



Performance studies of a low-radius time-of-flight particle ID detector concept with silicon LGADs

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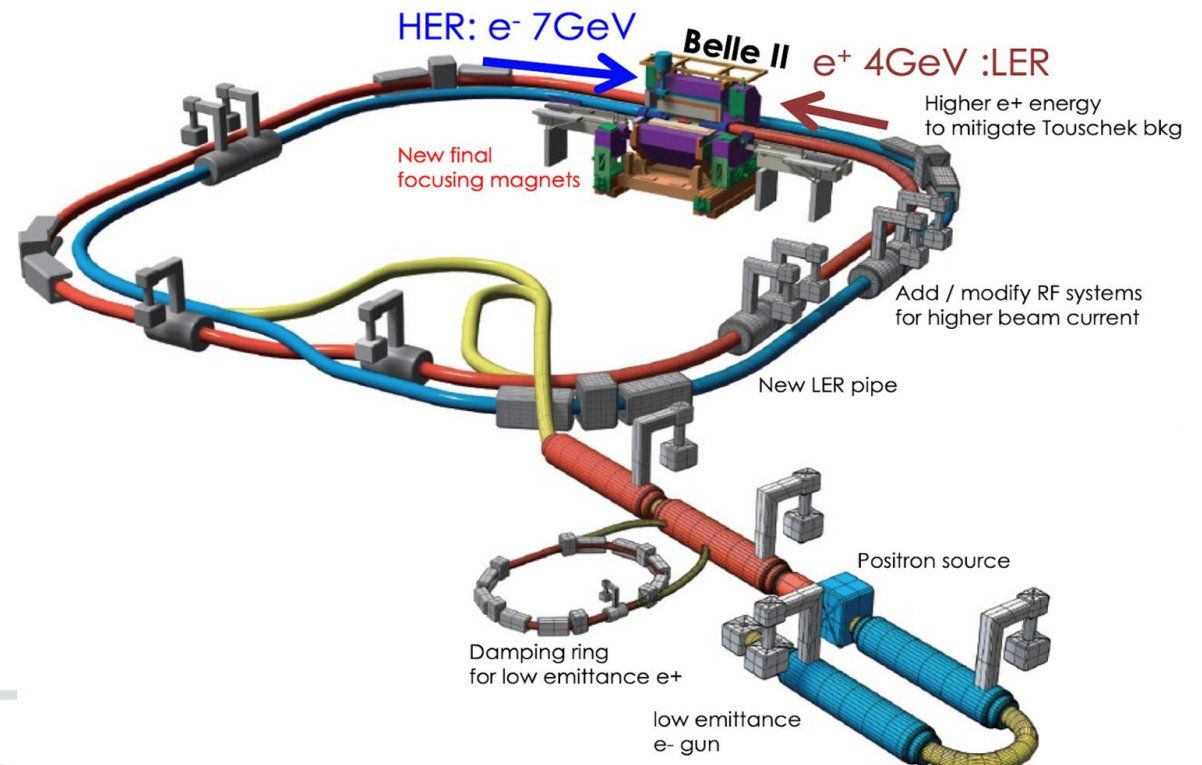
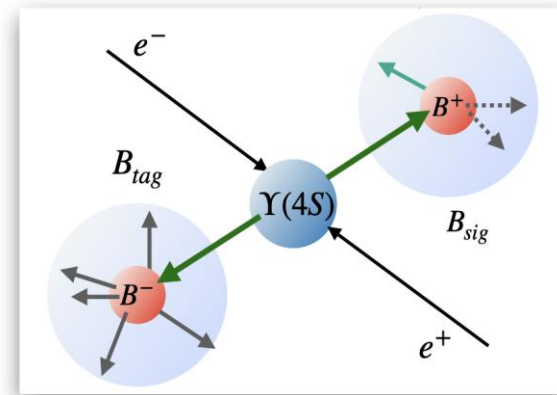
CPAD Workshop 2026

October 22, 2026

Belle II

SuperKEKB:

- Asymmetric $e^+(4\text{GeV})$ e^- (7GeV) collider in Tsukuba, Japan
- Operating around the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58 \text{ GeV}$)

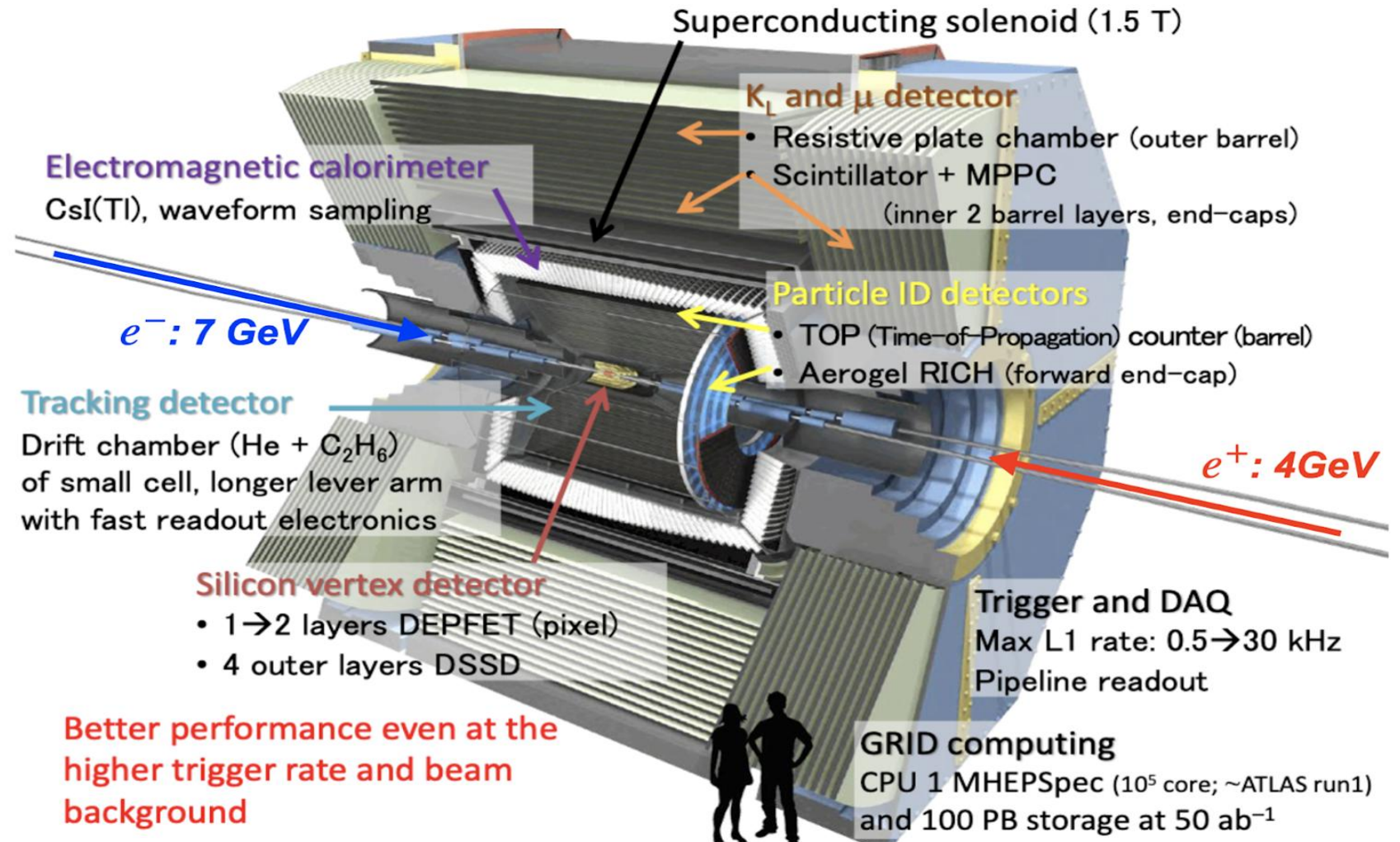


Belle II

Includes gaseous tracking detector system: central drift chamber

➤ Ageing challenges!

Silicon detector: upgrade in Long Shutdown 2 in 2032, from strip SVD & pixelated PXD to VTX

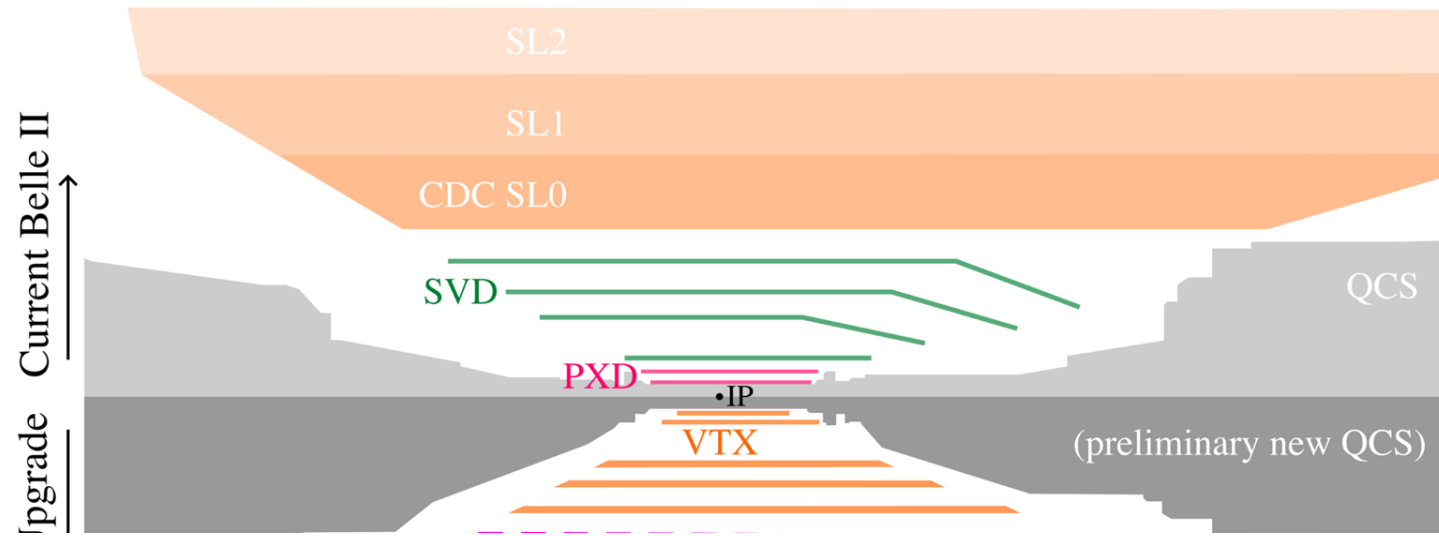


Intermediate Tracking and Timing volume

Upgrade of the Inner region:

- New oCDC without present SLO/1: leaving empty space in detector volume and particle ID coverage
- Available volume / radius determined by final VTX design, QCS envelope, CDC new inner radius:

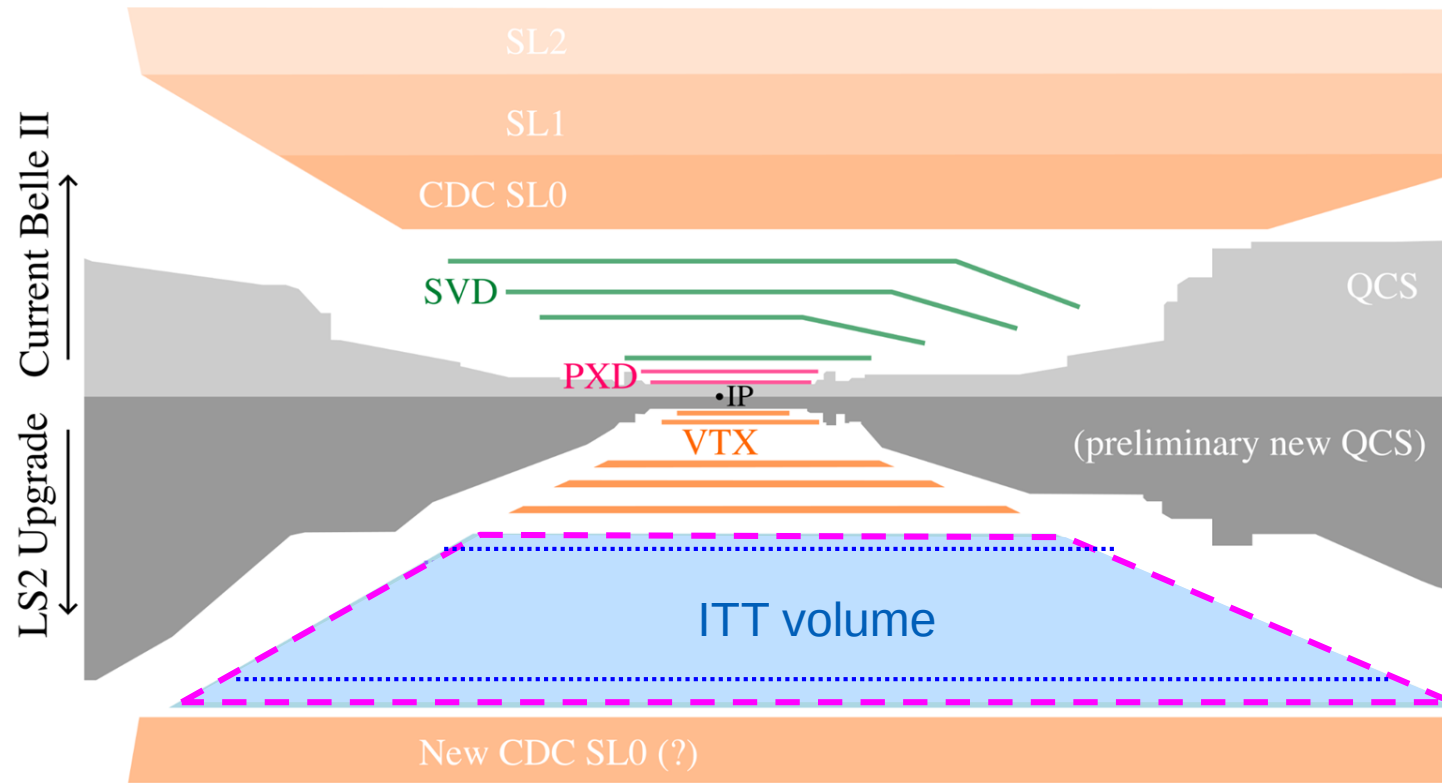
$$ca. 17\text{ cm} < r < 34\text{ cm}$$



Intermediate Tracking and Timing volume

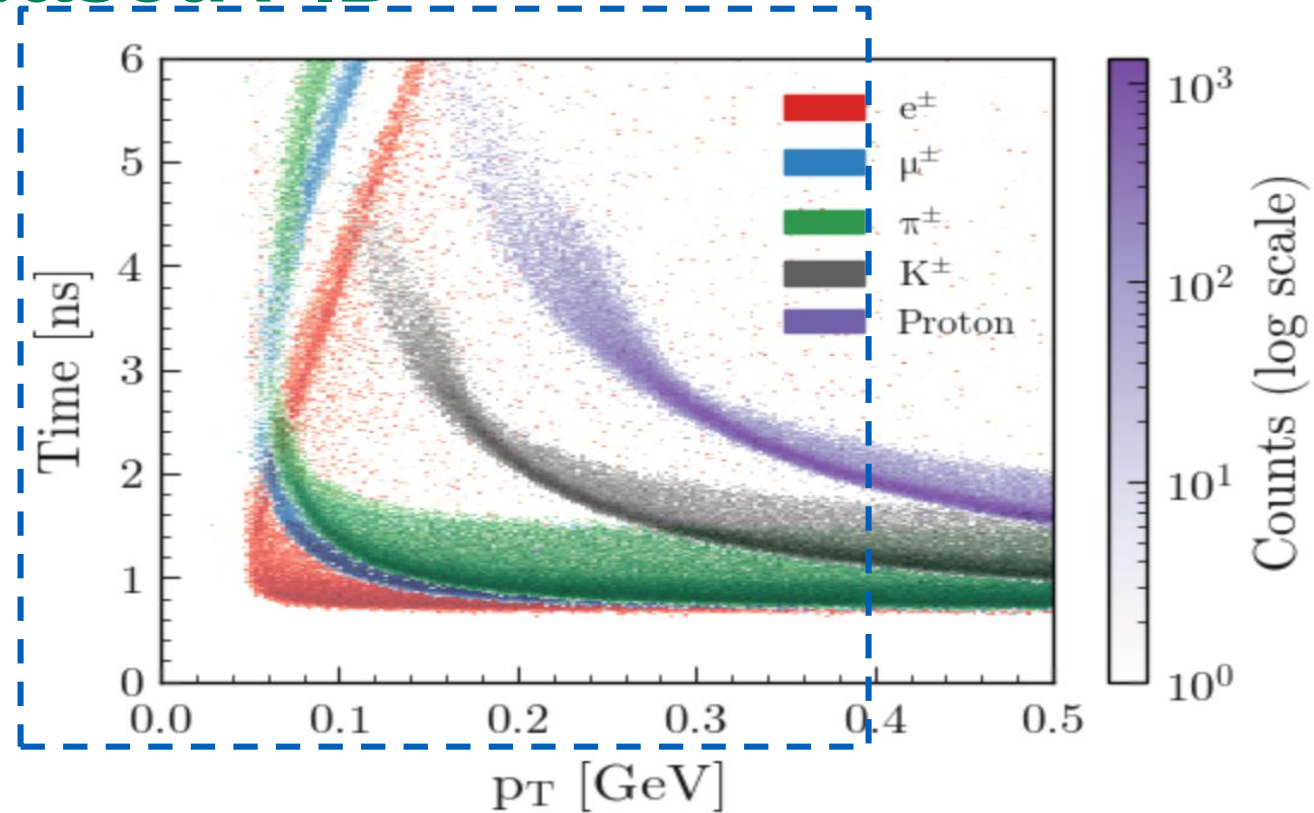
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 $ca. 17\text{ cm} < r < 34\text{ cm}$
- **Fast Timing Layer (FTL)?**
 - 1 layer of an AC-LGAD based detector
 - Timing resolution $\sim 50\text{ ps}$ at system level
- **Silicon Transition (Tracking) Layer (STL)?**



1. Investigation of impact on PID performance at low p_T
2. More generalized model beyond Belle II -specific geometry

Time-of-flight –based PID



Low p_T range especially for muons has been mostly discarded

- *Not only retention of PID performance, but creation of new capabilities by TOF PID?*

Initial simulations and detector requirements

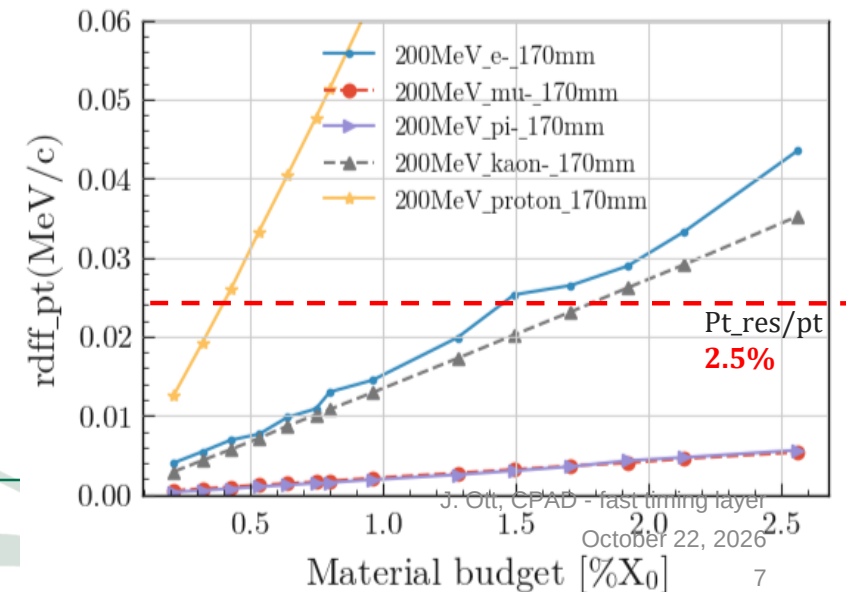
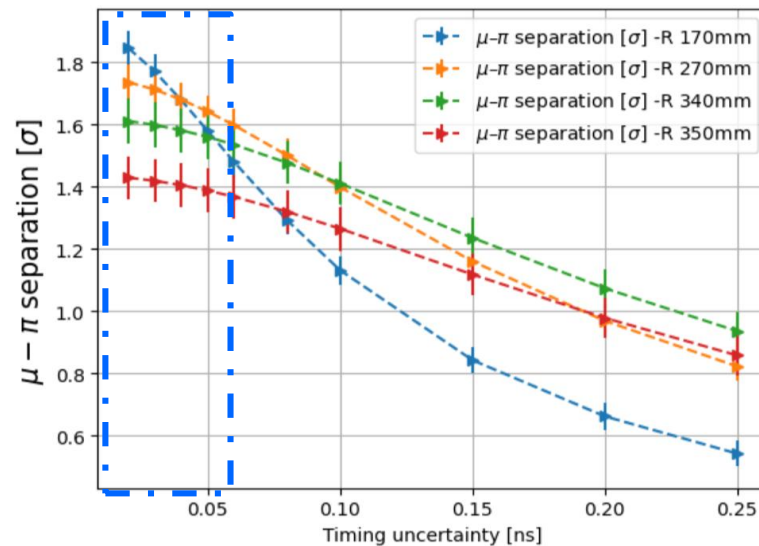
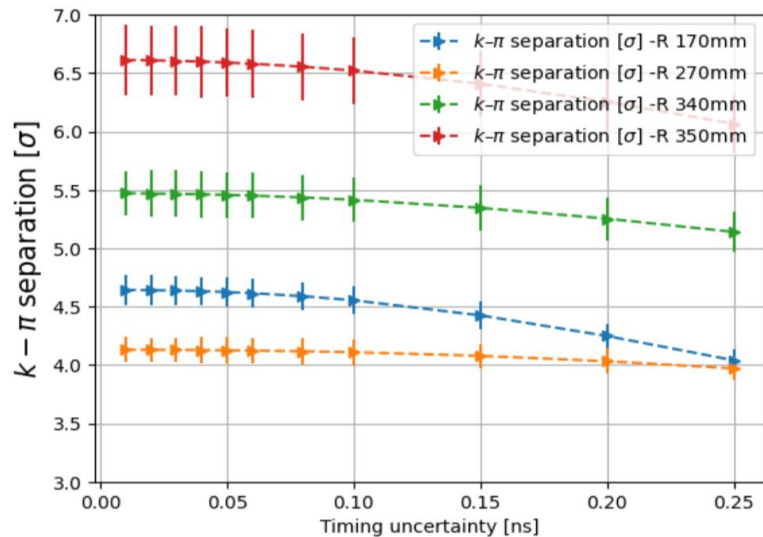
Initial work: Geant4 simulations to quantify impact on PID, exercise placement at different radii, set constraints on X/X_0

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

$k - \pi$ (ref.) and $\mu - \pi$ (novel impact physics) separation

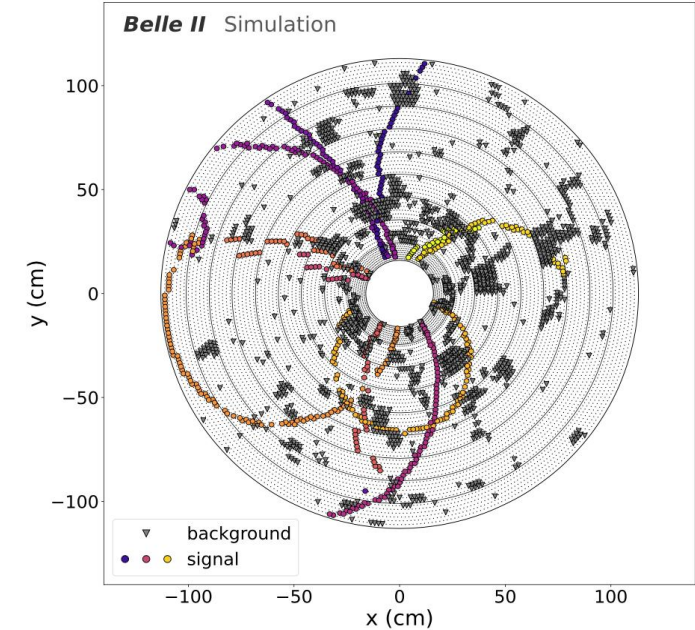
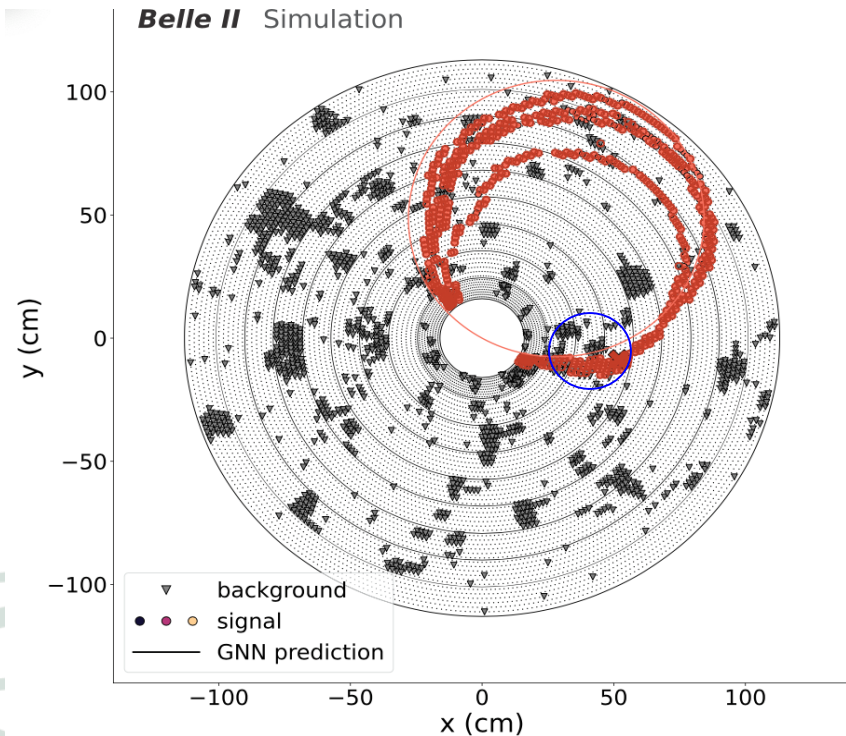
- Timing resolution: **50 ps**
- Material budget, low p_T tracks 100-200 MeV/c: **1.5 % X/X_0**

Impact on tracking resolution equivalent to current tracker – VTX material

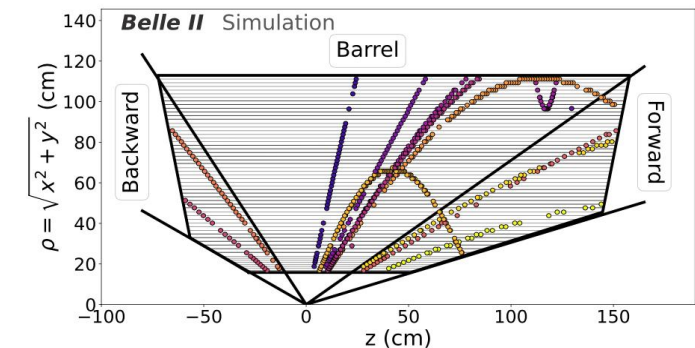


Particle ID by time-of-flight: low-momentum tracks

Particles with low momentum (< 200 MeV) are deflected in the magnetic field to “loop” around and pass detector layers multiple times

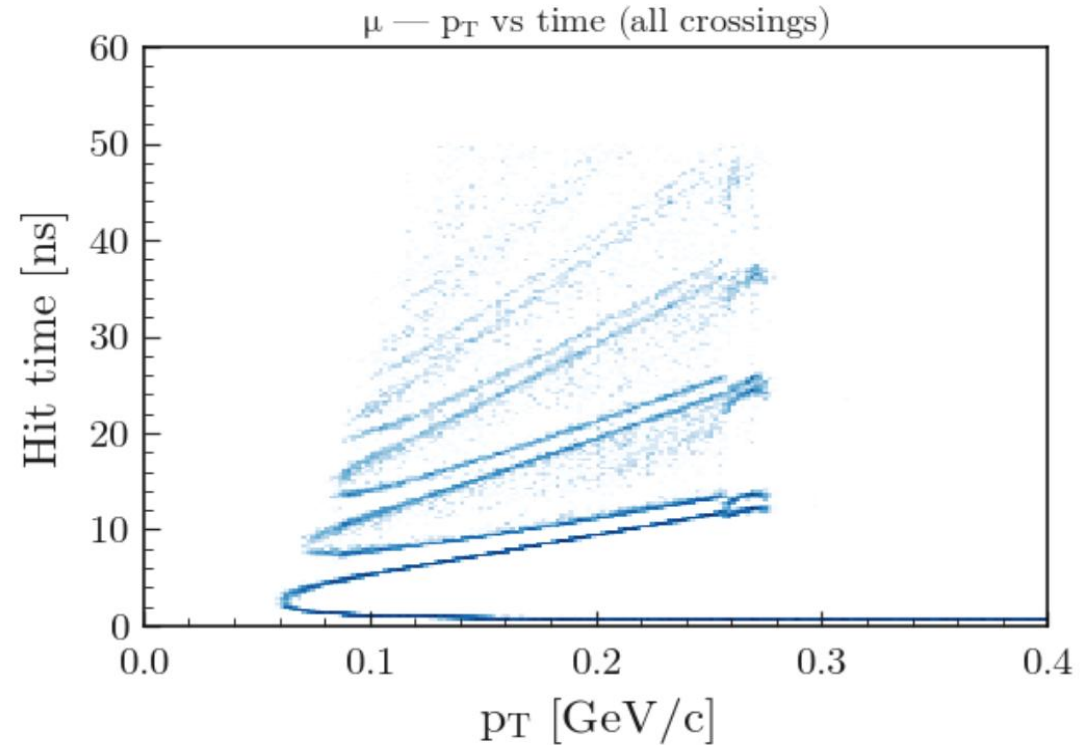
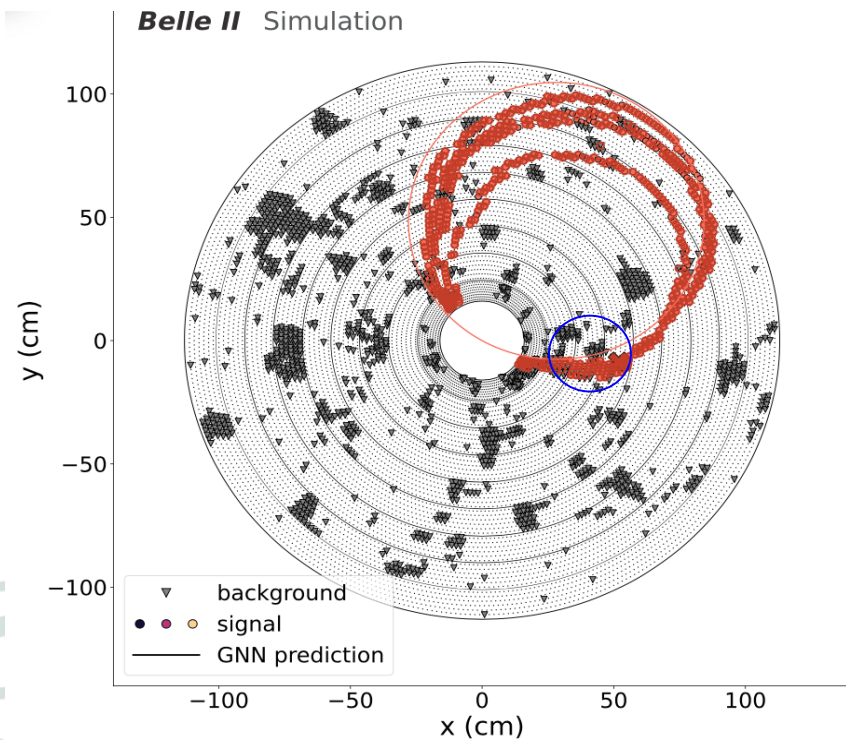


(a) Event display in the x - y plane.



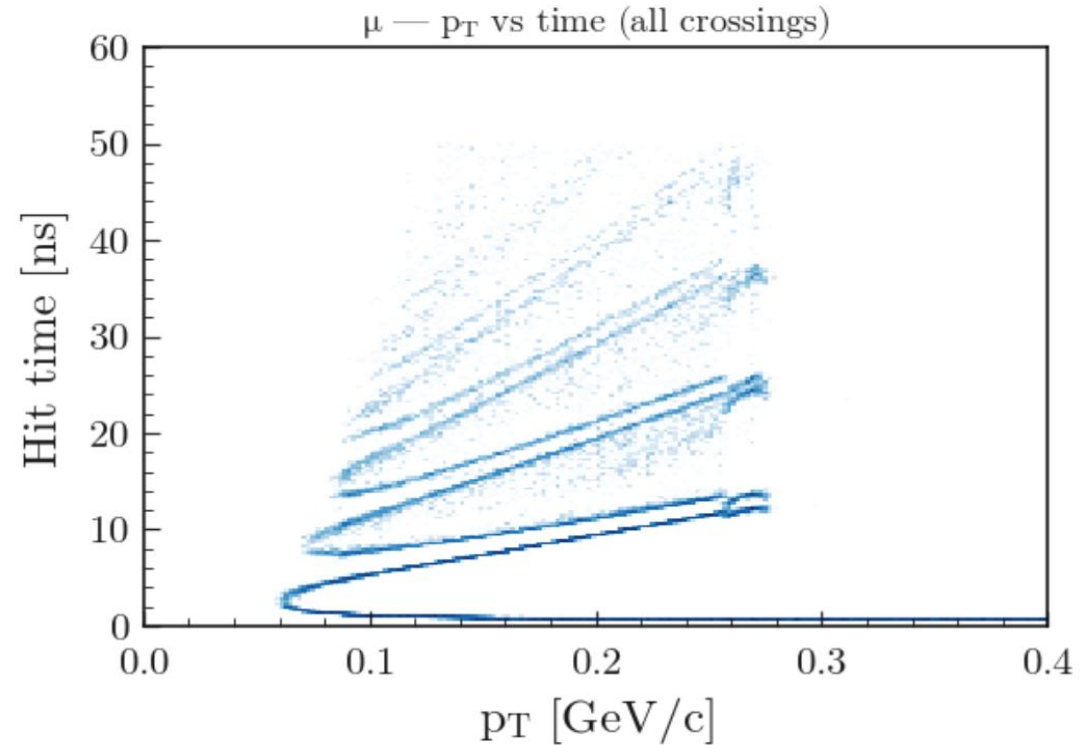
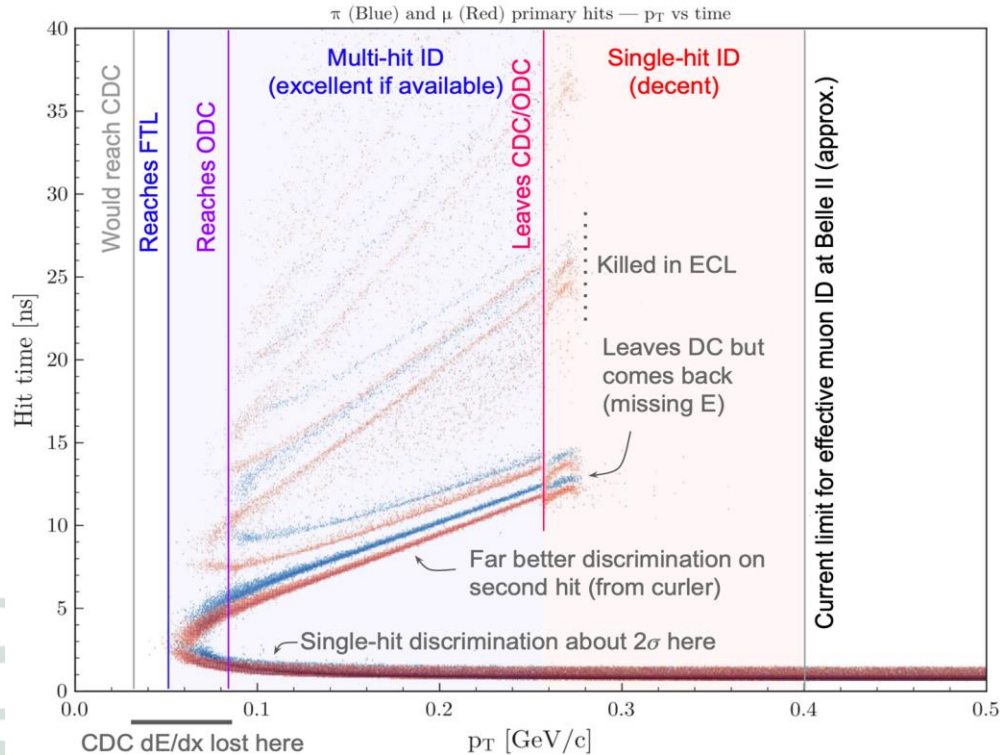
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Particle ID by time-of-flight: low-momentum tracks

- Differences in time-of-flight are enhanced by longer effective path length – even better separation between particle species

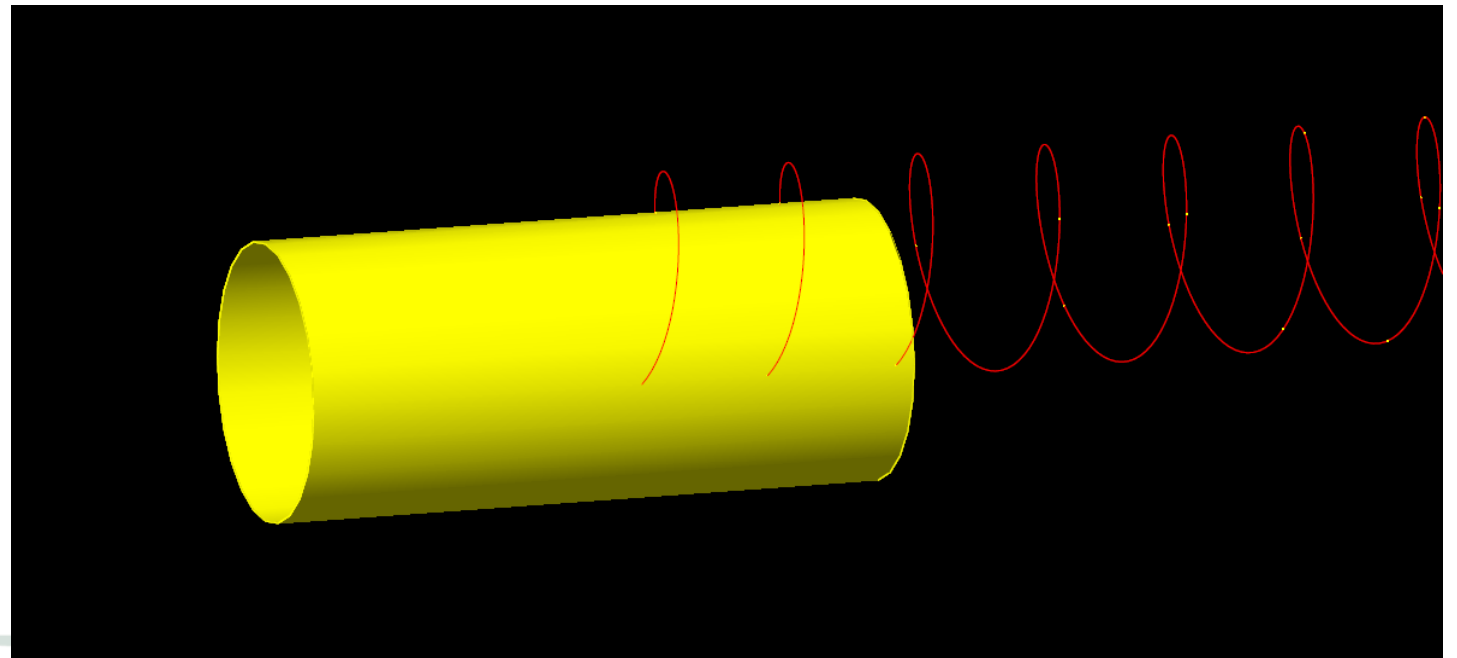


Pion / muon separation in Belle II preliminary upgrade scenario (not official and not up to date)

Standalone geometry and performance evaluation

- **Parametrization of observed patterns: t as function of mass, radius, magnetic field, transverse momentum, angle**
- **Simplified Geant4 geometry with adjustable Si layer thickness, material budget inside and outside TOF layer**

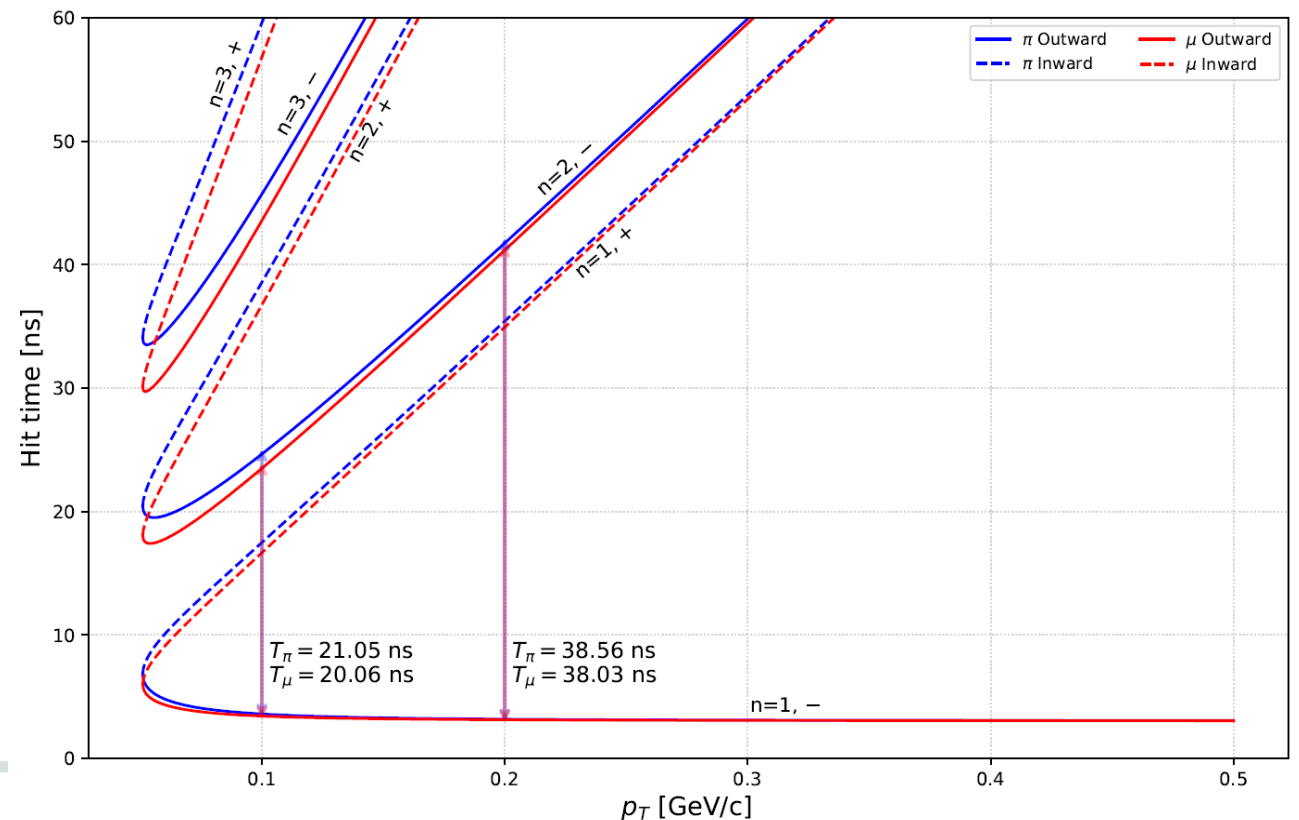
$$t(p_T, n) = \frac{\sqrt{(p_T / \sin \theta)^2 + m^2}}{qBc^2} \left[(2n + 1)\pi \mp \arccos\left(\frac{(qBcR_{det})^2}{2p_T^2} - 1\right) \right]$$



Standalone geometry and performance evaluation

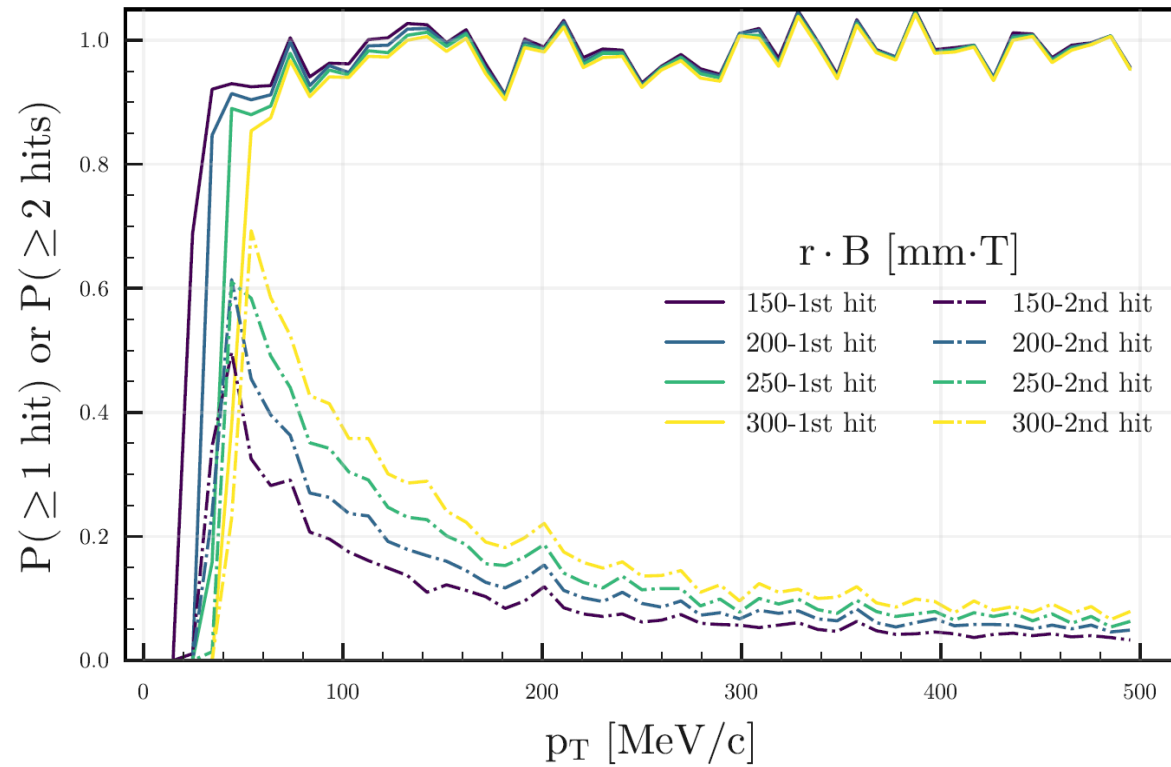
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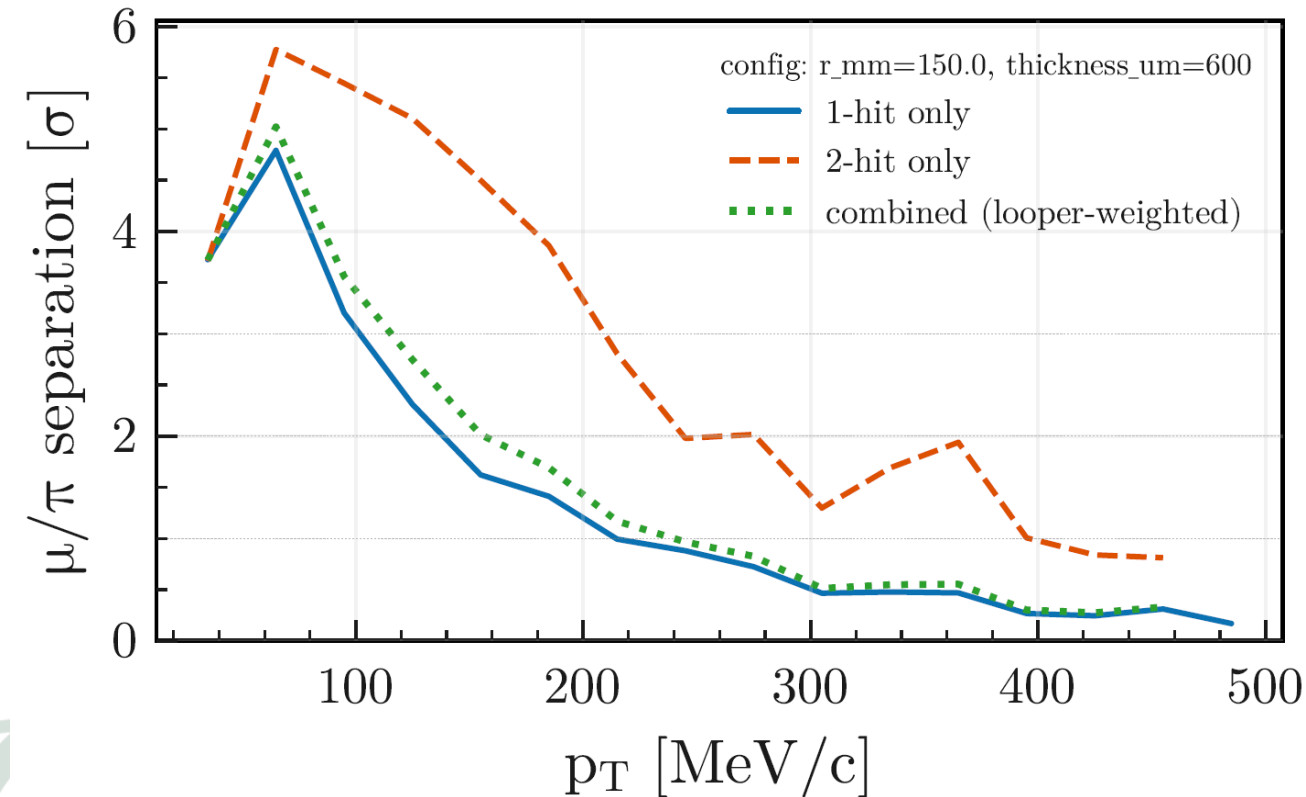


Standalone geometry and performance evaluation

Fraction of looping tracks

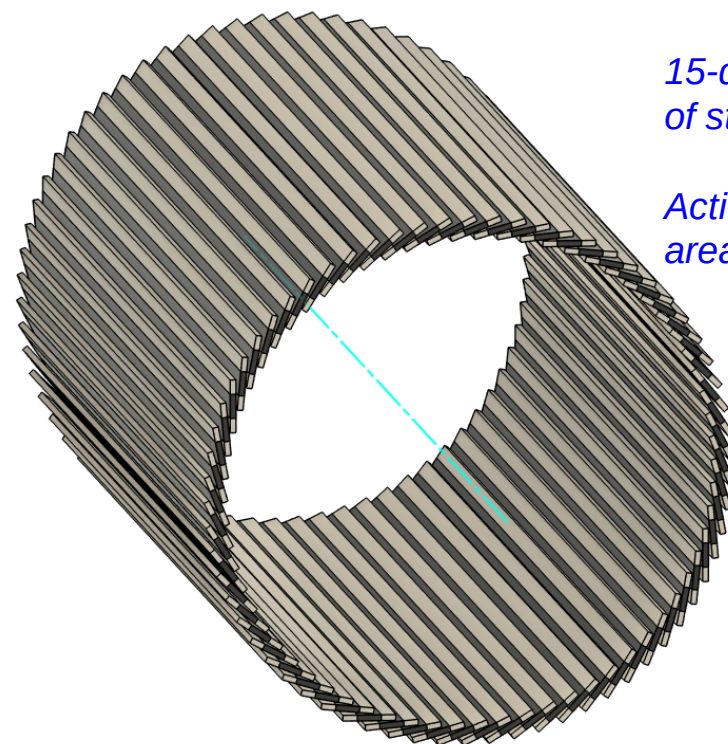
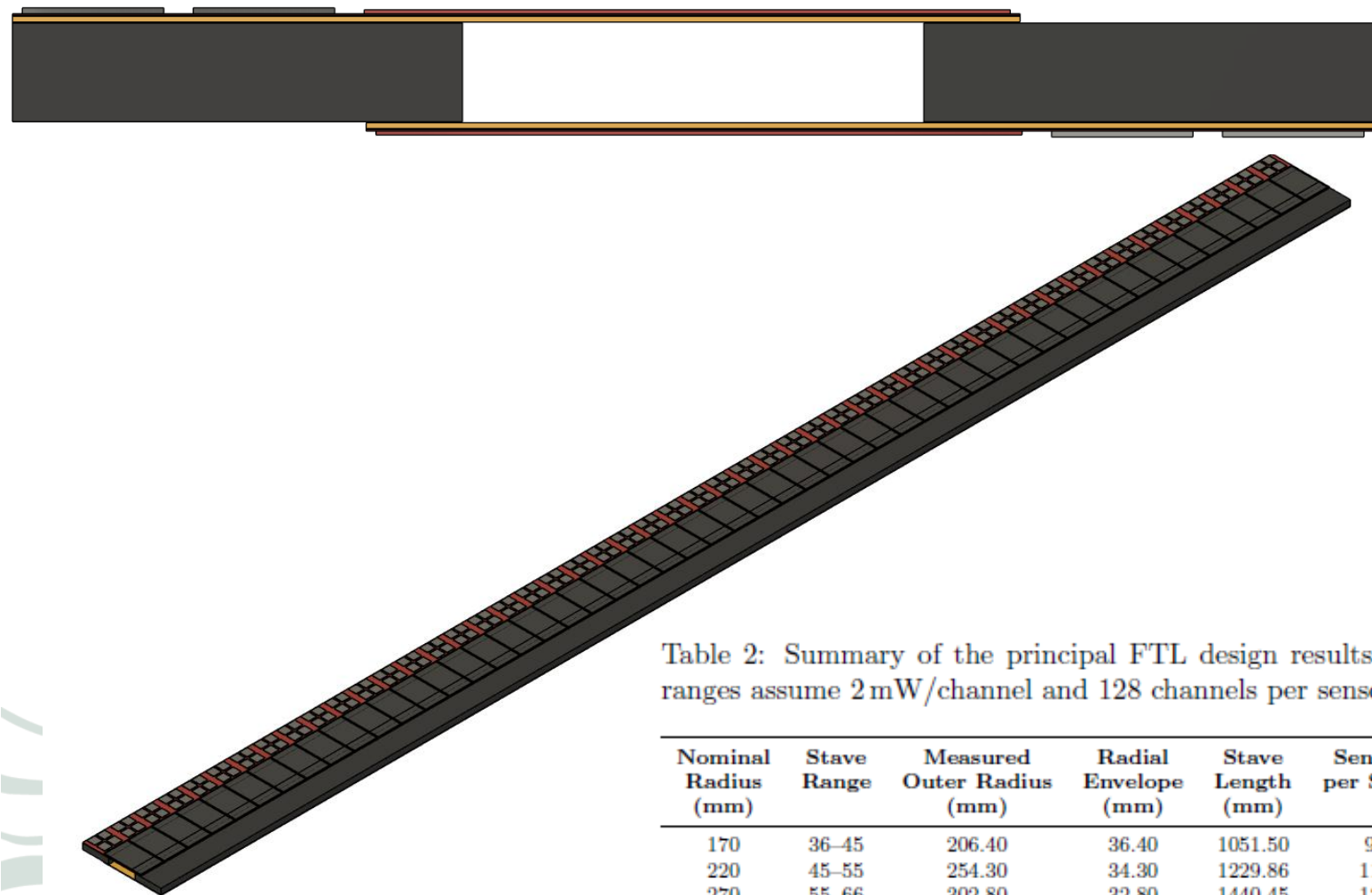


Separation with boosted decision tree, trained on single hit or two hits



Some examples – manuscript in preparation for a more extensive study, including radius and Si layer thickness variation

Towards the Belle II timing layer design



15-deg angle
of staves

Active sensing
area dark

Table 2: Summary of the principal FTL design results for each nominal detector radius. The power ranges assume 2 mW/channel and 128 channels per sensor.

Nominal Radius (mm)	Stave Range	Measured Outer Radius (mm)	Radial Envelope (mm)	Stave Length (mm)	Sensors per Stave	Total Sensor Range	Total ASIC Range	Readout Power Range (kW)
170	36–45	206.40	36.40	1051.50	99	3564–4455	14256–17820	0.912–1.140
220	45–55	254.30	34.30	1229.86	115	5175–6325	20700–25300	1.325–1.619
270	55–66	302.80	32.80	1440.45	135	7425–8910	29700–35640	1.901–2.281
320	66–77	351.80	31.80	1650.04	155	10230–11935	40920–47740	2.619–3.055

Assumes 2x3 cm sensor and maximal overlap: conservative layout.

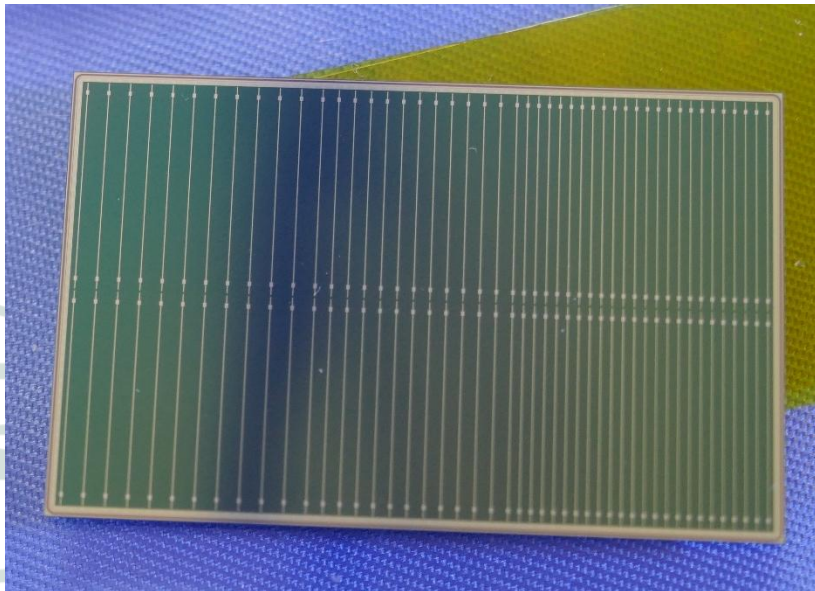
OLDER NUMBERS IN THIS TABLE



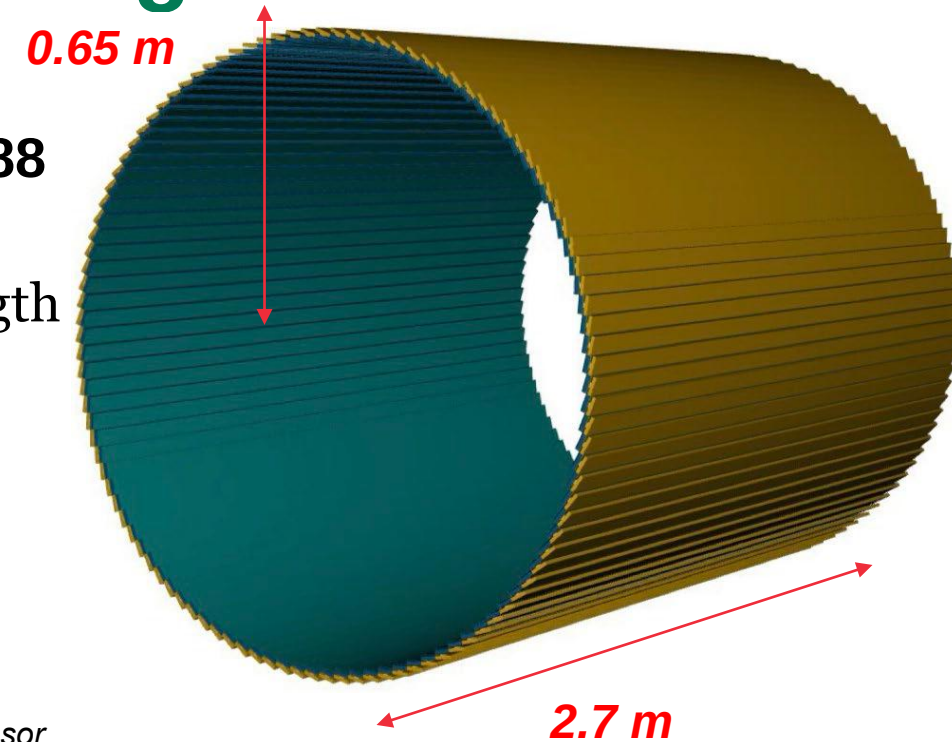
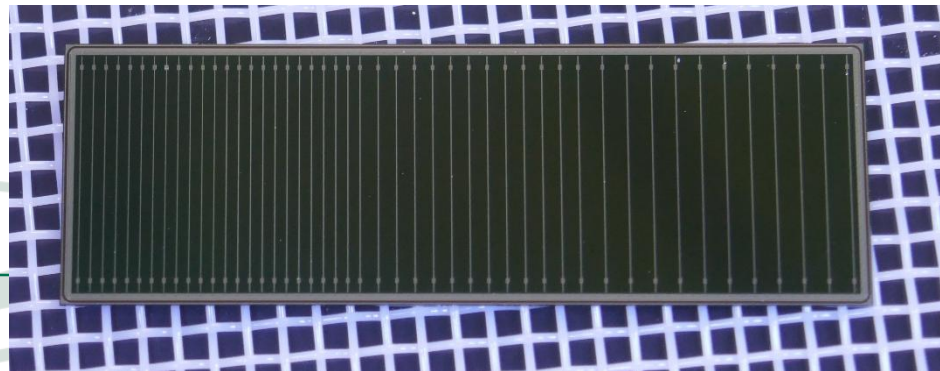
Inspiration: Electron-Ion Collider barrel-TOF design

- bTOF: $-1.33 < \eta < 1.74$
- Cylindrical shape: composed of 144 tilted staves (288 half-staves)
 - Length 1.4 m for each half-stave – 2.8 m total barrel length
 - Cooling: water or glycol mixture, RT or slightly below
 - Strip AC-LGAD sensors, 500 μm pitch

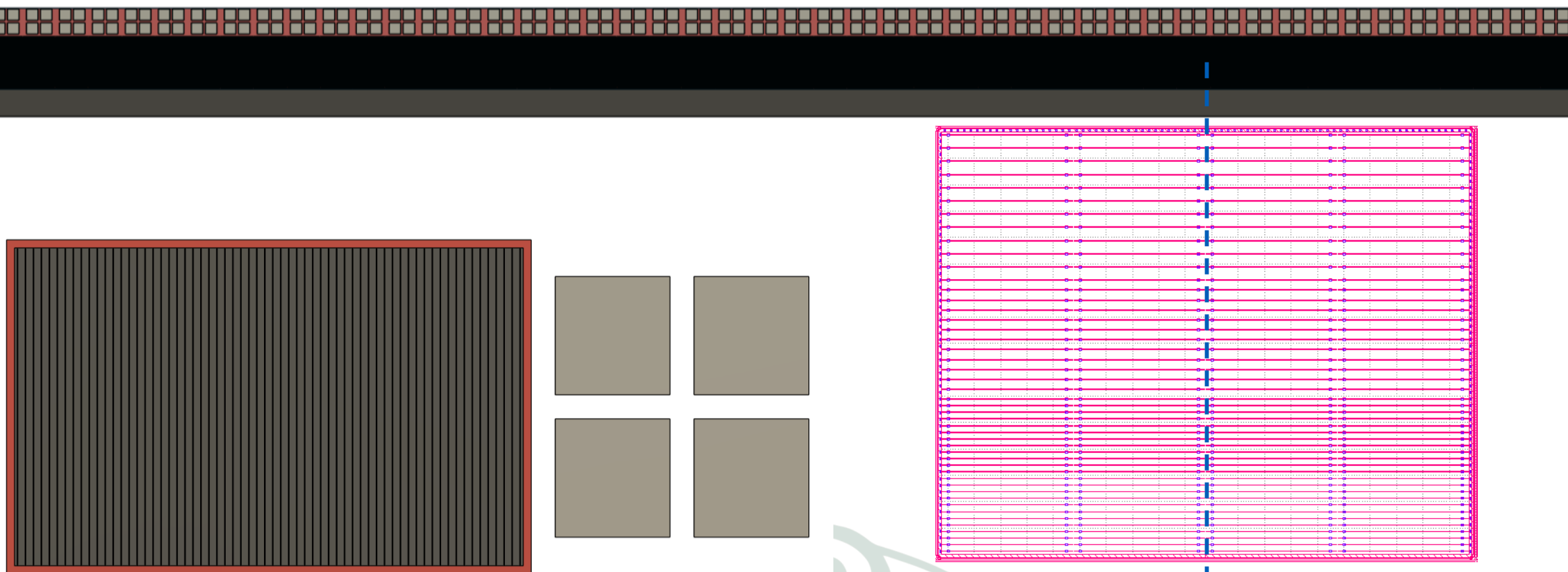
'Full-sized' prototype strip sensor



'Half-sized' prototype strip sensor



Stave layout



Strip sensor with 4 ASICs/sensor (to cover # of strips)

2x- or 4x 1 cm strip sensor

1. Oct, CPAD - fast timing layer

October 22, 2026

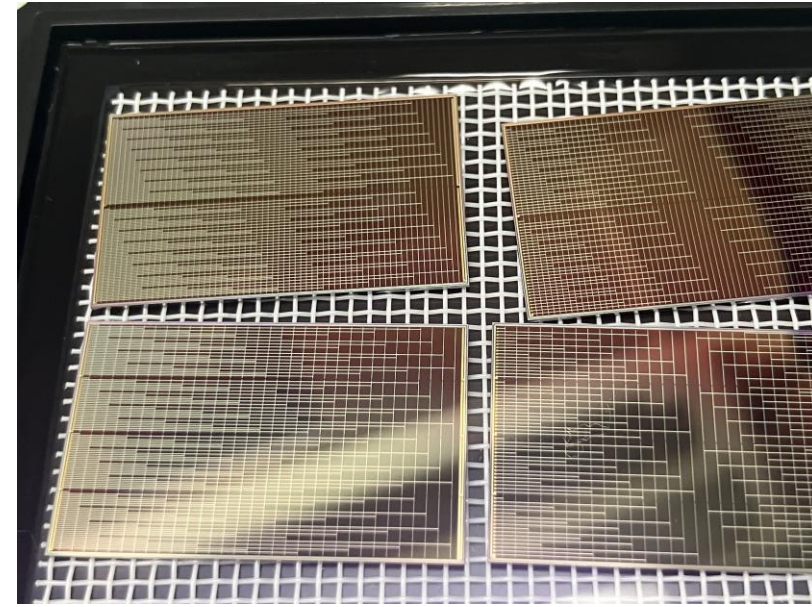
Low-mass LGAD sensors

First starting point: large AC-LGAD strip sensors, prototypes from BNL and HPK

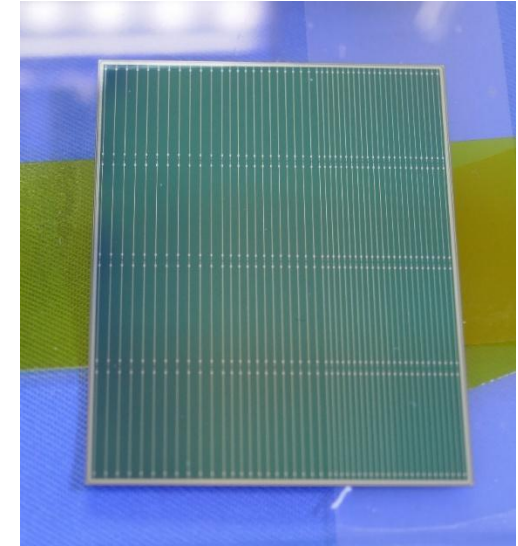
- To be thinned down to almost active thickness, 20/30/50 μm – bendable silicon

Active CMOS / MAPS with improved timing capabilities?

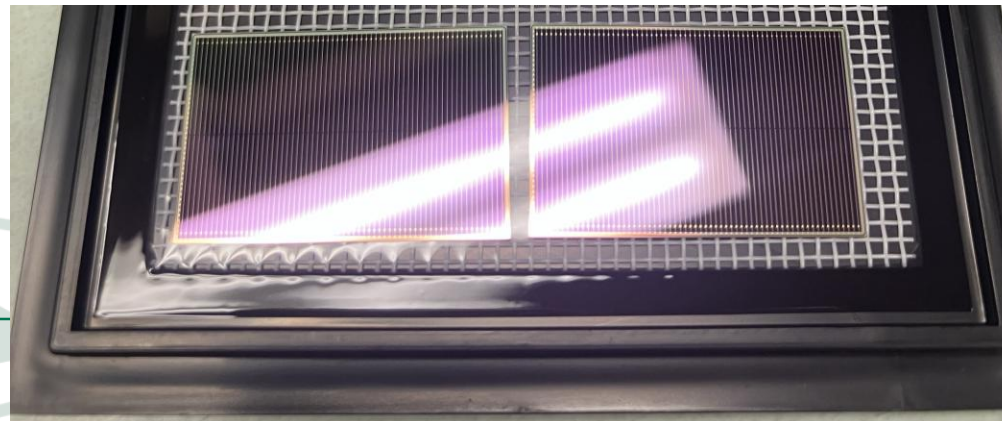
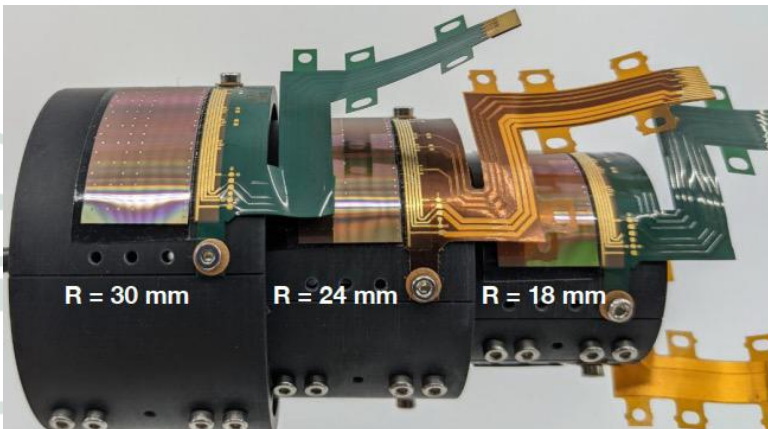
- *Discussed in several talks at this workshop, strong interest and ongoing efforts in the community!*



Double-metal strip sensor



'full-sized' uniform pitch strip sensor



ASIC options

1. FCFD (Fermilab Constant Fraction Discriminator)

- ASIC for ePIC barrel TOF

2. HP-SoC (Nalu High-Precision timing System on Chip)

- Fast TIA + high-rate waveform digitization
- Currently 9-channel prototype

3. (EICROCv1)

- Readout ASIC for ePIC forward TOF (pixelated sensors) and several other systems

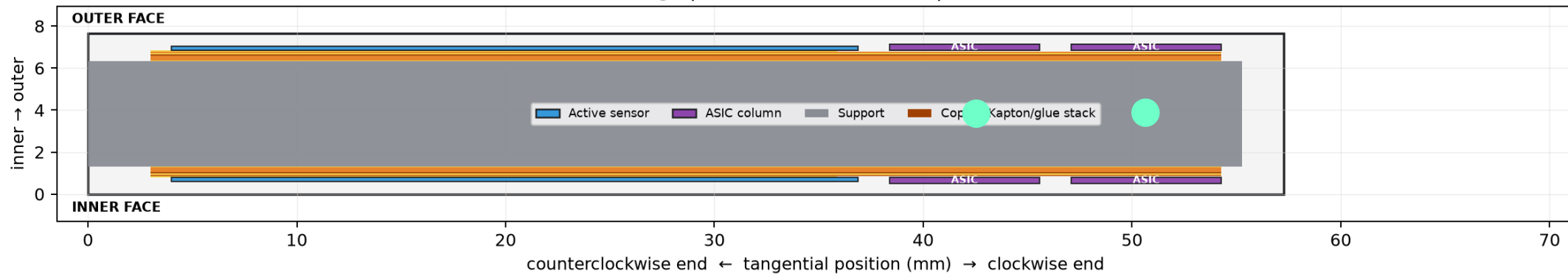
<https://indico.cern.ch/event/1600786/timetable/#4-review-of-4d-asics>

Based on talks at this workshop, other options might become mature and be realistic options at the time!

Stave layout

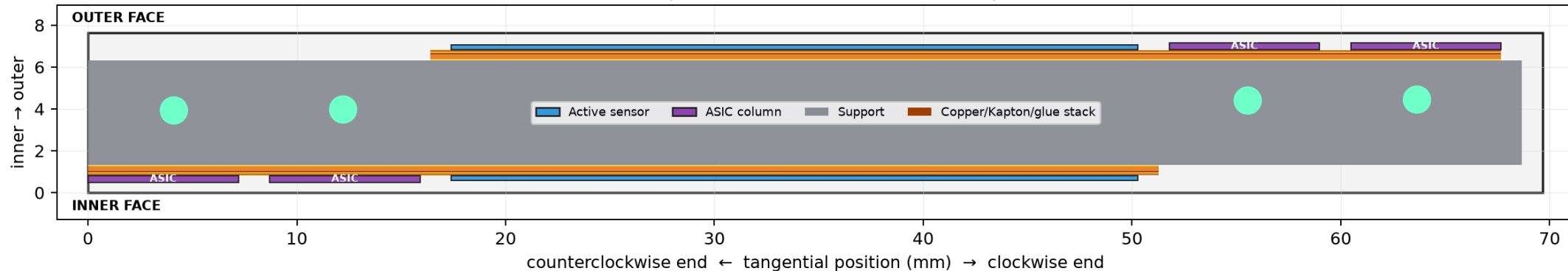
ASIC placement convention: optimized stave at the top of the barrel

Same-end-ASIC design | inner ASICs: clockwise | outer ASICs: clockwise



Same-side or opposite-side ASIC: mechanical considerations, and optimization of cooling

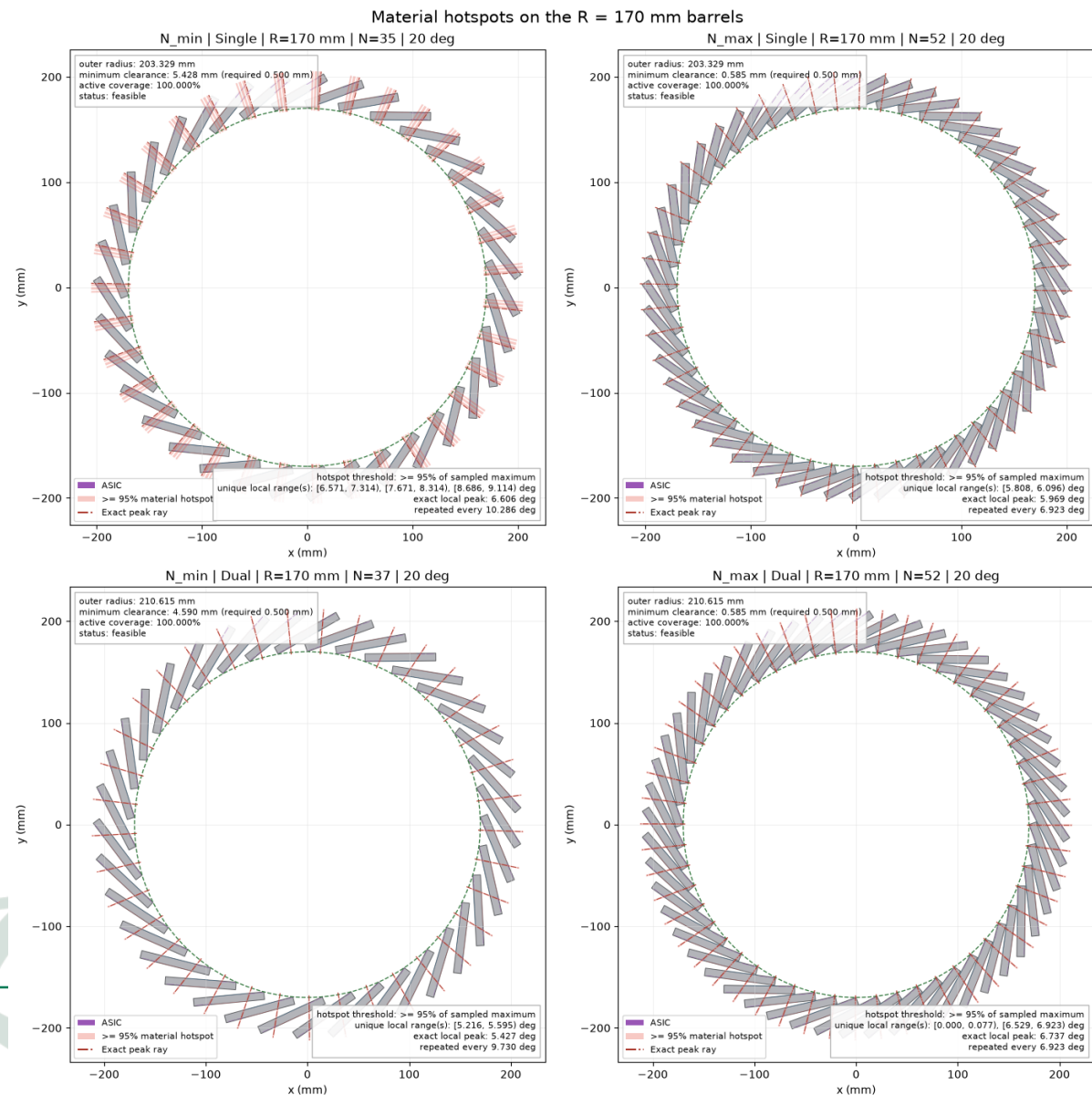
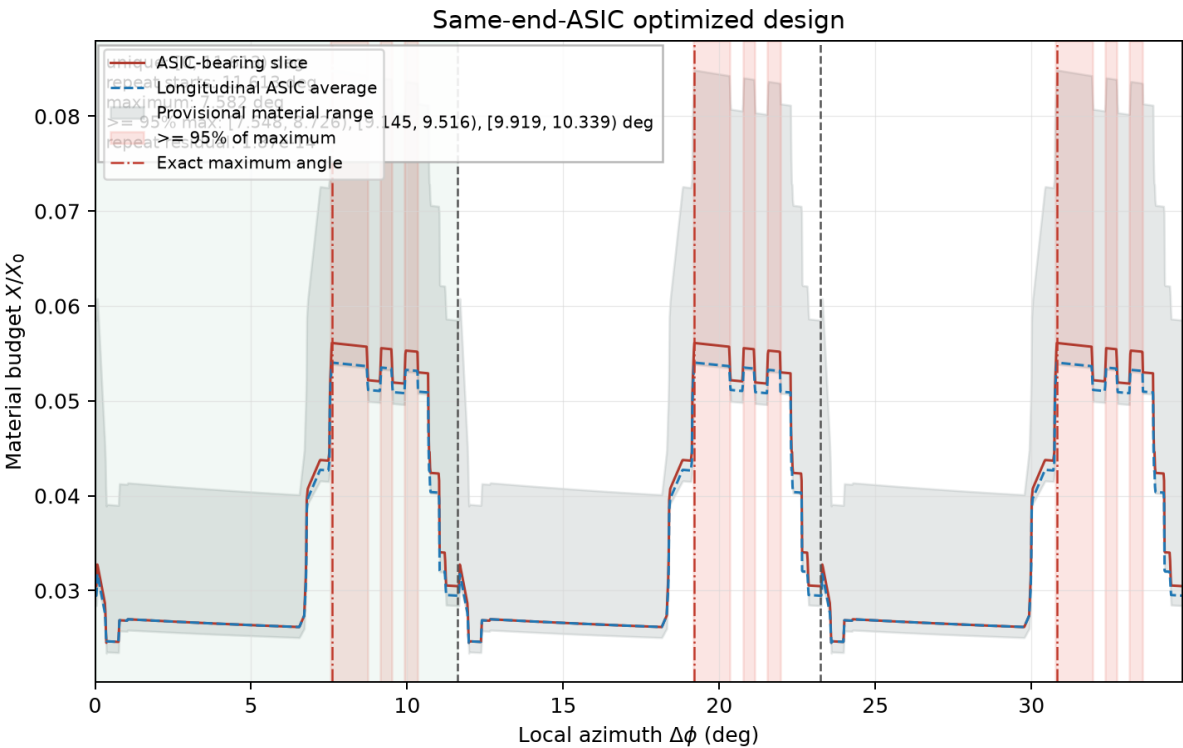
Opposite-end-ASIC design | inner ASICs: counterclockwise | outer ASICs: clockwise



Layout and optimization

Parameterizing as much as possible:
radius, tilt angle, number of stave,
length, sensor spacing, material budget,

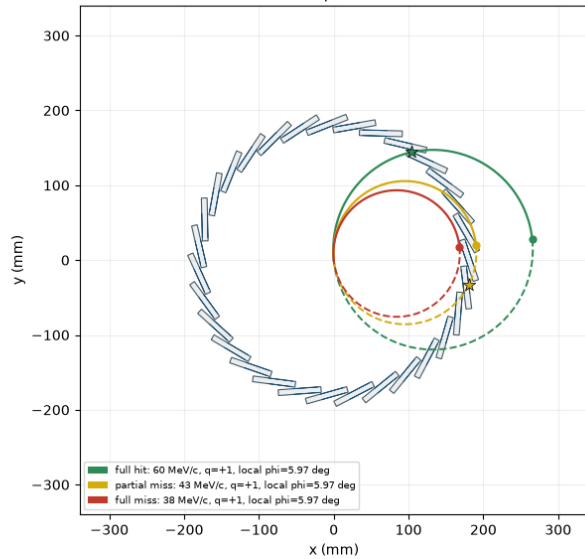
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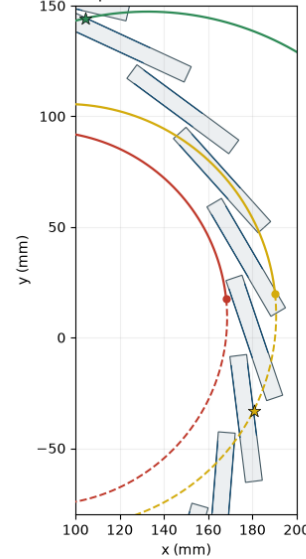
Momentum coverage vs material budget

Missing-track diagnostic | Single | R=170 mm, N=31, angle=10 deg

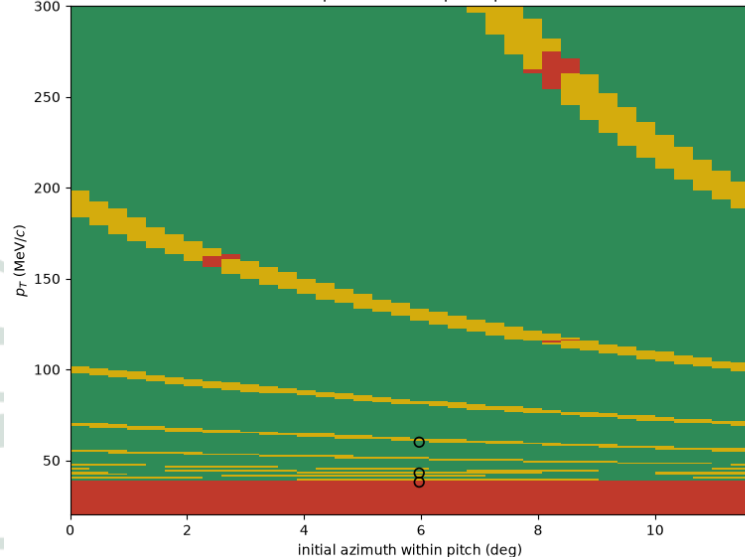
Full barrel and representative tracks



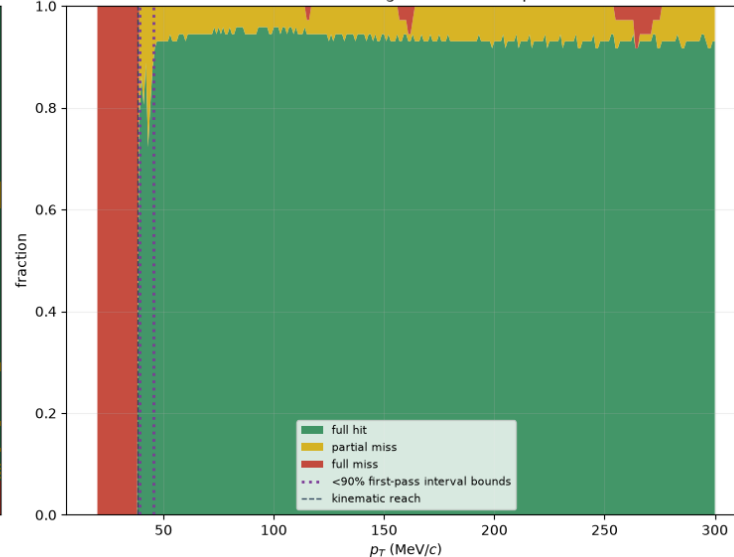
Track microscope (solid=outward, dashed=return)



One-pitch class map for q=+1



Fraction of charge-azimuth samples



Optimization study: material, vs missed hits

- low-momentum tracks with tight curvature can miss sensors

Trade-off in detector design: optimal layout for low- p_T and higher- p_T tracks may not be the same

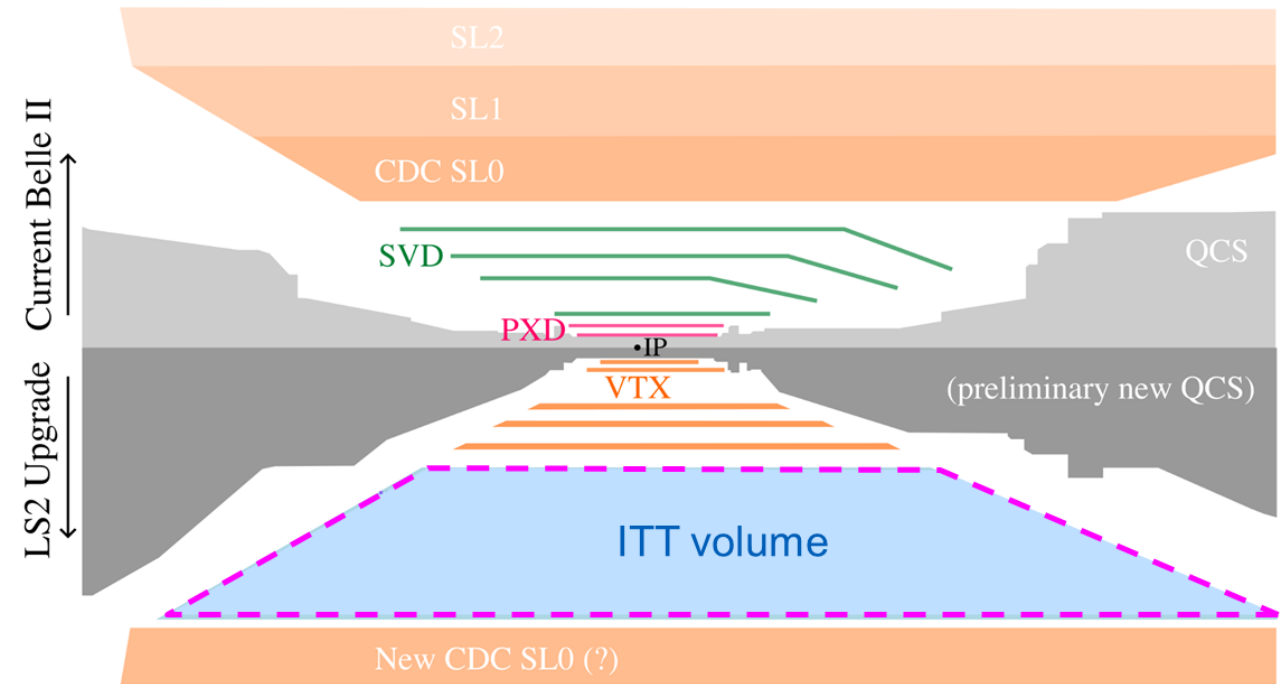
- PID performance improvement low- p_T tracks is most significant, but higher-momentum tracks are not to be neglected either...*

Summary (Belle II FTL)

Ongoing work:

- Beam background overlays
- Thermal and mechanical design, data / readout rate estimates
- *Potential for triggering?*

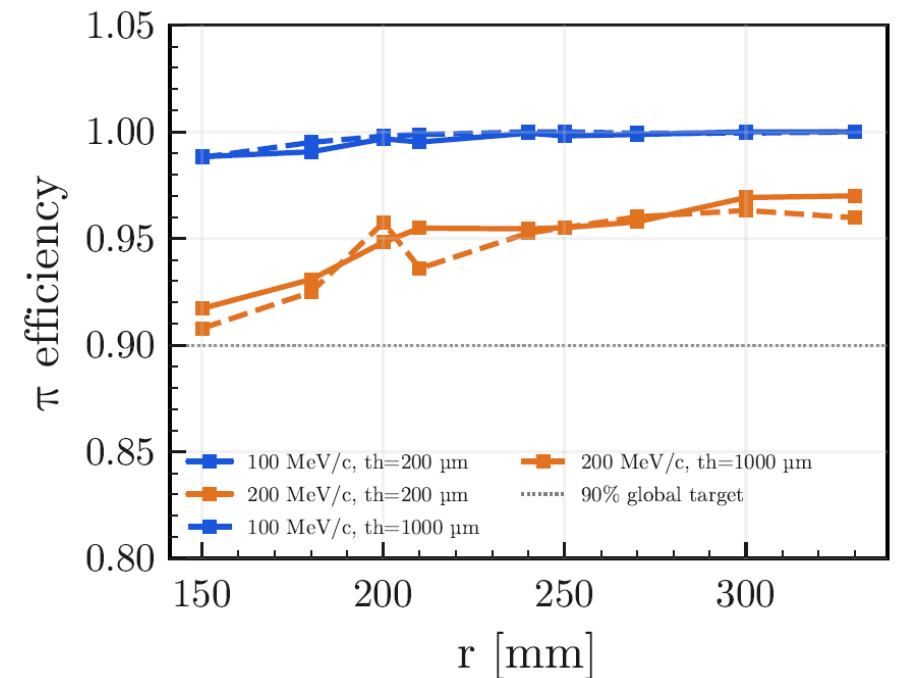
Timescale: no formal decision made, but an option seriously considered is to push the FTL installation to 2036 or beyond

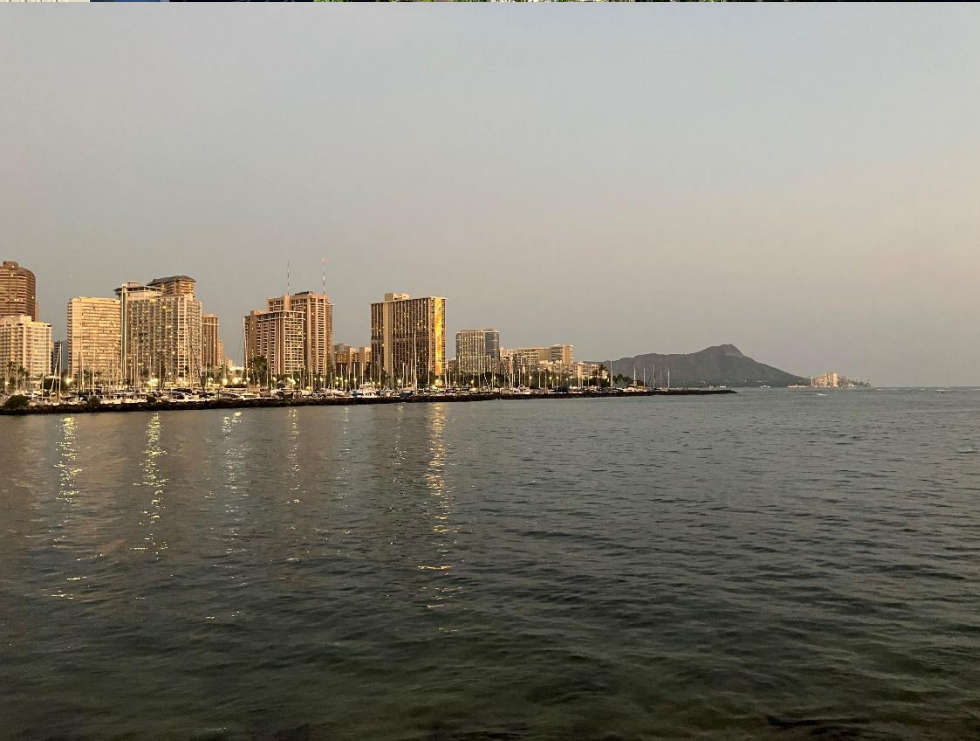


Summary

More generic R&D: intentional reconstruction, leveraging of low-momentum looping tracks with multiple TOF detector hits

- (AC-)LGAD timing layers at low radii not ‘only’ for tracking and vertexing, and background rejection, but also consciously for particle ID
- Opening new sensitivity in the low-momentum range
- Material budget becomes more critical at lower radii
- *Our assumptions here, of 30-50 ps, do not even push limits on sensor and TDC timing resolution! What is possible with system-level timing resolution around 10-15 ps?*





Thank you!
Mahalo!