Non-standard heavy vector bosons at the LHC

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1. **Introduction**
2. **Z' boson phenomenology with non-standard decays at LHC**
3. **Doubly-charged bilepton signal at LHC**
4. **Conclusions**

G.C. and S. Gentile, Nucl. Phys. B886 (2013) 293; G.C., EPJ C75 (2015) 264

Work in progress in collaboration with J. Araz, M. Frank and B. Fuks

G.C., C. Corianò, A. Costantini and P.H. Frampton, arXiv:1707.01381.

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

GUT-inspired U(1)', Sequential Standard Model, Kaluza–Klein models

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: $m_{Z'}$ >2.1-3.3 TeV

ATLAS Dileptons: $m(Z'_{\rm SSM})$ >4.1 TeV $m(Z'_{\rm GUT})$ >3.4-3.7 TeV Dijets $m_{Z'}$ >2-2.6 TeV

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

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. $Z' \to \tilde{\ell}^+\tilde{\ell}^- \Rightarrow m_{Z'} = m_{\tilde{\ell}^+\tilde{\ell}^-}$

Supersymmetric Z' decays allow study of unexplored phase space

Decays $Z' \to \tilde{\chi}^0_1\tilde{\chi}^0_1$: monojet events and Dark Matter candidates

Related work on supersymmetric Z' decays:
Gherghetta et al ('98), Kang & Langacker ('05), Baumgart et al ('07), Chang et al ('11)

U(1)' gauge groups in GUT-inspired models:

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

$$Z'(\theta) = Z'_\psi \cos\theta - Z'_\chi \sin\theta$$

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

Orthogonal combination to Z'_η: $\theta = \arccos\sqrt{5/8} - \pi/2 \Rightarrow Z'_I$

Secluded model (singlet S): $\theta = \arctan(\sqrt{15}/9) - \pi/2 \Rightarrow Z'_S$

Z'_N: Z'_χ-like with 'unconventional' SO(10) representations (**10** vs **6**, $\theta \to \theta + \arctan 15$)

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	$\arctan(\sqrt{15}/9) - \pi/2$

Analysis will be carried out for Z'_ψ and Z'_η models, which yield higher cross sections

Minimal Supersymmetric Standard Model and U(1)′ (a.k.a. UMSSM)

Extra singlet S to break U(1)′ and give 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: new $\tilde{Z}'$ and $\tilde{H}'$ imply two new 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: $\tilde{m}^2 = \tilde{m}_0^2 + \Delta\tilde{m}^2$ ($\tilde{m}_0$ soft mass at Z' scale)

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

New Z' decay modes besides the SM ones:

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

Benchmark: $m_{Z'} = 2$ TeV, consistency with SUSY exclusion and 125 GeV Higgs

$$M_1 = 400 \text{ GeV} \simeq M_2/2 \ , \ M' = 1 \text{ TeV} \ , \ \tan\beta = 30 \ , \ \mu = 200 \text{ GeV} \ , \ A_f \simeq 4 \text{ TeV}$$

U(1)'$_\psi$: $m^0_{\tilde{\ell}} = m^0_{\tilde{\nu}_\ell} = 1.2$ TeV , $m^0_{\tilde{q}} = 5.5$ TeV $(q = u, d, c, s)$,
$m^0_{\tilde{b}} = m^0_{\tilde{t}} = 2.2$ TeV $\quad (q_{1,2} \simeq q_{L,R},\ \ell_{1,2} \simeq \ell_{L,R})$ A. Arbey et al, arXiv:1112.3028

SARAH computes mass matrices at NLO, SPheno creates model files in the UFO format

$m_{\tilde{d}_1}$	$m_{\tilde{u}_1}$	$m_{\tilde{s}_1}$	$m_{\tilde{c}_1}$	$m_{\tilde{b}_1}$	$m_{\tilde{t}_1}$
5609.8	5609.4	5609.9	5609.5	2321.7	2397.2
$m_{\tilde{d}_2}$	$m_{\tilde{u}_2}$	$m_{\tilde{s}_2}$	$m_{\tilde{c}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{t}_2}$
5504.9	5508.7	5504.9	5508.7	2119.6	2036.3

$m_{\tilde{\ell}_1}$	$m_{\tilde{\ell}_2}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\nu}_{\ell,1}}$	$m_{\tilde{\nu}_{\ell,2}}$	$m_{\tilde{\nu}_{\tau,1}}$	$m_{\tilde{\nu}_{\tau,2}}$
1392.4	953.0	1398.9	971.1	1389.8	961.5	1395.9	961.5

m_h	m_H	$m_{H'}$	m_A	$m_{H^\pm}$
125.0	1989.7	4225.0	4225.0	4335.6

$m_{\tilde{\chi}^+_1}$	$m_{\tilde{\chi}^+_2}$	$m_{\tilde{\chi}^0_1}$	$m_{\tilde{\chi}^0_2}$	$m_{\tilde{\chi}^0_3}$	$m_{\tilde{\chi}^0_4}$	$m_{\tilde{\chi}^0_5}$	$m_{\tilde{\chi}^0_6}$
204.8	889.1	197.2	210.7	408.8	647.9	889.0	6193.5

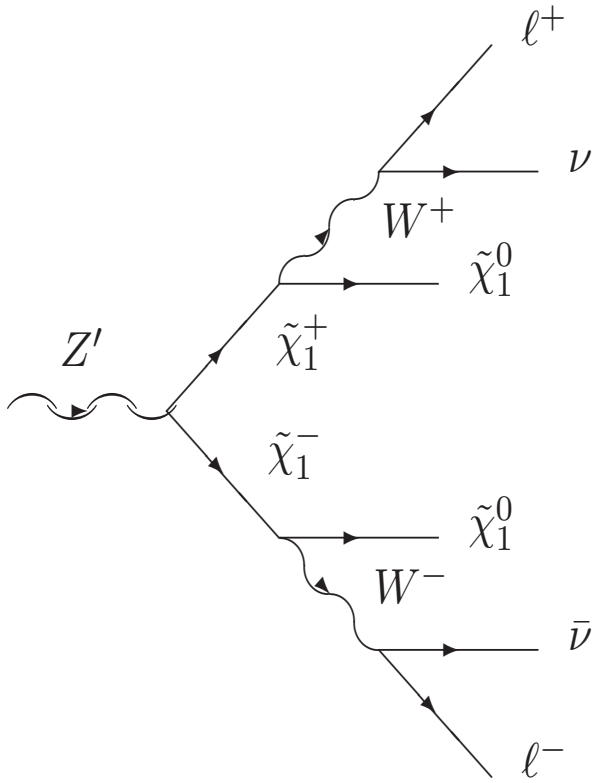
Branching ratios of Z'_ψ into SM ($\sim 70\%$) and BSM ($\sim 30\%$) final states

Final State	Z'_ψ Branching ratio (%)
$\tilde{\chi}_1^+\chi_1^-$	10.2
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	4.9
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	5.1
$\tilde{\chi}_4^0\tilde{\chi}_4^0$	8.0
hZ	1.4
W^+W^-	2.9
$\sum_i q\bar{q}$	50.1
$\sum_i \nu_i\bar{\nu}_i$	8.3
$\sum_i \ell_i^+\ell_i^-$	8.3

$Z'_\psi \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ exhibits the highest branching ratio: need to consider $\tilde{\chi}_1^\pm$ rates

Final State	χ_1^+ branching ratio (%)
$\tilde{\chi}_1^0\ u\bar{d}$	34.3
$\tilde{\chi}_1^0\ u\bar{c}$	1.8
$\tilde{\chi}_1^0\ c\bar{d}$	1.6
$\tilde{\chi}_1^0\ c\bar{s}$	29.3
$\tilde{\chi}_1^0\ \ell^+\nu_\ell$	32.9

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



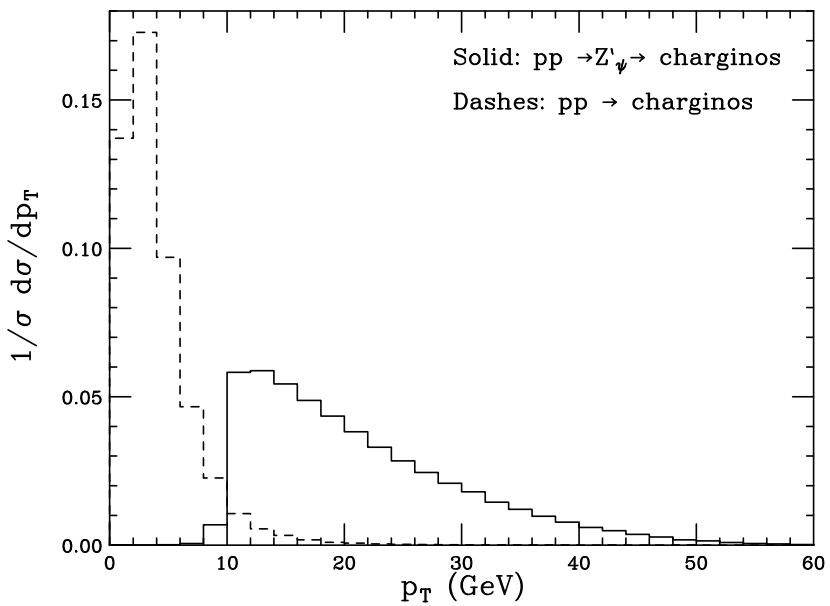
In the reference point, at $\sqrt{s} = 14$ TeV, using MadGraph and LO CTEQL1:

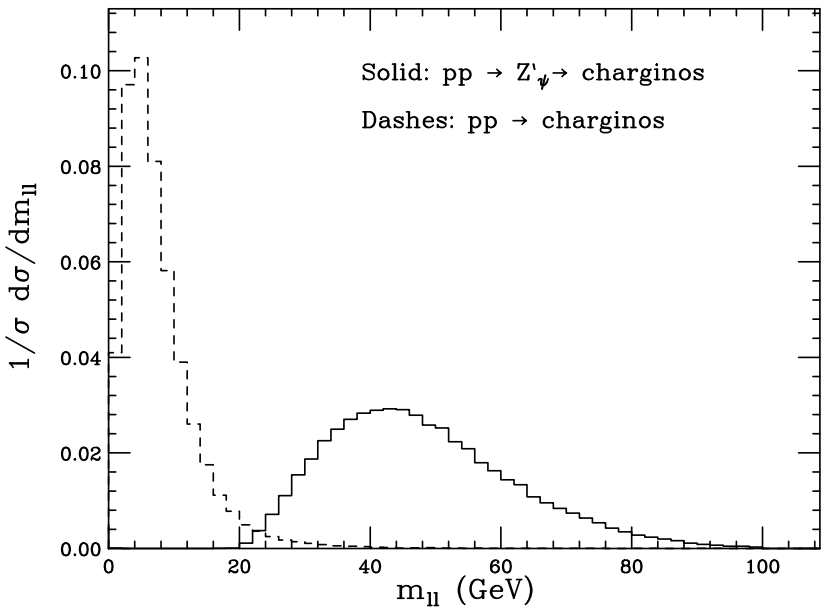
$$\sigma(pp \to Z'_\psi) \simeq 0.13 \text{ pb} \; ; \; \text{BR}(Z'_\psi \to \tilde{\chi}_1^+ \tilde{\chi}_1^-) \simeq 10.2\% \; ; \; \text{BR}(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \ell^+ \nu_\ell) \simeq 24\%$$

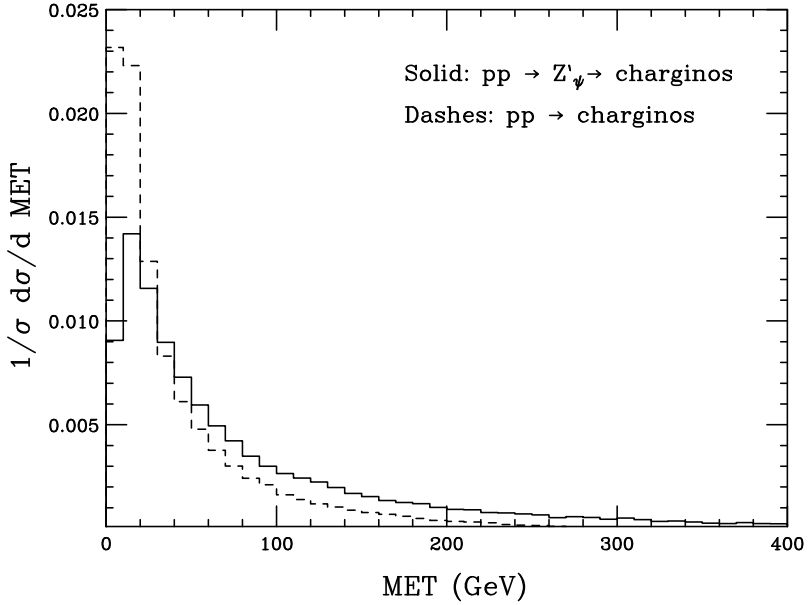
$$\sigma(pp \to Z'_\psi \to \ell^+\ell^- + \text{MET}) \simeq 8 \times 10^{-4} \text{ pb} \Rightarrow N \simeq 80 \; (100 \text{ fb}^{-1}) \; , \; N \simeq 240 \; (300 \text{ fb}^{-1})$$

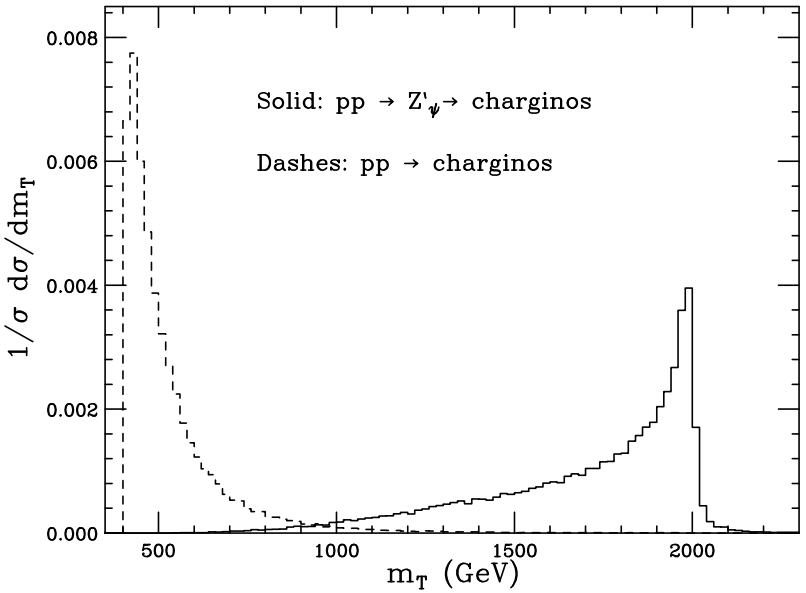
Competitive process: $pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to (\tilde{\chi}_1^0 \ell^+ \nu_\ell)(\tilde{\chi}_1^0 \ell^- \bar{\nu}_\ell)$ $(\sigma \simeq 1.15 \times 10^{-2}$ pb)

Phenomenology - $Z'_\psi \to$ charginos (MadGraph+HERWIG - $\sqrt{s} = 14$ TeV)





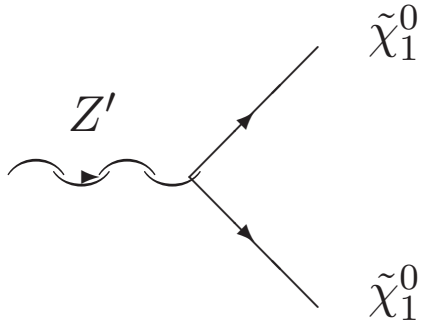




$$\text{MET} = \sqrt{\left(\sum_i p_{x,i}\right)^2 + \left(\sum_i p_{y,i}\right)^2} \quad (i = \nu, \tilde{\chi}_1^0) \; ; \quad m_T = \sqrt{\left(\sum_j E_{T,j}\right)^2 - \left(\sum_j \vec{p}_{T,j}\right)^2} \quad (j = \ell, \nu, \tilde{\chi}_1^0)$$

DM signals in Z' decays: $Z'_\psi \to \tilde{\chi}^0_1 \tilde{\chi}^0_1$

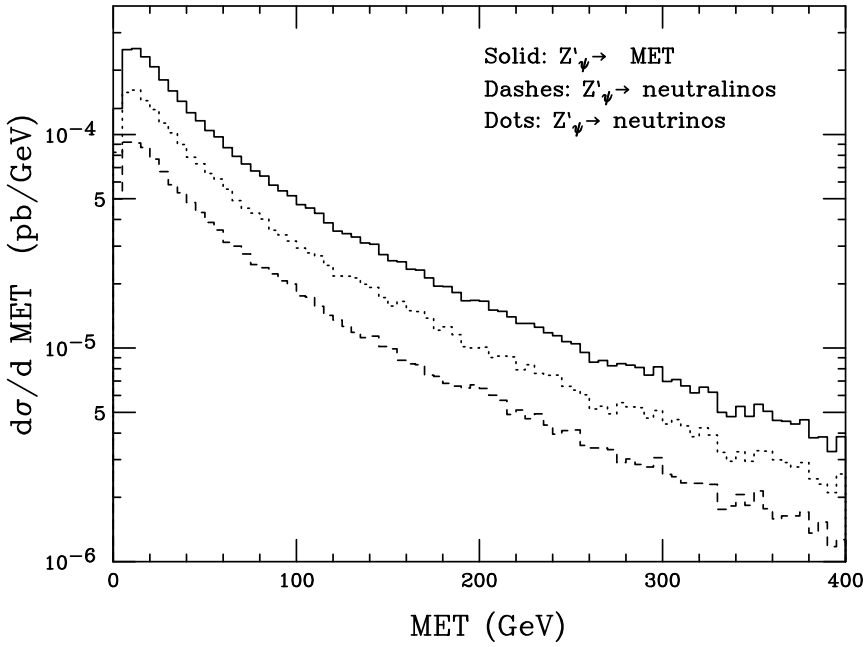
(MadGraph+HERWIG – χ^0_1 mostly higgsino)



$\mathrm{BR}(Z'_\psi \to \tilde{\chi}^0_1 \tilde{\chi}^0_1) \simeq 10\% \Rightarrow \sigma(pp \to Z'_\psi \to \tilde{\chi}^0_1 \tilde{\chi}^0_1) \simeq 6.4 \times 10^{-3}$ pb at 14 TeV

$N \simeq 640$ (100 fb^{-1}) or 2×10^3 (300 fb^{-1}) with possible Dark Matter candidates

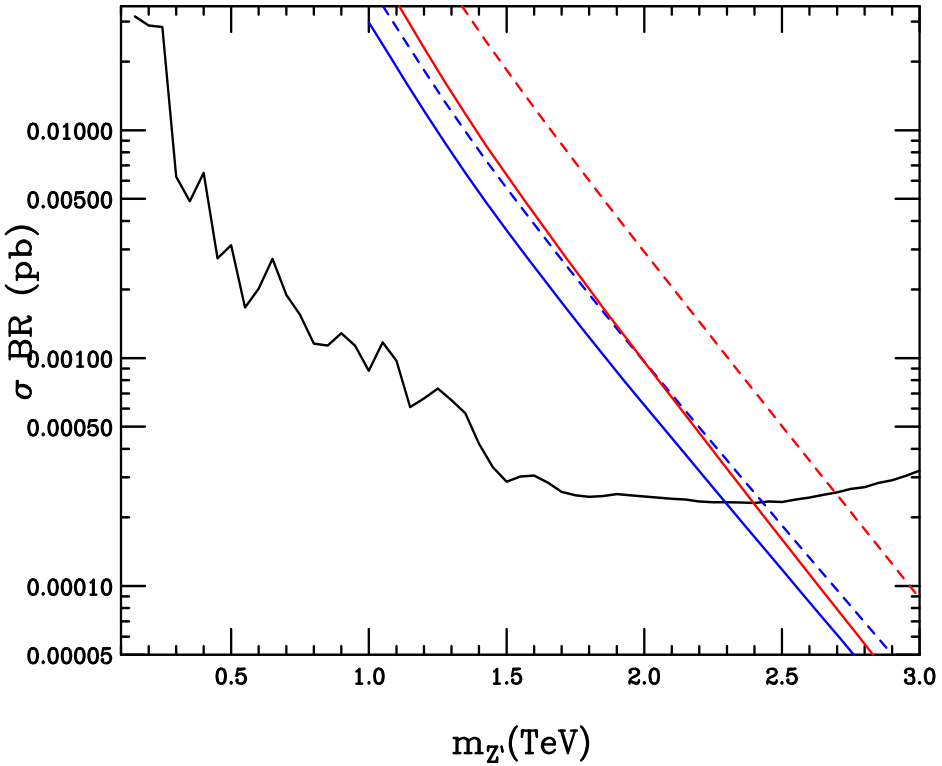
Competitive process: $Z'_\psi \to \nu\bar{\nu}$: $\sigma \simeq 1.1 \times 10^{-2}$; $N \simeq \mathcal{O}(10^3)$

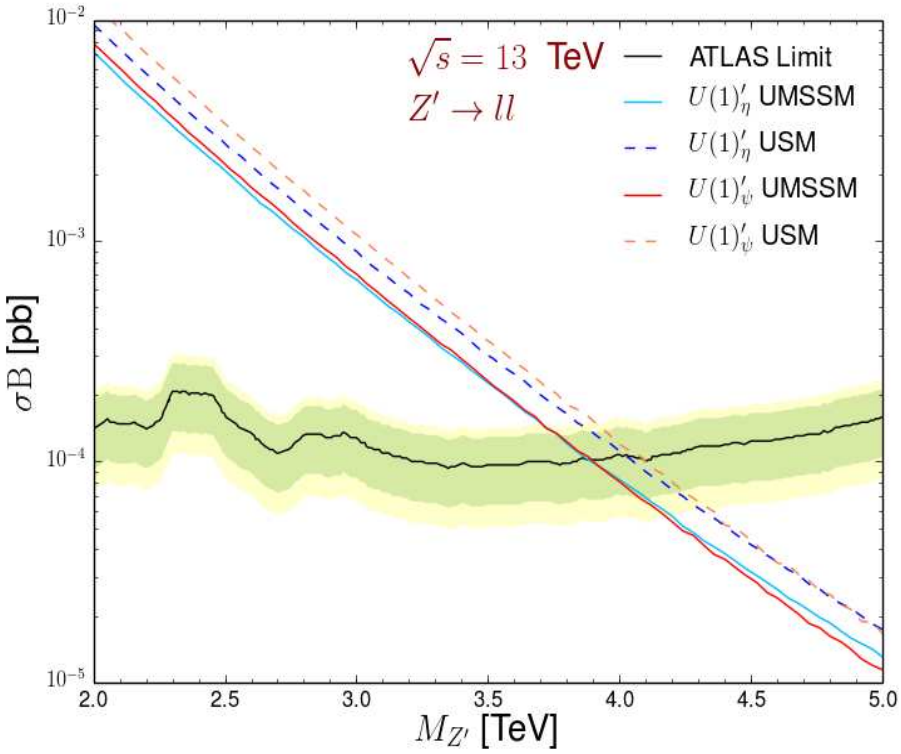


Similar shapes ($m_{\tilde{\chi}^0_1} \ll m_{Z'}$), but $\sigma(pp \to \mathrm{MET})$ increases by 60% adding neutralinos

In progress: implementation of jet/photon clustering algorithms

Mass exclusion limits in the SUSY reference point





Solid: SM+BSM decays ; Dashes: only SM decays;

Left: ATLAS at 7 TeV Red: $Z'_{\rm SSM}$; Blue: Z'_ψ

Right: ATLAS at 13 TeV Red: Z'_ψ; Blue: Z'_η (Plot by J.Araz, preliminary)

Excluded-mass shift: $Z'_{\rm SSM}$: $\Delta m \simeq 300$ GeV ; $Z'_{\psi,\eta}$: $\Delta m \simeq 200$ GeV

Bilepton Model (Frampton'92, Pisano-Pleitez'92) : $SU(3)_c \times SU(3)_L \times U(1)_X$

$$\text{Fermions}: Q_1 = \begin{pmatrix} u_L \\ d_L \\ D_L \end{pmatrix},\ Q_2 = \begin{pmatrix} c_L \\ s_L \\ S_L \end{pmatrix},\ Q_{1,2} \in (3, 3, -1/3),\quad q(D,S) = -\frac{4}{3}$$

$$Q_3 = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix},\quad Q_3 \in (3, \bar{3}, 2/3),\quad q(T) = +\frac{5}{3},\quad \ell = \begin{pmatrix} \ell_L \\ \nu_\ell \\ \bar{\ell}_R \end{pmatrix},\quad \ell \in (1, \bar{3}, 0)$$

$(d, s, b)_R \in (\bar{3}, 1, 1/3)$, $(u, c, t)_R \in (\bar{3}, 1, \text{-}2/3)$, $(D, S)_R \in (\bar{3}, 1, 4/3)$, $T_R \in (\bar{3}, 1, -5/3)$

$$\text{Scalars}: \ \rho = \begin{pmatrix} \rho^{++} \\ \rho^{+} \\ \rho^{0} \end{pmatrix} \in (1, 3, 1),\ \eta = \begin{pmatrix} \eta^{+} \\ \eta^{0} \\ \eta^{-} \end{pmatrix} \in (1, 3, 0),\ \chi = \begin{pmatrix} \chi^{0} \\ \chi^{-} \\ \chi^{--} \end{pmatrix} \in (1, 3, -1)$$

Anomaly cancellation between families as $N_C = N_{\text{families}}$; asymmetric 3rd family

Electroweak symmetry breaking : $SU(3)_L \times U(1)_X \to SU(2)_L \times U(1)_Y \to U(1)_{\text{em}}$

ρ^0, η^0 and χ^0 get vevs and give mass to new vector bosons Z', $Y^{\pm,\pm}$ and $Y^{\pm}$

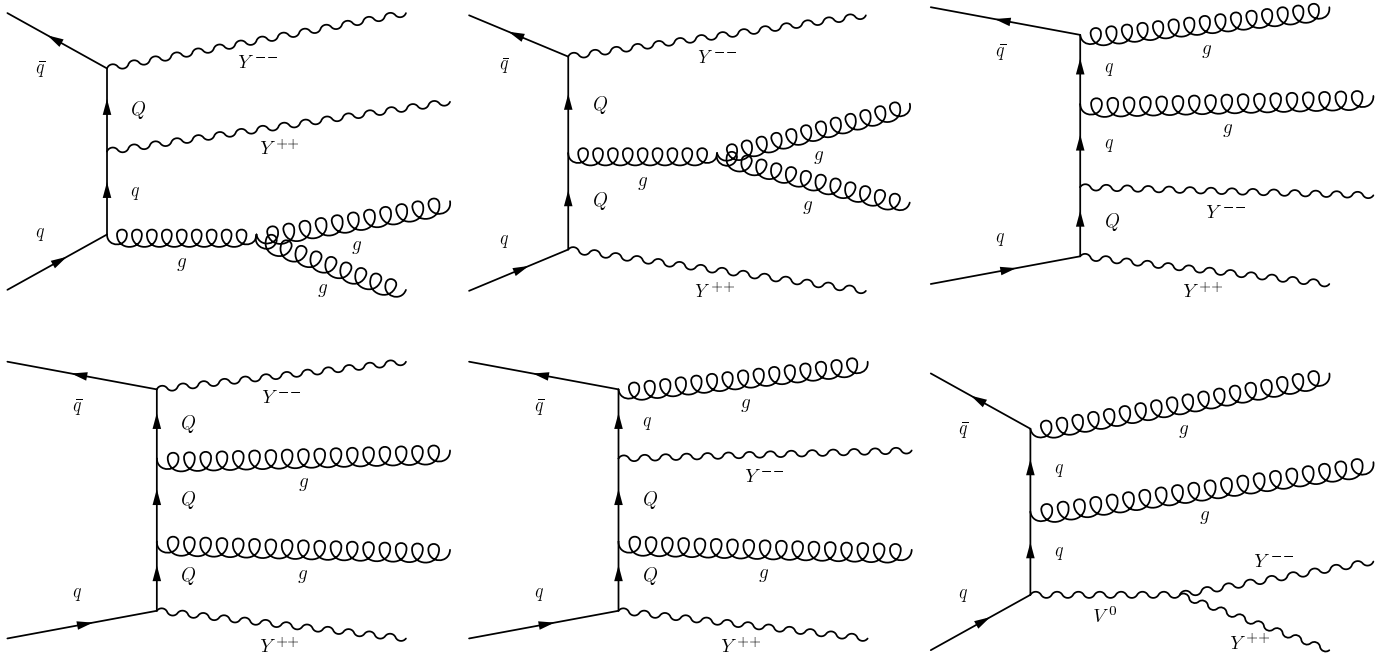
(Y^{++}, Y^{+}) (Y^{--}, Y^{-}) bileptons $L_Y = \pm 2$ m_Y >250-550 GeV from $H^{\pm,\pm}$ Nepomuceno'16

D, S and T: exotic quarks with $L(D, S) = +2$ and $L(T) = -2$

Higgs sector: h_1, h_2, h_3 (scalar); a_1 (pseudoscalar); $h_1^{\pm}$, $h_2^{\pm}$ and $h_1^{\pm\pm}$

Benchmark Point (SARAH)		
$m_{h_1} = 125.1$ GeV	$m_{h_2} = 3172$ GeV	$m_{h_3} = 3610$ GeV
$m_{a_1} = 3595$ GeV		
$m_{h_1^\pm} = 1857$ GeV	$m_{h_2^\pm} = 3590$ GeV	
$m_{h_1^{\pm\pm}} = 3734$ GeV		
$m_{Y^{\pm\pm}} = 873.3$ GeV	$m_{Y^\pm} = 875.7$ GeV	
$m_{Z'} = 3229$ GeV		
$m_D = 1650$ GeV	$m_S = 1660$ GeV	$m_T = 1700$ GeV

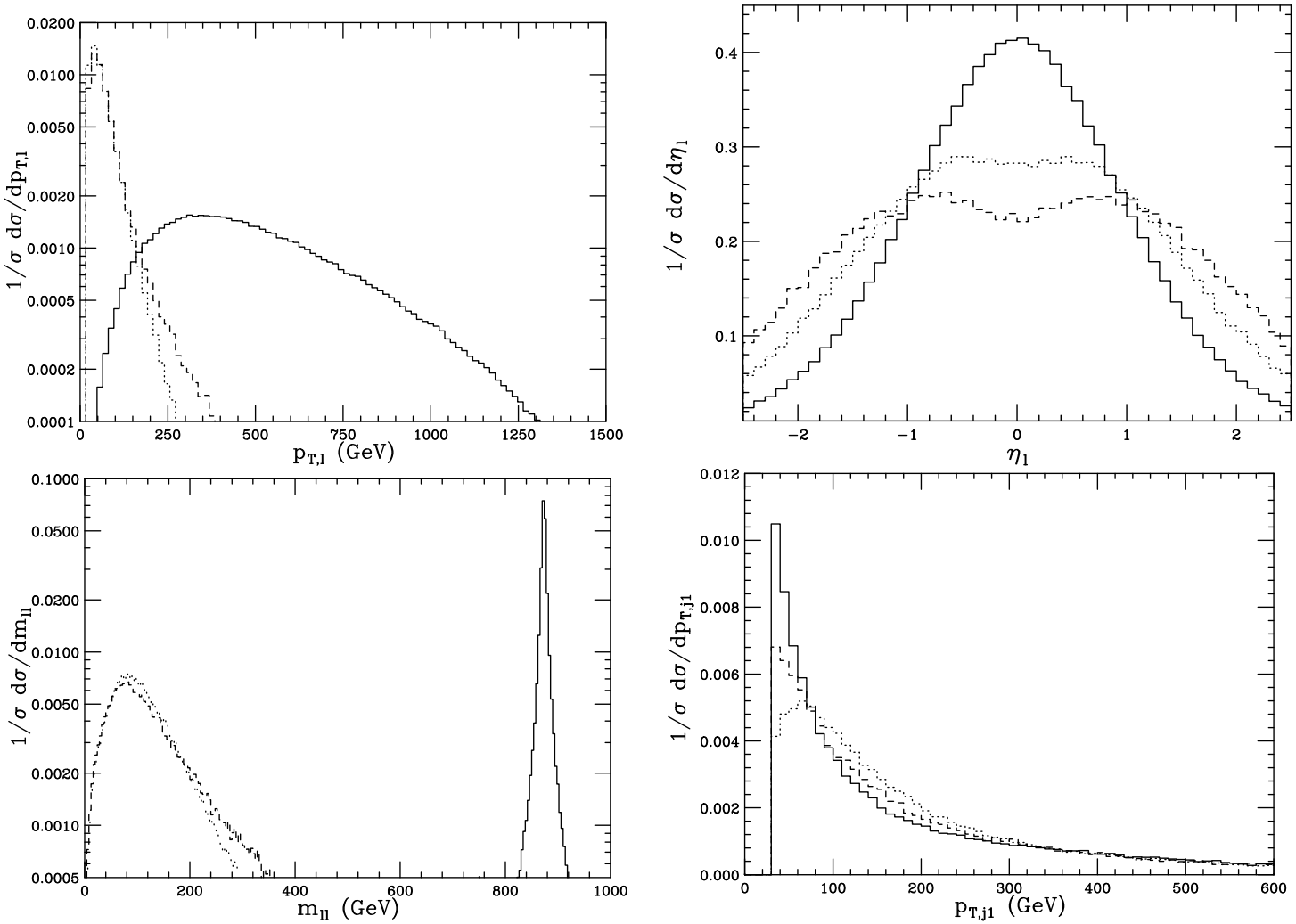
Final states with 2 jets and 2 same-sign leptons: $pp \to Y^{++}Y^{--}jj \to (\ell^+\ell^+)(\ell^-\ell^-)jj$



Simulation with MadGraph+HERWIG, $\sqrt{s} = 13$ TeV, k_T algorithm, $R = 1$

$p_{T,j} > 30$ GeV, $p_{T,\ell} > 20$ GeV, $|\eta_j| < 4.5$, $|\eta_\ell| < 2.5$, $\Delta R_{jj} > 0.4$, $\Delta R_{\ell\ell} > 0.1$, $\Delta R_{j\ell} > 0.4$

$\sigma(YYjj) \simeq 3.7$ fb; $\sigma(t\bar{t}Z) \simeq 8.6$ fb; $\sigma(ZZjj) \simeq 6.4$ fb (MET< 100 GeV for $t\bar{t}Z$)



Solid: signal; dashes: $ZZjj$; dots: $t\bar{t}Z$ (Acknowledgement to Lecce ATLAS group)

Dutta-Nandi '94, Dion et al '99, Barreto et al '09-'13, Alves et al '12, Nepomuceno'16: related work on 331 phenomenology

Conclusions and outlook

Investigation on non-standard Z' and bileptons $Y^{\pm\pm}$ at LHC

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

Discrimination from Z' dilepton decays and other supersymmetric modes is feasible

Z' decays into the lightest neutralinos channel: Dark Matter candidates

$(\Delta m_{Z'})_{\min} \approx$ 200-300 GeV for a reference point in the parameter space

Bilepton signal in final states with 2 jets and 2 same-sign charged-lepton pairs

SM background can be easily suppressed

In progress:

Implementation of Z' leptophobic model to enhance SUSY rates

Investigation of DM signals in mono-X events

QCD effects in production and decays of both Z' and $Y^{\pm,\pm}$ (NLO and resummations)

Investigation of further properties of the bilepton model

Discussion with exotics/SUSY WGs to undertake an actual experimental search