Methods of Experimental Particle Physics

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Lecture #26
Today

• Selected “physics at colliders” topics
  • Mostly some popular scenarios
  • We will briefly discuss their motivation and learn some of the jargon and main implications
CMS: Physics Potential

- CMS Physics Potential:
  - Higgs boson ("God’s particle")
  - Supersymmetry
    - May hold keys to explaining Dark Matter
  - Shed light on unification of forces (strong and EW)
  - Extra Space Dimensions and Gravitons (inspired by string theory)
  - Finding the unexpected:
    - Arguably the most likely outcome
    - ...and the most exciting too!
Higgs: Why Do We Need It?

- Proposed to explain masses of bosons:
  - In good renormalizable theories bosons must be massless
  - LEP collider has directly measured masses of W and Z and they are ~100 GeV, so they are hardly zero!
  - Higgs potential resolves that and gives masses to particles
    - As a result, the world around us is not symmetrical, but the theory explaining it is
    - Sounds like a trick?
- Many reasons why this is likely not the full story:
  - Large divergences in taking SM towards Plank scale (hierarchy problem)
  - EWSB potential comes completely out of the blue, no explanation...

Nice illustration from Gordy K.:
Symmetrical equation:
- \( x+y=4 \)
Solutions \( (x,y) \):
- Symmetrical: \((2, 2)\)
- And asymmetrical: \((1,3), (4,0),(3,1)\)...
Higgs: Can It Not Be There?

• Forget theorists and their smarty pants hierarchy problems…

• Here is a real deal:
  • Despite some new problems, SM (with Higgs) is still a pretty good model that passed many tests to enormous precision
  • Higgs regulates some striking divergences in SM
  • Consider WW scattering, take out Higgs and probability of WW→WW is greater than one above 1 TeV!
  • LHC will either see Higgs or, if it is not there, will see whatever is playing its role
Higgs Channels at the LHC

- Five main production modes and up to seven ways to decay (depends on the unknown Higgs mass):
  - Have to explore at least 35 different analyses
    - Actually much more as e.g. Z can decay to ee, \( \mu \mu \), \( \tau \tau \), neutrinos or quarks, \( \tau \)-leptons can decay to electron, muon or a hadronic jet
    - Some are impossible to do due to huge backgrounds, \( gg \rightarrow H \rightarrow bb \)
Higgs Today

- Almost every non-standard model of new physics has a SM-like Higgs boson
- Distinguishing these models from SM requires precision study of Higgs parameters
Higgs Measurements

• Almost every non-standard model of new physics has a SM-like Higgs boson
• Distinguishing these models from SM requires precision study of Higgs parameters

\[ \mu = 0.80 \pm 0.14 \]

- \( H \rightarrow bb \) (VH tag)
- \( H \rightarrow bb \) (ttH tag)
- \( H \rightarrow \gamma\gamma \) (untagged)
- \( H \rightarrow \gamma\gamma \) (VBF tag)
- \( H \rightarrow \gamma\gamma \) (VH tag)
- \( H \rightarrow WW \) (0/1 jet)
- \( H \rightarrow WW \) (VBF tag)
- \( H \rightarrow WW \) (VH tag)
- \( H \rightarrow \tau\tau \) (0/1 jet)
- \( H \rightarrow \tau\tau \) (VBF tag)
- \( H \rightarrow \tau\tau \) (VH tag)
- \( H \rightarrow ZZ \) (0/1 jet)
- \( H \rightarrow ZZ \) (2 jets)

\[ \text{Best fit} \, \sigma/\sigma_{\text{SM}} \]

\[ \text{Combined} \, \mu = 0.80 \pm 0.14 \]

\[ m_H = 125.7 \text{ GeV} \]

\[ p_{\text{SM}} = 0.94 \]

CMS Preliminary
By Decay Mode

• Arrange by:
  • Left: higgs decay modes
  • Right: production mechanism
Couplings

- Consider a hypothetic model where all higgs couplings to fermions are like SM ones multiplied by $k_F$
  - Same for bosonic, but $k_V$
- You get exactly SM if both $k$’s are equal to one
  - Plot combined likelihood to see what the data likes
Uncertainties Still Large

• Uncertainties on the couplings even in this very constrained scenario are of the order of 30% for both fermionic and bosonic higgs couplings
  • Models with Higgses with additional couplings (new decays) or moderately modified couplings are more than possible
• If you want to get it down to a 3% uncertainty, you need roughly 100 times more data:
  • 20 ifb -> 2,000 ifb
• 0.3% uncertainty requires additional two orders of magnitude
SuperSymmetry (SUSY)

- New symmetry:
  - fermions ↔ bosons
  - Doubles number of particles

- Almost “beautiful”:
  - Hierarchy problem resolved and Higgs mass stabilized
  - LSP is a candidate for dark matter
  - Unification possible
  - More Higgses: H, h, A, H+/-

<table>
<thead>
<tr>
<th>Particle</th>
<th>Super-partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>e, ν, u, d</td>
<td>e̅, ν̅, u̅, d̅</td>
</tr>
<tr>
<td>γ, W, Z, h</td>
<td>( \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm, \tilde{\chi}_1^0, \tilde{\chi}_2^0 )</td>
</tr>
</tbody>
</table>
Many Faces of SUSY

• Ain’t easy to find, e.g. SUSY:
  • Many parameters, different symmetry breaking scenarios and particle mass spectra
  • Experimental signatures vary wildly
• Benchmark “model lines”

<table>
<thead>
<tr>
<th>Scenario</th>
<th>LSP</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>(\tilde{\chi}^0_1)</td>
<td>leptons, jets+MET</td>
</tr>
<tr>
<td>mSUGRA</td>
<td>(\tilde{\chi}^0_1)</td>
<td>leptons, jets+MET</td>
</tr>
<tr>
<td>High (\tan \beta)</td>
<td>(\tilde{\chi}^0_1) (\tilde{\nu}_1)</td>
<td>light stop/stau, many taus in final state</td>
</tr>
<tr>
<td>RPV</td>
<td>varies</td>
<td>more leptons, less MET</td>
</tr>
<tr>
<td>GMSB</td>
<td>G</td>
<td>Leptons/photons+ MET</td>
</tr>
<tr>
<td>AMSB</td>
<td>(\tilde{\chi}^\pm_1) (\tilde{\chi}^0_1)</td>
<td>special treatment</td>
</tr>
</tbody>
</table>

• Or even better, look for signatures:
  – Bumps in the mass spectrum (new particles): e.g. Higgs(es)
  – Excess of events over SM prediction: e.g. tri-leptons
Supersymmetry

• **Low mass SUSY**
  • Means that super-particles should not be too heavy
  • The usual arguments why we want SUSY light:
    • In “normal” SUSY the dark matter candidate has to be fairly light to fit measured CMWB (not more than some hundreds of GeV)
    • The elegant order by order cancelation of Higgs divergences happens if SUSY particles requires them to be light
      • Otherwise heavy (or heavier?) fine-tuning required
Old Fashion Plots

- mSUGRA
- SuperGravity inspired modification of SUSY
Simplified Models
Electroweak Production

• Much less constrained, but still less and less room is left for simple SUSY
EXTRA DIMENSIONS
RS and TeV\(^{-1}\) Models

- Randall-Sundrum Model - a vigorous solution of hierarchy problem:
  - Small extra spatial dimensions
  - Curved bulk space: curvature \( \kappa \)
  - Graviton propagates in the Bulk
  - All other particles live on SM “TeV” brane
  - Coupling constant depends on \( \kappa / M_{PL} \)
    - Controls width of KK graviton resonances

- TeV\(^{-1}\) Extra dimension Models
  - Very similar to RS, but additional particles in the bulk (gauge bosons)
    - Many KK towers
  - Running of the couplings changed
    - Lowers GUT scale
  - Nearly equal energy level spacing of KK states
  - Natural to EW scale ED size \( \sim 1/\text{TeV} \)
  - But gravity is left out
Large Extra Dimensions

- Large flat Extra-Dimensions (ADD model)
  - Could be as large as a few μm (n = 1) or as small as a fm (n = 6)
  - Bulk only accessible by gravity
  - SM particles restricted to 3D brane
    - Gauss’ Law: $M_{PL}^2 = M_5^{2+n} R^n$
    - $M_5 \sim O(1)$ TeV $\rightarrow$ Hierarchy problem translated from UV to IR
  - Winding modes with energy spacing 1 meV – 100 MeV
    - Can’t resolve experimentally, look for enhancement in the spectrum
- Virtual Graviton Exchange $\rightarrow$ modifies (e.g. dilepton) mass continuum
- Direct production also possible: look for mono-jet or mono-photon signature (not in this talk)
Search with Dijets

- $L = 1.1 \text{ fb}^{-1}$
- Search for generic bumps in dijet spectrum
  - Worse resolution and larger backgrounds but much larger rate!

- Set limits on:
  - $Z'$, $W'$, RS graviton
  - $q'$, technirho, contact interactions
HIDDEN SECTORS
TeV Scale Dark Matter

PAMELA and Fermi (and now AMS) observe rising positron fraction towards higher energy:

• Unknown pulsar? Cosmic rays interacting with giant molecular clouds?
• Or heavy dark matter annihilation in the galactic halo with a large x-section:
  • Light dark photon $\gamma_D$: an attractive long-distance force between slow WIMPs
    • Sommerfeld enhancement
  • $\gamma_D$ can weakly couple to SM via kinetic mixing with photon
  • As no antiproton excess observed, $M(\gamma_D) \lesssim O(1 \text{ GeV})$

![Positron fraction measured by the Fermi LAT and by other experiments with error bars and the total uncertainty is shown as a shaded band.](arXiv:1109.0521v1)
NMMSM Phenomenology

• Modified superpotential:
  • MSSM: $\mu H_u H_d$
  • NMSSM: $\lambda S H_u H_d + \frac{1}{3} \kappa S^3$

• NMSSM less fine tuning and solves $\mu$-problem:
  • $\mu$ is generated by singlet field VEV and naturally has EW scale

• More complex Higgs sector:
  • 3 CP-even higgses $h_{1,2,3}$, 2 CP-odd higgses $a_{1,2}$
  • $a_1$ is hidden as it is mostly singlet and weakly couples to SM particles except through $h_1$

• Experimentally relevant decays:
  • $h_{1,2} \rightarrow a_1 a_1$ (Branchings depend on mixing)
  • $a_1 \rightarrow ff$ (standard higgs hierarchy)
    • Couplings are weak but it has to decay somewhere
Light Dark Sectors and Higgs

- **NMSSM:** $pp \rightarrow h_{1,2} \rightarrow a_1 a_1 \rightarrow 4\mu$
  - Either $h_1$ or $h_2$ (or both) can decay to $a_1 a_1$, BR depends on the singlet component
  - Production cross-section for $h$ and BR highly model dependent

- **Dark SUSY with light dark photons:**
  - $pp \rightarrow h \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D \rightarrow 2n_D + 4\mu$
  - Similar signature, but softer dimuons and missing energy
A “Long Living” Example

• A separate hidden strongly interacting sector coupling to SM only through a heavy $Z'$
  • Visible higgs(es) can naturally mix with the hidden higgs
    • If $Z'$ is heavy, “hidden pions” can easily have decay lengths $O(0-100 \text{ cm})$
      ▫ $Z$-like decay hierarchy for new hidden bosons
        • One can have models with higgs-like decays too

Strassler, Zurek, PLB 661 (2008)

• Striking signatures, relatively easy to look at
Hidden Sectors Search Strategies

- Produce something that links visible and hidden sectors and look for evidence of new hidden states:
  - In the dark SUSY the “stable” visible LSP has no choice but to decay to hidden states even if small couplings
    - If we can make the LSP either through squark/gluino production or Higgs, we can see its decay products
  - In the NMSSM new higgs states can have very weak coupling to SM, but appreciable coupling to the SM-like higgs due to mixing
    – look for exotic higgs decays
    - Similar story for the “long living” example model
- Brute force: make hidden sector particles
  - Because of typically small couplings, need high luminosity and/or super clean final states
Dark Photons in SUSY Cascades

• SUSY with squarks/gluinos accessible by LHC:
  ▪ MSSM LSP is a neutralino decaying to dark neutralino and light $\gamma^\text{dark}/h^\text{dark}$
  ▪ MSSM LSP is a squark decaying to q and light dark fermion and $\gamma^\text{dark}/h^\text{dark}$

• Dark photons decay as SM $\gamma$
THANKS!