Dark Matter Searches at CMS

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SUSY and Non-SUSY search in aspect of dark matter (e.g. SUSY stop and others)

TAMU Workshop on Dark Matter, March 8-10, 2013

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Outline

• CMS and LHC (photos)

• Introduction to CMS in 2 minutes (selected plots)
  – Higgs, Dimuon, W/Z, top, dijets

• Dark matter in monoX channels
  – $X = \text{photon, jets, } Z, W, \text{ top}$

• Dark matter in SUSY
  – CMSSM and SMS
    – Light stop and EWKino

• Conclusions
CMS Collaboration

3275 physicists (1535 students)
790 engineers
179 institutes
41 countries

Photo: Summer 2012
LHC pp Data

2010  7 GeV  35 pb⁻¹
2011  7 GeV  5 fb⁻¹
2012  8 GeV  20 fb⁻¹
2015-2017  14 TeV  200 fb⁻¹
Introduction to CMS

Selected Plots on Particle Productions at the LHC

http://cms.web.cern.ch/org/cms-papers-and-results
Higgs

Mass in ZZ(4leptons)

Mass = 125.8 +/- 0.5 (stat) +/- 0.2 (syst) GeV

Studies in progress: spin-parity, couplings

Moriond2013  M.Chen
http://cms.web.cern.ch/org/cms-papers-and-results

http://cms.web.cern.ch/org/cms-papers-and-results
Dimuon Signal in Compact Muon Solenoid

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
Weak Bosons

Production Cross Section, $\sigma_{\text{tot}}$ [pb]

- $W$: $\geq 1j$
  - $E_T^{\text{jet}} > 30$ GeV
  - $|\eta^{\text{jet}}| < 2.4$
  - 36, 19 pb$^{-1}$

- $Z$: $\geq 1j$
  - $E_T^{\gamma} > 15$ GeV
  - $\Delta R(\gamma, l) > 0.7$

- $W^\gamma$: $\geq 2j$
  - $E_T^{\gamma} > 15$ GeV
  - $\Delta R(\gamma, l) > 0.7$

- $Z^\gamma$: $\geq 3j$

- $W_\gamma$: $\geq 4j$

- $W W + W Z$: $\geq 4j$

- $W W$: $\geq 4j$
  - 5.0 fb$^{-1}$
  - 3.5 fb$^{-1}$
  - 1.1 fb$^{-1}$
  - 4.9 fb$^{-1}$

- $W Z$: $\geq 4j$
  - 4.9 fb$^{-1}$
  - 5.3 fb$^{-1}$

- $Z Z$: $\geq 4j$

7 TeV CMS measurement (stat + syst)
8 TeV CMS measurement (stat + syst)
7 TeV Theory prediction
8 TeV Theory prediction

References:
- JHEP10(2011)132
- JHEP01(2012)010
- CMS-PAS-SMP-12-011 (W/Z 8 TeV)
- CMS EWK-11-009
- CMS-PAS-EWK-11-010 (WZ)
- CMS-PAS-EWK-11-015 (WW7), 007(ZZ7), 013(WW8), 014(ZZ8), 015(WV)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

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Dark Matter Searched at CMS
TOP

Mass: 173.4 +/- 0.4 +/- 0.9 GeV

\( \sigma(tt): \) 136 pb (7 TeV)  
227 pb (8 TeV)

\( \sigma(t) : \) 67.2 pb (7 TeV) t-channel

http://cms.web.cern.ch/org/cms-papers-and-results
Dark Matter Searched at CMS

CMS Preliminary
\( \sqrt{s} = 8 \text{ TeV} \), \( L = 19.6 \text{ fb}^{-1} \)
\( |\eta| < 2.5 \), \( |\Delta \eta| < 1.3 \)
\( m_{jj} > 890 \text{ GeV} \), Wide Jets

http://cms.web.cern.ch/org/cms-papers-and-results
Dark Matter Searches in CMS

- Direct production of dark matter: (monoX + MET channels)
  - Monophoton (photon+MET) 1204.0821, PRL 108 (2012) 261803
  - Monojet (jets+MET) 1206.5663, JHEP09 (2012) 094
  - MonoW, MonoZ, MonoTop

- SUSY: LSP (lightest susy particle) is dark matter candidate
  - Search in CMSSM (Constrained Minimal Supersymmetric Standard Model)
    - Cascade decays
  - Search in SMS (Simplified Model Spectra)
    - Main parameters: masses of a few particles and decay modes
  - Light stop productions and decays
  - Light EWKino productions (via VBF) and decays

- Invisible Higgs - not discuss today -
  - Higgs decaying to SUSY LSP or 4th generation neutrino
  - Measure BR(H→χχ)
Dark Matter in MonoX

\[ q \xrightarrow{\text{g or } \gamma} W, Z \quad \text{(and top)} \]

\[ \bar{q} \quad \chi \]

\[ \bar{\chi} \]
Dark Matter Searches

1. Direct Detection Experiments
   - Dark Matter-nucleus scattering.
   - Low mass DM particles not probed yet.
   - Less sensitive to spin-dependent coupling.
   - XENON-100, CDMS, CoGeNT

2. Indirect Detection Experiments
   - Observe annihilation products.
   - Low mass DM particles not accessible.
   - Depends on DM density and annihilation model.
   - Super-Kamiokande, IceCube, Fermi-LAT, AMS2

3. Collider Experiments
   - Laboratory production of DM particles.
   - Sensitive to wide mass range.
   - Both spin-dependent and spin-independent couplings.
   - Tevatron, LHC

Strong evidences for the existence of dark matter. Needs independent verifications from various astrophysical and non-astrophysical experiments.
Search for Dark matter in monojet

MET 913 GeV

Low pt tracks are filtered out in this display.
Monojet Analysis

Event selection:

- MET > 250 - 550 GeV
- njets = 1 or 2 for $pt(jet)>30$ GeV
- no back-to-back jet, $\Delta\phi(J1,J2)<2.5$
- no lepton

Signal selection:

- MET cut, i.e. $Pt(\chi\chi)$, allowing jet split.

Background:

- $Z\nu\nu$ and $W_{e\nu,\mu\nu,\tau\nu}$ are major background and estimated using $Z\mu\mu$ and $W\mu\nu$ events.

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Dark Matter Search
Results (8 TeV, 19.5 fb$^{-1}$)

Event selection: (major cuts)
- $\text{MET} > 250 - 550 \text{ GeV}$
- $\Delta \phi(J1,J2) < 2.5$ for $p_t(J) > 30\text{ GeV}$
- no lepton ($p_t > 10 \text{ GeV}$)

Background ($> 400\text{ GeV}$)
- $Z\nu\nu$ 70%
- $W/\nu$ 29%
- others 1%

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV) \彪</th>
<th>$&gt; 250$</th>
<th>$&gt; 300$</th>
<th>$&gt; 350$</th>
<th>$&gt; 400$</th>
<th>$&gt; 450$</th>
<th>$&gt; 500$</th>
<th>$&gt; 550$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\nu\nu)$+jets</td>
<td>30600 ± 1493</td>
<td>12119 ± 640</td>
<td>5286 ± 323</td>
<td>2569 ± 188</td>
<td>1394 ± 127</td>
<td>671 ± 81</td>
<td>370 ± 58</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>17625 ± 681</td>
<td>6042 ± 236</td>
<td>2457 ± 102</td>
<td>1044 ± 51</td>
<td>516 ± 31</td>
<td>269 ± 20</td>
<td>128 ± 13</td>
</tr>
<tr>
<td>$tt$</td>
<td>470 ± 235</td>
<td>175 ± 87.5</td>
<td>72 ± 36</td>
<td>32 ± 16</td>
<td>13 ± 6.5</td>
<td>6 ± 3.0</td>
<td>3 ± 1.5</td>
</tr>
<tr>
<td>$Z(\ell\ell)$+jets</td>
<td>127 ± 63.5</td>
<td>43 ± 21.5</td>
<td>18 ± 9.0</td>
<td>8 ± 4.0</td>
<td>4 ± 2.0</td>
<td>2 ± 1.0</td>
<td>1 ± 0.5</td>
</tr>
<tr>
<td>Single t</td>
<td>156 ± 78.0</td>
<td>52 ± 26.0</td>
<td>20 ± 10.0</td>
<td>7 ± 3.5</td>
<td>2 ± 1.0</td>
<td>1 ± 0.5</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>QCD Multijets</td>
<td>177 ± 88.5</td>
<td>76 ± 38.0</td>
<td>23 ± 11.5</td>
<td>3 ± 1.5</td>
<td>2 ± 1.0</td>
<td>1 ± 0.5</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Total SM</td>
<td>49154 ± 1663</td>
<td>18506 ± 690</td>
<td>7875 ± 341</td>
<td>3663 ± 196</td>
<td>1931 ± 131</td>
<td>949 ± 83</td>
<td>501 ± 59</td>
</tr>
<tr>
<td>Data</td>
<td>50419</td>
<td>19108</td>
<td>8056</td>
<td>3677</td>
<td>1772</td>
<td>894</td>
<td>508</td>
</tr>
<tr>
<td>Exp. upper limit</td>
<td>3580</td>
<td>1500</td>
<td>773</td>
<td>424</td>
<td>229</td>
<td>165</td>
<td>125</td>
</tr>
<tr>
<td>Obs. upper limit</td>
<td>4695</td>
<td>2035</td>
<td>882</td>
<td>434</td>
<td>157</td>
<td>135</td>
<td>131</td>
</tr>
</tbody>
</table>
Monojet: Limits on $\Lambda$

$$\sigma(pp \rightarrow \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2$$

$$\Lambda \equiv \frac{M}{\sqrt{g_\chi g_q}}$$

$$\mathcal{O}_V = \frac{(\bar{\chi} \gamma_\mu \chi)(\bar{q} \gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O}_A = \frac{(\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{q} \gamma^\mu \gamma_5 q)}{\Lambda^2}$$

$\Lambda \approx \frac{1}{\Lambda^4} E^2$ for $M \rightarrow 40$ TeV (EFT)

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**Graphs:**

**CMS Preliminary**

$\sqrt{s} = 8$ TeV

$$\int L dt = 19.5$ fb$^{-1}$

- **Red** CMS 2012 Vector
- **Blue** CMS 2011 Vector

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**Graphs:**

**CMS Preliminary**

$\sqrt{s} = 8$ TeV

$$\int L dt = 19.5$ fb$^{-1}$

- **Red** CMS 2012 Axial Vector
- **Blue** CMS 2011 Axial Vector
**χ-Nucleon Scattering Cross Sections**

Interpretation from $\Lambda$ limits.

![Graph showing cross sections](image)

**Results:**

- CMS Preliminary
  - $\sqrt{s} = 8$ TeV
  - $\int L \, dt = 19.5 \, fb^{-1}$

- Spin Independent
  - CMS 2012 Vector
  - CMS 2011 Vector
  - CDF 2012
  - XENON-100 2012
  - COUPP 2012
  - SIMPLE 2012
  - CoGeNT 2011
  - CDMSII 2011
  - CDMSII 2010

- Spin Dependent
  - CMS 2012 Axial Vector
  - CMS 2011 Axial Vector
  - CDF 2012
  - SIMPLE 2012
  - CDMSII 2011
  - COUPP 2012
  - Super-K W$^+W^-$
  - IceCube W$^+W^-$

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Dark Matter Searched at CMS
Dependence on Mediator Mass and Width $\Gamma$

CMS Preliminary

$\sqrt{s} = 8$ TeV

$\int L \, dt = 19.5$ fb$^{-1}$

90% CL limit on $\Lambda$ [GeV]

- $m_\chi = 500$ GeV/c$^2$, $\Gamma = M/3$
- $m_\chi = 500$ GeV/c$^2$, $\Gamma = M/10$
- $m_\chi = 500$ GeV/c$^2$, $\Gamma = M/8\pi$
- $m_\chi = 50$ GeV/c$^2$, $\Gamma = M/3$
- $m_\chi = 50$ GeV/c$^2$, $\Gamma = M/10$
- $m_\chi = 50$ GeV/c$^2$, $\Gamma = M/8\pi$

1109.4393 showed this scan with ATLAS 1 fb$^{-1}$ results

Spin Independent Cross sections

- $2.5^{-41}$ cm$^2$
- $6.0^{-41}$ cm$^2$
- $1.9^{-40}$ cm$^2$
- $9.7^{-40}$ cm$^2$
- $1.5^{-39}$ cm$^2$

EFT calculation on previous page used mediator mass = 40 TeV In Madgraph
Long Lived Particles in monojet

Inelastic dark matter

Small $\Delta M = M(\chi^*) - M(\chi)$

$\Rightarrow$ “long” life time

Signature:

monojet +
decay vertex

$\mathcal{O}_1 = \frac{[\bar{u} \gamma_\mu \gamma_5 u] [\bar{\chi}^* \gamma^\mu \gamma_5 \chi]}{\Lambda_1^2}$,

$\mathcal{O}_2 = \frac{[\bar{u} \gamma_5 u] [\bar{\chi}^* \gamma_5 \chi]}{\Lambda_2^2}$,

$\mathcal{O}_3 = \frac{[\bar{u} u] [\bar{\chi}^* \chi]}{\Lambda_3^2}$,

$\mathcal{O}_4 = \frac{[\bar{u} \gamma_\mu u] [\bar{\chi}^* \gamma^\mu \chi]}{\Lambda_4^2}$.
Other Mono Signatures

1209.0231 monoZ
1212.3352

1208.4361 monoW

1302.3619 “Mono-everything …. ”
Discussing combined limits.

1106.6199 monoTop
1109.5963

1202.5653 CDF MonoTop results
Look for LSP ($\chi$) in SUSY
CMSSM and dark matter

Constrained MSSM

- Five parameters
  $m_0$, $m_{1/2}$, $\tan \beta$, $A_0$, sign($\mu$)

- LSP: neutralino
dark matter candidate

Dark matter relic density

WMAP preferred range
$0.102 < \Omega \chi h^2 < 0.123$
(green area)

1202.6580
Fits to Data: CMSSM and NUHM1

Data used:
- ATLAS, CMS
- $\text{BR}(\text{Bs} \rightarrow \mu^+\mu^-)$ from ATLAS, CDF, CMS, LHCb(*)
- XENON100

CMSSM (constrained MSSM)
- red: 95%CL
- blue: 68%CL
- dashed: LHC 1fb$^{-1}$

NUMH1 (non-universal Higgs mass)

http://mastercode.web.cern.ch/mastercode/

(*) New LHCb result (1211.2674) does not change favored regions significantly.
CMSSM
(constrained MSSM)

red: 95%CL
blue: 68%CL
dashed: LHC 1 fb⁻¹

NUMH1
(non-universal Higgs mass)

LSP
Simplified Model Spectra (SMS)

- **SMS limited a few new particles and 2-3 body decay chains**
  - New particles: gluino, squark, chargino, neutralino etc. (same name as SUSY particles)
  - Main parameters: masses and decay branching ratios

- **Set limits on SMS masses**
  - Assume SUSY production cross sections
  - Can be used as references and translated to different theoretical models

Examples:

- **T1**

- **T2tt**
# Excluded Mass Ranges (SMS)

## CMS preliminary

### $M(\text{mother}) - m(\text{LSP}) = 200 \text{ GeV}$ | $m(\text{LSP}) = 0 \text{ GeV}$

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Mass Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$: $\tilde{g} \to q\bar{q}\chi^0$</td>
<td>gluino</td>
</tr>
<tr>
<td>$T_1 bbbb$: $\tilde{g} \to b\bar{b}\chi^0$</td>
<td>gluino</td>
</tr>
<tr>
<td>$T_1 tttt$: $\tilde{g} \to t\bar{t}\chi^0$</td>
<td>gluino</td>
</tr>
<tr>
<td>$T_2$: $\tilde{q} \to q\chi^0$</td>
<td>squark</td>
</tr>
<tr>
<td>$T_2 bbb$: $\tilde{b} \to b\chi^0$</td>
<td>sbottom</td>
</tr>
<tr>
<td>$T_2 tt$: $\tilde{t} \to t\chi^0$</td>
<td>stop</td>
</tr>
<tr>
<td>$T_3 l$: $\tilde{g} \to q\bar{q}(\chi^0_2 \to t^+t^-\chi^0_1)$</td>
<td>gluino</td>
</tr>
<tr>
<td>$T_3 w$: $\tilde{g} \to q\bar{q}(\tilde{\chi}^\pm \to W\chi^0_1 \chi^0_1)$</td>
<td>gluino</td>
</tr>
<tr>
<td>$T_5 lnu$: $\tilde{\chi}^\pm \to l^\pm \nu\chi^0_1$</td>
<td>gluino</td>
</tr>
<tr>
<td>$T_5 zz$: $\tilde{g} \to q\bar{q}(\chi^0_2 \to Z\chi^0_1)$</td>
<td>gluino</td>
</tr>
<tr>
<td>$T_{\text{ChiSlepSlep}}$: $\tilde{\chi}^0_2 \tilde{\chi}^\pm \to t\bar{t}l\bar{l}\chi^0_1 \chi^0_1$</td>
<td>chargino/neutralino</td>
</tr>
<tr>
<td>$T_{\text{Chiwz}}$: $\tilde{\chi}^\pm \chi^0_2 \to WZ\chi^0_1 \chi^0_1$</td>
<td>chargino/neutralino</td>
</tr>
</tbody>
</table>

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http://cms.web.cern.ch/org/cms-papers-and-results

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Dark Matter Searched at CMS
\[ \Delta M = M(\text{stop}) - M(\text{LSP}) = 30 - 40\text{GeV} \] (green band in the plot) produces the relic abundance of B-ino LSP that consistent with the DM cosmological abundance via co-annihilation of stop – B-ino LSP.

Decays:
- \( \text{stop} \rightarrow c + \text{LSP} \)
- \( \text{stop} \rightarrow b + W^* + \text{LSP} \)

Signature:
- MET + soft jets

Plots:
- yellow – ATLAS
- light green – CMS
- red – analysis by A. Delgado et al. using CMS razor analysis method

Razor Analysis by A. Delgado et al. 1212.6847
Light stop in monojet events

Calculated from ATLAS/CMS monojet results
1211.2997  Z. Yu et al.

0808.2298, 1201.5714, 1211.2997

small
$\Delta M = M(\text{stop}) - M(\text{LSP})$

→ Soft charm jets
i.e. “invisible”

Signature:
→ monojet
VBF: SUSY EW Sectors

Light stop \rightarrow \text{direct stop production}
Light stau \rightarrow \text{direct EWKino production}
via Vector Boson Fusion

\[ \Delta M = M(\tilde{\tau}) - M(\tilde{\chi}_1^0) \rightarrow 0 \]
Effective cross sections (fb) after cuts & significance for 25 fb$^{-1}$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>$Z + \text{jets}$</td>
</tr>
<tr>
<td>VBF cuts</td>
<td>4.61</td>
</tr>
<tr>
<td>$p_T &gt; 75$, b-veto</td>
<td>4.33</td>
</tr>
<tr>
<td>$2 \tau$, inclusive</td>
<td>0.45</td>
</tr>
<tr>
<td>$(S/\sqrt{S+B})$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow \tilde{\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>$Z + \text{jets}$</td>
</tr>
<tr>
<td>VBF cuts</td>
<td>4.61</td>
</tr>
<tr>
<td>$p_T &gt; 75$, b-veto</td>
<td>4.33</td>
</tr>
<tr>
<td>$2 \mu$, inclusive</td>
<td>1.83</td>
</tr>
<tr>
<td>$(S/\sqrt{S+B})$</td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>0.87</td>
</tr>
<tr>
<td>$(S/\sqrt{S+B})$</td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^+$</td>
<td>0.96</td>
</tr>
<tr>
<td>$(S/\sqrt{S+B})$</td>
<td></td>
</tr>
</tbody>
</table>

$|\Delta\eta| > 4.2$
Vector Boson Fusion Processes as a Probe of Supersymmetric Electroweak Sectors at the LHC

Bhaskar Dutta\textsuperscript{1}, Alfredo Gurrola\textsuperscript{2}, Will Johns\textsuperscript{2}, Teruki Kamon\textsuperscript{1,3}, Paul Sheldon\textsuperscript{2}, and Kuver Sinha\textsuperscript{1}

\textsuperscript{1} Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics, Texas A\&M University, College Station, TX 77843-4242, USA
\textsuperscript{2} Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235
\textsuperscript{3} Department of Physics, Kyungpook National University, Daegu 702-701, South Korea

Vector boson fusion (VBF) processes offer a promising avenue to study the non-colored sectors of supersymmetric extensions of the Standard Model at the LHC. A feasibility study for searching for the chargino/neutralino system in the $R-$parity conserving Minimal Supersymmetric Standard Model is presented. The high $E_T$ forward jets in opposite hemispheres are utilized to trigger VBF events, so that the production of the lightest chargino $\tilde{\chi}_1^\pm$ and the second lightest neutralino $\tilde{\chi}_2^0$ can be probed without a bias by experimental triggers. Kinematic requirements are developed to search for signals of these supersymmetric states above Standard Model backgrounds in both $\tau$ and light lepton ($e$ and $\mu$) final states at $\sqrt{s} = 8$ TeV.
Conclusion

• 5 fb\(^{-1}\) and 20 fb\(^{-1}\) of pp data at 7 TeV and 8 TeV were collected in 2011 and 2012.

• Limits on dark matter have been updated with full 8 TeV data using monojet events.

• Many other analyses are in progress, for example
  – monoZ, monoW, monoTop
  – stop
  – stau in VBF

• 14 TeV run starts in 2015 and collects 200 fb\(^{-1}\) in three years.
  – Preparation for triggers and physics analyses needs to be done before the data taking starts.
  – Input to the preparation is welcome.
Additional Slides
RAZOR

- **Razor variables** $R$ and $M_R$ designed for final state topology characteristic of R-parity SUSY

- **Selection:**
  
  Group all final state objects (jets, leptons) into **two mega-jets**

\[
M_R = \sqrt{(|\vec{p}_{j1}| + |\vec{p}_{j2}|)^2 - (p_{z1}^j + p_{z2}^j)^2}
\]

\[
M_R^R = \sqrt{E_T^{\text{miss}}(p_T^{j1} + p_T^{j2}) - E_T^{\text{miss}} \cdot (p_T^{j1} + p_T^{j2})}
\]

\[
R = \frac{M_R^R}{M_R}
\]

In simple case:
- $S = $ squark
- $X = $ jet

Peaks at
\[
M_\Delta = \frac{M_S^2 - M_{\text{LSP}}^2}{M_S}
\]

Edge at $M_\Delta$

Ratio of two estimators of SUSY scale – describes transverse shape of event

M. Kazana

"SUSY at CMS", Cracow, 07.01.2013
FCNC in $B_s \rightarrow \mu\mu$

$\text{Br}(B_s \rightarrow \mu\mu) \propto$ 

$\text{Br}(B_s \rightarrow \mu\mu)$

SM \quad \sim 3 \times 10^{-9}$

SUSY \quad \sim \text{Br}(\text{SM}) \times (10 \sim 1000)$

$LHCb$

$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.2^{+1.4}_{-1.2}\text{(stat)} + 0.5\text{(syst)}) \times 10^{-9}$

ATLAS 2.4 fb^{-1}

D0 10 fb^{-1}

CMS 4.9 fb^{-1}

CDF 10 fb^{-1}

LHCb 2.1 fb^{-1}

SM Prediction

(68\% CL region)

January 2013

Candidates / (50 MeV/c^2)

5000 5500 6000

$\mu^+\mu^-$ [MeV/c^2]