New Physics via rare decays with LHCb: $b \to s\ell^+\ell^-$ transitions

Marie-Hélène Schune

Standard Model

accurately describes a very large number of measurements

is unable to answer key-questions:

- dark matter candidate ?
- source of baryon asymmetry generation ?
- origin of flavour (and what underlies the family replication) ?
- source of the hierarchy in the W couplings to the different quarks ?

We are not anymore « theory-guided »

⇒ precise measurements are the clue towards understanding

How to find cracks in the SM fortress ?

Direct evidence for new particles

Indirect evidence through precision measurements sensitive to the presence of virtual states present in the decay of SM particles

How to find cracks in the SM fortress ?

1964 $K_L \to \pi\pi$: CP violation
3 families

1987 B_d mixing $\sqrt{s}$=10 GeV (ARGUS)

$$\Delta m_d \sim 0.00002 \times \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1} \sim 0.5\ \mathrm{ps}^{-1}$$

$\Rightarrow m_t$ >50 GeV

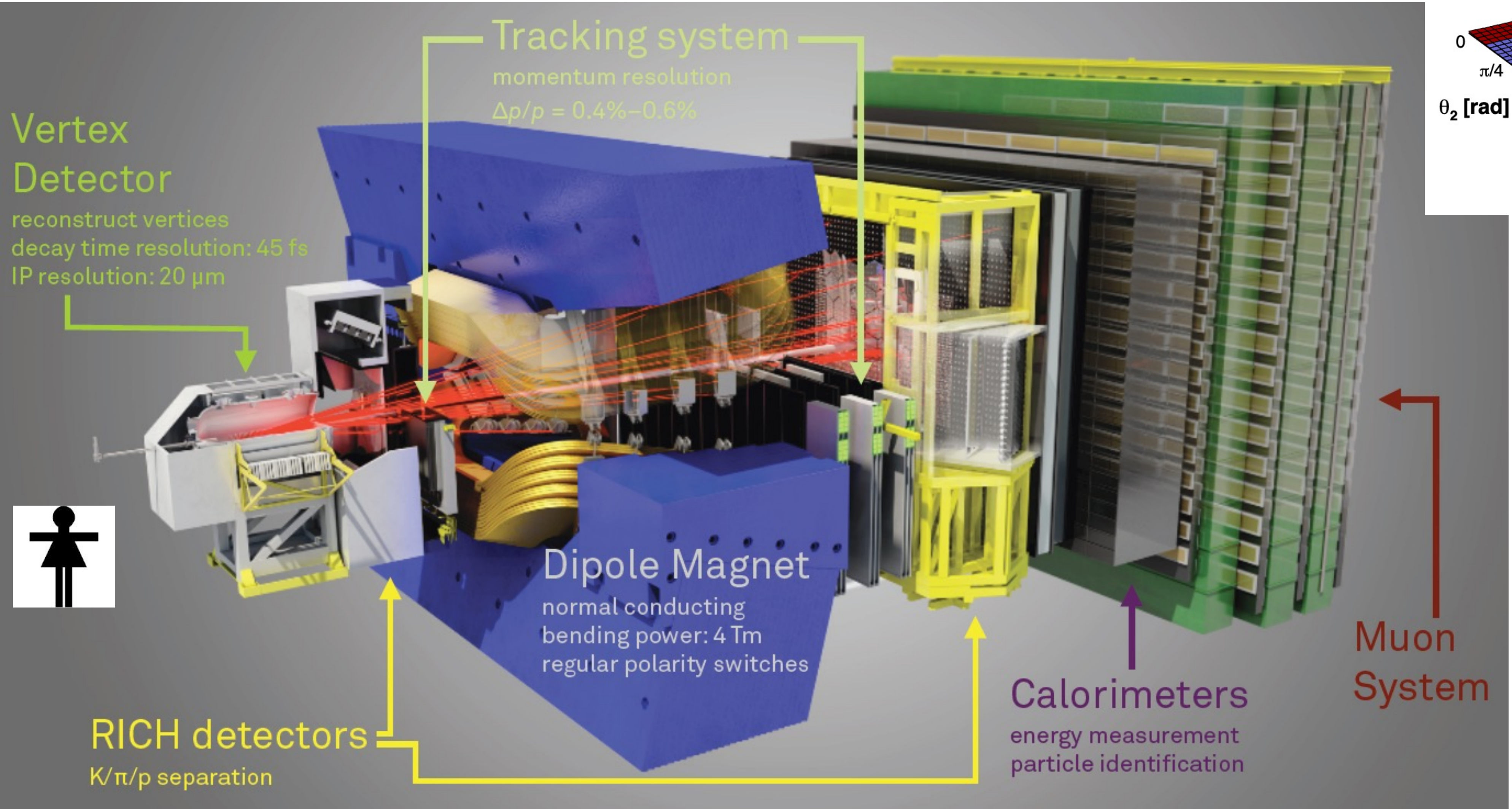
Direct evidence for new particles

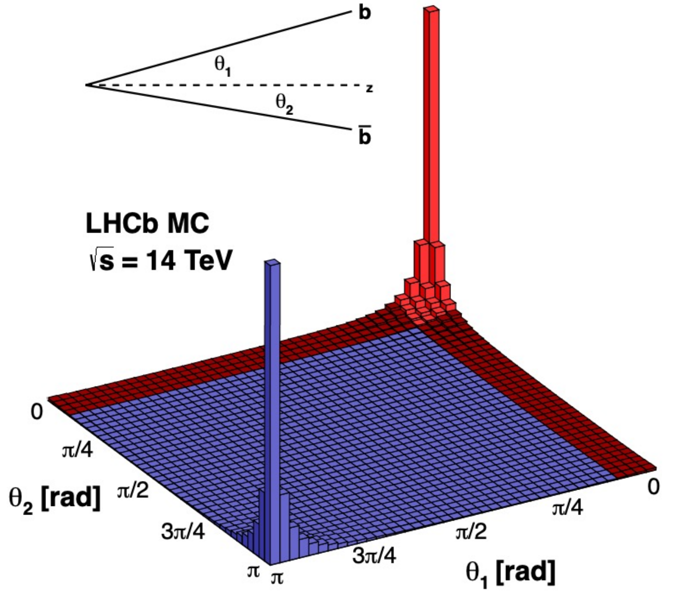
Indirect evidence through precision measurements sensitive to the presence of virtual states present in the decay of SM particles

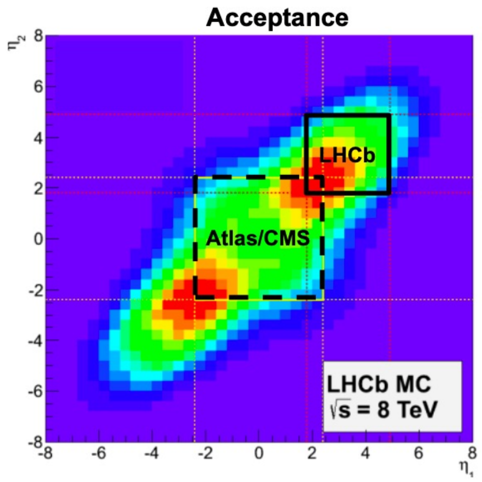
History is telling us that Flavour physics is a key-tool

The LHCb detector

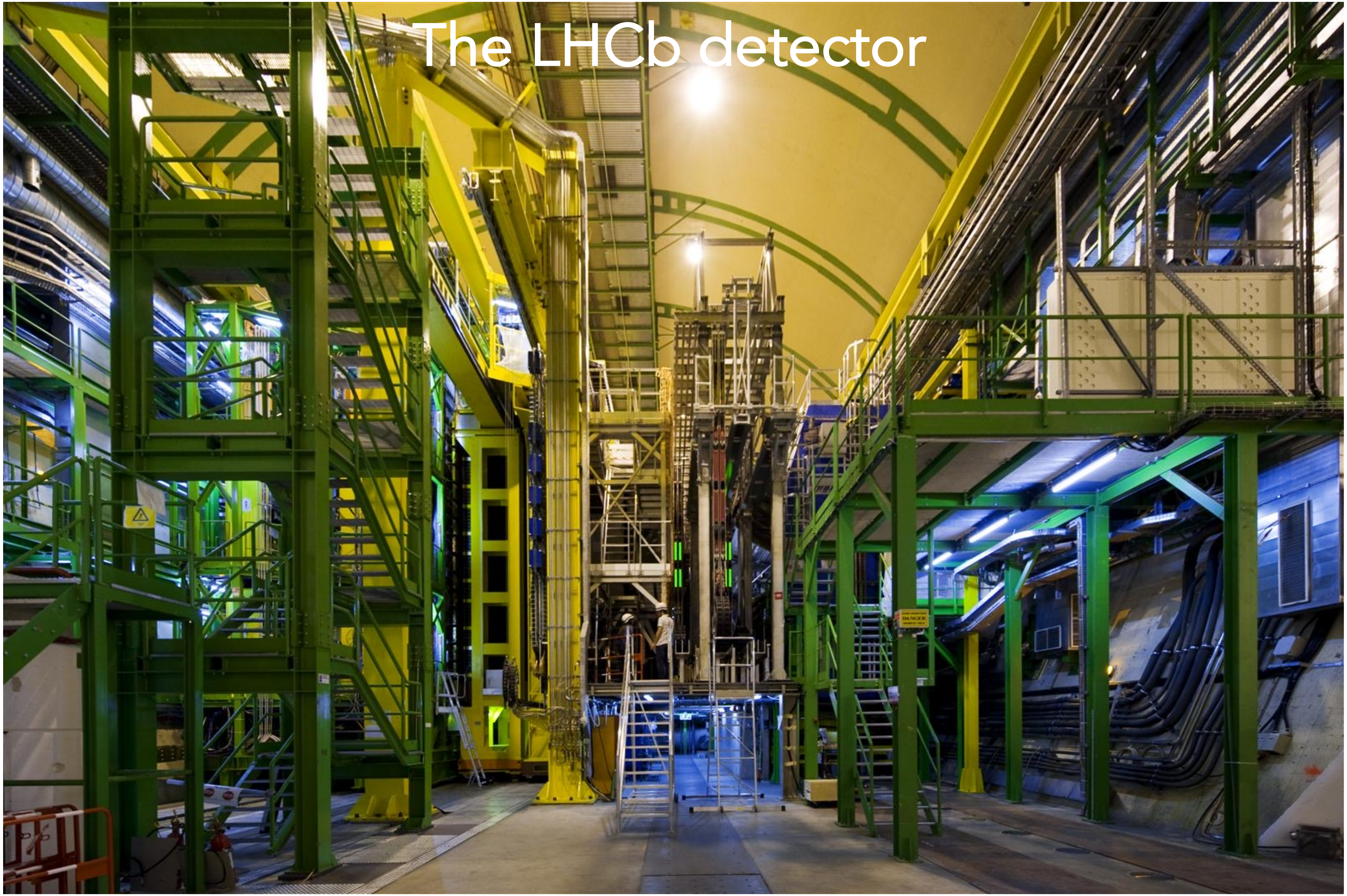
40% of the heavy quark production cross-section in 4% of the solid angle
All type of *b*-hadrons produced



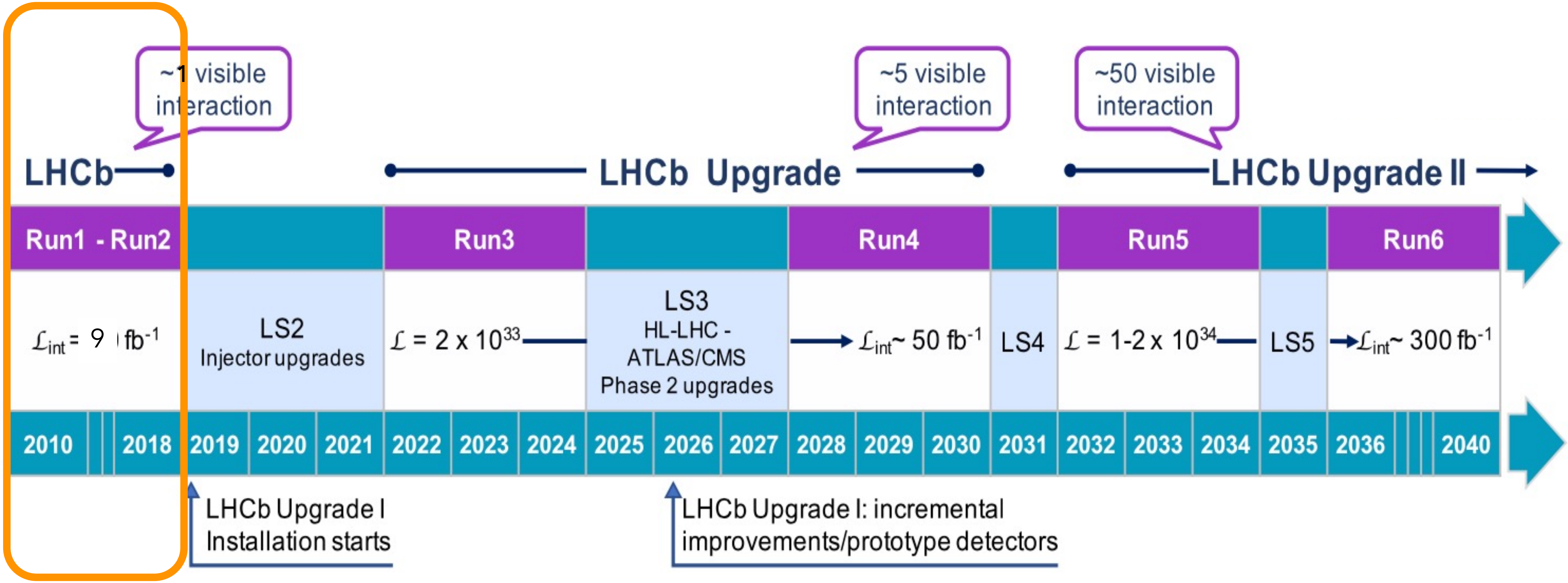




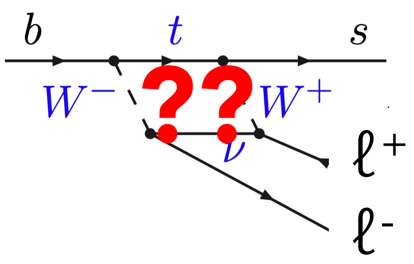
The LHCb detector

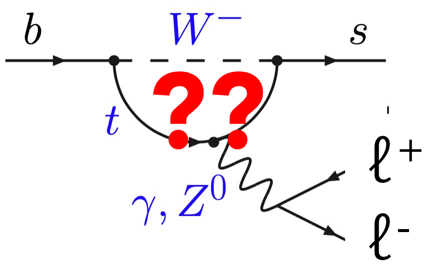


LHCb schedule



Rare decays : b → $s\ell^+\ell^-$ FCNC transitions

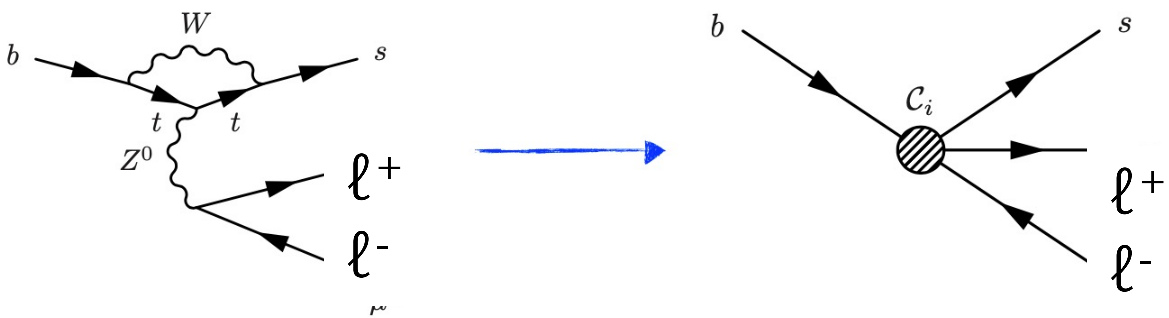




Forbidden at tree-level in SM → BR of $10^{-6} – 10^{-10}$
New physics contribution can be same order as SM

Relative importance of the different diagrams varies with $q^2 = M^2(\ell^+\ell^-)$

Full theory **Effective description**



~ Fermi's description of the neutron decay

Effective-Hamiltonian approach

$$\mathscr{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\sum_i C_i O_i + \text{h.c.}$$

NP enters here
$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$

Operator encoding
Lorentz structure

Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s\gamma$	X			
$B \to K^*\gamma$	X			
$B \to X_s\ell^+\ell^-$	X	X	X	
$B \to K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \to \mu^+\mu^-$			X	X

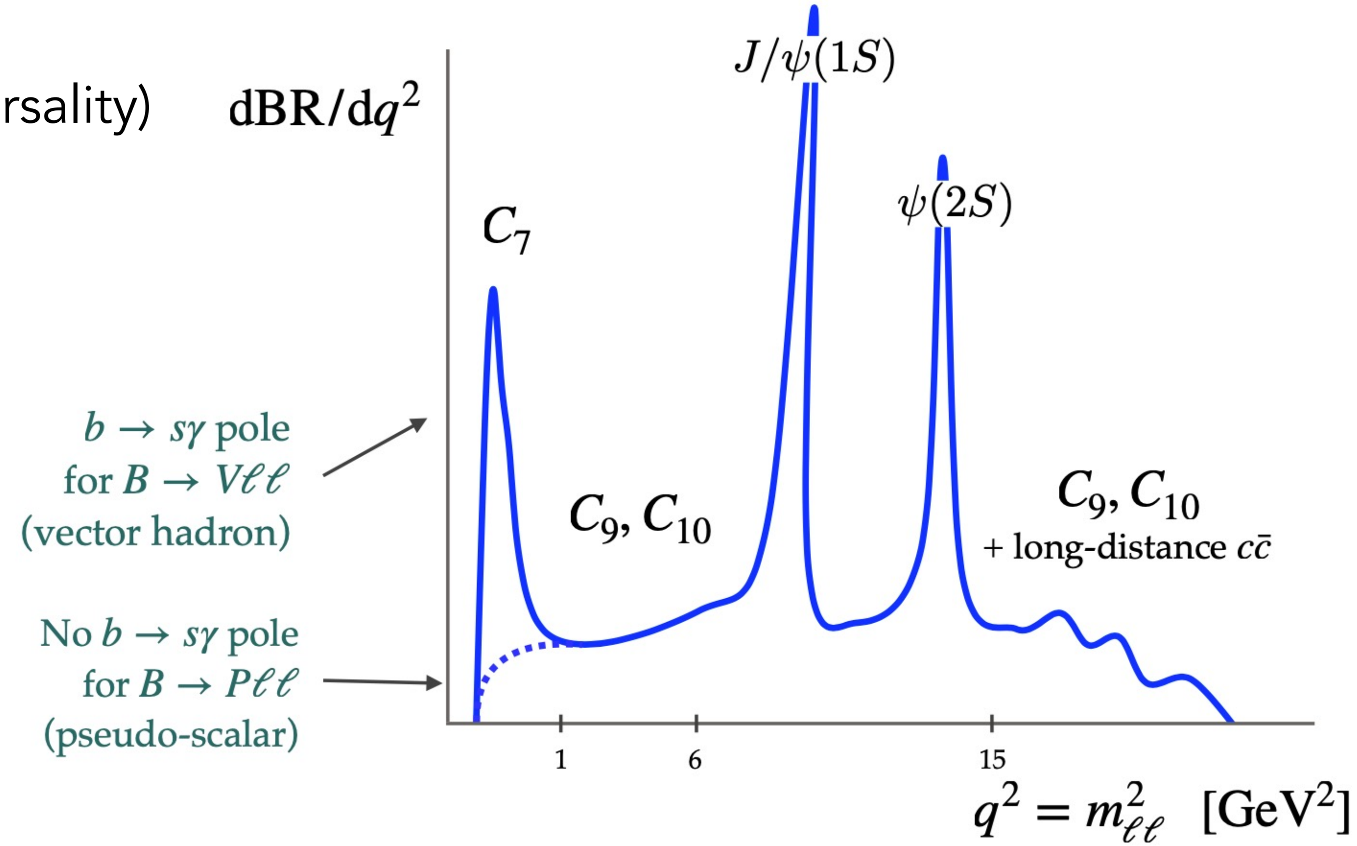
Rare decays: $b \to s\ell\ell$ transitions

$B \to K^{(*)}\ell\ell$, $B_s \to \phi\ell\ell$, $\Lambda_b \to \Lambda^{(*)}\ell\ell$ …

Less th. uncertainties

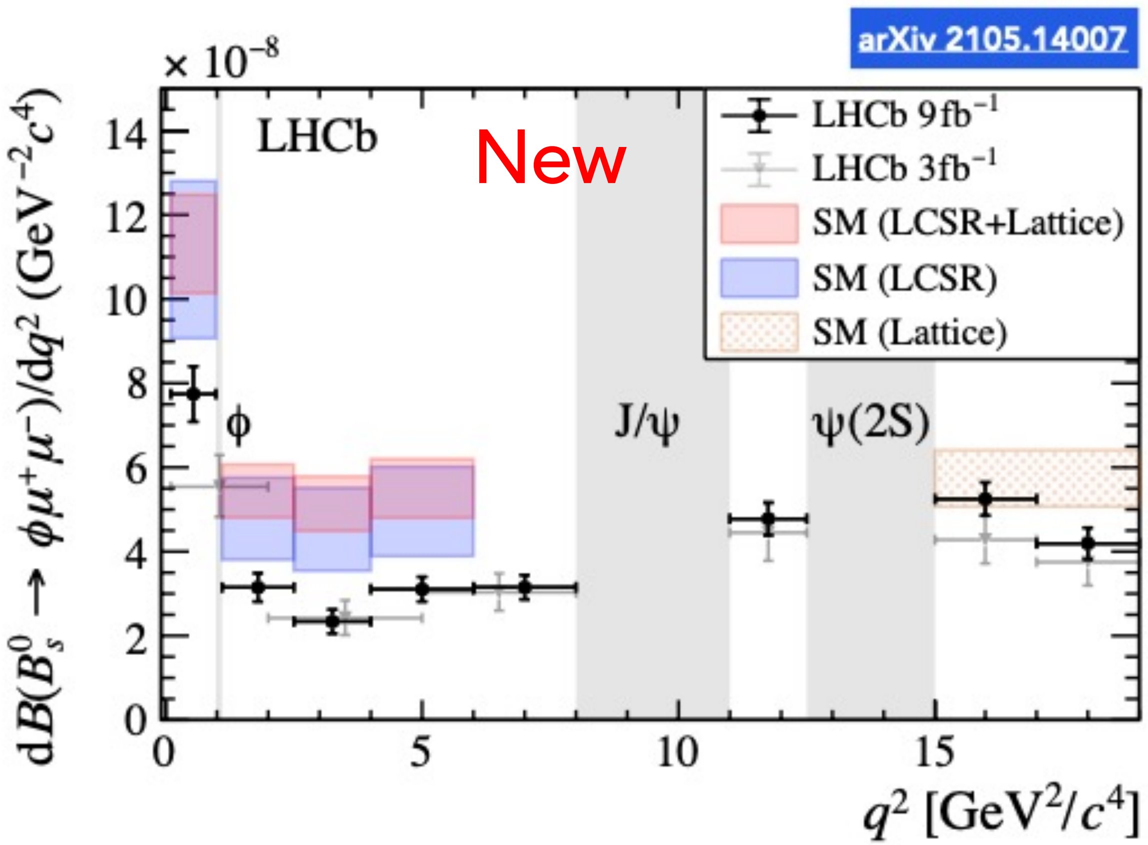
Rich phenomenology:

1. Branching fractions (but large theoretical uncertainties due to non-perturbative QCD
2. Angular observables
3. Ratios of BF (test of Lepton Universality)



1. Branching Fractions

Most recent measurement : $B_s \rightarrow \phi\mu\mu$



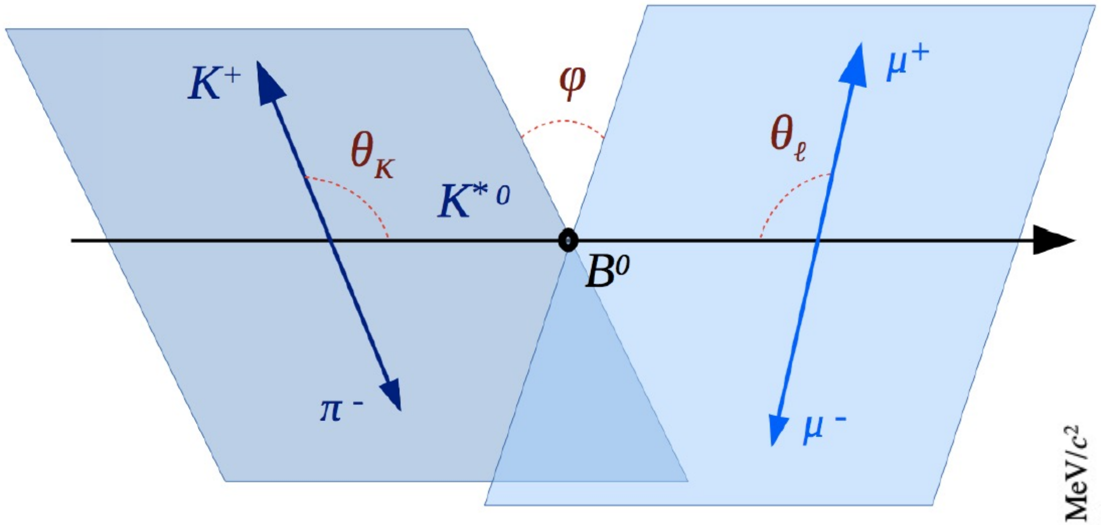
Coherent observation with many other $b \rightarrow s\ \mu\mu$ modes : measured BR lower than the predicted ones.

But origin could be:

- non-perturbative QCD
- NP

2. Angular analyses

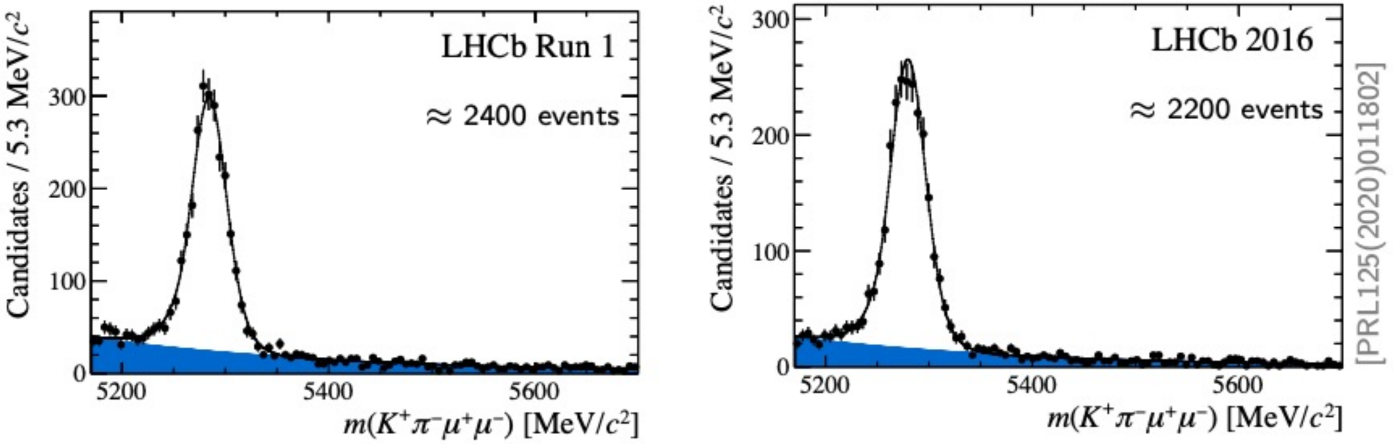
$B^{(+)} \to K^{*(+)} \mu\mu$, $B_s \to \phi \mu\mu$



Decay described by 3 angles and q^2
Clean (and large) samples

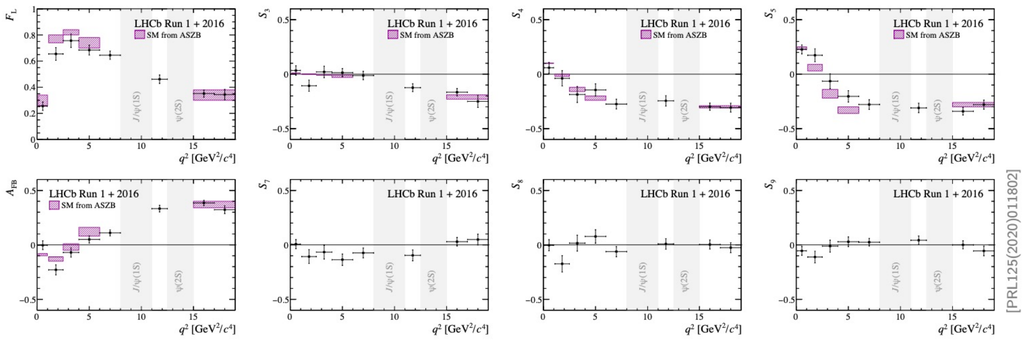
$B \to K^{*0} \mu\mu$

PRL 125(2020)01 1802

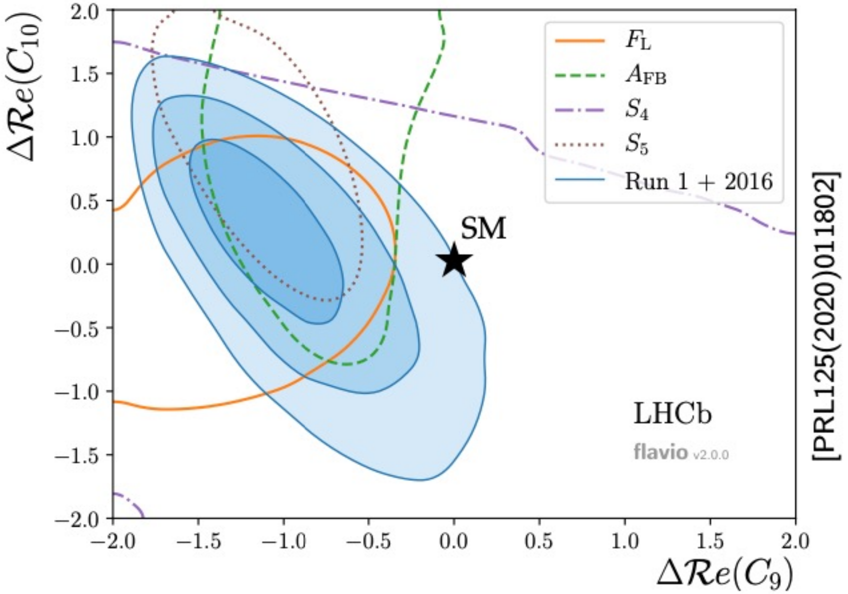


More observables
→ more information

NB : 2017 – 2018 data still to be analyzed

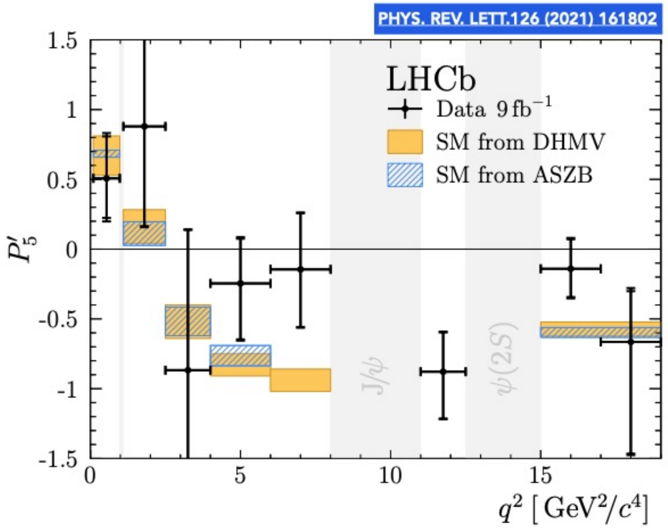


$B \to K^{*0}\,\mu\mu$



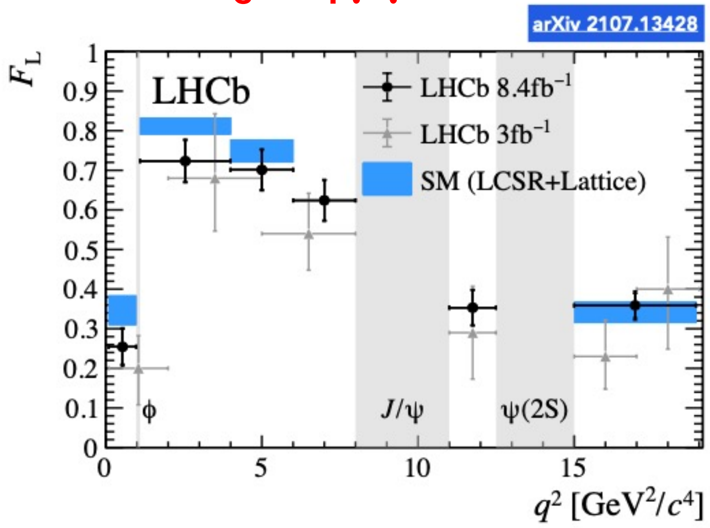
Global Wilson coefficients fit seems to indicate a pattern: different observables give a coherent picture

$B^+ \to K^{*+}\,\mu\mu$



Patterns consistent but theoretical debate about the impact of $c\bar{c}$ loops

$B_s \to \phi\mu\mu$



3. Ratios of BF (test of Lepton Universality)

$$R_{H_s} = \frac{\mathcal{B}(B \to H_s \mu^+\mu^-)}{\mathcal{B}(B \to H_s e^+e^-)} \overset{SM}{\simeq} 1$$

H_s = K, K*, ϕ ….

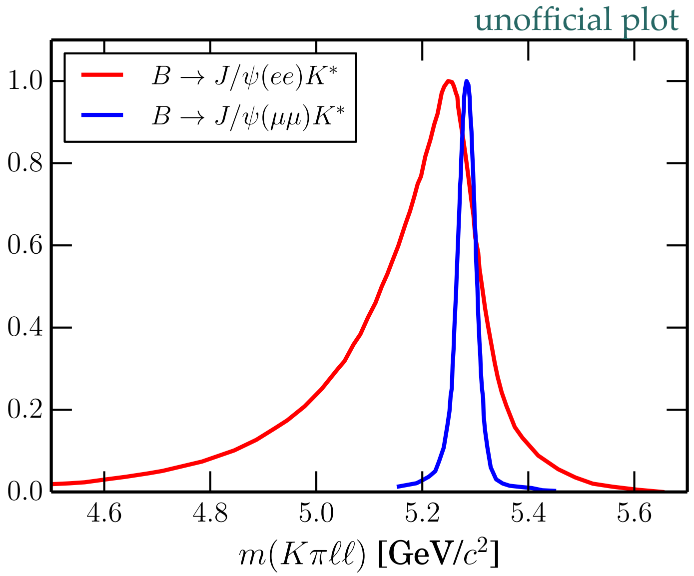
in a M_{ll}^2 (=q²) bin

but

Electrons and muons are experimentally very different :

- Bremsstrahlung emission
- Lower efficiency for the electron Trigger (L0)

- Control the Monte Carlo description with unbiased control samples from data



From Martino Borsato

- Check that the determination of the absolute electron/muon scale is under control via the measurement of

$$r_{J/\psi} = \frac{\mathcal{B}(B \to H_s J/\psi(\mu^+\mu^-))}{\mathcal{B}(B \to H_s J/\psi(e^+e^-))}$$

$$\frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(J/\psi \to \mu^+\mu^-)} = 1.0016 \pm 0.0031$$

PDG

- Use a double ratio

$$R_{H_s} = \frac{\mathcal{B}(B \to H_s \mu^+\mu^-)}{\mathcal{B}(B \to H_s J/\psi(\mu^+\mu^-))} \times \frac{\mathcal{B}(B \to H_s J/\psi(e^+e^-))}{\mathcal{B}(B \to H_s e^+e^-)} =$$

$$\frac{N(B \to H_s \mu^+\mu^-)}{N(B \to H_s J/\psi(\mu^+\mu^-))} \times \frac{N(B \to H_s J/\psi(e^+e^-))}{N(B \to H_s e^+e^-)} \times \boxed{\frac{\epsilon(B \to H_s J/\psi(\mu^+\mu^-))}{\epsilon(B \to H_s \mu^+\mu^-)}} \times \boxed{\frac{\epsilon(B \to H_s e^+e^-)}{\epsilon(B \to H_s J/\psi(e^+e^-))}}$$

Systematic uncertainties cancel to a large extent

$$R_{H_s} = \frac{\mathcal{B}(B \to H_s \mu^+ \mu^-)}{\mathcal{B}(B \to H_s e^+ e^-)}$$

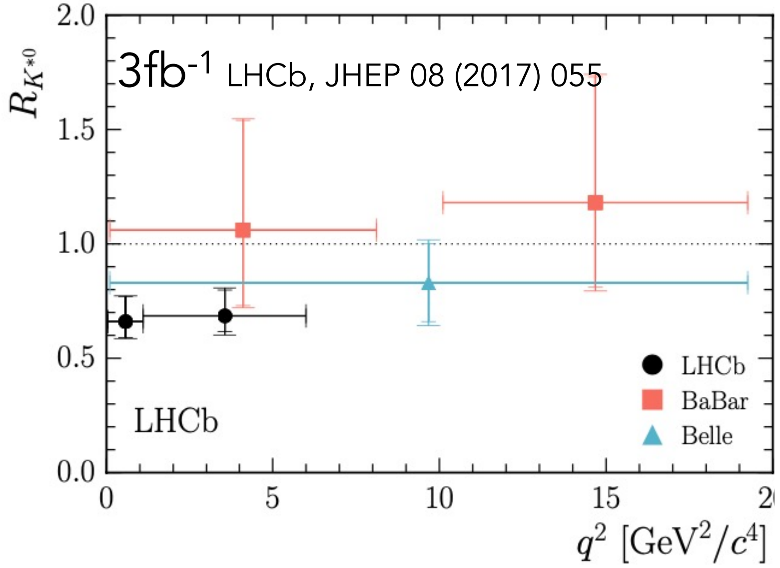
H_s = K, K*, ϕ …. in a M_{ll}^2 (=q²) bin

$$R_{K^0_S} = 0.66\,^{+0.20}_{-0.14}\,(\text{stat.})\,^{+0.02}_{-0.04}\,(\text{syst.})$$

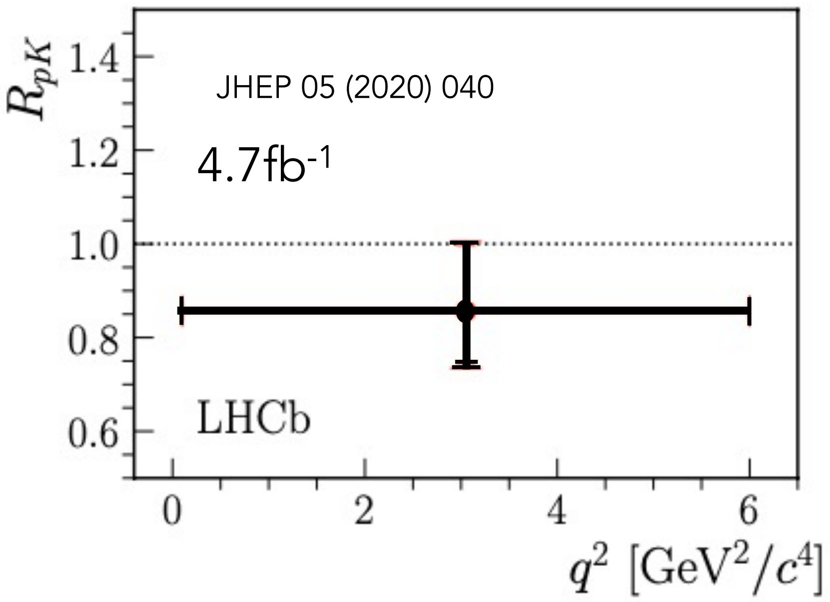
$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})\,^{+0.03}_{-0.04}\,(\text{syst.})$$

arXiv:2110.09501 NEW

H_s = K*

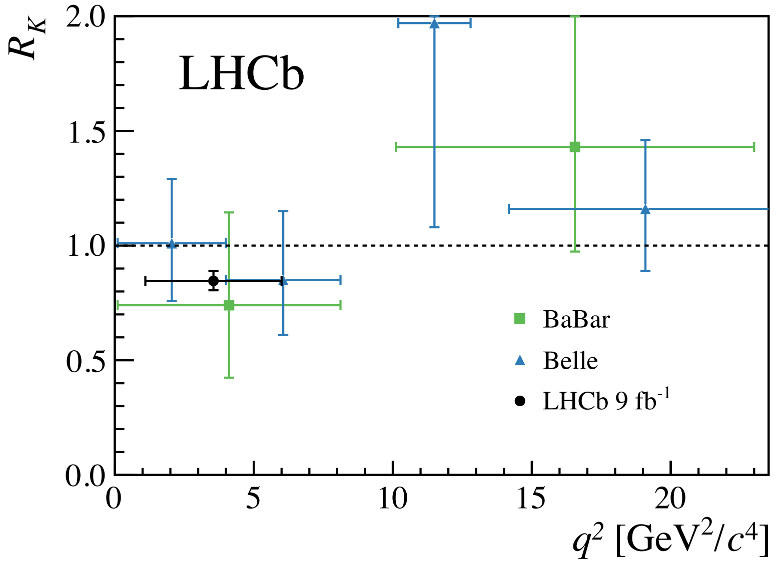


H_s = pK



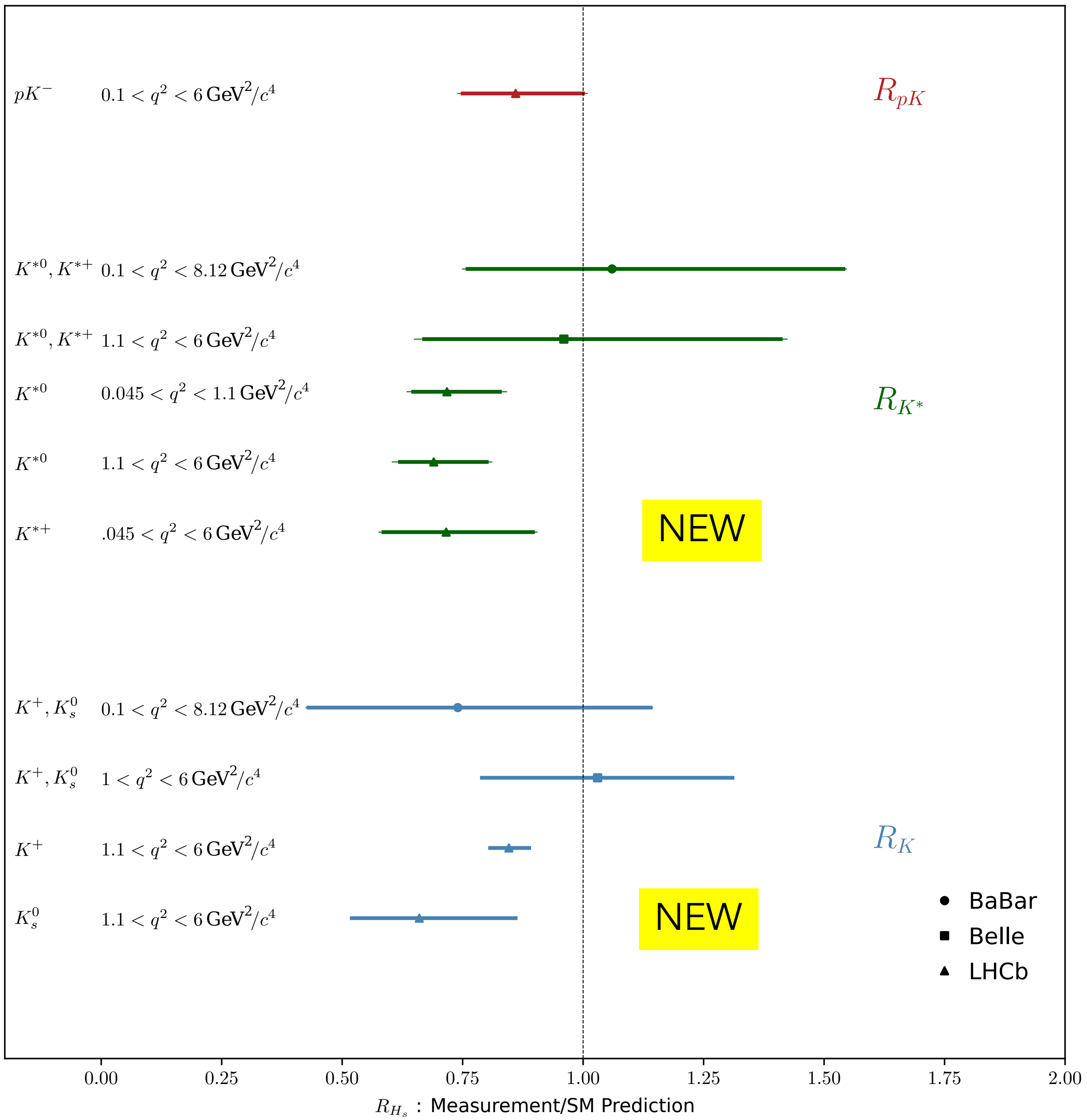
H_s = K

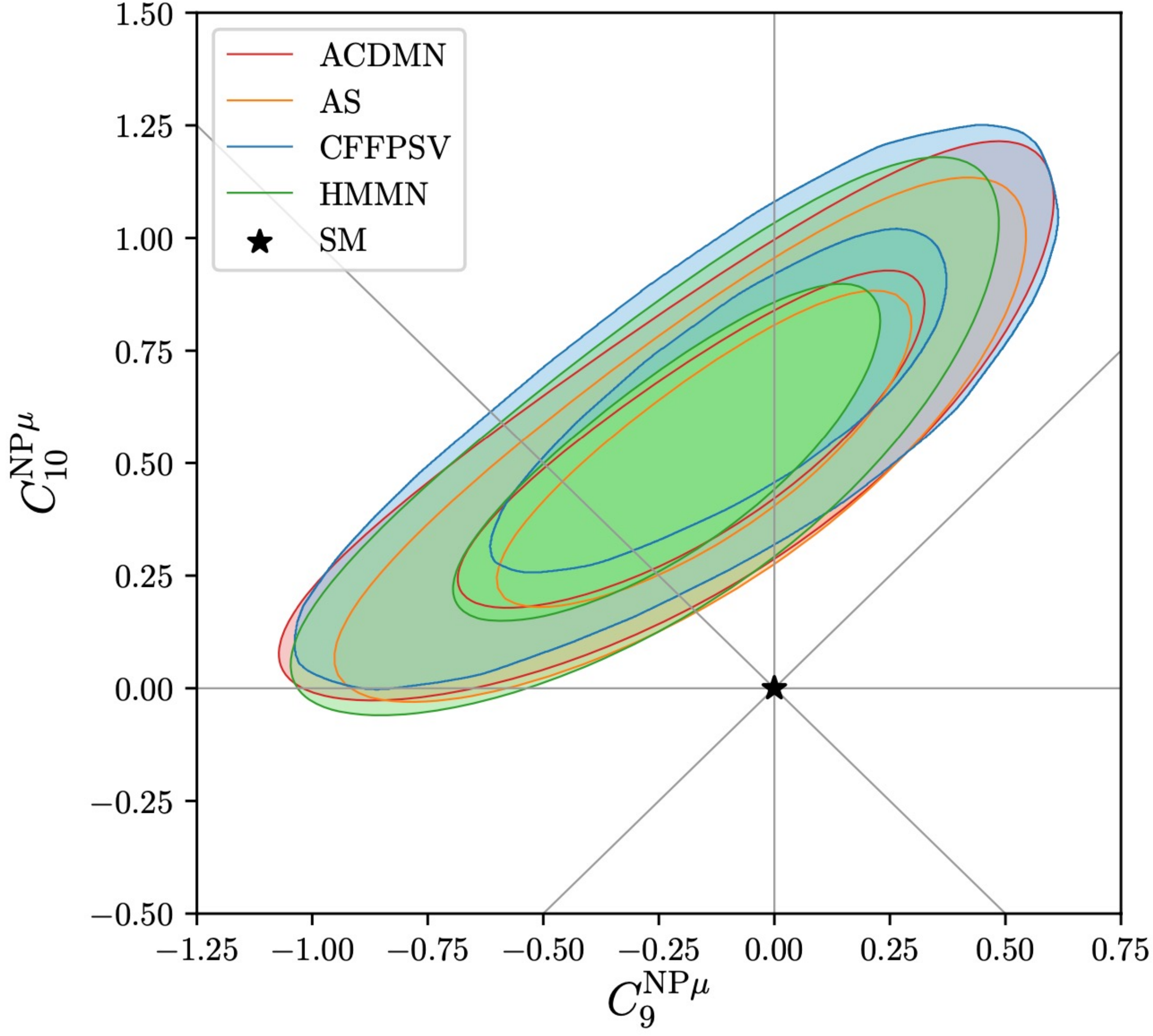
arXiv:2103.11769



3.1σ from SM prediction

Summary of R_{H_s} measurements



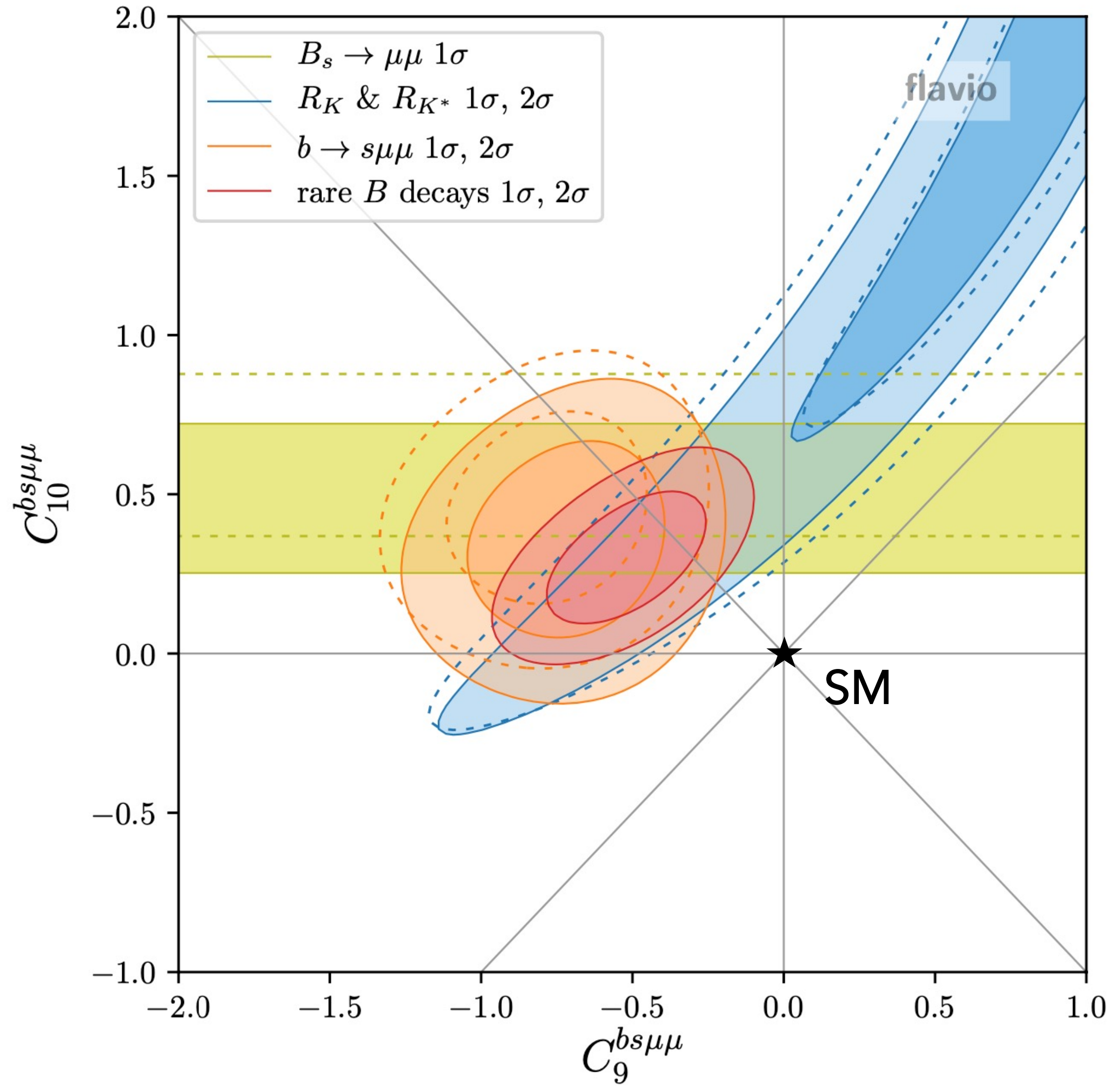


fit to LFU observables + $B_s \to \mu\mu$

Want to know more ?

Flavour Anomaly Workshop 2021

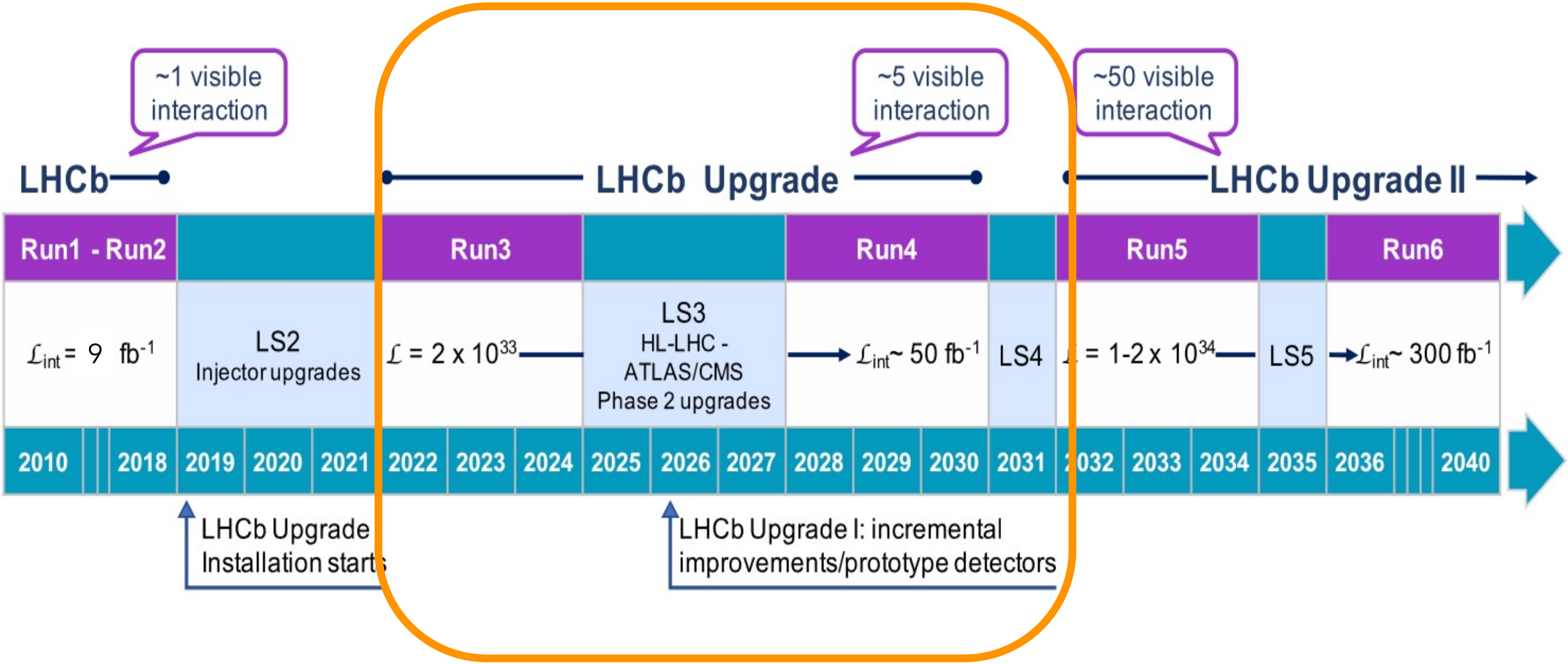
https://indico.cern.ch/event/1055780/contributions/4454282/attachments/2331140/3972619/b2sll_EFT.pdf arXiv:2103.13370



Angular observables and Lepton Universality measurements can be explained together

More data needed

LHCb Upgrade I

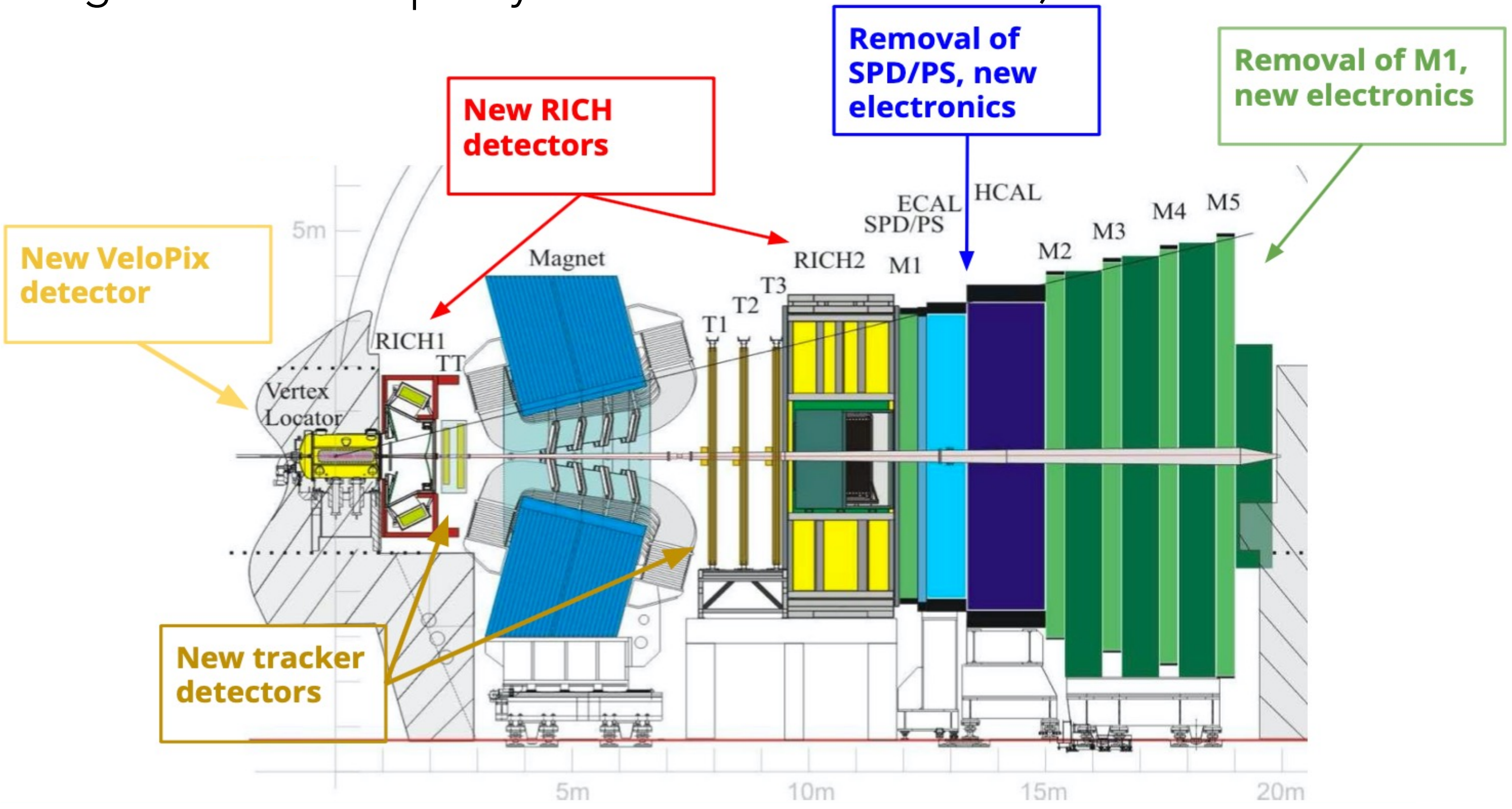


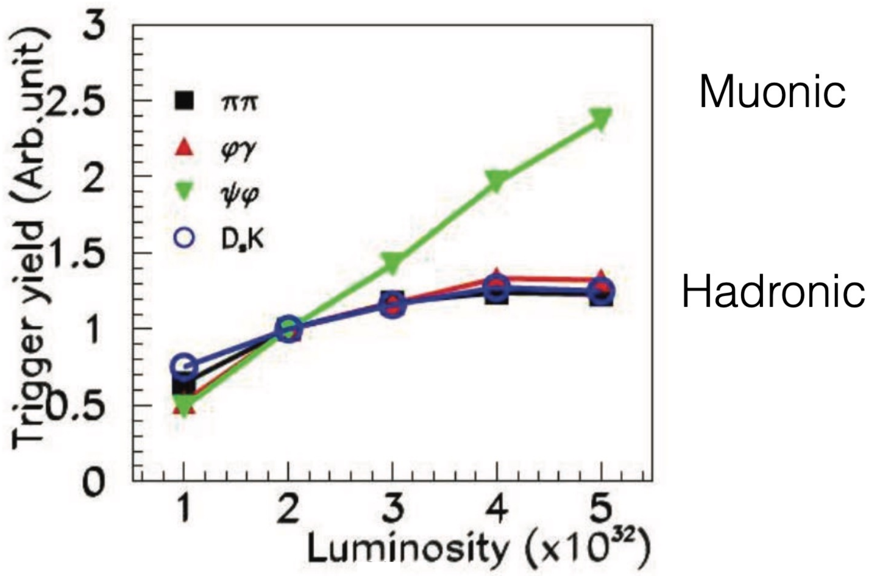
LHCb-Upgrade I : $\mathcal{L} = 2.\ 10^{33}\ cm^{-2}\ s^{-1}$ and removal of the L0

L0 is a bottleneck for electrons and hadronic modes

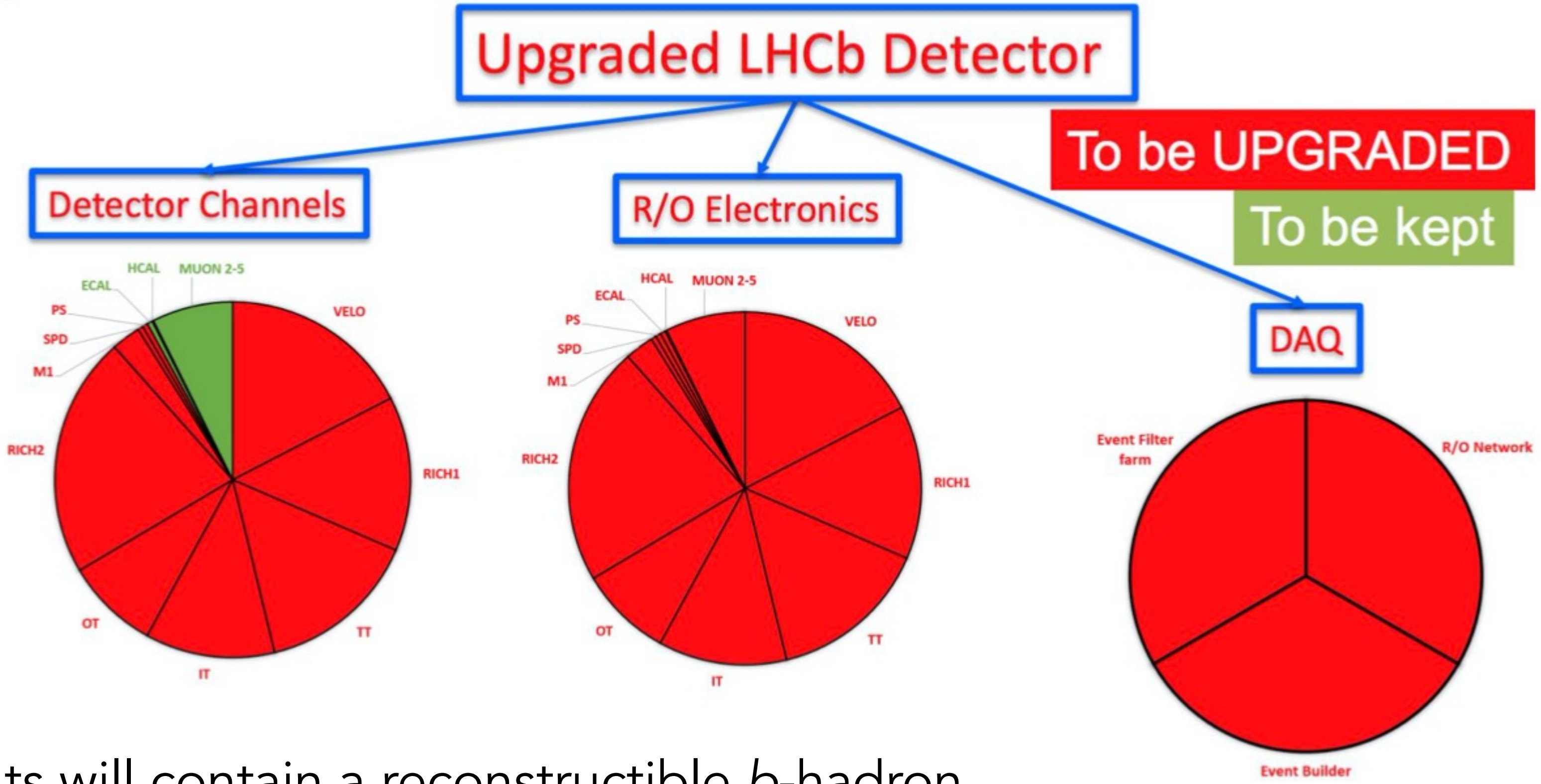
→ all detector read-out at 40 MHz (30 MHz collisions to be handled by the event filter farm)

luminosity x5 wrt Run2
5.5 visible interactions/crossing
Higher track multiplicity from ~<70> to ~<180>)





TDR
CERN-LHCC-2008-007
CERN-LHCC-2011-001
CERN-LHCC-2012-007
CERN-LHCC-2013-021
CERN-LHCC-2013-022
CERN-LHCC-2014-001
CERN-LHCC-2014-016
CERN-LHCC-2018-007
CERN-LHCC-2018-014
CERN-LHCC-2019-005
CERN-LHCC-2020-006



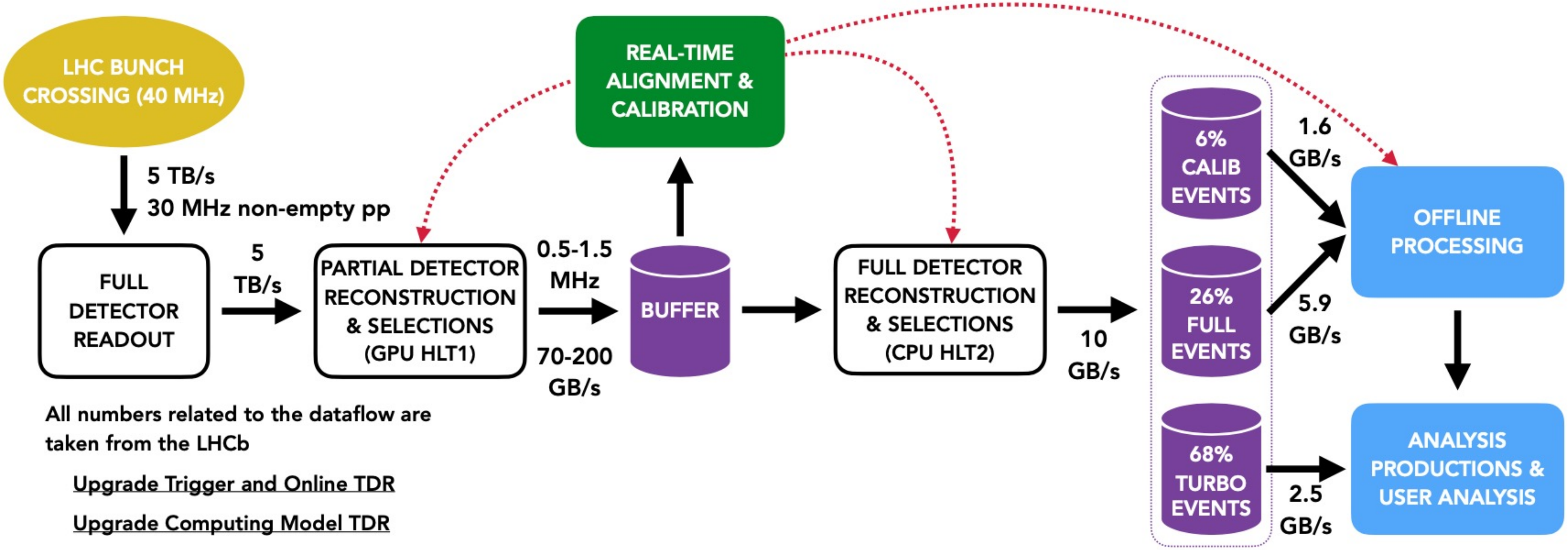
~2% of the events will contain a reconstructible *b*-hadron

Particle type	Run I (kHz)	Upgrade (kHz)
b-hadrons	17.3	270
c-hadrons	66.9	800
Light long-lived hadrons	22.8	264

includes expected trigger and reconstruction efficiencies.

Comput. Phys. Commun. 208 (2016) 35-42

System will mostly categorize signal !

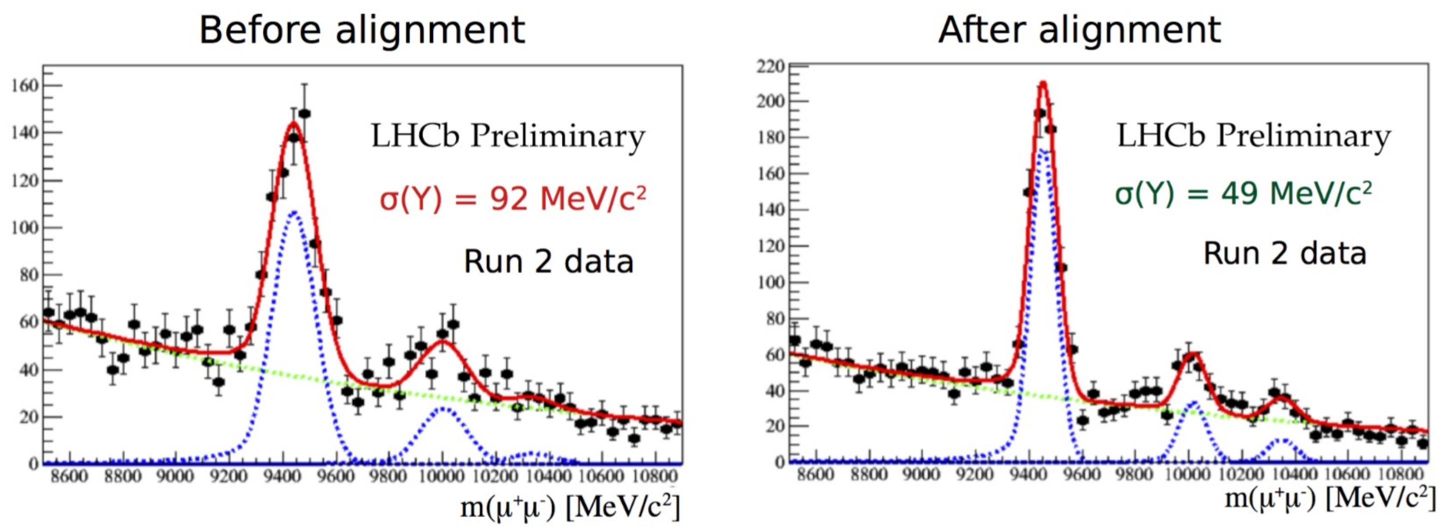


All numbers related to the dataflow are taken from the LHCb

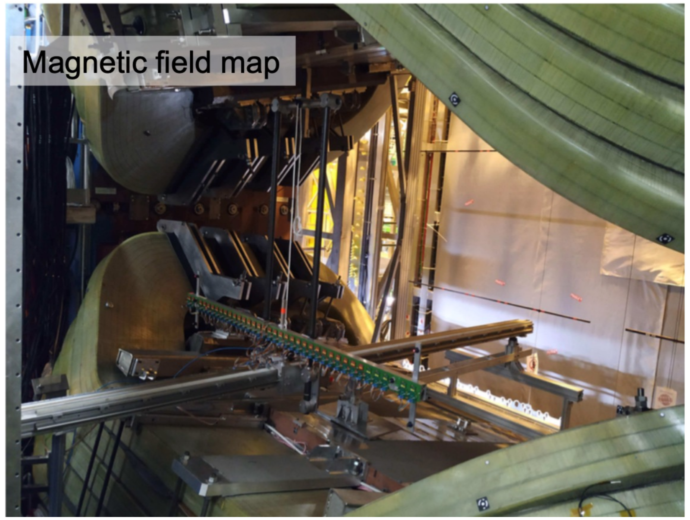
Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

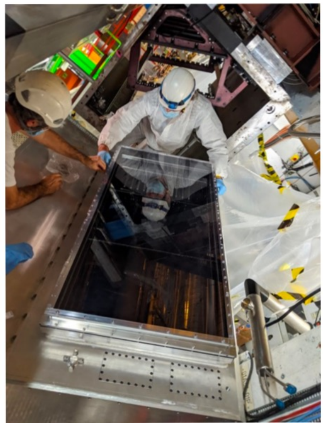
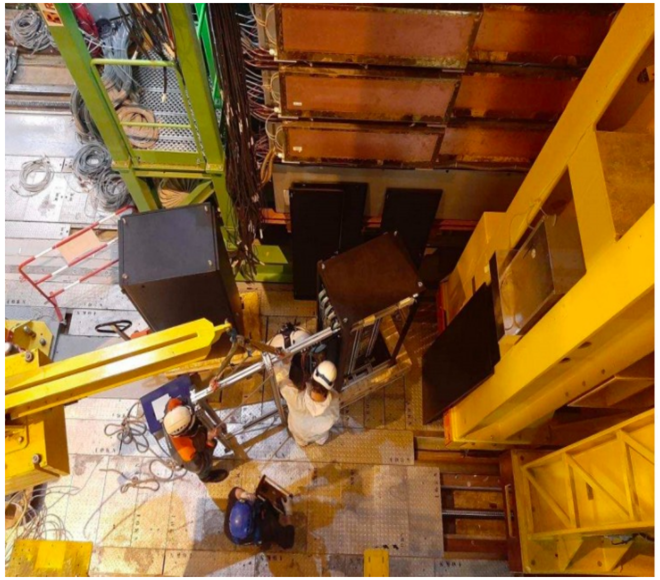
M. Alexander, LHCC March 2021



Upgrade I is on-going

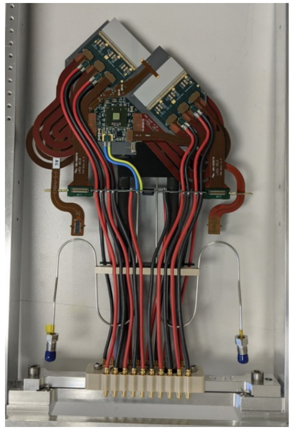


RICH1

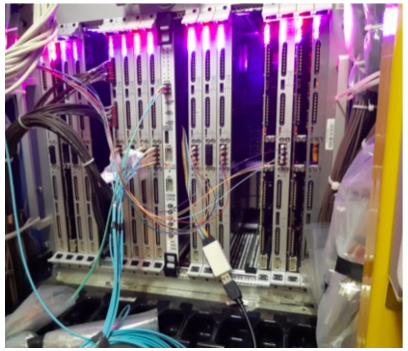




Installation work on the LHCb SciFi Tracker at LHCb

VELO



Calorimeter electronics



Huge work to keep on schedule despite the impact of the pandemic

Upgrade I is on-going : first stable beams

Summary

- Rare decays are quite interesting : tensions seen in $b \to s\,\ell\ell$ transitions (Lepton Universality (e/μ) questioning)

?

- Still many measurements to be done with the data at hand

- Upgrade I (for Run3 data-taking) :
  - Major upgrade of the detector is on-going
  - flexible fully-software trigger
  - expected data sample of ~50 fb^{-1}

Exciting times ahead !

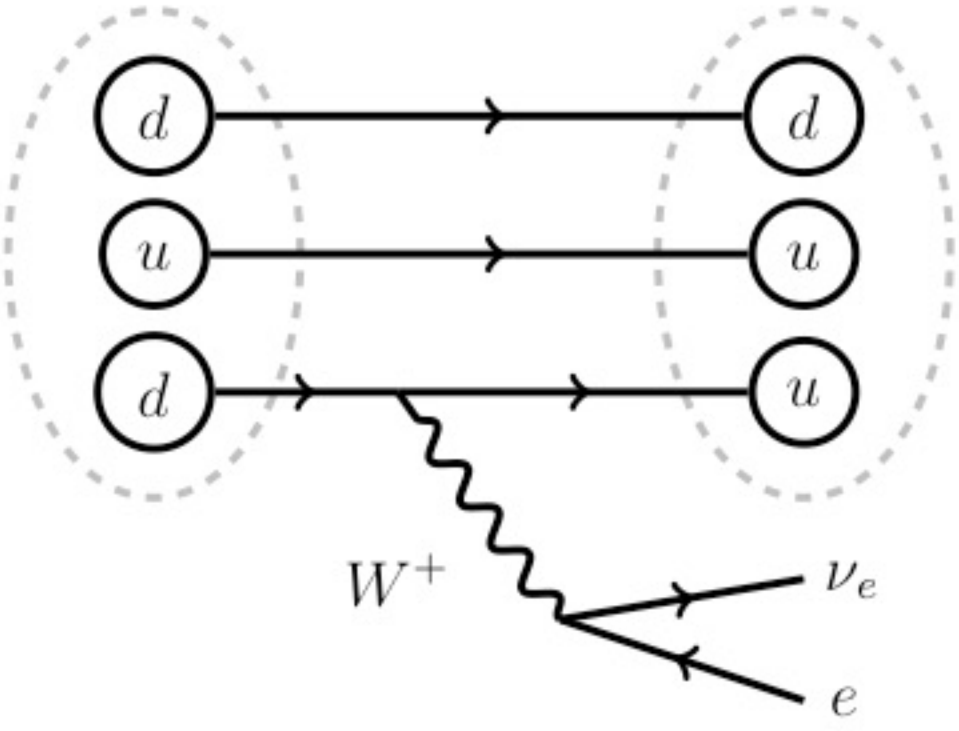
Back-up slides

Indirect searches

β decay of the neutron

Phenomena taking place at ~ 1 GeV reveals physics at the 100 GeV scale

M ~ 1 GeV



M ~ 1 GeV

History is telling us that Flavour physics is a key-tool

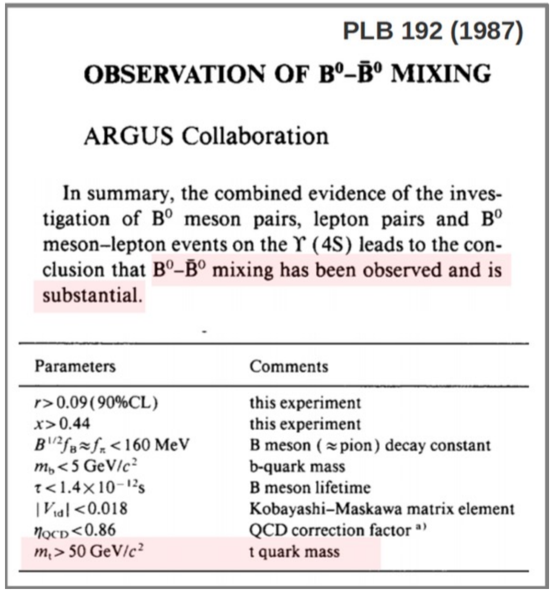
Probes scales >> 1 TeV (depending on c_{NP})

CP violation and FCNC : sensitive probes of short distance physics

Many tests limited by statistics not by systematics nor theory

$$A(\psi_i \to \psi_j + X) = A_0 \left(\frac{c_{\mathrm{SM}}}{v^2} + \frac{c_{\mathrm{NP}}}{\Lambda_{\mathrm{NP}}^2} \right)$$

NP scale and coupling



PLB 192 (1987)

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson–lepton events on the Υ (4S) leads to the conclusion that B^0–$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a]
$m_t > 50$ GeV/c^2	t quark mass

1987 B_d mixing $\sqrt{s}$=10 GeV (ARGUS)

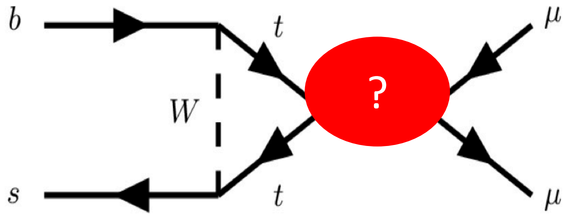
$$\Delta m_d \sim 0.00002 \times \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1} \sim 0.5\ \mathrm{ps}^{-1}$$

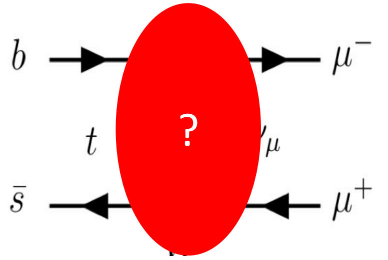
$\Rightarrow$ m_t >50 GeV

1964 $K_L \to \pi\pi$: CP violation
3 families

$B_{d,s} \to \mu\mu$

$$\mathcal{B}(B_q^0 \to \mu^+\mu^-)_{SM} = \frac{\tau_{B_q} G_F^4 M_W^4 \sin^4\theta_W}{8\pi^5} |C_{10}^{SM} V_{tb} V_{tq}^*|^2 f_{B_q}^2 m_{B_q} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_q}^2}} \frac{1}{1-y_q} \qquad q = d, s$$





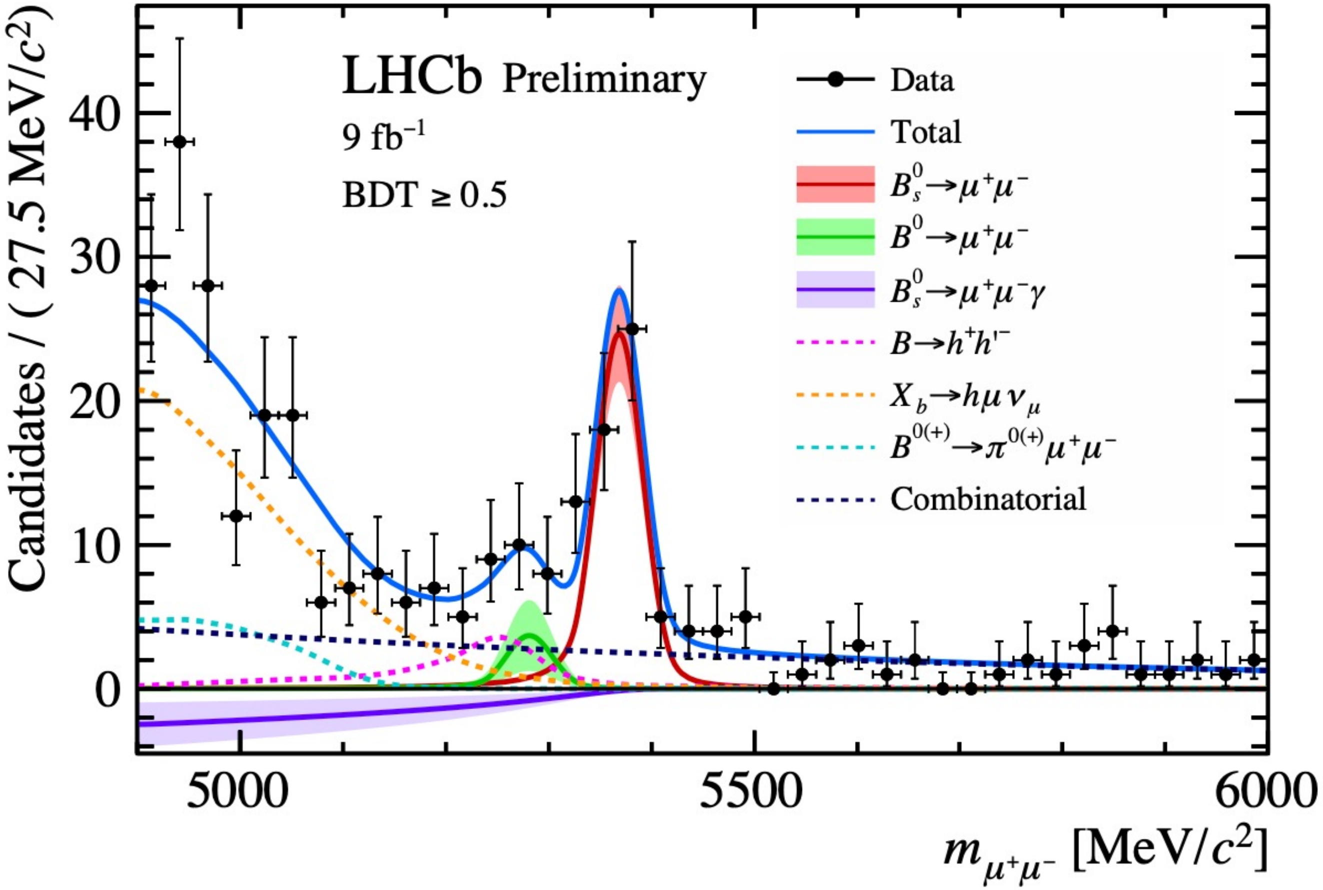
single Wilson coefficient & single hadronic constant (known at $\simeq 0.5\,\%$!)

[PRD 98 (2019) 074512]

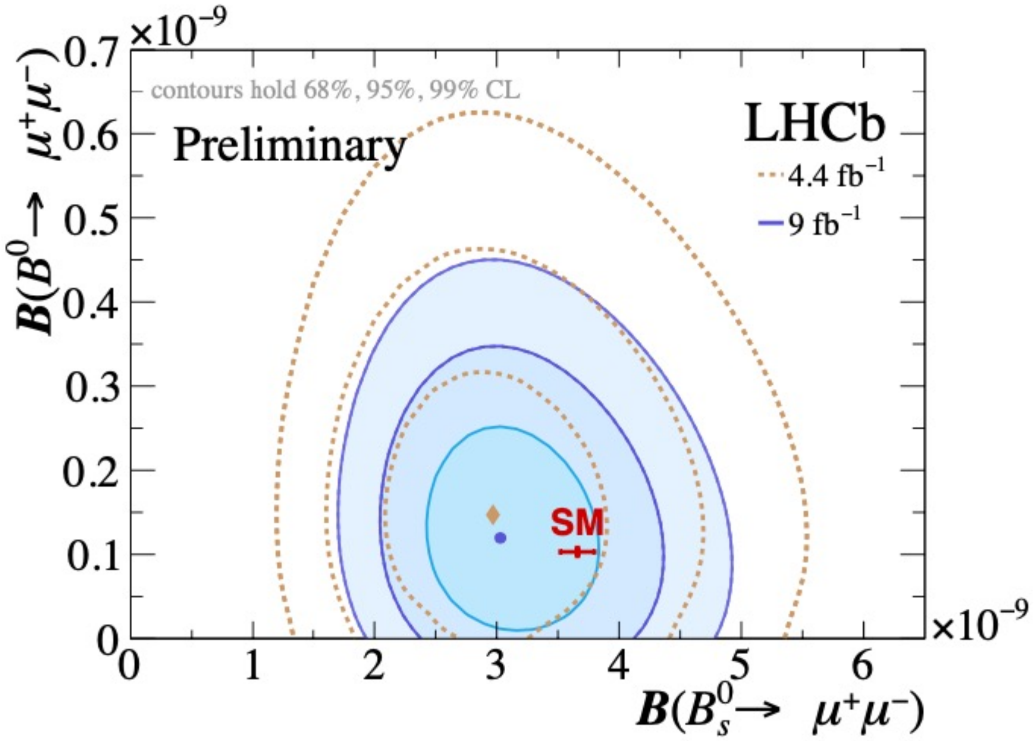
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{SM} = (1.03 \pm 0.05) \times 10^{-10}$$

[JHEP 10 (2019) 232]

- The rarest modes (helicity suppression)
- Due to the value of the CKM elements , the B_d mode is further suppressed
- Clean experimental signature



arXiv 2108.09284



- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ (10.8σ)

- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with background only at 1.7σ and 1.5σ

Compatible with the SM