LHC Experiments: Searches for Physics Beyond the Standard Model

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Signature-Based Searches

• If we are looking for SM Higgs bosons or have a particular model in mind, we benefit from developing a tailored event selection, but do we have to start from a model?
  – 1 physicist per model (parameter set) is not feasible
• Experimental focus includes hunting “features” in data that may correspond to a wide range of models
• This is a short tour of some well-motivated features that will be sought in early data

• In general, these searches are not quite as powerful as a dedicated search if parameters are known or constrained
Sample mSUGRA Sparticle Spectrum

SU1 mass spectrum

- $g$
- $\chi^0$
- $\chi^+$
- $h^0$
- $\chi_1^0$
- $\chi_1^+$
- $\tilde{d}_R$
- $\tilde{b}_1$
- $\tilde{t}_1$
- $\tilde{e}_L$
- $\tilde{\nu}_2$
- $\tilde{e}_R$
- $\tau_1$
Total Event Energy

• Outgoing particles in hard scatter set the event scale, which is near the mass of the particles
  – Whatever the outgoing particles in hard scatter, the subsequent decays preserve this rough event scale
• The total observed energy in the event is a good handle for pair-production of high-mass new particles $O(\text{TeV})$

• Focus on robust definition of event energy
  – $M_{\text{eff}}$ uses physics objects
  – $\Sigma E_T$ uses total energy in calorimeter (incl. pileup, etc.)
Example of Meff in SUSY Searches

After simple pre-selection, requiring 4 high-pT jets and large missing ET
Resonances in Leptons, Photons, Jets

- We heard arguments for higher-mass versions of SM particles: some of these correspond to resonances (invariant mass peaks) of simple objects
- Reconstruction of resonances is straightforward, if we have 4-vectors for all particles involved
Origin of Resonances in BSM Models

• Myriad possibilities as suggested earlier: higher-mass partners of SM particles needed for loop cancellation
  – $Z'$, $W'$, $t'$, KK towers confined in extra dimensions

• But what if the decay products are invisible? This is the natural case if a quantum number is conserved and the lightest particle with a non-zero value interacts weakly
  – SUSY: $pp \rightarrow X + \tilde{\ell}_R^+ \tilde{\ell}_R^- \rightarrow X + \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$
  – 4th-gen lepton: $X + \ell_4^+ \ell_4^- \rightarrow X + \nu_{\ell_4} W^+ \nu_{\ell_4} W^-$

• In this case the simple invariant mass will not work because we do not have a 4-vector for the invisible particle
Transverse Mass and Friends

• How can we reconstruct two-body decay, where one particle escapes undetected? \((W \rightarrow \text{en} \text{ or } \tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma)\)
  
  – Define transverse mass for massless decay products

\[
m_T^2 = 2E_{T1}E_{T2}[1 - \cos(\Delta \phi)]
\]
Modified Transverse Mass

- If two particles decay to invisible daughters, how to assign the correct missing energy to each side?
- Consider again $pp \rightarrow X + \tilde{l}_R^+ \tilde{l}_R^- \rightarrow X + l^+ l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$

$$m_{\tilde{\ell}}^2 \geq M_{T2}^2 \equiv \min_{p_1+p_2=p_T} \left[ \max \left\{ m_T^2(p_{Tl^-}, p_1), m_T^2(p_{Tl^+}, p_2) \right\} \right]$$

Lester & Summers, hep-ph/9906349

Must know $m(\chi)$ first to get an endpoint this clean!
Kinematic Edges for Mass Determination

Example: $\tilde{\chi}_2^0 \rightarrow \ell^\pm \ell^\mp \rightarrow \tilde{\chi}_1^0 \ell^\pm \ell^\mp \rightarrow \tilde{G} \gamma \ell^\pm \ell^\mp$

For full chain reconstruction, see Hinchliffe & Paige PRD 60, 095002 (1999)
Focusing Search in Specific Subsamples

- Preselection helps reduce overwhelming SM background
  - Requiring large missing $E_T$ helps focus on high mass
- Ideally, we could search for all of these edges and resonances in many specific regions of preselection: MET + jets, leptons+MET, leptons+jets
- Combinatorics can be overwhelming. In each sample:
  - Calculate trigger efficiency
  - Calculate background contributions
  - Select events and compare with expectations
General Searches using MUSiC Program

- Similar programs at H1, D0, CDF experiments
- Counts events in each of several high-p_T object classes (1µ1jet, 1e2jetMet, etc.) and compare to SM expectation
- Challenge is to describe completely the SM backgrounds for all signatures at once!
- Consider several distributions in each event class
  - Scalar pT sum of all high-p_T objects
  - Invariant mass (or transverse mass) of all objects
  - Missing transverse energy
- “3σ” discrepancies are “interesting” and will be followed up with a more careful study
Challenges for “Obese” Higgs

• Physical (true) width of Higgs increases substantially

\[ \Gamma_H = (0.5 \text{ TeV}) \left( \frac{m_H}{1 \text{ TeV}} \right)^3 \]

– With low production rate, difficult to pick it out of the signal + background distribution

• Is this still a particle, or is it a resonance in the “scattering” of its decay products?

• Width is even more important than detector resolution for particles at 500 GeV: \( \delta p_T/p_T = 6\% (\mu), 10\% (e/\gamma) \)
We heard the unitarity would seem to be violated in WW scattering at the 1 TeV scale, so measure this scattering

“Unitarizing” scattering can lead to WW resonances

How can we measure the invariant mass of the WW system if there are two neutrinos? Maybe we can select events where one W decays hadronically
Example of different possible resonances that may be seen in scattering (signal only shown here)