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Letter

Search for heavy long-lived charged particles with level-1 trigger scouting data from proton-proton collisions at $\sqrt{s} = 13.6$ TeV

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ABSTRACT

A search for heavy long-lived charged particles at the LHC is presented. Particles traversing the CMS muon detector across several bunch crossings are searched for using a data sample of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected with the CMS detector in 2024, corresponding to an integrated luminosity of 3.7 fb^{-1}. This is the first search using the novel level-1 trigger scouting data set collected without any trigger selection, allowing correlations between bunch crossings to be analyzed. The results are interpreted as upper limits on the cross sections of several benchmark processes with pair production of heavy long-lived charged particles. Upper limits on the fiducial cross section of a heavy long-lived charged particle with $p_T > 500$ GeV and $|\eta| < 0.83$ are also set in different ranges of $\beta = v/c$. This analysis is a proof of concept for the level-1 trigger data scouting system and complements existing searches for heavy long-lived charged particles by extending the sensitivity to lower β values.

1. Introduction

Heavy long-lived charged-particle searches are motivated by multiple beyond the standard model scenarios [1–3], such as supersymmetry, extra dimensions, and other theoretical frameworks. These particles are generically referred to as heavy stable charged particles (HSCPs), even if they may be metastable. If produced in proton-proton (pp) collisions at the CERN LHC, HSCPs would traverse the detector leaving distinctive experimental signatures. Because of their large mass and long lifetime, slow-moving HSCPs typically exhibit high ionization energy loss and unusually long time-of-flight.

Past collider searches for HSCPs at the CERN LEP [4–8], Fermilab Tevatron [9–12], and LHC [13–31] have set stringent constraints on various models, with limits on gluino R-hadrons, top squark R-hadrons, and fourth-generation leptons reaching the TeV scale. The recent HSCP search by the CMS Collaboration [30] looks for an isolated high transverse momentum (p_T) track that deposits an anomalous energy per unit length in the silicon tracker and relies on muon-based triggers to select events online. Because of this triggering strategy, it is sensitive to HSCPs with $\beta = v/c \gtrsim 0.6$, which can cross the CMS detector within a single bunch crossing (BX). To pass muon-based triggers, the muon tracks reconstructed in the tracker and in the muon detector must be in the same BX. Very slow particles may take several BXs to reach and cross the muon detector, causing the trigger to fail. While it is possible to indirectly trigger on missing transverse momentum in the calorimeters, such triggers typically have low and model-dependent signal efficiency. Even when the event can be triggered on, low-β particles may not be fully reconstructed if their trajectories span several BXs. Because of this limitation, past LHC searches have only targeted HSCP masses up to 3 TeV.

The analysis presented in this Letter avoids the triggering and reconstruction constraints by relying on the data collected without trigger conditions by the novel CMS level-1 trigger data scouting (L1DS) system [32–35]. It probes the existence of HSCPs with mass between 1 and 6.5 TeV leaving a signature in the muon detector before decaying. The search is based on data collected in the second half of 2024 in pp collisions at $\sqrt{s} = 13.6$ TeV, corresponding to an integrated luminosity of 3.7 fb^{-1}. This is the first analysis relying on data from the L1DS system and, as such, it is a crucial proof of concept for the physics potential of the L1DS. Tabulated results are provided in the HEPData record for this analysis [36].

2. The CMS detector and its hardware muon trigger

The CMS apparatus [33,37] is a multipurpose, nearly hermetic detector. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Events of interest are usually selected using a two-tiered trigger system, where the level-1 trigger (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [38].

The L1 muons in the barrel ($|\eta| < 0.83$) are reconstructed with the Kalman-filter-based barrel muon track finder (kBMTF) [33], which re-

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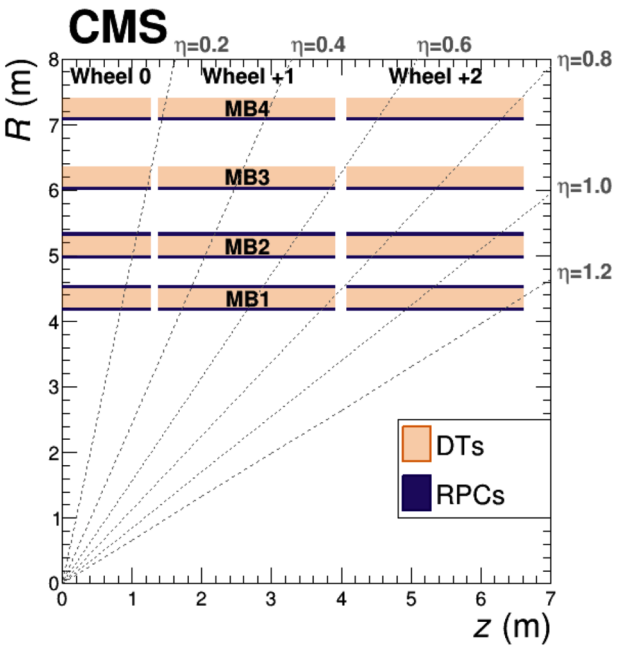

Fig. 1. The R–z projection of a quarter of the CMS barrel muon system, where R is the radial distance from the beamline.

lies on information from the drift tubes (DTs) and resistive-plate chambers (RPCs) of the muon detector in the barrel. The DT and RPC barrel systems consist of four cylindrical layers wrapped around the solenoid, called MB1–4 from the innermost to the outermost, each split into twelve wedges in ϕ and five wheels along the beam direction. The distance between MB1 and MB4 is about 3 m. The geometry of the muon detector in the barrel is illustrated in Fig. 1. The MB1 and MB2 layers both include two chambers of RPCs, whereas MB3 and MB4 only have one each.

The TwinMux system [39] merges segments in the DTs with RPC hits from the same layers into objects called stubs, which combine the better spatial resolution of the DTs with the more precise timing of the RPCs. The TwinMux processor sends the stubs to the kBMTF, which builds muon track candidates, assigns a quality to each, and measures the charge sign and p_T from the bending in the fringe field of the magnet yoke. Track quality is related to the estimated p_T resolution, and tracks with more stubs, particularly those in inner layers where the magnetic field is stronger, are assigned higher quality. Throughout the rest of the Letter, tracks refer to objects built from muon detector information only.

3. The L1 data scouting system

The L1DS system is a novel data collection scheme that acquires data directly from the L1 trigger, at the full BX rate of 40 MHz, corresponding to 25 ns between BXs [33]. It does not affect the L1 trigger accept decision. A subset of objects reconstructed by the L1 trigger (electrons, muons, hadronically decaying τ leptons, jets, energy sums, and muon stubs) are stored for events collected by the L1DS, corresponding to an average effective record size per BX of about four orders of magnitude smaller than that in regular CMS data taking. The L1DS system processes and stores data in orbits, each made of 3564 consecutive BXs. Unlike traditional data sets where the L1 trigger decision leads to reading out the detector information of a given BX, the L1DS system collects data from all BXs without any preselection. Because of storage limitations, the data are collected with a prescale factor N at the orbit level, corresponding to one orbit stored every N orbits. Different selection streams with requirements on L1 objects also exist, without any prescale factor.

While the L1DS system will reach its full capacity during the High-Luminosity LHC, a demonstrator started taking data in 2024. Since August 2024, stubs from the individual layers of the barrel muon detector

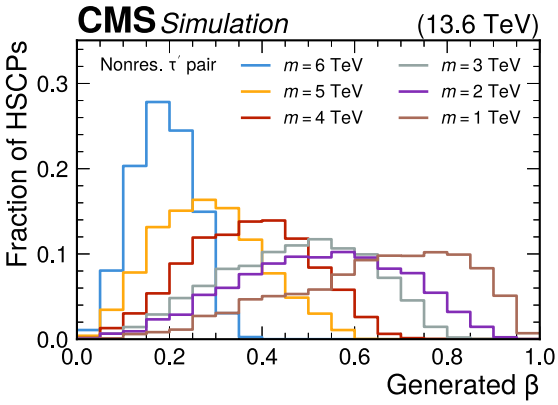

Fig. 2. Generated β distributions of the fourth-generation τ' leptons from nonresonant DY production, for various τ' masses m. The histograms are normalized to unity.

have been included in the L1DS output for each BX. Offline, the stubs from different BXs can be fitted as muon-like tracks, as detailed in Section 5, effectively enabling the reconstruction of unit-charge particles with $0.15 \lesssim \beta \lesssim 0.80$. Below 0.15, the particles mostly get stopped before crossing the muon detector, whereas above 0.80, the particle trajectory is reconstructed within a same BX. These data were collected with a prescale factor of $N = 15$, corresponding to an effective integrated luminosity of 3.7 fb^{-1}, from a delivered one of about 55 fb^{-1}.

4. Signal and background simulation

Two lepton-like and one hadron-like signal models are used to interpret the results. The first lepton-like model consists of modified Drell–Yan (DY) production of long-lived massive fourth-generation fermions (τ') with spin 1/2 and unit charge, as considered in Ref. [30]. As they are neutral under both $SU(3)_C$ and $SU(2)_L$ groups, they couple only to the photon and the Z boson. Simulated event samples for τ' fermions are produced with masses $m_{\tau'}$ ranging from 1.0 to 6.5 TeV. Their generated β distributions are shown in Fig. 2 for different $m_{\tau'}$. The second lepton-like model consists of resonant production of two τ' leptons from the decay of a heavy Z′ boson, using a minimal simplified model. It is inspired by Ref. [40] but considers only unit-charge HSCPs. Masses of the τ' lepton between 1 and 6 TeV are probed, with the Z′ boson masses $m_{Z'}$ in the range between twice and three times $m_{\tau'}$ to stay in the limit of low β, with a maximum $m_{Z'}$ of 12 TeV. Signal samples with the same ratio between $m_{Z'}$ and $m_{\tau'}$ have similar β distributions.

The hadron-like model consists of pair production of long-lived gluinos $\tilde{g}$, which is a common signature of mini-split supersymmetric models where the $\tilde{g}$ decay is highly suppressed by the large scalar quark mass [41–43]. In this analysis, a quasi-stable $\tilde{g}$ is assumed and no $\tilde{g}$ decay is considered. The fraction, f, of produced $\tilde{g}$ hadronizing into a $\tilde{g}$-gluon state (R-gluinoball) is a parameter of the hadronization model and corresponds to the fraction of R-hadrons that are neutral at production. We choose $f = 1$, such that these R-hadrons would escape analyses looking for anomalous ionization losses in the tracker, while they could leave a signature in the muon chambers if they become charged when crossing the detector through their interactions with matter, simulated using the model from Refs[44,45]. About one third of these R-hadrons are charged when they cross the muon detector. Their generated β distributions are similar to those shown in Fig. 2 for the fourth-generation τ' leptons produced in nonresonant DY production.

The leading-order (LO) PYTHIA generator v8.240 [46] with the tune CP5 [47] and the parton distribution function set NNPDF3.1 [48–50] at next-to-next-to-LO is used to simulate these three signal models. Backgrounds in the analysis are determined from data, but a DY simulation with dimuon decays (DY($\mu\mu$)) is used to calibrate the reconstructed

objects. The MADGRAPH5_aMC@NLO 2.6.5 event generator is used to generate DY($\mu\mu$) events at next-to-LO with the FxFx jet matching and merging [51]. The response of the CMS detector is simulated with the GEANT4 package [52]. The simulated events are reconstructed using the same algorithms as used for data. In all samples, simulated minimum bias events are overlaid with the primary collision to produce the effect of additional pp interactions in the same or adjacent BXs, referred to as "pileup" [53].

5. Muon track reconstruction

In this analysis, HSCPs are reconstructed as muons from the stubs stored in the L1DS data set, using a modified version of the kBMTF. While standard L1 muons are built online from stubs in the same BX, the modified kBMTF algorithm is run offline using stubs that are separated in time by at most eight BXs. No constraint on the time ordering of stubs is applied at this stage to preserve unphysical orderings for background estimation purposes, as detailed in Section 7. The fit is performed independently of the BX information of individual stubs. The average p_T resolution of the muon tracks is measured to be 18% in a simulated DY($\mu\mu$) sample. While the p_T resolution is independent of β, it gets worse at significantly higher p_T values. For $p_T \gtrsim 650$ GeV, the tracks in the muon detector are basically straight and different p_T values cannot be distinguished anymore.

The modified kBMTF reconstruction is validated in DY($\mu\mu$) events, which are also used to calibrate the p_T estimation and derive efficiency corrections used for simulated samples. The events are selected by requiring a pair of opposite-sign kBMTF tracks with $p_T > 15$ GeV and $|\eta| < 0.83$. The pair must have an invariant mass $m_{\mu\mu}$ larger than 50 GeV. The nonprompt background, originating mostly from processes like W + jets or QCD multijet events, with jets misidentified as leptons, is estimated by rescaling the data with same-sign kBMTF tracks to have perfect agreement between data and predictions in the opposite-sign events with $50 < m_{\mu\mu} < 55$ GeV. While the tracks can be built from stubs in different BXs, most DY($\mu\mu$) tracks are reconstructed within the same BX. Five p_T-independent parameters are determined for the simulation: a multiplicative factor of the predicted p_T (compatible with 1.0), the width of a Gaussian smearing of the predicted p_T (about 10%), and an efficiency correction per stub multiplicity (up to 11% for 4-stub tracks). Fig. 3 shows the dimuon invariant mass and the stub multiplicity per muon track after the corrections have been applied, where good agreement between predictions and data is obtained by construction. In these events, about 25 (45, 30)% of the reconstructed muons have 2 (3, 4) stubs.

Depending on their β, HSCPs are reconstructed within different ranges of BXs. Fig. 4 shows the fraction of the tracks reconstructed in different BX signatures for unit-charge HSCPs. For $\beta > 0.7$, particles mostly cross the muon detector within the same BX as the hard scattering (dark blue). The same experimental signature of stubs within the same BX appears for most HSCPs with β around 0.5, but in that case the particle takes one BX to reach the first layer of the muon detector then crosses all the layers within the BX following that of the collision (lighter blue). Up to 30% of HSCPs with β around 0.3 also have the same experimental signature, but with the muon detector layers crossed at least 2 BXs after the hard scattering (lightest blue). About half of the HSCPs with $\beta = 0.6$ cross the muon detector during the collision BX and the following one (dark orange). HSCPs with $\beta = 0.4$ mostly take one BX to reach the first layer of the muon detector, and reach the last muon detector layer one BX later than the first layer (lighter orange), whereas a significant fraction of HSCPs with $\beta \lesssim 0.3$ need at least 2 BXs to reach the first layer, and cross the last layer one BX later (lightest orange). Different shades of a same color, corresponding to different BX intervals with respect to the collision BX, are indistinguishable experimentally since the production BX cannot be determined. For $\beta \lesssim 0.3$, a significant fraction of the tracks are reconstructed across 3 or 4 BXs (red or purple histograms, respectively), whereas the efficiency goes to zero for $\beta \lesssim 0.15$ because the particles get stopped in the detector. For $\beta \lesssim 0.5$, the efficiency for the reconstructed tracks to satisfy the single-muon high-level trigger (HLT) selection is zero, showing that such slow particles cannot be directly triggered on.

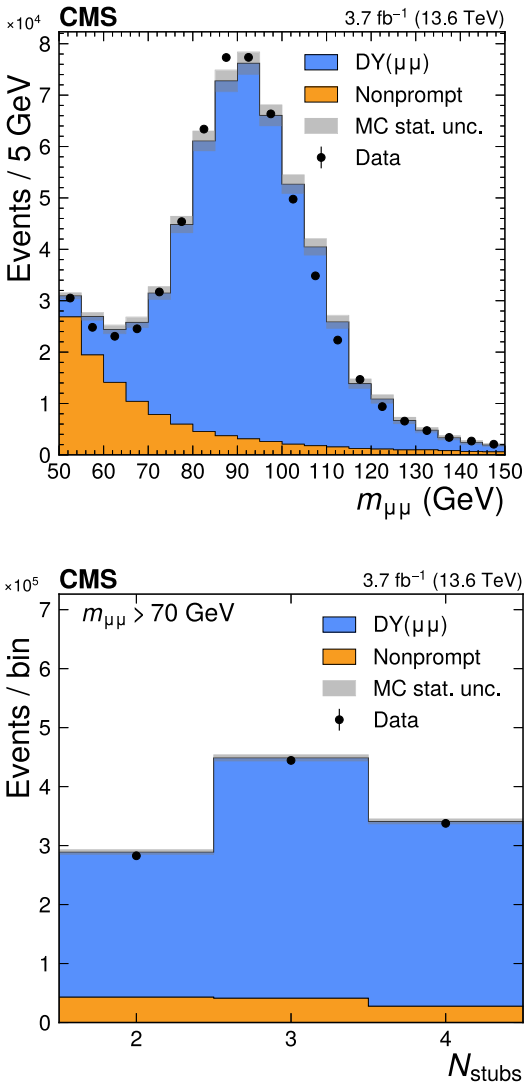

Fig. 3. Distributions of the dimuon invariant mass (upper) and per-track stub multiplicity (lower) for events with two opposite-sign modified kBMTF tracks reconstructed from individual stubs in the same or different BXs. The invariant mass is required to be greater than 70 GeV in the stub multiplicity distributions to increase the purity. The muons are selected with $p_T > 15$ GeV and $|\eta| < 0.83$. The nonprompt-background contribution is estimated by rescaling the data with two same-sign modified kBMTF tracks. The statistical uncertainty is indicated in the gray shaded area. The agreement between simulation and data is good by construction since the efficiency, energy scale, and energy smearing corrections derived from the same events have been applied.

6. Event selection, categories, and statistical analysis

Events containing at least one modified kBMTF track with 3 or 4 stubs, reconstructed across a minimum (maximum) of 2 (4) BXs, are selected. Tracks with 2 stubs are not considered because of the relatively larger background. Particles slow enough to cross the muon chambers in more than 4 BXs would mostly be stopped in the detector because of their large ionization losses. In the signal region (SR), hits must occur from the inner layers to the outer ones, i.e., a stub in an outer layer must be in the same BX or a later BX with respect to the stub in the

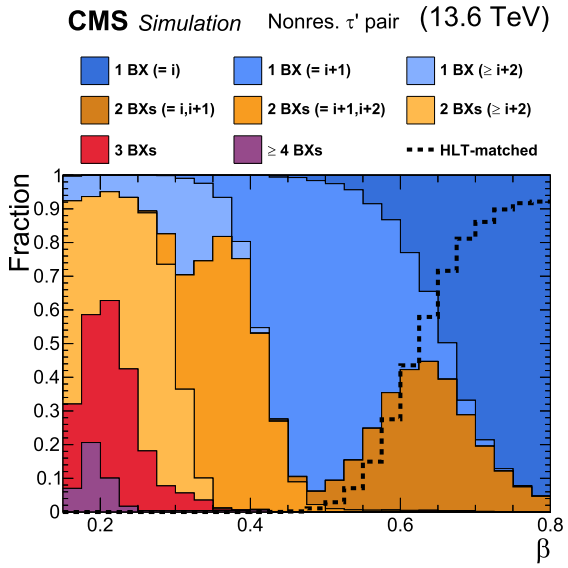

Fig. 4. Fractions of the BX signatures of tracks reconstructed with the modified kBMTF algorithm as functions of the generated particle β. This figure corresponds to the nonresonant fourth-generation lepton signal model with a mixture of HSCP masses between 1 and 6 TeV. The filled histograms are stacked to sum to unity. The blue histograms correspond to tracks reconstructed in a single BX. Different shades represent different BXs with respect to the collision BX (BX = i), as indicated in parentheses in the legend. The orange histograms correspond to tracks reconstructed over 2 BXs, with different shades corresponding to different BXs with respect to the collision BX. Different shades of the same color are indistinguishable experimentally since the production BX cannot be determined. The red and purple histograms represent tracks reconstructed over 3 or at least 4 BXs, respectively. The dashed line indicates the efficiency for the reconstructed tracks to satisfy the single-muon HLT selection. For $\beta < 0.15$, the efficiency goes to zero because the particles get stopped in the detector. For $\beta > 0.8$, the particles are increasingly reconstructed in the same BX, in which case the HLT selection is fully efficient.

closest inner layer. The muon tracks must have $|\eta| < 0.83$ and $p_T > 15$ GeV. If several such tracks are present, the slowest track (i.e., spanning the most BXs) is selected. If speeds are equal, the track with the largest stub multiplicity is chosen; if both the speed and stub multiplicity are equal, the highest p_T track is selected. The selected track is required to have a transverse distance of closest approach to the beamline center, d_{xy}, less than 32 cm, and to pass high-quality criteria calculated by the kBMTF algorithm. The coarse selection on d_{xy} is related to the low precision available from the L1 information and algorithms. Colliding bunches are determined per orbit on the basis of the LHC injection scheme. Events are discarded if the BX of the earliest stub and the five BXs preceding it are all noncolliding, since HSCPs cannot be produced in noncolliding bunches. For the simulated samples of the nonresonant DY production of τ' leptons, the product of the acceptance and efficiency of these selection criteria is 19% for $m_{\tau'} = 1$ TeV and as high as 47% for $m_{\tau'} = 5.5$ TeV.

Fourteen categories are built to target signals with different β, characterized by different crossing times of the detector. The categories are also based on the stub multiplicity since the signal-to-background ratio improves with the number of stubs. The categories are defined in Table 1. The most sensitive category, BX123, is illustrated in Fig. 5, whereas the illustrations of all categories can be found in Appendix A.

The categories with tracks across 2 BXs, namely with 3/2 or 4/2 layers/BXs, suffer from a large background from per-stub BX misidentification, which is below 1% for muon detector layers with two working layers of RPCs, and up to 6% when no layer of RPCs is working [54]. Additional model-dependent selection criteria based on the pair-production hypothesis can significantly reduce the background. In these categories,

Table 1
Categories based on muon detector layers with stubs and speed expressed as the number of crossed layers divided by the number of BXs spent to cross them. The BX1234 category includes 4-stub tracks for which the 4 stubs are in 4 subsequent BXs. For 3-stub (4-stub) tracks, the BX123 categories correspond to 3 (4) stubs in 3 different BXs across a range of 3 BXs, whereas the BX124/134 categories correspond to 3 (4) stubs in 3 different BXs across a range of 4 BXs. The 4-stub category BX1112 (1122, 1222) corresponds to 3 (2, 1) stubs in the first BX, and 1 (2, 3) stubs in the next BX. Similarly, the 3-stub categories BX112 (122) correspond to 2 (1) stubs in the first BX and 1 (2) stub in the next BX. The 3-stub categories are further separated into fast and slow subcategories: those denoted "fast" feature a track with the first stub in MB1 and the last one in MB4, corresponding to a longer distance crossed in the same amount of time as their "slow" counterparts, which do have exactly one stub within the innermost and outermost detector layers. The symbol $\oplus$ represents the exclusive "or", whereas $\wedge$ is the logical "and".

Stub config.	Layers / BXs				
	3/4	3/3 or 4/4	4/3	3/2	4/2
4 stubs	—	BX1234 BX124/134	BX123	—	BX1112 BX1122 BX1222
3 stubs, MB1 $\oplus$ MB4	BX124/134 slow	BX123 slow	—	BX112 slow BX122 slow	—
3 stubs, MB1 $\wedge$ MB4	—	BX124/134 fast	BX123 fast	—	BX112 fast BX122 fast

a second good-quality track with $|\eta| < 0.83$ and $p_T > 100$ GeV is required, with at least one stub in the same BX as one of the stubs of the first track. This reduces the background by almost two orders of magnitude, while retaining about half of the signal. The original categories without the additional selection criterion are kept to set model-independent limits on the fiducial cross section of slow particles, without relying on the description of the rest of the event.

The results are extracted with a maximum likelihood fit of binned distributions in each category. The observable is chosen to be the track p_T because the signal is characterized by harder objects than the background. Indeed, particles with low β reaching the muon chambers must be heavy and produced with significant momentum. To avoid overconstraining the background estimate from low-p_T bins with large event yields, the p_T threshold is increased to 50 (150) GeV in the categories with tracks across 2 BXs with (without) a requirement on the presence of a second track, and to 50 GeV in all categories across more than 2 BXs, except the BX1234 category where the p_T threshold is 15 GeV because of the lower background expectation.

7. Background estimation and validation

Backgrounds arise mostly from ultra-relativistic particles with BX misidentification in the individual muon detector layers, and from combining unrelated ultra-relativistic particles from different BXs at the same place in the detector, but also from noncollision processes and noise in the detector. Contributions from slow particles originating from the experimental cavern are negligible because the time ordering of their stubs is not compatible with a particle produced at the beam spot and exiting the CMS detector. The track p_T distribution of the backgrounds in each category is estimated using tracks with an asynchronous time ordering of the stubs within the muon detector layers. The synchronous signal-like ordering is when the stub in each layer occurs in the same or a later BX compared to the stubs in the layers inside it. The other synchronous ordering, where the inner stubs occur later, is not signal-like and signifies a track that enters the detector from the outside. Other combinations are asynchronous. Because of BX misidentification, some asynchronous combinations include significant contributions from physical processes entering the detector, such as slow neutrons originating from the experimental cavern, which may have a different p_T distribution from that of the backgrounds in the SR. To remove this

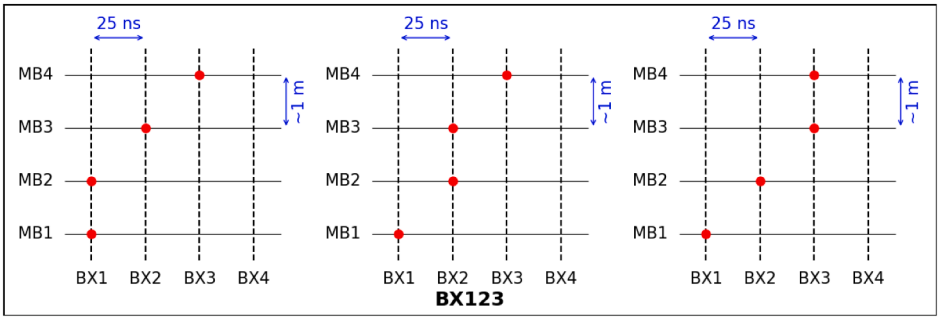

Fig. 5. Schematic definition of the BX123 category.

contribution, only the tracks where either the innermost stub is in the earliest BX or the outermost stub in the latest BX are used to estimate the background p_T distribution in the SR. Signal contributions to events with asynchronous orderings are below the percent level and therefore are neglected. The configurations considered to estimate the background in the BX1234 and BX1112 categories are illustrated in Appendix A. The background normalization is left floating in each category in the binned maximum likelihood fit, where it gets constrained by the signal-depleted low-p_T bins.

The background estimation is verified in two orthogonal validation regions (VRs): (i) events in colliding bunches where the track fails the quality criteria, and (ii) events with a high-quality track where the BX of the earliest stub and the five BXs preceding it are noncolliding. A maximum likelihood fit to the data is performed using the systematic uncertainties described in Section 8. In both VRs, good agreement between the observed data and predicted background is observed, as shown in Figs. 6 and 7. The VR with low track quality criteria is significantly more populated than the SR, making it a stringent test of the background estimation method. The noncolliding VR is significantly less populated than the SR, but provides a useful validation for events with signal-like high-quality tracks.

8. Systematic uncertainties

The dominant systematic uncertainties come from the background estimation. While the background normalization is left floating in the fit independently for each category, one systematic uncertainty affecting the p_T distribution is considered in each category. These uncertainties are incorporated in the likelihood as nuisance parameters with a Gaussian prior. The alternative p_T distributions corresponding to a ± 1 standard deviation (s.d.) are built from either a subset of the tracks used to estimate the nominal p_T distribution, or from an orthogonal set, as described in the next paragraphs and summarized in Table 2.

In the categories with tracks across more than 2 BXs, as well as in BX1122, the p_T-dependent systematic uncertainty corresponding to a $+1$ (-1) s.d. is determined by considering uniquely the subset of asynchronous orderings where the innermost (outermost) stub is in the earliest (latest) BX. This results in an uncertainty in the range 5–60% for tracks with $p_T > 450$ GeV.

This method does not work in the other categories because these two asynchronous orderings do not both exist or are not distinct. In BX1112 and BX1222, the alternative p_T distribution corresponding to a $+1$ (-1) s.d. is taken from the subset of asynchronous orderings where the stub detected in a different BX than the other three stubs is in MB2 (MB3), leading to normalization effects of 5–30% for events with tracks with $p_T > 450$ GeV.

In the remaining 3-stub categories spanning exactly 2 BXs, namely BX112 slow, BX112 fast, BX122 slow, and BX122 fast, the shape uncertainty is obtained by considering the p_T distribution of a different set of tracks with asynchronous orderings, failing the quality criteria, and symmetrizing it with respect to the nominal distribution. It has an effect of 5–75% for events with tracks with $p_T > 450$ GeV.

Table 2
Definition of asynchronous track orderings used to build the alternative p_T distributions corresponding to a ± 1 s.d. of the background systematic uncertainty.

Categories	+1 s.d.	−1 s.d.
BX1122, BX123, BX124/134, BX124/134 slow, BX124/134 fast, BX123 slow, BX123 fast, BX1234	Asynchronous orderings where the innermost stub is in the earliest BX	Asynchronous orderings where the outermost stub is in the latest BX
BX1112, BX1222	Asynchronous orderings where the stub detected in a different BX is in MB2	Asynchronous orderings where the stub detected in a different BX is in MB3
BX112 slow, BX112 fast, BX122 slow, BX122 fast	Asynchronous orderings failing the quality criteria	Symmetric distribution with respect to nominal

The background p_T-dependent uncertainties on average get constrained by the maximum likelihood fit to 50% of their initial magnitudes. Overall, systematic uncertainties have a small impact on the analysis, which is statistically limited by the number of events selected in the high-p_T bins of the SR.

The signal normalization uncertainty, coming from the selection efficiency, as well as the integrated luminosity, is determined from the efficiency correction derived from DY($\mu\mu$) events, which includes effects related to the reconstruction and identification of muon-like particles, as well as overall normalization effects, such as the DY($\mu\mu$) cross section and the integrated luminosity. An additional uncertainty comes from the limited size of the DY($\mu\mu$) simulation used to derive the correction. This results in an uncertainty of about 3 (2)% in categories with tracks with 3 (4) stubs, partially correlated between stub multiplicity categories.

9. Results

The results are extracted with a binned maximum likelihood fit to the observed p_T distributions in the different SRs. The systematic uncertainties described in Section 8 are considered as nuisance parameters in the statistical procedure. The results have been determined using the CMS statistical analysis tool COMBINE [55]. The SR distributions are shown in Fig. 8. No significant excess of data is observed above the standard model expectation.

Upper limits at 95% confidence level (CL) are computed using the modified frequentist CL_s criterion [56,57], using the asymptotic approximation [58]. The limits on the signal cross section are shown in Fig. 9, as a function of the HSCP mass for the nonresonant τ' (upper) and gluino R-hadron (lower) scenarios. The sensitivity is driven by 4-stub categories, in particular by the BX123 category, which features a 4-stub track across 3 BXs. The 3-stub categories perform better for hadron-like models than for lepton-like ones, because the hadron-like HSCPs tend to be reconstructed with fewer stubs. The relative sensitivity of the different categories is mass-dependent because heavier HSCPs typically have lower β and take longer to cross the muon chambers. The structure around $m = 3$ TeV arises from the significant fraction of HSCPs

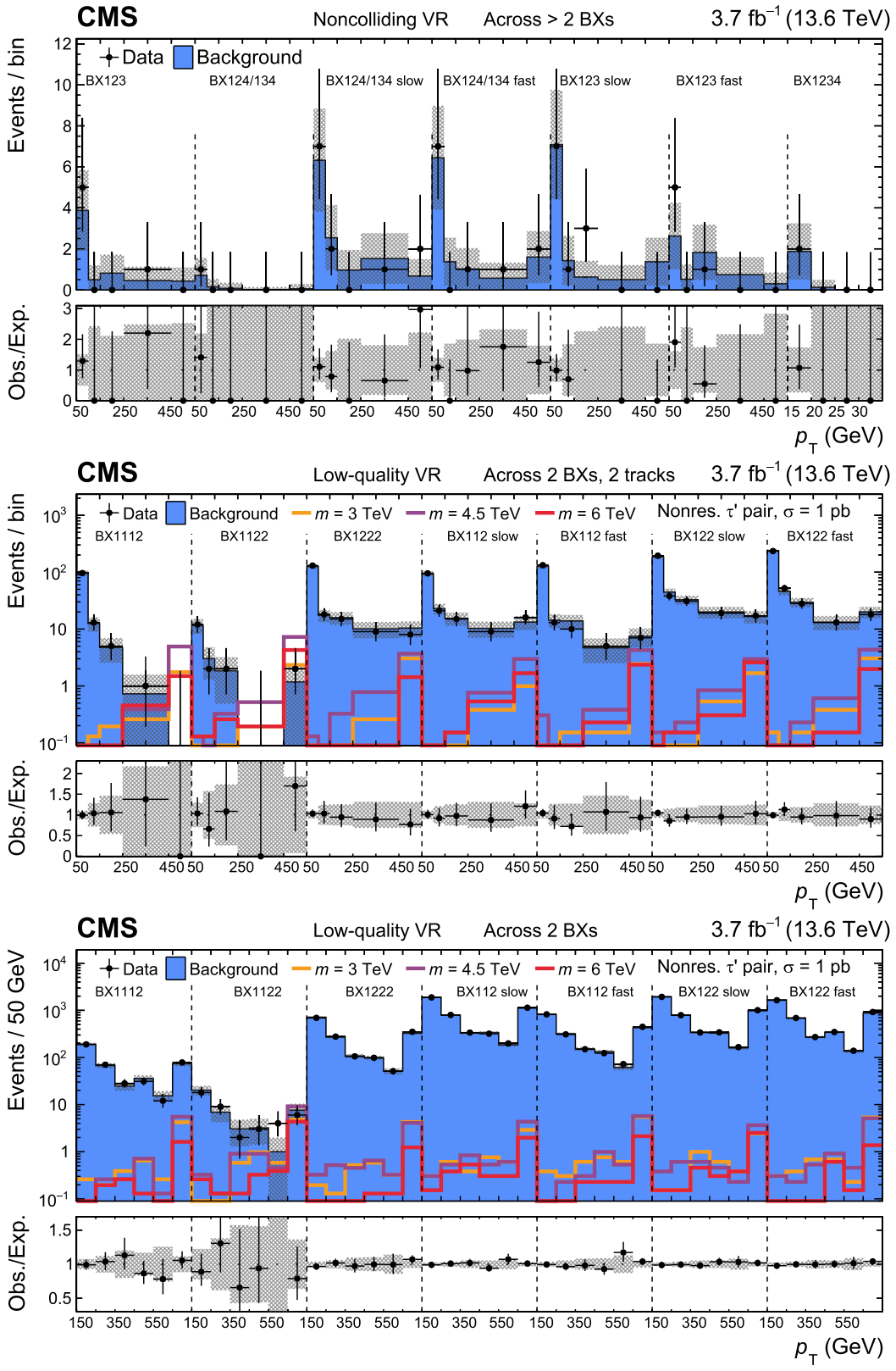

Fig. 6. Low-track-quality validation region distributions for the categories with tracks across >2 (=2, =2) BXs without (with, without) additional track requirement are shown in the upper (center, lower) part of the figure. The expected background distributions are the result of the maximum likelihood fit. The uncertainty bands account for all sources of background uncertainty, systematic as well as statistical, after the maximum likelihood fit. The signal is shown for a few mass hypotheses of the nonresonant fourth-generation lepton model, using a production cross section of 1 pb. The lower panels show the observed to expected ratio. The last p_T bins include the overflow.

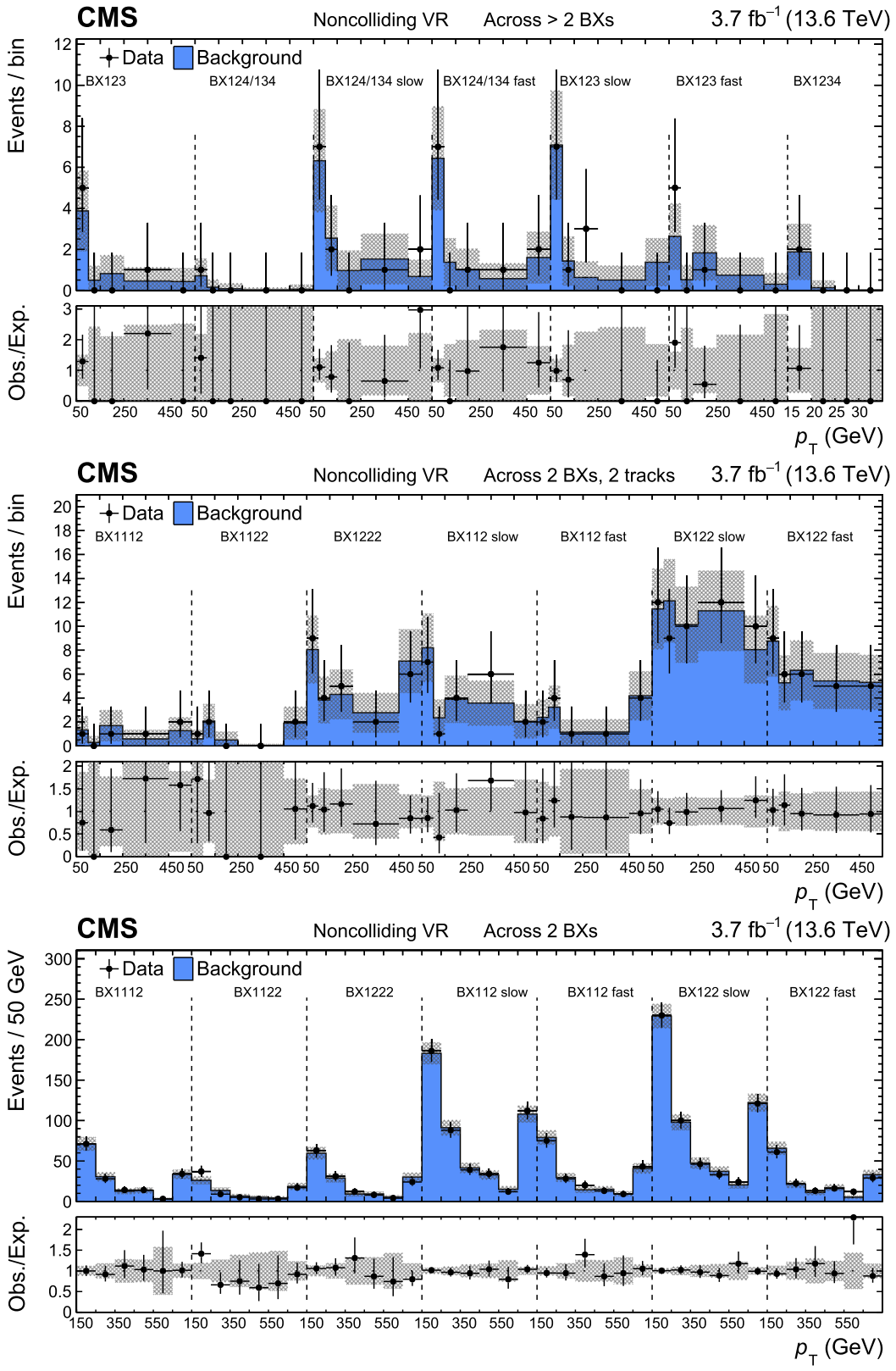

Fig. 7. Noncolliding validation region distributions for the categories with tracks across >2 (=2, =2) BXs without (with, without) additional track requirement are shown in the upper (center, lower) part of the figure. The expected background distributions are the result of the maximum likelihood fit. The uncertainty bands account for all sources of background uncertainty, systematic as well as statistical, after the maximum likelihood fit. The lower panels show the observed to expected ratio. The last p_T bins include the overflow.

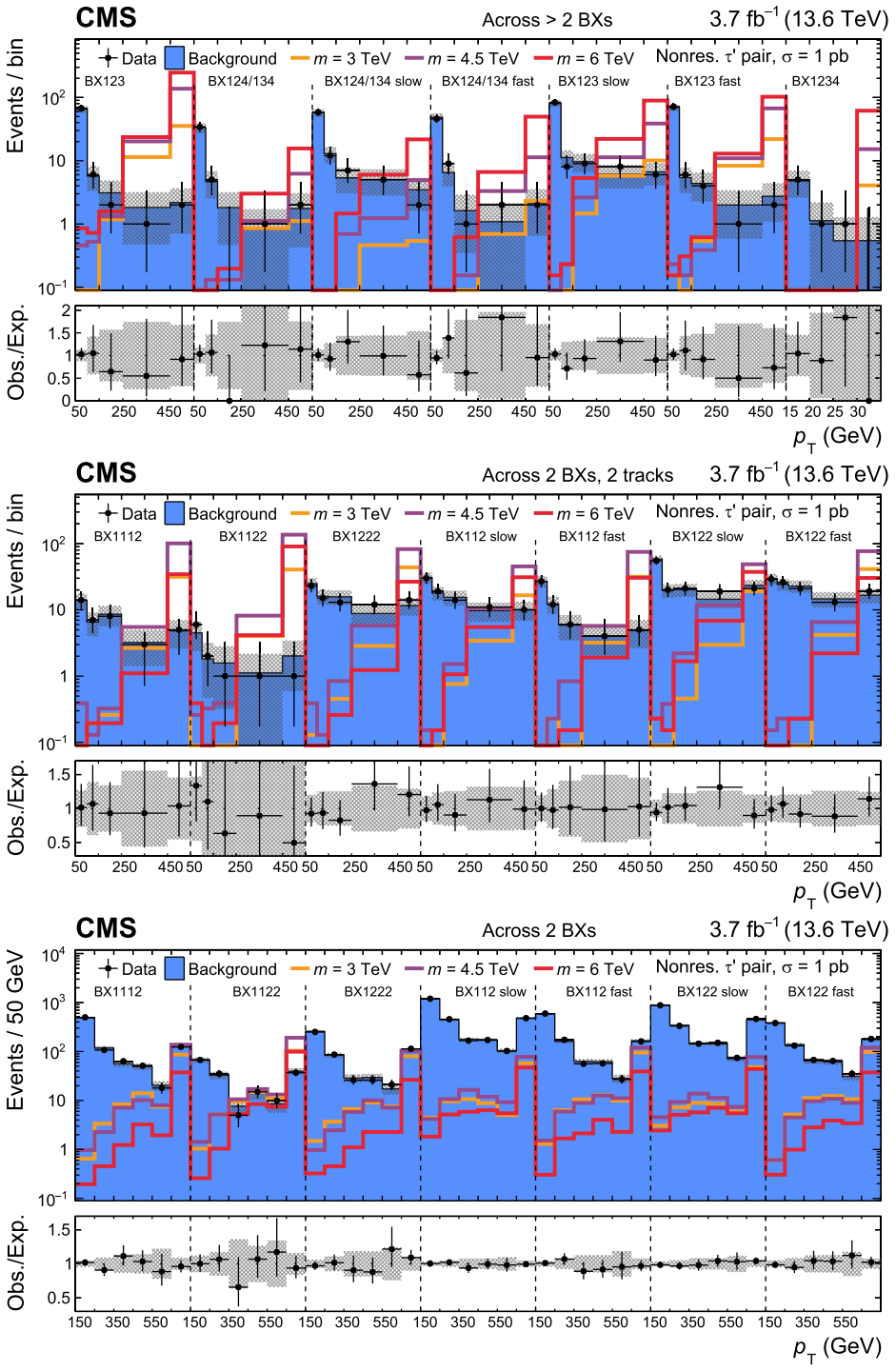

Fig. 8. The p_T distributions in the signal region for the categories with tracks across >2 (=2, =2) BXs without (with, without) additional track requirement are shown in the upper (center, lower) part of the figure. The expected background distributions are the result of the maximum likelihood fit. The uncertainty bands account for all sources of background uncertainty, systematic as well as statistical, after the maximum likelihood fit. The lower panels show the observed to expected ratio. The signal is shown for a few mass hypotheses of the nonresonant fourth-generation lepton model, using a production cross section of 1 pb. The last p_T bins include the overflow.

with $\beta \approx 0.5$, for which the analysis has limited acceptance since they tend to cross the muon detector entirely during the BX that follows the collision. Around $m = 6$ TeV, the limits degrade because the HSCPs are mostly produced with $\beta \lesssim 0.15$ and are stopped before crossing the muon detector. The previous CMS analysis based on an ionization-loss signature [30] provided an interpretation up to $m = 2.6$ TeV, where the limits are about two orders of magnitude tighter than the result presented in this paper, because of the larger data set available, larger η acceptance, and higher-level information. However, unlike the present search, the ionization-loss signature analysis does not have sensitivity to scenarios with $m \gtrsim 4.5$ TeV because its HLT efficiency is zero at such low β values. This analysis has unique sensitivity at high mass where all HSCPs have low β, and to the gluino R-hadron scenario with $f = 1$, where there is no ionization loss signature in the tracker since the R-hadron is neutral

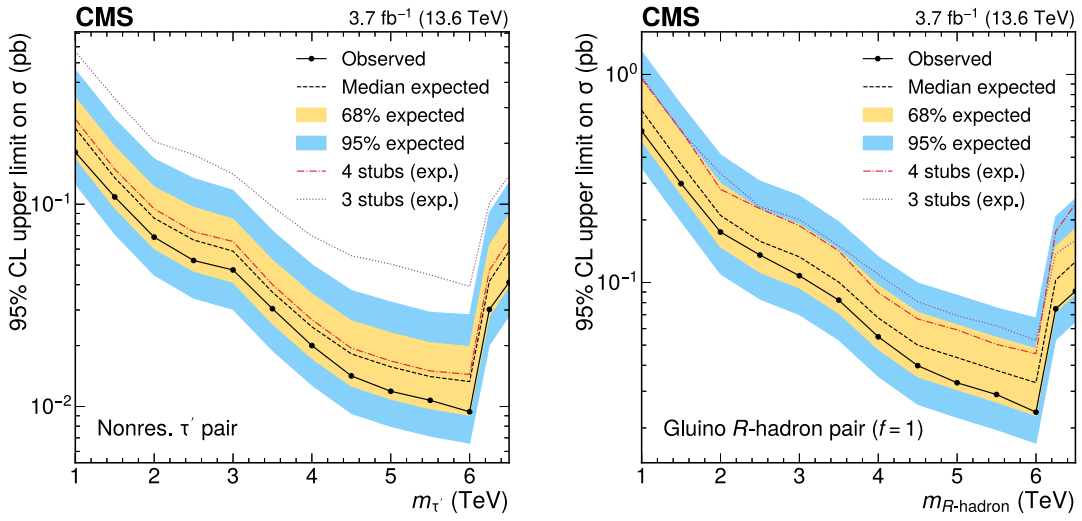

Fig. 9. Observed (solid line with markers) and expected (dashed black line) upper limits at 95% CL on the production cross section of heavy fourth-generation leptons through nonresonant DY production (left) and of a gluino R-hadron pair with $f = 1$ (right). The inner (yellow) and the outer (blue) bands indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The expected limits for the combinations of 3-stub (dashed purple line) and 4-stub (dashed-red line) categories are also shown.

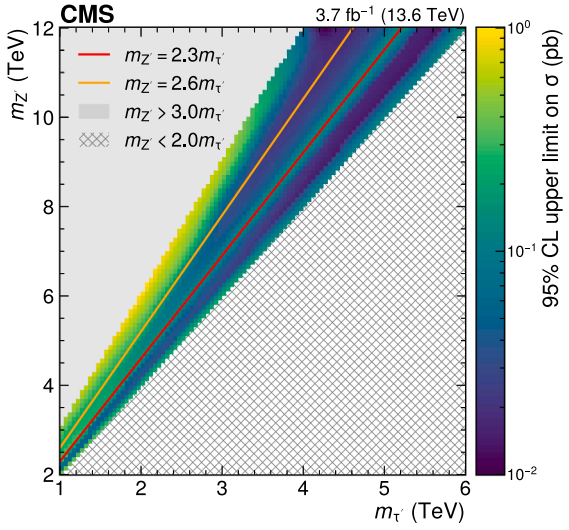

Fig. 10. Observed upper limits at 95% CL on the production cross section of heavy fourth-generation leptons through Z′ boson decays. Lines indicate different values of the ratio of Z′ to τ′ masses, for which β values are typically similar. Signal hypotheses with $2m_{\tau'} < m_{Z'} < 3m_{\tau'}$ are probed. For $m_{Z'} > 3m_{\tau'}$, the HSCPs typically have high β and are reconstructed in the same BX. The lowest limits are obtained for $m_{Z'}/m_{\tau'} \approx 2.15$ (2.60), for which HSCPs are dominantly produced with $\beta \approx 0.2$ (0.6). The higher limits for $m_{Z'}/m_{\tau'} \approx 2.30$ are related to the low analysis acceptance for HSCPs produced with $\beta \approx 0.5$ and largely reconstructed in a single BX.

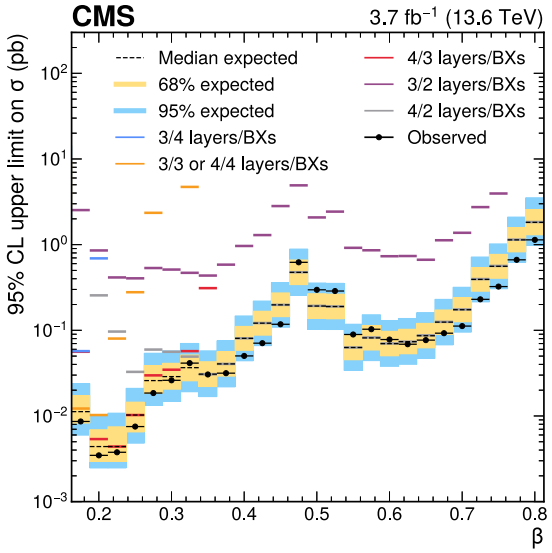

Fig. 11. Observed and expected upper limits at 95% CL on the fiducial cross section of a heavy particle leaving a signature in the muon detector with $|\eta| < 0.83$, $p_T > 500$ GeV, in bins of β. The inner (yellow) and the outer (blue) bands indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The expected limits for groups of categories corresponding to a given number of muon detector layers across a given number of BXs are also shown with colored dashed lines. The limited sensitivity around $\beta = 0.5$ corresponds to a loss of acceptance from particles reconstructed entirely in the BX that followed the collision.

in that part of the detector. Two-dimensional upper limits are shown in Fig. 10 for the τ′ pair production from a Z′ boson decay, with unique sensitivity for $m_{Z'} \lesssim 2.5m_{\tau'}$, corresponding to HSCPs with $\beta \lesssim 0.6$. For all mass points, the observed limits are within the band containing 68% of the limits expected under the background-only hypothesis.

Upper limits are also set on the fiducial cross section of a lepton-like particle leaving a signature in the muon detector and produced with $p_T > 500$ GeV, $|\eta| < 0.83$, and a given range of β, assuming there is no contribution from particles produced with other β values. These results are extracted from the SRs without additional track requirement in order not to rely on the pair production assumption. The signal distributions are built using particles from the simulated samples described in Section 4 satisfying $p_T > 500$ GeV, $|\eta| < 0.83$, and the β range restriction. These distributions are independent from the signal model. As shown in Fig. 11, upper limits as low as 3.5 fb can be set for particles produced with $0.1875 < \beta < 0.2125$, where the sensitivity mostly comes from the categories where the particle takes 3 BXs to cross all four muon layers. For lower β values, the sensitivity sharply decreases as the particles get stopped before entering the muon detector because of their large ionization loss. The patterns in the limits align with the signatures of the slow particles as a function of β, shown in Fig. 4. For $\beta > 0.35$, the

categories where the particle takes 2 BXs to cross the four muon layers dominate the sensitivity. The sensitivity is low around $\beta = 0.5$, because the particle is likely to be reconstructed entirely in the BX following the collision, where the analysis has no acceptance since the track experimentally looks like that of an ultra-relativistic particle.

10. Summary

A search for long-lived massive charged particles has been presented, exploiting a muon-like signature in the barrel muon detectors spread across several LHC proton bunch crossings. This is the first time that an analysis relies on the novel CMS level-1 trigger scouting data set, for which no trigger selection is applied. A method based on control samples in data is used to estimate the backgrounds, relying on tracks not compatible in time with the expectations from a slow particle exiting the detector. No significant excess of data above the predicted standard model backgrounds is observed. Upper limits are set on the production cross section of heavy stable charged particles in several models, and fiducial upper limits on the production cross section for different $\beta = v/c$ ranges are also set for a model-independent interpretation. The analysis has unique sensitivity to particles with $0.15 \lesssim \beta \lesssim 0.5$, which are challenging to trigger on, and to neutral particles that acquire a charge when crossing the detector, which do not leave an ionization-loss signature in the tracker. Upper limits as low as 3.5 fb at 95% confidence level are set on the fiducial production cross section of lepton-like charged particles with $|\eta| < 0.83$ and $p_{\mathrm{T}} > 500\,\mathrm{GeV}$, in several bins of β, extending the reach of the existing searches to higher masses and lower values of β.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Schematic illustration of the categories

The event categories are illustrated in Figs. A.12–A.14. The track configurations used to estimate the background in the BX1234 and BX1112 categories are illustrated in Figs. A.15 and A.16, respectively.

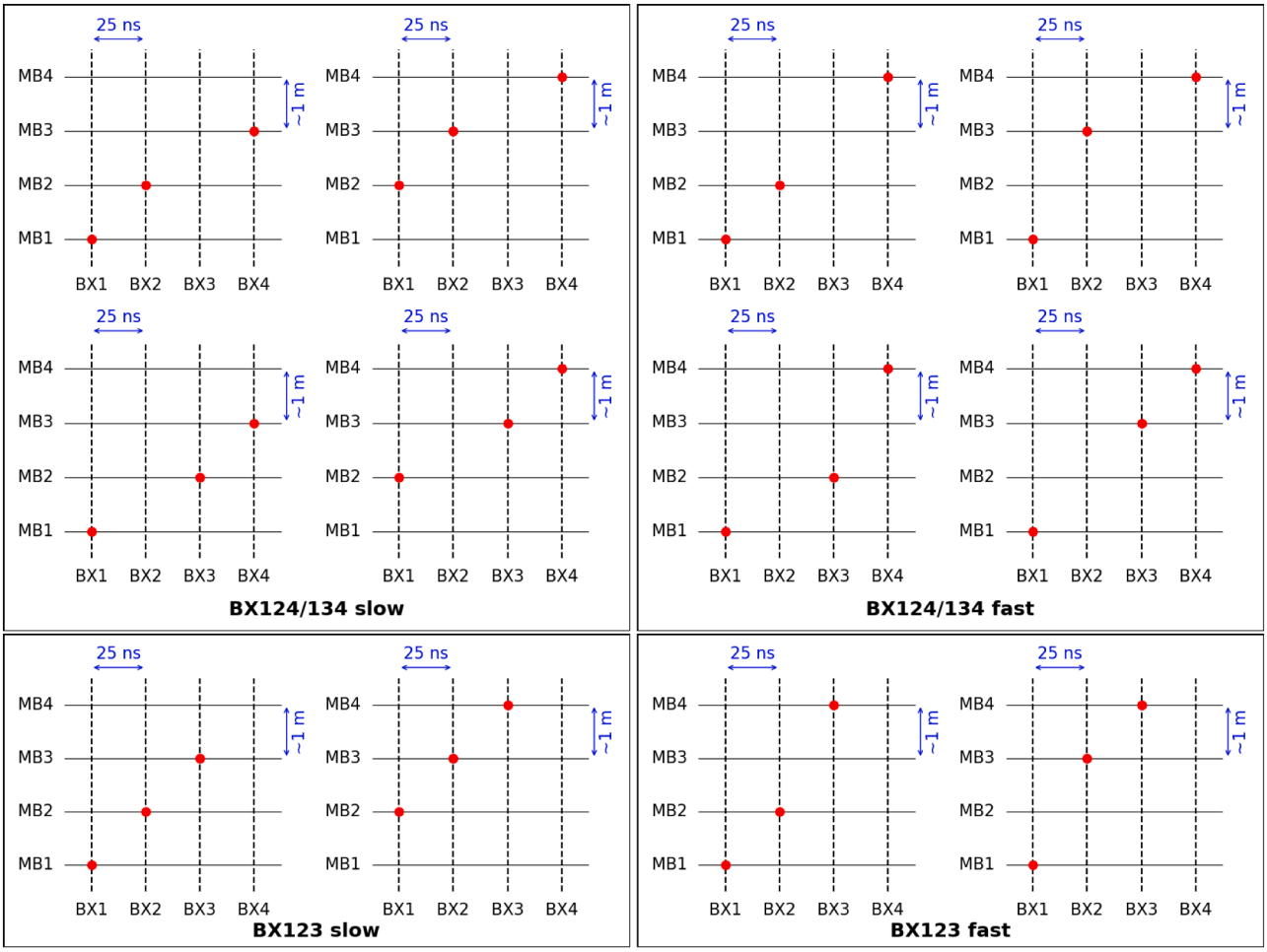

Fig. A.12. Schematic definition of the 3-stub categories with tracks across >2 BXs.

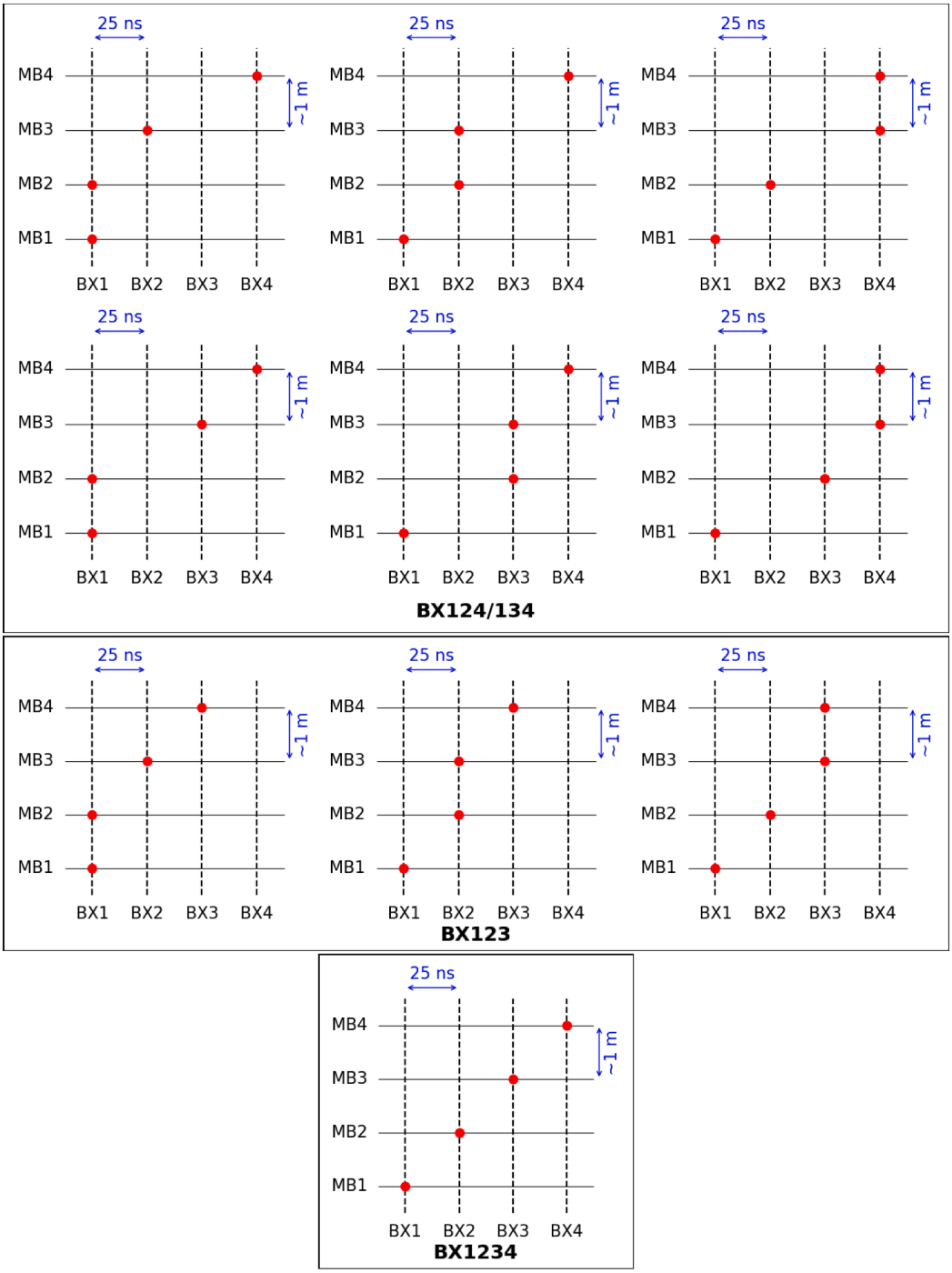

Fig. A.13. Schematic definition of the 4-stub categories with tracks across >2 BXs.

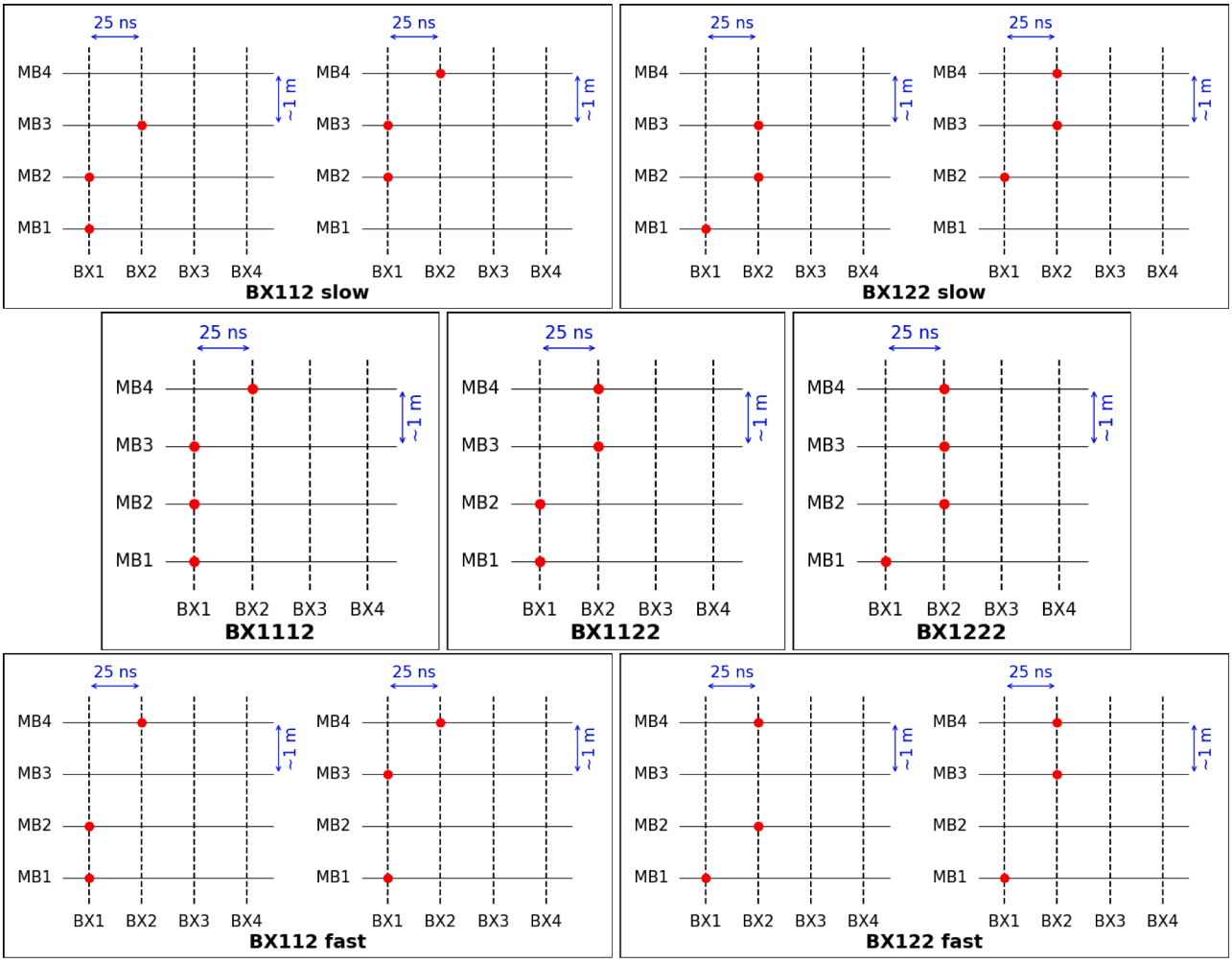

Fig. A.14. Schematic definition of the categories with tracks across 2 BXs.

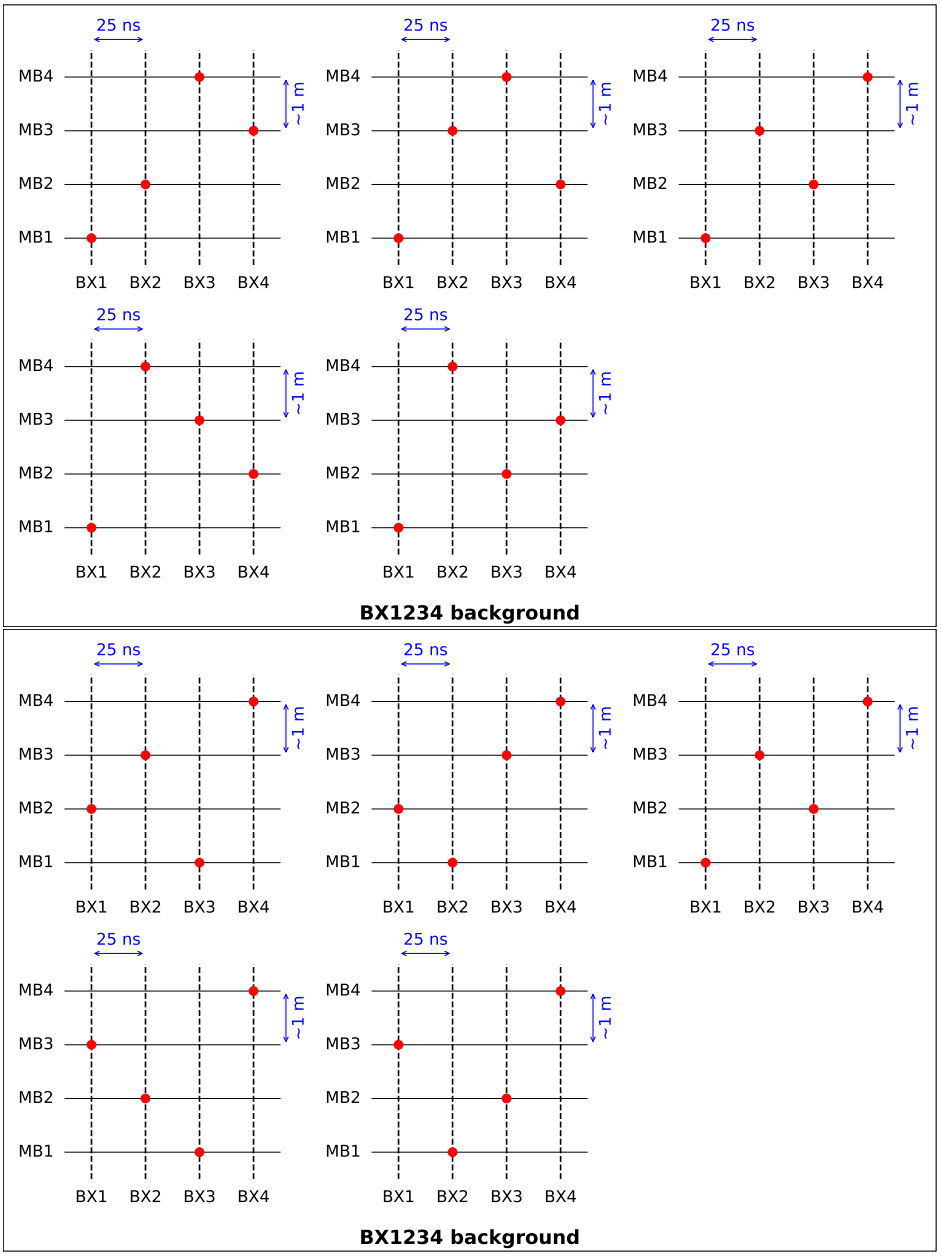

Fig. A.15. Schematic definition of the asynchronous orderings used to estimate the backgrounds in the BX1234 category. The upper (lower) half includes orderings with the first (last) stub in MB1 (MB4).

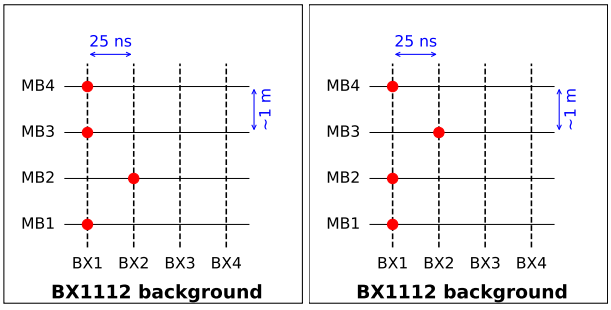

Fig. A.16. Schematic definition of the asynchronous orderings used to estimate the backgrounds in the BX1112 category. The left (right) diagram shows the ordering where the stub detected in a different BX than the other three stubs is in MB2 (MB3).

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