

DOUBLY CHARGED EXCITED LEPTONS*

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Implication of LHC results for TeV scale physics
CERN, March 26th –30th

*Based on the master thesis of S. Biondini presented at the University of Perugia on December 6th 2012. e-Print: [arXiv:1201.3764 \[hep-ph\]](https://arxiv.org/abs/1201.3764)

Outline

- 1 COMPOSITENESS AND EXCITED LEPTONS
- 2 EXTENDED WEAK ISO-SPIN MODEL
- 3 IMPLEMENTATION OF THE MODEL IN CALCHEP
- 4 SIGNAL AND BACKGROUND
- 5 CONCLUSIONS AND OUTLOOK

Composite Models of Quarks and Leptons

- **Proliferation** of Standard Model fermions hints at a level of substructure
- if SM quarks and leptons are composite

undeniable signals of Compositeness are expected:

- ⇒ **excited Leptons or Quarks** e^*, μ^*, u^*, d^* ... within each generation
- ⇒ **four fermion contact interactions** $qqqq, qqqq^*, qqq^*q^*, qqee^*, qqe^*e^*$
 - Eichten, Lane and Peskin, PRL 50, 811 (1983)
 - Baur, Spira and Zerwas, PRD 42, 815 (1990)
 - Cabibbo, Maiani and Srivastava, PLB 149, 459 (1984)
- **dynamic** origin of masses of quarks and leptons, (alternative to Higgs mechanism)
- the origin of the standard model families as simply higher-order excitations of the same system
- reinterpretation of the electroweak force as a residual interaction of a more fundamental one

Current Mass Bounds on e^*, μ^* from LHC (hybrid CI - gauge model):

$$m_e^* > 1070 \text{ GeV and } m_\mu^* > 1090 \text{ GeV at the 95 \% C.L.}$$

CMS Collab. PLB 704 (2011) 143-162.

NEW!! $m_e^* > 1.87 \text{ TeV and } m_\mu^* > 1.75 \text{ TeV at 95 C.L. ATLAS 1201.3293 [hep-ex]$

Weak and strong Isospin analogy

Weak isospin spectroscopy of excited quarks and leptons

Phy. Lett. B 146 (1984), Y.N. Srivastava and G. Pancheri

- compositeness of fermions in the light of **Weak Isospin Invariance**
- analogy with Strong Isospin \rightarrow learning about strong bound states long before discovering quarks and gluons

strong sector

- strong isospin multiplets \rightarrow lots of adronic resonances
- typical energy scale about $\simeq \mathcal{O}(1\text{GeV})$

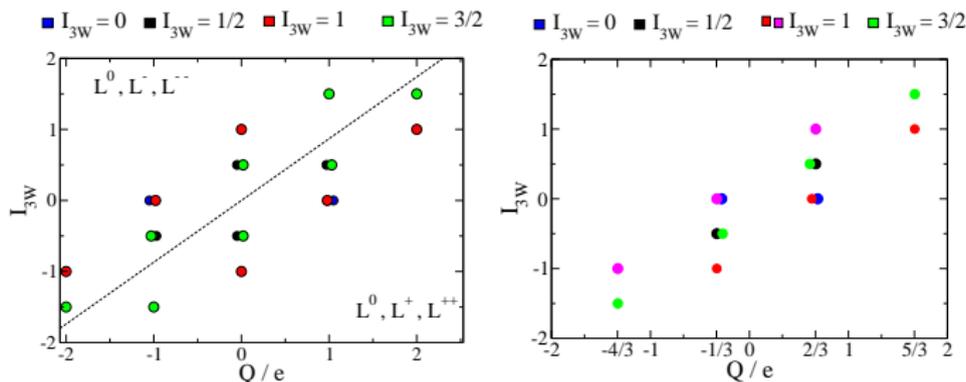
electroweak sector

- e-weak isospin multiplets \rightarrow excited fermions (exotic charges)
- which is the typical energy scale? \rightarrow it should be $\simeq \mathcal{O}(1\text{TeV})$

we could observe heavy massive fermions at TeV scale \rightarrow LHC could help us to achieve this goal!

Weak Isospin Model

- SM $q, \ell \in I_W = 0, \frac{1}{2}$ and $W^\pm, Z^0, \gamma \in I_W = 0, 1 \Rightarrow$ excited fermions $\in I_W \leq \frac{3}{2}$
- W^\pm, Z^0 bosons do not carry $\mathbf{Y} \rightarrow$ SM fermions couple with excited fermions with same \mathbf{Y}
- Gauge mediated interactions in terms of **transition currents**
 $\mathcal{L}_{eff} = g W_\mu J^\mu + g' B_\mu J_Y^\mu$ **production** and **decay** of excited fermions
- Provides exotic charged leptons (and *quarks**)



* work in progress on q^* with $Q = -\frac{4}{3}e; +\frac{5}{3}e$ (O. P., G. Pancheri, Y. Srivastava)
 Quarks with exotic e-charges ($Q = \frac{5}{3}e$) are predicted also in models with a composite higgs boson. G. Servant and R. Contino, JHEP 0806, 026 (2008)

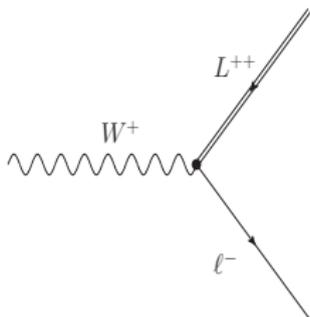
Exotic Leptons and transition currents

$$\begin{pmatrix} L^0 \\ L^- \\ L^{--} \end{pmatrix}, \quad I_W = 1, Y = -2 \qquad \begin{pmatrix} L^+ \\ L^0 \\ L^- \\ L^{--} \end{pmatrix}, \quad I_W = \frac{3}{2}, Y = -1$$

$$\mathcal{L}_{eff} = g W_\mu \mathbf{J}^\mu + g' B_\mu \mathbf{J}_Y^\mu$$

$$\mathcal{L} = \frac{gf_1}{m^*} (\bar{L}^{--} \sigma^{\mu\nu} Q_\nu \ell_R) W_\mu^- + h.c.$$

$$\mathcal{L} = \frac{gf_3}{m^*} (\bar{L}^{--} \sigma^{\mu\nu} Q_\nu \ell_L) W_\mu^- + h.c.$$



$$= -i \frac{g f_{1,3}}{m^*} Q^\nu \sigma_{\mu\nu} (1 \mp \gamma^5)$$

$f_{1,3}$ adimensional numerical constant
 $\approx \mathcal{O}(1)$

Implementing the model in CalcHEP

- A.Pukhov, CalcHEP (*arXiv:hep-ph/9908288*)
- Effective magnetic type interactions, \rightarrow **FeynRules**
 \rightarrow model in **CalcHEP** format

- parton cross section, $q\bar{q}'$ annihilation into W^+ :

$$\hat{\sigma}(q\bar{q}' \rightarrow L^{++} \ell^-)$$

- production cross section, involving parton density functions of protons colliding at LCH:

$$\sigma(pp \rightarrow L^{++} \ell^-)$$

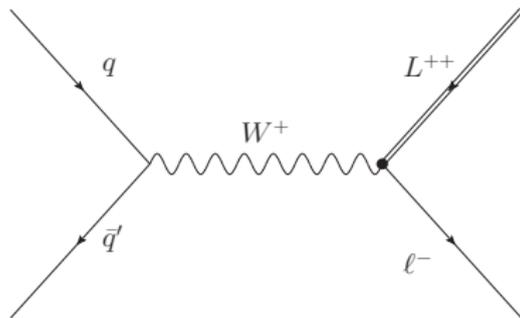
- ONLY ONE decay channel: $L^{++} \rightarrow W^+ \ell^+$

$$\mathcal{B}(L^{++} \rightarrow W^+ \ell^+) = 1$$

- Consider **leptonic decay of W^+** , \rightarrow final signature with **like sign dilepton**:

$$pp \rightarrow \ell^- \ell^+ \ell^+ \nu_\ell$$

- invariant mass of like sign leptons $M_{(\ell^+, \ell^+)}$ is strongly correlated with the mass of exotic doubly charged lepton, m^*

Parton Cross Section: $q\bar{q}' \rightarrow L^{++} \ell^-$ 

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} \simeq 1 - 1.5 \text{ TeV} \quad (7 \text{ TeV})$$

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} \simeq 2 - 3 \text{ TeV} \quad (14 \text{ TeV})$$

$$\Downarrow$$

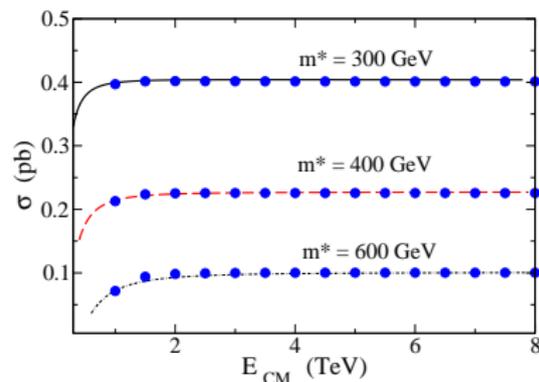
$$m_q, m_\ell \rightarrow 0 \quad m^* \neq 0$$

$$\frac{d\hat{\sigma}}{d\Omega} = \frac{g^4}{768\pi^2 m^{*2} \hat{s}} \frac{(\hat{s} - m^{*2})^2}{(\hat{s} - M_W^2)^2 + (M_W \Gamma_W)^2} \left\{ \frac{\hat{s}}{2} (1 - \cos^2 \theta) + \frac{m^{*2}}{2} (1 + \cos^2 \theta) \pm m^{*2} \cos \theta \right\}$$

$$\hat{\sigma} = \frac{\alpha^2}{\sin^4 \theta_W} \frac{\pi U_{qq'}}{36 \hat{s} m^{*2}} \frac{(\hat{s} - m^{*2})^2 (\hat{s} + 2m^{*2})}{(\hat{s} - M_W^2)^2 + (M_W \Gamma_W)^2}$$

$$\Rightarrow \frac{\alpha^2}{\sin^4 \theta_W} \frac{\pi U_{qq'}}{36 m^{*2}}$$

$$\text{se } s \gg m^2 \gg M_W^2$$

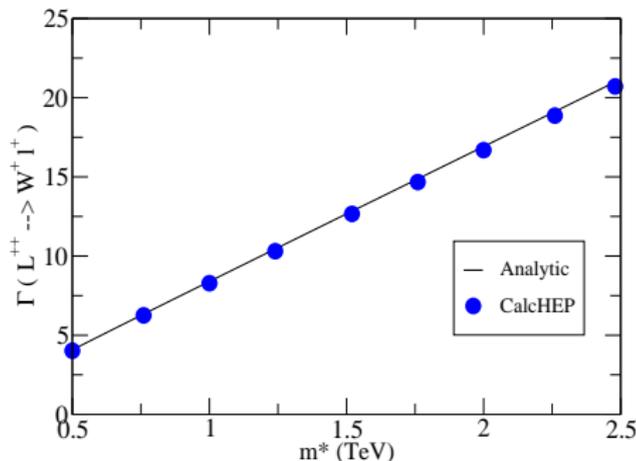


Unique Decay Channel of L^{++}

- **isospin structure** and **Y-conservation** allow only one channel for L decays

$$\Gamma_{L^{++}} = \Gamma(L^{++} \rightarrow W^+ \ell^+) = \left(\frac{f}{\sin\theta_W} \right)^2 \alpha_{QED} \frac{m^*}{4} \left(1 - \frac{3M_W^2}{2m^{*2}} + \frac{M_W^2}{2m^{*2}} \right)$$

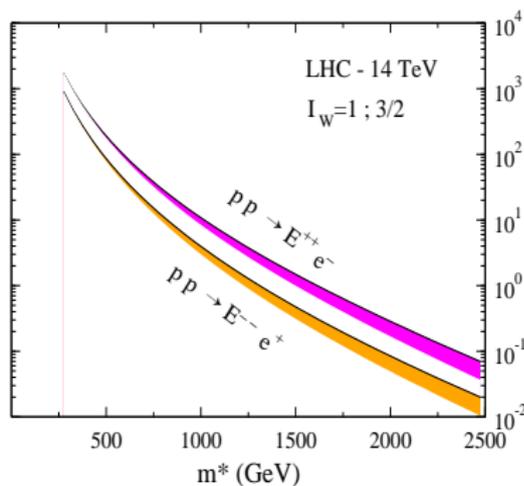
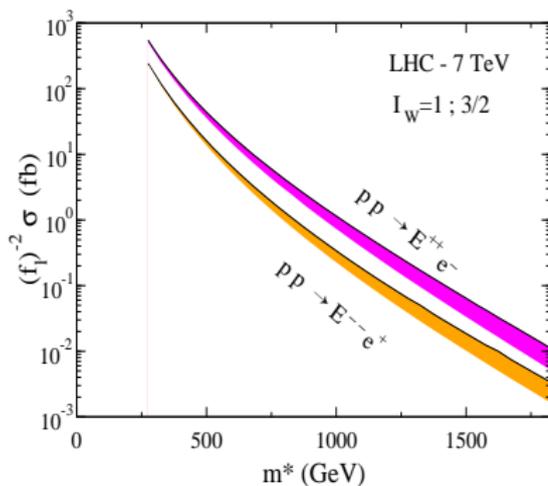
- because of $M_W \ll m^*$ we get $\Gamma = \kappa m^*$



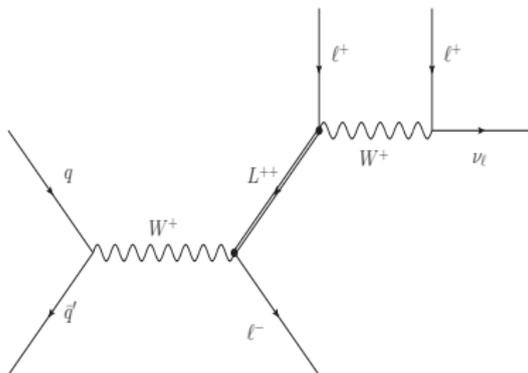
- the ratio $\frac{\Gamma}{m^*} \simeq \mathcal{O}(10^{-2}) \Rightarrow$ **good resolution for mass resonance**

Production Cross Section: $pp \rightarrow \ell^- L^{++}$

$$\frac{d\sigma}{d\tau}(ab \rightarrow L + \ell) = \sum_{ij} \frac{1}{1+\delta_{ij}} [f_i^a(x) f_j^b(\frac{\tau}{x}) + f_i^a(\frac{\tau}{x}) f_j^b(x)] d\hat{\sigma}(q_i, q_j \rightarrow L + \ell) \frac{dx}{x}$$



- $\sigma(L^{++}) = 1$ fb (LHC - 7 TeV) for an excited lepton with $m^* = 1$ TeV
- $\sigma(L^{++}) = 10$ fb (LHC - 14 TeV) for an excited lepton with $m^* = 1$ TeV
- PDFs : CTEQ6m (proton), from CalchHEP library

Final State Signature of L^{++} 

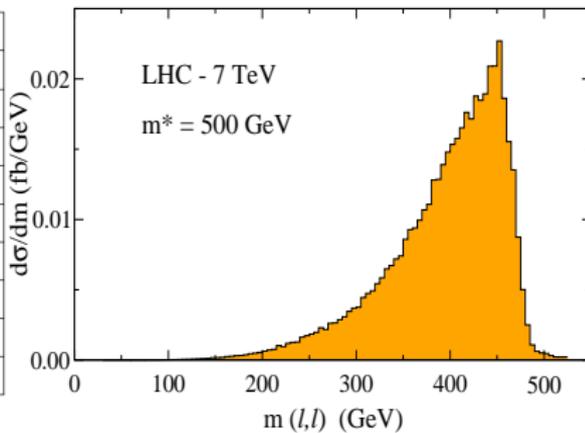
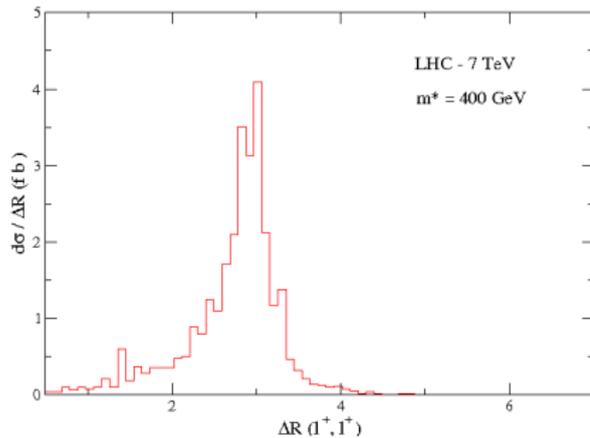
$$pp \rightarrow l^- (l^+ l^+) \nu_l$$

- back to back approximation

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

- dilepton topology

$$\left[m_{(l^+, l^+)}^2 \right]_{\max} \simeq m^{*2} - M_W^2$$



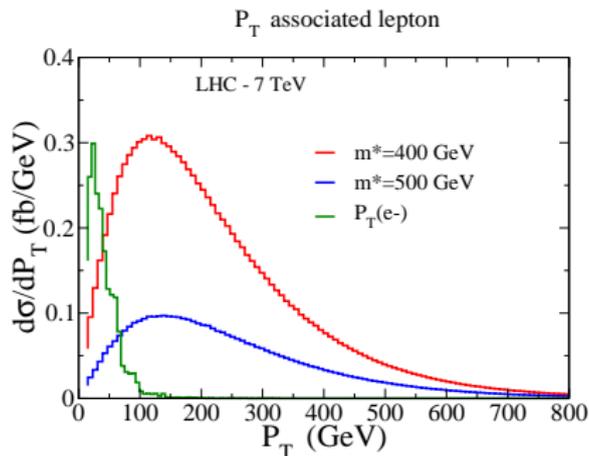
Standard Model Background

contributing processes:

- $pp \rightarrow W^+ Z^0 \rightarrow l^- l^+ l^+ \nu_l$
- $pp \rightarrow W^+ \gamma^* \rightarrow l^- l^+ l^+ \nu_l$
- $pp \rightarrow l^+ (\gamma^*/Z) \nu_l \rightarrow l^- l^+ l^+ \nu_l$

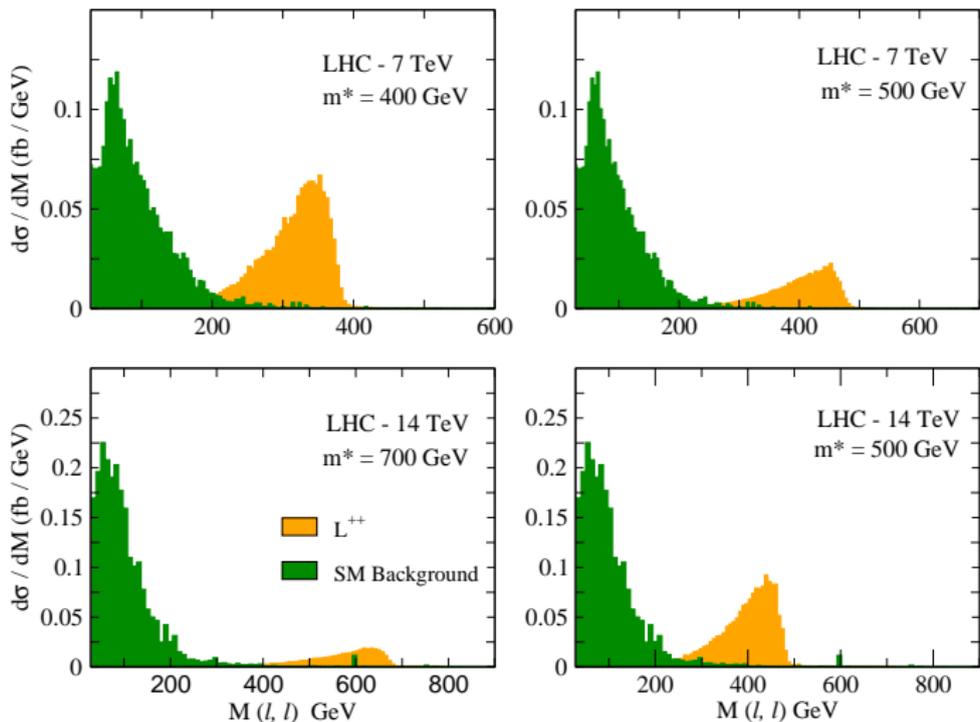
$W^+ Z^0$ dominates the SM background

leptons produced in association with L^{++} have the rather hard P_T distribution



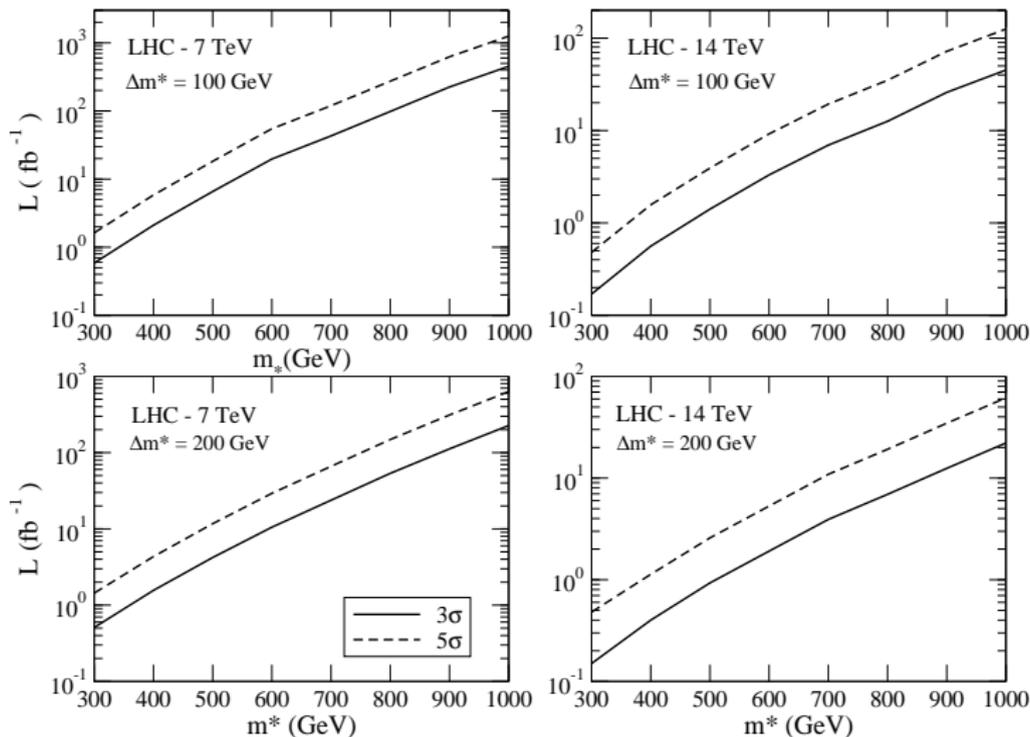
Base Kinematic Cuts:

$$p_T(\ell) > 15 \text{ GeV} \quad , \quad |\eta(\ell)| < 2.5 \quad , \quad E(\nu) > 25 \text{ GeV} \quad , \quad \Delta R(\ell^+, \ell^+) > 0.5$$

 $M_{(\ell^+, \ell^+)}$ distributions:

Luminosity Curves from statistical significance $N_s(\Delta m^*) = L \int_{m^* - \Delta m^*}^{m^*} \left(\frac{d\sigma_s}{dm} \right) dm$

From $s = \frac{N_s}{\sqrt{N_s + N_b}} \Rightarrow L = s^2 \left(\frac{\sigma_s + \sigma_b}{\sigma_s^2} \right)$:



reasonable L requirements ($m^* \simeq 500 \div 600$ GeV) \Rightarrow feasibility study of a complete analysis

Fast simulation of a generic detector response (PGS)

CALCHEP OBJECTS

- $q\bar{q}' \rightarrow l^-l^+l^+\nu_\ell$
- ideal detector

PGS OBJECTS

- $pp \rightarrow l^-l^+l^+\nu_\ell + X$
- Detector with efficiencies $\epsilon < 1$

$$N_{\text{physical}} \neq N_{\text{reconstructed}}$$

SELECTIONS CRITERIA AND KINEMATIC CUTS ON EVENTS (S)

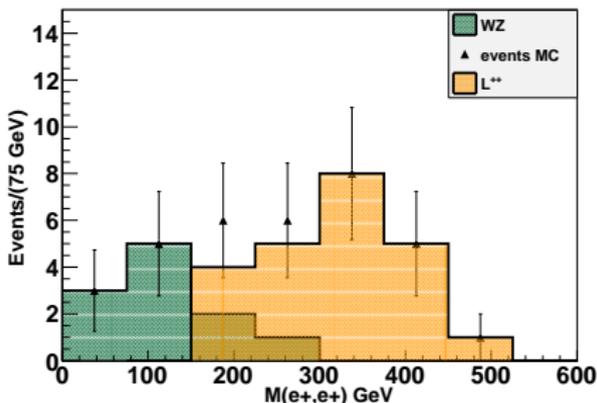
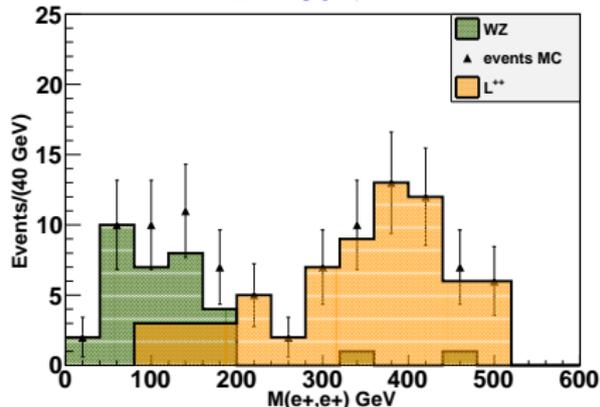
- S_1 : require at least three leptons univocally reconstructed ($l^-l^+l^+$)
- S_2 : at least one lepton with $P_T(\ell) > 50\text{GeV}$, trigger of **NEW PHYSICS**
- S_3 : Kinematic cuts to separate **SIGNAL** from **BG**

\Rightarrow simulation of a **RECONSTRUCTED OBJECT**: $P^\mu = (\mathbf{E}, \mathbf{p}_x, \mathbf{p}_y, \mathbf{p}_z)$

$$\text{variables : } \begin{cases} P_T(\ell) \\ \eta(\ell) \end{cases} \Rightarrow \begin{cases} \epsilon \text{ high for signal, } m^* = 500 \text{ GeV} \\ \epsilon \text{ low for bg, } W^+Z \end{cases}$$

Reconstructed Invariant mass distribution at ($m^* = 500\text{ GeV}$)

| Events | SIG ₅₀₀ | BKG (WZ) | eff_{sig} | eff_{bkg} |
|--|--------------------|----------|-------------|-------------|
| Generated Events | 1000 | 1000 | 1 | 1 |
| Reco ($e^+ e^+ e^-$) | 650 | 526 | 0.65 | 0.53 |
| $P_T(e) > 50\text{ GeV}$ | 650 | 406 | 1 | 0.77 |
| $ \eta(e_1^+) < 2 \quad P_T(e^-) > 80\text{ GeV}$ | 532 | 44 | 0.82 | 0.11 |

 $L = 10\text{fb}^{-1}$  $L = 30\text{fb}^{-1}$ 

Generic detector response preserves the separation of the invariant mass distribution of signal and bg

Conclusions

- Extended Weak Isospin Model with magnetic moment type transition currents: L^{++} phenomenology \rightarrow parton and production cross section - decay

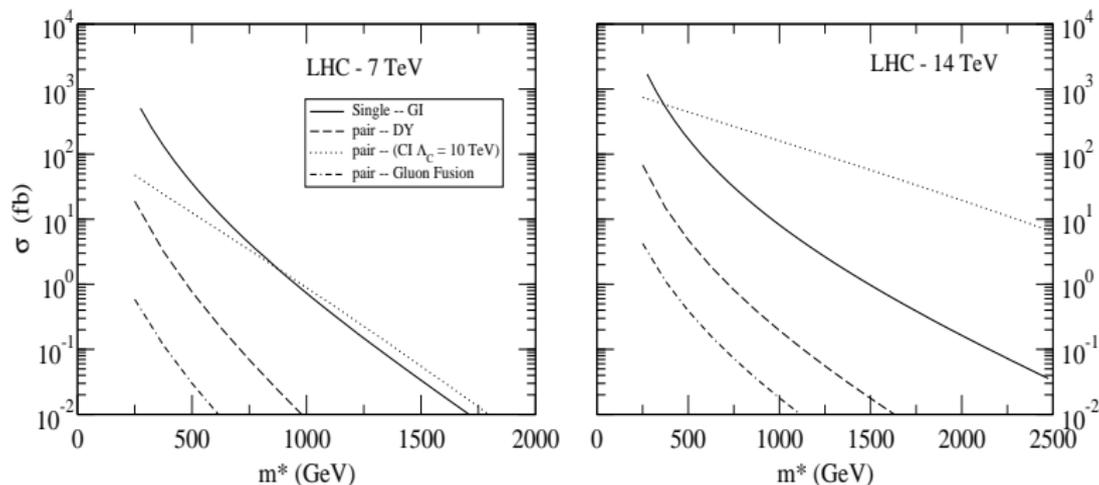
$$p p \rightarrow \ell^- L^{++} \rightarrow \ell^- W^+ \ell^+ \rightarrow \ell^- \ell^+ \ell^+ \nu_\ell$$

- $M_{(\ell^+, \ell^+)}$ as the **main variable** to study the **doubly charged excited leptons**
 $\sqrt{s} = 7$ TeV: **3-sigma** (5-sigma) for $m^* = 600$ GeV if **L=10 (20) fb⁻¹**
 $\sqrt{s} = 14$ TeV: **3-sigma** (5-sigma) for $m^* = 1000$ GeV if **L=20 (60) fb⁻¹**
- Interface of CalcHEP **LHE output** with the fast simulator (**PGS**)
 \rightarrow **generic detector response** simulation of RECONSTRUCTED OBJECTS
- In progress:**
 Study of other production mechanisms
 Implementation of Contact Interactions in CalcHEP
- In progress:**
 Phenomenology of exotic q^* with charge $Q = (+5/3)e, (-4/3)e$.
 Overlap with composite Higgs models
- Outlook** Exotic leptons and Quarks at CLIC/ILC

backup slides

Exotic doubly charged leptons can be **pair produced** with full gauge strength

- DY production
- gluon fusion via heavy quark loops (mainly top, bottom)
- via contact interactions $\Lambda_C > \sim 10$ TeV
(ATLAS Collab. arXiv:1112.4462 [hep-ex])



Single production is possible with flavor conserving but non diagonal contact interactions ($u\bar{d} \rightarrow L^{++}\ell^-$) [In progress]

Excited leptons belonging to $I_W = 0$ and $I_W = \frac{1}{2}$

- Phenomenological studies at the LHC (excited leptons)
Eboli and Lietti, Phys. Review D **65**, 075003 (2002)

gauge mediated framework and **decay** $e^* \rightarrow e \gamma$

$$pp \rightarrow e^\pm e^{*\pm} \rightarrow e^+ e^- \gamma \Rightarrow \frac{d\sigma}{dM_{e\gamma}}$$

- LHC results: CMS PLB 704 (2011) 143-162

Production $\rightarrow \mathcal{L}_{\text{Contact}} = \frac{(g^*)^2}{2\Lambda^2} J^\mu J_\mu$

Decay $\rightarrow \mathcal{L}_{\text{Gauge}} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma_{\mu\nu} \left\{ g \frac{\tau}{2} W^{\mu\nu} + g' \frac{Y}{2} B^{\mu\nu} \right\} f_L$

$$pp \rightarrow ee^* \rightarrow ee\gamma, \quad pp \rightarrow \mu^*\mu \rightarrow \mu\mu\gamma$$

According to **real data** and $\frac{d\sigma}{dM_{e\gamma}}$ $\frac{d\sigma}{dM_{\mu\gamma}}$ distributions

Mass Bounds: $m_e^* > 1070 \text{ GeV}$ and $m_\mu^* > 1090 \text{ GeV}$ at the 95 % C.L.

Event rates

- previous kinematic cuts - LHC-luminosity: $5 \text{ fb}^{-1} - \sqrt{s} = 7 \text{ TeV}$
 → **number of events** (N_s)

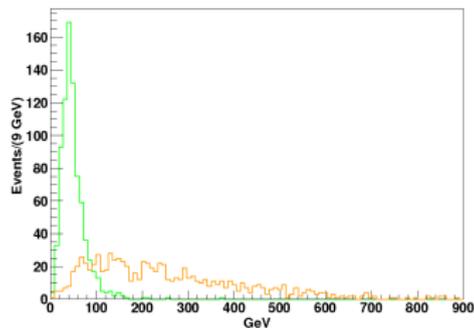
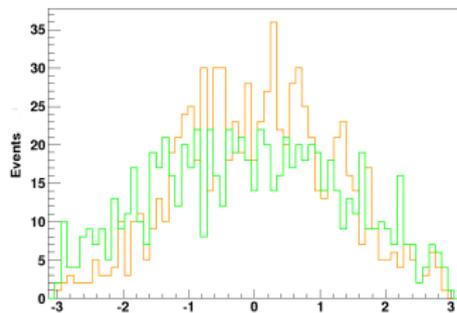
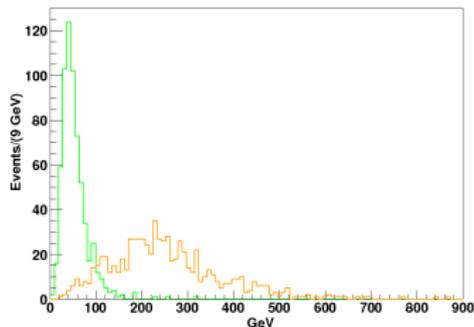
$$N_s(\Delta m^*) = L \int_{\Delta m^*}^{m^*} \left(\frac{d\sigma_s}{dm} \right) dm$$

where Δm^* provides a mass window below m^* . We choose to values:

$\Delta m^* = 100 \text{ GeV}$ and $\Delta m^* = 200 \text{ GeV}$

- | | |
|--|--|
| • $m^* = 400 \text{ GeV}$ $N_s = 21.5$ | • $m^* = 400 \text{ GeV}$ $N_s = 31.0$ |
| • $m^* = 500 \text{ GeV}$ $N_s = 7.0$ | • $m^* = 500 \text{ GeV}$ $N_s = 11.0$ |
| • $m^* = 600 \text{ GeV}$ $N_s = 2.5$ | • $m^* = 600 \text{ GeV}$ $N_s = 4.5$ |

Kinematic Variables

PT(e⁻)ETA(e⁻)PT(e⁺ leading)ETA leading e⁺