Instrumental asymmetries and $B^0 \to D^\star l\nu$ analysis at Belle II

Michele Mantovano

PhD school XXVII cycle - first year report

Supervisor: Mirco Dorigo

September 5, 2022

Overview

In my first year, I've been working on two topics:

- Measurement of instrumental asymmetries of kaons and pions:
    - Important service task for the Collaboration: provide crucial input for several Belle II measurements;
    - In collaboration with Debjit Ghosh.
- Analysis of $B^0 \to D^* l\nu$ decays:
    - First steps toward the first model-independent measurement of form factors for novel determination of $|V_{cb}|$;
    - Core topic of my PhD project.

Instrumental asymmetries at Belle II

Motivation

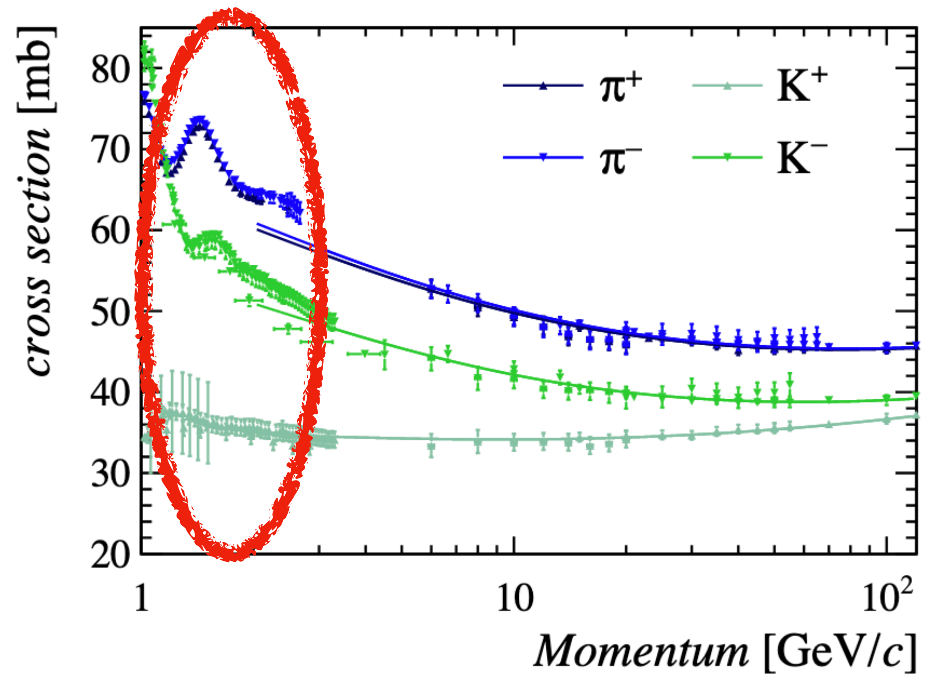
In particle physics, CP violation is the breaking of the combined charge-parity symmetry. Measurements of CP asymmetries ($\mathscr{A}_{CP}$) are a fundamental goal of Belle II physics program.

CP asymmetries are usually determined from signal-yield asymmetries, which comprise also other contributions:

$$\mathscr{A}_{raw} = \frac{N^+ - N^-}{N^+ + N^-} = \mathscr{A}_{CP} + \mathscr{A}_{det} + \dots$$

Instrumental asymmetries ($\mathscr{A}_{det}$) come from different sources:

- different reconstruction efficiency for +/- tracks;
- different interaction probabilities of particle/antiparticle with matters (i.e. K^+/K^-) ;
- etc..



Cannot trust simulation to obtain them → measure $\mathscr{A}_{det}$ in data.

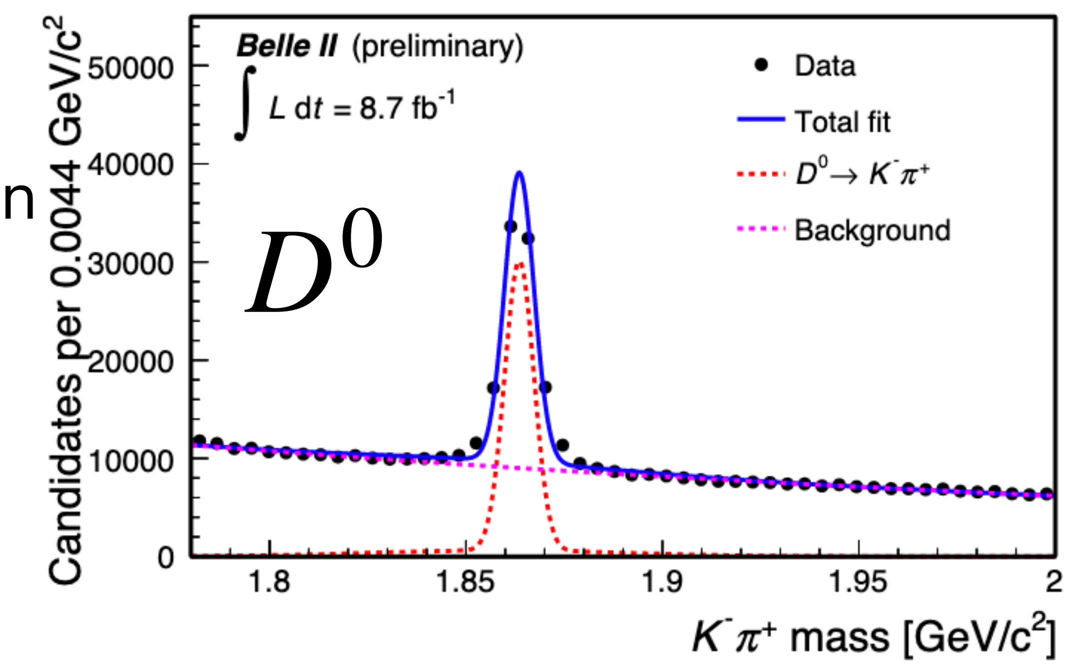
Status and improvements

$\mathscr{A}_{det}(K\pi)$ determined from $D^0 \to K^-\pi^+$ decays.

Can obtain $\mathscr{A}_{det}(K)$ using $\mathscr{A}_{det}(\pi)$ from $D^+ \to K_s^0\pi^+$ (Debjit's talk)

$$\mathscr{A}_{det}(K) \simeq \mathscr{A}_{det}(K\pi) - \mathscr{A}_{det}(\pi)$$

Measured in early data with $\mathscr{O}(1-3\%)$ precision (S.Raiz *et al.* **BELLE2-NOTE-TE-2020-024**).



Improve over this work by using larger dataset (190 fb^{-1}), a refined selection and by subtracting the $\mathscr{A}_{\mathrm{FB}}$ asymmetry (previously unaccounted).
We reach sub-percent precision.

$\mathscr{A}_{det}$ from D control channels

Observed charge asymmetries $\mathscr{A}_{\text{raw}}$:

$$\mathscr{A}_{\text{raw}} = \frac{N_D - N_{\bar{D}}}{N_D + N_{\bar{D}}} = \mathscr{A}_{CP} + \mathscr{A}_{det} + \mathscr{A}_{\text{FB}}$$

Observed asymmetry

CP-violating asymmetry

Instrumental asymmetry

Forward-backward asymmetry

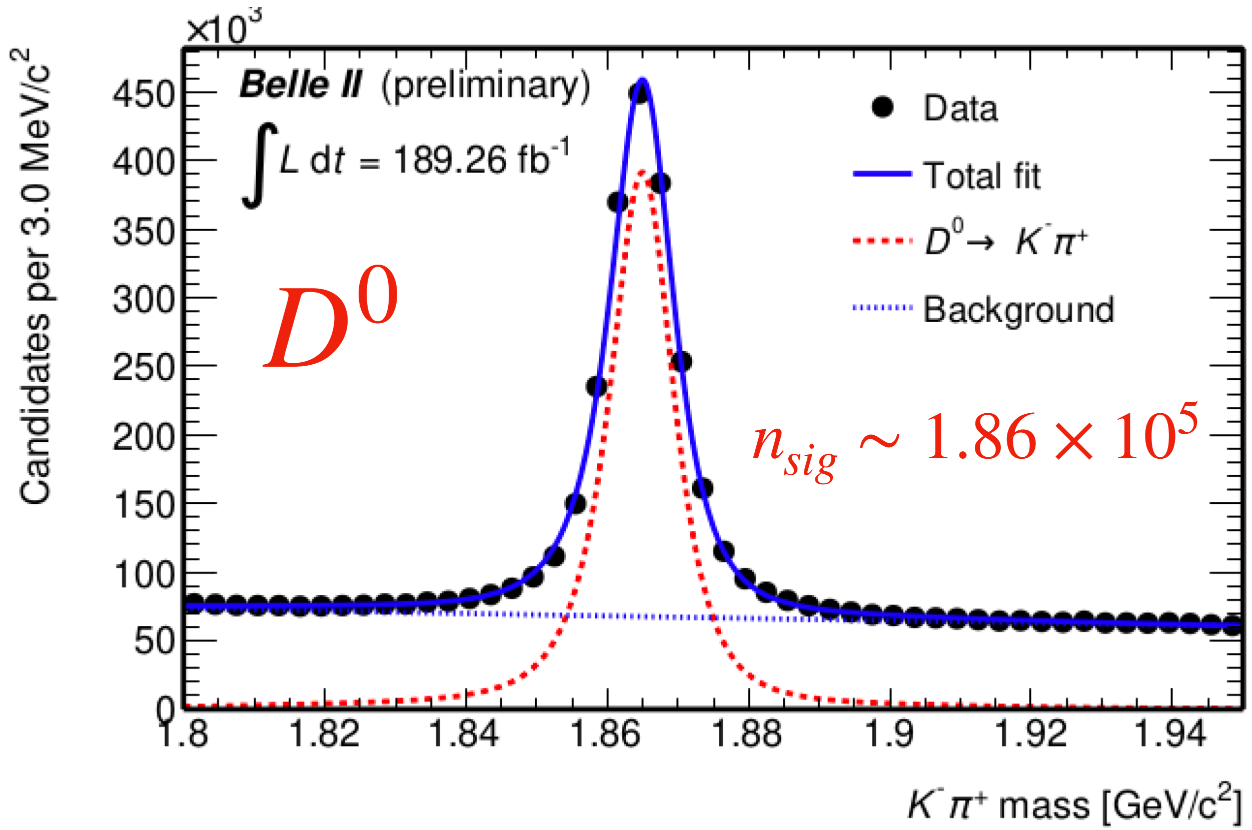
$\mathscr{A}_{\text{CP}}$ known for $D^0 \to K^-\pi^+$: $\mathscr{A}_{CP}(K\pi) = 0$

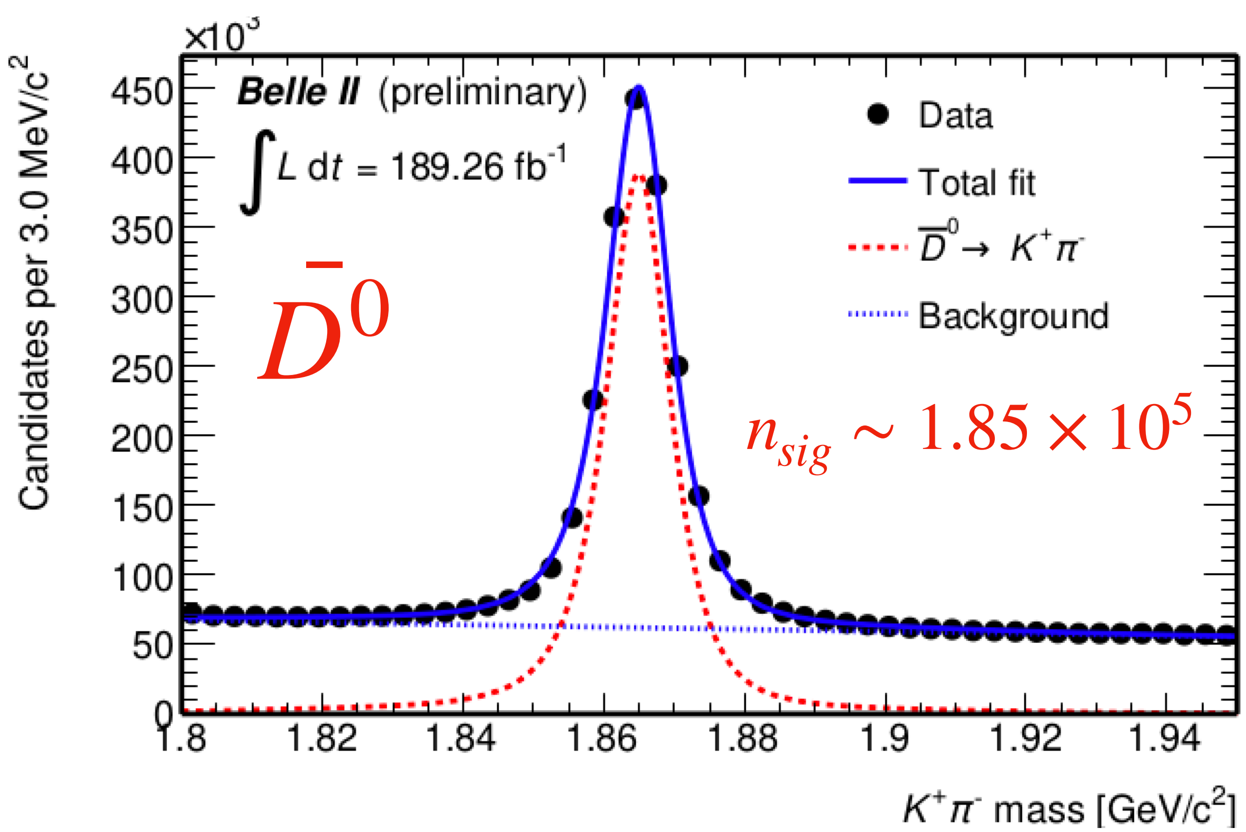
$\mathscr{A}_{FB}$ is the contribution due to $\gamma^* - Z^0$ interference in $e^+e^- \to c\bar{c}$ and it is an antisymmetric as a function of angle of D momentum in the CMS ($cos(\theta^*)$).

$\mathscr{A}_{FB}$ can be canceled by combining measurements of $\mathscr{A}_{\text{raw}}$ in opposite bins of $cos(\theta^*)$.

Knowing $\mathscr{A}_{\text{CP}}$ and $\mathscr{A}_{FB}$ contribution, $\mathscr{A}_{det}$ can be extract by measuring $\mathscr{A}_{\text{raw}}$.

$D^0 \to K^-\pi^+$ sample



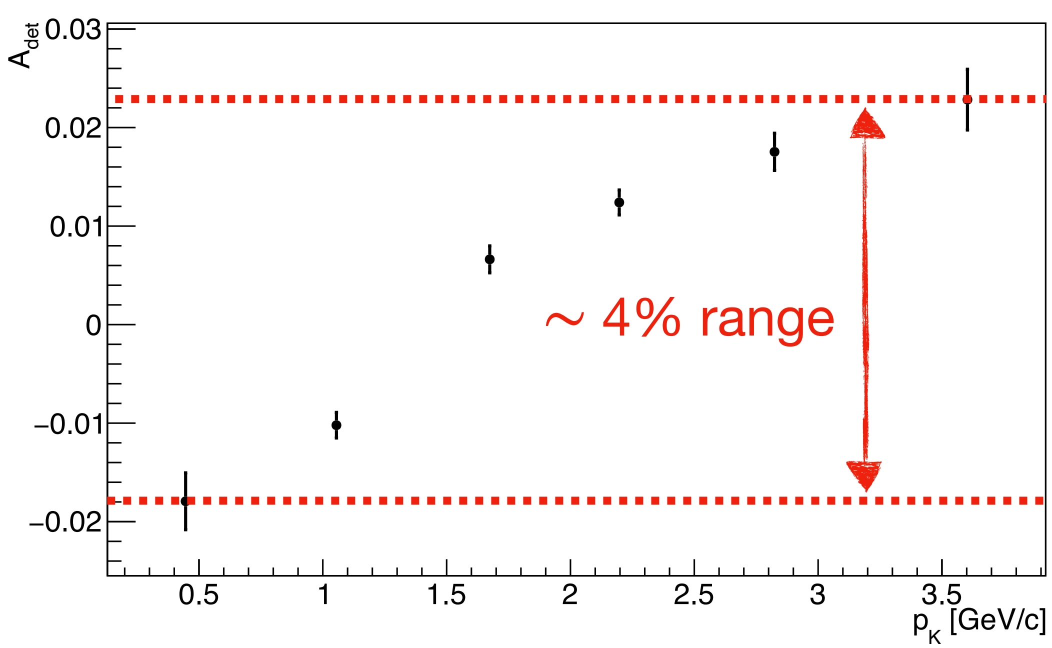


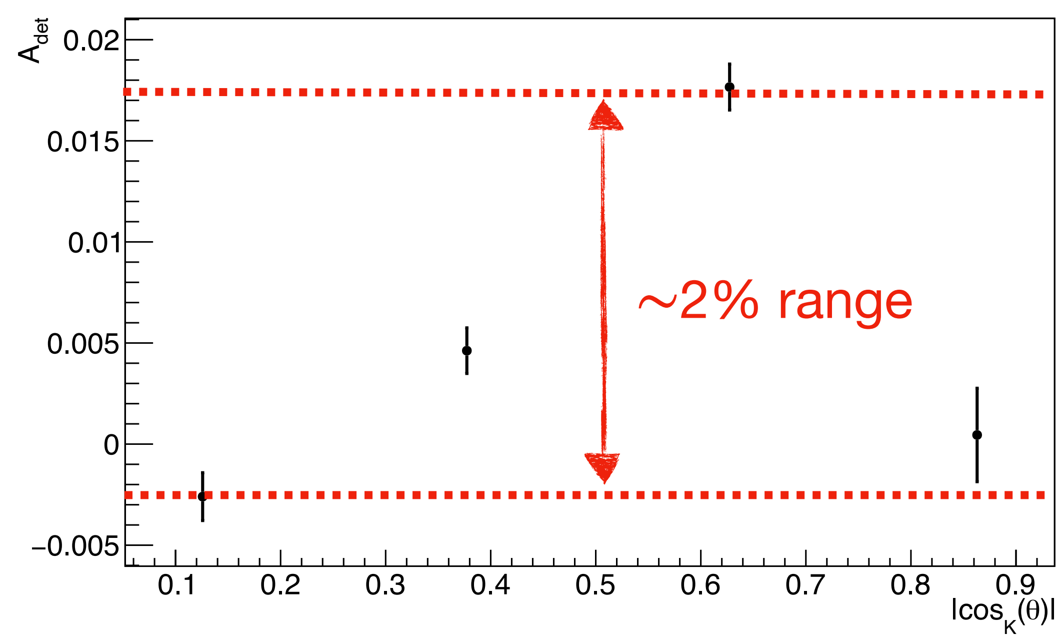
$$\mathscr{A}_{det}(K\pi) = 0.0043 \pm 0.0006(stat)$$

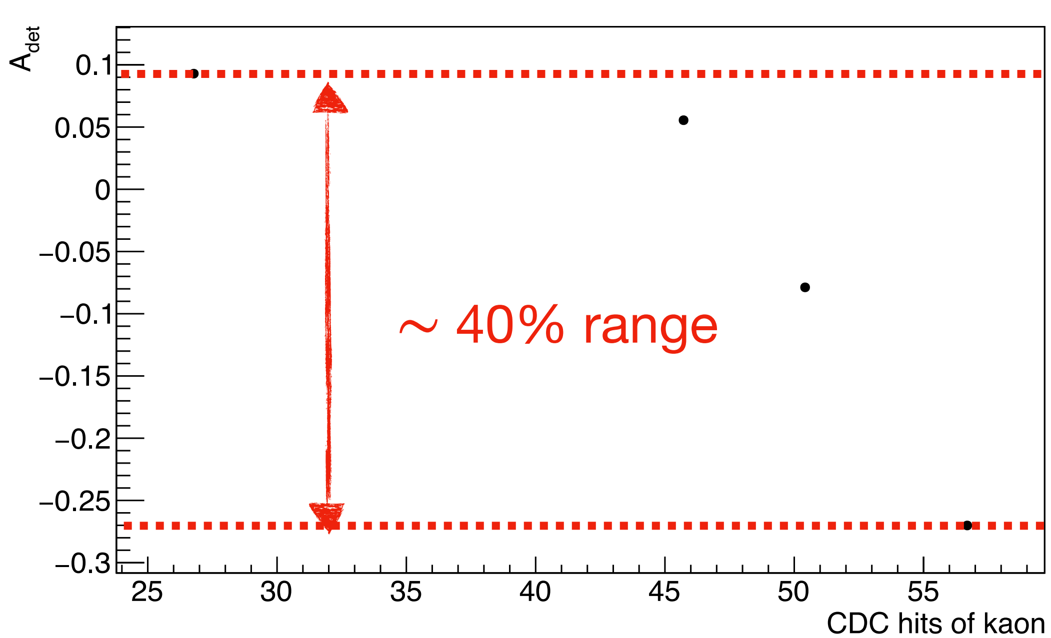
$\mathscr{A}_{det}(K\pi)$ dependencies

Study $\mathscr{A}_{det}(K\pi)$ dependencies as a function of:

- p: interaction probabilities with matter depend on momentum;
- $cos(\theta)$: different material budget traversed by the particle;
- CDC hits: tracking and dE/dx resolution depends on number of hits, and these differ on average for track opposite curvature.



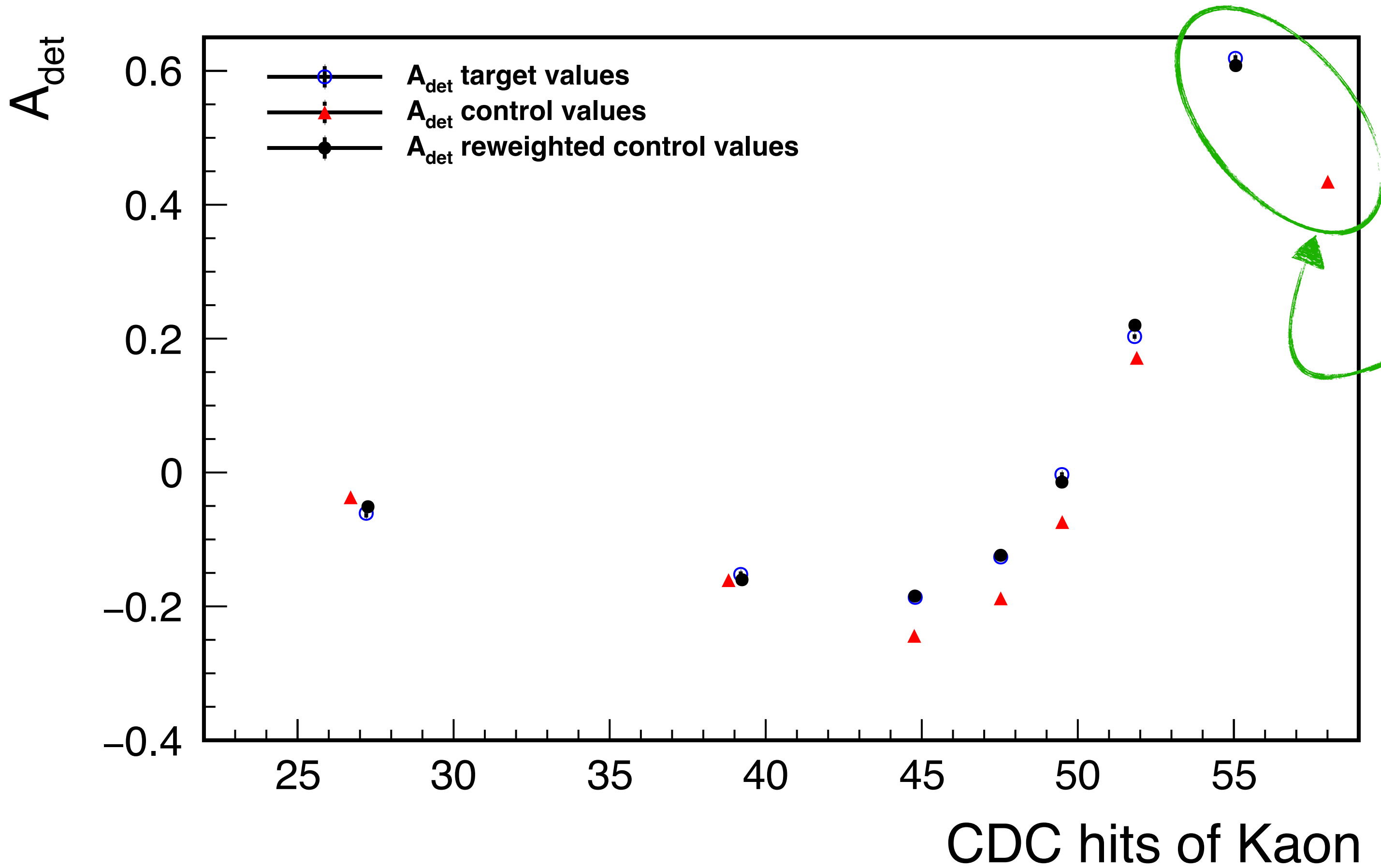


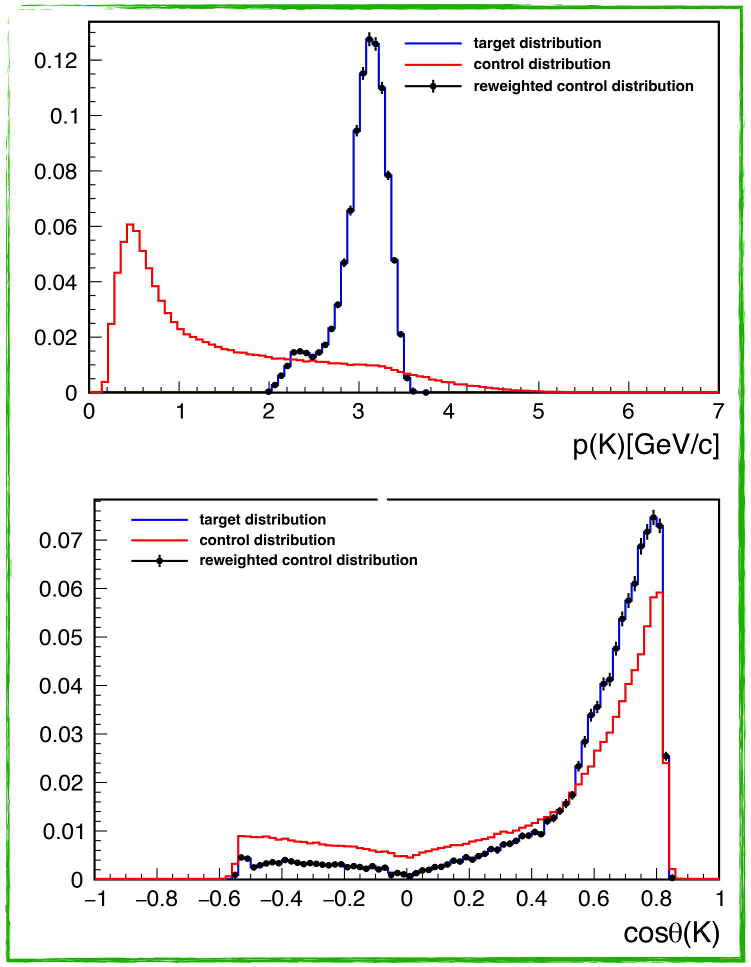


Also investigated other possible dependencies (p_{err}, ω_{err}...) but we identify these 3 as those only relevant at the current level of precision.

Sample dependence

We have developed a method (reweighting method) to take into account these dependencies and to calculate $\mathscr{A}_{det}$ for different decays.





The method is quite stable, so we decided to develop a new strategy.

Strategy: provide $\mathscr{A}_{det}$ using the control samples, assigning a systematic uncertainty due to how well we reproduce $\mathscr{A}_{det}$ with our control channels (in MC).

Provided the $\mathscr{A}_{det}$ values for $B^+ \to K^+\pi^0 (B^+ \to \pi^+\pi^0)$ with a total uncertainty of 1% for the $\mathscr{A}_{CP}$ measure shown at ICHEP 2022.

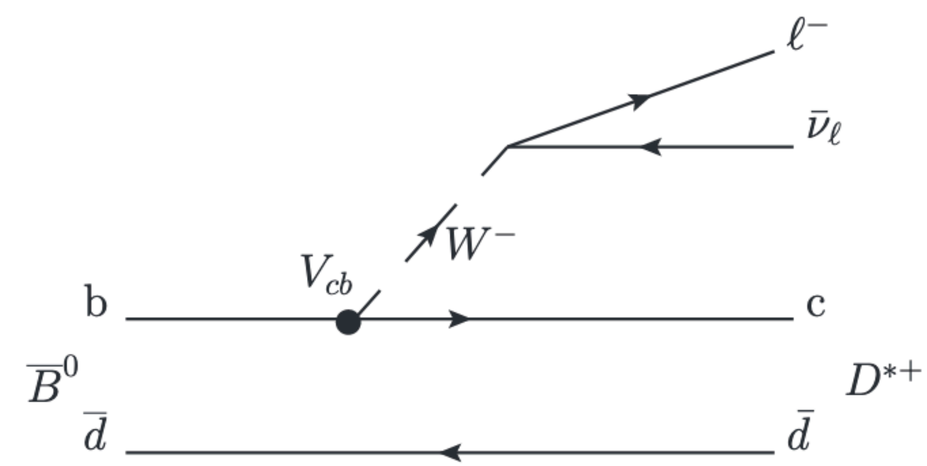
$B^0 \to D^\star l\nu$ untagged analysis at Belle II

Motivation

$B^0 \to D^\star l\nu$ decays are useful to extract the magnitude of Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{cb}|$, which gives the magnitude of the weak coupling between *b* and *c* quarks.

Two different $|V_{cb}|$ measurements:

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \text{ (inclusive)}$$
$$|V_{cb}| = (39.5 \pm 0.9) \times 10^{-3} \text{ (exclusive)}$$



The discrepancy underlines that precise measurements of $|V_{cb}|$ is still extremely important. In fact, the $|V_{cb}|$ measurement provides a strong constrain to unitarity of CKM matrix.

The determination of $|V_{cb}|$ from these decays relies on the description of strong-interaction effects for the *b* and *c* quarks bound in mesons (called “form factors”).

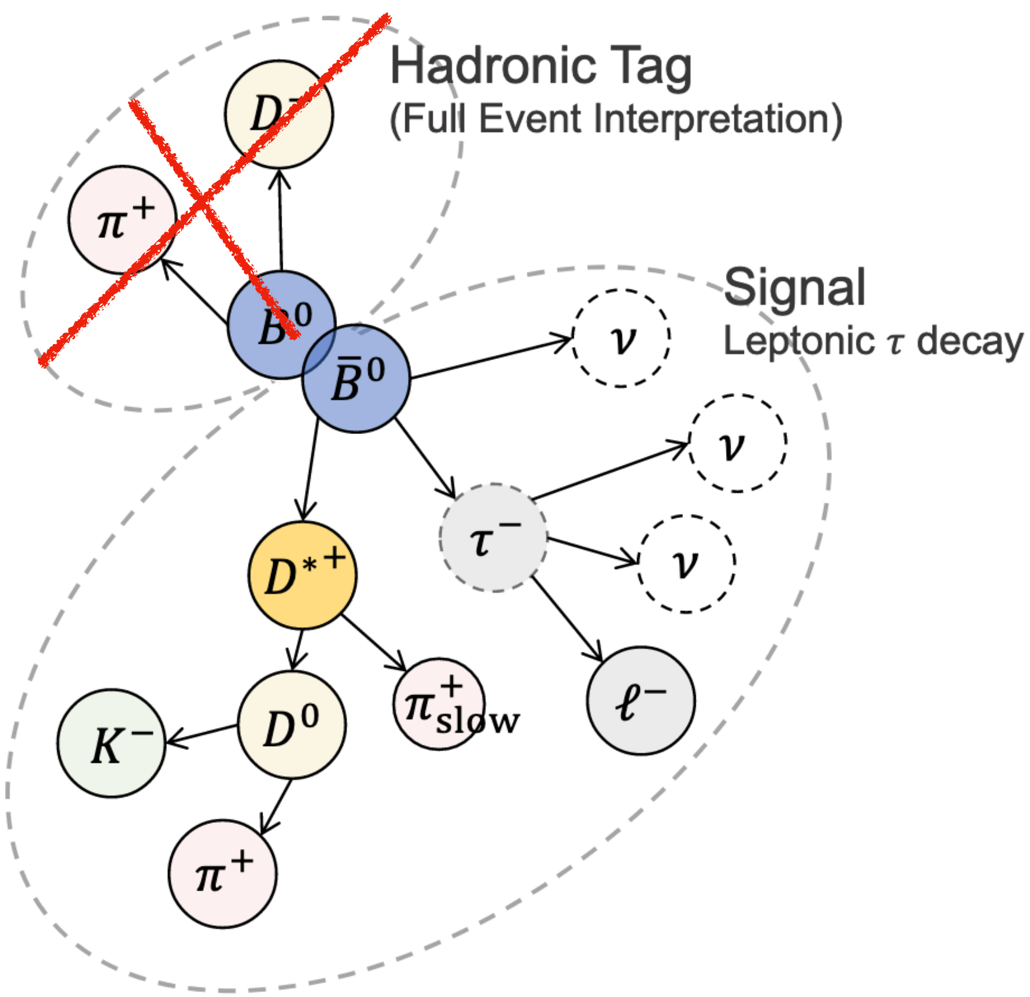
Goal: provide the first model-independent measurement of the form factors to yield a better determination of $|V_{cb}|$.

Untagged analysis

The form factors are functions of kinematic variables evaluated in the B rest frame. One of these kinematic variables is:

$$w = \frac{p_B \cdot p_{D^*}}{m_B m_{D^*}}$$

To measure w, we need to Know the B momentum. In the $B^0 \rightarrow D^\star l\nu$ the neutrino is not reconstructed → cannot reconstruct the B momentum.



Two different approach:

- Reconstruct the other B in the $e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$ decay. From momentum conservation in the CM, the B signal momentum can be extracted: low efficiency, high resolution.

- Don't reconstruct the other B, approximate kinematics: high efficiency, low resolution (<1%).

I expect my measurement to be statistically limited: I use the second approach.

Methods

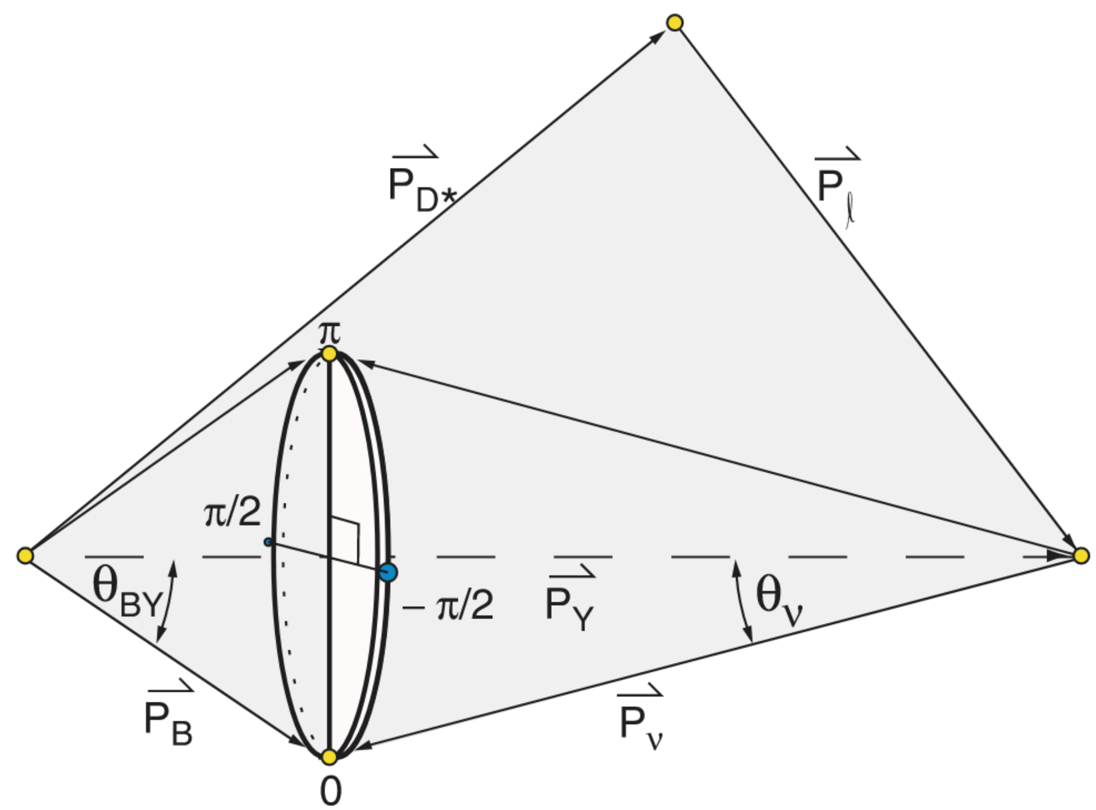
In the $B^0 \rightarrow D^{\star} l \nu$ we know the magnitude of B momentum in the CMS but not its direction. We can exploit these two informations:

A. B meson should lie on a cone around the $D^{*}l$ system;

B. B meson is more likely to be perpendicular to the beams.

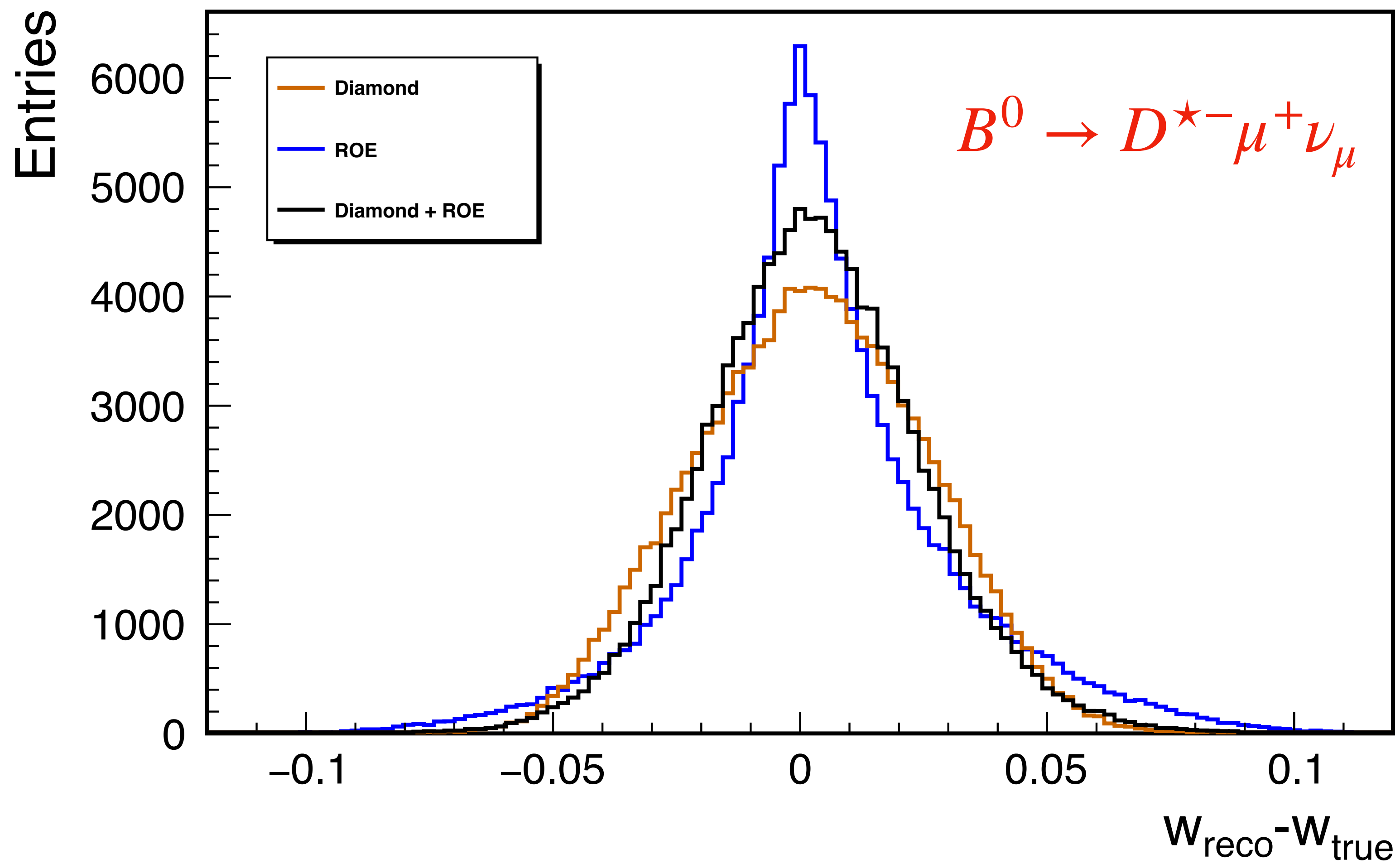
Three different methods to estimate the B's momentum direction:

1. Mediate 10 random directions by weighting them with B) probability;
2. Reconstruct the other B inclusive and look for the direction on the cone closest to the opposite direction of the other B.
3. Arithmetic average of 1. and 2. solutions.



Resolution plots

The first step of this study is to determine the resolution of the kinematic variables for each method.



ROE method reproduces the better results.

Next step: try adding information of the other B and combining it into a MVA regression algorithm to see if we get something better.

Goals 2^{nd} year

The goals proposed for the second-year are:

- Find a new method to get a better resolution for the kinematic variables (Sept 2022).

- Angular analysis of decay rates to extract the form factors as functions of *w*:
  - First test on MC to validate our proposal (Oct-Nov 2022).

- Improve the selection of events (Dec 2022).

- Study of background components (Jan-Feb 2023).

- Include all the experimental factors (resolution, acceptance ...) in the analysis. (Mar-Apr 2023)

Summary

Measured $\mathscr{A}_{det}$ for $K\pi$ using $D^0 \to K^-\pi^+$.

First study of the dependence of $\mathscr{A}_{det}$. Found a large dependence as a function of p, $cos(\theta)$ and CDC hits of tracks.

Developed a strategy to compute $\mathscr{A}_{det}$ from control channel for any physics decay (i.e. $B^+ \to h^+\pi^0$ (ICHEP 2022)).

Presented the instrumental asymmetries study at "17^{th} Belle II Italy Meeting (2022)" (https://agenda.infn.it/event/30284/contributions/170884/attachments/91655/124921/Instr_asym_BelleII_Italy.pdf) and at "42^{nd} B2GM (2022)" (https://indico.belle2.org/event/6872/contributions/37443/attachments/17110/25481/instr_asym_B2GM.pdf).

Belle II internal note: M.Dorigo, D.Ghosh and M.Mantovano, "Measurement of instrumental asymmetries of K and π", 2022, BELLE2-NOTE-TE-2022-XX.

Start $B^0 \to D^\star l\nu$ untagged analysis to provide the first model-independent measurement of the form factors to yield a better determination of $|V_{cb}|$.

Backup

Flavour physics at Belle II

Standard Model: $\mathcal{O}(1000)$ predictions from eV to TeV with only 20 parameters, but still incomplete (dark matter, matter-antimatter asymmetry...).

Weak interactions of quarks ("flavour physics"): powerful tool for indirect searches to test SM and its extensions. Search for discrepancies in low-energy processes.

- SuperKEKB: 7-on-4 e^+e^- collider at 10.58 GeV;
- Aim at 700 $B\bar{B}$ pairs/second in low-bkg environment;
- 400 fb^{-1} (400×10^6 $B\bar{B}$ pairs) of data collected;
- World record peak luminosity: $4.1 \times 10^{34} cm^{-2} s^{-1}$.