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Jérémy MARGUIN

DEVELOPMENT OF THE NEW VERTEX DETECTOR OF THE BELLE II EXPERIMENT

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ABSTRACT

L'expérience *Belle II* au sein de l'accélérateur *SuperKEKB* se prépare à une amélioration de son détecteur de vertex (*VTX*), pour pouvoir fonctionner à plus haute luminosité. Parmi les sources de bruit de fond issues directement des faisceaux d'électrons et de positrons, le rayonnement synchrotron est composé de photons X à basse énergie pouvant atteindre les couches de détection du détecteur de vertex et générer des signaux parasites. La paroi interne du tube à vide est à l'heure actuelle recouverte d'une fine couche protectrice de $10\,\mu\text{m}$ d'or afin d'absorber ces rayons X. En contrepartie, cette couche d'or contribue au budget de matière total, ce qui dégrade directement la résolution spatiale des vertex de désintégration reconstruits. Au cours de ce stage, un outil de simulation de type *Toy Monte Carlo* a été développé afin de modéliser le trajet et l'impact des photons X au travers d'une description précise des matériaux du *VTX* et de la paroi du tube à vide. Les résultats obtenus sous forme de figures de sensibilité sur la gamme d'énergie $0-100\,\text{keV}$ permettent d'étudier l'influence de la couche d'or sur la sensibilité au rayonnement synchrotron du *VTX*. Ils mettent notamment en évidence le rôle dominant de l'or dans l'absorption des rayons X, et permettent de quantifier l'augmentation de sensibilité induite par la réduction de l'épaisseur d'or.

Ces résultats sont une première étape vers l'évaluation de la faisabilité de la réduction de la couche protectrice. Une étude future sur le spectre de rayonnement synchrotron produit au sein de l'accélérateur permettra, avec les figures de sensibilité obtenues, de conclure sur la réduction de cette épaisseur d'or.

The *Belle II* experiment is currently preparing an upgrade of its vertex detector (*VTX*) to be able to operate at higher luminosity. Among the beam-induced background sources, synchrotron radiation is made of low energy X-ray photons that can reach the vertex detector layers and generate parasitic hits. In order to absorb these X-rays, the inner wall of the beam pipe is currently coated with a $10\,\mu\text{m}$ gold layer. However, this absorbing layer contributes to the total material budget which directly degrades the spatial resolution of the reconstructed decay vertex. During this internship, a *Toy Monte Carlo* simulation tool was developed to model the transport and generated hits of X-rays photons through a detailed description of the *VTX* materials and the beam pipe. The sensitivity maps obtained over the energy range $0-100\,\text{keV}$ allow us to study the influence of gold layer on the *VTX* sensitivity to synchrotron radiation. These results emphasise the dominant role of gold layer in X-ray absorption and quantify sensitivity evolution due to the reduction of gold thickness.

This is the first step towards evaluating the feasibility of reducing this protective layer. A future study of the synchrotron radiation spectrum produced within the accelerator with the obtained sensitivity maps will provide the necessary information to draw a conclusion regarding the gold layer thickness.

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INTRODUCTION

The internship took place at the IPHC (*Institut Pluridisciplinaire Hubert Curien*) within the *Belle II* group. *Belle II* experiment is an international collaboration dedicated to the search for signs of new physics beyond the Standard Model. The detector collects data at *SuperKEKB* accelerator (in Tsukuba, Japan), an asymmetric electron-positron collider operating at $\sqrt{s} = 10.58 \text{ GeV}$ to study $b\bar{b}$, $c\bar{c}$ and $\tau^+\tau^-$ pairs, thanks to a 7 GeV electron beam and a 4 GeV positron beam. *SuperKEKB* is currently the most luminous synchrotron collider in the world, with a current record of instantaneous luminosity at $5.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and aims to target an instantaneous luminosity of $6.0 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ in the next decade.

The vertex detector must be upgraded in order to operate under this higher luminosity condition, the jump by an order of magnitude is expected after 2032. Improving the resolution of reconstructed vertices is another goal. This future upgrade, named *VTX*, relies on faster silicon pixel sensors with improved granularity, and more resilient to a higher flux of particles. This last asset is the starting point of my internship which aims to quantify the impact of *synchrotron radiation* background on this future vertex detector.

Synchrotron radiations are produced by the electron and positron beams deflected by final focusing magnets inserted inside the experiment, close to the interaction point. They are low energy X-ray photons propagating through the beam pipe. These photons constitute a source of parasitic particles for the vertex detector. The current solution to reduce this background is a thin gold shielding layer of $10 \mu\text{m}$ deposited on the inner wall of the beam pipe, allowing it to absorb most of these X-rays before they reach the active layers of the vertex detector. However, this gold layer has the direct drawback of increasing the material budget crossed by particles and so worsens the vertex spatial resolution. *VTX* development with improved tolerance to the number of particles allows us to reconsider this absorbing gold layer and reduce its thickness.

The objective of this internship is to model the sensitivity of the future *VTX* detector to synchrotron X-ray radiation. It aims to quantify the effects of reducing the absorbing gold layer considering both the positive impact on vertex resolution improvement and the negative side of an increased sensitivity to synchrotron X-rays. During this internship, a dedicated simulation tool has been developed in C++, which relies on a *Toy Monte Carlo* approach to the transport of X-ray photons through the detector and their interaction, and a precise description of the *VTX* five layer geometry.

The first chapter introduces the experimental physics concepts necessary to understand photon transport within the accelerator and detector. The second chapter details the construction of the simulation tool and the implementation of the *VTX* and beam pipe geometry. Finally, the third chapter presents and discusses the obtained sensitivity maps, and the influence of the gold thickness on the *VTX* sensitivity to synchrotron radiation.

Chapter 1

Experimental elements

This chapter presents the necessary experimental elements about light-matter interactions and several elements about *Belle II* detector and *SuperKEKB*.

1.1 Belle II detector

The *Belle II* experiment, located at *SuperKEKB* (electron-positron collider), aims to search for signs of new physics by performing precision measurements. *Belle II* detector is a large cylindrical detector (Figure 1.1) composed of different concentric sub-detectors:

- a Vertex Detector (VXD) that measures vertex positions
- a Central Drift Chamber (CDC) that reconstructs trajectories and measures momenta
- two ring-imaging Cherenkov counters (TOP and ARICH)
- an electromagnetic calorimeter (ECL) composed of CsI(Tl) scintillator crystals and is located inside a 1.5 Tesla superconducting solenoid
- and a K_L / muon detector designed to detect these particles, which interact very poorly with other detectors

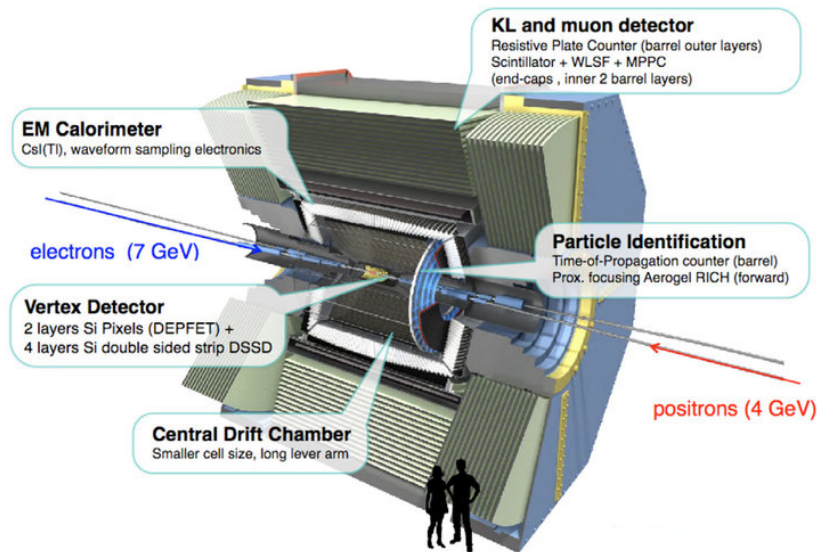


Figure 1.1: Belle II Detector [1]

1.2 The vertex detector upgrade

As *SuperKEKB* increases its luminosity, *Belle II* sub-detectors will face higher particle rate and higher detector occupancy (10 MHz/cm² today vs 30 MHz/cm² estimated after the upgrade). To be able to function at higher luminosity, the detectors are upgraded, such as the vertex detector with the *VTX* upgrade under development.

The *VTX* is composed of five detection layers (ladders) placed just around the beam pipe (see Figure 1.2), the sensors placed on each ladder are based on DMAPS (*Depleted Monolithic Active Pixel Sensor*) technology. Compared to the current VXD, the *VTX* provides better granularity thanks to smaller pixel pitch (30 μm vs 80 μm), and faster sensors (integration time of 100 ns vs 20 ms).

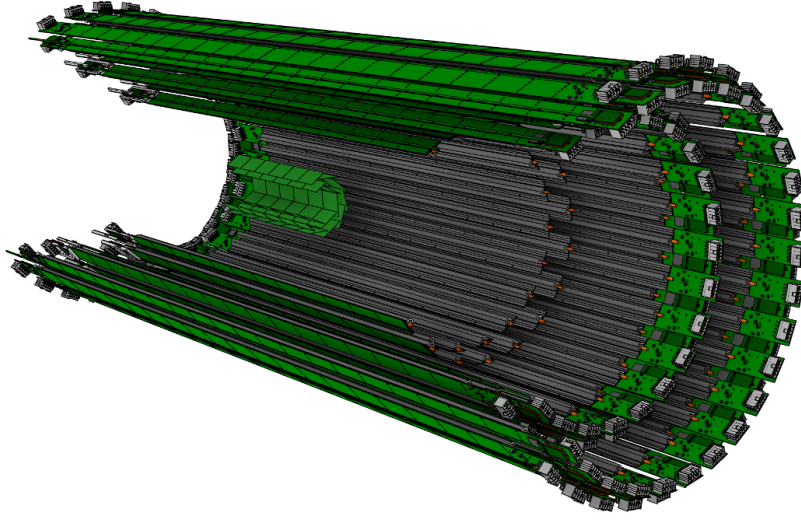


Figure 1.2: VTX ladders

The role of the vertex detector in the *Belle II* experiment is to be able to distinguish vertices (see Figure 1.3), especially for the studied B mesons for which the average distance between two vertices is 120 μm . The reconstructed vertex position can be used to constrain event selection and improve signal purity.

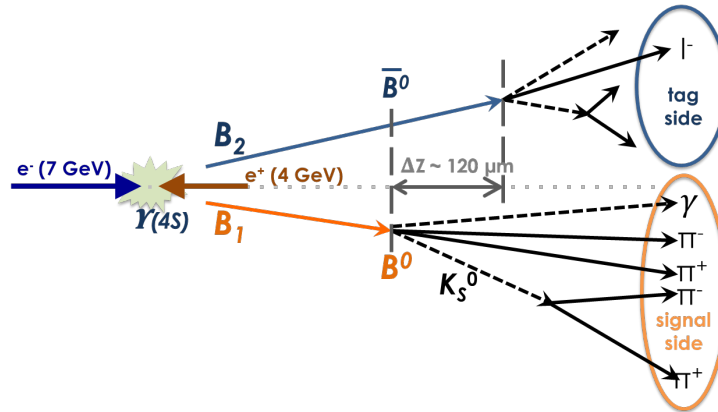


Figure 1.3: Principle of $B^0 \bar{B}^0$ tagging, with one meson fully reconstructed as signal and the other partially identified with one or few tracks used to determine the meson/anti-meson nature (tagging).

1.3 Synchrotron radiation at Belle II

A category of background that directly affects the instrumentation is the *beam-induced background*, produced by unwanted interactions between positrons and electrons within the beam pipe. Different sources of *beam-induced background* exist at *Belle II* [2], they are due to intra-bunch scattering, residual gas (inside the beam pipe) collisions, beam injection, or undesirable collisions such as Bhabha scattering ($e^+e^- \rightarrow e^+e^-\gamma$), or two photon processes ($e^+e^- \rightarrow e^+e^-e^+e^-$)...

In addition to those processes, *synchrotron radiation* also contributes to the detector background. It is produced when electrons and positrons are bent by the accelerator's magnetic fields (due to the final focus magnets near the interaction point), emitting X-ray photons.

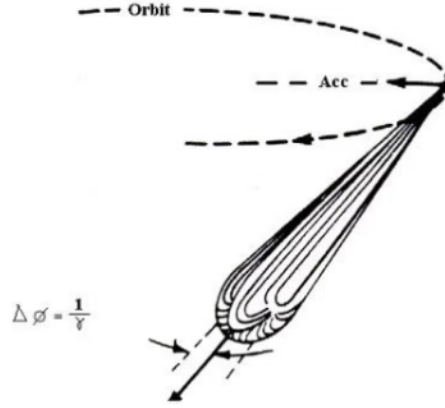


Figure 1.4: Emission of synchrotron radiation from an accelerated relativistic particle

The radiated power P_γ scales with the fourth power of the particle energy ($\gamma \propto \frac{E}{m_e c^2}$) and inversely with the square bending radius ρ [3].

$$P_\gamma = \frac{e^2 c}{6\pi\epsilon_0} \frac{\beta^4 \gamma^4}{\rho^2} \quad (1.1)$$

Thus, the *synchrotron background* is dominated by the electron beam (HER: *High Energy Ring*) at 7 GeV.

We can also define the *critical energy* E_c , which characterizes the energy scale of the synchrotron radiation spectrum:

$$E_c = \frac{3}{2} \hbar c \frac{\gamma^3}{\rho}. \quad (1.2)$$

In Belle II, the synchrotron radiation photons are estimated to be emitted in the low energy X-ray regime 0–100 keV [4], the accumulation of these photons can directly damage the sensitive layers of the vertex detector and their instantaneous rate can saturate the readout system.

The current solution consists of coating the inner beam pipe with a thin 10 μm layer of gold. This layer absorbs a large fraction of the X-rays before they can reach the sensitive layers of the vertex detector.

1.4 Light-matter interactions

In this internship, we focus on photon transport through matter. Several mechanisms coexist, and their probabilities depend on both the photon energy and the nature of the material.

1.4.1 Photoelectric effect

The photoelectric effect (Figure 1.5 (b)) is the ejection of a bound electron when a photon transfers all of its energy to this electron. The photon disappears, and the electron recoils with a kinetic energy equals to the difference between photon energy E_γ and the binding energy E_b of the electron:

$$T_e = E_\gamma - E_b \quad (1.3)$$

We refer to this effect as a destructive process because the photon is completely absorbed.

1.4.2 Compton scattering

Compton scattering (Figure 1.5 (c)) is an inelastic scattering (or incoherent) process in which a photon transfers part of its energy to an electron. It results in the photon continuing to propagate in a modified direction and with lower energy (longer wavelength), while the electron recoils. Equation 1.4 describes the change of wavelength $\lambda \rightarrow \lambda'$ of the scattered photon, with a scattering angle θ .

$$\lambda' - \lambda = \frac{h}{m_e c^2} (1 - \cos\theta) \quad (1.4)$$

This effect is not destructive, the scattered photon keeps propagating and can undergo further interactions.

1.4.3 Elastic scattering

Unlike Compton scattering, elastic scattering (or coherent scattering) - (Figure 1.5 (a)) involves photon interacting with an electron without energy transfer, photon is just scattered in another direction while conserving its initial energy.

1.4.4 Pair production

Pair production involves the conversion of a photon within the Coulomb field of a nucleus into a pair of an electron and a positron. The energy of the photon must be at least $E_\gamma = 1.022 \text{ MeV}$, which corresponds to twice the rest mass of the electron.

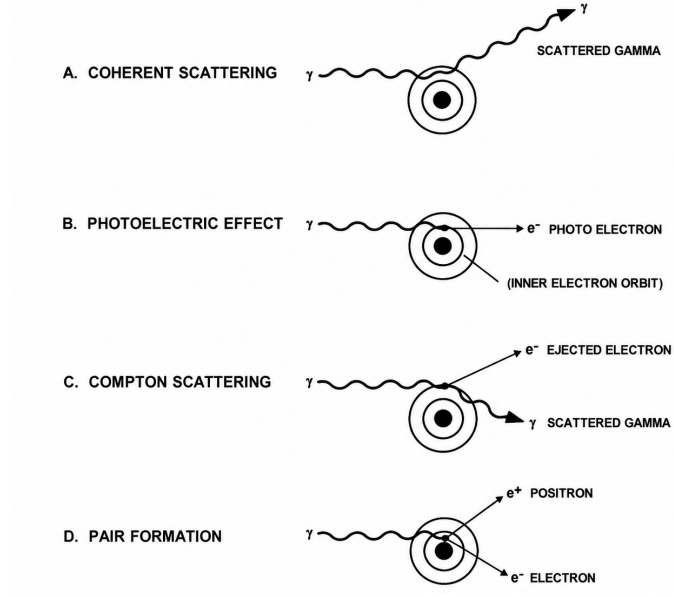


Figure 1.5: Four main processes in light-matter interactions [5]

1.4.5 Attenuation coefficient

To quantify the probability and importance of the different photon–matter interaction processes previously presented, we introduce the total attenuation coefficient, μ . A usual form of this coefficient, called the linear attenuation coefficient, is usually expressed in cm^{-1} , it represents the interaction probability of a photon per unit length in the material.

The total linear attenuation coefficient can be decomposed into the sum of individual contributions of each process (see Equation 1.5 and Figure 1.6).

$$\mu = \mu_{photoelec} + \mu_{compton} + \mu_{elastic} + \mu_{pair} \quad (1.5)$$

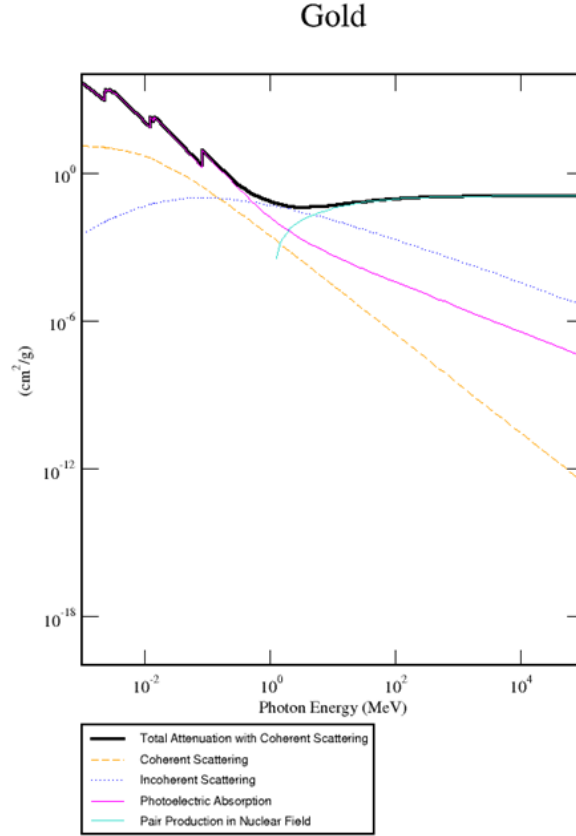


Figure 1.6: Total and partial mass attenuation coefficient for photons in Gold [6]

Each contribution varies with the photon energy E and the atomic number of the medium, Figure 1.7 shows the different interaction regimes depending on both these two parameters.

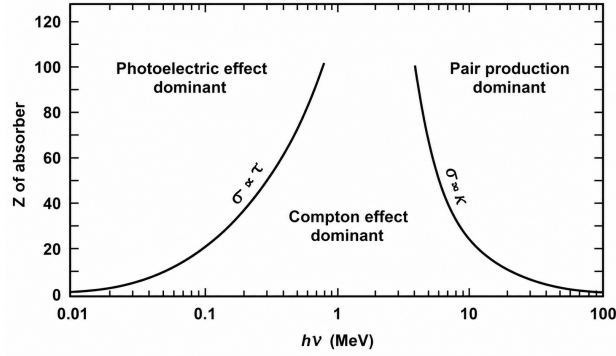


Figure 1.7: Interaction regimes for photon interactions with matter [5]

Above a few MeV, pair creation progressively dominates the total attenuation. At lower energies, the competition is between the photoelectric effect and Compton scattering, the photoelectric effect dominates in high Z materials, whereas Compton scattering becomes dominant in low Z materials and at intermediate photon energies.

1.5 Beer-lambert law

When photons cross a material, their number decreases according to the Beer-Lambert law, which describes the attenuation of a photon beam's intensity due to interactions within the medium.

$$dN = -\mu(x)N(x) dx \quad (1.6)$$

with $\mu(x)$ the linear attenuation coefficient and x is the distance crossed by the photon in the material,

which can be rewritten as this differential equation:

$$\frac{dN}{dx} = -\mu(x)N(x) \quad (1.7)$$

The solution for the number of surviving photons with the crossing distance x is:

$$N(x) = N_0 e^{-\int_0^x \mu(x') dx'} \quad (1.8)$$

To simplify the treatment of a varying attenuation coefficient along the trajectory, the optical depth is introduced:

$$\tau(x) = \int_0^x \mu(x') dx' \quad (1.9)$$

It represents the cumulative attenuation of the photon along its trajectory. In a multi-material layered configuration, each constituent layer contributes to the total optical depth.

Each layer i contributes individually:

$$\Delta\tau_i = \mu_i t_i^{\text{eff}} \quad (1.10)$$

with t_i^{eff} , the effective thickness of the layer i crossed by the photon and μ_i , its linear attenuation coefficient. This law will be used to model the interaction of photons in our simulation, see Chapter 2.

1.6 Impact of multiple scattering on spatial resolution of vertices

Reconstruction of vertices by a vertex detector is affected by spatial uncertainty due to the intrinsic precision of the detector's sensors and multiple scattering undergone by charged particles while traversing detector materials. Equation 1.11 parametrizes this uncertainty [7],

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}(\theta)} \quad (1.11)$$

where:

- a quantifies the intrinsic detector's sensor precision
- b the contribution from Coulomb scattering (multiple scattering)
- p and θ correspond respectively to the momentum of the particle and its polar angle

We focus in this internship on the second term b , Figure 1.8 illustrates the origin of this uncertainty while reconstructing vertex position using the two first detection layers of the *VTX*. As charged particles propagate through the beam pipe and the detection layers, they undergo several small angular deviations due to multiple Coulomb interactions between particle and the atoms composing the material. So going through a material results into a global angular deviation θ_{MS} .

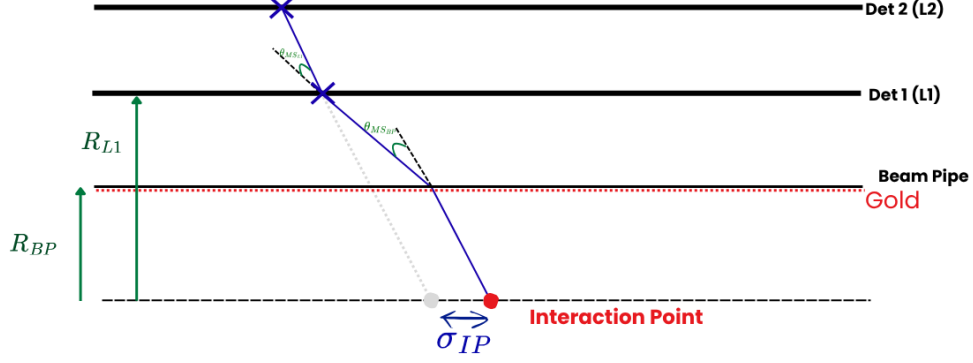


Figure 1.8: Reconstructed vertex uncertainty due to multiple scattering (here σ_{IP} corresponds to σ_{d_0})

I achieved an estimation of the geometry dependency of the factor b (see Appendix A):

$$b^2 \propto \left(R_{BP} \sqrt{\frac{X}{X_0}} \right)^2 + \left(R_{L1} \sqrt{\frac{X}{X_0}} \right)^2 \quad (1.12)$$

It is directly dependent on both position of L1 and the Beam Pipe, and their respective material budget $\frac{X}{X_0}$ where X is the thickness of the material crossed and X_0 the radiation length.

It shows that the angular dispersion increases with the material budget. Consequently, adding a gold layer close to the interaction point increases beam pipe's total material budget, and so multiple scattering dispersion which degrades the vertex spatial resolution. So reducing gold layer thickness, improves spatial resolution, these results are discussed in Chapter 3.

Chapter 2

Simulation of the impact of synchrotron radiation

This chapter presents the motivation and development of the tool used during this internship to model the impact of X-ray synchrotron radiation on the five layers of the *VTX*.

2.1 Simulation strategy

The software **BASF2** (*Belle II Analysis Software Framework*) [8] is developed by the *Belle II* collaboration as its main software used in all aspects of the data-processing chain, such as generating simulated data, reconstructing particle trajectories, clustering, and also in analysis. This software allows the reproduction of the geometry of the current *Belle II* detector and its future sub-detectors upgrades, such as the *VTX*. Currently, **BASF2** does not reproduce the structure of the *VTX* with precision, modeling the constitutive components with only a silicon layer, which thickness is adjusted to match the expected final material budget of the layer. We have little information about the complex structure of the *VTX* and the impact of each material on the light-matter interaction.

Consequently, a new simulation tool has been developed during this internship in **C++**, using an object-oriented architecture.

2.2 Geometry of the *VTX*

A realistic description of the *VTX* geometry is essential to accurately model the transport and interactions of X-ray photons within the detector. Each material (metals, silicon, carbon fiber...) is described [9] by its passive or active (sensitive) characteristics when being traversed by charged particles (*hit* generated by the sensitive layer).

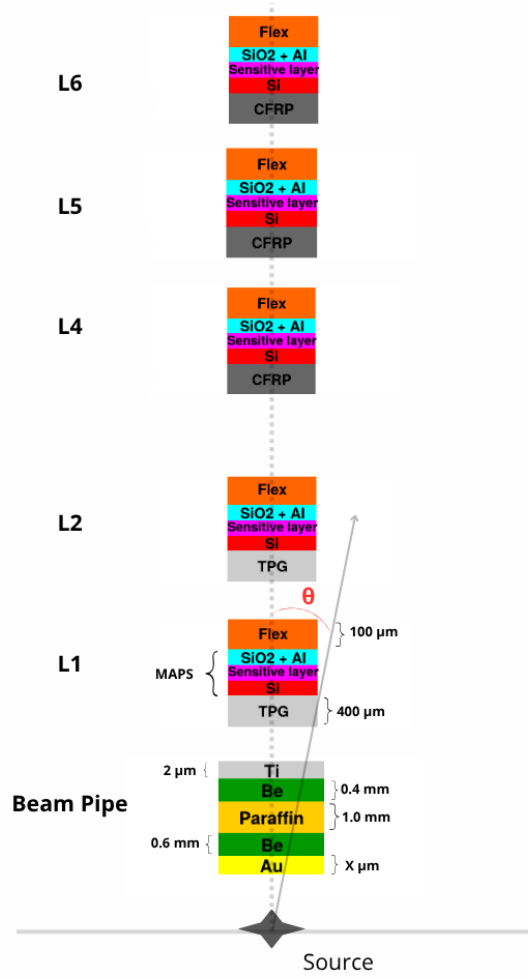


Figure 2.1: Simulated *VTX* geometry with the beam pipe

Figure 2.1 shows the implemented geometry for both the beam pipe wall and the vertex detector used in the newly developed simulation tool. Each layer of the *VTX* (L1, L2, L4, L5, L6¹) is composed of a sub **Sensitive layer**, which is their respective active 30 μm thick silicon sensor. The other materials (passive) correspond to mechanical supports, electronic components, shielding structure, cooling pipe... The incidence angle θ (defined with respect to the normal of the beam axis) of the initial photon flux directly affects the effective X-ray photon path length through the detector.

$$thickness_{eff} = \frac{thickness}{\cos \theta}, \quad (2.1)$$

Finally, the positions of the *VTX* layers are shown in Figure 2.2, with an air gap between each of them.

¹The layer numbering inherits from a previous geometry with 6 layers, to which the third layer was removed to reach the final configuration.

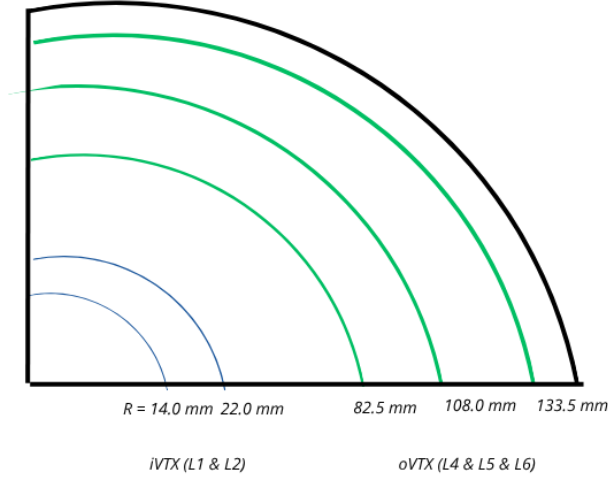


Figure 2.2: Position of *VTX* layers around the interaction point

Each material is associated with its own attenuation coefficient μ , which encodes the amplitude of light-matter interactions, these data are extracted from the *NIST XCOM Photon Cross Sections Database* [6].

2.3 Transport of photons

The next major step in tool development, following geometry construction, is to model photon transport through materials, so we used a **Monte Carlo** approach here.

2.3.1 Interaction probability

From the Beer-Lambert law (see Section 1.5), the photon survival probability after traveling a distance x in a homogeneous layer is given by:

$$P(X > x) = \frac{N(x)}{N_0} = e^{-\mu x} \quad (2.2)$$

It corresponds to the probability of a photon not interacting after traveling the distance x . Therefore, the probability of interaction before reaching x in a homogeneous layer is:

$$P(X < x) = F(x) = 1 - e^{-\mu x} \quad (2.3)$$

This is the cumulative distribution function, which is central for the **Monte Carlo** sampling method.

2.3.2 Monte Carlo sampling

By associating the 2.3 equation with an uniformly distributed random variable $u \sim \mathcal{U}(0, 1)$, such as:

$$u = F(x) = 1 - e^{-\mu x} \quad (2.4)$$

And after inversion, we obtain:

$$x = -\frac{1}{\mu} \ln(1 - u) \quad (2.5)$$

Directly sampling the interaction distance x is valid for a homogeneous material with a constant attenuation coefficient. Introducing the optical depth τ allows us to generalize the **Monte Carlo** method to a multilayer geometry with varying materials and, consequently, varying attenuation coefficients (by removing the dependence on μ).

$$\tau = \mu x = -\ln(1 - u) \quad (2.6)$$

For each simulated photon, an optical depth τ is sampled, which is then compared to the optical depth contribution of the current material thickness i crossed by the photon.

If $\tau < \Delta\tau_i = \mu_i t_i^{\text{eff}}$, the interaction occurs within this thickness i and then disappeared, otherwise, the photon survives.

If the photon survives, the optical depth contribution of the crossed material must be subtracted from the remaining interaction optical depth before reaching the next material thickness $i + 1$, and the **Monte Carlo** process is repeated.

$$\tau \leftarrow \tau - \Delta\tau_i \quad (2.7)$$

2.3.3 Simplified model

As presented in the previous section, the implemented algorithm considers photon interactions as a unique destructive process, the photon is removed from the simulation once the interaction occurs. This representation can be associated with the photoelectric effect, which is a destructive process.

So, in the developed tool, we consider a simplified transport of X-ray photons in which only the photoelectric effect occurs. This approximation is justified in the studied low energy X-ray regime 0–100 keV, on the one hand, pair production cannot occur because the photon energy is below 1.022 MeV. On the other hand, inelastic scattering may be significant in low Z materials (eg : Beryllium layer (Be) in the beam pipe), but their thickness is sufficiently thin for their contribution to stay limited.

2.4 Detection efficiency

To evaluate the impact of synchrotron X-ray radiation on the five *VTX* sensitive regions, the main observable is the photon detection efficiency (or sensitivity). For a fixed photon energy E , it is defined as the probability for an incident photon to produce a hit inside a sensitive detector region. This quantity is expressed as:

$$P_{\text{det}}(E) = \frac{N_{\text{det}}(E)}{N_i(E)} \quad (2.8)$$

where:

- $N_i(E)$ is the number of photons initially generated in the simulation and traversing the beam pipe
- $N_{\text{det}}(E)$ is the number of photons producing a hit in a sensitive detector region

2.5 Validation of the *Toy Monte Carlo* tool

The developed simulation tool and the simplified transport model (which neglects pair production and scattering processes) must be validated by comparison with simulations performed using the **BASF2** framework. Unlike the simplified model developed with the simulation tool, **BASF2** relies on the **GEANT4** framework, which includes a complete description of light-matter interaction processes.

To ensure a consistent and robust comparison, the *VTX* layers were reproduced in the simplified simulation using the same silicon-only description as implemented in the default **BASF2** geometry (Figure 2.3).

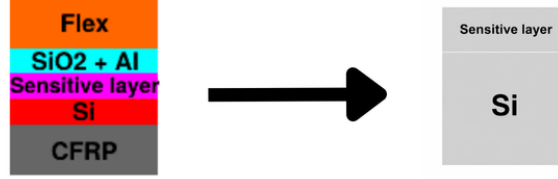


Figure 2.3: Adaptation of the *Toy Monte Carlo* geometry to compare with **BASF2**

Figure 2.4 displays detection probabilities defined by Equation 2.8 with the photon energy. It shows the detection efficiency obtained with the developed *Toy Monte Carlo* and **BASF2** is perfectly comparable on the entire energy scale studied. For clarity, only the first sensitive layer L1 and the last one L6 of the *VTX* are represented in the figure. Still, similar results were obtained for different photon incidence angles and for the remaining detection layers.

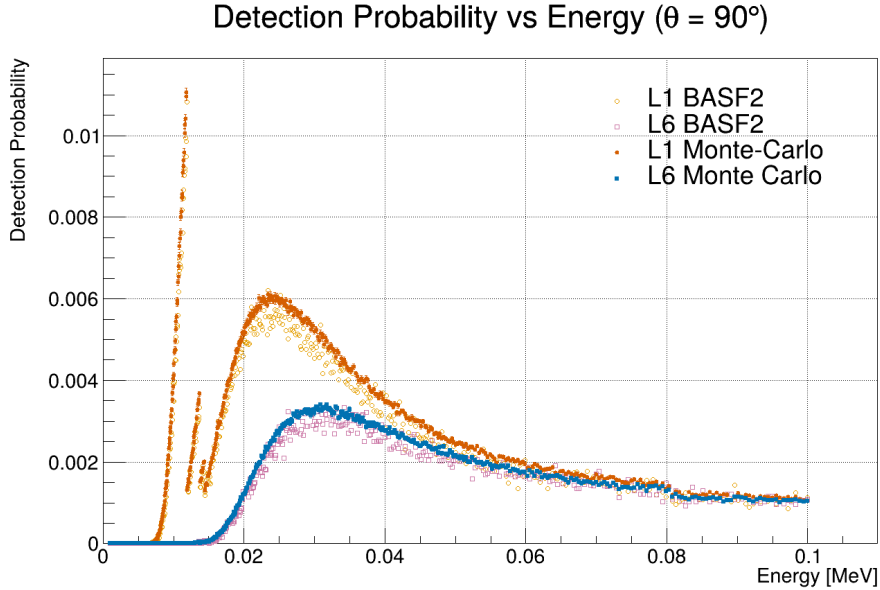


Figure 2.4: Comparison of L1 and L6 efficiency (photons in normal incidence conditions) for both *Toy Monte Carlo* (filled markers) and **BASF2** for the same *VTX* geometry

This comparison between a very precise simulation of photon transport (using **GEANT4**) and the developed *Toy Monte Carlo* tool validates the reliability of the simplified model.

Chapter 3

Sensitivity to the synchrotron radiation

This chapter presents results from the validated *Toy Monte Carlo* simulation tool, using the geometry described in 2.2, which provides the sensitivity map of the *VTX* to synchrotron radiation in a low X-ray energy regime (0–100 keV). For the following results, the incident photon flux angle θ is now defined with respect to the beam axis, in order to correspond to the standard used by the collaboration in *BASF2*.

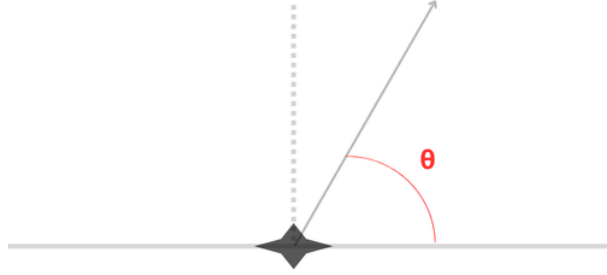


Figure 3.1: Incidence angle definition with respect to the beam axis

3.1 Sensitivity map

Figure 3.2 shows the detection efficiency defined by Equation 2.8 retrieved from each sensitive layer as a function of the incident photon energy, with photons in normal incidence conditions and a gold layer of 10 μm . Globally, the innermost detector L1 is more sensitive to the X-rays than the outer ones, such as L6. As the layer order increases, those photons pass through more material and are progressively attenuated.

The observed discontinuities below 20 keV show the influence of the gold layer on the dropped photon detection, and are associated with the gold absorption edges (*L-edges*), where X-ray absorption by gold suddenly increases. This phenomenon occurs when the photon energy is just above the binding energy of the second innermost electron shell of gold (*L-shell*). These discontinuities are consistent with the experimental measurements found in the literature [10]: L_3 (11.920 keV), L_2 (13.735 keV), L_1 (14.352 keV).

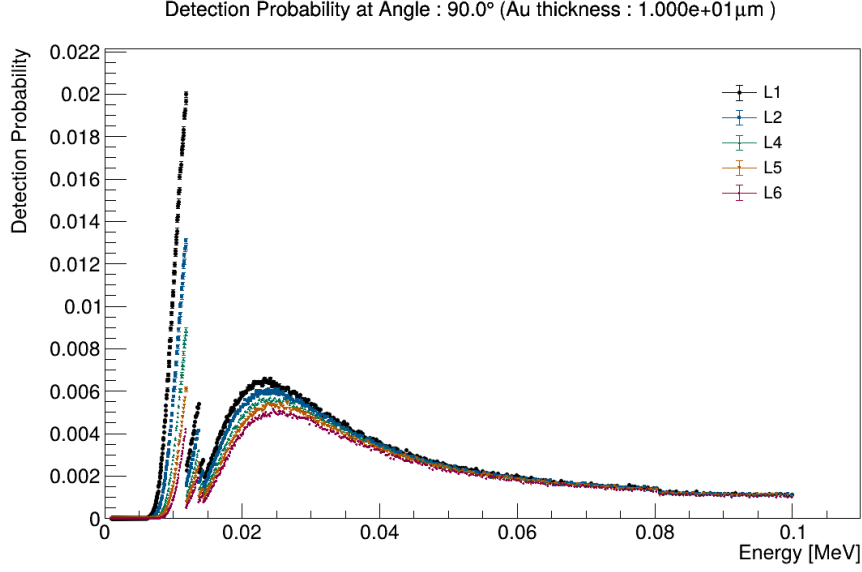


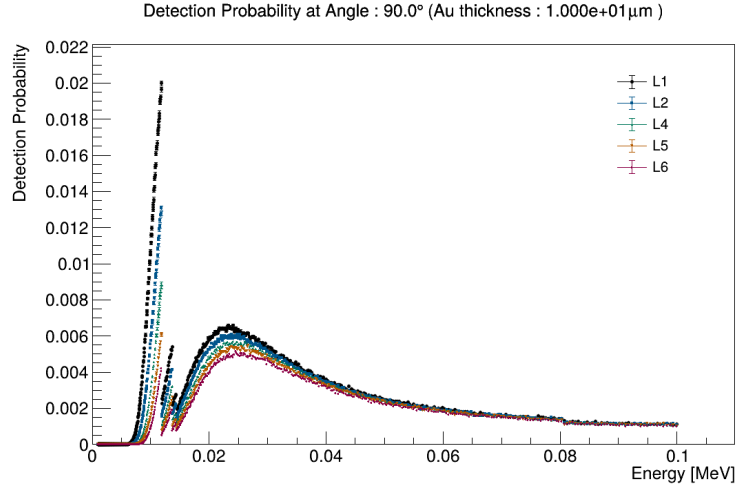
Figure 3.2: Sensitivity map of the VTX layers (photons in normal incidence conditions) with $10 \mu m$ of gold

3.2 Impact of the incidence angle

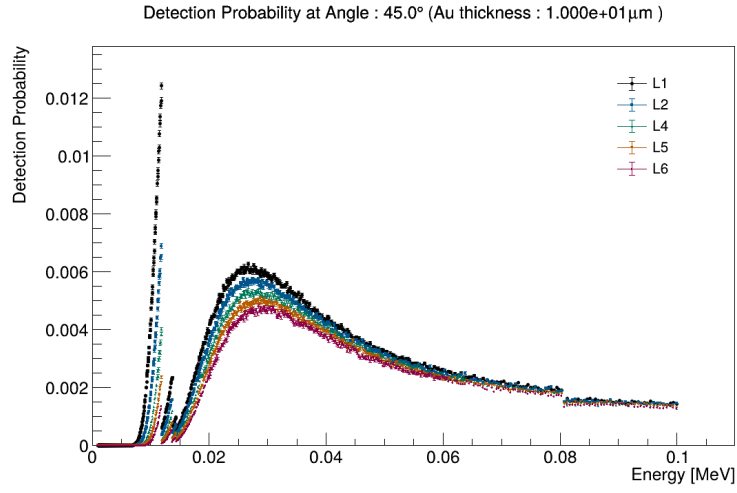
The direction from which the synchrotron radiation is coming is important for evaluating sensitivity. In particular, X-rays hitting the detection layers will likely originate from scattered synchrotron radiations. Normal incidence is not the most probable expected case. Figure 3.3 illustrates the influence of the photon incidence angle, the amplitudes of peaks below 20 keV decrease as the angle progressively deviates from normal incidence. This evolution comes from an increase in the effective path length, particularly the effective thickness of the gold layer, reinforcing its contribution to the overall detection sensitivity and especially the absorption of low energy photons.

We can also see a third discontinuity around 80 keV corresponding to the *K-edge* of gold.

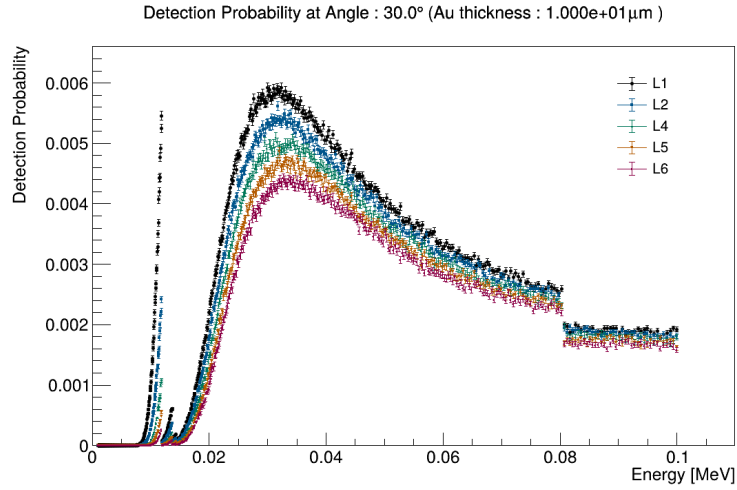
Results obtained without a gold layer on Figure 3.4 confirm the dominant role of the absorbing gold layer. The incidence angle has a very low shifting effect on the sensitivity map, showing that the influence of this angle on the other materials (beam pipe and *VTX*) is limited.



(a)

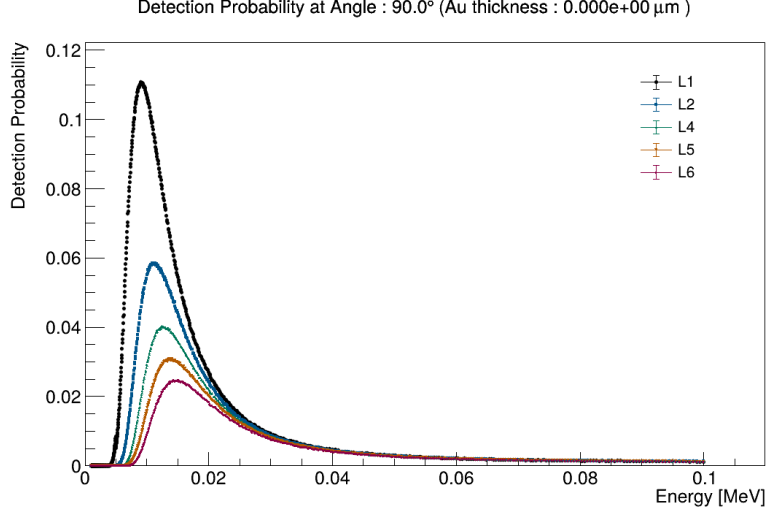


(b)

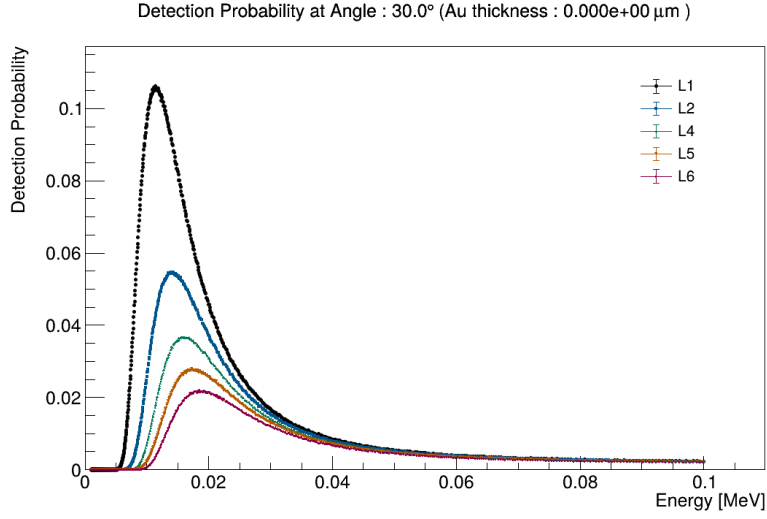


(c)

Figure 3.3: Influence of the incidence angle on the sensitivity map with a 10 μm thin gold absorbing layer: (a) 90°, (b) 45°, and (c) 30°.



(a)



(b)

Figure 3.4: Influence of the incidence angle on the sensitivity map without absorbing gold layer: (a) 90° and (b) 30° .

3.3 Impact of absorbing gold layer

The influence of beam pipe's gold layer on the detection efficiency for the first detection layer L1 with a 30° incidence angle, is illustrated in Figure 3.5. For clarity, only L1 is represented which is the most sensitive detection layer to synchrotron radiation, as discussed in section 3.1. A significant increase of the sensitivity is observed when the gold layer thickness is reduced, especially the maximum detection peak below 20 keV increases by approximately a factor of five between $10\ \mu\text{m}$ and $5\ \mu\text{m}$ gold configurations, and a factor ten between the $10\ \mu\text{m}$ configuration and the geometry without gold layer on the beam pipe.

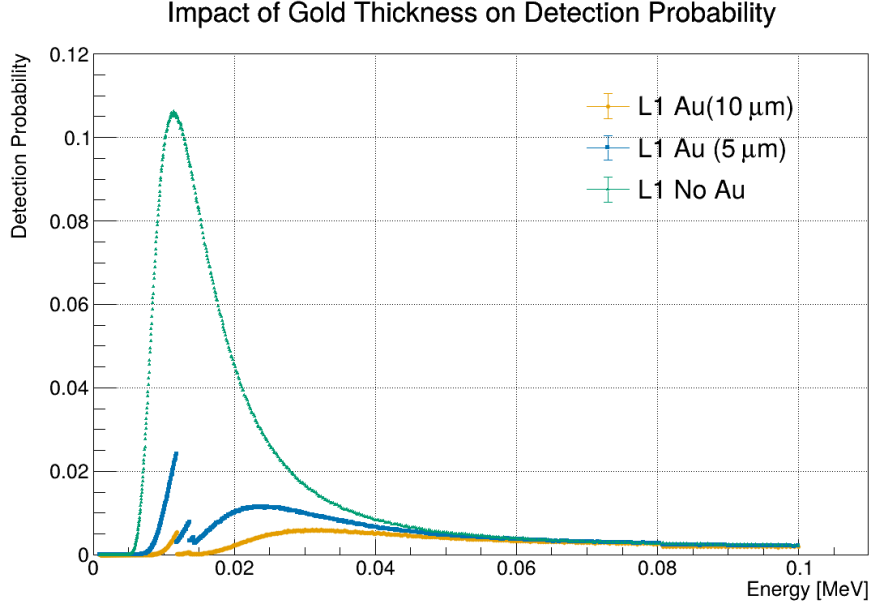


Figure 3.5: Impact of absorbing gold layer on the sensitivity of L1 to synchrotron radiation - see Appendix B for semi-logarithmic figure (incidence angle: 30°)

3.4 Additional discussion

After discussing the overall negative impact associated with the increase in detector sensitivity when reducing the gold thickness. It is also important to consider the positive effect of such a modification. Theoretical estimations indicate that reducing the gold layer, so reducing the material budget of the beam pipe, could improve the vertex spatial resolution by up to 12 %, compared to the current beam pipe configuration.

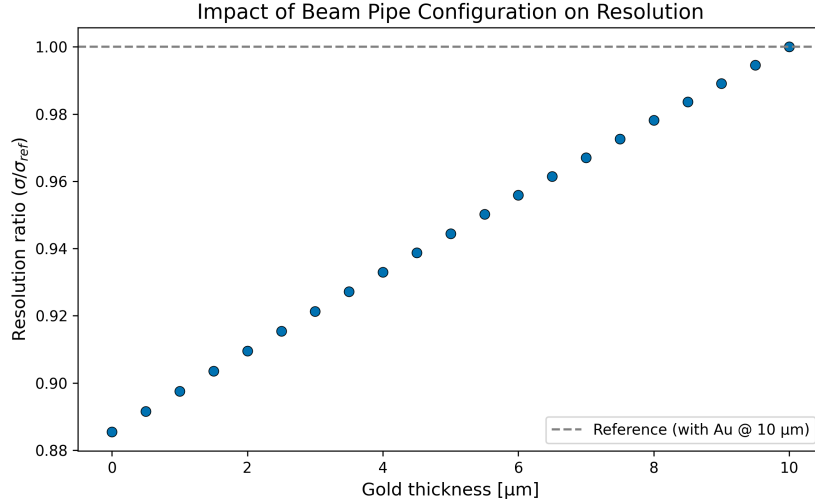


Figure 3.6: Evolution of vertex resolution

Conclusions regarding a possible reduction of the gold shielding cannot be drawn only from the sensitivity map. A synchrotron X-ray spectrum is required to evaluate the actual contribution of each photon energy range and with the sensitivity map, we will be able to estimate the corresponding hit rate within the detector layers.

Nevertheless, an encouraging result is obtained when comparing the future *VTX* detector to the current vertex detector, the *PXD* [9]. For the most exposed detection layer L1, the simulated sensitivity is approximately a factor of 2.5 lower than for the current vertex detector (see Figure 3.7). It shows a significant improvement in the future detector's tolerance specifically to synchrotron X-ray radiation and supports a possible reduction in the thickness of the gold layer.

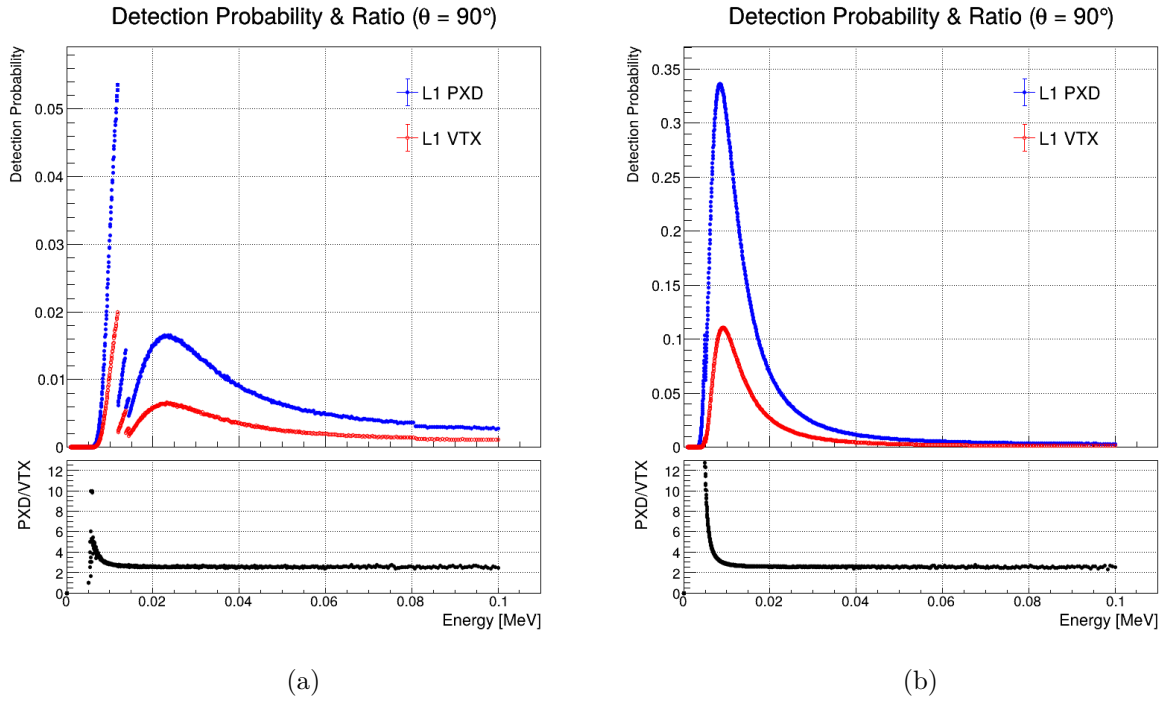


Figure 3.7: Comparison between L1 PXD and L1 VTX at 90° : (a) $10\mu m$ gold thickness and (b) no gold layer - large ratio fluctuations observed are due to differences in sensitivity range at low energy

CONCLUSION

The main objective of this internship was to model the sensitivity of the future *VTX* upgrade to synchrotron radiation X-rays, and to quantify the impact of reducing the $10\mu\text{m}$ gold shielding layer on the beam pipe.

A dedicated C++ simulation tool has been developed during this internship. The implemented framework relies on a simplified *Toy Monte Carlo* simulation of photon transport through a detailed description of the *VTX* geometry and beam pipe materials. Comparisons with a simulation tool including more exhaustively photon physical interactions but less detailed geometry (BASF2) validated this simplified model and validated the use of this tool to study sensitivity.

The obtained sensitivity maps emphasize the dominant role of the gold layer in the attenuation of low energy synchrotron photons. Reducing its thickness shows a significant increase in the *VTX* sensitivity especially below 20 keV. Also, this absorbing gold layer contributes to the total material budget and degrades the resolution of the reconstructed vertex. First estimations by considering the two innermost layers of the *VTX* (L1 and L2) indicate that reducing its thickness could improve the vertex resolution up to 12 %.

A comparison with the current vertex detector (*PXD*) tends to support a reduction of the gold shielding thickness. For the most exposed detection layer L1, the simulated sensitivity of the future *VTX* remains approximately a factor of 2.5 lower than for the current vertex detector. The next step will focus on obtaining a synchrotron radiation spectrum produced at *SuperKEKB*, and with the sensitivity maps to estimate the expected hit rate within the detector layers. This will provide the information to conclude on the reduction of the gold layer thickness feasibility while maintaining an acceptable level of background and improving the vertex spatial resolution.

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- [10] R. D. Deslattes *et al.*, *X-ray Transition Energies Database*, National Institute of Standards and Technology (NIST), [DOI:10.18434/T4859Z](#).
- [11] Timothy Carlisle, *Multiple Scattering (MSC) in Geant4*, [PRESENTATION PDF](#)

APPENDIX A

The objective is to provide an estimation of the impact of additional material close to the interaction point on the vertex spatial resolution. It is not a complete expression of parameter b , which depends on the complete five detection layer geometry, here we only illustrate the dominant geometrical and material dependency of the multiple scattering parameter.

To begin, we consider a charged particle produced at the interaction point and propagating with a polar angle θ through a material layer located at a radius R , multiple coulomb scattering induces a small angular deviation $\Delta\theta$.

From the geometry (see Fig 3.8), we can approximate the displacement of the impact parameter due to small angular deviation $\Delta\theta$:

$$d_0 = l \tan(\Delta\theta) \simeq l \Delta\theta \quad (3.1)$$

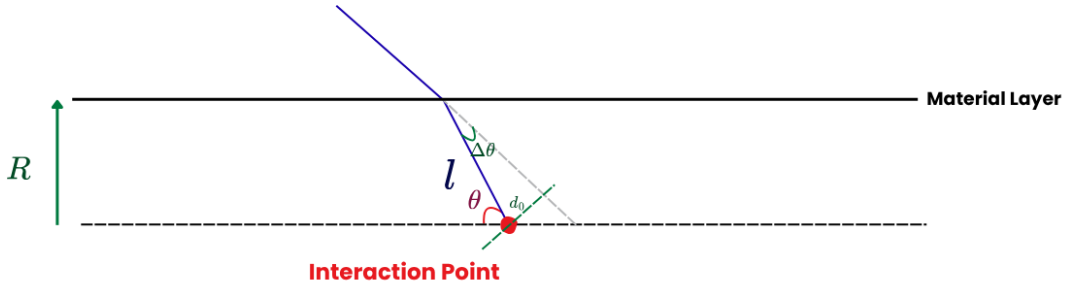


Figure 3.8: Multiple scattering on one material layer

Also from the geometry,

$$l = \frac{R}{\sin(\theta)} \quad (3.2)$$

Hence,

$$d_0 = \frac{R}{\sin(\theta)} \Delta\theta \quad (3.3)$$

Multiple scattering angular distribution is described by Moliere's theory and is in first approximation gaussian, the width of this distribution is given by Highland formula [11]:

$$\sigma_{\Delta\theta} = \frac{13.6 \text{ MeV}}{\beta pc} z \sqrt{\frac{X}{X_0 \sin(\theta)}} \left(1 + 0.038 \ln \left(\frac{X}{X_0 \sin(\theta)} \right) \right) \quad (3.4)$$

where : $\frac{X}{\sin(\theta)}$ is the effective path length of the charged particle through material depending of its polar angle θ .

Finally neglecting the logarithm term, we obtain:

$$\sigma_{d_0} = \frac{R}{\sin(\theta)} \sigma_{\Delta\theta} = \frac{13.6 \text{ MeV}}{\beta p \sin^{3/2} \theta} R \sqrt{\frac{X}{X_0}} \quad (3.5)$$

Comparing Equation 3.5 and 3.6.

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}(\theta)} \quad (3.6)$$

It shows that parameter b, scales as:

$$b \propto R \sqrt{\frac{X}{X_0}} \quad (3.7)$$

In Figure 1.8 the multiple scattering contribution comes both from the beam pipe and the first detection layer (L1), so it depends primary on the radius position and material budget of these two layers.

$$b^2 \propto \left(R_{BP} \sqrt{\frac{X}{X_{0_{BP}}}} \right)^2 + \left(R_{L1} \sqrt{\frac{X}{X_{0_{L1}}}} \right)^2 \quad (3.8)$$

APPENDIX B

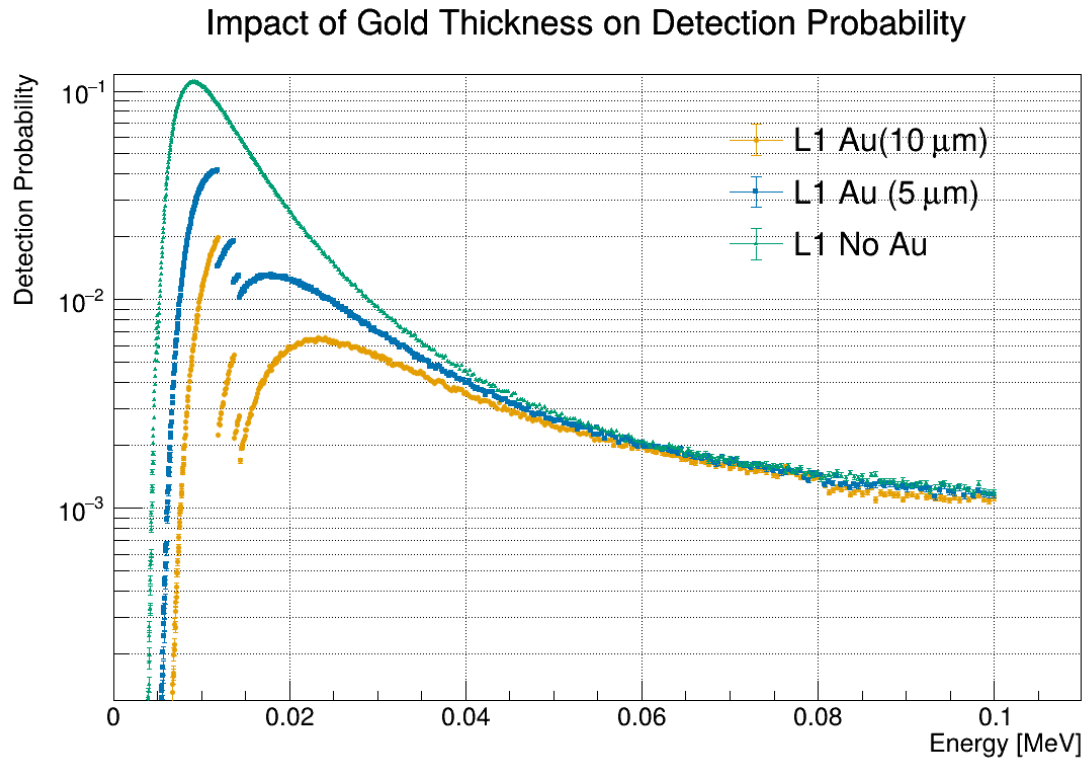


Figure 3.9: Impact of absorbing gold layer on the sensitivity of L1 to synchrotron radiation - semi-logarithmic figure (incidence angle: 30°)