GDR-Inf workshop
The future of the intensity frontier
01 – 02 Feb 2018
CERN

LHCb Upgrade(s)

R. Le Gac
CPPM IN2P3/CNRS

Preface

- LHCb covers many different domains:
  - Heavy flavour (*c* and *b* quarks)
  - Spectroscopy of hadrons (pentaquarks, Ω_c^0 , Ξ_{cc}^{++}, ...)
  - Electroweak physics in the forward region
  - Heavy Ion physics in the forward region (pPb, Pbp at 14 TeV)
  - Fix target like experiment (pNe, pAr, PbNe, PbAr, ...)
  - …
- This talk is mainly focus on the heavy flavour sector

Outline

Current LHCb (2010 – 2018)

- After CDF, LHCb has demonstrated that high precision measurements can be performed with an hadron collider by studying decays of *b* and *c* hadrons.

- With the Run1 and Run2 data, LHCb superseded main results obtained at the *b*-factories and provides many new ones in the B_s

Obs.	$\int \mathcal{L}$	Value	Ref.
γ	$5\,\mathrm{fb}^{-1}$	$(76.8^{+5.1}_{-5.7})^\circ$	LHCb-CONF-2017-004
$\phi_s^{c\bar{c}s}$	$3\,\mathrm{fb}^{-1}$	$1 \pm 37\,\mathrm{mrad}$	JHEP 08 (2017) 037
$\lvert V_{ub}\rvert$	$2\,\mathrm{fb}^{-1}$	$(4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3}$	Nature Physics 10 (2015) 1038
Δm_s	$1\,\mathrm{fb}^{-1}$	$17.768 \pm 0.023 \pm 0.006\,\mathrm{ps}^{-1}$	NJP 15 (2013) 053021
$R(D^*)$	$3\,\mathrm{fb}^{-1}$	$0.309 \pm 0.016 \pm 0.024$	arXiv:1708.08856
$B_d \to K^*\mu\mu$	$3\,\mathrm{fb}^{-1}$	$A_{FB}, F_L, q_0^2, P_5', \ldots$	JHEP 02 (2016) 104
$B(B_s \to \mu\mu)$	$4.4\,\mathrm{fb}^{-1}$	$(3 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$	PRL 118 (2017) 191801
$D^0 - \bar{D}^0$ mixing	$5\,\mathrm{fb}^{-1}$	$x'^2 = (3.9 \pm 2.7)^{-5}$	arXiv:1712.03220
		$y' = (5.28 \pm 0.52)^{-3}$	

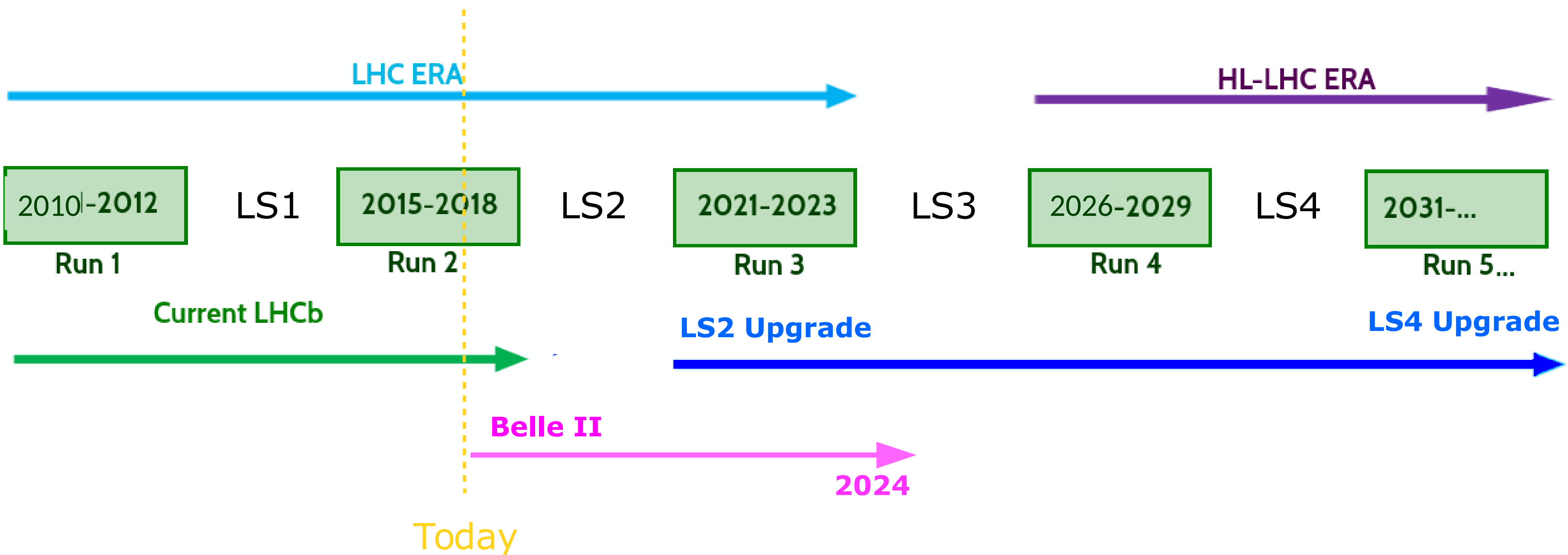
- In the future, the detector will be upgraded to reach unprecedented sensitivity on many key observables.

LHCb working point

Data taking time	7 years
$\sqrt{s}$	7, 8 and 13 TeV
Integrated Luminosity	8 fb^{-1}
Instantanous Luminosity	4×10^{32} $cm^{-2}s^{-1}$
Pileup	1.1

Schedule of LHCb Upgrade(s)

It is driven by the Long shut down (LS) of the LHC machine:



Consolidation phase foreseen during LS3. More details in LHCb-TALK-2017-339.

LS2 Upgrade (2021 – 2029)

- Approved by the LHCC and funded:
  - Letter of Intent for the LHCb Upgrade (CERN-LHCC-2011-001)
  - Framework TDR for the LHCb Upgrade (CERN-LHCC-2012-007)
  - LHCb VELO upgrade TDR (CERN-LHCC-2013-021)
  - LHCb PID Upgrade TDR (CERN-LHCC-2013-022)
  - LHCb Tracker Upgrade TDR (CERN-LHCC-2014-001)
  - LHCb Trigger and Online Upgrade TDR (CERN-LHCC-2014-016)

- To be installed during the LS2 (2019 – 2020)

- Main characteristics:

Data taking time	6 years	
Integrated Luminosity	50 fb^{-1}	×6 / LHCb
Instantanous Luminosity	2×10^{33} $cm^{-2}s^{-1}$	×5 / LHCb
Pileup	6	×6 / LHCb

LS4 Upgrade (2031 – ...)

- In a design phase. Not yet approved by the LHCC:
  - Expression of Interest for a Phase-II Upgrade: Opportunities in flavour phyiscs, and beyond, in the HL-LHC area (CERN-LHCC-2017-003).
  - LHCC encouraged us to continue with studies on Upgrade II
- Plan:
  - Submit LHCb LS4 Upgrade Physics case → May 2018
  - Submit Detector TDRs "à l'horizon" 2024
  - To be installed during the LS4 (2030)
- Main characteristics

Running	~ 5 years	
Integrated Luminosity	300 fb^{-1}	×6 / LHCb LS2
Instantaneous Luminosity	$1\text{-}2\times10^{34}\ cm^{-2}s^{-1}$	×10 / LHCb LS2
Pileup	~50	×10 / LHCb LS2

Flavour physics reach...

Anatomy of an LHCb event

- Yield per proton-proton collision:

	LHCb	LS2 Upgrade	LS4 Upgrade
Instantaneous $\mathscr{L}$	4×10^{32}	2×10^{33}	2×10^{34}
Pileup	1.1	6	~60
c-hadron	0.04	0.216	~2
b-hadron	0.003	0.019	~0.2
Light, long lived hadrons	0.511	2.084	~21

LHCb-PUB-2014-027

  - Candidates in geometrical acceptance $2 < \eta < 5$
  - Candidates with 2 tracks traversing at least 3 VELO modules
  - Candidates having all daughter tracks contains in the acceptance

- In the LS2 upgrade, every events will contains 2 light hadron decays with a displaced vertices → saturate any trigger.

- New paradigm is required: "offline" reconstruction an event classification in real time for all collisions.

Very high rate of heavy flavour production

Expected rates of reconstructible event:

	LHCb	LS2 Upgrade	LS4 Upgrade
c-hadron	67 kHz	800 kHz	~8 MHz
b-hadron	17 kHz	270 kHz	~3 MHz
Light, long lived hadrons	23 kHz	264 kHz	~ 3 MHz

LHCb-PUB-2014-027

- Candidate having at least two tracks in the LHCb acceptance
- Candidates partially reconstructed (vertex with 2 charged tracks)
- Candidates with a parent p_T above 2 GeV/c
- Candidates with a decay time above 0.2 ps

Size of signal samples for some rare decays

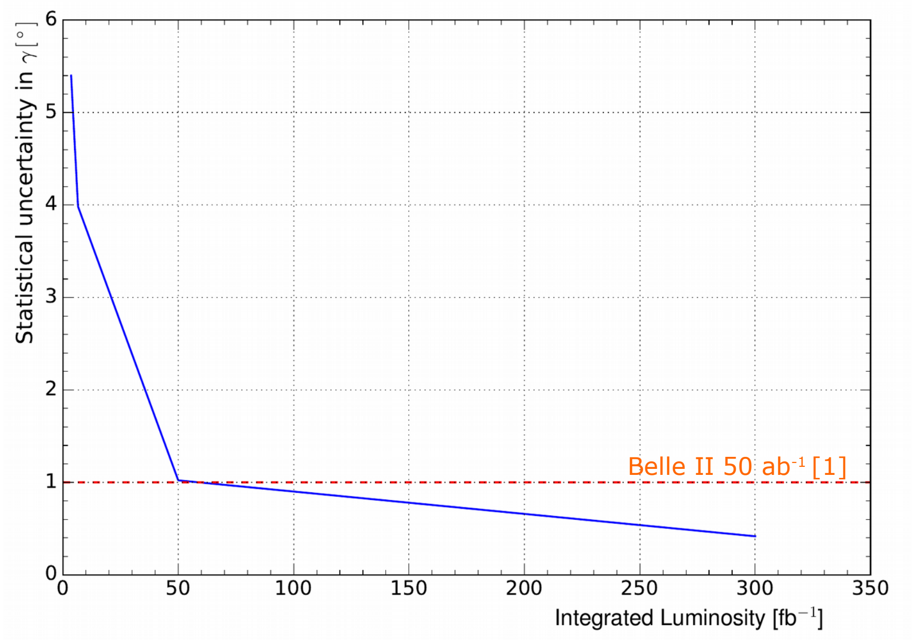
Extrapolated from current measurements:

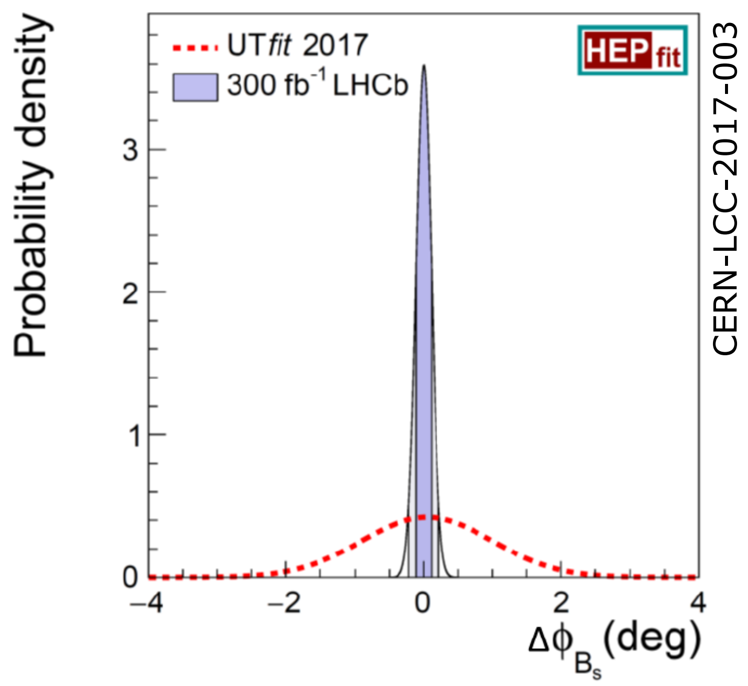
channel	Run 1	Run 2	Run 3,4 (50fb^{-1})
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$	2,400	9,000	80,000
$B^0 \to K^{*+}(K^0_S\pi^+)\mu^+\mu^-$	160	600	5,500
$B^0 \to K^0_S\mu^+\mu^-$	180	650	5,500
$B^+ \to K^+\mu^+\mu^-$	4,700	17,500	150,000
$\Lambda_b \to \Lambda\mu^+\mu^-$	370	1500	10,000
$B^+ \to \pi^+\mu^+\mu^-$	93	350	3,000
$B^0_s \to \mu^+\mu^-$	15	60	500
$B^0 \to K^{*0}e^+e^-$ (low q^2)	150	550	5,000
$B_s \to \phi\gamma$	4,000	15,000	150,000

Naively scaling with luminosity and linear scaling of $\sigma_{b\bar{b}}$ with $\sqrt{s}$

CP-violating phases γ

- Extrapolated from the current measurements:



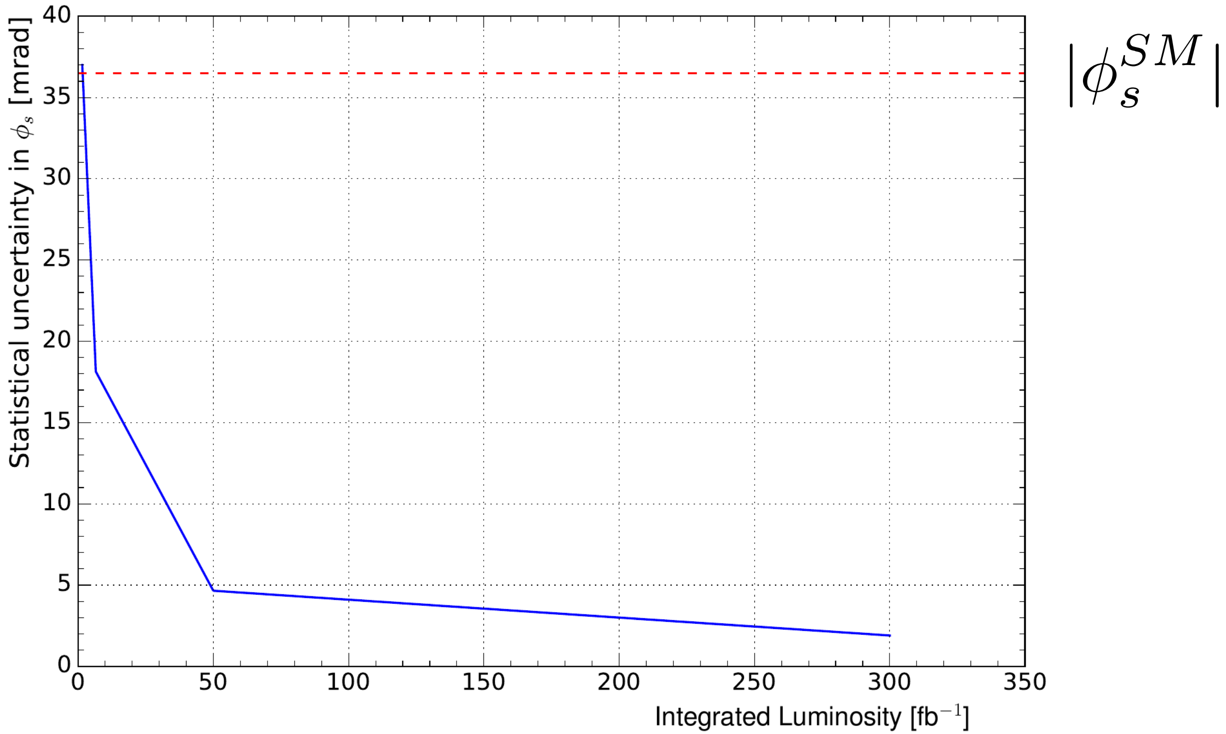


- Target a precision on γ of 0.4°

[1] P. Goldenzweig, La Thuile,11/3/2017

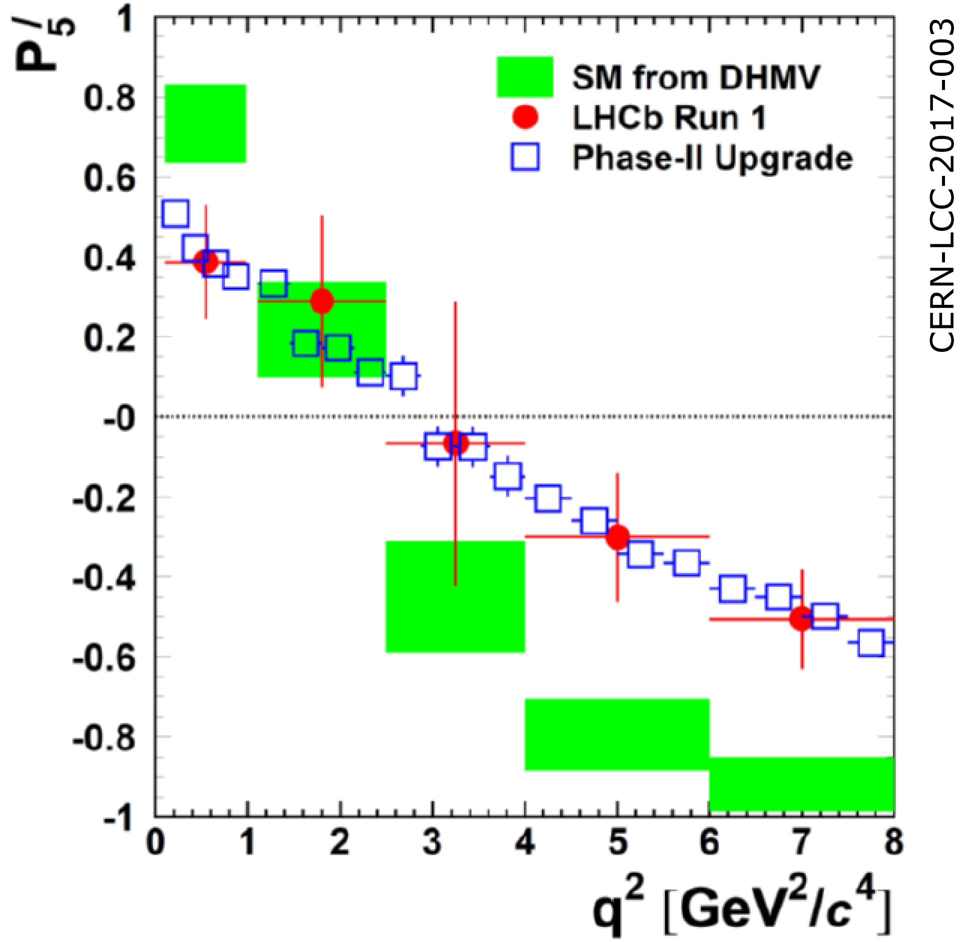
CP-violating phases ϕ_s

- Extrapolated from the current measurements:

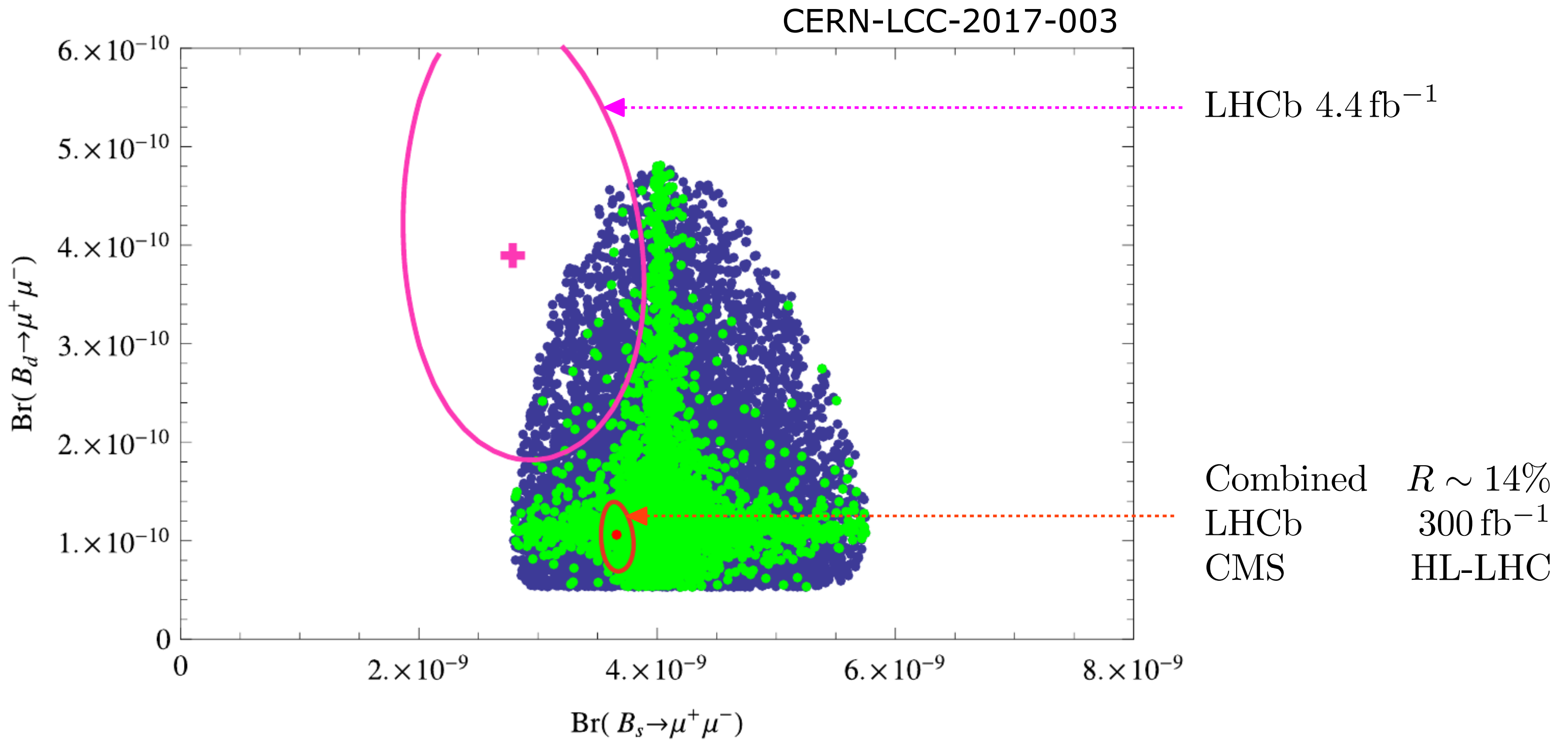


- Target a precision on ϕ_s of 3 mrad.

P_5' in $B^0 \to K^* \mu\mu$



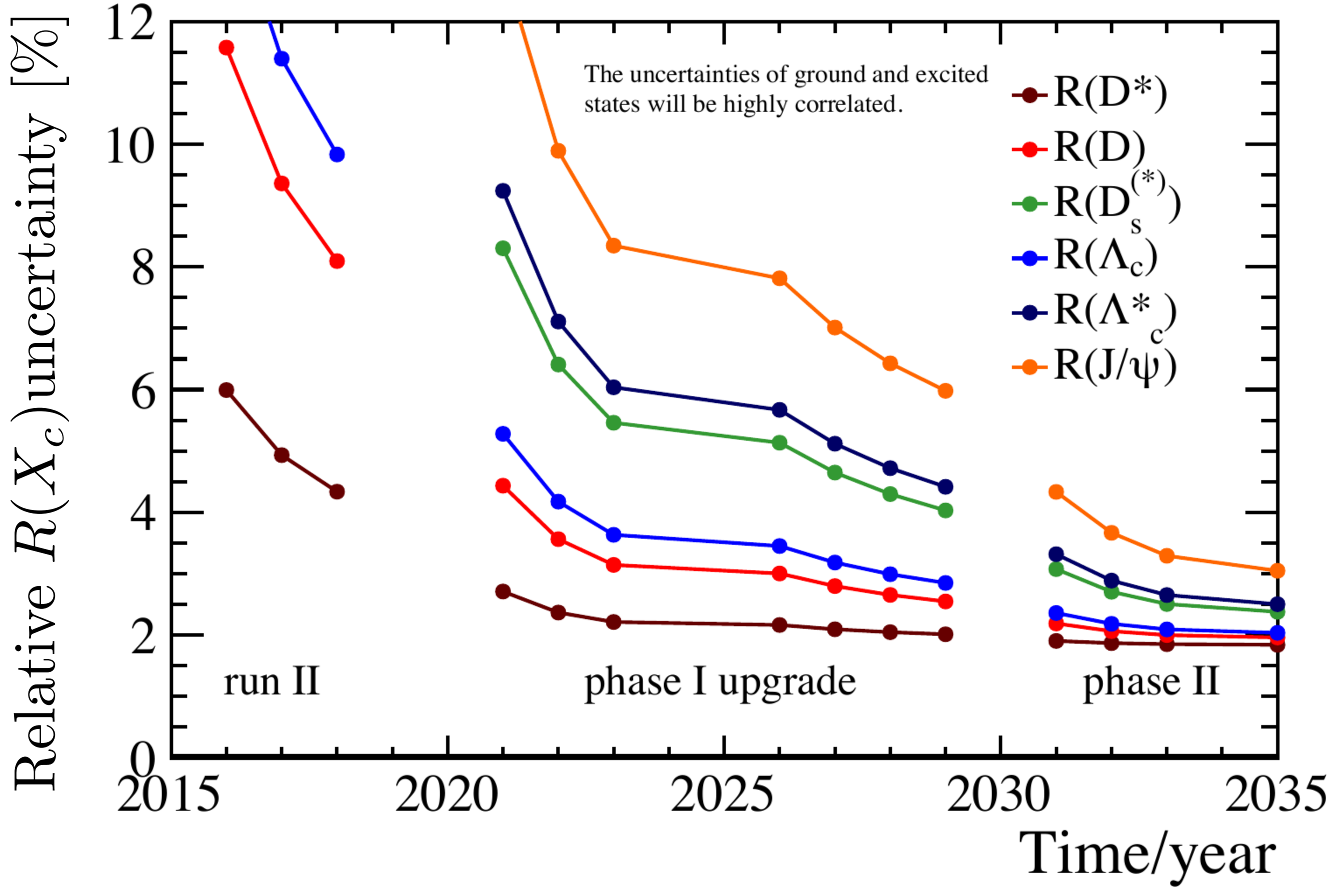
B^0 versus $B_s^0 \to \mu\mu$



- Measurement of $R = \mathcal{B}(B^0 \to \mu\mu)/\mathcal{B}(B_s^0 \to \mu\mu)$ with an uncertainty of 20% and the first precise measurements of $B_s^0 \to \mu\mu$ observables.
- Similar sensitivity from CMS, but the superior mass resolution of LHCb will allow a better control of systematic uncertainties.

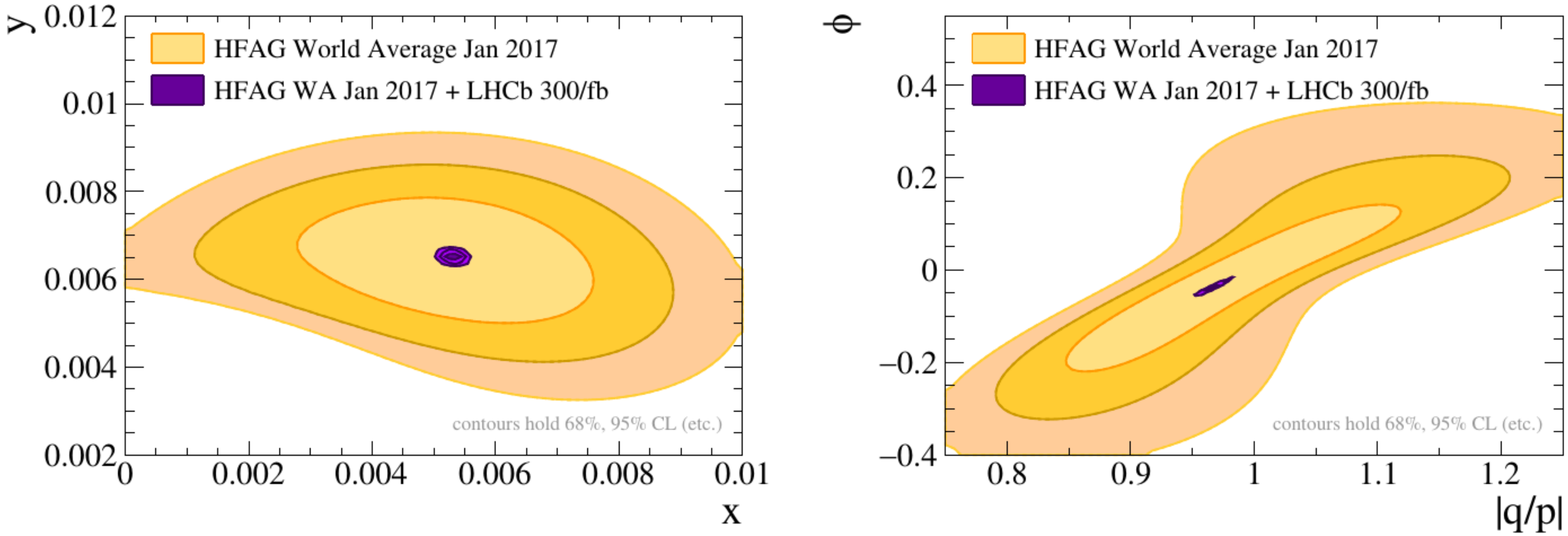
Lepton Flavor Universality

A wide range of lepton-universality tests:



Mixing and indirect CP-violation in charm

- Probe indirect CP-violation with a precision of 10^{-5} and measure charm mixing parameter with a precision of 10^{-4}:



CERN-LCC-2017-003

- Wide range of 3 and 4 body decays to explore thoroughly the charm-baryon sector.

LS2 upgrade...

Not review all the details. Mainly focus on the most challenging items...

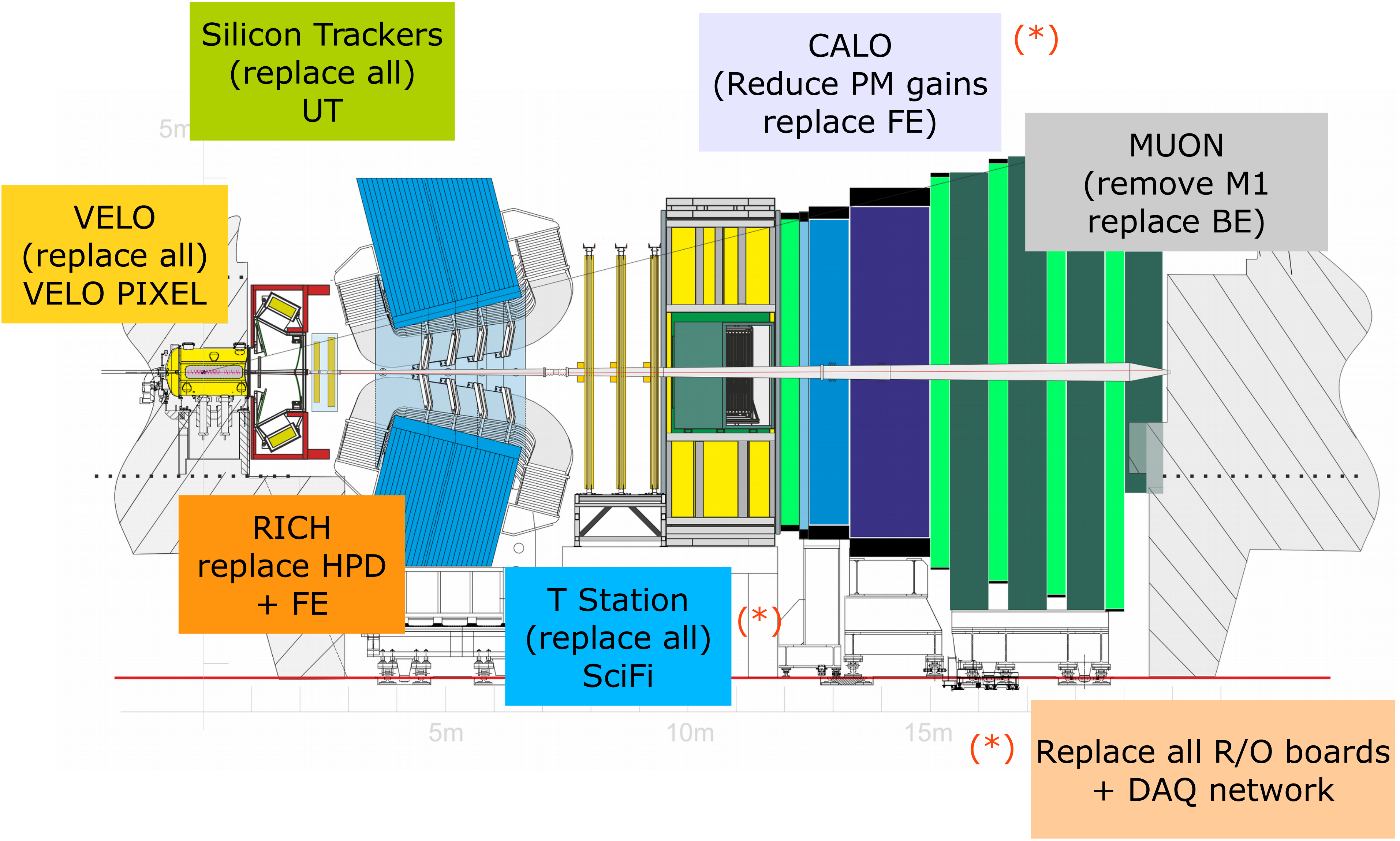
Aims of the LS2 upgrade

- Maximize the statistic of *b* and *c*-hadron decays by using a Trigger-less readout system with a pileup ~6:
  - Remove the bottleneck of the L0 Hardware trigger: yield for hadronic *b*-decays saturate with luminosity
  - Readout all beam-beam crossing (40 MHz)
  - Reconstruction of the event with offline quality in real time
  - Classification of *b* and *c*-decays in real time
  - Tunable output format

- Reconstruction efficiency, invariant mass and decay time resolutions similar to the current experiment of even better.

- Excellent Kaon, pion and muon identifications.

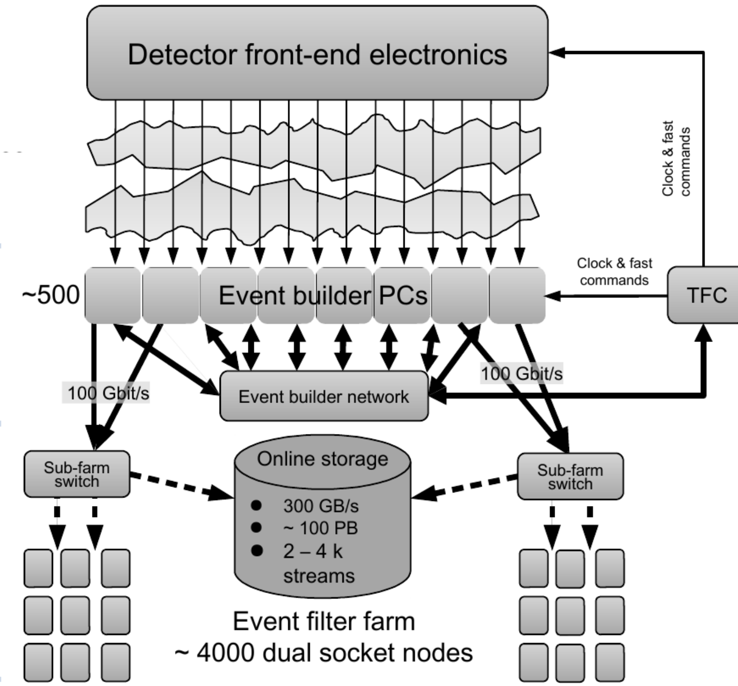
LS2 Upgrade in a nutshell



(*) French contributions

40 MHz readout – A first in the HEP community

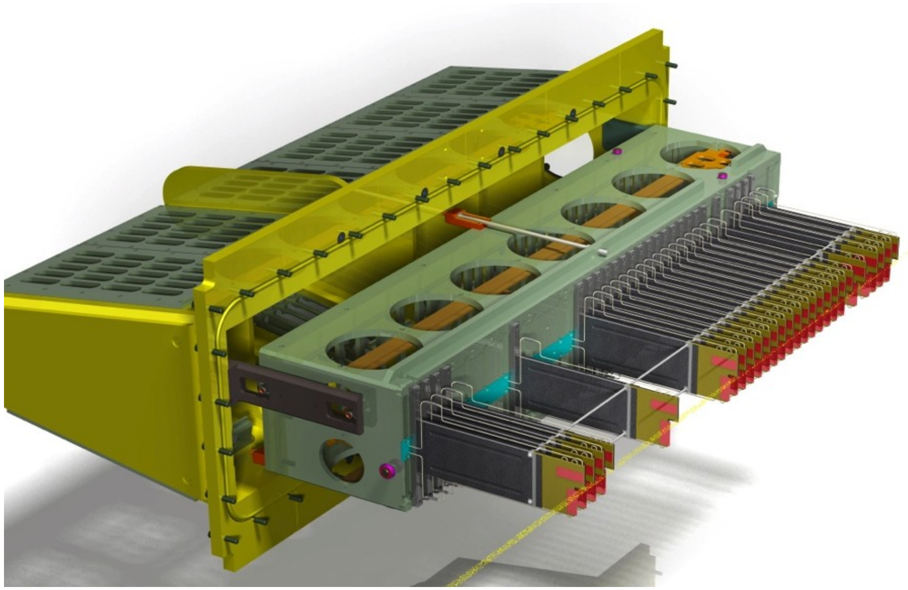
- Aggregate 40 Tb/s :
  - 500 PC servers interconnected via a high-bandwidth, bidirectional network (100 Gbit/s in both direction)
  - Custom made readout board interfacing the FE electronic with the PC servers
- Event Filter Farm processed events in three steps:
  - fast reconstruction (40 → 1 Tb/s)
  - Temporarily storage waiting calibration
  - Best reconstruction and selection (Output bandwidth between 2 and 10 GB/s)
- A challenge for the reconstruction software (C++, vectorization, task-based)



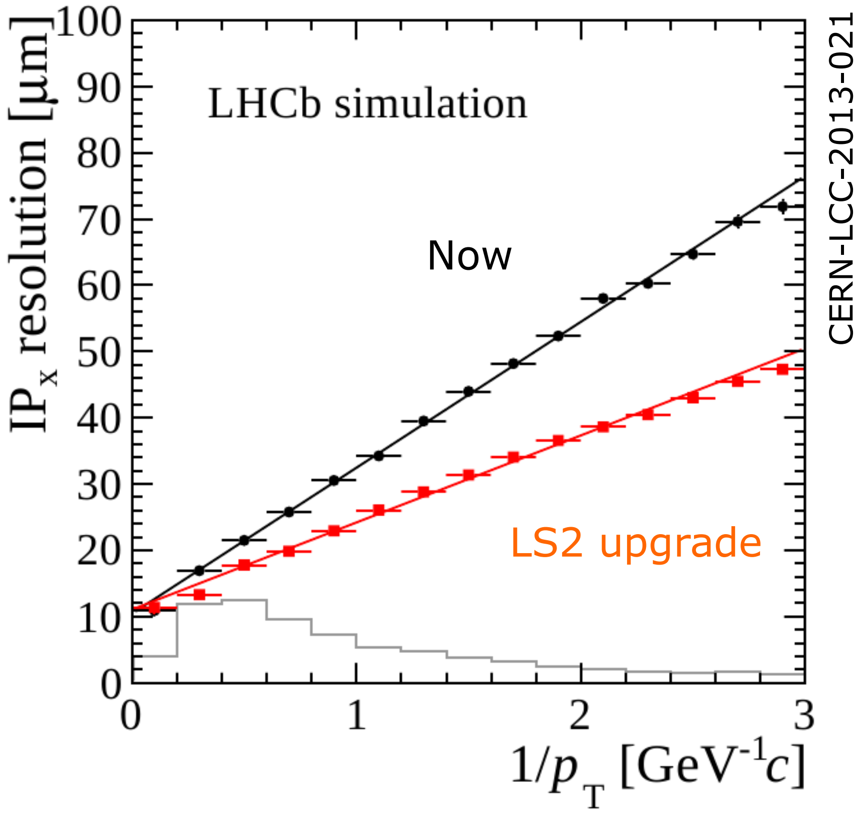
CERN-LCC-2014-016

VELO – Pixel

Half of VELO system:



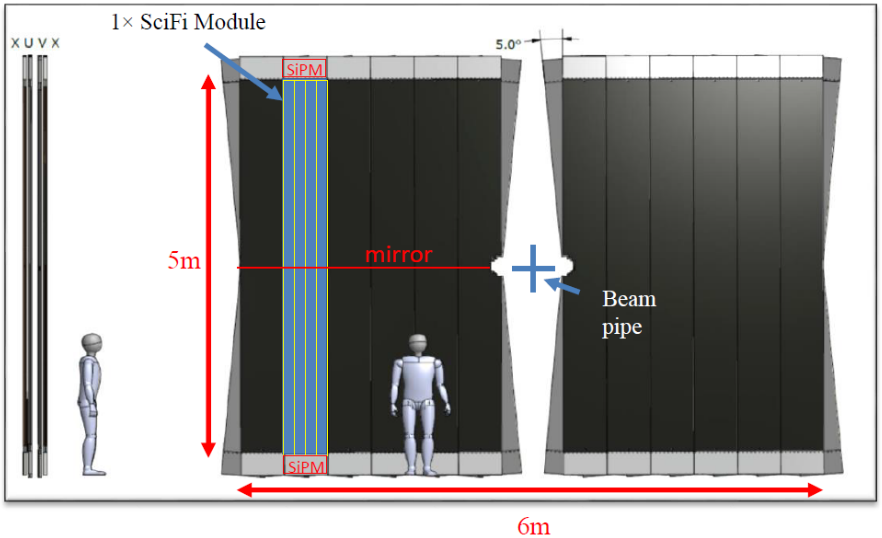
Improved performance:

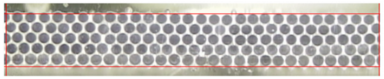


- Stations: 26
- Pixel size: .... 55×55 μm²
- Channels: .... 41×10^6
- Closest distance to beam: 5.1 mm
- Fluence:........................ 8.5×10^{15} $n_{eq}cm^2$
- Innovative evaporative CO_2 cooling via microchannels

SciFi – Scintillating Fiber detector

Large scale system

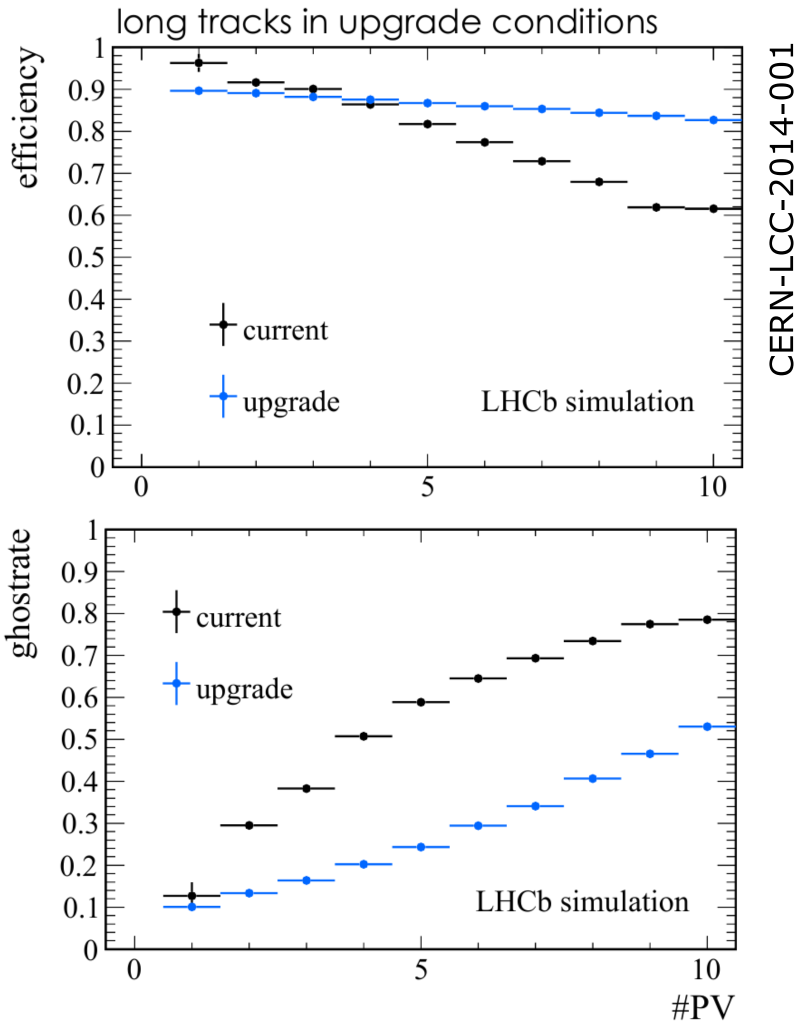




Plan with 5 layers of fibre

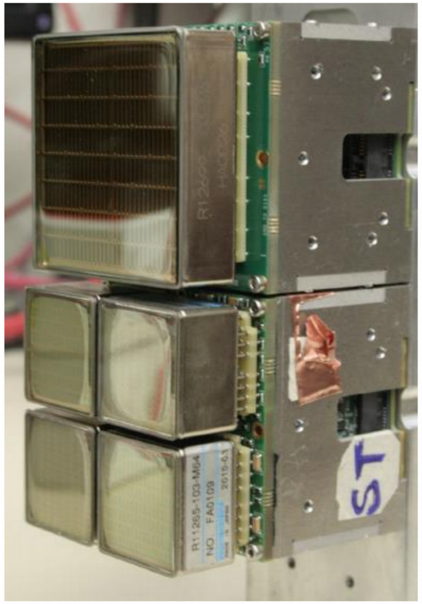
- Scintillating fiber: . 12 000 km
- Stations: .... 3 with 4 plans (*xuvx*)
- Pich: .... 250 μm
- Channels: .... 590×10^3
- Readout SiPM: 4608
- SiPM cooling: .... -40 °C

Improved tracking performance:



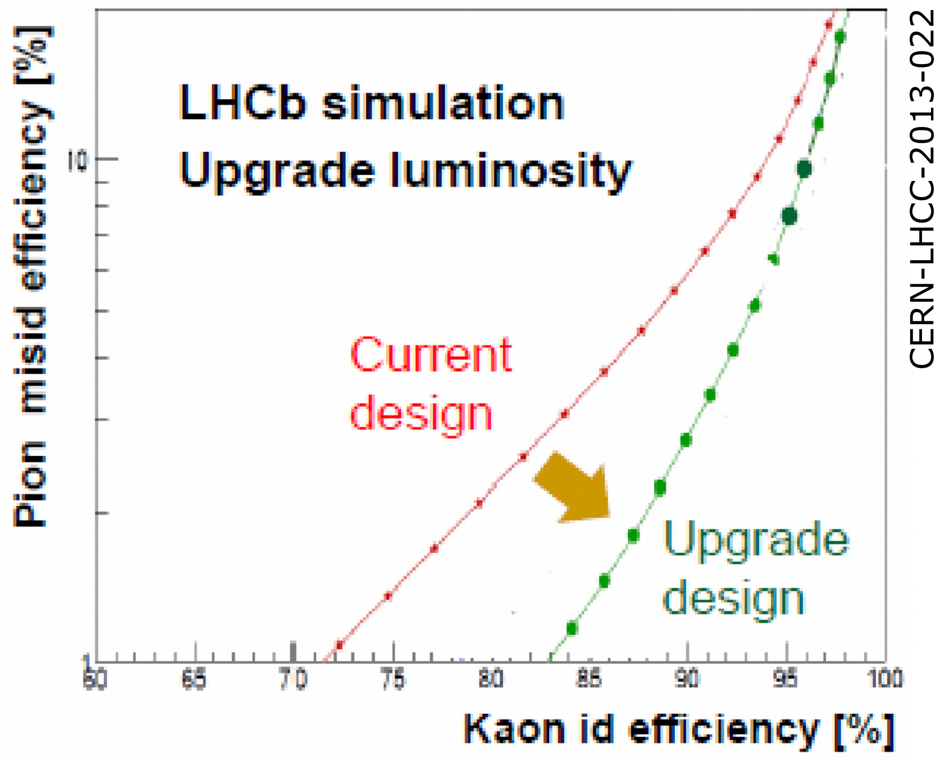
RICH

New photodetector:



- Stations:.............RICH1 + RICH2
- MaPMT: .... 1920 + 2560
- Channels: ....287×10^3

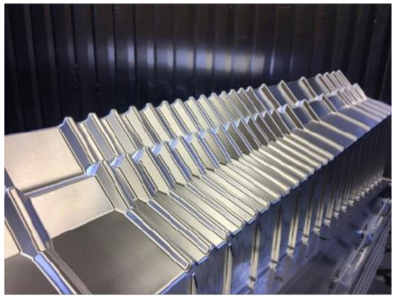
New optics:



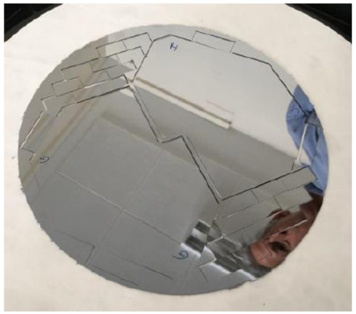
Status of the LS2 Upgrade

Prototype readout boards

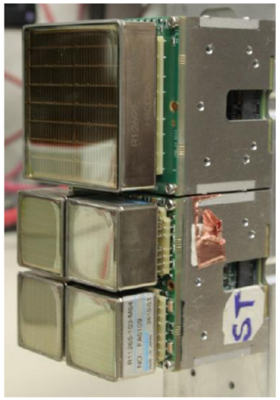
RF box for VELO



Diced wafer with microchannel cooling substrates for VELO

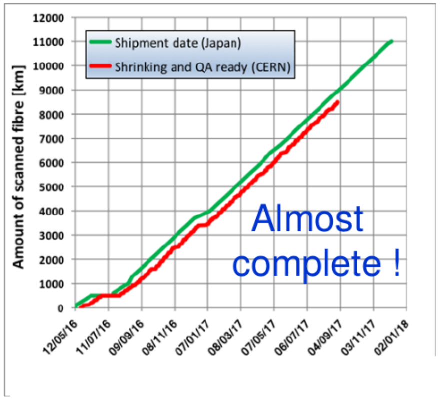


RICH photodetectors



Testing Upstream Tracker 'flex cables'

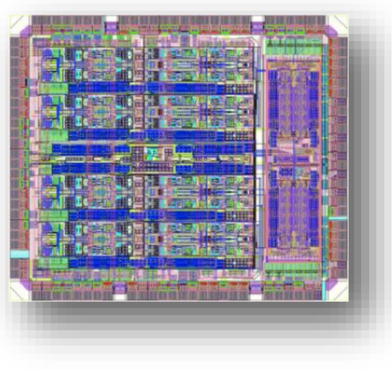
Delivery of tracker scintillating fibres (SciFi)



First batch of SciFi modules arriving at IP8

MWPC for muon system

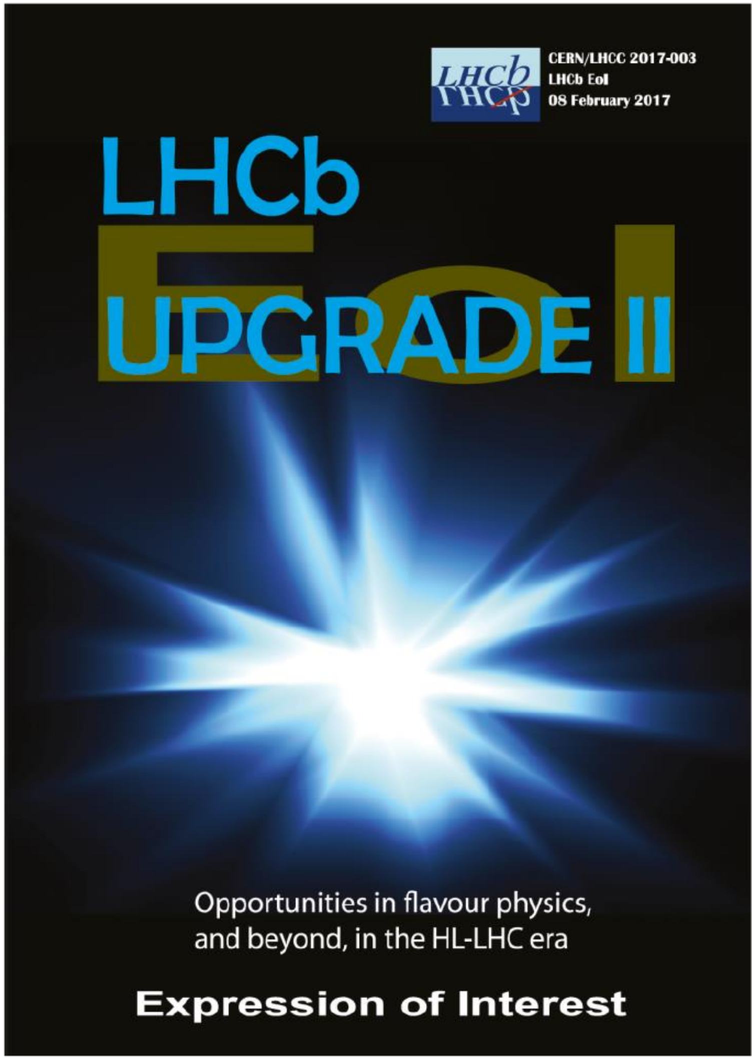
ECAL front-end ASIC



LS4 upgrade

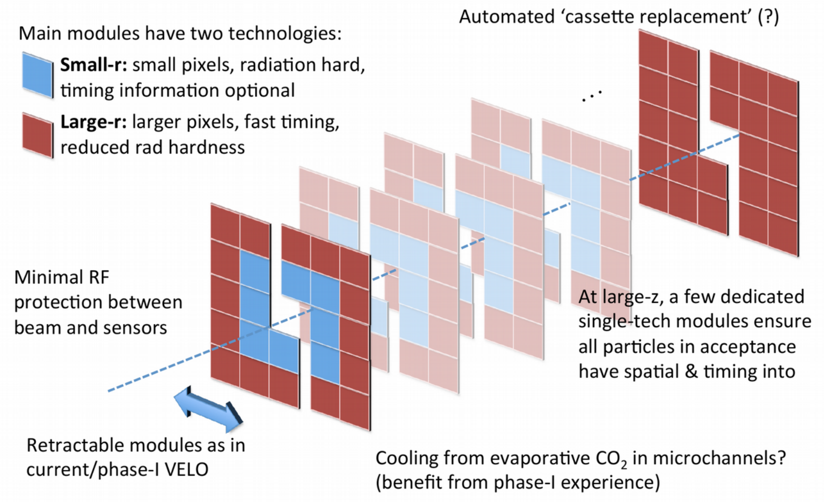
Aims of the LS4 upgrade

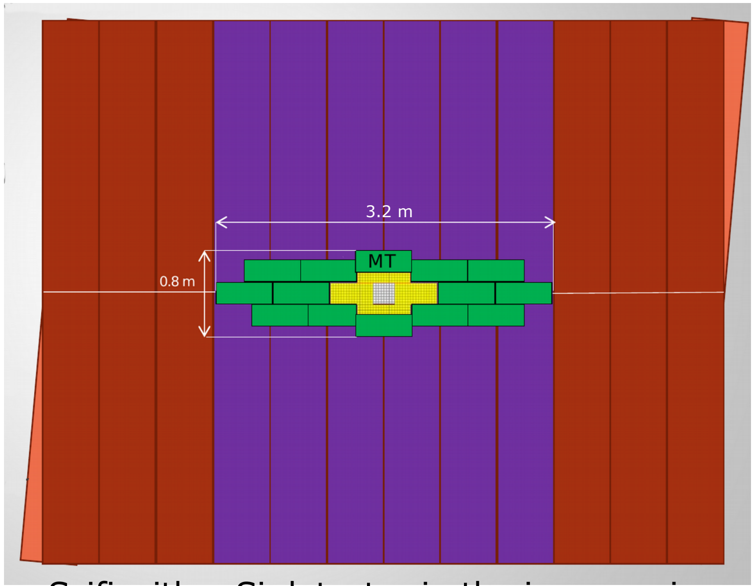
- Take full advantage of the flavour-physics opportunities at the High Luminosity LHC (HL-LHC).
- Retain current performance in key parameters, and also to improve capabilities in certain areas like γ, π^0 detections, low momentum tracking, *etc.*
- Improve granularity, radiation hardness and fast timing



Improvements under discussion

- New VELO pixel detector
  - Pixel size: $55 \rightarrow 27.5\mu\text{m}$
  - Rad hard: $8 \times 10^{16} \text{n}_{\text{eq}} \text{cm}^{-2}$
  - Timing measurement: $30\,\text{ps}$?
- Equip the the inner region of the SciFi with Si stations.
- TORCH detector to improve PID for particles with a low momentum bellow 10 GeV/c.
- Replace the inner module of the ECAL calorimeter with sampling tungsten scintillator calorimeter.
- ...



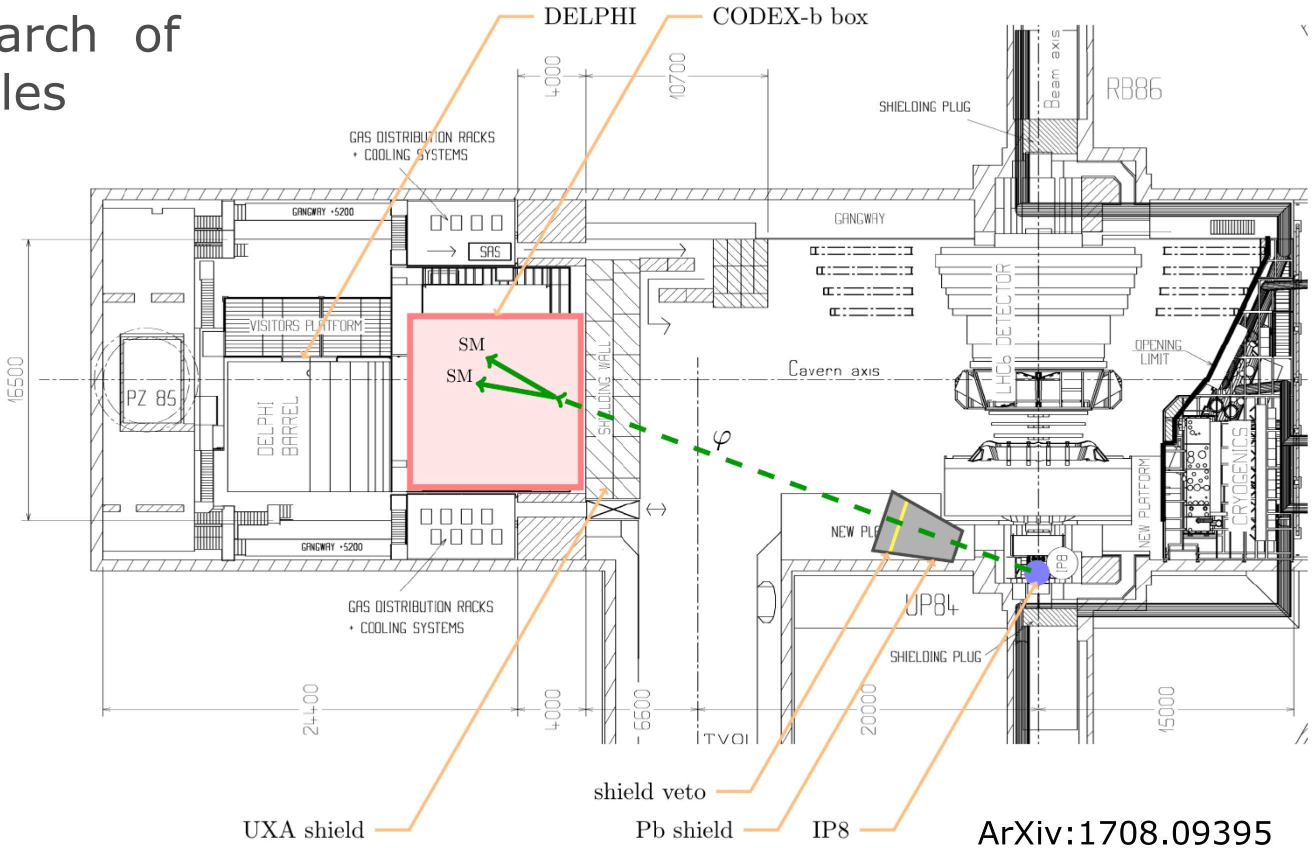


Scifi with a Si detector in the inner region

New ideas

- CODEX-b:

  A proposal for an extension / new subsystem of LHCb dedicated to search of long-lived particles



ArXiv:1708.09395

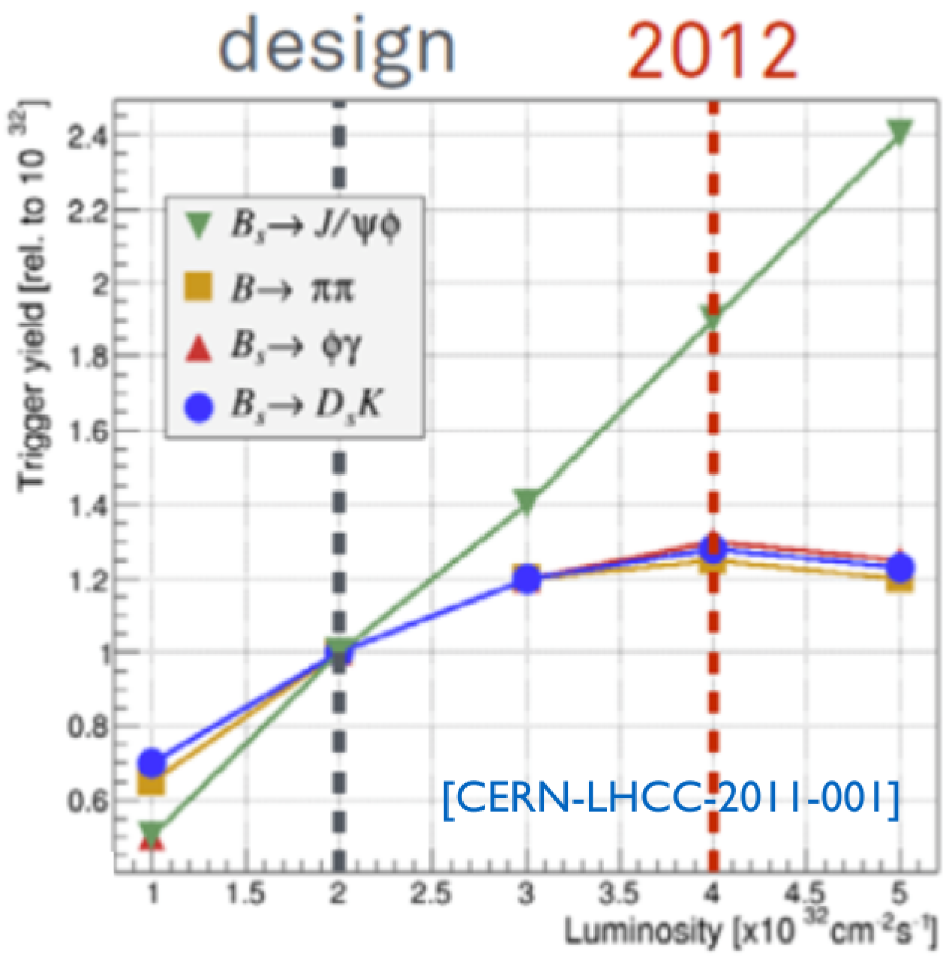
- ...

Conclusions

- The LS2 upgrade is progressing well. It shall be installed in time although the schedule is tight.
- Observed tensions with respect to predictions of the Standard model as well as the large increase in statistics provided by LHCb upgrade(s), open the door to essential progress in the understanding the flavour sector and possible extension to the SM.
- The LS4 upgrade is an opportunity to think again to an handful set of observables allowing to make a large breakthrough and to improve the experiment accordingly in order to reach unprecedented accuracies…
- The consolidation phase in LS3 and the LS4 upgrade are also opportunities for new groups to join the LHCb Collaboration...

Backup...

Saturation of the trigger yield for hadronic decays



LS2 Upgrade – Reconstruction sequence

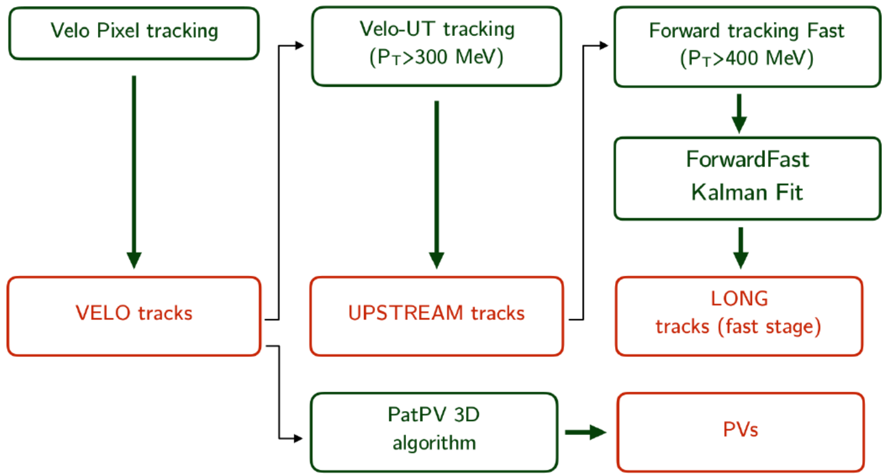


Figure 1: A schematic view of the fast tracking stage.

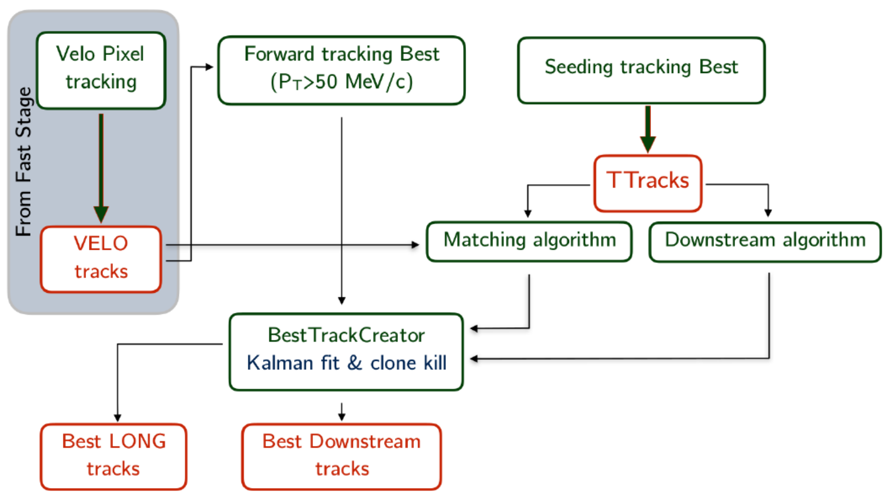


Figure 2: A schematic view of the best tracking stage.

LHCb-PUB-2017-005

LS2 Upgrade – statistical sensibilities

Table 3: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

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	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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**	–

CERN-LHCC-2012-007

TORCH detector

Innovative TOF system based on internally-reflected Cherenkov light produced by traversing charged particles in a thick quartz radiator (~1 cm)

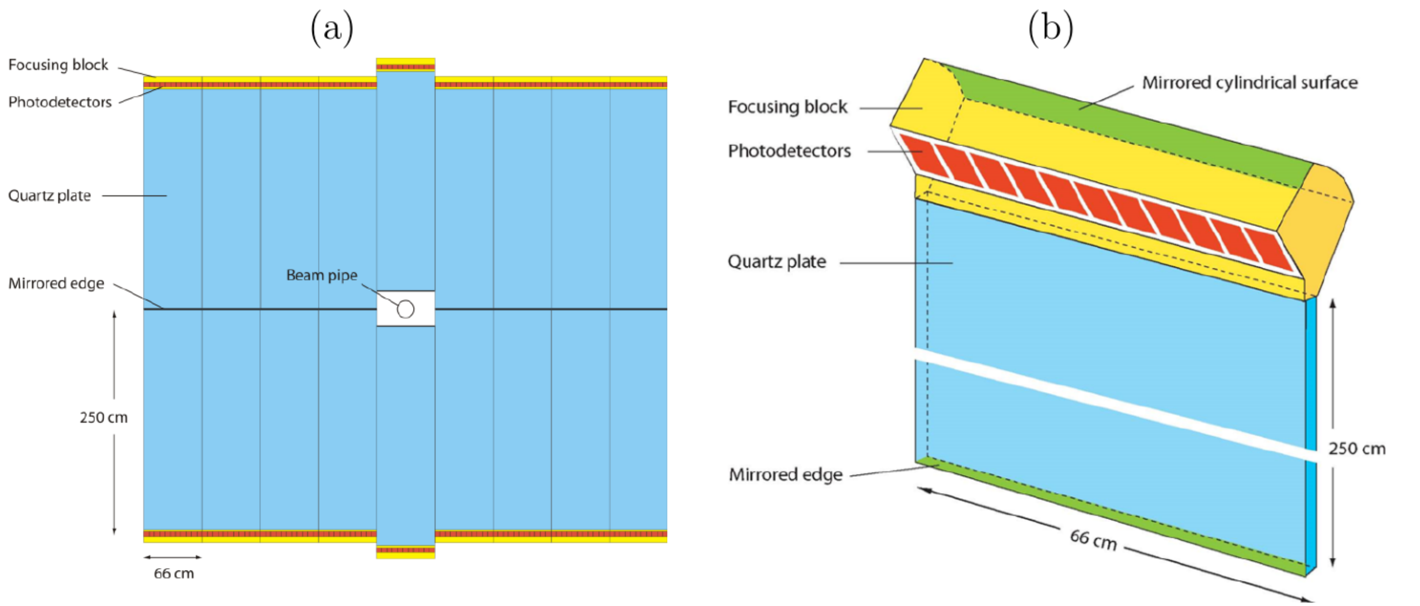


Figure 4.9: Schematic of TORCH detector for LHCb: (a) Front-on view of full detector; (b) View of single module showing focusing block and photodetector plane.

- Timing per photon: ...... ~70 ps
- Photodectectors: .... Micro-Channel Plate

LS4 Upgrade – Machine considerations

Table 3.1: Integrated luminosity projections at IP8 per year for different values of β^* and settings of the LHCb dipole polarity (– and +). Results are shown for different target luminosities for levelling, and also without levelling. The maximum instantaneous luminosity achievable at each setting is also given. The study assumes a performance efficiency of 50% and a minimum turn-around time of three hours [103].

β^* [m]	Maximum $\mathcal{L}$ [$\times 10^{34}$ cm^{-2}s^{-1}]		Target levelling $\mathcal{L}$ [$\times 10^{34}$ cm^{-2}s^{-1}]	Fill length [h]		Levelling time [h]		$\int \mathcal{L}\, dt$ [fb^{-1}/yr]	
	–	+		–	+	–	+	–	+
3	1.04	0.78	0.20	8.1	8.1	8.1	8.1	10	10
2	1.53	1.04	1.00	7.7	7.8	2.8	0.4	39	31
2	1.53	1.04	/	7.6	7.8	/	/	43	31
1	2.90	1.66	1.00	7.5	7.6	6.0	3.5	48	42
1	2.90	1.66	2.00	7.3	7.5	2.3	0	73	48
1	2.90	1.66	/	7.2	7.5	/	/	80	48