LC Vertex Detector Workshop – Apr. 30th – May 3rd 2017

Guariguanchi: Analytical Calculation Tool for Vertex Detector Studies

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Outline

- **Motivation**
- **Introduction**
- **Some Studies for ILD VXD**
- **Summary and Outlook**

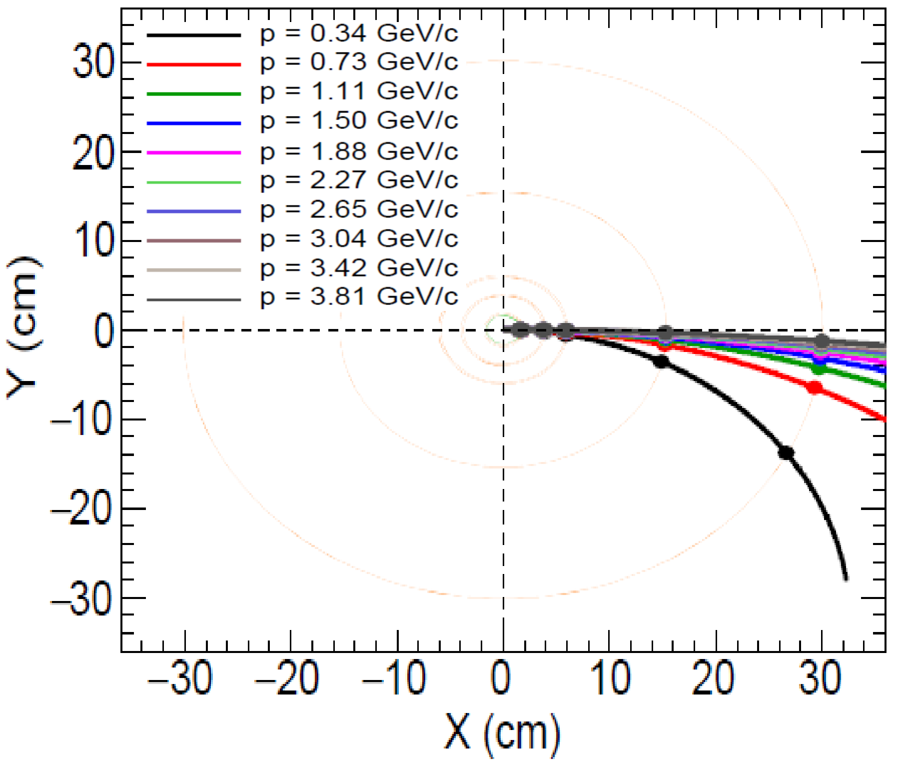
Introduction

Motivation

- **Track parameters resolution and efficiency main aspects for tracker design**
- **Those are mainly dependent on**
  - Detector geometry ⇒ material distribution
  - Sensitive elements performances ⇒ σ_{sp}, $t_{R.O.}$, ε_{det}
  - Hit density ⇒ Physics environment
- **For given momentum (p,θ,ϕ) it is possible to calculate the track parameter's average resolution**
- **Calculation ignores effects only accounted for with full simulation, but it has some advantages**
  - Quick calculation of tracking performances for several geometries
  - Can be used to identify the crucial parameters in detector optimization process
  - Identify subset of detector geometries for full simulation

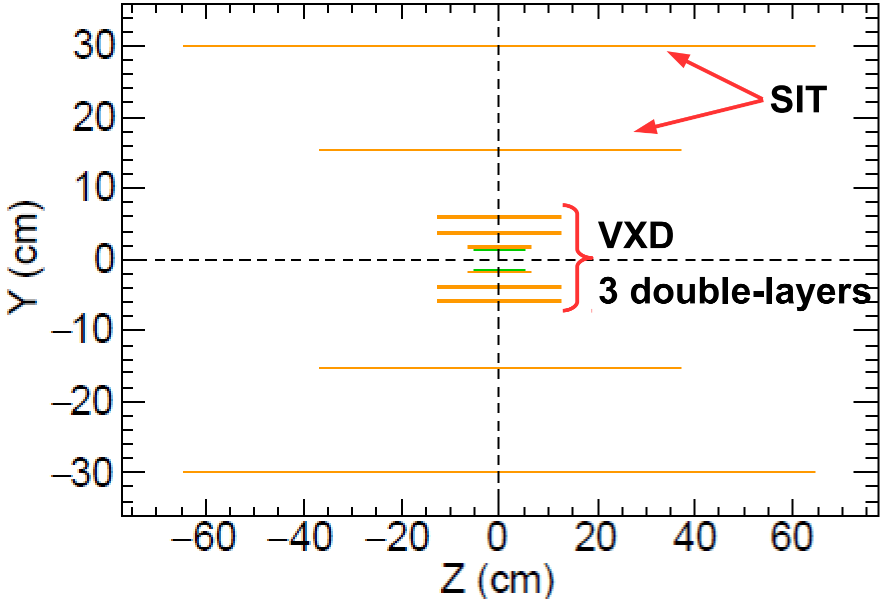
Introduction: Guariguanchi's Work-flow

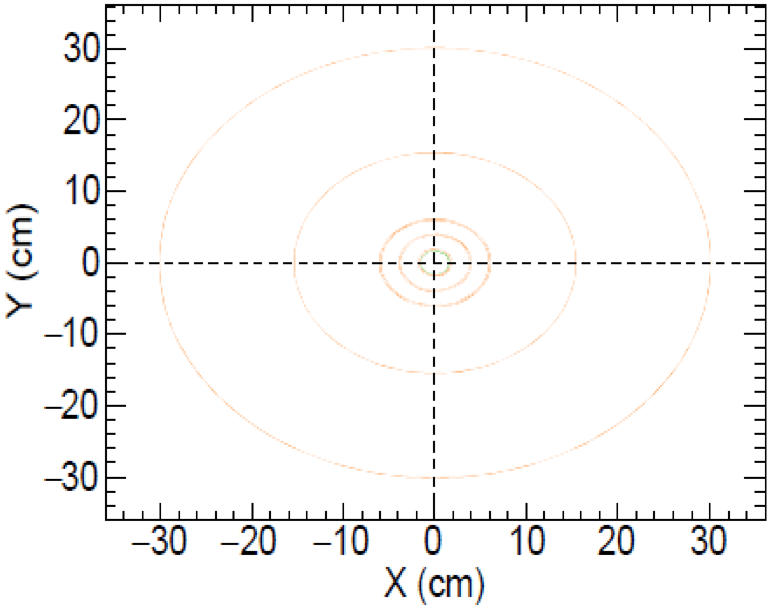
- **Work-flow**
  - From initial conditions (x_{init},p_{init}) ⇒ particle's intersections with geometry
  - Multiple-scattering (MS) cov-matrix of intersection coordinates ⇒ V_{MS}
  - Total cov-matrix ⇒ $V_{tot} = V_{SP} + V_{MS}$
  - Track parameter's covariance matrix
- **Different analyses**
  - Material budget seen vs (p,θ,ϕ)
  - Track parameter's resolutions vs (p,θ,ϕ)
  - Tracking pseudo-efficiency vs (p,θ,ϕ)
- **Different geometries can be compared for each analysis**



Introduction: Geometry

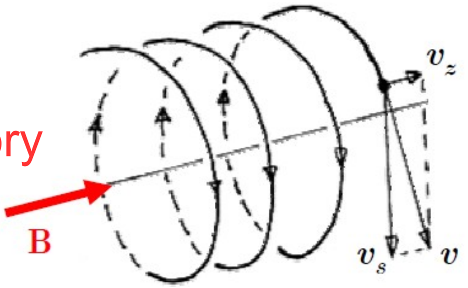
- **Full geometry is a combination of simple elemental objects**
  - Cylinder, Plane, Disk
- **Elements attributes**
  - Position, orientation, sensitive/insensitive dimensions
  - Material budget
  - Performances (if sensitive): ε_{det}, σ_{sp}, $t_{R.O.}$
- **Full geometries also have its own (constant) B-field**



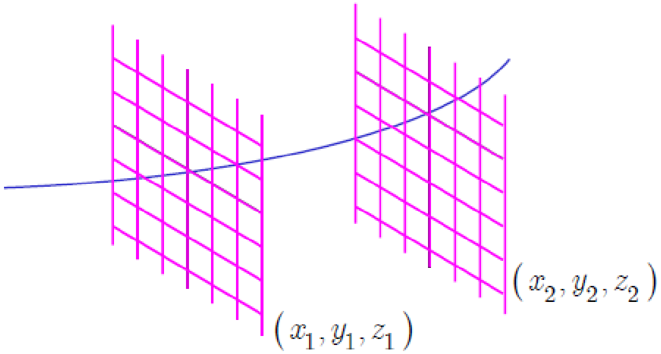


Introduction: Navigation

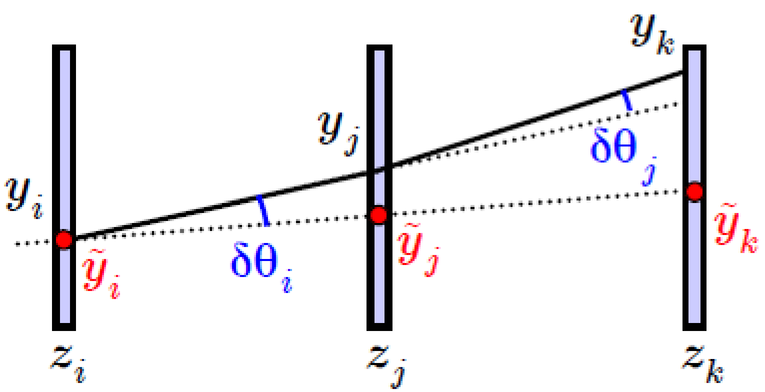
- **Solve motion's equation** $$\frac{d^2\mathbf{r}}{ds^2} = \frac{e}{p}\frac{d\mathbf{r}}{ds} \times \mathbf{B}$$ $\Rightarrow$ nominal trajectory



- **Navigate geometry**
  $\Rightarrow$ trajectory intersection with geometry elements



- **Calculate intersection coordinates correlations due to MS**



$$p(\delta\theta_i) = \frac{1}{\sqrt{2\pi}} e^{-\delta\theta_i/2\theta_0}$$

$$\theta_0 = \frac{13.6\,MeV}{\beta pc} z\sqrt{x/X_0}\left[1+0.038\ln(x/X_0)\right]$$

Introduction: Track parameters resolution

- **Track parametrization**

$$\begin{cases} x = & x_0 + d_\rho \cos\phi_0 & +\frac{\alpha}{\kappa}\{\cos\phi_0 - \cos(\phi_0+\phi)\} \\ y = & y_0 + d_\rho \sin\phi_0 & +\frac{\alpha}{\kappa}\{\sin\phi_0 - \sin(\phi_0+\phi)\} \\ z = & z_0 + d_z & -\frac{\alpha}{\kappa}\tan\lambda\cdot\phi, \end{cases}$$

$$\vec{\alpha} = \{d_\rho, \phi_{0,} d_z, \tan\lambda, \rho = \alpha/\kappa\} \qquad P_t(GeV/c) = 0.3\, B(T)\rho(m)$$

- **Track fitting**

$$\chi^2 = \sum_{i,j}\{\Gamma_i(\vec{\alpha}) - \Gamma_i^{meas}\}(V_{sp} + V_{MS})_{ij}^{-1}\{\Gamma_j(\vec{\alpha}) - \Gamma_j^{meas}\}$$

- **Track parameters cov-matrix**

$$(V_{\vec{\alpha}}^{-1})_{km} = \frac{\partial^2\chi^2}{\partial\alpha_k\partial\alpha_m} = \frac{\partial\Gamma_i(\vec{\alpha})}{\partial\alpha_k}(V_{sp} + V_{MS})_{ij}^{-1}\frac{\partial\Gamma_j(\vec{\alpha})}{\partial\alpha_m}$$

Introduction: Track parameters resolution

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$$\chi^2 = \sum_{i,j} \{\Gamma_i(\vec{\alpha}) - \Gamma_i^{meas}\}(V_{sp}+V_{MS})_{ij}^{-1}\{\Gamma_j(\vec{\alpha}) - \Gamma_j^{meas}\}$$

- **Track parameters cov-matrix**

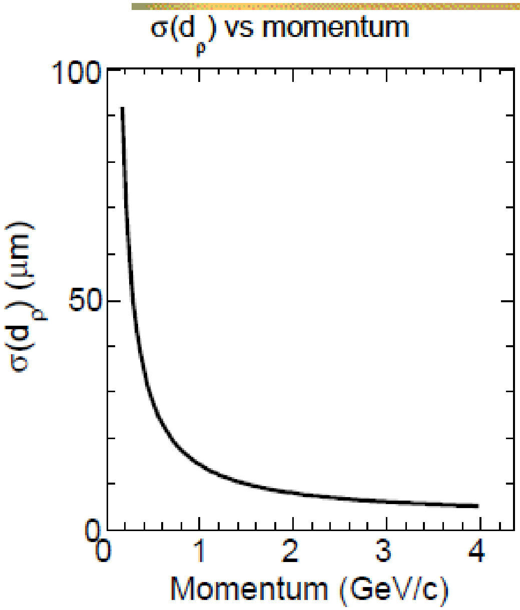
Sensor performance

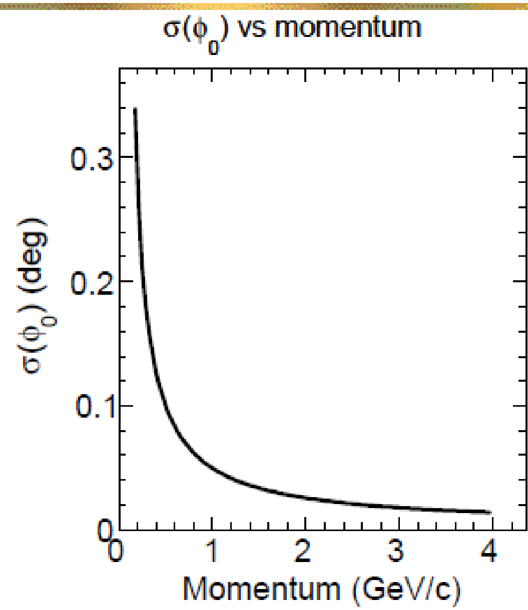
Geometry & p$^{-\delta}$

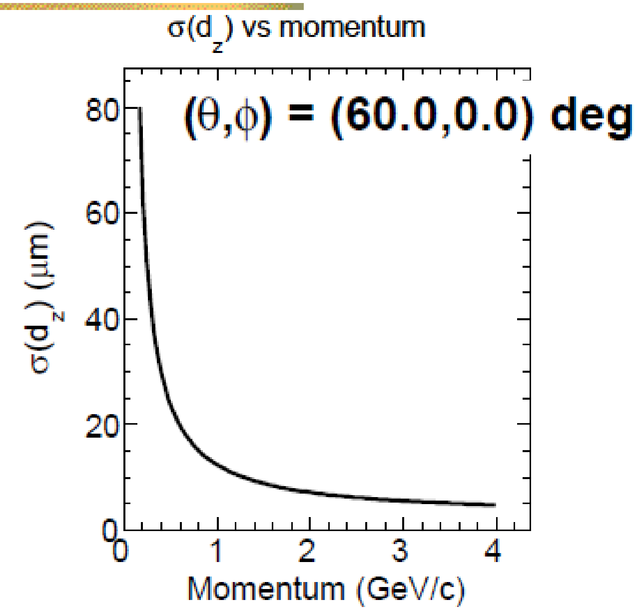
$$(V_{\vec{\alpha}}^{-1})_{km} = \frac{\partial^2\chi^2}{\partial\alpha_k\partial\alpha_m} = \frac{\partial\Gamma_i(\vec{\alpha})}{\partial\alpha_k}(V_{sp}+V_{MS})_{ij}^{-1}\frac{\partial\Gamma_j(\vec{\alpha})}{\partial\alpha_m}$$

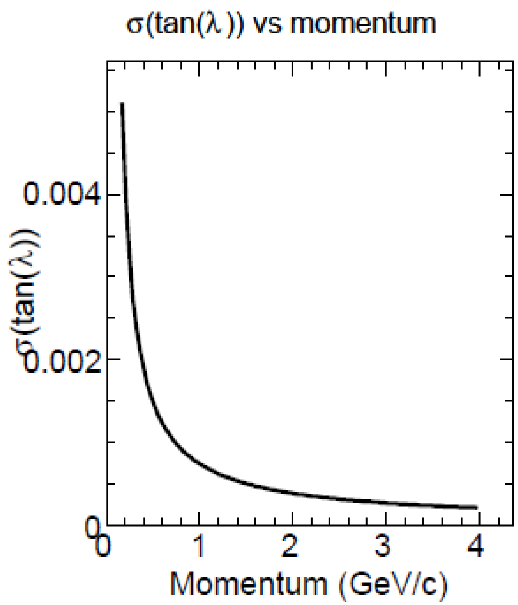
Geometry & p

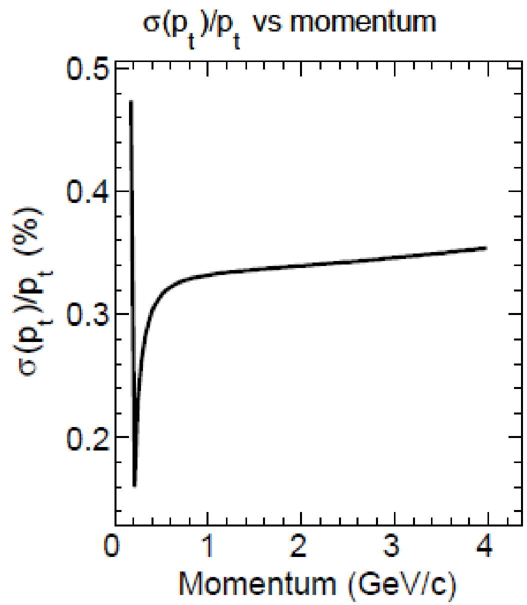
Introduction: Track parameters resolution (Example)









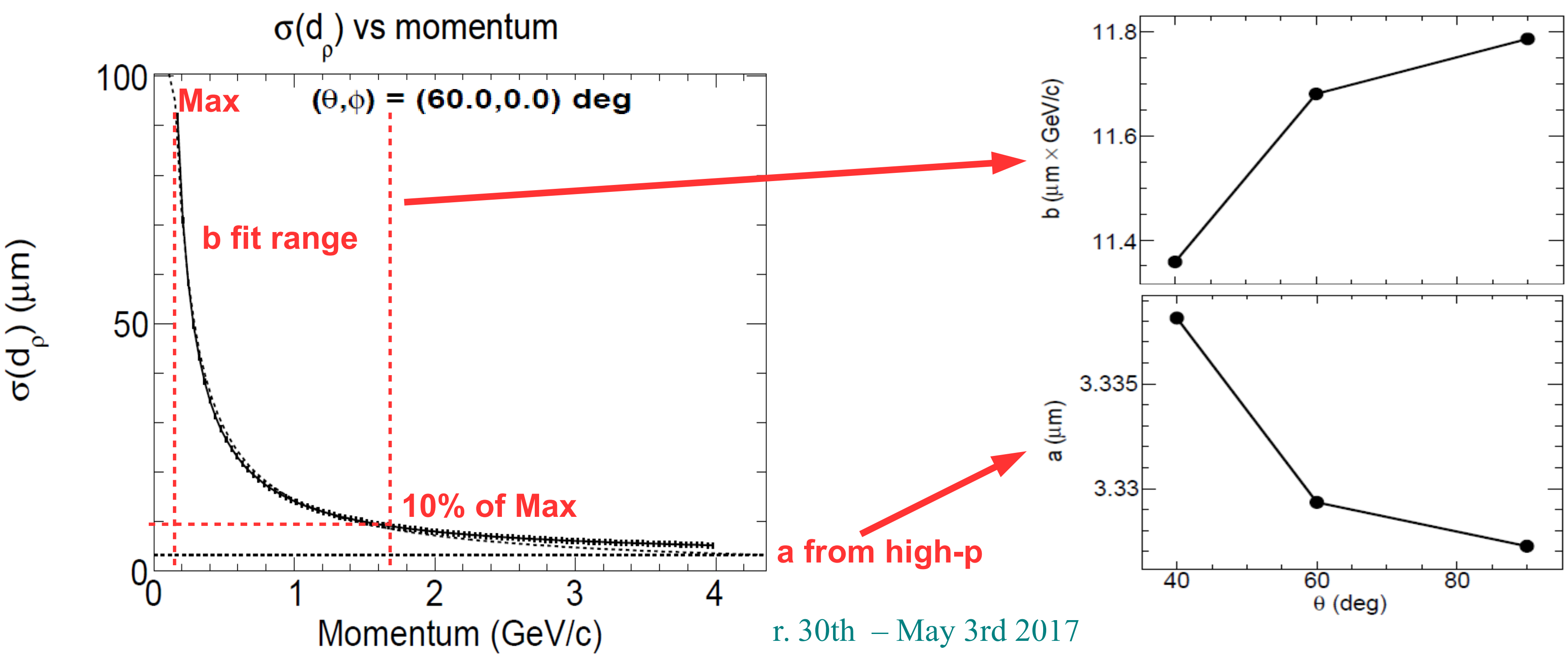


DBD Geometry: (B = 3.5 T)

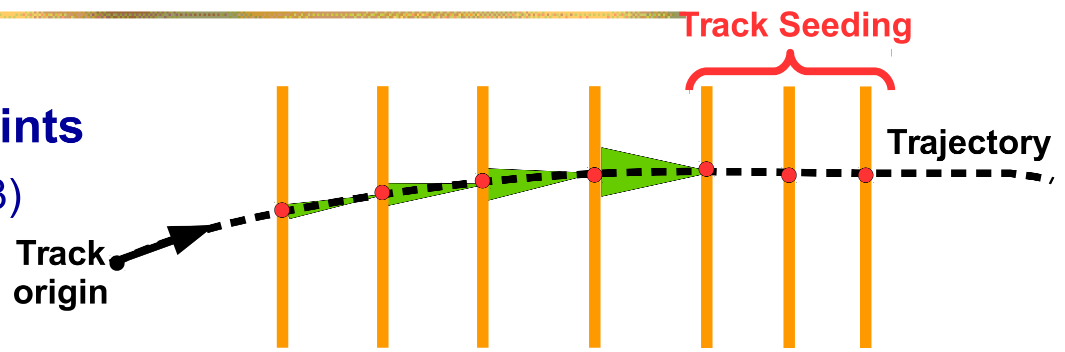
- VXD: 0.3% X/X_0 /double-layer
  - L1: 2.8 μm / 50 μs
  - L2: 6.0 μm / 10 μs
  - L3-6: 4.0 μm / 100 μs
- SIT: 0.65% X/X_0 /double-layer
  - L1-2: (7.0,50.0) μm / 308 ns

Introduction: Impact parameter parametrization

- **$\sigma(d_\rho)$ empirical parametrization vs (p,θ):** $a \oplus b / p\beta \sin^{3/2}\theta$
  - ILD bench-mark values: a = 5 μm & b = 10 μm × GeV/c
- **How a and b are calculated?**
  - **a:** $\sigma(d_\rho)$ at high-p (e.g. 300 GeV/c)
  - **b:** fit $\sigma(d_\rho)$ curve using empirical formula in low-p



Introduction: Pseudo-Efficiency



- **Track seeding with 3 outermost points**
  - ε_{seed} = Prob(χ^2/ndf < cut) (usually cut = 3)
- **Pointing to next layer lth. Hit-association probability depends on**
  - Track-pointing & hit resolution ($\sigma^{p,hit}_{r\phi}$, $\sigma^{p,hit}_{z}$),
  - Hit density in layer $\rho(r,\phi,z)$,
  - χ^2/ndf cut $\Rightarrow \gamma$ = frac. of hits lost

    (e.g. $\gamma \sim 5\%$, χ^2/ndf < 3, for ndf = 2)

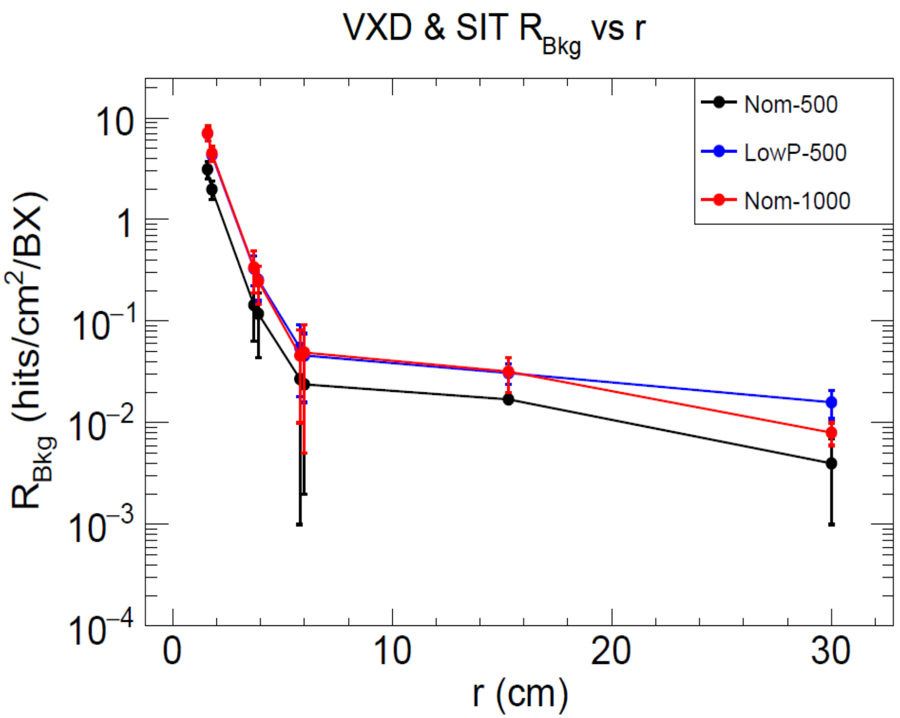
$$\begin{cases} P_{corr} = \dfrac{\varepsilon_{d,l}(1-\gamma^{1+2\pi\rho\sigma_{r\phi}\sigma_z})}{1+2\pi\rho\sigma_{r\phi}\sigma_z} \\ P_{null} = (1-\varepsilon_{d,l}+\varepsilon_{d,l}\gamma)\cdot\gamma^{(2\pi\rho\sigma_{r\phi}\sigma_z)} \\ P_{fake} = 1 - P_{null} - P_{corr}. \end{cases}$$

$$\sigma_{r\phi,z} = \sqrt{(\sigma^{p}_{r\phi,z})^2 + (\sigma^{hit}_{r\phi,z})^2}$$

- **Simplified picture:** $\varepsilon_{tot} = \varepsilon_{seed} \prod_l P_l$
- **Calculate all combinations $P_l = P_{corr}, P_{null}, P_{fake}$ consistent with requirements**
  - Min # hits, χ^2/ndf < cut
- **Total efficiency is sum of all combinations**

Introduction: Pseudo-Efficiency (hit-rates)

- **Hit-rates from machine background full-simulation**
- **$R_{bkg}(r)$ vs radius shape independent of E_{beam}**
- **Rates parametrization (salt & pepper model): $R_{bkg}(r) = R_0 \times [R_{bkg}(r)/R_{bkg}(r_{min})]$**
  - $R_{bkg}(r)/R_{bkg}(r_{min})$ from full-sim
  - R_0 is a parameter in the code (e.g. 10 MHz/cm^2 for E_{beam} = 250 GeV)
  - For the moment no (ϕ,z) dependence



Introduction: Pseudo-Efficiency (Example)

DBD Geometry: (B = 3.5 T)

- VXD: 0.3% X/X_0 /double-layer
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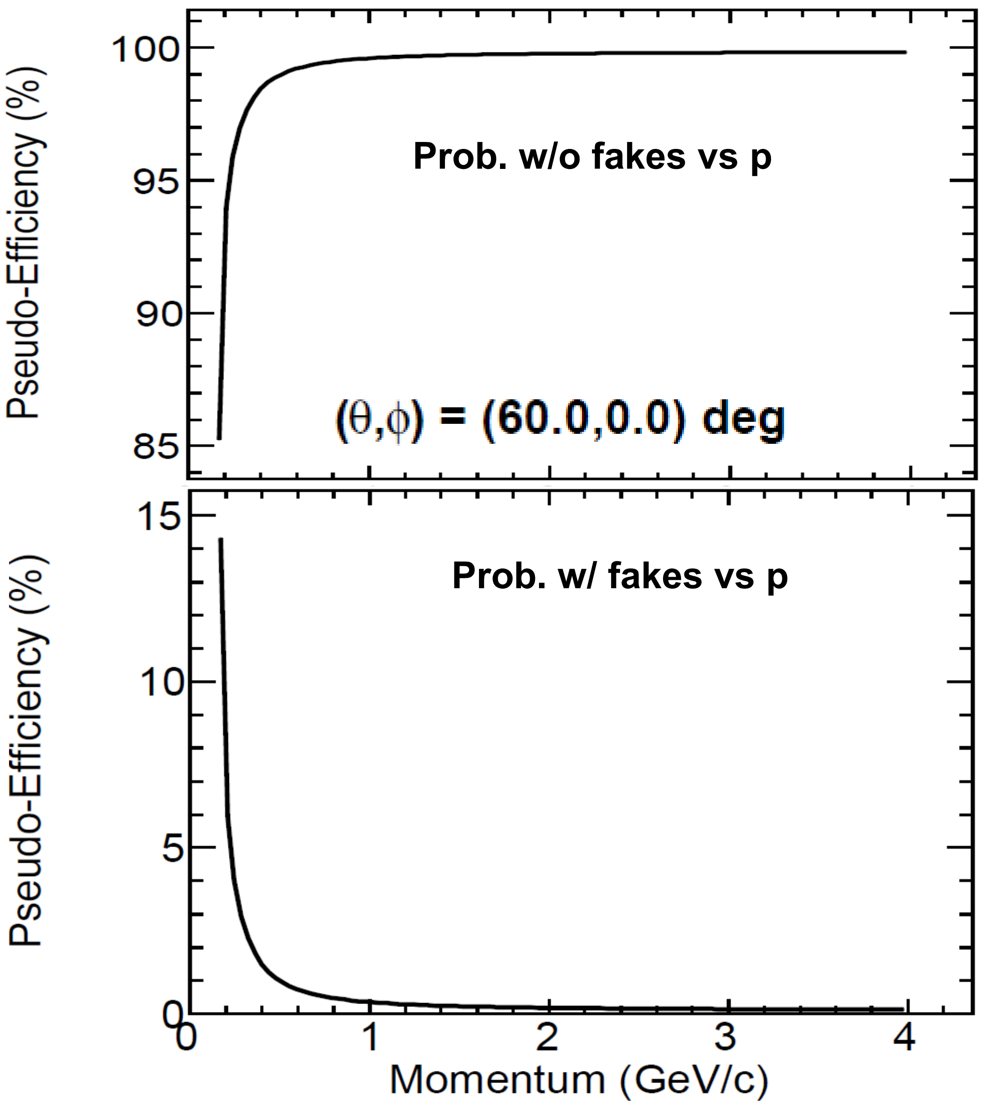
  - L3-6: 4.0 µm / 100 µs
- SIT: 0.65% X/X_0 /double-layer
  - L1-2: (7.0,50.0) µm / 308 ns

Min # hits = 5, χ^2/ndf < 3



Some Studies for ILD VXD

ILD VXD Studies: Introduction

- **Tracker: VXD + SIT with characteristics as in DBD (baseline)**

- **Cylindrical Geometries Studies (layers are cylinders)**
  - Sensors σ_{sp} and $t_{R.O.}$
  - Ladders spacing
  - Material budget
  - Innermost layer radius

- **More realistic geometries**
  - Material budget Studies

VXD characteristics

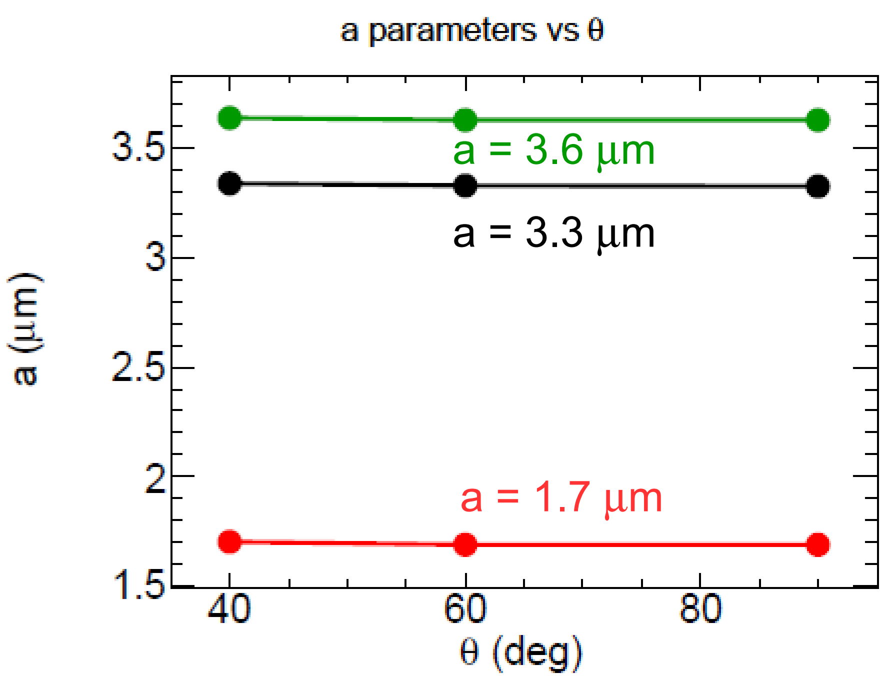
	R (mm)	$\lvert z \rvert$ (mm)	$\lvert \cos\theta \rvert$	σ (μm)	Readout time (μs)
Layer 1	16	62.5	0.97	2.8	50
Layer 2	18	62.5	0.96	6	10
Layer 3	37	125	0.96	4	100
Layer 4	39	125	0.95	4	100
Layer 5	58	125	0.91	4	100
Layer 6	60	125	0.9	4	100

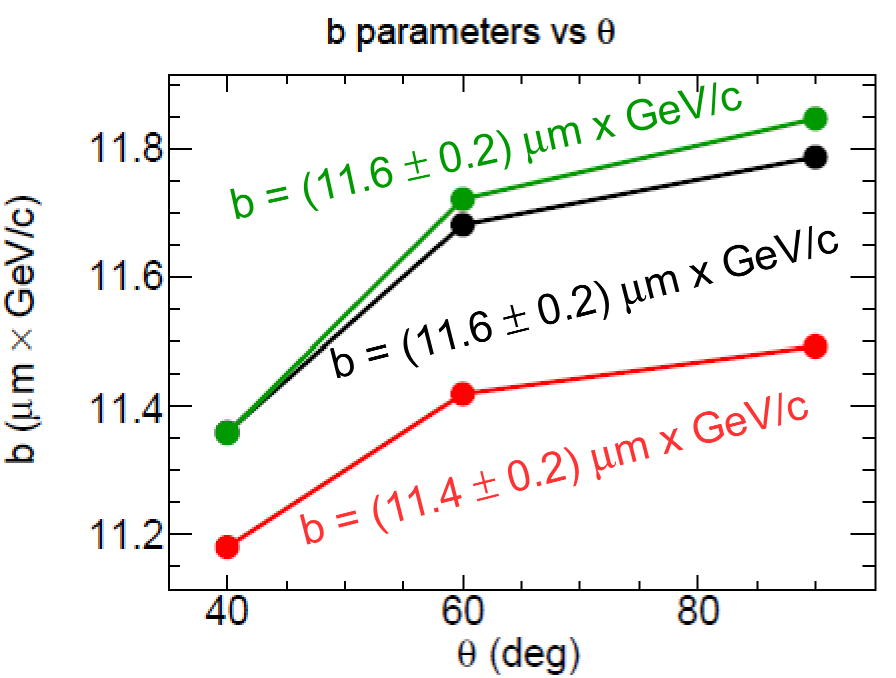
SIT characteristics (current baseline = false double-sided Si microstrips)

Geometry			Characteristics		Material
R[mm]	Z[mm]	cosθ	Resolution R-ϕ[μm]	Time [ns]	RL[%]
153	368	0.910	R: σ=7.0,	307.7 (153.8)	0.65
300	644	0.902	z: σ=50.0	σ=80.0	0.65

ILD VXD Studies: Cylindrical Geometries (1/5)

- **Varying σ_{sp} of VXD layers**
  - L1: 2.8 μm/ 50 μs, L2: 6 μm/10 μs, L3-6: 4 μm/ 100 μs (DBD)
  - L1: 1.0 μm/800 μs, L2: 6 μm/0.5 μs, L3-6: 4 μm/ 4 μs
  - L1-6: 4 μm/ 4 μs



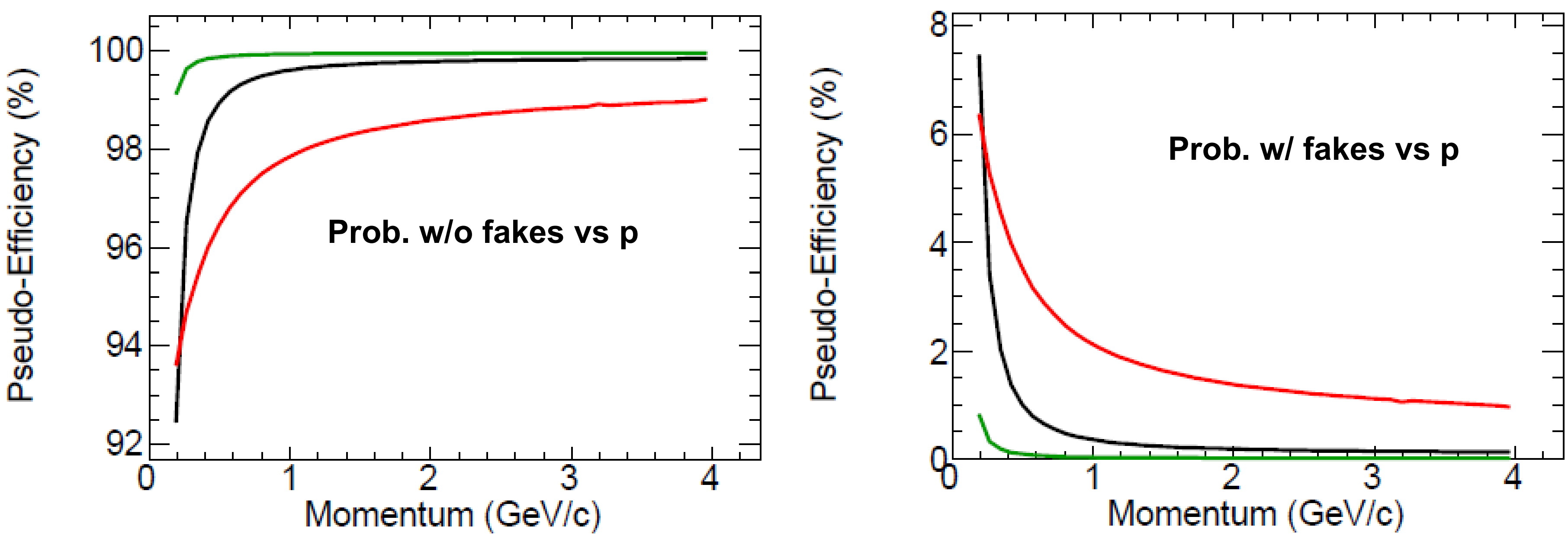


ILD VXD Studies: Cylindrical Geometries (2/5)

- **Varying $t_{R.O.}$ of VXD layers**
  - L1: 2.8 μm/ 50 μs, L2: 6 μm/10 μs, L3-6: 4 μm/ 100 μs (DBD)
  - L1: 1.0 μm/800 μs, L2: 6 μm/0.5 μs, L3-6: 4 μm/ 4 μs
  - L1-6: 4 μm/ 4 μs

(θ,φ) = (60.0,0.0) deg

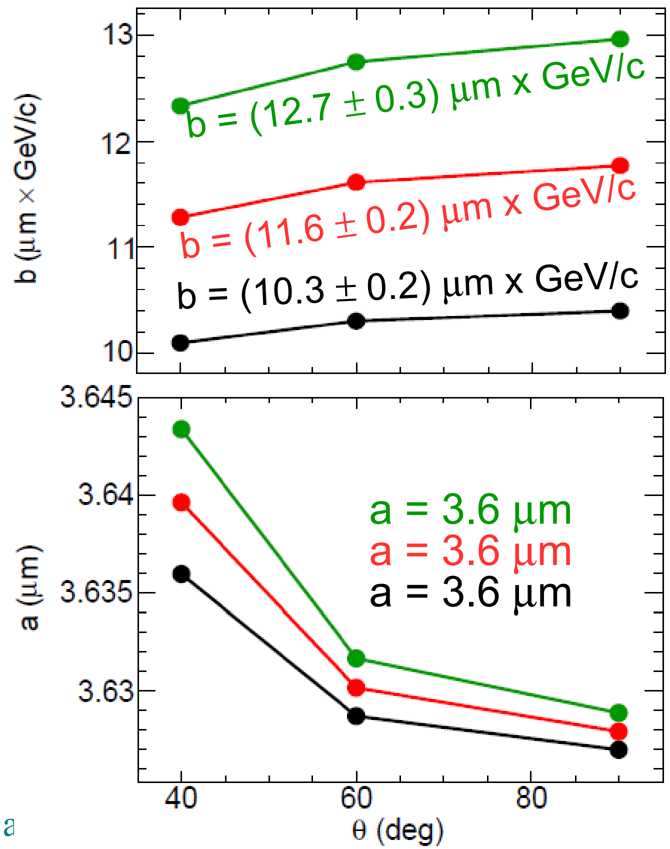
Min # hits = 5, χ^2/ndf < 3

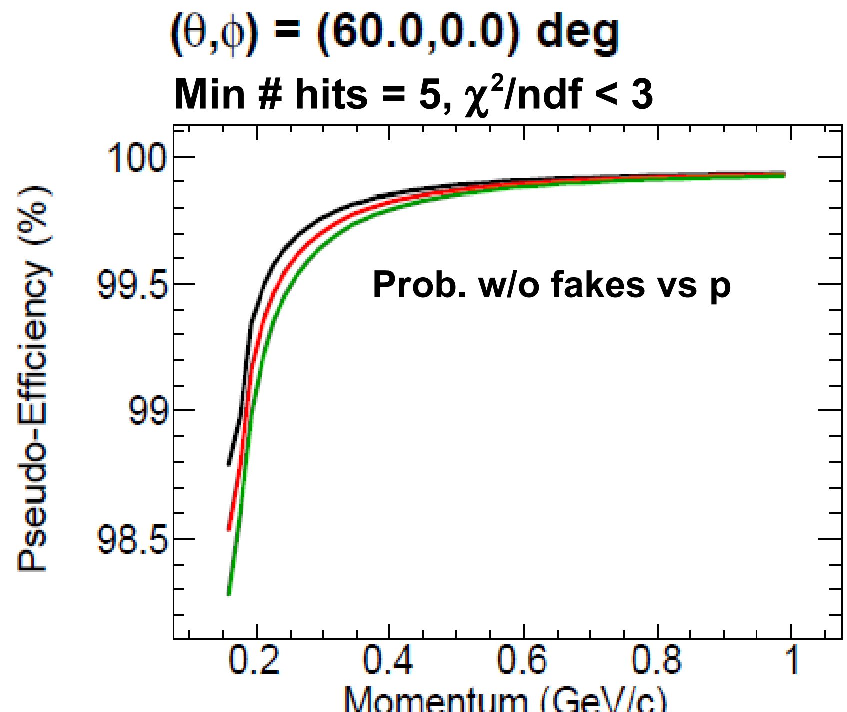


ILD VXD Studies: Cylindrical Geometries (3/5)

Varying VXD Material Budget

- L1-6: 4 μm/ 4 μs, X/X_0 = 0.2 % per double-layer
- L1-6: 4 μm/ 4 μs, X/X_0 = 0.3 % per double-layer
- L1-6: 4 μm/ 4 μs, X/X_0 = 0.4 % per double-layer

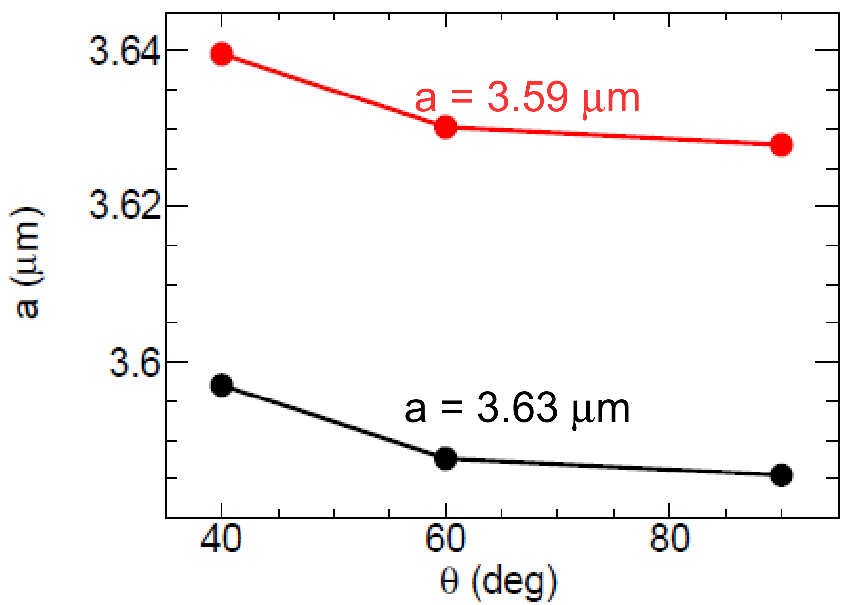


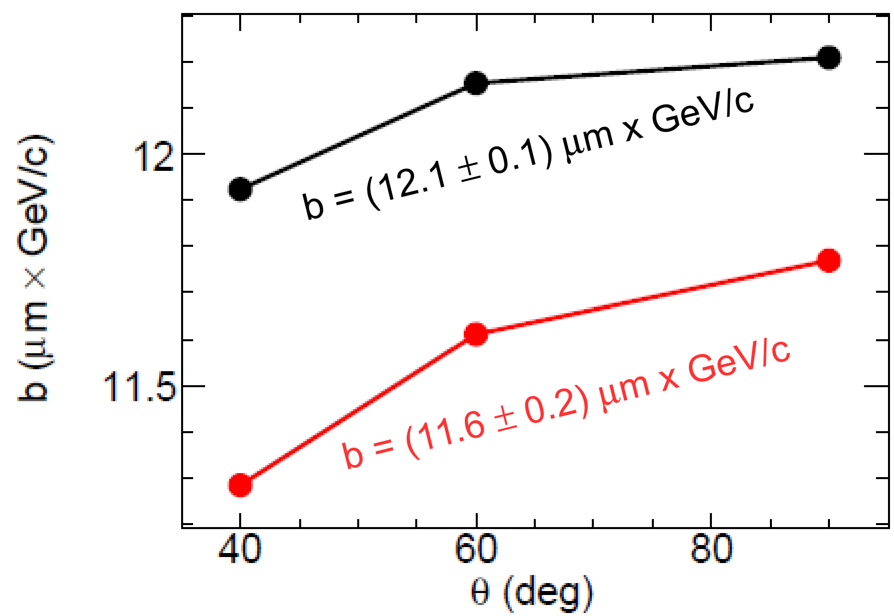


ILD VXD Studies: Cylindrical Geometries (4/5)

Varying Ladder Spacing

- L1-6: 4 µm/ 4 µs, spacing = 1.0 mm
- L1-6: 4 µm/ 4 µs, spacing = 2.0 mm (nominal)



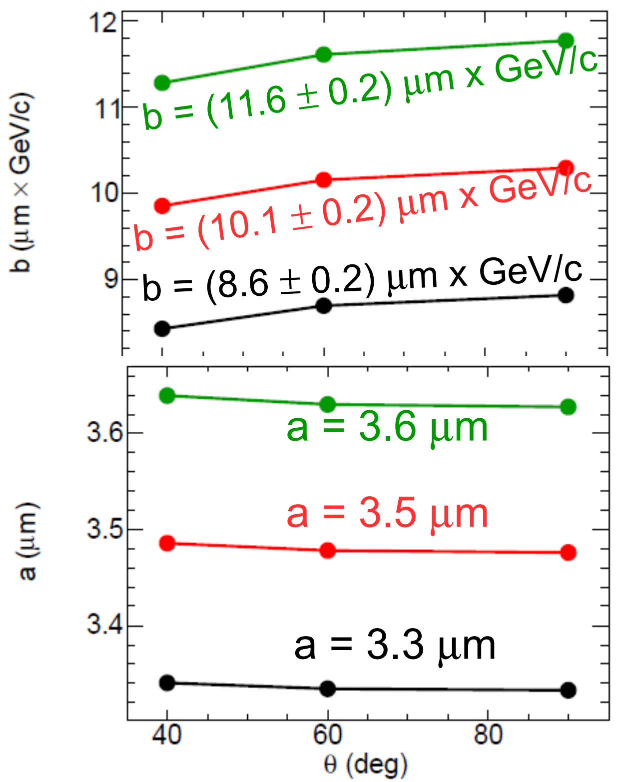


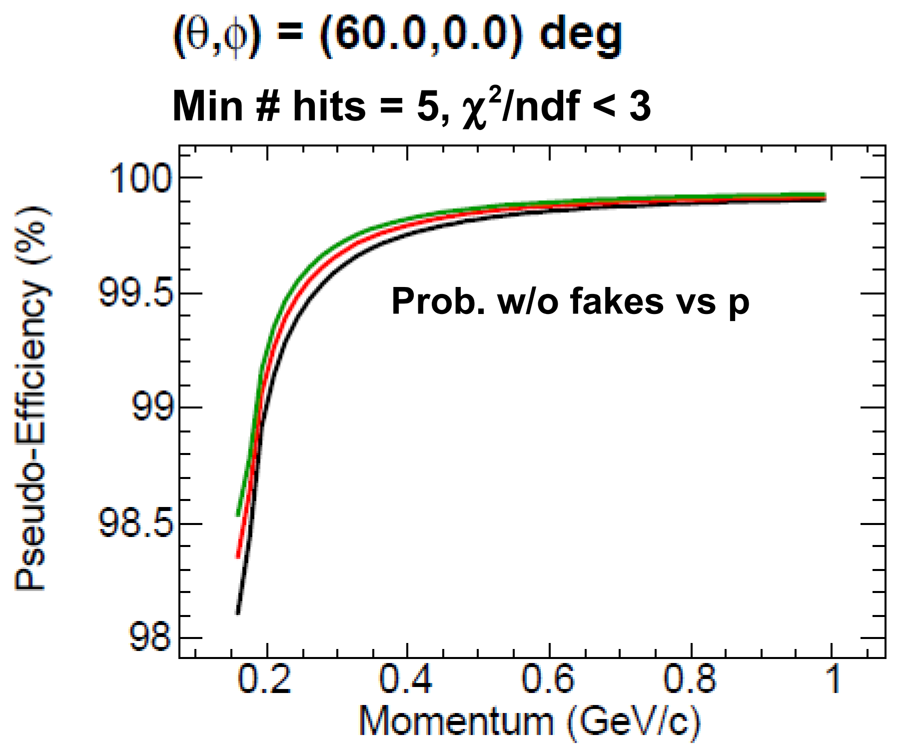
ILD VXD Studies: Cylindrical Geometries (5/5)

Varying L1 radius

- L1-6: 4 μm/ 4 μs, RL1 = 12 mm, R_{pipe} = 11 mm
- L1-6: 4 μm/ 4 μs, RL1 = 14 mm, R_{pipe} = 13 mm
- L1-6: 4 μm/ 4 μs, RL1 = 16 mm, R_{pipe} = 15 mm (Nominal)

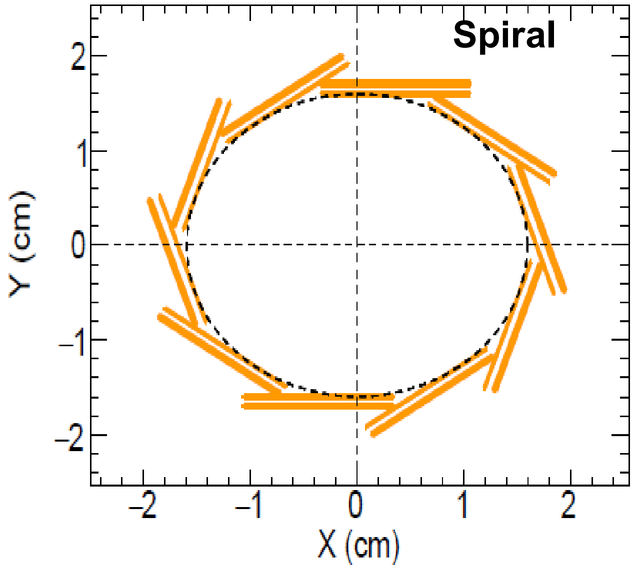
Beam-pipe thickness = 500 μm

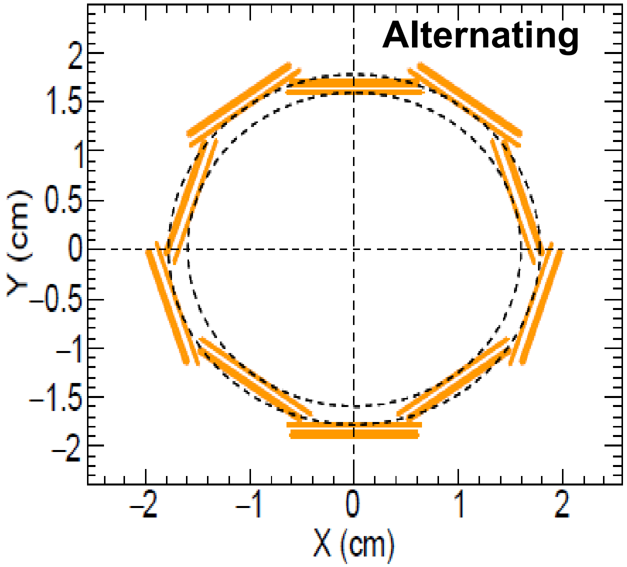




ILD VXD Studies: More Realistic Geometries (1/3)

- **Real life detector not cylinders but mosaic of ladders**
- **Ladders arrangement depends several factor**
  - Mechanical constrains
  - Ladder characteristics: sensor size, sensitive/insensitive surface, thickness, …
- **Start point for more realistic geometry**
  - Innermost double layer: tight region
  - Alternating geometry: easier mechanical implementation
  - Material budget studies

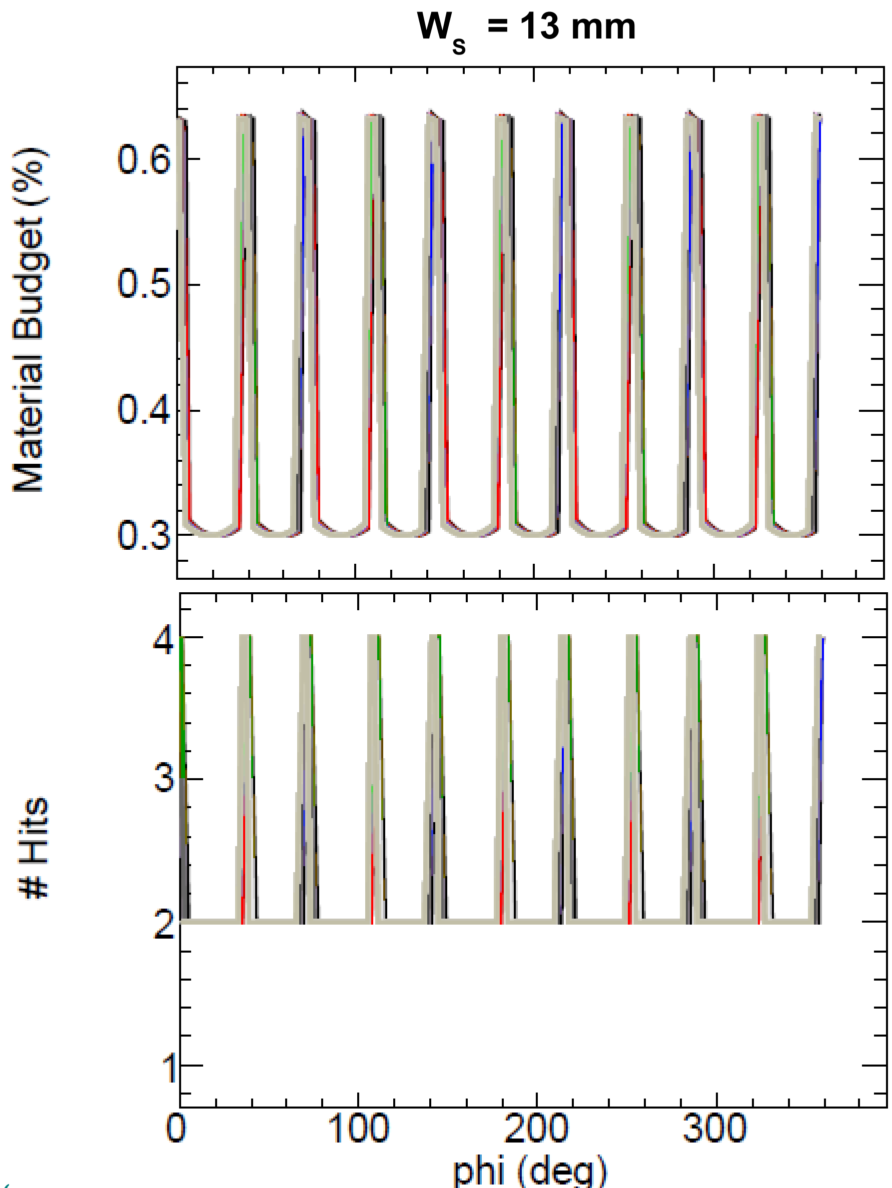




ILD VXD Studies: More Realistic Geometries (2/3)

- **Preliminary material budget studies**
  - L1 radius = 16 mm
  - Spacing = 1 mm
  - #ladders = 10
  - Insensitive width = 1 mm
  - Material budget vs sensitive width (W_S)

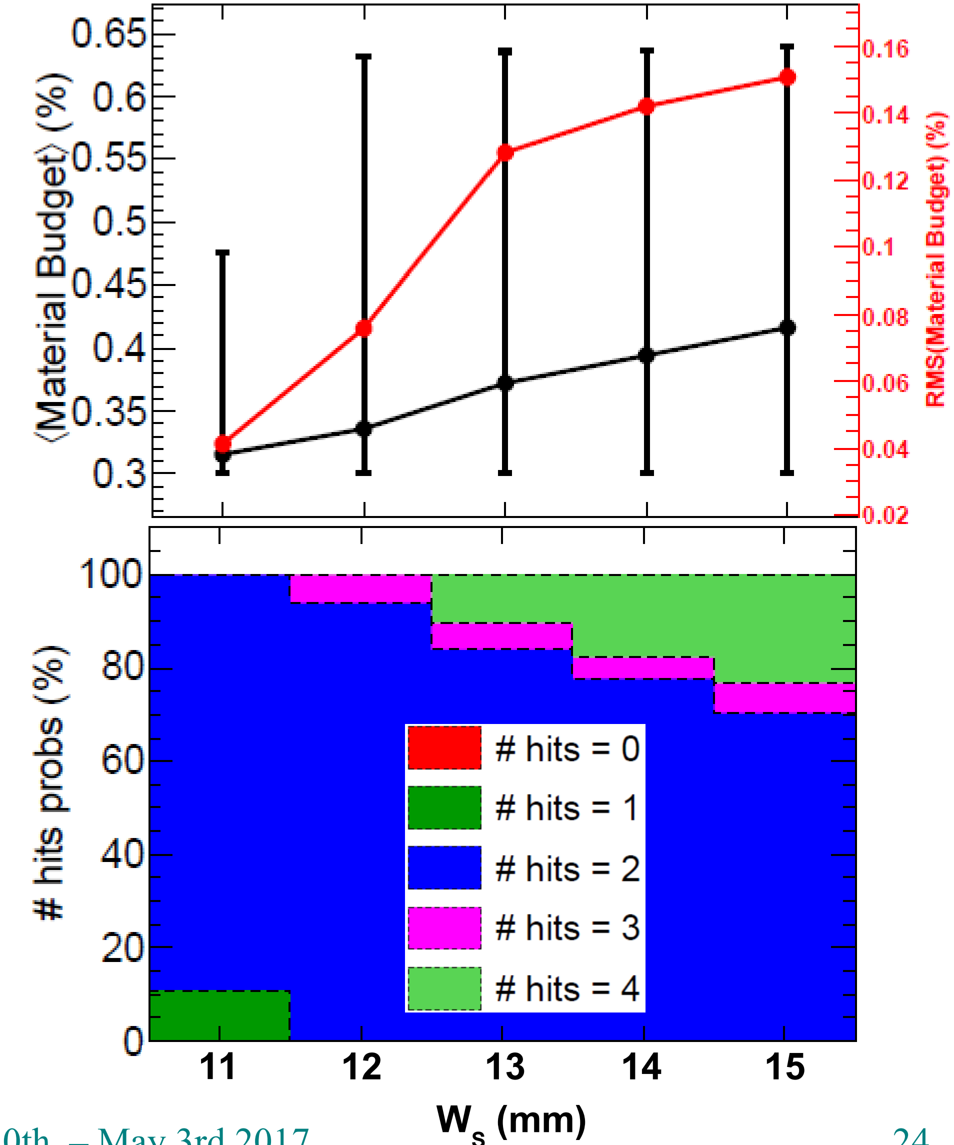
- **The method**
  - Shot pions with different (p,ϕ): (0.18,1.5) GeV/c & (0,360) deg
  - Material budget average w.r.t p & ϕ



ILD VXD Studies: More Realistic Geometries (3/3)

- **Preliminary material budget studies**
  - L1 radius = 16 mm
  - Spacing = 1 mm
  - #ladders = 10
  - Insensitive width = 1 mm
  - Material budget vs sensitive width (W_S)

- **The method**
  - Shot pions with different (p,ϕ): (0.18,1.5) GeV/c & (0,360) deg
  - Material budget average w.r.t p & ϕ



Summary and Outlook

Summary and Outlook

- **Guariguanchi Tool**
  - Tracking performances: track parameters resolution & pseudo-efficiency
  - Can quickly compare several geometries

- **Preliminary VXD studies: cylindrical geometry**
  - σ_{sp}: critical to achieve bench-mark track parameter performances
  - $t_{R.O.}$: too large values in L1 deteriorate significantly ε_{det}
  - $\sigma_{sp}/t_{R.O.}$ = 4µm/4µs achievable with current technologies gives good performances
  - Layers material budget, Ladder spacing, L1 radius $\Rightarrow$ not critical

- **Preliminary VXD studies: realistic geometry**
  - Material budget studies started on L1 with alternating geometry
  - Need to specify constrains on ladder construction for optimization studies

- **Outlook**
  - Would like to calibrate this tool by comparing with full simulation
  - Continue studies of more realistic geometries

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