Probing Leptoquarks at IceCube

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• Leptoquarks in theory
• Experimental limits: HERA and Tevatron
• Phenomenology: cross sections and inelasticity
• Sensitivity reach at IceCube

Work done with L. Anchordoqui, C. A. Garcia Canal, D. G. Dumm, F. Halzen,
hep-ph/0609214
Leptoquarks - Theory

• Carry SU(3) color, $B \neq 0$, $L \neq 0$ – decay
  \[ LQ \rightarrow \ell q \]

• Usually superheavy (e.g., heavy triplet in SU(5) Higgs 5)

• Can in principle be $\sim$ TeV, then exist bounds from EW precision data

• Example: $\Delta a_\mu$ K. Cheung, 2001

• Lower limit of $\sim 1$ TeV on leptoquark mass can be lowered if $L$ or $R$ coupling is suppressed

  e.g., in SUSY $R$ QLD$^c$ only $L$ coupling
Experimental Limits

- **HERA**: first generation, $M \gtrsim 300$ GeV

- but production depends on 1st gen Yukawa coupling – if small, bound can decrease

- **Tevatron**: QCD pair production – ID made through event topology

  - no dependence on trilinear couplings except through branching fractions

- For 2nd generation, final state topology $j_c j_{\bar{c}} \mu \bar{\mu}$

  \[ \rightarrow M \gtrsim 250 \text{ GeV} \]
2nd Generation - DZero limits

\[
s = \frac{1}{2}, \beta = 1
\]

\[
\sigma \times \beta^2 \, [\text{pb}]
\]

\[
D\varnothing \ 294 \ \text{pb}^{-1}
\]

\[
\text{Scalar leptoquark mass } m_{LQ} \ [\text{GeV}]
\]
Tevatron: 3rd Generation

• For 3rd generation, decay into $t\tau$ final state is suppressed for smaller $M$

• so final state topology $\bar{j}b\bar{j}b\nu_\tau\bar{\nu}_\tau$

2 $b$ jets + missing energy

$\rightarrow M \gtrsim 219$ GeV
3rd Generation - DZero limits

D0 Run II Preliminary

- Signal cross-section, $\mu = 1M_{LQ}$
- $B_{\nu}^2 \times [ \sigma \pm \sqrt{\delta^2_{\mu}(\sigma) + \delta^2_{PDF}(\sigma)} ]$, $B=1$
- $B_{\nu}^2 \times [ \sigma - \sqrt{\delta^2_{\mu}(\sigma) + \delta^2_{PDF}(\sigma)} ]$, $B=(1 - 0.5*F_{sp})$

- Observed, MHT, $310\text{pb}^{-1}$
- Observed, MUJET, $367\text{pb}^{-1}$

213 GeV

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- Effective Area $\approx 1 \text{ km}^2$
- $E_{\text{th}} \approx 100$ GeV
- 4800 PMT’s on 80 strings
- $\mu$–track angular resolution $\Rightarrow 1^\circ \times 1^\circ$ bin
- Calibration $\Leftrightarrow$ IceTop
  - $1 \text{ km}^2$ air-shower detector with 160 stations
Tracks: Cosmic muons and CC interactions $\nu_\mu \rightarrow \mu$

Very high energy $\nu_\tau \rightarrow \tau$

Showers: $\nu_e$ or $\nu_\tau$ CC interactions

All NC interactions

Muon bremsstrahlung near detector

- Cut $E_\nu > 10^6$ GeV, reduce $\mu$ brem, atmospheric b'g'd
Inelasticity

- In energy decade $10^{6.5} < E_\nu/\text{GeV} < 10^{7.5}$
  expect good energy resolution for

  - $\mu$ and $\tau$ ("double bang") tracks
  - hadron showers

- Allows determination of inelasticity $\gamma$

- $\gamma$-dependence of resonant LQ production $\neq \text{SM}$

- can do $\gamma$ cuts to increase S/N
The Model

- Take simple flavor-diagonal \(3-2-1\) invariant Lagrangian

\[
\mathcal{L}_{\text{LQ}} = \sum_i (g_L \overline{Q}_{iL}^c \, i\tau_2 \, L_{iL} + g_R \overline{u}_{iR}^c \, l_{iR}) \, S_i
\]

- Gives parton level amplitude

\[
\mathcal{M}_L = g_L^2 \frac{\overline{l}_L(k') \, U_{L}(p') \, \overline{D}_L^c(p) \, \nu_L(k)}{\hat{s} - M^2 - i\Gamma M}
\]

- For decay through \(R\) channel, \(g_L^2 \rightarrow g_L \, g_R\)
Cross sections

• With usual parton model and pole approximation

\[
\frac{d\sigma^{(i)}_{LQ}}{dy} = \frac{\pi}{2} \frac{g_L^2 (g_L^2 + g_R^2)(1 - \lambda_U)}{(g_L^2 + g_R^2)(1 - \lambda_U)^2 + g_L^2} \frac{D^{(i)}(M^2 / s)}{s}
\]

\[
\lambda_U = \frac{M_U^2}{M^2}, \quad \lambda_U < y < 1
\]

• Flat \( y \) distribution in contrast to SM

\[
\frac{d\sigma^{CC}_{SM}}{dy} = \frac{G_F^2}{\pi} s \int dx \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \times [xq(x, Q^2) + x\bar{q}(x, Q^2)(1 - y)^2]_{Q^2=sxy}
\]
Reach at IceCube: the Waxman-Bahcall Flux

• To probe $\sigma_{LQ}$, need to know $\nu^{(i)}$ fluxes Use Waxman-Bahcall (WB) flux

$$E_{\nu}^2 \phi_{WB}^\nu(E_{\nu}) \approx 6 \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

(all flavors)

• assumes (1) neutrinos from transparent CR sources

(2) adequate transfer of energy to pions in $pp$ collisions at source

• More neutrinos if Xgalactic CRs dominate at $10^9$ GeV – increase power requirement at source

Reach at IceCube: Background and Signal

- Use downward events

- **Focus on** $10^7 < E_\nu/\text{GeV} < 10^{7.5}$ – atmospheric flux negligible, extraterrestrial flux significant

- initial WB flux $\nu_\mu : \nu_e : \nu_\tau = 2 : 1 : 0 \rightarrow 1 : 1 : 1$ with oscillation

- **With** $\langle E_\nu \rangle = 10^{7.25} \text{ GeV}$ find SM b’g’d Gandhi, Quigg, Reno, Sarcevic and signal for each flavor $i$

\[ \mathcal{N}_B^{(i)} \simeq 2\pi n_T T \left. \sigma_{SM}^{CC}(\langle E_\nu \rangle) \right|_{y \geq 0.5} \phi_{WB}^{\nu_i}(\langle E_\nu \rangle) \Delta E_\nu \]
\[ = 2 \quad \text{for} \; T = 15 \; \text{yr} \]

\[ \mathcal{N}_S^{(i)} \simeq 2\pi n_T T \left. \sigma_{LQ}(\langle E_\nu \rangle) \right|_{y \geq 0.5} \phi_{WB}^{\nu_i}(\langle E_\nu \rangle) \Delta E_\nu \]
IceCube sensitivity

- Can determine domain of sensitivity of IceCube to LQ production

Suppose 2 $\nu_i$ events in fact observed with $y \geq 0.5$

- Then at 90% CL, there is an upper bound $N_S^{(i)} \leq 3.91$ on the signal mean

- This then would rule out regions of the $g_L - g_R - M$ parameter space

- Only with 6 events observed is there a lower bound of $\sim 1$ on the signal mean

Feldman and Cousins
Second generation sensitivity

IceCube Sensitivity 90% CL

95% CL Excluded Region

DO Collaboration

M (GeV)

200 220 240 260 280 300 320 340

0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4
Third generation sensitivity

IceCube Sensitivity
90% CL

95% CL Excluded Region
D0 Collaboration

M (GeV)
Summary and Conclusions

• Introduced cuts on inelasticity as tool for probing new physics in cosmic neutrino interactions

• Illustrative example: leptoquark production at IceCube

  Event rate comparable to atmosphere as detector calorimeter  
  M. C. Espirito Santo et al hep-ph/0508100

• IceCube $y$ capability allows SM b’g’d rejection

• Have shown that production of leptoquarks with $M \gtrsim 250$ GeV and diagonal generational couplings can be tested at Antarctic ice cap