LHCb Upgrade

Mark Tobin

LPHE-EPFL

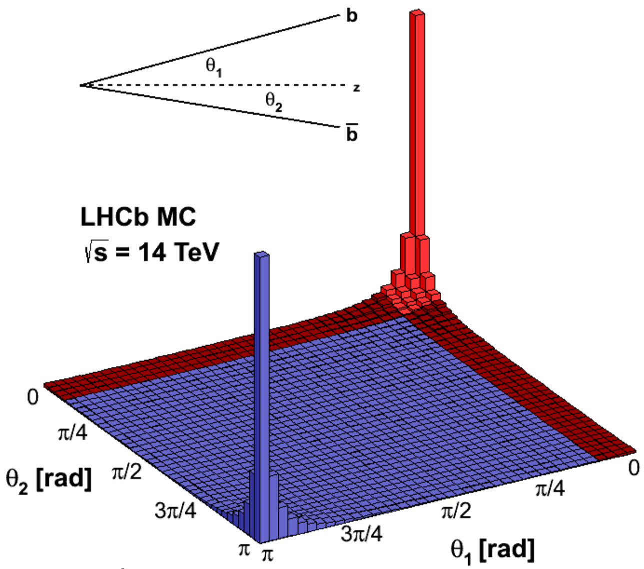
On behalf of the LHCb collaboration

Overview

- Introduction to LHCb:
  - Physics motivation.
  - Detector requirements.
  - Data taking performance.
- Upgrade of LHCb:
  - Motivation.
  - Trigger / physics!
  - Detector upgrades.
  - Schedule.
- Conclusions.

Why LHCb?

- Dedicated heavy flavour experiment at LHC.
- Measure CP-violation in *b* sector.
- Study rare *b*- and *c*- hadron decays.
- ***Indirect searches for New Physics***
- Forward production of b-pairs with low angle.
  – 27% of b-pairs in LHCb acceptance @ √s=7 TeV.



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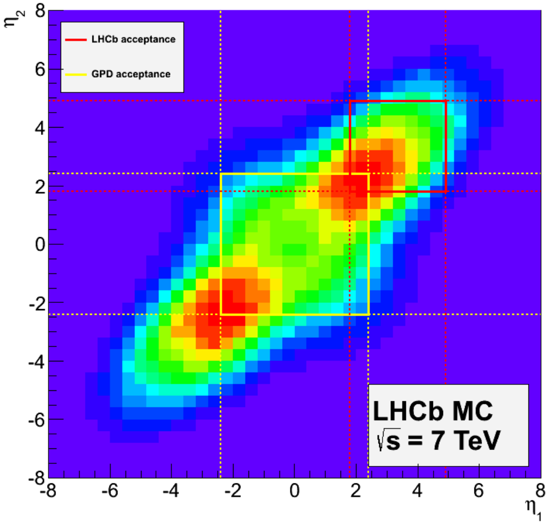
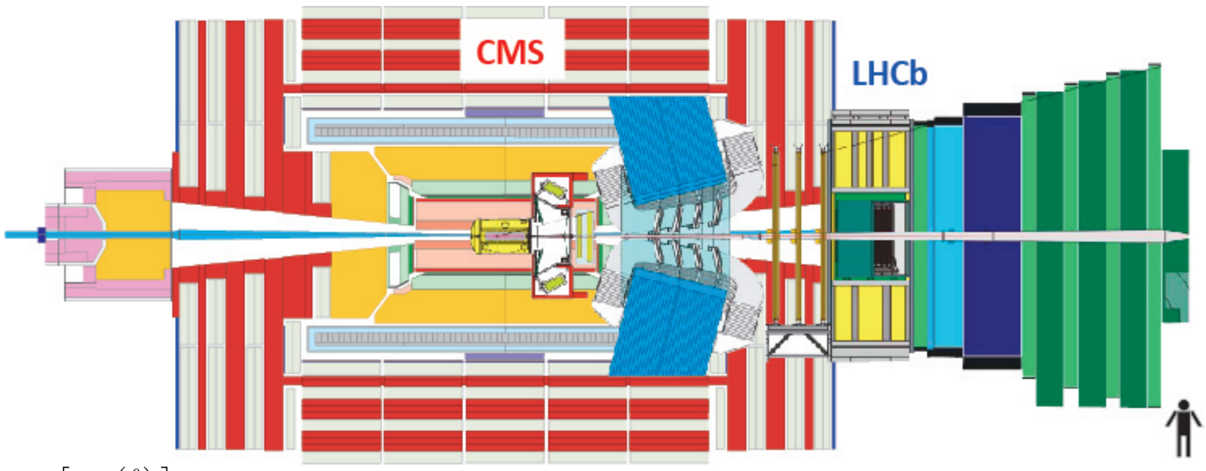
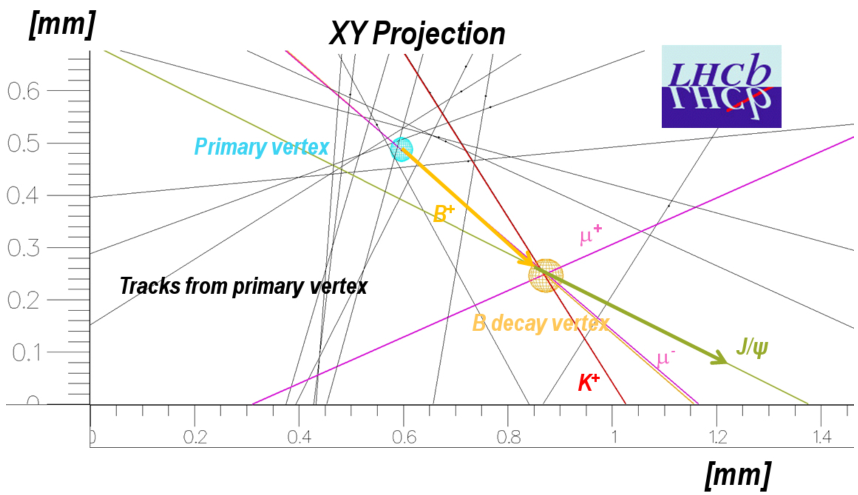
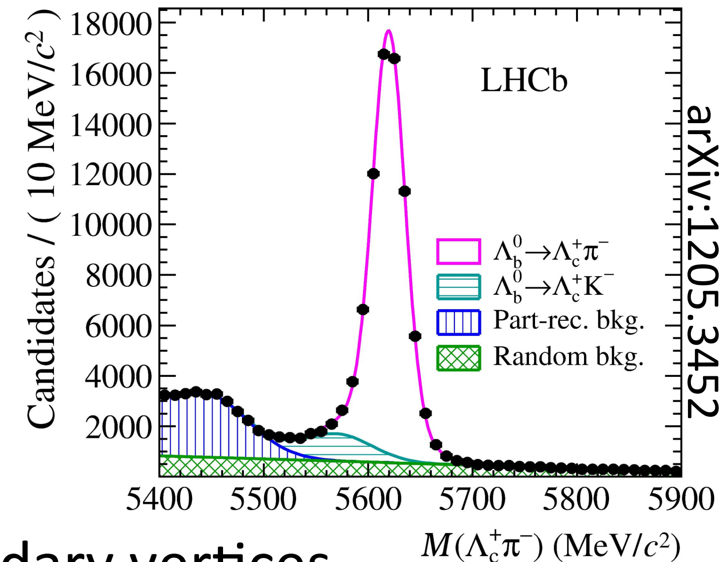




$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

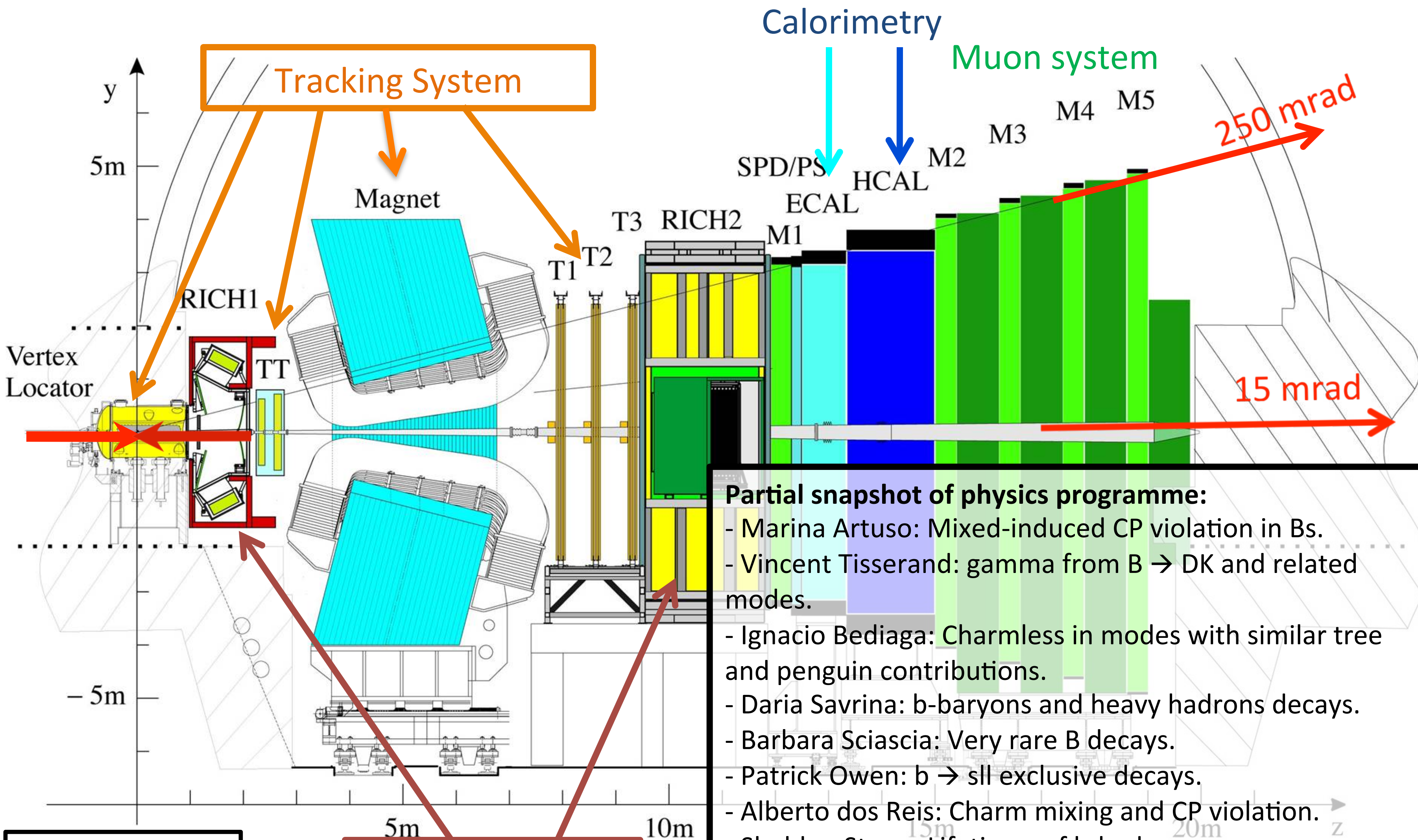
Detector Requirements





- Separation of primary and secondary vertices
- Excellent momentum resolution:
  - δp / p = 0.4% (5 GeV) to 0.6% (100 GeV)
- Particle Identification:
  - Separation between γ, e±, mu±, π, K, p.
- Trigger:
  - Efficient trigger for leptonic and hadronic final states.
  - Fast reconstruction of primary and secondary vertices.

LHCb detector



$2 < \eta < 5$

Partial snapshot of physics programme:
- Marina Artuso: Mixed-induced CP violation in Bs.
- Vincent Tisserand: gamma from B → DK and related modes.
- Ignacio Bediaga: Charmless in modes with similar tree and penguin contributions.
- Daria Savrina: b-baryons and heavy hadrons decays.
- Barbara Sciascia: Very rare B decays.
- Patrick Owen: b → sll exclusive decays.
- Alberto dos Reis: Charm mixing and CP violation.
- Sheldon Stone: Lifetimes of b-hadrons.
- Lucio Anderlini: Bc properties and decays.

LHC Page1 Fill: 3021 E: 4000 GeV t(SB): 09:27:32 02-09-12 18:36:25

PROTON PHYSICS: STABLE BEAMS

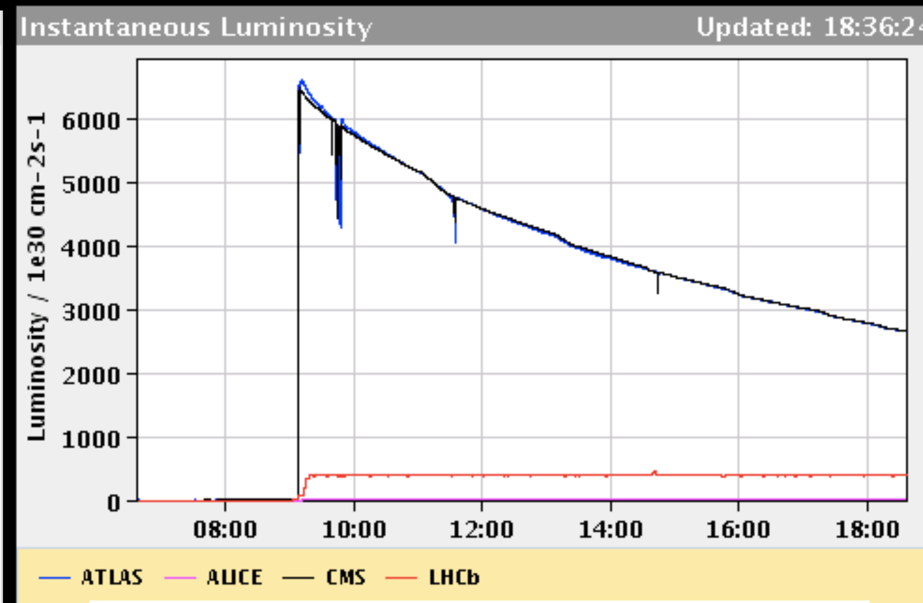
Energy: 4000 GeV I(B1): 1.55e+14 I(B2): 1.56e+14

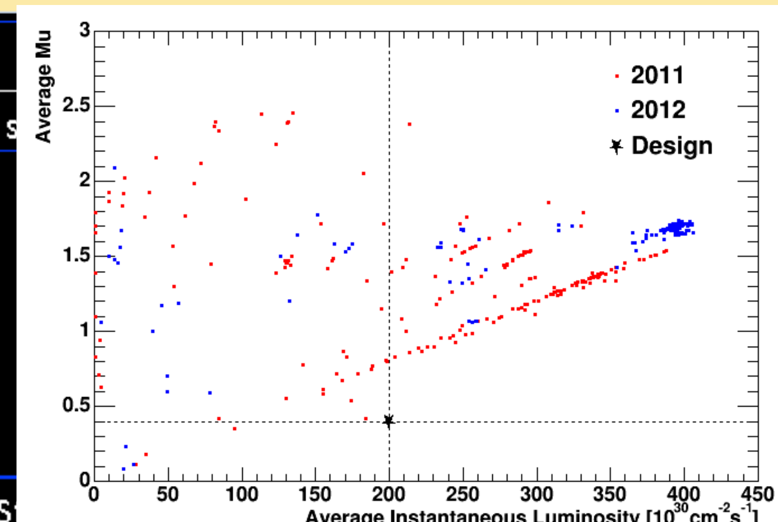
Design:

- $\sqrt{s}$ = 14 TeV
- 2622 bunches, 25 ns spacing.
- L = $2*10^{32}$ $cm^{-2}s^{-1}$.
- Average number of visible pp interactions / bunch crossing (μ) = 0.4.

Reality (2011+2012):

- $\sqrt{s}$=7 TeV / 8 TeV
- ≈1300 bunches, 50 ns spacing.
- L ≈ $2\text{-}4*10^{32}$ $cm^{-2}s^{-1}$.
- Higher pile-up.
  - <μ> ≈ 1.4 / 1.7
- Luminosity levelling.
- Exceeding design by factor two





AFS: 50ns_1374_1368_0_1262_144bpi12inj

2013 JINST 8 P04022

Trigger in 2012

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

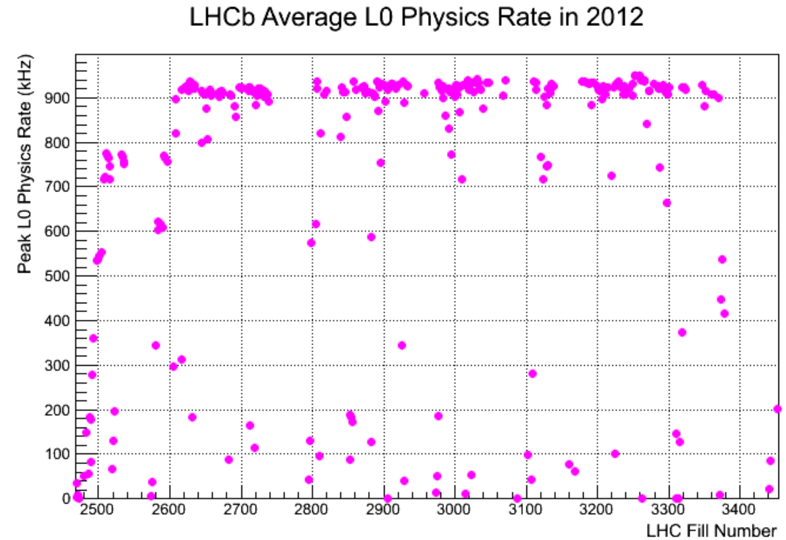
450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

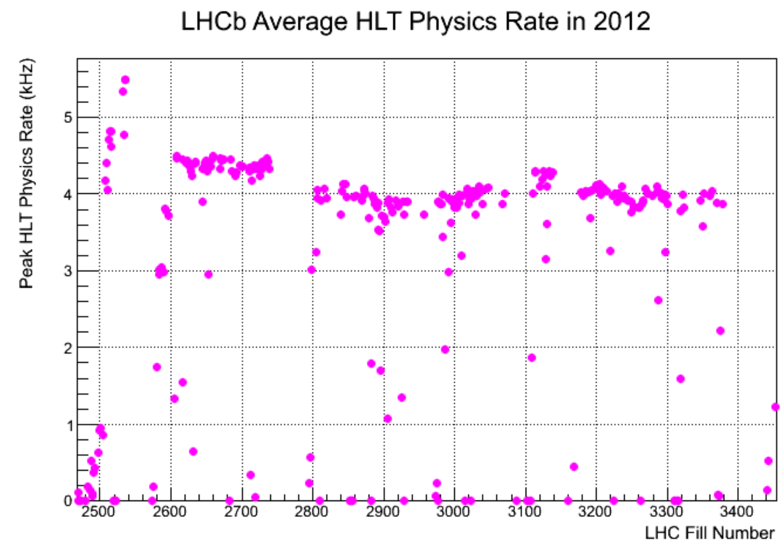
- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

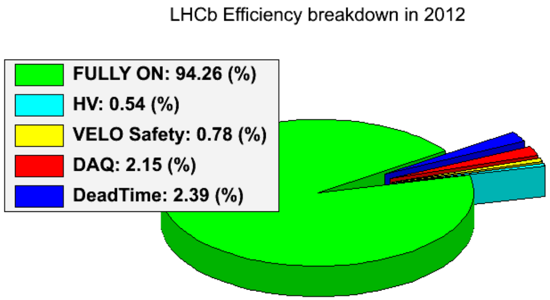


Hardware Trigger @ ≈ 1 MHz

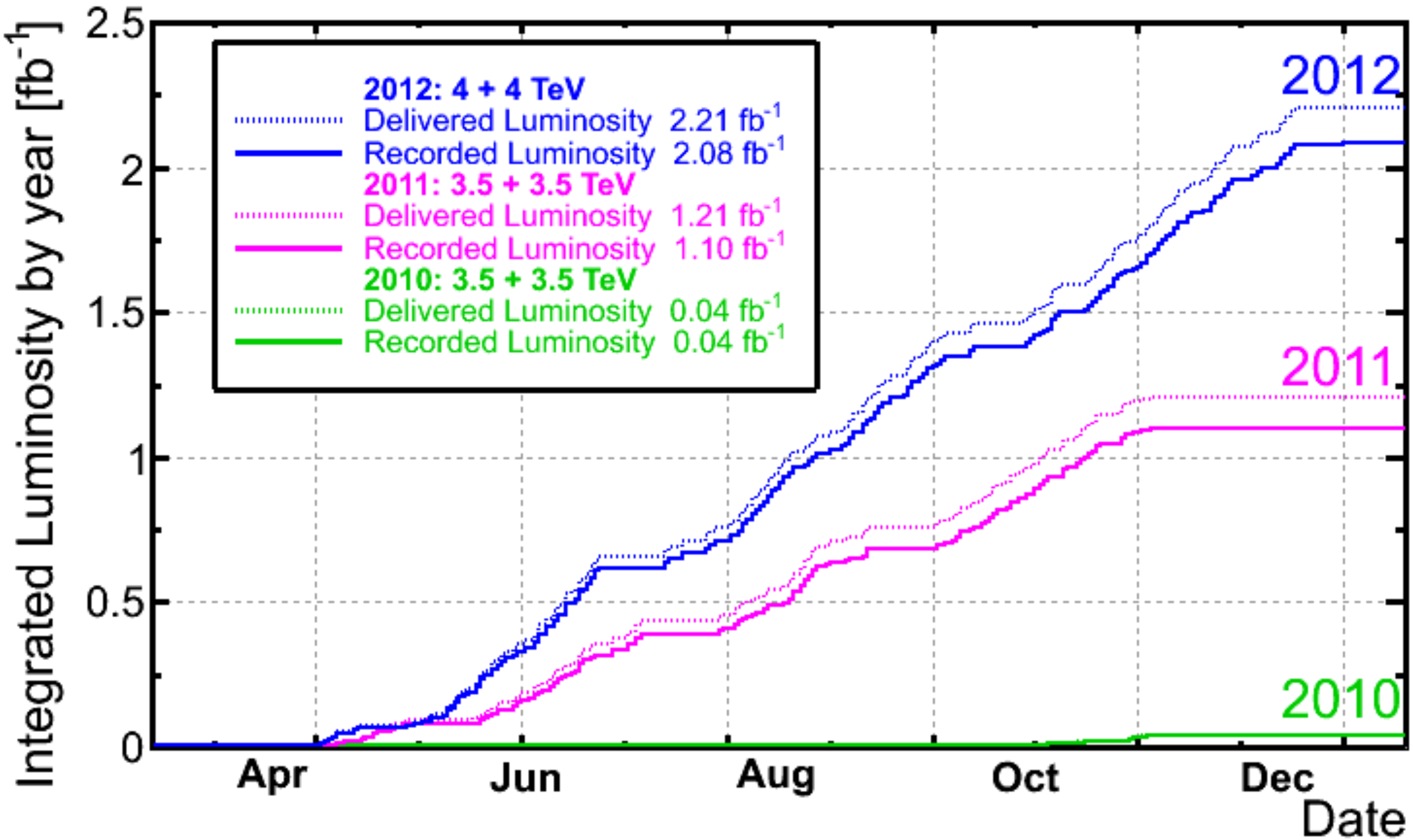


Software Trigger @ ≈ 5 kHz

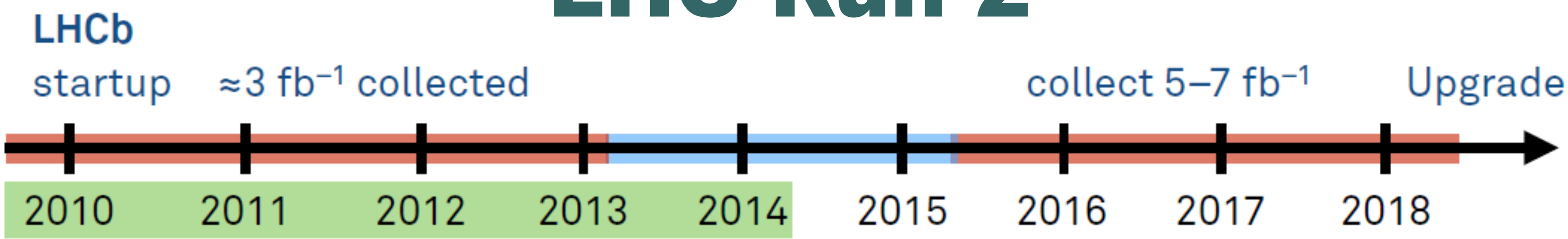
LHC Run 1



Integrated luminosity = 3.22 fb^{-1}



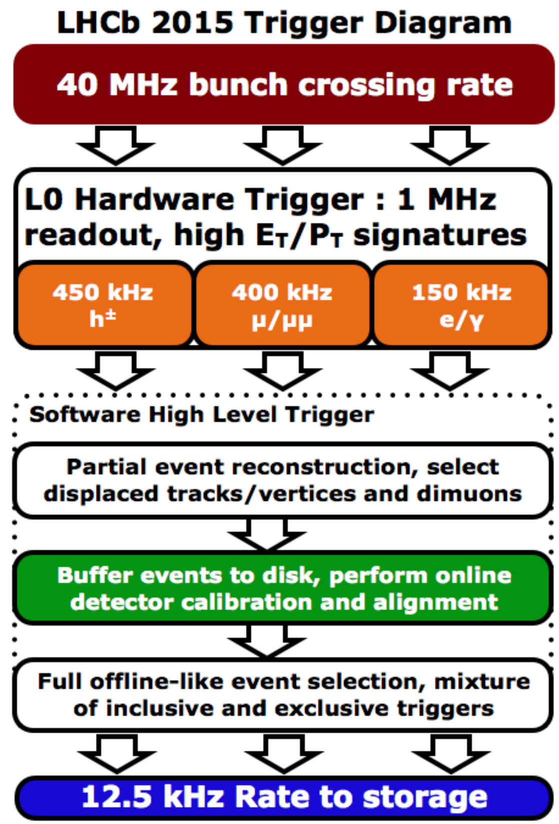
LHC Run 2



LHC Run I
- *pp* runs @50 ns
  - 7 TeV (2010,2011)
  - 8 TeV (2012)
- Pb Pb run @2.76 TeV
- *p* Pb run @5 TeV

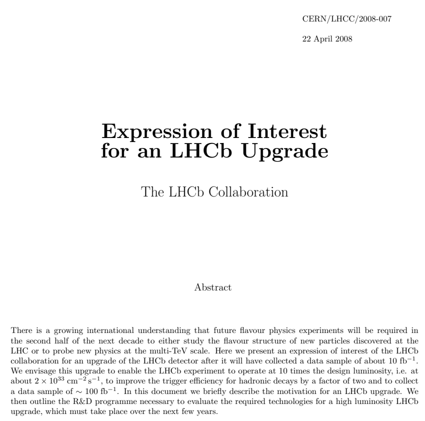
LHC LS1
- repair splices
- consolidation

LHC Run II
- *pp* runs 13 TeV @25 ns



Integrated luminosity ≈ 8—10 fb^{-1}

CERN-LHCC-2008-007



CERN/LHCC/2008-007

22 April 2008

Expression of Interest
for an LHCb Upgrade

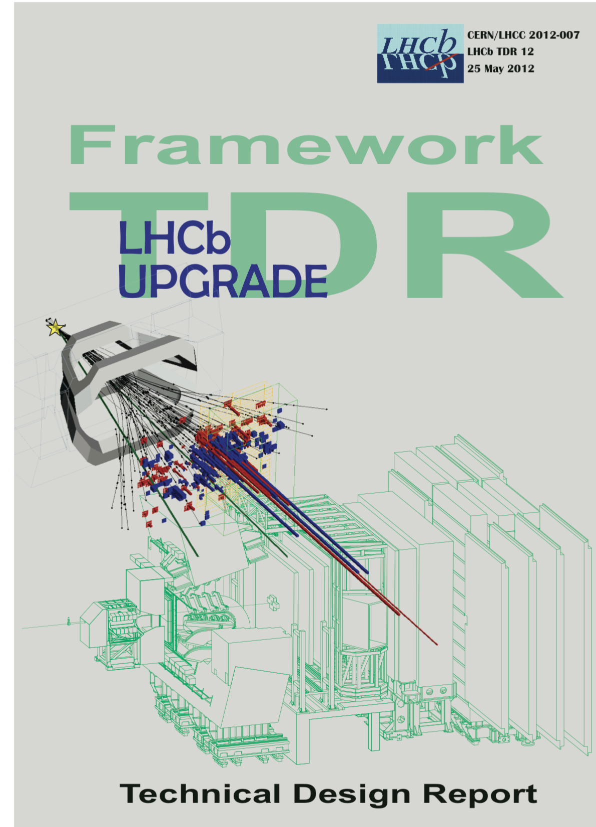
The LHCb Collaboration

Abstract

There is a growing international understanding that future flavour physics experiments will be required in the second half of the next decade to either study the flavour structure of new particles discovered at the LHC or to probe new physics at the multi-TeV scale. Here we present an expression of interest of the LHCb collaboration for an upgrade of the LHCb detector after it will have collected a data sample of about 10 fb^{-1}. We envisage this upgrade to enable the LHCb experiment to operate at 10 times the design luminosity, i.e. at about 2×10^{33} $cm^{-2} s^{-1}$, to improve the trigger efficiency for hadronic decays by a factor of two and to collect a data sample of ~ 100 fb^{-1}. In this document we briefly describe the motivation for an LHCb upgrade. We then outline the R&D programme necessary to evaluate the required technologies for a high luminosity LHCb upgrade, which must take place over the next few years.

CERN-LHCC-2011-001

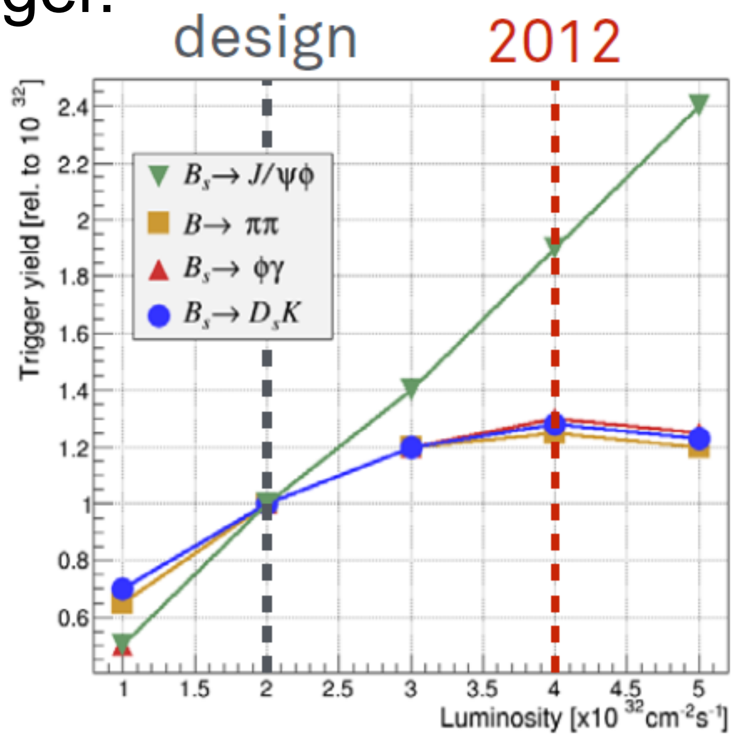
CERN-LHCC-2012-007



UPGRADE

Why upgrade?

- No evidence for New Physics in LHC Run 1.
  - Look for deviations from Standard Model.
  - More data to challenge theoretical predictions.
- Expand physics programme:
  - Electroweak, lepton flavour sector, exotica, QCD.
- Limited by Level-0 hardware trigger.
  - Maximum rate is 1.1 MHz.
- Higher luminosities:
  - Trigger yield saturates.
  - Harder cuts on E_T and p_T.
  - No real gain in statistics.
- Higher occupancy.
  - Degraded detector performance.
  - Radiation damage of detectors.



Upgrade strategy

- Remove Level-0 hardware trigger.
  - Read out every bunch crossing (40 MHz).
  - Replace all front-end electronics.
    - Replace also detectors with embedded read-out (VELO, Silicon Tracker, RICH, …)
- Trigger-less read-out system.
  - Full software trigger for every 25 ns bunch crossing.
- Run at higher instantaneous luminosities.
  - Higher occupancy.
    - Redesign several sub-detectors (OT, RICH).
- Install during LHC Long Shutdown 2.

Upgrade

- Conditions:
  - Instantaneous luminosity = $2*10^{33}$ $cm^{-2}s^{-1}$.
  - # visible interactions / crossing = 5.2
  - Integrated luminosity = 50 fb^{-1}.

- Challenge:
  - Maintain current reconstruction performance in harsher environment.
  - And read out the complete detector at 40 MHz.

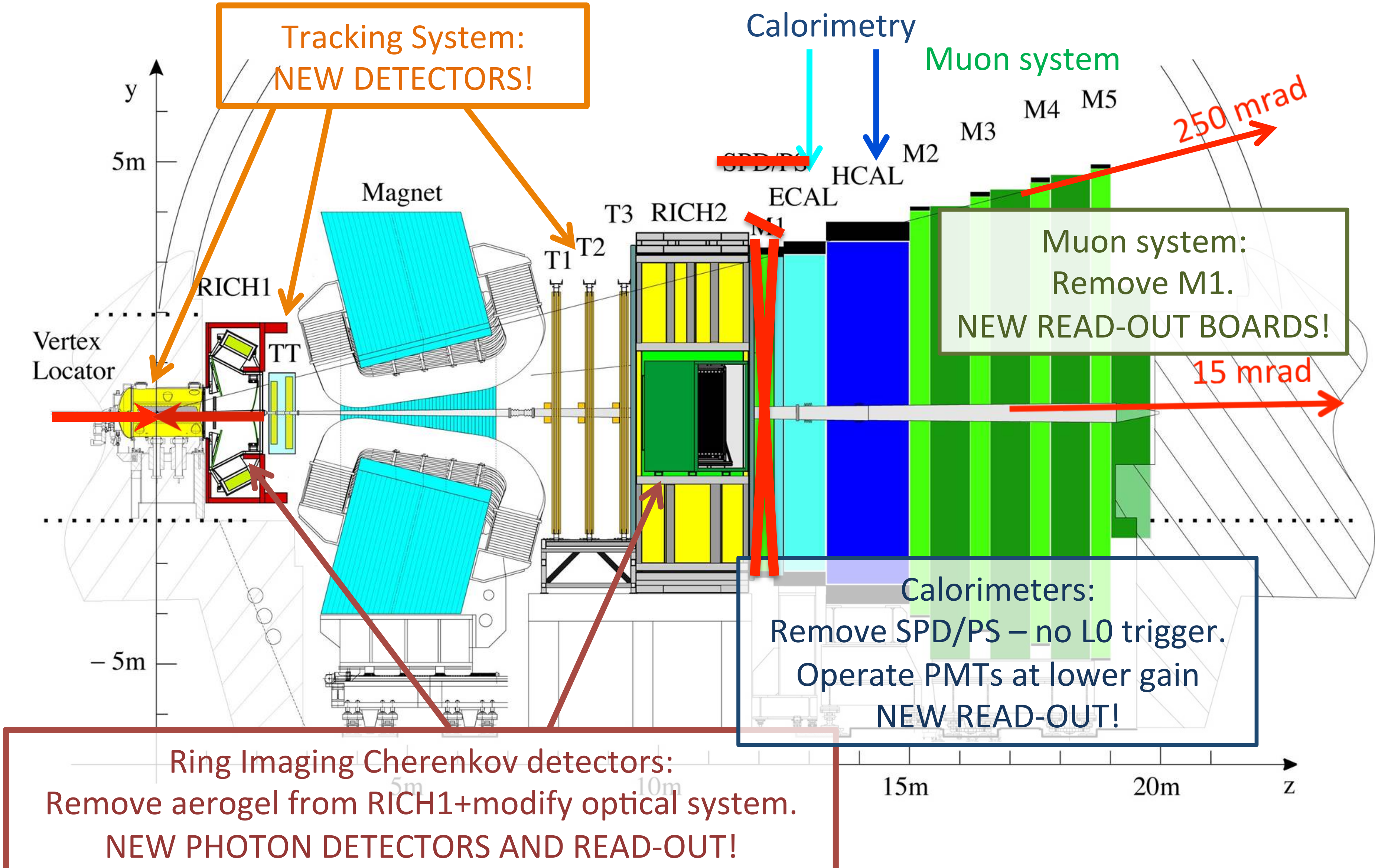
Eur. Phys. J. C(2013) 73:2373

Physics reach!

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B^0_s mixing	$2\beta_s$ ($B^0_s \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B^0_s \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B^0_s)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta^{\text{eff}}_s(B^0_s \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta^{\text{eff}}_s(B^0_s \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K^0_S)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta^{\text{eff}}_s(B^0_s \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ ($B^0_s \to D_sK$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K^0_S$)	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\text{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.

Upgraded LHCb detector



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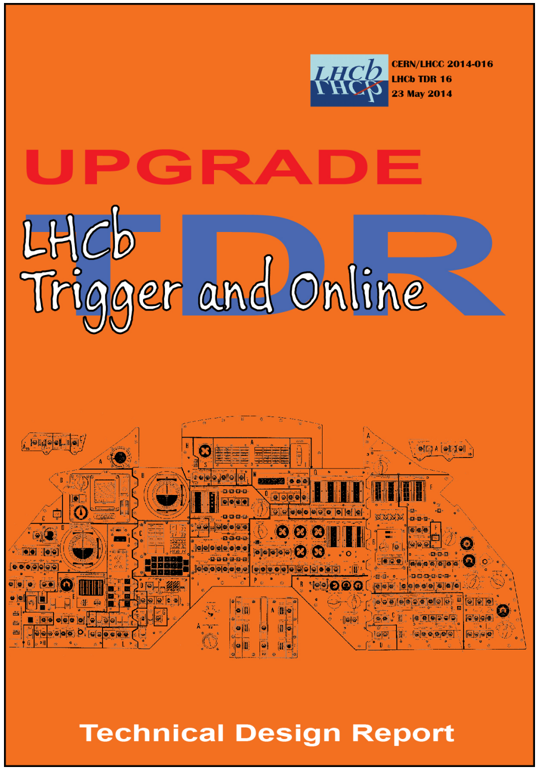
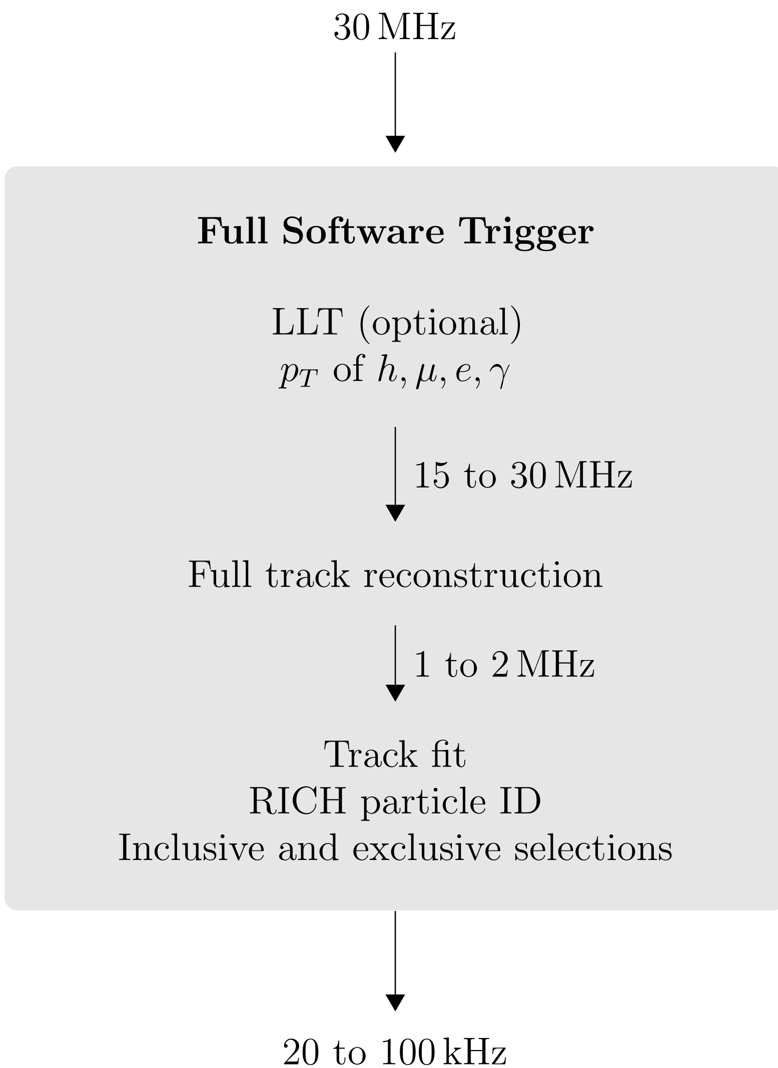


TRIGGER AND ONLINE

Upgrade Trigger



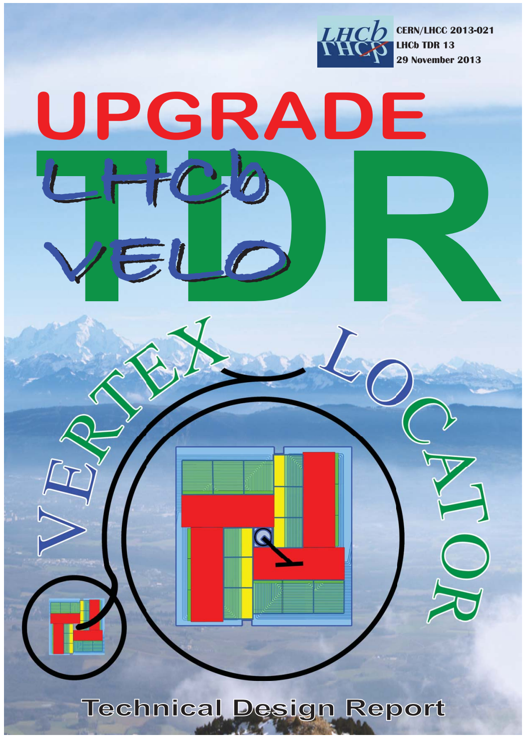
- Trigger-less read-out.
- Zero suppression in front-ends.
- Full detector data to Full Software Trigger.
- Inelastic collision rate is 30 MHz.

- Low level trigger as throttle.
- Partial information from muon system and calorimeters.

- Full event reconstruction.
- Run-by-run detector calibration.

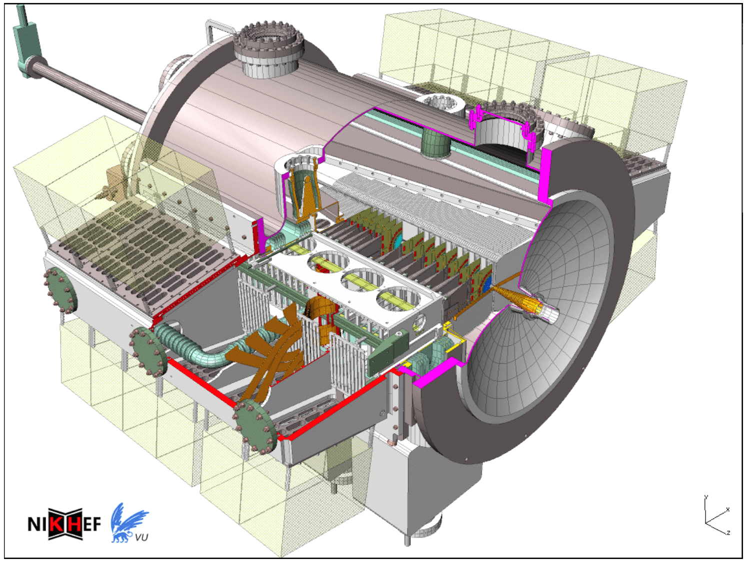
- Perform simplified Kalman track fit.
- Add RICH information.
- Inclusive and exclusive selections.

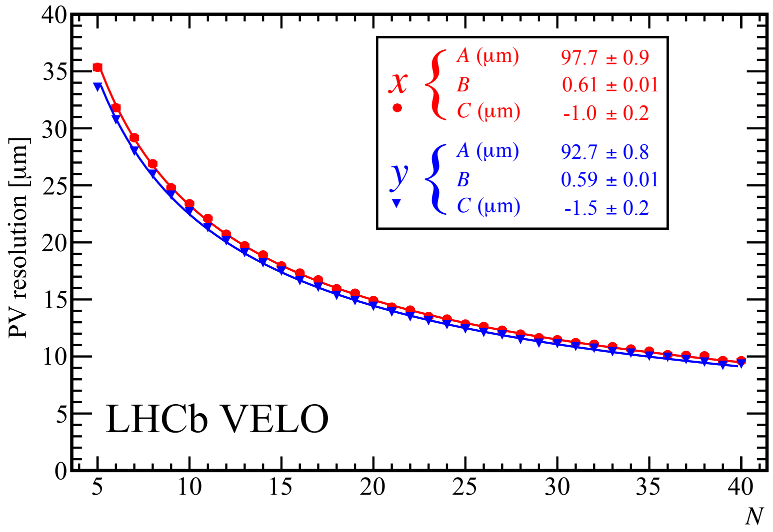
- 2 – 10 GBytes/s to storage.

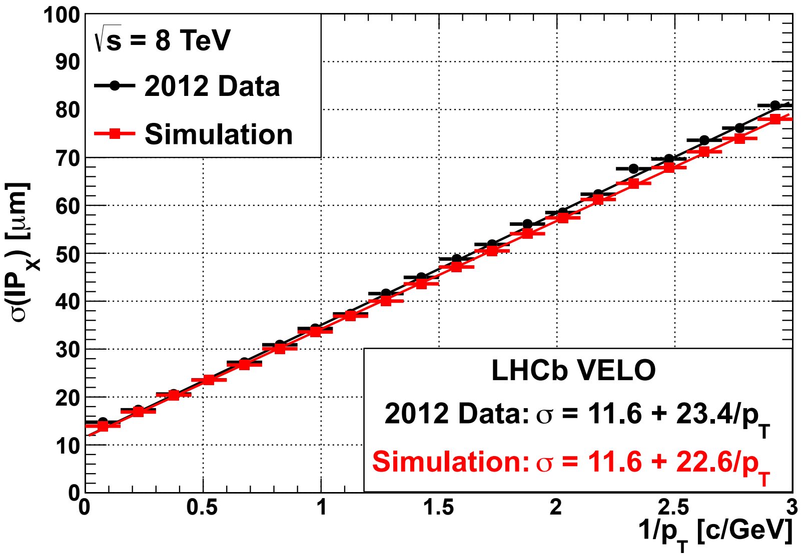


VERTEX LOCATOR

Current VErtex LOcator (VELO)



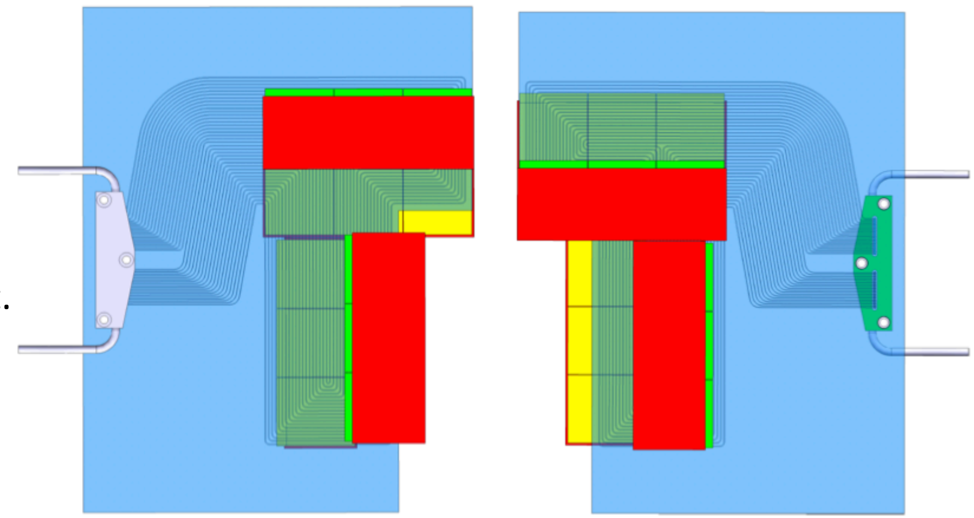


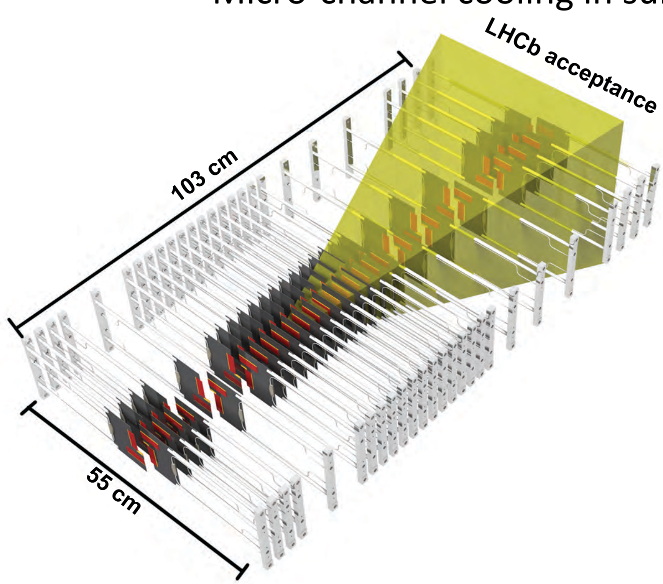


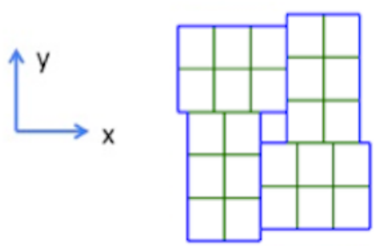
- Two retractable halves
  - 5 mm from beam when closed.
  - 30 mm during injection.
  - First measurement at 8.13 mm.
- Operates in secondary vacuum.
  - 300 μm aluminium foils separates detector from beam vacuum.
- 21 R-Φ modules per half.
  - Silicon microstrip sensors.
  - Pitch: 38 – 101 μm.
- Best resolution: 4 μm!

VELO II

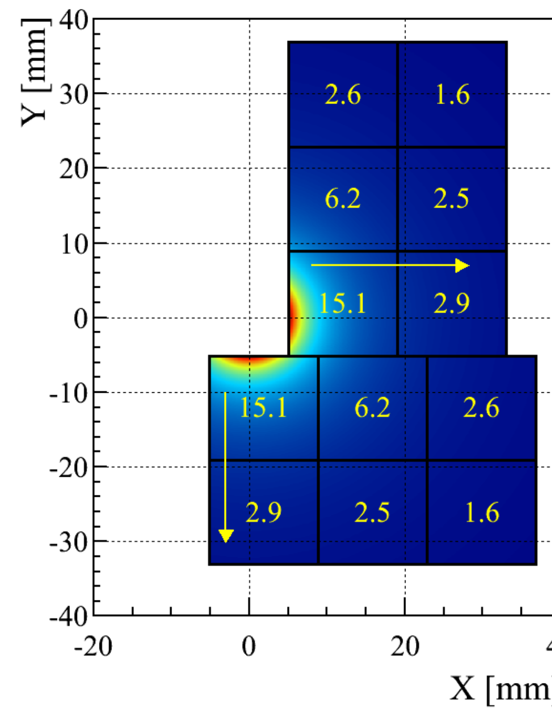
- Hybrid pixel detector.
  - Easier pattern recognition.
  - Thinner sensors (300 μm → 200 μm).
- Move closer to beam
  - First measurement: 8.13 mm → 5.1 mm.
- New RF foil.
  - Reduce material before first measurement.
- New ASIC (VeloPix)
  - Based on Medipix/TimePix.
  - 256x256 (55 μm x 55 μm)
  - 12 per module.
- Non-uniform irradiation.
  - Extremely high data rates.
  - Micro-channel cooling in substrate.



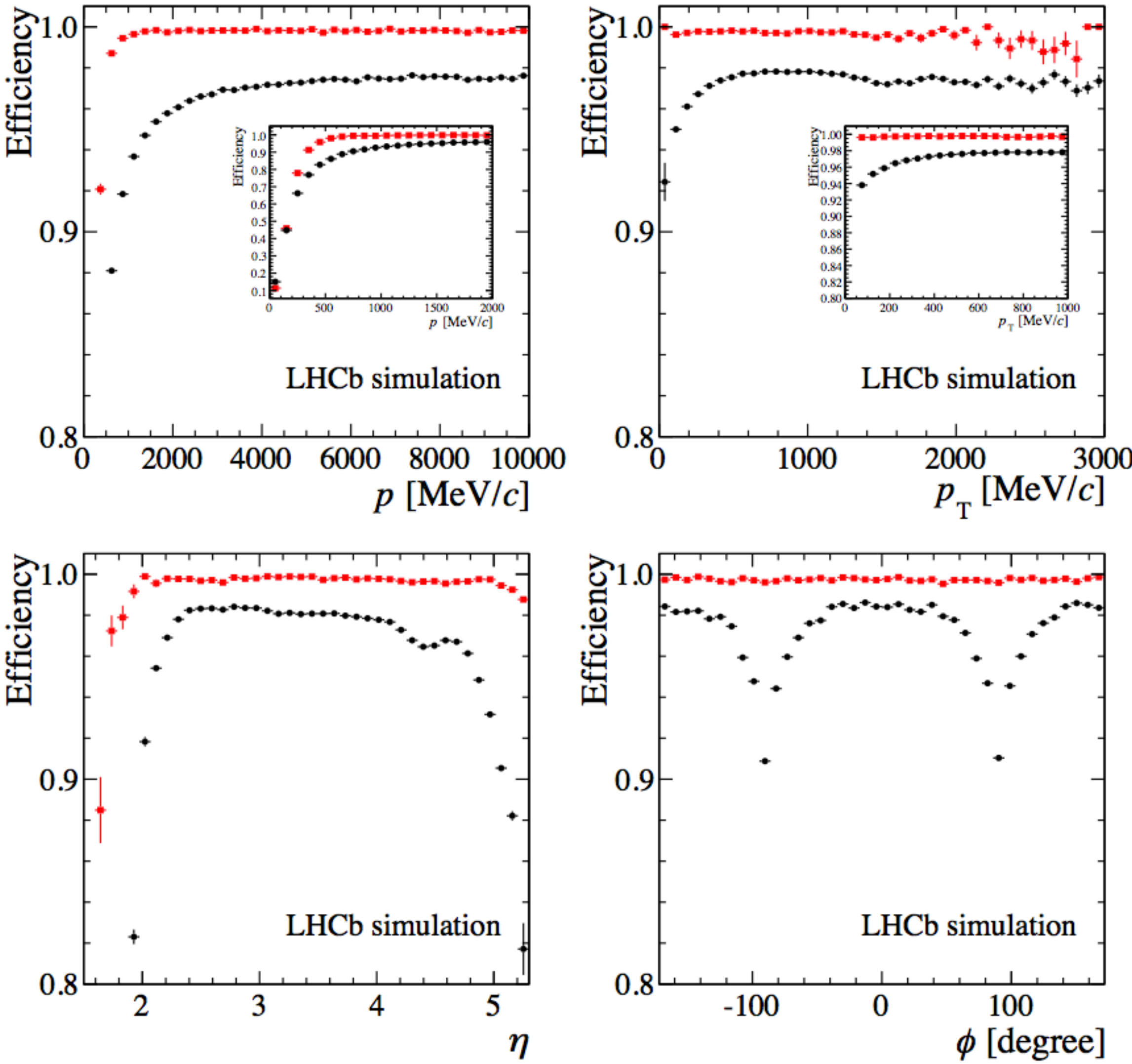


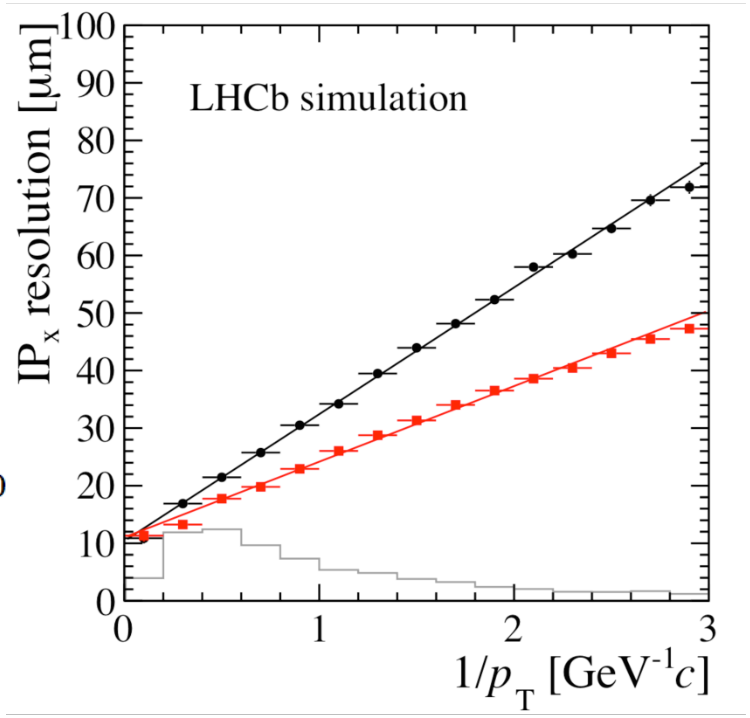


VELO fully closed
(stable beams)

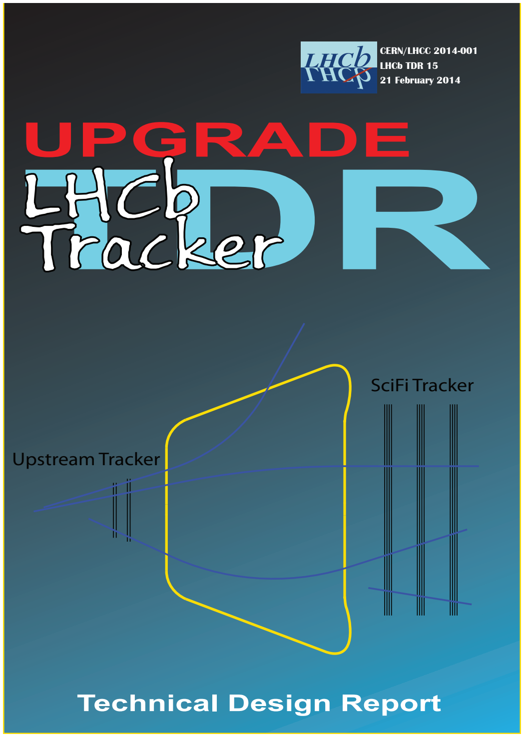


Expected performance





- Current VELO
- Upgraded VELO



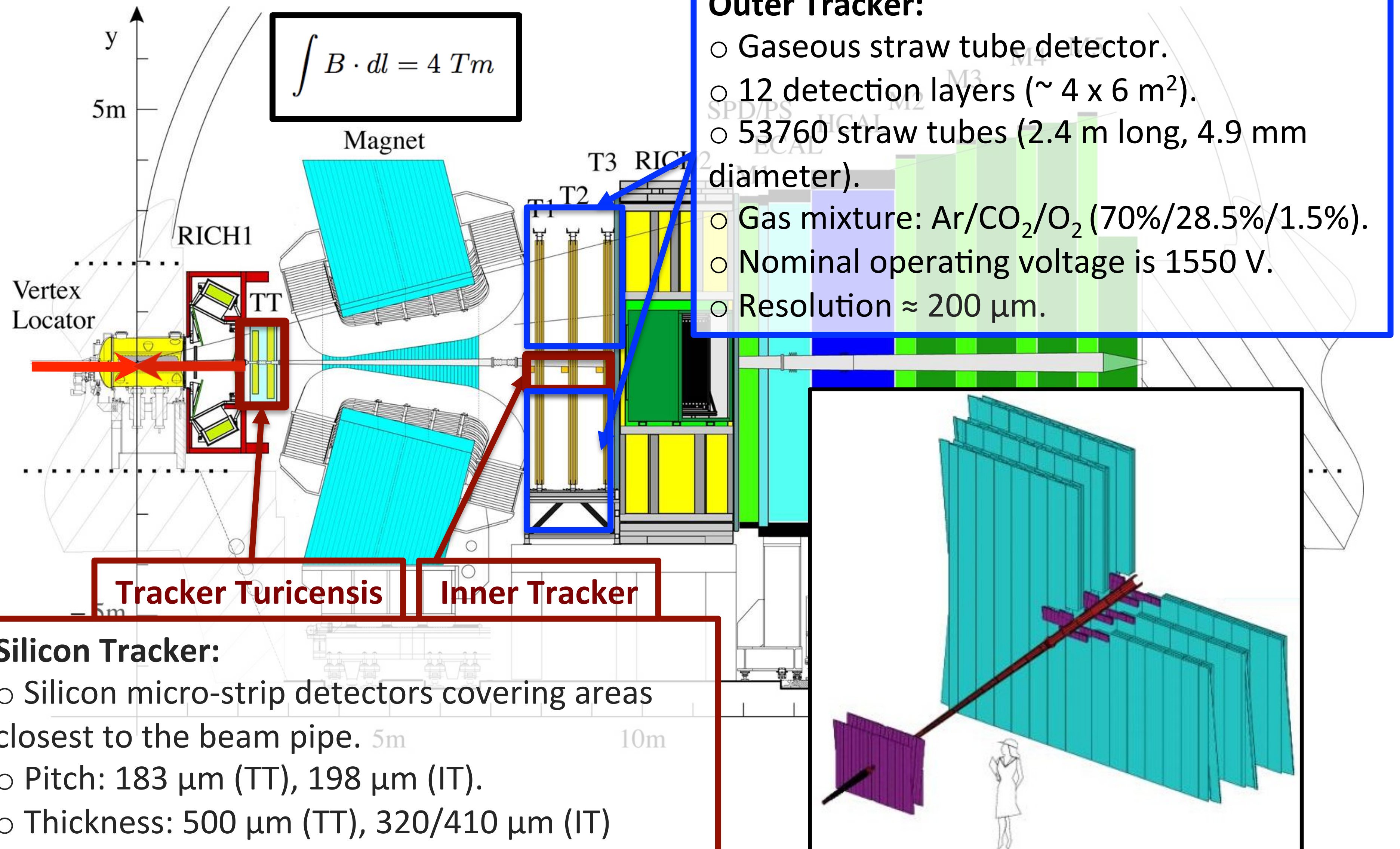
Upstream tracker

Scintillating Fibre Tracker

TRACKER

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Current Tracker



Outer Tracker:

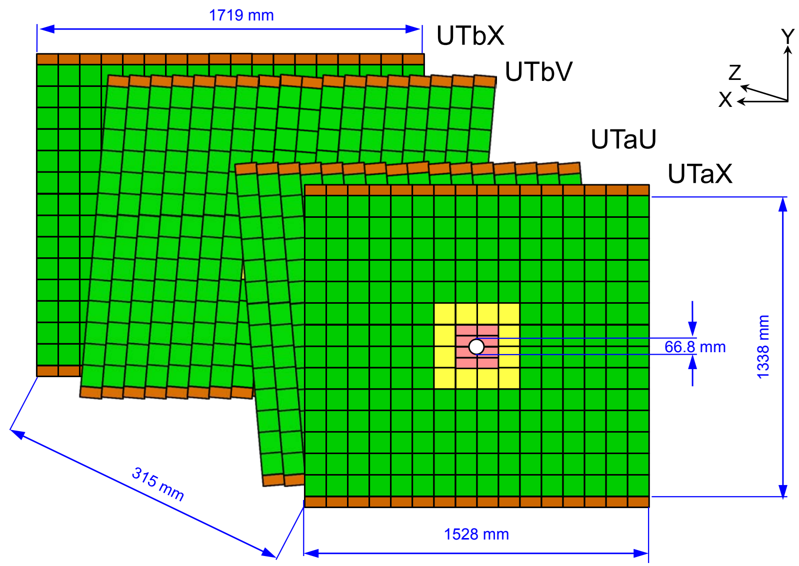
- ○ Gaseous straw tube detector.
- ○ 12 detection layers (~ 4 x 6 m^2).
- ○ 53760 straw tubes (2.4 m long, 4.9 mm diameter).
- ○ Gas mixture: Ar/CO_2/O_2 (70%/28.5%/1.5%).
- ○ Nominal operating voltage is 1550 V.
- ○ Resolution ≈ 200 µm.

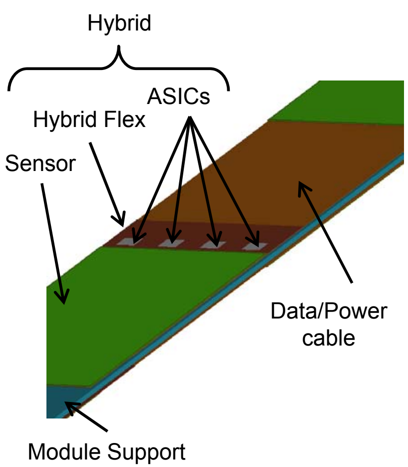
Silicon Tracker:

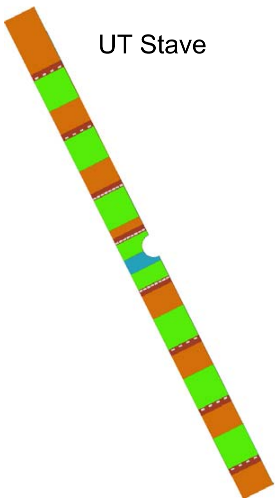
- ○ Silicon micro-strip detectors covering areas closest to the beam pipe.
- ○ Pitch: 183 µm (TT), 198 µm (IT).
- ○ Thickness: 500 µm (TT), 320/410 µm (IT)
- ○ Strips up to 37 cm long.
- ○ Resolution ≈ 50 µm.

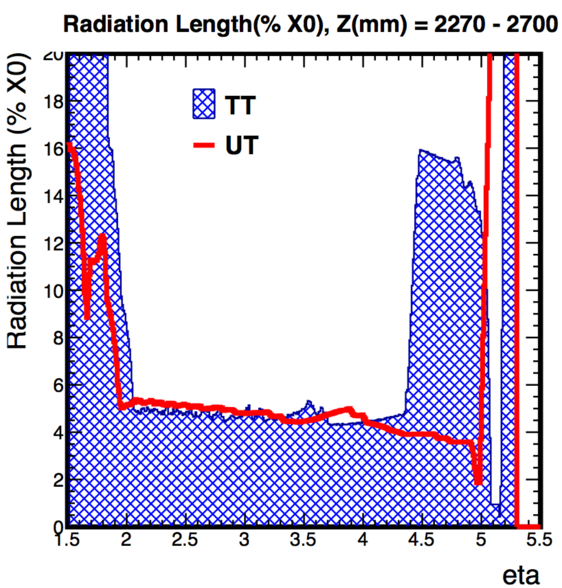
Upstream Tracker (UT)

- Replace TT with new silicon strip detector.
  - Four layers (x, u, v, x) as now.
- Finer segmentation around beam-pipe.
  - Increased occupancy.
- Reduce material.
  - Thinner sensors.
  - 500 µm → 300 µm.
- Move sensors closer to beam.
  - Optimise shape of inner sensors.
  - Increase acceptance at large η.
- New read-out chip (SALT).

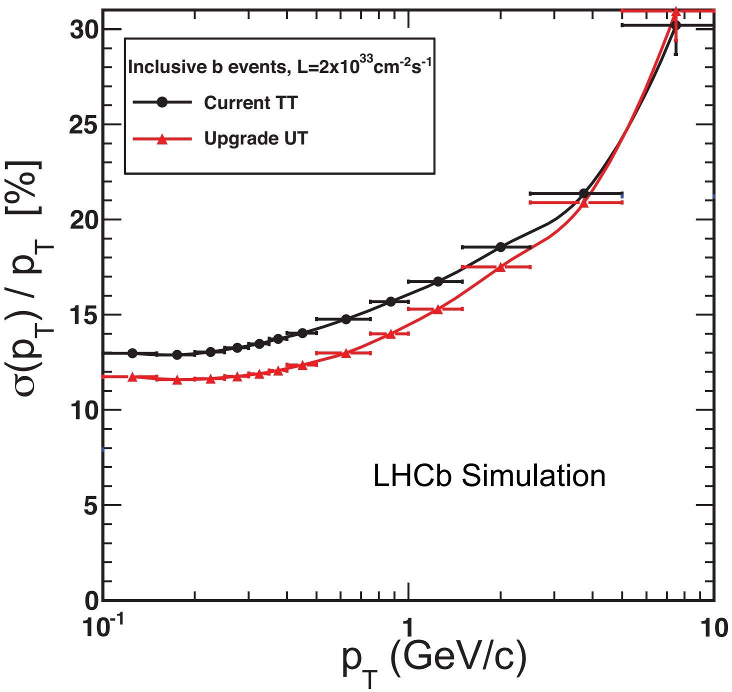


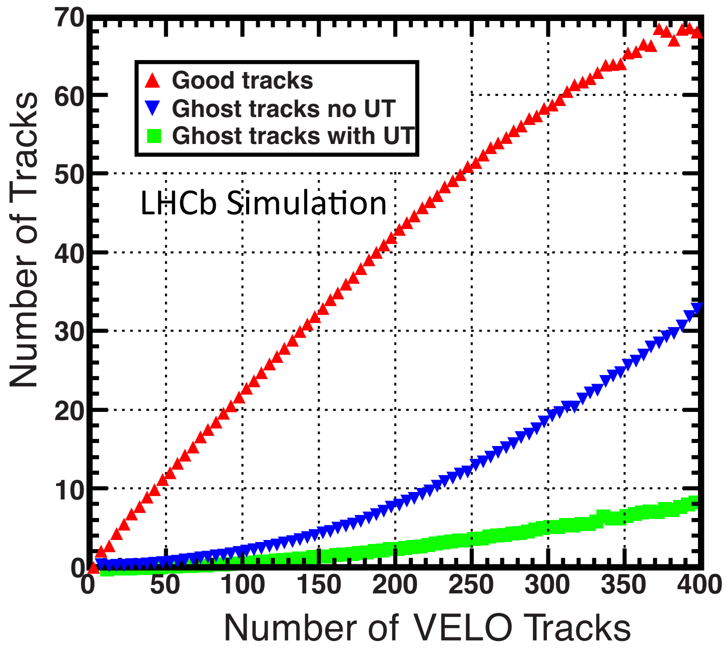






Upstream Tracker Performance

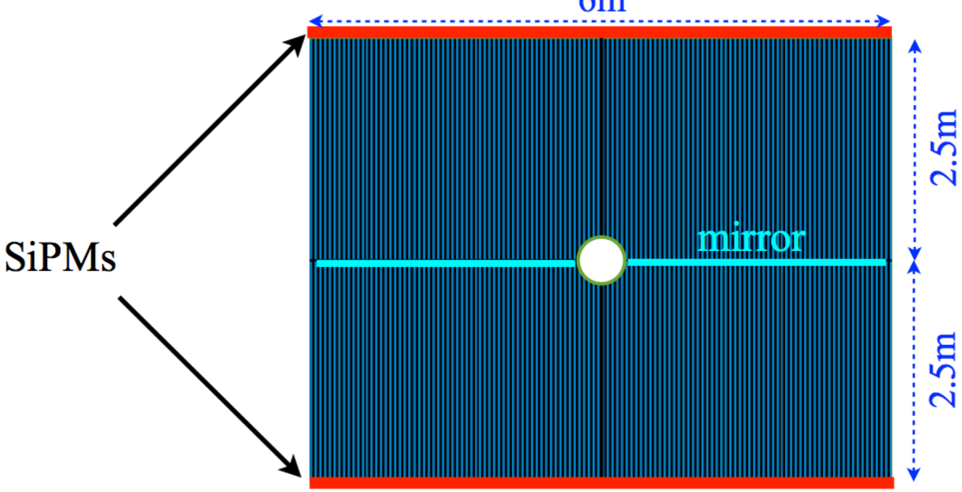




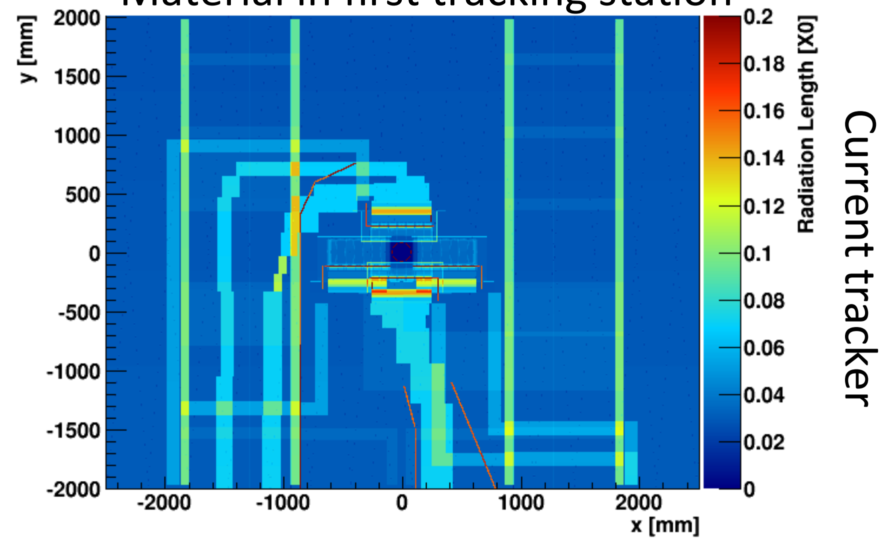
- Require hits on UT when matching VELO to downstream tracker.
- Use stray field to determine momentum.
- Reduce time taken for track reconstruction by factor 3.
- Allows UT to be used in trigger.
- Ghost rate reduced by requiring hits on UT.

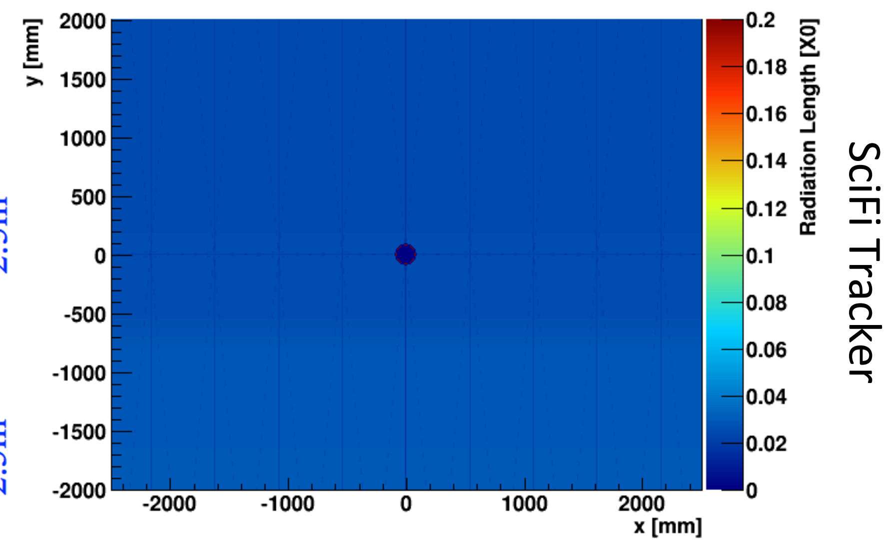
SciFi Tracker

- Replace IT+OT with single technology.
  - Occupancy too high in OT.
  - Electronics embedded in IT modules.
- Scintillating fibres read out with SiPMs.
  - 2.5 m long, 250 μm diameter.
  - Keep 12 layers (x, u, v, x) x 3
- SiPMs outside acceptance.
  - Radiation damage from neutrons.
  - Require cooling to -40°C.
- New ASIC for read-out (PACIFIC).
- Radiation hardness of fibres.
  - Measured to be ok.

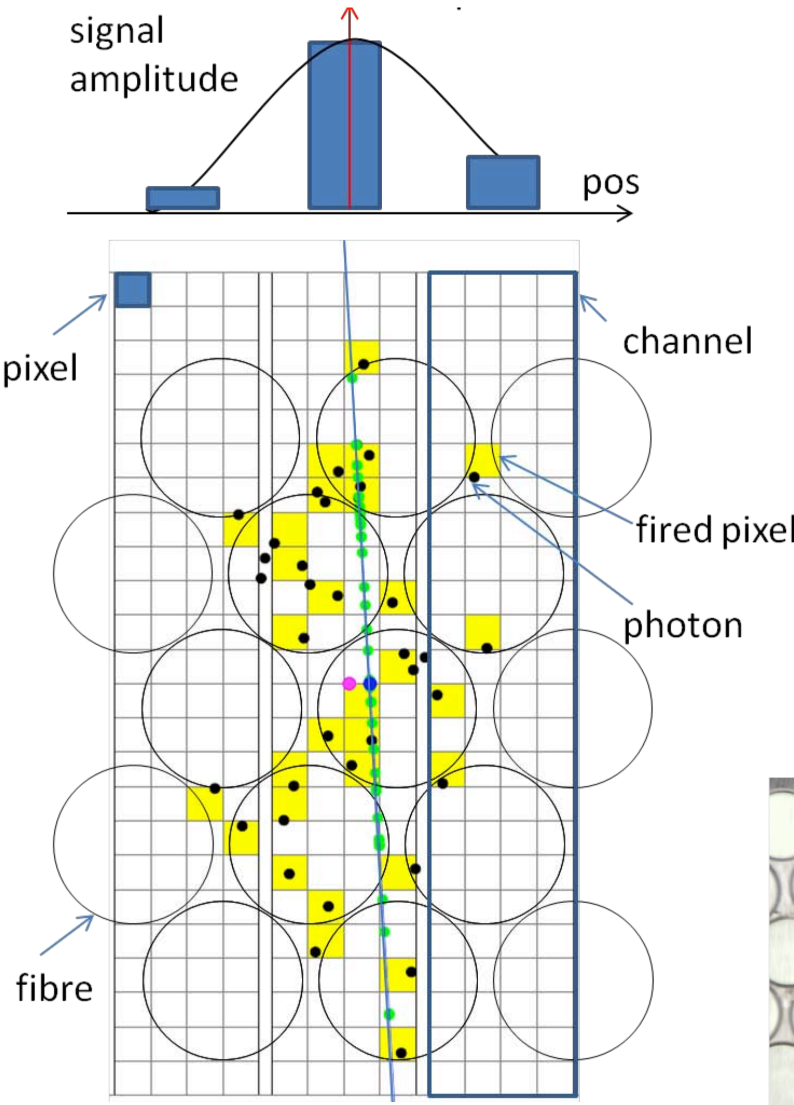


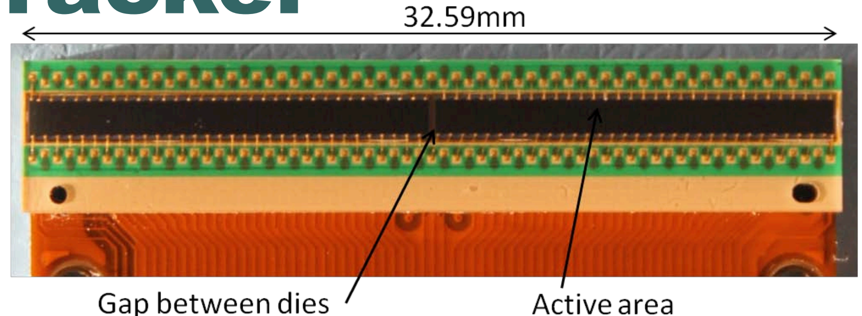
Material in first tracking station

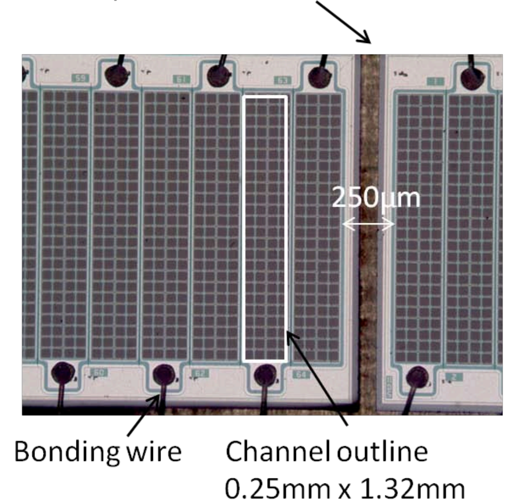


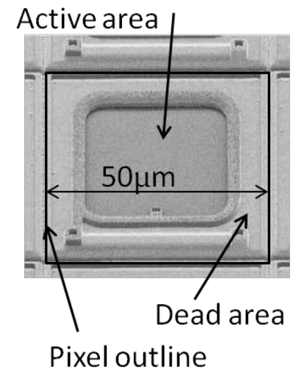


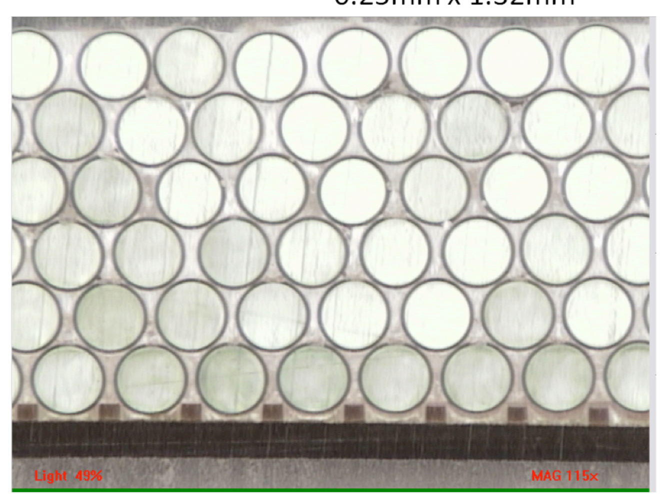
SciFi Tracker



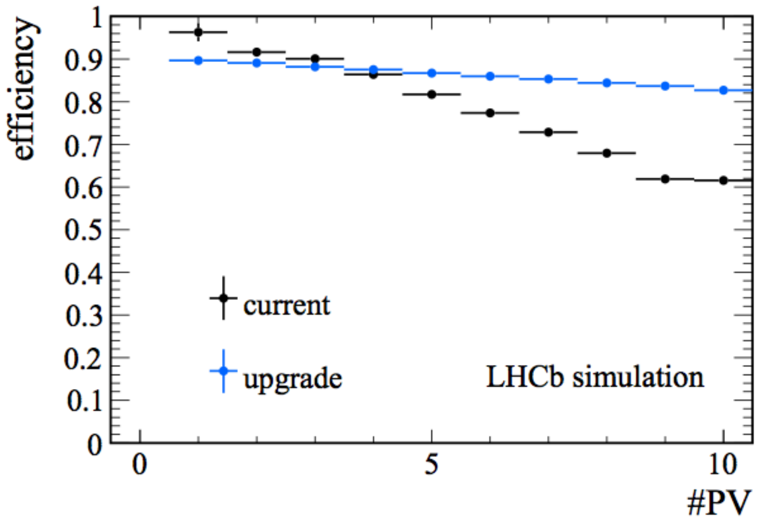


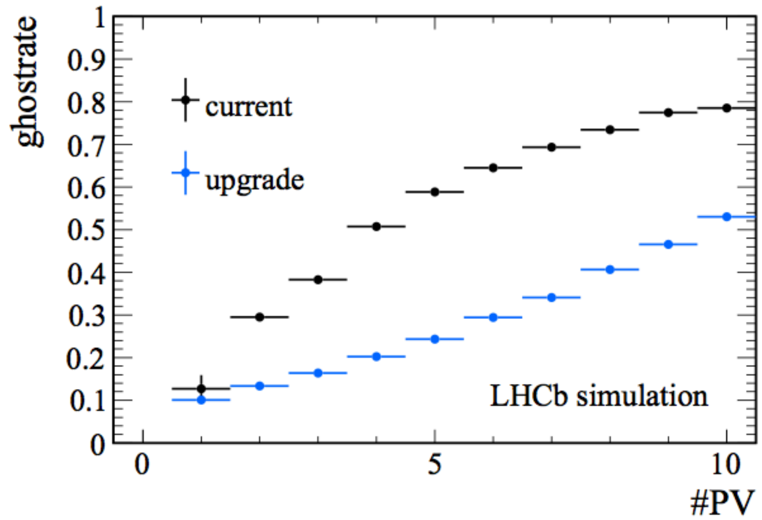


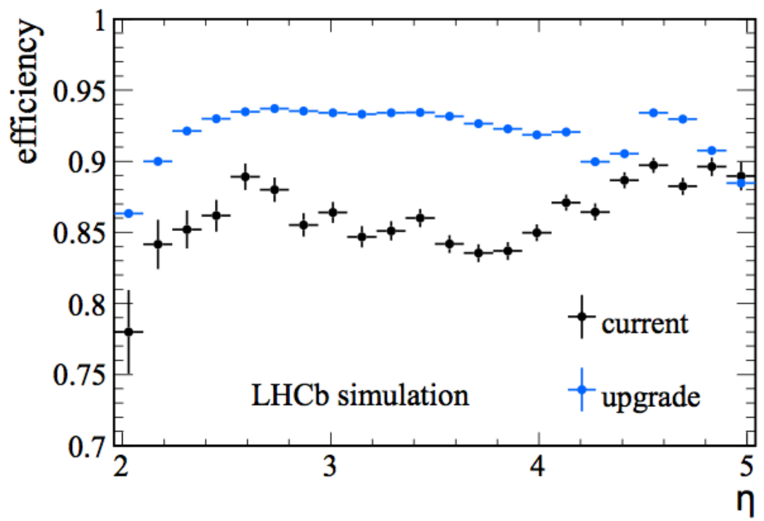


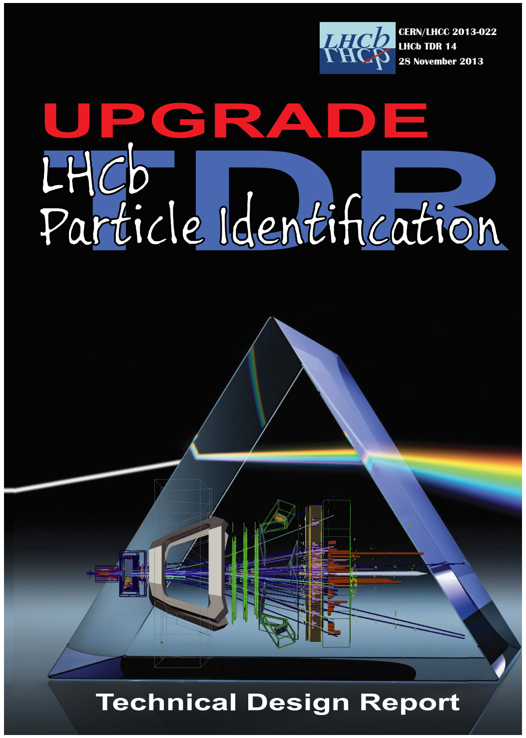


Tracker performance









Calorimeters

Ring Imaging Cherenkov (RICH) system

Muon detectors

PARTICLE IDENTIFICATION

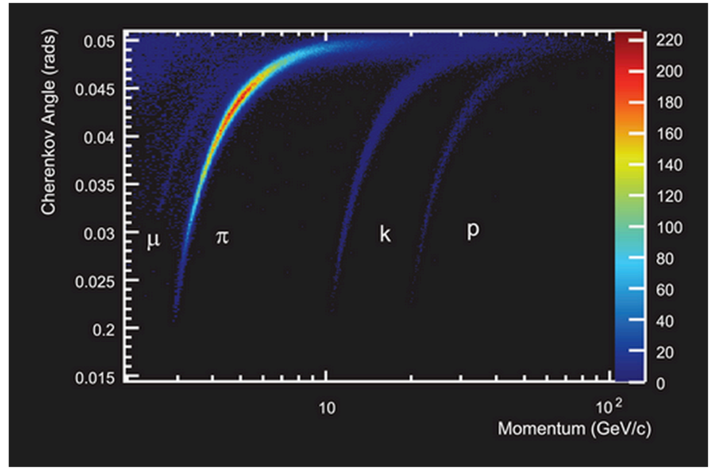
RICH

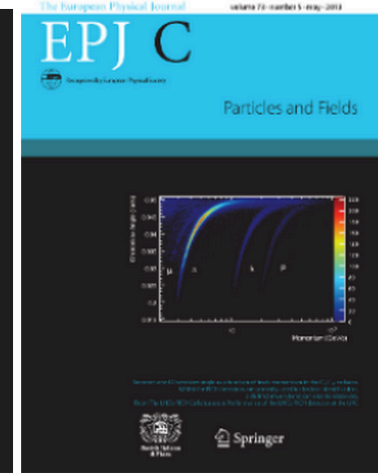
Current detectors:

- RICH 1:
  - Aerogel (low momenta)
  - C_4F_{10} (10 – 65 GeV/*c*).
- RICH 2
  - CF_4 (15 – 100 GeV/*c*).
- Hybrid Photon Detectors.
  - Embedded 1 MHz Front-end.

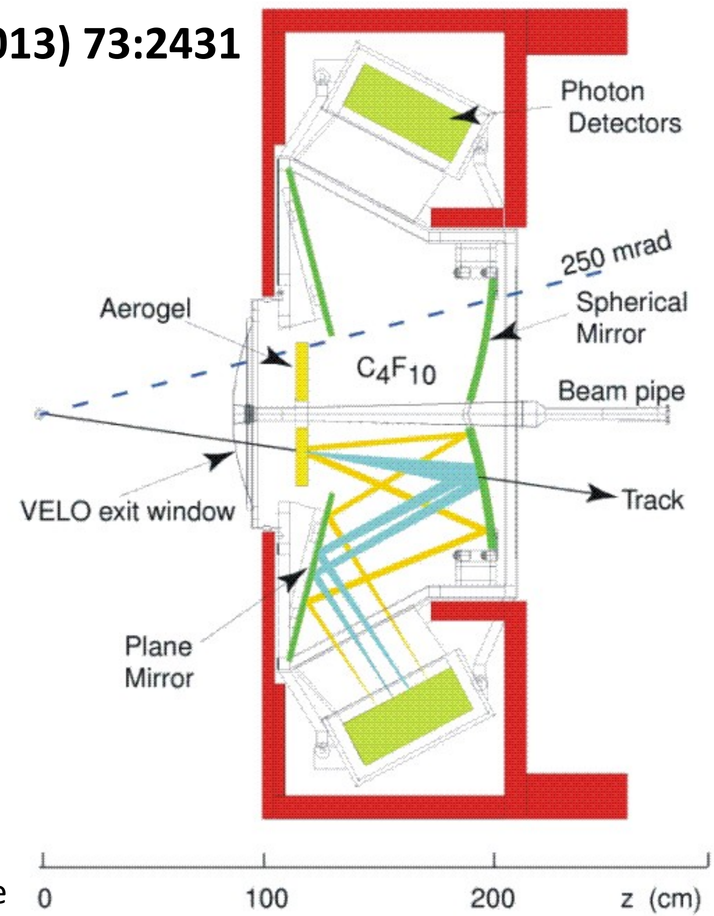
Upgrade:

- RICH 1
  - Remove aerogel.
    - Track density too high.
    - Remove already for LHC Run 2.
  - Modify optics to increase ring size.
  - Replace HPDs with MaPMTs.
- RICH 2:
  - Replace HPDs with MaPMTs.

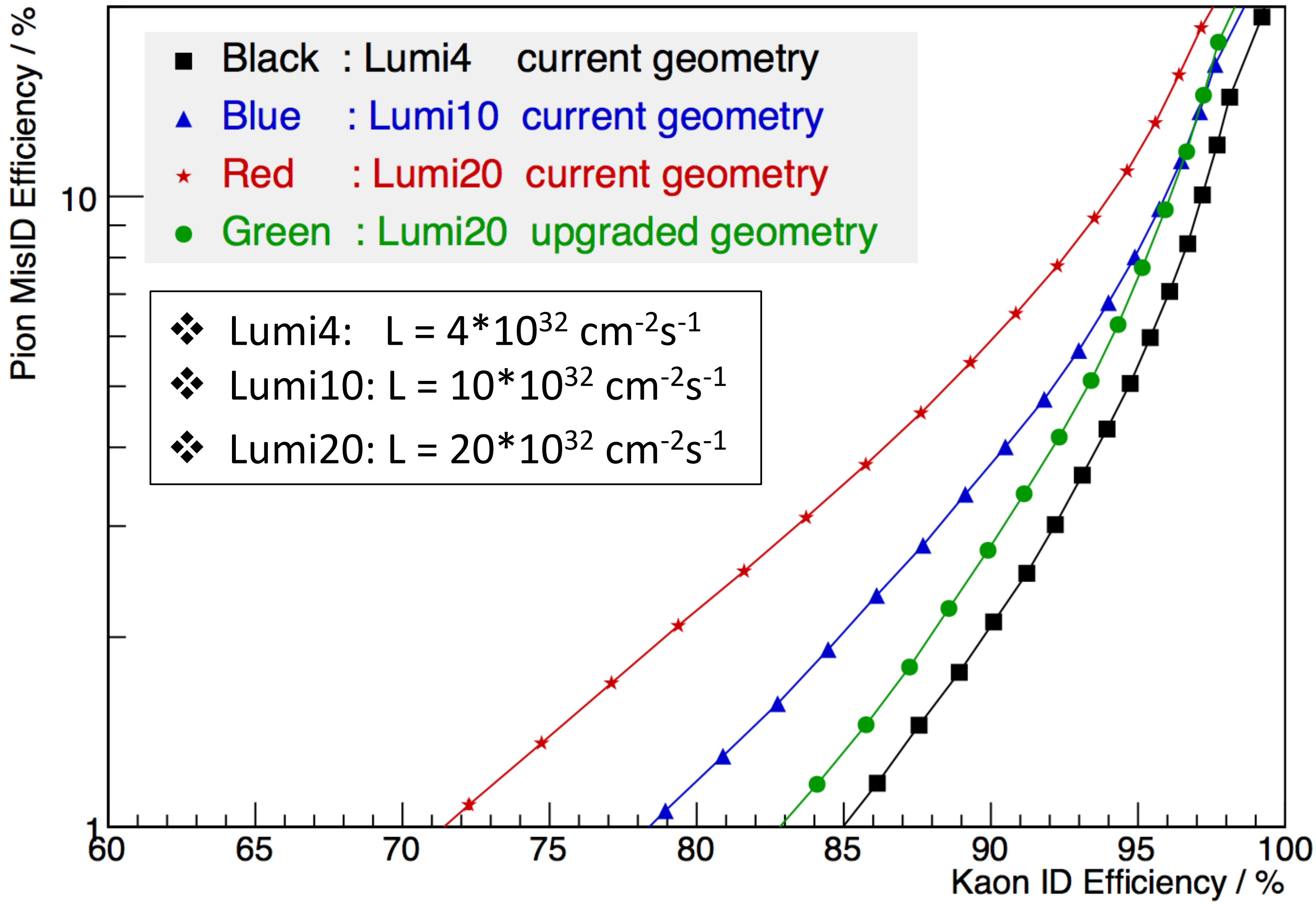




Eur. Phys. J. C(2013) 73:2431



RICH PID Performance



Calorimeters

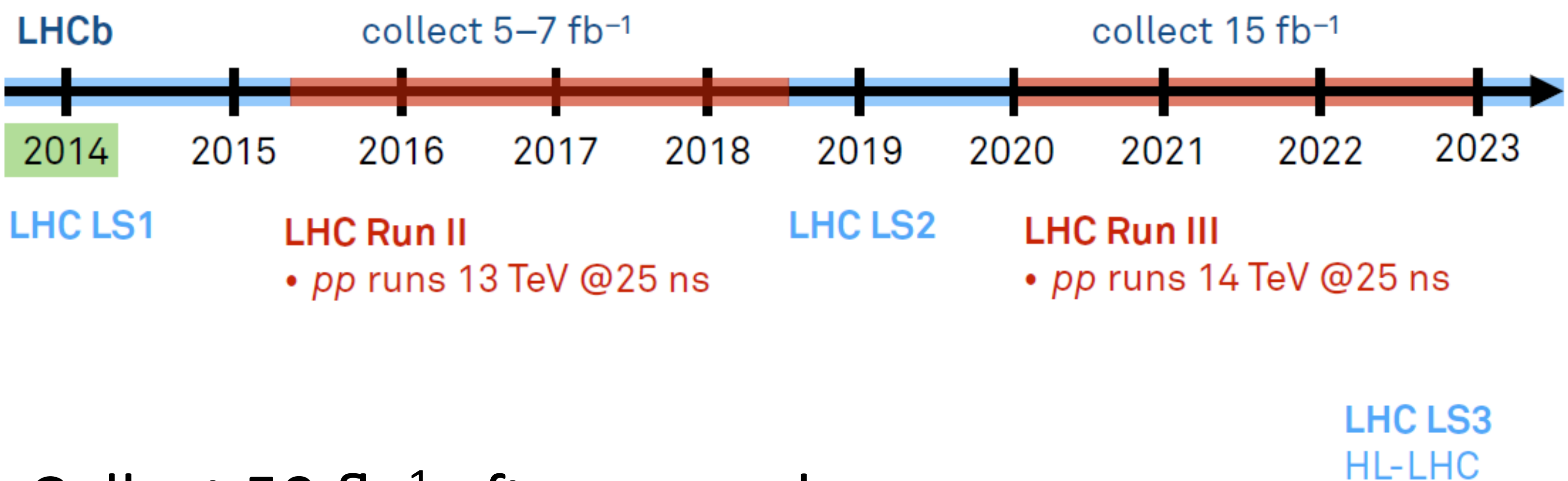
- Remove PS/SPD.
  - Occupancy too high
  - Level-0 removed.
- Reduce PMT gain to reduce effects of ageing.
  - Compensate by increasing gain in electronics.
- Exchange inner modules of ECAL
  - OK up to 20 fb^{-1}.
  - Can be replaced during LS3.
- Redesign front-end / back-end electronics.

Muon system

- Remove M1.
  - Occupancy too high.
- Install additional shielding in front of M2.
- Replace off-detector electronics.
  - More efficient read-out at 40 MHz.

SCHEDULE

Schedule / timeline



- Collect 50 fb^{-1} after upgrade.
- Continue taking data during HL-LHC.

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Conclusions I

Current detector:

- Excellent performance during LHC Run 1.
- Operated well above design parameters.
- Over 180 physics papers.
- Waiting for LHC Run 2.

Conclusions II

Upgraded detector:

- Remove Level-0 hardware trigger.
  - Read out full detector at 40 MHz.
- Trigger-less read-out system.
  - Full software trigger for every bunch crossing.
- Instantaneous luminosities up to $2*10^{33}$ $cm^{-2}s^{-1}$.
  - Redesign detector to cope with higher occupancies.
- Collect 50 fb^{-1} after upgrade.
  - Significantly improve statistical precision.
- Technical Design Reports submitted to LHCC.
- Installation in 2018/2019.
- Ready for data taking in 2020!

Stay tuned / join us!


Flavor Physics & CP Violation
FPCP
26 30 MAY 2014
Marseille France
To integrate past results with recent developments in flavor physics and CP violation, both in theory and experiment exploiting the potential to study new physics at the LHC and future facilities.
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Xiao-Gang He, NTU & SJTU
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http://fpcp2014.in2p3.fr
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OCEVU

Merci à tous!

More, more, more!

EXTRAS

Reconstruction sequence

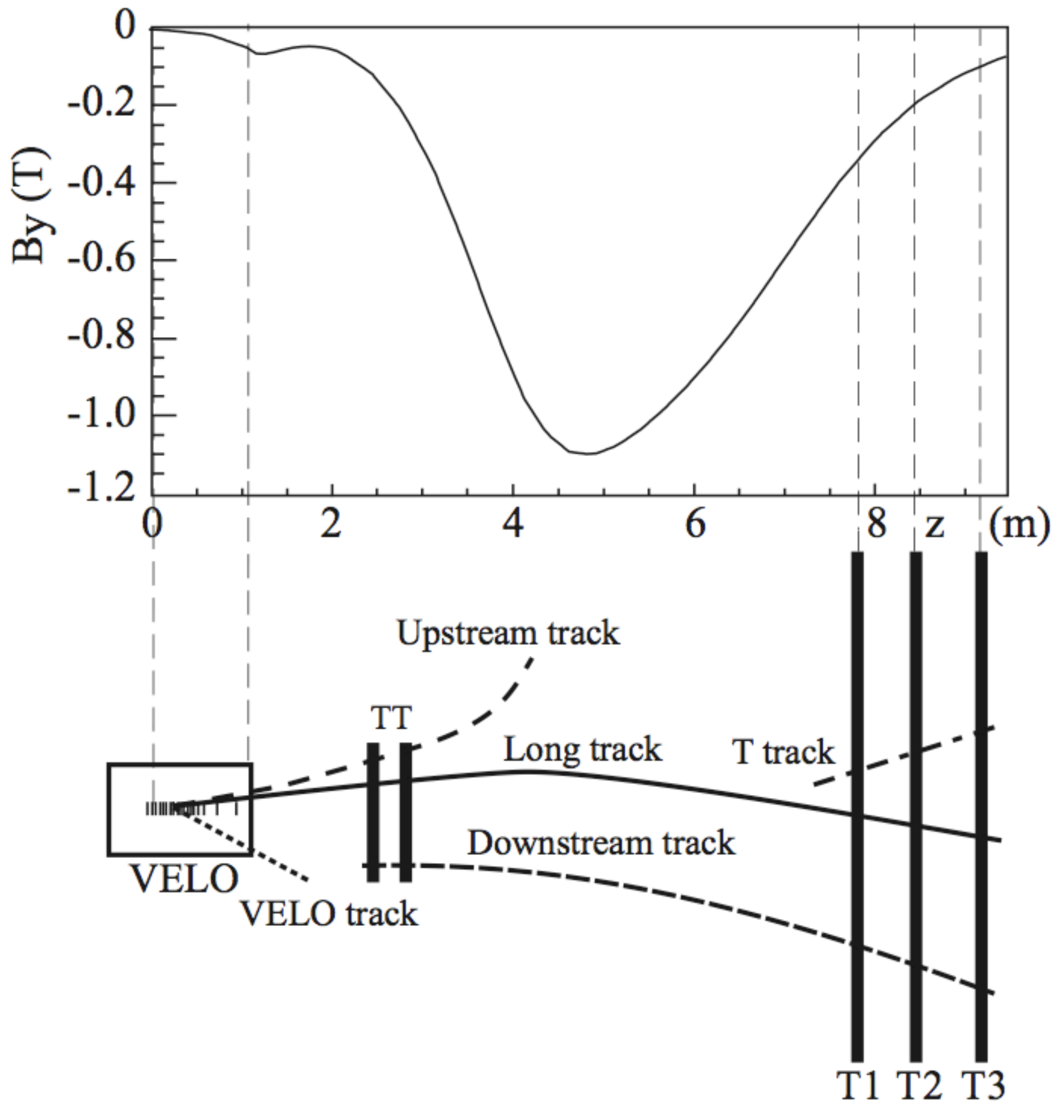
Offline

- VELO tracking
- VELO-UT
- Forward reco $p_T > 70$ MeV/c
- PV finding
- Full Kalman Fit
- RICH PID

Upgrade HLT

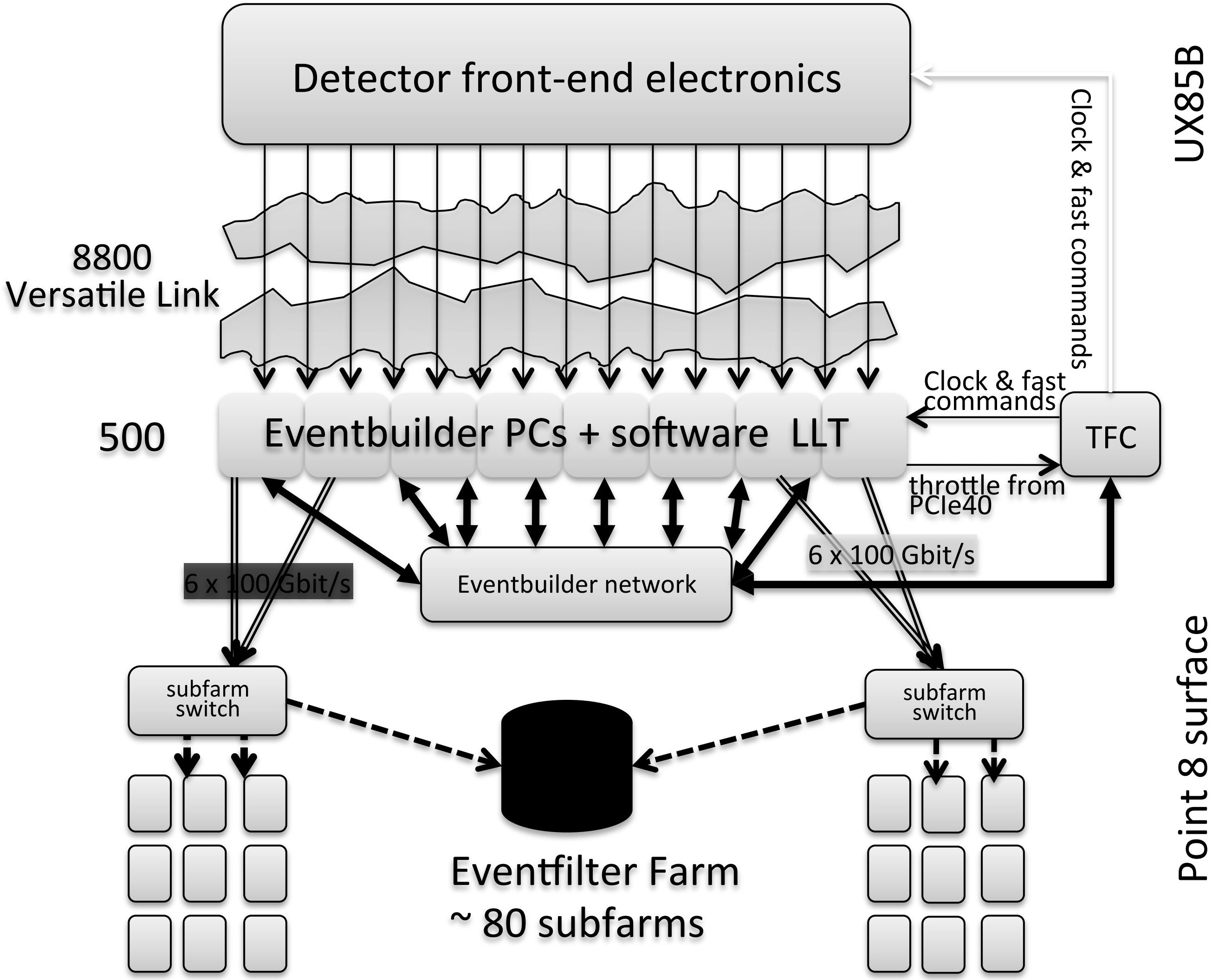
- VELO tracking
- VELO-UT $p_T > 200$ MeV/c
- Forward reco $p_T > 500$ MeV/c
- PV finding
- Trigger cuts to reduce rate to 1 MHz
- Muon ID
- Simplified Kalman Fit
- Online RICH PID

Track types

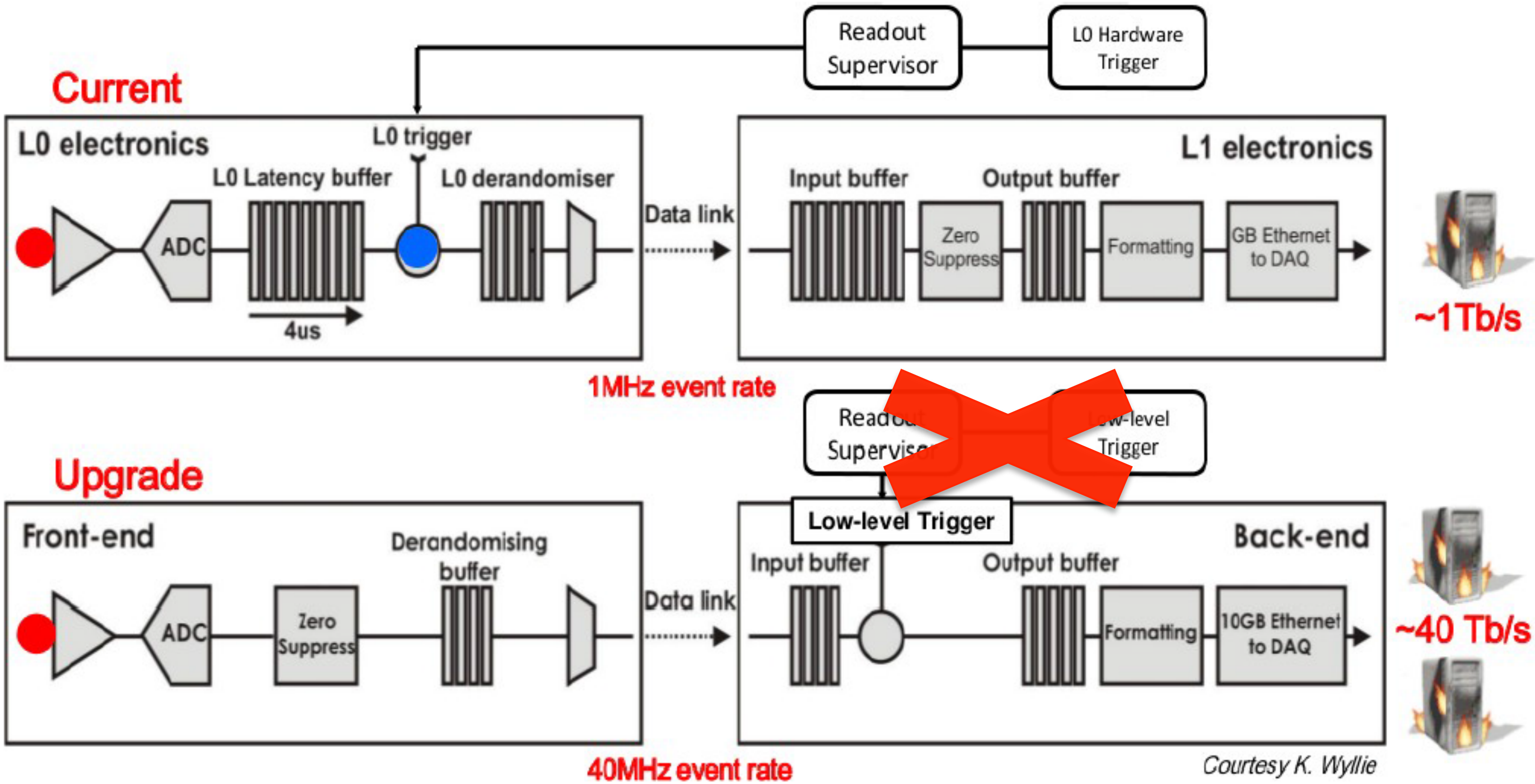


0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
By (T)
0
2
4
6
8
z (m)
Upstream track
TT
Long track
T track
VELO
VELO track
Downstream track
T1 T2 T3

Read-out architecture

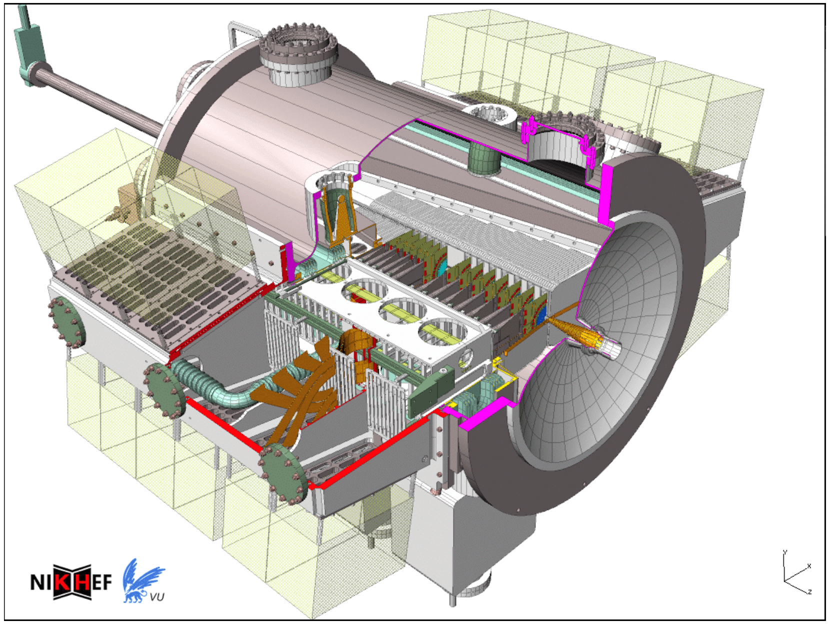


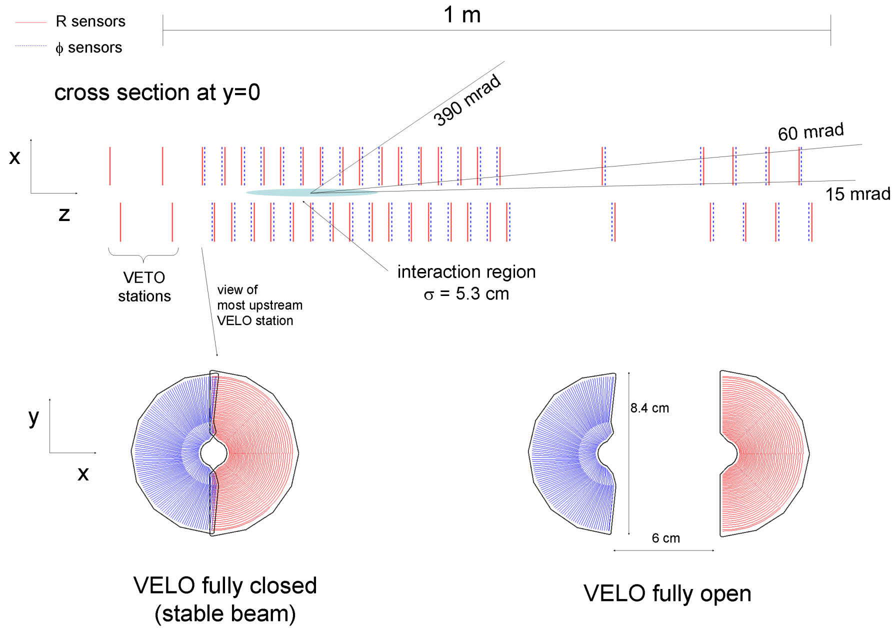
Read-out scheme



- Trigger-less read-out.
- Zero suppression in front-ends.
- Hardware LLT kept as back-up.

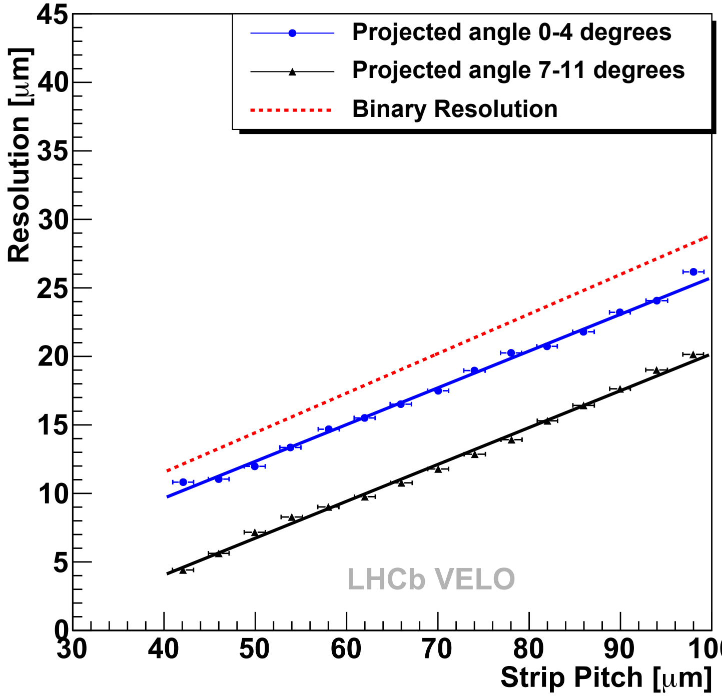
VErtex LOcator (VELO)

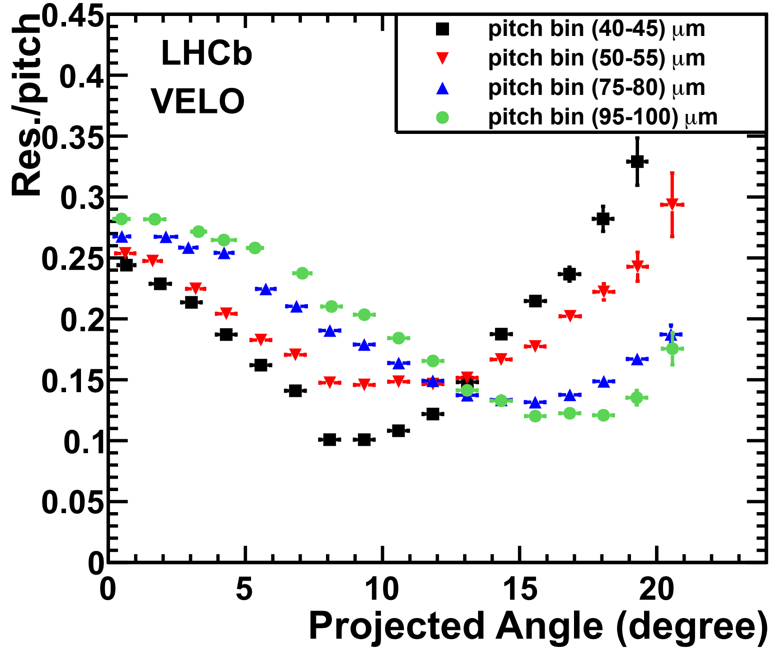




- Two retractable halves.
  - 5 mm from beam when closed, 30 mm during injection.
- 21 R-ϕ modules per half.
- Operates in secondary vacuum.
- 300 μm aluminium foils separates detector from beam vacuum.
- Cooling using bi-phase CO_2 system.
  - Operates @ -30°C, Sensors @ -10°C.

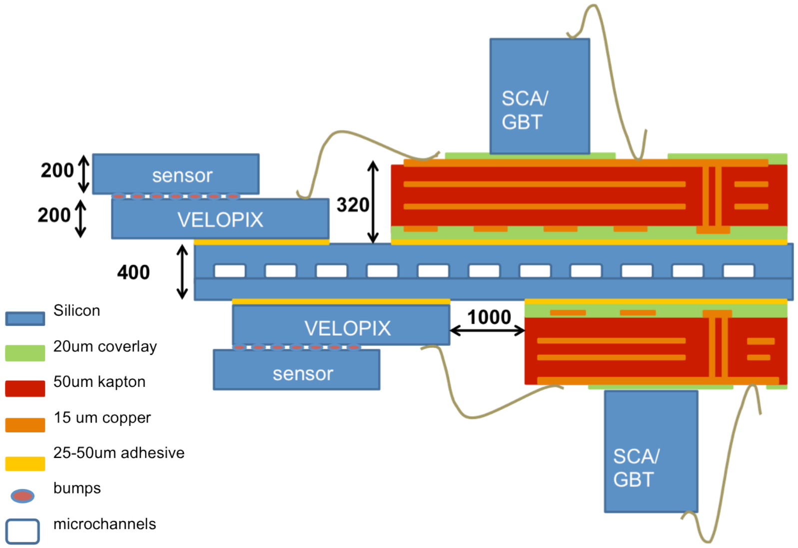
VELO Resolution

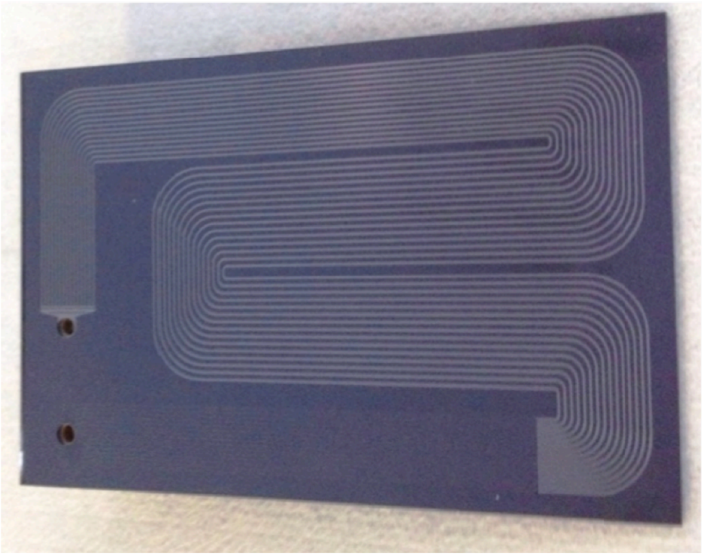


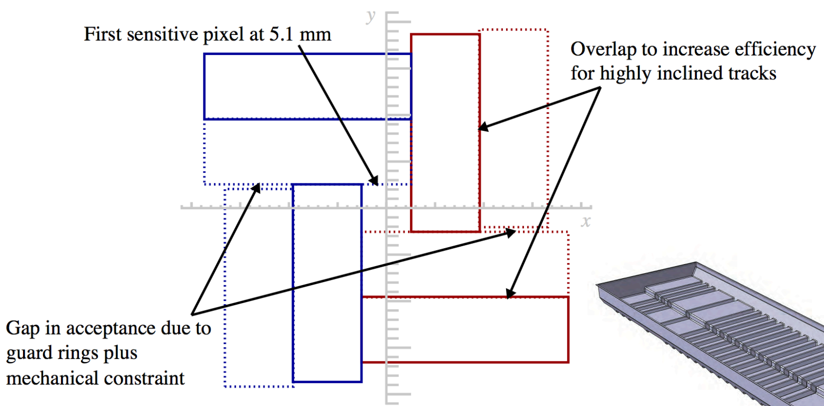


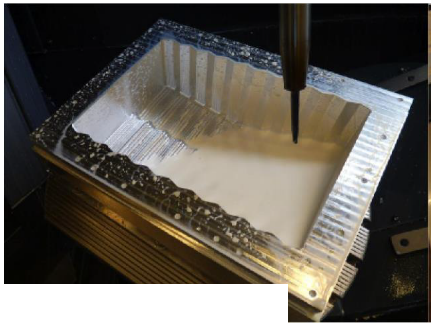
- Depends on pitch and projected track angle
  - Angle between track and strip in plane perpendicular to the track.
- Measure unbiased residuals of cluster to track.
- Best resolution achieved is 4 μm.

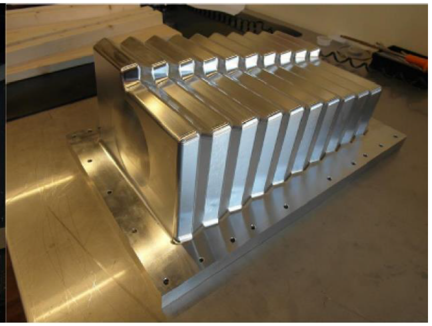
VELO II

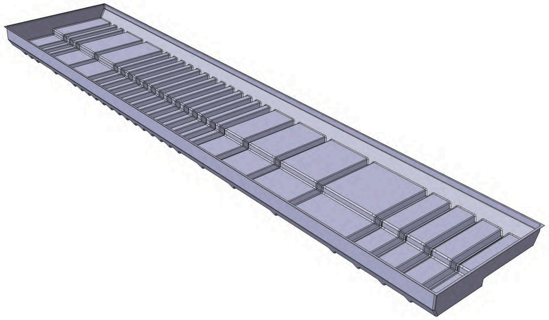

SCA/
GBT
200
sensor
200
VELOPIX
320
400
Silicon
20um coverlay
50um kapton
15 um copper
25-50um adhesive
bumps
microchannels
VELOPIX
1000
sensor
SCA/
GBT




First sensitive pixel at 5.1 mm
y
Overlap to increase efficiency
for highly inclined tracks
x
Gap in acceptance due to
guard rings plus
mechanical constraint







VELO II Performance

Table 5: Pattern recognition performance parameters for current and upgrade VELO at upgrade beam conditions ($\nu = 7.6$, $\sqrt{s} = 14\,\text{TeV}$) and for the current VELO at 2011 beam conditions ($\nu = 2$, $\sqrt{s} = 7\,\text{TeV}$). For the reconstruction efficiency, the following categories are considered: all particles reconstructible in the VELO with $p > 5\,\text{GeV}/c$, all particles reconstructible as long tracks with and without a momentum cut of $5\,\text{GeV}/c$, and particles from decays of b-hadrons with and without a momentum cut of $5\,\text{GeV}/c$. These parameters were measured using simulated events containing the decay $B^0 \to K^{*0}\mu^+\mu^-$.

	Existing VELO [%]		Upgraded VELO [%]
	$\nu = 2$	$\nu = 7.6$	$\nu = 7.6$
Ghost rate	6.2	25.0	2.5
Clone rate	0.7	0.9	1.0
Reconstruction efficiency			
VELO, $p > 5\,\text{GeV}/c$	95.0	92.7	98.9
long	97.9	93.7	99.4
long, $p > 5\,\text{GeV}/c$	98.6	95.7	99.6
b-hadron daughters	99.0	95.4	99.6
b-hadron daughters, $p > 5\,\text{GeV}/c$	99.1	96.6	99.8

Primary Vertex Resolution

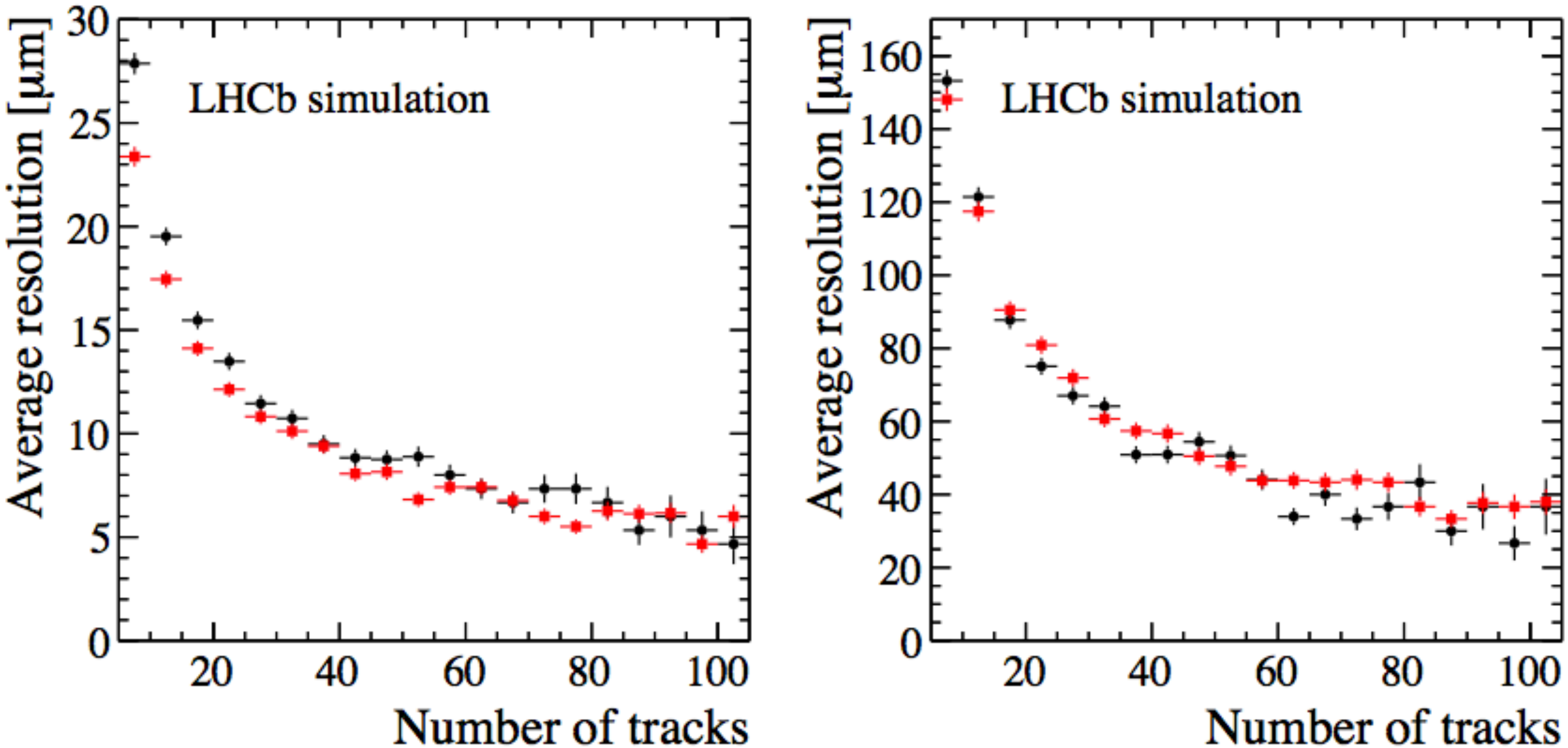
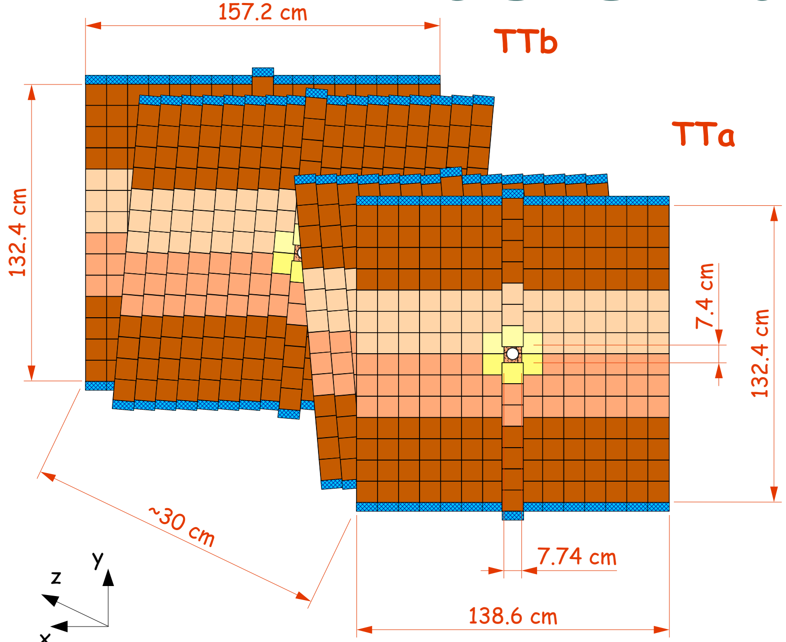
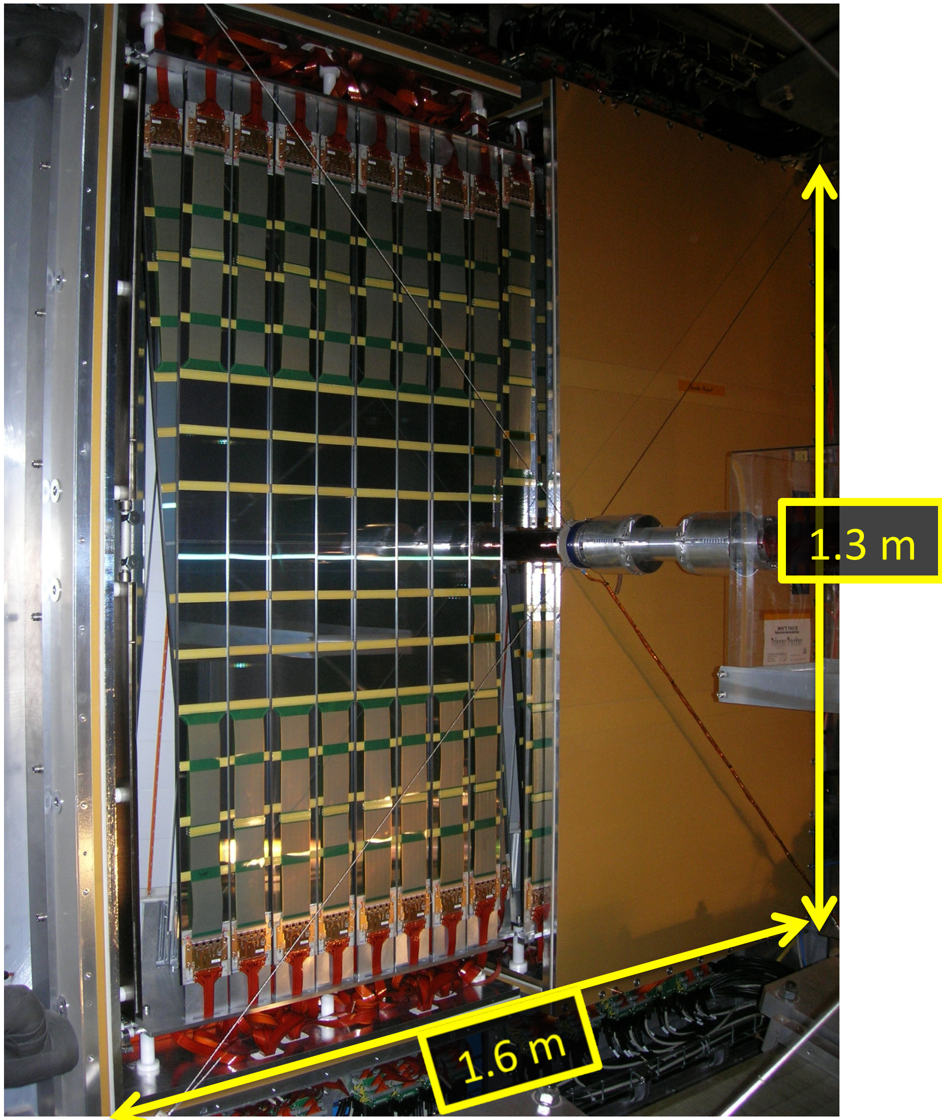


Figure 28: PV resolution in (left) x and (right) z as function of the number of reconstructed tracks in the vertex. The current VELO is shown with black circles and the upgrade VELO with red squares, both are evaluated at $\nu = 7.6$, $\sqrt{s} = 14\,\text{TeV}$. The resolutions in x and y are similar.

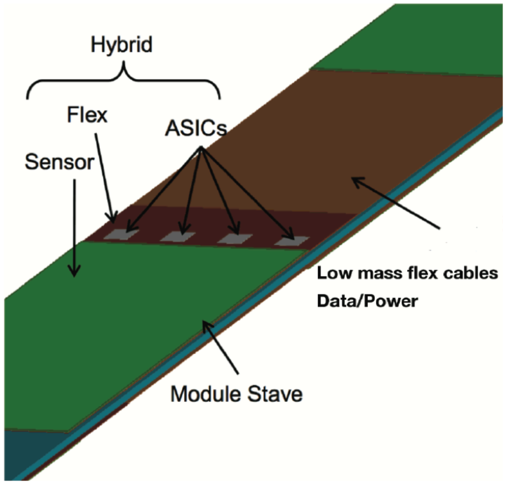
Tracker Turicensis (TT)

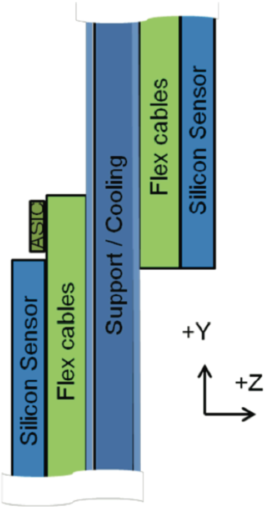


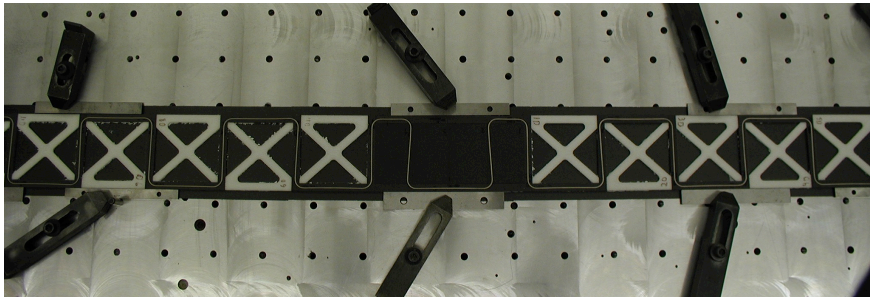


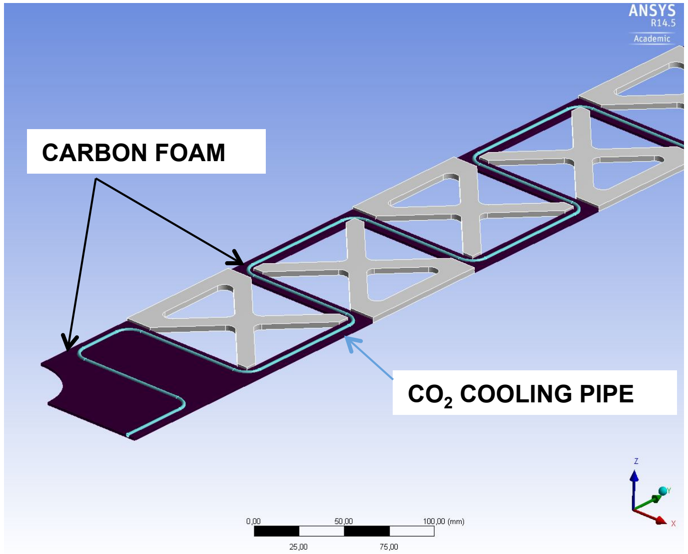
- Silicon micro-strip detectors.
  - p^+-on-n from Hamamatsu Photonics K.K.
- Four planes (0°, +5°, -5°, 0°).
- Pitch: 183 µm; Thickness: 500 µm.
- Long readout strips (up to 37 cm).
- 143360 readout channels.
- Total Silicon area is 8 m^2.
  - Covers full acceptance before magnet.
- Detectors operate at 0°C.
  - Sensors @ 8°C.

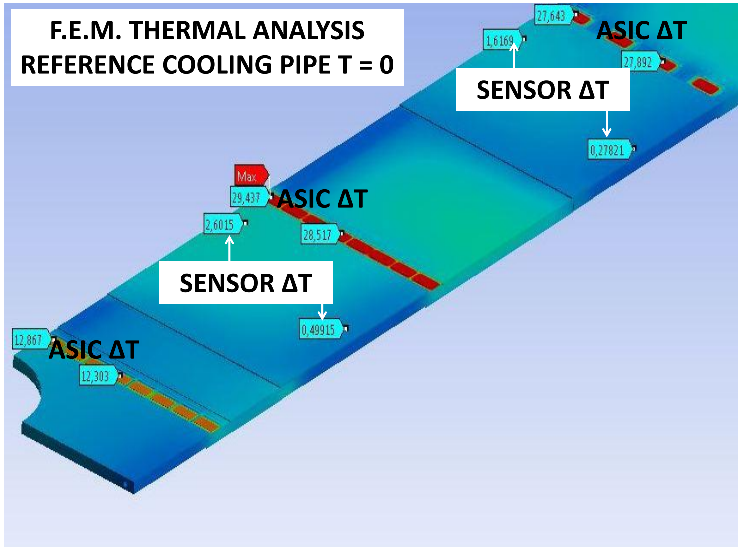
Upstream tracker



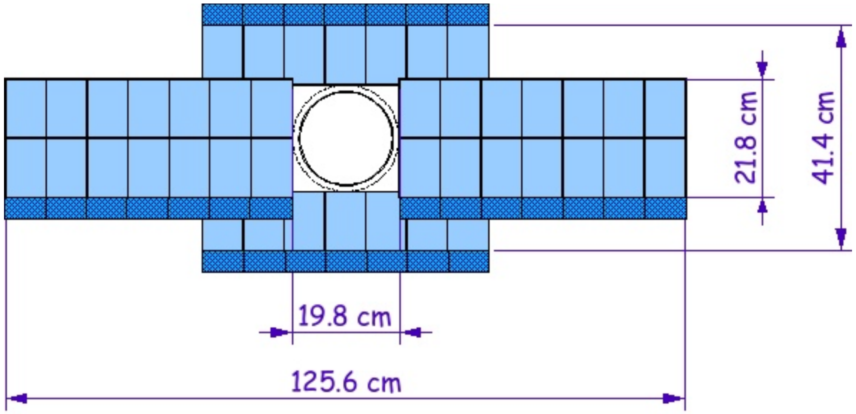


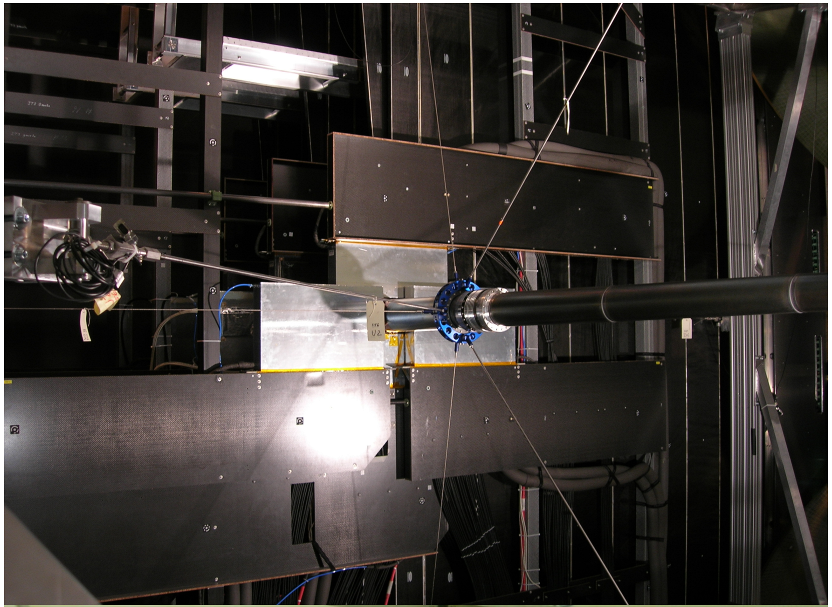


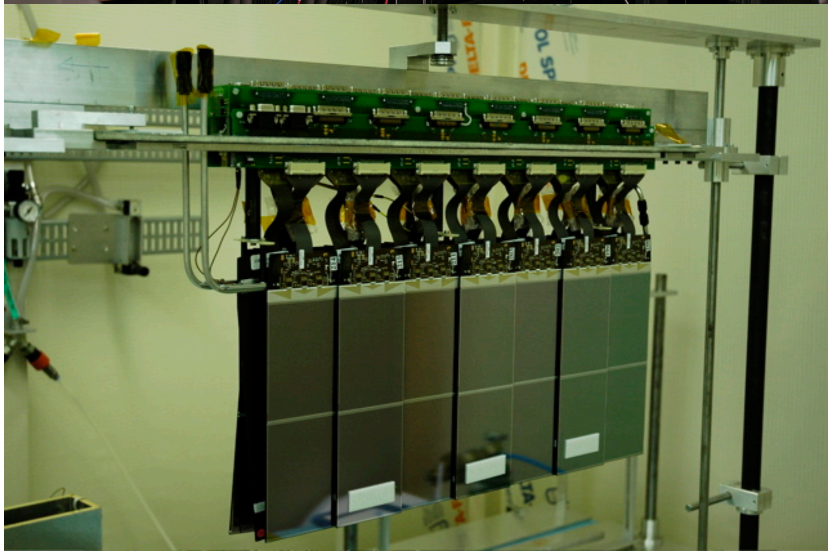




Inner Tracker (IT)

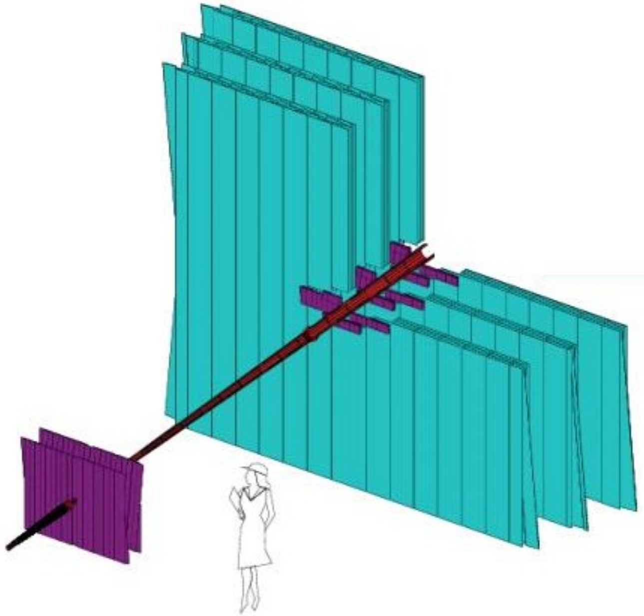


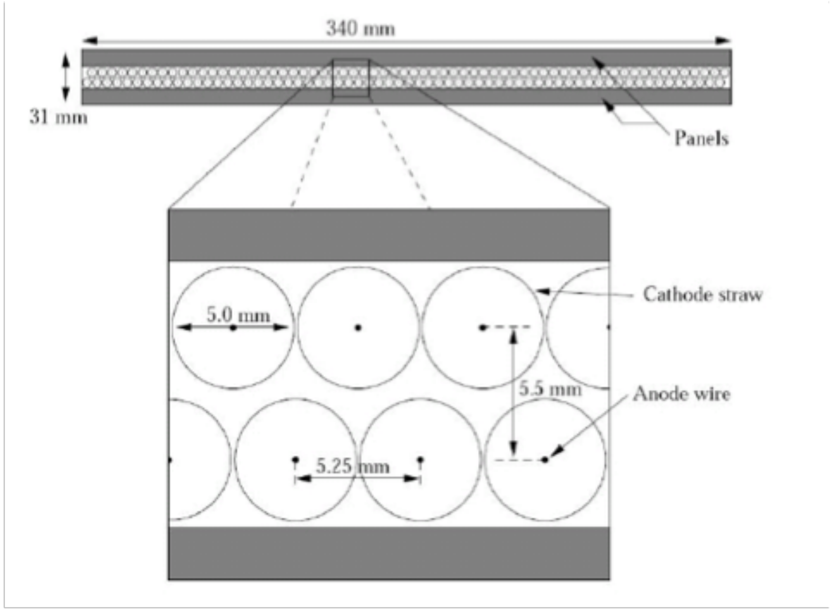




- Silicon micro-strip detectors.
  - p^+-on-n from Hamamatsu Photonics K.K.
- Three stations in z.
  - Four boxes in each station.
  - Four planes (0°, +5°, -5°, 0°)
- Pitch: 198 µm
- Thickness: 320 or 410µm
- 129024 readout channels.
- Total Silicon area is 4.2 m^2.
  - Covers region around beam with highest flux.
- Detectors operate at 0°C.
  - Sensors @ 8°C.

Outer Tracker





- Gaseous straw tube detector.
- 12 detection layers covering area ~ 4 x 6 m^2.
- 53760 straw tubes (2.4 m long, 4.9 mm diameter).
- Gas mixture: $Ar/CO_2/O_2$ (70%/28.5%/1.5%).
- Nominal operating voltage is 1550 V.

Tracking performance

Table 4.4: Pattern recognition performance parameters for *long* reconstructible particles reconstructed by the Forward tracking algorithm in the current and upgraded detector. Note that these numbers include the sum of the performance of the VELO and Forward pattern recognition. The tracks are fitted by a Kalman fit algorithm and a χ^2 cut of 5 is applied afterwards.

	Current LHCb [%]	Upgrade LHCb [%]	
	$\nu = 2$	$\nu = 3.8$	$\nu = 7.6$
Ghost rate	13.1	14.7	25.5
Reconstruction efficiency			
long	90.9	86.9	84.5
long, $p > 5\,\text{GeV}/c$	95.4	92.9	91.5
b-hadron daughters	93.9	91.9	90.6
b-hadron daughters, $p > 5\,\text{GeV}/c$	96.1	95.1	94.2

- Biggest difference for low momentum tracks.
- Ghost rate can be reduced by adding UT hits.

Nu, mu, pile-up

- ν (nu) : average number of *pp* interactions per bunch crossing.
- μ (mu): average number of visible *pp* interactions per bunch crossing.
- pile-up: average number of *pp* interactions in visible bunch crossings.

Upgrade conditions in 2012!