CMS: Detector & Physics

On behalf of the CMS Collaboration
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The IX Mexican Workshop on Particles and Fields
Nov. 18, 2003 - Ciudad de Colima, Mexico
History of particle physics

- Parallel experimental and theoretical developments
  - Discovery of several layers of fundamental particles
  - Gauge Invariance

- Where are we now?
Weak Force

- EM Lagrangian not gauge invariant if the photon has mass
  \[ L_{\text{em}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \quad (F_{\mu\nu} = \partial^{\nu}A^{\mu} - \partial^{\mu}A^{\nu}) \]
  \[ L_{\text{em}} = -\frac{1}{4} F_{\mu\nu} F_{\mu\nu} + (m^2/2)A^{\mu}A_{\mu} \text{ is not gauge invariant!} \]

- Weak Nuclear Force
  - Hints of SU(2) gauge symmetry
    - Doublets, Universal Coupling \( G_F \) ...
  - But short-range \( \Rightarrow \) massive gauge quanta
    - Coupling \( G_F \sim 1/M^2 \)

- How do we reconcile massive gauge quanta with gauge invariance?

- An example from Nature: Superconductivity
  \[ j^{\mu} = (-q^2/m) \mid \psi \mid \partial^{\mu}A^{\nu} \quad \text{(London)} \]
  - Cooper pair (boson) wave function \( \psi \) with non-zero fixed ground state.

\[ \partial^{\mu}\partial^{\nu}A^{\nu} - \partial^{\nu}(\partial^{\mu}A^{\nu}) = (-q^2/m) \mid \psi \mid \partial^{\mu}A^{\nu} \equiv -M^2A^{\nu} \rightarrow \text{massive photon!} \]

- Supercurrents screen the EM field making it effectively short-range.
EWK Symmetry Breaking

• **Glashow Weinberg Salam SU(2)⊗U(1)**

\[
L = -\frac{1}{4} W^{\mu\nu} \cdot W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}
\]

\[
W^{\mu\nu}_{\pm} = \partial^\nu W_{\mu} - \partial^\mu W_{\nu} + g\epsilon^{ijk} W_{\mu} W_{\nu} W_{k}
\]

and

\[
B^{\mu\nu} = \partial^\nu B_{\mu} - \partial^\mu B_{\nu}
\]

• Add a scalar doublet field

\[
\phi^\dagger = 2^{-1/2} (\phi_1 - i\phi_2, H - i\phi_o)
\]

with potential

\[
V(\phi) = \mu^2 \phi:\phi^\dagger + \lambda |\phi^\dagger|^2 (\lambda > 0)
\]

- The most general SU(2) invariant & renormalizable potential
- \(\mu^2 > 0\) symmetry retained \((T > T_c)\)
- \(\mu^2 < 0\) \(\Rightarrow \langle \phi \rangle_o \neq 0.0\) \((T < T_c)\)

\[
L_\phi = (D_\mu \phi)^\dagger(D_\mu \phi) - V(\phi)
\]

- where

\[
D_\mu = \partial_\mu + ig (\tau/2) \cdot W_\mu + ig'/2 B_\mu
\]

- choose a gauge with \(\phi^\dagger = 2^{-1/2} (0,v+H), \langle H \rangle_o = 0\)

– This choice breaks the symmetry!

• Lagrangian now has 3 Massive Vector Gauge Bosons and massless photon:

\[
W^{\pm}_\mu = 2^{-1/2} (W^1_\mu \pm W^2_\mu)
\]

\[
M_{W}^2 = \frac{1}{4} g^2 v^2
\]

\[
Z^o_\mu = (g^2 + g'^2)^{-1/2} (-g'B_\mu + g W_{\mu}^3)
\]

\[
M_{Z}^2 = \frac{1}{4} (g^2 + g'^2)v^2
\]

\[
A_\mu = (g^2 + g'^2)^{-1/2} (gB_\mu + g'W_{\mu}^3)
\]

\[
M_{A}^2 = 0
\]
The Higgs & its couplings

• Electroweak Couplings satisfy
  \( g \sin \theta_W = e = g' \cos \theta_W \)  \( (M_Z = M_W / \cos \theta_W) \)

From \( \mu \) decay \( G_F / 2^{1/2} = g^2 / 8M_W^2 = 1 / 2v^2 \)
Predict (after higher order corrections):
  \[ M_W \sim 80 \text{ GeV} \]
  \[ M_Z \sim 91 \text{ GeV} \]

also generate masses for fermions:

\[ L = \lambda_d \mathbf{Q}_d \phi \mathbf{d}_R \]
\[ \lambda_d = 2^{1/2} m_d / v \sim m_d / M_W \]

- Coupling proportional to fermion mass

Is the top quark special?
\[ \lambda_t = 2^{1/2} m_t / v = 2^{1/2} (174.1) / (246) = 1 \]

\[ \Gamma(H \rightarrow \mu \mu) = \frac{N_c g^2}{32 \pi} (m_\mu^2 / M_W^2) (1 - 4m_\mu^2 / M_H^2) M_H \]
\[ \Gamma(H \rightarrow W^+W^-) = \frac{g^2}{128 \pi} (M_H^2 / M_W^2) f(x) M_H \]

where \( f(x) = (1 - x)^{1/2} (1 - x + 3x^2 / 4) \)
and \( x = 4 M_W^2 / M_H^2 \)

\[ \Gamma(H \rightarrow W^+W^-) / \Gamma(H \rightarrow \mu \mu) \sim M_H^2 / m_\mu^2 \]

And the Higgs term itself:
\[ 2v^2 \lambda H^2 \Rightarrow M_H = (2\lambda)^{1/2} v \]

• We know everything about the
  Standard Model Higgs except
  - its mass
  - whether or not it exists
W right where it’s expected...

\[ W \rightarrow e\nu \text{ or } \mu\nu \]

**W-Boson Mass [GeV]**

- pp-colliders: \(80.448 \pm 0.062\)
- LEP2: \(80.401 \pm 0.048\)
- Average: \(80.419 \pm 0.038\)
- NuTeV/CCFR: \(80.25 \pm 0.11\)
- LEP1/SLD: \(80.368 \pm 0.034\)

\[ \chi^2/\text{DoF}: 0.4 / 1 \]

**CDF(1B) Preliminary**

- \(W \rightarrow e\nu\)
  - Backgrounds: \(\chi^2/\text{df} = 82.6/70 (50 < M_T < 120)\)
  - KS(prob) = 16%
- \(W \rightarrow \mu\nu\)
  - Backgrounds: \(\chi^2/\text{df} = 147/131 (50 < M_T < 120)\)
  - KS(prob) = 21%

**Transverse Mass (GeV)**

- # Events
  - 0
  - 50
  - 100
  - 150
  - 200
  - 250
  - 300
  - 350
  - 400
  - 450
  - 500
And the Z as well

The W and Z were discovered by UA2 and UA1 at CERN

Mass of the Z Boson

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( M_Z ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>91189.3 ± 3.1</td>
</tr>
<tr>
<td>DELPHI</td>
<td>91186.3 ± 2.8</td>
</tr>
<tr>
<td>L3</td>
<td>91189.4 ± 3.0</td>
</tr>
<tr>
<td>OPAL</td>
<td>91185.3 ± 2.9</td>
</tr>
<tr>
<td>LEP</td>
<td>91187.5 ± 2.1</td>
</tr>
</tbody>
</table>

\( \chi^2/\text{dof} = 2.2/3 \)

CDF(1B) Preliminary

\( Z \rightarrow \text{ee} \)

\( \chi^2/\text{df}=1.3 \)

\( Z \rightarrow \mu\mu \)

\( \chi^2/\text{df}=0.89 \)
SM Higgs Mass Bounds

- **Triviality:**
  - To avoid having the higgs self-coupling vanish, you need a cut-off $\Lambda$ at which new physics would be required.

- **Vacuum stability:**
  - Require $V(\phi_0) < V(0)$: for some masses this requires new physics above a scale $\Lambda$.

- **EWK Precision Measurements:**
  - $M_H < 188$ GeV at 95% CL
    - Taken with a grain of salt…

- **LEP II direct searches:**
  - $M_H \geq 114$ GeV at 95% CL
    - Taken with a shot of tequila
Beyond Standard Model

• Problems with the SM
  – Hierarchy Problem: the fundamental scale is the Planck scale ($M_p \sim 10^{19}$ GeV)?
    • What is the underlying reason for EWK symmetry breaking and why at such low energy?
  – Fermion and Higgs Masses?
    • What determines them?
  – Gravity?
    • How to reconcile with Quantum Mechanics?
• “Fundamental scalar theories are fundamentally pathological”
  • Quadratic divergences

• Candidates For Replacing the SM:
  – Supersymmetry (SUSY)
    • Symmetry: bosons $\leftrightarrow$ fermions
      – SUSY partner $\forall$ SM particle
      – Requires $\geq 2$ Higgs doublets
  – SUSY Is quite appealing
    • Superpartners cancel divergent terms in $M_H$.
    • As a local symmetry $\Rightarrow$ spin-2 graviton appears
    • Appears in string theories*
    • Gauge coupling unification if there are exactly 2 Higgs doublets (+ singlets)
  – And there are other possibilities…
Extra Dimensions (LED)

- Alternative solution to hierarchy problem
  - Apparent weakness of gravity due to the fact that much of it flows into other dimensions → Planck scale could be ~1 TeV

- δ extra dimensions with ‘large’ radius R
  - e.g. model of Arkani-Hamed, Dimopolous, Dvali: (ADD)*
    - SM propagates on 3+1 subspace
    - Graviton ($G_{KK}$) sees all (3+δ) + 1 dimensions
      - $G_{KK}$ massive to observers in 3+1 dimensions
        - Manifested as an excess of events with large missing energy
          - $M_D \sim 1$ TeV ⇒ deviations at distances $R < 10^{(32/\delta - 19)}$
            - ~150 μm has been probed ⇒ δ = 2 is already ruled out.

- Smaller extra dimensions (e.g. Randall & Sundrum)
  - Gravitons are much more massive:
    - Excess events with very energetic jets, leptons, photons …
    - Spin-2 character may be observable in angular distributions
Experimental focus today

• Some questions at the leading edge …
  1. Why is the visible universe predominantly matter?
  2. How do particles acquire mass?
     • What is the origin spontaneous symmetry breaking?
  3. What sets the known energy scales?
     \[ \Lambda_{\text{QCD}} \sim 0.2 \text{ GeV} \ll \text{EW vev} \sim 246 \text{ GeV} \ll M_{\text{GUT}} \sim 10^{16} \text{ GeV} \ll M_{\text{PL}} \sim 10^{19} \text{ GeV} \]
  4. I.e. what comes next?
     • Is the universe supersymmetric?
       – Is this what explains the galactic dark matter?
     • Are there extra dimensions?

• These are big questions, we’ll need a big hammer…
CERN Large Hadron Collider
CERN Large Hadron Collider

- 27 km around
- 1100 dipole magnets
  - 14 m long
  - 8.4 T field
  - dual aperture

- Proton on proton: 14 TeV
  - 25 ns between beam crossings
    - Peak Luminosity $10^{34}$ cm$^{-2}$ s$^{-1}$
    - 20 collisions per beam crossing
Why Collide Hadrons?

Hadron colliders are great discovery machines

Accelerators
- electron
- hadron

Constituent CM Energy (GeV)

Starting Year


LHC

Higgs boson

t quark

W, Z bosons

b quark

c quark

s quark

Prin-Stan

SPEAR

CESR

SppS

TRISTAN

SLC

LEPII

Tevatron

ISR

HADRON colliders are great discovery machines
Challenge and Reward

- Higher Energy
- Broadband production

⇒ Discovery machines

- BUT
  - Physics cross-section is high!!!
  - What’s interesting is rare

- The ability to find any of these events is a consequence of evolved detector design and technological innovations:
  - Multi-level trigger systems and high speed pipe-lined electronics
  - Precision, high rate, calorimetry
  - Radiation-tolerant Silicon microstrips and Pixel detectors
Hadron Collider Detectors

- Hadron calorimeter
- Electromagnetic calorimeter
- Drift Chamber
- Silicon Detector
- 1.4 T Solenoid
- Time of Flight
- Muon detectors

Example:

CDF Experiment

First operation of a Silicon detector in a hadron collider: May 12, 1992 (CDF).

\[ K^0 \rightarrow \pi^+\pi^- \text{, } \ldots \text{etc} \]
CDF and DØ successfully found the top quark with a cross section of ~ $10^{-10} \sigma_{\text{tot}}$.

- $168.4 \pm 12.8 \text{ GeV}/c^2$ Dilepton
- $173.3 \pm 7.6 \text{ GeV}/c^2$ Lepton+jets
- $172.1 \pm 7.1 \text{ GeV}/c^2$ Combined
- $167.4 \pm 11.4 \text{ GeV}/c^2$ Dilepton
- $175.8 \pm 7.2 \text{ GeV}/c^2$ Lepton+jets
- $186.6 \pm 11.5 \text{ GeV}/c^2$ All-Hadronic
- $178.0 \pm 8.5 \text{ GeV}/c^2$ Combined

$174.3 \pm 5.1 \text{ GeV}/c^2$ Tevatron combined
To a large extent, the quest for the Higgs drives the design of the LHC detectors.

Nevertheless, essentially all other physics of interest require the same capabilities.
Strategies for Finding SM Higgs

At LHC the SM Higgs is accessible in the entire mass range from the present LEP limit of 114.1 GeV up to 1 TeV.

Depending on mass different decay channels must be used based upon production and decay, and SM backgrounds:

\begin{align*}
90 \text{ GeV} & < m_H < 120 \text{ GeV} & H \rightarrow bb \text{ in WH, ttH} \\
100 \text{ GeV} & < m_H < 150 \text{ GeV} & H \rightarrow \gamma\gamma \text{ in incl. prod., WH, ttH} \\
130 \text{ GeV} & < m_H < 200 \text{ GeV} & H \rightarrow ZZ^* \rightarrow 4l \text{ (leptons)} \\
140 \text{ GeV} & < m_H < 180 \text{ GeV} & H \rightarrow WW^* \rightarrow l\nu l\nu \\
200 \text{ GeV} & < m_H < 750 \text{ GeV} & H \rightarrow ZZ \rightarrow 4l \\
500 \text{ GeV} & < m_H < 1000 \text{ GeV} & H \rightarrow ZZ \rightarrow 2l + 2\nu \\
m_H \sim 1 \text{ TeV} & & H \rightarrow WW \rightarrow l\nu + 2 \text{ Jets} \\
m_H \sim 1 \text{ TeV} & & H \rightarrow ZZ \rightarrow 2l + 2 \text{ Jets}
\end{align*}
CMS Experiment at CERN

Total Weight: 14,500 t.
Overall diameter: 14.60 m
Overall length: 21.60 m
Magnetic field: 4 Tesla

MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL.
HCAL.

VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
jib

X
Y
Z
• Inside of the 4 Tesla field of the largest SC Solenoid ever built
  – Pixels: at least 2 Layers everywhere
  – Inner Si Strips: 4 Layers
  – Outer Si Strips: 6 Layers
  – Forward Silicon strips: 9 large, and 3 small disks per end
  – EM Calorimeter: PbWO$_4$ crystals w/Si APD’s
  – Had Calorimeter: Cu+Scintillator Tiles
• Outside: Muon detectors in the return yoke
CMS Hadron Calorimeter

- Inside of the 4 Tesla Solenoid Field

**Hadronic Calorimeter:** Cu+Scintillator Tiles
CMS EM Calorimeter

$E = 280 \text{ GeV}$
\[\sigma/E = 0.45\%\]

Energy reconstructed in 3×3 crystals with 280 GeV electrons.

<table>
<thead>
<tr>
<th>CMS EM calorimeter</th>
<th>Barrel</th>
<th>End cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stochastic Term</td>
<td>$2.7% E^{-1/2}$</td>
<td>$5.7% E^{-1/2}$</td>
</tr>
<tr>
<td>Constant Term</td>
<td>$0.55%$</td>
<td>$0.55%$</td>
</tr>
<tr>
<td>Noise</td>
<td>155-210 MeV</td>
<td>205-245 MeV</td>
</tr>
<tr>
<td>No. PbWO$_4$ Crystals</td>
<td>17,000</td>
<td>5,382</td>
</tr>
</tbody>
</table>
Tracking Challenge

“Golden Channel”

Efficient & robust Tracking

⇒ Fine granularity to resolve nearby tracks
⇒ Fast response to resolve bunch crossings
⇒ Radiation resistant devices

Reconstruct high pt tracks and jets
⇒ ~1-2% $P_T$ resolution at ~ 100GeV ($\mu$’s)
Tag b/$\tau$ through secondary vertex
⇒ Asymptotic impact parameter $\sigma_d \sim 20\mu$m
CMS Tracker

- Pixels
- Inner Barrel & Disks (TIB & TID)
- Outer Barrel (TOB)
- End Caps (TEC 1&2)

Volume: 24.4 m³
Running temperature: -10 °C
• Why Pixels?
  – Fast primary vertex
    • 3D space points
    • Starting point for pattern recognition
  – Granularity
    • Peak occupancy ~ 0.01 %
  – Displaced track detection
    • Key to b jets
  – Radiation tolerance

• CMS Pixels
  – 45 million channels
  – 100 μm x 150 μm pixel size
  – Barrel radii: 4, 7 and 11 cm
Tracker Outer Barrel

Total Tracker is 230 square meters of silicon. The 2 Outer Barrels replace traditional drift chamber >105 square meters of silicon microstrips in 2 barrels.
Some Tracker Numbers

- 6,136 Thin wafers 300 µm
- 19,632 Thick wafers 500 µm
- 6,136 Thin detectors (1 sensor)
- 9,816 Thick detectors (2 sensors)
- 3112 + 1512 Thin modules (ss +ds)
- 4776 + 2520 Thick modules (ss +ds)
- 10,016,768 individual strips and readout electronics channels
- 78,256 APV chips
- ~26,000,000 Bond wires
- 470 m² of silicon wafers
- 223 m² of silicon sensors (175 m² + 48 m²)

$$\sigma/p_T \sim (15 \cdot p_T \oplus 0.5) \% \quad |\eta| \leq 1.6$$

$$\rightarrow 4.5 \text{ when combined with } \mu \text{ detectors}$$

$p_T \text{ in [TeV/c]}$
Detailed Simulations: High purity tracking with high efficiency

Isolated $\mu$ and $\pi$ have efficiencies of 98 and 90-95% resp. in central region

Tracking in jets $\sim$90%
The Challenge

L1: 40 MHz input
L1: 100 KHz output
Write to offline: 100 Hz

- Reconstruction on demand:
  - Never do anything until it is requested
- Not interested in reconstructing the full event at trigger anyway

region around a L1 calo jet
Construction is well underway
How might it all perform?
Irreducible backgrounds dominate:

- $qq \rightarrow \gamma \gamma$
- $gg \rightarrow \gamma \gamma$
- Isolated bremsstrahlung

EM Energy resolution is key

- The crystal electromagnetic calorimeter has been optimized for this channel.

$\Delta m_H/m_H < 1\%$ needed.
Background subtracted

$H \rightarrow \gamma \gamma$

Expected signal significance

$H \rightarrow \gamma \gamma$, CMS

Signal significance = $N_S / \sqrt{N_B}$

- 30 fb$^{-1}$ (low luminosity)
- 100 fb$^{-1}$ (high luminosity)
$t\bar{t}H \rightarrow l^\pm \nu q q b b b$

**H → bb**
Only associated production is feasible!

**Backgrounds:** $t\bar{t}Z$, $t\bar{t}bb$, $t\bar{t}jj$

**Results for $m_H = 115$ GeV:**
$S/\sqrt{B} = 5.3$, $\Delta m/m_H = 3.8\%$

$ttH$ and $H \rightarrow \gamma\gamma$ are all we have in the 115 GeV mass region!
\[ H \rightarrow ZZ^* \rightarrow 4\ell \]

\[ M_{\text{Higgs}} = 150 \text{ GeV} \]

\[ M_{4\ell}^\pm \text{(GeV)} \]

100 fb\(^{-1}\)
$4\mu$ Event

$H (150 \text{ GeV}) \rightarrow Z^0 Z^{0*} \rightarrow 4\mu$
$H \rightarrow ZZ^* \rightarrow 4e$

CMS full GEANT simulation of
$H(150 \text{ GeV}) \rightarrow ZZ^* \rightarrow 4e$
As Higgs width increases and production rates fall with higher masses one must use channels with larger branching ratios.

Select leptons, jets and missing energy.
**Standard Model Higgs in CMS**

**Significance for 100 fb⁻¹**

- **CMS**: Standard Model Higgs
- **H → WW → ℓℓνν**
- **H → ZZ, ZZ* → 4ℓ±**
- **γγ + ≥ 2 jets**

**Discovery Luminosity [fb⁻¹]**

- **LHC 14 TeV (SM NLO Cross Sections)**
- CMS 5σ

**Significance for 100 fb⁻¹**

- **S = N_S / √N_B**

**5 σ - Contours**

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*IX Mexican Workshop on Particles and Fields - Colima - Nov. 18, 2003 – J. Incandela – UC Santa Barbara*
Supersymmetric Higgs

- **Minimal Case of 2 doublets:**
  - \( \tan \beta = \frac{v_2}{v_1} \) and \( v_1^2 + v_2^2 = v^2 \)
  - After \( W, Z \) masses, 5 remaining d.o.f.
    - 5 physical higgs bosons \( h, H, A, H^\pm \)
    - masses expressed in terms of \( m_A \) and \( \tan \beta \)
  - Large radiative corrections (at one-loop)
    \[
    M_h^2 < M_Z^2 + \left( \frac{3G_F}{2^{1/2} \pi^2} \right) M_t^4 \ln(1 + m^2 / M_t^2)
    \]
    \[
    M_h < 130 \text{ GeV}
    \]
    \[
    < 150 \text{ GeV} \text{ (if } \exists \text{ Higgs singlet(s) in addition to the two doublets)}
    \]

- Couplings to \( W, Z \) shared by \( h \) and \( H \) but sum quadratically to SM
  \[
  g_{hoVV}^2 + g_{H0VV}^2 = g_{HV}^2 \text{ (SM)}
  \]

Can search in many of the same channels as the SM for the lightest higgs

- Fermion couplings also (S. Dawson hep-ph/9411325)
H, A → ττ, μμ (τ-channels enhanced over SM for large tanβ)

Mass reconstructed assuming ν directions parallel to lepton and τ-jet.
BR smaller than that for $\tau\tau$-channel by $(m_\mu/m_\tau)^2$. Somewhat compensated by better resolution for $\mu$’s. Useful for large $\tan\beta$. 
Charged Higgs

\[ gb \rightarrow tH^\pm, \ H^\pm \rightarrow \tau \nu, \ t \rightarrow qqb \]

R. Kinnunen

Transverse mass reconstructed from $\tau$-jet and $E_T^{\text{miss}}$ for $pp \rightarrow tH^\pm$
5σ reach for MSSM Higgs in 30 fb⁻¹
SUSY Particles

• Some Basics:
  – Supersymmetry must be a broken symmetry, otherwise the SUSY partners would have the same masses as their SM counterparts,
    • presumably we’d have seen them already.
  – Furthermore, if SUSY is relevant to electroweak symmetry breaking
    • gluino and squark masses should be ~ 1 TeV or so.

• Technicalities:
  – Since multiple SUSY particles can be produced simultaneously, a model with a consistent set of masses and branching ratios must be used in our simulations.
  – Traditionally CMS uses the Supergravity (SUGRA) model, which assumes that gravity is responsible for the mediation of SUSY breaking.
    • SUGRA provides a good candidate for galactic dark matter
  – Another possible model is the Gauge Mediated SUSY Breaking Model (GMSB) which assumes that Standard Model gauge interactions are responsible for the breaking.
    • It’s generally easier to detect SUSY particles in GMSB than SUGRA
MSSM particle content:

- squarks (spin-0): \( \tilde{d}_L, \tilde{u}_L, \tilde{s}_L, \tilde{c}_L, \tilde{b}_1, \tilde{t}_1, \tilde{d}_R, \tilde{u}_R, \tilde{s}_R, \tilde{c}_R, \tilde{b}_2, \tilde{t}_2 \)
- sleptons (spin-0): \( \tilde{e}_L, \tilde{\nu}_e L, \tilde{\nu}_L, \tilde{\nu}_\mu L, \tilde{\tau}_1, \tilde{\nu}_\tau L, \tilde{e}_R, \tilde{\nu}_R, \tilde{\tau}_2 \)
- charginos (spin-\( \frac{1}{2} \)): \( \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm \)
- neutralinos (spin-\( \frac{1}{2} \)): \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0 \)
- gluino (spin-\( \frac{1}{2} \)): \( \tilde{g} \)
- higgs bosons: (spin-0): \( h, H, A, H^\pm \)

MSSM parameters:

- \( m_{\tilde{g}}, m_{\tilde{\ell}}, m_\tilde{\ell}, A_t, A_b, \mu, m_A, \tan\beta \)

Minimal SUGRA parameter set:

- \( m_0, m_{1/2}, \tan\beta, A_0 \) and sign(\( \mu \))
Supersymmetric particles will have striking signatures due to cascade decays to final states with leptons, jets and missing energy.

Shown here is a $\tilde{q}\tilde{q}$ event:

$\tilde{q} \rightarrow \tilde{\chi}_2^0 q$

$\tilde{\mu} \mu$

$\tilde{\chi}_1^0 \mu$

$\tilde{q} \rightarrow \tilde{\chi}_1^\pm q$

$\tilde{e} \nu$

$\tilde{\chi}_1^0 e$
The figure shows the $\tilde{q}$, $\tilde{g}$ mass reach for various luminosities in the inclusive $E_T^{\text{miss}} + \text{jets}$ channel.

- SUSY could be discovered in one good month of operation …
Gluino reconstruction

\[ \text{pp } \rightarrow \tilde{g} \rightarrow b\tilde{b} \quad (26\%) \]

\[ \quad \rightarrow \tilde{\chi}_2^0 b \quad (35\%) \]

\[ \quad \rightarrow \tilde{\chi}_1^0 l^+ l^- \quad (0.2\%) \]

\[ \quad \rightarrow \tilde{l}^+ l^- \rightarrow \tilde{\chi}_1^0 l^+ l^- \quad (60\%) \]

**Event final state:**
- \( \geq 2 \) high \( p_t \) isolated leptons OS
- \( \geq 2 \) high \( p_t \) b jets
- missing \( E_t \)

M. Chiorboli
Gauge Mediated SUSY Breaking

LSP = Gravitino ($\tilde{G}$)  
NLSP = neutralino ($\tilde{N}_1$) or stau ($\tilde{\tau}$)

Lifetime of NLSP is a measure of the overall SUSY breaking scale.

- Long-lived $\tilde{\tau}$ looks like heavy (nonrelativistic) muon
- Neutralinos decaying far from interaction point give $\gamma$’s that don’t point back to the primary vertex

<table>
<thead>
<tr>
<th>NLSP</th>
<th>short lived</th>
<th>decaying</th>
<th>long lived</th>
</tr>
</thead>
</table>
| $\tilde{N}_1 \rightarrow \tilde{G} \gamma$ | like MSSM + 2$\gamma$ | c$\tau$ measurement by  
- ECAL counting  
- $\mu$CAL counting  
- ECAL/$\mu$CAL ratio  
- ECAL impact par.  
- $\mu$CAL slope | like MSSM |
| $\tilde{\tau}_1 \rightarrow \tilde{G} \tau$ | like MSSM + 2$\tau$ | both c$\tau$ and mass measurement | mass measurement by TOF method |

Experimental possibilities
If the \( \tilde{N}_1 \rightarrow \tilde{G} \gamma \) decay happens inside the muon system, the photon will develop an electromagnetic shower.

CMS can measure \( \tilde{N}_1 c\tau \) from 1 cm to 1 km for scenarios with \( \sigma_{\text{SUSY}} > 100 \, \text{fb} \)

M. Kazana, G. Wrochna, P. Zalewski
Mass of long-lived $\tilde{\tau}$

Time of Flight as measured in muon barrel drift tubes $\rightarrow \beta \rightarrow$ mass

CMS can measure $\tilde{\tau}$ mass from 90 to 700 GeV with $L = 100$ fb$^{-1}$. Upper limit corresponds to $\sigma_{\text{SUSY}} = 1$ fb and $\tilde{q}\tilde{g}$ masses of $\sim 4$ TeV.
Summary

• **HIGGS**
  - The Standard Model Higgs can be discovered over the entire expected mass range up to about 1 TeV with 100 fb$^{-1}$ of data.
  - Most of the MSSM Higgs boson parameter space can be explored with 100 fb$^{-1}$ and all of it can be covered with 300 fb$^{-1}$.

• **SUSY**
  - squarks and gluinos up to 2 to 2.5 TeV or more
    • SUSY should be observed regardless of the symmetry breaking mechanism …

• **Extra dimensions:**
  - LED: Sensitive to multi-TeV fundamental mass scale
  - SED: Gravitons up to 1-2 TeV in some models
• Not mentioned
  – If Electroweak symmetry breaking proceeds via new strong interactions something new has to show up
  – New gauge bosons with masses less than a few TeV can be discovered
  – If the true Planck scale is ~ 1 TeV, we may even create black holes and observe them evaporate…

There’s still a lot of hard work to go to finish the CMS detector
But the payoff could be wonderful…