Rare decays of hadrons

Marc-Olivier Bettler (CERN)

on behalf of the ATLAS, CMS and LHCb collaborations

including material provided by
Alessandro Cerri, Kai-Feng Chen, Andrea Contu, Francesco Dettori, Tim Gershon, Nuno Leonardo, Diego Martinez Santos, Fabrizio Palla, Darren Price, Pavel Řezníček, Frederic Teubert, Vincenzo Vagnoni, Benoit Viaud.

Luminosities

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

LHCb upgrade

additional ATLAS and CMS HL upgrades

The beauty production cross section is expected to double passing from 7 TeV to 14 TeV pp collisions.

Various level of projections, some very well documented and some are to be taken with more caution.

Why Flavour ?

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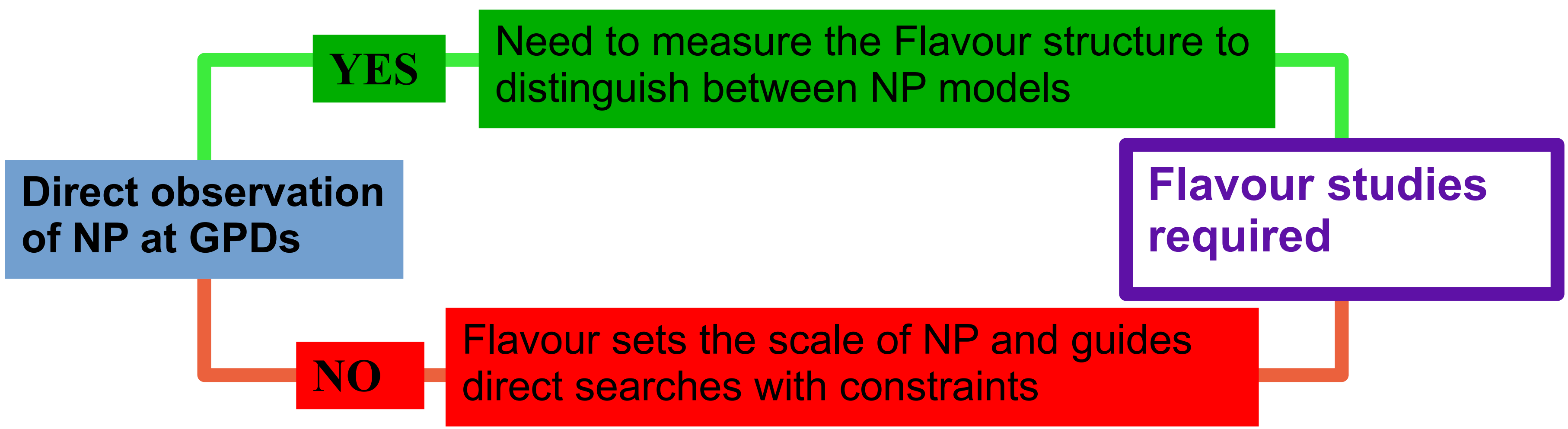
Directly: by producing 'real' new particles and observing their decays.
Reach **limited by available Energy.**

Indirectly: The effect of 'virtual' new particles in loop processes alter decays properties: branching fractions, angular distributions, asymmetries.
Tiny effects, **precision** is important, but sensitive to **higher scale.**



After the run I of the LHC, the motivation to study rare decays is stronger than ever.

Processes **suppressed in the SM** are excellent experimental **probes for BSM effects.**

In some cases the **SM** predictions are **precise** enough to allow **significant BSM discoveries**.

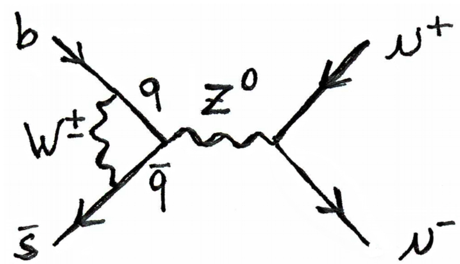
Cases that are **forbidden in the SM** provide even stronger **null-hypothesis tests.**

The use of **OPE** (separate short-distance and long distance effects, operator associated to **Wilson coefficient**) means that **meta-analyses** including multiple decays, observables, experiments are possible (and recommended). **Most relevant** way to exploit experimental results and to provide them for **interpretation.**

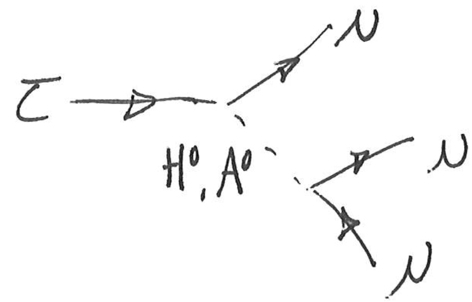
Increase in luminosity will benefit to rare and precisely predicted processes.

What rare decays?

Suppressed FCNC modes, good SM predictions

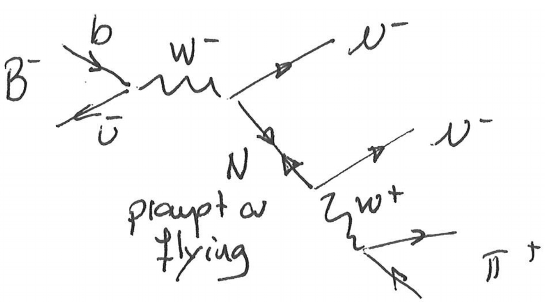


modes forbidden in the SM, as Lepton Flavour Violating.



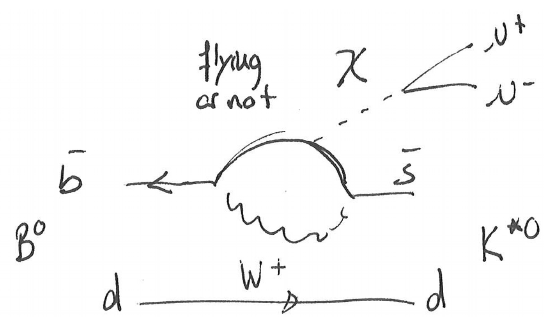
Search for short-lived new states

Search for Majorana neutrinos $B^- \to \pi^+ \mu^- \mu^-$ where N can fly or not.



Search for long-lived new states

Search for hidden sector particle in $B^0 \to K^{*0} \chi(\to \mu^+\mu^-)$ where χ can fly or not.



$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

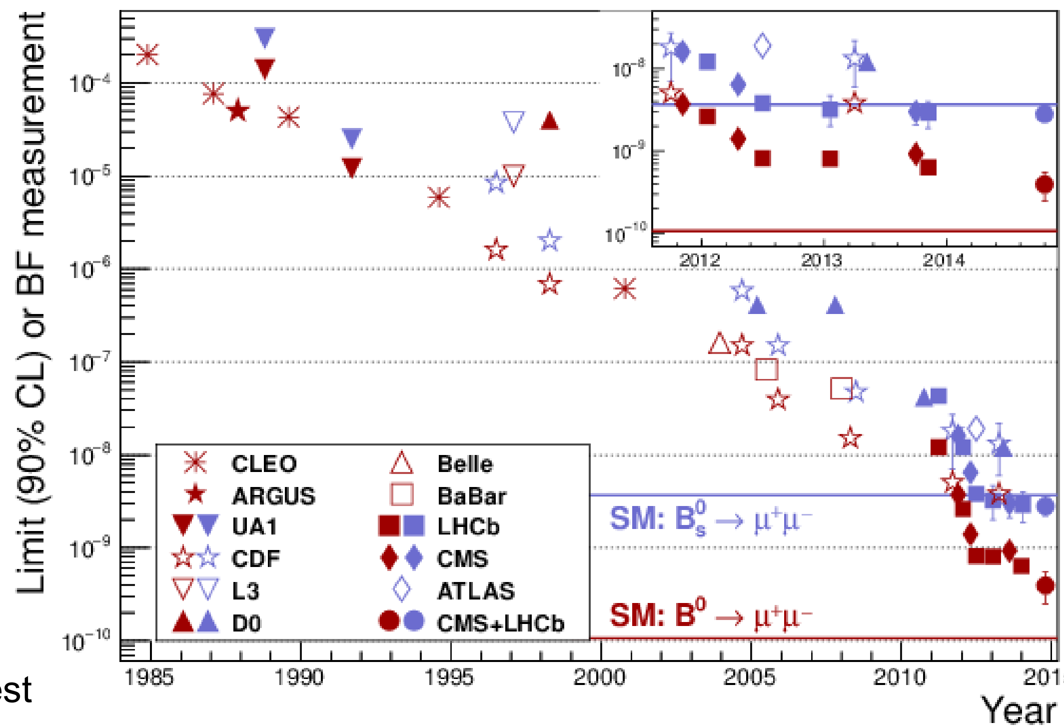
Typical example of FCNC decay very suppressed in the SM

GIM and helicity suppressed, **purely leptonic** final states allow clean theoretical prediction.

$$\mathcal{B}_{\rm SM}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}_{\rm SM}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[PRL 112 (2014) 101801]

Good NP-discovery potential:
=> searched for for 30 years
by 11 experiments including
ATLAS, CMS and LHCb.



From the PDG, with the addition of latest results by CMS and LHCb

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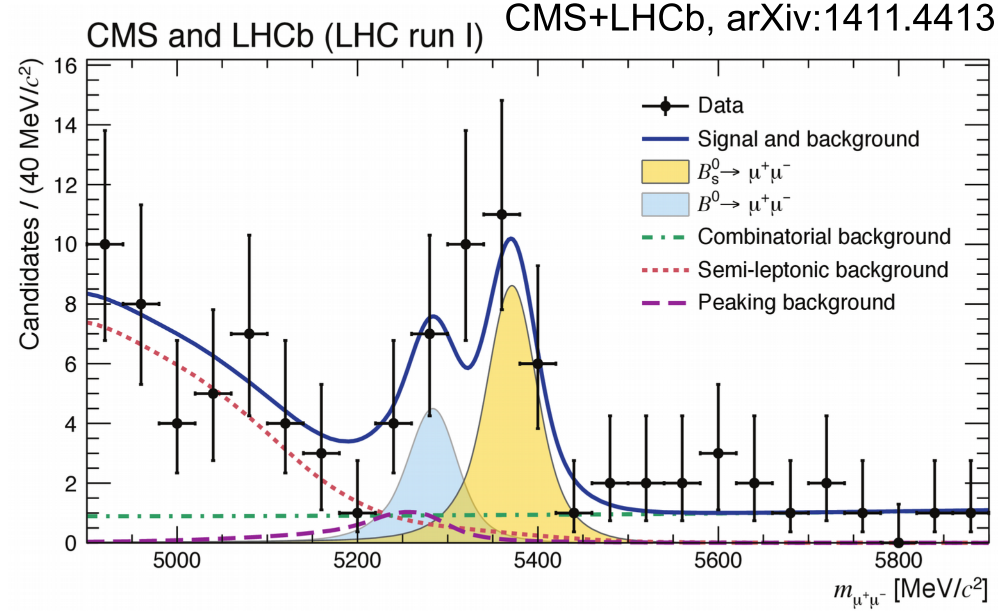
Combined analysis from CMS and LHCb of the full run I dataset.
Accepted for publication by Nature.
www.nature.com/nature/

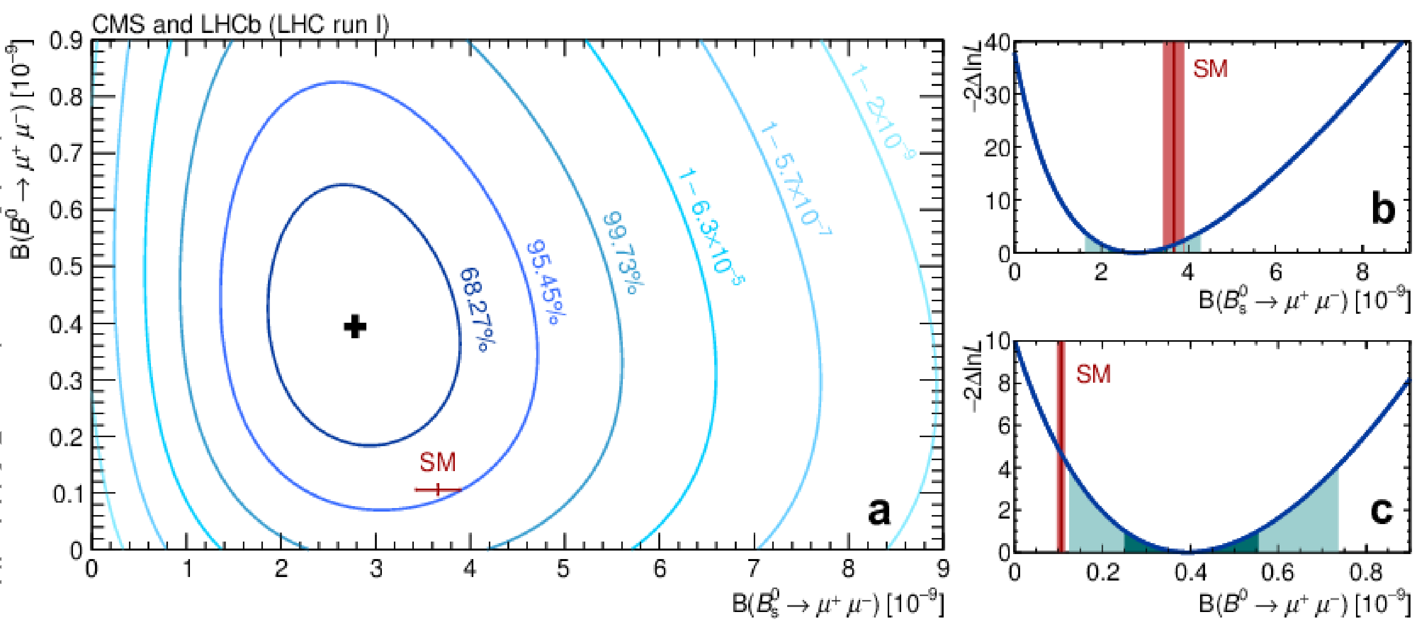
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

First observation of the B_s mode with 6.2σ. Excess of events with respect to background-only in the B^0 channel at 3σ.

CMS+LHCb, arXiv:1411.4413



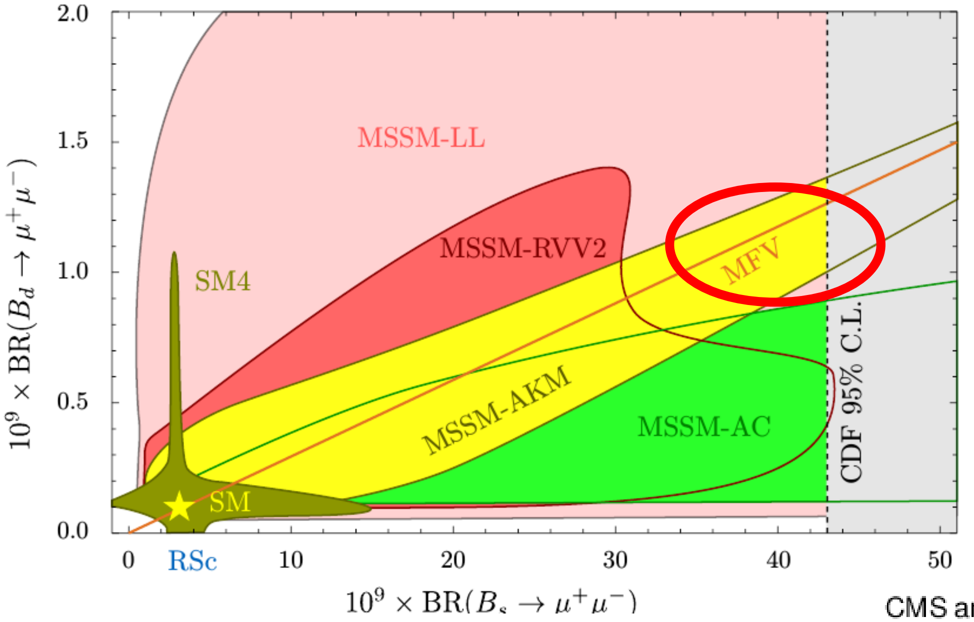


Both branching fractions compatible with the SM

at 1.2σ for the B_s mode

at 2.3σ for the B^0 mode

Straub, arXiv 1012.3893



The predicted value for the ratio of BF is identical in the SM and in MFV models.

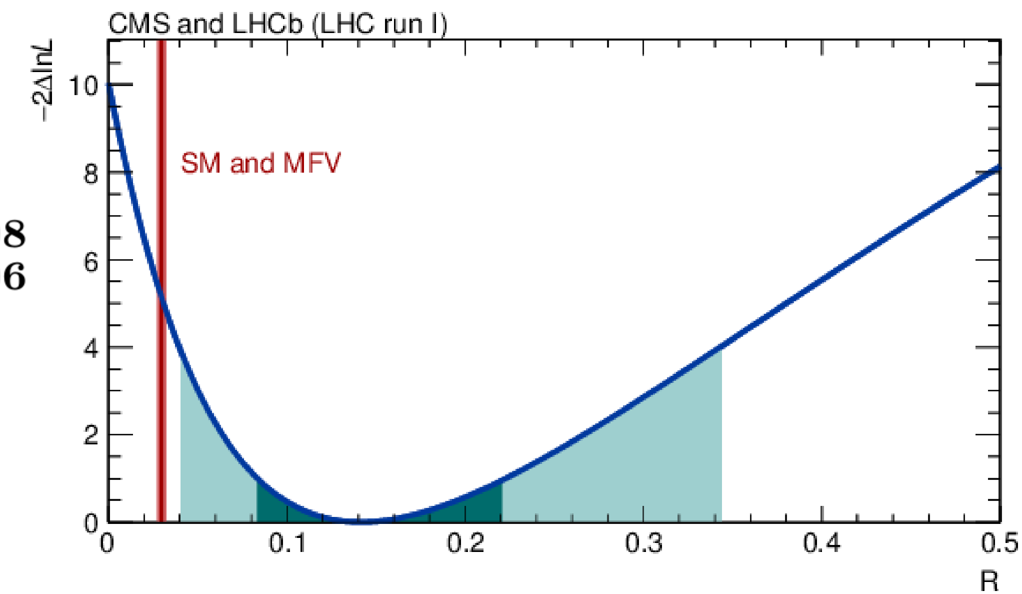
This ratio is an important quantity as its value is well defined for NP models with the property of **Minimal Flavour Violation (MFV)**

For the first time, one measures the ratio of BF

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)} = 0.14^{+0.08}_{-0.06}$$

.

2.3σ away from the SM and MFV value.

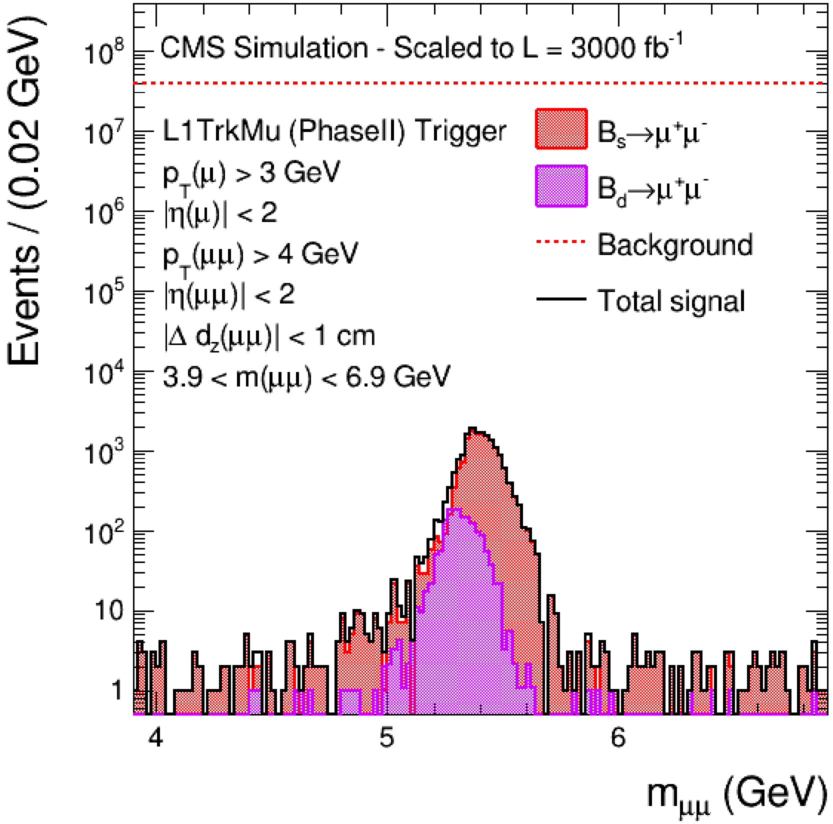


$B^0_s \to \mu^+\mu^-$ was studied as a benchmark channel for assessing CMS B physics reach after the phase II upgrade.

The main effects from the upgrade on this analysis originate from :
- **Tracker:** reduced material budget and increased resolution
- **L1 Trigger:** benefiting from the track trigger machinery.

Thus the analysis has been updated via
- the implementation of a **dedicated L1 track trigger** dedicated to these decays.
- the effect on the analysis of the **expected overall performance** improvements.

L1 track trigger for $B^0_{(s)} \to \mu^+\mu^-$



Low p_T dimuon trigger exploiting the capability of the upgraded CMS tracker.

The **L1 mass resolution** is expected to be about **70 MeV**

Trigger rate in the HL-LHC conditions (average of 140 PU events) is estimated to be **a few hundred Hz**

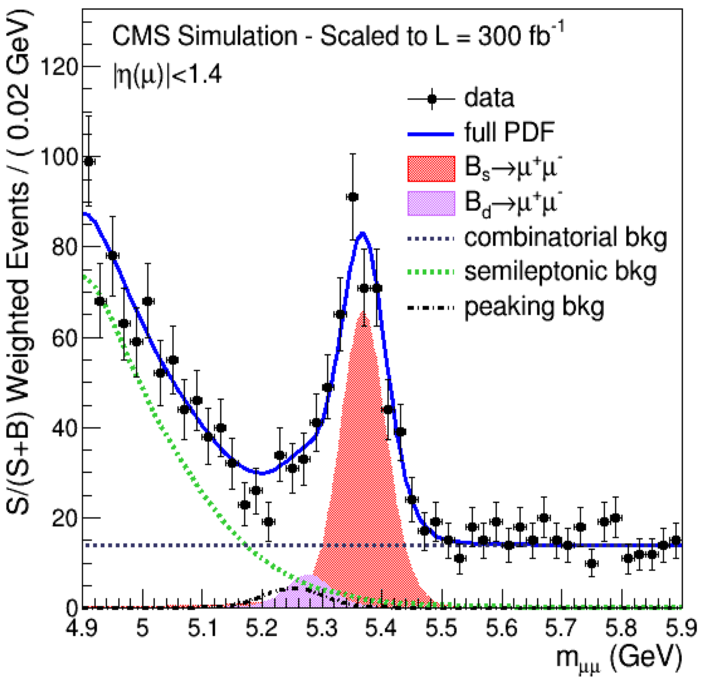
This study shows that the expected performances of the upgraded CMS L1 trigger are more than sufficient to implement trigger algorithm for $B^0_s \to \mu^+\mu^-$ having the same acceptance of the L1 trigger used in LHC Run 1

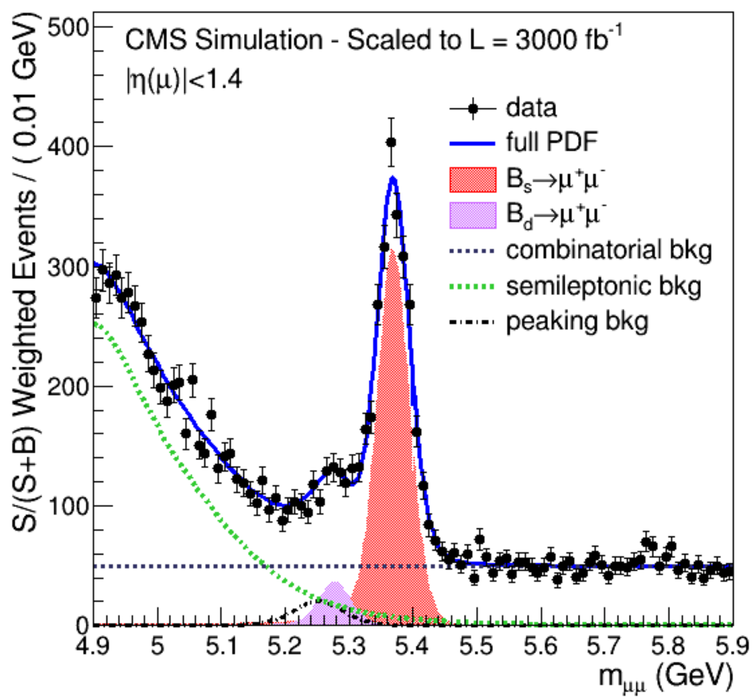
Pre HL-LHC, 300 fb^{-1}
mass resolution 42 MeV

- $\sigma\mathcal{B}(B^0_s \to \mu^+\mu^-)$: 13%
- $\sigma\mathcal{B}(B^0 \to \mu^+\mu^-)$: 48%
- σ(ratio): 50%
- $B^0 \to \mu^{+-}\mu^-$: 1.2 – 3.3σ

HL-LHC, 3000 fb^{-1}
mass resolution ~ 28 MeV

- $\sigma\mathcal{B}(B^0_s \to \mu^+\mu^-)$: 11%
- $\sigma\mathcal{B}(B^0 \to \mu^+\mu^-)$: 18%
- σ(ratio): 21%
- $B^0 \to \mu^{+-}\mu^-$: 6 - 8σ





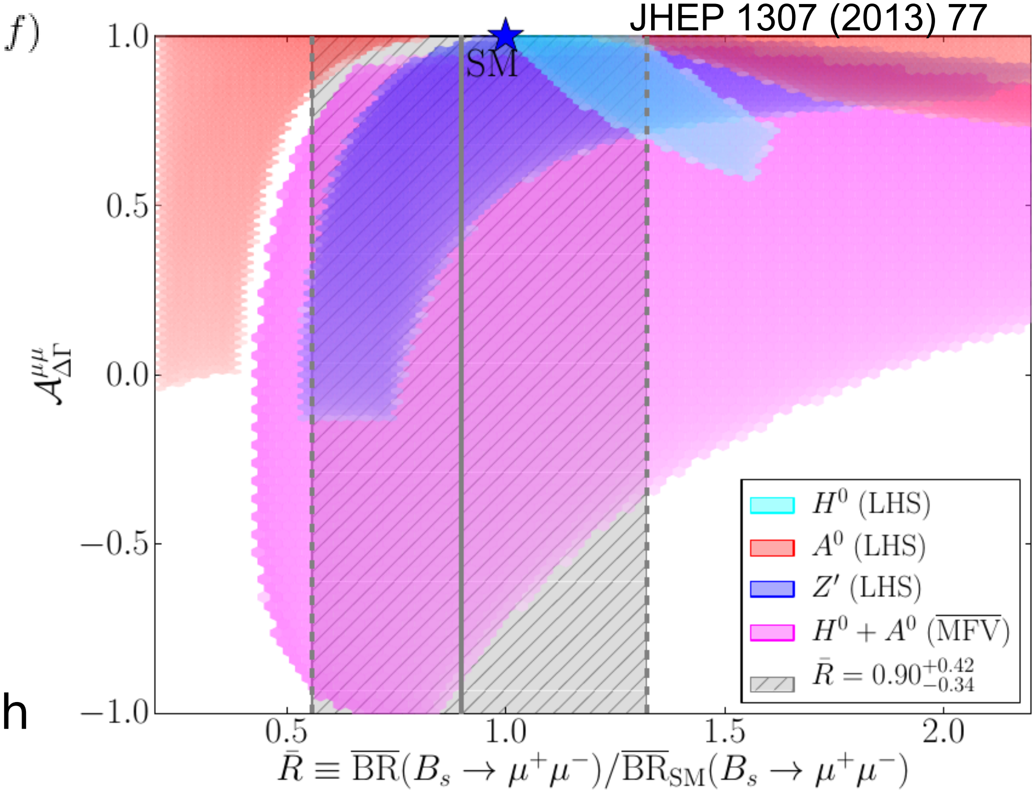
The light and heavy mass eigenstates of the B^0_s do not follow the same dynamics in $B^0_s \to \mu^+\mu^-$ giving rise to a **new observable sensitive to NP** and independent from the BF: **the effective lifetime**.

PRL 109, 041801 (2012)

$$\langle \Gamma(B_s(t) \to f) \rangle \equiv \Gamma(B^0_s(t) \to f) + \Gamma(\bar{B}^0_s(t) \to f)$$

$$\propto e^{-t/\tau_{B_s}} \left[\cosh(y_s t/\tau_{B_s}) + \mathcal{A}_{\Delta\Gamma} \sinh(y_s t/\tau_{B_s})\right]$$

JHEP 1307 (2013) 77

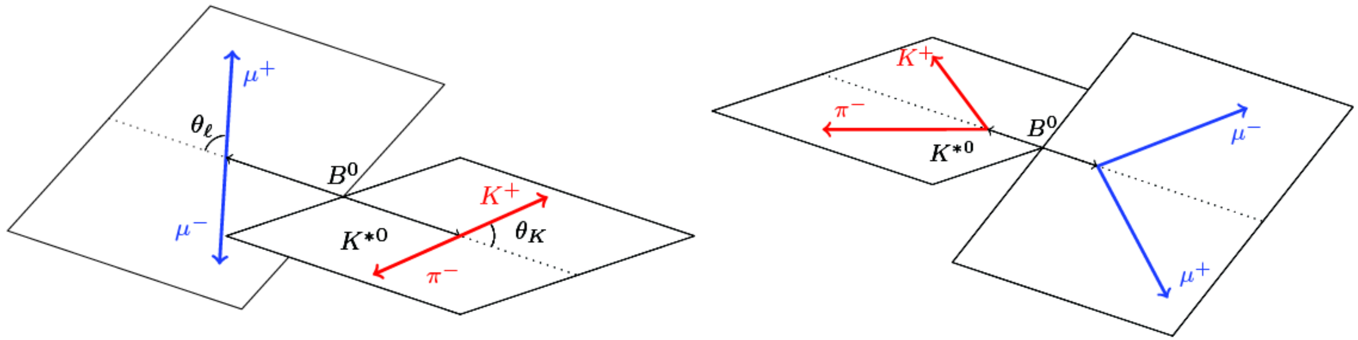


LHCb could reach a 5% uncertainty on the effective lifetime with $46\mathrm{fb}^{-1}$.

Another independent observable identified, but it requires **tagging**. Promising with high luminosity.

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

Four-particle final state allows for wealth of observables in angular distributions along **three angles (θ_l, θ_K, φ)** and the **dimuon invariant mass squared q^2.**

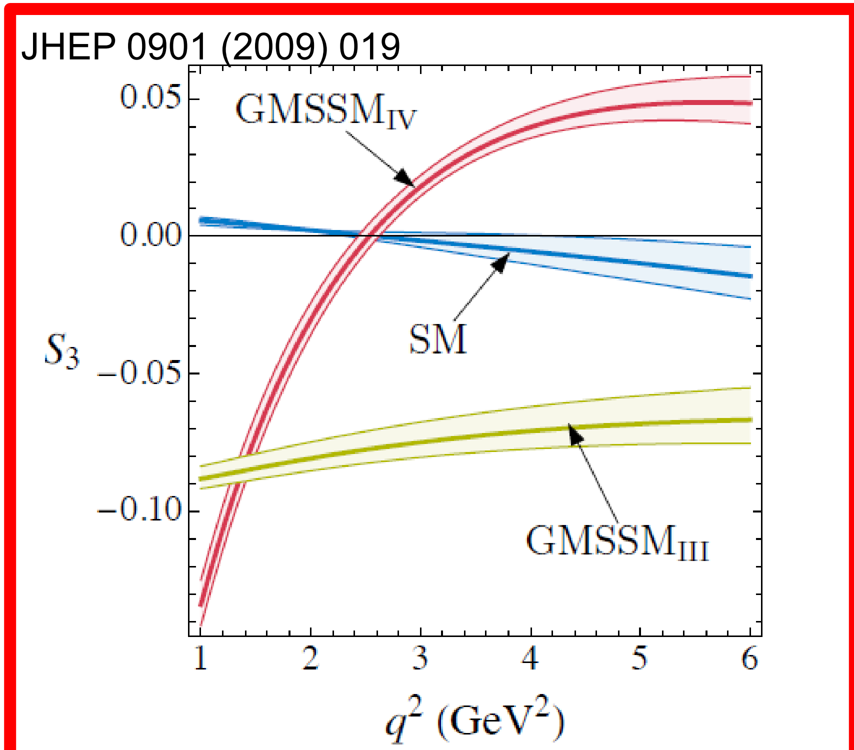


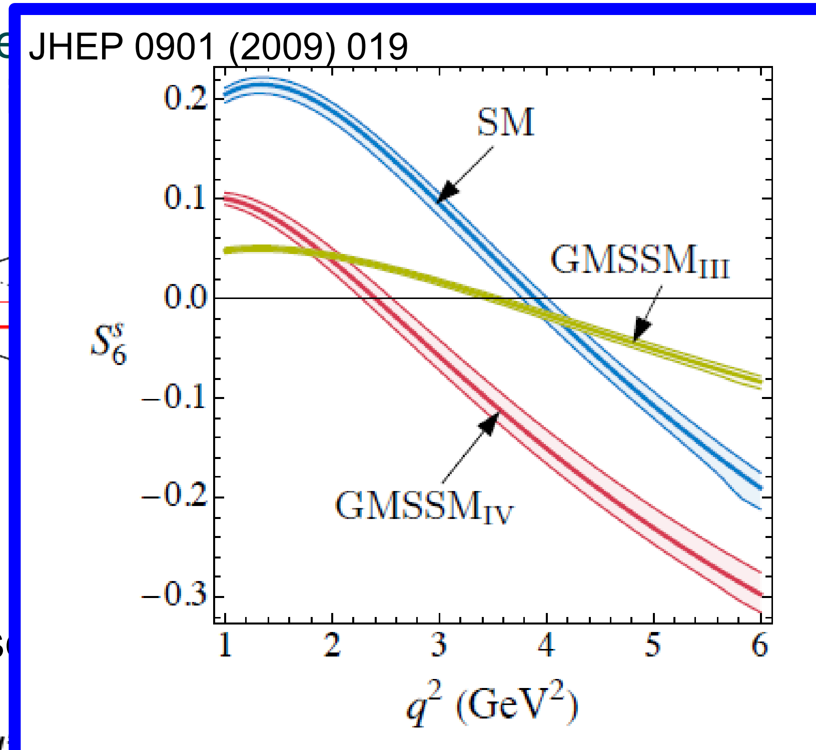
Differential BF and angular distribution, sensitive to NP:

$$\frac{\mathrm{d}^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}\cos\theta_\ell \,\mathrm{d}\cos\theta_K \,\mathrm{d}\phi \,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + J_6 \cos^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

Studied by number of experiments, including **ATLAS, CMS and LHCb.**

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis





$$J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi +$$
$$J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + J_6 \cos^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi +$$
$$J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

Studied by number of experiments, including **ATLAS, CMS and LHCb.**

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

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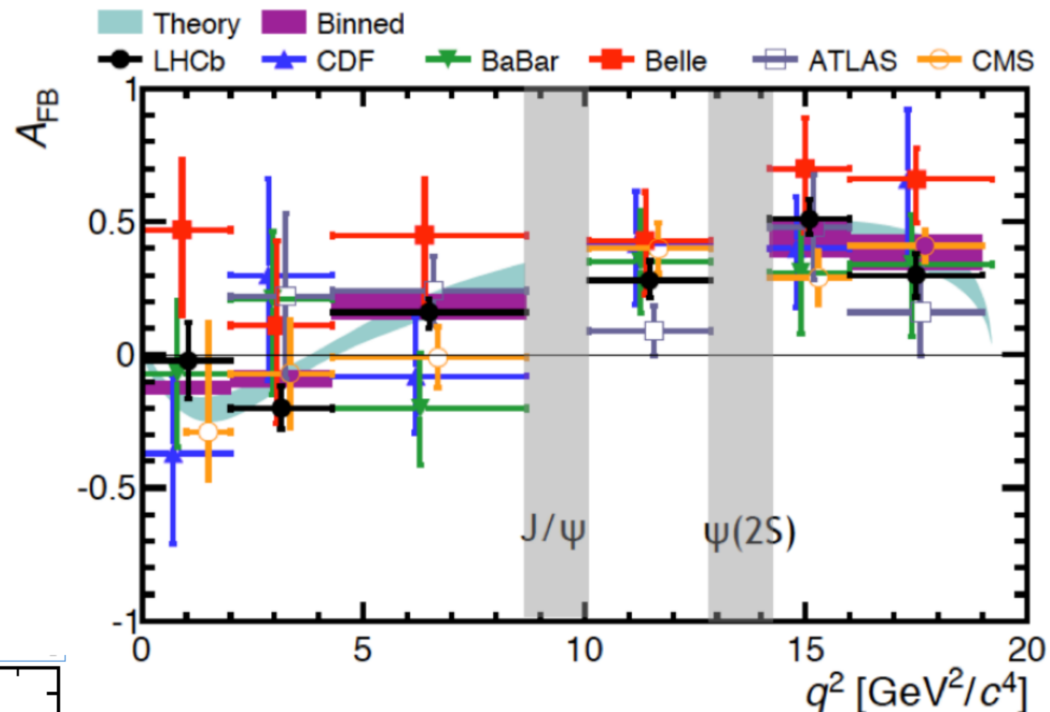
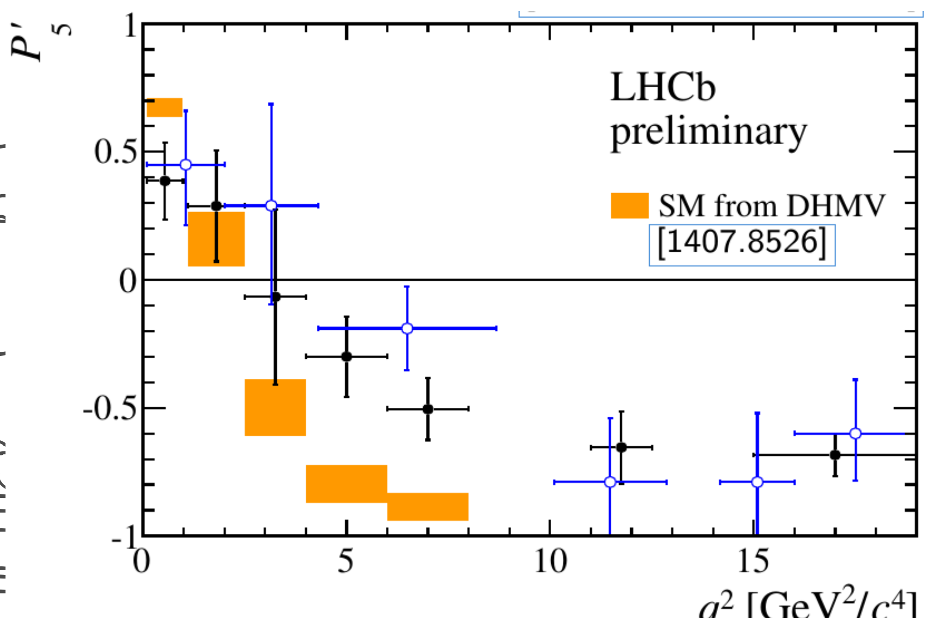
$$A_{FB} = \frac{\Gamma(\cos\theta_{B\ell^+} > 0) - \Gamma(\cos\theta_{B\ell^+} < 0)}{\Gamma(\cos\theta_{B\ell^+} > 0) + \Gamma(\cos\theta_{B\ell^+} < 0)}$$

The forward-backward asymmetry A_{FB} is the most studied, but new observables have been identified that are theoretically cleaner, as P'_5

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$





Anomaly (~3.7σ) in one bin of P'_5 in the 2011 data confirmed with 3fb^{-1}.

Triggered a lot of activity by theorists.
Meta-analysis is more powerful!
(include other observable in a global fit to the Wilson coefficients)

PRL 111, 191801 (2013), 1fb^{-1}

LHCb-CONF-2015-002, 3fb^{-1}

Test of lepton universality

In the SM, couplings to all leptons are universal (apart from tiny Higgs couplings)

Test lepton universality in $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$

$$R_K = \frac{\int_{q^2=1\,\mathrm{GeV}^2/c^4}^{q^2=6\,\mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2)\mathrm{d}q^2}{\int_{q^2=1\,\mathrm{GeV}^2/c^4}^{q^2=6\,\mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+e^+e^-]/\mathrm{d}q^2)\mathrm{d}q^2} = 1 \pm \mathcal{O}(10^{-3})$$

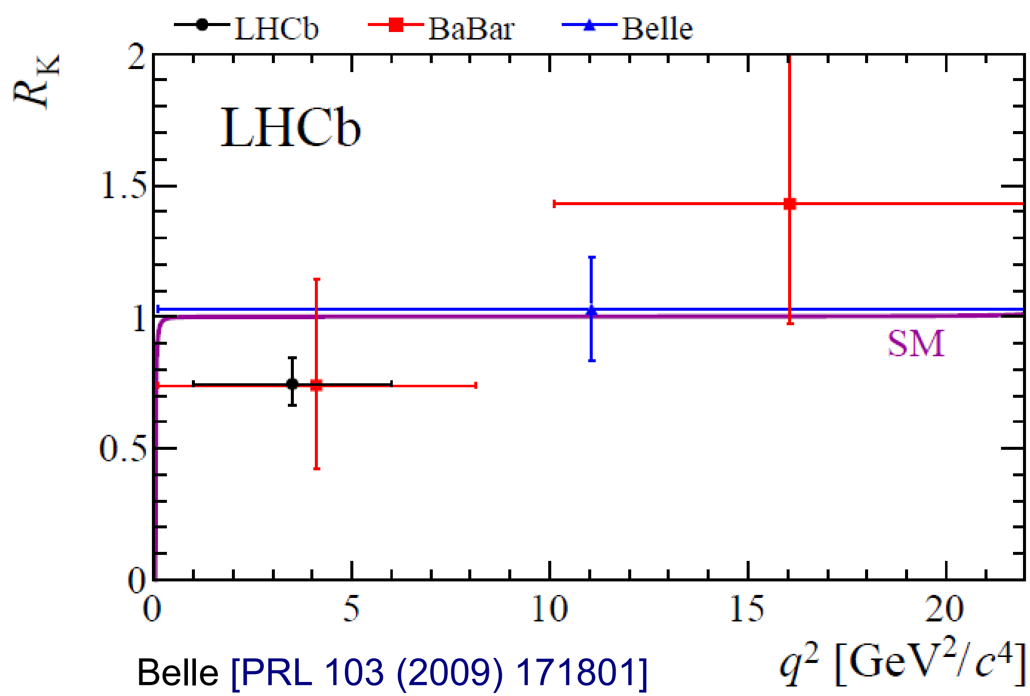
[JHEP 12 (2007) 040]

In 3 fb^{-1}, LHCb measures

$$R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat})^{+0.036}_{-0.036}(\mathrm{syst})$$

2.6σ away from the SM.

PRL 113 (2014) 151601



Belle [PRL 103 (2009) 171801]
Babar [PRD 86 (2012) 032012]

Other modes suitable for the same test, $B^0 \to K^{*0} l^+l^-$, $B_s \to \varphi\, l^+l^-$, $\Lambda_b \to \Lambda\, l^+l^-$

"We urge that **$B \to K^{(*)}\mu^\pm e^\mp$ and $B \to K^{(*)}\mu^\pm\tau^\mp$ and other LFV** be sought with renewed vigor in LHC Run II."

S.L. Glashow, PRL 114, 091801 (2015)

meta-analysis

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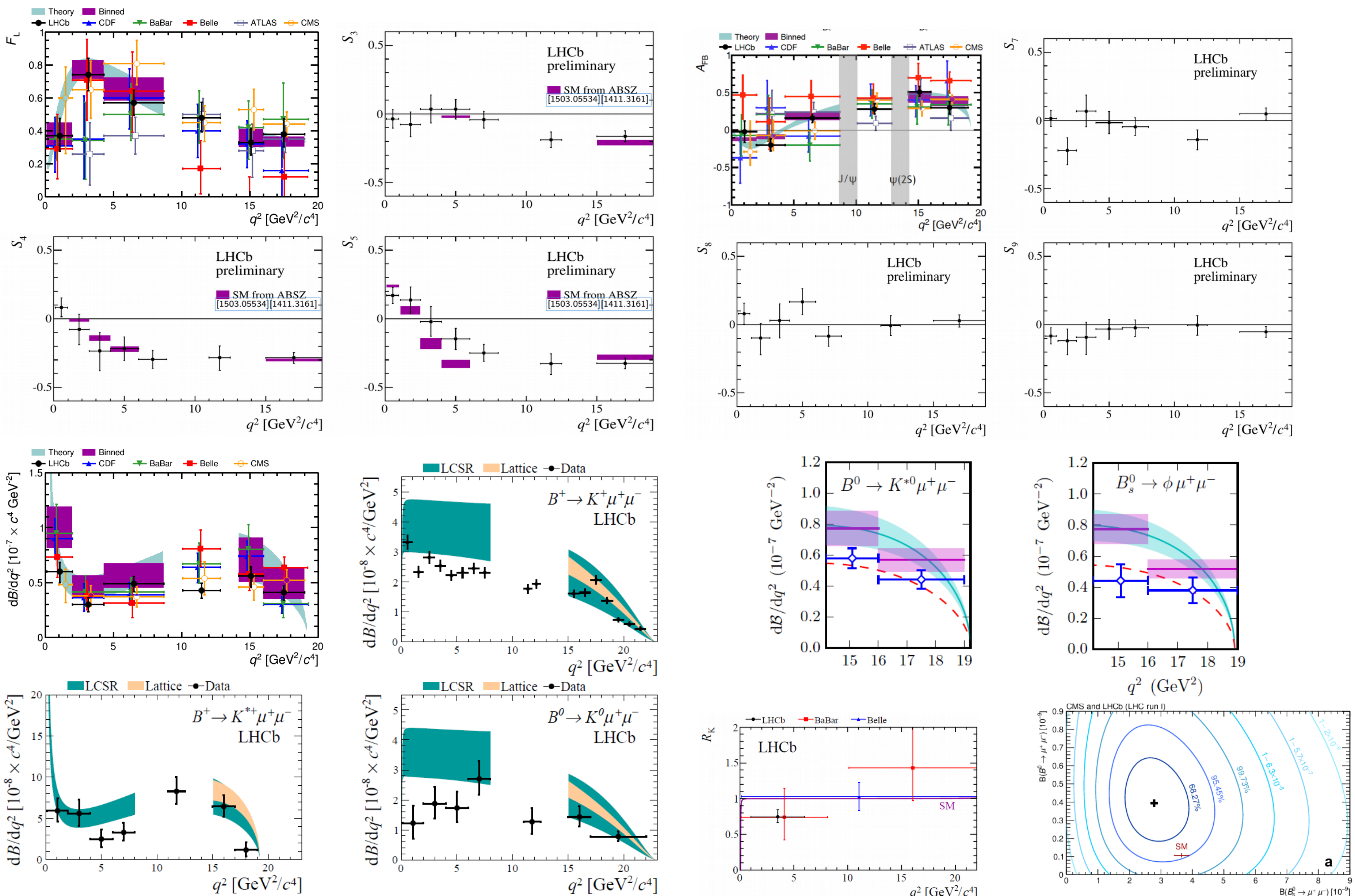
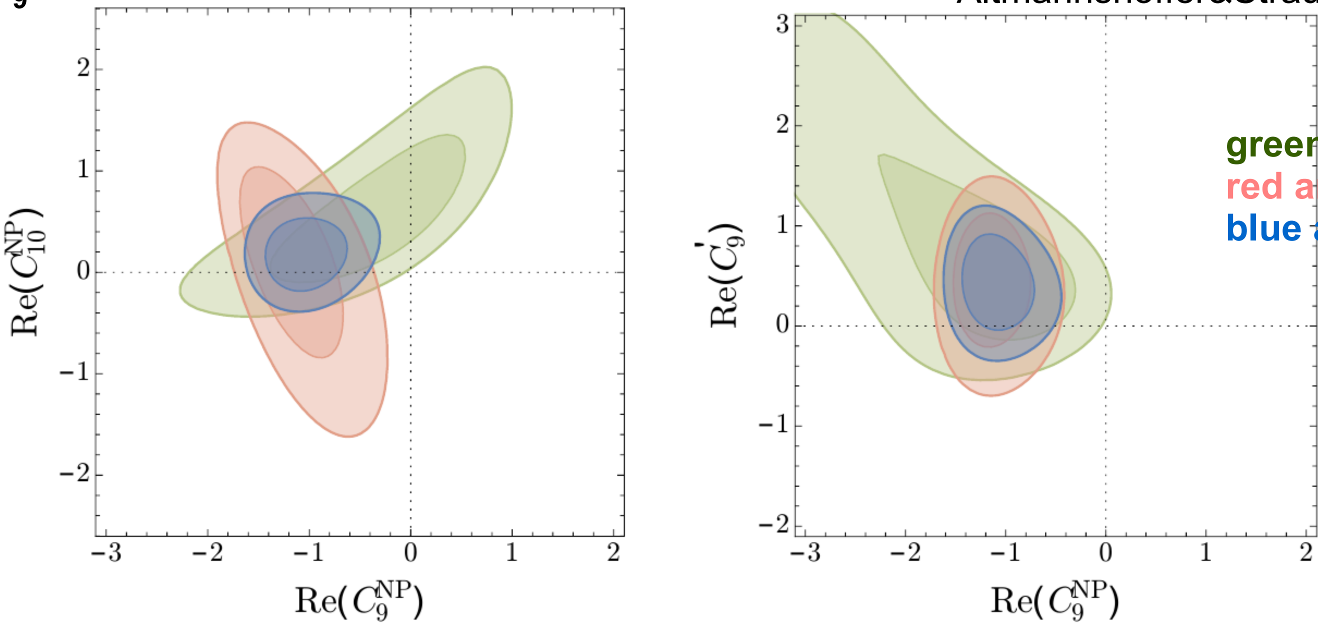
HL-LHC Rare decays of hadrons



Best fit to 88 measurements ► NP in the Wilson coefficient C_9

C^{NP}_9 = -1.07, 3.7σ away from SM.

Altmannshoffer&Straub [1503.06199]



green BF-data only
red angular data only
blue all

Consistent picture with different inputs PRD 88, 074002, arXiv:1411.3161, EPJC 74 2897, JHEP 04 097

Unexpectedly large hadronic effects, or charm loops, could be at play, but:

1. The hadronic effect cannot violate LFU, so if the violation of LFU in R_K (or any of the other observables suggested, e.g., in [12]) is confirmed, this hypothesis is refuted;

2. There is no *a priori* reason to expect that a hadronic effect should have the same q^2 dependence as a shift in C_9 induced by NP.

Altmannshoffer&Straub [1503.06199]

NP interpretation through a Z' arxiv:1310.1082, arxiv:1311.6729

Need more experimental inputs from all experiments

Call for anticipated collaboration

The discovery of NP, either directly, or in a single indirect measurement is the **dream scenario.**

However, **in case that the BSM effects are tiny** we will need to **combine channels to see it, and certainly to understand it.**

The complete exploitation of the LHC data requires combination of measurement of sensitive decays from all the players.

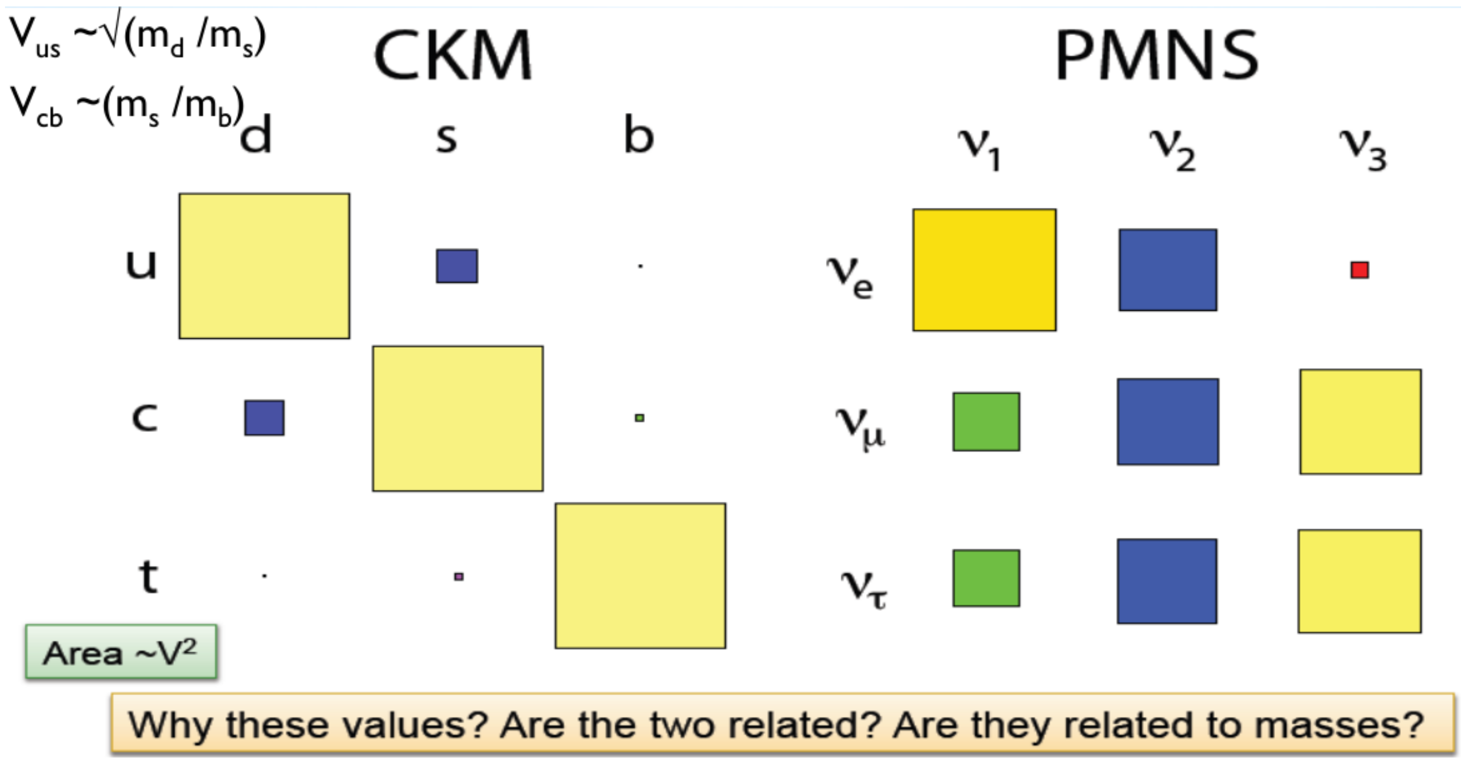
Flavour physics is a platform that is particularly suitable for (model-independent) combinations, through the OPE and the determination of Wilson coefficients.

We have to discuss **in advance** so that we produce **independently** results that can **be combined in an optimal way** later on.

Consider binning, hidden assumptions, correlated inputs, MC generator and Form Factors, B hadronisation probability, f_d/f_s.

Lepton Flavour Violation

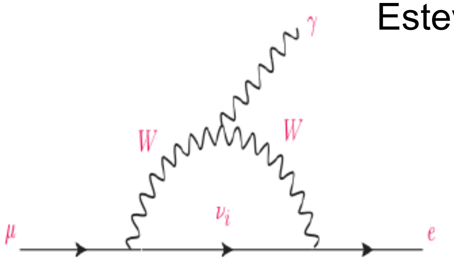
Since neutrinos are observed to oscillate, FCNC transitions exist in the lepton sector as well.



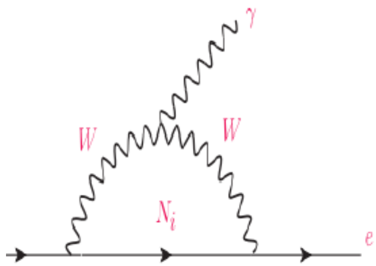
The **seesaw mechanism** could explain the very different flavour structure between the quarks and the leptons.

Dirac or Majorana?

Esteves et al., 2011



$$\mathrm{Br}(\mu \to e\gamma) \sim \frac{3\alpha}{32\pi}\Big(\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{m_W^2}\Big)^2 \lesssim 10^{-53}$$



$$\mathrm{Br}(\mu \to e\gamma) \sim \frac{\alpha^3 s_W^2}{256\pi^2} \frac{m_\mu^5}{m_W^4 \Gamma_\mu}\Big(\sum_i K^*_{\mu i} K_{ei} G\big(\frac{m^2_{N_k}}{m_W^2}\big)\Big)^2 \lesssim 9 \times 10^{-6}\Big(\sum K^*_{\mu i} K_{ei} G\big(\frac{m^2_{N_k}}{m_W^2}\big)\Big)^2$$

If **neutrinos are Dirac** particles, Charged Lepton Flavour Violation **(CLFV) is expected to be tiny** (out of experimental reach)

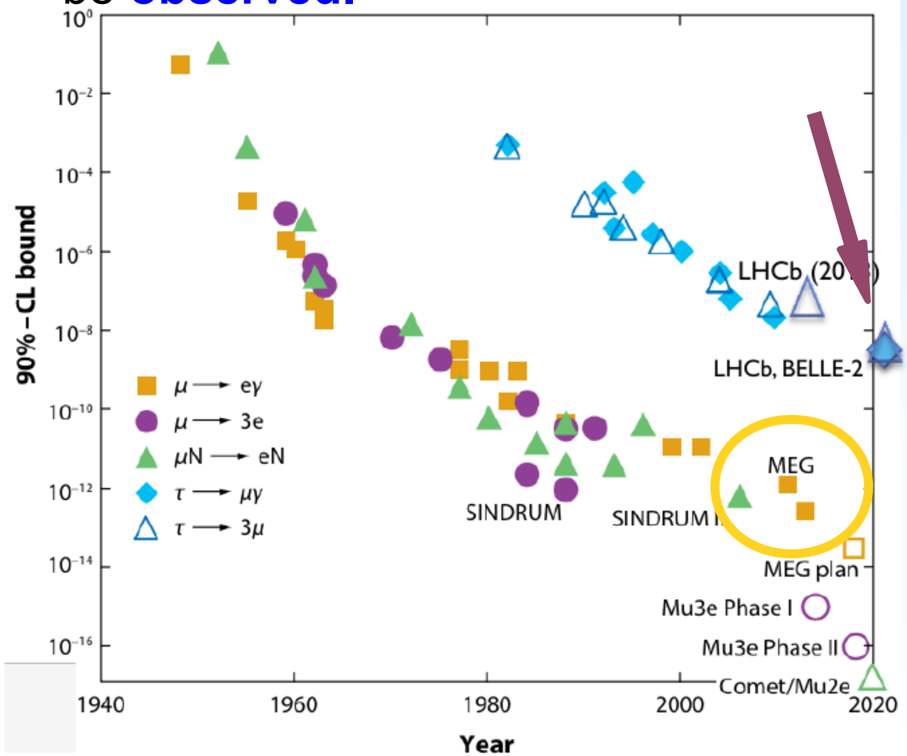
If **neutrinos are Majorana** particles, the and the seesaw mechanism at work, **CLFV can be** large enough to be **observed.**

In general, **any BSM** with new states **at ~TeV scale generates large CLFV**.

MEG at PSI has put limits at 5.7 10^{-13} on **$\mu \to e\gamma$!**

Even within this bound, **$\tau \to \mu\mu\mu$** can be enhanced up to 10^{-10}-10^{-9}.

Very close to the reach of LHCb and Belle2 by 2020.



Rare Kaon decays?

Minimal Flavour Violating NP is motivated if the scale of NP ~TeV
But is NP > few TeV, non-MFV becomes very interesting.

Short-distance FCNCs with the strongest CKM suppression:

G. Isidori

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

$\sim V_{ts} V_{td} \sim 10^{-4}$
for (short-distance) $s \rightarrow d$ transitions

Limited number of possible final states which allow clean studies of light weakly-coupled new particles.

Kaon decays are the most sensitive probes for possible to non-MFV couplings.

Enormous effective flux of K^0_S and hyperons, at LHCb more than 10^{13} K^0_S/year.

$K^0_L \to \mu^+\mu^-$ is a corner stone of the SM.

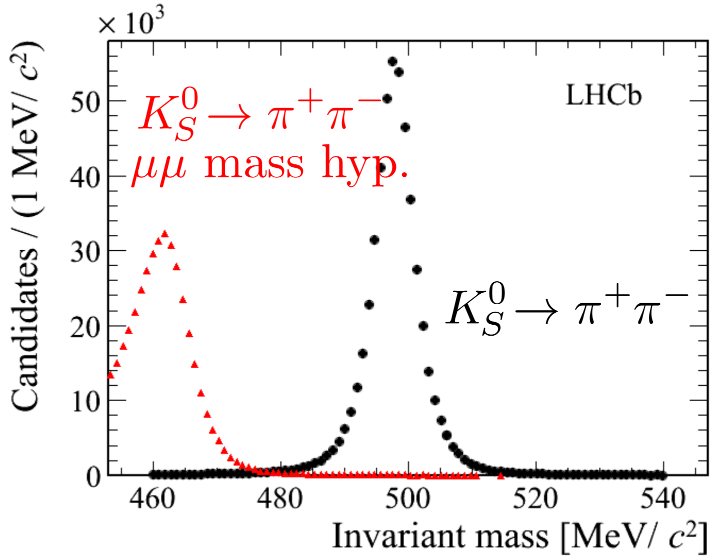
$K^0_s \to \mu^+\mu^-$ is still unobserved and its SM prediction $\mathcal{B}(K^0_s \to \mu^+\mu^-) = (5.1 \pm 1.5)\ 10^{-12}$

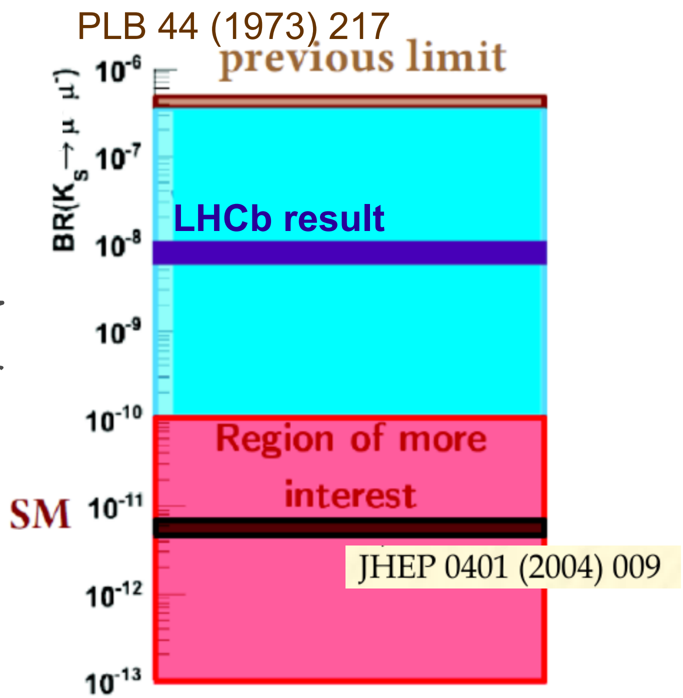
JHEP 0401 (2004) 009

Different physics is a play, its **BF can be NP-enhanced.**

$\mathcal{B}(K^0_s \to \mu^+\mu^-) < 9\ 10^{-9}$ at 90% CL, LHCb, 1fb^{-1}

[JHEP 01 (2013) 090]





mass resolution is crucial

The trigger is difficult, was already improved by a factor 3.

Great improvement (another factor greater than 10) expected from a fully software trigger after LS2.

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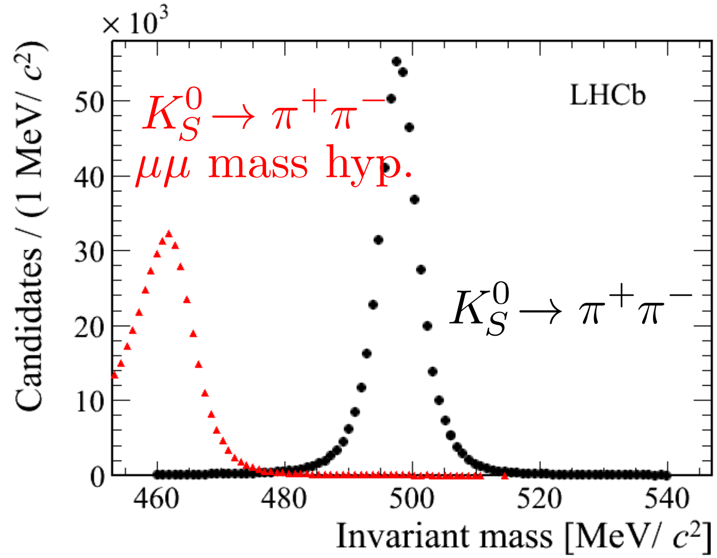

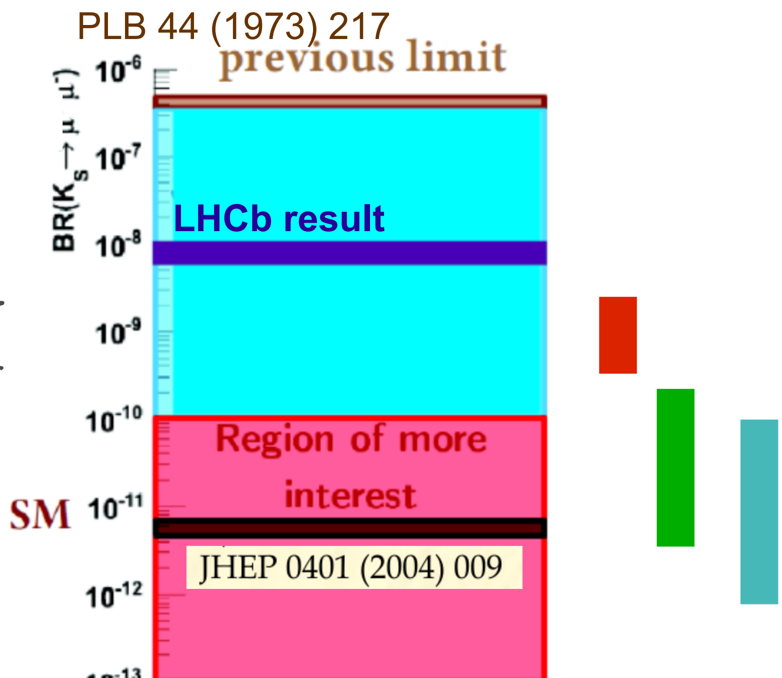

Sensitivity range for $\mathcal{B}(K^0_S \to \mu^+\mu^-)$, lower bound is optimistic.

8 fb^{-1} run II, [$4\cdot10^{-10}$, $2\cdot10^{-9}$]

23 fb^{-1}, [$4\cdot10^{-12}$, $2\cdot10^{-10}$] with software trigger. Possibility to probe SM level.

100 fb^{-1}, [10^{-12}, 10^{-10}]

Other rare Kaon decays?

$K^0_L \to \mu^+\mu^-$ is a corner stone of the SM.
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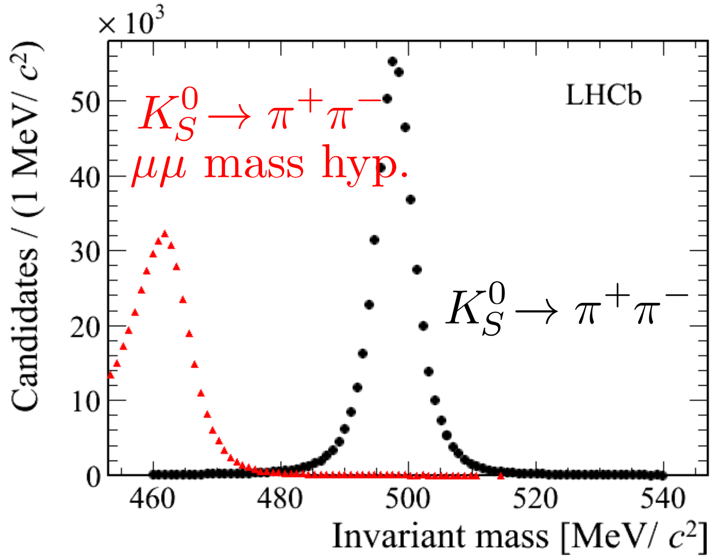
JHEP 0401 (2004) 009

Different physics is a play, its BF can be NP-enhanced.
$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 9\ 10^{-9}$ at 90% CL, LHCb, 1fb^{-1}



Sensitivity to other modes under study:

$K^0_S \to \pi^0\mu^+\mu^-$: $\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-)$ is sensitive to NP but limited by the experimental uncertainty on $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$.

$K^0_S \to \pi^+\pi^-\mu^+\mu^-$, $K^0_S \to \mu^+\mu^-\mu^+\mu^-$, electron modes
D'Ambrosio, Eur. Phys. J. C (2013) 73:2678

Dedicated triggers are being designed.

Prospects with rare charm decays

Decays are very suppressed in the SM (10^{-9}-10^{-10}), potential NP enhancement by an order of magnitude.

Modes	Run I	Run II	28fb^{-1}
$D^0 \rightarrow \mu^+\mu^-$	few 10^{-9}	fewer 10^{-9}	few 10^{-10}
$D^+ \rightarrow \pi^+\mu^+\mu^-$	few 10^{-8}	fewer 10^{-8}	few 10^{-9}
$D^+_s \rightarrow K^+\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}
$D^0 \rightarrow h^+h'^{(-)}\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}
$\Lambda_c \rightarrow p\mu\mu$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}
$D^0 \rightarrow \mu e$	few 10^{-8}	fewer 10^{-8}	few 10^{-9}
$\sigma A_{CP}(D^0 \rightarrow \phi\gamma)$	10%	5%	?

Based on current result, scaling for luminosity and cross section.

Current studies.
With more statistics, more NP-sensitive observables: asymmetries

These modes will benefit from a full-software trigger after LS2, with a jump >3 in efficiency (not included in prospects above)

Interest for a theoretical framework to **combine rare charm** measurements.

Rare decays have provided **very important constraints on NP** with LHC run I.

A few hints to be followed with more statistics and checked with **independent measurements and other experiments.**

Important to preserve our capabilities at higher instantaneous luminosity, actually prospects to improve the performance (trigger).

Expand the physics program with measurements that are less obvious.

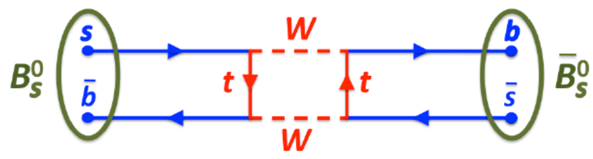
The **indirect approach** in the search of New Physics is **complementary to the direct one** and mandatory to **understand the nature of New Physics.**

Backup

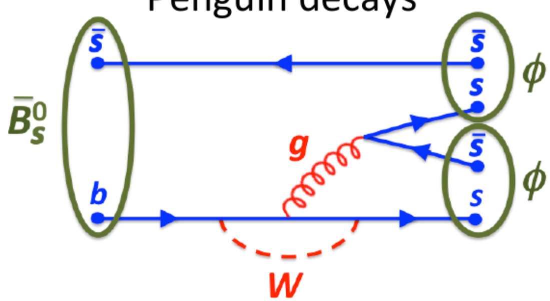
Flavour Physics

searching for new particles through their virtual effects

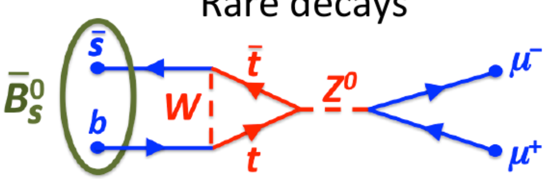
Mixing



Penguin decays



Rare decays



- Precision measurements of *CP* violation and rare decays
- If the SM contribution is not negligible, uncertainties on the SM coupling can hide NP effects
  - Need to focus on theoretically clean processes
- Who will win the reality vs virtuality race?

The Upgrade in a nutshell

Indirect search strategies for New Physics, *e.g.* precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive following the experience of LHC 1 run that direct signals are elusive

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond run II requires significant changes.

The LHCb Upgrade

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

2) Raise operational luminosity to 2×10^{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.

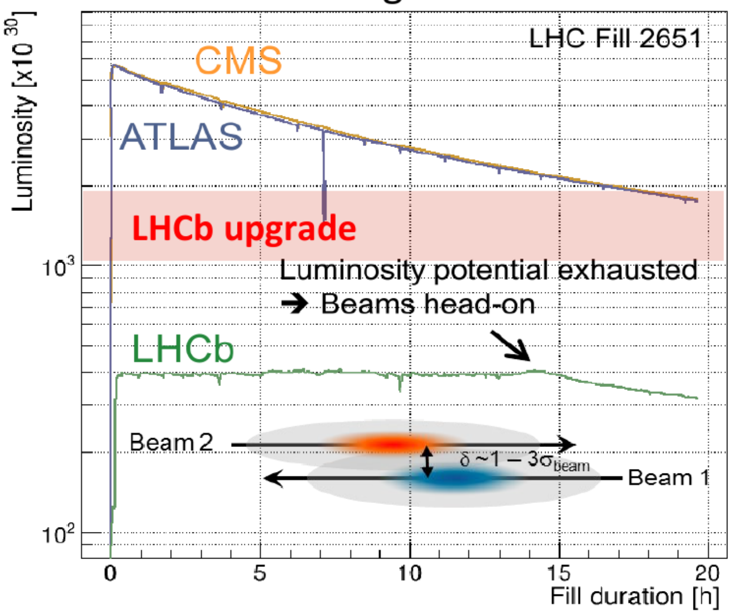
Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour ('a general purpose detector in the forward region')

How to increase LHCb statistics

Up to LS2

- running at levelled luminosity of $4\cdot10^{32}\,cm^{-2}s^{-1}$
- software trigger running at 1 MHz after hardware trigger
- record 10-12.5 kHz

2012 running conditions



LHCb upgrade

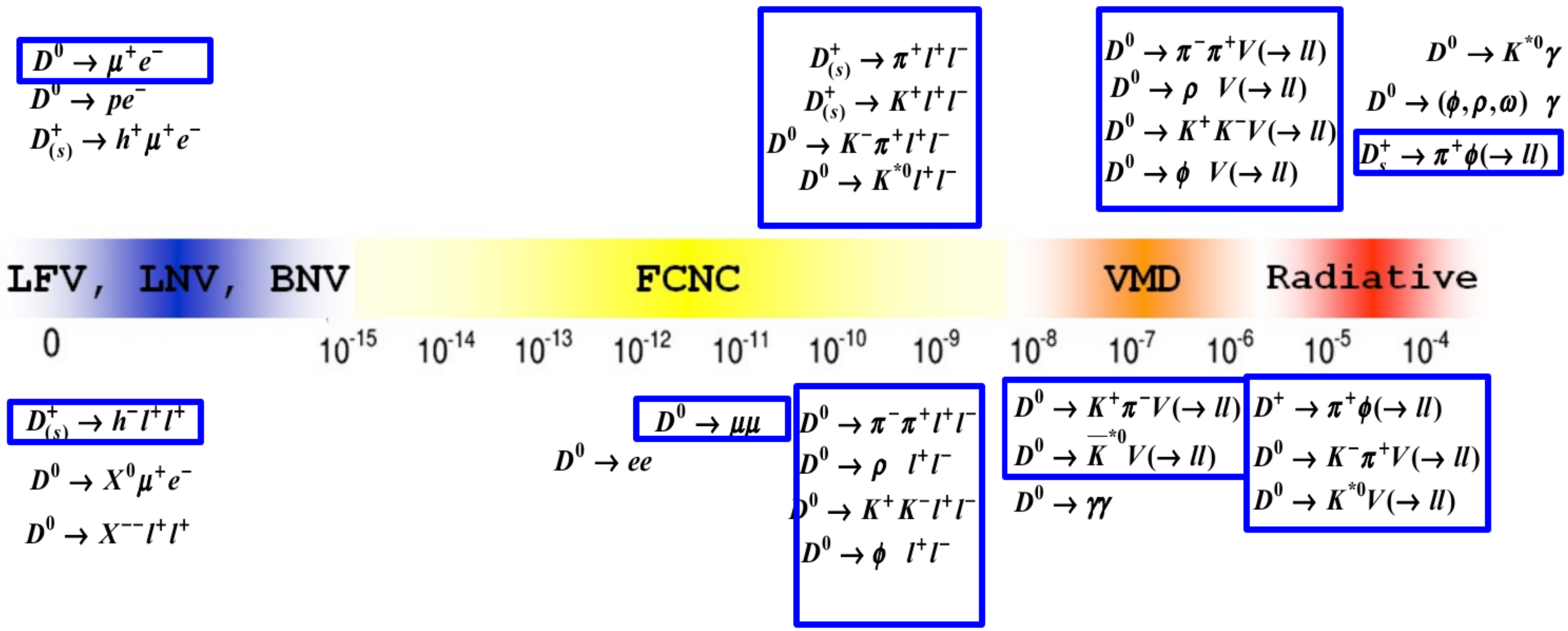
- running at $1\text{-}2\cdot10^{33}\,cm^{-2}s^{-1}$
- replace R/O, RICH photodetectors and tracking detectors
- full software trigger, running at 40 MHz
- record 20 -100 kHz

Large improvements in physics yields due to lower p_T and E_T cuts

- x10 in muonic *B* decays
- x20 in charm and hadronic *B* decays

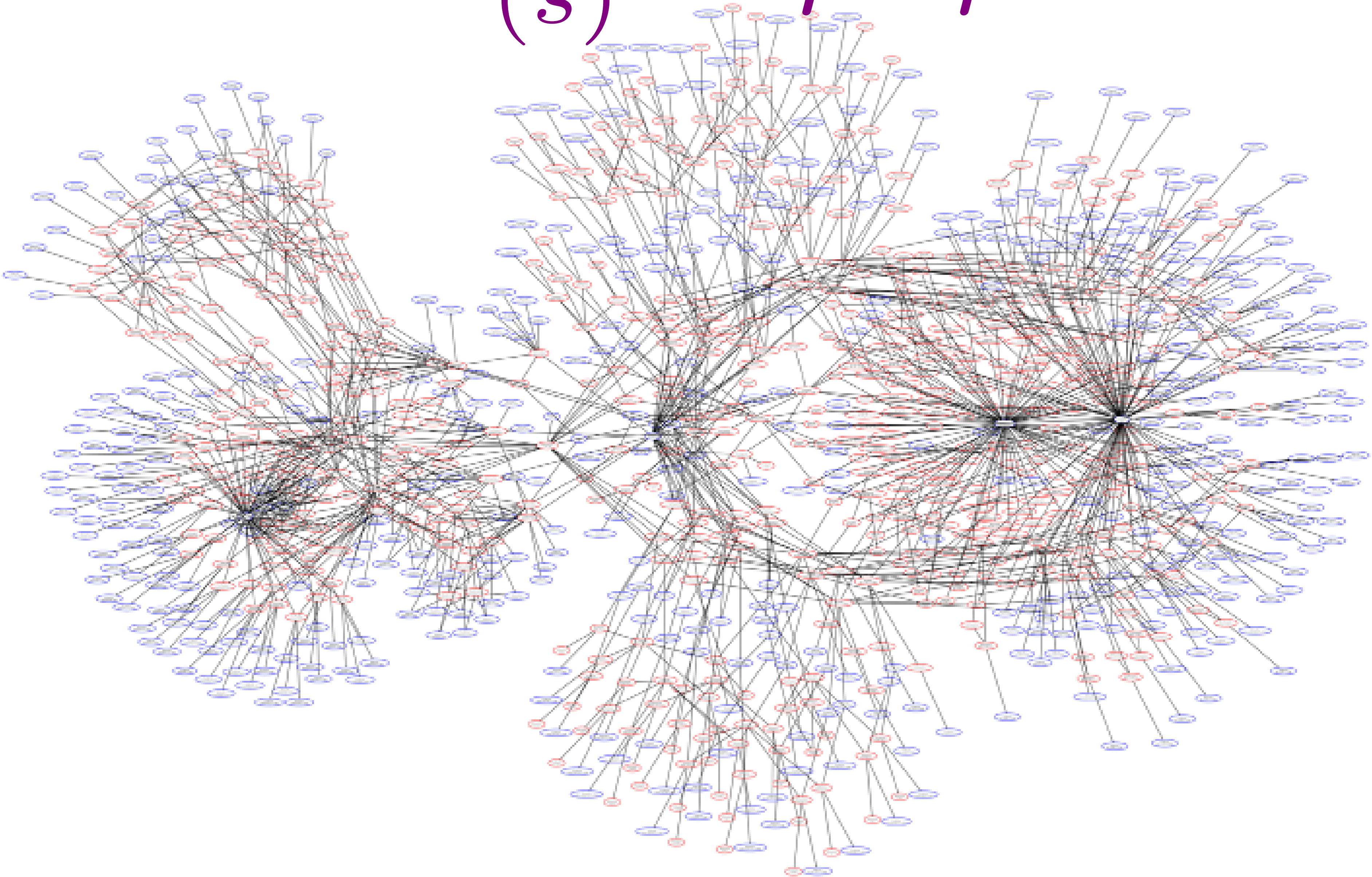
- Angular analysis of the $B^0 \to K^{*0}e^+e^-$ decay in the low-q^2 region [LHCb, to appear in JHEP, arXiv:1501.03038]
- Study of the rare B_s^0 and B^0 decays into the $\pi^+\pi^-\mu^+\mu^-$ final state [LHCb, Phys. Lett. B743 (2015) 46, arXiv:1412.6433]
- Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data [CMS and LHCb, submitted to Nature, arXiv:1411.4413]
- Search for the lepton flavour violating decay $\tau^- \to \mu^-\mu^+\mu^-$ [LHCb, JHEP 02 (2015) 121, arXiv:1409.8548]
- First observations of the rare decays $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ and $B^+ \to \phi K^+\mu^+\mu^-$ [LHCb, JHEP 10 (2014) 064, arXiv:1408.1137]
- Measurement of CP asymmetries in the decays $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$ [LHCb, JHEP 09 (2014) 177, arXiv:1408.0978]
- Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays [LHCb, Phys. Rev. Lett. 113 (2014) 151601, arXiv:1406.6482]
- Angular analysis of charged and neutral $B \to K\mu^+\mu^-$ decays [LHCb, JHEP 05 (2014) 082, arXiv:1403.8045]
- Differential branching fractions and isospin asymmetries of $B \to K^{(*)}\mu^+\mu^-$ decays [LHCb, JHEP 06 (2014) 133, arXiv:1403.8044]
- Observation of photon polarization in the $b \to s\gamma$ transition [LHCb, Phys. Rev. Lett. 112 (2014) 161801, arXiv:1402.6852]
- Search for Majorana neutrinos in $B^- \to \pi^+\mu^-\mu^-$ decays [LHCb, Phys. Rev. Lett. 112 (2014) 131802, arXiv:1401.5361]
- Measurement of form-factor-independent observables in the decay $B^0 \to K^{*0}\mu^+\mu^-$ [LHCb, Phys. Rev. Lett. 111 (2013) 191801, arXiv:1308.1707]
- Measurement of the CP asymmetry in $B^+ \to K^+\mu^+\mu^-$ decays [LHCb, Phys. Rev. Lett. 111 (2013) 151801, arXiv:1308.1340]
- Observation of a resonance in $B^+ \to K^+\mu^+\mu^-$ decays at low recoil [LHCb, Phys. Rev. Lett. 111 (2013) 112003, arXiv:1307.7595]
- Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and search for $B^0 \to \mu^+\mu^-$ decays at the LHCb experiment [LHCb, Phys. Rev. Lett. 111 (2013) 101805, arXiv:1307.5024]
- Search for the lepton-flavour-violating decays $B_s^0 \to e^\pm\mu^\mp$ and $B^0 \to e^\pm\mu^\mp$ [LHCb, Phys. Rev. Lett. 111 (2013) 141801, arXiv:1307.4889]
- Measurement of the differential branching fraction of the decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [LHCb, Phys. Lett. B725 (2013) 25, arXiv:1306.2577]
- Differential branching fraction and angular analysis of the decay $B_s^0 \to \phi\mu^+\mu^-$ [LHCb, JHEP 07 (2013) 084, arXiv:1305.2168]
- Measurement of the $B^0 \to K^{*0}e^+e^-$ branching fraction at low dilepton mass [LHCb, JHEP 05 (2013) 159, arXiv:1304.3035]
- Searches for violation of lepton flavour and baryon number in tau lepton decays at LHCb [LHCb, Phys. Lett. B724 (2013) 36, arXiv:1304.4518]
- Differential branching fraction and angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ [LHCb, JHEP 08 (2013) 131, arXiv:1304.6325]
- Search for rare $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays [LHCb, Phys. Rev. Lett. 110 (2013) 211801, arXiv:1303.1092]
- First evidence for the decay $B_s^0 \to \mu^+\mu^-$ [LHCb, Phys. Rev. Lett. 110 (2013) 021801, arXiv:1211.2674]
- First observation of the decay $B^+ \to \pi^+\mu^+\mu^-$ [LHCb, JHEP 12 (2012) 125, arXiv:1210.2645]
- Measurement of the CP asymmetry in $B^0 \to K^{*0}\mu^+\mu^-$ decays [LHCb, Phys. Rev. Lett. 110 (2013) 031801, arXiv:1210.4492]
- Differential branching fraction and angular analysis of the $B^+ \to K^+\mu^+\mu^-$ decay [LHCb, JHEP 02 (2013) 105, arXiv:1209.4284]
- Search for the rare decay $K_S^0 \to \mu^+\mu^-$ [LHCb, JHEP 01 (2013) 090, arXiv:1209.4029]
- Measurement of the ratio of branching fractions $\mathcal{B}(B^0 \to K^{*0}\gamma)/\mathcal{B}(B_s^0 \to \phi\gamma)$ and the direct CP asymmetry in $B^0 \to K^{*0}\gamma$ [LHCb, Nucl. Phys. B867 (2013) 1-18, arXiv:1209.0313]
- Measurement of the isospin asymmetry in $B \to K^{(*)}\mu^+\mu^-$ decays [LHCb, JHEP 07 (2012) 133, arXiv:1205.3422]
- Strong constraints on the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ [LHCb, Phys. Rev. Lett. 108 (2012) 231801, arXiv:1203.4493]
- Measurement of the ratio of branching fractions $\mathcal{B}(B^0 \to K^{*0}\gamma)/\mathcal{B}(B_s^0 \to \phi\gamma)$ [LHCb, Phys. Rev. D85 (2012) 112013, arXiv:1202.6267]
- Searches for Majorana neutrinos in B^- decays [LHCb, Phys. Rev. D85 (2012) 112004, arXiv:1201.5600]
- Differential branching fraction and angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ [LHCb, Phys. Rev. Lett. 108 (2012) 181806, arXiv:1112.3515]
- Search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ [LHCb, Phys. Lett. B708 (2012) 55, arXiv:1112.1600]
- Search for lepton number violating decays $B^+ \to \pi^-\mu^+\mu^+$ and $B^+ \to K^-\mu^+\mu^+$ [LHCb, Phys. Rev. Lett. 108 (2012) 101601, arXiv:1110.0730]

Rare Charm: several kinds of physics and many decays modes, ranging from forbidden to not so rare.



Studied at LHCb...

$B^0_{(s)} \to \mu^+\mu^-$



Study of the CMS Phase-2 upgrade performance for the B⟶μμ measurement

CMS Collaboration

B physics studies

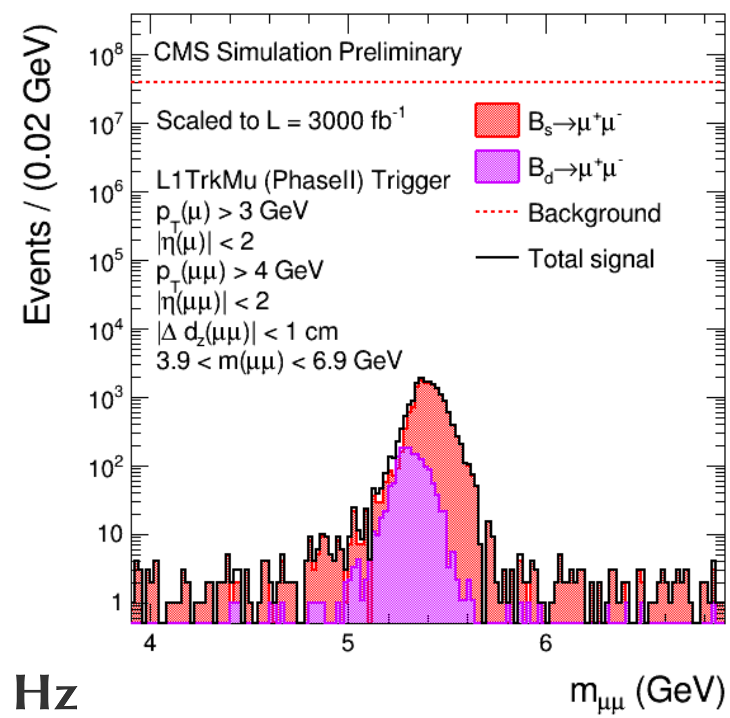
- One benchmark channel was studied for assessing the B-physics performance of the CMS Phase-2 upgraded detector: search for $B^0 \to \mu\mu$ decays and measurement of the $B^0_{(s)} \to \mu\mu$ branching fraction
  - Physics importance of the channel: the observation of the $B^0 \to \mu\mu$ decay and the precise determination of its branching fraction can pose stringent limits to new physics models
  - Other measurements are possible with the statistics collected at HL-LHC: cross section ratios, polarization, etc. Only some of them were considered in this study.

- For this study, we looked at two aspects of the analysis
  1) Implementation and performance of a L1 track trigger for the $B \to \mu\mu$ signal
  2) Effect of CMS upgrades to the final analysis performance

- The two CMS upgrades that affect more the analysis outcome are:
  - L1 Trigger: especially through the new track trigger machinery
  - Tracker: through the reduced material budget and increased resolution

L1 trigger for $B^o_{(s)} \to \mu\mu$

- We simulated a low-p_T di-muon L1 trigger algorithm exploiting the triggering capabilities of the upgraded CMS tracker
  - 2 opposite-charge L1 "Tk muons", reconstructed from a matching of the L1 tracks and L1 standalone muons
  - $p_T(\mu) > 3$ GeV
  - $|\eta(\mu)| < 2$
  - $p_T(\mu\mu) > 4$ GeV
  - $|\eta(\mu\mu)| < 2$
  - $\Delta d_z(\mu\mu) < 1$ cm
  - $3.9 < m(\mu\mu) < 6.9$ GeV



- Mass resolution at L1 is measured to be ≈ 70 MeV using Gaussian fits to the signal peaks
- Trigger rate in the HL-LHC conditions (average of 140 PU events) is estimated to be **a few hundred Hz**
  - It constitutes only a tiny fraction of the total L1 bandwidth
- This study shows that the expected performances of the upgraded CMS L1 trigger are more than sufficient to implement trigger algorithm for $B \to \mu\mu$ having the same acceptance of the L1 trigger used in LHC Run 1

Setup of toy experiments to estimate CMS performance

- We run toy experiments to estimate the analysis performance in two scenarios:
  - The Phase-1 scenario, corresponding to the expected performance of the CMS detector after the Phase-1 upgrades and to 300 fb^{-1} of integrated luminosity
  - The Phase-2 upgrade scenario, corresponding to the expected performance of the CMS detector after the full Phase-2 upgrades and to 3000 fb^{-1} of integrated luminosity
- In both cases we are using the public results of the Run-1 $B_s \to \mu\mu$ analysis as a starting point, incorporating also the improvements present in the CMS-LHCb combination (under preparation). These improvements are:
  - Changes in the way the signal efficiency depends on proper life time (increases B_s signal yield)
  - Change in the shape of the semi-leptonic background due to the use of an improved theoretical model
- The toy experiments use the **invariant mass resolution coming from the full Geant4 simulation** of the CMS detector as input:
  - In the case of the Phase-1 scenario, this is roughly equal to the resolution measured with the current CMS detector, i.e. ≈ 42 MeV when both muons are in the barrel ($|\eta| < 1.4$)
  - In the case of the Phase-2 scenario, this is ≈ 28 MeV when both muons are in the barrel ($|\eta| < 1.4$), with **an improvement of a factor 1.5 with respect to the Phase-1 scenario**
- Other inputs to the toy experiments come from extrapolations from the Run-1 analysis (detailed in the next slides)
- Input signal branching fractions from Standard Model predictions are assumed everywhere

Other inputs to the toy experiments: 300 fb^{-1}

- These are the details of the extrapolations made in order to find the inputs to the toy experiments for the Phase-1 300 fb^{-1} scenario:
    - Barrel only (muon $|\eta| < 1.4$)
    - Muon efficiency & fate rate: the same as 8 TeV analysis
    - Uncertainty on B^+ normalization channel: 5%
    - Uncertainty of the peaking backgrounds: 20%
    - Uncertainty of the semileptonic backgrounds: 25%
    - Uncertainty of the f_s/f_u ratio: 5%
    - Trigger & PU performance: same as 8 TeV analysis

- As written in slide 4, in addition to these extrapolations, the invariant mass resolution coming from the full Geant4 simulation of the Phase-1 CMS detector is used (≈ 42 MeV)

Other inputs to the toy experiments: 3000 fb^{-1}

- These are the details of the extrapolations made in order to find the inputs to the toy experiments for the Phase-2 3000 fb^{-1} scenario:
  - Barrel only (muon $|\eta| < 1.4$)
  - Muon efficiency & fate rate: the same as 8 TeV analysis
  - Uncertainty on B^+ normalization channel: 3%
  - Uncertainty of the peaking backgrounds: 10%
  - Uncertainty of the semileptonic backgrounds: 20%
  - Uncertainty of the f_s/f_u ratio: 5%
  - Trigger & PU performance:
    - 35% reduction of efficiency on signal and normalization channel
    - 30% reduction of efficiency on backgrounds

- As written in slide 4, in addition to these extrapolations, the invariant mass resolution coming from the full Geant4 simulation of the Phase-2 CMS detector is used (≈ 28 MeV)

Results of toy experiments

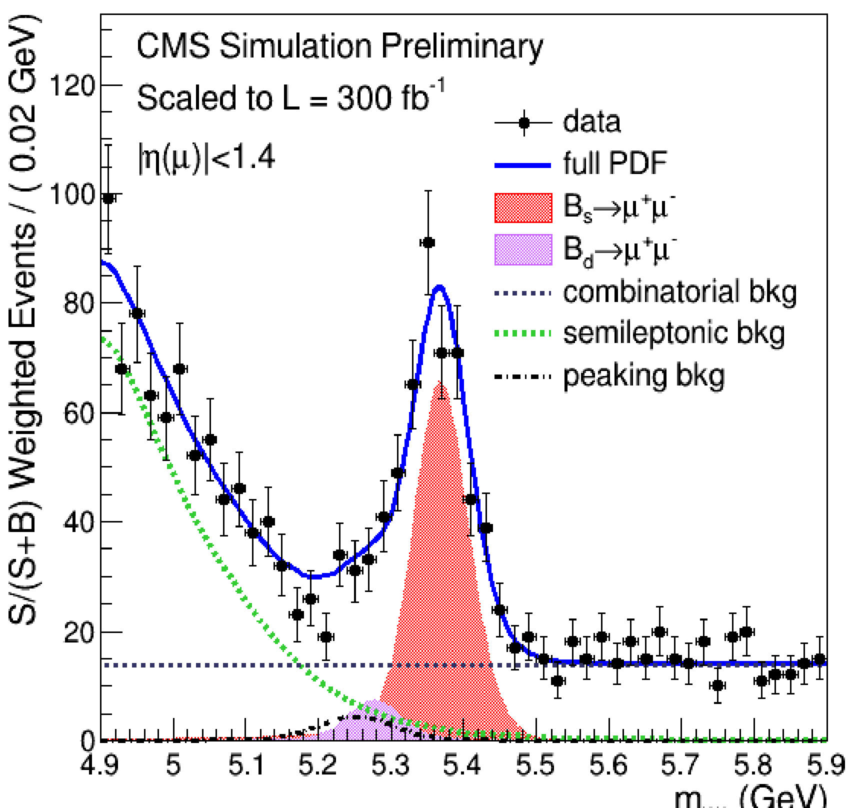
- The two plots below show the results of the toy experiments on the two scenarios
- The toy experiments also give the following estimates (left 300 fb^{-1}; right 3000 fb^{-1}):

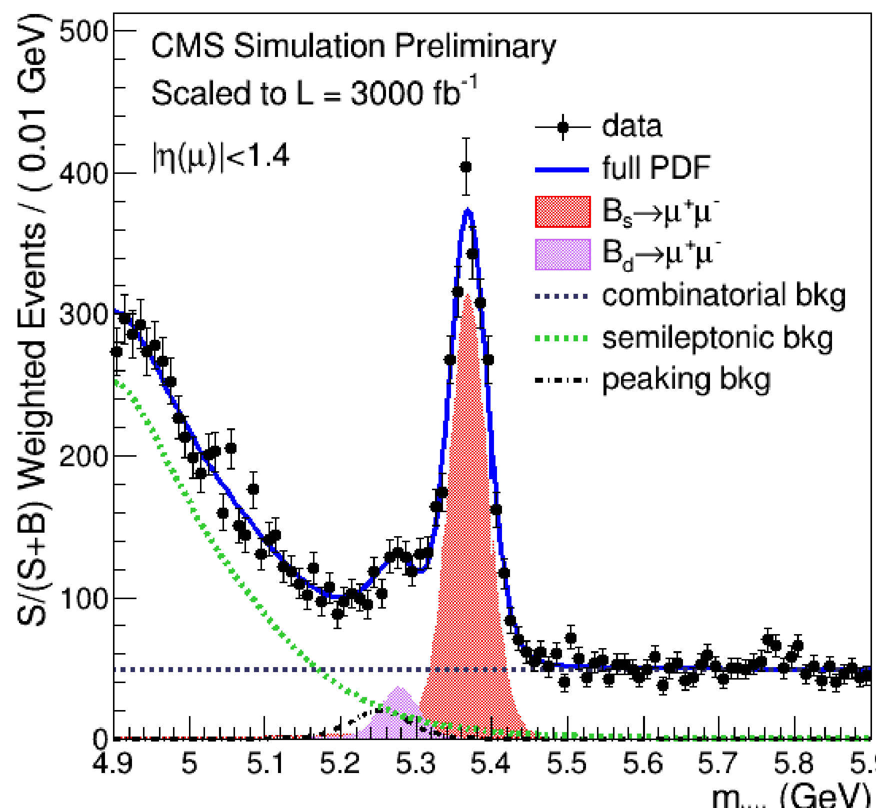
Left (300 fb^{-1}):

- **d$\mathcal{B}$($B_s \rightarrow \mu\mu$): 13%**
- **d$\mathcal{B}$($B^0 \rightarrow \mu\mu$): 48%**
- **d[$\mathcal{B}$($B_d \rightarrow \mu\mu$)/$\mathcal{B}$($B_s \rightarrow \mu\mu$)]: 50%**
- **$B^0 \rightarrow \mu\mu$ significance: ≈2.2 σ**

Right (3000 fb^{-1}):

- **d$\mathcal{B}$($B_s \rightarrow \mu\mu$): 11%**
- **d$\mathcal{B}$($B^0 \rightarrow \mu\mu$): 18%**
- **d[$\mathcal{B}$($B_d \rightarrow \mu\mu$)/$\mathcal{B}$($B_s \rightarrow \mu\mu$)]: 21%**
- **$B^0 \rightarrow \mu\mu$ significance: ≈6.8 σ**





for ECFA 2014

The B-Physics Programme of ATLAS in LHC Run-II and in HL-LHC

Alessandro Cerri, Darren Price, Pavel Řezníček
for the ATLAS B-Physics Group

ATLAS B-Physics Programme for Run-2

- The B-physics programme in Run-2 and beyond will follow the current Run-1 approach:
  - Precision measurements and rare processes that most benefit from high integrated luminosity and/or are inaccessible at B-factories. Focus on those with potential in beyond-SM effects
    - $B_s \to J/\psi\phi$, $\Lambda_b \to J/\psi\Lambda$, …, $B_{(s)} \to \mu\mu$, $b \to s\mu\mu$
  - Heavy flavour production at 14TeV
    - B-hadron and D-meson production x-section, prompt/non-prompt quarkonia production, quarkonia spin alignment measurement
  - Heavy flavour production in association with other physics objects
    - Vector boson + J/ψ, double J/ψ production etc.
  - Searches for new/exotic states and new decay modes
    - B_c decays, $B_c(2S)$, heavy baryons, X_b, exotic quarkonia states etc.

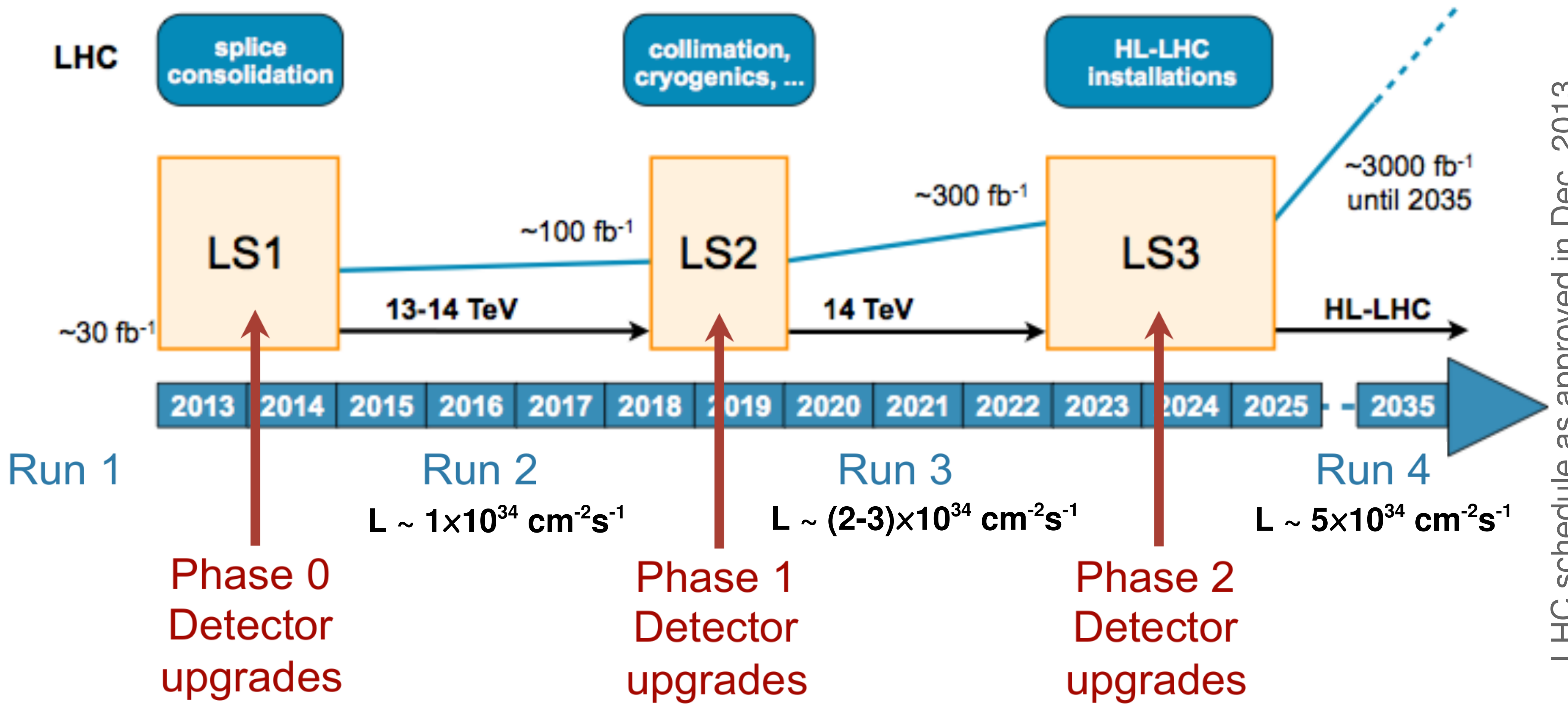
- The Run-1 of LHC experiments showed: in B-physics a sensitivity to potential effects **beyond SM** is only possible if the measurements are accomplished at unprecedentedly high precision => **need the future LHC Runs**

- To make that possible and keep similar or better performance, we need:
  - **trigger strategies** (keep relying on muonic final states) and
  - **detector upgrades** (namely tracking)

  able to face the harsher environment of the future Runs

The LHC Roadmap

- LHC and its experiments are doing very well, providing data at the energy frontier



- $\sqrt{s}$ = 14 TeV, high luminosity & pile-up =>
  - increased detector occupancy; saturation of the bandwidth
  - challenging for triggers to maintain sensitivity to physics
  - increased radiation damage and activation of the materials

B-Physics Programme

- **The B-physics programme in Run 2 and beyond will follow the current Run 1 approach:**
  - Precision measurements and rare processes that most benefit from high integrated luminosity and/or are inaccessible at B-factories. Focus on those with potential in beyond-SM effects
    - $B_s \to J/\psi\phi$, $\Lambda_b \to J/\psi\Lambda$, …, $B_{(s)} \to \mu\mu$, $b \to s\mu\mu$
  - Heavy flavour production at 14TeV
    - B-hadron and D-meson production x-section, prompt/non-prompt quarkonia production, quarkonia spin alignment
  - Heavy flavour production in association with other physics objects
    - Vector boson + J/ψ, double J/ψ production etc.
  - Searches for new/exotic states and new decay modes
    - χ_b, B_c decays, $B_c(2S)$, heavy baryons, exotic quarkonia etc.

- Trigger still ties us to muonic final states

B-Physics Programme cont.

- The Run 1 of LHC experiments showed: in B-physics a sensitivity to potential effects **beyond SM** is only possible if the measurements are accomplished at unprecedentedly high precision => **need the future LHC Runs**

- To make that possible and keep similar or better performance, we need:
  - **trigger strategies** and
  - **detector upgrades** (namely tracking)

  able to face the harsher environment of the future Runs

- 2nd part of the talk => study of the impact of the detector & trigger changes on $B_s \rightarrow J/\psi\phi$ measurement precision

Conclusions

- ATLAS will continue its B-physics program in the Run 2,3 and the HL-LHC era, focusing on precision measurements, rare decays and heavy flavour production and spectroscopy

- Detector upgrades (namely in **tracking** and **muon system**) and new **trigger strategies** and tools will help to cope with the high-luminosity environment and achieve precision needed to examine possible beyond-SM effects in the heavy-flavour production and decays

- Pilot study of $B_s \rightarrow J/\psi\phi$ CPV analysis:
  - shown improvements in the precision coming from the tracking detectors upgrade (already those for Run 2)
  - demonstrated strong dependence of the precision on the trigger thresholds/configurations
  - indicated weak effect on the analysis by the expected pile-up conditions in future LHC Runs