Phenomenology of excited doubly charged heavy leptons at present and future colliders

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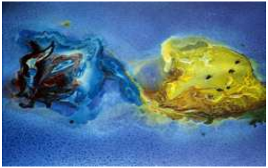
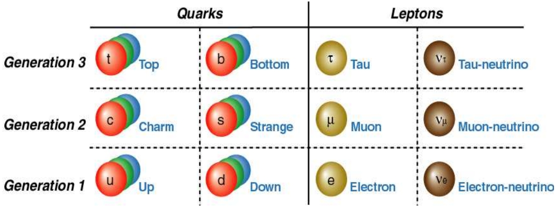


Outline

Elementary and composite particles

Elementary particles

- higher energies $\rightarrow$ smaller spatial dimensions
- atoms, nuclei, nucleons, quarks and leptons...



Proliferation of fundamental particles

- different generations, decays of more massive generations into lighter ones
- proliferation of Standard Model fermions hint at a possible substructure

Proliferation of SM particles

if Standard Model quarks and leptons are composite

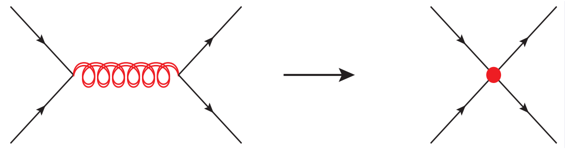
$\Rightarrow$ undeniable signal of Compositeness expected

- excited leptons and quarks e^*, μ^*, u^*, d^*,...
- four fermion contact interactions (same constituents)

$$qqqq,\ qqqq^*,\ qqq^*q^*,\ qqee^*,\ qqe^*e^* \ldots$$

Effective interactions

- some higher scale, $\Lambda \gg M_W$, hides the interaction of new constituents



- naturally leading to contact interactions to describe phenomenology

  Eitchen, Lane and Peskin, PRL 50, 811 (1983)
  Cabibbo, Maiani and Srivastava, PLB 149, 459 (1984)
  Baur, Spira and Zerwas, PLD 42, 815 (1990)

Contact and Gauge interaction

Contact interactions

$$\mathcal{L}_C = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu,$$

$$j^\mu = \eta_L \bar{f}_L \gamma^\mu f_L + \eta'_L \bar{f}^*_L \gamma^\mu f_L + \eta''_L \bar{f}^*_L \gamma^\mu f^*_L + h.c. + (L \to R)$$

Gauge interactions

- interaction mediated by SM gauge bosons, $W^\pm, Z^0$
- couple excited fermions with SM fermions by dynamical gauge bosons

$$\mathcal{L}_G = \frac{1}{2\Lambda} \bar{f}^*_R \, \sigma^{\mu\nu} \left(g\, f \frac{\tau}{2} \mathbf{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right) f_L + h.c.$$

- Can we know something about excited fermions quantum numbers?

  $\Rightarrow$ Weak isospin spectroscopy of excited quarks and leptons

Srivastava and Pancheri, PLB 146, 146 (1984)

Weak isospin multiplets

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

Strong sector

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

Electroweak sector

- e-weak isospin multiplets → excited fermions (exotic charges)
- the typical energy scale? it may be $\simeq \mathcal{O}(1-10 TeV)$

Construction of the multiplets:

1) Standard Model $q, \ell \in I_W = 0, \frac{1}{2}$ and $W^{\pm}, Z^0, \gamma \in I_W = 0, 1$

2) $\Rightarrow$ excited fermions $\in I_W \leq \frac{3}{2}$

Doubly charged leptons

Isospin multiplets: $q = I_{3W} + \frac{Y}{2}$, $L \equiv$ excited lepton

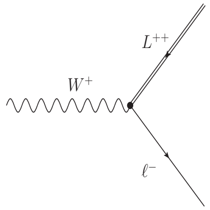
$$\begin{pmatrix} L^0 \\ L^- \\ L^{--} \end{pmatrix}, \quad I_W = 1, Y = -2$$

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

Transition current: $\mathcal{L}_G = g\, W_\mu \mathbf{J}^{\boldsymbol{\mu}} + g'\, B_\mu \mathbf{J}^{\boldsymbol{\mu}}_{\mathbf{Y}}$

$$\mathcal{L} = \frac{g\, f_1}{m^*} \left(\bar{L}^{--} \sigma^{\mu\nu} Q_\nu\, \ell_R \right) W^-_\mu + h.c.$$

$$\mathcal{L} = \frac{g\, f_3}{m^*} \left(\bar{L}^{--} \sigma^{\mu\nu} Q_\nu\, \ell_L \right) W^-_\mu + h.c.$$



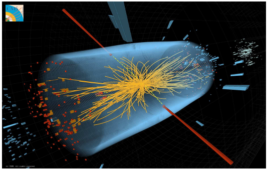
$$= -i\, \frac{g\, f_{1,3}}{m^*} Q^\nu \sigma_{\mu\nu} \left(1 \mp \gamma^5\right)$$

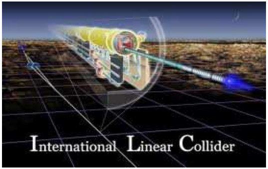
$f_{1,3}$ dimensionless numerical constant $\approx \mathcal{O}(1)$

High energy collisions

- Excited fermions, $f^* \equiv L^*, Q^*$, may reveal at the scale $\Lambda > M_W$

high energy collisions to produce heavy particles





- many particles are produced in such collisions
- high QCD activity (LHC) and Standard Model background

Look for exotic states of f^* $\rightarrow$ clear signatures

Examples: quark sector $q_{Q^*} = \frac{5}{3}$ or lepton sector $q_{L^*} = -2$

Implementation of the model *PRD 85,095018*

Implementing the model in CalcHEP, A.Pukhov, *hep-ph/9908288*

- Effective magnetic type interactions, $\rightarrow$ **FeynRules** $\rightarrow$ model in **CalcHEP** format

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

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

2) production cross section, parton density functions of protons at LCH:

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

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

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

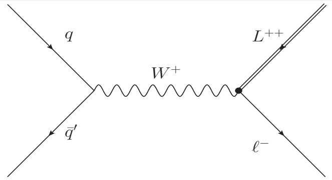
4) Consider leptonic decay of W^+, $\rightarrow$ final signature with like sign dilepton:

$$p\,p \rightarrow \ell^-\,\ell^+\,\ell^+\,\nu_\ell$$

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

Parton cross section

Process $q\bar{q}' \to L^{++}\ell^-$



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

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

$\Downarrow$

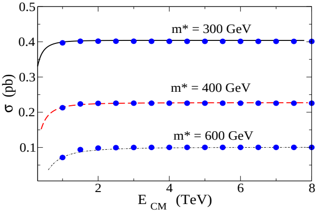
$m_q, m_\ell \to 0 \quad m^* \neq 0$

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

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

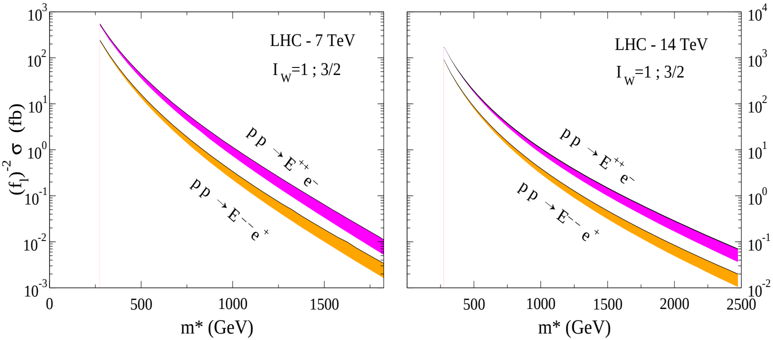
$$\Rightarrow \frac{\alpha^2}{\sin^4\theta_W}\frac{\pi\, U_{qq'}}{36\, m*^2}$$

se $s >> m^2 >> M_W^2$



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

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



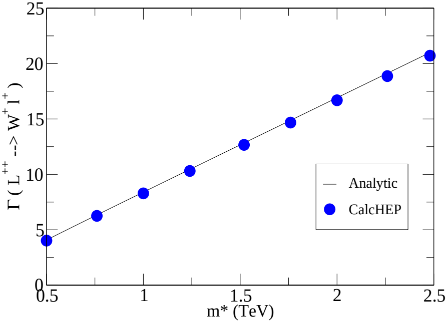
- $\sigma(L^{++}) = 1$ fb (LHC - 7 TeV) for an excited lepton with $m^* = 1$ TeV
- $\sigma(L^{++}) = 10$ fb (LHC - 14 TeV) for an excited lepton with $m^* = 1$ TeV
- **PDFs** : **CTEQ6m** (proton), from CalchHEP library

Decay of L^{++}: Unique Decay Channel in GI

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

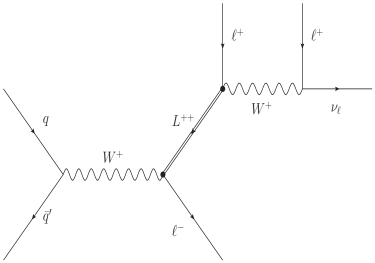
$$\Gamma_{L^{++}} = \Gamma(L^{++} \to W^+ \ell^+) = \left(\frac{f}{sin\theta_W}\right)^2 \alpha_{QED} \frac{m^*}{4} \left(1 - \frac{3M_W^2}{2m^{*2}} + \frac{M_W^2}{2m^{*2}}\right)$$

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



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

Final State Signature of L^{++}



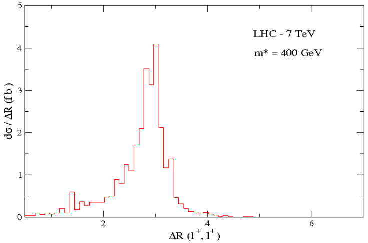
$pp \to \ell^- \, (\ell^+ \ell^+) \, \nu_\ell$

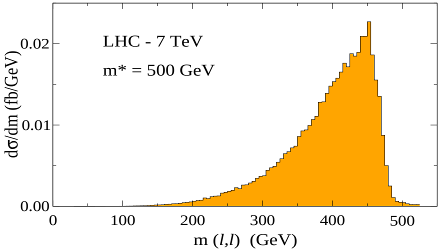
- back to back approximation

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

- dilepton topology

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



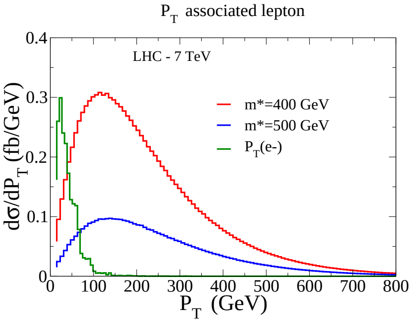


Standard Model Background

Contributing processes: $W^+ Z^0$ dominates the SM background

- $p\,p \to W^+ Z^0 \to \ell^- \ell^+ \ell^+ \nu_\ell$
- $p\,p \to W^+ \gamma^* \to \ell^- \ell^+ \ell^+ \nu_\ell$
- $p\,p \to \ell^+ (\gamma^*/Z)\, \nu_\ell \to \ell^- \ell^+ \ell^+ \nu_\ell$

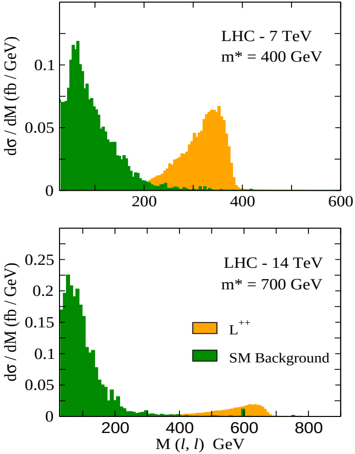
$\to$ leptons produced in association with L^{++} have the rather hard P_T distribution



Invariant mass distribution: $M_{(\ell^+,\ell^+)}$

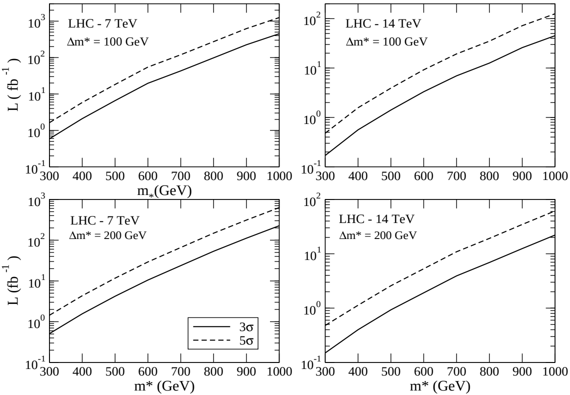
Base Kinematic Cuts:

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



Luminosity Curves, statistical significance

$N_s(\Delta m^*) = L \int_{m^*-\Delta m^*}^{m^*} \left(\frac{d\sigma_s}{dm}\right) dm$ and $s = \frac{N_s}{\sqrt{N_s+N_b}} \Rightarrow L = s^2 \left(\frac{\sigma_s+\sigma_b}{\sigma_s^2}\right)$:



reasonable L for $m^* \simeq 500 \div 600$ GeV $\Rightarrow$ analysis feasibility study

Fast simulation of a generic detector response (PGS)

CalcHEP Objects

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

PGS Objects

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

$$\mathbf{N_{physical}} \neq \mathbf{N_{recontructed}}$$

Selections criteria and kinematic cuts on events (S)

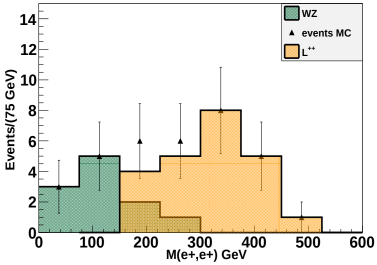
- S_1: require at least three leptons univocally reconstructed $(\ell^- \ell^+ \ell^+)$
- S_2: at least one lepton with $P_T(\ell) > 50\text{GeV}$, trigger of **NEW PHYSICS**
- S_3: Kinematic cuts to separate **SIGNAL** from **BG**

$\Rightarrow$ simulation of a **RECONSTRUCTED OBJECT**: $\mathbf{P^\mu = (E, p_x, p_y, p_z)}$

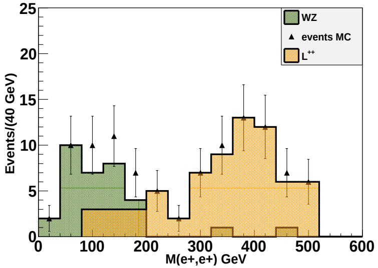
$$\text{variables}: \begin{cases} P_T(\ell) \\ \eta(\ell) \end{cases} \Rightarrow \begin{cases} \epsilon \text{ high for signal, } m^* = 500\text{ GeV} \\ \epsilon \text{ low for bg, } W^+ Z \end{cases}$$

Reconstructed $m_{(\ell^+,\ell^+)}$ for $m^* = 500\,GeV$

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
$P_T\ (e) > 50$ GeV	650	406	1	0.77
$\lvert\eta\ (e_1^+)\ \rvert < 2 \quad P_T\ (e^-) > 80$ GeV	532	44	0.82	0.11



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



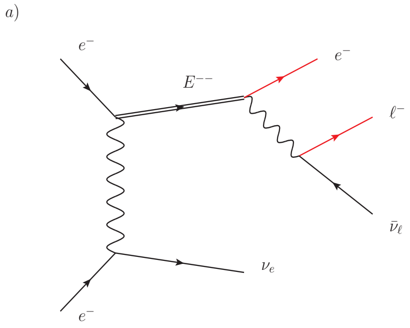
$L = 30\text{fb}^{-1}$

Doubly charged leptons at linear colliders

- At future ILC and CLIC different possibilities for colliding particles

$$e^-e^+ , \quad e^-e^- , \quad \gamma\gamma \quad (100\text{GeV} \div 3\text{TeV})$$

- the e^-e^- collisions are pretty interesting for E^{--} production

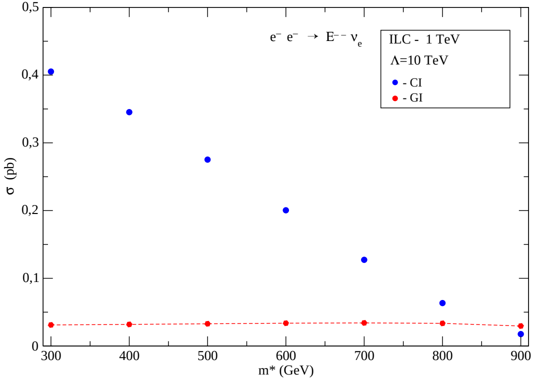


- t-channel
- just one heavy particle
- SSDL topology from decay cascade for leptonic channel $W^- \to \ell^-\nu_\ell$
- reduced SM and QCD background

First qualitative information on cross sections by CalcHEP

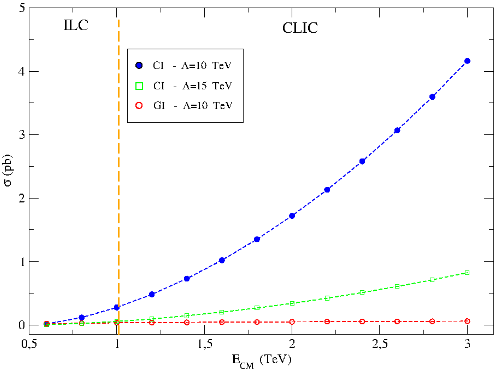
Preliminary cross sections-I

- Improve the CalcHEP model: keep m^* and Λ as different (*R. Leonardi*)
- Compare cross section from gauge and contact interactions



- $\sigma_{CI} > \sigma_{GI}$ almost everywhere
- σ_{CI} changes rather considerably with m^*
- σ_{GI} stays rather constant with m^*

Preliminary cross sections-II at $m^* = 500$ GeV



Hadron Collider VS Linear Collider

- suppressed QCD background in lepton colliders, no underline event
- L^* at $m^* = 500$ GeV via contact interactions with $\Lambda = 10$ TeV

$$\sigma_{pp} = 4 \text{ fb and } \sigma_{e^- e^-} = 270 \text{ fb}$$

Conclusions

- Proliferation of Standard Model fermions may hint to a substructure
- Composite fermions $\rightarrow$ excited fermions

- Contact and gauge interaction to describe excited fermions
- Weak isospin invariance and exotic charges: doubly charged leptons

- cross sections, decay modes, kinematic distributions for L^{--},L^{++} at LHC (only cross sections at ILC, CLIC)
- feasibility study for an experimental analysis, detection simulation: L^{++} may be detected at LHC for luminosity of order 10 if $m^* = 500$ TeV

Outlook

- Study contact interactions at LHC and compare with gauge interaction results (*R. Leonardi*)

- Go further with the linear collider environment, ILC and CLIC
- Compute analytically cross sections for contact and gauge models for E^{++},E^{--}
- Study kinematic distributions
- Feasibility study to get a realistic description of the process

$$e^- e^- \to E^{--}\nu_e \to (e^- \ell^-)\nu_e\bar{\nu}_\ell$$

Back up slide: Kinematic Variables