Search for CP, CPT symmetry violation and exotic hadrons at LHCb experiment

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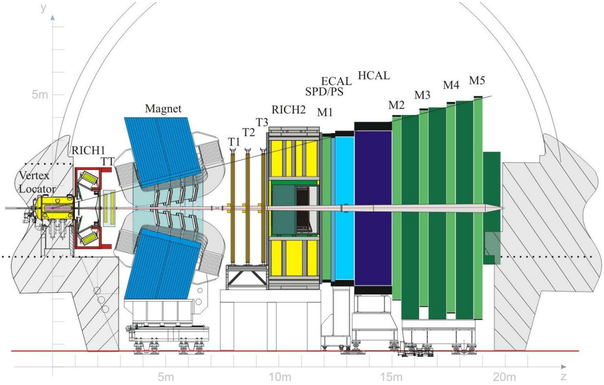
LHCb experiment

- LHCb is a single arm spectrometer which uses a correlated production of $b\bar{b}$ i $c\bar{c}$ pairs.
- Detector has been designed for CP violation measurements and search for rare decays.
- Detector allows for search of exotic hadrons.



NCBJ LHCb team

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2. dr K. Klimaszewski (DUZ)
3. dr W. Krzemień (DBP, zakład BP3)
4. dr D. Melnychuk (DBP, zakład BP3)
5. dr A. Szabelski (DBP, zakład BP3)
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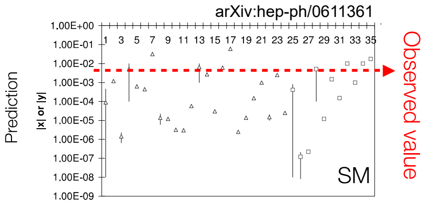
7. mgr V. Batozskaya (doktorantka)
8. mgr inż. H. Giemza (DUZ)

Research topics

- Physics analyses
  - Search for CP symmetry violation in decays of charmed baryons.
  - Determination of CP violating phase in $B_s \to J/\Psi\phi$ decays.
  - CPT symmetry tests in charm decays.
  - Search for exotic hadrons
- Technical and service tasks
  - Development of DIRAC, a general-purpose Interware software for distributed computing systems.
  - Technical service and development T2-level Grid node for data production

- In charm sector CPV is expected in the SM but so far it is not discovered here
- Expected value of CPV is small $\lesssim 10^{-3}$ but predictions very widely (much smaller than in the beauty sector)

New Physics contributions can enhance CPV up to 10^{-2}
Int.J.Mod.Phys.A21(2006)5381 ; Ann.Rev.Nucl.Part.Sci.58(2008)249



- The crucial point is to confirm or not CPV in charm sector
- Perfect place for New Physics searching (small background from the SM)

CP violation in charmed baryons. Strategy of analysis.

- If we do not see CPV in two body decays, nature next step is go to three body decays
- Three body decays are realized via resonant states which give necessary condition to observe CPV – large strong phases difference at transitions through the maximum mass of the resonant state

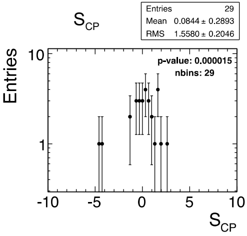
$$Asym_{CP} \sim |A_1||A_2| \underbrace{sin(\phi_1 - \phi_2)}_{\text{weak phases}} \underbrace{sin(\delta_1 - \delta_2)}_{\text{strong phases}}$$

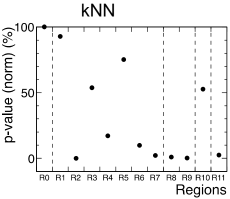
- It motivates to use the Dalitz plot analysis (resonant states are visible) and look for localized asymmetries
- No clear indication where CPV would appear in the Dalitz plot
- Preferable to perform searches based on techniques that are independent on amplitude modeling in the Dalitz plot:
  - ✧ binned S_{CP} method
  - ✧ unbinned kNN method

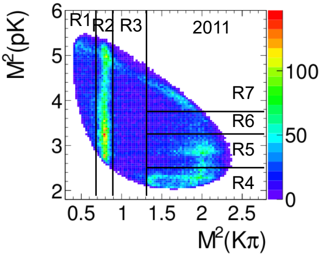
- Control channel and mass sidebands do not show localized asymmetries
  - ✧ no asymmetry observed in control $\Lambda^+_c \rightarrow p\, K^- \pi^+$ decays
  - ✧ no asymmetry observed in sidebands of $\Xi^+_c \rightarrow p\, K^- \pi^+$

- The toy MC data were used to check the sensitivity of both methods:
  - ✧ the S_{CP}: CP ≥ 5% in K* or ≥10% in Δ^{1232}
  - ✧ the kNN: CP ≥ 5% in K* or > 5% in Δ^{1232}

5% difference in K* amplitudes

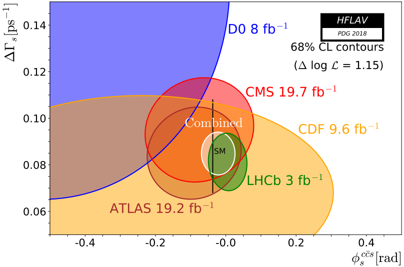






- There is no local asymmetries (not related to CPV) and production asymmetry is under control ⇒ the study can be unblind (EB permission is needed)

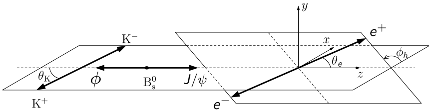
- In the Standard Model (SM) $\mathcal{CP}$ violation arises through a single phase ϕ_s in the CKM quark mixing matrix
- Phase in the SM is predicted to be small
  $\phi_s^{SM} = -37.6^{+0.7}_{-0.8}$ mrad [CKMFitter, PRD 84 (2011) 033005]
- Decay $B_s^0 \to J/\psi\phi$ allows the measurement of such a phase ϕ_s



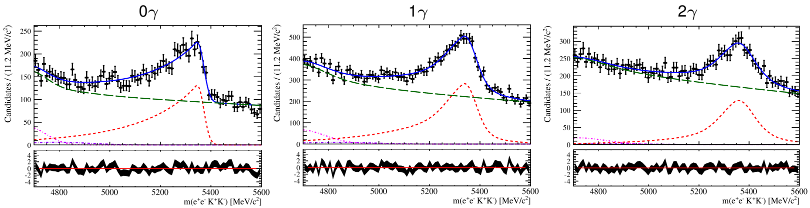
- LHCb result of ϕ_s performing a $\sim 96 \cdot 10^3$ (3 fb^{-1}) $B_s^0 \to J/\psi(\mu\mu)\phi(KK)$ decays is the most precise single measurements of quantity to date
- Combination with $B_s^0 \to J/\psi(\mu\mu)\pi^+\pi^-$ decay analysis gives
  $\phi_s = -10 \pm 39$ mrad [Phys.Rev.Lett. 114 (2015) 4, 041801]
- Measurement of ϕ_s also performed by LHCb using other B_s^0 decay modes: $D_s^+D_s^-$, $\psi(2S)(\mu\mu)\phi$, $J/\psi KK$ in high m(KK)

Measurement of *CP* violation in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$

- *Motivation*: measure phase ϕ_s using 3 fb^{-1} (2011-2012), similar channel to $B_s^0 \to J/\psi(\mu\mu)K^+K^-$
- Experimentally harder (Bremsstrahlung, reconstruction, trigger)
- N$_{sig}(B_s^0) \sim 12 \cdot 10^3$ that contains of 12% of muon mode
- Full analysis includes several components:
  - Sample of signal candidates
  - Angular part: θ_K, θ_e, ϕ
  - Decay time part: $t_{B_s^0}$
  - Flavour tagging: B_s^0 or $\bar{B}_s^0$
- Paper of the analysis is under preparation



Data



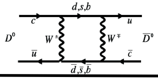
Search for CPT symmetry violation with neutral flavour mesons. (A.Szabelski, W.Krzemień))

Schwinger 1951 | Lüders 1954 | J S Bell 1954 | Pauli 1955 | Res Jost 1958

CPT theorem: Any Quantum Field Theory with locality, hermitian, Lorentz invariance must be CPT-symmetric.

Any deviation of CPT → Effects beyond the SM

Neutral flavour mesons oscillates between world of matter and antimatter:



$$|P_L\rangle = p\sqrt{1-z}|P^0\rangle + q\sqrt{1+z}|\bar{P}^0\rangle \qquad P(B^0, D^0, K^0)$$

$$|P_H\rangle = p\sqrt{1-z}|P^0\rangle - q\sqrt{1+z}|\bar{P}^0\rangle \qquad L, H\text{- mass eigenstates}$$

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z introduced to parametrize the CPT violation:

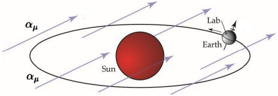
$$\boxed{z = \frac{\delta m - \frac{i}{2}(\delta\Gamma)}{\Delta m - \frac{i}{2}\Delta\Gamma}}$$

$\delta m = M_{11} - M_{22}$ and $\delta\Gamma = \Gamma_{11} - \Gamma_{22}$

$\Delta m = m_H - m_L$ and $\Delta\Gamma = \Gamma_H - \Gamma_L$

Two approaches:

- classical (z parameter as a phenomenological one)
- in the frame of the Standard Model Extension



The current PDG value
$B^0: \quad \Re(z) = -0.04 \pm 0.04; \quad \Im(z) = -0.008 \pm 0.004.$ Asymmetry modulation gives access to $\Im(z)$

$$A_{CPT}^{untagged} = A_D + a_{sl}^d/2 - (a_{sl}^d/2 - A_P)\cos\Delta mt + \boldsymbol{\Im(z)\sin\Delta mt},$$

The channel under study $B^0 \to D^-(\to K^+\pi^-\pi^-)\mu^+\nu$ is estimated to give statistical of $\Im(z)$ on the level of ± 0.0006.

- Can be performed in LHCb e.g. in the charm sector compared to previous best limit :

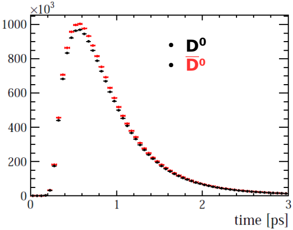
J. Link et al., Phys. Lett. B 556, 7 (2003)

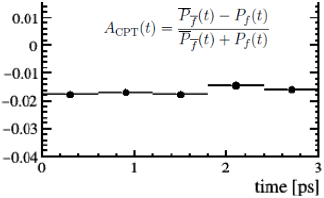
LHCb

- **1000 times higher statistics,**
- **much smaller systematical error for D time decay**

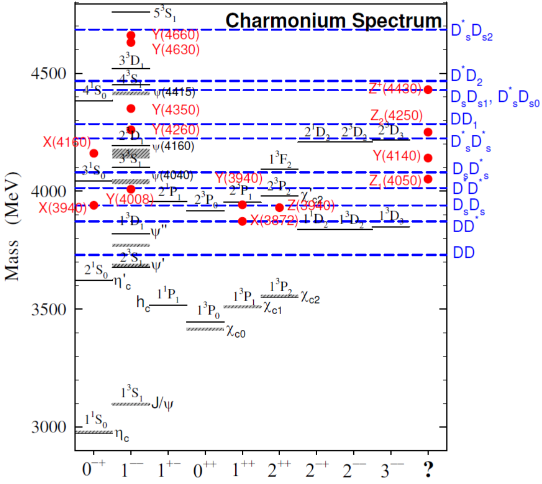
- Search for the CPT violation via the analysis of the time decay rates as a function of D meson lifetimes

$$P_f(t) \equiv |\langle f|T|D^0(t)\rangle|^2$$





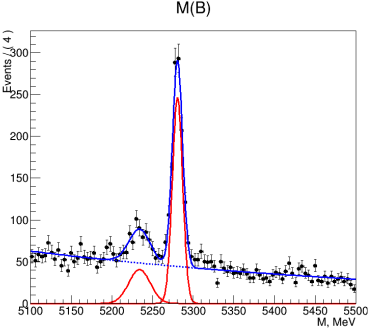
Search for exotic hadrons in $B^+ \to \chi_c \pi^+ \pi^- K^+$ (D.Melnychuk)



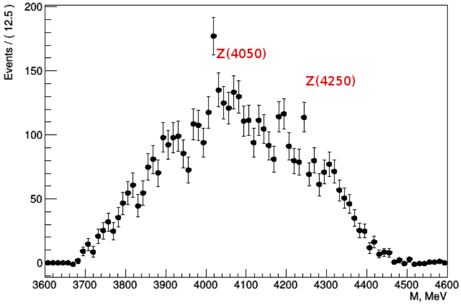
- The $Z^+(4050)$, $Z^+(4250)$ states have been observed by Belle experiment in $B^0 \to \chi_{c1}\pi^- K^+$ decay. Independent confirmation is desirable.
- The whole data sample from years 2011-2018 have been analyzed and the indication of these states have been observed. For definite statement an amplitude analysis is required.

Search for exotic hadrons in $B^+ \to \chi_c \pi^+ \pi^- K^+$

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



$\chi_{c1} \pi^+$

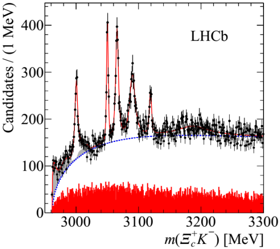


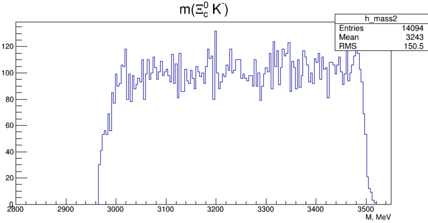
Ω_c states (D.Melnychuk)

- 5 Ω_c resonances have been observed by LHCb in $\Xi_c^+ K^-$.
- 2 narrowest of them could be pentaquarks
- If so, they should have isospin partner decaying to $\Xi_c^0 K^-$ and $\Xi_c^+ K_S$

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}, 95\%$ CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\mathrm{MeV}, 95\%$ CL		

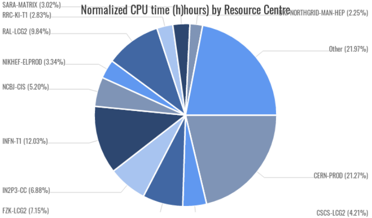
$$\Omega_c^- \to \Xi_c^0 K^-, \Xi_c^0 \to p K^- K^- \pi^+$$

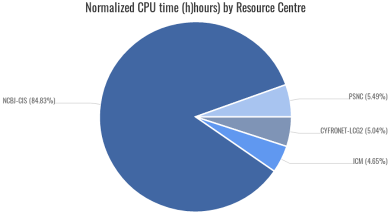




NCBJ is T2-level Grid node for LHCb and CMS; actual performance at T1 level for LHCb

Upgrade to T1 (at least for LHCb) is ongoing





- DIRAC modules for Message Queues and Message Senders; already used in production by LHCb
- Upgrade of system pilots' communication modules
- Development of multi-threading in electromagnetic Calo software; important for reconstruction speedup in LHCb upgrade

Future perspectives

- Continuation of CP violation search in decays of charmed and beautiful particles with increased statistics.
- Continuation of CPT violation test in charm decay.
- Search for exotic hadrons with charm and beauty quarks.
- Development of T2-level Grid node.
- Software development.