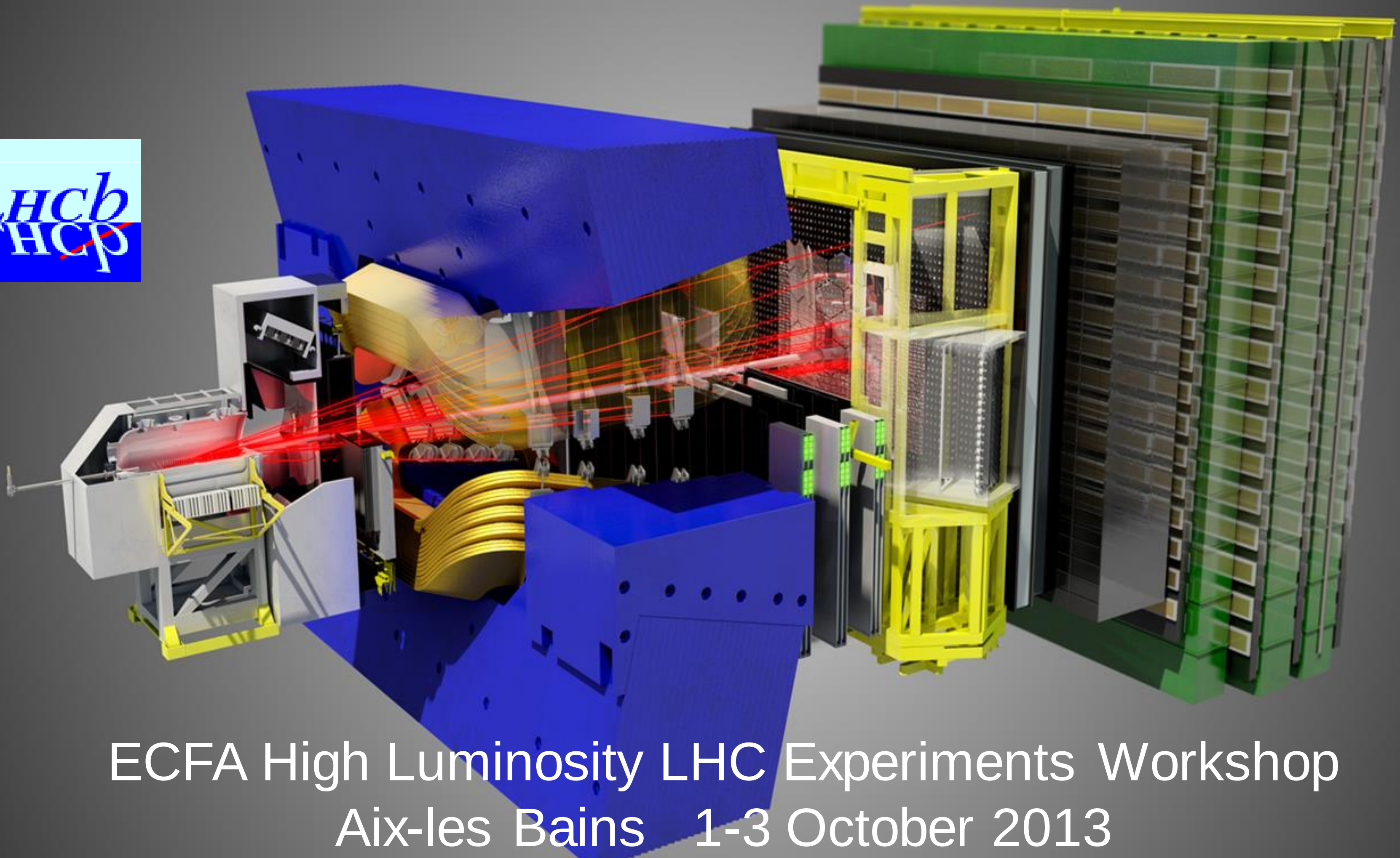
The LHCb Upgrade Program



ECFA High Luminosity LHC Experiments Workshop
Aix-les Bains 1-3 October 2013

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:

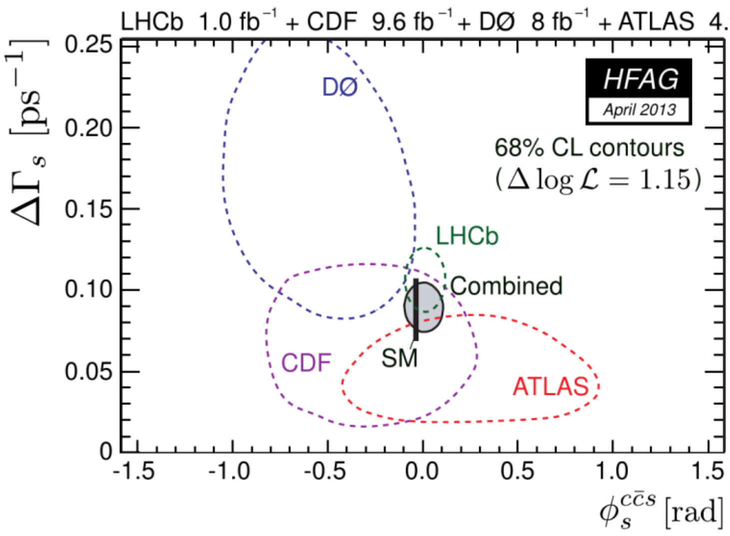
- ✓ flavour changing processes are consistent with the CKM mechanism
- ✓ large sources of flavour symmetry breaking are excluded at the TeV scale
- ✓ the flavour structure of the NP, if it exists, would be very peculiar at the TeV scale (MFV)

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

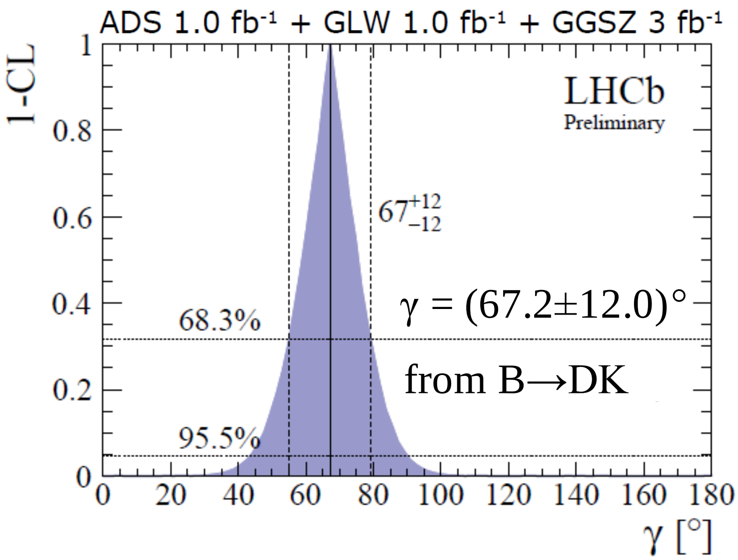
→ LHCb upgrade essential to increase statistical precision significantly

Few highlights of LHCb results

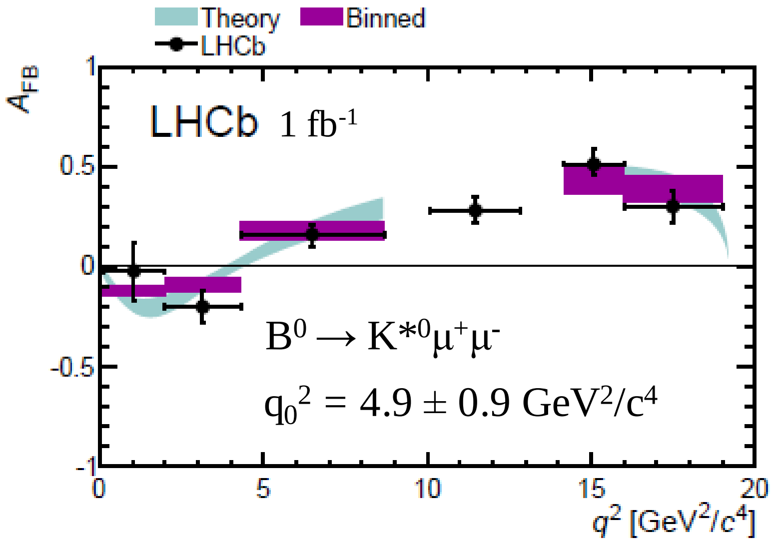


PRD 87 (2013) 112010

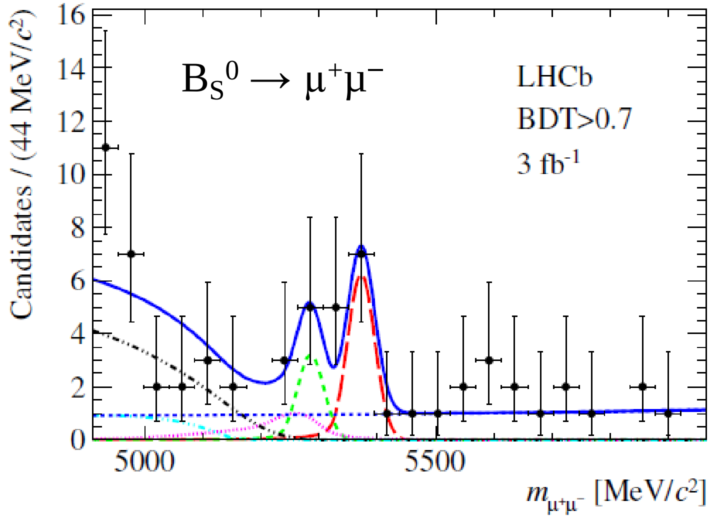
$\Phi_s = 0.01 \pm 0.07(stat) \pm 0.01(syst)$



LHCb-CONF-2013-006



JHEP 1308 (2013) 131



PRL 111 (2013) 101805

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

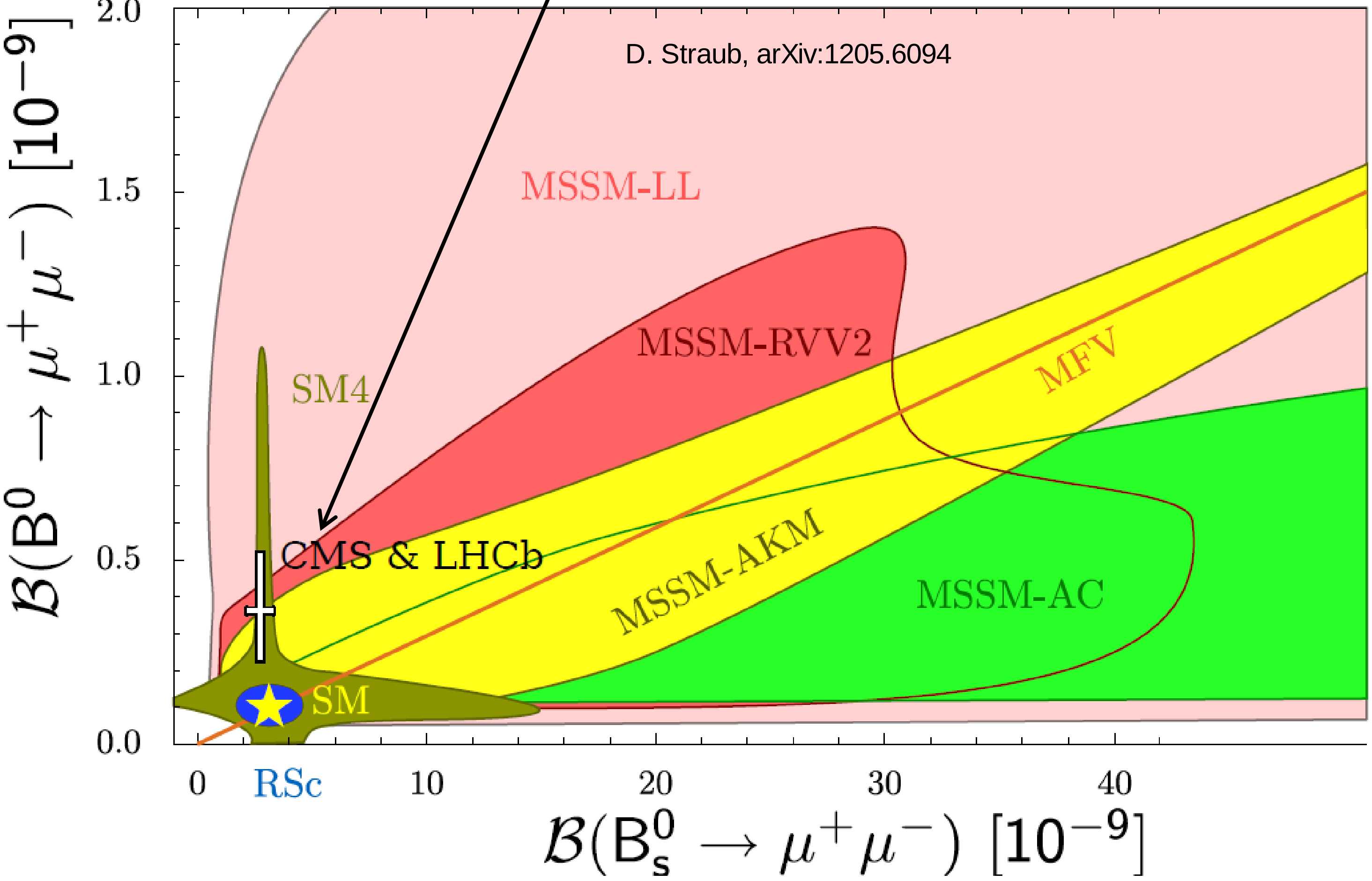
Example of impact on Super Symmetric Models

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

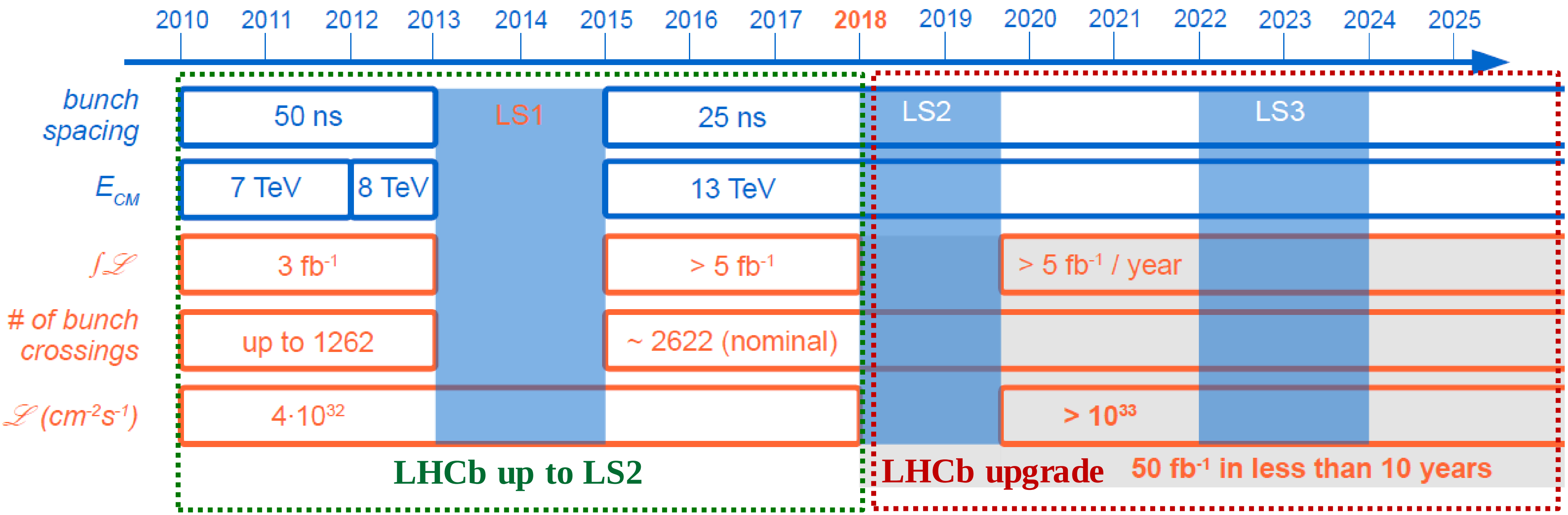
combining
CMS & LHCb →

$$BR(B^0 \rightarrow \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

$$BR(B^0_S \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$



Expected evolution of luminosity in LHCb



LHCb up to 2018 → ~ 8-10 fb^{-1}:

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

LHCb upgrade → ≥ 50 fb^{-1}:

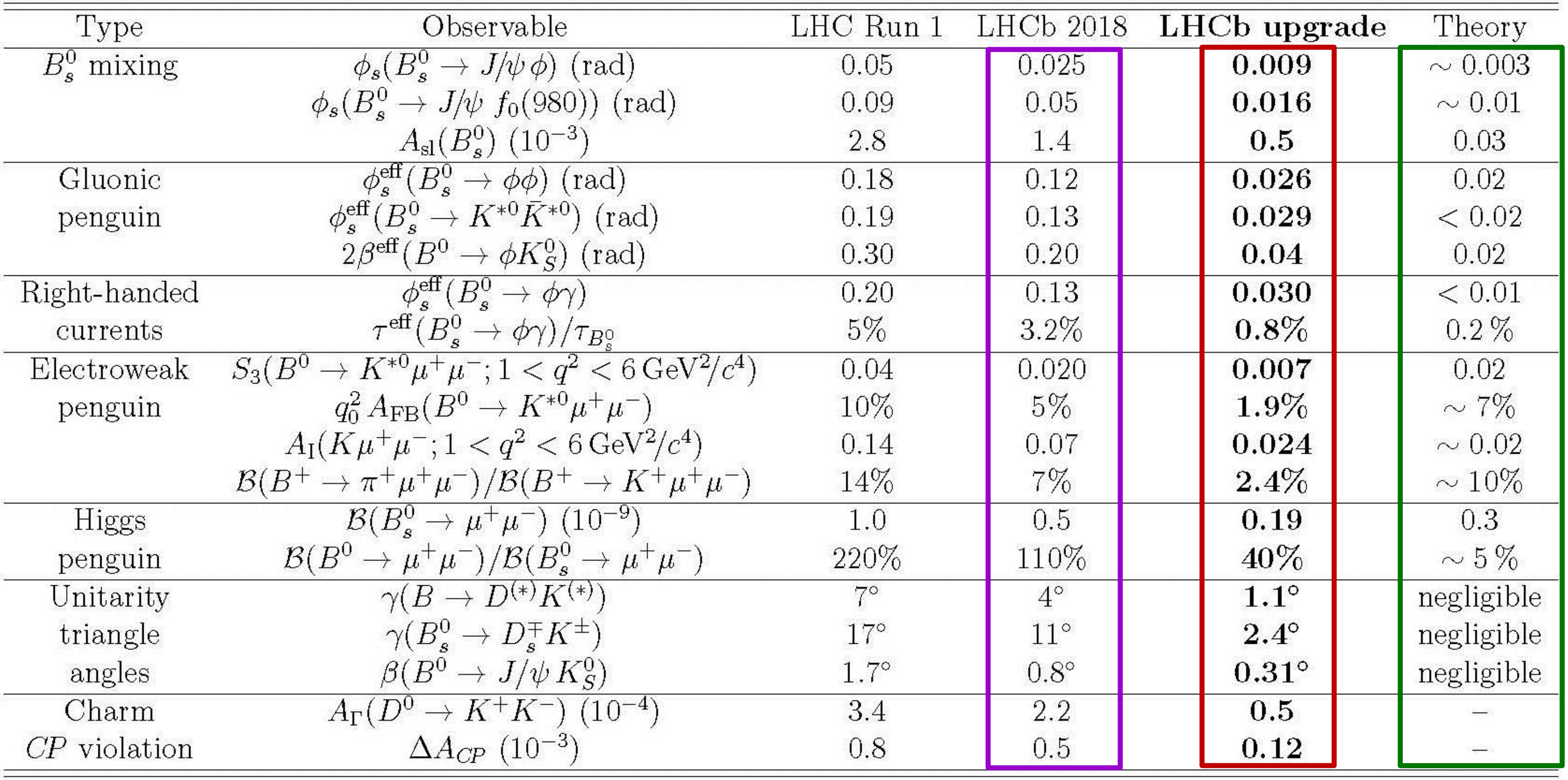
- ✓ increase precision on quark flavour physics observables
- ✓ aim at experimental sensitivities comparable to theoretical uncertainties
- ✓ reinforce LHCb as a general purpose forward detector

Note:

swap of LHCb B-field every ~2 weeks mandatory to control systematic errors

LHCb statistical sensitivity to flavour observables

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

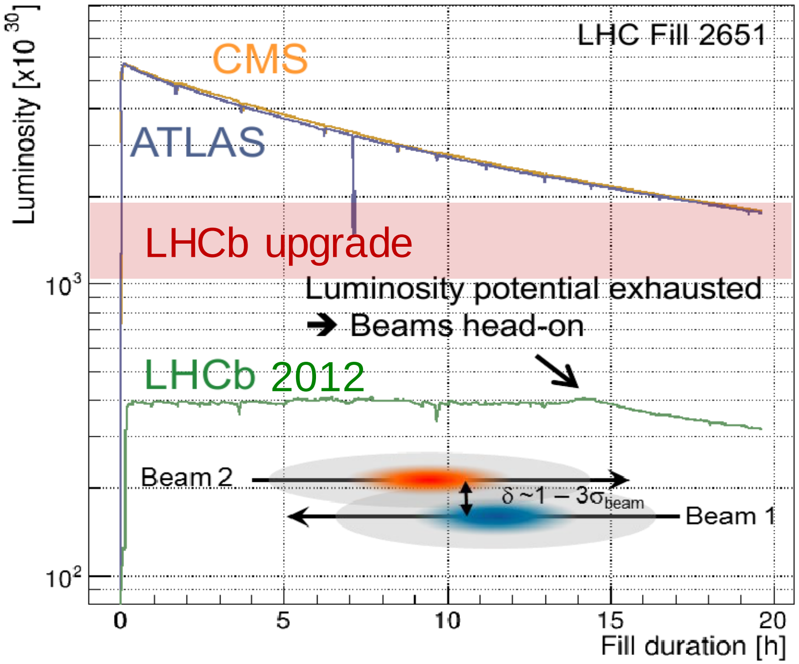


Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	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%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 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°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	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	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

→ see Flavour Physics talk this afternoon!

How to increase LHCb statistics significantly

2012 running conditions



← $1\text{-}2 \cdot 10^{33}\ cm^{-2}s^{-1}$

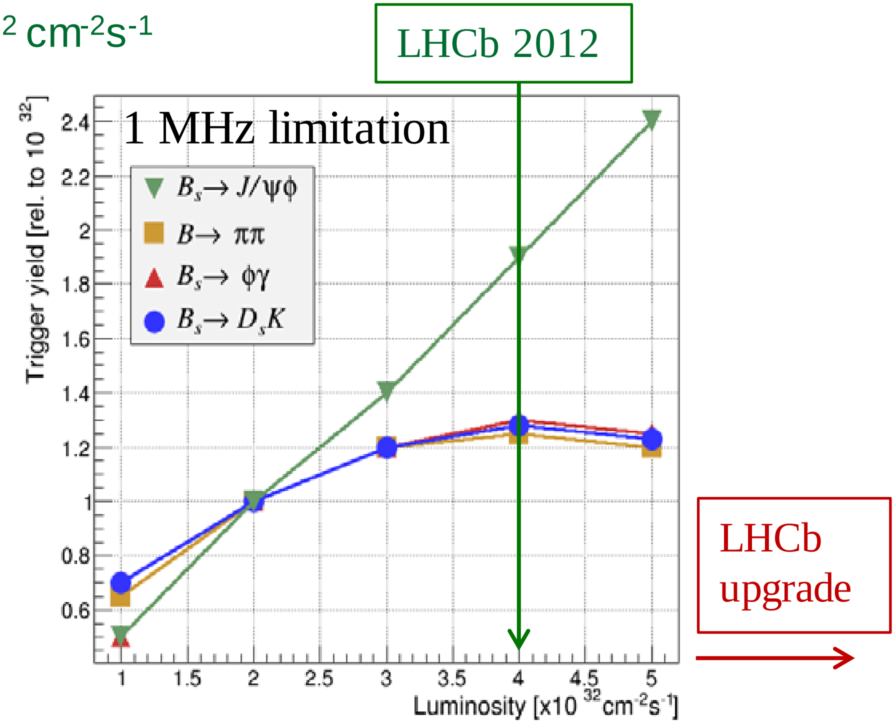
← ~ $4 \cdot 10^{32}\ cm^{-2}s^{-1}$

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 kHz

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



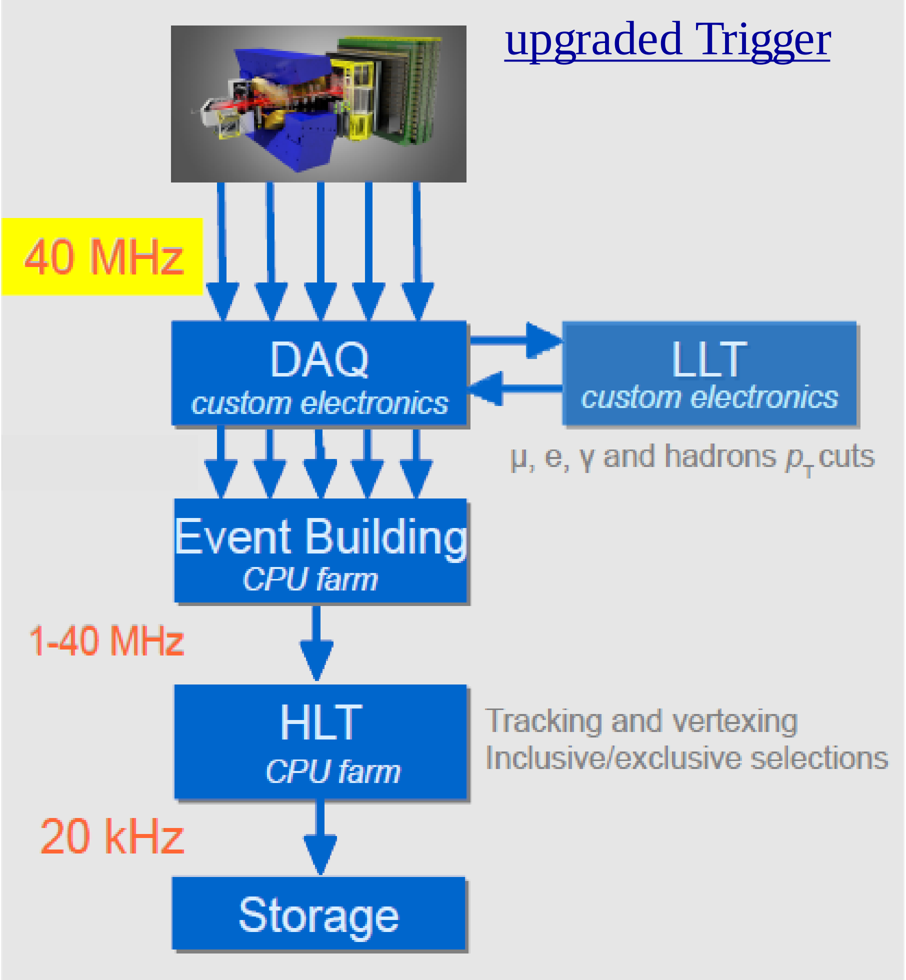
Trigger upgrade

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



40 MHz

DAQ
custom electronics

LLT
custom electronics

μ, e, γ and hadrons p_T cuts

Event Building
CPU farm

1-40 MHz

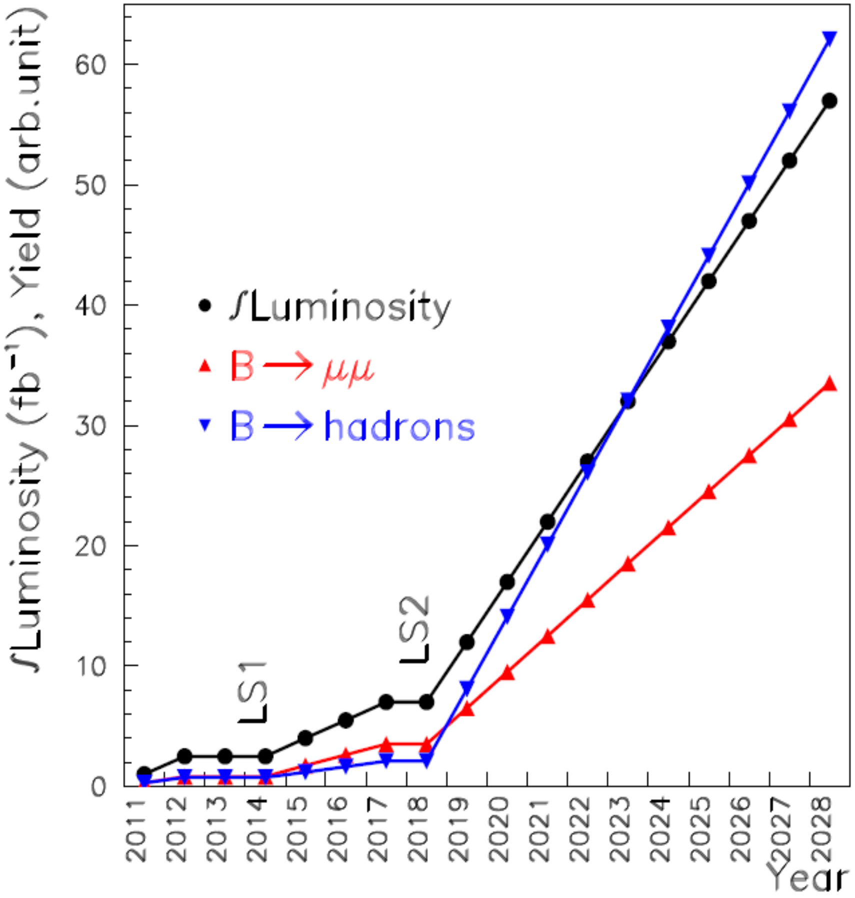
HLT
CPU farm

Tracking and vertexing
Inclusive/exclusive selections

20 kHz

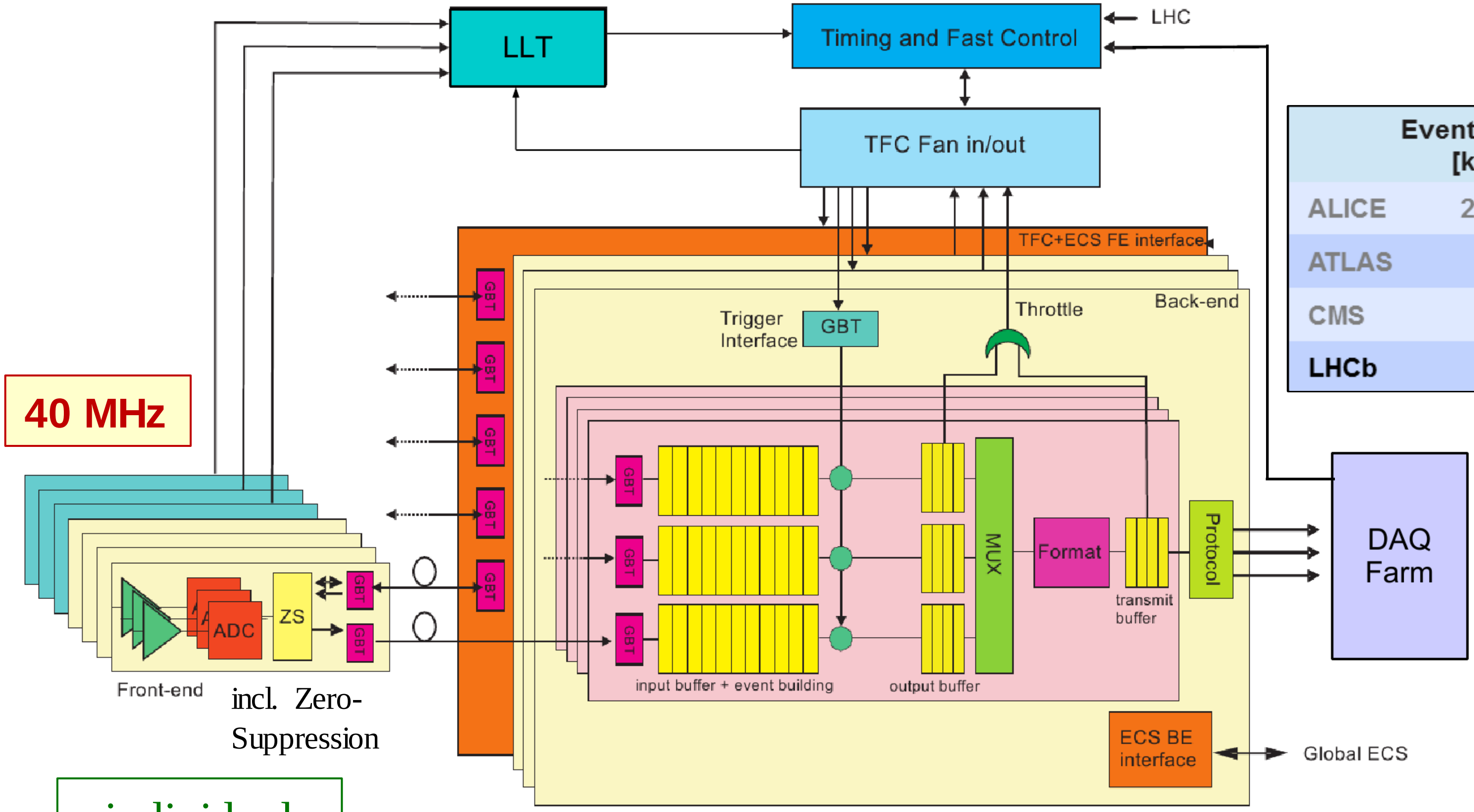
Storage

effect on luminosity and signal yields



40 MHz architecture overview

40 MHz



incl. Zero-Suppression

see N.Neufeld talk

	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**

20 KHz

individual sub-systems Front-End electronics → optical link via GBT → common Back-End readout boards TELL40 [or PCI express] → event building & HLT

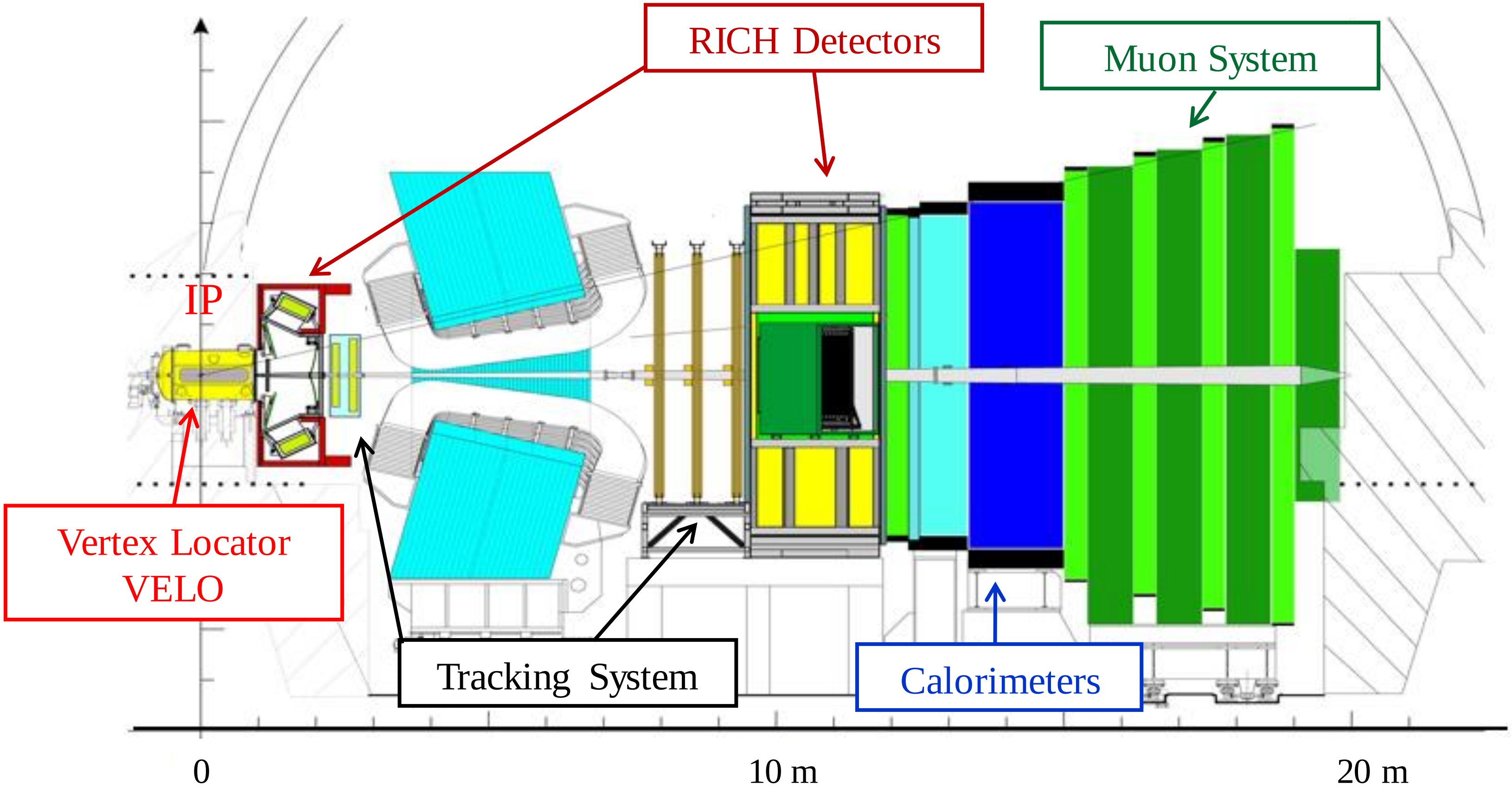
underground

~300m

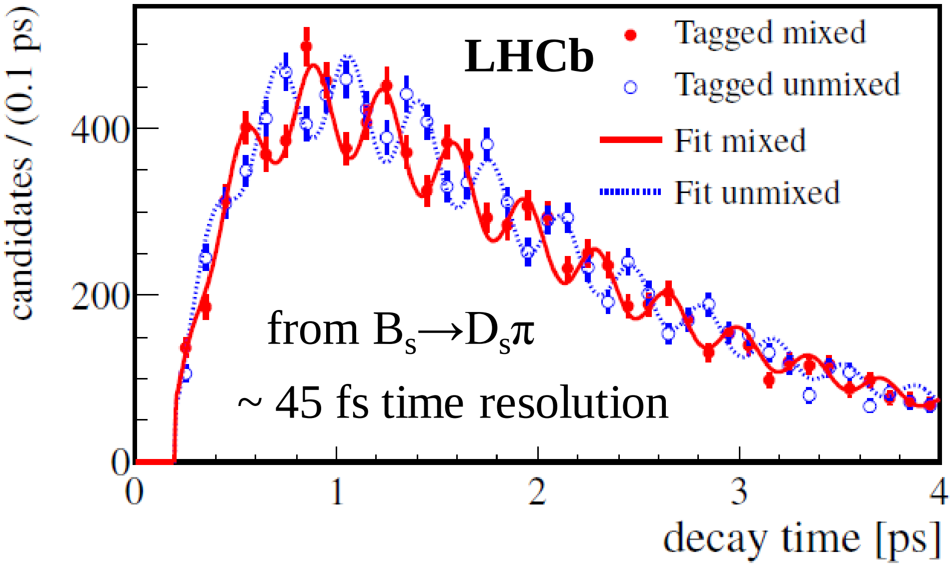
on surface

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



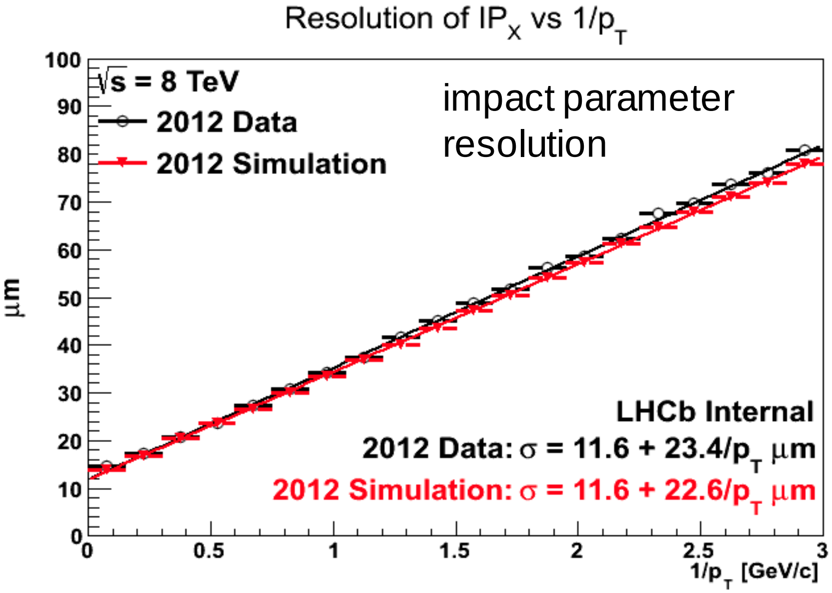
Vertex reconstruction with VELO



from $B_s \rightarrow D_s\pi$

~ 45 fs time resolution

New J. Phys. 15 (2013) 053021

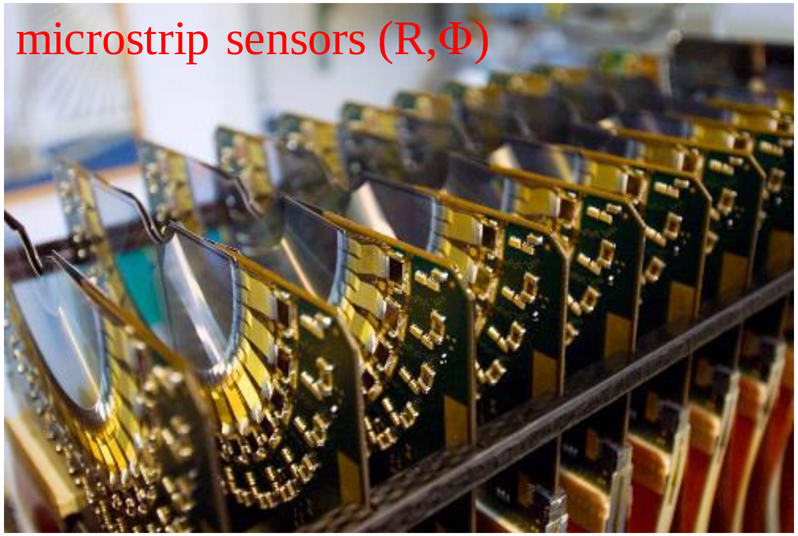


impact parameter resolution

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

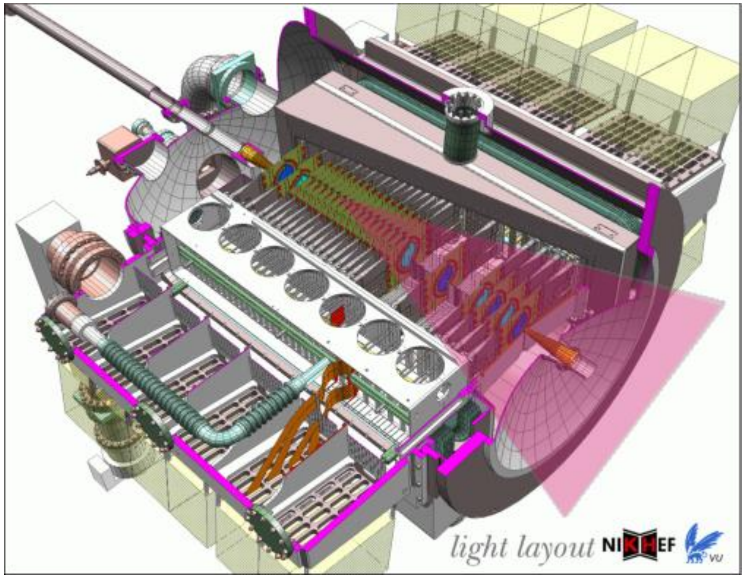
2012 Simulation: $\sigma = 11.6 + 22.6/p_T$ µm

Current detector

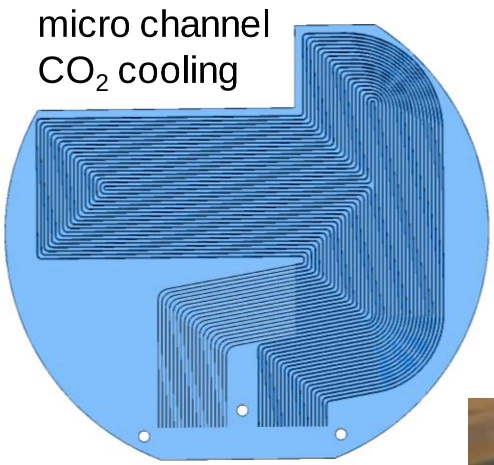


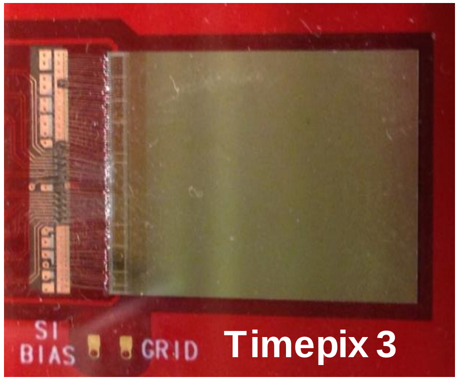
microstrip sensors (R,Φ)

movables halves → 5.5 mm from beam



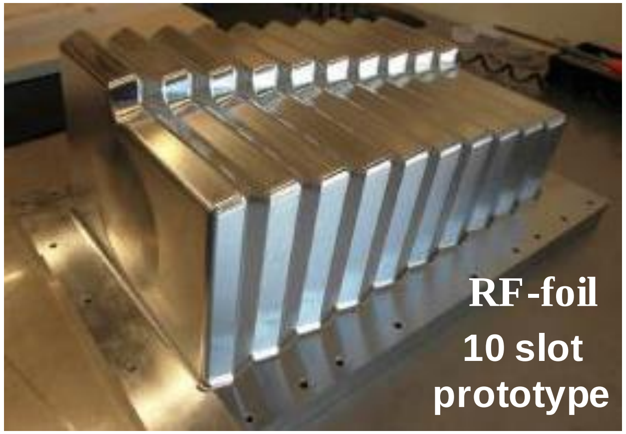
VELO upgrade





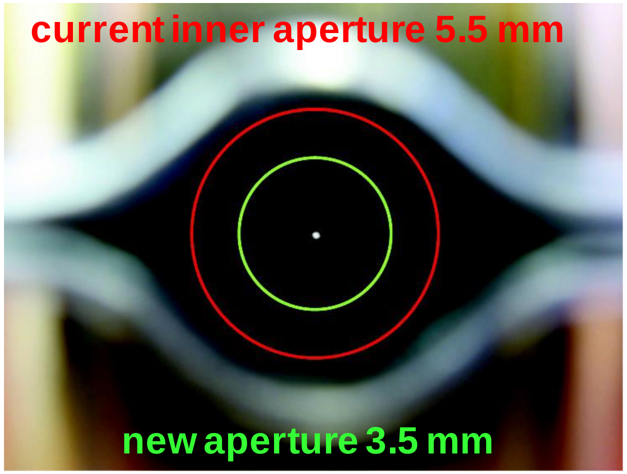
Upgrade challenge:

- ✓ withstand increased radiation (highly non-uniform radiation of up to $8\cdot10^{15}$ n_{eq}/cm^2 for 50 fb^{-1})
- ✓ handle high data volume
- ✓ keep (improve) current performance
  - ➢ lower materiel budget
  - ➢ enlarge acceptance

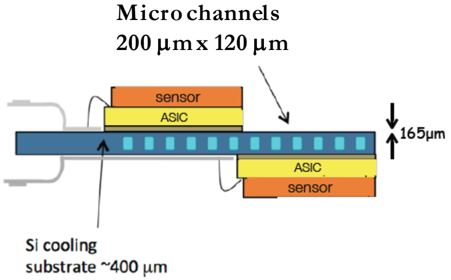


Technical choice :

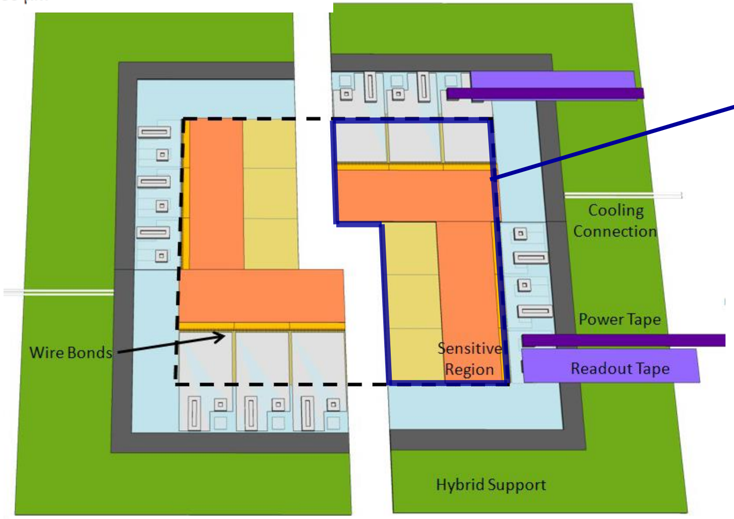
- ✓ 55x55 μm^2 pixel sensors with micro channel CO_2 cooling
- ✓ 40 MHz VELOPIX (evolution of TIMEPIX 3, Medipix)
  - ➢ 130 nm technology to sustain ~400 MRad in 10 years
  - ➢ VELOPIX hit-rate = ~8 x TIMEPIX 3 rate
- ✓ replace RF-foil between detector and beam vacuum
  - ➢ reduce thickness from 300 μm → ~150 μm
- ✓ move closer to the beam
  - ➢ reduce inner aperture from 5.5 mm → 3.5 mm

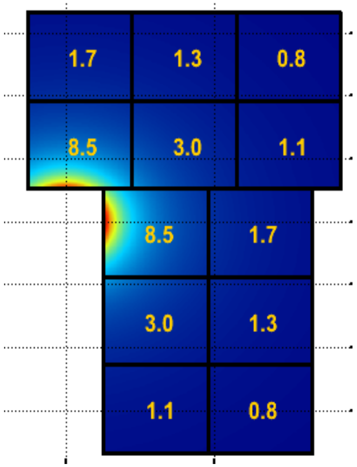


VELO upgrade



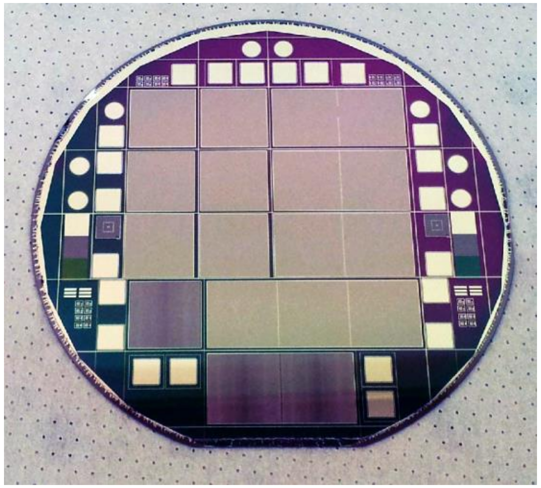
pixel detector with
micro channel cooling

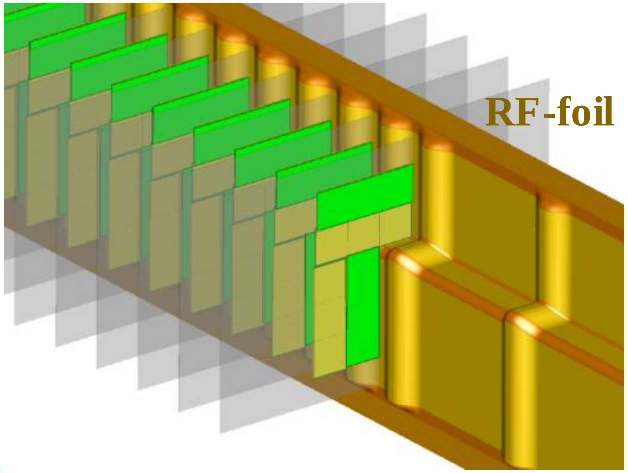


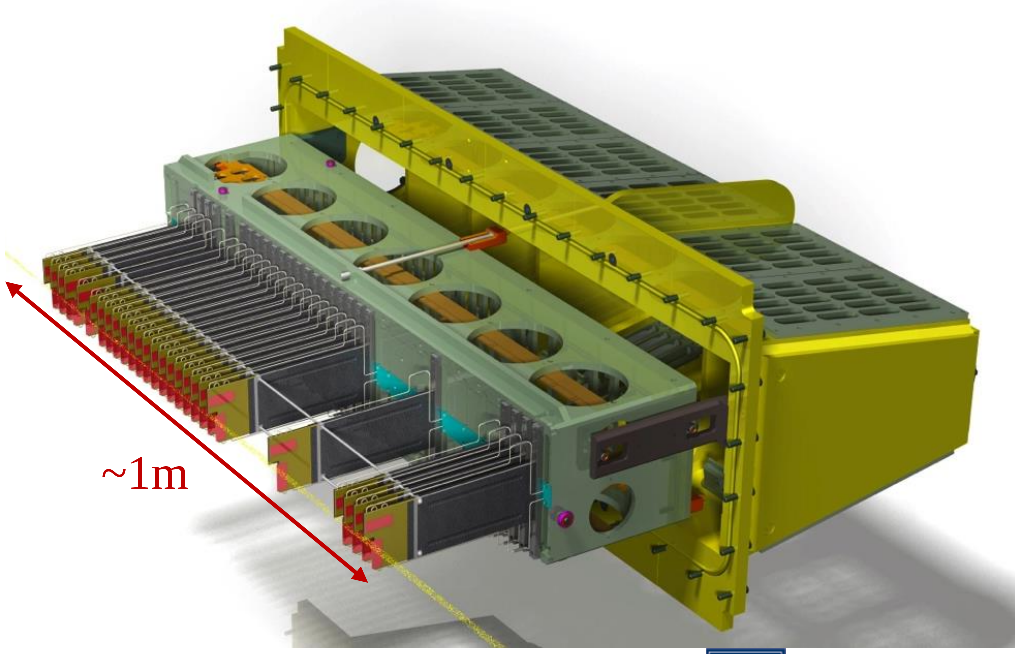


tracks/chip/event
at $L=2\cdot10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Prototype pixel sensor

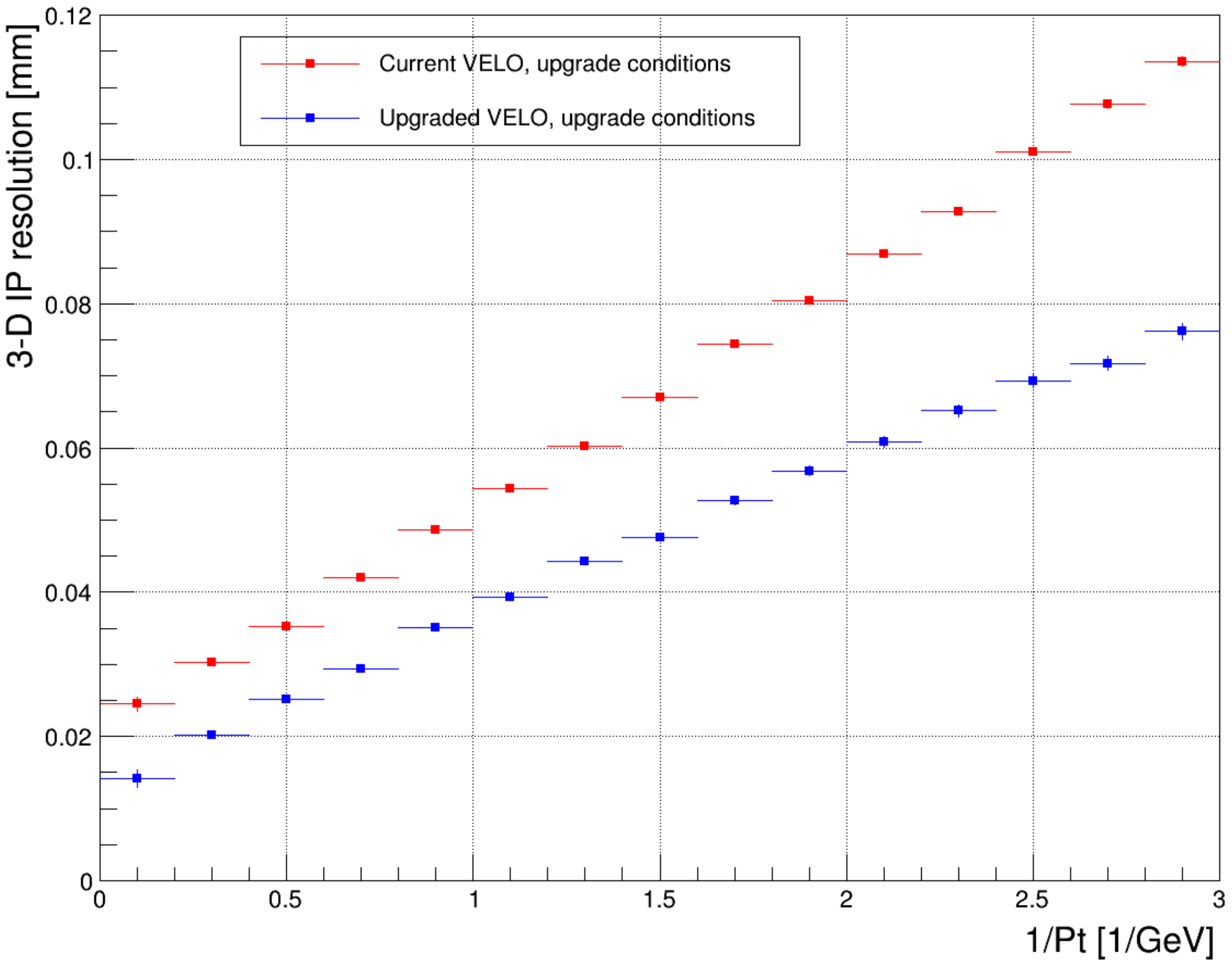






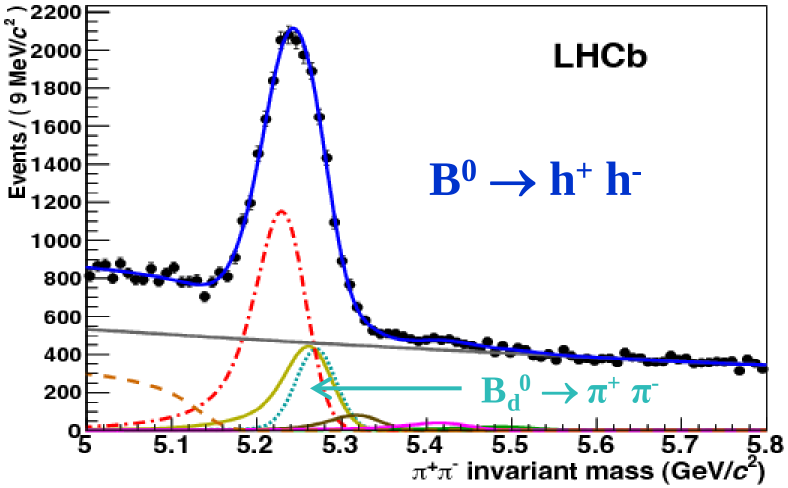
VELO upgrade

Impact Parameter resolution at $L=2\cdot10^{33}$ cm^{-2}s^{-1}



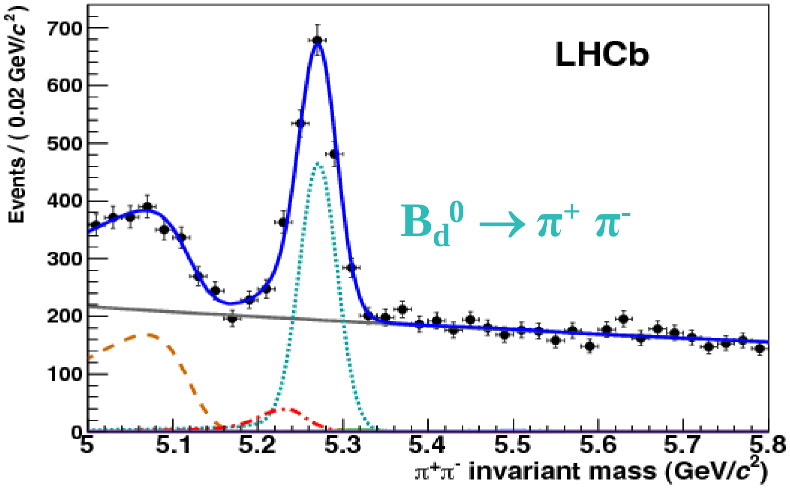
<u>note</u>: full GEANT Monte Carlo with standard LHCb simulation framework

Particle Identification with RICH



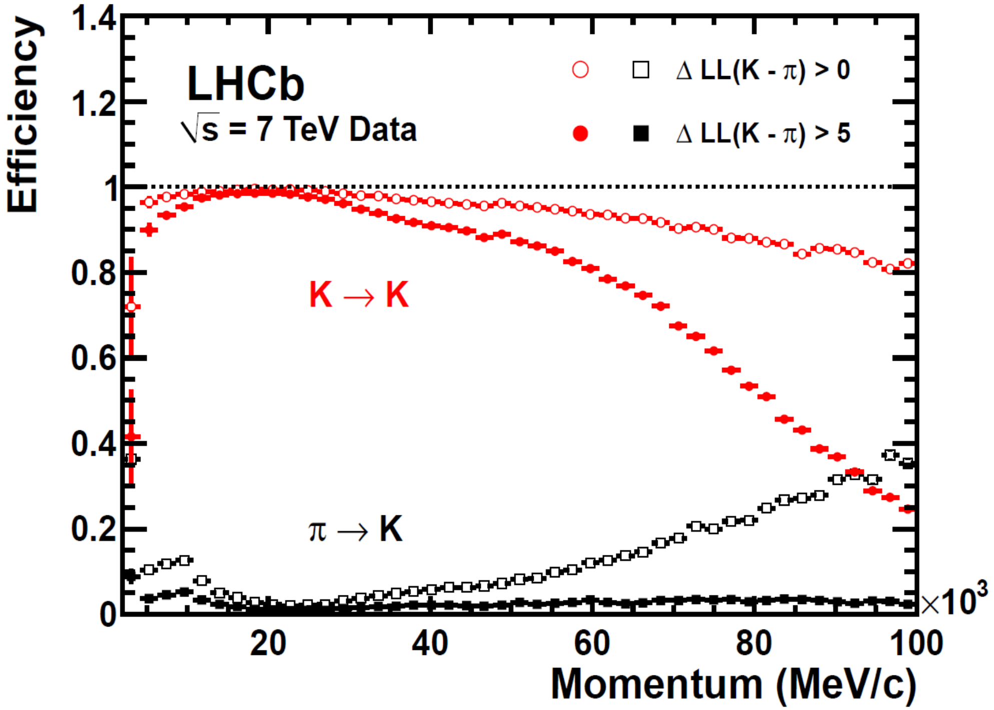
particle identification of 2 π

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



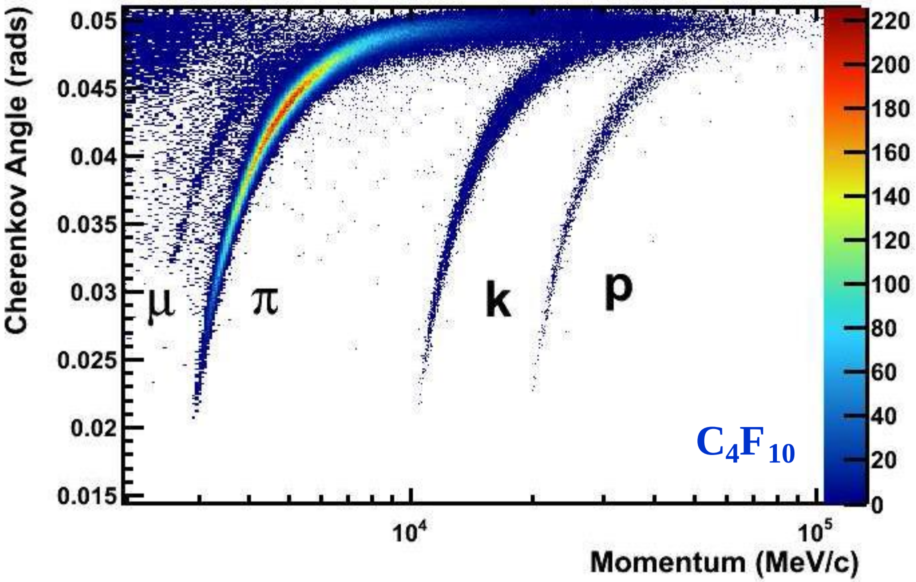
Efficient particle identification of π, K, p essential for selecting rare beauty and charm decays

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

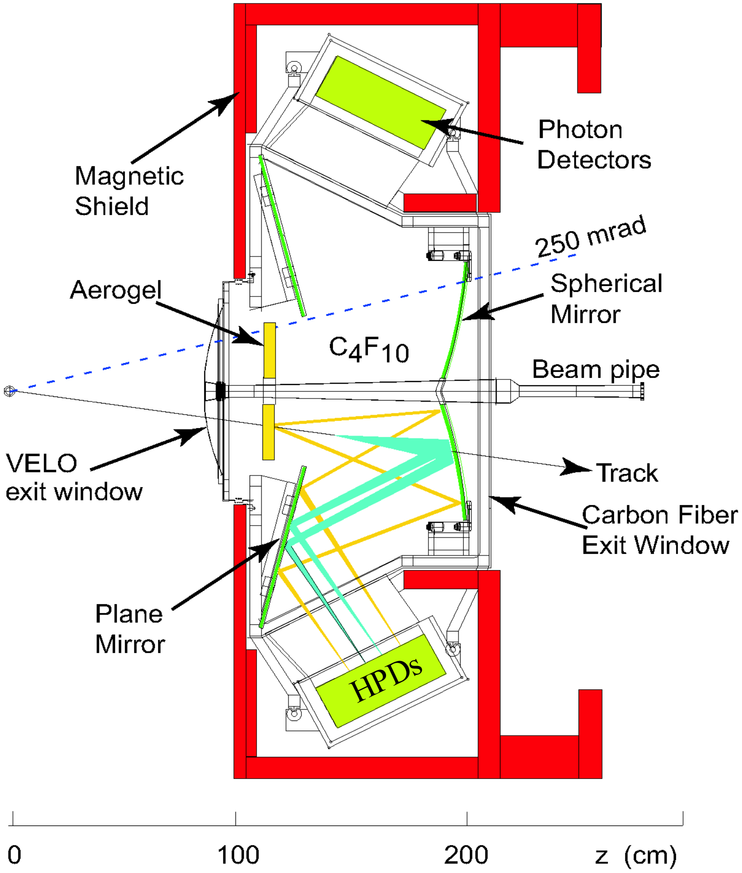


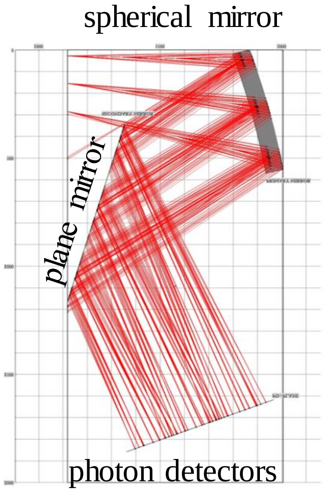
RICH(1) optics

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



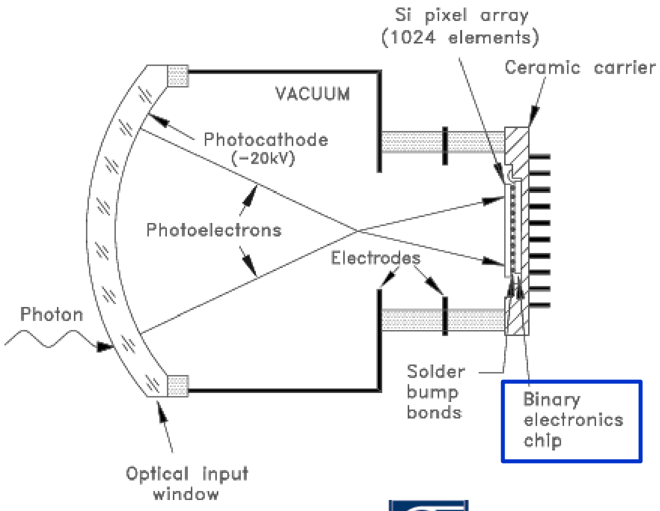
RICH 1





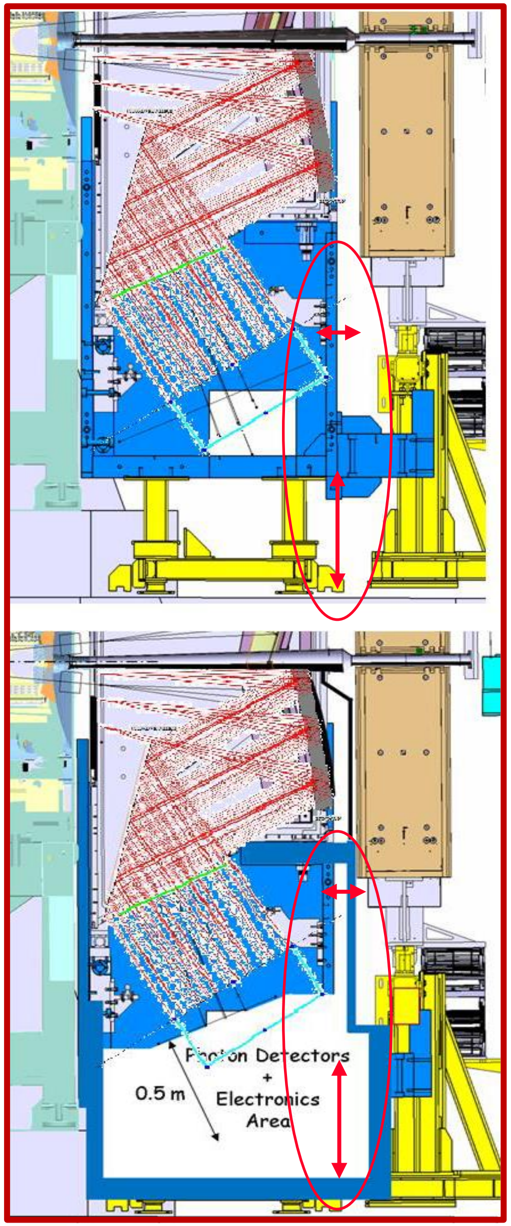
Hybrid Photon Detector

with embedded 1 MHz R/O chip



RICH upgrade

optimise RICH1 optics

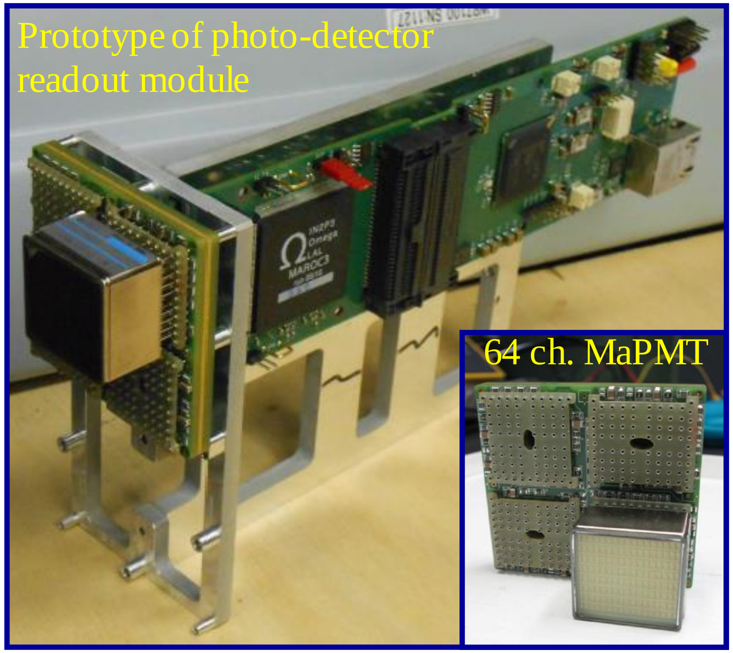


Luminosity of $2 \cdot 10^{33}$ cm^{-2}s^{-1} → adapt to high occupancies

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

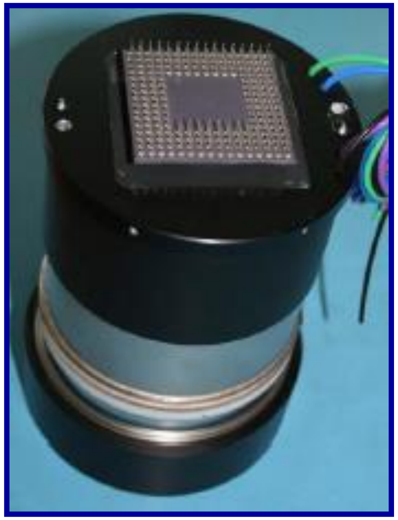
40 MHz readout → replace HPDs due to embedded FE

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

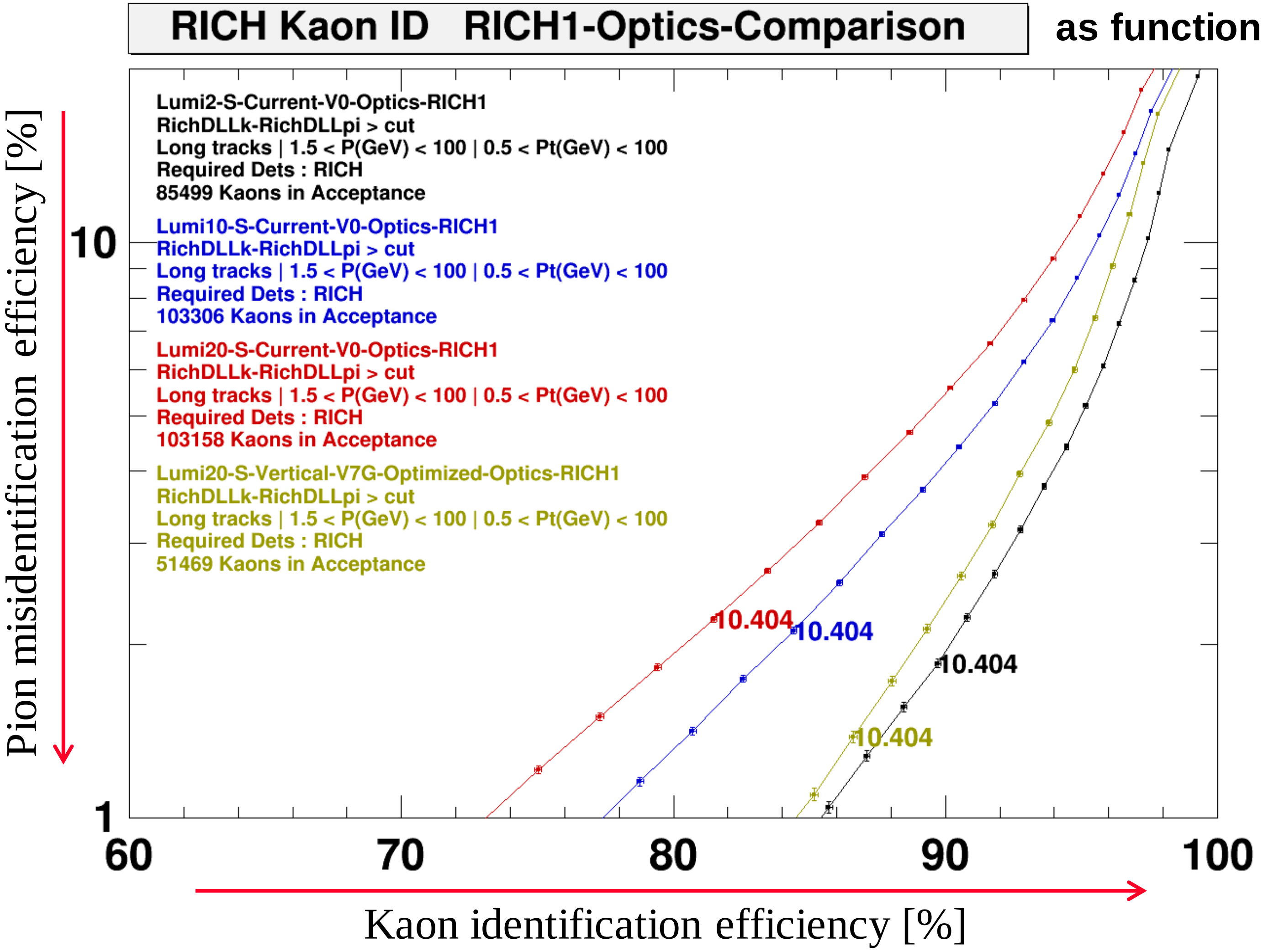

Prototype of photo-detector readout module

64 ch. MaPMT

HPD prototype with external electronics



RICH upgrade



as function of luminosity

Current RICH1

- ➢ $2\cdot10^{32}$ cm^{-2}s^{-1}
- ➢ $10\cdot10^{32}$ cm^{-2}s^{-1}
- ➢ $20\cdot10^{32}$ cm^{-2}s^{-1}

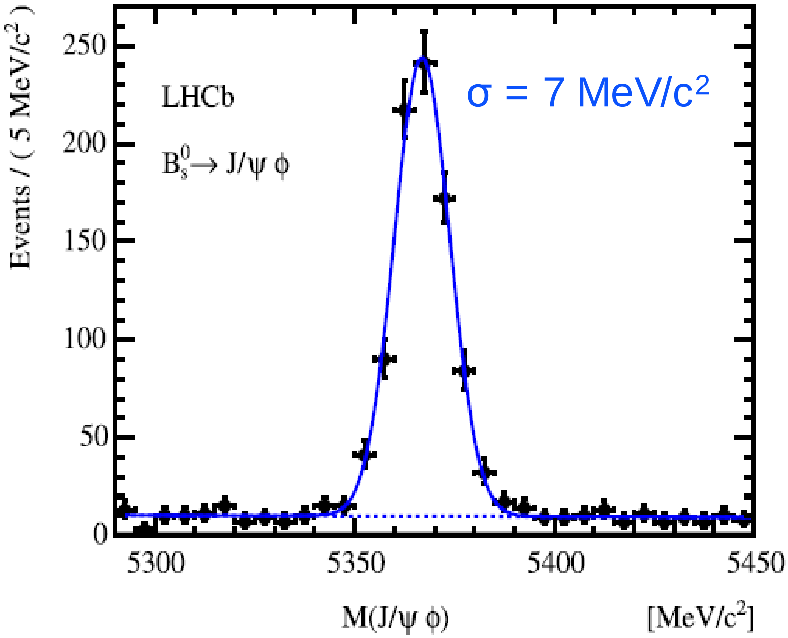
RICH1 upgrade

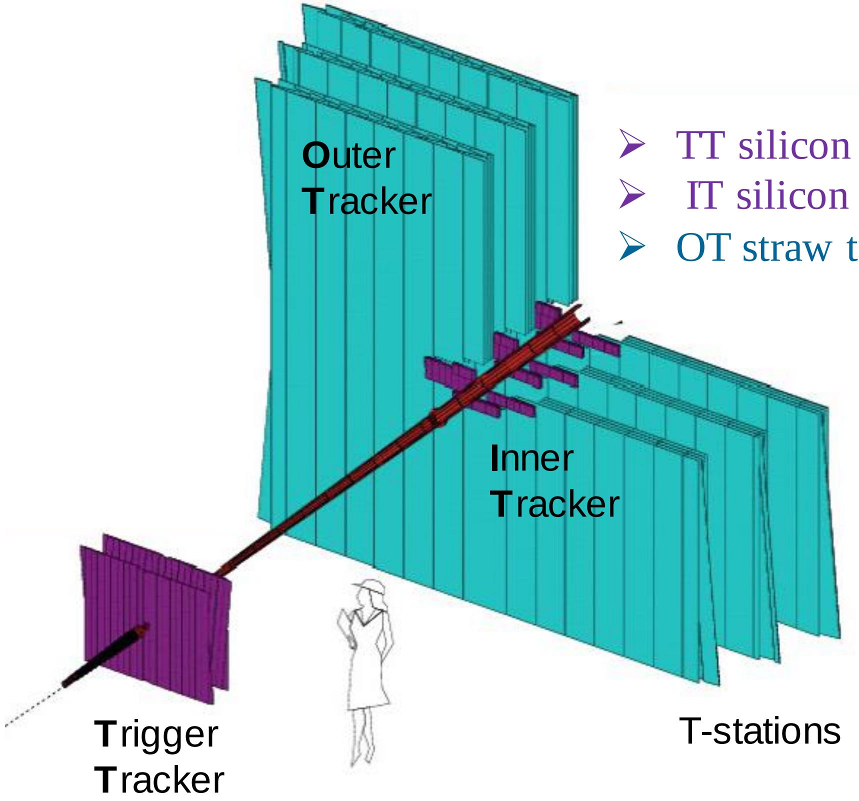
- ➢ $20\cdot10^{32}$ cm^{-2}s^{-1}

note:
full GEANT MC with standard LHCb simulation framework

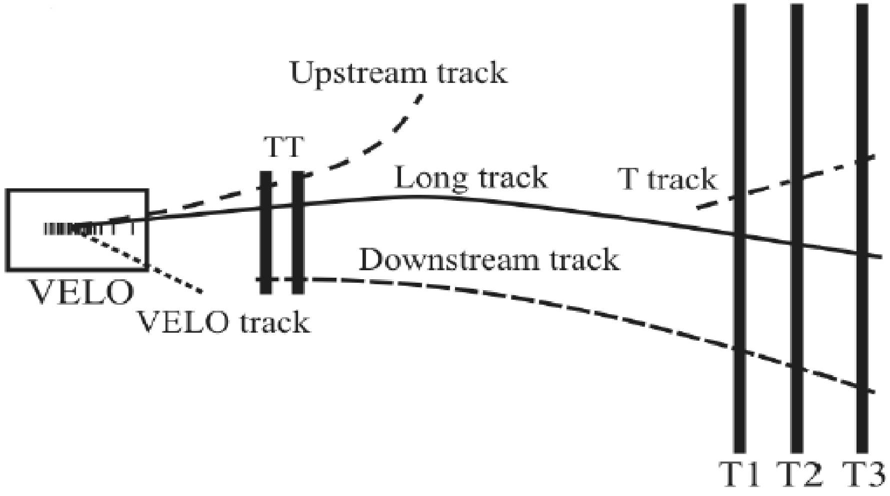
Tracking System

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

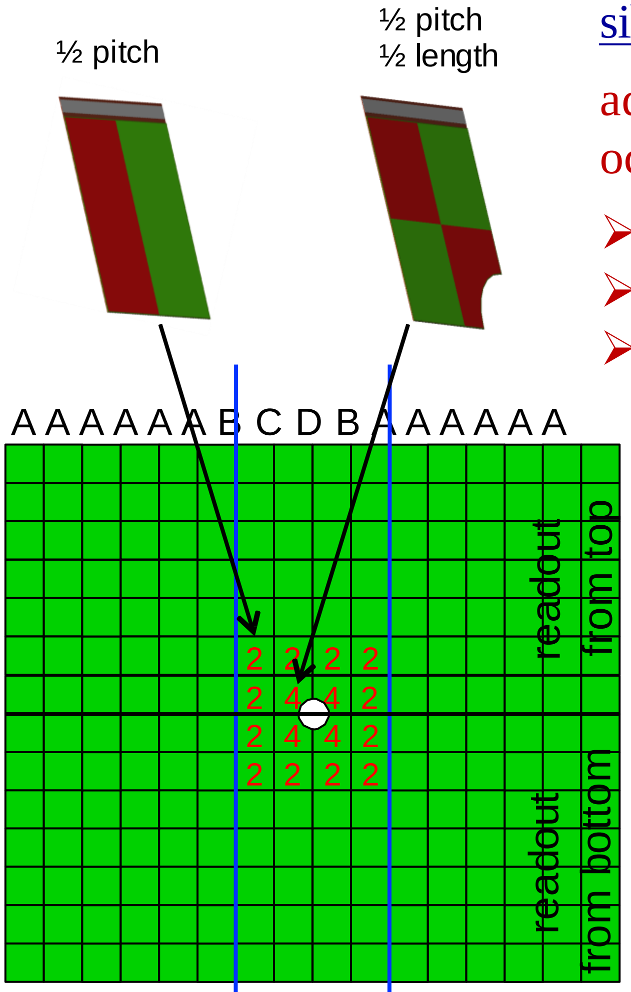




- TT silicon
- IT silicon
- OT straw tubes



TT upgrade: Upstream Tracker (UT)



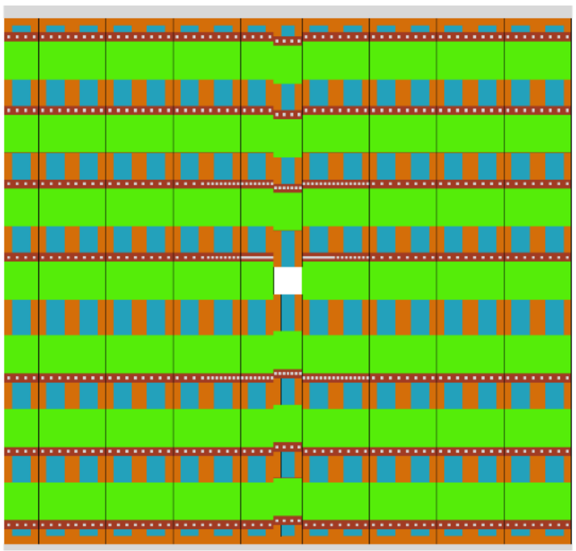
Region 0	Region 1	Region 2
6/7 modules	4 modules	6/7 modules
84/98 sectors	80 sectors	84/98 sectors

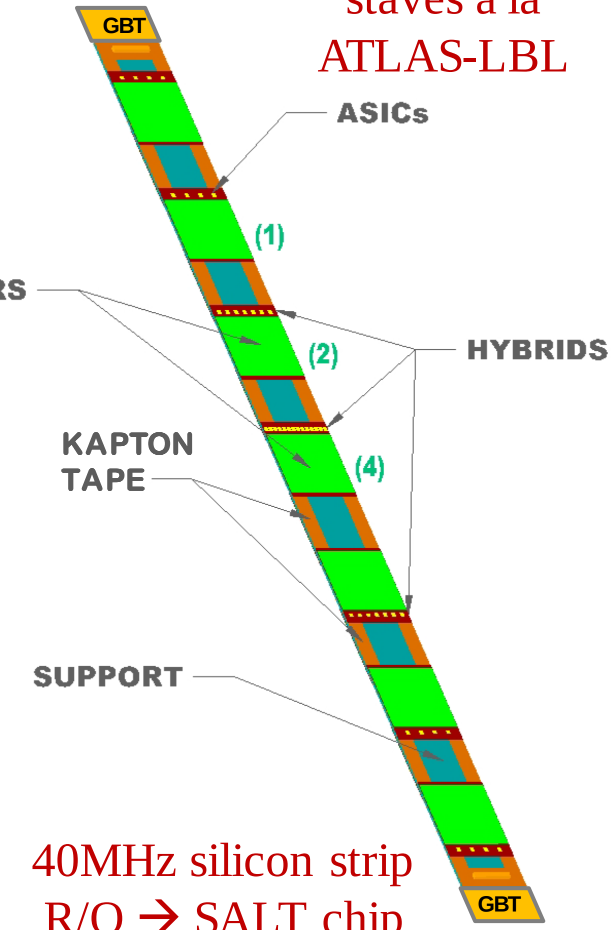
silicon strip detector

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

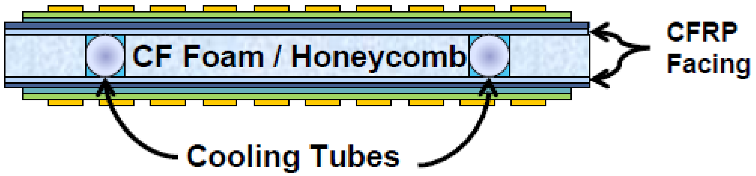
- 10 → 5 cm long silicon strips
- 180 → 90 μm pitch
- p-in-n → n-in-p

staves a la ATLAS-LBL

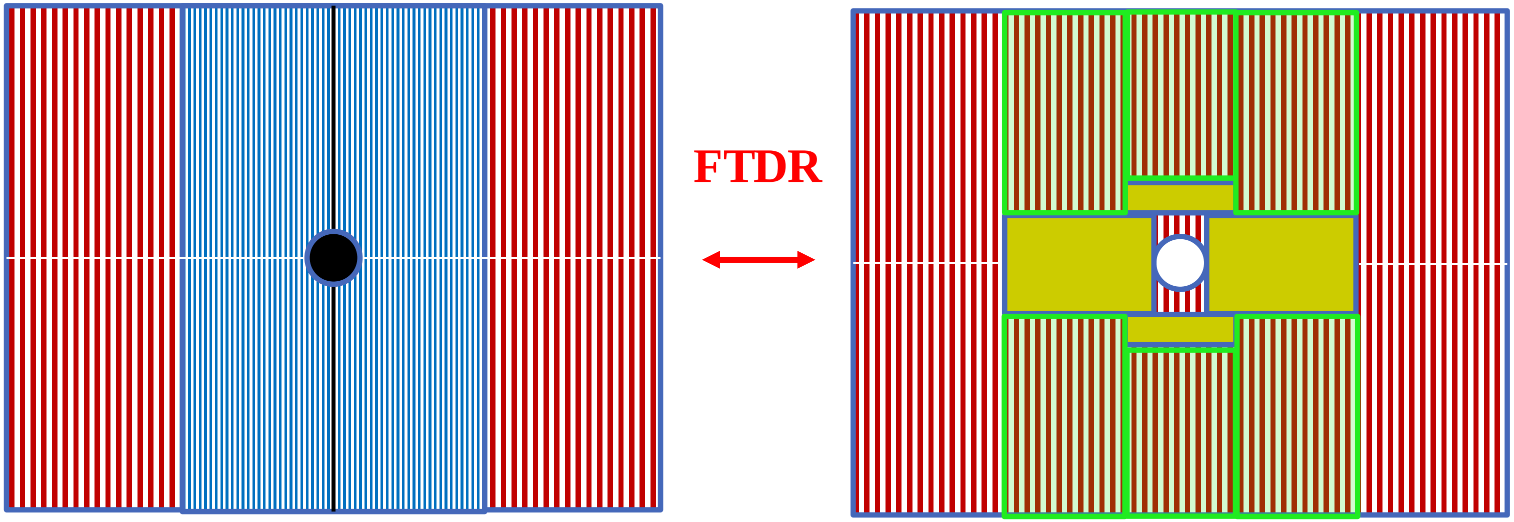




40MHz silicon strip R/O → SALT chip



T-stations upgrade: the options…


Central Tracker & Outer Tracker

Inner Tracker & Outer Tracker

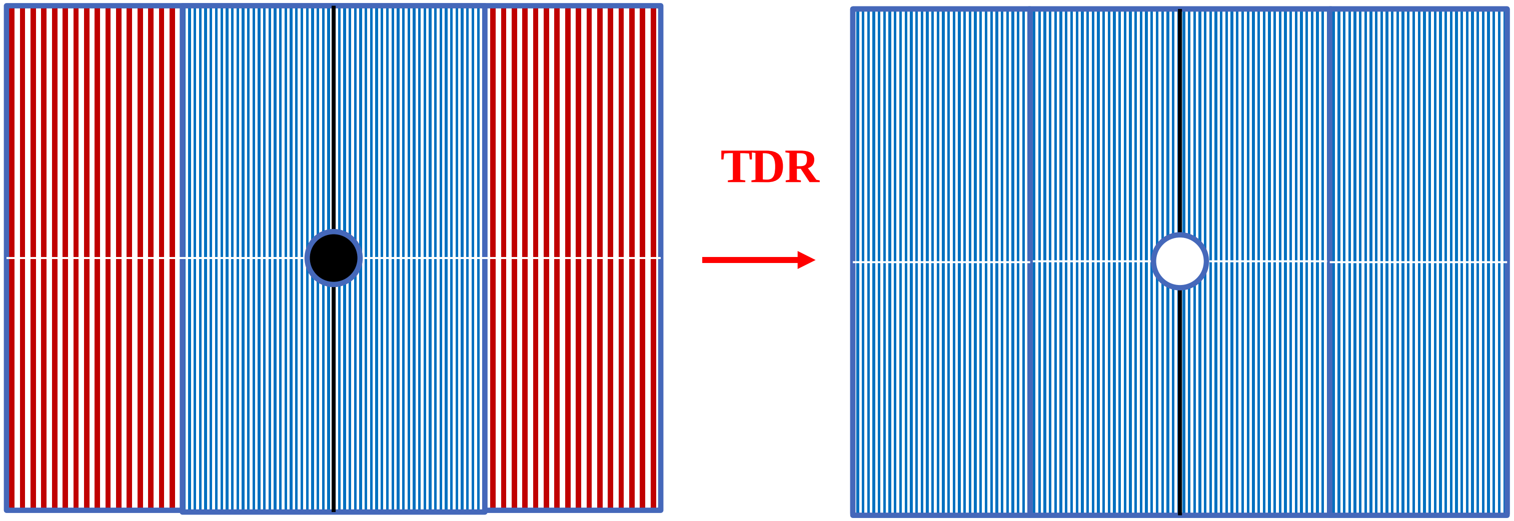
▥ Outer Tracker with straw tube technology

🟩 New straw tubes

▥ Central tracker with scintillating fibre technology

🟨 Inner Tracker with silicon strip technology

T-stations upgrade: the options…



Central Tracker & Outer Tracker

TDR

Full Fibre Tracker

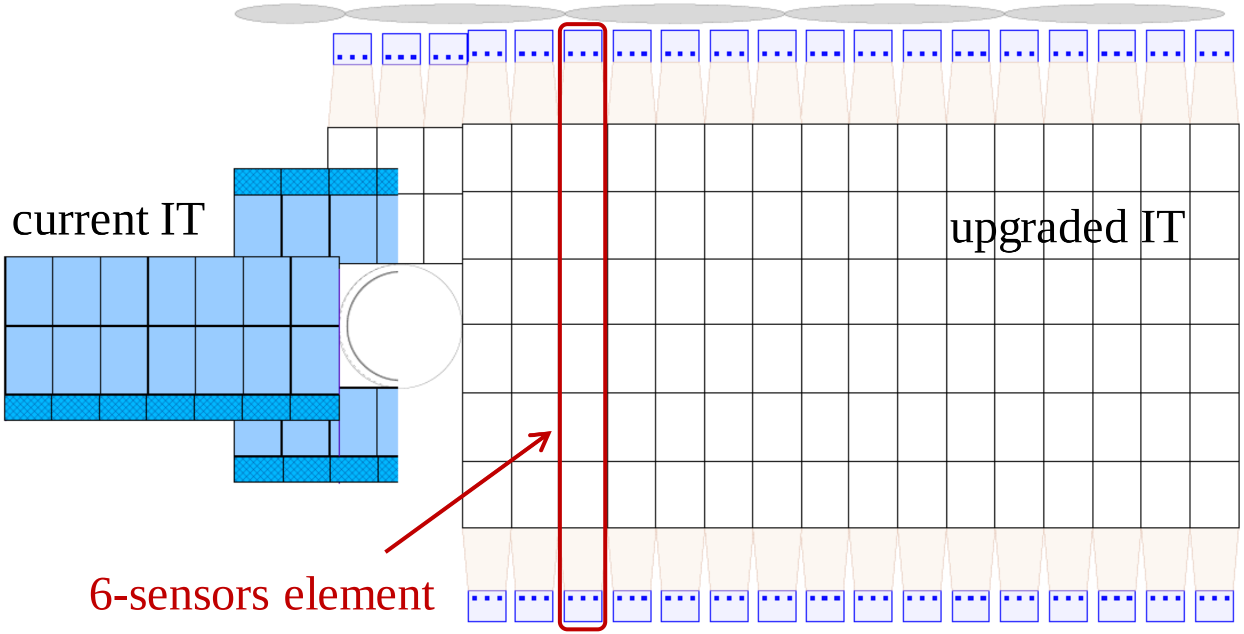
→ decision by December 2013

🟥 Outer Tracker with straw tube technology

🟦 Full tracker with scintillating fibre technology

T-stations upgrade: enlarged Inner Tracker (IT)

- ✓ increase IT area to reduce OT occupancy to < 25%
- ✓ minimise dead material in acceptance
- ➢ 6-sensors element on ultra light carbon support
- ➢ 40 MHz FE on either side with 3 SALT chips per element
- ➢ coverage for B-decay tracks: IT/(IT+OT)= 28% → 47%
- ➢ hit resolution 70 µm, $\frac{\Delta p}{p}$: 0.3-0.5%

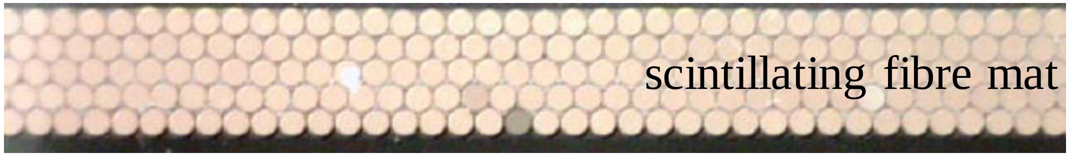


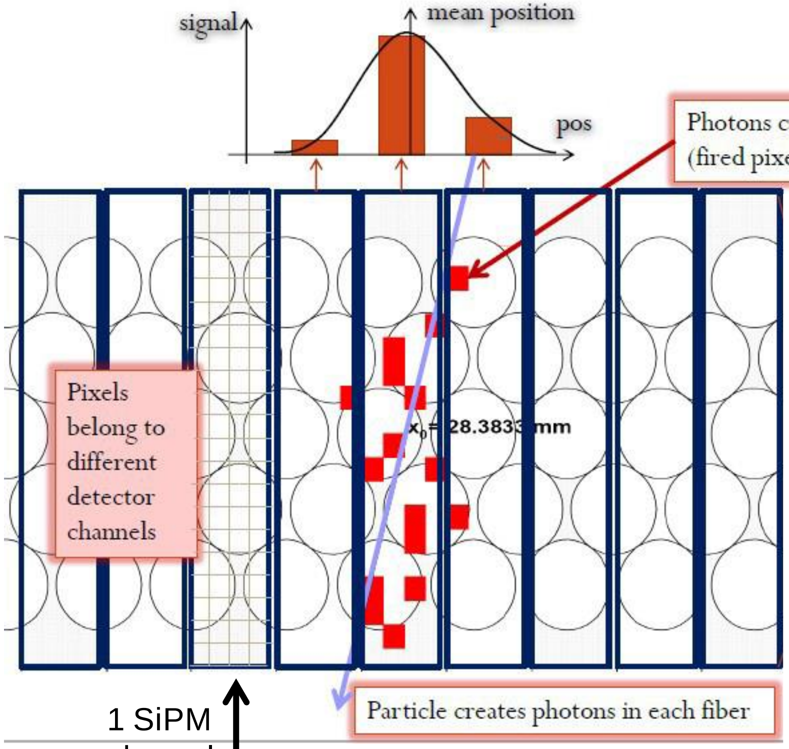
6-sensors element
with FE on each side

FE electronics

ultra light
carbon roving
support

T-stations upgrade: Fibre Tracker (FT)





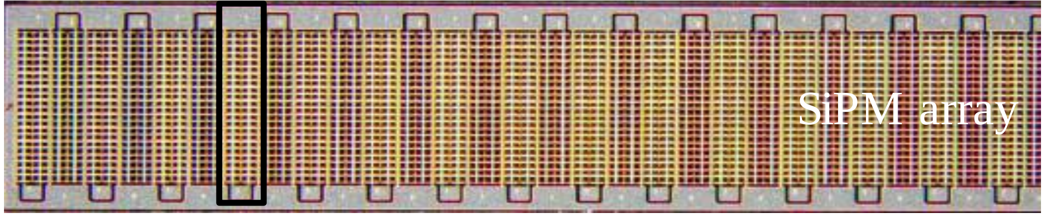
Photons can create signal (fired pixels are red)

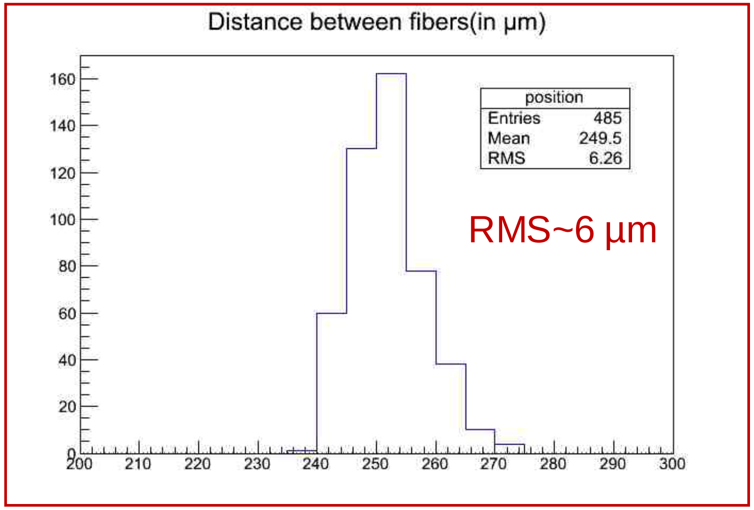
Pixels belong to different detector channels

Particle creates photons in each fiber

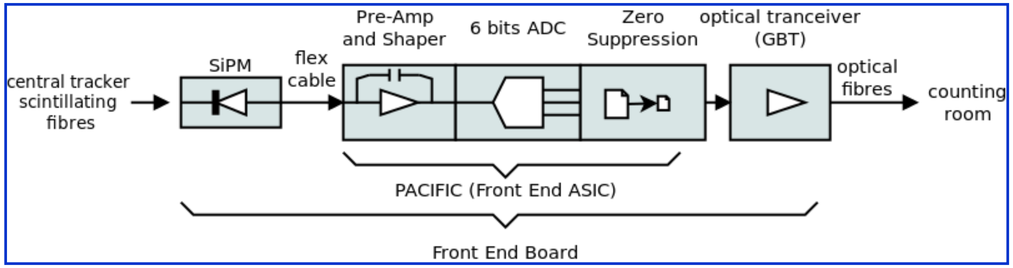
Fibres:
Ø = 250 µm

1 SiPM channel





RMS~6 µm



analog readout by dedicated
40 MHz PACIFIC chip

T-stations upgrade: Fibre Tracker (FT)

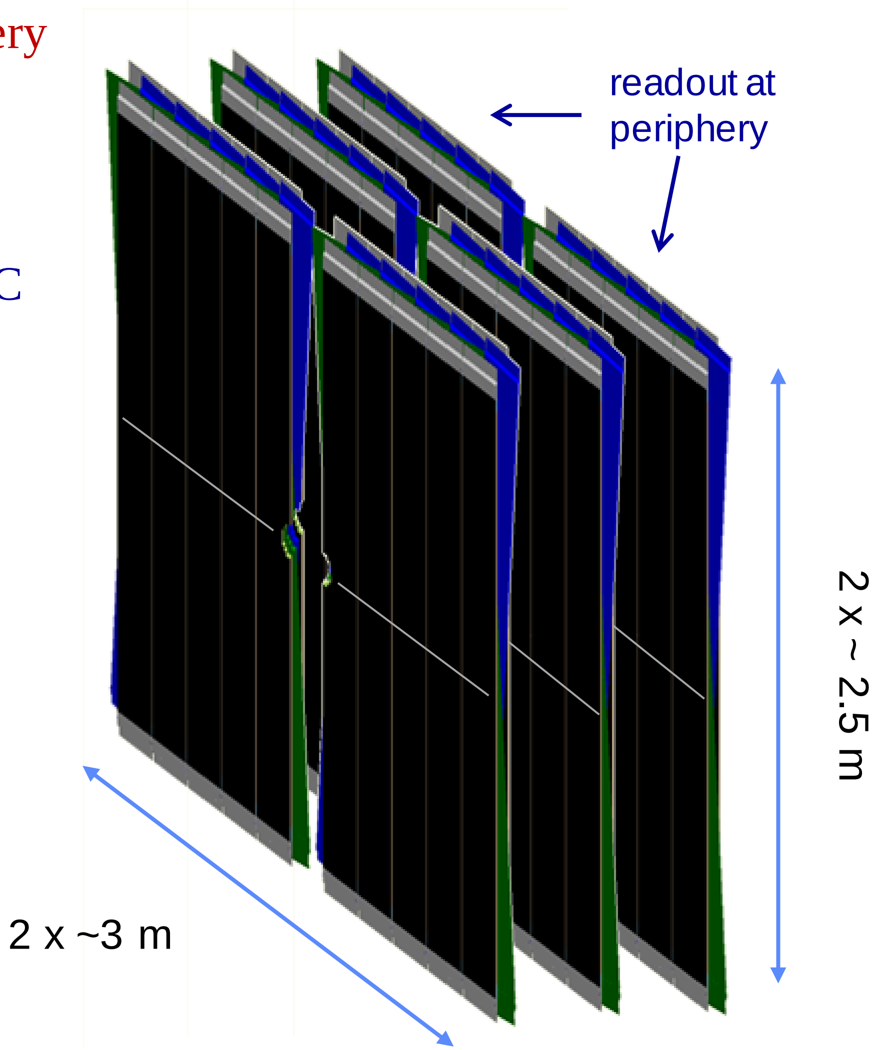
- 3 stations of X-U-V-X (±5° stereo angle) scintillating fibre planes
- every plane made of 5 layers of Ø=250 µm fibres, 2.5 m long
- 40 MHz readout and Silicon PMs at periphery

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



Tracking algorithm for the Trigger

Expected available average time for processing an event with the upgraded trigger: ~16 ms (with ~10 times more powerful CPU farm than 2012)

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

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

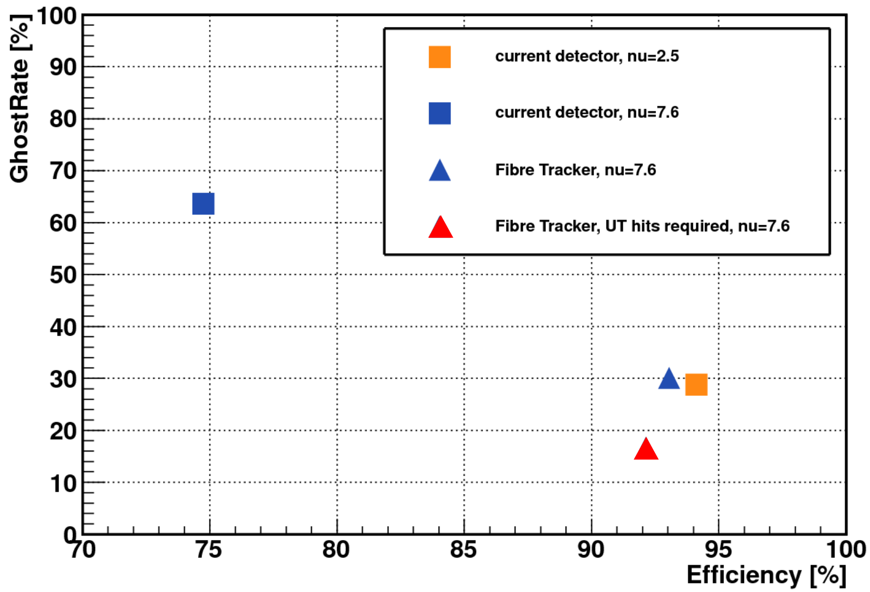
→ leaves ~5 ms for a trigger decision

Tracking performance with upgraded Tracker:

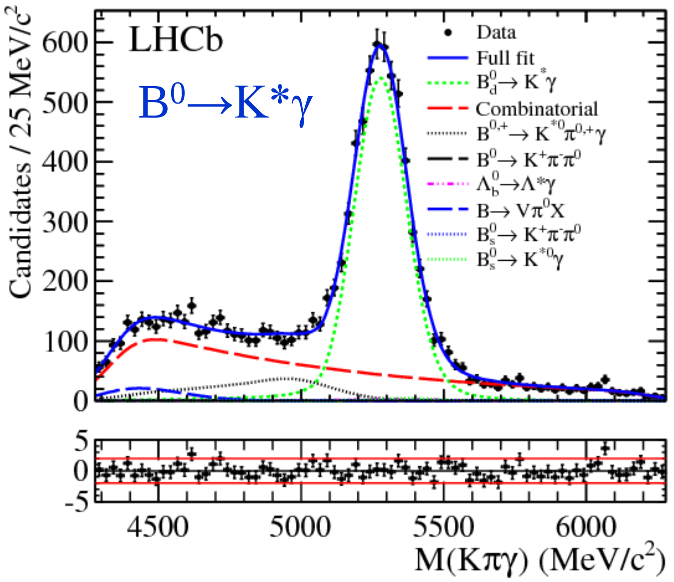
- ■ current detector at $2 \cdot 10^{32}$ cm^{-2}s^{-1}
- ■ current detector at $20 \cdot 10^{32}$ cm^{-2}s^{-1}
- ▲ upgrade FT at $20 \cdot 10^{32}$ cm^{-2}s^{-1}
- ▲ upgrade FT & UT at $20 \cdot 10^{32}$ cm^{-2}s^{-1}

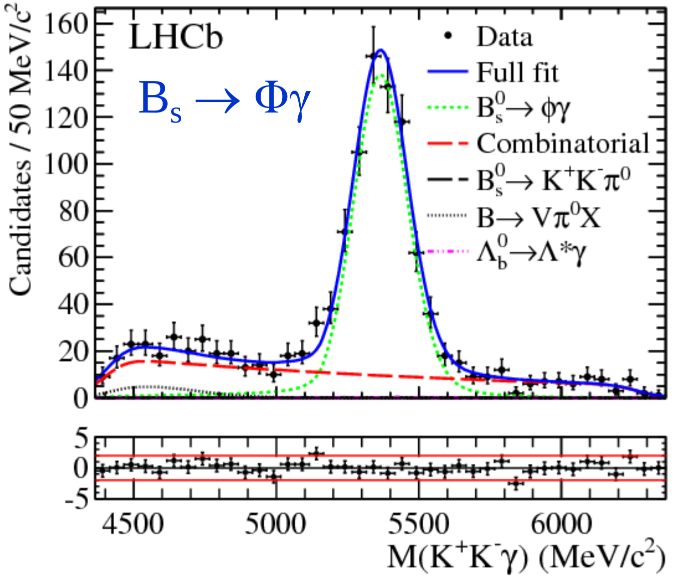
→ restore tracking performance at upgrade luminosity with Fibre Tracker

→ half the ghost rate using UT information



Particle identification with Calorimeters

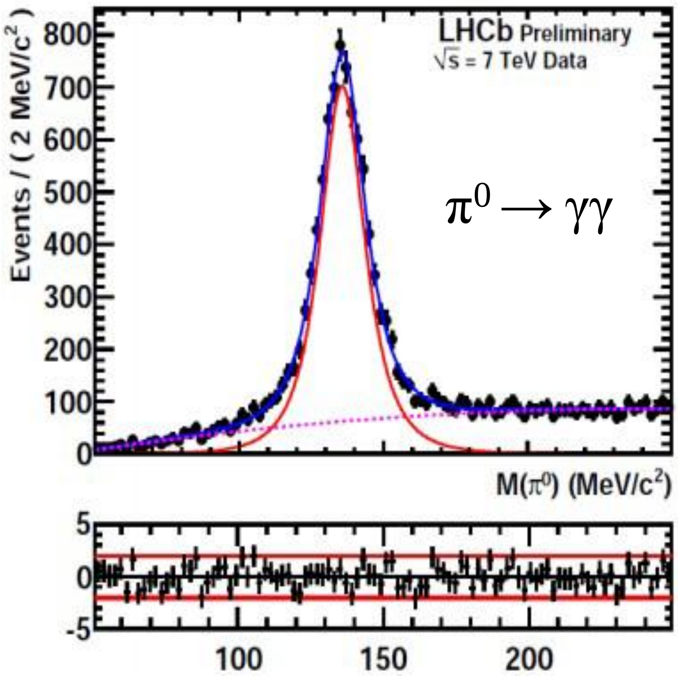




Nuclear Physics, Section B 867 (2013) 1

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



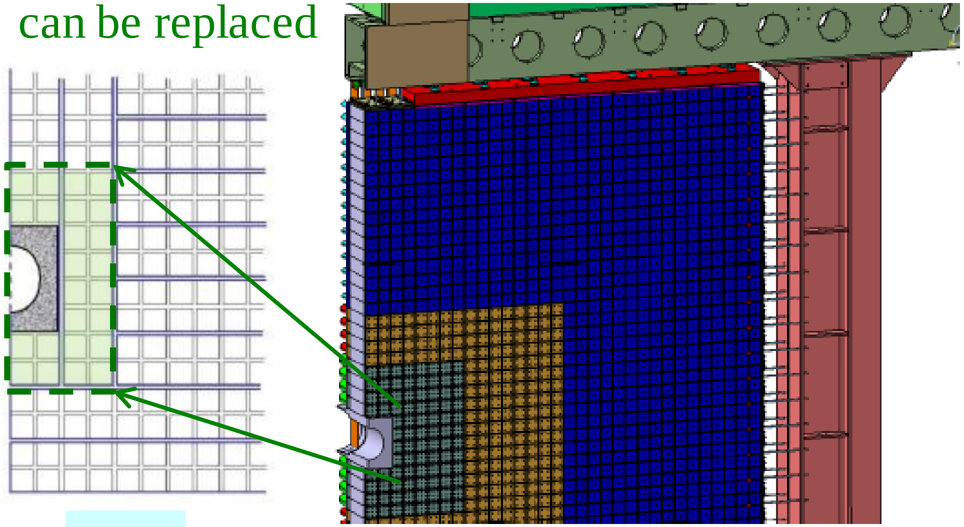
Calorimeters upgrade

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

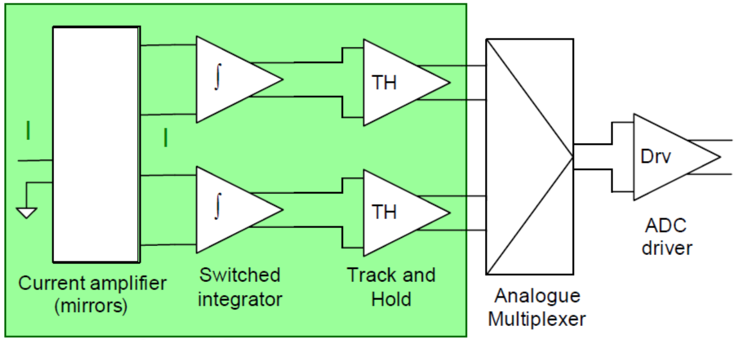
E beam, GeV	module #1 (irradiated 2Mrad) light yield ph.el./GeV	module #1 (irradiated 2Mrad) resolution, %	module #2 (not irradiated) light yield, ph.el./GeV	module #2 (not irradiated) resolution, %
50	583±12	2.16±0.04	2598±52	1.37±0.04
100	576±12	1.57±0.03	2611±52	1.01±0.03
120	571±12	1.36±0.03	2604±52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

most inner ECAL modules around beam-pipe can be replaced

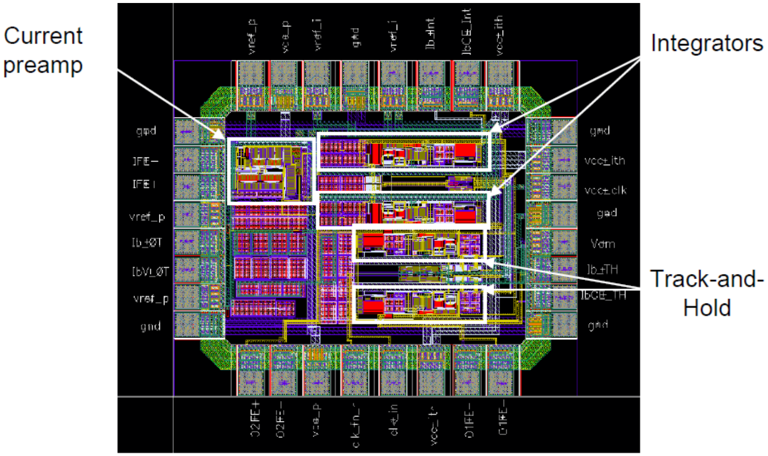


40 MHz readout electronics:

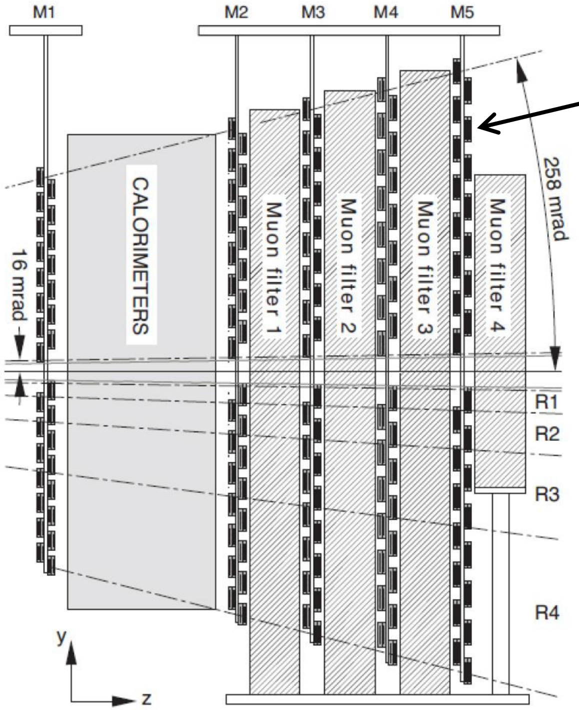
- ➢ reduce photomultiplier gain
- ➢ two interleaved integrators at 20 MHz
- ➢ fully differential implementation
- ➢ Track and Hold



Second Prototype: ICECAL2

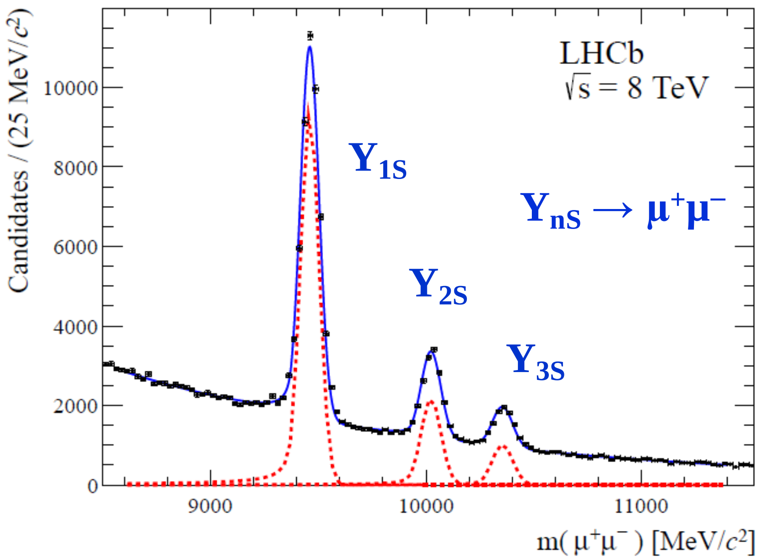


Particle identification with Muon System



MWPC

5 stations
M1 to M5



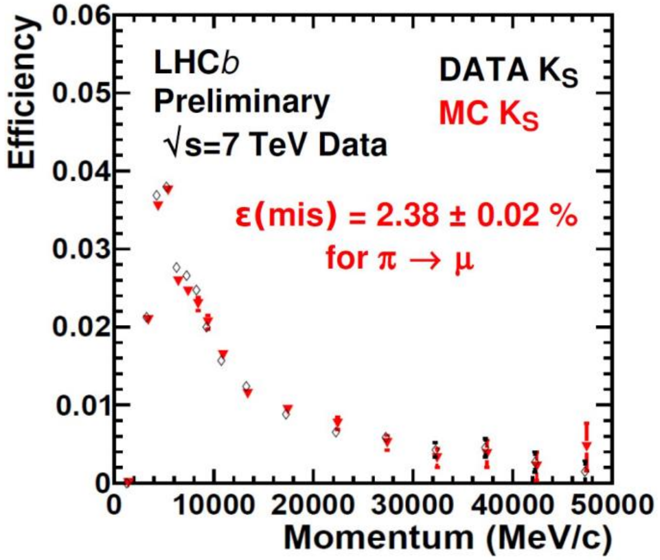
high detection efficiency: ε(μ) = (97.3±1.2)%

low misidentification rates:

ε(p → μ) = (0.21 ± 0.05)%

ε(π→ μ) = (2.38 ± 0.02)%

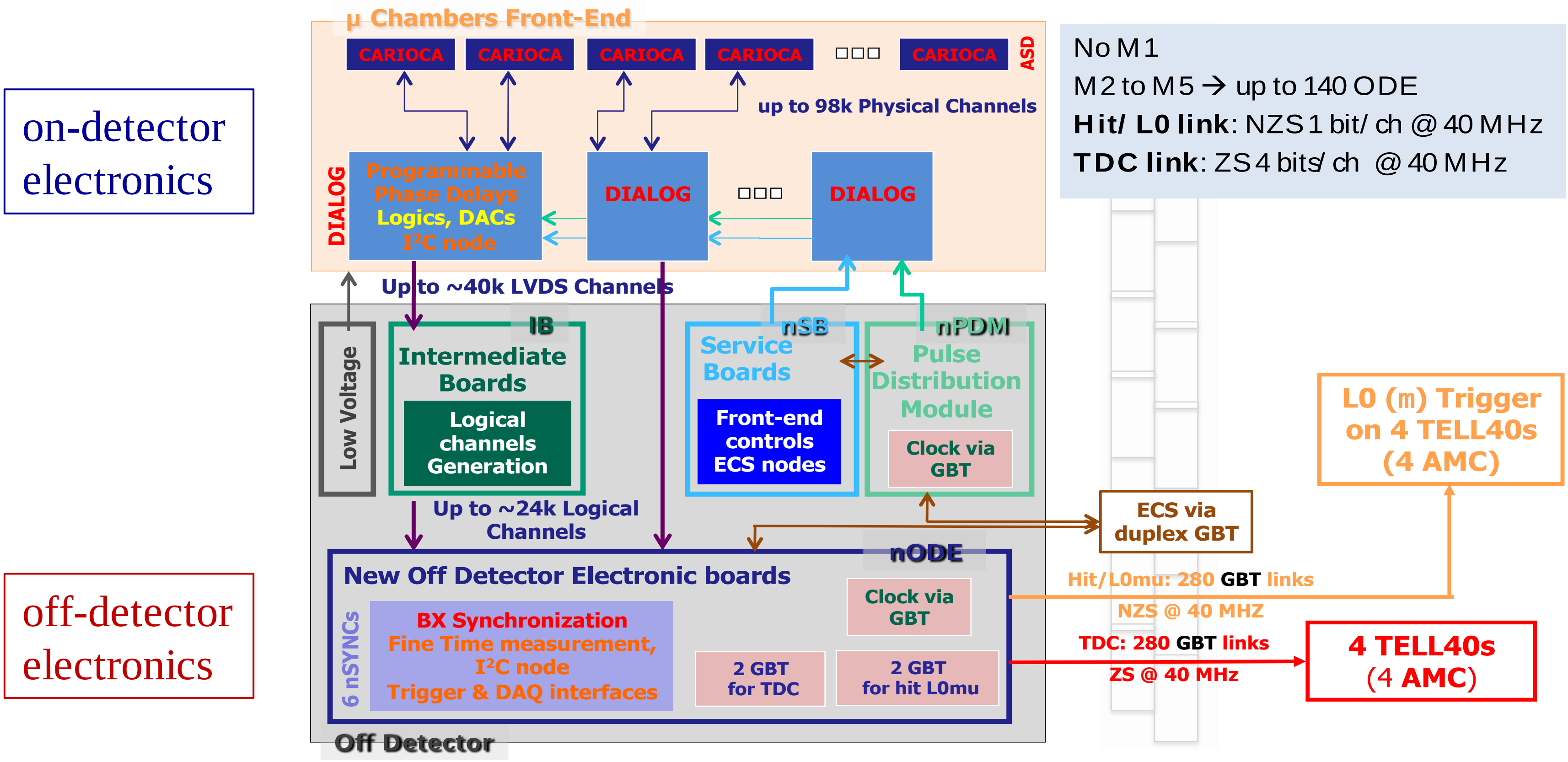
ε(K→ μ) = (1.67 ± 0.06)%



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 TELL40
- production of spare MWPC for installation in LS3 in hottest regions



on-detector electronics

off-detector electronics

μ Chambers Front-End

CARIOCA CARIOCA CARIOCA CARIOCA □□□ CARIOCA

ASD

up to 98k Physical Channels

DIALOG

Programmable Phase Delays Logics, DACs I^2C node

DIALOG □□□ DIALOG

Up to ~40k LVDS Channels

Low Voltage

IB Intermediate Boards

Logical channels Generation

Up to ~24k Logical Channels

nSB Service Boards

Front-end controls ECS nodes

nPDM Pulse Distribution Module

Clock via GBT

nODE New Off Detector Electronic boards

6 nSYNCs

BX Synchronization
Fine Time measurement,
I^2C node
Trigger & DAQ interfaces

Clock via GBT

2 GBT for TDC

2 GBT for hit L0mu

Off Detector

No M1
M2 to M5 → up to 140 ODE
Hit/ L0 link: NZS 1 bit/ ch @ 40 MHz
TDC link: ZS 4 bits/ ch @ 40 MHz

ECS via duplex GBT

L0 (m) Trigger on 4 TELL40s (4 AMC)

Hit/L0mu: 280 GBT links
NZS @ 40 MHZ

TDC: 280 GBT links
ZS @ 40 MHz

4 TELL40s (4 AMC)

Roadmap of the LHCb upgrade

2011	LoI submitted & encouraged to proceed to TDRs
2012	"Framework TDR" submitted, endorsed & approved
	→ **"LHCb upgrade approved to be part of the long-term exploitation of the LHC"**
2012	Submission of MoU for Common Projects
2012 /13	R&D towards technical choices
2013	Technical reviews & choice of technologies
2013/14	Technical Design Reports & MoUs of sub-systems
2014	Prototype validation & Engineering Design Reviews
2014-16	Tendering & serial production
2016-17	Quality control & acceptance tests
2018/19	18 months installation during LS2

CERN-LHCC-2011-001

CERN-LHCC-2012-007

- ➢ 18 months installation time during LS2 is mandatory
- ➢ a later start of LS2 in 2019 would be advantageous for LHCb
- ➢ further delay of the start of LS2 beyond 2019 would be disfavoured

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 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 2018, with a preferred installation in 2019
- the installation during LS2 requires an 18 months shutdown