Contents

Abstract

1. Belle II e SKB accelerator (SuperKEKB)

In this chapter we will see a summary of the principal physics measurements conducted by Belle II experiment, focusing on the ones which could take particularly advantage from the upgrade of the vertex detector, discussed in this work. We will also go through the structure and the operation of the SuperKEKB accelerator and Belle II detector, to conclude (end) with a short view on the actual state of measurements.

1.1 Physics program of the B-factories

Belle II is a general-purpose experiment, committed to making precision measurements of the Standard Model's parameters (SM) and to searching(looking) for the physics Beyond the Standard Model (BSM). In particular the experiment studies the Charge-Parity (CP) violation in the B mesons system and it also searches for New Physics (NP) evidences in the decays of B and D mesons, in τ leptons and in the dark matter sector (DM), in particular searching for dark photons.

The SM is a physics theory that describe three of the fundamental interactions involving elementary particles, which are(?) strong, weak and electromagnetic [interaction] (excluding/with the exclusion of the gravitational one). It classifies all known particles up to now in 4 main groups: quark, leptons, bosons and Higgs (1.1 on the following page).

Despite its tremendous success achieved over the years, predicting with high precision new particles and mechanisms, unknown until that moment, there are a lot of (many) aspects of the (in) Nature, on which it is unable to give answers. Some of them are listed in the following.

- three generations of quark and leptons are known, but it is not known wheter they should be the only ones and the reasons behind their mass hierarchy.

- Higgs mechanism is able to explain the cause of elementary particles' masses through spontaneous electro-weak symmetry breaking, but it doesn't justify neutrinos' ones (masses).

- SM could also predict other bosons Higgs-like, potentially vector bosons (?), whose existance would be justified in some SUper-SYmmetry theories (SUSY) or others of New Physics.

Figure 1.1: Particle classification in the Standard Model

- Another opened question is the matter-antimatter asymmetry in the Universe. Even though CP violation is necessary to explain the current state of the unievrse, the observed quantity is several orders of magnitude less than needed to explain the matter domination over antimatter, which have allowed the evolution of the universe as we know it today.

- The elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which complex phase is at the foundation of CP violation in the quark flavor sector, are diagonal e it could be suggested the existance of a new symmetry, that exists unbroken at high energy (greater than the order (magnitude) of TeV).

All these opened questions encourage the research of new particles and processes (mechanism) that could give reasonable answers. At the energy frontier, experiments like (such as) Large Hadron Collider (LHC) in Geneve, are looking for new particles created (generated) from the proton-proton collision with a center mass energy up to 14 TeV.
At luminosity frontier instead, the mark (trace) of new particles and mechanisms is searched in precision measurements of suppressed reactions in flavour physics or in the deviations from SM. The discrepancies indeed, could be interpreted as a clue (sign) of new physics beyond SM.
The last is the Belle II approach.
So in the following we will see the main physics channels of Belle II, focusing on those that would benefit the most from the upgrade of the whole detector and in particular of the vertex detector.

1.1.1 Belle II Physics channels

As we will see in chapter 2 (reference), all the proposed upgrades fot the VXD (VerteX Detector) aim to reduce the occupancy levels, increasing the robustness

against trasking efficiency and resolution losses from beam background (section 2.1?). [This implies improved tracking efficiency with $p_T <$ 200 MeV/c.] In particular there are three fundamental aspects in physics performance concern VXD and its upgrade:

- Low momentum track finding;
- Vertex and IP resolution;
- Triggers.

Let's see now (????) the main physics channels in Belle II.

FLAVOR PHISICS

CP-violating phases in quark sector :

- as we mentioned above, the amount of CP violation in the SM is not enough to explain the difference observed between baryon-antibaryon matter. New clues could find studying the difference between B^0 and $\bar{B}_0$ decay rates, so measuring the time-dependent CP violation in penguin transition of b → s and b → d quarks (such as B → ϕK^0 and B → $\eta' K^0$). In fact in the SM this violation is expected to be very small, so any significant observation of CPV can be interpreted as a signal beyond the SM.

- Also the CP violation in charm mixing, negligible in the SM, could draw attention to new phenomena in the up-type quark sector.

- Another aspect that need to be understood is the large amount of CP violation in the time-integrated rates of charmless hadronic B decays, such as B → $K\pi$ and B → $K\pi\pi$, observed by other B factories and LHCb.

Ultimate measurements of time-dependent CP violation require a combination of data size and high precision measurement of ΔZ, the distance between the tag and signal in B meson decay vertices. In this respect, the upgrade of the vertex detector could improve a lot the flavor tagging efficiency losses. (??????)

Multiple Higgs bosons : Another fundamental channel is the measurement of the Branching Ratio (BR) of B → $\tau\nu$, which is particularly sensitive to the charged Higgs boson (in addition to a neutral SM-like Higgs) that in general couples more strongly to heavier particles, but also of the decay B → $D^{(*)}\tau\nu$, where BaBar, Belle and LHCb had already reported some anomalies. Moreover extended Higgs mechanism could introduce extra sources of CP violation. We could notice that semi-tauonic decay measurements, rely on efficient and pure tag side B full reconstruction, and so also on the performance of the Vertex Detector. In general the detection of b → τ → l transitions requires good lepton identification below 700 MeV/c (Low momentum track finding).

Flavor Changing Neutral Current (FCNC) :

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- For this purpose, measurements of time-dependent CP violation in (...), triple product CP violation asmmetrie in B → VV decays, and semileptonic decays B → Vlν, V= D^*, ρ are the main approaches.

- It is also important measure b → s$\nu\bar{\nu}$ transitions (such as...) which belong to a class of decays with large missing energy.

- ???? Moreover it's necessary to improve FCNC measurements of b → d, b → s, and c → u transitions.

Most analyses with missing energy in the final state utilise hadronic or semileptonic B full reconstruction techniques and the performance of these method is most dependent on low momentum track finding and so on the capabilities of the vertex detector as well.

Sources of Lepton Flavor Violation (LFV) : LFV in charged lepton decay (at rates of 10^{-8}) is a key prediction in many neutrinos mass generation mechanism and other models of physics BSM. Belle II has an unrivalled sensitivity to τ decays, because of their production in a clean (almost) e^+e^- collision background and the large dataset. The experiment analyze τ leptons to search for LF and CP violation and measurement of the electric dipole moment and (g-2) of the τ.

NON FLAVOR PHISICS

Dark Sector : Belle II has a unique sensitivity to dark matter via missing energy decays. Although most research for NP are indirect, there are different model that predict the existance of new particles at the MeV to GeV scale, that couple to the SM via new gauge asymmetries and they also predict a vast range of hidden particles, including dark matter candidates and new gauge bosons.

In these last two areas, τ and dark sectors physics, the aim is to probe forbidden and ultra-rare transition in low-multiplicity final states with as large dataset as possible. This is mostbly rely on trigger efficiency and new trigger strategies, that could take advantage from the upgrade. Many of these processes can only be accesed at Belle II, so it is fundamental increase the perfomance of the detector.

Binding Hadrons : As time goes on, in other B factories and hadron colliders, a large numbers of states not predicted by conventional mesons interpretation, are discovered, changing our understanding of QCD in the low-energy regime. For this reason, study of quarkonia is a fundamental purpose for Belle II. In fact new particles can be produce near resonance, achievable by adjusting the machine energy, or by intial state radiation, which effectively provides a continuum of center of mass energies.

CKM matrix : Belle II is also dealing with the measurements of CKM observable, the matrix elements and their phases, with unprecedented precision.

1.1.2 Vertex reconstruction in Belle II

1.2 SuperKEKB accelerator

The Belle II sensitivity in the precision measurements that we sift throug in the previous section, is feasible expecially thanks to the complexity and the extraordinary performance of the SuperKEKB accelerator which host the (almost) hermetic detector. This complex facility is the result of efforts and efficient collaboration between the researches of KEK laboratory and all the international working groups that partecipate(take part, contribute) to the experiment.

1.2.1 The facility

SuperKEKB is an asymmetric e^+e^- collider with a circumference of 3 km, and a center of mass energy peak equal to $\sqrt{s} = 10.58$ GeV, which corresponds to the mass of the $\Upsilon(4S)$ resonance. Compared to its predecessor KEKB (which started its operation in 1998 and concluded in 2010), the current accelerator has made it possible to obtain the primacy in luminosity ever achieved, equal to $4.7\dot{1}0^{34}cm^{-2}s^{-1}$ in July 2022, using a new scheme to accelerate and collide the beams, through some improvements and additions in the components of the accelerator itself. Moreover the new upgrade of the machine, still under study, will also include (provide for) other intervention expecially to cope with higher background level, in view of further increase of the luminosity.
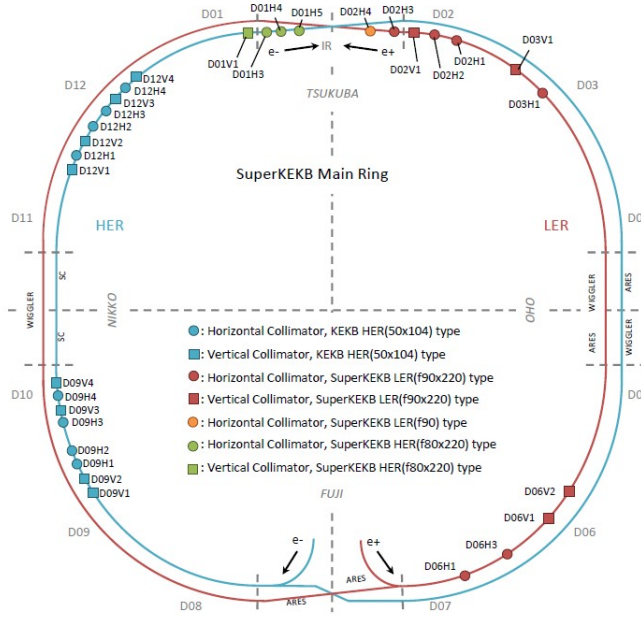

Figure 1.2: SuperKEKB accelerator in 2021. The letters V and H denote respectively vertical and horizontal collimators. Each ring is divided in 12 sections, from the first called D01 to the last D12.

We will briefly see the main features(characteristics) and parameters of the accelerator.

Luminosity

Luminosity is one of the key parameters of an accelerator, it represents the interaction rate per unit of cross section between colliding particles:

$$L = \frac{1}{\sigma}\frac{dN}{dt} \tag{1.1}$$

from which, reversing the equation to obtain N, namely the number of observable physical events:

$$N = \int_0^T L\sigma dt \tag{1.2}$$

where T is the duration of the experiment, σ the cross section of the physical process of interest. (Specifically) In particular luminosity is strictly dependent from machine parameters and from the main features (characteristics) of the beam. With respect to this, it can be expressed as:

$$L = ... \tag{1.3}$$

where ......

As we have already seen, SuperKEKB holds the actual world record in luminosity, with a peak of $4.7\dot{1}0^{34} cm^{-2}s^{-1}$ with $\beta_y^* = 1.0$ mm. In the near future the target will be to reach a luminosity of $6.3 \; \dot{1}0^{35} \; cm^{-2}s^{-1}$, increasing current beams and reducing their section in the Interaction Point (IP), squeezing the betatron function up to (a value of??) $\beta_y^* = 0.3mm$. (the monitoring/management) For these reasons, monitoring the beams background becomes one of the most important aspect both to reach the target (goal) and to improve the possible precision measurement of physics.

At the moment (currently, now) it is estimated that the background should remain accettable up to a luminosity value equal to $2{,}8\dot{1}0^{35}cm^{-2}s^{-1}$ with $\beta_y^* = 0.6$ mm.

As we shall (?) see, the opportunity (change, possibility) to achieve higher luminosity is closely (strictly) linked (dependent, relate) to an upgrade plan of both the detector and the accelerator.

???????? Most part of the measurements are rare dacays, with small branching fraction, so it is necessary to have a lot of events. [CONTINUA]

Beam energy

Energy beams is mostly decided by the physics program interesting for the experiment. Currently SuperKEKB collides an electron beam with energy of 7 GeV (High Energy Ring, HER) , with a positron beam of 4 GeV (Low Energy Ring, LER), reaching a center of mass energy peaked to $\Upsilon(4S)$ resonance. Also the choice of colliding (using) asymmetric beam (like its predecessor KEKB, which collided (got collide) electrons beam of 8 GeV with a positrons beam of 3.5 GeV) is necessary to identify and measure decay vertices of particles created in the collision. Indeed this mechanism allows to boost the decay products, improving the vertices reconstruction and increasing the sensitivity of the physics measurement, too. In particular this makes possbile time-dependet measurements, expecially in CP violation. We have already seen some of the physics
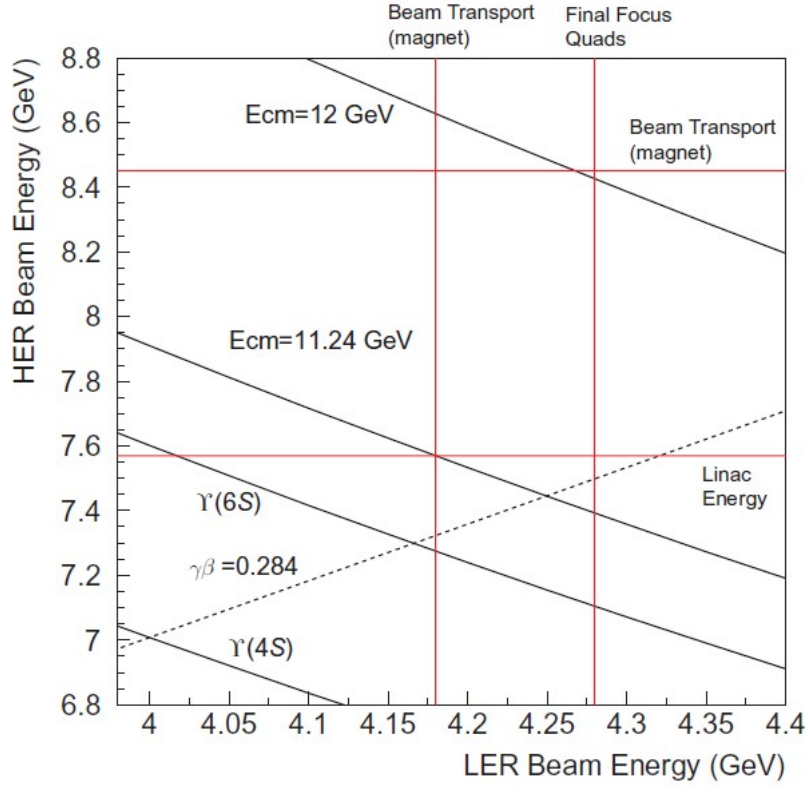
Figure 1.3: Beam energies to reach center of mass energy equal to $\Upsilon(4S)$, $\Upsilon(6S)$,11.24 GeV and 12 GeV. Horizontal axis represents the energy of LER and the vertical one the energy of HER.

behind this choice in section ?????.

In figure ?? on page ?? the flexibility of the energy of both beams LER and HER is showed. The possible range covers energies which goes from the $\Upsilon(1S)$ resonance to the $\Upsilon(6S)$, qith a peak in 11.24 GeV.

1.2.2 "Nano-beam" scheme

As mentioned in the previous section, a key elemnt to define the luminosity is the *beta function* β in the Interaction Point (IP). To be able to increase luminosity, it's necessary to decrease the value of β depending on the variation of the other machine parameters, but not only, which are part of its definition (richiama equazione con parametri macchina). The mechanism used in SuperKEKB is called *nano-beam scheme*, and it allowed to obtain luminosity 40 times greater than that of KEKB, managing to (succeding) decrease of $1/20$ the β function in the IP.

This new scheme, designed by P. Raimondi, dictates that the beams collide at large angle, in SuperKEKB equal to 83 mrad (keeping beams divided through quadruople magnets), in order to reduce the *hourglass effect*, which succeed when the bunches in the beam are much longer.

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We can see briefly the most important parameters that influence the mechanism?????

The overlap area of the beams is localized and its lenght is given by:

$$d = \frac{\sigma_x^*}{sin\phi_x} \qquad (1.4)$$

with ϕ_x defined as half of the crossing angle. The overlap lenght d represent the real lenght of the bunch to consider in the evaluation of the hourglass effect, and it is smaller than the effective bunch lenght along the direction of the beam axis. To reduce this effect, it's necessary to get:

$$\beta_y^* \geq d = \frac{\sigma_x^*}{sin\phi_x} \qquad (1.5)$$

Therefore to increase the β function in the IP, the value of d has to diminish, decreasing as aconsequence the horizontal section in the IP and also icreasing the crossing angle. Using a crossing angle large enough, has other positive implications on the operation of the accelerator:

- allows the placement of a new focusing system in the IP with a superconducting quadrupole magnet;

- allows to have two distinct line which host HER and LER beams;

- diminisches the *fringe fields* effect in the IP, wihch are the residuals of the magnets (magnetic fields) in the proximity (nearby).

In figure 1.4 on the facing page are reported the main machine parameters (default value) of the SUperKEKB accelerator.

1.2.3   Background monitoring system

Background is one of the most important problem for a particle detector, both for precision measurements of physics and for the performance of the different layer detector which constitute (make up) Belle II. For this reason deveral detectors are used to obtain measurements of radiation dose on both detector and delicate regions of the accelerator, to intervene as soon as possible in case of too high levels are reached. Indeed large doses of radiation could cause accidental damages on the detector, decreasing its performance.

In the chapter 2 (reference) we will go through the main (primary, leading) reasons of background. For now we mention some of the monitoring devices for the backgorund in SuperKEKB.

- Diamonds detector (called "Diamonds') which control the rate of the radiation dose in the interaction region of the beam pipe. These also are part (take part) of the "fast beam abort system", which is a control system that collect (consider) data from different detector to evalute (valutare nel senso di decidere) the beam "turning off", in order to avoid that events out of control could cause damage (harm) to the whole structure.

- CLAWS (sCintillation Light And Waveform Sensors), made by scintillator of plastic material and silicon photomultipliers, and used to monitor the

	LER		HER	Unit
E	4.000		7.007	GeV
I	3.6		2.6	A
N_b		2500		
C		3016.315		m
ε_x	3.2		4.6	nm
ε_y	8.64		11.5	pm
β_x^*	32		25	mm
β_y^*	270		300	μm
$2\phi_x$		83		mrad
α_p	3.25×10^{-4}		4.55×10^{-4}	
σ_δ	8.08×10^{-4}		6.37×10^{-4}	
V_c	9.4		15.0	MV
σ_z	6		5	mm
ν_s	-0.0247		-0.0280	
ν_x	44.53		45.53	
ν_y	44.57		43.57	
U_0	1.87		2.43	MeV
τ_x/τ_s	43.1/21.6		58.0/29.0	msec
ξ_x	0.0028		0.0012	
ξ_y	0.0881		0.0807	
L		8×10^{35}		$\mathrm{cm^{-2}\,s^{-1}}$

Figure 1.4: Machine parameters of SuperKEKB. The mark "*" indicate values in the IP.

Belle II background in the nearby (proximity) of the beam injection (main ring).

Con i diamanti fa parte della logica del sistema di aborto del fascio.

- TPC's (Time Projection Chambers) che fornisce misure sulla direzione del flusso dei neutroni nel tunnel che ospita l'acceleratore.

- Tubi di He^3 per il conteggio dei neutroni termici (con energie cinetiche inferiori a 1/10 di eV, generalmente intorno a 0.025 eV) intorno al rivelatore Belle II.

1.3 Il rivelatore Belle II

1.3.1 Vertex Detector (VXD)

1.3.2 Central Drift Chamber (CDC)

1.3.3 Particle identification system (TOP e ARICH)

1.3.4 Calorimetro elettromagnetico (ECL)

1.3.5 K_L muon detector (KLM)

1.3.6 Sistema di trigger

1.4 Stato attuale e prospettive delle prese dati

1.4.1 Alcune ulteriori modifiche rispetto a KEKB

2. Upgrade di Belle II

2.1 Sorgenti di background e limitazioni di Belle II

2.1.1 Effetto Touschek

2.1.2 Beam-gas scattering

2.1.3 Radiative Bhabha scattering e processi a due fotoni

2.1.4 Radiazione di sincrotrone (SR)

2.1.5 Instabilità "Head-tail"

2.1.6 Stato attuale del background e implicazioni future

2.2 Motivazioni per l'upgrade

2.3 Sommario di possibili upgrade

2.3.1 DEPFET

2.3.2 Thin sensor

2.3.3 CMOS MAPS

2.3.4 SOI

3. Il rivelatore VTX

3.1 Layout del rivelatore VTX

3.1.1 iVTX

3.1.2 oVTX

3.2 Simulazioni di performance

3.3 Caratteristiche chip sensore

3.4 Struttura meccanica

4. Sensori CMOS MAPS

4.1   Rivelatori a semiconduttore

4.2   Sensori a pixel monolitici/ibridi

4.3   Tecnologia CMOS MAPS

4.4   Storia degli sviluppi di Monopix

5. TJ-Monopix 2 characterization ??

5.1 Matrix and flavors

5.1.1 Mask (operation) and noisy pixels

5.1.2 Analog and digital readout

5.1.2.1 BCID reset

5.1.2.2 Main registers (and conversion?)

5.1.3 Comparison of trends from data with simulation

5.2 Characterization by injection

In the prototype under test (study), W14R12 chip, some problems (raised up) arose right from the beginning, linked (concerned) pixels of the matrix both for the analog and digital part. Despite its predecessor Tj-Monopix 1, Tj-Monopix 2 is equipped with a circuit which allows the *threshold tuning.*In other words it can adjust, even if only few DAC, every pixel threshold, in order to have a global threshold on the matrix as uniform as possible, or in any case a dispersion as small as possible.

Preliminarly it's necessary to study the threshold distribution on the whole matrix. We have separately analyzed the four flavors, to be able to study their main difference in working (performance) and features.

The ultimate purpose of this measurement is to describe (depict, mark out) the behaviour of each pixel, injecting a charge equivalent to the typical energy released from electrons emitted in radioactive decays (decays of radioactive materials) and in particular those produced by the electronic capture of ^{55}Fe (presente in laboratorio). As explained in the previous section (reference), the ^{55}Fe has an emission spectrum (lines) with lines quite peaked (sharp) and this allows to compare data more easily. The first line is at 5.9 KeV which corresponds on average to about 1616 e^- released (through the pixel??). For this reason during the injection measurement, it's mandatory to know the conversion between DAC and e^- (reference) and to inject charges in order to study pixel behaviour the right region, which are more interesting from a physical point of view.
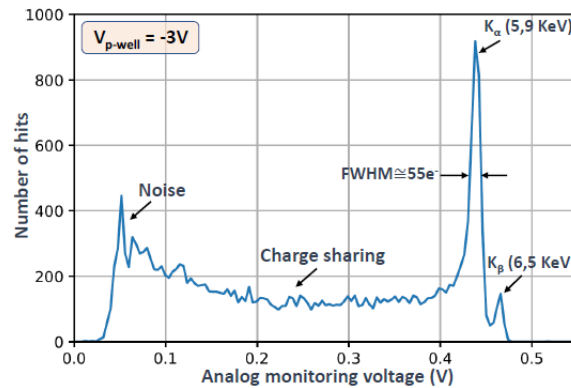
Figure 5.1: ^{55}Fe (radiactive source) emission spectrum using the analog output of a PMOS reset front-end of TJ-Monopix 1. (referenceeeeee)

5.2.1 Problema nel circuito di iniezione

5.2.2 Misura dello shift medio sul valore di threshold per cariche iniettate superiori a 140 DAC

5.2.3 Curva S e threshold

5.2.3.1 Normal FE

5.2.3.2 Cascode FE

5.2.3.3 HV-Cascode FE

5.2.3.4 HV-Normal FE

5.2.4 Noise and Equivalent Noise Charge (ENC)

5.2.5 Curve del Time Over Threshold (TOT) e fit

5.3 Caratterizzazione con le sorgenti radioattive

Fe55, Am241, Cd109, Sr190

5.3.1 Calibrazione della capacità di iniezione

6. Conclusioni