Progress on IDEA vertex detector in full simulation ...

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... and performance of an ALICE ITS3-like vertex detector for FCC-ee

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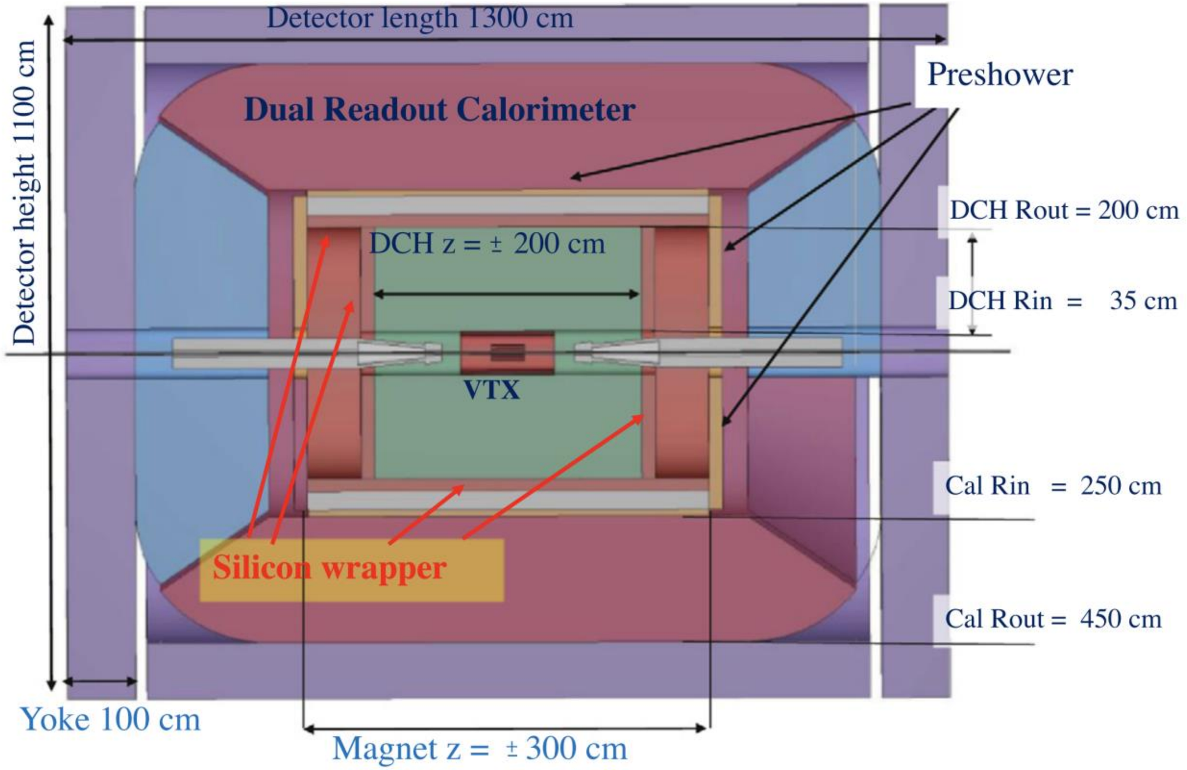
Vertexing at FCC-ee

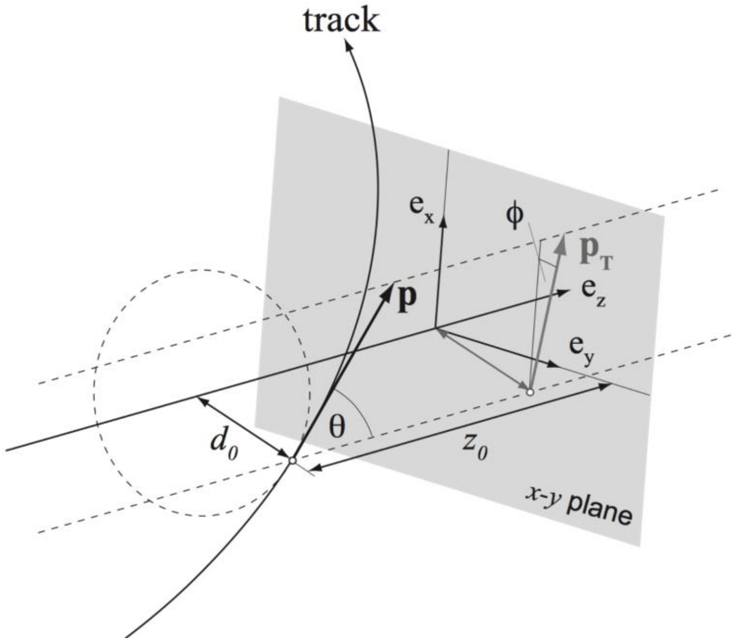
FCC-ee running at the Z pole generates extremely large statistics. To benefit from this, the systematic uncertainties need to be kept down to 10^{-4}–10^{-5}

→ Stringent requirements on FCC-ee vertex detector

- *b*, *c* jet tagging relies on reconstructing tracks with secondary vertices
- Tau lifetime
- Physics objectives: Higgs couplings to b&c, flavor physics…

IDEA detector concept for FCC-ee



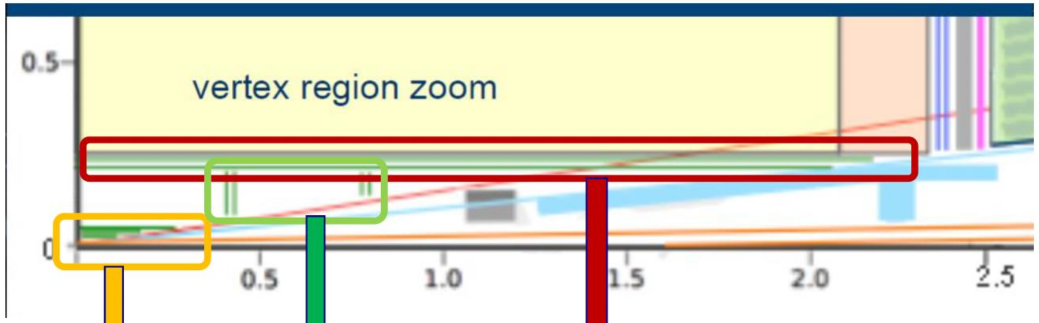


Particle trajectory reconstruction

- Many position measurements
- Transverse & longitudinal impact parameters
- d_0 = distance of closest approach to the beam line
- z_0 = z-coordinate of the point of closest approach

IDEA vertex detector

- IDEA vertex detector (VXD) design is constantly evolving, but conceptually
  - Barrel: Single layers close to beam pipe, with very small pixels (~25x25 μm^2)
  - End-cap: Disks with larger pixels (~150x50 μm^2)
  - Outer barrel: Two outer barrel layers, also with larger pixels (~150x50 µm2)
- Layout by Fabrizio Palla and Filippo Bosi (INFN Pisa), see talk by Franco Bedeschi yesterday
  - Drawn in CAD, modules consisting of ARCADIA and ATLASPix3
  - Rather realistic geometrical layout, e.g includes mechanical supports, hybrids, readout bus



Layer	R [mm]	L [mm]	Si eq. thick. [µm]	X_0 [%]	pixel size [mm^2]	area [cm^2]	# of channels
1	17	±110	300	0.3	0.02×0.02	235	60M
2	23	±150	300	0.3	0.02×0.02	434	110M
3	31	±200	300	0.3	0.02×0.02	780	200M
4	200	±2040	450	0.5	0.05×1.0	52K	105M
5	220	±2240	450	0.5	0.05×1.0	62K	124M

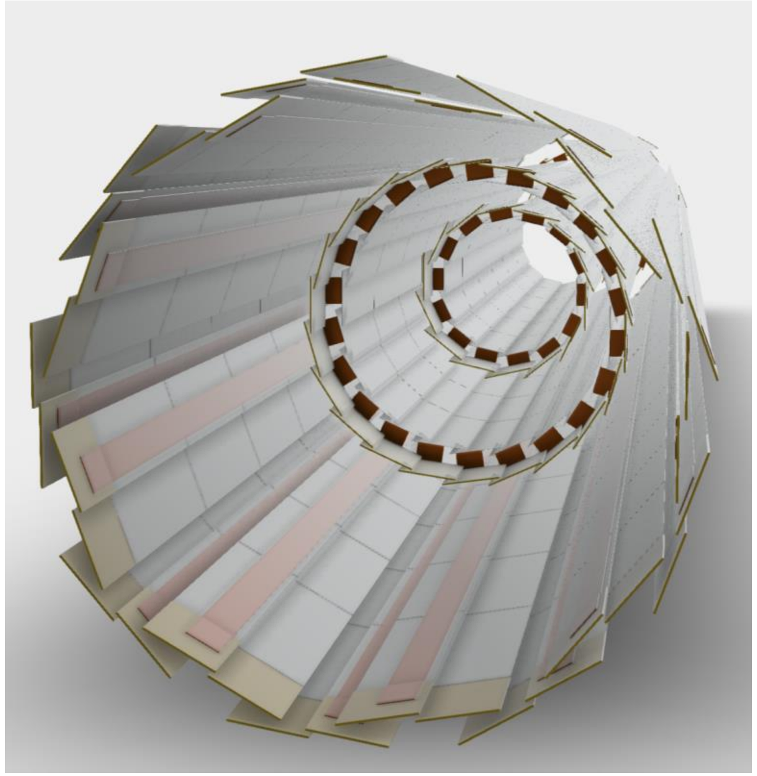
Disks	R_{in} [mm]	R_{out} [mm]	z [mm]	Si eq. thick. [µm]	X_0 [%]	pixel size [mm^2]	area [cm^2]	# of channels
1	42	190	±400	300	0.3	0.05×0.05	2.2K	87M
2	44	190	±420	300	0.3	0.05×0.05	2.2K	86M
3	78	190	±760	300	0.3	0.05×0.05	1.9K	76M
4	80	190	±780	300	0.3	0.05×0.05	1.9K	75M

A. Andreazza at FCC Week 2021 (outdated!)

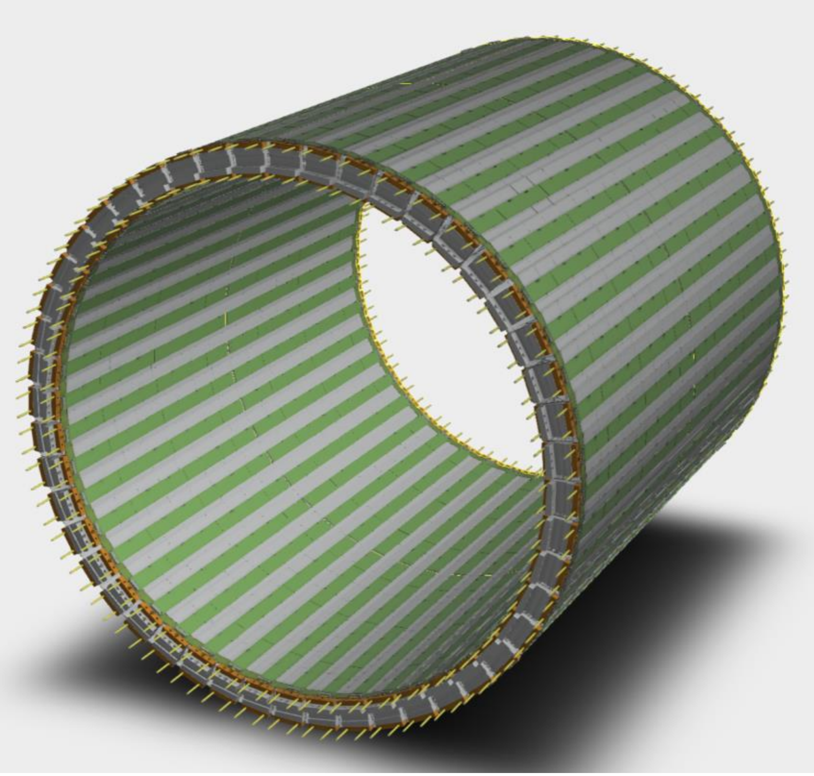
Thanks to Fabrizio and Filippo for providing the step files and the discussions!

IDEA VXD: current design*

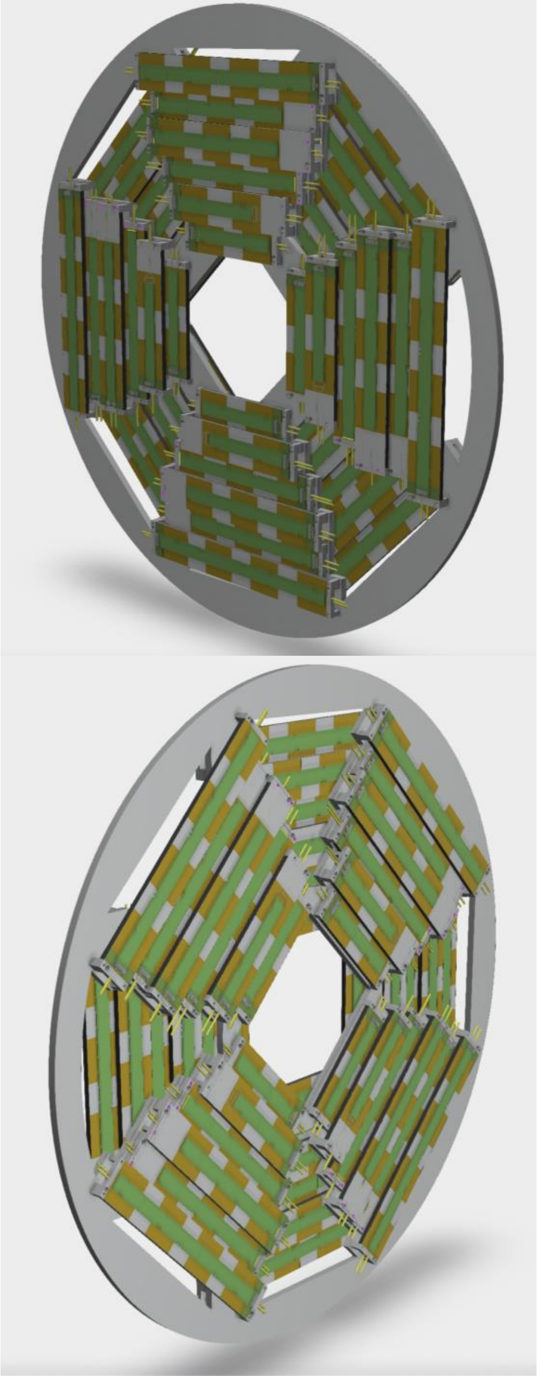
*outdated, based on [talk in November detector concept meeting]



Inner barrel of three layers,
R_1 = 1.2 cm, R_2 = 2 cm, R_1 = 3.2 cm,



Outer barrel of two layers,
R_1 = 28.5 cm, R_2 = 31.5 cm



End-cap with three disks per side

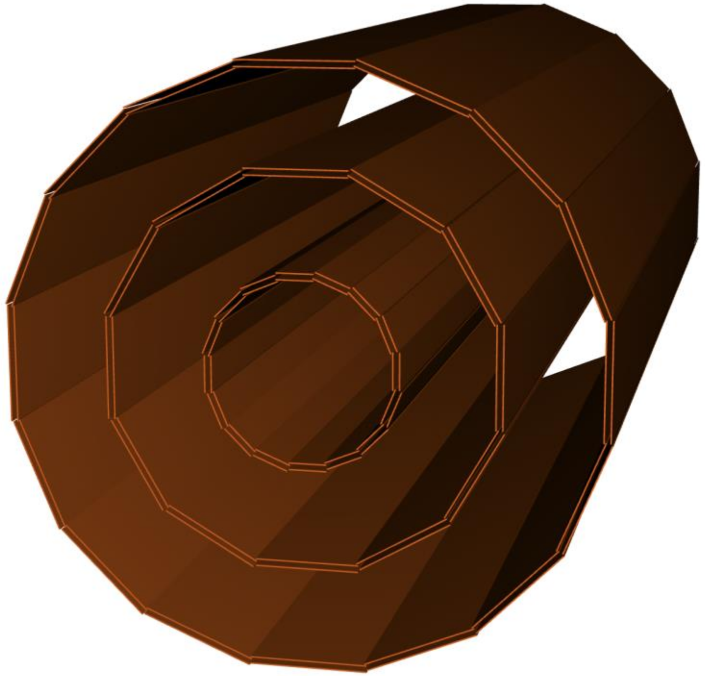
Use this layout as basis for full simulation implementation

→ Needed for performance estimation

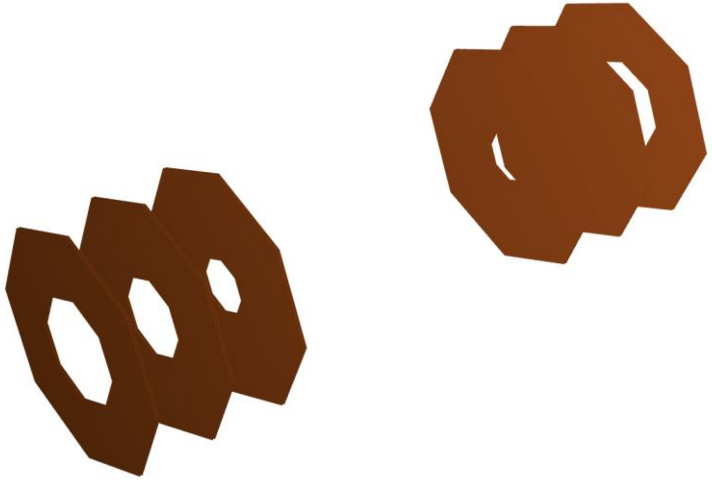
IDEA VXD: fullSim implementation

First full simulation implementation of the IDEA vertex detector in DD4hep (merge request to FCCDetectors)

- Building on top of CLD description
  - Two components per stave: Sensor, support
  - Endcaps made of simple petals made of silicon and air only
- Want to improve realism:
  - Add simple readout along barrel staves
  - Readout and support components made up of stack of different materials
  - Individual sensors, with the passive sensor periphery in place → can check for holes



CLD fullSim vertex barrel



CLD fullSim vertex endcaps

If interested, download the geometry and open it using https://root.cern/js/latest/

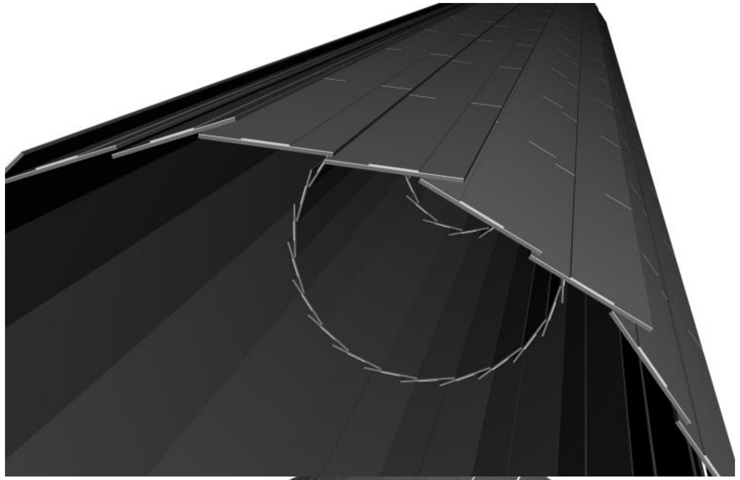
IDEA vertex detector: Current status of fullSim

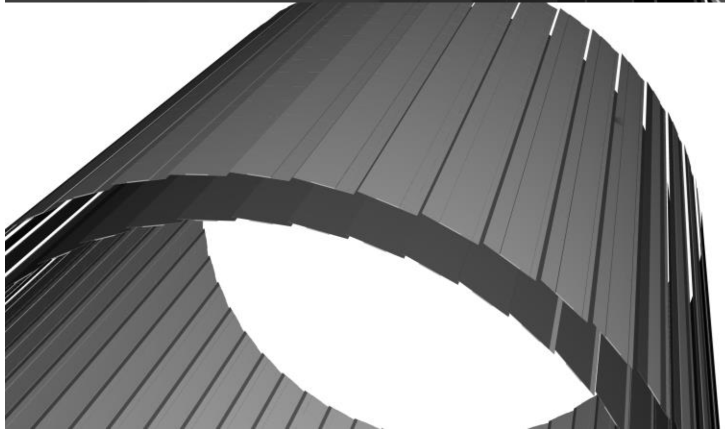
Status:

- Inner and outer barrel complete, but need to implement latest changes (e.g layer at r=15 cm)
- Need to implement correct passive sensor periphery geometry in outer barrel still

Next steps:

- Realistic endcap implementation (with individual sensor modules making up the disks)
- Si wrapper with timing to finalise implementation of IDEA in DD4hep
- Adapting to ongoing changes in vertex design (e.g additional barrel layer)
- Try to import complicated support structures from CAD (see CHEP2021 from Frank, Gaede, Petric, Sailer)
- Check performance of tracking system in full simulation





How can FCC-ee vertex detectors be further improved?

… and performance of an ALICE ITS3-like vertex detector for FCC-ee

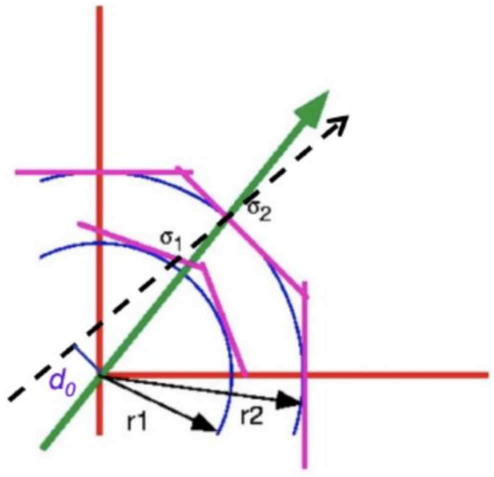
Leila Freitag, University of Zürich

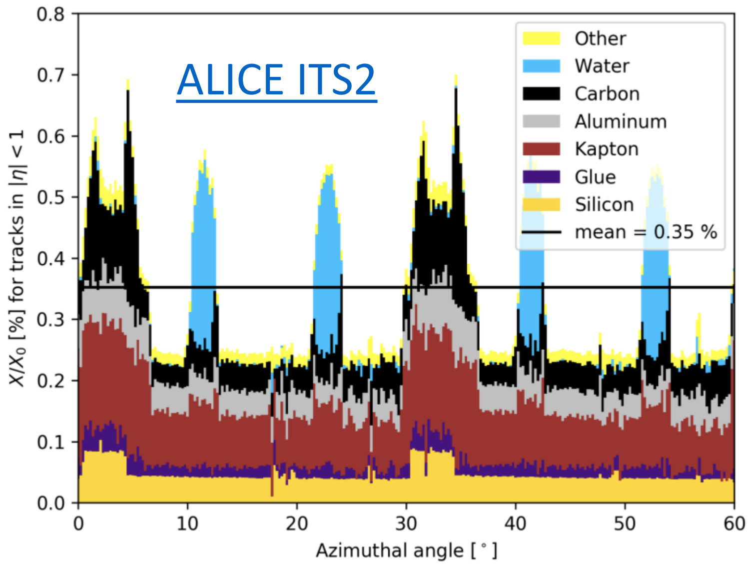
Role of material budget

- Impact parameter resolution

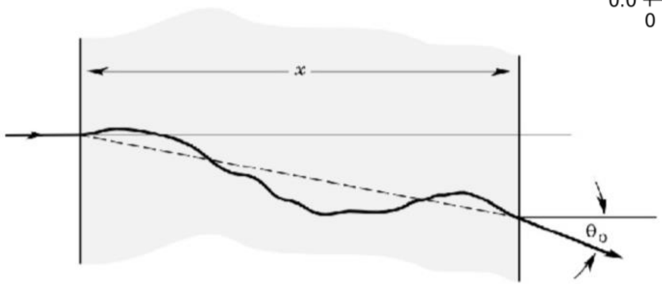
$$\sigma_{d_0} = a \oplus b/p\sin^{3/2}\theta = (a^2 + b^2/(p^2\sin^3\theta))^{1/2}$$

Intrinsic detector resolution
Material budget





- Multiple coulomb scattering
  → small random changes in direction

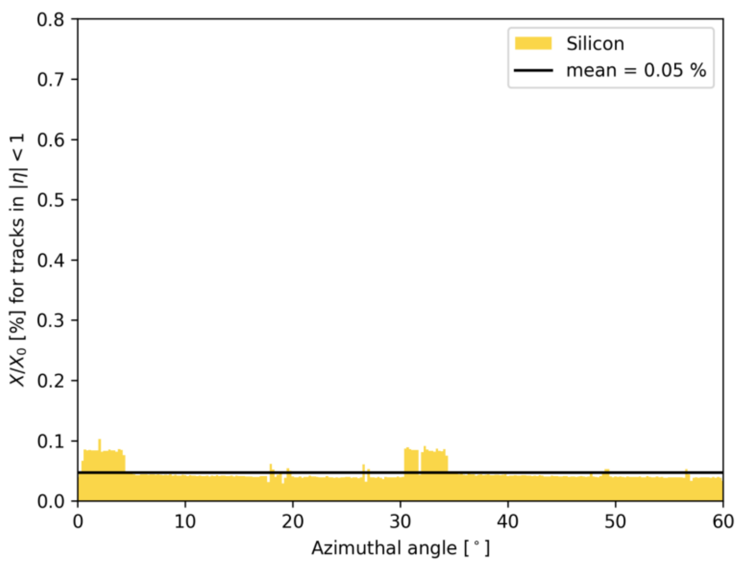


- Material budget includes sensors, electronics, cooling...

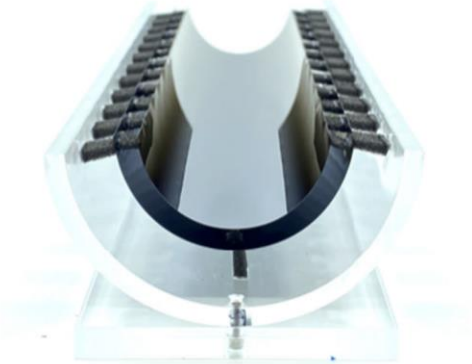
→ lightweight and thin detectors to measure, but not disturb particle tracks

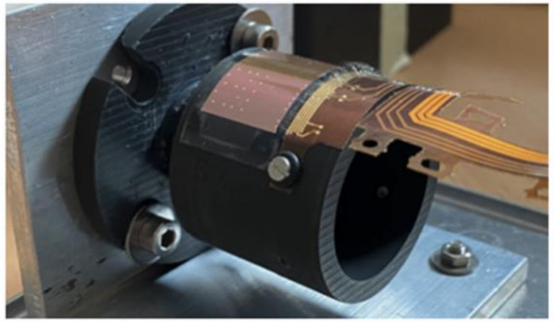
How to reduce material budget to the very minimum?

ALICE ITS3 and MAPS



- Monolithic Active Pixel Sensors
  - Readout electronics integrated on sensor
- Ultra-light inner barrel detector with **curved** silicon sensors (20-40 μm thickness required to be bent)
  - 65 nm TPSCo process supporting 12-inch wafers → wafer-scale sensors
  - Less material, more uniform material, smaller average radius





← Schematic and prototype

What would such a vertex detector mean for the FCC-ee?

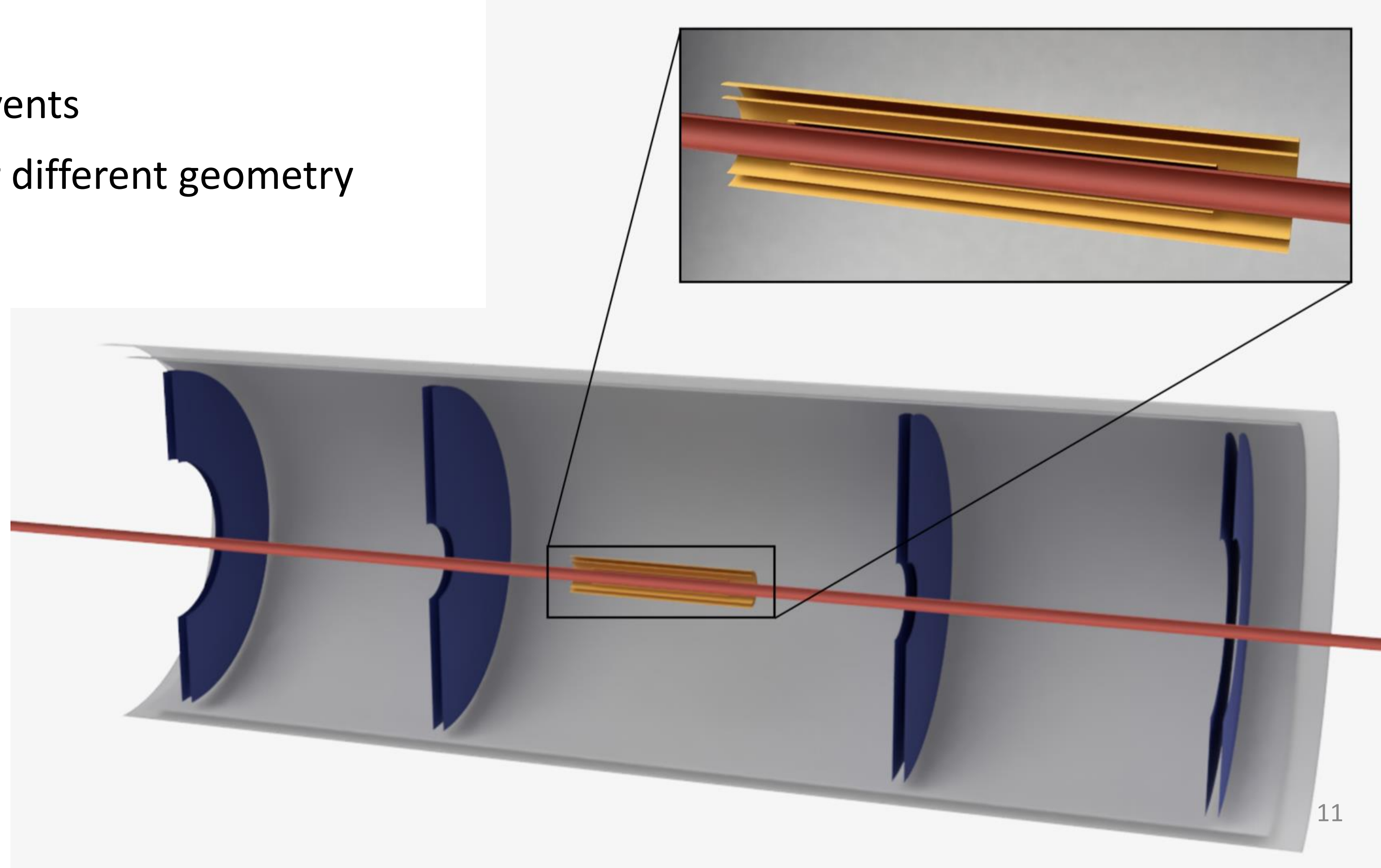
Methods

Change geometry (distance of first vertex layer, material budget)

1. Generate $Z \rightarrow \mu^+\mu^-$ events
   - Compare performance in terms of impact parameter resolution
2. Generate particle gun muons
   - High vs low momentum muons (impact parameter resolution)
3. Generate strange B meson (B_s) decay events
   - Flight distance and secondary vertex resolution

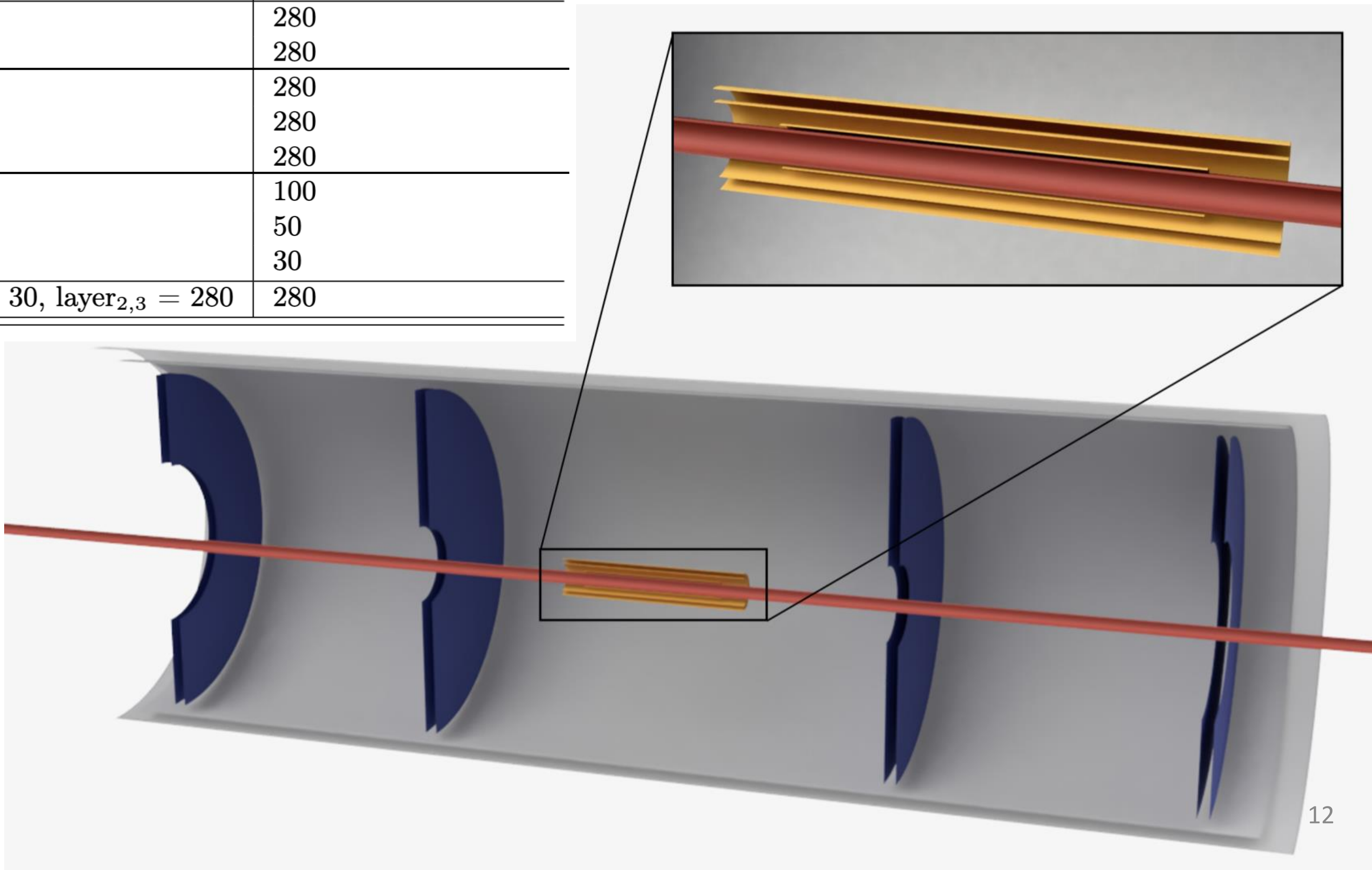
Detector simulation & geometries

- DELPHES fast parametric detector simulation of IDEA detector concept
- Pythia8 + EvtGen to generate events
- Modified detector config file for different geometry

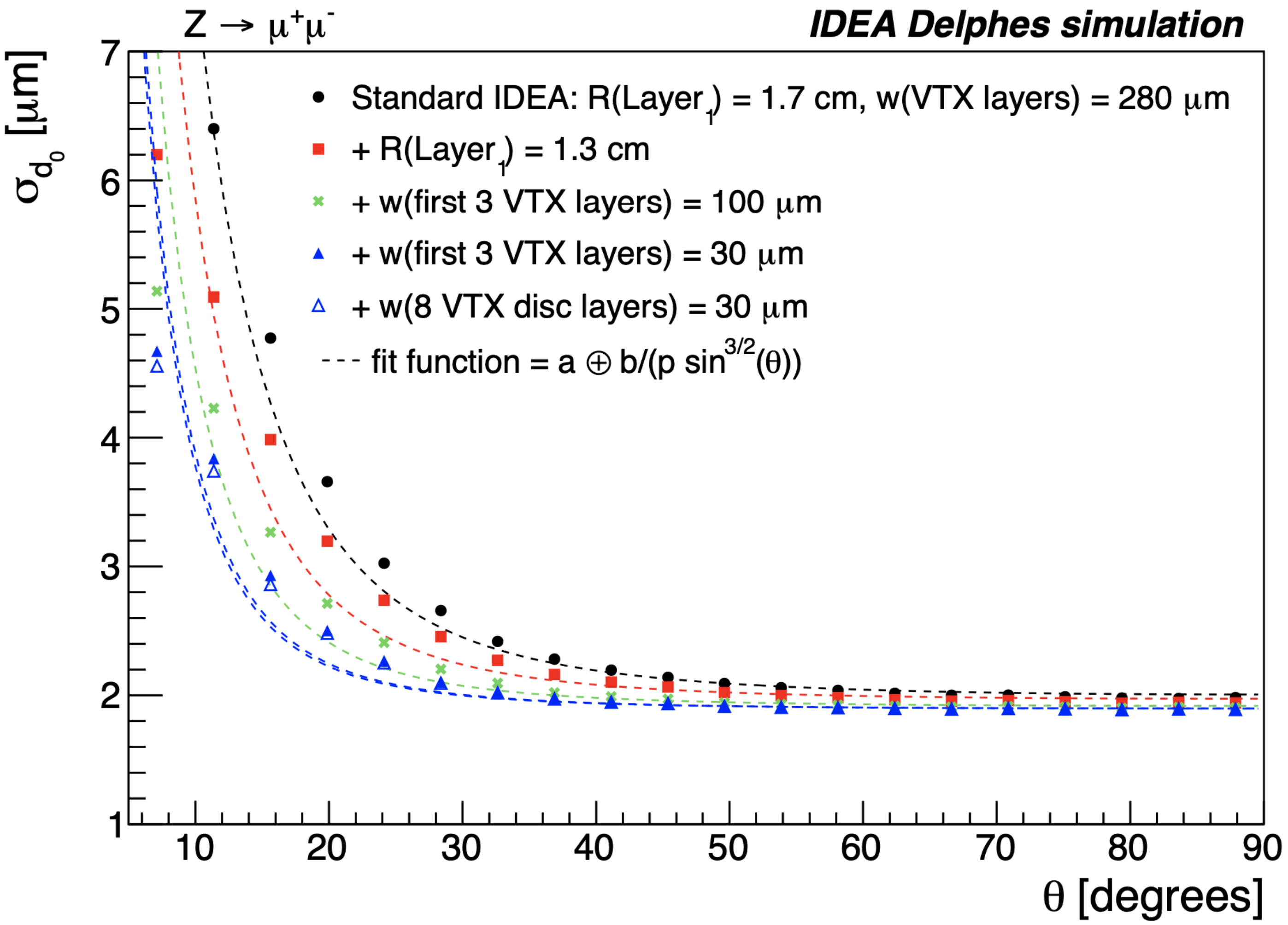


Detector simulation & geometries

Name	Beam pipe radius [cm]	VTX $layer_1$ radius [cm]	Thickness of first 3 VTX layers [μm]	Thickness of 8 VTX disc layers [μm]
standard IDEA	1.5	1.7	280	280
+R1.3	1	1.3	280	280
+w100	1	1.3	100	280
+w50	1	1.3	50	280
+w30	1	1.3	30	280
+w100_DSK	1	1.3	100	100
+w50_DSK	1	1.3	50	50
+w30_DSK	1	1.3	30	30
+L1_w30	1	1.3	$layer_1 = 30$, $layer_{2,3} = 280$	280

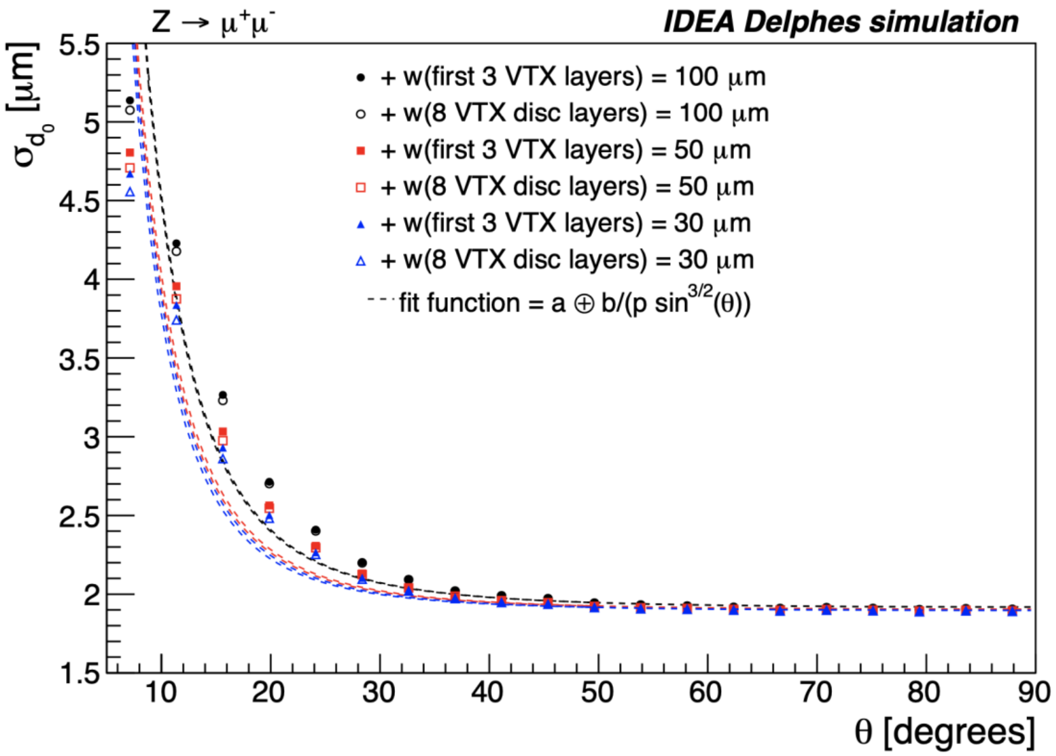


$Z \rightarrow \mu^+\mu^-$ Impact Parameter Resolution

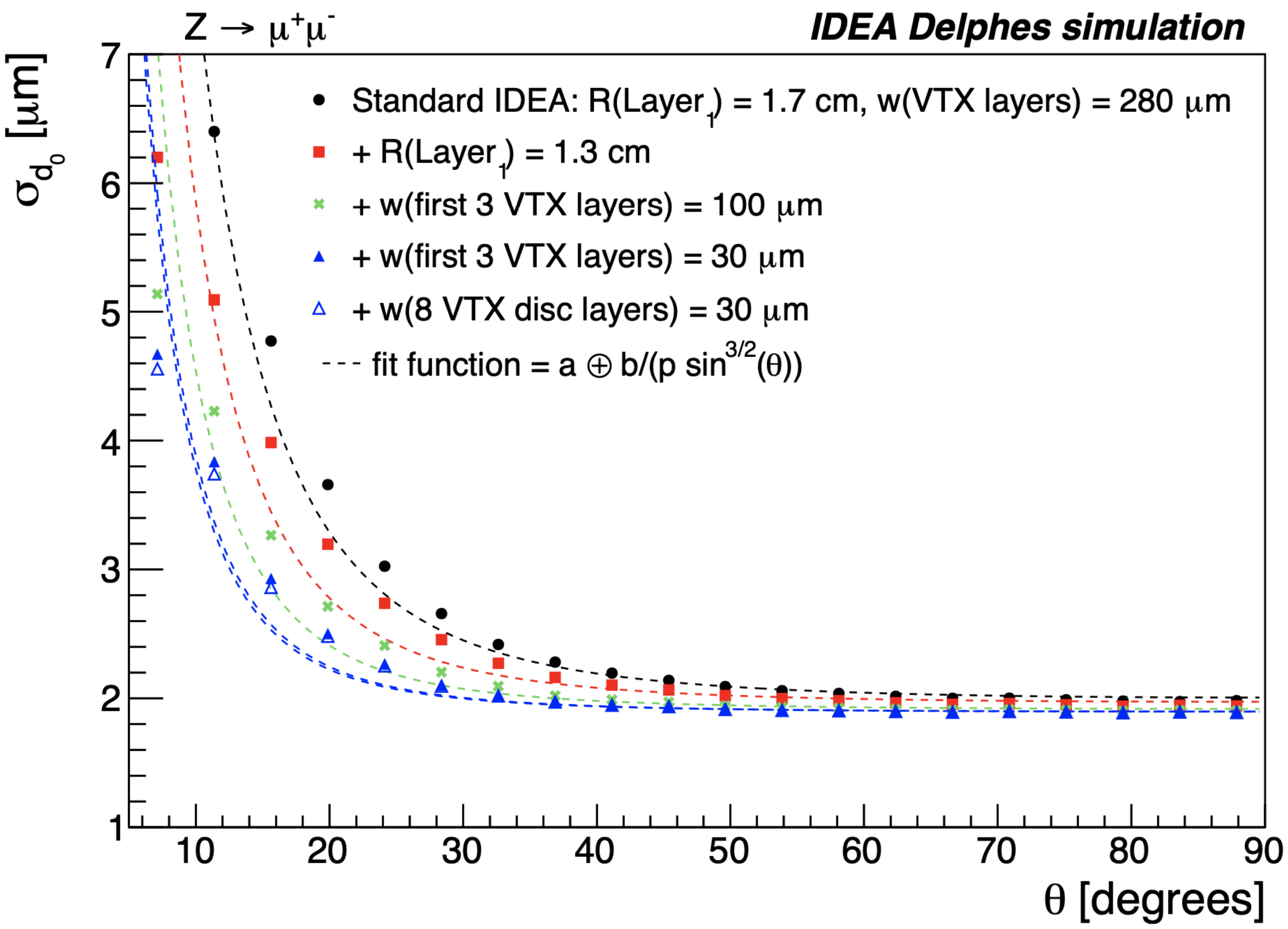


Transverse impact parameter resolution vs. θ

- Angular dependence: lower resolution in forward region
- Improved with closer first layer and reduced material budget



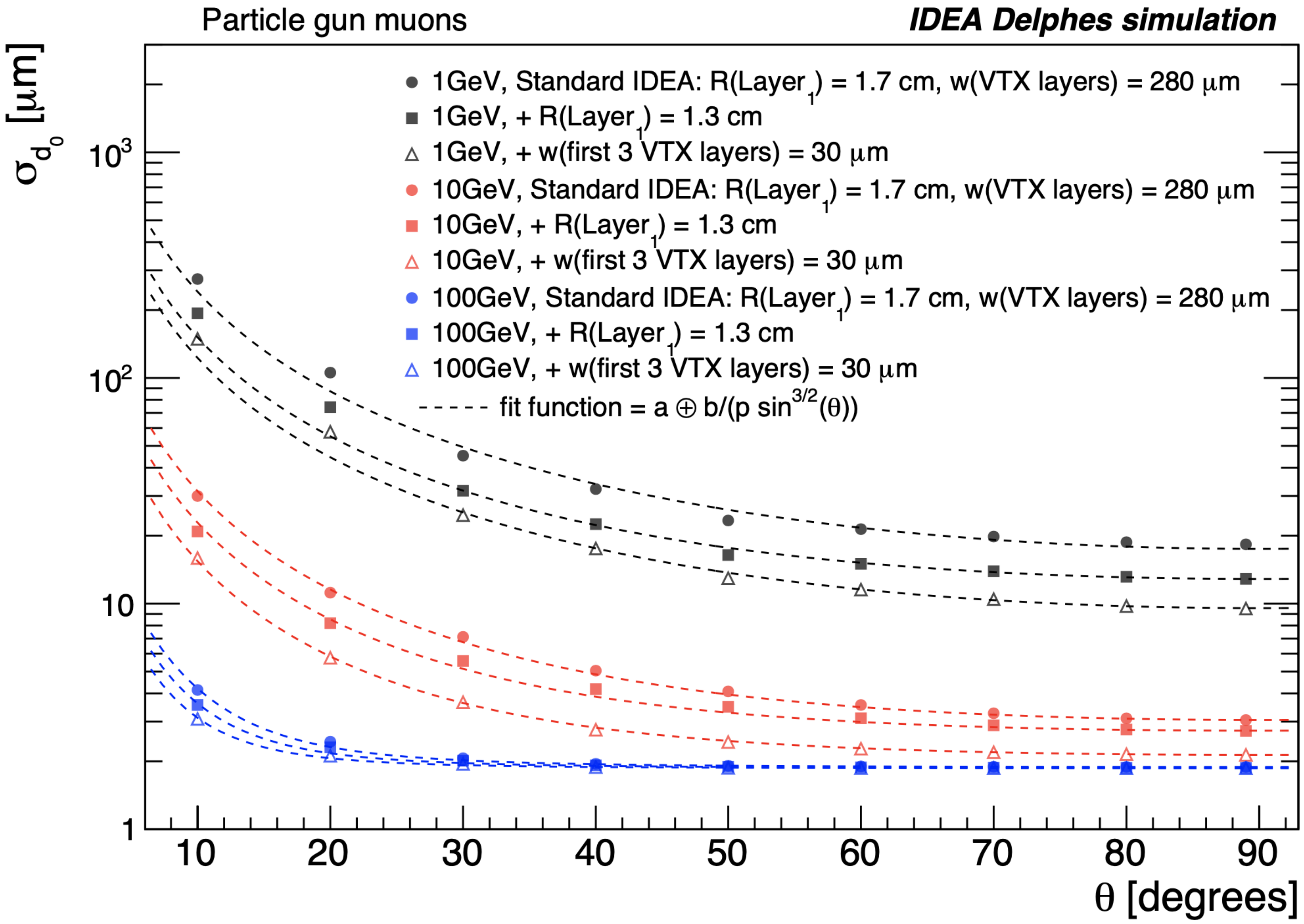
$Z \to \mu^+\mu^-$ Impact Parameter Resolution



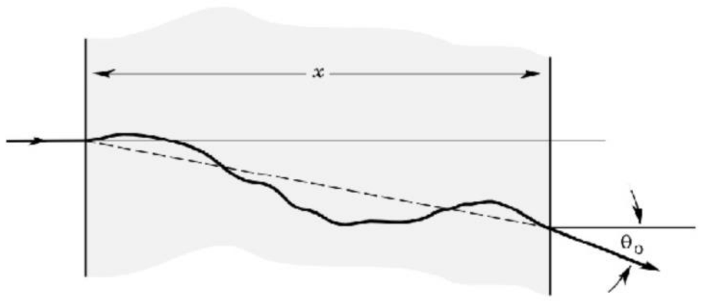
Geometry	Intrinsic uncertainty Parameter a [μm]	Multiple scattering Parameter b [$\mu m \cdot GeV$]
Standard IDEA	1.9346 ± 0.0020	21.40 ± 0.06
+R1.3	1.9326 ± 0.0015	16.33 ± 0.92
+L1_w30	1.9375 ± 0.0012	14.36 ± 0.65
+w100	1.8948 ± 0.0011	13.03 ± 0.64
+w100_DSK	1.8959 ± 0.0010	12.91 ± 0.65
+w50	1.8863 ± 0.0009	11.78 ± 0.68
+w50_DSK	1.8873 ± 0.0009	11.60 ± 0.71
+w30	1.8811 ± 0.0008	11.44 ± 0.68
+w30_DSK	1.8829 ± 0.0008	11.19 ± 0.69

- *b* reduced by ≈ **5** μm·GeV when thickness of first three VTX layers is reduced from 280μm to 30 μm

Particle Gun

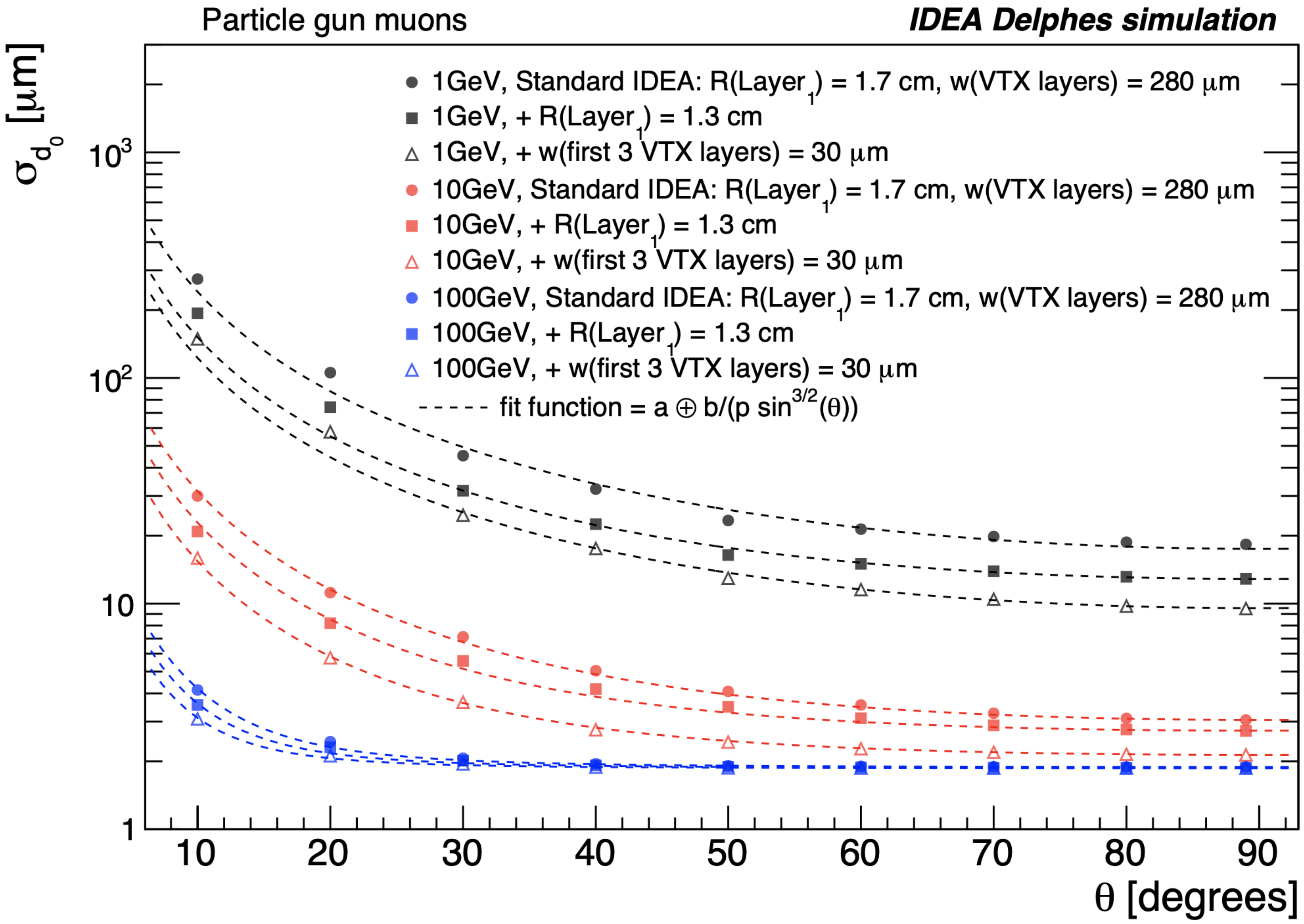


- Lower momentum muons have worse impact parameter resolution
- Material budget change has a greater effect on low momentum muons
  - Reducing barrel layers to 30 μm → improvement one order of magnitude greater for 1GeV than 10GeV

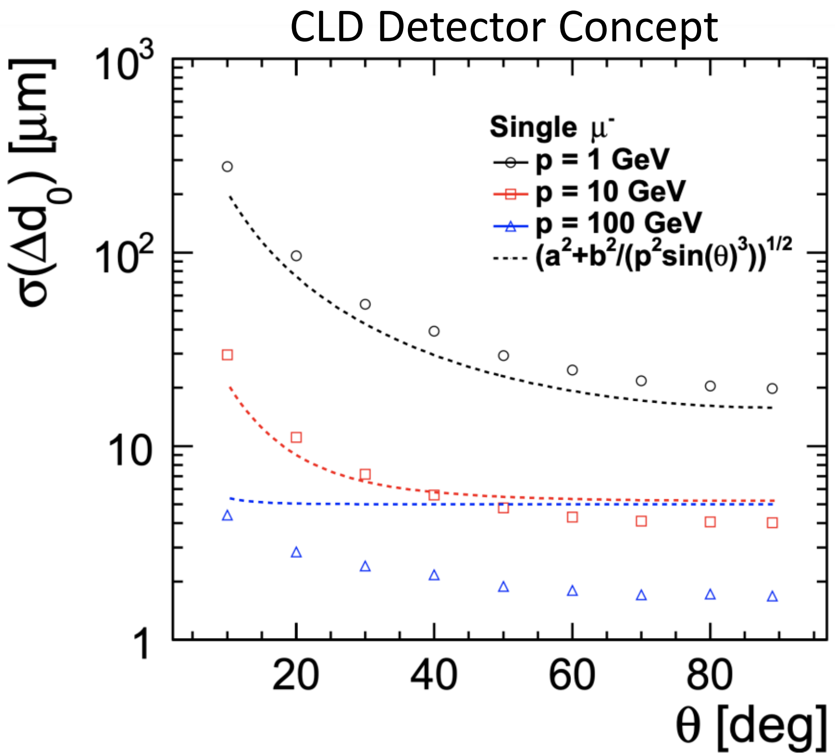


$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

Particle Gun: Comparison to CLD



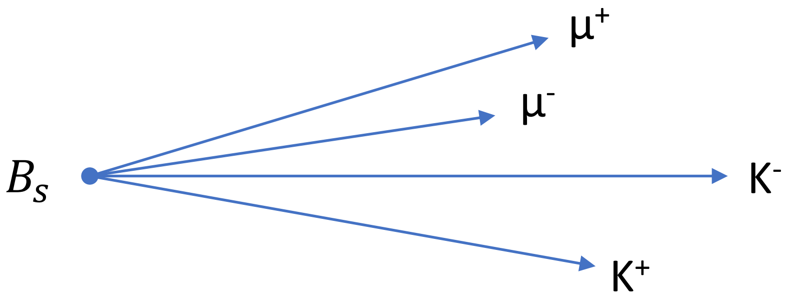
- Compare **standard IDEA (**circles on LHS) to CLD: similar performance



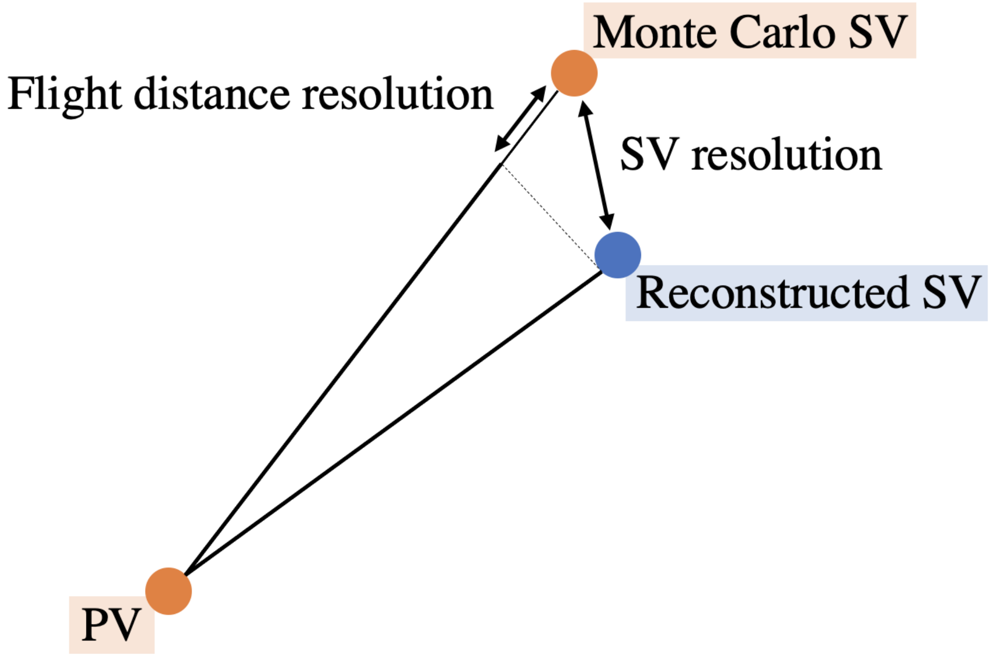
B_s decay

$$B_s^0\,(s\bar{b}) \longrightarrow J/\Psi\,(c\bar{c})\,\Phi\,(s\bar{s}) \longrightarrow \mu^+\mu^- K^+\,(u\bar{s})\,K^-\,(s\bar{u})$$

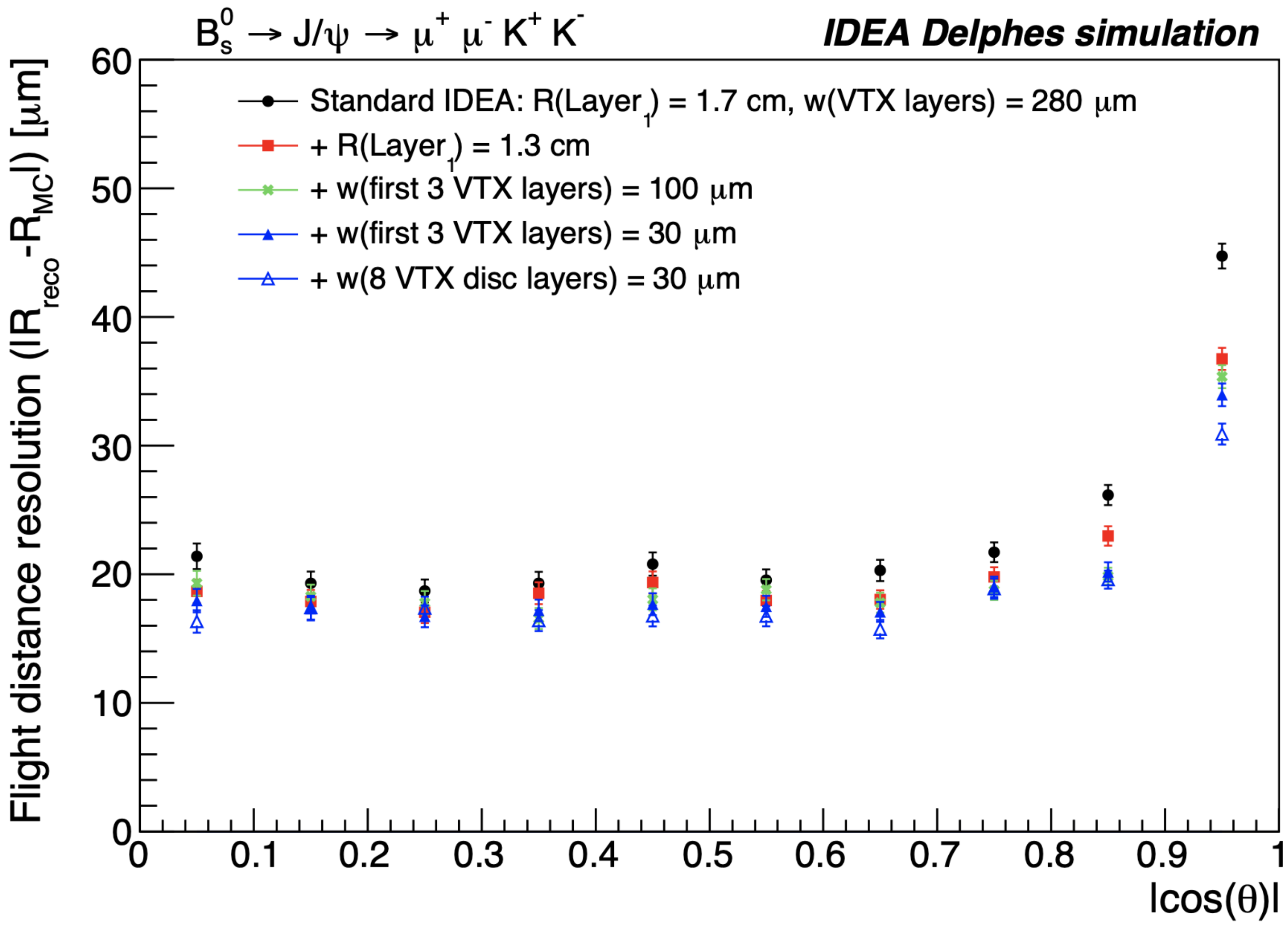
- Flight distance and secondary vertex resolution
- Using analysis from FCCeePhysicsPerformance
- 100,000 events (Pythia8 and EvtGen)



B_s decay


Monte Carlo SV
Flight distance resolution
SV resolution
Reconstructed SV
PV

B_s decay: flight distance resolution



- Reconstructed PV
- SV = LCFI+ reconstructed SV closest to the MC SV

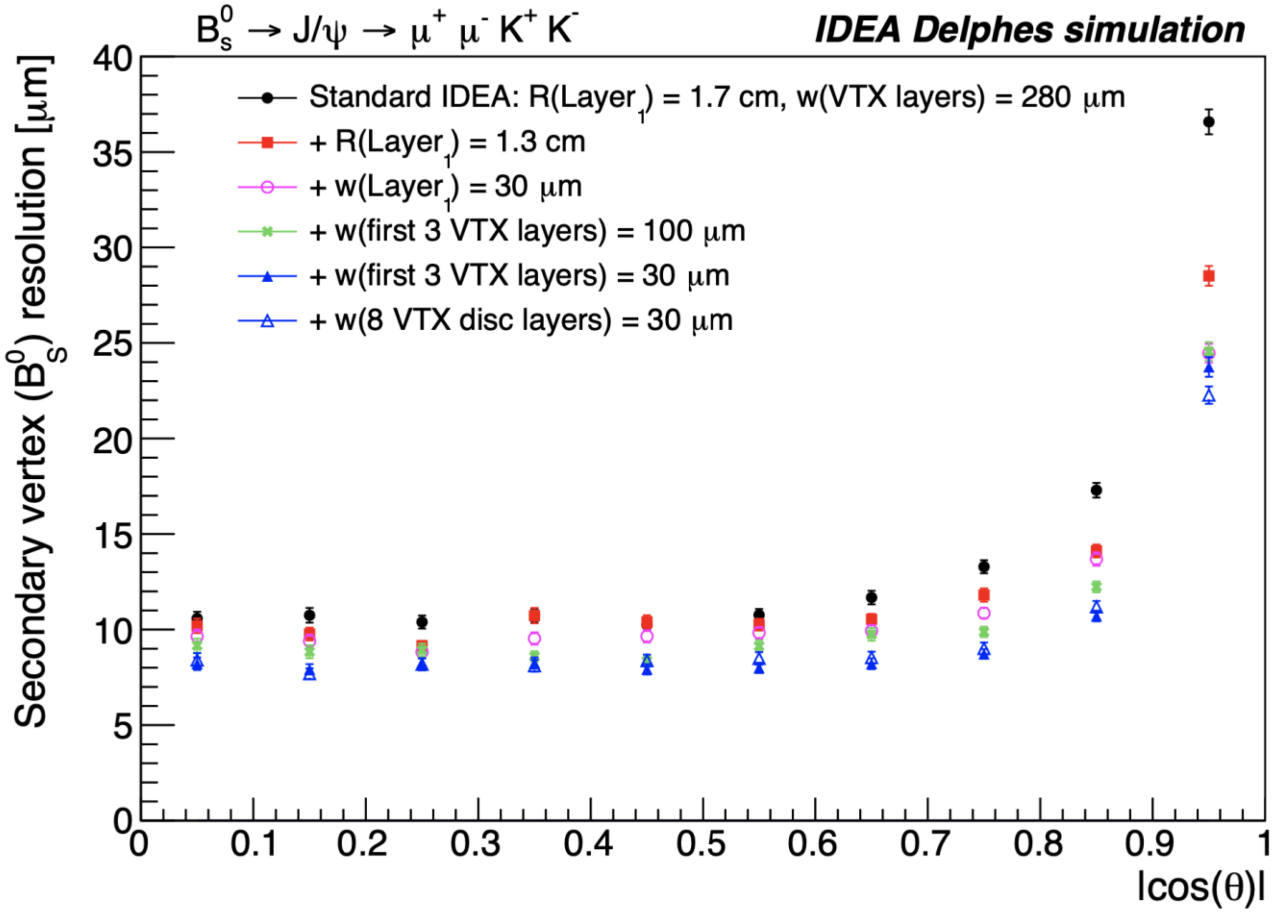
(using LCFI+ SV implementation by Kunal and Armin)

Initial geometry	Final geometry	Percent change in FD reso [%]
Standard IDEA	+R1.3	-9.79 ± 1.69
+R1.3	+w100	-2.69 ± 1.90
+R1.3	+w30	-5.64 ± 1.86
+R1.3	+w30_DSK	-9.31 ± 1.81

Reducing barrel layers to 30 μm thickness:
→ 6% improvement

Additionally reducing the disc layer thickness:
→ 9% improvement

B_s decay: secondary vertex resolution

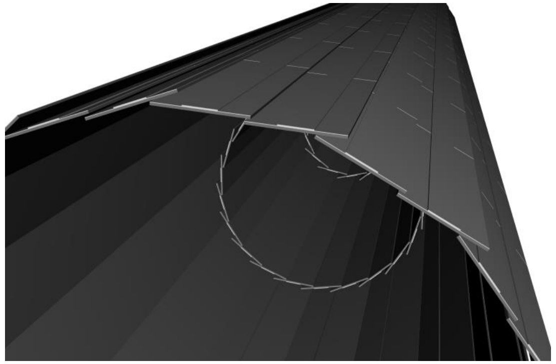


Initial geometry	Final geometry	Percent change in SV reso [%]
Standard IDEA	+R1.3	-8.91 ± 1.25
+R1.3	+L1_w30	-6.63 ± 1.29
+R1.3	+w100	-12.36 ± 1.24
+R1.3	+w30	-20.70 ± 1.13
+R1.3	+w30_DSK	-19.60 ± 1.20

Reducing barrel layers to 30 μm thickness:
→ 20% improvement

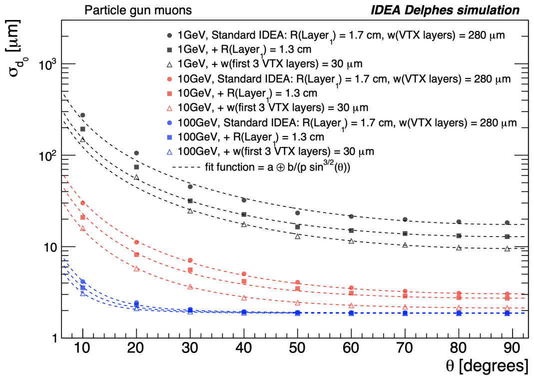
Reducing only the thickness of innermost layer:
→ 6% improvement

Progress on IDEA vertex detector in full simulation …



Good progress on realistic implementation of IDEA vertex detector in DD4hep

- Endcap to be done, will also work on Si wrapper with timing
- Check performance once complete tracking system (vertex+DCH+Si wrapper) is there
- Implement an ALICE ITS3-like vertex detector in DD4hep as well and compare!
  - Also started/starting to work on 65 nm sensors at UZH together with ALICE ITS3 and IPHC Strasbourg → **Open to collaborate!**



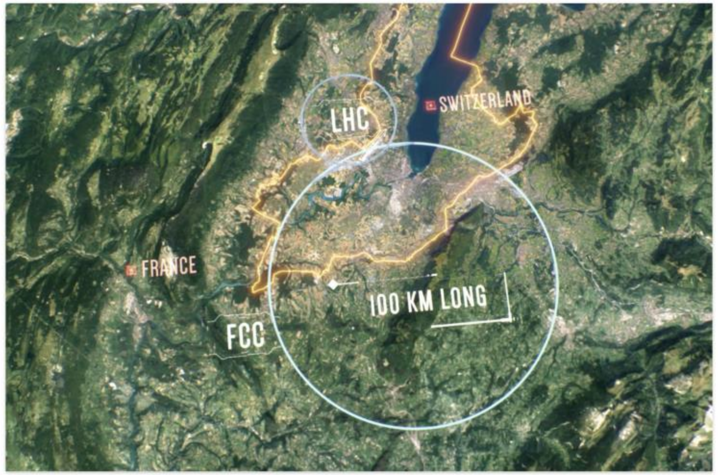
… and performance of an ALICE ITS3-like vertex detector for FCC-ee

Clear benefits of minimizing the vertex detector material budget

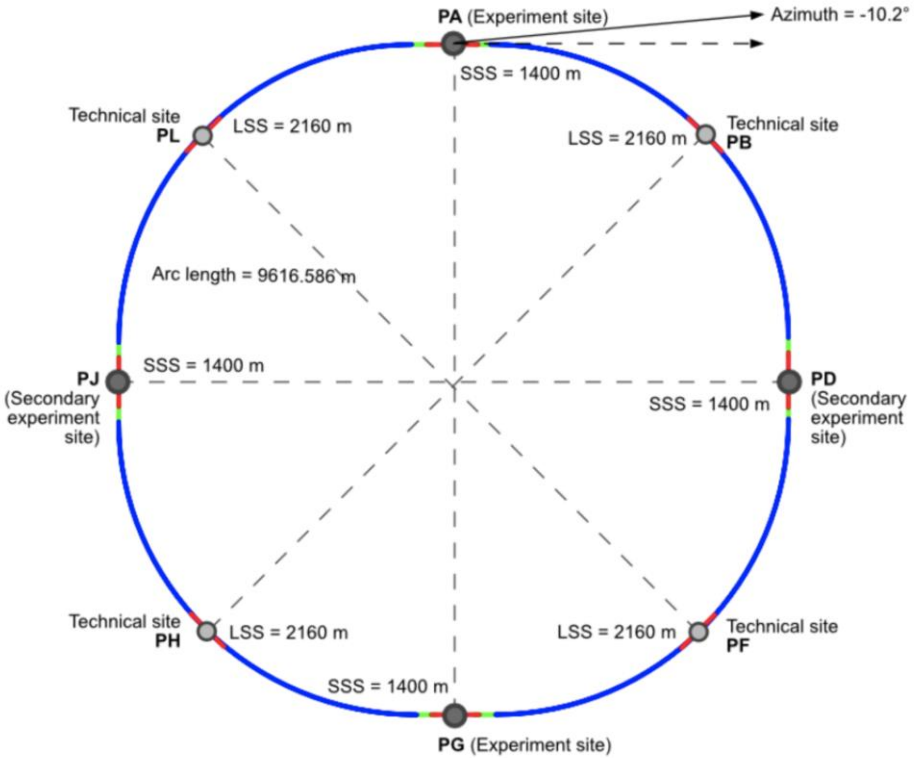
- Quantified with improvement in impact parameter, flight distance, and secondary vertex resolution
- Ideally reduce thickness of 3 innermost barrel layers from 280 μm to 30 μm
- Only reducing the thickness of the first barrel layer is already beneficial
- Additional improvement in forward direction from DSK layers

BACKUP

Future Circular Collider Project

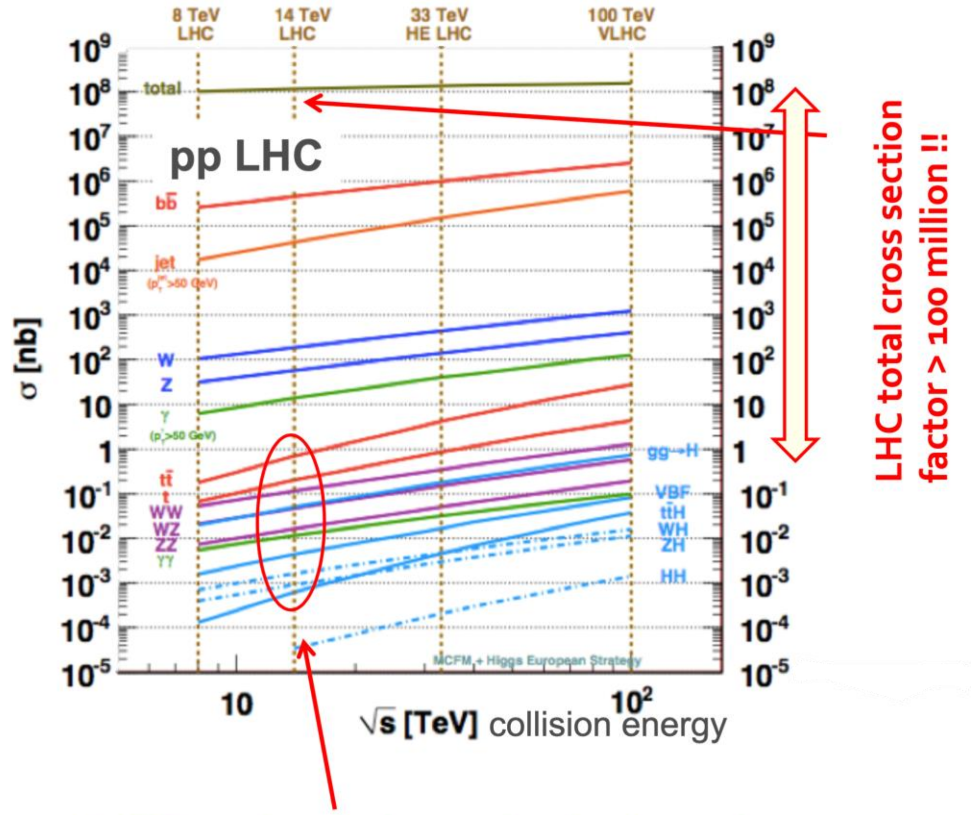


- ~100km circumference
- FCC-ee → FCC-hh
- High luminosity lepton collider
  - Precision measurements, in new energy ranges



Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})
FCC-ee-Z	4	88-95	150
FCC-ee-W	2	158-162	12
FCC-ee-H	3	240	5
FCC-ee-tt	5	345-365	1.5

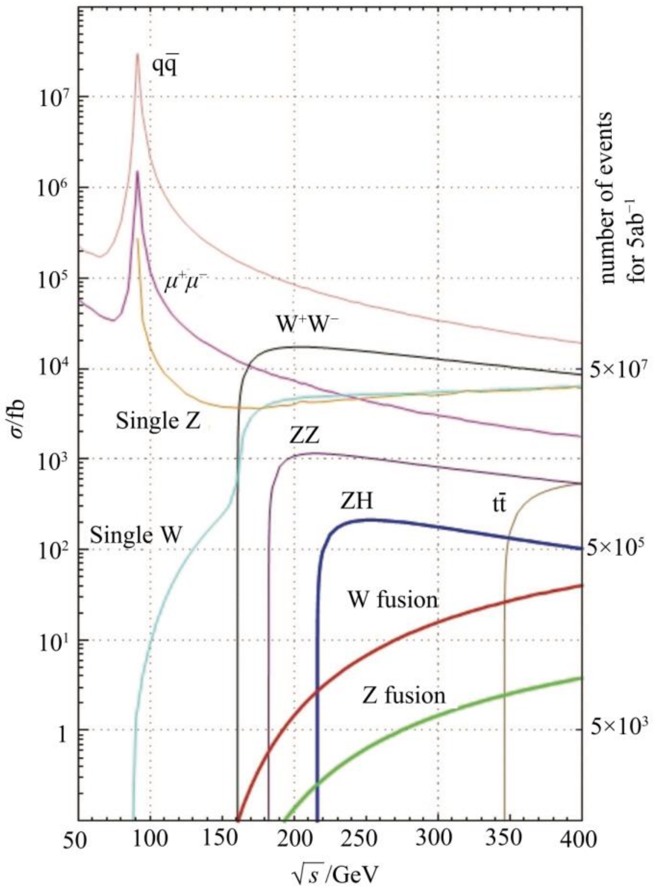
Why lepton collisions?



At LHC, much of the interesting physics needs to be found among a huge number of collisions

In e^+e^- collisions the total cross section ~ equals the electroweak cross section.

e^+e^- events are "clean"



Detector simulation

The Key4Hep release used in this work is **key4hep-stack/2023-01-09**

- DELPHES fast parametric detector simulation of IDEA detector concept
- Pythia8 + EvtGen to generate events
- Modified detector config file for different geometry

$$E = E_0 e^{-x/X_0}$$

$$X_{0,\,Silicon} = 9.370\ cm$$

# barrel	name	zmin	zmax	r	w (m)	X0	n_meas	th_up (rad)	th_down (rad)	reso_up (m)	reso_down (m)	flag
1	PIPE	-100	100	0.015	0.001655	0.2805	0	0	0	0	0	0
1	VTXLOW	-0.12	0.12	0.017	0.00028	0.0937	2	0	1.5708	3e-006	3e-006	1
1	VTXLOW	-0.16	0.16	0.023	0.00028	0.0937	2	0	1.5708	3e-006	3e-006	1
1	VTXLOW	-0.16	0.16	0.031	0.00028	0.0937	2	0	1.5708	3e-006	3e-006	1
1	VTXHIGH	-1	1	0.32	0.00047	0.0937	2	0	1.5708	7e-006	7e-006	1
1	VTXHIGH	-1.05	1.05	0.34	0.00047	0.0937	2	0	1.5708	7e-006	7e-006	1

# endcap	name	rmin	rmax	z	w (m)	X0	n_meas	th_up (rad)	th_down (rad)	reso_up (m)	reso_down (m)	flag
2	VTXDSK	0.141	0.3	-0.92	0.00028	0.0937	2	0	1.5708	7e-006	7e-006	1
2	VTXDSK	0.138	0.3	-0.9	0.00028	0.0937	2	0	1.5708	7e-006	7e-006	1
2	VTXDSK	0.065	0.3	-0.42	0.00028	0.0937	2	0	1.5708	7e-006	7e-006	1
2	VTXDSK	0.062	0.3	-0.4	0.00028	0.0937	2	0	1.5708	7e-006	7e-006	1
2	VTXDSK	0.062	0.3	0.4	0.00028	0.0937	2	0	1.5708	7e-006	7e-006	1
2	VTXDSK	0.065	0.3	0.42	0.00028	0.0937	2	0	1.5708	7e-006	7e-006	1
2	VTXDSK	0.138	0.3	0.9	0.00028	0.0937	2	0	1.5708	7e-006	7e-006	1
2	VTXDSK	0.141	0.3	0.92	0.00028	0.0937	2	0	1.5708	7e-006	7e-006	1

Detector simulation: Material budget

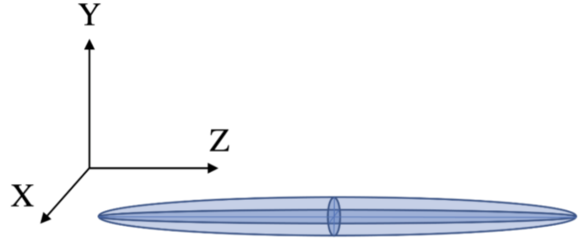
Material budget = x/X_0

Component	X [m]	X_0 [m]	X/X_0 [%]
Beam pipe	0.00165	0.2805	0.588
IDEA Standard layer (280 µm)	0.000280	0.0937	0.299
IDEA Thin layer (100µm)	0.000100	0.0937	0.106
IDEA Thin layer (30µm)	0.000030	0.0937	0.032

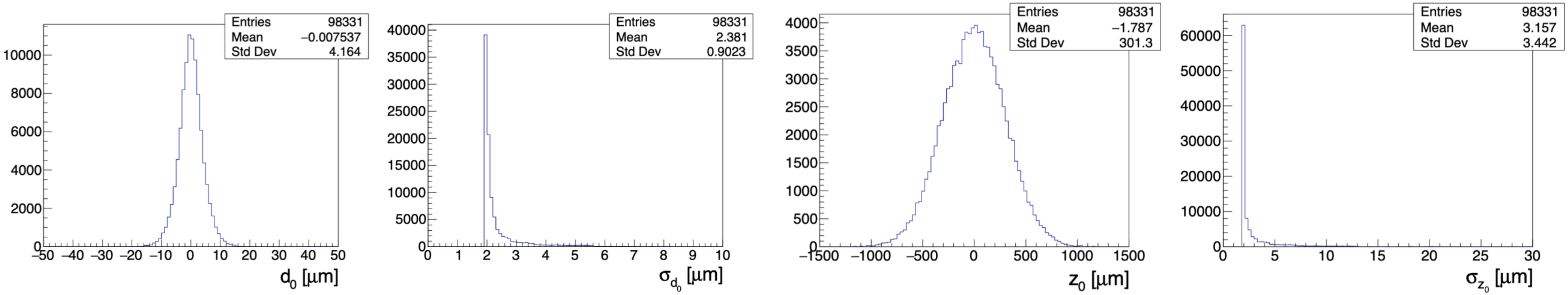
Detector simulation

Z → μ+μ- Events

- Pythia8 to generate 50,000 events with COM collision energy 91.188 GeV
- Beam energy spread of 0.0602 GeV, vertex smearing
- (pythia config card) (analysis script used)



Vertex smearing:
sigmaVertexX $= 4.50 \times 10^{-3}$ mm
sigmaVertexY $= 20.0 \times 10^{-6}$ mm
sigmaVertexZ $= 0.03$ mm



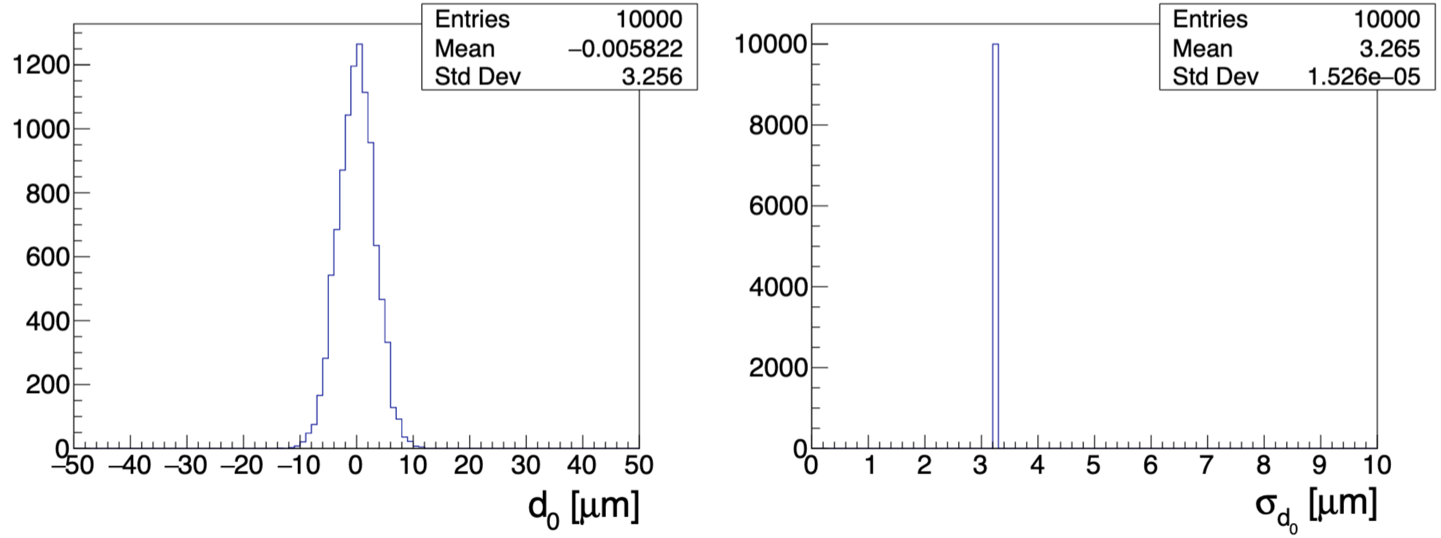
Impact parameter distributions for standard IDEA geometry

Detector simulation

$$p_{\mathrm{T}} = \frac{|\mathbf{p}|}{\cosh\left(-\ln\left(\tan\left(\frac{\theta}{2}\right)\right)\right)}$$

Particle gun muons

- Constant p_T particle gun from k4SimDelphes to generate collections of 10,000 muons
- momenta 1, 10, 100GeV
- flying out of the origin at polar angles of 10, 20, 30, 40, 50, 60, 70, 80, 89 degrees



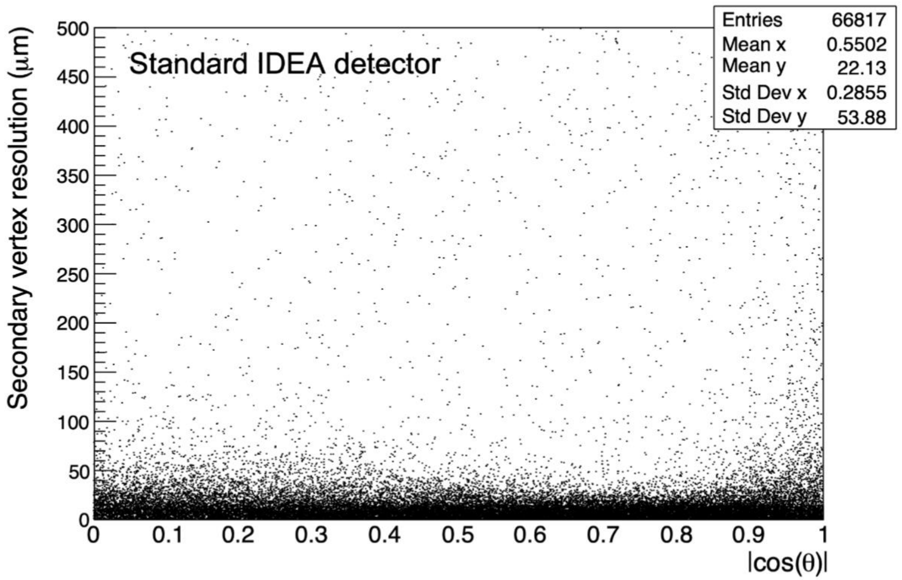
Detector simulation

Strange B meson decay

- EvtGen and Pythia8 to generate 100,000 events where B mesons (s, bbar) are produced in $e+e-$ collisions at center of mass energy = 91.188 GeV
- (Pythia8 config file) (EvtGen config file)

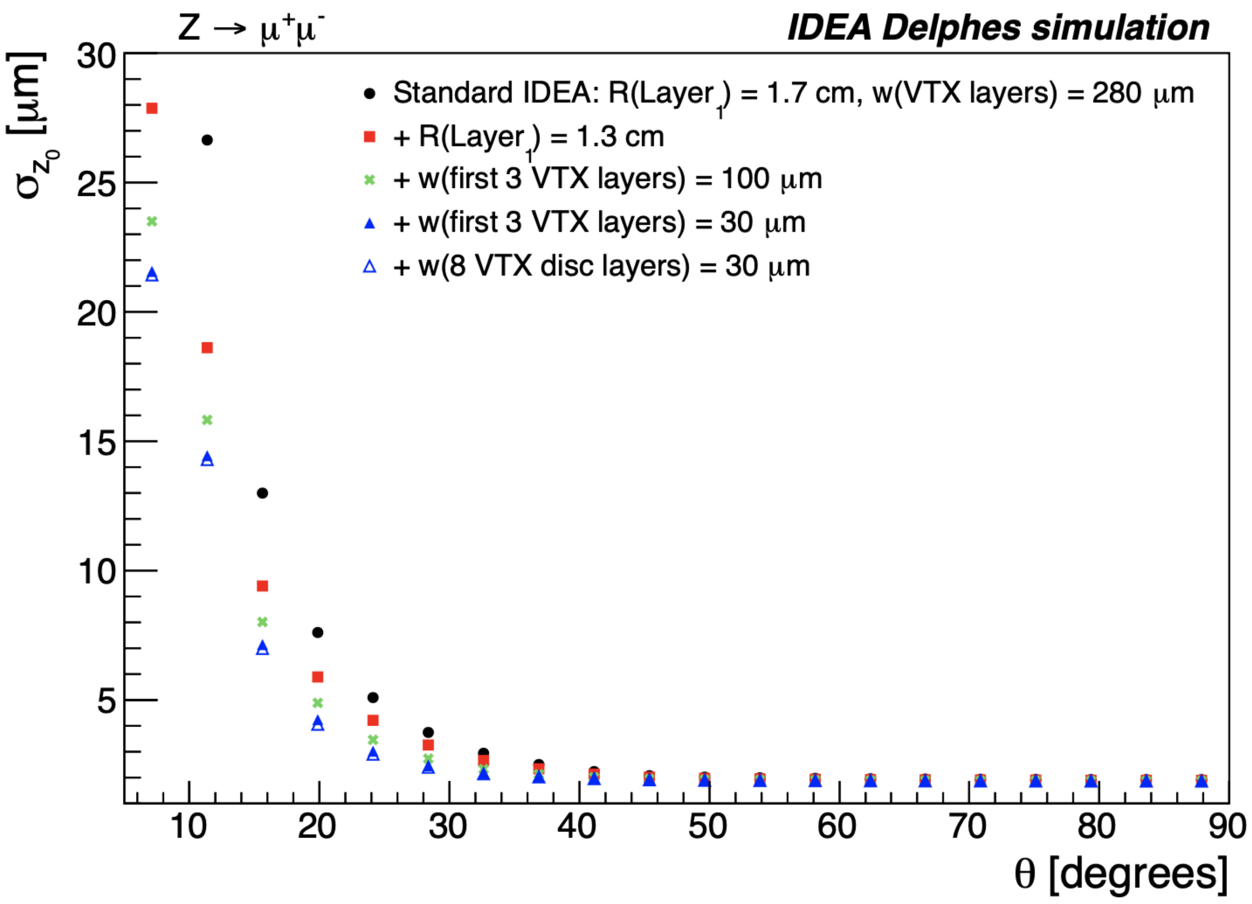
$$\text{flight distance resolution} = ||\vec{x}_{\text{MC SV}} - \vec{x}_{\text{PV}}| - |\vec{x}_{\text{Reco SV}} - \vec{x}_{\text{PV}}||$$

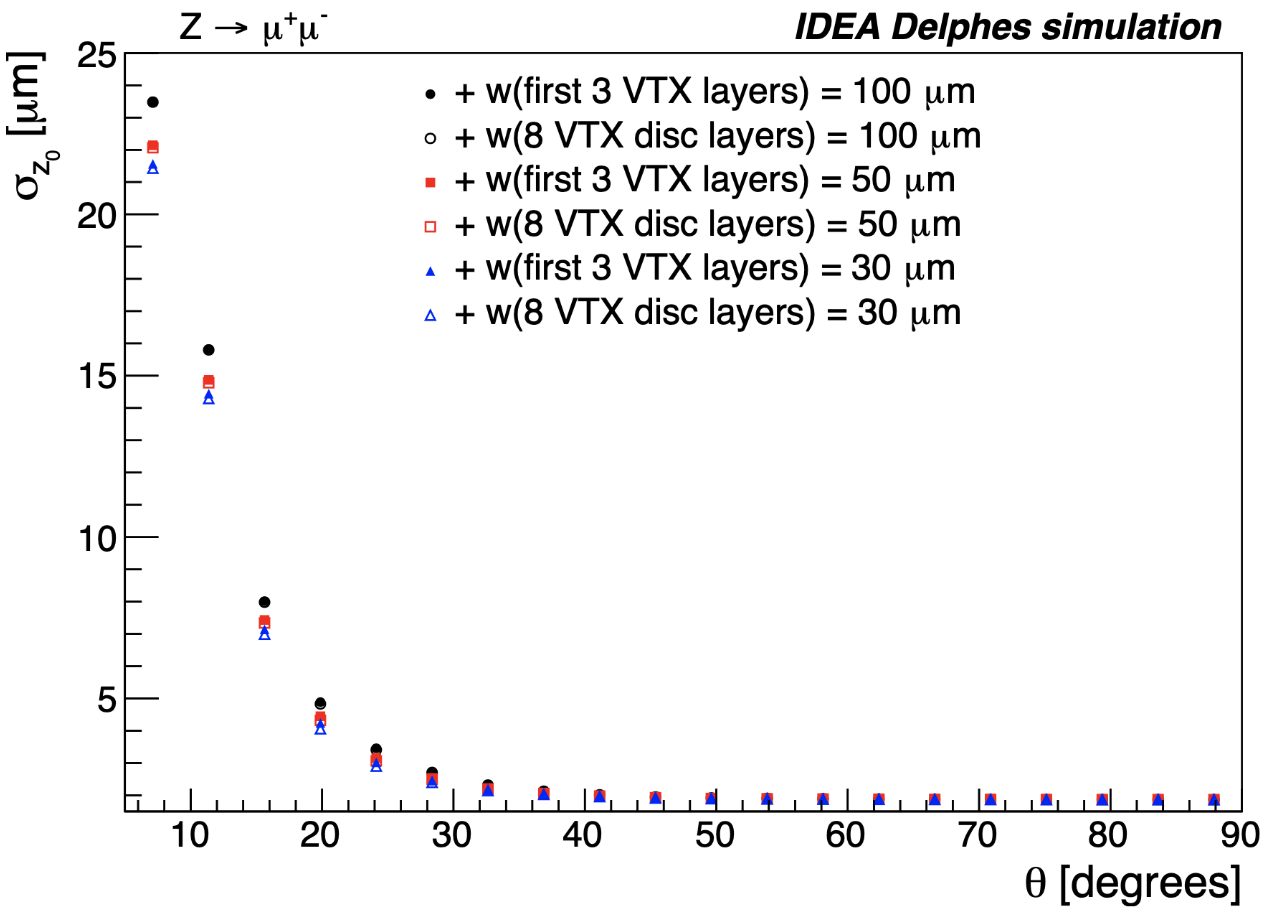
$$\text{secondary vertex resolution} = |\vec{x}_{\text{MC SV}} - \vec{x}_{\text{Reco SV}}|$$



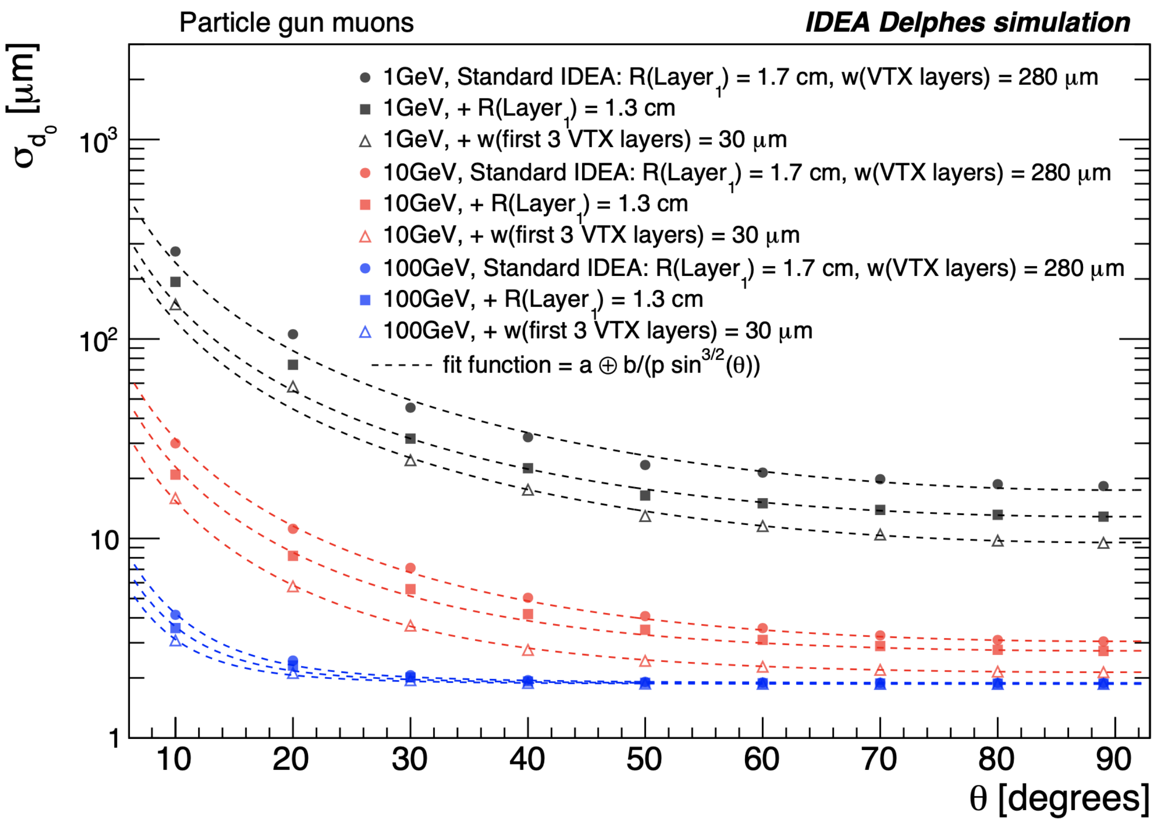
Scatter plot of SV resolution with cut at 500 µm

$Z \to \mu^+\mu^-$ Longitudinal Impact Parameter Resolution





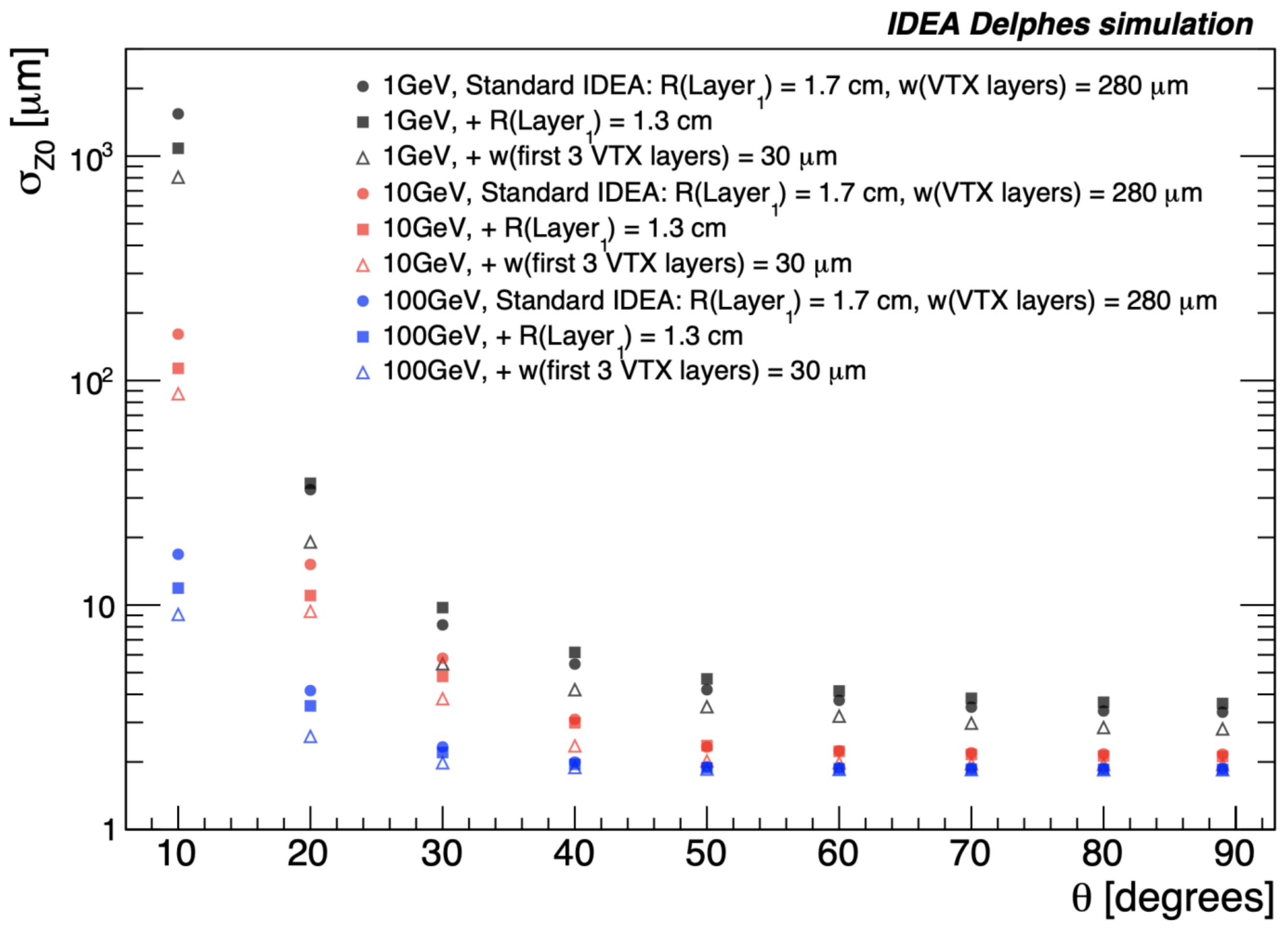
Particle gun: d0 fit parameters



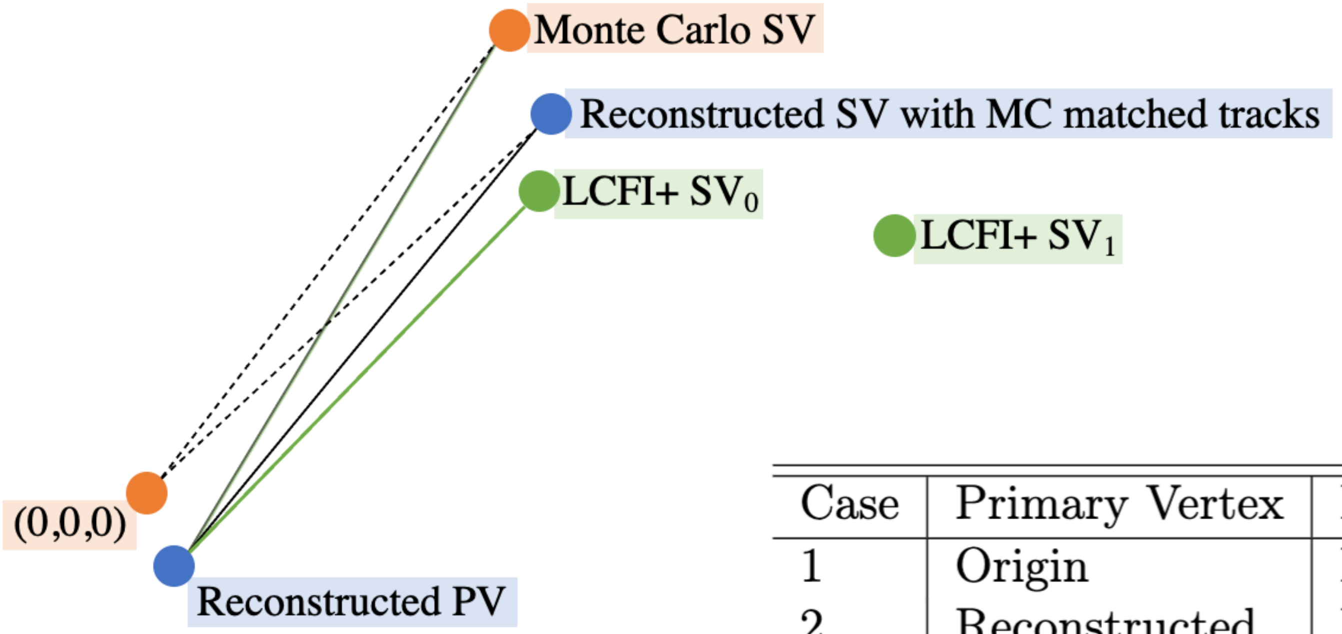
Geometry	Momentum [GeV]	Parameter a [μm]	Parameter b [μm · GeV]
Standard IDEA	1	1.00000*	17.4524 ± 0.000002
+R1.3	1	6.76067 ± 0.0000105	10.9413 ± 0.000006
+w30	1	3.51491 ± 0.0000178	8.87756 ± 0.000006
Standard IDEA	10	1.81603 ± 0.0000317	24.4841 ± 0.000228
+R1.3	10	2.18280 ± 0.0000083	16.4586 ± 0.000103
+w30	10	1.82604 ± 0.0000045	11.0777 ± 0.000072
Standard IDEA	100	1.86872 ± 0.0000007	27.2306 ± 0.000199
+R1.3	100	1.85984 ± 0.0000005	22.3703 ± 0.000156
+w30	100	1.85420 ± 0.0000003	18.1184 ± 0.000231

Table 4.2: Parameters extracted from the fit of Equation (2.2) on the transverse impact parameter resolution in Figure 4.3a. *This fit parameter did not properly converge, and always takes the value of the lower parameter limit. Also, the errors listed are those returned by the fit and are unreasonably small.

Particle gun: z0 resolution



B_s decay flight distance scenarios



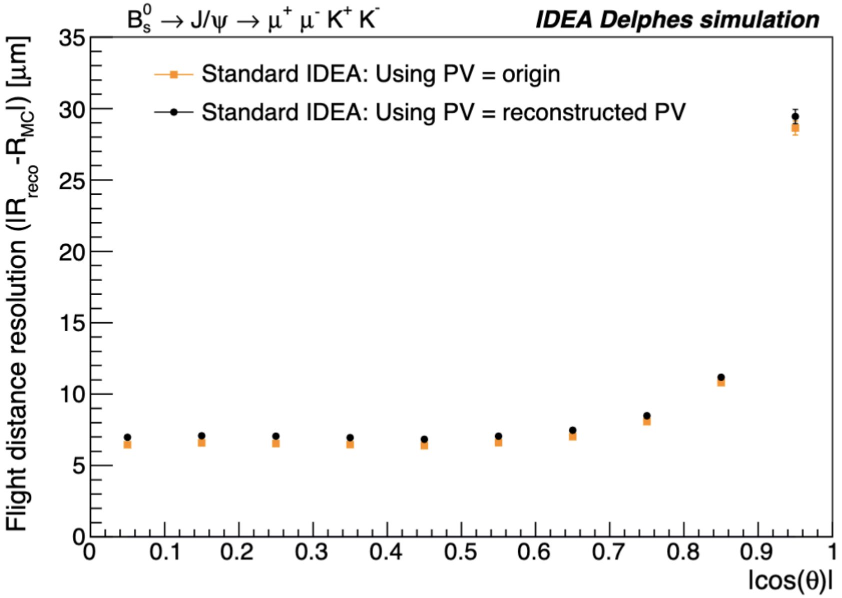
Case	Primary Vertex	Reconstructed Secondary Vertex
1	Origin	Reconstructed with MC matched tracks
2	Reconstructed	Reconstructed with MC matched tracks
3	Reconstructed	All reconstructed LCFI+ SV
4	Reconstructed	Closest reconstructed LCFI+ SV to MC SV

Table 4.3: Flight distance scenarios.

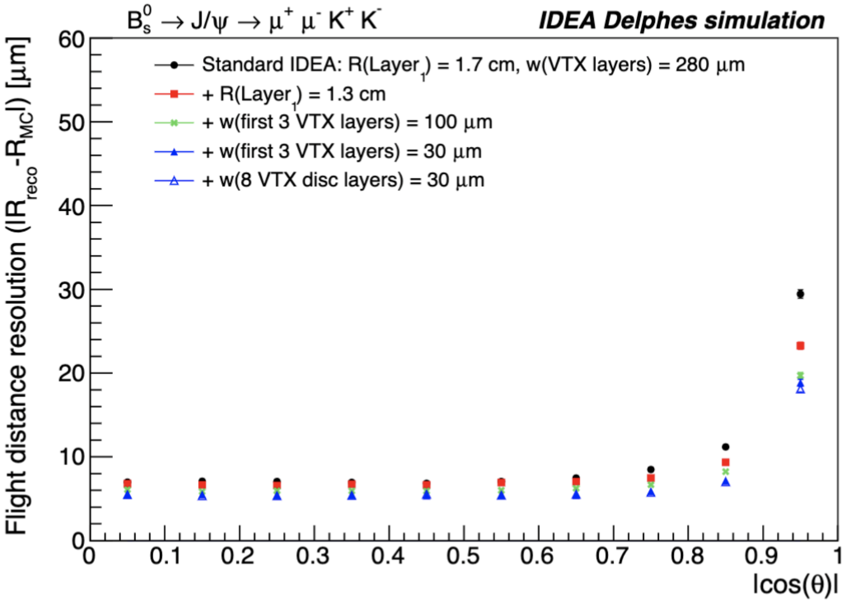
B_s decay

Case	Primary Vertex	Reconstructed Secondary Vertex
1	Origin	Reconstructed with MC matched tracks
2	Reconstructed	Reconstructed with MC matched tracks
3	Reconstructed	All reconstructed LCFI+ SV
4	Reconstructed	Closest reconstructed LCFI+ SV to MC SV

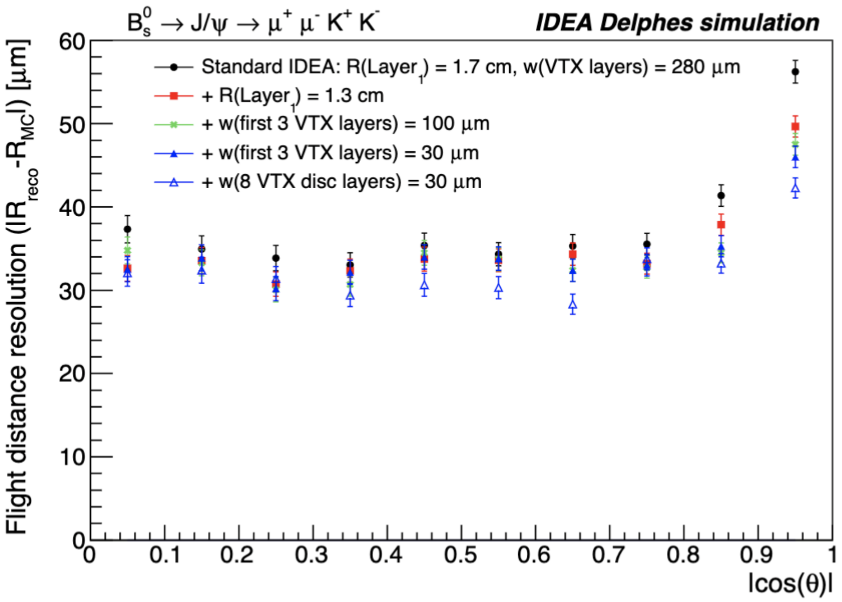
Table 4.3: Flight distance scenarios.



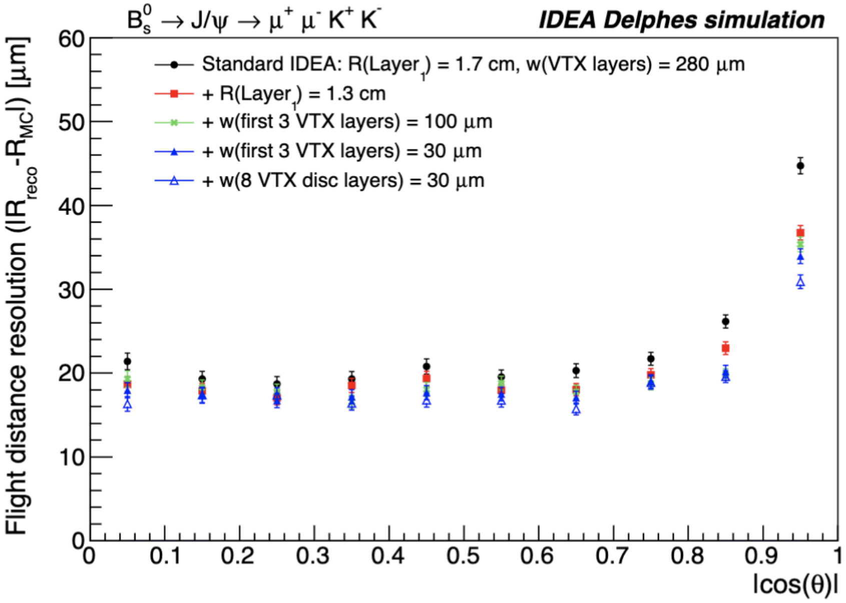
(a) Case 1 vs. Case 2



(b) Case 2

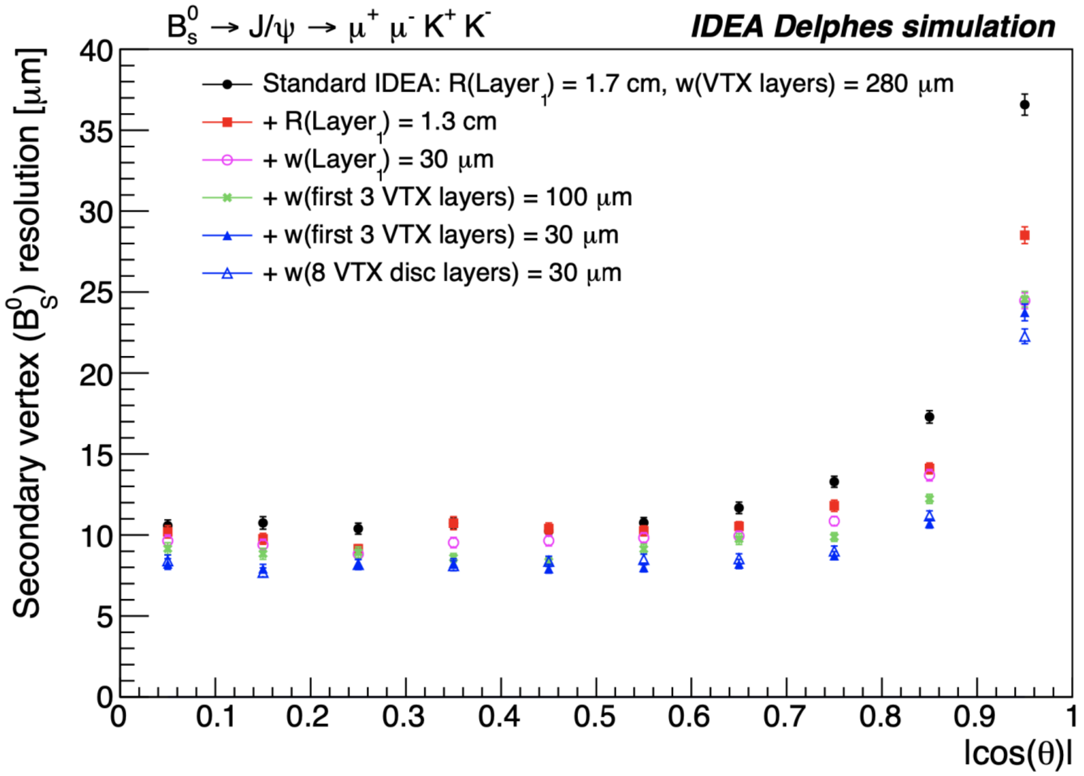


(c) Case 3



(d) Case 4

B_s decay SV resolution binned improvement



Initial geometry	Final geometry	Percent change in SV reso [%]
Standard IDEA	+R1.3	-8.91 ± 1.25
+R1.3	+L1_w30	-6.63 ± 1.29
+R1.3	+w100	-12.36 ± 1.24
+R1.3	+w30	-20.70 ± 1.13
+R1.3	+w30_DSK	-19.60 ± 1.20

Table 4.5: Average percent change of flight distance resolution between different combinations of initial and final geometry.

Initial geometry	Final geometry	Percent change in SV reso in bins 1-5 [%]	Percent change in SV reso in bins 5-10 [%]
Standard IDEA	+R1.3	-4.62 ± 2.03	-13.20 ± 1.46
+R1.3	+L1_w30	-6.26 ± 2.03	-7.01 ± 1.59
+R1.3	+w100	-12.33 ± 1.96	-12.39 ± 1.53
+R1.3	+w30	-19.19 ± 1.80	-22.21 ± 1.36
+R1.3	+w30_DSK	-18.69 ± 1.88	-20.51 ± 1.48

Table 4.6: Percent change of flight distance resolution between different combinations of initial and final geometry, averaging separately over the first 5 bins ($\cos(\theta) < 0.5$) and last 5 bins ($\cos(\theta) > 0.5$) of the data.

- When the smaller beam pipe is adopted (standard IDEA to +R1.3), the improvement in SV resolution is very much concentrated in the forward direction.
- The smaller beam pipe allows for the innermost vertex layer to be moved closer to the origin, which increases its angular coverage from 54.78 degrees to 47.29 degrees