“Pure logical thinking cannot yield us any knowledge of the empirical world; all knowledge of reality starts from experience and ends in it.”
A. Einstein (1933)

"I am sure we all agree that a giraffe is truly beautiful, but she doesn’t seem to serve any purpose”
J. Weiss (1974)

"Theories are like fishing: only he who casts can catch”
Novalis (1772-1801)

**Mandate:** “Cover the broad scope of the many various SUSY searches by both CMS and ATLAS at the LHC and their possible future prospects”
Part II: Status of SUSY searches at LHC & Prospects

1. R-Parity Conserving [RPC] inclusive searches
2. Natural RPC: stop, sbottom, EWK-inos
3. Long Lived particles
4. R-Parity Violating [RPV] signatures
5. Monojets ↔ Dark Matter production
6. MSSM Higgs Searches
7. Future prospects

"Theories are like fishing: only he who casts can catch"
Novalis (1772-1801)

SUSY Related papers in ATLAS/CMS*
• 2010 (7 TeV, 0.03 fb⁻¹): 12 / 10+2 papers
• 2011 (7 TeV, 1-5 fb⁻¹): 16 / 8+3

SUSY Related CONF notes in ATLAS/CMS*
• 2010 (7 TeV, 0.03 fb⁻¹): 7 / 3+0
• 2011 (7 TeV, 1-5 fb⁻¹): 25 / 16+4
• 2012 (8 TeV, 4 fb⁻¹): 0 / 3+

~ 100 analyses in 2 years!

Show most powerful 7 TeV, 1-5fb⁻¹ searches
Give general status of each topical search

All information on ATLAS/CMS Public pages:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Sus supersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

* CMS= SUSY + RPV LongLived in EXOTIC

See Dan Hooper
See Vivek Sharma
See Ulrich Heintz for 8 TeV results
Lecture Overview (2)

**Mass Spectrum**

The “Nuclear Family” of the Higgs

- $\tilde{q}_1, \tilde{b}_R, \tilde{l}$
- “Distant Cousins”

- $\tilde{t}_1, \tilde{t}_2$
- $\tilde{b}_R, \tilde{b}_L$

- $\tilde{q}_1, \tilde{q}_2, \tilde{q}_3$
- $\tilde{l}_1, \tilde{l}_2, \tilde{l}_3$

Closeness to Higgs

**Production**

- $\sigma_{\tilde{t}/\tilde{b}} [pb] : pp \rightarrow SUSY$
- $\sqrt{s} = 7 \text{ TeV}$

- $M_{\text{SUSY}}$ (GeV)

- $\Delta M$

- $\Delta m$

- (missing)

**Decay**

- $M_{\text{SUSY}}$

**Theory guide**

1. Strong production (low, high $\Delta M/M_{\text{SUSY}}$)

2. Natural spectrum

3. Degenerate masses (low $\Delta m$), tiny RPV

4. ‘Sizeable’ RPV

5. No hint. New SUSY Theories?

**Experimental side**

- Inclusive jets+MET

- Dedicated searches with bjets, multileptons, jet/Z veto

- Long Lived particles, displaced vertex/Z/\gamma

- Multileptons (inc. tau), No Z, jet/emu resonances

- Improve analysis technics, 8 TeV, 14 TeV
Inclusive searches

1. Strong production dominates (low, high $\Delta M/M_{\text{SUSY}}$) $\Rightarrow$ Inclusive jets+MET

- LSP=$\tilde{\chi}^0_1$
  - squarks/gluino cascade: 0 lepton + 1-9 jets + MET
  - squark/gluino cascade + leptonic gaugino/slepton decay: 1 lepton (e, \(\mu\)) + jets + MET

- LSP=$\tilde{\gamma}$
  - squark/gluino cascade in GMSB / GGM:
    - $\gamma +$jets +MET
    - 2 opp. Sign leptons + jets +MET (Z or non Z)
    - (1)2taus + jets +MET

$M_{\text{SUSY}}$ (GeV)

$\Delta M \sim$ MET

$H_T = \sum p_T (\text{jet}) [+ p_T (l, \gamma)]$
Inclusive searches (1)

- ‘Standard’ 0lepton + jets + MET searches : Most inclusive!
  - 0lepton: highest branching ratios generally in $\tilde{q} \rightarrow \tilde{q} \chi_1^0$ and $\tilde{g} \rightarrow q \tilde{q} \chi_1^0$
  - $\tilde{q} \tilde{q}$: 0lepton + >=2, (3, 4) jets + MET $\rightarrow$ LO, (NLO or $\chi_1^{+/-} \rightarrow q \tilde{q} \chi_1^0$)
  - $\tilde{q} \tilde{q}$: 0lepton + >=3, (4, 5) jets + MET $\rightarrow$ LO, (NLO or $\chi_1^{+/-} \rightarrow q \tilde{q} \chi_1^0$)
  - $\tilde{q} \tilde{q}$: 0lepton + >=4, (5, 6) jets + MET $\rightarrow$ LO, (NLO or $\chi_1^{+/-} \rightarrow q \tilde{q} \chi_1^0$)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>A 2j</th>
<th>A’ 2j</th>
<th>B 3j</th>
<th>C 4j</th>
<th>D 5j</th>
<th>E 6j</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}} [\text{GeV}] &gt;$</td>
<td></td>
<td></td>
<td></td>
<td>160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T(j_1) [\text{GeV}] &gt;$</td>
<td></td>
<td></td>
<td></td>
<td>130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T(j_2) [\text{GeV}] &gt;$</td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T(j_3) [\text{GeV}] &gt;$</td>
<td></td>
<td></td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$p_T(j_4) [\text{GeV}] &gt;$</td>
<td></td>
<td></td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$p_T(j_5) [\text{GeV}] &gt;$</td>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>$p_T(j_6) [\text{GeV}] &gt;$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>$\Delta \phi(\text{jet}, E_T^{\text{miss}})_{\text{min}} &gt;$</td>
<td>0.4 ($i = {1, 2, 3}$)</td>
<td>0.4 ($i = {1, 2, 3}$), 0.2 ($p_T &gt; 40$ GeV jets)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}} / N_{\text{jets}} (N_j) &gt;$</td>
<td>0.3 (2j)</td>
<td>0.4 (2j)</td>
<td>0.25 (3j)</td>
<td>0.25 (4j)</td>
<td>0.2 (5j)</td>
<td>0.15 (6j)</td>
</tr>
<tr>
<td>$m_{\text{eff (incl.)}} [\text{GeV}] &gt;$</td>
<td>1900/1200</td>
<td>1900/1200</td>
<td>1500/1200</td>
<td>1500/1200</td>
<td>1500/1200</td>
<td>1400/1200/900</td>
</tr>
</tbody>
</table>

$\Rightarrow$ 11 Signal regions split in **Tight (5)** and **Medium/Loose (6)**
Inclusive searches (2)

- **5 Tight Signal Regions cover highest $M_{\text{SUSY}}$, large $\Delta M/M_{\text{SUSY}}**
  - Background methods detailed yesterday
  - Dominated by $Z\rightarrow vv$ +jets / $t\bar{t}$bar / $W$+jets

**SR**

<table>
<thead>
<tr>
<th>SR</th>
<th>At 2j</th>
<th>Bt 3j</th>
<th>Ct 4j</th>
<th>Dt 5j</th>
<th>Et 6j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Est. back.</td>
<td>$7 \pm 0.999 \pm 2.26$</td>
<td>$5.39 \pm 0.951 \pm 2.01$</td>
<td>$5.68 \pm 1.79 \pm 1.51$</td>
<td>$6.84 \pm 1.7 \pm 2.1$</td>
<td>$12.1 \pm 4.59 \pm 3.04$</td>
</tr>
<tr>
<td>Data</td>
<td>1</td>
<td>1</td>
<td>14</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>local $p_0$ (Gaus. $\sigma$)</td>
<td>$0.98(-2.1)$</td>
<td>$0.95(-1.7)$</td>
<td>$0.018(2.1)$</td>
<td>$0.29(0.55)$</td>
<td>$0.45(0.13)$</td>
</tr>
</tbody>
</table>

= SR above the arrow

Stat competes with syst
Inclusive searches (3)

- Interpretations for high $M_{\text{SUSY}}$, large $\Delta M/M_{\text{SUSY}}$
  - No significant excess $\rightarrow$ set limits in specific model
  - For each point take the signal region that gives the best expected limit

- For $m(\text{squarks}) = m(\text{gluinos})$, set limit at $\sim 1.4 \text{ TeV}$
Inclusive searches (4)

What if low $\Delta M/M_{\text{SUSY}}$?
- 6 signal regions with Medium/Loose $M_{\text{Eff}}$ also exists

**SR’ (≥2j)**

<table>
<thead>
<tr>
<th>SR</th>
<th>CI 4j</th>
<th>EL 6j</th>
<th>A m 2j</th>
<th>A’ 2j</th>
<th>C m</th>
<th>Em 6j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Est. back.</td>
<td>$214 \pm 24.9 \pm 13$</td>
<td>$119 \pm 32.6 \pm 11.6$</td>
<td>$64.8 \pm 10.2 \pm 6.92$</td>
<td>$115 \pm 19 \pm 9.69$</td>
<td>$38.6 \pm 6.68 \pm 4.77$</td>
<td>$34 \pm 4.47 \pm 5.57$</td>
</tr>
<tr>
<td>Data</td>
<td>210</td>
<td>148</td>
<td>59</td>
<td>85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local $p_0$ (Gauss. $\sigma$)</td>
<td>$0.55(-0.14)$</td>
<td>$0.21(0.8)$</td>
<td>$0.65(-0.4)$</td>
<td>$0.9(-1.3)$</td>
<td>$0.6(-0.26)$</td>
<td>$0.85(-1)$</td>
</tr>
</tbody>
</table>

Now dominated by syst.
Inclusive searches (5)

- **Interpretations for lower ΔM/M_{SUSY}** (‘compressed spectra’)
  - Assume for example M(squarks)= 0.96 M(gluinos), a la MSUGRA

- Gaining in the compressed spectra for m(gluino)<1.2 TeV

\[ \Delta M/M_{SUSY} \approx \begin{cases} \approx 0.85 & \text{mSUGRA} \\ 0.5 & \text{PRD84 (2011) 015004, 1111.6897} \\ \approx 0.15 & \end{cases} \]
Inclusive searches (6)

- What if Meff variable is not sensitive enough or biased?
  - Use different discriminating variables: cruder MET (MHT), $\alpha_T$, $M_{T2}$

Gluino cascade (only 1\textsuperscript{st}/2\textsuperscript{nd} generation of squarks)

Near the diagonal high syst. from ISR ~30-40 \%

- Similar limit: $m($gluinos$) < 1$ TeV and $m($LSP$)<400$ GeV
Inclusive searches (7)

- What if trigger is killing our SUSY signal?

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{miss}$ [GeV]</td>
<td>A</td>
</tr>
<tr>
<td>$p_T(j_1)$ [GeV]</td>
<td>160</td>
</tr>
<tr>
<td>$E_T^{miss}/\sqrt{H_T}$</td>
<td>130</td>
</tr>
</tbody>
</table>

- Multijet trigger
  - 0 lepton + 6-9 jets, lower MET
  - QCD and ttbar all hadronic dominated
  - $g$ med. charginos ($\chi_1^{+/-} \rightarrow q\bar{q}\chi_1^0$) gives long decay chain: (6,7), 8 (9) jets

- Only MET trigger
  - Very nice complementarity with ‘standard’ 0lepton
  - Sensitive to compressed spectra, ISR tagged

See Dan Hooper

---

1. P. Pralavorio

2. SUSY Searches at LHC

3. SLAC (31/07/12)
What if ‘one’ lepton (e, \(\mu\)) is present in the decay chain?

- Generate high \(p_T\) lepton when \(\chi_1^{+/0} \rightarrow l\chi_1^0\) or intermediate slepton
  - Single lepton trigger is sufficient
  - Lower QCD multi-jet background: can remove \(\Delta\phi(j,\text{MET})\), and relax \(p_T(jets)\)

### Background estimation strategy

<table>
<thead>
<tr>
<th>High (M_{\text{SUSY}})</th>
<th>Compressed (\Delta M / M_{\text{SUSY}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>Single electron or muon (+jet)</td>
</tr>
<tr>
<td>(N_{\text{lep}})</td>
<td>1</td>
</tr>
<tr>
<td>(p_T^1) (GeV)</td>
<td>&gt; 25 (20)</td>
</tr>
<tr>
<td>(p_T^2) (GeV)</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>(N_{\text{jet}})</td>
<td>(\geq 3)</td>
</tr>
<tr>
<td>(p_T^1) (GeV)</td>
<td>&gt; 100, 25, 25</td>
</tr>
<tr>
<td>(p_T^2) (GeV)</td>
<td>&lt; 80</td>
</tr>
<tr>
<td>(E_T^{\text{miss}}) (GeV)</td>
<td>&gt; 250</td>
</tr>
<tr>
<td>(m_T) (GeV)</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>(E_T^{\text{miss}}/m_{\text{eff}})</td>
<td>&gt; 0.3</td>
</tr>
<tr>
<td>(m_{\text{eff}}) (GeV)</td>
<td>&gt; 1200</td>
</tr>
</tbody>
</table>

Background: \(5.7 \pm 4.0\) (JES) \(8.3 \pm 3.1\) (JES) \(32 \pm 11\) (JES) (Dominant Syst)

- Only Low \(p_T\)
  - 1 high \(p_T\) jet (ISR)
  - 1 low \(p_T\)
  - W killer

\(\Rightarrow\) More flexibility than in 0lepton, but lower signal BR
Inclusive searches (9)

- Quite complementary wrt 0lepton search
  - Compare by considering gluino mediated charginos

\[ m_{\chi_1^{\pm}} = \frac{(m_g + m_{\chi_0})}{2} \]

\[ \tilde{g} \rightarrow j j \tilde{\chi} \]

\[ \tilde{\chi}_0, \tilde{\chi}_1, j jv, j j j \]

\[ \chi^{\pm} \]

\[ \chi^0 \]

\[ 0\text{lepton} \]

- Slightly below 0lepton reach but much better near the diagonal!
What if ‘two’ leptons with same sign (e, \(\mu\))?

- In MSSM, gluino are Majorana particles: gives equally \(\tilde{q}\) and anti-\(\tilde{q}\)
  - same sign leptons from the two legs in \(\frac{1}{2}\) of the case + jets +MET

- SM killer which compensates for low branching ratios.

\[m_{\tilde{n}} (GeV)\]

\[m_{n/2} (GeV)\]

\[L_{\text{int}} = 4.98 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}\]

\[\text{Observed Limit (NLO+NLL with uncertainties)}\]

\[\text{Expected Limit (NLO+NLL)}\]

\[\text{NLO Obs. Limit (L } m_{\tilde{n}} = 35 \text{ pb}^{-1}\)]

\[\text{Non-Correlated Rate}\]

\[\text{NO EWBS}\]

\[\text{CMS}\]

\[\text{LEP2 II}\]

\[\text{LEP2 I}\]

\[m_{\tilde{g}} = 1500\]

\[m_{\tilde{g}} = 1000\]

\[m_{\tilde{g}} = 500\]

\[m_{\tilde{g}} = 200\]

\[m_{\tilde{g}} = 100\]

\[m_{\tilde{g}} = 50\]

\[m_{\tilde{g}} = 25\]

\[m_{\tilde{g}} = 10\]

\[m_{\tilde{g}} = 5\]

\[m_{\tilde{g}} = 1\]

\[\text{ttbar} + W \text{ or } Z : \sigma \sim 0.1 \text{ pb}\]

\[1 \text{ Real } +1 \text{ Fake lepton (jets)}\]

\[\text{Background Error } \sim 35-50\%\]

\[\text{Selection}\]

- Trigger: Dilepton+HT
- 2 leptons low/high pT
- MET, \(H_T\) Cuts

\[\text{Competitive with 0lepton searches at high m0!}\]
Inclusive searches (11)

**Motivation for multi-leptonic / photonic signatures**

- Can not compete with inclusive 0-lepton, 1-lepton channels because of branching ratios
- GMSB: LSP is the gravitino and NLSP determines the event final states

► Can seriously enhanced $Z+jets+MET$, $\tau+X+jets+MET$, OS $ll+jets+MET$, $\gamma+X+MET$

► Note: 0-lepton, 1-lepton and SS dileptons also very strong
Inclusive searches (12)

- Two leptons (e, µ) opposite sign + jets + MET
  - NLSP type | Relevant final states (+MET)
  - slepton | multileptons, SS dileptons, OS dileptons, ℓ+jets, jets
  - 3 categories: ee, µµ and eµ + jets + MET
  - Main background: ttbar dileptonic (semi data driven)

Selection
- Trigger: Single lepton
- =2 leptons pT>25 GeV
- ≥3 jets pT >80, 40, 40 GeV
- MET>220 GeV

Background
- ~ttbar dileptonic (semi data-driven)
  - N_{S}=13±3.2(syst.)+2.4(stat)
  - Main Syst. = ttbar ISR/FSR

Signal
- Syst is 20%/15% exp/theo around the limit
Inclusive searches (13)

- Two $\tau_{\text{had}}$ of opposite sign + jets + MET
  - Stau can also be light if high mixing
  - Experimental challenge: understand the fake $\tau$, $\tau$ energy scale for pT($\tau$)>20 GeV
    ✅ Dominate background systematics

<table>
<thead>
<tr>
<th>NLSP type</th>
<th>Relevant final states (+MET)</th>
</tr>
</thead>
<tbody>
<tr>
<td>slepton</td>
<td>multileptons, SS dileptons, OS dileptons, $\ell$+jets, jets</td>
</tr>
</tbody>
</table>

- Trigger: Jet+MET
- $\geq 2$ ‘loose’ taus pT>20 GeV
- $\geq 3$ jets pt >130,30,30 GeV
- MET>160, $m_{\text{Eff}}$>700 GeV

Background

$\bar{t}t$/W+jets: 1 fake + 1 real $\tau$

Semi data-driven

$N_B=5.3\pm2.6$ (50% syst.)

Signal

Syst is 20%/15% exp/theo around the limit

➡ More challenging but a nice addition to consider taus for SUSY!
Inclusive searches (14)

- Two leptons opposite sign from $Z$ (ee, $\mu\mu$) + jets + MET
  
<table>
<thead>
<tr>
<th>NLSP type</th>
<th>Relevant final states (+MET)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$-rich higgsino</td>
<td>$Z(l^+l^-)+$jets, $Z(l^+l^-)Z(l^+l^-)$, SS dileptons, jets</td>
</tr>
</tbody>
</table>

  - Experimental challenge: Fake MET from SM $Z$+jets hard to estimate
    
    ✓ JZB (data driven) = imbalance between $p_T(Z)$ and jets: symmetric around 0 for $Z$+jets but not for ttbar
    
    ✓ Can also use MET templates ($\gamma$+jets and QCD) to estimate tails at high MET. Not shown here

  - Trigger: double leptons
  - 2 lep. Opp. Sign Same Flavor
  - $81 < M(Z) < 101$ GeV
  - $\geq 2,3$ jets $p_T > 30$ GeV
  - JZB $> 250$ GeV

  Background
  
  JZB method
  
  NB=2.0±0.8 (40% stat)

  ➔ Sensitivity suppressed for signal with symmetric JZB
Inclusive searches (15)

- Two photons in the final state
  - Experimental Challenge: determine fake $\gamma$ and tail at high MET (see Part I)
  - 3 variables MET, $H_T$, and $\Delta \phi (\gamma, \text{MET})$ to increase sensitivity

- After 2 $\gamma$ selection

- Selection (SRA/B)
  - 2 $\gamma$ $p_T > 50$ GeV
  - MET $> 200/100$ GeV
  - $H_T > 600/1100$ GeV
  - $\Delta \phi (\gamma, \text{MET}) > 0.5/0$

- Background
  - $N_B = 0.1 \pm 0.03 \text{(stat)} \pm 0.07 \text{(syst)}$
  - Syst dominated by fake $\gamma$

- Signal
  - Syst is 10%/30% for exp/theo around the limit

- Quite strong in the LSP bino case ($M_{\tilde{g}} > 1.1$ TeV). Similar for $M_{\tilde{q}}$!
Summary on Inclusive searches

- These searches are covering a wide range of SUSY models!

**ATLAS 2-5 fb⁻¹ (CMS similar)**

### ATLAS SUSY Searches* - 95% CL Lower Limits (Status: ICHEP 2012)

<table>
<thead>
<tr>
<th>Mass scale [TeV]</th>
<th>LSP = ( \tilde{\chi}^0_1 ) and pMSSM</th>
<th>LSP = ( \tilde{g} ) and GGM Models (1 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{s} ) [TeV]</td>
<td>7, 7, 8 (proj)</td>
<td>7, 23, 32, 45</td>
</tr>
<tr>
<td>( % ) of SUSY models excluded</td>
<td>7, 23, 32, 45</td>
<td>Recasting results from ATLAS/CMS with 1 fb⁻¹ in GGM</td>
</tr>
</tbody>
</table>

- \( m_{\tilde{g}} \) and \( m_{\tilde{g}} \) already reach the 1 TeV limit (was ~300-400 GeV before LHC !)

- Can cover ‘all’ pMSSM and GGM with LHC (14 TeV) ?
Natural SUSY

A “natural” SUSY spectrum

Theory view

Experimental view

Light squarks, sleptons:
«decoupled»

Gluino:
Direct production: jets + MET (+leptons)
but cross-section may be low

3rd generation:
Direct production: bs, Ws, ts + MET
Gluino mediated: same +jets

EWK-inos=Gauginos ($\tilde{\chi}^0_1$=LSP):
Direct production: leptons, MET, Jet veto
Gluino mediated: leptons, jets, MET

⇒Dedicated b-jet, multileptons and jet veto analyses

L. Hall (LBL Workshop, 21-Oct11)
The simplest case: direct sbottom

- Assume all other particles high mass and decoupled (Simplified Model)

A simple final state (though experimentally challenging): 2b + MET
Design an exclusive 2b jet + MET analysis

Requirements

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etmiss [GeV] &gt;</td>
<td>130</td>
</tr>
<tr>
<td>Pt (j1) [GeV] &gt;</td>
<td>130</td>
</tr>
<tr>
<td>Pt (j2) [GeV] &gt;</td>
<td>50</td>
</tr>
<tr>
<td>Lepton and 3rd jet veto</td>
<td></td>
</tr>
<tr>
<td>Δφ (jet-MET) &gt;</td>
<td>0.4</td>
</tr>
<tr>
<td>MET/Meff &gt;</td>
<td>0.25</td>
</tr>
<tr>
<td>N(bjets)=</td>
<td>2 Tight (ε=0.6)</td>
</tr>
<tr>
<td>M_{CT} &gt;</td>
<td>0, 100, 150, 200</td>
</tr>
</tbody>
</table>

Trigger-driven

Pile-up-driven

QCD-killers

Discriminating variables

[\text{m}_{CT}(ttbar)<135 \text{ GeV}]

Background determination:

- **QCD**: jet smearing method (cf. 0-lepton)
- **top, Wb**: Control Region with =1 lep + 2 bjets + MET > 80 GeV
- **Z(vv)bb**: Control Region with Z mass constraint + 2 b-jets

Signal:

- Systematically limited (~40%) because of b-tagging

\[ N_B [m_{CT}>200 \text{ GeV}] = 8.1 \pm 3.5 \]

\[ \Rightarrow \] Error dominated by stat in Control Regions
Direct Sbottom (3)

- Interpretation of the results

Compressed spectrum:
1. Lower pT cut on jets
2. Move to MET trigger only
3. Add one more jet (ISR)

Can still gain a lot in sensitivity
**Direct Stop (1)**

- **A bit more complicated case: direct stop**
  - At $\sqrt{s}=7$TeV, $\sigma$(ttbar) = $177\pm11$ pb is measured by ATLAS
  - $\Rightarrow$ Exclude $m$(stop)$<100$ GeV

<table>
<thead>
<tr>
<th>$\tilde{t}\tilde{t}$ [pb]</th>
<th>300±50</th>
<th>$\tilde{t}$ topology + soft objects/MET</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$[5fb$^{-1}$]</td>
<td>1,500,000</td>
<td>150,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sigma$(ttbar)[pb]</th>
<th>30±5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$[5fb$^{-1}$]</td>
<td>150,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sigma$(ttbar)[pb]</th>
<th>0.05±0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$[5fb$^{-1}$]</td>
<td>250</td>
</tr>
</tbody>
</table>

**Not enough stat at 7 TeV**

- **Most promising final states** $2b + 2(4)$jets + 0(1)lepton + MET
- **Build few exclusive analyses to catch the beast!**
Example $m(\text{stop}) < m(\text{top})$: $\geq 2l + \geq 1\text{b-jet} + \geq 1\text{jet} + \text{MET}$

- Like searching for top with a lighter mass
- Background completely dominated by $t\bar{t}b\bar{b}$

Selection (2LSR2)

- Trigger: 1 Lepton
- Soft $p_T$-cuts on $l$, $b$, $j$ ($20$), MET ($40$ GeV)
- Upper cuts on $Z$: $31 < m_{ll} < 80$ (sub)
- Global Mass cuts: $\sqrt{s_{\min}}$, $m_{lljj} < 140$ GeV

Background

$N_B = 46\pm8$
Syst dominated (top theory)

Signal

Errors are $\sim15\%$ for $\exp + \text{theo}$ around the limit

Consider also $\geq 1l + 2\text{ b-jet} \& \geq 2l + pt(l) < 30$ GeV, …
Example $m(\text{stop}) > m(\text{top}) : =1l + \geq1\text{-}b\text{-}jet + \geq4\text{jets} + \text{MET}$

- Like searching for top with a high MET ➔ Design 5 Signal Regions (show only SRA here)
- Background completely dominated by ttbar

**Selection (SRA)**

- Trigger: 1 Lepton
- $p_T(l)>20 + p_T(j)>80, 60, 40, 25$ GeV
- $\Delta\phi(j,\text{MET})_{\text{min}}>0.8$
- Reconstruct had. top ($\Delta R$ method)
- $m_T>120$ GeV, $\sqrt{H_T}>7$ GeV$^{1/2}$
- MET$>150$ GeV

**Background**

$N_B=42\pm6$

Syst dominated (top theory)

**Signal**

Errors are $\sim15\%$ for exp$\oplus$theo around the limit

Consider also: $=0\ l + 1$-$2\ b\text{-}jet + \geq5$-$4$ jets & $=2\ l + \geq2$ jets
Direct Stop (4)

- **Current summary after 5 fb⁻¹**

  "If you cover the white then Weak scale SUSY is probably dead"  R. Barbieri (ICHEP2012)

**Diagram:**

- **Stop → cχ₁⁰** or stop → bff χ₂⁰ can dominate
- Very close to ttbar topology:
  - Soft objects
  - Can may be use precise top cross-section/polarisation on measurement

**Equations:**

- \( m_{\nu_1} > m_{\nu_1} (=106 \text{ GeV}) \)
- \( m_1 < 106 \text{ GeV} \)
- \( m_1 < 200 \text{ GeV} \)
- \( m_1 > 200 \text{ GeV} \)
- \( M(\text{Stop}) < m(\text{Top}) \)
- \( M(\text{Stop}) > m(\text{Top}) \)

**Legend:**

- 0-lepton
- 1-lepton
- 2-lepton
- 1/2-leptons + b-jets (m₁ = 106 GeV)
- 1/2-leptons + b-jets (m₁ = 2 × m₁)

**Text:**

- Stop → cχ₁⁰ or stop → bff χ₂⁰ can dominate
- Very close to ttbar topology:
  - Soft objects
  - Can may be use precise top cross-section/polarisation on measurement

**Equation:**

- \( M(\text{Stop}) < m(\text{Top}) \)
- \( M(\text{Stop}) > m(\text{Top}) \)
Gluino Mediated stop (1)

- Increase again complexity: $m_{\tilde{g}} \sim O(1 \text{ TeV})$
  - Stop in gluino cascade dominates
  - Stop on-shell (2 body) or off-shell (3 body decay)

Final state (4 tops !!): $=4b, 4W + \text{High MET}

→ Need ttbar killers: 0l + $\geq 3b$-jets + MET, Same Sign 2l (+ bjet) + MET, 0l+6-9 jets

1205.3933, 1205.6615

1206.1760
0lepton + ≥3 bjets analyses

- Experimental challenge: Understand and measure ttbar+jets background in Signal Regions
- 2 Signal Regions w Njets≥6 jets: adjust btagging operating points, MET and M_{eff} cuts

**Selection (SR6-T)**

- Trigger : Jet +MET
- Jets: pT(lead.)>160 +≥5 jets pT>50 GeV
- Lepton veto
- 3 bjets Loose (ε=0.75)
- Δφ(j,MET)_{min}>0.4, MET/M_{eff}>0.2
- Discr.: MET>200, M_{eff}>900 GeV

**Background**

N_{B}=10±3
Syst dominated (top theory)

**Signal**

Errors are ~30-10% ⊕ 10-30% for exp ⊕ theo around the limit

⇒ The most optimised for these scenarios
Gluino Mediated stop (3)

- **On-shell stop**
  - $g \rightarrow t \tilde{t}_1$
  - $m_{\text{LSP}} = 60$ GeV

- **Off-shell stop**
  - $t_1 \rightarrow g \tilde{t}$

**Diagram 1:**
- $\tilde{g} \rightarrow \tilde{t}_{1} \tilde{t}_{1}$, production, $\tilde{t}_{1} \rightarrow b + W b$
- $L^{\text{ATLAS}} = 4.71$ fb$^{-1}$, $\mathcal{L} = 7$ TeV

**Diagram 2:**
- $\tilde{g} \rightarrow \tilde{t}_{1} \tilde{t}_{1}$, production, $\tilde{g} \rightarrow \tilde{t}_{1} \tilde{t}_{1}$
- $m(\tilde{g}) > m(\tilde{t}_{1})$
- $m(\tilde{t}_{1}) = 60$ GeV, $m(\tilde{g}) > m(\tilde{t}_{1})$

**Graphs:**
- 3 b-jets channel
- ATLAS Preliminary
- All limits at 95% CL
- $m(\tilde{t}_{1}) = 60$ GeV, $m(\tilde{g}) > m(\tilde{t}_{1})$
Direct Gauginos (1)

- If $\tilde{q}$ / $\tilde{g}$ too heavy $\Rightarrow$ only EWK Production!
  - Gauginos produced in s-channel mediated by $\gamma$, $Z$, $W$ or $h^0/H^0/A^0$
  - Accessible $\at 5 \text{fb}^{-1}$: $\chi_1^\pm \chi_2^0$ and $\chi_1^+ \chi_1^-$

Focus on gaugino leptonic decays to remove hadronic background
  - Via an intermediate lepton (BR=50%$l$, 50%$\nu$)
  - Via an onshell/offshell $W$ (BR~33%) or $Z$ (BR~10%)

$\Rightarrow$ 2 or 3 leptons in final states and no jets
Direct Gauginos (2)

Search for Direct Chargino ➔ =2 leptons + MET +jet veto

- Experimental challenge: consider low pT lepton to gain acceptance
- Dominant background: ttbar dileptonic, WW and Z+jets

Selection (SR-M_{T2})

- Trigger: Lepton OR Dilepton
- Pt (lepton) >20,10 GeV + Jet veto
- Z veto
- MET(rel)>40 GeV
- Discr.: MT2>90 GeV

Background

$N_B=33\pm7$ (20±7 for Same flavor)
Syst dominated. Mainly from lepton energy scale/resolution + trigger eff. )

Signal

Errors are 10-20% dominated by theo. signal uncertainty

Sensitive also to direct slepton production (beyond LEP!)
Search for $\chi_1^\pm \chi_2^0 \rightarrow 3$ leptons + MET

- Similar experimental challenge, but dominant background is now WZ!
- Consider 3 signal regions (w/wo Z veto or w/wo W veto)

**Selection (SR1a)**
- Trigger: Lepton OR Dilepton
- $P_T$ (lepton) $>20, 10, 10$ GeV
- Jet veto, Z veto, bjet veto
- Discr. MET $>75$ GeV

**Background**
- $N_B = 25 \pm 6$
- Syst dominated. Mainly from WZ theo uncertainties.

**Signal**
- Errors are 10-20% dominated by theo. signal uncertainty

$\Rightarrow$ Exclude $m(\chi_1^\pm)=m(\chi_2^0)<500$ GeV for massless LSP
Direct Gauginos (4)

- Closer to a real SUSY model ~pMSSM
  - Mixing of eigenstates = f(M1 [Bino Mass], M2 [Wino masses], tanβ, µ [Higgses])
  - Trilinear mixing all set to 0 except for the stop
  - Will benefit of the combination 2l + 3l (in the making)
Summary on Natural searches

- Start to bite seriously in the natural SUSY region
  - Note: all generic searches also partially sensitive to these decays
  - Consider other LSP flavors: if higgsino-like, expect nearly degenerate $\chi_1^0, \chi_1^\pm, \chi_2^0$ masses
  - Consider other decays: stop $\rightarrow$ cLSP, Higgs, add taus
  - Quantify robustness of present analysis wrt these more complex cases

- Still viable (R. Sundrum ICHEP2012)!
Long-Lived particles

- Some examples (more in back-up)
  1. Very weak coupling with $\tilde{G}=\text{LSP}$ [GMSB]
  2. Lifetime proportional to $\lambda^2, \lambda'^2, \lambda''^2$ [R-Parity violation]
  3. Low mass difference $\Delta M(\tilde{\chi}_1^+-\tilde{\chi}_1^0) \sim 100$ MeV [AMSB]
  4. Stable Massive Particle (mix of 1 and 3)

- Non pointing $\gamma$ or $Z$
- Displaced vertex if $\lambda, \lambda', \lambda'' < 10^{-7}$
- Low $\pi$ emitted, kinked track
- R-hadron ($\tilde{g}$ or $\tilde{q}$) or sleptons

A bunch of striking signatures, not present in the standard Model!!
Long-Lived particles (1)

Mass reconstruction of pair produced stable particles

1. Start from one (or two) high pT isolated track → p

2. Measure β (calo or calo+Muon Spectrometer)

3. Measure βγ (invert Bethe-Bloch) from track clusters

Add the 2 or 3 information together and compute M = p/βγ
## Long-Lived particles (2)

### Event selection

<table>
<thead>
<tr>
<th>Requirements</th>
<th>R-hadrons (ID-only)</th>
<th>Stable R-hadrons (ID+calo-only)</th>
<th>Stable R-hadrons (Full Detector)</th>
<th>Stable Sleptons (Full detector, 2 cand.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Type</td>
<td>Metastable or Charged→Neutral</td>
<td>Charged→Neutral</td>
<td>Charged</td>
<td>Charged</td>
</tr>
<tr>
<td>Trigger</td>
<td>MET turn-on</td>
<td></td>
<td>Slow β</td>
<td></td>
</tr>
<tr>
<td>Track quality</td>
<td>d0, z0, n (ID-hits)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Track kinematics</td>
<td>pT&gt;50, p&gt;100 GeV</td>
<td></td>
<td>pT&gt;70 GeV</td>
<td></td>
</tr>
<tr>
<td>β Consistency between detectors</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>β &lt; [m(g, q, l) dependent]</td>
<td>No</td>
<td>0.8-0.9</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>βγ &gt; [m(g, q, l) dependent]</td>
<td>MIP</td>
<td>1.5-2.0</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>M_p range (TeV)</td>
<td>No</td>
<td>0.2-1.1 ; 3.0</td>
<td>0.1-3.0 ;</td>
<td>0.1-3.0 ;</td>
</tr>
<tr>
<td>M_βγ range (TeV)</td>
<td>0.2-1.1 ; 3.0</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Signal Efficiency (%)</td>
<td>6 [m(g)=900 GeV]</td>
<td>7 [m(g)=900 GeV]</td>
<td>11 [m(g)=900 GeV]</td>
<td>40</td>
</tr>
<tr>
<td>Systematics (%)</td>
<td>6 (S), 13 (B)</td>
<td>12 (S), 15 (B)</td>
<td>12 (S), 15 (B)</td>
<td>6 (S), 13 (B)</td>
</tr>
</tbody>
</table>

- **Background type**: high pT muons (tracks) with mis-measured β (dE/dx)
- **Background estimate**: generate mass spectrum from S/B<<1 → p-templates + β (βγ)-PDF templates
- **Signal**: Different interaction models, gluino ball fractions (10%, 50 %, 100%).

---

### Optimised

**Heavy Muon**

\[ \tilde{g} + \bar{q}, g + qqq, \tilde{b}/t + \bar{q}, qq \] + ISR
Mass distributions

- Cut and count in mass ranges. Very low level of background

R-hadrons: Full detector

Slepton searches (2 candidates)

Exclude 1 TeV R-hadron (g) and ~600-700 GeV R-hadron (t, b)

Exclude ~300 GeV sleptons (assuming direct production)
Direct sleptons from prompt to stable

Intermediate region (metastable slepton, i.e. displaced vertex w 1lepton) not covered
R-hadrons can also stop and decay later

- Very well motivated (Split SUSY): stopped gluino only particle reachable at LHC!
- High pT jets in absence of collisions (gaps of LHC beam structure)
- Background = calorimeter noise, cosmics and beam halo not SM!

→ Control samples: 2010 low lumi run, cosmic runs, beam halo tag&probe in opposite endcaps

→ $M_{\tilde{g}} < 640$ GeV and $M_{\tilde{t}} < 340$ GeV excluded for $10 \mu s < \tau < 15$ min
R-parity violating search at LHC

$$W = W_{\text{MSSM}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

**Lepton Number Violation (LFV)**

- Proton decays only forbids simultaneous violation of lepton and baryon number

**Baryon Number Violation (BNV)**

- Multilepton production (including taus)

<table>
<thead>
<tr>
<th>Signature</th>
<th>From H. Dreiner</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) 4 charged leptons: $e^+e^+\mu^-\mu^-$</td>
<td>$\chi_1^0$-LSP, $LL\bar{E}$, $\bar{\tau}$-LSP, $LL\bar{E}$</td>
<td></td>
</tr>
<tr>
<td>2) 2 leptons, 2 taus: $e^+e^+\tau^-\tau^-$</td>
<td>$\chi_1^0$-LSP, $LL\bar{E}$, $\bar{\tau}$-LSP, $LQ\bar{D}$</td>
<td></td>
</tr>
<tr>
<td>3) 6 jets or 2 w/ substructure</td>
<td>$\chi_1^0$-LSP</td>
<td>$\bar{U}\bar{D}\bar{D}$</td>
</tr>
<tr>
<td>4) like-sign dileptons + jets</td>
<td>$\chi_1^0$-LSP, $LQ\bar{D}$</td>
<td></td>
</tr>
<tr>
<td>5) dilepton resonance</td>
<td>$LL\bar{E} \otimes LQ\bar{D}$</td>
<td></td>
</tr>
<tr>
<td>6) mono lepton</td>
<td>$LQ\bar{D}$</td>
<td></td>
</tr>
<tr>
<td>7) dijet resonance</td>
<td>pure $LQ\bar{D}$</td>
<td></td>
</tr>
<tr>
<td>8) like sign ditau’s $\tau^-\tau^- + 6$jets</td>
<td>$\bar{\tau}$-LSP, $LQ\bar{D}$</td>
<td></td>
</tr>
</tbody>
</table>

- Resonances (2jets, 2x2 jets, 2x3 jets, eµ, eτ, µτ)

Note: Absence of Z and Importance of taus

⇒ Generally: lower background (no LFV nor BNV in SM) and MET than RPC
RPV (1)

- **Multilepton (≥3 isolated e, \(\mu\) or \(\tau_{\text{had}}\)) search**
  - General search targeting many BSM theories (not only SUSY) \(\to\) 52 signal regions
  - Background: lots of small contribution (ZZ, WZ, \(\gamma\gamma\) conversion, tt+X)
  - 3 Discriminating variables: N tau, Zeto Veto (ZV), \(S_T = \frac{M_{\text{Eff}}}{\text{low} / \text{Medium or High cuts}}\)

<table>
<thead>
<tr>
<th>Selection</th>
<th>(N(\gamma=0))</th>
<th>(N(\gamma=1))</th>
<th>(N(\gamma=2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4# Lepton Results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4f) (DY0) (S_T) (High)</td>
<td>0.0009 ± 0.0009</td>
<td>0.01 ± 0.09</td>
<td>0.17 ± 0.07</td>
</tr>
<tr>
<td>(4f) (DY0) (S_T) (Mild)</td>
<td>0.0004 ± 0.0002</td>
<td>0.27 ± 0.10</td>
<td>2.5 ± 1.1</td>
</tr>
<tr>
<td>(4f) (DY0) (S_T) (Low)</td>
<td>0.01 ± 0.07</td>
<td>0.28 ± 0.16</td>
<td>1.3 ± 1.0</td>
</tr>
<tr>
<td>(4f) (DY1ZV) (S_T) (High)</td>
<td>0.0009 ± 0.0004</td>
<td>0.09 ± 0.07</td>
<td>0.11 ± 0.13</td>
</tr>
<tr>
<td>(4f) (DY1ZV) (S_T) (Mild)</td>
<td>0.0009 ± 0.0004</td>
<td>0.45 ± 0.14</td>
<td>0.22 ± 0.15</td>
</tr>
<tr>
<td>(4f) (DY1ZV) (S_T) (Low)</td>
<td>0.0005 ± 0.001</td>
<td>0.83 ± 0.24</td>
<td>1.02 ± 0.29</td>
</tr>
<tr>
<td>(4f) (DY1ZV) (S_T) (VeryLow)</td>
<td>0.0003 ± 0.001</td>
<td>5.9 ± 1.1</td>
<td>3.4 ± 0.9</td>
</tr>
<tr>
<td>(4f) (DY2ZV) (S_T) (High)</td>
<td>0.0008 ± 0.0004</td>
<td>5.1 ± 2.2</td>
<td>19.6 ± 6.7</td>
</tr>
<tr>
<td>(4f) (DY2ZV) (S_T) (Mild)</td>
<td>0.01 ± 0.07</td>
<td>10.9 ± 4.6</td>
<td>95 ± 34</td>
</tr>
<tr>
<td>(4f) (DY2ZV) (S_T) (Low)</td>
<td>0.02 ± 0.07</td>
<td>19.9 ± 4.6</td>
<td>95 ± 34</td>
</tr>
<tr>
<td>(4f) (DY2ZV) (S_T) (VeryLow)</td>
<td>0.02 ± 0.07</td>
<td>24.7 ± 4.4</td>
<td>95 ± 34</td>
</tr>
</tbody>
</table>

- **Also sensitive to direct gauginos production**

Leptonic RPV in strong production

- \(M(\text{LSP-Bino})=300\ \text{GeV}\)
- \(\lambda_{\text{eff}} \neq 0\)

Hadronic RPV in strong production

- \(M(\text{bino})=500\ \text{GeV}\)
- \(M(\text{sleptons})=300\ \text{GeV}\)
- \(M(\text{LSP-Wino})=150\ \text{GeV}\)
- \(\lambda' \neq 0 \text{: LSP} \rightarrow jjj\)
- Lepton flavor violation resonance
  - Lepton flavor violation brought by sneutrinos decay (s-channel)
  - Look in $e\mu$ spectrum inside +/-3 $\sigma$

$\Delta \phi (e, \mu) \sim \pi$, MET=132 GeV, no Jet!

Signal efficiency ~ 50-60%
2x3 jets resonance

- Selection: 6 jets + $M_{jjj} < \Sigma p_T(jjj)$ - $\Delta$: reduce combinatorial (signal & background), search for a mass peak
- Interpret the results in RPV models with gluino $\rightarrow jjj$
- Note: ISR systematics not taken into account for signal

$\Rightarrow$ Exclude Gluino masses [200;460] GeV with 35pb$^{-1}$ and 5 fb$^{-1}$
Summary on LLP/RPV searches

- An increasing center of interest!
  - Lots of very striking signature to discover SUSY (may be hiding in the current data)
  - One of the best motivated explanation to the absence of signal in inclusive/natural searches

R. Sundrum (ICHEP 2012)

May be the (only) possible future of SUSY?
LHC Future Prospects

- **Discovery reach @ 8 and 14 TeV**
  - For energy frontier (gluinos, squarks)
    - Extend $m_g$ by 100 GeV if $\sqrt{s_{\text{new}}} [\text{TeV}] = \sqrt{s_{\text{orig}}} + 1$ or $L_{\text{new}} [\text{fb}^{-1}] = 10 \times L_{\text{orig}}$
  - For stop / sbottom / gauginos ~ top mass
    - Generally ttbar main background: $S/B$ constant vs $\sqrt{s_{\text{new}}}$ but $S/\sqrt{B}$ increases

- **CTEQ6L1: Partron Luminosity Ratios**
  - http://lutece.fnal.gov/PartonLum11/

- **Chargino(N1)-Neutralino(N2) Cross Section (mSUGRA, m0=1000GeV)**
  - Limit for $M(\text{LSP})=0$ @ 5 fb$^{-1}$
  - Limit for $M(\text{LSP})=0$ @ 5 fb$^{-1}$
Conclusions (1)

- Very active search of Weak scale SUSY at LHC

1. Inclusive searches
2. Natural SUSY
3. Long-Lived Particles
4. RPV

Reach the 1 TeV limit and huge improvement compared to previous experiments!
Conclusions (2)

- Weak scale SUSY is (still) a natural and front-runner theory beyond SM …
  - Provided it is right around the corner
  - Remember that cross-sections can be quite low for many SUSY processes (lots of scalar)
    ➔ for Higgs it took ~40 years !
    ➔ Complicated by RPV/LLP ?

- ... But, let’s be fair also, no sign of it (yet)
  - LEP+LHC: no hint … SUSY not around the corner ??
    ➔ Need a sign before the closing of LHC (presently keep all possibilities open) !
  - May be it’s not weak-scale SUSY but Split SUSY (not natural) ?
  - Or may be SUSY is not driving beyond SM (Strong coupling to the Higgs)
Conclusions (3)

The three main scenarios

LHC scenarios

1 **Catastrophic**: No Higgs, no new physics

   Can only occur if the LHC is not enough to fully probe the EW scale: unitarity violations impose one or the other (eg new vector bosons) or both

2 **Theorist projection**: non standard Higgs and new physics

   A lot of model building in this direction

3 **Pure SM**: A light scalar Higgs, no new physics at the EW scale

   If so, nature does not abhor fine tuning at all
   This is the paradigm that experiment must try to falsify

→ Clearly we are evading 1 and (hopefully) moving to 2!
Some usefull links

- Bibliography: http://pralavop.web.cern.ch/pralavop/phd.html
- ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- CMS public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- LHC Status: http://lhc.web.cern.ch/lhc/
- Questions: pralavor@cppm.in2p3.fr
Appetizers for tomorrow

- Weak-scale SUSY searches **before** first LHC SUSY results

### MSSM: 29 sparticles + 5 Higgs undiscovered

<table>
<thead>
<tr>
<th>Names</th>
<th>Spin</th>
<th>$P_R$</th>
<th>Gauge Eigenstates</th>
<th>Mass Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$H^0_u$ $H^0_d$ $H^+_u$ $H^-_d$</td>
<td>$h^0$ $H^0$ $A^0$ $H^\pm$</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>−1</td>
<td>$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{s}_L$ $\tilde{s}_R$ $\tilde{c}_L$ $\tilde{c}_R$</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{t}_L$ $\tilde{t}_R$ $\tilde{b}_L$ $\tilde{b}_R$</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$</td>
<td></td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>−1</td>
<td>$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\mu}_L$ $\tilde{\mu}<em>R$ $\tilde{\nu}</em>\mu$</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\tau}_L$ $\tilde{\tau}<em>R$ $\tilde{\nu}</em>\tau$</td>
<td>(same)</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>−1</td>
<td>$\tilde{B}^0$ $\tilde{W}^0$ $\tilde{H}^0_u$ $\tilde{H}^0_d$</td>
<td>$\tilde{N}_1$ $\tilde{N}_2$ $\tilde{N}_3$ $\tilde{N}_4$</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>−1</td>
<td>$\tilde{W}^\pm$ $\tilde{H}^+_u$ $\tilde{H}^-_d$</td>
<td>$\tilde{C}^\pm$ $\tilde{C}^+_3$</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>−1</td>
<td>$\tilde{g}$</td>
<td>(same)</td>
</tr>
<tr>
<td>goldstino (gravitino)</td>
<td>1/2 (3/2)</td>
<td>−1</td>
<td>$\tilde{G}$</td>
<td>(same)</td>
</tr>
</tbody>
</table>

**Mass Limits from PDG2010 (95% CL)**

$\tilde{\chi}^0_1$ = LSP, RPC, degenerate squarks (except $\tilde{b}, \tilde{t}$), $|l|=l_R$. Gaugino mass unification at GUT scale

$114.4, 92.8, 93.4, 79.3$ GeV (m$_h^{max}$ benchmark scenarios)

$379$ GeV

$95.7, 89$ GeV

$107$ GeV

$94$ GeV

$81.9$ GeV

$46, 62.4, 99.9, 116$ GeV

$94$ GeV

$308$ GeV

Note: These limits are also model dependent

Covers most of SUSY production and decays ... But most in the 0-100 GeV range limited by $\sqrt{s}$

∗ Come back tomorrow to explore the 0.1-1 TeV range!
CMS Multilepton Generic Search (1)

Three or more electrons, muons or taus. Up to two tau’s reconstructed.
54-channel ST table and 52 channel MET/HT results on and off Z
Signal (low-bkgnd) and control (high bkgnd) channels treated uniformly.

CMS multileptons in this talk:
a) **Strong production** GMSB slepton co-NLSP
b) **R-parity Violation (Leptonic)**
c) Sensitive to **accidents of spectrum** (strong production captured by lepton sector)
d) Missing MET: e.g. **RPV (Hadronic)**: $S_T$ comes handy
e) **Electroweak Production**: cut-and-count (shown), [fitting MET/MT in progress]

**SURPRISES** (detailed background studies)
- Very rare four lepton event(s) in 2011, still outstanding.
- Next: Trimuon Z (!!!???) and **impact on Higgs**
Sensitivity to direct gauginos (=3 leptons + MET)

- $\chi_1^\pm/\chi_2^0$ wino-like, $\chi_1^0$ bino-like

Force decay to lepton to 100 % (do not consider $\nu$)

Dedicated search more powerful
Sensitivity to direct gauginos (=3 leptons + MET)

- \( \chi_1^\pm, \chi_2^0 \) wino-like, \( \chi_1^0 \) bino-like: Decay through W and Z (not intermediate lepton), M(LSP)=0

\( \chi_1^\pm \)

\( \chi_2^0 \)

\( \chi_1^0 \)

\( \chi_2^0 \)

Barely sensitive

No yet sensitive
Closer to a real SUSY model ~pMSSM

- Mixing of eigenstates = f(M1 [Bino Mass], M2 [Wino masses], \( \tan \beta \), \( \mu \) [Higgses])
- Trilinear mixing all set to 0 except for the stop

\[
\text{M1=140 GeV, medium mass splitting between } \chi_1^{\pm} \text{ and } \chi_1^0 \Rightarrow \text{medium Acc.}
\]
Closer to a real SUSY model \( \sim p\text{MSSM} \)

- Mixing of eigenstates = \( f(M1 \text{ [Bino Mass]}, M2 \text{ [Wino masses]}, \tan\beta, \mu \text{ [Higgses]} \)
- Trilinear mixing all set to 0 except for the stop

\[ M1=250 \text{ GeV}, \text{ low mass splitting between } \chi^\pm_1 \text{ and } \chi^0_1 \Rightarrow \text{ low Acc.} \]
Increase again complexity: $m_{\tilde{g}} \sim O(1 \text{ TeV})$
- Stop in gluino cascade dominates
- Stop on-shell (2 body) or off-shell (3 body decay)

Final state: $4b + \text{MET}$

$\Rightarrow$ ttbar killers should be best: $0l + \geq 3\text{-jets} + \text{MET} \ & \ \text{Same Sign } 2l + \text{bjet} + \text{MET}$
Gluino Mediated sbottom (2)

- On-shell sbottom
- Off-shell sbottom

\[ \tilde{g} \rightarrow b \tilde{b}_1 \]

\[ m_{\text{LSP}} = 60 \text{ GeV} \]

**ATLAS**

3 b-jets channel

- ATLAS $b\bar{b}$, 2.05 fb$^{-1}$
- CDF $b\bar{b}$, 2.65 fb$^{-1}$
- DØ $b\bar{b}$, 5.2 fb$^{-1}$
- CDF $g\bar{g} \rightarrow b\bar{b}$, 2.5 fb$^{-1}$

$\tilde{g} \rightarrow b\tilde{b}_1$, forbidden

=2 btag analysis

\[ \tilde{g} \rightarrow b\tilde{b}_1 \]

L$^\text{obs} = 4.7$ fb$^{-1}$, $\sqrt{s} = 7$ TeV

All limits at 95% CL
Multivariate (MVA) for SUSY?

- **Usefulness considerations ...**
  - MVA less useful in case of strongly varying signal predictions and inclusive search
  - MVA classification useful in presence of several not too strongly correlated variables
  - Useful in case of bad signal to background ratio in signal region
  - Less useful in case of one or two very strong variables with little correlation
  - Maybe: analyses that strongly benefit from more statistics are good use cases for MVA classification, while analyses depending mostly on highest CM energy are less so
  - MVA training requires supervision by a signal model: useful if good generic or specific signal model exists

- **Looking at the current SUSY analyses ...**
  - Probably not much needed for: inclusive 0/1-lepton, multijet, monojet, photon/tau + jets + MET searches → driven by highest effective mass tails with good S/B ratio
  - However, compressed scenarios in these analyses might be an MVA use case
  - Potentially useful for direct stop / gaugino / slepton searches
  - Probably not so useful for RPV scenarios (?)
LSP decay

Neutralino-LSP decay

- $\tilde{\chi}_1^0$ could decay via non-zero $\lambda, \lambda'$ couplings:
  
  $LL\bar{E}(\lambda) : \tilde{\chi}_1^0 \rightarrow ll' + \nu$

  $LQ\bar{D}(\lambda') : \tilde{\chi}_1^0 \rightarrow \left(\frac{e, \mu, \tau}{\nu}\right) + 2 \text{ jets}$

- The lifetime is proportional to $(\lambda)^2, (\lambda')^2$

- Decay prompt for $\lambda, \lambda' \approx 10^{-5}$.

- If the RPV coupling is smaller than that (e.g. $\approx 10^{-7}$), a decay vertex with a significant distance from its production point can be seen.

- → Perform a search using a displaced vertex (DV) reconstruction technique.

  - The result presented today is based on 2010 data, non-zero $\lambda'$ with muon final states.

  - More to come using 2011 full dataset covering variety of signatures:
    - Final states including e/tau
AMS Metastable $\chi_1^\pm (1)$

- **Layout of the analysis**

  - **Requirements**
    - $E_t^{\text{miss}}$ [GeV] $> 130$
    - $P_t$ (1) [GeV] $> 130$
    - $P_t$ (2) [GeV] $> 60$
    - $P_t$ (3) [GeV] $> 60$
    - Lepton veto
    - $1$ track $p_T >$ [GeV] $10$
    - DR (track, $p_T > 0.5$ GeV) $> 0.1$
    - $N(\text{TRT outer}) = 5$

  - **SUSY signal (LL01): AMSB model**
    - $m_0 = 1.5$ TeV, $m_{3/2} = 32$ TeV
    - $\sigma = 0.07$ pb, $\tau_{\chi_1^+/\chi_1^-} = 1$ ns
    - $m_{\chi_1^0} = 90.2$ GeV,
    - $\text{BR } (\chi_1^- \rightarrow \chi_0^0 \pi^-) = 100\%$

  - **Diagram**
    - Truncated tracks versus Normal tracks
    - ATLAS Preliminary
    - Background MC
    - Signal events ($LL01, \tau(\tilde{\chi}_1^0) = 1$ ns)
    - Charginos in signal events (decay radius > 863 mm)
    - $Ldt = 4.7$ fb$^{-1}$
    - $13 = 7$ TeV
    - $N_{\text{TRT}^{\text{outer}}}$

  - **Legend**
    - Data
    - Background MC
    - Signal events ($LL01, \tau(\tilde{\chi}_1^0) = 1$ ns)
    - Charginos in signal events (decay radius > 863 mm)
    - $Ldt = 4.7$ fb$^{-1}$
    - $13 = 7$ TeV
    - $N_{\text{TRT}^{\text{outer}}}$
AMSB Metastable $\chi_1^{\pm} (2)$

- Background estimate

- Data driven background: small uncertainties
Interpretation of the results (some examples)

For the AMSB metastable \( \chi_1^\pm \) (3):

- **Exceed previous LEP2 limit** \( m\chi_1^\pm \geq 92 \text{ GeV} \)!

**SUSY signal (LL02): AMSB model**
- \( \sigma = 0.009 \text{ pb}, \ \tau_{\chi_1^\pm} = 1 \text{ ns} \)
- \( m\chi_1^\pm = 117.8 \text{ GeV} \),
- \( \text{BR}(\chi_1^\pm \rightarrow \chi_0^\pi^*) = 100\% \)

**SUSY signal (LL01): AMSB model**
- \( \sigma = 0.07 \text{ pb}, \ \tau_{\chi_1^\pm} = 1 \text{ ns} \)
- \( m\chi_1^\pm = 90.2 \text{ GeV} \),
- \( \text{BR}(\chi_1^\pm \rightarrow \chi_0^\pi^*) = 100\% \)
Direct Sbottom (inclusive)

- Results from generic searches

[Graph showing CMS Preliminary results for m_{Sp} vs. m_{Sbottom} with expected limits and observed limits indicated.]
## 1-2 lepton (ATLAS)

<table>
<thead>
<tr>
<th>Exclusive Signal Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft-lepton, 2-jets</td>
</tr>
<tr>
<td>Hard-lepton, 3-jets</td>
</tr>
<tr>
<td>Hard-lepton, 4-jets</td>
</tr>
<tr>
<td>2-leptons, 2-jets</td>
</tr>
<tr>
<td>2-leptons, 4-jets</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{T,\text{miss}} )-triggers</td>
</tr>
<tr>
<td>Single electron and muon (+jet) triggers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dominant Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+jets, ttbar</td>
</tr>
<tr>
<td>ttbar, W+jets</td>
</tr>
<tr>
<td>ttbar, Z+jets</td>
</tr>
</tbody>
</table>

Estimated in dedicated control regions

<table>
<thead>
<tr>
<th>Other Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD - estimated with data-driven matrix method</td>
</tr>
<tr>
<td>Single Top, Diboson,... (taken from MC)</td>
</tr>
</tbody>
</table>

### Transfer factors to go from Control Regions to Signal Regions (MC-based)

**Fake background:**
- Matrix Method using fake rates measured via relaxed ID & isolation cuts, evaluating hf separately
- Soft-lepton: Fake rates from Same-Sign Same-Flavor pairs
- real+fake background for multilepton taken from MC and cross checked via matrix method
$JZB_{\text{bkgd}}^{\text{pred}} = |JZB_{\text{neg}}|^{\text{SFZP}} + \frac{1}{3} |JZB_{\text{pos}}|^{\text{OFZP}} - \frac{1}{3} |JZB_{\text{neg}}|^{\text{OFZP}}$

$+ \frac{1}{3} |JZB_{\text{pos}}|^{\text{SFSB}} - \frac{1}{3} |JZB_{\text{neg}}|^{\text{SFSB}}$

$+ \frac{1}{3} |JZB_{\text{pos}}|^{\text{OFSB}} - \frac{1}{3} |JZB_{\text{neg}}|^{\text{OFSB}}$
JZB (2)

SF (e+e-, m+m-)  OF (e+m-, e-m+)

Zmass

Zsideband

Equality of ttbar yield in OF and SF final states

\[ JZB_{\text{red}}^{\text{bkgd}} = \left| JZB_{\text{SFZ P}}^{\text{neg}} \right| + \frac{1}{3} \left| JZB_{\text{OFZP}}^{\text{pos}} \right| - \frac{1}{3} \left| JZB_{\text{OFZP}}^{\text{neg}} \right| \]

\[ + \frac{1}{3} JZB_{\text{pos}}^{\text{SFSB}} \]

\[ - \frac{1}{3} JZB_{\text{neg}}^{\text{SFSB}} \]
Prospects

Parton luminosity (ratio 8 to 7 TeV): http://lutece.fnal.gov/PartonLum11/
Gtt uncertainties

ATLAS

Theoretical uncertainty [%]

Experimental uncertainty [%]

m_{\tilde{g}} [GeV]

m_{\tilde{\chi}} [GeV]