Identifying new quarks and leptons at LHC: the role of multi-lepton signals

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Why multi-leptons?

1. Beyond new physics discovery: Model discrimination
   - Jet multiplicity $\neq$ parton multiplicity
   - On the other hand, charged leptons (e, μ) are clean objects
   - Most convenient signal classification: lepton multiplicity
   - Leptons ☞ leading role in model discrimination
   - Further classification: # of Z candidates, b jets
2. Multi-lepton signals may provide early discoveries
   - Smaller backgrounds
   - Need less detector calibration

Why multi-leptons?

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

- MSSM [ATLAS CSC book '09]
- Minimal seesaw I-III [Aguila, JAAS NPB '09]
- Heavy leptons (seesaw or not) [JAAS '09]
- Heavy quarks [JAAS '09]
- …

What is in this talk

1. Pair production of heavy leptons with special attention to seesaw
   - Seesaw III, with heavy Majorana (M) or Dirac (D) neutrinos
   - Seesaw I (M / D) plus a new Z' boson
   - A lepton doublet $(N\ E)$
2. Pair production of heavy quarks coupling to 3rd family
   - Isosinglets T ☞ charge $2/3$
   - Isosinglets B ☞ charge $-1/3$
   - Isodoublets $(T\ B)$
   - Isodoublets $(X\ T)$ ☞ X has charge $5/3$
   - Isodoublets $(B\ Y)$ ☞ Y has charge $-4/3$

What is not in this talk

1. Minimal seesaw I ➙ Paco's talk
2. Seesaw II ➙ Paco's talk
3. $W' + N$ ➙ easy discrimination from other models with new leptons
4. 4^{th} generation ➙ easy discrimination from models with vector-like quarks

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

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

upon integration of heavy fields N, Δ or Σ

Seesaw most popular, but alternative mechanisms also possible…

Why LHC?

Large colliders offer the best hope to probe the neutrino mass origin

- $\beta\beta0\nu$ cannot reveal mechanism for ν mass generation
- If $\Lambda \sim v$, seesaw messengers N, Δ, Σ could be directly produced at colliders and indirect effects could be seen in dim 6 operators
- If $\Lambda \gg v$, indirect effects of seesaw not observed either

☞ … and LHC startup is near

A new paradigm for seesaw at LHC

Old paradigm: like-sign dileptons for seesaw

Like-sign dileptons: smoking gun for heavy singlet N

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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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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

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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

☞ trilepton signals are always produced and in most cases have the highest statistical significance

Trileptons: the golden channel for seesaw at LHC

Majorana triplet production and decay

Each triplet Σ ➞ two heavy leptons E, N ▸ More

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

$$\left[\begin{array}{ll} E^- \to W^- \nu & 50\% \\ E^- \to Z\, l^- & 25\% \\ E^- \to H\, l^- & 25\% \end{array}\right. \qquad \left[\begin{array}{ll} N \to W^+ l^- & 25\% \\ N \to W^- l^+ & 25\% \\ N \to Z\,\nu & 25\% \\ N \to H\,\nu & 25\% \end{array}\right.$$

☞ 18 channels + CC $\otimes$ W, Z, H decays

Dirac triplet production and decay

Two triplets $\Sigma_{1,2}$ ➞ three heavy leptons E_1^-, E_2^+, N ▸ More

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

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

☞ 13 channels + CC $\otimes$ W, Z, H decays

Lepton doublet production and decay

Heavy 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

$$\left[\begin{array}{lll} E^- & \to W^- \nu & - \\ E^- & \to Z\, l^- & 50\% \\ E^- & \to H\, l^- & 50\% \end{array} \right] \quad \left[\begin{array}{lll} N & \to W^+ l^- & 100\% \\ N & \to Z\, \nu & - \\ N & \to H\, \nu & - \end{array} \right]$$

☞ 6 channels + CC $\otimes$ W, Z, H decays

N singlet pair production with Z'

Heavy Majorana or Dirac singlets N (seesaw I) with a Z'

Leptophobic Z' [Aguila, JAAS JHEP '07]

but several similar models [Blanchet et al. '09]

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

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

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

☞ 10 / 6 channels + CC $\otimes$ W, Z, H decays

N singlet pair production with Z'

Note that branching ratio for $NN \to \ell^\pm \ell^\pm \ell^\mp + 2j$

$$(1/2 \times 1/2) \times (2/9 \times 6/9 \times 2) \simeq 0.074$$

is larger than for $NN \to \ell^\pm \ell^\pm + 4j$ for Majorana N

$$(1/4 \times 1/4 \times 2) \times (6/9 \times 6/9) \simeq 0.056$$

and backgrounds are much smaller!

Model discrimination

Important comments

1. Several decay channels contribute to each final state:
   Complete signal generation crucial ☞ `Triada`
2. Different final states tested ☞ model discrimination
3. For discovery potential and model discrimination $e = \mu$
   ☞ sum e, μ in signals and backgrounds
4. Analyses quite generic, small cut optimisation
   ☞ adequate for model-independent NP searches
5. After discovery, separate $N \to eW, \mu W, \tau W$ and combine with neutrino oscillation data

Results

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

Discovery luminosities, in fb^{-1}

	$\ell^\pm \ell^\pm \ell^\mp$ (no Z)	$\ell^\pm \ell^\pm \ell^\mp$ (Z)	$\ell^\pm \ell^\pm$ (no $\not{p}_t$)	$\ell^\pm \ell^\pm$ ($\not{p}_t$)	$\ell^+ \ell^+ \ell^- \ell^-$
Σ_{M}	3.3	25	2.1	3.5	6.6
Σ_{D}	1.5	17	–	1.8	1.8
EN_{d}	1.1	–	–	–	3.0
$Z' N_{\mathrm{M}}$	2.1 P	–	2.3 P	13	–
$Z' N_{\mathrm{D}}$	1.1 P	–	–	22	–

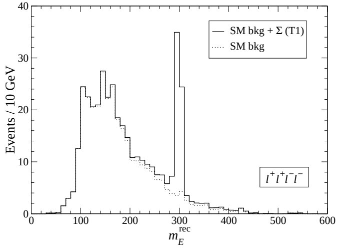
→ Easy model discrimination!

Results

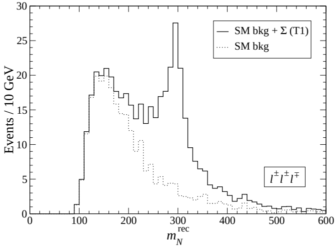
$m_{E,N} = 300$ GeV

Synergy between channels for E, N discovery

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



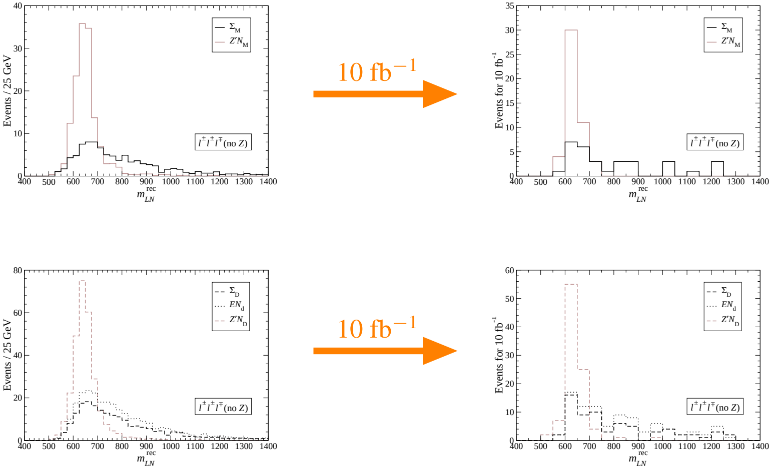
$\ell^\pm\ell^\pm\ell^\mp \quad \rightarrow \quad m(\ell^+\ell^-\not{p}) = m_N$



- $\ell^+\ell^+\ell^-\ell^-$ → 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)

Results $m_N = 300$ GeV, $M_{Z'_\lambda} = 650$ GeV

Z' mass reconstruction ($\ell^\pm \ell^\pm \ell^\mp$)



Conclusions I

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. Approximate mass reach in trilepton channel for 100 fb^{-1} ▸ More
   - Δ: 700 GeV (900 GeV) for NH (IH)
   - Lepton triplets: 675 (800) GeV for Σ_M (Σ_D)
   - Lepton doublets: 850 GeV
   - $Z' + N$: 850 GeV (1 TeV) for $Z' N_\text{M}$ ($Z' N_\text{D}$)

Heavy vector-like quark pair production

New quarks coupling to 3rd family can appear in many SM extensions and many $SU(2)_L \times U(1)_Y$ representations:

- vector-like singlets and doublets

$$T_{L,R} \quad B_{L,R} \quad (T\ B)_{L,R} \quad (X\ T)_{L,R} \quad (B\ Y)_{L,R}$$

- chiral (4th family)
- higher representations (triplets)

The discrimination among these possibilities is very easy at the Lagrangian level but Lagrangians are not directly observed at LHC

Heavy quark identification

Important comments

1. All quarks produced by QCD, distinguished by decays
   ☞ single production $\propto V_{\rm mix}^2$ ignored here
2. Each decay must be identified in a suitable final state and distinguished from similar signals from other quarks
3. Quark charges determined in suitable decays (*e.g.* with Z bosons)
4. 12 different final states tested for model discrimination
   ☞ four examples shown here

Heavy vector-like quark pair decays

$T_{L,R}$, $(T\ B)_{L,R}$

$T \to W^+ b$

$T \to Zt \to ZW^+ b$

$T \to Ht \to HW^+ b$

$(X\ T)_{L,R}$

$T \to Zt \to ZW^+ b$

$T \to Ht \to HW^+ b$

$(X\ T)_{L,R}$

$X \to W^+ t \to W^+ W^+ b$

$(B\ Y)_{L,R}$

$Y \to W^- b$

$(B\ Y)_{L,R}$

$B \to Zb$

$B \to Hb$

$B_{L,R}$, $(T\ B)_{L,R}$

$B \to W^- t \to W^- W^+ b$

$B \to Zb$

$B \to Hb$

$T\bar{T}$, $B\bar{B}$, $X\bar{X}$, $Y\bar{Y}$ production ☞ signatures often similar

Quark identification

Each decay must be identified in a suitable final state and distinguished from similar signals from other quarks

Example: T, B singlets and $(T\ B)$ doublet in $\ell^\pm \ell^\pm \ell^\mp$ (Z) final state

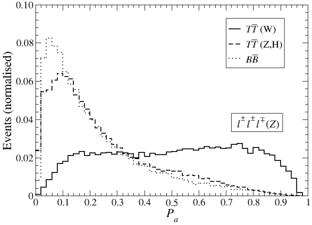
$$T\bar T \to Zt\, W^- \bar b \to ZW^+ bW^- \bar b \qquad Z \to \ell^+\ell^-,\, WW \to \ell\nu q\bar q'$$
$$T\bar T \to Zt\, V\bar t \to ZW^+ b\, VW^- \bar b \qquad Z \to \ell^+\ell^-,\, WW \to \ell\nu q\bar q',\, V \to q\bar q/\nu\bar\nu$$
$$B\bar B \to Zb\, W^+ \bar t \to Zb\, W^+ W^- \bar b \qquad Z \to \ell^+\ell^-,\, WW \to \ell\nu q\bar q'$$

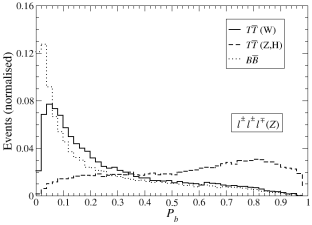
(almost) same final state but different invariant mass peaks

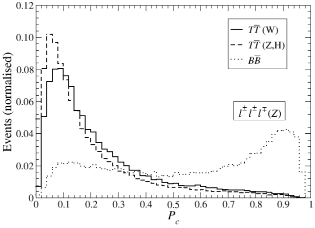
☞ must use a probabilistic method based on kinematics to classify signals as $T\bar T$ or $B\bar B$ efficiently ▸ More

(the same for $\ell^+\ell^-$ (Z) final state, with $WW \to q\bar q' q\bar q'$)

T, B quark identification $\ell^\pm \ell^\pm \ell^\mp$ (Z)





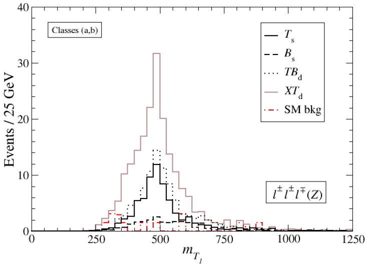


Classification

Class	$P_a >$	$P_b >$	$P_c >$
(a)	0.61	0.24	0.15
(b)	0.19	0.69	0.12
(c)	0.15	0.20	0.65

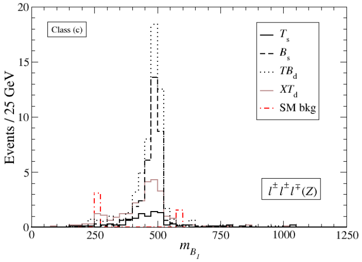
T, B quark identification $\ell^\pm\ell^\pm\ell^\mp$ (Z)

events classified as $T\bar{T}$



$T \rightarrow Zt$ established
T has charge $2/3$

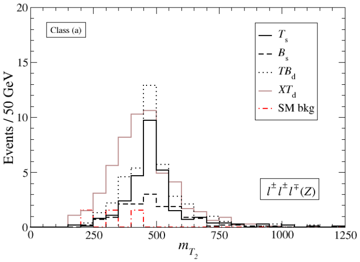
events classified as $B\bar{B}$



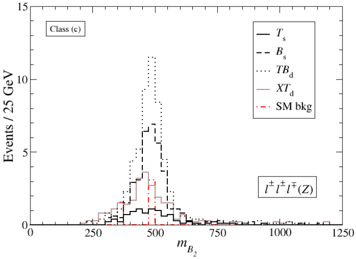
$B \rightarrow Zb$ established
B has charge $-1/3$

T, B quark identification $\ell^\pm\ell^\pm\ell^\mp\ (Z)$

events classified as $T\bar{T}\ (a)$



events classified as $B\bar{B}$

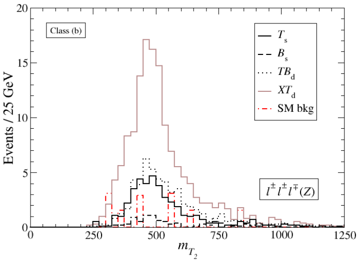


$T \to Wb$ established
but better in $\ell^\pm\ (2b)$

$B \to Wt$ established
☞ not $(B\ Y)$

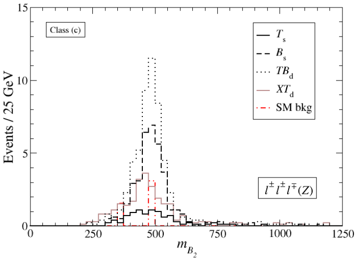
T, B quark identification $\ell^\pm \ell^\pm \ell^\mp \ (Z)$

events classified as $T\bar{T}$ (*b*)



$T \longrightarrow Vt$ ambiguous:
need other channels

events classified as $B\bar{B}$

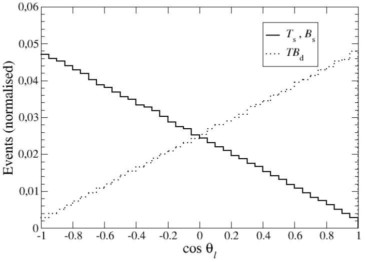


$B \longrightarrow Wt$ established
☞ not $(B\ Y)$

T, B quark identification $\ell^\pm \ell^\pm \ell^\mp$ (Z)

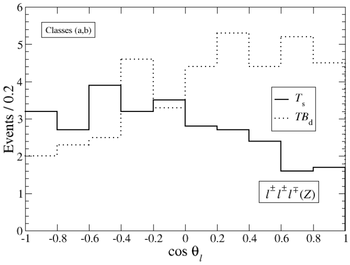
T, B or $(T\ B)$? ☞ ℓ distribution in t rest frame

Theoretical



$P = \pm 0.91$, helicity axis

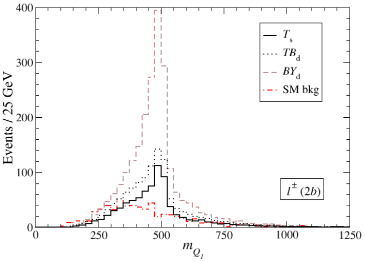
events classified as $T\bar{T}$



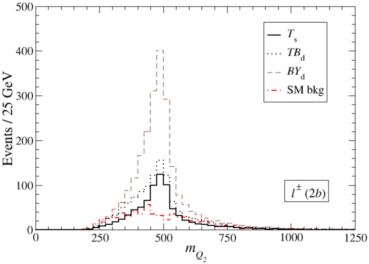
2.4σ difference in A_{FB} for 30 fb^{-1}

T, B, Y quark identification $\ell^\pm\ (2b)$

$Q \to Wb$, W hadronic



$Q \to Wb$, W leptonic



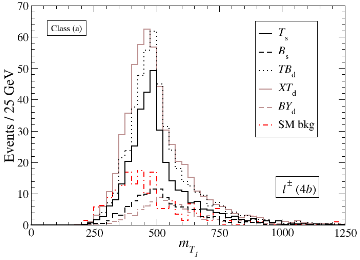
Note: small signal for B and $(X\ T)$ and much larger for $(B\ Y)$

$Q \to Wb$ established
Q charge $2/3$, $-4/3$

Discovery of $T \to Ht$, $B \to Hb$ $\ell^{\pm}$ $(4b)$

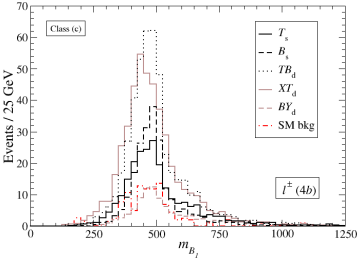
$T\bar{T}$ or $B\bar{B}$? ☞ signal classification by kinematics

events classified as $T\bar{T}$ (a)



peak in $m(tH)$
$T \to Ht$ established

events classified as $B\bar{B}$

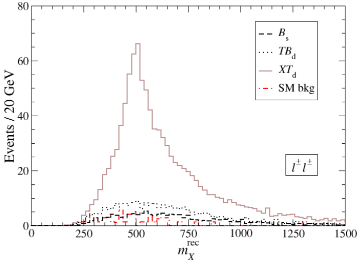


peak in $m(bH)$
$B \to Hb$ established

X quark identification $\ell^\pm\ell^\pm$

$X \to Wt \to WWb$

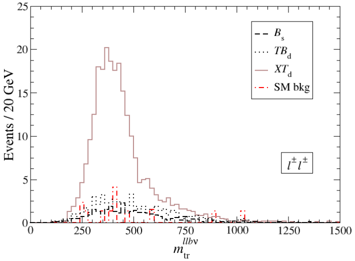
WW hadronic



X charge $-1/3$, $5/3$

$X \to Wt \to WWb$

WW leptonic



$\bar{X}$ charge $-5/3$, $-7/3$

Summary: final states analysed

Discovery luminosities in fb^{-1} $m_Q = 500$ GeV

		T_s	B_s	TB_d	XT_d	BY_d
$\ell^+\ell^+\ell^-\ell^-$	(ZZ)	–	24	18	23	10
$\ell^+\ell^+\ell^-\ell^-$	(Z)	11	14	5.7	3.3	50
$\ell^+\ell^+\ell^-\ell^-$	(no Z)	35	25	11	3.5	–
$\ell^\pm\ell^\pm\ell^\mp$	(Z)	3.4	3.4	1.1	0.72	26
$\ell^\pm\ell^\pm\ell^\mp$	(no Z)	11	3.5	1.1	0.25	–
$\ell^\pm\ell^\pm$		17	4.1	1.5	0.23	–
$\ell^+\ell^-$	(Z)	22	4.5	2.4	4.4	1.8
$\ell^+\ell^-$	(Z, 4b)	–	–	30	–	9.2
$\ell^+\ell^-$	(no Z)	2.7	9.3	0.83	1.1	0.87
$\ell^\pm$	(2b)	1.1	–	0.60	–	0.18
$\ell^\pm$	(4b)	0.70	1.9	0.25	0.16	6.2
$\ell^\pm$	(6b)	11	–	9.4	2.7	–

Summary: roadmap to quark identification

★ T singlet and $T \in (T\ B)$

- discovered in $\ell^\pm$ ($4b$)
- identified in $\ell^\pm$ ($2b$) and $\ell^\pm \ell^\pm \ell^\mp$ (Z)

★ $T \in (X\ T)$

- discovered in $\ell^\pm$ ($4b$), enhanced signal
- no signal in $\ell^\pm$ ($2b$)
- enhanced signal in $\ell^\pm \ell^\pm \ell^\mp$ (Z)

★ $X \in (X\ T)$

- discovered in $\ell^\pm \ell^\pm$ and $\ell^\pm \ell^\pm \ell^\mp$ (no Z)
- also visible in $\ell^+ \ell^+ \ell^- \ell^-$ (no Z)

Summary: roadmap to quark identification

★ B singlet and $B \in (T\ B)$

- discovered in $\ell^\pm$ ($4b$)
- identified in $\ell^\pm \ell^\pm \ell^\mp$ (Z)
- further evidence from $\ell^\pm \ell^\pm \ell^\mp$ (no Z)

★ $B \in (B\ Y)$

- discovered in $\ell^+ \ell^-$ (Z), enhanced signal
- does not give $\ell^\pm \ell^\pm \ell^\mp$ (Z, no Z)
- enhanced $\ell^+ \ell^+ \ell^- \ell^-$ (ZZ)

★ $Y \in (B\ Y)$

- discovered in $\ell^\pm$ ($2b$), enhanced signal
- further evidence from enhanced $\ell^+ \ell^-$ (no Z)
- signals with Z absent

Conclusions II

1. Strategy designed for identification of top partners: vector-like quarks coupling to the third generation

2. Single lepton signals are best for discovery

   but quark identification requires multi-lepton signals

3. Approximate mass reach for 100 fb^{-1} More

   - 800 GeV for T
   - 720 GeV for B
   - 850 GeV for $(T\ B)$
   - 900 GeV for $(X\ T)$
   - 820 GeV for $(B\ Y)$

Final remarks

1. Discovering event excesses at LHC is not enough: we want to identify the new physics giving the signals
2. Identifying a model is much harder than discovering a signal in one's favourite channel
3. With LHC start approaching, a strategy is necessary to extract the best of data as soon as possible
   - a guide to identify particles
   - a list of their possible signatures
   - a guide of final states to examine if some signal is seen
4. The usefulness of this analysis is to provide such guide for new quarks and leptons

Minimal 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

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

E, N have small mixing $\sim 10^{-6}$ with the SM leptons l, ν
but unsuppressed gauge interactions with W, Z, γ

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Dirac variant of seesaw III

The Lagrangian

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

two (quasi-)degenerate neutrinos N_1, N_2 with $Y_{lN_2} = iY_{lN_1}$

opposite CP parities

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

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

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

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T singlet

The Lagrangian – weak basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \, \bar{u}'_{Li} \gamma^\mu d'_{Li} \, W^+_\mu + \text{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[\bar{u}'_{Li} \gamma^\mu u'_{Li} - 2 s_W^2 J^\mu_{\text{EM}} \right] Z_\mu$$

$$\mathcal{L}_\text{Y} = -\text{Y}^u_{i\beta} \, \bar{q}'_{Li} u'_{R\beta} \, \tilde{\phi} + \text{H.c.}$$

$$\mathcal{L}_\text{bare} = -M \bar{u}'_{L4} u'_{R4} + \text{H.c.}$$

T singlet

The Lagrangian – mass eigenstate basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\, \bar{u}_{L\alpha} \gamma^{\mu} \mathrm{V}_{\alpha j} d_{Lj}\, W_{\mu}^{+} + \mathrm{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[\bar{u}_{L\alpha} \gamma^{\mu} \mathrm{X}_{\alpha\beta} u_{L\beta} - 2 s_W^2 J_{\mathrm{EM}}^{\mu} \right] Z_{\mu}$$

$$\mathcal{L}_H = -\frac{g}{2M_W} \left[\bar{u}_{L\alpha} \mathrm{X}_{\alpha\beta}\, m_{\beta}^{u} u_{R\beta} + \bar{u}_{R\alpha} m_{\alpha}^{u} \mathrm{X}_{\alpha\beta} u_{L\beta} \right] H$$

B singlet

The Lagrangian – weak basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \, \bar{u}'_{Li} \gamma^\mu d'_{Li} \, W^+_\mu + \text{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[-\bar{d}'_{Li} \gamma^\mu d'_{Li} - 2 s_W^2 J^\mu_{\text{EM}} \right] Z_\mu$$

$$\mathcal{L}_\text{Y} = -\text{Y}^d_{i\beta} \, \bar{q}'_{Li} d'_{R\beta} \, \phi + \text{H.c.}$$

$$\mathcal{L}_\text{bare} = -M \bar{d}'_{L4} d'_{R4} + \text{H.c.}$$

B singlet

The Lagrangian – mass eigenstate basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \, \bar{u}_{Li} \gamma^\mu \mathrm{V}_{i\beta} d_{L\beta} \, W_\mu^+ + \mathrm{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[-\bar{d}_{L\alpha} \gamma^\mu \mathrm{X}_{\alpha\beta} d_{L\beta} - 2 s_W^2 J_{\mathrm{EM}}^\mu \right] Z_\mu$$

$$\mathcal{L}_H = -\frac{g}{2M_W} \left[\bar{d}_{L\alpha} \mathrm{X}_{\alpha\beta} \, m_\beta^d d_{R\beta} + \bar{d}_{R\alpha} m_\alpha^d \mathrm{X}_{\alpha\beta} d_{L\beta} \right] H$$

$(T\ B)$ doublet

The Lagrangian – weak basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[\bar{u}'_{L\alpha} \gamma^\mu d'_{L\alpha} + \bar{u}'_{R4} \gamma^\mu d'_{R4} \right] W_\mu^+ + \text{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[\bar{u}'_{L\alpha} \gamma^\mu u'_{L\alpha} + \bar{u}'_{R4} \gamma^\mu u'_{R4} - \bar{d}'_{L\alpha} \gamma^\mu d'_{L\alpha} - \bar{d}'_{R4} \gamma^\mu d'_{R4} \right.$$
$$\left. -2 s_W^2 J^\mu_{\text{EM}} \right] Z_\mu$$

$$\mathcal{L}_\text{Y} = -\text{Y}^u_{\alpha j}\; \bar{q}'_{L\alpha} u'_{Rj}\, \tilde{\phi} - \text{Y}^d_{\alpha j}\; \bar{q}'_{L\alpha} d'_{Rj}\, \phi + \text{H.c.}$$

$$\mathcal{L}_\text{bare} = -M \bar{q}'_{L4} q'_{R4} + \text{H.c.}$$

$(T\ B)$ doublet

The Lagrangian – mass eigenstate basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[\bar{u}_{Li} \gamma^\mu \mathrm{V}^L_{ij} d_{Lj} + \bar{T}_L \gamma^\mu B_L + \bar{u}_{R\alpha} \gamma^\mu \mathrm{V}^R_{\alpha\beta} d_{R\beta} \right] W^+_\mu + \mathrm{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[\bar{u}_{L\alpha} \gamma^\mu u_{L\alpha} + \bar{u}_{R\alpha} \gamma^\mu \mathrm{X}^u_{\alpha\beta} u_{R\beta} \right.$$
$$\left. - \bar{d}_{L\alpha} \gamma^\mu d_{L\alpha} - \bar{d}_{R\alpha} \gamma^\mu \mathrm{X}^d_{\alpha\beta} d_{R\beta} - 2 s_W^2 J^\mu_{\mathrm{EM}} \right] Z_\mu$$

$$\mathcal{L}_H = -\frac{g}{2M_W} \left[\bar{u}_{L\alpha} m^u_\alpha (\delta_{\alpha\beta} - \mathrm{X}^u_{\alpha\beta}) u_{R\beta} + \bar{u}_{R\alpha} (\delta_{\alpha\beta} - \mathrm{X}^u_{\alpha\beta}) m^u_\beta u_{L\beta} \right.$$
$$\left. + \bar{d}_{L\alpha} m^d_\alpha (\delta_{\alpha\beta} - \mathrm{X}^d_{\alpha\beta}) d_{R\beta} + \bar{d}_{R\alpha} (\delta_{\alpha\beta} - \mathrm{X}^d_{\alpha\beta}) m^d_\beta d_{L\beta} \right] H$$

$(X\ T)$ doublet

The Lagrangian – weak basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[\bar{u}'_{Li} \gamma^\mu d'_{Li} + \bar{X}_L \gamma^\mu u'_{L4} + \bar{X}_R \gamma^\mu u'_{R4} \right] W^+_\mu + \text{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[\bar{u}'_{Li} \gamma^\mu u'_{Li} - \bar{u}'_{L4} \gamma^\mu u'_{L4} - \bar{u}'_{R4} \gamma^\mu u'_{R4} + \bar{X} \gamma^\mu X - 2 s_W^2 J^\mu_{\text{EM}} \right] Z_\mu$$

$$\mathcal{L}_\text{Y} = -\text{Y}^u_{ij}\ \bar{q}'_{Li} u'_{Rj}\ \tilde{\phi} - \text{Y}^u_{4j}\ \overline{(\bar{X}_L\ \bar{u}'_{L4})}\ u'_{Rj}\ \phi + \text{H.c.}$$

$$\mathcal{L}_\text{bare} = -M\ (\bar{X}_L\ \bar{u}'_{L4}) \begin{pmatrix} X_R \\ u'_{R4} \end{pmatrix} + \text{H.c.}$$

$(X\ T)$ doublet

The Lagrangian – mass eigenstate basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[\bar{u}_{Li} \gamma^\mu \mathrm{V}^L_{ij} d_{Lj} + \bar{X}_L \gamma^\mu T_L + \bar{X}_R \gamma^\mu \mathrm{V}^R_{4\beta} u_{R\beta} \right] W^+_\mu + \mathrm{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[\bar{u}_{Li} \gamma^\mu u_{Li} - \bar{T}_L \gamma^\mu T_L - \bar{u}_{R\alpha} \gamma^\mu \mathrm{X}_{\alpha\beta} u_{R\beta} + \bar{X} \gamma^\mu X \right.$$
$$\left. -2 s_W^2 J^\mu_{\mathrm{EM}} \right] Z_\mu$$

$$\mathcal{L}_H = -\frac{g}{2M_W} \left[\bar{u}_{L\alpha} m^u_\alpha (\delta_{\alpha\beta} - \mathrm{X}_{\alpha\beta}) u_{R\beta} + \bar{u}_{R\alpha} (\delta_{\alpha\beta} - \mathrm{X}_{\alpha\beta}) m^u_\beta u_{L\beta} \right] H$$

The Lagrangian – weak basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[\bar{u}'_{Li} \gamma^\mu d'_{Li} + \bar{d}'_{L4} \gamma^\mu Y_L + \bar{d}'_{R4} \gamma^\mu Y_R \right] W^+_\mu + \text{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[-\bar{d}'_{Li} \gamma^\mu d'_{Li} + \bar{d}'_{L4} \gamma^\mu d'_{L4} + \bar{d}'_{R4} \gamma^\mu d'_{R4} - \bar{Y} \gamma^\mu Y \right.$$
$$\left. -2 s_W^2 J^\mu_{\text{EM}} \right] Z_\mu$$

$$\mathcal{L}_\text{Y} = -\text{Y}^d_{ij} \, \bar{q}'_{Li} d'_{Rj} \, \phi - \text{Y}^d_{4j} \, \overline{(\bar{d}'_{L4} \ \bar{Y}_L)} \, d'_{Rj} \, \tilde{\phi} + \text{H.c.}$$

$$\mathcal{L}_\text{bare} = -M \left(\bar{d}'_{L4} \ \bar{Y}_L \right) \begin{pmatrix} d'_{R4} \\ X_R \end{pmatrix} + \text{H.c.}$$

$(B\ Y)$ doublet

The Lagrangian – mass eigenstate basis

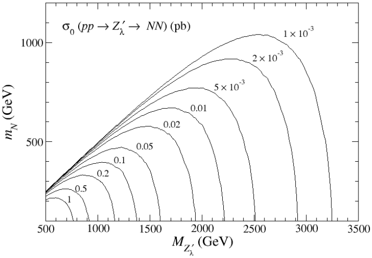
$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[\bar{u}_{Li} \gamma^\mu \mathrm{V}^L_{ij} d_{Lj} + \bar{B}_L \gamma^\mu Y_L + \bar{d}_{R\alpha} \gamma^\mu \mathrm{V}^R_{\alpha 4} Y_R \right] W^+_\mu + \text{H.c.}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[-\bar{d}_{Li} \gamma^\mu d_{Li} + \bar{B}_L \gamma^\mu B_L + \bar{d}_{R\alpha} \gamma^\mu \mathrm{X}_{\alpha\beta} d_{R\beta} - \bar{Y} \gamma^\mu Y \right.$$
$$\left. -2 s_W^2 J^\mu_{\mathrm{EM}} \right] Z_\mu$$

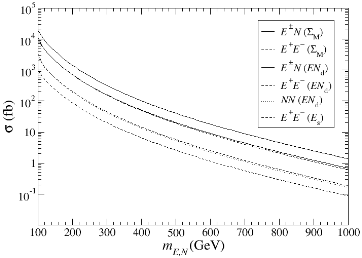
$$\mathcal{L}_H = -\frac{g}{2M_W} \left[\bar{d}_{L\alpha} m^d_\alpha (\delta_{\alpha\beta} - \mathrm{X}_{\alpha\beta}) d_{R\beta} + \bar{d}_{R\alpha} (\delta_{\alpha\beta} - \mathrm{X}_{\alpha\beta}) m^d_\beta d_{L\beta} \right] H$$

Cross sections

$Z'_\lambda + N_{\rm M}$



$\Sigma_{\rm M}$, $\Sigma_{\rm D}$, $EN_{\rm d}$



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Signals and backgrounds $\ell^\pm\ell^\pm\ell^\mp$ (no Z)

	Pre.	Sel.	Peak		Pre.	Sel.	Peak
E^+E^- (Σ_M)	58.1	26.3	5.7	E^+E^- (EN_d)	38.3	23.7	5.4
$E^\pm N$ (Σ_M)	269.2	192.2	86.3	$E^\pm N$ (EN_d)	393.2	355.1	183.8
$E_1^+E_1^-$ (Σ_D)	127.2	80.9	20.0	NN (EN_d)	164.4	155.7	87.8
$E_2^+E_2^-$ (Σ_D)	0.0	0.0	0.0	E^+E^- (E_s)	8.2	3.1	0.7
$E_1^\pm N$ (Σ_D)	502.1	370.2	181.9	NN ($Z'N_\mathrm{M}$)	311.0	252.6	143.2
$E_2^\pm N$ (Σ_D)	36.1	28.1	3.3	NN ($Z'N_\mathrm{D}$)	576.2	481.9	285.5
$t\bar{t}nj$	236	156	0	$WZnj$	1540	38	2
$Wt\bar{t}nj$	54	47	6	$ZZnj$	86	5	0
$Zt\bar{t}nj$	151	20	3	$WWWnj$	17	12	3

$p_T > 30$ GeV ($\ell^\pm\ell^\pm$) $p_T > 10$ GeV ($\ell^\mp$) 2 jets $p_T > 20$ GeV

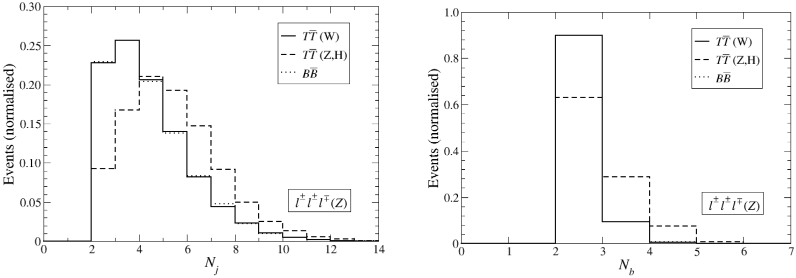
$|m_{\ell^+\ell^-} - M_Z| > 10$ GeV

	Pre.	Sel.	Peak		Pre.	Sel.	Peak
E^+E^- (Σ_M)	21.7	1.6	0.3	E^+E^- (EN_d)	10.5	1.2	0.3
$E^\pm N$ (Σ_M)	658.0	240.0	144.8	$E^\pm N$ (EN_d)	111.8	6.2	1.9
$E_1^+E_1^-$ (Σ_D)	25.6	4.2	0.7	NN (EN_d)	47.7	1.9	0.8
$E_2^+E_2^-$ (Σ_D)	0.0	0.0	0.0	E^+E^- (E_s)	2.5	0.0	0.0
$E_1^\pm N$ (Σ_D)	174.4	9.4	2.7	NN ($Z'N_\mathrm{M}$)	433.5	202.1	132.0
$E_2^\pm N$ (Σ_D)	472.0	2.9	0.9	NN ($Z'N_\mathrm{D}$)	206.0	8.1	3.1
$t\bar{t}nj$	1412	194	7	$WWnj$	245	15	3
tW	96	6	0	$WZnj$	1056	24	1
$Wt\bar{t}nj$	184	12	1	$ZZnj$	110	7	1

$p_T > 30$ GeV ($\ell^\pm \ell^\pm$) $\not{p}_t < 30$ GeV   4 jets $p_T > 20$ GeV

Distributions

$\ell^{\pm}\ell^{\pm}\ell^{\mp}$ (Z)



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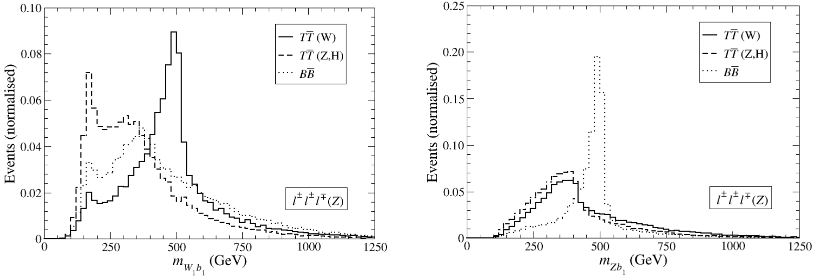

0.10
0.08
0.06
0.04
0.02
0
Events (normalised)
0 250 500 750 1000 1250
$m_{W_1 b_1}$ (GeV)
$T\bar{T}$ (W)
$T\bar{T}$ (Z,H)
$B\bar{B}$
$l^\pm l^\pm l^\mp$(Z)
0.25
0.20
0.15
0.10
0.05
0
Events (normalised)
0 250 500 750 1000 1250
m_{Zb_1} (GeV)
$T\bar{T}$ (W)
$T\bar{T}$ (Z,H)
$B\bar{B}$
$l^\pm l^\pm l^\mp$(Z)

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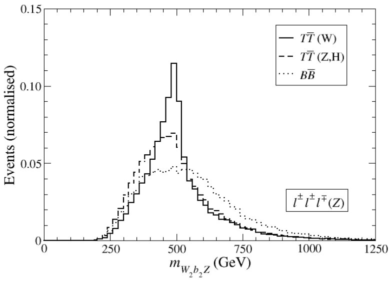
0.15
0.10
0.05
0
Events (normalised)
0
250
500
750
1000
1250
$m_{W_2b_2Z}$ (GeV)
$T\overline{T}$ (W)
$T\overline{T}$ (Z,H)
$B\overline{B}$
$l^{\pm}l^{\pm}l^{\mp}$(Z)
0.10
0.08
0.06
0.04
0.02
0
Events (normalised)
$m_{W_1W_2b_2}$ (GeV)

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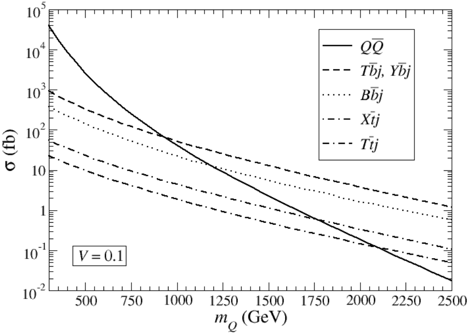
Cross sections



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Comparison with 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 ☞

> in mSUGRA signals with 0/1 lepton are the most significant ones in contrast with seesaw I–III where they are irrelevant

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
mSUGRA (SU4)	113 + 113	25	33.7	24.7	19.9	24.4

☞ with same *M*, multi-lepton signals larger in seesaw II, III

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

Comparison with 4$^{\text{th}}$ generation

Indirect data prefer $m_{t'} - m_{b'} = 60$ GeV

t' decay	either	$t' \to W^+ b$	☞	$t' \to Zt$ absent, no B
	or	$t' \to W^+ b'$	☞	not present for singlets

b' decay $\quad b' \to W^- t \quad$ ☞ $\quad b' \to Zb$ absent