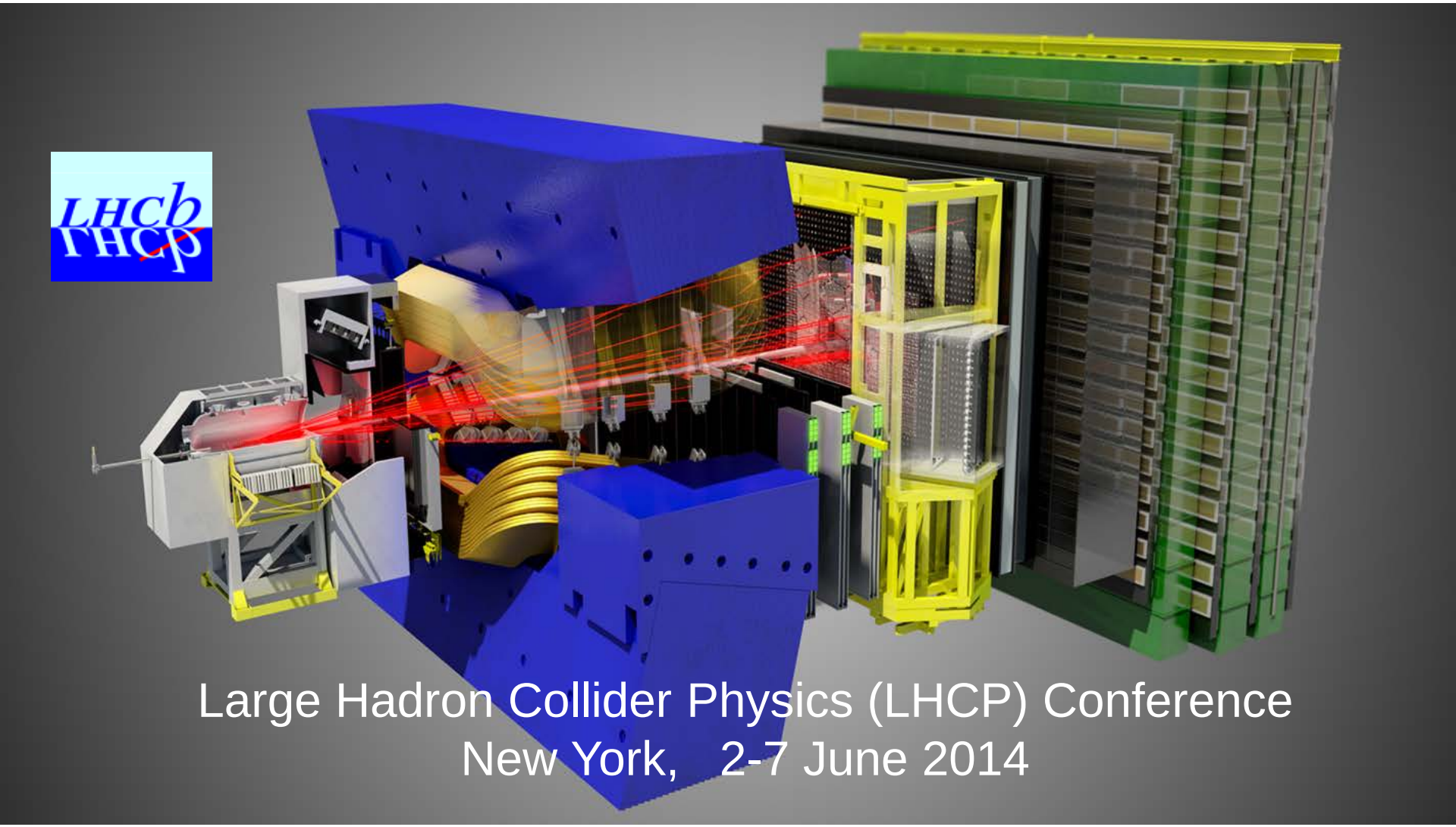
The LHCb Upgrade



Large Hadron Collider Physics (LHCP) Conference
New York, 2-7 June 2014

Andreas Schopper on behalf of

Motivation

LHCb is a high precision experiment devoted to the search for New Physics (NP) beyond the Standard Model (SM) by

- studying CP violation and rare decays in the b and c-quark sectors
- searching for deviations from the SM due to virtual contributions of new heavy particles in loop diagrams
- being sensitive to new particles above the TeV scale not accessible to direct searches

Past and running experiments have shown that:

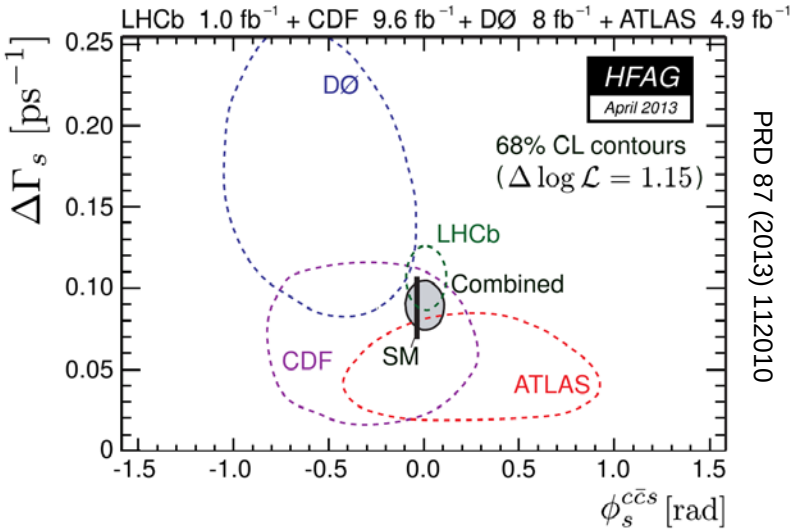
- ✓ flavour changing processes are consistent with the CKM mechanism
- ✓ large sources of flavour symmetry breaking are excluded at the TeV scale
- ✓ the flavour structure of the NP, if it exists, would be very peculiar at the TeV scale (MFV)

However:

- measurable deviations from the standard model are still expected, but should be small
- need to go to very high precision measurements to probe the most clean observables

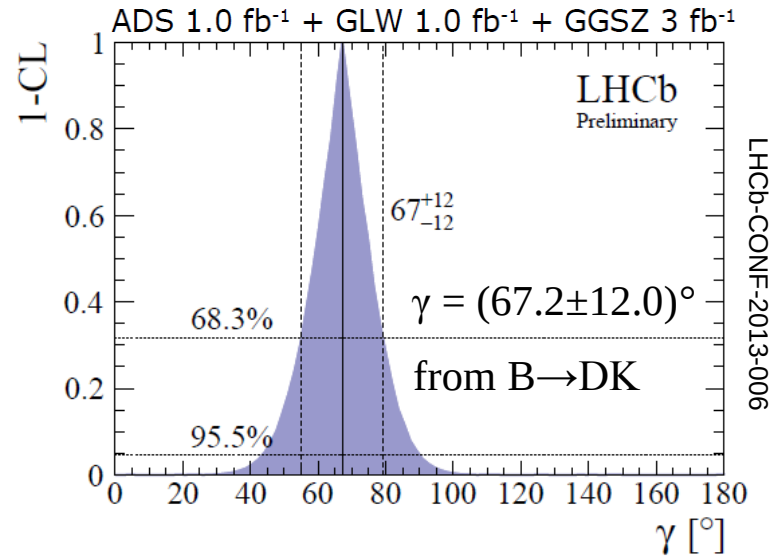
→ LHCb upgrade essential to increase statistical precision significantly

Few highlights of LHCb results

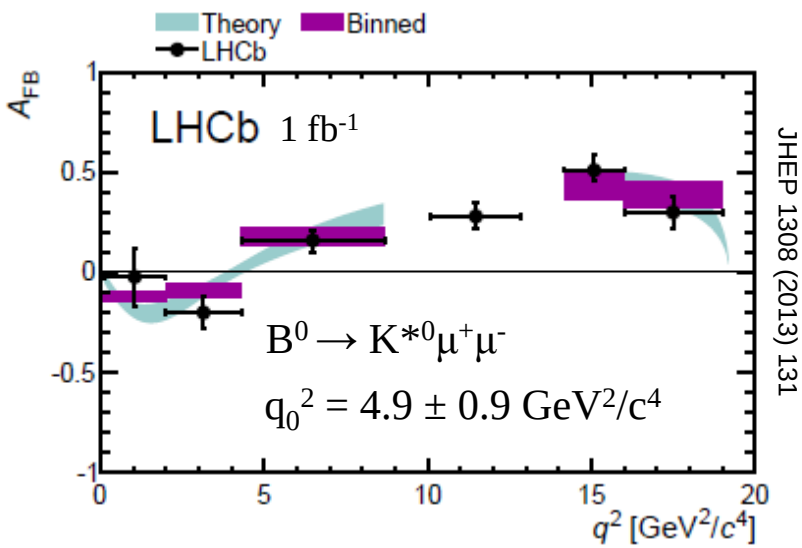


PRD 87 (2013) 112010

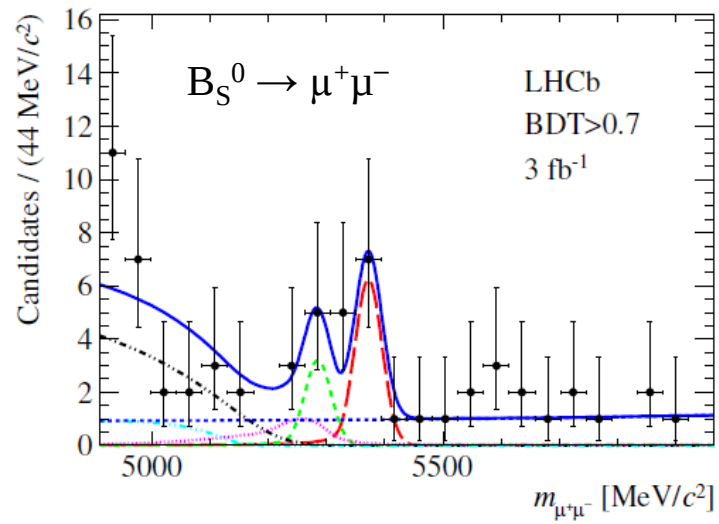
$\Phi_s = 0.01 \pm 0.07(stat) \pm 0.01(syst)$



LHCb-CONF-2013-006



JHEP 1308 (2013) 131



PRL 111 (2013) 101805

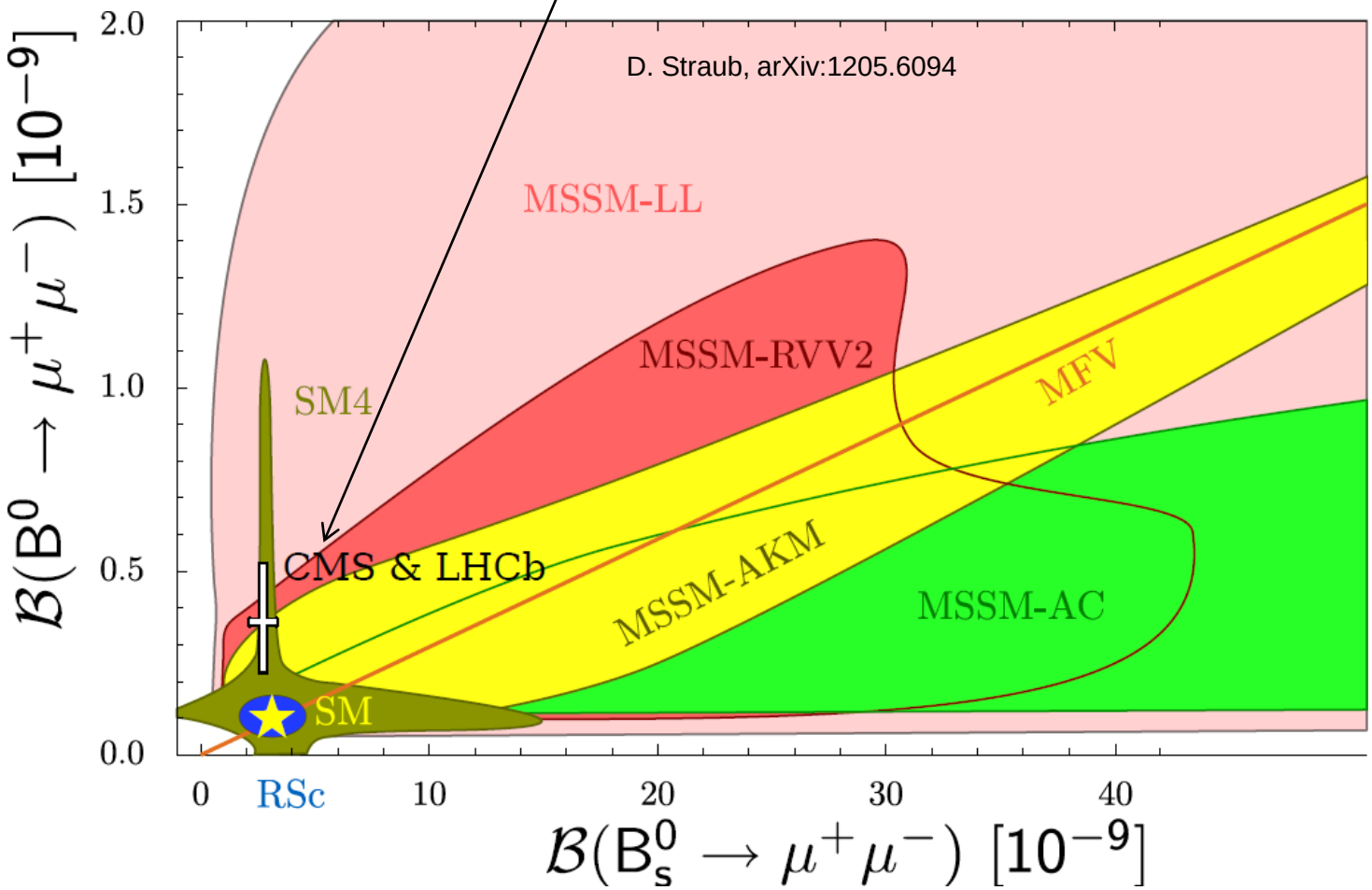
$$BR(B_S^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

Example of impact on Super Symmetric Models

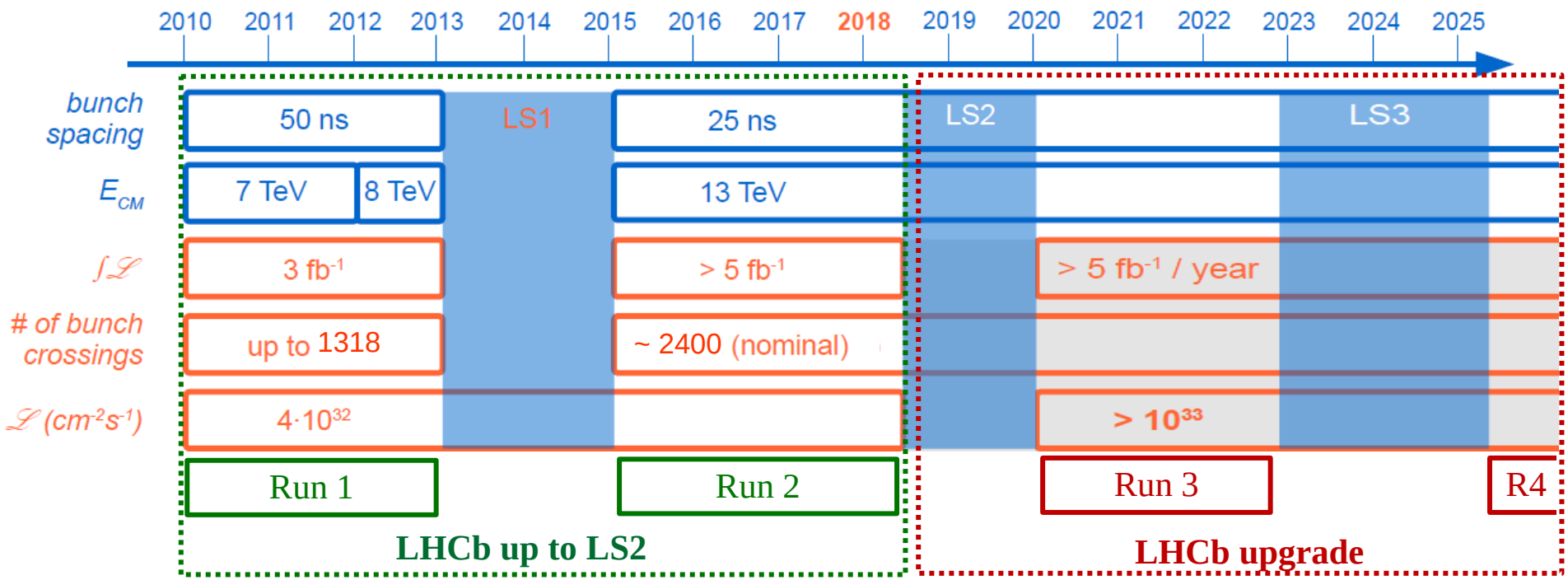
CMS-PAS-BPH-13-007
LHCb-CONF-2013-012

combining
CMS & LHCb →

$$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$
$$BR(B^0_S \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$



Expected evolution of luminosity in LHCb



LHCb up to 2018 → ≳ 8 fb^{-1}:

- ✓ find or rule-out large sources of flavour symmetry breaking at the TeV scale

LHCb upgrade → ≥ 50 fb^{-1}:

- ✓ increase precision on quark flavour physics observables
- ✓ aim at experimental sensitivities comparable to theoretical uncertainties
- ✓ reinforce LHCb as a general purpose forward detector

LHCb statistical sensitivity to flavour observables

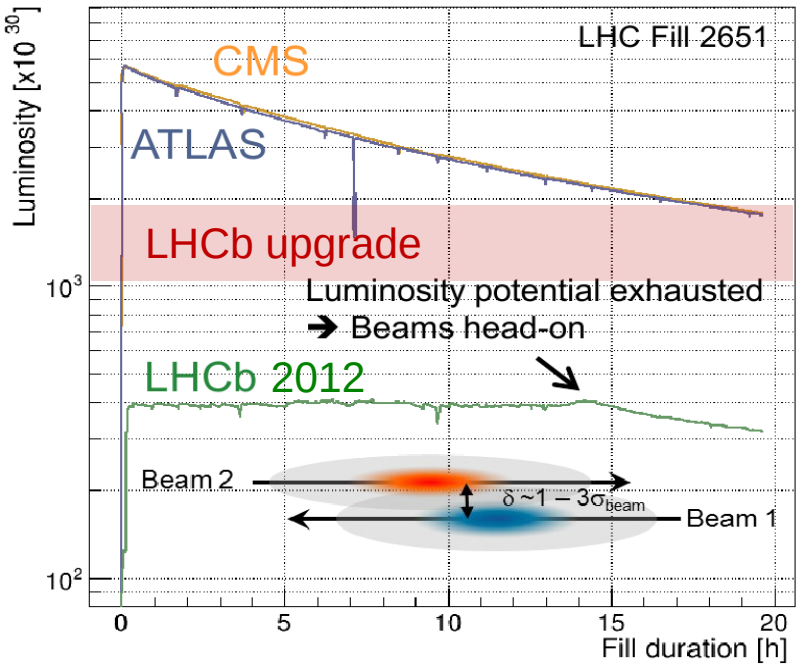
Expected statistical uncertainties on a few selected physics channels before and after the upgrade, compared to theory

	LHCb up to LS2		LHCb upgrade		Theory
	Run 1	Run 2	Run 3	Run 4	Theory uncertainty
Integrated lumi	$3\ fb^{-1}$	$8\ fb^{-1}$	$23\ fb^{-1}$	$46\ fb^{-1}$	
$\frac{Br(B_d \to \mu\mu)}{Br(B_s \to \mu\mu)}$	-	110 %	60%	40%	5%
$q_0^2 A_{FB}(B_d \to K^{*0}\mu\mu)$	10%	5%	2.8%	1.9%	7%
$\phi_s(B_s \to J/\psi\phi, B_s \to J/\psi\pi\pi)$	0.05	0.025	0.013	0.009	0.003
$\phi_s(B_s \to \phi\phi)$	0.18	0.12	0.04	0.026	0.02
γ	7°	4°	1.7°	1.1°	negl.
$A_\Gamma(D^0 \to KK)$	$3.4\ 10^{-4}$	$2.2\ 10^{-4}$	$0.9\ 10^{-4}$	$0.5\ 10^{-4}$	-

From "Heavy Flavour Physics in the HL-LHC era" document prepared for the Aix-les-Bains ECFA Workshop – Oct 2013

How to increase LHCb statistics significantly

2012 running conditions

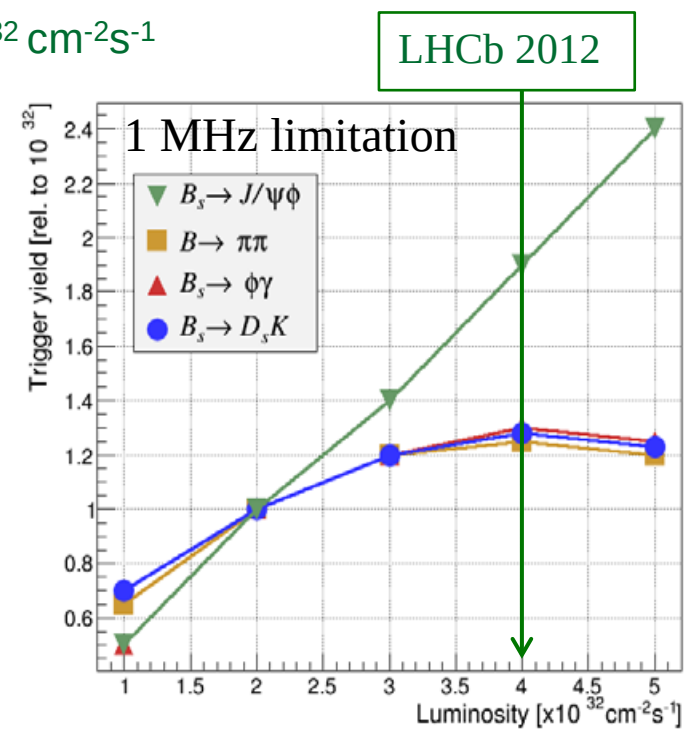


← 1-2·10^{33} cm^{-2}s^{-1}

← ~ 4·10^{32} cm^{-2}s^{-1}

LHCb up to LS2

- running at levelled luminosity of ~ 4·10^{32} cm^{-2}s^{-1}, pile-up~1
- first level hardware trigger running at ~1 MHz
- record ~3-5 kHz



LHCb upgrade →

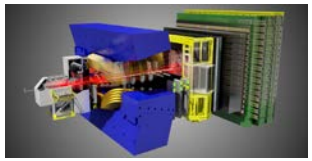
LHCb upgrade

- increase luminosity to a levelled 1-2·10^{33} cm^{-2}s^{-1}, pile-up~5
- run fully flexible & efficient software trigger up to 40 MHz
- record ~20-100 kHz

Trigger upgrade

run an efficient and selective software trigger with access to the full detector information at every 25 ns bunch crossing → increase luminosity and signal yields

upgraded Trigger



30 MHz

↓ inelastic collision rate

Full Software Trigger

LLT (optional)

p_T of h, μ, e, γ

↓ (15 to) 30 MHz

Full track reconstruction

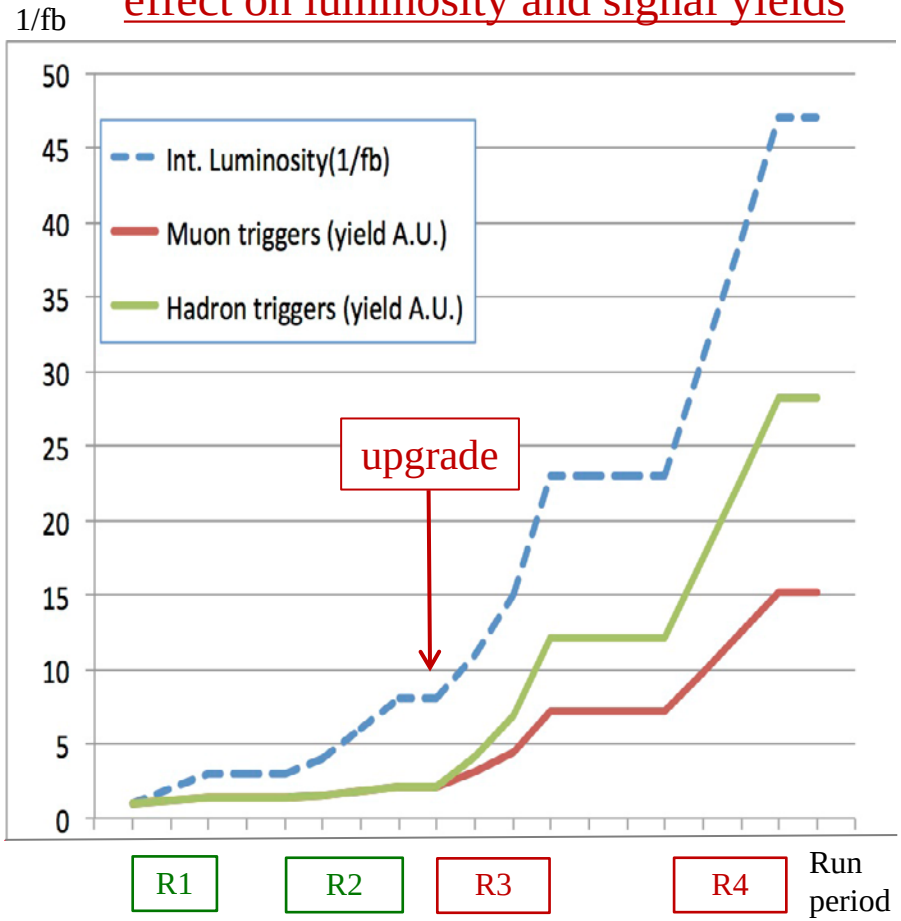
↓ (1 to) 2 MHz

Track fit
RICH particle ID
Inclusive and exclusive selections

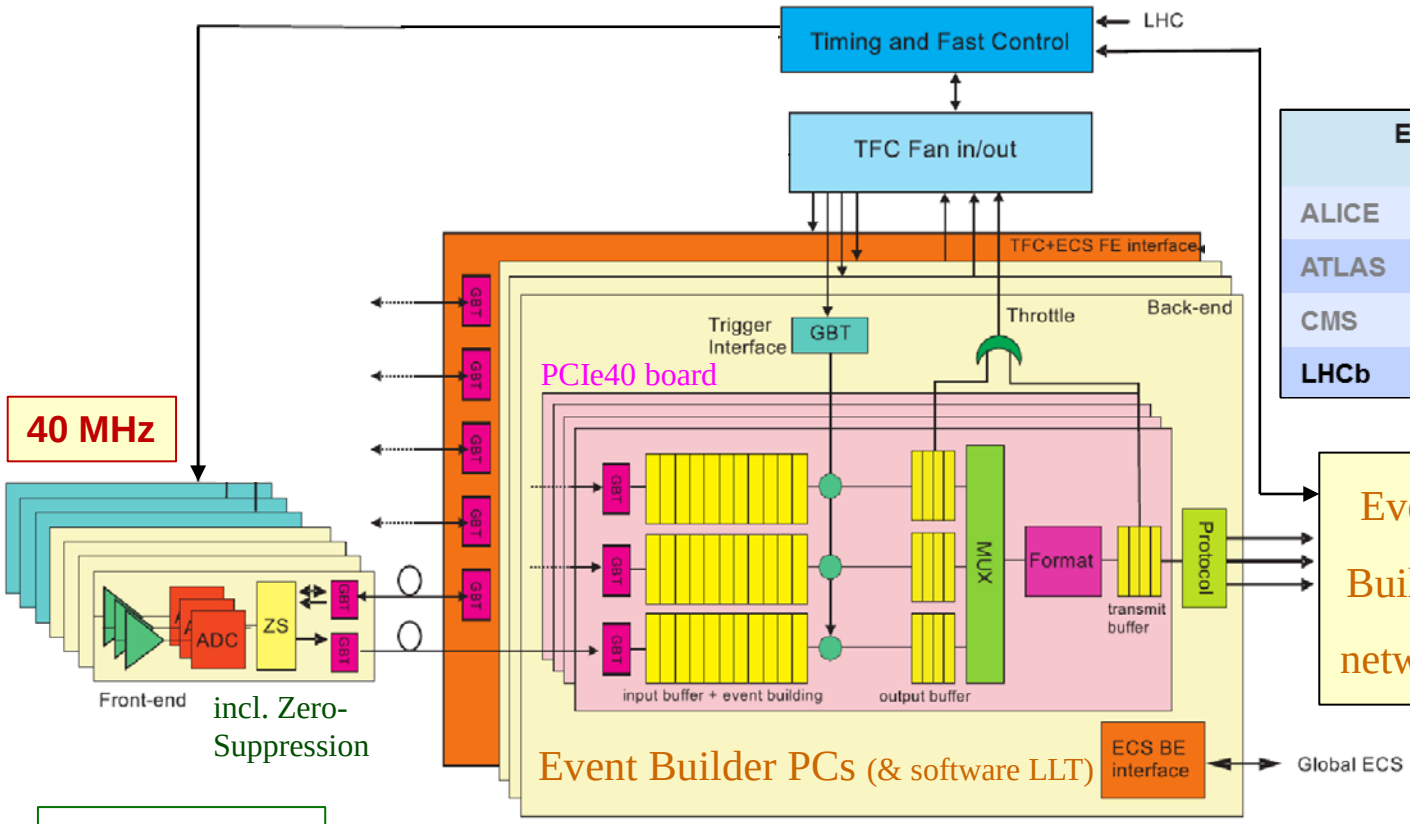
↓ to storage

20 to 100 kHz

effect on luminosity and signal yields



40 MHz architecture overview



[status: ECFA-Workshop 10/2013]

	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year
ALICE	20 000	50	8 000	2019
ATLAS	4 000	200	6 400	2022
CMS	4 000	1000	32 000	2022
LHCb	**100**	**40 000**	**32 000**	**2019**

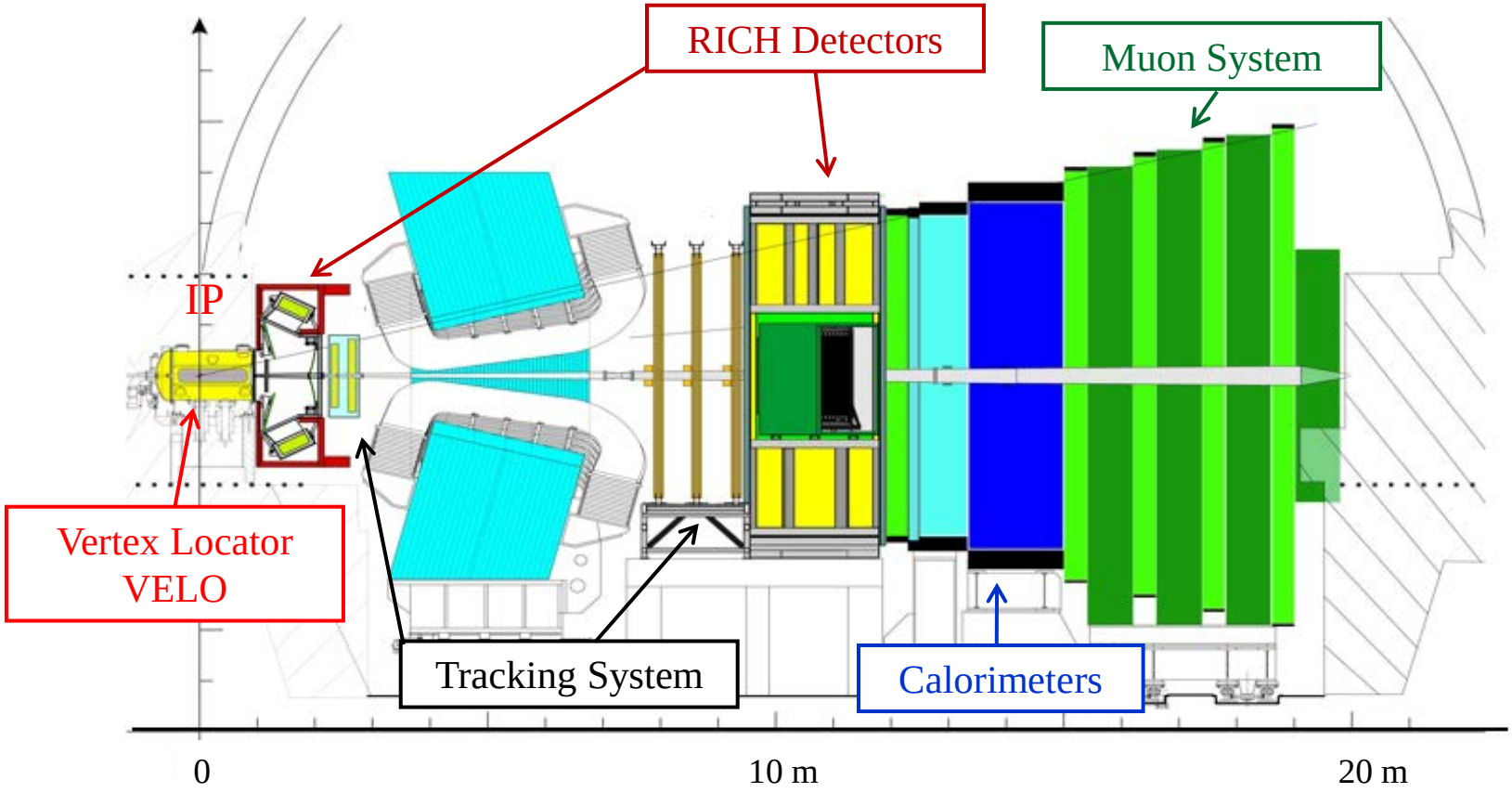
Event Builder network → HLT Farm → **20 KHz**

individual sub-systems Front-End electronics → optical link via GBT → PC servers with PCIe40 R/O LLT and Event Building → pure software trigger

underground | ~300m | on surface

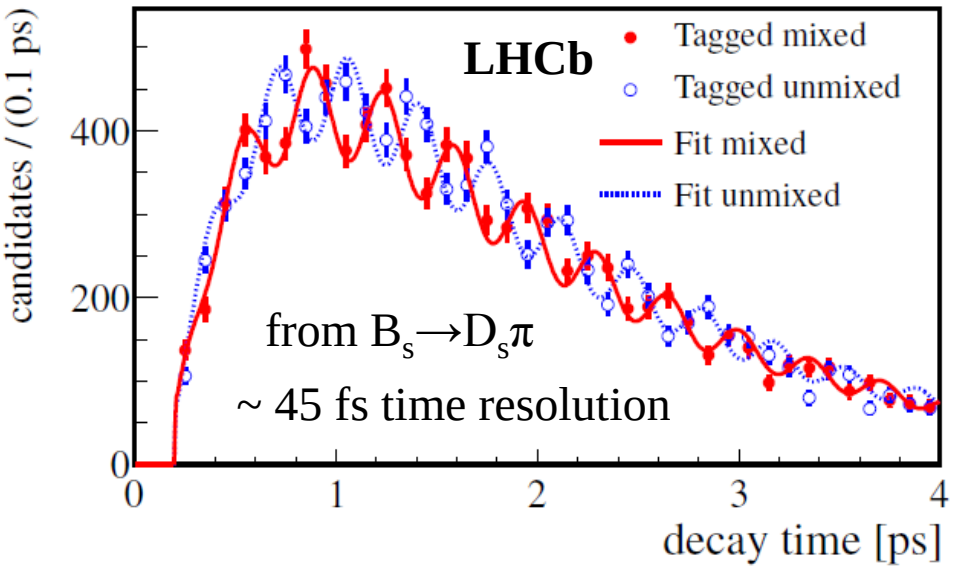
Detector upgrade to 40 MHz readout

- ✓ upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- ✓ replace complete sub-systems with embedded FE electronics
- ✓ adapt sub-systems to increased occupancies due to higher luminosity
- ➢ keep excellent performance of sub-systems with 5 times higher luminosity and 40 MHz R/O

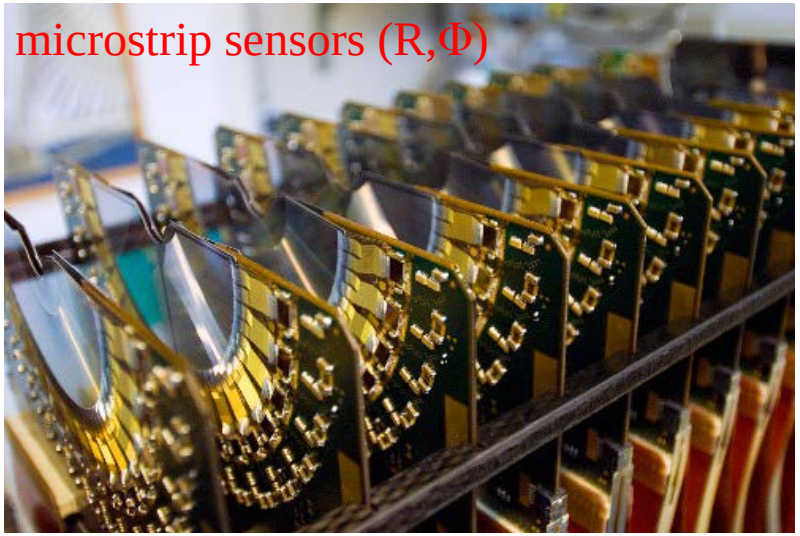


Vertex reconstruction with VELO

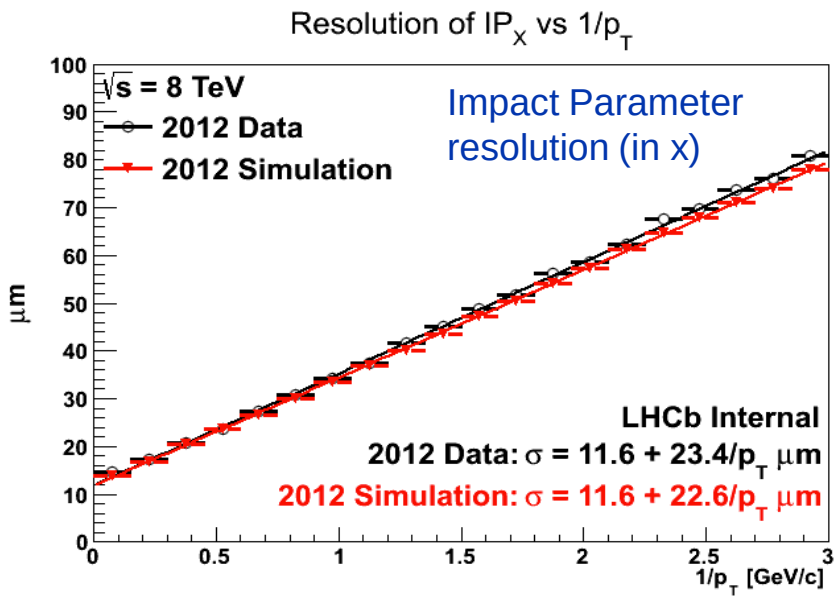
Current detector

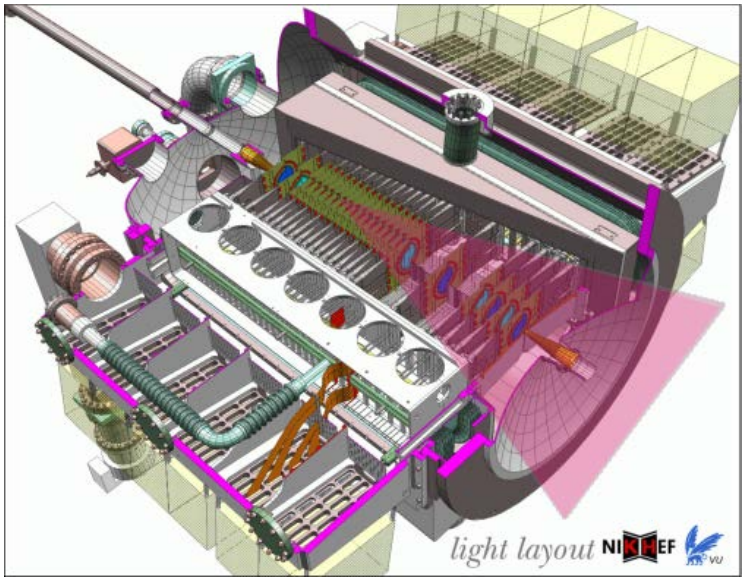


New J. Phys. 15 (2013) 053021

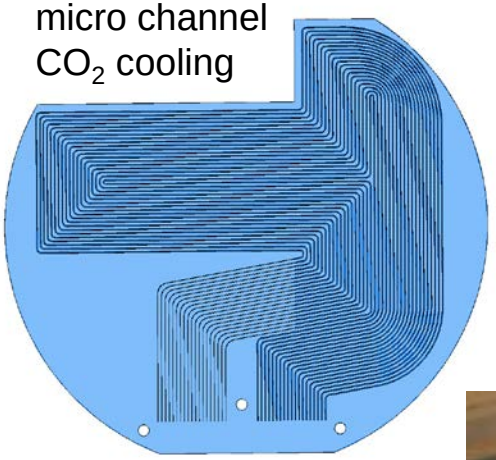


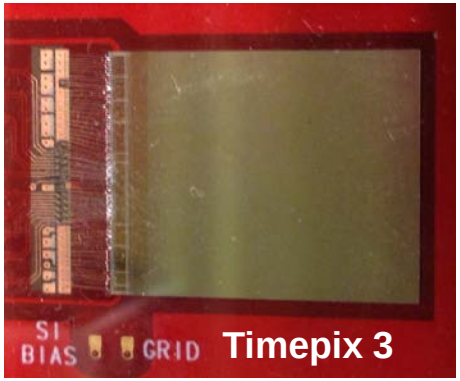
movables halves → 5.5 mm from beam

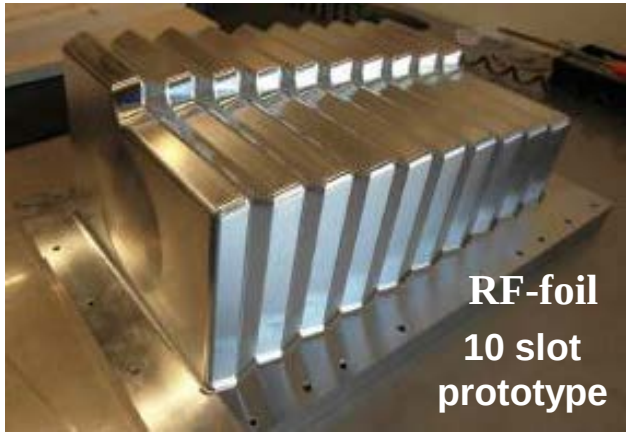


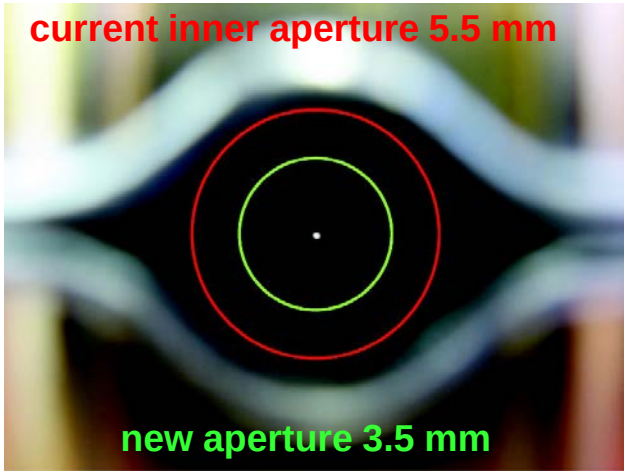


VELO upgrade









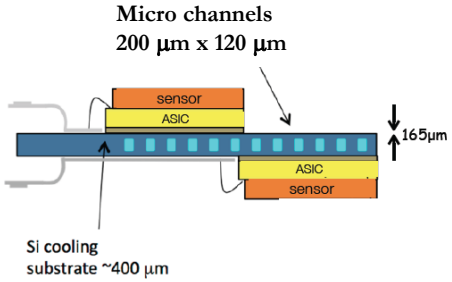
Upgrade challenge:

- ✓ withstand increased radiation (highly non-uniform radiation of up to $8 \cdot 10^{15}$ n_{eq}/cm^2 for 50 fb^{-1})
- ✓ handle high data volume
- ✓ keep (improve) current performance
  - ➢ lower materiel budget
  - ➢ enlarge acceptance

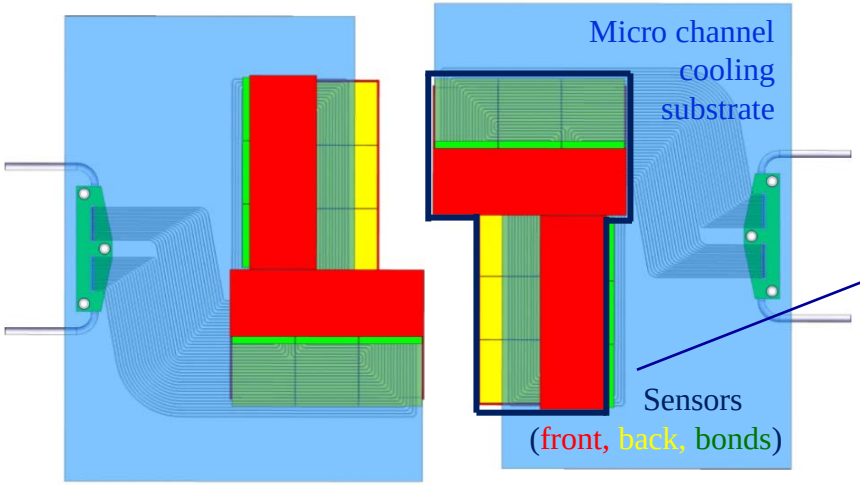
Technical choice :

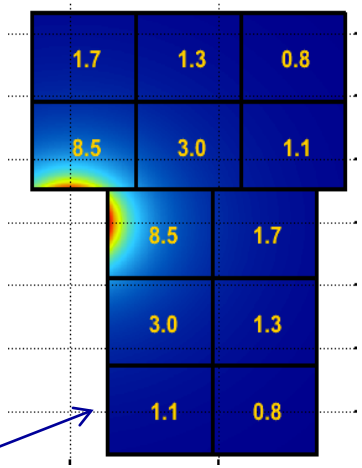
- ✓ 55x55 μm^2 pixel sensors with micro channel CO_2 cooling
- ✓ 40 MHz VELOPIX (evolution of TIMEPIX 3, Medipix)
  - ➢ 130 nm technology to sustain ~400 MRad in 10 years
  - ➢ VELOPIX hit-rate = ~8 x TIMEPIX 3 rate
- ✓ replace RF-foil between detector and beam vacuum
  - ➢ reduce thickness from 300 $\mu m \rightarrow \leq 250$ μm
- ✓ move closer to the beam
  - ➢ reduce inner aperture from 5.5 mm → 3.5 mm

VELO upgrade



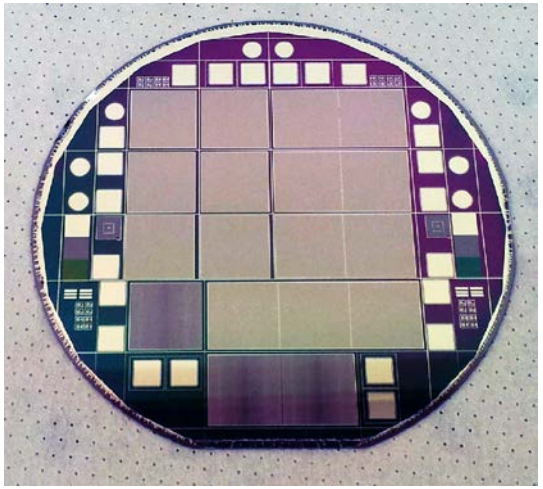
pixel detector with
micro channel cooling

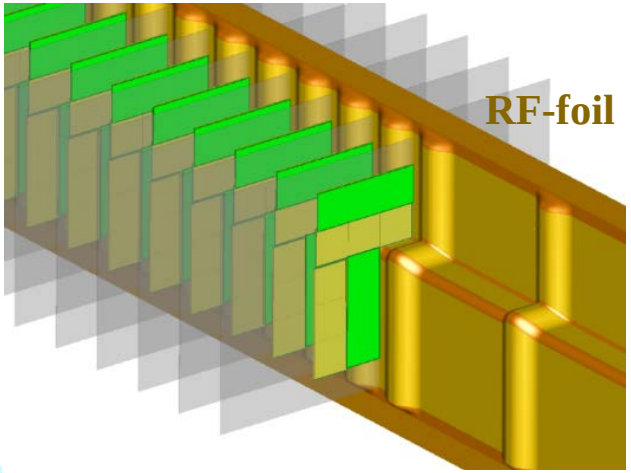


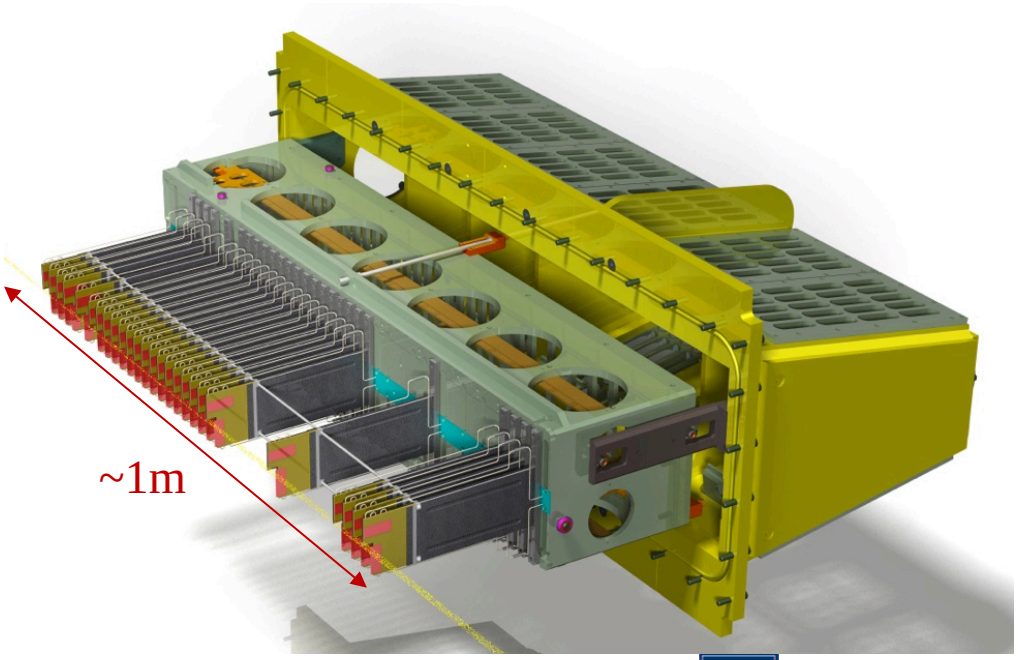


tracks/chip/event
at $L=2\cdot10^{33}$ cm^{-2}s^{-1}

Prototype pixel sensor

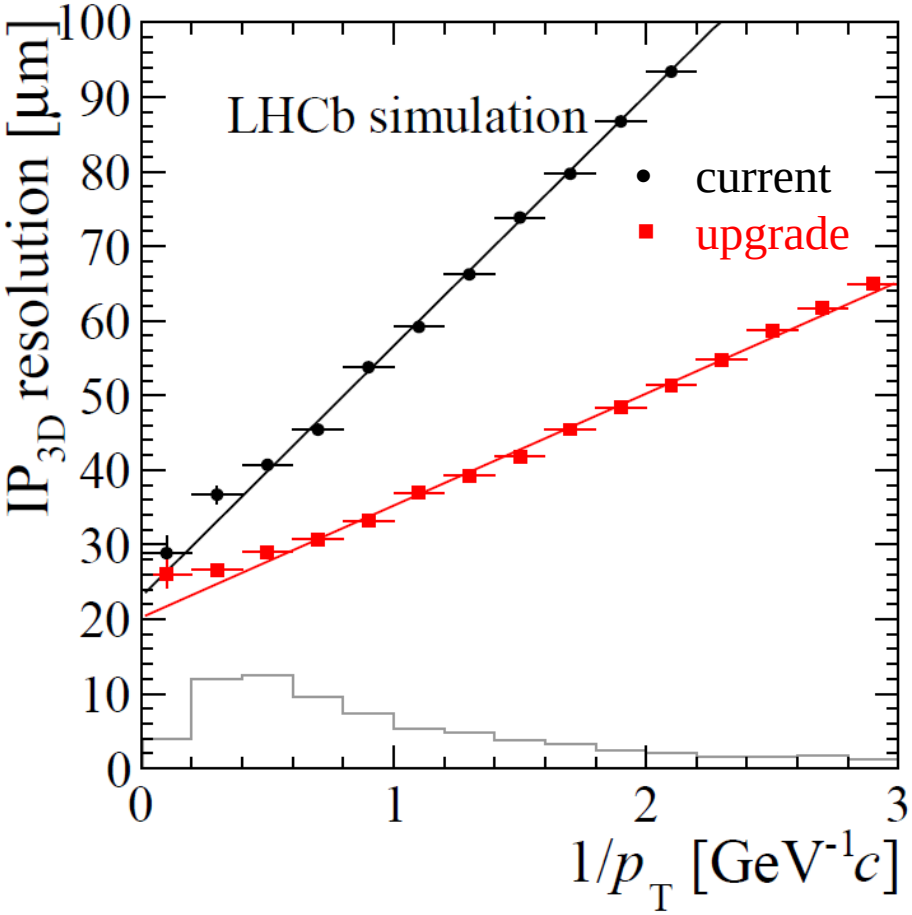






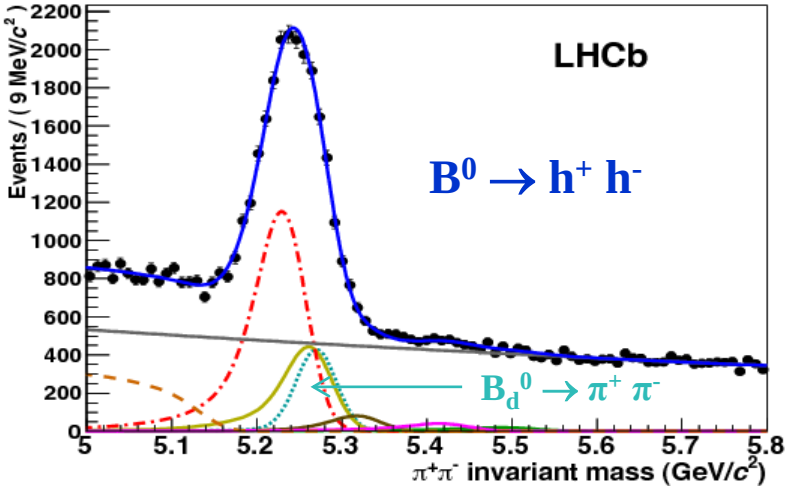
VELO upgrade

3D Impact-Parameter resolution at $L = 2 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



note: full GEANT Monte Carlo with standard LHCb simulation framework

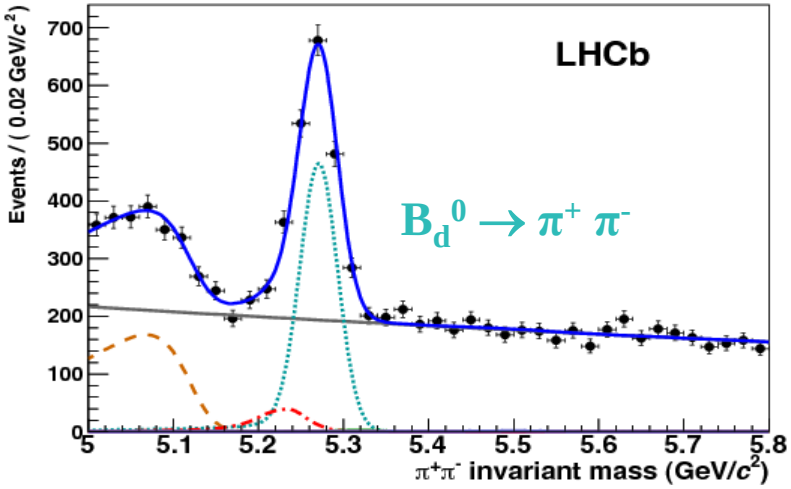
Particle Identification with RICH



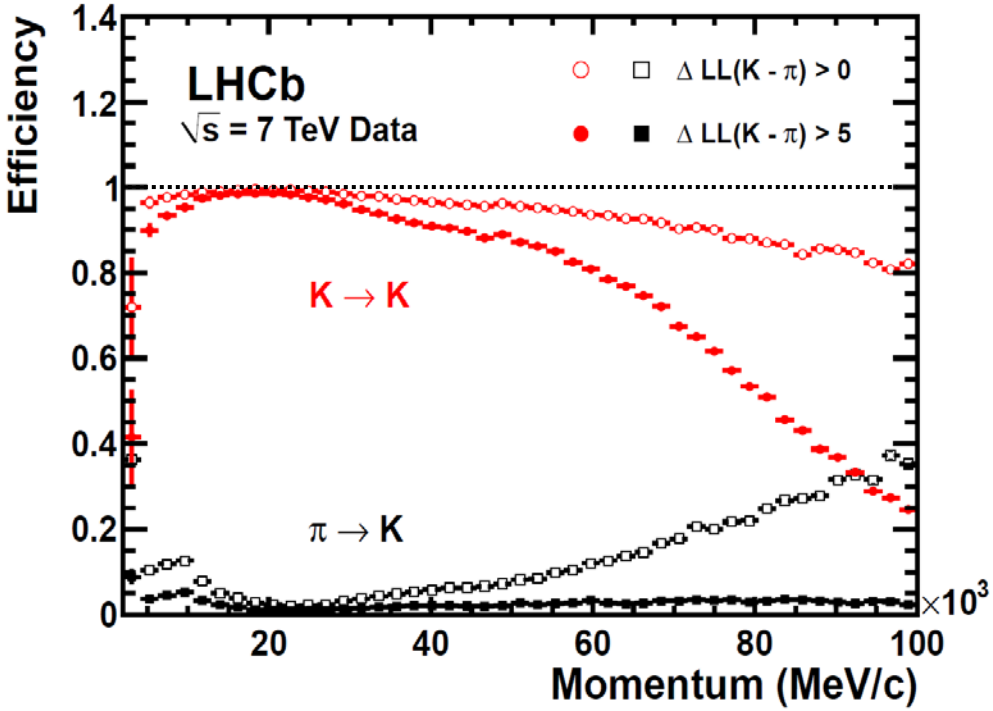
Efficient particle identification of π, K, p essential for selecting rare beauty and charm decays

↓ particle identification of 2 π

$BR(B \to \pi^+\pi^-) = 5 \times 10^{-6}$!

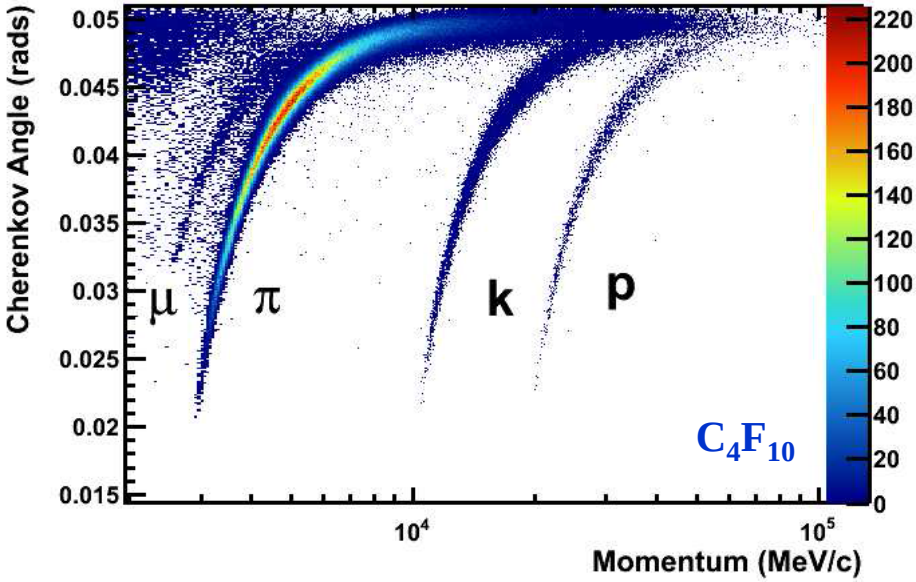


K-identification and π-misidentification efficiencies vs. particle momentum

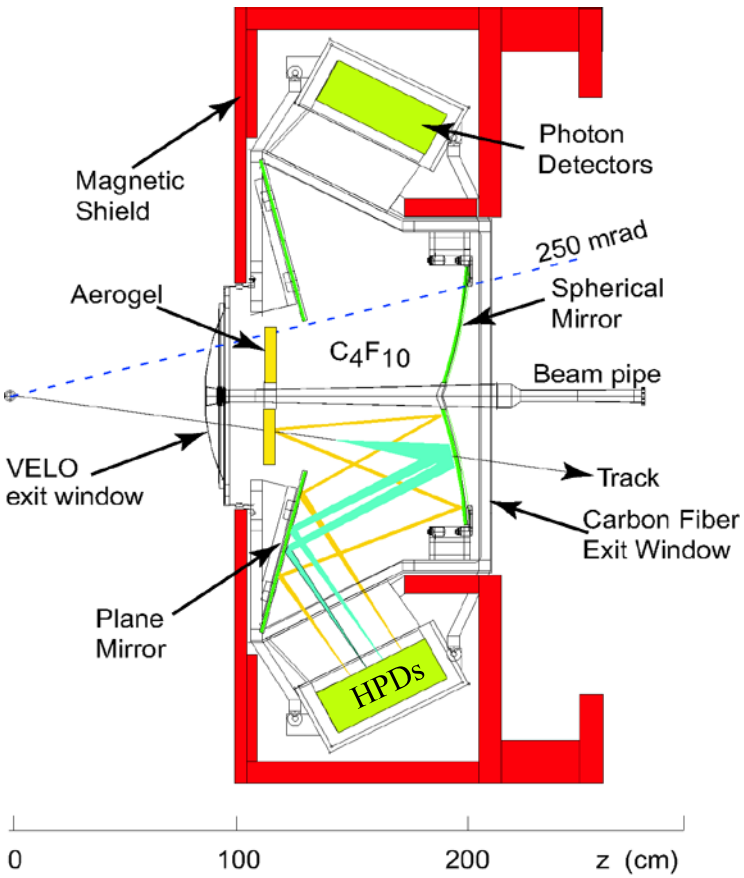


RICH(1) optics

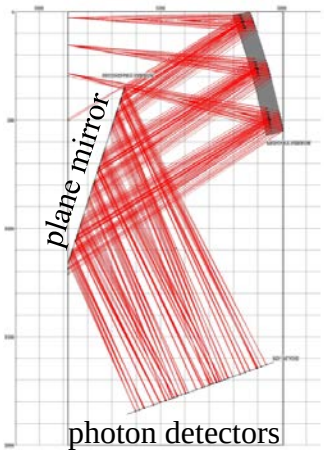
Particles traversing radiator produce Cherenkov light rings on an array of HPDs located outside the acceptance



RICH 1

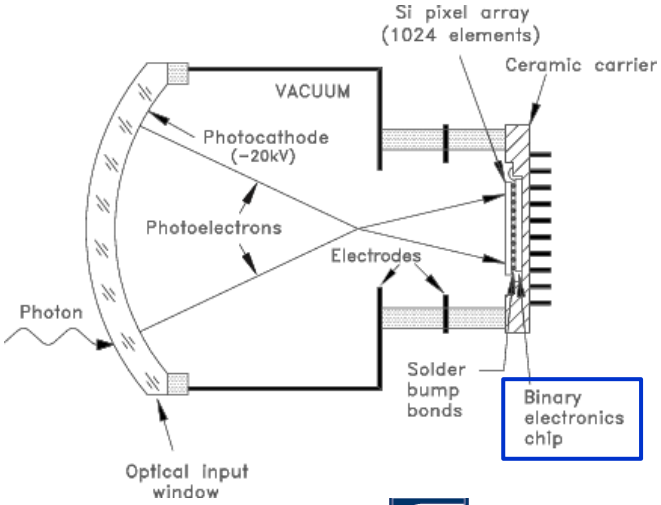


spherical mirror



Hybrid
Photon
Detector

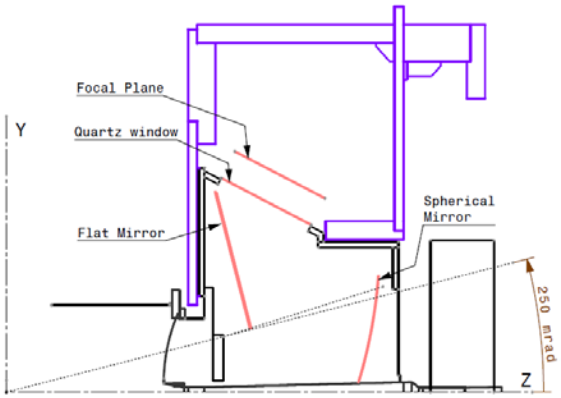
with embedded 1 MHz R/O chip



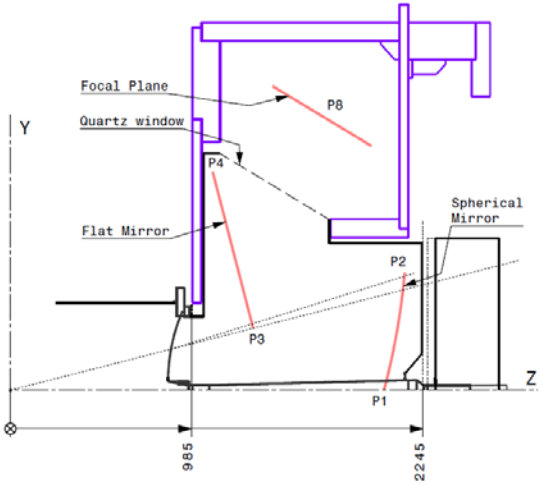
RICH upgrade

optimise RICH1 optics

current



upgrade

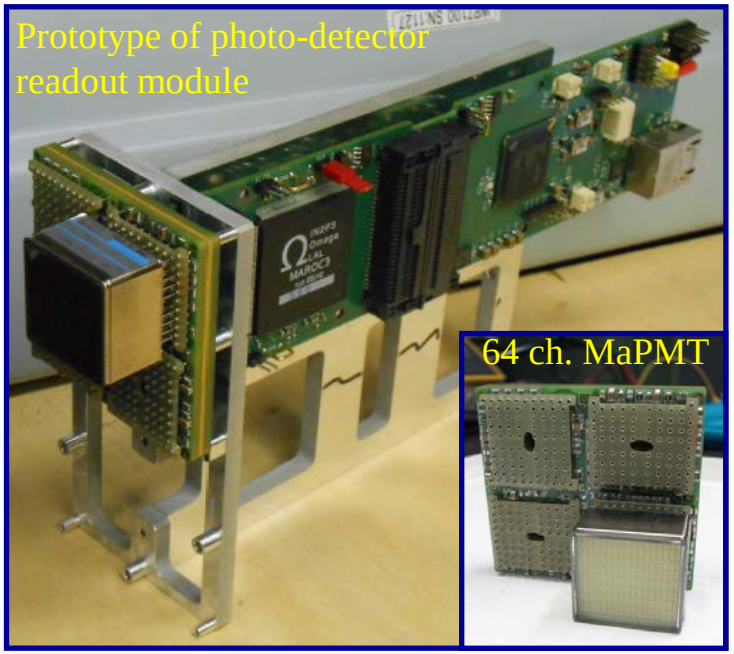


Luminosity of $2 \cdot 10^{33}$ $cm^{-2}s^{-1}$ → adapt to high occupancies

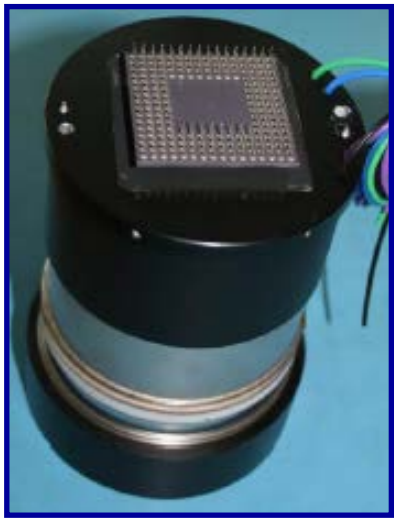
- aerogel radiator removed
- modify optics of RICH1 to spread out Cherenkov rings (optimise gas enclosure without modifying B-shield)

40 MHz readout → replace HPDs due to embedded FE

- 64 ch. multi-anode PMTs (baseline)
- 40 MHz Front-End: CLARO chip (or MAROC)

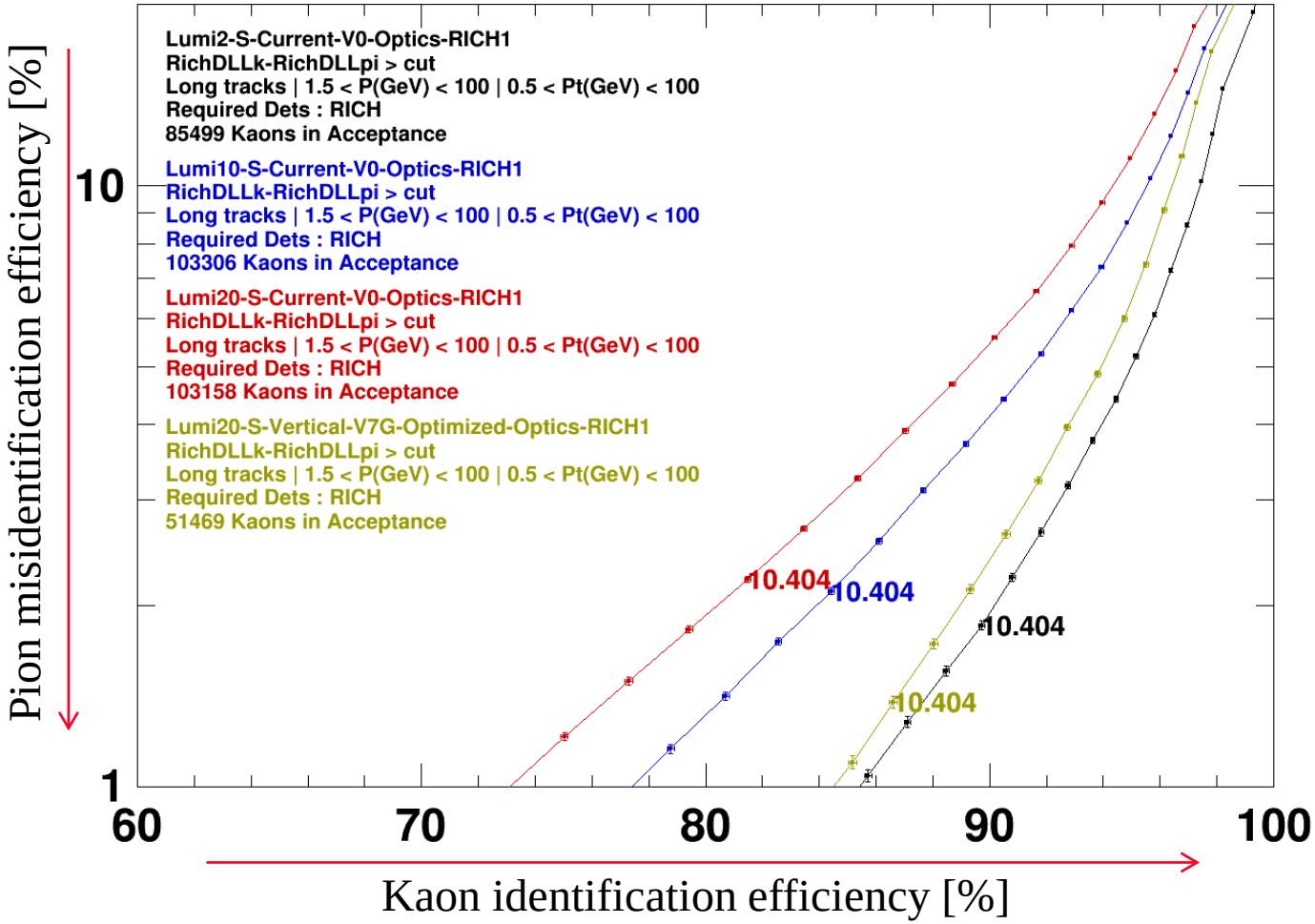


HPD prototype with external electronics



RICH upgrade

RICH Kaon ID RICH1-Optics-Comparison **as function of luminosity**



Current RICH1

- $2 \cdot 10^{32}$ cm^{-2}s^{-1}
- $10 \cdot 10^{32}$ cm^{-2}s^{-1}
- $20 \cdot 10^{32}$ cm^{-2}s^{-1}

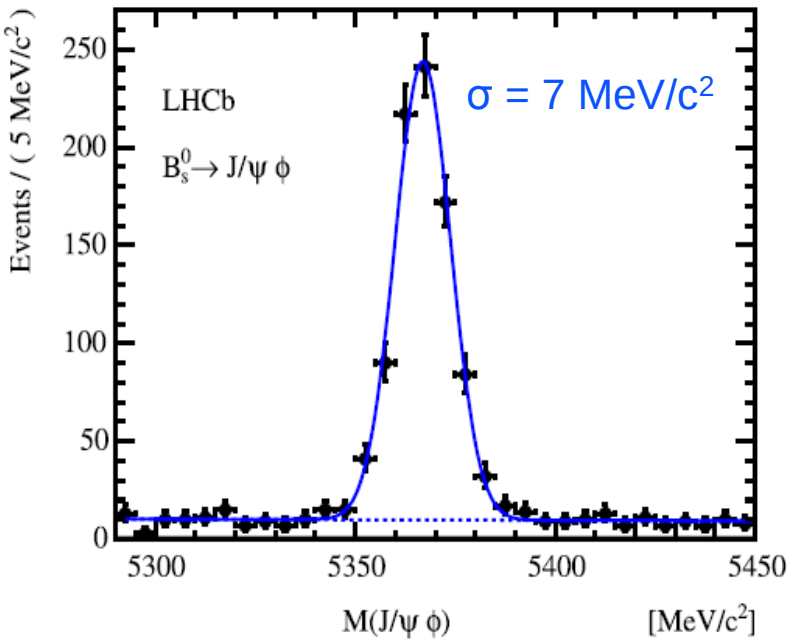
RICH1 upgrade

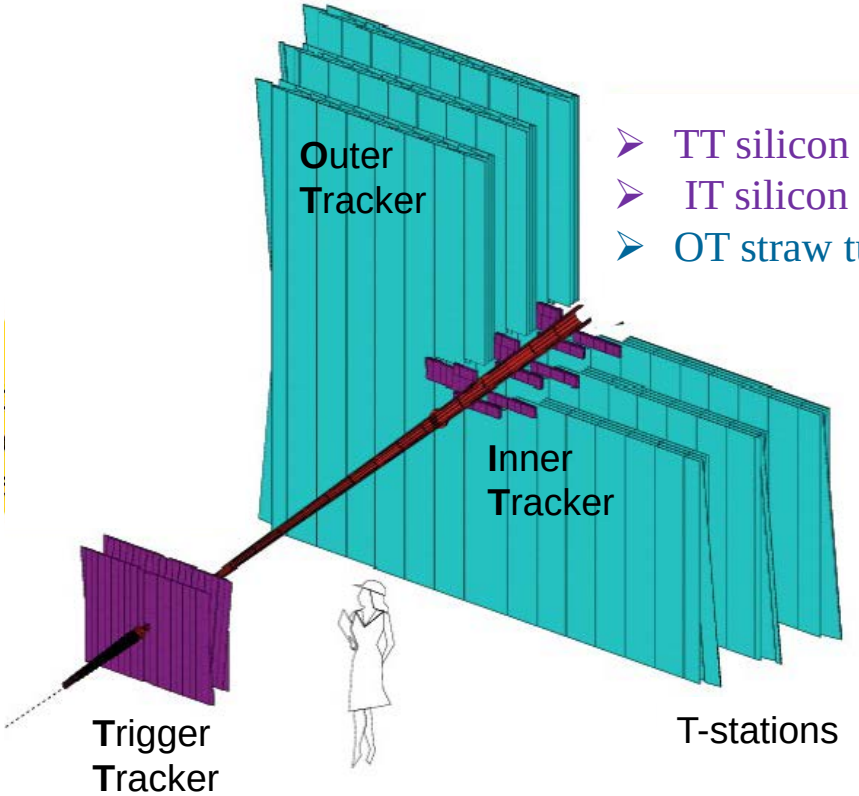
- $20 \cdot 10^{32}$ cm^{-2}s^{-1}

note:
full GEANT MC with standard LHCb simulation framework

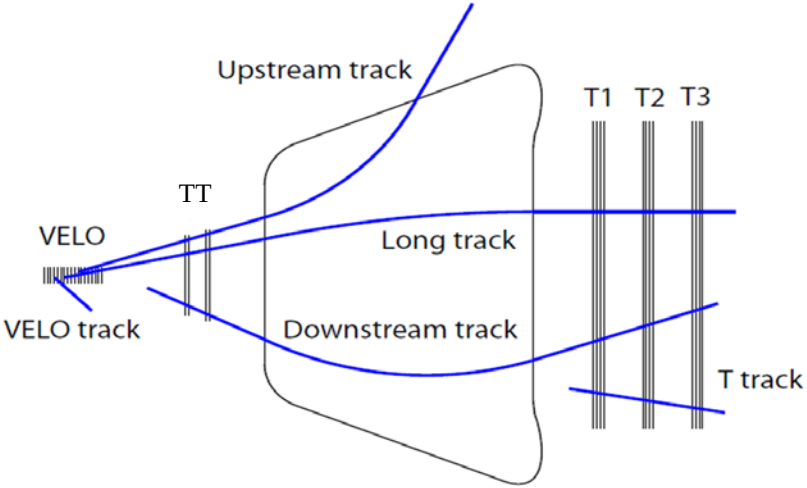
Tracking System

- excellent mass resolution
- very low background, comparable to e^+e^- machines
- world's best mass measurements [PLB 708 (2012) 241]



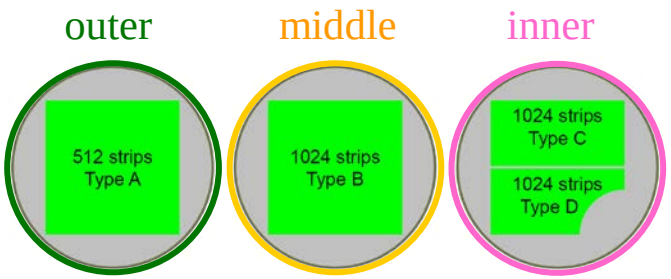


- TT silicon
- IT silicon
- OT straw tubes



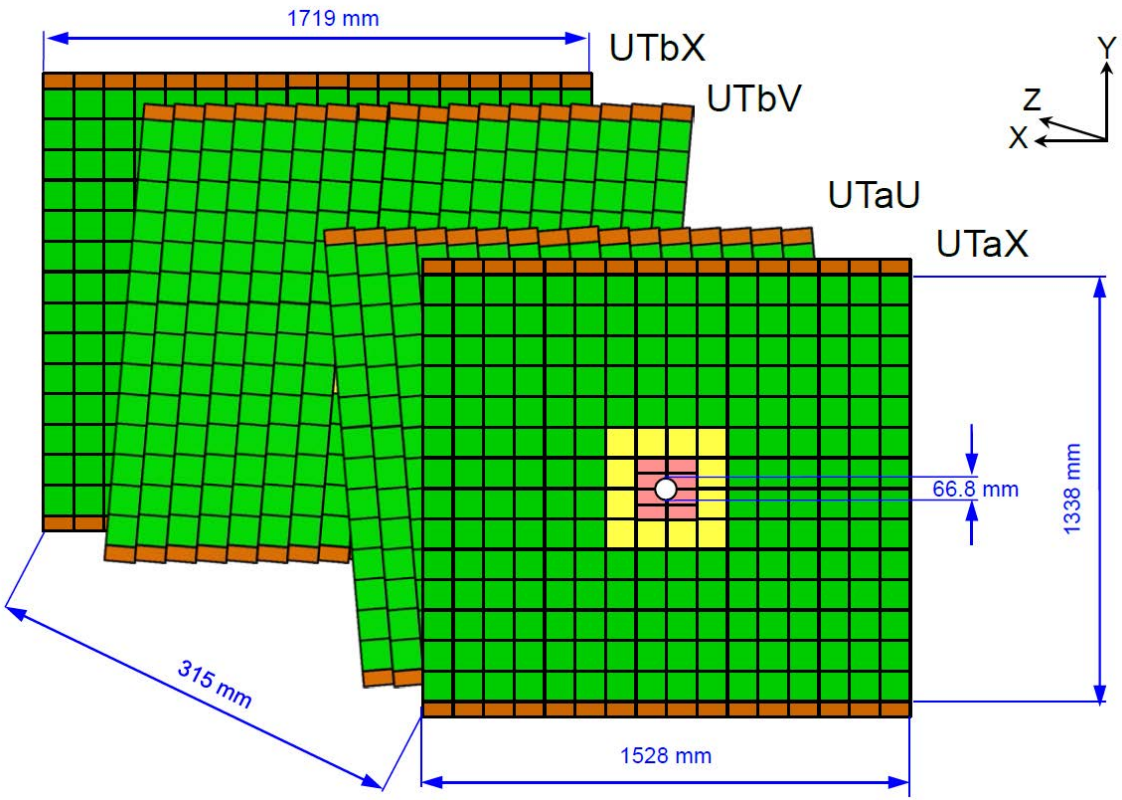
TT upgrade: Upstream Tracker (UT)

silicon strip detector

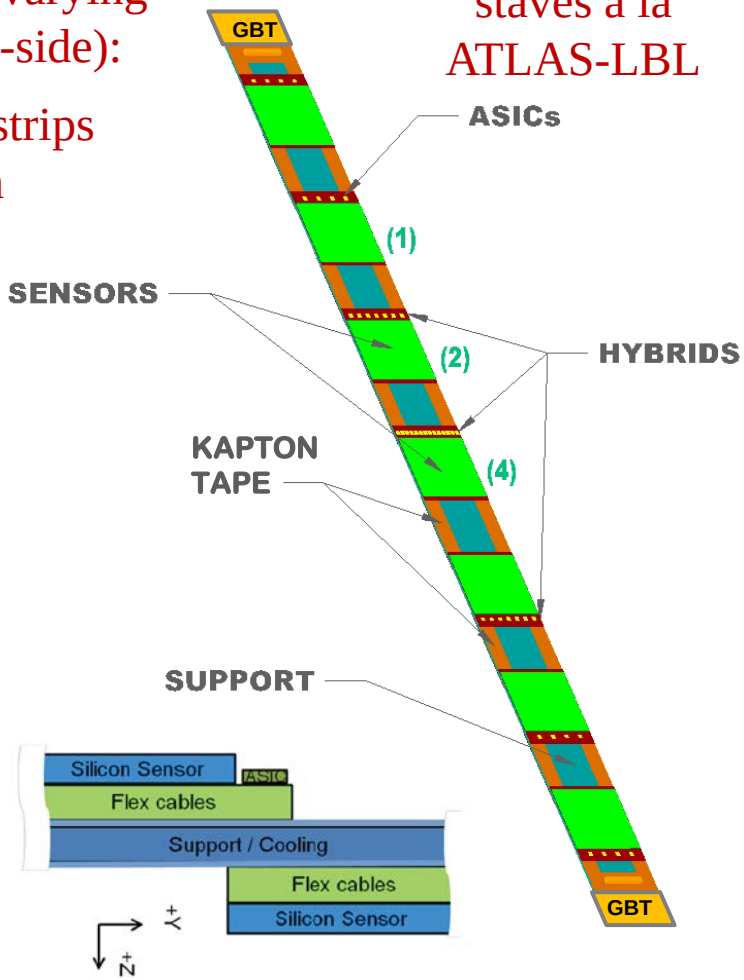


adapt segmentation to varying occupancies (out → in-side):

- 98 → 49 mm long strips
- 190 → 95 µm pitch
- p^+-in-n → n^+-in-p

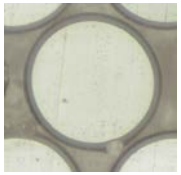


staves a la ATLAS-LBL



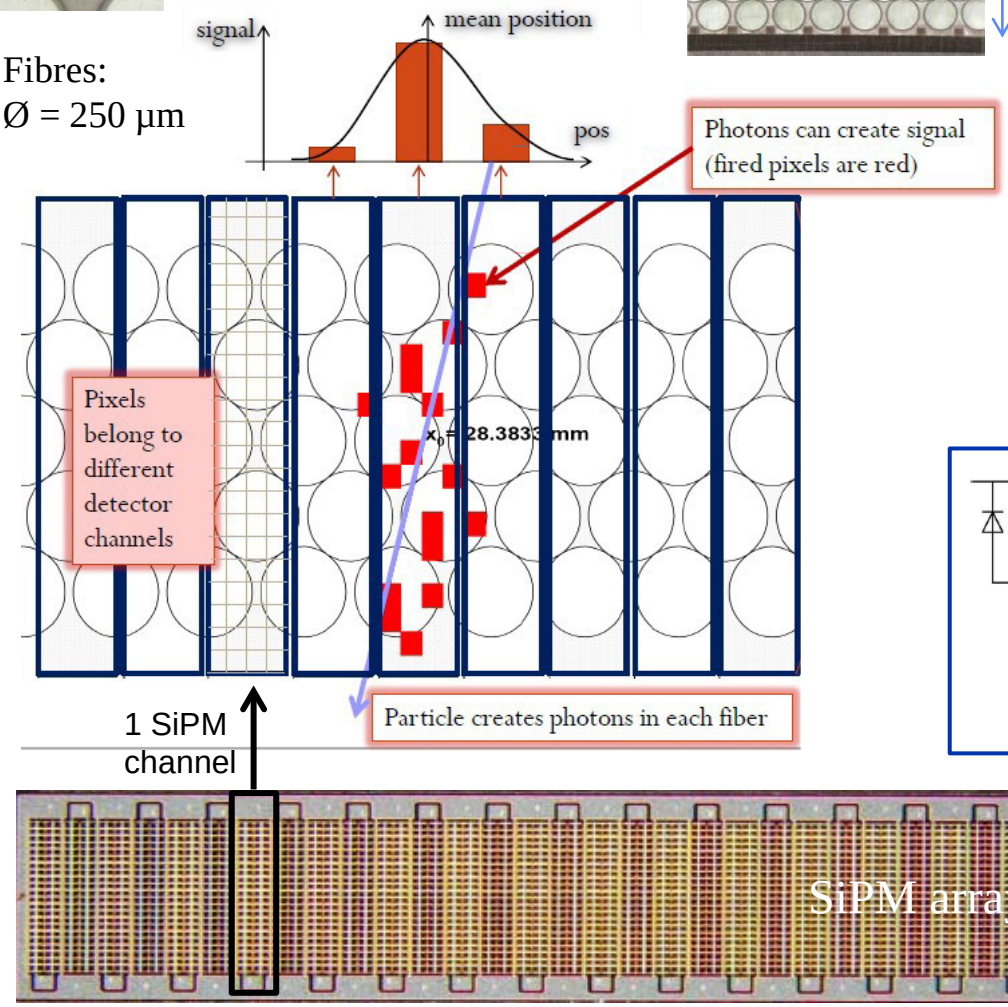
40MHz silicon strip R/O → SALT chip

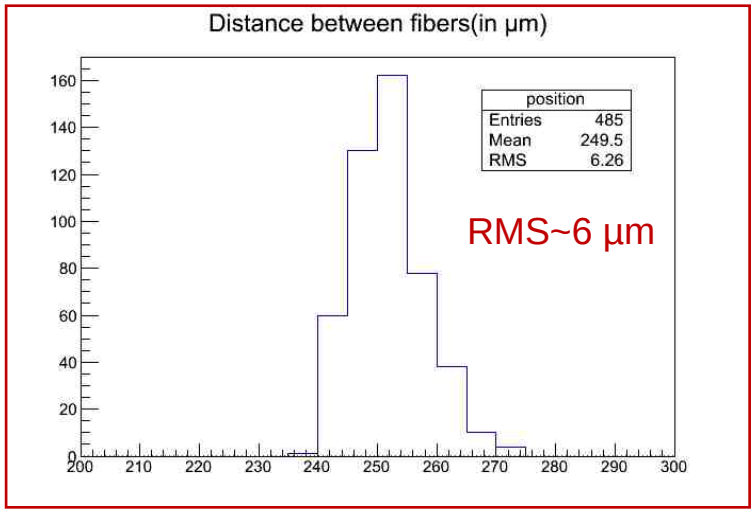
T-stations upgrade: Fibre Tracker (FT)

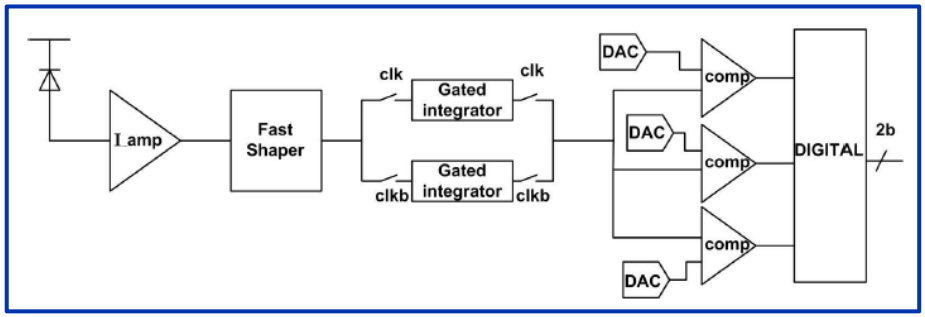


Fibres:
Ø = 250 µm

scintillating-fibre mat
(5-6 layers)





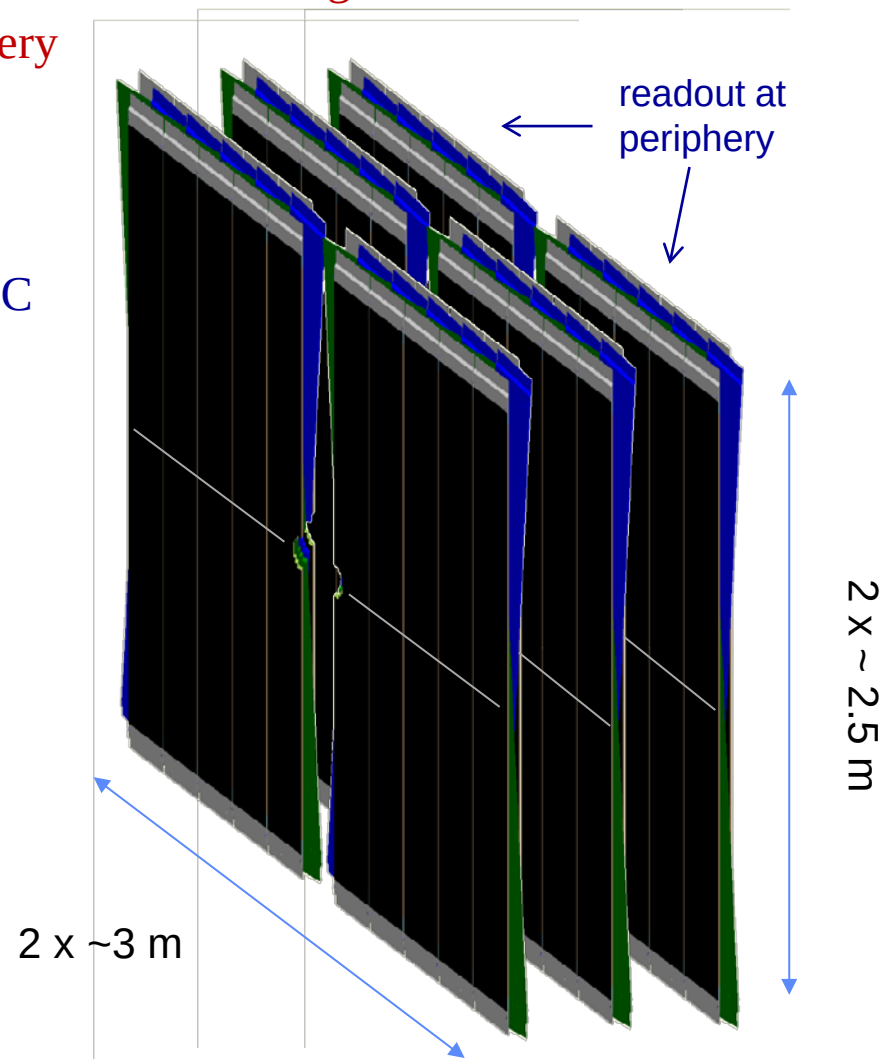


Readout by dedicated 128 ch.
40 MHz PACIFIC chip

- 3 thresholds (2 bits)
- sum threshold (FPGA)

T-stations upgrade: Fibre Tracker (FT)

- 3 stations of X-U-V-X (±5° stereo angle) scintillating fibre planes
- every plane made of 5 layers of Ø=250 µm fibres, 2.5 m long
- 40 MHz readout and Silicon PMs at periphery



Challenges → radiation environment

- ionization damage to fibres → tested ok
- neutron damage to SiPM → operate at -40°C

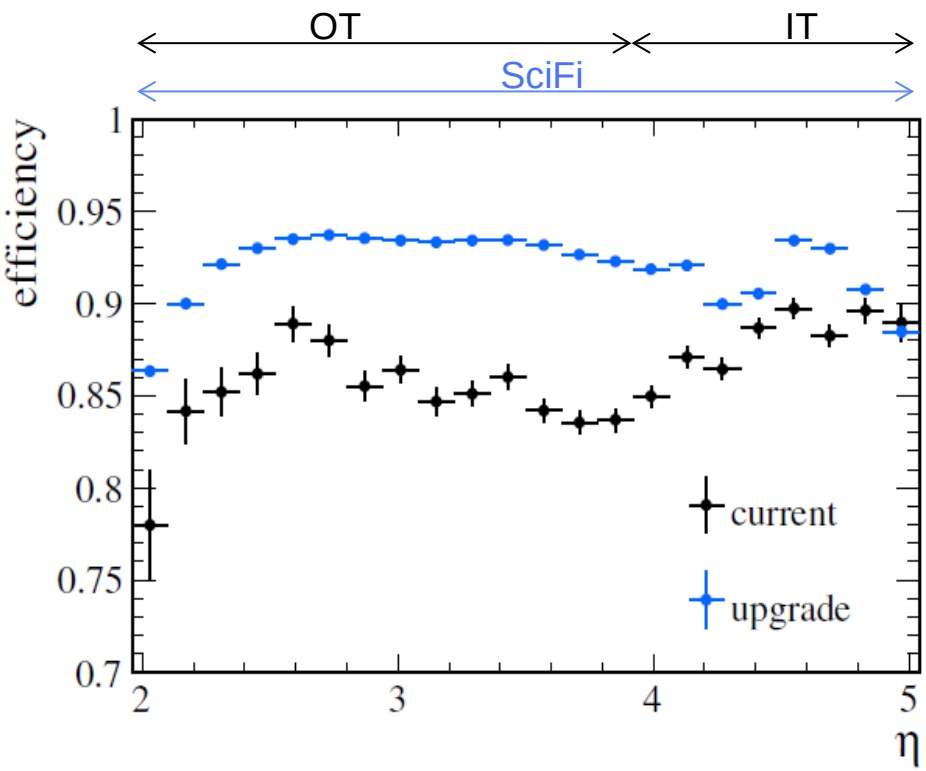
Benefits of the SciFi concept:

- ✓ a single technology to operate
- ✓ uniform material budget
- ✓ SiPM + infrastructure outside acceptance
- ✓ fine channel granularity of 250 µm
- ✓ x-position resolution of 50 – 75 µm
- ✓ high hit detection efficiency (≥ 99%)
- ✓ fast pattern recognition for HLT

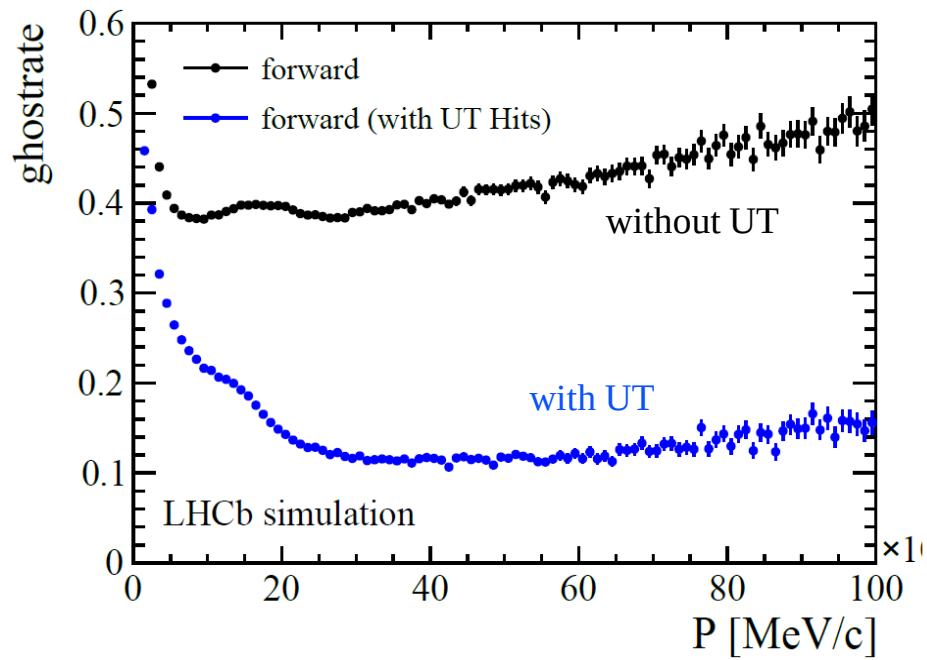
Tracking performance

Performance of the forward pattern recognition algorithm

Efficiency for $B_s \rightarrow \Phi\Phi$ events at upgrade conditions: current and upgraded T-stations



Ghost rate for long tracks for $B_s \rightarrow \Phi\Phi$ events: without UT and with UT (≥ 3hits)



→ improve tracking performance at upgrade luminosity with Fibre Tracker

→ reduce significantly the ghost rate using the Upstream Tracker information

Tracking algorithm for the Trigger

Expected CPU budget with upgraded Event Filter Farm: ~13 ms (10 x current CPU farm)

Performance of HLT tracking with upgraded VELO, UT and FT:

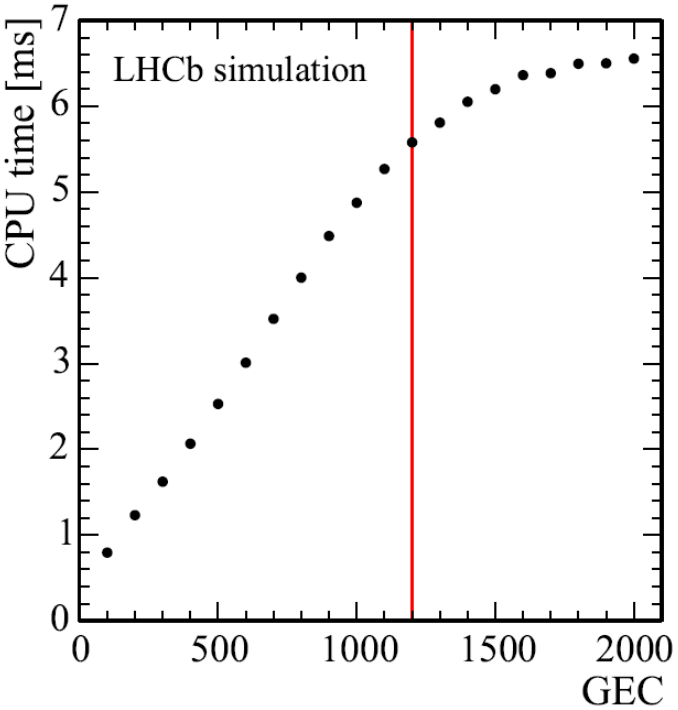
Tracking Algorithm	CPU time[ms] No GEC	CPU time[ms] GEC = 1200
VELO tracking	2.3	2.0
VELO-UT tracking	1.4	1.3
Forward tracking	2.5	1.9
PV finding	0.40	0.38
Total @29 MHz		5.6
Total	6.6	5.4 ms

→ leaves ~ 6-7 ms for a trigger decision

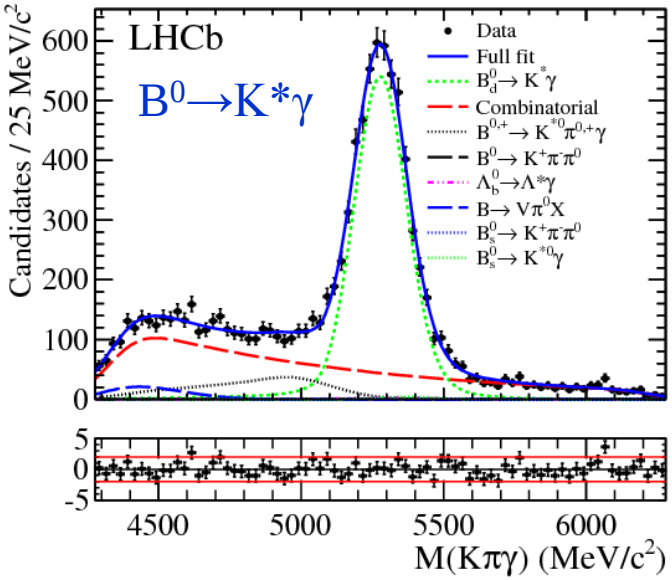
	no GEC	GEC< 1200	relative
Ghost rate	10.9%	5.9%	-
long	42.7%	42.9%	50.4%
long, from B	72.5%	72.8%	80.3%
long, $p_T > 0.5\,\mathrm{GeV}/c$	86.9%	87.4%	97.2%
long, from B, $p_T > 0.5\,\mathrm{GeV}/c$	92.3%	92.5%	98.7%

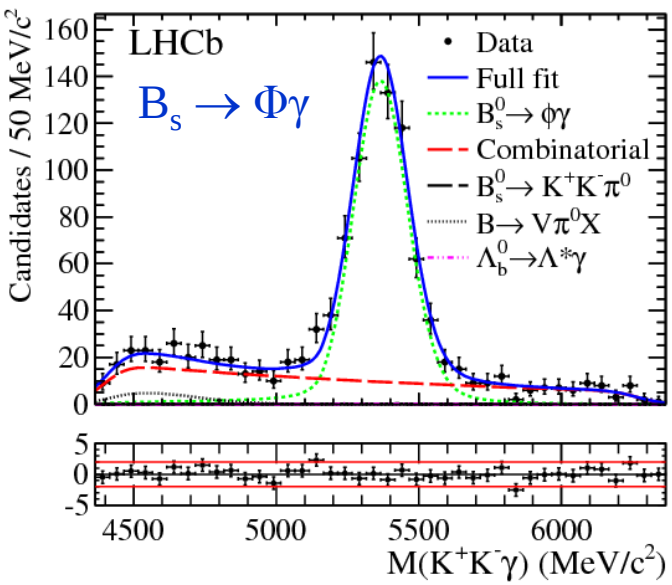
→ high efficiency (even with GEC)

GEC (Global Event Cut) → multiplicity cut to remove pathological events (e.g. hit multiplicity of sub-detector)



Particle identification with Calorimeters





Nuclear Physics, Section B 867 (2013) 1

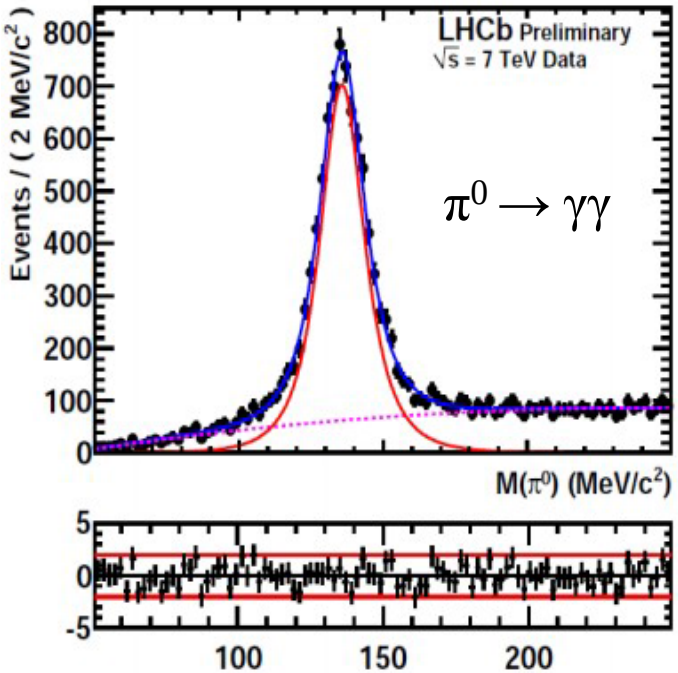
A_{CP} ($B^0 \to K^*\gamma$) = (0.8 ±1.7±0.9) %

and worlds best branching ratio measurement:

$BR(B_s \to \Phi\gamma) = (3.5 \pm 0.4) \cdot 10^{-5}$

with invariant mass resolution ~ 94 MeV/c^2

Typical π^0 mass resolution ~7-10 MeV/c^2
(depending on number of converted photons)



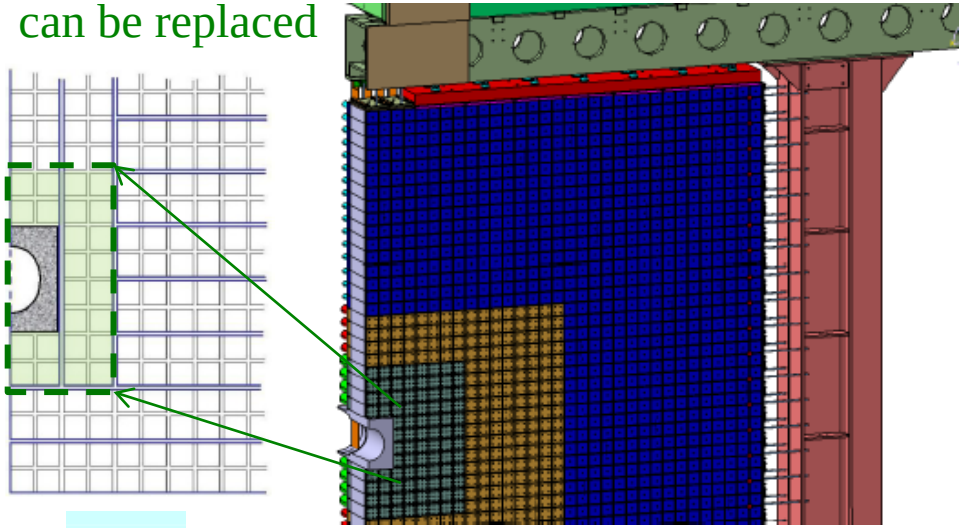
Calorimeters upgrade

Radiation damage and occupancies:

- ✓ Preshower and SPD removed
- ✓ HCAL modules ok up to ~50 fb^{-1}
- ✓ irradiation tests show that most exposed ECAL modules resist up to ~20 fb^{-1} → LS3

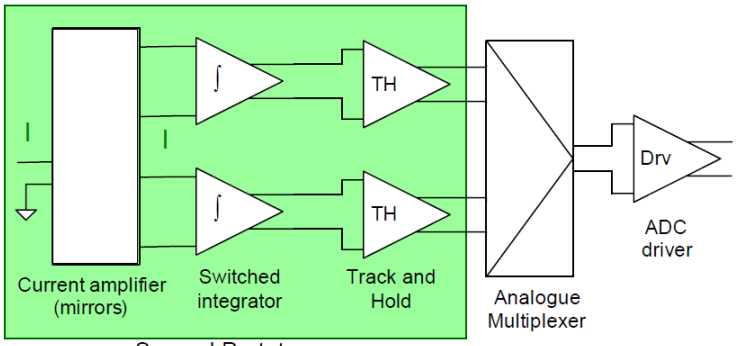
E beam, GeV	module #1 (irradiated 2Mrad) light yield ph.el./GeV	resolution, %	module #2 (not irradiated) light yield, ph.el./GeV	resolution, %
50	583±12	2.16±0.04	2598±52	1.37±0.04
100	576±12	1.57±0.03	2611±52	1.01±0.03
120	571±12	1.36±0.03	2604±52	0.98±0.03

most inner ECAL modules around beam-pipe can be replaced

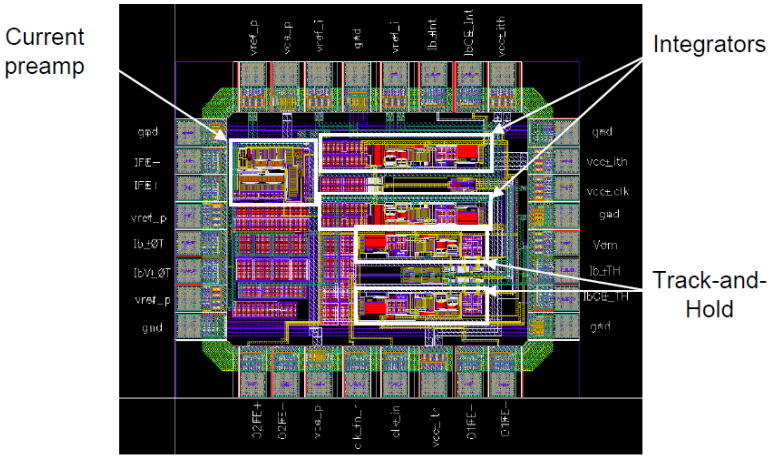


40 MHz readout electronics:

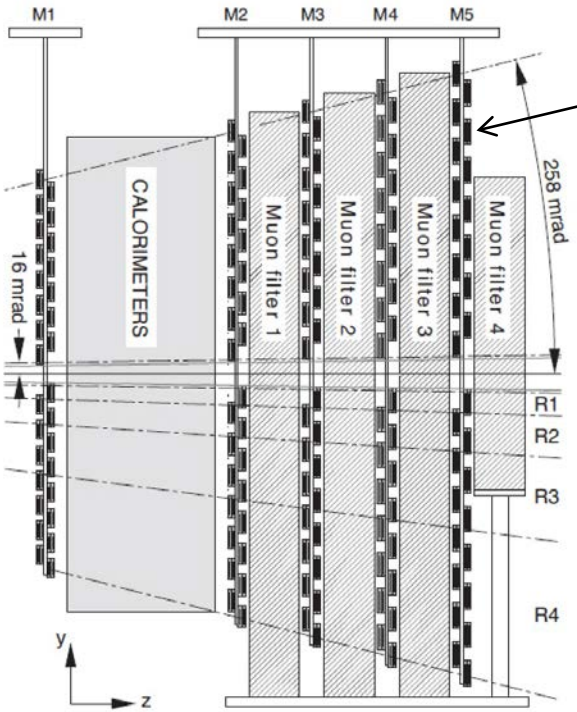
- ➢ reduce photomultiplier gain
- ➢ two interleaved integrators at 20 MHz
- ➢ fully differential implementation
- ➢ Track and Hold



Second Prototype: ICECAL2

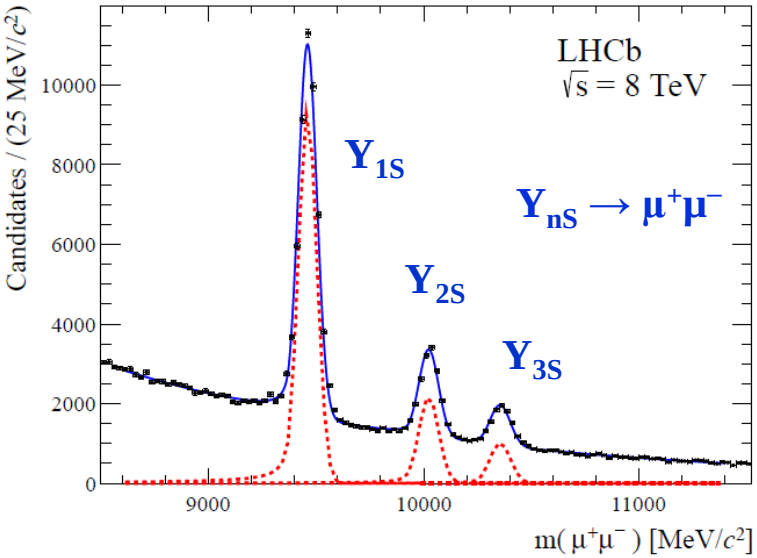


Particle identification with Muon System



MWPC

5 stations
M1 to M5



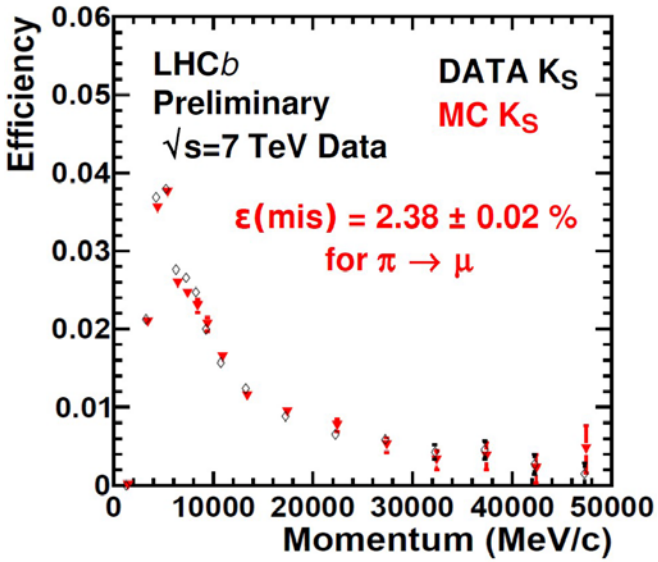
high detection efficiency: $\varepsilon(\mu) = (97.3 \pm 1.2)\%$

low misidentification rates:

$\varepsilon(p \rightarrow \mu) = (0.21 \pm 0.05)\%$

$\varepsilon(\pi \rightarrow \mu) = (2.38 \pm 0.02)\%$

$\varepsilon(K \rightarrow \mu) = (1.67 \pm 0.06)\%$



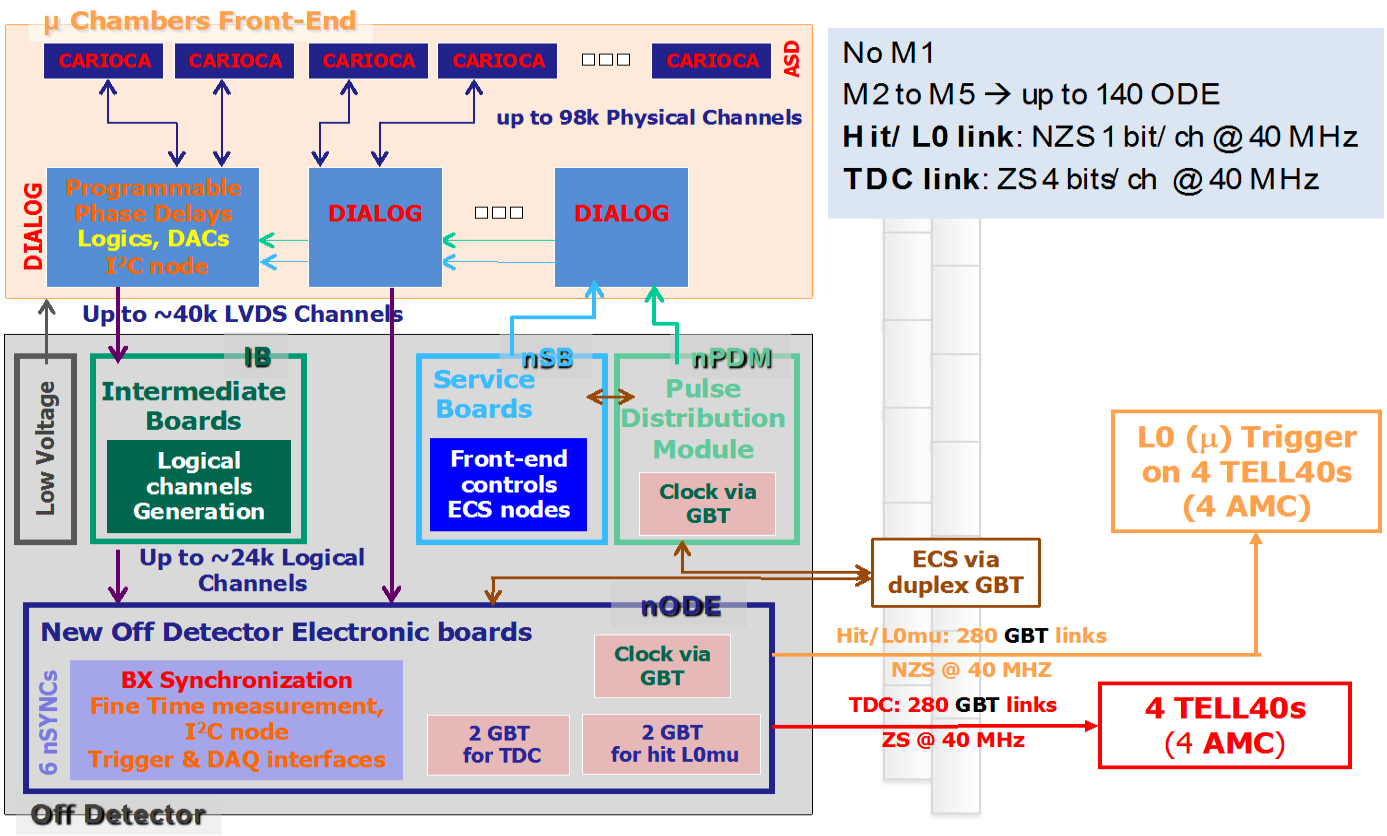
Muon System upgrade

Modifications due to higher luminosity and 40 MHz readout:

- remove M1 due to too high occupancies
- keep on-detector electronics (CARIOCA), already at 40 MHz readout
- new off-detector electronics for an efficient readout via PCIe40 R/O boards
- additional shielding behind HCAL to reduce the rate in the inner region of M2

on-detector electronics

off-detector electronics



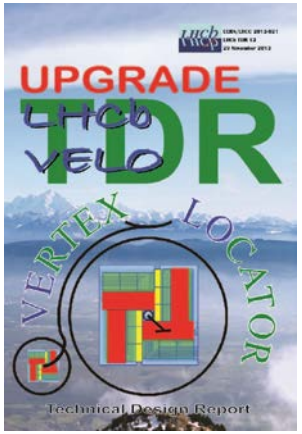
Status of the LHCb upgrade

- LHCb upgrade fully approved by CERN management for installation in 2018/19

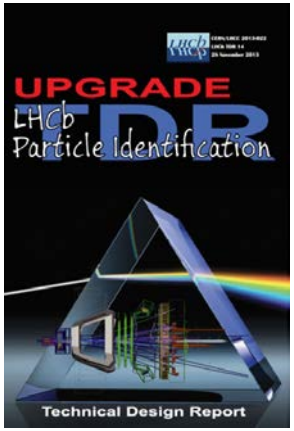
CERN-LHCC-2011-001

CERN-LHCC-2012-007

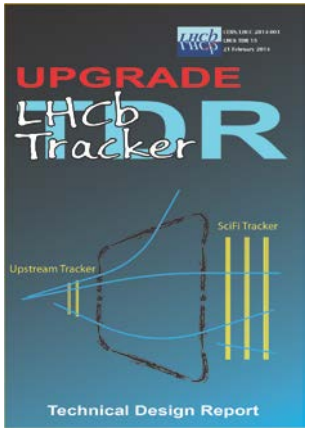
- All TDRs submitted (2 approved, 1 under recommendation, 1 under review)



CERN-LHCC-2013-021



CERN-LHCC-2013-022



CERN-LHCC-2014-001

CERN-LHCC-2014-016

- MoU for Common Projects submitted for signature to Funding Agencies

Summary

- due to its excellent detector performance LHCb is producing world best measurements in the b and c-quark sector
- by 2018 with ~8 fb^{-1} LHCb will find or rule-out large sources of flavour symmetry breaking at the TeV scale
- the LHCb upgrade is mandatory to reach experimental precisions of the order of the theoretical uncertainties
- an efficient and selective software trigger with access to the full detector information at every 25 ns bunch crossing will allow to collect the necessary ≥50 fb^{-1} within ~10 years
- the LHCb upgrade is fully approved, with the last TDR under review
- the detector upgrade to 40 MHz readout sustaining a levelled luminosity of $2 \cdot 10^{33}$ $cm^{-2}s^{-1}$ at 25 ns bunch spacing will be ready for installation in 2019 and operational at the beginning of 2020