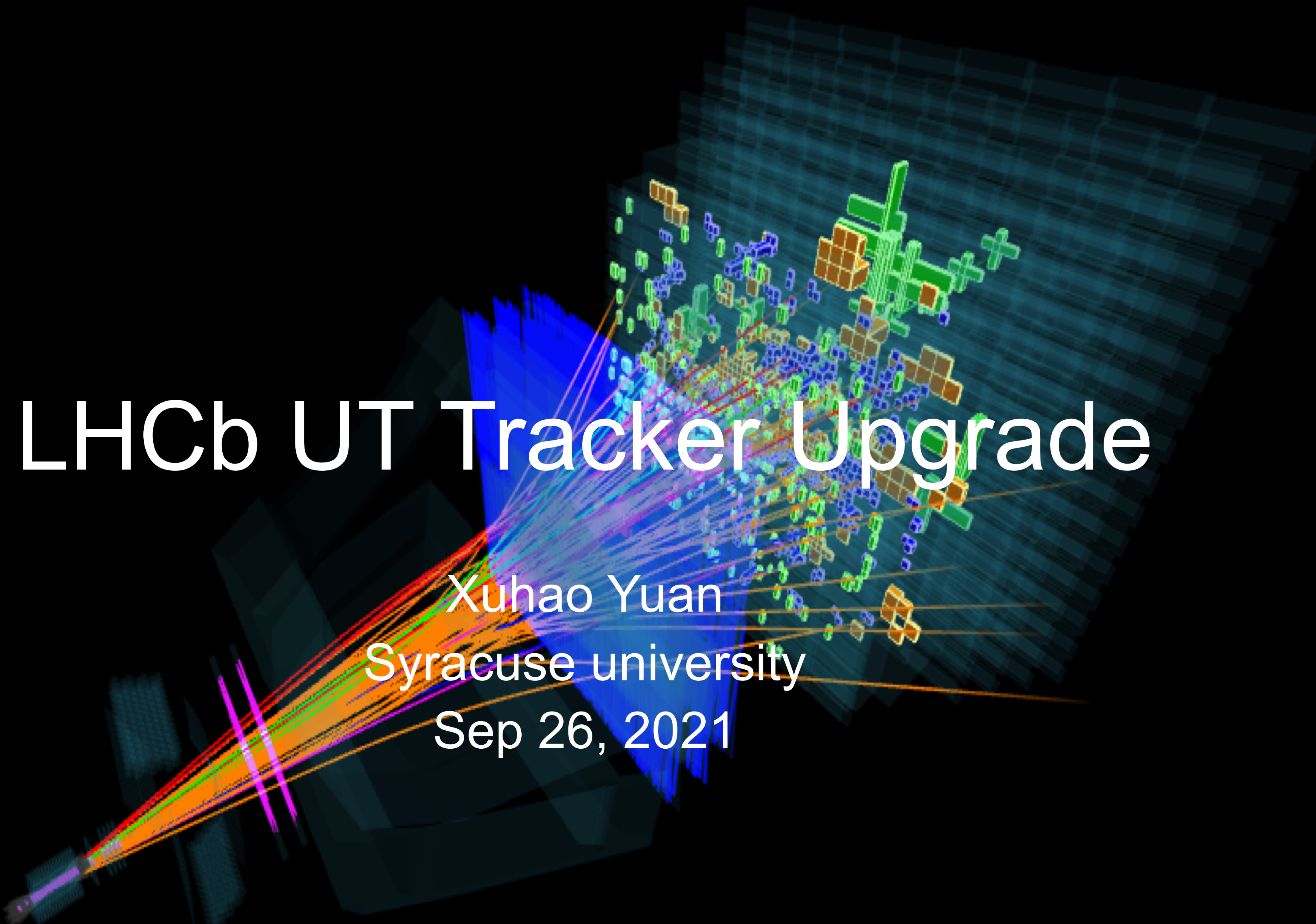


LHCb UT Tracker Upgrade

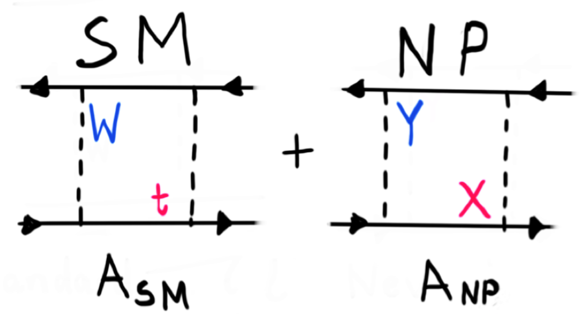
Xuhao Yuan
Syracuse university

Sep 26, 2021

Flavor Physics Road to NP

LHCb located at Large Hadron Collider (LHC)

- Search for New Physics in b & c sectors



Sensitive to heavy particles in the loops

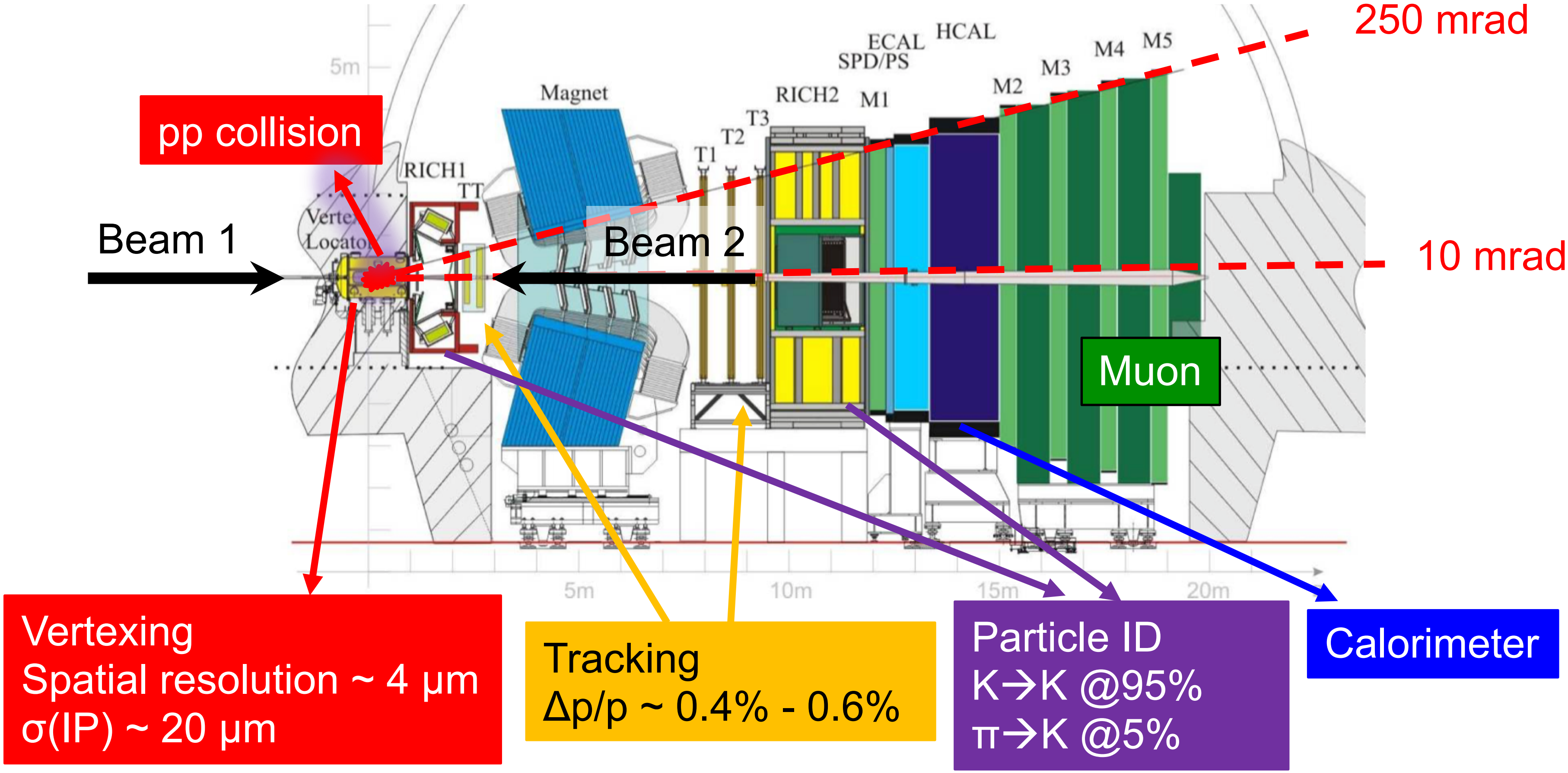
- Observables with very small theoretical uncertainty
  - e.g. CKM angle γ, φ_s, $\Delta\Gamma_s$…
- Rare processes (suppressed or forbidden in SM)
  - e.g. $B_{(s)}^0 \rightarrow \mu^+\mu^-$, LFV …

Experiment != SM prediction : New Physics

LHCb Detector Before 2019

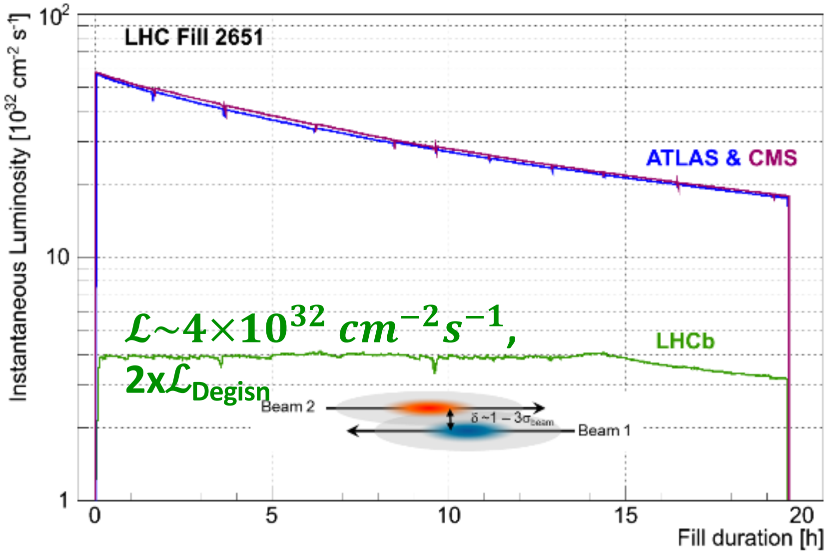
LHCb covers the forward region: $2 < \eta < 5$ ($\sim 4\%$ solid angle)

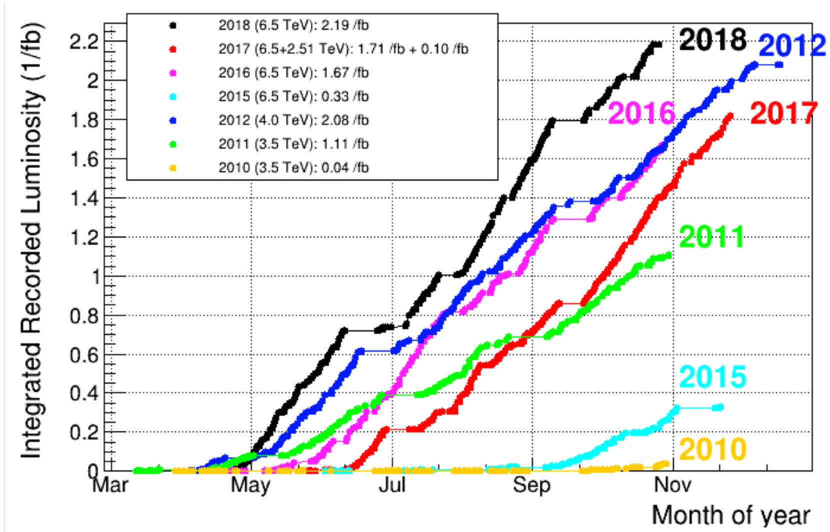
- Boost in Z: 27% for b or $\bar{b}$ quarks; 25% for $b\bar{b}$ pairs



LHCb Operation

- Optimized $\mathcal{L}\sim 4\times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, ~1.7 visible int./Xing
- Flat luminosity within each fill



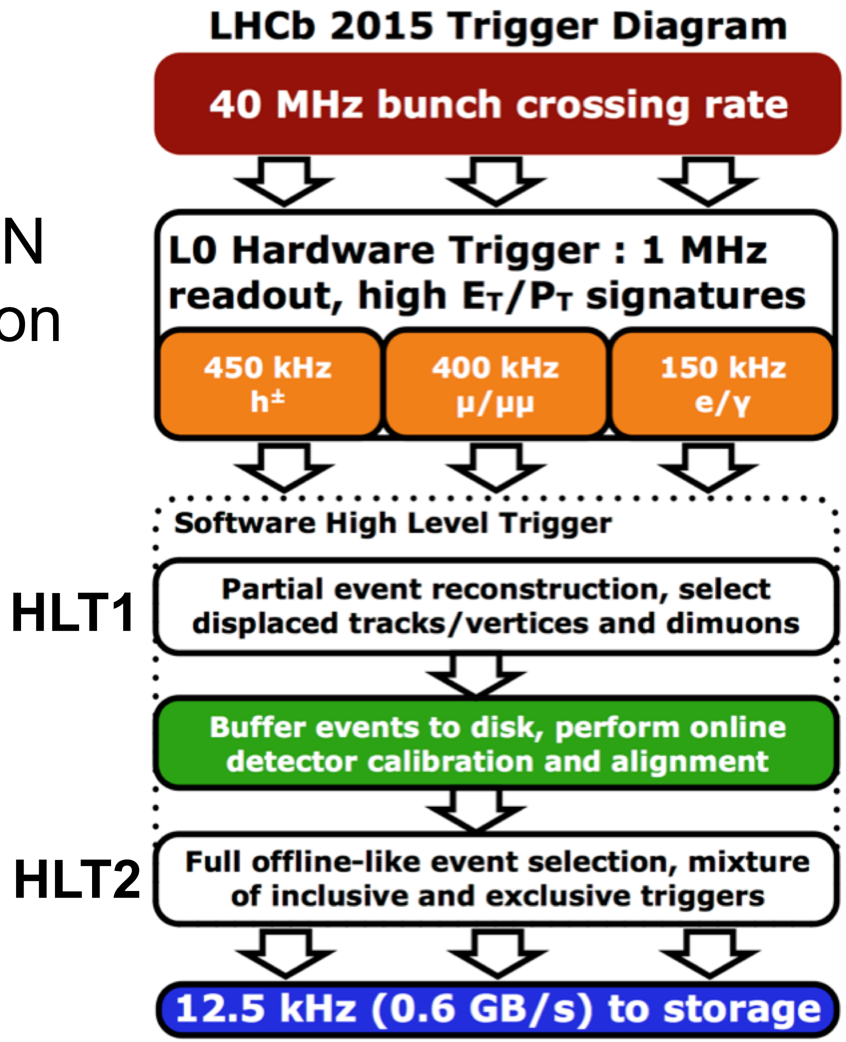


Data collection

- Totally ~ $9\ \mathrm{fb}^{-1}$ pp collisions data @ 7/8/13 TeV
- Run1: 2011-2012 @ 7/8 TeV
- Run2: 2015-2018 @ 13 TeV

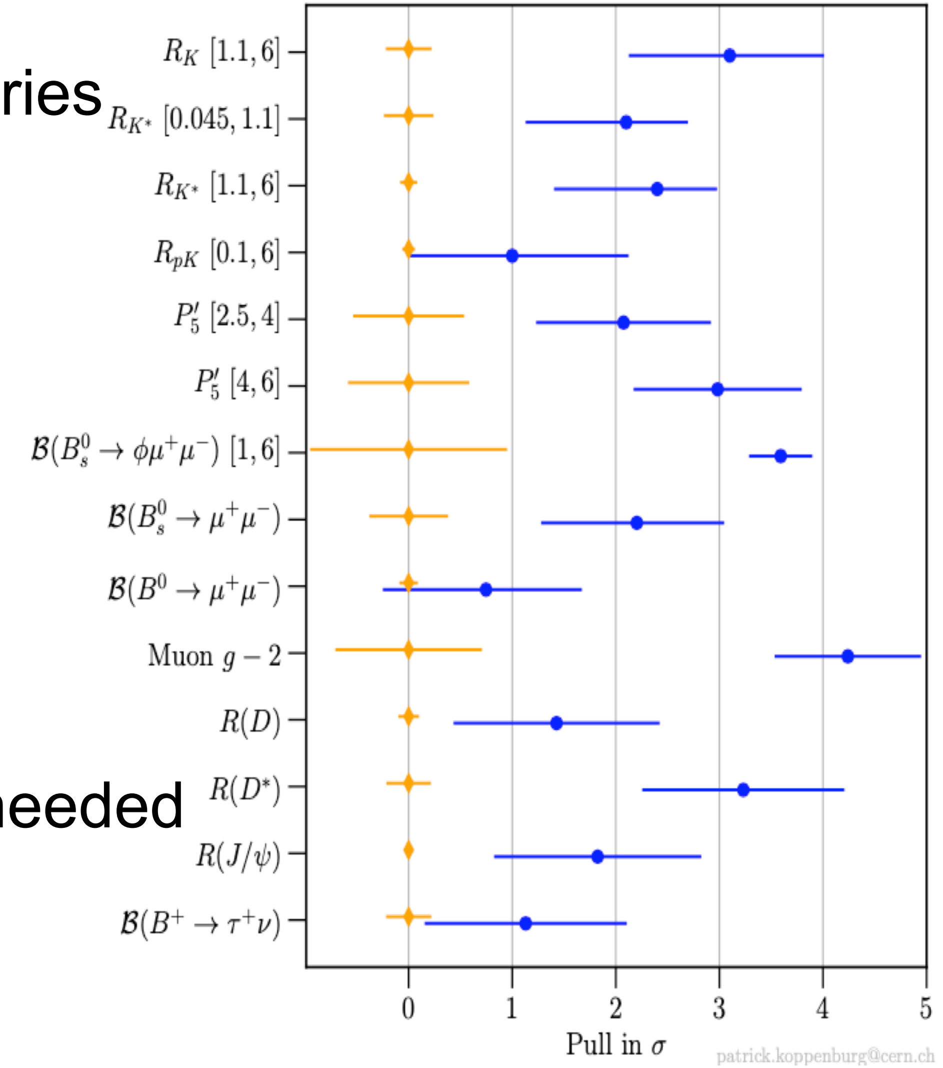
LHCb Trigger

- ➢ Three-level trigger: L0/HLT1/HLT2
- ➢ L0 (hardware) using CALO & MUON
  - ❑ High p_T muon OR high E_T hadron
- ➢ L0 reduces rate 40MHz → 1MHz
  - ❑ Detector readout rate
- ➢ Two-stage software HLT
  - ❑ Partial & full reconstruction
  - ❑ Rate reduced to ~12kHz



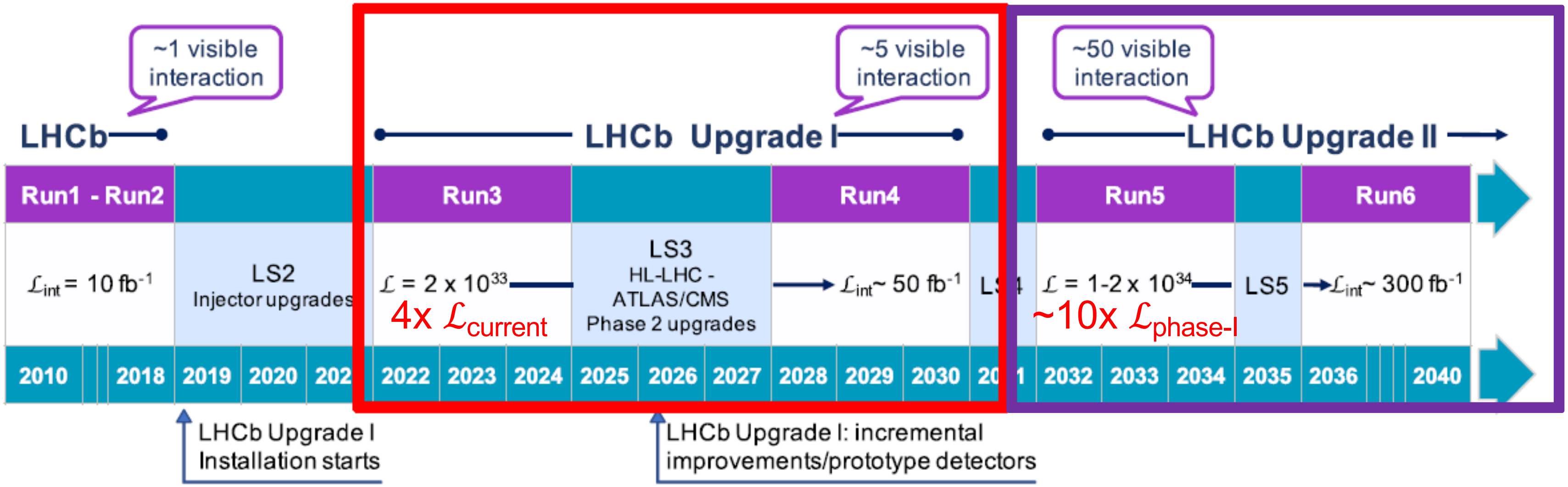
LHCb Discoveries

- A decade of important discoveries
  - Remarkable precision in γ, Δm_s, φ_s, A_Γ, A_{sl} etc
  - Rare decays
  - Ξ_{cc}, P_c, T_{cc}…
  - Flavor anomalies
- SM or BSM? Open questions
- More precise measurements needed



LHCb Upgrade

LHCb Upgrade Plan



- LHCb Phase-I upgrade during LS2 for Run3 & Run4
  - $\mathcal{L} = 2\times10^{33}\ cm^{-2}s^{-1}$, 4x $\mathcal{L}_{current}$
  - $\mathcal{L}_{int} = 50\ fb^{-1}$

Focus on Phase-I

- LHCb Phase-II upgrade during LS4
  - $\mathcal{L} = 1\sim2\times10^{34}\ cm^{-2}s^{-1}$, ~10x $\mathcal{L}_{phase-I}$
  - $\mathcal{L}_{int} = 300\ fb^{-1}$

Phase-I upgrade

Current

- Bottle necks: 1MHz readout bandwidth from hardware trigger
- Designed for 5 years @ 0.5x $\mathcal{L}_{LHCb}$(current)
  - More radiation damage & performance degradation
- CPU time for event reconstruction exponentially increases
  - Track & primary vertex multiplicity and combinatory increase

Upgrade-I

- No L0 & read out @ 40 MHz
  - All read at each bunching crossing
  - New electronics
- Work at a higher luminosity
  - High granularity
  - Radiation resilience
- Flexible software trigger on CPU/GPU
  - Full information for trigger
  - Max ε_{signal} @ high rate

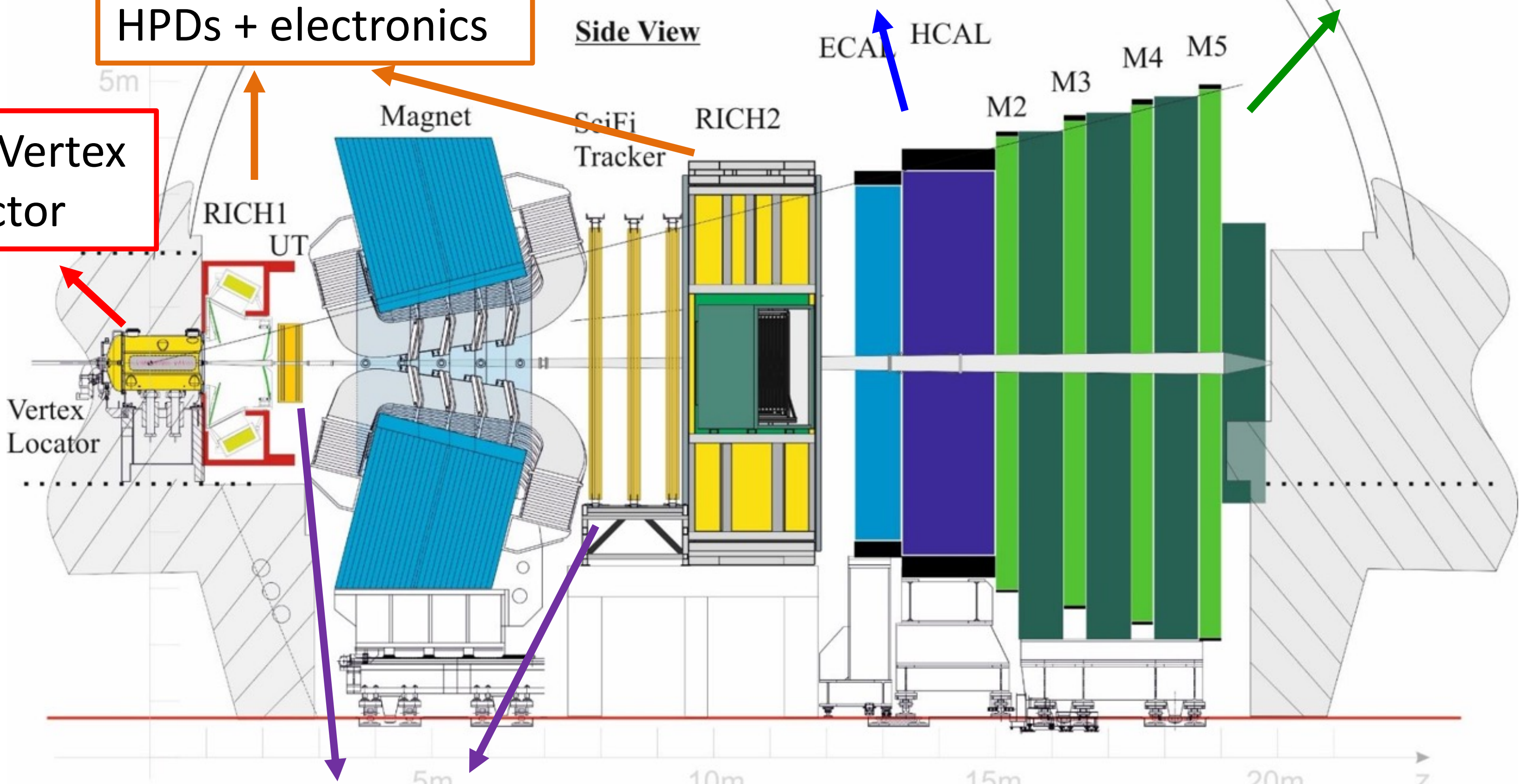
Upgrade-I LHCb detector

Particle ID replace HPDs + electronics

Calorimeters reduce PMT gain + electronics

Muon new electronics

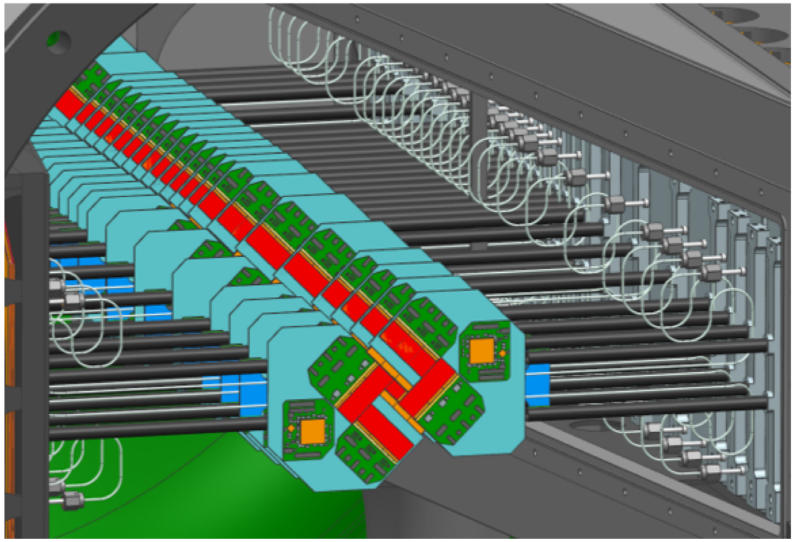
New Vertex detector



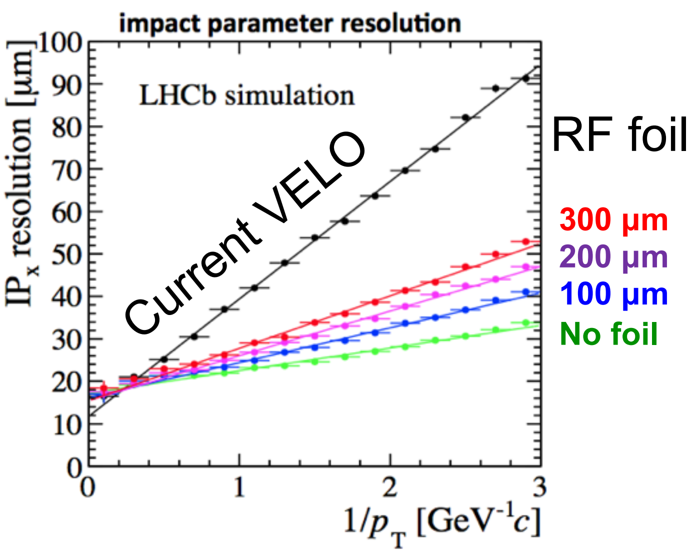
New Tracking detector

+ trigger-less readout & sw trigger on GPUs

VELO Upgrade



- Similar geometry as the current one, but
  - ❑ Two movable halves closer to beam (5mm to 3.5mm) ➔ better σ_{IP}
- New Si pixel sensors, pixel size 55x55 μm^2
  - ❑ n-in-p sensor, Φ_{max} ~ 8×10^{15} $n_{eq} cm^{-2}$
  - ❑ Reduced thickness 300 ➔ 200 μm

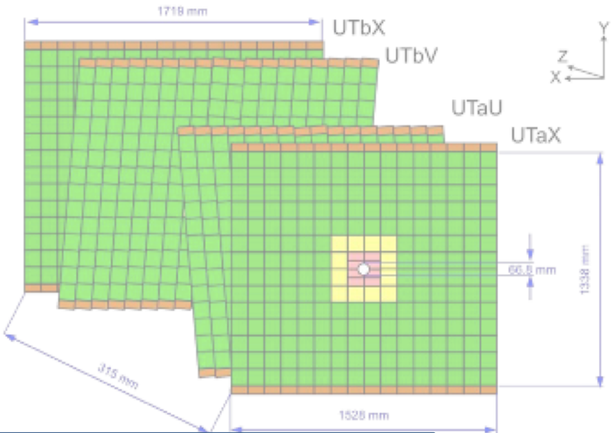


- Thinner RF foil, 300 → 250 μm
- Read out by 3 VeloPix ASICs per sensor
  - ❑ ~20 Gbps in hottest ASIC, total ~3Tbps
  - ❑ Bump bonding
- Cooling down by bi-phase CO_2 passing under the chips in etched micro-channels

UT

- Replace TT, similar geometric
- Much improved coverage
  - Circular hole surround beam pipe
  - Sensor overlap in X&Y directions
- Higher segmentation, especially in central

More details discussed later

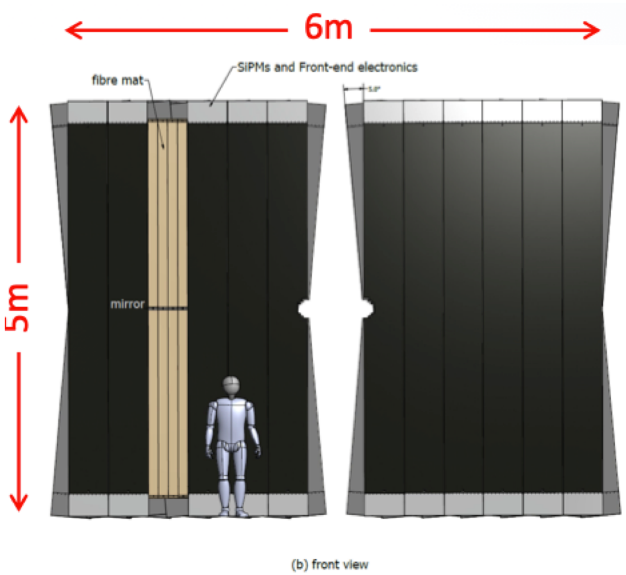


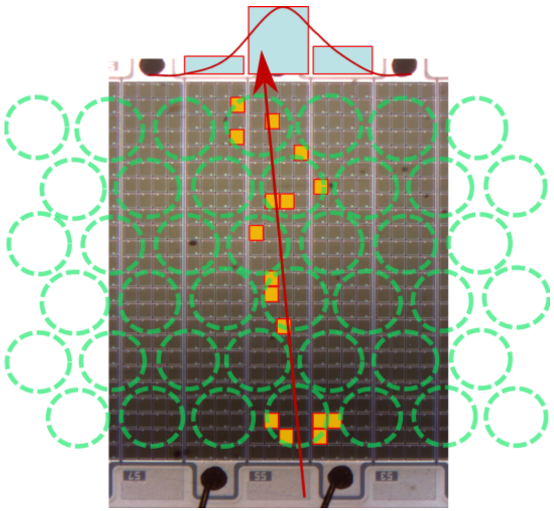
Higher segmentation

- Sensor more radiation resilience
  - Φ_{max}~$5x10^{14}n_{eq}cm^{-2}$
  - Reduce material at small angle
- 40MHz readout SALT ASICs
- Digital event packed in ASIC, sent out at detector end via optical fibers

Scintillation Fiber Detector

- T1,2,3 trackers replaced by 12-plane scintillation fiber detector
- Each plane made of 6-layer staggered Ø250 μm fiber mats
- Total ~ 10,000 Km long fibers
- Read out with arrays of SiPMs (-40℃) + custom made PACIFIC ASIC
  - ❑ Lights from fibers detected by SiPMs
- Spatial resolution ~ 80 μm
- Single hit efficiency ~ 99%

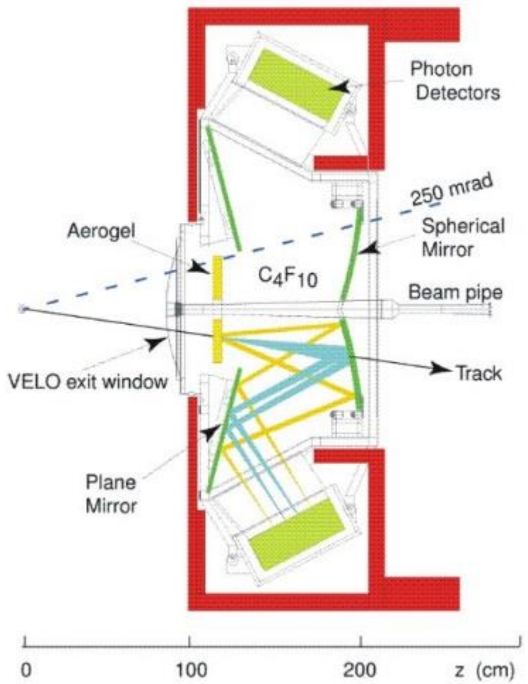


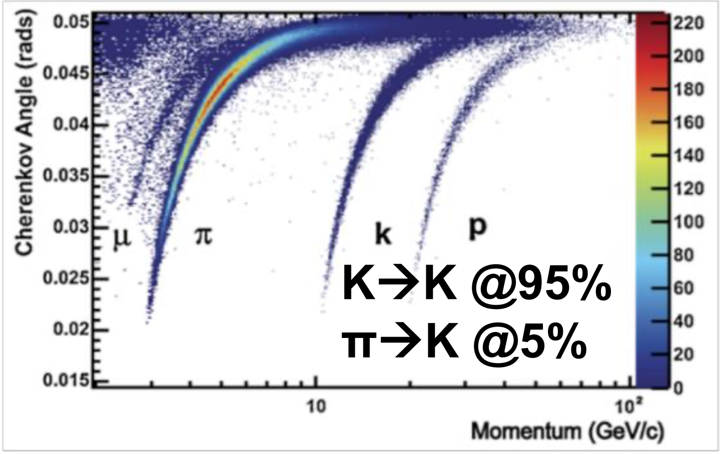


RICHs

- 2 Ring Imaging Cherenkov Detectors
  - ❑ RICH1 (aerogel+C_4F_{10}) for 2<P<60 GeV
  - ❑ RICH2 (CF_4) for 15<P<100 GeV

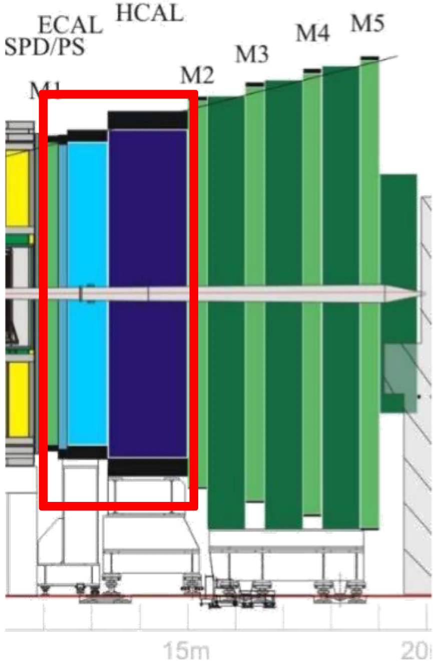
- Cherenkov photons on HPD plane
  - ❑ Embedded FE electronics, 1MHz readout





- Remove aerogel radiator
- Optics modified
- Replace HPD with Multi-Anode PMT
- New 40MHz electronics

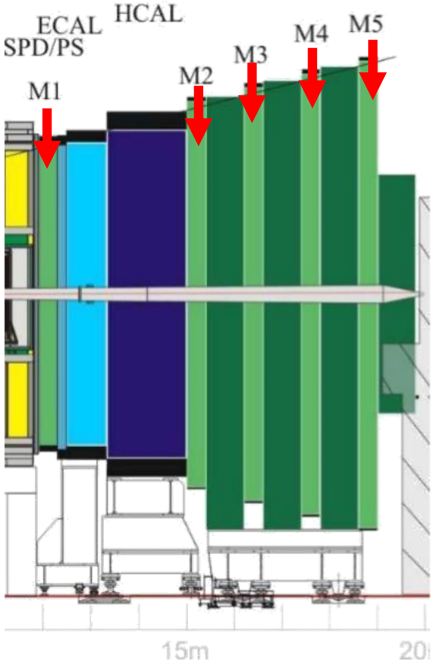
CALO



- ➢ High E_T e/γ/h for L0
- ➢ e/γ/h ID, energy & position
- ➢ Based on scint./WLS technique
  - ❑ Light readout by PMT
- ➢ Fine segmentation at center

- ➢ No SPD & PS
- ➢ To replace inner ECAL after ~20 fb^{-1}
- ➢ PMT gain reduce by factor of 5
  - ❑ PMT degradation
- ➢ New FE electronics for 40MHz readout

Muon



- ➢ Total 5 stations M1-M5
- ➢ Triple-GEM (Gas Electron Multiplier)+ MWPCs (Multi-Wire Proportional Chamber)
  - ❑ GEM @ center of M1 for high hit rates
- ➢ Alone gives δp/p ~ 20% for L0

- ➢ Remove M1
- ➢ Add shield in front of M2 @ center
  - ❑ Reduce rate
- ➢ New readout electronics

LHCb UT project

LHCb

CERN

Syracuse University

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

INFN
Istituto Nazionale di Fisica Nucleare

AGH

Massachusetts Institute of Technology

University of Zurich UZH

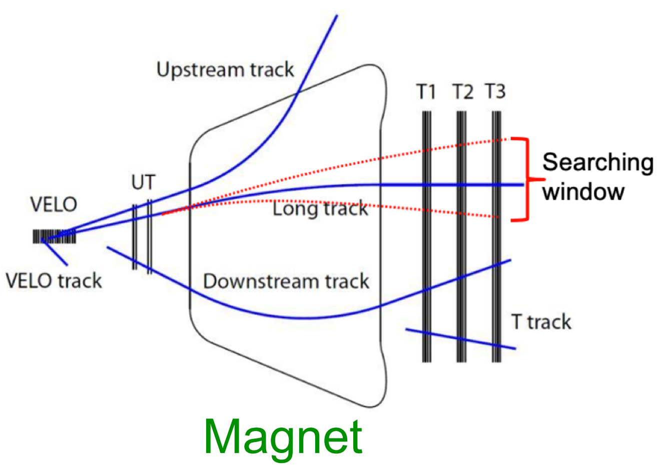
University of Cincinnati

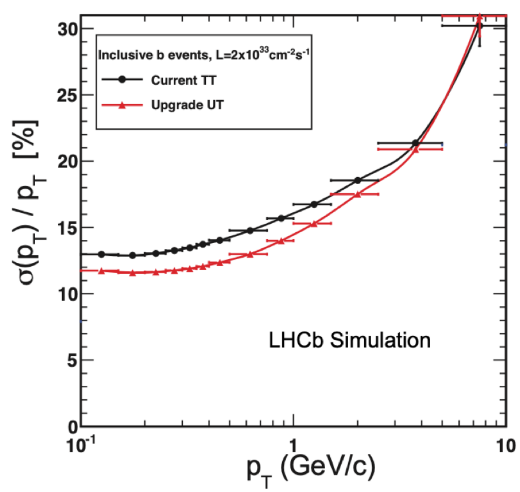
University of Maryland

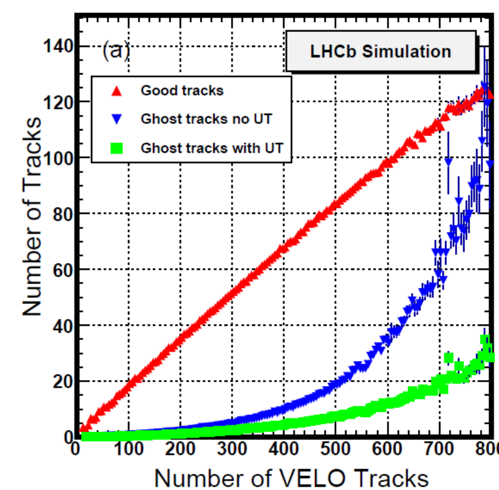
University of Michigan

UT In LHCb Tracking System

- Provide fast track reconstruction in software trigger
  - Searching window in SciFi tighten
  - Charge determined
- Reduce ghost rate in long tracks
- Increase reconstruction efficiency of long lived particles: e.g. $K_s^0 \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$

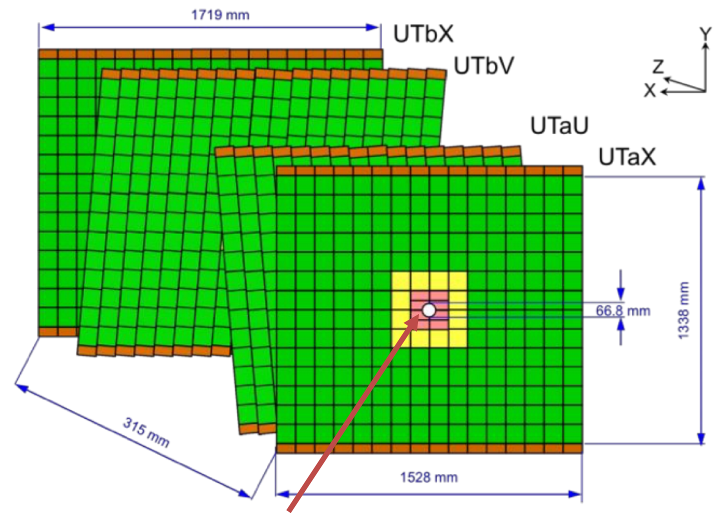






UT

- Replace TT, similar geometric
- Much improved coverage
  - Circular hole surround beam pipe
  - Sensor overlap in X&Y directions
- Higher segmentation, especially in central, <2% strip occupancy
- Sensor more radiation resilience
  - Φ_{max}~$5x10^{14}n_{eq}cm^{-2}$ after 50 fb^{-1}
  - Reduce material at small angle
- 40MHz readout SALT ASICs

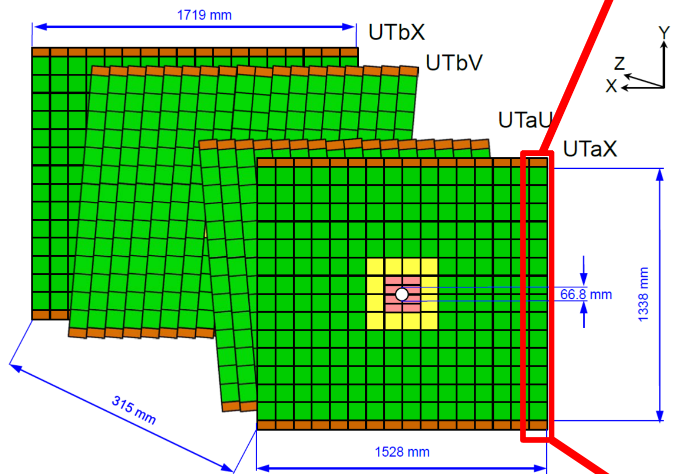


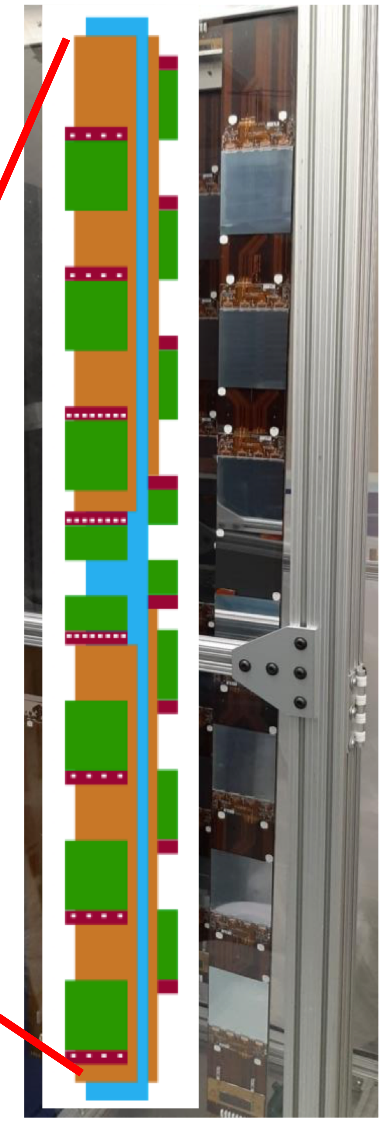
Hole for beam pipe

UT Design

- 4 UT layers (X, U, V, X) @ (0°,+5°,-5°, 0°), provide stereo measurements, precision horizontally

- UT layers consist of Staves
  - 16/16/18/18 staves on UT layers

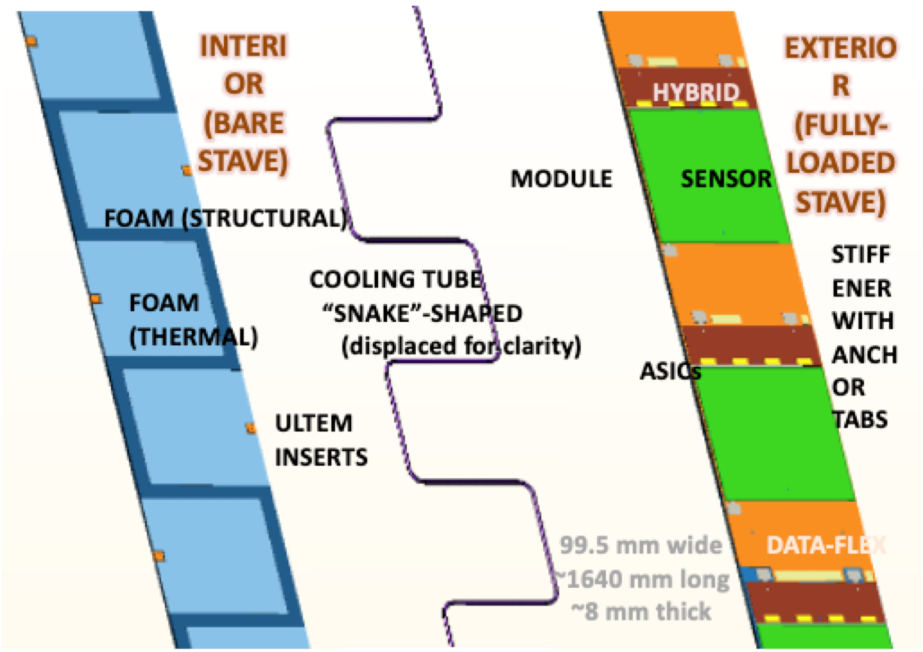




- Stave:
  - Two sides
  - Support structure
  - Integrated with cooling tubes

Staves

- Sandwich structure & all epoxy construction
  - Foam core + ”snake” shape cooling tube (Ti)
  - 2 CFRP (Carbin fiber reinforce polymer) face sheets attached to foam core



UT Module

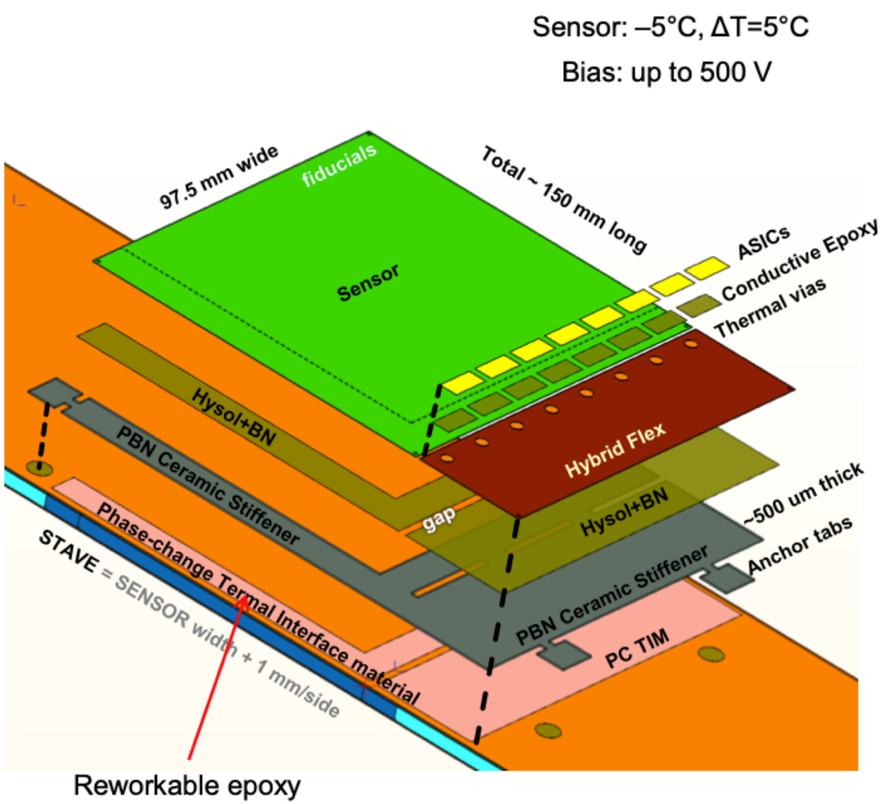
- Module
  - Basic detector unit
  - Capture particle hits and processes signals

Hybrid:
Electrical connections to SALT

SALT (Silicon ASIC for LHCb Tracker) :
Signal amplifier & processing

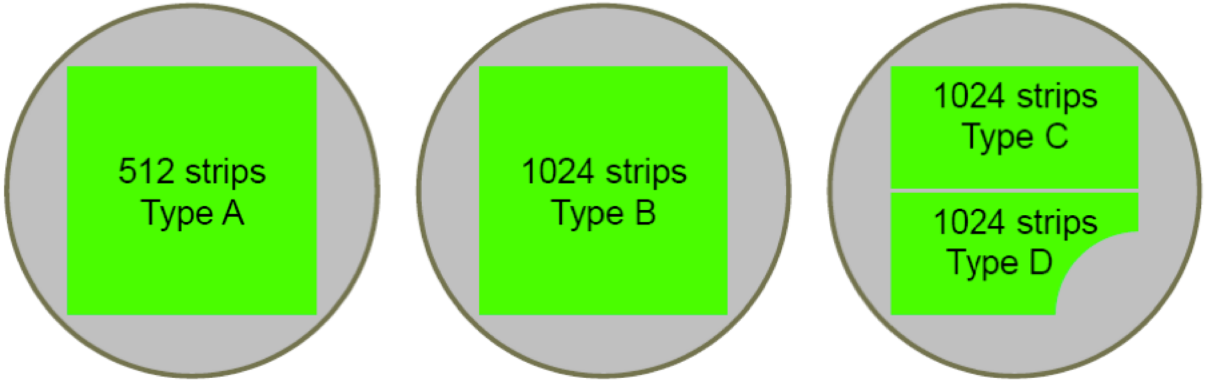
Silicon sensor:
Single sided silicon micro-strip devices

Details in UT Module



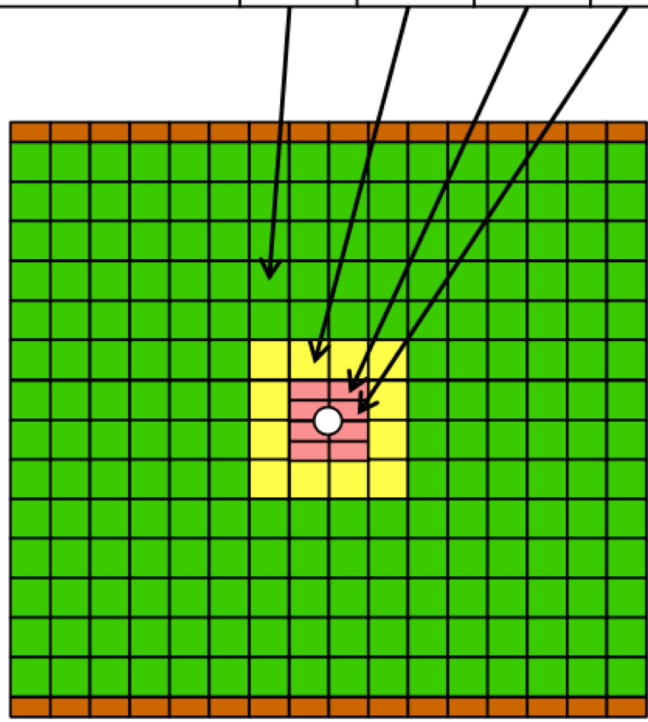
- Structure for Si sensor & FE electronics (SLATs, hybrid)
- Heat transfer from ASIC to stave
- Isolate sensor bias from stave facing (ground)
- No over-constrain sensor, allows for bow

Silicon sensor



Silicon Strip Sensors

Sensor	A	B	C	D
Pitch (μm)	187	94	94	94
Length (mm)	98	98	49	49
Strips/sensor	512	1024	1024	1024
Number	888	48	16	16



Four types of sensor:

A-type (~92%): p^+-in-n, 320 μm thick

Strip pitch 187 μm

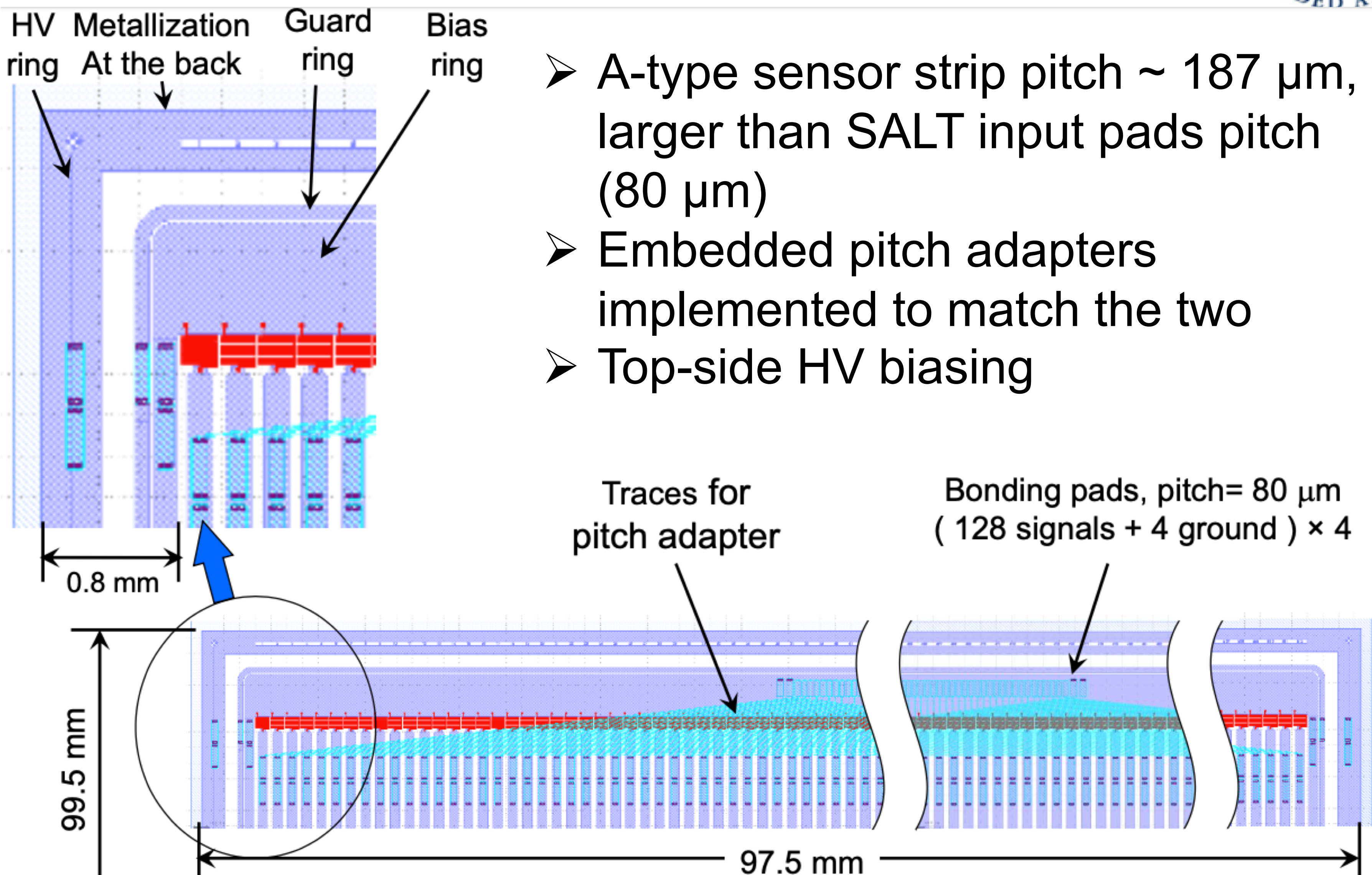
B/C/D-type: n^+-in-p, 250 μm thick

C&D-type: half length

Strip pitch 94 μm

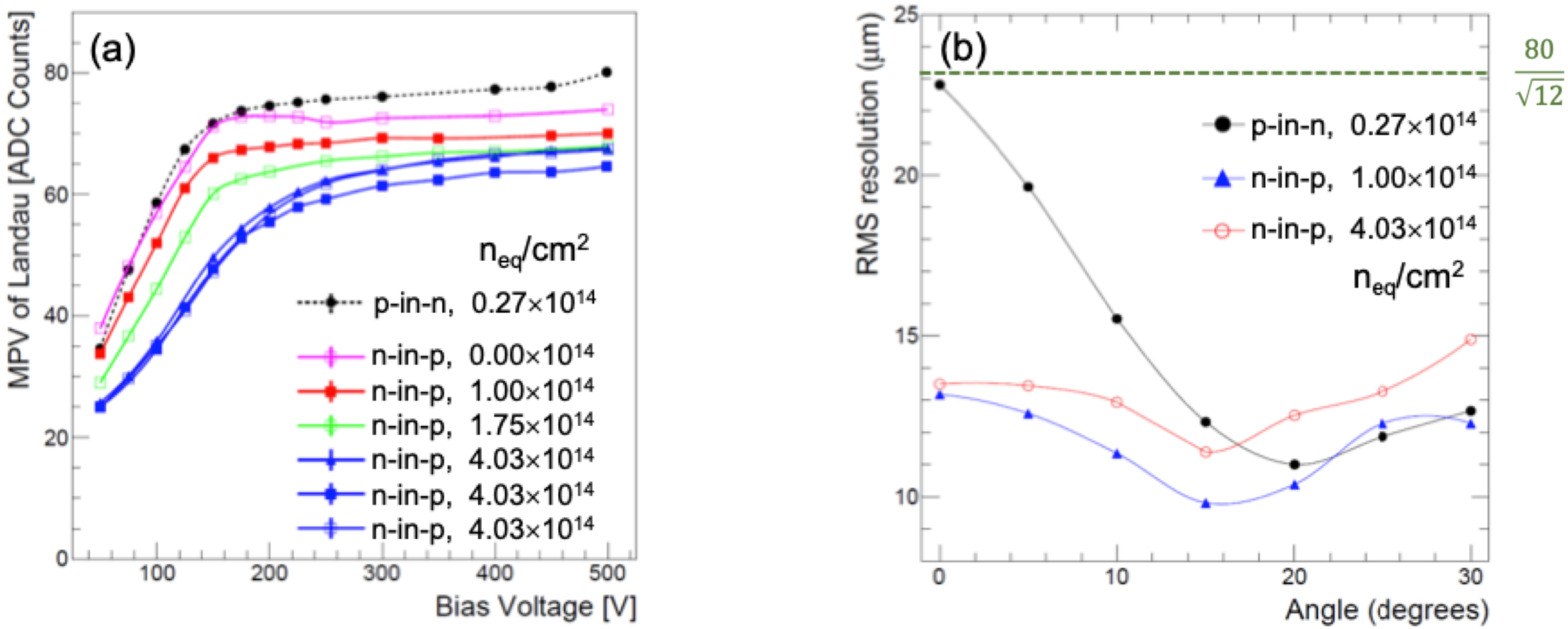
Finer granularity in central region

Sensor Layout



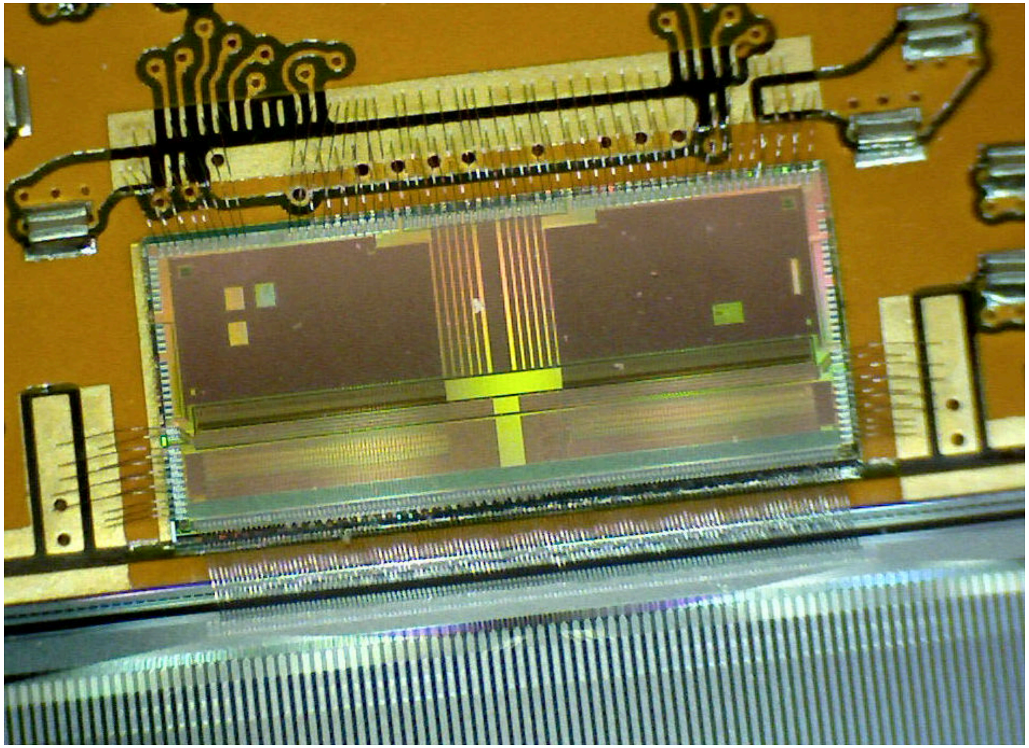
- A-type sensor strip pitch ~ 187 μm, larger than SALT input pads pitch (80 μm)
- Embedded pitch adapters implemented to match the two
- Top-side HV biasing

Performance In Test Beam



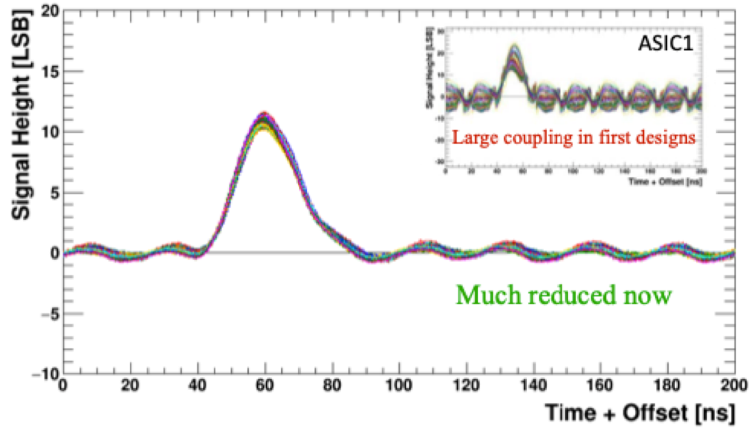
- For the n^+-in-p sensors, gradual loss in total charge collected with increased radiation dose.
- All sensors reach plateaued @ 300-400V, S/N rate >~ 15. Should be efficient after 50 fb^{-1} ($5x10^{14}$ neq/cm^2).
- More charge sharing at normal incidence for irradiated n^+-in-p sensors.

SALT (Silicon ASIC for LHCb Tracking)



SALT

- One SALT chip reads out 128 Si strips
  - CMOS 130 nm technology (TSMC)
- Fast shaping time/return to baseline
  - $T_{peak} \leq 25$ ns, less than 5% after $2T_{peak}$
- Major functions:
  - Analogue FE and ADC for each sensor strip
  - CMS to reduce coherent noise
  - Compress data output
  - SEU mitigation
- In SALT output, normal hit signal by 12 bits
  - 7-bits for location of strip
  - 5-bits for amplitude

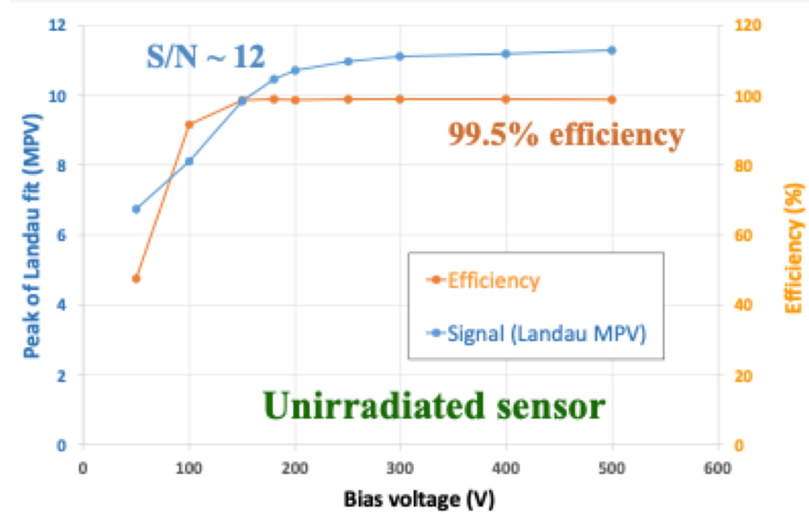


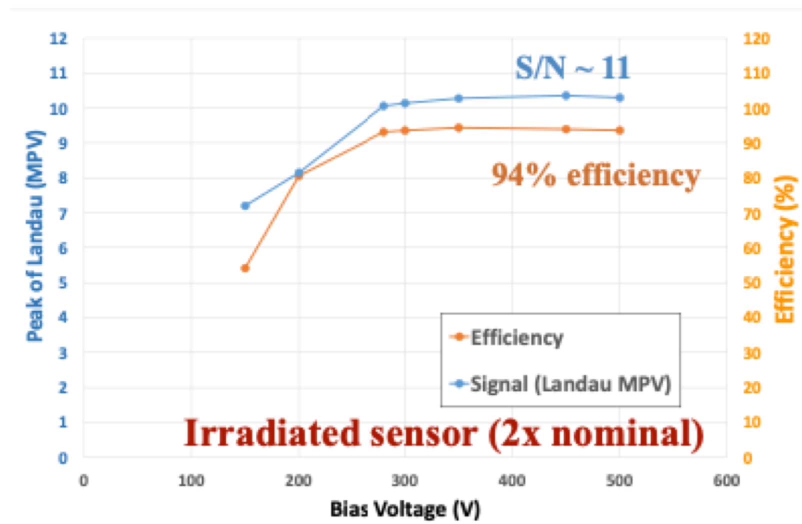
After a bumpy road and a few iterations, performance is now more than satisfactory

Sensor+ASIC performance

- Beam test @ Fermilab (Mar 2019)
- A-type unirradiated sensor
  - 99.5% efficiency and S/N ~ 12
- B-type irradiated to 2x max dose
  - 94% efficiency and S/N ~ 11
  - Partly due to readout limitation most efficiency to be recovered with LHCb readout

Final system expected to have signle-hit high efficiency (>99%) and good signal-to-nise ratio throughout experiment lifetime

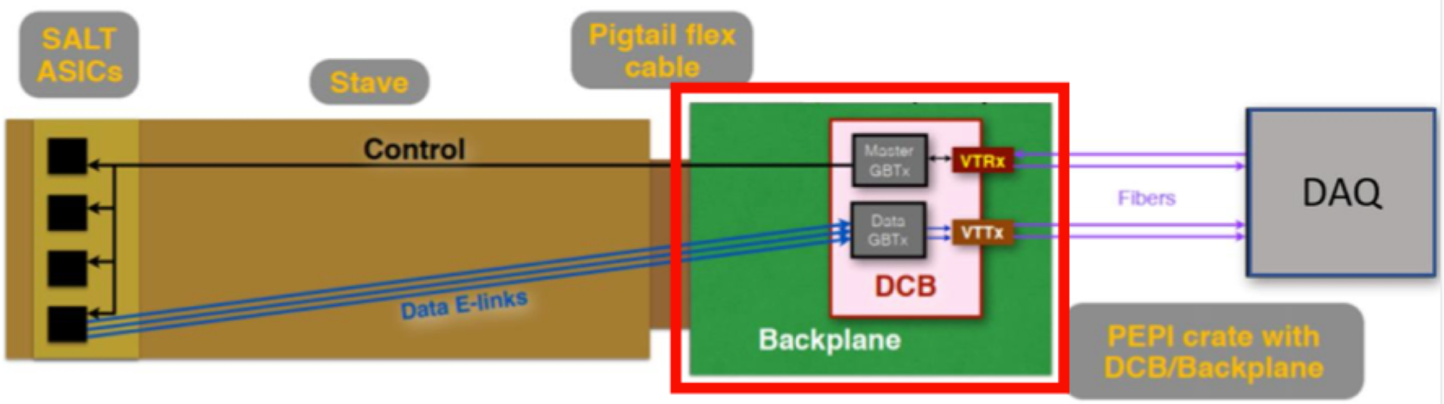




Event data Transportation and Integration

Event data Transportation

ASICs → hybrid flex → 'pigtail' flex cables → backplanes (BP) →
→Data control boards (DCBs) → DAQ

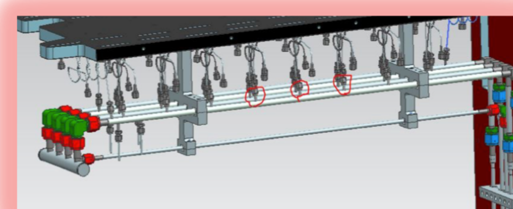


BPs & DCBs inside periphery electronics processing interface (PEPI)

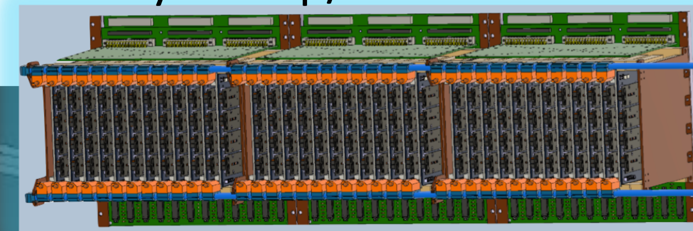
- BPs route data & control signals to and from DCBs
- DCBs (x248): 6 Data GBTx + 1 Master GBTx
  - ❑ SALTs digital-form input → Optical signals output to DAQ
  - ❑ Monitoring and slow control;

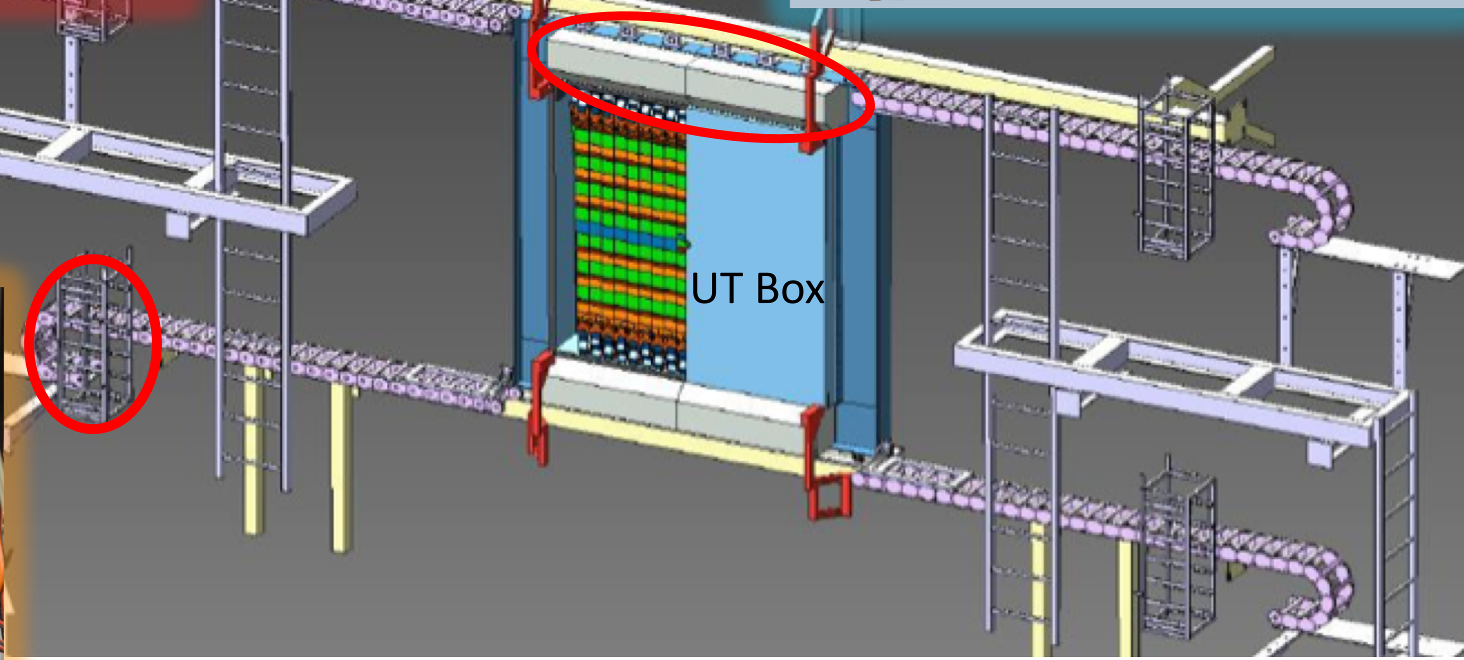
UT Integration

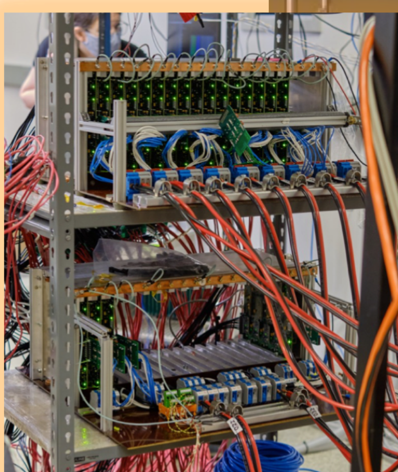
Staves cooled by CO_2, tested btw -30°C and 20°C



PEPI cooled by water, boxes sit directly on top/below staves



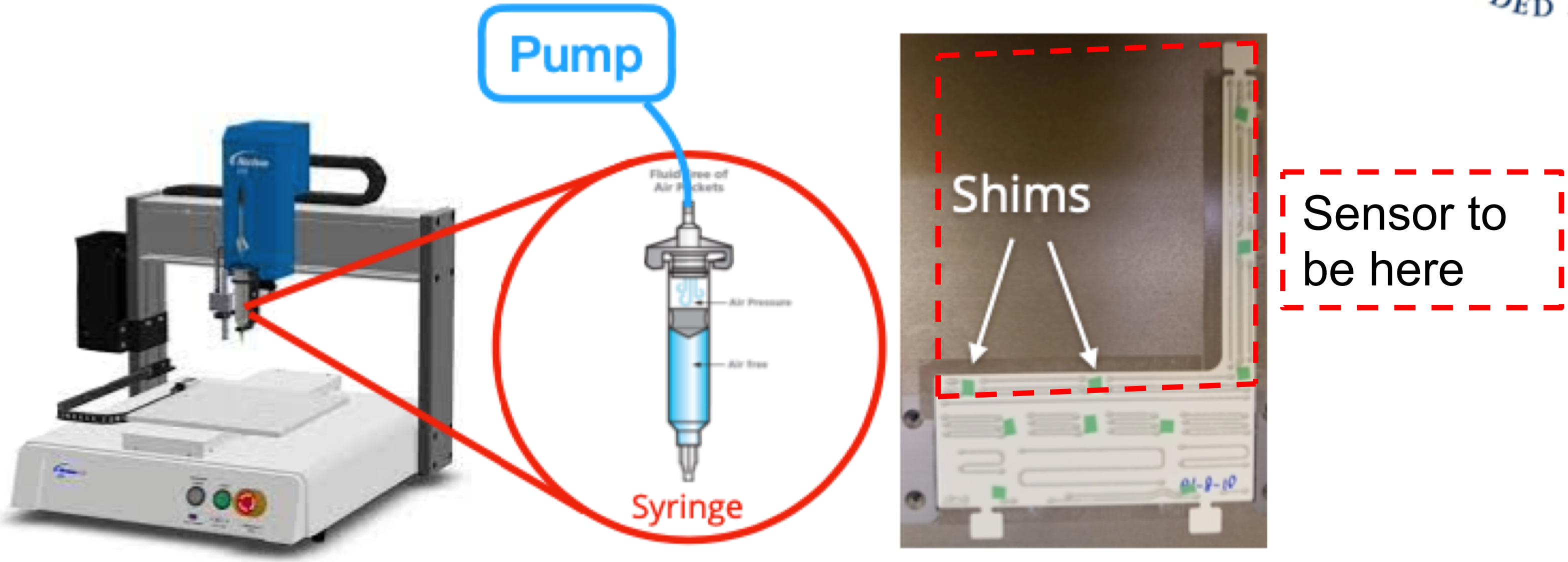




LV & HV regulation at service bays

Highlights in Construction

Glue dispensing



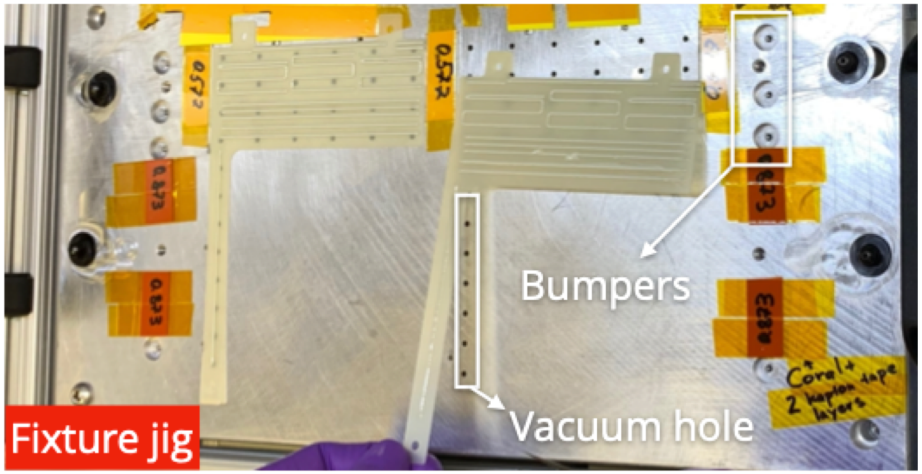
Challenging

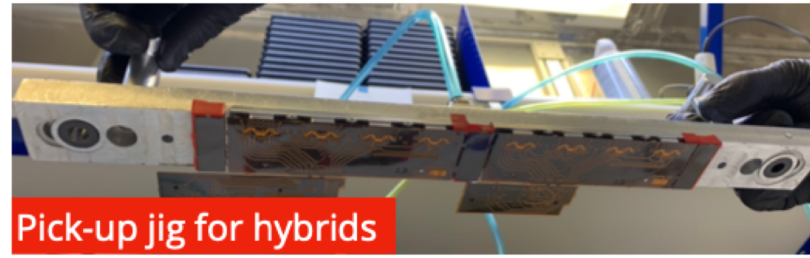
- Cover glue to very edge but no spill-over
- Glue viscosity time dependent

Solution

- Programmable glue dispenser
- Adjust pressure/time/speed for amount of glue ~ mg accuracy

Module assembly

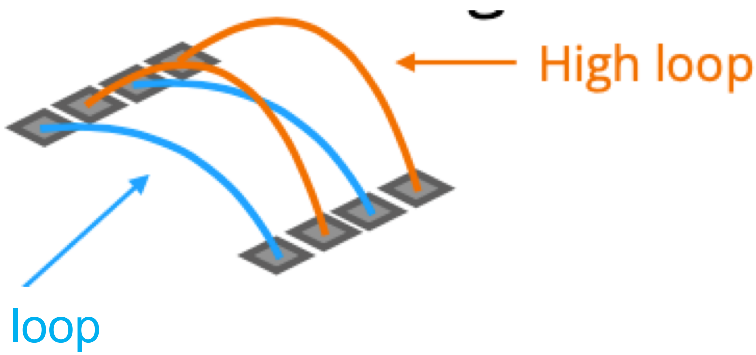


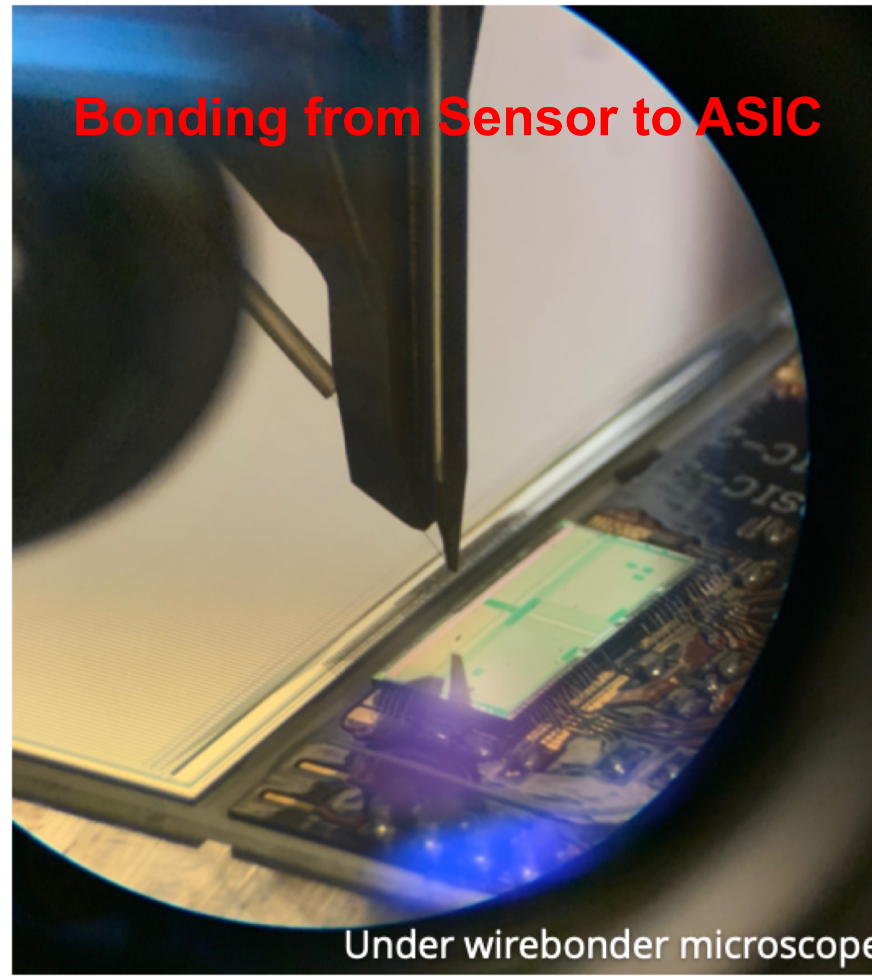


- Operated on precise vacuum jigs
- Glue gap maintained by bumpers & shims
  - QA by SmartScope for each jig
- Curing hours w/ vacuum on

Wire bonding

- WireBonds requires
  - BF>5g & <0.1% failure
- WireBonder optimized for ø25μm aluminum wire
  - We have: BF>8g w/ RMS~1g
- Dense bonds ~60 μm interval
  - Alternate loop height ➔ No shorting





Module Mounting

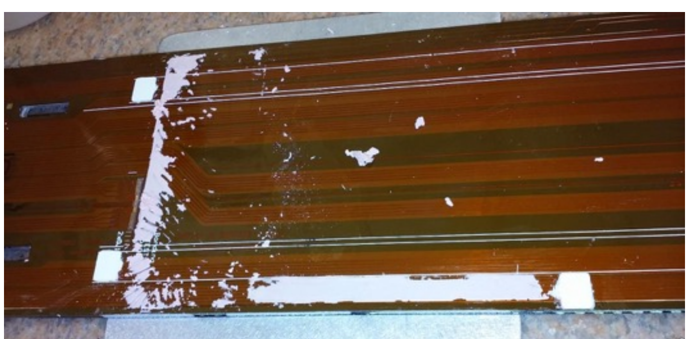
Baseplate fixture for module attachment

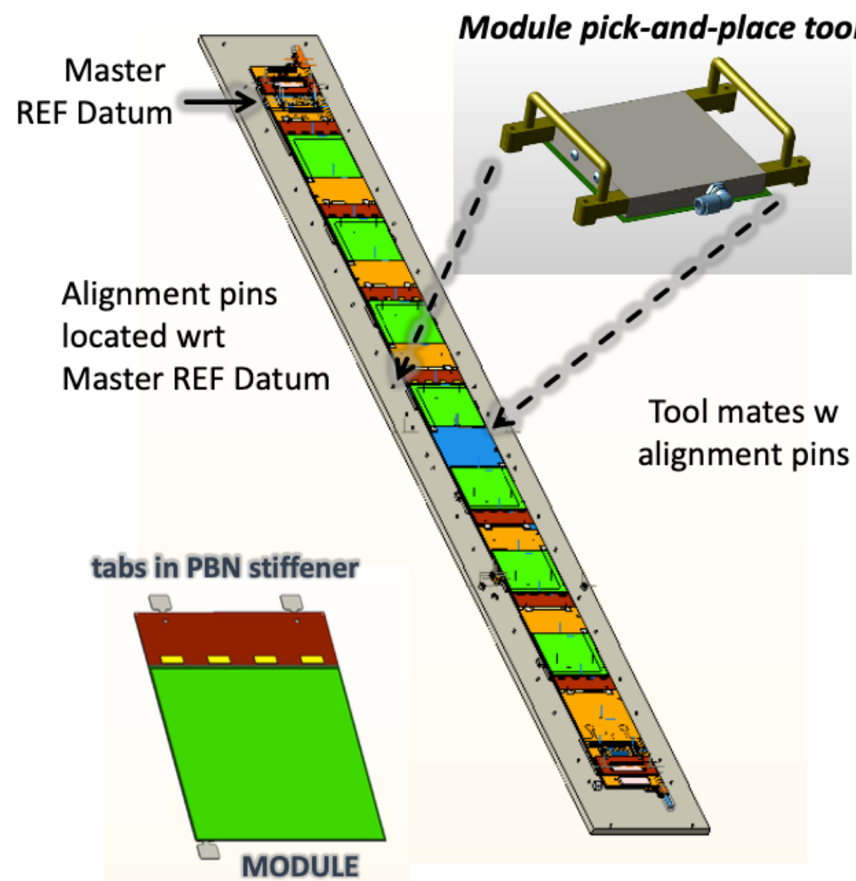
- Array of alignment pins determine module location wrt master REF

Thermal interface TIM: heat to 65℃

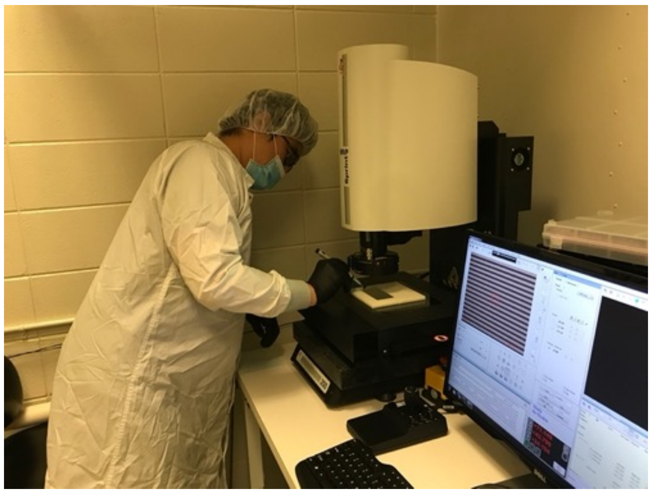
Module removal

- In case broken
- Cut tabs (with hard epoxy)



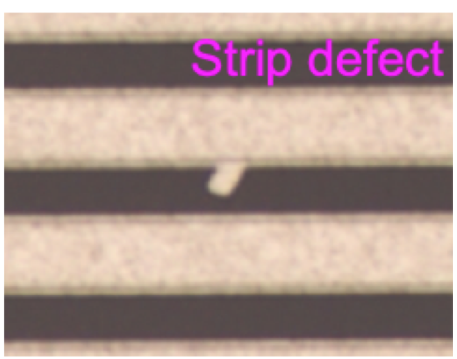


Sensor QA



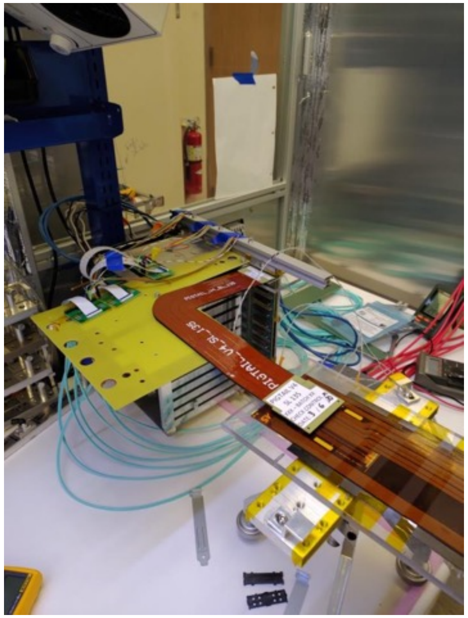
QA on sensors before construction

- Automated visual inspection (SmartScope + script) & bowing (geometry)
- IV/CV curves



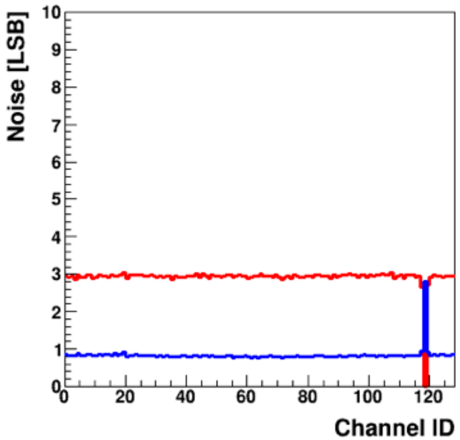
Module/Stave QA

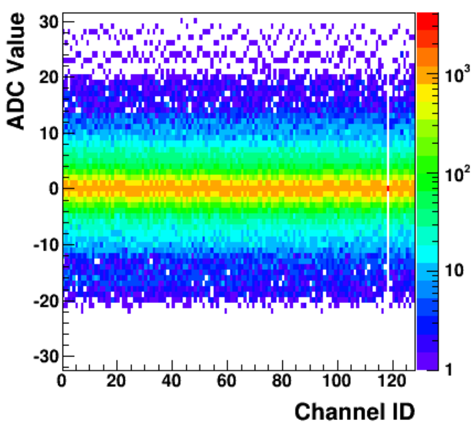
MiniDAQ systems for module & stave test



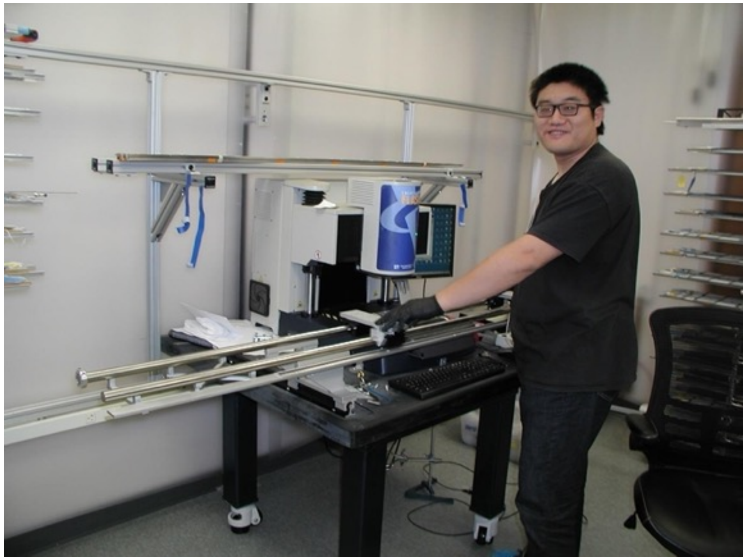

Checks
- ➢ Communication to SALTs
- ➢ Read outs
- ➢ HV at 500V

Module passes the test w/ <=2 bad channel out of 512





Optical QA



SmartScope measurements

- Critical locations (Sensor wrt REF)
- Construction feedback
- Input for Detector online alignment

Rail system built for stave measurement

- Calibrated by Straight Edge
- Sensor location measured with error < 35 μm

Summary

Two-phase upgrade planned for LHCb experiment

- Aim for 50fb-1 by the end of Run4 and 300fb-1 in Run5-6
- More data → more precision measurements for searching new physics or further test in Standard Model

Phase-I upgrade

- New trackers
  - UT: fine segmentation strip detector replace of TT

UT construction near to the end, expected finished by 2022

Exciting times ahead at LHCb

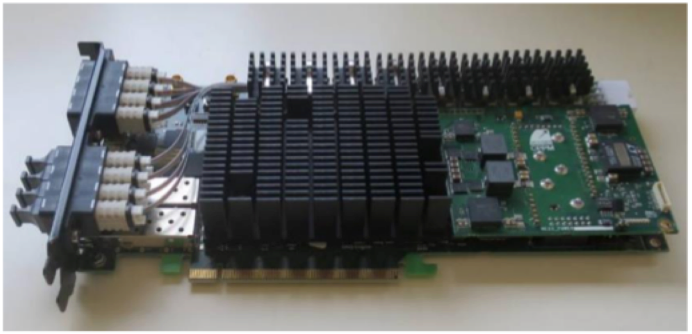
Thanks for your attentions

Backup

DAQ

Hardware of DAQ is a PCIe40 board

- Common to all LHCb detector



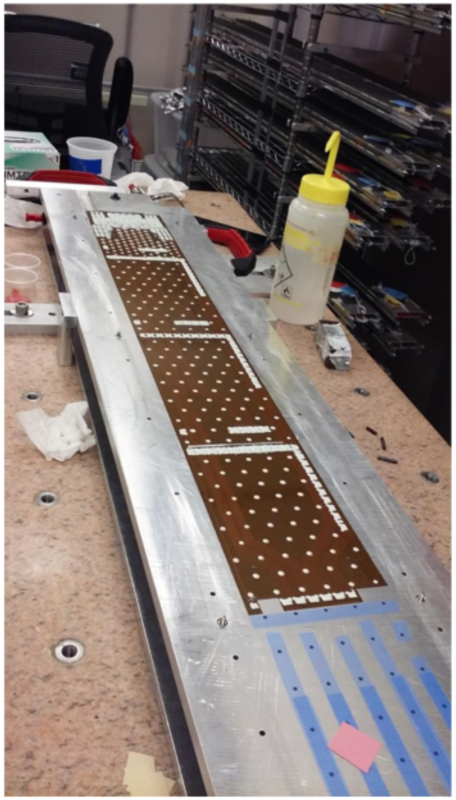
PCIe40 board

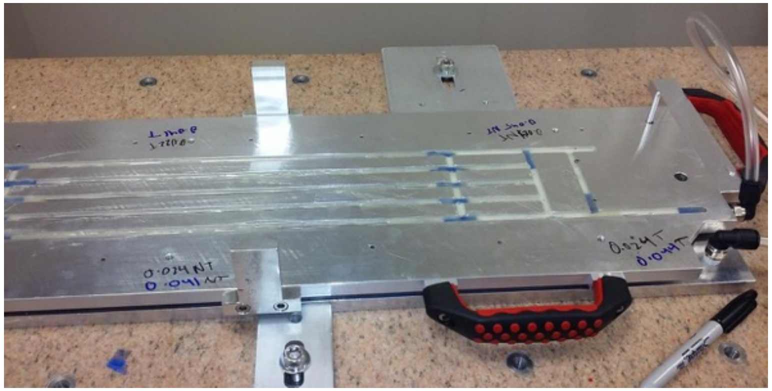
Major functions

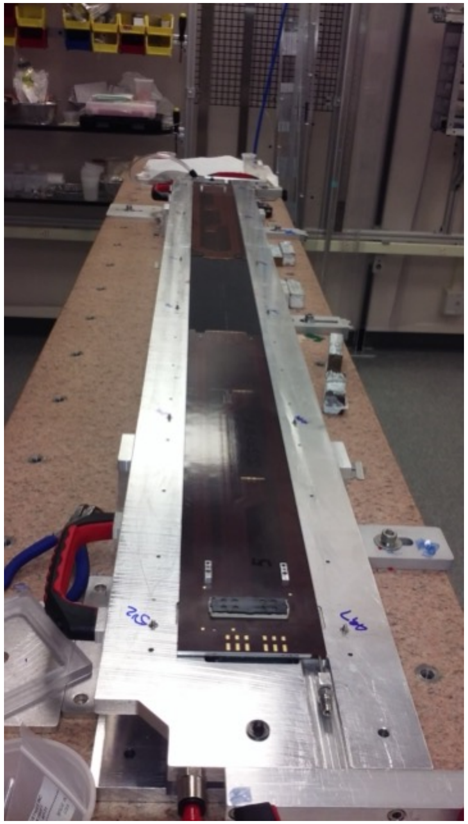
- FE control
  - ❑ Control/monitor SALT, DCBs, and itself
  - ❑ One DAQ → several DCBs with CLK, reset, slow control, etc
  - ❑ Synchronizes with other DAQs, so all DCBs and SALTs synchronized
- Data processing
  - ❑ Purge input data stream, only hit info. saved
  - ❑ All particle hits in same CLK collected
  - ❑ Hit events packed and Ready for storage and offline processing

Bare Stave Construction

Construction including
- Bare stave construction
- Attachment of data flex cables
- Module mounting





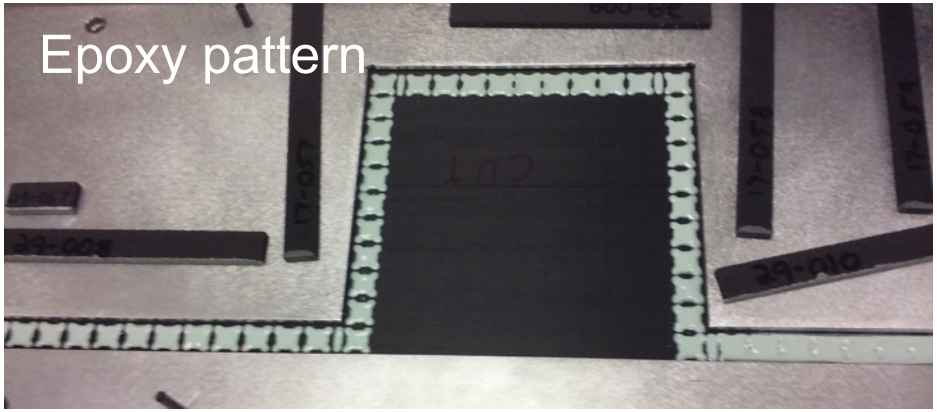


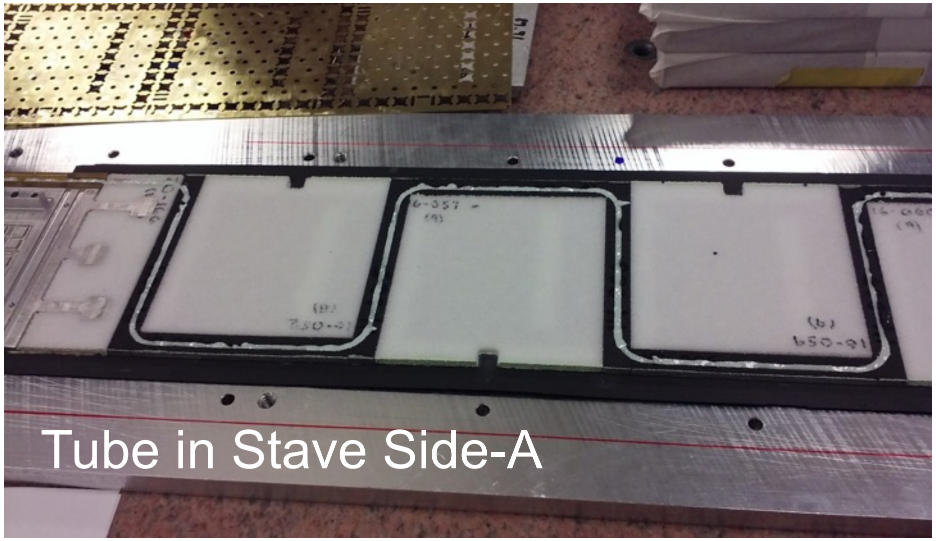
Stave Construction

Construction including
- Bare stave construction
- Attachment of flex cables
- Module mounting

Bare stave
- Lay down facing on vacuum baseplane fixture
- Epoxy patterns w/ stencils
- Components (Carbon foam, EOS, Rohacell) positioning by fixturing, pins, ref edges, etc

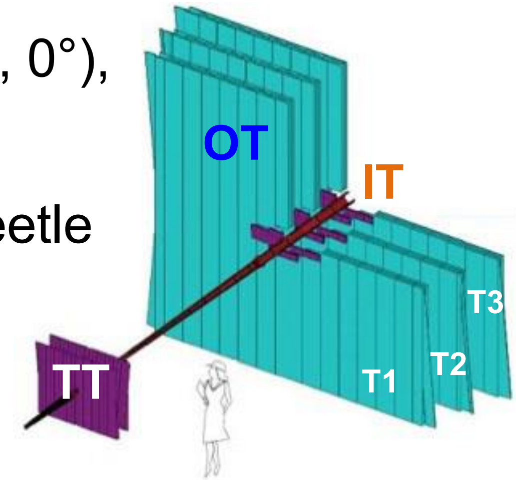
Vacuum pickup tool for flex cables attachment as well

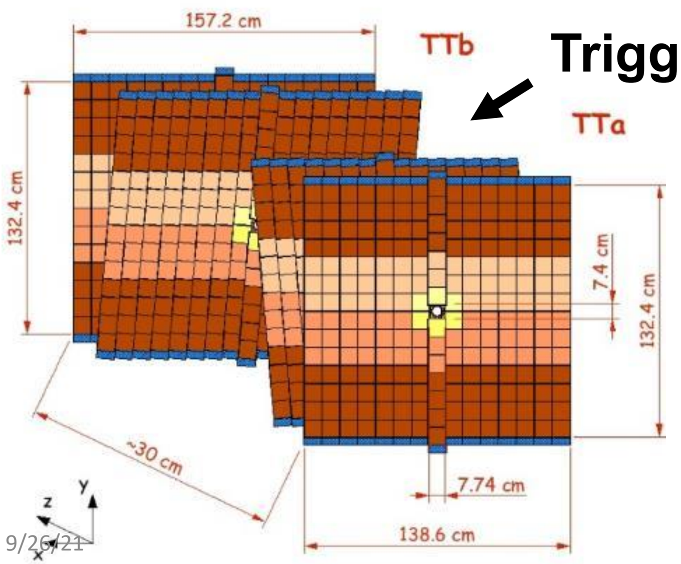




Current LHCb Tracker

- 4 planes TT before Mag, 3x4 planes of IT&OT after Mag
- Four planes (X,U,V,X) of each group are @ (0°,+5°,-5°, 0°), provide stereo measurements, precision horizontally
- TT&IT are p-type silicon strip detectors, read out by Beetle ASICs outside active area
- OT: Kapton/Al Straw Drift Tubes, provide ~ 0.2mm resolution

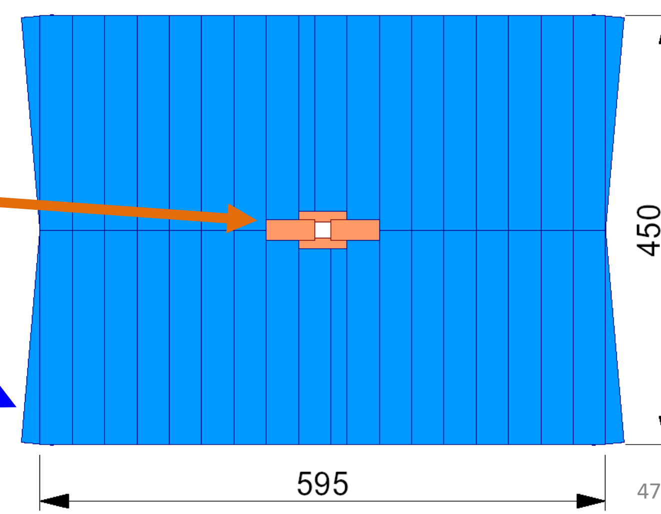




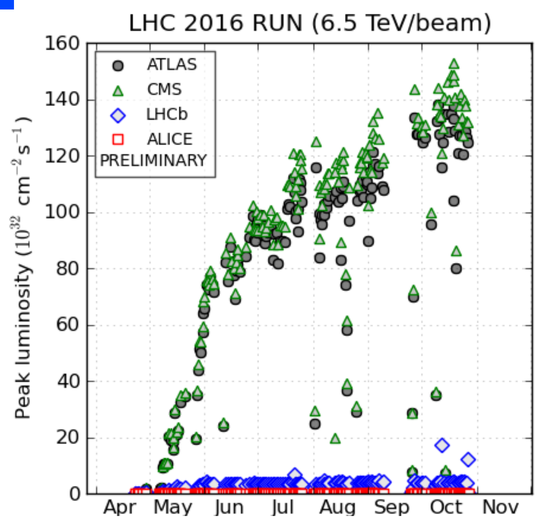
Trigger Tracker (TT)

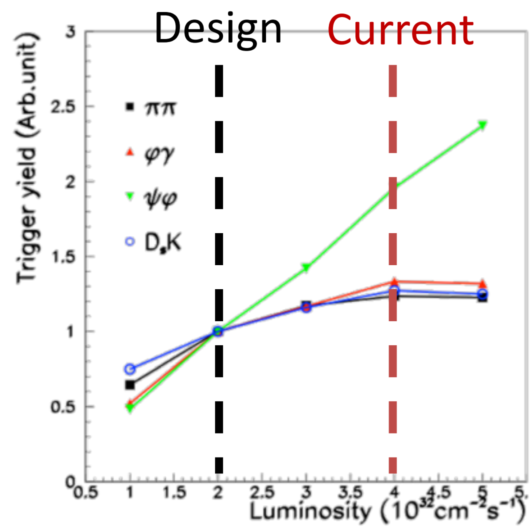
Inner Tracker (IT)

Outer Tracker (OT)



Limitation on LHCb

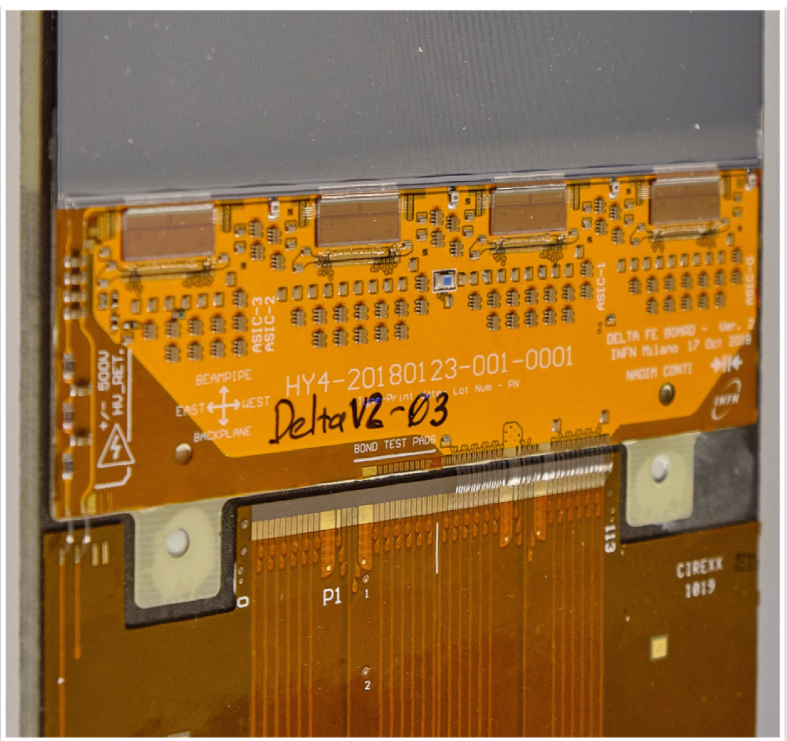




- LHC could deliver LHCb higher $\mathcal{L}$ (ATLAS/CMS @ x40 $\mathcal{L}_{LHCb}$)
- Bottle necks: 1MHz readout bandwidth + hardware trigger
  - Physics yields (hadronic channels) saturate with larger $\mathcal{L}$
- Designed for 5 years @ 0.5x $\mathcal{L}_{LHCb}$(current)
  - More radiation damage & performance degradation
- CPU time for event reconstruction exponentially increases
  - Track & primary vertex multiplicity and combinatory increase

Hybrids and Flex Cable

- ASICs mounted on hybrid flex boards
  - 4 (A sensor) & 8 (B/C/D sensors) ASIC variants



- Hybrid then readout by flex cables
  - 100 Ω differential input impedance traces
  - Up to 1kV btw adjacent lines
  - Less than 500 mV roudtrip voltage drops