Search for Hadronic Resonances at CDF and CMS

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Outline

• Motivation
• A few words on Hadron Colliders
• Introduction to the Jet Ensemble Technique
• CDF Search for Hadronic Resonances
• CMS Search for Hadronic Resonances
• Summary
Motivation

• Most exotic searches at colliders involve MET and/or leptons/photons.
  – Strong production
  – ElectroWeak decays
  – Backgrounds suppressed

• New physics $\rightarrow$ Jets?
  – Strong production cross-section
  – Strong decays (multi-jet)
  – Backgrounds severe
New Physics in Multijets

• New Physics Search in Multijet final state
  – What if new physics is hidden behind a strong coupling?
• Model-independent search for:
  – $p\bar{p} \rightarrow XX'$, where $X, X' \rightarrow 3$jets
  – Signal similar to SM ttbar to all hadronic decay (6 jet final state)
• Challenge
  – Large QCD multijets background
• NEW Technique
  – Make use of kinematic features and an ensemble of jets
  – Technique may also be useful for jets produced with leptons, MET, photons and we are studying this to be applied to other analyses
Hadron Colliders: The Tevatron

- **Tevatron at Fermilab**
  - Proton- anti-proton collisions
  - 6.5 km circumference
  - 25 feet underground
  - $E_{\text{beam}} \sim 980$ GeV, $E_{\text{cm}} \sim 2$ TeV
  - Celebrated the 25th anniversary of its first collisions last December
  - Top quark discovered by CDF and DØ in 1995 during Run I of Tevatron
  - Run II "precision era" since 2001-present
  - Tevatron turned off on September 30th
    - End of an era
Particle Detectors

- Goal is to completely surround collision by arranging different types of detectors in layers.
- We know how particles interact with matter and we identify them (to the best of our ability!) by exploiting differences in showering, interaction with matter.
- What do we want to know about the particles?
  - Their momentum and charge (magnetic field)
  - Their energy (particles are absorbed)
  - Their species (we exploit differences)
Experimentalist = Tracker

BACKYARD SNOW TRACKING GUIDE

CAT
MOOSE AND SQUIRREL
LONGCAT
MOUSE RIDING BICYCLE
RABBIT STOPPING TO USE HAIR DRYER
LEGOLAS
BOBCAT ON POGO STICK
KNIGHT
KID WITH TRANSMOGRIFFER
KID WITH DUPPLICATOR
PRIUS
HIGGS BOSON
How much data have the experiments collected?

- Before I answer that, I need to tell you that this is quantified by the integrated rate of collisions or the luminosity
  - unit of 1/cross section = 1/cm² or inverse-barns, where 1 barn = 10⁻²⁴ cm²
- If two bunches containing \( n_1 \) and \( n_2 \) particles collide with frequency \( f \), the luminosity is
  \[
  L = f\frac{n_1 n_2}{4\pi\sigma_x \sigma_y} \approx f\frac{n_b N_p^2}{4\pi\sigma_x \sigma_y}
  \]
  - where \( \sigma_x \) and \( \sigma_y \) characterize the size of transverse beam (RMS assuming Gaussian spot size)
  - \( n_b \) is the number of bunches
  - \( N_p \) is the number of particles (protons/antiprotons) per bunch
CDF Detector

- Multipurpose detector:
  - Tracking system
  - ~2 Tesla field
  - Electromagnetic and Hadronic calorimeters
  - Muon System

Tevatron and CDF performed excellently until the very end!

> 11.9 fb\(^{-1}\) delivered
> 9.9 fb\(^{-1}\) acquired
Coordinate System

- Natural coordinates are cylindrical around the beam-pipe
  - $\theta$ polar angle, $\phi$ azimuthal angle
- Polar angle $\theta$ is not Lorentz-invariant
- Pseudorapidity is a function of polar angle
  - $\eta \equiv -\log \tan(\theta/2)$
Jet Ensemble Method

- We use an ensemble of jet combinations

- We have at least \( \binom{6}{3} = 20 \) combinations

- Strategy:
  - Build triplets out of all final state jets and calculate
    - Invariant mass \( M_{jjj} \)
    - Scalar sum \( p_T \sum |p_T|_{jjj} \)
  - Plot one vs. the other for each combination (at least 20 combinations for each event)
Jet Ensemble Method Example:

- **ttbar Monte Carlo**

  - **Projection on to mass axis**
    - Signal still contains jet combinatorial confusion
    - QCD has a similar shape

  - **Diagonal cut:**
    - For any triplet require: $M_{jjj} < \Sigma |p_T|_{jjj}$ – diagonal offset
    - Reduces background from combinatorial confusion and QCD

  - Offset 190 GeV

  - PYTHIA $t\bar{t}$
    - $m=172.5$ GeV/$c^2$
    - $\geq 20$ entries per event

CDF RUN II

Hadronic Resonance Search at CDF & CMS

E. Halkiadakis
A few comments on the technique

- We look for just one 3-jet mass resonance in a multi-jet environment.
  - No attempt to fully reconstruct both decays.
  - Nothing model dependent: no b-quarks, no internal resonances, no requirements on geometry (hemisphere, ΔR, etc.)

- New physics with strong couplings will have large cross sections.
  - Recall ttbar production is ~7 pb at the Tevatron.
  - Pair produced gluinos from (RPV) SUSY are similar
    - ~2.3 x σ_{ttbar} at m_{top}
  - The power of this technique is in the focus on boosted decays. Reduces QCD and combinatoric backgrounds.
CDF Event Selection

- **Dataset**: 3.2 fb$^{-1}$ of CDF data
  - Trigger: 4 jets $p_T > 15$ GeV (raw) and $\text{Sum}E_T > 175$ GeV (raw)

- $N_{\text{jets}} \geq 6$
  - Jet $p_T > 15$ GeV, $|\eta| < 2.5$
  - $|z_0| \leq 60$ cm
  - $\Sigma_{6\text{jets}} p_T > 250$ GeV for 6 highest $p_T$ jets
  - Request that jets originate from the same $z$ position

- $1 \leq N_{\text{vertices}} \leq 4$
- $\text{MET} < 50$ GeV

Note: JetClu $\Delta R$ 0.4 cone jets used

This lowers our acceptance for forward clusters
QCD Background Estimate

• Use Monte Carlo Simulation?
  - Difficult to calculate $\rightarrow$ not well understood
  - Would take a long time to generate a large enough sample

• Data-driven method
  - Estimate QCD shape from exclusive 5-jet sample
  - Rescale 5-jet triplet $\Sigma|p_T|$ distribution to match triplets in the 6-jet sample
  - Use Landau function to parameterize background
  - Use as input parameters for similar fits in the 6-jet sample
  - Landau parameters vary smoothly as a function of diagonal cut
QCD Background Estimate: 5-jet Data

5-jet Landau Fit

We use 5-jet fit parameters as input for 6-jet fit.
6-jet Landau Fit

We use 5-jet fit parameters as input for 6-jet fit.

Top quark mass region is blinded in the fit
Fitting for signal in data

Fit for possible signal with Landau + Gaussian

CDF RUN II Preliminary 3.2 fb$^{-1}$

- ≥ 6jet Data
- QCD Landau prediction + Gaussian fit fixed at m=112 GeV/c$^2$

(diagonal cut value 155 GeV/c)

Diagonal cut = 155 GeV
Mass = 112 GeV

3 jet invariant mass [GeV/c$^2$]
Background Procedure

Diagonal cut = 134 GeV
CDF RUN II Preliminary 3.2 fb⁻¹

5-jet

Diagonal cut = 165 GeV
CDF RUN II Preliminary 3.2 fb⁻¹

6-jet
Background Parameters

- Landau parameters vary smoothly as a function of diagonal cut
- We fix parameters when we fit for signal
  - Red curves
Optimizing the diagonal cut

• What is the best diagonal cut for a given $m_{\text{gluino}}$?
  – Use signal MC (see next slide)
• Use signal/background as metric
  – We have a (data-driven) background estimate as function of diagonal offset.
  – Make pseudo-experiments by adding signal MC
  – Vary diagonal cut, fit. Extract optimal diagonal offset.

\[ \sigma(p\bar{p} \rightarrow XX') \times \text{BR}(g\bar{g} \rightarrow 3\text{jet} + 3\text{jet}) \]

where $X, X' = \tilde{g}, \tilde{q}, \tilde{\bar{q}}$ with $\tilde{q}, \tilde{\bar{q}} \rightarrow \tilde{g} + \text{jet}$
Diagonal cut: Optimized vs. Mass

\[ \sigma(p\bar{p} \to XX') \times BR(\tilde{g}\tilde{g} \to 3\text{jet} + 3\text{jet}) \]

where \( X, X' = \tilde{g}, \tilde{q}, \tilde{\bar{q}} \) with \( \tilde{q}, \tilde{\bar{q}} \to \tilde{g} + \text{jet} \)
Fitting for signal in data

Search in the range of 77 – 240 GeV

- **m = 94 GeV**
  - Offset 134 GeV

- **m = 112 GeV**
  - Offset 155 GeV

- **m = 175 GeV**
  - Offset 190 GeV

Largest excess near $m_{\text{top}}$: $2 \sigma$

More on this later.

No evidence for new physics above SM background
Signal: RPV Gluino

• Although search is for generic 3-jet resonance, limits interpreted in context of RPV SUSY

• Monte Carlo simulation (PYTHIA) for the process:
  \[ \sigma(p\bar{p} \rightarrow XX') \times BR(\tilde{g}\tilde{g} \rightarrow 3\text{jet} + 3\text{jet}) \]
  where \( X, X' = \tilde{g}, \tilde{q}, \bar{\tilde{q}} \) with \( \tilde{q}, \bar{\tilde{q}} \rightarrow \tilde{g} + \text{jet} \)

• Acceptance (CDF):
  - \( a = \frac{N_{\text{selected}}}{N_{\text{generated}}} \)
    \( = (4.9 \pm 1.9) \times 10^{-5} \)
  - Observed to be roughly independent of mass

Gaussian integral
(after all analysis cuts)
CDF Limits on Hadronic Resonances

- We translate observed events into cross section
- **Bayesian** method to calculate 95% C.L. limits
- **Systematic Uncertainties (38%)**
  - Acceptance Uncertainty
    - Jet Energy Scale (31%)
    - ISR & FSR (20%)
    - Parton Distribution Functions (10%)
    - Luminosity (6%)
  - Background Shape Uncertainty
- Consider **two different models** for gluino production
  - Heavy intermediate squark $0.5 \text{ TeV} < m_{\tilde{q}} < 0.7 \text{ TeV}$
  - Nearly degenerate squark mass $m_{\tilde{q}} = m_{\tilde{g}} + 10 \text{ GeV}$
CDF Limits on Hadronic Resonances

- Limits on gluino pair production
  - Heavy intermediate squark
    - 144 GeV
  - Nearly degenerate squark mass
    - 154 GeV
- Largest excess around $m_{\text{top}}$
  - Expectation ~ 1 triplet
  - Observation $11 \pm 5$ triplet
  - Significance of 2 $\sigma$
- First search for 3-jet resonances
- Published in PRL!
  - PRL 107, 042001 (2011)

Model cross sections from Pythia, corrected with NLO k-factors from Prospino
Tevatron $\Rightarrow$ LHC

- Searched for Hadronic Resonances at the Tevatron
  - No new physics

- Also performed same search with the CMS detector
  - LHC cross sections are high
    - $\sim 325$ pb at $m_{\text{gluino}}=200$ GeV, to $\sim 1$ pb at $m_{\text{gluino}}=500$ GeV.
Hadron Colliders: The LHC

- Large Hadron Collider at CERN
  - Proton-proton collisions
  - 27 km circumference
  - 100 m underground
  - $E_{\text{beam}} = 7 \text{ TeV}, E_{\text{cm}} = 14 \text{ TeV}$ design
  - $E_{\text{beam}} = 3.5 \text{ TeV}, E_{\text{cm}} = 7 \text{ TeV}$ (2010-12)
    - 7 TeV collisions started end of March 2010!
    - Collected/Delivered $> 5 \text{ fb}^{-1}$ in 2011
  - Also heavy ion collisions (Pb-Pb)
    - Shorter running periods (~1 month/year)

I am a member of the CMS experiment
CMS Search for Hadronic Resonances

- Main Differences between CMS and CDF for this analysis:
  - ~4 Tesla magnetic field
  - CMS tracking down to $|\eta| < 2.4$
  - Hadron calorimeter granularity of $0.087 \times 0.087$ in $\eta - \phi$
  - Anti-$k_T$ cone 0.5 jets
    - Using Particle Flow Jets

This analysis currently uses 2010 dataset.
To scale

Fig. 3. The CMS detector with the CDF detector inset (to scale) for comparison.

J. Incandela
CMS Event Selection

- **Dataset:** 35 pb$^{-1}$ 2010 Data
- Trigger is $H_T$ ($\sum |p_T|$ of all jets) >100, 150 GeV (depending on run period)
- $N_{jets} \geq 6$
  - Jet $p_T$>45 GeV, $|\eta| < 3$
  - $\sum_{6jets} p_T > 425$ GeV
    - Trigger 100% efficient
- $N_{vertices} \geq 1$
Jet Ensemble Technique at CMS

- Analysis Technique
  - Same as CDF
- Diagonal offset optimized
  - Common value of 130 GeV for all masses
- $m_{\text{gluino}}$ varied from 200-500 GeV
- Signal acceptance:
  - Parameterized as a function of gluino mass
  - Ranges from 0.4 to 5%.
QCD Background Estimate at CMS

- Background parameterized as an exponential
  - Cross checked with Landau and a 3-parameter fit (e.g. as in Dijet resonances search PRL 105, 211801 (2010))

- Use similar technique as CDF
- We scale the Njet=4 to describe the Njet>6 sample
  - Cross check with Njet=5 gives good agreement
CMS Data

Three-jet mass for final selection

- Fit range 170-800 GeV
- Hypothetical gluino signal for mass 250 GeV shown, normalized to data
- No significant excess observed
CMS Limits on Hadronic Resonances

• We translate observed events into cross section
• **Bayesian** likelihood method to calculate 95% C.L. limits
  – Uncertainties treated as Gaussian nuisance parameters
• **Systematic Uncertainties (10-19%)**
  – Acceptance Uncertainty
    – Jet Energy Scale (7-16%)
    – ISR & FSR (2-4%)
  – Multiple Interactions (1-6%)
  – Parton Distribution Functions (4%)
  – Luminosity (4%)
  – Background Shape Uncertainty
CMS Limits on Hadronic Resonances

- Exclusion for gluinos (RPV decay) for masses 200 < m < 280 GeV
- Largest excess seen at 390 GeV corresponding to 1.9σ (with look-elsewhere effect)
- 1st limits from the LHC
- Highest limits to date
- Published in PRL
  - PRL 107, 101801 (2011)
  - And highlighted by PRL reviewer!

Limits interpreted in context of RPV SUSY, same model as at CDF

Model cross sections from Pythia, corrected with NLO k-factors from Prospino.
All superpartners except gluino taken to be decoupled.
CDF and CMS Limits

CDF RUN II 3.2 fb⁻¹

- $0.5 \text{ TeV/c}^2 < m_{\tilde{q}} < 0.7 \text{ TeV/c}^2$
- $m_{\tilde{q}} = m_{\tilde{g}} + 10 \text{ GeV/c}^2$

95% C.L. limit observed
95% C.L. limit expected
± 1σ on expected limit

Excluded gluino mass < 144 GeV

CMS Preliminary
$\int L = 35.1 \text{ pb}^{-1}$

- Expected
- Observed

± 1σ
± 2σ
$\sigma^{\text{NLO}}(\text{Gluino})$

Excluded gluino mass < 280 GeV

Hadronic Resonance Search at CDF & CMS

E. Halkiadakis
Summary

- **Jet ensemble** technique works to extract boosted hadronic resonances from QCD background.
- Performed a search for such resonances related to possible new physics scenarios at CDF and CMS.
- **Set first limits** on \( \sigma(pp \rightarrow XX') \times BR(\tilde{g}\tilde{g} \rightarrow 3\text{jet} + 3\text{jet}) \)
  where \( X, X' = \tilde{g}, \tilde{q}, \bar{q} \) with \( \tilde{q}, \bar{q} \rightarrow \tilde{g} + \text{jet} \)
- At CDF largest excess around the top quark mass \( \sim 2\sigma \)
  - Many cross checks performed
- At CMS largest excess at 390 GeV \( < 2\sigma \)
  - Looking forward to results with 2011 data!