A bottom-up reconstruction of new physics at Large Hadron Collider

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at

Tata Institute of Fundamental Research

Mumbai, January 13, 2010
1. The Standard Model
   - Building block
   - The particles and forces

2. Beyond the Standard Model
   - The approach
   - New physics
   - New particles

3. New physics with top quark
   - Top quark at the edge
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4. Search for Extra-dimensions
   - Features of the extra-dimension
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5. Conclusions
The Standard Model

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New physics at LHC
It was long believed that matter is made of atoms and by mid 19th century it was an established fact. By early 20th century we started to probe the Sub-atomic world. Nucleus was identified in 1911. Particle list:

1932: $e^-$, $p^+$, $n^-$ were the fundamental building blocks.

1950: $e^-$, $p^+$, $n^-$, $\mu^-$, $\nu_e$, $\nu_\mu$, $\pi^+$, $\pi^-$, $\pi^0$, $K^0$, $K^\pm$ etc.

So many of particle cannot be fundamental. Certain pattern emerged among the zoo of particles. ⇒ These particle must be build of something else.
Sub-atomic world

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The quark model

The matter particles were divide in two groups:

- **Hadrons**: $p, n, \pi^\pm, \pi^0, K^\pm$ etc. particles that *can* interact strongly.
- **Leptons**: $e, \nu_e, \mu, \nu_\mu, \tau$, etc. particles that *cannot* interact strongly.
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Quarks carry color quantum number and fractional electric charges. (bottom-up)
Structure of the Standard Model

### Three Generations of Matter (Fermions)

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### Additional Particle: Higgs Boson

- SU(3)_c singlet
- SU(2)_L doublet
- Y = 1

Leads to masses of the particles via spontaneous symmetry breaking.

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#### Quarks

- **d**: down, mass $\leq 2.2$ eV, spin $\frac{1}{2}$
- **s**: strange, mass $<0.17$ MeV, spin $\frac{1}{2}$
- **b**: bottom, mass $<15.5$ MeV, spin $\frac{1}{2}$
- **g**: gluon, mass $91.2$ GeV, spin $0$

#### Leptons

- **e**: electron, mass $0.511$ MeV, spin $\frac{1}{2}$
- **μ**: muon, mass $105.7$ MeV, spin $\frac{1}{2}$
- **τ**: tau, mass $1.777$ GeV, spin $\frac{1}{2}$
- **ν_e**: electron neutrino, mass $\leq 2.2$ eV, spin $\frac{1}{2}$
- **ν_μ**: muon neutrino, mass $<0.17$ MeV, spin $\frac{1}{2}$
- **ν_τ**: tau neutrino, mass $<15.5$ MeV, spin $\frac{1}{2}$

#### Bosons (Forces)

- **Z**: weak force, mass $91.2$ GeV, spin $0$
- **W**: weak force, mass $80.4$ GeV, spin $1$

Gravity not included.

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(top-down)

Describes almost all observed phenomena.

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Bottom-up vs Top-down

**Top-down**

- Symmetry: gauge symmetry, space time symmetry etc.
- Matter content: fermions, scalars and their quantum number under symmetries $\Rightarrow$ Lagrangian.
- Self consistancy of Lagrangian: gauge anomaly etc.
- Mechanisms: spontaneous symmetry breaking, phase transitions etc.
- Predictions for experiments.

**Bottom-up**

- Observables: $\sigma$, asymmetries, correlations etc.
- Particle content: observed or required to explain observations.
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An example of top-quark

**Top-down**

- Mass: Heavy
- Charge: +2/3
- Color Quantum number: 3
- Iso-spin: +1/2
- Hypercharge: +1
- Spin: 1/2
- Decay modes:
  - $t \rightarrow b \ W^+ + \bar{t} \rightarrow b \ H^+$
  - $t \rightarrow c \ Z^0$ (Br < 0.1)

**Bottom-up**

- Mass: 173.1 ± 1.3 GeV
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Polarization observables and decay pattern are most important features to study new particles.
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gaugino, higgsino, heavy fermion partners.

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threshold behaviour, polarization, 2-body decay, cascade decay.

**Fermions**
gaugino, higgsino, heavy fermion partners.

**Productions:**
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**Vectors**
KK-excitations of gauge bosons, heavy bosons.

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New particles

All new physics models introduce new symmetries and particles.

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- Higgs, sfermions, techni-pions etc.

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Ritesh Singh

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Polarization observables and decay pattern are most important features to study new particles.
New physics with top quark
Top quark: A looking glass

The mass of the top-quark is very large ($m_t \sim 173$GeV)
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**We have a clean looking glass for new physics.**
Anomalous $tbW$ vertex:

$$\Gamma^\mu = \frac{g}{\sqrt{2}} \left[ \gamma^\mu (f_{1L} P_L + f_{1R} P_R) - \frac{i \sigma^{\mu\nu}}{m_W} (p_t - p_b)_\nu (f_{2L} P_L + f_{2R} P_R) \right]$$
Anomalous top decay

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- Contribution from $f_{1R}, f_{2L}$ are proportional to $m_b$.

$$\frac{1}{\Gamma_t} \frac{d\Gamma_t}{d \cos \theta_f} = \frac{1}{2} \left( 1 + \alpha_f P_t \cos \theta_f \right)$$

$$\alpha_l = 1 - O(f_i^2)$$

$$\alpha_b = - \left[ \frac{m_t^2 - 2 m_W^2}{m_t^2 + 2 m_W^2} \right] + \Re(f_{2R}) \left[ \frac{8 m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2 m_W^2)^2} \right] + O \left( \frac{m_b}{m_W}, f_i^2 \right)$$
Lepton distribution

\[ AB \rightarrow t P_1 \ldots P_{n-1} b W^+ \rightarrow l^+ \nu \]

Lepton distribution is independent of anomalous \( t b W \) coupling if the \( t \)-quark is on-shell; narrow-width approximation for the \( t \)-quark, anomalous couplings \( f_1 R \), \( f_2 R \) and \( f_2 L \) are small, narrow-width approximation for the \( W \)-boson, \( b \)-quark is mass-less, \( t \rightarrow b W (\ell \nu) \) is the only decay channel for the \( t \)-quark.

\[ \text{⇒ Lepton distribution from top decay is pure probe of possible new physics in the top production process.} \]
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$\Rightarrow$ Lepton distribution from top decay is pure probe of possible new physics in the top production process.
Polarization or $t$-quark: top-down

Polarized cross-sections

$$\sigma(\lambda, \lambda') = \int \frac{d^3 p_t}{2E_t(2\pi)^3} \left( \prod_{i=1}^{n-1} \frac{d^3 p_i}{2E_i(2\pi)^3} \right) \frac{(2\pi)^4}{2l} \delta^4 \left( k_A + k_B - p_t - \left( \sum_{i=1}^{n-1} p_i \right) \right) \rho(\lambda, \lambda')$$

where $\rho(\lambda, \lambda') = M(\lambda, \ldots) M^*(\lambda', \ldots)$
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where $\rho(\lambda, \lambda') = \mathcal{M}(\lambda, \ldots) \mathcal{M}^*(\lambda', \ldots)$

Total cross-section: $\sigma_{tot} = \sigma(+, +) + \sigma(-, -)$
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**Total cross-section:** $\sigma_{tot} = \sigma(+, +) + \sigma(-, -)$

Polarization density matrix :

$$
P_t = \frac{1}{2} \begin{pmatrix} 1 + \eta_3 & \eta_1 - i\eta_2 \\ \eta_1 + i\eta_2 & 1 - \eta_3 \end{pmatrix},
$$

$$
\eta_3 = \frac{(\sigma(+, +) - \sigma(-, -))}{\sigma_{tot}}
$$

$$
\eta_1 = \frac{(\sigma(+, -) + \sigma(-, +))}{\sigma_{tot}}
$$

$$
i \eta_2 = \frac{(\sigma(+, -) - \sigma(-, +))}{\sigma_{tot}}
$$
Polarization or $t$-quark: bottom-up

Polarization of $t$-quark through decay asymmetries:

\[
\begin{align*}
\alpha_f \frac{\eta_3}{2} &= \frac{\sigma(p_f.s_3 < 0) - \sigma(p_f.s_3 > 0)}{\sigma(p_f.s_3 < 0) + \sigma(p_f.s_3 > 0)} \\
\alpha_b &= -0.4 \\
\alpha_f \frac{\eta_2}{2} &= \frac{\sigma(p_f.s_2 < 0) - \sigma(p_f.s_2 > 0)}{\sigma(p_f.s_2 < 0) + \sigma(p_f.s_2 > 0)} \\
\alpha_f \frac{\eta_1}{2} &= \frac{\sigma(p_f.s_1 < 0) - \sigma(p_f.s_1 > 0)}{\sigma(p_f.s_1 < 0) + \sigma(p_f.s_1 > 0)}
\end{align*}
\]

\[s_i.s_j = -\delta_{ij} \quad p_t.s_i = 0\]

For \( p_t^\mu = E_t(1, \beta_t \sin \theta_t, 0, \beta_t \cos \theta_t) \), we have

\[s_1^\mu = (0, -\cos \theta_t, 0, \sin \theta_t), \quad s_2^\mu = (0, 0, 1, 0), \quad s_3^\mu = E_t(\beta_t, \sin \theta_t, 0, \cos \theta_t)/m_t.\]

\textbf{Ptlong} is implemented in \textsc{SHERPA}.
Lepton’s azimuthal distribution

Lab frame azimuthal distribution of leptons:

\[ A_\ell = \frac{\sigma(\cos \phi_1 > 0) - \sigma(\cos \phi_1 < 0)}{\sigma(\cos \phi_1 > 0) + \sigma(\cos \phi_1 < 0)} \]

Used for:
- \( Z' \) at LHC (Les Houches 05)
- \( g^{(1)} \) in RS model at LHC (Nucl. Phys. B797, 1, (2008))
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\[ A_\ell(m_{tt}) = \frac{\sigma(\cos \phi_l > 0) - \sigma(\cos \phi_l < 0)}{\sigma(\cos \phi_l > 0) + \sigma(\cos \phi_l < 0)} \]

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Lab frame azimuthal distribution of leptons:

\[ P_p = (0.8, -0.6) \]
\[ \eta_3 = +0.559, \eta_1 = -0.504 \]

Distribution of all the decay particles.
Top polarization at LHC

\[ pp \rightarrow tj \rightarrow bl^+\nu_{lj} \]

\[ \Delta_{lb} = \frac{1}{\sigma} \left| \frac{d\sigma}{d\phi_l} - \frac{d\sigma}{d\phi_b} \right| \]

Depends upon:
- Top polarization
- \( p_T \) distribution

\[ \sigma = 131 \text{ pb} \quad \eta_3 = -0.196 \]
\[ \Delta_{lb} = 0.35 \]

Cuts: No cuts

Model: SM
Top polarization at LHC

\[ pp \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow t\chi^0_1 \bar{t}\chi^0_1 \]

\[ \Delta_{lb} = \frac{1}{\sigma} \left| \frac{d\sigma}{d\phi_l} - \frac{d\sigma}{d\phi_b} \right| \]

Depends upon:
- Top polarization
- \( p_T \) distribution

\( \sigma = 1.44 \text{ fb} \quad \eta_3 = +0.184 \)
\( \Delta_{lb} = 0.12 \)

Cuts: No cuts

Model: MSSM
\( M_{\tilde{t}_1} = 355 \text{ GeV}, \quad m_\chi = 164 \)
\( \text{GeV} \quad Br(\tilde{t}_1 \rightarrow t\chi^0_1) = 0.76 \)
Top polarization at LHC

\[ pp \rightarrow t\bar{t} \rightarrow b l^+ \nu \] \[ \rightarrow b l^- \bar{\nu} \]

\[ (1/\sigma) \frac{d\sigma}{d\Phi} \]

Lepton  

b-quark

\[ \Delta_{lb} = \frac{1}{\sigma} \left| \frac{d\sigma}{d\phi_l} - \frac{d\sigma}{d\phi_b} \right| \]

Depends upon:
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- \( p_T \) distribution

\[ \sigma = 3.36 \text{ pb} \quad \eta_3 = +0.819 \]

\[ \Delta_{lb} = 0.40 \]

Cuts: \[ m_{tt} \in [2.5, 3.5] \text{ TeV} \]

Model: SM + \( g^{(1)} \)

\[ M_g = 3 \text{ TeV}, \Gamma_g = 500 \text{ GeV} \]
Search for Extra-dimensions
In models with extra space dimensions, the additional dimensions are compact.

**Particle in a box**

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In models with extra space dimensions, the additional dimensions are compact.

**Particle in a box**

**Compact extra dim**

In a box model, a particle in a box has an infinite potential well, which corresponds to a particle in an extra dimension. The particle states are equi-spaced, and the mass spectrum is given by $0, (R^{-1})\text{GeV}, 2(R^{-1})\text{GeV}, ...$ near-degenerate spectrum. All particles have an infinite tower of states. We have particles like $\gamma(1), Z(1), g(1), t(1)$, etc. at nearly the same mass $(R^{-1})\text{GeV}$. Several particles with the same quantum numbers (QN) as in the standard model (SM) and large $(R^{-1})$ but near-degenerate mass.
World with extra-dimensions

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**Mass spectrum of photon:**

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\[ q\bar{q} \rightarrow V \rightarrow t\bar{t} \]
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\[ V \equiv \gamma, \ Z, \ g, \ \gamma^{(1)}, \ Z^{(1)}, \ g^{(1)} \]
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$$gg \rightarrow t\bar{t}$$
Flat extra-dimensions and top quarks

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All KK-excitations contribute to a resonance in \( m_{t\bar{t}} \) distribution. The presence of \( Z \) and \( Z^{(1)} \) is responsible for finite polarization of top quark.
Flat extra-dimensions and top quarks

Under progress

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Ritesh Singh

New physics at LHC
For $M_{KK} = 2$ TeV, and $|m_{t\bar{t}} - M_{KK}| < 50$ GeV,

<table>
<thead>
<tr>
<th>Models</th>
<th>$\sigma(pp \rightarrow t\bar{t})$ (fb)</th>
<th>$P_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SM$</td>
<td>77.9</td>
<td>$-1.33 \times 10^{-3}$</td>
</tr>
<tr>
<td>$SM + \gamma^{(1)}$</td>
<td>185</td>
<td>$-2.55 \times 10^{-4}$</td>
</tr>
<tr>
<td>$SM + Z^{(1)}$</td>
<td>150</td>
<td>$-3.26 \times 10^{-1}$</td>
</tr>
<tr>
<td>$SM + g^{(1)}$</td>
<td>1700</td>
<td>$-6.13 \times 10^{-5}$</td>
</tr>
<tr>
<td>$SM + V_{KK}$</td>
<td>1900</td>
<td>$-5.78 \times 10^{-2}$</td>
</tr>
</tbody>
</table>
Flat extra-dimensions and top quarks

Weak resonance model, \( f_i \bar{f}_i V := A_V T^f_i + B_V Q^{f_i} ; i = L, R \)

- Flat extra-dimensions and top quarks
- Under progress

Ritesh Singh
New physics at LHC
Flat extra-dimensions and top quarks

Strong resonance model, \( f \bar{f} V := R_V P_L + L_V P_L \)

\[
\begin{align*}
\sigma_S \text{[pb]} & \\
R_V & \\
L_V & 
\end{align*}
\]
Warped extra-dimension and top quark

In universal wrapped extra dimension model, with fermion localization in the fifth dimensions, one has differing couplings of $V_{KK}$.
Warped extra-dimension and top quark

In universal wrapped extra dimension model, with fermion localization in the fifth dimensions, one has differing couplings of $V_{KK}$.

For electro weak boson:

$$f_i \bar{f}_i V := \left( A_V T_3^f_i + B_V Q^f_i \right) Q_V(f_i) ; i = L, R$$
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- can explain fermion mass hierarchy,
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- can explain $A_{FB}^b$ anomaly through $Z - Z'(1)$ mixing,
Warped extra-dimension and top quark

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- can explain fermion mass hierarchy,
- can explain \( A_{FB}^b \) anomaly thoughg \( Z - Z'(1) \) mixing,
- can explain \( A_{FB}^t \) anomaly thoughg \( g^{(1)} \) contribution at Tevatron,
Warped extra-dimension and top quark

In universal wrapped extra dimension model, with fermion localization in the fifth dimensions, one has differing couplings of $V_{KK}$.

For electro weak boson:

$$f_i f_i V := \left( A_V T^f_3 + B_V Q^f_i \right) Q_V(f_i) ; i = L, R$$

For strong boson:

$$f f V := Q_V(f_R) R_V P_R + Q_V(f_L) L_V P_L$$

- can explain fermion mass hierarchy,
- can explain $A^b_{FB}$ anomaly though $Z - Z'(1)$ mixing,
- can explain $A^t_{FB}$ anomaly though $g^{(1)}$ contribution at Tevatron,
- can be probed at LHC upto $M_{KK} = 3$ TeV through polarization.
Warped extra-dimension and top quark

$$\Gamma_{g^{(1)}} = 627 \text{ GeV}, \Gamma_{Z^{(1)}} = 75 \text{ GeV}, \Gamma_{\gamma^{(1)}} = 137 \text{ GeV}$$

(Nucl. Phys. B797, 1, (2008))
In the case of warped extra-dimension:

- there are too many free parameters for the fit.
- the ”Weak resonance model” fails
- the ”Strong resonance model” fits well with ”wrong” values of the couplings.
- more observables are needed to establish the presence of extra-dimensions.
to conclude ....
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- There are many models of physics beyond the SM.
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Many of the models will have similar collider signature.

We need a model-independent i.e. a bottom-up approach to the signatures to establish or rule out some models.
Beyond the conclusions....

- Spin measurement using azimuthal distribution (arXiv:0903.4705)
- Spin assessment in off-shell decays: A case of gluino (Under progress)
- MCMC analysis of CPV-MSSM and GHU-MSSM (Under progress)