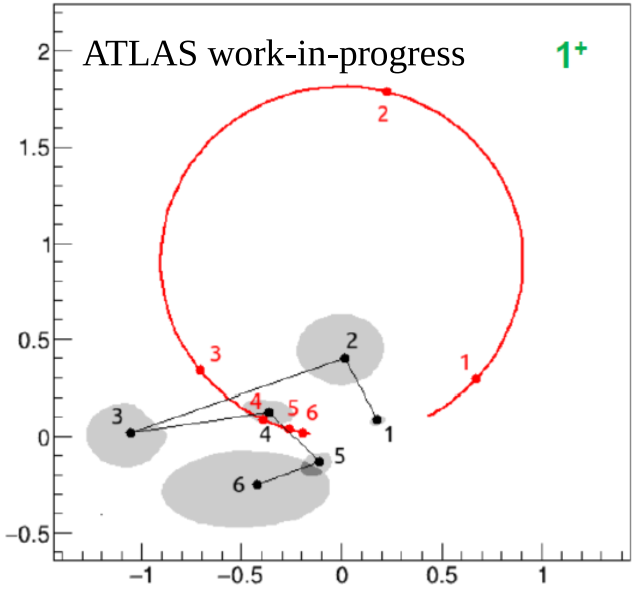
Plot shows distribution of number of generated events in 10K pseudo-data sets.

Appendix5 Argand diagrams





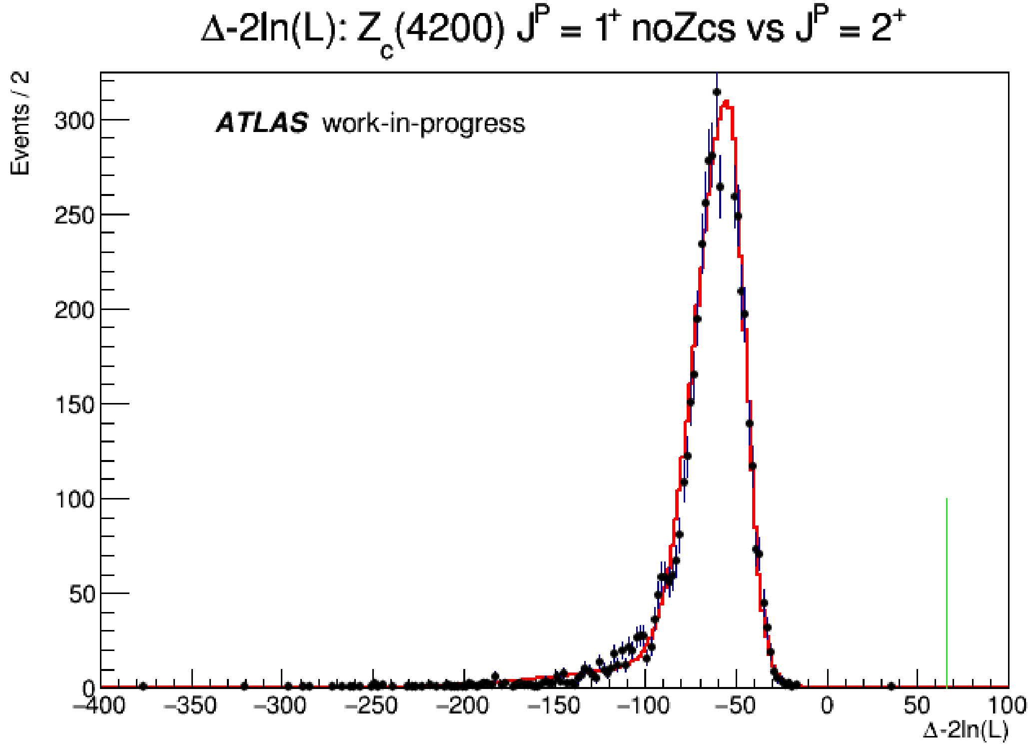
$Z_c(4200)$ $J^P=1^+$ model shows poor agreement with Breit-Wigner amplitude behavior



Appendix6 Sources of systematic uncertainties

- $\{\delta_0\}$ The uncertainty in the modeling of the $B^0 \to J/\psi K\pi$ decays:
  - uncertainties of the masses and widths of the leading K^* resonances;
  - variation of the matrix element of the non-resonant $K\pi$ component;
- $\{\delta_1\}$ The uncertainty of the $B^0 \to J/\psi K\pi$ yield in the global region w.r.t. it's impact on the signal regions. Uncertainty is obtained from step 2 of the fit procedure;
- $\{\delta_2\}$ The uncertainty of the $B_s \to J/\psi KK$ yield in the global region w.r.t. it's impact on the signal regions. Uncertainty is obtained from step 2 of the fit procedure;
- $\{\delta_3\}$ The uncertainty in the modeling of $\Lambda_b^0 \to J/\psi pK^-$ decays:
  - adding the fourth ($P_c(4380)$) pentaquark state to the default model with three narrow pentaquarks;
  - adding $Z_{cs}(4000)$ and $Z_{cs}(4220)$ contributions to the default model with three narrow pentaquarks;
- $\{\delta_4\}$ The uncertainty in the modeling of the $B_s \to J/\psi KK$ decays:
  - uncertainties of the masses and widths of the leading f or ϕ resonances;
  - variation of the matrix element of the non-resonant KK component;
- $\{\delta_5\}$ The uncertainties in B-hadron production modeling and detector reconstruction:
  - B-hadron p_T reweighting uncertainties;
  - muon selection scale factors;
- $\{\delta_6\}$ The uncertainties in the combinatorial background data-driven approach in the B^0 signal region;
- $\{\delta_7\}$ The uncertainties in the combinatorial background data-driven approach in the B_s signal region;
- $\{\delta_8\}$ The extension and reduction of the size of the B^0 signal region;
- $\{\delta_9\}$ Smearing of the hadron tracks p_T;
- $\{\delta_{10}\}$ Uncertainties in the $Z_{cs}(4000)$ and $Z_{cs}(4220)$ states modeling:
  - alternative 1^- spin/parity for the $Z_{cs}(4220)$ state;
  - $Z_{cs}(4000)$ and $Z_{cs}(4220)$ masses and widths variations;
- $\{\delta_{11}\}$ Variations of the analytic form for the shape of combinatorial background in the global region;
- $\{\delta_{12}\}$ Variations of the scale-factor d entering the Blatt-Weisskopf factors;

Appendix7 ToyMC (significance of Z_{cs} contribution)



Model	ΔL	ΔL with syst.	n.d.f.	Significance Toy MC
$Z_c(4200)\ 2^+$, $Z_c(3900)$, $Z_c(4430)$ $Z_{cs}(4000)$, $Z_{cs}(4220)$ vs. $Z_c(4200)\ 1^+$, $Z_c(3900)$, $Z_c(4430)$	65.6	54.1	14	>3.35

from fit: **6.8σ**