STOPGAP
a Time-of-Flight Extension for the TOP Belle II Barrel PID System

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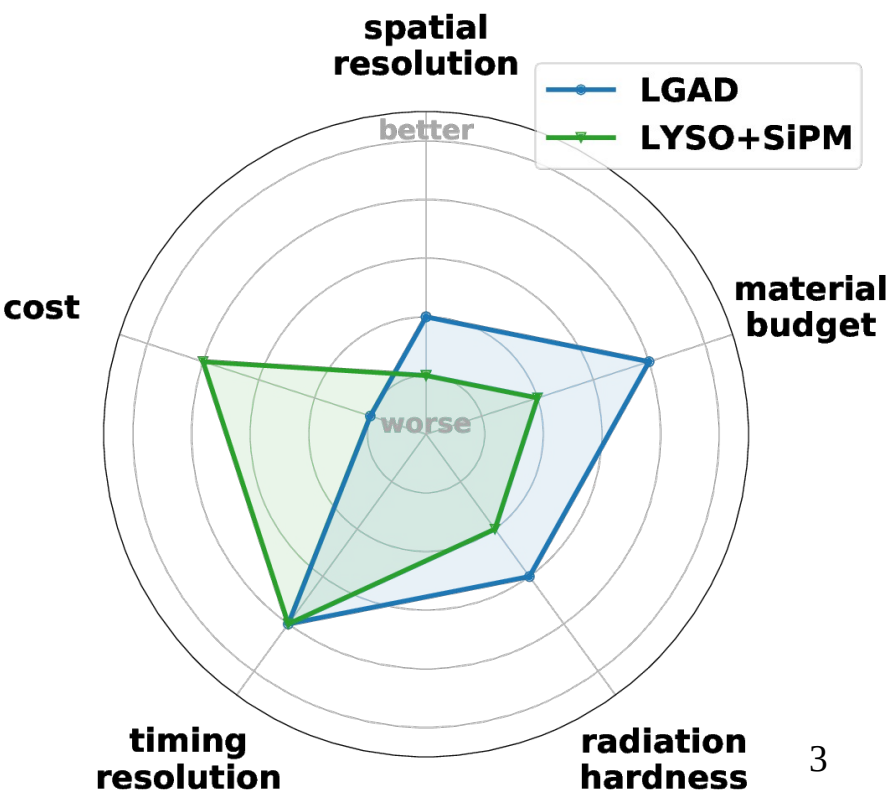
Fast Timing in High Energy Physics

- Ongoing upgrades plan for fast (30-50ps single MIP) timing layers
  - ATLAS endcap, CMS barrel + endcap for pileup suppression
  - LHCb for time-of-flight pion/kaon separation
  - Higgs factory detectors study timing in Particle Flow reconstructions
- The future of HEP instrumentation is timing!
  - Ideally: thin 4D tracking detectors with large areas
- Belle II also interest in fast timing technologies
  - Time-of-flight particle identification
  - Timing layer(s) in tracking upgrade and as track trigger

Fast MIP Timing Sensors

- State-of-the-art for HL-LHC upgrades: ~30ps for MIPs
- LGAD is expensive,
  ~mm^2 pixels, only 95% efficient
- LYSO+SiPM is thick,
  limited to ~cm^2 granularity



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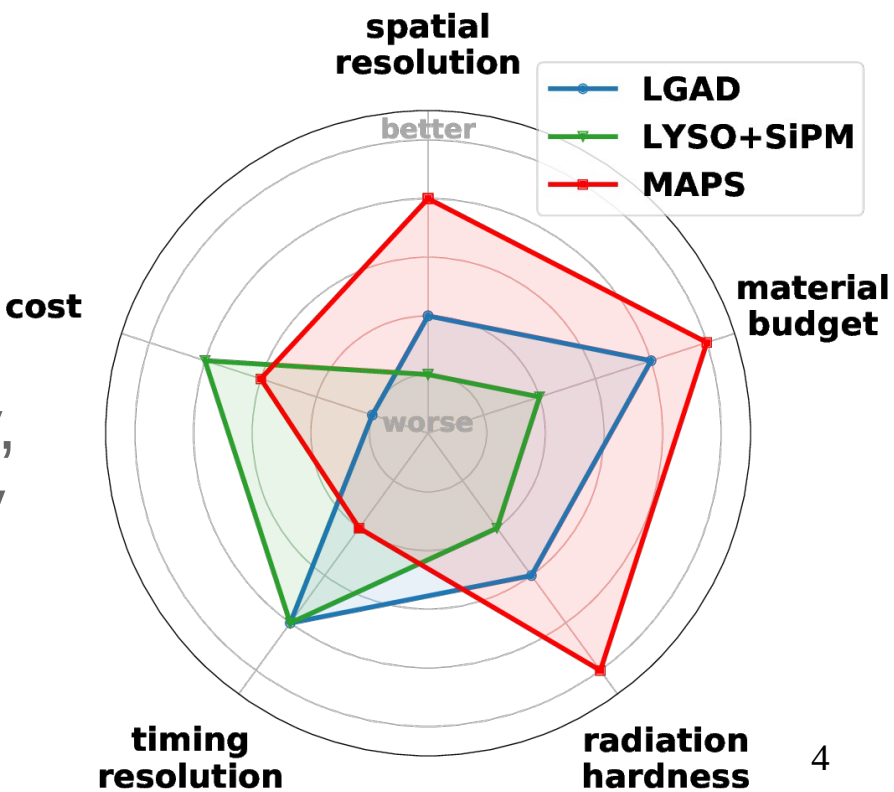
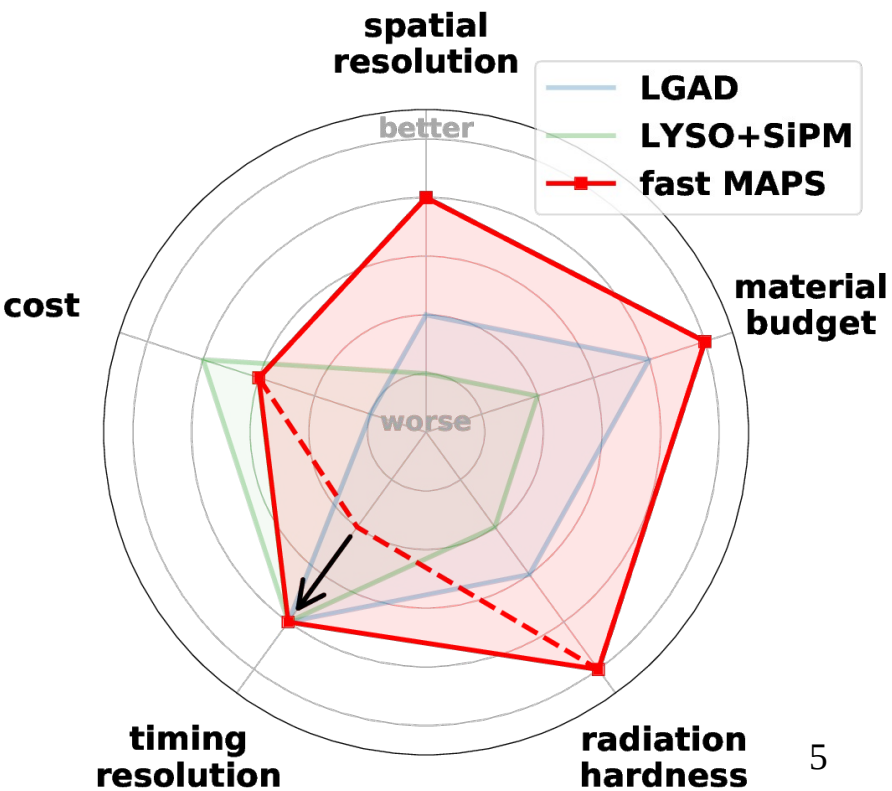
- MAPS are thin, high granularity,
  cost effective - but not currently
  competitive in time resolution



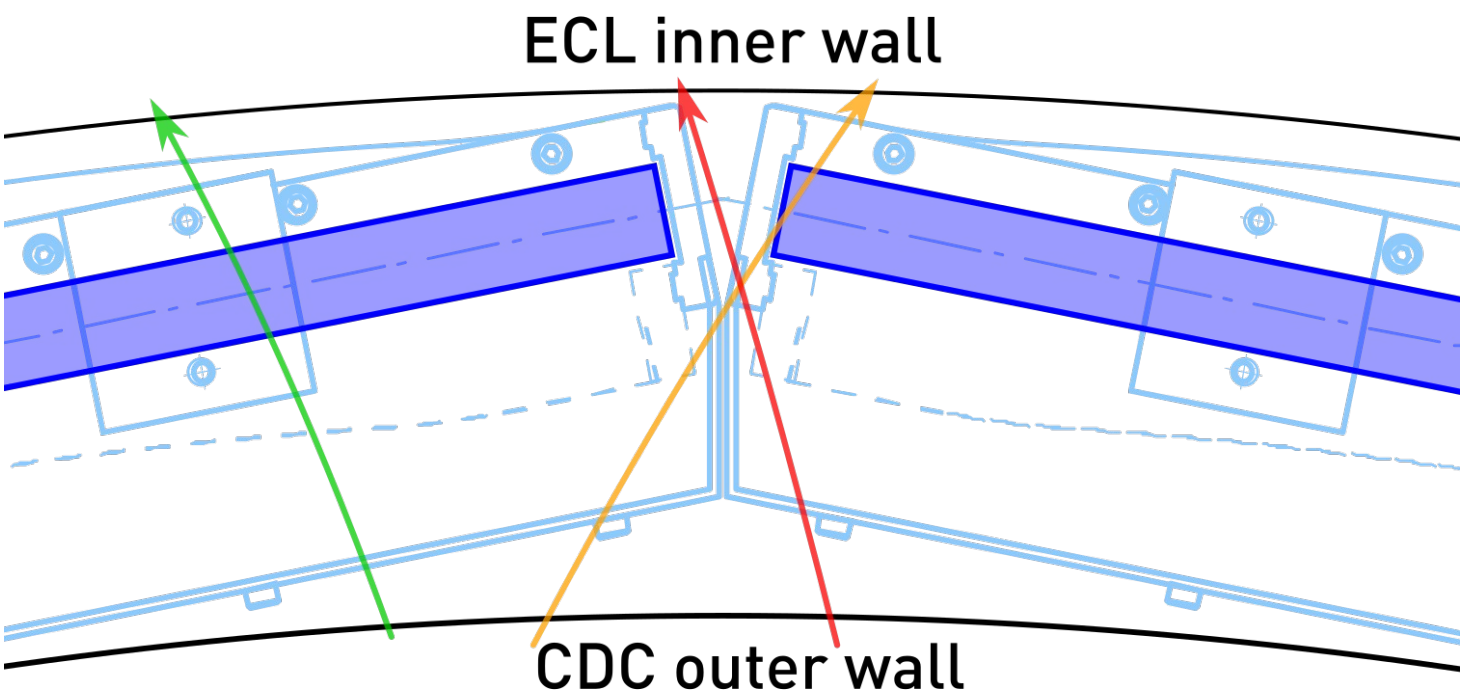
Establishing Fast MAPS

- <100ps time resolution achievable without internal amplification by integrating fast, low noise amplifier and threshold comparator into each pixel
  - W. Riegler and G. Aglieri Rinella: 2017 *JINST* **12** P11017
    - *"it's possible"*
  - L. Paolozzi et al.: 2020 *JINST* **15** P11025
    - *"it works with small pixels"*
  - Y. Değerli et al.: 2020 *JINST* **15** P06011
    - *"progress with ~mm² pixels"*
- Established Fast MAPS would be a game changer for fast HEP sensors
  - Feasible option for fully integrated large area 4D tracking detectors
- Every new technology needs a suitable breakthrough application



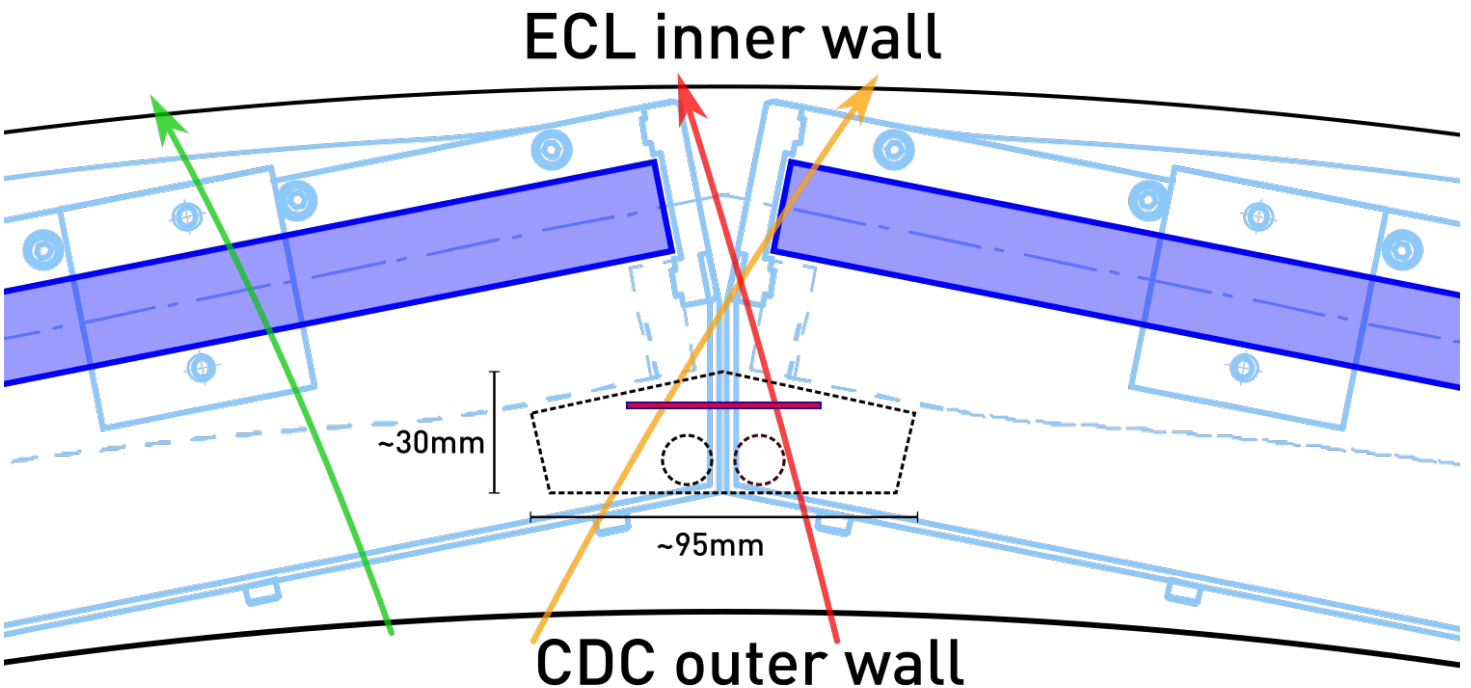
STOPGAP

- Belle II TOP PID system is not hermetic
  - 6% of tracks miss active volume, 3% degraded from edge effects



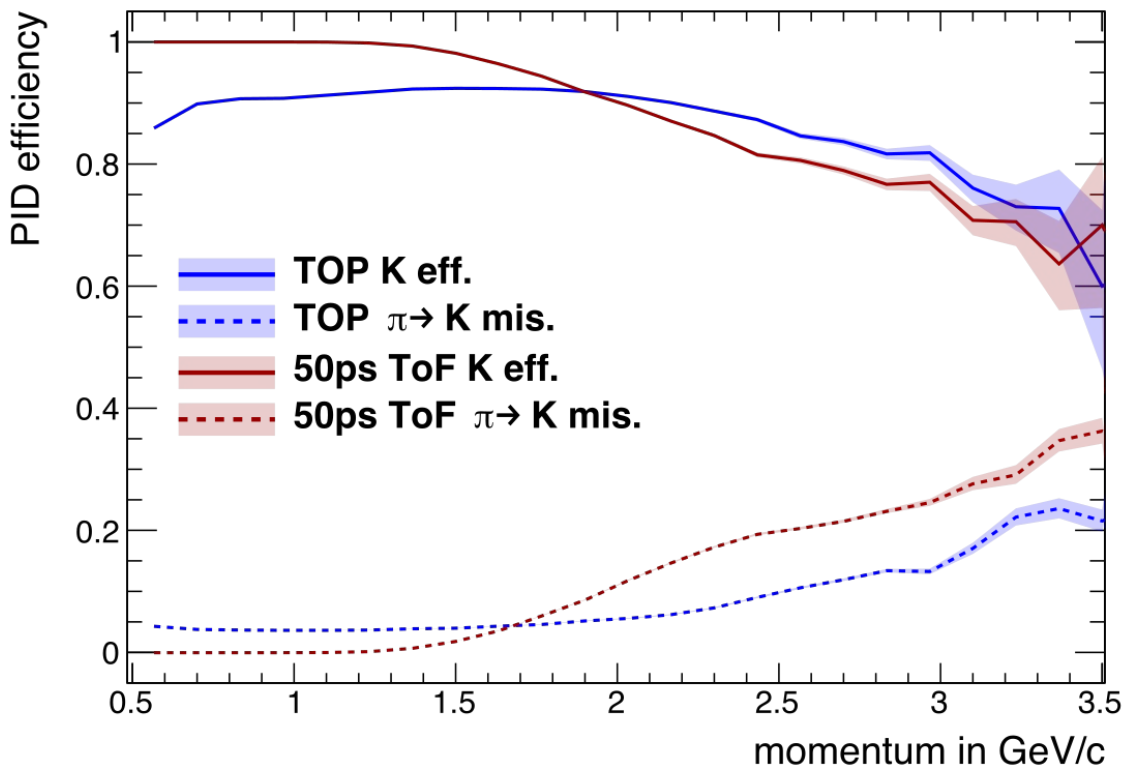
STOPGAP

- Belle II TOP PID system is not hermetic
  - 6% of tracks miss active volume, 3% degraded from edge effects
- Our proposal: Supplemental TOP Gap Instrumentation (STOPGAP) with time-of-flight sensors to recover PID hermeticity
  - Expect improvements in flavour tagging & full event reconstruction efficiency



Time-of-flight PID in Belle II

- Detailed study on STOPGAP based on Time-of-Flight: requires around 50-70ps MIP time resolution sensors
  - Based on full Belle II simulation and reconstruction of $B\overline{B}$ events
- TOP never reaches 100% efficiency/0% mis-ID



STOPGAP: a Fast MAPS Demonstrator

- Timing is most important for STOPGAP, other requirements are “tame”
  - Ideal initial application for fast MAPS
- Build small scale STOPGAP prototype module and install into Belle II
  - Few cm^2 is enough, could contain more than one sensor technology, “integrated external” readout (e.g. CERN picoTDC or similar)
  - Belle II endcap regions have reasonable accessibility during most summer shutdowns
- Demonstrate fast MAPS timing performance in “real deal” conditions
- Aim for installation of full STOPGAP during extensive Belle II + SuperKEKB shutdown expected in $2026^{(+x)}$?
  - Fast timing with MAPS is also of great interest for a timing layer in a possible Belle II silicon tracking upgrade

Summary

- All future HEP experiments will incorporate fast timing in some way
  - Existing technologies fill individual niche requirements
- Novel fast MAPS sensors promise to reach <<100ps MIP timing
  - Cost effective, thin, radiation hard process, …
  - First attempts at such sensor are very encouraging
- Instrumenting TOP quartz gaps will improve barrel PID coverage by 6(+3)%
  - Expect 50-70ps single MIP timing sensors to do very well, no strong further requirements
- STOPGAP is an exciting opportunity to establish fast timing CMOS sensors in the landscape of HEP instrumentation
  - Opportunities to install a demonstrator module in Belle II
  - Interest in Belle II also for tracking timing layer at lower radius
- A step towards monolithic, large area 4D tracking detectors

Backup

MC Study: π/K efficiencies/mis-ID rates

- Detailed study on STOPGAP based on Time-of-Flight: feasible with **50-70ps** MIP time resolution sensors
  - Based full Belle II simulation and reconstruction of $B\bar{B}$ events
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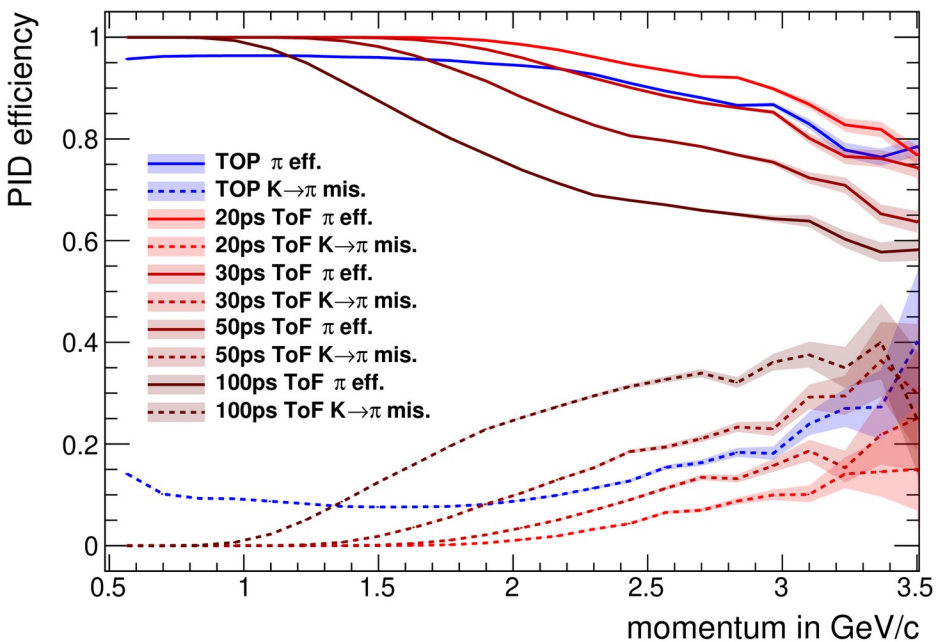
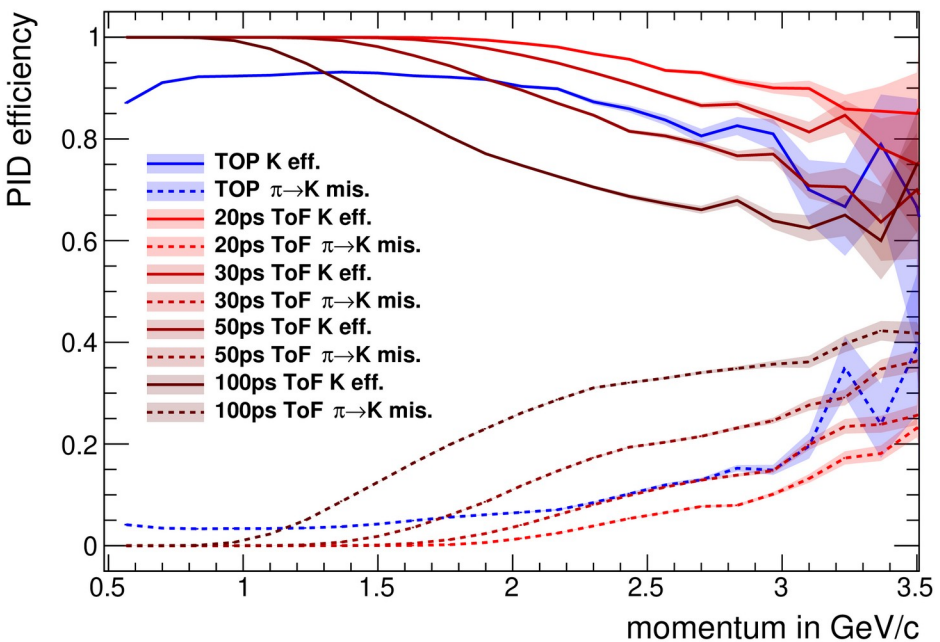
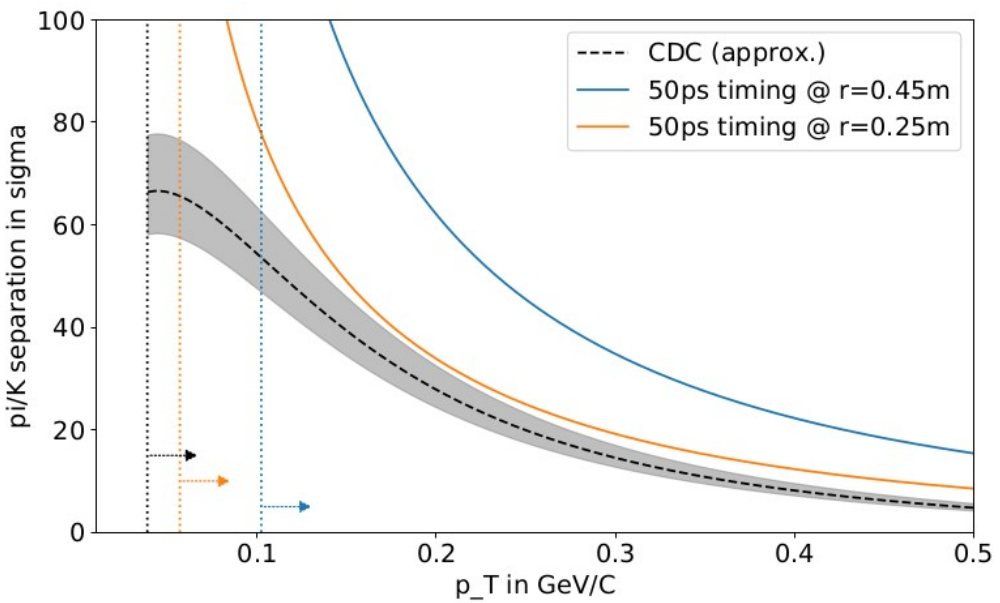
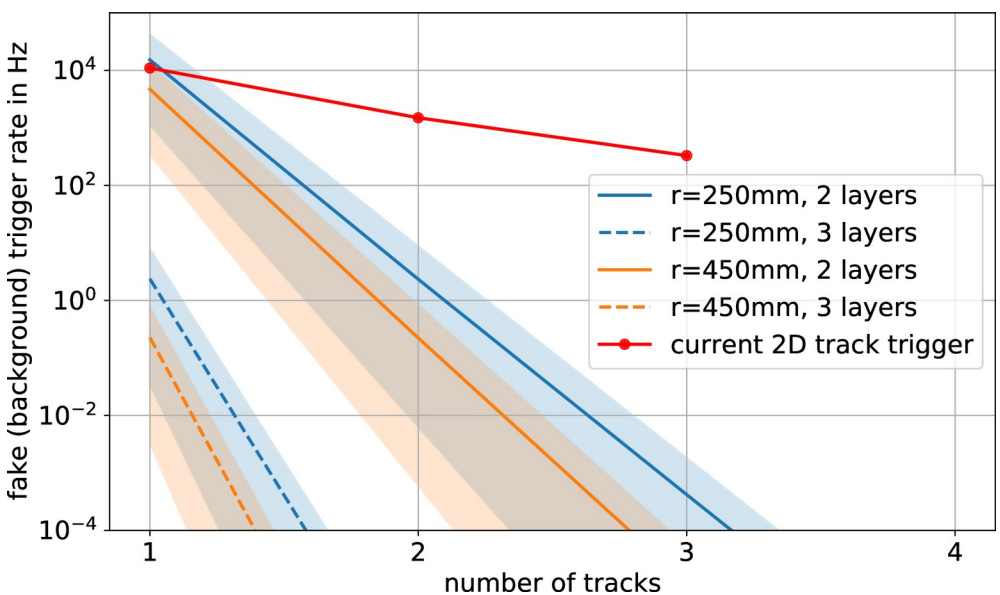




Track Trigger in Belle II Tracking Upgrade

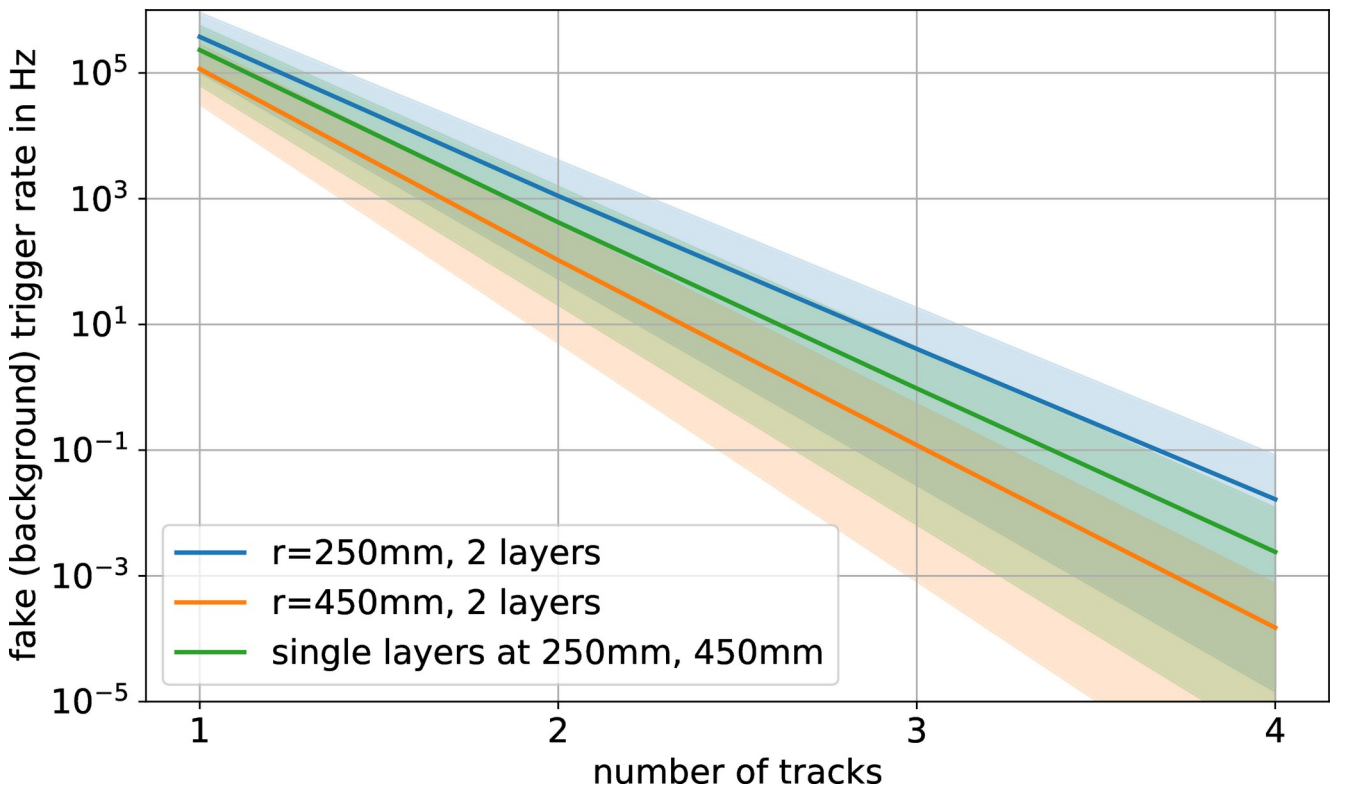
- Current Belle II tracking system might suffer at full luminosity due to beam backgrounds, several upgrade plans under discussion
  - Most concepts propose to increase the inner radius of the outer gas tracking system → need to recover track triggering performance and low momentum from missing dE/dx
- Toy study: a double timing layer with (very) moderate requirements can reliably provide track trigger information from time coincidence alone
  - Also provides excellent pion/kaon separation for $p_T < 1$GeV





A True Double Timing Layer

- Instead of double layer, two single layers at 250mm, 450mm
  - Track charge, momentum, Z reconstruction → IP vertex cut
  - Improved ToF PID down to 50MeV



Fast MAPS for DESY-II Beam Monitoring

- DESY-II injections yield stray charges 2ns before/after main bunch
  - Fast MAPS timing can easily distinguish between bunches → Automatic measurement during first STOPGAP test beam campaigns at DESY
- Limited by statistics: test beam intensity and sensor readout speed
  - Measuring side bunch charges for each injection cycle might become possible for the first time
- Important for DESY-IV: injections into PETRA-IV should be clean from side-bunches