Search for Hadronic Resonances at CDF and CMS

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Outline

• Motivation
• 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?

• Search for:
  – $p\bar{p} \rightarrow XX'$, where $X, X' = \tilde{g}, \tilde{q}, \tilde{\bar{q}}$
  – R-parity violating decay into 3 jets (no MET)
  – Signal similar to SM $tt\bar{t}$ to all hadronic decay

• Challenge
  – Large QCD background
  – Make use of kinematic features and an ensemble of jets

• Techniques may also be useful for jets produced with leptons, MET, photons and we plan to study this later
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 \( p_T \Sigma |p_T|_{jjj} \)
- 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: $M_{jjj} < \sum |p_T|_{jjj}$ – diagonal offset
  - Reduces background from combinatorial confusion and QCD

Offset 190 GeV
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.
  - RPV gluinos 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 Detector

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

Tevatron and CDF performing excellently!
CDF Event Selection

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

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

• \(1 \leq N_{\text{vertices}} \leq 4\)

• MET < 50 GeV

Note: JetClu \(\Delta R \) 0.4 cone jets used
QCD Background Estimate

• Use Monte Carlo Simulation?
  – Difficult to calculate → 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.

CDF RUN II Preliminary 3.2 fb⁻¹

3 jet invariant mass [GeV/c²]

Hadronic Resonance Search at CDF & CMS

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QCD Background Estimate: 6-jet Data

6-jet Landau Fit

CDF RUN II Preliminary 3.2 fb^{-1}

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/c²

(diagonal cut value 155 GeV/c)

Diagonal cut = 155 GeV
Mass = 112 GeV

3 jet invariant mass [GeV/c²]
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

CDF RUN II Preliminary 3.2 fb⁻¹

Hadronic Resonance Search at CDF & CMS

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• 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.
Diagonal cut: Optimized vs. Mass

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

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

Search in the range of 77 – 240 GeV

- m = 94 GeV
  Offset 134 GeV
- m = 175 GeV
  Offset 190 GeV
- m = 112 GeV
  Offset 155 GeV

Largest excess near $m_{\text{top}}$: 2σ
More on this later.

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

- 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 \(X, X' = \tilde{g}, \tilde{q}, \tilde{\bar{q}}\) with \(\tilde{q}, \tilde{\bar{q}} \rightarrow \tilde{g} + \text{jet}\)

- 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
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 $\sim 1$ triplet
  - Observation $11 \pm 5$ triplet
  - Significance of $2 \sigma$
- Accepted by PRL!

Model cross sections from Pythia, corrected with NLO k-factors from Prospino
CDF Cross Checks on ttbar contribution

- Noticeable (2σ) excess near $m_{\text{top}}$
- MC expectation for known SM process ttbar $\sim 1$ triplet for diagonal cut $= 190$ GeV
  - Cross checked with MC@NLO, Alpgen, varied ISR/FSR, varied PDFs: expectation between 0.5 -1.1 triplets
  - Also cross checked with b-tagging, dijet mass of non-btagged jets
- Fit gives $11 \pm 5$ triplets in $\pm 1\sigma$ window around Gaussian
  - QCD Landau fit in same window gives $8 \pm 1$ triplets
CDF Cross Check with more data: 5.9 fb$^{-1}$

- Used Jet100 trigger
- $\geq 4$ jets, Jet $p_T > 20$ GeV (apart from trigger jet), Diagonal cut = 190 GeV

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No b-tagging

$2\sigma$ excess remains

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B-tag in event

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B-tag in triplet

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$M_{jj}$ of non b-tagged jets
Tevatron → LHC

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

• Also performed same search with the CMS detector
  - LHC cross sections are high
  - ~325 pb at $m_{\text{gluino}}=200$ GeV, to ~1 pb at $m_{\text{gluino}}=500$ GeV.
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
CMS Event Selection

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

Control region with all 20 jet triplets: used to test quality of 2 parameter fit
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 lookelsewhere effect)
- 1st limits from the LHC
- Highest limits to date

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 TeV/c^2 < m_{\tilde{q}} < 0.7 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

Expected
Observed

Excluded gluino mass < 144 GeV

Excluded gluino mass < 280 GeV

CMS Preliminary

∫ L = 35.1 \text{ pb}^{-1}

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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 $\sigma(p\bar{p} \rightarrow XX') \times BR(\tilde{g}\tilde{g} \rightarrow 3\text{jet} + 3\text{jet})$
  where $X,X' = \tilde{g},\tilde{q},\bar{q}$ 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
Additional Information

• CDF result accepted by PRL!
  – FERMILAB-PUB-11-220-E-PPD
  – More information about CDF analysis:
    – http://www-cdf.fnal.gov/physics/exotic/r2a/20110203.multijets/
      – FERMILAB-MASTERS-2011-01

• More information on CMS Analysis
  – https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11001
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