Loopholes in Z' searches: exploring supersymmetry and leptophobia

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1. **Introduction**
2. **Z'-boson phenomenology with non-standard decays at LHC**
3. **Leptophobic and supersymmetric Z' scenarios**
4. **Conclusions**

J.Y. Araz, G.C., M. Frank and B. Fuks, JHEP02 (2018) 092; HL/HE-LHC Yellow Report

Searches for heavy gauge bosons Z' among the main objectives of LHC

GUT-inspired U(1)′, Sequential Standard Model, Kaluza–Klein modes

LHC analyses focus on SM decays, e.g. high-mass dileptons or dijets

CMS Dileptons: $m(Z'_{\rm SSM})$ >4.0 TeV $m(Z'_{\rm GUT})$ >3.5 TeV Dijets: $m_{Z'}$ >2.7 TeV

ATLAS Dileptons: $m(Z'_{\rm SSM})$ >4.5 TeV $m(Z'_{\rm GUT})$ >3.8-4.1 TeV Dijets $m_{Z'}$ >2.7 TeV

In BSM analyses, one may consider BSM Z' decays, e.g. in supersymmetry (UMSSM)

Lower SM branching ratios with BSM decays $\Rightarrow$ lower Z' mass exclusion limits

Z' standard decays still useful for searches, BSM modes for supersymmetry

Z' constrains sparticle invariant masses, e.g. $Z' \to \tilde{\ell}^+\tilde{\ell}^- \Rightarrow m_{Z'} = m_{\tilde{\ell}^+\tilde{\ell}^-}$

Specific realizations of UMSSM, based on kinetic mixing of $\mathrm{U}(1)'$ and $\mathrm{U}(1)_Y$ yield a leptophobic Z': charged leptons only in SUSY cascades

Related work on supersymmetric/leptophobic Z' decays:
K. Babu et al'96, T.Gherghetta et al'98, C.W.Chang et al'11, G.C.,S.Gentile '13-'15

Z' bosons in Grand Unification Theories: start from rank-6 E_6

$$\mathrm{E}_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)'_\psi \to \mathrm{SU}(5) \times \mathrm{U}(1)'_\chi \times \mathrm{U}(1)'_\psi \to \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_{\mathrm{em}} \times \mathrm{U}(1)'$$

$$\mathrm{U}(1)' = \mathrm{U}(1)'_\psi \cos\theta - \mathrm{U}(1)'_\chi \sin\theta \Rightarrow Z'(\theta) = Z'_\psi \cos\theta - Z'_\chi \sin\theta$$

$$\mathrm{E}_6 \to \mathrm{SM} \times \mathrm{U}(1)'_\eta \Rightarrow \quad \theta = \arccos\sqrt{5/8} \;\Rightarrow\; Z'_\eta$$

Model	θ
Z'_χ	$-\pi/2$
Z'_ψ	0
Z'_η	$\arccos\sqrt{5/8}$
Z'_I	$\arccos\sqrt{5/8} - \pi/2$
Z'_N	$\arctan\sqrt{15} - \pi/2$
Z'_S	$\arctan(\sqrt{15}/9) - \pi/2$

	$2\sqrt{10}\,Q'_\chi$	$2\sqrt{6}\,Q'_\psi$	$2\sqrt{15}\,Q'_\eta$
Q	-1	1	2
U	-1	1	2
D	3	1	-1
L	3	1	-1
E	-1	1	2
N	-5	1	5
H_d	-2	-2	-1
H_u	2	-2	-4
S	0	4	5
Q_D	2	-2	-4
$\bar{Q}_D$	-2	-2	-1

$$g' = \sqrt{\frac{5}{3}}\, g_1 \quad ; \quad Q'(\Phi) = Q'_\psi(\Phi)\cos\theta - Q'_\chi(\Phi)\sin\theta$$

$$Q = (u \;\; d)_L \;,\; L = (e \;\; \nu_e)_L \;,\; D = d_R \;,\; U = u_R \;,\; E = e_R \;,\; N = \nu_R$$

In supersymmetric extensions: superfields with scalar and fermion components

UMSSM electroweak symmetry breaking

Extra singlet S breaks U(1)$'$ and gives mass to the Z'

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} , \; H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} , \; S = S^0$$

Higgs sector after EWSB: h, H, A, $H^\pm$ (MSSM) and a new scalar H'

Three vacuum expectation values v_u, v_d, v_S, $\tan\beta = v_u/v_d$

Gauginos: $\tilde{Z}'$ and $\tilde{H}'$ yield two extra neutralinos: $\tilde{\chi}_1^0, \ldots \tilde{\chi}_6^0$ ($\tilde{\chi}_{5,6}^0$ very heavy)

Chargino sector is unchanged, as the Z' is neutral

D-term correction to sfermion masses: $\tilde{m}^2 = \tilde{m}_0^2 + \Delta\tilde{m}^2$

$$\Delta\tilde{m}_a^2 = g'^2 Q'_a (Q'_{H_u} v_u^2 + Q'_{H_d} v_d^2 + Q'_S v_S^2)/2 \quad ; \quad g' = \sqrt{\frac{5}{3}}\, g_1 \text{ (GUT)}$$

New Z' decay modes: $Z' \to \tilde{q}\tilde{q}^*$, $\tilde{\ell}^+\tilde{\ell}^-$, $\tilde{\nu}\tilde{\nu}^*$, $\tilde{\chi}_i^0\tilde{\chi}_j^0$, $\tilde{\chi}_{1,2}^+\tilde{\chi}_{1,2}^-$, ZH, Zh, H^+H^-

Z' mass and Higgs vevs: $M_{Z'} = g'^2(Q'_{H_u} v_u^2 + Q'_{H_d} v_d^2 + Q'_S v_S^2)$

$\langle S \rangle \gg \langle H_{u,d}^0 \rangle$: H' singlet-like degenerate with Z', H degenerate with A and $H^\pm$

Mixing and leptophobia

Z/Z' mass mixing, parametrized by $\alpha_{ZZ'} \sim \mathcal{O}(10^{-3})$ is negligible (J.Erler et al, '09)

Kinetic mixing between U(1)′ and U(1)$_Y$ and diagonalization

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}\hat{B}^{\mu\nu}\hat{B}_{\mu\nu} - \frac{1}{4}\hat{Z}'^{\mu\nu}\hat{Z}'_{\mu\nu} - \frac{\sin\chi}{2}\hat{B}^{\mu\nu}\hat{Z}'_{\mu\nu} \quad , \quad \begin{pmatrix}\hat{B}_\mu \\ \hat{Z}'_\mu\end{pmatrix} = \begin{pmatrix}1 & -\tan\chi \\ 0 & \frac{1}{\cos\chi}\end{pmatrix}\begin{pmatrix}B_\mu \\ Z'_\mu\end{pmatrix}$$

Interaction Lagrangian: $\mathcal{L}_{\rm int} = \bar{\psi}_i\gamma^\mu(g_1 Y_i \hat{B}_\mu + g' Q'_i \hat{Z}'_\mu)\psi_i$ in terms of B_μ and Z'_μ:

$$\mathcal{L}_{\rm int} = \bar{\psi}_i\gamma^\mu(g_1 Y_i B_\mu + g' \bar{Q}_i Z'_\mu)\psi \ , \ \text{with} \ \ \bar{Q}_i = \frac{Q'_i}{\cos\chi} - \frac{g_1}{g'} Y_i \tan\chi$$

Leptophobic Z': $\bar{Q}_L = \bar{Q}_E = 0$ implies $\mathrm{BR}(Z' \to \ell^+\ell^-) = 0$

From lepton hypercharges: $Y_L = -1/2$, $Y_E = 1 \Rightarrow Q'_E = -2Q'_L$ (Z'_η model)

Requiring $g' = \sqrt{\frac{5}{3}}\, g_1 \Rightarrow \ |\sin\chi| \simeq 0.3$

Supersymmetry and leptophobia: leptons may still come from supersymmetric decays, e.g., $Z' \to \tilde{\chi}_1^+\tilde{\chi}_1^-$, followed by $\tilde{\chi}_1^+ \to W^+\tilde{\chi}_1^0 \to (\ell^+\nu_\ell)\tilde{\chi}_1^0$

Scenario not yet explored in the experimental analyses (only SM decays)

Parameter-space scan and constraints

Two scenarios: $g'(M_{\rm GUT}) = \sqrt{\frac{5}{3}}\, g_1(M_{\rm GUT})$; $g'(M_{Z'}) = \sqrt{\frac{5}{3}}\, g_1(M_{Z'})$ (this talk)

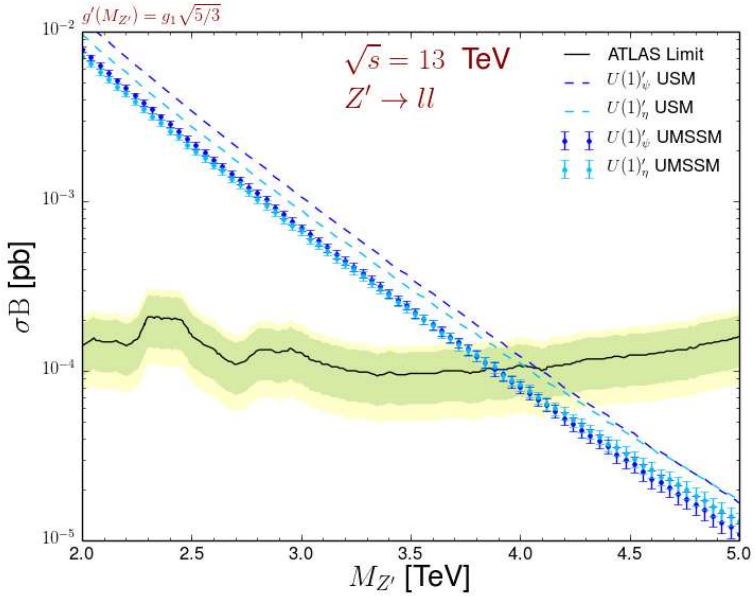
Parameter	Scanned range	Parameter	Scanned range
M_0	$[0, 3]$ TeV	$\mu_{\rm eff}$	$[-2, 2]$ TeV
$M_{1/2}$	$[0, 5]$ TeV	A_λ	$[-7, 7]$ TeV
A_0	$[-3, 3]$ TeV	$M_{Z'}$	$[1.98, 5.2]$ TeV
$\tan\beta$	$[0, 60]$	θ	$[-\pi, \pi]$
$m^2_{\tilde{q},\tilde{u},\tilde{d}}$	$[0, 16]$ TeV^2	$M_{1,2,3,4}$	$[0, 3]$ TeV
$m^2_{\tilde{e},\tilde{l}}$	$[0, 1]$ TeV^2	$m^2_{\tilde{\nu}}$	$[-6.8, 9]$ TeV^2

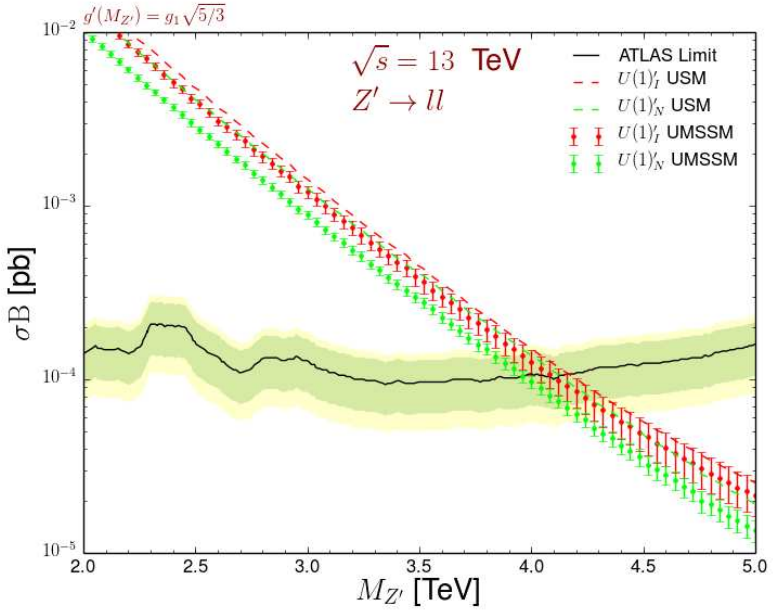
Observable	Constraints	Observable	Constraints
M_h	125.09 ± 3 GeV (theo)	$\chi^2(\hat{\mu})$	≤ 70
$\lvert\alpha_{ZZ'}\rvert$	$\mathcal{O}(10^{-3})$	$M_{\tilde{g}}$	> 1.75 TeV
$M_{\tilde{\chi}^0_2}$	> 62.4 GeV	$M_{\tilde{\chi}^0_3}$	> 99.9 GeV
$M_{\tilde{\chi}^0_4}$	> 116 GeV	$M_{\tilde{\chi}^\pm_i}$	> 103.5 GeV
$M_{\tilde{\tau}}$	> 81 GeV	$M_{\tilde{e}}$	> 107 GeV
$M_{\tilde{\mu}}$	> 94 GeV	$M_{\tilde{t}}$	> 900 GeV
BR$(B^0_s \to \mu^+\mu^-)$	$[1.1 \times 10^{-9}, 6.4 \times 10^{-9}]$	$\frac{\rm BR(B \to \tau\nu_\tau)}{\rm BR_{SM}(B \to \tau\nu_\tau)}$	$[0.15, 2.41]$
BR$(B^0 \to X_s\gamma)$	$[2.99, 3.87] \times 10^{-4}$		

Particle spectrum generated through SARAH, interfaced to SPHENO

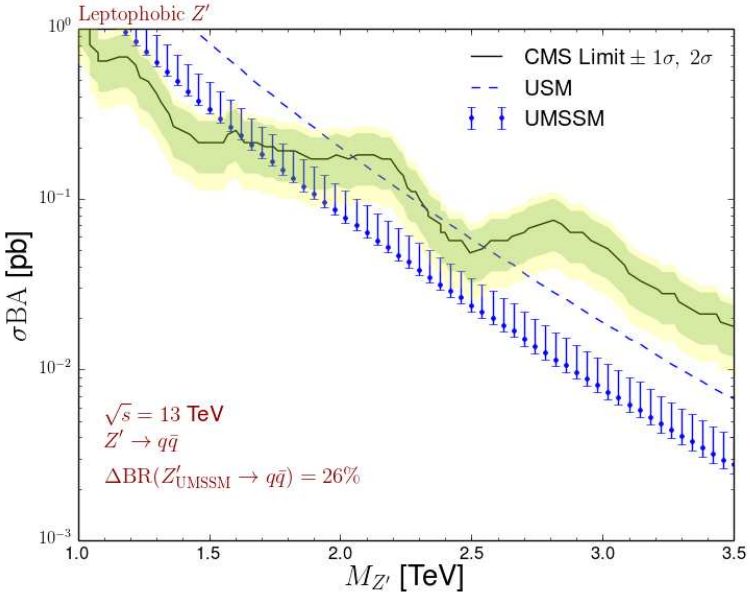
Z' production cross section computed in NLO QCD by MadGraph+aMC@NLO

Limits from dileptons including supersymmetry $\Delta M_{Z'} \simeq 200 - 300$ GeV





Limits from dijets including supersymmetry and leptophobia $\Delta M_{Z'} \simeq 1$ TeV



Leptophobic Z': two benchmarks and low-scale unification (BM I $\sim$ U(1)$'_\eta$)

Parameter	θ	$\tan\beta$	$\mu_{\rm eff}$ [GeV]	$M_{Z'}$ [TeV]	M_0 [TeV]	M_1 [GeV]
BM I	$-0.79\ \pi$	9.11	218.9	2.5	2.6	106.5
BM II	$0.2\ \pi$	16.08	345.3	2.5	1.9	186.7
Parameter	M_2 [GeV]	M_3 [TeV]	M'_1 [GeV]	A_0 [TeV]	A_λ [TeV]	$\sin\chi$
BM I	230.0	3.6	198.9	2	5.9	-0.35
BM II	545.5	5.5	551.7	1.5	5.1	0.33

Mass spectrum in BM I

$M_{\tilde g}$	$M_{\tilde d_1}$	$M_{\tilde u_1}$	$M_{\tilde s_1}$	$M_{\tilde c_1}$	$M_{\tilde b_1}$	$M_{\tilde t_1}$
3745.1	2988.8	2937.3	3380.3	3025.9	3380.4	3379.4
	$M_{\tilde d_2}$	$M_{\tilde u_2}$	$M_{\tilde s_2}$	$M_{\tilde c_2}$	$M_{\tilde b_2}$	$M_{\tilde t_2}$
	3525.2	3379.4	3541.2	3699.0	3541.2	3699.0
	$M_{\tilde e_1}$	$M_{\tilde e_2}$	$M_{\tilde\mu_1}$	$M_{\tilde\mu_2}$	$M_{\tilde\tau_1}$	$M_{\tilde\tau_2}$
	171.1	345.7	196.4	392.3	239.4	409.6
	$M_{\tilde\nu_{e,1}}$	$M_{\tilde\nu_{e,2}}$	$M_{\tilde\nu_{\mu,1}}$	$M_{\tilde\nu_{\mu,2}}$	$M_{\tilde\nu_{\tau,1}}$	$M_{\tilde\nu_{\tau,2}}$
	336.4	1663.1	384.1	1674.2	401.6	1683.6
M_h	M_H	$M_{H'}$	M_A	$M_{H^\pm}$	$M_{\tilde\chi_1^+}$	$M_{\tilde\chi_2^+}$
122.5	3371.5	2507.0	3371.5	3372.7	177.1	302.3
	$M_{\tilde\chi_1^0}$	$M_{\tilde\chi_2^0}$	$M_{\tilde\chi_3^0}$	$M_{\tilde\chi_4^0}$	$M_{\tilde\chi_5^0}$	$M_{\tilde\chi_6^0}$
	95.5	181.3	232.2	302.4	2405.1	2602.0

Mass spectrum in BM II ⇒

$M_{\tilde{g}}$	$M_{\tilde{d}_1}$	$M_{\tilde{u}_1}$	$M_{\tilde{s}_1}$	$M_{\tilde{c}_1}$	$M_{\tilde{b}_1}$	$M_{\tilde{t}_1}$
5669.3	4405.5	4141.5	4927.6	4418.1	4927.7	4926.9
	$M_{\tilde{d}_2}$	$M_{\tilde{u}_2}$	$M_{\tilde{s}_2}$	$M_{\tilde{c}_2}$	$M_{\tilde{b}_2}$	$M_{\tilde{t}_2}$
	5069.8	4927.0	5146.3	5117.1	5146.3	5117.1
	$M_{\tilde{e}_1}$	$M_{\tilde{e}_2}$	$M_{\tilde{\mu}_1}$	$M_{\tilde{\mu}_2}$	$M_{\tilde{\tau}_1}$	$M_{\tilde{\tau}_2}$
	665.1	871.5	679.2	1067.9	743.9	1075.6
	$M_{\tilde{\nu}_{e,1}}$	$M_{\tilde{\nu}_{e,2}}$	$M_{\tilde{\nu}_{\mu,1}}$	$M_{\tilde{\nu}_{\mu,2}}$	$M_{\tilde{\nu}_{\tau,1}}$	$M_{\tilde{\nu}_{\tau,2}}$
	660.4	1049.6	674.3	1079.4	739.3	1106.2
M_h	M_H	$M_{H'}$	M_A	$M_{H^\pm}$	$M_{\tilde{\chi}_1^+}$	$M_{\tilde{\chi}_2^+}$
127.4	5237.8	2498.2	5238.0	5238.8	343.8	593.5
	$M_{\tilde{\chi}_1^0}$	$M_{\tilde{\chi}_2^0}$	$M_{\tilde{\chi}_3^0}$	$M_{\tilde{\chi}_4^0}$	$M_{\tilde{\chi}_5^0}$	$M_{\tilde{\chi}_6^0}$
	178.1	346.9	360.0	593.2	2239.1	2785.9

Decay	BR [%] (**I**)	BR [%] (**II**)
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	1.7	6.3
$\tilde{\chi}_2^+\tilde{\chi}_2^-$	2.1	-
$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$	3.9	-
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	-	1.5
$\tilde{\chi}_2^0\tilde{\chi}_3^0$	1.7	3.3
$\tilde{\chi}_3^0\tilde{\chi}_3^0$	1.9	1.9
$\tilde{\chi}_3^0\tilde{\chi}_4^0$	2.2	-
$\sum_i \tilde{\nu}_i\tilde{\nu}_i^\dagger$	-	1.6
hZ	1.9	1.9
W^+W^-	3.6	3.8
$\sum_i d_i\bar{d}_i$	15.8	14.8
$\sum_i u_i\bar{u}_i$	39.8	40.0
$\sum_i \nu_i\bar{\nu}_i$	23.4	22.8

Substantial BRs in charginos and neutralinos

in both BM I and BM II

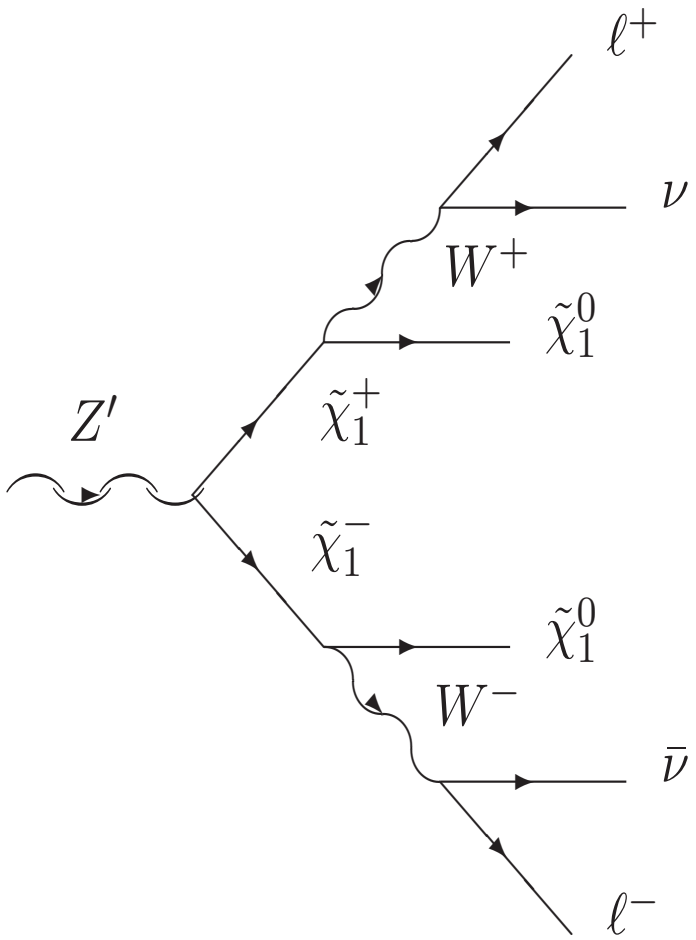
SM decay modes still dominate

No BR into lepton pairs

BM I: $M_{\tilde{\chi}_1^+} - M_{\tilde{\chi}_1^0} \simeq M_W$ (compressed spectrum)

BM II: $M_{\tilde{\chi}_1^+} - M_{\tilde{\chi}_1^0} \simeq 2M_W$

Final states with leptons ($\ell = e, \mu$) and missing transverse energy



At $\sqrt{s} = 14$ TeV and NLO in QCD: $\sigma(pp \to Z') \simeq 120$ fb in both BM I and BM II

$\mathrm{BR}(Z' \to \tilde{\chi}_1^+ \tilde{\chi}_1^-) \simeq 1.7\%$ (BM I), 6.3% (BM II), $\mathrm{BR}(\tilde{\chi}_1^+ \to W^+ \tilde{\chi}_1^0) \simeq 100\%$

Background processes: V+jets, VV+jets, $t\bar{t}$ and single top

Selection strategy ($\sqrt{s} = 14$ TeV, $\mathcal{L} = 3000$ fb^{-1}:)

$p_{T,\ell} > 20$ GeV, $p_{T,j} > 40$ GeV, $|\eta_\ell| < 1.5$, $|\eta_j| < 2.4$, $\Delta R(j,\ell) > 0.4$, $\Delta R(\ell_1,\ell_2) > 2.5$

Further cuts on signal lepton and missing energy:

$p_T(\ell_1) > 300$ GeV, $p_T(\ell_2) > 200$ GeV, $\not{E}_T > 100$ GeV, $I^\mu_{\rm rel} < 0.15$

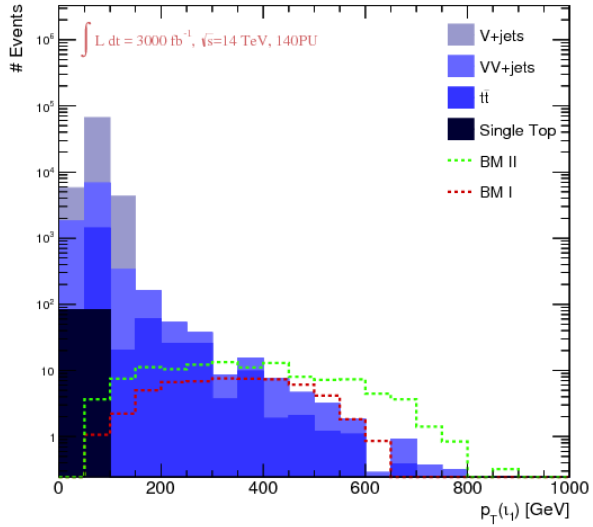
Cutflows and significance $s = S/\sqrt{B + \sigma_B^2}$ for $\sigma_B \simeq 0.2 \times B$

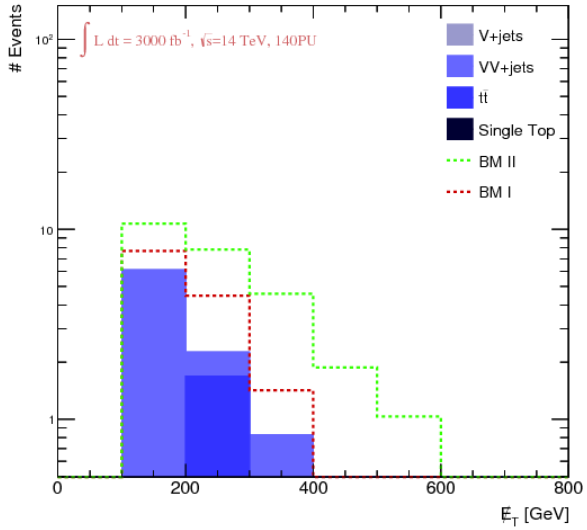
Step	Requirements	Background	**BM I**	**BM II**
0	Initial	1.7×10^{11}	8.8×10^3	1.9×10^4
1	$N^l = 2$	6.1×10^8	401	860
2	Electron veto	2.9×10^8	100	230
3	$\|\eta^l\| < 1.5$	1.7×10^8	76	170
4	$I^\mu_{\rm rel} < 0.15$	7.9×10^5	63	130
5	$\Delta R(l_1, l_2) > 2.5$	7.9×10^5	62	130
6	Jet veto	7.7×10^4	57	120
7	$p_T(l_1) > 300$ GeV	44	36	71
8	$p_T(l_2) > 200$ GeV	20	19	32
9	$\not{E}_T > 100$ GeV	10	14	27
	s		3.77σ	7.14σ

Both benchmarks yield visible signals at 4σ-7σ

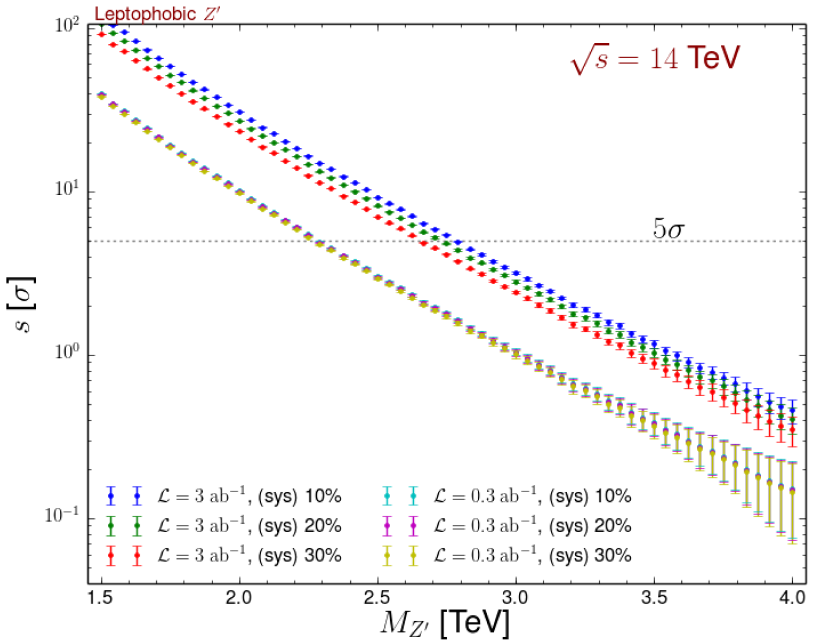
Simulation with MadGraph+PYTHIA 8 including hadronization and detector effects

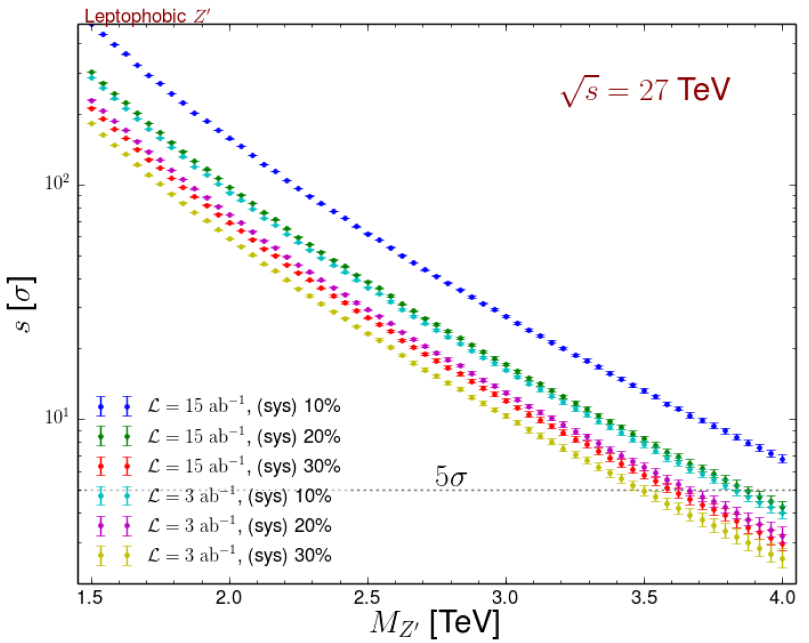
Leading-muon p_T (left) and missing energy (right)





Significance s in terms of $\mathcal{L}$, $\sigma_B(\%B)$ and $M_{Z'}$ in BM II at 14 and 27 TeV





Conclusions and outlook

Present absence of new physics at LHC calls for exploring unconventional scenarios

Investigation on non-standard Z' at LHC

Supersymmetric Z' modes decrease SM rates; Z' constrains sparticle invariant masses

Leptophobic models should deserve novel investigation

$(\Delta m_{Z'})_{\min} \approx$ 200-300 GeV in dilepton analyses due to supersymmetry

$(\Delta m_{Z'})_{\min} \approx$ 1 TeV in dijet analysis with supersymmetry and leptophobia

Possible leptophobic signals visible at HL-LHC with a 4σ-7σ significance

In progress:

Discussion with ATLAS/CMS exotics/SUSY WGs towards joint analyses