Instrumental asymmetries and $B \to K\tau\tau$ analysis at Belle II

Debjit Ghosh

PhD school XXVII cycle - first year report
Supervisor: Diego Tonelli

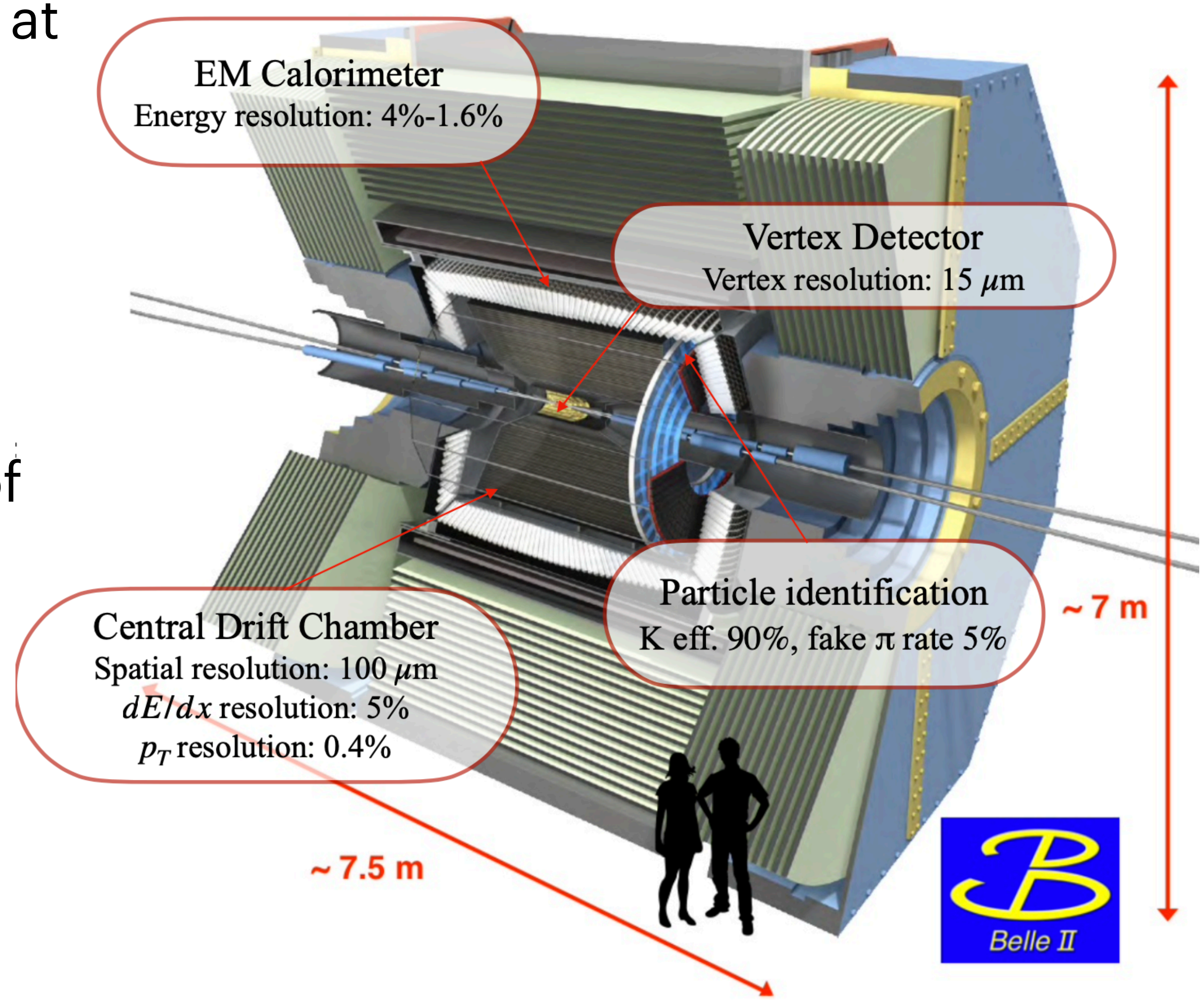
September 5, 2022

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-background environment;
- 400 fb^{-1} (400×10^6 $B\bar{B}$ pairs) of data collected;
- World record peak luminosity: $4.1 \times 10^{34} cm^{-2} s^{-1}$.
- Unique reach on final states with multiple neutrinos.



Instrumental asymmetries

Measurement of CP asymmetries are a fundamental goal of Belle II physics.

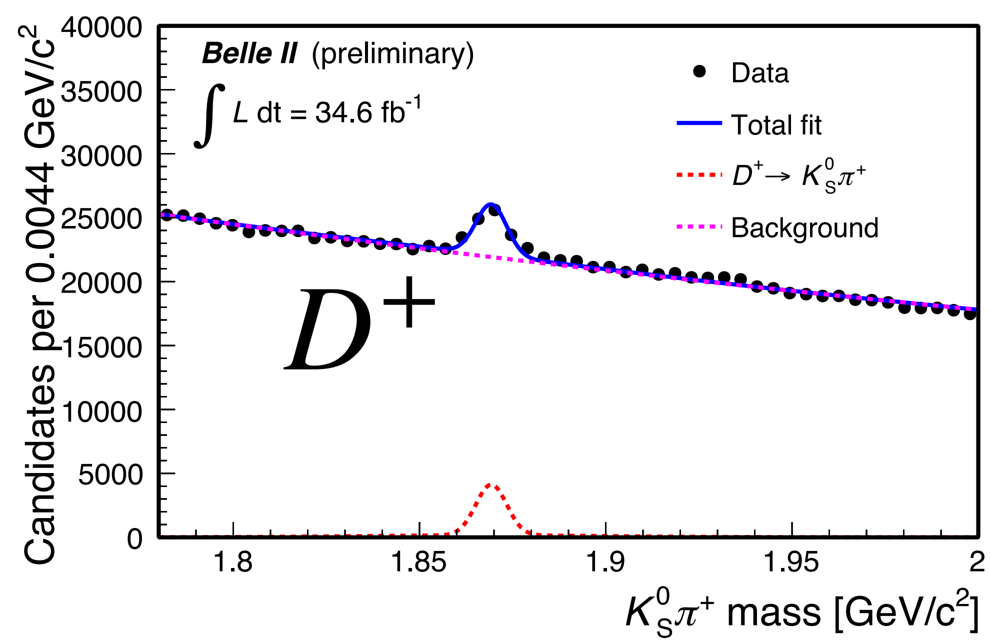
For correct measurement, detector asymmetries must be removed.

$$\mathscr{A}_{raw} = \mathscr{A}_{CP} + \mathscr{A}_{det} + \mathscr{A}_{\mathrm{FB}} \cdots$$

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

Can obtain $\mathscr{A}_{det}(K)$ using $\mathscr{A}_{det}(K\pi)$ from $D^0 \to K^- \pi^+$ (Michele'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.

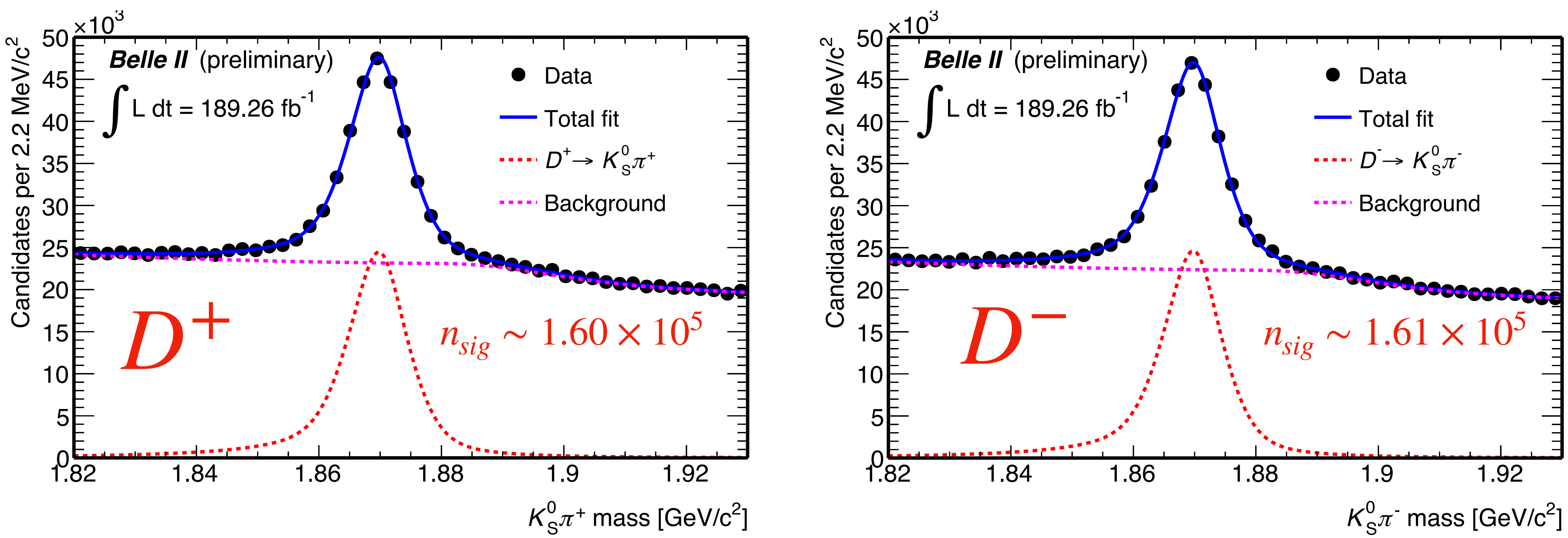
$\mathscr{A}_{det}(\pi)$ from D control channels

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

Observed asymmetry | CP-violating asymmetry | Instrumental asymmetry | Forward-backward asymmetry

$\mathscr{A}_{\text{CP}}$ known for $D^+ \to K_S^0\pi^+$: $\mathscr{A}_{CP}(K_S^0\pi^+) = -0.41 \pm 0.09\,\%$; $\mathscr{A}_{\text{det}}(K_S^0) = 0$

$\mathscr{A}_{FB}$ is antisymmetric as a function of angle of D momentum in the CMS ($cos(\theta^*)$).
$\mathscr{A}_{FB}$ can be cancel by average measurements of $\mathscr{A}_{\text{raw}}$ in opposite bins of $cos(\theta^*)$.

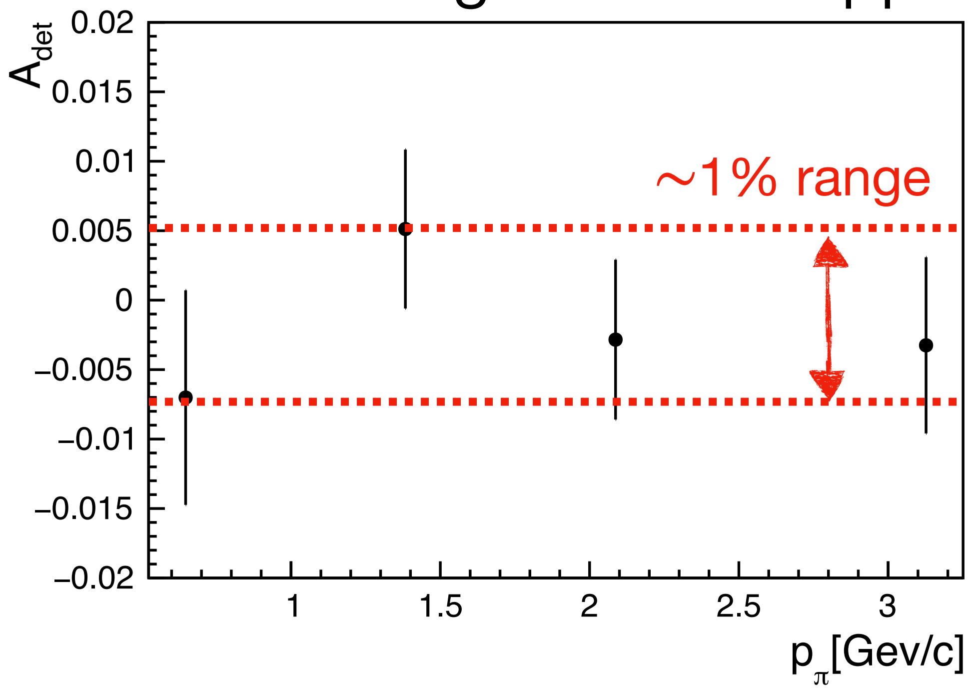


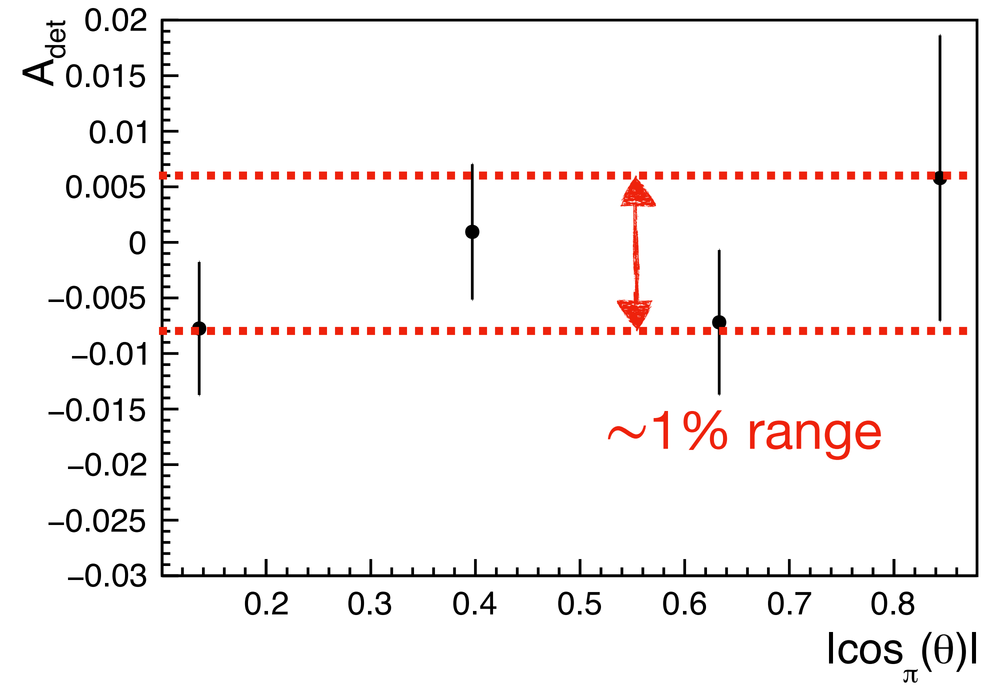
$$\mathscr{A}_{det}(\pi^+) = 0.0010 \pm 0.0034\,(stat)$$

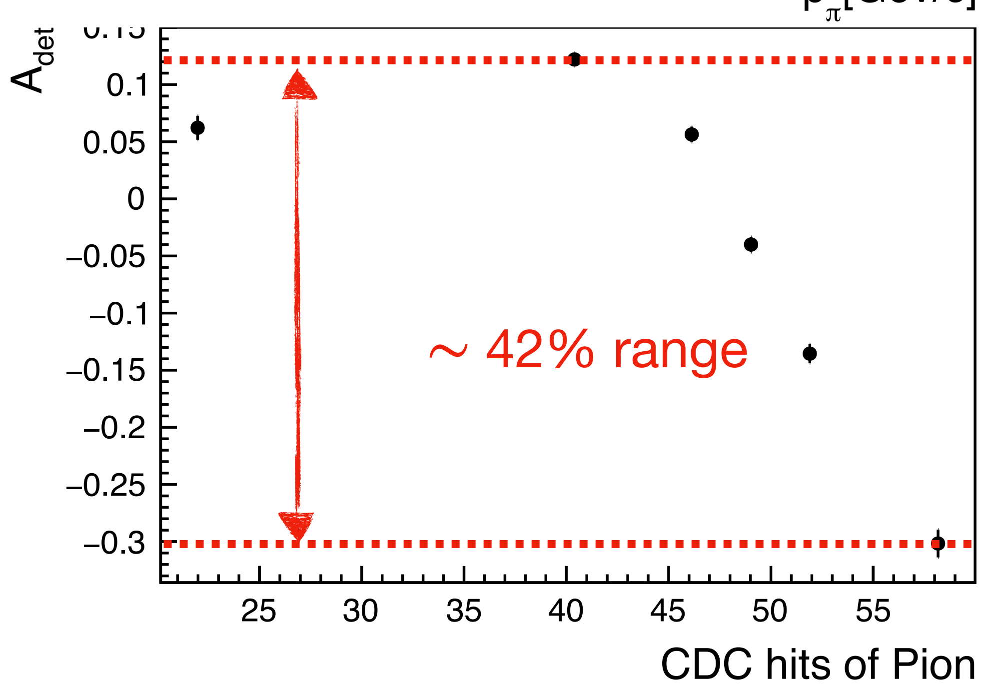
$\mathscr{A}_{det}(\pi)$ dependencies

Study $\mathscr{A}_{det}(\pi)$ 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.



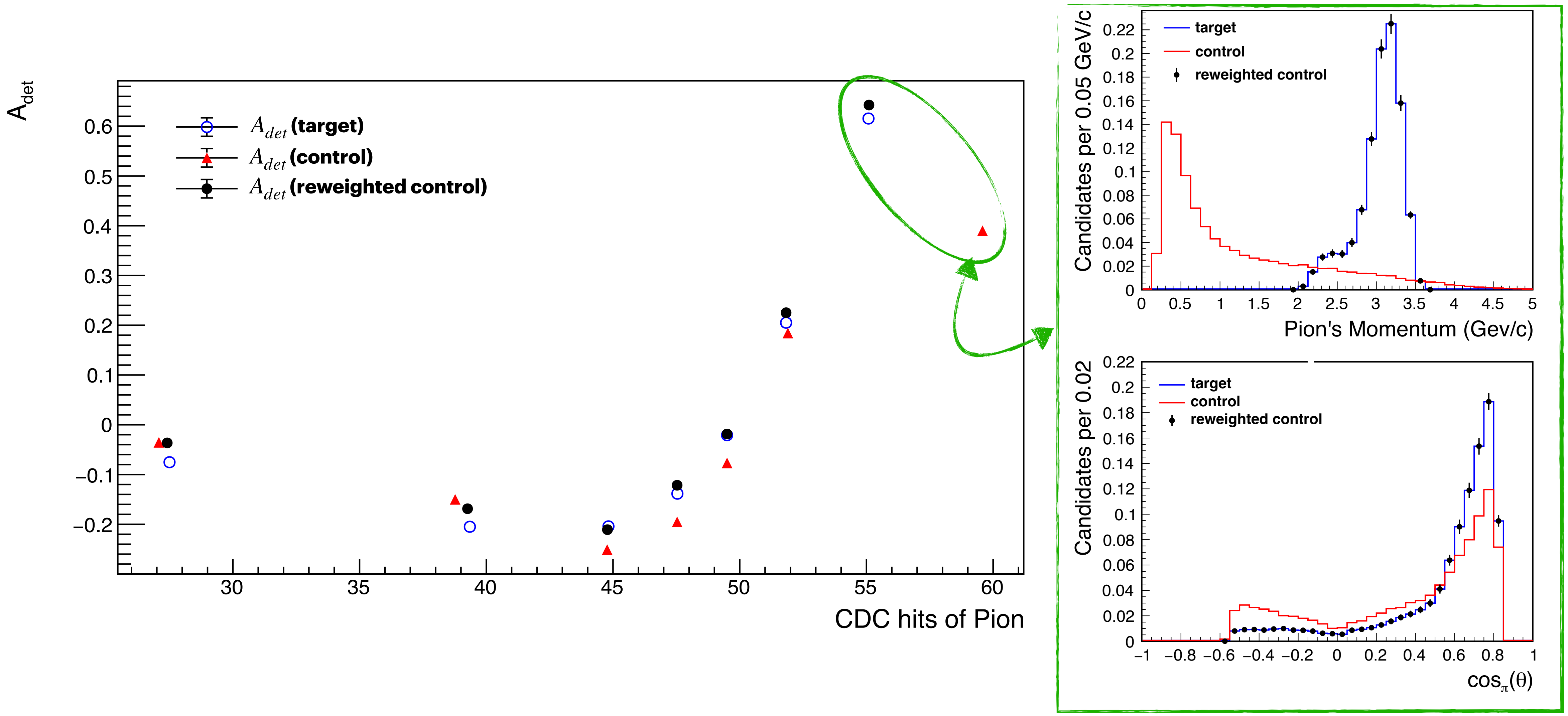




Also investigated other possible dependencies (p_{err}, ω_{err}) but we identify these 3 are the most relevant at the current level of precision.

Sample dependence

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

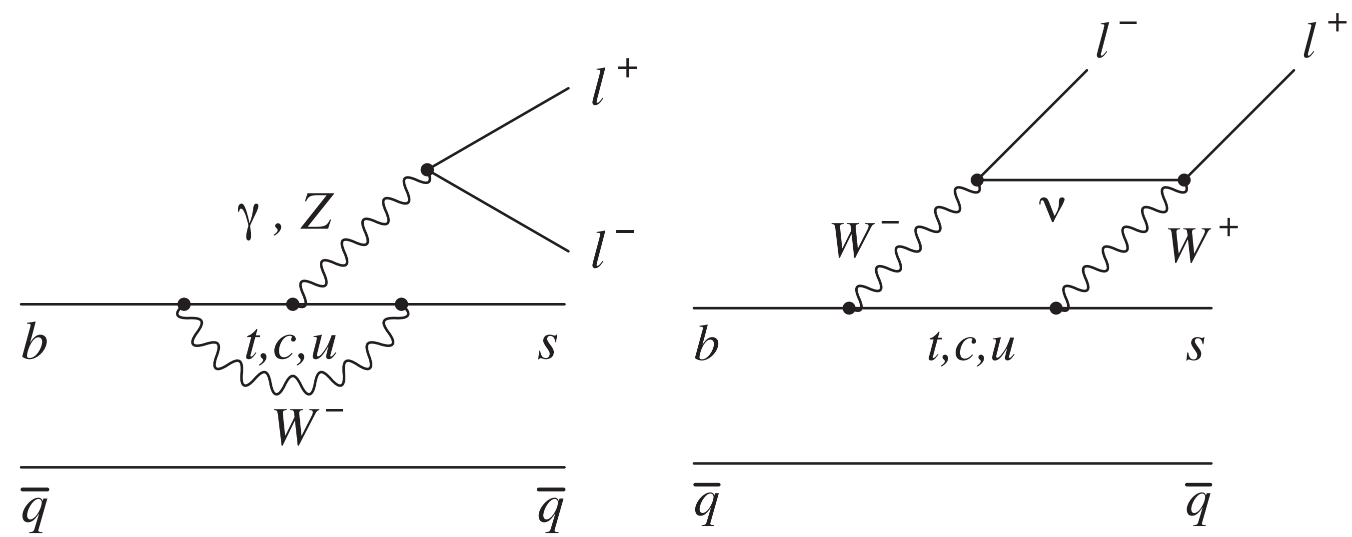


Strategy: provide $\mathscr{A}_{det}$ using the control samples, assigning a systematic uncertainty due to how well we reproduce $\mathscr{A}_{det}$ with our control channels (in MC).

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

$B \to K\tau\tau$ analysis using hadronic tagging

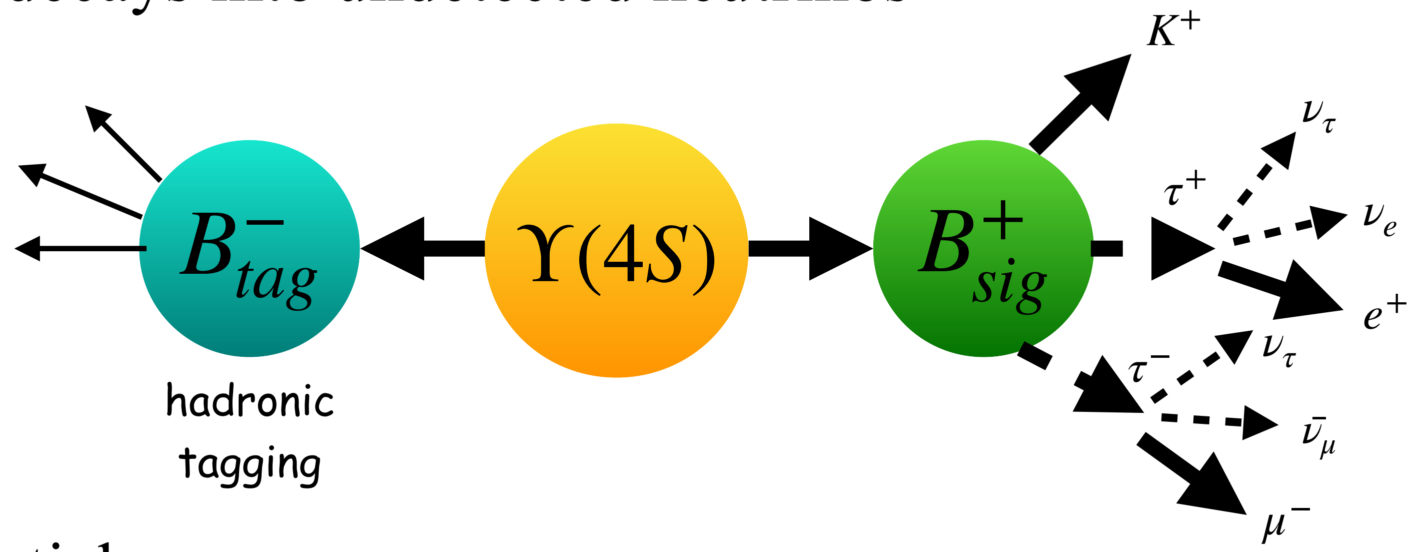
- Flavour changing neutral current is highly suppressed in SM, $\mathcal{O}(10^{-7})$.
- In SM, these decays are forbidden at tree level and only occurs via loop diagram.
- 3^{rd} generation(τ) strongly couples to new physics models.



- *BABAR* collaboration put an upper limit, $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ at 90% C.L.
- Belle did a preliminary study of $B^+ \to K^+\tau^+\tau^-$ and set the upper limit to $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 3.17 \times 10^{-4}$ at 90% C.L.
- Start working on $B^+ \to K^+\tau^+\tau^-$ to do a combined Belle + Belle II analysis (targeting next summer to complete).
- A similar study I will perform later on $B^0 \to K^0_S\tau^+\tau^-$: nobody has measured its branching fraction yet.

Hadronic tagging

- Main challenge: τ reconstruction as it decays into undetected neutrinos eg. $\tau \to \mu \bar{\nu}_\mu \nu_\tau$



- Multiple τ reconstructions are unfeasible at LHC
- Feature of Belle II experiment:
  - Efficient detection of final state particles
  - Good hermetic: 4π acceptance
  - Precisely measured initial kinematics of the beam.
- Tagging: reconstruct one arbitrary B meson (B_{tag}) and put decay constraint on the signal B meson
- Signal side can be reconstructed from beam and B_{tag} kinematics
- Hadronic tagging only uses hadronic decay channels for B_{tag} reconstruction.
- High in purity, but low in efficiency at the order of 0.1 %
- Highly statistically limited

Analysis flow

Reconstruction: process simulated data needed in the analysis applying pre-selection of $B^+ \to K^+\tau^+\tau^-$

done!

reconstruction efficiency(ϵ) $= 1.25 \times 10^{-3}$

Background studies: continuum suppression and potential background sources

Sept 22 - Oct 22

Optimise selection: identify selection that maximises signal-over background using simulation

Nov 22 - Feb 23

Signal extraction
or
upper limit

Mar 23 - Apr 23

Systematics: assess the relevant contribution to systematic uncertainties

May 23 - Jun 23

if time allows similar study with $B^0 \to K^0_S\tau^+\tau^-$

Summary

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

First $\mathscr{A}_{det}$ dependence study. 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 in Belle II's working physics subgroup.

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.

Started $B^+ \to K^+\tau^+\tau^-$ analysis using hadronic tagging to measure its branching fraction. Nobody has measured $\mathscr{B}(B^0 \to K_S^0\tau^+\tau^-)$.

Backup

Motivation

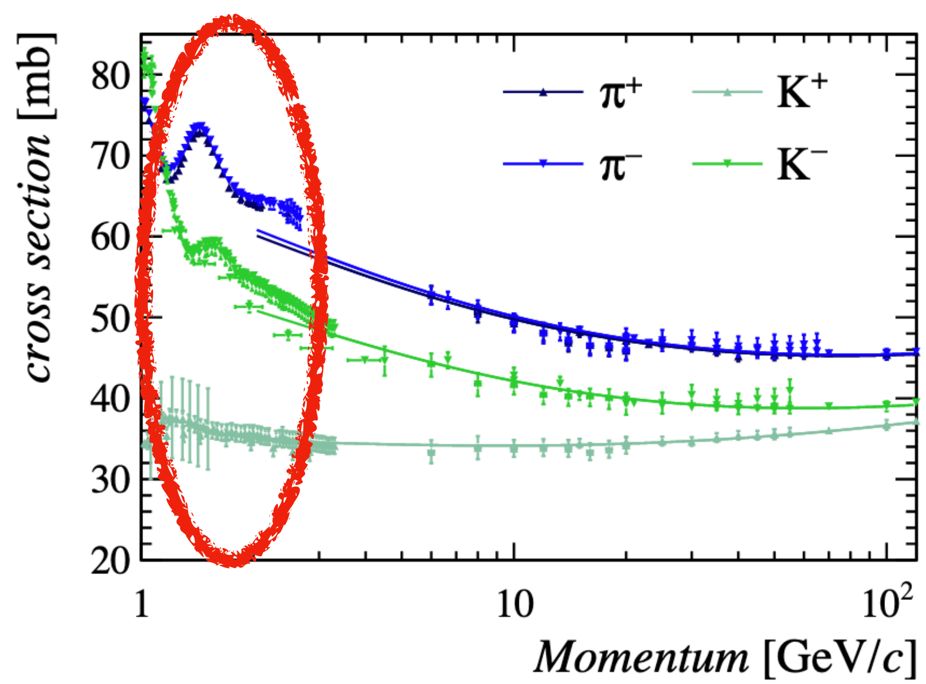
In particle physics, CP violation is the breaking of the combined charge-parity symmetry. Measurements of CP asymmetries ($\mathscr{A}_{CP}$) are a fundamental goal of Belle II physics program.

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.