Collider techniques

for New Physics searches at the LHC

Lian-Tao Wang
University of Chicago

TASI 2011
Outline:

- Basics:
  - Rate estimates. SUSY example.
  - Kinematical variables:
    - Resonance, $M_T$, edge, endpoint. SUSY example.

- Jets.
  - Factorization, IR safety.
  - Nature of QCD radiation.
  - Jets: algorithm, shape and substructure.
  - Monte Carlo with QCD.
Before we start

- This is a huge subject.

- Focus more on intuitive understanding, generic feature, less on specifics.

Hopefully, this serves as the starting point of your further study.
Basics
Two possible ways of discovery:

- **Rate:** final states with more energetic (hard) objects, for example:
  
  \[ W^\pm \rightarrow \text{charged leptons} \ell^\pm + \nu + \bar{\nu} \]  

  Neutrino stays undetected:  

  \[ \not \! E_T \]

  \[ Z \rightarrow \ell^\pm + \bar{\nu} + \nu, \text{charged lepton} \]

  \[ \text{rate estimate} \geq 2 \text{ hard jets} \]

  \[ 10^5 \text{ Hz} \]

  \[
  \begin{array}{ll}
  \text{in addition} & \\
  \text{hard jet} & 10^2 \text{ Hz} \\
  \text{or } E_T \gtrsim 10^2 \text{ GeV} & \sim 10^2 \text{ Hz} \\
  \text{or 1 lepton} & 10^2 \text{ Hz} \\
  \text{or 2 leptons} & 1 \text{ Hz} \\
  \text{or } 2\ell = e^\pm + \mu^\pm & 10^{-4} \text{ Hz} \\
  \end{array}
  \]

  \[ \geq 3 \text{ jets} + \not \! E_T \]

  \[ \geq 2 \text{ jets} + (\geq 1\ell) + \not \! E_T \]

- **Special kinematical features, resonances, edges, ...**
Rates: production.

• Schematics of production at hadron colliders.

• Dominated by parton densities and thresholds (mass and cut).

\[
\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}
\]

Partonic cross section
Parton Distribution Function

\[ x = \frac{p_{\text{parton}}}{P_{\text{proton}}} \]
Parton luminosity

- The cross section can be written as

\[
\sigma = \sum_{a,b} \int d\tau \frac{dL_{ab}}{d\tau} \hat{\sigma}
\]

parton luminosity \hspace{1cm} \tau = \frac{\hat{S}}{S} = x_1 x_2

\[
L_{ab}(\tau) = \frac{1}{1 + \delta_{ab}} \int_{\tau}^{1} \frac{dx}{x} \left[ f_a(x) f_b \left( \frac{\tau}{x} \right) + f_a \left( \frac{\tau}{x} \right) f_b(x) \right]
\]

Very sharp falling

\[\propto \frac{1}{\tau^{3-3.5}}\]

Falls by a factor of 10 for every 600 GeV

Production dominantly on threshold
7 TeV vs 14 TeV

\[ \frac{P.L.[7 - TeV]}{P.L.[14 - TeV]} \]

\[ \sqrt{s - \text{hat}} \]

TeV

\[ 0.50 \]

\[ 0.70 \]

\[ 0.01 \]

\[ 0.1 \]

\[ 1 \]

\[ qq, 7\text{TeV} \]

\[ gg, 7\text{TeV} \]
Why is it hard to discover TeV-scale new physics at the LHC

- $p\ p$ collider, “prefers” to produce lighter states.
- Production rates scale roughly as $\sigma_{pp\to M} \sim \frac{1}{M^6}$
- TeV new physics $M_{NP} \sim 5 - 10 \times M_{SM(W,Z,t,...)}$
  - $\sigma_{SM} \geq 10^6 \times \sigma_{NP}$
- Dominated by QCD: A messy environment.

- Need:
  - Precise knowledge of the SM processes.
  - Anticipation of potential new physics states and their properties.
Phase space

- General phase space factor:

\[ d \Pi_n = \Pi_f \left( \int \frac{d^3 p_f}{(2\pi)^3} \frac{1}{2E_f} \right) (2\pi)^4 \delta^{(4)}(p_a + p_b - \sum p_f) \]

- One additional final state particle

\[ \sim \text{an additional factor of} \ \frac{1}{16\pi^2} \]

- For example

\[ d \Pi_2 = \frac{1}{4\pi} \frac{1}{2} \lambda^{1/2} (1, m_1^2/\hat{s}, m_2^2/\hat{s}) d... \]

\[ d \Pi_3 = \frac{1}{(4\pi)^3} \lambda^{1/2} (1, m_1^2/m_{23}^2, m_2^2/m_{23}^2) 2|\vec{p}_1|dE_1d... \]
Rate also depends on

- Coupling constants
  - More final state particles, higher power of coupling constants.
- QCD process dominates over weak processes.
- Singularities (enhancements) of matrix elements
  - Resonances.
- Collinear and soft regime...
Final state Objects

- Colored particles: cluster of hardonic energy, jet
- Leptons: electron, muon
- Photon
- Heavy flavor: bottom (charm)
- Missing energy (MET)
From SM processes

• QCD: quark, gluon $\rightarrow$ jets

• QCD heavy flavor: b, c.

• Z: $Z \rightarrow (q\bar{q}, \ell^+\ell^-, \nu\bar{\nu}) \rightarrow$ jets, lepton pair, $E_T$

• W: $W^\pm \rightarrow (q\bar{q}', \ell^\pm\nu) \rightarrow$ jets, lepton+ $E_T$

• Top: $t \rightarrow b + (W \rightarrow q\bar{q}' \text{ or } \ell\nu)$

• Tau lepton: narrow jet(s), lepton.
SM Rates at 7 TeV:

- **QCD di-jet:** $p_T^j > 100$ GeV, 300 nb
- **Heavy flavor:** $b\bar{b}$, $p_T^b > 100$ GeV, 1 nb
- **$W^\pm...$:** $W^\pm \rightarrow \ell \nu$, 14 nb
  - $W^\pm (\rightarrow \ell \nu) + 1 \text{ jet}$, $p_T^j > 100$ GeV, 70 pb
  - $W^\pm (\rightarrow \ell \nu) + 2 \text{ jet}$, $p_T^j > 100$ GeV, 2 pb
  - $W^\pm (\rightarrow \ell \nu) + 1 \text{ jet}$, $p_T^j > 200$ GeV, 5 pb
- **$Z + ...$:** $Z (\rightarrow \ell^+ \ell^-)$, 1.4 nb
  - $Z (\rightarrow \ell^+ \ell^-) + 1 \text{ jet}$, $p_T^j > 100$ GeV , 10 pb

New Physics: $\sim$ pb
SM rates at 7 TeV

• **di-boson:**

\[ W^+W^- : 30 \text{ pb} \]

\[ W^+W^- + 1 \text{ jet, } p_T^j > 100 \text{ GeV, } 2 \text{ pb} \]

\[ \text{di-lepton+jet+MET } \sim 0.1 \text{ pb} \]

\[ W^+Z : 7 \text{ pb}, W^-Z : 3.7 \text{ pb} \]

\[ \text{tri-lepton + MET } \sim 0.1 \text{ pb} \]

• **top pair:**

160 pb! Always has 6 objects.

\[ t\bar{t} \rightarrow bbW^+W^- \rightarrow bbj\ell\nu, b\ell\nu\ell\nu, bbjjjj \]

• (MET+lepton+Jet 40%, Heavy flavor...)

• Looks like new physics, pair production of a massive particle followed by a decay cascade.
Simple kinematical features
Resonance

\[ \frac{d\hat{\sigma}}{dm_{ee}^2 \, dp_{eT}^2} \propto \frac{\Gamma_Z M_Z}{(m_{ee}^2 - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \frac{1}{m_{ee}^2 \sqrt{1 - 4p_{eT}^2/m_{ee}^2}} \frac{d\hat{\sigma}}{d \cos \theta^*}. \]

Breit-Wigner
Almost a resonance: $m_T$

\[
m_{e\nu T}^2 = (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2
\approx 2\vec{p}_{eT} \cdot \vec{p}_{\nu T} \approx 2E_{eT}E_T (1 - \cos \phi_{e\nu}),
\]

\[
0 \leq m_{e\nu T} \leq m_{e\nu}.
\]

\[
\frac{d\hat{\sigma}}{dm_{e\nu}^2 \, dm_{e\nu,T}^2} \propto \frac{\Gamma_W M_W}{(m_{e\nu}^2 - M_W^2)^2 + \Gamma_W^2 M_W^2} \frac{1}{m_{e\nu} \sqrt{m_{e\nu}^2 - m_{e\nu,T}^2}}.
\]

“Jacobian peak”
New physics example: zprime

\[ \sigma (pb) \]

- LHC 7 TeV
- Tevatron
- LHC 14 TeV

\[ M_Z \ (GeV) \]
Complicated New physics signals

Partners:
New physics states with similar interactions to those of the Standard Model particles, such as the superpartners in Supersymmetry.
TeV Supersymmetry (SUSY)

- Supersymmetry. \(|\text{boson}\rangle \Leftrightarrow |\text{fermion}\rangle\)

- An extension of spacetime symmetry.

- New states: “Partners”

- Couplings relate to SM interactions via supersymmetry.

\[ \begin{array}{ccc}
\text{spin} & \text{spin} \\
gluon, g & 1 & \text{gluino: } \tilde{g} & 1/2 \\
W^\pm, Z & 1 & \text{gaugino: } \tilde{W}^\pm, \tilde{Z} & 1/2 \\
quark: q & 1/2 & \text{squark: } \tilde{q} & 0 \\
\text{SM} & \text{(super)partner} \\
\end{array} \]

- Couplings relate to SM interactions via supersymmetry.

\[ \sim \text{ same strength.} \]

SUSY production

- SUSY or SUSY-like theories.
  - NP: partners.

- Discrete symmetry: $\mathbb{Z}_2$ superpartners are odd.
  - Pair production.
  - Neutral stable superpartner, missing energy, in the end.
Production of colored superpartners

- Squark and gluino production.
Colored-uncolored mixed production.

- Intermediate rate.
- Could be important to measuring the identity of the weakly interacting particles.
Production of electroweak-inos

- Electroweak-inos: Bino, Wino, Higgsino.
  - Neutral.
    - Mix after EWSB. 4 neutralinos.
  - Charged.
    - Mix after EWSB. 2 Dirac charginos.
- Smaller (1/100) rate. Weak coupling. From q-qbar initial states.
Dominated by the production of colored states.
Similar pattern for other scenarios. Overall rates scaled by spin factors.
Decay: gluino and squark (colored)

• Gluino always decays into squark (on or off-shell).
  – Glunino -> squark + Jets

• Squark decay.
  – Jet +
    • To gluino, then go through off-shell squark.
    • To chargino or neutralino.
Chargino and neutralino decay.

- To W or Z (maybe Higgs.)

- Lepton (suppressed by W/Z-> lepton BR.)
  - 1 or 2 leptons.

- Jets (softer, constrained by W and Z mass).
Long decay chains.

- Putting the pieces together.
- Many channels, many final states.

\[
\begin{align*}
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1q_2\tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1q_2[\tilde{N}_i] \rightarrow q_1q_2[Z]\tilde{N}_0 \rightarrow q_1q_2q_3q_4\tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1q_2[\tilde{C}_i] \rightarrow q_1q_2[W]\tilde{N}_0 \rightarrow q_1q_2q_3q_4\tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1q_2[\tilde{N}_i] \rightarrow q_1q_2[Z]\tilde{N}_0 \rightarrow q_1q_2\ell^+\ell^-\tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1q_2[\tilde{N}_i] \rightarrow q_1q_2q_3q_4(\ell^+\ell^-)\tilde{N}_0
\end{align*}
\]
Examples of counts: organized by lepton multiplicity.

- **Trilepton.**

  
  \[
  \begin{align*}
  \tilde{g} &\rightarrow \tilde{q} \rightarrow \tilde{N} \rightarrow \tilde{N} \\
  \tilde{g} &\rightarrow \tilde{q} \rightarrow \tilde{C} \nonumber \rightarrow \tilde{N} \\
  \tilde{g} &\rightarrow \tilde{q} \rightarrow \tilde{C} \nonumber \rightarrow \tilde{N} \\
  \end{align*}
  \]

  - 4-lepton possible with two 2-lepton chains.
    - Generic for on-shell slepton
    - Suppressed by Z lepton BR without on-shell slepton.
Same sign di-lepton (Majorana gluino.)

• A very useful channel.
  – From gluino decay.
    • Charge: $++ = --$
  
  
  – From same sign squark (possible for pp collider.)
    • Charge: $++ > --$

  
  – From gluino+squark associate production.
    • In between.
Simple rules.

- Typically, there are many channels through which a superpartner can decay.
- 2 body mode (almost) always dominate over 3-body mode.
  - A factor $1/100$ suppression from phase space.
- Charge channel often bigger than the neutral channels.
- Higgsino prefers 3$^{\text{rd}}$ generation.
- Wino prefers left-handed.
- Typically, only one or two modes dominates.
  - Signature easier to understand.

Exercise:
Choose a SUSY spectrum, such as one of the so called SNOWMASS Points and Slopes (SPS) benchmarks, [http://arxiv.org/abs/hep-ph/0202233](http://arxiv.org/abs/hep-ph/0202233)
Use a spectrum and coupling calculator such as SUSPECT, SoftSUSY, or just PYTHIA...
Understand the output.
Signature of partners

- Many studies in the past 2 decades.

- If we are reasonably lucky and partners are not heavy, we can have multi-jets multi-lepton channels. Good discovery potential. For example:
  
  At 7 TeV and 1 fb$^{-1}$: $\sim 10^3 \tilde{q}$ and $\tilde{g}$ ($\sim 500$ GeV)

- Can be early discovery.

partners:
Same gauge interactions as the SM particles

$\tilde{g}, \tilde{q}, \tilde{W}, \tilde{Z}, \tilde{\ell}...$

$\tilde{g}^{KK}, \tilde{q}^{KK}, \tilde{W}^{KK}, \tilde{Z}^{KK}, \tilde{\ell}^{KK}...$
Typical variables I: counts.

- Inclusive counts. Useful for signal $\gg$ background.

\[
\begin{align*}
    n_j \times \text{jet} & & \quad b\text{-jet} \\
    + & & \quad \text{non-b-jet} \\
    n_\ell \times \text{lepton} & & \quad \ell \text{ all flavor and charge combo: e.g. } 2\ell \rightarrow 21 \text{ comb.} \\
    + & \\
    n_\gamma \times \gamma & \\
\end{align*}
\]
Kinematical features: transverse variables.

- Multiple hard objects.
- No resonance.
- Transverse variables made of several energetic objects. $M_{\text{eff}} \ H_T$

$$M_{\text{eff}} = \mathcal{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4}$$

Be careful.

Gianotti and Mangano, 2005
Special case: off-shell Z

- 3-body. End-point in di-lepton invariant mass.
  - Same flavor di-lepton.
  - Combinatorials can be suppressed with flavor subtraction.

\[ M_{\tilde{N}_2} - M_{\tilde{N}_1} < m_Z \rightarrow \tilde{N}_2 \rightarrow \tilde{N}_1 + \ell^+ + \ell^- \quad \text{Only 3-body} \]

\[ m_{\ell\ell} = \sqrt{(p_{\ell^+}^2 + p_{\ell^-}^2)} \rightarrow \text{end-point at } M_{\tilde{N}_2} - M_{\tilde{N}_1} \]
Luckier scenario: slepton in the decay chain.

• A lot of leptons. No branching ratio suppression.
• On shell slepton, very distinctive feature.
  – Edge in di-lepton invariant mass.

\[
m_{\tilde{\ell}} < M_{\tilde{N}_2} \rightarrow \tilde{N}_2 \rightarrow \tilde{N}_1 + [\tilde{\ell}] \rightarrow \tilde{N}_1 + \ell^+ + \ell^-
\]

\[
M_{\ell\ell}^{\text{max}} = M_{\tilde{N}_1} \sqrt{1 - \frac{m_{\tilde{\ell}}^2}{M_{\tilde{N}_2}^2}} \sqrt{1 - \frac{M_{\tilde{N}_1}^2}{m_{\tilde{\ell}}^2}}
\]

• More complicated edges useful, but need high statistics.

See several papers by: Miller, Osland.
Kinematical variables: invariant masses

- Most useful: di-lepton edges and endpoints. (Mentioned earlier in neutralino decay).
  - Clean.
- Invariant mass distribution also carry spin information. Probably needs high statistics.

  For a review: See LW and I. Yavin, 2008

- More complicated invariant masses in longer decay chains possibly useful, but feature is less sharp. May need high statistics as well.

  For example, see Miller and Osland. A set of papers.
Topology: model independent approach

partners:
Same gauge interactions as the SM particles
Similar signatures.

http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=94910
http://www.lhcnewphysics.org/web/Overview.html

Workshop at SLAC: Sept. 22-25
Signals can be challenging to understand.

- After the discovery, we can derive some basic properties, such as whether the new particles are colored or not, whether they decay to leptons, and so on.

- Many possible interpretations.

Degeneracies! Quantum number, mass, spin...
For example: in supersymmetry, bino vs wino, squark vs gluino...

Hard work, but we will be able to figure it out.
Possible degeneracies in:

- The identity of new physics particles. For example:
  - Two different SUSY spectra.
  - \( \tilde{q}, \tilde{g}, \ldots \) \( \tilde{q}, \tilde{g}, \ldots \)
  - \( \tilde{W}, \tilde{B} \) \( \tilde{B}, \tilde{W} \)
  - Identity swap, hard to distinguish

- Spin.
  - SUSY: 1/2 spin difference from the SM particle.
  - Extra-dimension: same spin.

Model independent mass Measurements.

- Likely, not enough information to fully reconstruct the kinematics of the event.

- Simple variables only measure mass differences.

\[ \sum p_T, E, \ldots \propto M_1 - M_2 \]

- More detailed kinematical information, special kinematical configurations and subtle features.

\[ M_{T2}, MAOs, \hat{s}_{\text{min}}, \ldots \]

Cheng et. al.; Choi et. al.; Barr et. al.; Han et. al.; Matchev et. al.
Spin measurements. Supersymmetry?

例：

- No universally applicable method. Different strategies will be used in different scenarios.
  A review: LTW and Yavin, arXiv:0802.2726
- More information of the signal, masses and underlying processes, is crucial.
Extra slides
1 Introduction
The LHC has recently started delivering proton-proton collisions at a centre-of-mass energy of 7 TeV. It is foreseen to run at this energy through autumn 2011, with a target integrated luminosity of $1 \text{ fb}^{-1}$. The physics reach of CMS has been described in detail in Ref. [1], assuming the LHC design centre-of-mass energy (14 TeV). Several studies have been also made at 10 TeV, as shown during the 2009 Summer Conferences [2].

Some examples of the expected physics reach of CMS, at a proton-proton centre-of-mass energy of 7 TeV, are described in this short note. Integrated luminosities between $100 \text{ pb}^{-1}$ and $1 \text{ fb}^{-1}$ are considered. The estimates are generally based on extrapolations from existing studies at higher energies, by applying simple scaling of cross sections for signal and backgrounds. No attempts of analysis reoptimization at 7 TeV have been made. As such, the results given in this note should be considered as a rough indication of the new physics reach of CMS at 7 TeV, pending more detailed studies.

In the next Section, a few examples of the expected CMS physics performance at 7 TeV, for various Beyond-the-Standard-Model scenarios (called Exotica in this note), are shown. In Section 3 it is shown that, at a centre-of-mass energy of 7 TeV, two representative analyses can significantly extend the experimental investigation of the Minimal Supersymmetric Standard Model (MSSM). Finally in the last section, the main plots related to the search for the Standard Model Higgs boson are updated at 7 TeV. One example of an alternative scenario (neutral Higgs boson in the MSSM) is also shown.

2 Scaling of Selected Exotica Results
In this section we discuss the scaling to 7 TeV of several recent Exotica results, originally obtained for 10 TeV or 14 TeV LHC running scenarios [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. In most of the cases, this scaling has been done using parton luminosity ratios for $q \bar{q}$ and $gg$ interactions as a function of the invariant mass of the system [13]. These ratios were obtained using MSTW2008NLO parton distribution functions [14] and are shown in Fig. 1.

As already mentioned, none of the results presented here were obtained via full analysis with proper reoptimization of the cuts, so they should be considered as conservative rough estimates of the true reach at 7 TeV. Nevertheless, the scaling results give a pretty consistent picture that running the machine at 7 TeV requires approximately three times higher integrated luminosity compared to that in a 10 TeV run in order to reach the same sensitivity.

For the $b' \to tW$ analysis the parton luminosity ratio was not used; instead we used LO PYTHIA [15] cross sections for the signal and backgrounds at 7 TeV. The sensitivity of the search is shown in Fig. 2 for integrated luminosities of $200$ and $600 \text{ pb}^{-1}$. Compared to the results of Ref. [3], approximately 3.5 times more integrated luminosity is required for a 7 TeV LHC run to match the reach at 10 TeV. With $\sim 100 \text{ pb}^{-1}$ of 7 TeV data, our sensitivity is expected to surpass the current Tevatron lower $b'$ mass limit of 325 GeV (95\% C.L.) [16].