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Phenomenology of doubly charged excited leptons at LHC

S. Biondini, O. Panella, L. Fanò, Y. Srivastava, G. Pancheri

Dipartimento di Fisica Università di Perugia and INFN Sezione di Perugia

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1. Elementarity and Compositeness
2. Effective Lagrangian Approach

   $\longrightarrow$ **Weak Isospin Model**
3. Excited doubly charged leptons phenomenology L^{++}, L^{--}

   $\longrightarrow$ cross sections and decays

   $\longrightarrow$ $M_{(\ell^+,\ell^+)}$ and events at LHC

What is fundamental?

What is an elementary object in Particle Physics?

- our definition of what is elementary or fundamental is always tentative and must rely on experimental verification

higher energies $\longrightarrow$ smaller spatial dimensions

- The concept of elementary particle changed several times during the last century

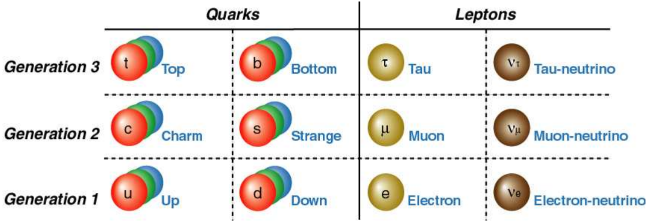
Atoms $\longrightarrow$ Nuclei $\longrightarrow$ Nucleons $\longrightarrow$ Quarks and Leptons $\longrightarrow$???

WHY and WHEN it happened?

- **proliferation** of the so called *fundamental building block* of the matter
- observation of **excited states** of objects thought previously as fundamental

Proliferation of Standard Model fermions

replica of Standard Model families → **proliferation** of fundamental objects



Colored QUARKS and LEPTONS → **24 elementary particles**!

- we have (MAYBE) too many elementary particles
- each generation seems an heavier copy of the previous one
- decays between elementary quarks and leptons are observed

Are quarks and leptons composite objects (→ TeV scale) ?

Models for Composite Quarks and Leptons

- Proliferation of Standard Model fermions hints at a possible compositeness
- if quarks and leptons have substructure EXCITED STATES are expected

excited Leptons or Quarks e^*, μ^*, u^***,** d^* **... within each generation**

$\Downarrow$

undeniable signal of **Compositeness**

QUARKS and LEPTONS COMPOSITENESS

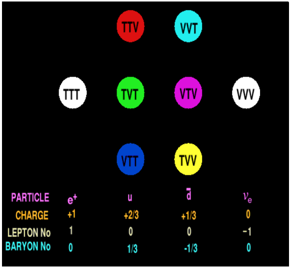
1. the origin of the standard model families as simply higher-order excitations of the same system
2. a **dynamic** origin for the mass of quarks and leptons, in alternative to Higgs solution
3. reinterpretation of the electroweak force as a residual interaction of a more fundamental one

Effective Lagrangian Approach

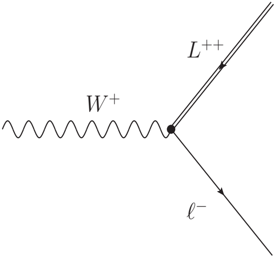
The **effective lagrangian** approach provides physical observables without referring to PREONS

Mathematical Tool: Effective action $\Rightarrow$ **Effective lagrangian**

High energy dynamics $\mathcal{L}_{preon}$



Low energy effective dynamic $\mathcal{L}_{eff}$



Weak and strong Isospin

"Weak isospin spectroscopy of excited quarks and leptons" Phy. Lett. B 146 (1984) - *Y.N. Srivastava and G. Pancheri*

- compositeness of quarks and leptons in the light of Weak Isospin
- analogy with Strong Isospin $\longrightarrow$ learning about strong bound states long before discovering quarks and gluons

strong sector

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

electroweak sector

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

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

Weak Isospin Model

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

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

- $W^{\pm}$, Z^0 bosons do not carry $\mathbf{Y}$ $\longrightarrow$ SM fermions couple with excited fermions with same $\mathbf{Y}$
- we use an effective lagrangian in term of **transition currents**

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

$$\Downarrow$$

gauge mediated interactions

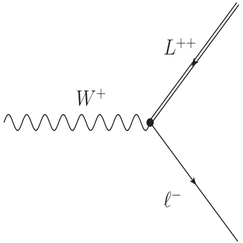
for both **production** and **decay** of excited fermions

- $J^\mu = \frac{g\,f}{m^*}\,\overline{L}(k)\,\{\sigma^{\mu\nu}\,q_\nu\}\,u(k') \longrightarrow q_\mu J^\mu = 0$: **magnetic moment type**

$$I_{3W} = 1 \;\rightarrow\; \mathbf{L} = \begin{pmatrix} L^0 \\ L^- \\ L^{--} \end{pmatrix} \qquad I_{3W} = \tfrac{3}{2} \;\rightarrow\; \mathbf{L} = \begin{pmatrix} L^+ \\ L^0 \\ L^- \\ L^{--} \end{pmatrix}$$

$$J_\mu\,(I_W = 1) = \frac{f_1}{m^*}\left(\bar{\mathbf{L}}\sigma_{\mu\nu}Q^\nu \ell_R + h.c.\right) \rightarrow \mathcal{L} = \frac{gf_1}{m^*}\left(\bar{L}^{--}\sigma^{\mu\nu}Q_\nu\,\ell_R\right) W^-_\mu + h.c.$$

$$J_\mu\left(I_W = \frac{3}{2}\right) = \frac{f_3}{m^*}\left(\bar{\mathbf{L}}\sigma_{\mu\nu}Q^\nu \ell_L + h.c.\right) \rightarrow \mathcal{L} = \frac{gf_3}{m^*}\left(\bar{L}^{--}\sigma^{\mu\nu}Q_\nu\,\ell_L\right) W^-_\mu + h.c.$$



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

Implementing the model in CalcHEP

- A.Pukhov, CalcHEP 3.0: A package for evaluation of Feynman diagrams and integration over multi particle phase space (*arXiv:hep-ph/9908288*)
- the effective lagrangian, with the magnetic type interaction, is written in coordinate space and used as input for **FeynRules**, a MATHEMATICA package, to generate the Feynman rules of the model in a format readable by **CalcHEP**

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coupling vertices for excited leptons

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cross sections (σ) - decay width (Γ)

$\Downarrow$

distributions of different kinematic observables

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possibility to generate events files in LHE format

Doubly charged excited lepton Phenomenology

- parton cross section, every quark combinations that couple with W^+:

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

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

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

- ONLY ONE decay channel

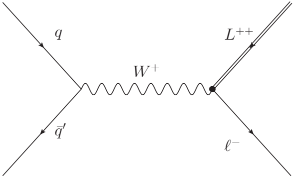
$$\mathcal{BR}(L^{++}) = 1 : \Gamma(L^{++} \to W^+\ell^+)$$

- Considering leptonic decay for W^+, we study the following signature through invariant mass distribution

$$p\,p \to \ell^-\,\ell^+\,\ell^+\,\nu_\ell \ , \ \ M_{(\ell^+,\ell^+)}$$

$M_{(\ell^+,\ell^+)}$ is connected with the mass of excited lepton, m^*

Parton Cross Section $u\bar{d} \to L^{++}\ell^-$ (I)



$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{L^{++}} = \frac{(g\, f_{1,3})^2}{48\pi\, s\, m^{*2}} \mathcal{D}(s) \left\{ \left(\frac{g^2}{4}\right) \left[m^{*2}(s - m^{*2}) + 2ut\right] \pm 2 \left(-\frac{g^2}{8}\right) m^{*2}(t - u) \right\}$$

$$\mathcal{D}(s) = \frac{1}{\left(s - M_W^2\right)^2 + (\Gamma_W M_W)^2}$$

- $+sign \to I_w = \vec{1}$ and $-sign \to I_w = \vec{\frac{3}{2}}$
- For $\bar{u}d \to L^{--}\ell^+$ one have to chose the opposite signs
- **charge conjugation** implies **the exchange of isospin multiplets**:

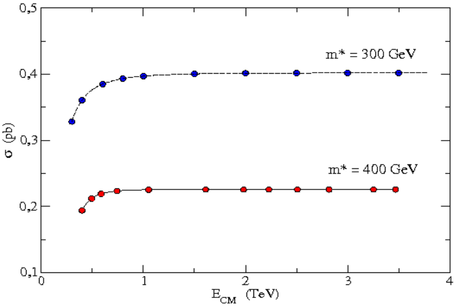
$$L^{++} \leftrightarrow L^{--} \Rightarrow I_w = 1 \leftrightarrow I_w = \frac{3}{2}$$

Parton Cross Section (II)

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

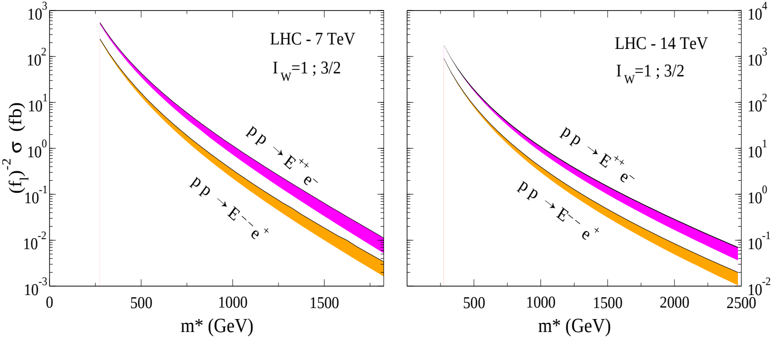
$$\Downarrow$$

$$\sigma = \frac{\alpha\,\pi\, U_{qq'}}{36\, s\, m^{*2}} \frac{(s - m^{*2})^2 (s + 2m^{*2})}{(s - M_W^2)^2 + (M_W \Gamma_W)^2} \rightarrow \frac{\alpha\,\pi\, U_{qq'}}{36\, m^{*2}} \quad ,\ s >> m^{*2} >> M_W^2$$



Production Cross Section: CTEQ6M (proton)

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



$\sigma(L^{++}) = 1$ fb (LHC - 7 TeV) for an excited lepton with $m^* = 1$ TeV

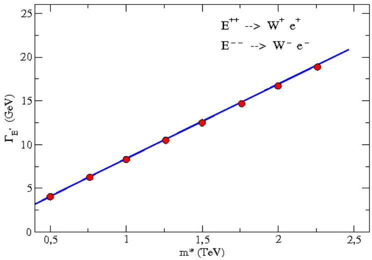
$\sigma(L^{++}) = 10$ fb (LHC - 14 TeV) for an excited lepton with $m^* = 1$ TeV

Unique Decay Channel of L^{++}

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

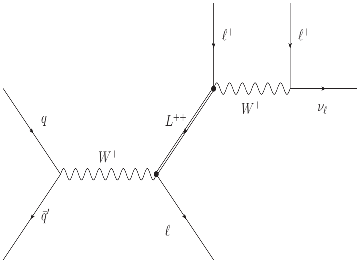
Final State Signature - Lepton Channel

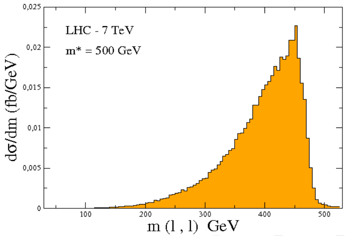
- $L^{++} \to W^+ \ell^+$, $W^+ \to \ell^+ \nu_l$ we get the signature

$$p\, p \to \ell^- \, (\ell^+ \, \ell^+)_{SSDL} \, \nu_\ell$$

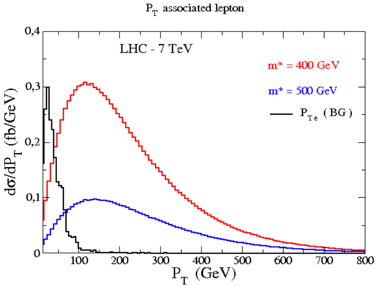
- associated negative lepton $\ell^- \to$ high transverse momentum
- $\nu_\ell \to$ missing energy (*unseen particle*)
- $(\ell^+ \, \ell^+)_{SSDL}$ analyzed by mass invariant distribution: **dilepton topology**

$$M^2_{(\ell^+,\ell^+)} = \frac{\left(m^{*2} - m_W^2\right)\left(m_W^2 - m_\nu^2\right)}{m_W^2} \to M^2_{(\ell^+,\ell^+)} = m^{*2} - m_W^2 \simeq m^{*2}$$





- leptons produced in association with L have the rather hard P_T distribution



considered background Standard Model processes

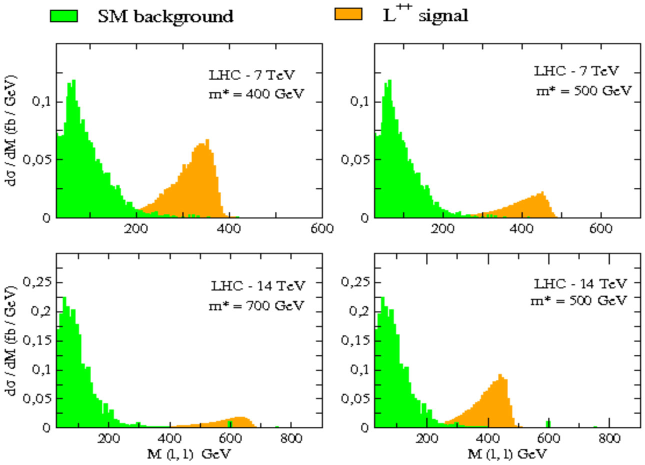
$$p\,p \;\rightarrow\; W^+\,Z^0 \;\rightarrow\; \ell^-\,\ell^+\,\ell^+\,\nu_\ell$$

$$p\,p \;\rightarrow\; W^+\,\gamma^* \;\rightarrow\; \ell^-\,\ell^+\,\ell^+\,\nu_\ell$$

$$p\,p \;\rightarrow\; \ell^+\,(\gamma^*/Z)\,\nu_\ell \;\rightarrow\; \ell^-\,\ell^+\,\ell^+\,\nu_\ell$$

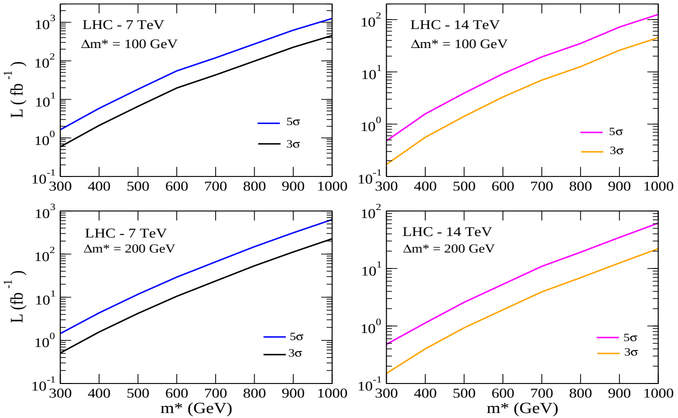
Base Kinematic Cuts and $M_{(\ell^+,\ell^+)}$ distributions

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



Luminosity vs Statistical Significance

From the definition of statistical significance $s = \frac{N_s}{\sqrt{N_s + N_b}}$ we get $L = s^2 \left(\frac{\sigma_s + \sigma_b}{\sigma_s^2} \right)$:



- final evidence for compositeness of quarks and leptons $\rightarrow$ **excited states**
- Weak Isospin Model $\in$ EQFT: 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}**

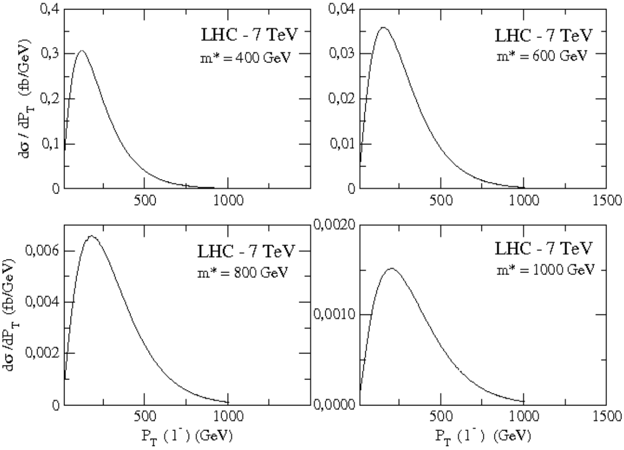
- In progress: interface **LHE output** of CalcHEP with a fast simulator (**PGS**)

  $\Rightarrow$ **generic detector response** $\rightarrow$ **reconstructed objects**

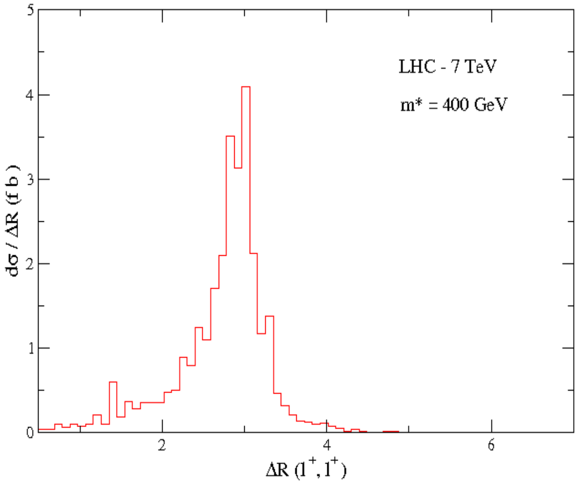
- In progress: improvement of the transition current. Generalize the transition current including a term in γ^μ always requesting $q_\mu J^\mu = 0$

BACK UP SLIDES

Associated ℓ^- transverse momentum



$\Delta R(\ell^+, \ell^+)$ DISTRIBUTION: MAINLY BACK TO BACK

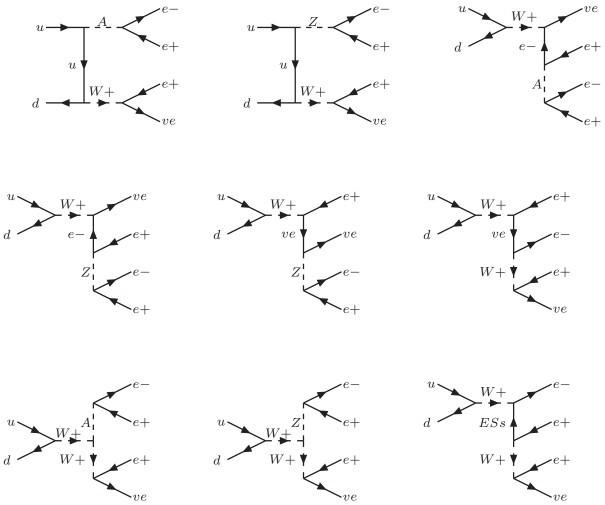


Signal and Background Cross Sections

m^* (GeV)	$\sigma_{L^{++}}$ (fb)	σ_{BG} (fb)
400	11.7	25
500	4.3	25
600	1.8	25
800	0.4	25
1000	0.1	25

Signal and Background Feynman Diagrams

$$u\bar{d} \rightarrow \nu_e e^- e^+ e^+$$



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** $e^* \to e\,\gamma$

$$p\,p \to e^{\pm}\,e^{*\pm} \to e^{+}\,e^{-}\,\gamma \quad \Rightarrow \frac{d\sigma}{dM_{e\gamma}}$$

- Experimental studies: *CMS-EXO-10-016, arXiv/hep-ex:1107.1773v1*

Production $\to \mathcal{L}_{c\,i} = \frac{1}{32\pi^2\Lambda^2}\,J^{\mu}J_{\mu}$

Decay $\to \mathcal{L}_{g\,m} = \frac{1}{2\Lambda}\bar{f}^{*}{}_{R}\sigma_{\mu\nu}\left\{g\,\frac{\tau}{2}W^{\mu\nu} + g'\,\frac{Y}{2}B^{\mu\nu}\right\}f_L$

$$p\,p \to ee^{*} \to e\,e\,\gamma \quad , \quad p\,p \to \mu^{*}\mu \to \mu\mu\,\gamma$$

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

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

Events counting

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

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

where Δm^* provides a mass window below m^*. We choose to values:
$\Delta m^* = 100\ GeV$ and $\Delta m^* = 200\ GeV$

- $m^* = 300\ GeV$ $N_s = 15.8$
- $m^* = 400\ GeV$ $N_s = 4.3$
- $m^* = 500\ GeV$ $N_s = 1.4$
- $m^* = 600\ GeV$ $N_s = 0.5$

- $m^* = 300\ GeV$ $N_s = 20.6$
- $m^* = 400\ GeV$ $N_s = 6.2$
- $m^* = 500\ GeV$ $N_s = 2.2$
- $m^* = 600\ GeV$ $N_s = 0.9$

$$\mathcal{L} = \left(\frac{g\, f_1}{m^*}\right) \left\{ \left(\bar{L}^0, \bar{L}^-, \bar{L}^{--}\right)_L \sigma_{\mu\nu}\, Q^\nu \ell_R \begin{pmatrix} W_\mu^+ \\ W_\mu^0 \\ W_\mu^- \end{pmatrix} + h.c. \right\}$$

References

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