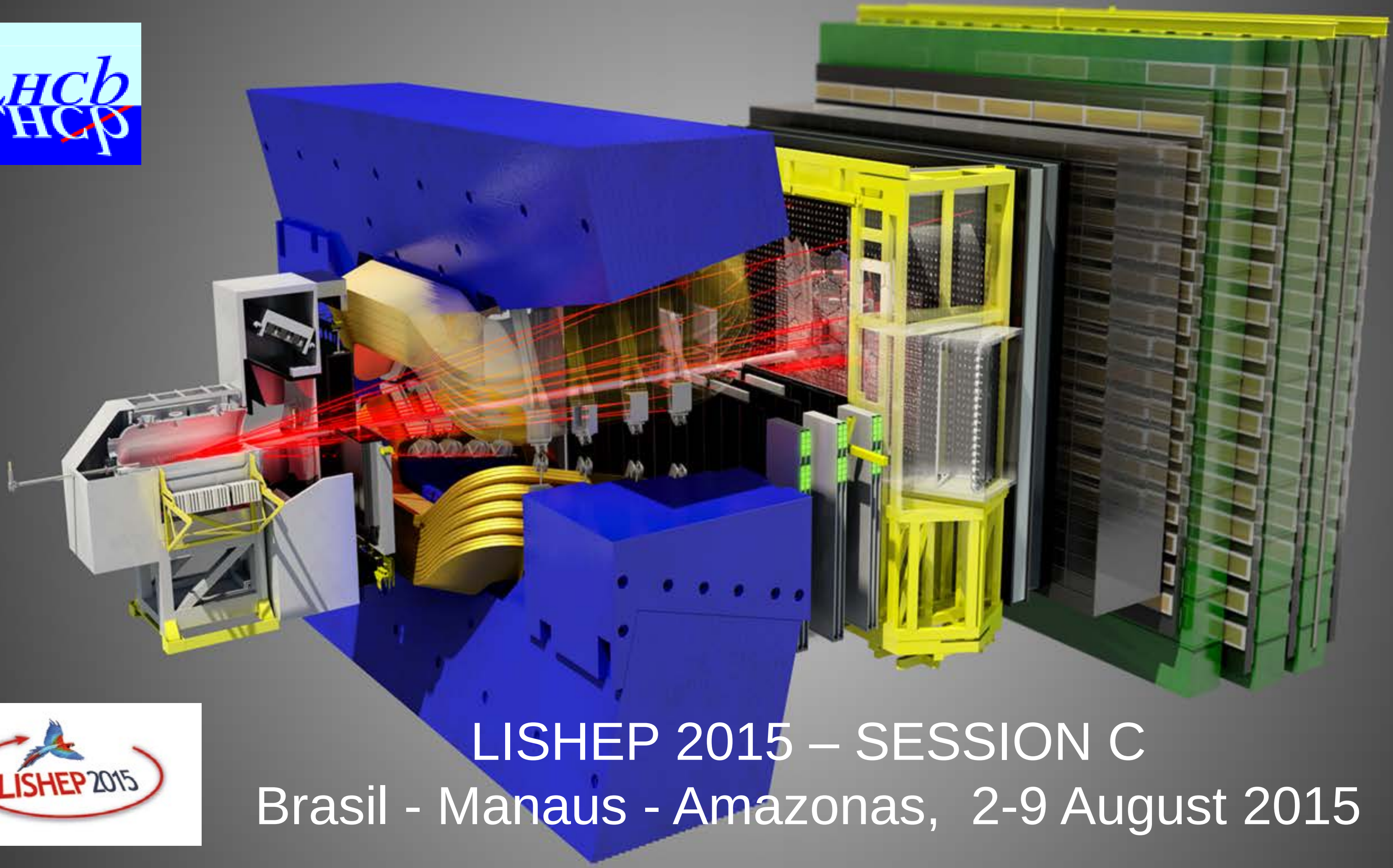
The LHCb Upgrade



LISHEP 2015 – SESSION C

Brasil - Manaus - Amazonas, 2-9 August 2015

Andreas Schopper on behalf of LHCb

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:

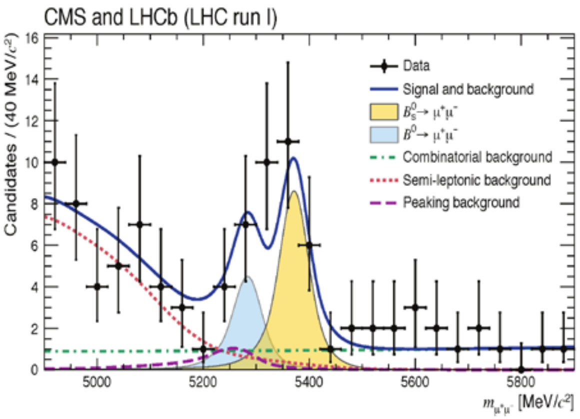
- measurable deviations from the standard model are still expected, but should be small
- need to go to very high precision measurements to probe the most clean observables

→ LHCb upgrade essential to increase statistical precision significantly

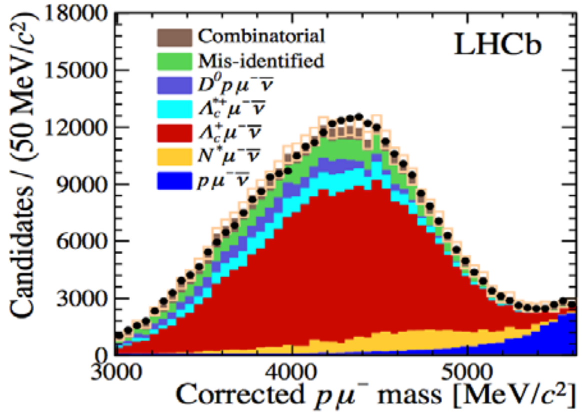
Few highlights of LHCb results

(see LHCb talks: A. Hicheur, M. Rangel, X. Did Vidal, B. Suza De Paula, J. Serrano)

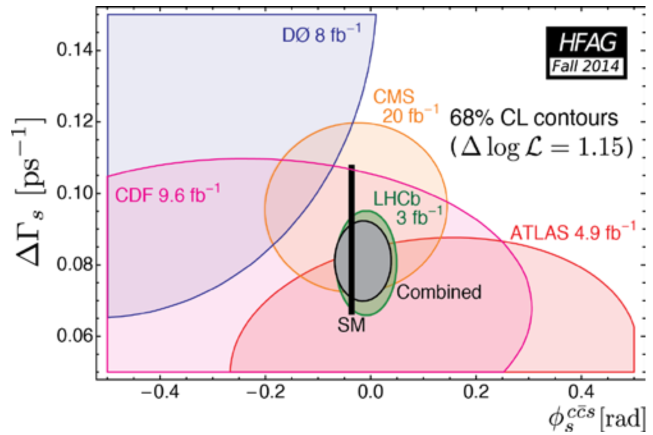
Observation of $B_s \rightarrow \mu\mu$



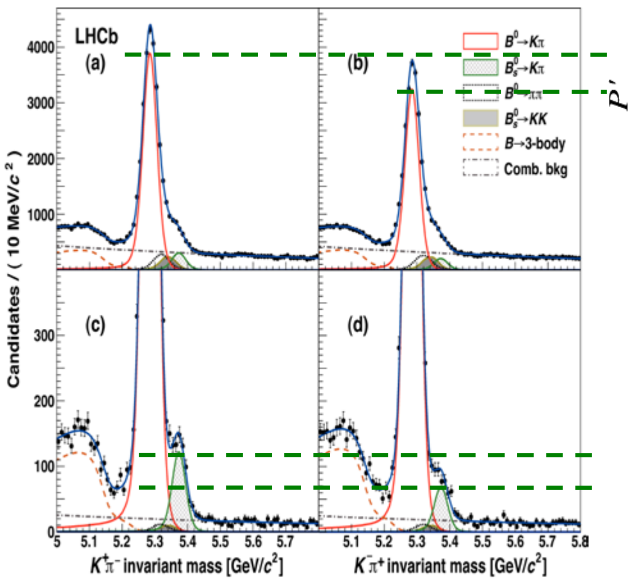
Measurement of V_{ub} in $\Lambda_b \rightarrow p\mu\nu$



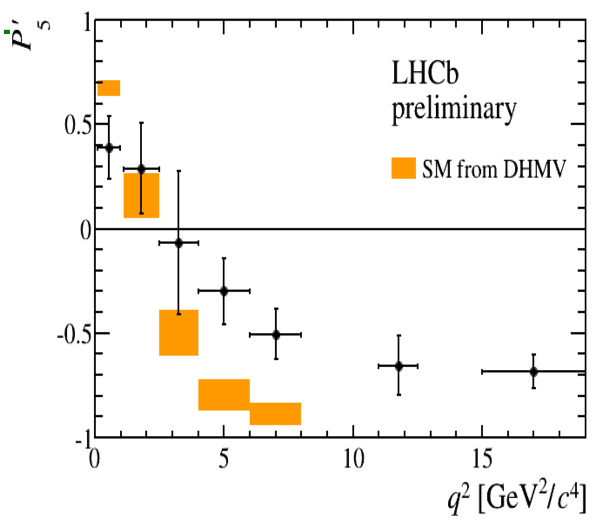
Best measurement of ϕ_s in $B_s \rightarrow J/\psi\phi$



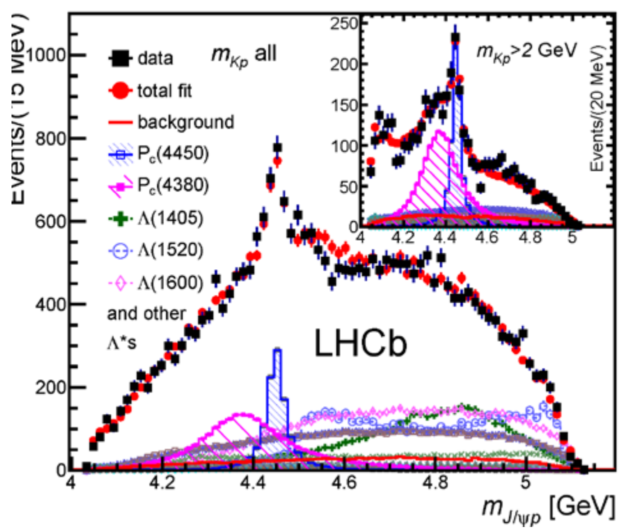
Observation of direct CP violation



Angular analysis in $B^0 \rightarrow K^{*0}\mu\mu$



Observation of pentaquarks

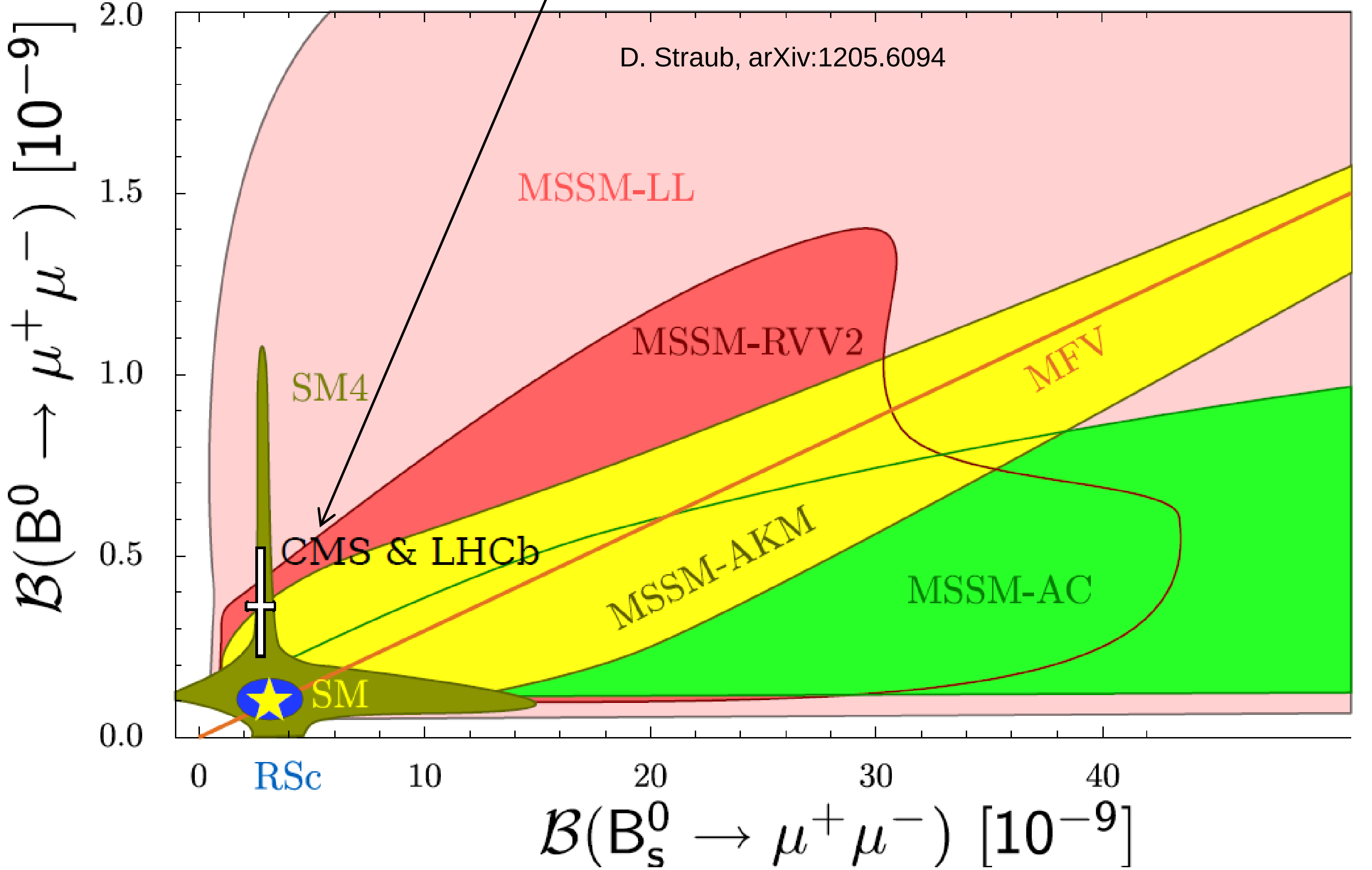


Example of impact on Super Symmetric Models

combined CMS & LHCb → result

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

Nature 522, 68–72



Expected evolution of luminosity in LHCb

	LHC era		HL-LHC era		
Run # (year)	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-23)	Run 4 (2025-28)	Run 5+ (2030+)
Integrated luminosity	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}
	LHCb up to LS2		**after LHCb upgrade**		

Upgrade of LHCb during LS2 in 2019/20

LHCb up to 2019 → $\gtrsim$ 8 fb^{-1}:

- ✓ find or rule-out large sources of flavour symmetry breaking at the TeV scale
- ✓ explore forward region as general purpose detector (electroweak, QCD, exotica, heavy ions, …)

LHCb upgrade → $\geq$ 50 fb^{-1}:

- ✓ increase precision on quark flavour physics observables
- ✓ aim at experimental sensitivities comparable to theoretical uncertainties
- ✓ fully exploit LHC physics in the forward region

LHCb statistical sensitivity to flavour observables

Expected statistical uncertainties before and after the upgrade, compared to theory

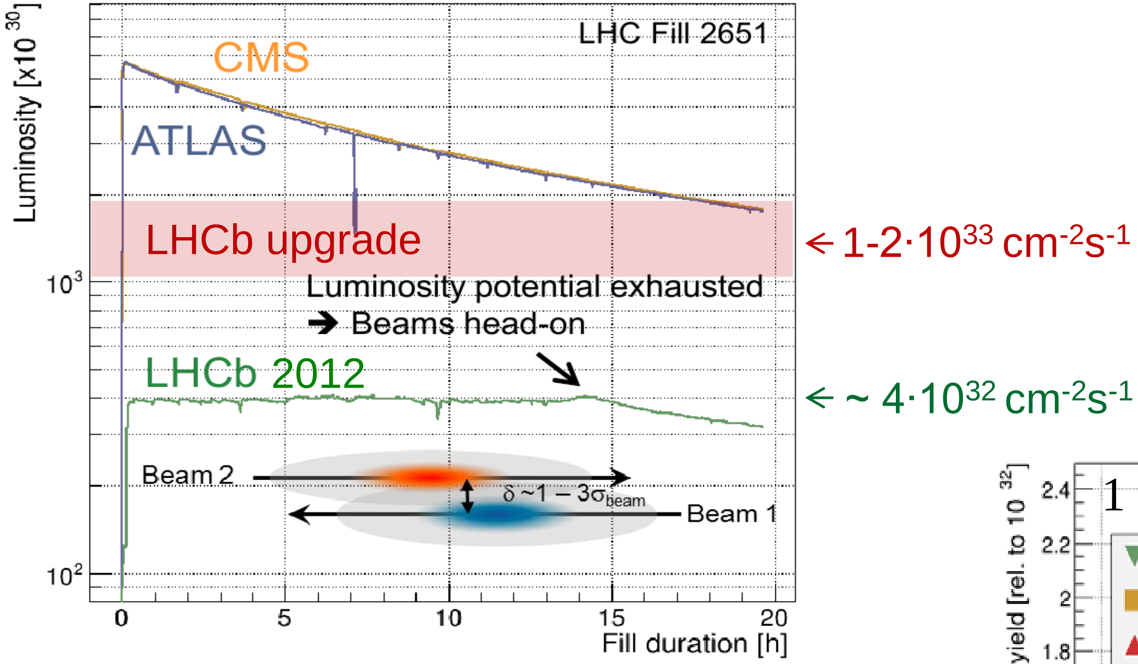
Type	Observable	LHC Run 1	LHCb 2018	Upgrade 50/fb	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

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

→ Experimental precision with upgraded detector comparable to theoretical uncertainties!

How to increase LHCb statistics significantly

2012 running conditions

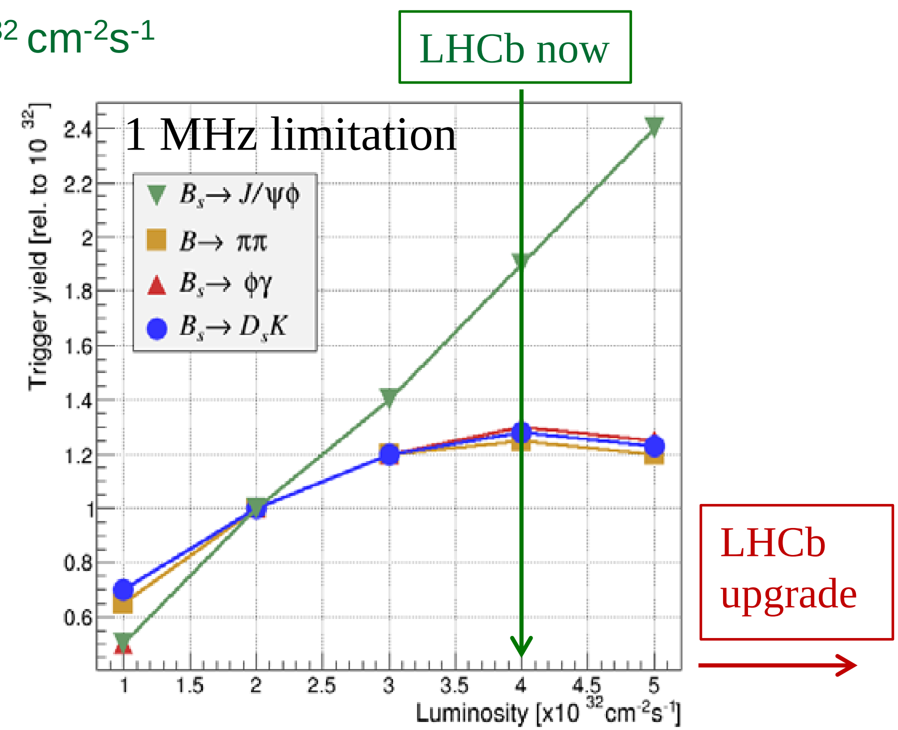


LHCb up to LS2

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

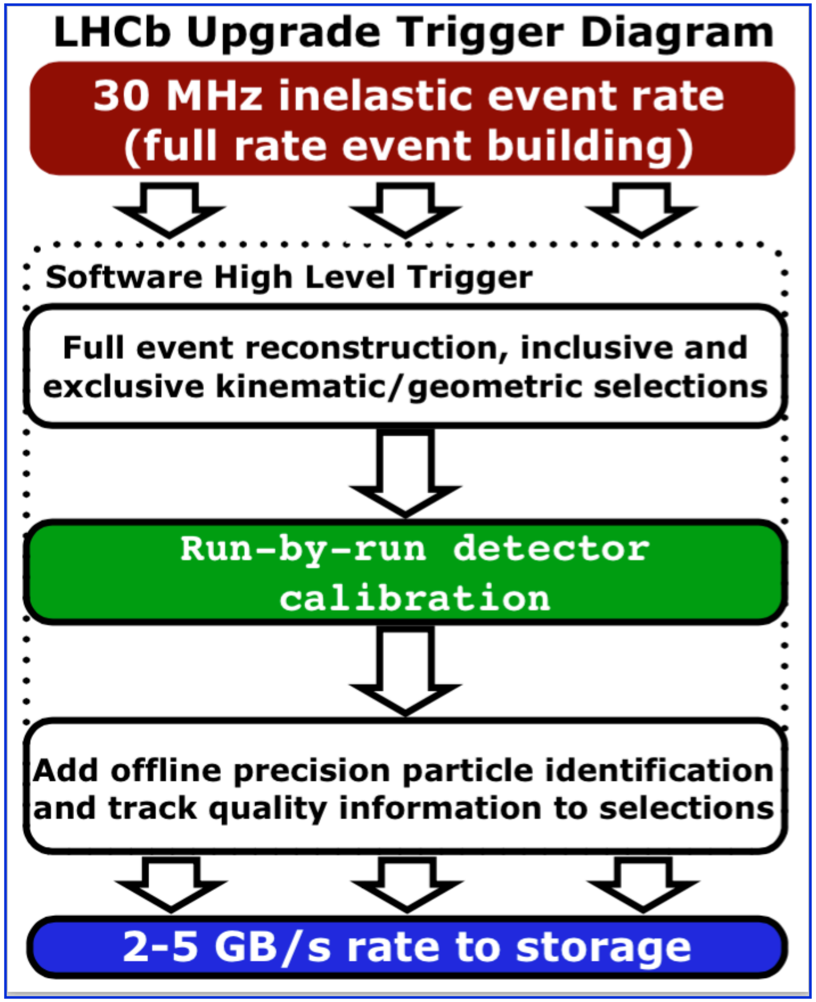
LHCb upgrade

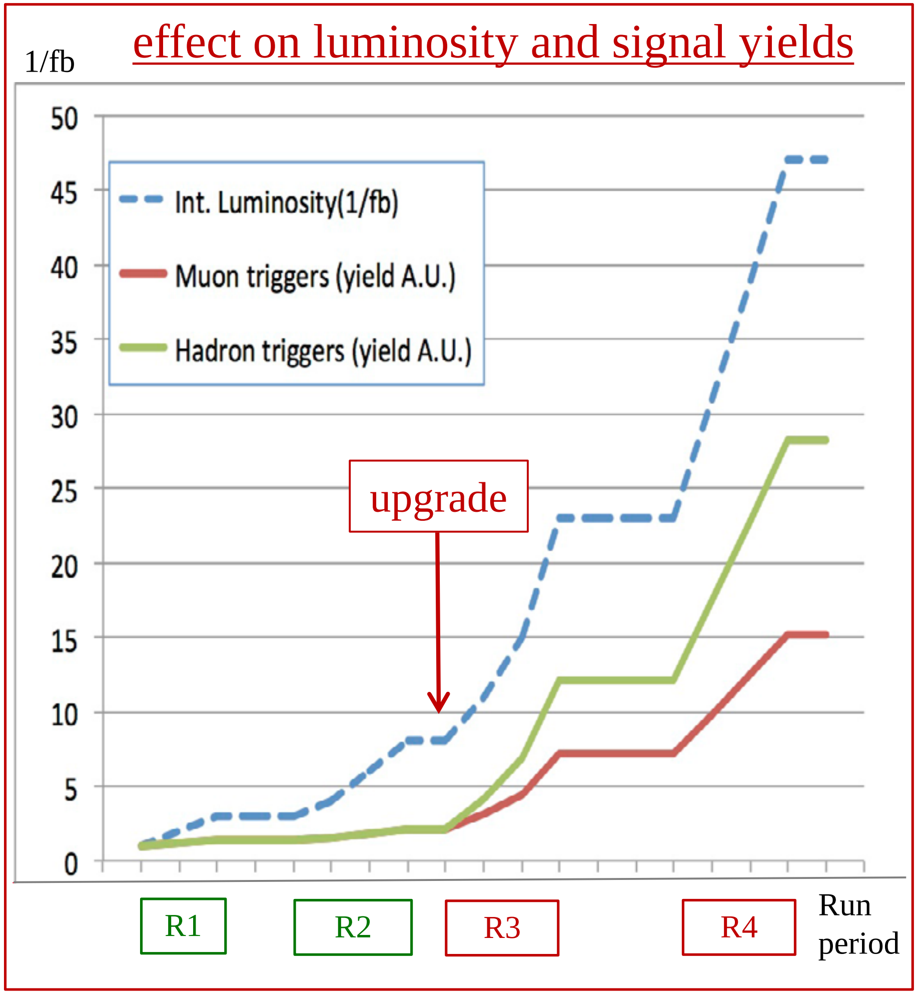
- increase luminosity to a levelled $1\text{-}2 \cdot 10^{33}\ cm^{-2}s^{-1}$, pile-up ~5
- run fully flexible & efficient software trigger up to 40 MHz
- record ~20-50 kHz



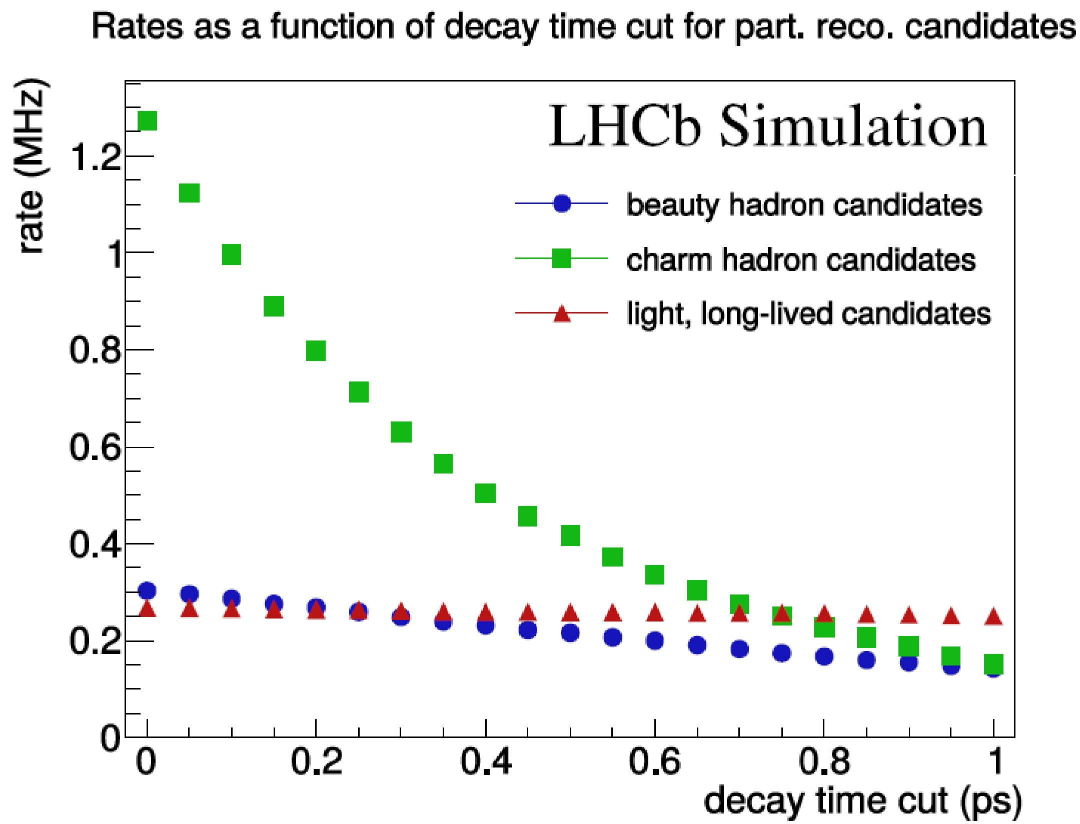
Trigger upgrade

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





Expected signal rates



<u>Rate of reconstructible hadrons</u>:

c-hadrons: 80 GB/s

b-hadrons: 27 GB/s

light, long-lived hadrons: 26 GB/s

<u>compared to 2-5 GB/s allowed to tape</u>

→ turbo stream = real time data analysis!
(already implemented for Run 2)

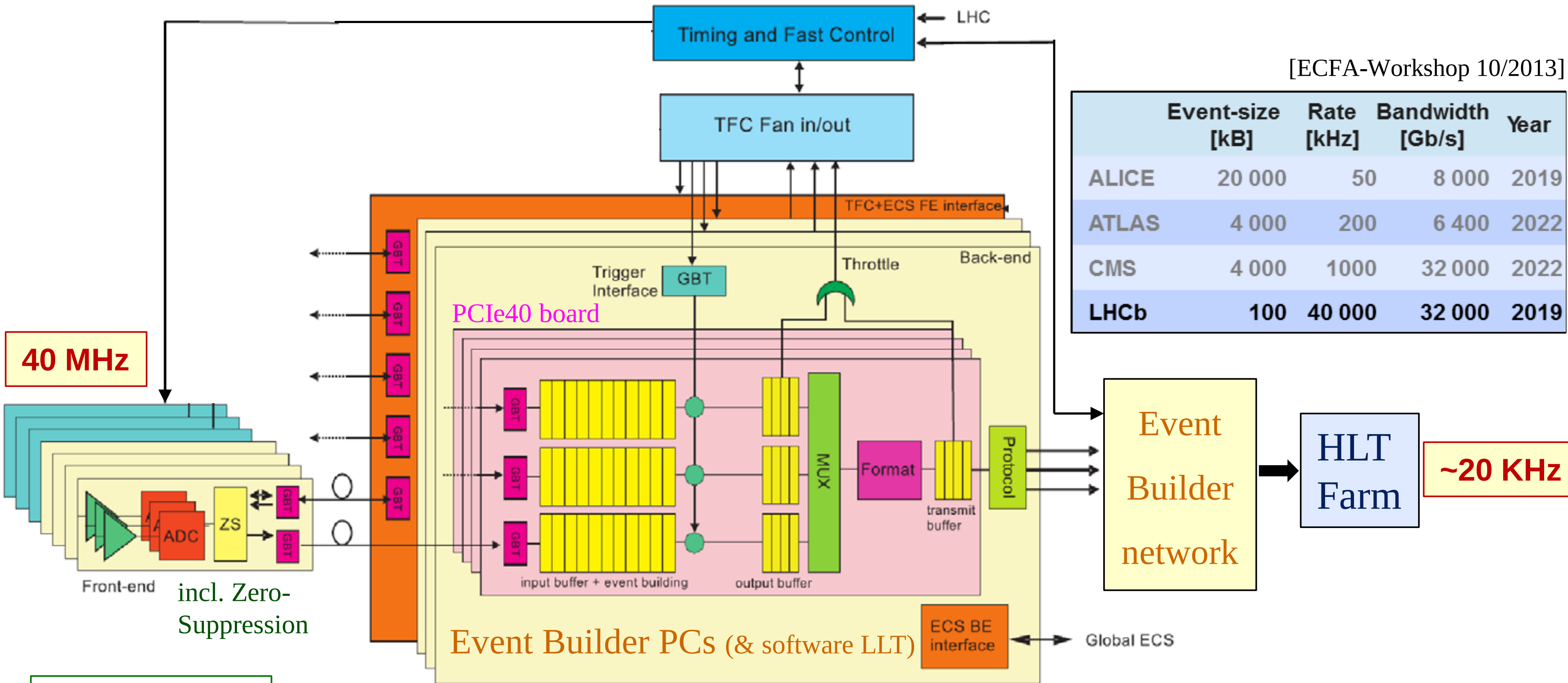
The future of triggers

Triggers today

Triggers in the future

Gligorov 2014

40 MHz architecture overview



[ECFA-Workshop 10/2013]

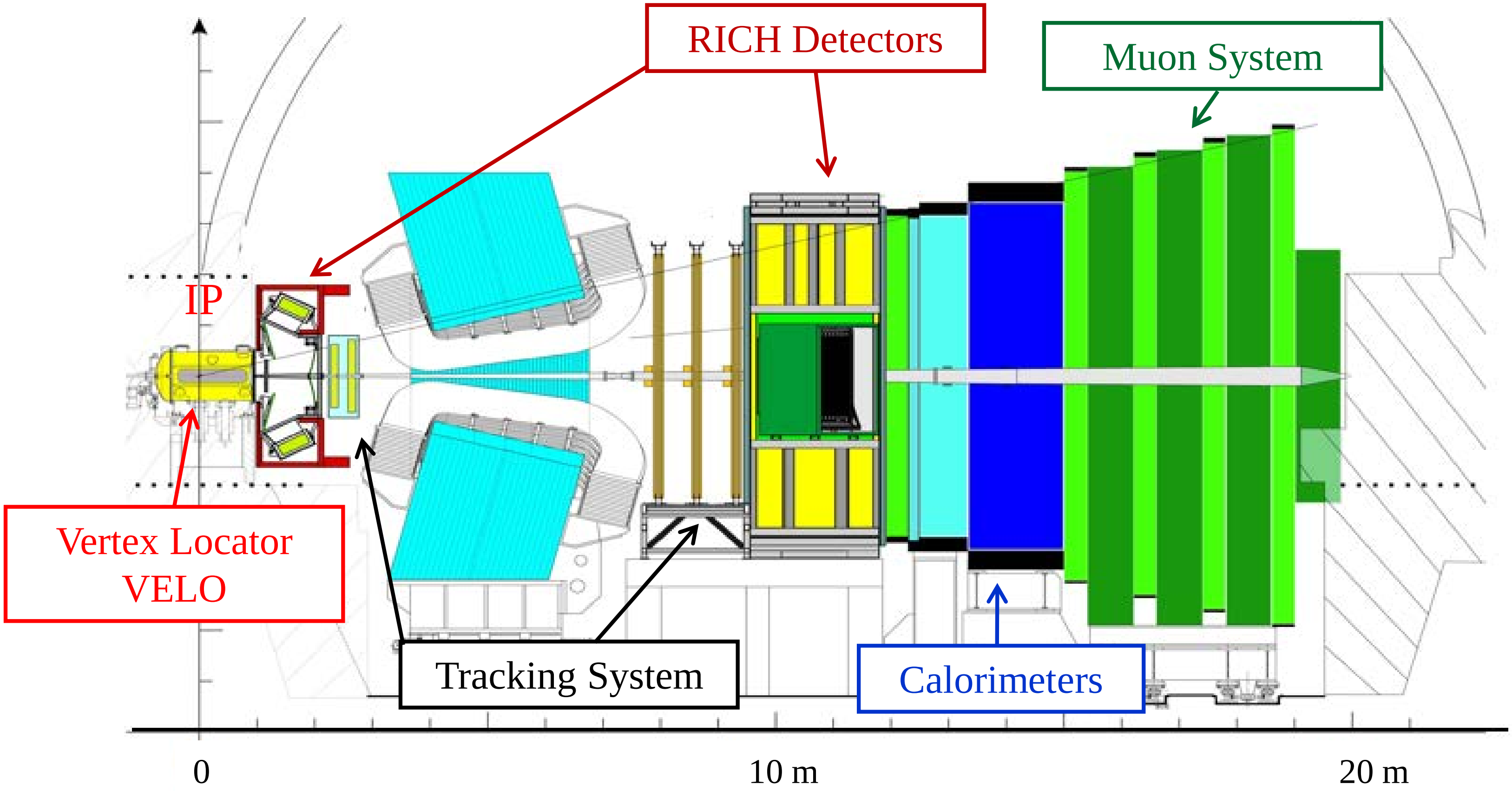
	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year
ALICE	20 000	50	8 000	2019
ATLAS	4 000	200	6 400	2022
CMS	4 000	1000	32 000	2022
LHCb	**100**	**40 000**	**32 000**	**2019**

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

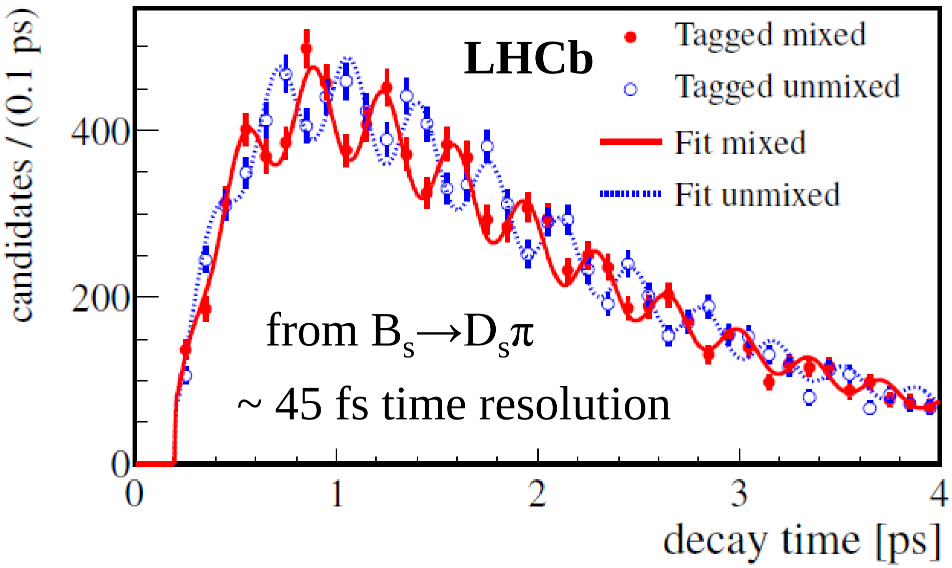
- ✓ upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- ✓ replace complete sub-systems with embedded FE electronics
- ✓ adapt sub-systems to increased occupancies due to higher luminosity
- ➢ keep excellent performance of sub-systems with 5 times higher luminosity and 40 MHz R/O



Vertex reconstruction with VELO

J. Instrum. 9 (2014) P09007

Current detector

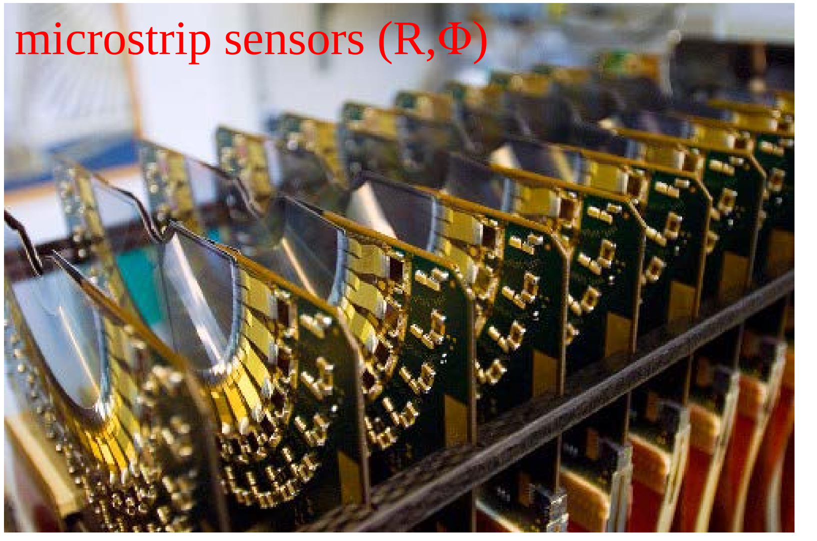


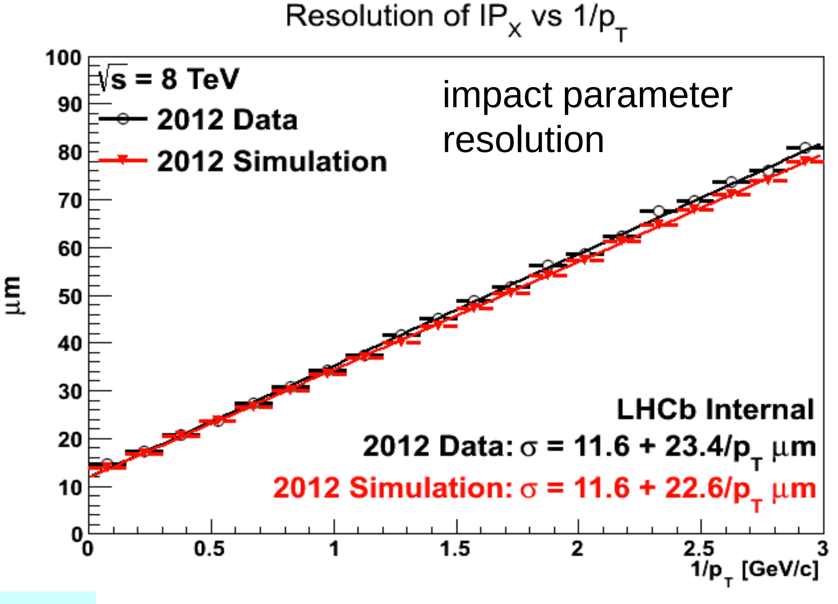
from $B_s \to D_s \pi$

~ 45 fs time resolution

New J. Phys. 15 (2013) 053021

microstrip sensors (R,Φ)



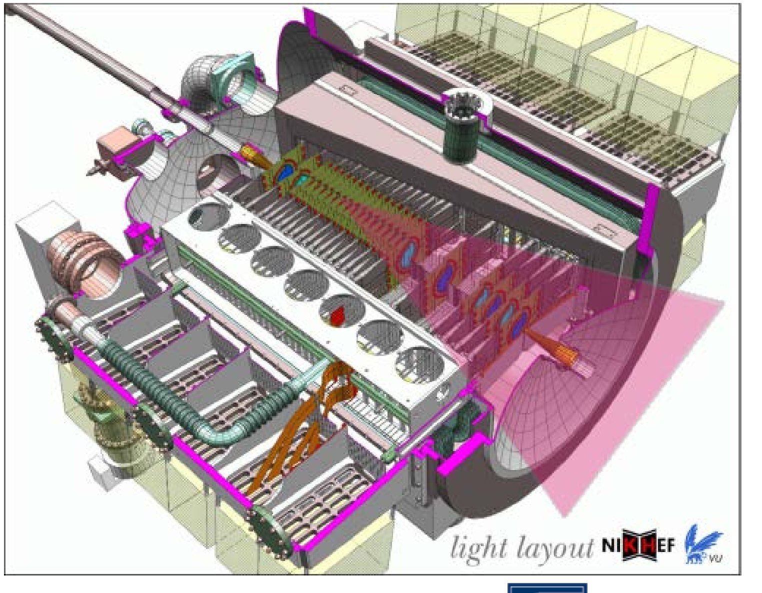


impact parameter resolution

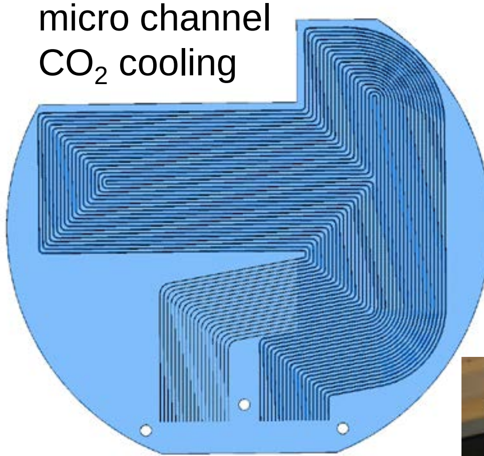
2012 Data: $\sigma = 11.6 + 23.4/p_T$ μm

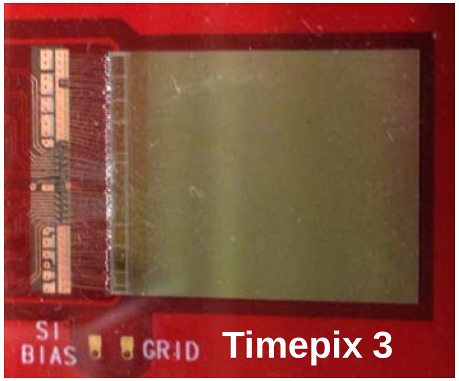
2012 Simulation: $\sigma = 11.6 + 22.6/p_T$ μm

movables halves → 5.5 mm from beam



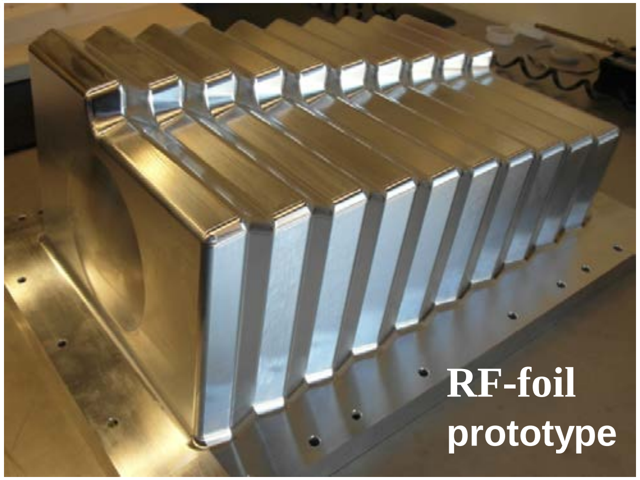
VELO upgrade





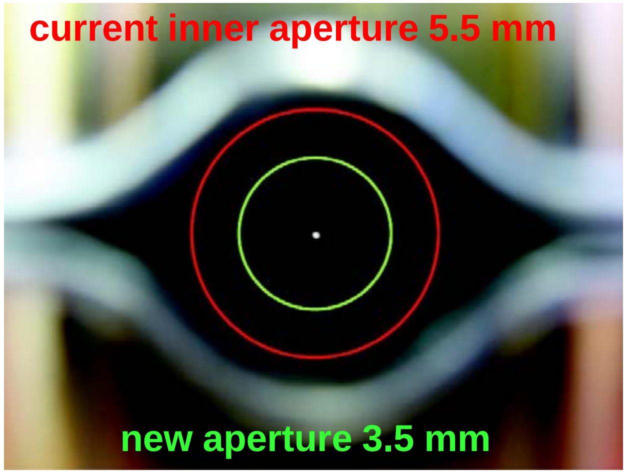
Upgrade challenge:

- ✓ 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



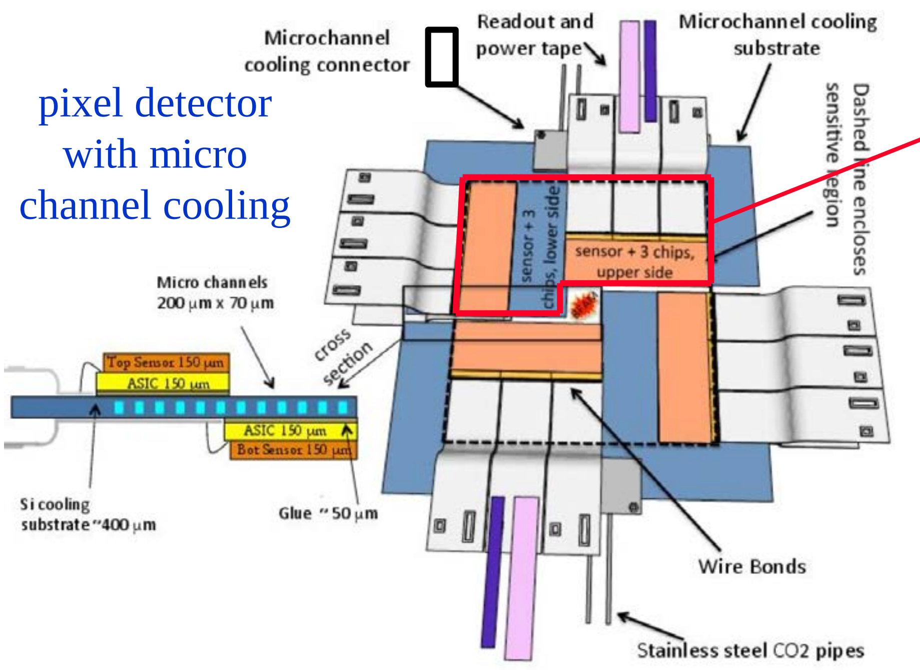
Technical choice :

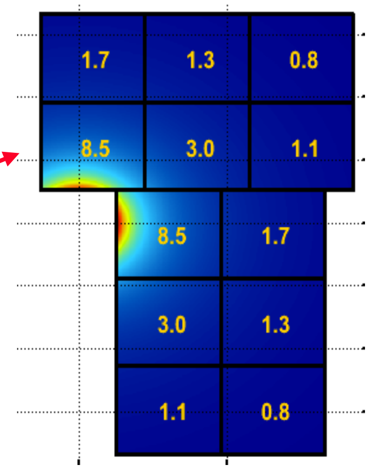
- ✓ 55x55 μm^2 pixel sensors with micro channel CO_2 cooling
- ✓ 40 MHz VELOPIX (evolution of TIMEPIX 3, Medipix)
  - ➢ 130 nm technology to sustain ~400 MRad in 10 years
  - ➢ VELOPIX hit-rate = ~8 x TIMEPIX 3 rate
- ✓ replace RF-foil between detector and beam vacuum
  - ➢ reduce thickness from 300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



VELO upgrade

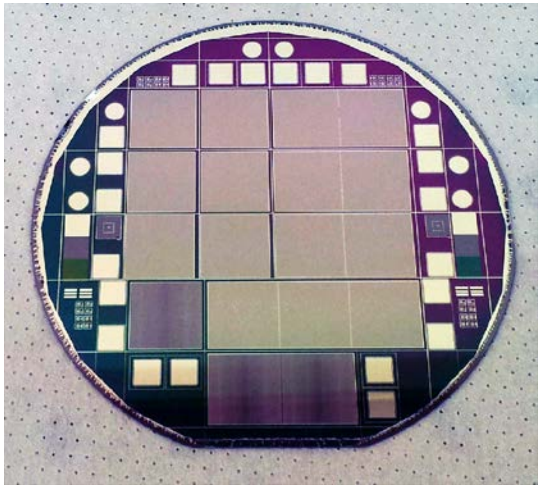
pixel detector with micro channel cooling

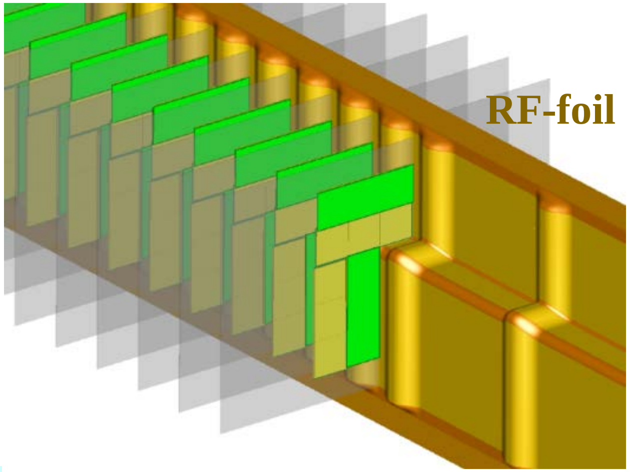


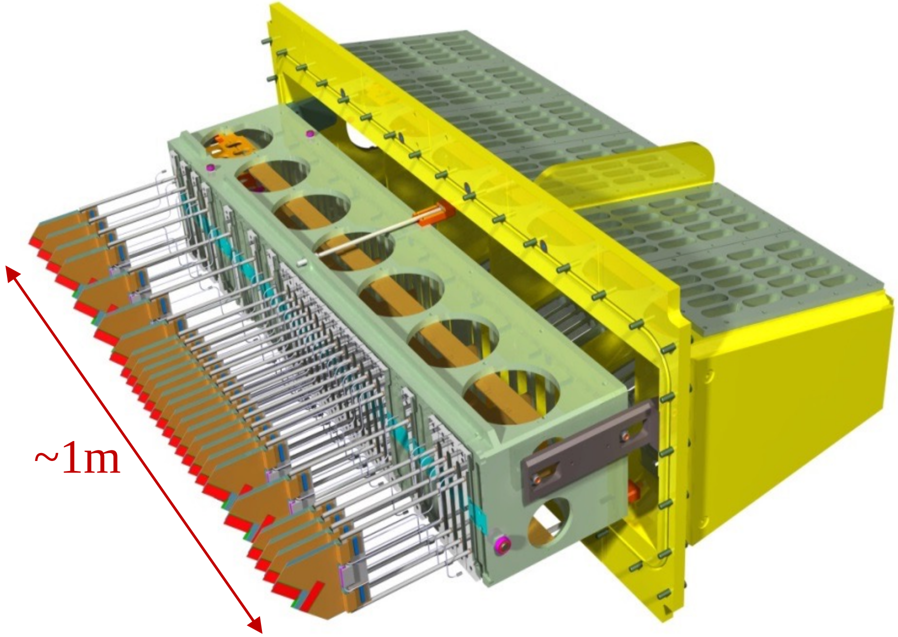


tracks/chip/event at $L=2\cdot10^{33}\ \mathrm{cm^{-2}s^{-1}}$

Prototype pixel sensor

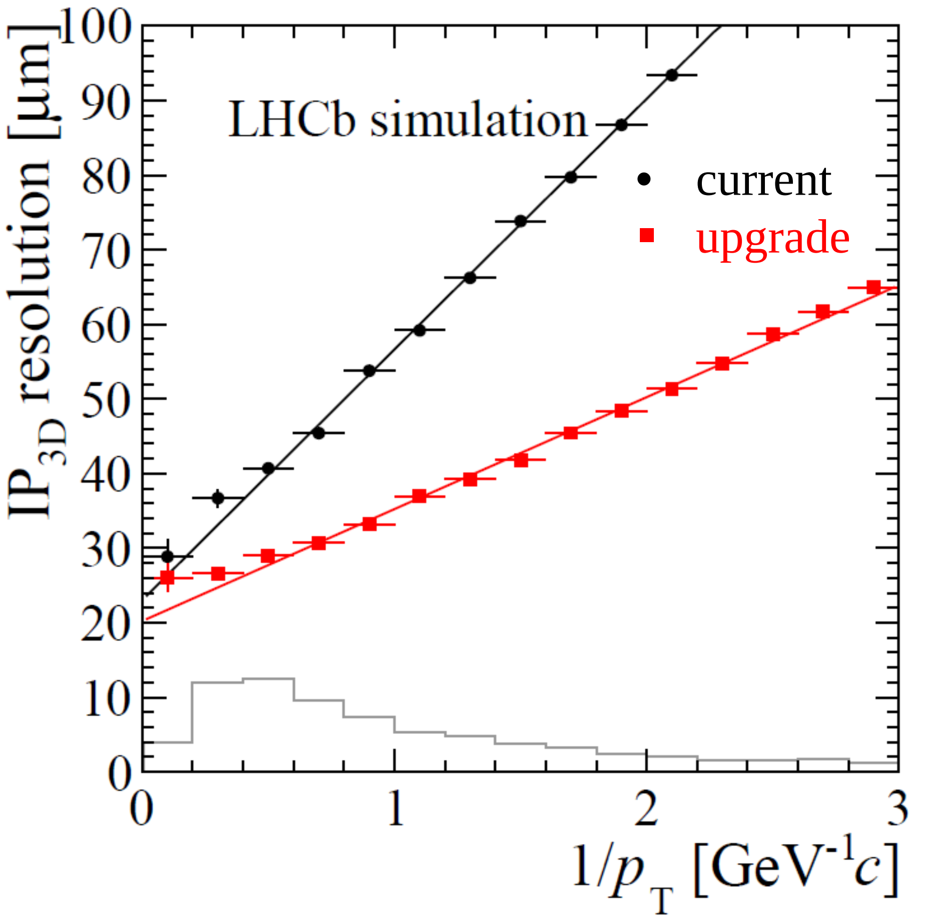






VELO upgrade

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

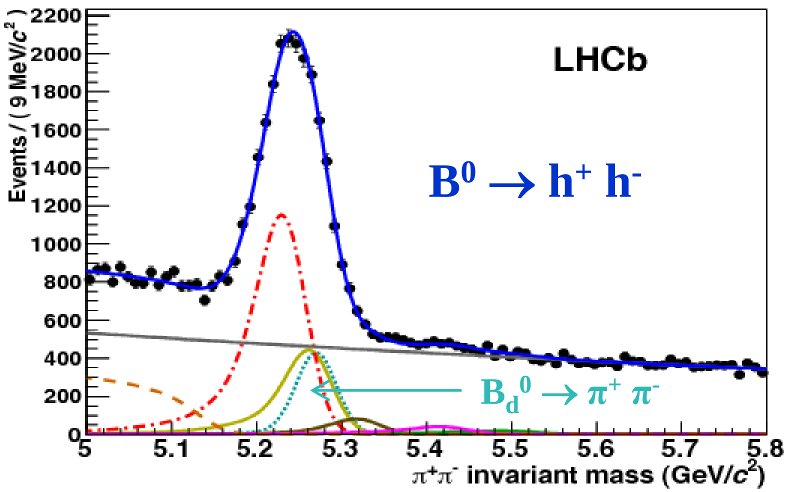


note: full GEANT Monte Carlo with standard LHCb simulation framework

Particle Identification with RICH

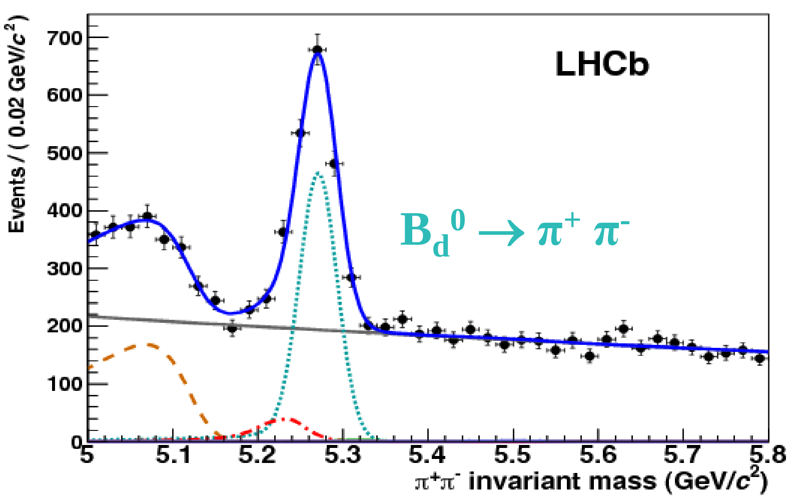
Eur. Phys. J. C 73 (2013) 2431

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

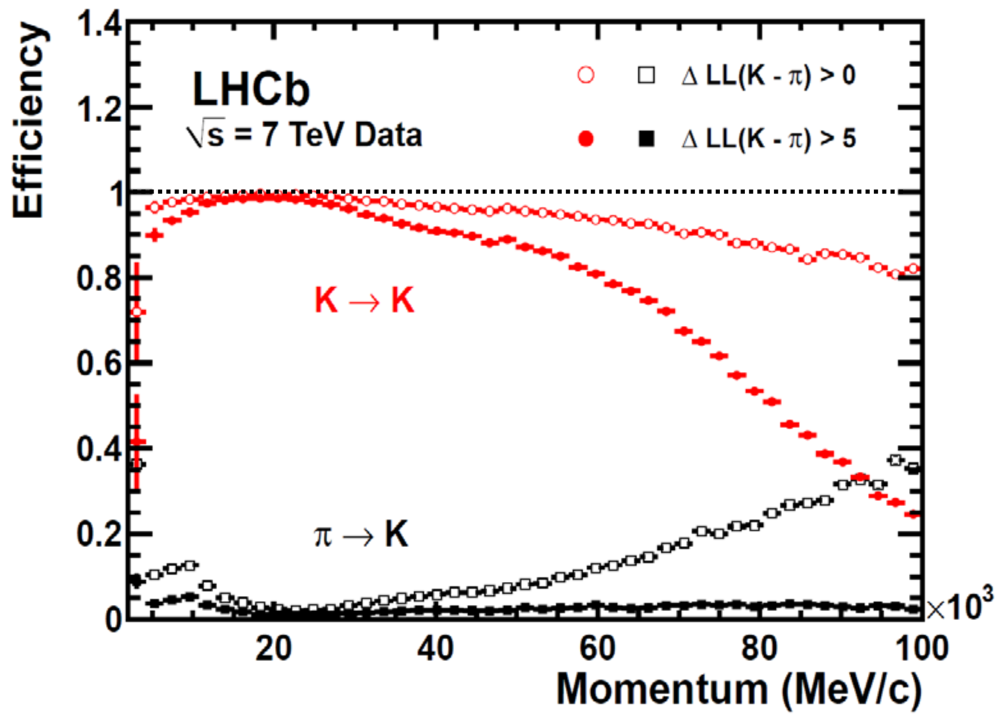


↓ particle identification of 2 π

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

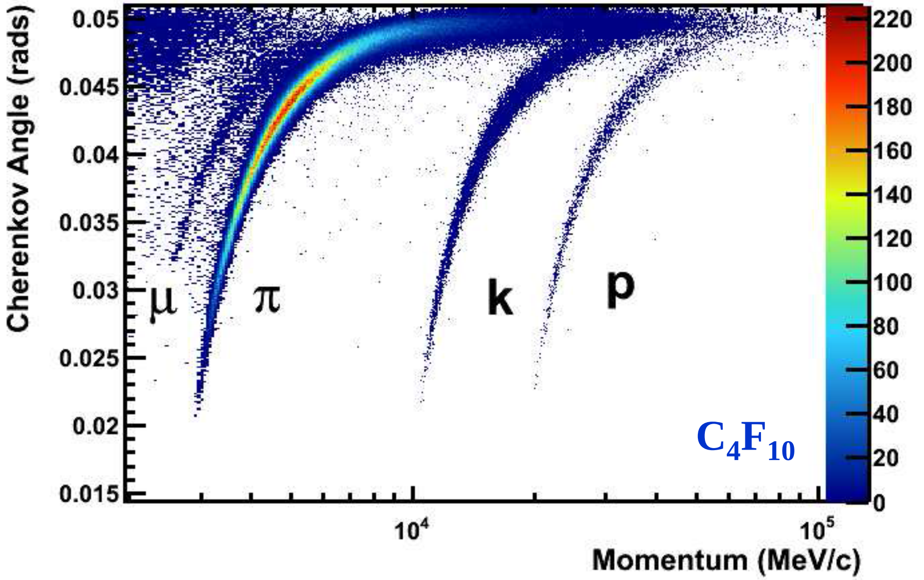


K-identification and π-misidentification efficiencies vs. particle momentum

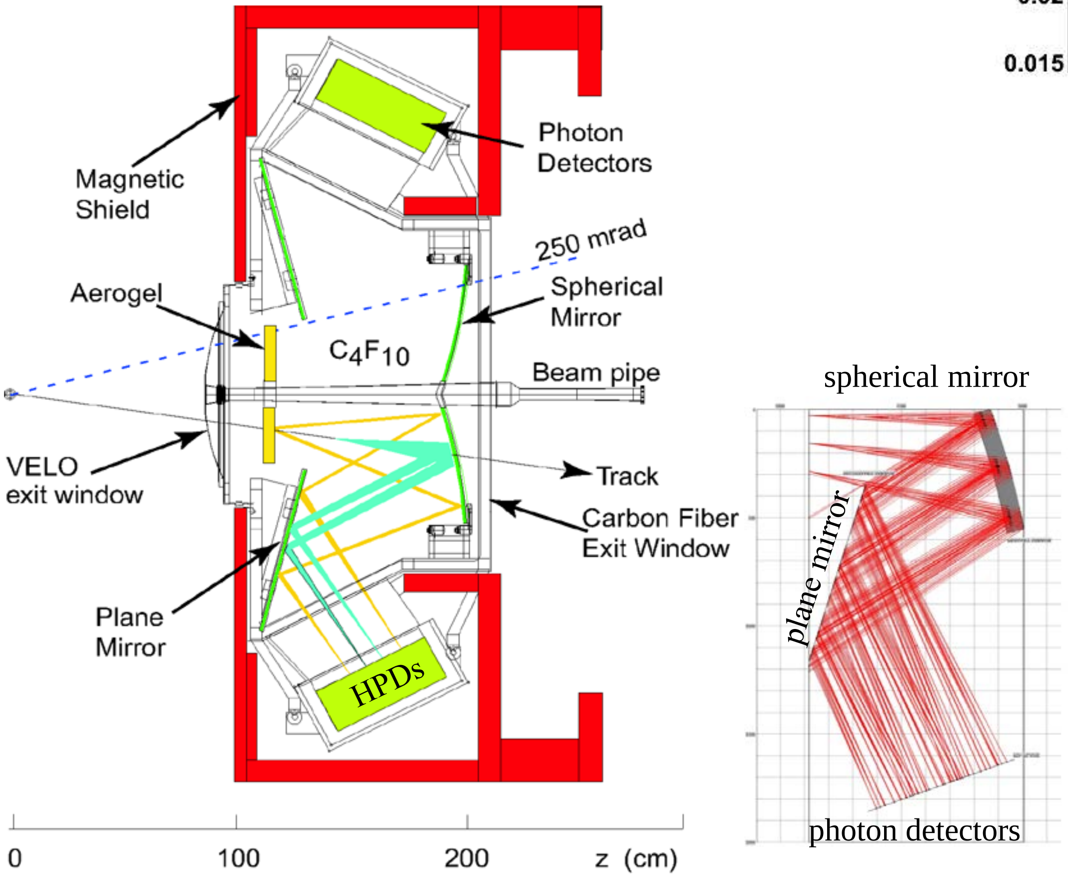


RICH(1) optics

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

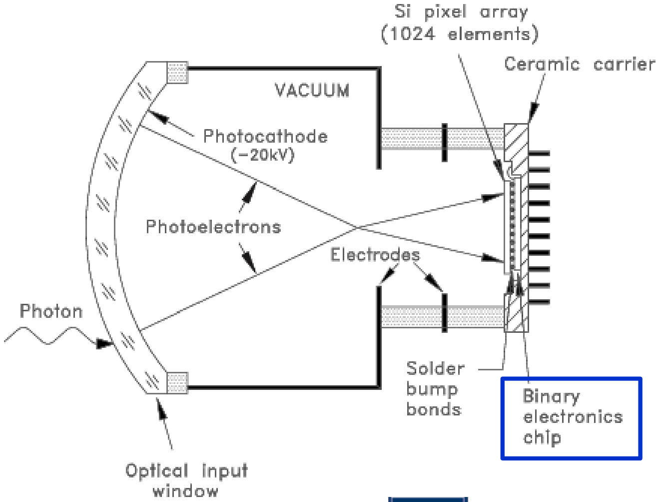


RICH 1



Hybrid **P**hoton **D**etector

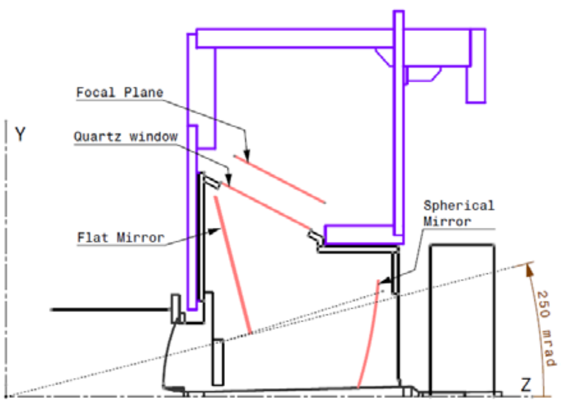
with embedded 1 MHz R/O chip



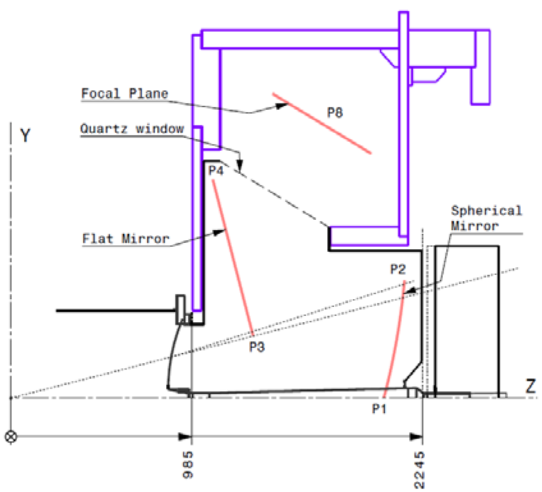
RICH upgrade

optimise RICH1 optics

current



upgrade

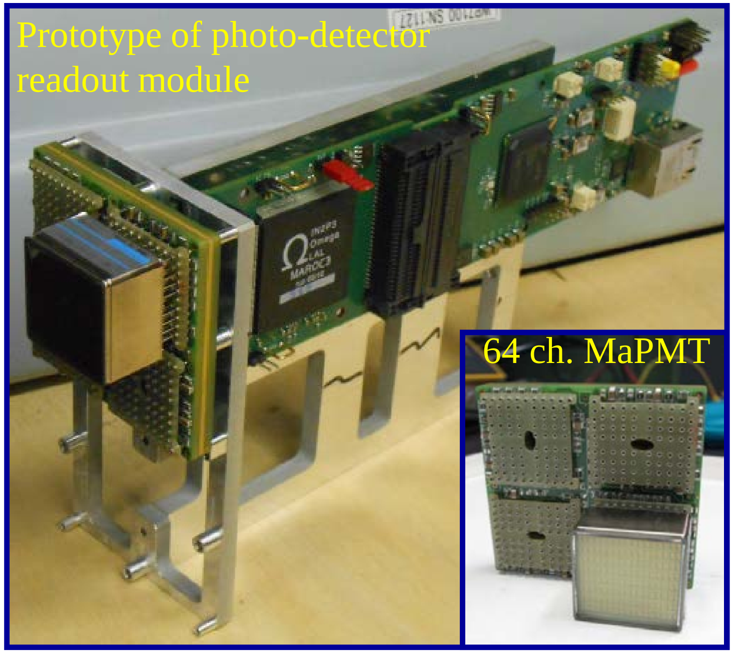


Luminosity of $2 \cdot 10^{33}$ cm^{-2}s^{-1} → adapt to high occupancies

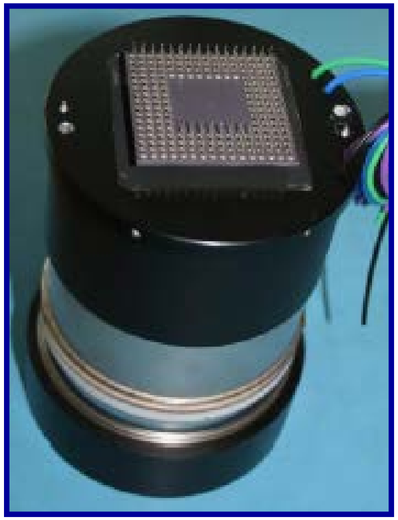
- aerogel radiator removed
- modify optics of RICH1 to spread out Cherenkov rings (optimise gas enclosure without modifying B-shield)

40 MHz readout → replace HPDs due to embedded FE

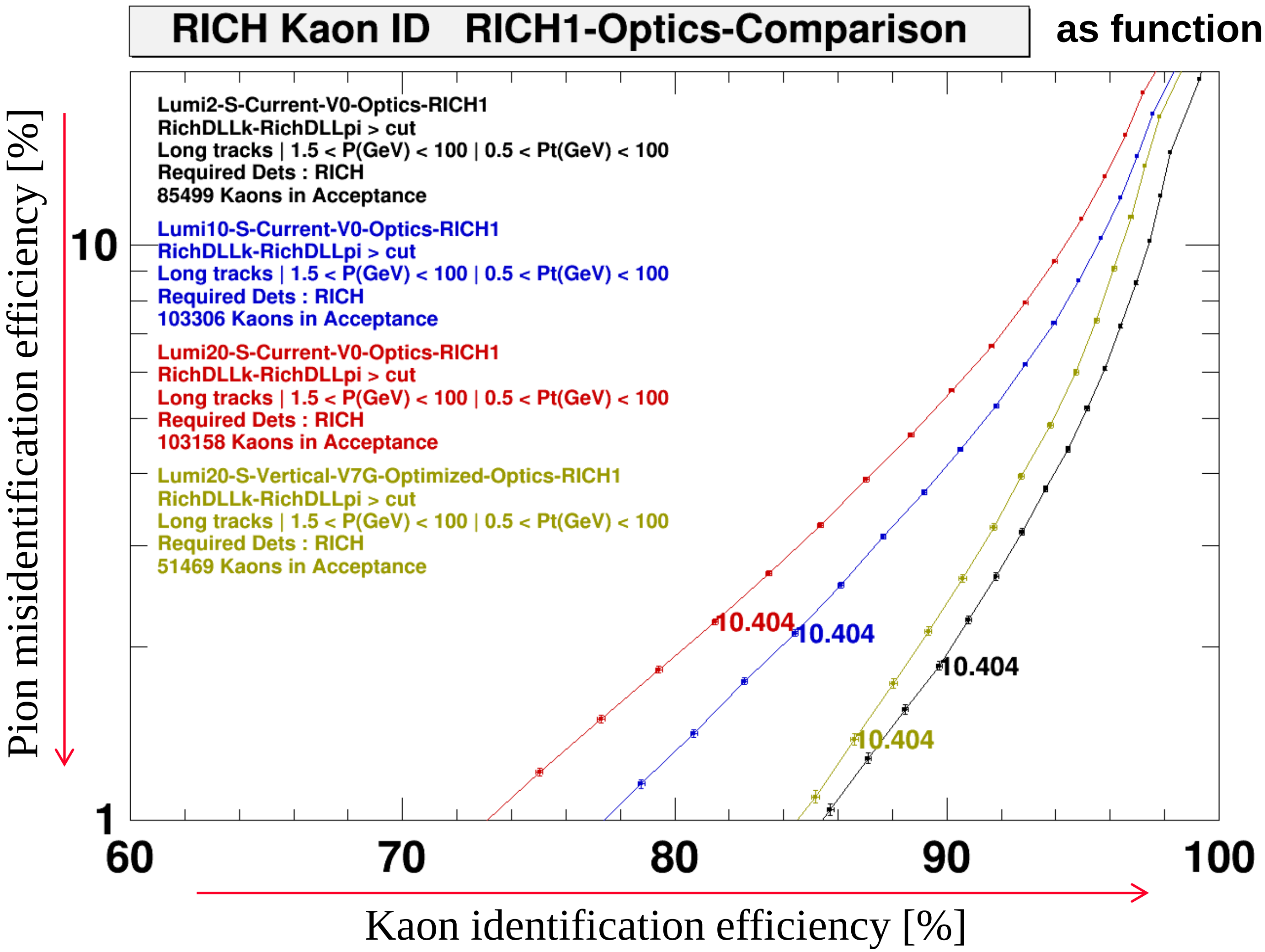
- 64 ch. multi-anode PMTs (baseline)
- 40 MHz Front-End: CLARO chip



HPD R&D with external electronics



RICH upgrade



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

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

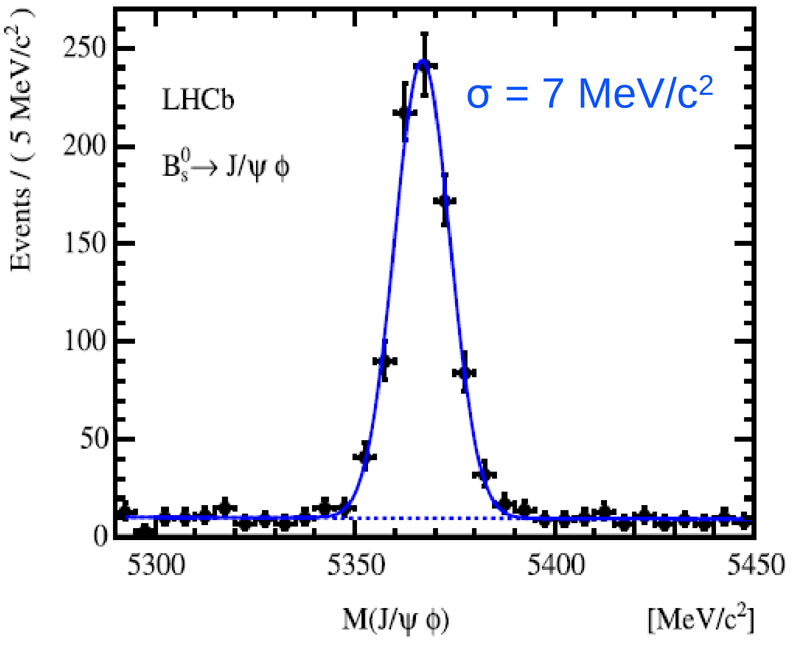
note:
full GEANT MC with standard LHCb simulation framework

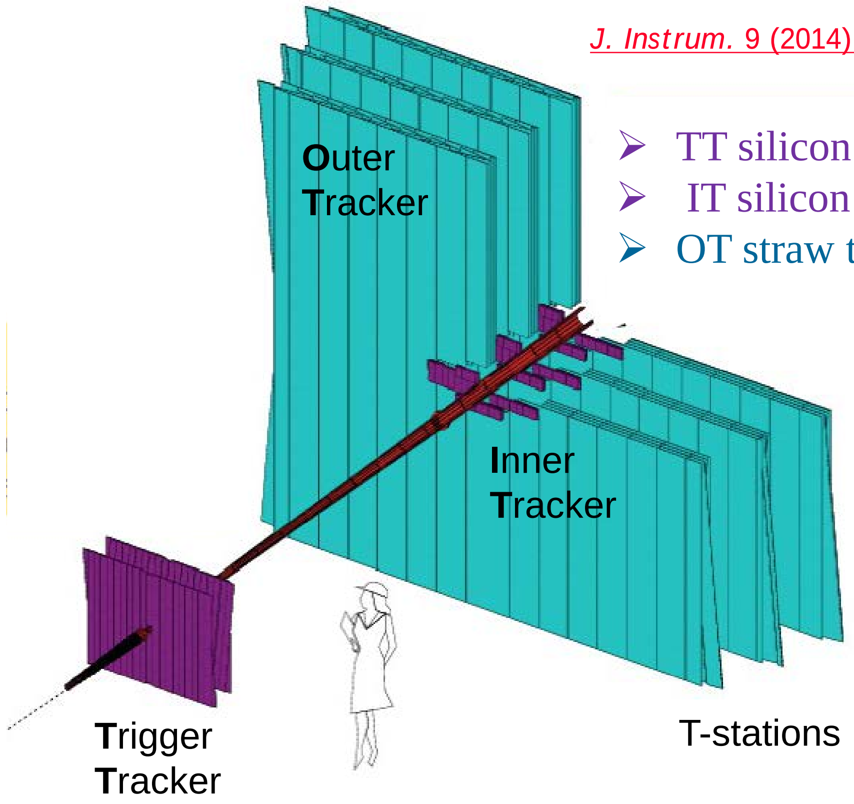
Tracking System

J. Instrum. 9 (2014) P01002

- excellent mass resolution
- very low background, comparable to e^+e^- machines
- worlds best mass measurements

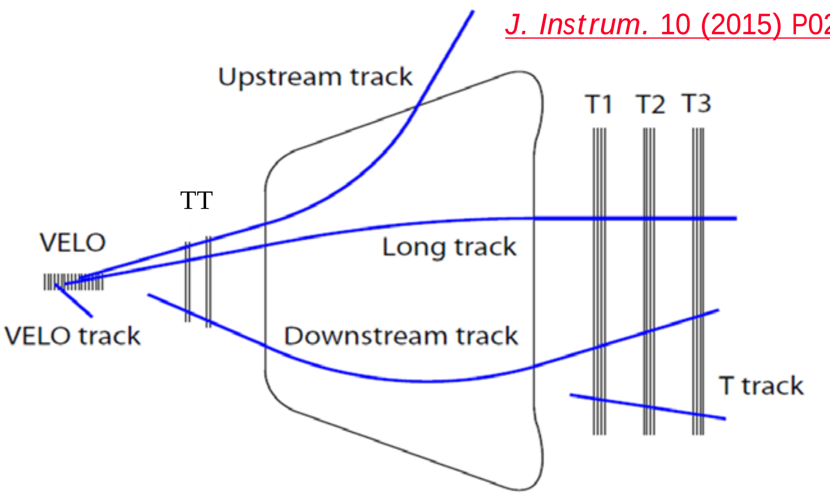
PLB 708 (2012) 241





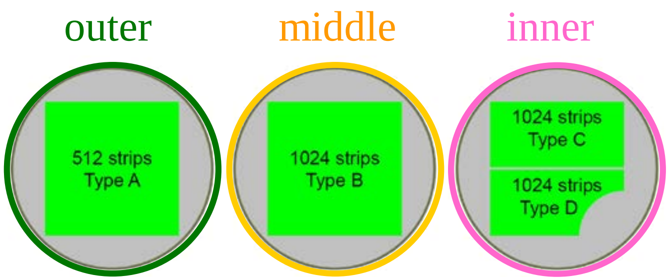
- TT silicon
- IT silicon
- OT straw tubes

J. Instrum. 10 (2015) P02007



TT upgrade: Upstream Tracker (UT)

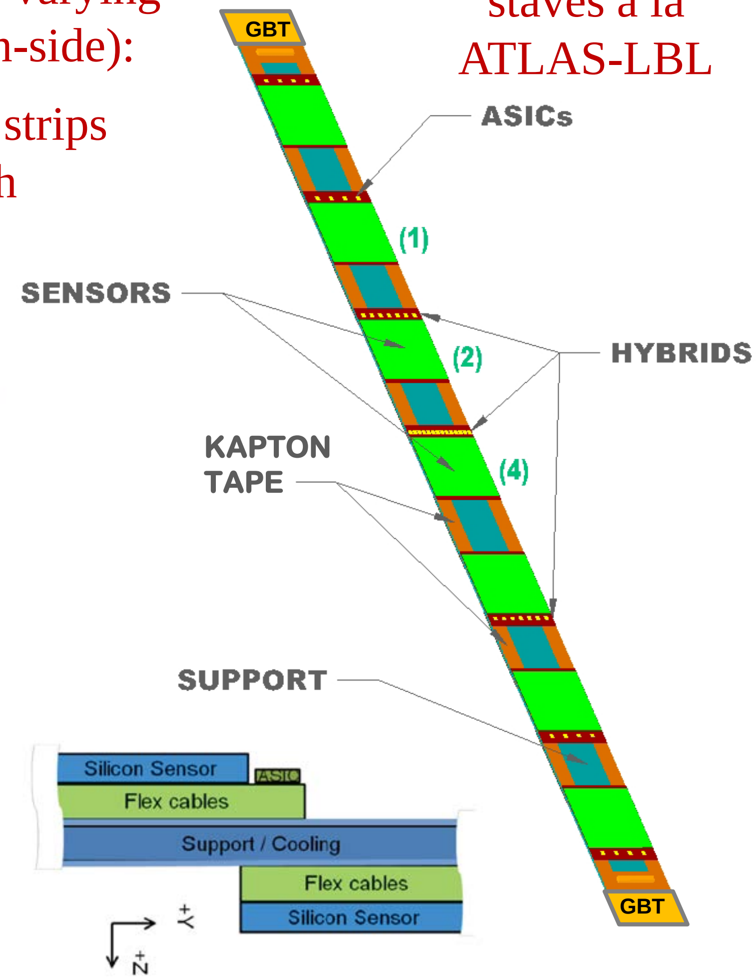
silicon strip detector

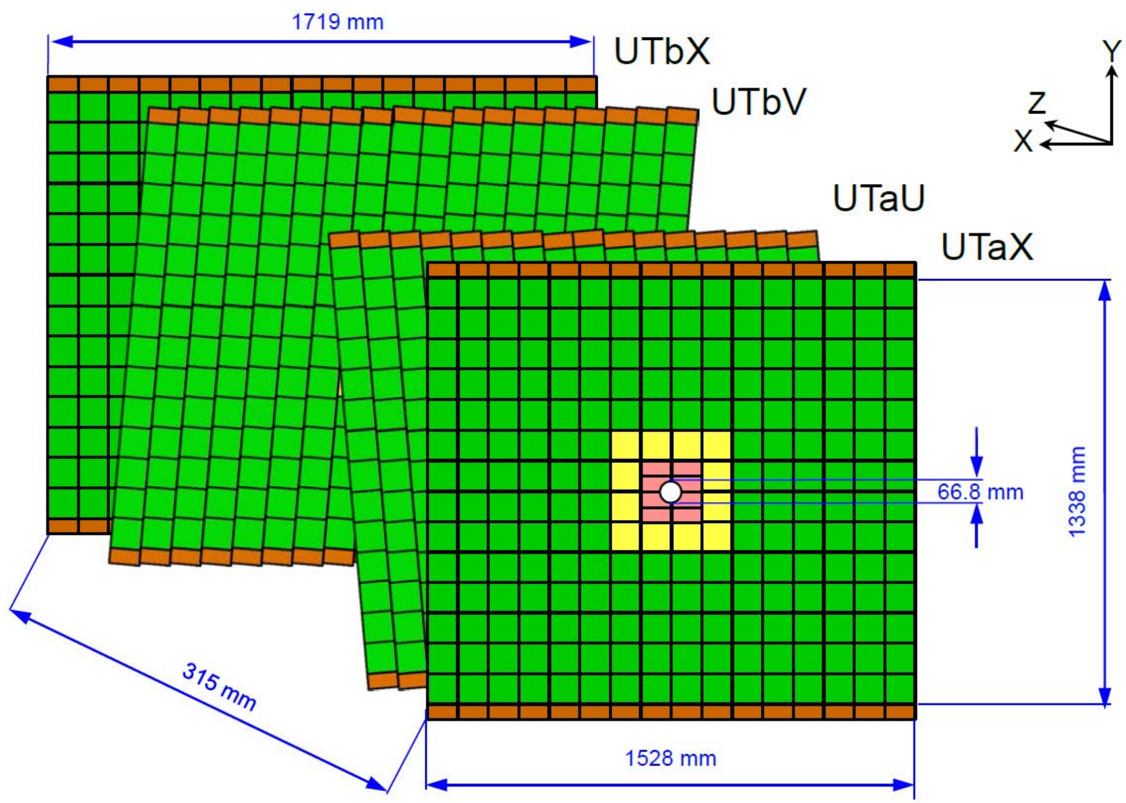


adapt segmentation to varying occupancies (out → in-side):

- 99 → 51 mm long strips
- 190 → 95 μm pitch
- p^+-in-n → n^+-in-p

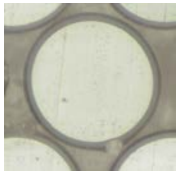
staves a la ATLAS-LBL





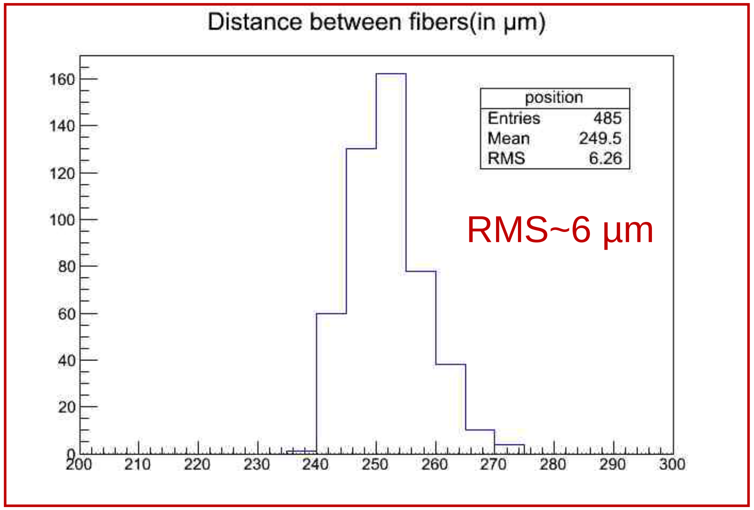
40MHz silicon strip R/O → SALT chip

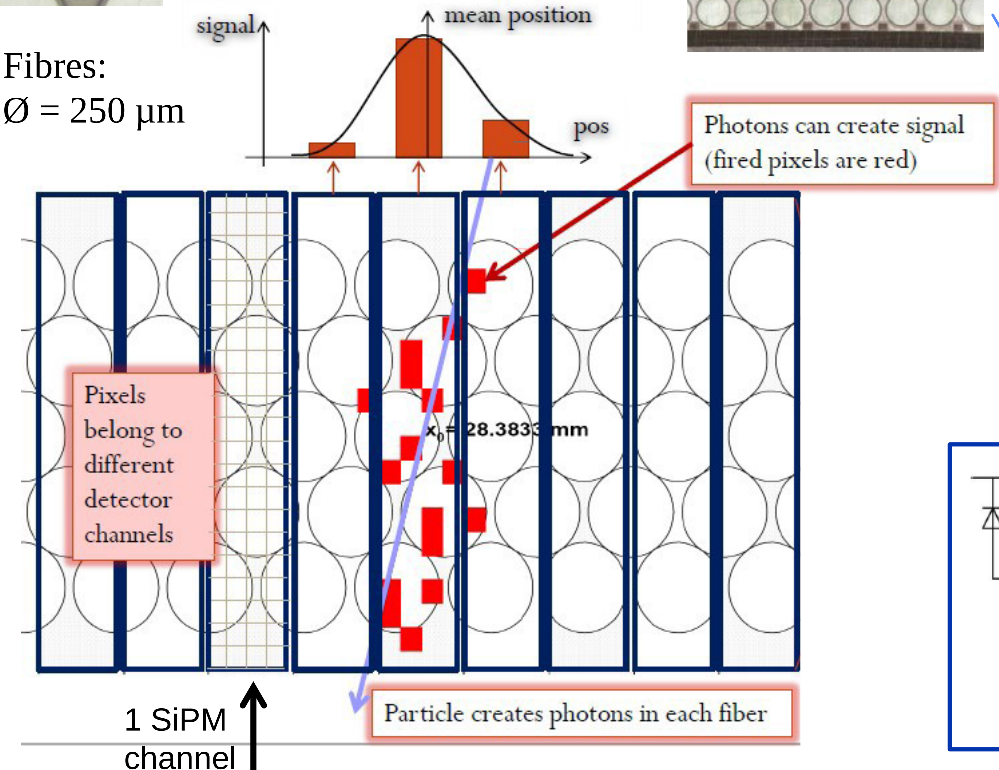
T-stations upgrade: Fibre Tracker (FT)

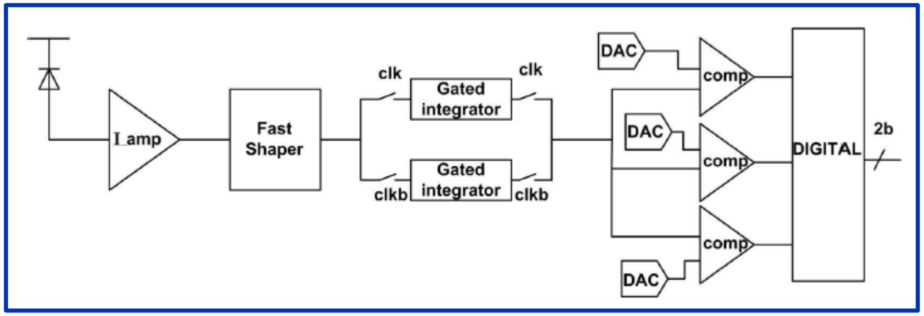


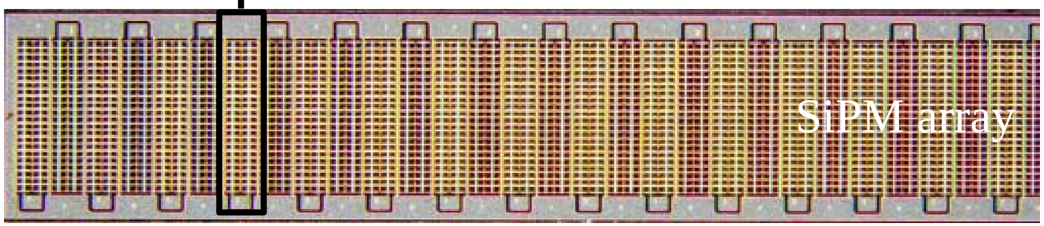
Fibres:
Ø = 250 μm

scintillating-fibre mat with 6 layers









readout by dedicated 128 ch.
40 MHz PACIFIC chip

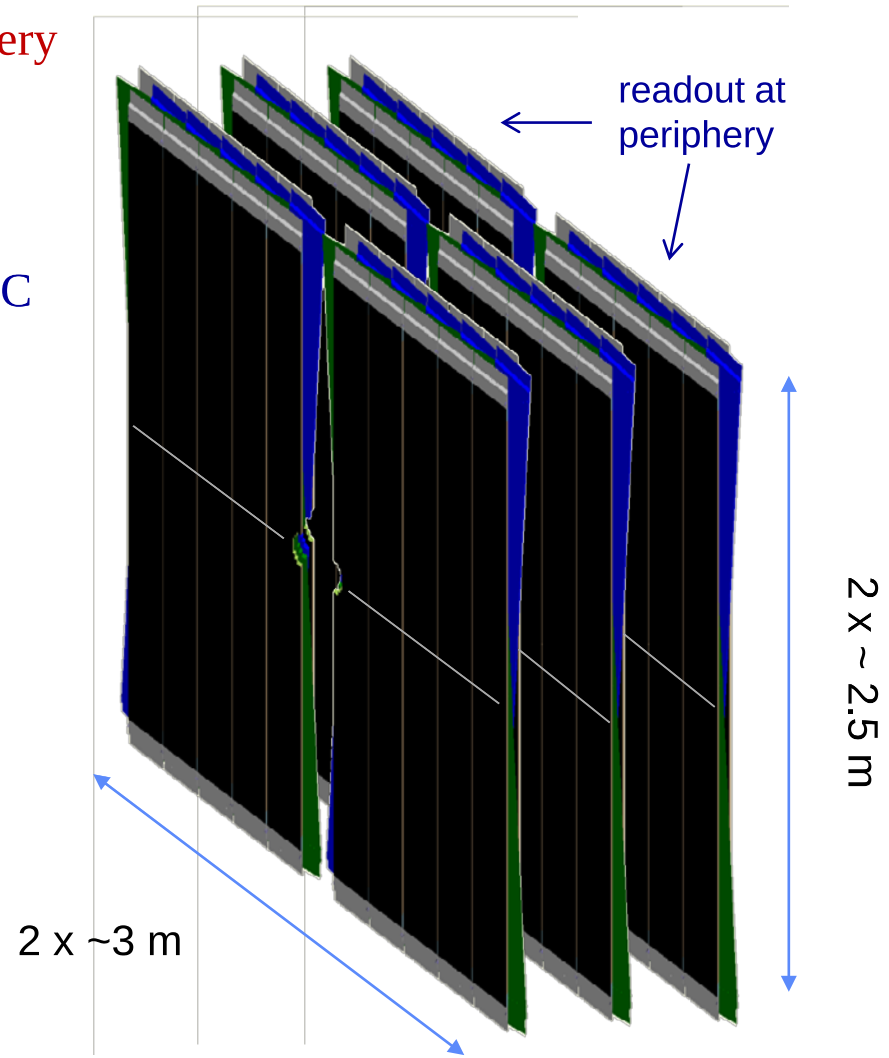
- 3 thresholds (2 bits)
- sum threshold (FPGA)

T-stations upgrade: Fibre Tracker (FT)

- 3 stations of X-U-V-X (±5° stereo angle) scintillating fibre planes
- every plane made of 6 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

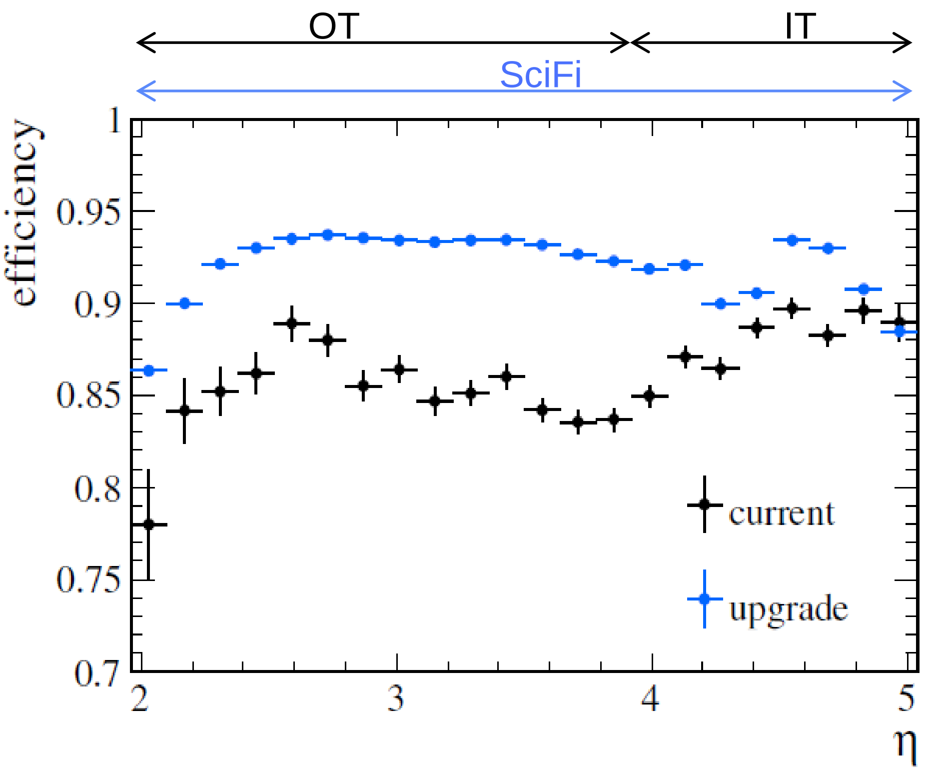
Benefits of the SciFi concept:
- ✓ a single technology to operate
- ✓ uniform material budget
- ✓ SiPM + infrastructure outside acceptance
- ✓ fine channel granularity of 250 μm
- ✓ x-position resolution of ~75 μm
- ✓ high hit detection efficiency (≥ 99%)
- ✓ fast pattern recognition for HLT



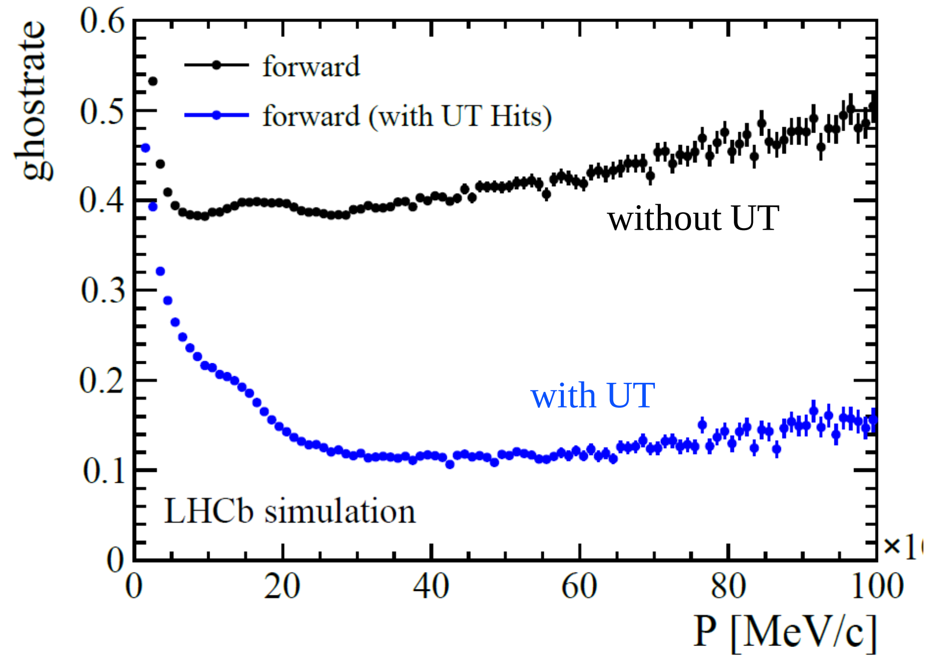
Tracking performance

Performance of the forward pattern recognition algorithm

Efficiency for $B_s \rightarrow \Phi\Phi$ events at upgrade conditions: current and upgraded detector



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 available CPU budget with upgraded Event Filter Farm: ~13 ms (10 times 2012)

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

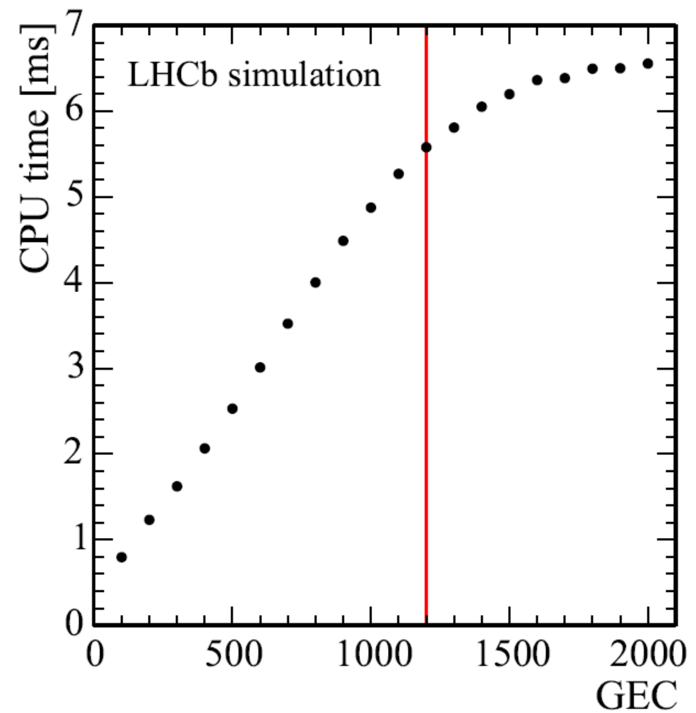
Tracking Algorithm	CPU time[ms] No GEC	CPU time[ms] GEC = 1200	
VELO tracking	2.3	2.0	
VELO-UT tracking	1.4	1.3	
Forward tracking	2.5	1.9	
PV finding	0.40	0.38	
Total @29 MHz		5.6	
Total	6.6	5.4	ms

→ 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)

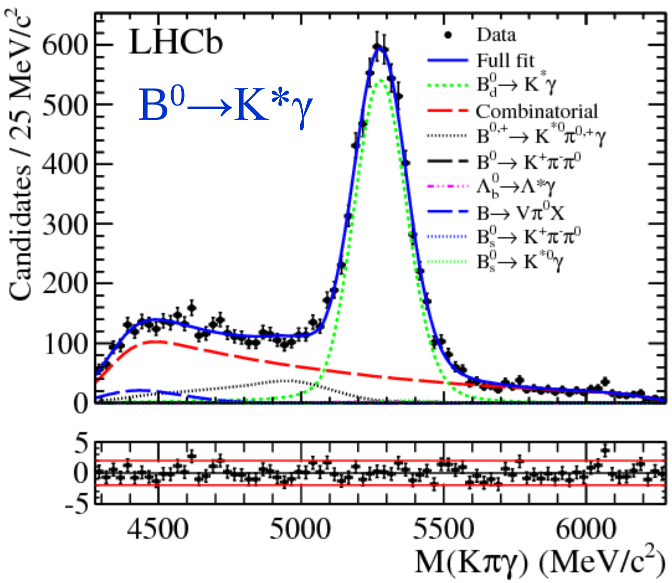
GEC: Global Event Cut
→ cut on event multiplicity
(e.g. hit multiplicity of sub-detector)

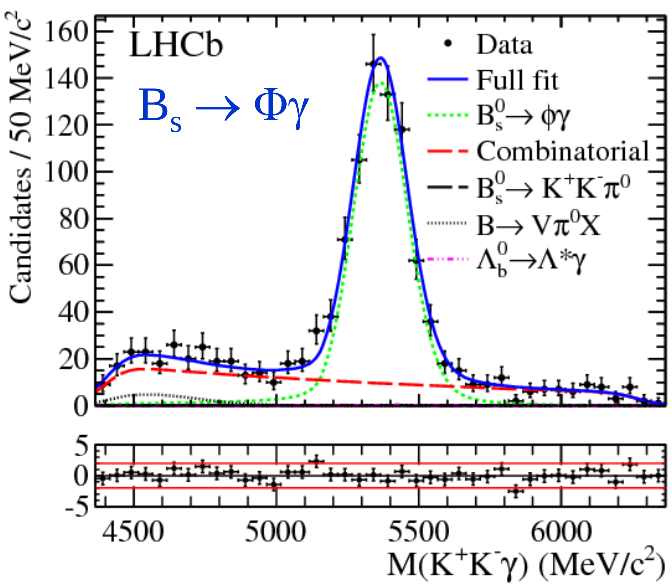


Particle identification with Calorimeters

Int. J. Mod. Phys. A 30 (2015)

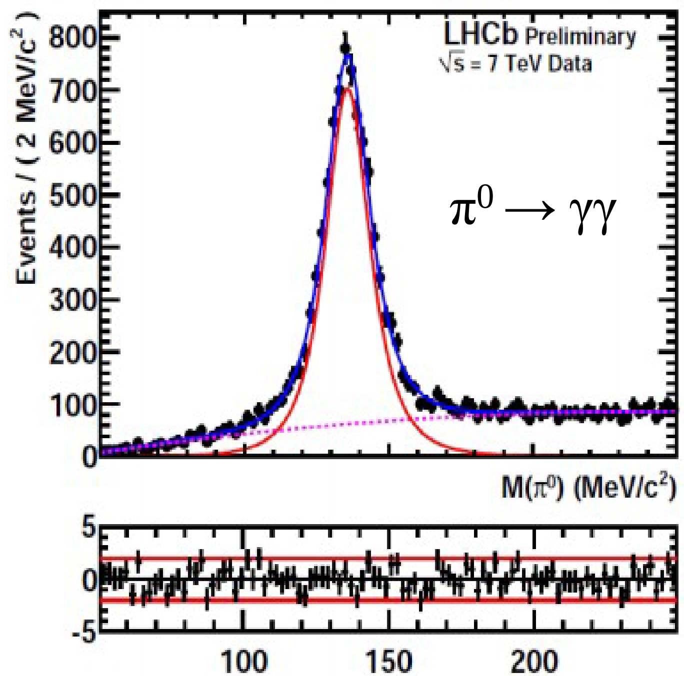
A_{CP} ($B^0 \to K^*\gamma$) = (0.8 ±1.7±0.9) %
and worlds best branching ratio measurement:
BR($B_s \to \Phi\gamma$) = (3.5 ± 0.4) $\cdot 10^{-5}$
with invariant mass resolution ~ 94 MeV/c^2





Nuclear Physics, Section B 867 (2013) 1

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



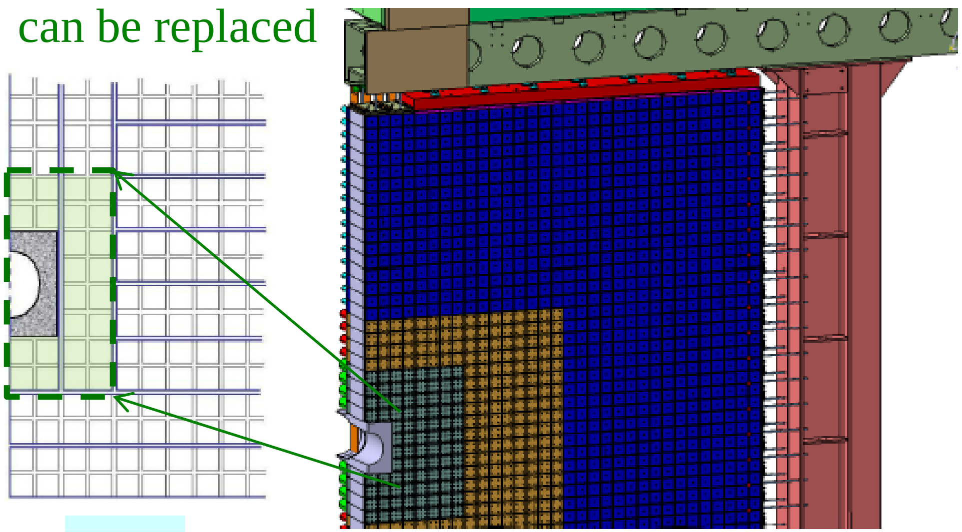
Calorimeters upgrade

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

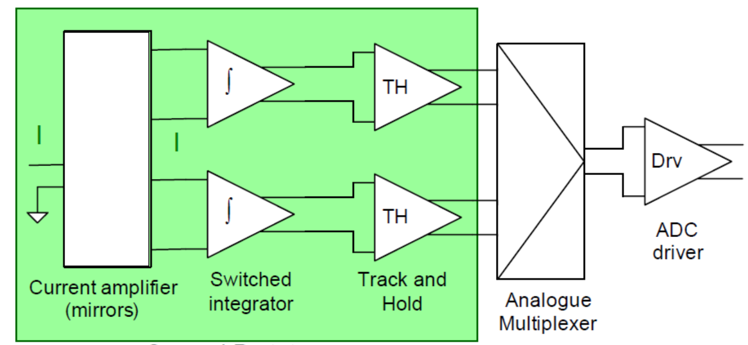
E beam, GeV	module #1 (irradiated 2Mrad) light yield ph.el./GeV	module #1 (irradiated 2Mrad) resolution, %	module #2 (not irradiated) light yield, ph.el./GeV	module #2 (not irradiated) resolution, %
50	583±12	2.16±0.04	2598±52	1.37±0.04
100	576±12	1.57±0.03	2611±52	1.01±0.03
120	571±12	1.36±0.03	2604±52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

most inner ECAL modules around beam-pipe can be replaced

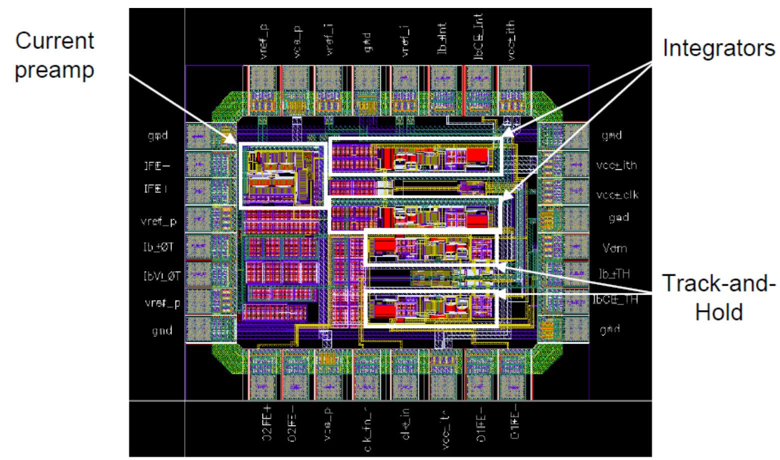


40 MHz readout electronics:

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

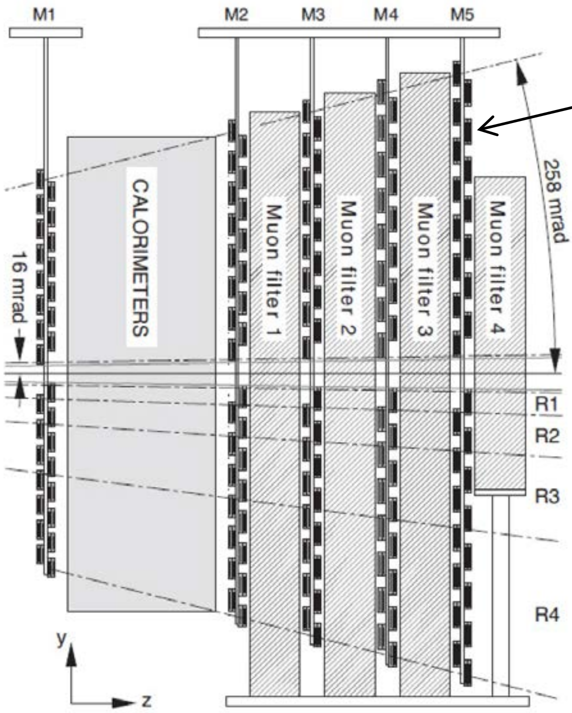


Second Prototype: ICECAL2



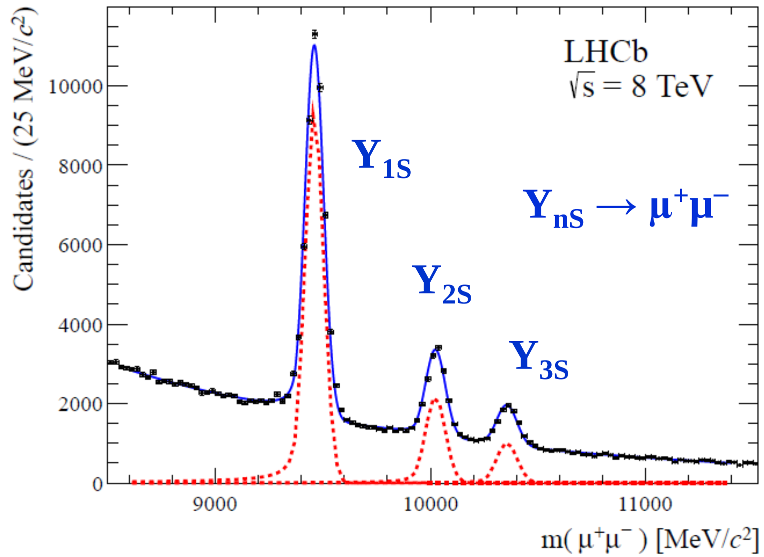
Particle identification with Muon System

J. Instrum. 8 (2013) P02022



MWPC

5 stations M1 to M5



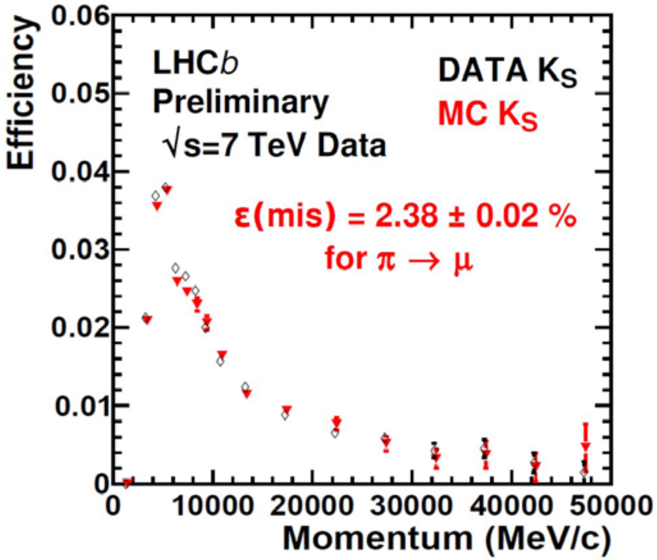
high detection efficiency: $\varepsilon(\mu) = (97.3\pm1.2)\%$

low misidentification rates:

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

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

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

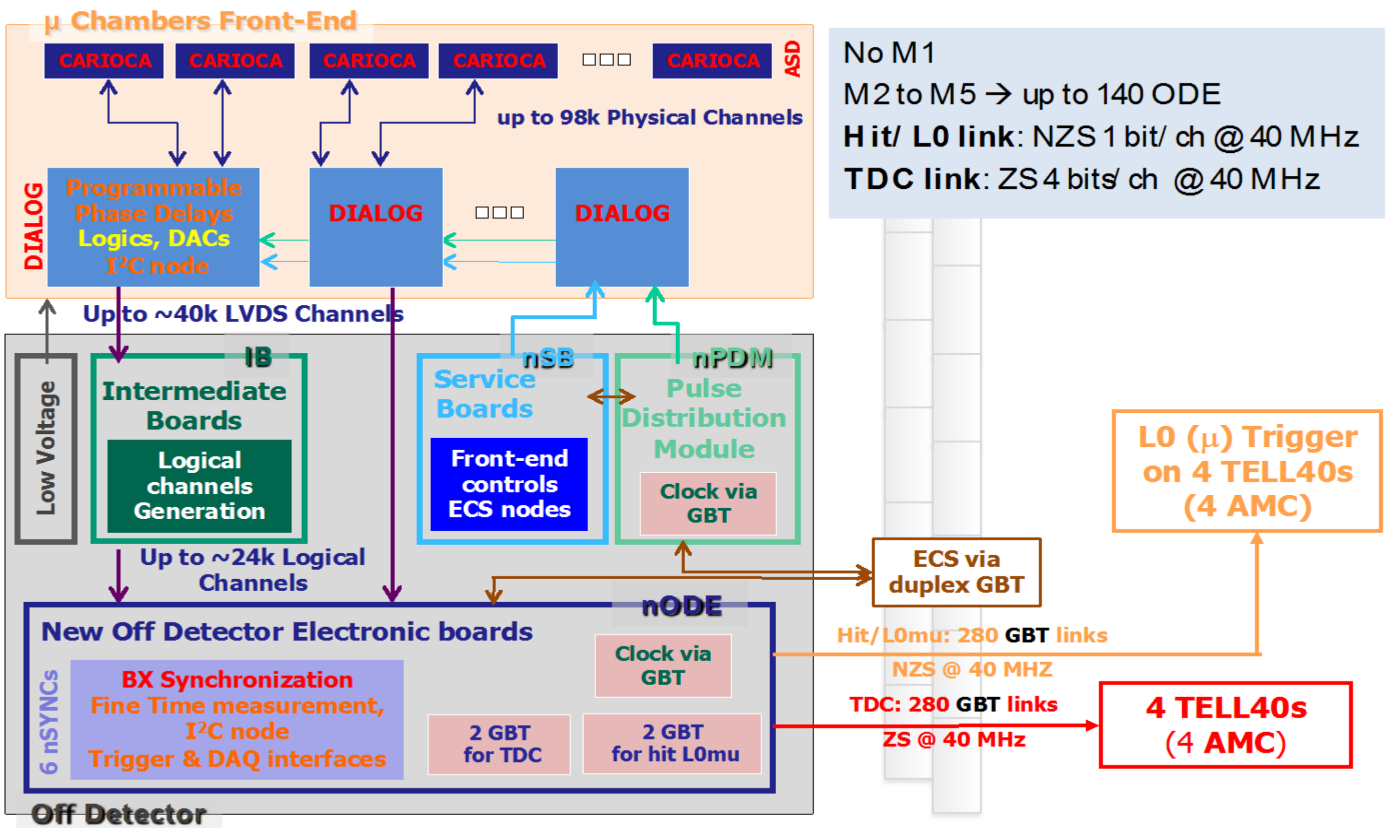


Muon System upgrade

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
- production of spare MWPC for installation in LS3 in hottest regions

on-detector electronics

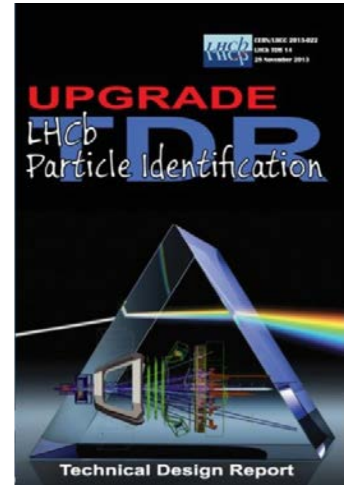


off-detector electronics

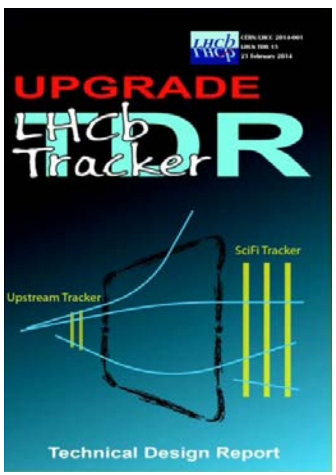
Status of the LHCb upgrade

CERN-LHCC-2011-001

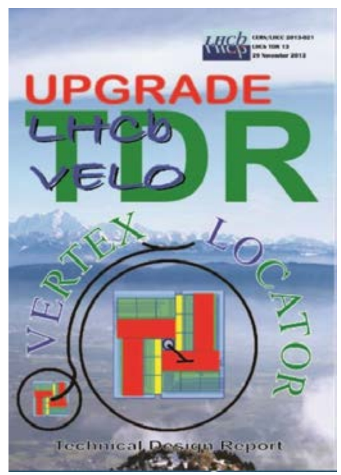
CERN-LHCC-2012-007



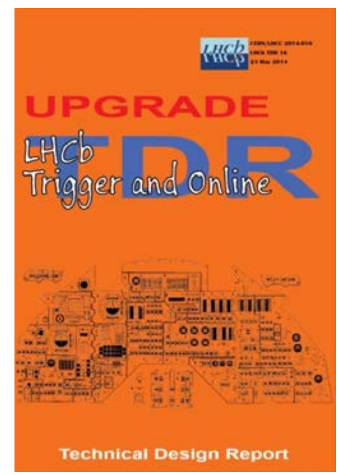
CERN-LHCC-2013-001



CERN-LHCC-2013-021



CERN-LHCC-2014-001



CERN-LHCC-2014-016

- ➢ LHCb upgrade fully approved for installation in 2019/20

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 $\geq$50 fb^{-1} within ~10 years
- the LHCb upgrade is fully approved and funds are secured
- 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 end of 2020