Determination of branching fraction of $B^{\pm} \to \chi_{c1}\pi^{+}\pi^{-}K^{\pm}$ and search for exotic resonances in $\chi_{c}\pi$ state

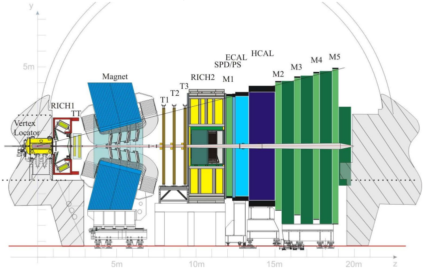
D. Melnychuk, BP3

16.12.2022

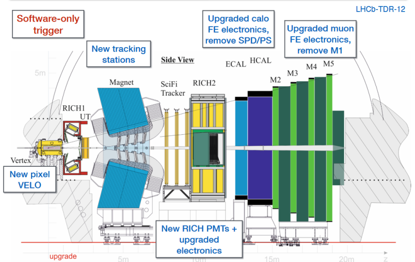
LHCb experiment

- LHCb is a single arm spectrometer designed for CP violation measurements and search for rare decays.
- Detector performed as a very powerful tool for hadron spectroscopy.
- Collected data: Run 1 (2011-2012) 3.2 fb^{-1} at 3.5-4 TeV, Run 2 (2015-2018) 5.7 fb^{-1} at 6.5 TeV, expected Run 3 (2023-2025) 23 fb^{-1}

Run1+2



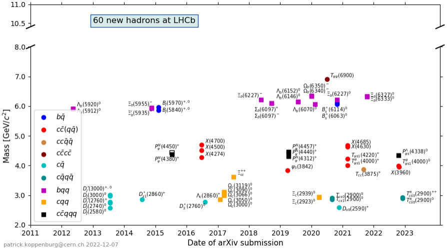
Run3

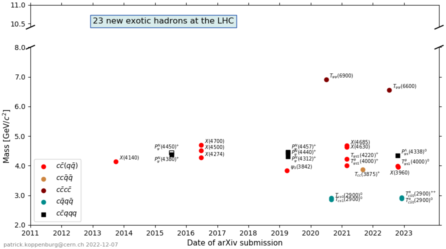


NCBJ LHCb team and research topics

- Prof. dr hab. W. Wiślicki (DUZ) - Head of the group
- Search for CP symmetry violation in decays of charmed baryons
  (dr hab A. Ukleja (DBP, BP3))
- CPT symmetry tests in charm decays
  (dr W. Krzemień (DBP, BP3), dr A. Szabelski (DBP, BP3), mgr M. Kmieć (PhD student, DBP))
- CPT symmetry tests in semileptonic B-decays
  (dr K. Klimaszewski (DUZ), dr A. Szabelski (DBP, BP3))
- Search for physics beyond the Standard Model in decays of B and D mesons into two hadrons
  (dr A. Szabelski (DBP, BP3))
- Search for exotic hadrons
  (dr D. Melnychuk (DBP, BP3), mgr Salil Joshi (PhD student, DBP))
- ML solutions for cluster reconstruction in planar calorimeters with CNNs
  (mgr M. Mazurek (PhD student, DBP), dr W. Krzemień (DBP, BP3))
- Development of Gauss and Gaussino: the LHCb simulation software
  (mgr M. Mazurek (PhD student, DBP))
- Support of T2-level Grid site (from next year T1-level site)
  mgr inż. H. Giemza (DUZ)

New particles discovered at the LHC



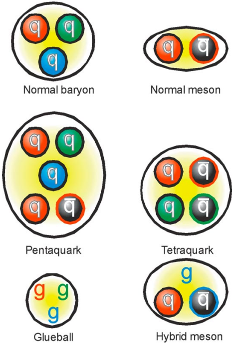


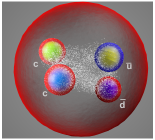
LHCb collaboration, List of hadrons observed at the LHC, LHCb-FIGURE-2021- 001, 2021, Up-to-date list maintained at https://www.nikhef.nl/ pkoppenb/ particles.html

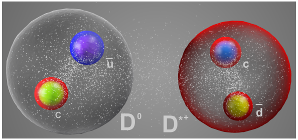
Exotic hadrons

- Exotic are particles with properties different from the rest of the spectrum (not described by naive quark model).
- Tightly-bound tetraquark/pentaquark - each quark sees the color charges of all other quarks, hadronic molecule - two color singlets interacting by light meson exchange.
- The "molecular" states are expected to have masses that are near constituent particles mass threshold
- Exotic hadrons were labelled X, Y, Z, P according to some not-always-followed rules:

  X - neutral resonance appearing in B decays, Y - states produced in ISR processes, Z - charged charmonium like states (and their isospin partner), P - pentaquark







New naming convention

- Symbols are assigned based on measured quantum numbers, rather than speculation about the degrees of freedom within the hadron.
- States with minimum four-quark content are labelled T; states with minimum five-quark content are labelled P.
- Subscripts Υ, Ψ and ϕ are added to denote hidden beauty, charm and strangeness.

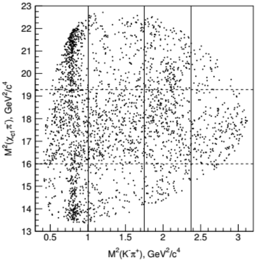
Table 5: Summary of the impact of the exotic hadron naming scheme on various states, based on current knowledge of their properties. Quantum numbers that are not specified or marked "?" are unknown and the corresponding super-/sub-scripts not given. The current name indicated is that used in the PDG listings [16].

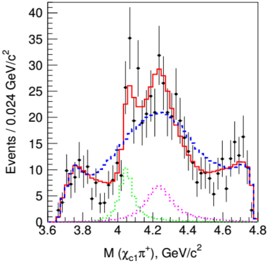
Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G=1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I=\frac{1}{2}$, $J^P=1^+$	$T^\theta_{\psi s1}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I=\frac{1}{2}$, $J^P=1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G=0^+$, $J^{PC}=?^{?+}$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P=0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P=1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\Upsilon 1}(10610)^+$	[36]
$c\bar{c}uud$	$P_c(4312)^+$	$I=\frac{1}{2}$	$P^N_\psi(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I=0$	$P^\Lambda_{\psi s}(4459)^0$	[20]

Motivation

- Belle experiment declared observation of $B^{\pm} \to \chi_{c1}\pi^{+}\pi^{-}K^{\pm}$ decay and later measured measured (Phys.Rev D 93, 052016) its BF $(3.74 \pm 0.18 \pm 0.24) \cdot 10^{-4}$. Performed analysis gives an independent measurement of that branching fraction
- The search for resonant structures in $\chi_c\pi$ has been performed motivated by Belle observation of $Z^{+}(4050)$ and $Z^{+}(4250)$ states (Phys. Rev. D 78, 072004)

Search for Z(4050)+ and Z(4250)+ at Belle





(Phys. Rev. D 78, 072004)

- A signal yield of $2126 \pm 56(stat) \pm 42(syst)$ $B^0 \to K^+\pi^-\chi_{c1}$ events
- Two-Z hypothesis is favoured over the single-Z hypothesis by 8σ
- Fit results:
  $M_{Z(4050)^+} = 4051 \pm 14^{+20}_{-41}\ MeV/c^2$
  $\Gamma_{Z(4050)^+} = 82^{+21+47}_{-17-22}\ MeV/c^2$
  $M_{Z(4250)^+} = 4248^{+44+180}_{-29-35}\ MeV/c^2$
  $\Gamma_{Z(4250)^+} = 177^{+54+316}_{-39-61}\ MeV/c^2$

Goals of study. Selection of reference channel

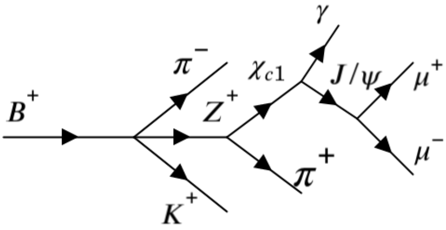
Goals of study:

- Measurement of BF for decay

  $B^{\pm} \to \chi_{c1}\pi^{+}\pi^{-}K^{\pm}$,
  $\chi_{c1} \to J/\psi\gamma$, $J/\psi \to \mu\mu$

  with respect to reference channel:

  $\mathrm{B}^{\pm} \to \chi_{c1}\mathrm{K}^{\pm}$

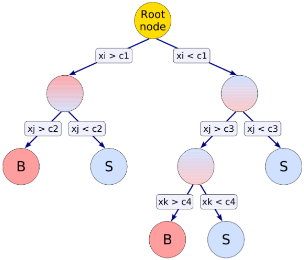


- Measurement of the ratio: $\frac{\mathcal{B}(\mathrm{B}^{\pm}\to\chi_{c2}\pi^{+}\pi^{-}\mathrm{K}^{\pm})}{\mathcal{B}(\mathrm{B}^{\pm}\to\chi_{c1}\pi^{+}\pi^{-}\mathrm{K}^{\pm})}$
- Search of possible resonant structure in $m(\chi_{c1}\pi^{+})$, $m(\chi_{c1}\pi^{-})$, $m(\chi_{c1}K^{+})$ mass distribution
- Full Run1 and Run2 dataset analyzed

Analysis strategy

- $B^{\pm} \to \chi_{c1}\pi^{+}\pi^{-}K^{\pm}$
  - Selection of J/ψ, combining with photons with wide mass window around χ_{c1} mass, adding pion pair and kaon with loose selection criteria, perform kinematic fit with DecayTreeFitter
  - Test of variety of different BoostedDecisionTree (BDT) selections with different list of variables and different background sources (same-sign pions, mass side bands)
- $B^{\pm} \to \chi_{c1}K^{\pm}$
  - Combination of particles and loose selection the same as in main channel
  - BDT selection with mass side bands as background
- Fit of invariant mass distribution to extract number of reconstructed B-mesons and sWeights to weight m($\chi_{c1}\pi^{+}$), m($\chi_{c1}K^{+}$) distributions

Boosted Decision Tree (BDT) selection



BDT algorithm:

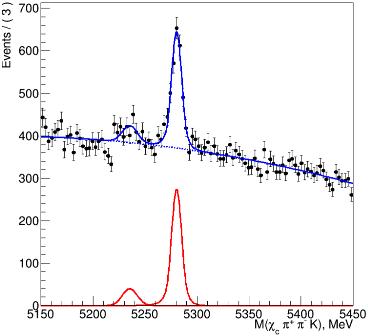
- DT: sequential application of cuts splits the data into nodes where the final nodes classify an event as signal or background
- BDT: combine forest of DTs with differently weighted events in each tree

BDT selection is implemented using kinematic and topological variables to suppress combinatorial background.
BDT variables:

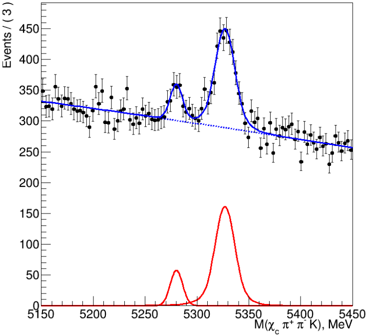
- Kinematic variables: transverse momentum of B, photon, Kaon and pions ($p_{\mathrm{T}}(\mathrm{B}^+)$, $p_{\mathrm{T}}(\gamma)$, $p_{\mathrm{T}}(\pi^\pm)$, $p_{\mathrm{T}}(\mathrm{K}^+)$)
- Topological variables: χ^2 of impact parameters of B, pions and kaon and χ^2 of DecayTreeFit for B-meson
- Photon-related variables: variables described cluster shapes in calorimeter

$B^{\pm} \to \chi_{c1}\pi^+\pi^-K^{\pm}$ mass fit

Fit with χ_{c1} mass constraint



Fit with χ_{c2} mass constraint



- Fit model: double-sided Crystall Ball function for main peak, gauss for χ_{c2} peak and combinatorial background is parametrized by second order Chebychev polynomial function.

Measurement of the branching fraction

$$\frac{\mathcal{B}(\mathrm{B}^{\pm} \to \chi_{c1}\pi^{+}\pi^{-}\mathrm{K}^{\pm})}{\mathcal{B}(\mathrm{B}^{\pm} \to \chi_{c1}\mathrm{K}^{\pm})} = \frac{N_{\mathrm{B}^{\pm}\to\chi_{c1}\pi^{+}\pi^{-}\mathrm{K}^{\pm}}}{N_{\mathrm{B}^{\pm}\to\chi_{c1}\mathrm{K}^{\pm}}} \times \frac{\varepsilon_{\mathrm{B}^{\pm}\to\chi_{c1}\mathrm{K}^{\pm}}}{\varepsilon_{\mathrm{B}^{\pm}\to\chi_{c1}\pi^{+}\pi^{-}\mathrm{K}^{\pm}}}$$

ε is the product of the geometrical acceptance, the detection, reconstruction, selection and trigger efficiencies.

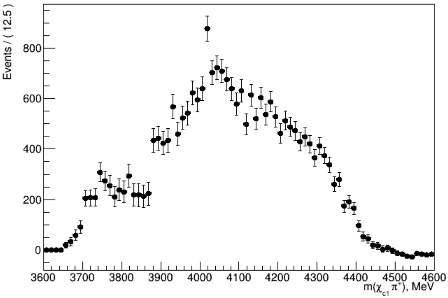
$$\frac{\mathcal{B}(\mathrm{B}^{\pm} \to \chi_{c2}\pi^{+}\pi^{-}\mathrm{K}^{\pm})}{\mathcal{B}(\mathrm{B}^{\pm} \to \chi_{c1}\pi^{+}\pi^{-}\mathrm{K}^{\pm})} = \frac{N_{\mathrm{B}^{\pm}\to\chi_{c2}\pi^{+}\pi^{-}\mathrm{K}^{\pm}}}{N_{\mathrm{B}^{\pm}\to\chi_{c1}\pi^{+}\pi^{-}\mathrm{K}^{\pm}}} \times \frac{\varepsilon_{\mathrm{B}^{\pm}\to\chi_{c1}\pi^{+}\pi^{-}\mathrm{K}^{\pm}}}{\varepsilon_{\mathrm{B}^{\pm}\to\chi_{c2}\pi^{+}\pi^{-}\mathrm{K}^{\pm}}} \times \frac{\mathcal{B}(\chi_{c1} \to \mathrm{J}/\psi\gamma)}{\mathcal{B}(\chi_{c2} \to \mathrm{J}/\psi\gamma)}$$

$$\frac{\mathcal{B}(\mathrm{B}^{\pm}\to\chi_{c1}\pi^{+}\pi^{-}\mathrm{K}^{\pm})}{\mathcal{B}(\mathrm{B}^{\pm}\to\chi_{c1}\mathrm{K}^{\pm})} = 0.660 \pm 0.015 \pm 0.046$$

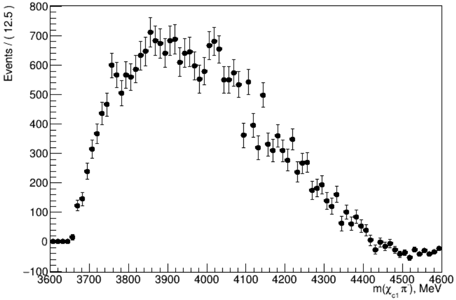
$$\frac{\mathcal{B}(\mathrm{B}^{\pm}\to\chi_{c2}\pi^{+}\pi^{-}\mathrm{K}^{\pm})}{\mathcal{B}(\mathrm{B}^{\pm}\to\chi_{c1}\pi^{+}\pi^{-}\mathrm{K}^{\pm})} = 0.40 \pm 0.04 \pm 0.01$$

$m(\chi_{c1}\pi^+)$, $m(\chi_{c1}\pi^-)$

$m(\chi_{c1}\pi^+)$



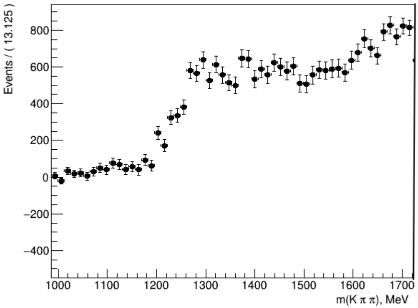
$m(\chi_{c1}\pi^-)$



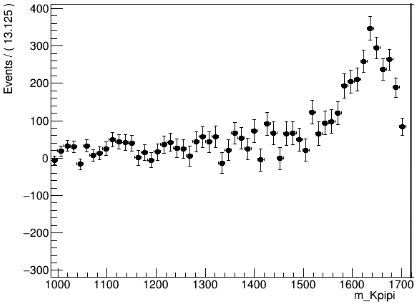
- Intresting structure around 4050 MeV for both distribution
- Left plot means pions of the same sign and right of the opposite sign as B-meson with charge conjugation implied.
- Difference in both plots can be attributed to reflections from $K_1(1270)$ decay where π^+ and π^- contribute asymmetrically wrt. to kaon charge.

$m(K\pi\pi)$

$B^{\pm} \rightarrow \chi_{c1}\pi^+\pi^-K^{\pm}$



$B^{\pm} \rightarrow \chi_{c2}\pi^+\pi^-K^{\pm}$



- Decay via χ_{c1} has significant contribution from $K_1(1270)$, which has $K\rho(\rightarrow \pi^+\pi^-)$, $K_0^*(1430)(\rightarrow K\pi)\pi$ and $K^*(892)(\rightarrow K\pi)\pi$ main decay modes.
- Decay via χ_{c2} is dominated by higher K^* resonances such as $K^*(1680)$ decaying to $K\rho$ and $K^*(892)(\rightarrow K\pi)\pi$

Outlook

- Determination of the nature of observed structure requires an amplitude analysis to be performed
- In contrast to Phenomenological modeling Amplitude analysis use only core features of quantum field theory: unitarity, analyticity of scattering amplitudes, crossing symmetry. Amplitudes are modeled by using only functions obeying these constraints.
- Several formalisms could be applied to describe 4-body decay, most common is Covariant Spin Tensor Formalism.
- AmpGen (a library and set of applications for fitting and generating multi-body particle decays using the isobar model) is considered as a tool to proceed with amplitude analysis of presented decay.