Inner Tracking and Timing

Jennifer Ott on behalf of the ITT team

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Belle II Trigger/DAQ workshop

October 22, 2025

Belle II upgrade

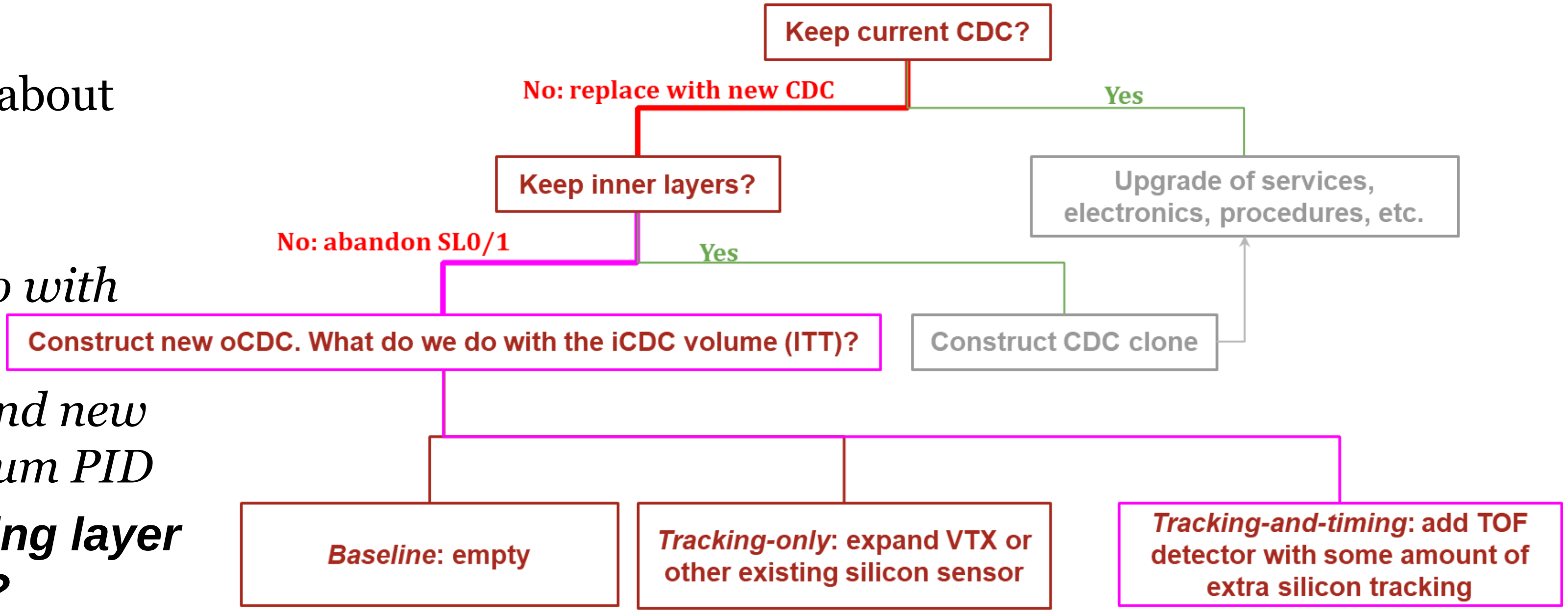
Upgrade of the Inner region:

- IR: New QCS - ongoing discussions about different upgrade options
- PXD + SVD → 6-layer VTX
  - CDC: gas aging issue → *what to do with this volume?*
  - *If left empty: Gap between VTX and new CDC layer degrades low-momentum PID*

➢ ***Can it be recovered by a fast timing layer through time-of-flight particle ID?***

Target not only this, but aim to generate additional value:

➢ ***TOF would give low-p_T PID capabilities totally new to B-factories***



This is the 'working scenario' as of now

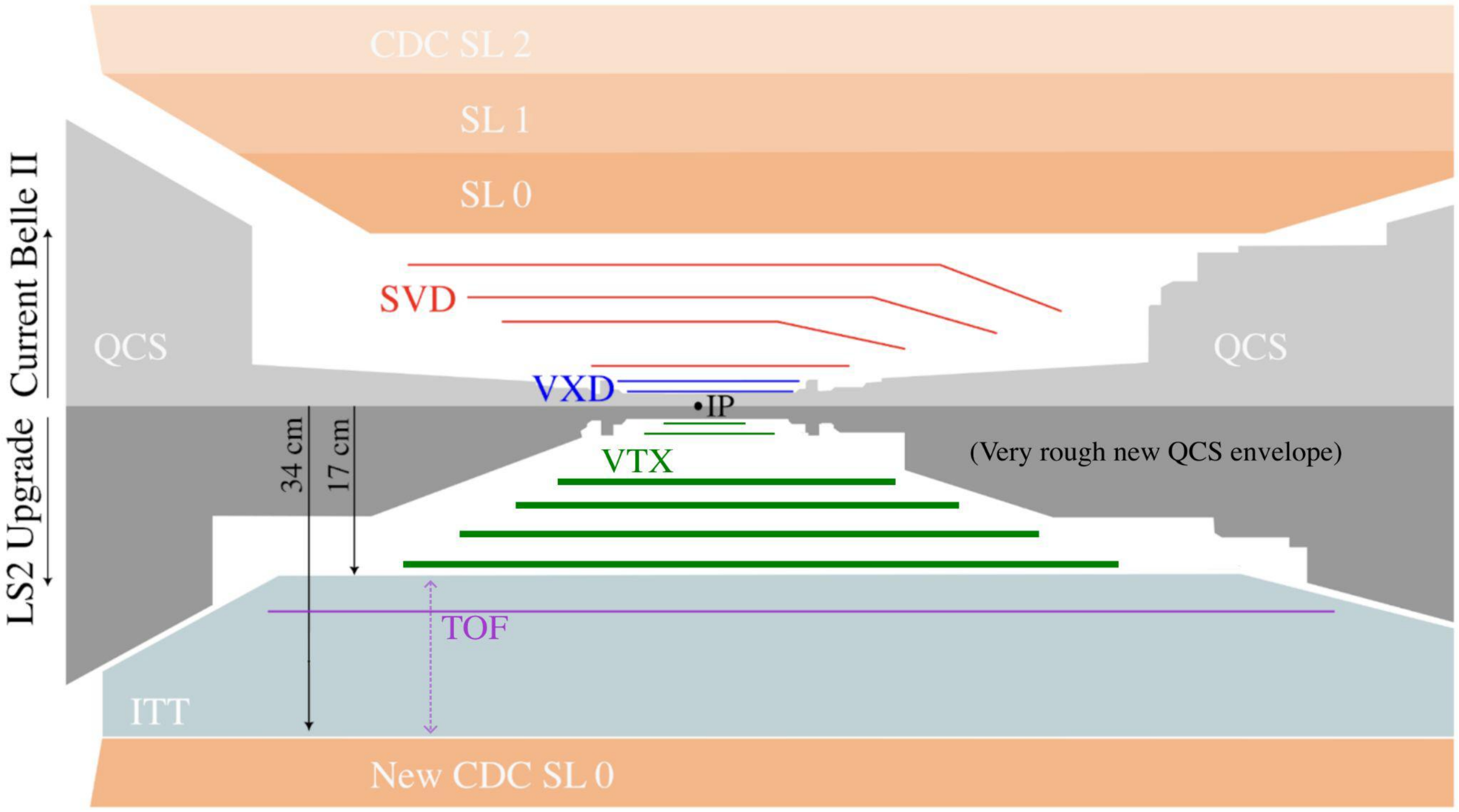
➢ **Approximate doubling of efficiency for channels with low-momentum muons, for example leptonic tau decays (*R*(*D**), $K \to \tau\tau$, etc)**

Implementing a TOF layer?

Available volume radius without CDC SL0 and SL1: 17 < r < 34 cm

To consider:

- Radius of TOF layer?
- 1 layer with timing, or more? (>2 unlikely, due to material budget)
- Relation to VTX design as well: lowest possible r for TOF defined by VTX l. 6 potentially moving further out from original 14 cm



- Additional tracking layer in ITT, outside of TOF with less stringent spatial resolution? – needs to be thought of separately from VTX; may be too material-budget constrained

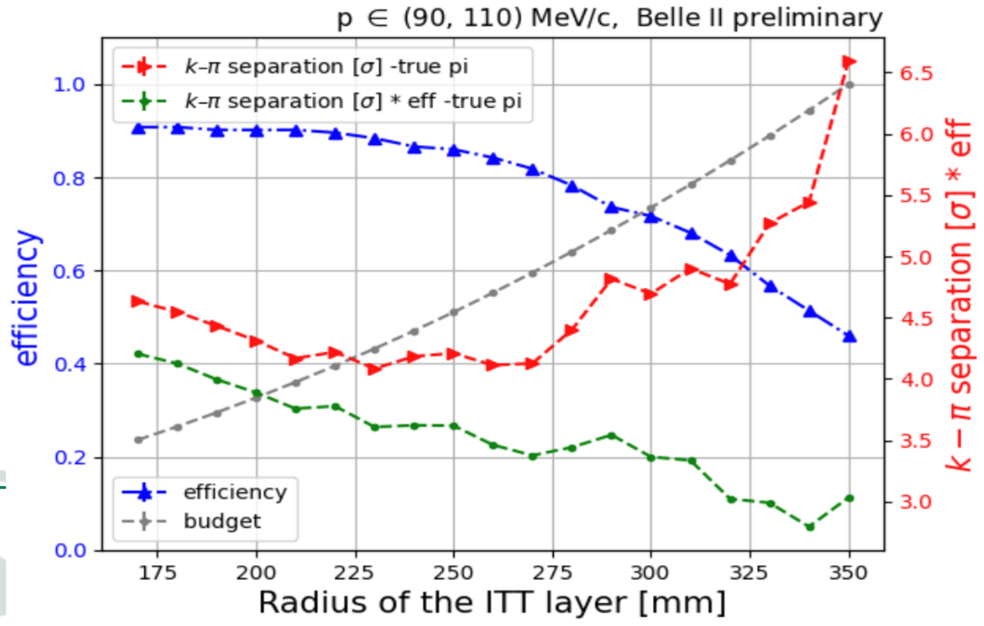
Initial simulations and detector requirements

Initial work: Geant4 simulations to quantify impact on PID, exercise placement at different radii, set constraints on X/X_0

- *Simple cylindrical volume with some specified radius, thickness and timing resolution – sensor technology, mechanical design etc not defined*

Details in Yubo's presentation at ITT session and in Upgrade WG

Example: $k - \pi$ separation

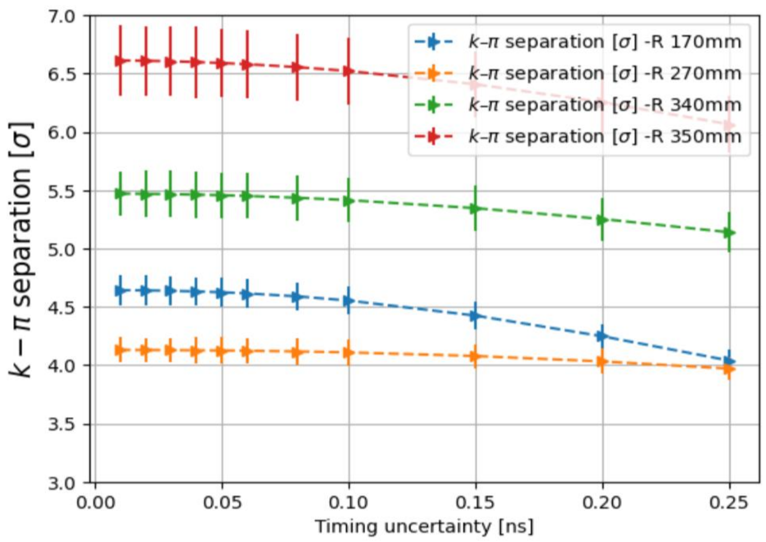


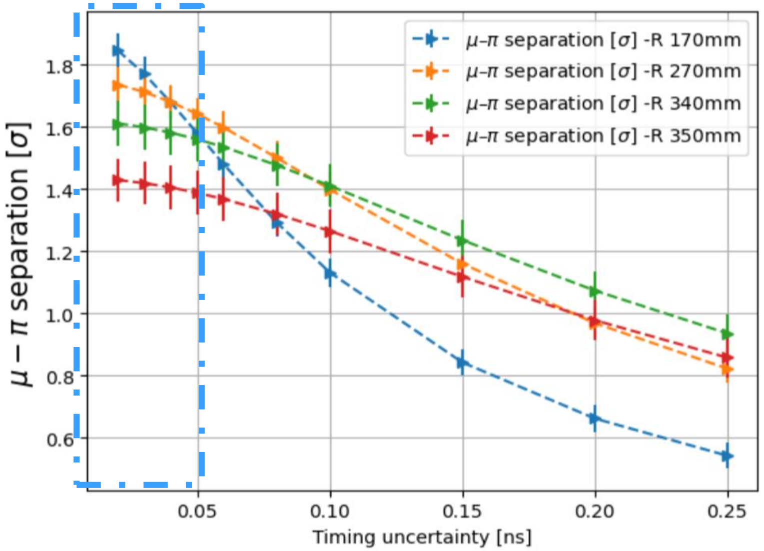
Initial simulations and detector requirements

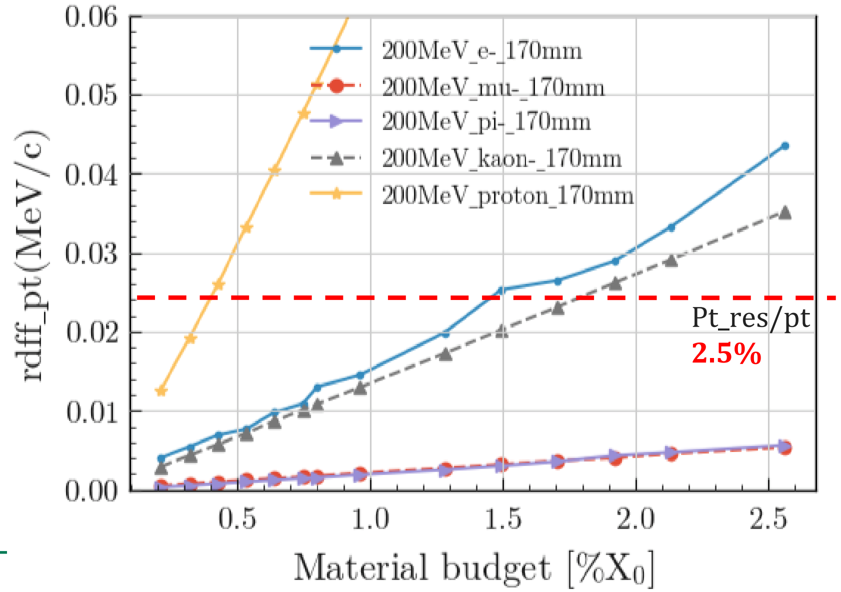
k – π (ref.) and μ – π (novel impact physics) separation

- **Timing resolution: 50 ps**
- **Material budget, low p_T tracks 100-200 MeV/c: 1.5 % X/X_0**

Impact on tracking resolution equivalent to current tracker – VTX material







Sensor technology and performance

Initial simulations have been agnostic to sensor technology

... but have been inspired by performance of silicon LGAD sensors

ITT technical session at recent B2GM: presentations on sensor technologies, as well as current R&D status and planning of other future timing detectors

- A lot to be learned from past and current fast timing R&D, as well as development of ATLAS and CMS timing layers
- **AC-LGAD –based Time-of-Flight detector to be built at the Electron-Ion Collider: very similar architecture**

13:00				
	Overview	*Yubo Han*	*Meeting room 3, KEK Kenkyu-honkan*	13:15 - 13:30
	Survey of sensor options	*Jennifer Ott*	*Meeting room 3, KEK Kenkyu-honkan*	13:30 - 13:45
	ePIC barrel TOF	*Simone Mazza*	*Meeting room 3, KEK Kenkyu-honkan*	13:45 - 14:00
14:00	**LGAD options, R&D status**	*Koji Nakamura*	*Meeting room 3, KEK Kenkyu-honkan*	14:00 - 14:15
	AC-LGADs and sensor thinning	*Jennifer Ott*	*Meeting room 3, KEK Kenkyu-honkan*	14:15 - 14:30
	Performance of LGAD at ATLAS	*Yunyun Fan*	*Meeting room 3, KEK Kenkyu-honkan*	14:30 - 14:45
	Survey of gas options	*Peter Lewis*	*Meeting room 3, KEK Kenkyu-honkan*	14:45 - 15:00
15:00	**CMOS strips**	*Ingrid-Maria Gregor*	*Meeting room 3, KEK Kenkyu-honkan*	15:00 - 15:15
	Discussion	*Peter Lewis*	*Meeting room 3, KEK Kenkyu-honkan*	15:15 - 15:45

ITT summary talk also at B2GM:
https://indico.belle2.org/event/16060/contributions/100245/

https://indico.belle2.org/event/16060/sessions/5082/#20250930

Questions from & to TRIG-DAQ

1. *Could present [or, upgrade] DAQ be used for ITT? Are new features needed?*

- **No decisions have been made yet on what the readout for ITT will be**
  - ASIC not chosen or developed yet, let alone FE boards, …
- **In terms of DAQ and trigger, the operation of the detector system that most closely resembles ITT – ePIC at the EIC – has a fundamentally different approach, in that it is oriented towards 'streaming readout'**
  - Specifications to be set – AC-LGAD time-of-flight layer is not under the most pressure to reduce data rates compared to some other systems

➢ **Rather, ITT front-end should be designed to match / integrate well with current DAQ, keeping in mind changes in the upgrade**

Questions from & to TRIG-DAQ

1. ***Could ITT provide L1 trigger?***

- ***This question could be interpreted in two ways – replacing trigger currently provided other detectors, or participate alongside current as a new additional trigger?***

a. If there is only 1 layer with fast timing resolution, is it even meaningful to have a timing trigger?

- If surrounding layers, i.e. VTX and CDC, have ~1-5 ns timing resolution, what value is a 50-70 ps trigger?
- *Could it be used for partial online reconstruction or track finding?*

Questions from & to TRIG-DAQ

1. ***Could ITT provide L1 trigger?***

- ***This question could be interpreted in two ways – replacing trigger currently provided other detectors, or participate alongside current as a new additional trigger?***

b. **Could this replace *n_tracks* from silicon layers / VTX and CDC?**
   - ITT could provide a number of <u>in-time</u> tracks…
   - Role in background rejection?

c. **If this is the fastest detector, is it of interest to use it to provide a global timestamp or timing trigger?**
   - i.e. including some impact on detectors/triggers which do not rely on tracks

Questions from & to TRIG-DAQ

1. *Could ITT provide L1 trigger?*

- **In principle yes – but TRIG/DAQ group should tell us what is needed, or what is the most helpful ☺**
- **To be specified – especially role of timing in trigger or reconstruction?**
- **Fundamental question, whether ITT will be part of tracking – to be addressed over the next months**

A few related notes on Tracking

Inclusion of ITT and impact of ITT on tracking: simulation efforts ongoing

First update from Yubo Han in Upgrade meeting:
https://indico.belle2.org/event/16590/

- **Placement radius of ITT**
  - right outside VTX L6, in the very middle, or close to CDC?
- **Material budget estimates so far indicate that > 1 layer of ITT would be unlikely**
  - Multiple layers would open up even more capabilities for timestamps and trigger, and 4D tracking…
- **Another thought: fast timing layer for PID, another layer – e.g. CMOS strips – more purely for tracking to compensate gap between VTX and CDC**
  - Material budget??
  - Tracking could be provided by ITT as well..?
  - No simulations studies at all yet

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COLLEGE OF ENGINEERING
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Thank you!

References

ePIC collaboration meeting, July 2025:

https://indico.jlab.org/event/934/

FNAL test beam and front-end articles:

- I. Dutta et al, Results for pixel and strip centimeter-scale AC-LGAD sensors with a 120 GeV proton beam, NIM A, 170224, 2025, https://doi.org/10.1016/j.nima.2025.170224
- C. Madrid et al, First survey of centimeter-scale AC-LGAD strip sensors with a 120 GeV proton beam, *JINST* 18 P06013, 2023, https://doi.org/10.1088/1748-0221/18/06/P06013
- R. Heller *et al,* Characterization of BNL and HPK AC-LGAD sensors with a 120 GeV proton beam, *JINST* 17 P05001, 2022, https://doi.org/10.1088/1748-0221/17/05/P05001
- S. Xie et al, Design and performance of the Fermilab Constant Fraction Discriminator ASIC, NIM A, 168655, 2023, https://doi.org/10.1016/j.nima.2023.168655

UCSC irradiation and angular incidence studies:

G. Stage et al, Performance of neutron and proton irradiated AC-LGAD sensors, https://arxiv.org/abs/2503.16658 (accepted to NIM A, 2025)

Electron-Ion Collider

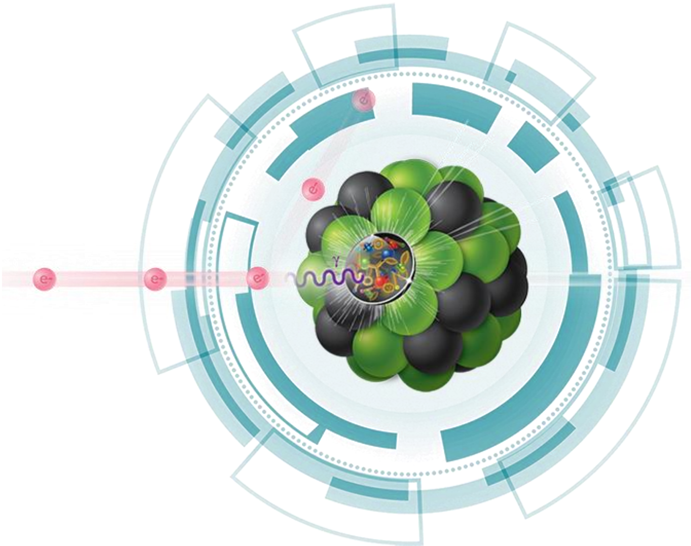
- Nucleon and nuclei structure, mass and spin; QCD at extreme densities; ‘imaging’ of nuclei
- Jointly hosted by Brookhaven and Jefferson National Laboratories
  - ➢ **Detector 1 at the EIC: ePIC**

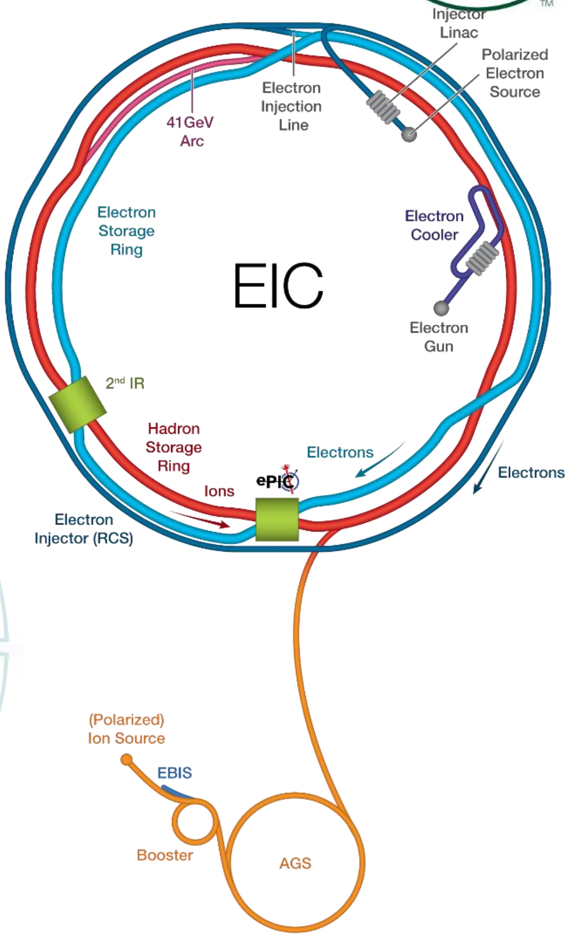
Operations scheduled to begin 2032-2034

Center-of-mass energy: 20 –140 GeV

- electrons: 2.5 –18 GeV
- protons: 40 –275 GeV (ions: Z/A * E_p)

Luminosity: 1-2x10^{34} cm^{-2}s^{-1}





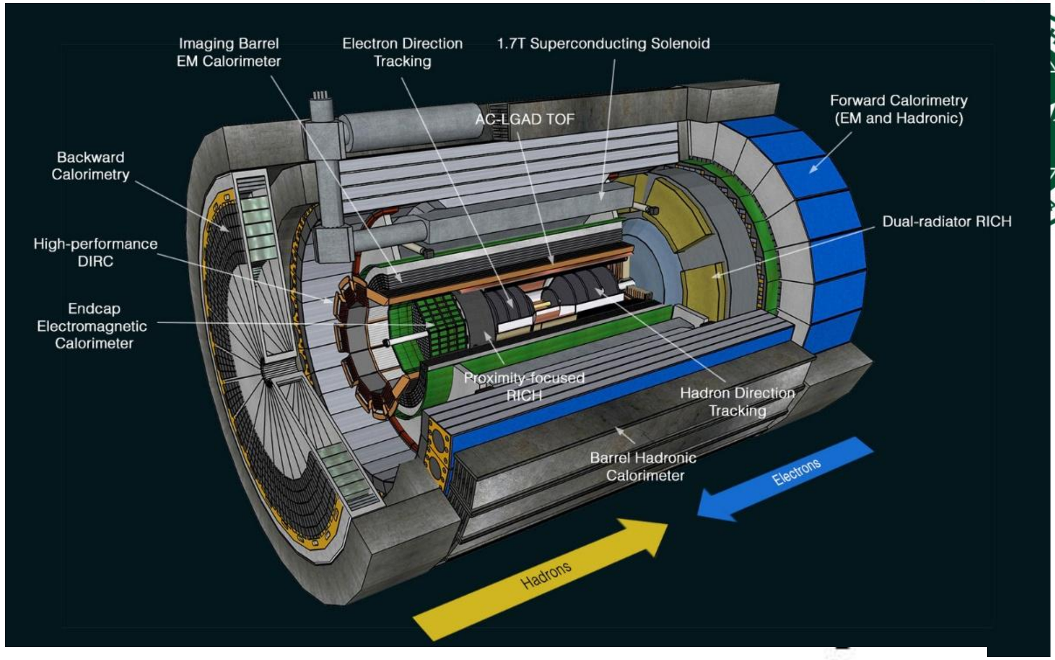
Particle ID

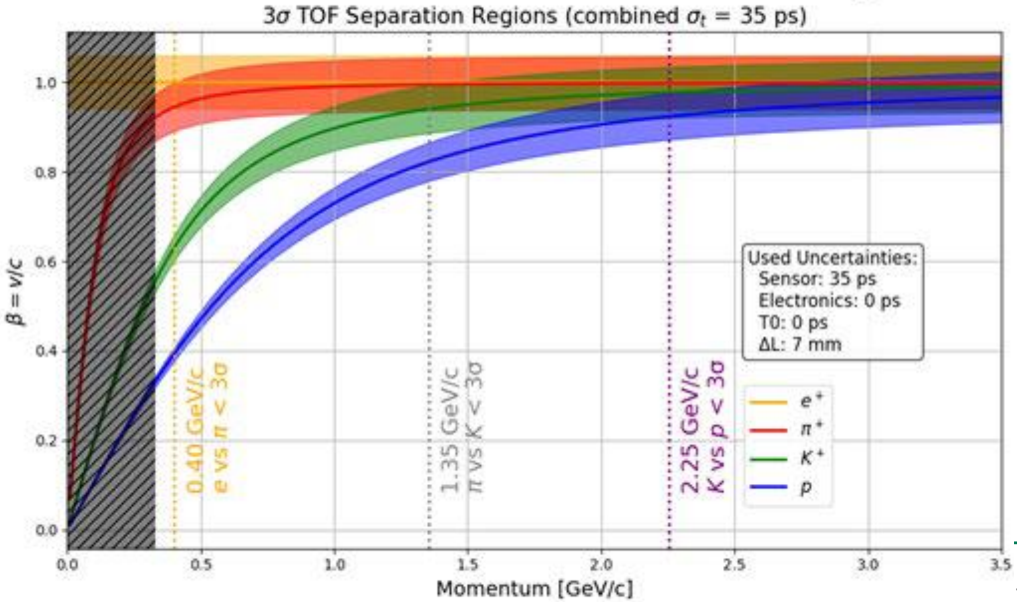
Several detectors for particle ID in inner or outer barrel layers, hadronic endcap, electron endcap

- Momentum and rapidity range cannot be covered by a single technology
- Leveraging variants of Cherenkov detectors

- **Time-of-flight particle ID layer: silicon AC-LGADs**
- **T_0 timestamp(?)**
- **Additional layer in tracking**

- AC-LGADs replaced by picosecond photodetectors in electron (backward) endcap
- Excellent performance in distinction of charged particle species at low momenta < 3 GeV





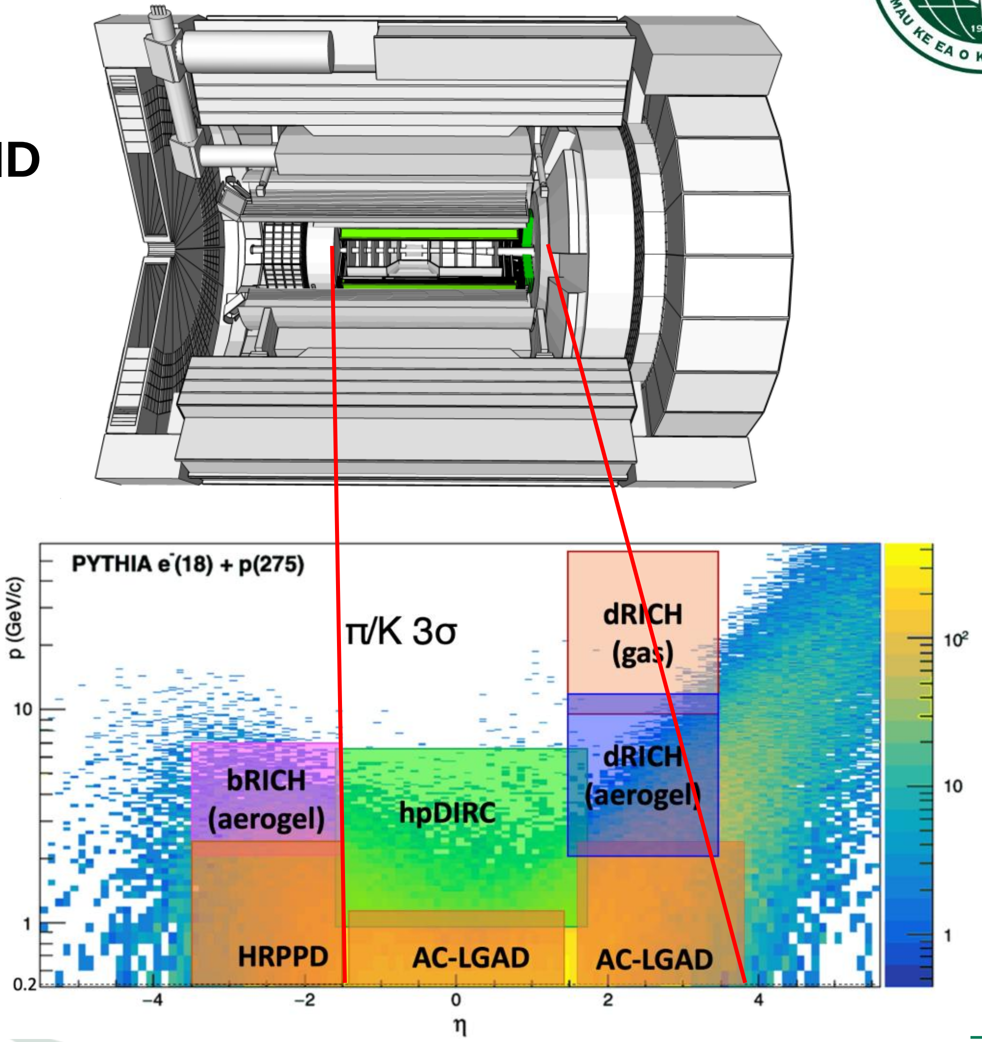
AC-LGADs in ePIC

AC-LGAD barrel and forward-endcap Time-of-Flight PID

- **Combination of precise temporal and spatial resolution: 25 ps and 30 µm / hit**
- Low material budget

Current sensor design baseline:

- Barrel: **strips, 500 µm pitch and 1 cm length**
- Hadronic endcap (and Roman Pots): **pads, 500 x 500 µm**



Particle ID systems in ePIC

AC-LGADs in ePIC

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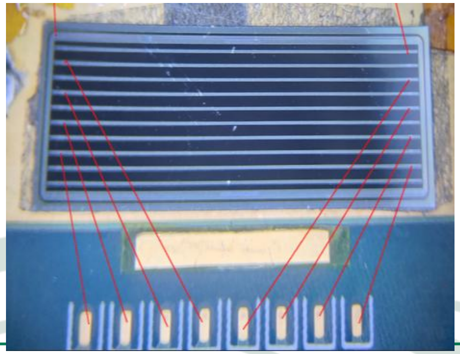
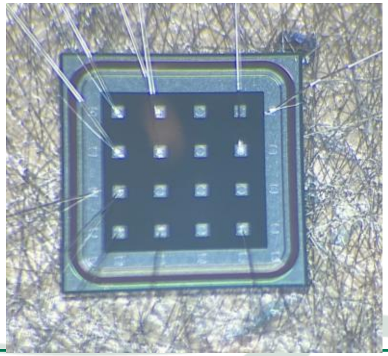
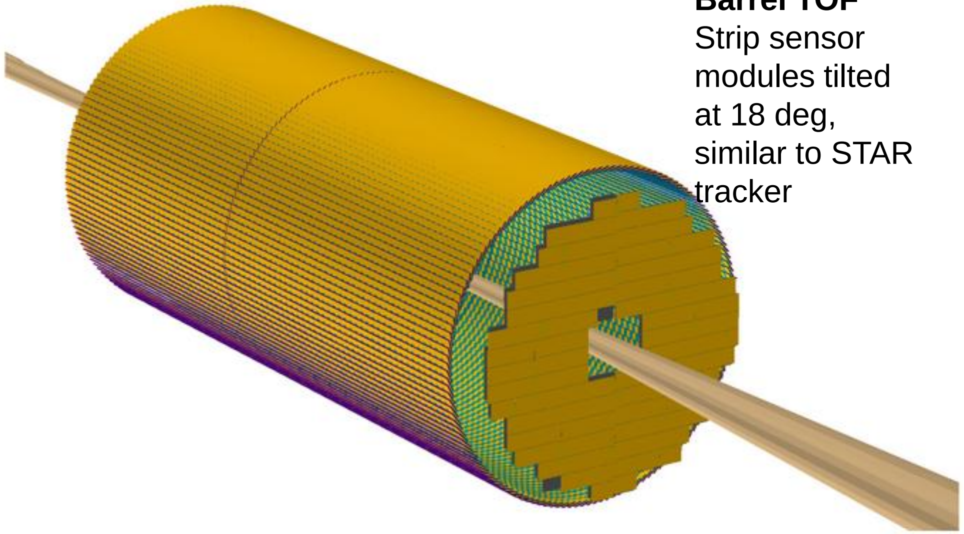




Barrel TOF
Strip sensor modules tilted at 18 deg, similar to STAR tracker



Forward TOF
Similar to CMS ETL

Readout

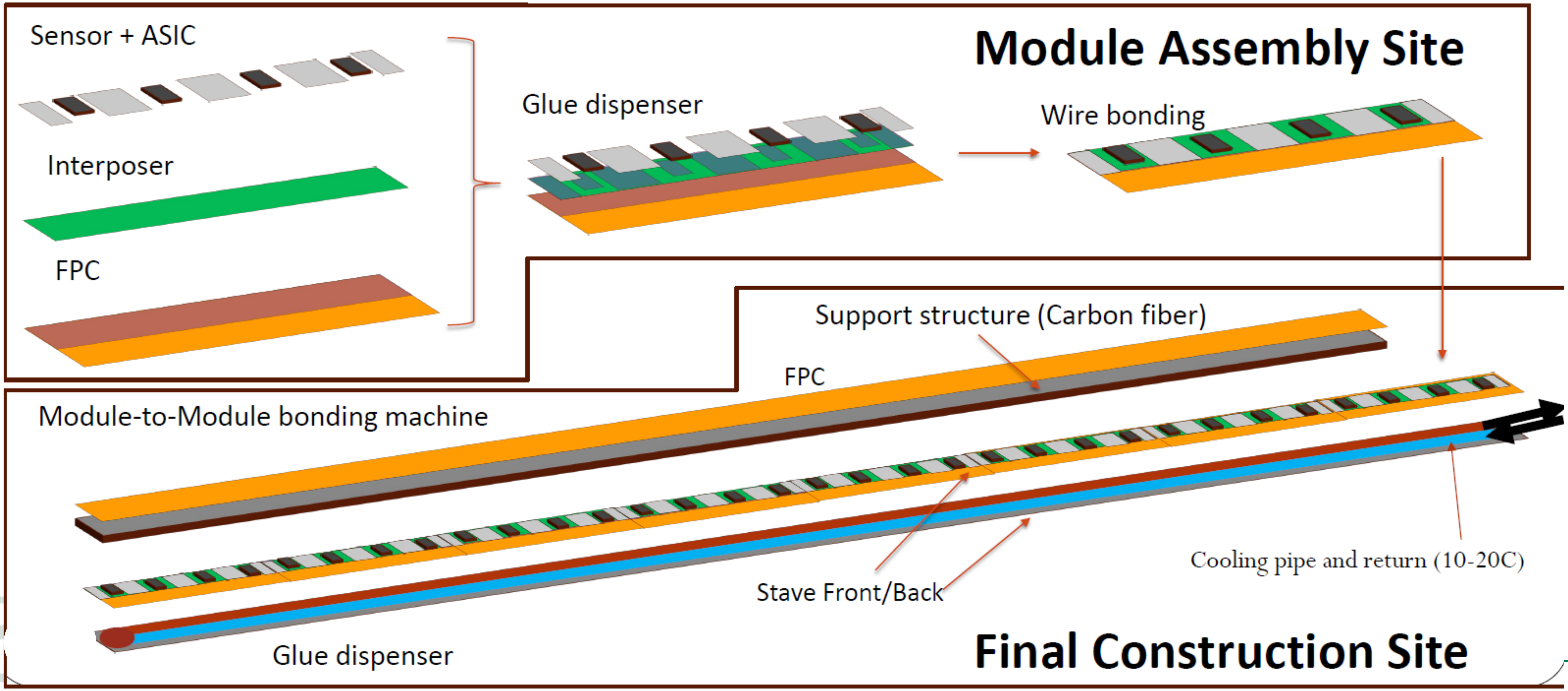
Forward-TOF – and several other detector systems: EICROC

- **Based on ATLAS ALTIROC front-end architecture**
- Current status and schedule: EICROCv0, 16 channels – EICROCv1 to full sensor size, 32x32 ch., Q4 2025 – Q1 2026
- Power consumption: << 1mW/channel desired

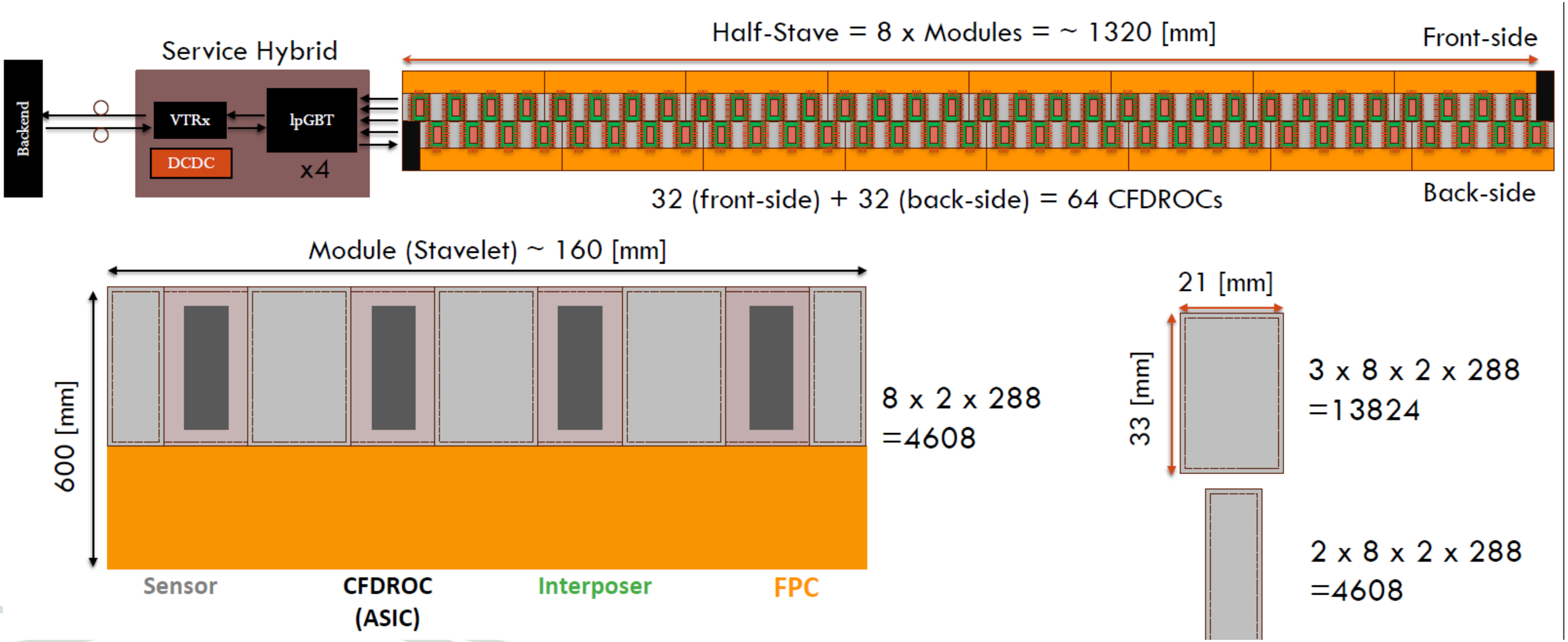
Challenge: optimized for low power and noise in pixelated sensors – not ideal for large input capacitances of long strip sensors

Barrel TOF: Fermilab Constant Fraction Discrimination chip

Barrel-TOF assembly and prototyping



Barrel-TOF services

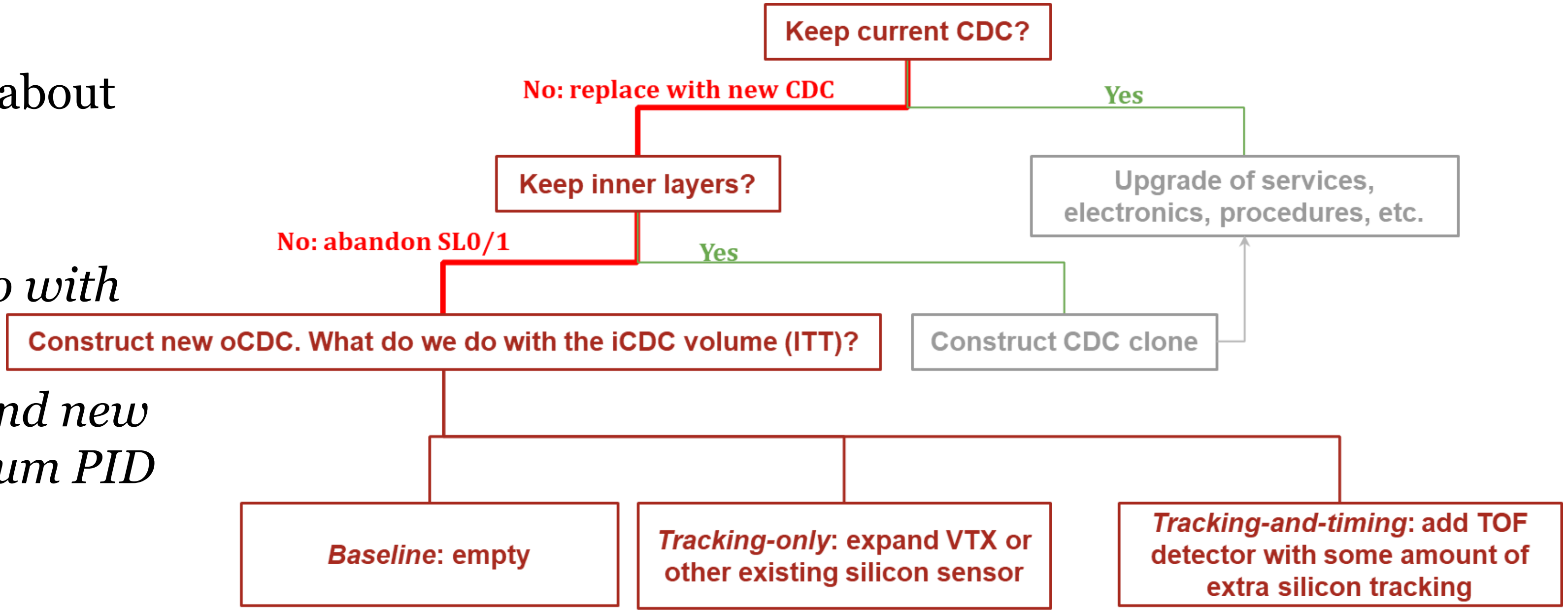


$X/X_0 < 3\%$ including support structure

Belle II upgrade

Upgrade of the Inner region:

- IR: New QCS - ongoing discussions about different upgrade options
- PXD + SVD → 6-layer VTX
  - CDC: gas aging issue → *what to do with this volume?*
  - *If left empty: Gap between VTX and new CDC layer degrades low-momentum PID*



Implementing a TOF layer?

Abandoning of CDC SL0 and SL1 degrades PID

- ***Can it be recovered by a fast timing layer through time-of-flight particle ID?***

Target not only this, but generating additional value:

- ***TOF would give low-p_T PID capabilities totally new to B-factories***
- **Approximate doubling of efficiency for channels with low-momentum muons, for example leptonic tau decays (*R*(*D**), $K \rightarrow \tau\,\tau$, etc)**

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