Future flavour – a glimpse of upcoming experimental possibilities

Future flavour experiments

- Beyond the b – frontier physics with (charged) leptons, kaons *etc.*
- Future prospects in b (& c) physics
- Conclusions

Guy Wilkinson
University of Oxford
IPPP, September 2017

Beyond the b: frontier physics with (charged) leptons, kaons, *etc.*

- Charged LFV searches
- MDS, EDMs and all that
- Kaon physics

Charged LFV searches

μ→eγ

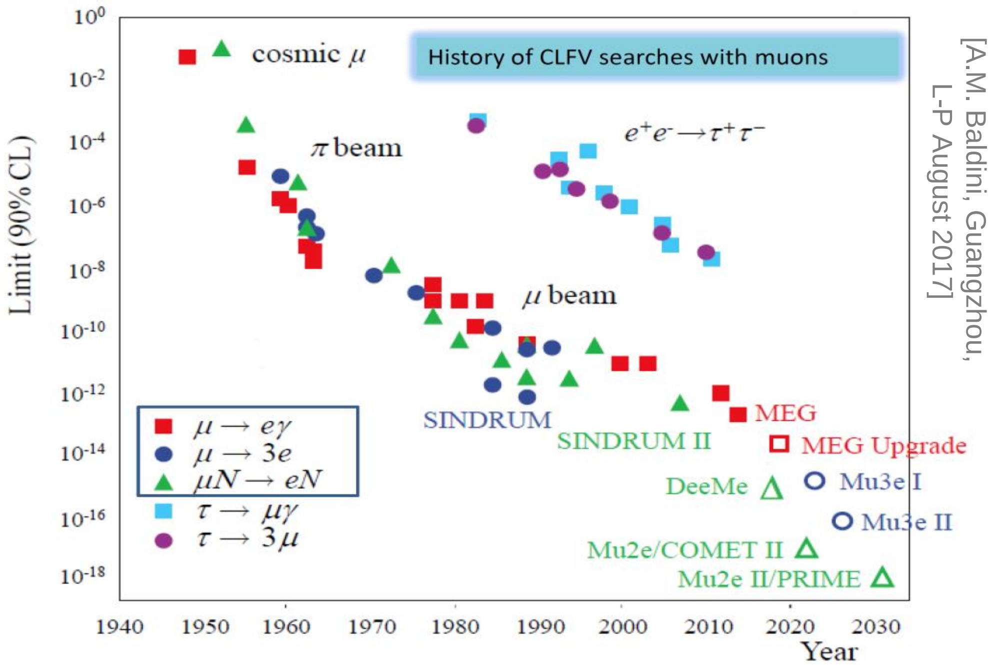
- MEG: < 4.2 x 10^{-13} (90% C.L.) [EPJC 76 (2016) 434].
- MEG-II will collect data 2019-21 to improve limit by order of mag.

μ→eee

- Mu3e experiment at PSI.
- Ph. 1 (2019-21) aims for 10^{-15}.
- Ph. 2 (?) to go further.

μN→eN

- COMET (JPARC) & Mu2e (FNAL).
- COMET Ph. 1: ~3 x 10^{-15} by 2019.
- Aim for ~3 x 10^{-17} by 202?.

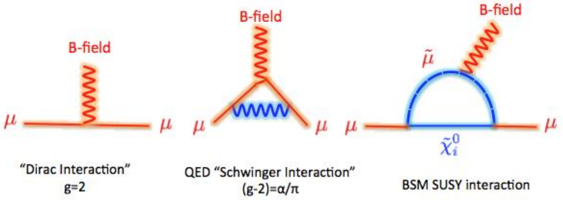


[A.M. Baldini, Guangzhou, L-P August 2017]

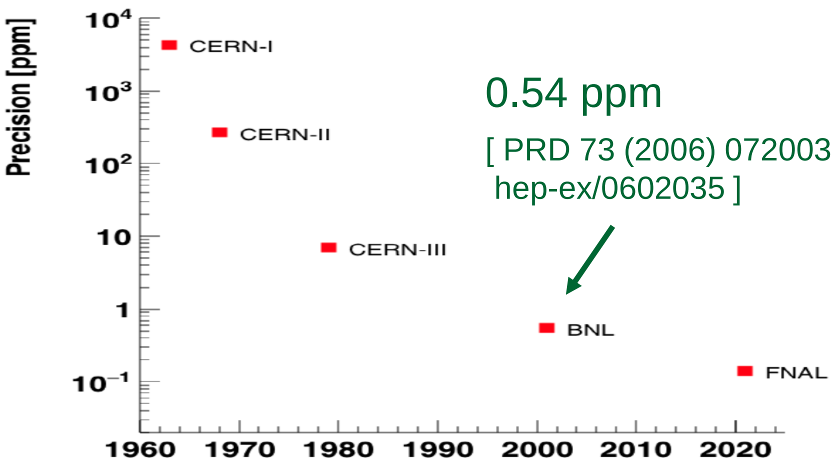
τ LFV decays

- < 10^{-8} from B-factories in many modes.
- Belle-II aims for a few 10^{-10} in cleanest decays (*e.g.* τ→μμμ).
- Good prospects (10^{-11} ?) for dedicated experiment situated upstream of SHiP.

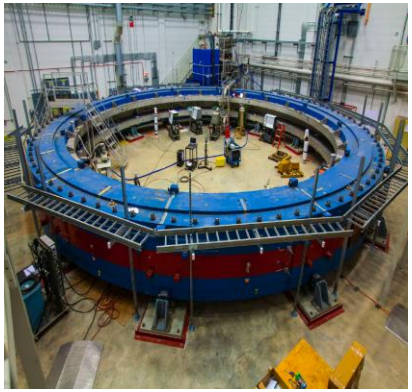
MDMs and EDMs



Legacy of BNL 821 (& enormous theory effort): 3.5σ tension with SM



FNAL experiment aims to reduce uncertainty x 1/4



- First stored beam May 2017
- BNL-like stats by mid-2018
- x20 stats, 2020

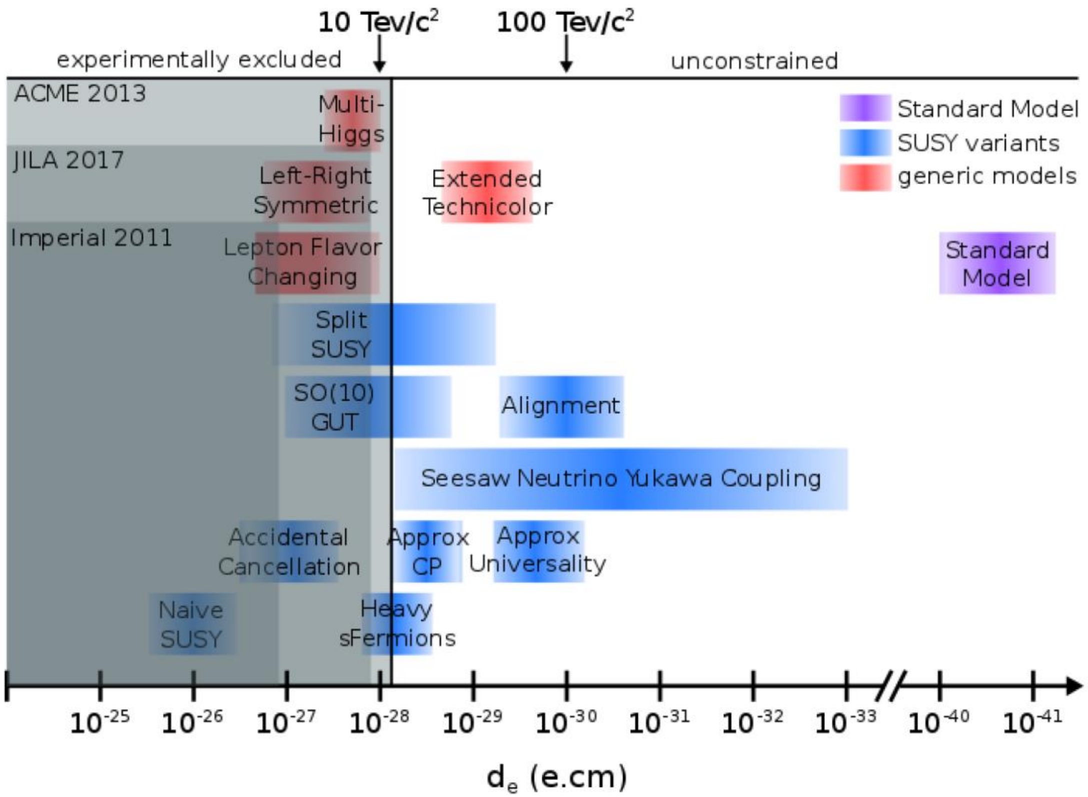
J-PARC project, due to start operation in 2020 , will have similar precision, but very different systematics (minimise divergence by reducing beam p_T).

Meanwhile, wide programme of search for non-zero EDMs in many systems:

- Neutron EDM: current leader is PSI, with potential to reach 10^{-27} *e* cm early next decade; new experiment at Oak Ridge (2022→) aims for 5 x 10^{-28} *e* cm.
- Interest in proton EDM experiment (CERN?) with sensitivity 10^{-29} *e* cm.
- Proposal to probe for charm baryon EDMs at LHC with bending crystal to ~10^{-17} *e* cm.

Electron EDMs

Most impressive absolute limits are from atomic physics, and constraints on electron EDMs through molecules.



polarization

$$d_{mol} = \eta E_{eff} d_e$$

effective electric field (GV/cm)

YbF: Imperial College London

[Nature 473 (2011) 493]

ThO: ACME collaboration (Harvard/Yale)

[Science 343 (2014) 269]

HfF^+: JILA (Boulder, Colorado)

[arXiv:1704.07928]

Ongoing new-generation Imperial experiment aims for 10^{-29} *e* cm.

Kaon experiments: $K \to \pi \nu \bar{\nu}$

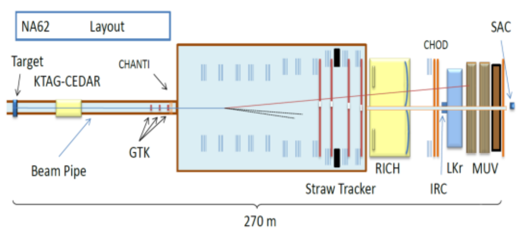
Let's focus on the golden modes of kaon physics: K^+, $K_L \to \pi^{+,0} \nu\bar{\nu}$ (but remembering that there are many other observables to measure).

Precisely predicted modes with SM BRs of 3 (K^+) and 8 (K_L) x 10^{-11}.

$K^+ \to \pi^+ \nu\bar{\nu}$

NA62 at CERN

- Data taking until end of 2018. Aim for ~10% precision.

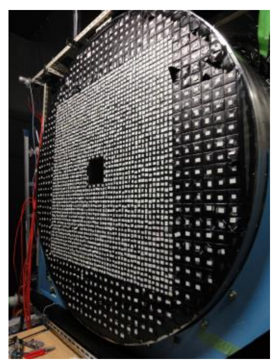


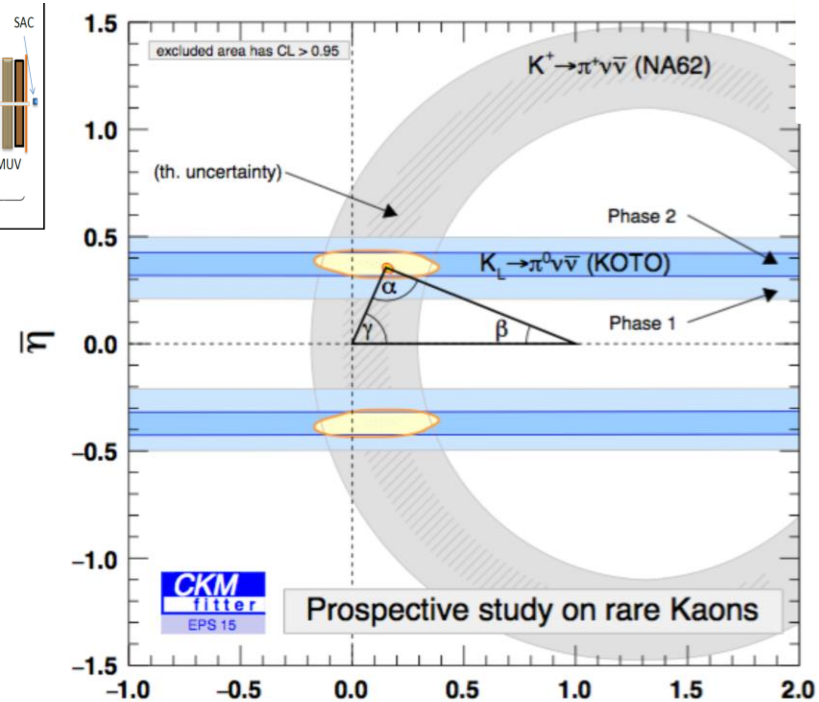
10^{12} / s protons from SPS (400 GeV/c) on Be target (~1 λ)

$K_L \to \pi^0 \nu\bar{\nu}$

KOTO at J-PARC

- Aims to have SM sensitivity with data collected up to ~2019 (?).
- Extension of hadron hall will allow for KOTO Step 2 & goal of ~10% precision.





[S. Descotes-Genon]

Proposal for complementary experiment with similar sensitivity at SPS (KLEVER).

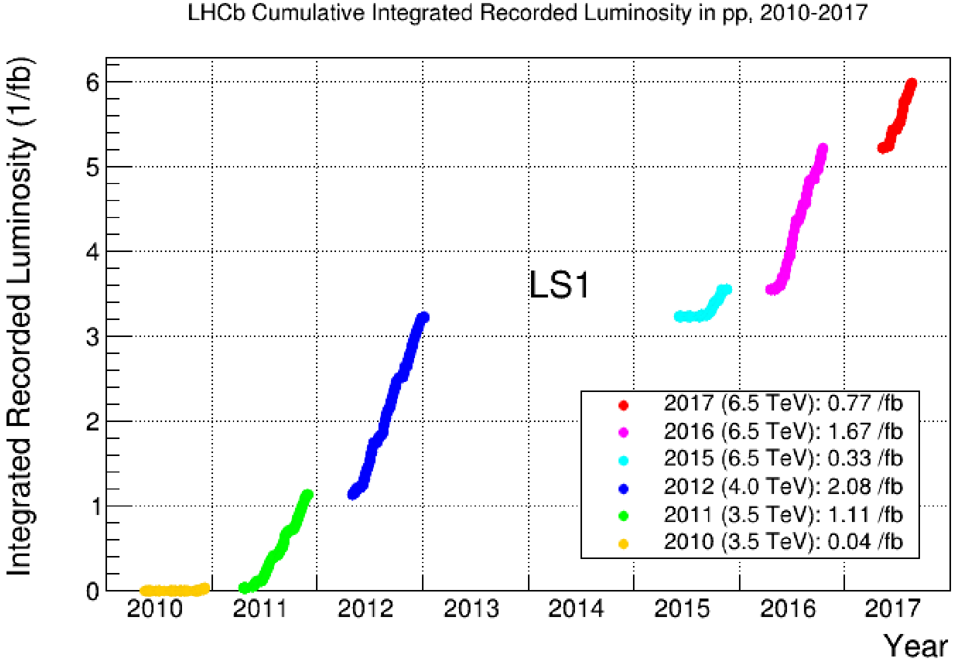
Future prospects in b (& c) physics

- LHCb – immediate future
- Why go on ?
- Belle II
- The GPD Phase II Upgrades
- LHCb Phase I + II Upgrades

The immediate future: LHCb prospects in run 2

Currently on tape:

- Run 1: 3 fb^{-1} at 7+8 TeV
- Run 2: 2.8 fb^{-1} at 13 TeV

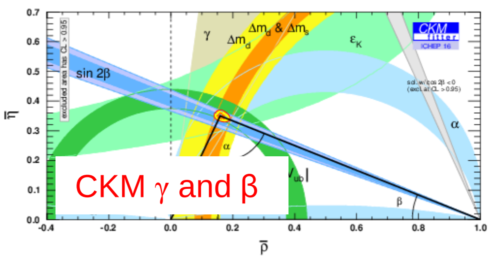


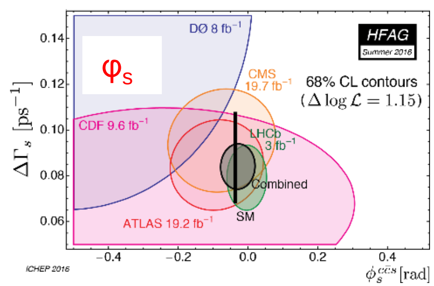
Hope for another 2-3 fb^{-1} before LS2. This, and higher x-section, means that sample sizes in key channels should increase by ~4-5 x w.r.t. run 1, neglecting trigger improvements (which in many cases, *e.g.* charm, have significant benefits).

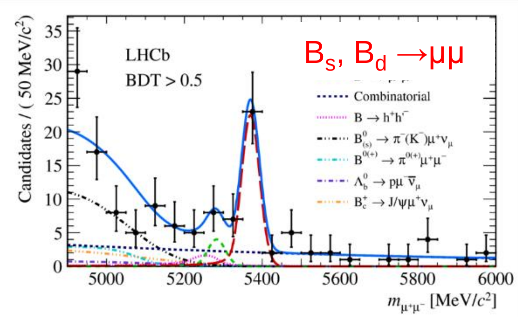
2018: the end of LHC run 2, the end of b-physics ?

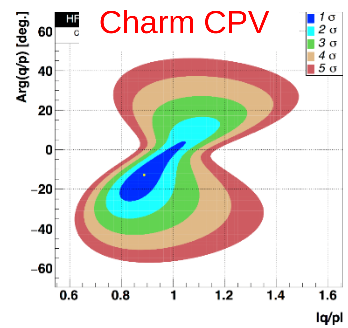
By start of LS2 b(& c)-physics will have enjoyed ~20 years of detailed study, with a landscape that is well explored &, by then, largely familiar. Why then continue ?

- Already, deep into LHC run 2, there is no sign of New Physics discovery from direct searches. Vital to keep probing through indirect approach, given the sensitivity to high mass scales (plus the encouraging hints from run 1).
- Knowledge of the most important flavour observables will still be statistics limited after run 2 (and, in many cases, beyond).



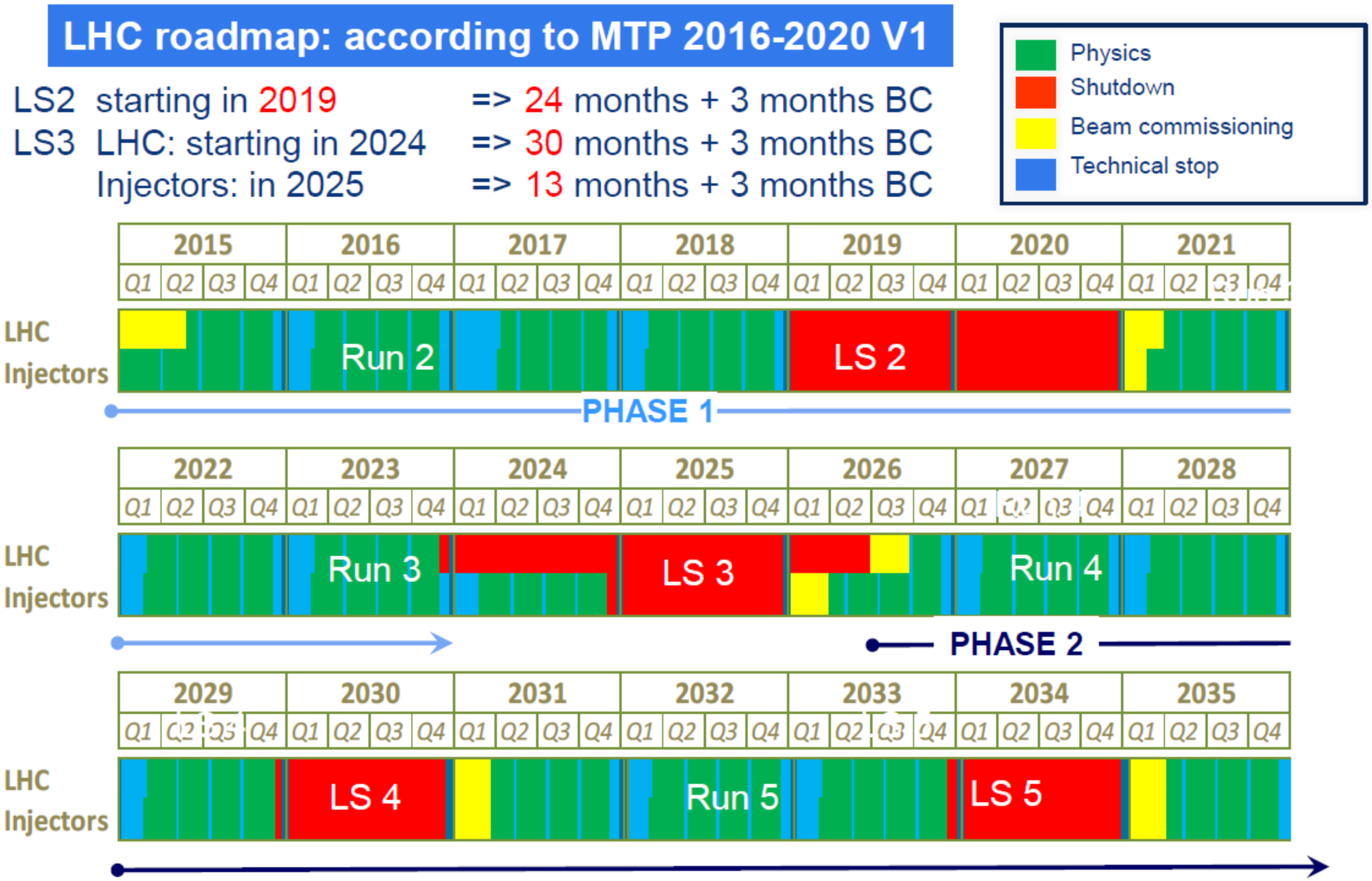




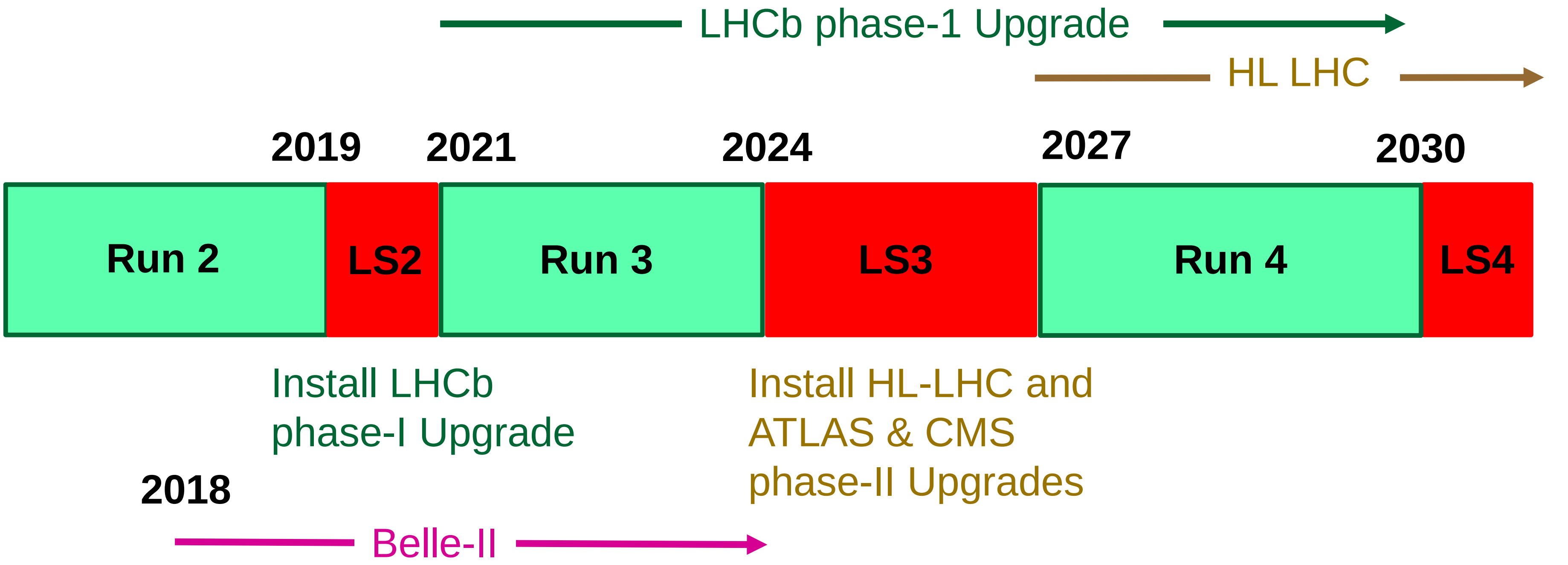


- Not unlikely that situation with current flavour anomalies will be ambiguous, even after run 2, and much higher precision will be required for clarity.
- Opportunity ! LHC will continue as main show in town, with a luminosity that is ample for flavour physics studies; meanwhile new accelerator developments will have reopened e^+e^- frontier.

The LHC schedule

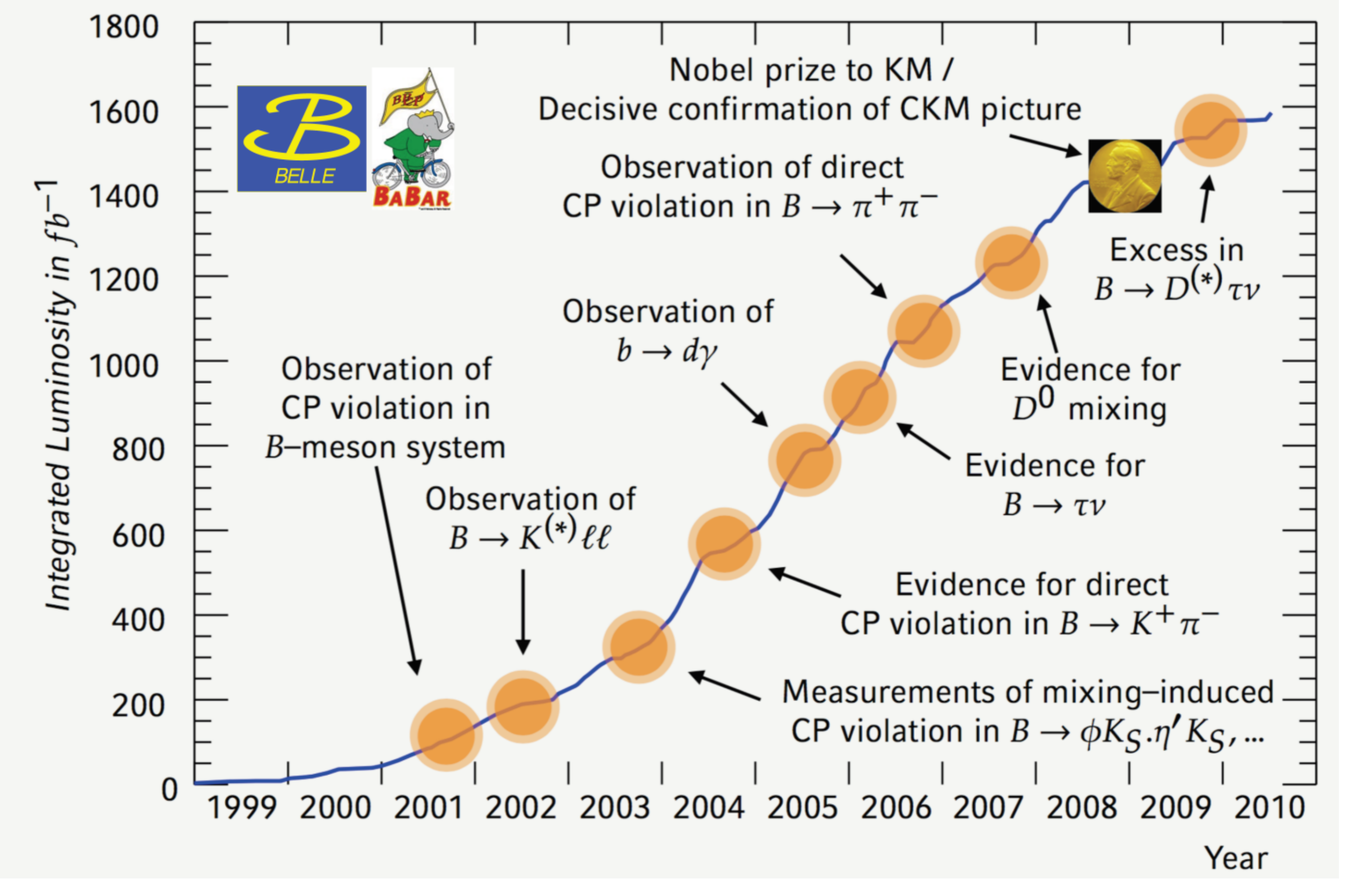


The LHC schedule up to 2030



Why Belle II ?

BaBar & Belle were astonishingly successful experiments. Most importantly, they demonstrated that CKM mechanism drives CP violation (at least at 1st order).

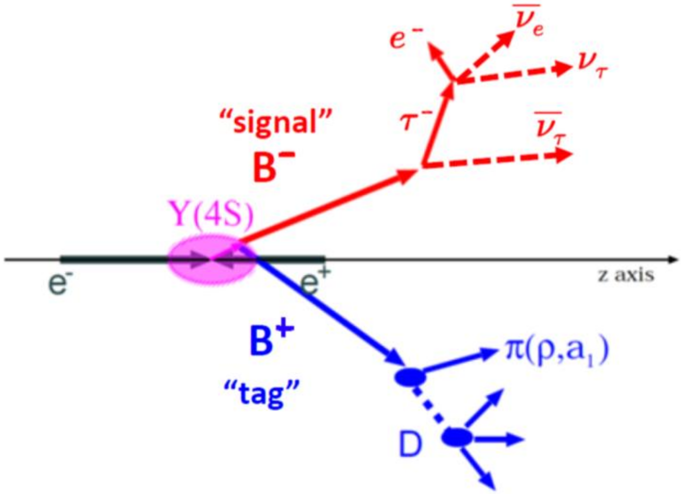


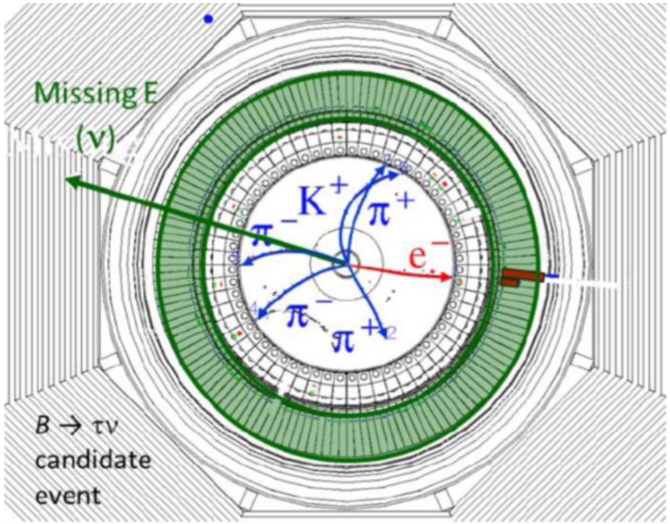
Why Belle II ?

B production at the Υ(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

e.g. B→τν



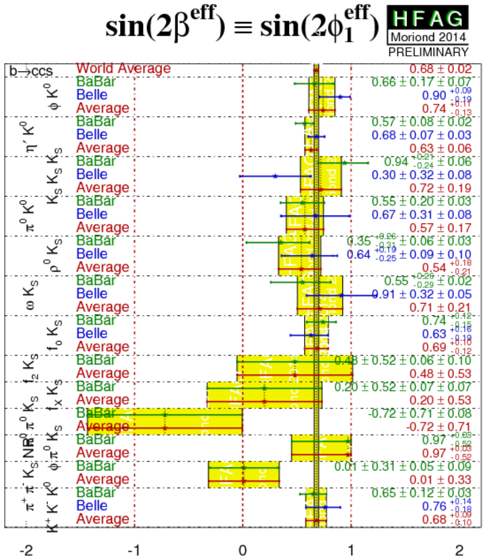


Why Belle II ?

B production at the Υ(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).
- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

e.g. most modes suitable for sin2β measurements involving Penguin loops (b→ccbar s) are rather tough at LHCb…



…and other important decays *e.g.* $D^0 \to \gamma\gamma$, $B^0 \to \pi^0\pi^0$… are essentially inaccessible.

Why Belle II ?

B production at the Υ(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

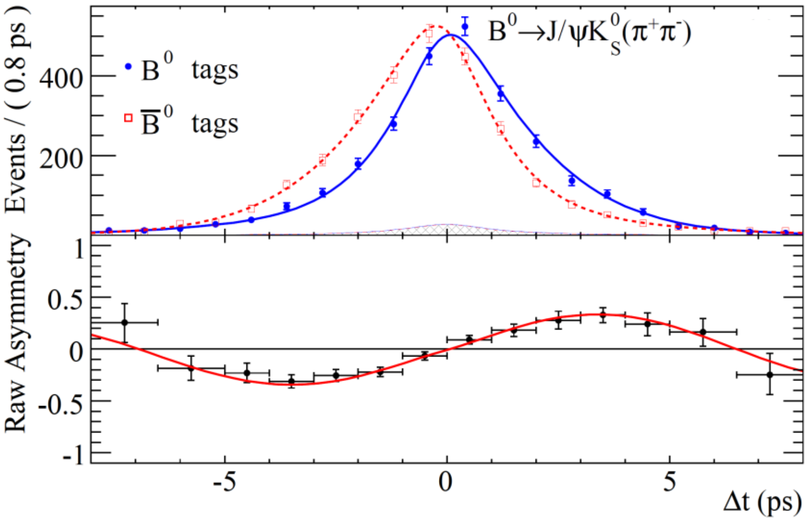
- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

- Coherent B^0B^0bar production at Υ(4S) makes flavour tagging easier and compensates for lower sample sizes in time-dependent CP measurements

e.g. in sin2β measurement with $B^0 \to J/\psi K_S$

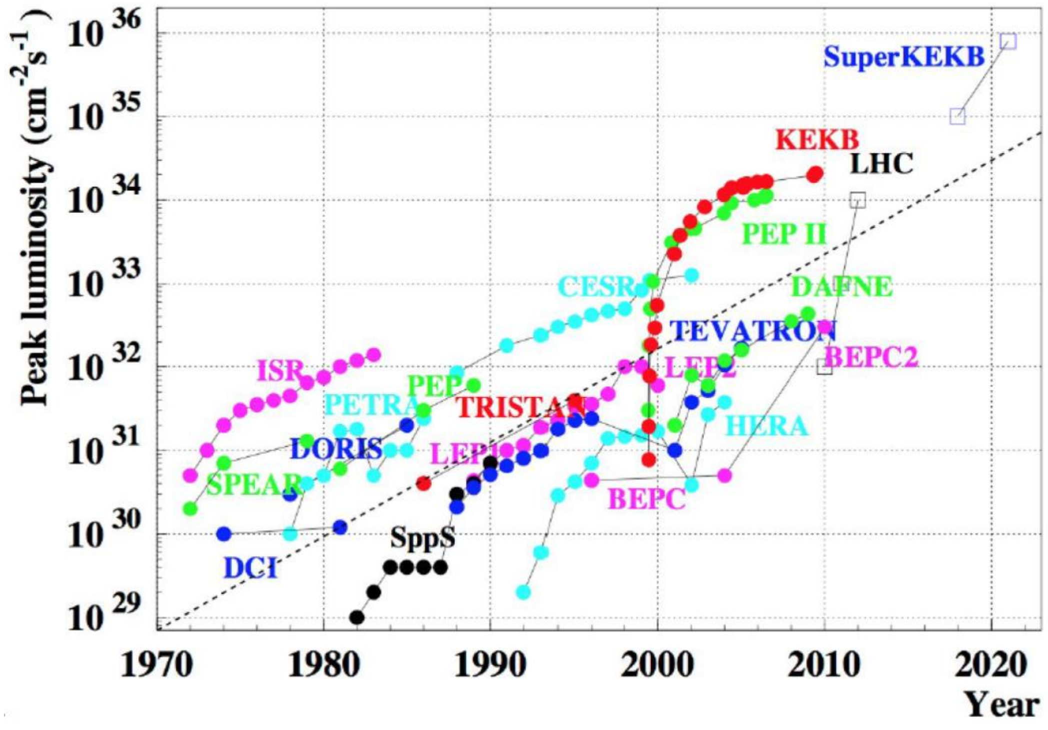
ε (tag effective) BaBar ~ 31 %
[PRD 79 (2009) 072009]

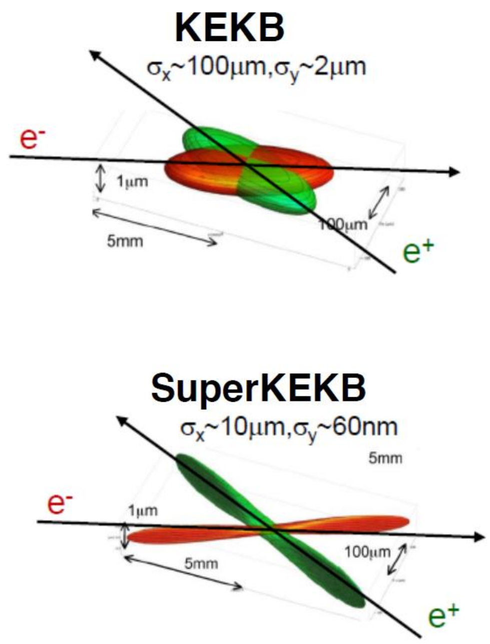
ε (tag effective) LHCb ~ 3 %
[PRL 115 (2015) 031601]



SuperKEKB

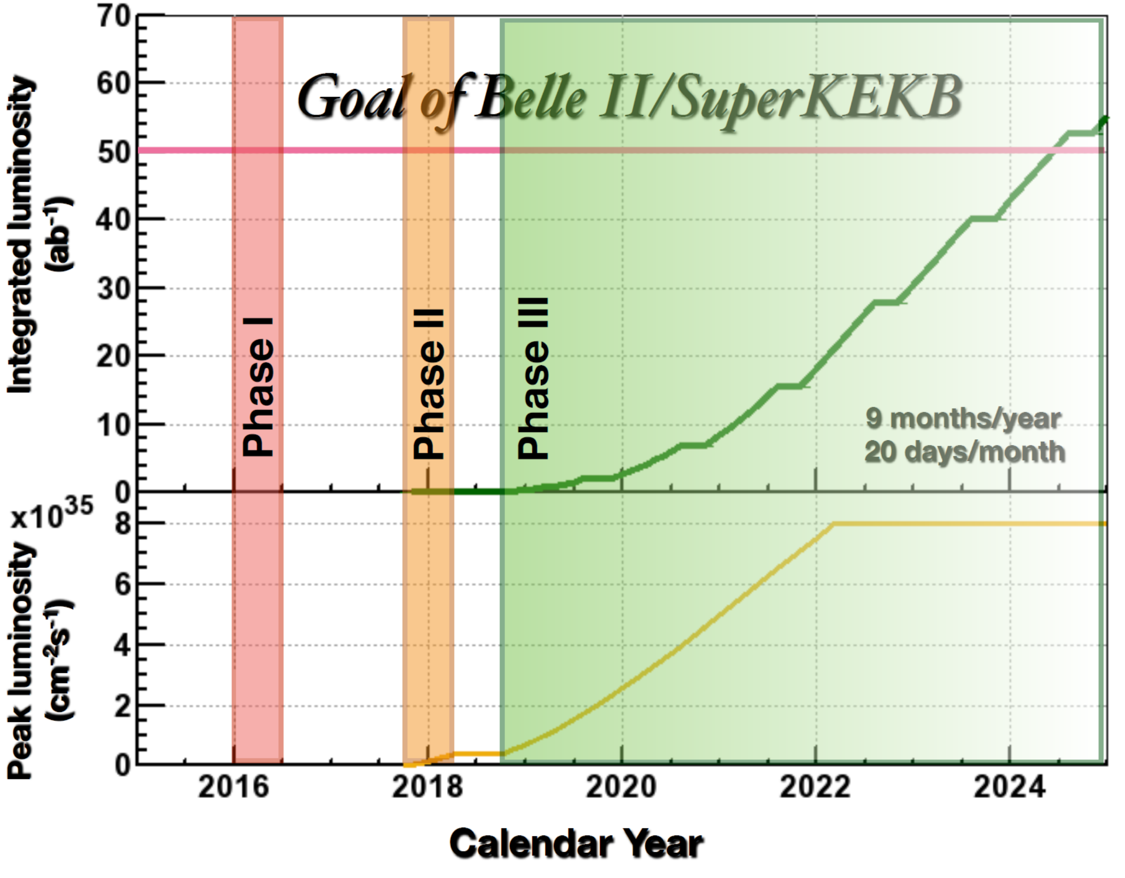
SuperKEKB goals: luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ and 50 ab^{-1} by 2024





An ambitious 40-fold increase in luminosity on KEKB, to be achieved by squeezing the beams by ~1/20 and doubling the currents.

SuperKEKB and Belle II roadmap



Phase 1 (completed)

- Circulate beams (no collisions)
- Tune optics *etc.*

Phase 2 (2017-2018)

- First collisions
- Physics run, without vertex detector

Phase 3 (2018-)

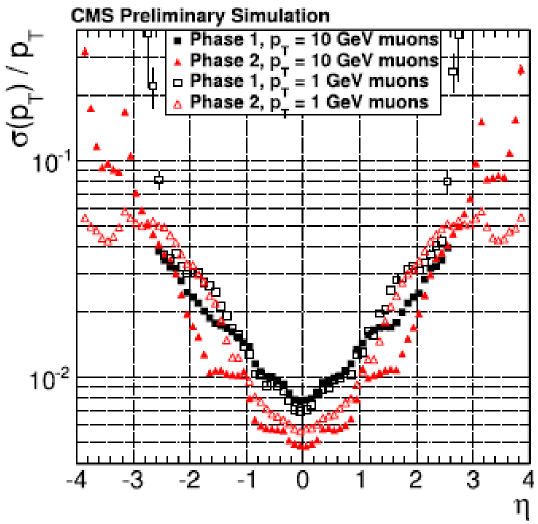
- Physics run with full Belle II

GPD phase-II Upgrades

In run 1 ATLAS and CMS have already made high quality B-physics measurements in modes with di-muon final states.

New capabilities of GPDs after Phase-II Upgrade (CMS in particular) will strengthen their capabilities in flavour physics

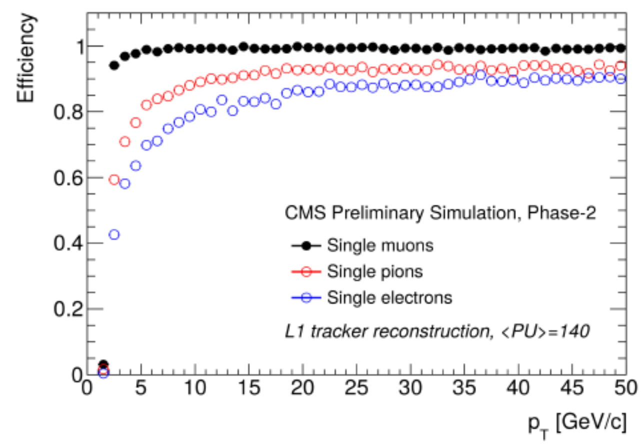
e.g. new CMS tracker



Jeremiah Mans, ECFA HL LHC, Aix-les-Bains, Oct 2014

Significantly improved p resolution

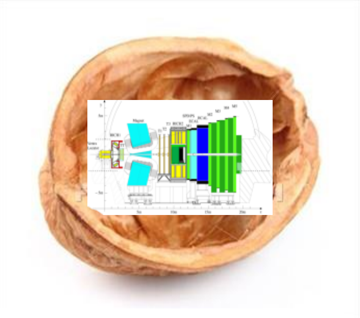
e.g. CMS new L1 track trigger



Anders Ryd, ECFA HL LHC, Aix-les-Bains, Oct 2014

Could allow CMS to accumulate large samples even in hadronic modes!

LHCb Upgrade in a nutshell



An LHCb Upgrade is scheduled, with installation in LS2 and first data-taking in run 3. The motivation is to take increased advantage of the huge rate of heavy-flavour production at the LHC.

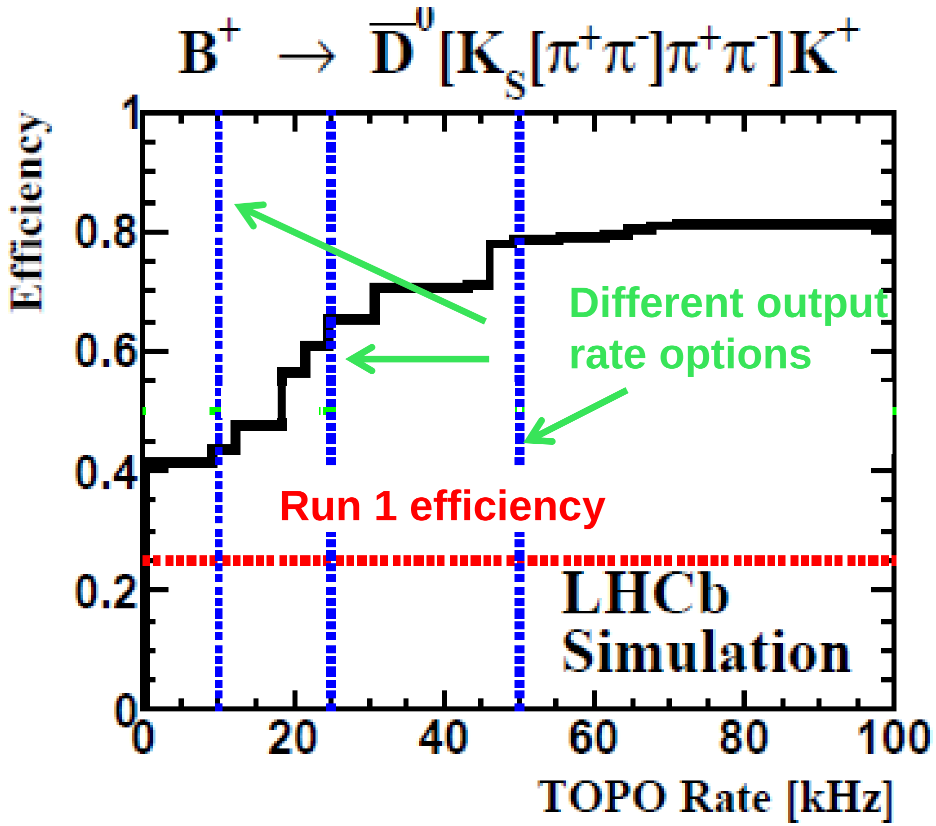
The LHCb Upgrade

1) *Full* software trigger

- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

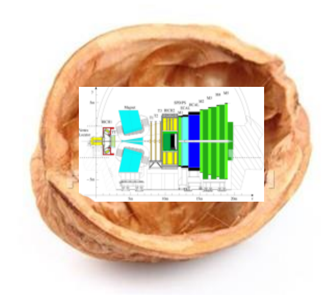
Running a full software trigger

Have access to full events information, & being able to exploit lifetime & decay topology information, at earliest trigger level will bring big gains in efficiency.



Effect will be most marked for hadronic decays, where efficiency increases of at least factor 2 can be expected. Such a trigger can also run at higher lumi, in contrast to existing L0, which would saturate and bring no net benefit.

LHCb Upgrade in a nutshell



An LHCb Upgrade is scheduled, with installation in LS2 and first data-taking in run 3. The motivation is to take increased advantage of the huge rate of heavy-flavour production at the LHC.

The LHCb Upgrade

1) *Full* software trigger
- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

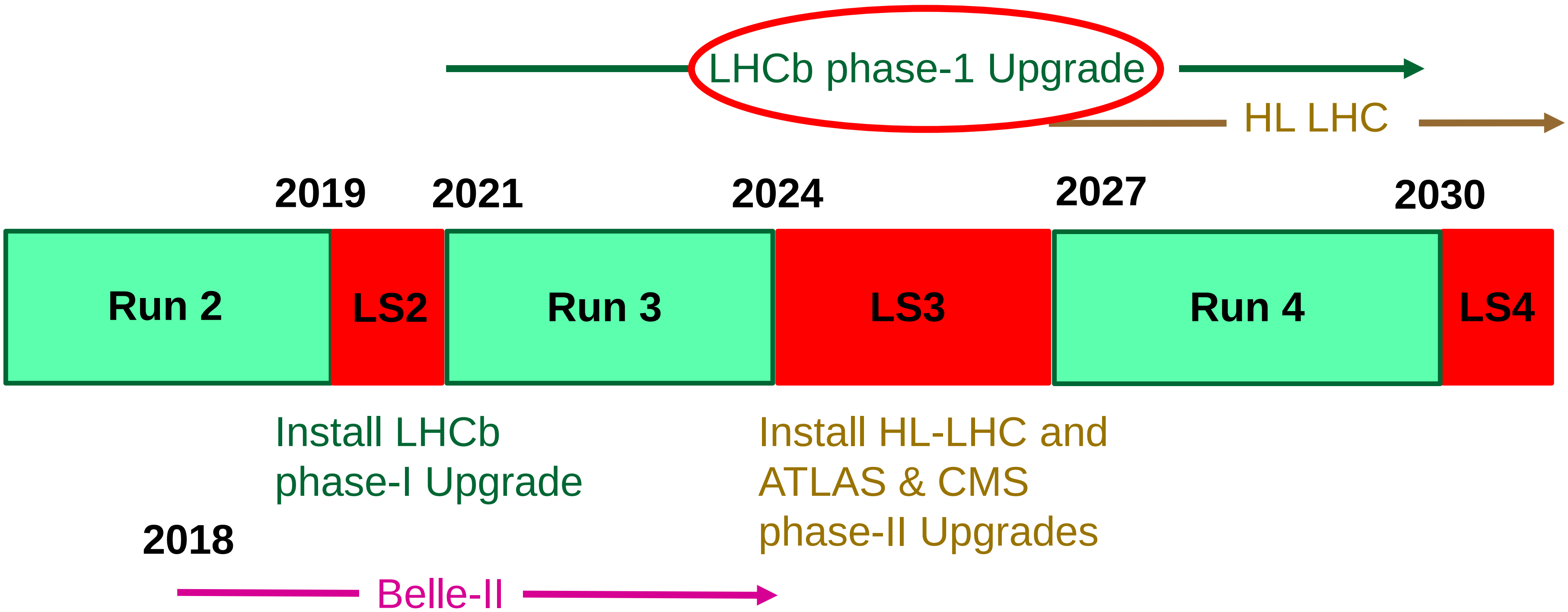
2) Raise operational luminosity by factor five to 2 x 10^{33} cm^{-2} s^{-1}

Necessitates redesign of several sub-detectors & overhaul of readout

Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector.

Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour ('a general purpose detector in the forward region')

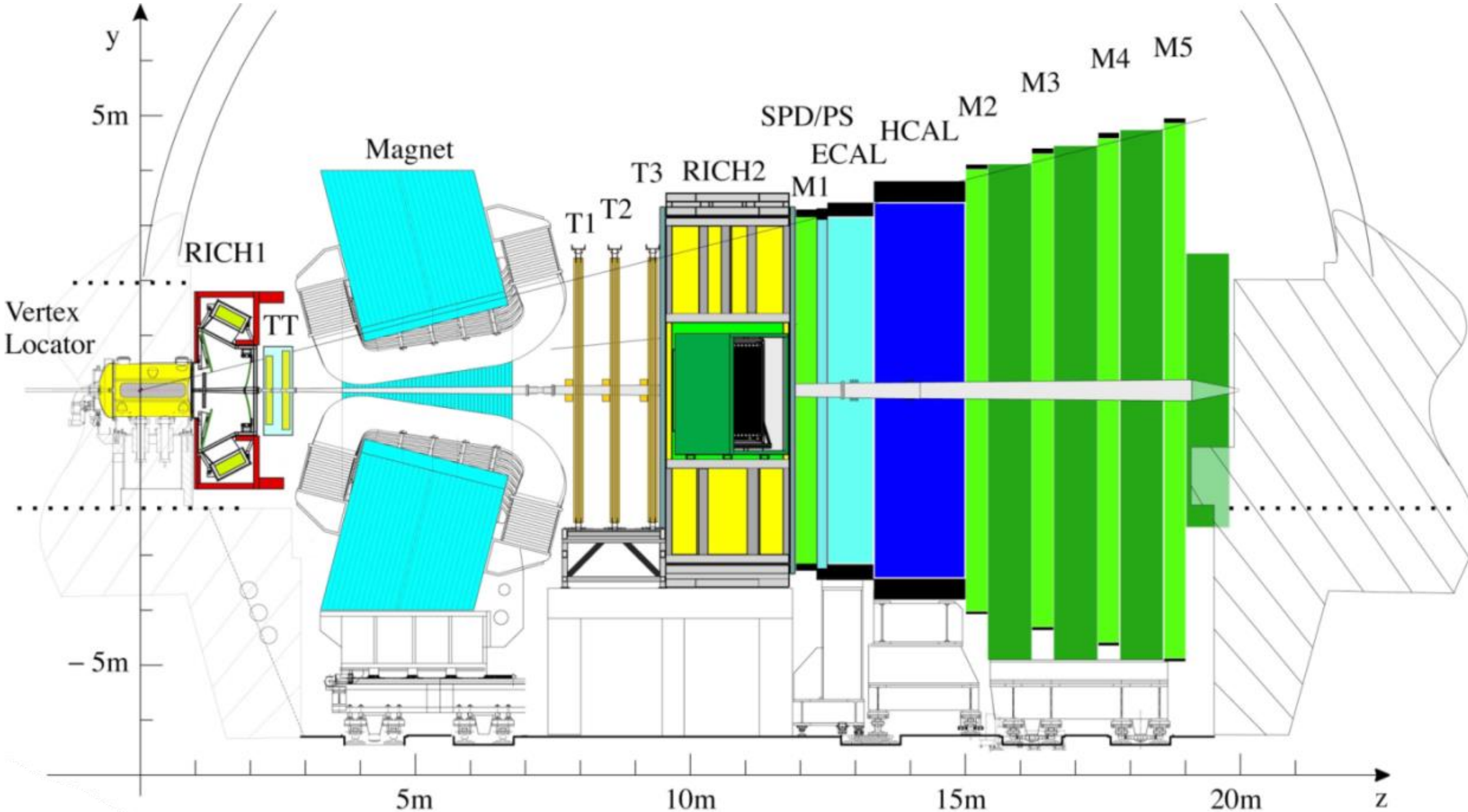
The LHC schedule up to 2030



Target goal: to integrate ~50 fb^{-1} (including run 1, run 2) by end of run 4.

Upgrade overview

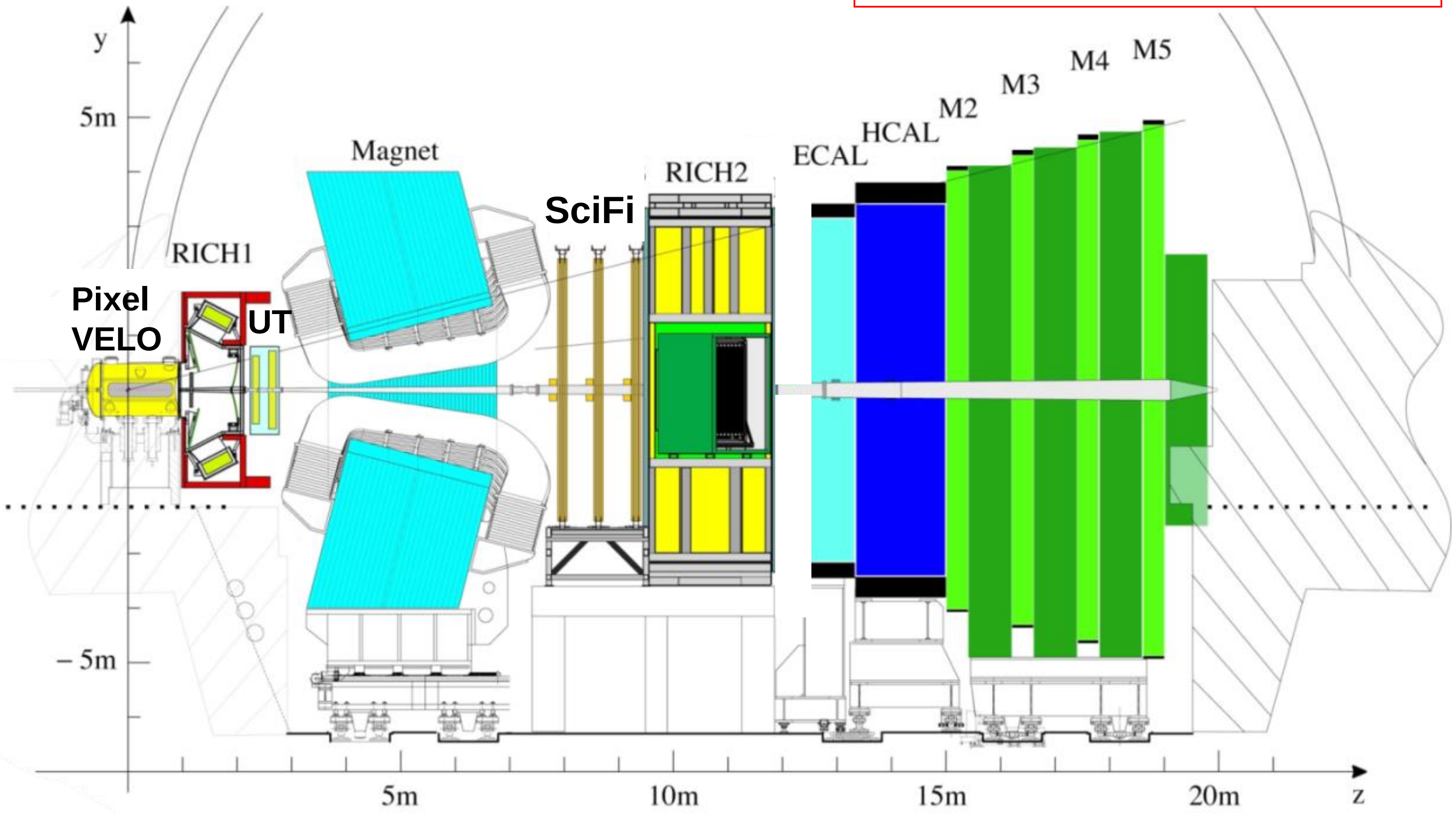
Current detector



Upgrade overview

Current detector → upgraded detector

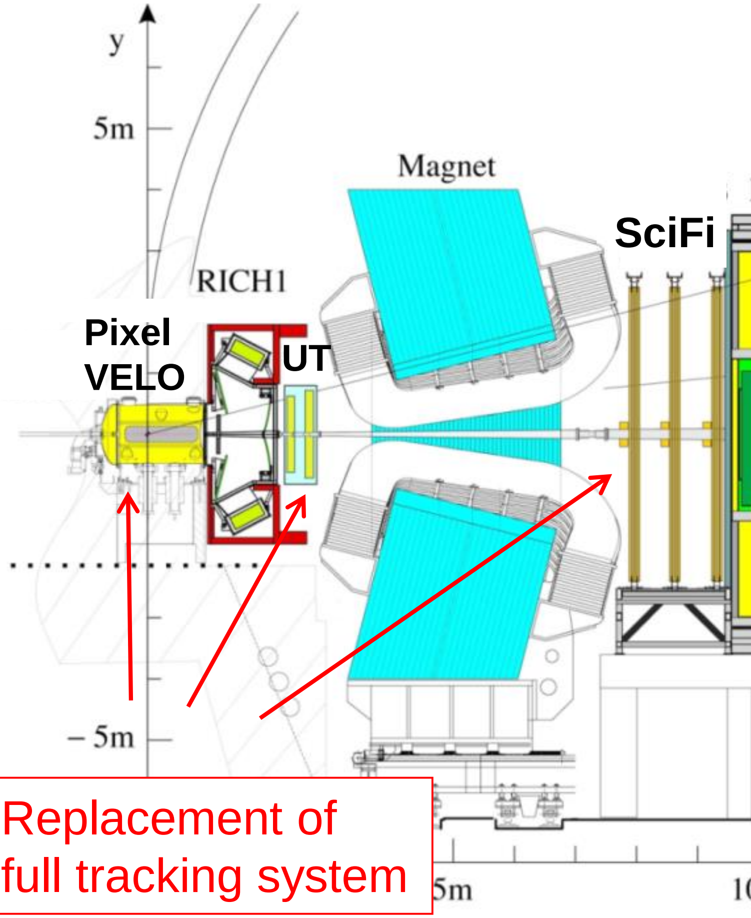
All sub-detectors read out at 40 MHz for software trigger



Upgrade overview

Current detector → upgraded detector

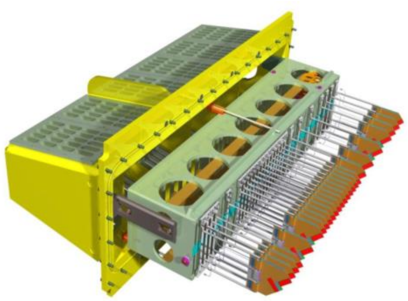
All sub-detectors read out at 40 MHz for software trigger



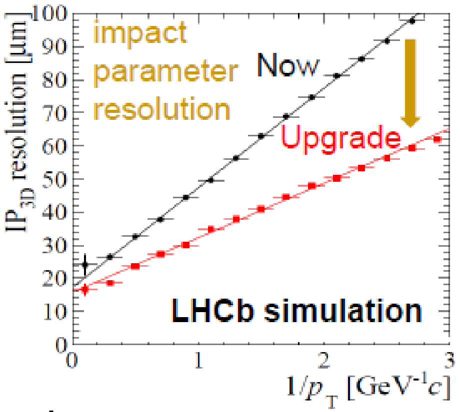
Replacement of full tracking system

Pixel Vertex Locator (VELO)

Half of VELO system



Improved performance

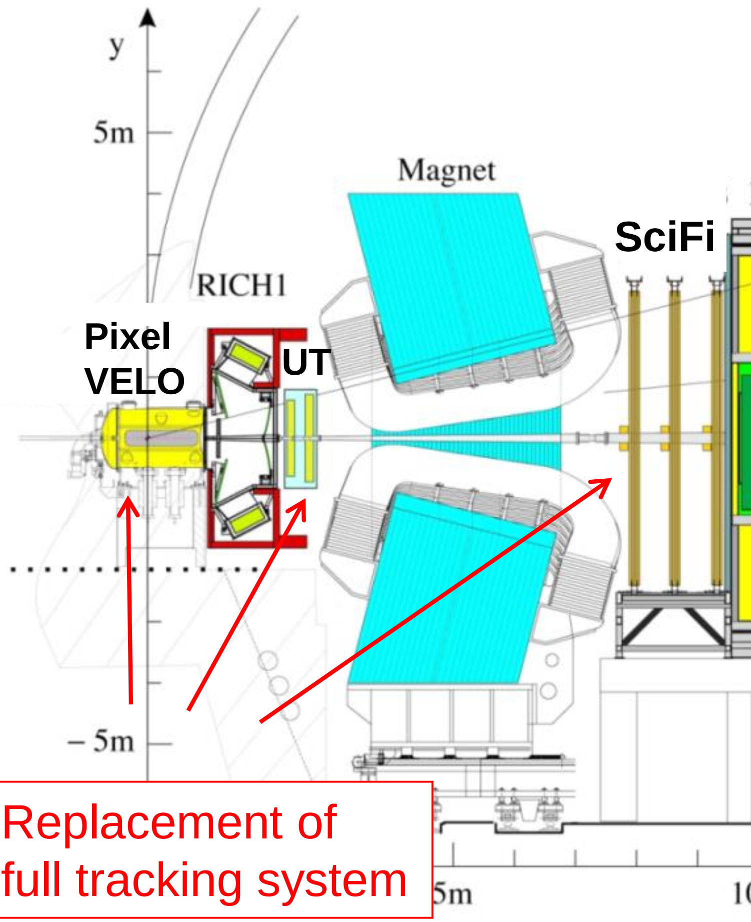


('UT' = 'Upstream tracker', a high performance Si strip detector)

Upgrade overview

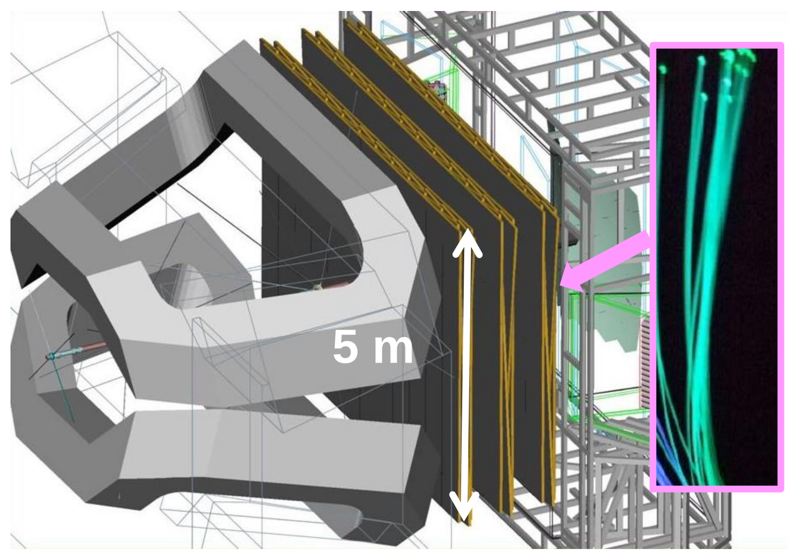
Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger



Replacement of full tracking system

Scintillating Fibre Tracker



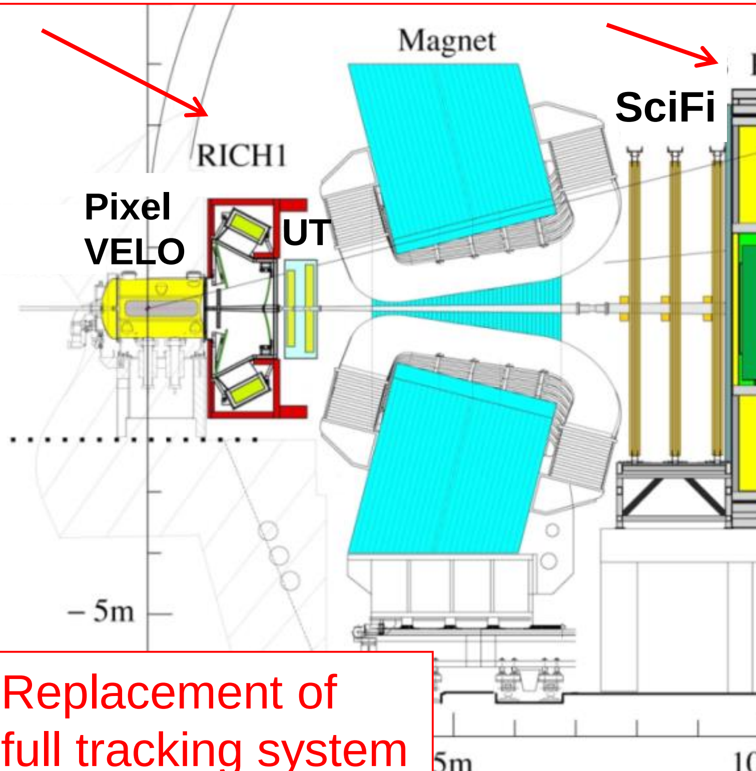
Large scale system (~12,000 km of fibres)

Upgrade overview

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger

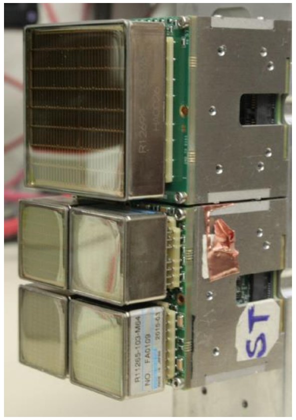
RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2



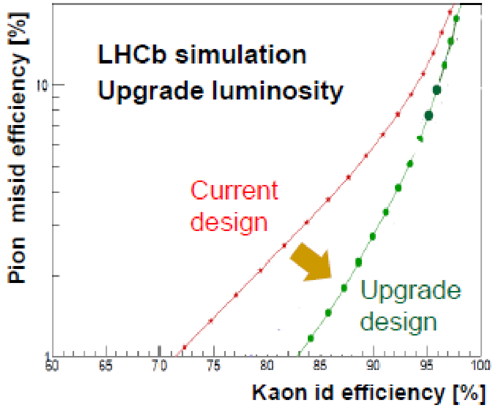
Replacement of full tracking system

RICH system

New photodetector



New optics….



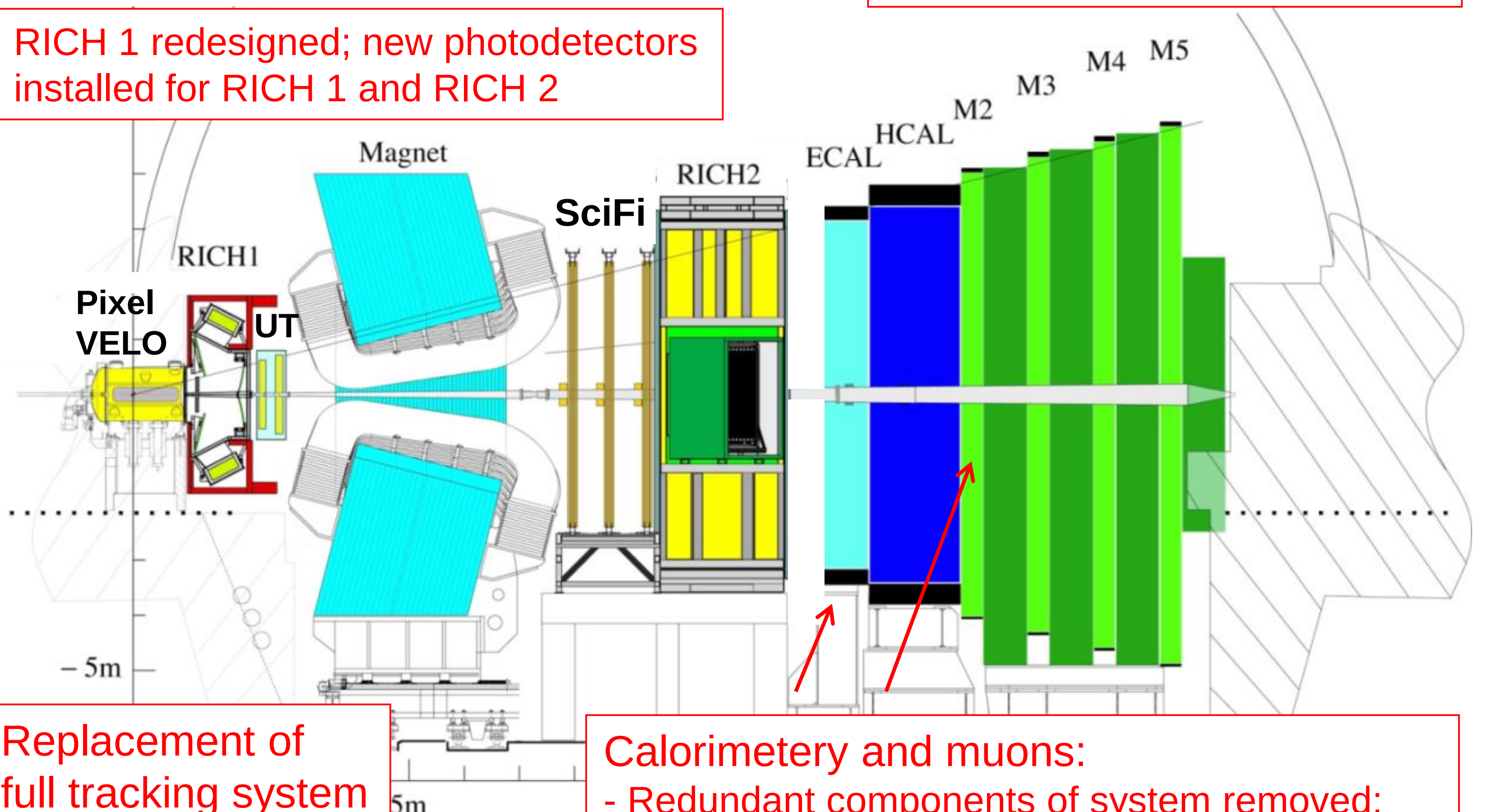
…good performance at high luminosity

Upgrade overview

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger

RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2



Replacement of full tracking system

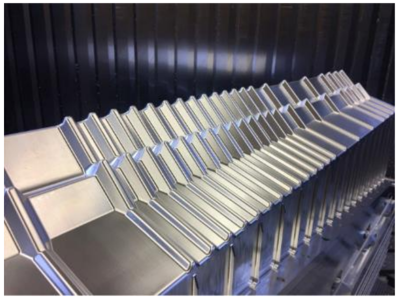
Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

Upgrade progress

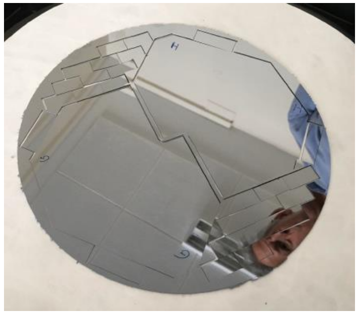
Excellent progress on all aspects of the Upgrade project.

Prototype readout boards

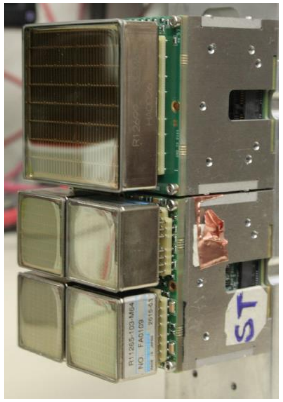
RF box for VELO



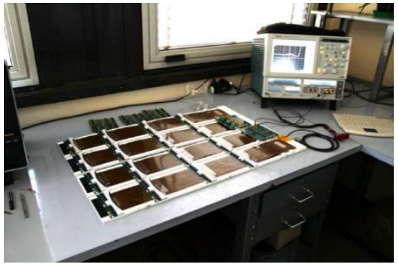
Diced wafer with microchannel cooling substrates for VELO



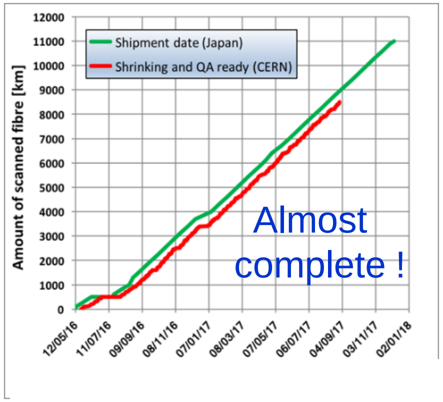
RICH photodetectors



Testing Upstream Tracker 'flex cables'



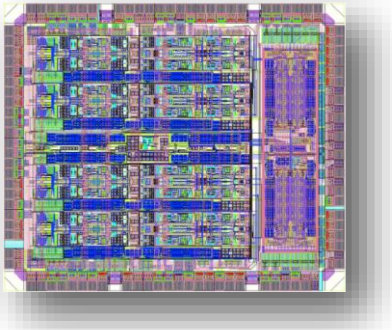
Delivery of tracker scintillating fibres (SciFi)



First batch of SciFi modules arriving at IP8

MWPC for muon system

ECAL front-end ASIC



Timescale tight, but still on-track for installation in LS2.

How will the next generation of flavour experiments perform ?

Projections exist, but the numbers are, IMHO, merely indicative, *e.g.* LHCb Upgrade

['old' table from EPJ C 73 (2013) 2373; arXiv:1208.3355.if re-made with current numbers the argument would remain]

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

How will the next generation of flavour experiments perform ?

Projections exist, but the numbers are, IMHO, merely indicative, *e.g.* Belle II

B2TiP Report (in progress)

Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$S(B_s \to J/\psi\phi)$	***	0.01	LHCb
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II
$\lvert V_{ub}\rvert$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	**	0.1	LHCb
$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb

CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	**	0.1	LHCb
$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	***	0.05	LHCb
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II
$q_0^2 A_{\rm FB}(B \to K^*\mu\mu)$	**	0.05	LHCb/Belle II
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	***	< 2	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb/Belle II
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	**	0.1	LHCb
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle Ii
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-9}]$	***	< 5	Belle II
$\tau \to e\gamma$ $[10^{-9}]$	***	< 10	Belle II
$\tau \to \mu\mu\mu$ $[10^{-9}]$	***	< 0.3	Belle II/LHCb

P. Goldenzweig,
La Thuile,11/3/2017

How will the next generation of flavour experiments perform ?

Projections exist, but the numbers are, IMHO, merely indicative, *e.g.* Belle II

Key facts.

Belle II's aim is to collect ~50 x more than BaBar + Belle, plus benefit from several detector improvements.

LHCb Upgrade (+ run 2) aims to collect:

~60 x more than LHCb run 1 in hadronic modes and
~30 x more than LHCb run 1 in muonic modes,

where difference is driven by full software trigger.

So order of magnitude improvement in precision expected !

Observables
UT angles & sid
ϕ_1 [°]
ϕ_2 [°]
ϕ_3 [°]
$S(B_s \to J/\psi\phi)$
$|V_{cb}|$ incl.
$|V_{cb}|$ excl.
$|V_{ub}|$ incl.
$|V_{ub}|$ excl.
CPV
$S(B \to \phi K^0)$
$S(B \to \eta' K^0)$
$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [r
$\beta_s^{\rm eff}(B_s \to K^{*0} \bar{K}$
$\mathcal{A}(B \to K^0\pi^0)$[1
$\mathcal{A}(B \to K^+\pi^-)$
(Semi-)leptonic
$\mathcal{B}(B \to \tau\nu)$ [10$^-$
$\mathcal{B}(B \to \mu\nu)$ [10$^-$
$R(B \to D\tau\nu)$
$R(B \to D^*\tau\nu)$

Belle II
Belle II
LHCb
LHCb
Belle II
LHCb/Belle II

Belle II
Belle II
Belle II
Belle II/LHCb

Belle II
Belle II
Belle II
LHCb
Belle II
Belle II
Belle II
Belle II
LHCb/Belle II
Belle II
LHCb/Belle II

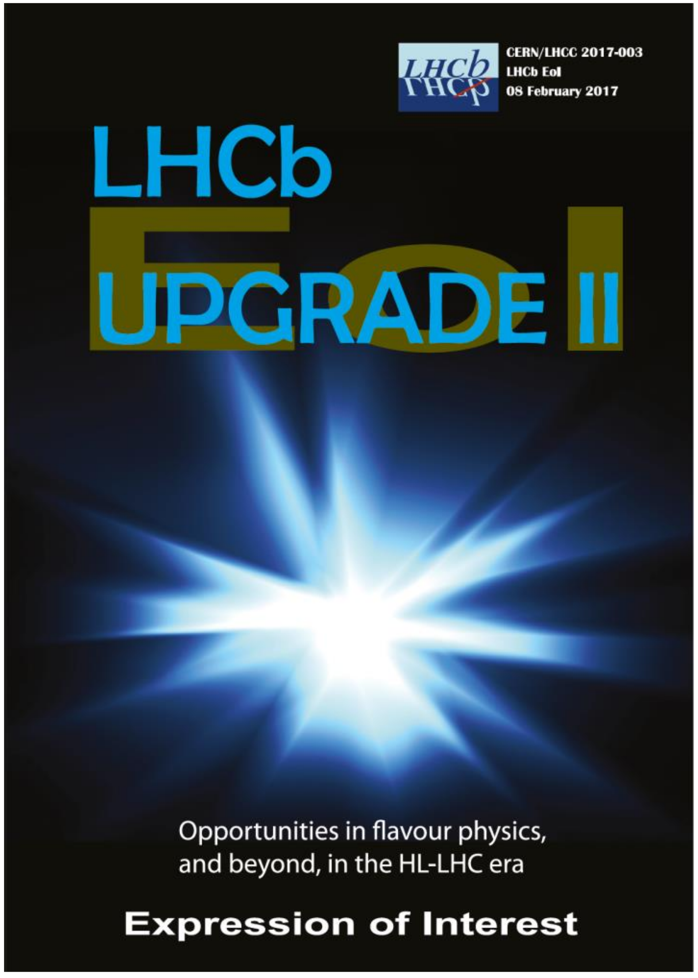
Belle II
Belle II
LHCb
Belle II
Belle Ii
Belle II

Belle II
Belle II

$\tau \to \mu\mu\mu$ [10^{-9}]	***	< 0.3	Belle II/LHCb

P. Golder
La Thuile, 11/3/2017

LHCb Phase-II Upgrade

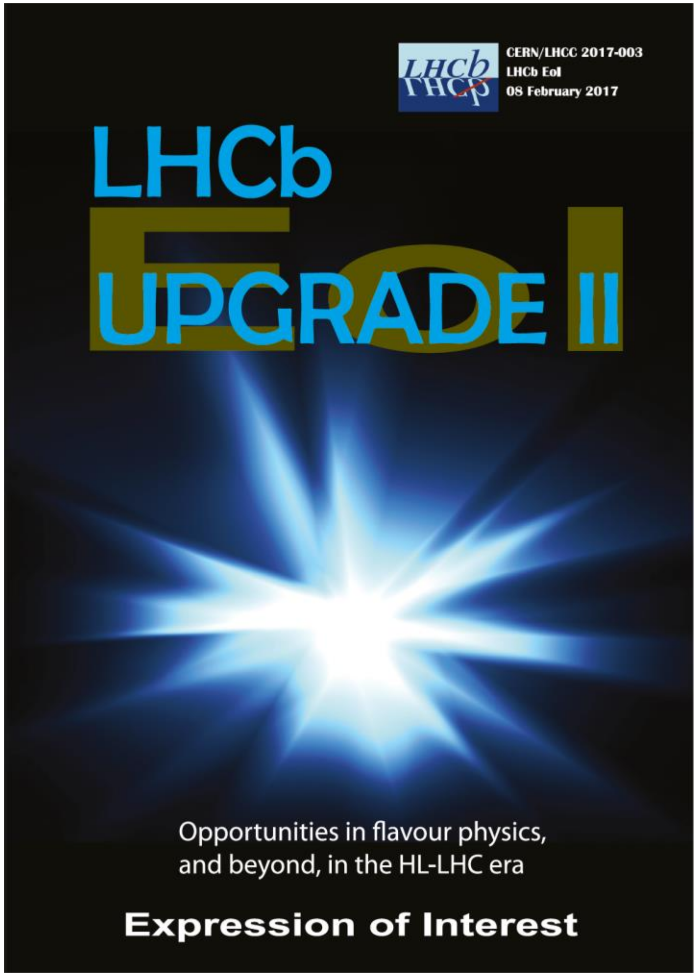


Expression of Interest submitted to February LHCC [CERN-LHCC-2017-003]

"It is proposed to upgrade the LHCb experiment in order to take full advantage of the flavour-physics opportunities at the High Luminosity LHC (HL-LHC).
…..

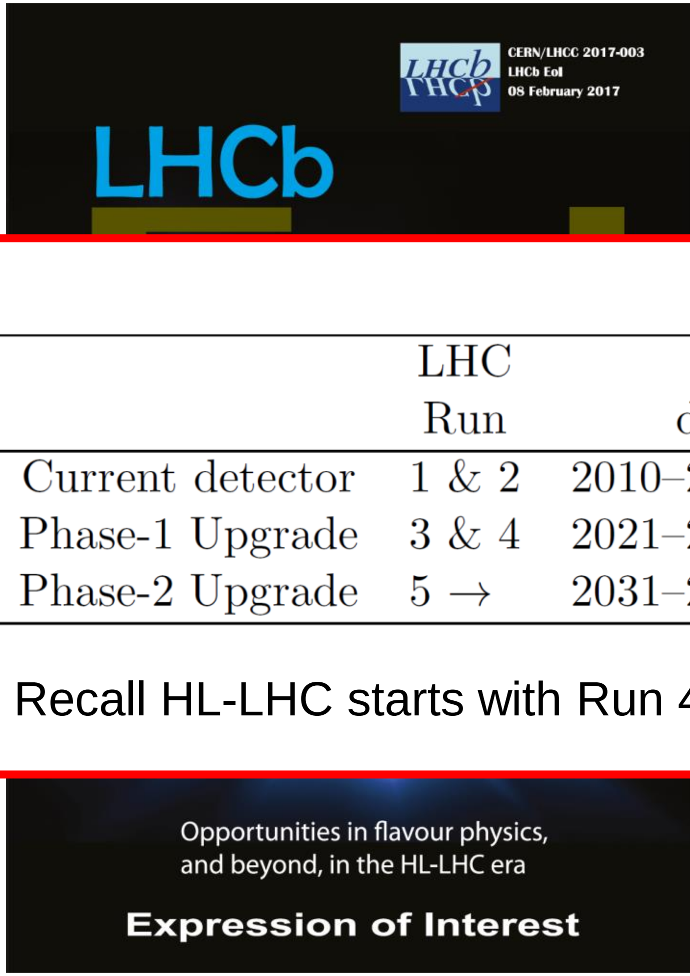
This project will extend the HL-LHC's capabilities to search for physics beyond the Standard Model, and implements the highest-priority recommendation of the European Strategy for Particle Physics (Update 2013), which is to exploit the ***full potential of the LHC*** for a variety of physics goals, including flavour."

LHCb Phase-II Upgrade



- Install in LS4 (~2030), after Phase-I Upgrade.
- Detector to be able to operate at ~2 x 10^{34} $cm^{-2}s^{-1}$
- Integrate ~300 fb^{-1}
- Comprehensive flavour physics programme + general-purpose forward physics (as now), but targeting clean measurements currently limited by statistics, and new observables
- Straw-man detector design with candidate solutions to challenges, including new capabilities in key areas
- Define initial R&D plan, and possible first steps in LS3, which will help physics of Phase I

LHCb Phase-II Upgrade



- Install in LS4 (~2030), after Phase-I Upgrade.
- Detector to be able to operate at ~2 x 10^{34} cm^{-2}s^{-1}

	LHC Run	Period of data taking	Maximum $\mathcal{L}$ [cm^{-2}s^{-1}]	Cumulative $\int \mathcal{L}\,dt$ [fb^{-1}]
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	8
Phase-1 Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50
Phase-2 Upgrade	5 $\rightarrow$	2031–2033, 2035 $\rightarrow$	2×10^{34}	300

Recall HL-LHC starts with Run 4

including new capabilities in key areas

- Define initial R&D plan, and possible first steps in LS3, which will help physics of Phase I

Physics goals and potential

Phase-I Upgrade, together with Belle II, should bring big advances in our knowledge of the flavour sector. But still many important, theoretically clean, observables will remain statistics limited, and others will be out of reach.

Phase-II Upgrade will be capable of a broad spectrum of important measurements in flavour sector. Some key goals are as follows:

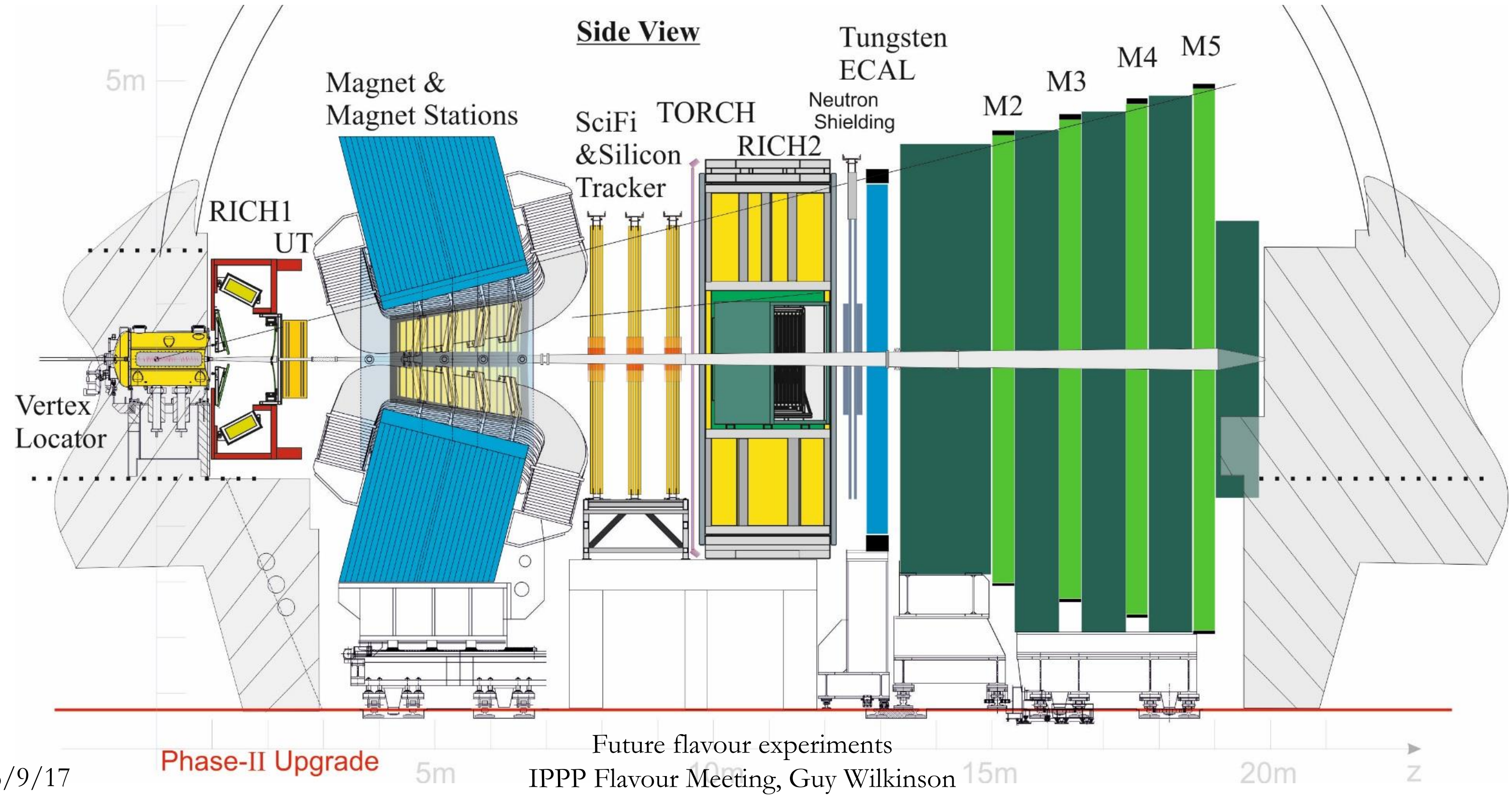
- Comprehensive measurement programme of observables in $b \to s l^+ l^-$ and $b \to d l^+ l^-$, employing both muon and electron modes;
- Measurement of CPV phases γ and φ_s, with precision of 0.4^o and 3 mrad respectively;
- Measurement of $BR(B_d \to \mu\mu)/BR(B_s \to \mu\mu)$ to < 20%, and first precise measurement of associated observables
- Wide ranging lepton universality measurements in $b \to cl\nu$, exploiting full range of b hadrons;
- CPV in charm down to 10^{-5}.

Also will be able to make major discoveries in spectroscopy, and pursue a wide and unique programme of general physics measurements in forward region.

EoI proposes candidate solutions for challenges of performing flavour physics in environment of up to 50 pile-up interactions and high irradiation.

Aim is to retain current performance in key parameters, & also to improve capabilities in certain areas (*e.g.* ECAL, low momentum tracking *etc.*) Hence improvement in physics reach will be significantly greater than merely going from 50 $fb^{-1} \rightarrow 300\ fb^{-1}$.

Common themes: improved granularity, radiation hardness and fast timing.



Conclusions

Precise flavour measurements will continue to be a powerful tool to probe for New Physics.

Exciting prospects in cLFV, MDM/EDM measurements & kaon physics.

Although the B factories and LHCb, during LHC run 1, delivered much, we can look forward to an order of magnitude increase in sensitivity in the coming 10-15 years:

- Belle II, due to start physics operation very soon will reboot the B-factory programme with ultra-high luminosity;
- The LHCb Phase-I Upgrade will deploy a full software trigger, which will allow a corresponding rise in luminosity.

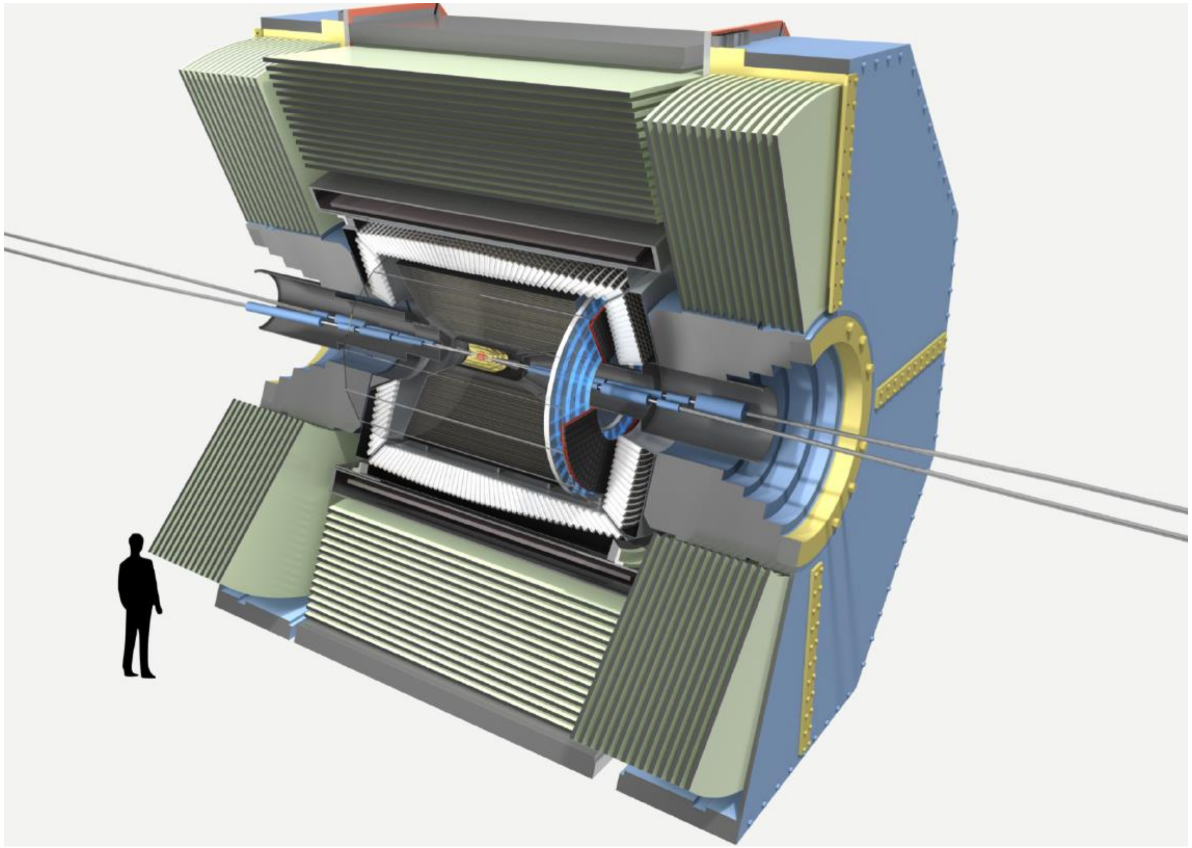
Even then, the HL-LHC will still have huge untapped possibilities to offer in terms of flavour → strong motivation for a Phase-II LHCb Upgrade that can operate in the 10^{34} $cm^{-2}s^{-1}$ regime.


Exciting times ahead !

Backups

Belle II detector

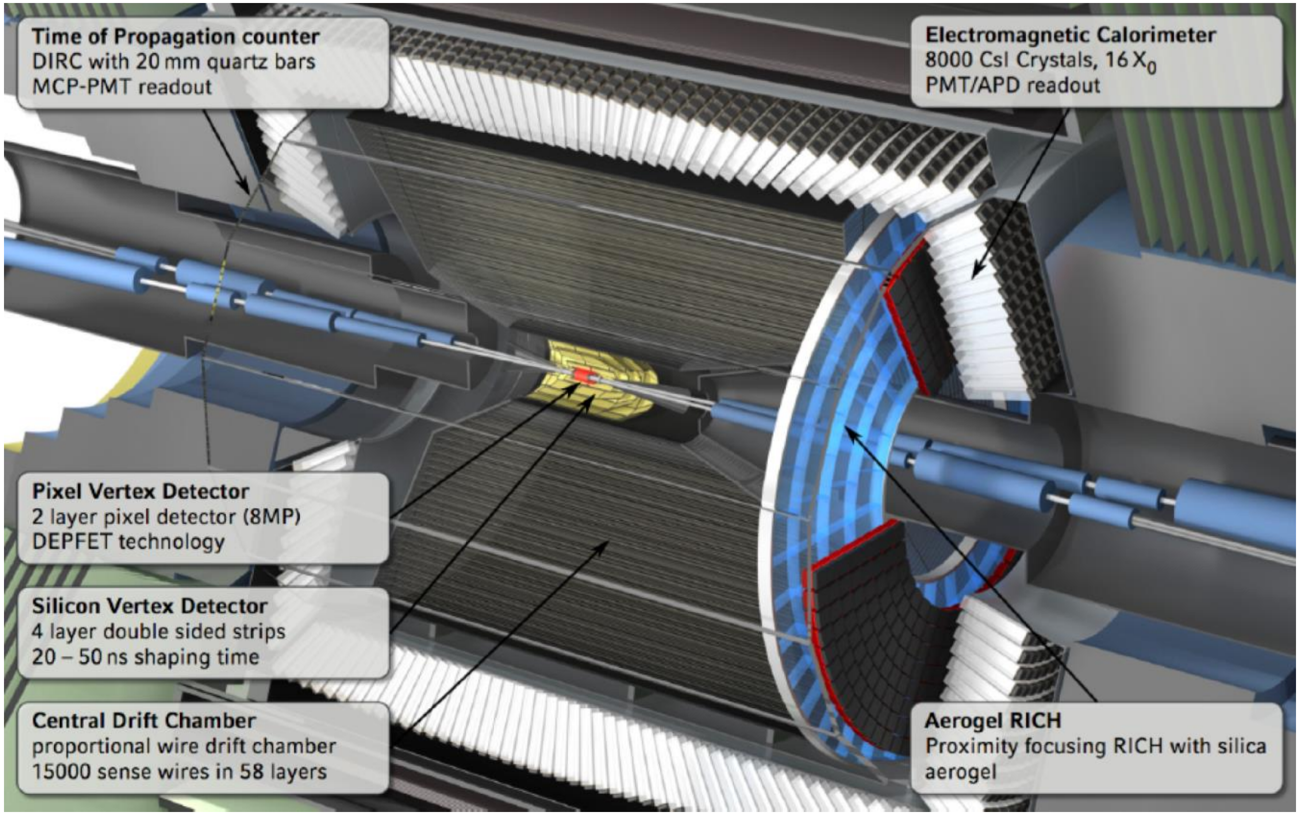
All sub-detectors upgraded from Belle, except for ECL crystals and part of the barrel KLM



Belle II detector

Targeted improvements w.r.t. Belle

- Improved K_S efficiency
- Improved IP and vertex efficiency
- Improved K/π separation
- Improved π^0 efficiency
- Hadron & muon ID in endcaps



Possible scenarios in HEP post LHC run 2

Scenario 1

New Physics is found during run 2 in direct searches.

→ precision measurements in b- and c-physics essential to characterise its flavour structure.

Scenario 2

New Physics is found during run 2 in flavour sector.

→ follow-up measurements essential.

Scenario 3

No clear signal of New Physics found anywhere

→ continue to benefit from very high mass scales that can be probed in flavour measurements, and focus on observables that are theoretically clean, or have not yet been accessed with meaningful precision.

Possible scenarios in HEP post LHC run 2

Scenario 1

New Physics is found during run 2 in direct searches.

→ precision measurements in b- and c-physics essential
to

Scenario

New

→ fo

Scenario

No clear signal of New Physics found anywhere

→ continue to benefit from very high mass scales that can be probed in flavour measurements, and focus on observables that are theoretically clean, or have not yet been accessed with meaningful precision.

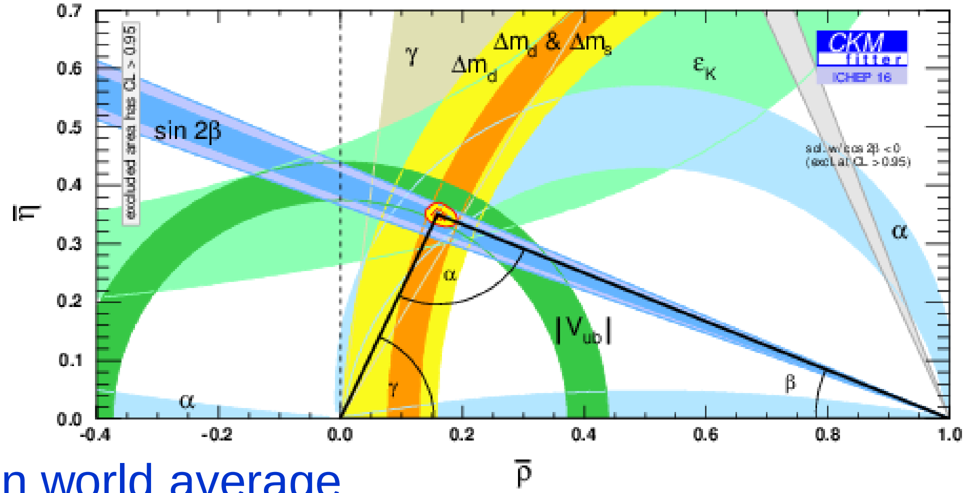
In all cases excellent and widely-accepted arguments for a new generation of flavour-physics experiments.

- Belle-II
- LHCb Phase-II Upgrade

(and not forgetting the role of ATLAS and CMS, particularly after their Phase-II Upgrades).

Where will flavour physics be after run 2 ?

CKM Unitarity Triangle tests



- Angle γ measured to ~3º at LHCb

  No experimental systematics showstopper foreseen; negligible theory uncertainty.

- Improvements on sin2β

  Can expect modest improvement In world average from LHCb run 2; data driven methods can control 'Penguin pollution'. Significant increase in precision requires step-function up in sample size.

- V_{ub}

  Expect further insight from analysis of B_s and Λ_b modes by LHCb.

- Improvements in lattice QCD will help knowledge of V_{ub} & 'mixing side'.

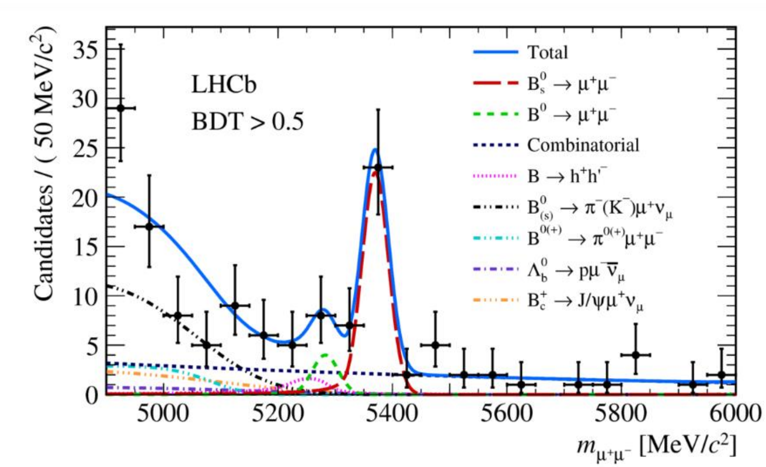
- Important inputs from kaon physics: NA62 ($K^+ \to \pi^+$vvbar) & KOTO ($K_L \to \pi^0$vvbar)

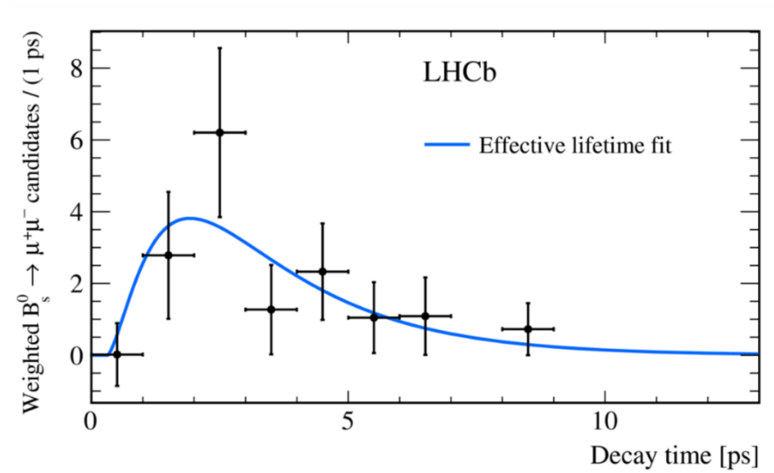
Where will flavour physics be after run 2 ?

B_s and $B_d \to \mu\mu$ – lots to do !

BR($B_s \to \mu\mu$) must be measured as well as possible. A long way to go before hitting current theoretical uncertainty (~6%). Latest LHCb result is 22% precision.

With sufficient candidates, can study new observables, which carry complementary NP sensitivity, *e.g.* effective lifetime [De Bruyne *et al.*, PRL 109 (2012) 041801], Here LHCb has performed a first proof-of-principle measurement:



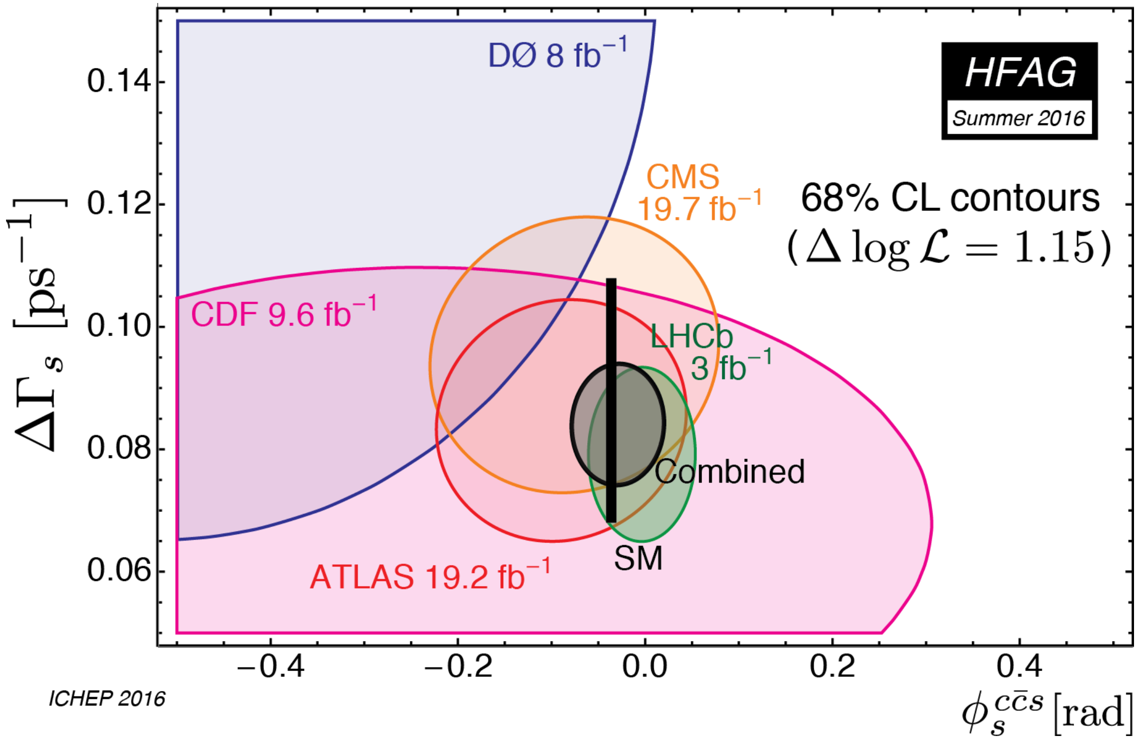


[arXiv:1703.05747]

$B_d \to \mu\mu$ still to be observed. When seen, it will be necessary to measure BR($B_d \to \mu\mu$)/BR($B_s \to \mu\mu$) (=0.03 in SM, with uncertainty of ~10%), which is another powerful discriminant of NP models, *e.g.* test of Minimal Flavour Violation.

Where will flavour physics be after run 2 ?

CPV in B_s mixing-decay interference: φ_s



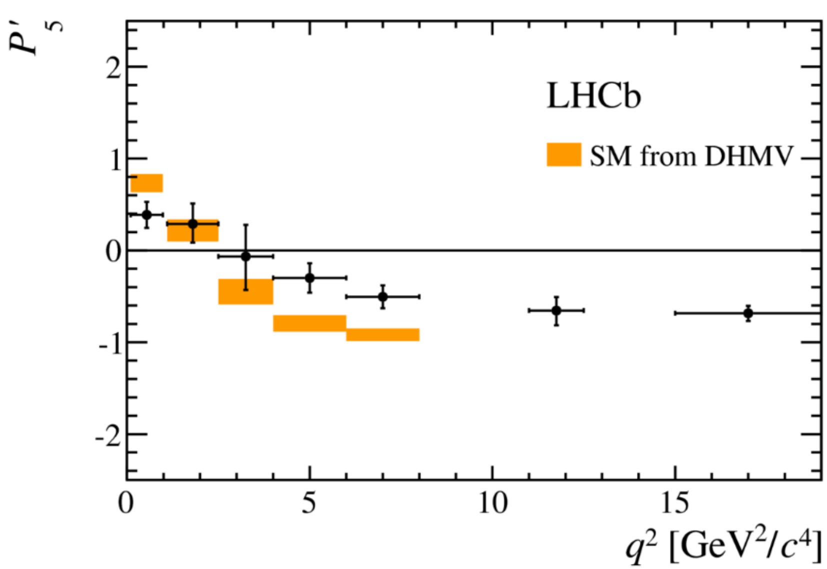
Another theoretically clean observable, which must be measured as well as possible. LHCb uncertainty will halve in run 2. Will need still higher precision to reach regime of real interest, and to probe for deviations from SM expectation.

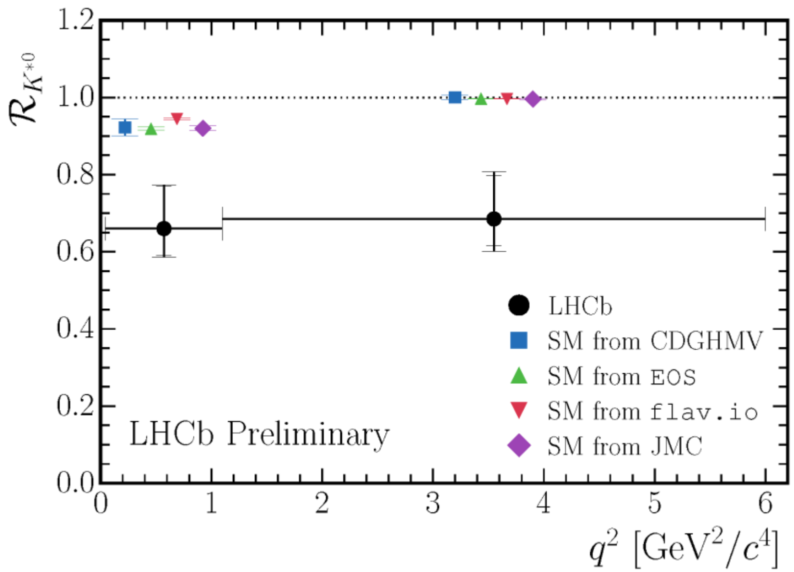
Where will flavour physics be after run 2 ?

$b \to (s,d) l^+ l^-$ observables

With current central values run 2 would probably allow a NP discovery in R_K, R_{K^*}.

For observables such as P_5' the goal would be to measure it in related modes, also with electrons, and to start to probe $b \to dl+l-$ transitions with good precision.





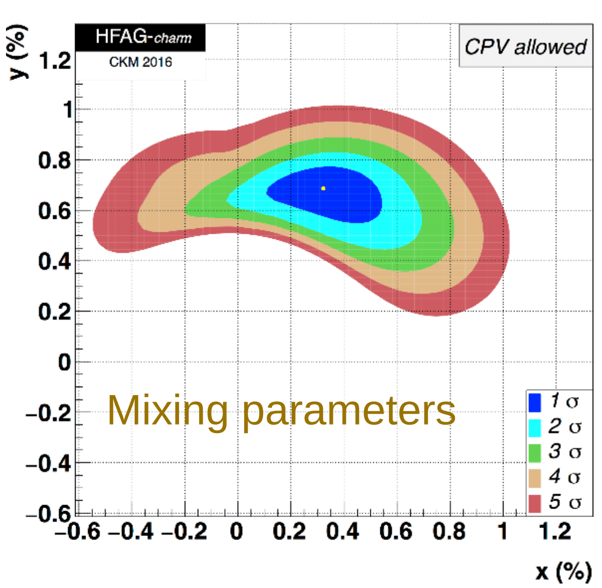
Precise measurements in as many observables as possible, to build up global picture to characterise NP, and to provide robustness against theory uncertainties.

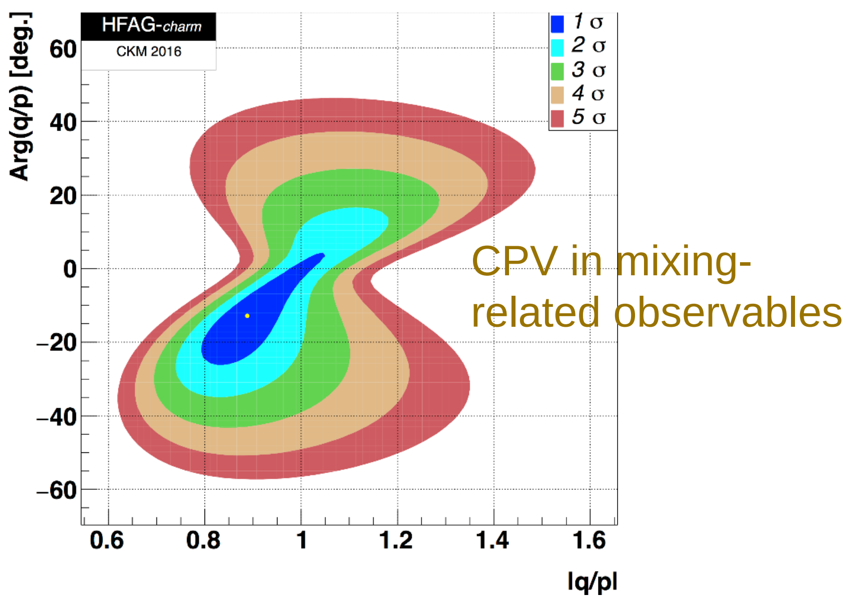
Where will flavour physics be after run 2 ?

CPV in charm

With run 2 samples we should be able to measure x mixing parameter well.

If we are lucky, some of hints for direct CPV may crystalise into something more solid – certainly we will be entering the regime where effects should show. When this happens we must begin a comprehensive measurement campaign.



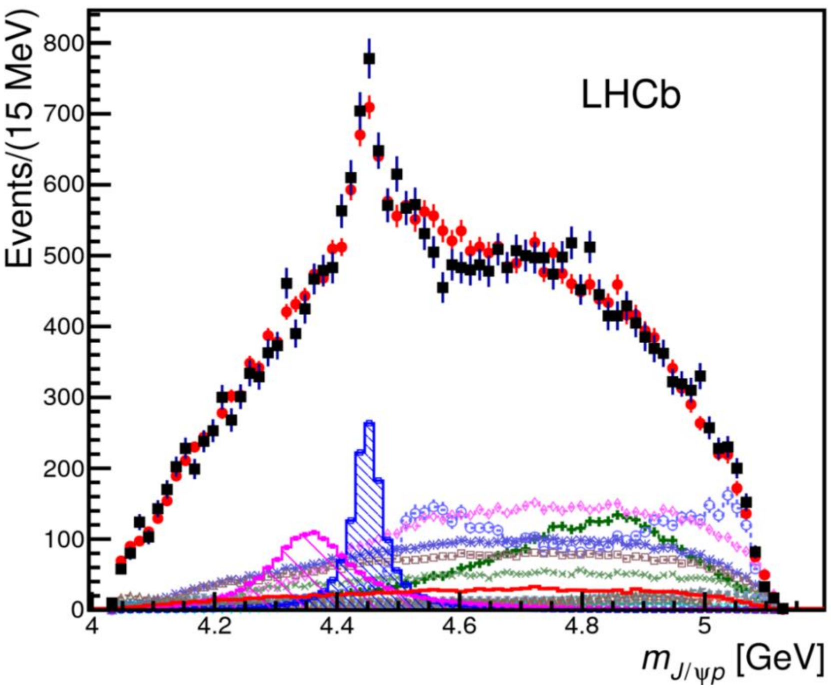


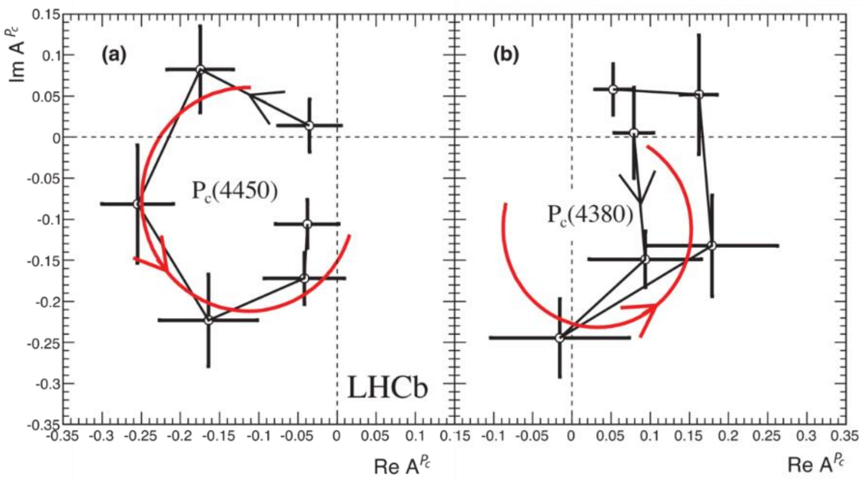
Unlikely that run 2 will yield an observation of indirect CPV. More stats needed !

Where will flavour physics be after run 2 ?

Exotic hadron spectroscopy

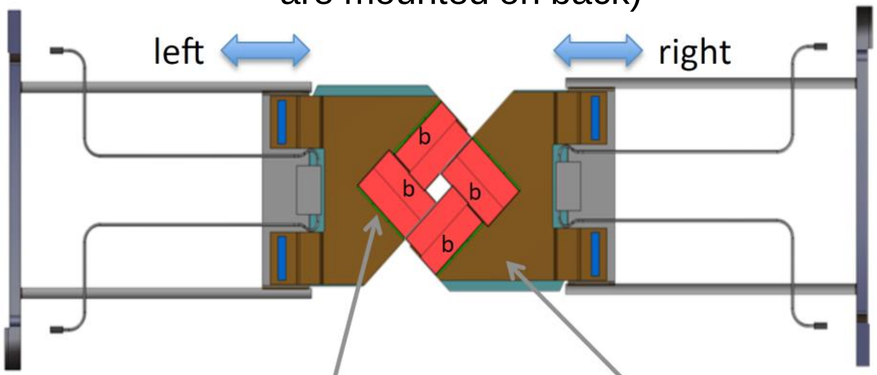
Run 2 data will allow more precise studies of existing signals and is Likely to throw up new surprises. However, lesson of run 1 is that amplitude analyses are required – not just a bump-hunting exercise – so large samples are mandatory.



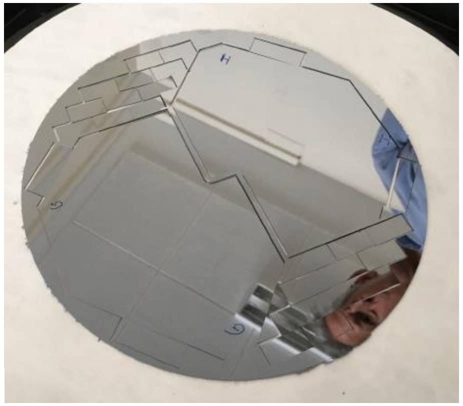


The LHCb VELO Upgrade

(Sensors marked ‘b’
are mounted on back)



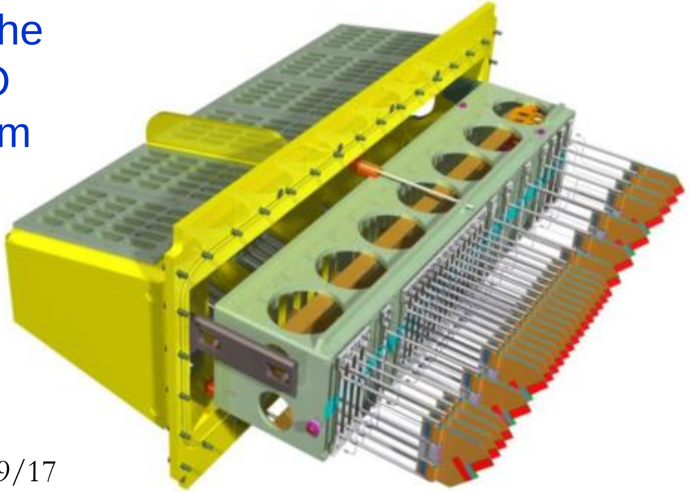
Wafer with two bonded microchannel substrates



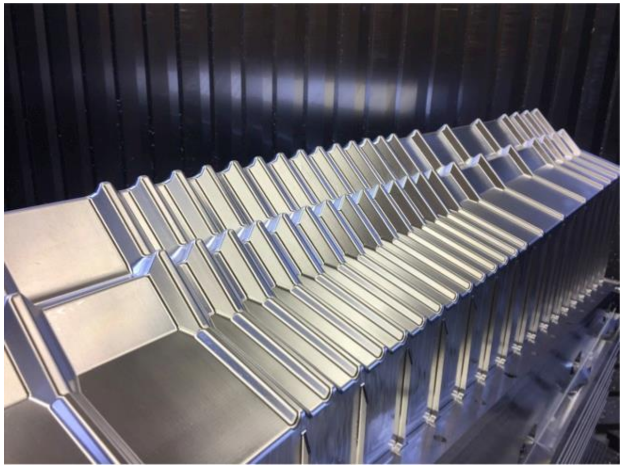
Four pixel sensors per module, Bump-bonded to dedicated ‘VeloPix’ ASIC

Cooling provided by silicon substrate, etched with internal microchannels (baseline plan) to provide $C0_2$ cooling

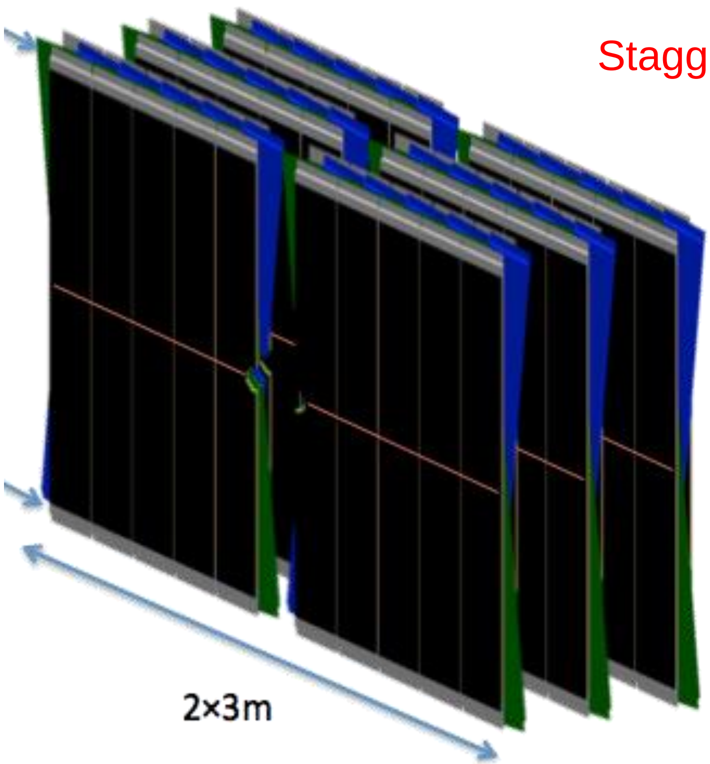
Half the VELO system



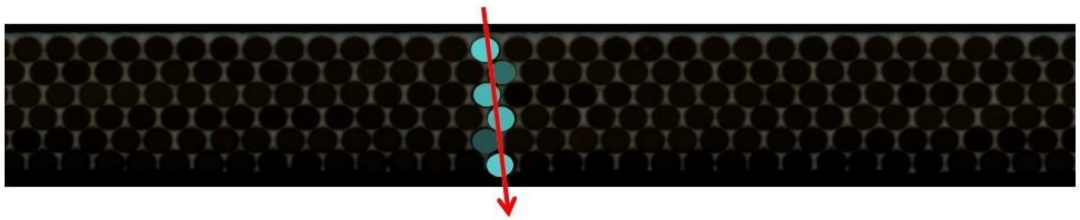
Prototype full scale RF-foil box



The LHCb SciFi project

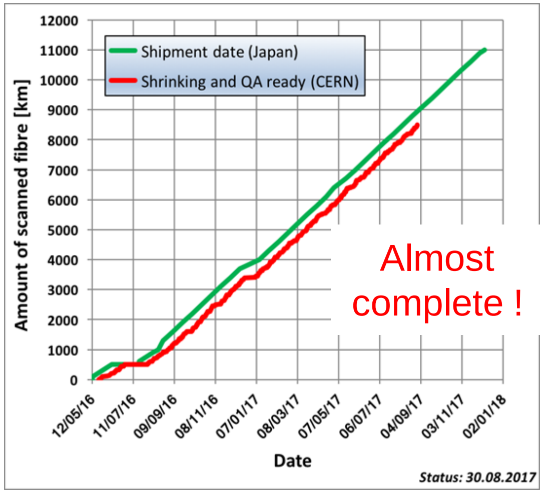


Staggered layers of 250 μm fibres, read out by SiPM array



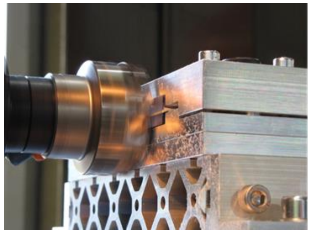
Cross-section through mat

Fibre supplier is now in steady-state delivery mode: 300 km / 2 weeks.

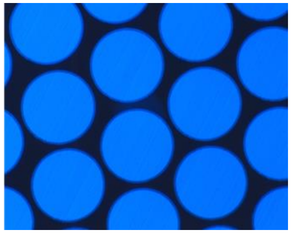


Almost complete !

First batch of completed modules arriving at IP8

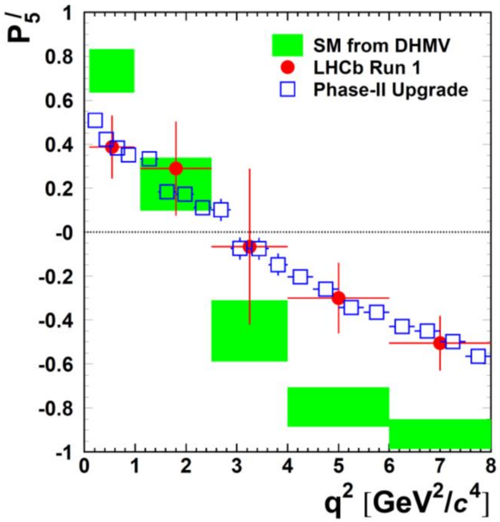


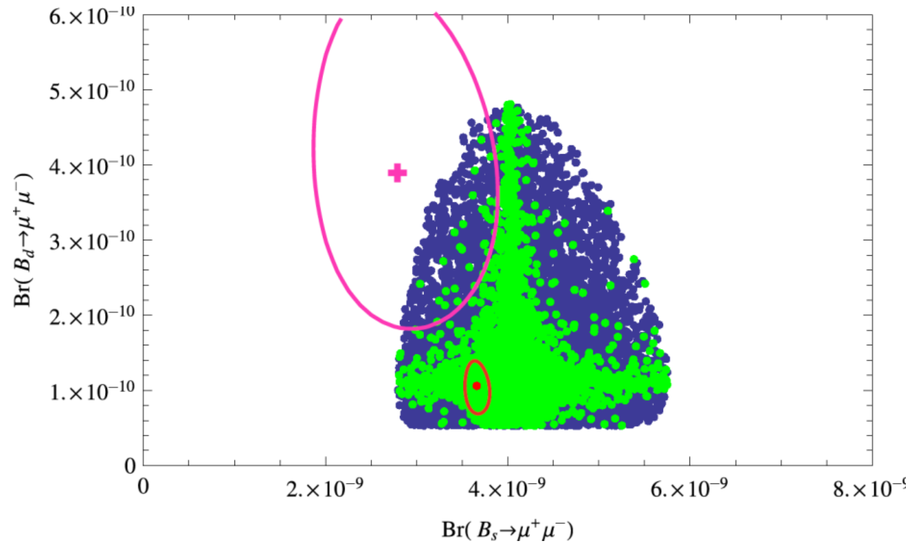
Milling of mat endpiece

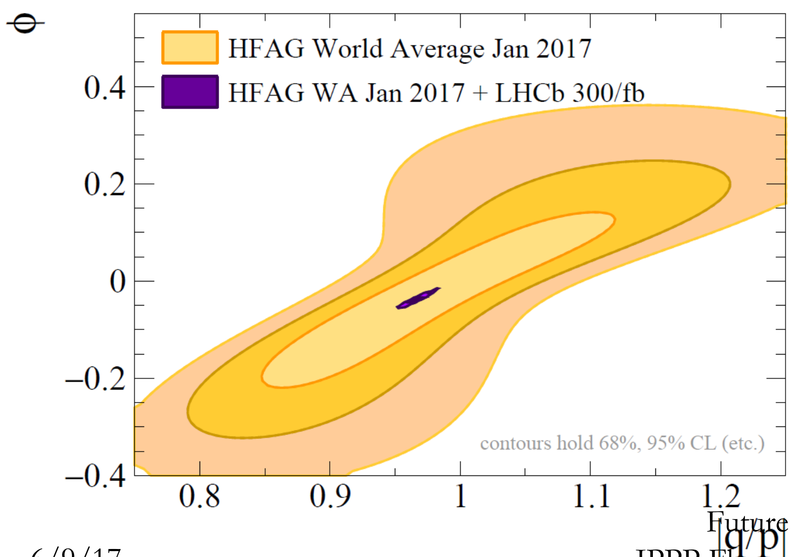


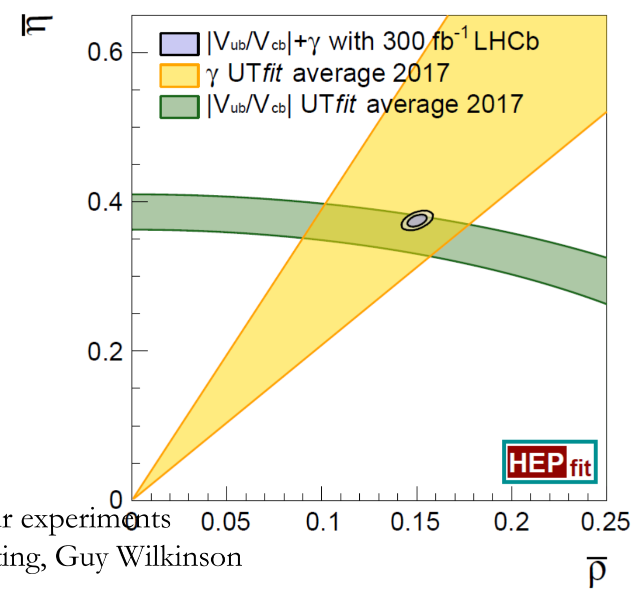
Fibres after machining

Physics goals and potential









Machine considerations

	β^* [m]	Maximum $\mathcal{L}$ [$\times 10^{34}$ cm^{-2}s^{-1}] −	Maximum $\mathcal{L}$ +	Target levelling $\mathcal{L}$ [$\times 10^{34}$ cm^{-2}s^{-1}]	Fill length [h] −	Fill length [h] +	Levelling time [h] −	Levelling time [h] +	$\int \mathcal{L}\, dt$ [fb^{-1}/yr] −	$\int \mathcal{L}\, dt$ [fb^{-1}/yr] +	
	3	1.04	0.78	0.20	8.1	8.1	8.1	8.1	10	10	Phase-I (best case)
Can be done	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	No levelling
Will be very tough	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	No levelling

- Lots of work from our machine friends, but all results still preliminary.
- In particular, further work needed to understand beam-beam effects and what it means for both us and ATLAS/CMS.
- Need to reduce β*. Value of 2 m achievable; value between 1 m & 2 m hopefully possible, but needs more studies, in particular feasibility of vertical x-ing angle.

Machine considerations

β^* [m]	Maximum $\mathcal{L}$ [$\times10^{34}\,\mathrm{cm^{-2}s^{-1}}$] −	Maximum $\mathcal{L}$ +	Target levelling $\mathcal{L}$ [$\times10^{34}\,\mathrm{cm^{-2}s^{-1}}$]	Fill length [h] −	Fill length [h] +	Levelling time [h] −	Levelling time [h] +	$\int\mathcal{L}\,dt$ [$\mathrm{fb^{-1}/yr}$] −	$\int\mathcal{L}\,dt$ +	
3	1.04	0.78	0.20	8.1	8.1	8.1	8.1	10	10	Phase-I (best case)
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	No levelling
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	No levelling

Can be done (β^* = 2 rows)

Will be very tough (β^* = 1 rows)

- Increase in annual yield of 4-8 w.r.t. Phase I, depending on final value of β* and consequence of beam-beam effects.
- Will no longer be possible to level throughout fill
- At highest luminosity the performance will differ between polarities.
- Additional shielding needed to protect triplets & other machine elements.

Machine considerations

β^*	Maximum $\mathcal{L}$	Target levelling $\mathcal{L}$	Fill length	Levelling time	$\int \mathcal{L}\, dt$	
[m					/yr]	
					+	
3					10	Phase-I (best case)
2					31	
2					31	No levelling
1					42	
1					48	
1					48	No levelling

Can be done

Will be very tough

Current limit on maximum integrated luminosity of 300 fb^{-1}

- Set by lifetime of inner triplets
- Assumes improved shielding
- Achievable within a couple of LHC runs (*i.e.* within lifetime of HL-LHC)

Maybe this number can be extended, after post-mortem results available from current IP1/5 triplets, which will be extracted for replacement during LS3, but this is speculation.

- In… va…
- W…
- At highest luminosity the performance will differ between polarities.
- Additional shielding needed to protect triplets & other machine elements.

Detector challenges

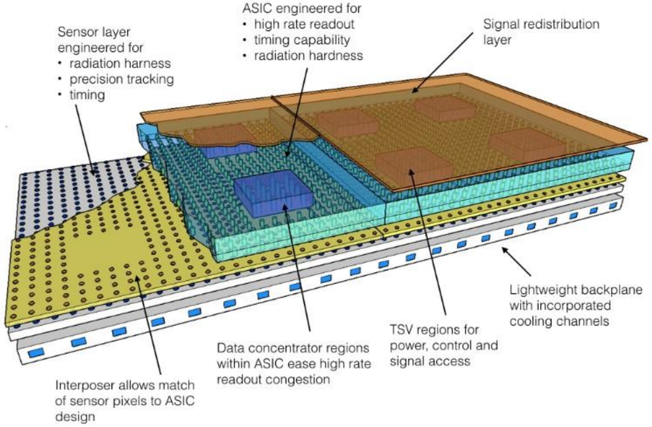
Candidate solutions proposed for each sub-system. All of these need to be further developed, but the intention is to show that there are no immediate show-stoppers.

VELO

Halve pixel dimensions
Halve sensor thickness
→ ~ recover current performance

Fast-timing necessary – Timepix4 may already have many of the features necessary for ASIC.

Reduction / removal of RF foil v. interesting.

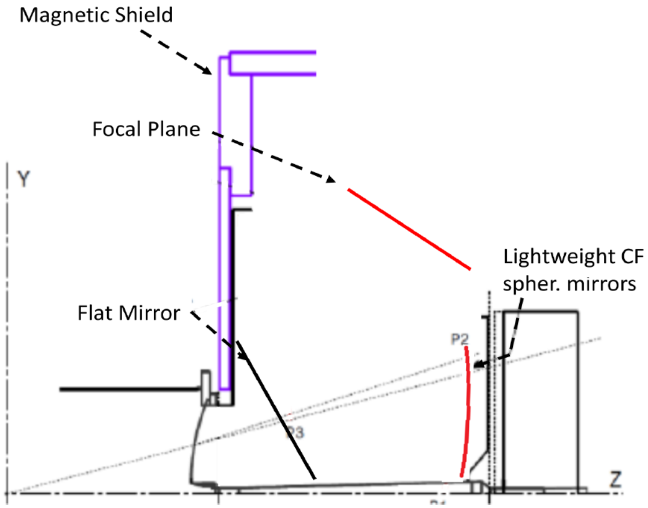


RICH

Go to photodetectors with ~1/5 pixel area

Change optics

Improve response in visible (*e.g.* SiPMs)

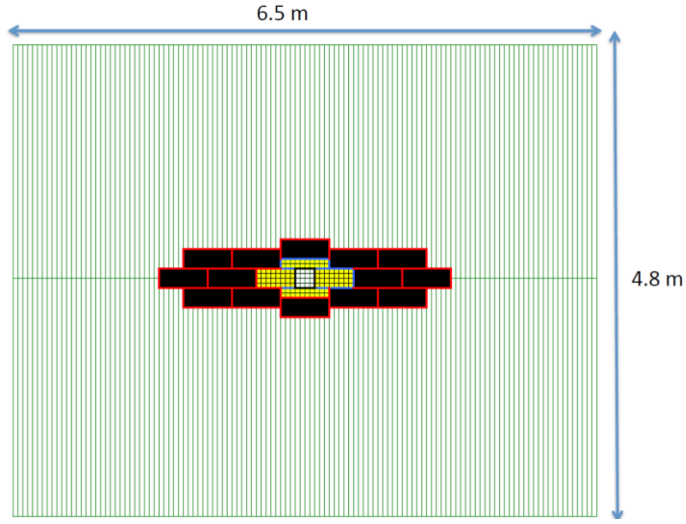


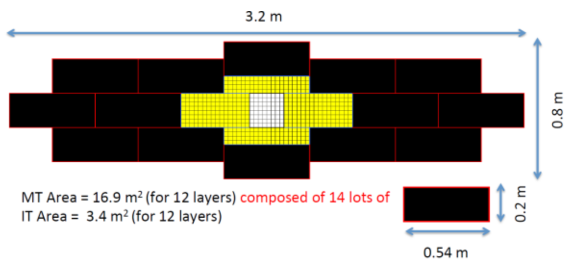
Detector challenges

Candidate solutions proposed for each sub-system. All of these need to be further developed, but the intention is to show that there are no immediate show-stoppers.

Tracker

Hybrid solution with fibres in outer region and silicon in inner / middle regions.





Muon system

Replace HCAL with iron slabs to halve rate in chambers.

New high-rate chambers in hottest regions.

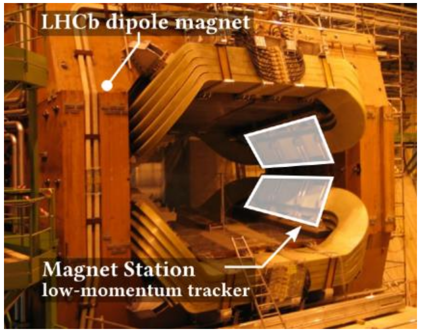
Detector *improvements*

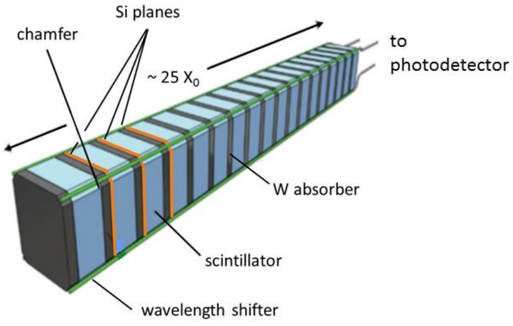
Possible to conceive of detector enhancements which will bring additional physics reach on top of what will come from the increase in integrated luminosity.

- Increased tracking acceptance

  Magnet stations

  Approach closer to beam pipe in downstream tracker





- Improved ECAL

- Improved low-momentum PID (*i.e.* TORCH)

- Thinning / removal of VELO RF foil

- Improved downstream trigger capabilities