# CP and CPT symmetry violation and exotic hadrons in LHCb experiment

dr Dmytro Melnychuk, BP3

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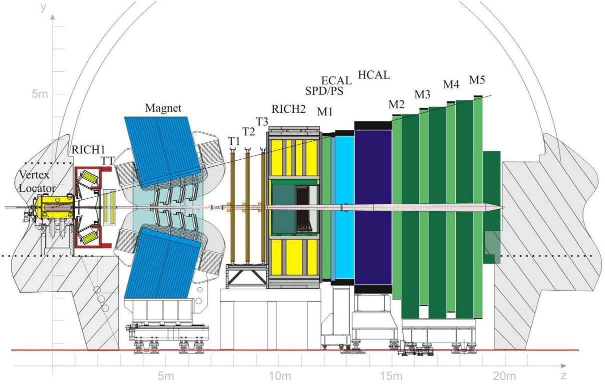
# LHCb experiment

- 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.



# 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.
  - Work on software for RTA (Real-time analysis).

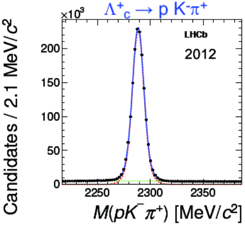
# Search for CP violation in $\Xi_c^+ \to pK^-\pi^+$ decays (A.Ukleja)

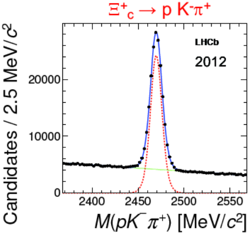
- The goal is to perform searches for CPV in $\Xi^+_c \to p K^-\pi^+$ single-Cabibbo suppressed charm baryon (prompt) decays using Run 1 data
- $\Lambda^+_c \to p K^-\pi^+$ Cabibbo Favoured is used as a control decay
- 3-body hadronic decays: make use of the Dalitz plot to look for localized asymmetries
- 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
- If CPV is found, the p-value can be converted into a significance for a signal, otherwise it gives no limits for CPV
- Expected value of CPV is small $\lesssim 10^{-3}$ and predictions vary very widely (much smaller than observed in the beauty sector)

LHCb-PAPER-2019-026 in publication process

$\Lambda_c$: 1 910 843 candidates (purity 97%)

$\Xi_c$: 193 830 candidates (purity 78%)



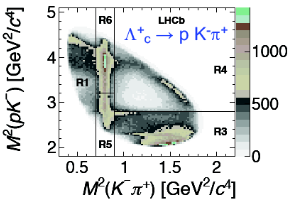



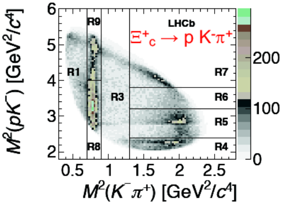

$$Asym_{CP} \sim |A_1||A_2|sin(\phi_1 - \phi_2)sin(\delta_1 - \delta_2)$$

weak phases — strong phases

To increase the power of the kNN method, the Dalitz plot is divided into regions

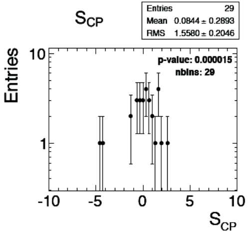
The regions are defined around the resonances

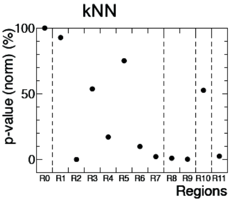


- Control channel and mass sidebands do not show localized asymmetries
  - ✧ no asymmetry observed in control $\Lambda^+_c \to p K^-\pi^+$ decays
  - ✧ no asymmetry observed in sidebands of $\Xi^+_c \to p K^-\pi^+$
- The toy MC data are used to check the sensitivity of both methods:
  - ✧ the $S_{CP}$: CP ≥ 5% in K* or ≥10% in $\Delta^{1232}$
  - ✧ the kNN: CP ≥ 5% in K* or > 5% in $\Delta^{1232}$

**5%** difference in K* amplitudes



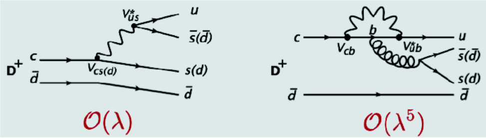




There is no local asymmetries (not related to CPV) and production asymmetry is under control
⇒ the study is unblind (April 2019)

- Results is going to published soon as LHCb-PAPER-2019-026
  Currently it is in Collaboration Wide Review
- Next step to do it: Run 2 and use the new method Kernel Density Function
  Supervising PhD Thesis Jakub Ryżka, Cracow, AGH

Collaboration with Rio Group

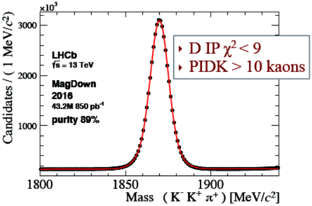
- Direct CP violation in charm is tiny and results, via the CKM mechanism, from the small contribution of penguin diagrams in Cabibbo-suppressed (CS) decays




- The large charm samples in Run 2 provide a potential place for observation of direct CPV
- The 3-body channels, in particular, benefit from the rich resonant structure where interferences may potentialise CPV effects in specific regions of the phase space

| Potential discovery modes: CS |
|---|
| ✳ $D^+ \to K^-K^+\pi^+$ |
| ✳ $D^+ \to \pi^-\pi^+\pi^+$ |
| ✳ $D^+_s \to K^- K^+K^+$ |
| ✳ $D^+_s \to \pi^-\pi^+K^+$ |

| Search for NP effects: DCS |
|---|
| ✳ $D^+ \to K^-K^+K^+$ |
| ✳ $D^+ \to \pi^-\pi^+K^+$ |
| ✳ $D^+_s \to \pi^- K^+K^+$ |



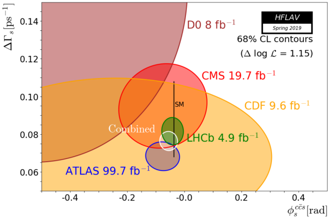

Full run II: $D^+ \to K^-K^+\pi^+$ signal yield of ~300M with 90% purity

- Within the SM $\not{C}\not{P}$ violation arises due to mixing-decay interference $\Rightarrow$ can be expressed as a single phase $\phi_s$
- Phase $\phi_s$ within the SM is predicted to be small with very good precision

[CKMFitter]: $-36.88^{+0.96}_{-0.68}$ mrad

[UTfit]: $-37.0 \pm 1.0$ mrad

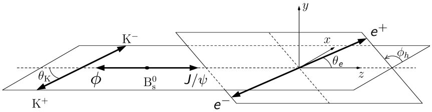
- Decay $B_s^0 \to J/\psi\phi$ provides experimental access to the phase $\phi_s$



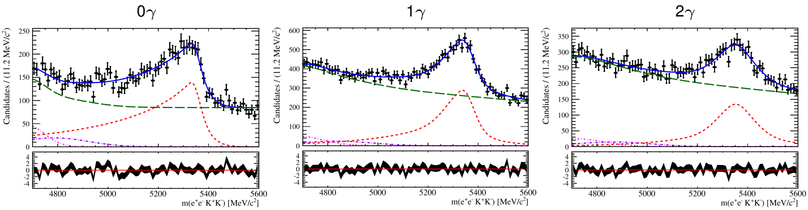

- The most precise measurements of this quantity to date have been performed by LHCb using $\sim 96 \cdot 10^3$ (3.0/fb) + $\sim 117 \cdot 10^3$ (1.9/fb) $B_s^0 \to J/\psi(\mu\mu)\phi(KK)$
- Combination with results from other $B_s^0$ decays: $J/\psi(\mu\mu)\pi^+\pi^-$ (4.9/fb) and $D_s^+ D_s^-$, $\psi(2S)(\mu\mu)\phi$, $J/\psi KK$ in high m($KK$) (3.0/fb)

$\phi_s = -41 \pm 25$ mrad [EPJ C79 (2019) 706]

- *Motivation*: measure phase $\phi_s$ using 3/fb (2011-2012) in similar channel to $B_s^0 \to J/\psi(\mu\mu)K^+K^-$
- Experimentally harder (Bremsstrahlung, reconstruction, trigger)
- $N_{sig}(B_s^0) \sim 13 \cdot 10^3$ that corresponds to 13% of the muon mode
- Full analysis includes several components:
  - Sample of signal candidates
  - Angular part: $\theta_K, \theta_e, \phi$
  - Decay time part: $t_{B_s^0}, \sigma_t$
  - Flavour tagging: $B_s^0$ or $\bar{B}_s^0$
- Paper with results of this analysis is under collaboration review




Data



## CPT parameterisation (in mixing) (A.Szabelski, W. Krzemień)

CPT violation can be involved in the standard model by introducing a CPT violating parameter $z$

For a given neutral meson $P(B^0, D^0, K^0)$ mixing can be described:

$$|P_L\rangle = p\sqrt{1-z}|P^0\rangle + q\sqrt{1+z}|\bar{P}^0\rangle$$
$$|P_H\rangle = p\sqrt{1-z}|P^0\rangle - q\sqrt{1+z}|\bar{P}^0\rangle,$$

$L, H$- mass eigenstates (light and heavy).

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

where:

- $\delta m = M_{11} - M_{22}$ and $\delta\Gamma = \Gamma_{11} - \Gamma_{22}$
- $\Delta m = m_H - m_L$ and $\Delta\Gamma = \Gamma_H - \Gamma_L$

- Conservation of CP or CPT $\Rightarrow z = 0$
- Conservation of CP or T $\Rightarrow \left|\frac{q}{p}\right| = 1$

- Theoretical framework to test CPT violation in broad classes of experiments (Kostelecky, PRD55 (1997) 6760),
- Effective QFT with components breaking Lorentz and CPT symmetries,
- All properties of "good" QFT remain (renormalisation, locality, spin-statistics relation etc.);

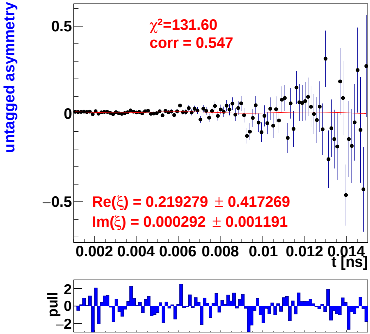
$$z \simeq \frac{\beta^{\mu} \Delta a_{\mu}}{\Delta m - \frac{i}{2}\Delta\Gamma/2},$$

$\beta^{\mu} - \gamma(1, \vec{\beta})$ meson four-velocity i the observer frame,
$\Delta a_{\mu} \simeq a_{\mu}^{q_1} - a_{\mu}^{q_2}$ have to be real, hence:

$$\Delta\Gamma \Re(z) = -2\Delta m \Im(z)$$

# beauty sector

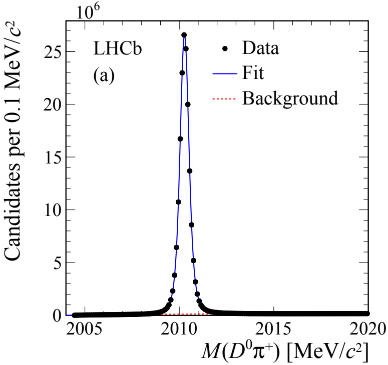
Semileptonic channel
$B^0 \to D^-(\to K^-\pi^+\pi^-)\mu^+\nu_\mu$



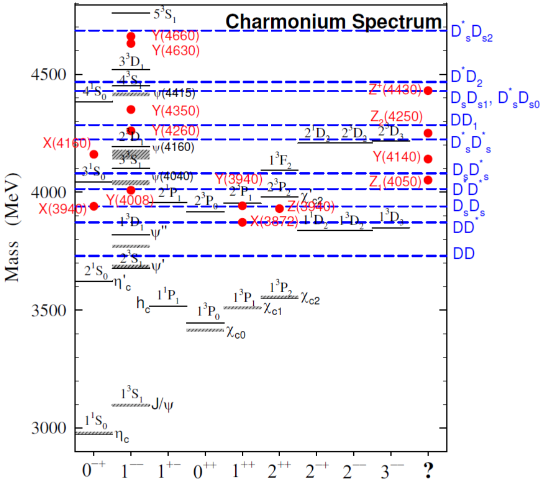

Estimated statistical unccertainty on $\Im(z) \sim 10^{-4}$

# charm sector

hadronic decay
$D^{*+} \to D^0(\to K^-\pi^+)\pi_s^+$
Flavour tagged by the slow pion.

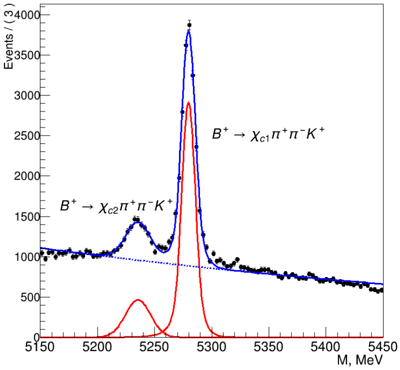


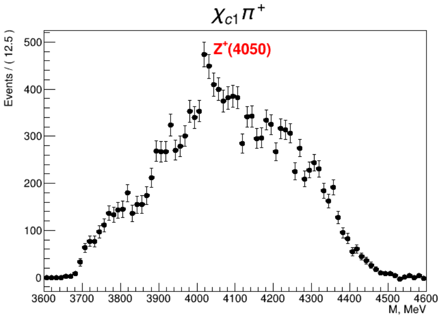

$1.77 \times 10^8$ events from run 1 and 2.



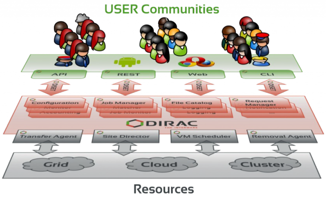

- The $Z^+(4050)$, $Z^+(4250)$ states have been observed by Belle experiment in $B^0 \to \chi_{c1} \pi^- K^+$ decay. Independent confirmation is desirable.
- The branching ratio for the decay $B^+ \to \chi_c \pi^+ \pi^- K^+$ has been also measured by Belle, however with big uncertainty. The BR of decay via $\chi_{c2}$ is expected to be small wrt. to decay via $\chi_{c2}$ since it's factorization forbidden.

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



# Development of Pilot logging system in the frame of distributed computing platform DIRAC (W. Krzemień, D. Potoka)




DIRAC (**D**istributed **I**nfrastructure with **R**emote **A**gent **C**ontrol) is a platform for distributed computing used by various HEP experiments e.g. LHCb, BES-III, BELLE-2 and others.

DIRAC philosophy is based on **pilot** concept – distributed agents responsible for installation and environment configuration on working nodes independent on its type (GRID, Cloud etc.)

Development of **“pilot logging”** system – extension of DIRAC by introducing the distributed agents providing log information about errors during installation, configuration or data processing phases.

Addressing Scalability with Message Queues: Architecture and Use Cases for DIRAC Interware
W. Krzemień et al. EPJ Web of Conferences 214, 03018 (2019)

F. Stagni, W. Krzemień et al. J.Phys.Conf.Ser. 898 (2017) no.9, 092024

# Real-time analysis

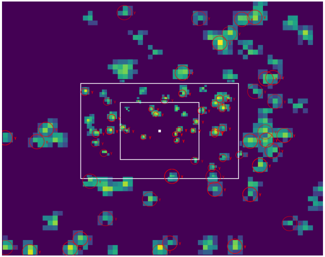
LHCb project for triggerless readout in 2021 - LHCB-TDR-017.
40MHz collision rate reduced to 7.5kHz by full data reconstruction.
NCBJ group works on improvement and optimalization of calorimeter software.

Drawing V. Gligorov

# NCBJ group contribution to RTA

Electromagnetic calorimeter data reconstrunction software.

- Code refactorization.
- Transformation to fully multithread-safe code.
- Optimization of cluster-track matching algorithm.
- Optimization and rewriting of cluster correction procedures.
- Studies on application of Machine Learning algorithms to replace clusterization and track macthing algorithms.
- Benchmarking



# 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 for RTA.

# NCBJ LHCb team

1. Prof. dr hab. W. Wiślicki (DUZ)
2. dr V. Batozskaya (DBP, BP3)
3. dr K. Klimaszewski (DUZ)
4. dr W. Krzemień (DBP, BP3)
5. dr D. Melnychuk (DBP, BP3)
6. dr A. Szabelski (DBP, BP3)
7. dr A. Ukleja (DBP, BP3)
8. mgr M. Mazurek (doktorant, DBP)
9. D. Potoka (DUZ)
10. mgr inż. H. Giemza (DUZ)