Suche nach Elektroweakinos mit dem ATLAS Detektor

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Dissertation

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Part I

Fundamental concepts

Part II

The 1-lepton analysis

Chapter 6

Background estimation

A reliable estimation of the expected Standard Model of Particle Physics (SM) background rates in the signal regions (SRs) is crucial for exercising the statistical machinery laid out in chapter 3 and making conclusive statistical statements. The background estimation approaches used in the following either rely on semi-data-driven techniques or on Monte Carlo (MC)-only estimations. As estimating backgrounds only from MC simulation is often problematic due to e.g. mis-modelings in the phase space regions targeted not appropriately covered by the uncertainties, a (semi-)data-driven approach is often favoured. In the following, the major backgrounds $t\bar{t}$, single top and $W+$jets are estimated using a semi-data-driven approach, while the expected rates from the remaining smaller backgrounds rely purely on MC simulations and are normalised to their theoretical cross section.

6.1 General strategy

6.1.1 Transfer factor approach

Estimating background contributions in SRs in a semi-data-driven approach, usually involves the introduction of so-called control regions (CRs) used to control dominant background processes by comparing their expected event rates to data. The CRs are designed to be enriched in events of a given background process (or type) while being approximately free of signal contamination. If $N_p^{\mathrm{MC}}(\mathrm{SR})$ and $N_p^{\mathrm{MC}}(\mathrm{CR})$ are the expected rates for a given background process p from MC simulation in a given SR and CR, respectively, then the transfer factor $N_p^{\mathrm{MC}}(\mathrm{SR})/N_p^{\mathrm{MC}}(\mathrm{CR})$ allows to convert the number of observed background events in the CRs, $N_p^{\mathrm{obs.}}(\mathrm{CR})$ into a background estimate in the SRs,$N_p^{\mathrm{est.}}(\mathrm{SR})$, through

$$N_p^{\mathrm{est.}}(\mathrm{SR}) = N_p^{\mathrm{obs.}}(\mathrm{CR}) \frac{N_p^{\mathrm{MC}}(\mathrm{SR})}{N_p^{\mathrm{MC}}(\mathrm{CR})} = \mu_p N_p^{\mathrm{MC}}(\mathrm{SR}). \tag{6.1}$$

An important benefit of this approach is that the impact of systematic uncertainties on the estimated background rates can be evaluated on the transfer factors, that are ratios of MC estimates. As such, systematic uncertainties can be canceled in the extrapolation to the SR. The uncertainty on the background estimate is then a combination of statistical uncertainties

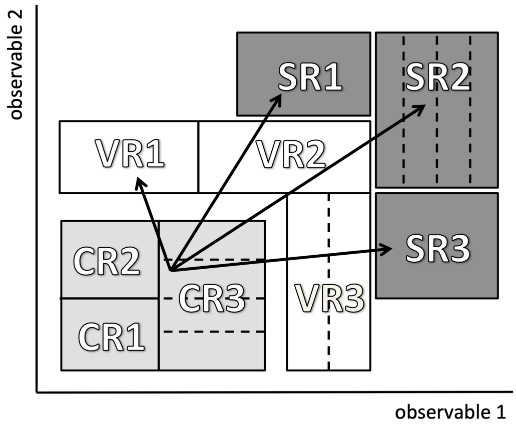


Figure 6.1: Schematic view of an analysis strategy including multiple control, validation and signal regions with one or multiple bins each. Extrapolations from the control regions into the signal regions can be verified in the validation regions lying in the phase space extrapolated over. Figure adapted from [149].

in the CR and remaining uncertainties affecting the extrapolation. For this reason, CRs are usually deliberately chosen to have large statistics, effectively reducing the uncertainties on the extrapolation to the SRs.

As indicated in eq. (6.1), the transfer factor approach is formally equivalent to using the process-specific normalisation factor introduced in section 3.1, effectively *normalising* the number of background events expected from MC in the CR to the number of observed events. In the profile likelihood fit setups used in the following, implemented using HistFitter [149], the normalisation factor μ_b is fitted to data instead of background as expected from MC simulation. In the following, multiple disjoint CRs are used to simultaneously normalise multiple background processes to data in a combined fit. In order not to have an underdetermined minimisation problem, at least the same number of CRs as normalisation factors needs to be used. Two different profile likelihood fit configurations are used in the following, a *background-only* fit configuration assuming no signal contribution and typically only including the CRs, and a *model-dependent* fit configuration with nominal signal contribution using CRs as well as SR.

In order to verify the quality of the extrapolation from the CRs to the SRs, so-called validation region (VR) are defined. VRs do not participate in the actual fit of the model parameters to data, but serve as intermediate regions to verify the extrapolation. For this reason, VRs are typically placed in the region between the CRs and SRs that is extrapolated over. A schematic view of an analysis strategy using all three types of regions is shown in fig. 6.1. All three types of regions can have more than one bin and are separated using suitable observables that are extrapolated over.

6.1.2 Analysis blinding

An important concept in the design phase of searches for new physics is the idea of *blinding* regions of interest [234], meaning that measured data are not looked at in these regions. This avoids issues of *experimenter's bias*, i.e. unintended influences on the design of the analysis based on the observed data. If data were already known when designing the signal regions (and therefore the outcome of the analysis would be known to some extent), experimenter's bias could for example occur during the selection of the final signal region definitions.

During the design of a search for new physics, signal regions are generally kept blinded until the complete analysis strategy is fixed. Once the SRs have been designed, the next step is to develop suitable CRs with negligible signal contamination. This is followed by design of VRs that can be unblinded once the CRs are fixed. The SRs are only unblinded after the extrapolation from the CRs has been verified in the VRs, allowing to either quantify potential excesses in data or set limits on model parameters.

6.1.3 Data versus Monte Carlo plots

In this chapter, all plots comparing data versus MC are *pre-fit*, meaning that no background-only fit has been run in order to determine the normalisation factors and total systematic uncertainties for the background estimate. The contributions from the dominant backgrounds $t\bar{t}$, $W+$jets and single top are normalised simultaneously in the control regions by solving the system of i equations

$$n_{\text{data}}^{\text{CR}_i} = \mu_{t\bar{t}} B_{t\bar{t}}^{\text{CR}_i} + \mu_W B_W^{\text{CR}_i} + \mu_{\text{ST}} B_{\text{ST}}^{\text{CR}_i} + B_{\text{other}}^{\text{CR}_i}, \tag{6.2}$$

where i runs over the list of CRs introduced in section 6.2 and $\mu_{t\bar{t}}$, μ_{W} and μ_{ST} are the normalisation factors of the $t\bar{t}$, $W+$jets and single top backgrounds, respectively, that are to be determined. $B_{t\bar{t}}^{\text{CR}_i}$, $B_{\text{ST}}^{\text{CR}_i}$, $B_{\text{ST}}^{\text{CR}_i}$ and $B_{\text{other}}^{\text{CR}_i}$ are the background rates expected from MC simulation in the i-th CR. Normalisation factors obtained are 0.96 for $t\bar{t}$, 1.24 for $W+$jets and 0.73 for single top. As will be shown in **??**, the normalisation factors obtained using the full statistical procedure will be close to these values.

Additionally, the uncertainty bands on the background estimation include only MC statistical uncertainty as well as experimental uncertainties. The variations of the experimental uncertainties are normalised to the nominal background estimate in the case of $t\bar{t}$, $W+$jets and single top, such that only the shapes of the dominant backgrounds are affected. For the remaining minor backgrounds, the experimental uncertainties can affect both normalisation and shape. All experimental uncertainties are assumed to be fully correlated over all processes and bins, allowing them to be added together in quadrature. The uncertainty bars on the data points correspond to the 68% confidence interval, assuming data to be Poisson distributed.

6.2 Control regions

The contributions from $t\bar{t}$, $W+$jets production and single top processes are normalised to data in dedicated CRs. Other processes like $Z+$jets, diboson and multiboson, $t\bar{t}+V$, $t\bar{t}+h$ and $V+h$ are estimated directly from MC simulation and normalised to their theoretical cross sections. All CRs are designed to be kinematically as close as possible to the respective SRs, such that the normalisation factors derived in the CRs are also valid in the SRs. The CRs are mutually exclusive and made orthogonal to the SRs through their requirements on m_{T}, m_{CT} and $m_{b\bar{b}}$. Apart from the requirements on these three observables as well as the requirement on $m_{\ell b_1}$ (removed altogether in the CRs), the CRs share the same set of cuts as the SRs. Figure 6.4(a) illustrates the configuration of all CRs, especially highlighting the fact that all CRs are located in sideband regions off the $m_{b\bar{b}}$ window, significantly reducing signal contamination. Table 6.1

Table 6.1: Overview of the CR and VR definitions. All regions partially share the same selection as the SR for all variables except $m_{\ell b_1}$, which is not used in the CR and VR definitions.

CR	**TR-LM**	**TR-MM**	**TR-HM**	**WR**	**STR**	
$m_{b\bar{b}}$ [GeV]		<100 or >140		$\in [50, 80]$	>195	
m_{T} [GeV]	$\in [100, 160]$	$\in [160, 240]$	>240	$\in [50, 100]$	>100	
m_{CT} [GeV]		<180		>180	>180	
VR	**VR-onLM**	**VR-onMM**	**VR-onHM**	**VR-offLM**	**VR-offMM**	**VR-offHM**
$m_{b\bar{b}}$ [GeV]		$\in [100, 140]$		$\in [50, 80] \cup [160, 195]$	$\in [50, 80] \cup [160, 195]$	$\in [50, 75] \cup [165, 195]$
m_{T} [GeV]	$\in [100, 160]$	$\in [160, 240]$	>240	$\in [100, 160]$	$\in [160, 240]$	>240
m_{CT} [GeV]		<180			>180	

summarises the kinematic requirements separating the CRs from other regions of interest in the analysis.

Control regions for $t\bar{t}$

As events from $t\bar{t}$ processes constitute the dominant SM background in all SRs, it is necessary to have a precise and reliable estimation of their contributions. Three CRs are defined for $t\bar{t}$, following the same binning in m_{T}, and thus called TRLM, TRMM and TRHM in the following. A good purity of $t\bar{t}$ processes as well as the necessary high MC are achieved by inverting the requirements on $m_{b\bar{b}}$ and m_{CT}. The achieved $t\bar{t}$ purities are 79.6% in TRLM, 85.9% in TRMM and 84.1% in TRHM. The composition of the different $t\bar{t}$ decay modes in each CR is found to be similar as in the respective SR. The maximum signal contamination over the entire signal grid is 0.8%, 1.1% and 1.9% for TRLM, TRMM and TRHM, respectively, and thus negligible. Figures 6.3(a) to 6.3(c) show the signal contamination over the entire signal grid.

Control region for $W +$ jets

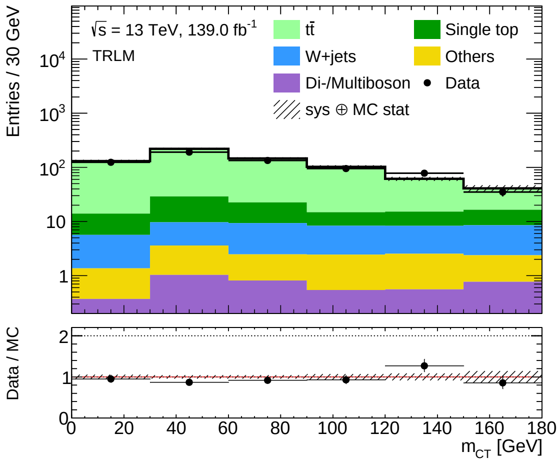
Events from $W +$ jets production represent the second largest contribution of SM background events in the SRs. A single $W +$ jets CR (WR) is defined by replacing the requirements on m_{T} and $m_{b\bar{b}}$ with $50\,\mathrm{GeV} < mt < 100\,\mathrm{GeV}$ and $50\,\mathrm{GeV} < m_{b\bar{b}} < 80\,\mathrm{GeV}$, respectively. No bins in m_{CT} are defined for WR. As for the $t\bar{t}$ control regions, moving WR off the Higgs mass peak allows to achieve a tolerable maximum signal contamination of about 2.4% (with most signal points having significantly less than 1% signal contamination in WR), as shown in fig. 6.3(d). Applying a low requirement on m_{T} allows to predominantly select events in front of the kinematic endpoint of the transverse mass of the W boson, resulting in a high statistics control region with a $W +$ jets purity of roughly 52.5%.

Control region for single top

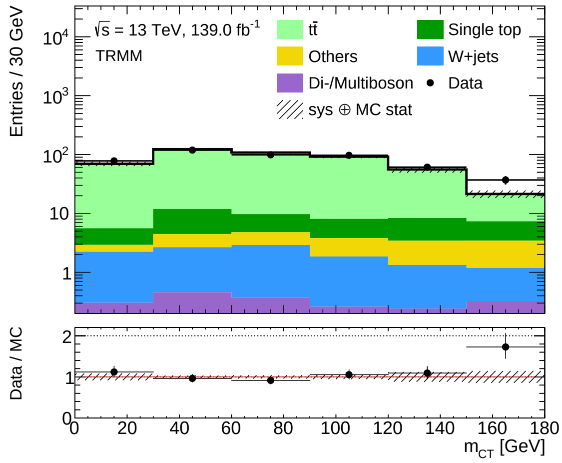
Single top processes result in significant background contributions in some SRs, necessitating a proper semi-data-driven estimation. A single top CR (STR) is defined by replacing the Higgs mass window cut on $m_{b\bar{b}}$ with $m_{b\bar{b}} > 195\,\mathrm{GeV}$ and removing the bins in m_{CT}. Off the Higgs mass peak guarantees a low maximum signal contamination of roughly 0.8% and a high purity of single top processes of about 51.7%. The signal contamination across the entire signal grid is shown in fig. 6.3(e).

6.3 Validation regions

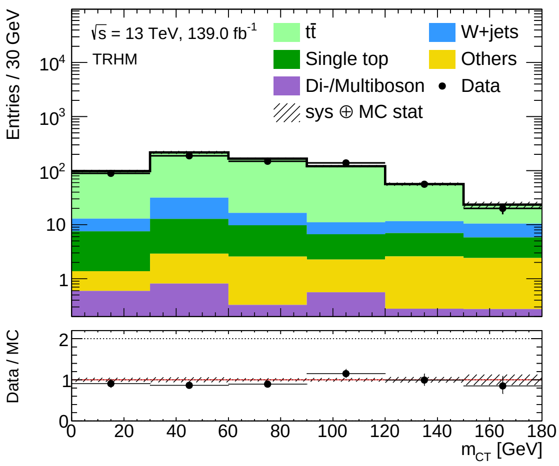
Two sets of VRs regions are introduced in order to verify the extrapolation over the different distributions. The first set, called VRon is situated on the Higgs boson mass peak but with the m_{CT} requirement inverted to $m_{\mathrm{CT}} < 180\,\mathrm{GeV}$, allowing it to be used for validating the extrapolation in m_{CT}. The second set of VRs is located on both sides off the Higgs boson mass peak at same values in m_{CT} than the SRs. This set of off-peak VRs, called VRoff, can be used to validate the extrapolation in $m_{b\bar{b}}$. All VRs use the same binning in m_{T} as the SRs such that the extrapolation into their respective associated SR can be validated. The different bins are consequently called VRonLM, VRonMM VRonHM and VRoffLM, VRoffMM, VRoffHM. The selections defining the VRs are summarised in table 6.1.



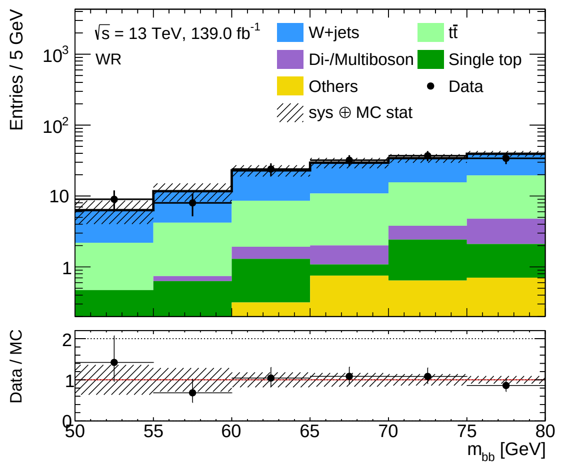
(a) TRLM



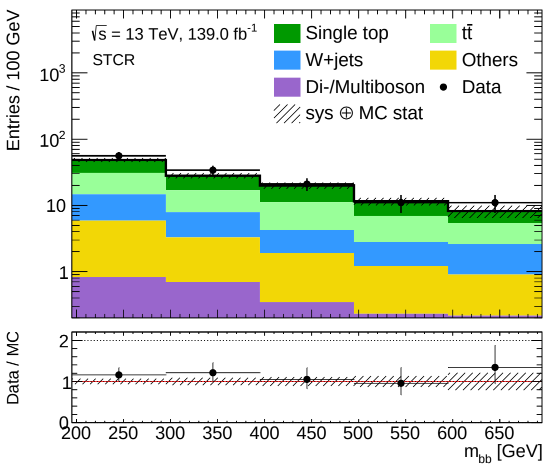
(b) TRMM



(c) TRHM

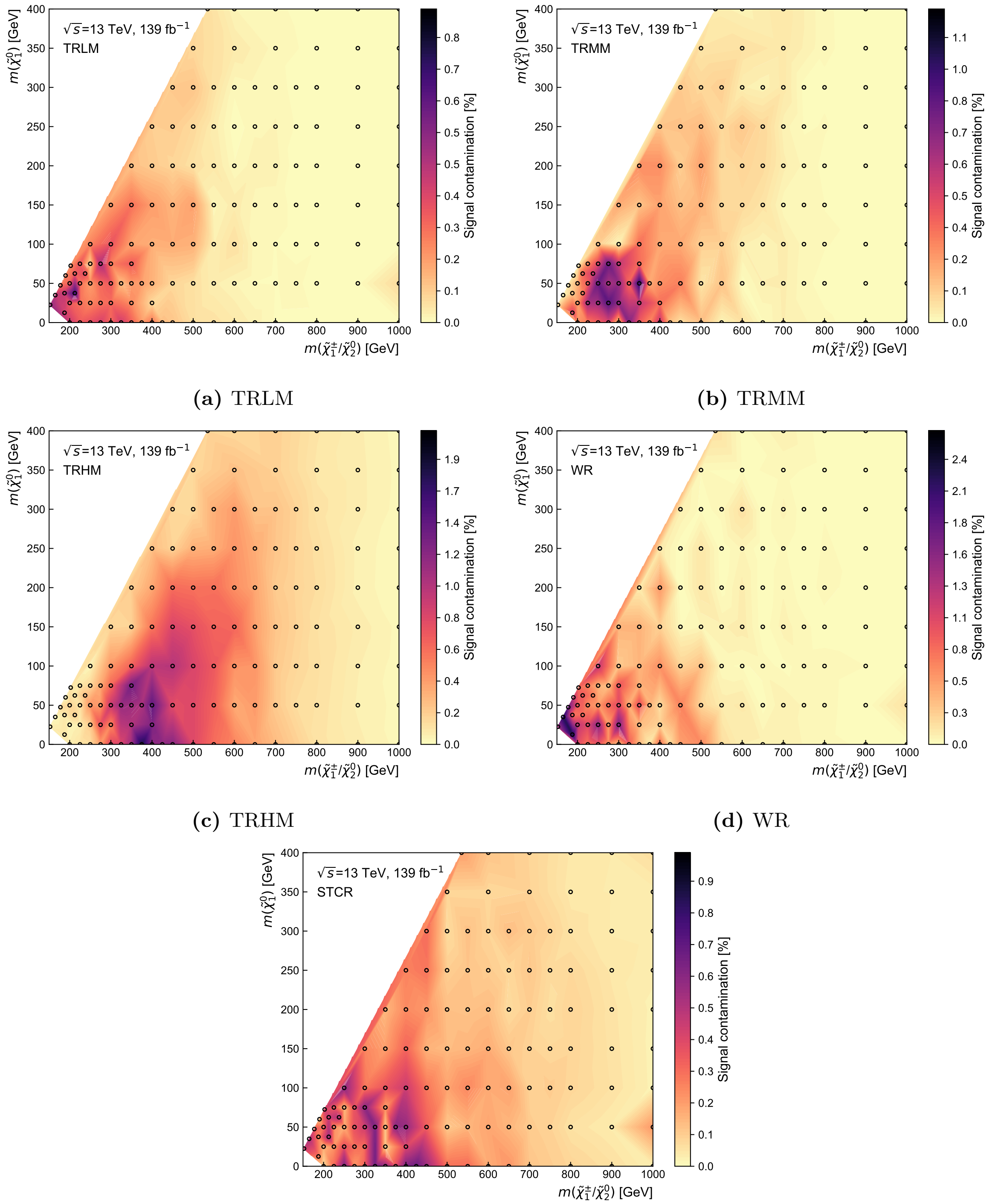


(d) WR



(e) STCR

Figure 6.2: Exemplary distribution shown in each control region. As laid out in the beginning of this chapter, the shaded region includes MC statistical uncertainty as well as experimental uncertainties, added in quadrature. A good agreement between MC expectation and data is observed in all CRs.



(a) TRLM

(b) TRMM

(c) TRHM

(d) WR

(e) STCR

Figure 6.3: Signal contamination (shown on the *z-axis*) for all CRs throughout the signal grid. The space between the signal points (indicated by the black circles) is interpolated using Delaunay triangles.

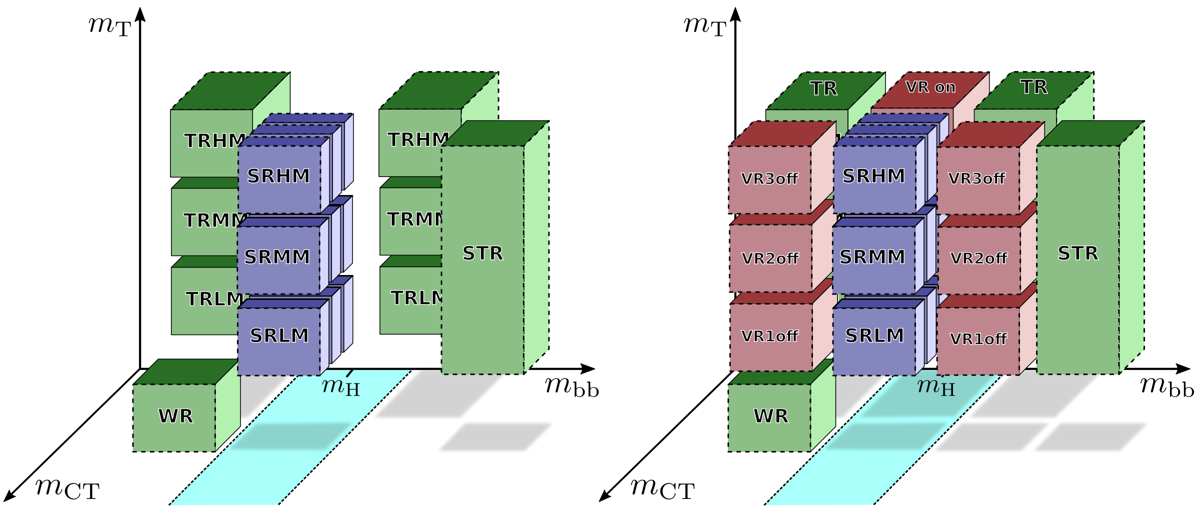


Figure 6.4: Configuration of (a) the control regions placed around the signal regions off the $m_{b\bar{b}}$ window as well as (b) the validation regions in the phase space between the CRs and SRs. The VRs are arranged such that each of the extrapolations can be validated.

Part III

Reinterpretation

Part IV

Summary and Outlook

Part V

Appendix

Abbreviations

CR control region. 93–96, 98–100

MC Monte Carlo. 93–96, 98

SM Standard Model of Particle Physics. 93, 96

SR signal region. 93–97, 100

VR validation region. 94, 95, 97, 100

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