

# Searching for supersymmetry in $Z'$ decays at LHC

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

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:

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

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

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

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

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

Model  $Z'_N$ : equivalent to  $Z'_\chi$  with 'unconventional'  $SO(10)$  representations

Model	$\theta$
$Z'_\chi$	$-\pi/2$
$Z'_\psi$	0
$Z'_\eta$	$\arccos \sqrt{5/8}$
$Z'_I$	$\arccos \sqrt{5/8} - \pi/2$
$Z'_N$	$\arctan \sqrt{15} - \pi/2$
$Z'_S$	$\arctan(\sqrt{15}/9) - \pi/2$

Analysis will be carried out for  $Z'_\psi$  and  $Z'_\eta$  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:

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

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

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

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

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

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

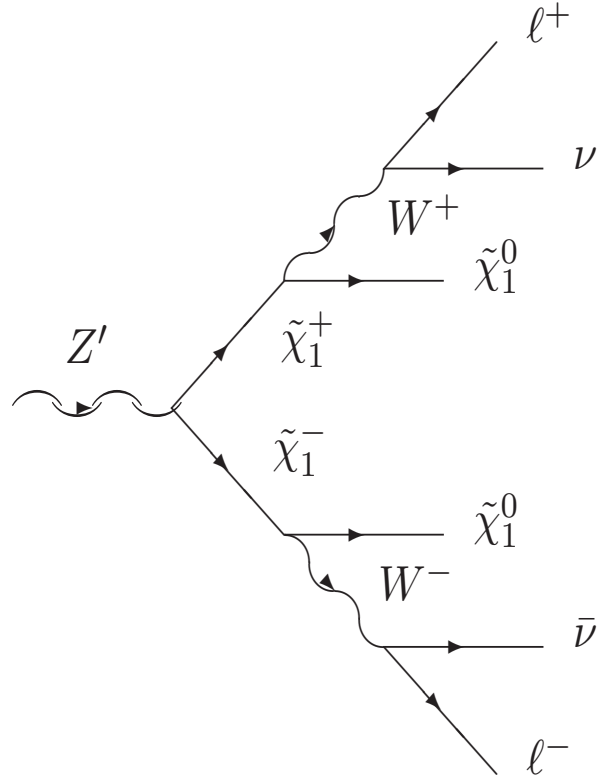
Branching ratios of  $Z'_\psi$  into SM ( $\sim 70\%$ ) and BSM ( $\sim 30\%$ ) final states

Final State	$Z'_\psi$ 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



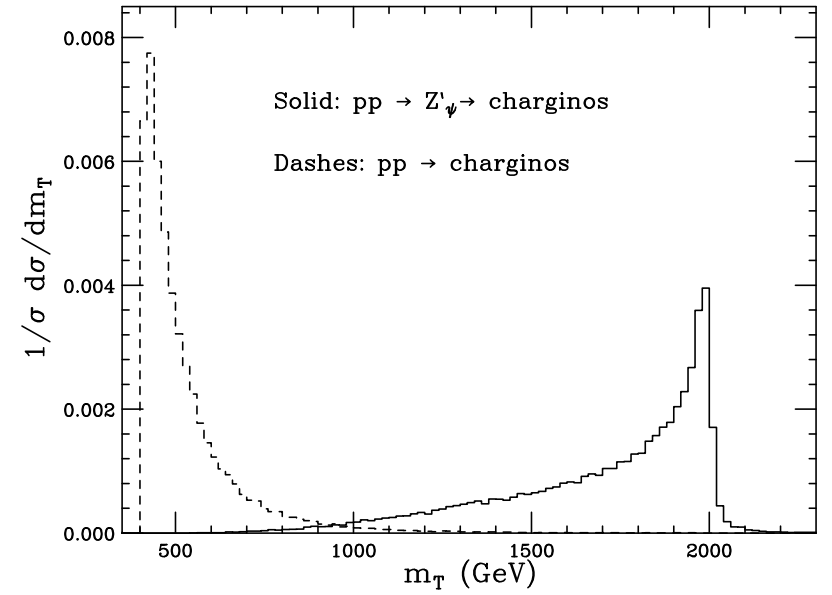
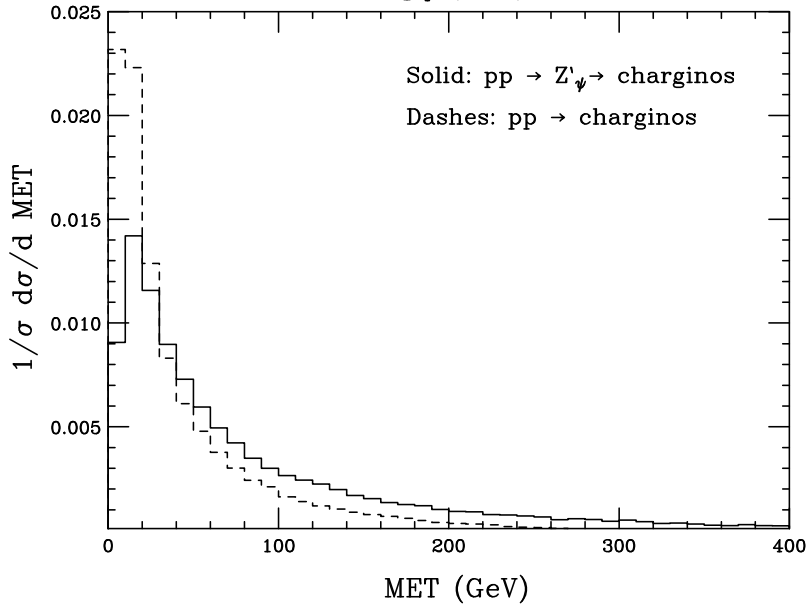
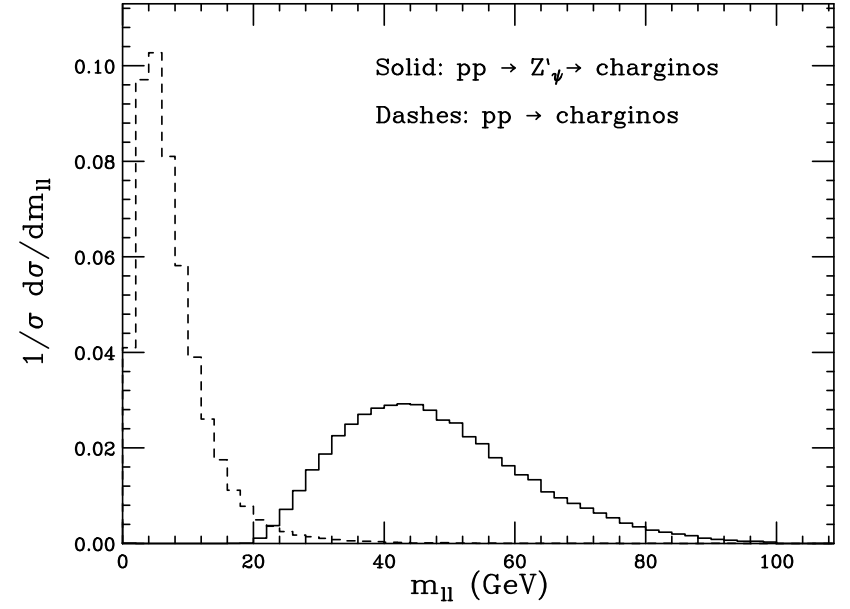
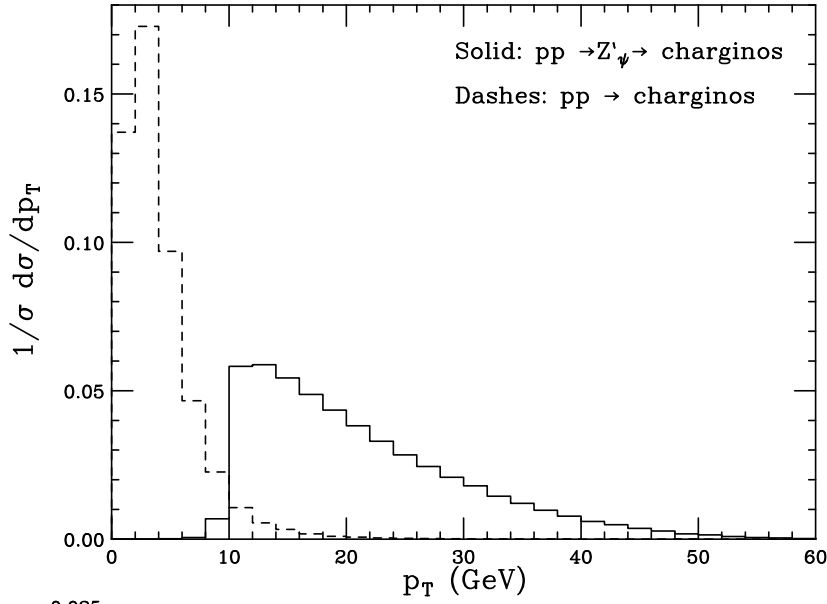
In the reference point, at  $\sqrt{s} = 14$  TeV, using MadGraph and LO CTEQL1:

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

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

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

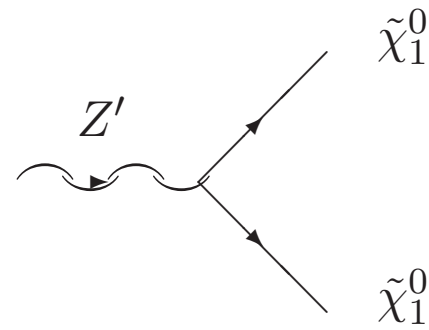
# Phenomenology - $Z'_\psi \rightarrow$ charginos (MadGraph+HERWIG - $\sqrt{s} = 14$ TeV)



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



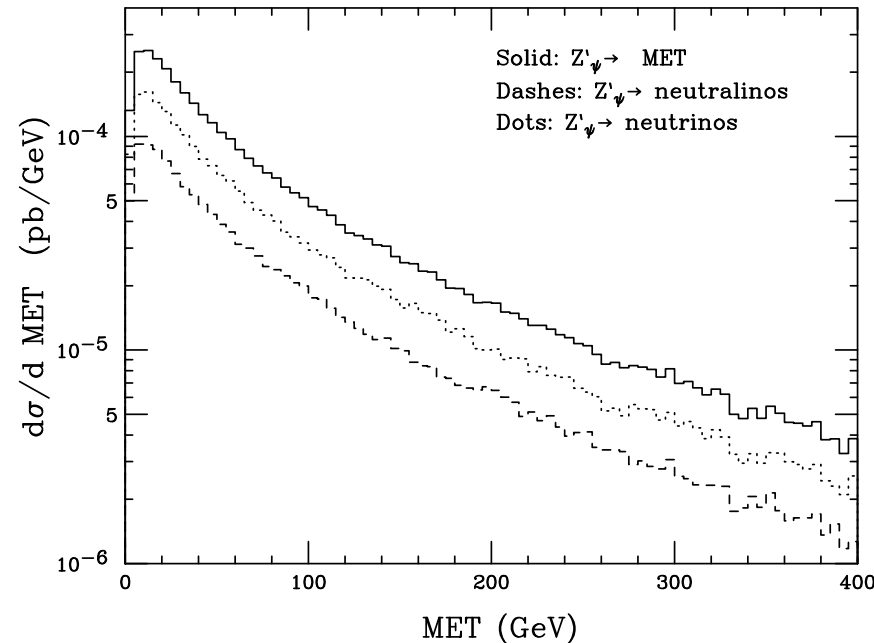
DM signals in  $Z'$  decays:  $Z'_\psi \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$   
 (MadGraph+HERWIG –  $\tilde{\chi}_1^0$  mostly higgsino)



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

$N \simeq 640$  ( $100 \text{ fb}^{-1}$ ) or  $2 \times 10^3$  ( $300 \text{ fb}^{-1}$ ) 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

$U(1)'_{\eta}$  model:  $m_{\tilde{\ell}}^0 = m_{\tilde{\nu}_{\ell}}^0 = 1.5 \text{ TeV}$  ,  $m_{\tilde{q}}^0 = 3 \text{ TeV}$  (degenerate squarks)

$m_{\tilde{d}_1}$	$m_{\tilde{u}_1}$	$m_{\tilde{s}_1}$	$m_{\tilde{c}_1}$	$m_{\tilde{b}_1}$	$m_{\tilde{t}_1}$
3130.8	3129.8	3130.8	3129.8	3130.8	3175.5
$m_{\tilde{d}_2}$	$m_{\tilde{u}_2}$	$m_{\tilde{s}_2}$	$m_{\tilde{c}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{t}_2}$
3065.9	2863.6	3065.9	2863.6	3065.9	2823.5

$m_{\tilde{\ell}_1}$	$m_{\tilde{\ell}_2}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\nu}_{\ell,1}}$	$m_{\tilde{\nu}_{\ell,2}}$	$m_{\tilde{\nu}_{\tau,1}}$	$m_{\tilde{\nu}_{\tau,2}}$
1194.6	1364.5	1208.8	1307.7	1361.8	456.0	1368.0	456.05

$m_h$	$m_H$	$m_{H'}$	$m_A$	$m_{H^+}$
124.9	2004.2	4229.4	4229.4	4230.0

$m_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_2^+}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_5^0}$	$m_{\tilde{\chi}_6^0}$
206.5	882.4	199.3	212.5	408.2	882.3	1562.8	2569.2

Branching ratios of  $Z'_\eta$  into SM ( $\sim 78\%$ ) and BSM ( $\sim 22\%$ ) final states

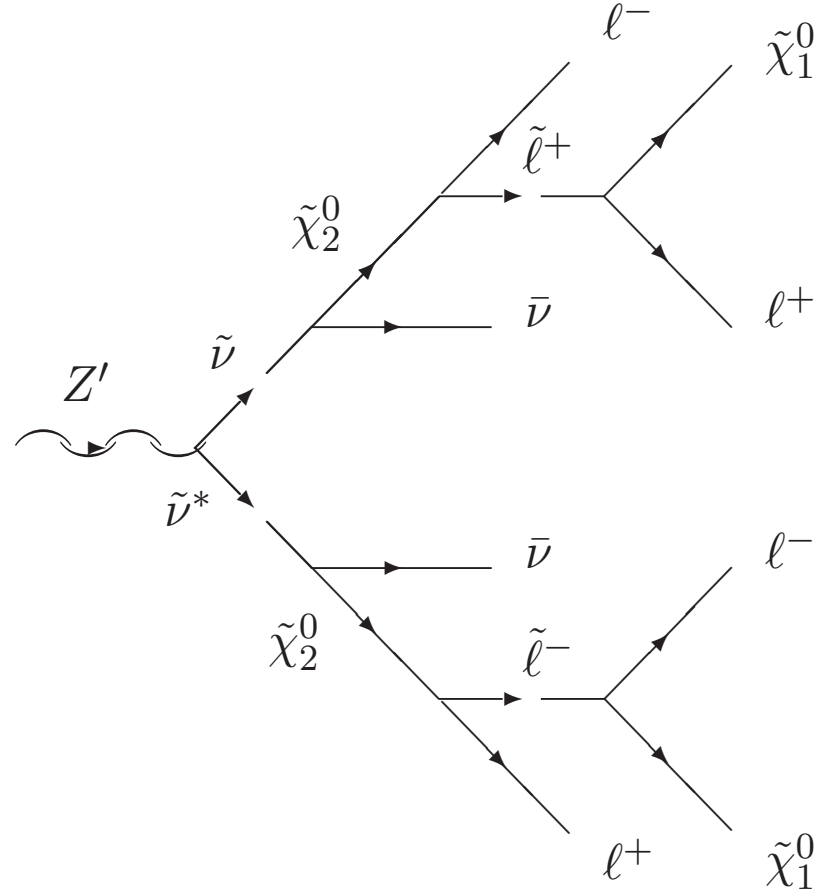
Final State	$Z'_\eta$ Branching ratio (%)
$\tilde{\chi}_1^+ \chi_1^-$	5.6
$\tilde{\chi}_1^0 \tilde{\chi}_1^0$	1.9
$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	2.1
$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	1.5
$\sum_\ell \tilde{\nu}_{\ell,2} \tilde{\nu}_{\ell,2}^*$	9.4
$W^+ W^-$	3.0
$\sum_i q_i \bar{q}_i$	41.6
$\sum_i \nu_i \bar{\nu}_i$	27.8
$\sum_i l_i^+ l_i^-$	5.3

$Z' \rightarrow \tilde{\nu}_2 \tilde{\nu}_2^*$  exhibits the largest branching fraction

$\tilde{\nu}_2$ Final State	Branching ratio (%)	$\tilde{\chi}_2^0$ Final State	Branching ratio (%)
$\tilde{\chi}_1^0 \nu_2$	4.0	$\sum_i \tilde{\chi}_1^0 q_i \bar{q}_i$	63.3
$\tilde{\chi}_2^0 \nu_2$	37.3	$\sum_i \tilde{\chi}_1^0 l_i^+ l_i^-$	13.4
$\tilde{\chi}_3^0 \nu_2$	58.7	$\sum_i \tilde{\chi}_1^0 \nu_i \bar{\nu}_i$	20.6

Main  $\tilde{\chi}_3^0$  decay:  $\text{BR}(\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^\pm W^\mp) \simeq 56\%$

## Final states with leptons and missing transverse energy



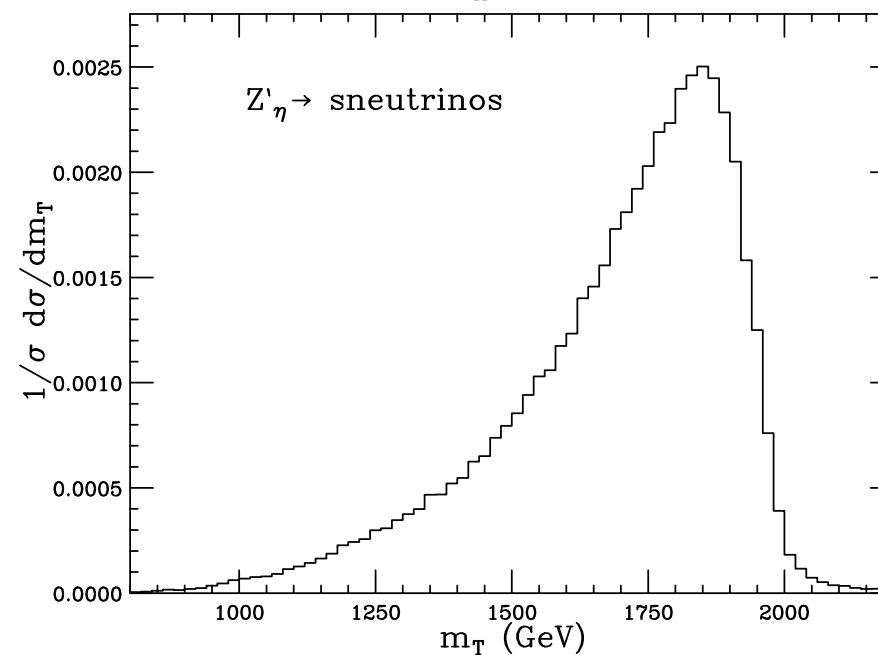
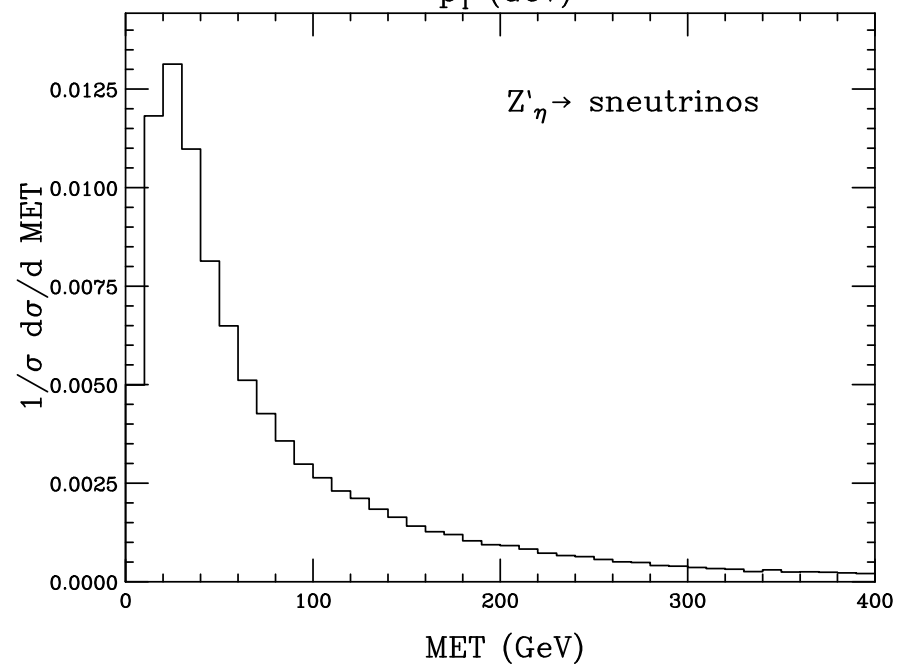
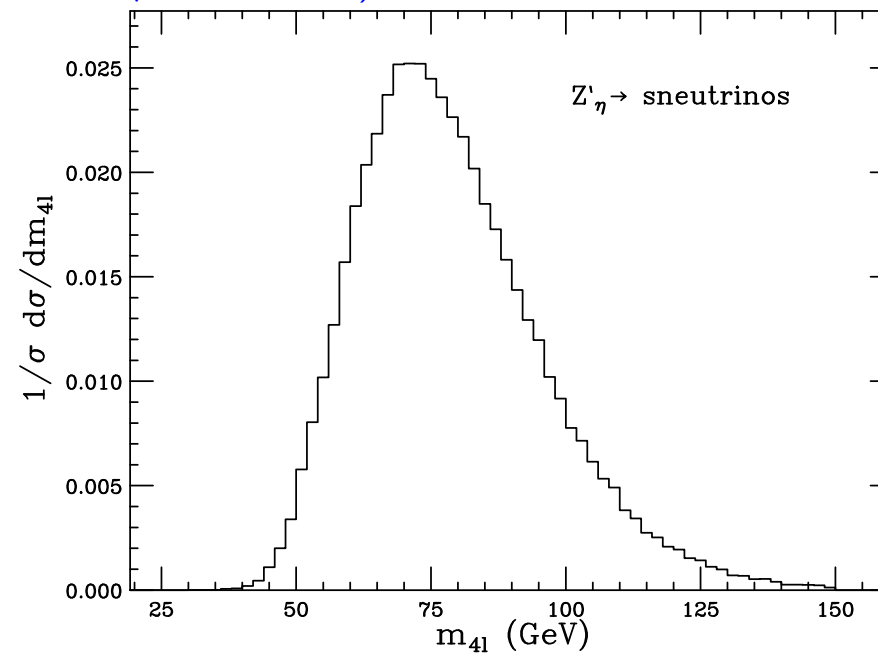
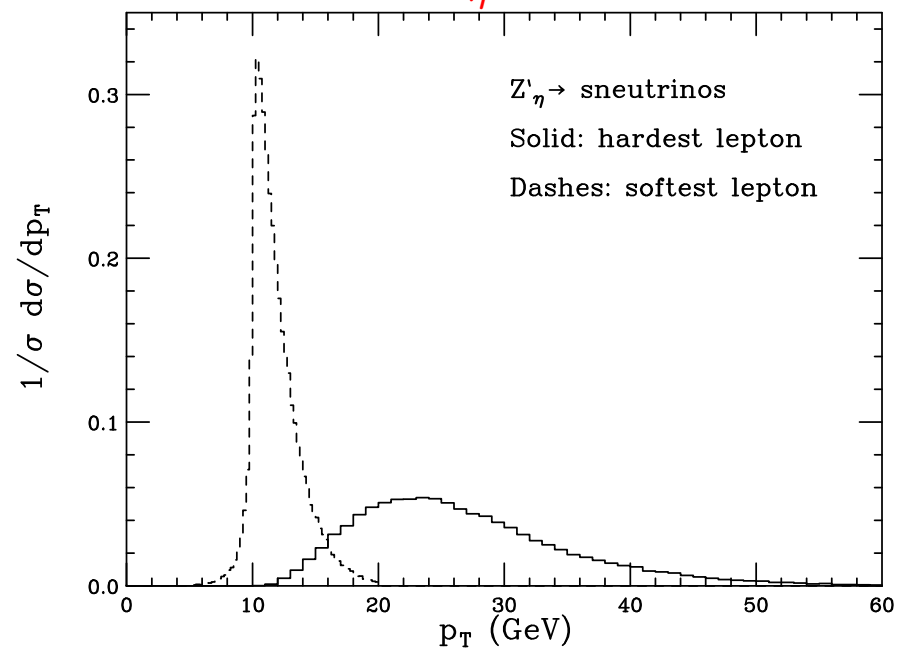
In the reference point, at  $\sqrt{s} = 14$  TeV (MadGraph and LO CTEQL1):

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

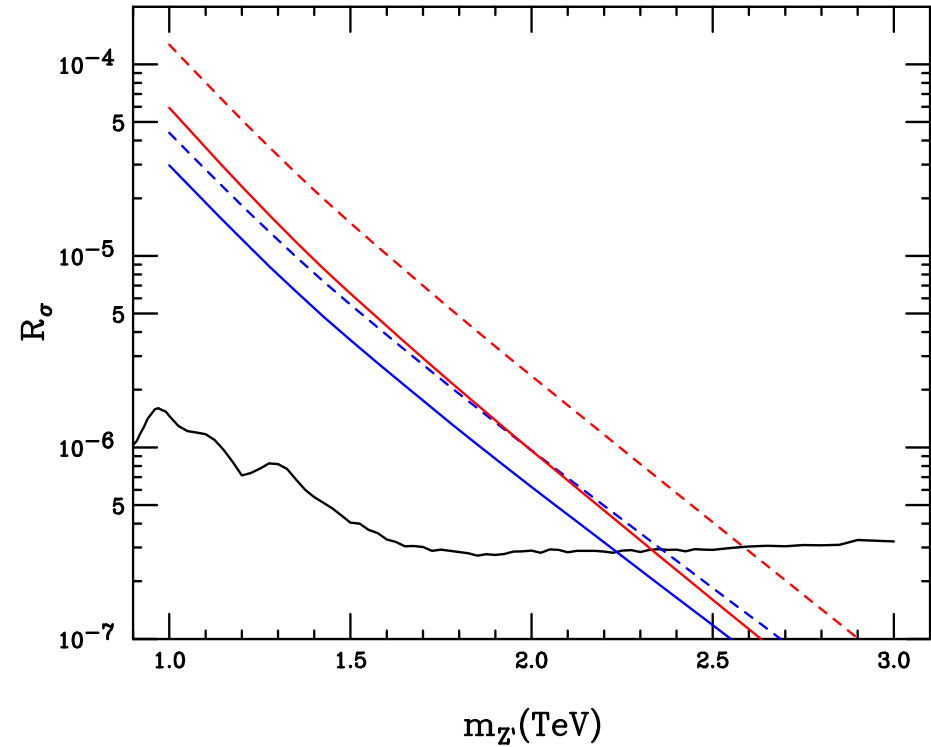
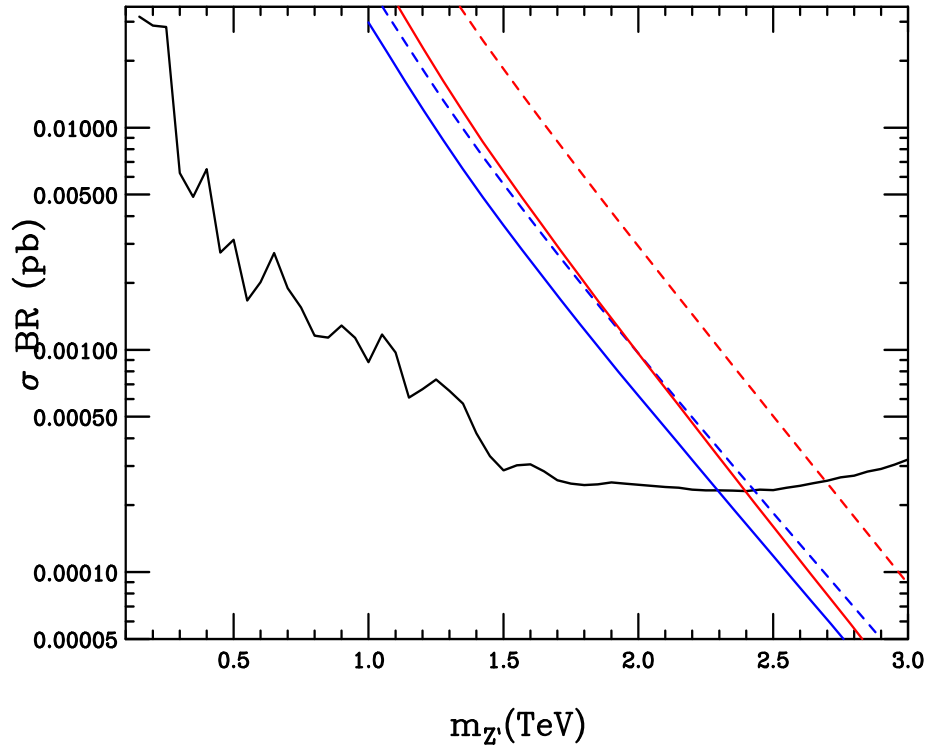
$$\text{BR}(\tilde{\nu}_2 \rightarrow \tilde{\chi}_2^0 \nu_2) \times \text{B}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-) \simeq 3.3\%$$

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

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



# Mass exclusion limits in the SUSY reference point (Run I data)



Solid: SM+BSM decays ; Dashes: only SM decays;  $R_\sigma = (\sigma BR)_{Z'}/(\sigma BR)_Z$

Black: CMS (right) and ATLAS (left) 95% C.L. limits; Red:  $Z'_{SSM}$ ; Blue:  $Z'_\psi$

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

In progress: extension to 13 TeV and comparison with the latest LHC data

## 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