The Silicon Upstream Tracker for the LHCb Upgrade

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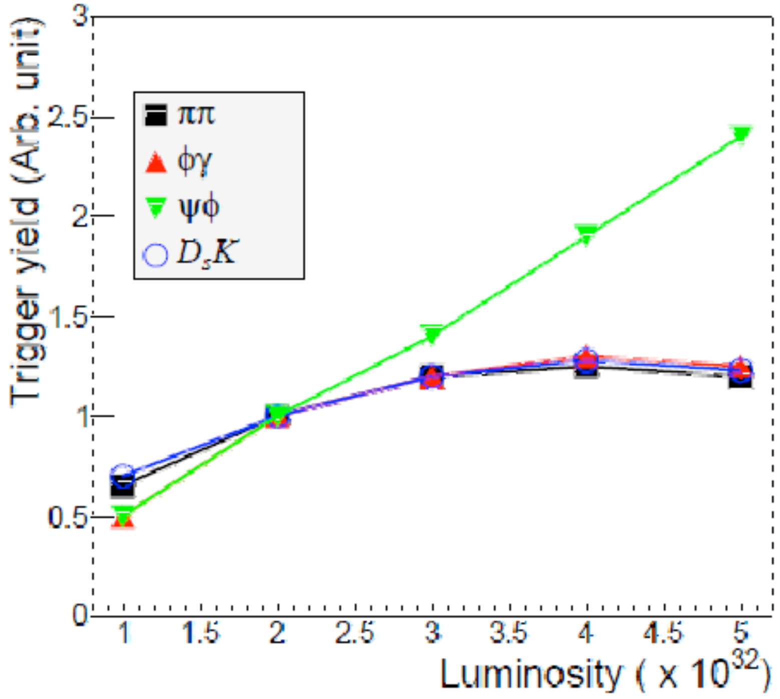
Outline

- The LHCb upgrade
- Importance of UT in track reconstruction
- Conceptual design of UT
- Status of R&D
- Summary

The LHCb upgrade

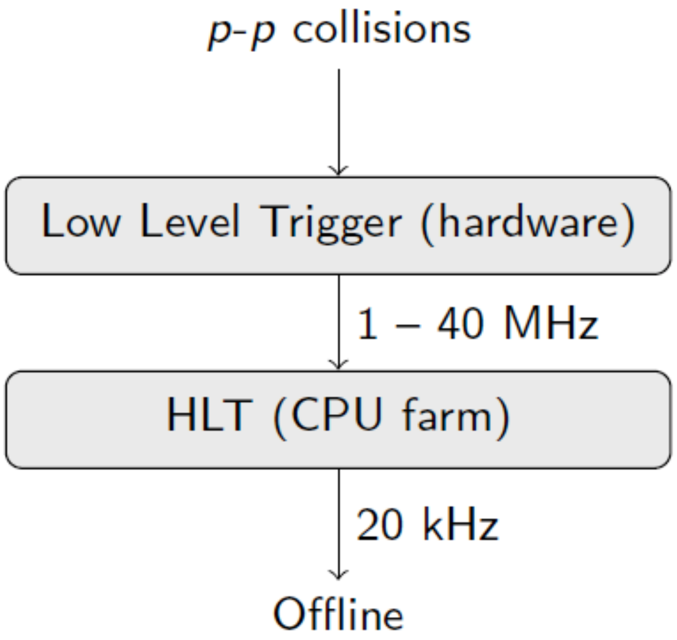
General motivations for the upgrade

- Heavy flavor physics has a great discovery potential
  - many “theory clean” measurements
  - statistical error is dominant in most cases
  - much larger statistics is crucial for new physics searches beyond the energy scale of the LHC
- Present LHCb detector cannot operate at higher luminosity (i.e. $L=2\cdot10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
  - limit of 1 MHz detector readout rate vs 40 MHz beam crossing
  - limited discriminating power of L0 trigger: saturation of trigger yield for *B* hadronic decay modes



Upgrade strategy

- Target luminosity $2 \cdot 10^{33}$ cm^{-2}s^{-1}. Plan to collect 50 fb^{-1} in 10 years
    - signal yield 10 (20) times larger for muonic (hadronic) *B* decays wrt 2011
- Readout the entire event at each bunch crossing (i.e. every 25 ns)
    - use 40 MHz readout electronics for all subdetectors
    - optimize detector design to cope with higher particle rates
- Adopt new highly flexible trigger architecture
    - foreseen improved trigger performances for *B* and *D* hadronic decays


p-*p* collisions

Low Level Trigger (hardware)

1 – 40 MHz

HLT (CPU farm)

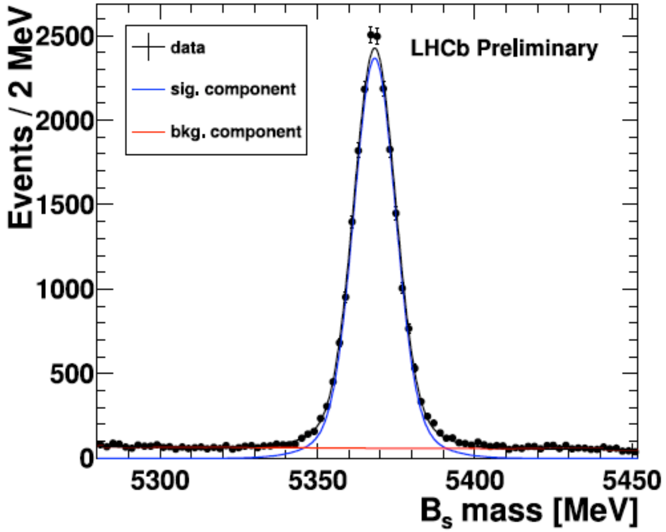
20 kHz

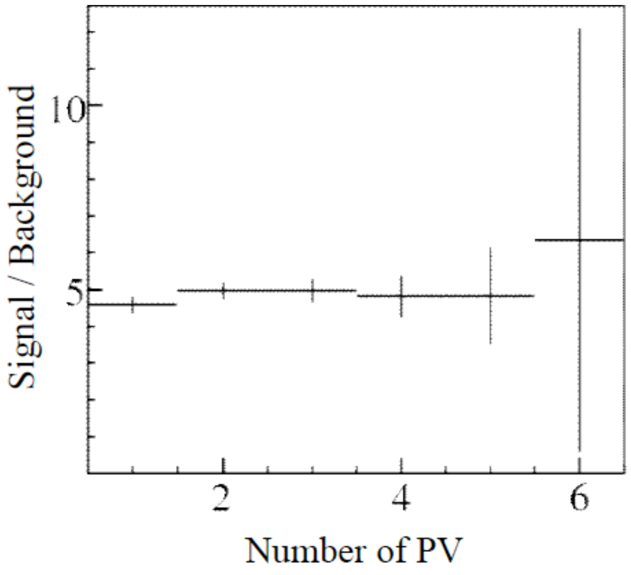
Offline

- Low Level Trigger: muonic, e+γ, hadronic hardware based trigger. Adapt trigger bandwidth to available CPU power
- High Level Trigger: software based trigger

LHCb upgrade environment

- LHCb proved to be able to cope with sizable pile-up* (up to μ=2.5) similar to upgrade conditions
- However, 25 ns bunch spacing is essential for LHCb upgrade to limit pile-up of *pp* interactions
  - cons, bunch-to-bunch spillover
- Challenges for detector design at high luminosity
  - maintain high tracking efficiency and low rates of fake tracks (ghosts) vs #primary vertex (PV), track multiplicity





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* multiple visible interactions per bunch crossing

Importance of UT* in charged particle reconstruction

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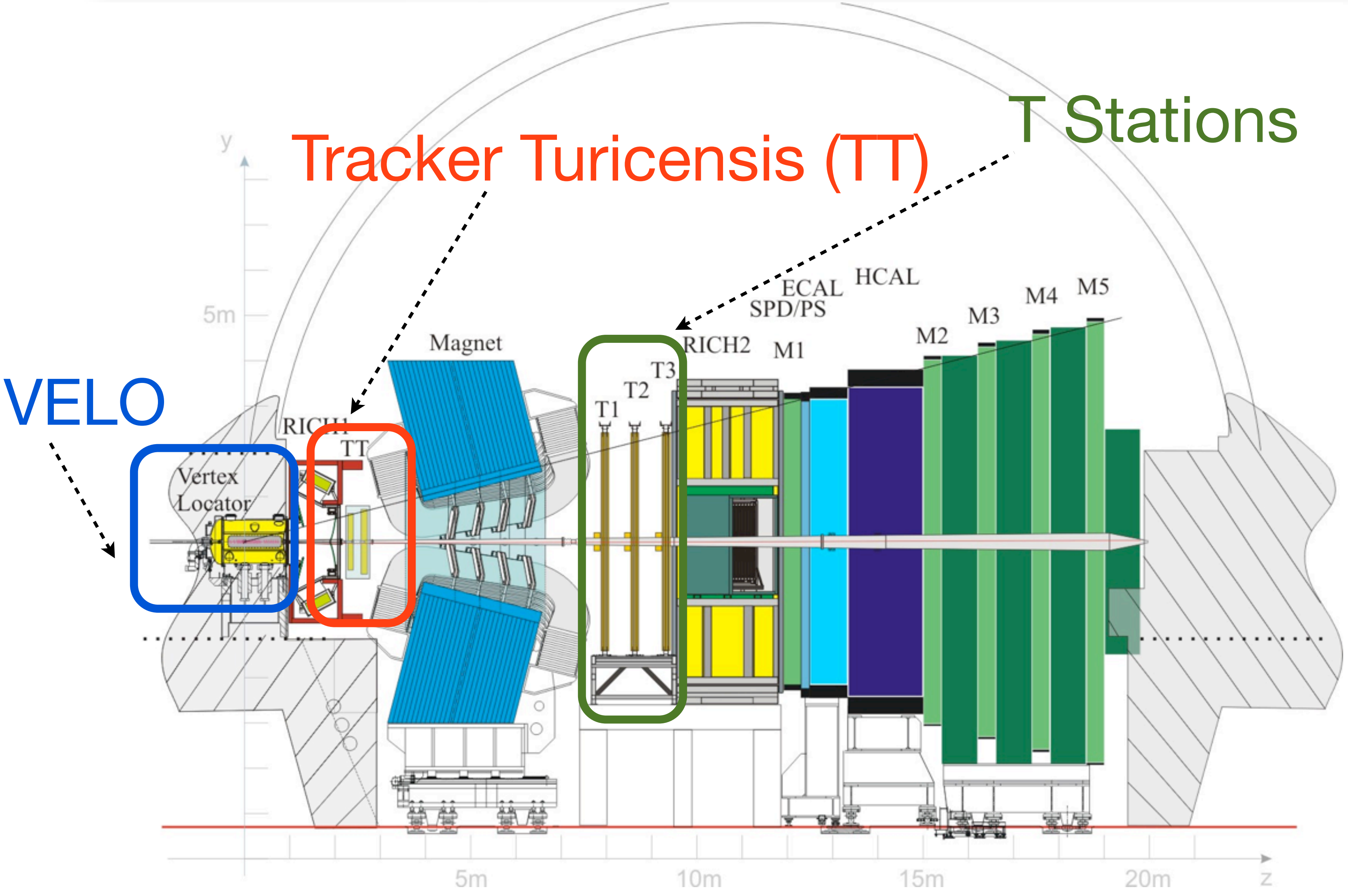
* The Upstream Tracker (UT), upstream of the magnet, indicates the upgrade of the Tracker Turicensis (TT)

LHCb detector



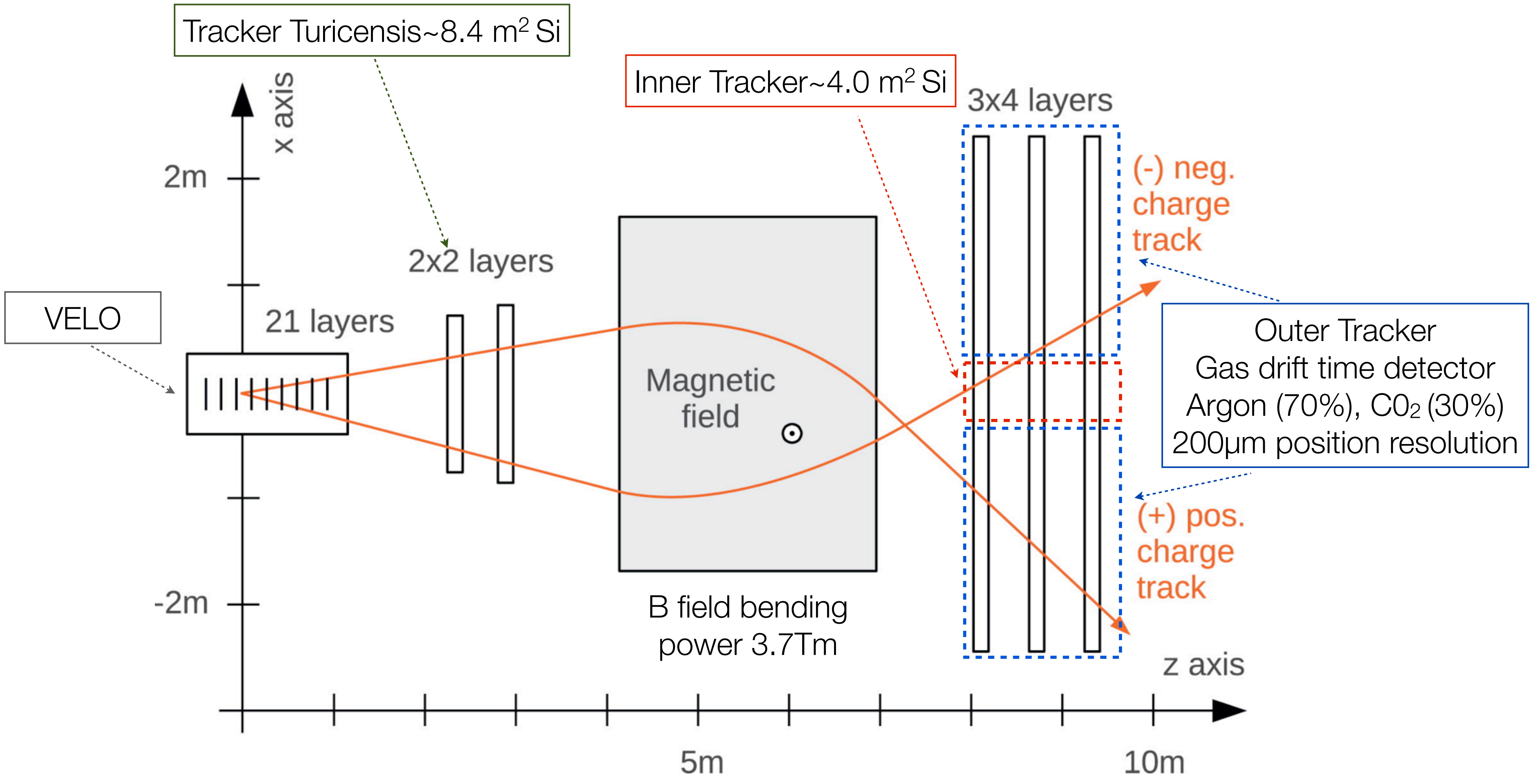
Tracker Turicensis (TT)

T Stations

VELO

LHCb tracking system

TT: 500μm thick, single sided Si strip detector, pitch~100-200μm, vertical and stereo angle strips arrangement (x-u-v-x)=(0°,-5°,+5°,0°)



Tracker Turicensis~8.4 m^2 Si

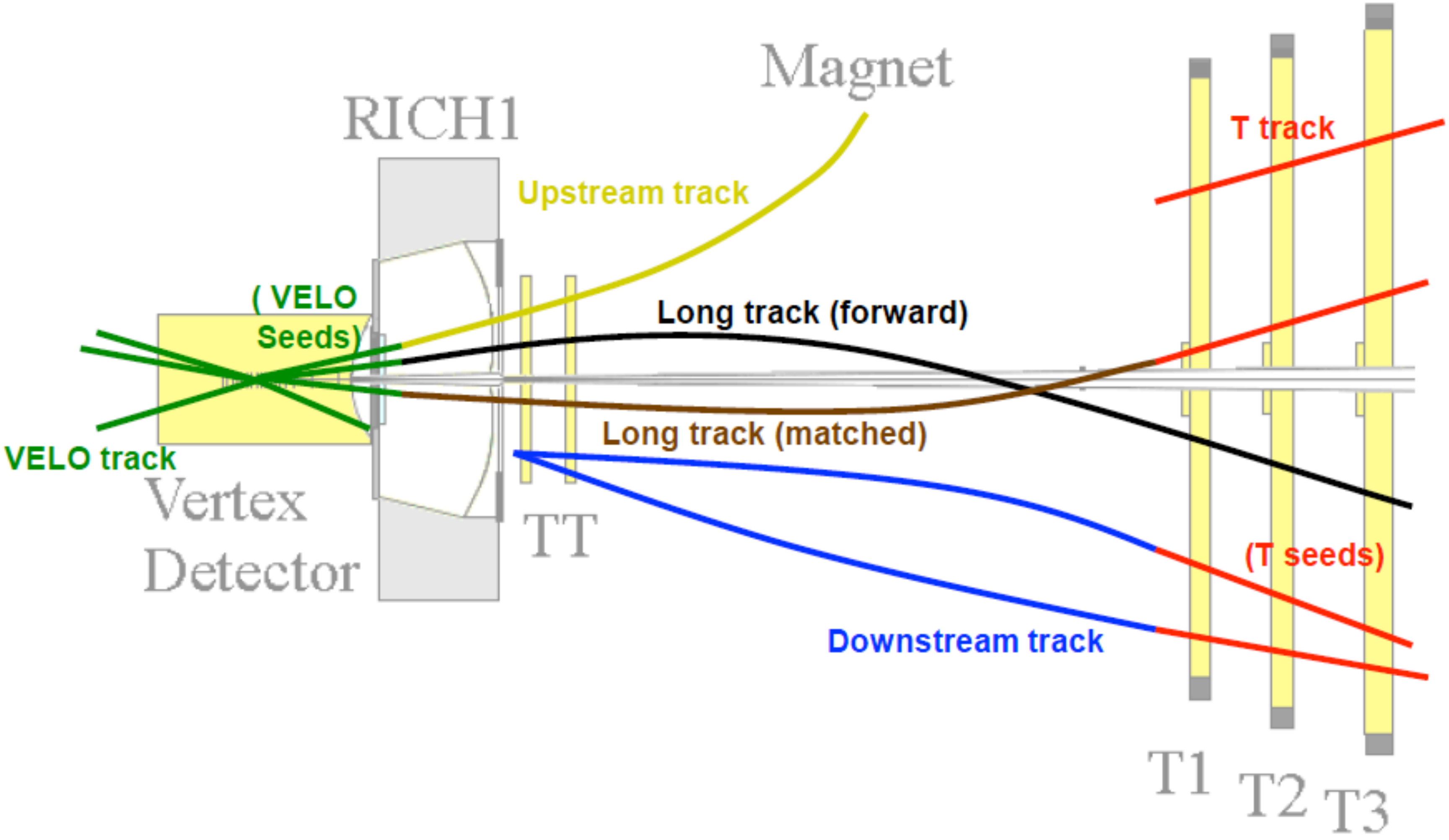
Inner Tracker~4.0 m^2 Si

VELO

Outer Tracker
Gas drift time detector
Argon (70%), CO_2 (30%)
200μm position resolution

B field bending power 3.7Tm

Track definitions at LHCb



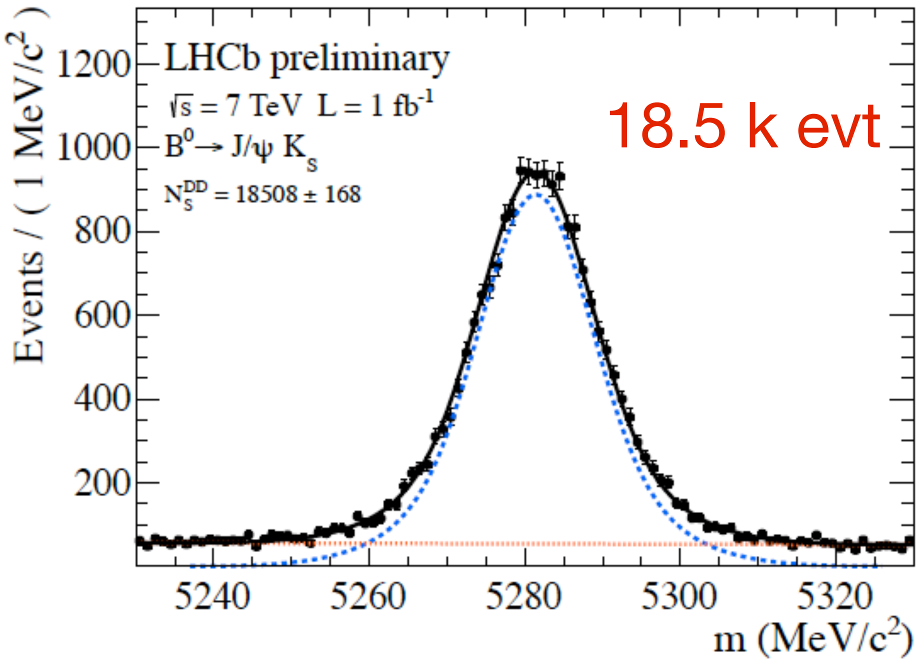
Ghost track = is a fake track. For example it can be formed by matching a real track segment in the VELO (VELO seed) with a real track segment in the downstream tracker (T seed)

Relevance of UT

- Reconstruction of particles decaying after the VELO (e.g. $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$)
- Reconstruction of low momentum particles that bend out of the acceptance before reaching T stations
- Provide additional hits to match track segments in the VELO and T stations and suppress ghost tracks
- Provide p_t estimate of charged tracks. $\sigma(p_t)/p_t \sim 15\%$ is achievable in the p_t range of 0.5-10 GeV/c
- Reject low momentum tracks and dramatically speed up track reconstruction for trigger decisions (HLT) by using VELO-UT tracks

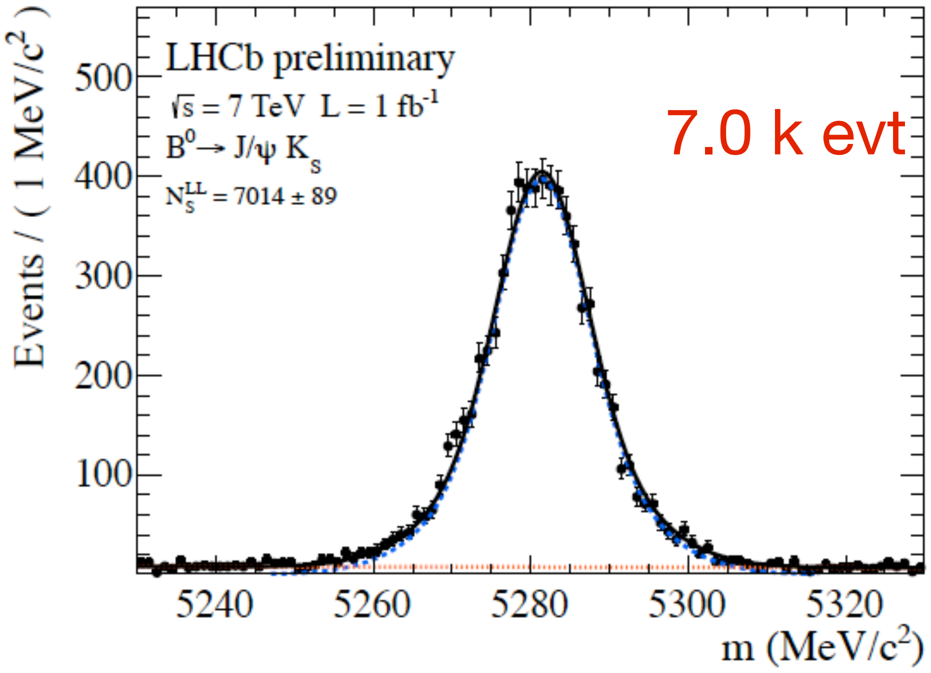
Impact of TT in $B^0 \rightarrow J/\Psi K_S$ reconstruction

From TT + T station hits



18.5 k evt

From VELO + T station hits

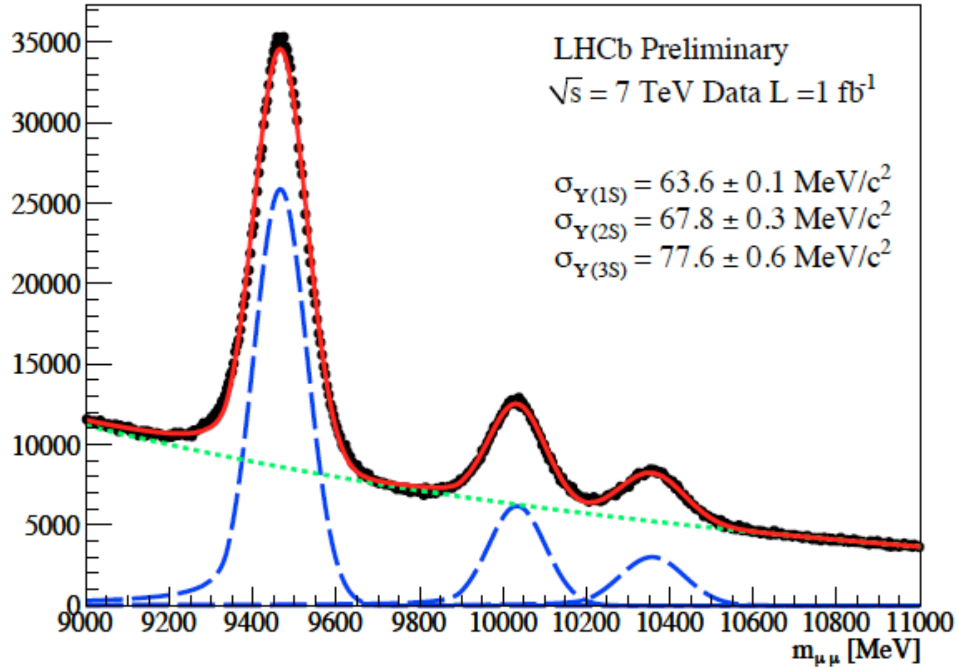


7.0 k evt

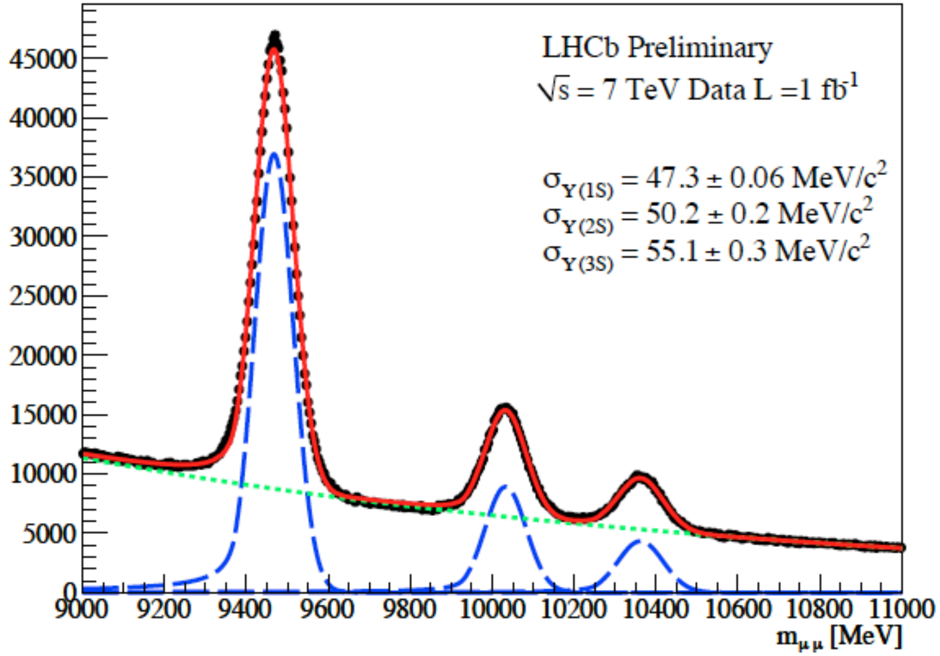
- Most K_S decay after VELO
- 73% of signal events reconstructed using TT and T station information only

Impact of TT on $\mu^+\mu^-$ invariant mass

$\mu^+\mu^-$ tracks with no TT hits



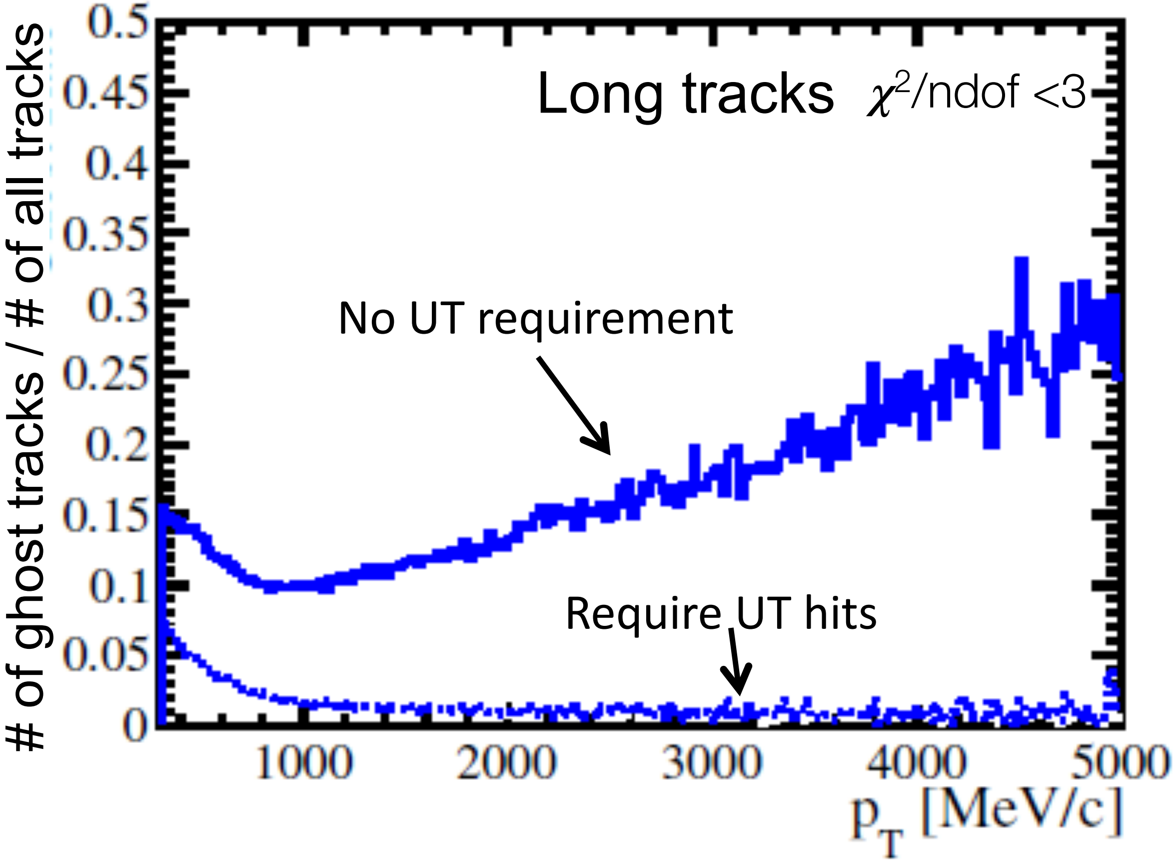
$\mu^+\mu^-$ tracks with TT hits



- Adding TT hits dimuon invariant mass resolution improves of about 25%

Reduction of ghost tracks

- Simulation corresponding to $L=2\cdot10^{33}\text{cm}^{-2}\text{s}^{-1}$
- Sizable ghost contribution from matching VELO seeds with T segments
- Significant ghost reduction when requiring UT hits
- Ghost reduction is crucial for speeding up trigger timings and for background suppression in physics analyses



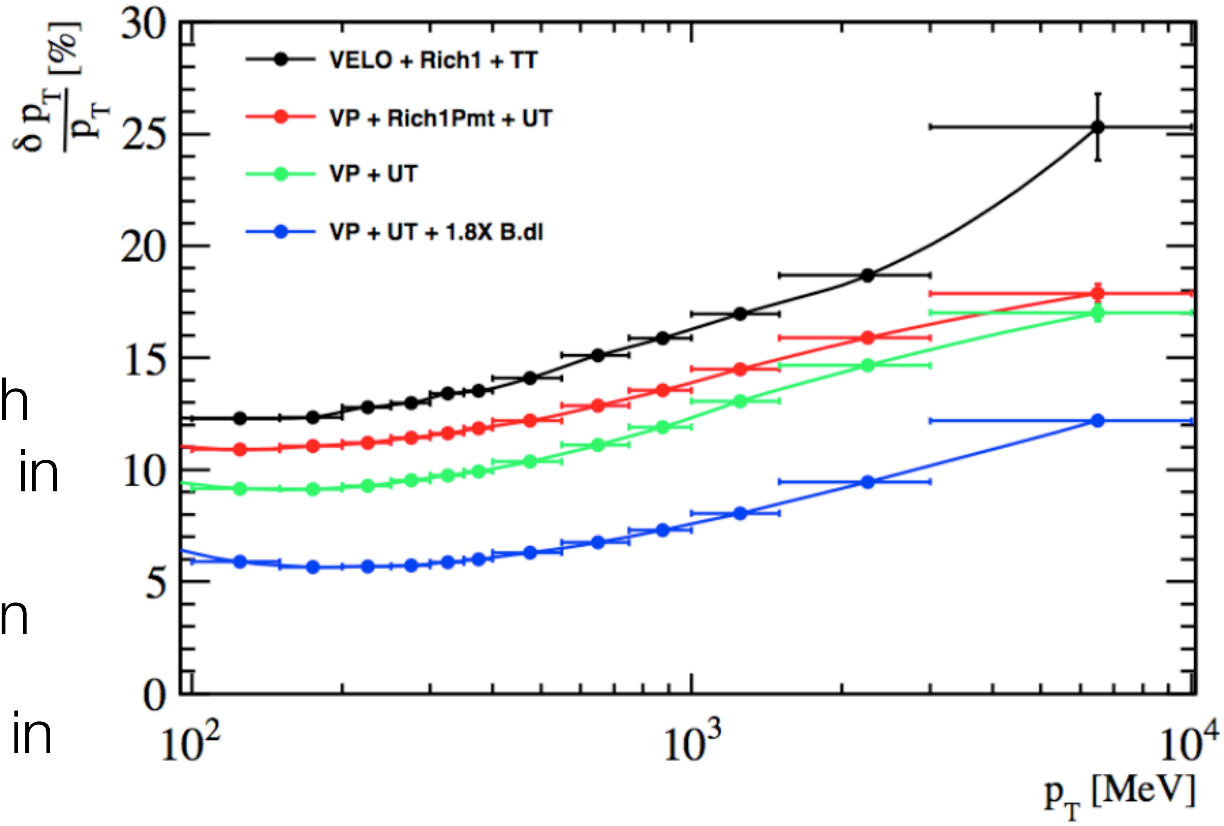
Momentum measurement before the magnet

- Momentum resolution dominated by multiple scattering. Material budget as small as possible

- Increased B field in the UT tracking volume, with respect to current value in TT volume, would improve p_t determination

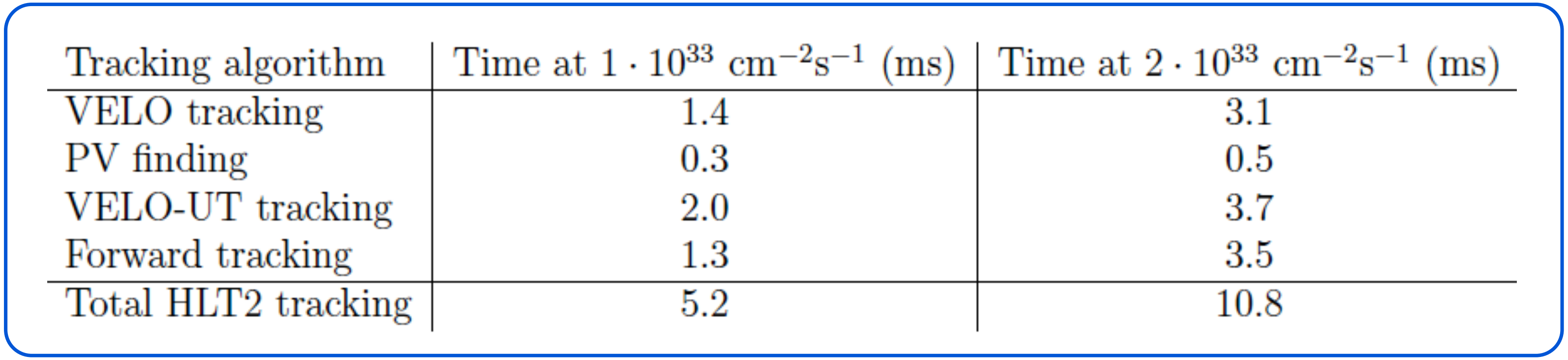
- Present bending power in TT is 0.11 Tm

Momentum resolution for VELO-TT tracks



Impact of UT on trigger strategy

- Emulation of trigger tracking sequence for the upgrade. Low ghost rate (few percent) for VELO-UT tracks, no Kalman fit performed
- Reject low momentum tracks using VELO-UT information
- Forward tracking for all tracks with $p_t > 0.5$ GeV/c: reduced combinatoric



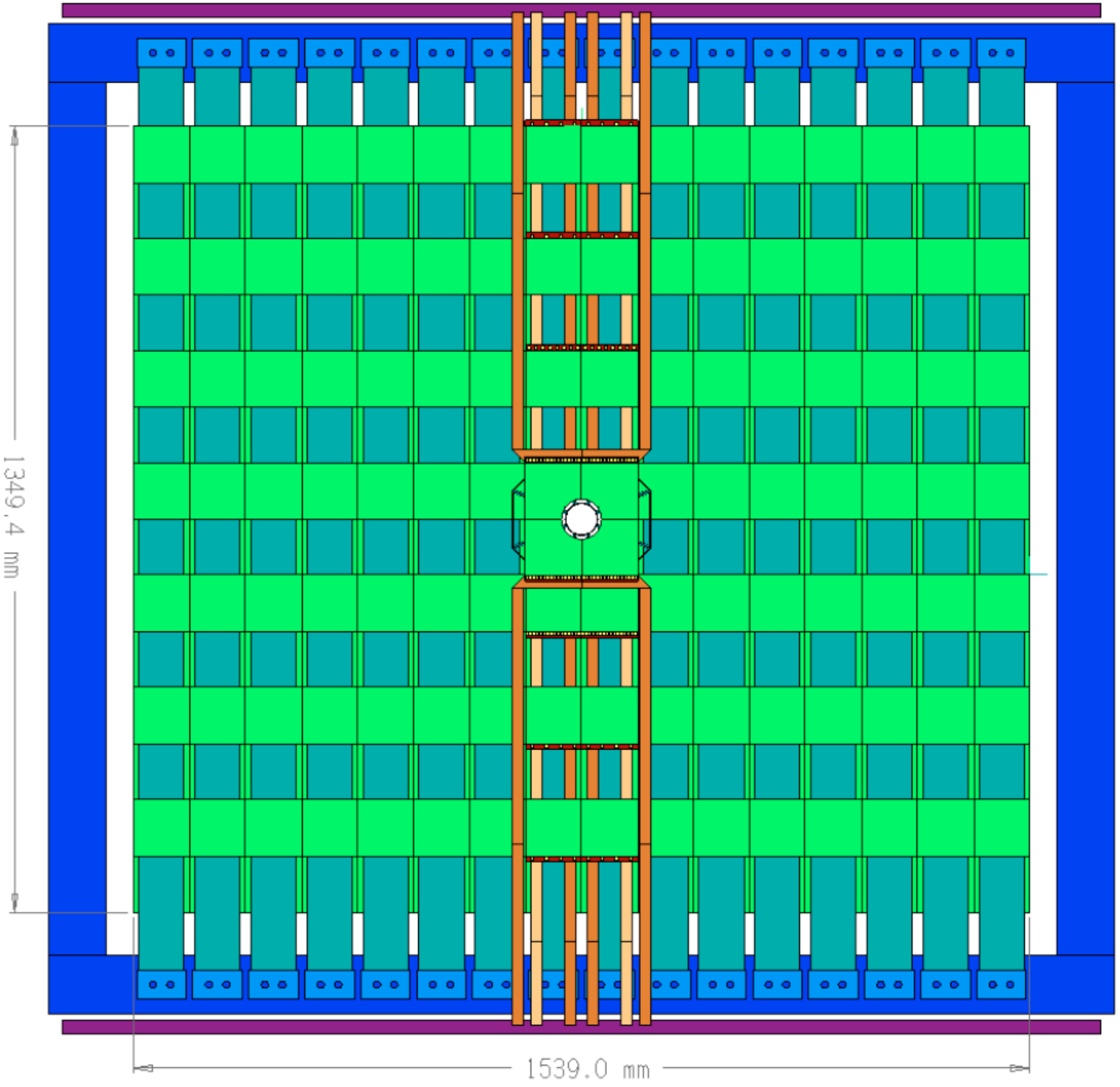
Tracking algorithm	Time at $1 \cdot 10^{33}$ cm^{-2}s^{-1} (ms)	Time at $2 \cdot 10^{33}$ cm^{-2}s^{-1} (ms)
VELO tracking	1.4	3.1
PV finding	0.3	0.5
VELO-UT tracking	2.0	3.7
Forward tracking	1.3	3.5
Total HLT2 tracking	5.2	10.8

- If VELO-UT momentum estimate is not used in the forward tracking algorithm, the timing increases more than a factor 2

Conceptual design of UT

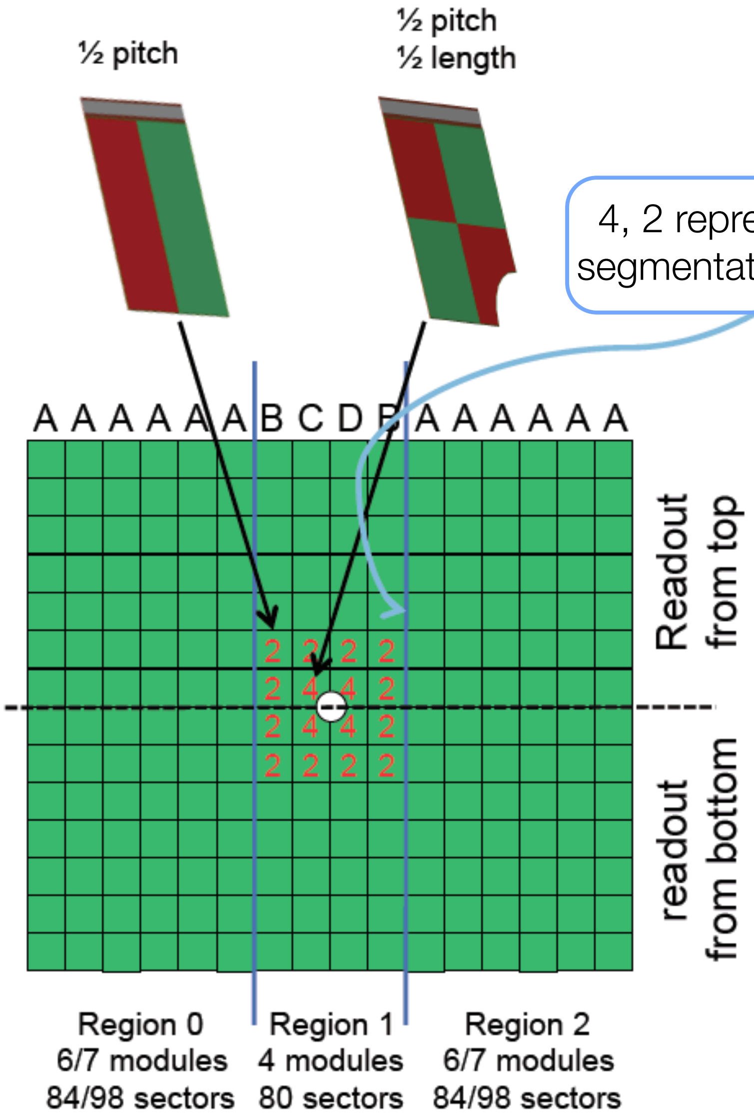
Detector geometry

- 4 planes (X-U-V-X) of single sided silicon strip detectors. X planes measure the horizontal coordinate, U, V planes are tilted of -5°, +5°
- cover completely the spectrometer acceptance: ±300 mrad (X), ±250 mrad (Y), 10-25 mrad inner radius
- full Z region of UT is 2270-2700 mm from IP
- sensor circular cut-out around the beampipe to increase acceptance. Beampipe radius ~32-33 mm, keep 6.5 mm clearance



Silicon sensors and segmentation

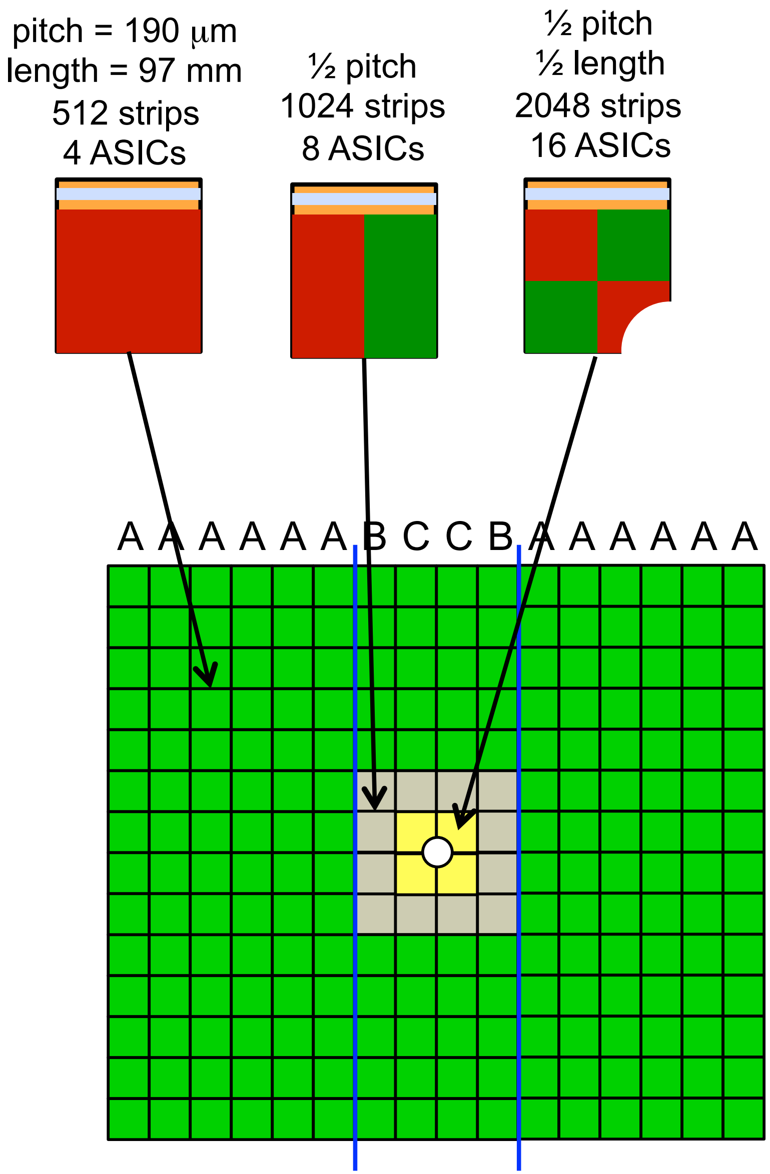
- Rad hard detectors, maximum radiation ~35 MRad at the inner region
- sensor operated at T=-5 °C to prevent thermal runaway at the inner region
- sensor dimensions about 10 x 10 cm^2
- sensor thickness about 250 μm
- ~180 μm strip pitch. 90 μm pitch at inner region where the particle flux is higher



4, 2 represents the segmentation density

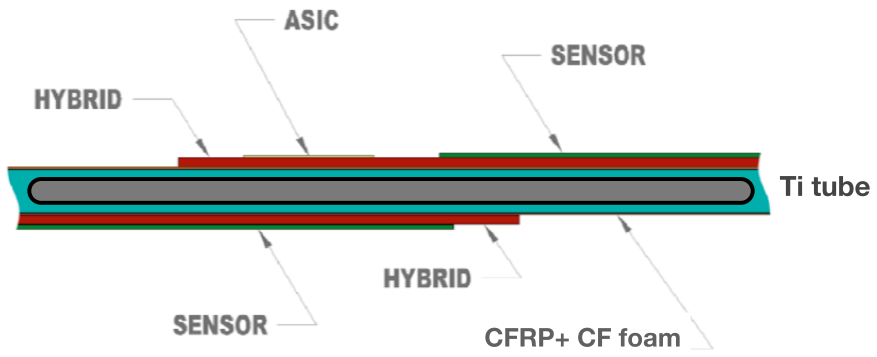
UT granularity and occupancy

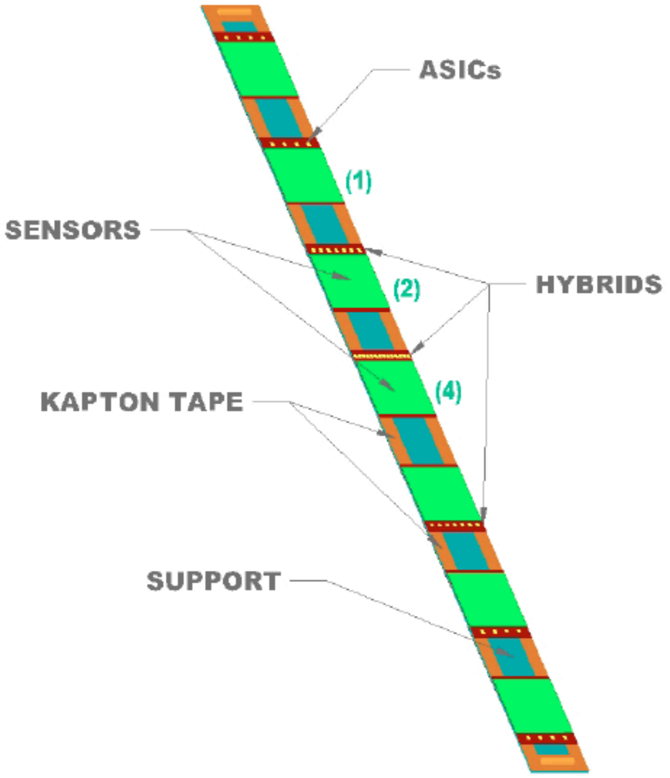
- Occupancies in the UT are ~1% in the inner region and below 0.1% in the outer region with L=2·10^{33}cm^{-2}s^{-1}
- Baseline detector has finer granularity near the beampipe. Having a poorer Y granularity in the central sensors, the ghost rate of VELO-UT tracks increases significantly



Mechanics and cooling

- Material budget kept to minimum ~1% X_0 per plane. Light mechanics and cooling is a challenge
- Design inspired by ATLAS IBL stave:
  - CFRP facings for structural support + CF foam for heat transfer
  - Embedded Ti cooling tube
  - CO_2 bi-phase cooling (T~-35 °C)
- Sensor and FEE alternates on the two sides of the stave



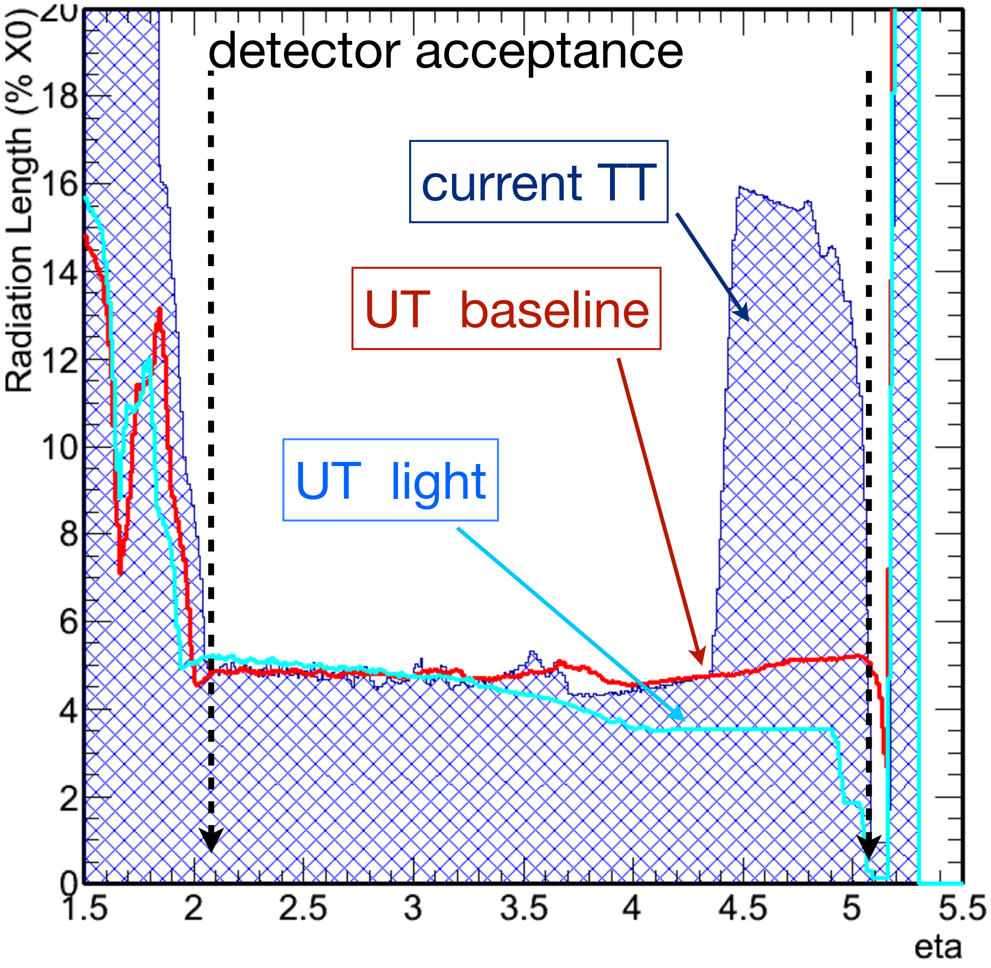


Material budget

- Multiple scattering dominates the momentum resolution at LHCb⇒ minimize material

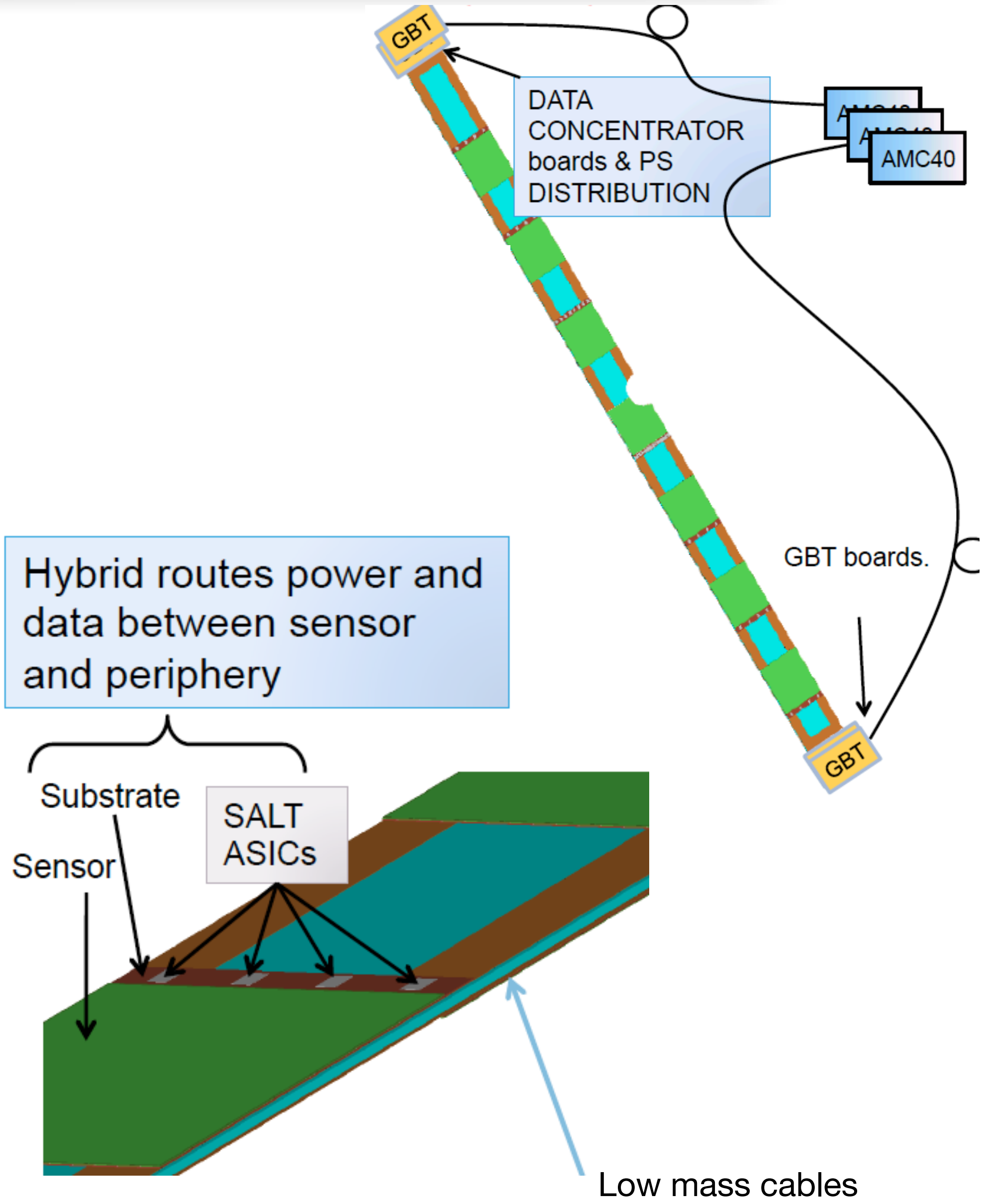
  budget of tracking system
- Current design achieves ~1% X_0 per plane
- New design of the beampipe jacket: use of aerogel as thermal insulator. Significant reduction of material budget at η~4.5-5.0.

Material budget vs η for current TT and two different UT stave solutions



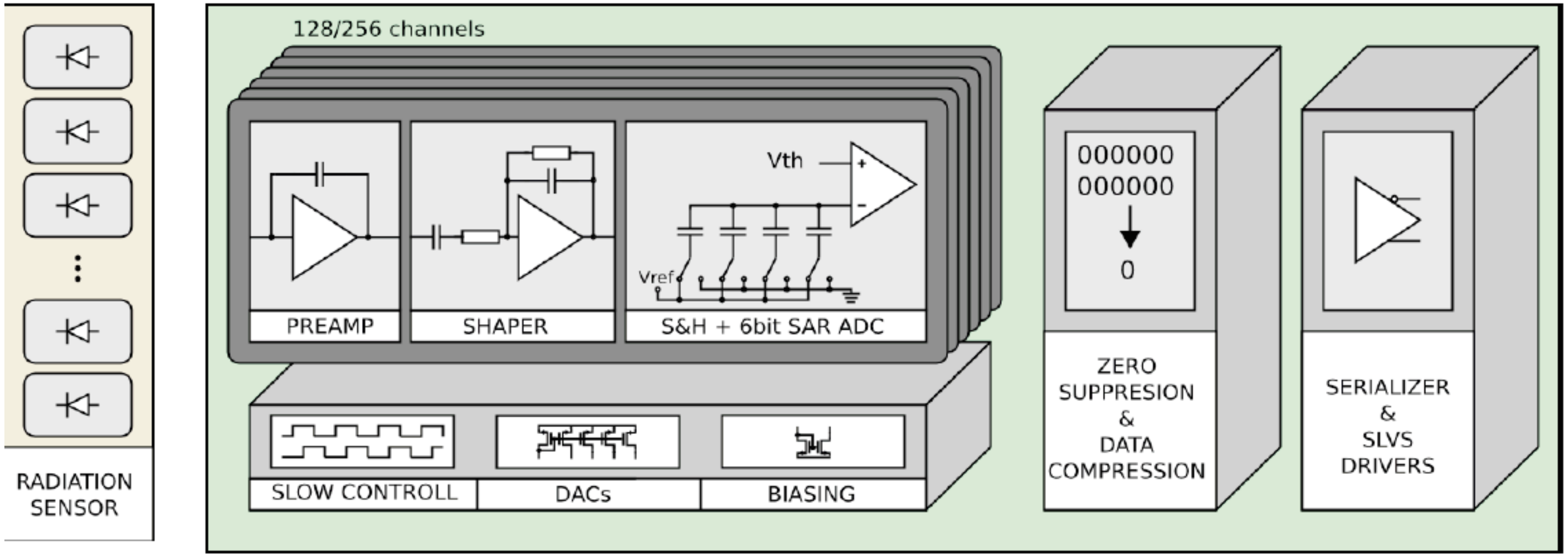
Electronics overview

- FEE provides zero suppressed digital signal (6 bit ADC)
- FEE close to sensor (small input capacitance to premp.) in the active area.
- Hybrids circuit host the FEE: pitch adapter and good thermal bridge for cooling
- Low mass flex cables for signal and power based on kapton and copper (aluminum)
- Data line to GBT board providing transition to optical



Hybrid routes power and data between sensor and periphery

Front end electronics



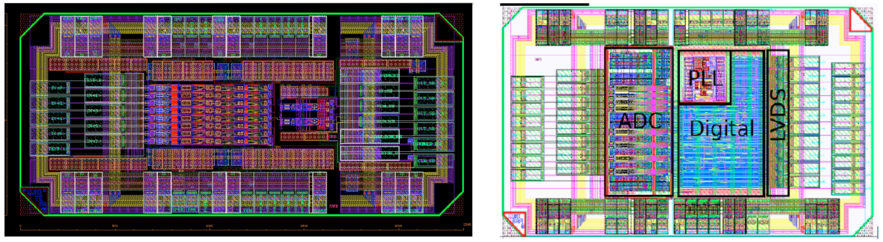
- Asics in 130 nm CMOS technology, 128 channels
- Radiation tolerance ~50MRad
- Power consumption < 6 mW/channel, 0.77 W/chip
- Input capacitance 5-35 pF
- shaper peaking time 25 ns
- fast baseline restore to limit spillover: 5% signal remainder after 25 ns

Status of R&D

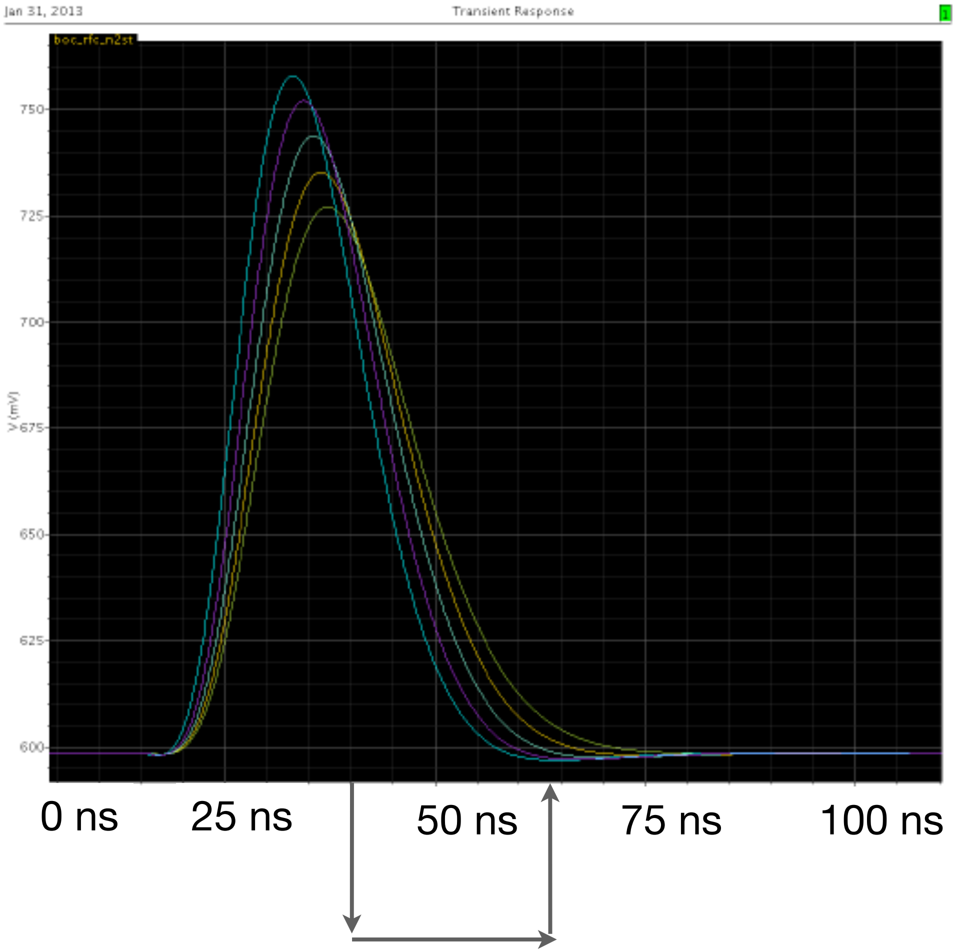
Silicon sensors

- We have 3 sensor designs in the system, that need to be studied in R&D phase:
  - 5 cm strips/≈90 μm pitch, with beam-pipe cut-outs [expected radiation tolerance needed ~1x10^{14} n_{eq}/cm^2 (n-in-p)]
  - ≈90 μm pitch no cut-out (n-in-p) [5 cm and 10 cm long]
  - ≈180 μm pitch/10 cm long strips, no radiation concern (p-in-n)
- R&D on technology choices and prototype for the inner sensors initiated with 2 different vendors: dedicated design, masks almost finalized for n-in-p, 9.8 cmx 9.8 cm sensors

40 MHz readout with SALT chip



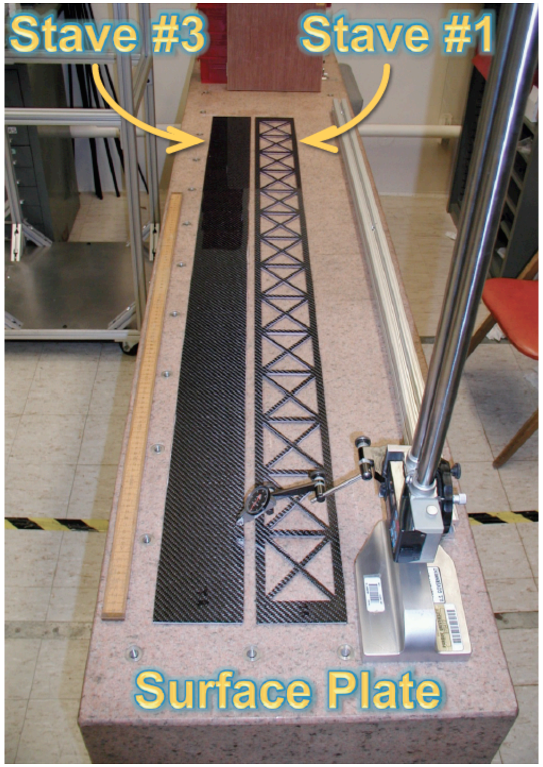
- 8 channel prototypes preamp./ shaper and 6 bit ADC produced
- 6 bit ADC tested OK, low power
- Next: include additional blocks, integrate analog and mixed analog/ digital blocks processing chain

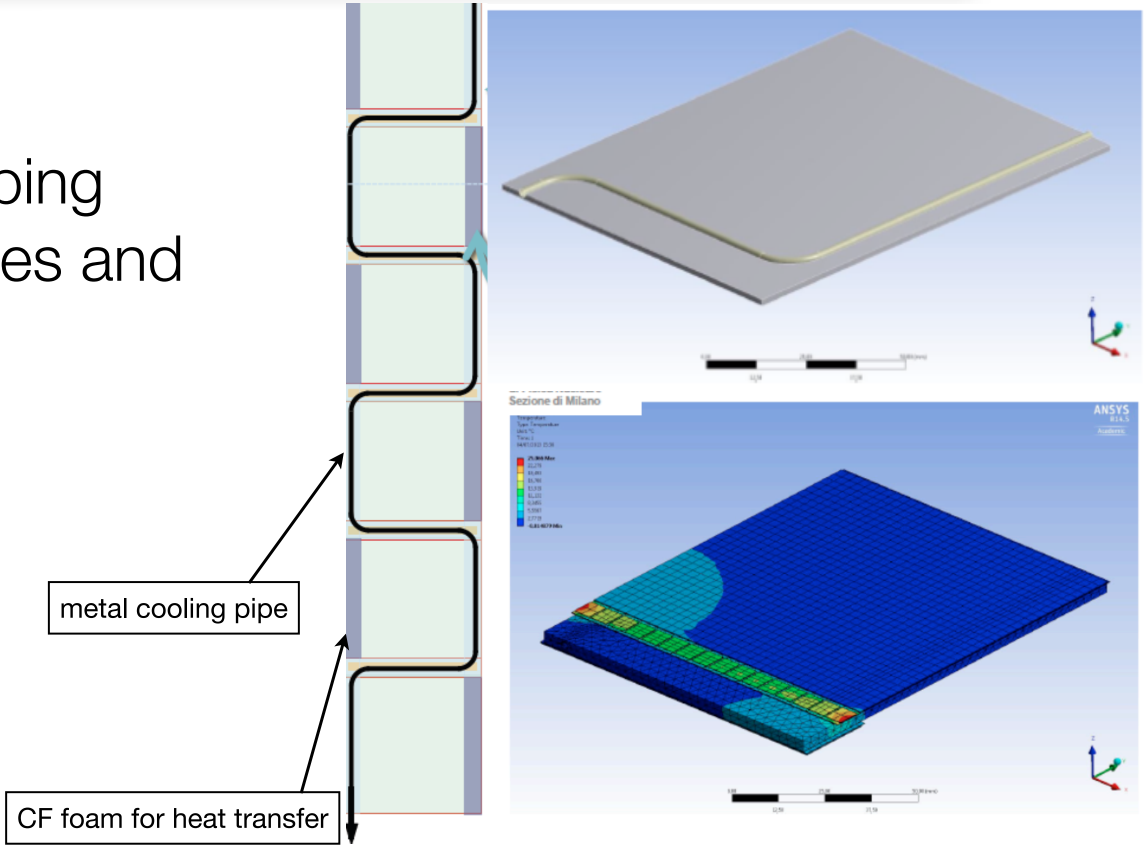


Small spillover 25 ns after the peak

Mechanics and cooling

- First full size stave prototypes for developing construction techniques and quality assessment





- "Snake pipe" thermal simulation for inner sensor (16 asics): very promising results with CO_2 bi-phase cooling
- Alternatives solutions under study (e.g. straight 1 or 2 pipes plus TPG)

Readout system

Data processing in SALT chip

Analog, n=128

Digitization

Digital, n=128

Pedestal subtraction

Noisy / dead channel rejection

N = 128 –

Common mode noise suppression

Discrimination & Zero Suppression

N = nhits

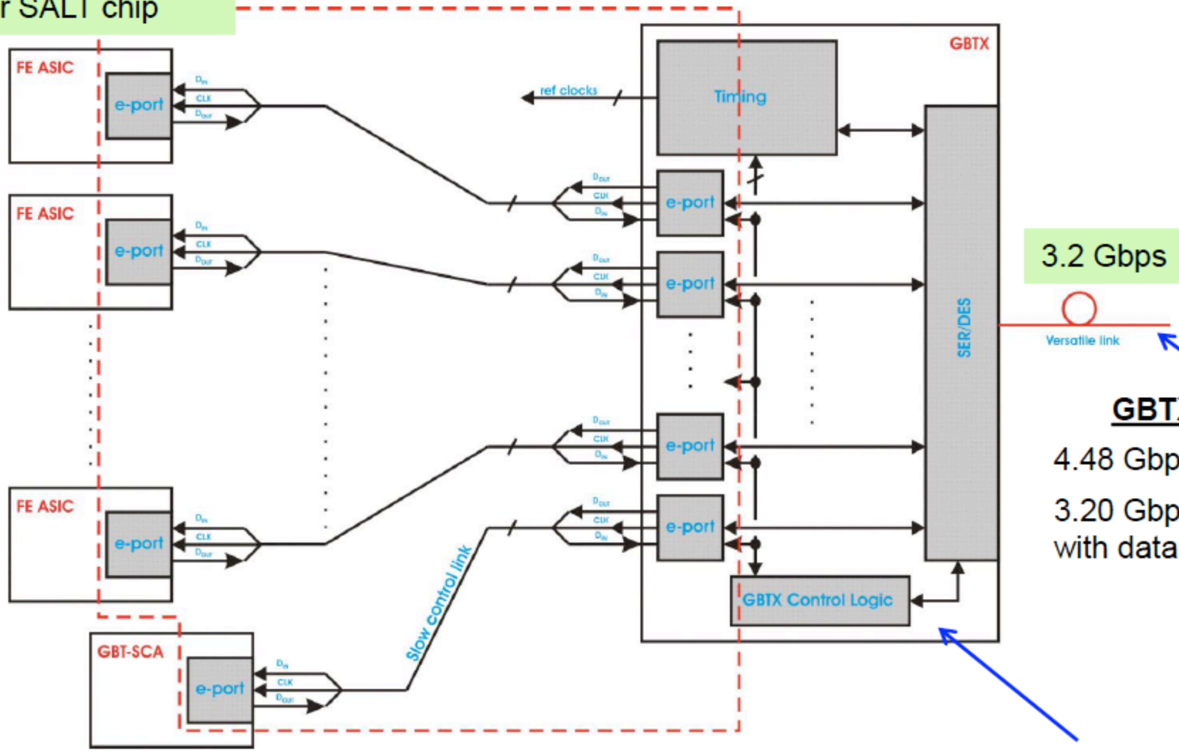
Packing event data

Event block

Transfer data via e-ports

- small charge sharing: strip pitch 180 μm, 90 μm and thickness 250 μm
- clustering and spillover rejection functions in AMC40 board firmware

Data flow architecture



≤4 e-ports (320 Mbps) per SALT chip

3.2 Gbps

GBTX Data Rate

4.48 Gbps for width =112

3.20 Gbps for width = 80 with data recovery.

Data concentrator board

Summary

Summary

- UT is crucial for charged particle tracking and trigger decisions in the LHCb upgrade. Important speed up of trigger timings using VELO-UT momentum estimate (factor 2-3)
- UT conceptual design: reduced material budget (~1% X_0 per plane), increased acceptance using circular cut-out sensors close to the beampipe
- Mechanics and coolings are a challenge: ATLAS like stave with embedded $C0_2$ bi-phase cooling is a promising solution
- Conceptual review of the project in November in Syracuse. Aim to publish the UT TDR in spring 2014

LHCb UT Upgrade Collaboration

- AGH Krakow
- INFN - Sezione di Milano & Università di Milano
- MIT
- Syracuse University
- University of Cincinnati
- University of Maryland
- University of Zurich