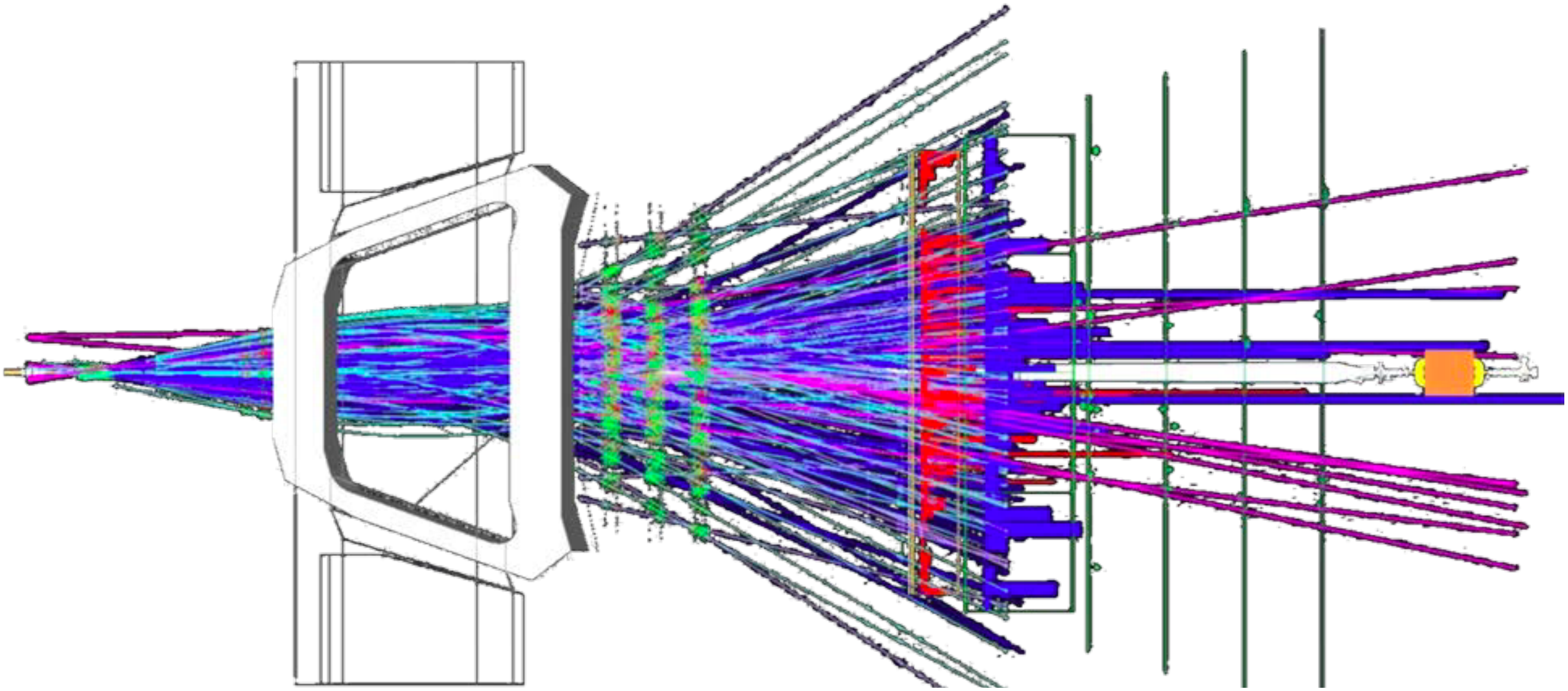
The LHCb Upgrade

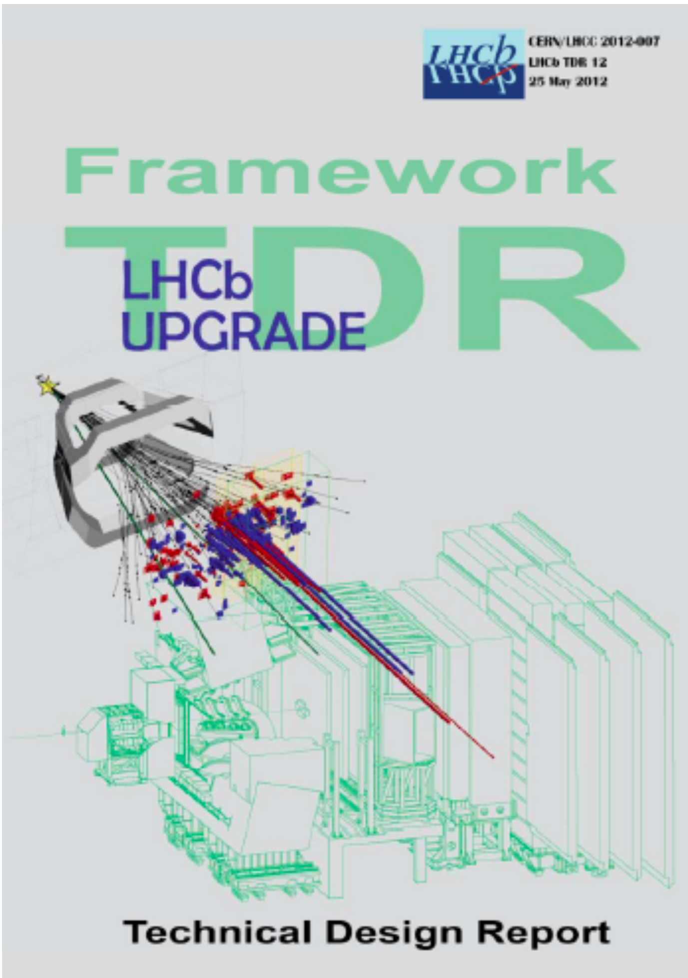


U. Marconi, I.N.F.N. Bologna, CSN1 May 28th, 2012

Toward the "Framework TDR"

- The LoI upgrade submitted to LHCC by the beginning of March 2011. [CERN-LHCC-2011-001]
  - Physics case fully endorsed and 40 MHz architecture reviewed.
- LHCC recommendation in June 2011 to proceed to detector TDRs, in time for installing the detectors and electronics in 2018.
- The LHCb Collaboration proposed to the LHCC to go for a "Framework TDR" aiming to:
  - Convince our LHC machine colleagues that the HL-LHC will have to deal with at least 3 IPs.
  - Ease the negotiations with our funding agencies.
  - Proceed a.s.a.p. with the MoUs.
- The proposal has been very well received by the LHCC referees on March 2012.

Content of "Framework TDR"



- 1st chapter.
  - Introduction explaining the evolution since LoI, with update on expected physics performance.
  - Update on the evolution of the detectors requirements and main technical options.
- 2nd chapter.
  - Update on evolution of sub-systems R&D since LoI.
- 3rd chapter. (Content agreed with LHCC).
  - Schedule
  - Cost
  - Declaration of interest of institutes.
    Subject to funding.

CERN/LHCC 2012-007, LHCb TDR 12, 25 May 2012

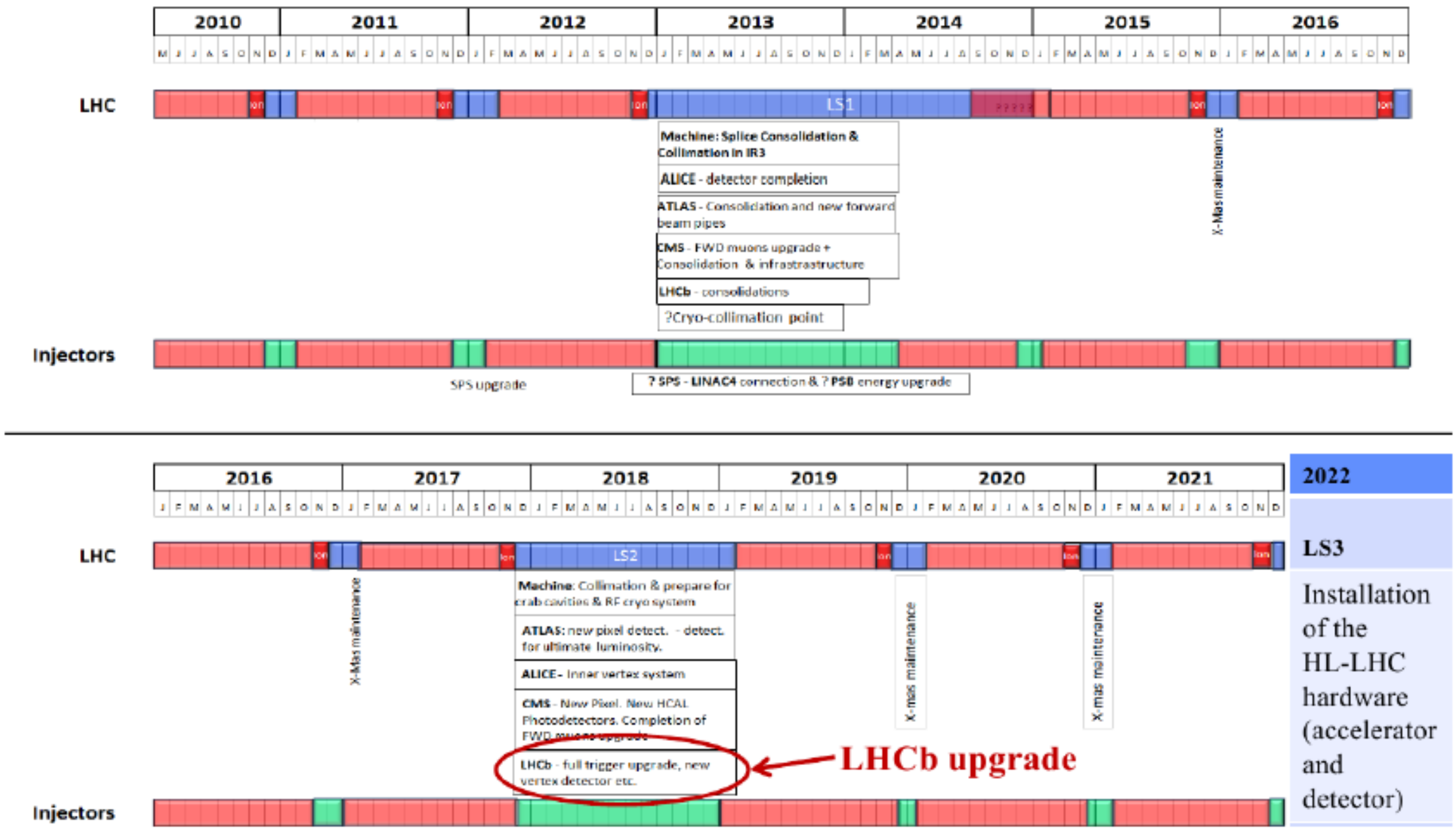
Main assumptions

- In the LoI LHCb declared its interest to upgrade the detector such to:
- Run at a nominal luminosity of L=1.*10^{33} $cm^{-2}s^{-1}$.
- Exploit a fully flexible software trigger, selecting events synchronously with the BX clock, at 40 MHz.
- Increase signal efficiency for leptonic channels by a factor 5 and for hadronic channels up to a factor 10.
- Accumulate 50 fb^{-1} over 10 years.
- For reasons of flexibility and to allow for possible evolutions of the trigger, LHCb decided to design those detectors that need replacement for the upgrade such that they can sustain a minimal luminosity of L=2*10^{33} cm^{-2} s^{-1}.

Major milestones

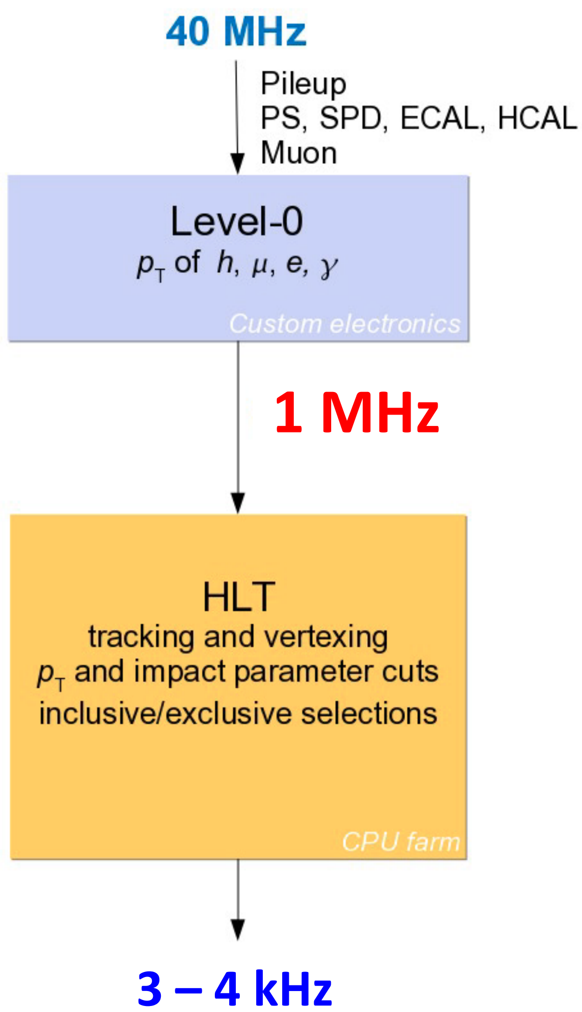
- **2011**: LoI (fully endorsed in June).
- **Mid 2012**: "Framework TDR".
- **2012**: Continue with R&D towards technical choices.
- **2012/13**: Technical review and choice of technology.
- **2013**: TDR and prototype validation.
- **2014**: Tendering and serial production.
- **2016-17**: Quality control and acceptance tests
- **2018**: Installation

LHC 10 years plan

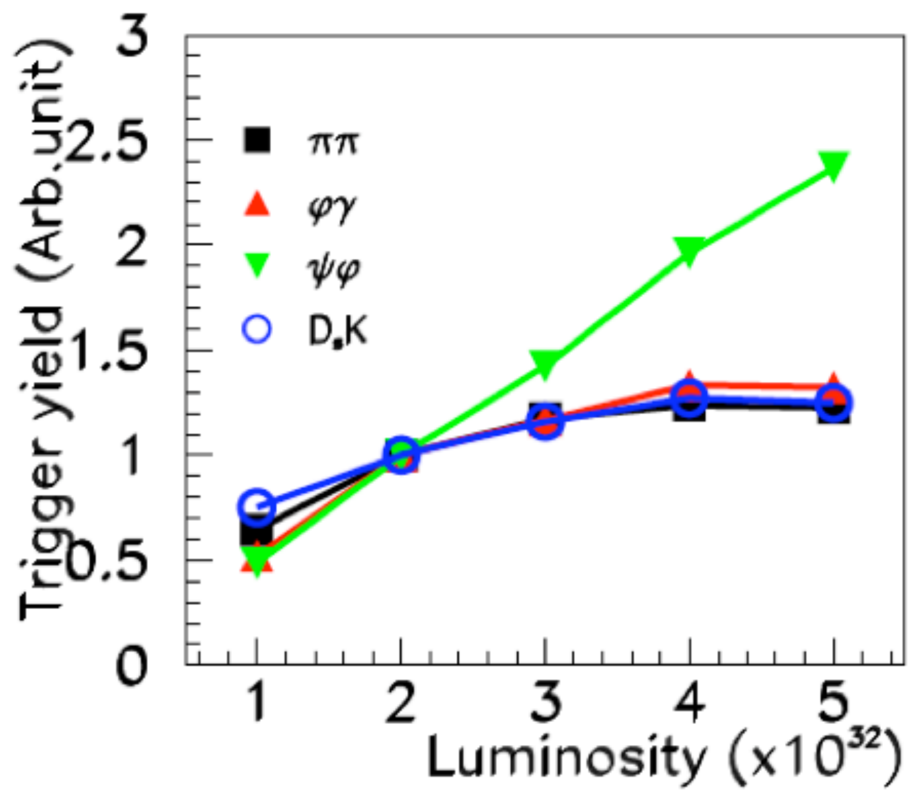


More details: S. Meyer, LHC machine status and prospects including upgrades, EPS 2011, Grenoble, France

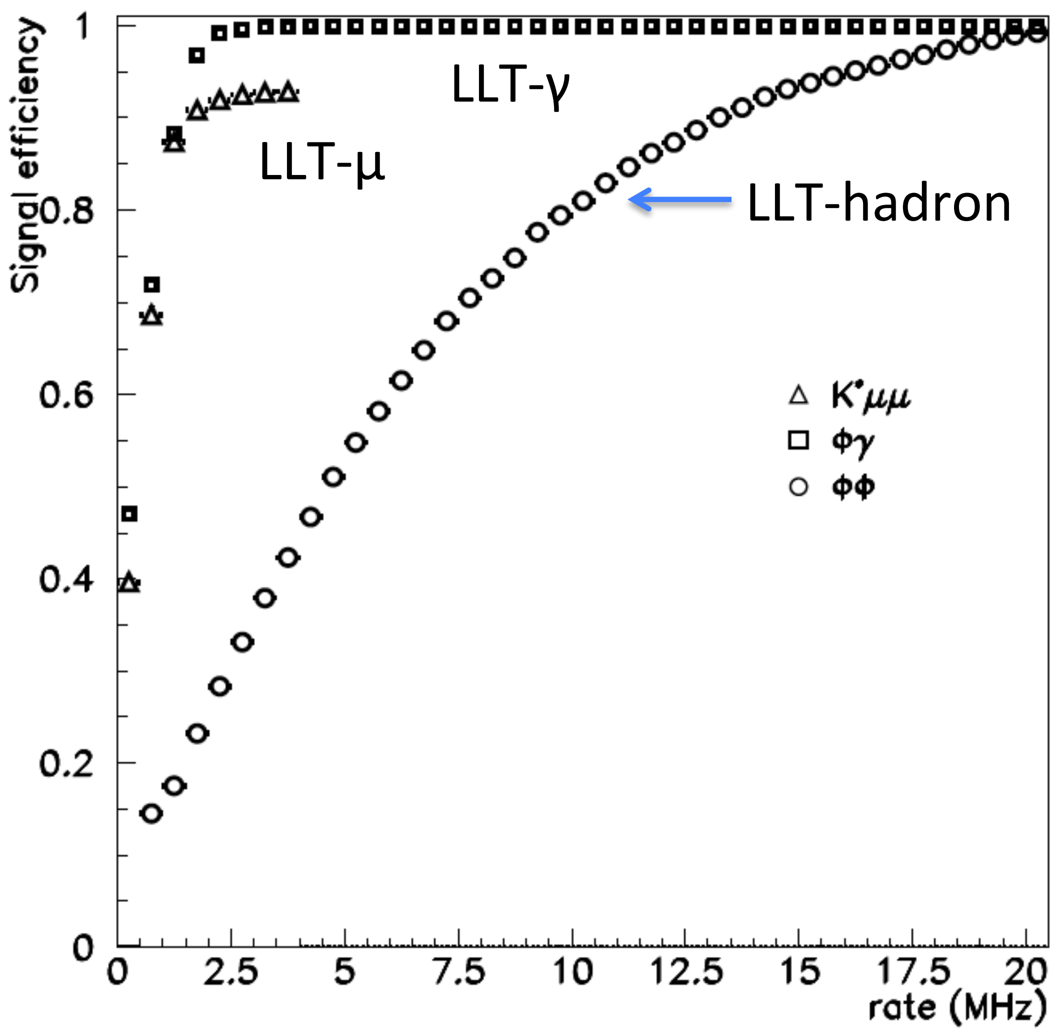
The present L0 trigger architecture



1 MHz L0 trigger rate limitation



LLT efficiency vs LLT output rate



LLT efficiency

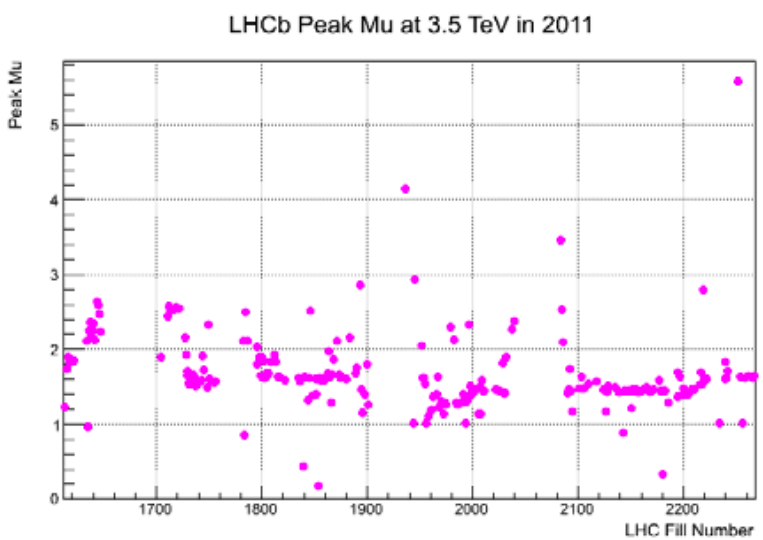
LLT-rate (MHz)	1	5	10
$B_s \to \phi\phi$	0.12	0.51	0.82
$B^0 \to K^* \mu\mu$	0.36	0.89	0.97
$B_s \to \phi\gamma$	0.39	0.92	1.00

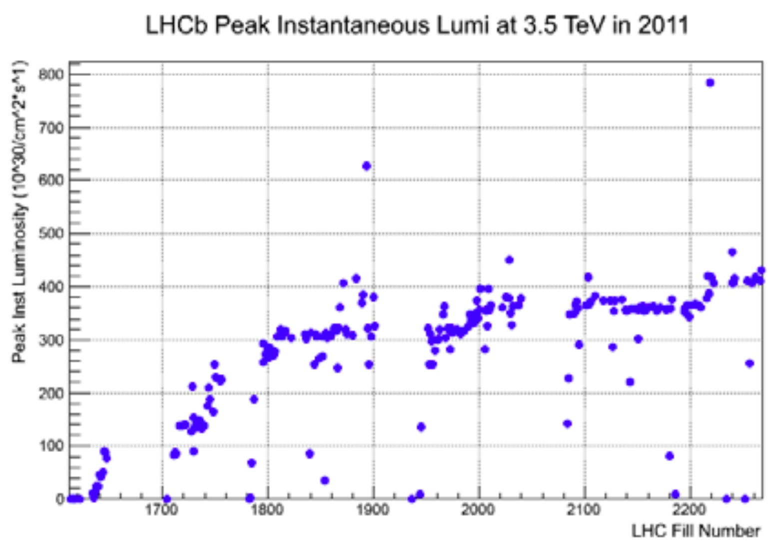
Relative rates LLT-μ : LLT-hadron: LLT-e/γ = 1:3:1.

Running conditions

- Max input rate to the HLT of non empty events ~ **30MHz**
- N**umber of colliding bunches** × **revolution frequency**

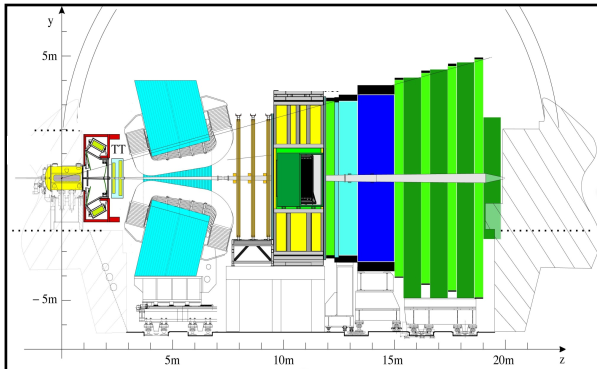
  → LHCb: $n_b \times f = 2622 \times 11245 =$ **29.5 MHz**
- Events with at least one interaction per crossing:
  - At **L = 1. × 10^{33} cm^{-2}s^{-1}** : 29.5 × (1. – exp(-**2.**)) = **26. MHz**
  - At **L = 2. × 10^{33} cm^{-2}s^{-1}** : 29.5 × (1. – exp(-4.)) = **29. MHz**
  - Average pileup $\sigma_{pp}(\sqrt{s}=14\text{TeV})$= 60 mb (inelastic) the average pileup: **$\mu := \langle pileup \rangle = L \times \sigma_{pp} / (n_b \times f)$**





Trigger: the key to higher luminosity

All the sub-detectors information to the readout at 40 MHz



40 MHz

LLT

p_T of h,μ, e/γ

Custom electronics

Accept

FCTS

LLT trigger rate 10 – 30 MHz

40 MHz

READ-OUT

TELL40

Custom electronics

Bandwidth presently limited to 1MHz

40 MHz

HLT

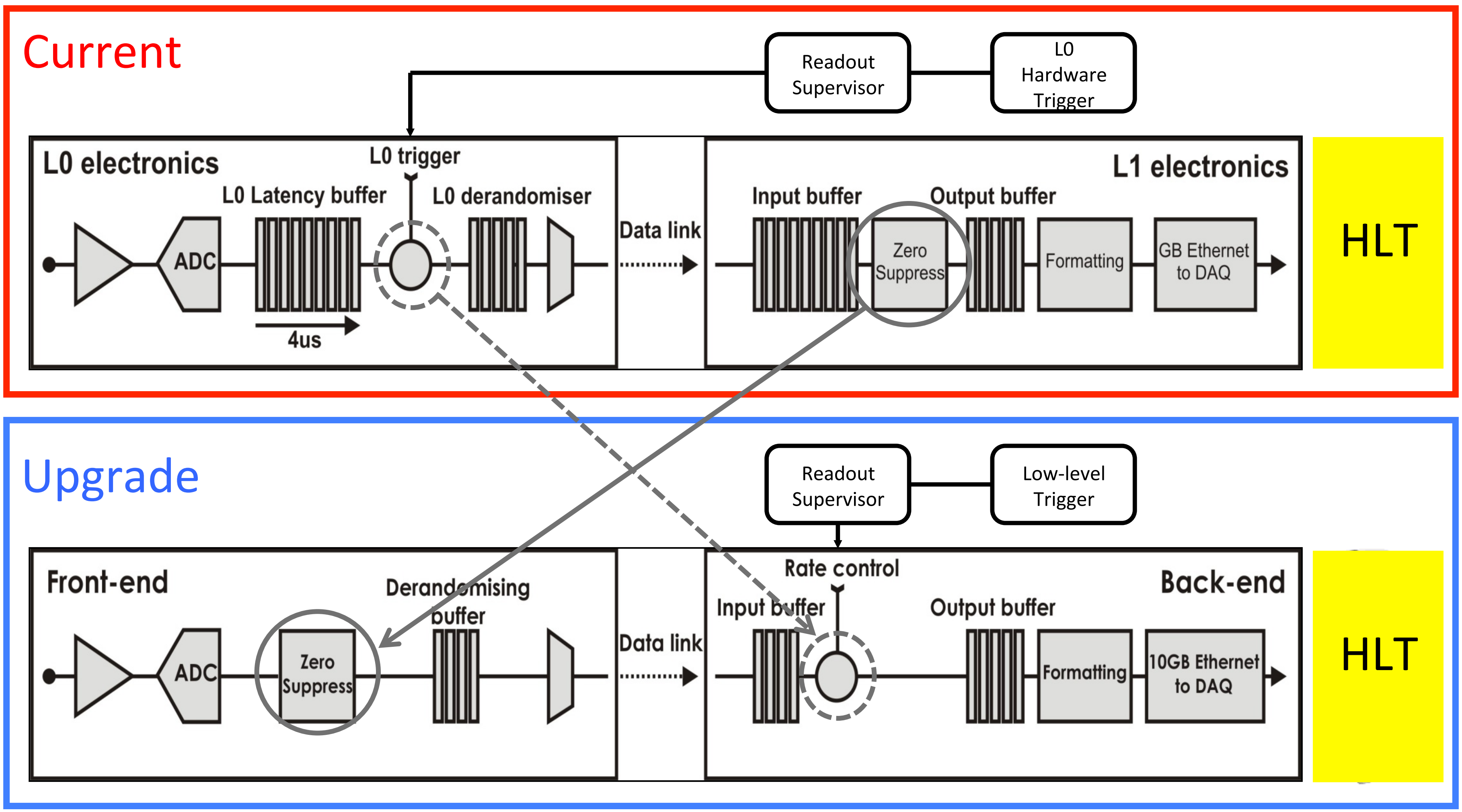
Tracking and vertexing

p_T and impact parameter cuts

Inclusive/exclusive selections

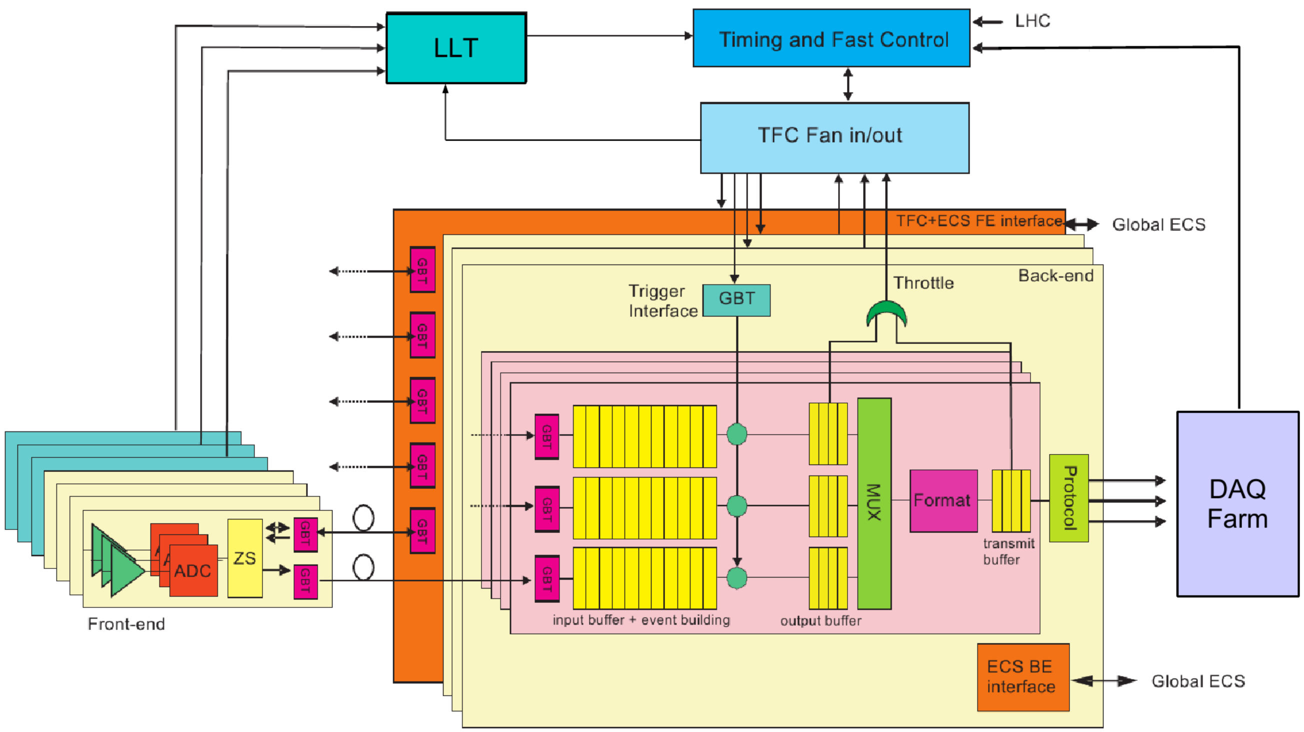
Event Filter Farm

40 MHz electronics



Architectural Overview

40 MHz



20 kHz

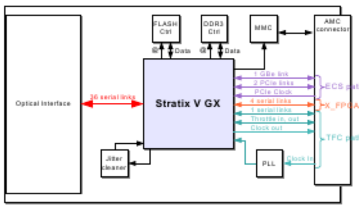
Front-end

TELL40

Readout at 40 MHz

- Data throughput from the FEE to the read-out boards (TELL40).
  - 40. MHz × 4. (pileup) × 35. kB/evt ~ 45. × 10^{12} bit/s
- Number of GBT links:
  45 × 10^{12} bit/s / 3.2 × 10^{9} bit/s ~ 14000 links
  Current detector has already 8300 links installed.
- Number of TELL40 readout boards: ~ 200

TELL40 adaptable board

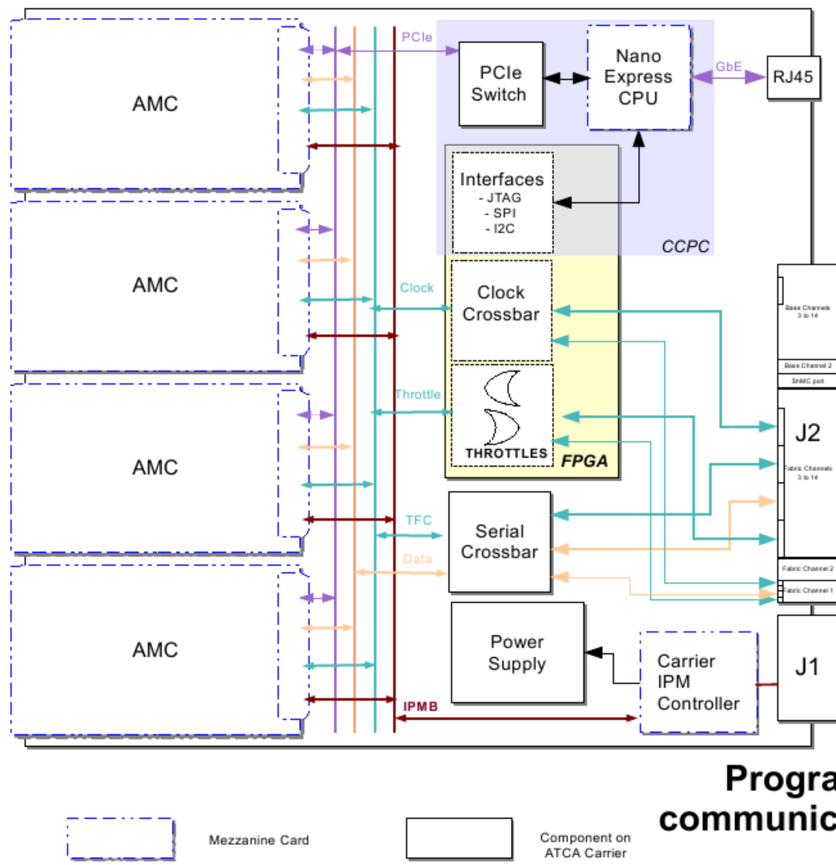


Optics and processing mezzanine board

\+

Flexible and reconfigurable carrier board

CCPC for slow control



Programmable communication matrix

24 optical input per AMC mezzanine board

Adaptable board to cover all the functionalities required by the timing, control, low level trigger and data acquisition systems.
First prototype to be fully tested by end 2012

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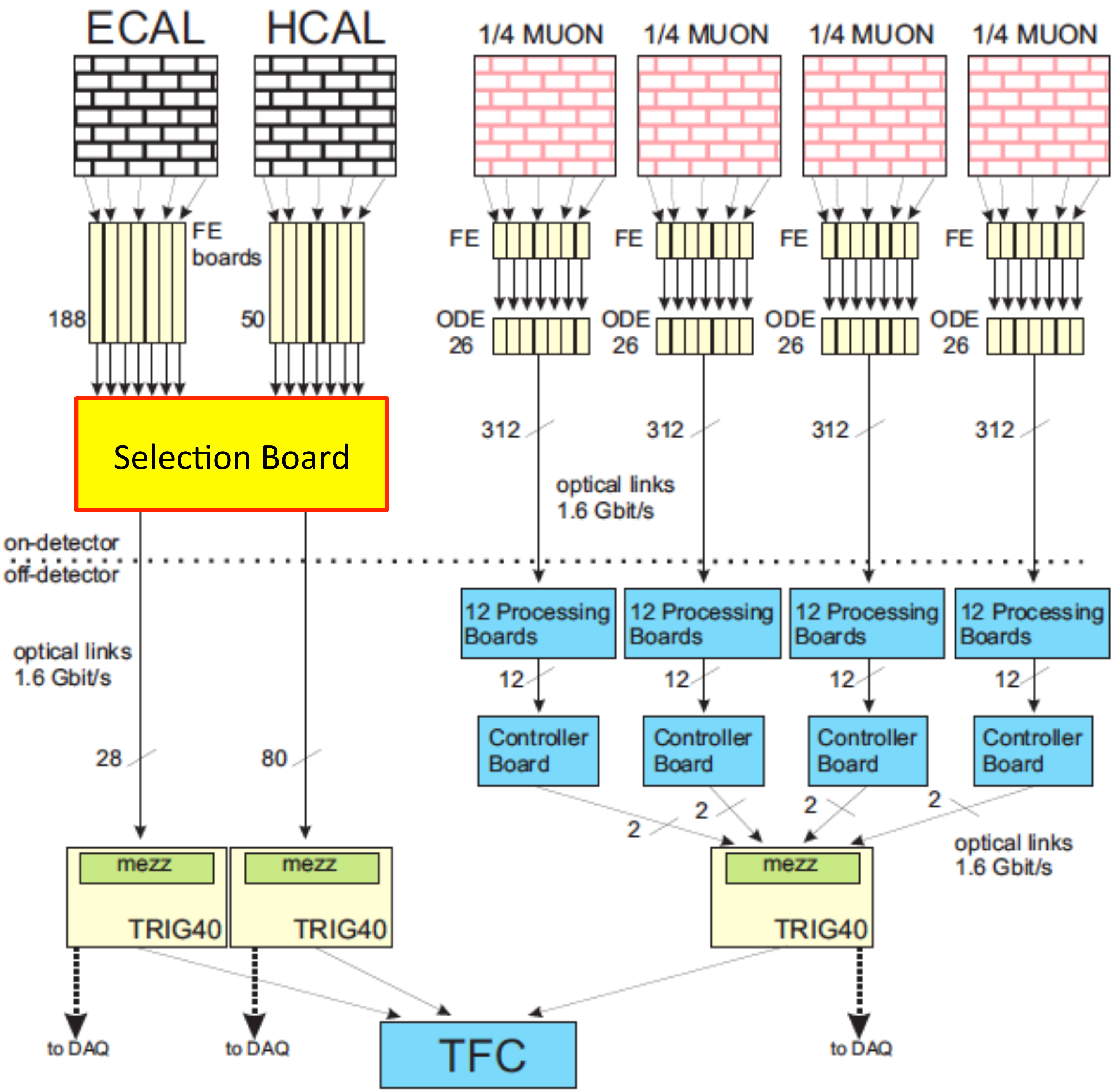
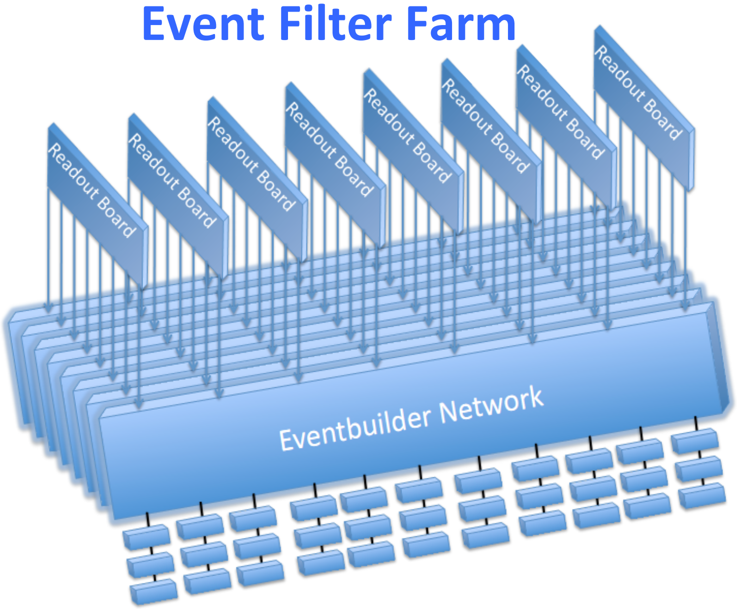
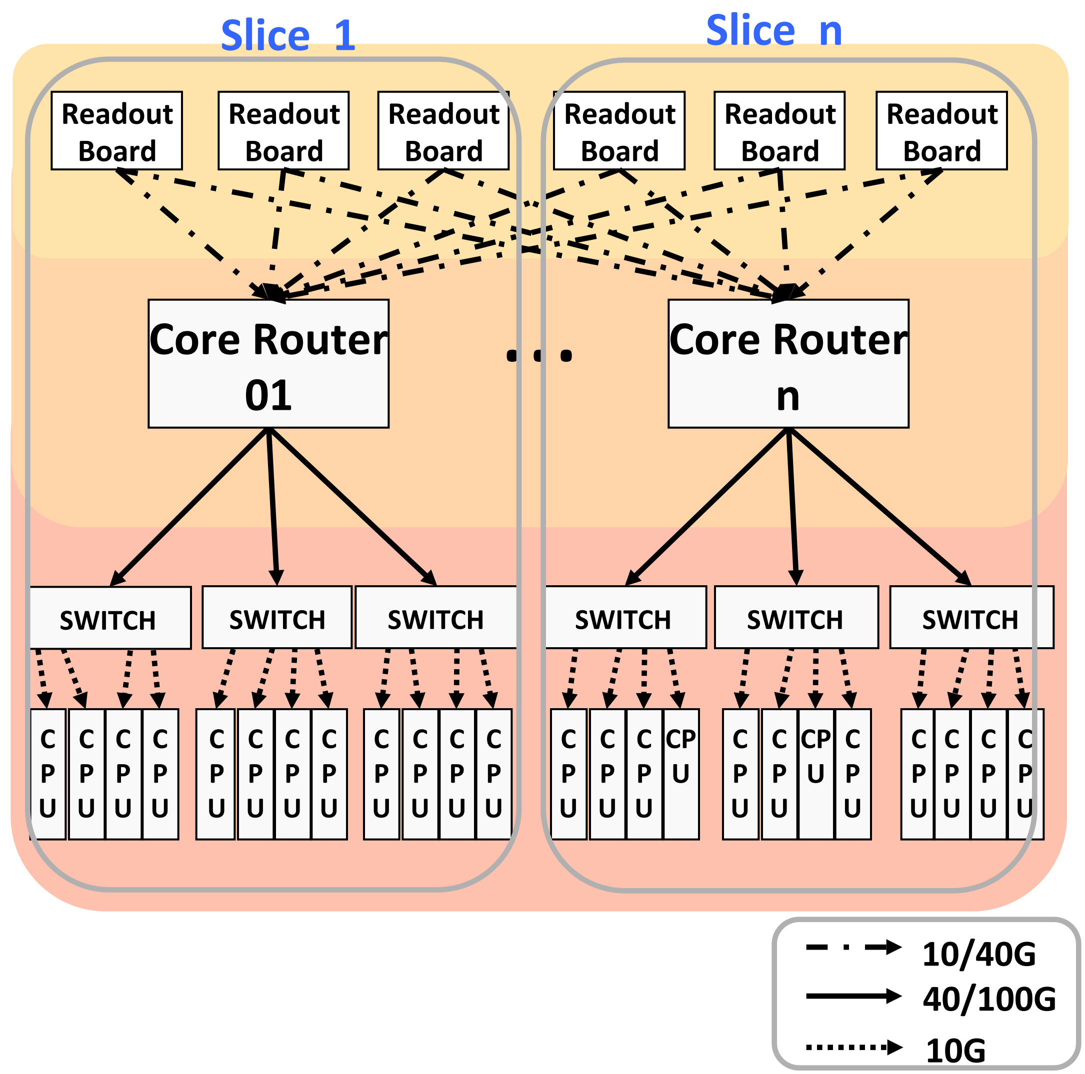

ECAL
HCAL
1/4 MUON
1/4 MUON
1/4 MUON
1/4 MUON
FE
boards
188
50
FE
ODE
26
Selection Board
312
optical links
1.6 Gbit/s
on-detector
off-detector
optical links
1.6 Gbit/s
12 Processing
Boards
12
Controller
Board
28
80
2
2
2
2
optical links
1.6 Gbit/s
mezz
TRIG40
to DAQ
TFC

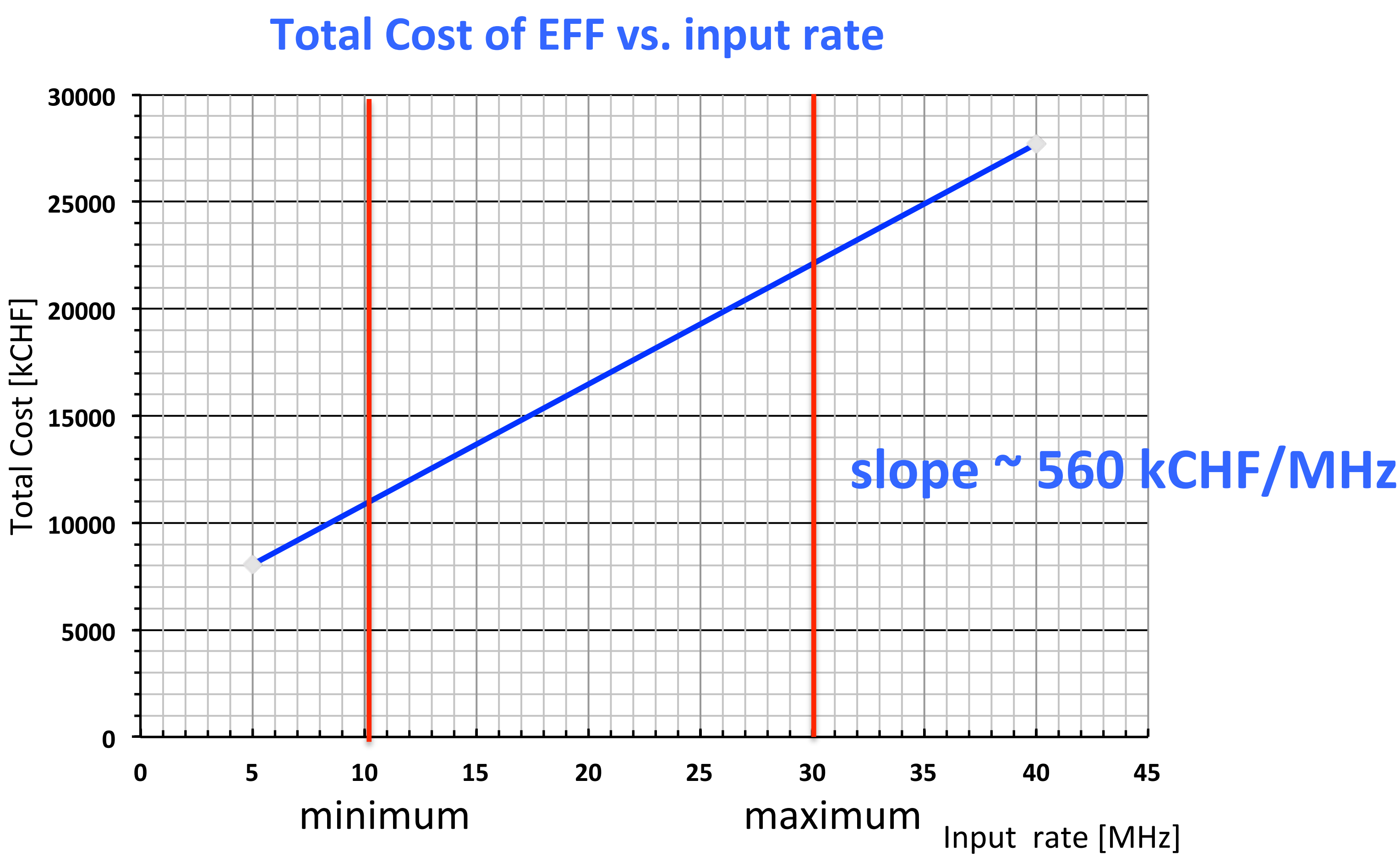
The DAQ network

- The network as a modular system: split the network into several sub-networks (slices).
- Each readout board is connected to all the sub-network.



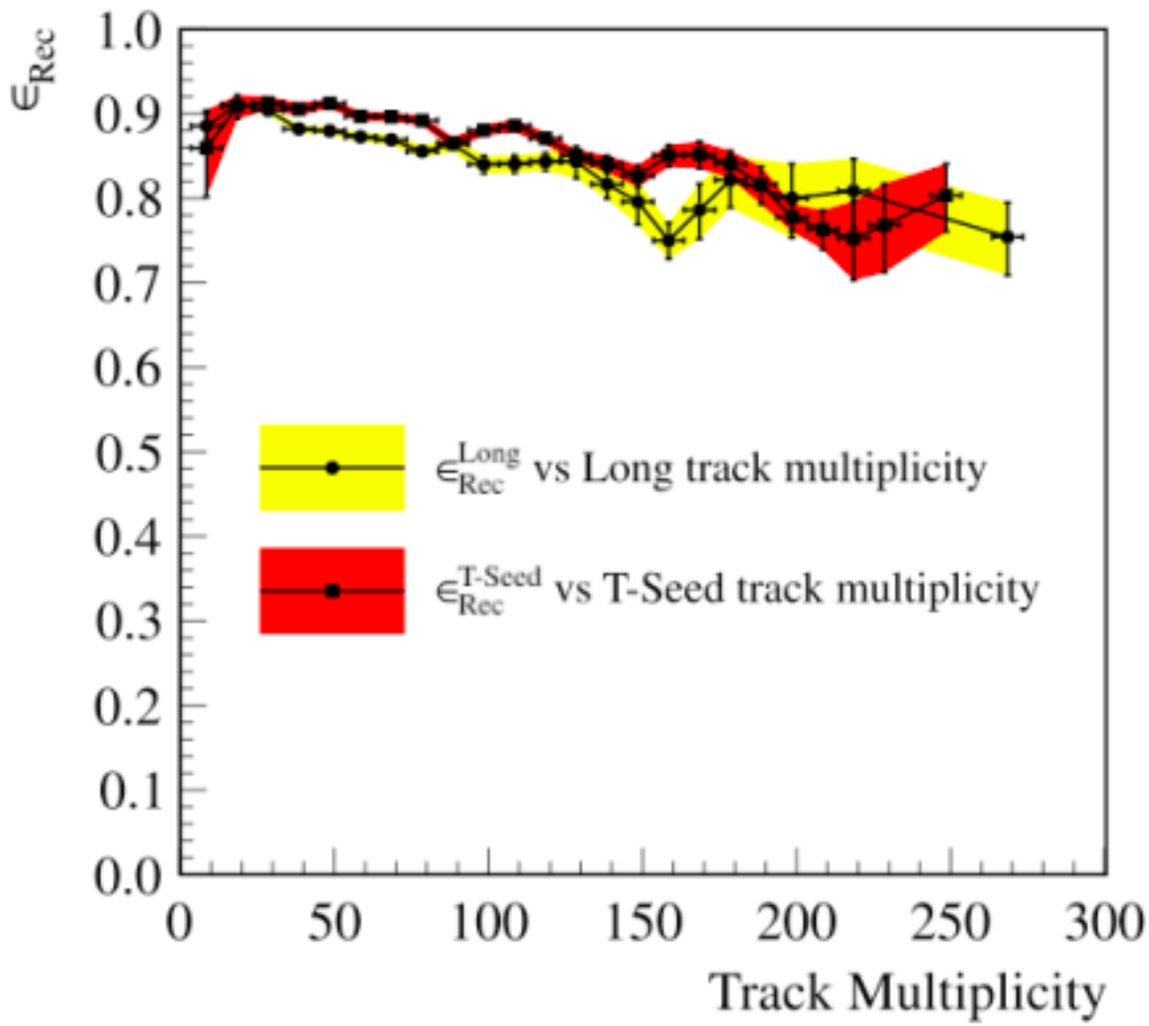


Cost of the Event Filter Farm (HLT)



Assuming a HLT mean processing time of 20 ms/event

Tracking efficiency vs multiplicity



Efficiencies

Luminosity of 10^{33} cm^{-2}s^{-1}: average pileup of 2

EFF size	5×2011	10×2011
LLT-rate (MHz)	5.1	10.5
HLT1-rate (kHz)	270	570
HLT2-rate (kHz)	16	26
Total signal efficiency		
$B_s \to \phi\phi$	0.29	0.50
$B^0 \to K^* \mu\mu$	0.75	0.85
$B_s \to \phi\gamma$	0.43	0.53

Increasing the EFF allow to relax the trigger cuts.

The bandwidth division minimises the overall loss in efficiency by minimising:

$$\chi^2 = \sum_{\text{channels}} \sum_{\text{lines}} \left(1 - \frac{\varepsilon^{\text{channel, line}}}{\varepsilon^{\text{channel, line}}_{\text{max}}}\right)^2$$

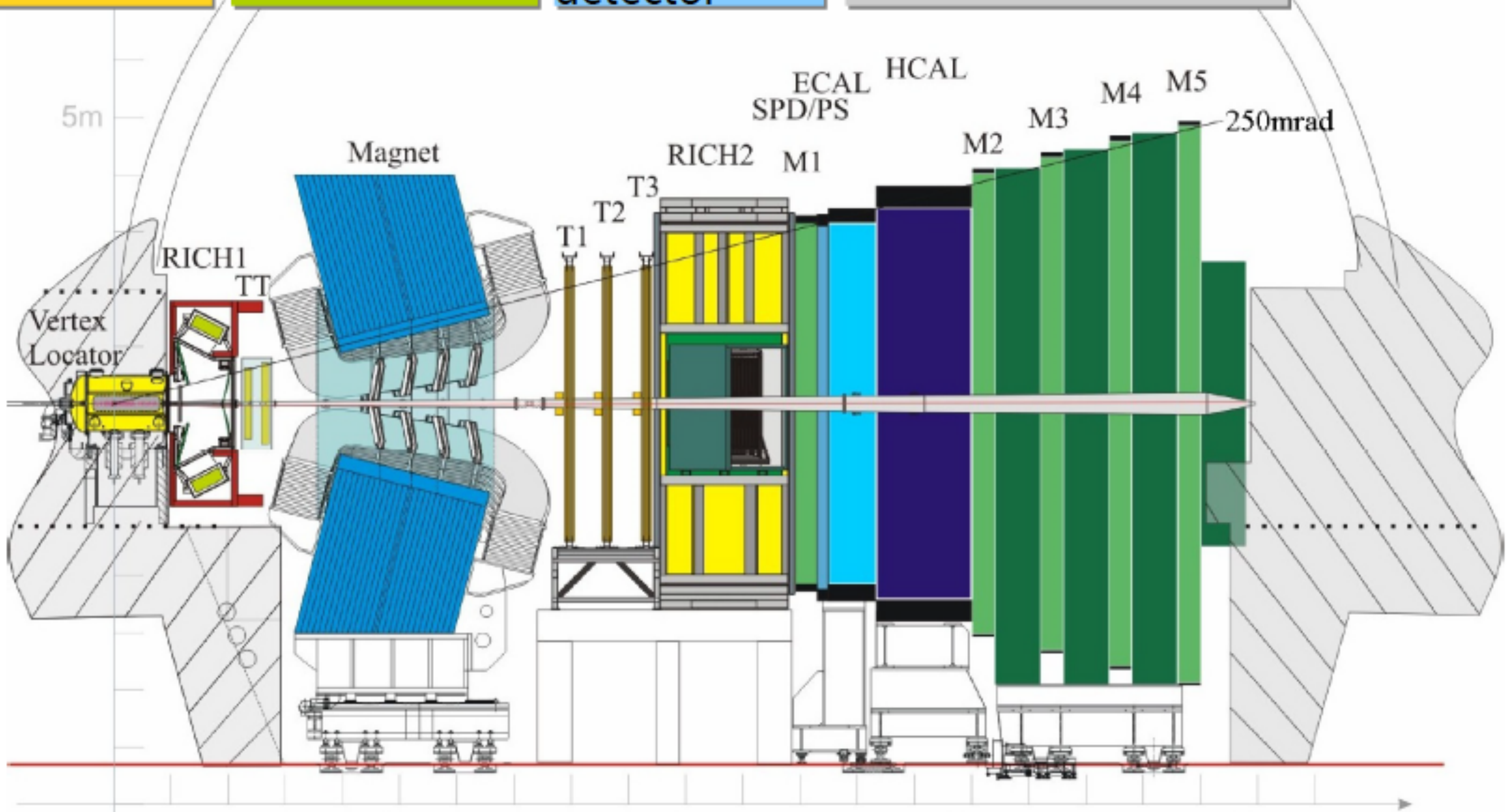
Detector modifications

VELO
New pixel system

TRACKING
New TT and IT

RICH
New photon detector

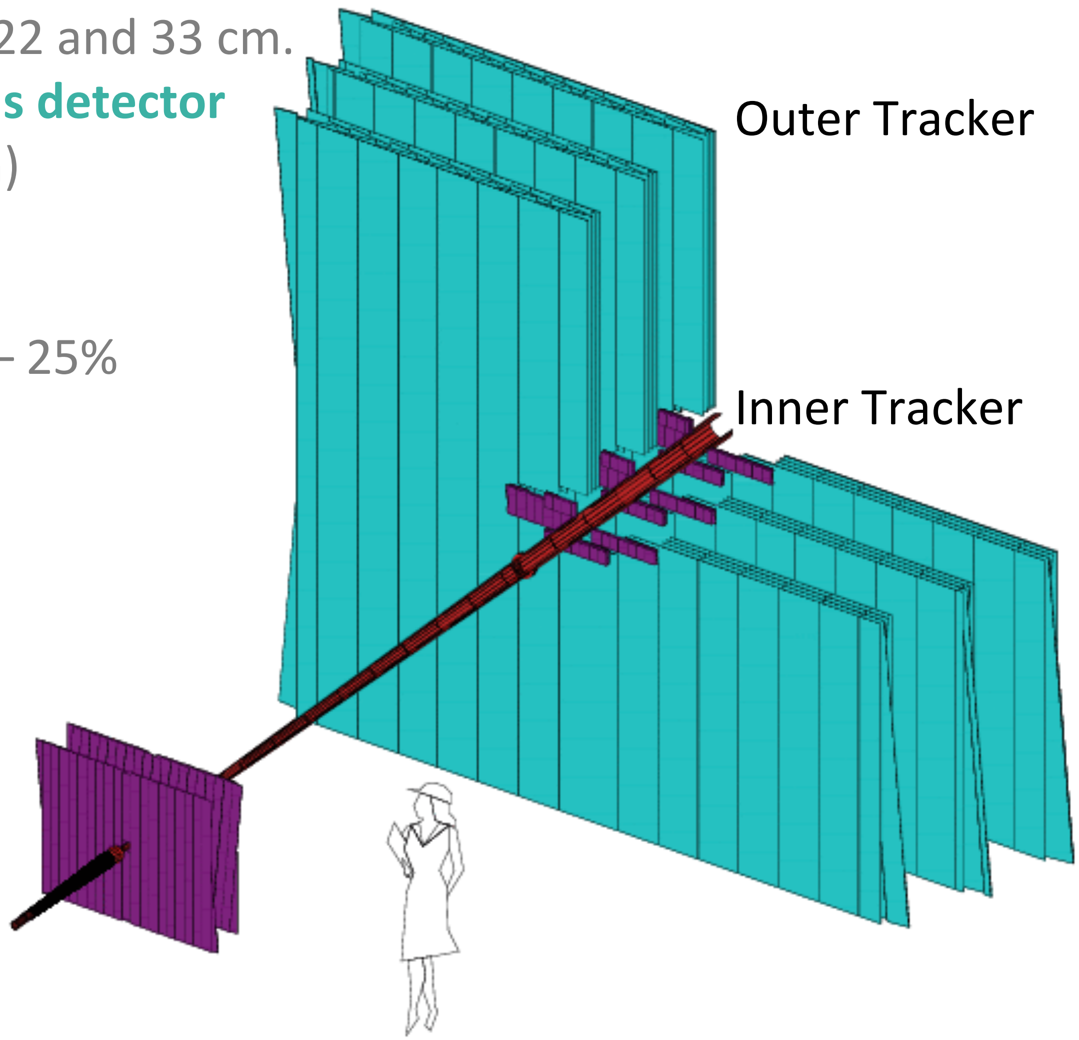
CALO + MUON
Remove M1, SPD, PS



Replace all the front-end electronics + DAQ network

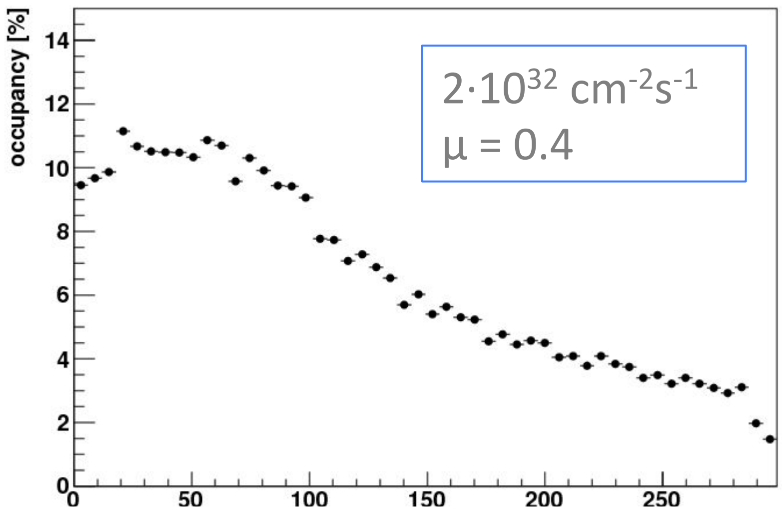
The LHCb tracking system

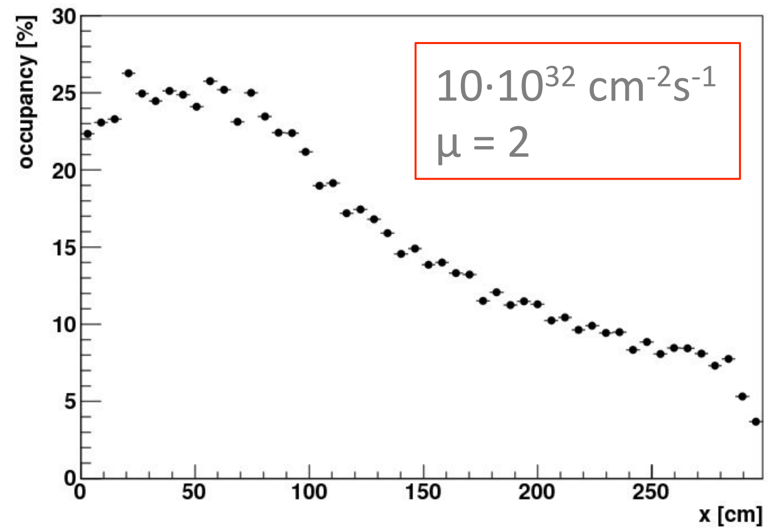
TT and IT are **microstrips silicon detector**.
Pitch 200 μm, length 11, 22 and 33 cm.
Outer tracker is a gaseous detector
based on very thin (5 mm)
and very long straw
tube (2.4 – 5 m).
Occupancy limited to 20 – 25%



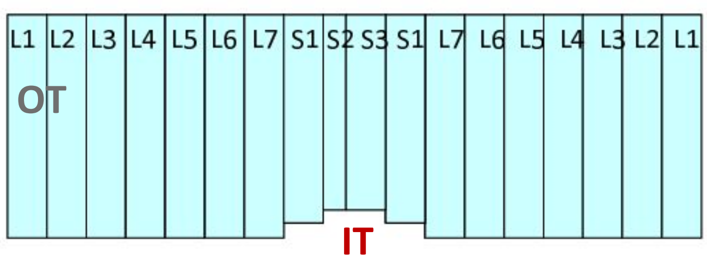
Tracking upgrade

Increased occupancy in the inner region of the tracking system





Current Detector

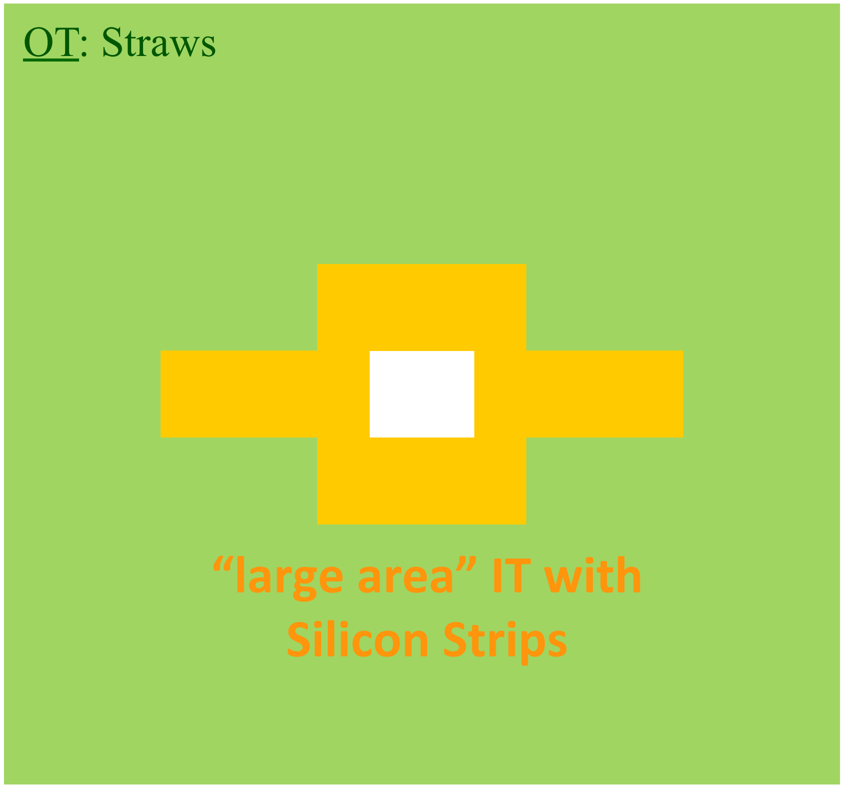


Note:

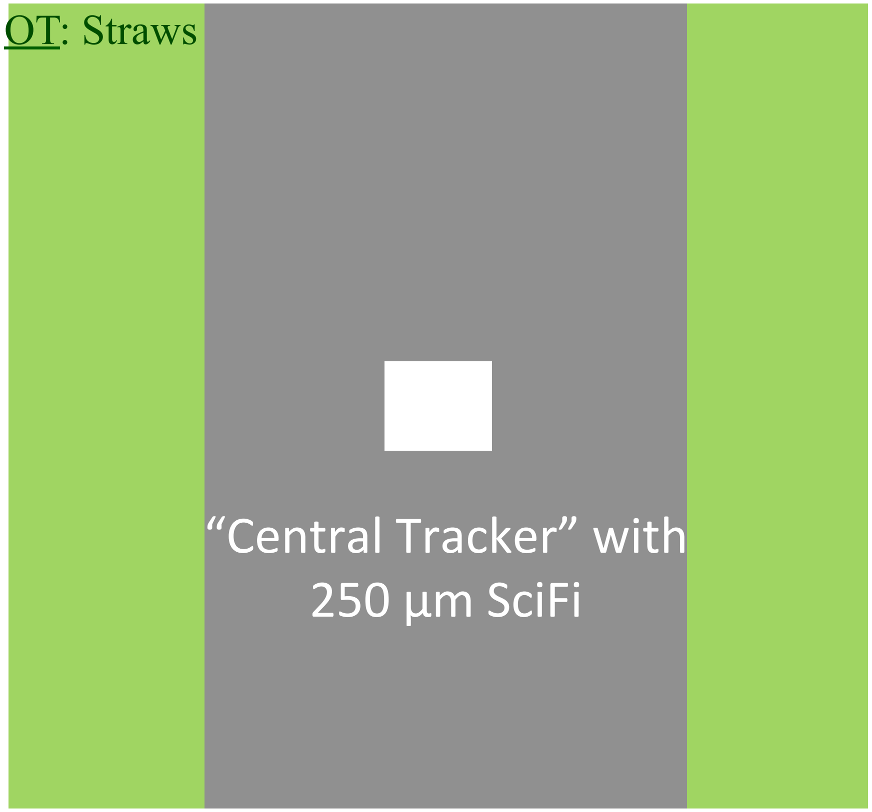
- LHCb have been running already at pileup μ ~ 2.5
- The current geometry limiting to $\mathcal{L} \leq 10 \cdot 10^{32}$ cm^{-2}s^{-1}
- No safety margins.

Tracker options

Silicon Strip Inner Tracker

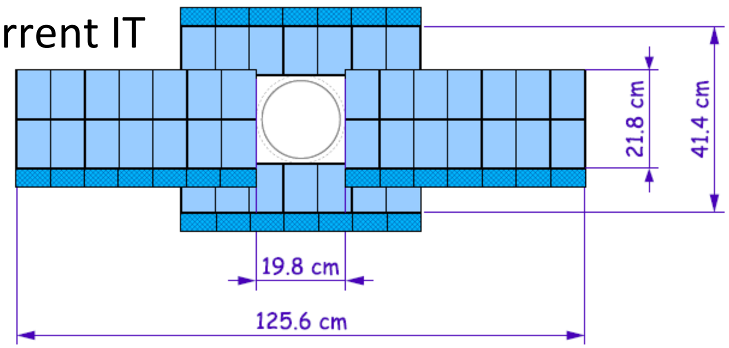


250 µm Scintillating Fiber
"Central Tracker"

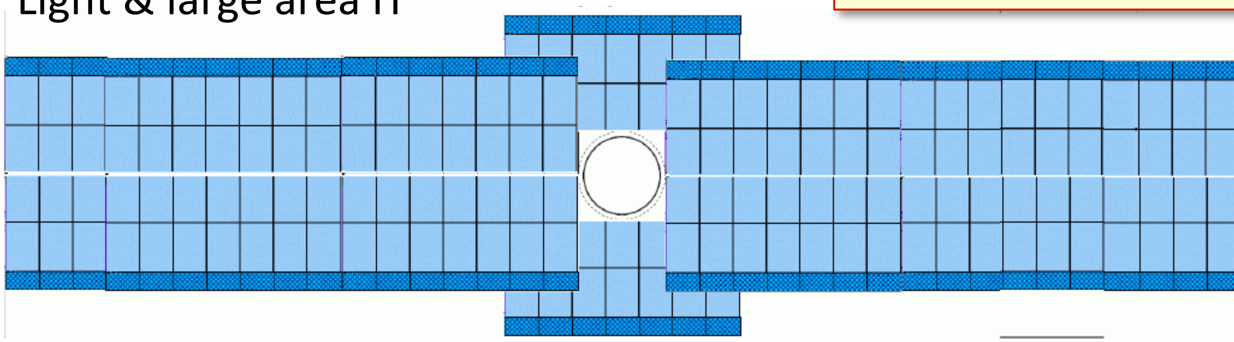


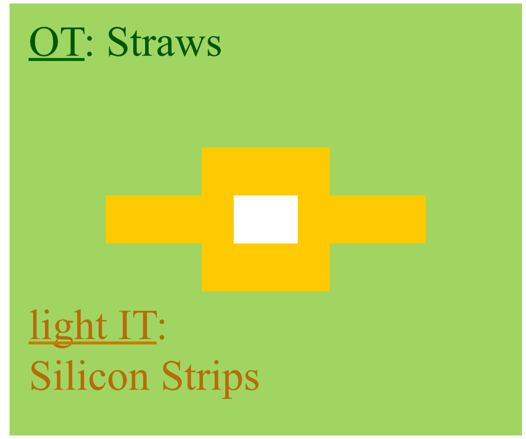
Large area IT with Silicon strips

Current IT



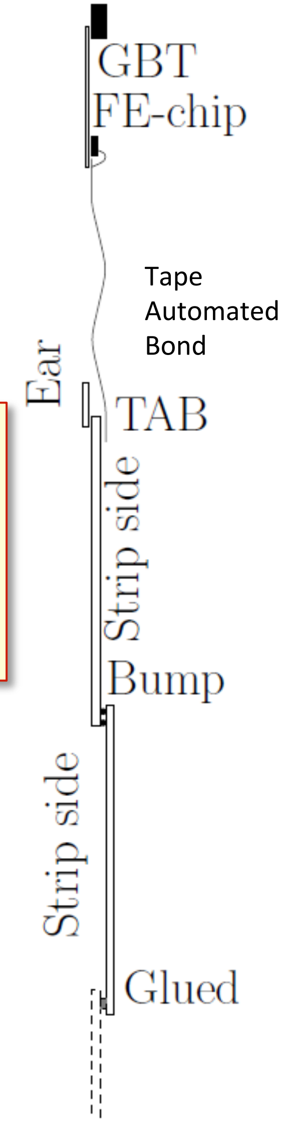
Light & large area IT





Effort started

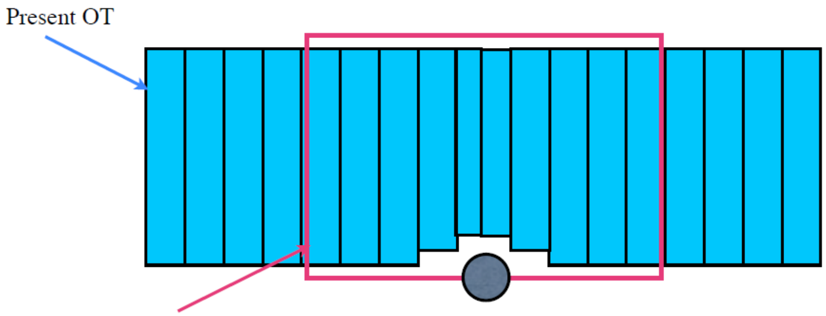
- strip chip design
- cooling proof of concept (air flow)
- received 10 sensors for testing TAB, module assembly, HV, etc.



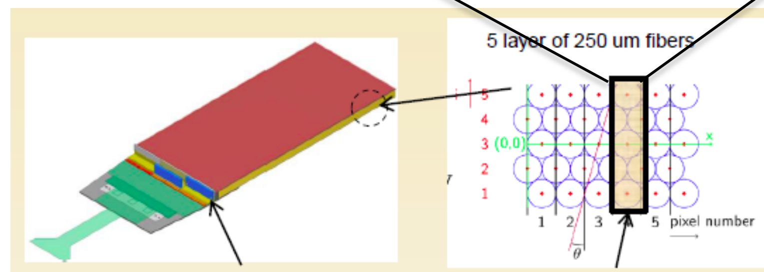
- light: reduce X/X0 ~ 2
- large: increase area by ~ 3.3-4 : from 126x22(42)cm to 255x42(63)cm
- optimise station layout: now 3x(xuvx)=12 layers in-front of T3 to 2x(xuxvx)=10 layers behind T1 & T3

Fiber Central Tracker

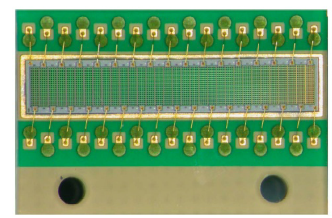
32 channels Si PM: 0.25 x 1 mm^2
128 channels SiPM available

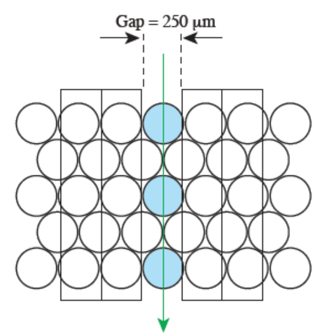


Replace the central part with a fiber detector, with 250 µm fibers. Assume a coverage 3x2.5m^2



- 5 layers of densely packed 250µm diameter fibers
- readout with 128-channel Silicon Photomultipliers (SiPM)
- 2×2.5m long fibers, readout on top and at bottom of stations



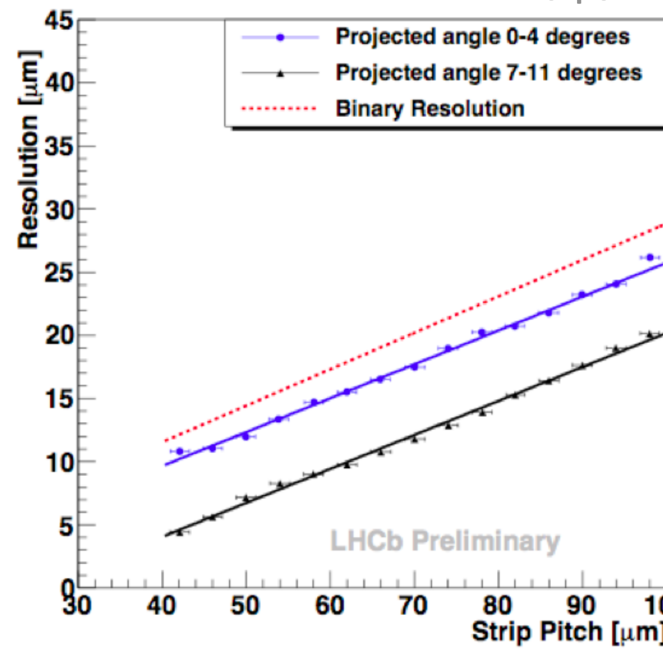


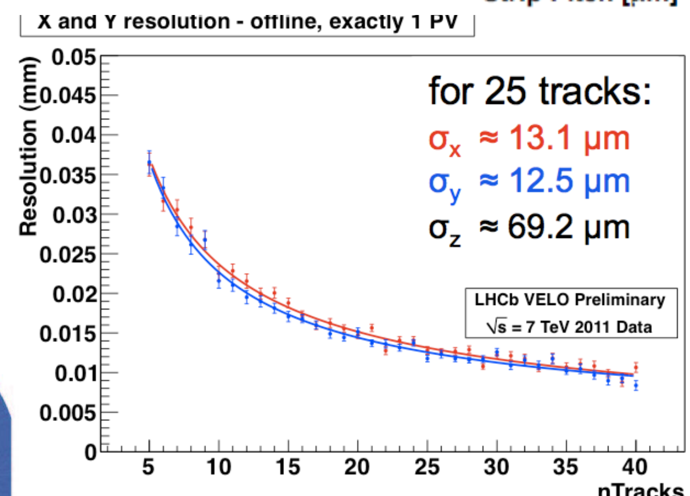
Advantages:
- only sensitive material in acceptance (no cables, no cooling, ...)
- uniformity in material distribution
- 50-60 µm resolution (to be demonstrated with test beam data)

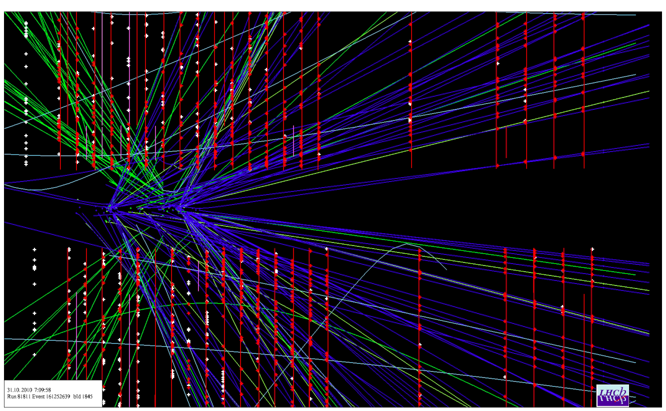
The VELO detector

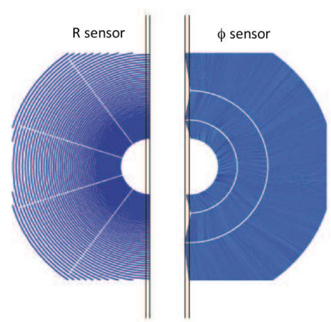
- Silicon strip detector with 24 back to back modules: strips in radial and angular directions, **readout at 1 MHz**.
- Proximity to proton beams: 7mm
- Detector sits in vacuum in high radiation environment.
- The whole thing moves …

IP resolution ~ 13 + 25/p_T µm

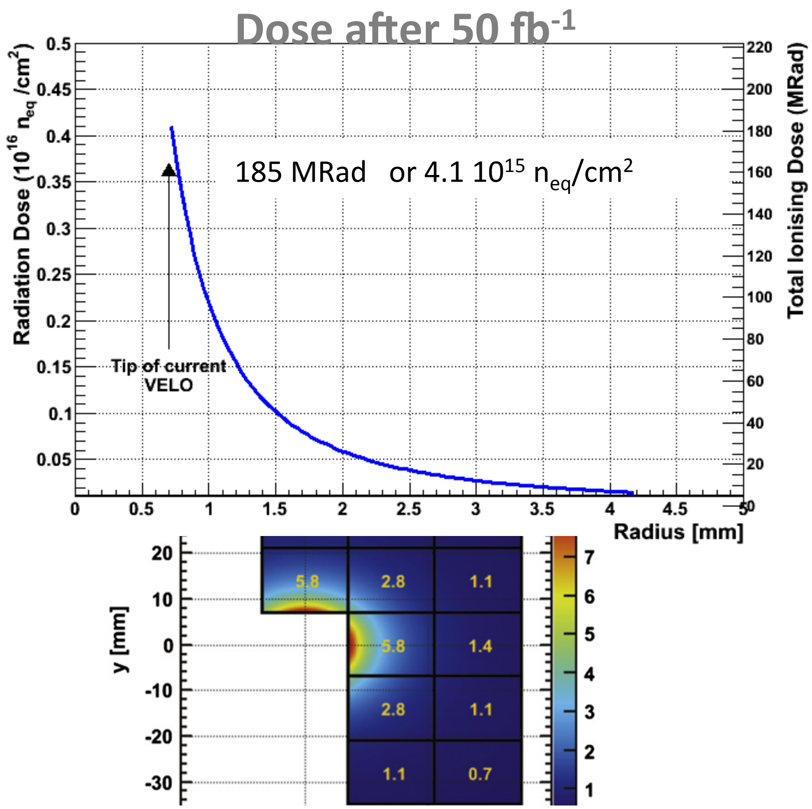




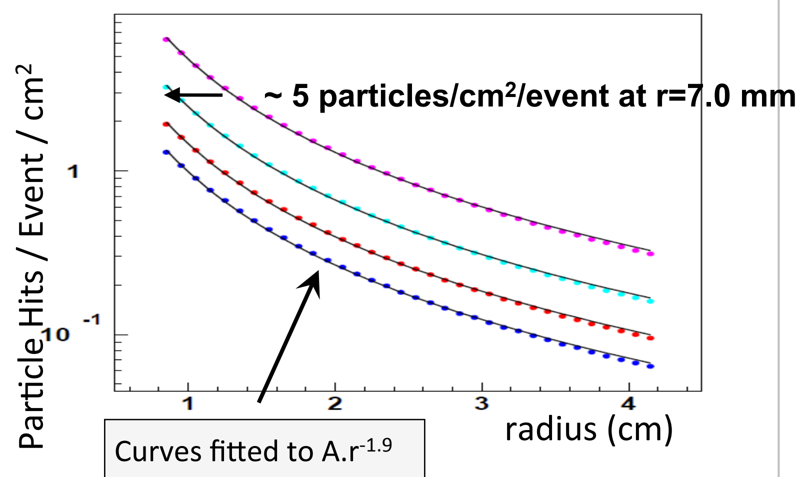




VELO upgrade: requirements



Particle occupancy per event



Luminosity ($cm^{-2}s^{-1}$)	2.10^{32} Current	5.10^{32}	**10.10^{32}**	20.10^{32}
A=	0.98	1.46	**2.46**	4.80

Rad-hard up to ~ 5×10^{15} 1 MeV $n_{eq}cm^{-2}$

Electronics has to digitize, zero suppress and transmit event data at 40 MHz.

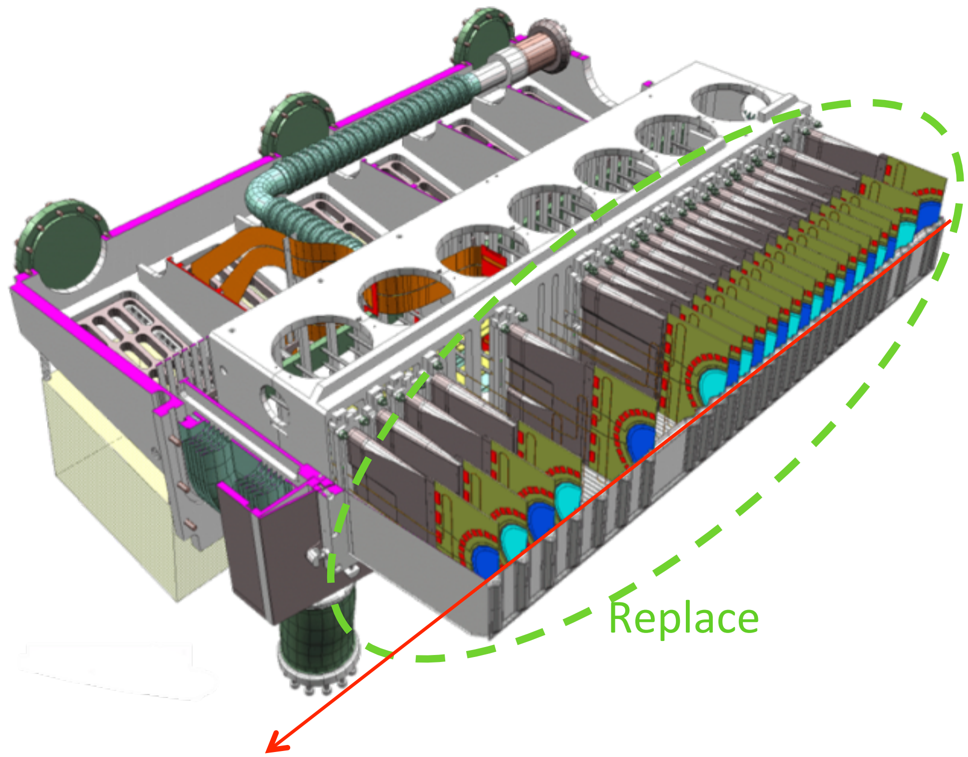
The total data rate is approximately 2.8 Tb/s.

The occupancy of the VELO is miniscule, but the data rate is rather high:

1 chip O(1cm^2) has to transmit ~13 Gb/ s

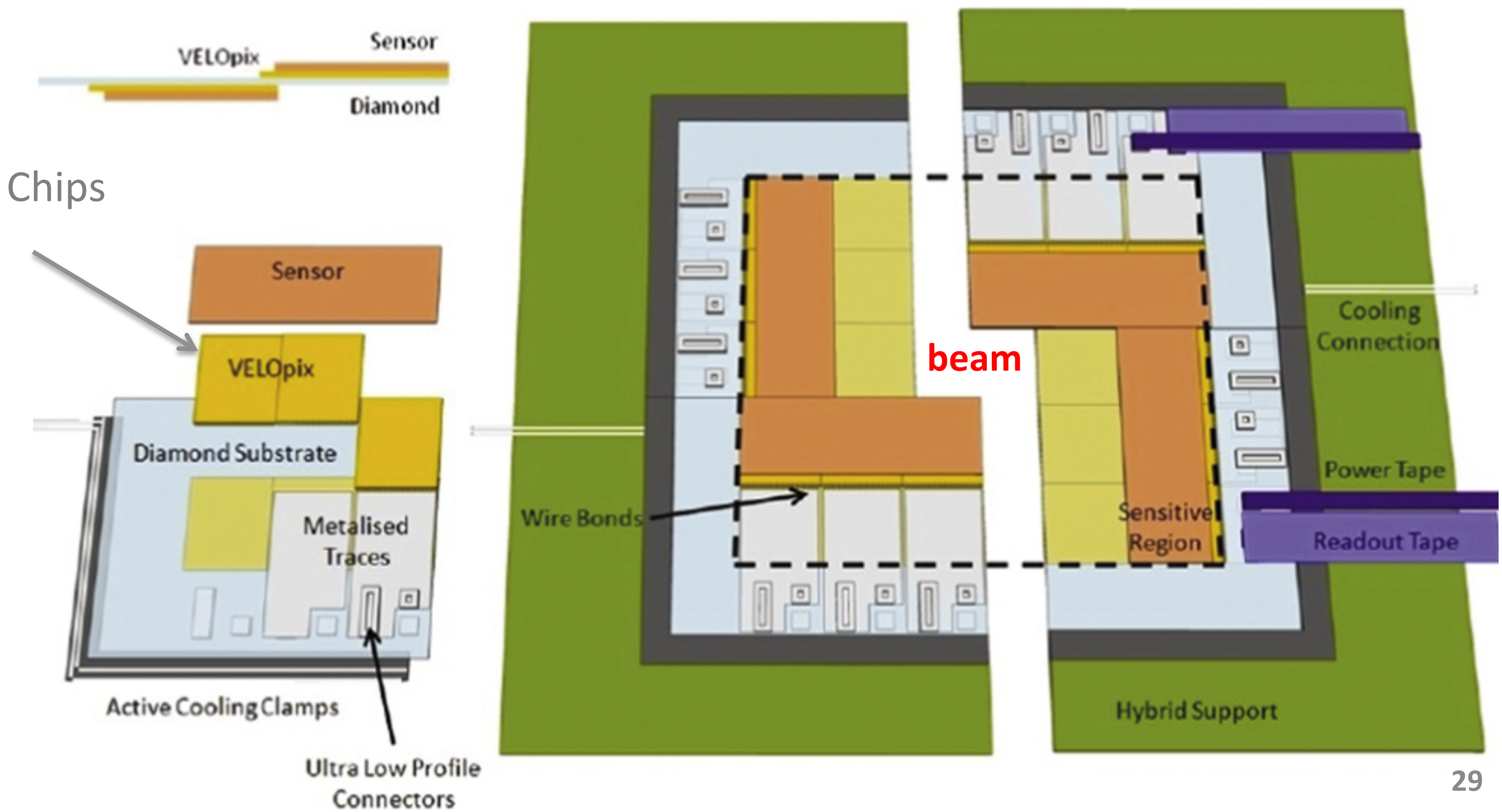
VELO Upgrade plan

- Different systems of the current VELO will be retained:
  - CO_2 cooling plant
  - LV & HV power supply systems
  - Vacuum vessel and equipment
  - Motion system
- Major new components:
  - Detector modules based on pixel sensors
  - New readout ASIC: ´**VELOPIX**´
  - Enhance module cooling interface
  - New design of low material RF foil between beam and detector vacua
  - Multi Gb s^{-1} readout system
- Main design concerns:
  - Efficient cooling to avoid thermal runaway
  - Handle the huge data rate
  - Reduce material budget
  - Maintain if not improve the excellent performance[2]:
    - Proper time resolution ~ 50 fs
    - IP resolution ~ 13 + 25/pT µm



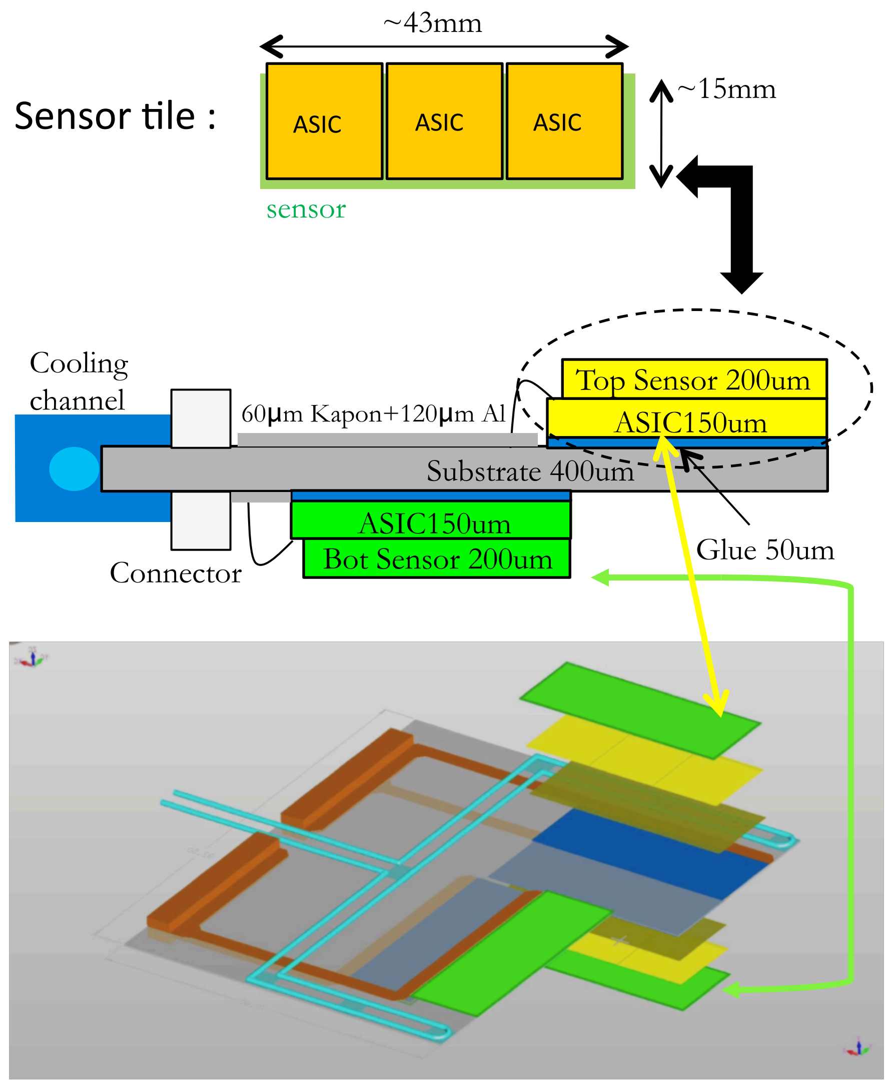
VELO upgrade

26 modules equipped with hybrid pixel sensors, arranged around the beam axis, each consisting of four 3-chip pixel ladders assembled in an L-shaped arrangement on alternating sides of a diamond substrate, which acts as a cooling interface



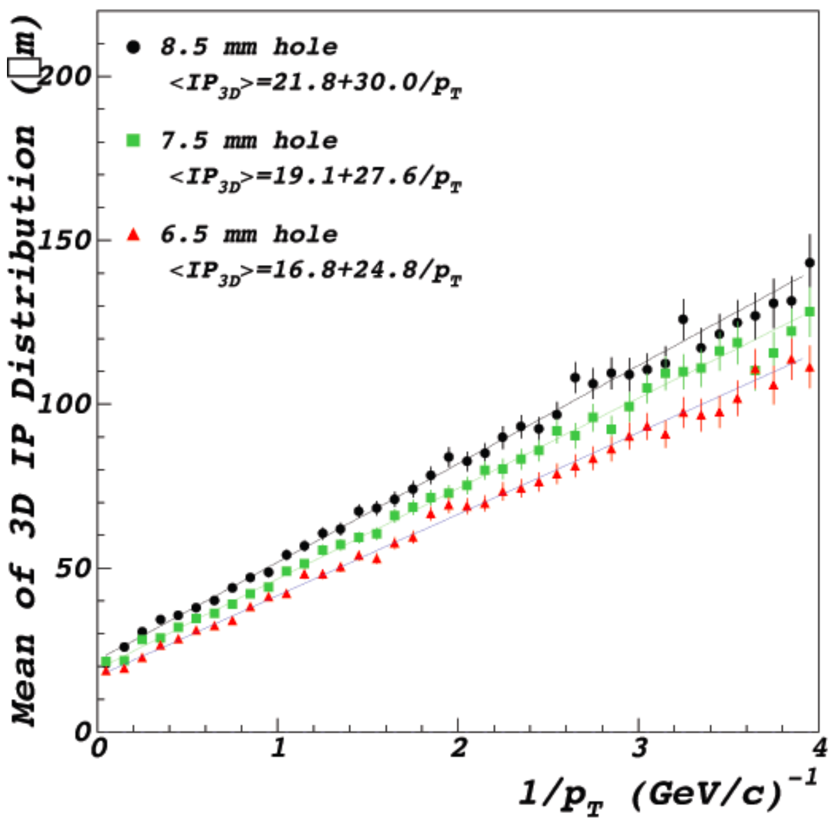
Velo Pixel module

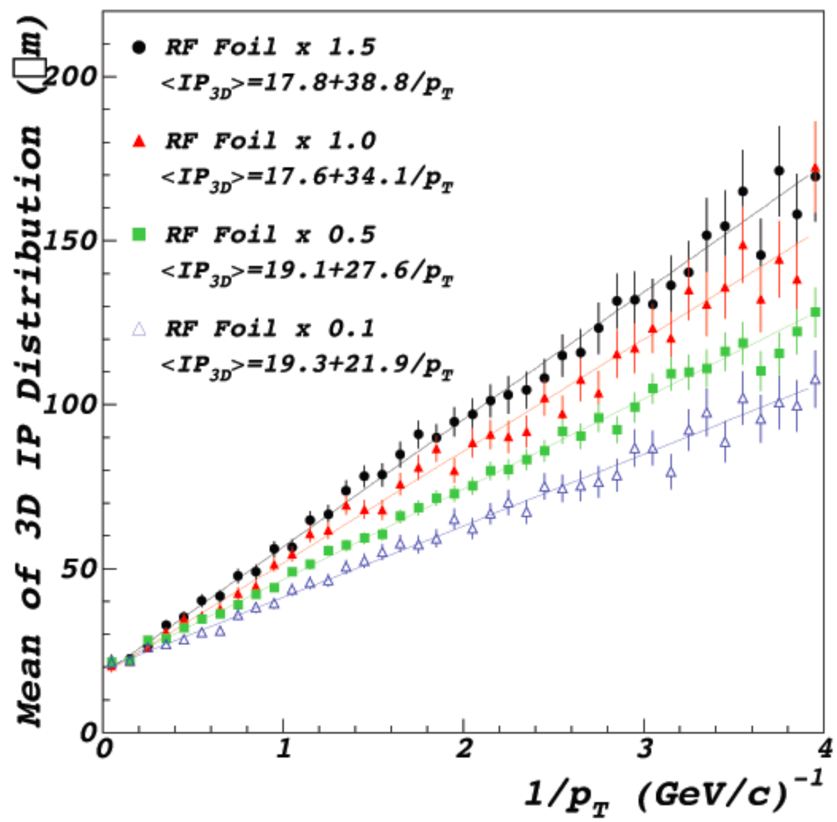
- Sensor tiles: 3 readout ASICs on a single sensor, with a guard ring ~500 µm
- 2 sensor tiles are mounted on opposite sides of a substrate:
  - Readout & power traces on the substrate
- Substrate choices:
  - CVD diamond : excellent mechanical & thermal properties: => low mass
  - Carbon fibre/TPG or Al/TPG
- Material in sensitive region ~ 0.8%X_0
- Prototype work started using Timepix ROCs (@ CNM).



VELO Upgrade

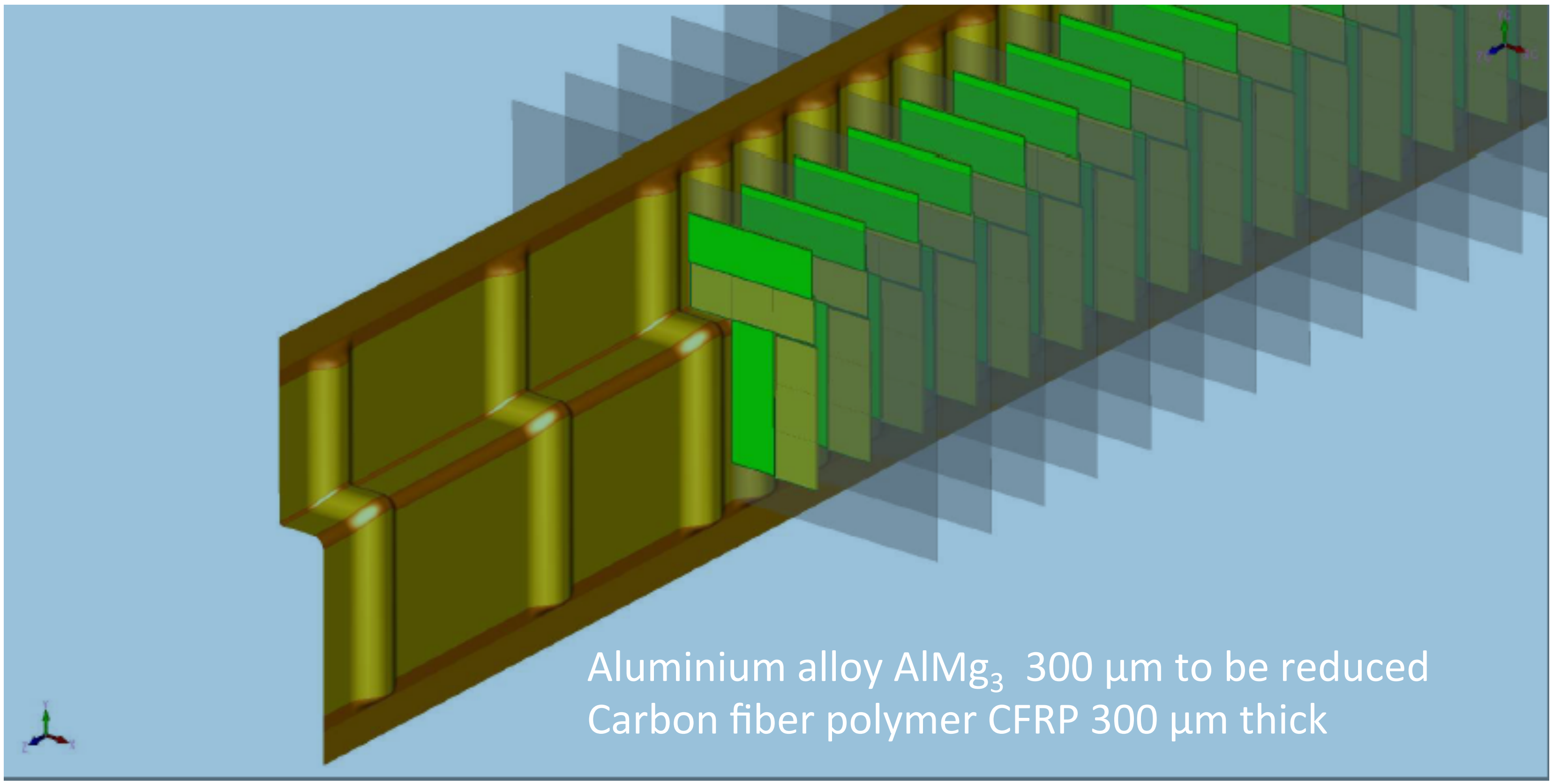
$$\sigma_{\mathrm{IP}}^2 = \frac{r_1^2}{p_{\mathrm{T}}^2\sqrt{2}}\left(0.0136\sqrt{\frac{x}{X_0}}\left(1+0.038\ \ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2 + \Delta_{01}^2\sigma_2^2}{\Delta_{12}^2}$$



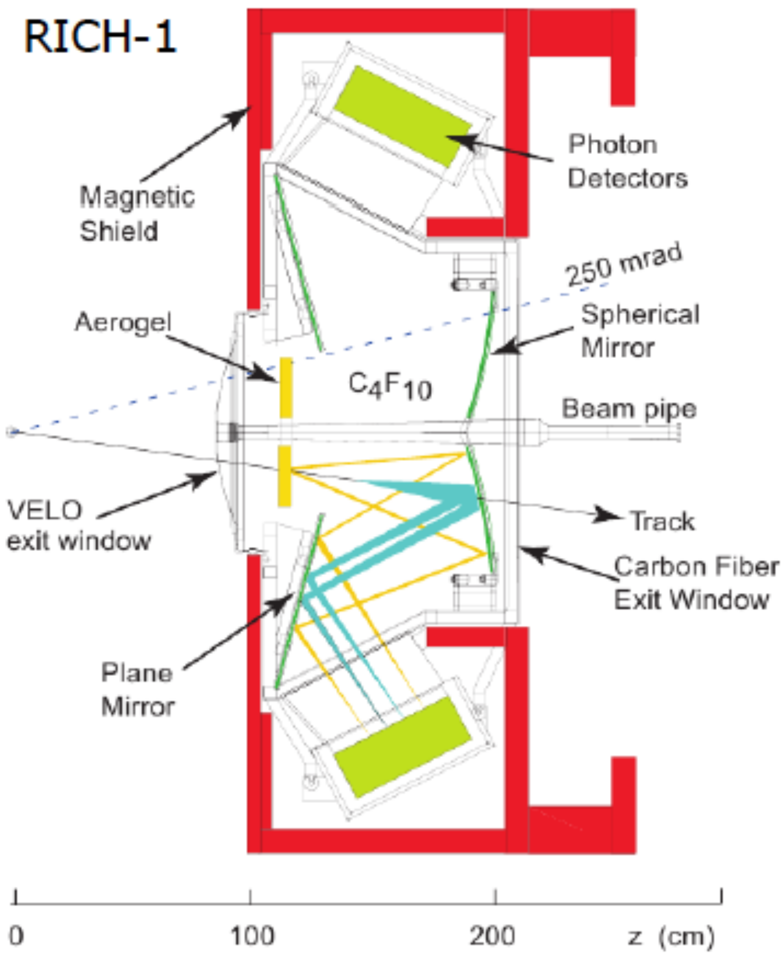


VELO upgrade

Thickness of RF foil is a critical item for the performance of the upgraded detector



RICH upgrade



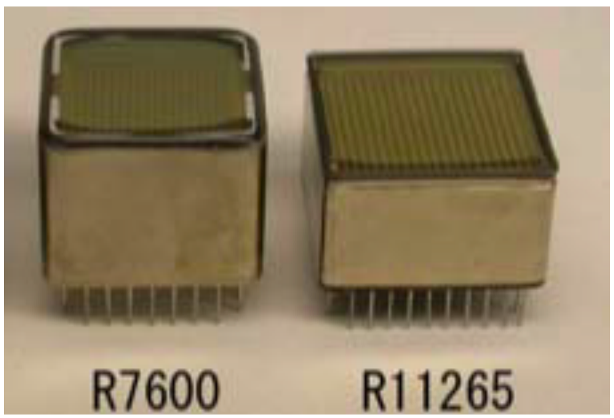
- RICH-1 and RICH-2 remains:
  - Replace HPD by MaPMT readout by a 40 MHz chip (MAROC-3 or custom)
  - Remove aerogel not exploitable at 10^{33} $cm^{-2}s^{-1}$

    Will be replaced by a time-of-flight detector TORCH.

RICH upgrade

RICH-1 and RICH-2 detectors are retained, replace pixel HPDs with 1 MHz readout chip integrated by MaPMTs and readout with 40 MHz custom ASIC.

MaPMTs(Hamamatsu)



R7600 vsR11265 :

8x8 pixels, 2.0x2.0 mm^2, 2.3 mm pitch (2.9 mm)

18.1x18.1 mm^2active area (23.5x23.5 mm^2)

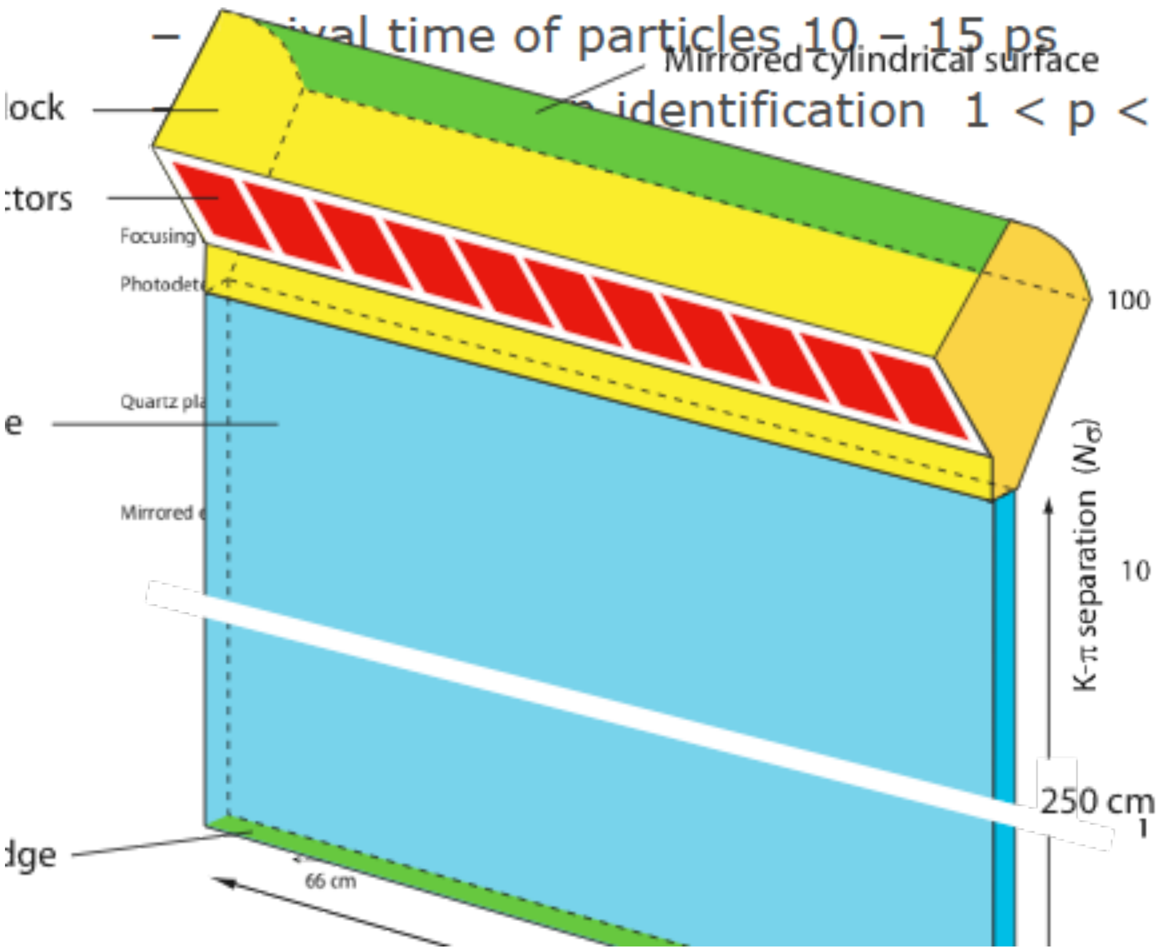
CE (simulation) : 80% (90%)

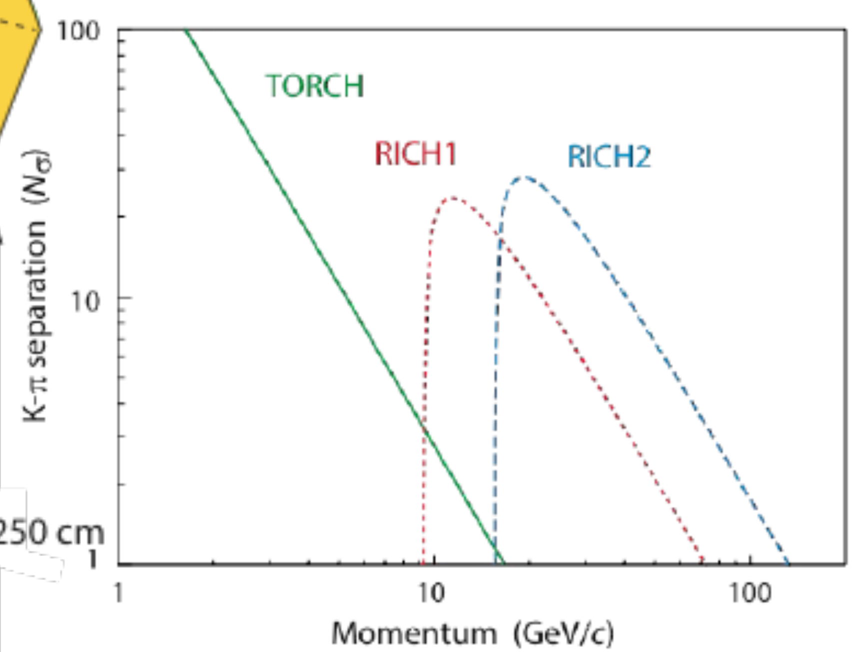
Fractional coverage: 50% (80%)Prototyping using 40 MHz Maroc-3 R/O chipGain compensation

Binary output

TORCH detector

- Novel detector:
  - TOF of Cerenkov photon generated in 1 cm thick quartz plate
  - Photon detector Micro Channels Plate
  - ival time of particles 10 – 15 ps
  - identification $1 < p < 10$ GeV





PID upgrade: RICH detectors

- RICH-1 and RICH-2 detectors are retained, replace HPDs (1 MHz internal Readout):
  - Baseline readout: replace pixel HPDs by MaPMTs & readout with 40 MHz custom ASIC

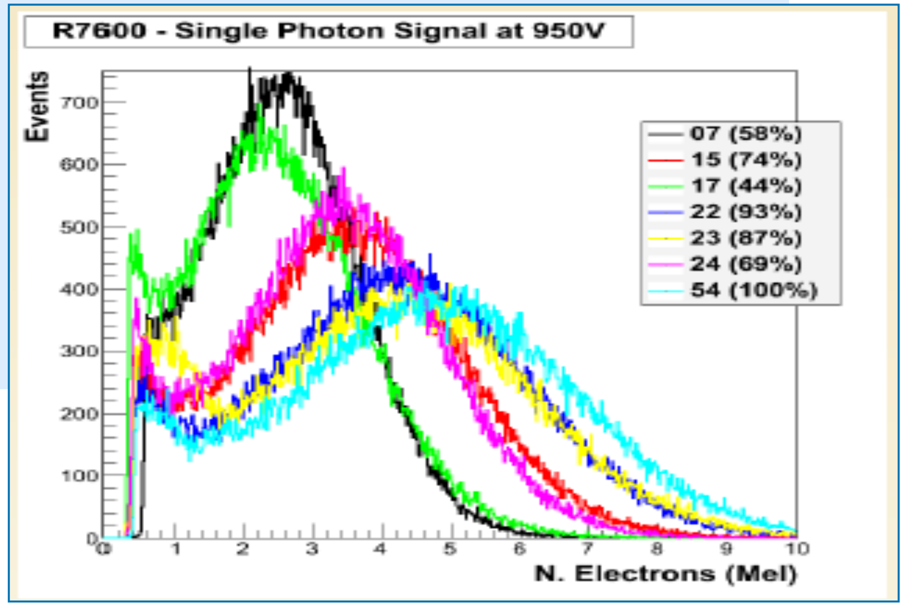
- Baseline MaPMTs (Hamamatsu):

R7600 vs R11265 (baseline):

8x8 pixels, 2.0x2.0 mm^2, 2.3 mm pitch (2.9 mm)
18.1x18.1 mm^2 active area (23.5x23.5 mm^2)
CE (simulation) : 80% (90%)
Fractional coverage: 50% (80%)

Prototyping using 40 MHz Maroc-3 RO chip:
- Gain compensation
- Binary output

Digital functions in ACTEL Flash FPGA FE module.



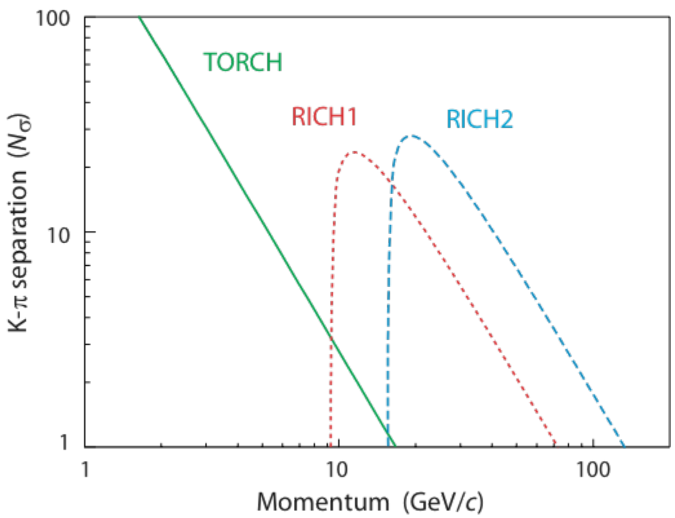
R7600 characterization:
- Channel to channel gain variation (correction in FE)
- Excellent cross-talk (below 1%)
- ~10% gain reduction in 50 gauss B_L-field (25 gauss max B_L-field in LHCb)

3712 R7600/R11265 units for RICH1&2 ~238k #

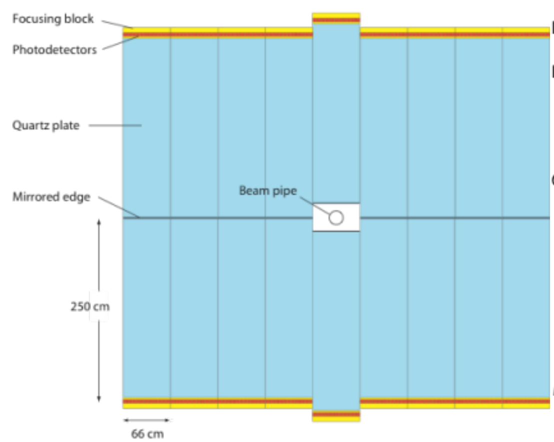
PID upgrade: TORCH

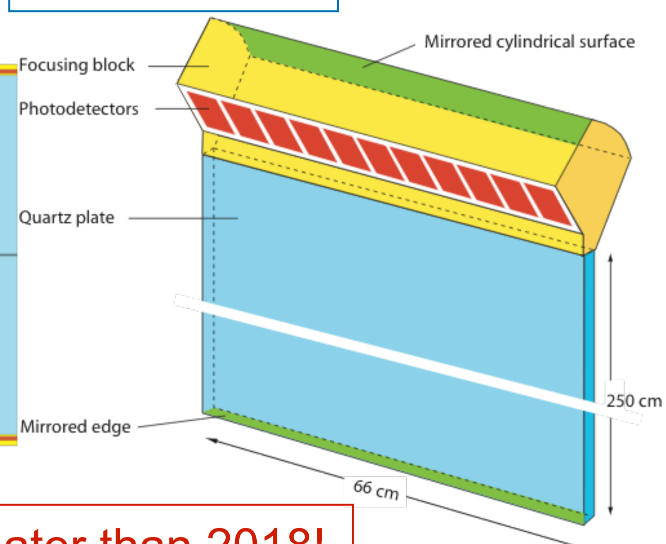
- Time of Flight detector based on a 1 cm quartz plate, for the identification of p<10 GeV hadrons (replacing Aerogel) combined with DIRC technology:
  - TORCH=Time Of internally Reflected Cherencov light*
  - reconstruct photon flight time and direction in specially designed standoff box
  - Measure ToF of tracks with ~15 ps (~70 ps per photon)

K-π separation vs p in upgrade:



TORCH detector:





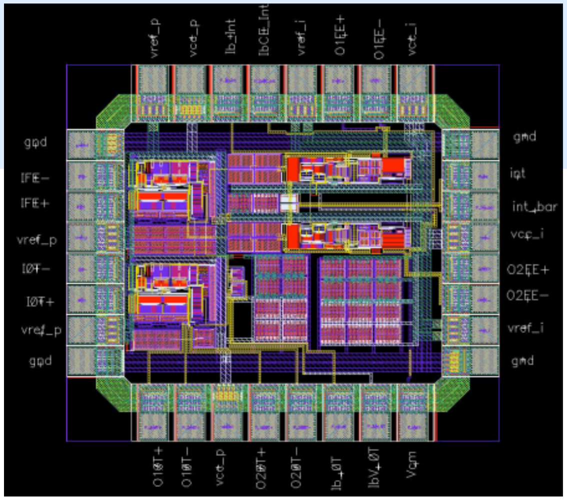
→ could be installed later than 2018!

* See talk by Neville Harnew

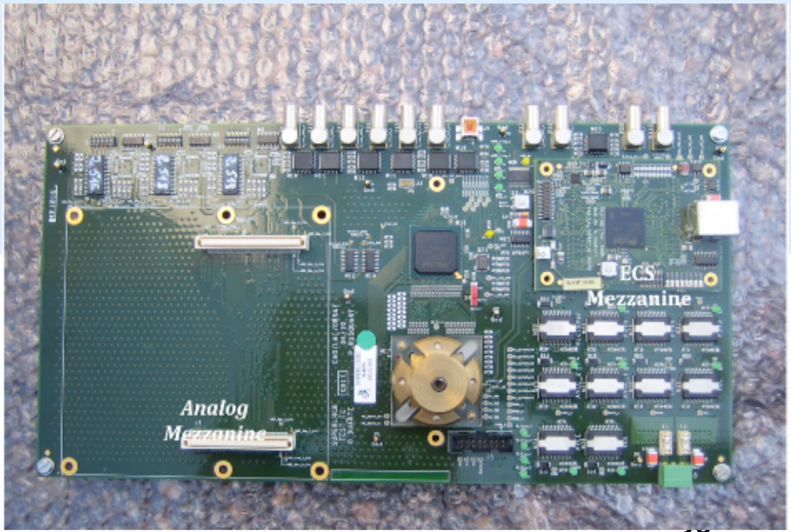
Calorimeters Upgrade

- ECAL and HCAL remain
  - Keep all modules & PMTs
    - Radiation tolerance of inner modules being assessed @ LHC tunnel
  - Reduce the PMTs gain by a factor 5 to keep same <current>
- PS and SPD might be removed (under study)
  - (e/γ/hadron separation later in HLT with the whole detector info.)
- <u>New FEE to compensate for lower gain and to allow 40 MHz readout:</u>
  - Analogue part: ASIC or Discrete* components solutions (keeping noise ≤1 ADC cnt (ENC < 5-6 fC))
  - Digital part: prototype board to test FPGAs (flash/antifuse) for:
    - Radiation tolerance
    - Packing of Data @ 40 MHz

ASIC prototype



New digital electronics prototype



- The current system was designed in order to stand incident particle rates up to 1 MHz per front-end channel without any loss of efficiency due to space charge effects and without any degradation of the time resolution.

Muon Detector Upgrade

- Muon detectors are already read out at 40 MHz in current L0 trigger
  - ➢ Front-end electronics can be kept
  - ➢ Remove detector M1 (background and upgraded L0(LLT), room for TORCH)
- Investigations:
  - ➢ MWPC aging :
    - ➢ tested at two sites up to 0.25 C/cm and 0.44 C/cm with no loss of performance
    - ➢ 1C/cm is considered as an upper limit for safe operation of MWPC chambers
  - ➢ Rate limitations of chambers and FE:
    - ➢ High-rate performance tested @ CERN-GIF no saturation effect up to 30nA/cm^2 (factor 2 for 10^{33})
    - ➢ No deterioration in the FE electronics up to 1MHz

Accumulated charge (C/cm) for 50 fb^{-1}

	R1	R2	R3	R4
M2	0.67	0.42	0.10	0.02
M3	0.17	0.08	0.02	0.01
M4	0.22	0.06	0.01	0.004
M5	0.15	0.03	0.01	0.003

R

Z

Maximum rates/channel MHz @ 10^{33} cm^{-2}s^{-1}

	R1	R2	R3	R4
M2	0.81	0.55	0.12	0.10
M3	0.24	0.11	0.03	0.04
M4	0.09	0.07	0.04	0.03
M5	0.07	0.07	0.04	0.02

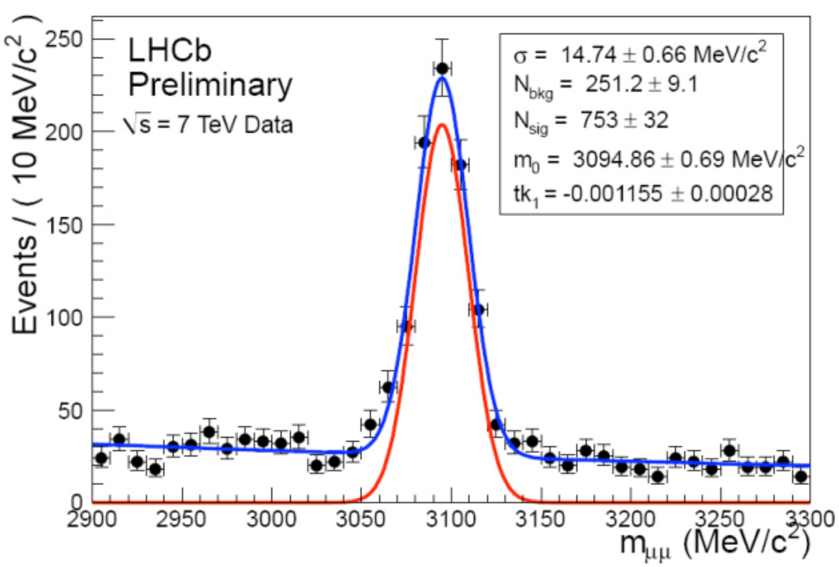
R

Z

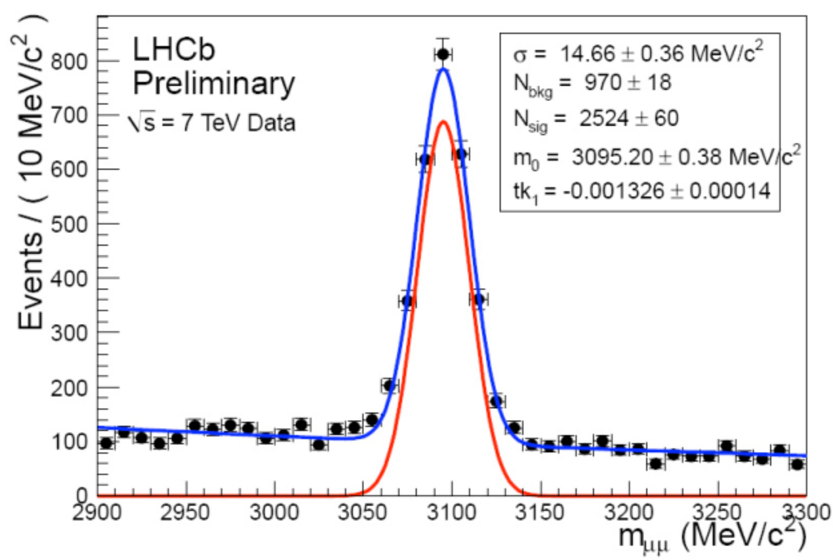
Muon Detector Upgrade

- Performance at higher occupancy: OK
  - ➢ Studied with real data July-October 2010 <PV> ≥ 2.
  - ➢ After retuning the Muon ID algorithm the J/ψ :
    - Worsening S/B ≤ 15%
    - Efficiency loss ≤ 5%

J/ψ → $\mu^+ \mu^-$ for single PV events



J/ψ → $\mu^+ \mu^-$ for events with <PV>=2.3



Interests to sub-systems

Subsystem	BRASIL	CHINA	FRANCE IN2P3	GERMANY BMBF	GERMANY MPG	ITALY INFN	NETHERLANDS	POLAND	ROMANIA	RUSSIA	SPAIN	SWITZERLAND	UK	UKRAINE	CERN	IRELAND	USA
VELO	x	x					x	x		x	x		x		x		x
SiStrip-TT								x									x
SiFi-CT		x	x	x						x	x	x	x		x		
large SiStrip-IT	?							x		x					x		
short OT modules				x			x										
OT electronics				x			x	?									
RICH						x							x		x		
Calo electronics			x								x						
Muon system						x				x					x		
Tell40 & LLT	x	x	x			x									x		
DAQ & CPU 10MHz ECS & TFC GBT Infrastructure Computing	Common Projects																

Common fund part amounts to ~ 30%

still evolving …

Sensitivity to key channels

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	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
	$A_{\mathrm{fs}}(B^0_s)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic	$2\beta_s^{\mathrm{eff}}(B^0_s \to \phi\phi)$	–	0.17	0.03	0.02
penguin	$2\beta_s^{\mathrm{eff}}(B^0_s \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K^0_S)$	0.17 [18]	0.30	0.05	0.02
Right-handed	$2\beta_s^{\mathrm{eff}}(B^0_s \to \phi\gamma)$	–	0.09	0.02	< 0.01
currents	$\tau^{\mathrm{eff}}(B^0_s \to \phi\gamma)$	–	0.13 %	0.03 %	0.02 %
Electroweak	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
penguin	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	8 %	2.5 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	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 %	~ 10 %
Higgs	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
penguin	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$ [19]	4°	0.9°	negligible
triangle	$\gamma\ (B^0_s \to D_s K)$	–	11°	2.0°	negligible
angles	$\beta\ (B^0 \to J/\psi\ K^0_S)$	0.8° [18]	0.6°	0.2°	negligible
Charm	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
CP violation	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 $50\,\mathrm{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-neglible for the most precisely measured quantities.