Flavor Physics perspectives with the LHCb upgrade

(*looking beyond Standard Model with Flavor Physics*)

May 28th, 2016 - Vulcano Workshop
Frontier Objects in Astrophysics and Particle Physics

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Why Flavor Physics (FP) at LHC after 2020 (end of Run3) ?

Standard Model solidity still remains largely unexplained, despite cosmological and theoretical mysteries (dark matter and energy, neutrino masses, Higgs stability)

- Precision physics in Flavor is an alternate approach to direct searches (ATLAS & CMS) which can probe masses at larger scales
- Future new phenomena discoveries must obey stringent Flavor tests

Fully exploit LHC capabilities

- Large cross sections for b- and c-quark production, "clean" environment, relatively high trigger efficency
- (statement on FP in European Strategy for Particle Physics in 2013)

Technology can improve statistics beyond simple luminosity increase

- Better trigger selection, faster reconstruction, smarter detectors
- Experimenter's dream: less data on tape, but more useful physics events

This is why LHCb is planning to take data in Run 4 (2022) and beyond, including operating at HL-LHC)

Selected topics which will be still theoretically hot at the end of Run 3, when statistics will be still not enough to make ultimate tests of SM predictions

- Is the $B_d \rightarrow \mu\mu$ decay rate compatible with that predicted by SM theory ?
- To what extent a precise measurement of the CKM angle γ constrained with other SM parameters can bring us to discover New Physics ?
- Is CP violating phase ϕ_S measured in $B_S \rightarrow J/\psi\ \phi$ the one predicted by SM ?

+ several other very interesting questions still necessitating more data on *flavor observables*, new exotics states (e.g. *pentaquarks*), electroweak tests, study of heavy quark resonance dynamics, etc…

Precision data from Flavor Physics (i.e. decays of B and D mesons) will provide further, stronger constraints for any model coming from possible discoveries in direct searches (ATLAS & CMS). A clear example is coming from essays on building models with the 750 GeV di-photon excess

The physics of the LHCb upgrade *

Cumulative Luminosity	Run 1 $3\ fb^{-1}$	Run 2 $8\ fb^{-1}$	Run 3 $23\ fb^{-1}$	Run 4 $46\ fb^{-1}$	Theory uncertainty
$\frac{Br(B_d \to \mu\mu)}{Br(B_s \to \mu\mu)}$	-	110 %	60%	40%	5%
$q_0^2 A_{FB}(K^{*0}\mu\mu)$	10%	5%	2.8%	1.9%	7%
$\phi_s(B_s \to J/\psi\phi)$	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.
$A_\Gamma(D^0 \to KK)$	$3.4\ 10^{-4}$	$2.2\ 10^{-4}$	$0.9\ 10^{-4}$	$0.5\ 10^{-4}$	-

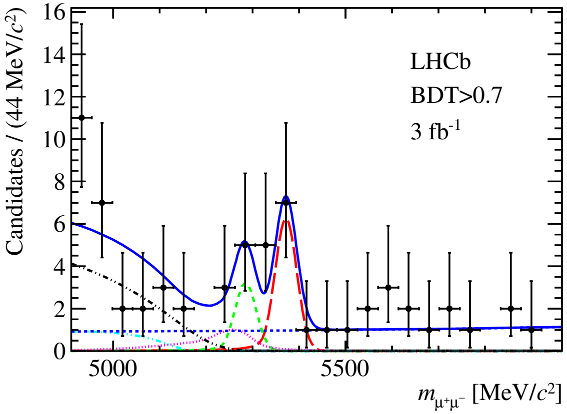
NOW (Run 1) UPGRADE (Run 3, Run 4)

plus many other physics channels …

* From "Heavy Flavour Physics in the HL-LHC era" / Aix-les-Bains ECFA Workshop – Oct 2013

LHCb and CMS, united we stand [in B_s (B_d) → μμ]

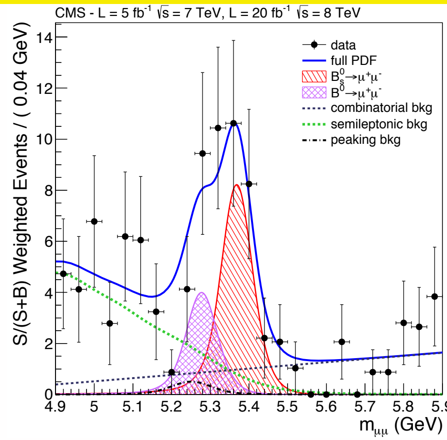
LHCb: arXiv:1307.5024, PRL.111.101805 (2013)



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}) \times 10^{-10}$$

--> 4.0σ

CMS: arXiv:1307.5025, PRL. 111.101804 (2013)



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0\,^{+1.0}_{-0.9}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.5\,^{+2.1}_{-1.8}) \times 10^{-10}$$

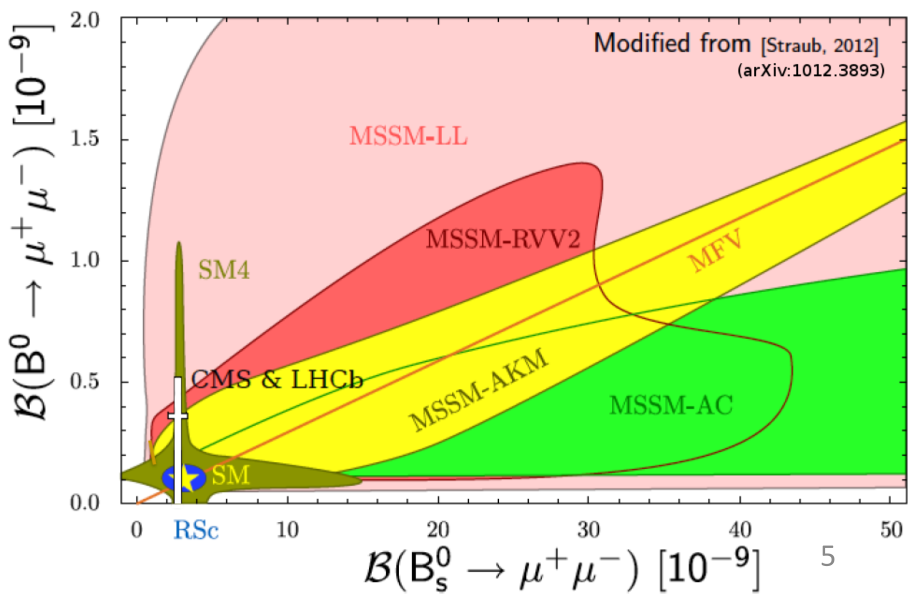
--> 4.3σ

Central value of B_d decay rate different from the one expected from theory

- $Br(B_d\text{->}\mu\mu) = (1.1 \pm 0.2)\ 10^{-10}$
- $Br(B_s\text{->}\mu\mu) = (3.5 \pm 0.2)\ 10^{-9}$

Ratio of B_d/B_s decays is a very clear test of SM and sensitive to New Physics

Many more puzzles with di-μ in Run1, but maybe they will be solved with Run2

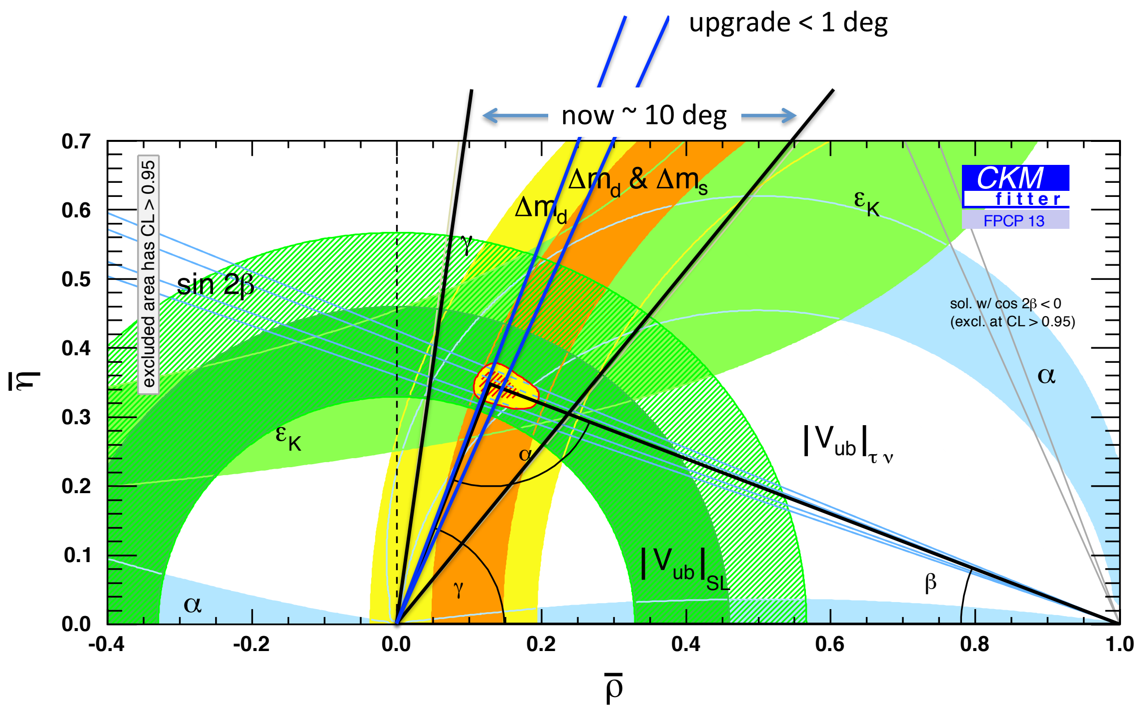


Increasing the precision on CKM γ angle

1. We know that Standard Model CP violation (through CKM matrix) cannot explain baryogenesis : we need new sources of CP violation.

2. These new sources should (generally) affect different observables in different ways.

3. Overconstraining the apex therefore tests the consistency of the Standard Model picture of CP violation : we want to know at what level it breaks down.



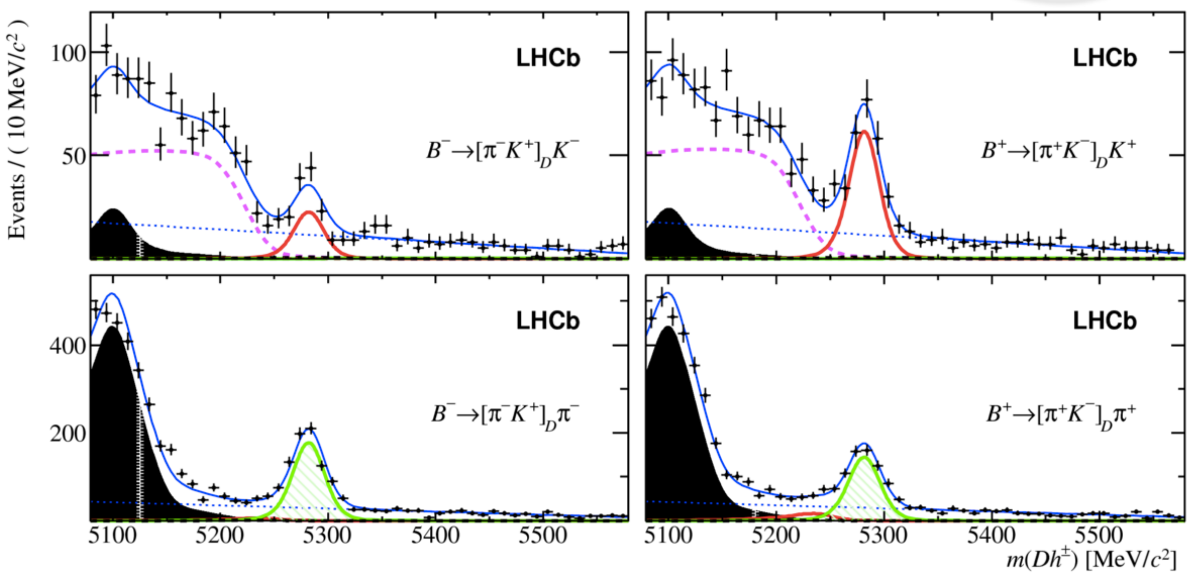
Probing New Physics at high mass scales

Probe	Λ_{NP} for (N)MFV NP	Λ_{NP} for gen. FV NP	$B\overline{B}$ pairs
γ from $B \to DK$ [1)]	$\Lambda \sim \mathcal{O}(10^2\ \text{TeV})$	$\Lambda \sim \mathcal{O}(10^3\ \text{TeV})$	$\sim 10^{18}$
$B \to \tau\nu$ [2)]	$\Lambda \sim \mathcal{O}(\ \text{TeV})$	$\Lambda \sim \mathcal{O}(30\ \text{TeV})$	$\sim 10^{13}$
$b \to ss\overline{d}$ [3)]	$\Lambda \sim \mathcal{O}(\ \text{TeV})$	$\Lambda \sim \mathcal{O}(10^3\ \text{TeV})$	$\sim 10^{13}$
β from $B \to J/\psi K_S$ [4)]	$\Lambda \sim \mathcal{O}(50\ \text{TeV})$	$\Lambda \sim \mathcal{O}(200\ \text{TeV})$	$\sim 10^{12}$
$K - \overline{K}$ mixing [5)]	$\Lambda > 0.4$ TeV (6 TeV)	$\Lambda > 10^{3(4)}$ TeV	now

Zupan – arXiv 1101.0134

Particularly efficient but B meson consuming !

The "ADS" B→DK decay mode, total decay rate ~10^{-7}



LHCb can measure γ in many channels combining all together at 1^0 degree accuracy

And also through more complicate transitions ("loops") and compare the result with direct one ("tree") to identify theory flaws.
KEK B factory is a strong competitor

The LHCb upgrade in brief

Goals

- Run at ~ 2 10^{33} $cm^{-2}s^{-1}$ – 5x the current luminosity
- Exploit a trigger-less data taking (all events are acquired at ~40 MHz and then processed in a farm of CPUs)
- A full software trigger allows the increase in efficiency for hadronic channels by a factor 2 (typical example is $B_s \rightarrow \phi \phi \rightarrow KKKK$)
- Reach an experimental error (stat+syst) approaching the theoretical one collecting at least 50/fb (now after Run 1, 3/fb collected)

Impact on detector

- Upgrade the vertex and tracking systems (due to increased occupancy)
- Change the FEE electronics (to acquire at 40 MHz – LHC collision rate)
- Modifications to Particle Identification systems to cope with occupancy

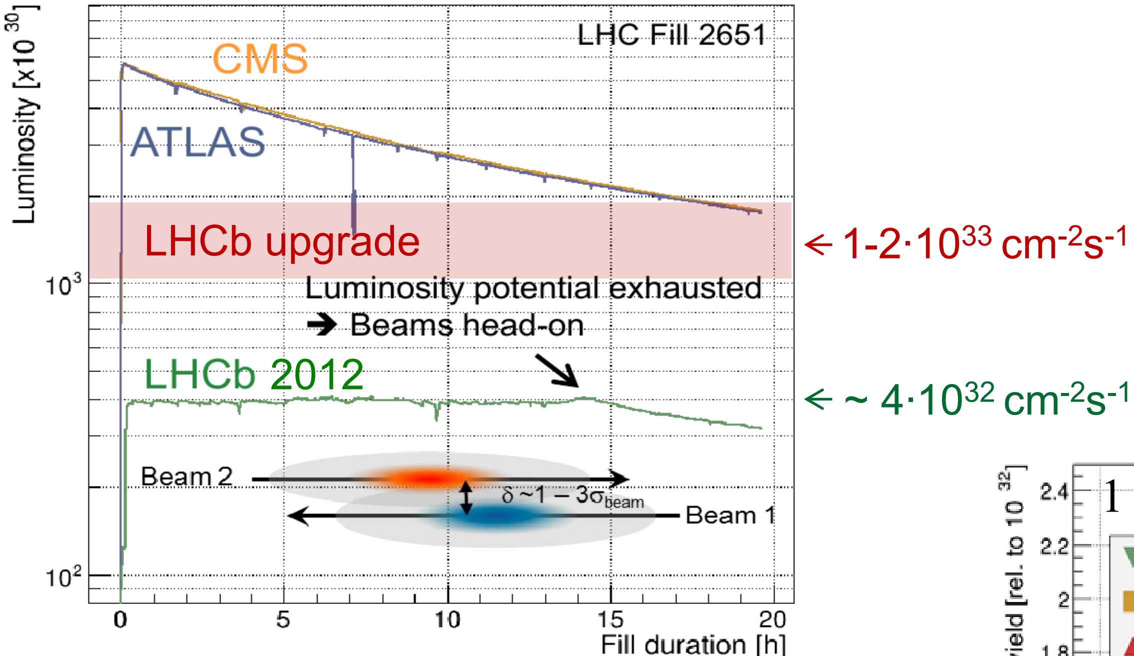
Time scale

Install upgrade in LS2 (2019-20) and start data taking in 2021

Take ~50/fb during Run 3 (2021-23) and Run 4 (2027-29)

How to increase LHCb statistics significantly

2012 running conditions

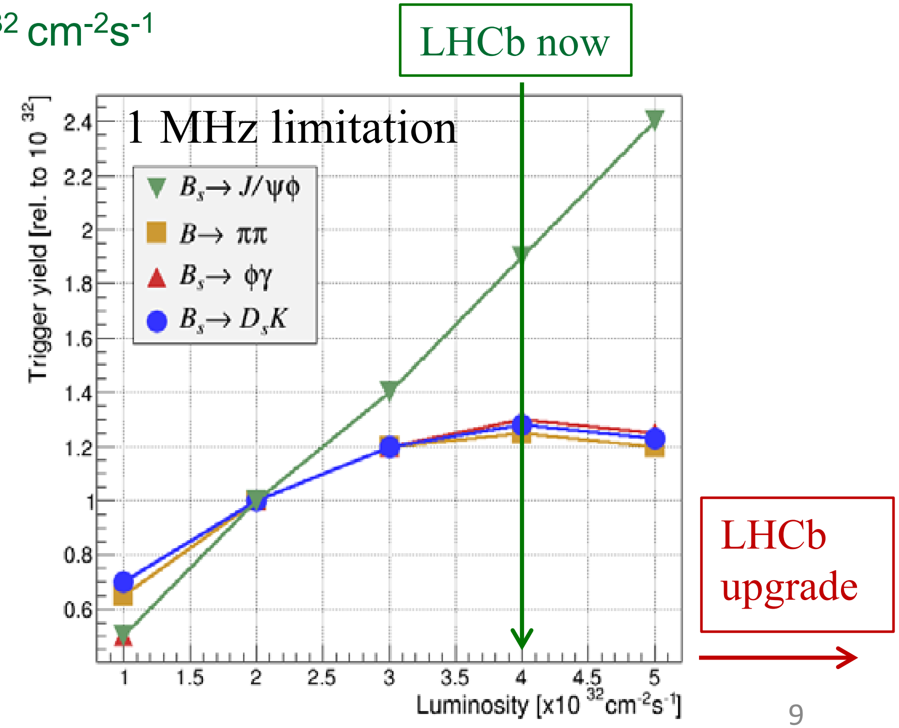


LHCb up to LS2

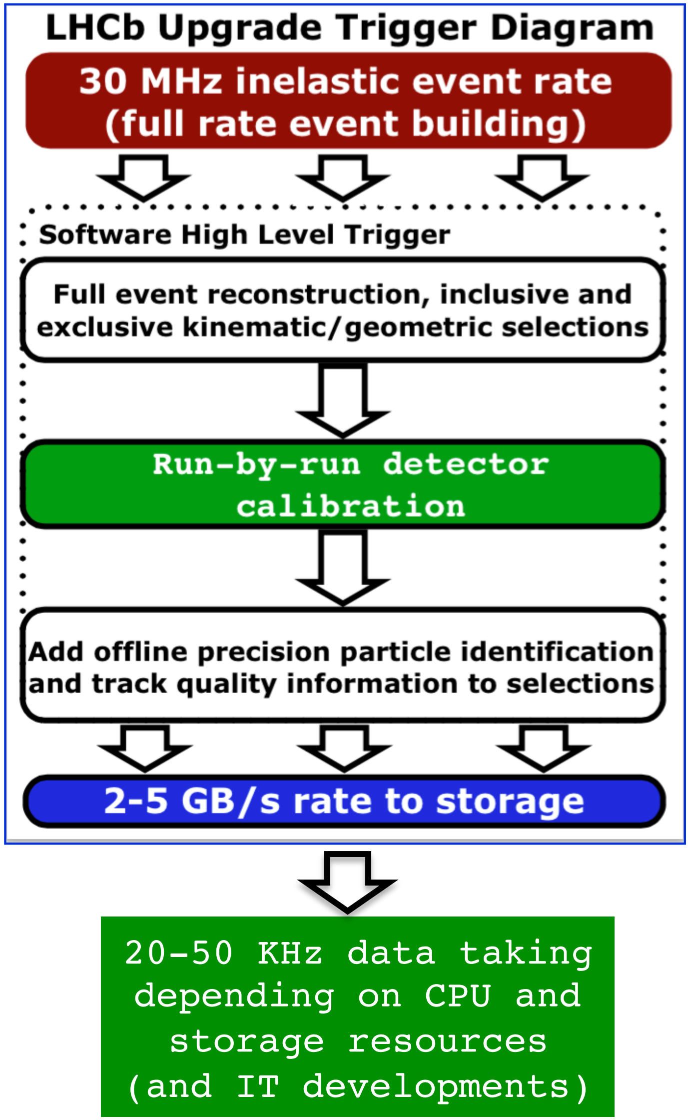
- running at levelled luminosity of ~ $4 \cdot 10^{32}$ cm^{-2}s^{-1}, pile-up ~1
- first level hardware trigger running at ~1 MHz
- record ~3-5 kHz

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



The LHCb software trigger ansatz



EFFICIENCY GAIN WRT TO RUN I

	Run 3 2019–21	Run 4 2024–26	Run 5+ 2028–30+
E_{T} cut (GeV)	3.2	2.4	2.4
$\phi_s(B_s^0 \to \phi\phi)$	1.35	1.6	1.6
$\gamma(B^+ \to DK^+)$	1.35	1.6	1.6
$A_\Gamma(D^0 \to K^+K^-)$	1.4	2.1	2.1

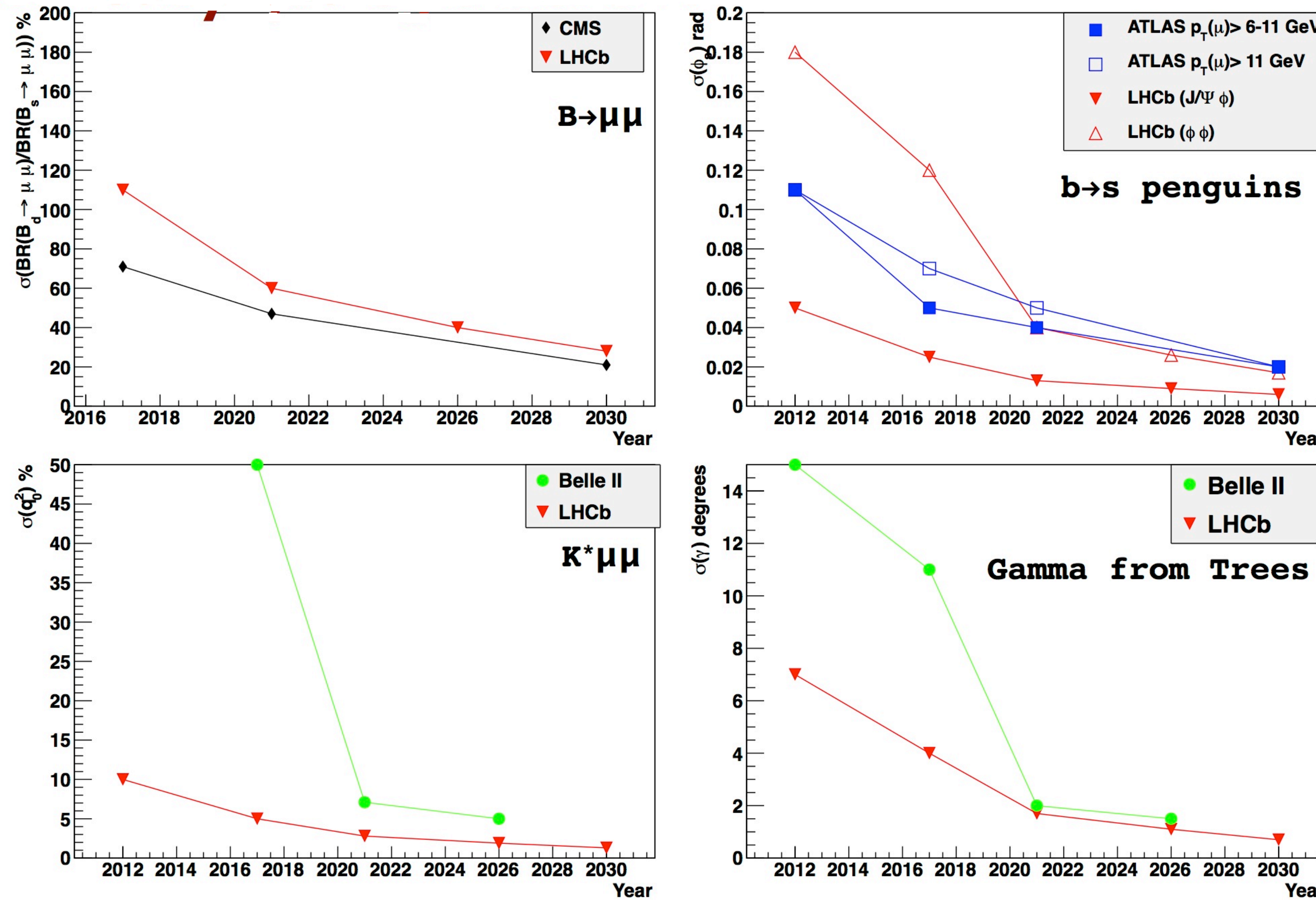
Gain 50-100% efficiency for hadronic final states

Aim to eventually run "quasi-triggerless" : implement offline reconstruction and selections in the trigger for any final state which can be reconstructed by the detector.

Despite lower energy cuts and therefore higher throughput, the Software High Level Trigger can still manage the huge bandwidth

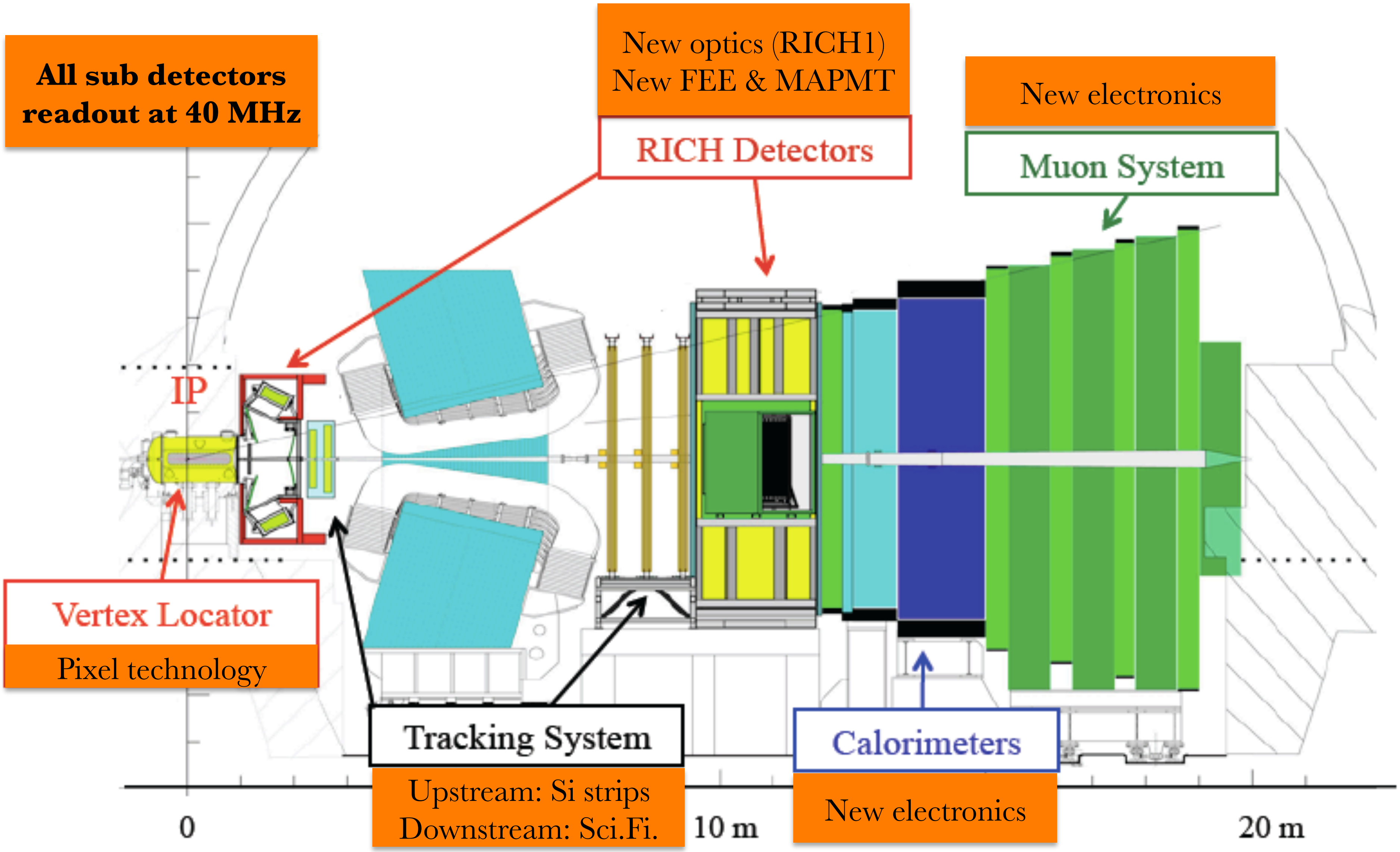
Overall, higher efficiencies on hadronic channels

The struggle for precision physics*

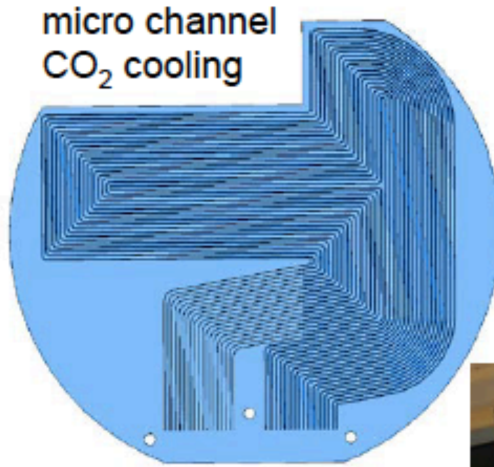


* From "Heavy Flavour Physics in the HL-LHC era"
Document prepared for the Aix-les-Bains ECFA Workshop – Oct 2013 (Schedules to be adjourned)

LHCb detector modifications for the upgrade

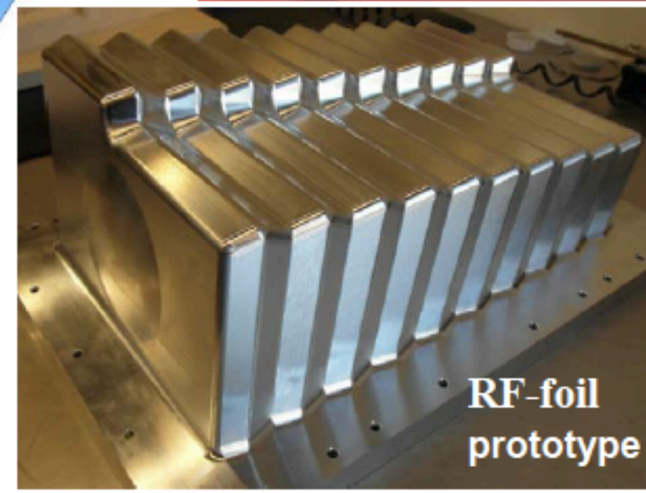


VELO upgrade



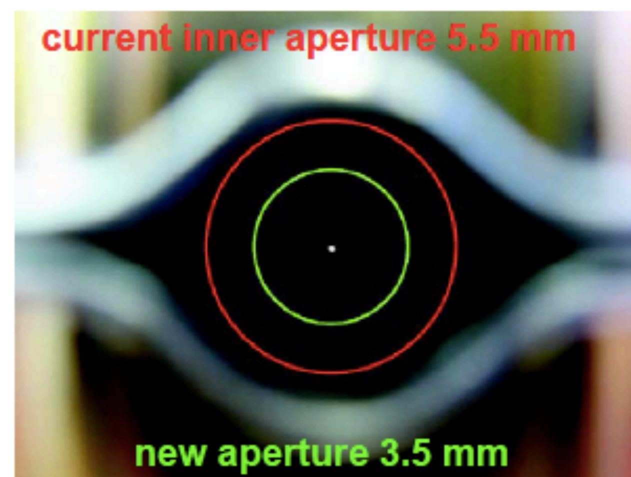
Upgrade challenge:

- ✓ 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



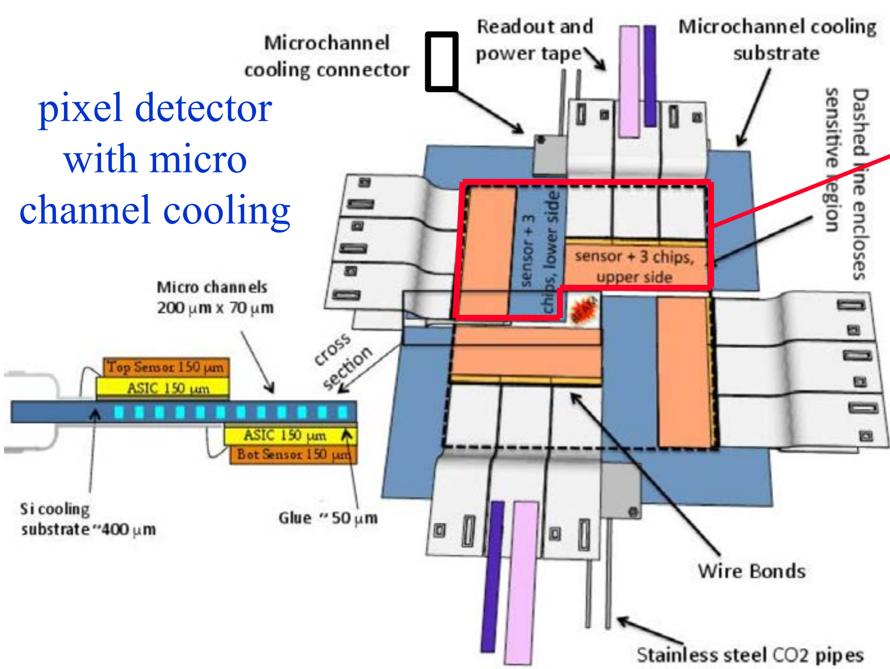
Technical choice :

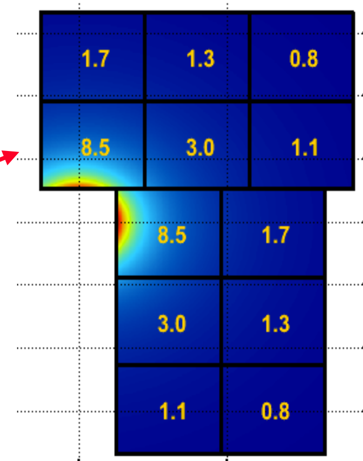
- ✓ 55x55 μm^2 pixel sensors with micro channel CO_2 cooling
- ✓ 40 MHz VELOPIX (evolution of TIMEPIX 3, Medipix)
  - ➢ 130 nm technology to sustain ~400 MRad in 10 years
  - ➢ VELOPIX hit-rate = ~8 x TIMEPIX 3 rate
- ✓ replace RF-foil between detector and beam vacuum
  - ➢ reduce thickness from 300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



VELO upgrade

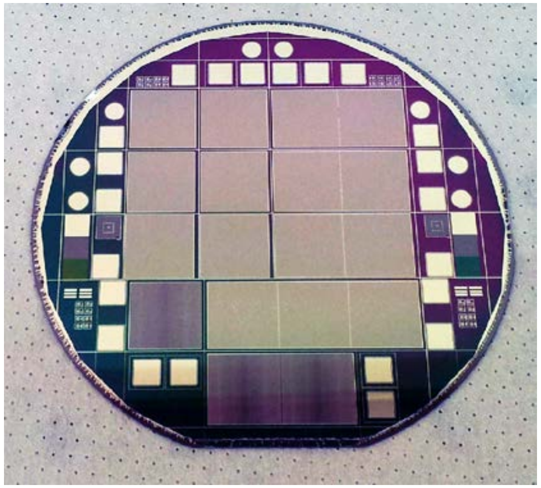
pixel detector with micro channel cooling

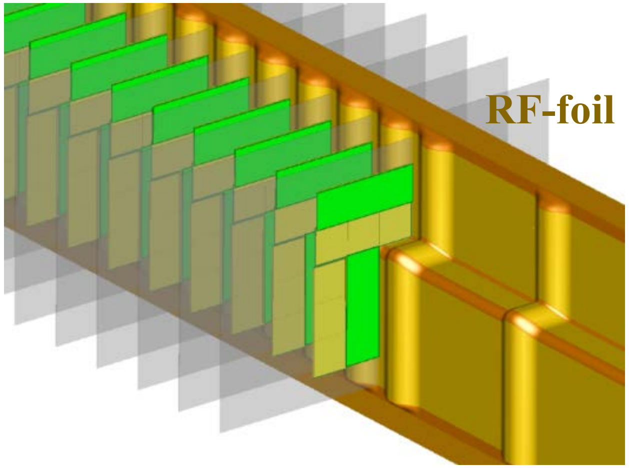


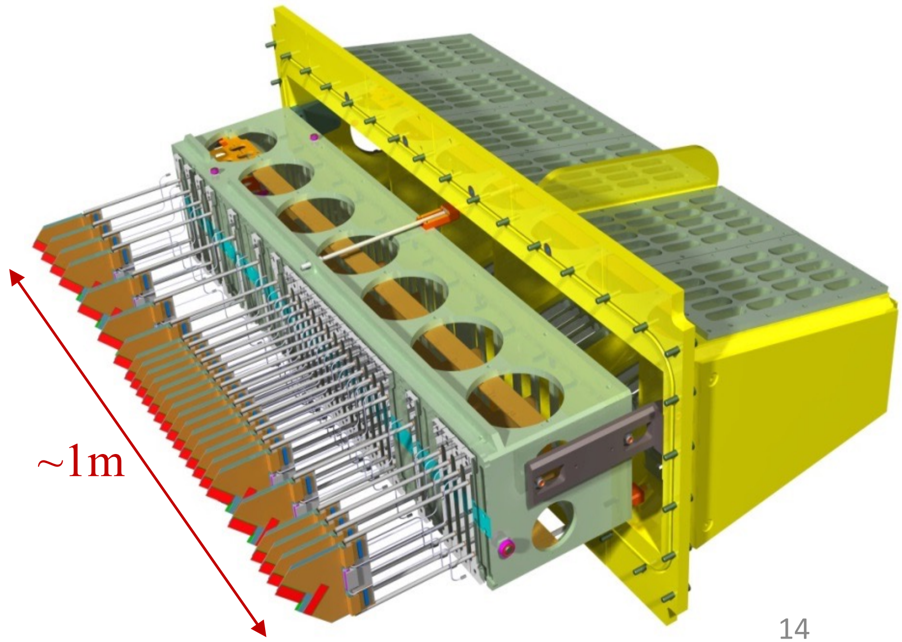


tracks/chip/event
at $L=2\cdot10^{33}\,\mathrm{cm^{-2}s^{-1}}$

Prototype pixel sensor

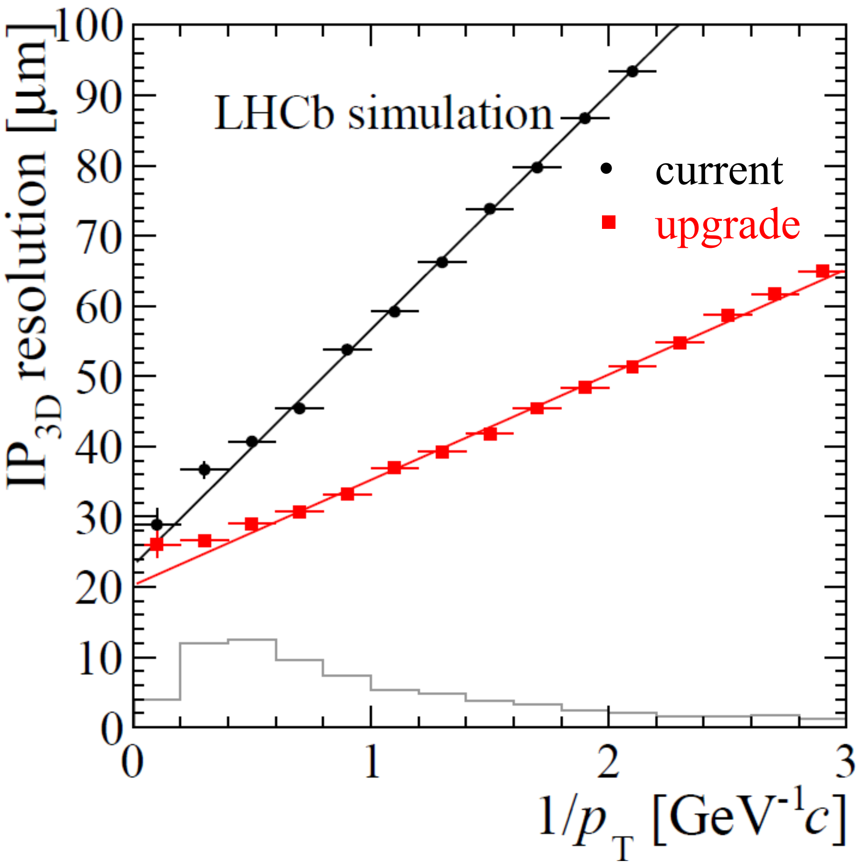




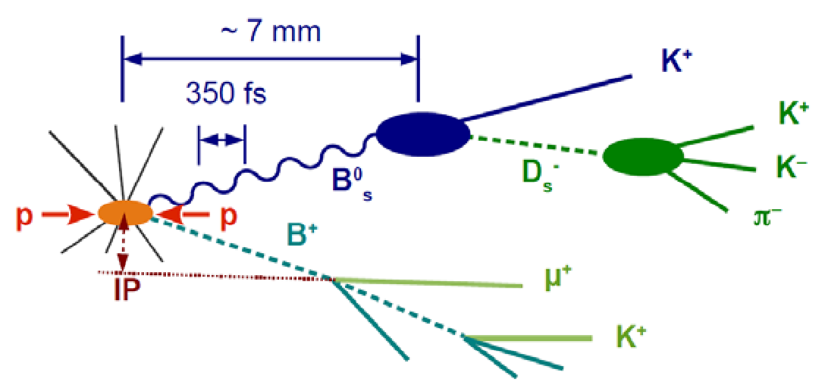


VELO upgrade

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



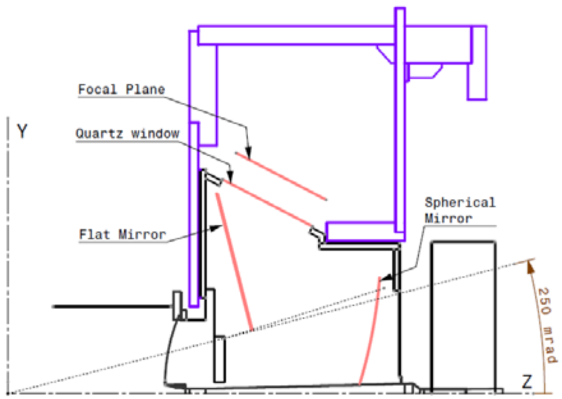
Enhanced resolution in tri-dimensional reconstruction is the key asset to fight against pile-up (several interactions in the same beam crossing, up to 6-7 per event) and to tag efficiently decays of B and D mesons



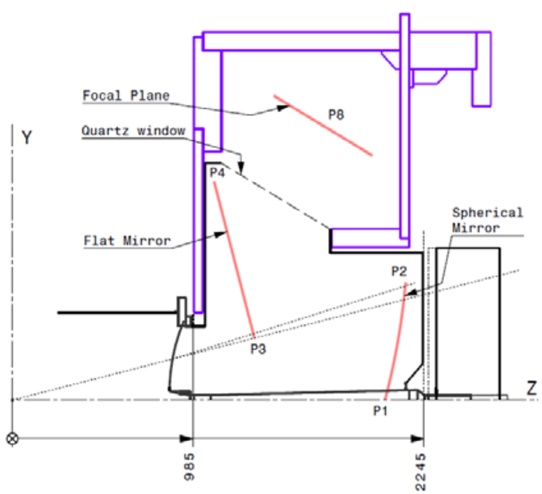
RICH upgrade

optimise RICH1 optics

current



upgrade

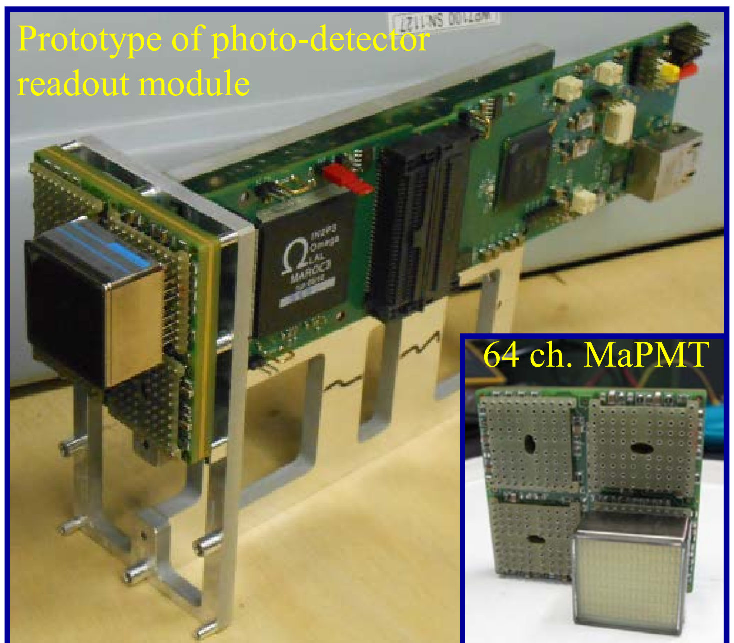


Luminosity of $2 \cdot 10^{33}$ $cm^{-2}s^{-1}$ → adapt to high occupancies

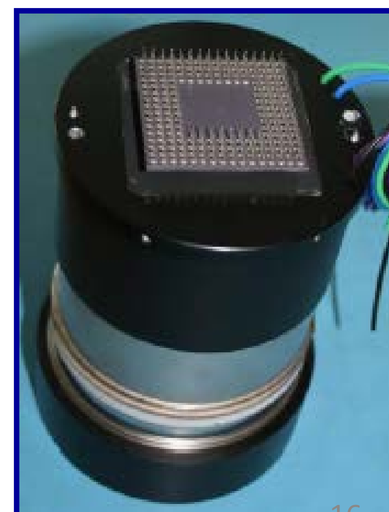
- aerogel radiator removed
- modify optics of RICH1 to spread out Cherenkov rings (optimise gas enclosure without modifying B-shield)

40 MHz readout → replace HPDs due to embedded FE

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

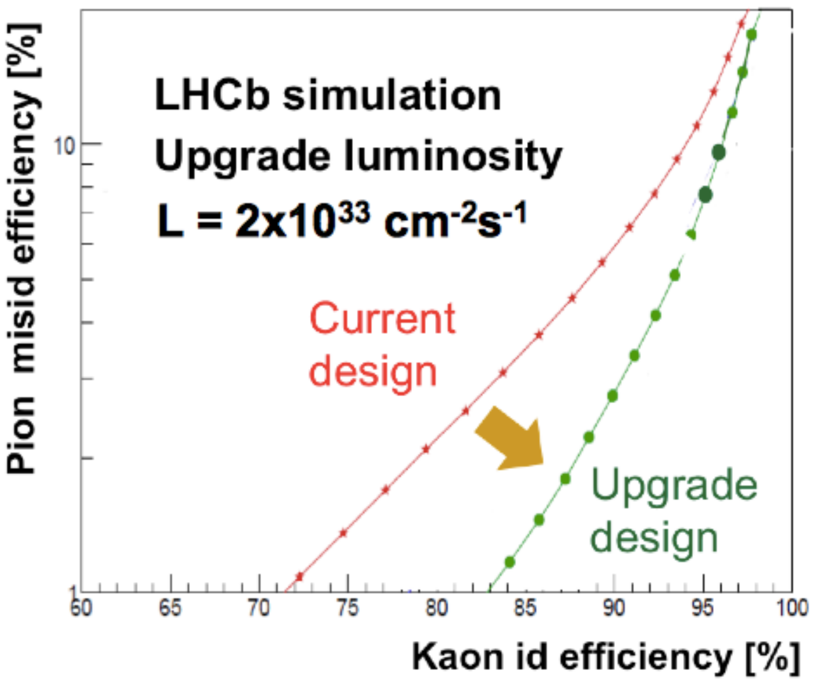


HPD R&D with external electronics

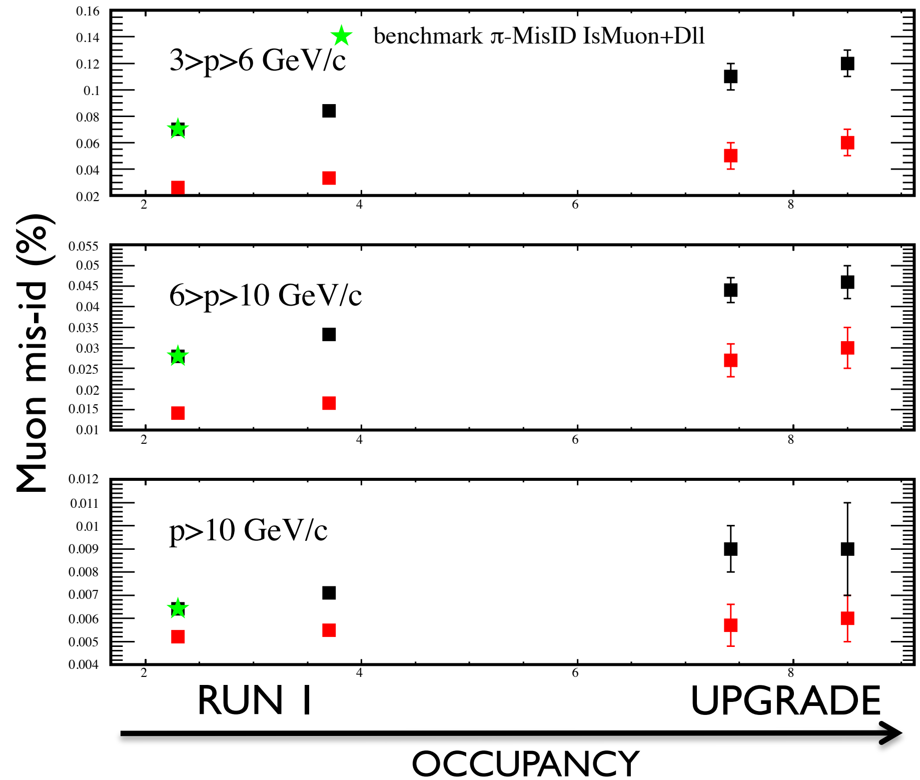


Particle Identification performance at Upgrade

K/π separation performance



μ Identification performance

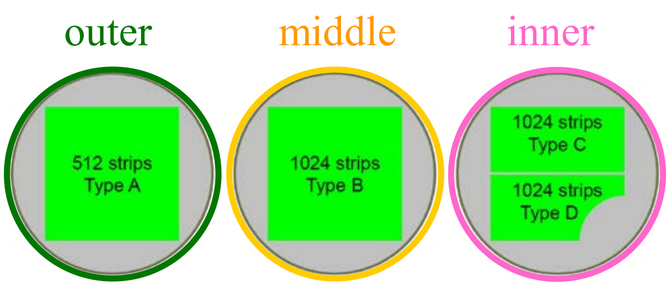


Identification of kaons remains a flagship of LHCb experiment (unique wrt ATLAS and CMS): gorgeous opportunities for b and c quark physics

Identification of muons is relevant as it keeps LHCb at the leading edge of many searches in rare channels with di-μ in the final state

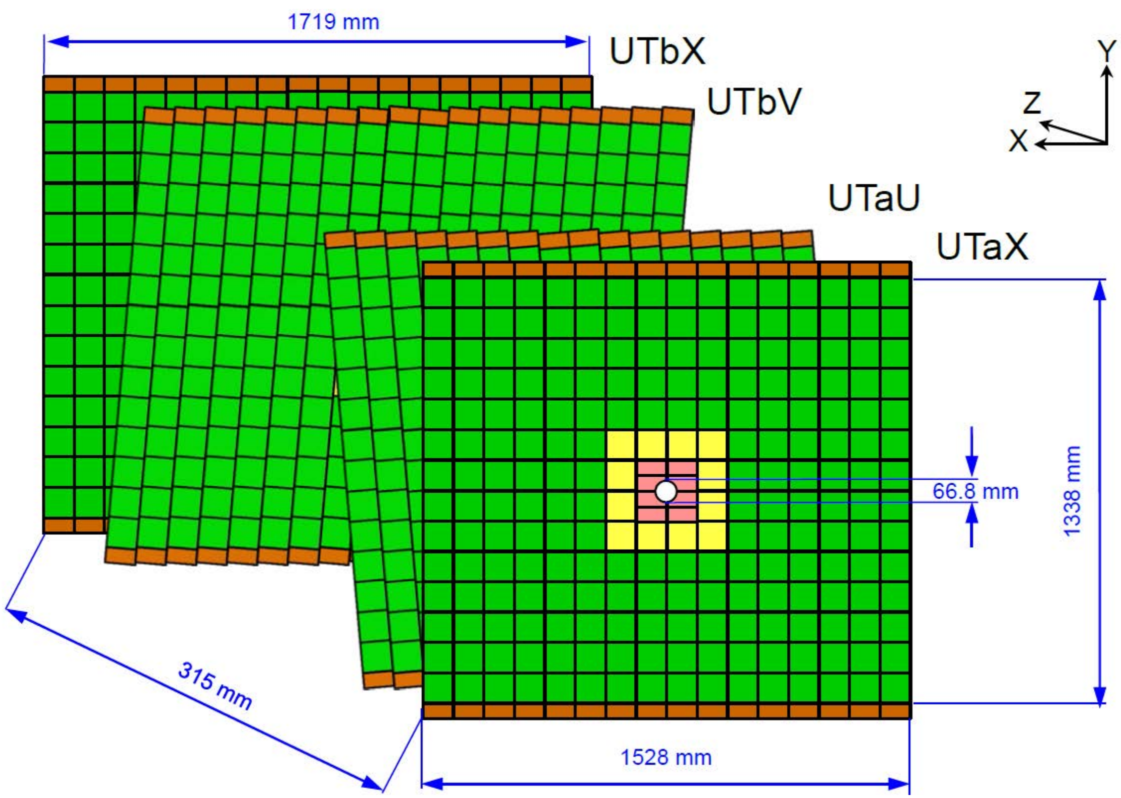
TT upgrade: Upstream Tracker (UT)

silicon strip detector

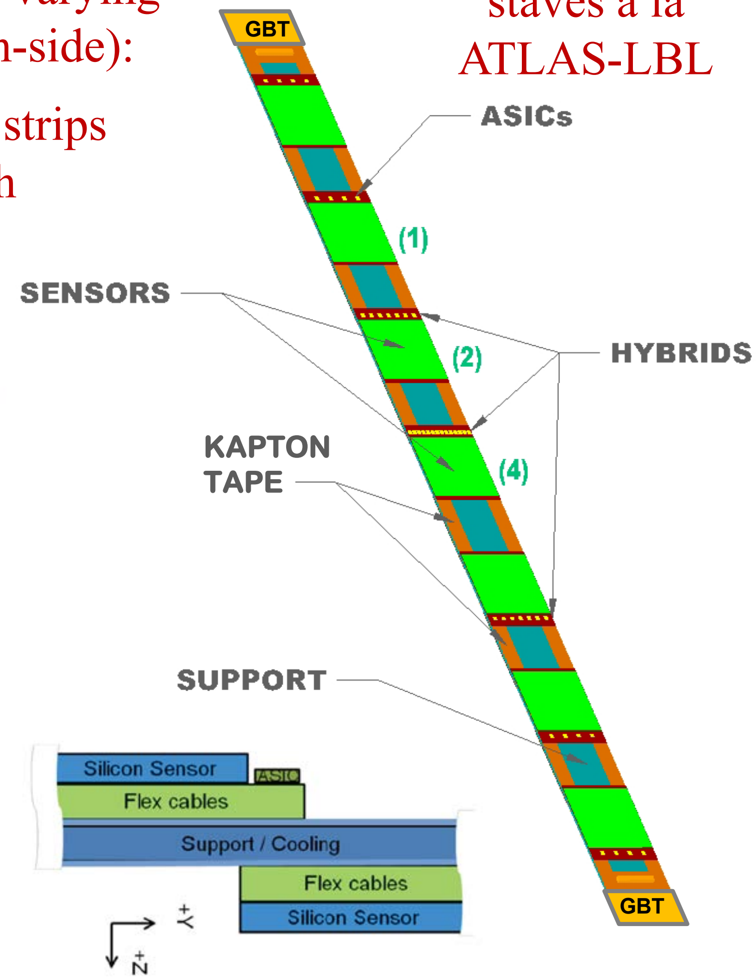


adapt segmentation to varying occupancies (out → in-side):

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



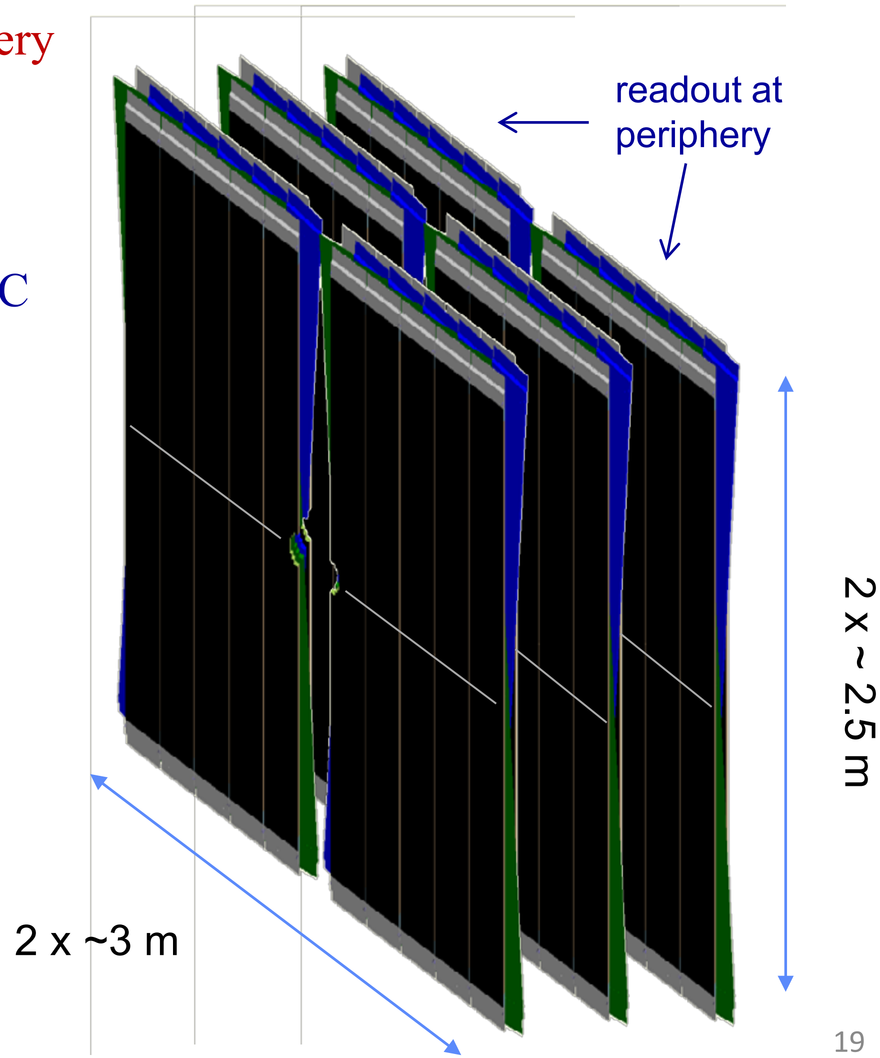
staves a la ATLAS-LBL



40MHz silicon strip R/O → SALT chip

T-stations upgrade: Fibre Tracker (FT)

- 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



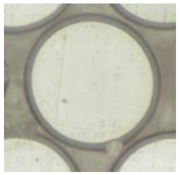
Challenges → radiation environment

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

Benefits of the SciFi concept:

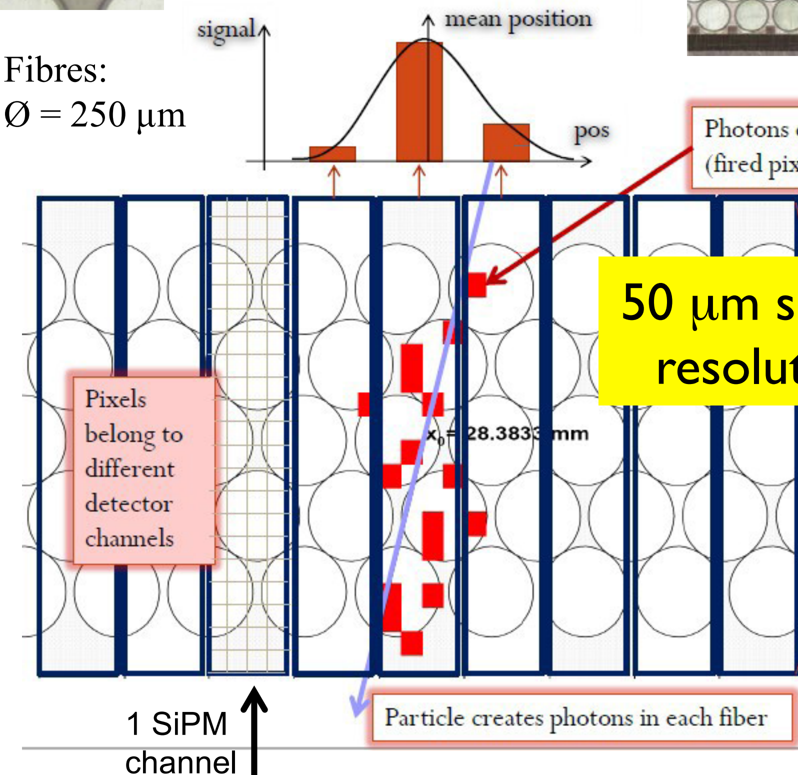
- ✓ a single technology to operate
- ✓ uniform material budget
- ✓ SiPM + infrastructure outside acceptance
- ✓ fine channel granularity of 250 μm
- ✓ x-position resolution of ~75 μm
- ✓ high hit detection efficiency (≥ 99%)
- ✓ fast pattern recognition for HLT

T-stations upgrade: Fibre Tracker (FT)

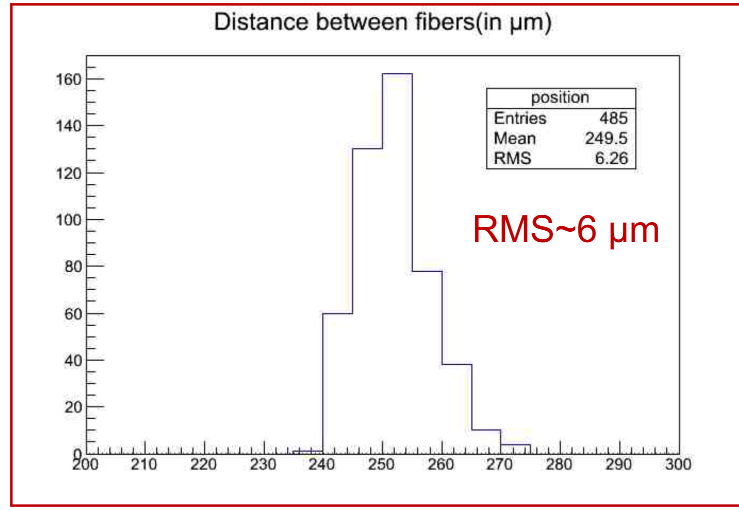


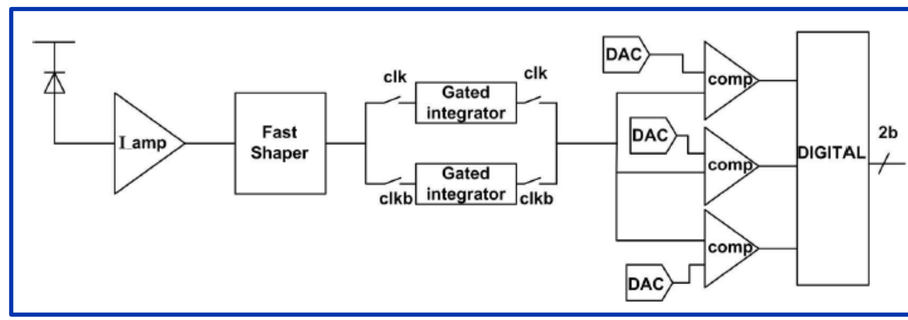
Fibres:
Ø = 250 µm

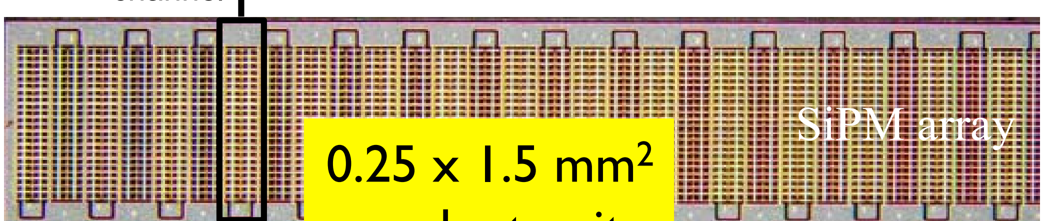
scintillating-fibre mat with 6 layers



50 µm spatial resolution





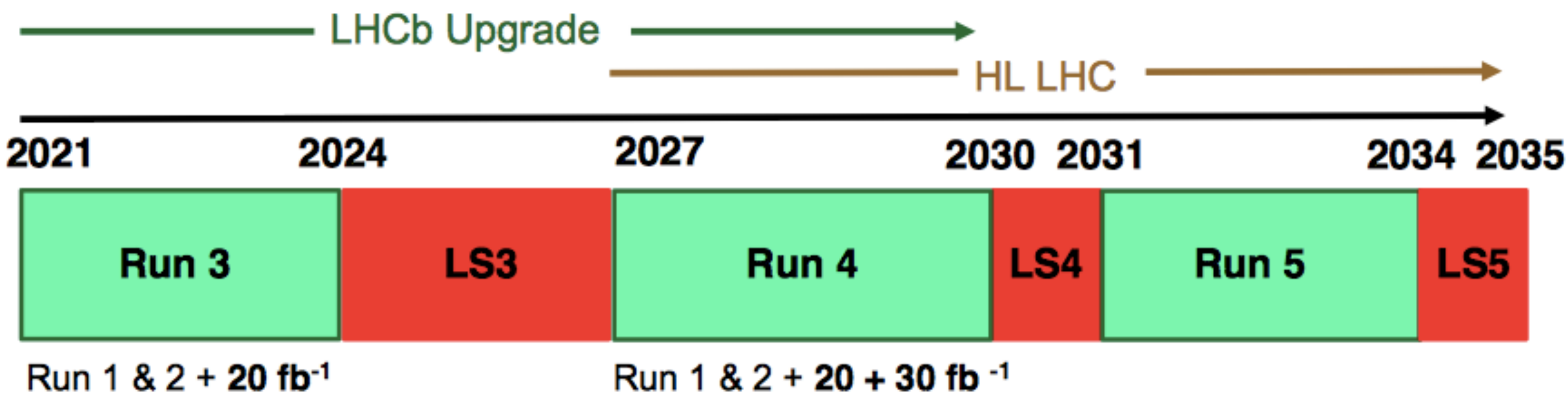


$0.25 \times 1.5\ mm^2$ readout unit

readout by dedicated 128 ch.
40 MHz PACIFIC chip

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

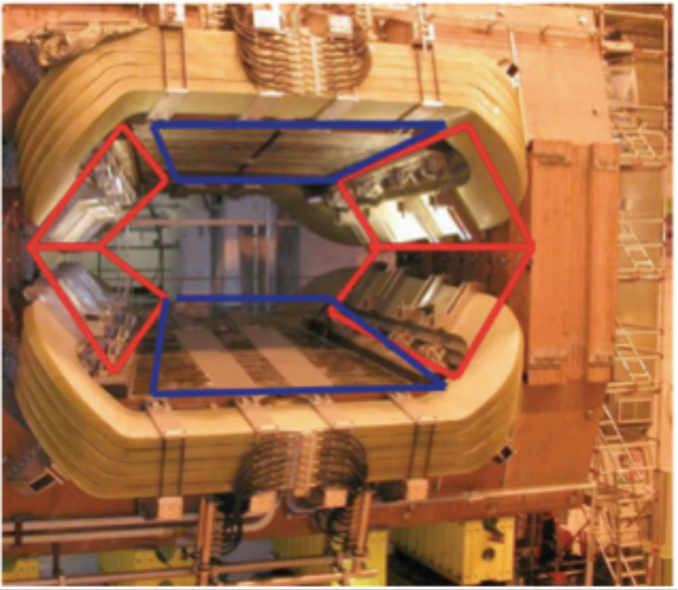
LHCb @ HL-LHC: a future after the near future



While preparing the upgrade and understanding LHCb possibilities, we asked ourselves if something could be done during the VERY LONG LS3 to improve further our detector and the luminosity collected.
Several ideas on the table. Some adiabatic, some more extreme with unprecedented technologies: vertex track reconstruction at the [10 μm, 10 ps] level

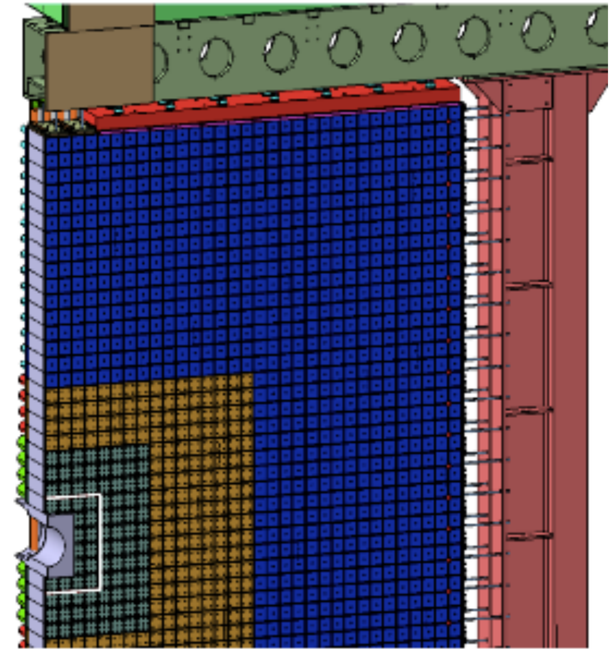
LHC colleagues are demonstrating that without large works, LHCb interaction region can be operated at 1-2 10^{34} cm^{-2} s^{-1}

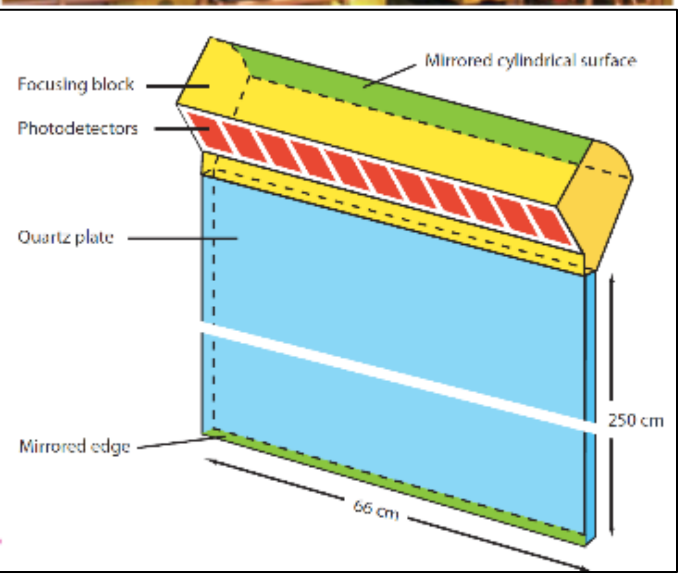
LHCb has started a brainstorming process to profit of this further opportunity to decrease the statistical error: goal in mind, to collect up to ~200-300 fb^{-1} (> Run 5)



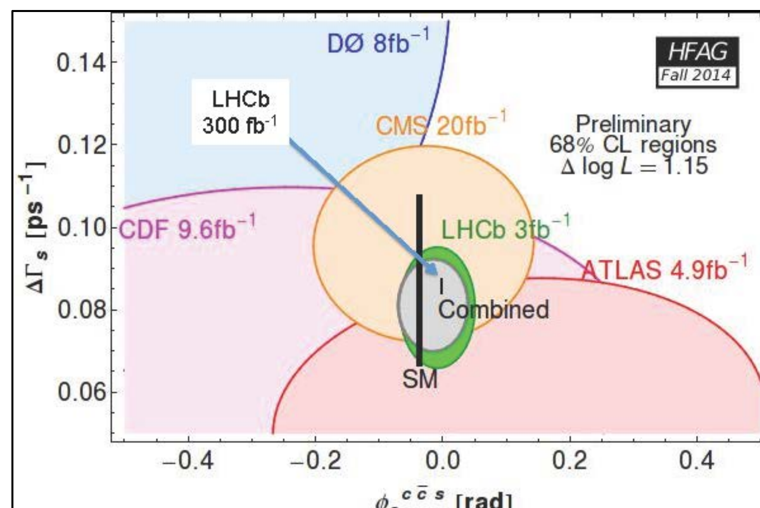
← Covering side parts of the magnet to increase tagging with low energy pions (i.e. D*→Dπ)

New central part of the ECAL with very precise timing and high spatial resolution for photons →





← New quartz bars for very precise O(10ps) charged particle timing via Cherenkov effect



With these statistics, measuring ϕ_s CP violation → phase at the same level of theoretical error (0.003)

Conclusion

There are several reasons to continue Flavor Physics at LHC after 2020, the main one being the capability of precision physics to observe possible flaws in Standard Model or to help building models after discoveries at ATLAS & CMS

LHCb has started a challenging and highly rewarding (in terms of physics reach) upgrade program of the detector, to bring statistics up to 50/fb, to pin down experimental error close to theoretical one

A trigger-less configuration is the flagship project of the upgrade, together with the effort of improvement of detector performance in tracking & particle ID, when LHC luminosity will be x5 the current one (but physics rate more than x10 in several hadronic channels)

Tracking granularity, readout speed, bandwidth and radiation resistance are the main difficulties of the LHCb upgrade

Even more challenging (and exciting) is to think to a LHCb detector for HL-LHC, operating at ~50 times the current instantaneous luminosity

(*I also acknowledge the several LHCb colleagues to whom I "stole" the slides …*)

The forge of Vulcan – Velazquez (1630)

Vulcan: the Roman god of FIRE and DESTRUCTION

Every volcanologist knows that looking to the external appearance we should infer what is hidden below the top of the volcan …

This also resembles the mission of the astro-particle experimentalists looking for a deeper understanding of Nature
(*I liked the "precision of ignorance" statement*)

Vesuvio

Dark matter – many sprouts, nothing serious

Vesuvio

New Physics from LHC – silent so far

GW – we see it now clearly
We don't know where it comes from

Dark energy – very difficult to study