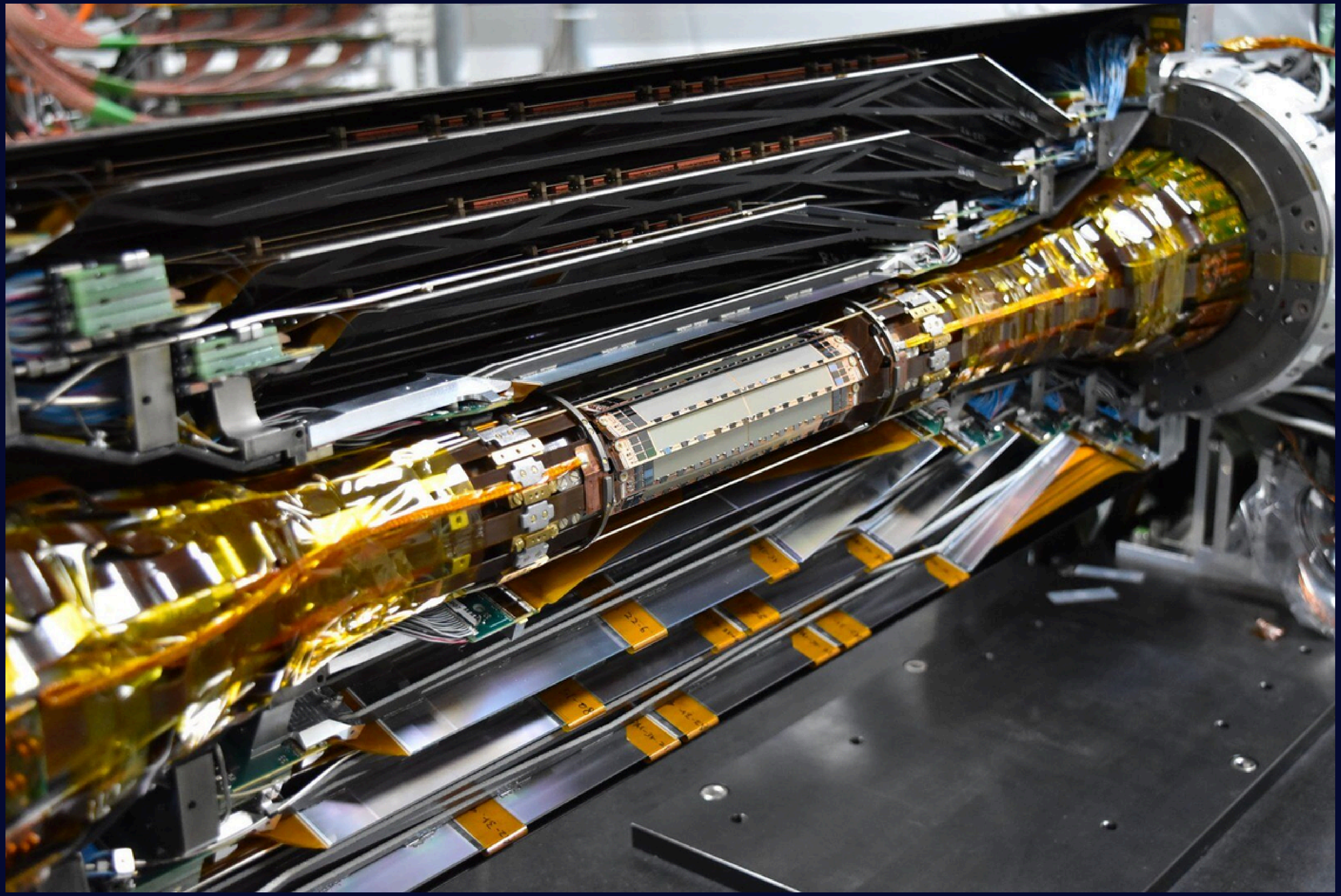
DEVELOPMENT OF THE NEW VERTEX DETECTOR OF THE BELLE II EXPERIMENT IMPACT OF THE SYNCHROTRON BACKGROUND ON THE VTX



Belle II VTX

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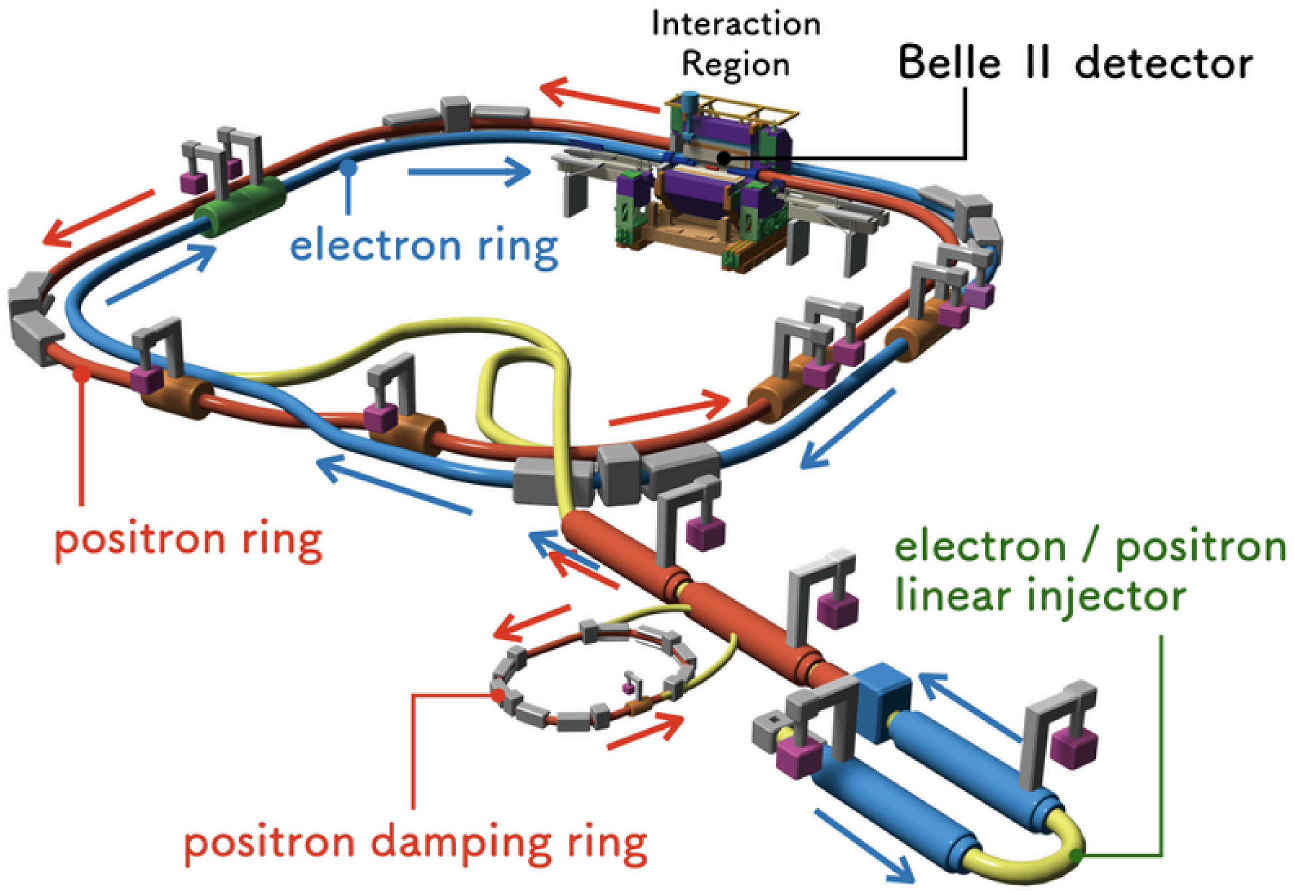
MARGUIN Jérémy

Supervisor : BAUDOT Jérôme

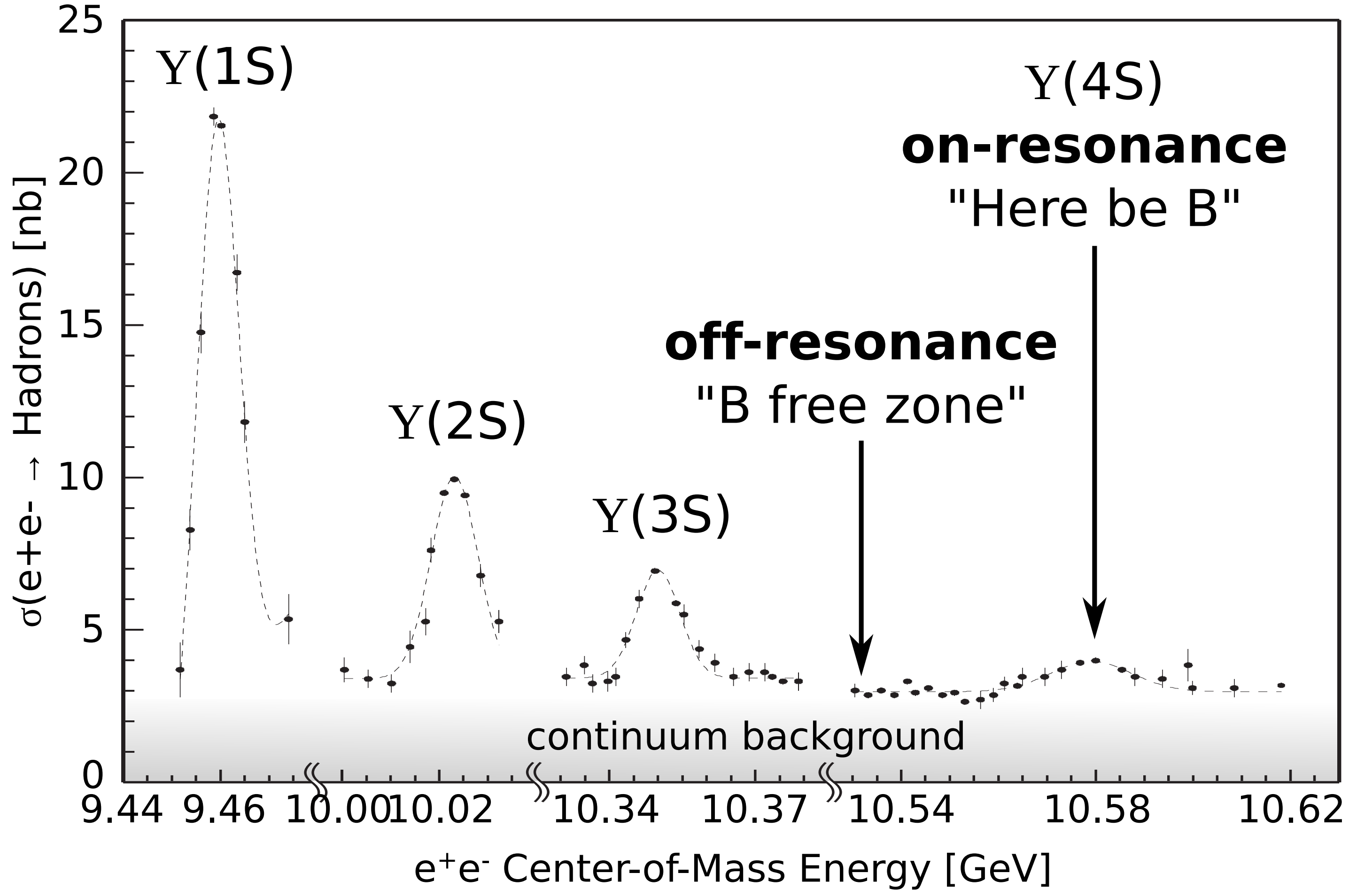
Data taking at SuperKEKB

Asymmetric collider - 7 GeV /4 GeV (e-/e+)



Most Luminous synchrotron collider

$\mathscr{L}$: 5.2 × 10^{34} cm^{-2} s^{-1} (TODAY) → 6.0× 10^{35} cm^{-2} s^{-1} (2032)

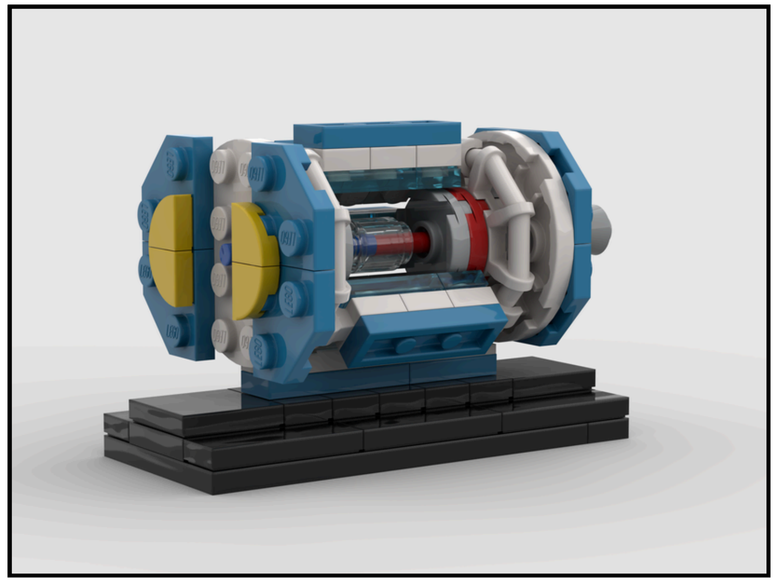


On-resonance data taking Υ(4S) : 10.58 GeV

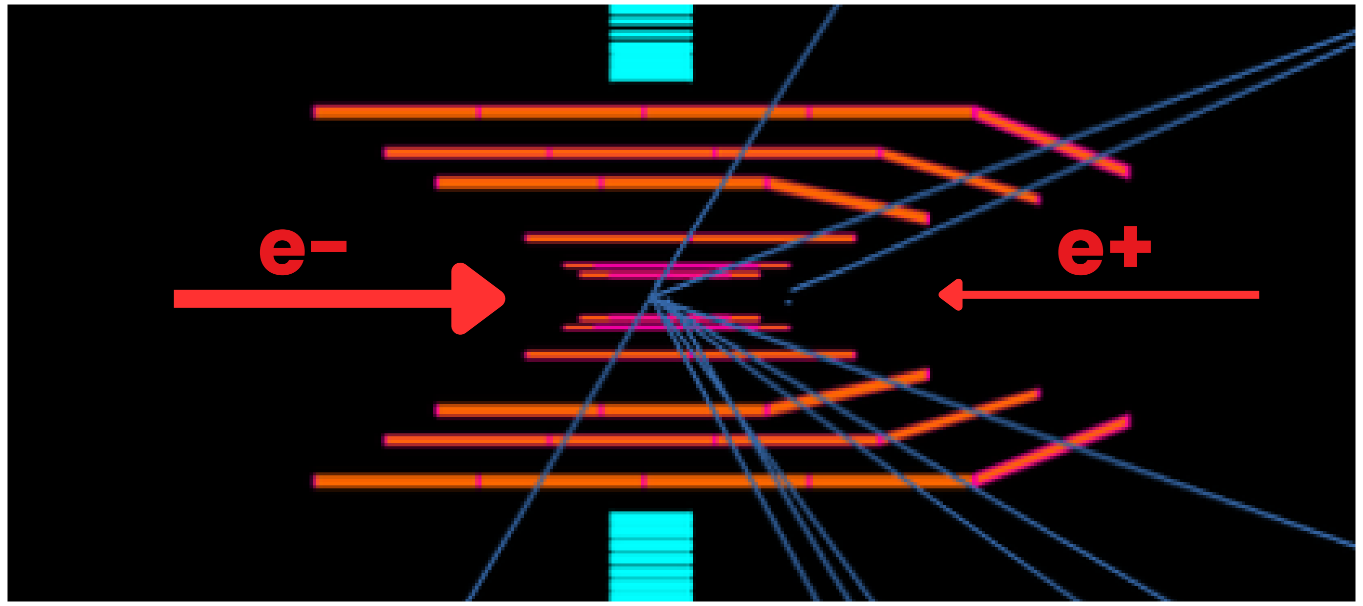
$\sigma(e^+e^- \to b\bar{b}) \sim 1$ nb

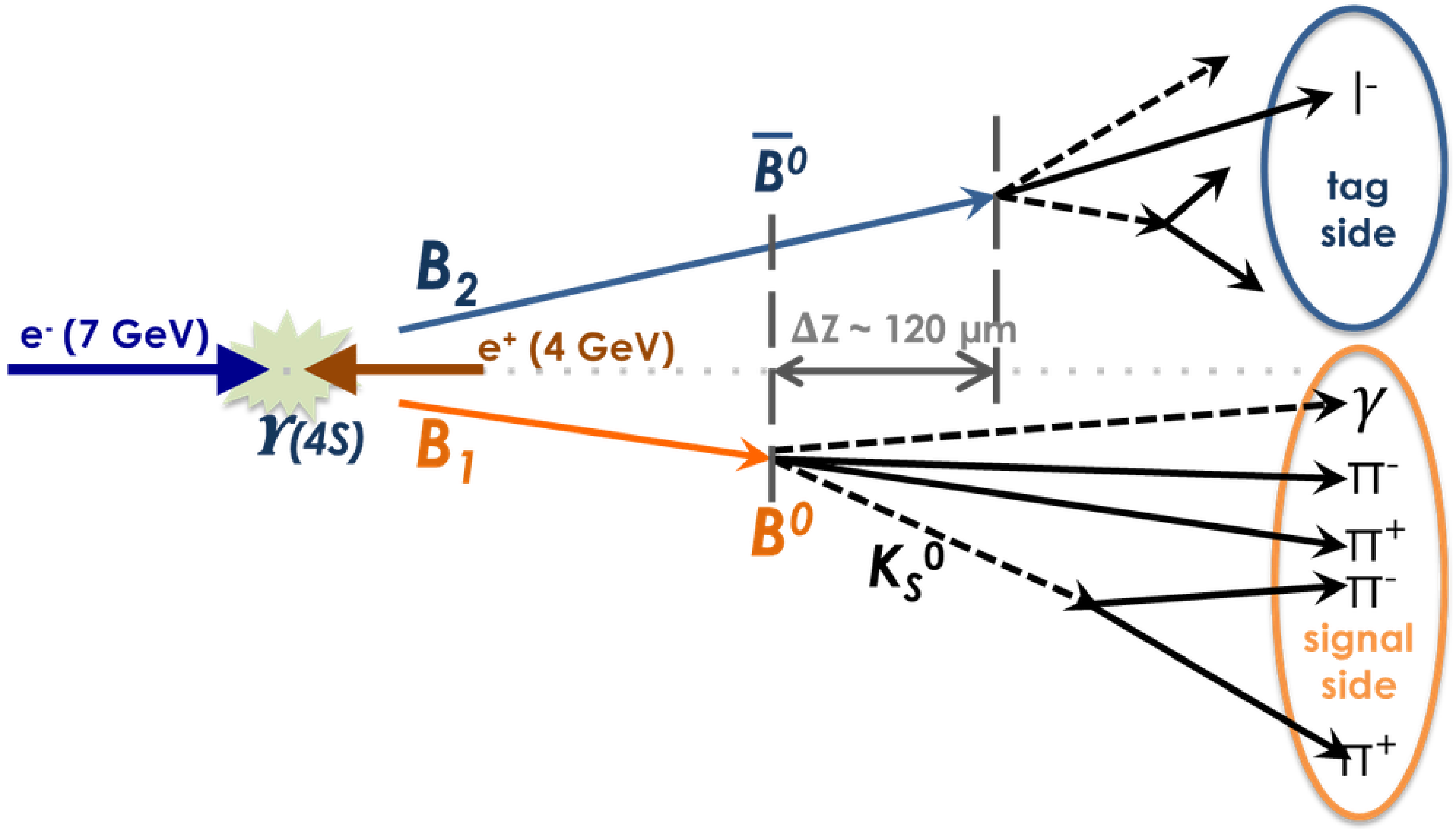
$\sigma(e^+e^- \to c\bar{c}) \sim 1$ nb

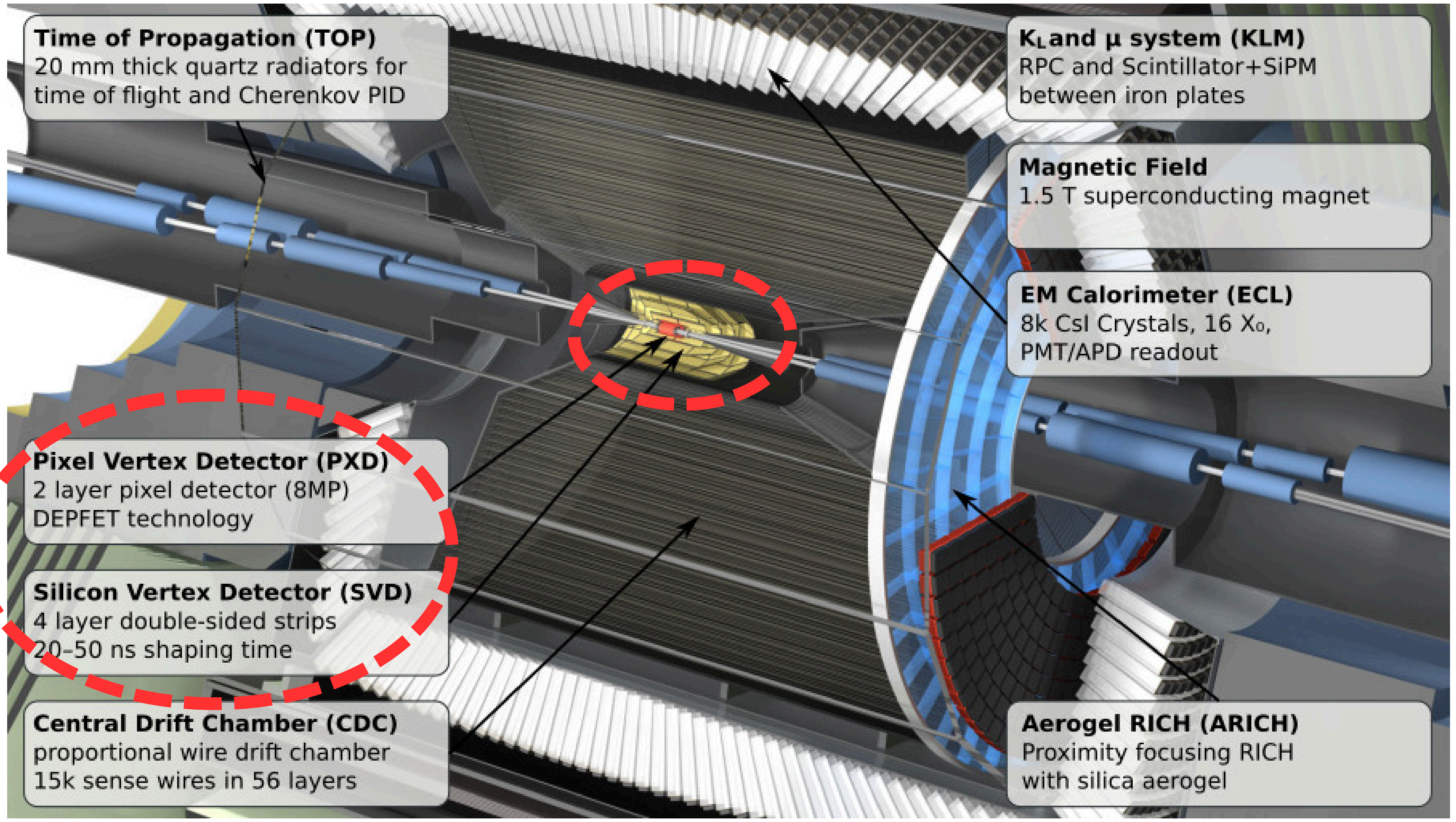
$\sigma(e^+e^- \to \tau^+\tau^-) \sim 1$ nb



Belle II & vertex detector







vertex position used to constrain event selection and improve signal purity

Specifications for VTX upgrade

- better spatial resolution

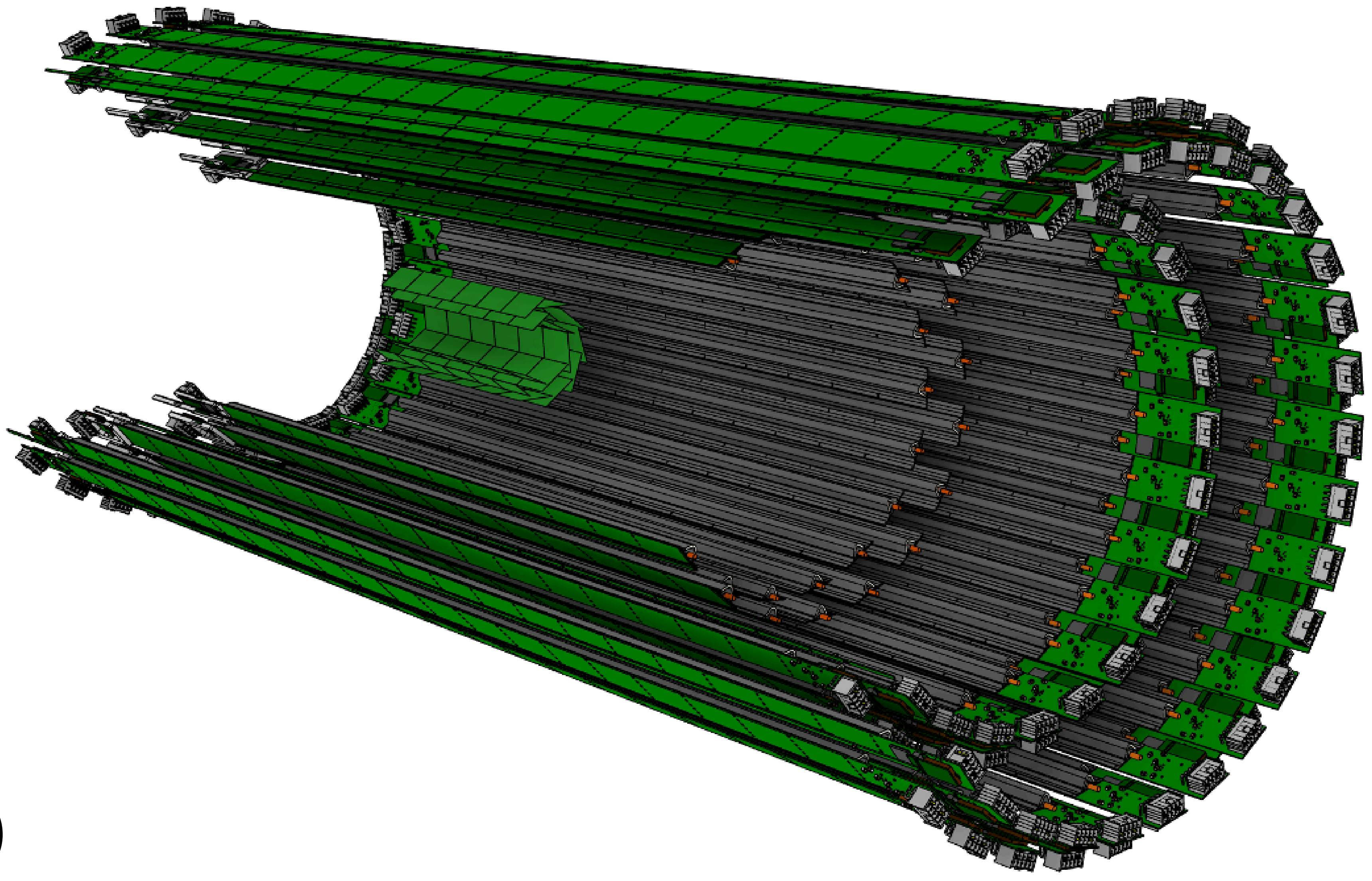
  → smaller pixel pitch (30 μm vs 80 μm)

  → low material budget

- **operating at high hit rate (120 MHz/cm²)**

  → integration time (100 ns vs 20 μs)

...



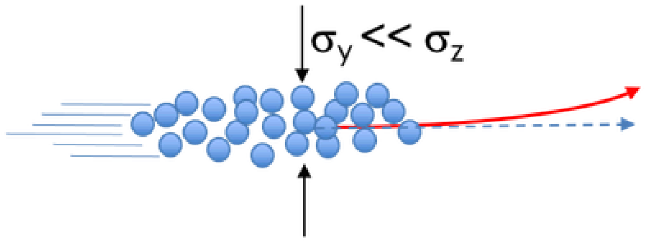
5 concentric VTX ladders

- ***2 inner → vertex resolution***
- ***3 outer → track seeding***

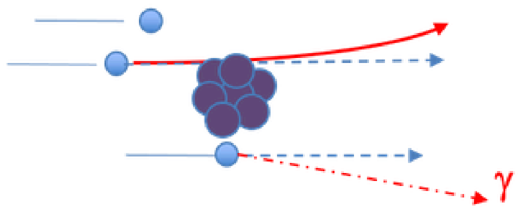
Synchrotron Radiation

beam-induced background

- Single beam effects
  - Touschek ← intra-beam scattering
    - rate $\propto \frac{I_{bunch}^2 \, N_{bunch}}{(\sigma_x \, \sigma_y) \, E_{beam}^3} = \frac{I_{beam}^2}{(\sigma_x \, \sigma_y) \, E_{beam}^3 \, N_{bunch}}$

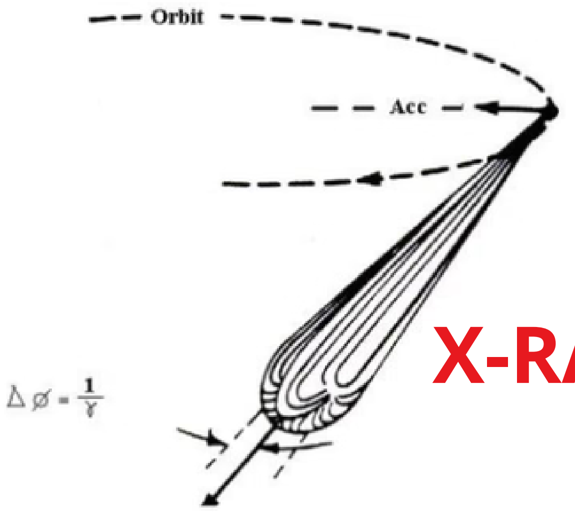


  - Beam gas ← vacuum residues
    - rate $\propto I_{\text{bunch}} \times N_{\text{bunch}} \times P(I)$
    - Dynamic pressure $P(I) = (p_0 + p_1 I_{beam})$



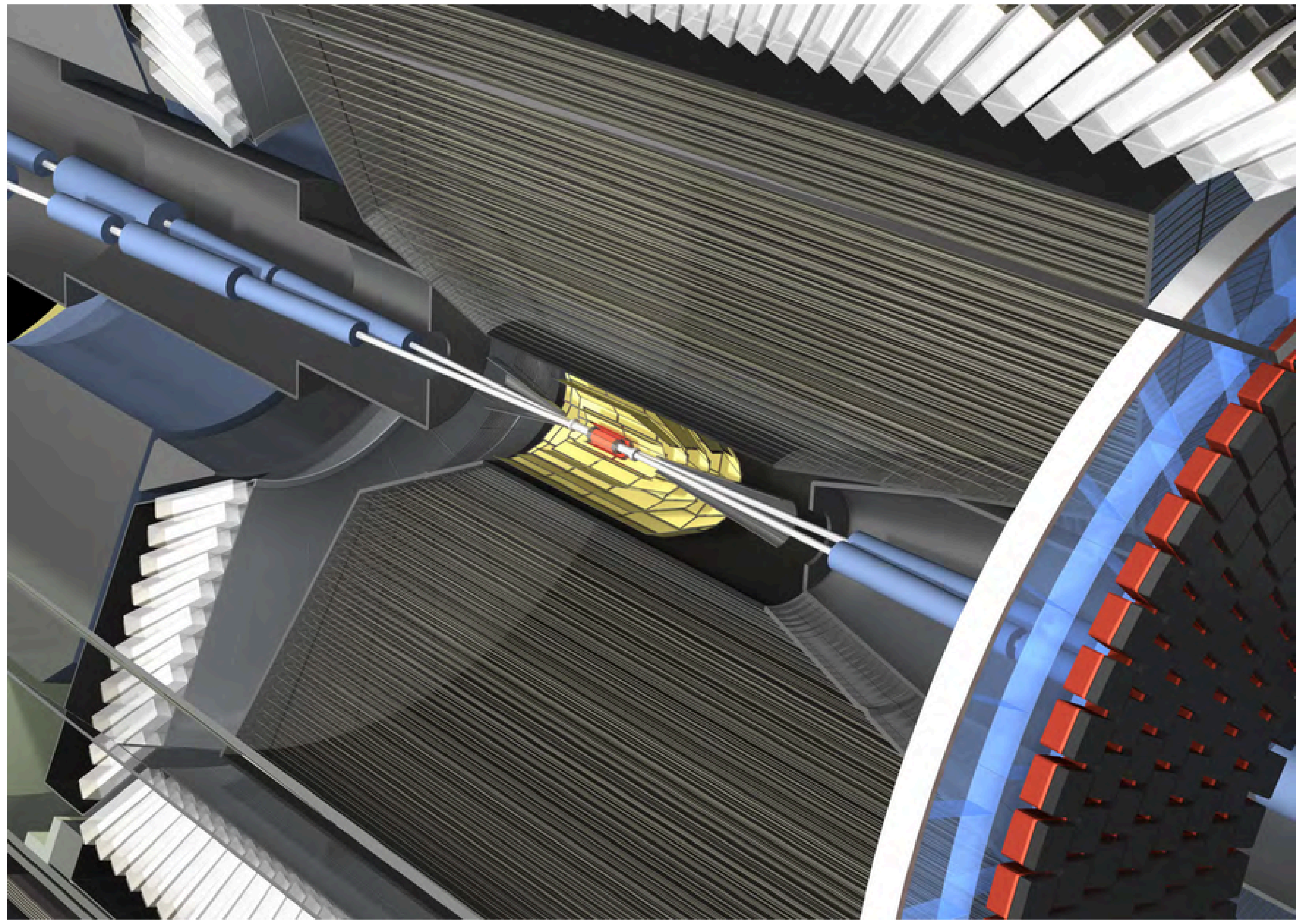
- Synchrotron radiation ← magnet bending
  - rate $\propto I_{\text{beam}}$

e+/e- bent by focus magnets



X-RAYS

⬆ Background on the detector
+ saturation of the readout system

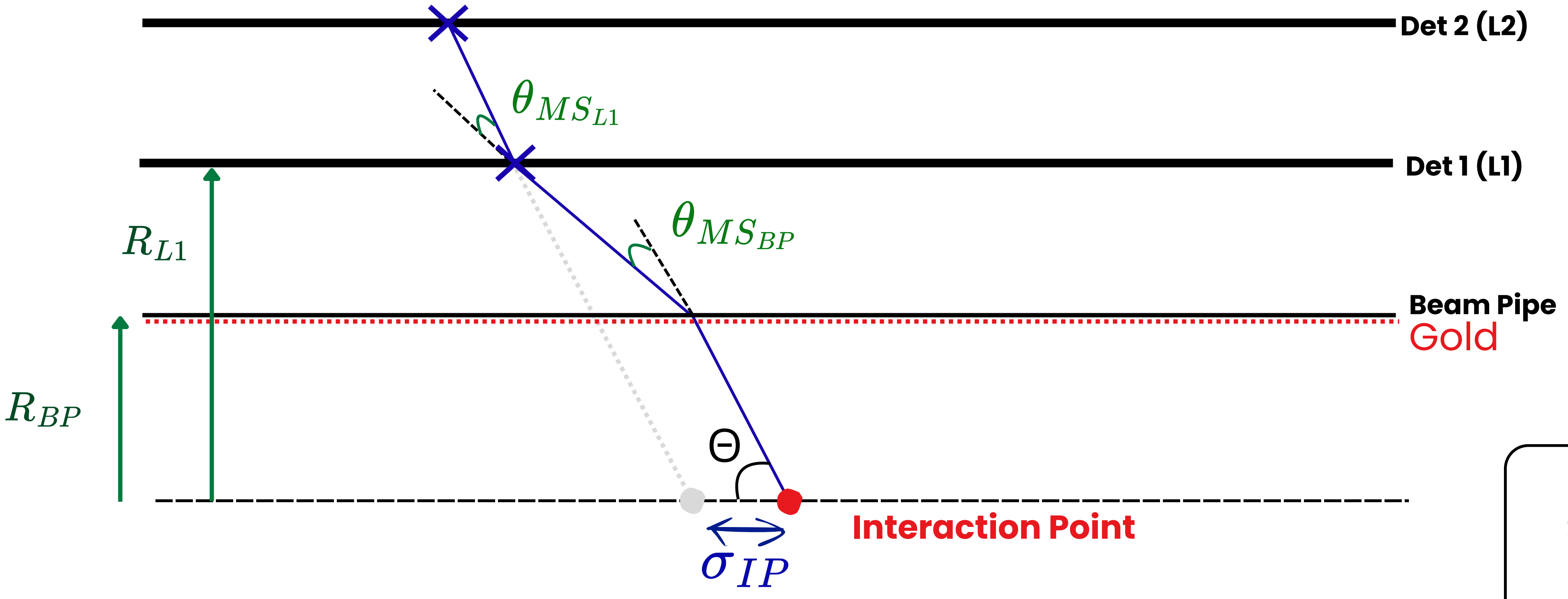


Solution ?

GOLD COATING (10 μm) on the beam pipe

Drawback : degrades the vertex spatial resolution

Vertex spatial resolution



intrinsic sensor precision

multiple scattering

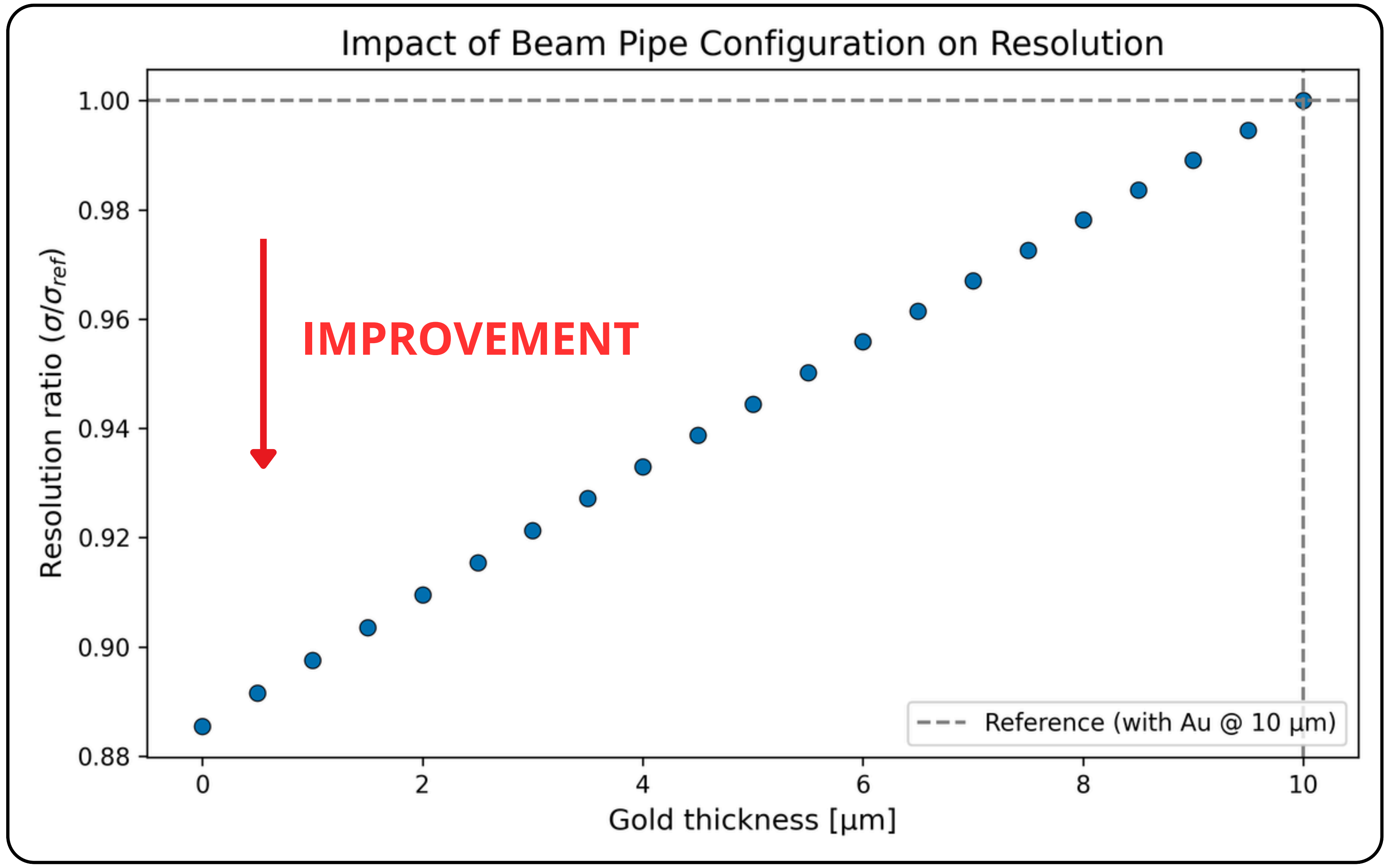
$$\sigma_{IP} = a \oplus \frac{b}{p sin\Theta^{\frac{3}{2}}}$$

$$b^2 \propto \left(\sqrt{\frac{X}{X_0}} \times R\right)^2_{BP} + \left(\sqrt{\frac{X}{X_0}} \times R\right)^2_{L1}$$

Multiple scattering

$$\sigma_{\theta_{MS}} \propto \frac{13.6MeV}{\beta pc} z \sqrt{\frac{X}{X_0} \frac{1}{sin\left(\Theta\right)}}$$

Material Budget



To Sum Up

- VTX is **more resilient**
- Synchrotron Radiation **stopped by gold**

Do the new VTX sensors allow a reduction of the gold layer thickness ?

First study : Estimate X-ray sensitivity

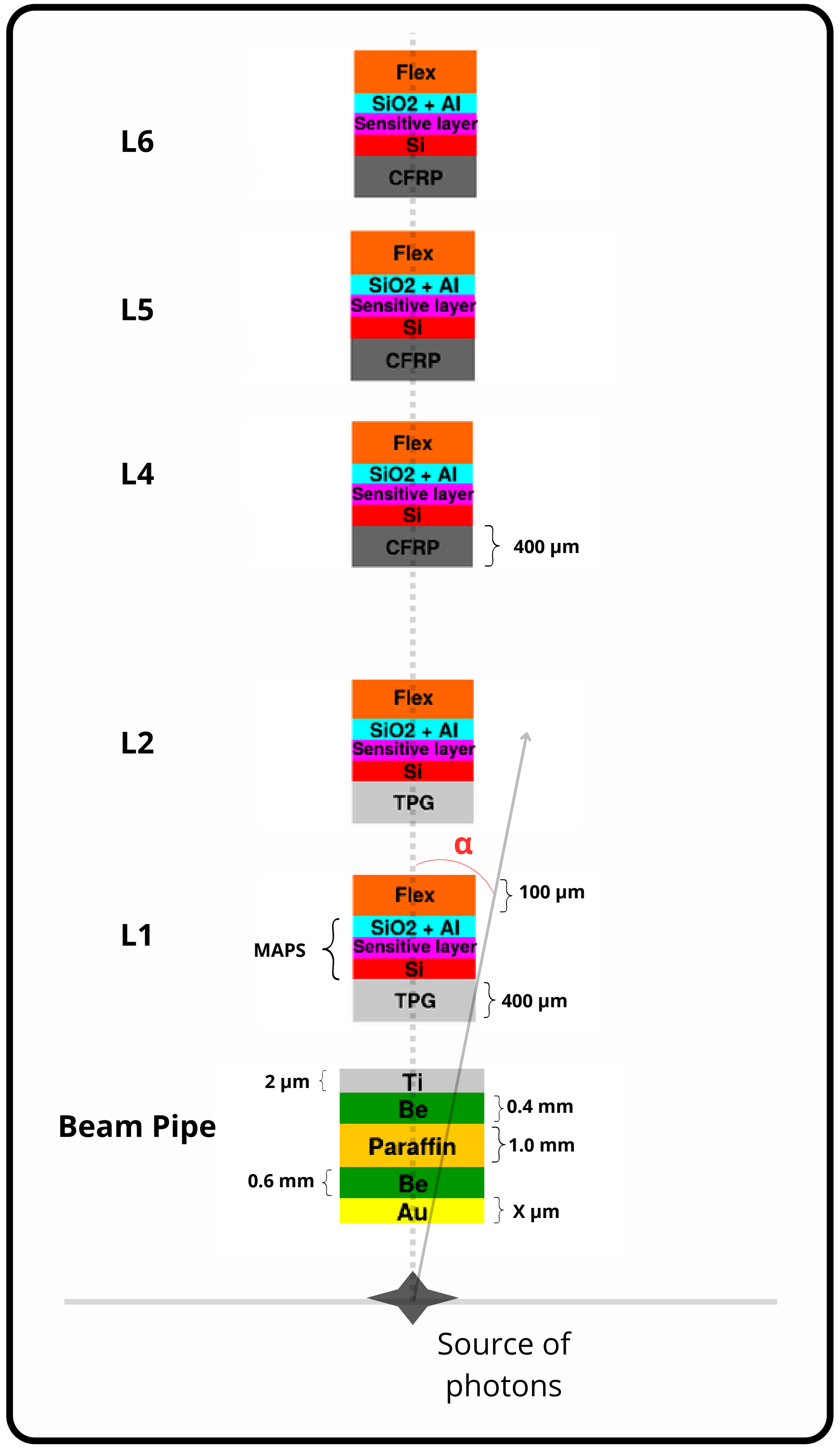
Toy Monte Carlo

- simplified light-matter interactions
- With a **precise geometry** of the VTX ✓

Belle II Framework

- GEANT4
- VTX geometry **not implemented** ✗

Geometry of the VTX and X-ray simulation

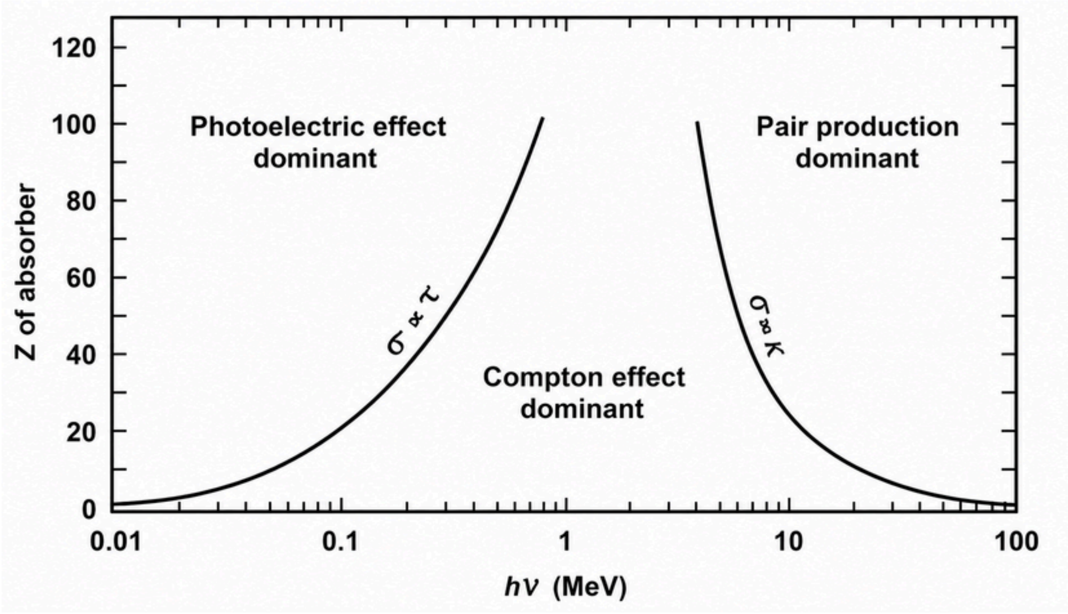


Beer's Law :

$$dN(z,E) = -\mu(z,E)N dz$$

Hypotheses :

- Energy : [1 keV, 100 keV]
- Only Photoelectric effect



$$\mu = \mu_{photoelec} + \mu_{compton} + \mu_{elastic} + \mu_{pair}$$

Incidence angle α :

$$thickness_{eff} = \frac{thickness}{cos(\alpha)}$$

Transport of Photons (Monte Carlo)

Probability of a photon to interact :

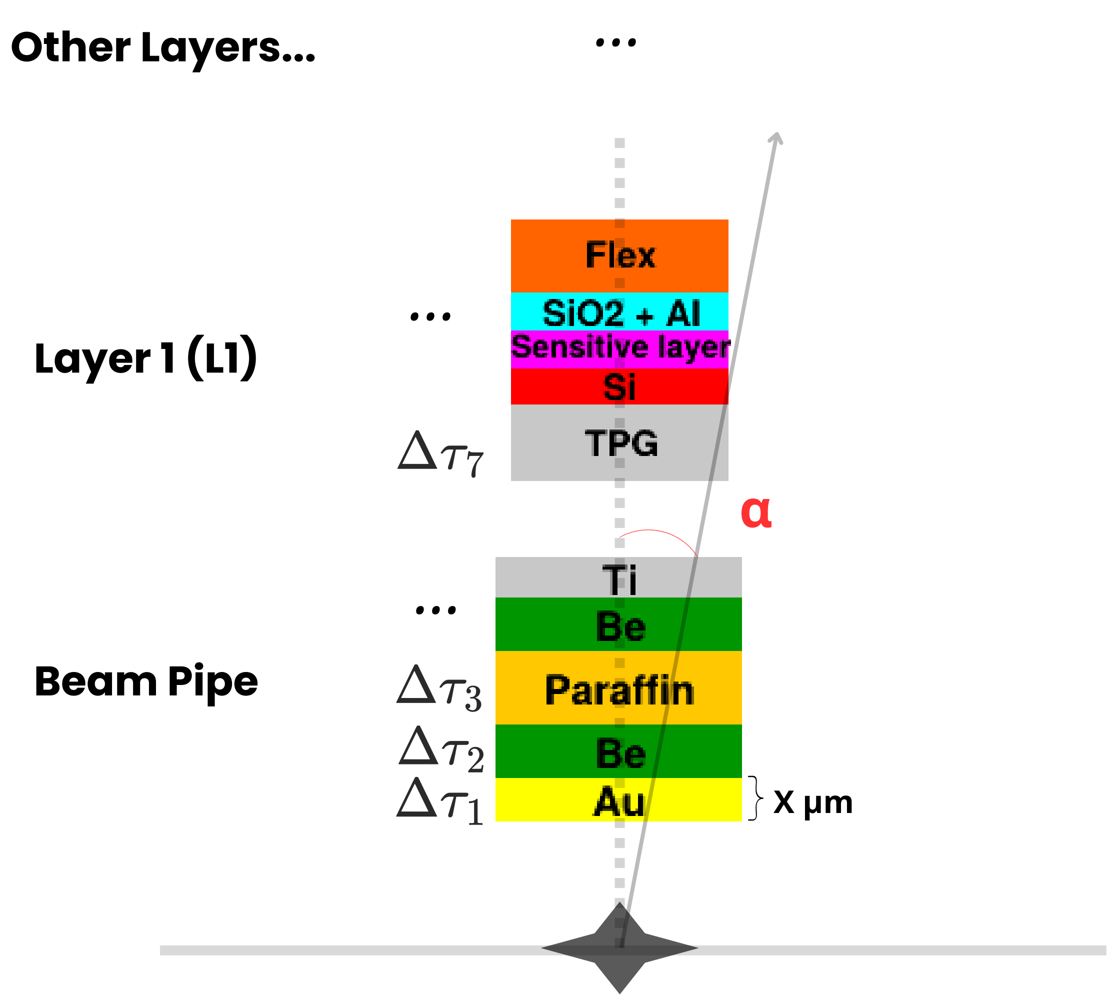
$$P(X < x) = F(x) = 1 - e^{-\int_0^x \mu dx'}$$

$$u \sim U(0,1) \quad u = F(x) = 1 - e^{-\tau(x)}$$

Monte Carlo process → Sample optical depth :

$$\tau = -ln(1-u)$$

$$\tau < \Delta\tau_i = \mu_i t_i^{eff} \ ? \begin{cases} \text{Yes, photon absorbed by material i} \\ \text{No, } \tau \leftarrow \tau - \Delta\tau_i \ \ \& \ \ \tau < \Delta\tau_{i+1} = \mu_{i+1} t_{i+1}^{eff} \end{cases}$$

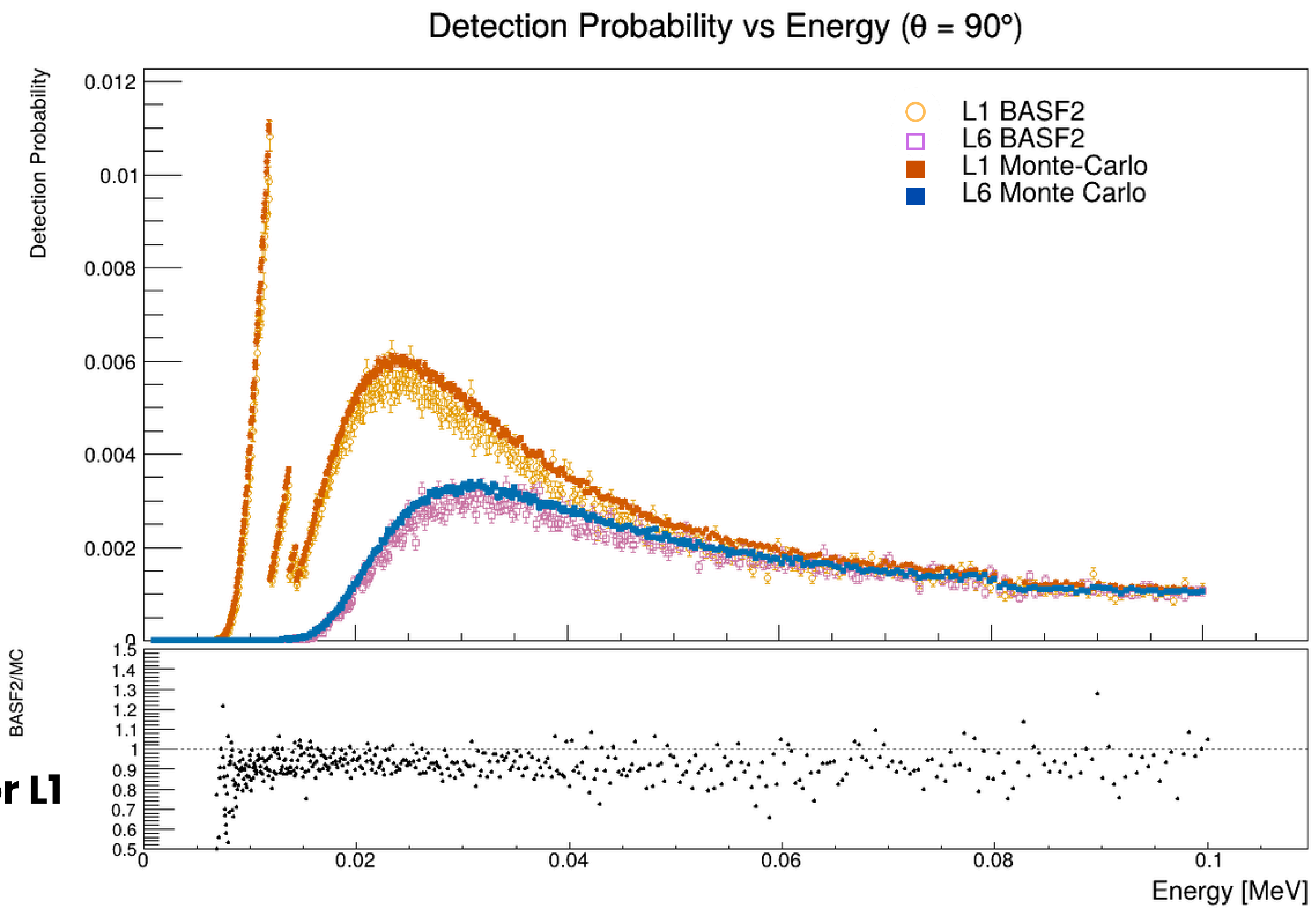


Detection efficiency (sensitivity) :

$$P_{det}(E,\theta) = \frac{N_{det}(E,\alpha)}{N_{sim}}$$

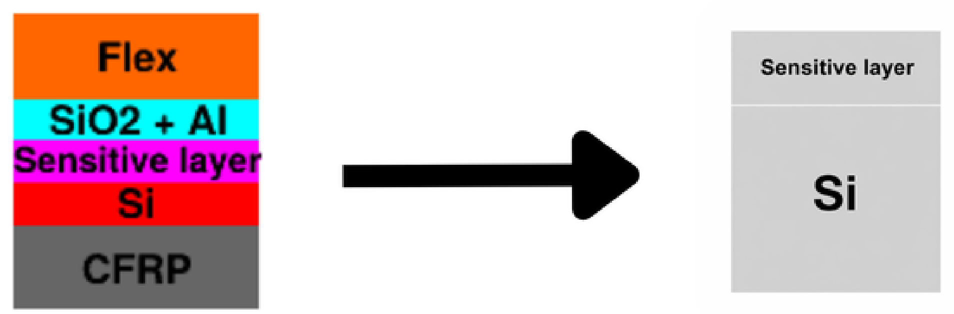
At fixed photon energy **E** and fixed **α** angle
Retrieve from each "*Sensitive Layer*" of VTX

Validation of the Toy Monte Carlo



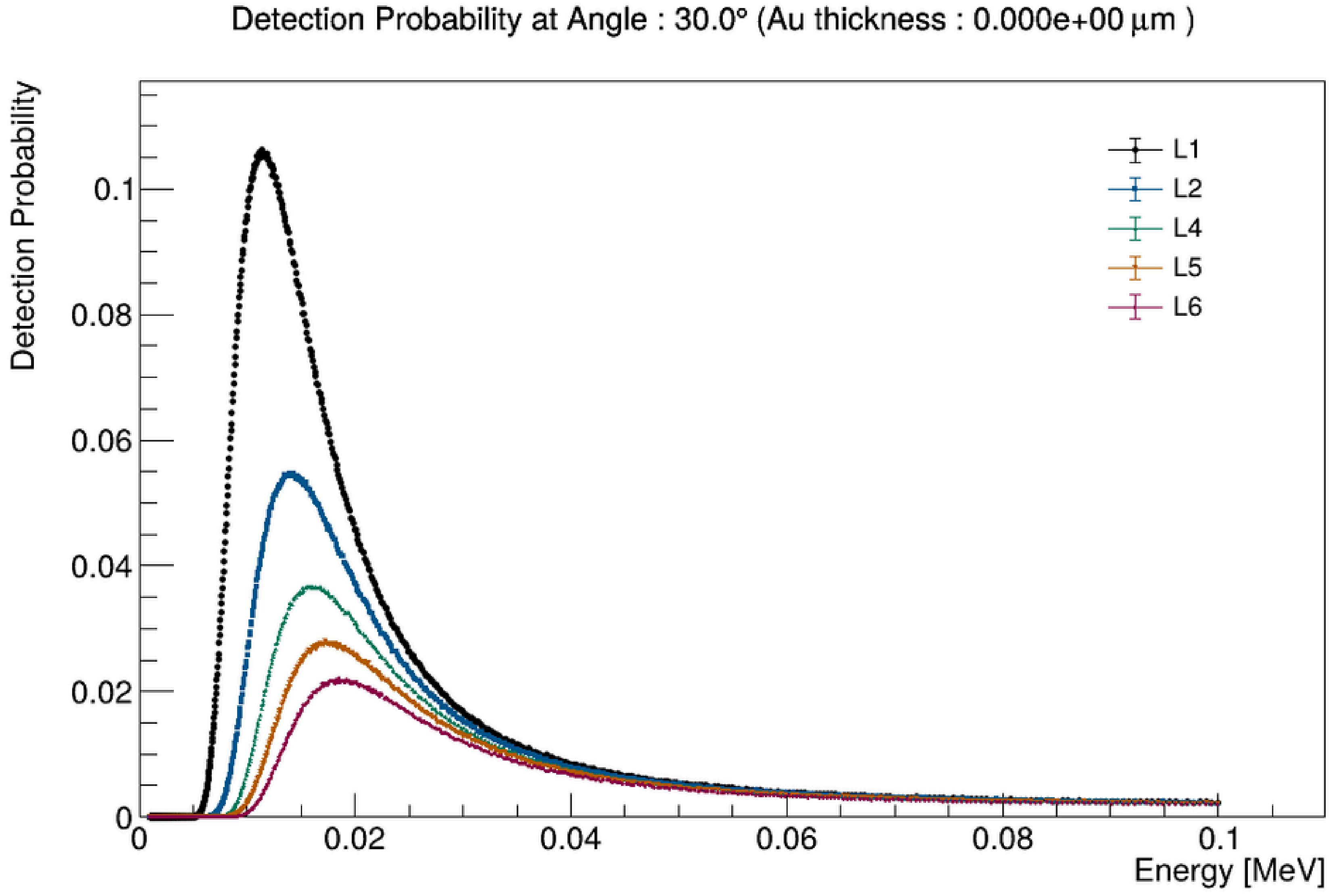
for L1

- Comparison between simplified model & BASF2 (GEANT4 physics list), for same VTX geometry.

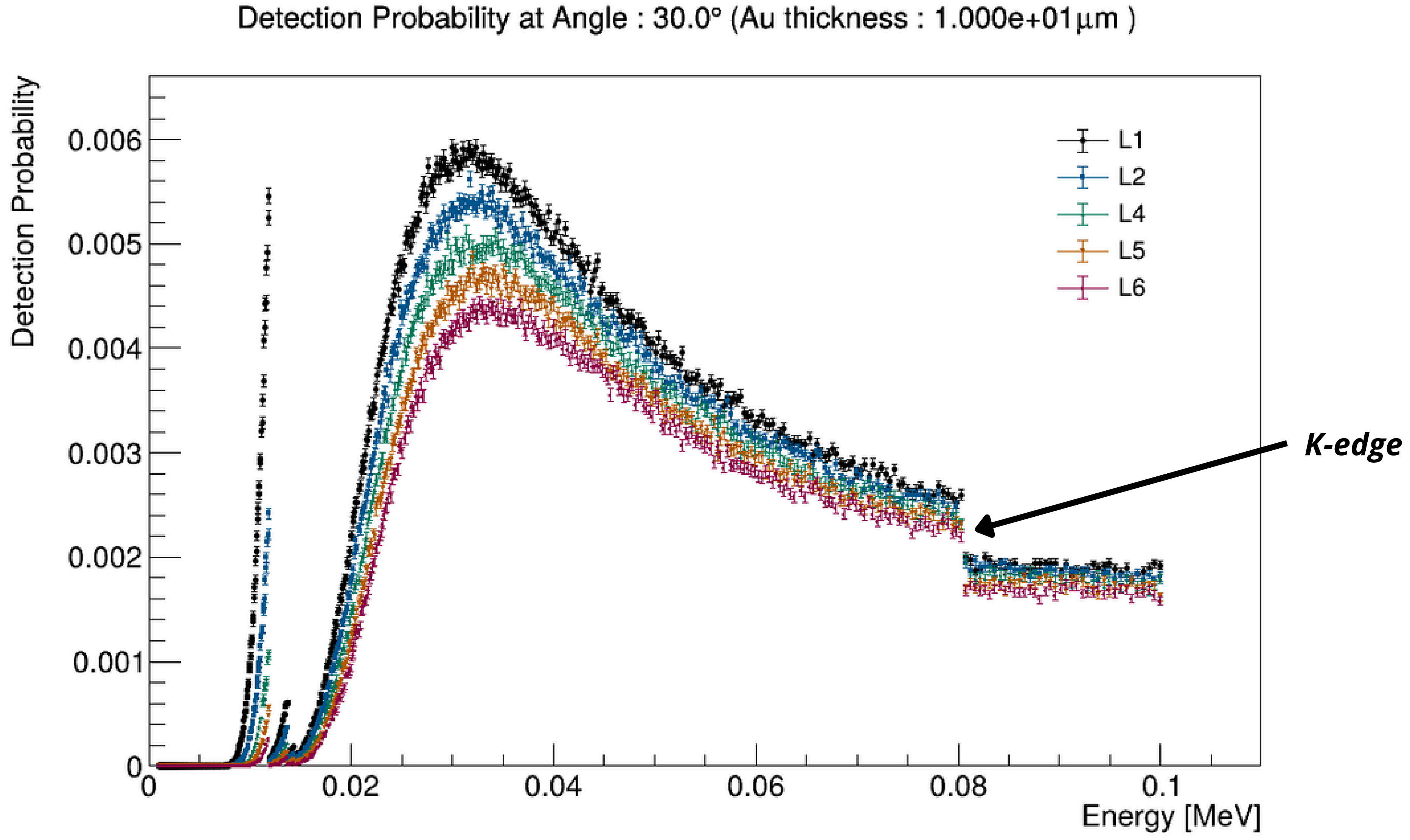


- **Validation of simplified model,** only photoelectric effect considered.

Sensitivity map



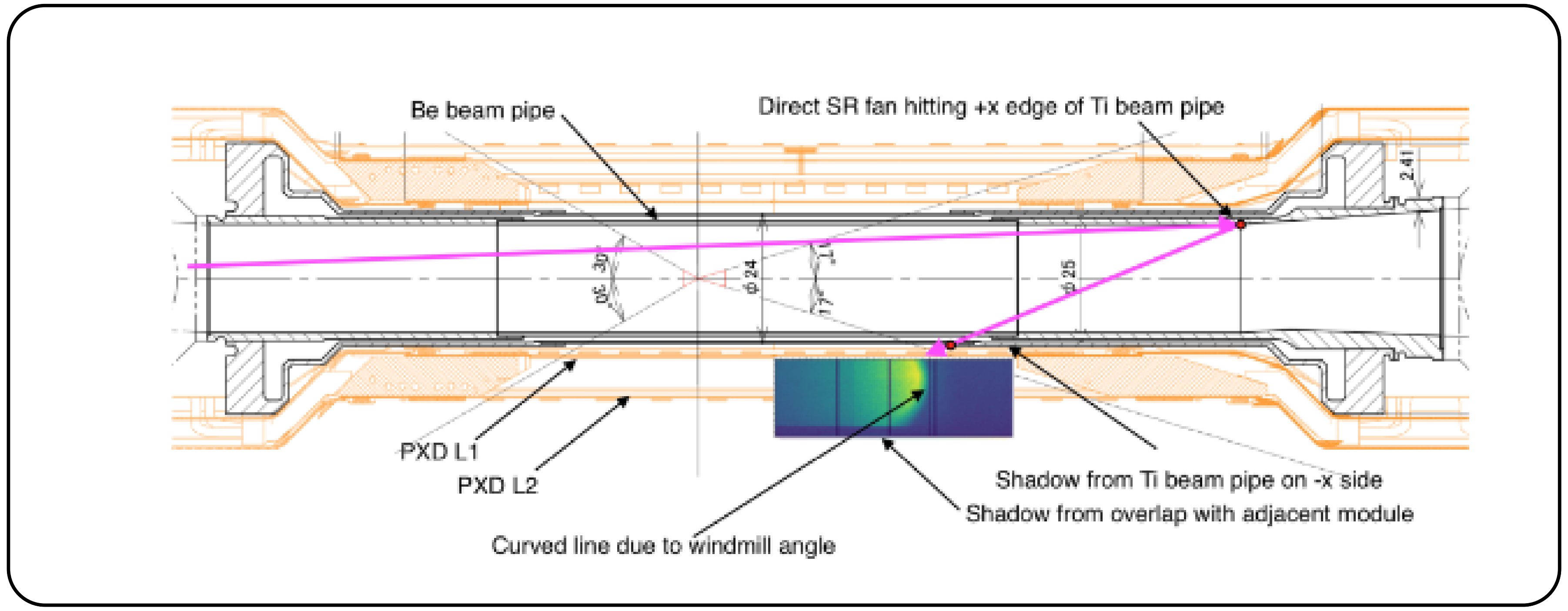
Without gold



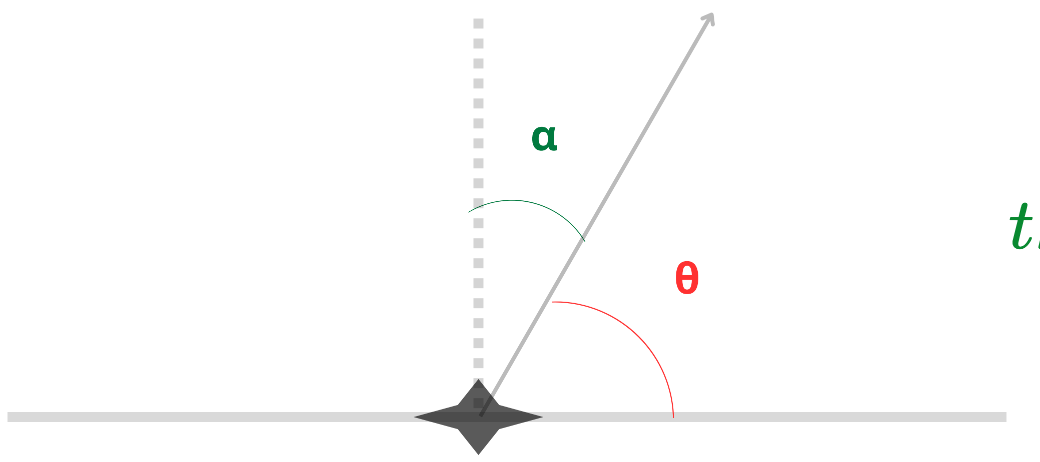
With gold (10 µm)

L1 is the most sensitive to X-rays

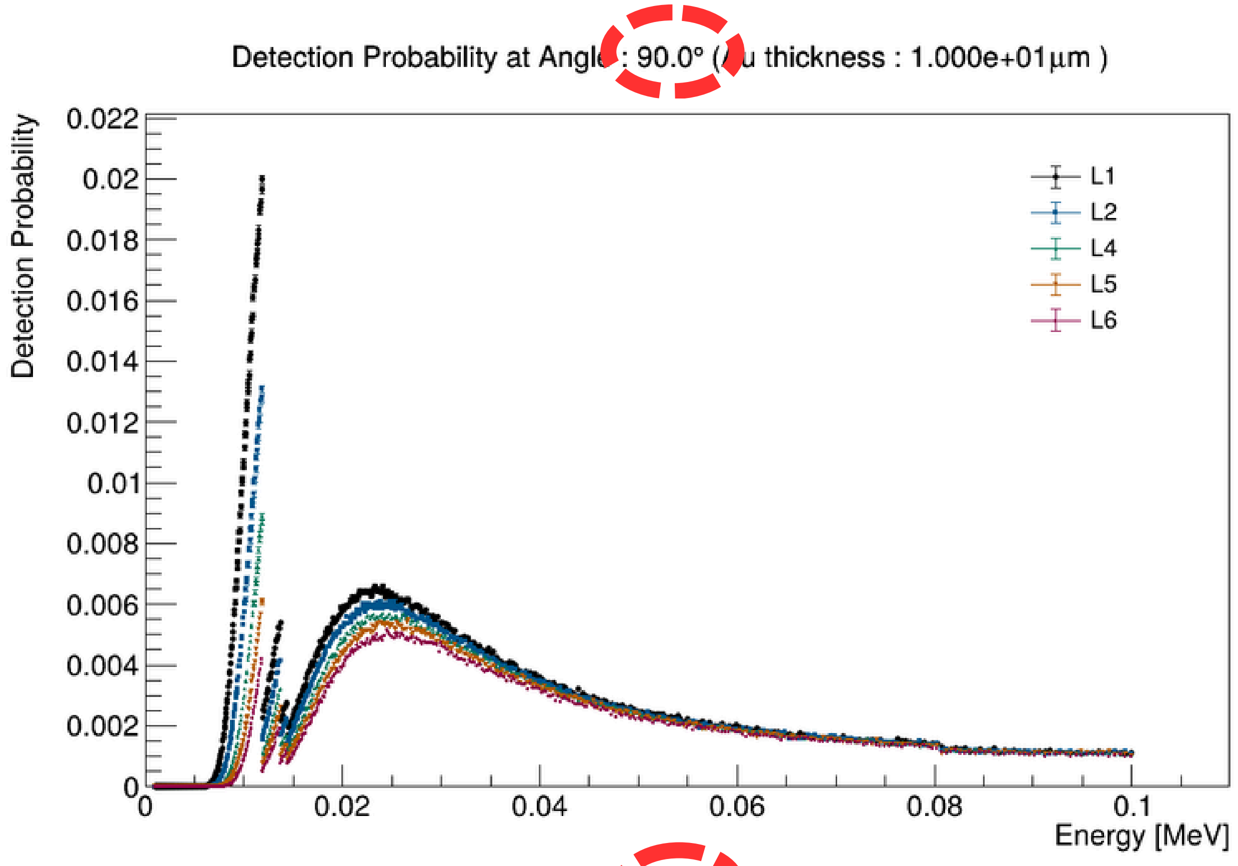
Impact of incidence angle

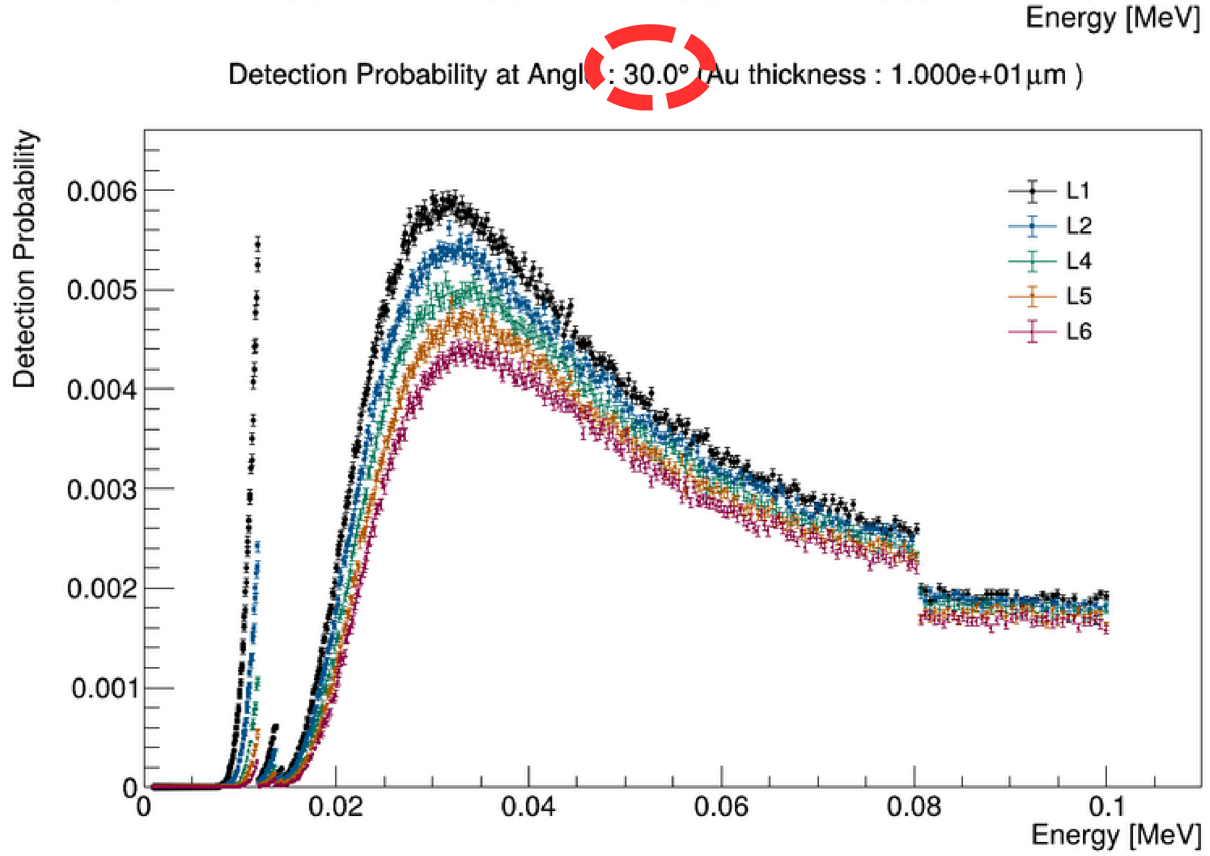


Background evaluation at SuperKEKB and Belle II - 24 - 28 February, 2020



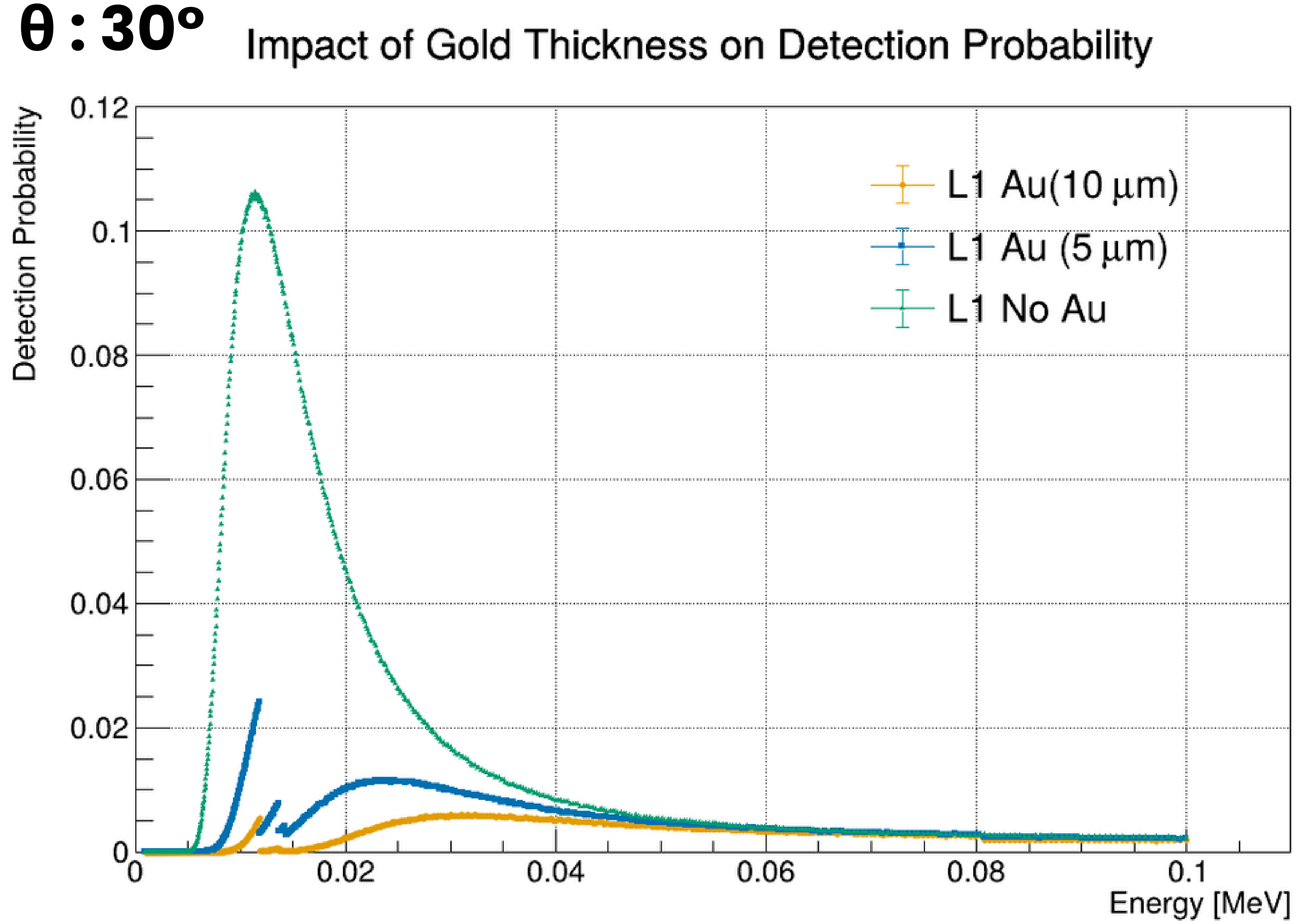
$$thickness_{eff} = \frac{thickness}{cos\,(\alpha)}$$

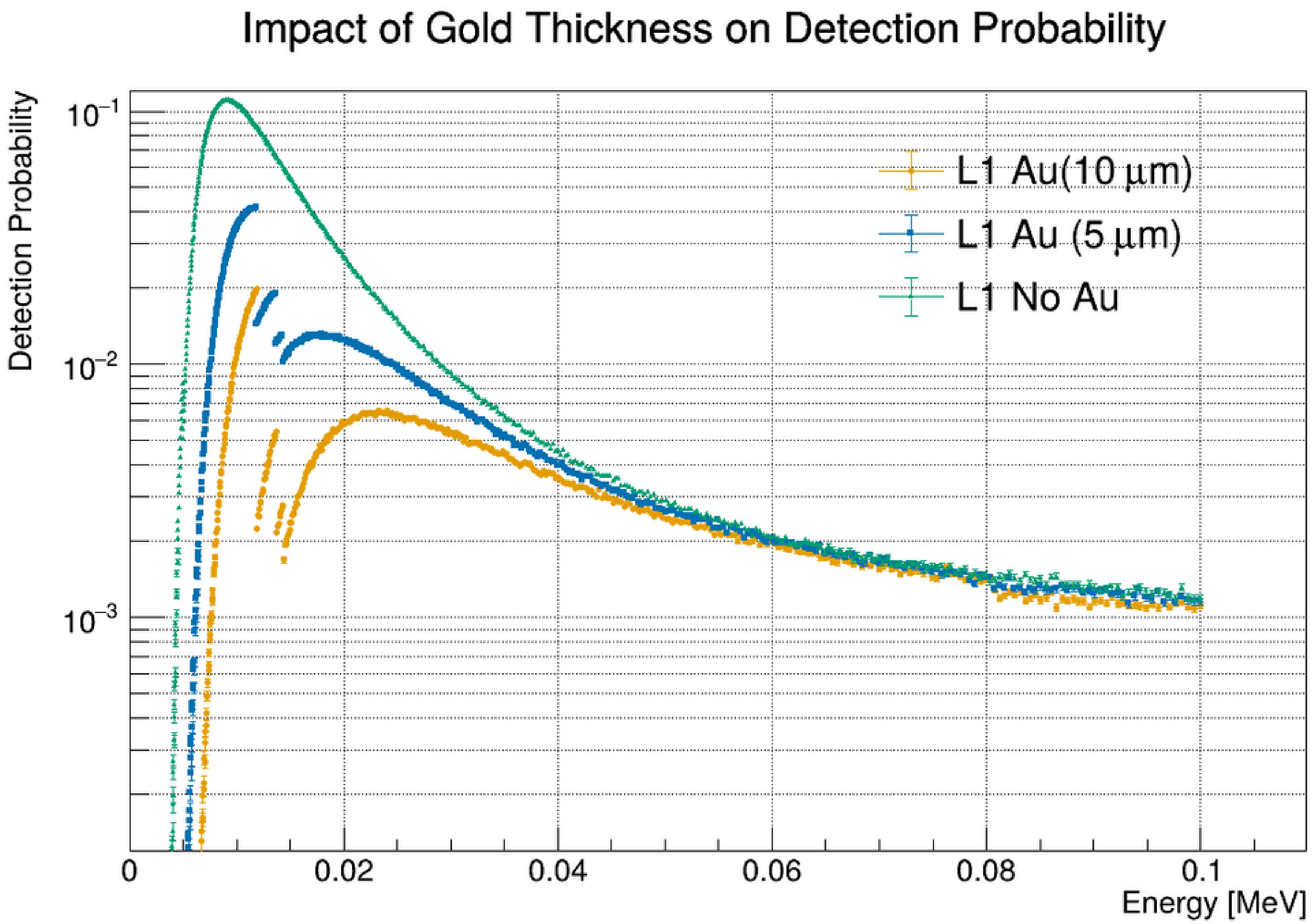




Reducing gold thickness

θ : 30°





A **significant increase** of the sensitivity at low energy

So Far : I obtained sensitivity maps

Need : Synchrotron Radiation Spectrum

$$HitRate = SR * MAP$$

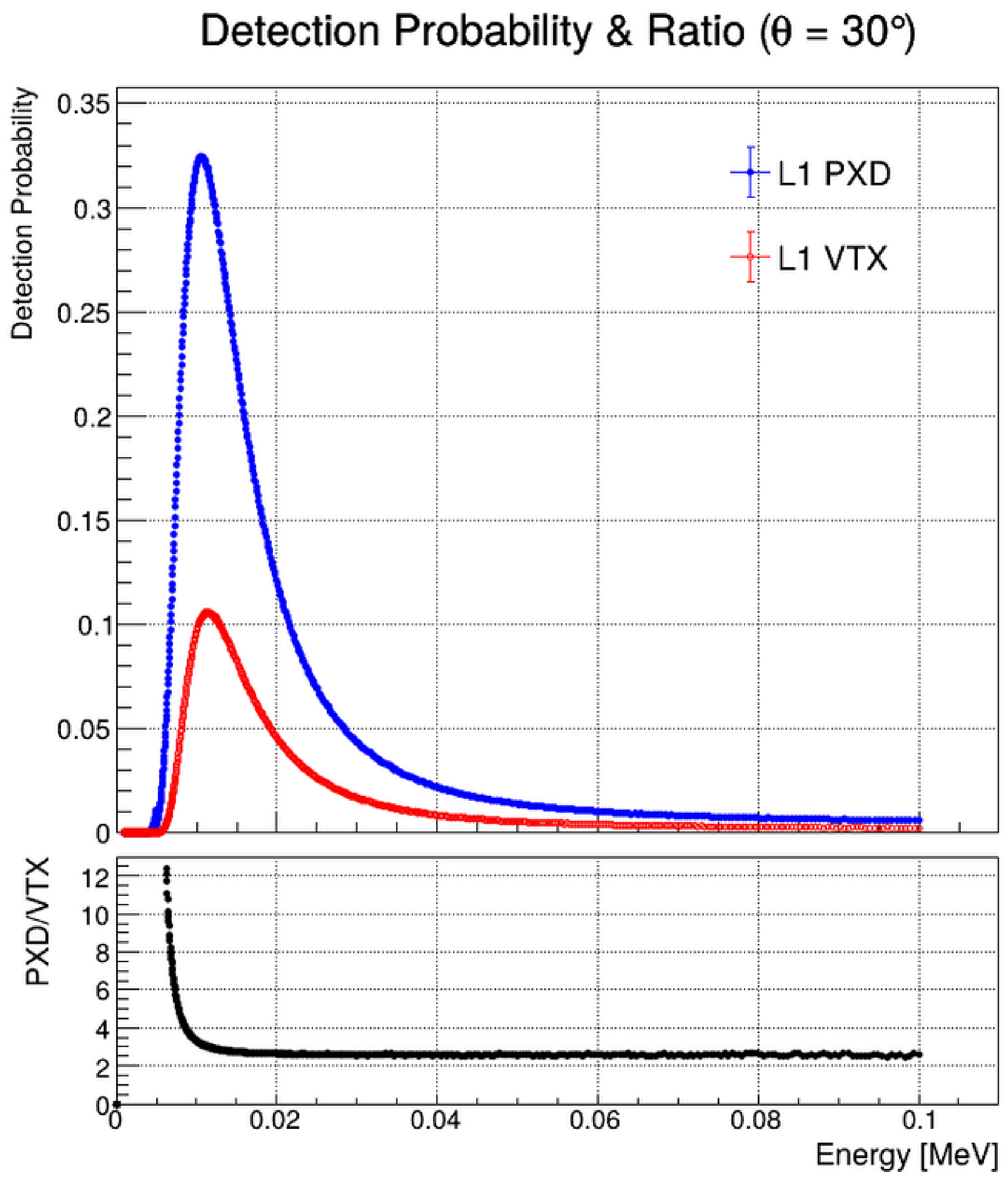
Known Hit Rate (w/ 10 µm gold)

Today (current vertex detector) ~ 10 MHz/cm^2 (10% is SR)

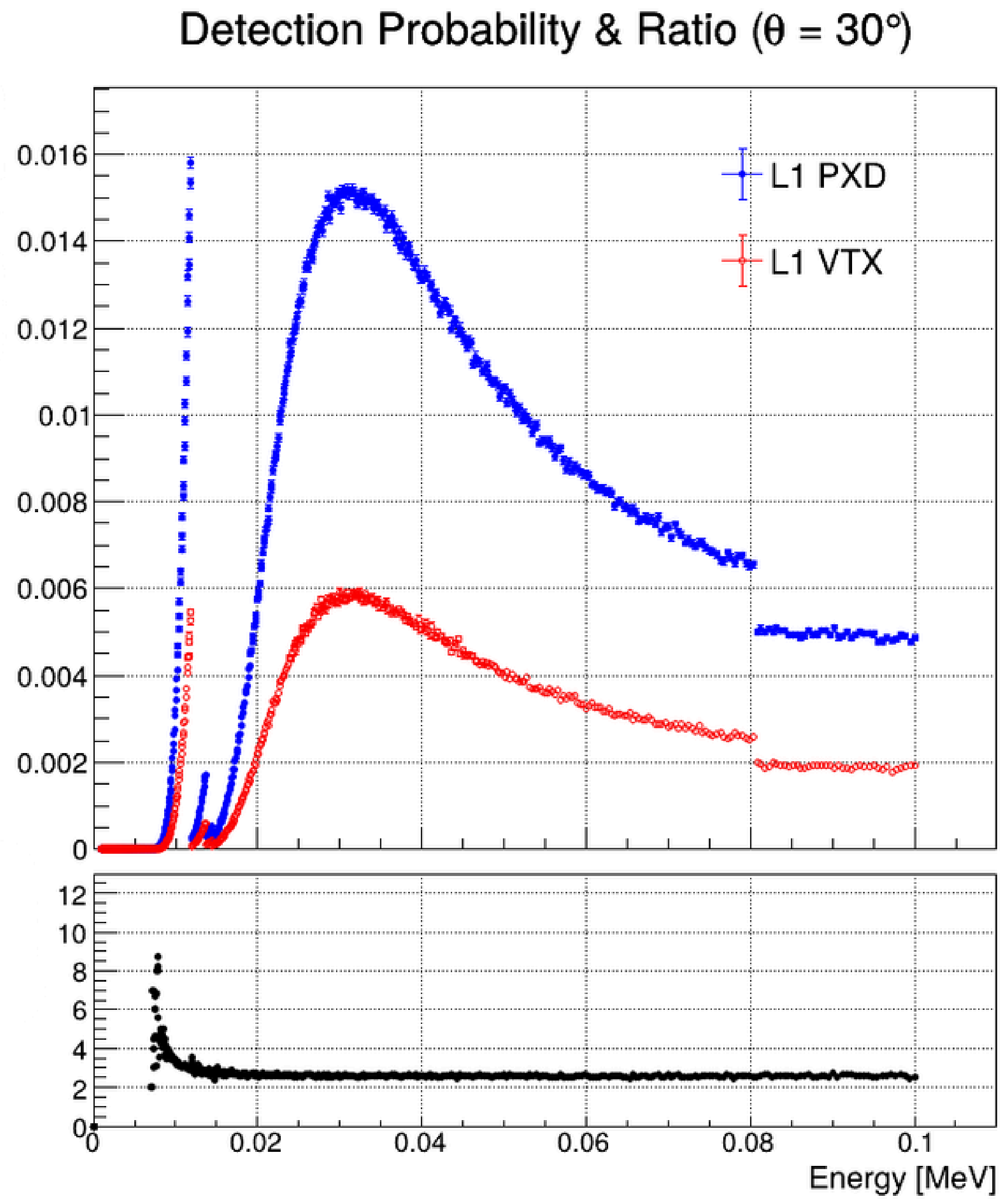
Expected (VTX without SR) ~ 30 MHz/cm^2

Compare : Hit Rate w/ VTX spec. : 120 MHz/cm^2 ⟷ ***a factor 4 of safety***

Comparison with current vertex detector



Without gold



With gold (10 µm)

VTX 2.5x less sensitive than PXD

Sensitive Parts (Si)

PXD : 75 µm

VTX : 30 µm

- **Main objective** : sensitivity maps

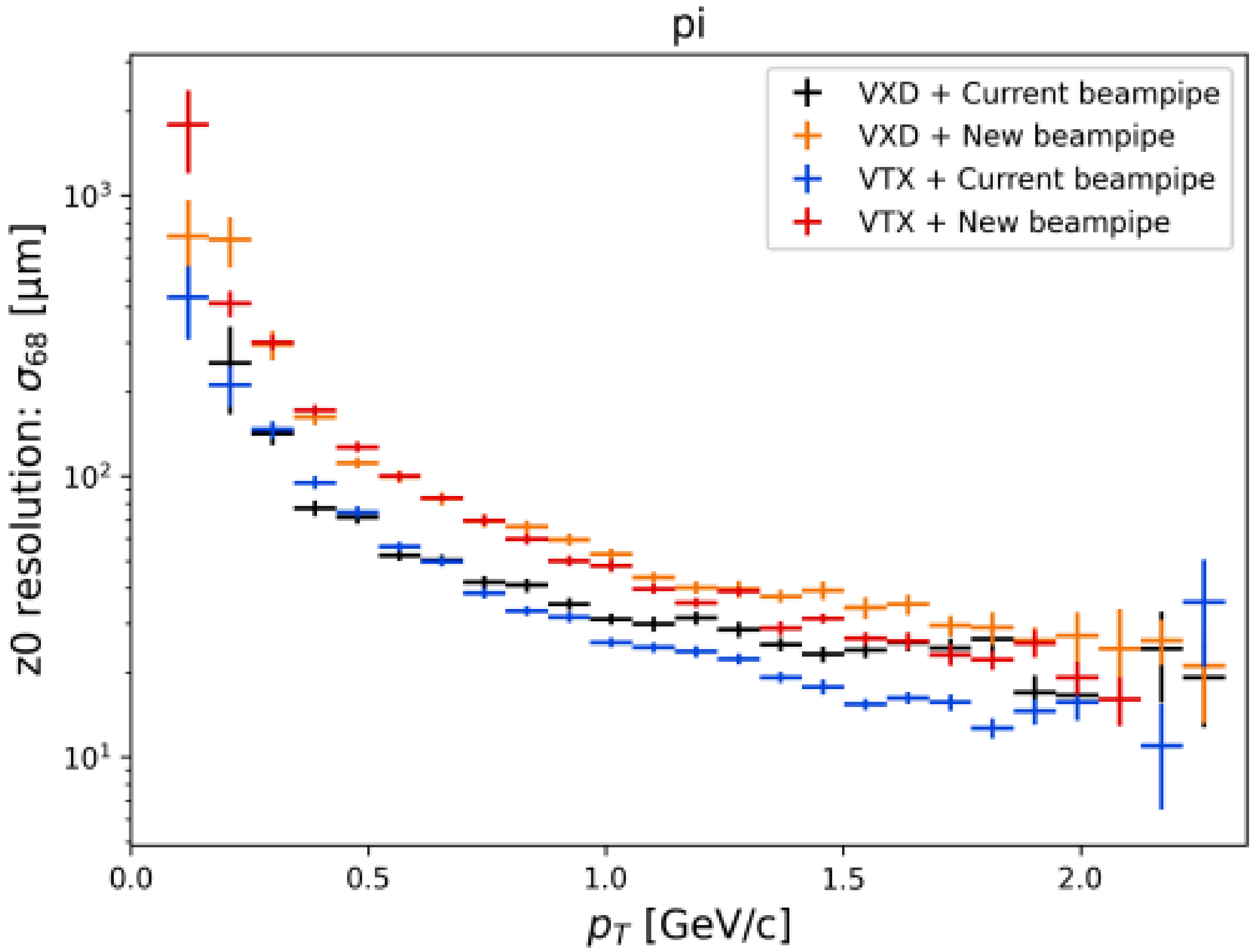
- **Next steps :**
  - obtaining synchrotron radiation spectrum from simulation
  - convolving it with sensitivity maps
  - Infer spectrum from current vertex detector case (PXD)

Thank you !

BACKUP

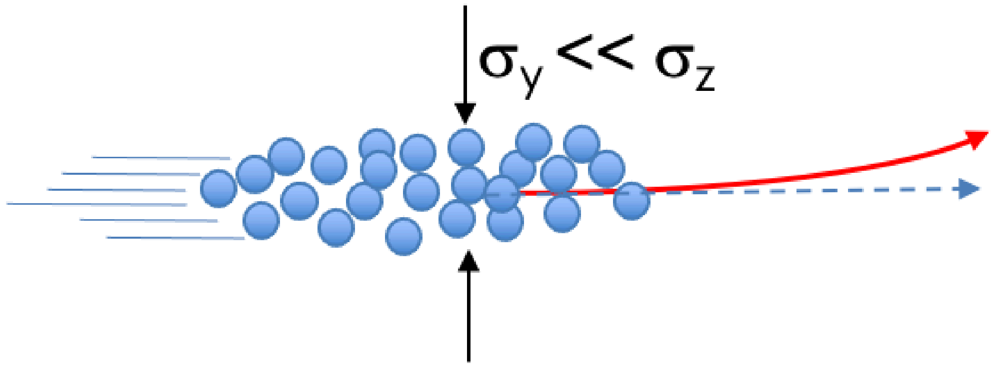
Backup : Resolution

$$\sigma_{IP} = a \oplus \frac{b}{p sin\Theta^{\frac{3}{2}}}$$

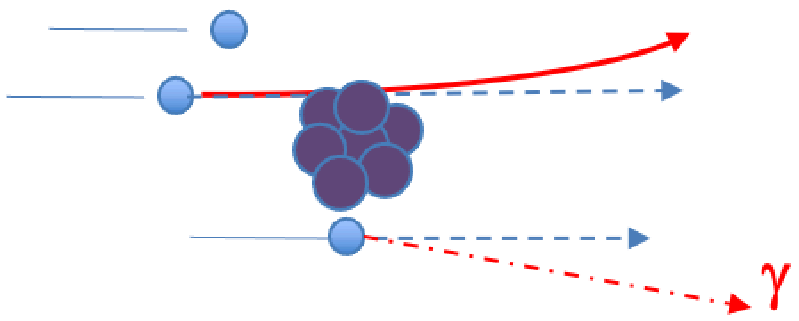


Backup : Background

- **Single beam effects**
  - Touschek ← intra-beam scattering
    - rate $\propto \frac{I_{bunch}^2 \; N_{bunch}}{(\sigma_x \, \sigma_y) \; E_{beam}^3} = \frac{I_{beam}^2}{(\sigma_x \, \sigma_y) \; E_{beam}^3 \, N_{bunch}}$

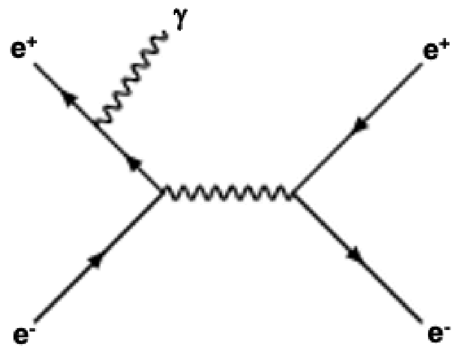


  - Beam gas ← vacuum residues
    - rate $\propto I_{\text{bunch}} \times N_{\text{bunch}} \times P(I)$
    - Dynamic pressure $P(I) = (p_0 + p_1 I_{beam})$

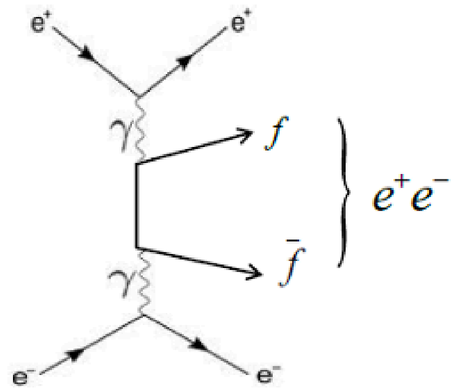


  - Synchrotron radiation ← magnet bending
    - rate $\propto I_{\text{beam}}$

- **Beam-beam effects (QED)**
  - rate $\propto$ Luminosity

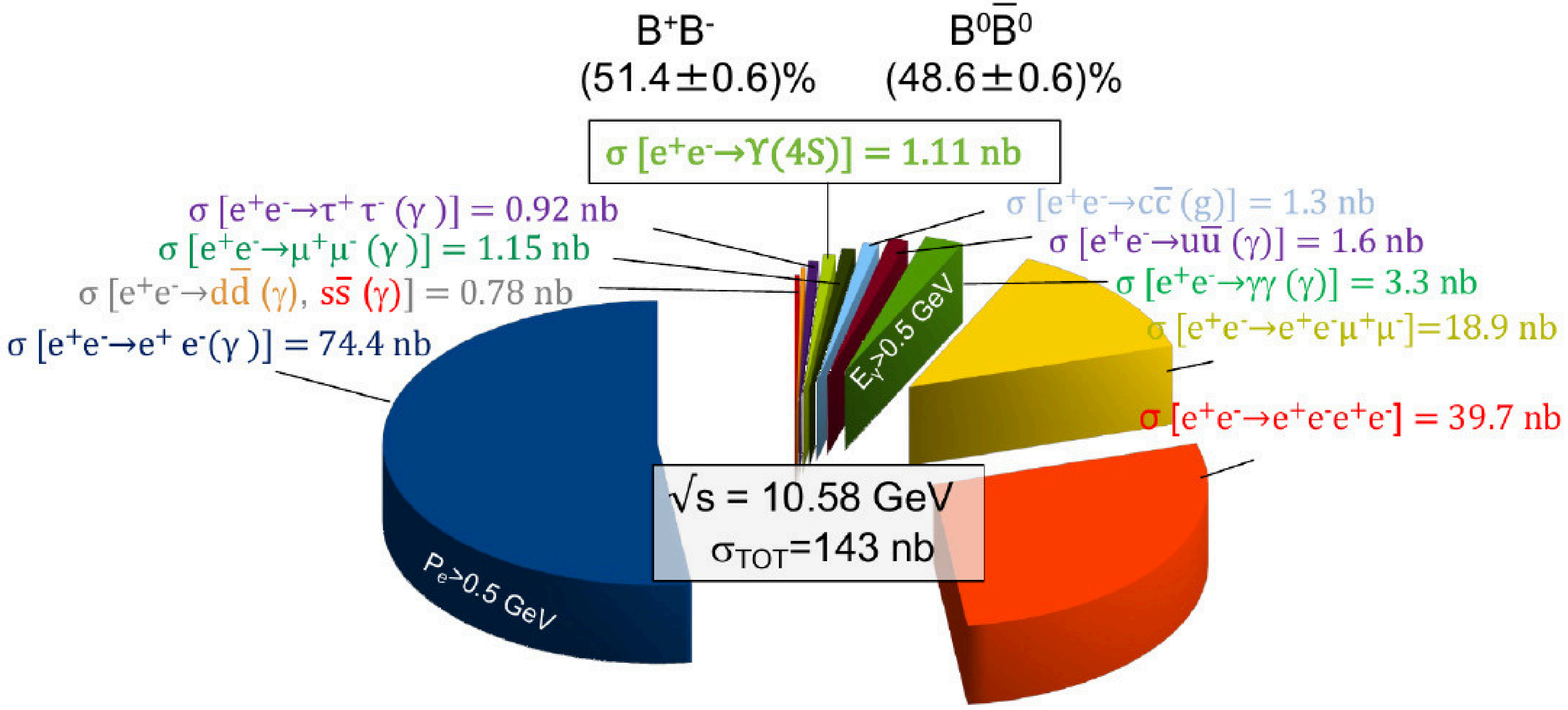


Radiative Bhabha scattering

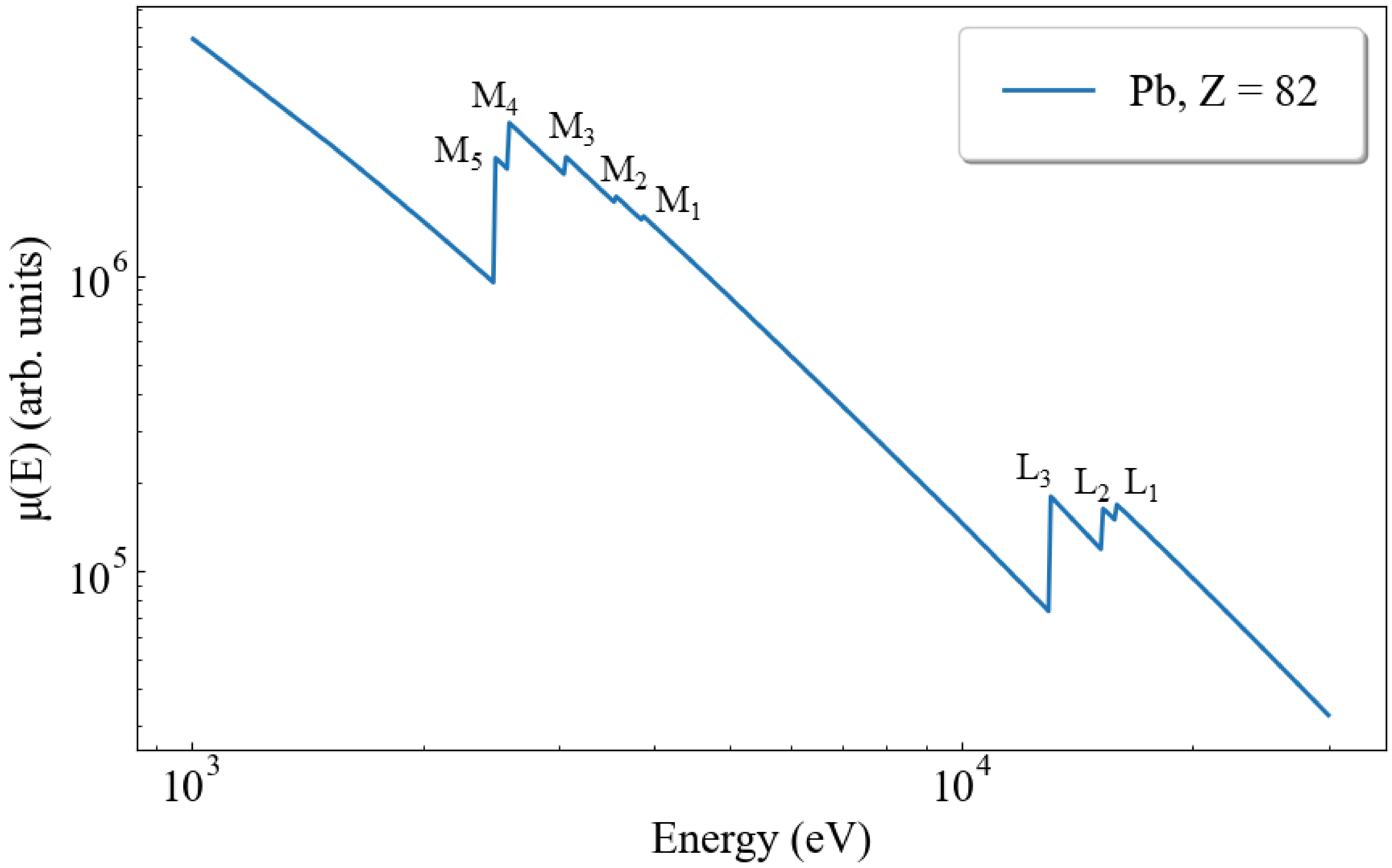


2-photon interaction

Backup : Cross Section

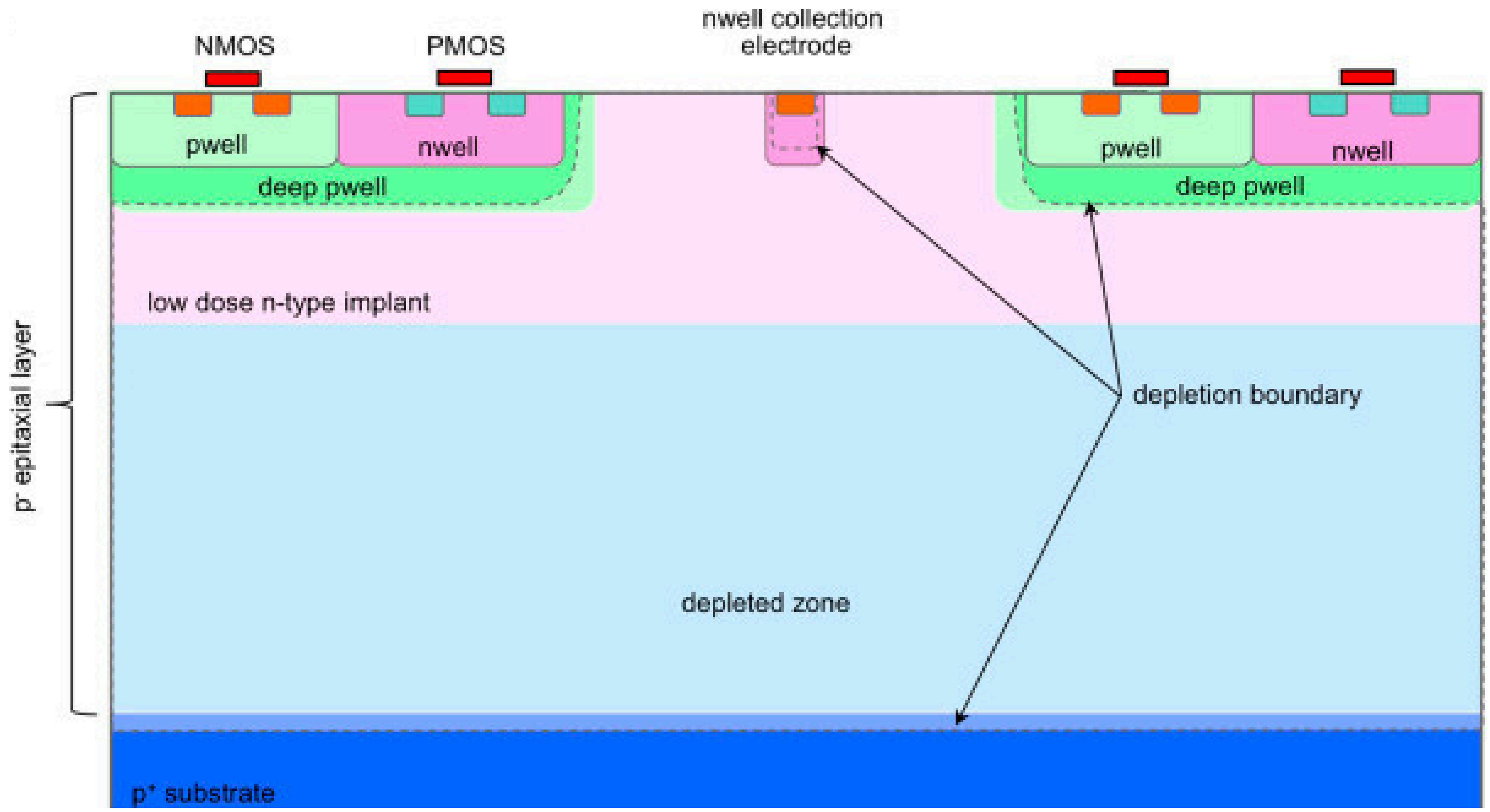


Backup : Absorption Edge



Data : NIST

Backup : CMOS Technology

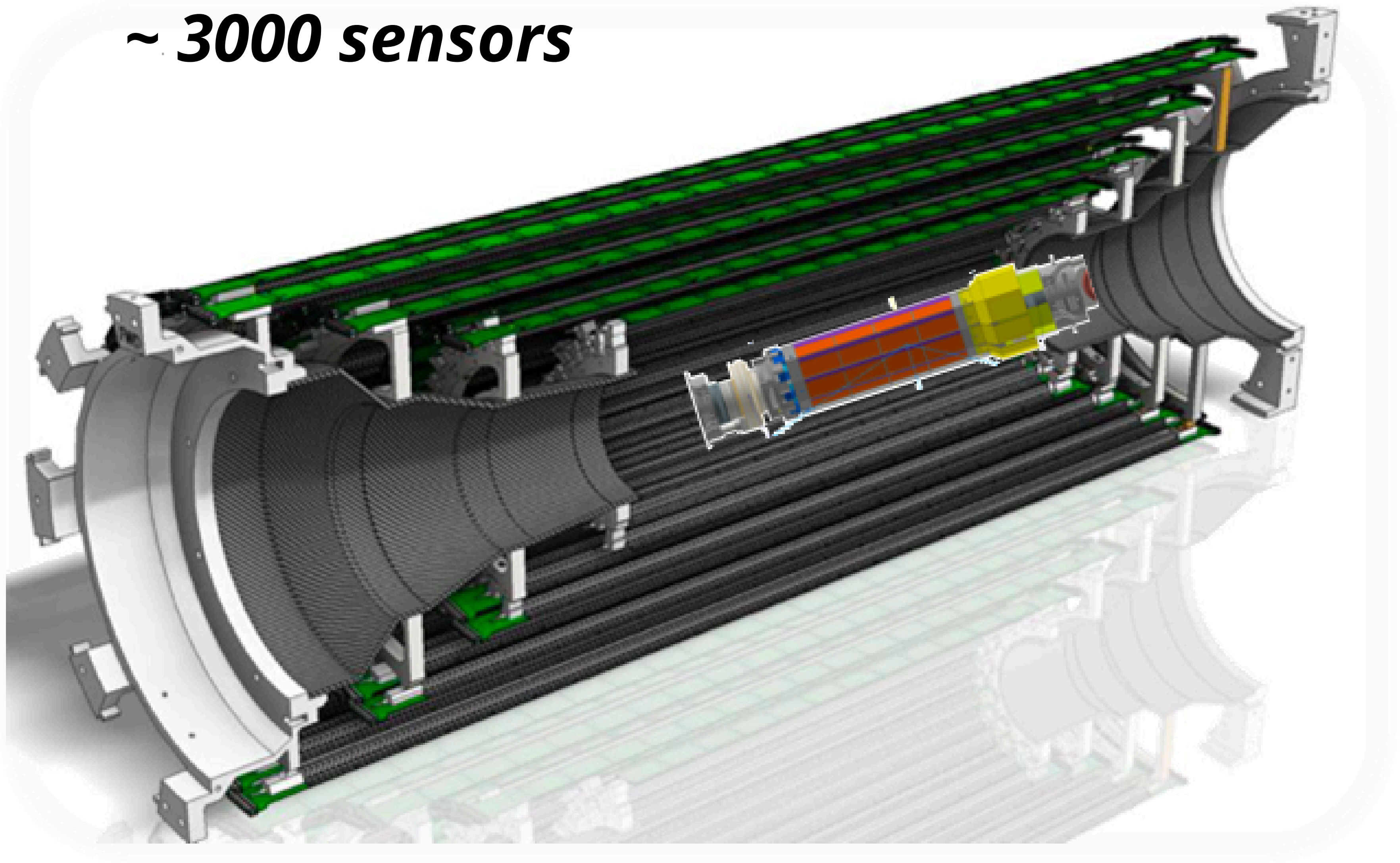


Backup : Attenuation Length

Material	Density (g/cm³) @ 20°C	Attenuation Length @ 1 keV (cm)	@10 keV (cm)	@30 keV (cm)	@60 keV (cm)	@100 keV (cm)
Kapton	1,43	0,000256	0,222	2,44	3,83	4,48
Au	19,3	0,0000111	0,000439	0,00188	0,0114	0,01
C	2,26	0,0002	0,186	1,73	2,52	2,92
Be	1,84	0,0009	0,841	3,03	3,64	4,09
Si	2,33	0,000273	0,0127	0,299	1,34	2,34

Backup : VTX

R_out : 14 cm
70 cm long
116 g of silicon distributed over 1 m²



Backup : Expected Signal

$B \rightarrow K_s\pi^+\pi^-\gamma$

$$barn = 10^{-24} cm^2$$

$\sigma(e^+e^- \rightarrow B^0\bar{B}^0) \sim 1$ nb
$\times$ 2 (2 mesons B per event)
$\times \mathfrak{B}(B \rightarrow K_s\pi^+\pi^-\gamma) \sim 10^{-5}$
$\rightarrow \sigma \sim 20$ fb

$\mathscr{L}$_int = 1 ab^{-1} collect data :

N = $\mathscr{L}$_int × σ ~ 20 000 event produced

With an event reconstruction efficiency of ε ~ 10% :

N ~ 2 000 events reconstructed

Backup : Physics List

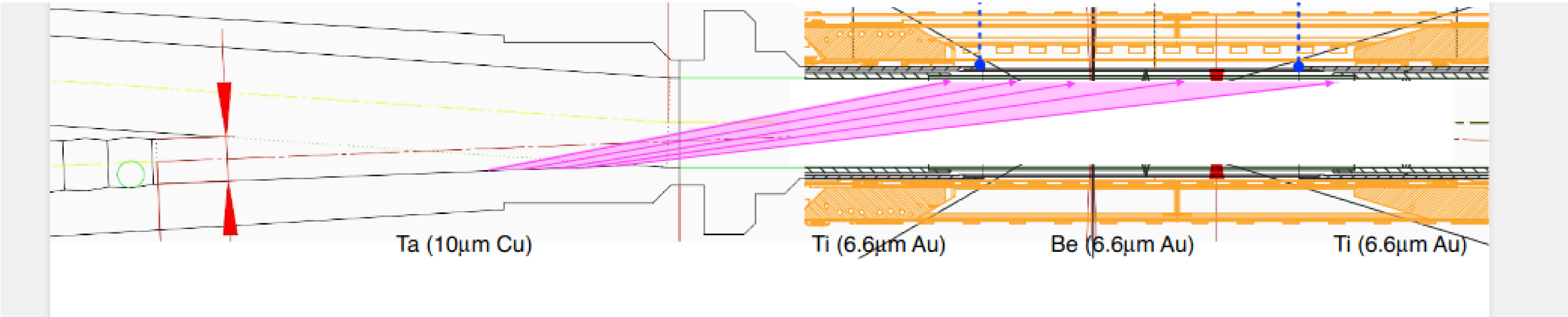
- G4EmStandardPhysics_option1
- G4DecayPhysics
- G4OpticalPhysics

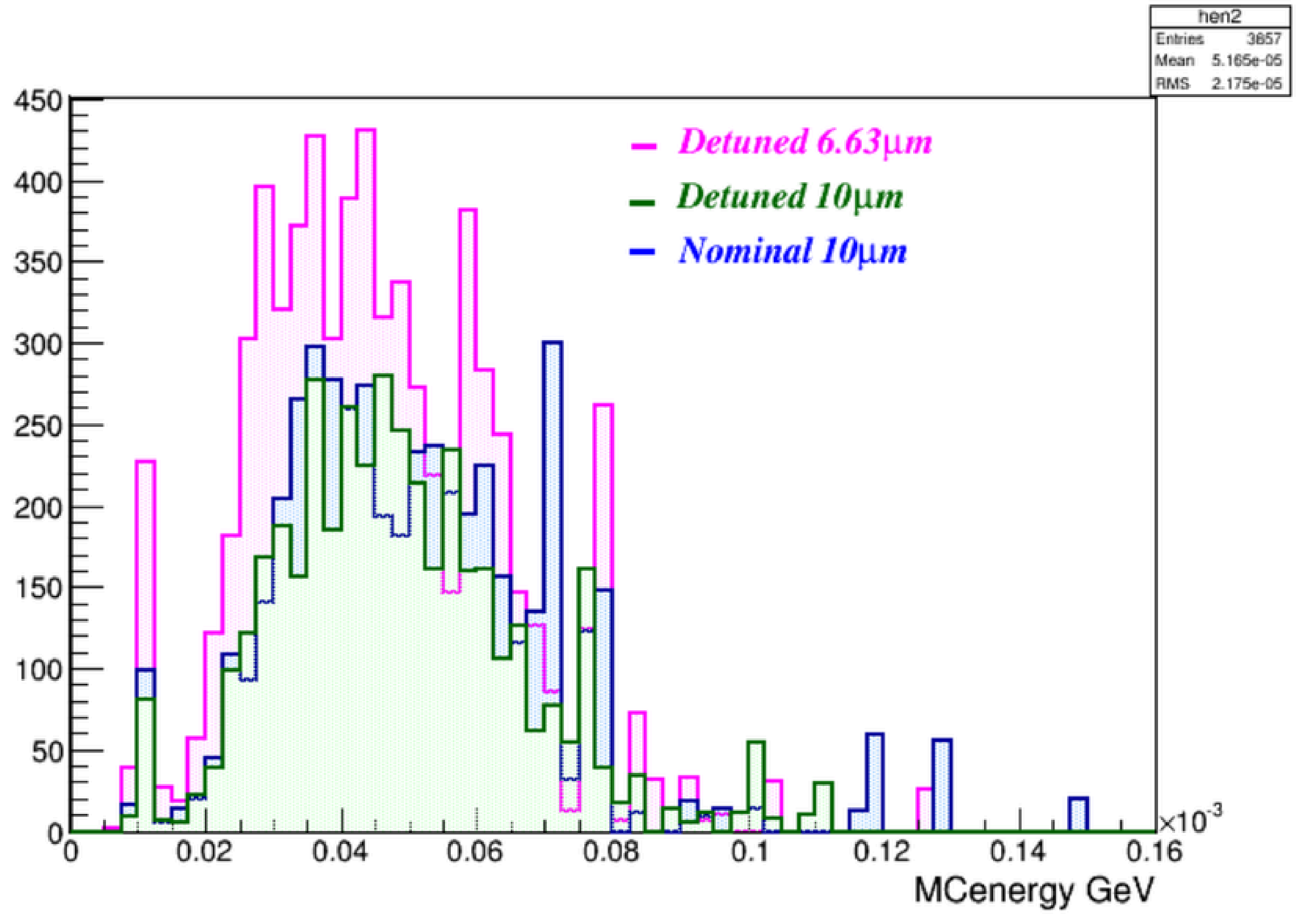
standard Geant4 distribution

- ProtonPhysics
- NeutronPhysics
- PionPhysics
- KaonPhysics
- HyperonPhysics
- AntiBaryonPhysics
- IonPhysics
- GammaLeptoNuclearPhysics

BASF2 implementation

Backup : Synchrotron Radiation





First SR study (Belle II) - Yuri Soloviev

Backup : Incidence Angle