Rare decays in the quarks sector

On behalf of ATLAS, Belle-2, CMS and LHCb collaborations

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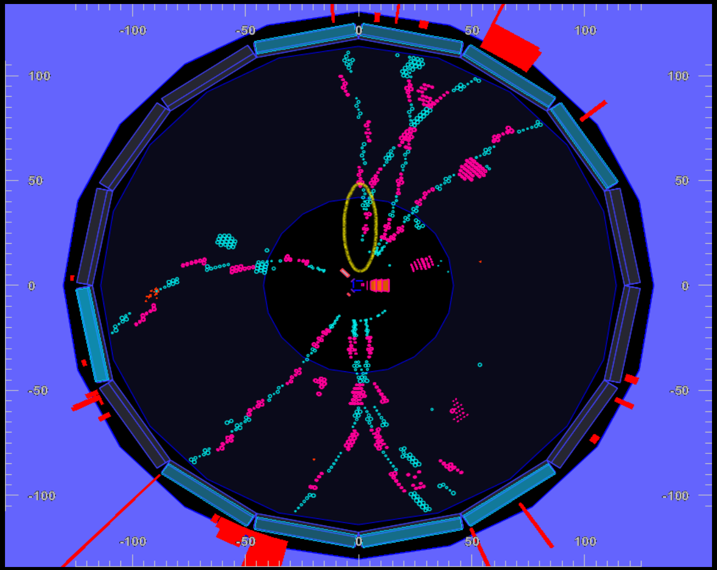
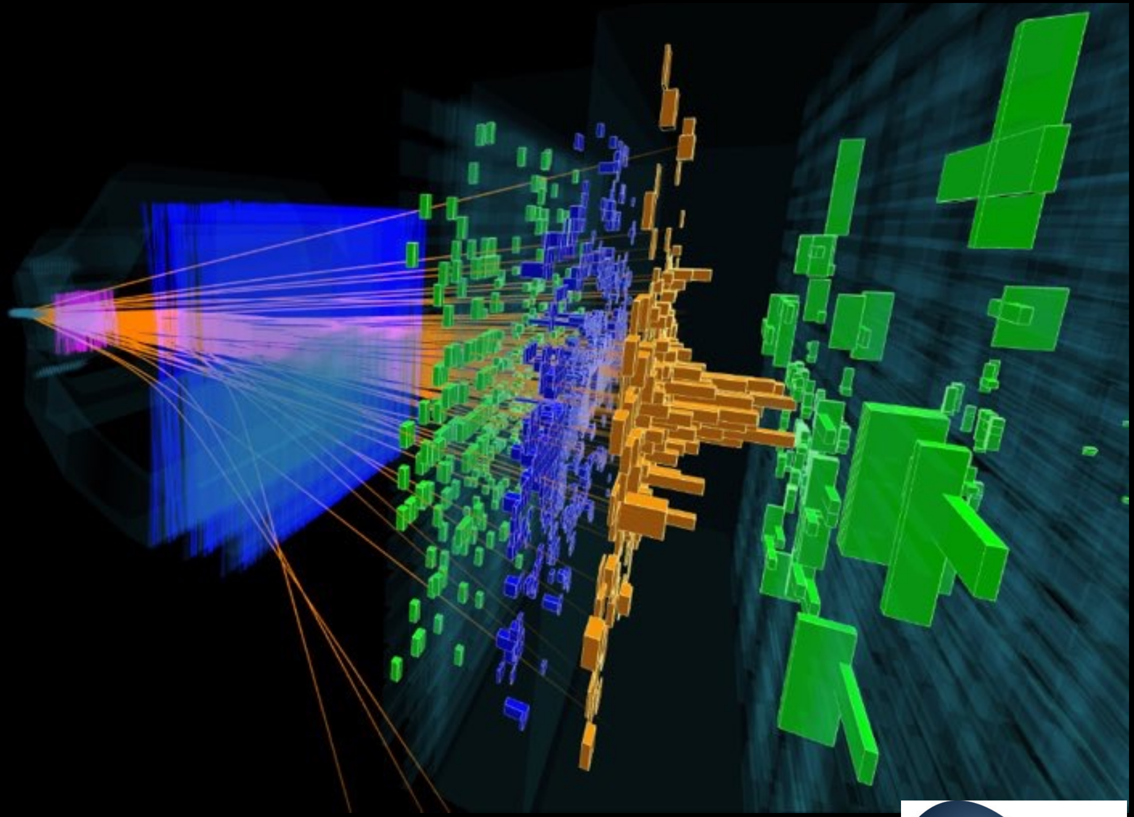
IJCLab – CNRS Univ. Paris-Saclay





Why rare decays ?

- Change of paradigm: not any more theory driven
- Which are the sources of flavour symmetry breaking we observed ?
- History is telling us that rare decays are powerful tools

Rule of the game

- Precisely predicted
- Precise measurements (as much as possible !)

What is rare ?

$BR_{eff} < 10^{-6}$

A game of couplings and scale

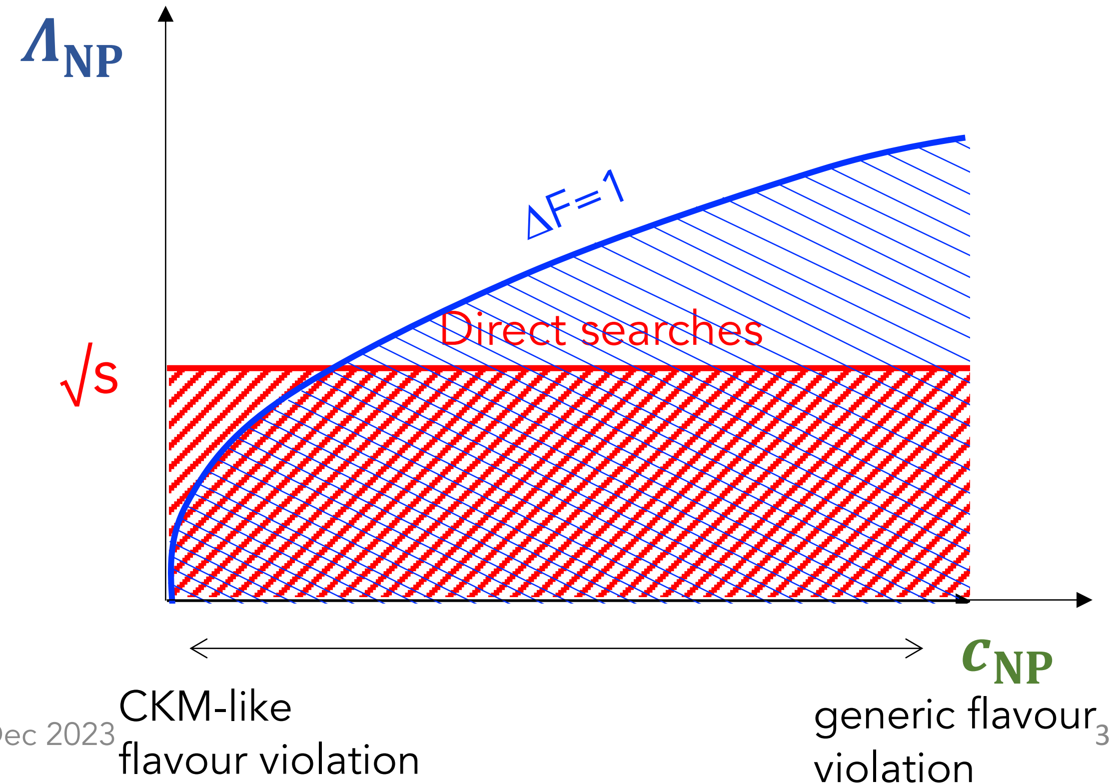
- Flavour Changing Neutral Currents: mediated by box and loop diagrams (strongly suppressed in the SM): New Physics can compete and modify the properties of the decays

- Access to larger scales than direct searches

$$\mathcal{H}_{NP} \propto \frac{c_{\mathrm{NP}}}{\Lambda_{\mathrm{NP}}^{2}}$$

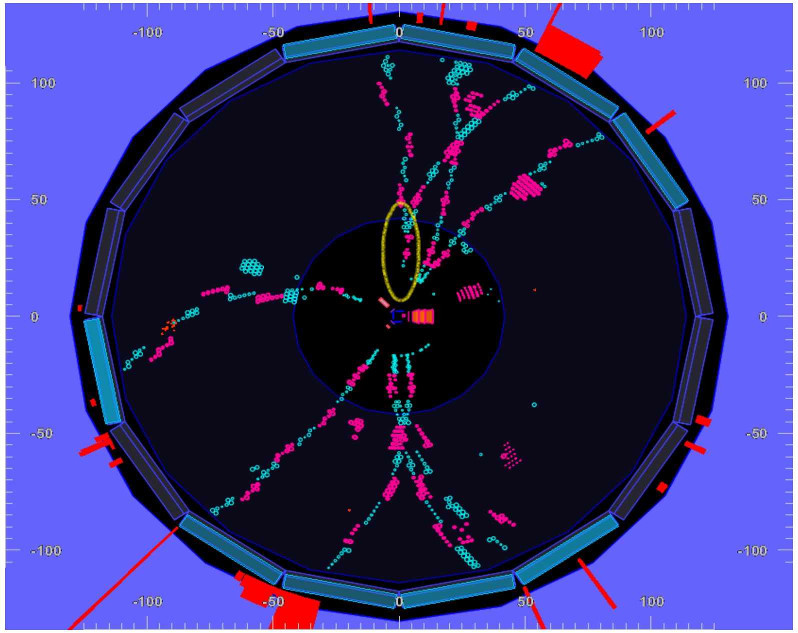
NP coupling

NP scale



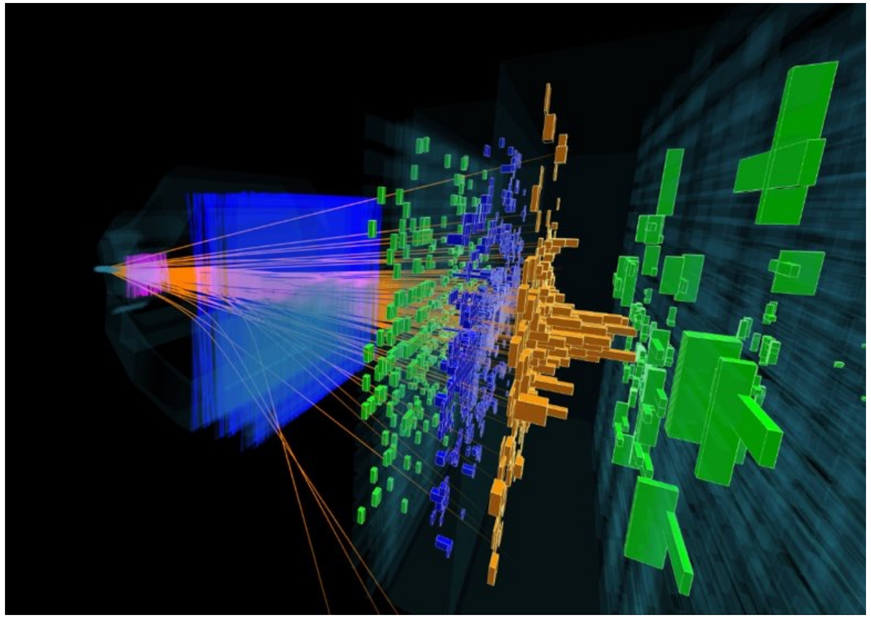
Different experimental environments

Belle-2 @ $\Upsilon(4S)$



- Trigger fully efficient on B events
- Modes with neutrals
- Inclusive measurements
- Statistical limitation

LHCb

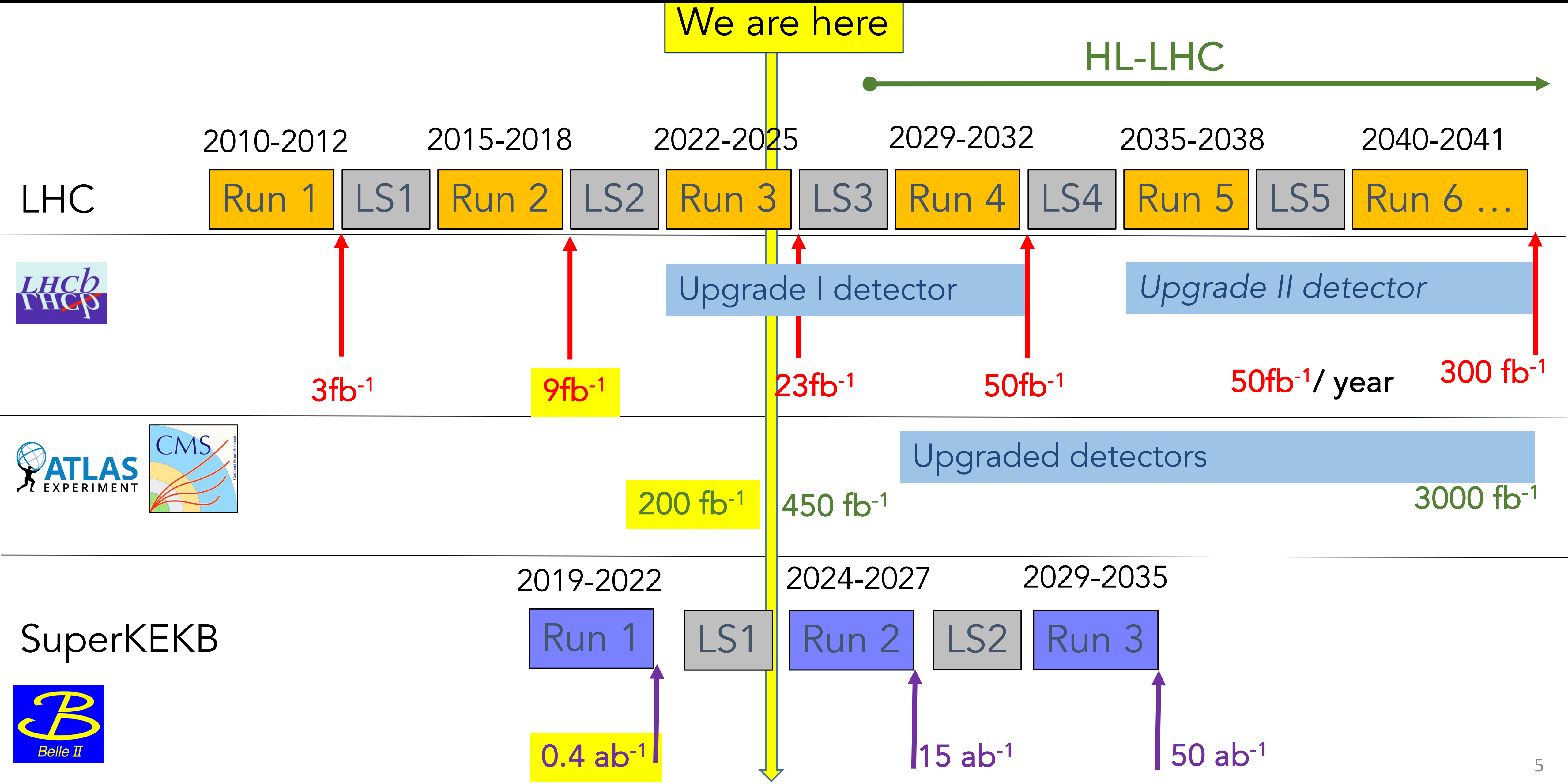


- Access to tiny BRs
- All *b*-hadrons types
- LHC complex environment

but also CMS and ATLAS for specific modes ($B_{(s)} \to \mu\,\mu$)

Very different environments ⇒ complementarity !

Belle-2 and LHCb datasets: present and future



Cherry-picked results: $B_{d,s} \to \mu\mu$

The rarest modes (helicity suppression)

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

SM predictions

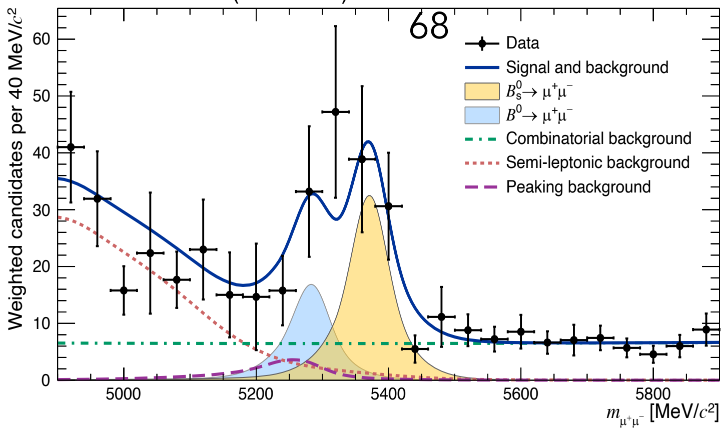
LHC only

JHEP10 (2019) 232

Due to CKM, the B_d modes are further suppressed by a factor 1/30

- Sensitive to the scalar sector. New Physics models with an extended Higgs sector
- First searches in 1985: CLEO BR < 10^{-4} @ 90% CL
  (Phys. Rev. D 30, 2279)
- Observation by CMS and LHCb in 2014
- Clean experimental signature: ATLAS, CMS and LHCb

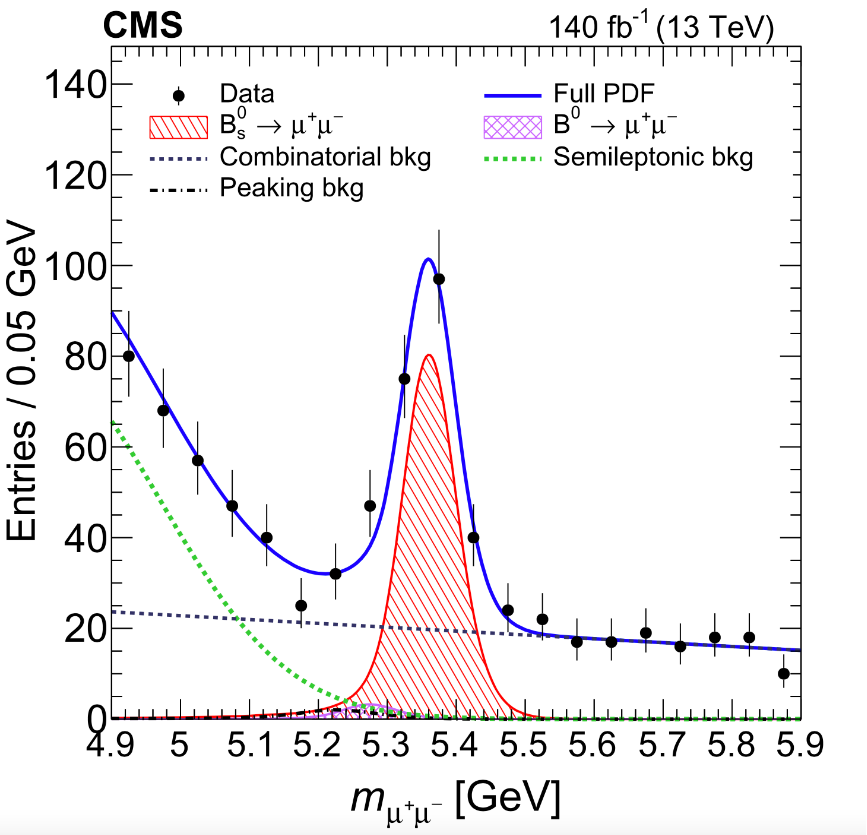
Nature 522 (2015) 68

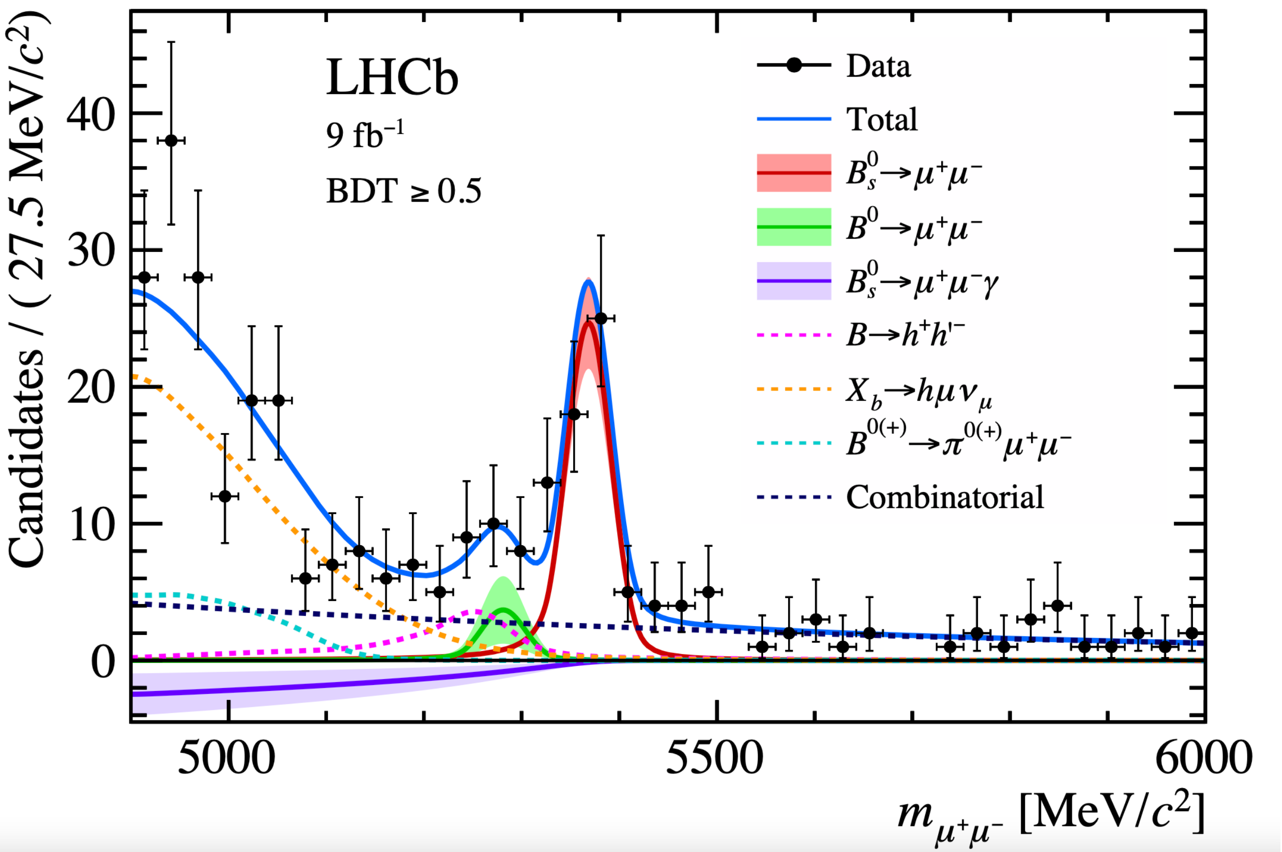


Two most precise measurements: CMS & LHCb

https://doi.org/10.1016/j.physletb.2023.137955

LHCb-PAPER-2021-007





$$\mathcal{B}(B_s \to \mu\mu) = \left(3.83^{+0.38}_{-0.36}{}^{+0.19}_{-0.16}{}^{+0.14}_{-0.13}(f_s/f_u)\right) \times 10^{-9}$$

$$\mathcal{B}(B_d \to \mu\mu) < 1.9 \times 10^{-10} \ @\ 95\ \%\ CL$$

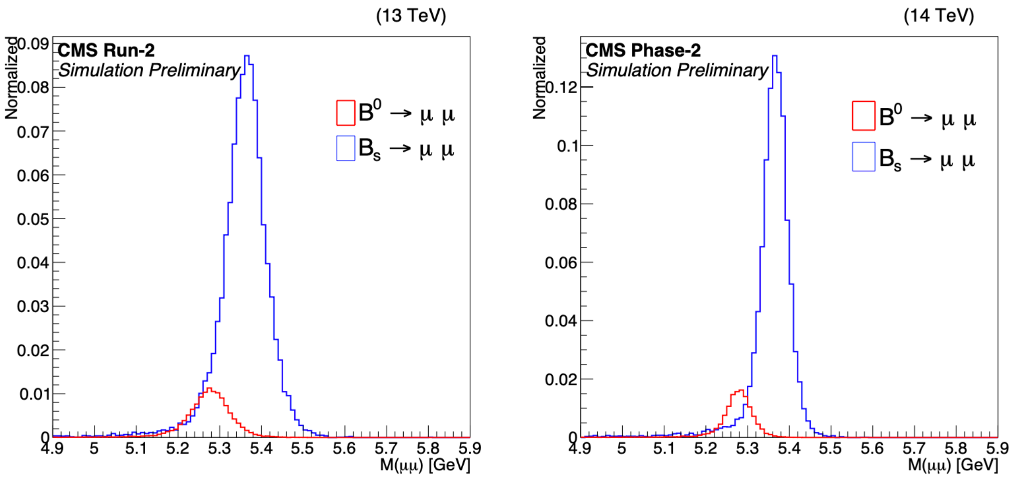
$$\mathcal{B}(B_s \to \mu\mu) = \left(3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}\right) \times 10^{-9}$$

$$\mathcal{B}(B_d \to \mu\mu) < 2.6 \times 10^{-10} \ @\ 95\ \%\ CL$$

Pioneer measurements for the effective lifetime already available

Future challenges/measurements:

CMS-PAS FTR-18-013



CMS-current ⟹ CMS-Upgrade

Key experimental points:

- mass resolution
- understanding of the backgrounds ($\pi \rightarrow \mu$, $K \rightarrow \mu$)

Key phenomenological points:

- Measurements close to the SM uncertainty (CKM matrix elements, B_s decay constant)

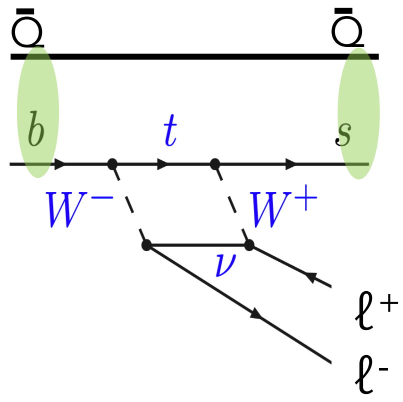
At HL-LHC:

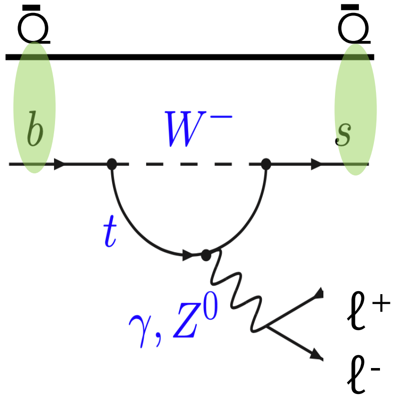
- (f_s/f_d) systematics will dominate BR($\mathbf{B_s \rightarrow \mu\mu}$)
- BR($\mathbf{B_d \rightarrow \mu\mu}$) still statistically dominated
- effective lifetime (2-3 % precision for CMS (3 ab^{-1}) and LHCb (300 fb^{-1}))
- time dependent CP asymmetry (sensitive to NP phase) . Accessible only to LHCb with 300 fb^{-1}

CMS-PAS FTR-18-013
LHCb PUB 2018-019

Cherry-picked results: $H_b \rightarrow H_s \ell\ell$

ℓ=mostly μ





Q=u	Q=d	Q=s
$B^- \rightarrow K^- \ell\ell$ $B^- \rightarrow K^{*-} \ell\ell$	$B^0 \rightarrow K_s \ell\ell$ $B^0 \rightarrow K^{*0} \ell\ell$	$B_s \rightarrow \phi \ell\ell$

+ *b*-baryons ….
(and B_c)

Contributions of the various diagrams vary

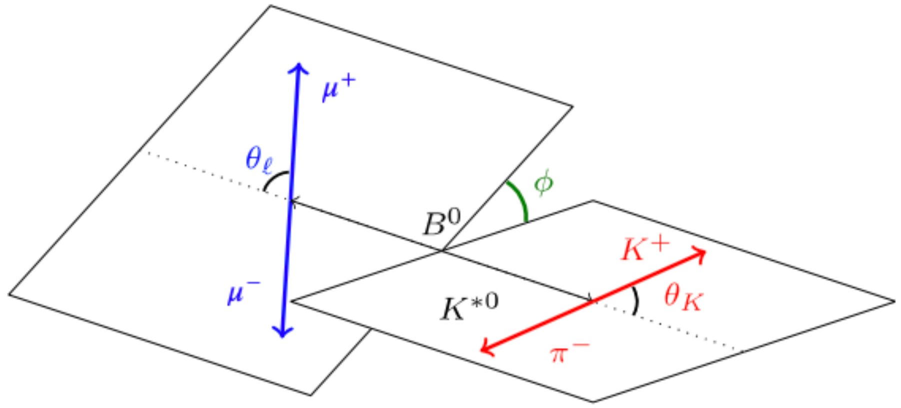
- with $q^2 = M^2(\ell\ell)$
- with the different decay modes

Branching Fractions

Angular observables

Tests of Lepton Universality

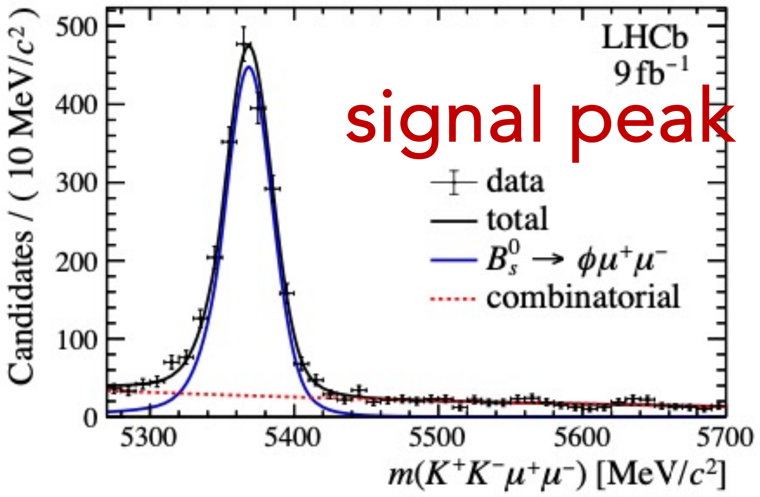
theoretical cleanness



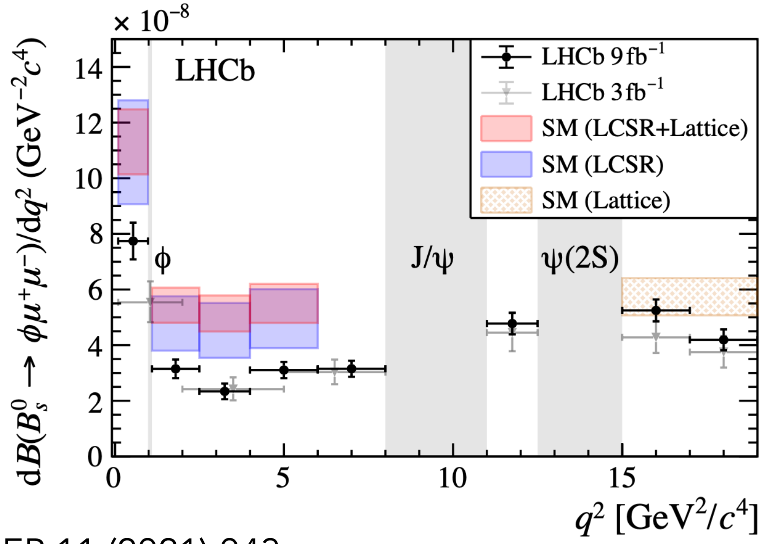
In brief (from several experiments):

- Very clean signal peaks
- BR measurements below predictions (which are correlated from a bin to another. Better agreement at higher-q^2 (LQCD)
- Tensions in the angular observables measurements

JHEP 11 (2021) 043



dBR($B_s \to \phi\ \mu\mu$)/dq^2



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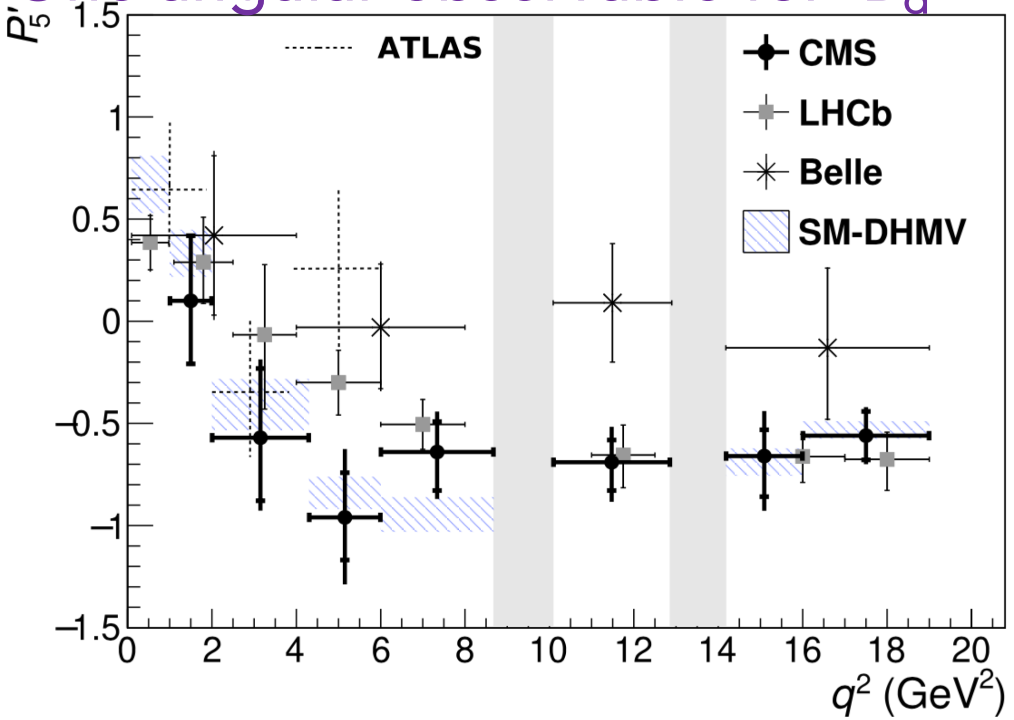
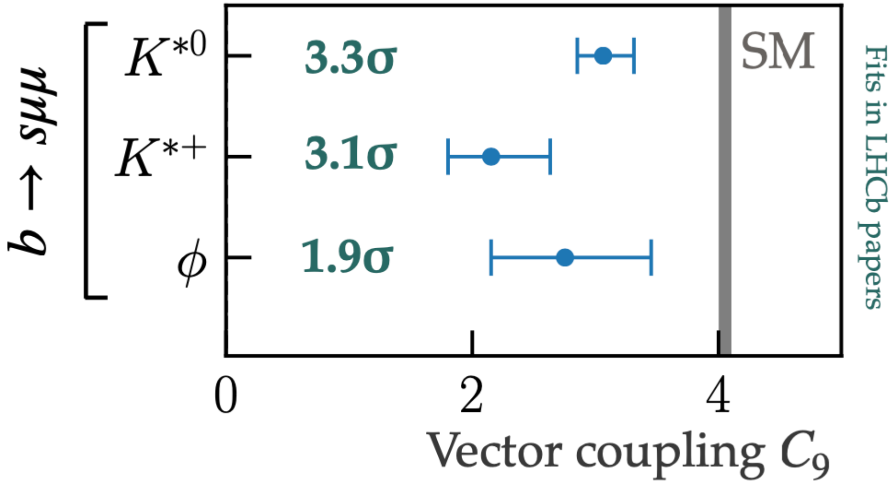
One angular observable for $B_d \to K^{*0}\ \mu\ \mu$

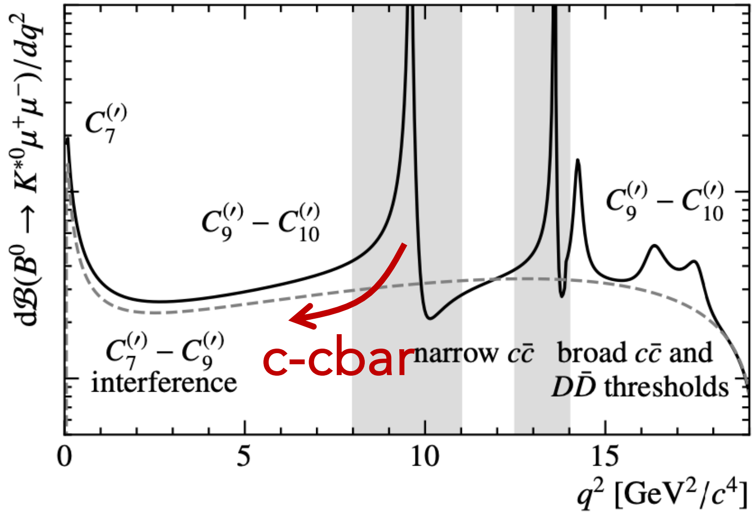


U. Egede and J. Serrano
Compte-rendus académie des Sciences
Volume 21, issue 1 (2020), p. 93-106.

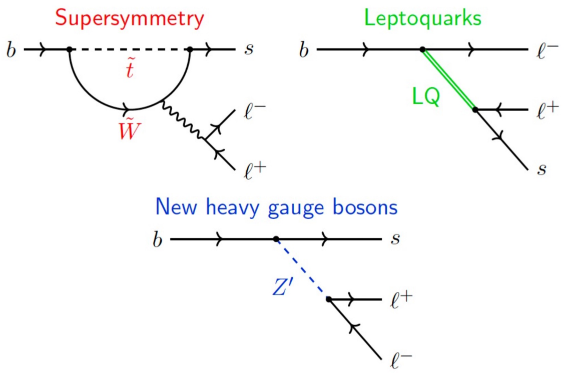
Some (coherent) tensions with respect to SM predictions on angular observables

[*] based on Flavio software, only C_9 floated





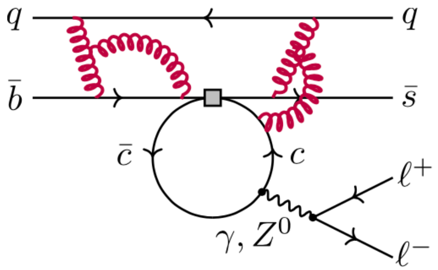
New Physics showing up



or

?

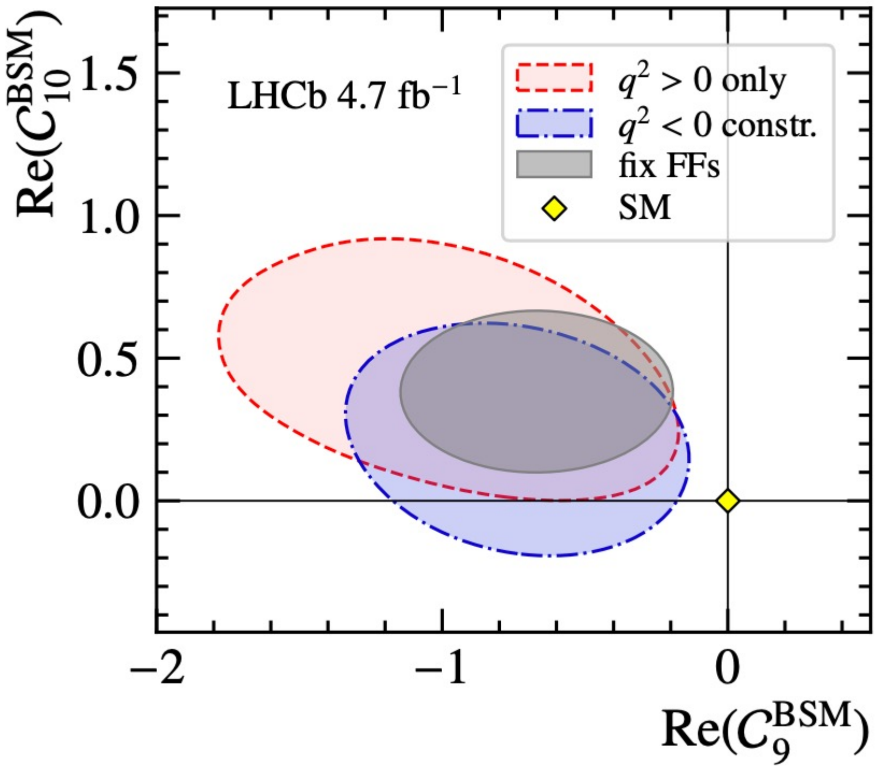
Mismodelling of SM (non perturbative QCD) predictions



Future challenges/measurements:

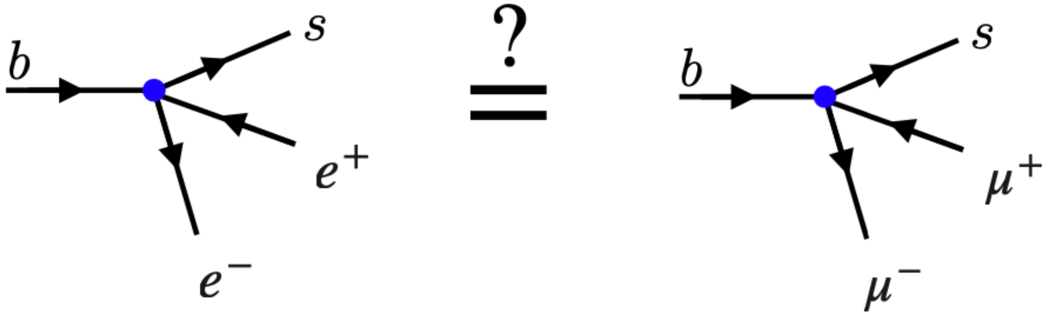
LHCb-PAPER-2023-032
LHCb-PAPER-2023-033
in preparation

- More modes
- More data ⇒ finer q^2 binning
- Extract the $c\bar{c}$ loop from data directly



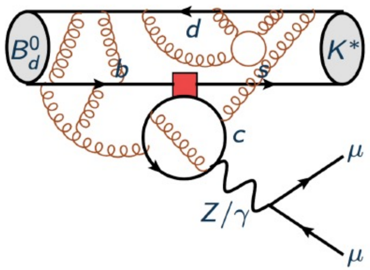
Probably a long way to go to clear up the situation.
A joint experimentalists - theorists effort

Lepton Flavour Universality tests



$$R_{H_s} = \frac{\mathrm{BR}\left(H_b \to H_s \mu^+ \mu^-\right)}{\mathrm{BR}\left(H_b \to H_s e^+ e^-\right)} \overset{\mathrm{SM}}{=} 1.00 \pm 0.01$$

- Theoretically very clean (~ 1% precision)

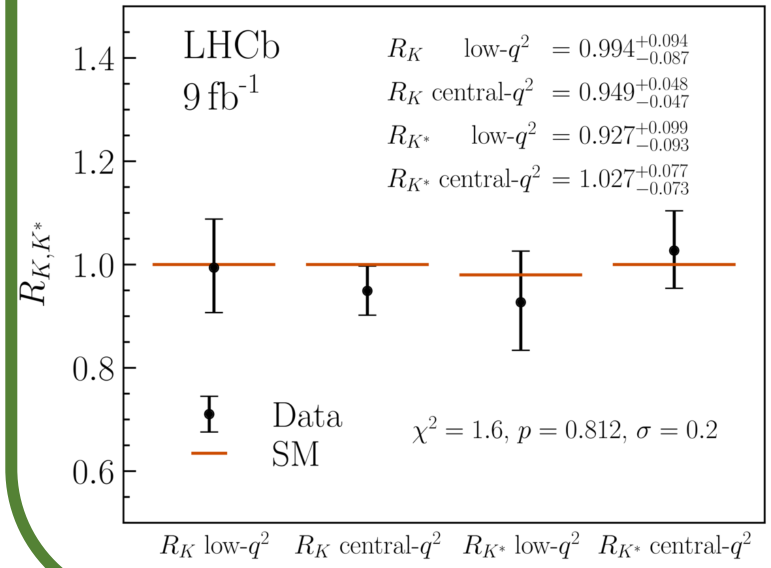


is flavour universal

- Experimentally challenging

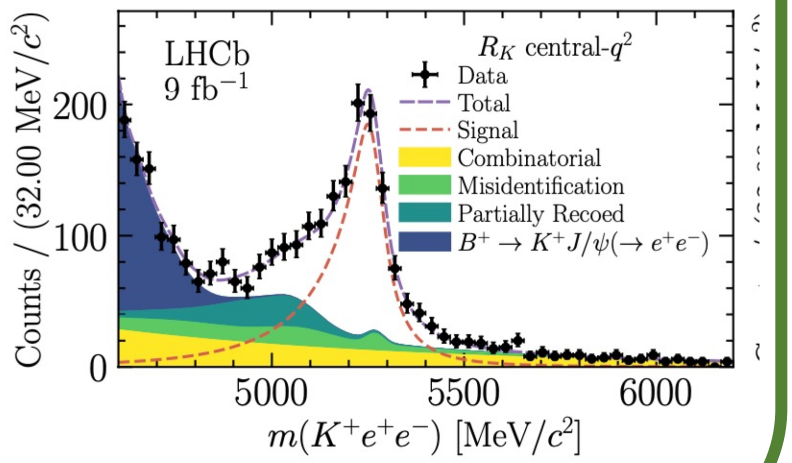
LHCb: $B_{u(d)} \to K^{+(*0)} \ell\ell$, two q^2 kinematical regions

Phys. Rev. D 108 (2023) 032002
Phys. Rev. Lett. 131 (2023) 051803

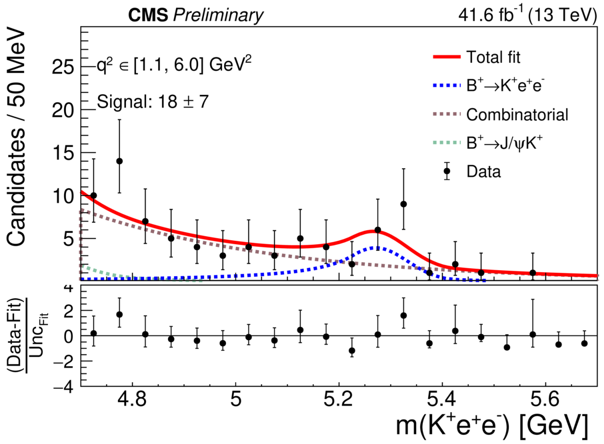


- Compatible with the SM at 0.2 σ
- 5 to 10 % precision
- dominated by statistical uncertainty

$B^+ \to K^+ee$, $1<q^2<6$ (central q^2)



CMS: $B_u \to K^+ \ell\ell$



$B^+ \to K^+ee$
$1<q^2<6$ (central q^2)

$$R(K) = 0.78^{+0.47}_{-0.23}$$

CMS-PAS-BPH-22-005

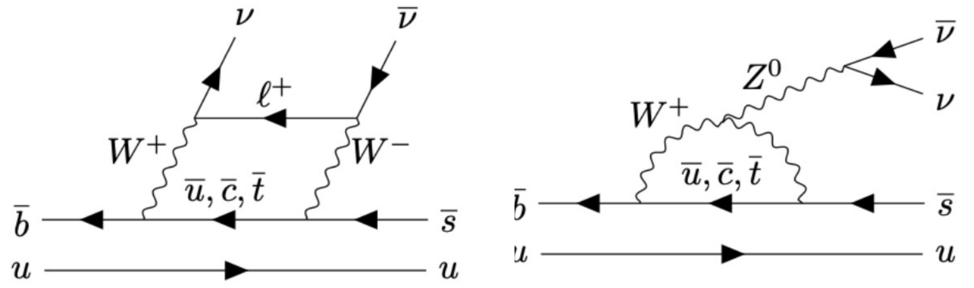
- More data to come
- Test of LFU using ratios of angular observables (pioneer result from Belle (PRL 118 (2017) 111801)
- Important role of Belle-II due to very different environment but statistical limitation

New modes: $B\to K\nu\bar{\nu}$

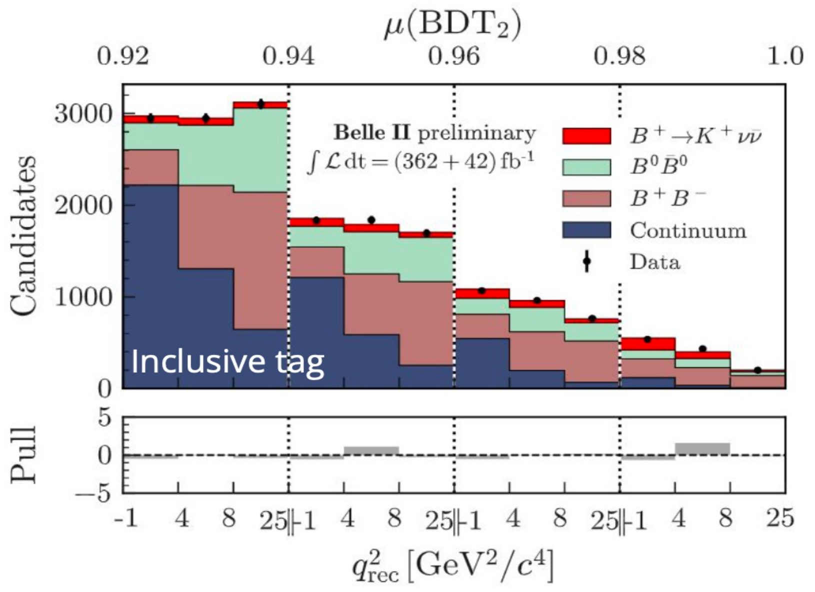
Theoretically cleaner ⇒ precise SM prediction:

$B(B\to K\nu\bar{\nu}) = (5.6 \pm 0.4)\ 10^{-6}$

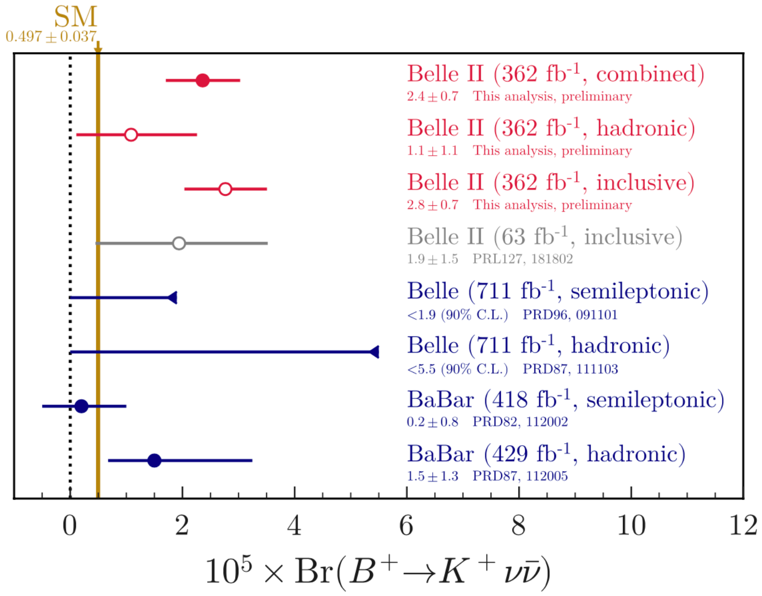
PRD 107, 119903 (2023)



Belle-II has developed a novel inclusive tagging technique



$$\mathcal{B}(B^+\to K^+\nu\bar{\nu}) = [2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})] \times 10^{-5}$$



arXiv:2311.14647

Many measurements: global picture

- Experimental precision at best 5 to 10%
- No obvious sign of NP in $B_s \rightarrow \mu\mu$ (C_{10} is SM)
- What was thought to be precisely predicted seems more complicated ($b \rightarrow s\ell\ell$)
- New modes: ($B \rightarrow K\nu\bar{\nu}$) @ Belle-II

History tells us that we should be more precise !

Wrapping up

- Very active field: many more results than shown !

- Importance to have both the e^+e^- and pp environments

- Study of $b \to d\ell\ell$ transitions starting. Still need at least 20 times more data … probably more

- FCCee running at the Z^0 pole ($> 6.10^{12}$ Z^0) with detectors tailored for Flavour Physics: unique opportunity