International School Cargese 2012 : Accross the TeV frontier with the LHC

New Resonances at the Pierre Auger Observatory

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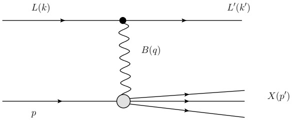
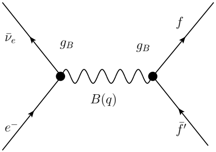
August, 27 2012

Introduction

W', Z' bosons @ PAO

Deep Inelastic Scattering (DIS), Glashow Resonance (GR) @ LO





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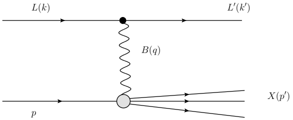

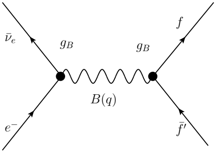

Motivations

- **Ultra-high energy neutrino** $\sim 10^{10}\mathrm{GeV} \Rightarrow \sqrt{s} \simeq 100\,TeV$
- Possibility of probing new physics scenarios beyond the reach of the LHC
- GR contributes only in BSM models making it a very good probe (@PAO)

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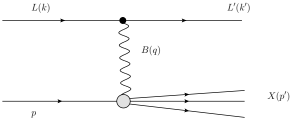

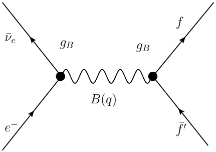

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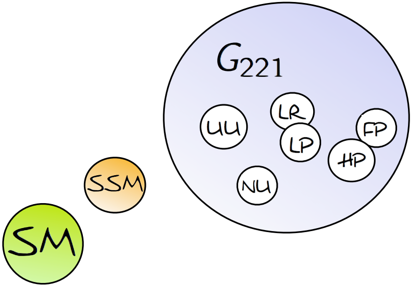
Models studied



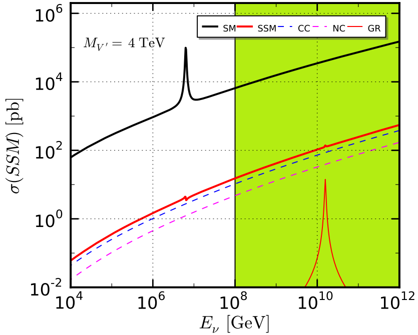
UU : Un-unified
NU : Non-universal
HP : Hadro-phobic
FP : Fermio-phobic
LR : Left-Right
LP : Lepto-phobic
SSM : Sequential SM

SSM, a heavy copy of the SM i.e. $M_{B'} = \alpha M_B$

G_{221}

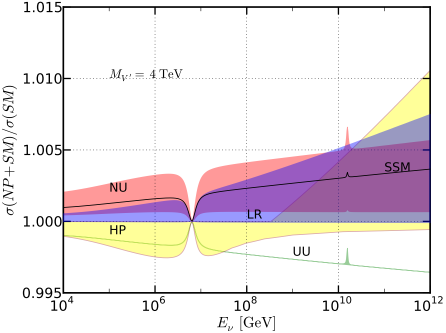
- $G_{221} \equiv SU(2)_1 \times SU(2)_2 \times U(1)_X$
- Two parameters: $\tan\phi$, $M_{B'}$
- Breaking Pattern, Higgs Sector, Particle content $\Rightarrow UU, NU, LR/LP, HP/FP$

Cross Sections



GR' in the PAO energy range of sensitivity

Modification up to 1%



Event Rates

Observable

- ν_μ, ν_e downward-going neutrinos
- CC, NC, GR interferences for all the models above

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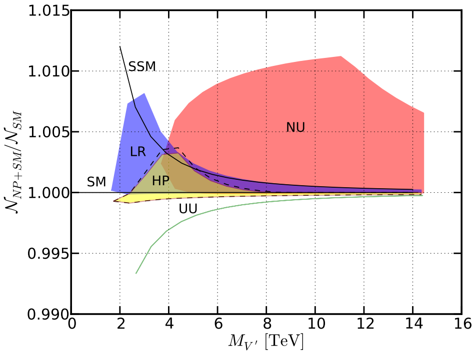

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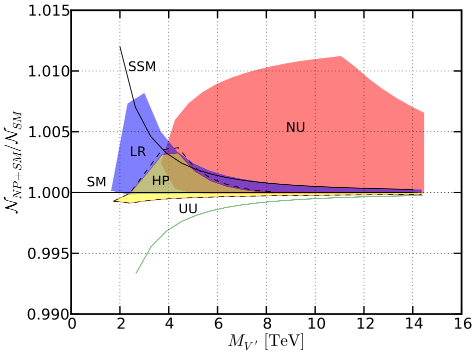


- Mass suppression dominant as compared to the coupling enhancement
- NP contributions modify the SM up to 1%

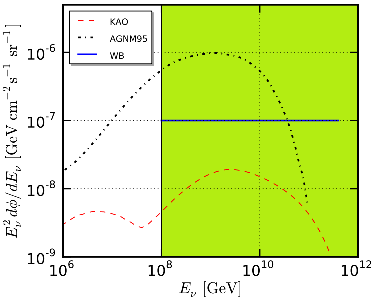
Neutrino cosmogenic flux

$p + \gamma_{CMB/IR} \rightarrow \Delta \rightarrow p + \pi^0$ or
$p + \gamma_{CMB/IR} \rightarrow \Delta \rightarrow n + \pi^+$

$\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu$

$\pi^0 \rightarrow \gamma\gamma \; P = 0.92$ or
$\pi^0 \rightarrow \gamma + e^- + e^+ \; P{=}0.012$

$n \rightarrow p + e^- + \bar{\nu}_e$



The couplings of Z′- and W′-bosons to the SM fermions in the category of left-handed models can be written as:

$$C^{W'}_{1,L} \simeq \frac{1}{t} \qquad C^{W'}_{1,R} = 0 \qquad (1)$$

$$C^{W'}_{2,L} \simeq -t \qquad C^{W'}_{2,R} = 0 \qquad (2)$$

$$C^{Z'}_{1,L} \simeq T_3(f)c_\theta \frac{1}{t} \qquad C^{Z'}_{1,R} \simeq 0 \qquad (3)$$

$$C^{Z'}_{2,L} \simeq -T_3(f)c_\theta t \qquad C^{Z'}_{2,R} \simeq 0\ , \qquad (4)$$

where label index 1 is a placeholder for q in Un-unified and $1^{\text{st}}, 2^{\text{nd}}$ in Non-universal model, while label index 2 is a placeholder for l in Un-unified and 3^{rd} for Non-universal model.

Theory motivated extensions of the SM

G_{221} models

- $SU(2)_1 \times SU(2)_2 \times U(1)_X \to G_{221}\, class$
- Different breaking patterns give the following models

$$1)\ \underbrace{\underbrace{SU(2)_1 \times SU(2)_2}_{SU(2)_L} \times \underbrace{U(1)_X}_{U(1)_Y}}_{U(1)_{e.m.}} \to \text{Un-Unified, Non-Universal}$$

$$2)\ \underbrace{\underbrace{SU(2)_1}_{SU(2)_L} \times \underbrace{SU(2)_2 \times U(1)_X}_{U(1)_Y}}_{U(1)_{e.m.}} \to \text{Left-Right, Lepto-Phobic}$$

Theory motivated extensions of the SM

Cat.	Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
Left-handed	Un-unified (UU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	Y_{SM} for all fermions.
	Non-universal (NU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1^{st},2^{nd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1^{st},2^{nd}}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3^{rd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3^{rd}}$	Y_{SM} for all fermions.
Right-handed	Left-right (LR)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $-\frac{1}{2}$ for leptons.
	Lepto-phobic (LP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, Y_{SM} for leptons.

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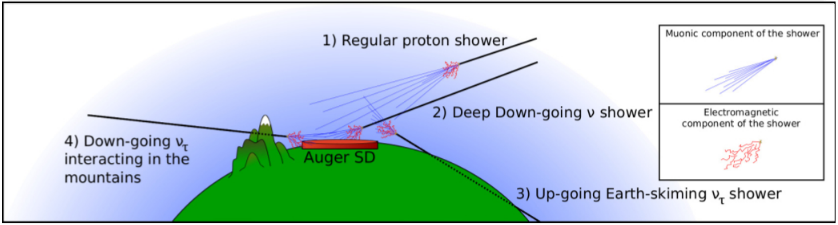
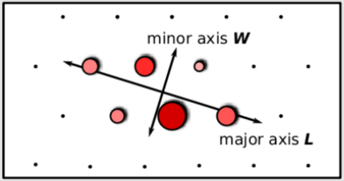
- Free parameters: t, $M_{W'}$, $M_{Z'}$; $M_{Z'} = f(M_{W'}, t)$
- $t \equiv \tan\phi$, first stage symmetry breaking angle



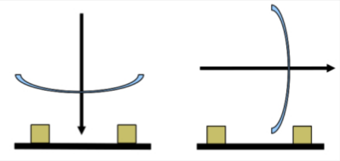
Elongated footprint



Propagation of the speed of light

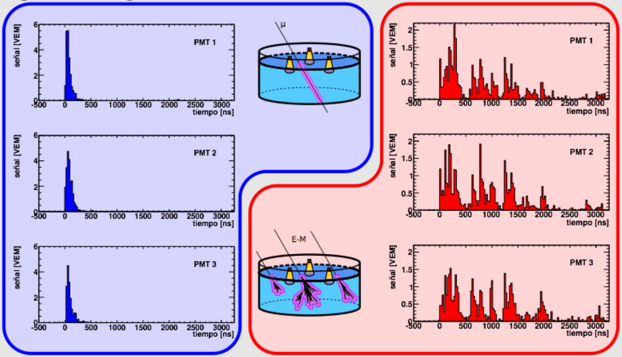
Vertical shower $V \gg c$

Horizontal shower $V \sim c$



Water Cherenkov stations

Signals are digitised with 25 ns time resolution



Zp couplings

	$\bar{u}\gamma^\mu u$	$\bar{d}\gamma^\mu d$	$\bar{\nu}\gamma^\mu \nu$	$\bar{e}\gamma^\mu e$
LR	$(\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_2 - \frac{1}{6}s_{\tilde{\phi}}\tilde{g}_X)P_R - \frac{1}{6}s_{\tilde{\phi}}\tilde{g}_X P_L$	$(-\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_2 - \frac{1}{6}s_{\tilde{\phi}}\tilde{g}_X)P_R - \frac{1}{6}s_{\tilde{\phi}}\tilde{g}_X P_L$	$(\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_2 + \frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X)P_R + \frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X P_L$	$(-\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_2 + \frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X)P_R + \frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X P_L$
LP	$(\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_2 - \frac{1}{6}s_{\tilde{\phi}}\tilde{g}_X)P_R - \frac{1}{6}s_{\tilde{\phi}}\tilde{g}_X P_L$	$(-\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_2 - \frac{1}{6}s_{\tilde{\phi}}\tilde{g}_X)P_R - \frac{1}{6}s_{\tilde{\phi}}\tilde{g}_X P_L$	$\frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X P_L$	$s_{\tilde{\phi}}\tilde{g}_X(\frac{1}{2}P_L + P_R)$
HP	$-s_{\tilde{\phi}}\tilde{g}_X(\frac{1}{6}P_L + \frac{2}{3}P_R)$	$-s_{\tilde{\phi}}\tilde{g}_X(\frac{1}{6}P_L - \frac{1}{3}P_R)$	$(\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_2 + \frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X)P_R + \frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X P_L$	$(-\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_2 + \frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X)P_R + \frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X P_L$
FP	$-s_{\tilde{\phi}}\tilde{g}_X(\frac{1}{6}P_L + \frac{2}{3}P_R)$	$-s_{\tilde{\phi}}\tilde{g}_X(\frac{1}{6}P_L - \frac{1}{3}P_R)$	$\frac{1}{2}s_{\tilde{\phi}}\tilde{g}_X P_L$	$s_{\tilde{\phi}}\tilde{g}_X(\frac{1}{2}P_L + P_R)$
UU	$\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_1 P_L$	$-\frac{1}{2}c_{\tilde{\phi}}\tilde{g}_1 P_L$	$-\frac{1}{2}s_{\tilde{\phi}}\tilde{g}_2 P_L$	$\frac{1}{2}s_{\tilde{\phi}}\tilde{g}_2 P_L$
NU	$\frac{1}{2}\begin{pmatrix} c_{\tilde{\phi}}\tilde{g}_1 \\ -s_{\tilde{\phi}}\tilde{g}_2 \end{pmatrix} P_L$	$-\frac{1}{2}\begin{pmatrix} c_{\tilde{\phi}}\tilde{g}_1 \\ -s_{\tilde{\phi}}\tilde{g}_2 \end{pmatrix} P_L$	$\frac{1}{2}\begin{pmatrix} c_{\tilde{\phi}}\tilde{g}_1 \\ -s_{\tilde{\phi}}\tilde{g}_2 \end{pmatrix} P_L$	$-\frac{1}{2}\begin{pmatrix} c_{\tilde{\phi}}\tilde{g}_1 \\ -s_{\tilde{\phi}}\tilde{g}_2 \end{pmatrix} P_L$

Wp couplings

	$\bar{d}\gamma^\mu u$	$\bar{e}\gamma^\mu \nu$
LR	$\frac{1}{\sqrt{2}}\tilde{g}_2 P_R$	$\frac{1}{\sqrt{2}}\tilde{g}_2 P_R$
LP	$\frac{1}{\sqrt{2}}\tilde{g}_2 P_R$	0
HP	0	$\frac{1}{\sqrt{2}}\tilde{g}_2 P_R$
FP	0	0
UU	$\frac{1}{\sqrt{2}} c_{\tilde{\phi}}\tilde{g}_1 P_L$	$-\frac{1}{\sqrt{2}} s_{\tilde{\phi}}\tilde{g}_2 P_L$
NU	$\frac{1}{\sqrt{2}}\begin{pmatrix} c_{\tilde{\phi}}\tilde{g}_1 \\ -s_{\tilde{\phi}}\tilde{g}_2 \end{pmatrix} P_L$	$\frac{1}{\sqrt{2}}\begin{pmatrix} c_{\tilde{\phi}}\tilde{g}_1 \\ -s_{\tilde{\phi}}\tilde{g}_2 \end{pmatrix} P_L$