Particle Physics
- Many precise measurements consistent with the Standard Model (SM)

Astrophysics and Cosmology
- Abundant evidence for physics beyond the SM

Experiments at the TeV scale could potentially help to bridge the gap

Dark Matter
- Relic Density for non-baryonic dark matter:
  - \( 0.094 < \Omega_{DM} h^2 < 0.129 \) (95%CL)
  - \( h = 0.71 \) (km/s)/Mpc (Hubble)

Weak scale SUSY with R-Parity conservation
- Appealing characteristics including a dark matter candidate with the right relic density
The temptation unification

\[ \frac{1}{\alpha_i} \]

\[ i = 1 \quad \text{no SUSY} \]

\[ i = 2 \quad \text{with SUSY} \]

\[ i = 3 \]

Energy (GeV)

\[ 10^2 \quad 10^6 \quad 10^{10} \quad 10^{14} \quad 10^{18} \]
The absence of SUSY at LEP and the Tevatron, coupled with the complicated array of results from cosmology and astrophysics experiments, has motivated many alternative models:

- Little Higgs (with T Parity)
- Universal extra dimensions (with KK parity)
- Strong dynamics
- Extra dimensions (Large and warped)
- Hidden Valleys
- Split SUSY
- ...

If you don’t exactly know what you’re looking for, a hadron collider is a great tool to be using.
Hadron Colliders

- Broad range of energies
- High mass scales and energies
- Large physics cross-section

Discovery machines …

- But, interesting things are rare:
  - It takes great experiments (and sometimes a bit of luck...)
Big things come early...and late.

- SPS & Tevatron Discoveries
  - SPS turn-on led to quick major discoveries by UA1 and UA2
  - Not true at the Tevatron
- SPS had a lot of data
  - Already probed a lot higher than the mean constituent com energy of ~100 GeV
- Tevatron needed to ~match SPS integrated luminosity
  - in order to probe a “new” energy domain and then discovered top!
- Early discoveries have been followed by other important results at hadron colliders
  - but these generally come late
September 1981: first (small) run for UA2

First observation of jets in hadronic collisions
LHC will explore very new territory

- At 1 TeV constituent c.o.m. energy
  - 1 fb\(^{-1}\) q\(\bar{q}\) at Tevatron is like 1 pb\(^{-1}\) gg at 14 TeV LHC
Parton Luminosity falls steeply

- At the LHC it falls x10 every 600 GeV in multi-TeV region:
  - If you have a limit \( M > 1 \) TeV for a pair-produced particle, your sensitivity improves by \(~ (600/2)=300\) GeV = 30% for 10 times more integrated luminosity

- New states always produced near threshold
  - If nothing new is found relatively early, one may have to wait a long time

Improving sensitivity is tough.... but you can turn evidence into an observation
Past versus future discoveries

- **W & Z**
  - Masses and production rates were predicted
  - Signals stood out “like being hit on the head with a hammer”
  - Interpretation was unambiguous

- **Top**
  - Signal was a bit harder to dig out (initially a counting experiment) and less straightforward to interpret but…
  - We knew it had to be “somewhere”
  - Production and decay properties were predicted

- **Higgs**
  - Somewhat like top – for a given mass, we know its production and decay properties in the SM and alternative BSMs. For some masses, counting experiments may be the first sign.
  - Somewhat like W & Z – the signal could appear as a striking mass peak

- **New Physics**
  - Don’t know what to expect. Theory provides examples, some are compelling, none are guaranteed ...
BSM Physics at the LHC: pp @ 14 TeV

- New Gauge Bosons?
- Hidden Valleys?
- ZZ/WW resonances?
- Technicolor?
- Extra Dimensions?
- Black Holes???
- Little Higgs?
- Split Susy?

Starts to look like we have more models than theorists.

We do not know what is out there for us...
A few thoughts …

- Models provide ideas for unexpected signatures
  - Very uncertain that any of these models will be seen, but there is an important benefit
  - We prepare more broadly and look at generic things from a different perspective
    - e.g. very boosted top quarks, very high $E_T$ leptons, triggering on jets when there’s no beam!
- The number and variety of theories are indicative of the fact that what’s really needed is data!

New Physics Signatures

Many channels in New Physics: Typical signals
- Di-leptons (like sign/same sign)
- Leptons + MET
- Photons + MET
- Multi-jets (2 → ~10)
- Multi-jets + MET (few 10 → few 100 GeV)
- Multi jets + leptons + MET…
- B/τ final states…

Also: new unusual signatures
- Large displaced vertices
- Heavy ionizing particles (heavy stable charged particles)
- Non-pointing photons
- Special showers in the calorimeters
- Unexpected jet structures
- Very short tracks (stubs)…

Albert De Roeck
The Standard Model at $\leq 10$ TeV

- **Low initial luminosity**
  - Study Min Bias, $dN^{\pm}/d\eta$ etc
    - Refine triggers
    - Constrain Underlying Event, PDFs
      - Tune MC's
  - Jets
    - Optimize algorithms for resolution & scale
    - Study lepton fakes, b tagging, photons.
  - Then more complex final states

- Also calibrate with known objects
  - Study “candles” for leptons and photons
    - $\pi^0, \psi, \ U$ initially to understand detector, tracking, leptons & other objects
    - Extend to $W$ or $Z \rightarrow$ leptons

- Compare to MC $V+$Jets ($V=W,Z,\gamma$)
- Extend into $t\bar{t}$ core region and then
- Deal with tails…

A new window on Nature
Parts of SM we have not seen.
Somewhat familiar but more jets
Inclusive charged hadron production*

- “first-paper” analysis...

- constrain QCD models of hadron production

*14 TeV shown recently repeated at 900 GeV and 10 TeV
Explore the SM at 7-14 TeV

$J/\psi \rightarrow \mu \mu \ \ \ \gamma \rightarrow \mu \mu \ \ \ \ Z \rightarrow \mu \mu \ \ \ \ W \rightarrow \mu \nu$

$\gamma^{1s}$

Bkg w/o vertex cuts

ATLAS preliminary

ATLAS preliminary

CMS Preliminary

$\sqrt{s} = 10$ TeV

$W \rightarrow \mu \nu$

$QCD \rightarrow \mu X$

$Z \rightarrow \tau \tau$

$t \bar{t} \rightarrow q_1 q_2 b \bar{b} \mu \nu$

$M_3$ [GeV/c^2]

Entries

CMS Preliminary @ 10pb^{-1}
- LHC ≠ Tevatron
  - Small momentum fractions $x$ for many key searches:
  - Large phase space for gluon emission
    - For $p_T^\text{jet} \gtrsim 20$ GeV, all $t\bar{t}$ events have additional jets
    - Ratio of LHC to Tevatron production cross sections for $W/Z + n$ jets grows fast as $n$ increases

![Graph showing the dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_T\text{min}$, together with the top pair production cross sections at LO and NLO.](Huston)

Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_T\text{min}$, together with the top pair production cross sections at LO and NLO.
- Additional jets complicate reconstruction of $t\bar{t}$
  - First we need to understand the control regions:
    - $W,Z,\gamma + n$ jets for low $n$, and QCD jets faking $e, \mu$
    - Then we can begin to tackle the core regions of $t\bar{t}$.
- But the devil is in the details
SEARCHING FOR SOMETHING NEW
Early Searches for New Physics

- Following the data
  - There is a lot of indirect evidence for the Higgs, direct evidence for Dark Matter (DM), and a good chance we can make one or both at the LHC

- Higgs (lecture 1)
  - Either a rare process or difficult to discriminate from background so...it will take a lot of data.
    - Not likely we can say that much about it in the upcoming run.

- Dark Matter
  - We don’t know what it is
  - We can think of early SUSY searches as effectively looking for Dark Matter
    - The topologies, methods, backgrounds relevant to SUSY apply to broad class of Dark Matter theories
- **Missing Energy:**
  - from LSP

- **Multi-Jets:**
  - from cascade decay (gaugino) particles like top, W, Z

- **Multi-Leptons:**
  - from decay of the Nj
Extra dimensions, Little Higgs, Technicolor, etc

- **Missing Energy:**
  - Neutral Weakly Interacting Massive Particle (NWIMP)
  - NWIMP appears at the end of the cascade (which could be shorter or longer…)

- **Multi-Jets:**
  - from decay of the N’s (possibly via heavy SM particles like top, W, Z)

- **Multi-Leptons:**
  - from decay of the Nj
Extra dimensions, Little Higgs, Technicolor, etc

For SUSY we use mSUGRA at about ~10 points x in parameter space (LMx and HMx, in CMS and SUx in ATLAS x=1,2,3,...). This is not because we believe only in mSUGRA but because we focus on different event signatures. We are now doing this more systematically.

**“SUSY search”**

- **Missing Energy:**
  - Neutral Weakly Interacting Massive Particle (NWIMP)
  - NWIMP appears at the end of the cascade (which could be shorter or longer…)

- **Multi-Jets:**
  - from decay of the N’s (possibly via heavy SM particles like top, W, Z)

- **Multi-Leptons:**
  - from decay of the Nj
Jets + $E_T^{\text{miss}}$ - Inclusive Search

$E_T^{\text{jet1}} = 330$ GeV  
$E_T^{\text{jet2}} = 140$ GeV  
$E_T^{\text{jet3}} = 60$ GeV

The simplest topology and the greatest potential

Analysis Strategy: be brave!

- Fight background and noise
- Use data control samples
- Estimate background from data

Run II V. Shary CALORo4
An illustrative example: $Z \rightarrow \nu\nu + \text{jets}$
An irreducible background for $\text{Jets} + \text{MET}$ search

Define control samples and understand their strength and weaknesses:
An illustrative example: \( Z \rightarrow \nu \nu + \text{jets} \)

An irreducible background for Jets + MET search

Define control samples and understand their strength and weaknesses:

\( Z \rightarrow \mu \mu + \text{jets} \)

Ignore the 2 \( \mu \)'s and you have a good stand in for \( Z \rightarrow \nu \nu \)

very clean but low statistics:

factor 6 suppressed compared with \( Z \rightarrow \nu \nu \)
Data Driven Background Estimations

An illustrative example: $Z \rightarrow \nu \nu + \text{jets}$
An irreducible background for Jets + MET search

Define control samples and understand their strength and weaknesses:

$Z \rightarrow \mu \mu + \text{jets}$
Ignore the 2 $\mu$’s and you have a good stand in for $Z \rightarrow \nu \nu$
very clean but low statistics:
factor 6 suppressed compared with $Z \rightarrow \nu \nu$

$W \rightarrow \mu \nu + \text{jets}$
Ignore the $\mu$ ...
Larger statistics but not so clean, SM tt and signal contamination

MET = missing $E_T$
Data Driven Background Estimations

An illustrative example: \( Z \rightarrow \nu \nu + \text{jets} \)
An irreducible background for Jets + MET search

Define control samples and understand their strength and weaknesses:

- \( Z \rightarrow \mu \mu + \text{jets} \)
  - Ignore the 2 \( \mu \)'s and you have a good stand in for \( Z \rightarrow \nu \nu \)
  - Very clean but low statistics: factor 6 suppressed compared with \( Z \rightarrow \nu \nu \)

- \( W \rightarrow \mu \nu + \text{jets} \)
  - Ignore the \( \mu \) ...
  - Larger statistics but not so clean, SM \( tt \) and signal contamination

- \( \gamma + \text{jets} \)
  - Ignore the \( \gamma \) ...
  - Large statistics, clean for \( E_\gamma > 200 \) GeV

\( \text{MET} = \text{missing } E_T \)
Predicting $Z \rightarrow \nu \bar{\nu}$ 100 pb$^{-1}$

Search region (MET> 200GeV)

$\gamma$ + jets: 124 Events per 100 pb$^{-1}$ (14 TeV)
- Photon backgrounds estimated from data
  - QCD, electrons
  - QFT correction to reproduce Z spectrum
  - NB: Out-of-box agreement is already good without QFT corrections

W + jets: 24 events with $W \rightarrow \mu \nu$
- Backgrounds estimated from data
  - QCD, $t\bar{t}$, Z
- Well known correspondence to Z+jets

| $Z \rightarrow \nu \bar{\nu}$ background estimate (100 pb$^{-1}$) |
|--------------------------|------------------|
| MC-truth | 35 |
| From $\gamma$+jets | $29 \pm 3$ (stat) $\pm 5$ (sys) **uncorrected** |
| From W+jets | $35 \pm 10$ (stat) $\pm 8$ (sys) $\pm 3$ (theory) |

$Z \rightarrow \mu \mu$ + jets: only 4 events pass the search cuts
QCD is harder...

- Need to predict MET in multijet events without using MC
  - Jet response functions
    - Gaussian piece from jet+photon events, using transverse energy of photon to determine “true” jet $E_T$
    - Non-Gaussian piece from multijet events in which MET is aligned with a jet
  - Apply to data
    - Use jet response to smear $E_T$ of jets in multi-jet events that have no significant MET associated with the jets
SUSY search with dijet events using $\alpha_T$

- Case of a short cascade
  - $q\bar{q}$ production with $q' \rightarrow q + \text{LSP}$

- Signature:
  - 2 jets + MET

- Kinematic cuts:
  - $\Delta \phi < 2/3 \pi$
  - $\alpha_T > 0.55$

\[ \alpha_T = \frac{E_{Tj_2}}{M_{Tj_1j_2}} = \sqrt{\frac{E_{Tj_2}}{E_{Tj_1}}} / \sqrt{2(1 - \cos \Delta \phi)} \]

- (inspired by arXiv0806.1049)

- Use kinematics of dijets:
  - No direct calorimetric MET dependence

- Has been extended to n-jet systems
- Signal enriched/depleted regions
  - Split sample via:
    - Leading jet central
    - Leading jet forward
  - SUSY is central \( \Rightarrow \) use following ratio of event counts in forward regions (\( |\eta| \geq 2.5 \)) to predict central background (\( |\eta| < 2.5 \)).

\[
R_\alpha \equiv \frac{N(\alpha_T > 0.55)}{N(\alpha_T < 0.55)}
\]

\[
\begin{array}{c|cc}
|\eta| & D & C \\
\hline
2.5 & B & A \\
\hline
(0,0) & 0.55 & \alpha_T \\
\end{array}
\]

\[
R_\alpha = \frac{N_C}{N_D}: \text{ assumed to be constant over } \eta \text{ and } \sim \text{ signal free}
\]

Background in signal region A:

\[
N_A = N_B \times R_\alpha
\]
Without SUSY (closure test)

- Predicted
- Simulated

Simulated: 77 ± 3
Predicted: 68 ± 12

With SUSY LM1

- Predicted
- Simulated

Simulated: 517 ± 13
Predicted: 91 ± 14
Lower rates and backgrounds

Similar approach as for MET + Jets
  - Expected yields & backgrounds smaller

N=1 Lepton: Backgrounds
  - W+jets, tt involving single leptonic W decay
  - Z+jets, tt with 2 leptonic W decays
    - In both cases, a lepton is lost (outside acceptance) or not identified (overlaps a jet, or involves significant Bremstrahlung etc.)
  - QCD Multijets
    - A jet fakes a lepton and there’s large MET from jet mismeasurement

N=2 Leptons: Background
  - W+jets, tt involving single leptonic W decay
    - Now a jet fakes the second lepton
    - Z+jets, tt with 2 leptonic W decays
  - Small contributions from single top, dibosons etc.
First Kinematic Measurements

…With a bit of luck we might see this

- Two undetected particles of unknown mass in the final state so cannot reconstruct mass peaks
- Edges, endpoints give 1st detailed info on underlying spectrum

Jets + MET+ 2 Leptons of Same Flavor and Opposite Signs (SFOS)

\[ M_{\ell\ell}^{\text{max}} = M(\tilde{\chi}_2^0) \sqrt{1 - \frac{M^2(\ell_R^0)}{M^2(\tilde{\chi}_2^0)}} \sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\ell_R^0)}} \]

- Estimate SF t\bar{t} and WW bkgd from e\mu events
- Relatively precise extraction of $M_{\ell\ell}^{\text{max}}$ early

$\Delta M_{ee}^{\text{max}} = 1.07_{\text{stat}}^{+0.36}_{-0.30} \text{ GeV for 1 fb}^{-1}$

$\Delta M_{\mu\mu}^{\text{max}} = 0.75_{\text{stat}}^{+0.18}_{-0.12} \text{ GeV for 1 fb}^{-1}$
SU3 (bulk point), two body decays
Fitting function: triangle smeared with a gaussian

SU4 (low-mass point near Tevatron limits), three body decay.
Fitting function: theoretical three-body decay shape with Gaussian smearing

More luminosity is needed to discriminate 2-body and 3-body decays. With 1 fb\(^{-1}\) both fitting functions give reasonable c\(^2\).
What we see may be difficult to interpret

- Minimal Universal Extra Dimensions
  - 1 Extra compact dimension: R
  - Everything propagates in Bulk
  - KK tower of “SM-like” states

Datta, Matchev, Kong

CMS AN 2006/008
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Signatures like low mass SUSY!
  - Many Jets
  - Large MET (KK parity → stable LKP)
  - Leptons
    - With OS dilepton mass edges
  - High cross-section
    - Early Physics Potential

- Current constraints:
  - \( R^{-1} > 600 \text{ GeV} \) (for \( m_H > 115 \text{ GeV} \))

Datta, Matchev, Kong

CMS AN 2006/008

Joe Incandela
UC Santa Barbara
Higgs/BSM@LHC – SLAC Summer Institute 2009
August 6-7, 2009
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Datta, Matchev, Kong

CMS AN 2006/008

CMS Luminosity for $5\sigma_{SP}$ (1/fb)

$\Lambda R = 20$
$m_H = 120$ GeV/c$^2$

‘First data’ uncertainty

Joe Incandela
UC Santa Barbara
Higgs/BSM@LHC – SLAC Summer Institute 2009
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Gauge mediated SUSY breaking (GMSB)

- SUSY breaking
  - Takes place in hidden sector via messenger particles having SM gauge interactions
    - Mass scale of messengers (which form complete SU(5) representations) is $M_m \ll M_P$
    - Gravitino $\tilde{G}$: $M_{\tilde{G}} \ll 1$ GeV is always the LSP
  - SUSY particle masses depend on the number of messenger generations $N_m$
    - They obtain their masses radiatively via gauge interactions with the messengers
    - $N_m$ also determines which is the NLSP

- $N_m = 1$
  - NSLP = Neutralino
    - Decays to $\gamma \tilde{G}$

- $N_m = 2$
  - NSLP = stau
    - Decays to $\tau \tilde{G}$
  - The intrinsic SUSY-breaking order parameter ($F$) may not equal that seen by the messengers ($F_m$)
    - The larger $C = F/F_m$ is, the longer the NLSP Lives

- Bottom line:
  - The NLSP determines the phenomenology
- NLSP with $cT \sim 0$: Excess of events with $2\gamma$’s or $2\tau$’s
- NLSP with $cT \sim \text{few ns}$: See $\gamma$’s or $\tau$’s that do not point back to the event vertex
- NLSP with $cT \gtrsim 10 \text{ ns}$: Look for heavy stable charged particles
Longitudinal segmentation of the ECAL of ATLAS allows for precise determination of the polar angle of a non-pointing photon with very good resolution of $0.06 / \sqrt{E_\gamma / \text{GeV}}$. Moreover, the arrival time could be measured with 100 ps resolution.
Heavy Stable Charged Particles (HSCP)

- Heavy $\Rightarrow m \approx 100$ GeV
  - Stable or long lived $\Rightarrow c\tau \sim$ meters
  - Charged electrically or colored (R-hadron in final state)

- Signature: high momentum “muon-like”
  - No brehmsstrahlung
  - R-hadrons have nuclear interactions in which they pick up (are “dressed” by) light quarks or gluons
    - Can flip electric charge (“charge flipping”) or become neutral

- They’re very slow
  - Time of flight
    - $\beta = 0.3$: reaches muon chambers in $\sim 38$ ns (25 ns late)
    - Large ionization energy loss in tracker can also be used to estimate $\beta$
\[ \beta^{-1} = \sqrt{K \frac{dE}{dX}} \]

- O(10) \( dE/dx \) independent measurements from silicon strip tracker
- K can be obtained from protons
- Background
  - Tails from SM particles

\[
0.1 < \beta \gamma < 0.9 \text{ region}
\]
- $\beta_{DT} < 0.80$ and $\sigma_{\beta-1} < 0.1$
- $\beta_{Tk} < 0.80$
- $m_{\text{avg}} > 100$ GeV

Error bar: 50% syst on trigger efficiency - background free analysis

Goal: <1 bg event for $L=1 \text{fb}^{-1}$
HSCP arise in many models

Models here:

a) **SUSY GMSB** long lived Stau NLSP, LSP = gravitino dominant production: from decay chain of squark/gluino
direct pair production of KK tau

b) **mUED** – long-lived KK states
direct pair production of KK tau

c) **Split SUSY** (all scalar particles have high mass)
long-lived gluino (R-hadron)
d) **MSSM** with light stop as NLSP and small $\Delta M = M(st-\chi^0)$

| Data Sample | Cross section (pb) | HSCP in $|\eta| < 2.4$ (%) |
|-------------|-------------------|----------------------------|
| $\tilde{\tau}_1$ (156 GeV) | 1.19 | 97.6 |
| $\tilde{\tau}_1$ (247 GeV) | 0.097 | 97.5 |
| KK tau (300 GeV) | 0.020 | 84.7 |
| $\tilde{g}$ (200 GeV) | $2.2 \times 10^3$ | 89.7 |
| $\tilde{g}$ (300 GeV) | 100 | 91.7 |
| $\tilde{g}$ (600 GeV) | 5.00 | 93.7 |
| $\tilde{g}$ (900 GeV) | 0.46 | 92.6 |
| $\tilde{g}$ (1200 GeV) | $61 \times 10^{-3}$ | 91.4 |
| $\tilde{g}$ (1500 GeV) | $10 \times 10^{-3}$ | 90.4 |
| $\tilde{t}_1$ (130 GeV) | $1.11 \times 10^3$ | 87.8 |
| $\tilde{t}_1$ (200 GeV) | $1.77 \times 10^2$ | 90.9 |
| $\tilde{t}_1$ (300 GeV) | 27.4 | 92.8 |
| $\tilde{t}_1$ (500 GeV) | 1.27 | 95.3 |
| $\tilde{t}_1$ (800 GeV) | $7.81 \times 10^{-2}$ | 96.9 |

Heavy: mass > 100 GeV (non relativistic)
Semi-stable: $c$ tau > few m (escape the detector)

After production, $\tilde{g}$ and $\tilde{t}$ hadronise to metastable particle by combining with light quarks and gluons generically called **R-hadon**
Stopped R-hadrons

SPLIT SUSY Long-lived gluinos to jet(s)(+MET)

~10-20% of R-hadrons in mass range 100-2000 GeV get trapped in the detector (calorimeter, muon Fe ...)

Look for odd shaped jets when there is no beam in the detector
Significance of observation versus days of operation at E32 (i.e. low) luminosity

300 GeV gluino and 100 GeV neutralino
Not all that easy:

- **Muons**
  - $p_T$ resolution at high energies
  - Sensitivity to mis-alignments
  - Bremstrahlung at higher momenta

- **Electrons**
  - Calo saturation at very high energy
  - Leakage into had calorimeter reduces utility of longitudinal shower shape variables
  - Isolation affected by bremsstrahlung photon conversions

Not easy to understand efficiencies, systematics

- No resonance yielding ~TeV leptons to use (until you have discovered one 😊)
- MC efficiencies flat from control to signal regions… hopefully this is true in reality!

Use $e\mu$ events to estimate flavor symmetric backgrounds like $tt$
Larger misalignments increase the integrated luminosity required for a statistically significant signal.

But in the past year, LHC experiments have used cosmics to align their tracking and muon systems.
- Split track validation method
  - Split track at the Point of Closest Approach (PCA) to the nominal beam line
  - Refit separately top and bottom legs and compare the track parameters at the PCA

Alignments already as originally expected for $\approx$ somewhere between 10 and 100 pb$^{-1}$

Mass resolution $\sim 7$ (10) % at 1 (2) TeV with alignments expected for 100 pb$^{-1}$

1-2 TeV Z$'$ should be visible
$Z'$, Graviton, large extra dimensions...

Luminosity needed for discovery

<table>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>$\sigma$ [fb]</th>
<th>$A^*E$</th>
<th>$N$</th>
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<tbody>
<tr>
<td>1000</td>
<td>230</td>
<td>0.67</td>
<td>31</td>
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<tr>
<td>1250</td>
<td>83</td>
<td>0.68</td>
<td>11</td>
</tr>
<tr>
<td>1500</td>
<td>33</td>
<td>0.69</td>
<td>5</td>
</tr>
</tbody>
</table>

200 pb$^{-1}$ at 10 TeV
Discovery potential for $Z' \rightarrow ee, \mu\mu$

$Z' \rightarrow ee$

$Z' \rightarrow \mu\mu$

200 pb$^{-1}$
Similar to but harder than $Z'$ search.
SM Backgrounds $W$, $t\bar{t}$ etc.
Extra Dimensions and Black Holes
Search for Black Holes

Could be an overwhelming signal if the true Planck scale is \(~1\) TeV
<table>
<thead>
<tr>
<th>Model</th>
<th>Mass reach</th>
<th>Luminosity (fb⁻¹)</th>
<th>Early Systematic Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Interaction</td>
<td>( \Lambda &lt; 2.8 \text{ TeV} )</td>
<td>0.01</td>
<td>Jet Eff., Energy Scale</td>
</tr>
<tr>
<td>Z’ ALRM</td>
<td>( M \sim 1 \text{ TeV} )</td>
<td>0.01</td>
<td>Alignment</td>
</tr>
<tr>
<td>Z’ SSM</td>
<td>( M \sim 1 \text{ TeV} )</td>
<td>0.02</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>Z’ LRM</td>
<td>( M \sim 1 \text{ TeV} )</td>
<td>0.03</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>Z’ E6, SO(10)</td>
<td>( M \sim 1 \text{ TeV} )</td>
<td>0.03 – 0.1</td>
<td>Jet Energy Scale</td>
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<tr>
<td>Excited Quark</td>
<td>( M \sim 0.7 – 3.6 \text{ TeV} )</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>Axigluon or Colouron</td>
<td>( M \sim 0.7 – 3.5 \text{ TeV} )</td>
<td>0.1</td>
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<tr>
<td>E6 diquarks</td>
<td>( M \sim 0.7 – 4.0 \text{ TeV} )</td>
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<tr>
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<td>( M \sim 0.7 – 2.4 \text{ TeV} )</td>
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<tr>
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<td>( M_D \sim 4.3 - 3 \text{ TeV}, n = 3-6 )</td>
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<td>( M_D \sim 5 - 4 \text{ TeV}, n = 3-6 )</td>
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<td>MET, Jet/photon Scale</td>
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<td>Jet Energy Scale</td>
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<tr>
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<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>mUED</td>
<td>( M \sim 0.3 \text{ TeV} )</td>
<td>0.01</td>
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<tr>
<td>TeV⁻¹ (( Z_{KK}^{(1)} ))</td>
<td>( M_{z1} &lt; 5 \text{ TeV} )</td>
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<tr>
<td>RS1</td>
<td>( M_{G1} \sim 0.7- 0.8 \text{ TeV}, c=0.1 )</td>
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<td>Jet Energy Scale</td>
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<tr>
<td></td>
<td>( M_{G1} \sim 0.8- 2.3 \text{ TeV}, c=0.01-0.1 )</td>
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<td>Alignment</td>
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</table>
## Early LHC Discovery Potential

### Early LHC Runs: 0.1 to 1 fb⁻¹

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass reach</th>
<th>Luminosity (fb⁻¹)</th>
<th>Early Systematic Challenges</th>
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<tr>
<td>Contact Interaction</td>
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<td>Jet Eff., Energy Scale</td>
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<tr>
<td>Z' LRM</td>
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<tr>
<td>Z' E6, SO(10)</td>
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<td>Jet Energy Scale</td>
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<tr>
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<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
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<td>Technirho</td>
<td>$M \sim 0.7 – 2.4$ TeV</td>
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<td>Jet Energy Scale</td>
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<tr>
<td>ADD Virtual $G_{KK}$</td>
<td>$M_D \sim 4.3 - 3$ TeV, $n = 3-6$</td>
<td>1</td>
<td>Alignment</td>
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<tr>
<td>ADD Direct $G_{KK}$</td>
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<tr>
<td>SUSY</td>
<td>$M \sim 1.5 – 1.8$ TeV</td>
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<td>MET, Jet/photons Scale</td>
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<tr>
<td>Jet+MET+0 lepton</td>
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<td>MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backgroundsv</td>
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<td>Jet+MET+1 lepton</td>
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<tr>
<td>Jet+MET+2 leptons</td>
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<td>mUED</td>
<td>$M \sim 0.3$ TeV</td>
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<tr>
<td>TeV⁻¹ ($Z_{KK}^{(1)}$)</td>
<td>$M_{Z_1} &lt; 5$ TeV</td>
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<tr>
<td>RS1</td>
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<td>Jet Energy Scale</td>
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<td>di-jets</td>
<td>$M_{G_1} \sim 0.8 - 2.3$ TeV, $c=0.01-0.1$</td>
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<td>di-muons</td>
<td></td>
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</tr>
</tbody>
</table>
The LHC modifications are nearly completed.

- A long run will start late this year

ATLAS and CMS are ready

- We will commission everything: detector, online, and physics analyses
- Then explore the Standard Model at 10 TeV
  - Start to understand the “LHC environment”
- We may see something early
  - Fingers crossed
End
Many thanks to many people

- Sarah Eno, Chris Hill, Ian Hinchliffe, Karl Jacobs, Oliver Buchmuller, Ian Low, Albert De Roeck, Peter Jenni, Henry Frisch, Paris Sphicas, Claudio Campagnari, Chris Quigg, Philip Schuster, Natalia Toro, …and…
  - … many others from UA1, UA2, CDF, D0, OPAL, ALEPH, CMS, ATLAS…

And especially to all the people who did the work represented in these slides
ADDITIONAL INFORMATION
Bibliography: Comprehensive physics reports

- **ATLAS**
  - **Expected Performance of the ATLAS Experiment**

- **CMS**
  - **CMS physics : Technical Design Report**

- **Recent results**
  - **CMS Physics recent results**
  - **ATLAS Physics recent results**
**Higgs**
- HIG-08-003: Search for Higgs to ZZ* (January 2009).
- HIG-08-006: Search for Higgs to WW* (January 2009). This analysis supersedes the following older analysis: HIG-07-001: Higgs to WW*
- HIG-08-008: Higgs to tau-tau (October 2008)
- HIG-08-001: qqH production, with H->tau-tau

**Searches for New Physics**
- EXO-08-013: Search for Low Mass b' Production (July 2009)
- EXO-09-003: Searching for Majorana Neutrinos in the Like-Sign Dilepton Final State at 10 TeV (July 2009)
- EXO-08-008: Search for Exotic Partners of the Top Quark (July 2009)
- EXO-09-012: Search for A Fourth Generation b' Quark in tW Final State at 10 TeV (July 2009)
- EXO-09-010: Search for Second Generation Scalar Leptoquarks (July 2009)
- EXO-09-007: Search for Technicolor (July 2009)
- SUS-09-001: Search strategy for exclusive multi-jet events from supersymmetry (July 2009)
- EXO-09-011: Search for Scalar and Tensor Unparticles in the Diphoton Final State (July 2009)
- EXO-09-009: Search for Randall-Sundrum Gravitons in the Diphoton Final State (July 2009)
- EXO-09-004: Search for large Extra Dimensions in the diphoton final state (June 2009)
- SUS-09-004: Data-Driven Background Estimates for SUSY Di-Photon Searches (July 2009)
- EXO-09-008: Search for heavy narrow t-tbar resonances in muon-plus-jets final states with the CMS detector (July 2009)
- EXO-09-006: Search for high-mass resonances decaying into an electron pair -- at 10 TeV with 100 pb−1 (July 2009)
- EXO-09-013: Search for Mono-Jet Final States from ADD Extra-Dimensions at 10 TeV (July 2009)
- SUS-09-002: Discovery potential and measurement of a dilepton mass edge in SUSY events at 10 TeV (July 2009)
- EXO-09-002: Search for High-Mass Resonances Decaying into Top-Antitop Pairs in the All-Hadronic Mode (July 2009)
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- EXO-08-009: Search for a b’ (October 2008)
- EXO-08-011: Search for extra dimensions with monojets (October 2008)
- EXO-08-005: MUSIC -- deviations between data and Monte Carlo simulation (September 2008)
- SUS-08-005: SUSY search with dijet events (September 2008)
- SUS-08-001: Dilepton+Jet+MET channel: Observation and Measurement of x2 --> x1 ll (July 2008)
- SUS-08-002: Data driven estimation of the Z-->invisible background for the early SUSY searches (July 2008)
- EXO-08-001: Search for Z'-->ee (July 2008)
- EXO-08-004: Search for W'-->enu (July 2008)
- SBM-07-002: Search for Z' --> mumu
- SBM-07-001: Searches for New Physics using high ET dijet events
- EXO-08-003: Search for Heavy Stable Charged Particles
- JME-09-010: Performance of Track-Corrected Missing ET in CMS (July 2009)
- JME-09-007: Measurement of the Jet Energy Resolutions and Jet Reconstruction Efficiency at CMS (July 2009)
- JME-09-005: Determination of the jet energy scale using $Z\rightarrow e^+e^- + \text{jet}$ pT balance and a procedure for combining data-driven corrections (July 2009)
- JME-09-004: Jet energy calibration with photon+jet events (July 2009)
- JME-09-002: Jet Plus Tracks Algorithm for Calorimeter Jet Energy Corrections (July 2009)
- BTV-09-001: Algorithms for b Jet Identification in CMS (July 2009)
- JME-09-001: A Cambridge-Aachen (C-A) based Jet Algorithm for boosted top-jet tagging (July 2009)
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- JME-09-003: Offset Energy Correction for Cone Jets (May 2009)
- JME-08-003: Determination of the Relative Jet Energy Scale from Dijet Balance (May 2009)
- PFT-09-001: Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and ETmiss (April 2009)
- JME-08-001: Performance of Jet Reconstruction with Charged Tracks only (September 2008)
- PFT-08-001: Tau Reconstruction using the Particle Flow Technique (July 2008)
- JME-07-002: Plans for Jet Energy Corrections at CMS (July 2008)
- BTV-07-003: Effect of misalignment on b-tagging (July 2008)
- JME-07-003: Performance of Jet Algorithms in CMS
- JME-07-001: Performance of missing ET reconstruction
- BTV-07-001: b tag efficiency from System 8 & Ptrel Method
- BTV-07-002: Measuring uds mistag rate of b tag using negative tags
- EGM-07-001: Measuring Electron Efficiencies with Early Data
Inclusive Jets + MET analysis
Figure 1: The rapidity $y_W$ and transverse momentum $p_{T,W}$ distributions of the $W$-bosons and their charge asymmetries for the $p\bar{p}$ (a, c) and $pp$ (b, d) collisions.
• only SM Higgs has a well-defined signal (like top, single top, etc)
• Want big cross section and clean signature
• The earliest results may come from something that couples to gluons and a final state with high $p_T$ leptons (or other dramatic signature)

Figure 1: MSTW 2008 NLO PDFs at $Q^2 = 10$ GeV$^2$ and $Q^2 = 10^4$ GeV$^2$. 
Heavy Bosons to $ee, \mu\mu$

Predicted in many theories: TeV$^{-1}$ ED, RS ED, little higgs, L-R symmetric, etc.

Main background is DY production. Smoothly and quickly falling with mass.
Dijet Resonances with Dijet Ratio

- Dijet ratio from signal + QCD compared to statistical errors for QCD alone
  - Resonances normalized with q* cross section for |η|<1.3 to see effect of spin.

- Convincing signal for 2 TeV strong resonance in 100 pb⁻¹ regardless of spin.

- Promising technique for discovery, confirmation, and eventually spin measurement.

Dijet Ratio for q*

Dijet Ratio for Spin ½, 1, 2
Contact interactions create large rate at high $P_T$ and immediate discovery possible

- Error dominated by jet energy scale (~10%) in early running (10 pb$^{-1}$)
  - $\Delta E \sim 10\%$ not as big an effect as $\Lambda^+ = 3$ TeV for $P_T > 1$ TeV.
- PDF “errors” and statistical errors (10 pb$^{-1}$) smaller than $E$ scale error

With 10 pb$^{-1}$ we can see new physics beyond Tevatron exclusion of $\Lambda^+ < 2.7$ TeV.

**Rate of QCD and Contact Interactions**

**Sensitivity with 10 pb$^{-1}$**
Unconstrained MSSM is the most “economic” version of SUSY

Minimal gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$

Minimal particle content; tree generation of spin $\frac{1}{2}$ quarks and leptons
[no right handed neutrino] as in SM; The two Higgs doublets leads to five Higgs particles: two CP even $h, H$ bosons, a pseudoscalar $A$ boson and two charged $H^+/-$ bosons

R parity conservation: $R_p = (-1)^{2S+3B+L}$

Minimal set of soft SUSY-breaking terms

Unconstrained MSSM has 124 free parameters (104 from SUSY breaking terms + 19 parameters of the SM)

Constrained MSSM (or phenomenological MSSM) reduces number of free parameters to 22

all the soft SUSY-breaking parameters are real => no new source of CP-violation in addition to the one from CKM matrix

no FCNC at tree level

the soft SUSY-breaking masses and trilinear couplings of the $1^{st}$ and $2^{nd}$ sfermion generations are the same at low energy

To go beyond this kind of generic discussion, need to introduce models.

May not be right, but like those practice problems in the back of the book, is very useful to get us trained.
• Thus, the idea is the following:
  • The many (>100) parameters of weak-scale SUSY should be derived from a minimal set of parameters at the unification scale.
• mSUGRA: the “canonical” model
  • 5 main parameters
    • \( m_0 \), \( m_{1/2} \), \( A_0 \), \( \tan(\beta) \), and \( \text{sign}(\mu) \)
    • \( m_0 \), \( m_{1/2} \) are universal scalar and fermion masses
      • Like the couplings, one assumes that the spectra of fundamental particles derives from fundamental masses
    • \( m_{3/2} \) is a 6\(^{th}\) free parameter
      • Gravitino - could be LSP but in most of the literature it is assumed to be very heavy and ignored.
EWK symmetry breaking
"Vanilla" SUSY: mSUGRA

- Region 1: in this region, the gluinos are heavier than any of the squarks. The decay chains of the produced sparticles are expected to be

\[ \tilde{g} \rightarrow \tilde{q}q, \tilde{q} \rightarrow q\chi \]

- Region 2: in this region some squarks are heavier, other are lighter than the gluino. Hence, rather complicated decay chains are possible, for instance

\[ \tilde{q}_L \rightarrow \tilde{g}q, \tilde{g} \rightarrow \tilde{b}\tilde{b}, \tilde{b} \rightarrow b\chi \] (3.6)

as the $\tilde{q}_L$ of the first two generations are expected to be among the heaviest squarks and the $\tilde{b}_1$ (and $\tilde{b}_2$) among the lightest.

- Region 3: in this region, the gluinos are lighter than any of the squarks. A typical decay chain is then

\[ \tilde{q} \rightarrow \tilde{g}q, \tilde{g} \rightarrow q\bar{q}\chi \]

More jets, softer MET

Less jets, harder MET

$q_L$ tend to decay directly to lsp, $q_R$ has non-negligible BR to below

\[ \tilde{\chi}_2^0 \rightarrow \tilde{t}_L \]
(13.8)
\[ \tilde{\chi}_2^0 \rightarrow \tilde{\nu}_L \]
(13.9)
\[ \tilde{\chi}_2^0 \rightarrow h^0 \tilde{\chi}_1^0 \]
(13.10)
\[ \tilde{\chi}_2^0 \rightarrow Z^0 \tilde{\chi}_1^0 \]
(13.11)
\[ \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_L \tilde{\tau}_L \]
(13.12)

\[ \tilde{\chi}_1^\pm \rightarrow \tilde{\nu}_L \tilde{\tau}_L \]
(13.13)
\[ \tilde{\chi}_1^\pm \rightarrow \tilde{\nu}_L \tilde{t}_L \]
(13.14)
\[ \tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0 \]
(13.15)
\[ \tilde{\chi}_1^\pm \rightarrow H^\pm \tilde{\chi}_1^0 \]
(13.16)
\[ \tilde{\chi}_1^\pm \rightarrow H^\pm \tilde{\chi}_1^0 \]
(13.17)

Figure 13.2: Regions of the $m_0$ versus $m_{1/2}$ plane with main $\chi_2^0$ decays (left) and main decays of $\tilde{\chi}_1^\pm$ (right).
• **Point LM1:**
  - Same as post-WMAP benchmark point B' and near DAQ TDR point 4.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}\bar{q}$ is dominant
  - $B(\chi_{2}^{0} \rightarrow \tilde{l}_{R}l) = 11.2\%$, $B(\chi_{2}^{0} \rightarrow \tilde{\tau}_{1}\tau) = 46\%$, $B(\chi_{1}^{\pm} \rightarrow \tilde{\nu}\ell) = 36\%$

• **Point LM2:**
  - Almost identical to post-WMAP benchmark point Γ'.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}\bar{q}$ is dominant ($b_{1}b$ is 25%)
  - $B(\chi_{2}^{0} \rightarrow \tilde{\tau}_{1}\tau) = 96\%$ $B(\chi_{1}^{\pm} \rightarrow \tilde{\nu}\ell) = 95\%$

• **Point LM3:**
  - Same as NUHM point γ and near DAQ TDR point 6.
  - $m(\tilde{g}) < m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}\bar{q}$ is forbidden except $B(\tilde{g} \rightarrow b_{1}b) = 85\%$
  - $B(\chi_{2}^{0} \rightarrow h\chi_{1}^{0}) = 3.3\%$, $B(\chi_{2}^{0} \rightarrow \tau\chi_{1}^{0}) = 2.2\%$, $B(\chi_{1}^{\pm} \rightarrow W^{\pm}\chi_{1}^{0}) = 100\%$

• **Point LM4:**
  - Near NUHM point α in the on-shell $Z^{0}$ decay region
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}\bar{q}$ is dominant with $\tilde{g} \rightarrow b_{1}b$ is 24%
  - $B(\chi_{2}^{0} \rightarrow Z^{0}\chi_{1}^{0}) = 97\%$, $B(\chi_{1}^{\pm} \rightarrow W^{\pm}\chi_{1}^{0}) = 100\%$

• **Point LM5:**
  - In the $h^{0}$ decay region, same as NUHM point β.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}\bar{q}$ is dominant with $B(\tilde{g} \rightarrow b_{1}b) = 19.7\%$ and $B(\tilde{g} \rightarrow t_{1}t) = 23.4\%$
  - $B(\chi_{2}^{0} \rightarrow h^{0}\chi_{1}^{0}) = 85\%$, $B(\chi_{2}^{0} \rightarrow Z^{0}\chi_{1}^{0}) = 11.5\%$, $B(\chi_{1}^{\pm} \rightarrow W^{\pm}\chi_{1}^{0}) = 97\%$

• **Point LM6:**
  - Same as post-WMAP benchmark point C'.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}\bar{q}$ is dominant
  - $B(\chi_{2}^{0} \rightarrow \tilde{l}_{R}l) = 10.8\%$, $B(\chi_{2}^{0} \rightarrow \tilde{l}_{L}l) = 1.9\%$, $B(\chi_{2}^{0} \rightarrow \tilde{\tau}_{1}\tau) = 14\%$, $B(\chi_{1}^{\pm} \rightarrow \tilde{\nu}\ell) = 44\%$

**Lots of leptons and taus**

**Lots of taus, few e,mu**

**Lots of W’s, b’s**

**On-shell Z’s and W’s, b’s**

**Lots of higgs to bbbar**

**Like LM1, but fewer taus**
• Point LM7:
  - Very heavy squarks, outside reach, but light gluino.
  - $m(\tilde{g}) = 678\text{ GeV}/c^2$, hence $\tilde{g} \rightarrow 3\text{-body}$ is dominant
  - $B(\tilde{\chi}_2^0 \rightarrow t\tilde{\chi}_1^0) = 10\%, B(\tilde{\chi}_1^+ \rightarrow \nu\tilde{\chi}_1^0) = 33\%$
  - EW chargino-neutralino production cross-section is about 73% of total.

• Point LMS8:
  - Gluino lighter than squarks, except $\tilde{b}_1$ and $\tilde{t}_1$
  - $m(\tilde{g}) = 745\text{ GeV}/c^2$, $M(\tilde{t}_1) = 548\text{ GeV}/c^2$, $\tilde{g} \rightarrow \tilde{t}_1 t$ is dominant
  - $B(\tilde{g} \rightarrow \tilde{t}_1 t) = 81\%, B(\tilde{g} \rightarrow \tilde{b}_1 b) = 14\%, B(\tilde{g} \rightarrow q\tilde{\chi}_2^0) = 26 - 27\%$
  - $B(\tilde{\chi}_2^0 \rightarrow Z^0\tilde{\chi}_1^0) = 100\%, B(\tilde{\chi}_1^+ \rightarrow W^+\tilde{\chi}_1^0) = 100\%$

• Point LM9:
  - Heavy squarks, light gluino. Consistent with EGRET data on diffuse gamma ray spectrum, WMAP results on CDM and mSUGRA [674]. Similar to LM7.
  - $m(\tilde{g}) = 507\text{ GeV}/c^2$, hence $\tilde{g} \rightarrow 3\text{-body}$ is dominant
  - $B(\tilde{\chi}_2^0 \rightarrow t\tilde{\chi}_1^0) = 6.5\%, B(\tilde{\chi}_1^+ \rightarrow \nu\tilde{\chi}_1^0) = 22\%$

• Point LM10:
  - Similar to LM7, but heavier gauginos.
  - Very heavy squarks, outside reach, but light gluino.
  - $m(\tilde{g}) = 1295\text{ GeV}/c^2$, hence $\tilde{g} \rightarrow 3\text{-body}$ is dominant
  - $B(\tilde{g} \rightarrow t\tilde{\chi}_2^0) = 11\%, B(\tilde{g} \rightarrow \bar{t}b\tilde{\chi}_1^0) = 27\%$
Benchmarks have been chosen requiring that neutralino relic density matches DM constraints

\[ SU_{n} = mSU_{gra} \text{ benchmark } n \] (no reference to symmetry groups!)
SU1  $m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan \beta = 10$, $\mu > 0$. Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{t}$.

SU2  $m_0 = 3550$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan \beta = 10$, $\mu > 0$. Focus point region near the boundary where $\mu^2 < 0$. This is the only region in mSUGRA where the $\tilde{\chi}_1^0$ has a high higgsino component, thereby enhancing the annihilation cross-section for processes such as $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow WW$.

SU3  $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan \beta = 6$, $\mu > 0$. Bulk region: LSP annihilation happens through the exchange of light sleptons.

SU4  $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan \beta = 10$, $\mu > 0$. Low mass point close to Tevatron bound.

SU6  $m_0 = 320$ GeV, $m_{1/2} = 375$ GeV, $A_0 = 0$, $\tan \beta = 50$, $\mu > 0$. The funnel region where $2m_{2\tilde{g}} \approx m_A$. Since $\tan \beta \gg 1$, the width of the pseudoscalar Higgs boson $A$ is large and $\tau$ decays dominate.

SU8.1 $m_0 = 210$ GeV, $m_{1/2} = 360$ GeV, $A_0 = 0$, $\tan \beta = 40$, $\mu > 0$. Variant of coannihilation region with $\tan \beta \gg 1$, so that only $m_{\tilde{t}_1} - m_{\tilde{g}}$ is small.

SU9  $m_0 = 300$ GeV, $m_{1/2} = 425$ GeV, $A_0 = 20$, $\tan \beta = 20$, $\mu > 0$. Point in the bulk region with enhanced Higgs production.

<table>
<thead>
<tr>
<th>Particle</th>
<th>SU1</th>
<th>SU2</th>
<th>SU3</th>
<th>SU4</th>
<th>SU6</th>
<th>SU8.1</th>
<th>SU9</th>
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Key element: measurement of velocity $\beta$
Two techniques:
- time of flight measurement by muon DT
- using specific ionisation in tracker

calculate particle mass $m = \frac{p}{(\beta \gamma c)}$

HSCP triggering:
- Timing issue important:
  L1/HLT not prepared for slow particle
  which can be reco in different BX

- Two main trigger paths:
  - Muon HLT path: trigger by HSCP or SM muon
  - MET HLT path: MET present in many models
    (from cascade) – indep of timing problems

Lepton-like HSCP
- Can penetrate the whole detector
- High ionization energy loss
- Delayed with respect to lightspeed particles

R-Hadron-like HSCP
- Heavy parton behaves as a spectator
- Does not shower in the calorimeters
- The charge can change in hadronic interactions with matter while crossing the detector

Final trigger efficiency:
~70% for lepton-like HSCP
~40-95% for R-Hadrons
Significant amount of R-hadrons are stopped in the detector: mostly in calorimeters and in return yokes
Long-lived gluinos

- ~15% of R-hadrons is stopped in detector volume
- Flat in the mass range of interest
Example: selection for $Z' \rightarrow ee$:
- 2 electrons in $|\eta| < 2.5$, $p_t > 30$ GeV
- electron ID (cluster-track matching)
- e isolated in tracker/ECAL/HCAL

High pt electron reconstruction
Efficiencies relative to acceptance:

Main backgrounds:
Drell-Yan (irreducible)
ttbar, W+jets, QCD (reducible)

Tevatron limit is: 700-1000 GeV