2nd part:
Using $B^0 \to K_S^0 \pi^+\pi^-\gamma$ decays to study the performance of an upgrade to the Belle II Vertex Detector

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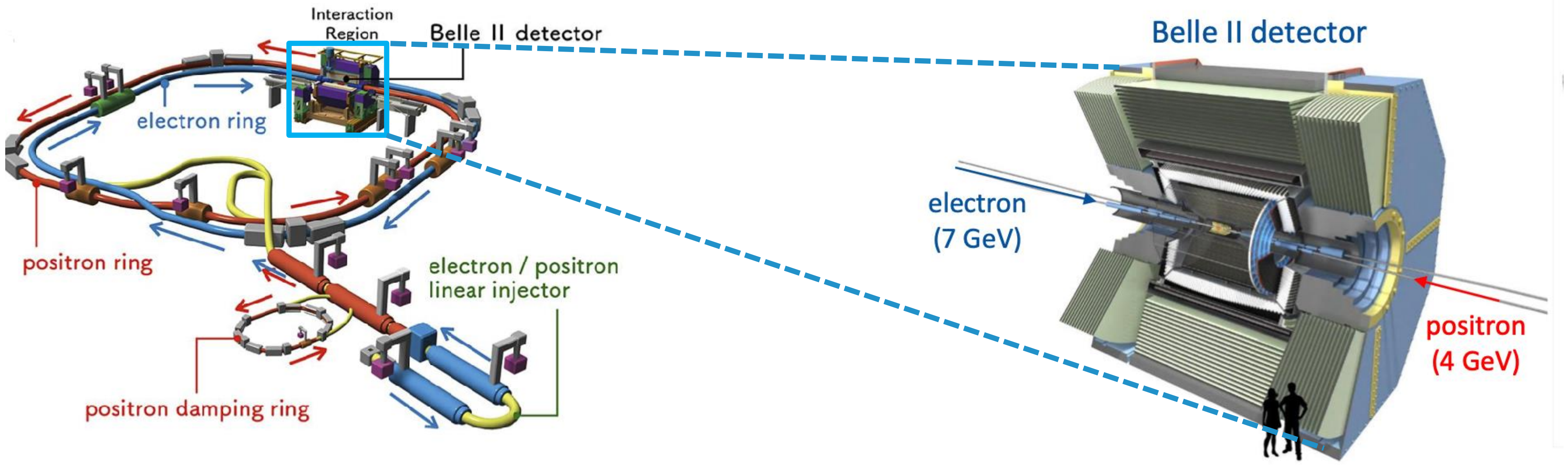
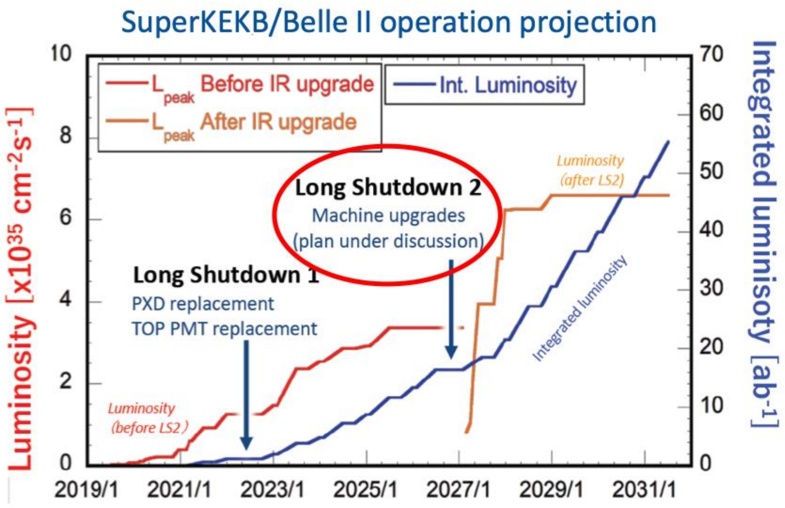
GDR-InF annual workshop at Lyon, November 2nd 2022

SuperKEKB & the Belle II detector

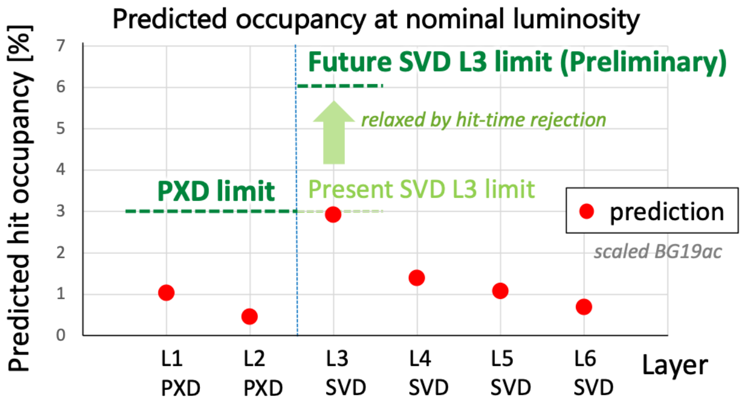


- SuperKEKB: the "brightest" e^+e^- collider:
  - Current peak instantaneous luminosity: 4.7×10^{34} cm^{-2}s^{-1} (**WR**)
  - Target instantaneous luminosity: 6.5×10^{35} cm^{-2}s^{-1} ($\sim$30 times larger than at KEKB) achieved by **nano-beam scheme**
  - Already at 427 fb^{-1} $\approx$ BaBar dataset (target: 50 ab^{-1})

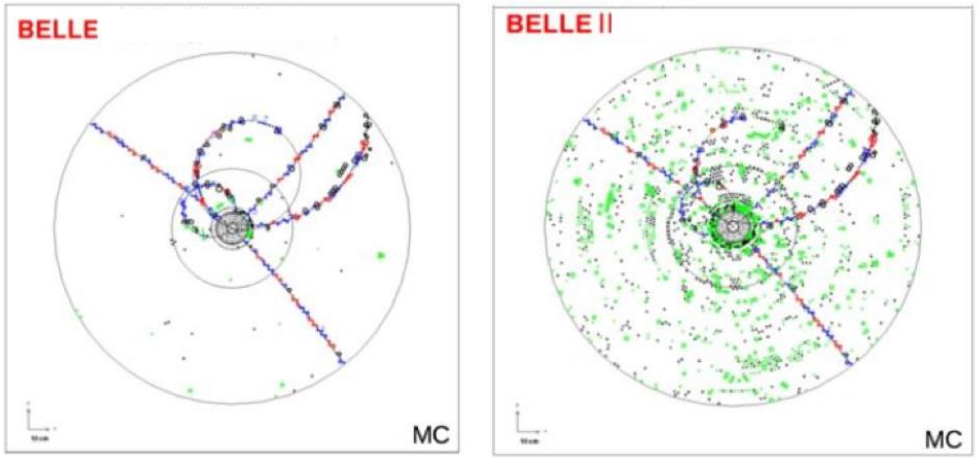


SuperKEKB & the Belle II detector

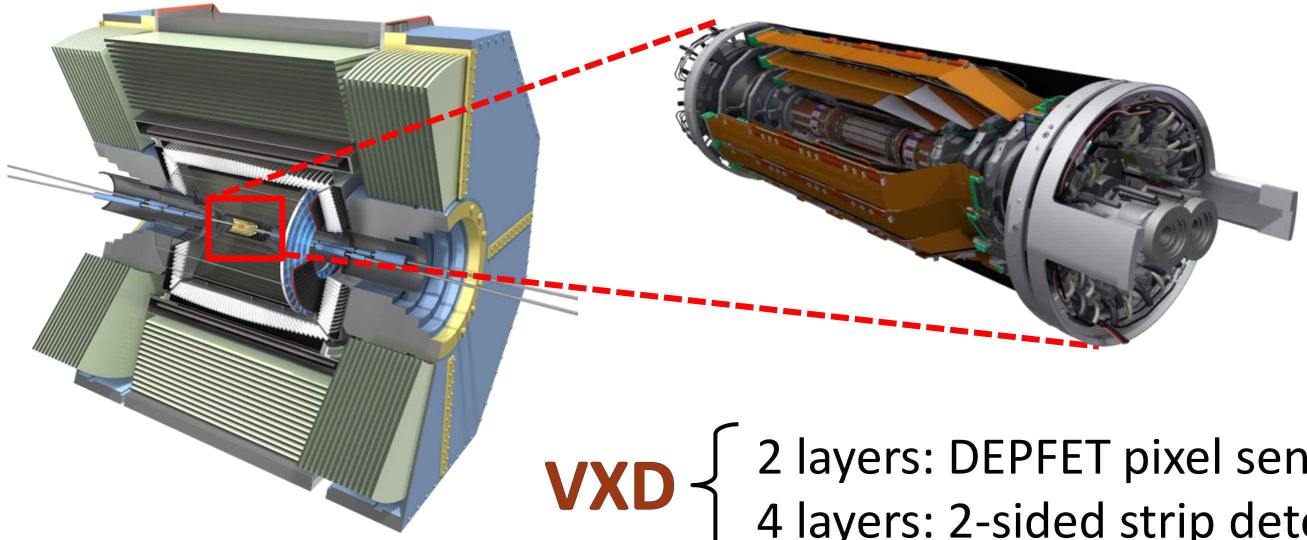
- Extremely high luminosity poses **experimental challenge**: beam-induced backgrounds that generate parasitic particles degrading detector performance
- Central Drift Chamber (CDC) and Vertex Detector (VXD) struggle to keep up with increased hit rate (see last year's talk by C. Finck)
- Opportunity for detector upgrade during 2026 - 27 (Long Shutdown 2)

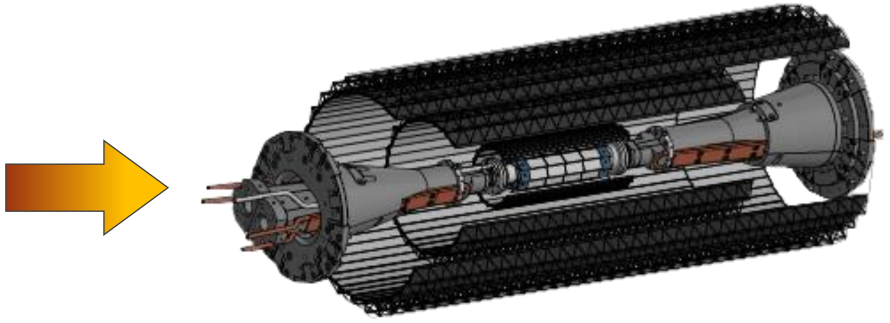


(with large uncertainties…)



Vertex detector upgrade





VXD { 2 layers: DEPFET pixel sensors
4 layers: 2-sided strip detectors

VTX: 5 (7) layers of CMOS pixel sensors

✓ Cope with increased hit rate (or occupancy) by reducing pixel size (30 to 40 μm pixel pitch) and integration time (≤ 100 ns)

$$Occupancy \propto \frac{readout\ time}{granularity}$$

➢ Is the sensitivity of Belle II to new physics improved?

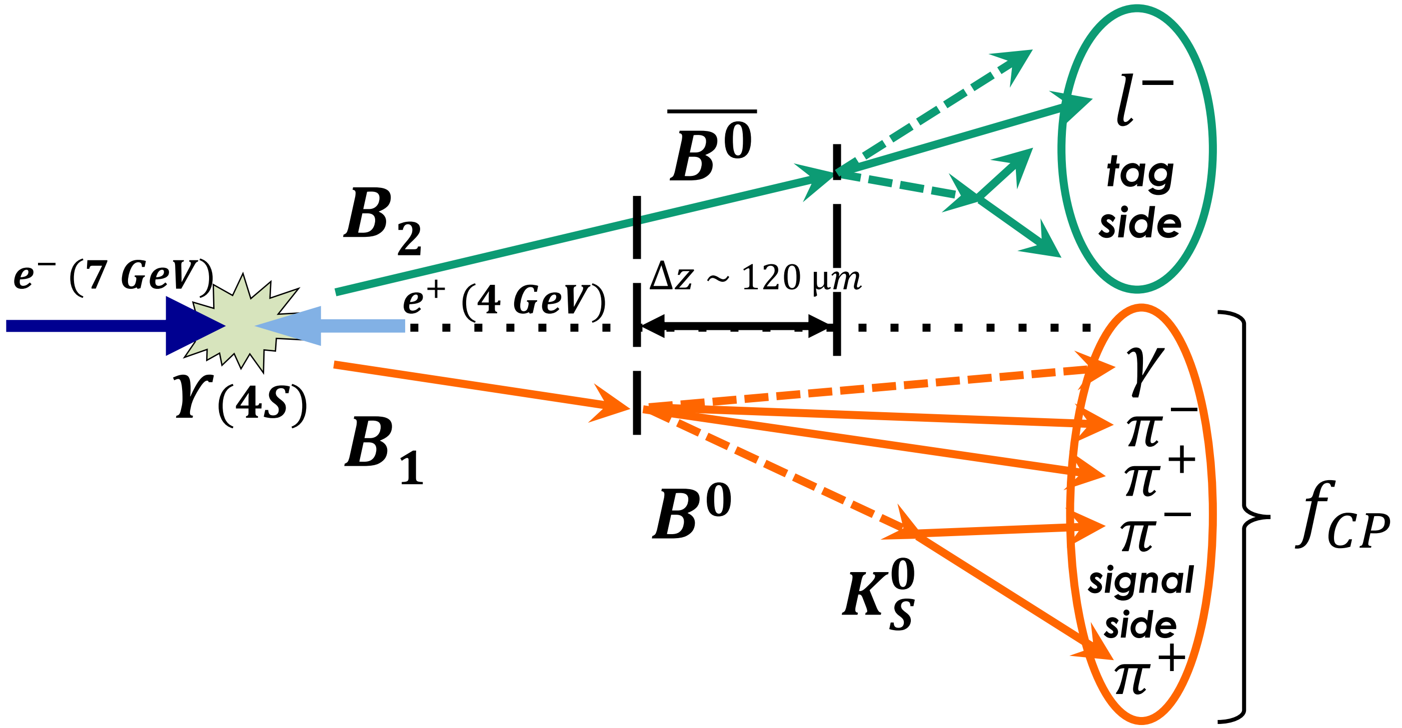
➢ Are the upgraded geometries optimised for physics?

Benchmark measurement

Observable: $$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})}$$

Measurement requires:

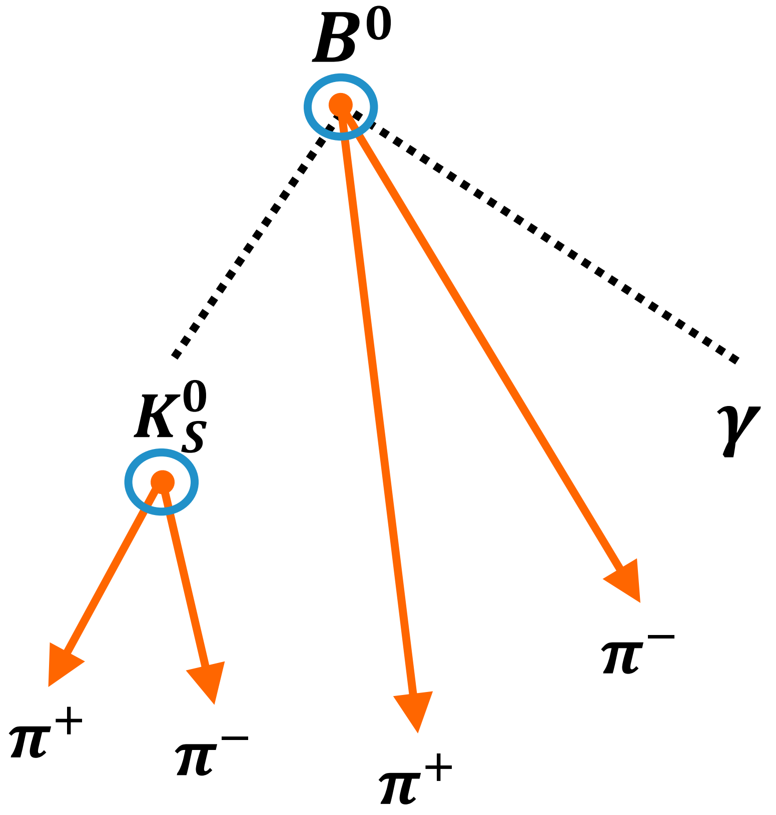
- Efficient reconstruction of f_{CP}
- Great resolution on Δt ($\sim$ ps) between two B meson decays (Δt resolution $\propto$ Δz resolution)
- Capacity to determine B^0 flavor (B^0 or $\bar{B}^0$)



Decay channel

- $B^0(\bar{B}^0) \rightarrow K_S^0\, \pi^+\pi^-\gamma$ decays contain charge particle **tracks** and particle decay **vertices** ⇒ good channel to **benchmark** performance of vertex detector

- Phenomenologically, such decays contain $b \rightarrow s\, \gamma$ transitions and probe BSM physics via a time-dependent CP asymmetry (**TDCPA**) measurement



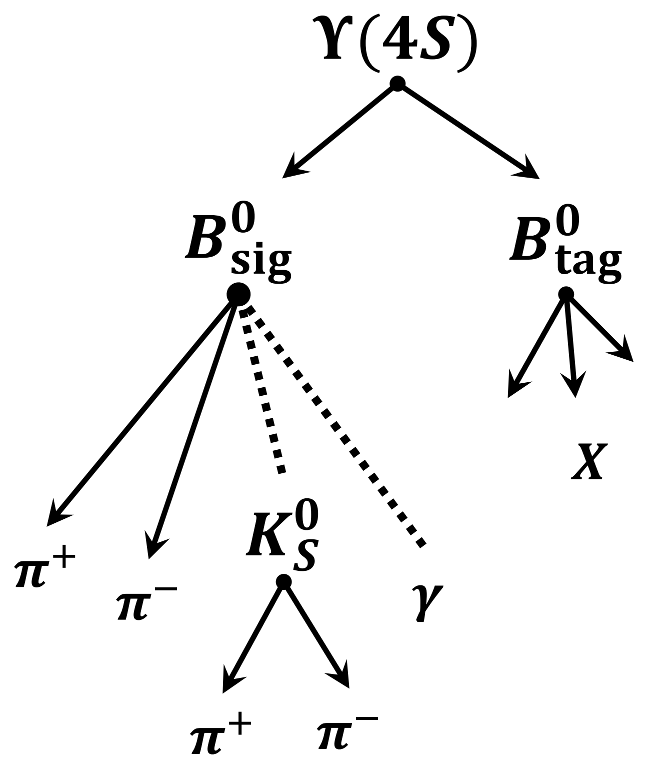
$$\mathcal{B}r\left(B^0(\bar{B}^0) \rightarrow K_S^0\, \pi^+\pi^-\gamma\right) \sim 10^{-5}$$

Simulation of signal events

I. **Generation** of $\Upsilon(4S)$ events each containing the illustrated B^0_{sig} decay ($B^0(\bar{B}^0) \rightarrow K^0_S\pi^+\pi^-\gamma$) and a generic B^0_{tag} decay

II. **Simulation** for VXD, 5 layer VTX & 7 layer VTX detector geometries with beam background hits overlaid (phase 3)

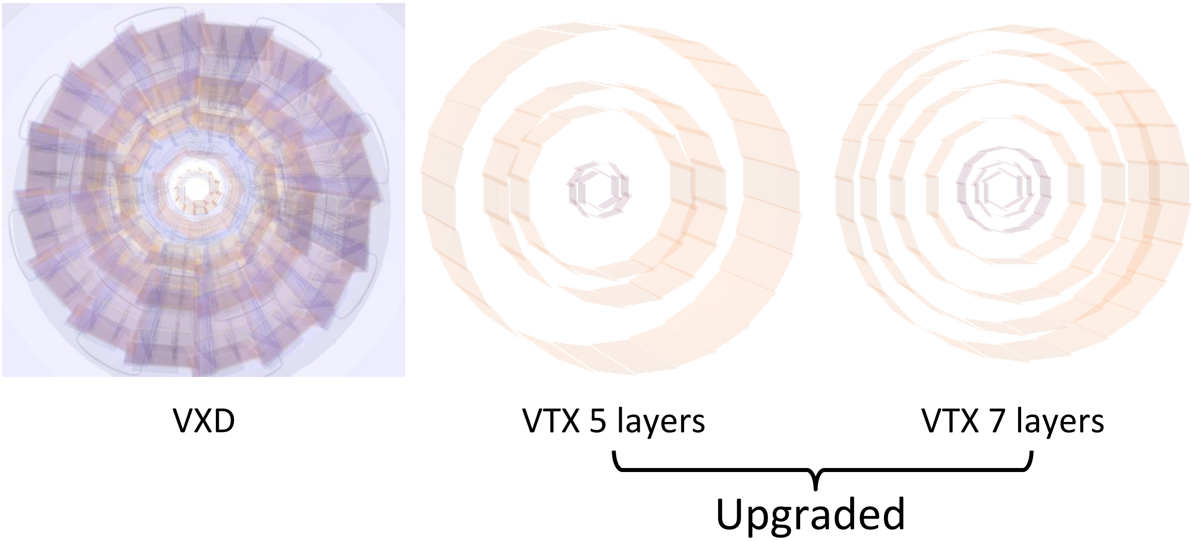
III. **Reconstruction** of *signal*- and *tag*-side B^0's from final state particles and V0's (i. e. K^0_S)

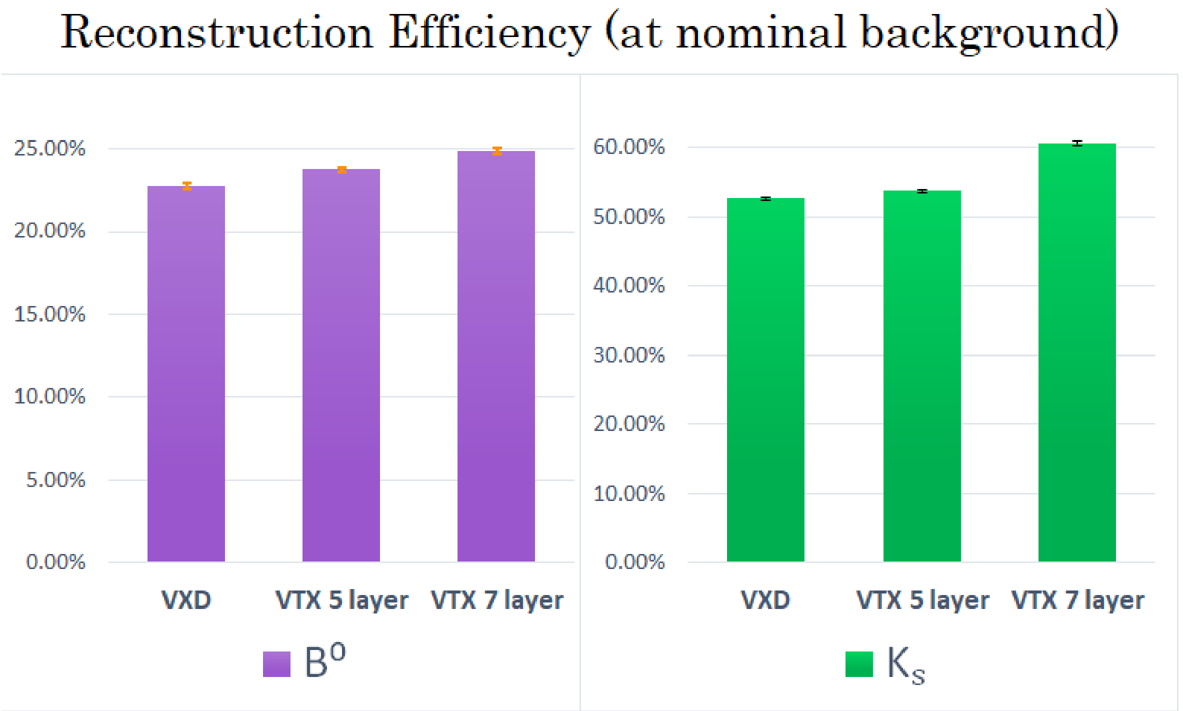


- Analysis goal: compare performances of detector geometries in Monte Carlo simulations of $\boldsymbol{B^0 \rightarrow K^0_S\,\pi^+\pi^-\gamma}$ decays
- Focus on **reconstruction efficiency** and **vertex resolution** of B^0's and K^0_S's

Reconstruction Efficiency

3 available vertex detector geometries





- B^0 efficiency mainly driven by K_S^0 efficiency
- VTX geometries **outperform** VXD at expected level of beam background

Vertex Resolution

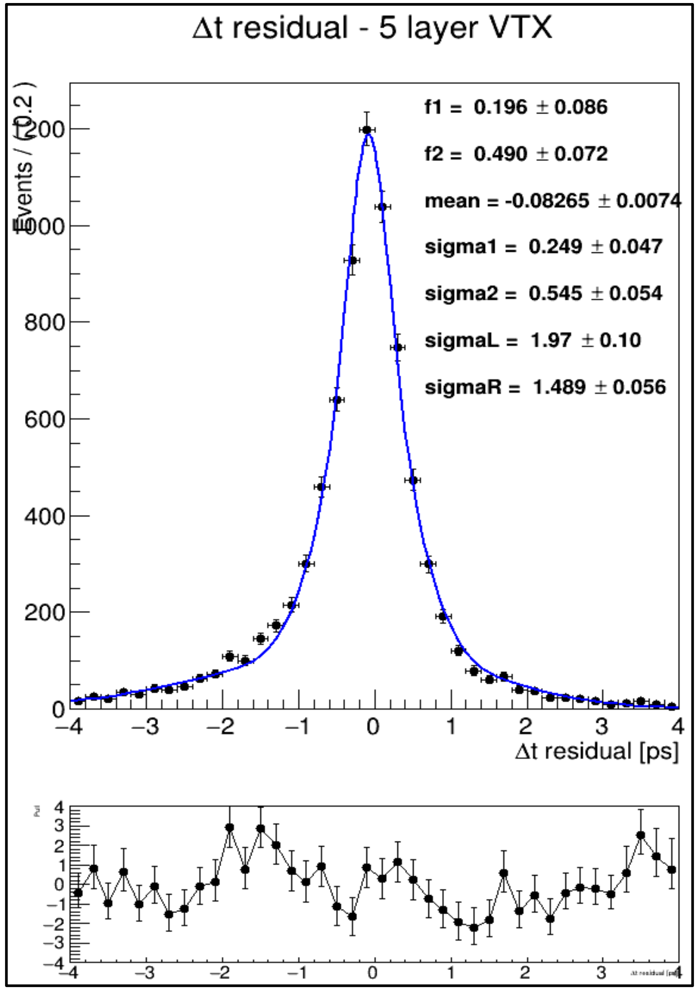
e.g. Fit for 5 layer geometry

- Fit Δt residual with the *sum* of 3 Gaussian distributions:
  2 symmetric ones and 1 bifurcated

- The Δt resolution is then quoted as the *weighted sum* of the sigmas obtained from the fit:

$$\sigma_{\Delta t} = \sum_i w_i \sigma_i \ , i = 1, 2, 3$$

w_i: integral fraction of i-th Gaussian



- For all geometries:

Detector Geometry	Δt Resolution (ps)
VXD	1.09 ± 0.06
VTX 5 layers	0.86 ± 0.03
VTX 7 layers	0.90 ± 0.04

$^*\Delta t\ residual = \Delta t_{reconstructed} - \Delta t_{true}$

Conclusions & outlook

- ✓ The A_{CP} measurement in the $B^0 \to K_S^0\,\pi^+\pi^-\gamma$ channel can **benefit** greatly from improvements to the Belle II vertex detector
- ✓ The proposed VTX **improves** on projected performances of the VXD at phase 3 luminosity, in terms of Δt resolution and reconstruction efficiency of signal B^0's and K_S^0's
- ✓ One of **several** benchmark studies (to be) completed in preparation for the Conceptual Design Report of the VTX to be written by the end of 2022

➢ Outlook:

- Calibration of the Flavor tagger and Resolution function parameters to be used in the future analysis
- Start working on the analysis itself

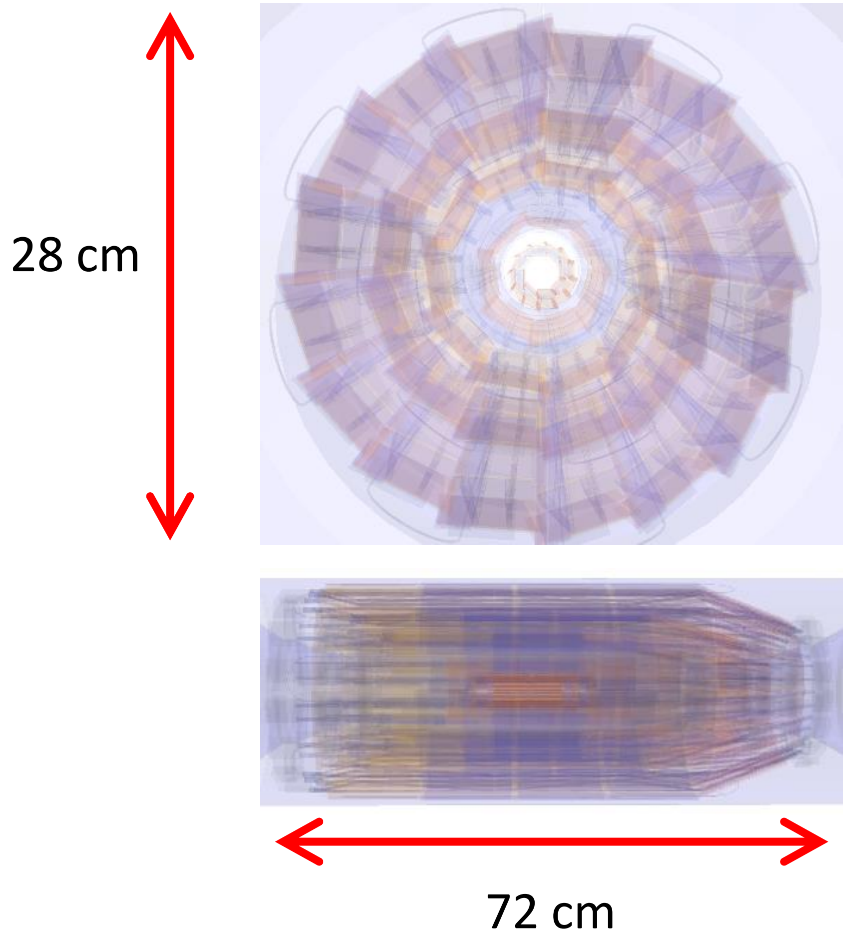
Thank You!

Questions?

Backup

Current vertex detector geometry

VXD = PXD + SVD

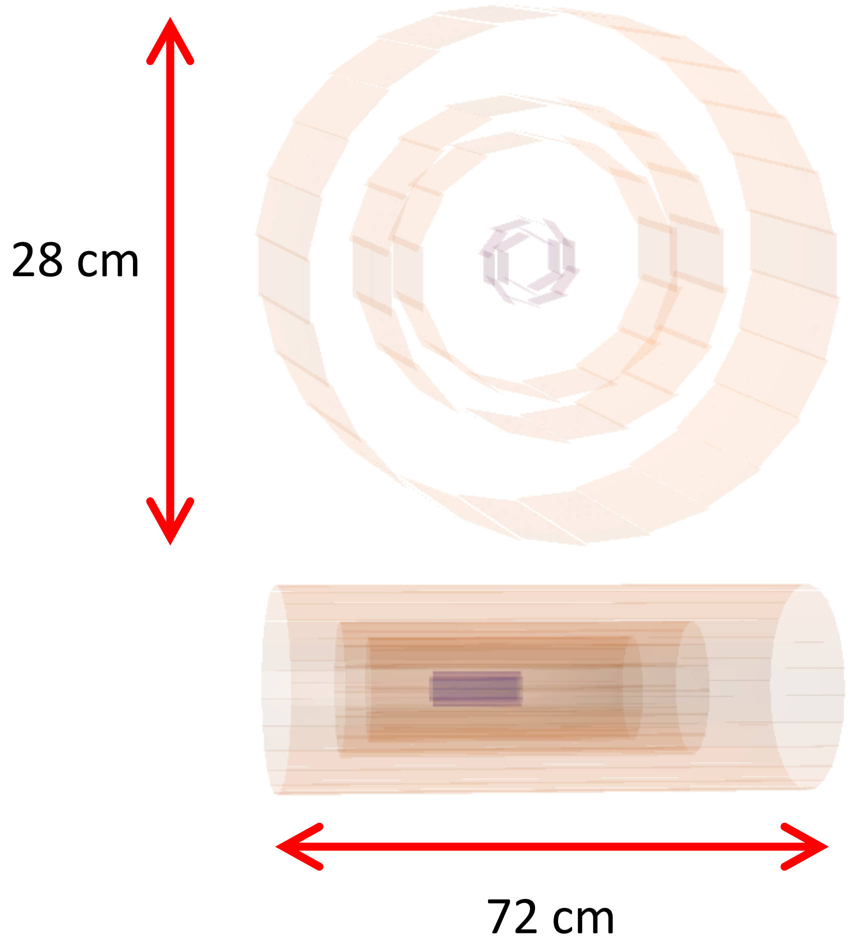


Total material budget: 3.2 % X_0

Layer no.	1	2	3	4	5	6
Radius (mm)	14.2	21.8	39.0	80.0	104.0	135.2
# Ladders	8	12	7	10	12	16
# Sensors per ladder	2	2	2	3	4	5

Vertex detector upgrade geometry

VTX 5 layers

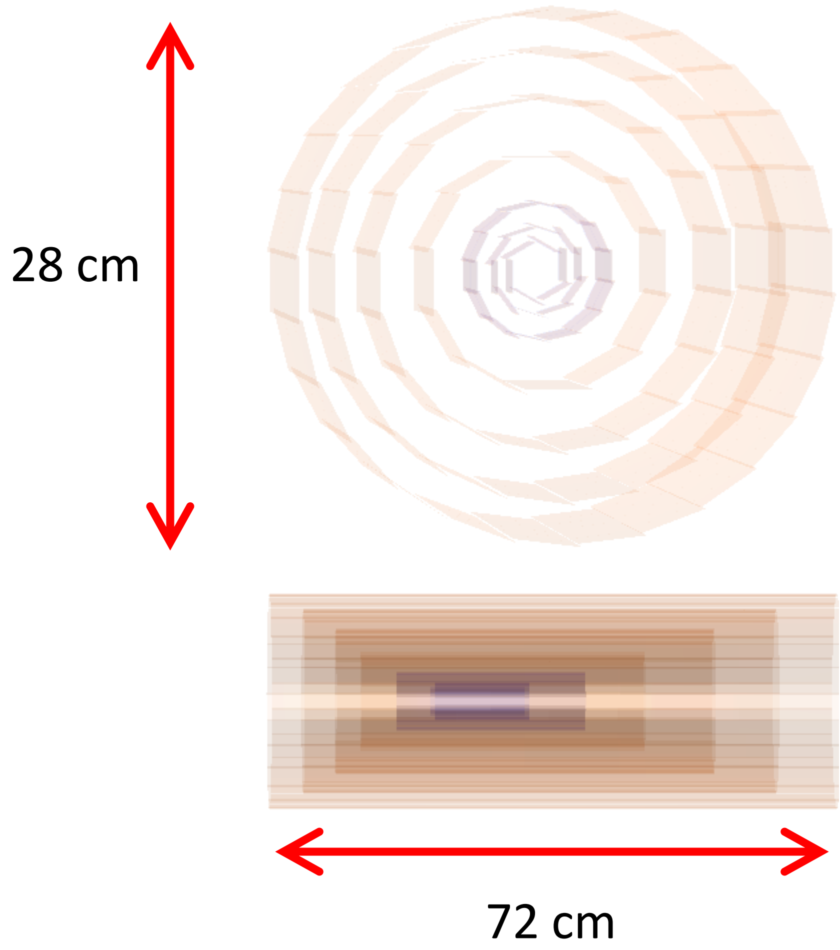


Total material budget: 1.1 % X_0
(over-optimistic)

Layer no.	1	2	3	4	5
Radius (mm)	14.1	22.1	69.1	89.5	140.0
# Ladders	6	10	14	18	26
# Sensors per ladder	4	4	12	16	24

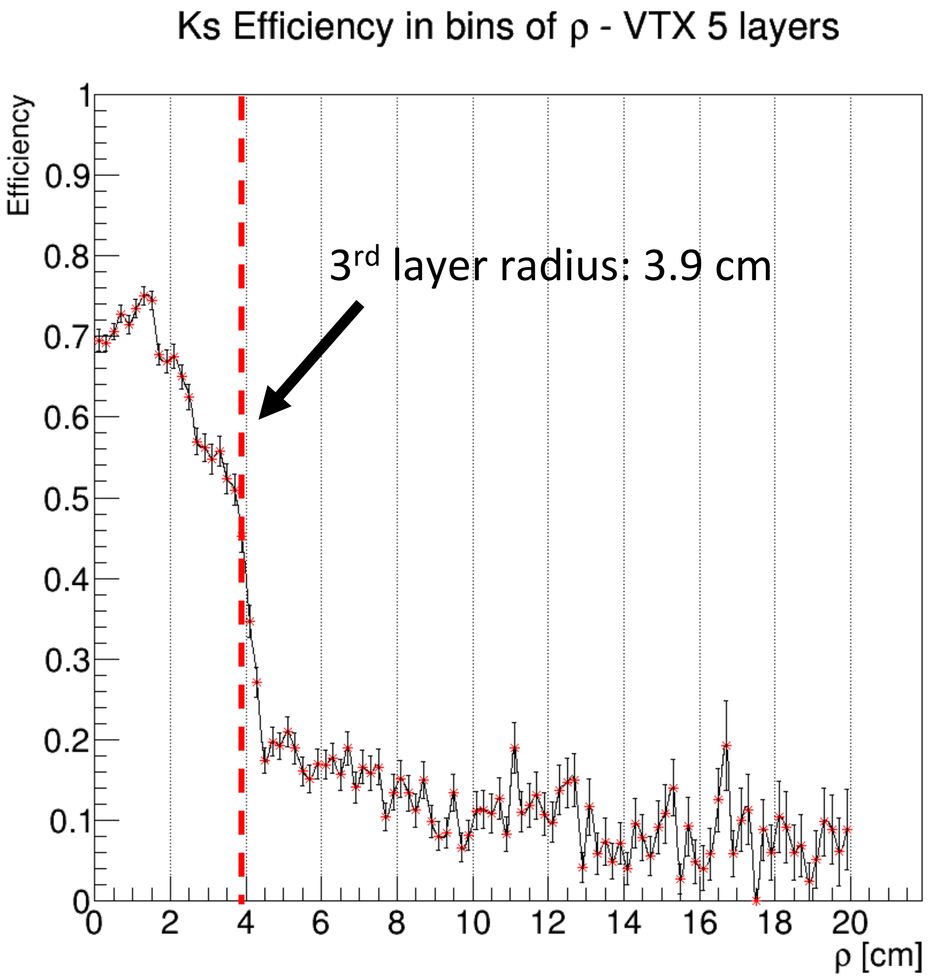
Vertex detector upgrade geometry

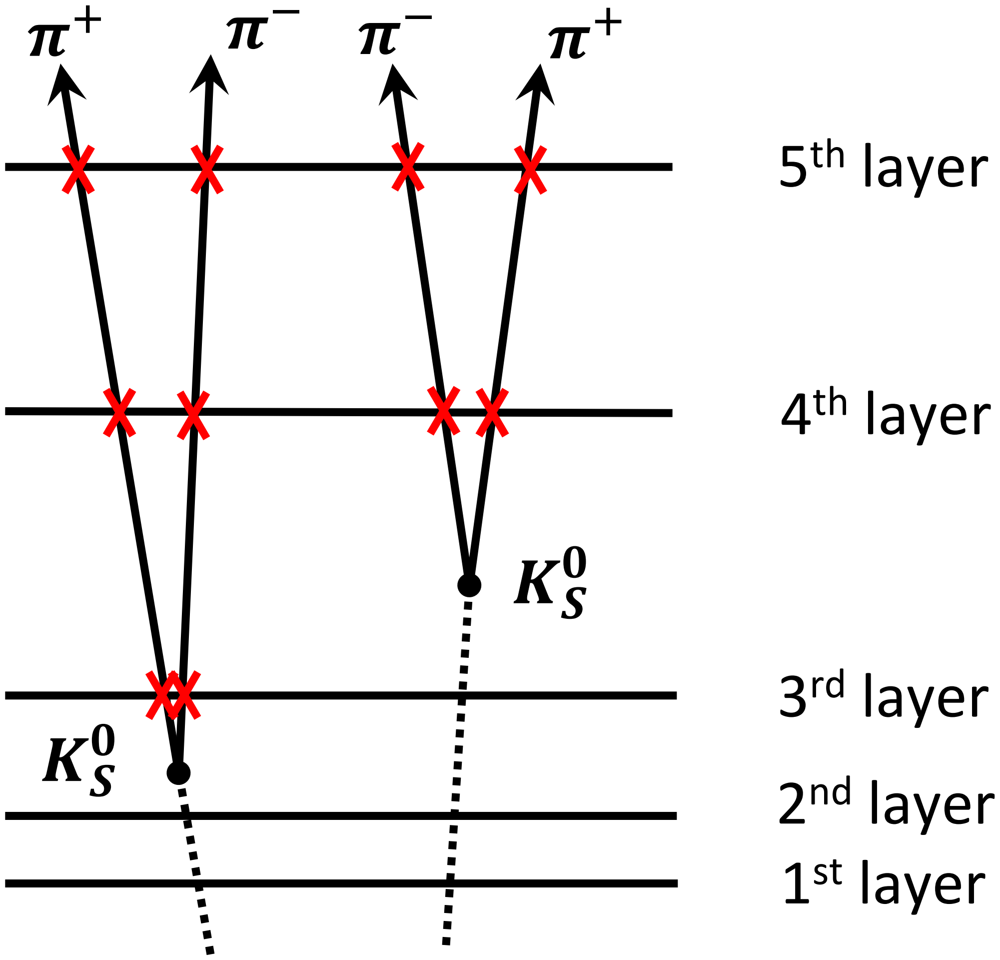
VTX 7 layers



Layer no.	1	2	3	4	5	6	7
Radius (mm)	14.1	22.1	35.1	60.1	90.1	115.0	135.0
# Ladders	6	10	14	12	18	22	26
# Sensors per ladder	4	4	8	12	16	20	24

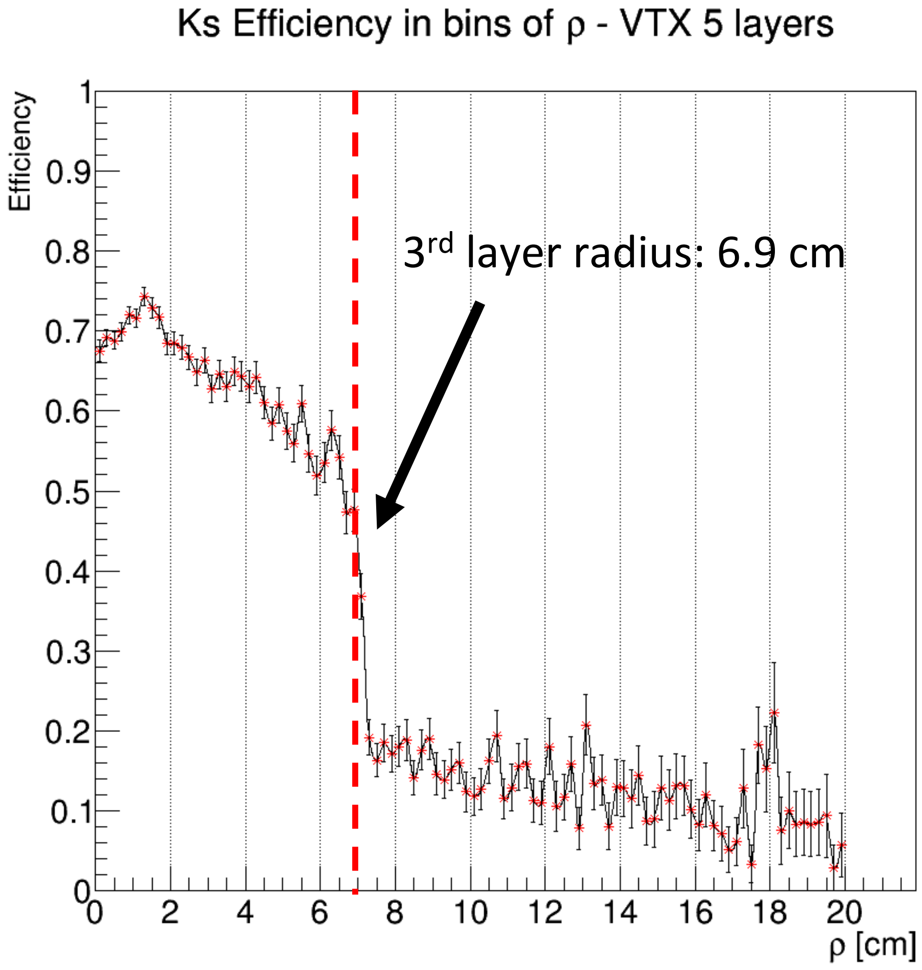
Reconstruction Efficiency

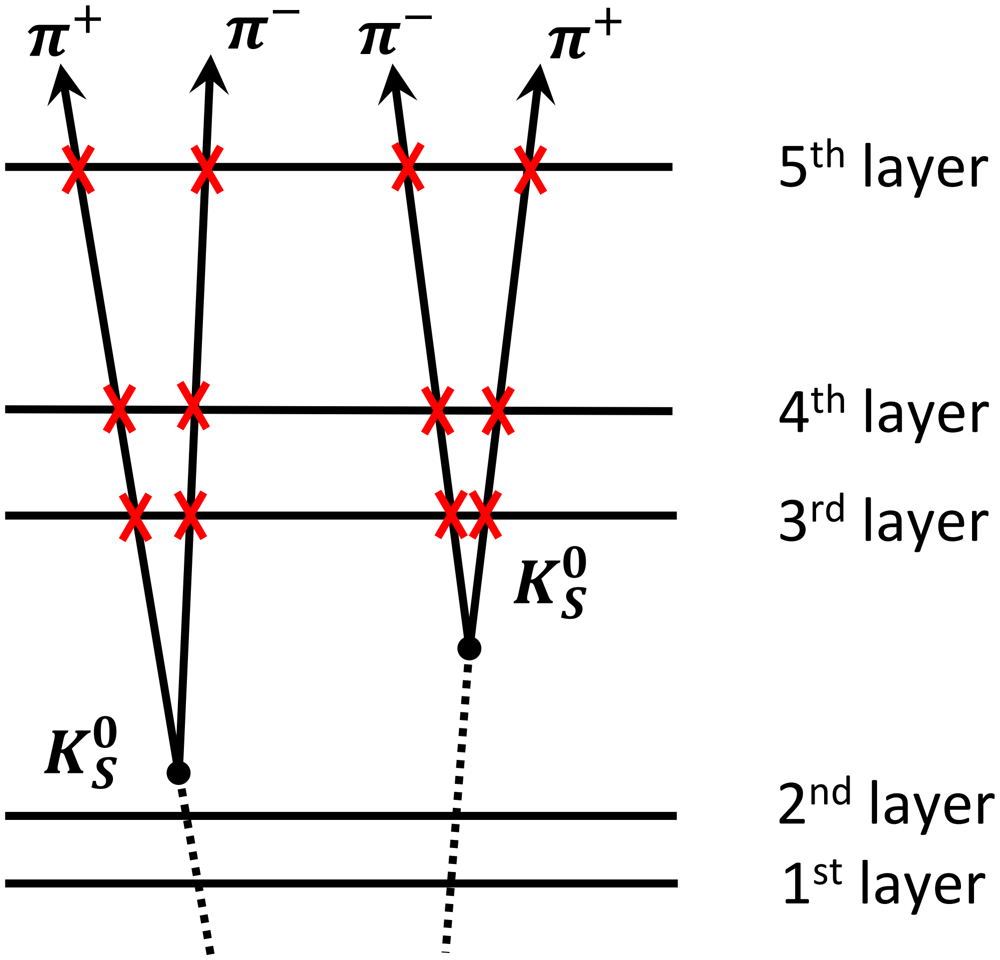




*ρ: transverse flight distance

Reconstruction Efficiency

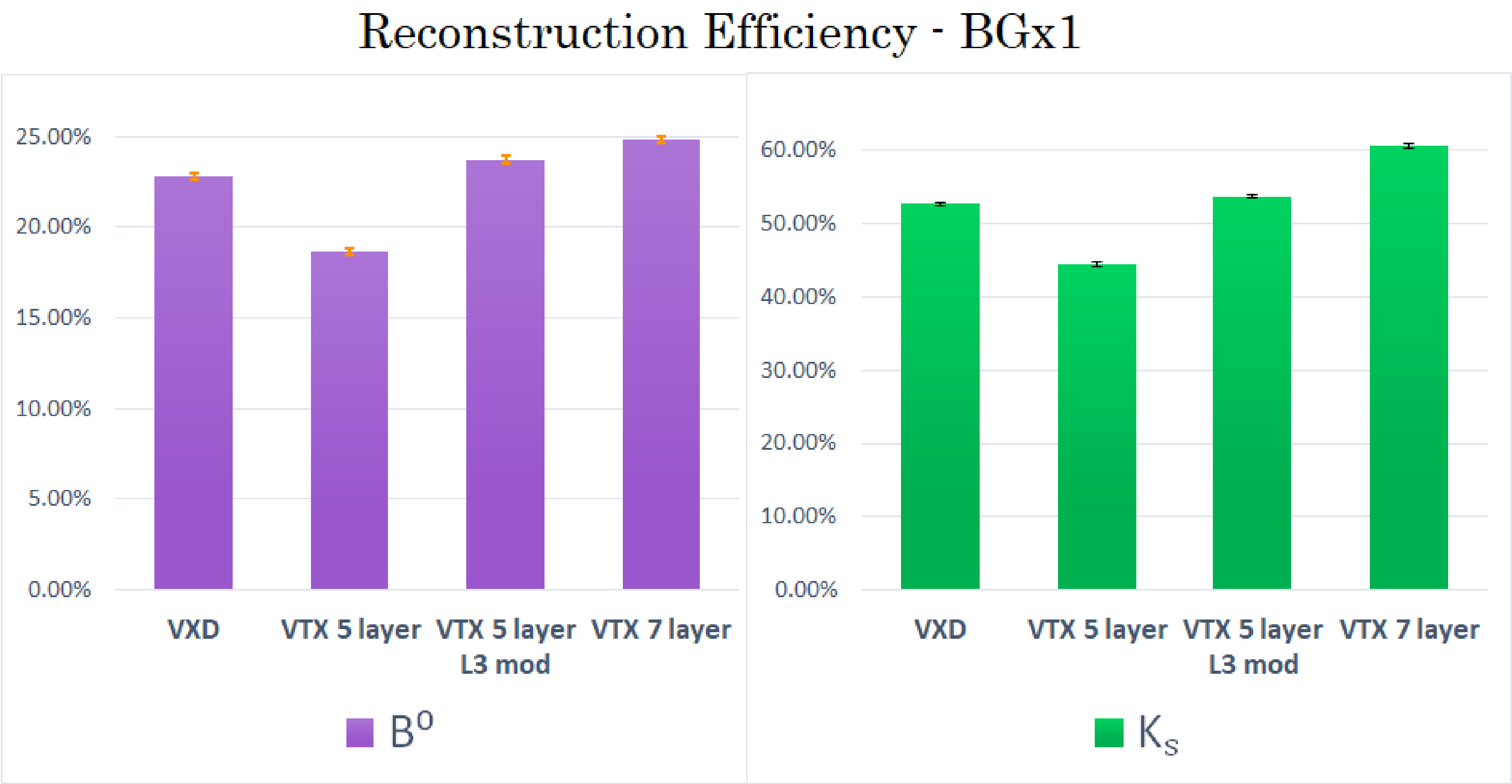




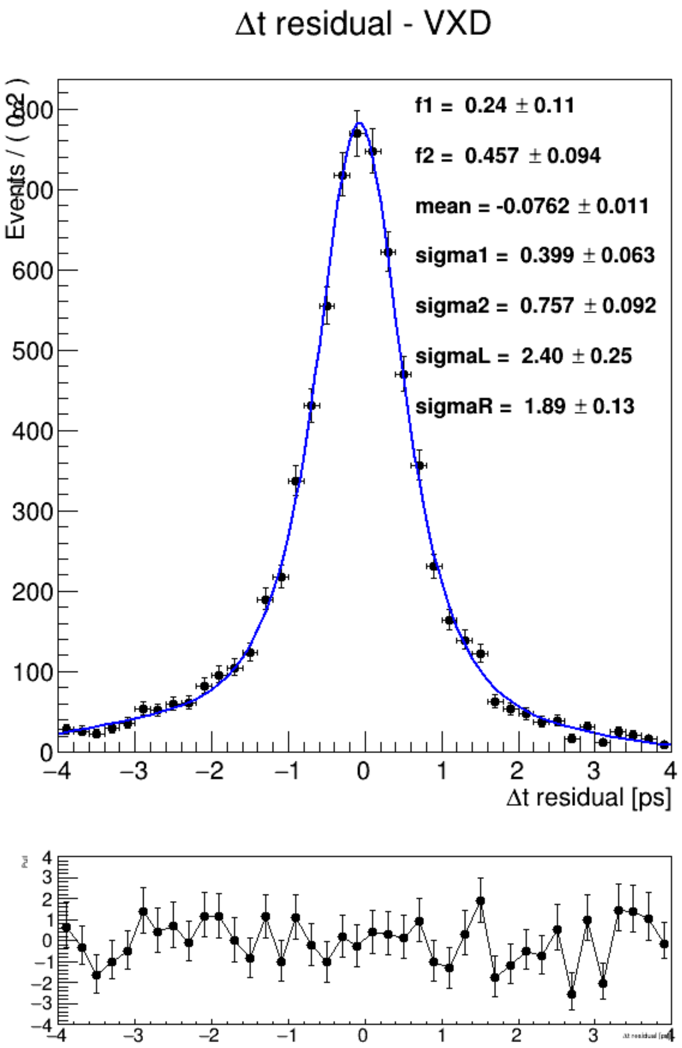
*ρ: transverse flight distance

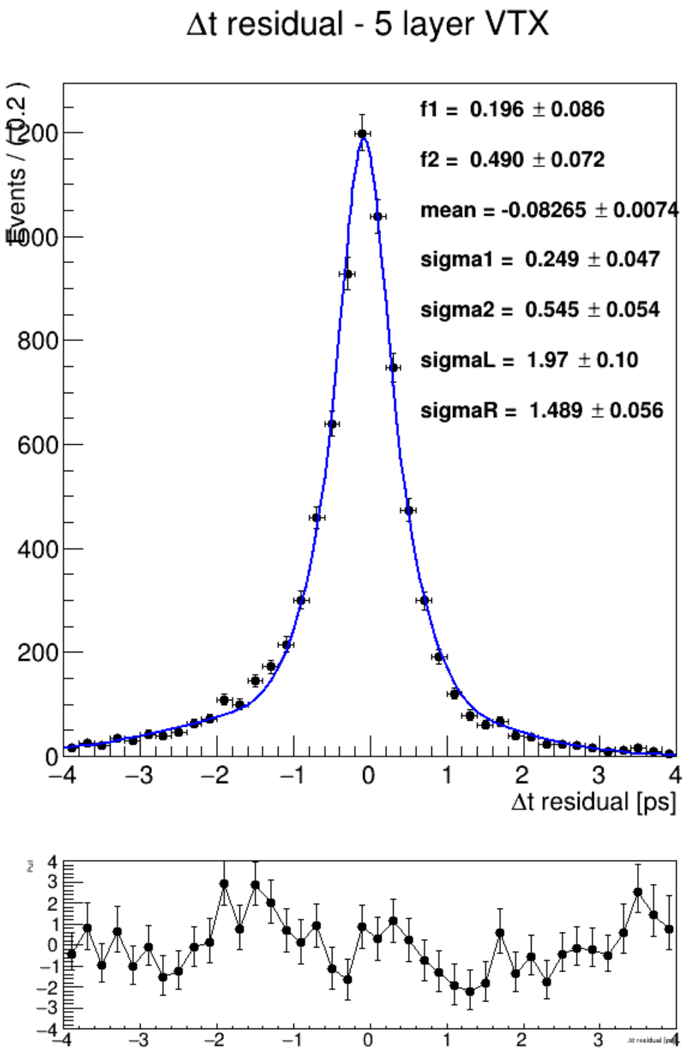
Reconstruction Efficiency

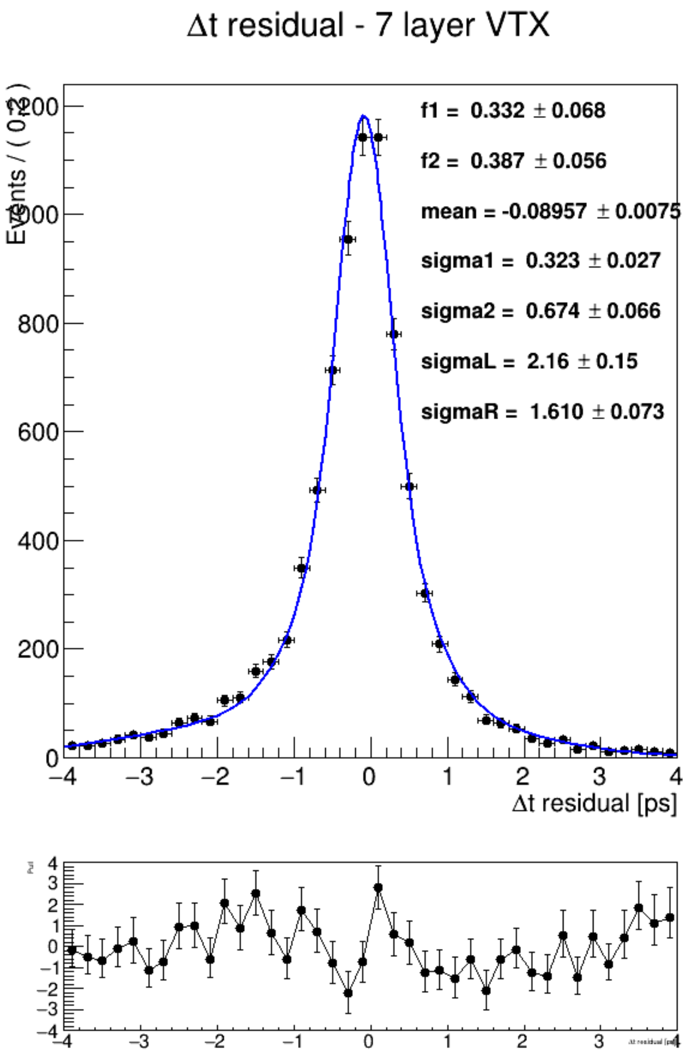
- Moving the 3rd layer:



Vertex Resolution







Vertex Resolution

$$\sigma_{\Delta t} = \sum_i w_i \sigma_i = w_1\sigma_1 + w_2\sigma_2 + w_3\sigma_3 = \frac{1}{I_{\text{tot}}}(I_1\sigma_1 + I_2\sigma_2 + I_3\sigma_3)$$

with: $I_i = N_i\sigma_i \cdot \sqrt{2\pi}$ and $I_{tot} = \sum_i I_i = \sqrt{2\pi} \cdot (\sum_i N_i\sigma_i)$

where N_i is the normalization and σ_i the std deviation of the i-th Gaussian

$$\sigma_{(\sigma_{\Delta t})} = \sqrt{\sum_i \left(w_i \sigma_{\sigma_i}\right)^2} = \frac{1}{I_{\text{tot}}}\sqrt{I_1^2\sigma_{\sigma_1}^2 + I_2^2\sigma_{\sigma_2}^2 + I_3^2\sigma_{\sigma_3}^2}$$