Supersymmetric signals in Z' decays at the 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 fb^{-1} $\Rightarrow$ $m(Z'_{\rm SSM}) > 4.0$ TeV , $m(Z'_{\rm GUT}) > 3.50$ TeV

ATLAS (13 TeV): $\mathcal{L}$=36.1 fb^{-1} $\Rightarrow$ $m(Z'_{\rm SSM}) > 4.5$ TeV , $m(Z'_{\rm GUT})$ >3.8-4.1 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:

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

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

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

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

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

Model Z'_N: Z'_χ-like, 'unconventional' SO(10) representations (10 vs 6, $\delta\theta = \arctan 15$)

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

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

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^-, WW

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 $(q_{1,2} \simeq q_{L,R}, \ \ell_{1,2} \simeq \ell_{L,R})$ 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

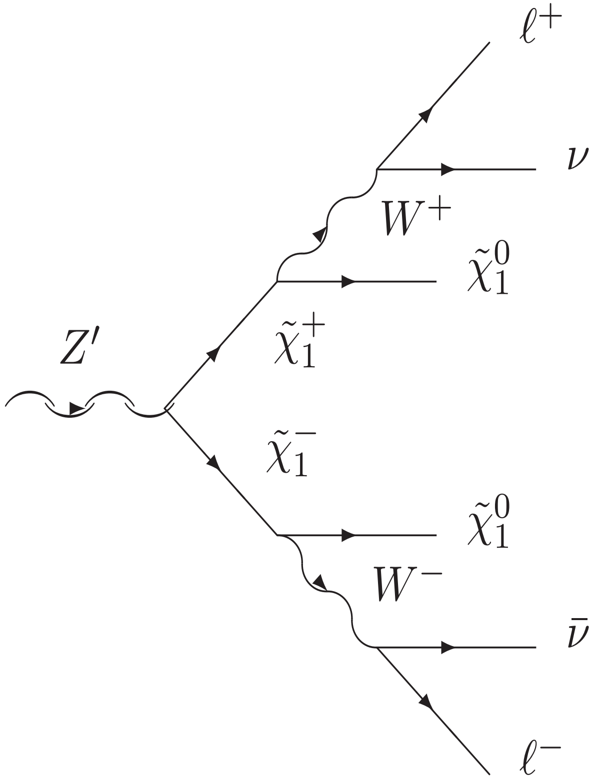
Branching ratios of Z'_ψ into SM ($\sim 70\%$) and BSM ($\sim 30\%$) final states

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



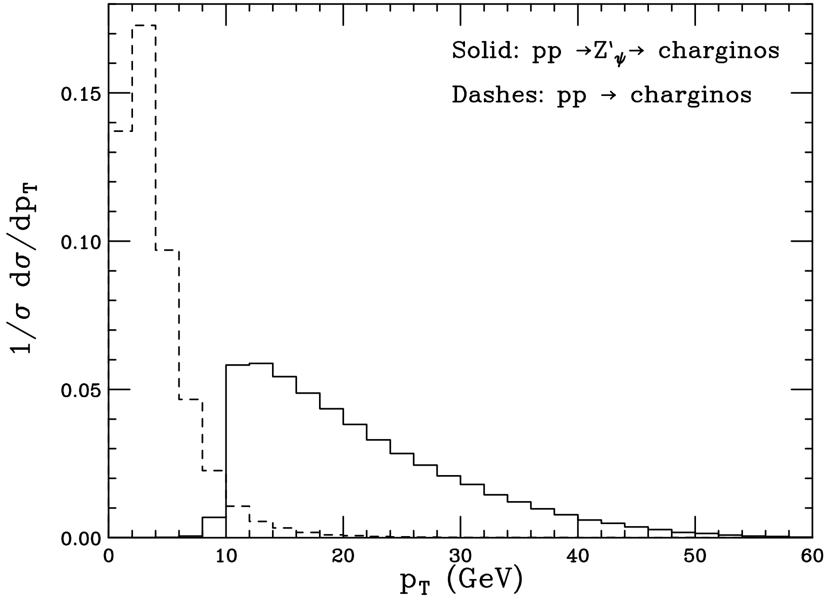
In the reference point, at $\sqrt{s} = 14$ TeV, using MadGraph and LO CTEQL1:

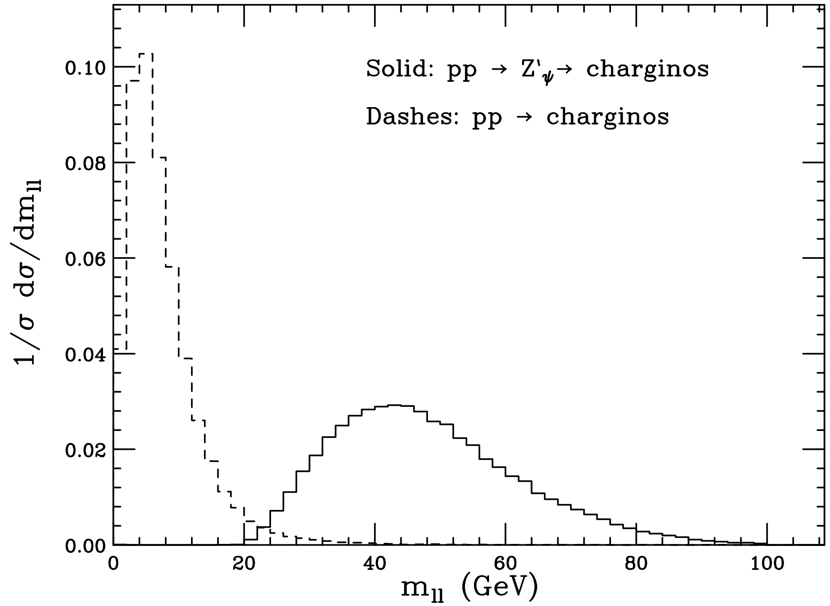
$$\sigma(pp \to Z'_\psi) \simeq 0.13 \text{ pb} \; ; \; \text{BR}(Z'_\psi \to \tilde{\chi}_1^+ \tilde{\chi}_1^-) \simeq 10.2\% \; ; \; \text{BR}(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \ell^+ \nu_\ell) \simeq 24\%$$

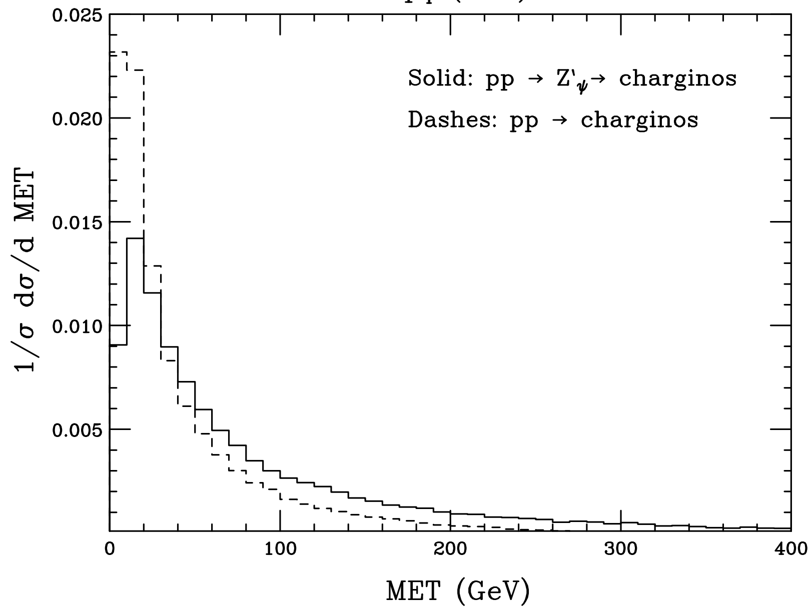
$$\sigma(pp \to Z'_\psi \to \ell^+ \ell^- + \text{MET}) \simeq 8 \times 10^{-4} \, \text{pb} \Rightarrow N \simeq 80 \, (100 \, \text{fb}^{-1}) \, , \, N \simeq 240 \, (300 \, \text{fb}^{-1})$$

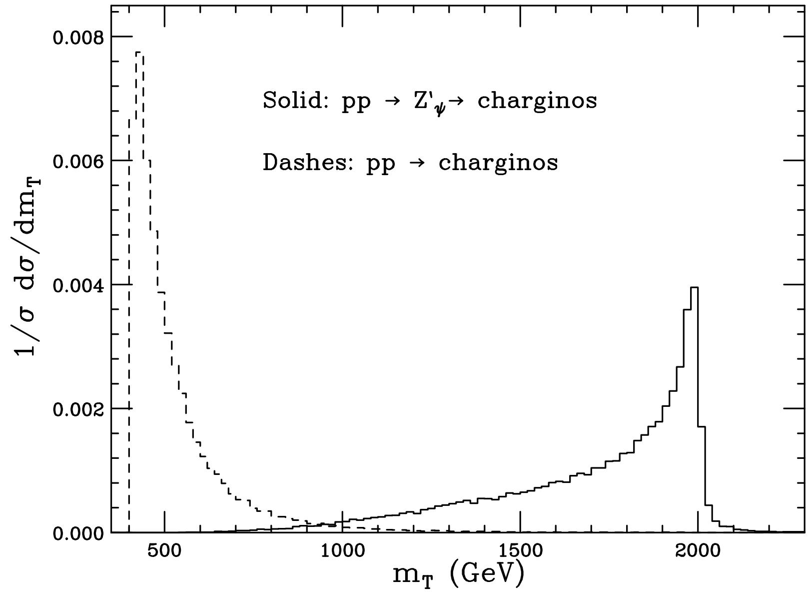
Competitive process: $pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to (\tilde{\chi}_1^0 \ell^+ \nu_\ell)(\tilde{\chi}_1^0 \ell^- \bar{\nu}_\ell)$ ($\sigma \simeq 1.15 \times 10^{-2}$ pb)

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



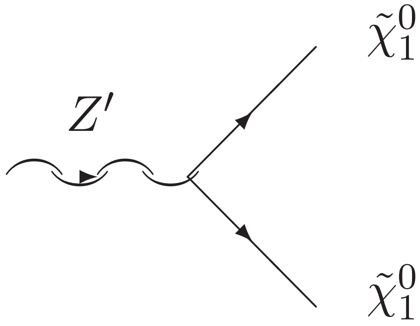






$$\mathrm{MET} = \sqrt{\left(\sum_i p_{x,i}\right)^2 + \left(\sum_i p_{y,i}\right)^2} \quad (i = \nu, \tilde{\chi}_1^0)\ ; \quad m_T = \sqrt{\left(\sum_j E_{T,j}\right)^2 - \left(\sum_j \vec{p}_{T,j}\right)^2} \quad (j = \ell, \nu, \tilde{\chi}_1^0)$$

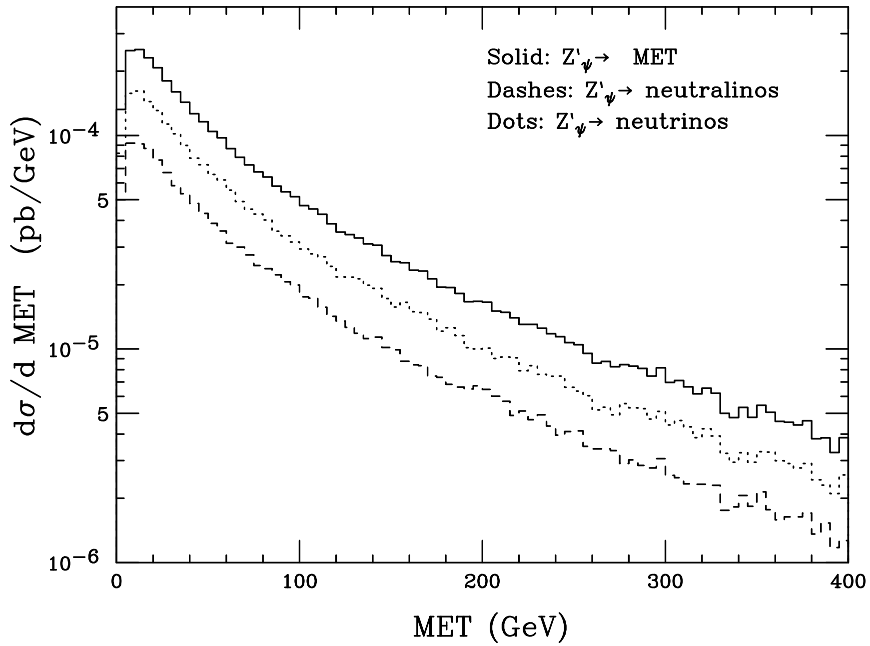
DM signals in Z' decays: $Z'_\psi \to \tilde{\chi}^0_1 \tilde{\chi}^0_1$
(MadGraph+HERWIG – χ^0_1 mostly higgsino)



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

$U(1)'_\eta$ model: $m^0_{\tilde{\ell}} = m^0_{\tilde{\nu}_\ell} = 1.5$ TeV , $m^0_{\tilde{q}} = 3$ 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'_η into SM ($\sim 78\%$) and BSM ($\sim 22\%$) final states

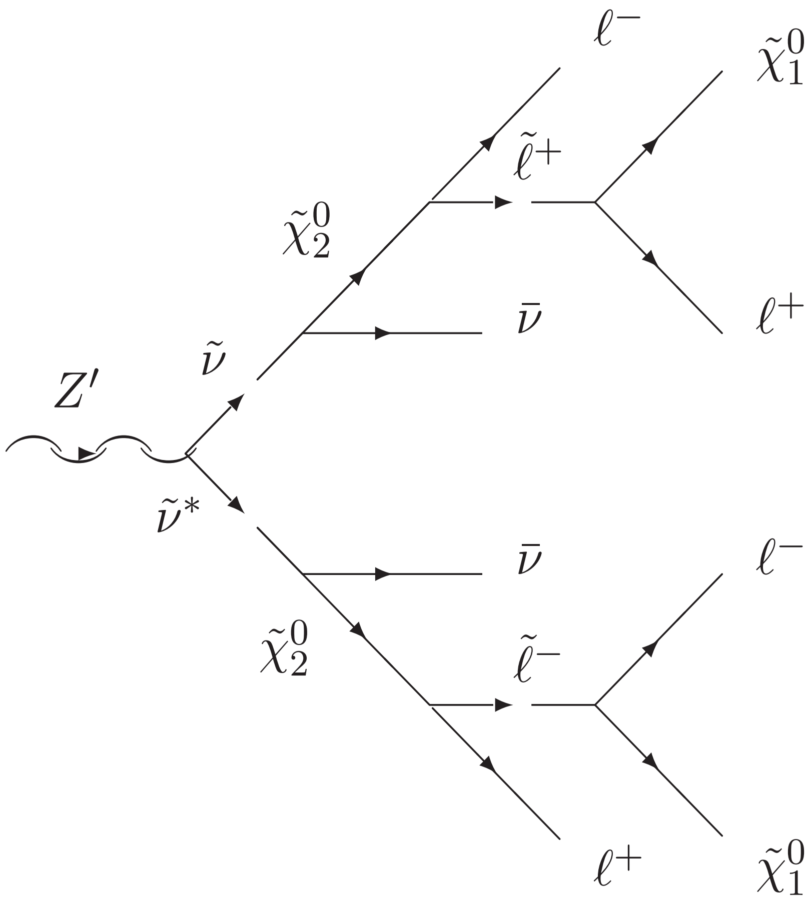
Final State	Z'_η Branching ratio (%)
$\tilde{\chi}_1^+\chi_1^-$	5.6
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	1.9
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	2.1
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	1.5
$\sum_\ell \tilde{\nu}_{\ell,2}\tilde{\nu}^*_{\ell,2}$	9.4
W^+W^-	3.0
$\sum_i q_i\bar{q}_i$	41.6
$\sum_i \nu_i\bar{\nu}_i$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

$Z' \to \tilde{\nu}_2\tilde{\nu}_2^*$ 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		$\sum_i \tilde{\chi}_1^0\ell_i^+\ell_i^-$	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: BR($\tilde{\chi}_3^0 \to \tilde{\chi}_1^\pm W^\mp$) $\simeq 56\%$

Final states with leptons and missing transverse energy



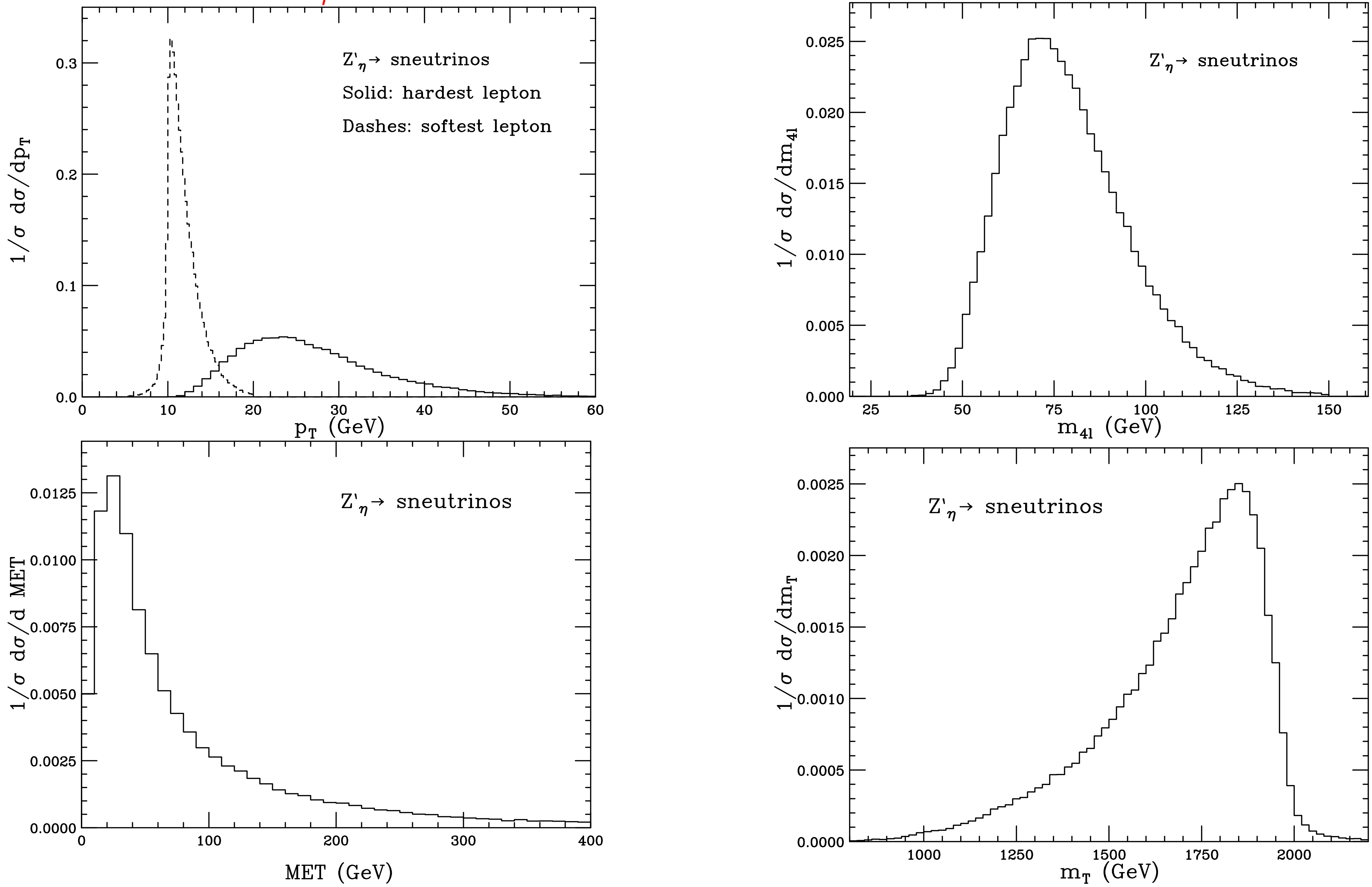
In the reference point, at $\sqrt{s} = 14$ TeV (MadGraph and LO CTEQL1):

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

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

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

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



Supersymmetric extensions of the SSM (S-SSM): the Z' couples to fermions, sfermions and gauginos like the Z ($Z' \to WW$ must be suppressed because of unitarity)

Effective model: $\tilde{Z}'$ is too heavy to be relevant at LHC

$m_{\tilde{d}_1}$	$m_{\tilde{u}_1}$	$m_{\tilde{s}_1}$	$m_{\tilde{c}_1}$	$m_{\tilde{b}_1}$	$m_{\tilde{t}_1}$
5000.0	5000.0	5000.0	5000.0	1480.6	1486.8
$m_{\tilde{d}_2}$	$m_{\tilde{u}_2}$	$m_{\tilde{s}_2}$	$m_{\tilde{c}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{t}_2}$
5000.0	5000.0	5000.0	5000.0	1460.7	1390.2

$m_{\tilde{\ell}_1}$	$m_{\tilde{\ell}_2}$	$m_{\tilde{\nu}_{1,\ell}}$	$m_{\tilde{\nu}_{2,\ell}}$
502.0	502.0	495.0	495.0

m_h	m_H	m_A	m_{H^+}
125.8	638.7	632.8	637.8

$m_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_2^+}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$
198.6	835.8	193.5	197.7	413.6	836.0

Branching ratios of $Z'_{\mathrm{S-SSM}}$ into SM and BSM final states

Final State	Z' Branching ratio (%)
$\tilde{\chi}_1^+ \chi_1^-$	16.6
$\tilde{\chi}_3^0 \tilde{\chi}_4^0$	3.4
$\sum_i \tilde{\nu}_i \tilde{\nu}_i^*$	4.0
$\tilde{\chi}_2^+ \tilde{\chi}_2^-$	2.5
hZ	2.0
$\sum_i q_i \bar{q}_i$	47.8
$\sum_i \nu_i \bar{\nu}_i$	12.2
$\sum_i \ell_i^+ \ell_i^-$	6.1

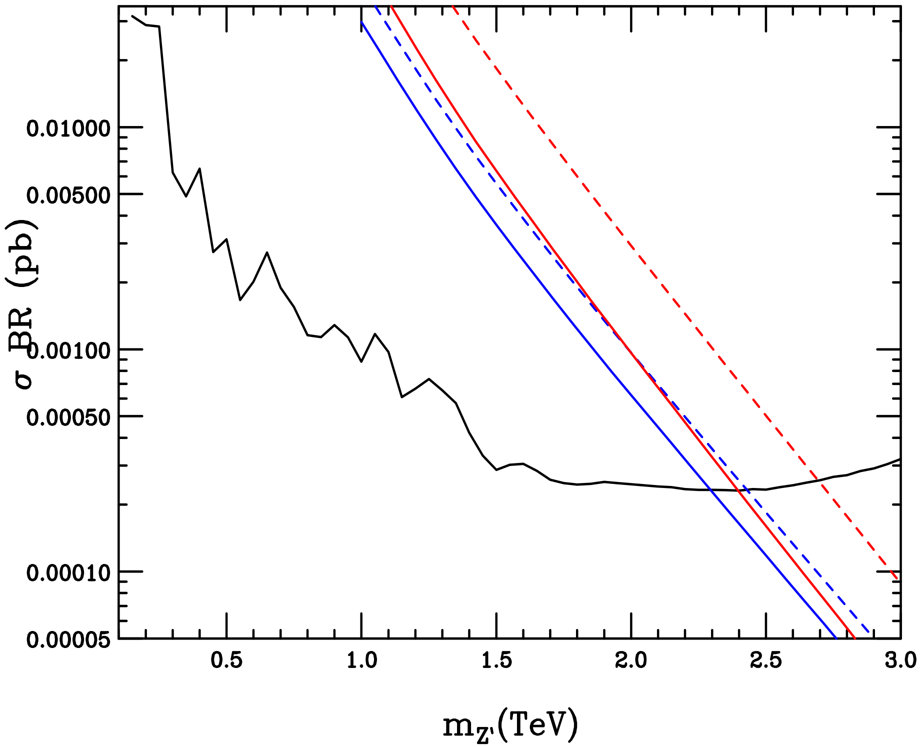
As in Z'_ψ case, the mode $Z'_{\mathrm{S-SSM}} \to \tilde{\chi}_1^+ \chi_1^-$ has the highest BR

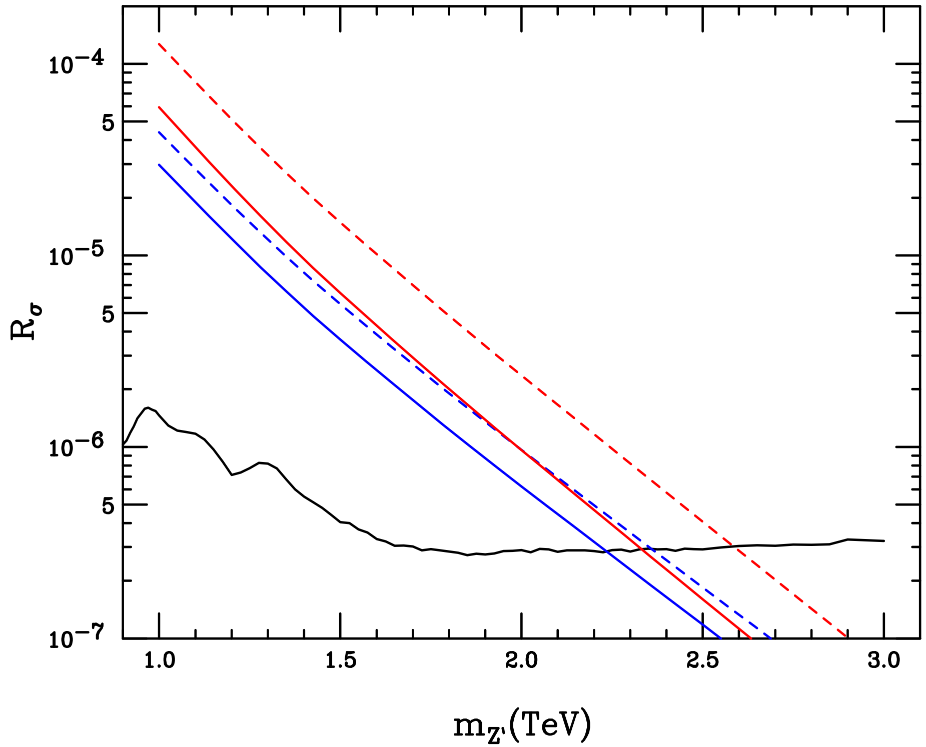
Final State	$\tilde{\chi}_1^+$ branching ratio (%)
$\tilde{\chi}_1^0 \; u\bar{d}$	38.9
$\tilde{\chi}_1^0 \; c\bar{s}$	28.9
$\tilde{\chi}_1^0 \; \ell + \nu_\ell$	30.9

$$\sigma(pp \to Z'_{\mathrm{S-SSM}} \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \ell^+ \ell^- + \mathrm{MET}) \simeq 6 \times 10^{-3} \ \mathrm{pb}$$

$N \simeq 600$ ($\mathcal{L}$=100 fb^{-1}), $N \simeq 2 \times 10^3$ ($\mathcal{L}$=300 fb^{-1}), with same spectra as Z'_ψ

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





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

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

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

$(\Delta m_{Z'})_{\rm min} \approx$ 200-300 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

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

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

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

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

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

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

Representations of E_6, $\mathrm{SO}(10)$ and $\mathrm{SU}(5)$:

$$\mathrm{E}_6 \quad : \quad 27 = (Q, u^c, e^c, L, d^c, \nu^c, H, D^c, H^c, D, S^c)_L$$

$$\mathrm{SU}(5) : 10 = (Q, u^c, e^c), \bar{5} = (L, d^c), 1 = (\nu^c), \bar{5} = (H, D^c), 5 = (H^c, D), 1 = (S^c)$$

$$\text{`Conventional' SO(10)} \;:\; 16 = (Q, u^c, e^c, L, d^c, \nu^c) \;,\; 10 = (H, D^c, H^c, D) \;,\; 1 = (S^c)$$

$$\text{`Unconventional' SO(10)} \;:\; 16 = (Q, u^c, e^c, H, D^c, \nu^c), 10 = (L, d^c, H^c, D) \;,\; 1 = (S^c)$$

From conventional to unconventional SO(10) (Nardi–Rizzo '94): $\theta \to \theta + \arctan\sqrt{15}$

U(1)' coupling and charges in the conventional assignments:

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^c	-1	1	2
d^c	3	1	-1
L	3	1	-1
e^c	-1	1	2
ν_e^c	-5	1	5
H	-2	-2	-1
H^c	2	-2	-4
S^c	0	4	5
D	2	-2	-4
D^c	-2	-2	-1

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

$$Q=(u\ \ d)_L\ ,\ L=(e\ \ \nu_e)_L\ ,\ D:\text{(s)quarks}\ ,\ H:\text{(s)leptons},\ S:\text{singlet}$$

Assumption: D and H are exotic quarks and leptons much heavier than the Z'

ZZ' mixing is also neglected (J.Erler et al., JHEP09: $\sin\theta_{ZZ'}\sim 10^{-3}$-$10^{-4}$)

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