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NLO+NLL limits on W' and Z' gauge boson masses in general extensions of the Standard Model

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Abstract: QCD resummation predictions for the production of charged (W') and neutral (Z') heavy gauge bosons decaying leptonically are presented. The results of our resummation code at next-to-leading order and next-to-leading logarithmic (NLO+NLL) accuracy are compared to Monte Carlo predictions obtained with PYTHIA at leading order (LO) supplemented with parton showers (PS) and FEWZ at NLO and next-to-next-to-leading order (NNLO) for the p_T-differential and total cross sections in the Sequential Standard Model (SSM) and general SU(2)×SU(2)×U(1) models. The LO+PS Monte Carlo and NNLO fixed-order predictions are shown to agree approximately with those at NLO+NLL at small and intermediate p_T, respectively, and the importance of resummation for total cross sections is shown to increase with the gauge boson mass. The theoretical uncertainties are estimated by variations of the renormalisation/factorisation scales and of the parton densities, the former being significantly reduced by the resummation procedure. New limits at NLO+NLL on W' and Z' boson masses are obtained by reinterpreting the latest ATLAS and CMS results in general extensions of the Standard Model.

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Contents

1 Introduction

New charged and neutral resonances are predicted in many well-motivated extensions of the Standard Model (SM) such as Grand Unified Theories (GUTs) or models with extra spatial dimensions [1]. These extensions generally do not predict the precise energy scale, at which the new heavy states should manifest themselves. However, for various theoretical reasons (e.g. the hierarchy problem), new physics is expected to appear at the TeV scale and is searched for at the Large Hadron Collider (LHC), which will soon operate at centre-of-mass energies of $\sqrt{S} = 13\,\text{TeV}$ (LHC13) and $14\,\text{TeV}$ (LHC14).

Experimental searches for W' and Z' bosons have so far mostly been performed in the Sequential Standard Model (SSM) [2] (see table 1), where identical couplings for the new and SM gauge bosons are assumed and which thus serves as a benchmark for comparisons among different experiments, but is theoretically unmotivated. While we also adopt this model as a baseline to compare predictions with different theoretical accuracy, we then enlarge our analysis to a general $\text{G}(221) \equiv \text{SU}(2)_1 \times \text{SU}(2)_2 \times \text{U}(1)_X$ gauge group, which represents a well-motivated intermediate step towards the unification of the SM gauge groups. In this framework, constraints on the parameter space from low-energy precision observables have been derived [3], and several aspects of the collider phenomenology have already been studied [4–7]. Furthermore, the effect of the new spin-one resonances on the interactions of ultra-high energy neutrinos in the atmosphere has been analysed [8].

Several well-known models emerge naturally from different ways of breaking the G(221) symmetry down to the SM gauge group [3], in particular Left-Right (LR) [9–11], Un-Unified (UU) [12, 13], Non-Universal (NU) [14, 15], Lepto-Phobic (LP), Hadro-Phobic (HP), and Fermio-Phobic (FP) [16, 17] models.

The ATLAS and CMS collaborations have performed extensive searches of new spin-one resonances at the LHC for a large number of final states. In table 1, we summarise these searches, that exploited data from the pp runs in 2010 and 2011 at $\sqrt{S} = 7\,\mathrm{TeV}$ (LHC7) and from the pp run in 2012 at $\sqrt{S} = 8\,\mathrm{TeV}$ (LHC8), as well as the corresponding constraints on W' and Z' gauge boson masses. As can be seen, the most stringent limits come from searches with purely leptonic final states, $W' \to \ell\nu$ [18–22, 43–47] and $Z' \to \ell\ell$ [32–35, 58–61] (with $\ell = e, \mu$, neutrino flavours and antiparticles understood), leading to (preliminary) lower mass limits of $M_{W'} \gtrsim 3.3\,\mathrm{TeV}$ [21, 47] and $M_{Z'} \gtrsim 2.9\,\mathrm{TeV}$ [35, 61] for gauge bosons in the SSM. In LR models, exclusion contours in the right-handed weak boson (W_R) and neutrino (N) mass plane have been obtained by exploiting also semileptonic [24, 25, 28, 49, 53, 54, 56] and even fully hadronic final states [31]. In addition, upper limits on the production cross section times the branching ratio, $\sigma \times \mathrm{Br}$, were presented, which can be used to constrain a few other specific models such as extended gauge models with modified couplings of the new to the SM gauge bosons [23, 36, 39–41, 52, 63]. However, other G(221) models such as UU and NU models have so far not been analysed. Furthermore, the mass limits are mostly obtained using LO+PS Monte Carlo simulations with PYTHIA [68] rescaled to NNLO with FEWZ [69, 70], where both programs do a priori not include the important interference effects of new and SM gauge boson exchanges.

In this paper, we present new QCD resummation predictions, which include these interference effects, at next-to-leading order and next-to-leading logarithmic (NLO+NLL) accuracy for the production of charged and neutral heavy gauge boson (W' and Z') decaying into charged leptons and neutrinos. For SM weak gauge boson production, the importance of resummation calculations has been demonstrated most recently using Soft-Collinear Effective Theory (SCET) by an improved agreement with Tevatron and LHC data and reduced theoretical scale uncertainties [71–73]. In the context of new physics searches at the LHC, soft-gluon resummation has already been applied to the production of Z' bosons [74] as well as to the production of supersymmetric (SUSY) particles such as squarks and gluinos [75], sleptons [76–79], and gauginos [80–83]. For the Z' boson and weak SUSY channels, the NLO+NLL code RESUMMINO is publicly available [84]. We have now also added the possibility to make predictions for W' bosons with general gauge couplings for transverse momentum (p_T) spectra, resummed as $p_T \to 0$ in impact parameter space, and for total cross sections, resummed near partonic threshold in Mellin space.[1]

The results of our resummation code are compared using different benchmark models to p_T distributions and total cross sections obtained with the LO+PS Monte Carlo generator PYTHIA [68], in which we have implemented the new weak bosons including the interferences with the SM gauge bosons. In addition, we compare with the theoretical predictions in fixed order perturbation theory at NLO and NNLO QCD calculated with the

[1]Our code is available at `http://www.resummino.org`.

Reference	$\sqrt{S}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	Mode	Limits [TeV]	Comments
ATLAS:					
PLB701(2011)50 [18]	7	0.036	$W' \to \ell\nu$	$M_{W'} > 1.49$	SSM
PLB705(2011)28 [19]	7	1.04	$W' \to \ell\nu$	$M_{W'} > 2.15$	SSM
EPJC72(2012)2241 [20]	7	4.7	$W' \to \ell\nu$	$M_{W'} > 2.55$	SSM
ATLAS-CONF-2014-017 [21]	8	20.3	$W' \to \ell\nu$	$M_{W'} > \mathbf{3.27}$	SSM
JHEP09(2014)037 [22]	8	20.3	$W' \to \ell\nu$	$M_{W'} > 3.24$	SSM
PRD85(2012)112012 [23]	7	1.02	$W' \to WZ \to \ell\nu\ell'\ell'$	$\sigma\times$Br	
PRL109(2012)081801 [24]	7	1.04	$W' \to tb \to \ell\nu jj$	$M_{W'_R} > 1.13$	LR Model
EPJC72(2012)2056 [25]	7	2.1	$W'_R \to \ell N \to \ell\ell jj$	$(M_{W'_R}, M_N)$ exclusions	LR Model
PRD87(2013)112006 [26]	7	4.7	$W' \to WZ \to \ell\nu jj$	$M_{W'} > 0.95$	
JHEP01(2013)29 [27]	7	4.8	$W' \to jj$	$M_{W'} > 1.68$	
ATLAS-CONF-2013-050 [28]	8	14	$W' \to tb \to \ell\nu bb$	$M_{W'_L} > 1.74$, $M_{W'_R} > 1.84$	LR Model
CERN-PH-EP-2014-147 [29]	8	20.3	$W' \to jj$	$M_{W'} > 2.45$	SSM
PLB737(2014)223 [30]	8	20.3	$W' \to WZ \to \ell\nu\ell'\ell'$	$M_{W'} > 1.52$	
CERN-PH-EP-2014-152 [31]	8	20.3	$W' \to tb \to qqbb$	$M_{W'_L} > 1.68$, $M_{W'_R} > 1.76$	LR Model
PLB700(2011)163 [32]	7	0.04	$Z' \to \ell\ell$	$M_{Z'} > 1.048$	SSM
PRL107(2011)272002 [33]	7	1.08-1.21	$Z' \to \ell\ell$	$M_{Z'} > 1.83$	SSM
JHEP11(2012)138 [34]	7	4.9	$Z' \to \ell\ell$	$M_{Z'} > 2.22$	SSM
CERN-PH-EP-2014-053 [35]	8	20.3-20.5	$Z' \to \ell\ell$	$M_{Z'} > \mathbf{2.90}$	SSM
EPJC72(2012)2083 [36]	7	2.05	$Z' \to tt$	$\sigma\times$Br	
PRD87(2013)052002 [37]	7	4.6	$\ell\ell\ell$	$\sigma^{\text{vis.}}$	
PLB719(2013)242 [38]	7	4.6	$Z' \to \tau\tau$	$M_{Z'} > 1.4$	SSM
PRD88(2013)012004 [39]	7	4.7	$Z' \to tt$	$\sigma\times$Br	Narrow Z'
JHEP01(2013)116 [40]	7	4.7	$Z' \to tt$	$\sigma\times$Br	
ATLAS-CONF-2013-052 [41]	8	14	$Z' \to tt$	$\sigma\times$Br	Narrow Z'
ATLAS-CONF-2013-066 [42]	8	19.5	$Z' \to \tau\tau$	$M_{Z'} > 1.9$	SSM
CMS:					
PLB698(2011)21 [43]	7	0.036	$W' \to e\nu_e$	$M_{W'} > 1.36$	SSM
PLB701(2011)160 [44]	7	0.036	$W' \to \mu\nu_\mu$	$M_{W'} > 1.4$	SSM
JHEP08(2012)023 [45]	7	5	$W' \to \ell\nu$	$M_{W'_L} > 2.43$-2.63, $M_{W'_R} > 2.5$	LR Model
PRD87(2013)072005 [46]	7-8	5-3.7	$W' \to \ell\nu$	$M_{W'} > 2.9$	SSM
CERN-PH-EP-2014-176 [47]	8	19.7	$W' \to \ell\nu$	$M_{W'} > \mathbf{3.28}$	SSM
PLB704(2011)123 [48]	7	1	$W' \to jj$	$M_{W'} > 1.51$	SSM
PRL109(2012)261802 [49]	7	5	$W'_R \to \ell N$	$(M_{W'_R}, M_N)$ exclusions	LR Model
PRL109(2012)141801 [50]	7	5	$W' \to WZ \to 3\ell\nu$	$M_{W'} > 1.143$	SSM
JHEP02(2013)036 [51]	7	5	$W' \to WZ \to \ell\ell jj$	$M_{W'} > 0.94$	SSM
PLB723(2013)280 [52]	7	5	$W' \to WZ \to 4j$	$\sigma\times$Br	SSM
PLB718(2013)1229 [53]	7	5	$W' \to tb \to \ell\nu bb$	$M_{W'_L} > 1.51$, $M_{W'_R} > 1.85$	LR Model
PLB717(2012)351 [54]	7	5	$W' \to ttj$	$M_{W'_R} > 0.84$	LR Model
CMS-PAS-EXO-12-025 [55]	8	19.5	$W' \to WZ$	$M_{W'} > 1.47$	SSM
CERN-PH-EP-2014-161 [56]	8	19.7	$W'_R \to \ell N$	$(M_{W'_R}, M_N)$ exclusions	LR Model
JHEP08(2014)173 [57]	8	19.7	$W' \to WZ \to jjX$	$M_{W'} > 1.7$	SSM
JHEP05(2011)093 [58]	7	0.04	$Z' \to \ell\ell$	$M_{Z'} > 1.14$	SSM
PLB714(2012)158 [59]	7	5	$Z' \to \ell\ell$	$M_{Z'} > 2.33$	SSM
PLB720(2013)63 [60]	7-8	5.3-4.1	$Z' \to \ell\ell$	$M_{Z'} > 2.59$	SSM
CMS-PAS-EXO-12-061 [61]	8	19.6-20.6	$Z' \to \ell\ell$	$M_{Z'} > \mathbf{2.96}$	SSM
PLB716(2012)82 [62]	7	4.9	$Z' \to \tau\tau$	$M_{Z'} > 1.4$	SSM
JHEP09(2012)029 [63]	7	5	$Z' \to tt$	$\sigma\times$Br	
JHEP01(2013)013 [64]	7	5	$Z', W' \to jjX$, $Z' \to bb$	$M_{W'} > 1.92$, $M_{Z'} > 1.47$	SSM
PRD87(2013)114015 [65]	8	4	$Z', W' \to jj$	$M_{W'} > 1.73$, $M_{Z'} > 1.62$	
CMS-PAS-EXO-12-059 [66]	8	19.6	$Z', W' \to jj$	$M_{W'} > 2.29$, $M_{Z'} > 1.68$	SSM
CMS-PAS-EXO-12-023 [67]	8	19.6	$Z' \to bb$	$M_{Z'} > 1.68$	SSM

Table 1. ATLAS and CMS searches for new spin-one gauge bosons (W' and Z') at the LHC using data from the pp runs in 2010 and 2011 at $\sqrt{S} = 7$ TeV and from the pp run in 2012 at $\sqrt{S} = 8$ TeV.

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FEWZ program, which unfortunately lacks the interference terms [69, 70]. The theoretical uncertainties are estimated by variations of the renormalisation/factorisation scales and parton distribution functions (PDFs). Using the example of Z' bosons, we demonstrate that the resummation contributions become more important with increasing mass of the new gauge boson, which will further increase their importance in future LHC analyses. In an exemplary way, we reinterpret the most recent ATLAS W' [21] and CMS Z' [61] analyses using our NLO+NLL predictions, including interference, and three different new physics models.

The remainder of this paper is organised as follows: in section 2 we describe the relevant features of the three theoretical approaches (PYTHIA, FEWZ, and RESUMMINO) that we develop, employ and compare in this paper. Theoretical numerical predictions, i.e. differential and total cross sections for the production of charged and neutral heavy gauge bosons decaying to leptons at the LHC and their associated theoretical uncertainties, are presented in section 3. The reanalyses of the ATLAS and CMS experimental results are described in section 4. Finally, we summarise our results and draw our conclusions in section 5.

2 Theoretical setup

In this section, we describe the main features of the three different theoretical frameworks (PYTHIA, FEWZ, and RESUMMINO) that we have (in particular in the cases of PYTHIA and RESUMMINO) developed further and that we employ and compare numerically in sections 3 and 4.

2.1 PYTHIA Monte Carlo at LO+PS

Following common experimental practice, we first simulate the production of new charged (W') and neutral (Z') gauge bosons decaying leptonically into $\ell\nu$ and $\ell\ell$ (with $\ell = e, \mu$, neutrino flavours and antiparticles understood) at LO, $\mathcal{O}(\alpha^2\,\alpha_s^0)$, using PYTHIA 6.4.27 [68]. The description of kinematic distributions is improved to leading-logarithmic accuracy by a virtuality-ordered PS, applied in this case only to the initial partons and introducing a weak dependence on the strong coupling constant α_s (or equivalently the QCD scale Λ) even at this order. Still, we estimate the scale uncertainty of the PYTHIA LO+PS prediction by varying only the factorisation scale μ_F by a factor of two about the central value, set by the new gauge boson mass. We use PDFs from the MSTW 2008 parameterisation, i.e. in this case the central fit MSTW 2008 LO [85].

In PYTHIA, the Z' and W' bosons (PDG codes 32 and 34) constitute hypothetical physical (mass eigenstate) vector bosons. The W' boson couples, e.g., to the SM fermions with strengths

$$\bar{\nu}_\ell \ell W'^{+}, \bar{\ell}\nu_\ell W'^{-} \sim \frac{g}{2\sqrt{2}}\gamma^\mu(V_\ell - A_\ell\gamma_5)\,, \quad \bar{q}q' W'^{\pm} \sim \frac{g}{2\sqrt{2}} U_{\rm CKM}\gamma^\mu(V_q - A_q\gamma_5)\,. \qquad (2.1)$$

Here, g is the SU(()2) coupling constant related to the fine structure constant $\alpha = g^2 \sin^2\theta_W/\ (4\pi)$ through the weak mixing angle θ_W and calculated numerically at the scale of the new gauge boson mass using input values from the Particle Data Group [1]. We thus obtain $\alpha(M_Z) = 1/128.97$ and $\alpha(M_{V'} = 4\,\text{TeV}) = 1/123.36$. U_{CKM} is the quark mixing matrix, and the couplings $V_{\ell,q}$ and $A_{\ell,q}$ are dimensionless, real, and fermion generation independent. Their default values are $V_{\ell,q} = 1$ and $A_{\ell,q} = -1$ as in the SSM. Similarly, the Z' boson couplings are set to their SSM values, but may be modified by the user. It is also possible to allow additional couplings to SM vector and Higgs bosons when necessary, e.g., for general extended gauge models. The total decay widths $\Gamma_{V'}$ of the new vector bosons (V') are calculated perturbatively in an automated fashion as a sum of the decay widths into SM fermions, taking into account the user-provided values of $V_{\ell,q}$ and $A_{\ell,q}$. We have verified that in the models that we will consider (SSM, UU and NU models) the decays into pairs of gauge and Higgs bosons contribute only 1-2% to the total decay widths, so that we may safely neglect them. In other models there may of course be regions of parameter space where these decays are not negligible [7]. In the Breit-Wigner propagator, a centre-of-mass energy (s) dependence may furthermore be introduced in the terms dependent on the total decay width, $M_{V'}\Gamma_{V'} \to s\Gamma_{V'}/M_{V'}$, to improve the description of the resonance shape [86].

Since the $2 \to 1 \to 2$ structure of the PYTHIA implementation of new vector boson production and decay does not easily lend itself to taking into account interference effects and since these can be quite important for kinematic distributions and also for total cross sections depending on experimental cuts [87, 88], we have implemented the full processes $qq^{(\prime)} \to \ell\ell\,(\ell\nu)$ including also interferences of SM and new gauge bosons, but still neglecting the masses of the final state leptons. Here, the couplings have been implemented both in a general fashion (see above) and for specific G(221) models. This has also been done in the routines calculating the total decay widths.[2]

2.2 Perturbative QCD at NLO and NNLO

In fixed-order perturbative QCD, the hadronic production of Z' and W' bosons can be calculated at NLO, $\mathcal{O}(\alpha^2\alpha_s)$, and NNLO, $\mathcal{O}(\alpha^2\alpha_s^2)$, with the publicly available program FEWZ [69, 70] in a fully exclusive way and including the leptonic decay of the gauge bosons with full spin correlations and finite width effects. FEWZ thus allows one to investigate the total production cross section as well as the transverse momentum and invariant/transverse mass spectra under arbitrary kinematic cuts on the gauge boson and/or lepton-pair. Unfortunately, since the code assumes the existence of one neutral/charged vector boson only, the important interference effects between two different gauge bosons are not taken into account. The pure SM background is, however, far below the new physics signal, at least for the new gauge boson masses and models considered here, and can thus safely be neglected.

Since the user is allowed to tune the gauge boson properties such as the mass, width and partial width into leptonic states, FEWZ can in principle be used to extrapolate SM predictions to the production rate of Z' and W' bosons in various extensions of the SM. Unfortunately, it is not possible to enter the gauge boson couplings to SM fermions directly, so that additional rescaling of the observables may be required. In order to calculate the

[2] The modified PYTHIA code is available from the authors upon request.

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observables of the heavy resonance in a given extension of the SM, we proceed therefore in three steps: (i) we obtain the Z' and W' boson properties from our extended version of PYTHIA, discussed in the previous section, and feed them into FEWZ; (ii) we calculate the total cross section and desired distributions of a Z' or W' resonance with SM couplings; (iii) we rescale the observables by the relevant combination of Z' and W' boson couplings to SM fermions. This rescaling of the cross section must be done carefully and is in certain models impossible. The squared matrix element calculated in FEWZ is given by [89]

$$|\mathcal{M}|^2 = \frac{H^{\mu\nu} L_{\mu\nu}}{\left(Q^2 - M_{V'}^2\right)^2 + M_{V'}^2 \Gamma_{V'}^2}\,, \tag{2.2}$$

where Q^2 is the invariant mass of the di-lepton pair, $H^{\mu\nu}$ is the hadronic tensor including the QCD corrections, and $L_{\mu\nu}$ is the leptonic tensor. For ease of use, $L_{\mu\nu}$ is expressed in terms of $M_{V'}$ and $\mathrm{Br}(Z', W' \to \ell\ell, \ell\nu)$ rather than in terms of the corresponding couplings to leptons. Consequently, when considering Z' and W' resonances, only their couplings to the initial quarks must be rescaled. We estimate the scale uncertainty of the FEWZ prediction by varying the renormalisation scale μ_R and factorisation scale μ_F simultaneously by a factor of two about the central value, the new gauge boson mass. The central PDF parameterisations are MSTW 2008 NLO and NNLO, respectively, and their uncertainties are estimated with the 40 sets of error PDFs at 68% confidence level as implemented in the FEWZ code [85].

2.3 Resummation at NLO and NLL

In this section, we briefly review the formalism that allows us to resum the QCD corrections to all orders at large invariant mass (Q) and/or small transverse momentum (p_T) of a lepton pair produced through weak gauge bosons in hadronic collisions [84].

Thanks to the QCD factorisation theorem, the double differential cross section

$$Q^2 \frac{\mathrm{d}^2\sigma_{AB}}{\mathrm{d}Q^2 \mathrm{d}p_T^2}(\tau) = \sum_{ab} \int_0^1 \mathrm{d}x_a \mathrm{d}x_b \mathrm{d}z [x_a f_{a/A}(x_a, \mu_F^2)][x_b f_{b/B}(x_b, \mu_F^2)]\, [z\, \mathrm{d}\sigma_{ab}(z, Q^2, p_T^2, \mu_F^2)] \times \delta(\tau - x_a x_b z) \tag{2.3}$$

can be obtained by convolving the partonic cross section $\mathrm{d}\sigma_{ab}$ with the universal densities $f_{a,b/A,B}$ of the partons a, b, carrying the momentum fractions $x_{a,b}$ of the colliding hadrons A, B, at the factorisation scale μ_F. The application of a Mellin transform

$$F(N) = \int_0^1 \mathrm{d}y\, y^{N-1} F(y) \tag{2.4}$$

to the quantities $F \in \{\sigma_{AB},\ \sigma_{ab},\ f_{a/A},\ f_{b/B}\}$ with $y \in \{\tau = Q^2/S,\ z = Q^2/s,\ x_a,\ x_b\}$ allows to express the hadronic cross section in moment space as a simple product,

$$Q^2 \frac{\mathrm{d}^2\sigma_{AB}}{\mathrm{d}Q^2 \mathrm{d}p_T^2}(N-1) = \sum_{ab} f_{a/A}(N, \mu_F^2) f_{b/B}(N, \mu_F^2) \sigma_{ab}(N, Q^2, p_T^2, \mu_F^2). \tag{2.5}$$

Furthermore, the application of a Fourier transform to the partonic cross section σ_{ab} allows to correctly take into account transverse-momentum conservation, so that in moment (N)

and impact parameter (b) space it can be written as

$$\sigma_{ab}(N,Q^2,p_T^2,\mu_F^2) = \int_0^\infty \mathrm{d}b \frac{b}{2} J_0(bp_T)\sigma_{ab}(N,Q^2,b^2,\mu_F^2). \tag{2.6}$$

Here, $J_0(y)$ denotes the 0^{th}-order Bessel function and

$$\sigma_{ab}(N,Q^2,b^2,\mu_F^2) = \sum_{n=0}^{\infty} a_s^n(\mu_R^2)\, \sigma_{ab}^{(n)}(N,Q^2,b^2,\mu_F^2,\mu_R^2) \tag{2.7}$$

is usually expanded perturbatively in the strong coupling constant $a_s(\mu^2) = \alpha_s(\mu^2)/(2\pi)$ at the renormalisation scale μ_R. For simplicity, we identify in the following the factorisation and renormalisation scales, *i.e.* $\mu_F = \mu_R = \mu$.

In the Born approximation, the production of lepton pairs is induced by quarks q and antiquarks $\bar{q}'$ in the initial (anti-)protons and is mediated by s-channel electroweak gauge-boson exchanges, whose mass and couplings determine the partonic cross section $\sigma_{q\bar{q}'}^{(0)}$. At $\mathcal{O}(a_s)$, virtual loop and real parton emission corrections must be taken into account. The latter induce not only a deviation of the partonic centre-of-mass energy s from the squared invariant mass Q^2 of the lepton pair, but also non-zero transverse momenta p_T, that extend typically to values of the order of the weak gauge boson mass. Close to the partonic production threshold, where $z = Q^2/s \to 1$ or $N \to \infty$, the convergence of the perturbative expansion is spoiled due to soft gluon radiation, which induces large logarithms

$$a_s^n \left(\frac{\ln^m(1-z)}{1-z} \right)_+ \to a_s^n \ln^{m+1} \bar{N} + \dots \tag{2.8}$$

with $m \leq 2n-1$ and $\bar{N} = Ne^{\gamma_E}$ [77, 81]. Similarly, in the small-p_T (or large-b) region, where the bulk of the events is produced, the convergence of the perturbative expansion is again spoiled by soft gluon radiation, which induces large logarithms

$$\alpha_s^n \left(\frac{1}{p_T^2} \ln^m \frac{Q^2}{p_T^2} \right)_+ \to \alpha_s^n \ln^{m+1} \bar{b}^2 + \dots \tag{2.9}$$

with $m \leq 2n-1$ and $\bar{b} = bQe^{\gamma_E}/2$ [76, 80]. An important observation, first made by Li [90] and then further developped by Laenen, Sterman, and Vogelsang [91, 92] is that the common kinematic origin of these divergences allows for a joint resummation of the large logarithms in the partonic cross section. In the corresponding kinematic limits and with proper adjustments, the jointly resummed cross section reduces to the one for transverse-momentum [80] and threshold resummation [81], respectively.

While the large logarithms must clearly be resummed close to the production threshold, when $z \to 1$ and $\bar{N} \to \infty$, and/or at small values of $p_T \to 0$, when $\bar{b} \to \infty$, they account only partially for the full perturbative cross section away from these regions. In order to obtain a valid cross section at all values of z and p_T, the fixed-order (f.o.) and the resummed (res.) calculations must be combined consistently by subtracting from their sum the perturbatively expanded (exp.) resummed component,

$$\sigma_{ab} = \sigma_{ab}^{(\text{res.})} + \sigma_{ab}^{(\text{f.o.})} - \sigma_{ab}^{(\text{exp.})}. \tag{2.10}$$

The latter is easily obtained by expanding eq. (2.6) to the desired accuracy.

After the resummation of the partonic cross section has been performed in N- and b-space, we have to multiply the resummed cross section and its perturbative expansion with the moments of the PDFs $f_{a/A}(N, \mu^2)$ and transform the hadronic cross section obtained in this way back to the physical z- and p_T-spaces. The moments of the PDFs are obtained through a numerical fit to the publicly available PDF parameterisations in x-space.

Our NLO fixed order and NLO+NLL resummation calculations have been implemented in the computer code RESUMMINO that is publicly available [84]. For our numerical results at both NLO and NLO+NLL, we employ the PDF parameterisation of MSTW 2008 NLO and estimate the theoretical scale error by varying again simultaneously the renormalisation and factorisation scales by a factor of two about the new gauge boson mass.

3 Numerical results

In this section, we present numerical results using the three different theoretical approaches discussed above. We first fix the SM input parameters [1], select three new physics models [2, 3], impose constraints on their parameter spaces from a previous global analysis [3], and select five specific benchmark points in these models. We then compare the transverse momentum spectra of SSM W' bosons in the three theoretical approaches, finding approximate agreement in the relevant kinematic regions, and we also compute the corresponding scale uncertainties. Total cross sections are then presented for all five selected benchmark points within the three theoretical frameworks, without and with interference effects, and including not only scale, but also PDF uncertainties. Finally, we demonstrate, using the example of SSM Z' bosons, that the importance of resummation effects increases with the invariant mass of the decay lepton pair.

3.1 Input parameters

The numerical results in this section are computed for pp collisions at the LHC with a hadronic centre-of-mass energy of $\sqrt{S} = 14\,\text{TeV}$ (LHC14). The PDFs are taken from the MSTW 2008 global fits at LO, NLO and NNLO, respectively, and the corresponding error sets at 68% C.L., following the prescription in eqs. (50)–(52) of ref. [85]. The renormalisation and factorisation scales μ_R and μ_F are identified with the new gauge boson mass $M_{V'}$, varied by a common factor of two up and down to estimate the scale uncertainty. At LO, the strong coupling constant influences only differential cross sections calculated with the PYTHIA PS, so that the corresponding default value is retained. Beyond this order, α_s enters directly and is adopted from the PDG value at NLO and NLL, as are the electromagnetic fine structure constant α and the squared sine of the weak mixing angle θ_W [1], and from the (almost identical) MSTW 2008 global fit value at NNLO [85]. This information is summarised in table 2.

Apart from the SSM with identical fermion couplings of SM and new gauge bosons [2], we study also the so-called G(221) models [3], which are based on the intermediate semi-simple group $\text{SU}(2)_1 \times \text{SU}(2)_2 \times \text{U}(1)_X$ with gauge couplings g_i, $i \in \{1, 2, X\}$. They can be categorised in two classes: (i) Models, in which the first SU(2) subgroup is identified

Theory	PDFs	$\mu_{R,F}$	$\alpha_s(M_Z)$	$\alpha(M_Z)$	$\sin^2\theta_W$
PYTHIA LO+PS	MSTW 2008 LO	$M_{V'}$	0.130	1/128.97	0.23116
FEWZ NLO	MSTW 2008 NLO	$M_{V'}$	0.118	1/128.97	0.23116
FEWZ NNLO	MSTW 2008 NNLO	$M_{V'}$	0.117	1/128.97	0.23116
RESUMMINO LO	MSTW 2008 LO	$M_{V'}$	0.118	1/128.97	0.23116
RESUMMINO NLO	MSTW 2008 NLO	$M_{V'}$	0.118	1/128.97	0.23116
RESUMMINO NLO+NLL	MSTW 2008 NLO	$M_{V'}$	0.118	1/128.97	0.23116

Table 2. PDF and scale choices as well as SM input parameters used in our different theoretical calculations. At LO, the strong coupling constant influences only differential cross sections calculated with the PYTHIA PS, so that the corresponding default value is retained.

with the $SU(2)_L$ of the SM and one breaks $SU(2)_2 \times U(1)_X \to U(1)_Y$ at some high scale u with Higgs doublets or triplets. They include in particular the LR model [9–11], motivated by non-zero neutrino masses and the prospects of parity restoration and the existence of right-handed neutrinos and studied already in part by the ATLAS and CMS collaborations. They also include the LP, HP and FP models [16, 17], irrelevant for the leptonic channels at the LHC studied here. (ii) Models, in which the U(1) subroup is identified with the $U(1)_Y$ of the SM and one breaks $SU(2)_1 \times SU(2)_2 \to SU(2)_L$ with a Higgs bi-doublet, include the Un-Unified (UU) [12, 13] and Non-Universal (NU) [14, 15] models. They are motivated by the large mass hierarchy of the SM fermions, in particular of quarks vs. leptons or of first and second generation vs. third generation fermions, and are accessible in leptonic channels at the LHC. In these models, $M^2_{Z'}/M^2_{W'} = 1 + \mathcal{O}(v^2/u^2)$, where $v = 246\,\text{GeV}$ is the vacuum expectation value (VEV) of the (SM-like) Higgs field of the second stage breaking and one assumes that the first stage Higgs VEV $u^2 \gg v^2$. Apart from u or, equivalently, $M_{V'} = M_{W'} \simeq M_{Z'}$, their second free parameter is the tangent of the mixing angle ϕ at the first breaking stage,

$$t = \tan\phi = \frac{g_2}{g_1}, \tag{3.1}$$

to which the fermionic left-handed Z' and W' boson couplings are, modulo small corrections of $\mathcal{O}(\epsilon \sim \frac{t}{G_F M^2_{V'}})$, proportional or anti-proportional. This implies in particular for the rescaling of the FEWZ predictions that they must be multiplied by a factor t^2 or $1/t^2$.

In figure 1, we have translated perturbativity ($g_i < \sqrt{4\pi}$) as well as the low-energy and electroweak precision constraints obtained in ref. [3] into allowed regions in the physical parameters t and $M_{V'}$. Coupling corrections of $\mathcal{O}(\epsilon)$ are indicated as shaded bands and remain small in the allowed regions. As one can see, these indirect constraints can be quite competitive compared to the direct LHC limits (cf. table 1; note that these have mostly been obtained in the SSM) and amount to $M_{V'} > 2.5\,\text{TeV}$ and $3.6\,\text{TeV}$ in the UU and NU models, respectively.

For our benchmark points, listed in table 3, we therefore choose in all models, including the SSM, a new gauge boson mass of 4 TeV. The allowed ranges in $|t|$ are then $[0.18; 1.2]$ for the UU and $[0.69; 1.47]$ for the NU model. In these ranges, we select two values of t different from one, which would be similar to the SSM. While for the upper values we take

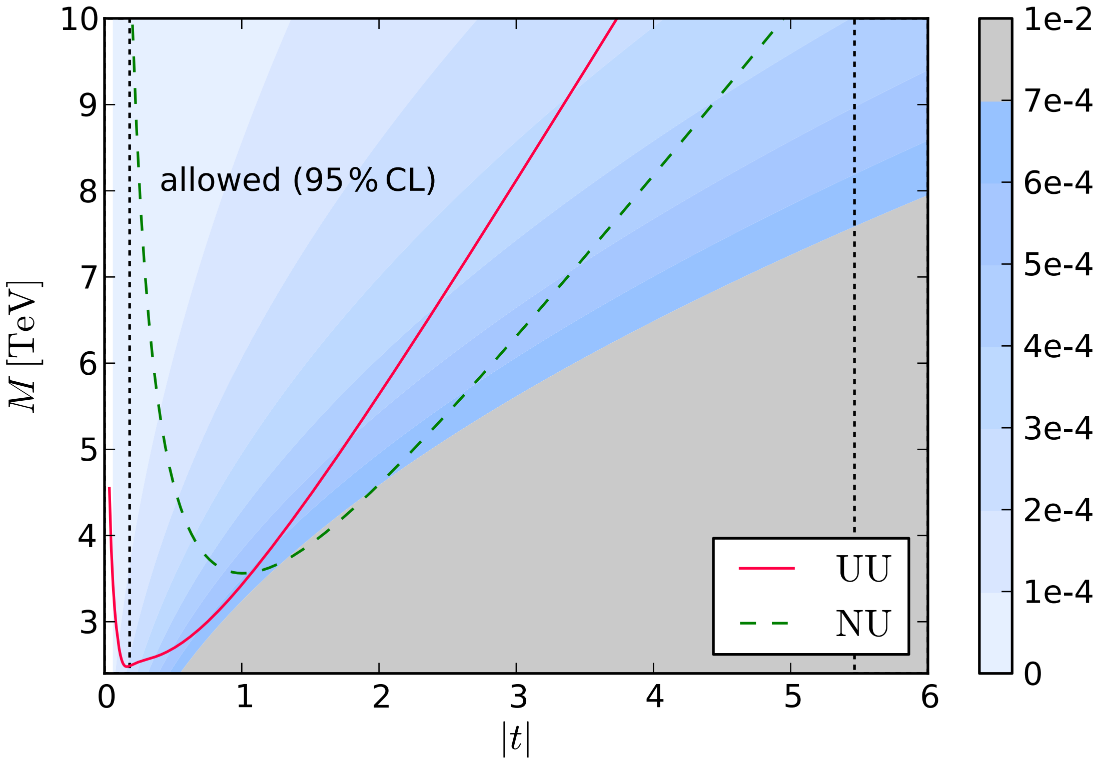

Figure 1. Exclusion limits for left-handed G(221) models. The red (full) and green (dashed) lines represent 95% confidence level contours of allowed regions in the UU and NU models. In regions outside the area bounded by dotted lines at least one of the gauge couplings becomes non-perturbative. Shaded contours represent values of $\epsilon(t, M_{V'})$.

Name	Model	$M_{W'}$ [TeV]	t	$\Gamma_{W'}$ [GeV]	$\Gamma_{W'\to\ell\nu}$ [GeV]
B_1	SSM	4	—	142.85	11.69
B_2	UU	4	0.7	237.15	5.73
B_3	UU	4	1.2	125.35	16.83
B_4	NU	4	0.7	217.80	23.85
B_5	NU	4	1.4	141.82	5.96

Table 3. Definitions of our SSM and G(221) benchmark points and their corresponding total and leptonic decay widths.

(almost) maximal choices, the fact that we limit ourselves for the lower values to 0.7 also in the UU model is due to the observation that below this value the total decay width of the W' boson becomes very large and even comparable to its mass.

3.2 Transverse momentum distributions

At LO of perturbative QCD, weak gauge bosons are produced through the Drell-Yan process with vanishing transverse momentum p_T. This changes at NLO (and beyond), when the p_T of the vector boson can be balanced by one (or more) hadronic jet(s). Due to the incomplete cancellation of soft gluon radiation, the p_T spectrum diverges at fixed

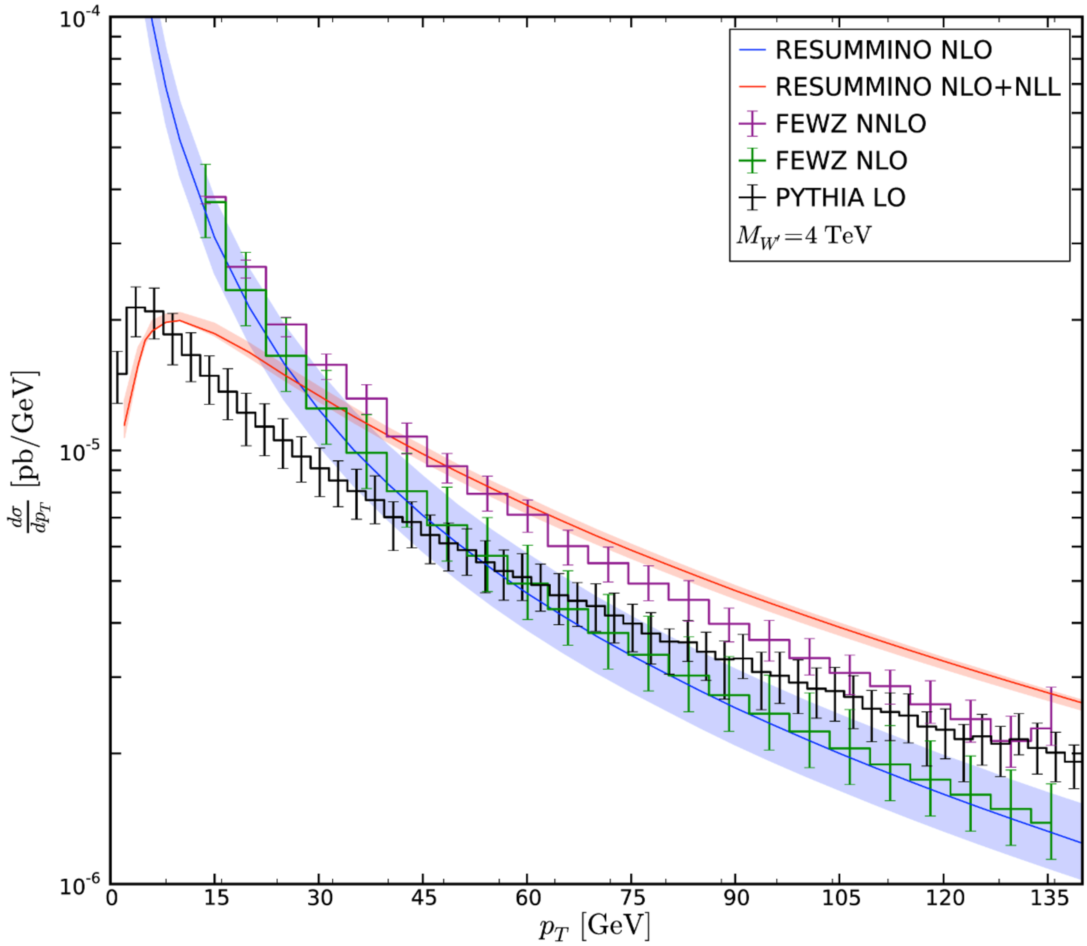

Figure 2. Transverse momentum distributions of W' bosons with a mass of 4 TeV at the LHC14 in the SSM. We compare our NLO and NLO+NLL predictions with RESUMMINO to those obtained with PYTHIA LO+PS, FEWZ NLO and NNLO.

order (see section 2), and only after resummation of the QCD corrections to all orders a finite spectrum is obtained.

This can be observed in figure 2 for positively charged W' bosons of mass 4 TeV produced at LHC14 in the SSM and assumed to decay into a positron and an electron neutrino. In order to enhance the contribution from the new gauge boson and limit the one from the SM W boson as well as interference effects, we have implemented a cut on the invariant mass of the lepton pair of $Q > 3M_{W'}/4$. The NLO predictions obtained with FEWZ and RESUMMINO then agree very nicely, both for their central values and for their scale uncertainties, and both diverge as $p_T \to 0$. In contrast, the LO δ-distribution (not shown) is modified by the PYTHIA PS to a finite distribution, which exhibits a maximum around $p_T \sim 7$ GeV. A similar turnover, with a maximum at slightly larger values of $p_T \sim 10$ GeV, is exhibited by the resummation calculation at NLO+NLL. The difference in shapes can be attributed to different logarithmic accuracies (LL in PYTHIA, NLL in RESUMMINO), while the one in normalisation comes mostly from the different

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Model	RESUMMINO LO	PYTHIA LO	RESUMMINO NLO	FEWZ NLO	RESUMMINO NLO+NLL	FEWZ NNLO
B_1	$1338.6^{-155.5}_{+186.7}$	$1333.0^{+188.9}_{-155.4}$	$1469.2^{+119.7}_{-134.7}$	$1492.9^{+74.7}_{-79.4}\pm^{+127.9}_{-89.2}$	$1411.2^{-88.7}_{-37.2}$	$1509.1^{+25.7}_{-34.5}\pm^{+146.9}_{-92.3}$
B_2	$799.2^{+92.5}_{-111.4}$	$799.6^{+112.2}_{-91.6}$	$874.6^{+73.8}_{-83.9}$	$893.5^{+44.7}_{-47.3}\pm^{+74.9}_{-52.0}$	$843.3^{-47.5}_{-26.0}$	$902.7^{+12.7}_{-18.4}\pm^{+86.5}_{-54.3}$
B_3	$1515.4^{+175.3}_{-213.6}$	$1520.0^{+214.9}_{-176.4}$	$1672.7^{+138.9}_{-156.2}$	$1689.2^{+85.5}_{-90.3}\pm^{+145.2}_{-101.4}$	$1605.7^{-99.7}_{-44.2}$	$1705.1^{+24.2}_{-35.3}\pm^{+168.1}_{-105.7}$
B_4	$3630.9^{+420.3}_{-506.5}$	$3636.9^{+504.5}_{-427.1}$	$3986.9^{+339.9}_{-375.4}$	$4053.5^{+203.3}_{-215.3}\pm^{+341.0}_{-236.9}$	$3841.5^{-214.4}_{-112.1}$	$4094.5^{+57.6}_{-83.7}\pm^{+394.3}_{-247.6}$
B_5	$351.2^{+41.1}_{-49.0}$	$349.6^{+48.9}_{-40.6}$	$385.2^{+31.3}_{-35.7}$	$388.9^{+19.6}_{-20.8}\pm^{+47.8}_{-33.4}$	$369.9^{-23.4}_{-10.2}$	$392.6^{+5.5}_{-8.1}\pm^{+38.5}_{-24.2}$

Table 4. Total cross section predictions for positively charged W' bosons decaying into a positron and a neutrino at LHC14 (in attobarns) for the benchmark points defined in table 3. Interference terms between W and W' gauge bosons and the pure SM contribution are neglected. The invariant mass of the lepton pair is restricted to $Q > 3M_{W'}/4$.

Model	PYTHIA w/o int.	PYTHIA w/ int.	RESUMMINO LO	RESUMMINO NLO	RESUMMINO NLO+NLL
B_1	$1333.0^{+188.9}_{-155.4}$	$1237.7^{+175.4}_{-145.5}$	$1241.7^{+147.6}_{-176.1}$	$1379.5^{+113.4}_{-121.1}$	$1313.3^{-92.3}_{-27.9}$
B_2	$799.6^{+112.2}_{-91.6}$	$953.2^{+128.1}_{-108.6}$	$949.0^{+107.6}_{-129.5}$	$1013.8^{+90.3}_{-105.7}$	$993.1^{-37.7}_{-40.0}$
B_3	$1520.0^{+214.9}_{-176.4}$	$1684.3^{+234.3}_{-194.4}$	$1676.9^{+193.5}_{-233.0}$	$1831.2^{+158.9}_{-177.3}$	$1775.6^{-86.7}_{-57.2}$
B_4	$3636.9^{+504.5}_{-427.1}$	$3418.0^{+478.2}_{-404.0}$	$3419.4^{+398.8}_{-481.6}$	$3781.1^{+318.5}_{-343.2}$	$3618.7^{-228.5}_{-90.3}$
B_5	$349.6^{+48.9}_{-40.6}$	$317.9^{+45.3}_{-37.8}$	$317.9^{+37.6}_{-45.8}$	$351.9^{+29.5}_{-32.9}$	$332.7^{-25.4}_{-9.0}$

Table 5. Same as table 4, but with interference terms now included.

perturbative order (LO in PYTHIA, NLO+NLL in RESUMMINO). At higher p_T values, the NLO+NLL resummation calculation agrees better with the fixed-order one by FEWZ at NNLO than at NLO, indicating that important contributions beyond NLO are captured in the resummation approach. Also the scale errors of these higher-order calculations are then comparable.

3.3 Total cross sections

If we integrate (by eye) over the transverse momentum distribution in figure 2, we see that in the SSM (and similarly in the UU and NU models) one can expect the total cross sections for positively charged W' bosons of mass 4 TeV decaying into positrons and neutrinos to reach about 1 fb at LHC14. This is indeed the case, as one observes in tables 4 and 5 for our five different benchmark points defined in table 3. Since from now on we will only be concerned with total cross sections, we will of course apply only threshold (and not p_T) resummation.

For a more precise comparison, it is first mandatory to remove interference effects from the PYTHIA and RESUMMINO predictions, as these are not implemented in FEWZ. Then, the predictions with comparable accuracy in table 4 can be seen to agree within 1-2 percent for their central values and also, although somewhat less precisely, for their scale errors. First, this is the case for PYTHIA LO, where the PS does not alter the total cross section, FEWZ LO (not shown), and RESUMMINO LO, all computed with MSTW 2008 LO PDFs. Second, this is also the case, although somewhat less precisely due to missing explicit information on the FEWZ renormalisation scheme, for the NLO predictions of RESUMMINO and FEWZ.[3] Finally, the RESUMMINO NLO+NLL predictions are seen

[3]Unfortunately, our attempts to bring the RESUMMINO and FEWZ NLO predictions in agreement with

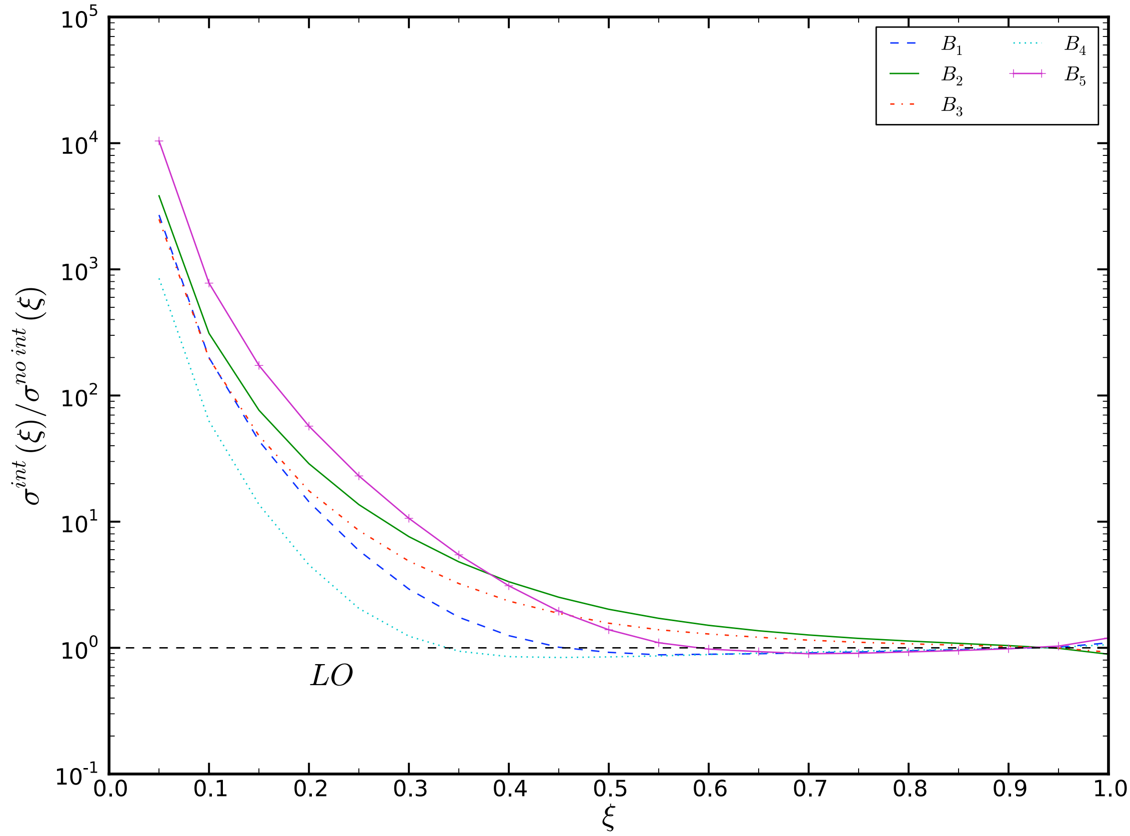

Figure 3. Ratios of the total cross section at LO with and without interference terms as a function of the minimal invariant mass cut $Q > \xi M_{W'}$ for our five benchmark points.

to be stabilised with respect to their NLO central values and scale errors, i.e. the difference from NLO+NLL to NLO is smaller than the one from NLO to LO and the NLO+NLL scale errors are significantly smaller than those at NLO. The FEWZ full NNLO predictions are again somewhat larger. The larger disagreement between RESUMMINO and FEWZ at this level can be traced to the fact that we are not yet close enough to the threshold region, where resummation calculations are most reliable. In the last column, we also give the PDF error computed with FEWZ at NNLO using MSTW 2008 NNLO error PDFs. As one can see, at this precision these errors largely dominate over the scale errors, since they are not only sensitive to higher-order corrections, but also to the experimental errors entering the global fit procedure.

Looking at table 5, we observe that interference effects can quite significantly affect the total cross section predictions despite the invariant mass cut of $Q > 3M_{W'}/4$. Depending on the model and benchmark point, the PYTHIA LO predictions decrease or increase by up to +14% (for B_2) and -17% (for B_5). When interference effects are also included

those of the W' versions of MC@NLO and POWHEG [93] failed after replacing there the default squared scales $\mu_R^2 = \mu_F^2 = ut/s - Q^2$ with our default choice $M_{W'}^2$ and intensive discussions with the authors and despite the fact that inferferences seem to be implemented there correctly.

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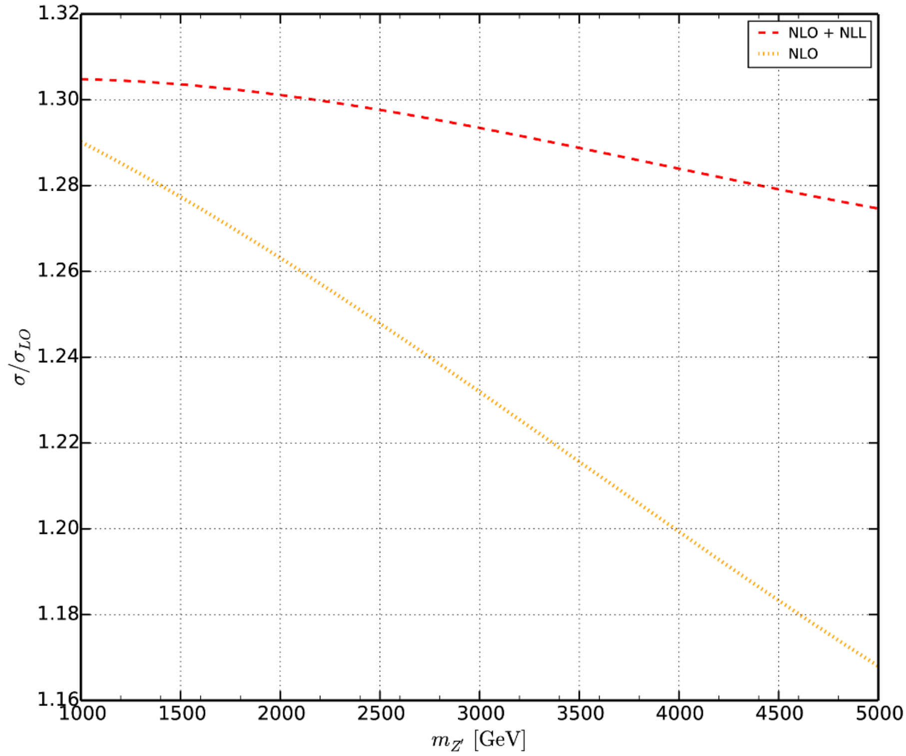

Figure 4. Ratios of Z' production cross sections at LHC14 at NLO and NLO+NLL over the LO cross section in the SSM and as a function of the heavy gauge boson mass.

in RESUMMINO, the agreement with PYTHIA at LO is nevertheless as good as before. Again, a significant increase in total cross section at NLO is followed by a stabilisation at NLO+NLL, both in the central value and in the reduction of the scale error.

Let us investigate somewhat further the effect of the invariant mass cut on the importance of interference contributions. As one can see in figure 3, these become quickly dominant as the invariant mass cut falls below 50%. This will become important in section 4, when we reanalyse the latest ATLAS and CMS results on W' and Z' boson production. But note that even for a cut of 75% as we employ here, the interference terms can still modify the total cross section prediction by almost 20% as we have also observed above. Depending on the model and the applied cut, the change can be both positive and negative.

To end this section, we study in figure 4 the dependence of the resummation contributions on the new gauge boson mass, using now the example of a neutral Z' gauge boson produced at LHC14. Since we show the ratios of NLO and NLO+NLL cross sections over the LO one, the decay channel is not relevant. As usual, the NLO QCD corrections to the total cross section are quite important. For the Z' boson masses considered here, they amount to 29-17%, i.e. seem to decrease with increasing mass. A look at the NLO+NLL prediction shows that as one approaches the threshold region the resummation of loga-

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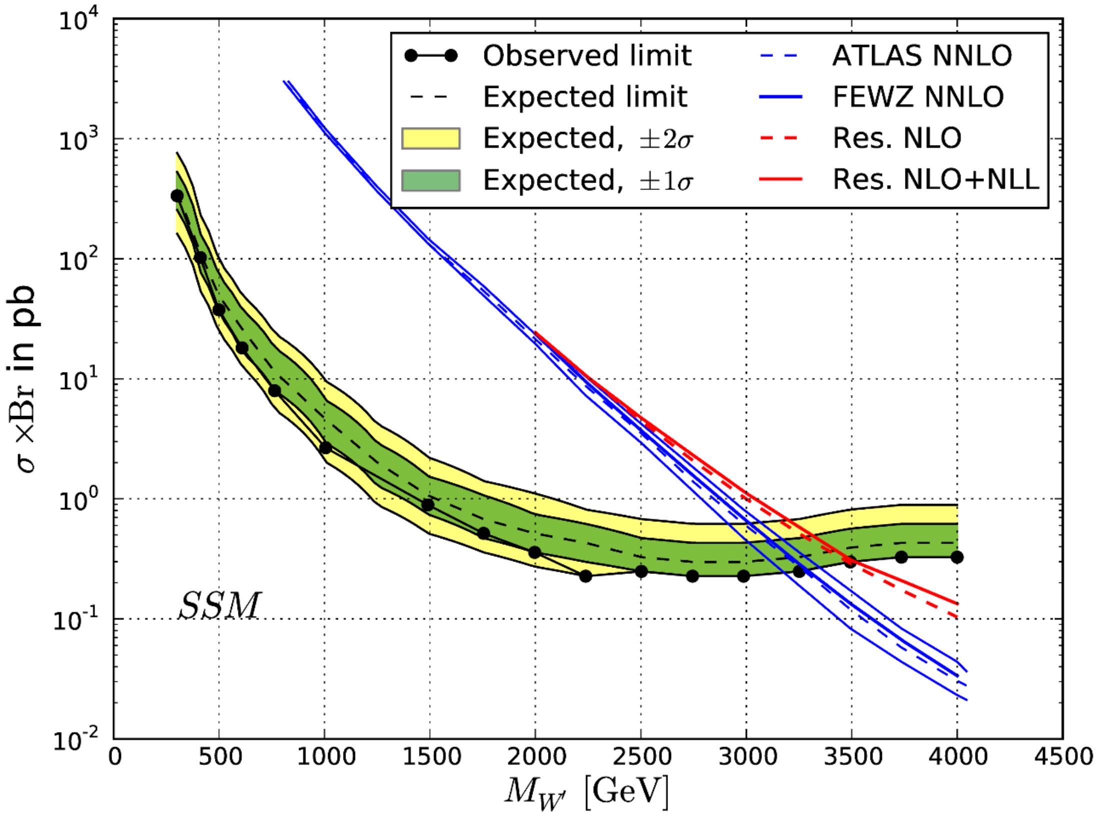

Figure 5. Cross sections times branching ratios for SSM W' bosons decaying into electrons or muons and neutrinos at LHC8. The limits expected (dashed black) and observed (full black) in the preliminary ATLAS analysis [21], using a cut of $Q > 0.4M_{W'}$ at the generator level, and their corresponding uncertainties at the 1σ (green) and 2σ (yellow) level are compared to predictions without interference at NNLO in ZWPROD (with the dominating PDF uncertainties, dashed blue) and in FEWZ (central only, full blue) and with interference at NLO (central only, dashed red) and at NLO+NLL (central only, full red) using RESUMMINO.

rithms becomes increasingly important, i.e. the QCD corrections remain at a similar level of about 28% even in the high mass region. Therefore our resummation calculations will become even more relevant as the LHC explores higher and higher mass regions.

4 Gauge boson mass limits in general SM extensions

In this section, we reanalyse the latest experimental searches by the ATLAS and CMS collaborations for W' and Z' bosons in their leptonic decay channels, performed at LHC8 in the SSM. We use our resummation predictions at NLO+NLL and do this not only in the SSM, but also in the UU and NU models that have previously not been considered.

4.1 ATLAS limits on W' boson masses

The preliminary ATLAS limit of $M_{W'} > 3.27$ TeV [21] in the SSM is almost identical to the corresponding CMS limit of 3.28 TeV [47]. In their preliminary analysis, the ATLAS collaboration employ an invariant mass cut of $Q > 0.4M_{W'}$ at the generator level, which we can directly implement in our theoretical predictions with RESUMMINO, in contrast to a minimal cut on the missing transverse mass. This minimal cut is the distinctive variable in the final ATLAS [22] and CMS [47] analyses, where the former led to $M_{W'} > 3.24$ TeV, i.e. again almost identical to the preliminary ATLAS result. This similarity can be traced to the fact that the invariant mass cut mimicks very well the other experimental cuts; in particular, practically no signal cross section is lost. We can therefore be confident that our reanalysis of the preliminary ATLAS results also holds with very good accuracy for the published ATLAS results.

Both the preliminary and final ATLAS analyses are performed by simulating the W' signal with PYTHIA LO+PS, adding negative and positive charges, and rescaling it to NNLO total cross section accuracy with ZWPROD [94]. This means, however, that interference effects between SM W bosons and SSM W' bosons are not included. As one can see by comparing the original ATLAS NNLO prediction with ZWPROD (dashed blue curve) to ours with FEWZ (full blue curve) in figure 5, they are basically identical, validating our re-analysis for settings identical to those in the ATLAS analysis. The theoretical error (blue band), dominated at NNLO by the PDF uncertainties as parameterised in the MSTW 2008 NNLO error sets at 68% C.L., increases with the mass of the W' boson to about ±30% at $M_{W'} = 4$ TeV. Looking at the RESUMMINO predictions that include interference effects, these are seen to be very important, since the invariant mass cut is relatively low (cf. figure 3), and they lead to an increase of $\sigma \times \mathrm{Br}$ of about a factor of two at the highest mass considered here. There, the resummation effects are also best visible, and they increase the NLO prediction (dashed red) by about 20% at NLO+NLL (full red). Note that these numbers can not be directly compared to those in tables 4 and 5, where the invariant mass cut was $Q > 3M_{W'}/4$. In the SSM, we can then exclude W' bosons with masses below 3.5 TeV.

The results for the UU model are presented in figure 6. There, the expected and observed ATLAS limits are first compared to FEWZ NNLO (blue) results without interference. For each W' boson mass, the variation of the t parameter in the allowed range (see figure 1) leads to a spread of theoretical predictions. This is reflected in the shown areas, which basically overlap for FEWZ NNLO and RESUMMINO NLO+NLL (not shown). Note, however, that part of these areas correspond to values of t below 0.7, where the W' width in the UU model becomes very large. The inclusion of interference effects in RESUMMINO leads to an increase of the predicted cross sections by almost an order of magnitude at $M_{W'} = 4$ TeV. There, the predictions at NLO (light red) are increased by less than 20% at NLO+NLL (dark red). Below masses of 2.5 TeV, where the UU model is already excluded by low-energy and precision constraints [3], the areas have been shrunk to a single line, calculated for a hypothetical t-value of 0.18 pertinent at the same time to the minimal allowed mass and the perturbativity limit. At NLO+NLL and including interference

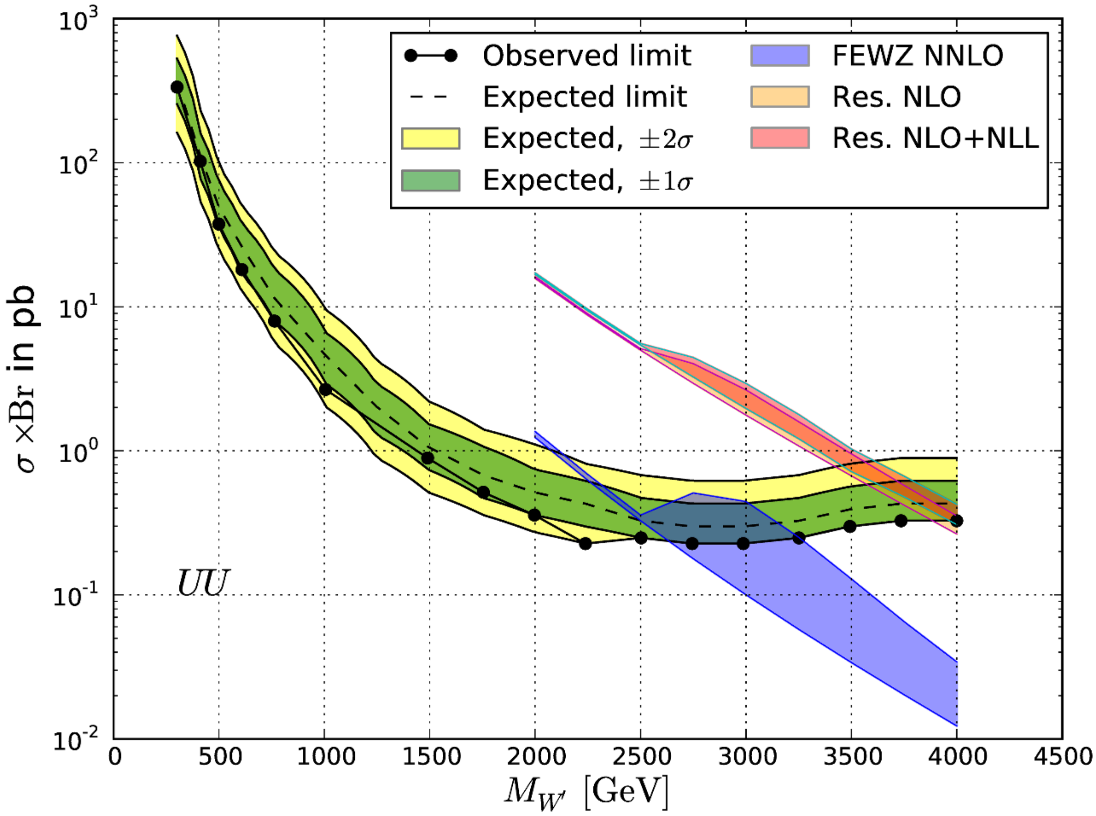

Figure 6. Same as figure 5 for UU model W' bosons.

effects, our reanalysis excludes W' bosons in the UU model with masses below 3.9-4 TeV, which considerably improves the limits from low-energy and precision constraints. As in this model $M_{Z'} \simeq M_{W'}$ up to corrections of $\mathcal{O}(v^2/u^2)$, this implies an identical mass limit for Z' bosons in the UU model.

Our analysis in the NU model is shown in figure 7. Without interference, the FEWZ NNLO (blue) and RESUMMINO NLO+NLL (not shown) results agree again, i.e. the regions spanned by the allowed t values above the minimal mass of 3.6 TeV overlap. Inteference effects increase the predicted cross sections by about a factor of two in the high mass region, while the NLO+NLL results (dark red) are about 20% larger than the NLO results (light red), both computed with RESUMMINO. In this case, the ATLAS data do not improve on the low-energy and precision constraints, but only lead to a slightly weaker exclusion bound of W' bosons in the NU model of about 3.5 TeV. As above, the same limit applies also to Z' boson masses in the NU model.

4.2 CMS limits on Z' boson masses

The CMS collaboration have searched for narrow resonances in the dilepton (electron or muon) mass spectrum and set mass limits of 2.96 TeV and 2.6 TeV on SSM Z' bosons and a specific class of superstring-inspired Z' bosons, respectively [61]. The final ATLAS SSM

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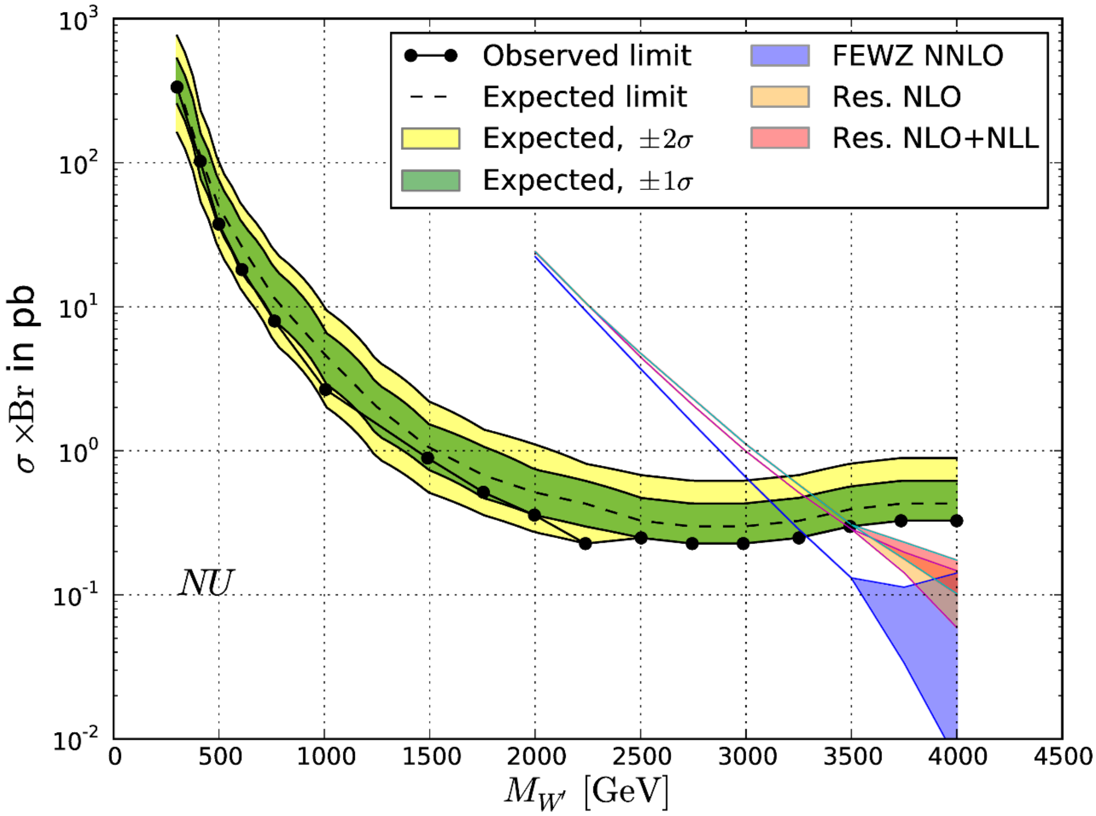

Figure 7. Same as figure 5 for NU model W' bosons.

limit of 2.90 TeV is only slightly weaker [35]. While the ATLAS collaboration set limits directly on the new gauge boson production cross section times branching ratio, $\sigma \times$Br, the CMS collaboration set limits on the ratio R_σ of this quantity for the Z'-boson to the one for the SM Z-Boson.

The mass limits are obtained by comparing expected and observed experimental limits on R_σ with expectations from PYTHIA LO+PS, rescaled to NNLO with ZWPROD. For the SSM, we show the result in figure 8, where one can read off the limit cited above. While interferences between the Z' boson and SM contributions are not included in the numerator, those of SM Z bosons and photons have been included in the denominator of this ratio, as we have verified by comparing with FEWZ at NNLO. Adding the interferences also in the numerator leads to a considerable increase of the prediction, computed by us with RESUMMINO at NLO+NLL, so that the SSM exclusion limit moves to 3.2 TeV.

For Z' bosons in the UU model, we simulate in figure 9 the ratio R_σ without interference in the numerator using RESUMMINO at NLO accuracy (blue area). Interference effects then increase again the prediction (light red) by about an order of magnitude, while the additional radiative corrections at NLO+NLL (dark red) do not alter the result significantly. This is very likely due to the fact that these corrections affect both the numerator and the denominator in a similar way. In the UU model, we then obtain Z' boson mass

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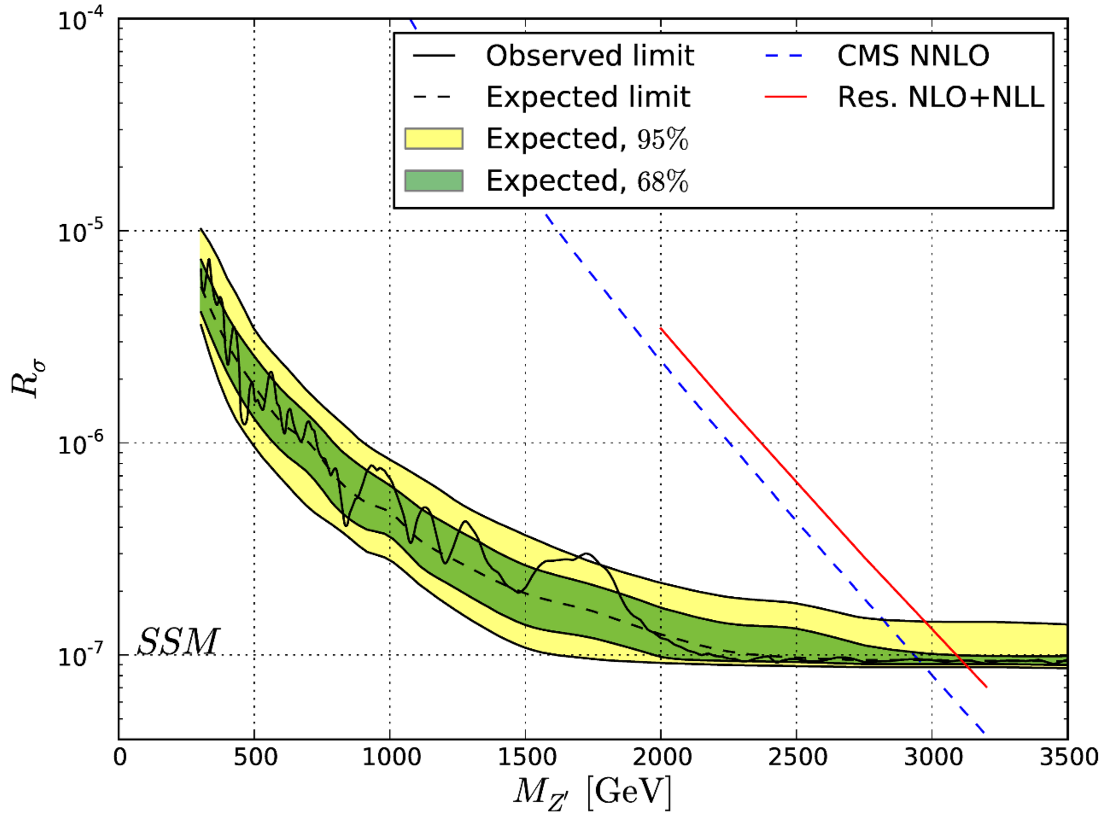

Figure 8. Ratios of new physics over SM cross sections for SSM Z' bosons decaying into electron or muon pairs at LHC8. The limits expected (dashed black) and observed (full black) in the final CMS analysis [61], using a cut of $0.6M_{Z'} < Q < 1.4M_{Z'}$, and their corresponding uncertainties at the 68% (green) and 95% (yellow) C.L. are compared to predictions without photon, Z and Z' interference at NNLO in ZWPROD (dashed blue) and with full interference at NLO+NLL (full red) using RESUMMINO.

limits ranging from 2.75 TeV up to 3.2 TeV, depending on the chosen value of the parameter t. These are in all cases stronger than the previously obtained indirect limit of 2.5 TeV.

For NU model Z' bosons, shown in figure 10, the interference effect is somewhat less pronounced, but still clearly visible, while radiative effects are again relatively small in the ratio R_σ. Similarly to our reanalysis of the ATLAS W' search, we can only set a lower mass limit of 3.25 TeV, which does not exceed the one of 3.6 TeV obtained from precision measurements and at lower energy.

5 Conclusion

In this paper, we have presented resummation calculations at NLO+NLL accuracy for the production of leptonically decaying W' and Z' bosons in hadronic collisions at small transverse momenta and/or close to production threshold. Our calculations include the full interference structure of new and SM gauge bosons, which is unfortunately missing

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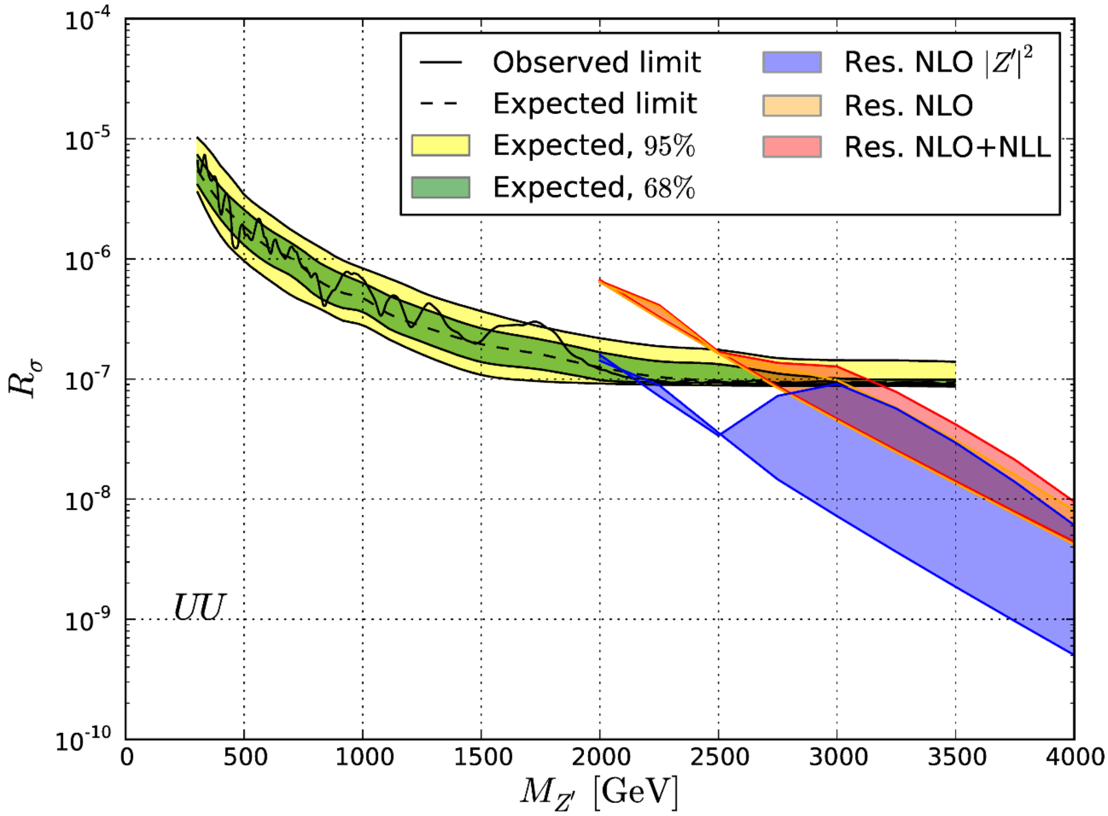

Figure 9. Same as figure 8 for UU model Z' bosons.

from full NNLO calculations. They therefore currently provide the best available theoretical precision for realistic cross section estimates. To facilitate a comparison with LO+PS calculations, we furthermore implemented interference effects in PYTHIA by adding a new $2 \to 2$ process, i.e. without relying on resonant production or the narrow width approximation.

We demonstrated that in the SSM the PYTHIA transverse momentum spectrum of W' bosons with a mass of 4 TeV agrees qualitatively with our resummation calculations at low p_T, whereas at intermediate p_T the resummed predictions lie close to those at NNLO, showing that a substantial fraction of higher-order corrections is captured by the resummation procedure.

The total cross sections were shown to be stabilised at NLO+NLL compared to the NLO predictions with respect to variations of the renormalisation and factorisation scales, so that the theoretical error became dominated for large masses by the PDF uncertainties. Full agreement could be found at LO with PYTHIA and at NLO with FEWZ — albeit only without interference. The interference effects were shown to depend strongly on the minimal cut on the invariant mass of the lepton pair, and the resummation contributions were shown to become increasingly important with the new gauge boson mass.

We did not restrict our analysis to the SSM, but generalised it to G(221) models with an extended gauge group that could be realised at intermediate scales. In particular,

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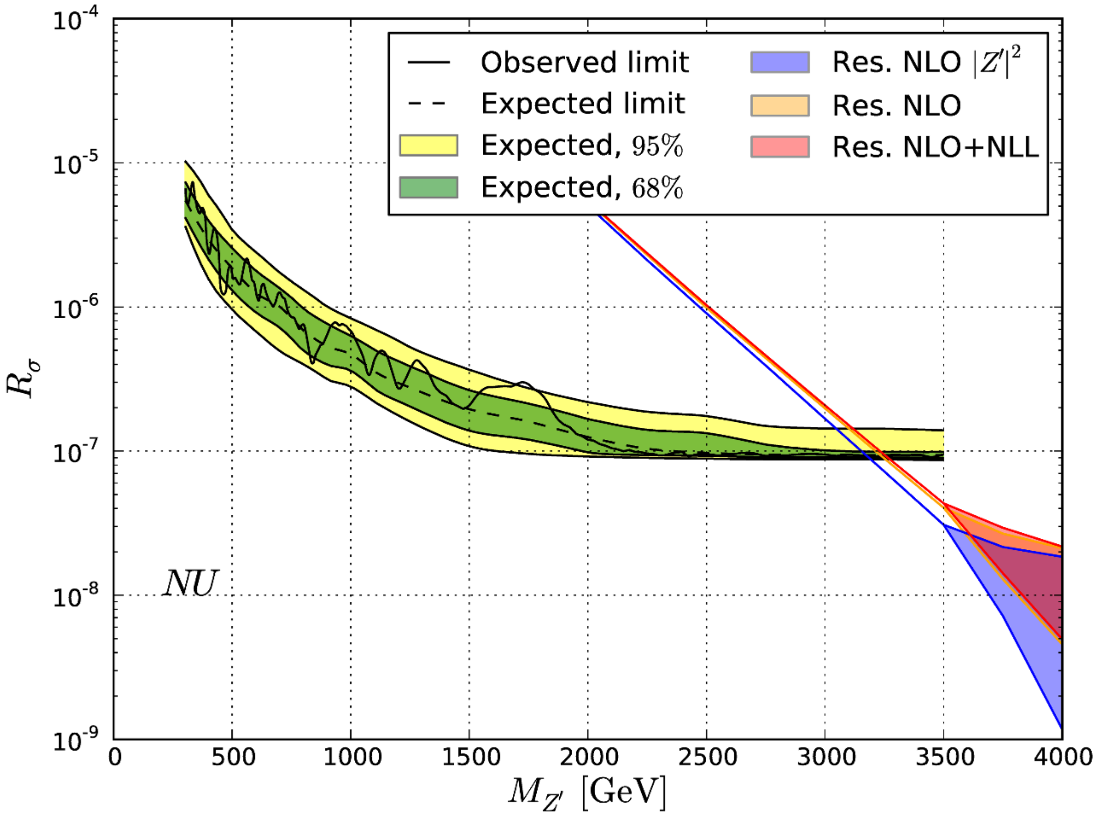

Figure 10. Same as figure 8 for NU model Z' bosons.

through a reanalysis of the currently strongest ATLAS exclusion limits of W' boson masses in the SSM, we showed that W' boson masses could be excluded below 3.9-4 TeV in the UU model, while the limit of 3.5 TeV in the NU model turned out to be slightly weaker than the existing low-energy and precision limit of 3.6 TeV. Similarly, a reanalysis of the currently strongest CMS exclusion limits of Z' boson masses in the SSM led to exclusion limits of 2.75-3.2 TeV and 3.25 TeV, which were again stronger in the UU model and slightly weaker in the NU model than the low-energy and precision constraints of 2.5 and 3.6 TeV, respectively. For convenience, our final results in the SSM, UU and NU models for the old and our new W' and Z' boson mass limits have been collected in table 6.

Note added. While in general not much attention has been paid to G(221) models, the NU model has recently been studied in ref. [95]. Simulations with standard PYTHIA6.4 (i.e. at LO+PS and without interferences) of $\ell\ell$, jj, $\tau\tau$ and tt final states for Z'-bosons and of $\ell\nu$ for W'-bosons have been compared to ATLAS and CMS data, resulting in mass limits of 2 TeV in both cases. These are considerably weaker than our limits, which turned out to be almost as strong as those obtained from low-energy and precision measurements.

Model	New gauge boson	Previous mass limit [TeV]	New mass limit [TeV]
SSM	W'	3.27-3.28	3.5
SSM	Z'	2.90-2.96	3.2
UU	W'	2.48	3.9-4.0
UU	Z'	2.48	2.8-3.2
NU	W'	3.56	(3.5)
NU	Z'	3.56	(3.3)

Table 6. Previously obtained exclusion limits, using ATLAS [21, 35] and CMS data [47, 61] for the SSM as well as low-energy and precision data for the UU and NU models [3], and new exclusion limits, including all interference effects and NLO+NLL corrections, for W' and Z' gauge bosons.

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