Multi-lepton signals from non-sequential quarks and leptons

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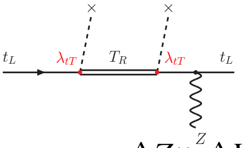
1. Introduction: why and what
2. Models of new quarks and their signals
3. Seesaw and other models for new leptons

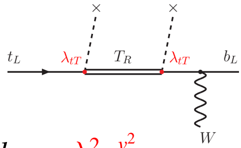
Motivation

Despite the tremendous (recent) popularity of 4^{th} generation…

- There are other possibilities for new fermions
- Alternative models give even more striking signals at LHC
- They can also explain discrepancies in B physics
- Let experiments decide!

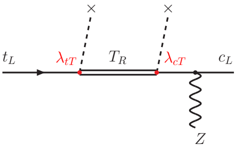
Direct vs indirect signals of new fermions



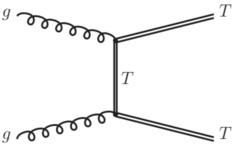


$$\Delta Ztt, \Delta Wtb \ \propto \ \lambda_{tT}^2 \frac{v^2}{M^2}$$

[Aguila, Perez-Victoria, Santiago JHEP '00]

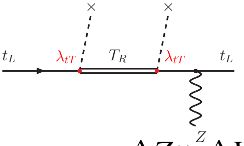


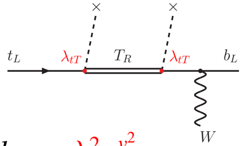
$$t \to Zc \ \propto \ \lambda_{tT}^2 \lambda_{cT}^2 \frac{v^4}{M^4}$$



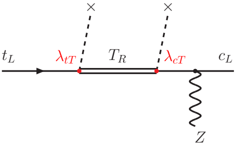
$$\sigma \propto \frac{1}{M} \frac{1}{\mathrm{PDF}(2M)}$$

Direct vs indirect signals of new fermions





$$\Delta Ztt, \Delta Wtb \;\propto\; \lambda_{tT}^2 \frac{v^2}{\ldots}$$



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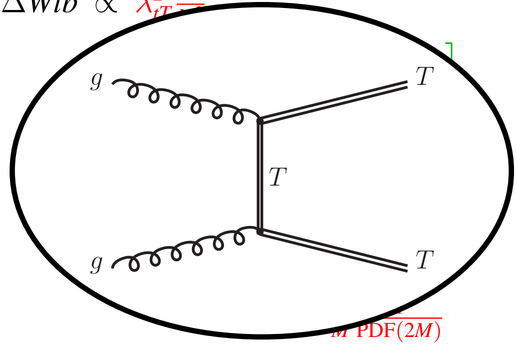
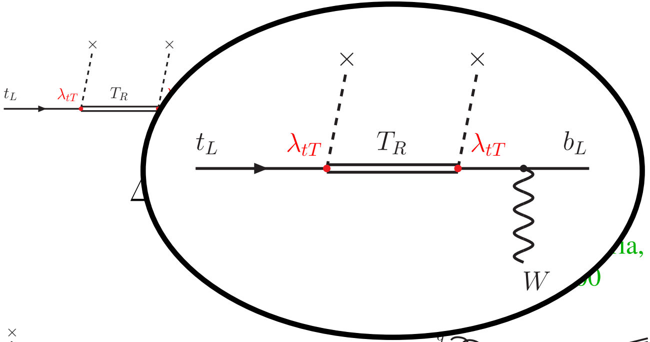
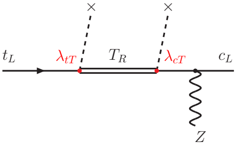
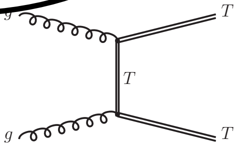


M PDF$(2M)$

Direct vs indirect signals of new fermions



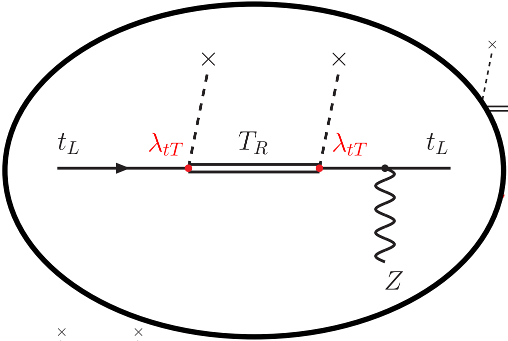


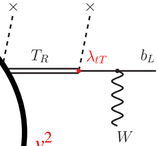


$$t \to Zc \;\propto\; \lambda_{tT}^2 \lambda_{cT}^2 \frac{v^4}{M^4}$$

$$\sigma \;\propto\; \frac{1}{M} \frac{1}{\mathrm{PDF}(2M)}$$

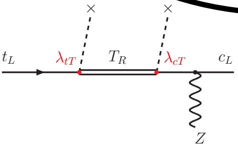
Direct vs indirect signals of new fermions

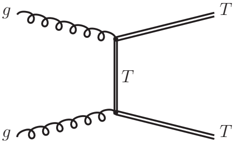




$\frac{v^2}{M^2}$

[Aguila, Perez-Victoria, Santiago JHEP '00]

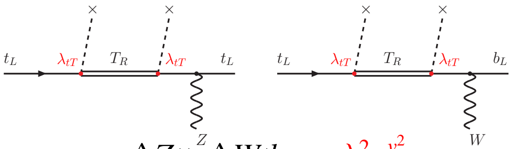




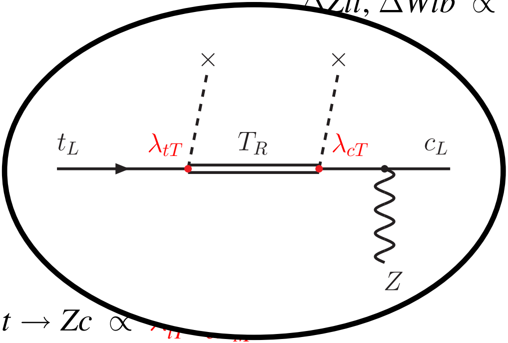
$$t \to Zc \;\propto\; \lambda_{tT}^2 \lambda_{cT}^2 \frac{v^4}{M^4}$$

$$\sigma \propto \frac{1}{M} \frac{1}{\mathrm{PDF}(2M)}$$

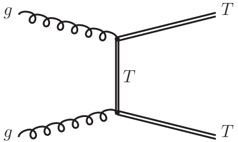
Direct vs indirect signals of new fermions



$$\Delta Ztt, \Delta Wtb \;\propto\; \lambda_{tT}^2 \frac{v^2}{M^2}$$



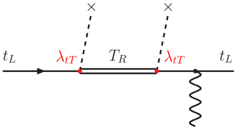
[Aguila, Perez-Victoria, Santiago JHEP '00]

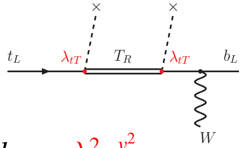


$t \to Zc \;\propto$

$$\sigma \propto \frac{1}{M}\,\frac{1}{\mathrm{PDF}(2M)}$$

Direct vs indirect signals of new fermions



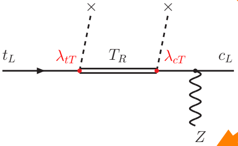


$$\Delta Ztt, \Delta Wtb \;\propto\; \lambda_{tT}^2 \frac{v^2}{M^2}$$

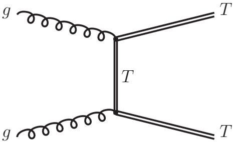
[Aguila, Perez-Victoria, Santiago JHEP '00]

EW precision constraints

B, K physics



$$t \to Zc \;\propto\; \lambda_{tT}^2 \lambda_{cT}^2 \frac{v^4}{M^4}$$



$$\sigma \propto \frac{1}{M} \frac{1}{\mathrm{PDF}(2M)}$$

Direct vs indirect signals of new fermions

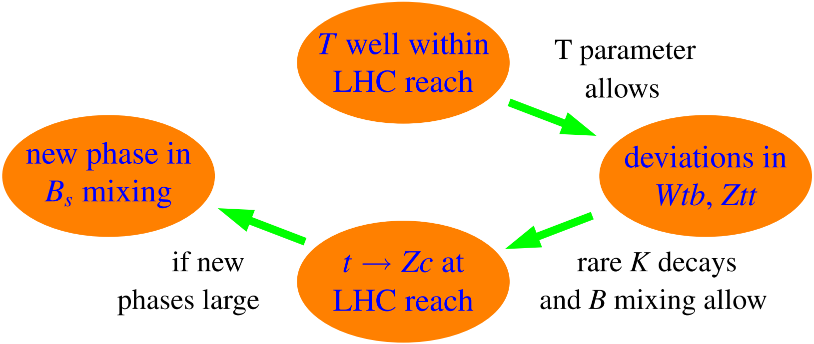
PDF suppression is stronger in principle, but …

- λ_{tT} constrained by precision data
- λ_{cT} tightly constrained by low energy physics

… then, dominant effect depends on the type of new physics

Direct vs indirect signals of new fermions

E.g. vector-like singlet T [JAAS, Botella, Branco, Nebot NPB ’05]



phase in B_s mixing ($a_{J/\psi\phi}$) encourages search for other effects

☞ if T not seen at LHC, forget everything else …

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
- Minimal seesaw I, II, III
- Heavy leptons (seesaw or not)
- Heavy quarks
- ...

What is in this talk

1. Pair production of heavy quarks coupling to 3^{rd} family
2. Pair production of heavy leptons with special attention to seesaw

What is not in this talk

1. Minimal seesaw I → small signals
2. Seesaw II → not fermions; clear identification
3. $W' + N$ → easy discrimination from other models with new leptons
4. 4^{th} generation → easy discrimination from models with vector-like quarks

Models with new quarks

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

Models with new quarks

"Top partners" ☞ new quarks mainly coupling to 3rd generation

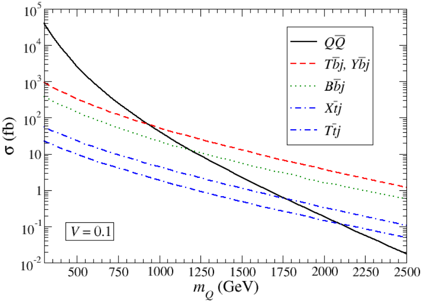
Models

multiplet	charges	coupling to	label
$T_{L,R}$	$2/3$	t, b	T_s
$B_{L,R}$	$-1/3$	t, b	B_s
$(T\ B)_{L,R}$	$2/3, -1/3$	t, b	TB_{d_1}
$(T\ B)_{L,R}$	$2/3, -1/3$	t	TB_{d_2}
$(X\ T)_{L,R}$	$5/3, 2/3$	t	XT_d
$(B\ Y)_{L,R}$	$-1/3, -4/3$	b	BY_d

They appear in extra dimensions, little Higgs, ...

Heavy vector-like quark production

Production cross section



Processes

- Pair production (QCD) only depends on mass
- Single production (EW) $\sigma \propto V^2$

Heavy vector-like quark decays

T_s , TB_{d_1}

$T \to W^+ b$

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

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

BY_d

$Y \to W^- b$

TB_{d_2} , XT_d

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

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

BY_d

$B \to Zb$

$B \to Hb$

TB_{d_2}

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

XT_d

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

B_s , TB_{d_1}

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

$B \to Zb$

$B \to Hb$

Heavy quark identification

Important comments

1. All quarks produced by QCD, distinguished by decays
   ☞ single production $\propto V_{\text{mix}}^2$ 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
   ☞ only two examples shown here

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

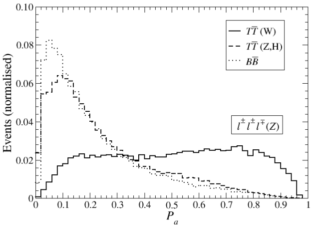
$$T\bar{T} \to Zt\,W^-\bar{b} \to ZW^+bW^-\bar{b} \qquad Z \to \ell^+\ell^-\,, WW \to \ell\nu q\bar{q}'$$
$$T\bar{T} \to Zt\,V\bar{t} \to ZW^+b\,VW^-\bar{b} \qquad Z \to \ell^+\ell^-\,, WW \to \ell\nu q\bar{q}'\,, V \to q\bar{q}/\nu\bar{\nu}$$
$$B\bar{B} \to Zb\,W^+\bar{t} \to Zb\,W^+W^-\bar{b} \qquad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

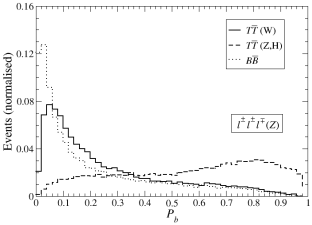
(almost) same final state but different invariant mass peaks

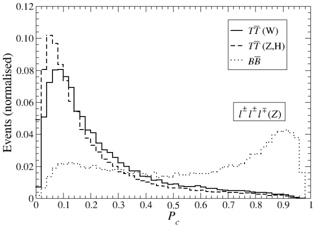
☞ must use a probabilistic method based on kinematics to classify signals as $T\bar{T}$ or $B\bar{B}$ efficiently ▸ More

(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)





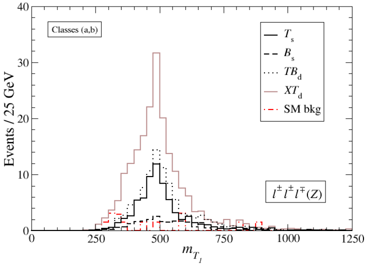


Classification

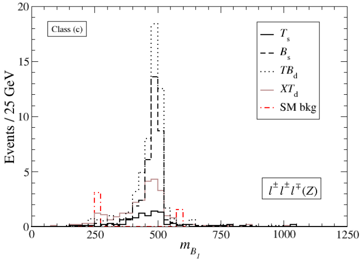
Class	$P_a >$	$P_b >$	$P_c >$
(a)	0.61	0.24	0.15
(b)	0.19	0.69	0.12
(c)	0.15	0.20	0.65

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

events classified as $T\bar{T}$



events classified as $B\bar{B}$

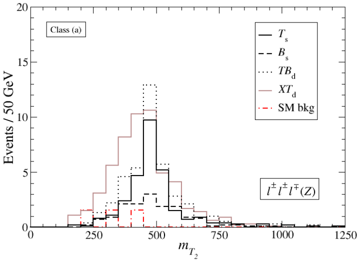


$T \to Zt$ established
T has charge $2/3$

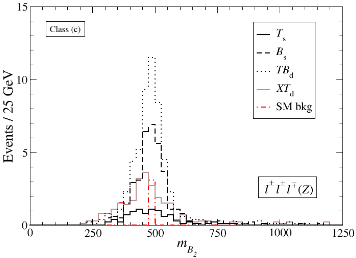
$B \to Zb$ established
B has charge $-1/3$

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

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



events classified as $B\bar{B}$

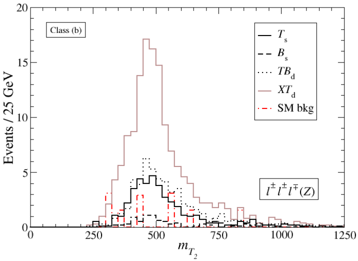


$T \longrightarrow Wb$ established
but better in $\ell^\pm$ $(2b)$

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

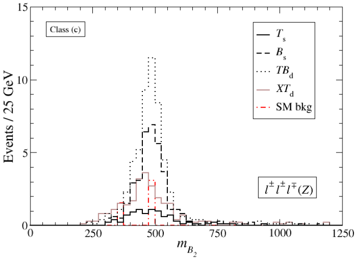
T, B quark identification $\qquad \ell^\pm \ell^\pm \ell^\mp$ (Z)

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



$T \longrightarrow Vt$ ambiguous:
need other channels

events classified as $B\bar{B}$

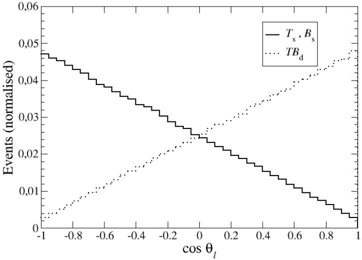


$B \longrightarrow Wt$ established
☞ not $(B\ Y)$

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

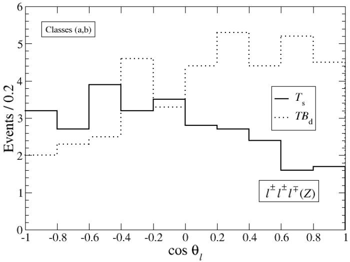
T, B or $(T\ B)$? ☞ ℓ distribution in t rest frame

Theoretical



$P = \pm 0.91$, helicity axis

events classified as $T\bar{T}$



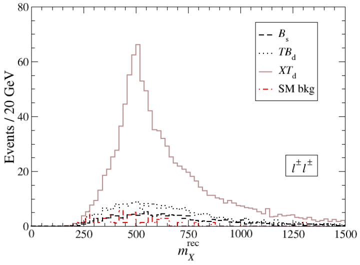
2.4σ difference in A_{FB} for 30 fb^{-1}

X quark identification

$\ell^\pm \ell^\pm$

$X \to Wt \to WWb$

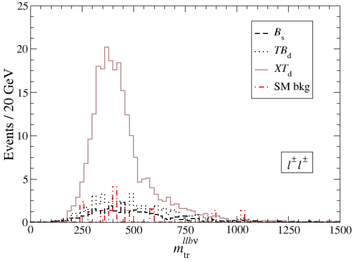
WW hadronic



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

$X \to Wt \to WWb$

WW leptonic



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

Comparison: multi-lepton signals from heavy quarks

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

		T_s	B_s	TB_{d_1}	TB_{d_2}	XT_d	BY_d
$\ell^+\ell^+\ell^-\ell^-$	(ZZ)	–	24	18	23	23	10
$\ell^+\ell^+\ell^-\ell^-$	(Z)	11	14	5.7	3.4	3.3	50
$\ell^+\ell^+\ell^-\ell^-$	(no Z)	35	25	11	3.3	3.5	–
$\ell^\pm\ell^\pm\ell^\mp$	(Z)	3.4	3.4	1.1	0.73	0.72	26
$\ell^\pm\ell^\pm\ell^\mp$	(no Z)	11	3.5	1.1	0.25	0.25	–
$\ell^\pm\ell^\pm$		17	4.1	1.5	0.23	0.23	–
$\ell^+\ell^-$	(Z)	22	4.5	2.4	4.4	4.4	1.8
$\ell^+\ell^-$	(Z, 4b)	–	–	30	–	–	9.2
$\ell^+\ell^-$	(no Z)	2.7	9.3	0.83	1.1	1.1	0.87
$\ell^\pm$	(2b)	1.1	–	0.60	–	–	0.18
$\ell^\pm$	(4b)	0.70	1.9	0.25	0.16	0.16	6.2
$\ell^\pm$	(6b)	11	–	9.4	2.7	2.7	–

Fast simulation results [JAAS JHEP '09]

Summary: roadmap to quark identification

★ T singlet; $T \in (T\ B)_1$

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

★ $T \in (T\ B)_2$; $T \in (X\ T)$

- 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; $B \in (T\ B)_1$

- 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)

★ $B \in (T\ B)_2$

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

Summary: roadmap to quark identification

★ $Y \in \begin{pmatrix} B & Y \end{pmatrix}$

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

Motivation for heavy leptons

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…

Motivation for heavy leptons at 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

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]

popular 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

Some models with new leptons

Heavy leptons (seesaw messengers) can couple to e, μ, τ in general

Assume they mainly couple to e, μ

Models

multiplet	particles	D/M	label
N_R	N	M	$Z' N_{\rm M}$
N_{1R}, N_{2R}	N	D	$Z' N_{\rm D}$
Σ_R	E^-, N	M	$\Sigma_{\rm M}$
Σ_{1R}, Σ_{2R}	E_1^-, N, E_2^+	D	$\Sigma_{\rm D}$
$(N\ E)_{L,R}$	E^-, N	D	$NE_{\rm d}$
$E_{L,R}$	E^-	–	$E_{\rm s}$

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

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

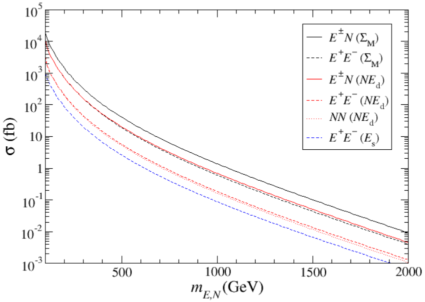
$$\{\ N_{1R}, N_{2R}\ \} \quad \longrightarrow \quad N_L \equiv \frac{1}{\sqrt{2}}(N_{1R}^c + iN_{2R}^c) \quad N_R \equiv \frac{1}{\sqrt{2}}(N_{1R} + iN_{2R})$$

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

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

Heavy lepton pair production

Production cross section



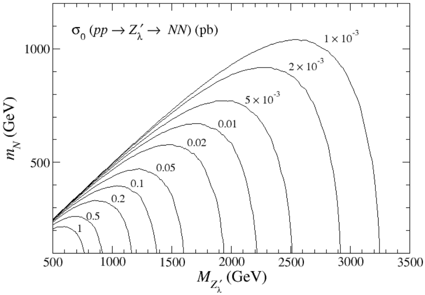
Processes

- $q\bar{q}' \to W^* \to EN$
- $q\bar{q} \to Z^*/\gamma^* \to E^+E^-$
- $q\bar{q} \to Z' \to NN$

  (if Z' with $M_{Z'} > 2m_N$)

Heavy lepton pair production

Production cross section



Processes

- $q\bar{q}' \to W^* \to EN$
- $q\bar{q} \to Z^*/\gamma^* \to E^+E^-$
- $q\bar{q} \to Z' \to NN$

  (if Z' with $M_{Z'} > 2m_N$)

Heavy lepton decays

N_M , Σ_M

$N \to W^+ \ell^-$

$N \to W^- \ell^+$

$N \to Z\nu$

$N \to H\nu$

Σ_M

$E^- \to W^- \nu$

$E^- \to Z\ell^-$

$E^- \to H\ell^-$

N_D , Σ_D

$N \to W^+ \ell^-$

$N \to Z\nu$

$N \to H\nu$

NE_d

$N \to W^+ \ell^-$

NE_d

$E^- \to Z\ell^-$

$E^- \to H\ell^-$

Σ_D

$E_1^- \to Z\ell^-$

$E_1^- \to H\ell^-$

$E_2^+ \to W^+ \nu$

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

Comparison: multi-lepton signals from heavy leptons

Discovery luminosities in fb^{-1} $m_L = 300$ GeV $M_{Z'_\lambda} = 650$ GeV

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

→ Easy model discrimination!

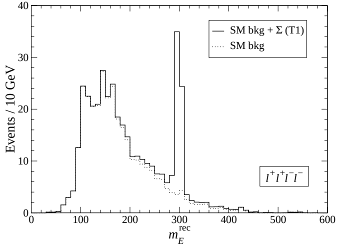
Fast simulation results [JAAS NPB '09]

Results

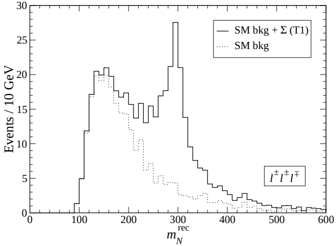
$m_{E,N} = 300$ GeV

Synergy between channels for E, N discovery

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



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



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

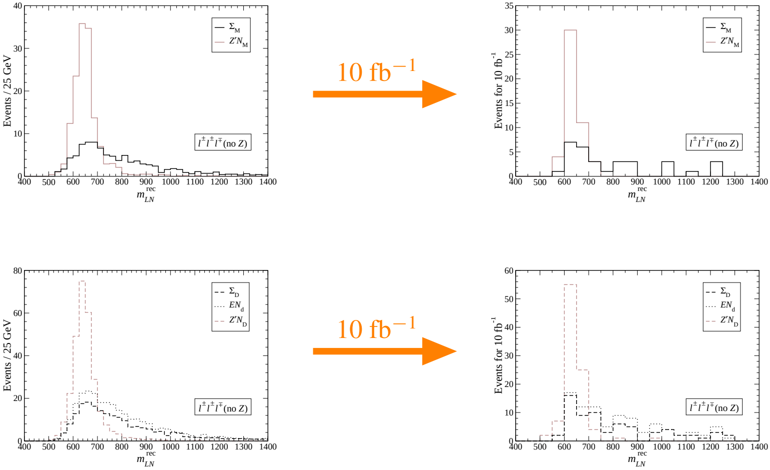
$\ell^\pm\ell^\pm\ell^\mp$ → Evidence of N production (resonance with charge 0)

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

Results

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

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



Summary

- ★ Strategy designed for discovery of seesaw messengers and model discrimination
- ★ Trilepton signals are the golden mode for seesaw searches but model identification relies on other multi-lepton signals
- ★ In particular, heavy lepton peaks can be identified in trilepton and four lepton final states

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

Final remarks

5. The Monte Carlo `Protos` generates all these signals and more, interface with `Athena` ready

6. Approximate mass reach for 100 fb^{-1}
   - 800 GeV for T
   - 720 GeV for B
   - 850 GeV for $(T\ B)_1$
   - 900 GeV for $(T\ B)_2$, $(X\ T)$
   - 820 GeV for $(B\ Y)$
   - 675 (800) GeV for Σ_M (Σ_D)
   - 850 GeV for $(N\ E)$
   - 850 GeV (1 TeV) for $Z' N_\mathrm{M}$ ($Z' N_\mathrm{D}$)
   - 700 GeV (900 GeV) for Δ NH (IH)

Additional Slides

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

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

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

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

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

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

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

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

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

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

$(X\ T)$ doublet

The Lagrangian – mass eigenstate basis

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

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

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

$(B\ Y)$ doublet

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

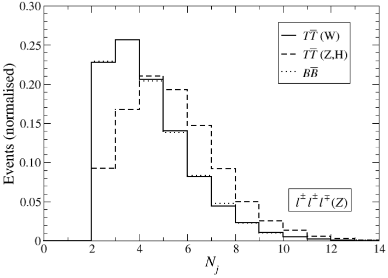
$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[\bar{u}_{Li} \gamma^\mu \mathrm{V}^L_{ij} d_{Lj} + \bar{B}_L \gamma^\mu Y_L + \bar{d}_{R\alpha} \gamma^\mu \mathrm{V}^R_{\alpha 4} Y_R \right] W^+_\mu + \mathrm{H.c.}$$

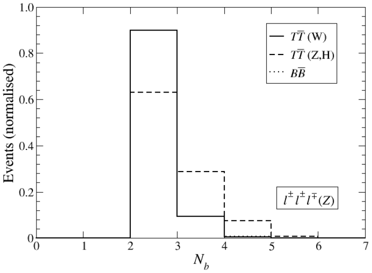
$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[-\bar{d}_{Li} \gamma^\mu d_{Li} + \bar{B}_L \gamma^\mu B_L + \bar{d}_{R\alpha} \gamma^\mu \mathrm{X}_{\alpha\beta} d_{R\beta} - \bar{Y} \gamma^\mu Y \right.$$
$$\left. -2 s_W^2 J^\mu_{\mathrm{EM}} \right] Z_\mu$$

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

Distributions

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





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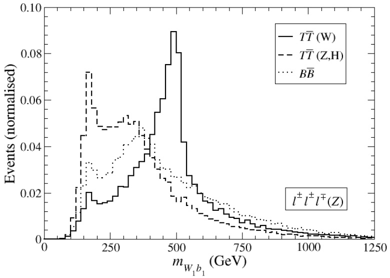
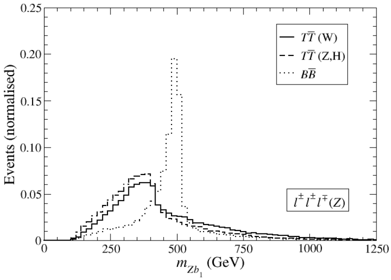
Distributions

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





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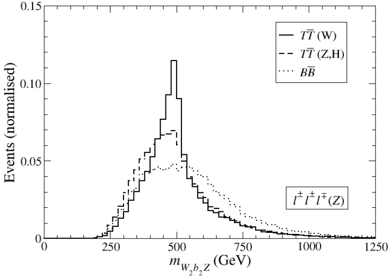
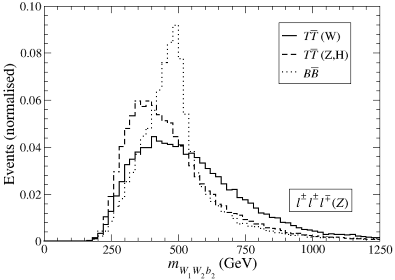
Distributions

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





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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 4th 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 $b' \to W^- t$ ☞ $b' \to Zb$ absent

Constraints from T parameter