OPTIMISATION OF AN UPGRADE TO THE BELLE II EXPERIMENT'S INNER TRACKER WITH A MEASUREMENT BASED ON $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$ DECAYS

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Université de Strasbourg

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QMat
QUANTUM SCIENCE AND NANOMATERIALS

Outline

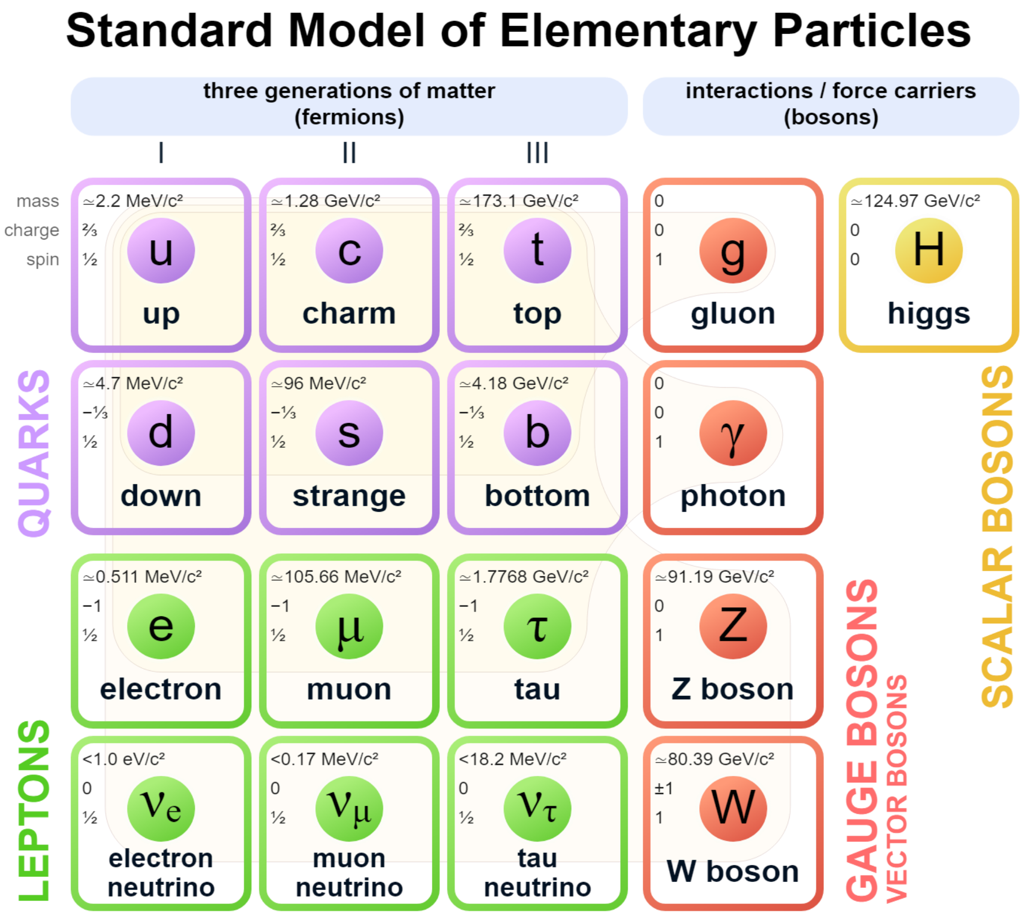
- ❖ Introduction
- ❖ Upgrade of the Belle II vertex detector
- ❖ The benchmark channel
- ❖ Performance study
- ❖ Discussion of results
- ❖ Conclusion & outlook

The Standard Model

- Theoretical framework that describes interactions between elementary particles

- Extremely successful but there are holes: nature of dark matter, origin of neutrino masses, matter – antimatter asymmetry, etc.

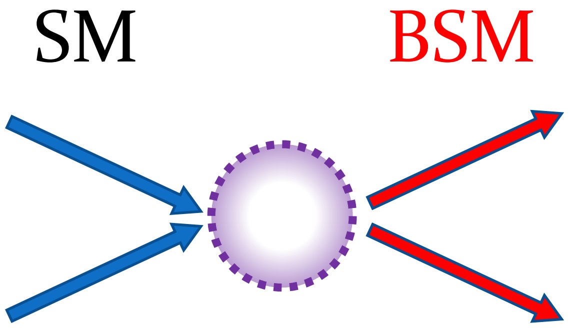
- Not the end of the story → deep motivation to search for physics beyond the Standard Model (SM)



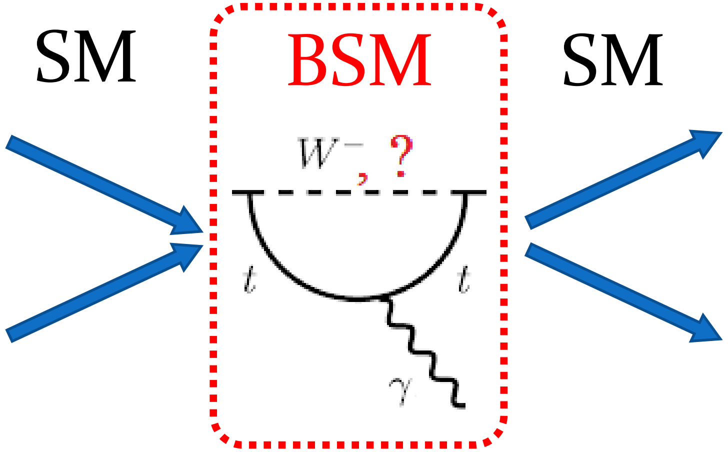
Searching for physics beyond the SM

How to look for beyond SM (BSM) physics?

- **Direct searches**:
  Look for new particles **manifested** in high energy particle collisions
  ⇒ Energy Frontier



- **Indirect searches**:
  Measure **deviations** from SM predictions that indicate the existence of new physics
  ⇒ Intensity Frontier



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YOU ARE HERE

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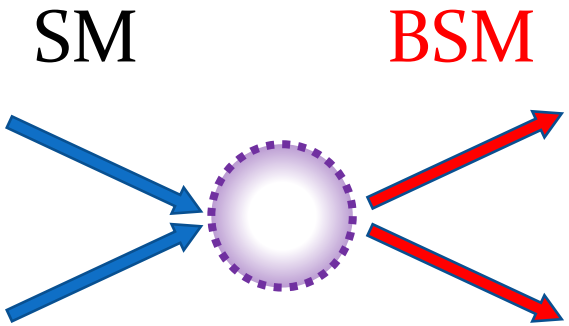
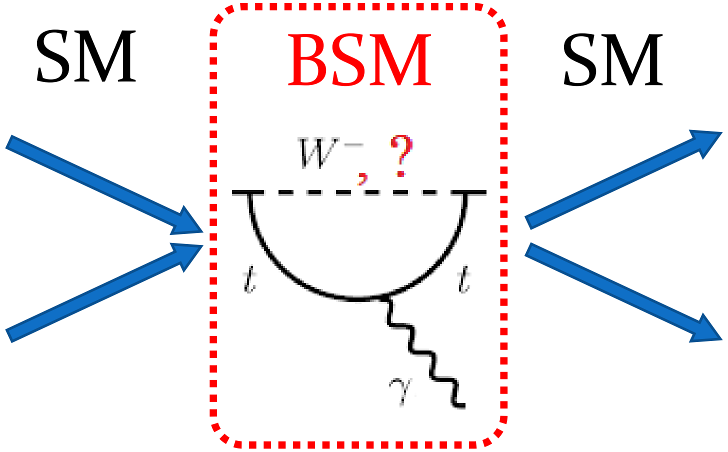
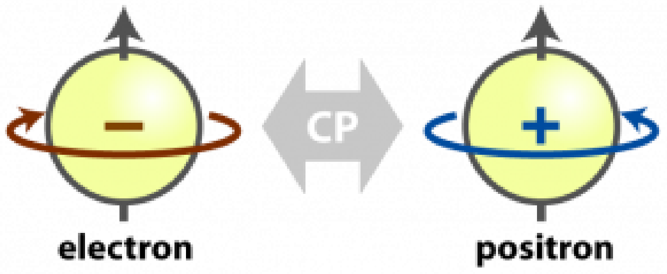




CP symmetry

- Charge-Parity (CP) transformation relates matter with antimatter particles



- **CP violation** already observed in SM decays involving mesons

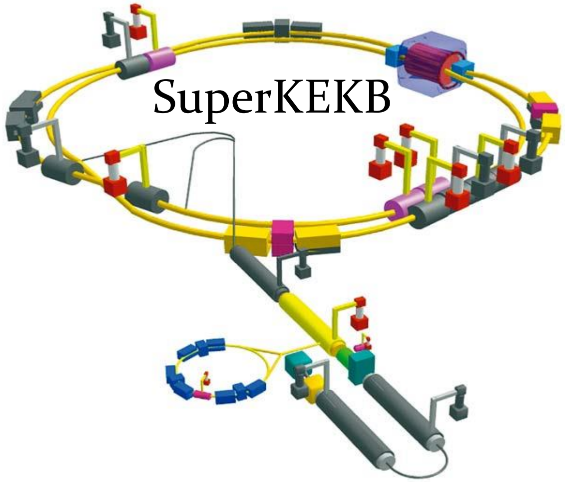
- Observables like the **CP asymmetry** are useful probes of BSM processes

Example of CP violation in neutral kaon mixing:

$$P(K^0 \rightarrow \bar{K}^0) \neq P(\bar{K}^0 \rightarrow K^0)$$

The Belle II experiment

- SuperKEKB collides e^+e^- at **world record** instantaneous luminosity (current WR: $4.5 \cdot 10^{\mathbf{34}} cm^{-2} s^{-1}$)
- High collision rate → increased statistics
- Collisions between e^+e^- with **different energies** → facilitate measurement on CP violation parameters and lifetimes



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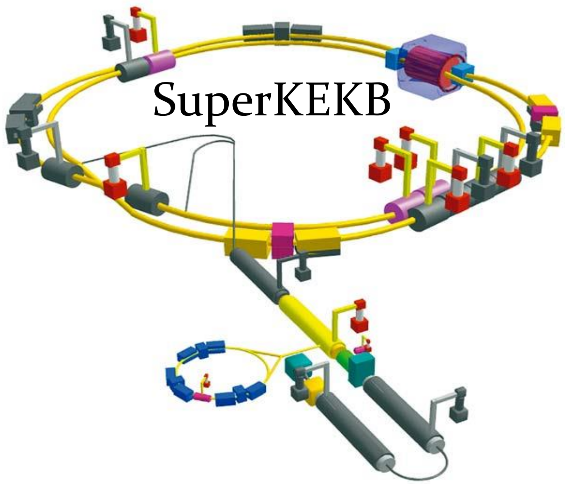
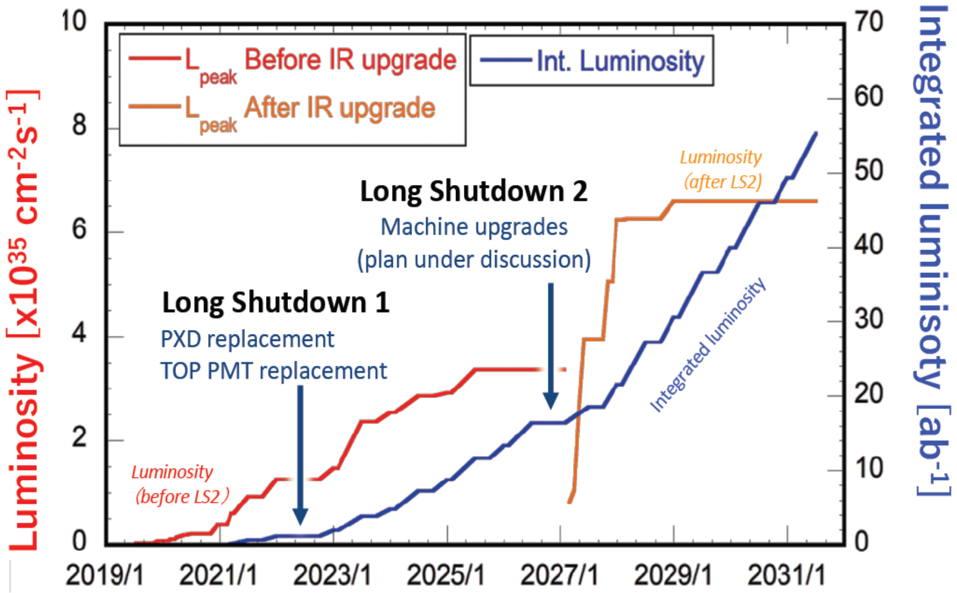
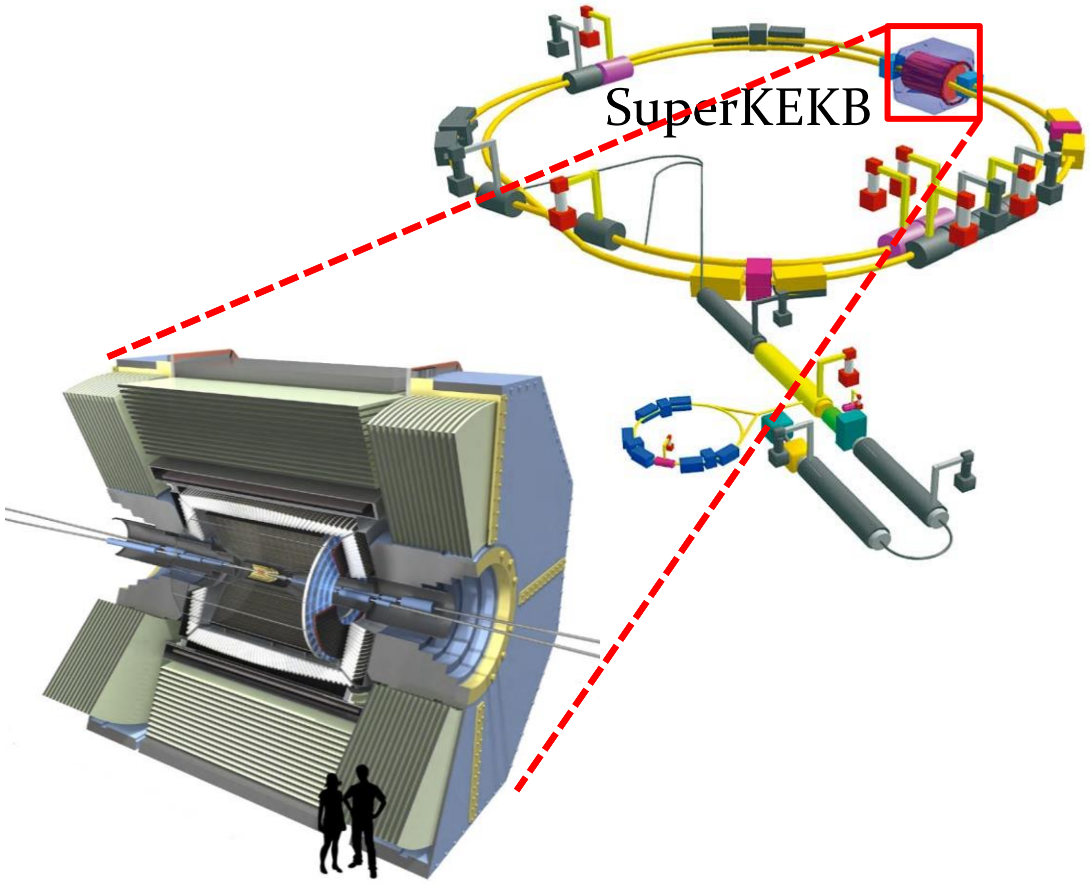
- Plan to **upgrade** the collider using a nano-beam scheme (target: $6 \cdot 10^{35} cm^{-2} s^{-1}$)





The Belle II experiment

- Belle II detector records result of e^+e^- collisions
- BUT: Increased collision rate degrades innermost subdetector; the vertex detector or VXD
- High collision rate → more parasite particles from nano-beams, or **beam background**



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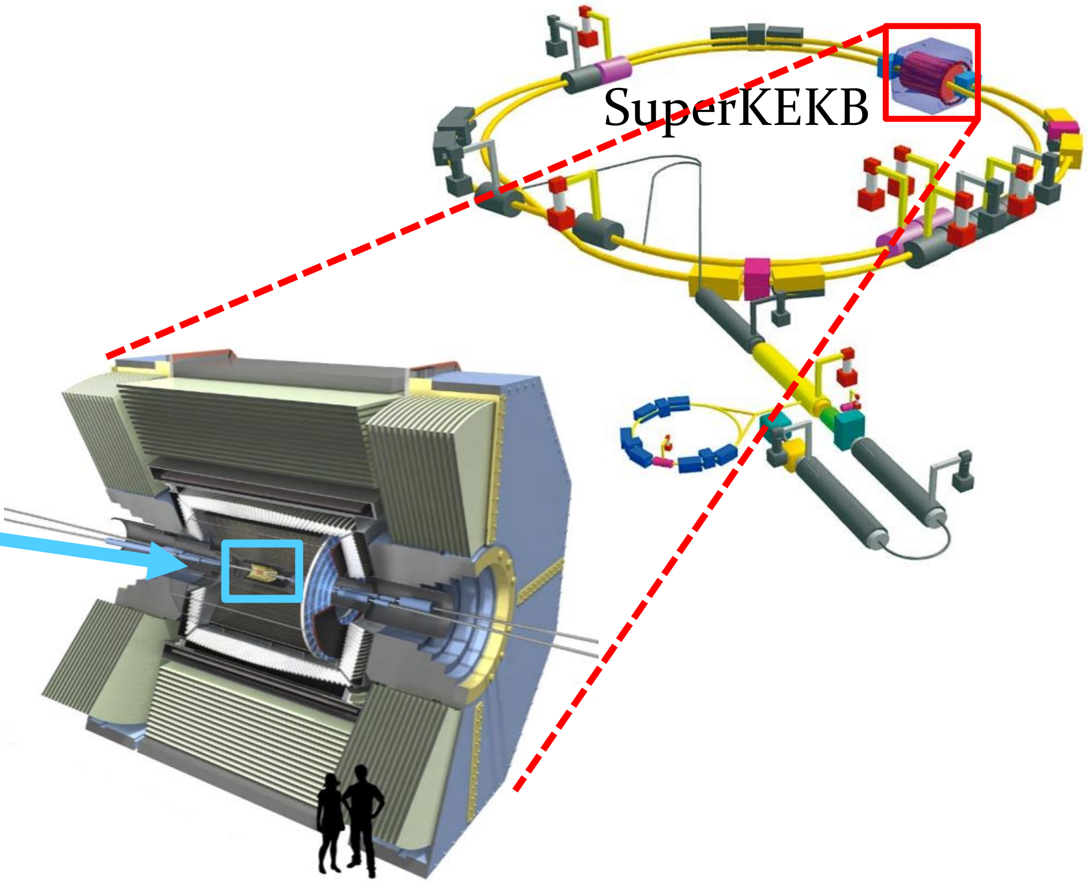
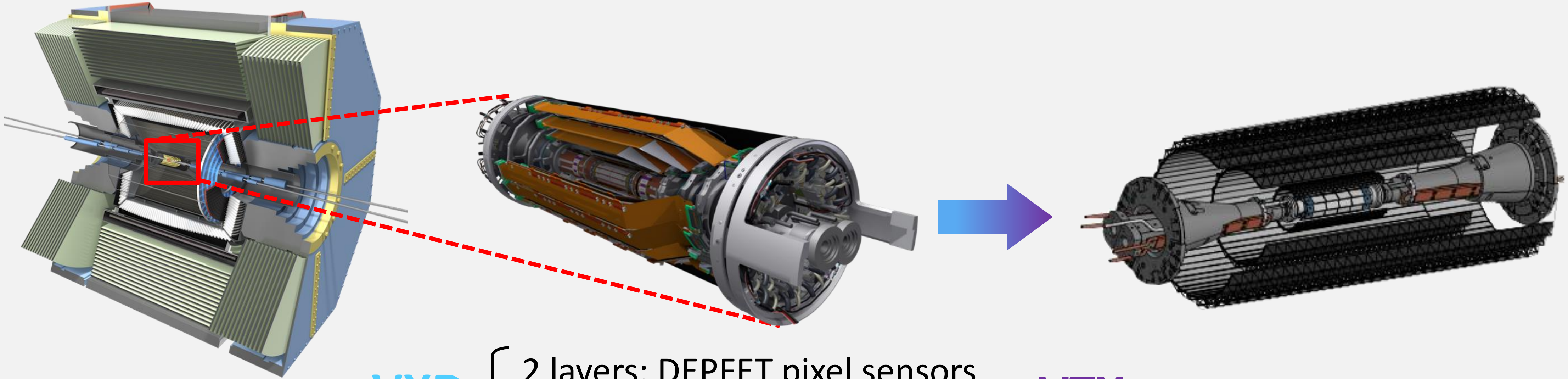


Vertex detector upgrade

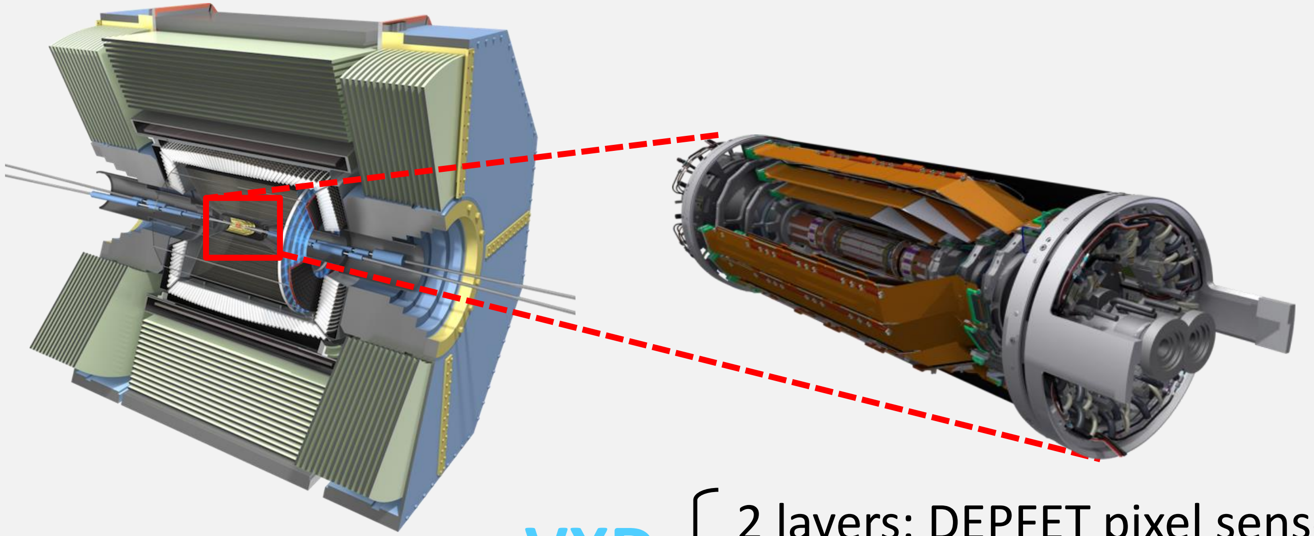


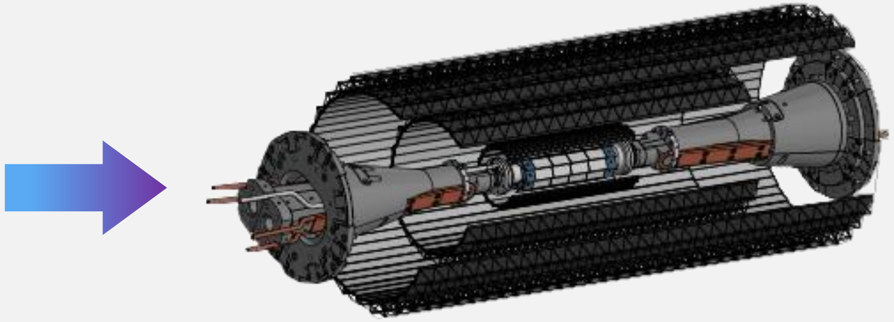
VXD
- 2 layers: DEPFET pixel sensors
- 4 layers: 2-sided strip detectors

VTX: 5 (7) layers of CMOS pixel sensors

- Cope with increased hit rate by reducing pixel size and integration time

Vertex detector upgrade





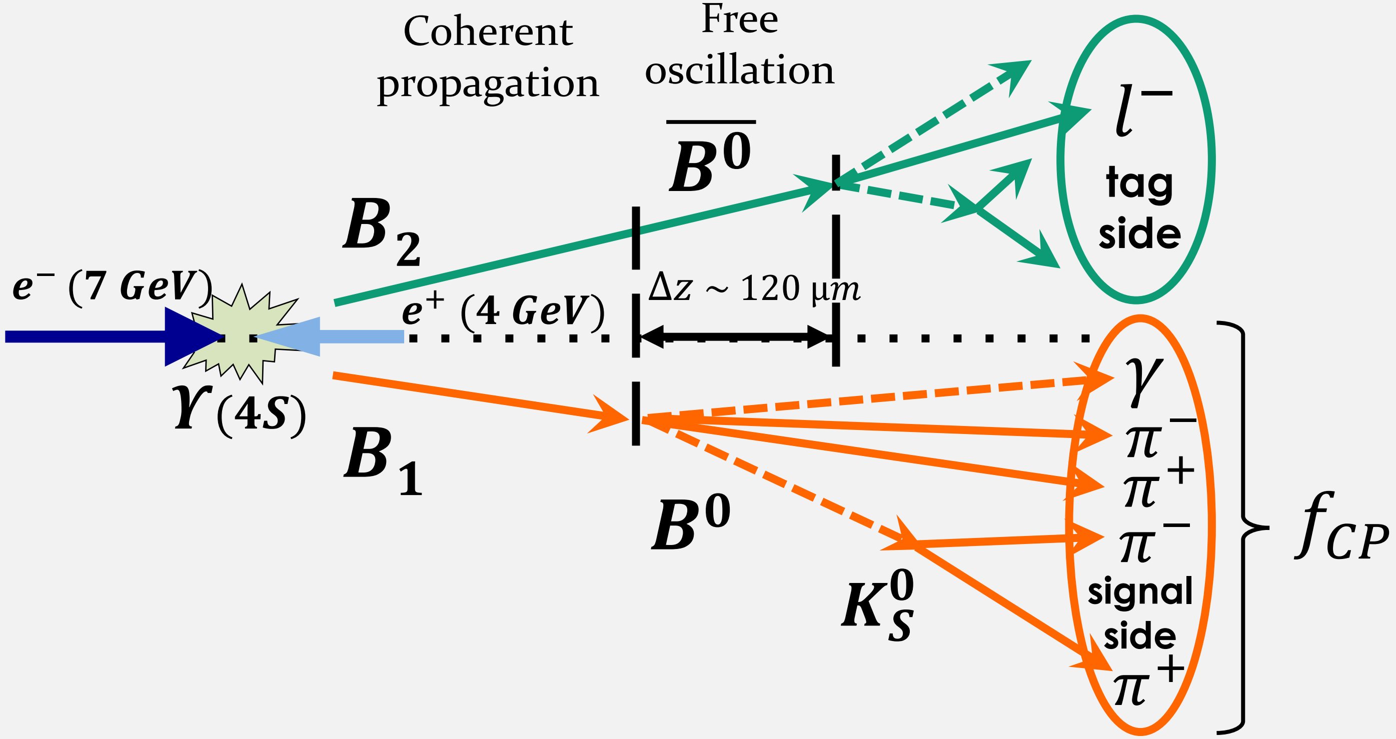
VXD
- 2 layers: DEPFET pixel sensors
- 4 layers: 2-sided strip detectors

VTX: 5 (7) layers of CMOS pixel sensors

- Cope with increased hit rate by reducing pixel size and integration time
- Is the sensitivity of Belle II to new physics improved?
  Are the upgraded geometries optimised for physics?

Benchmark measurement

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



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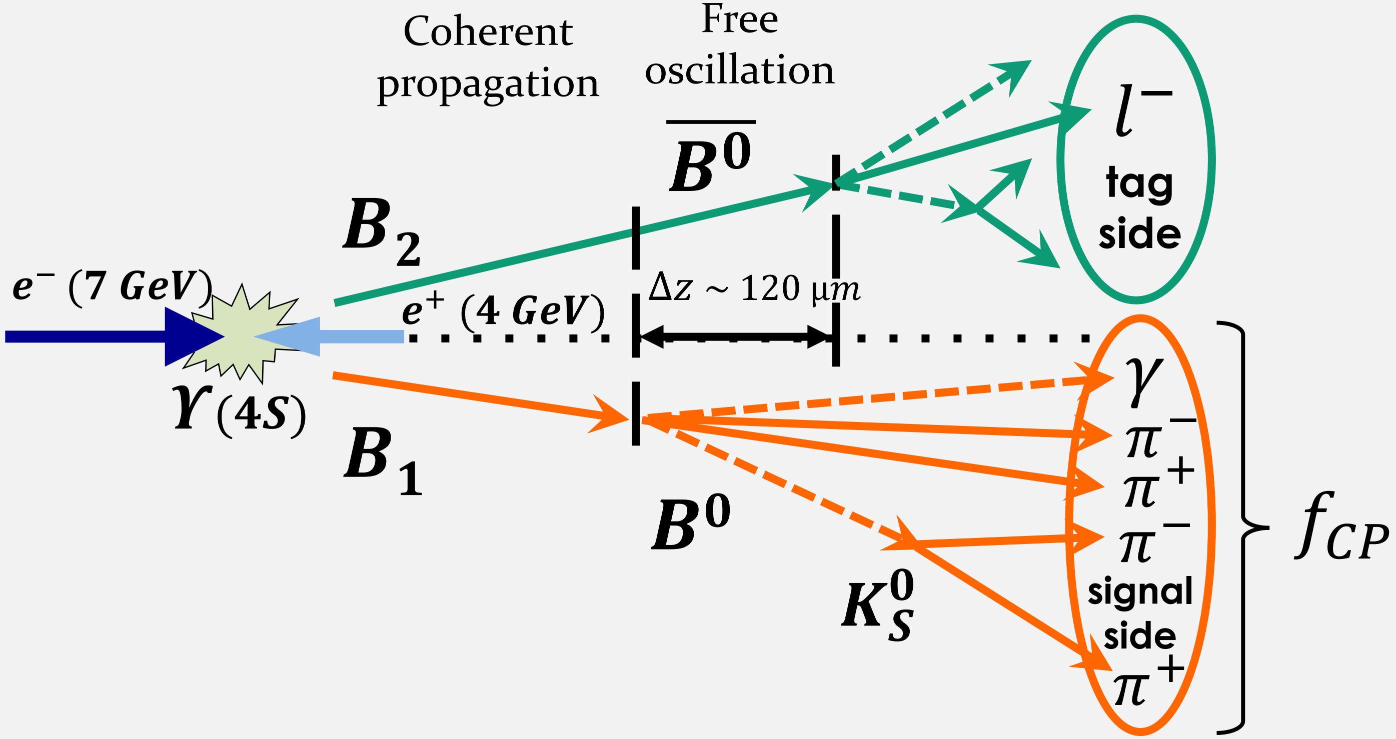
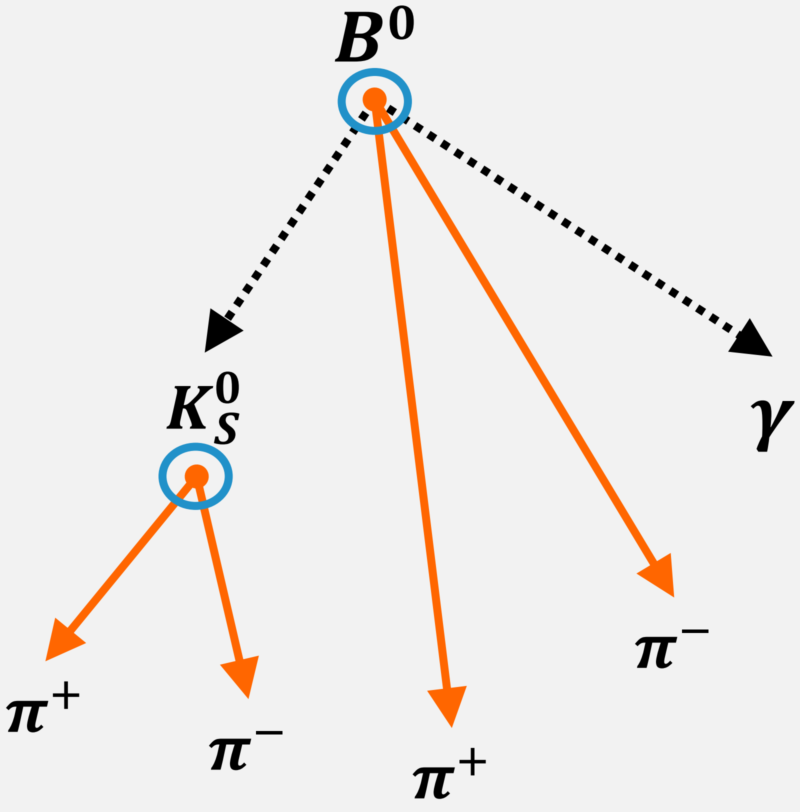
Measurement requires:

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



f_{CP}: practical motivation

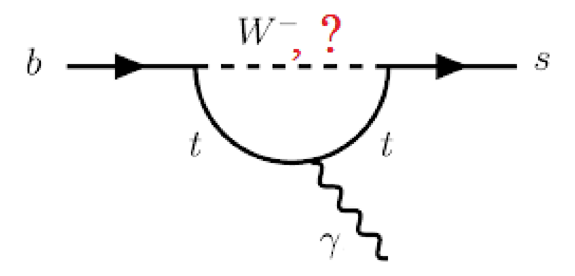
- Chosen decay channel: $\boldsymbol{B^0 \rightarrow K_S^0\, \pi^+ \pi^- \gamma}$
- Ideal benchmark for vertex detector's performance because they contain:
  1. Charged particle tracks
  2. Particle decay vertices



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

f_{CP}: phenomenological motivation

- $B^0 \to K_S^0\, \pi^+\pi^-\, \gamma$ decays involve $b \to s\, \gamma$ transitions, sensitive to new physics ⇒ possibly affects $\boldsymbol{\mathcal{A}}_{CP}(\Delta t)$ measurement



f_{CP}: phenomenological motivation

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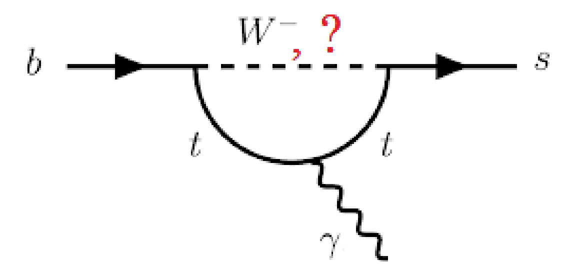
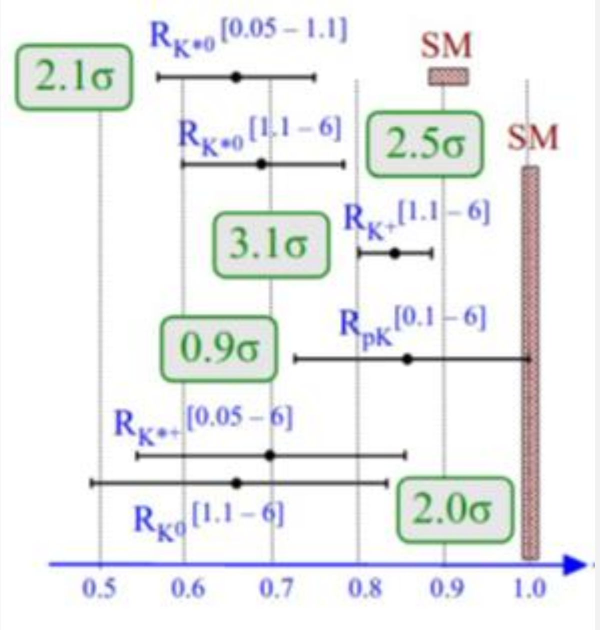
- Anomalies (tensions with SM) already seen in channels with $b \to sll$ and $b \to c$ transitions





[PRL 127 052302]

Work: MC simulation process

For each detector geometry, the process involved:

1. **Generating** 40.000 events each containing a $\boldsymbol{B^0(\bar{B}^0) \rightarrow K_S^0\,\pi^+\pi^-\gamma}$ decay (~10 times the signal events in the current Belle II dataset)

2. **Simulating** signal final state particles in each event alongside the beam background and **reconstructing** those objects (K_S^0, $\pi^{\pm}$, γ and others)

3. **Reconstructing** the two B^0 mesons in each event using the reconstructed objects from the previous step

Work: Performance analysis

- 3 vertex detector geometries implemented in Belle II software: VXD, VTX w/ 5 layers, VTX w/ 7 layers

- GOAL: compare performances of geometries in Monte Carlo simulations of $\boldsymbol{B^0 \rightarrow K_S^0\, \pi^+\pi^-\gamma}$ decays

- Focus on **reconstruction efficiency** and **vertex resolution** of B^0's and K_S^0's

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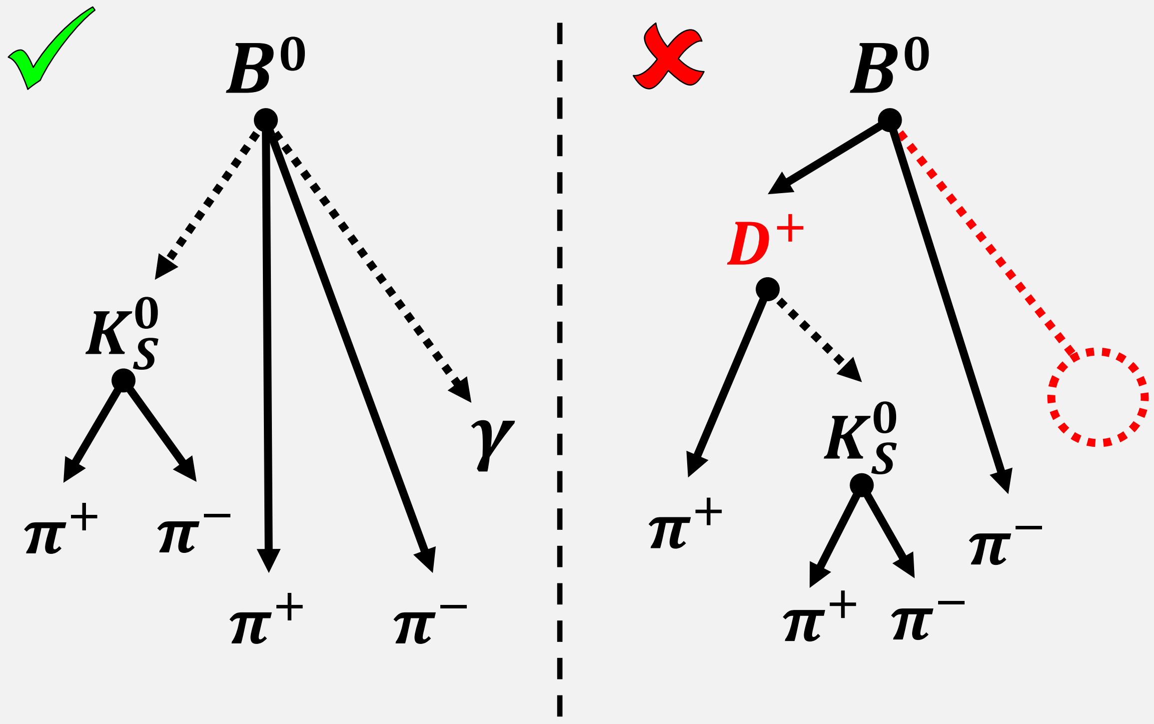
Does the decay chain match?

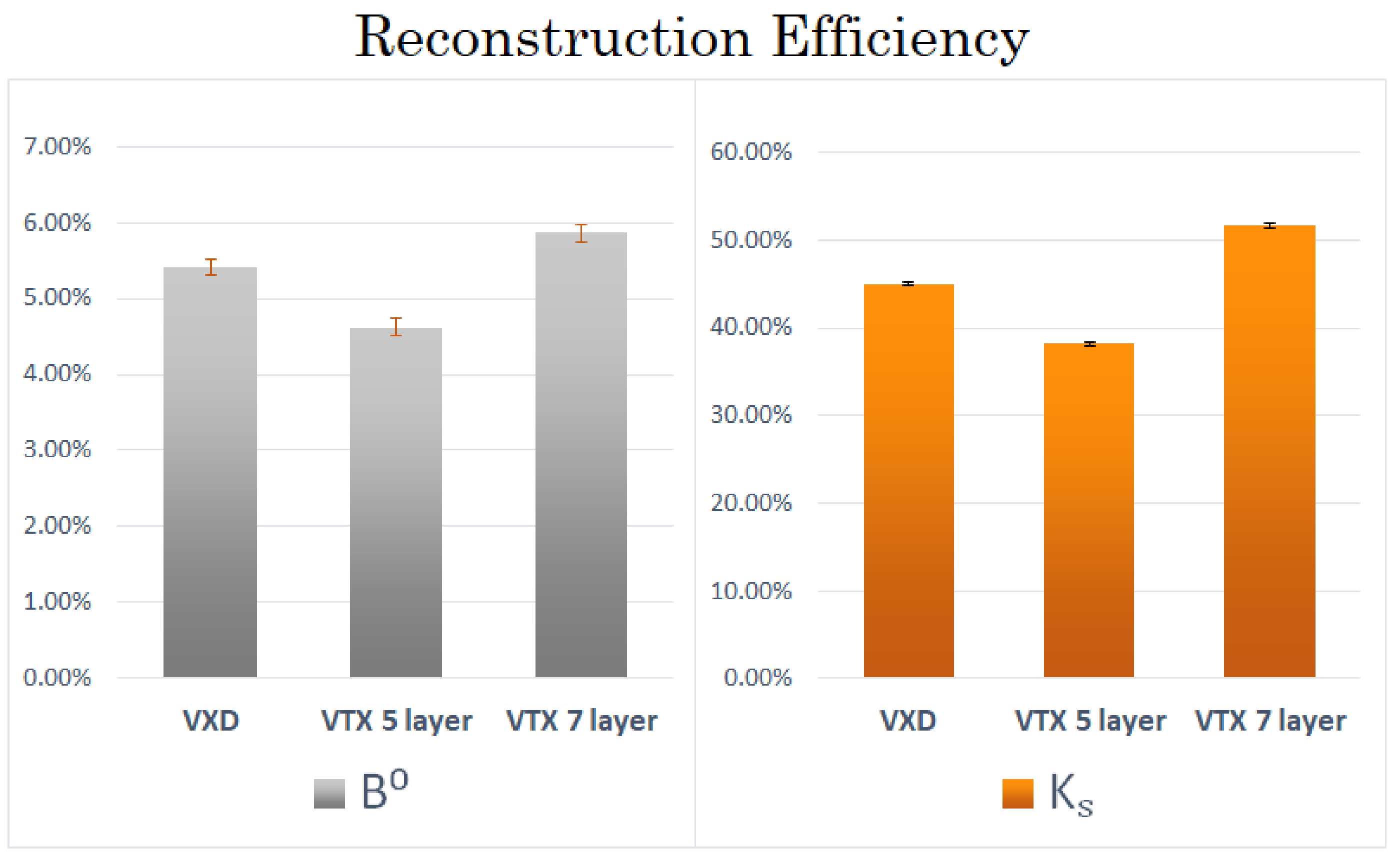


$$\mathcal{B}(✓) \simeq \mathcal{B}(✗)$$

Results: Reconstruction Efficiency

- ➢ K_S^0 and B^0 reconstruction degrades in 5 layer VTX geometry compared to VXD

- ➢ 7 layer VTX performs better than VXD



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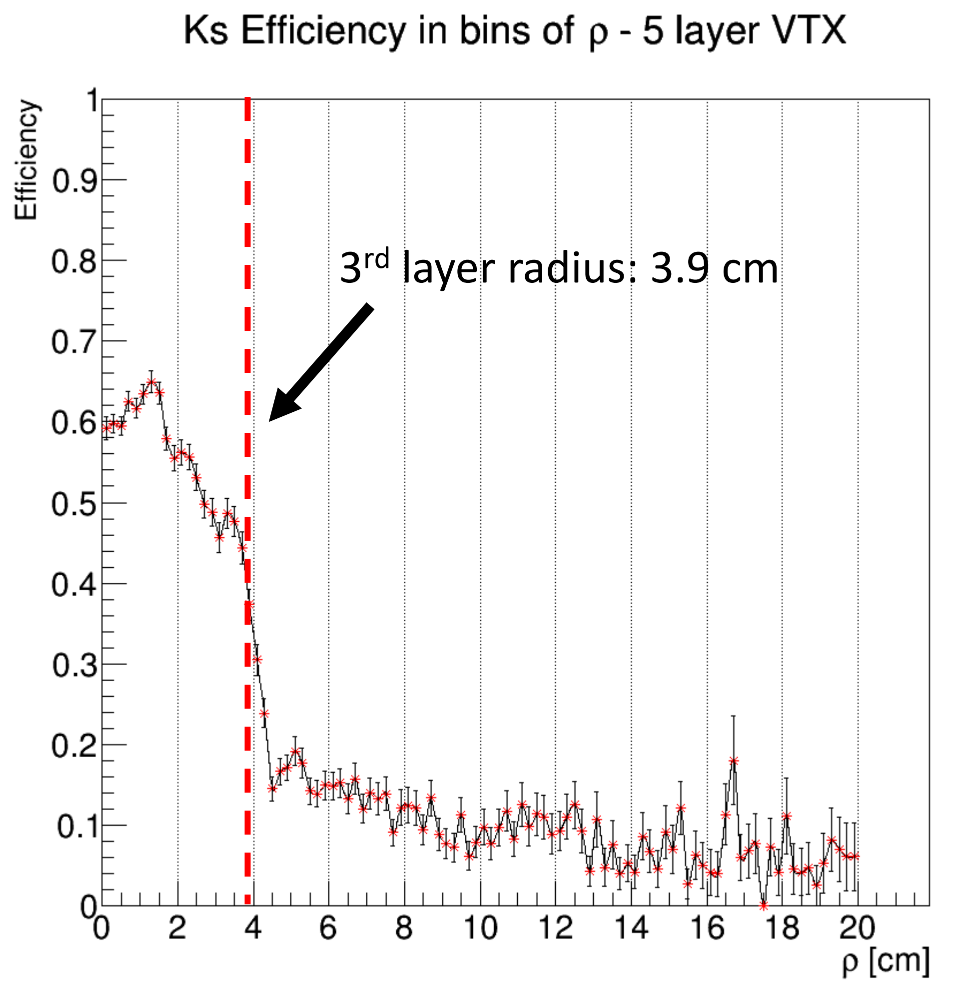
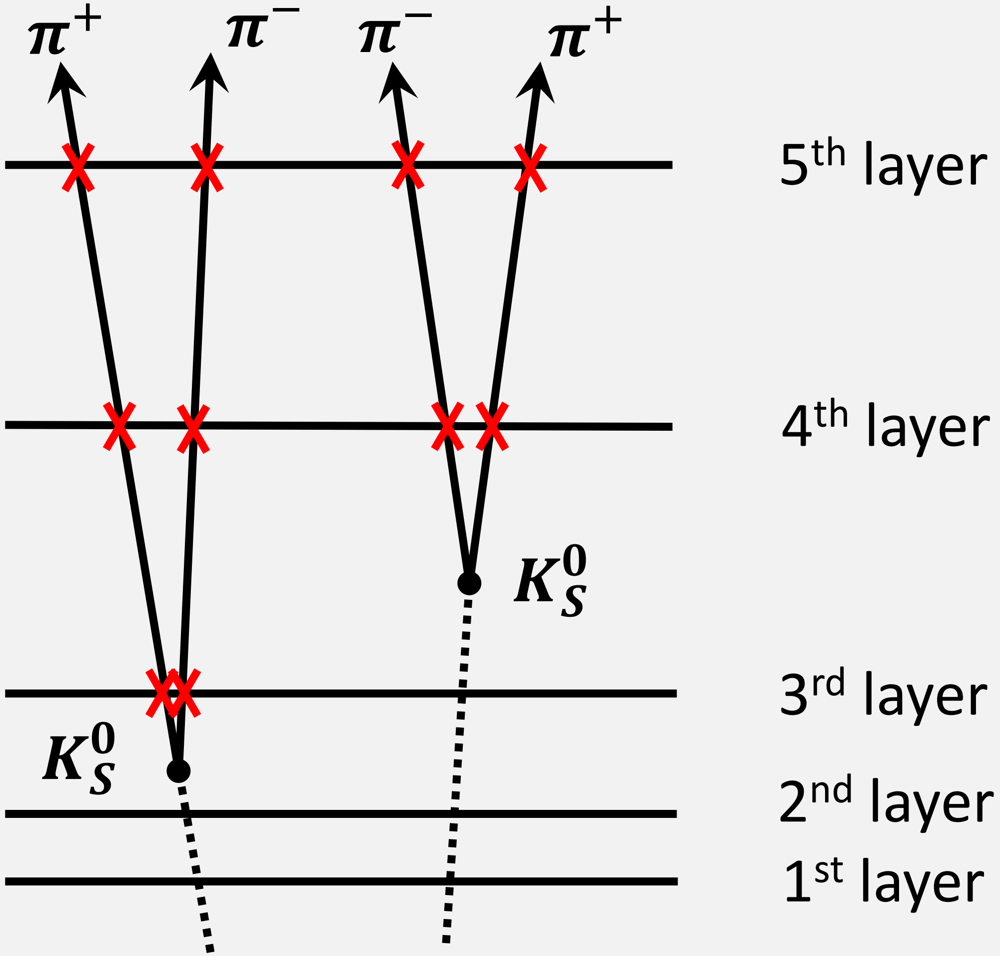
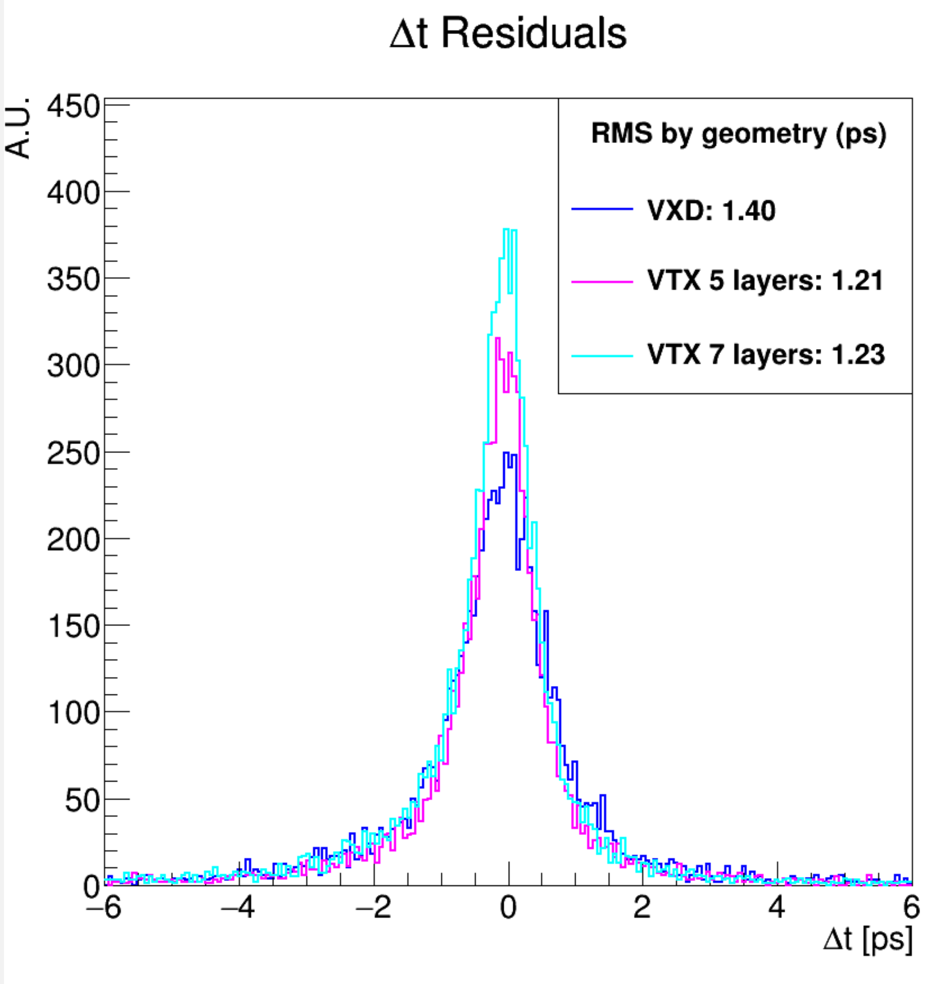




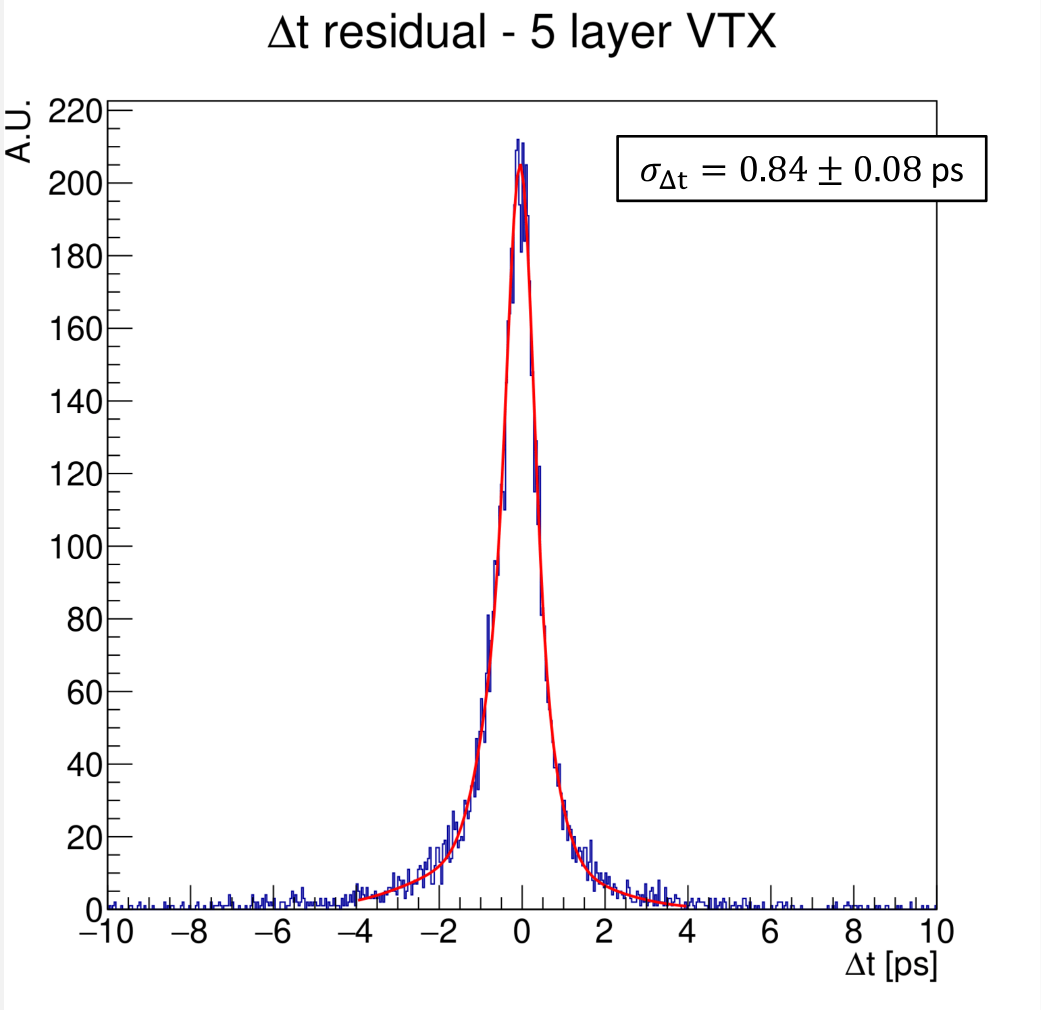
*ρ: transverse flight distance

Results: Vertex Resolution



*Residual: true value – reconstructed value

Results: Vertex Resolution



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Fit with sum of 3 Gaussians

Detector Geometry	Δt Resolution (ps)
VXD	1.12 ± 0.11
VTX 5 layers	0.84 ± 0.08
VTX 7 layers	0.91 ± 0.08

- Noticeable improvement to resolution observed in both VTX geometries
- Slight degradation in 7 layer VTX geometry compared to 5 layer VTX

Conclusion & prospects

- ✓ My analysis shows the **VTX** overall performs better than the **VXD** in terms of reconstruction efficiency and vertex resolution at the target instantaneous luminosity

- ➢ Possible improvements for reconstruction efficiency:
  1. Optimise radius of middle layer in 5 layer VTX geometry
  2. Add an extra detection layer → 6 layer VTX geometry

- ➢ Outlook: analysis on flavor tagging and on higher beam background levels

THANK YOU!

Questions?

Backup – CKM matrix and unitarity triangles

Wolfenstein parameterization (A, λ, ρ, η)

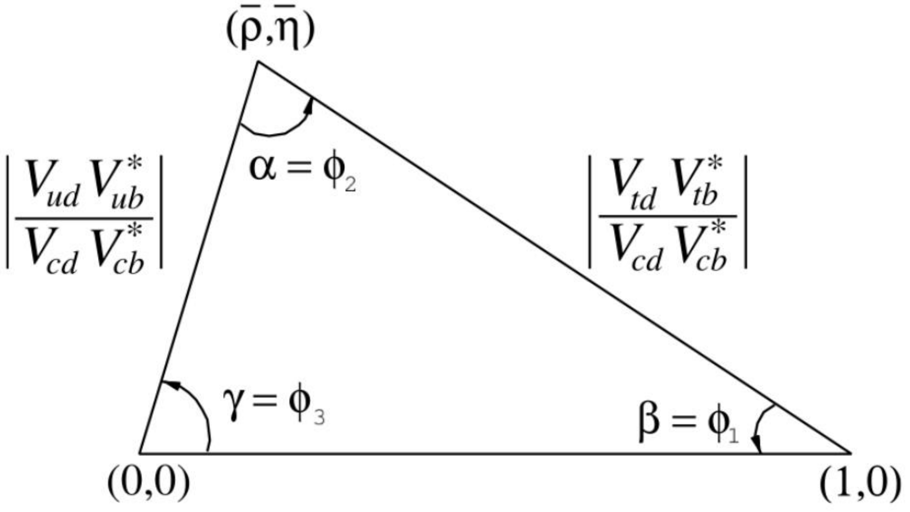
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

<u>Unitarity relations:</u>

$$\left.\sum_k V_{ki}V^*_{kj} = \delta_{ij}\right\}$$

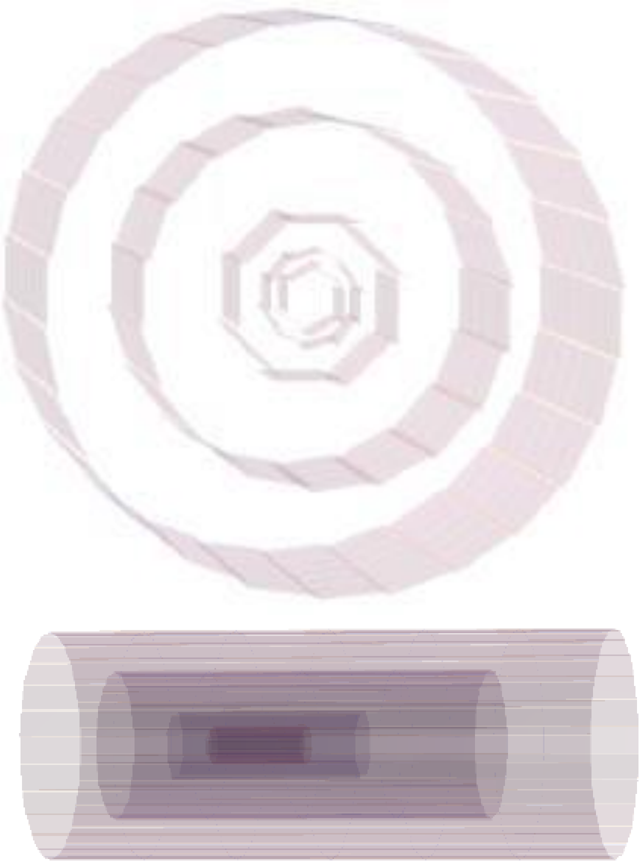
6 Unitarity relations → 6 Unitarity triangles

i, j: down-type quarks
k: up-type quarks

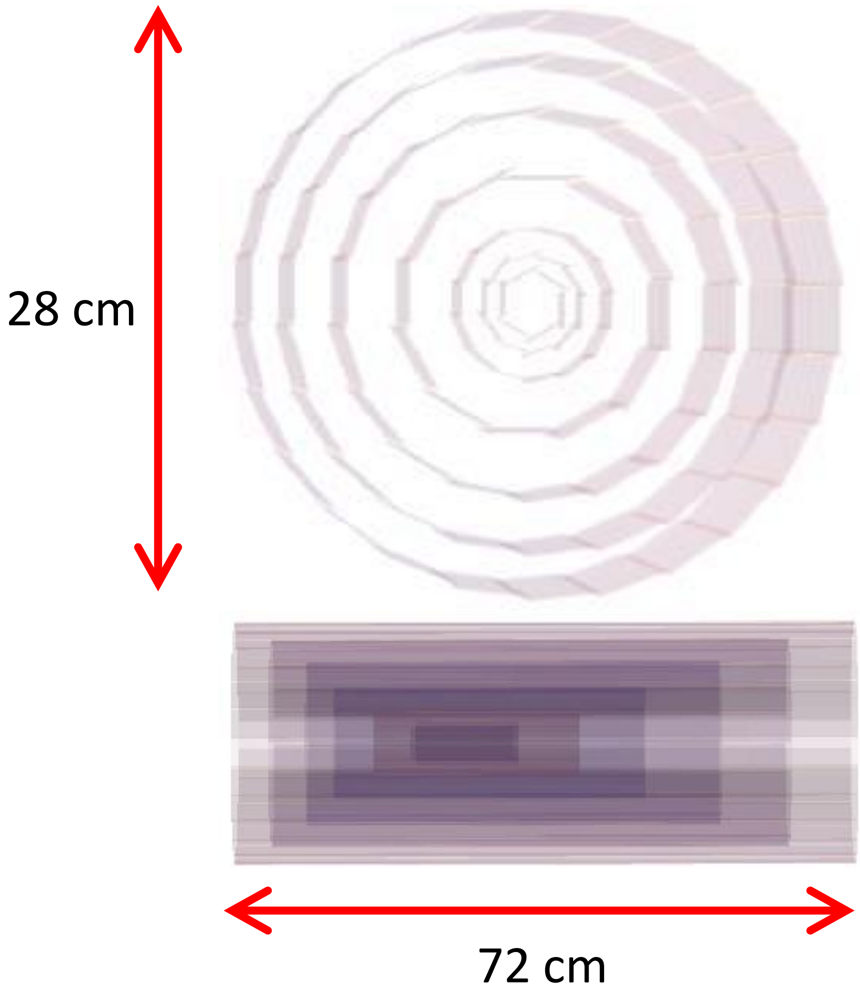


Backup – VTX geometries

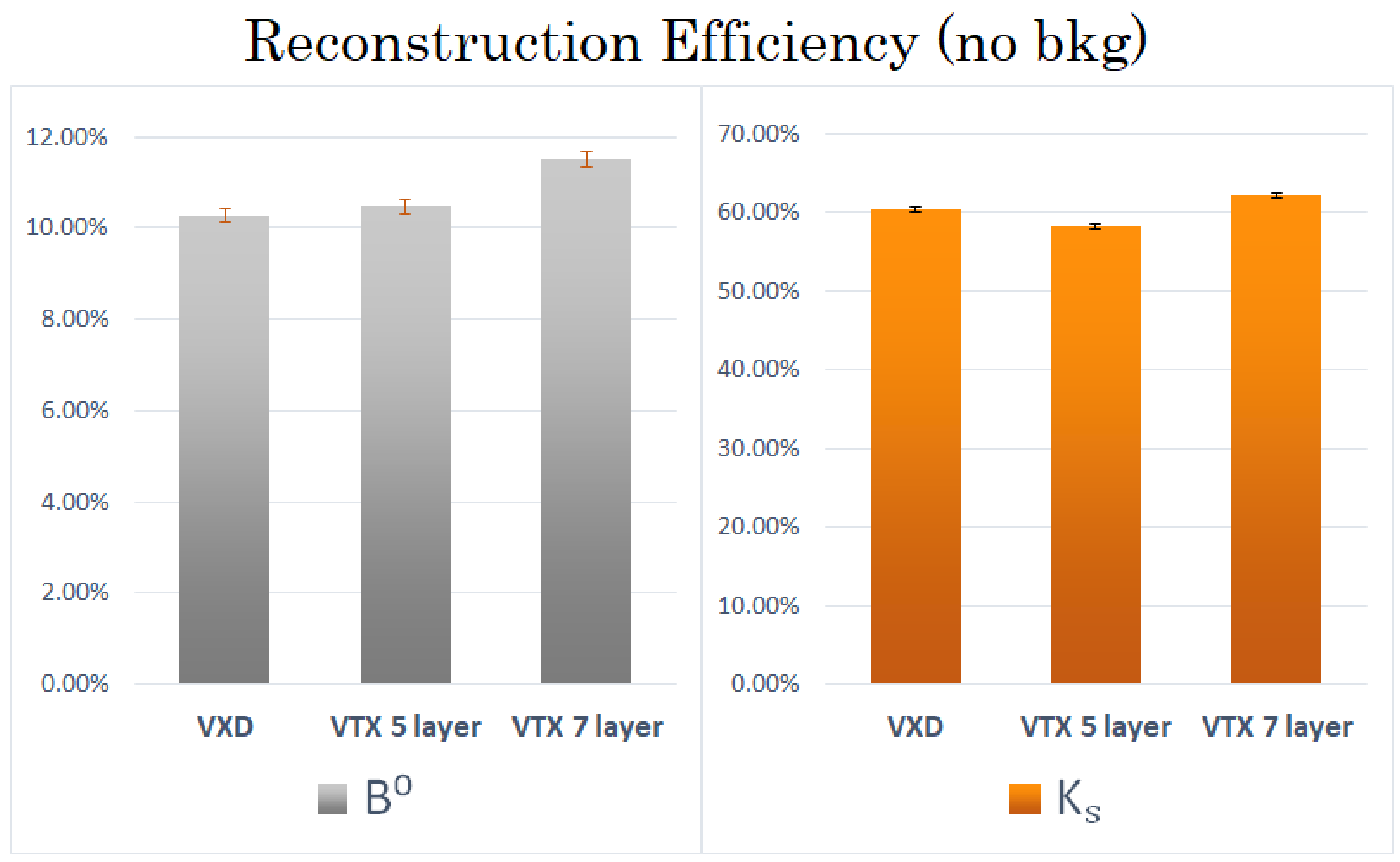
VTX 5 layer



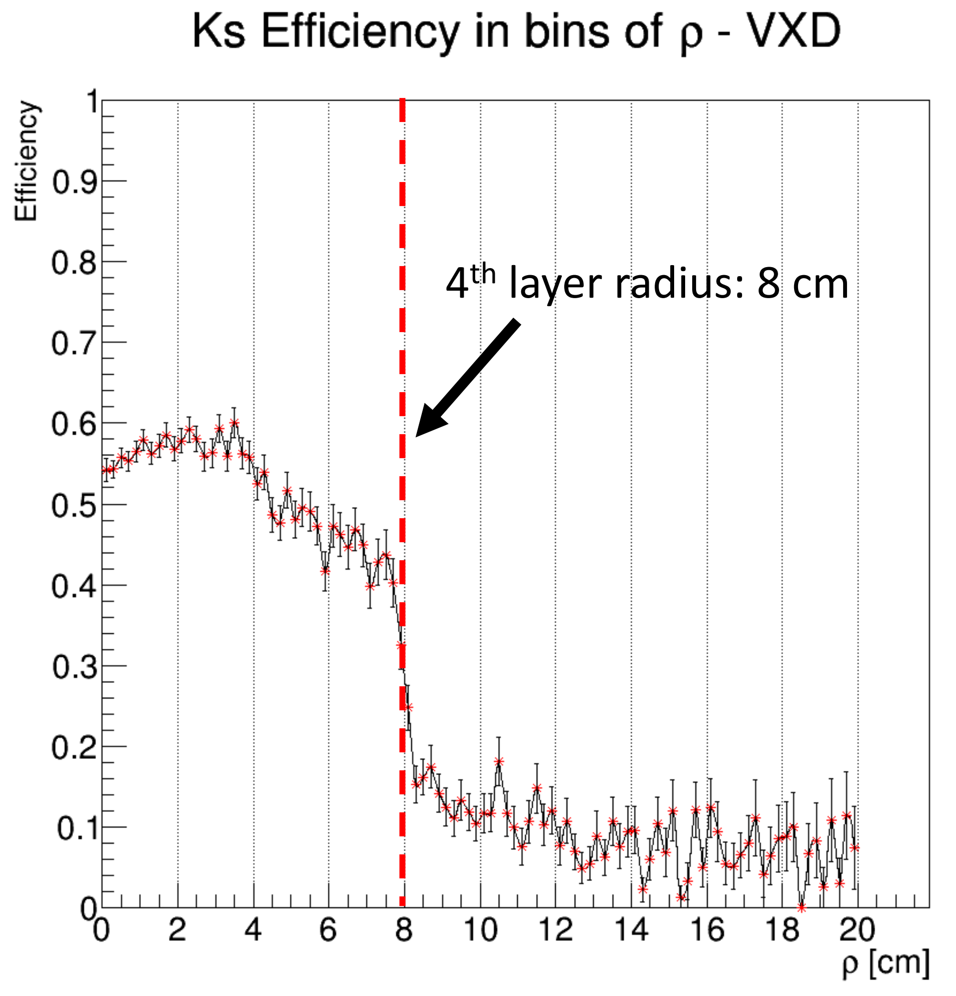
VTX 7 layer



Backup – Reconstruction Efficiency



Backup – Efficiency vs. transverse flight distance



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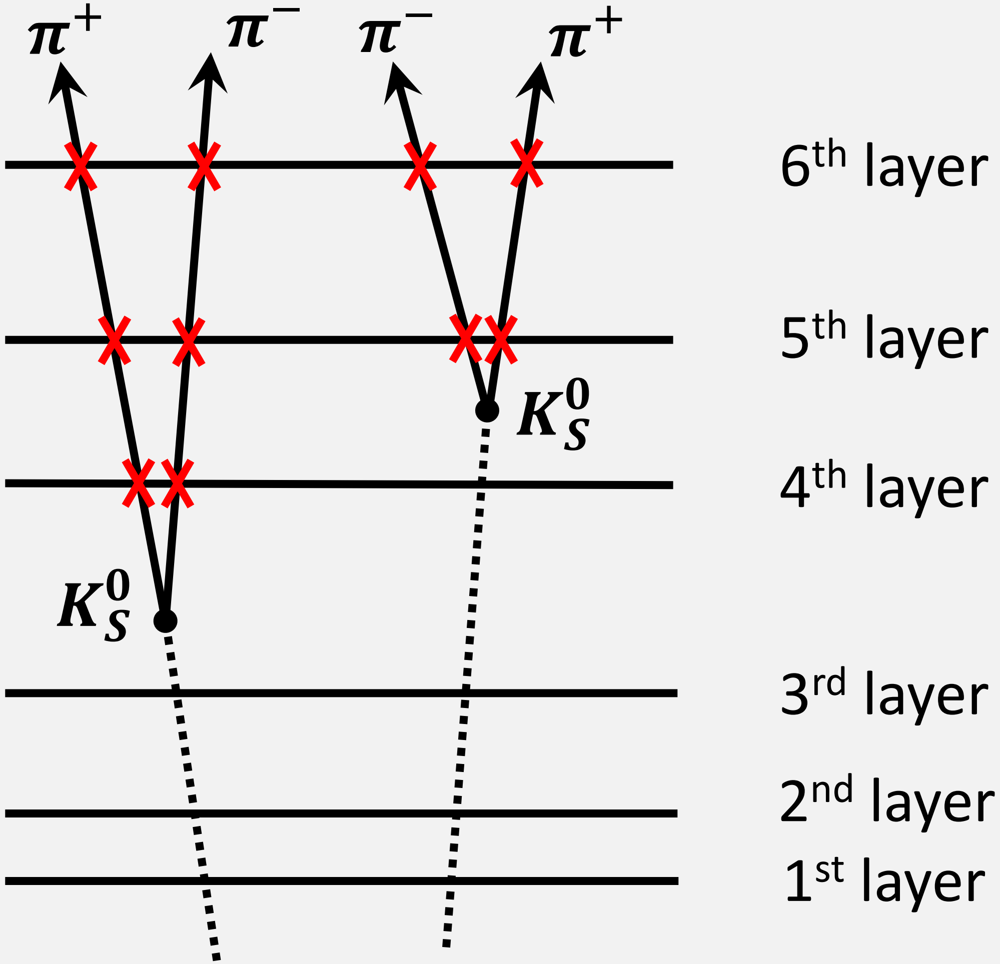
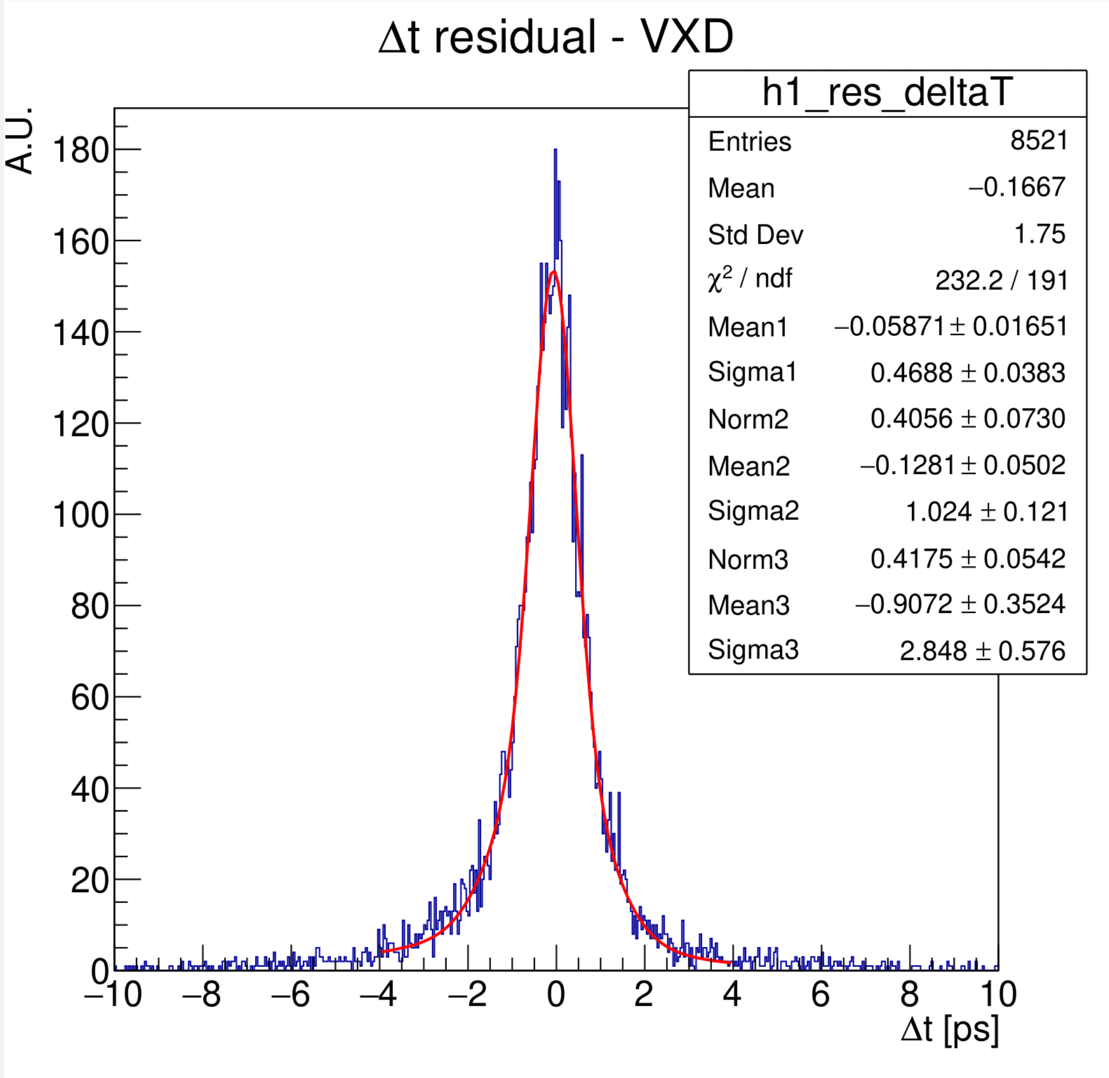


Backup – Δt Residual Fits



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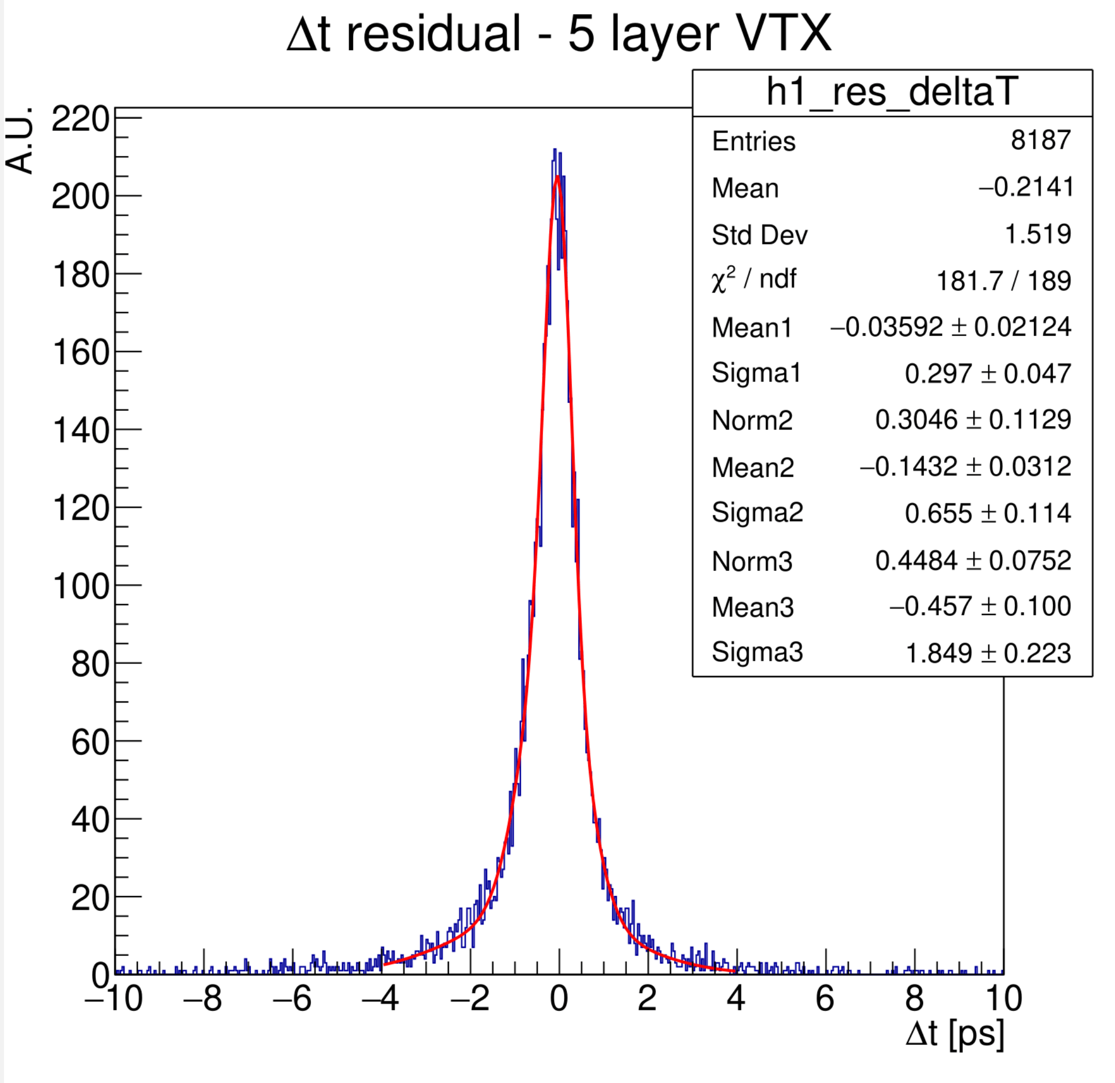

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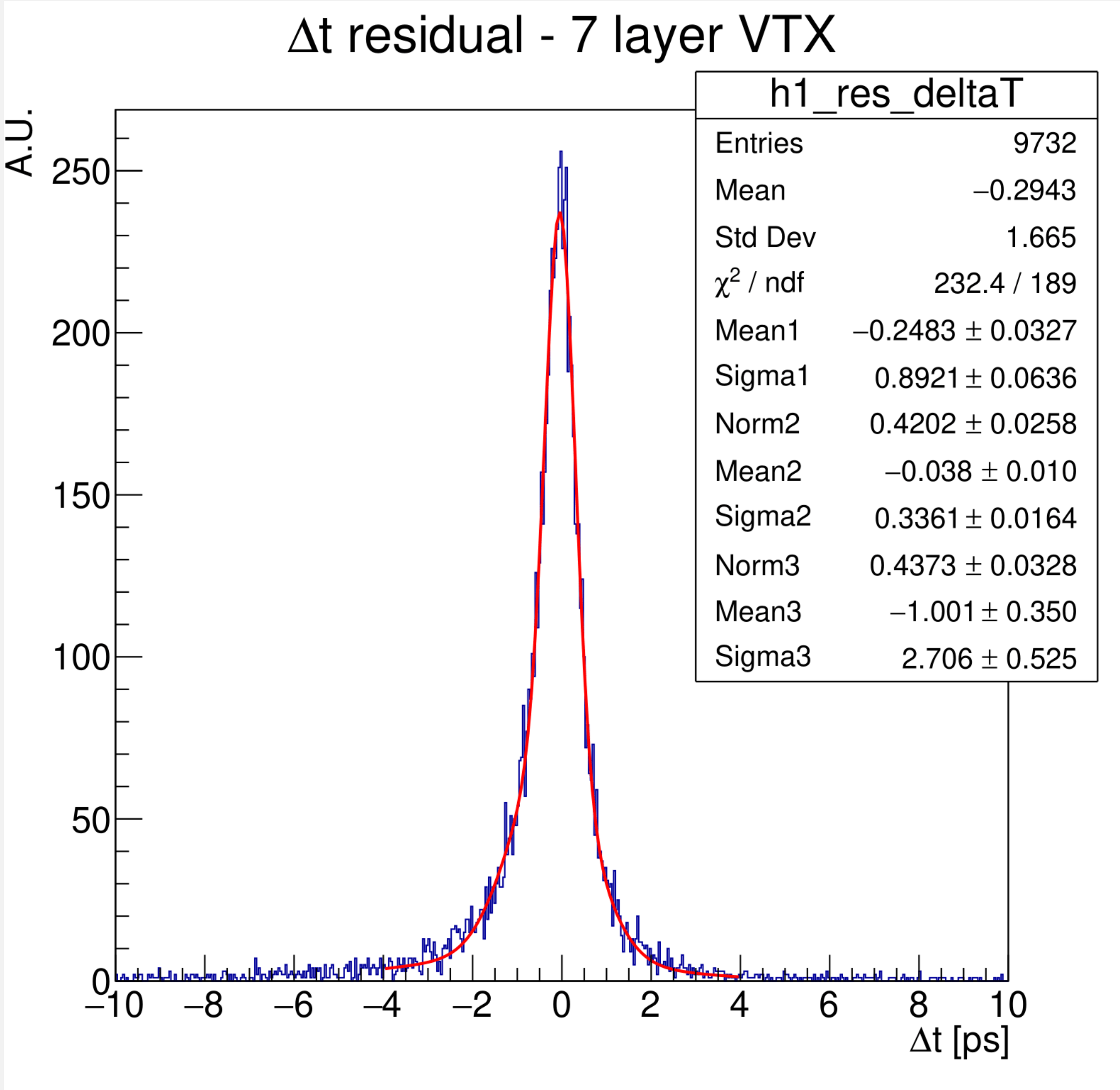

h1_res_deltaT	
Entries	9732
Mean	–0.2943
Std Dev	1.665
χ^2 / ndf	232.4 / 189
Mean1	–0.2483 ± 0.0327
Sigma1	0.8921 ± 0.0636
Norm2	0.4202 ± 0.0258
Mean2	–0.038 ± 0.010
Sigma2	0.3361 ± 0.0164
Norm3	0.4373 ± 0.0328
Mean3	–1.001 ± 0.350
Sigma3	2.706 ± 0.525

Backup – Δt 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

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

Backup – S parameter uncertainty

- Possible to determine uncertainty on the **S** parameter (describing the time-dependent CP asymmetry) using a Toy Monte Carlo model

$$\boxed{\mathcal{A}_{CP}(\Delta t) \approx \boldsymbol{S} \cdot \sin(\Delta m_{\mathrm{d}} \cdot \Delta t)}$$

$\boldsymbol{\Delta m_{\mathrm{d}}}$: Mass difference between two B mesons

- ~7% improvement on the **S** parameter uncertainty from VXD to VTX geometries ⇒ VTX performs at least as well as VXD

Backup – Toy MC model

- 1000 pseudo-experiments (with detector performance parameterised)
- 50 ab^{-1} integrated luminosity
- Δt distribution fit using 3 Gaussians