RTG Student Lecture: Measurement of $|V_{ub}|$ at the LHCb experiment, lecture II

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In the first lecture we discussed the CKM mechanism and how its parameters can experimentally be measured. Today we will continue with an introduction of the LHCb experiment, and how branching ratios can be measured at hadron colliders.

3 The LHCb experiment

The 4 major experiments located at the Large Hadron Collider (LHC) at CERN, ATLAS, CMS, ALICE, and LHCb, fulfil different purposes. While ATLAS and CMS are so-called general purpose detectors, ALICE is specialised in recording Heavy Ion collisions. The LHCb experiment is designed to detect decays of beauty- and charm-hadrons.

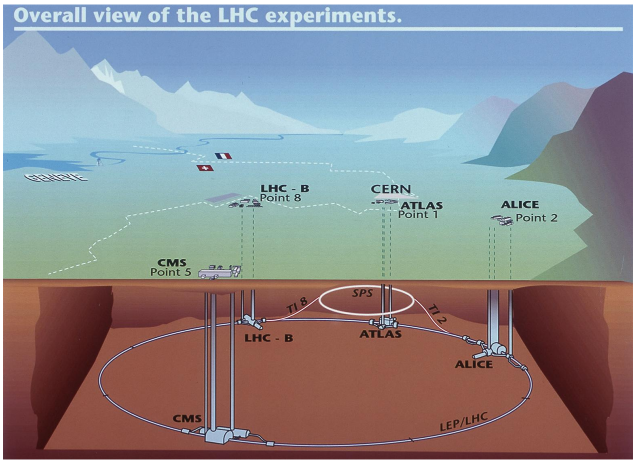


Figure 1: Schematic view of the Large Hadron Collider

The LHCb detector, shown in fig. 2, is build in forward direction, covering an angular acceptance of 10 to 400 mrad. This design exploits the fact that beauty- and charm-hadrons are typically strongly boosted along the beam direction due to their small mass.

The LHCb experiment records about 10^{12} $b\bar{b}$ pairs per year, and about 20 times as many $c\bar{c}$ pairs, and thus has the largest dataset of $\underline{h}$adron decays ever collected, making

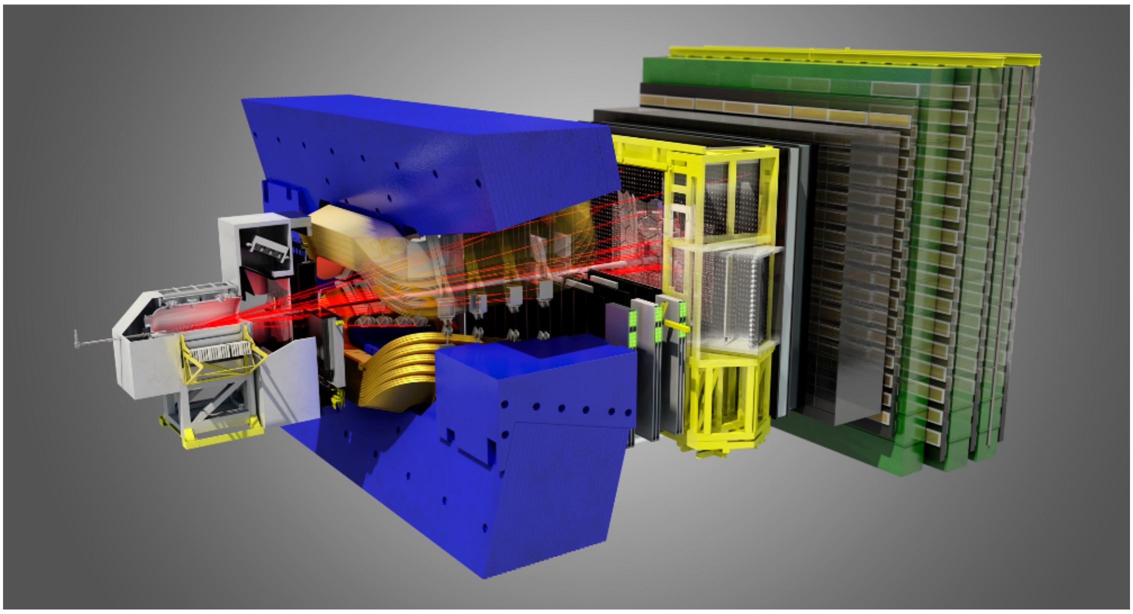


Figure 2: The LHCb detector

statistically precise measurements possible.
Features that make precision Physics possible are the excellent momentum resolution of $< 1\%$, high vertex resolution due to the Vertex Locator (VeLo), and good particle identification by the Ring Imaging CHerenkov detectors (RICH).

4 Branching ratio measurements at hadron colliders

4.1 How to measure a branching ratio?

In the last lecture we already treated the general way to measure the branching ratio of a certain decay mode:

$$\mathcal{B}(B \to \text{sig}) = \frac{\mathrm{N}_{\mathrm{B}\to\mathrm{sig}}}{\mathrm{N}_{\mathrm{B,produced}}} = \frac{\mathrm{N}_{\mathrm{B}\to\mathrm{sig,measured}}}{\mathrm{N}_{\mathrm{B,produced}}} \cdot \frac{1}{\epsilon_{\mathrm{sig,meas.}}}. \tag{1}$$

While at the discussed B-factories the number of originally produced b hadrons $N_{B,\text{produced}}$ is very precisely known, this is much harder at a hadron collider, where the initial state of the collision is unknown. It can however be calculated via

$$N_{B_q,\text{produced}} = \sigma(pp \to b\bar{b}) \cdot f_q \cdot \mathcal{L}, \tag{2}$$

where $_q$ indicates the flavour of the b hadron (i.e. B^+, B^0, B^0_s, B^+_c), $\sigma(pp \to b\bar{b})$ is the cross section of creating a $b\bar{b}$ pair from a proton-proton collision, f_q the fraction of b quarks hadronising to the respective b hadron, and $\mathcal{L}$ the luminosity. Individually, all these parameters have measurement uncertainties of $5 - 10\%$, which would make this

approach of calculating the branching ratio rather unprecise.
Instead, relative branching ratios are measured, using a so-called normalisation mode with a well-known branching ratio. This relative branching ratio is calculated as

$$\frac{\mathcal{B}(B_q \to \mathrm{sig})}{\mathcal{B}(B_{q'} \to \mathrm{norm})} = \frac{N_{B_q \to \mathrm{sig,measured}}}{N_{B_{q'} \to \mathrm{norm,measured}}} \frac{\epsilon_{\mathrm{norm,meas.}}}{\epsilon_{\mathrm{sig,meas.}}} \frac{f_{q'}}{f_q}, \tag{3}$$

where we assume the general case, where normalisation and signal decay don't necessarily originate from the same b hadron flavour. Due to this relative measurement, a lot of systematic uncertainties, e.g. in the efficiency determination, are cancelled.
In the remainder of today's lecture, we will discuss how the ingredients to this calculations are determined on the example of the decay modes $B^0_{(s)} \to \mu^+\mu^-$.

4.2 $B^0_{(s)} \to \mu^+\mu^-$ at LHCb

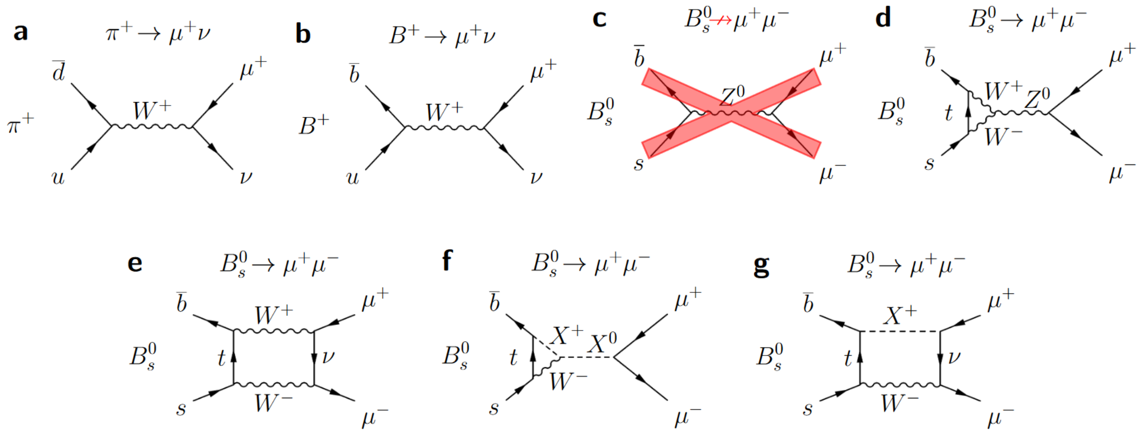


Figure 3: Feynman diagrams connected to the decays $B^0_{(s)} \to \mu^+\mu^-$, including possible New Physics contributions [1]

The decays $B^0_{(s)} \to \mu^+\mu^-$ can happen in the Standard Model only through loop or box diagrams, as shown in fig. 3. Due to GIM-like suppression, the Standard Model branching ratios are of the order 10^{-9}, making these processes very sensitive to New Physics contributions in the loop.
Experimentally, the clean signature of two muons is easy to detect. However, due to the low branching ratio, the event selection has to be evaluated carefully, to protect from mis-identifaction backgrounds.
The normalisation modes used for this measurement are $B^+ \to J/\psi K^+$ and $B^0_s \to K^+\pi^-$, where the latter mode is used as an additional cross check. In the following, we will discuss the candidate selection, the determination of the relative efficiencies, and the extraction of the signal and normalisation yields.

4.2.1 Event selection

As mentioned above, the signal branching ratio is extremely small. Due to that there are significant influences from mis-identified background sources (such as $B^0_{(s)} \to h^+h^-$, where both hadrons are mis-identified as muons) and continuum backgrounds (from random two-muon combinations). Especially important are the requirements on the particle identification variables, as they reject the Physics background from mis-identified particles. Figure 4 shows the mis-identification rate for pions and kaons as muons, respectively. As the branching ratios of $B^0_{(s)} \to h^+h^-$ are many orders of magnitude higher than the signal decays, even small percentages can lead to significant polution of the signal.

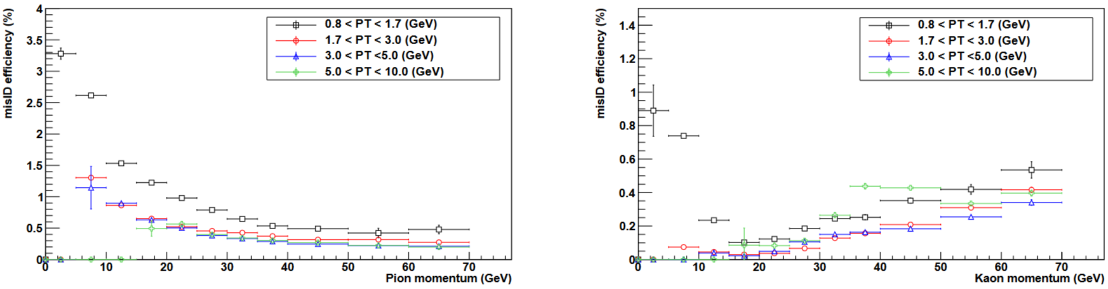


Figure 4: Mis-identifaction rates of pions and kaons as muons.

Tight requirements are set on signal candidates, shown in fig. 5, which reduces background contributions significantly, while keeping a significant part of the signal (about 6%). In addition to that, the selection used for the normalisation modes is shown.

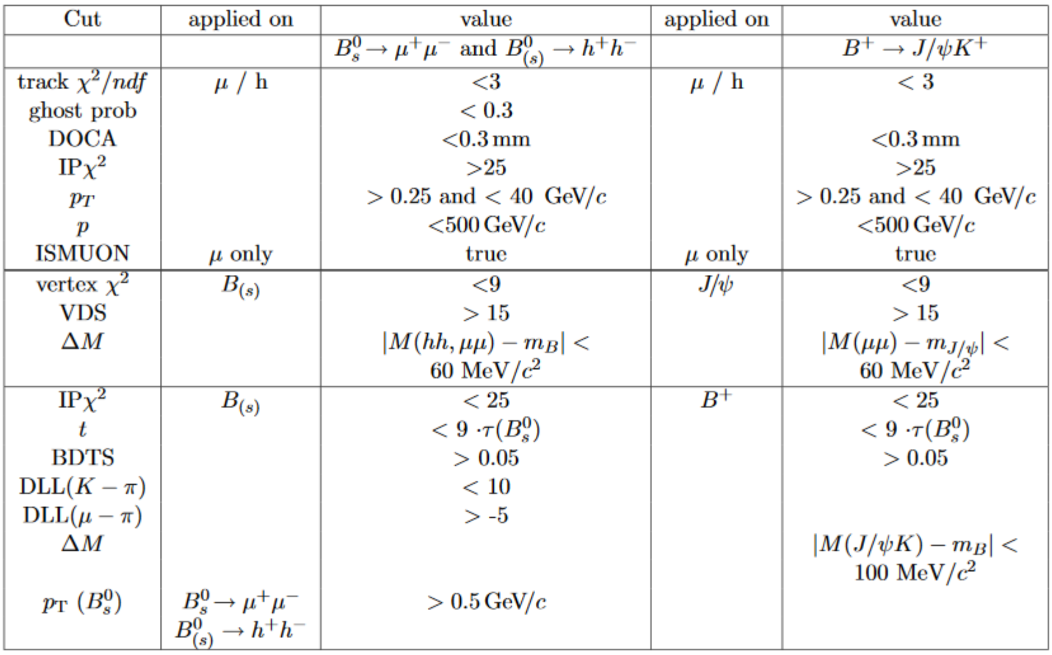
To reduce combinatorial background further a multivariate analysis in form of a Boosted Decision Tree (BDT) is applied. The set of input variables used by this BDT are shown in fig. 6, along with short explanations of their meaning. With the full selection applied, 38/4 signal candidates are expected for $B^0_s/B^0 \to \mu^+\mu^-$ decays in the run I data set of LHCb.

4.2.2 Relative efficiencies

The relative measurement efficiencies for signal and normalisation modes can be factorised into

$$\frac{\epsilon_{\rm norm}}{\epsilon_{\rm sig}} = \frac{\epsilon^{acc}_{\rm norm}}{\epsilon^{acc}_{\rm sig}} \cdot \frac{\epsilon^{sel\&rec|acc}_{\rm norm}}{\epsilon^{sel\&rec|acc}_{\rm sig}} \cdot \frac{\epsilon^{trig|sel}_{\rm norm}}{\epsilon^{trig|sel}_{\rm sig}}, \tag{4}$$

where ϵ^{acc} is the efficiency to have the decay products entering LHCb acceptance, $\epsilon^{sel\&rec|acc}$ the efficiency to reconstruct and select (with the given selection) the candidate when in acceptance, and $\epsilon^{trig|sel}$ the efficiency to trigger such an event. There are different approaches on how these efficiencies can be measured.



Cut	applied on	value	applied on	value
		$B_s^0 \to \mu^+\mu^-$ and $B_{(s)}^0 \to h^+h^-$		$B^+ \to J/\psi K^+$
track χ^2/ndf	μ / h	<3	μ / h	< 3
ghost prob		< 0.3		
DOCA		<0.3 mm		<0.3 mm
IPχ^2		>25		>25
p_T		> 0.25 and < 40 GeV/c		> 0.25 and < 40 GeV/c
p		<500 GeV/c		<500 GeV/c
ISMUON	μ only	true	μ only	true
vertex χ^2	$B_{(s)}$	<9	J/ψ	<9
VDS		> 15		> 15
ΔM		$\lvert M(hh,\mu\mu) - m_B \rvert <$ 60 MeV/c^2		$\lvert M(\mu\mu) - m_{J/\psi} \rvert <$ 60 MeV/c^2
IPχ^2	$B_{(s)}$	< 25	B^+	< 25
t		$< 9 \cdot \tau(B_s^0)$		$< 9 \cdot \tau(B_s^0)$
BDTS		> 0.05		> 0.05
DLL$(K - \pi)$		< 10		
DLL$(\mu - \pi)$		$>$ -5		
ΔM				$\lvert M(J/\psi K) - m_B \rvert <$ 100 MeV/c^2
p_{T} (B_s^0)	$B_s^0 \to \mu^+\mu^-$ $B_{(s)}^0 \to h^+h^-$	> 0.5 GeV/c		

Figure 5: Cuts applied to select $B_{(s)}^0 \to \mu^+\mu^-$ and normalisation candidates.

- As there is no data-driven way to determine how many events happen outside the acceptance of the detector, ϵ^{acc} is taken strictly from simulation. This of course introduces a certain model dependency, which is usually evaluated as a systematic uncertainty.

- Selection and reconstruction efficiencies are usually determined using simulation as well, however, these are corrected in data-driven ways to account for known differences between data and simulation. As an example, the track reconstruction efficiencies are evaluated using tag-and-probe $J/\psi \to \mu^+\mu^-$ events. These are both determined for data and simulation, which provides correction factors depending on the track kinematics, as shown in fig. 7. In similar ways, PID, track resolution, and multiple other parameters are corrected.

- The trigger efficiency can be determined data-driven using the so-called TISTOS technique [2], which will not be elaborated upon further.

4.2.3 Yield extraction

With the full selection applied, the yields for both signal and normalisation modes are determined from fits to the invariant masses of the decay products. Figure 8 shows the fits for both normalisation modes. One can see that the $B^+ \to J/\psi K^+$ is much cleaner, which is the reason it gives the more precise normalisation. The fit to the $\mu^+\mu^-$ masses are shown

- B meson proper time (t),
- minimum impact parameter significance of the muons ($IPS(\mu)$),
- the impact parameter of the B ($IP(B)$),
- distance of closest approach between the two muons ($DOCA$),
- the isolation of the two muons with respect to any other track in the event ($I(\mu)$),
- the transverse momentum of the B meson ($p_T(B)$),
- the cosine of the angle between the muon momentum in the dimuon rest frame and the vector perpendicular to the B momentum and the beam axis ($\cos P$),
- the B isolation based on the CDF definition ($I(B)$),
- angle between the B candidate's momentum and the thrust momentum of the B, defined as the sum of momenta of all the long tracks coming from the B PV and excluding those coming from long lived particles. If no such tracks are available, the variable is set to 0 (other B angle),
- angle between the direction of the positive muon candidate in the rest frame of the B and the thrust momentum in the B rest frame (B boost),
- absolute value of the difference between the pseudorapidity of the two muon candidates ($\Delta\eta$),
- absolute value of the difference between the spherical ϕ coordinate of the two muon candidates ($\Delta\phi$).

Figure 6: BDT input variables.

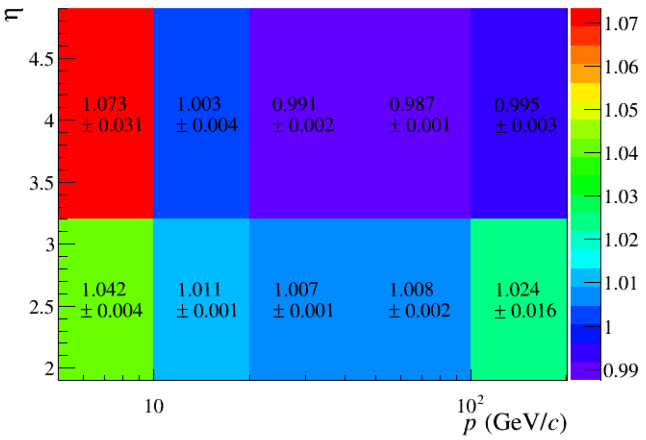


Figure 7: Tracking efficiency correction table for data/simulation discrepancies.

in fig. 9. Both signal modes are clearly showing distinct peaks, but also contributions from other decay modes, which are part of the fit model: the magenta line shows mis-identified $B^0_{(s)} \to h^+h^-$ decays, the black dotted line $B^0_{(s)} \to \pi^-/K^-\mu^+\nu$ decays, and the light blue curve $B^{0/+} \to \pi^{0/+}\mu^+\mu^-$ decays. As expected, very few signal events are left after the selection.

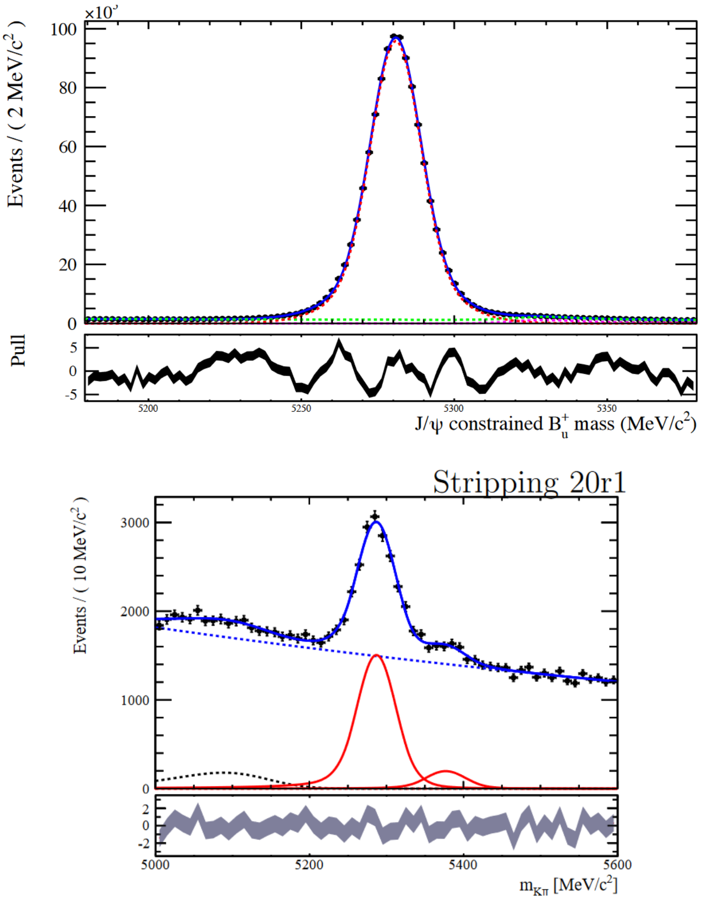


Figure 8: Mass fits to the $K^+\mu^+\mu^-$ and $K^{+/-}\pi^{-/+}$ invariant masses.

4.3 Results

The branching ratios calculated from the measurements for the two signal modes are [3]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{sys})) \cdot 10^{-9} \tag{5}$$

and

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{sys})) \cdot 10^{-10}, \tag{6}$$

which are compatible with the Standard Model predictions of

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.35 \pm 0.28) \cdot 10^{-9} \tag{7}$$

and

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.05) \cdot 10^{-10}. \tag{8}$$

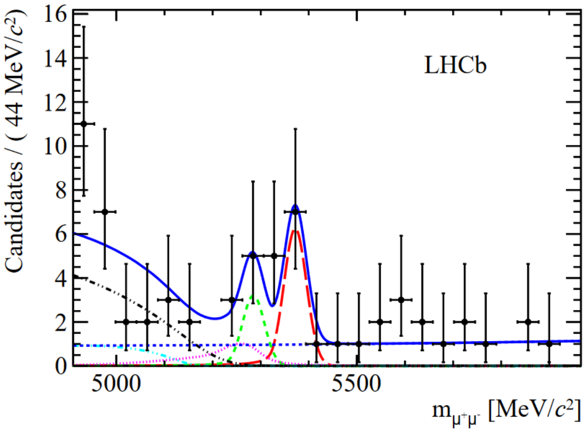


Figure 9: Mass fits to the $\mu^+\mu^-$ invariant mass.

Together with the CMS collaboration a combined analysis [1] was done, which is much more complicated due to the different datasets. Figure 10 shows the result of this measurement. Here a clear access of more than 2 standard deviations was observed for the $B^0 \to \mu^+ \mu^-$ decay. A lot of speculation of New Physics models has been discussed since then. However, only the larger data set of run II data of the LHC will help to resolve this issue.

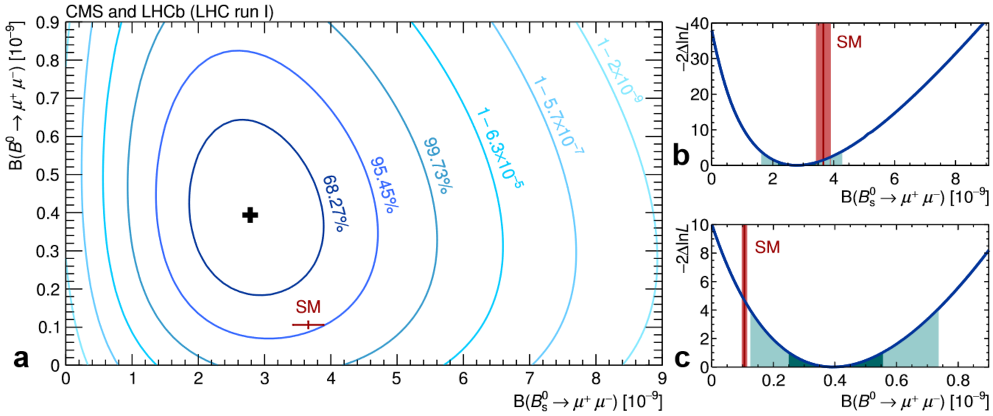


Figure 10: Certainty levels of branching ratio results in the combination of LHCb and CMS data.

References

[1] T. CMS and L. Collaborations, *Observation of the rare* $b_s^0 \to {}^{+-}$ *decay from the combined analysis of cms and lhcb data*, `1411.44131411.4413`.

[2] S. Tolk, J. Albrecht, F. Dettori, and A. Pellegrino, *Data driven trigger efficiency determination at LHCb*, Tech. Rep. LHCb-PUB-2014-039. CERN-LHCb-PUB-2014-039, CERN, Geneva, May, 2014.

[3] L. collaboration *et al.*, *Measurement of the* $b_s^0 \to {}^{+-}$ *branching fraction and search for* $b^0 \to {}^{+-}$ *decays at the lhcb experiment*, `1307.50241307.5024`.