Minimal matter at the LHC

arXiv:0908.1567

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Outline

popular "motivated" BSM

- Supersymmetry
- Kaluza-Klein
- Little Higgs

Experiments $\Rightarrow$ Matter Parity

no $\varphi_{NP}\Phi_{SM}\Phi_{SM}$ interactions

Matter Parity

- symmetry to provide a DM candidate
- easy-to-hide new physics

Minimal "useless" Matter

$$\mathcal{L} \supset \lambda\, \varphi_{NP}\Phi_{SM}\Phi_{SM}$$

- Lorentz invariance
- SM gauge G_{SM} invariance

Experiments $\Rightarrow \lambda \ll 1$

"effective parity"

and ...

- DM candidate through higher reps of G_{SM}

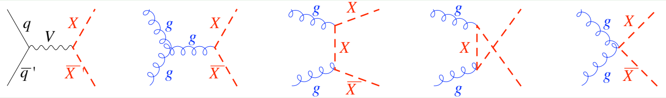
$\mathcal{L} \supset \lambda\, \varphi_{NP} \Phi_{SM} \Phi_{SM} + \mathcal{L}_{mass}$

Framework

- neglect higher dimensional operators ok because of weak coupling
- no new interactions i.e. no new vectors

  (for new vectors see Kilic,Okui,Sundrum **arXiv:0906.0577**, Barbieri,Corcella,Hernandez,Torre,Trincherini **arXiv:0911.1942**)
- add only one spin 0 or $\frac{1}{2}$ particle

Predictive scenario: gauge production



model independent searches

- quantum numbers are the only assumption

- the pheno of a **set** of new multiplets could be very different

Scalars: couplings and decays

Name	spin	$\mathrm{U}(1)_Y$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(3)_c$	$\lvert Q\rvert = \lvert T_3 + Y\rvert$	couplings to	type
H'	0	$\frac{1}{2}$	2	1	$0, 1$	$\bar{L}\bar{E}, QU, \bar{Q}\bar{D}$	second Higgs
$\tilde{E}$	0	1	1	1	1	LL	LL
$\tilde{E}^2$	0	2	1	1	2	$\bar{E}\bar{E}$	LL
$\tilde{E}_3$	0	1	3	1	$0, 1, 2$	LL, H^*H^*	type-II see-saw
$\tilde{Q}$	0	$\frac{1}{6}$	2	3	$1/3, 2/3$	LD	LQ
$\tilde{Q}^{7/6}$	0	$\frac{7}{6}$	2	3	$2/3, 5/3$	$LU, \bar{E}\bar{Q}$	LQ
$\tilde{D}$	0	$\frac{1}{3}$	1	$\bar{3}$	$1/3$	$LQ, \bar{E}\bar{U}, UD, \bar{Q}\bar{Q}$	LQ/QQ
$\tilde{D}_3$	0	$\frac{1}{3}$	3	$\bar{3}$	$1/3, 2/3, 4/3$	$LQ, \bar{Q}\bar{Q}$	LQ/QQ
$\tilde{D}_6$	0	$\frac{1}{3}$	1	6	$1/3$	$UD, \bar{Q}\bar{Q}$	QQ
$\tilde{D}_{36}$	0	$\frac{1}{3}$	3	6	$1/3, 2/3, 4/3$	$\bar{Q}\bar{Q}$	QQ
$\tilde{U}$	0	$\frac{2}{3}$	1	$\bar{3}$	$2/3$	$\bar{D}\bar{D}$	QQ
$\tilde{U}_6$	0	$\frac{2}{3}$	1	$\bar{6}$	$2/3$	$\bar{D}\bar{D}$	QQ
$\tilde{q}^{4/3}$	0	$\frac{4}{3}$	1	$\bar{3}$	$4/3$	$UU, \bar{E}\bar{D}$	QQ
$\tilde{q}_6^{4/3}$	0	$\frac{4}{3}$	1	6	$4/3$	UU	QQ
H_8	0	$\frac{1}{2}$	2	8	$0, 1$	$QU, \bar{Q}\bar{D}$	QQ

signatures of new scalars

- *QQ*: heavy quarks
  di-jet resonances
- *LL*, *EE*: heavy leptons
  clean leptonic signals
- LQ: leptoquarks

- **exotic charges**

old and new friends

Leptoquarks, See-Saw mediators, supermodel candidates, ...

only quantum numbers matter

no heavy flavors involved in the decay, i.e. in some model the search could be easier

Fermions: couplings and decays

Name	spin	$U(1)_Y$	$SU(2)_L$	$SU(3)_c$	$\lvert Q\rvert = \lvert T_3 + Y\rvert$	couplings to	type
N	$\frac{1}{2}$	0	1	1	0	LH	type-I see-saw
L'	$\frac{1}{2}$	$-\frac{1}{2}$	2	1	$0, 1$	EH^*	LH
E'	$\frac{1}{2}$	1	1	1	1	LH^*	LH
N_3	$\frac{1}{2}$	0	3	1	$0, 1$	LH	type-III see-saw
E_3	$\frac{1}{2}$	1	3	1	$0, 1, 2$	LH^*	LH
$L^{3/2}$	$\frac{1}{2}$	$\frac{3}{2}$	2	1	$1, 2$	$\bar{E}H^*$	LH
Q'	$\frac{1}{2}$	$\frac{1}{6}$	2	3	$1/3, 2/3$	HU, H^*D	QH
U'	$\frac{1}{2}$	$-\frac{2}{3}$	1	$\bar{3}$	$2/3$	HQ	QH
D'	$\frac{1}{2}$	$\frac{1}{3}$	1	$\bar{3}$	$1/3$	H^*Q	QH
U_3	$\frac{1}{2}$	$\frac{2}{3}$	3	3	$1/3, 2/3, 5/3$	$\bar{Q}H^*$	QH
D_3	$\frac{1}{2}$	$\frac{1}{3}$	3	$\bar{3}$	$1/3, 2/3, 4/3$	QH^*	QH
$Q^{5/6}$	$\frac{1}{2}$	$\frac{5}{6}$	2	$\bar{3}$	$1/3, 4/3$	$\bar{D}H^*$	QH
$Q^{7/6}$	$\frac{1}{2}$	$\frac{7}{6}$	2	3	$2/3, 5/3$	UH^*	QH

signatures of new fermions

- QH: heavy quarks
  jet + V
- LH: heavy leptons
  ℓ + V
  mET + V

- **sources of SM vectors**
- **exotic charges**

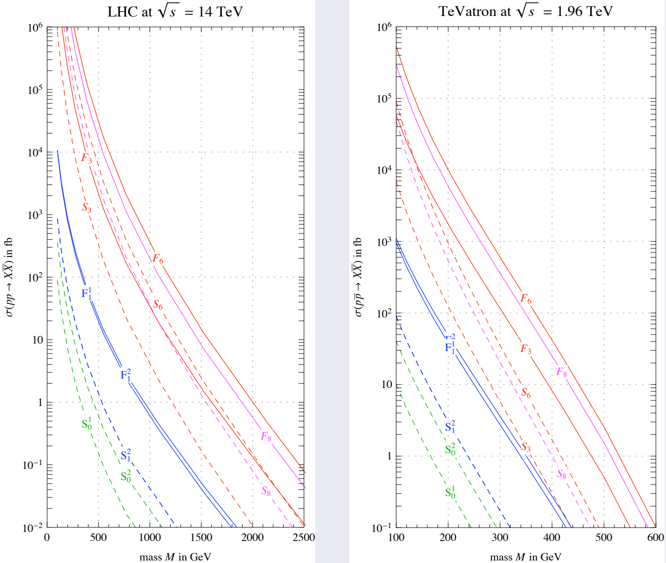
old and new friends

exotic fermions, fourth vectorial generation, fermionic see-saw mediators, etc.

only quantum numbers matter

no heavy flavors involved in the decay, i.e. in some model the search could be easier

Tevatron: with $\mathcal{L} \sim 10/fb$ the generic bound is $\sigma \lesssim 1 - 10$ fb



small splittings: soft is hard to detect

On top of the gauge invariant mass term $M\bar{\psi}\psi$ or $M^2|\phi|^2$ a mass splitting arises at loop level:

$\Delta M = M_{Q+1} - M_Q = (1 + 2Q + \frac{2Y}{\cos\theta_W})\alpha_2 M_W \sin^2\frac{\theta_W}{2} = 166\,\mathrm{MeV}\cdot(1 + 2Q + \frac{2Y}{\cos\theta_W})$

without other sources of splitting this poses serious experimental issues (track algorithm, fakes, QCD longlived ...)

$$\Gamma(X_{Q+1} \to X_Q\pi^+) = c\frac{G_F^2 V_{ud}^2\,\Delta M^3 f_\pi^2}{\pi}\sqrt{1 - \frac{m_\pi^2}{\Delta M^2}} \sim \frac{1}{\mathrm{mm}}$$

$$\Gamma \sim \frac{M\lambda^2}{4\pi} \sim \frac{1}{3\,\mathrm{cm}}\frac{M}{\mathrm{TeV}}\frac{\lambda^2}{10^{-16}}$$

$1 \neq$ many

$$\mathcal{L} = M\bar{\psi}\psi + m\bar{\chi}\chi + \kappa\bar{\chi}\psi + \ldots$$

significant mixing can produce decay chains with hard visible particles

EWSB: eating a Goldstone boson

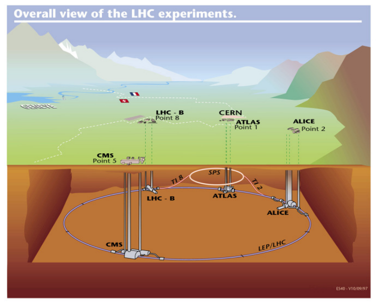
$\lambda H \bar{\Psi} \psi_{SM} \to \lambda v \bar{\Psi} \psi$ and the mass matrix $\begin{pmatrix} M & \lambda v \\ \lambda v & 0 \end{pmatrix}$ is made diagonal with $\psi_{SM} \to \psi_{SM} + \frac{\lambda v}{M} \Psi$, $\Psi \to \Psi - \frac{\lambda v}{M} \psi_{SM}$ obtaining a interaction

$$\frac{\lambda g v}{M} W^{\mu} \bar{\Psi} \gamma_{\mu} \psi_{SM}$$

- definite prediction for the BR of fermions into states with $W^{\pm}$,Z^{0},h
- no decay into photons
- electroweak symmetry still visible in the absence of some vertex i.e. the interaction $L^{3/2} E H^{*}$ do not generate the decay $L^{3/2,+} \to \nu W^{+}$

Signatures summary

- scalar di-quark resonances
  4j
- scalar di-lepton resonances
  $\ell\ell\bar{\ell}\bar{\ell}$, $\ell\bar{\ell}$ mET
- heavy leptons
  $\ell\ell VV$ ($\ell^+\ell^+\ell^-$ mET, $\ell^+\ell^+\ell^-$ mETjj, ...)
- heavy quarks
  2j2V (4$j\ell$ mET, 4j2ℓ, ...)
- leptoquarks



scheduled and unscheduled

European Organization for Nuclear Research

News: 6 November 2009

LHC "bird-bread" strike

On Tuesday 3 November, a bird carrying a baguette bread caused a short circuit in an electrical outdoor installation that serves sectors 7-8 and 8-1 of the LHC. The knock-on effects included an interruption to the operation of the LHC cryogenics system. The bird escaped unharmed but lost its bread.

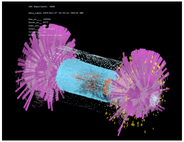
The standard failsafe systems came into operation and after the cause was identified, re-cooling of the machine began and the sectors were back at operating temperature last night. The incident was similar in effect to a standard power cut, for which the machine protection systems are very well prepared.

CERN logo

European Organization for Nuclear Research

News: 9 November 2009

Particles have gone half way round the LHC

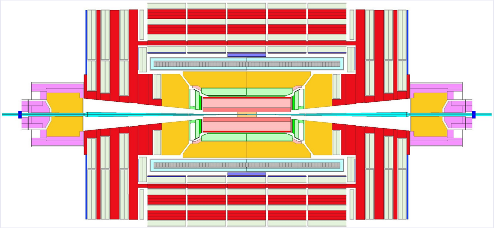


Splash event recorded by the CMS experiment on 7 November. The electromagnetic calorimeter is in red, the hadronic calorimeter in blue, the muon system is yellow and magenta. The barrel muon detector was on standby and the inner tracking detector was off.

pp collisions at design regime

- C.o.M. Energy=14 TeV
- $\mathcal{L} = 10^{34} \cdot cm^{-2} s^{-1}$
- $\sim 10^4$ protons per bunch
- ~ 25 *pp* interactions per crossing
- bunch crossed each 25 ns

General Purpose Detector (CMS)

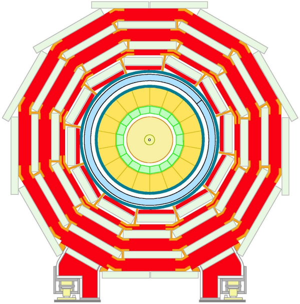


$\vec{p} = (p_T, \eta, \phi)$

$$p_T = \sqrt{p_x^2 + p_y^2} = p \cdot \sin\theta$$

$$\eta = \ln \cot \frac{\theta}{2}$$

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



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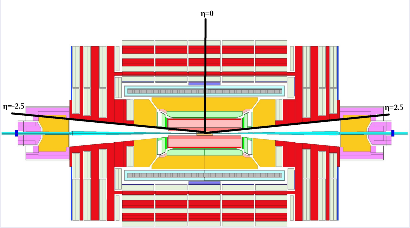

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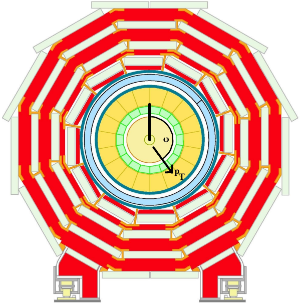

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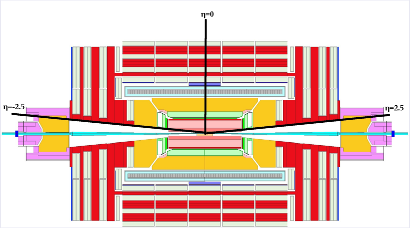

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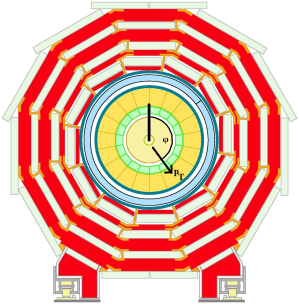
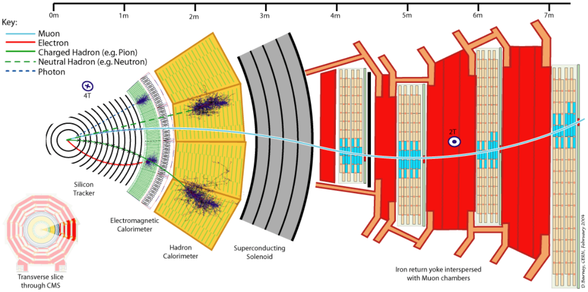
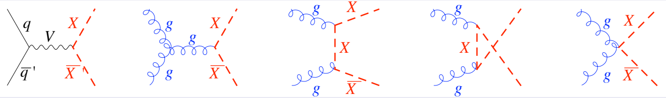
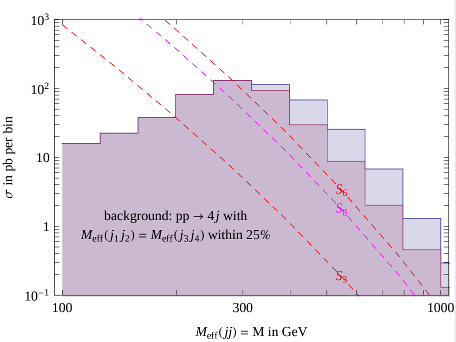




$pp \to X\bar{X} \to 4j$

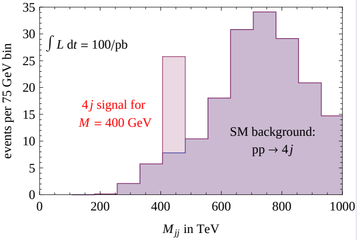


- large cross section
- inclusive search (only Q#s)
- no clues to determine the charge
- 4 hard QCD jets (Madgraph)
- $\Delta R > 0.4$, $|\eta| < 2.5$
- $p_T > \max(100\text{ GeV}, r\,M)$
- $H_T > 2M$
- $|m(j_a, j_b)/m(j_c, j_d) - 1| < 0.25$



Give a shape to the background if you do not like it!

a 400 GeV example



The signal emerges out of a low-tail of the BG (slight changes from parton-shower are expected).

- $\Delta R > 0.4, \eta < 2.5$
- $p_T > 0.6M = 250$ GeV
- $\Delta\eta_{jj} < 1.7$

$$m^2(j_a, j_b) \simeq p_T^{(a)} p_T^{(b)} \Delta R^2$$

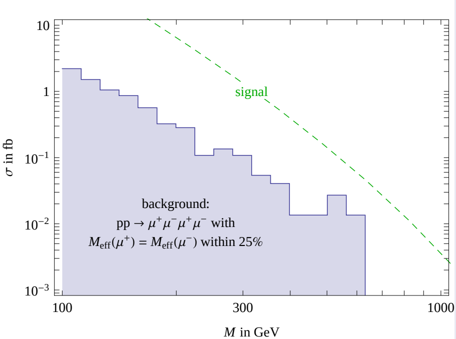
The BG is incoherent hence it has no reason to have jet pairs with invariant mass much smaller than the hard $p_T^{(j)}$.

applicable to other searches

- $h \to WW$ under examination with A. Wulzer

$(1,1)_2$ that is to say $\mathcal{L} \supset \lambda \tilde{E}_2 EE$

$$pp \to E^{++}E^{--} \to \ell\ell\bar{\ell}\bar{\ell}$$



- negligible BG (mostly from ZZ)
- $|1 - m(\ell,\ell)/m(\bar{\ell},\bar{\ell})| < 0.25$

- low production σ (only mediated by hypercharge)

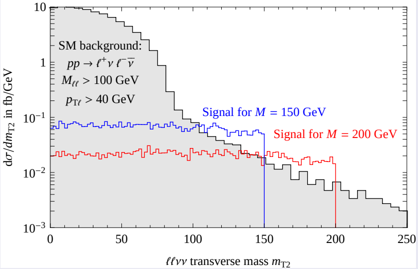
- very clean final state
- discovery only suffers lack of events
- Tevatron type-II-SS dedicated search says $M > 130$ GeV

- easy discovery, intersting with $\mathcal{L} \gtrsim$100/pb

- all sorts of rare lepton fakes must be considered (mostly detector effects)

$(1,1)_1$ that is to say $\mathcal{L} \supset \lambda \tilde{E} L L$

$$pp \to \ell_i \bar{\ell}_j \text{ mET}$$



- BG mostly from WW
- $p_T^\ell > 40$ GeV

- low production σ
  (only mediated by hypercharge)

$$m_{T2} \equiv \min_{\mathbf{p}_T^{\nu 2} - \mathbf{p}_T^{\nu 1}} \max \left[m_T(\bar{\ell}, \nu_2), m_T(\ell, \nu_1) \right]$$

- end-point feature in the region $m_{T2} > m_W$

- clean despite neutrinos, interesting for $\mathcal{L} \gtrsim 1/fb$

- all sorts of rare lepton fakes must be considered
  (mostly detector effects)

$(1,3)_1$ coupled as $\lambda E_3 L H^*$
$(1,2)_{3/2}$ coupled as $\lambda L^{3/2} E H$

$$pp \to E^{++}E^- \to W^+\ell^+\ell^- Z \to \ell^+\ell^+\ell^- \text{ mET}$$

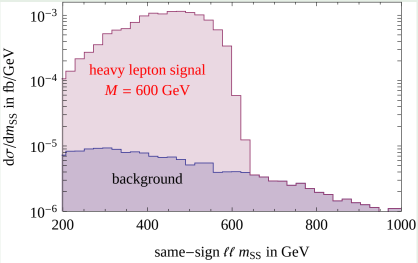
The same final state is available for $L^{3/2}$ as well.

- $m_{OS} > 100$ GeV

- $\ell^+\ell^- W^- \sim 10$ fb
- $W^+W^+W^- \sim 1$ fb
- $\bar{t}tW^+ \sim 0.1$ fb using jet veto

- mET > 200 GeV
- $m_{SS} > 150$ GeV

- showering is included (Pythia 8)



- visible with at least 10/fb

Early birds (preliminar and not complete)

- Detector effects are desperately needed to say s.t. meaningful

- While we talk Tevatron sets new limits

100/pb (the whole 2010 data-take?)

- 4j signal with di-jet resonaces with $M \sim 400$ GeV
- $\ell^+\ell^+\ell^- jj$ mET from heavy leptons with charge two $M \sim 300$ GeV
- $\ell^+\ell^+\ell^-\ell^-$ from scalar di-leptons of charge two $M \sim 150$ GeV

roughly same discovery potential despite the very different rates

1/fb (at least 2012)

- $\ell_i \ell_j$ mET from scalar leptons $M \sim 150$ GeV

Conclusions: Just assuming quantum numbers a lot of collider physics!

- generic experimental difficulties for the gauge decays (though unlikely to be relevant)
- many "minimal" signatures have been studied
- rough discovery reach applicable to a yet-to-formulate BSM ... if any
- resonant signatures for the first year of data-taking: 4j, $\ell\ell\bar{\ell}\bar{\ell}$, $\bar{\ell}\bar{\ell}\ell$ mETjj
- many particles with degenerate signatures (yet another hint that LHC can't write a $\mathcal{L}$agrangian)
- events of new physics without mET (how to disprove matter parity?)
- indirect effects can be important as well (change UV sensitive couplings like the loop-generated *ggH*; change the running of SM couplings)

heavy flavor is always better

Not a theorem ... but close to

handswaiving proof for b quarks

- *b* quarks can be tagged (and mistagged ... of course)
- single-flavor background has to be less than many-flavor background
- *b* can be produced in top decay (typically subdominat)

t quark is more tricky

- BR($t \to b\ell$ mET) $\simeq 0.2$

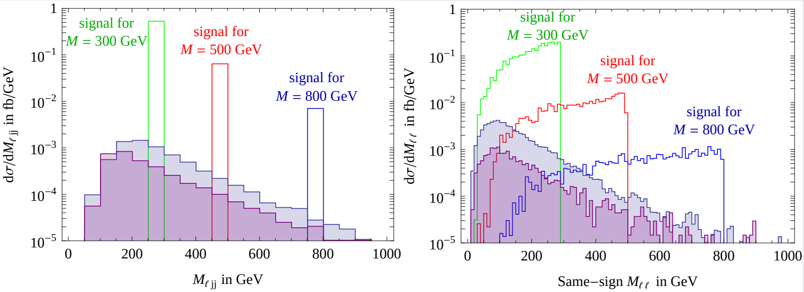
trading a light quark for a top always gives back a jet, though softer because $p_b \sim p_t/2$ and in 20% of cases gives also a lepton.

- $\sigma(BG + 1t) < \sigma(BG + g)$ (plus you typically must produce $\bar{t}t$)
- $\sigma(BG + 1\ell) \sim \alpha_{ew} \cdot \sigma(BG)$

- for hadronic top could be more delicate to establish

other signatures

$pp \to E^{++}E^{--} \to \ell^+\ell^+\ell^- jj$ mET

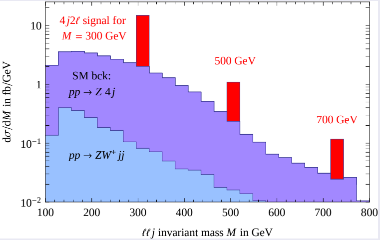


- $t\bar{t}W^+ \sim 3$ fb
- $t\bar{t}$ need a hard lepton from a b (tail effect, computer-intensive)

- as it is it can give a handful of events already with $\sim 200/$ pb we focus on VV=ZZ or ZW (WW is well studied)

2jZW+2jZZ

$$pp \to 4j\ell^-\ell^+$$

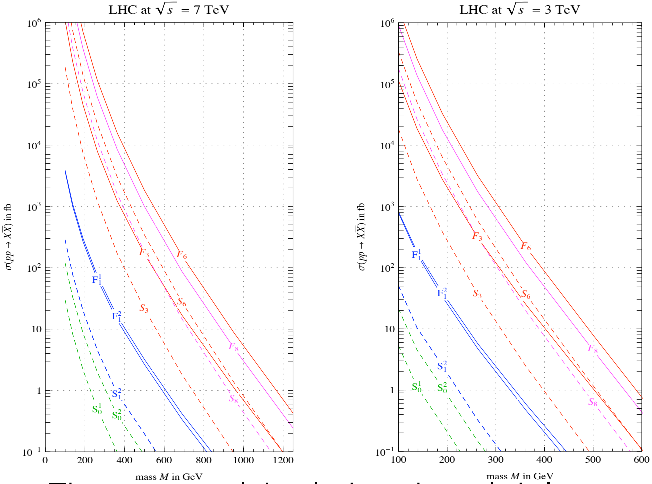


- $Z4j \sim 10$ pb
- $ZW2j \sim 0.4$ pb
- $\bar{t}tjj$ and $4j2W$ are eliminated by $m(\ell^+,\ell^-) = m_Z$

- $m(j,j) - m_W| < 10$ GeV
- $|m(\ell^+,\ell^-,j)/m(3j) - 1| < 0.1$

- 6j could be feasible as well using the trick of $p_T/M \sim 1$ as seen for the di-jet resonances
- chances to detect exotic charges (4/3 or 5/3) in an high rate of signals with W

Pair production at ‘weakened’ LHC



They seem equal, but look at the scale below:

$$\sigma(M, \sqrt{s}) \approx \sigma(M/2, \sqrt{s}/2)$$