Hidden SUSY

Rethinking the experimental strategy for SUSY-(like) searches?

Some personal concluding remarks

Albert De Roeck
11/9/2011 UC-Davis
Looking for Hidden SUSY:

Last two months:

CERN “impact of LHC data on future colliders workshop”
Preparation for the European strategy meeting on particle physics

London: “Rethinking the experimental strategy for SUSY-(like) searches”

Berkeley: “Searches for Supersymmetry at the LHC”

Firenze: “Searching for new physics at the LHC”

Davis: “Hidden SUSY”

IPPP, Durham (January): “BSM 4 LHC”
Recent Discussions@ workshops

- A special role of the third generation? Look for stop, sbottom, stau…
- Split SUSY with all fermion partners very heavy, but light gauginos and gluinos
- Compressed spectra, so we see only soft particles
- FSU(5)-like models, with O(10) jets.
- Dark Matter related searches with low jet multiplicities
- Gaugino production: Multi-leptons/no jets
Recent Ideas@ workshops

- Which model regions are we missing now and should we try to 'recover'.
- More weight on optimizing 3rd generation searches?
- How well do we understand ISR (TH/EXP)?
- Optimized lepton analyses: benchmarks?
- Many jet analyses (>= 8)? Many jets + lepton ($S_T$), no MET, triple b-tagging
- Study boosted objects?
- Special signatures (LLPs, GMSB, stubs, kinks…)
- Running: few 100 pb$^{-1}$ with low pile-up conditions?
- 2012 energy: higher energy or same energy:
LHC: ~ a year ago

“Data are coming! Data are coming!”
Note that during 3-4 years BC (Before Collisions) we –LHC experimentalists- got more models to deal with than we needed…

Some theorists found it a challenge to invent a model with signatures difficult for the experiments: heavy stable charged particles, hidden valley models, Quirks…

NOW WE STRIKE BACK!!

But remember that these are still early days!!
H. Murayama
ICFA Seminar October 2011

How does it feel to be a (BSM) Theorist?
Expected 95% CL exclusion mass range: 130-440 GeV
Observed 95% CL exclusion mass range: 145-216, 226-288, 310-400 GeV

Combine ATLAS+CMS (Mid November)?
Next: full 2011 data analysis Spring 2012? LHC+Tevatron combination?
A Light Higgs: Consequences

A light Higgs implies that the Standard Model cannot be stable up to the GUT or Planck scale ($10^{19}$ GeV).

The effective potential blows up, due to heavy top quark mass.

Allowed corridor but needs strong fine-tuning...

The electroweak vacuum is unstable to corrections from scales $\Lambda >> v = 246$ GeV.

New physics expected in TeV range.

Harigaya
Matsumoto
Murayama
Search for BSM Higgses

MSSM Higgs $\rightarrow \tau\tau$

Impressive Exclusion Limits

Double Charged Higgs
SUSY Search: Jets + Missing E_T Channel

Limits in a simplified model

Using 1 fb^{-1}

Limits in CMSSM

Up to masses of 1 TeV excluded for equal gluino-squark masses
Extends the 2010 data limits by ~ 250 GeV
Impact of the HL-LHC

Extend the discovery region for squarks and gluinos by roughly 0.5 TeV, i.e. from ~2.5 TeV → 3 TeV

This extension involved high $E_T$ jets/leptons and large missing $E_T$ ⇒ Not much compromised by increased pile-up at SLHC

$m_{1/2}$: universal gaugino mass at GUT scale
$m_0$: universal scalar mass at GUT scale
SUSY Searches (Example CMS)

Having a large number of different analyses (a virtue!)

Different approaches for ATLAS and CMS (healthy!)

So far bit too much emphasis on “optimizing” for CMSSM (beauty contest?)
How to present best the experimental data? Clearly an important discussion with the community; see also eg CERN workshop
## Search Ranges (ATLAS)

### ATLAS SUSY Searches - 95% CL Lower Limits (Status: BSM-LHC 2011)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Mass Limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM, 0-lep + j's + $E_T$, m_{stop}</td>
<td>-1.88</td>
</tr>
<tr>
<td>MSUGRA/CMSSM, 1-lep + j's + $E_T$, m_{stop}</td>
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</tr>
<tr>
<td>Phenomenological MSSM, (light $Z^0_1$), 2-lep + j's + $E_T$, m_{stop}</td>
<td>-1.88</td>
</tr>
<tr>
<td>Phenomenological MSSM, (light $Z^0_1$), 1-lep + j's + $E_T$, m_{stop}</td>
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</tr>
<tr>
<td>GMSB (GGM) + Simple model, (light $Z^0_1$), 1-lep + j's + $E_T$, m_{stop}</td>
<td>-1.88</td>
</tr>
<tr>
<td>GMSB (stable $Z^0_1$), 1-lep + j's + $E_T$, m_{stop}</td>
<td>-1.88</td>
</tr>
<tr>
<td>Stable massive particles: R-hadrons</td>
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<tr>
<td>Hypercolour scalar gluons, $m_{h} = m_{f}$</td>
<td>M_{stop}</td>
</tr>
<tr>
<td>RPV ($\lambda_{ij} = 0.10, \lambda_{ij} = 0.05$), high-mass eq.</td>
<td>M_{stop}</td>
</tr>
<tr>
<td>Bilinear RPV ($c_{ij} = 15 mm)$, 1-lep + j's + $E_T$, m_{stop}</td>
<td>M_{stop}</td>
</tr>
</tbody>
</table>

\[ \int L = 0.034 - 1.34 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

\[ \text{the search is well underway} \]

*Only a selection of the available results leading to mass limits shown.*

G. Watts (UW/Seattle)
Limits, limits everywhere...

Summary of limits on GGM NLSP types with gluino production
Kats, Meade, Reece & DS (1110.6444)

Where is SUSY hiding??
• Event with five jets and large missing transverse energy
• Total sum of transverse momentum $H_T = 1132$ GeV and missing transverse energy $H_{T\text{Miss}} = 693$ GeV
Impact of LHC Summer Results on SUSY

“Predict” on the basis of present data what the preferred region for SUSY is (in constrained MSSM SUSY)

Include the 1 fb$^{-1}$ SUSY searches (jet+MET), $B_S \rightarrow \mu \mu$ and XENON100

$\chi^2$ probability: $P(\chi^2)$ for CMSSM
Before EPS/LP11: 43% Including EPS/LP11 results: <16%

LHC direct searches significantly constrain allowed CMSSM parameter space!
What is Next?

• Think beyond the simplest or most constrained models and optimize searches
  – pMSSM
  – NMSSM
  – Degenerate mass spectra
  – Light 3rd generation
  – Split SUSY
  – RPV SUSY
  – …

• How much of the “theory space” do we really cover? May have to revise our searches for other scenarios

• More ideas at the LPCC Workshop@CERN (Aug’11- June ’12)

LHC Implications for TeV scale physics

A lot!!

Missing something?

• Important to push limits up, but with more statistics more important to systematically close windows for light sparticles with suppressed xsec...

... e.g.

“Flavor-Split” spectra (heavy 1st-2nd gen squarks, gluino below 1-1.5 TeV, light 3rd gen)

“Squashed” spectra (everything below ~500GeV but splittings are small, O(10GeV))

Low MET scenarios (not necessarily RPV)
What is really needed from SUSY

N. Arkani-Ahmed
CERN 1/11/11

Papucci, Ruderman, Weiler arXiv:1110.6926

LHC data
Stops > 200-300 GeV
Gluino > 600-800 GeV

Natural SUSY survived LHC so far, but we are getting close
Beyond Minimal

Theorists Natural Delight

1500 \rightarrow \bar{g}

400 \rightarrow \tilde{u}^c, \tilde{b} \rightarrow \tilde{t}_{L,R}, \tilde{b}_L

120 \rightarrow \tilde{h}, \tilde{h}_L
...Or as shown here...

a natural spectrum

\[
\begin{align*}
\tilde{g} & \quad \tilde{t}_L \quad \tilde{t}_R \\
\tilde{b}_L & \quad \tilde{b}_R \\
\tilde{H} & \\
\bar{B} & \quad \tilde{\tilde{q}}_{1,2}, \tilde{u}_{1,2}, \tilde{d}_{1,2} \\
\tilde{\tilde{t}}_{1,1} & \\
\tilde{\tilde{c}}_1 & \\
\tilde{\tilde{b}}_R & \\
\end{align*}
\]

natural SUSY \quad \text{decoupled SUSY}

not a new idea:

Barbieri, Dvali, Hall 1995.
Cohen, Kaplan, Nelson 1996.

etc

J. Ruderman
Recasting Published Analyses

(Lefty) stop v bino

Left-Handed Stop / Sbottom

ATLAS 2–4 j. 1.04 fb$^{-1}$
CMS $\alpha_T$, 1.14 fb$^{-1}$
CMS $H_T$/MET, 1.1 fb$^{-1}$
CMS $M_{T2}$, 1.1 fb$^{-1}$
D0 $b\bar{b}$, 5.2 fb$^{-1}$

$\tilde{t}_L$ $\tilde{b}_L$ $b$

$W^* \rightarrow t\bar{b}$

‘Generic’ analyses in the experiments have a say on this!
Recasting Published Analyses

- We find limits that are still consistent with $\sim 1/3$ fine tuning.

\[
m_{\tilde{H}} \gtrsim 100 \text{ GeV} \\
m_{\tilde{\chi}} \gtrsim 300 \text{ GeV} \\
m_{\tilde{g}} \gtrsim 700 \text{ GeV}
\]
So SUSY is Fine!

Off record comments...???

Somewhere between denial and anger right now...?
The Undiscovered SUSY
Why Do Models Get Missed by ATLAS?

Some of the most common contributing reasons are:

- small signal rates due to suppressed c’s which are possibly correlated with ‘larger’ sparticle masses
- spectrum forbids hard leptons in cascades & nj01 buried in systematics
- small mass splittings w/ the LSP (compressed spectra)
- decay chains long or ending in stable sparticles \( \rightarrow \) low MET!
- inaccessibility of direct electroweak gaugino production
- will comment a bit about each of these

\[ \rightarrow \text{ BUT there are many more subtle situations that have to be examined on a case-by-case basis} \]
Model space coverage: pMSSM studies

Example of a ‘failure’

Example: Very Degenerate Spectrum

A nightmare waiting to happen…

Heavy LSP + all $\sim 1$ TeV
Model space coverage: pMSSM studies

Particles below 1 TeV

- What fraction of the model sets should not (yet) have been discovered?

→ The coverage is quite good for both model sets!
Compressed Spectra

Theory ideas: Compressed spectra

For low compression, signal E (4 jets, inclusive $m_{\text{eff}}$) wins, but as the compression increases, B (3 jets) and then A (2 jets) take over.

Steve Martin

SUSY Status Report, D. Stuart, Nov. 2011, Hidden SUSY, UC Davis
Compressed Spectra

Rethink search strategies to optimize better for such scenarios

Theory ideas: Compressed spectra

Suggestions:

- Require fewer jets (or lower $p_T$ threshold for subleading jets), but sum over more of them in defining $m_{\text{eff}}$,

  AND/OR

- Choose lower cut on $m_{\text{eff}}$ (750 GeV?), and a higher cut on $\frac{E_T^{\text{miss}}}{m_{\text{eff}}}$ (0.35?) to compensate.

- Collect more data and be patient…
New Analyses...

Multi-leptons 3 or 4 leptons → 53 categories with low/high MET/HT, with or without Z veto

Multi-jets: 6 to 8 jets

Some small excesses in data in 3 lepton/Z veto channels but less than 2σ significance

Experiments push on... More to come this winter! Based on 4.7-5 fb⁻¹!!
Searches for the Third Generation

- Extend the searches using also to leptons and jets coming from $b$-quarks
- Sensitive to different part of the SUSY phase space

Gluinos have to be heavier than $\sim 550$ GeV from this search
Search for Gauge Mediated SUSY

$\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$

- 2 photons ($p_T > 30, 20$ GeV)
- $E_T^{\text{miss}} > 125$ GeV
- $N_{\text{signal}} = 0$
- $N_{\text{background}} = 0.10 \pm 0.04 \text{(stat)} \pm 0.05 \text{(syst)}$

**ATLAS**

- Data 2010 ($\sqrt{s} = 7$ TeV)
- GGM $m_{\tilde{g}} = 600$ GeV, $m_{\tilde{\chi}} = 300$ GeV ($\times 100$)
- UED 1/R = 900 GeV ($\times 100$)

**GGM: bino-like neutralino, $\tan\beta = 2$, $c_t < 0.1 \text{ mm}$**

- upper limit is set on the cross section for new physics of
  - $\sigma < 0.38 - 0.65 \text{ pb}$.
- Mass (gluinos) > 560 [GeV]

**ATLAS**

- ATLAS expected CL$_s$ limit
- ATLAS observed CL$_s$ limit
- $+1\sigma$
- CMS observed limit (35 pb$^{-1}$)
RP Violating SUSY Searches

Sparticle decays into 3 jets

Use a diagonal cut to remove combinatorial background as well as QCD background:

\[ m_{jjj} < \sum |p_T(\text{triplet})| - \alpha \text{ (Offset)} \]

No signal for gluino masses up to 280 GeV
High mass excursion is less than 2\(\sigma\) taking into account look elsewhere effect

arXiv:1107.3084
Z’ → tt Search

- Search in the all hadronic decay channel for the tops
- Tops are boosted for high mass Z’, jets merge
- Start from Cambridge-Aachen FAT jets and apply jet pruning to find sub-jets
- QCD background estimate from data (mistag method)

Particle flow an asset for this study!

Exclude KK-Gluons 1<M<1.5 TeV
Light Top NLSP in GMSB model

D. Shih

D0 publication did not provide enough information (e.g. the definition of these discriminants) to allow us to reinterpret this search.

It would be very interesting for D0 to apply this analysis to stop NLSP, it could be a strong limit!!

Suggestions for future analyses

The $b$-jets from light stops are soft:

<table>
<thead>
<tr>
<th>$b$-jet $p_T$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$120$ GeV</td>
</tr>
<tr>
<td>$150$ GeV</td>
</tr>
<tr>
<td>$180$ GeV</td>
</tr>
<tr>
<td>$200$ GeV</td>
</tr>
</tbody>
</table>

The transverse mass of the $W$ is a good discriminator:

<table>
<thead>
<tr>
<th>$m_{\text{tr}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$7$ TeV LHC</td>
</tr>
</tbody>
</table>

The $b$-jets invariant mass has been suggested a while ago but never used.


You don't even have to get the combinatorics right:

<table>
<thead>
<tr>
<th>$m_{b\bar{b}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$7$ TeV LHC correct pairing</td>
</tr>
<tr>
<td>$7$ TeV LHC random pairing</td>
</tr>
</tbody>
</table>

Results: LHC

(Kats, Meade, Reece, DS 1110.6444)

"Stop NLSP"

ATLAS $\bar{t}b+\text{MET}$ will have good coverage over widest range of stop mass.

A surprise: a number of 1 fb SUSY searches could be sensitive to light stops!

Dashed lines indicate ultra-low acceptances ($\sim 10^{-4}$ to $10^{-5}$) where we don't trust our simulation of the signal tails.

There are still no firm LHC limits on direct stop pair production. Stop could still be lighter than the top?!!!

Suggestions: leptonic MT2

(for details, see 1110.6444)

- $mT2$: generalization of $W$ transverse mass to events with double decay chains ending in invisible particles. (Barr, Lester, Stephens, Summers,...)
- $mT2$ has been used for measurements of top properties, but in all cases, the full event was used (leptons+$b$-jets+$\text{MET}$). Expect an endpoint at the top mass, but combinatorics is an issue.
- $\bar{t}b$ is the dominant background to stop NLSP, especially at the LHC. We propose computing $mT2$ using only the leptons and $\text{MET}$ to reject $\bar{t}b$ background. Expect an endpoint at $W$ mass and no combinatorial confusion.
Collective RPV

RPV through interaction with new fields

J. Ruderman

collective RPV

$$W \supset \lambda_1 u d D + \lambda_2 U d D + \lambda_3 U d d$$

- any decay from a superpartner to SM fields must use all three couplings
- but only one couplings needs to be probed at a time, if the decays are sequential

$$m_{\tilde{N}_1} > m_D > m_{\tilde{U}}$$

Expect many objects
Soft?

• probing more couplings means higher-multiplicity final states:

$$\tilde{N}_1 \rightarrow 5j$$
Collective RPV

there are many other ways to implement cRPV

\[ W \supset \lambda_1 l\bar{e} + \lambda_2 L\bar{l}E + \lambda_3 Ll\bar{e} \]

a lepton factory!

\[ \tilde{N}_1 \rightarrow 4l + 1\nu \]
\[ 2l + 3\nu \]

4, 6, 8 leptons per event
LHC pheno will depend on LSP

LSP not stable: can be charged, colored!

Up-type squarks: \( M_U^2 = m_{\text{soft}}^2 \left( \frac{1 + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger}{\delta^* Y_u} \frac{\delta^* Y_d}{1 + \gamma Y_u^\dagger Y_u} \right) + \ldots \)

Down-type: \( M_D^2 = m_{\text{soft}}^2 \left( \frac{1 + \alpha' Y_u Y_u^\dagger + \beta' Y_d Y_d^\dagger}{\delta' Y_d} \frac{\delta' Y_d}{1 + \gamma' Y_d^\dagger Y_d} \right) + \ldots \)

One stop naturally light; \( \tilde{b}_L \) also possible LSP

stau LSP \( \rightarrow \) nearly degenerate spectrum

Neutralino, chargino, gluino also possible LSPs
4 jets, two of which are b’s

\[
\tilde{t} \rightarrow s \tilde{b} \\
\frac{c \tau_t}{\sin^2 \theta_t} \sim (2 \mu m) \left( \frac{10}{\tan \beta} \right)^4 \left( \frac{300 \text{ GeV}}{m_t} \right) \left( \frac{1}{2 \sin^2 \theta_t} \right) \\
90\% b + s, 8\% b + d, 2\% d + s
\]

- Generically prompt (no $E_T$, no displaced vertices)
- No tops / leptons in final state... more $b$-jets, resonance?

Channels with top also possible
Stealth SUSY

M. Reece

Small MET

The “stealth” sector should remain nearly supersymmetric

$\mu$-term: $M_{\text{SUSY}} \sim M_{\text{EWK}}$

$M_{\text{SUSY}} \sim \epsilon M_{\text{EWK}}$

flavor blind mediation

MSSM

Stealth

$\epsilon$

weak MSSM/stealth coupling
- Gluino LVSP
- 6-jet Final States
- Low missing $E_T$
- *False resonances*

---

**LHC Limit**

- $m_S = 100$ GeV
- ATLAS 2–4 j + MET
- ATLAS 6–8 j + MET
- CMS HT (2010)
- CMS HT (2011)

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Stealth SUSY
Long Lived Particles

Split Supersymmetry

• Assumes nature is fine tuned and SUSY is broken at some high scale
• The only light particles are the Higgs and the gauginos
  - Gluino can live long: sec, min, years!
  - R-hadron formation (eg: gluino+ gluon): slow, heavy particles
Unusual interactions with material eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

• In some models/phase space the gravitino is the LSP
• ⇒ NLSP (neutralino, stau lepton) can live ‘long’. Displaceded vertices
• ⇒ non-pointing photons

Hidden Valleys , RPV,…

⇒ Challenge to the experiments!

K. Hamaguchi, M Nojiri, ADR hep-ph/0612060
ADR, J. Ellis et al. hep-ph/0508198

Sparticles stopped in the detector, walls of the cavern, or dense ‘stopper’ detector. They decay after hours---months…
Triggers....

triggering is grim...
... and getting grimmer

bunch spacing, protons in bunch, beam tunes and focus

your favorite trigger squeezed here

rate limit driven by $$ disk, cpu, etc.

unprescaled @ end of 2011

em: 1e@22, 2e@12, 1e@12+2e@6, 1γ@80, 2γ@20, 1e@20+{E_T}^{miss} > 40
muon: 1μ@18, 1μ@40sl, 1μ@15+1μ@10, 1μ@15+{E_T}^{miss} > 30
tau: 1τ@125, 1τ@29+1τ@20, 1τ@29+{E_T}^{miss} > 35
jets: 1j@250, 3j@100, 4j@45, 5j@30, 1j@75+{E_T}^{miss} > 55, 1j@100+{H_T} > 400,
      4j@40+{H_T} > 350
combo: 1μ@18+1j@10, 1e@5+1μ@6, 1τ@20+1e@15, 1τ@20+1μ@15
“Hidden Valley”-like triggers

Maybe SUSY/New Physics is “hidden” in such topologies
displaced vertices

scal
e additional scenarios allowing for such a signature include split-supersymmetry [22], hidden-valley [23], dark-sector gauge bosons [24], stealth supersymmetry [25], or a meta-stable supersymmetry-breaking sector [26].

SUSY++
L=33 pb⁻¹

vertex reconstruction
standard
use tracks that have no pixel hits
reject vertices near material

Efficiency
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
0 20 40 60 80 100 120 140 160
r_Du [mm]

ATLAS simulation
760 GeV q̄, 108 GeV P_1

Event selection
Vertex selection
Neutron selection
Search for RPV SUSY

Using events with a "displaced vertex"

Event from a jet-trigger data sample, where a high-mass vertex (circled) is the result of an apparently random, large-angle intersection between a track and a low-mass hadronic-interaction vertex produced in a pixel module. The beam pipe and some pixel modules are shown.

No signal found

- $\sigma \times \text{detector acceptance} \times \varepsilon < 0.09 \text{pb} @ 95\% \text{ Confidence level}$
Search for Stopped Gluinos

- Out-of-time decay of heavy particles stopped in the detector
- Look for signal **without** collisions:
  - When no beam in the machine
  - Between bunch trains

**Bunch Train**

- 50 ns
- Gap

**Lifetime = 1 µs**

**CMS-EXO-11-020**

- Too short-lived to be out-of-time 100 ns
- Too long-lived to have decayed yet 1 month

**13 orders of magnitude!**
Search for Stopped Gluinos

Search for Heavy Stable Charged Particles that stop in the detectors and decay a long time afterwards (nsec, sec, hrs…)
Special data taking after the beams are dumped and during beam abort gaps

95% CL Limits: Stopped Gluinos > 600 GeV, Stopped Stop quarks > 337 GeV
Suggestions at this workshop

• Analyses with multi-b’s, 3 and more, (3 b-resonances?)
• Going beyond cut and count: shape analyses...
• Monojet analyses for SUSY
• Rethink Search strategies for compressed spectra.
• Leptonic MT2
• Look out for stable charginos? Stubs? Other long lived particles?
• RPV with heavy flavor? Four jet resonances? 4 or more leptons? Boosted jets & jet substructure analysis
• Look out for stable charginos? Stubs?
• 4jet events with two b’s (stop anti-stop production in MFVS)

Triggering remains an important concern

Analyses relying on ISR: how well can we rely on programs like MadGraph?
How can LHC data be maximally useful/usable

-Simplified models: are these really used? Suggest more SMS/analysis channel
- An experiment certified fast simulation? Not likely
- Acceptance maps and cuts stored with each analysis? Possible (e.g. Rivet)
- Recast of analyses? Not for some time I think...
There will be an LPC workshop on 28 November (2 p.m.) to collect all information regarding requests for 2012 running from the experiments in preparation for the Chamonix LHC workshop at the beginning of Feb. 2012.

**Machine parameters:**
- what energy ? (3.5 TeV, 4 TeV)
- which bunch spacing ? (50ns, 25ns)
- which beta* in IP1/5 ? (0.7m, 1m ?) * crossing angle, geometric factor, operational efficiency (tight collim settings!)
- transverse emittance, bunch length?

**Draft schedule 2012**
Thanks!

To the organizers of this meeting
The UC-Davis folks!
BACKUP