Simple and Complex Objects: Strategies for Event Reconstruction at the LHC

Lecture III:
Combining Objects- Top, Higgs, SUSY

Marjorie Shapiro
UC Berkeley/LBNL
August 12
**Outline**

- **Top**
  - Production and Decay
  - Analysis Strategy
  - Object 7: b-quark jets
  - Mass Reconstruction

- **Higgs**
  - Production Modes
  - Decay Modes
  - Object 8: Photons
  - Some example searches

- **SUSY**
  - Why?
  - Production
  - Analysis Strategy
  - An example analysis
The Top Quark

- First discovered at Tevatron more than 10 years ago
  - But still have only isolated hundreds of events
- What do we know?
  - Mass: $171.4 \pm 2.1$ GeV (CDF/D0 combined)
  - $\sigma_{\text{Tevatron}}: 7.3 \pm 0.5\,(\text{stat}) \pm 0.5\,(\text{sys}) \pm 0.4\,(\text{lumi})\,\text{pb\,(CDF)}$
    
    $$8.6^{+1.3}_{-1.7}\,(\text{stat}) \pm 1.1\,(\text{sys}) \pm 0.6\,(\text{lumi})\,(\text{D0})$$
  - BR ($t \rightarrow Wb$): $> 0.61$ 95% CL (CDF)
- LHC will produce 1 ttbar pair per second
  - Opportunity for precision measurements
- Excellent sample for testing complex reconstruction strategies
Top Production

- Strong Production: Tops are pair produced
  - (EW production of single top also possible: $W \rightarrow tb$)
- At Tevatron, production suppressed but to high top mass (small parton luminosities)
- S:B much better at LHC

90% gg, 10% qq at LHC
15% gg, 85% qq at Tevatron
Top Decay

- $t \rightarrow Wb$ BR 100% in Standard Model
- Top lifetime $\approx 5 \times 10^{-25}$ sec:
  - Decays before it hadronizes
- Top pair production gives:
  - $l + 4\text{jets}$
  - $\tau$
  - $2l + 2\text{jets}$
  - 6 jets
  - Fully hadronic: 4/9
  - Single lepton: 4/9
  - Dilepton: 1/9

\[\text{Diagram showing different decay channels.}\]
• Top pairs yield 6 high $P_T$ objects

• Separate search strategies for dilepton, single lepton and all-hadronic modes
  - Dileptons clean, but 2 $\nu$ so full reconstruction of mass not possible
  - Single lepton: Good S:B. This is the golden channel
  - All-hadronic: Must separate signal from QCD background: possible with b-tagging (more later)
Top Analysis Strategy

• Goal: Maximize top signal while reducing QCD background
• Top decays products central and at high $P_T$
  – Typical Tevatron cuts: $P_T > 15$ GeV and $\eta < 2$
• Di- and single lepton channels have missing $E_T$
• All channels have large total energy in our objects:
  – Define $H_T = \sum E_T$ over the reconstructed objects
• Two b-jets in final state: identification of jets from b-quarks greatly reduces background
Object 7: Jets Produced from b-quarks

- Characteristics of B decays:
  - B lifetime long: $c\tau \sim 460 \mu$
  - Semileptonic BR 10% per lepton species

- Two methods of b-tagging
  - Displaced vertex (or track from it)
  - “Soft” leptons close inside jets

- Vertex tagging has higher efficiency and better purity
  - But can combine both techniques
B-Tagging From Secondary Vertices

- Study track impact parameter
- Two options:
  - Secondary Vertex Finding: 2 or more tracks consistent with a single vertex
  - Jet Probability: Combined likelihood that all tracks come from primary vertex

Details of algorithm discussed in Aaron Dominguez's talk Monday
b-Tagging Performance Depends on Background

- Charm also long-lived: less rejection
- Performance $E_T$ dependent
Reconstructing Top in Single Lepton Channel

- Sample contains lepton, missing energy and 4 jets
  - 2 jets reconstruct to $W$ mass
  - 2 jets are $b$-jets
  - $W+b$-jet reconstructs to Top

- Many possible combinations: Can apply above constraints to pick right matching or use all combinations with appropriate probabilities

- Signal can be observed without b-tagging if strong $H_T$ cut applied
  - b-tagging reduces combinatorial background
With b-tagging, Top dominated sample can be selected at Tevatron

**Single b-tag and HT>200 GeV**

**Double Tag**
Using b-tags to Select Correct Combination in Top Events

Signal only: All combinations of jets to form 2 Top Decays

- b-tagging increases probability of selecting correct combination: improved resolution
Top at the LHC

3 jet invariant mass

No b-tagging

Cut on W Mass

W+Jet background

After Requiring 2 b-tags:
Higgs Production at LHC
(reminder from Sally Dawson's talk)

gluon fusion

vector boson fusion

W(Z)-strahlung

Each channel has its own signature
Decays the SM Higgs

- Higgs decay modes depend on Higgs' mass
- Couples to heaviest accessible particles
- Some modes easier to observe than others
- Greatest experimental difficulties in the low mass region
Low Mass Higgs: \( h \rightarrow \gamma \gamma \)

- Direct Production has largest rate
- But cannot see dominant \( h \rightarrow bb \) decay above background
- Photon decay mode rare, but very good mass resolution possible (ECAL design critical)
- Will require every trick in the book
Object 8: Photons

- Use same variables as for electron selection, with tighter cuts
  - Unconverted photons have track veto
  - Converted photons independently analyzed by looking for the second track
  - Emphasis on shower shape variables
    - Photons shower later than electrons
    - $\pi^0$ decay to $2\gamma$ so probability of early shower twice as large
- Isolation is critical

ATLAS and CMS have different emphasis due to different detector designs, but overall performance for Higgs similar
Efficiency and Background Rejection for Higgs Photons

Atlas: Efficiency: Low and High Luminosity

CMS

Conversion Probability vs $\eta$

Atlas Jet Rejection

CMS

Pt Tracks/Et ECAL
• Even best particle ID cuts can't remove real photons
• Background from QCD production of di-photons large
  - Must subtract large background statistically

ATLAS: 100 fb$^{-1}$
Other Higgs Modes: See Sally's Talk for More

\( M_{bb} \) for \( tt\)-higgs Events

\( M_H = 100 \text{ GeV} \)

Issues:
- \( bb \) peak close to threshold
- uncertainty in rate
- large background
- difficult, busy events

\( M_{ee\mu\mu} \) for \( ZZ^* \) Events

\( M_H = 130 \text{ GeV} \)

Clean Signal, little background
Higgs Sensitivity vs Mass

3 Years Initial Luminosity Running
Supersymmetry (SUSY)

- Partner for every know particle
  - fermions have spin 0 partners
  - bosons have spin $\frac{1}{2}$ partners
- Theoretically favored extension to SM
  - Solves hierarchy problem (sparticle and particle loops cancel)
  - Provides Dark Matter candidate
  - Required by String Theory
- Requires 5 Higgs bosons (h, H, A, H+-)
If SUSY the source of EWSB, then expect sparticles at the TeV Scale

- Since each know particle has a partner, large number of sparticles to be discovered
- Spectrum of masses very model dependent
- In general, strongly interacting particles the heaviest: they decay to gauginos
- Lightest SUSY particle (LSP) stable (or quasi-stable)
  
  Signals with apparent missing momentum
How Fast Can SUSY be Found?

- Plot shows reach in SUSY space
- Solid regions not allowed
- Hatched region ruled out by LEP
- Contours in luminosity for specified squark and gluino masses
- Example: 100 pb-1 discovers gluino of 1 TeV

We must be ready for Physics on Day 1!
How SUSY Might First Be Observed

- Select events $\geq 4$ jets and missing $E_t$
- $M_{\text{eff}}$: Sum of 4 jet and missing $E_t$'s
- Peak correlates well with SUSY mass scale
- Example has Susy masses $\sim 700$ GeV
- Signal characteristic of any model with new particles (strongly coupled) at large mass
If SUSY is Found, Will Require Many Measurements to Constrain Model

- Different SUSY models will have different phenomenology
  - Must explore different regions in SUSY parameter space
- Basic Principle: Work down decay chains
  - Measure masses and mass differences
  - Test universality among generations
Using Kinematics to Constrain SUSY models

- As an example, take the squark decay to $q\, e^+\, e^-$
  - Dilepton mass has endpoint at $\chi_2-\chi_1$ mass difference
- SUSY is pair produced: For event selection require:
  - $2$ isolated leptons (opposite charge, same species)
  - $2$ high Pt jets
- Plot dilepton invariant mass

Clear kinematic bound observed in mass spectrum

Many other examples explored
Many Other Things are Possible Besides SUSY

- We don't know what causes EWSB
- No reason to believe SUSY is right
- Many other possibilities for new phenomena
  - New W or Z
  - WW, ZZ resonances (a la technicolor)
  - Extra Dimensions

But whatever we find, it will decay into the particles of the SM and its backgrounds will be the SM
A Mini-Black Hole as Simulated in the ATLAS Experiment

Are you ready to find this?
Conclusions

• Clean samples of the fundamental objects (jets, charged leptons, neutrinos, photon, b-jets) can be reconstructed as LHC

• Selection criteria must be optimized for relevant physics

• Simple objects can be combined to find more complex ones: W, Z, Top, Higgs, SUSY, Black Holes ...

• There's an exciting new world about to open up

You will all be part of it!