Update on Searches for New Physics in CMS

CERN PH-LHC Seminar
January 31, 2012

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Rutgers, the State University of NJ
For the CMS Collaboration
Spectacular performance of the LHC in 2011
Thank you for delivering 5.7 fb$^{-1}$!
Eagerly awaiting this year’s data

Total integrated luminosity

Integrated luminosity/day

Excellent performance of CMS experiment
→ 91% data-taking efficiency
Outline

• I will cover “exotic” and SUSY searches:
  – Heavy Resonances and Extra Dimensions
    → ordered in increasing complexity of final state
  – 4\textsuperscript{th} Generation Quarks
  – Leptoquarks
  – Long-lived Particles
  – SUSY and RPV SUSY

• Many new physics results with 2011 data
  – Analyses today done with \(\sim 1 - 4.7 \text{ fb}^{-1}\)
    → 5 new analyses with full dataset!
  – Impossible to cover everything

• All CMS new physics results can be found at:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
Searches for Heavy Resonances

• **Search for excesses in invariant mass spectra**
  - Bump hunt
  - Generic, powerful and track record for discovery in the past
  - Predicted by several BSM models with extended gauge symmetries
    - Z’ and W’ with SM-like couplings
    - Kaluza-Klein excitations from RS model of extra dimensions
    - E6 models
    - Technicolor
    - ....
Searches for Non-Resonant Signatures

- Searches non-resonant excess in kinematic distributions and mass spectra
- Predicted by many Extra Dimension Models
  - Universal Extra Dimensions (UED)
    - All particles propagate the bulk
  - Large Extra Dimensions: e.g. ADD
    - Only Graviton propagates the bulk
  - Warped Extra Dimensions: e.g. Randall-Sundrum
    - Warped geometry

\[ M^2_{Pl} \sim M_D^{2+n} R^n \]
Dijet Resonances

High sensitivity to strongly produced new resonances decaying to pairs of jets predicted in numerous models: string phenomena, excited quarks, colorons, diquarks

Mass limits up to 4 TeV

<table>
<thead>
<tr>
<th>Model</th>
<th>Excluded Mass (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>String Resonances</td>
<td>4.00</td>
</tr>
<tr>
<td>E₆ Diquarks</td>
<td>3.52</td>
</tr>
<tr>
<td>Excited Quarks</td>
<td>2.49</td>
</tr>
<tr>
<td>Axigluons/Colorons</td>
<td>2.47</td>
</tr>
<tr>
<td>W’ Bosons</td>
<td>1.51</td>
</tr>
</tbody>
</table>

First search published with 1 fb⁻¹
PLB 704, 123 (2011)
Paired Dijet Resonances

Extension of inclusive dijet resonance search
Paired dijet production predicted by several models: coloron, axigluon, hyperpions

- Consider 4 leading jets with $p_T > 150$ GeV
  - Require dijet mass pairs to be equal, within resolution
  - Consider average dijet masses
- To further suppress QCD, cut in 2D plane of $\text{SumPt}(jj)$ and $M_{jj}(\text{avg})$
  
  \[ \Delta = \sum_{i=1,2} (P_T)_i - m_{\text{avg}} \]
  - Ensures a smoothly falling background
  - Enhances the resonant part of the signal
    → Would appear as a vertical stripe in plot on the right

QCD shaped by $p_T$ thresholds
Paired Dijet Resonances

First such search from CMS

Use 4-parameter parameterization as in the inclusive Dijet Resonance search

Largest fluctuation \( \sim 615 \text{ GeV} \)

\( 2.7\sigma \rightarrow 1.5\sigma \) after LEE

No evidence for new physics

Exclude pair production of colorons with mass between 320 – 580 GeV
High Paired Dijet Mass Event

Run : 166380
Event : 417060509

Pair1 (1,4) - mass = 1.075 TeV
Pair2 (2,3) - mass = 1.081 TeV

Anti-k_t 5 Jet $p_T$

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>944 GeV</td>
</tr>
<tr>
<td>2</td>
<td>771 GeV</td>
</tr>
<tr>
<td>3</td>
<td>380 GeV</td>
</tr>
<tr>
<td>4</td>
<td>270 GeV</td>
</tr>
</tbody>
</table>
Diphoton Mass Spectrum

Search for resonant and non-resonant diphoton production

- Select two photons in barrel with $E_T > 70$ GeV and $M_{\gamma\gamma} > 140$ GeV
- Optimal search region for ADD $M_{\gamma\gamma} > 0.9$ TeV
  - Observed: 2 events
  - Background: $1.5 \pm 0.3$ events
    - Primarily SM diphoton production
    - Estimated with Pythia + NLO (DIPHOX+GAMMA2MC)
Limits on Extra Dimensions and RS gravitons

Exclusion limits on RS gravitons (0.86-1.84 TeV) and several ADD models (2.3-3.8 TeV)

Effective Planck scale (TeV) in ADD

<table>
<thead>
<tr>
<th>$K$ factor</th>
<th>GRW</th>
<th>Hewett</th>
<th>HLZ ($n_{\text{ED}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pos.</td>
<td>neg.</td>
<td>2</td>
</tr>
<tr>
<td>1.0</td>
<td>2.94</td>
<td>2.63</td>
<td>2.28</td>
</tr>
<tr>
<td>1.6</td>
<td>3.18</td>
<td>2.84</td>
<td>2.41</td>
</tr>
</tbody>
</table>

RS gravitons: Mass (TeV)

<table>
<thead>
<tr>
<th>$\tilde{k}$</th>
<th>$M_1$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.86</td>
</tr>
<tr>
<td>0.02</td>
<td>1.13</td>
</tr>
<tr>
<td>0.03</td>
<td>1.27</td>
</tr>
<tr>
<td>0.04</td>
<td>1.39</td>
</tr>
<tr>
<td>0.05</td>
<td>1.50</td>
</tr>
</tbody>
</table>

2.2 fb$^{-1}$
Dilepton Mass Spectra

Search for non-resonant excess in $M_{\ell\ell}$

 CMS PAS-EXO-11-087
~2 fb$^{-1}$

CMS $\sqrt{s} = 7$ TeV, $\int L\, dt = 2.3$ fb$^{-1}$

**di-muons**

<table>
<thead>
<tr>
<th>Events / 20 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10$^4$</td>
</tr>
<tr>
<td>10$^3$</td>
</tr>
<tr>
<td>10$^2$</td>
</tr>
<tr>
<td>10$^1$</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>10$^{-1}$</td>
</tr>
<tr>
<td>10$^{-2}$</td>
</tr>
<tr>
<td>10$^{-3}$</td>
</tr>
</tbody>
</table>

$M_{\mu\mu}$ [GeV]

---

**di-electrons**

<table>
<thead>
<tr>
<th>Events / 20 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10$^6$</td>
</tr>
<tr>
<td>10$^5$</td>
</tr>
<tr>
<td>10$^4$</td>
</tr>
<tr>
<td>10$^3$</td>
</tr>
<tr>
<td>10$^2$</td>
</tr>
<tr>
<td>10$^1$</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>10$^{-1}$</td>
</tr>
<tr>
<td>10$^{-2}$</td>
</tr>
</tbody>
</table>

$M_{ee}$ [GeV]
Search for excess above 1.1 TeV

Combined ee and $\mu\mu$ exclusion limits for ADD models for several parameters (2.5-3.8 TeV)

<table>
<thead>
<tr>
<th>ADD K-factor</th>
<th>$\Lambda_T$ [TeV] (GRW)</th>
<th>$M_s$ [TeV] (HLZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n = 2$</td>
<td>$n = 3$</td>
</tr>
<tr>
<td>$1.3$ (ee), $1.6$ ($\gamma\gamma$)</td>
<td>3.3</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Lepton+MET Channel

Look for an excess in the transverse mass spectrum

\[ M_T = \sqrt{2 \cdot p_T^\ell \cdot E_{T}^{\text{miss}} \cdot (1 - \cos \Delta \phi_{\ell,\nu})} \]
Highest $M_T$ Events

$\mu + \text{MET}$

$M_T = 2.4$ TeV

$e + \text{MET}$

$M_T = 1.6$ TeV

Update on Searches for New Physics in CMS

E. Halkiadakis
Limits on $W'$

- Exclusion limits for different $W'$ models:
  - RH $W'$ with SM-like couplings
  - LH $W'$ including their interference with the SM $W$
  - Kaluza-Klein $W'_{KK}$-states in the framework of UED
- First exclusion limits where interference has been considered for the leptonic channels
- $W'$ with SM-like couplings is excluded below 2.5 TeV

Including interference, we exclude below:
- $2.63$ TeV (constructive)
- $2.43$ TeV (destructive)
ttbar Resonances

Boosted All-Hadronic State

Top decay products either partially or fully merged into one jet.
Top-tagging tools using jet substructure with Cambridge-Aachen R=0.8 jets.

- 1+1 or Type 1
  - dijet event: two fully merged top candidates

- 1+2 or Type 2
  - trijet event: one fully merged top jet in one hemisphere, and two jets in the other (a b-jet and a merged W-jet)

W mass within jets in $\mu$ + boosted jet sample used to measure subjet energy scale
ttbar Resonances

Type 1+1 mass

- Type 1 jet $p_T > 350$ GeV
- $W$ jet $p_T > 200$ GeV
- Other jet $p_T > 30$ GeV
- Plus jet mass and mass drop requirements consistent with top and $W$
- Data-driven techniques used in QCD background estimate

Type 1+2 mass

CMS PAS-EXO-11-006

$4.6$ fb$^{-1}$
ttbar Resonances

Exclusion limits on $Z'$ of varying widths with SM couplings and RS KK gluon models

New physics enhancements to $\sigma_{\text{ttbar}}$ must be less than 2.8 times NLO for $M_{\text{ttbar}} > 1 \text{ TeV}$

$\begin{align*}
1.0 < M_{Z'} < 1.4 \text{ TeV} & \quad (1.2\% \text{ width}) \\
1.0 < M_{Z'} < 1.7 \text{ TeV} & \quad (3\% \text{ width}) \\
1.0 < M_{Z'} < 1.9 \text{ TeV} & \quad (10\% \text{ width})
\end{align*}$

CMS PAS-EXO-11-006

4.6 fb$^{-1}$
Black Holes

Searches for New Physics at CMS

E. Halkiadakis

BH production in ADD model (large flat extra spatial dimensions)

- Democratic and isotropic decay
- High $S_T$ events (total transverse energy)
- High total multiplicity (e.g. $\geq 4$)

Use $N=2$, 3 for background model.

$N=10$, $S_T = 1.1$ TeV

CMS PAS-EXO-11-071

4.7 fb$^{-1}$
Limits on Black Holes

Model-specific limits on minimum black hole (ADD), string balls, and quantum black holes (NEW)

3.8 – 5.3 TeV range for large variety of model parameters

Also model-independent limits
Searches for 4\textsuperscript{th} Generation Quarks

Searches for the extension of the generations of fermions
Heavy Top-like Quark

Search for production of: \( t' \bar{t}' \rightarrow bW^+\bar{b}W^- \)

In dilepton channels: \( ee, e\mu, \mu\mu \) with opposite sign

Use \( M_{lb}(\text{min}) \): minimum value of four possible combinations
Select events with \( M_{lb}(\text{min}) > 170 \text{ GeV} \) to reduce \( ttbar \) background

**Backgrounds:**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category I (data-driven)</td>
<td>0.74 ( \pm ) 0.79</td>
</tr>
<tr>
<td>Category II (data-driven)</td>
<td>0(^{+0.4}_{-0.0})</td>
</tr>
<tr>
<td>Category III (simulated)</td>
<td>0.99 ( \pm ) 0.69</td>
</tr>
<tr>
<td>Total prediction</td>
<td>1.73 ( \pm ) 1.12</td>
</tr>
<tr>
<td>Data</td>
<td>1</td>
</tr>
</tbody>
</table>

- Category I: events with mistagged b(s) and 2 real leptons
- Category II: events with misidentified lepton(s) and 2 real bs
- Category III: events with 2 real bs and 2 real leptons
- Category IV: events with mistagged b(s) and misidentified lepton(s).

\( \leftarrow \) negligible

Update on Searches for New Physics in CMS  E. Halkiadakis

CMS PAS-EXO-11-050

4.7 \( fb^{-1} \)
Limits on Heavy Top-like Quark Production

$t'$ excluded below 552 GeV

<table>
<thead>
<tr>
<th>$M_{t'}$ (GeV/c²)</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (pb)</td>
<td>3.200</td>
<td>1.406</td>
<td>0.622</td>
<td>0.330</td>
<td>0.171</td>
<td>0.092</td>
</tr>
<tr>
<td>Expected (pb)</td>
<td>0.560</td>
<td>0.309</td>
<td>0.256</td>
<td>0.219</td>
<td>0.187</td>
<td>0.166</td>
</tr>
<tr>
<td>Observed (pb)</td>
<td>0.503</td>
<td>0.278</td>
<td>0.230</td>
<td>0.196</td>
<td>0.168</td>
<td>0.149</td>
</tr>
</tbody>
</table>

4.7 fb⁻¹
Searches for Leptoquarks

Fractionally charged colored boson
\( \rightarrow \) quark + charged lepton (BR=\( \beta \))
\( \textbf{OR} \)
\( \rightarrow \) quark + neutrino (BR=1-\( \beta \))

- **2\textsuperscript{nd} generation decays and signatures:**
  - \( \mu \)-q-\( \mu \)-q (2\( \mu \)+2j) , \( \mu \)-q-\( \nu \)-q (1\( \mu \)+MET) [also, \( \nu \)-q-\( \nu \)-q]
  - Analyze in \( S_T = \Sigma \) muon \( p_T \) + jet \( p_T \) (+MET)

- **3\textsuperscript{rd} generation:**
  - \( \nu \)-b-\( \nu \)-b (2b-jets+MET) [also, \( \tau \)-b-\( \tau \)-b & \( \tau \)-b-\( \nu \)-b]
  - Analyze with razor variable \( R \) (dimensionless, related to MET)
Leptoquarks (2nd generation) 2.0 fb\(^{-1}\)

Cut thresholds on kinematic variables including \(S_T\) optimized for LQ mass

Example: \(S_T\) for 550 GeV LQ signal shown below in \(\mu q-\mu q\) channel (\(\beta=1\))

Overall consistency with SM predictions

\[630 \ (523) \ \text{GeV exclusion for } \beta=1 \ (0.5)\]
Leptoquarks (3\textsuperscript{rd} generation)  1.8 fb\(^{-1}\)

Signal region optimized for razor variables: \(M_R > 400\) GeV, and \(R^2\) (varying with LQ mass)

Backgrounds: \(t\bar{t}\)bar and multijet shapes data-driven

Overall consistency with SM predictions

350 GeV exclusion for \(\beta = 1\)
Long lived particles

• Predicted in many extensions of the SM: SUSY, hidden valley, etc.

• Several ways to look for them
  – Displaced tracks
  – Highly ionizing tracks
  – Out-of-time particles
  – Non-pointing photons
  – …

• I will focus on two new results
  – Long lived particles decaying to photons
  – Heavy Stable Charged Particles (HSCP)

Somewhat Lazy Photons

- Long-lived neutral $\rightarrow$ Non-prompt Photon + invisibles (MET)
  - $c\tau$ not that large, $\sim$2 to 20cm, e.g. GMSB neutralino below

- Pair production (diphotons)
- Accompanying jets
- Converted photon $\rightarrow$ (displaced) vertex

Technique:

Sensitive to lifetimes $\mathcal{O}(0.1\text{ns})$
Non-prompt (mildly displaced) photons

CMS PAS-EXO-11-067

Select:
\[ E_{T}(\gamma) > 45 \text{ GeV} \]
\[ \geq 2 \text{ jets (80/50 GeV)} \]
\[ \text{MET} > 30 \text{ GeV} \]

Backgrounds:
Photon + jets, Misid jets
Evaluated in MET<20 GeV region

Limits on neutralino cross section as a function of neutralino lifetime
Searches for Heavy Stable Charged Particles

- **R-hadron**: Strongly interacting particle forms bound state in process of hadronization
  - squarks or gluinos hadronize with quarks/gluons
- **Long-lived NLSP**
  - Split-SUSY, GMSB, UED etc.
- **Characteristic**: High momentum, but slower than light
  - Tracker hits show high \( \text{d}E/\text{d}x \) (\( \rightarrow \) particle mass)
  - Late arrival: Long Time Of Flight (TOF) to the muon system
  - Charge exchange possible in material: live without muon hits
- **Two approaches** \( \rightarrow \) model independent
  - Inner tracker only
  - Full tracking (reconstruct as a muon) and require TOF

4.7 fb\(^{-1}\) CMS PAS-EXO-11-022
Searches for Heavy Stable Charged Particles

HSCP makes it through CMS
(looks like a muon)
Tracker + TOF analysis

HSCP through CMS, suffering charge exchange in the hadron calorimeter
Inner tracker only analysis

--- HSCP

--- HSCP (becoming neutral)

Update on Searches for New Physics in CMS  E. Halkiadakis 32
Searches for Heavy Stable Charged Particles

In both Tk-only and Tk+TOF analyses, data consistent with expected background, estimated with a data-driven technique.

Limits on a variety of models: $M(\text{gluino}) > 1091$ GeV, $M(\text{scalar top}) > 734$ GeV, $M(\text{scalar tau}) > 221$ GeV, and on hyper-K and hyper-$\rho$.
Supersymmetry

Why SUSY?

• Symmetry between bosons and fermions
• Unification of forces
• Provides a dark matter candidate
• No “fine-tuning”

I will focus on these new results

• Razor analysis
• Multilepton final state
• Z+jets+MET final state
  → Two complementary analyses
  → First SUSY result with full dataset! (More coming soon....)
A number of channels and methods pursued

Focus has been on simple signatures
- Common to wide variety of models

Gearing toward dedicated sbottom and stop searches
- Stay tuned!

Our results have been most commonly presented in the CMSSM $m_0$ vs $m_{1/2}$ plane
- Shows breadth of analyses and large gain in coverage
Interpretation of Limits

Results interpreted in terms of simplified model spectra (SMS)

- Use limited set of new hypothetical particles and decays to produce a given topological signature
- Excluded mass scales for gluinos and squarks, where large mass splittings between them are assumed, as well as for varying neutralino masses
- Limits are quite dependent on model assumptions.
  - But they are quantified

1 fb\(^{-1}\) summary

<table>
<thead>
<tr>
<th>Range of exclusion limits for gluinos and squarks, varying (m(\chi^0))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T1: \tilde{g} \rightarrow q\tilde{\chi}^0) (E_T + \text{jets}, 1.1\text{ fb}^{-1}, \text{gluino})</td>
</tr>
<tr>
<td>(T1: \tilde{g} \rightarrow q\tilde{\chi}^0) MT2, 1.1 fb(^{-1}), gluino</td>
</tr>
<tr>
<td>(T2: \tilde{g} \rightarrow q\tilde{\chi}^0) (\alpha_T, 1.1\text{ fb}^{-1}, \text{squark})</td>
</tr>
<tr>
<td>(T2: \tilde{g} \rightarrow q\tilde{\chi}^0) (E_T + \text{jets}, 1.1\text{ fb}^{-1}, \text{squark})</td>
</tr>
<tr>
<td>(T1b) (\tilde{g} \rightarrow b\tilde{\chi}^0) (E_T + b, 1.1\text{ fb}^{-1}, \text{gluino})</td>
</tr>
<tr>
<td>(T1b) (\tilde{g} \rightarrow b\tilde{\chi}^0) MT2, 1.1 fb(^{-1}), gluino</td>
</tr>
<tr>
<td>(T1) (\tilde{g} \rightarrow \tilde{q}\tilde{\chi}^0) (l^\pm l^\pm, 0.98\text{ fb}^{-1}, \text{gluino})</td>
</tr>
<tr>
<td>(T1) (\tilde{g} \rightarrow \tilde{q}\tilde{\chi}^0) (l^\pm l^\pm, 0.98\text{ fb}^{-1}, \text{gluino})</td>
</tr>
<tr>
<td>(T2) (\tilde{g} \rightarrow \tilde{q}\tilde{\chi}^0) (l^\pm l^\pm, 0.98\text{ fb}^{-1}, \text{gluino})</td>
</tr>
<tr>
<td>(T2) (\tilde{g} \rightarrow \tilde{q}\tilde{\chi}^0) (l^\pm l^\pm, 0.98\text{ fb}^{-1}, \text{gluino})</td>
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<tr>
<td>(T2) (\tilde{g} \rightarrow \tilde{q}\tilde{\chi}^0) (l^\pm l^\pm, 0.98\text{ fb}^{-1}, \text{gluino})</td>
</tr>
</tbody>
</table>

For limits on \(m(\tilde{g}), m(\tilde{q}) > m(\tilde{\chi})\) (and vice versa), \(\sigma_{\text{mod}} = \sigma_{\text{mod}}^{\tilde{\chi}_0, \tilde{\chi}_0}\).

\(m(\tilde{\chi}^0)\) is varied from 0 GeV/c\(^2\) (dark blue) to \(m(\tilde{g})\sim 200\text{ GeV}/c^2\) (light blue).
Search for SUSY using Razor variables \( \sim 1 \text{ fb}^{-1} \)

- Search for pair production heavy particles
  - squarks and gluinos
- Objects grouped into two “megajets”
  - perform event-by-event test that they represent visible portion of decays
- Use two kinematic variables: \( M_R \) and \( R \)
  - Evaluated in *razor* frame:
    - \( M_R \) is invariant under this longitudinal boost
    \[
    M_R \equiv \sqrt{(E_{j1} + E_{j2})^2 - (p_{z1}^1 + p_{z2}^2)^2}.
    \]
    \( \Rightarrow \) \( M_R \) peaks at \( M_\Delta \)
  - \( M_\Delta \) edge in \( M_T^R \)
    \[
    M_T^R \equiv \sqrt{\mathbb{H}_T (p_T^{j1} + p_T^{j2}) - \mathbb{H}_T \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})} \]
    \( \Rightarrow \) \( M_\Delta \) edge in \( M_T^R \)
  - \( R \) is ratio of the two and related to MET
    \[
    R \equiv \frac{M_T^R}{M_R}.
    \]
Search for SUSY using Razor variables

- **Search is done in 2D:** $R^2$ & $M_R$
  - Backgrounds expected to fall exponentially in both variables
  - Signal would ~ peak in $M_R$
- **Background modeling based on data**
- **Shapes predicted from 2D fit to low $(M_R, R^2)$ in multi-jet, lepton & dilepton control samples**
  - Extrapolate to signal region

![Graphs and plots showing search results](image)

**Limit in CMSSM $\rightarrow$ plane**

**Update on Searches for New Physics in CMS**
E. Halkiadakis

CMS PAS-SUS-11-008 ~1 fb$^{-1}$
Multileptons ($e, \mu, \tau$)

- A universal low-background signature ($\geq 3$ leptons)
  - R-Parity-conserving & RPV-SUSY
    - GMSB, mSUGRA/EWK production
    - high $\tan\beta$ (with tau’s)
  - (Fermiophobic) Higgs
  - 4$^{th}$ generation (b’) (with b tags), See-saw...
- Search: $\geq 3$ e,\(\mu\),\(\tau\) with or w/o $H_T$, MET & on-Z/off-Z, binned in $S_T$
- Backgrounds: Drell Yan, ttbar, Dibosons (irreducible)
  - With high statistics: ttW, ttZ, WH, ttH (!!!)
- A broad model-independent multichannel search
- Exclusive channels ordered by SM background
  - Large background channels also control (validation) regions
Multileptons ($e, \mu, \tau$)

A surprise on the way to the result: Internal conversion background

Asymmetric internal (Dalitz) conversion of FSR from Z followed by the loss of soft lepton

Affects mostly an on-Z control channel for this analysis

But corresponding $W\gamma^*$ internal conversion affects H to WW search (Now being taken into account by CMS and ATLAS)
Multileptons \((e, \mu, \tau)\)

Many channels explored – overall agreement with SM predictions.

Example bin: \(3(e/\mu)\) channel \(S_T\) distributions

CMS Preliminary \(\sqrt{s} = 7\) TeV, \(L_{int} = 2.1\) fb\(^{-1}\)

![Graphs showing \(S_T\) distributions for ON Z and OFF Z channels.](image)
Interpretation of Multileptons

Sensitive to gluino-squark production via q-g and g-g interactions

RP conserving limit in gluino-wino-like chargino plane (left)

RPV limit in the squark-gluino plane (right)

\[ \sqrt{s} = 7 \text{ TeV}, \quad L_{\text{int}} = 2.1 \text{ fb}^{-1} \]

slepton co-NLSP scenario

Leptonic RPV: \( \lambda_{123} = \lambda_{\text{e} \mu \tau} \)
Search for SUSY in Z + jets + MET events

Two complementary searches: MET and JetZBalance

Backgrounds: dominantly top (predicted from $e\mu$ events) and $Z+$jets (use MET templates or JZB symmetry)

**MET Search**

CMS Preliminary $\sqrt{s} = 7$ TeV, $L_{\text{int}} = 4.7$ fb$^{-1}$

**JZB Search**

CMS, $\sqrt{s} = 7$ TeV, $L_{\text{int}} = 4.7$ fb$^{-1}$

Preliminary

$JZB = \left| -E_T^{\text{miss}} - \overline{p}_T^{(Z)} - \overline{\overline{p}}_T^{(Z)} \right|$
Interpretation of Results

• Good agreement with SM \( \rightarrow \) set upper limits on SMS scenarios

• Scenario inspired by mSUGRA where the LSP is the lightest neutralino
  – Results are parameterized as a function of the gluino and the LSP masses
  – Mass of the intermediate neutralino is
    \[ M(\chi_2) = M(\text{LSP}) + x \left( M(\text{glu}) - M(\text{LSP}) \right) \]
    – \( x = 0.5 \) and \( x = 0.75 \)

• Also consider scenario inspired by GMSB where the LSP is the gravitino
  – Results are parametrized as a function of the gluino and neutralino masses

• We also provide additional information for model testing
  – Generator level efficiencies as a function of JZB and MET
Limits on Neutralino LSP Scenario

**JZB Search**
Signal efficiency, including acceptance, for JZB>150GeV (left)
Cross section limit (right)

**MET Search**
Signal efficiency, including acceptance, for MET>100GeV (left)
Cross section limit (right)
Conclusions

• Rich program of searches for physics beyond the SM
• Many analyses performed with \( \sim 1 - 4.7 \text{ fb}^{-1} \)
  – Lots more analyses with full dataset coming for Moriond
  – Preparing for 2012 run
• Advanced analysis techniques
• Stringent limits on many benchmark models
• No evidence of new physics yet
  – Keep looking until either we find something
  – The exploration of Terascale physics has only just started!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
Backup
Paired Dijet Resonances

QCD with and without $\Delta$ cut

CMS Simulation

QCD Simulation
- w/o $\Delta > 25$ GeV
- with $\Delta > 25$ GeV

Arbitrary Unit

Paired dijet average mass (GeV)
Black Holes

N = 2 and N = 3. Fit $S_T$ between 1200 and 2800 GeV
Razor frame

longitudinal boost (R-frame)

R-frame \sim \text{CM frame}

\begin{align*}
m_j1 & \quad m_j2 \\
\hat{q}_1 & \quad \hat{q}_2
\end{align*}

beam axis

\begin{align*}
j_1 & \quad j_2 \\
j_3
\end{align*}

\begin{align*}
\text{MET} & \quad \text{beam axis}
\end{align*}

\begin{align*}
\beta_T^{\text{CM}} & \quad -\beta_T^{\text{CM}} \\
\beta_L^{\text{R}*} & \quad -\beta_L^{\text{R}*}
\end{align*}

\begin{align*}
p_{j1} & \quad p_{j1} \\
p_{j2} & \quad p_{j2}
\end{align*}

\begin{align*}
p_{R,j1} & \quad p^*_j1 \\
p_{R,j2} & \quad p^*_j2
\end{align*}

RAZOR CONDITION

|p_{R,j1}| = |p_{R,j2}|
Multileptons

<table>
<thead>
<tr>
<th>Selection</th>
<th>N(τ)=0 expected SM</th>
<th>N(τ)=1 expected SM</th>
<th>N(τ)=2 expected SM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>obs</td>
<td>obs</td>
<td>obs</td>
</tr>
<tr>
<td>≥FOUR Lepton Results</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>MET&gt;50, H_T &gt; 200, noZ</td>
<td>0 0.003 ± 0.002</td>
<td>0 0.01 ± 0.05</td>
<td>0 0.30 ± 0.22</td>
</tr>
<tr>
<td>MET&gt;50, H_T &gt; 200, Z</td>
<td>0 0.06 ± 0.04</td>
<td>0 0.13 ± 0.10</td>
<td>0 0.15 ± 0.23</td>
</tr>
<tr>
<td>MET&gt;50, H_T &lt; 200, noZ</td>
<td>1 0.014 ± 0.005</td>
<td>0 0.22 ± 0.10</td>
<td>0 0.59 ± 0.25</td>
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<tr>
<td>MET&gt;50, H_T &lt; 200, Z</td>
<td>0 0.43 ± 0.15</td>
<td>2 0.91 ± 0.28</td>
<td>0 0.34 ± 0.15</td>
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<tr>
<td>MET&lt;50, H_T &gt; 200, noZ</td>
<td>0 0.0013 ± 0.0008</td>
<td>0 0.01 ± 0.05</td>
<td>0 0.18 ± 0.07</td>
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<tr>
<td>MET&lt;50, H_T &gt; 200, Z</td>
<td>1 0.28 ± 0.11</td>
<td>0 0.13 ± 0.10</td>
<td>0 0.52 ± 0.19</td>
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<tr>
<td>MET&lt;50, H_T &lt; 200, noZ</td>
<td>0 0.08 ± 0.03</td>
<td>4 0.73 ± 0.20</td>
<td>6 6.9 ± 3.8</td>
</tr>
<tr>
<td>MET&lt;50, H_T &lt; 200, Z</td>
<td>11 9.5 ± 3.8</td>
<td>14 5.7 ± 1.4</td>
<td>39 21 ± 11</td>
</tr>
<tr>
<td>THREE Lepton Results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MET&gt;50, H_T &gt; 200, no-OSSF</td>
<td>2 0.87 ± 0.33</td>
<td>21 14.3 ± 4.8</td>
<td>12 10.4 ± 2.2</td>
</tr>
<tr>
<td>MET&gt;50, H_T &lt; 200, no-OSSF</td>
<td>4 3.7 ± 1.2</td>
<td>88 68 ± 17</td>
<td>76 100 ± 17</td>
</tr>
<tr>
<td>MET&lt;50, H_T &gt; 200, no-OSSF</td>
<td>1 0.50 ± 0.33</td>
<td>12 7.7 ± 2.3</td>
<td>22 24.7 ± 4.0</td>
</tr>
<tr>
<td>MET&lt;50, H_T &lt; 200, no-OSSF</td>
<td>7 5.0 ± 1.7</td>
<td>245 208 ± 39</td>
<td>976 1157 ± 323</td>
</tr>
<tr>
<td>MET&gt;50, H_T &gt; 200, noZ</td>
<td>5 1.9 ± 0.5</td>
<td>7 10.8 ± 3.3</td>
<td>- -</td>
</tr>
<tr>
<td>MET&gt;50, H_T &gt; 200, Z</td>
<td>8 8.1 ± 2.7</td>
<td>10 11.2 ± 2.5</td>
<td>- -</td>
</tr>
<tr>
<td>MET&gt;50, H_T &lt; 200, noZ</td>
<td>19 11.6 ± 3.2</td>
<td>64 52 ± 13</td>
<td>- -</td>
</tr>
<tr>
<td>MET&lt;50, H_T &gt; 200, Z</td>
<td>5 2.0 ± 0.7</td>
<td>24 26.6 ± 3.3</td>
<td>- -</td>
</tr>
<tr>
<td>MET&lt;50, H_T &lt; 200, Z</td>
<td>58 57 ± 21</td>
<td>47 44.1 ± 7.0</td>
<td>- -</td>
</tr>
<tr>
<td>MET&lt;50, H_T &gt; 200, Z</td>
<td>5 8.2 ± 2.0</td>
<td>2 90 119 ± 14</td>
<td>- -</td>
</tr>
<tr>
<td>MET&lt;50, H_T &lt; 200, noZ</td>
<td>86 82 ± 21</td>
<td>2566 1965 ± 438</td>
<td>- -</td>
</tr>
<tr>
<td>MET&lt;50, H_T &gt; 200, Z</td>
<td>335 359 ± 89</td>
<td>9720 7740 ± 1698</td>
<td>- -</td>
</tr>
<tr>
<td>Totals 4L</td>
<td>13.0 10.4 ± 3.8</td>
<td>20.0 7.8 ± 1.5</td>
<td>45 30 ± 12</td>
</tr>
<tr>
<td>Totals 3L</td>
<td>536 539 ± 94</td>
<td>12894 10267 ± 1754</td>
<td>1086 1291 ± 324</td>
</tr>
</tbody>
</table>

Table 3: Results from 2.1 fb⁻¹ of 2011 data summed over electron and muon flavors. The labels going down the side refer to whether or not there are OSSF pairs, whether or not Z → ℓ⁺ℓ⁻ was excluded (noZ), and the H_T and MET requirements. Labels along the top of the table give the number of τ candidates, 0, 1, or 2. All channels are exclusive. The τ channels serve as “signal” channels for SUSY signals assuming high tan(β) values, for example.
## Multileptons

Table 2: Number of events observed in 2.1 fb$^{-1}$ data (obs), the SM expectation, and expected event counts from typical signals. The rows indicate the total number of isolated leptons in the event. The columns indicate the number of $\tau$'s among the isolated objects. The number of Drell-Yan pairs is specified by DY$n$; the $S_T$ ranges are in GeV are Low (< 300 GeV), Mid (300 < $S_T$ < 600 GeV), and High (> 600 GeV); and ZV stands for Z-Veto, indicating there are no OS/SS lepton pairs with invariant mass in the Z window. For example, the entry in row marked “3 (DY1)$S_T$(Mid)” and column marked “$\tau=1$” would be the number of three lepton events which have one opposite-sign electron or muon (same flavor) pair in it, one tau candidate and the total event $S_T$ in the 300 to 600 GeV range. The channel right above it requires a Z-veto in addition, and thus suffers from significantly less background. The channels are exclusive, i.e., non-overlapping. The column labeled sigA is for the L-RPV signal with $\lambda_{123}$ coupling for squark and gluino masses of 1100 GeV/c$^2$ and 1000 GeV/c$^2$, while the column labeled sigB is for $\lambda_{123}$, 1000 GeV/c$^2$ and 1100 GeV/c$^2$, respectively. Note that the shift in signal between $\tau=0$ and $\tau=1$ channels because $\lambda_{123}$ is tau rich. The totals at the bottom are for informational purposes.

<table>
<thead>
<tr>
<th># Bodies (Selection)</th>
<th>obs</th>
<th>SM</th>
<th>sigA</th>
<th>sigB</th>
<th>obs</th>
<th>SM</th>
<th>sigA</th>
<th>sigB</th>
<th>obs</th>
<th>SM</th>
<th>sigA</th>
<th>sigB</th>
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</thead>
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<td>&gt; FOUR Lepton Results</td>
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</tr>
<tr>
<td>4 (DY1)$S_T$(High)</td>
<td>0</td>
<td>0.0000 ± 0.0007</td>
<td>2.9</td>
<td>0.3</td>
<td>0</td>
<td>0.00 ± 0.09</td>
<td>2.0</td>
<td>2.5</td>
<td>0</td>
<td>0.09 ± 0.07</td>
<td>0.5</td>
<td>7.0</td>
</tr>
<tr>
<td>4 (DY1)$S_T$(Mid)</td>
<td>0</td>
<td>0.0011 ± 0.0002</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.11 ± 0.10</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.68 ± 0.30</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>4 (DY1)$S_T$(Low)</td>
<td>0</td>
<td>0.02 ± 0.02</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>1.69 ± 0.27</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>1.54 ± 0.41</td>
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<tr>
<td>4 (DY1,ZV)$S_T$(High)</td>
<td>1</td>
<td>0.002 ± 0.001</td>
<td>12.6</td>
<td>1.1</td>
<td>0</td>
<td>0.02 ± 0.07</td>
<td>6.1</td>
<td>5.5</td>
<td>0</td>
<td>0.10 ± 0.07</td>
<td>0.7</td>
<td>2.4</td>
</tr>
<tr>
<td>4 (DY1)$S_T$(High)</td>
<td>1</td>
<td>0.010 ± 0.004</td>
<td>2.9</td>
<td>0.4</td>
<td>0</td>
<td>0.22 ± 0.10</td>
<td>1.6</td>
<td>1.8</td>
<td>0</td>
<td>0.15 ± 0.07</td>
<td>0.0</td>
<td>0.3</td>
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<tr>
<td>4 (DY1,ZV)$S_T$(Mid)</td>
<td>0</td>
<td>0.008 ± 0.003</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.20 ± 0.09</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.45 ± 0.19</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4 (DY1,ZV)$S_T$(Low)</td>
<td>0</td>
<td>0.027 ± 0.011</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>1.38 ± 0.38</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.83 ± 0.44</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4 (DY1,ZV)$S_T$(Low)</td>
<td>0</td>
<td>0.03 ± 0.01</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>2.2 ± 0.14</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>10.0 ± 7.8</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>4 (DY1)$S_T$(Low)</td>
<td>0</td>
<td>0.05 ± 0.013</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>6.6 ± 1.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>56.3 ± 22.0</td>
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<td>0.0</td>
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<tr>
<td>4 (DY1,ZV)$S_T$(High)</td>
<td>0</td>
<td>0.005 ± 0.002</td>
<td>7.7</td>
<td>0.8</td>
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<tr>
<td>4 (DY1)$S_T$(High)</td>
<td>0</td>
<td>0.03 ± 0.013</td>
<td>3.9</td>
<td>0.5</td>
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<tr>
<td>4 (DY1,ZV)$S_T$(Mid)</td>
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<td>0.022 ± 0.009</td>
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<tr>
<td>4 (DY2)$S_T$(High)</td>
<td>1</td>
<td>0.022 ± 0.009</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>4 (DY1)$S_T$(Low)</td>
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<td>0.04 ± 0.02</td>
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<tr>
<td>3 (DY1,ZV)$S_T$(Low)</td>
<td>0</td>
<td>0.05 ± 0.02</td>
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<tr>
<td>3 (DY1)$S_T$(Low)</td>
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<td>0.07 ± 0.02</td>
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<tr>
<td>THREE Lepton Results</td>
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<tr>
<td>3 (DY1)$S_T$(High)</td>
<td>2</td>
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<td>5.5 ± 1.9</td>
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<td>10</td>
<td>15.3 ± 3.6</td>
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<td>6.6</td>
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<tr>
<td>3 (DY1)$S_T$(Mid)</td>
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<td>3.8 ± 1.5</td>
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<td>63</td>
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<td>106</td>
<td>114 ± 16</td>
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<tr>
<td>3 (DY1)$S_T$(Low)</td>
<td>9</td>
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<td>31</td>
<td>236 ± 42</td>
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<td>0.0</td>
<td>1590</td>
<td>2054 ± 404</td>
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<tr>
<td>3 (DY1)$S_T$(High)</td>
<td>4</td>
<td>1.34 ± 0.40</td>
<td>19.9</td>
<td>8.4</td>
<td>5</td>
<td>8.8 ± 1.6</td>
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<tr>
<td>3 (DY1)$S_T$(Mid)</td>
<td>8</td>
<td>7.9 ± 2.6</td>
<td>3.2</td>
<td>2.4</td>
<td>21</td>
<td>18.5 ± 2.7</td>
<td>0.3</td>
<td>0.7</td>
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<tr>
<td>3 (DY1)$S_T$(Low)</td>
<td>20</td>
<td>10.2 ± 2.8</td>
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<td>0.0</td>
<td>71</td>
<td>64 ± 12</td>
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<tr>
<td>3 (DY1)$S_T$(High)</td>
<td>31</td>
<td>43 ± 13</td>
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<td>0.0</td>
<td>216</td>
<td>222 ± 23</td>
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<tr>
<td>3 (DY1)$S_T$(Mid)</td>
<td>88</td>
<td>85 ± 21</td>
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<td>2579</td>
<td>2004 ± 441</td>
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<tr>
<td>3 (DY1)$S_T$(Low)</td>
<td>368</td>
<td>381 ± 92</td>
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<td>9611</td>
<td>7839 ± 1725</td>
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<tr>
<td>Totals</td>
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<td>549 ± 95</td>
<td>59.0</td>
<td>17.0</td>
<td>12897</td>
<td>10456 ± 1791</td>
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<td>37.0</td>
<td>1977</td>
<td>2228 ± 405</td>
<td>2.0</td>
<td>16.0</td>
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<tr>
<td>Totals 4L</td>
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<td>10.4 ± 3.1</td>
<td>29.9</td>
<td>3.1</td>
<td>20</td>
<td>12.4 ± 2.1</td>
<td>9.7</td>
<td>9.8</td>
<td>72</td>
<td>44 ± 23</td>
<td>1.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Totals 3L</td>
<td>533</td>
<td>530 ± 95</td>
<td>29.0</td>
<td>14.0</td>
<td>12667</td>
<td>10443 ± 1791</td>
<td>7.0</td>
<td>27.0</td>
<td>1706</td>
<td>2184 ± 404</td>
<td>0.0</td>
<td>7.0</td>
</tr>
</tbody>
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