Physics opportunities with an upgraded LHCb detector at HL-LHC

V. VAGNONI

CERN AND INFN BOLOGNA

TENSIONS IN FLAVOUR MEASUREMENTS: A PATH TOWARD PHYSICS BEYOND THE STANDARD MODEL

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Naples

After one failed attempt to find a suitable place...

...and even a second one!

Setting the scene

- LHCb Phase-I upgrade
  - Detector will be operated at $2x10^{33}$ $cm^{-2}s^{-1}$
  - Under construction
  - Will be ready for LHC Run 3
- LHCb Phase-II upgrade
  - Run at a factor 10 higher luminosity
  - Need significant changes to the detector
  - Envisaged for LHC Run 5
    - i.e. not clashing with ATLAS and CMS Phase-II upgrades
  - Expression of interest submitted to the LHCC

Luminosity prospects

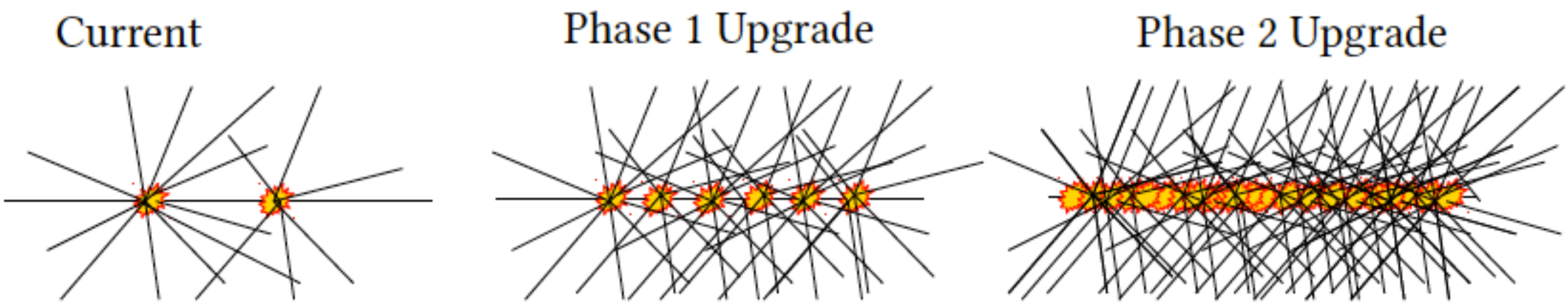
- HL-LHC can supply an instantaneous luminosity at the LHCb interaction point (IP) of around 2×10^{34} $cm^{-2}s^{-1}$ at start of fill
- The lifetime of the inner triplets at the IP is expected to correspond to an integrated luminosity of about 300 fb^{-1}
  - improved understanding of the triplets' response to radiation damage may allow a larger value to be achieved
- This can be made within the planned HL-LHC operation schedule!

	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-I Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50
Phase-II Upgrade	5 $\rightarrow$	2031–2033, 2035 $\rightarrow$	2×10^{34}	300

Key goals

- The Phase-II Upgrade will be capable of improving on a broad spectrum of important flavour-physics measurements
  - A comprehensive programme of measurements of $b \to s l^+ l^-$ and $b \to d l^+ l^-$ transitions, employing both muon and electron modes
  - Measurement of γ with a precision of 0.4^o
  - Measurement of ϕ_s with a precision of 3 mrad
  - Measurement of the ratio $B(B^0 \to \mu\mu)/B(B_s \to \mu\mu)$ with an uncertainty of about 10%, and the first precise measurements of relevant $B_s \to \mu\mu$ observables such as effective lifetime and *CP* violation
  - A wide-ranging set of lepton-universality tests in $b \to c l \nu$ decays, exploiting the full range of b-hadrons
  - *CP*-violation measurements in charm with 10^{-5} precision
- In addition, the Phase-II Upgrade will be capable of major discoveries in hadron spectroscopy, and pursuing a wide and unique programme of general physics measurements, complementary to those of ATLAS and CMS

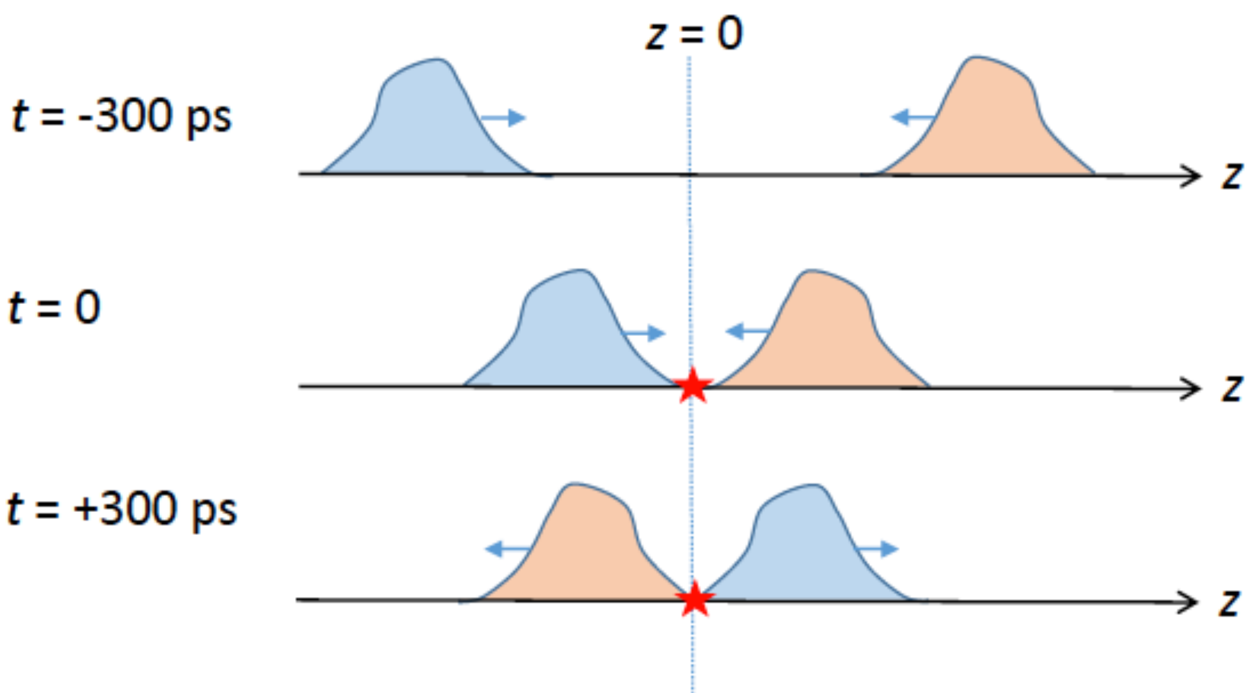
Challenges ahead



- The project is very challenging
  - otherwise we would have done it already...
- The mean number of interactions per event will be around 50
  - The increased particle multiplicity and rates will present significant problems for all detectors, notaby including increased radiation damage
- An essential attribute will be precise timing in the VELO detector, and also downstream of the magnet for both charged tracks and neutrals
  - A time resolution of a few tens of ps for charged tracks and photons will dramatically simplify pattern recognition and improve association of particles to the correct interaction vertex where they were produced
  - Furthermore, a high granularity tungsten sampling electromagnetic calorimeter will extend the experiment's capabilities in final states involving photons, π^0s and electrons

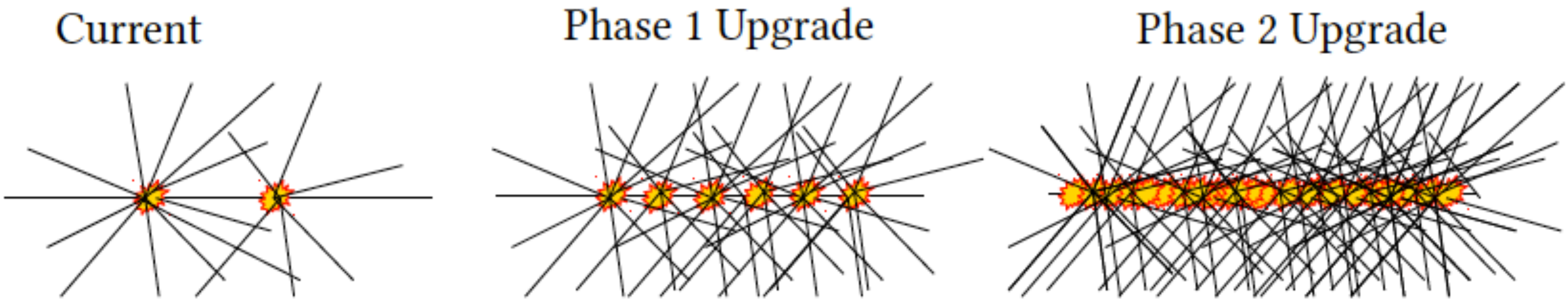
Timing information

- In high pileup conditions, vertex reconstruction and assignment to a given decay becomes a limiting factor
  - Particles produced at same position can have very different production times
- Consider two beam bunches crossing at the interaction point

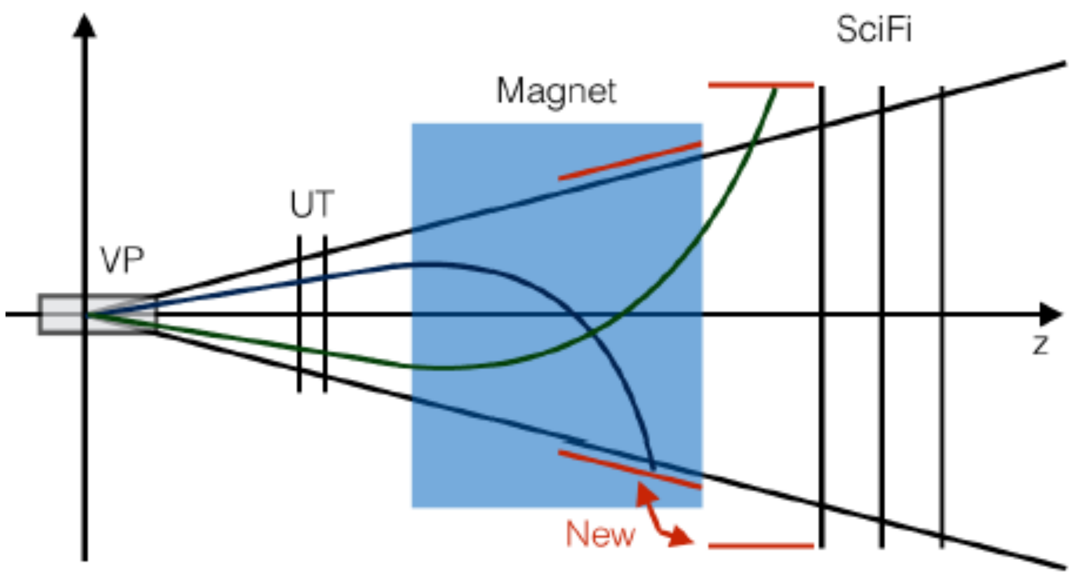


- In this cartoon, interactions at same *z* but separated by 300 ps
- If we would have precise enough time information for charged particles and neutral, the complexity of high-pileup events could be reduced to the present situation

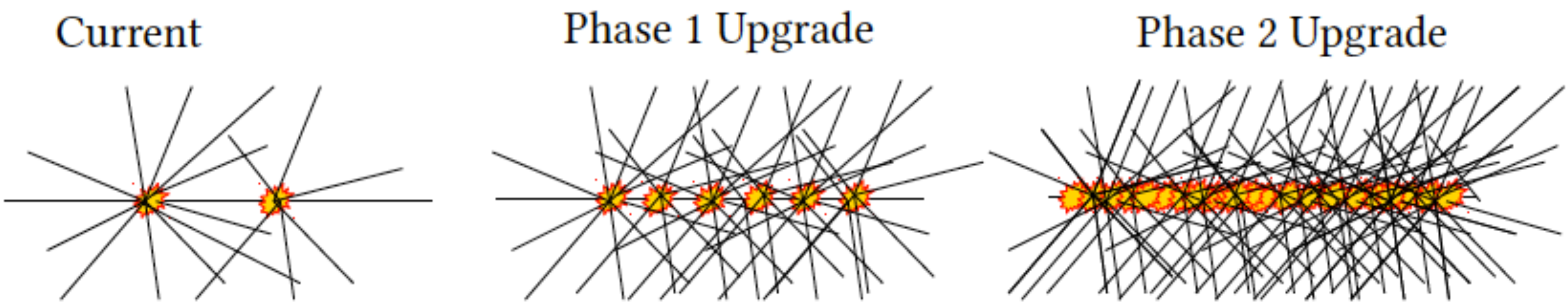
Challenges ahead



- By instrumenting the side walls of the dipole magnet, the tracking acceptance can be significantly increased for soft tracks, improving detector efficiency for high multiplicity decays



Challenges ahead

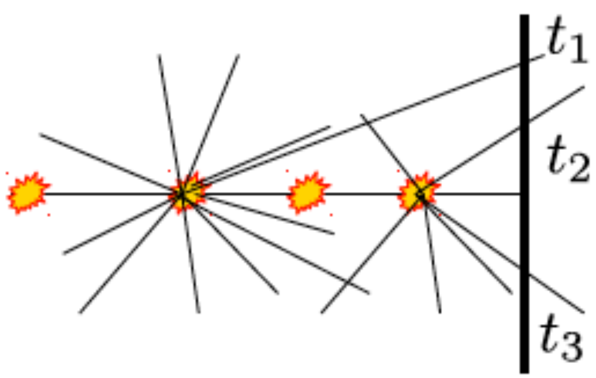


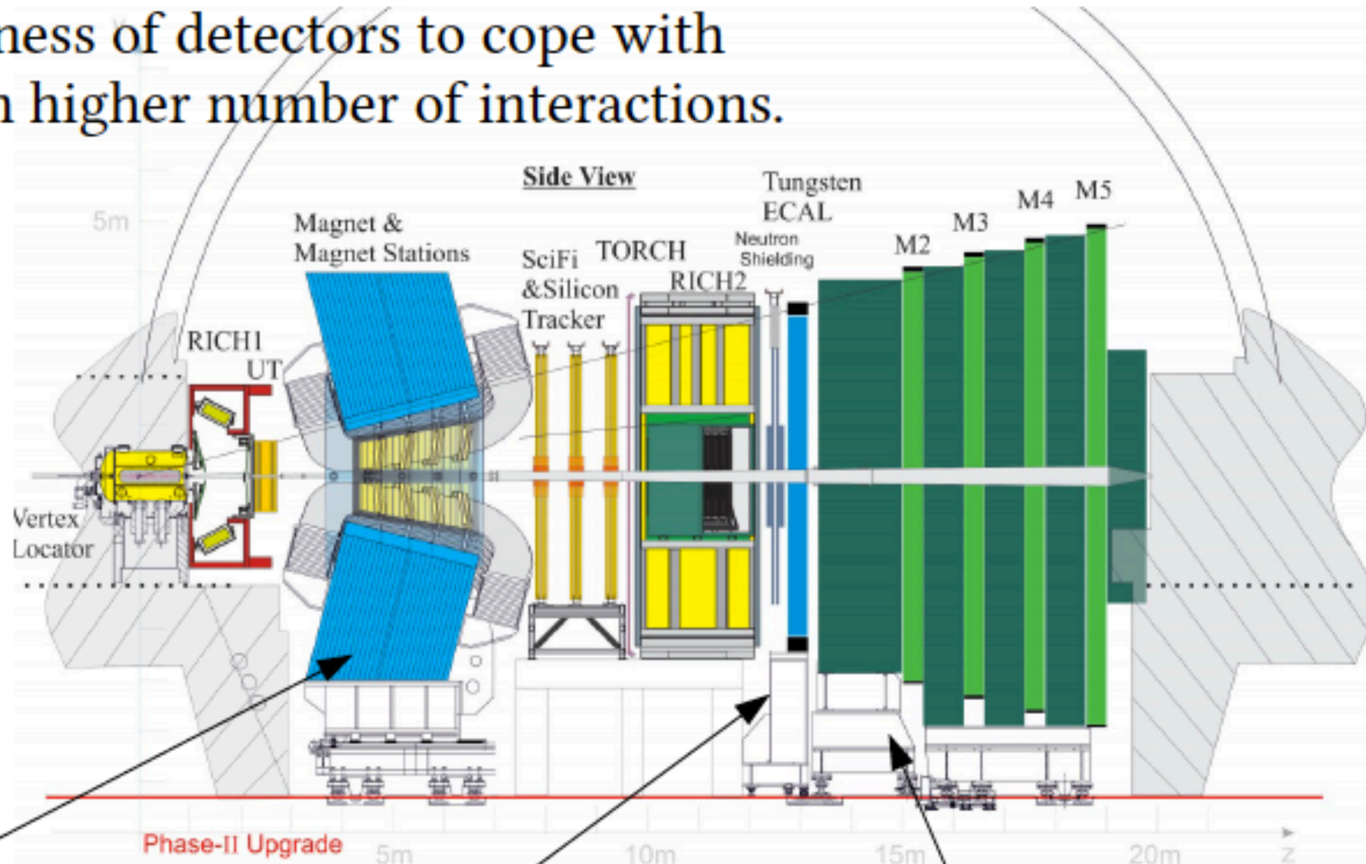
- Downstream fast-timing capabilities will allow improved rejection of combinatoric background and can also be used for improving particle identication at low momentum, along with improvements in the RICH system
- Initial steps of a limited number of these detector upgrade projects could already be installed for Run 4, allowing the Phase-I experiment to improve its physics reach even before the Phase-II upgrade takes place

Matching the LHCb layout

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.

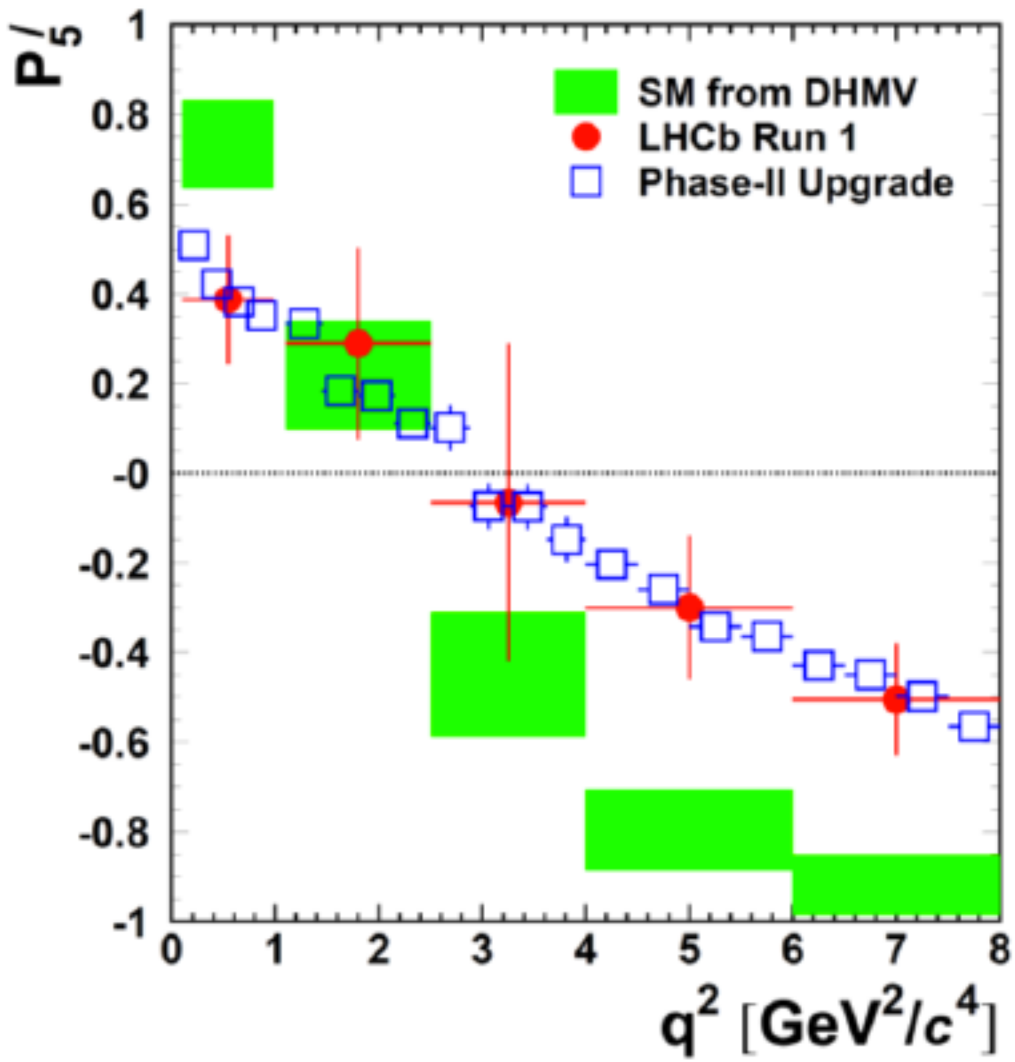
5. Better shielding for muons.

$b \to sl^+l^-$ transitions and LFU

- LHCb has already reported important results for many of these modes with Run-1 data
- The main systematic uncertainties are expected to scale with integrated luminosity, motivating continued study of these decay channels at the Phase-II Upgrade
- Although LFU measurements comparing rates with muons and electrons are theoretically clean, for absolute branching fractions and angular observables the size of possible charm-loop effects may introduce additional theoretical uncertainties
- Besides improvements in the known problematic modes, new observables e.g. in the B_s and Λ_b sectors, will be measured with excellent sensitivity, thus providing a broader picture

P_5' demo

- For example, the region $4 < q^2 < 8$ GeV^2 in P_5' where there's the famous hint of a discrepancy between data and prediction will be mapped out with very high precision
  - LHCb Run-1 results compared with expected sensitivity with 300 fb^{-1}



$b \to dl^+l^-$ transitions and radiative decays

- Similar arguments hold for studies of $b \to dl^+l^-$ transitions, albeit with lower statistical precision
- The angular analysis of $B_s \to \bar{K}^{*0}\mu\mu$ with the data sample collected by the Phase-II Upgrade will be more precise than the Run-1 result for $B^0 \to K^{*0}\mu\mu$, enabling a powerful comparison between different flavour transitions
- A time-dependent analysis will become feasible for the mode $B^0 \to \rho^0 l^+l^-$, and with large sample sizes and improved π^0 reconstruction with upgraded ECAL other relevant modes with neutrals will become accessible
- The upgraded ECAL will also be very valuable in improving the sensitivity of the experiment to studies of $b \to s\gamma$ and $b \to d\gamma$
  - for example enabling the photon polarisation in $B_s \to \phi\gamma$ to be measured with a sensitivity comparable to the precision on the SM prediction
  - also polarisation measurements with rare baryon decays, such as $\Lambda_b \to \Lambda\gamma$, $\Xi_b \to \Xi\gamma$ and $\Omega_b \to \Omega\gamma$

Scaling yields up

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 [62]	9175	70480	435393
Yield $B^0_s \to \phi\mu^+\mu^-$	432 ± 24 [63]	1653	12697	78436
Yield $B^+ \to K^+\mu^+\mu^-$	4746 ± 81 [70]	18159	139491	861709
Yield $B^+ \to \pi^+\mu^+\mu^-$	93 ± 12 [71]	355	2725	16831
Yield $\Lambda^0_b \to \Lambda\mu^+\mu^-$	373 ± 25 [72]	1426	10957	67688
Yield $B^+ \to K^+e^+e^-$ $(1 < q^2 < 6\,\text{GeV}^2/c^4)$	254 ± 29 [64]	972	7465	46118
$\text{d}\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-, 1.0 < q^2 < 6\,\text{GeV}^2/c^4)/\text{d}q^2[10^{-9}\,\text{GeV}^{-2}c^4]$	$0.91 \pm 0.21 \pm 0.03$ [71]	0.11	0.04	0.02
$\text{d}\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-, 15 < q^2 < 22\,\text{GeV}^2/c^4)/\text{d}q^2[10^{-9}\,\text{GeV}^{-2}c^4]$	$0.47 \pm 0.12 \pm 0.01$ [71]	0.06	0.02	0.01
$A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\text{GeV}^2/c^4)$	$-0.075 \pm 0.034 \pm 0.007$ [62]	0.017	0.006	0.003
$A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\text{GeV}^2/c^4)$	$0.355 \pm 0.027 \pm 0.009$ [62]	0.014	0.005	0.002
$S_5(B^0 \to K^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\text{GeV}^2/c^4)$	$-0.023 \pm 0.050 \pm 0.005$ [62]	0.026	0.009	0.004
$S_5(B^0 \to K^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\text{GeV}^2/c^4)$	$-0.325 \pm 0.037 \pm 0.009$ [62]	0.019	0.007	0.003
$S_5(B^0_s \to \overline{K}^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\text{GeV}^2/c^4)$	-	-	0.087	0.035
$S_5(B^0_s \to \overline{K}^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\text{GeV}^2/c^4)$	-	-	0.064	0.026
$\mathcal{R}_K(1 < q^2 < 6\,\text{GeV}^2/c^4)$	$0.745 \pm 0.090 \pm 0.036$ [64]	0.046	0.017	0.007

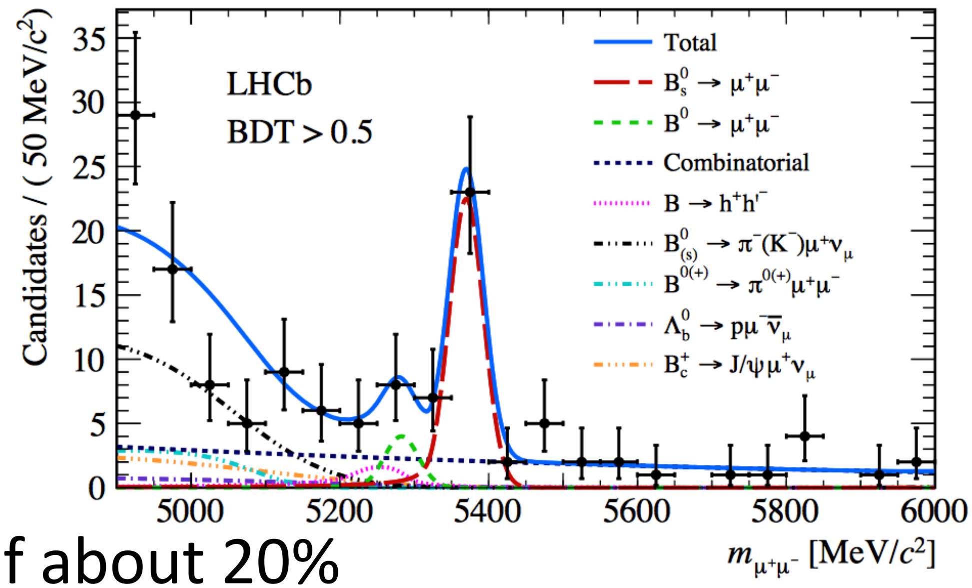
- Opportunity to make comprehensive tests by looking at very wide range of observables in different modes and different lepton final states

Similar (new) physics in $b \to c l \nu$?

- Lepton universality studies in $b \to c l \nu$ transitions provide complementary/alternative constraints on possible NP models
- The present 4 sigma-ish tension with R(D) and R(D*) is a pure experimental problem and will be clarified in the coming years with LHCb and Belle-II
  - Also because LHCb can provide further related measurements such as $B_c \to J/\psi l \nu$, $\Lambda_b \to \Lambda_c l \nu$, etc., some of which coming soon
- The Phase-II Upgrade will allow LHCb to test both τ-μ and μ-e universality in $b \to c l \nu$ transitions at better than the percent level across the full range of decaying b-hadrons
  - The yields of $B \to D(*) \tau \nu$ decays will be sufficiently large to allow for precise polarisation studies of the final-state particles

Very rare decays

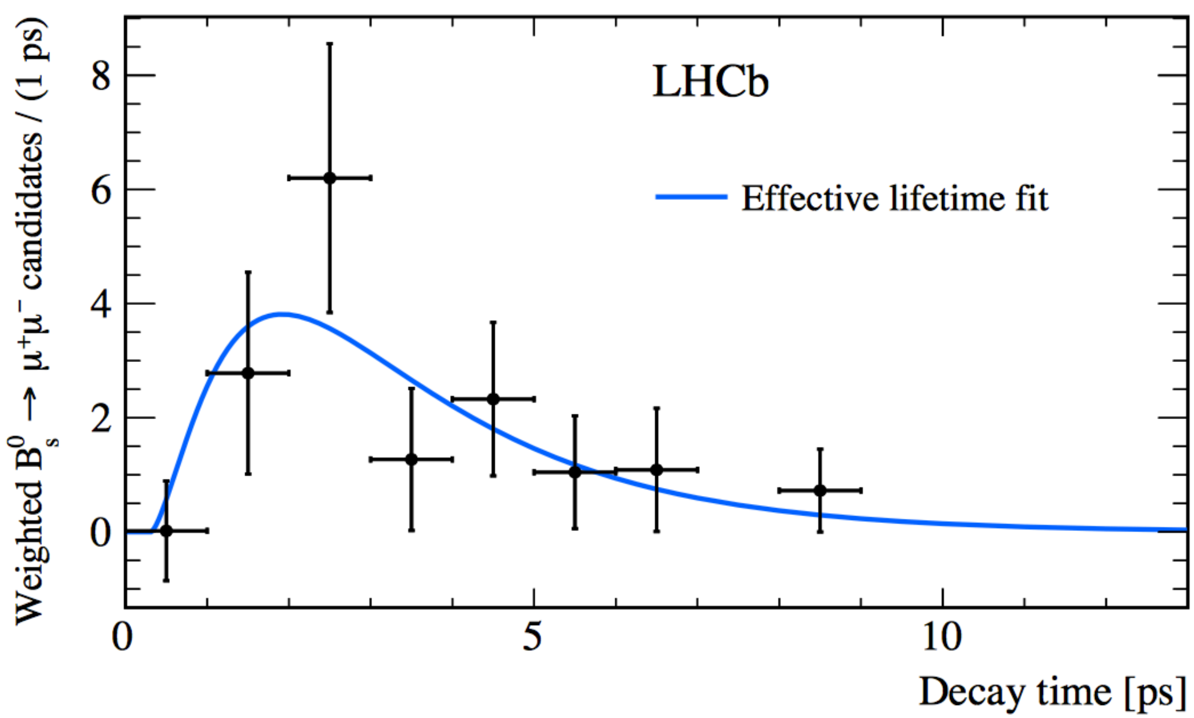
- The $B_s \rightarrow \mu\mu$ decay has been successfully observed at the LHC, and in particular at LHCb for the first time from a single experiment
  - branching ratio measured to be consistent with the SM predictions with a precision of about 20%



- For the $B^0 \rightarrow \mu\mu$, no significant signal has been established yet
- Assuming SM, LHCb can achieve with a Phase-II upgrade a precision of about 10% on the ratio $B(B^0 \rightarrow \mu\mu)/B(B_s \rightarrow \mu\mu)$, a very powerful observable to constrain the flavour structure of NP models beyond the SM
  - CMS is expected to attain a somewhat worse statistical sensitivity, but hadron particle identification capabilities at LHCb will be more powerful for suppressing backgrounds and control systematic uncertainties

Very rare decays

- Moreover the large $B_s \rightarrow \mu\mu$ yield will allow the study of new observables such as the effective lifetime, for which a proof of concept has been already published, and *CP* asymmetries
  - These observables will be particularly relevant for discriminating between NP models in the event that effects beyond the SM are observed by that time



Prospects with γ

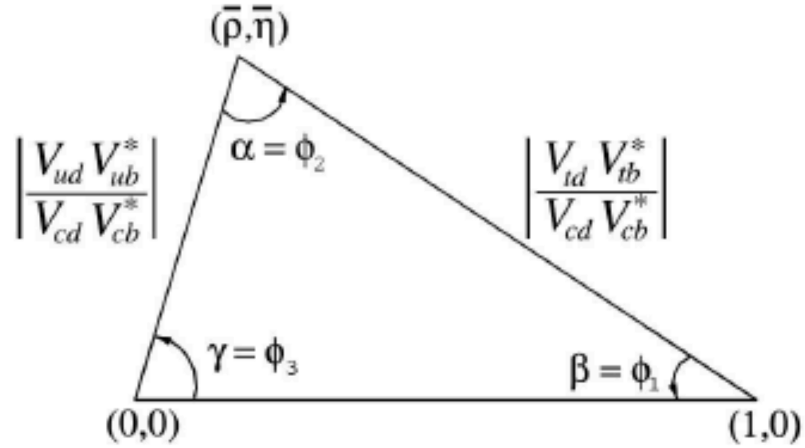
- Extremely clean determination of angle γ from family of

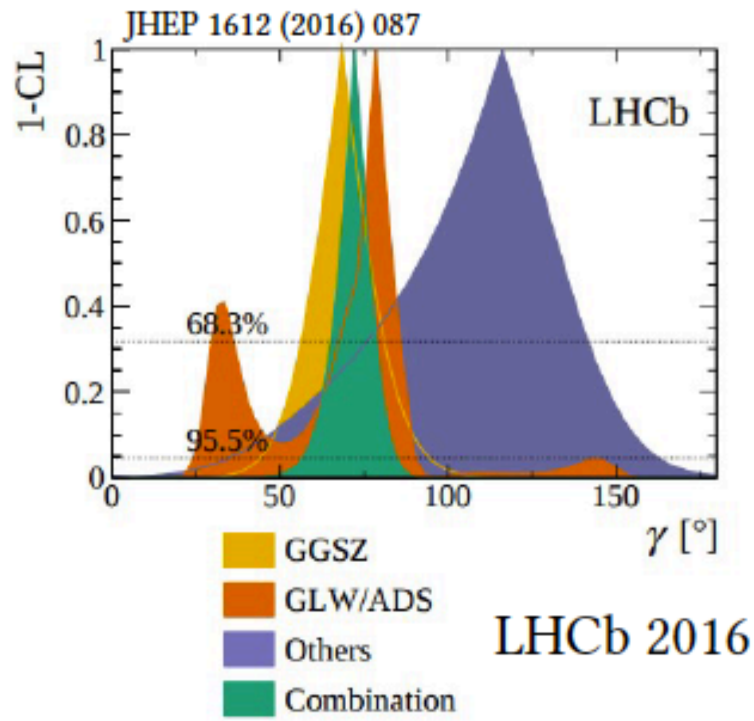
$$B^- \to Dh^-(h = K, \pi)$$

- 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

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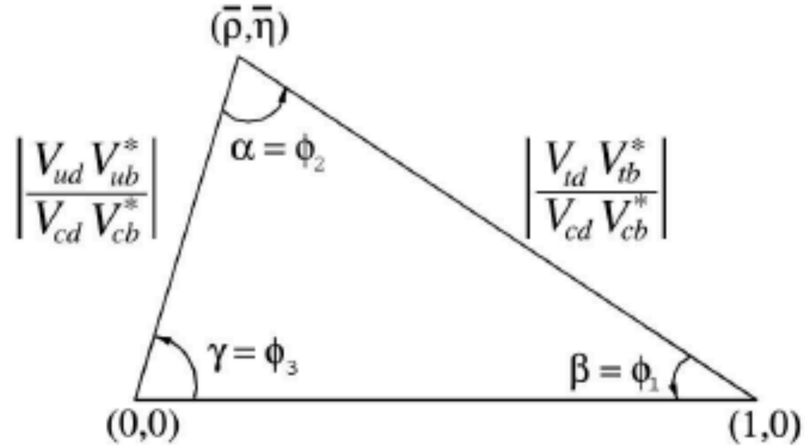
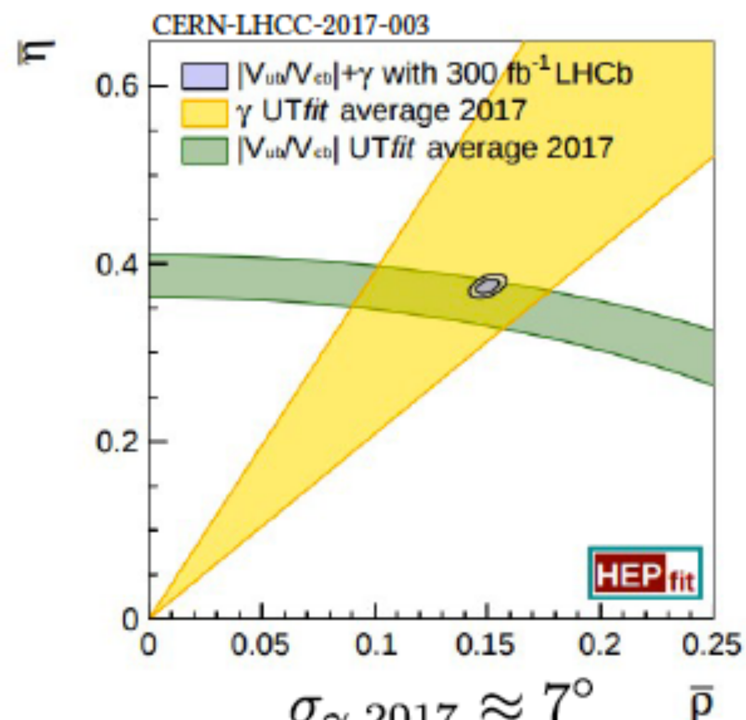


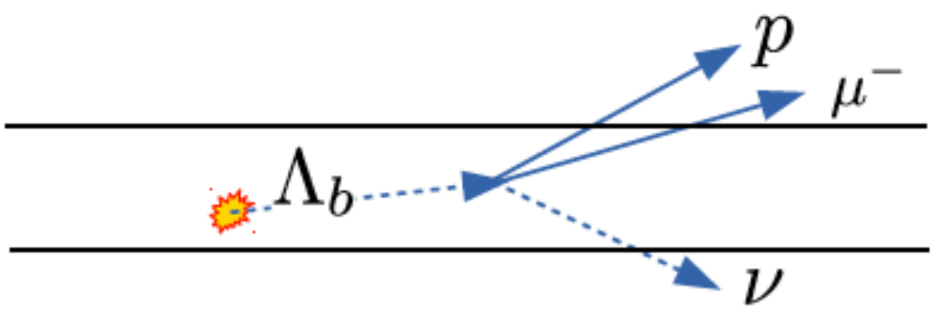


$\sigma_{\gamma,2017} \approx 7^\circ$

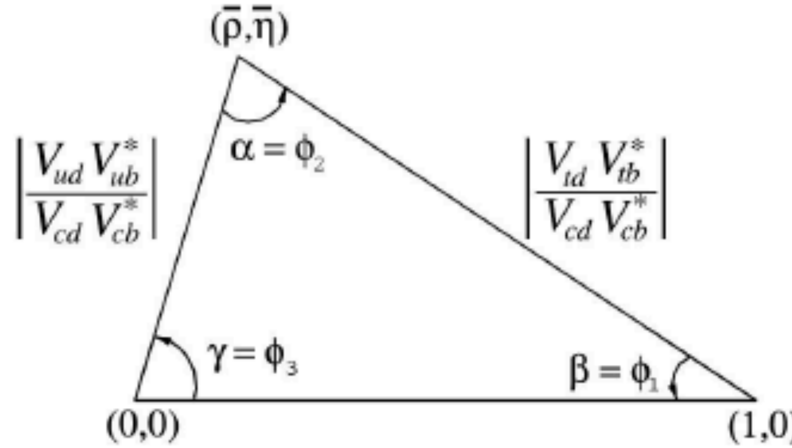
$\sigma_{\gamma,\mathrm{phase\ 2}} \approx 0.4^\circ$

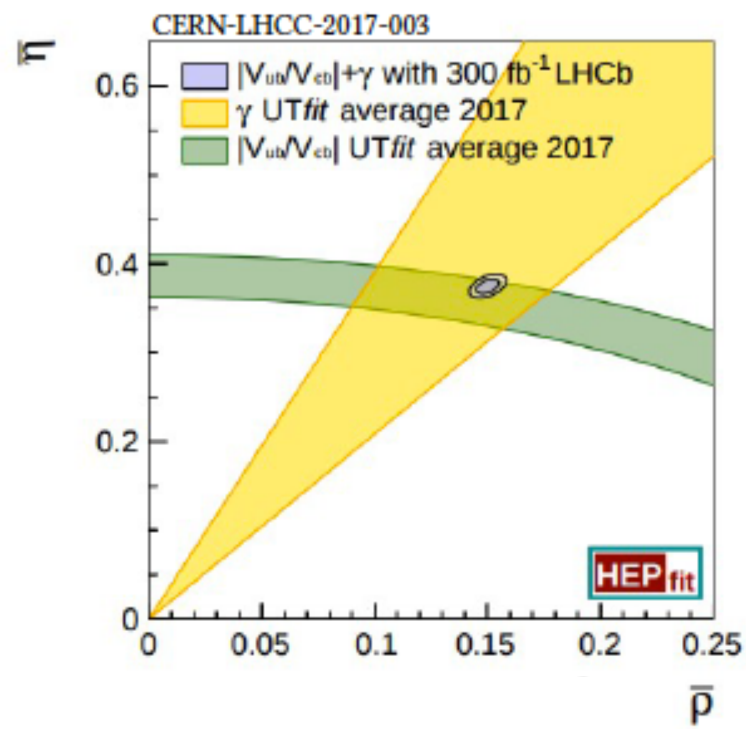
Improvements on V_{ub}/V_{cb}

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



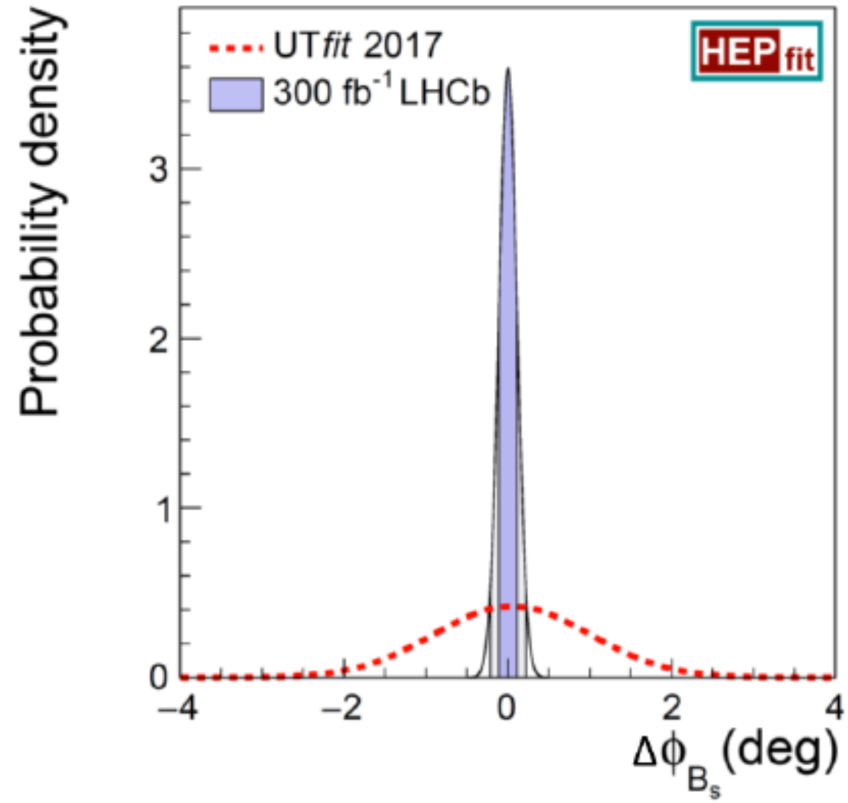
- Vertex resolution crucial
- Improve isolation of exclusive decays, e.g. $\Lambda_b \rightarrow p\mu\nu$ vs $\Lambda_b \rightarrow \Lambda_c(\rightarrow phh')\mu\nu$
- Shopping list for Phase2 Upgrade:
  - Decrease or remove material before first sensor
  - Improved reconstruction of neutrals



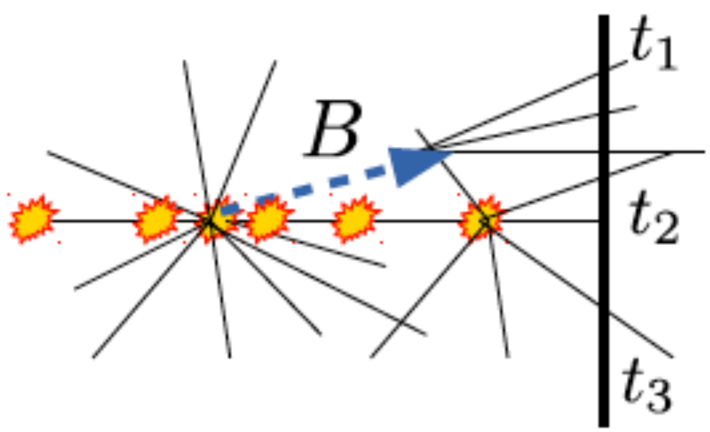


Prospects for ϕ_s measurements

- 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



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



- Analysis can greatly benefit from timing information at very high pileup

Control of penguin amplitudes

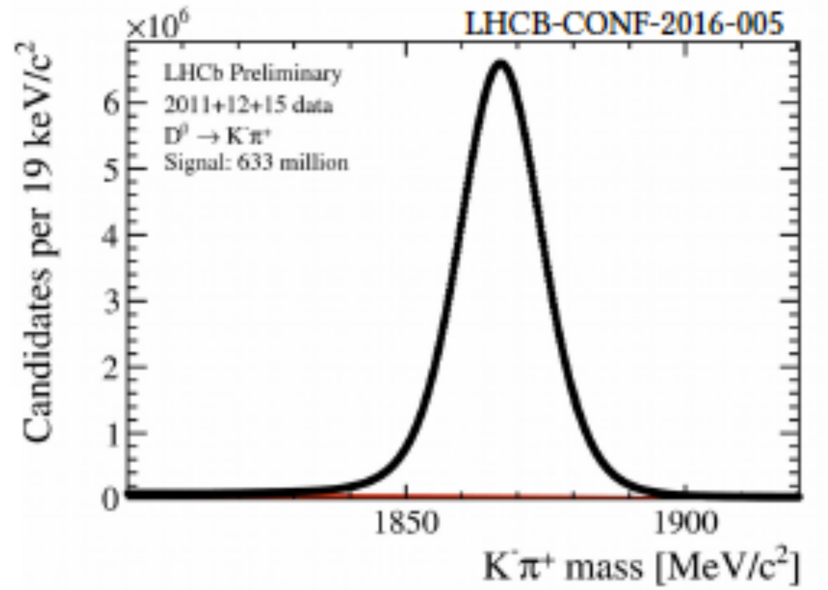
- In order to interpret properly the time-dependent analysis of $B_s \rightarrow J/\psi\phi$ in terms of ϕ_s, the size of any potential contributions from doubly Cabibbo-suppressed penguin decays must be determined
  - for example using control channels such as $B^0 \rightarrow J/\psi\rho^0$ and $B_s \rightarrow J/\psi K^{*0}$, which benefit from the hadron identication capabilities of LHCb
- With the data accumulated after the Phase-II Upgrade, it is expected that the effect of such penguin diagrams on ϕ_s will be known with a precision better than 1.5 mrad

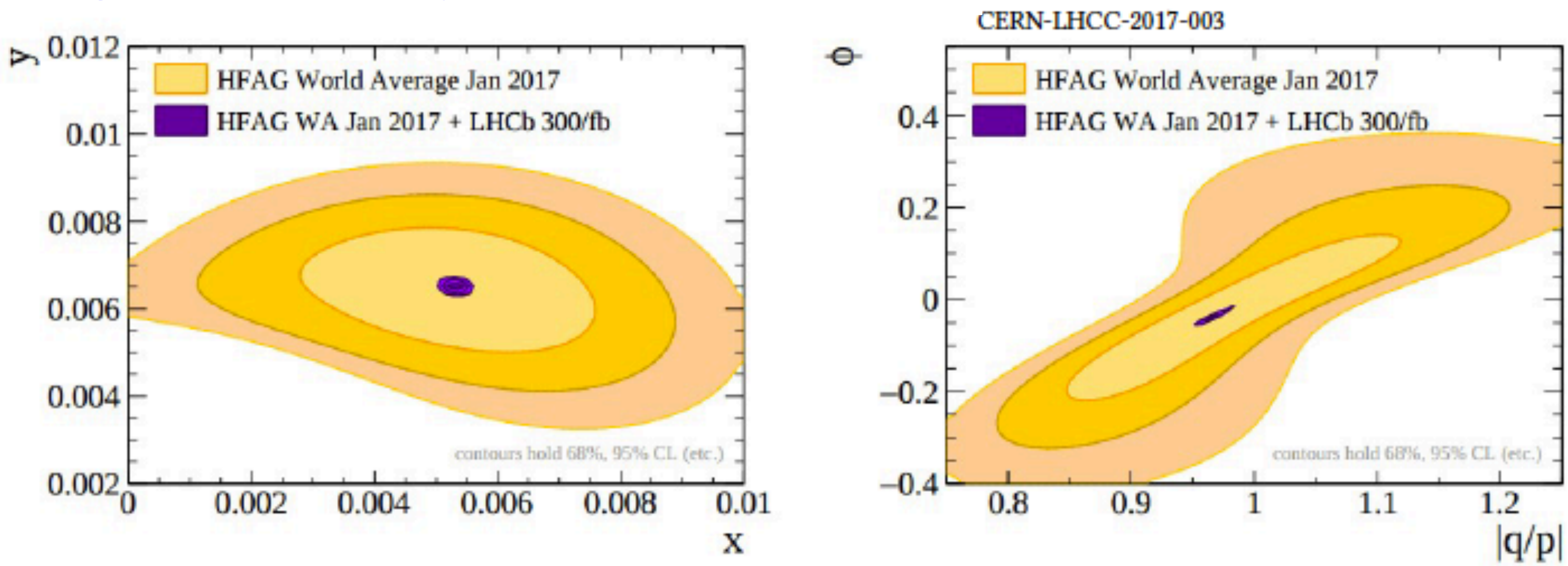
Other related measurements

- Moreover, studies of the weak phase in complementary $b \to s\bar{s}s$ decay modes such as $B_s \to \phi\phi$, where current measurements are limited by statistics, will be able to reach sensitivities of 8 mrad with the Phase-II Upgrade sample
- Similar improvements will be possible in related charmless decays $B_s \to K\pi K\pi$, $B_s \to K_S hh$ ($h=\pi,K$) and $B_s \to KK\pi^0$, where the improved capabilities of the Phase-II ECAL will play an important role
- Furthermore, LHCb will continue to make important CKM tests in the B^0 system
  - for example the Phase-II Upgrade will allow LHCb to measure Γ_d with sufficient precision to be sensitive to a non-zero value at the predicted SM level
- Further relevant measurements are those of semileptonic asymmetries
  - it will e.g. be possible to reach a precision close to the SM value for a^d_{sl}

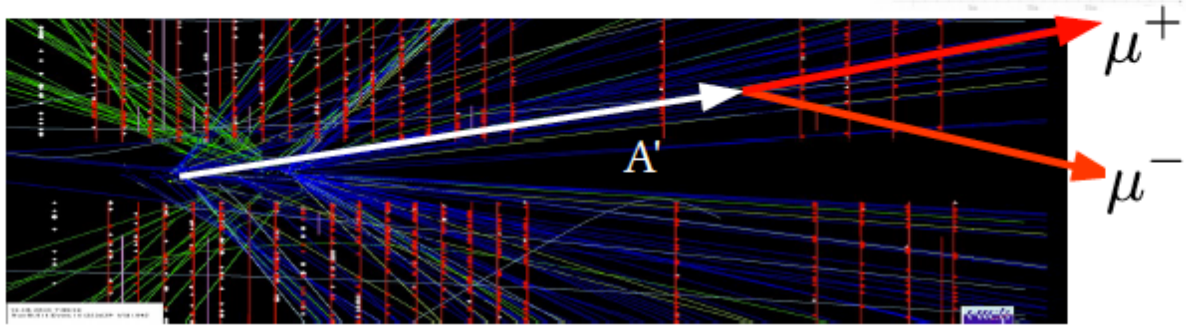
Prospects with Charm (and strange) physics

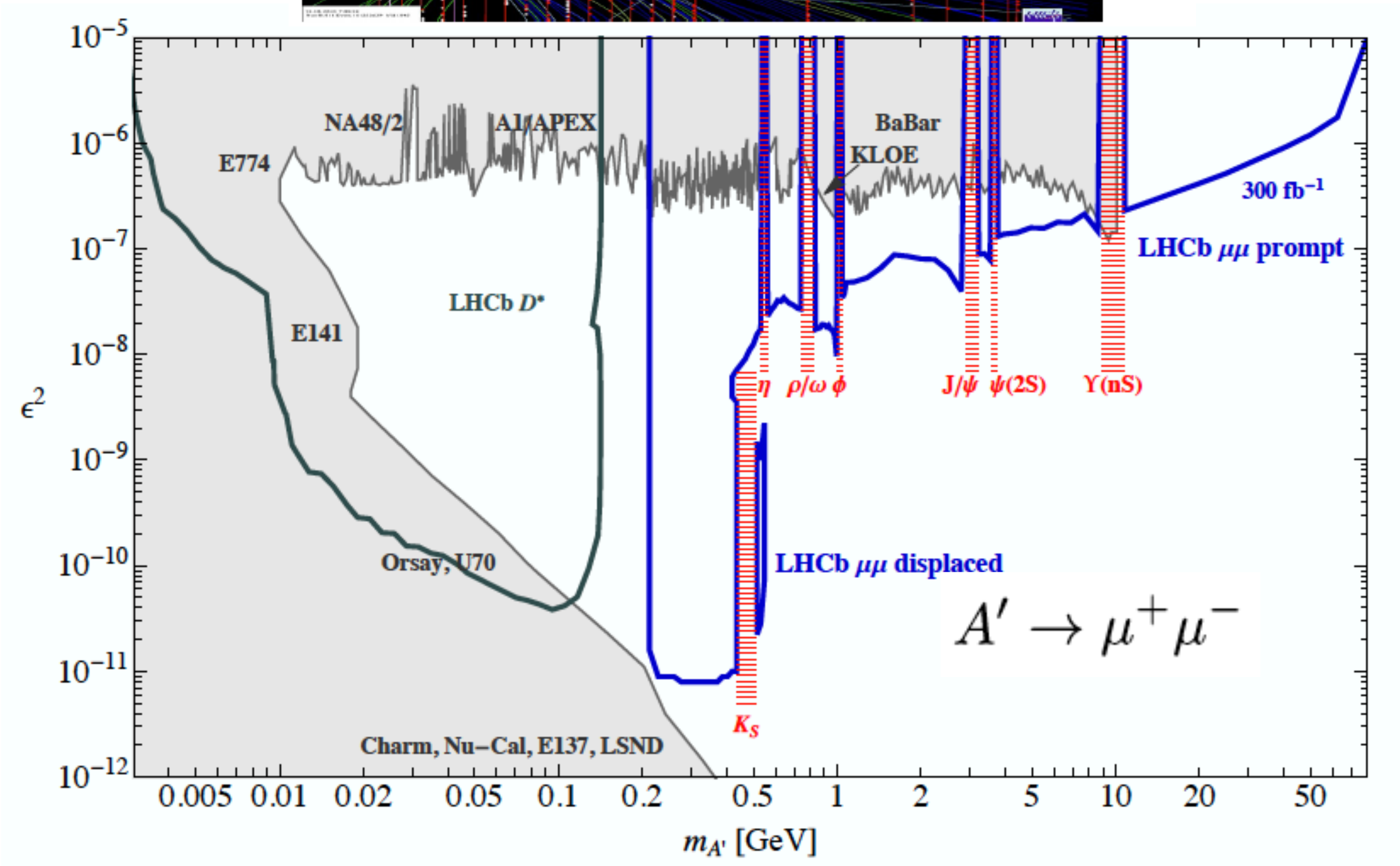
- Billions of charm and strange hadrons
  - Production rates of tens and hundreds of MHz
  - Incredible statistical precision
- Phase-II LHCb upgrade will make precision measurements of charm CPV → no other existing or planned experiment can collect such large charm samples





Search for dark photons





Summary of Phase-II upgrade prospects

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
ϕ_s with $B_s^0 \to J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$	Uncertainty on $\phi_s \approx 3\,\text{mrad}$	in CP observables from Phase-II
$\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$	Uncertainty on $\phi_s^{s\bar{s}s} \approx 8\,\text{mrad}$	ECAL and low-p tracking.
$\Delta\Gamma_d/\Gamma_d$	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.

Further steps to be made next week

- Comprehensive workshop on Phase-2 Upgrade to be held at La Biodola

https://agenda.infn.it/conferenceDisplay.py?ovw=True&confId=12253

Summary

- If present flavour anomalies are not due to fluctuations and inaccurate knowledge of QCD effects, we will know that quite soon
  - confirmation from Belle-II will be as important as first measurements!
- If we are really seeing the first cracks in the SM, then it will be of paramount importance to unveil the full picture, and it would be a shame not to exploit the full potential of the LHC for flavour physics till the last drop of protons with an LHCb Phase-II upgrade
- In the event that present anomalies will fade out, and that no direct evidence for NP will pop out of LHC, flavour physics is one of the fundamental tools to explore new directions for future adventures