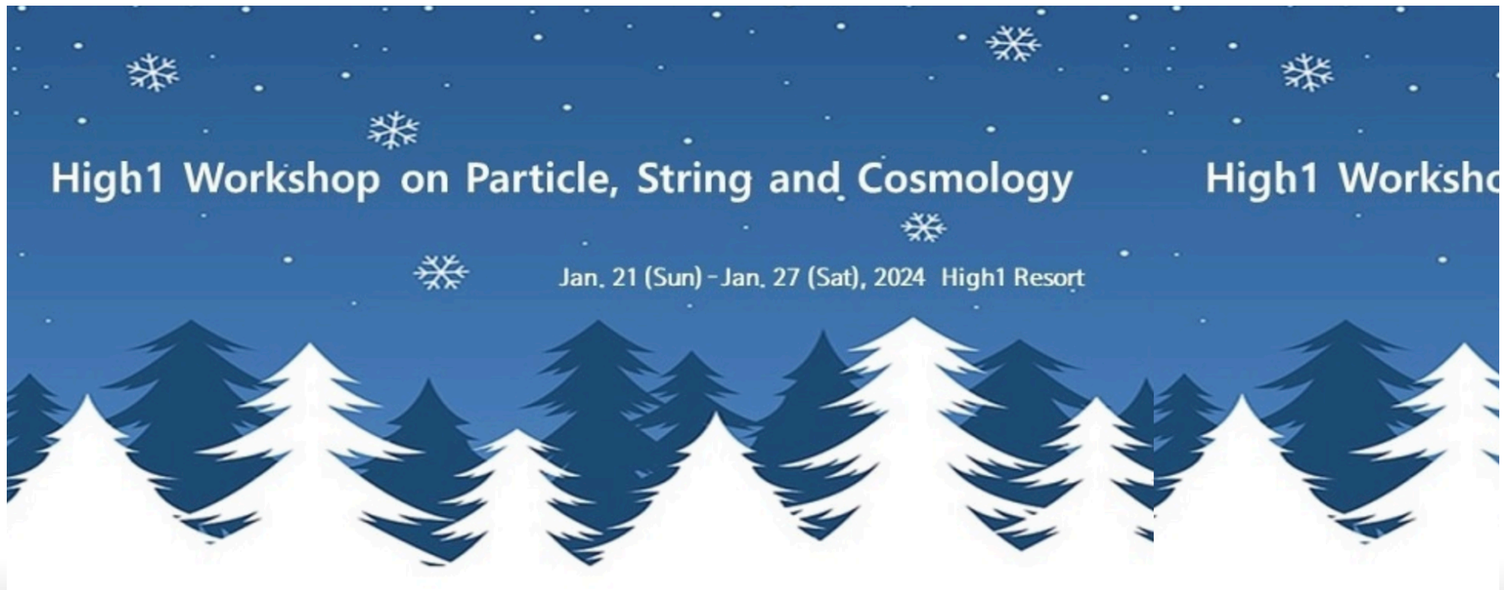
Right-handed charged gauge bosons at the Large Hadron Collider



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High1 Workshop
25 January 2024

Based on 2312.08521

w/ Mariana Frank, Benjamin Fuks, Stefano Moretti, and Ozer Ozdal

1. Introduction

Parity violation in the Standard Model

- The weak sector of the SM maximally breaks the parity symmetry.
- This feature does not exist in electromagnetic, gravitational or strong interactions.
- For W-boson decays, only right-handed antineutrinos or left-handed neutrinos are produced.

$\Longrightarrow$ Left-handed and right-handed fermions transform differently under the SM gauge group.

$\Longrightarrow$ Neutrinos are naturally massless in the Standard (NOT OK with experimental data).

New physics beyond the SM may shed some lights on parity violation.

2. Model

The minimal left-right symmetric model

- The minimal left-right symmetric model (mLRSM) extends the SM gauge group by another $SU(2)_R$

  G. Senjanović, R. N. Mohapatra, PRD 12 (1975); G. Senjanović, PRL 44 (1980)

- The resulting gauge group is $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

  (See V. Tello, 2012; J. Chakrabottry et al., PRD 89 (2014) 9; A. Maeizza et al., PRD 94 (2016) 3 for more details)

  $\Longrightarrow$ Matter fields: q_L, q_R, ℓ_L, ℓ_R

  $\Longrightarrow$ There are five gauge bosons: $W^{\pm}_{L,R}$, $Z^0_{L,R}$ and γ

  $\Longrightarrow$ Gauge couplings are denoted by g_L, g_R, g_{B-L}

- At the scale of mLRSM, parity is conserved $\Longrightarrow$ the Lagrangian is invariant under the following symmetry: $\{W_R, f_R\} \longleftrightarrow \{W_L, f_L\} \implies g_L = g_R \equiv g$

[1]There is a possibility to use the charge symmetry instead of parity. Here, the Lagrangian is invariant under $\{W_R, f_R\} \longleftrightarrow \{W_L^{\dagger}, f_L^c\}$

mLRSM: Symmetry breaking

Minimum three scalar multiplets are required to achieve electroweak symmetry breaking

$$\Phi \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}_{(\mathbf{2},\mathbf{2},0)} \qquad \Delta_L \equiv \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \delta_L^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}_{(\mathbf{3},\mathbf{1},2)} \qquad \Delta_R \equiv \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \delta_R^0 & -\frac{\delta_R^+}{\sqrt{2}} \end{pmatrix}_{(\mathbf{1},\mathbf{3},2)}$$

The symmetry breaking of the mLRSM is done in two stages:

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \xrightarrow[\langle \Delta_R \rangle]{} SU(2)_L \otimes U(1)_Y \xrightarrow[\langle \Delta_L \rangle]{\langle \Phi \rangle} U(1)_{\text{em}}$$

$$\langle \Phi \rangle \equiv \text{diag}\left(v_1, \ -v_2 e^{-i\alpha}\right) \quad \langle \Delta_{L,R} \rangle \equiv v_{L,R}$$

$$v \equiv \sqrt{v_1^2 + v_2^2} \ \textbf{(same as the 2HDM)}$$

Experimental data $\Longrightarrow v_L \ll v \ll v_R$

$$M_{W_L}^2 \approx \frac{1}{2} g v^2 \qquad M_{W_R}^2 \approx g v_R^2$$

mLRSM: Neutrino mass

- **Neutrino mass through Seesaw mechanism**

  G. Senjanović, V. Tello, PRL 119 (2017), PRD 100 (2019)

$$M_\nu = \frac{v_L}{v_R} U_e^T M_N^* U_e - M_D^T \frac{1}{M_N} M_D$$

- **The mLRSM connects the high-energy (M_N) and low-energy (M_ν) sectors.**

- **Such correlations can be disentangled using various phenomena: lepton-flavor violation and lepton-number violation for example.**

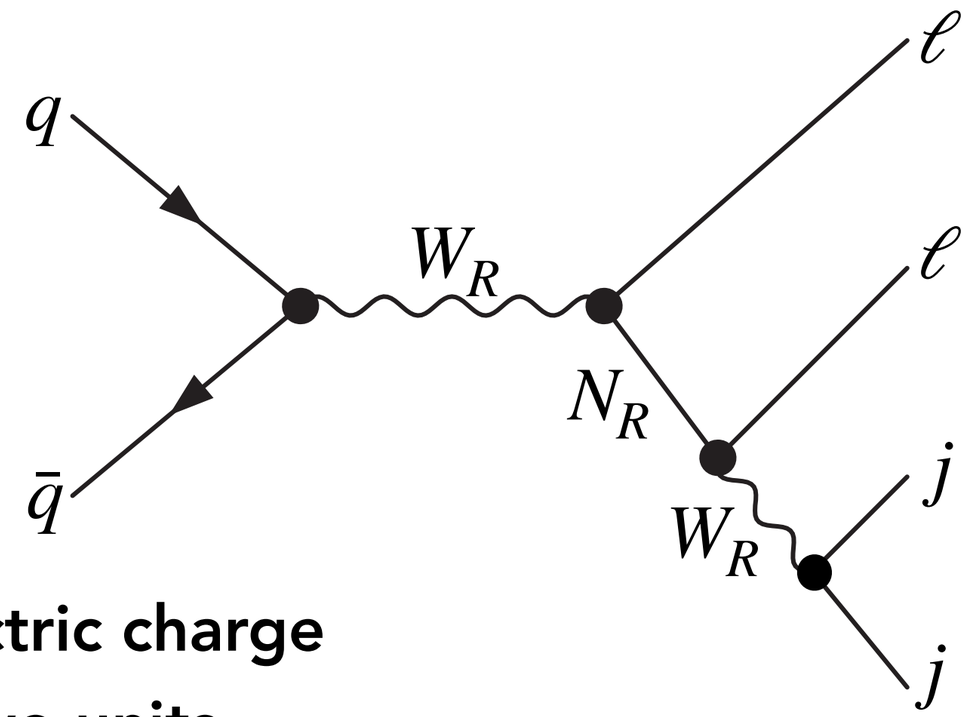
- **Since neutrinos are Majorana particles $\Longrightarrow$ breaks lepton number by two units $\Longrightarrow$ Neutrinoless double beta decays ($0\nu\beta\beta$) $\Longrightarrow$ Keung-Senjanovic process at hadron colliders.**

The Keung-Senjanovic process

- Smoking gun for the production of W_R and N_R in the mLRSMs

  W. Y. Keung and G. Senjanovic, PRL 50 (1983)

- Produce a W_R (on-shell or off-shell) through a Drell-Yan type process. The W_R subsequently decays into a charged lepton (ℓ) and N_R which undergoes the three-body decay: $N_R \to \ell jj$ (j is a jet initiated from a light quark).



- If the two charged leptons have the same electric charge $\Longrightarrow$ this process violates lepton number by two units.

High-energy analog of $0\nu\beta\beta$

3. Bounds

Low-energy bounds

- **Lepton flavour violation**

  V. Cirigliano et al. PRD 70 (2004)

- **Electroweak Precision Observables**

  K. Ksieh et al., PRD 82 (2010); V. Bernard et al., JHEP 09 (2020) 088

- $B^0 - \bar{B}^0$ **and** $K^0 - \bar{K}^0$ **oscillations and** $(\varepsilon'/\varepsilon)$

  S. Bertolini et al., PRD 89 (2014), A. Maeizza et al. PRD 82 (2010), Y. Zhang et al., NPB 802

- **Electric Dipole Moments (EDMs)**

  F. Xu et al., *JHEP* 03 (2010) 088, M. Ramsey-Musolf et al., *PLB* 815 (2021)

- $0\nu\beta\beta$ **decays**

  V. Cirigliano et al., JHEP 12 (2018).

A comprehensive global analysis using low-energy data has been done by W. Dekens et al., JHEP 11 (2021) 127

LHC searches of W_R bosons

- $pp \to W_R X \to \ell N_R\ (E_T^{\rm miss}) + X$:
  ATLAS ($M_{W_R} > 6$ TeV) **and CMS** ($M_{W_R} > 5.7$ TeV)

- $pp \to W_R \to \ell N_R \to \ell\ell jj$:
  ATLAS ($M_{W_R} > 3.8 - 5$ TeV) **and CMS** ($M_{W_R} > 4.7 - 5$ TeV)

- $pp \to W_R \to W_L H,\ \ pp \to W_R \to Z_L W_L$:
  $M_{W_R} > 3.9$ TeV

- $pp \to W' \to tb$:
  $M_{W'} > 4.4$ TeV

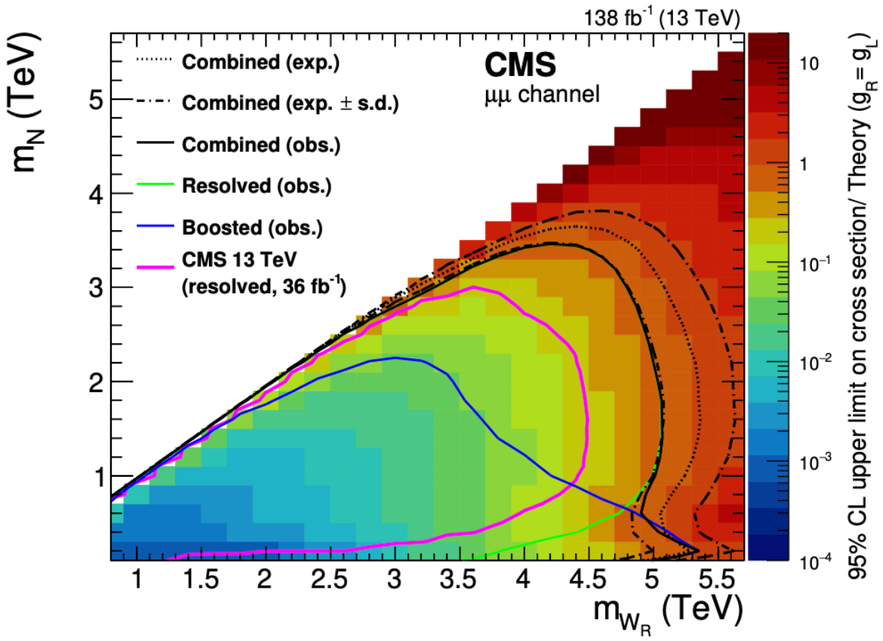
Reinterpretation of the CMS search of W_R

- Main focus for this study is on the search of W_R through the Keung-Senjanovic process

$$pp \rightarrow W_R \rightarrow N_R\,(\rightarrow \ell jj)\;\ell \quad (\ell = e, \mu)$$ CMS, JHEP 04 (2022) 047

- The final state consists of two charged leptons (SF) and two jets with large transverse momentum. Bounds on M_{W_R} depends on the channel (electron or muon) and the mass splitting ($\Delta \equiv M_{W_R} - M_{N_R}$)

- The CMS search used theory calculations at Leading Order and applied global K-factors — M. Mitra et al., PRD 94 (2016) —.
- We do not extract the bounds from official CMS result but we perform our own reinterpretation of the search in MadAnalysis 5.
- Bounds are estimated with theory predictions at Next-to-Leading Order (NLO) in QCD.



CMS, JHEP 04 (2022) 047

Reinterpretation of the CMS search of W_R

Validation

- **Our analysis is validated against the official results published by CMS on HepData (https://www.hepdata.net/record/ins1986733) for six benchmark points in both the electron and muon channels (More details can be found in 2312.08521).**

	CMS		MadAnalysis		
$\{M_{W_R}, M_{N_R}\} = (3000, 1400)$ GeV	Events	ε	Events	ε	δ [%]
Initial	1175.4	-	1174.4	-	-
$N_\ell \geq 2$ with $p_T^\ell > 60$ (53) GeV	379.5	0.323	363.5 ± 3.0	0.309	4.1
≥ 2 AK4 jets with $p_T > 40$ GeV	363.1	0.957	363.0 ± 3.0	0.999	4.4
$\Delta R > 0.4$ between all pairs of objects	355.4	0.979	363.0 ± 3.0	1.000	2.2
$m_{\ell\ell} > 200$ GeV	335.6	0.944	358.3 ± 3.0	0.987	4.5
$m_{\ell\ell jj} > 800$ GeV	335.6	1.000	357.1 ± 3.0	0.997	0.3
$m_{\ell\ell} > 400$ GeV	324.1	0.966	339.5 ± 2.9	0.951	1.6

ee

	CMS		MadAnalysis		
$\{M_{W_R}, M_{N_R}\} = (3000, 1400)$ GeV	Events	ε	Events	ε	δ [%]
Initial	586.6	-	587.2	-	-
$N_\ell \geq 2$ with $p_T^\ell > 60$ (53) GeV	494.5	0.843	498.6 ± 1.9	0.849	0.7
≥ 2 AK4 jets with $p_T > 40$ GeV	473.2	0.957	450.6 ± 2.2	0.904	5.6
$\Delta R > 0.4$ between all pairs of objects	443.1	0.936	450.6 ± 2.2	1.000	6.8
$m_{\ell\ell} > 200$ GeV	420.8	0.950	447.3 ± 2.2	0.993	4.5
$m_{\ell\ell jj} > 800$ GeV	420.7	1.000	447.2 ± 2.2	1.000	0.0
$m_{\ell\ell} > 400$ GeV	407.3	0.968	431.6 ± 2.2	0.965	0.3

$\mu\mu$

Implementation of a search for right-handed W-boson and heavy neutrino in the dilepton+dijet channel (138 fb-1; 13 TeV; CMS-EXO-20-002)

Version 1.1

Jueid, Adil; Fuks, Benjamin, 2023, "Implementation of a search for right-handed W-boson and heavy neutrino in the dilepton+dijet channel (138 fb-1; 13 TeV; CMS-EXO-20-002)", https://doi.org/10.14428/DVN/UMGIDL, Open Data @ UCLouvain, V1

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Keung-Senjanovic process: the role of precision

- The results were shown for the process with signal events simulated at LO in QCD.
  $\Longrightarrow$ Large uncertainties due to scale variations.
  $\Longrightarrow$ Poor PDF fits at LO may imply unstable results for heavy W_R.
- Differences with respect to LO when considering NLO calculations
  $\Longrightarrow$ Smaller uncertainties due to scale and PDF variations.
  $\Longrightarrow$ Better agreement between the different PDF sets

C. Borchensky et al., JHEP 11 (2022) 006, C. Borchensky et al., JHEP 02 (2022) 157.

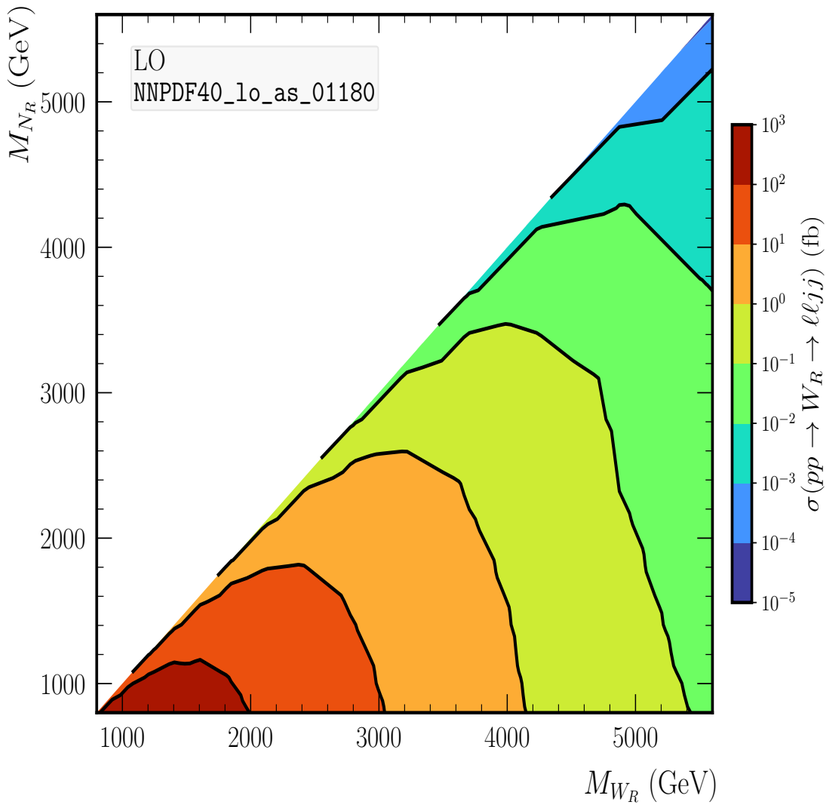
$\Longrightarrow$ Nontrivial impact on the kinematic distributions of the physical objects.

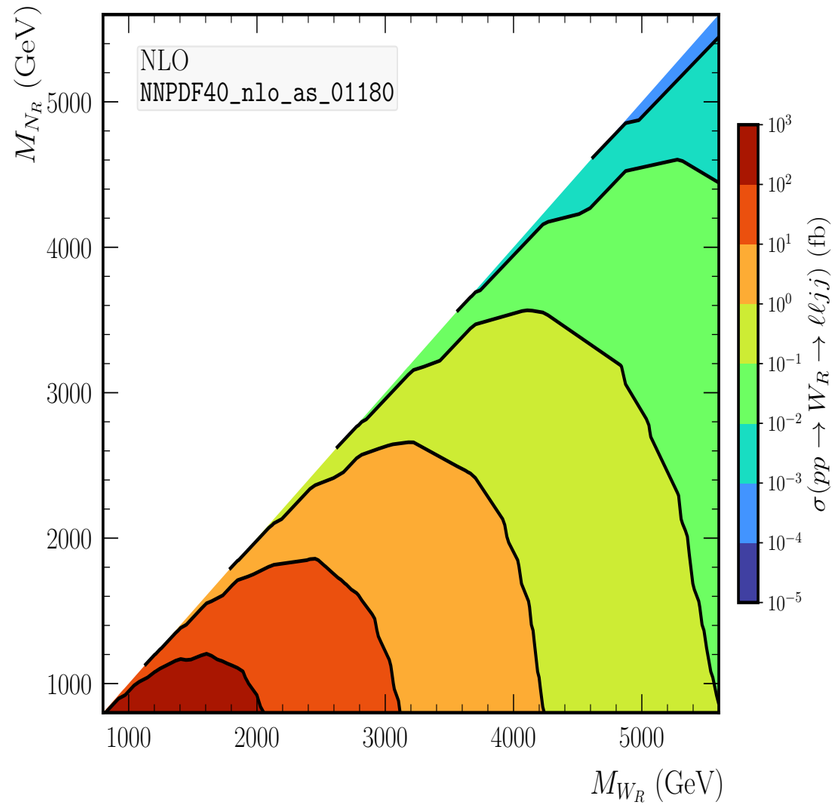
- Since we consider the regime where $M_{N_R} \leq M_{W_R}$, we can factorise the whole process into a production part and a decay part, i.e.

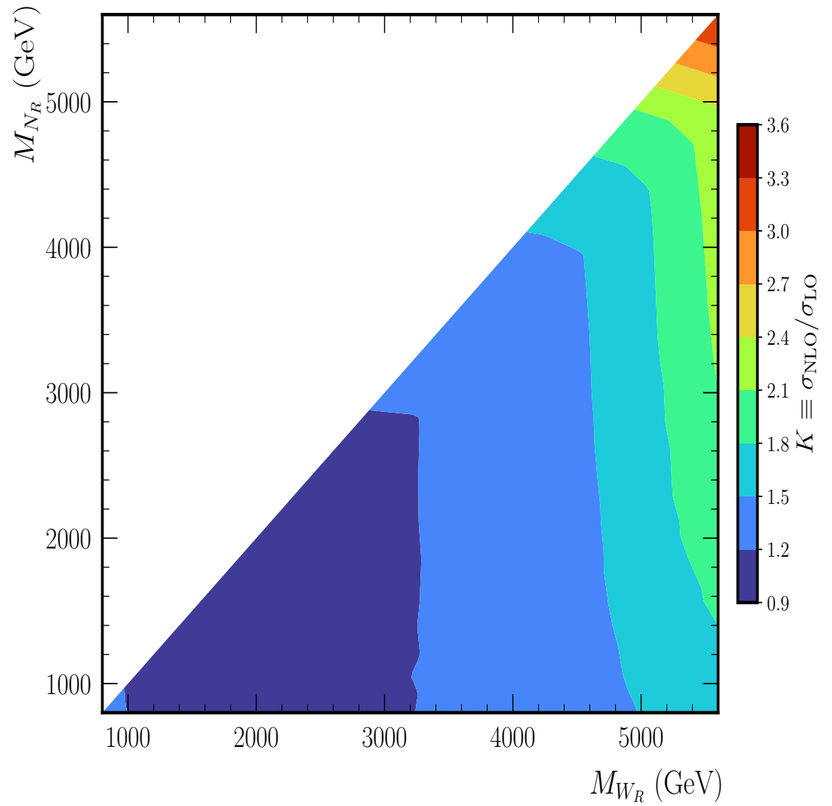
$$\sigma(pp \to \ell\ell jj)^{\mathrm{NLO}} \equiv \sigma(pp \to N_R \ell)^{\mathrm{NLO}} \times \mathrm{BR}(N_R \to \ell jj)^{\mathrm{LO}}$$

Valid since $\Gamma_{N_R} < \mathcal{O}(10)$ MeV

The Keung-Senjanovic process: the role of precision



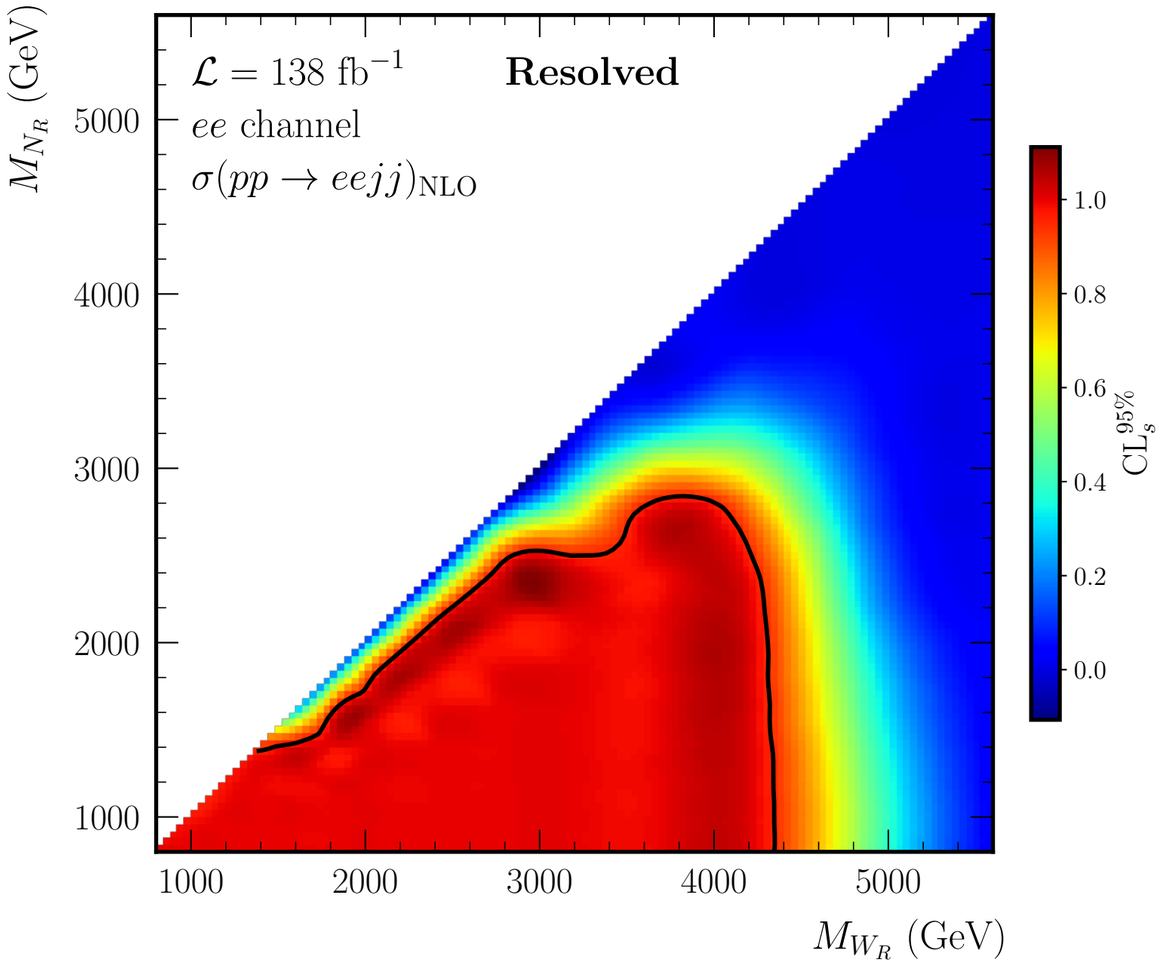


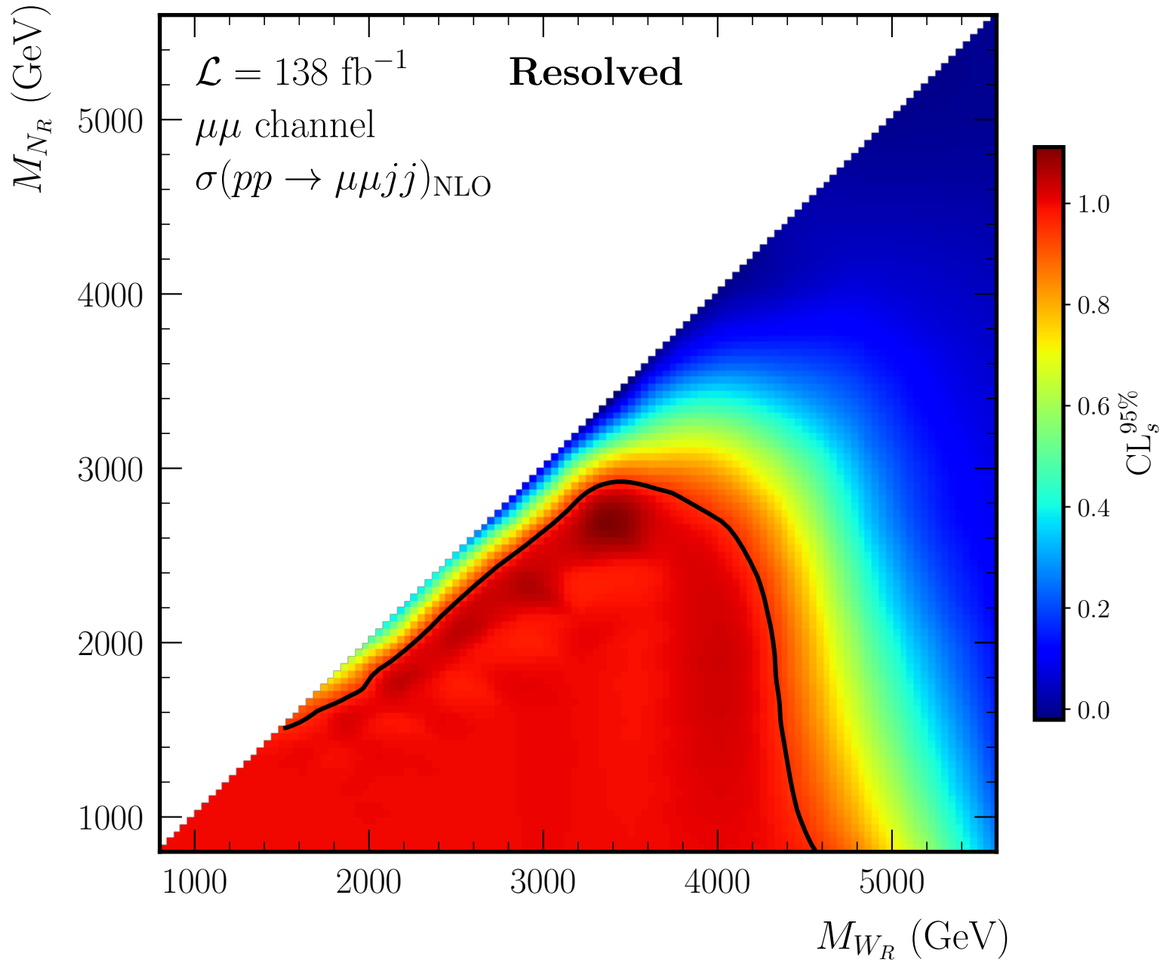


The results of the cross sections show that the K-factors are very large for heavy W_R.

The bounds will be estimated therefore using the signal events at NLO in QCD.

Results of the reinterpretation





4. A novel search strategy

Introduction

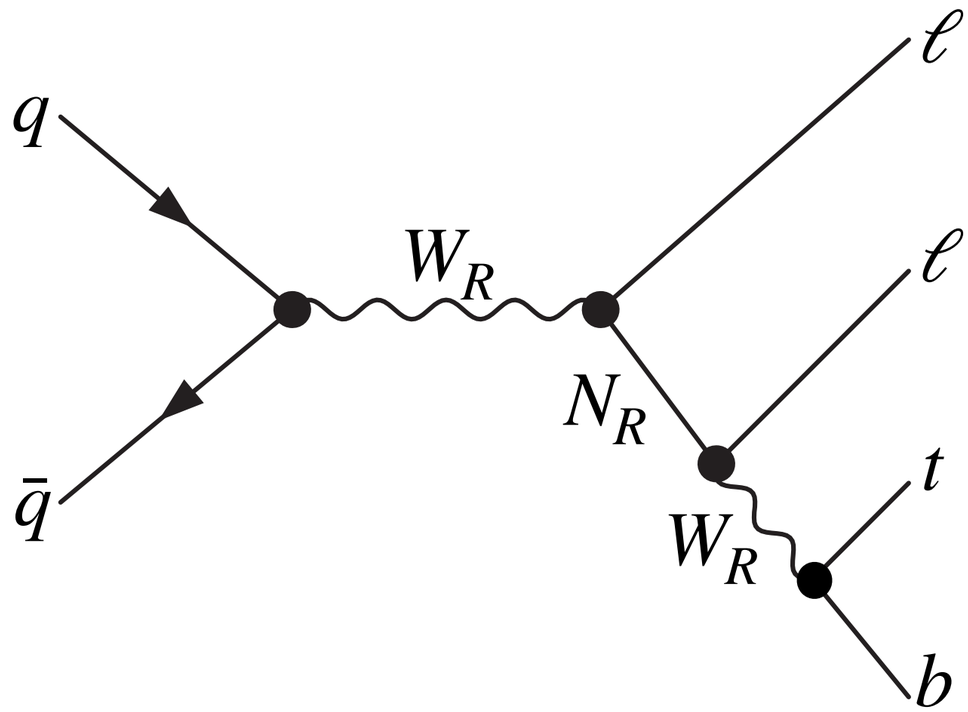
- Let us consider top and bottom quarks instead of light quarks

$$pp \;\to\; W_R \;\to\; N_R\,(\to \ell t\bar{b})\;\ell + \mathrm{h.c.}$$

- This channel has advantages with respect to conventional Keung-Senjanovic process

  $\Longrightarrow$ Lower backgrounds.

  $\Longrightarrow$ Complementary information.



Process	σ_{LO} [fb]	σ_{NLO} [fb]	$K \equiv \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$
$pp \to t\,\bar{t}\,H$	345.5	503.8	1.45
$pp \to t\,\bar{t}\,Z$	519.1	838.9	1.61
$pp \to t\,\bar{t}\,W^{\pm}$	434.0	670.2	1.54
$pp \to t\,Zj + \mathrm{c.c.}$ [100]	821.4	903.5	1.10
$pp \to t\,W^{-}\bar{b} + \mathrm{c.c.}$ [101]	976.4	1331.5	1.36

Backgrounds for hadronic top decays

Benchmark points

Twelve benchmark points ($BPe1$-$BPe6$; $BP\mu1$-$BP\mu6$)

Electron channel	Muon channel
$M_{W_R} = 4800,\ 5500$ GeV	$M_{W_R} = 5100,\ 5500$ GeV

For each choice of M_{W_R} we select three values of M_{N_R}:

$$M_{N_R} \in \left\{ \frac{M_{W_R}}{5},\ \frac{M_{W_R}}{2},\ M_{W_R} - 400\ \text{GeV} \right\}$$

Characteristics of these benchmark points:

- **Signal cross sections:** $\sigma \approx 10^{-3} - 10^{-1}$ fb.
- **Width-to-mass ratios:** $\Gamma_{W_R}/M_{W_R} \approx 3\,\%$ **and** $\Gamma_{N_R}/M_{N_R} \approx 10^{-6} - 10^{-5}$

Description of the analysis

Final state (top quark is boosted for most of the cases)

- **Exactly two charged leptons with $p_T > 25$ GeV and $|\eta| < 2.4$**
- **At least one b-tagged jet with $p_T > 30$ GeV and $|\eta| < 2.5$**
- **One fat jet (Cambridge-Aachen with $R = 1.5$) with $p_T > 200$ GeV and $|\eta| < 2$**
- **To enhance the visibility we use the HEPTopTagger algorithm (T. Plehn et al., JHEP 10 (2010) 078)**

Event selection

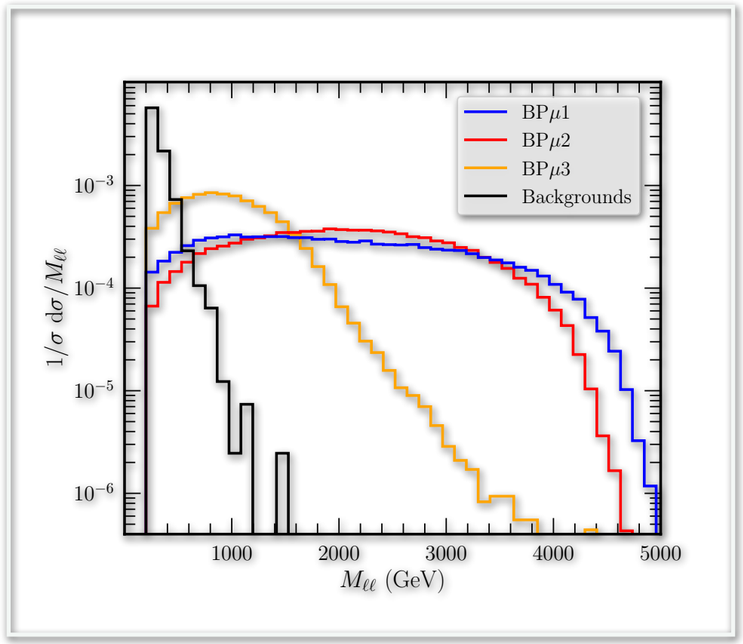
- **The leading and subleading charged leptons must satisfy $p_T > 60,\ 53$ GeV respectively.**
- **The invariant of the top quark candidate (M_{HTT}) must fall in the window $]145,\ 210[$ GeV.**
- **The invariant mass of the two leading leptons must satisfy: $M_{\ell\ell} > 200$ GeV (similar to CMS)**

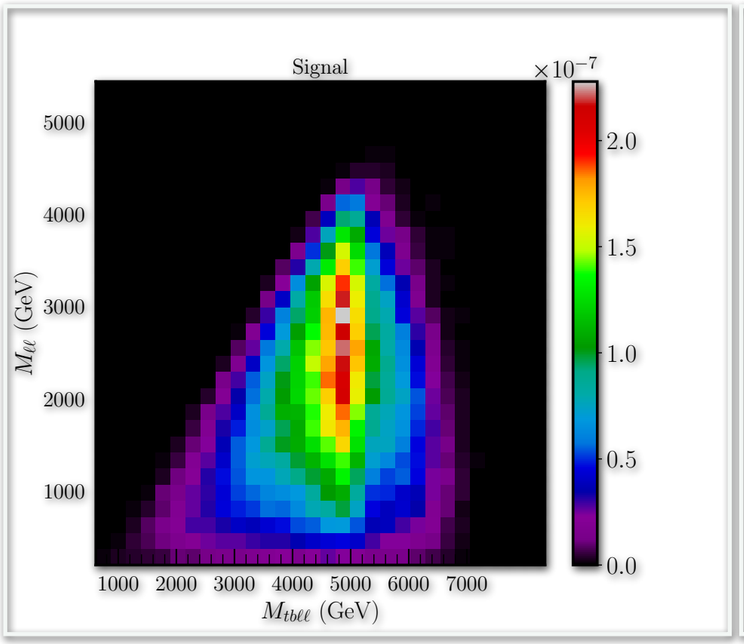
After this selection we get

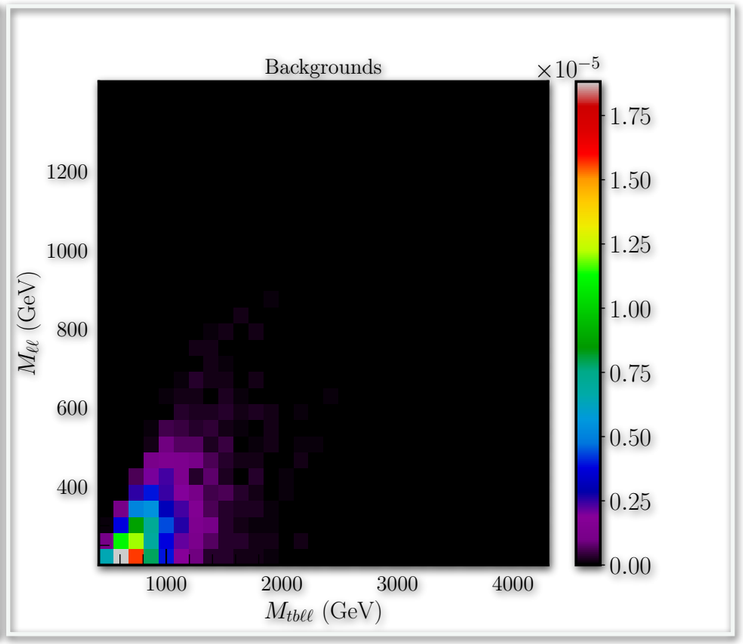
$$\epsilon_{t+X} \approx 10^{-4} \qquad \epsilon_S \in [3\,\%\,,\ 18\%]$$
$$\epsilon_{t\bar{t}+X} \approx 10^{-3}$$

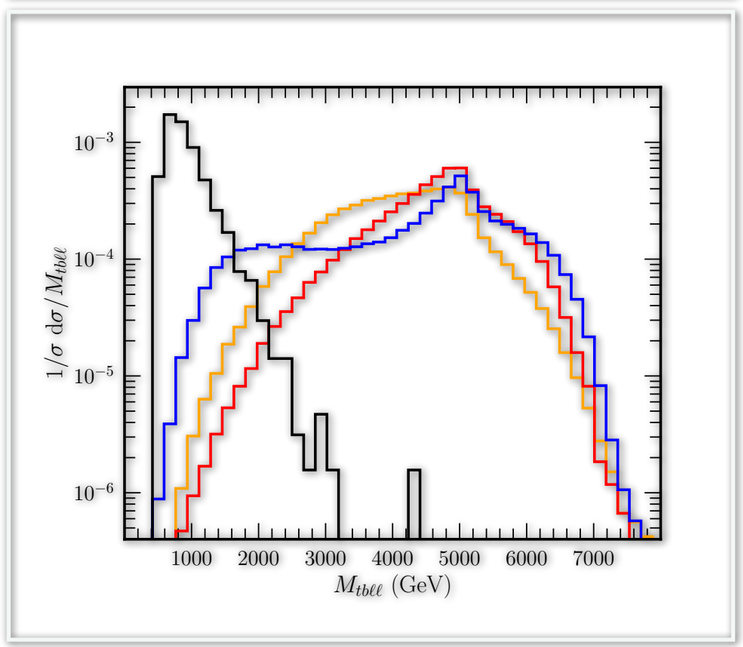
How to improve the significance?

Kinematics features









Correlations between $M_{\ell\ell}$ and $M_{\ell\ell tb}$ give useful information on the best search strategy without:

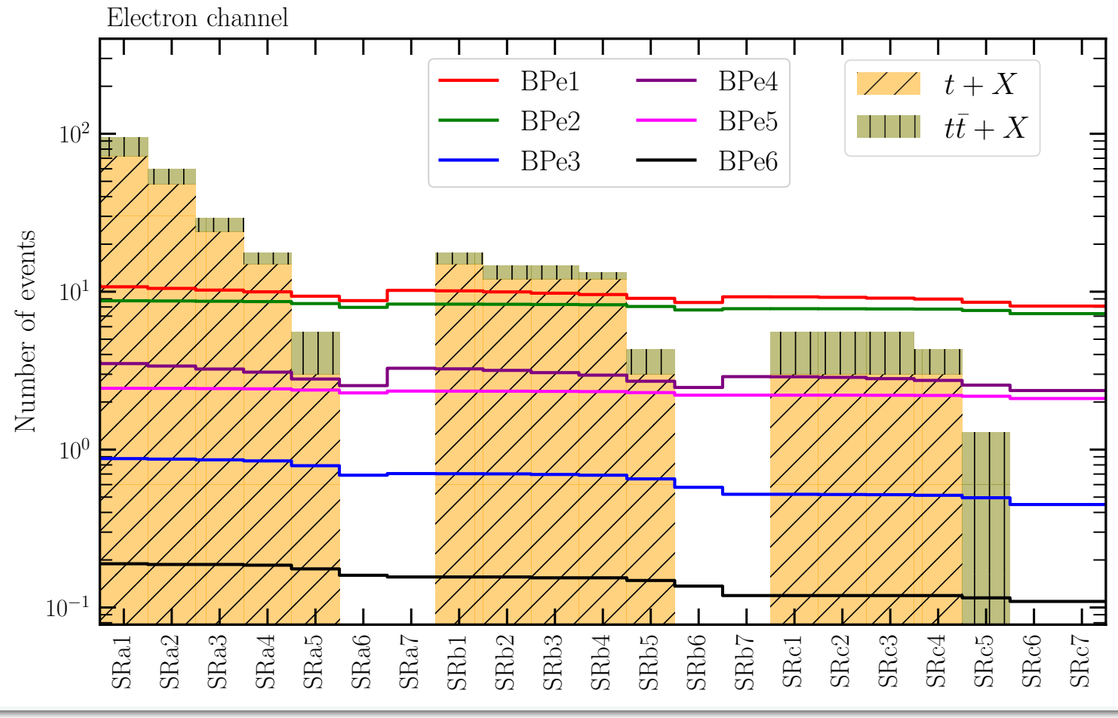
- **Relying on the mass hypothesis for N_R.**
- **Using advanced Machine Learning techniques.**

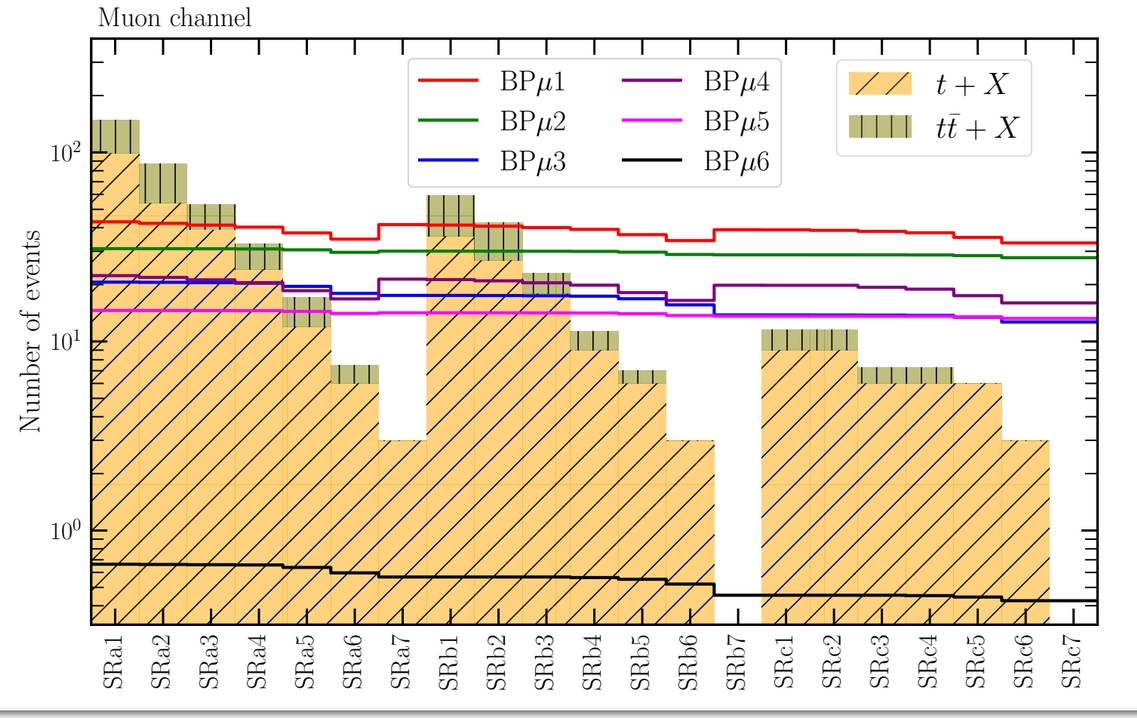
Signal regions will be based on $M_{\ell\ell}$ and $M_{\ell\ell tb}$

Signal regions

$M_{\ell\ell tb}$ \ $M_{\ell\ell}$	$]400,\infty)$	$]600,\infty)$	$]800,\infty)$
$]1200,\infty)$	SRa1	SRb1	SRc1
$]1400,\infty)$	SRa2	SRb2	SRc2
$]1600,\infty)$	SRa3	SRb3	SRc3
$]1800,\infty)$	SRa4	SRb4	SRc4
$]2000,\infty)$	SRa5	SRb5	SRc5
$]2500,\infty)$	SRa6	SRb6	SRc6
$]3000,\infty)$	SRa7	SRb7	SRc7

Event yields in the SRs

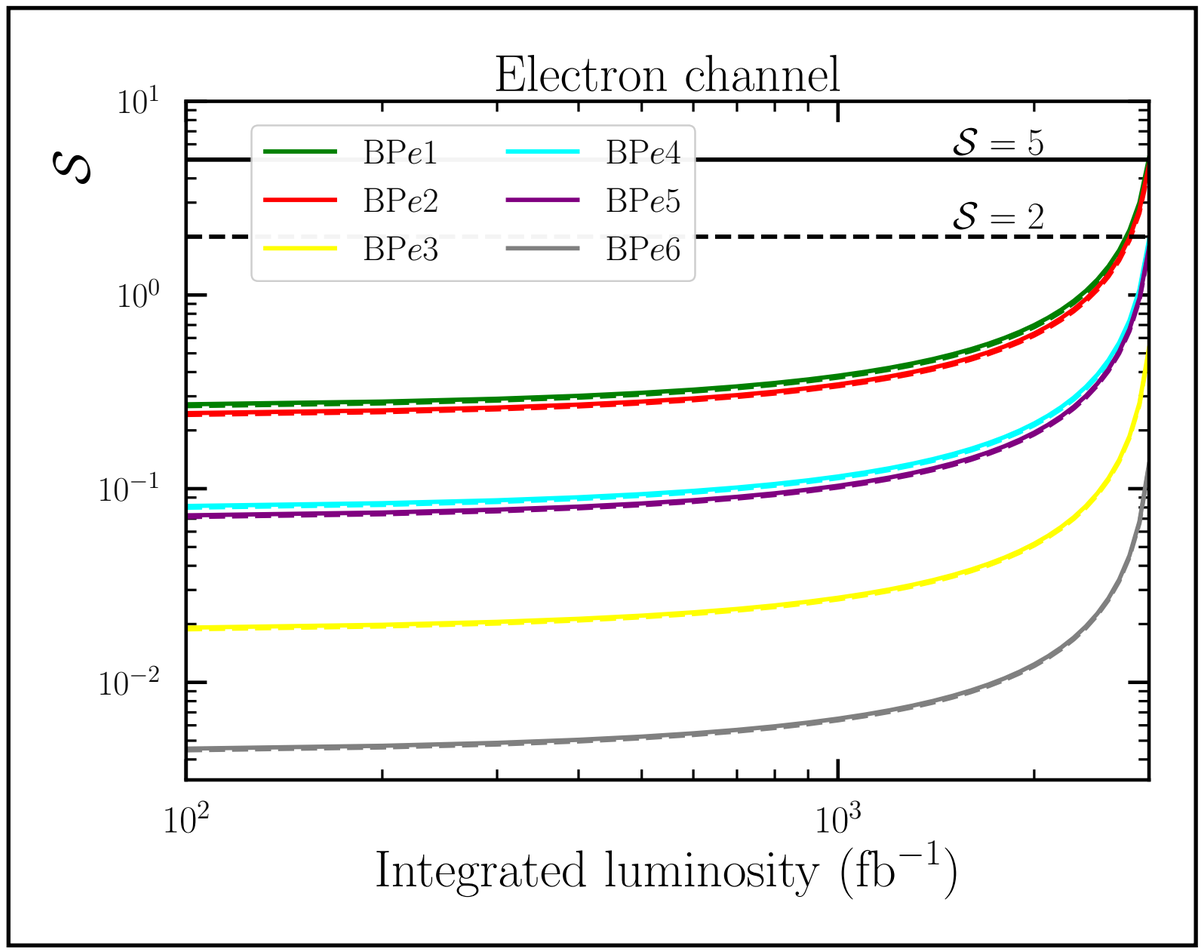


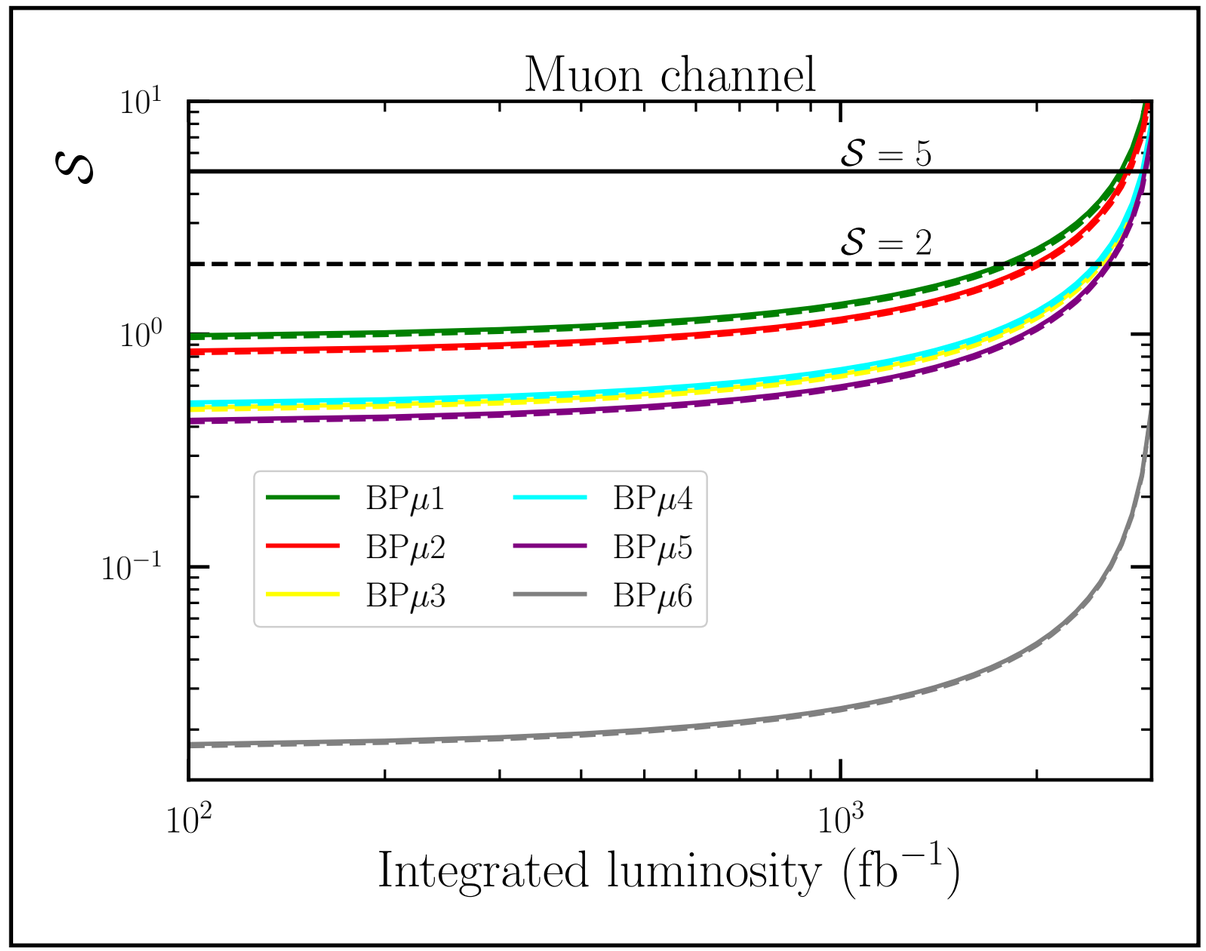


Some observations:

- **Some signal regions are background-free ($n_b = 0$).**
- **Event rates are higher in the muon channel than in the electron channel.**

Significance



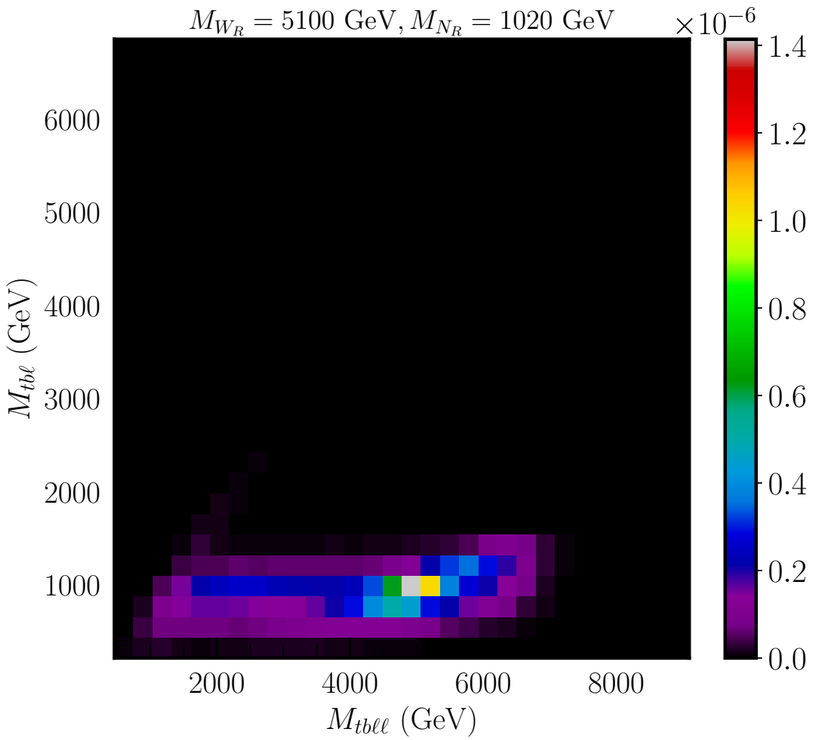


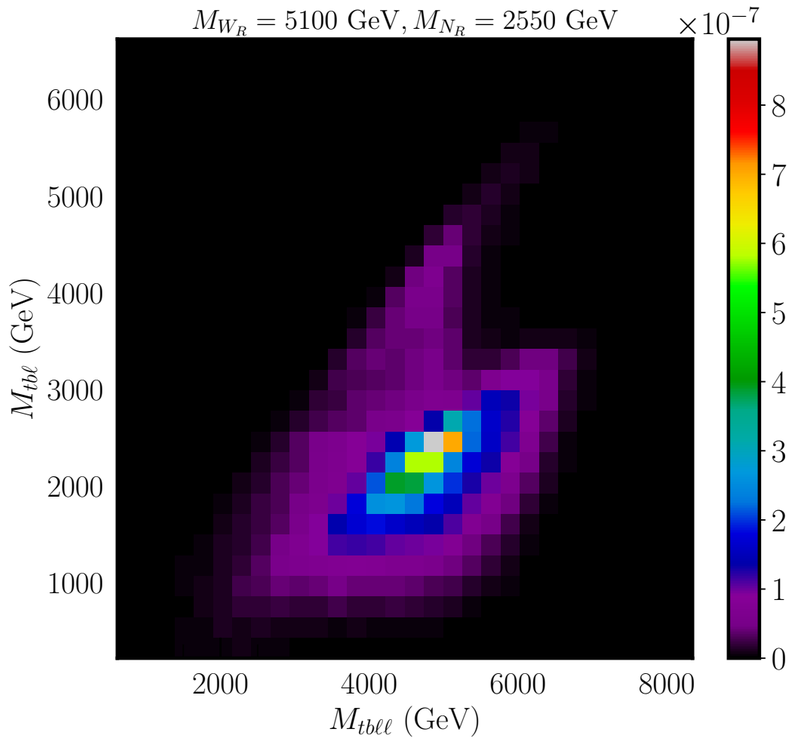
$$\mathcal{S}=\sqrt{2}\left[(n_s+n_b)\log\left(\frac{(n_s+n_b)(n_b+\delta_b^2)}{n_b^2+(n_s+n_b)\delta_b^2}\right)-\frac{n_b^2}{\delta_b^2}\log\left(1+\frac{\delta_b^2 n_s}{n_b(n_b+\delta_b^2)}\right)\right]^{1/2}$$

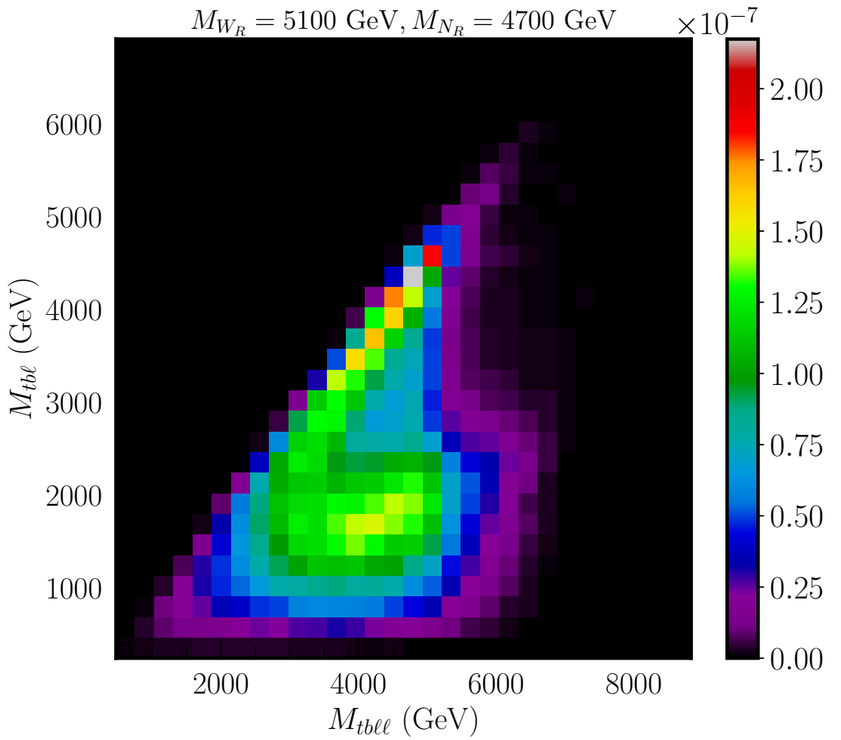
To be conservative:

- **We assume that $n_b = 1$ for all Lumi.**
- **Add a $20\,\%$ flat uncertainty on n_b.**

Characterization







- Our analysis is able to reconstruct the mass of N_R.
- Correlations between $M_{\ell tb}$ (N_R) and $M_{\ell\ell tb}$ in one of the populated SRs are very good tools for post-discovery studies.

5. Conclusions

Conclusions

- We have suggested a novel search strategy for right-handed charged gauge bosons at the Large Hadron Collider.
- The search is inspired from the Keung-Senjanovic process but top and bottom jets instead of light ones.
- For phenomenologically viable benchmark points, we found very good sensitivity reach especially for the muon channel.
- Improvements can be made if one uses:
  - Better electron and muon identification efficiencies can increase the fiducial signal rates.
  - More sophisticated jet substructure techniques to further reduce the backgrounds.
  - Machine Learning techniques can further find better correlations between the kinematical variables.
- This search can also be used for flavour number violating and lepton number violating cases for which the backgrounds are even much smaller.