VTX performance: status and plans

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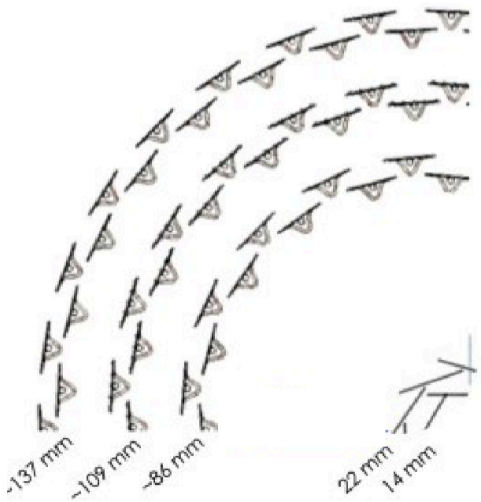
on behalf of the VTX performance group

21 April 2026

Current baseline geometry

Name: VTX-5layer-2025-baseline

Layer	radius (mm)	# ladders	# sensors per ladder
1	14	6	4
2	22	10	4
3	82.5 - 89	36	16
4	106 - 112.5	48	20
5	133.5 - 140	60	24



0.3% X_0 for L1 and L2; 0.8% X_0 for L3-5 each assigned to active material.

Staggered ladders for L3-5 and individual sensors with realistic gaps.

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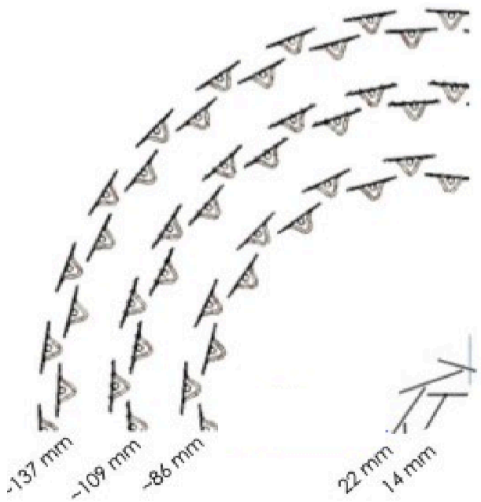


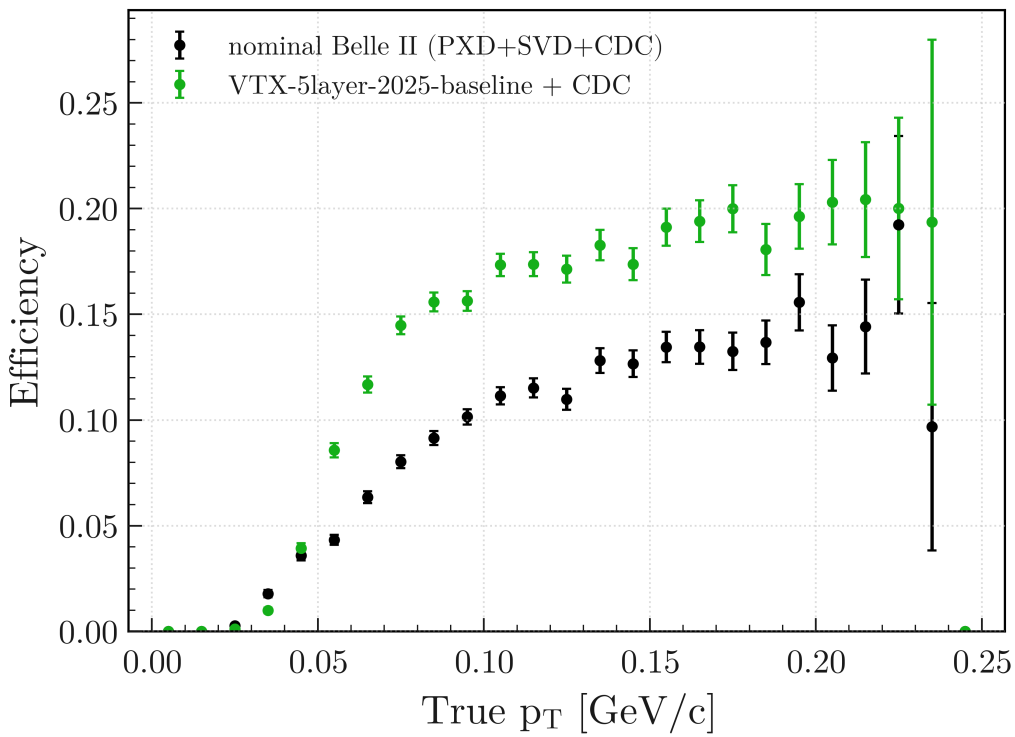
Christian Finck will be the geometry contact person for Upgrade performance group.

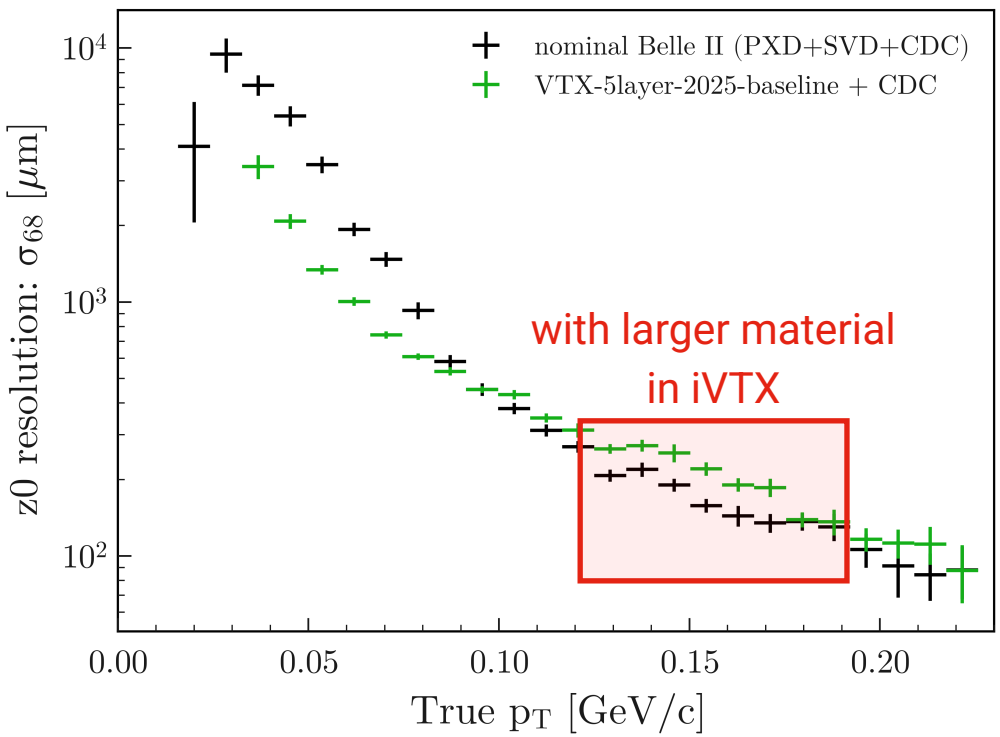
Note that this baseline may still evolve, with a different QCS geometry and/or different scenarios for the main tracking volume (CDC/STL/FTL).

Status of performance studies

- Full simulation and reconstruction available in `basf2`'s `upgrade` branch.
- BG overlay files available based on projections used in CDR
- Tracking metrics, slow-pion and K_S^0 studies performed on some variations of geometries

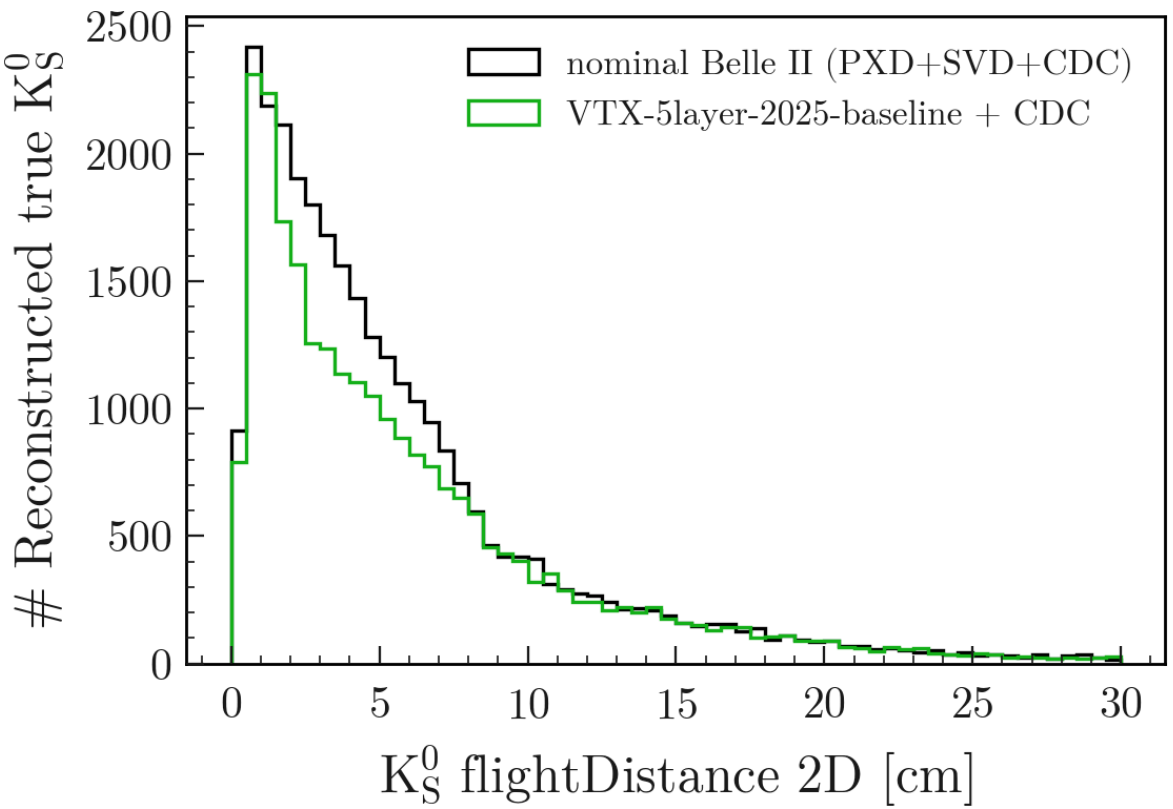
Efficiency and resolution vs. p_T





~60% higher slow pion reconstruction efficiency with better IP resolution too!

Efficiency and resolution of K_S^0



~15% lower K_S^0 efficiency.

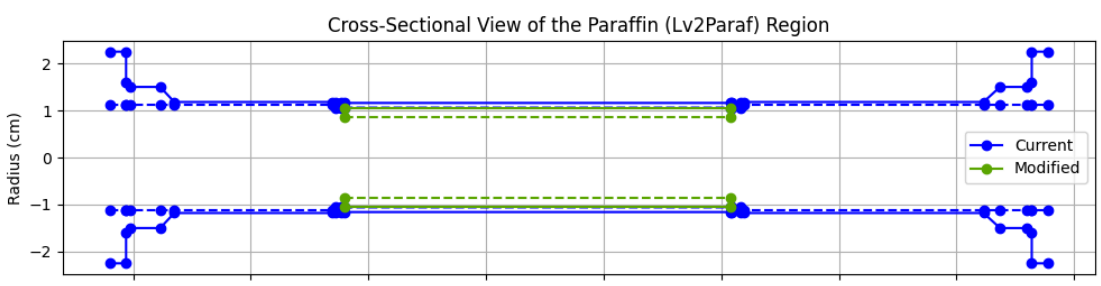
Was recovered with 6-layers but compensated by higher material budget and now 5-layers.

But provides ~30% better B vertex resolution: $25\mu\mathrm{m} \rightarrow 17\mu\mathrm{m}$ in v3 (conservative) background.

New beam pipe design

- Proposal:
  - Smaller inner radius: $10\ \mathrm{mm} \rightarrow 8\ \mathrm{mm}$
  - Thicker paraffin: $1\ \mathrm{mm} \rightarrow 1.8\ \mathrm{mm} \Rightarrow$ Overall material: 0.80% $\mathrm{X}_0 \rightarrow$ 0.96% X_0

For now, modified[1] only the physics region and left the rest (which will have an impact on beam background and should be studied later on).



[1] Implemented in [!4707] and validated with material scan

Impact of proposed beam pipe

The change in the track IP resolution can be calculated analytically:

$$\sigma^2 \propto \left(\theta_{\mathrm{BP}} \times R_{\mathrm{BP}}^{\mathrm{inner}}\right)^2 + \left(\theta_{\mathrm{L1}} \times R_{\mathrm{L1}}\right)^2$$

Verified with full simulation for proposed design as well.

Impact of proposed beam pipe

Taking fixed θ^2_{L1}: 0.3% X_0,

θ^2_{BP} [% X_0]	$R^{\mathrm{inner}}_{\mathrm{BP}}$ [cm]	$R^{\mathrm{inner}}_{\mathrm{L1}}$ [cm]	Ratio: $\frac{\sigma_{\mathrm{new}}}{\sigma_{\mathrm{current}}}$	Hit rate in VTX L1 [MHz/cm^2] in v3 (conservative) background
0.8	1.0	1.4	1	34.1 ± 0.3
0.8	0.8	1.4	0.887	
0.96	1.0	1.4	1.052	
0.96	0.8	1.4	0.927	35.2 ± 0.3

Change

Proposed

The proposed beam pipe improves the IP resolution!

No significant increase seen in the hit rate (based on our background modeling).
Calculating radiation damage is not that trivial.

VTX closer to interaction region?

θ^2_{BP} [% X_0]	$R^{\mathrm{inner}}_{\mathrm{BP}}$ [cm]	$R^{\mathrm{inner}}_{\mathrm{L1}}$ [cm]	Ratio: $\frac{\sigma_{\mathrm{new}}}{\sigma_{\mathrm{current}}}$	Hit rate in VTX L1 [MHz/cm^2] in v3 (conservative) background
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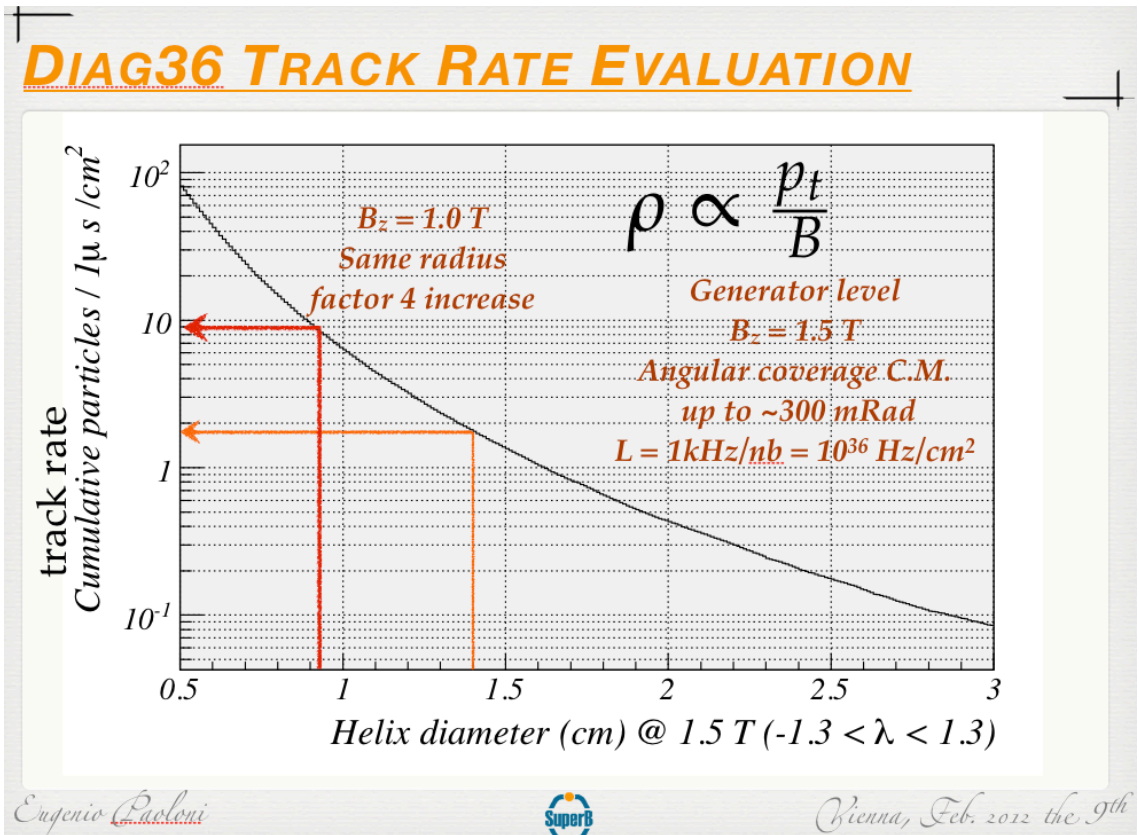
0.96	0.8	1.4	0.927	35.2 ± 0.3
0.8	1.0	1.1	0.912	
0.96	0.8	1.1	0.836	~~35.6 ± 0.3~~
0.50	0.8	1.4	0.806	

Moving the VTX L1 closer ($1.4\ \mathrm{cm} \rightarrow 1.1\ \mathrm{cm}$) can further improve the IP resolution, but hit rate expected to increase by a factor ~3. Did not manage to reproduce.

Hit rate with L1 closer to interaction point



- [ ] Isolate two-photon component in our background estimations
- [ ] Contact background group to understand if we are doing something wrong.

Next step: Lower acceptance?

To reduce forward acceptance will move to 22°, reduce the # sensors per ladder.

Layer	Current # sensors	New # sensors
1	4	3
2	4	3
3	16	12
4	20	16
5	24	20

Expected ~10% reconstruction efficiency drop of $B \to D^* \pi$, and scales with multiplicity like $B \to D^* [D [\to K \pi \pi \pi] \pi] \pi \pi \pi$. This is important for FEI performance.

Summary and next steps

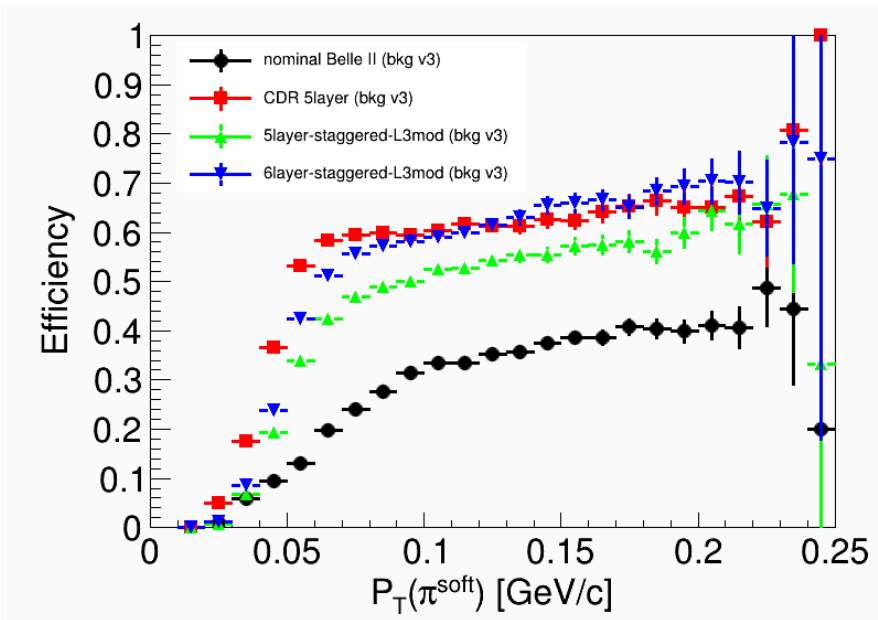
- We have a new “baseline” geometry: `VTX-5layer-2025-baseline`
  - Simulation, some tracking retraining, BG overlay available: vtxdvpmt docs.
- Overall good performance and studies with new beam-pipe design shows slightly better IP resolution.

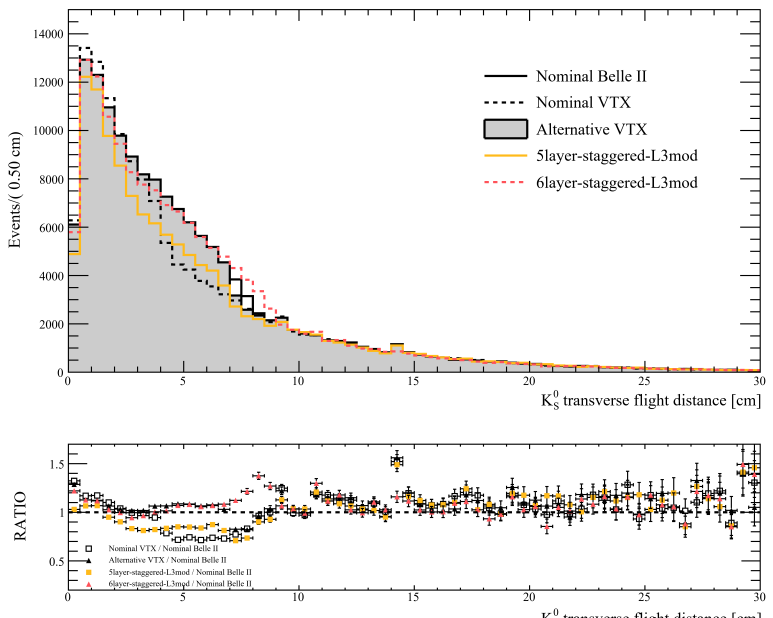
To-do/Ongoing:

- Study performance with geometry with fewer # sensrs and lower boost.
- Study the impact on FEI and tagged-analysis
- Study the background levels/occupancy with L1 closer to IP.
- Investigate the Ks reconstruction efficiency drop.
- Detailed description of passive material (mechanical supports, flex, services, …) in simulation?

Backup

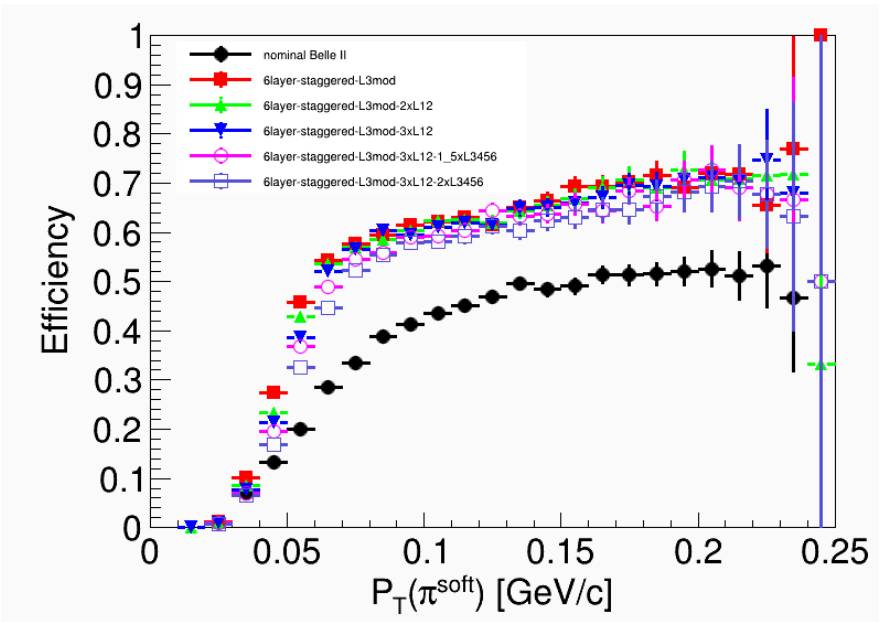
6-layer vs CDR 5-layer

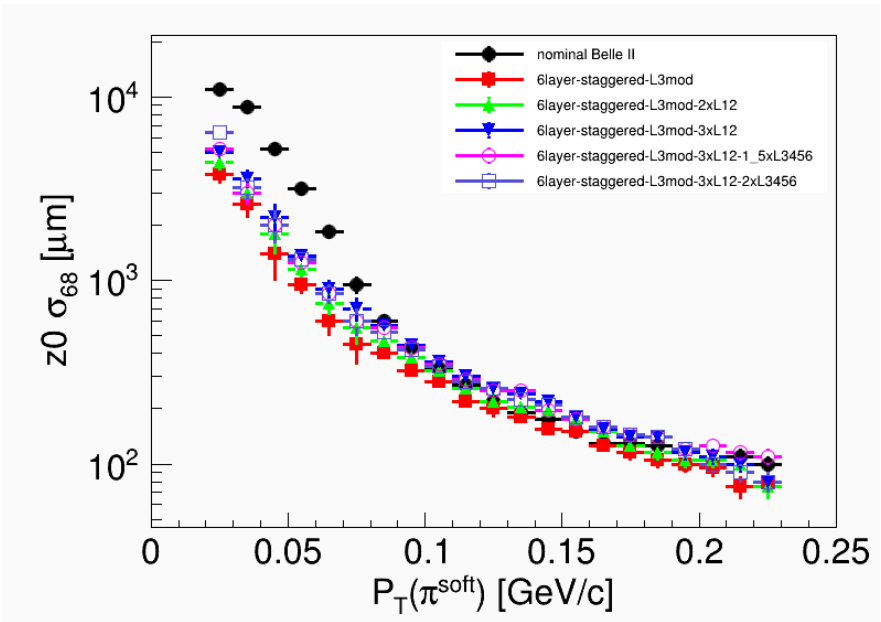




Studies showed that the new 6-layer geometry performed better (recovered K^0_S efficiency) compared to CDR 5-layer geometry.

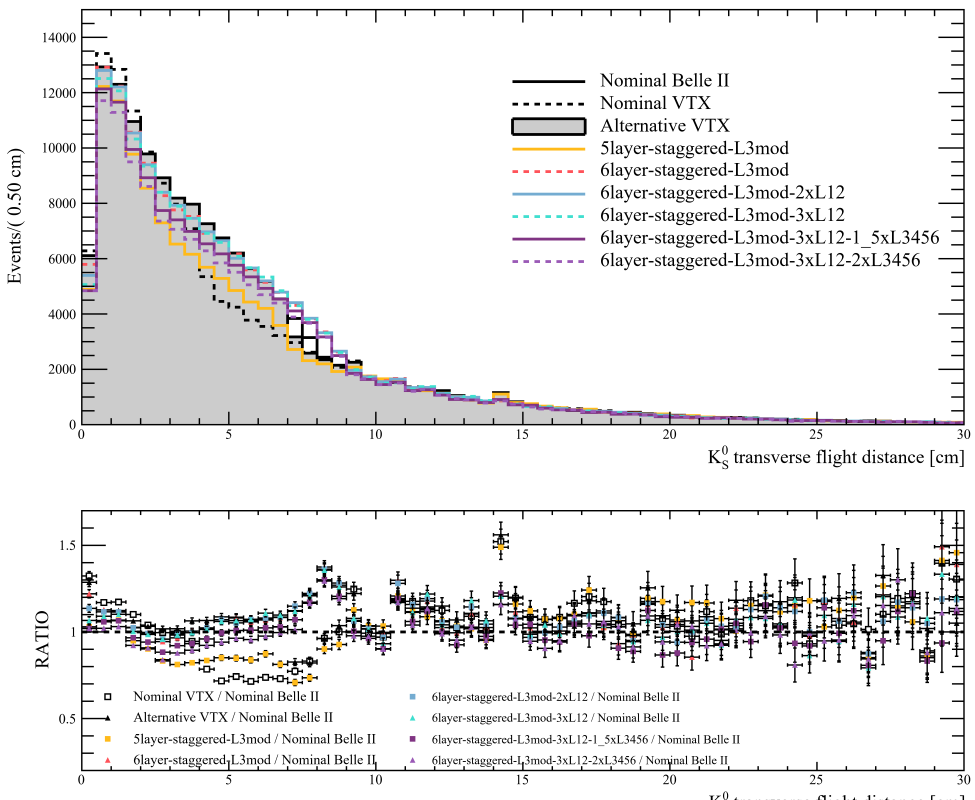
6-layer: Material budget





Higher material budget degrades both the slow π^+ efficiency and impact parameter resolution.

6-layer: Material budget



B_{sig} z vertex resoluton (μm)	Bkg(v1)	Bkg(v2)	Bkg(v3)
Belle II	20.9	22.3	24.5
Nominal VTX	13.9	14.0	13.9
Alternative VTX	13.7	13.7	13.6
5layer-staggered-L3mod	16.7	16.9	17.1
6layer-staggered-L3mod	16.1	16.1	16.4
6layer-staggered-L3mod-2xL12		17.8	
6layer-staggered-L3mod-3xL12		19.0	
6layer-staggered-L3mod-3xL12-1_5xL3456		19.0	
6layer-staggered-L3mod-3xL12-2xL3456		19.1	

Higher material budget lowers the K^0_S efficiency (lower than nominal Belle II), but provides better vertex resolution.

Chose 0.3% X_0 for L1 and L2;
0.8% X_0 for L3-6 to be realistic.

Simulations without L3/4

New QCS geometry: engineering difficulties to accommodate 6 layers $\Rightarrow \searrow$ 5 layers?

Layer/radius (mm)	reference	woL3	woL4
1	14	14	14
2	22	22	22
3	69	-	69
4	82.5 - 89	82.5 - 89	-
5	106 - 112.5	106 - 112.5	106 - 112.5
6	133.5 - 140	133.5 - 140	133.5 - 140

Using 0.3% X_0 material budget for L1 and L2; 0.8% X_0 for L3-6 each.

Note that we do not have staggering implemented in L3 here yet.

Studies without L3/4

Overall[1] full[2] tracking performance with v3[3] background:

Metric	Nominal Belle II	VTX 6layer	woL3	woL4
Finding efficiency	0.920	0.945	0.940	0.934
Hit efficiency	0.773	0.765	0.762	0.768
Clone rate	0.037	0.087	0.078	0.094
Fake rate	0.196	0.103	0.129	0.143

Only a minor impact (within statistical uncertainty) when removing a layer.

[1] over entire p_T and $\cos(\theta)$ range

[2] (VTX +) full CDC

[3] conservative

Definitions

$$\text{PR-track} = \text{Pattern recognition track}$$

$$\text{Finding Efficiency} = \frac{\#\text{true tracks found and matched by a PR-track}}{\text{Total } \#\text{true tracks}}$$

$$\text{Hit Efficiency} = \frac{\#\text{true hits successfully included in the PR-track}}{\text{Total } \#\text{true hits belonging to the MC-track}}$$

K_S^0 efficiency

Configuration	Efficiency
nominal Belle II	0.152
6layer-L3mod-3xL12-2xL3456	0.143
6layer-L3mod-3xL12-2xL3456-wo69	0.131
6layer-L3mod-3xL12-2xL3456-wo82	0.134

Note: this is reconstruction efficiency of entire $B \to J/\psi K_S^0$, and currently $J/\psi \to \ell\ell$ efficiency is assumed to be similar.

To be normalized to extract just K_S^0 efficiency.

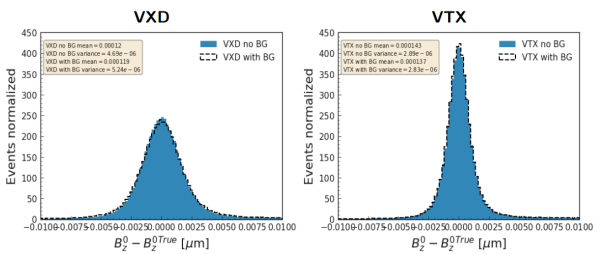
Slow π^+ efficiency

Configuration	Efficiency
nominal Belle II	0.083
6layer-L3mod-3xL12-2xL3456	0.135
6layer-L3mod-3xL12-2xL3456-wo69	0.129
6layer-L3mod-3xL12-2xL3456-wo82	0.135

Note: this is reconstruction efficiency of entire $B \to D^{*+}\pi^-$

TDCPV performance

$B^0 \to J/\psi(\mu\mu)\, K_S(\pi\pi)$



FWHM (signal side)

	VXD	VTX
BGx0	0.0034 μm	0.0018 μm
BG v1	0.0035 μm	0.0018 μm

FWHM (tag side)

	VXD	VTX
BGx0	0.0060 μm	0.0041 μm
BG v1	0.0064 μm	0.0040 μm

Efficiency

	VXD BGx0	VTX BGx0
J/ψ	$(84.76 \pm 0.06)\%$	$(84.84 \pm 0.06)\%$
K_S	$(76.62 \pm 0.06)\%$	$(75.23 \pm 0.07)\%$
B^0	$(58.97 \pm 0.07)\%$	$(57.46 \pm 0.07)\%$

sin (2β)-fit

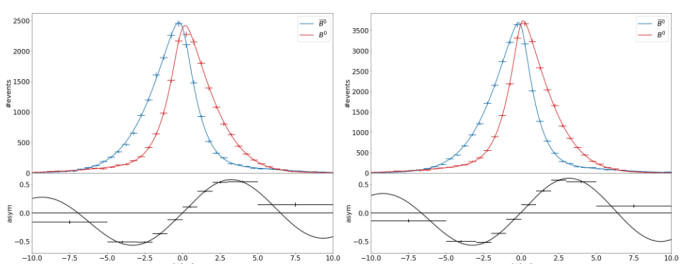
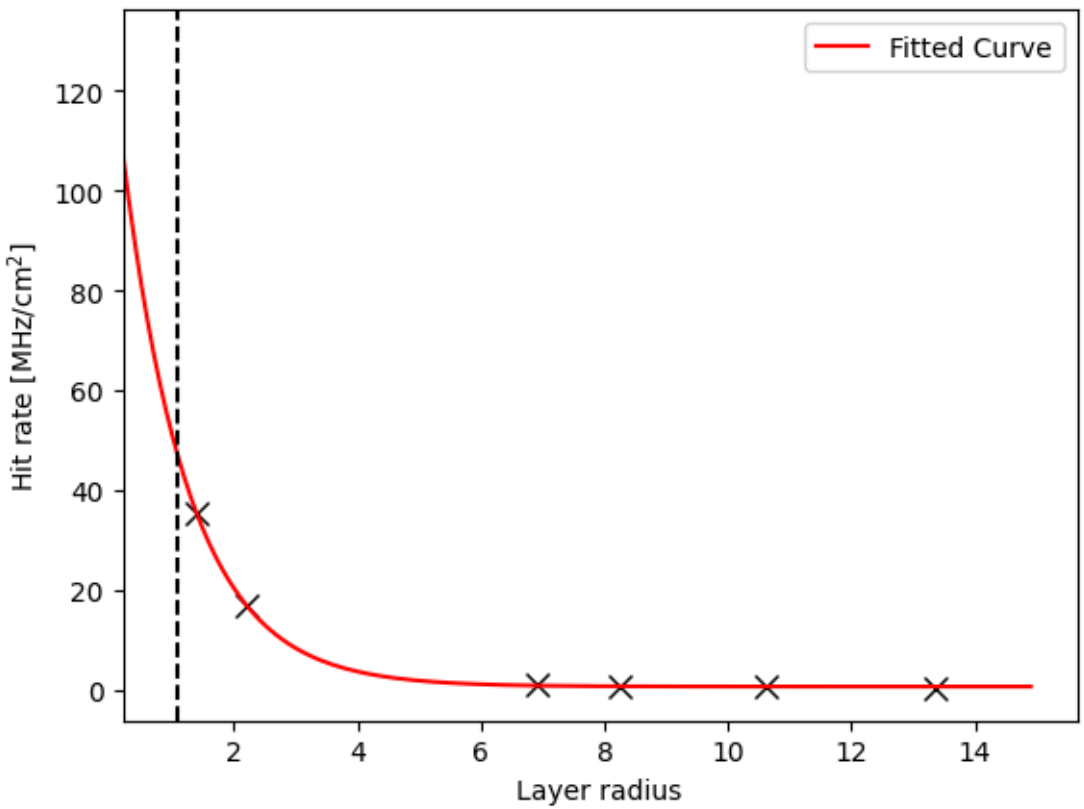


Figure: VXD Figure: VTX

	VXD BGx0	VTX BGx0	VXD BG v1	VTX BGv1
acp	-0.002 ± 0.004	-0.001 ± 0.004	-0.001 ± 0.005	-0.004 ± 0.004
scp	0.681 ± 0.005	0.675 ± 0.005	0.688 ± 0.006	0.674 ± 0.006

Significantly better vertex resolution, but limited by K^0_S efficiency

Hit rate vs radius



Material budget of the current beam pipe

Material	Inner radius (cm)	Outer radius (cm)	Thickness
Gold	0.999	1.0	10 μm
Inner Be	1.0	1.06	0.6 mm
Paraffin	1.06	1.16	1 mm
Outer Be	1.16	1.20	0.4 mm
Outer Ti	1.20	1.2002	2 μm

From Geant4

Material	Radiation Length (cm)
Gold	0.3344
Beryllium	35.2760
Titanium	3.5602
Paraffin	47.5705

Total material budget: $\frac{0.001}{0.334} + \frac{0.06}{35.28} + \frac{0.1}{47.57} + \frac{0.04}{35.28} + \frac{0.0002}{3.56} = 0.799\%$

Proposal for changes in beam pipe

Current				Proposed			
Material	Inner r (cm)	Outer r (cm)	Thickness	Material	Inner r (cm)	Outer r (cm)	Thickness
Gold	0.999	1.0	10 μm	Gold	**0.799**	0.8	10 μm
Inner Be	1.0	1.06	0.6 mm	Inner Be	0.8	0.86	0.6 mm
Paraffin	1.06	1.16	1 mm	Paraffin	0.86	1.04	**1.8 mm**
Outer Be	1.16	1.20	0.4 mm	Outer Be	1.04	1.08	0.4 mm
Outer Ti	1.20	1.2002	2 μm	Outer Ti	1.08	1.0802	2 μm

Total material budget: $\frac{0.001}{0.334} + \frac{0.06}{35.28} + \frac{0.18}{47.57} + \frac{0.04}{35.28} + \frac{0.0002}{3.56}$
$= 0.967\%$