Particle ID in the Belle II Experiment

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SuperKEKB & Belle II

• Next generation B factory at the intensity frontier
  - Asymmetric $e^+ e^-$ collider
  - Center of mass energy tuned to $Y(4[5/6]s)$
  - Located at KEK (Tsukuba, Japan)

• Accelerator upgrade
  KEKB $\rightarrow$ SuperKEKB
  - 40 fold increase in instantaneous lumi.
  - 50 times integrated lumi. over KEKB/Belle
Belle II Particle Identification

• B physics requires reconstruction of final state particles
• $e^\pm$, $\gamma$: ECL + tracking
• $\mu^\pm$, $K_L^0$: KLM + tracking
  – Bad energy resolution for $K_L^0$, using propagation direction
• $\pi^\pm$, $K^\pm$, $p^\pm$: TOP/ARICH + tracking (dE/dx)
  – Mass differences: Cherenkov opening angle, time of flight
Endcap Particle ID: ARICH

- Aerogel Ring Imaging Cherenkov Detector
- Two aerogel layers with different refractive indices
- Hamamatsu Hybrid Avalanche Photo Detector sensors
  - Avalanche photo diode in vacuum tube
Barrel Particle ID Requirements

• $\pi^\pm$-$K^\pm$ separation in Belle2 barrel region
  – Momentum range up to 5GeV
  – ~95% efficiency at 5% fake rate

• Geometry defined by available space between tracker and calorimeter:
TOP: Concept

• 16 Quartz Cherenkov radiator bars
  - 270cm * 45cm * 2cm each
  - Small expansion volume
• Cherenkov photons propagate to sensors via total internal reflection
TOP: Total Internal Reflection

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Module Production Process

Optics: alignment, gluing, curing and aging (~2 weeks).

Enclosure: gluing CCDs and LEDs, integrating fiber mounts.

QBB: strong back flattening, button & enclosure gluing.

Put on a cart. PMT and front-end integration, performance check.

QBB assembly and gas sealing.

Move optics to QBB using the “lifting jig”.

Installation Complete
TOP: Reconstruction

- Detect 20-30 photons/particle/event
  - +5-10 photons from beam background
- Pion/kaon likelihood analysis of spatial/temporal distribution of photons
  - PDFs depend on exact particle trajectory
  - Generated event-by-event in reconstruction

MC w/o chromatic dispersion

![Graph showing time of propagation vs. x cm for different hypotheses and single event photons.](image)
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TOP: Electronics Requirements

• Goal: <100ps single photon time resolution
• Sensor requirements:
  – single photon efficiency
  – <50ps single photon time resolution
  – ~few mm spatial resolution
  – Operation in 1.5T B-field
• Readout requirements:
  – 30kHz trigger rate
  – <50ps electronics time resolution
  – <50ps clock distribution jitter
Micro-Channel-Plate Photomultipliers

- Similar gain, photon efficiency as PMTs, but smaller
- (Mostly) resistant to B-fields
- Pixelated anodes for spatial resolution
- Very good time resolution for single photons

38ps!
Readout Electronics: Requirements

- Reads MCP-PMT signals
- Time resolution ~30ps
  - ~Gsa/s sampling
  - ~500MHz bandwidth
- 8192 channels
- Affordable
- Low power
- Small form factor
- Online data processing
- etc. etc.
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IRSX ASIC

- Waveform sampling ASIC
  - Designed by IDLAB, UH (Prof. Gary Varner)
- 2-4GSa/s sampling speed
  - Operated at 2.7GSa/s in TOP
  - 12bit resolution
  - ~600MHz analog bandwidth
  - 32k analog storage cells (~10us)
  - Sampling/digitisation w/o deadtime
- 8 channels
  - ~100mW/channel
Online Data Reduction

• Raw IRSX output bandwidth of TOP would be 265 Tbit/s!
• Only digitise relevant IRAX samples
  – Based on global trigger, IRSX channel triggers
• Apply all raw data conditioning in frontend
  – Pedestal subtraction
  – Time base calibrations
• Extract waveform features in frontend
  – Photon timing
  – Pulse amplitude, shape parameters etc. for debugging
• Write out only feature parameters
  – Waveforms transferred only for debugging and quality check
Boardstacks

- Tower of 1 SCROD + 4 carriers + HV board
  - Mechanically and thermally coupled
- Directly connects to 8 MCP-PMTs each
  - Four boardstacks per TOP module
Carrier Board

- PMT preamplifiers, 4 IRSX ASICs + Zynq 7030 SoC
- Zynq: FPGA + ARM processor core
  - FPGA interfaces four ASICs, pushes data to SCROD
  - ARM on carrier mostly idle, but could do data processing
SCROD Board

• Single (large) Zynq 7045 SoC
  – FPGA receives data from carriers, manages transceivers
  – Processor performs online data processing

• Two fiber transceivers: datalink + trigger timestamps
Timing Reconstruction

\[
\Delta t = \frac{\Delta u}{U} \cdot t_r = \frac{\Delta u}{U \sqrt{n}} \cdot t_r = \frac{\Delta u}{U} \cdot \frac{t_r}{\sqrt{t_r \cdot f_s}} = \frac{\Delta u}{U} \cdot \frac{\sqrt{t_r}}{\sqrt{f_s}} = \frac{\Delta u}{U} \cdot \frac{1}{\sqrt{3 f_s \cdot f_{3dB}}}
\]

\[
\frac{\Delta u}{\Delta t} = \frac{U}{t_r}
\]

\[
t_r \approx \frac{1}{3 f_{3dB}}
\]

*Diagram, formulas from Stefan Ritt*
Feature Extraction

- Constant fraction discrimination
- Template fit to photon pulses
  - Computationally complex, possible on Zynq DSPs?
  - but only needed for low amplitude hits

50% threshold

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Univ. of Hawaii/ RU Bochum
Feature Extraction Implementation Status

Reference pulse

Chn 1

Single p.e. laser pulses

Chn 2
Global Cosmic Ray Campaign

• Full dress rehearsal of outer subdetectors
  – With full solenoid field
• Tracking chamber, calorimeters, TOP integrated into DAQ
  – Synchronous datataking, realistic data flow to HLT and storage
• True global triggers
• First cosmic ray tests with a new detector
  – This happens maybe every ~10 years
  – What a time to be part of this now!
First Bent Track in CDC+ECL+TOP
First Shower in CDC+ECL+TOP
First Track in CDC+ECL+TOP+KLM
TOP Timing Calibration

- Calibrating IRSX time base with injected double pulses
- <30ps single edge timing resolution of electronics in installed A modules
  - Calibrated in-situ
  - Comparable to module qualification tests

U. Tamponi
INFN Torino
TOP Module Timing Offsets

- Relative module timing offsets estimated from cosmics runs, laser pulses
  - Laser calibration does not resolve all contributions
  - Anyway good correlation between results
- Expect alignment to <1ps from cosmics
  - To be crosschecked with di-muons

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TOP Channel Timing Offsets

- Calibrate channel timings with laser pulses
- Total time resolution for laser pulses <200ps
  - 150ps contribution from laser pulse propagation smearing
→ ~120ps time resolution on optical photons with current calibrations

W. Yuang
INFN Padova
Summary and Outlook

- TOP is installed and alive
- Front end electronics are (almost) fully operational
  - Performance so far according to specifications
  - Firmware work continues
  - Paper submitted to NIM A, now in revision
- Successful global cosmic ray campaign
  - Integrating all outer sub-detectors
- Phase II: Outer sub-detectors only
  - First collisions March 2018
- Phase III: Physics operation
  - Starting early 2019