Physics opportunities with an upgraded LHCb detector in the HL-LHC era

Sascha Stahl, CERN

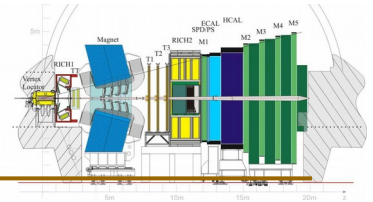
on behalf of the
LHCb collaboration

Les Rencontres de Physique
de la Vallée d'Aoste

11/03/2017

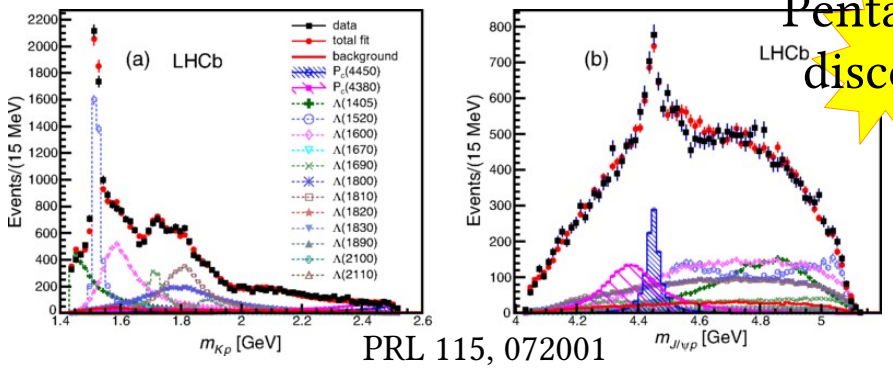
Some slides inspired by the very nice experimental and theoretical flavour physics talks from this week.

LHCb physics goals



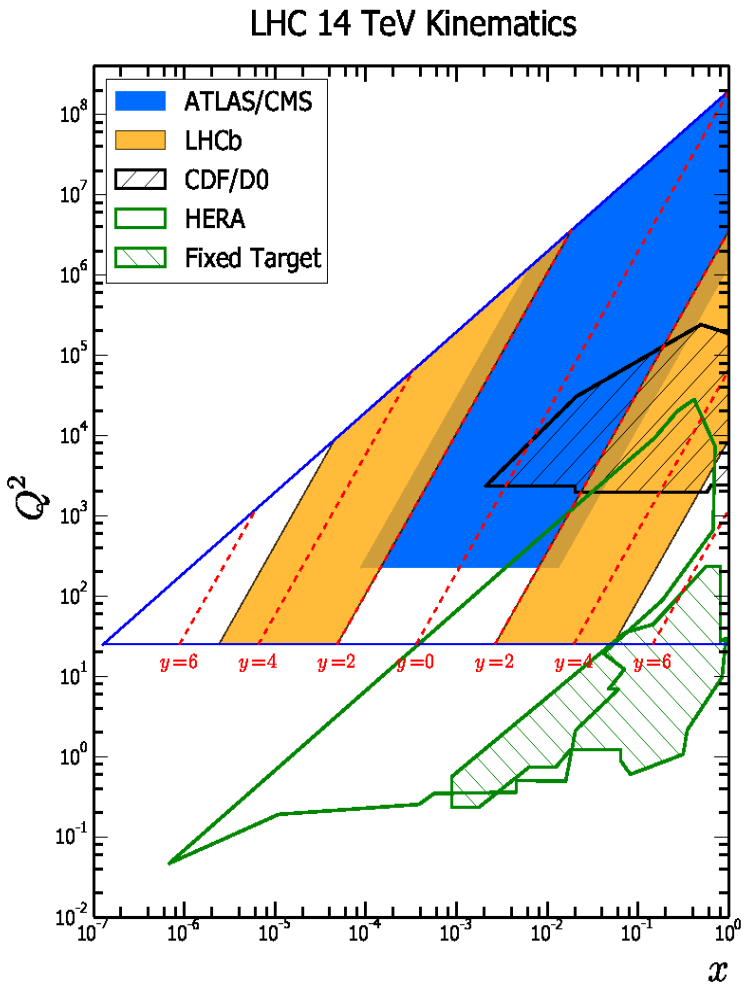
LHCb – General purpose detector in forward direction

- Unique rapidity coverage
- Rich program of:
  - Electroweak physics
  - Production and spectroscopy
  - Heavy Ion and fixed target physics
  - **Heavy Flavour physics**
- Complementary and competitive measurements

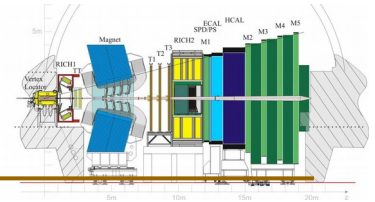


PRL 115, 072001

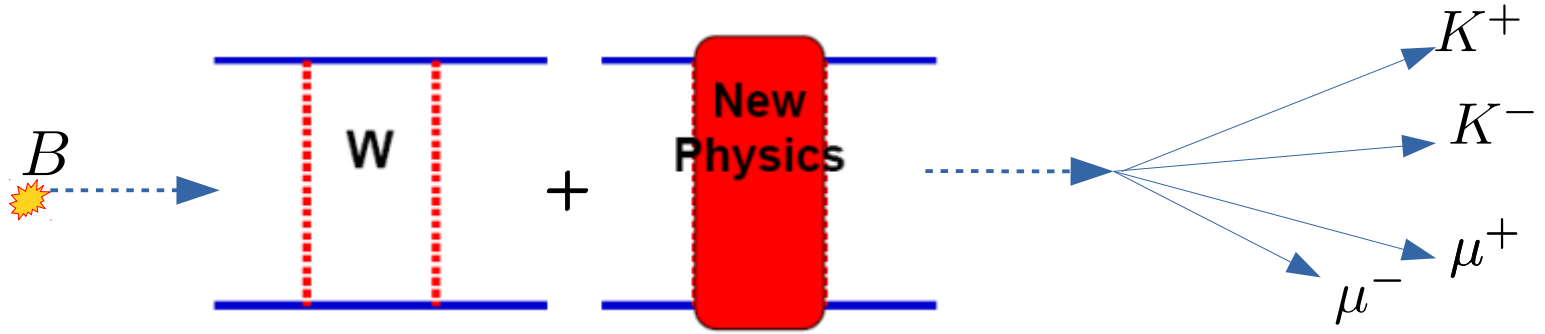
Pentaquark discovery



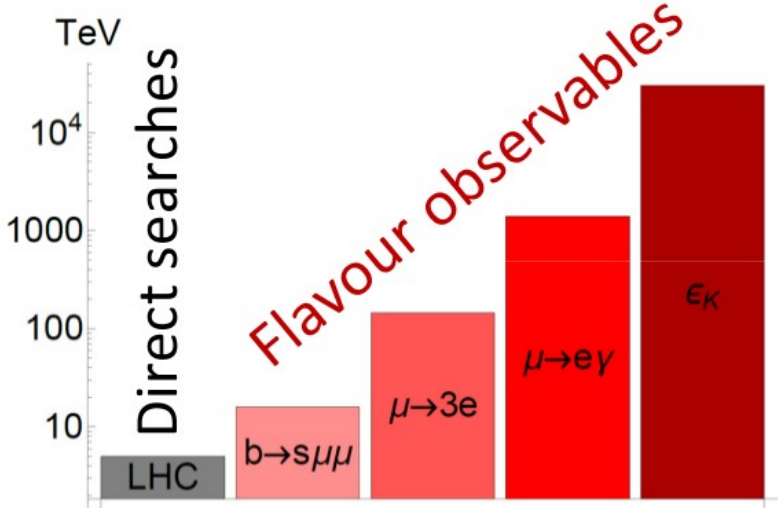
LHCb physics goals



Heavy Flavour Physics:
Study decays of b and c hadrons to look for anomalous effects beyond the Standard Model

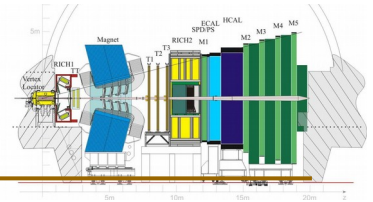


- Indirect observation of unknown particles via quantum corrections
- Complementary to production of on-shell particles at LHC, **O(1 TeV)**
- Probe higher mass scales, **O(10 TeV)**

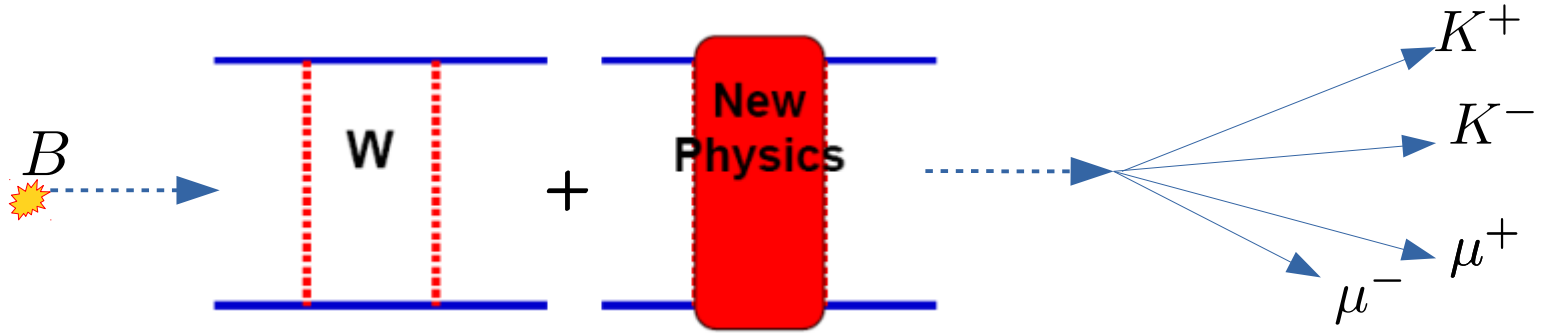


A. Crivellin, La Thuile 2017

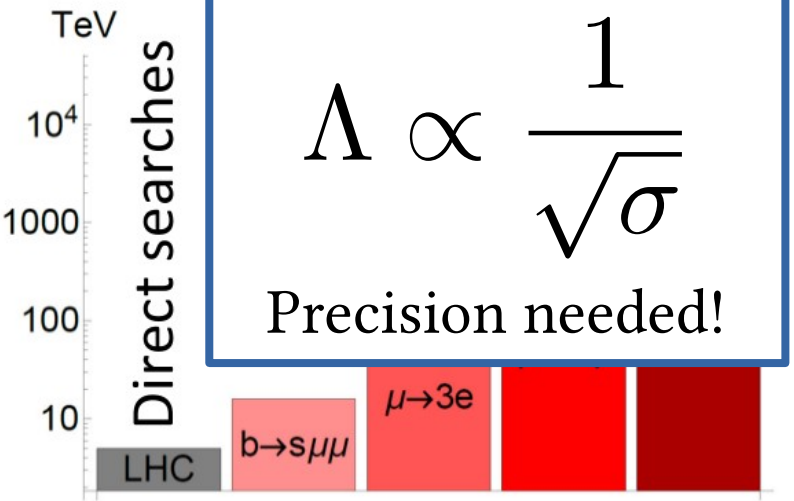
LHCb physics goals



Heavy Flavour Physics:
Study decays of b and c hadrons to look for anomalous effects beyond the Standard Model

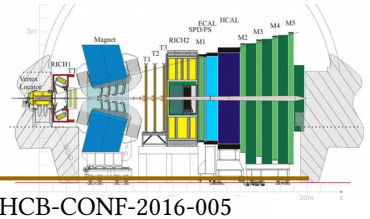


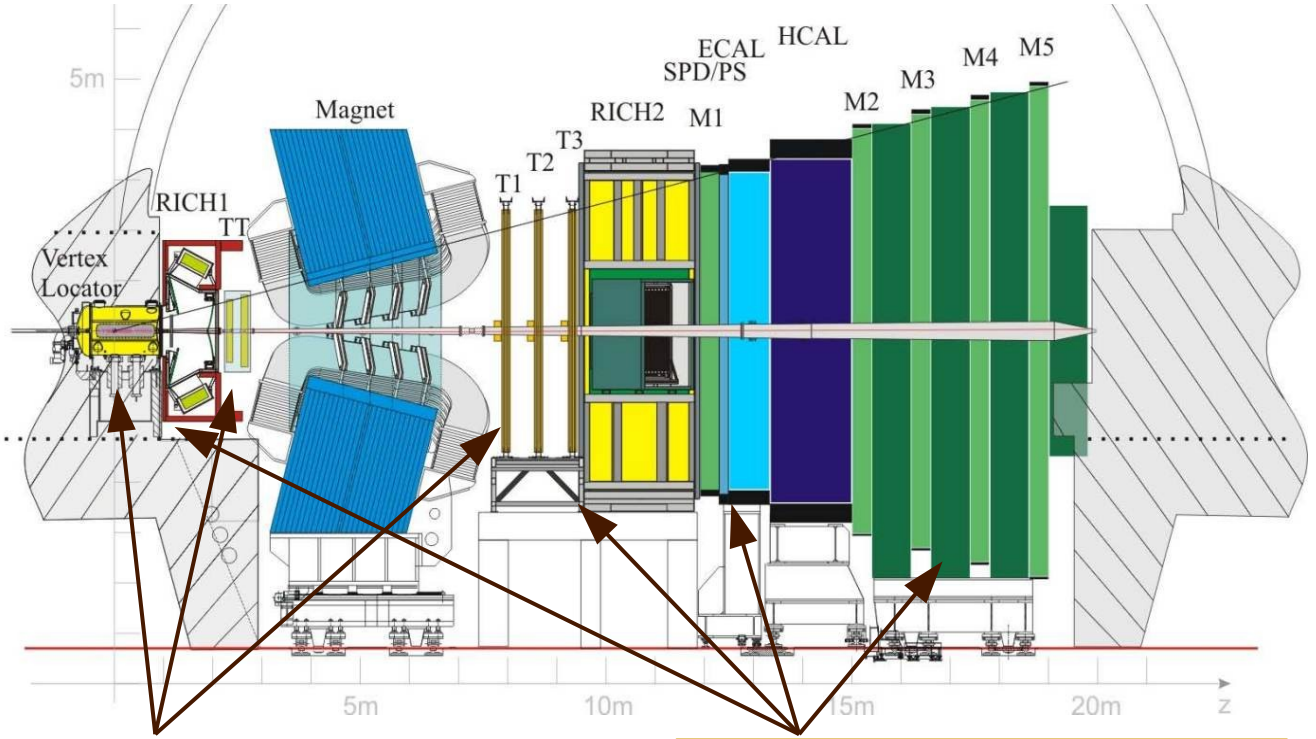
- Indirect observation of unknown particles via quantum corrections
- Complementary to production of on-shell particles at LHC, **O(1 TeV)**
- Probe higher mass scales, **O(10 TeV)**



A. Crivellin, La Thuile 2017

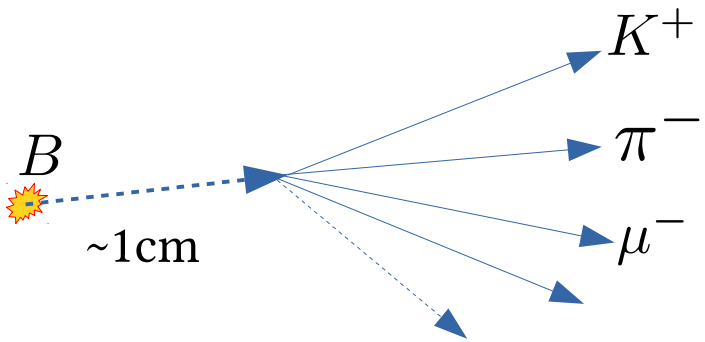
The LHCb experiment

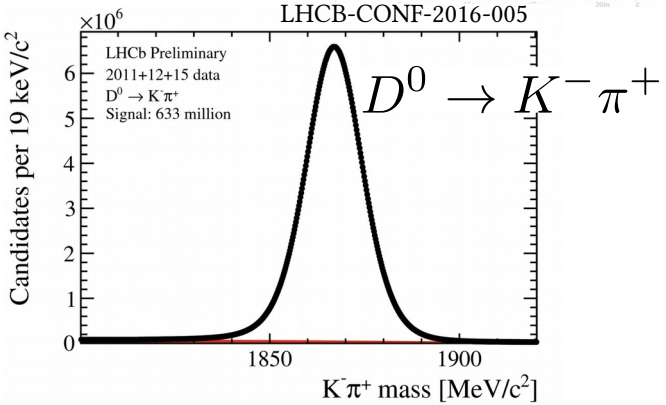


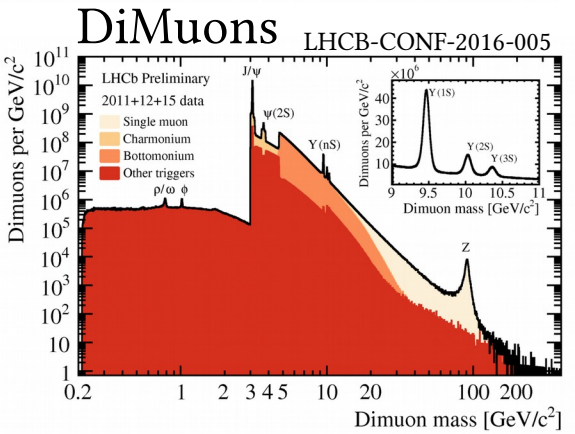


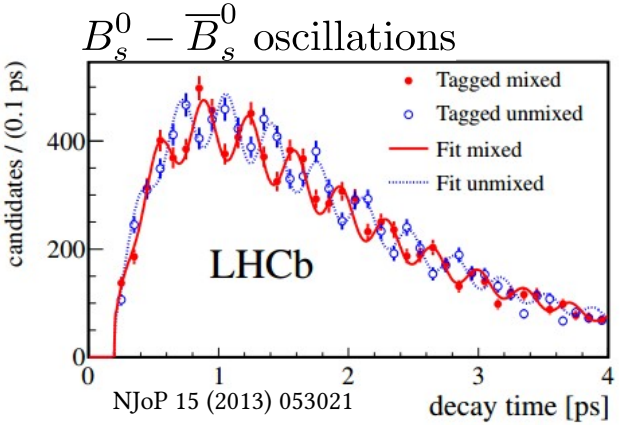
Vertex and track finding

Particle identification

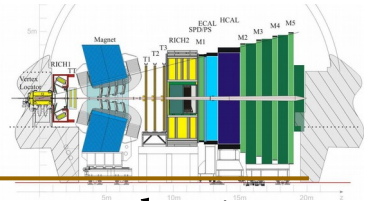






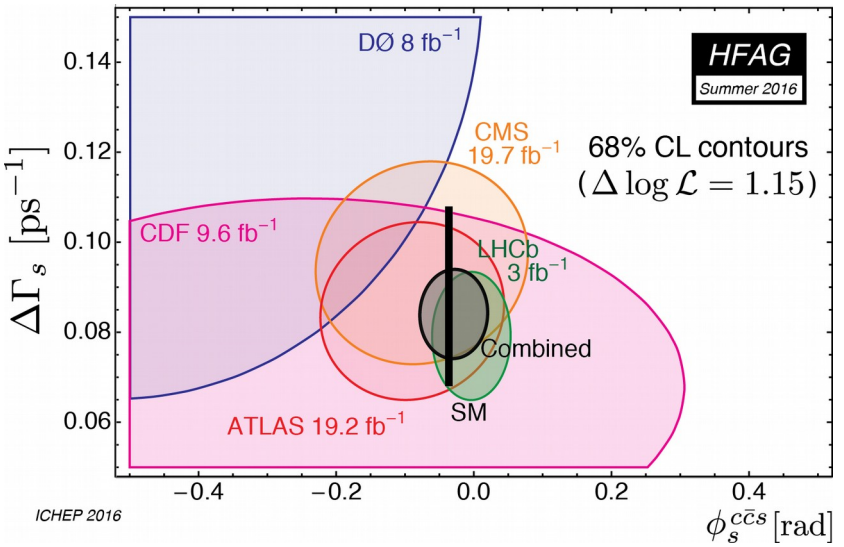


Lessons* from LHC Run 1



*very selective

- Some observables spot on with SM
  - E.g. high precision measurement of mixing phase in B_s oscillations

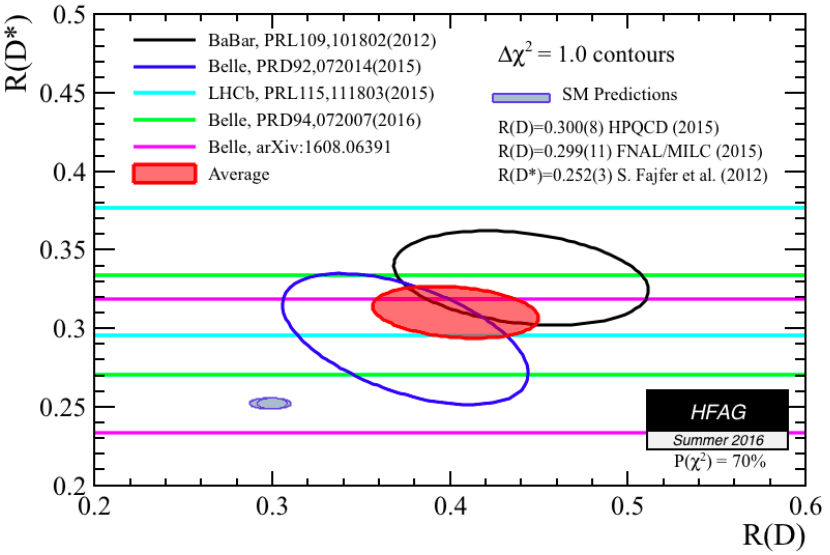


- Some first cracks in the SM?
  - Does lepton universality hold?

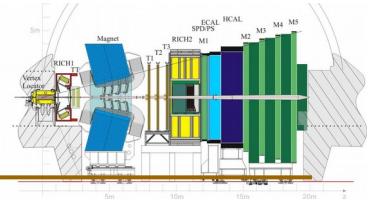
$$R(D^{*+}) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

(PRL 113, 151601)



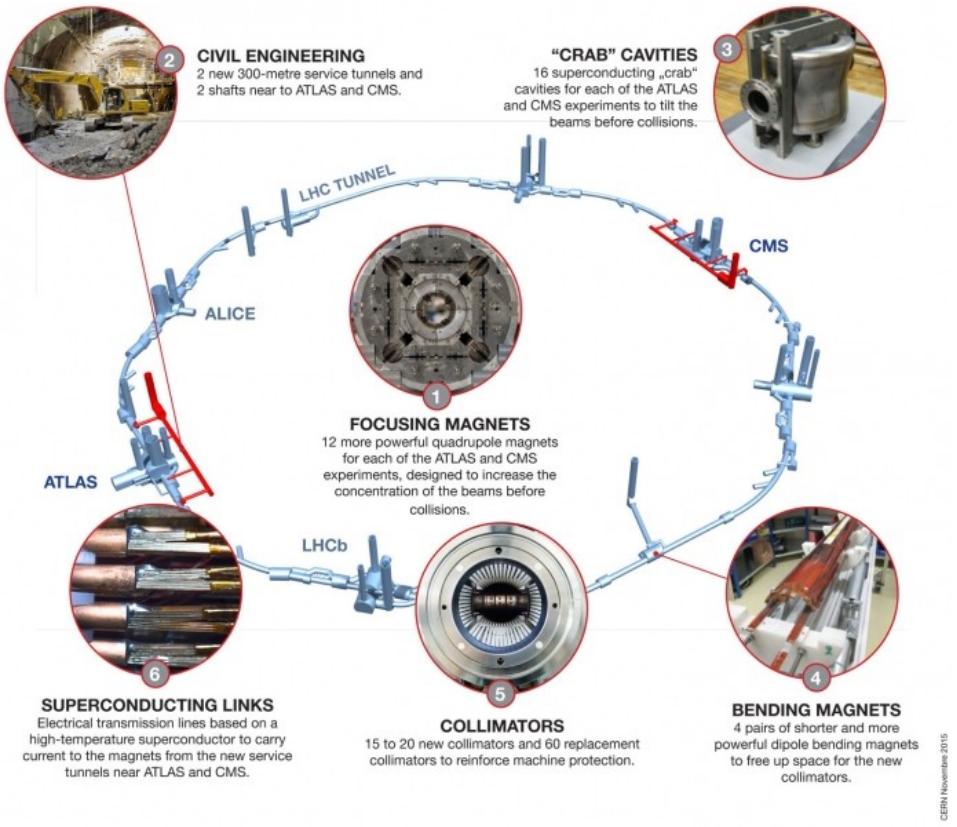
High Lumi LHC



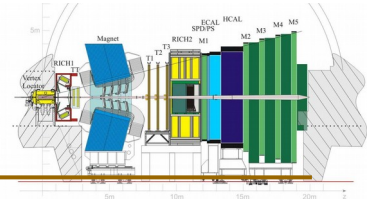
"**Europe's top priority** should be the exploitation of the full potential of the LHC, **including the high-luminosity upgrade** of the machine and detectors with a view to collecting **ten times more data** than in the initial design, by around 2030. This upgrade programme will also provide further **exciting opportunities for the study of flavour physics** and the quark-gluon plasma.

European Strategy for Particle Physics 2013

Highlights by me.

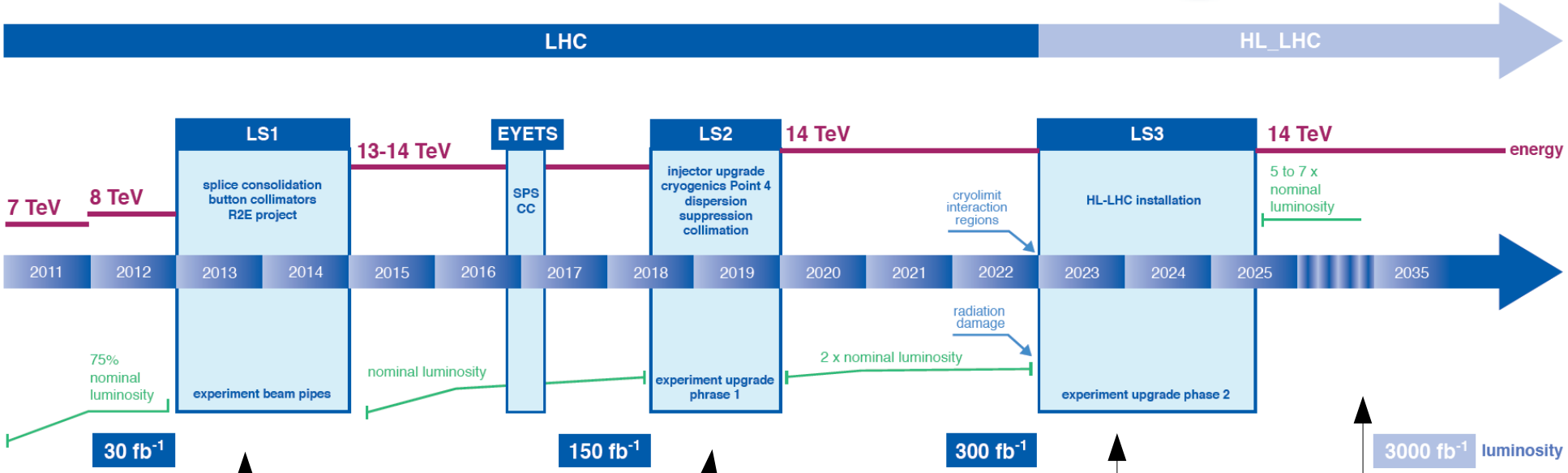


HL-LHC and LHCb timeline



LHC / HL-LHC Plan

High Luminosity LHC



LHCb:

Detector maintenance, Trigger upgrade

2019

LHCb Upgrade
- New tracking system
- Improved particle identification
- Triggerless readout

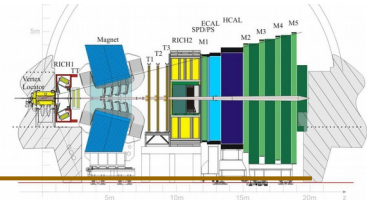
2023

LHCb Phase 2 Upgrade preparations?

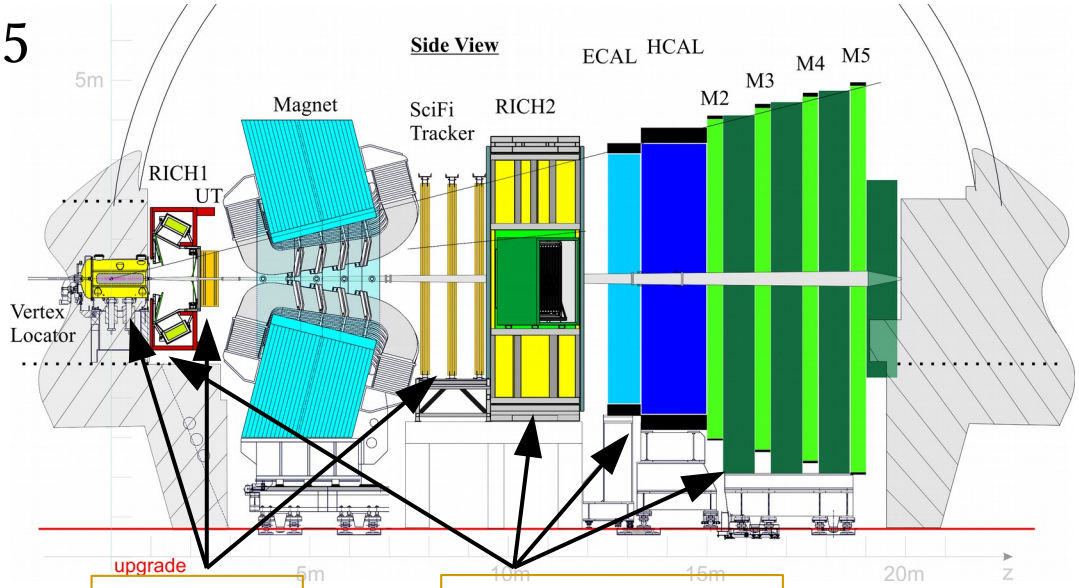
2030

LHCb Phase 2 Upgrade?

Interlude: LHCb Phase 1 Upgrade



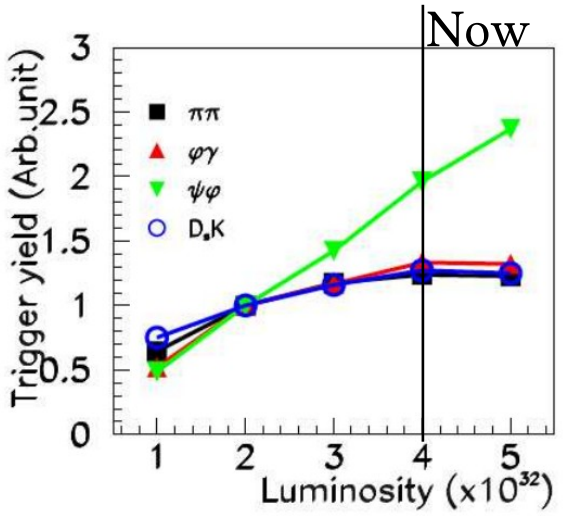
- Luminosity increases by factor 5
- New and improved detectors
- Trigger-less readout
  - Versatile and more efficient software trigger
  - Real-time calibration and alignment of detector
  - Real-time analysis to increase physics rate
- Project well on track
  - Real-time analysis approach demonstrated in Run 2
  - Installation in LS2 in 2019
  - Start taking data after LS2



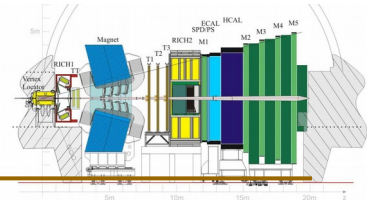
New

Improved

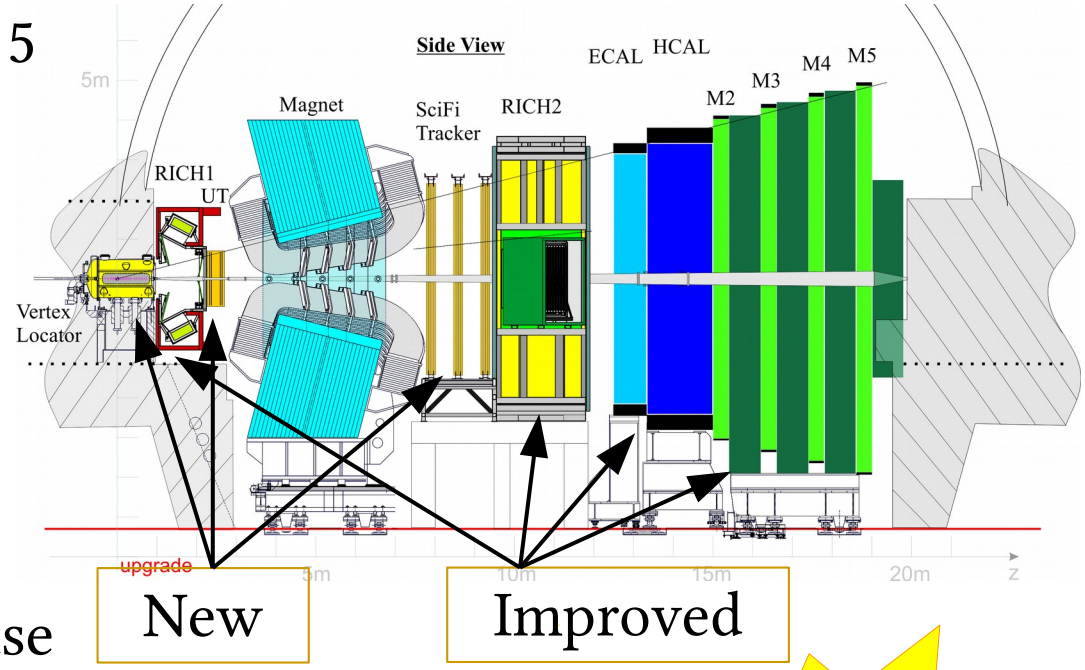
With current hardware trigger

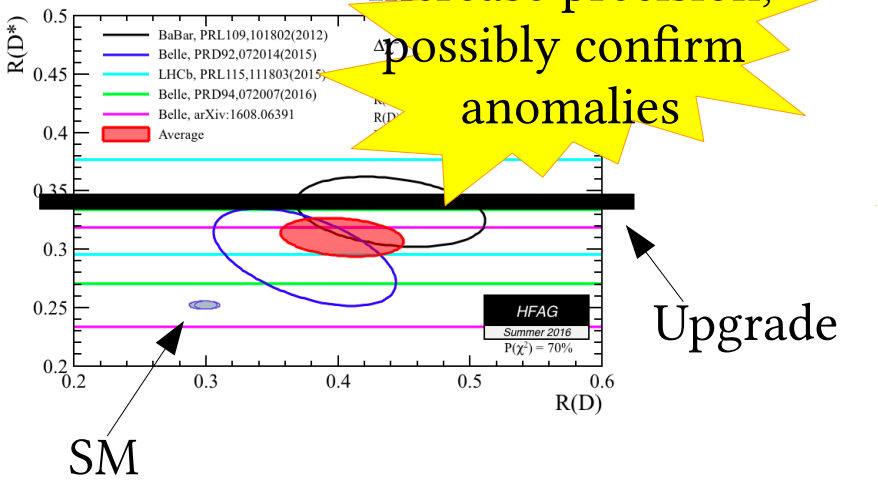


Interlude: LHCb Phase 1 Upgrade

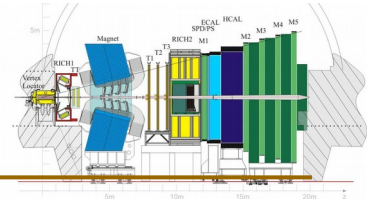


- Luminosity increases by factor 5
- New and improved detectors
- Trigger-less readout
  - Versatile and more efficient software trigger
  - Real-time calibration and alignment of detector
  - Real-time analysis to increase physics rate
- Project well on track
  - Real-time analysis approach demonstrated in Run 2
  - Installation in LS2 in 2019
  - Start taking data after LS2





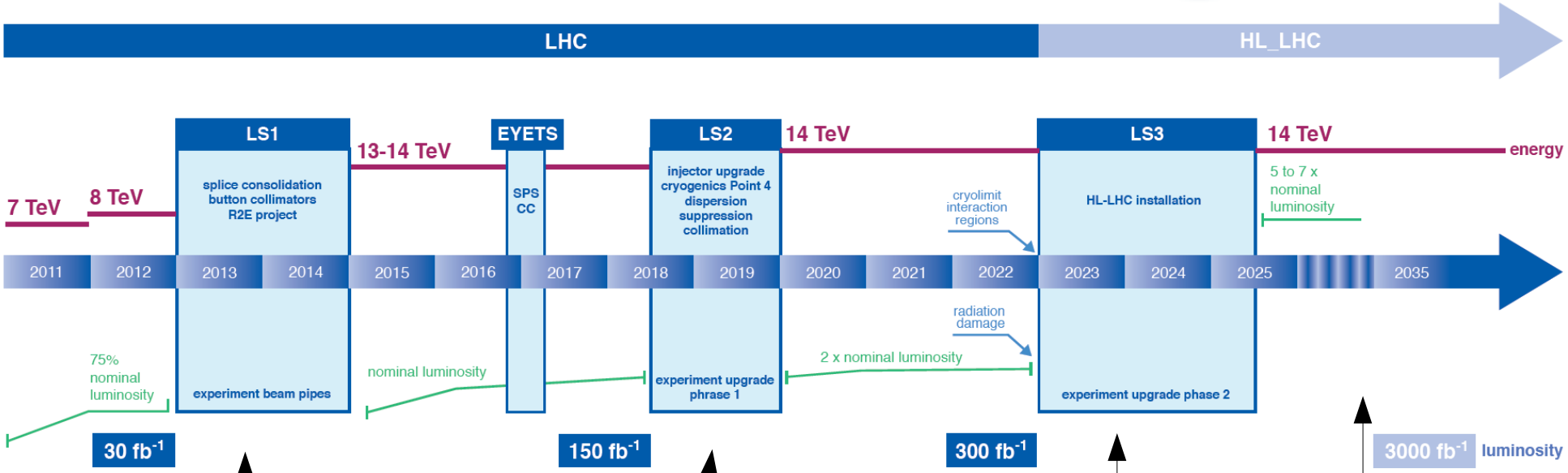
HL-LHC and LHCb timeline



Reference

LHC / HL-LHC Plan

High Luminosity LHC



LHCb:

Detector maintenance, Trigger upgrade

2019

LHCb Upgrade
- New tracking system
- Improved particle identification
- Triggerless readout

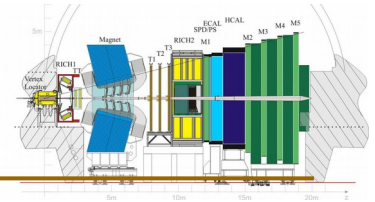
2023

LHCb Phase 2 Upgrade preparations?

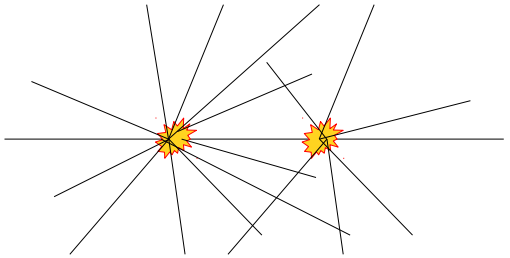
2030

LHCb Phase 2 Upgrade?

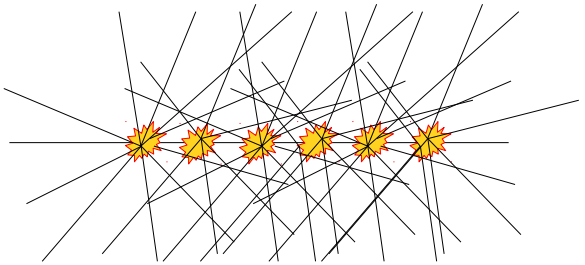
Luminosity goals



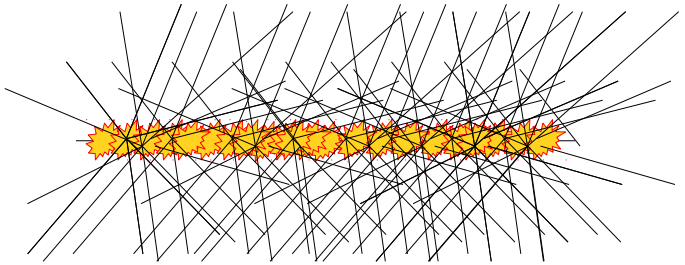
Current



Phase 1 Upgrade



Phase 2 Upgrade

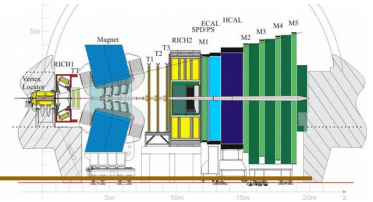


	LHC Run	Period of data taking	Maximum $\mathcal{L}$ [$\mathrm{cm^{-2}s^{-1}}$]	Cumulative $\int \mathcal{L}\,dt$ [$\mathrm{fb^{-1}}$]
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	8
Phase-I Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50
Phase-II Upgrade	5 →	2031–2033, 2035 →	2×10^{34}	300

(Limited by LHC considerations)

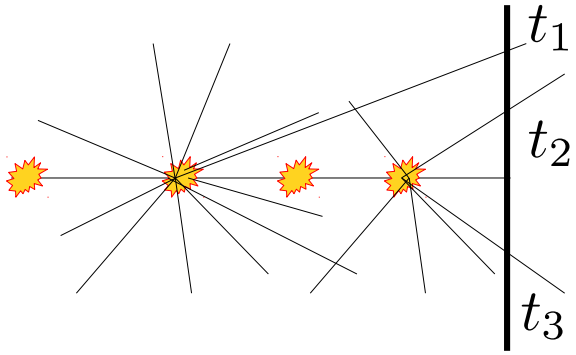
How do we adapt detector layout to profit from higher luminosity and extend the physics reach of LHCb?

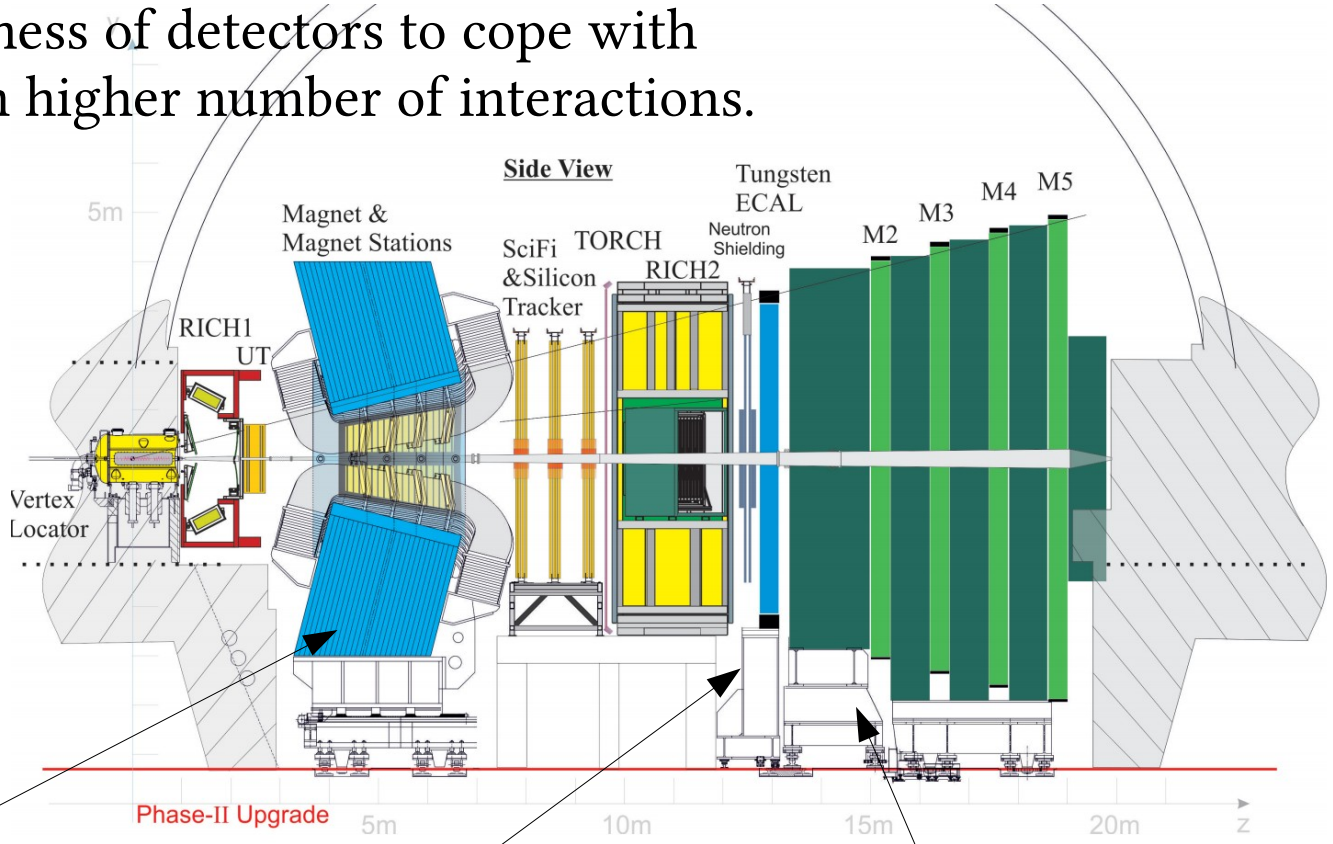
Phase 2 upgrade in a nutshell



1. Improve granularity and radiation hardness of detectors to cope with much higher number of interactions.

2. Add timing information to detectors to associate signals to a collision.



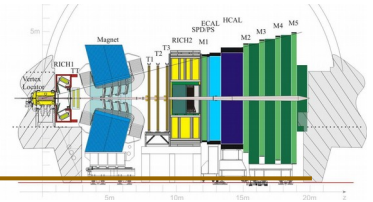


3. Improve low momentum tracking.

4. Highly improved electromagnetic calorimeter.

5. Better shielding for muons.

Physics opportunities of Phase 2

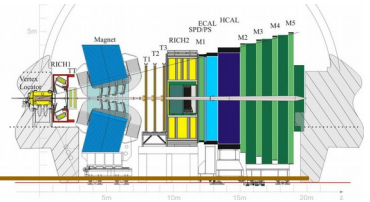


Continue testing all corners of the flavour sector.
Many theoretically clean observables stay statistically limited.
Measure new observables with high precision.

Rare processes and lepton-universality tests
Precision tests of CKM paradigm
Lower pt signatures (charm and strange)
(Exotic hadrons and spectroscopy)
(Forward and high-pt physics)
(Ion and fixed target physics)

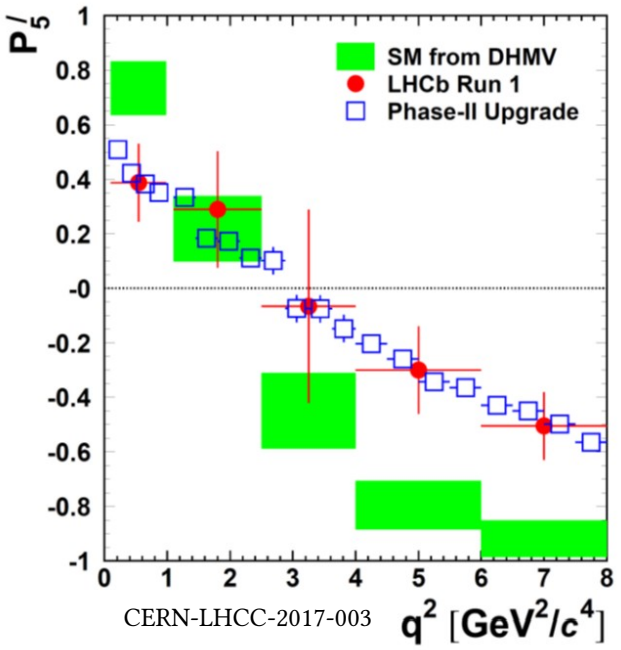
Not a full list discussed here, see CERN-LHCC-2017-003

Rare processes and LFU



- Continue mapping observables in $b \to s l^+ l^-$ and $b \to d l^+ l^-$ transitions
  - Data driven methods to reduce theory uncertainties*
  - Test lepton universality by comparing electron and muon fina$B_s^0 \to \overline{K}^* \mu^+ \mu$
  - Reach competitive precision with suppressed modes like
  - Make time dependent measurements, e.g. in $B_s^0 \to \phi \mu^+ \mu^-, B^0 \to \rho^0 \mu^+ \mu^-$
  - Increased luminosity will enable measurements with baryons

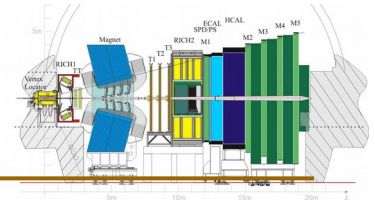
$B^0 \to K^* \mu^+ \mu^-$



*See K. De Bruyn on Thursday

- Accompany with measurements of radiative decays $b \to s\gamma$
- Improved **electron** and **photon** reconstruction essential

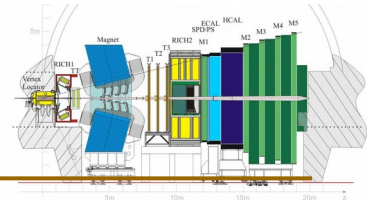
Rare processes and LFU



Opportunity to make comprehensive test by looking at very wide range of observables in different modes and different lepton final states

Observable	Run 1 result		$8\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
Yield $B^0 \to K^{*0}\mu^+\mu^-$	2398 ± 57	63	9175	70480	435393
Yield $B_s^0 \to \phi\mu^+\mu^-$	432 ± 24	64	1653	12697	78436
Yield $B^+ \to K^+\mu^+\mu^-$	4746 ± 81	71	18159	139491	861709
Yield $B^+ \to \pi^+\mu^+\mu^-$	93 ± 12	72	355	2725	16831
Yield $\Lambda_b^0 \to \Lambda\mu^+\mu^-$	373 ± 25	73	1426	10957	67688
Yield $B^+ \to K^+e^+e^-$ $(1 < q^2 < 6\,\text{GeV}^2/c^4)$	254 ± 29	65	972	7465	46118
$\text{d}\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-, 1.0 < q^2 < 6\,\text{GeV}^2/c^4)/\text{d}q^2 [10^{-9}\,\text{GeV}^{-2}c^4]$	$0.91 \pm 0.21 \pm 0.03$	72	0.11	0.04	0.02
$\text{d}\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-, 15 < q^2 < 22\,\text{GeV}^2/c^4)/\text{d}q^2 [10^{-9}\,\text{GeV}^{-2}c^4]$	$0.47 \pm 0.12 \pm 0.01$	72	0.06	0.02	0.01
$A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\text{GeV}^2/c^4)$	$-0.075 \pm 0.034 \pm 0.007$	63	0.017	0.006	0.003
$A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\text{GeV}^2/c^4)$	$0.355 \pm 0.027 \pm 0.009$	63	0.014	0.005	0.002
$S_5(B^0 \to K^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\text{GeV}^2/c^4)$	$-0.023 \pm 0.050 \pm 0.005$	63	0.026	0.009	0.004
$S_5(B^0 \to K^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\text{GeV}^2/c^4)$	$-0.325 \pm 0.037 \pm 0.009$	63	0.019	0.007	0.003
$S_5(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\text{GeV}^2/c^4)$		-	-	0.087	0.035
$S_5(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\text{GeV}^2/c^4)$		-	-	0.064	0.026
$\mathcal{R}_K(1 < q^2 < 6\,\text{GeV}^2/c^4)$	$0.745 \pm 0.090 \pm 0.036$	65	0.046	0.017	0.007

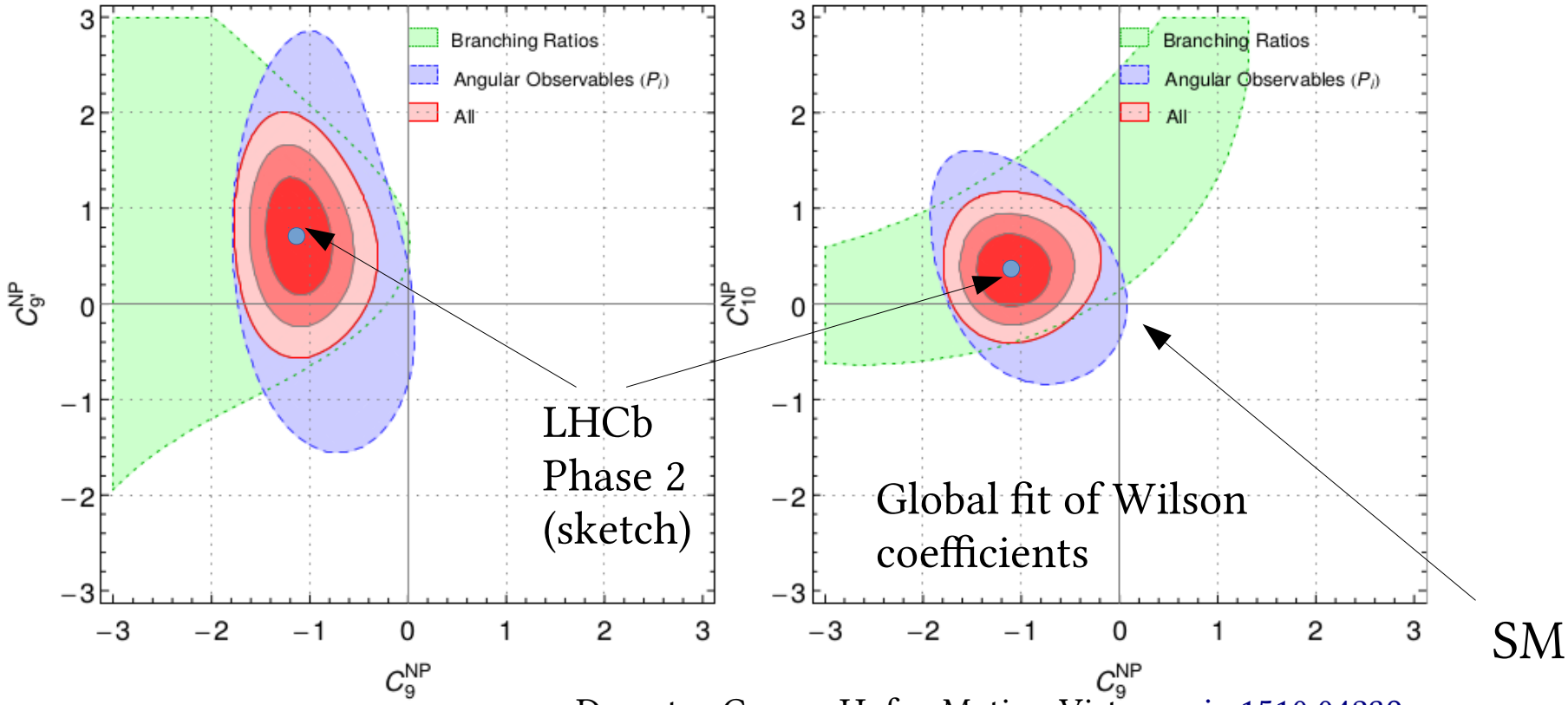
Rare processes and LFU



Opportunity to make comprehensive test by looking at very wide range of observables in different modes and different lepton final states

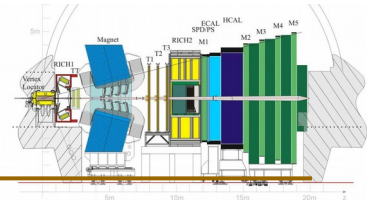
$$\mathcal{H}^{SM}_{\Delta F=1} \propto \sum V^*_{ts} V_{tb} C_i \mathcal{O}_i + \dots$$

From talk by S. Descotes-Genon on Thursday

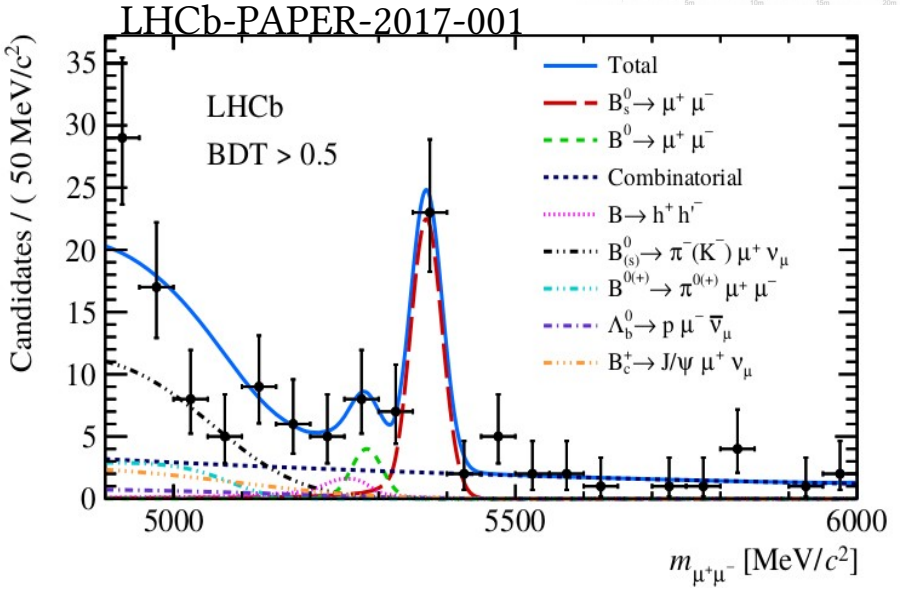


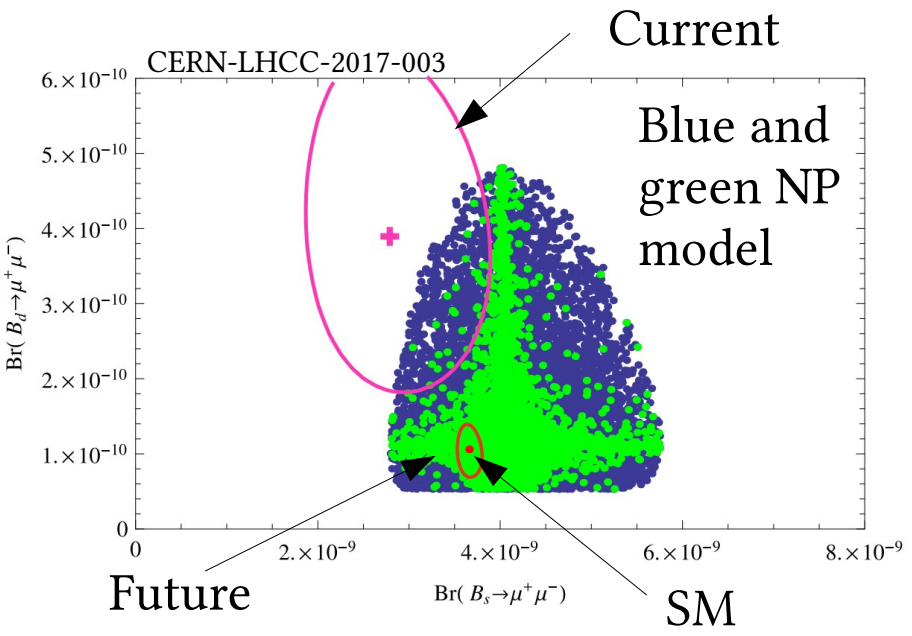
Descotes-Genon, Hofer, Matias, Virto, arxiv:1510.04239

Very rare processes

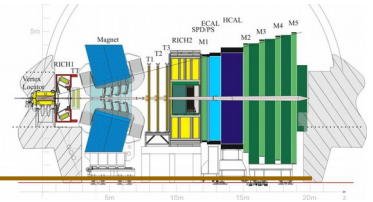


- Measure very rare decays
- E.g. the golden $B^0_{(s)} \to \mu^+\mu^-$
  - New observables like effective lifetime accessible
  - Can reach 10-20% precision on ratio of branching fractions
- Combine with GPD measurements
- Profits from high luminosity and further development of analysis

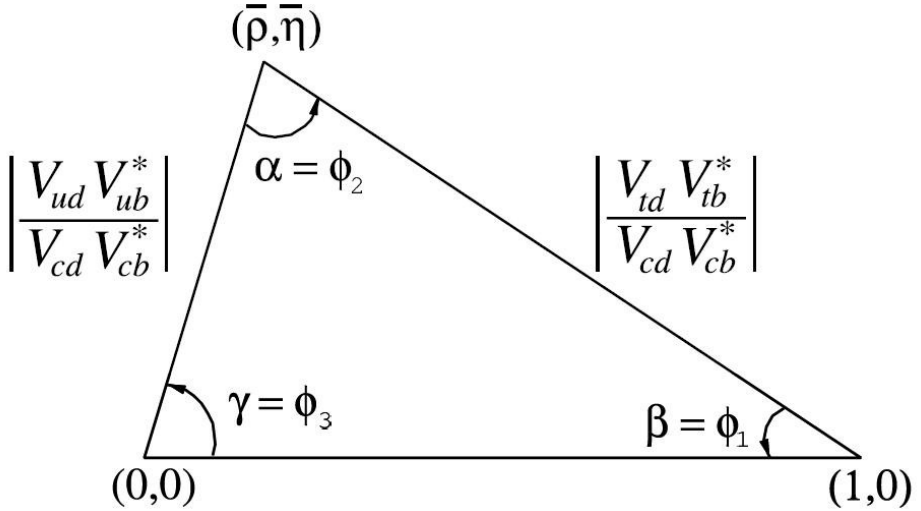




Precision tests of CKM paradigm

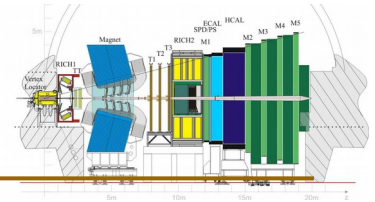


- No prediction of weak flavour couplings in Standard Model
- Unitary CKM matrix imposes relations between parameters (4 parameters)



- Challenge standard model by:
  - Measuring each parameter in different decay modes for internal consistency checks
  - Measuring many flavour transitions to over-constrain triangle

Hadronic final states



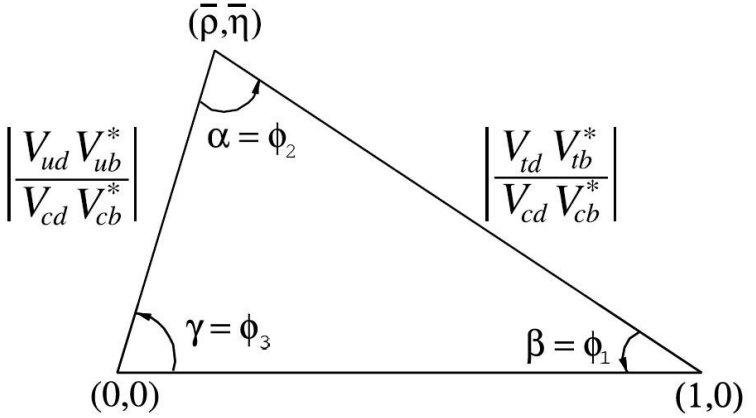
- Extremely clean determination of angle γ from family of

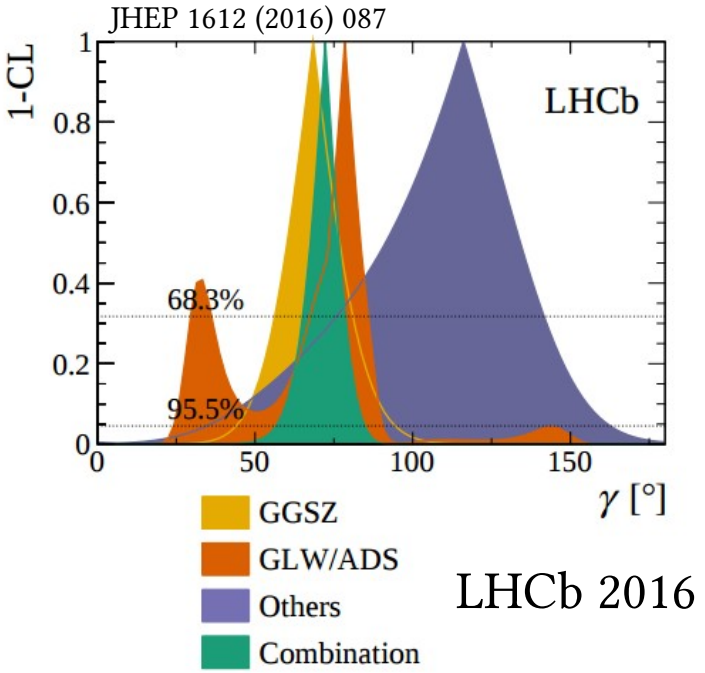
$$B^- \to Dh^-(h = K, \pi)$$

- More D decay modes count

  e.g. $D^0 \to \pi^+\pi^-\pi^0, D^0 \to \pi^+\pi^-\pi^+\pi^-$

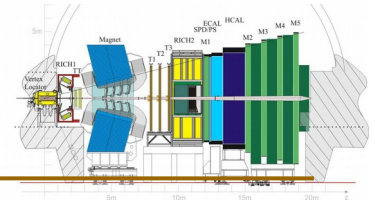
- Phase 2 Upgrade:
  - Better reconstruction of π^0 modes
  - Better low momentum tracking for high multiplicity modes
  - (Not included in sensitivity estimate)





LHCb 2016

Hadronic final states



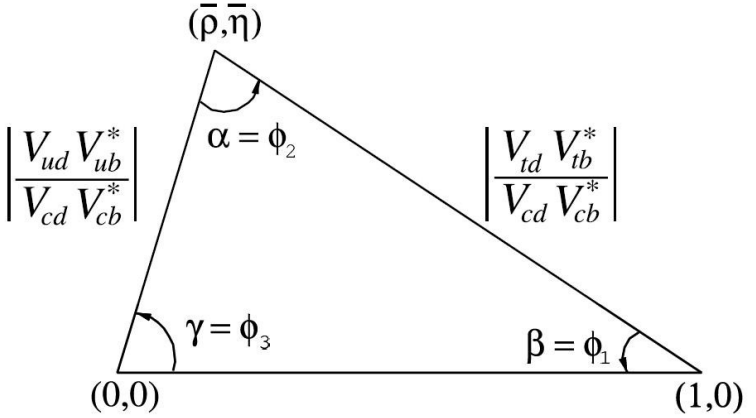
- Extremely clean determination of angle γ from family of

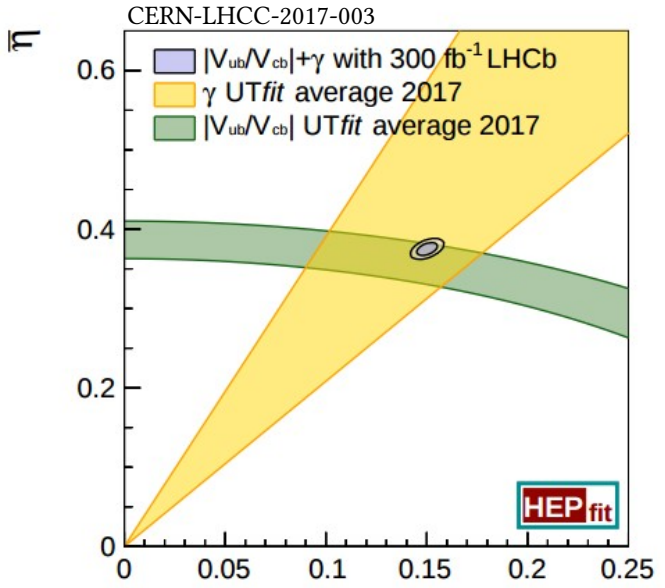
$$B^- \to Dh^-(h = K, \pi)$$

- More D decay modes count

  e.g. $D^0 \to \pi^+\pi^-\pi^0, D^0 \to \pi^+\pi^-\pi^+\pi^-$

- Phase 2 Upgrade:
  - Better reconstruction of π^0 modes
  - Better low momentum tracking for high multiplicity modes
  - (Not included in sensitivity estimate)



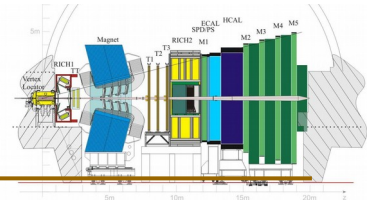


$\sigma_{\gamma,2017} \approx 7^\circ$

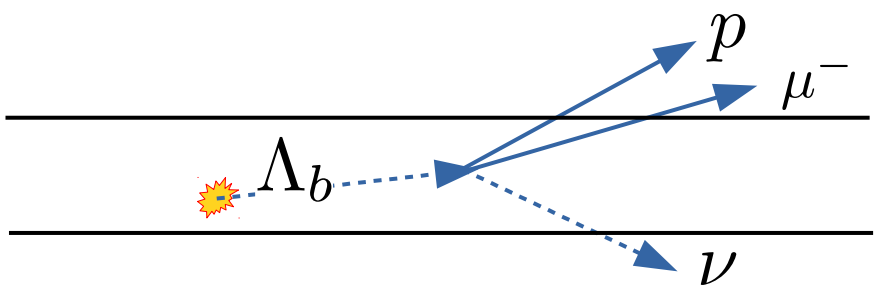
$\sigma_{\gamma,\text{phase 1}} \approx 1.0^\circ$

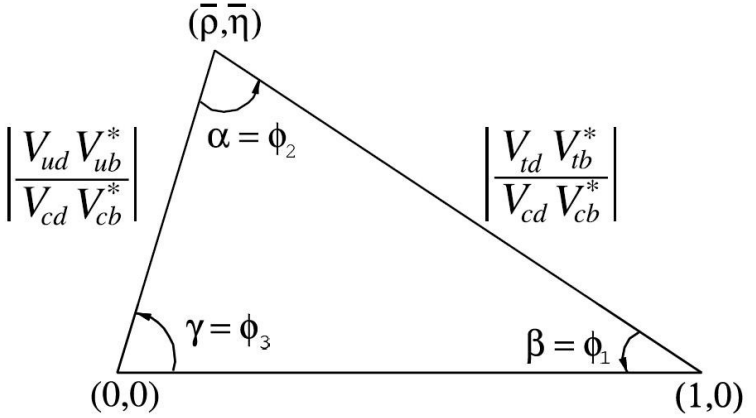
$\sigma_{\gamma,\text{phase 2}} \approx 0.4^\circ$

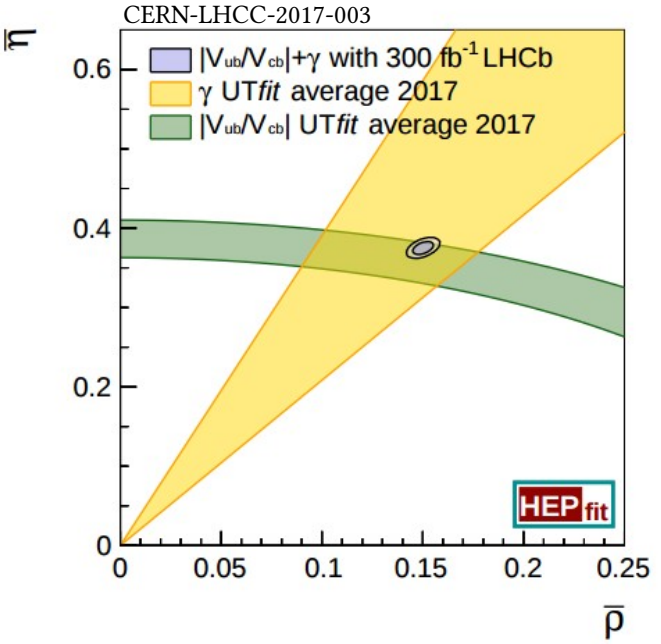
Semileptonic decays



- Measurement of Vub/Vcb via semileptonic decays of $\mathbf{B_s}$, $\mathbf{B_c}$ and $\mathbf{\Lambda_b}$

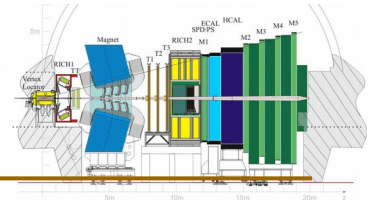




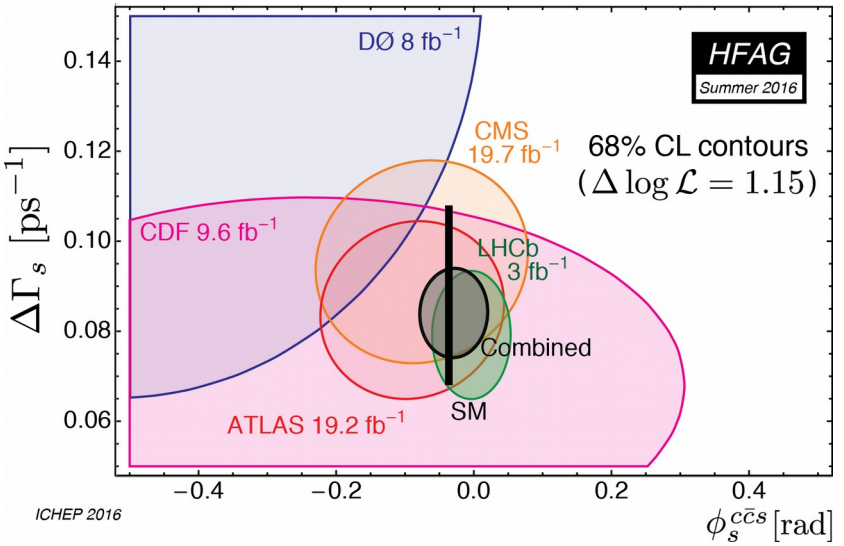


- Vertex resolution crucial
- Improve isolation of exclusive decays, e.g. $\Lambda_b \to p\mu\nu$ vs $\Lambda_b \to \Lambda_c(\to phh')\mu\nu$
- Shopping list for Phase2 Upgrade:
  - Decrease or remove material before first sensor
  - Improved reconstruction of neutrals

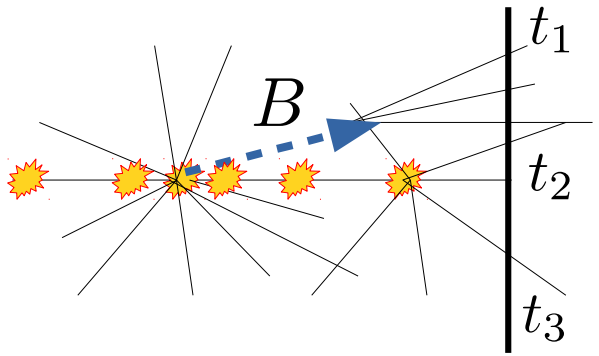
B mixing measurements



- Measure B_s mixing phase with highest precision
- Exploit different decay modes $B_s \to J/\Psi\Phi, B_s \to \Phi\Phi, B_s \to K^+K^-\pi^0 \ldots$
- Compare with indirect measurement from tree processes
- Primary collision association challenging



$$\sigma_{\phi_s,\text{phase 2}} \approx 3\,\text{mrad}$$

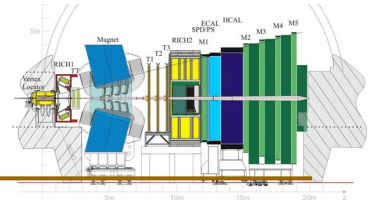


LHCb Phase 1 and Belle 2

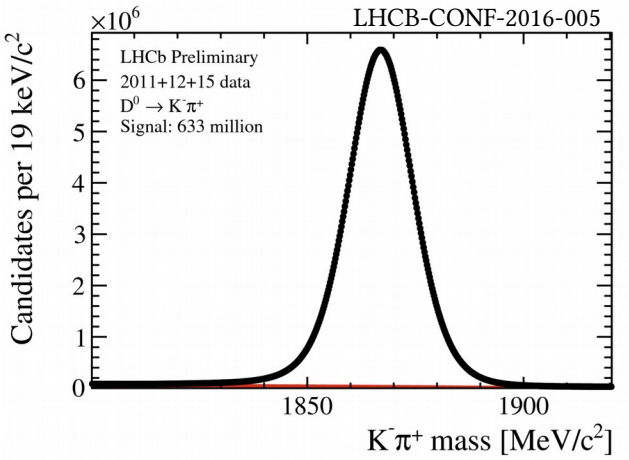
Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

[Charles et al., 1309.2293]

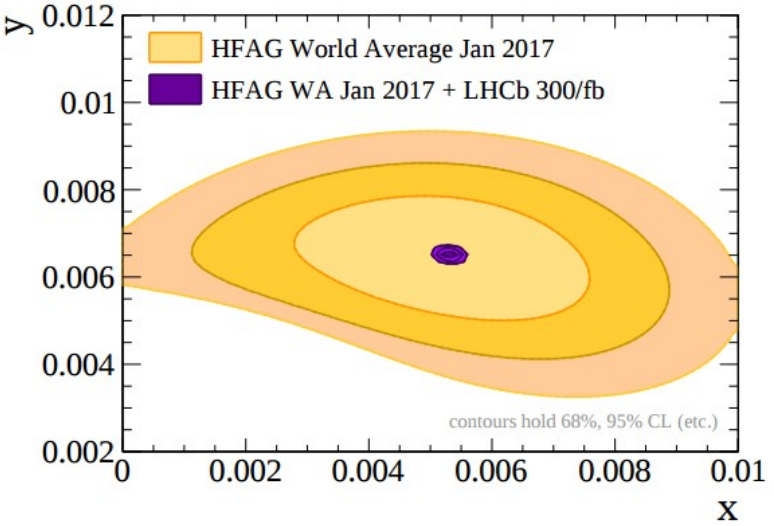
Charm and strange physics

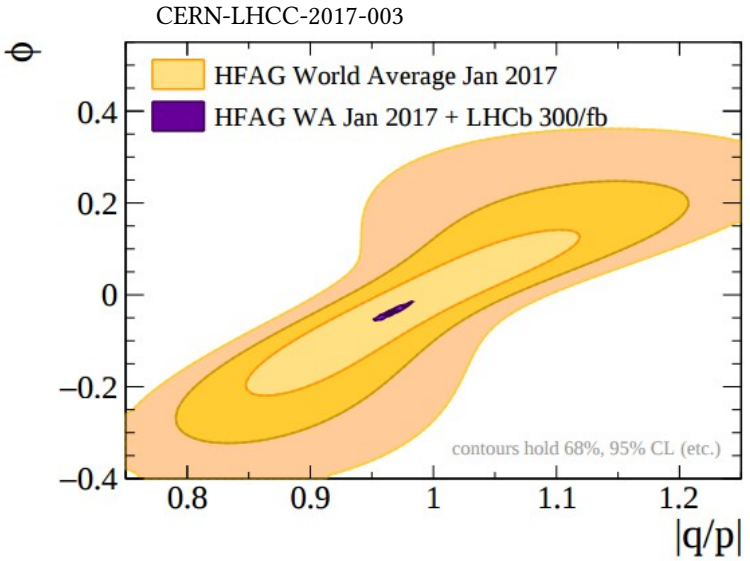


- Billions of charm and strange hadrons
  - Production rates of tens and hundreds of MHz
  - Incredible statistical precision
- Main challenge keep data size "reasonable" with full software trigger (save only the necessary information)

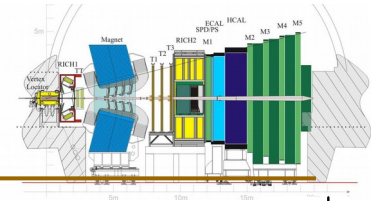


D meson mixing parameters:



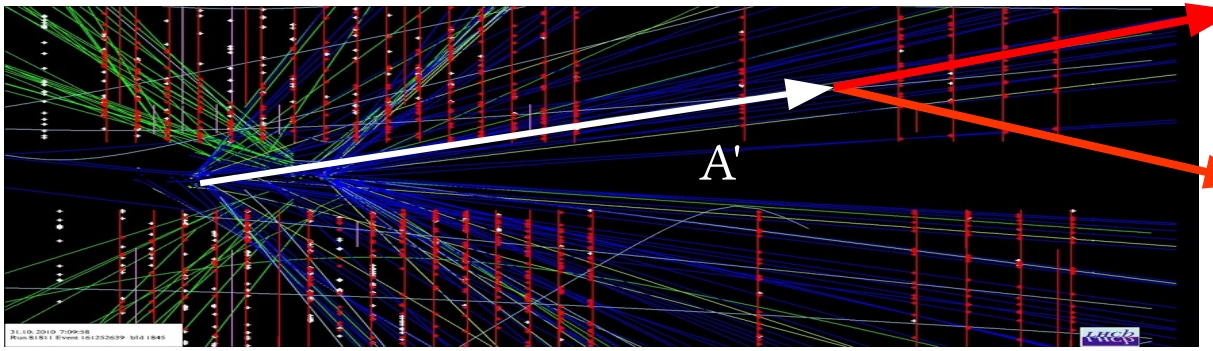


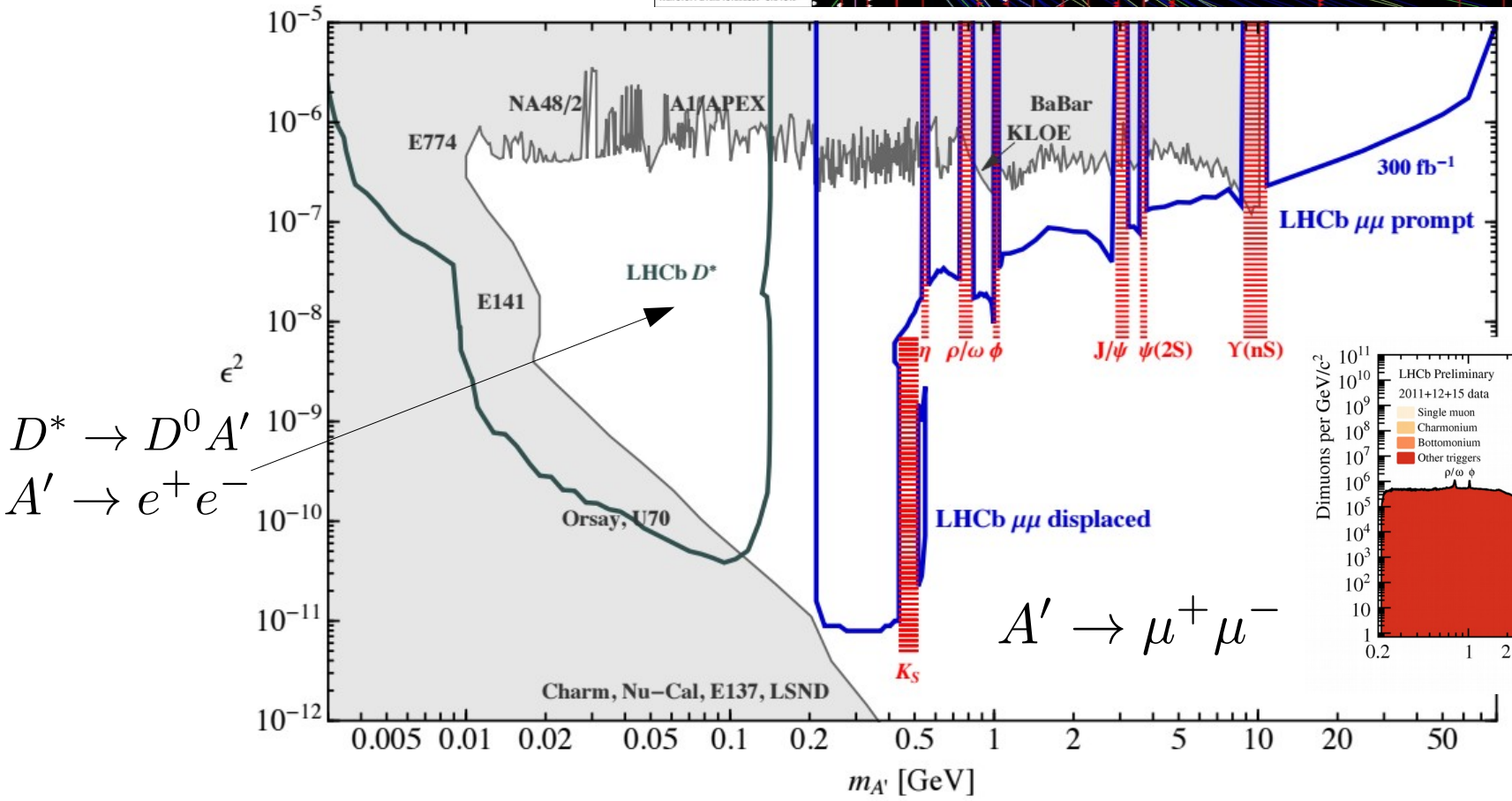
Exotica: Possible discoveries

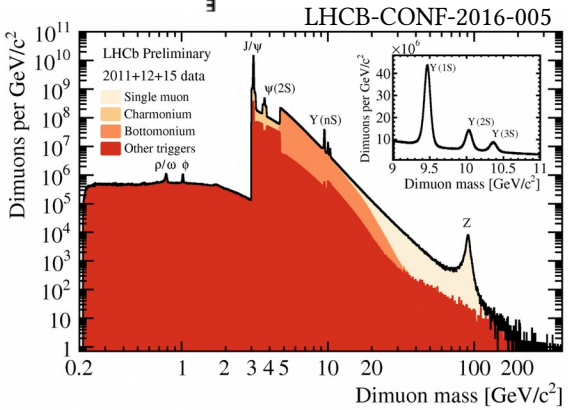


- Exotica searches, e.g. Dark photons
  PRL 116, 251803
  PRD92 (2015) no.11, 115017

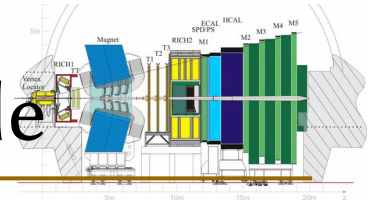
CERN-LHCC-2017-003

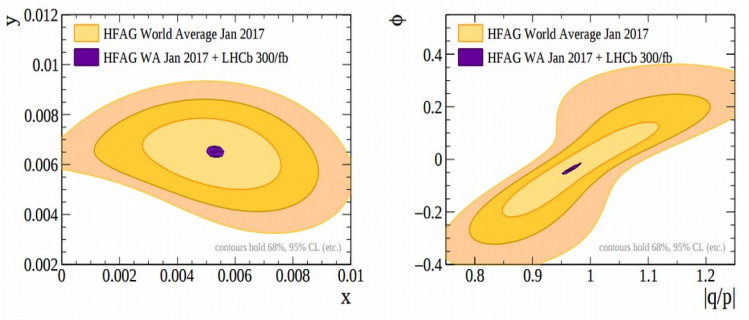


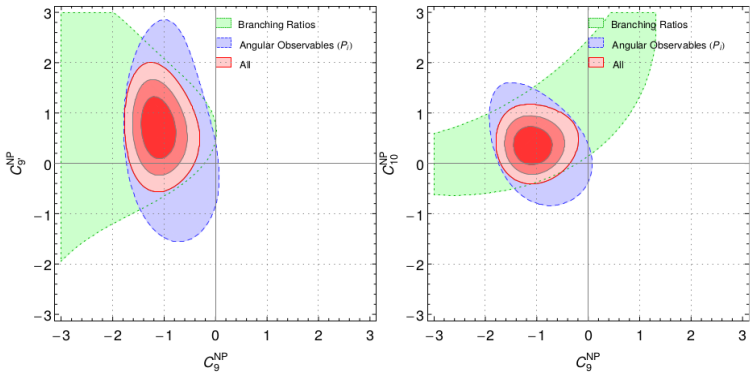


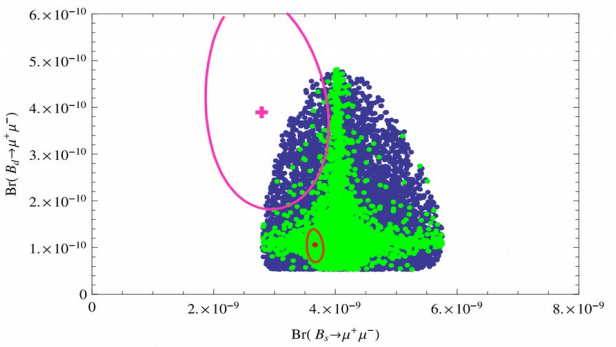


Physics opportunities of LHCb Phase 2 Upgrade

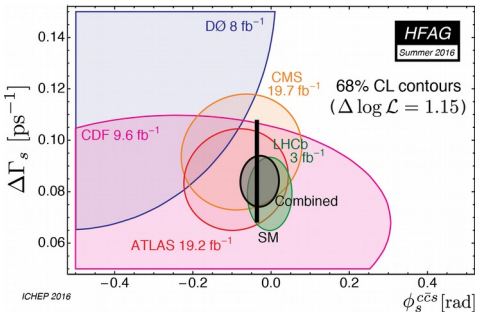


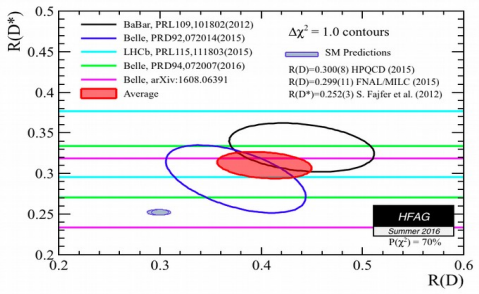


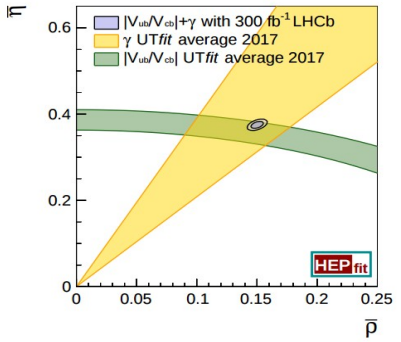




Phase 2 Upgrade will enable global test of Standard Model flavour sector and the potential to discriminate between New Physics scenarios.







Next steps for the Phase 2 Upgrade

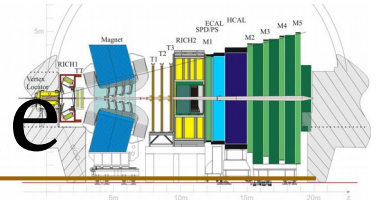
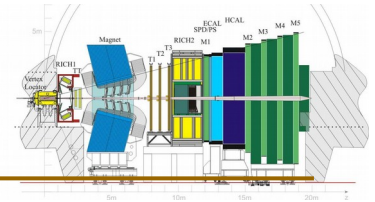


Table 5.1: Summary of the modifications under consideration for LS3, and those for Phase-II (LS4). Priorities will be assigned for the LS3 activities after further studies.

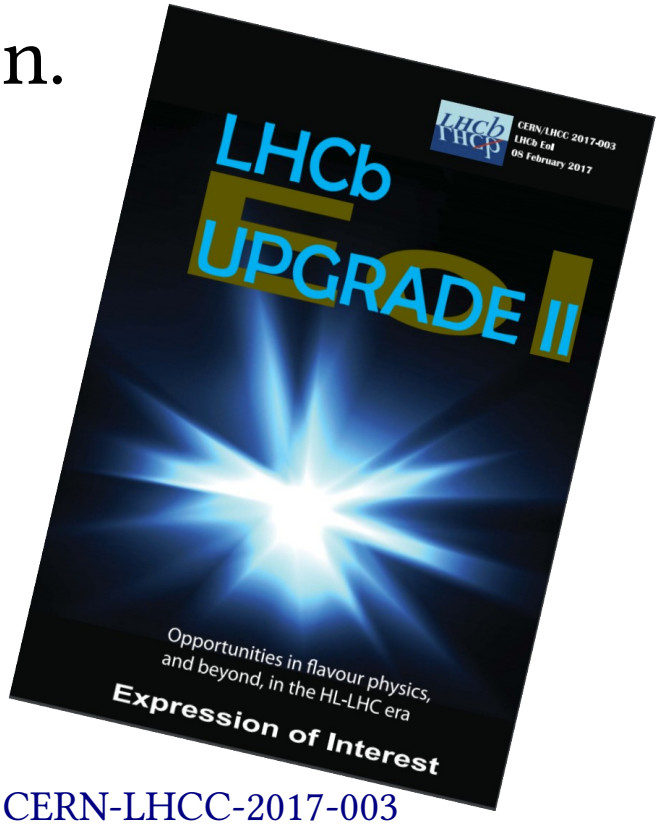
Detector	LS3	Phase-II
VELO	Deployment of prototype modules	New detector with fast timing
Tracking	Insert silicon IT, modify SciFi; install MS	Silicon UT and IT, SciFi OT
RICH	New photodetectors for selected regions; use of timing information	New optics; full replacement of photodetectors
TORCH	Installation for low-p hadron identification	Higher granularity photodetectors
CALO	Tungsten sampling modules installed in inner region	New modules in middle and outer regions
Muon	Replace HCAL with iron shielding; installation of high-rate chambers	Complete chamber installation
Trigger and data processing	Adiabatic software improvements; review of offline processing; installation of downstream track-finding processor	Expansion/replacement of links, readout boards and servers

- Start R&D of new detector components
- Identify possible upgrades or prototype installations in LS3 (2023), further studies required to decide priority
- Continue machine studies with LHC to set luminosity goals

Conclusion

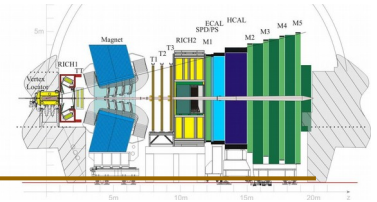


The LHCb experiment is eager
to continue challenging the world
of particle physics
to the highest precision.



CERN-LHCC-2017-003

Backups



Summary

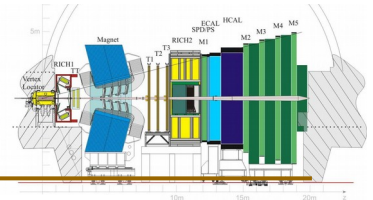
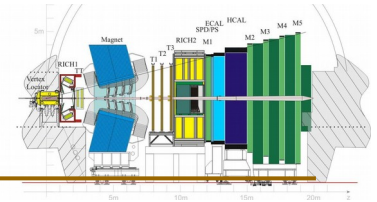


Table 2.1: Summary of prospects for Phase-II measurements of selected flavour observables.

Topics and observables	Experimental reach	Remarks
EW Penguins		
Global tests in many $b \to s\mu^+\mu^-$ modes with full set of precision observables; lepton universality tests; $b \to dl^+l^-$ studies	*e.g.* 440k $B^0 \to K^*\mu^+\mu^-$ & 70k $\Lambda_b^0 \to \Lambda\mu^+\mu^-$; Phase-II $b \to d\mu^+\mu^-$ $\approx$ Run-1 $b \to s\mu^+\mu^-$ sensitivity.	Phase-II ECAL required for lepton universality tests.
Photon polarisation		
$\mathcal{A}^\Delta$ in $B_s^0 \to \phi\gamma$; $B^0 \to K^*e^+e^-$; baryonic modes	Uncertainty on $\mathcal{A}^\Delta \approx 0.02$; $\sim 10k$ $\Lambda_b^0 \to \Lambda\gamma$, $\Xi_b \to \Xi\gamma$, $\Omega_b^- \to \Omega\gamma$	Strongly dependent on performance of ECAL.
$b \to cl^-\bar{\nu}_l$ lepton-universality tests		
Polarisation studies with $B \to D^{(*)}\tau^-\bar{\nu}_\tau$; τ^-/μ^- ratios with B_s^0, Λ_b^0 and B_c^+ modes	*e.g.* 8M $B \to D^*\tau^-\bar{\nu}_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ & $\sim 100k$ $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$	Additional sensitivity expected from low-p tracking.
$B_s^0, B^0 \to \mu^+\mu^-$		
$R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$; $\tau_{B_s^0 \to \mu^+\mu^-}$; CP asymmetry	Uncertainty on $R \approx 20\%$ Uncertainty on $\tau_{B_s^0 \to \mu^+\mu^-} \approx 0.03\,\text{ps}$	
LFV τ decays		
$\tau^- \to \mu^+\mu^-\mu^-$, $\tau^- \to h^+\mu^-\mu^-$, $\tau^- \to \phi\mu^-$	Sensitive to $\tau^- \to \mu^+\mu^-\mu^-$ at 10^{-9}	Phase-II ECAL valuable for background suppression.
CKM tests		
γ with $B^- \to DK^-$, $B_s^0 \to D_s^+K^-$ *etc.*	Uncertainty on $\gamma \approx 0.4°$	Additional sensitivity expected in CP observables from Phase-II ECAL and low-p tracking.
ϕ_s with $B_s^0 \to J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$	Uncertainty on $\phi_s \approx 3\,\text{mrad}$	
$\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$	Uncertainty on $\phi_s^{s\bar{s}s} \approx 8\,\text{mrad}$	
$\Delta\Gamma_d/\Gamma_d$	Uncertainty on $\Delta\Gamma_d/\Gamma_d \sim 10^{-3}$	Approach SM value.
Semileptonic asymmetries $a_{\text{sl}}^{d,s}$	Uncertainties on $a_{\text{sl}}^{d,s} \sim 10^{-4}$	Approach SM value for a_{sl}^d.
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ with Λ_b^0, B_s^0 and B_c^+ modes	*e.g.* $120k$ $B_c^+ \to D^0\mu^-\bar{\nu}_\mu$	Significant gains achievable from thinning or removing RF-foil.
Charm		
CP-violation studies with $D^0 \to h^+h^-$, $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K^\mp\pi^\pm\pi^+\pi^-$	*e.g.* 4×10^9 $D^0 \to K^+K^-$; Uncertainty on $A_\Gamma \sim 10^{-5}$	Access CP violation at SM values.
Strange		
Rare decay searches	Sensitive to $K_S^0 \to \mu^+\mu^-$ at 10^{-12}	Additional sensitivity possible with downstream trigger enhancements.

CERN-LHCC-2017-003

The Unitarity triangle



- State of 2010 and 2016