Exotic physics at LHC – Part II

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Workshop *"Flavour in the era of the LHC"*
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Overview

1. Heavy neutrinos
   - F. del Aguila et al.
   - M. Kirsanov
2. Z' bosons
   - B. Clerbaux for CMS
   - G. Moreau
3. W' bosons
   - C. Kourkoumelis
4. Conclusions

Disclaimer

This is the summary of a summary = $(\text{summary})^2$. Further relevant information, detailed results, etc. can be found in the proceedings and the original references.

Heavy neutrinos

Light neutrino masses ☞ evidence of NP beyond “original” SM

Simplest explanation: “minimal” seesaw ☞ $M_N \sim 10^{14}$ GeV untestable

Other mechanisms, testable:

1. Non-minimal seesaw (flavour symmetries)
2. Triplet seesaw
3. R parity violation
4. Little Higgs models
5. Extra dimensions

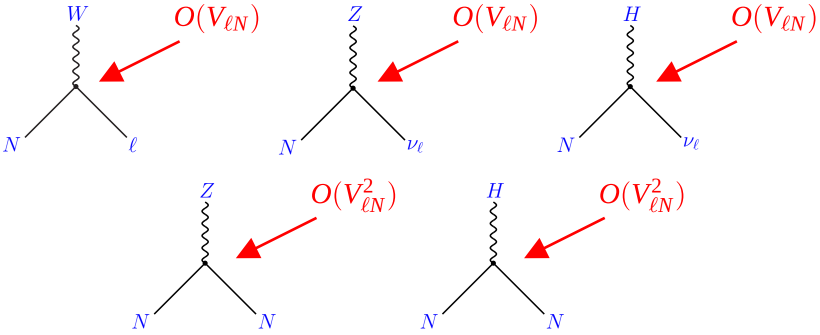
Some mechanisms involve heavy neutrinos N at collider scale

Their direct observation would be determinant to unveil the m_ν generation mechanism

I review LHC prospects for two extreme cases:

- Minimal scenario: N are singlets under $SU(2)_L \times U(1)_Y$ no additional interactions
- "Golden" scenario: LR models: additional $SU(2)_R$ and $M_{W'} > m_N$

Neutrino singlets: interactions



$$|V_{eN}|^2 \leq 0.0054 \quad |V_{\mu N}|^2 \leq 0.0096 \quad |V_{\tau N}|^2 \leq 0.016$$

☞ Production xsec small compared to other EW processes

Production of neutrino singlets

Possible final states (+ CC) — W, Z, H possibly off-shell

	$pp \to W^+ \to \ell_1^+ N$	$pp \to Z \to \nu N$	$pp \to H \to \nu N$
$N \to \ell_2^- W^+$	$\ell_1^+ \ell_2^- W^+$	$\ell_2^- \nu W^+$	$\ell_2^- \nu W^+$
$N \to \ell_2^+ W^-$	$\ell_1^+ \ell_2^+ W^-$	$\ell_2^+ \nu W^-$	$\ell_2^+ \nu W^-$
$N \to \nu Z$	$\ell_1^+ \nu Z$	$\nu\nu Z$	$\nu\nu Z$
$N \to \nu H$	$\ell_1^+ \nu H$	$\nu\nu H$	$\nu\nu H$

Smaller backgrounds for

$\ell_1^+ \ell_2^+ W^- \to \ell_1^+ \ell_2^+ jj$	(M only)	LNV
$\ell_1^+ \ell_2^- W^+ \to \ell_1^+ \ell_2^- jj,\ \ell_1 \neq \ell_2$	(M and D)	LFV

Example: same-sign dileptons $\mu^\pm\mu^\pm jj$

Simulation in [del Aguila et al., hep-ph/0703261]

Background-free? (often claimed) No!

Background events for 30 fb^{-1} (pre-selection):

- $t\bar{t}nj$ semileptonic, second μ from $b/\bar{b}$: 2294.4
- $Wb\bar{b}nj$, second μ from $b/\bar{b}$: 763.8
- $WZnj$: 615.5
- $W^\pm W^\pm nj$: 316.4 ☜ The one naively expected
- …

Compare with signal: 92.9 events for $\begin{array}{l} m_N = 150 \text{ GeV} \\ |V_{\mu N}|^2 = 0.0096 \end{array}$

Example: same-sign dileptons $\mu^\pm\mu^\pm jj$

To learn from this example: (applicable to other LNV signals)

① $t\bar{t}$, $Wb\bar{b}$ dangerous source of same-sign dileptons

② Parton-level analyses underestimate background by $10 - 100\times$ ☞ at least fast simulation required

③ b quarks give $10\times$ more "apparently isolated" e than μ (e in EM calorimeter, μ in muon chamber)

④ nj important:
$tt = 747.8$ $ttj = 730.3$ $tt2j = 405.0$ $tt3j = 240.9$

5σ Sensitivity: $m_N = 175$ GeV, $|V_{\mu N}|^2 = 0.0096$ $(V_{eN} = V_{\tau N} = 0)$

Flavour dependence

Expectations for other channels (estimations)

- $e^\pm e^\pm jj$: $m_N \simeq 130$ GeV for $|V_{eN}|^2 = 0.0054$ More
- $e^\pm \mu^\pm jj$: $m_N \simeq 160$ GeV for $|V_{eN}|^2 = 0.0054$, $|V_{\mu N}|^2 = 0.0096$
- $e^\pm \mu^\mp jj$: additional backgrounds → $t\bar{t}nj$ dilep, W^+W^-nj
- e^+e^-jj, $\mu^+\mu^-jj$: the same $+Znj$
- τ final states: always large backgrounds…

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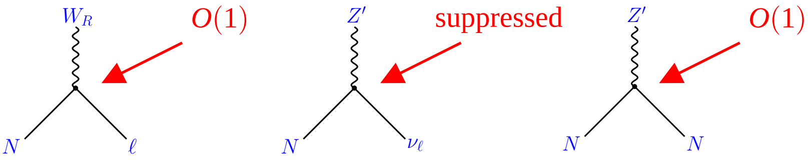
LR models: new interactions



$pp \to W_R \to N\ell$ → not suppressed by mixing nor phase space

Best scenario: $m_{W_R} \geq m_N$ → not suppressed by W_R propagator

Differences with N singlets

① Larger cross section ☞ allows to reach larger m_N

② Larger m_N ☞ Signal concentrated on tails of SM background distributions

③ Small backgrounds ☞ good sensitivity also for e^+e^-jj final states

Example: *eejj* final state $M_{W_R} = 2$ TeV $m_N = 500$ GeV

Full simulation [Gninenko et al., CMS NOTE 2006/098]

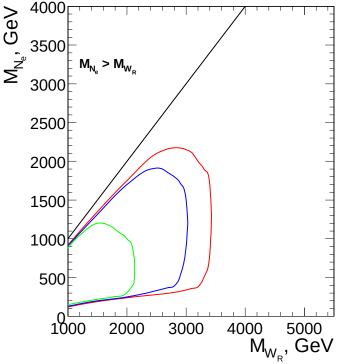
Background suppression with large invariant mass requirements

Events for 30 fb^{-1} (selection)

- Signal: 938
- $t\bar{t}$: 198
- Z: 96

☞ Full $t\bar{t}nj$ expected to be $\sim 2\times$ (?) larger
but results do not change dramatically

Limits on M_{W_R}, m_N



30 fb^{-1}: $M_{W_R} \sim 3$ TeV, $m_N \sim 2$ TeV

1 fb^{-1}: $M_{W_R} \sim 2$ TeV, $m_N \sim 1$ TeV

- Dependent on g_R and RH mixing
- Actually, what is seen is W_R (compare with Z', W' later)
- Sensitivity much smaller for $m_N > M_{W_R}$

Z' bosons

Z' bosons appear in a variety of SM extensions
- GUTs (ex. E_6)
- extra dimensions
- little Higgs
- …

Many Z' variants, but typically:

① Z' couple to quarks ➔ $q\bar{q} \to Z'$ possible at LHC

② Z' couple to charged leptons ➔ $Z' \to \ell^+\ell^-$ is sizeable

If not ① ☞ it seems we must wait for ILC, CLIC

If not ② ☞ see later

Z' bosons in the dilepton channel

$pp \to Z' \to \ell^+\ell^-$ predicted in many models

Today: simulations are done to make predictions
Results are model-dependent ☞ use "benchmark" models

Summer 2008: imagine $\ell^+\ell^-$ excess discovered at high $m_{\ell\ell}$

- is it really Z'?
- which one?

Discrimination methods ready and waiting for data...

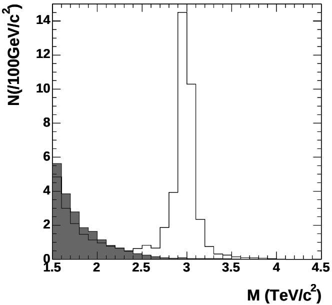
Note: model identification is always a problem
but for Z' there are more choices

Z' discovery potential in the dilepton channel

e^+e^-, $\mu^+\mu^-$ signal is very clean

Z background is very large but concentrated on low $m_{\ell\ell}$

Example: e^+e^- channel [Clerbaux et al., CMS NOTE 2006/083]



Z' with same couplings as Z

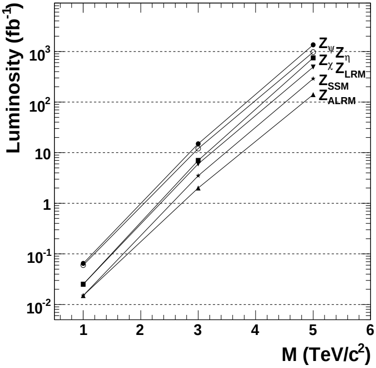
$M_{Z'} = 3$ TeV

Discovered with ~ 3 fb^{-1}

300 fb^{-1} ☞ up to 5 TeV

Z' discovery potential in the dilepton channel

Mass reach in e^+e^- for different models



Z' up to $4 - 5$ TeV can be discovered in most cases, the problem will be to identify it

Z' identification

In $\ell^+\ell^-$ events ($\ell = e, \mu$) we can measure

- Mass of the resonance
- Cross section at the peak
- Angular distribution of $\ell^+\ell^-$

Z' identification

In $\ell^+\ell^-$ events ($\ell = e, \mu$) we can measure

- Mass of the resonance → little information about models
- Cross section at the peak
- Angular distribution of $\ell^+\ell^-$

Z' identification

In $\ell^+\ell^-$ events ($\ell = e, \mu$) we can measure

- Mass of the resonance
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→ information about couplings

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In $\ell^+\ell^-$ events ($\ell = e, \mu$) we can measure

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→ information about spin and couplings

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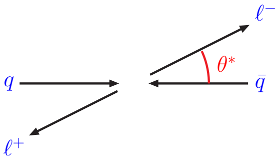
θ^* → angle between ℓ^- and q in $\ell^+\ell^-$ rest frame



Z' versus graviton

Spin-1 particle exchange (Z, γ, Z')

$$\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}[1+\cos^2\theta^*] + A_{\text{FB}}\cos\theta^*$$

Spin-2 graviton exchange

$$\frac{d\sigma}{d\cos\theta^*} = \frac{5}{8}[1-3\epsilon_q\cos^2\theta^* + (\epsilon_g - 4\epsilon_q)\cos^4\theta^*]$$

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depends on couplings

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fraction of $q\bar{q}$

fraction of gg

Z' versus graviton

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depends on couplings

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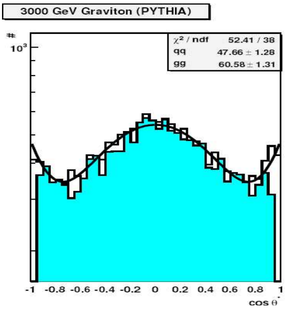
fraction of $q\bar{q}$

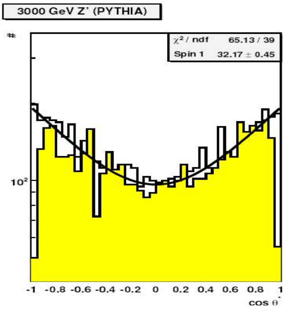
fraction of gg

depend only on graviton mass

Z' versus graviton

Method proposed in [Cousins et al., JHEP '05]
and applied for $\mu^+\mu^-$ in [Belotelov et al., CMS NOTE 2006/104]





With $\simeq$ 150 signal events ($B \simeq 20$) ☞ Z' and G distinguished at 2σ
Distinguishing from a scalar is harder

Z' versus graviton

Not to be forgotten:

- $Z' \not\to \gamma\gamma$ at tree level
- $G \to \gamma\gamma$, with similar sensitivity as $G \to e^+e^-$, $G \to \mu^+\mu^-$ channels

Z' model discrimination

Most obvious observable: FB asymmetry at Z' peak

$$\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}[1+\cos^2\theta^*] + A_{\rm FB}\cos\theta^*$$

$u\bar{u}$: $$\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}[1+\cos^2\theta^*] + A_{\rm FB}^u\cos\theta^* \qquad A_{\rm FB}^u = \tfrac{3}{4}\mathcal{A}_u\mathcal{A}_\ell$$

$d\bar{d}$: $$\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}[1+\cos^2\theta^*] + A_{\rm FB}^d\cos\theta^* \qquad A_{\rm FB}^d = \tfrac{3}{4}\mathcal{A}_d\mathcal{A}_\ell$$

$u\bar{u}$, $d\bar{d}$ fractions determined by PDFs (depending on $M_{Z'}$) and couplings

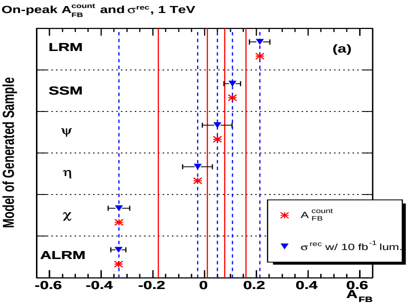
$$\mathcal{A}_f = \frac{|g_L^f|^2 - |g_R^f|^2}{|g_L^f|^2 + |g_R^f|^2}$$

Theoretical predictions for $A_{\rm FB}$ in each model

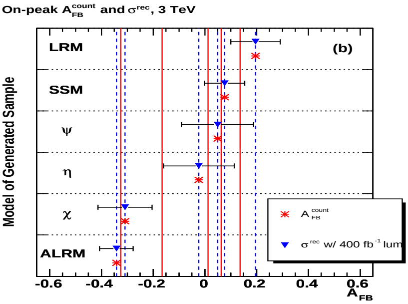
Z' model discrimination

Results from [Cousins et al., CMS NOTE 2005/022]

$M_{Z'} = 1$ TeV, $L = 10$ fb^{-1}



$M_{Z'} = 3$ TeV, $L = 400$ fb^{-1}



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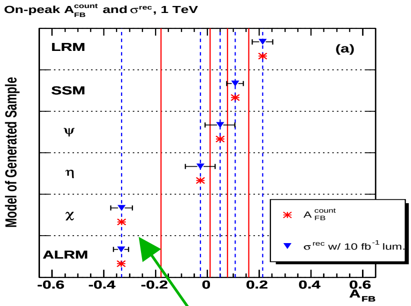

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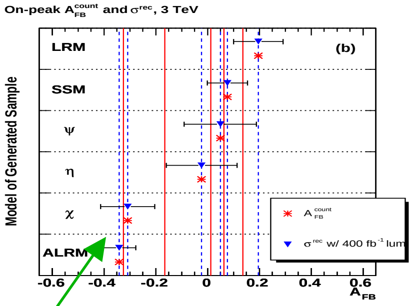


Cannot be distinguished
just with A_{FB}

Z' model discrimination

Additional observables proposed:

- Rapidity distributions [del Aguila et al., PRD '93] [Dittmar et al., PLB '04]

  Measure $\dfrac{|g_L^u|^2 + |g_R^u|^2}{|g_L^d|^2 + |g_R^d|^2}$ or similar quantities

- Off-peak $A_{\rm FB}$ [Rosner, PRD '87]

  Interference with γ, Z → different dependence on couplings

And of course, additional particles, decay modes...

☞ Example: $\mathrm{SU}(2)_R$ has W' with $M_{W'} \sim M_{Z'}$ (next section)

Leptophobic Z' bosons

If Z' is produced, but does not decay to leptons

- $q\bar{q}$ final states: not sensitive, large backgrounds

  [Gumus et al., CMS NOTE 2006/070]

- $b\bar{b}$ final states: expected better but not much

- $t\bar{t}$ final states: interesting

  From results in [Cogneras, Pallin, ATL-PHYS-PUB 2006-033]
  discovery limit estimated → up to $M_{Z'} = O(2)$ TeV

  In $t\bar{t}$ final states: $t\bar{t}$ spin correlations ☜ N. Castro's talk

W' bosons

Additional SU(2) → W', Z' bosons — LR models / littlest Higgs / ...

Cleanest decay channels: $W' \to e\nu, \mu\nu$

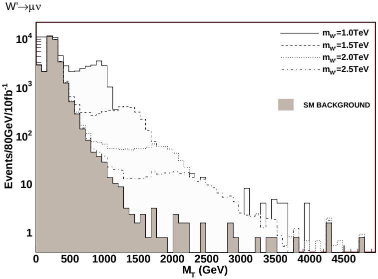
Might be interesting: $W' \to t\bar{b}$ ☞ new contribution to single top at high invariant mass

W' searches are important to identify additional gauge groups

W' discovery potential

Example: $\mu\nu$ channel [Kourkoumelis et al.]

W background concentrates on low $m_T^2 = (p_T^\mu + \not{p}_T)^2$



W' with same couplings as W

$M_{W'} = 3$ TeV discovered with ~ 0.3 fb^{-1}

300 fb^{-1} ☞ up to 6 TeV

Conclusions

Our aim:

Non-supersymmetric SM extensions predict new fermions and bosons. We have summarised the LHC discovery potential for (some of) these new particles in different scenarios.

This summary has focused on

particles ☞ what will (may) be discovered at LHC

rather than on

models ☞ what we want to uncover

but emphasising how discoveries will (may) give information on new physics

That means:

At this point in the game the question is not only

Prospects for particle discoveries

but rather

Prospects for models if particles are discovered

☞ This question has not been completely answered yet
Still work to do in many areas …

New quarks

- New quarks Q (charge $2/3$, $-1/3$) can be discovered up to masses $m_Q \gtrsim 1$ TeV in pair production
- In single production, limits $m_Q \sim 1.5$ TeV for the maximum EW mixings allowed by present constraints (LEP, CKM unitarity…)
- ☞ And if not observed, their contribution to low energy physics should be small

New quarks

- Decays indicate nature of the new quark:

4^{th} generation	☞	No FCN decays (at tree-level)
SU(2) singlet	☞	FCN decays always present with similar Br and sensitivity as CC ones

- Some new decay channels related to low energy physics

Example: In minimal model with charge $2/3$ singlet T
δm_{D^0} and $K^+ \to \pi^+ \nu \bar{\nu} \sim$ determine $t \to cZ$

New quarks

- For light Higgs and masses $m_Q \lesssim 600$ GeV, Q decays to H would provide the leading Higgs discovery channel:

charge	$2/3$	☞	$T \to Ht$	7 fb^{-1}	($m_T = 500$ GeV)
charge	$-1/3$	☞	$D \to Hd$	8 fb^{-1}	($m_D = 500$ GeV)

- 4^{th} generation contributes to $gg \to H$ loops and enhances Higgs production
- Lots of possible scenarios and signatures…
- Other quark charges (ex. $5/3$) would give characteristic final state signatures

Comments:

- Higher order backgrounds (ex. $t\bar{t}j$, $t\bar{t}2j$, $t\bar{t}3j\ldots$) found to be very important in the discovery region for new quarks (high p_T).

Heavy neutrinos

- Minimal scenario: LHC has sensitivity to neutrino singlets with masses $m_N \lesssim 175$ GeV
- "Golden" scenario: in LR models with $M_W > m_N$ the sensitivity is up to $m_N \sim 2$ TeV

Comments:

- Processes with b quarks (ex. $t\bar{t}nj$, $Wb\bar{b}nj$) are a large source of same-sign dileptons, especially di-electrons
- Same-sign dilepton final states are no longer background-free

Z' bosons

- Z' could be first LHC discovery: if $M_{Z'} \sim 1$ TeV one day (0.1 fb^{-1}) is enough for 5σ
- In all LHC lifetime, $M_{Z'} \leq 5$ TeV will be explored
- Big effort in the past 20 years devising methods to identify model behind Z' from various observables

Comments:

- Some Z' scenarios seem not sufficiently explored yet
- If Z' is discovered, ILC/CLIC would be welcome

W' bosons

- W' could be quickly discovered too
- Mass reach similar for Z' and W'

  ☞ extra $\mathrm{U}(1)$ and $\mathrm{SU}(2)$ distinguishable in principle (this is a model-dependent comment…)

N singlets and flavour mixing

Beware: indirect limits on lepton flavour/number violation
(evaded if cancellations allowed)

$\mu \to e\gamma$ suggests $V_{eN} V_{\mu N} \sim 10^{-4}$

☞ If larger, requires cancellation with N_2

$\beta\beta_{0\nu}$ suggests $V_{eN}^2 \sim 10^{-4}$ for $m_N \sim 100$ GeV

☞ If larger, requires cancellation with N_2

☞ Dirac N: cancellation also in signal

In any case, it is legitimate to ask for direct limits

Back