

Supersymmetric signals in Z' decays

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

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 dilepton resonances

CMS (13 TeV): $\mathcal{L}=13 \text{ fb}^{-1} \Rightarrow m(Z'_{\text{SSM}}) > 4.0 \text{ TeV} , m(Z'_{\text{GUT}}) > 3.50 \text{ TeV}$

ATLAS (13 TeV): $\mathcal{L}=13.3 \text{ fb}^{-1} \Rightarrow m(Z'_{\text{SSM}}) > 4.05 \text{ TeV} , m(Z'_{\text{GUT}}) > 3.36\text{-}3.66 \text{ TeV}$

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

Supersymmetric Z' decays allow study of unexplored phase space

Decays $Z' \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$: 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:

$$E_6 \rightarrow SO(10) \times U(1)'_{\psi} \rightarrow SU(5) \times U(1)'_{\chi} \times U(1)'_{\psi}$$

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

$$E_6 \rightarrow SM \times U(1)'_{\eta} \quad \theta = \arccos \sqrt{5/8} \Rightarrow Z'_{\eta}$$

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**, $\theta \rightarrow \theta + \arctan 15$)

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'

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

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: $\tilde{\chi}_1^0, \dots, \tilde{\chi}_6^0$ ($\tilde{\chi}_{5,6}^0$ 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)

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

New Z' decay modes besides the SM ones:

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

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

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

$$U(1)'_\psi: m_{\tilde{\ell}}^0 = m_{\tilde{\nu}_\ell}^0 = 1.2 \text{ TeV}, \quad m_{\tilde{q}}^0 = 5.5 \text{ TeV} \quad (q = u, d, c, s),$$

$$m_{\tilde{b}}^0 = m_{\tilde{t}}^0 = 2.2 \text{ TeV} \quad (q_{1,2} \simeq q_{L,R}, \ell_{1,2} \simeq \ell_{L,R}) \quad \text{A. Arbey et al, arXiv:1112.3028}$$

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

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

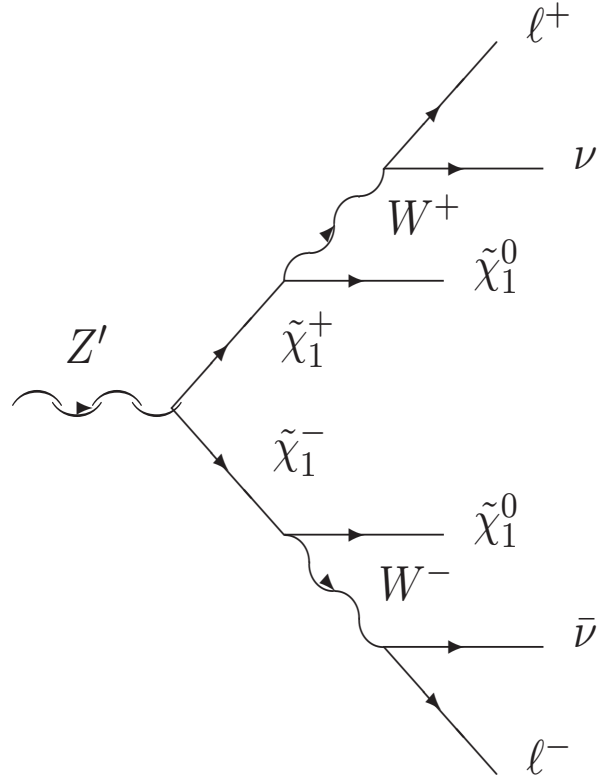
Branching ratios of Z'_ψ into SM ($\sim 70\%$) and BSM ($\sim 30\%$) final states

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

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

Final State	$\tilde{\chi}_1^+$ 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



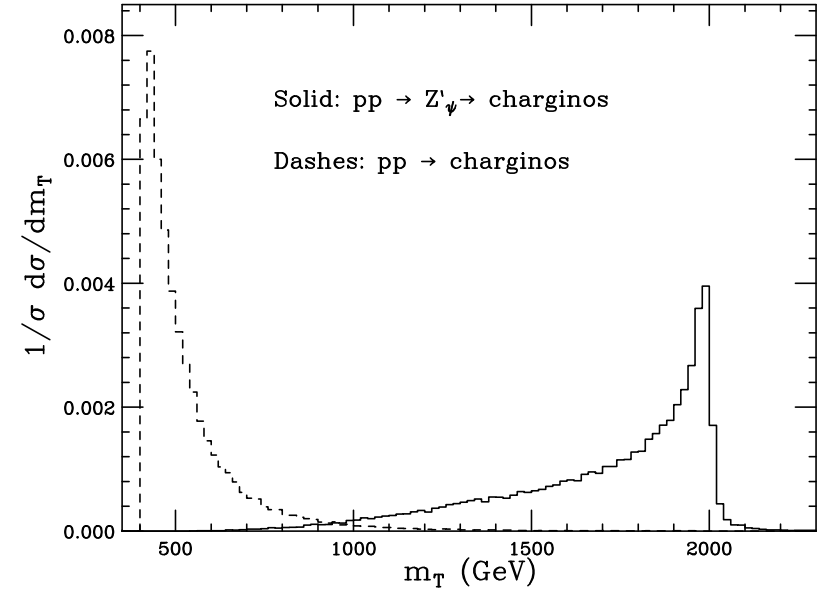
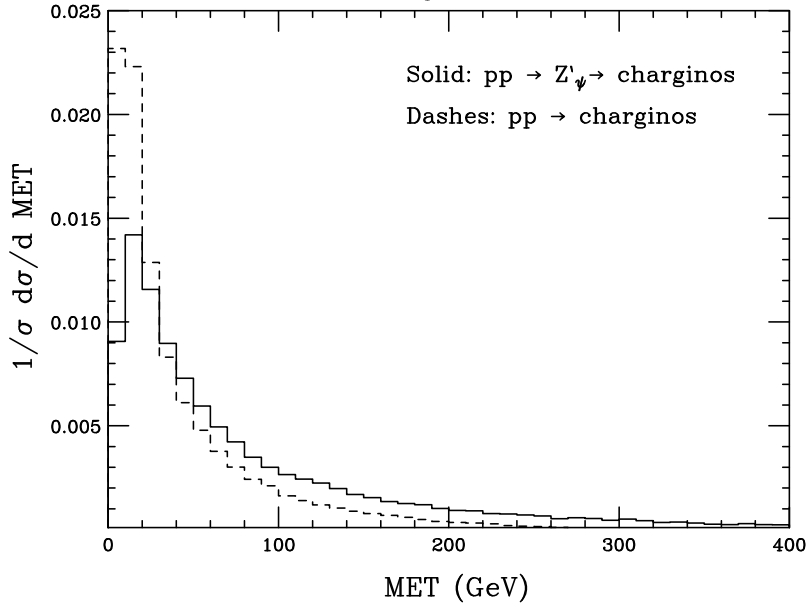
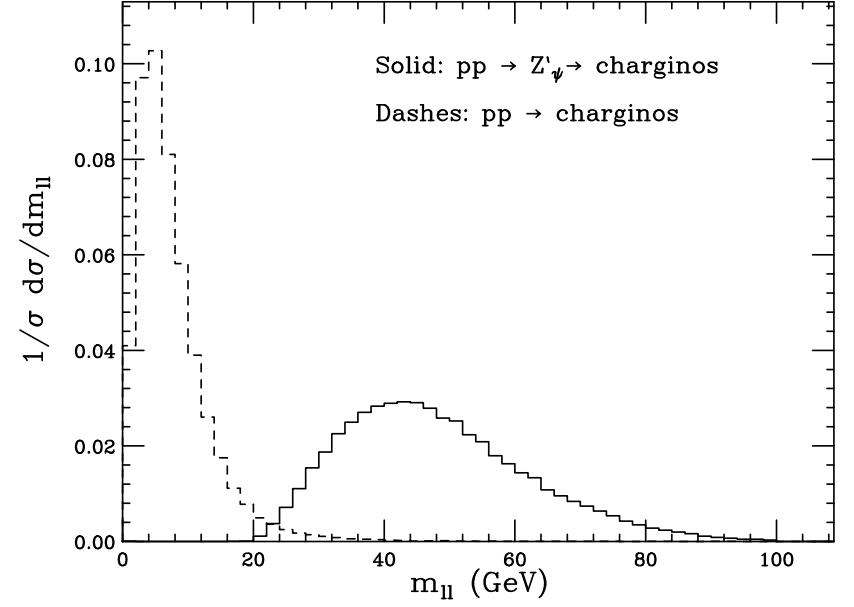
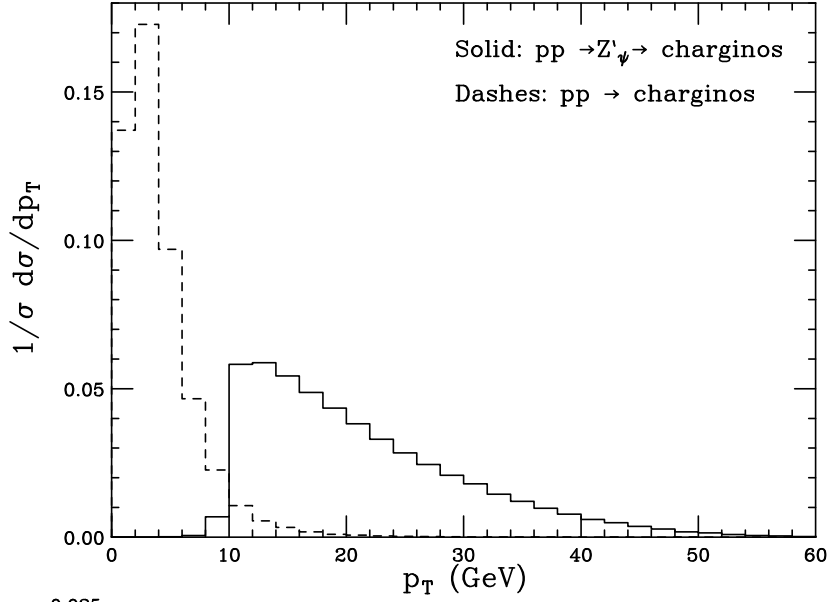
In the reference point, at $\sqrt{s} = 14$ TeV, using MadGraph and LO CTEQL1:

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

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

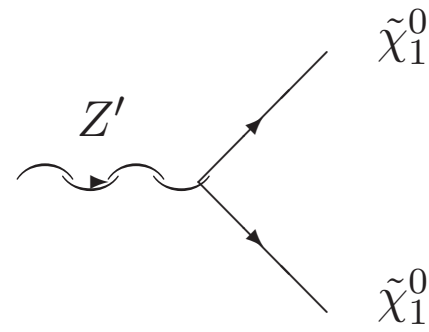
$$\text{Competitive process: } pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (\tilde{\chi}_1^0 \ell^+ \nu_\ell)(\tilde{\chi}_1^0 \ell^- \bar{\nu}_\ell) \quad (\sigma \simeq 1.15 \times 10^{-2} \text{ pb})$$

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



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

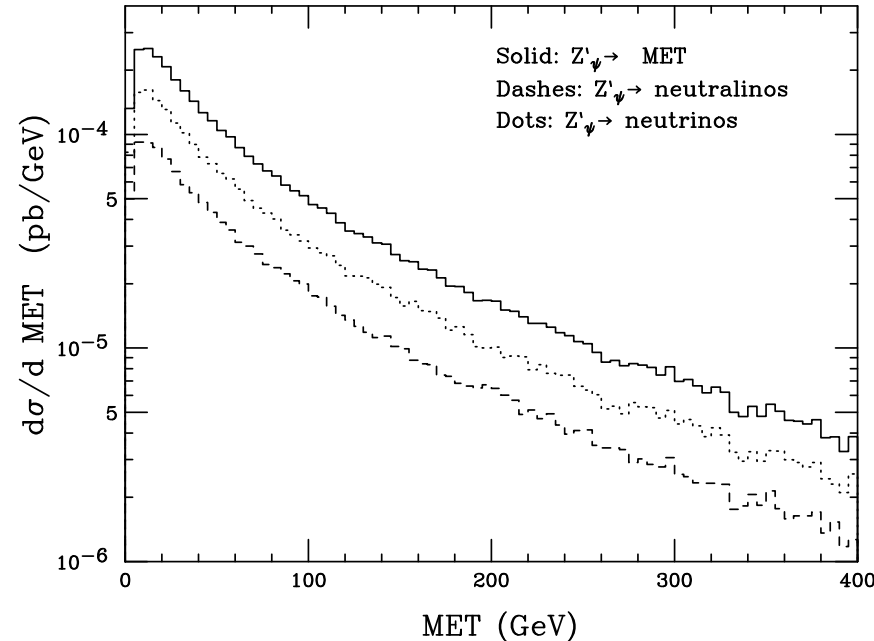
DM signals in Z' decays: $Z'_\psi \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$
(MadGraph+HERWIG – $\tilde{\chi}_1^0$ mostly higgsino)



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

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

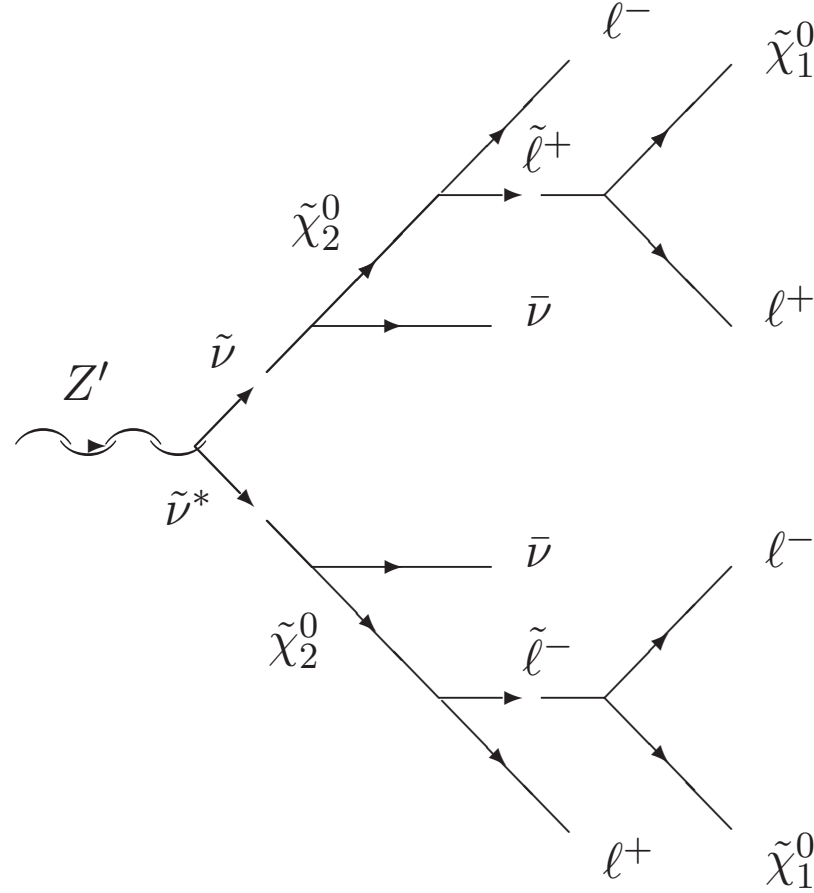
Competitive process: $Z'_\psi \rightarrow \nu \bar{\nu}$: $\sigma \simeq 1.1 \times 10^{-2}$; $N \simeq \mathcal{O}(10^3)$



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

In progress: implementation of jet/photon clustering algorithms

$U(1)'_{\eta}$: $Z' \rightarrow \tilde{\nu}\tilde{\nu}^*$ yields the highest rate:



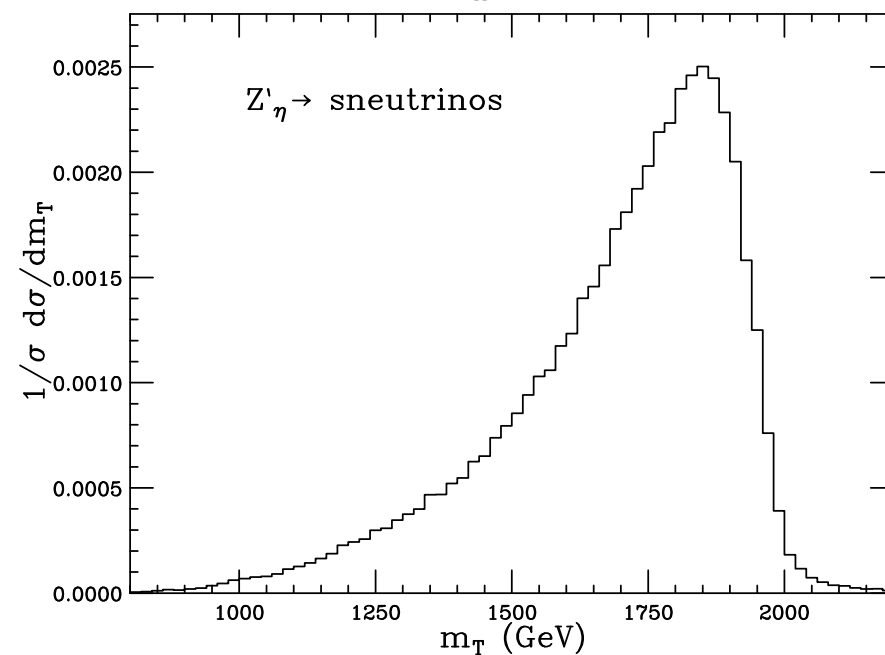
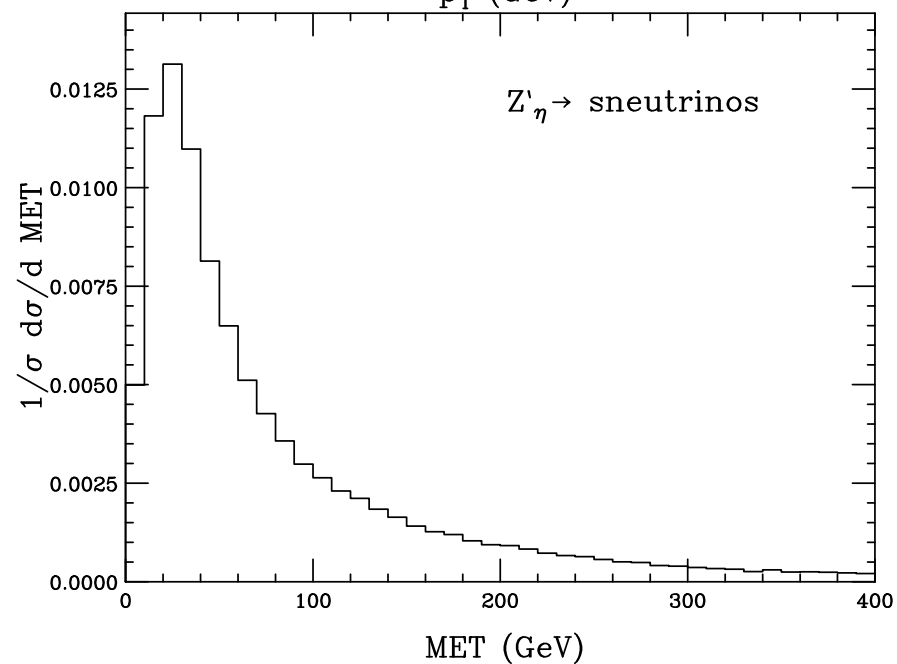
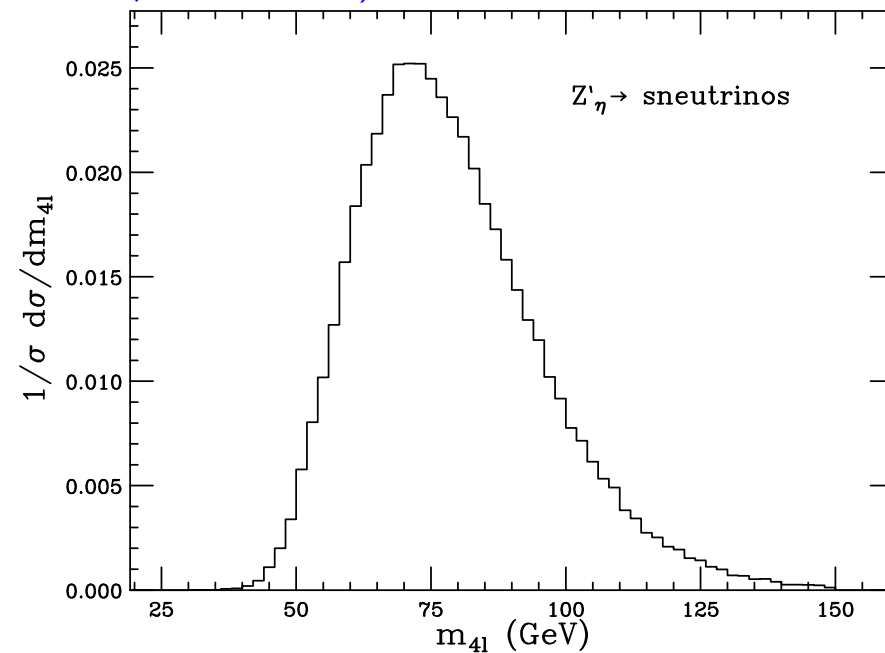
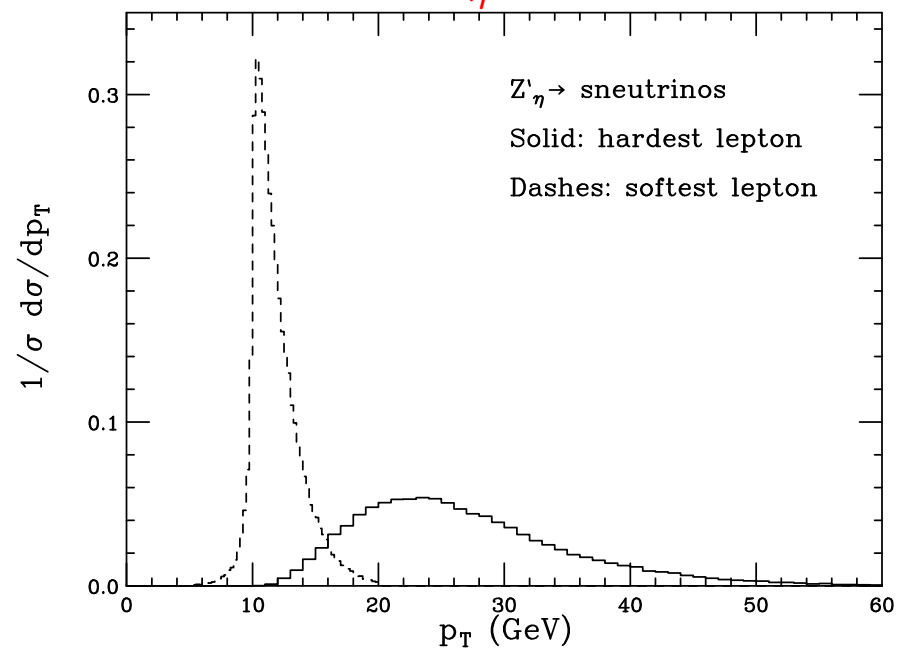
In the reference point, at $\sqrt{s} = 14$ TeV (MadGraph and LO CTEQL1):

$$\sigma(pp \rightarrow Z'_{\eta}) \simeq 0.18 \text{ pb} ; \text{BR}(Z'_{\eta} \rightarrow \tilde{\nu}_2 \tilde{\nu}_2^*) \simeq 9.4\%$$

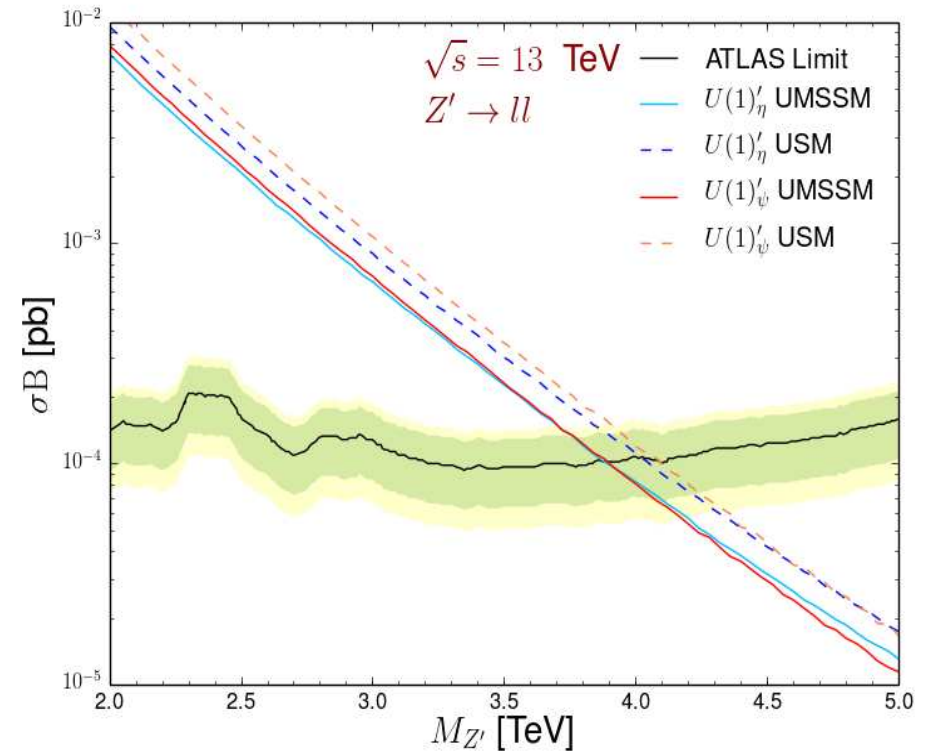
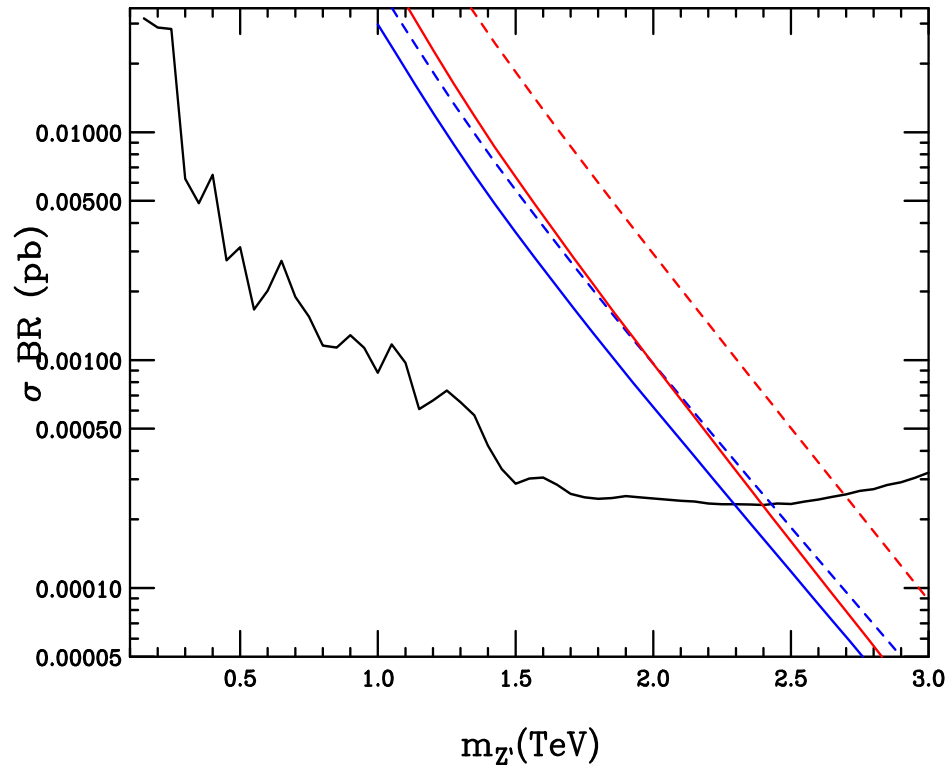
$$\text{BR}(\tilde{\nu}_2 \rightarrow \tilde{\chi}_2^0 \nu_2) \times \text{B}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-) \simeq 3.3\%$$

$$\sigma(pp \rightarrow Z'_{\eta} \rightarrow 4\ell + \text{MET}) \simeq 1.90 \times 10^{-4} \text{ pb} \Rightarrow N \simeq 20 (100 \text{ fb}^{-1}), N \simeq 60 (300 \text{ fb}^{-1})$$

Phenomenology - $Z'_\eta \rightarrow$ sneutrinos (MadGraph+HERWIG - $\sqrt{s} = 14$ TeV)



Mass exclusion limits in the SUSY reference point



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

Left: ATLAS at 7 TeV Red: Z'_{SSM} ; Blue: Z'_{ψ}

Right: ATLAS at 13 TeV Red: Z'_{ψ} ; Blue: Z'_{η} (Plot by J.Araz, preliminary)

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

Conclusions and outlook

Novel investigation on Z' phenomenology in supersymmetry at the LHC

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

BSM branching ratios can be 30% in $U(1)'$ models

Up to $\mathcal{O}(10^3)$ events with leptons and missing energy via Z' decays

Discrimination from dilepton decays and other supersymmetric modes is feasible

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

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

In progress:

Implementation of the leptophobic model to enhance SUSY rates

Investigation of DM signals in mono-X events

Comparison with 13 TeV exclusion limits and Standard Model backgrounds (ALPGEN)

Inclusion of higher-order QCD effects in production and decay cross sections

Same methods can be applied to any Z' decays in BSM channels