Multi-lepton signals at LHC: the key to model discrimination

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Why multi-leptons?

Charged leptons (e, μ) are clean objects

① Multi-lepton signals may provide early discoveries

- Smaller backgrounds
- Need less detector calibration

② Beyond new physics discovery: Model discrimination

- Jet multiplicity $\neq$ parton multiplicity
- Most convenient signal classification: lepton multiplicity
- Leptons ☞ leading role in model discrimination
- Example: signal with $\not{p}_t$ + jets not enough to establish SUSY

Why multi-leptons?

③ Multi-leptons originate from cascade decays in most NP models

- MSSM [ATLAS CSC book '09]
- Seesaw I-III [Aguila, JAAS NPB & PLB '09]
- New heavy quarks
- ...

Multi-leptons in MSSM

MSSM → multi-leptons

Multi-lepton signals with large missing energy can be produced in mSUGRA when gauginos are light ($m_{1/2}$ small)

(other SUSY scenarios: photons, long-lived particles ...)

Inclusive analysis based on lepton multiplicities [ATLAS CSC book] reveals which are the most characteristic signatures in sample points

model discrimination ☞

most characteristic mSUGRA signal is $\not{p}_t$ + jets but it is not always the most significant ... nor conclusive!

Multi-leptons in MSSM

ATLAS CSC book addresses early discoveries, in particular SUSY

All signal contributions included (lots of processes)

Several characteristic scenarios SU1, SU2 … examined

Significance with 1 fb^{-1}

	$M_1 + M_2$	0ℓ	$\ell^\pm$	$\ell^+\ell^-$	$\ell^\pm\ell^\pm$	$\ell^\pm\ell^\pm\ell^\mp$
mSUGRA (SU1)	$264 + 262$	6.3	18.0	6.9	7.2	1.3
mSUGRA (SU2)	$160 + 149$	0.9	6.0	1.07	1.9	2.7
mSUGRA (SU3)	$219 + 218$	13	17.7	11.5	7.7	11.5
mSUGRA (SU4)	$113 + 113$	25	33.7	24.7	19.9	24.4

Multi-leptons from MSSM

The moral

Multi-lepton signals are crucial in SUSY to establish the model: any SM extension with a DM candidate gives $\not{p}_t$

☞ model discrimination from multi-leptons

Multi-leptons crucial to measure sparticle masses from endpoint analyses

☞ measure model parameters with multi-leptons

Study must include *all* signal contributions to a given channel

☞ very complicated analysis!

Why seesaw?

SM neutrinos are massive

Three types of seesaw mechanism
- ① heavy neutrino singlets N
- ② a scalar triplet Δ
- ③ fermion triplets Σ

can yield an effective Majorana mass term for light neutrinos

$$(O_5)_{ij} = \frac{1}{\Lambda} \overline{L^c_{iL}} \tilde{\phi}^* \tilde{\phi}^\dagger L_{jL}$$

upon integration of heavy fields N, Δ or Σ

Seesaw most popular, but alternative mechanisms also possible. . .

A new paradigm for seesaw at LHC

Old paradigm: like-sign dileptons for seesaw

Like-sign dileptons: smoking gun for heavy singlet N

A new paradigm for seesaw at LHC

Old paradigm: like-sign dileptons for seesaw

Like-sign dileptons: smoking gun for heavy singlet N

and also for heavy N with new W'

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… and for heavy N with new Z'

Like-sign dileptons: smoking gun for heavy triplet Σ

Like-sign dileptons: smoking gun for new $Q = 5/3$ quarks

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. . . and for heavy N with new Z'

Like-sign dileptons: smoking gun for heavy triplet Σ

Like-sign dileptons: smoking gun for new $Q = 5/3$ quarks

Like-sign dileptons: smoking gun for SUSY, of course!

A new paradigm for seesaw at LHC

Old paradigm: like-sign dileptons for seesaw

Like-sign dileptons: smoking gun for heavy singlet N

and also for heavy N with new W'

… and for heavy N with new Z'

Like-sign dileptons: smoking gun for heavy triplet Σ

Like-sign dileptons: smoking gun for new $Q = 5/3$ quarks

Like-sign dileptons: smoking gun for SUSY, of course!

☞ too much smoke, can't distinguish anything!

A new paradigm for seesaw at LHC

New paradigm: multi-leptons for seesaw

Not all seesaw models involve heavy Majorana states

☞ in fact, heavy Dirac states at the TeV scale are often regarded as more natural [Kersten, Smirnov PRD '07]

like-sign dileptons are just a piece in the global puzzle

Signals with 2, 3 and 4 leptons discriminate among several models

☞ and the trilepton final state is the one always present

Trileptons: the golden channel for seesaw at LHC

Seesaw I

The Lagrangian

Heavy neutrinos N_i are $\mathrm{SU}(3) \times \mathrm{SU}(2)_Y \times \mathrm{U}(1)_Y$ singlets

They have Yukawa interactions with SM leptons

$$-Y_{ij}\,\overline{L'_{iL}} N'_{jR}\,\tilde{\phi} \quad \xrightarrow{\langle \phi^0 \rangle = v/\sqrt{2}} \quad -\frac{v}{\sqrt{2}} Y_{ij}\,\bar{\nu}'_{iL}\,N'_{jR}$$

and a Majorana mass term

$$-\frac{1}{2}\,M_{ij}\overline{N'^{c}_{iR}}\,N'_{jR}$$

Gauge interactions with SM leptons proportional to small mixing and heavy-heavy interactions are quadratically suppressed

Seesaw I

The Lagrangian: Dirac case

Two (quasi-)degenerate neutrinos N_1, N_2 with $Y_{lN_2} = iY_{lN_1}$
opposite CP parities

☞ $N_1 + N_2$ (almost) conserve lepton number

In this case, it is easier to introduce a heavy (quasi-)Dirac neutrino

$$\{\ N_{1R}, N_{2R}\ \} \quad \longrightarrow \quad N_L \equiv \frac{1}{\sqrt{2}}(N_{1R}^c + iN_{2R}^c) \quad N_R \equiv \frac{1}{\sqrt{2}}(N_{1R} + iN_{2R})$$

to describe physics, instead of two interfering Majorana neutrinos

Heavy neutrino production and decay

Most interesting production process

$$q\bar{q}' \to W^* \to l^\pm N$$

but suppressed by mixing $V^2 \lesssim 10^{-2}$

Decays $\left[\begin{array}{ll} N \to W^+ l^- & 25\% \\ N \to W^- l^+ & 25\% \\ N \to Z\,\nu & 25\% \\ N \to H\,\nu & 25\% \end{array} \right.$ (M) $\left[\begin{array}{ll} N \to W^+ l^- & 50\% \\ N \to Z\,\nu & 25\% \\ N \to H\,\nu & 25\% \end{array} \right.$ (D)

☞ most interesting: like-sign dilepton and trilepton

Comments

1. Discovery limited to $m_N \gtrsim 100$ GeV by cross section ($V^2 \lesssim 10^{-2}$)

2. At small p_T, SM dilepton and trilepton backgrounds large

   ☞ $b \to c\ell\nu$ give isolated e and μ, lots of $b\bar{b}$ and $t\bar{t}$

3. For discovery potential $e \neq \mu$: backgrounds with μ much smaller

4. Detector simulation absolutely necessary

   ☞ $t\bar{t}$ and $b\bar{b}$ are the largest backgrounds when $b \to c\ell\nu$

Comments

⑤ Analyses require high optimisation to suppress background [Aguila, JAAS, Pittau JHEP '07]

⑥ We show here results with smaller optimisation to test observability in more "generic" searches and compare with seesaw II and III

Results

$m_N = 100$ GeV $\quad V_{eN}^2 = 0.0030$ / $V_{\mu N}^2 = 0.0032$

Non-optimised analysis

Luminosity needed for discovery of Dirac and Majorana neutrinos coupling to the electron or muon (ignoring systematics)

	M (e)	D (e)	M (μ)	D (μ)
$\ell^\pm\ell^\pm\ell^\mp$	100 fb^{-1}	43 fb^{-1}	39 fb^{-1}	13 fb^{-1}
$\ell^\pm\ell^\pm$	210 fb^{-1}	–	84 fb^{-1}	–

- LHC sensitive to heavy Dirac neutrinos
- Dirac and Majorana N distinguishable by $\ell^\pm\ell^\pm$ signals
- Small mass window where they can be observed

Seesaw II

The Lagrangian

A scalar triplet Δ induces a light neutrino mass matrix M

$$\frac{1}{\sqrt{2}} Y_{ij} \, \overline{\tilde{L}_{iL}} \, (\vec{\tau} \cdot \vec{\Delta}) \, L_{jL} \quad \xrightarrow{\langle \Delta^0 \rangle = v_\Delta} \quad -Y^*_{ij} v_\Delta \, \bar{\nu}_{iL} \, \nu_{jR} \equiv -\frac{1}{2} M_{ij} \, \bar{\nu}_{iL} \, \nu_{jR}$$

The same term gives Δ couplings to leptons

$$\frac{1}{\sqrt{2}} Y_{ij} \, \overline{\tilde{L}_{iL}} \, (\vec{\tau} \cdot \vec{\Delta}) \, L_{jL} \quad \longrightarrow \quad Y_{ij} \, \overline{l^c_{iL}} \, l_{jL} \, \Delta^{++} + \sqrt{2} Y_{ij} \, \overline{\nu_{iR}} \, l_{jL} \, \Delta^{+}$$

Δ has unsuppressed gauge interactions with W, Z, γ

☞ Produced with typical EW cross section

Scalar triplet production

Several production processes

$$q\bar{q} \to Z^* / \gamma^* \to \Delta^{++}\Delta^{--}$$

$$q\bar{q}' \to W^* \to \Delta^{\pm\pm}\Delta^{\mp}$$

$$q\bar{q} \to Z^* / \gamma^* \to \Delta^{+}\Delta^{-}$$

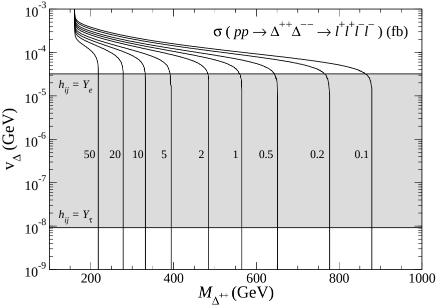
$$\dots$$

Many decay channels depending on
- relative value of Y_{ij}, v_Δ
- $\Delta^{\pm\pm} - \Delta^{\pm}$ mass splitting

Scalar triplet decay

We assume $M_{\Delta^{++}} \simeq M_{\Delta^{+}}$ (reasonable)

$pp \to \Delta^{++}\Delta^{--} \to \ell^+\ell^+\ell^-\ell^-$



For $Y \sim$ SM Yukawas

$\Delta^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ dominates

☞ Focus on this channel

Scalar triplet decay

$\Delta^{++} \to l_i^+ l_j^+$: a high energy window to ν physics

Branching ratios determined by
- ν mass (NH, IH)
- ν mixing (angles)
- leptonic CP violation (phases)

Note: BR of $\Delta^{\pm\pm} \to l_i l_j$ may allow to reconstruct MNS matrix
[Garayoa, Schwetz JHEP '08]

For us ☞ Triplet discovery potential depends on low-energy ν physics and realistic scenarios must be used for simulations

Scalar triplet decay

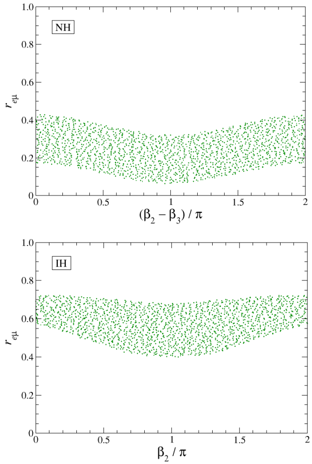
Approximate branching ratios

	e^+e^+	$\mu^+\mu^+$	$\mu^+\tau^+$	$\tau^+\tau^+$
NH	0.00	0.20	0.49	0.29
IH	0.50	0.15	0.25	0.10

Relevant quantity

$$r_{e\mu} \equiv \mathrm{Br}(\Delta^{\pm\pm} \to e^\pm e^\pm / \mu^\pm \mu^\pm / e^\pm \mu^\pm)$$

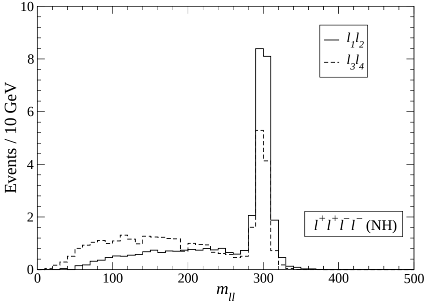
depends on m_ν, θ, δ, β



Scalar triplet decay

Secondary decays $\tau \to e\nu\bar{\nu}$, $\tau \to \mu\nu\bar{\nu}$ must be included (not merely a scaling factor)

☞ Especially important for NH where τ decays dominate!



In NH, τ decays produce combinatorial background larger than SM background

☞ reduces peak height

Comments

① Different processes and final states must be combined

$$\begin{array}{lcl} \Delta^{++}\Delta^{--} & \to & \ell^+\ell^+\ell^-\ell^- \, , \quad \ell^\pm\ell^\pm\ell^\mp \, , \quad \ell^\pm\ell^\pm \, , \dots \\ \Delta^{++}\Delta^{-} & \to & \ell^\pm\ell^\pm\ell^\mp \, , \quad \ell^\pm\ell^\pm \, , \quad \ell^+\ell^- \, , \dots \\ \Delta^{+}\Delta^{-} & \to & \ell^+\ell^- \, , \dots \end{array}$$

(the trilepton final state turns out to be the best one)

② For discovery potential and model discrimination $e = \mu$

☞ sum e, μ in signals and backgrounds

Comments

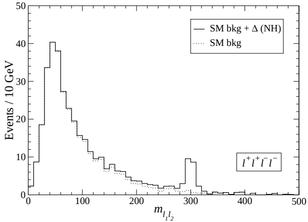
③ Detector simulation necessary: charged leptons missed, SM backgrounds, etc.

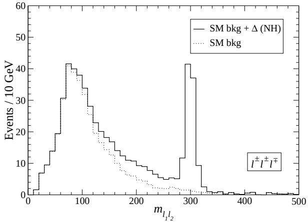
④ Analyses quite generic, small cut optimisation

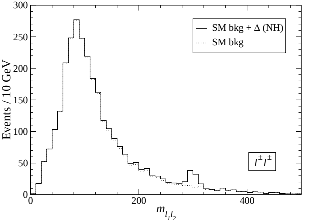
☞ adequate for model-independent NP searches

Results

$M_\Delta = 300$ GeV





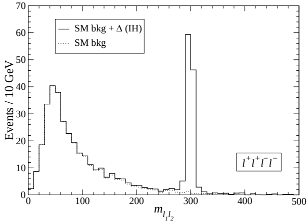


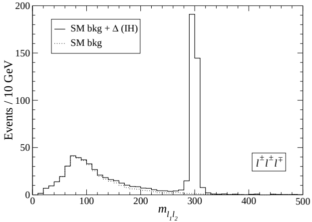
Luminosity for discovery (NH)

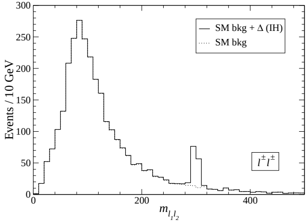
$\ell^+\ell^+\ell^-\ell^-$	➜	18.6 fb^{-1}
$\ell^\pm\ell^\pm\ell^\mp$	➜	3.6 fb^{-1}
$\ell^\pm\ell^\pm$	➜	17.4 fb^{-1}

Results

$M_\Delta = 300$ GeV







Luminosity for discovery (IH)

$\ell^+\ell^+\ell^-\ell^-$ → 2.8 fb^{-1}

$\ell^\pm\ell^\pm\ell^\mp$ → 0.87 fb^{-1}

$\ell^\pm\ell^\pm$ → 4.4 fb^{-1}

Seesaw III

The Lagrangian

Triplets Σ_i contain a charged lepton E_i^- and a Majorana N_i

They have Yukawa interactions with SM leptons

$$-Y_{ij}\,\bar{L}'_{iL}(\vec{\Sigma}_j \cdot \vec{\tau})\,\tilde{\phi} \quad \xrightarrow{\langle\phi^0\rangle = v/\sqrt{2}} \quad -\frac{v}{\sqrt{2}} Y_{ij}\,\bar{\nu}'_{iL}\,N'_{jR}$$

and a Majorana mass term

$$-\frac{1}{2}\,M_{ij}\,\overline{\vec{\Sigma}^c_i} \cdot \vec{\Sigma}_j \longrightarrow -\frac{1}{2}\,M_{ij}\overline{N'^{\,c}_{iR}}\,N'_{jR}$$

E, N have small mixing $\sim 10^{-6}$ with the SM leptons l, ν

but production by unsuppressed gauge interactions with W, Z, γ

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and a Majorana mass term

$$-\frac{1}{2}\,M_{ij}\,\overline{\vec{\Sigma}_i^c} \cdot \vec{\Sigma}_j \longrightarrow -\frac{1}{2}\,M_{ij}\overline{N'^c_{iR}}\,N'_{jR}$$

Large mixing allowed if Σ couples to a new doublet with small VEV but phenomenology different [Hirsch et al. PRD '09]

Seesaw III

The Lagrangian: Dirac case

Alternative: degenerate triplets Σ_1, Σ_2 can form (quasi-)Dirac triplet and lepton number is (approximately) conserved

$$\{\ N_{1R}, N_{2R}\ \} \quad \longrightarrow \quad N_L \equiv \frac{1}{\sqrt{2}}(N_{1R}^c + iN_{2R}^c) \quad N_R \equiv \frac{1}{\sqrt{2}}(N_{1R} + iN_{2R})$$

$$\left\{ \begin{array}{c} E_{1L}, E_{1R} \\ E_{2L}, E_{2R} \end{array} \right\} \quad \longrightarrow \quad \begin{array}{ll} E_{1L}^- \equiv \frac{1}{\sqrt{2}}(E_{1L} + iE_{2L}) & E_{1R}^- \equiv \frac{1}{\sqrt{2}}(E_{1R} + iE_{2R}) \\ E_{2L}^+ \equiv \frac{1}{\sqrt{2}}(E_{1R}^c + iE_{2R}^c) & E_{2R}^+ \equiv \frac{1}{\sqrt{2}}(E_{1L}^c + iE_{2L}^c) \end{array}$$

N neutral; E_1^- and E_2^+ charged Dirac fermions

Lepton triplet production and decay

Majorana case: two production processes [Aguila, JAAS NPB '09]

$$q\bar{q}' \to W^* \to E^\pm N$$

$$q\bar{q} \to Z^* / \gamma^* \to E^+ E^-$$

Many final states

E^-	$\to W^- \nu$	50%
E^-	$\to Z\, l^-$	25%
E^-	$\to H\, l^-$	25%

N	$\to W^+ l^-$	25%
N	$\to W^- l^+$	25%
N	$\to Z\, \nu$	25%
N	$\to H\, \nu$	25%

☞ multi-lepton final states involving many decay channels (289 final states for E^+E^-, 748 for $E^\pm N$)

Lepton triplet production and decay

Dirac case: four production processes [Aguila, JAAS PLB '09]

$$q\bar{q}' \to W^* \to E_i^{\pm} N$$

$$q\bar{q} \to Z^* / \gamma^* \to E_i^+ E_i^-$$

Many final states $\left[\begin{array}{lll} E_2^+ \to W^+ \nu & 100\% \\ E_1^- \to Z\, l^- & 50\% \\ E_1^- \to H\, l^- & 50\% \end{array}\right.$ $\left[\begin{array}{lll} N \to W^+ l^- & 50\% \\ N \to Z\, \nu & 25\% \\ N \to H\, \nu & 25\% \end{array}\right.$

☞ multi-lepton final states involving many decay channels
(169 final states for $E_i^+ E_i^-$, 578 for $E_i^{\pm} N$)

Lepton triplet against other models

Another possibility: lepton isodoublet $L = (N\ E)^T$

☞ N is a Dirac fermion, mass term $\mathcal{L} = -m_D \bar{L} L$

Three production processes [Aguila et al. NPB '90]

$$q\bar{q}' \to W^* \to E^\pm N$$

$$q\bar{q} \to Z^* / \gamma^* \to E^+ E^-$$

$$q\bar{q} \to Z^* \to N\bar{N}$$

Decays are different $\left[\begin{array}{ll} E^- \to W^- \nu & - \\ E^- \to Z\, l^- & 50\% \\ E^- \to H\, l^- & 50\% \end{array} \right.$ $\left[\begin{array}{ll} N \to W^+ l^- & 100\% \\ N \to Z\, \nu & - \\ N \to H\, \nu & - \end{array} \right.$

Lepton triplet against other models

Majorana singlet N (seesaw I) with a new Z'

Production enhanced [Aguila, JAAS JHEP '07]

$$q\bar{q} \to Z' \to NN$$

Decays are the same

$$\left[\begin{array}{ll} N \to W^+ l^- & 25\% \\ N \to W^- l^+ & 25\% \\ N \to Z\,\nu & 25\% \\ N \to H\,\nu & 25\% \end{array} \right.$$

Comments

① Several decay channels contribute to each final state

② Different final states tested ☞ model discrimination

② For discovery potential and model discrimination $e = \mu$

☞ sum e, μ in signals and backgrounds

③ Detector simulation necessary: charged leptons missed, SM backgrounds, etc.

④ Analyses quite generic, small cut optimisation

☞ adequate for model-independent NP searches

Results

$m_N = m_E = 300$ GeV $\quad M_{Z'_\lambda} = 650$ GeV

Signals in many final states with 1 to 6 leptons

Only one triplet Σ / one doublet $(N\ E)$ / one singlet N assumed for these numbers

Number of events after cuts $\quad 30\ \text{fb}^{-1}$

	$\ell^\pm\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$
Σ (M)	23.5	55.7	110.3	177.8
Σ (D)	19.8	173.4	194.4	4.4
$(N\ E)$	14.8	52.9	253.7	1.7
$Z'_\lambda + N$ (M)	0.5^*	22.0^*	165.9^*	156.1^*
$Z'_\lambda + N$ (D)	0.7^*	35.4^*	325.0^*	3.8^*
SM bkg	12.1	14.3	15.9	19.5

Results

$m_N = m_E = 300$ GeV $\quad M_{Z'_\lambda} = 650$ GeV

Signals in many final states with 1 to 6 leptons

Only one triplet Σ / one doublet $(N\ E)$ / one singlet N assumed for these numbers

Ratio between signals (3ℓ always present)

	$\ell^\pm\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$
Σ (M)	0.2	0.5	1	1.6
Σ (D)	0.1	0.9	1	0
$(N\ E)$	0.1	0.2	1	0
$Z'_\lambda + N$ (M)	0	0.1	1	0.9
$Z'_\lambda + N$ (D)	0	0.1	1	0

Easy & early model discrimination!

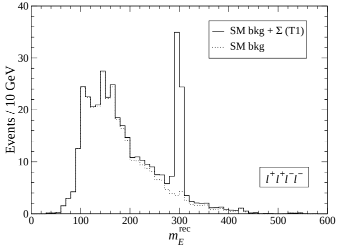
More

Results

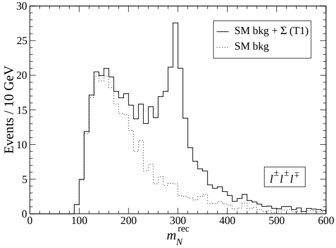
$m_N = m_E = 300$ GeV

Synergy between channels for E, N discovery

$\ell^+\ell^+\ell^-\ell^-$ ➡ $m(\ell^+\ell^-\ell^\pm) = m_E$



$\ell^\pm\ell^\pm\ell^\mp$ ➡ $m(\ell^+\ell^-\not{p}) = m_N$



$\ell^+\ell^+\ell^-\ell^-$ ➡ Evidence of E production (resonance with charge ±1)

$\ell^\pm\ell^\pm\ell^\mp$ ➡ Evidence of N production (resonance with charge 0)

$\ell^\pm\ell^\pm$ ➡ N is Majorana (signal) or Dirac (no signal)

Comparison with MSSM

Significance with 1 fb^{-1}

	$M_1 + M_2$	0ℓ	$\ell^\pm$	$\ell^+\ell^-$	$\ell^\pm\ell^\pm$	$\ell^\pm\ell^\pm\ell^\mp$
Δ (NH)	$300+300$	–	–	1.9	2.2	4.2
Δ (IH)	$300+300$	–	–	1.1	3.1	8.3
Σ (M)	$300+300$	–	–	1.4	(5.0)	3.9
Σ (D)	$300+300$	–	–	4.7	–	6.2
mSUGRA (SU1)	$264+262$	6.3	18.0	6.9	7.2	1.3
mSUGRA (SU2)	$160+149$	0.9	6.0	1.07	1.9	2.7
mSUGRA (SU3)	$219+218$	13	17.7	11.5	7.7	11.5
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☞ with same M, multi-lepton signals larger in seesaw II, III

Note: seesaw signals not optimised (scaled from 30 fb^{-1} analysis)

Conclusion

1. Strategy designed for discovery of seesaw messengers and model discrimination
2. Trilepton signals are the golden mode for seesaw searches but model identification relies on other multi-lepton signals
3. Generator `Triada` for all channels of lepton triplet production and decay has been developed
4. Lepton doublets and $Z' \to NN$ to be added soon
5. `Triada` interface to ATLAS framework almost ready

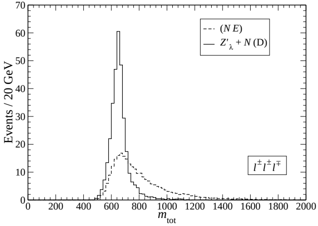
Conclusion

⑥ Full simulation studies still have to be performed to address charge misidentification, fake leptons, …

⑦ Approximate mass reach

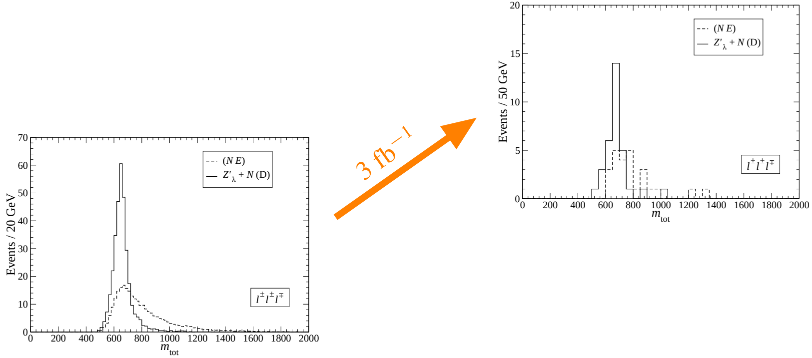
- N: 120 (150) GeV for D / M coupling to e (μ)
- Δ: 600 (800) GeV for NH (IH)
- Σ: 750 (700) GeV for Majorana (Dirac) coupling to e or μ

Z' mass reconstruction



Back

Z' mass reconstruction



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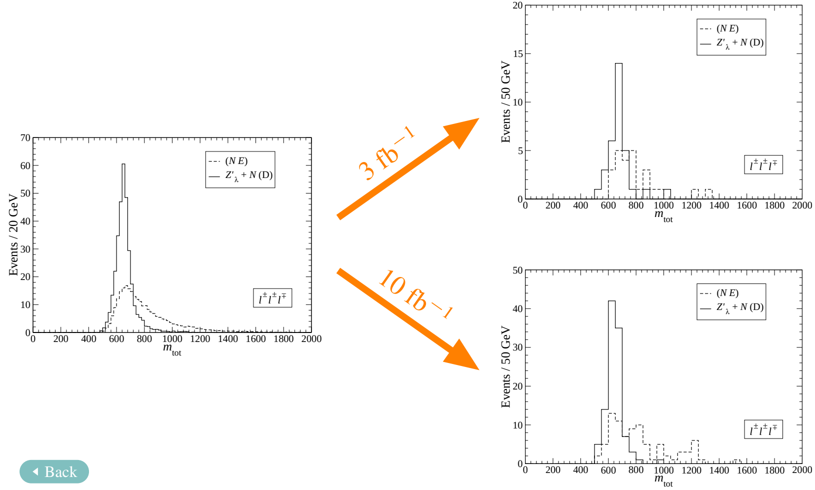
Z' mass reconstruction



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More results for Δ ...

- $\ell^\pm \ell^\pm \ell^\mp$ events with large $\not{p}_t$ ☞ evidence for $\Delta^{++}\Delta^-$ production
- Production angle ☞ Δ^{++} scalar ▸ See
- Signal in $\ell^+ \ell^- j_\tau$ visible ▸ See

More results for Σ …

- Resonances seen in $\ell^\pm \ell^\pm$ but charges not measured ▸ See

- Signal in $\ell^+ \ell^- 4j$ visible ▸ See

  Note: little advantage in LFV $e^\pm \mu^\mp$ final states over $\ell^+ \ell^-$

- Signal in $\ell^\pm 4j$ barely visible ▸ See

  Wnj and $t\bar{t}nj$ backgrounds huge and difficult to remove

Model discrimination

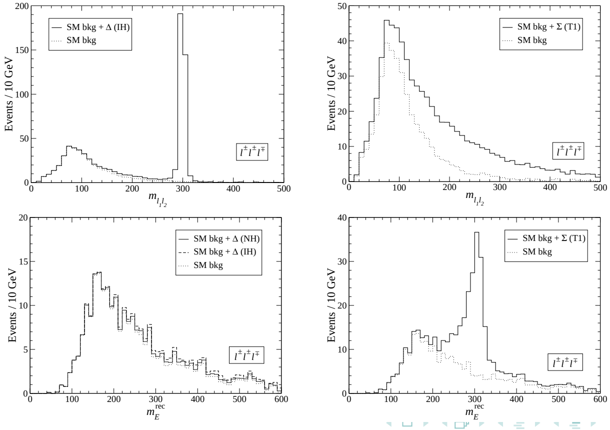
$m_\Sigma = 300$ GeV

Mass reconstruction for scalar and fermion triplets (in $\ell^\pm \ell^\pm \ell^\mp$)

scalar | fermion

$m_{\ell_1 \ell_2}$ →

m_E^{rec} →



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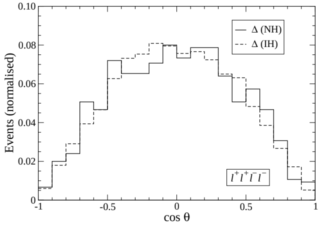
Opening angle distribution $\ell^+\ell^+\ell^-\ell^-$



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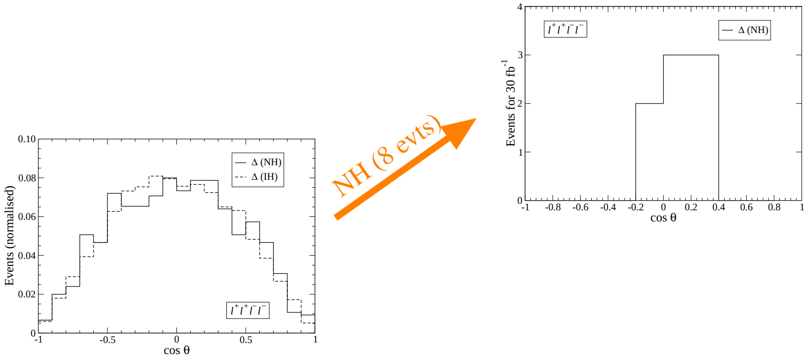
Opening angle distribution

$\ell^+\ell^+\ell^-\ell^-$



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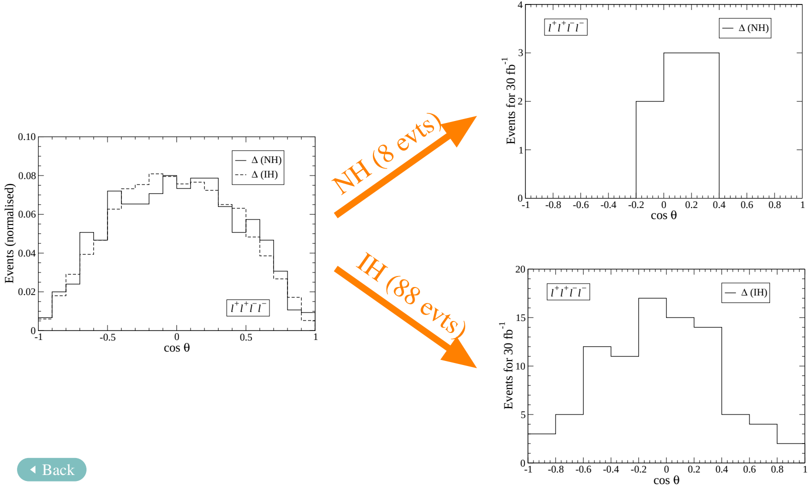
Opening angle distribution

$\ell^+\ell^+\ell^-\ell^-$



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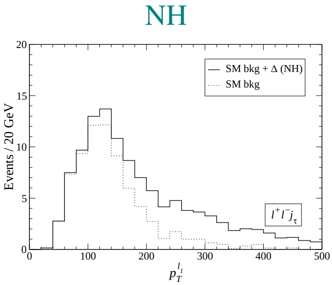
Opposite-sign dilepton signal

$M_\Delta = 300$ GeV

Excess of $\ell^+\ell^- j_\tau$ events observed at high p_T of leading lepton

Broad $m_{\ell^+\ell^-}$ distribution (leptons from different Δ)



Large $\not{p}_t$ and one τ required to reduce backgrounds

Z^*/γ^* negligible ☞ no need to look for different ℓ

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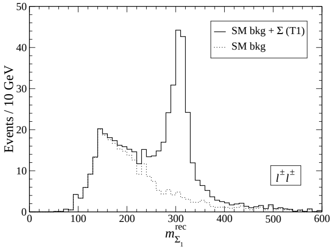
Like-sign dilepton signal

$m_\Sigma = 300$ GeV

Inclusive $\ell^\pm \ell^\pm$ signal visible without jet requirements

Four jets asked for reconstruction (further background suppression)



Good signal BR and small background but charges not measured

Significance may degrade significantly with mistags

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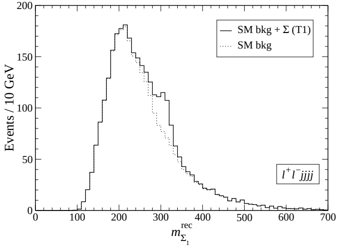
Opposite-sign dilepton signal

$m_\Sigma = 300$ GeV

Similar to $\ell^\pm \ell^\pm$ but larger background

Four jets required for reconstruction and background suppression



Little improvement requiring different ℓ: large $t\bar{t}$ and W^+W^- bkg

Significance depends on systematic uncertainties

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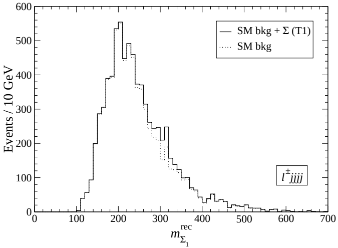
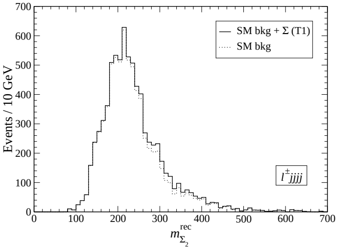
Single lepton signal

$m_{\Sigma} = 300$ GeV

Four jets required for reconstruction and background suppression

Large $\not{p}_t$ and transverse mass M_T required to reduce background





M_T cut does not completely remove $t\bar{t}nj$ (dilepton channel with τ) nor Wnj (energy mismeasurement)

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