Search for Higgs and SUSY in the CMS experiment at LHC

Zimányi Winter School, Budapest, 3-7 Dec 2012

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on behalf of the CMS Collaboration

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Outline

- The Higgs boson of the Standard Model.
- Its \textit{(possible)} observation at LHC.
- Supersymmetry (SUSY).
- Exclusion of the simplest versions.
- New search strategy: simplified models.
- Results of 2011-12.
- Plans and hopes.

With the support of the Hungarian OTKA Grant NK-81447
References


Public Physics Analysis Summaries of CMS on Higgs search


The Zoo of the Standard Model

3 fermion families:
1 pair of quarks and
1 pair of leptons in each

3 kinds of gauge bosons:
the force carriers
All identified and studied!

+ the Higgs boson (?)

Color: the charge of the strong interaction
colored quarks $\Rightarrow$ colorless composite hadrons of 2 kinds
hadrons = mesons ($q\bar{q}$) + baryons ($qqq$)

Nucleons ($I = \frac{1}{2}$): $p = (uud)$ $n = (udd)$ $\bar{p} = (\bar{u}\bar{u}\bar{d})$

Pions, the lightest mesons:
$\pi^+ = (u\bar{d})$ $\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ $\pi^- = (\bar{u}d)$
The Standard Model

Derive 3 interactions of local $U(1)$, $SU(2)$ and $SU(3)$ symmetries

Unify and separate e-m $U(1)$ and weak $SU(2)$ interactions using spontaneous symmetry breaking:

(Anderson-Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism, 1963-64)

Add a 4-component, symmetry breaking field to vacuum.

Separate a good $U(1)$ local symmetry from the ruined $U(1) \otimes SU(2)$

\[ \Downarrow \]

electromagnetism + zero-mass photon, OK!

Turn 3 d.f. of Higgs-field to create masses for $Z$, $W^+$, $W^-$, get a correct weak interaction with 3 heavy gauge bosons.

4th degree of freedom: heavy scalar boson.
Glory Road of the Standard Model

Status in 2012

Includes hundreds of measurements of all experiments

| Expt – theory |
expt. uncertainty

Slightly deviating quantity used to change

Now it is forward-backward asymmetry of

\( e^+e^- \rightarrow Z \rightarrow b\bar{b} \)

LEP Electroweak Working Group:
http://lepewwg.web.cern.ch/

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<td>( \Delta \alpha^{(5)}_{\text{had}}(m_Z) )</td>
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<td>( m_Z ) [GeV]</td>
<td>91.1875 ± 0.0021</td>
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<td>( \Gamma_Z ) [GeV]</td>
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<td>( \sigma^0_{\text{had}} ) [nb]</td>
<td>41.540 ± 0.037</td>
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<td>( R_l )</td>
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<tr>
<td>( R_b )</td>
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<td>( R_c )</td>
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<td>( A_l(\text{SLD}) )</td>
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<td>( \Gamma_W ) [GeV]</td>
<td>2.085 ± 0.042</td>
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<td>( m_t ) [GeV]</td>
<td>173.20 ± 0.90</td>
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March 2012
The Higgs boson of the Standard Model

Spontaneous symmetry breaking:
Spinless, neutral, heavy particle
The scalar particle needed for renormalisation
Does it really exist? SM: it must!

Many jokes of the Higgs boson in press...
The Higgs boson walks into a bar. The bartender says "Watch out, there were some guys looking for you."

The Higgs boson walks into a church. The priest says „Your kind is not welcome here”. The boson replies: „But without me how can you have mass?”
Where is the Higgs boson?

By-product of spontaneous symmetry breaking of the SM
Most wanted particle of physics as the only missing piece of the Standard Model.

Experimentally not observed before 2012,
LEP (2002): $M(H) > 114.4$ GeV

„It was in 1972 … that my life as a boson really began”

Peter Higgs:
*My Life as a Boson: The Story of „The Higgs”*,
Accelerators of CERN

- **LHC**: Large Hadron Collider
- **SPS**: Super Proton Synchrotron
- **AD**: Antiproton Decelerator
- **ISOLDE**: Isotope Separator On Line Device
- **PSB**: Proton Synchrotron Booster
- **PS**: Proton Synchrotron
- **LINAC**: LINear ACcelerator
- **LEIR**: Low Energy Ion Ring
- **CNGS**: Cern Neutrinos to Gran Sasso
LHC and its main experiments

$\text{p} \quad 14 \text{ TeV} \quad \text{p}$
Steering magnets of LHC

1232 superconducting magnets (before installation)

\( L = 15 \text{ m}, \; M = 35 \text{ t}, \; T = 1.9 \text{ K}, \; B = 8.3 \text{ T} \)
Dipole magnets of LHC in the tunnel
Luminosity

Luminosity: \[ L = fn \frac{N_1 N_2}{A} \]

\[ [L] = s^{-1} \text{cm}^{-2} \quad (\sim \text{flux}) \]

- \( f \): circulation frequency;
- \( n \): nr. of bunches in ring;
- \( N_1, N_2 \): particles/bunch;
- \( A \): spatial overlap

Rate of reaction with cross section \( \sigma \) at \( \epsilon \) efficiency

\[ R = \epsilon \sigma L \]

Integrated luminosity: \[ \int_{t_1}^{t_2} L \, dt; \quad [\text{pb}^{-1}, \text{fb}^{-1}] \]

Amazing performance of LHC!

2010: 0.04 fb\(^{-1}\) at 7 TeV; 2011: 5.6 fb\(^{-1}\) at 7 TeV;
2012: so far 22 fb\(^{-1}\) at 8 TeV (expect \( \sim 25 \text{ fb}^{-1} \))

LHC is like Formula 1: boring without collisions
CMS: Compact Muon Solenoid

14000 ton digital camera:
100 M pixel, 20 M pictures/sec, 1000 GB/sec data
Processes max 400 pictures/sec ⇒ intelligent filter!!
The CMS Collaboration (2012)

- 179 institutions of 41 countries
- 3275 physicists (incl. 1535 students)
- 790 engineers and technicians
- Participants by countries of institutes:
  USA: 1149, Italy: 439, Germany: 298, Russia: 234

Huge joint effort:
3000 people worked on it for 20 years!
Formation of the SM Higgs boson in p-p collisions at LHC

SM Higgs production

\[ \sigma \text{ [fb]} \]

- \( gg \rightarrow h \)
- \( qq \rightarrow qqh \)
- \( bb \rightarrow h \)
- \( qq \rightarrow Wh \)
- \( qq \rightarrow Zh \)
- \( gg,qq \rightarrow tth \)

\( m_h \text{ [GeV]} \)

- Gluon fusion
- Vector boson fusion

Horváth Dezső: Search for Higgs and SUSY in CMS
Zimanyi Winter School, Budapest, 2012 – p. 16
March 2012

Not excluded by 2011 CMS data:

$114 < M_H < 127$ GeV (at 95% CL)

(where many decay processes contest)

Best identified:

$H \rightarrow \gamma\gamma$

Excess observed

$2 - 3\sigma$ at $\sim 125$ GeV!
CMS: elektromagnetic calorimeter

optimized for studying $H \rightarrow \gamma \gamma$

75,848 PbWO$_4$ single crystal scintillators
A CMS event: $H \rightarrow \gamma\gamma$ candidate
4 July 2012: we have something!

**ATLAS and CMS**, at LHC collision energies 7 and 8 TeV, in two decay channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$, at invariant mass of $m \approx 126$ GeV see a new boson at a convincing statistical significance of $5\sigma$ conf. level each with properties corresponding to those of the SM Higgs boson.

$H \rightarrow \gamma\gamma \Rightarrow S_H = 0$ or 2

Data analysis was optimized for SM Higgs search...

Nevertheless, it has to be shown to be the SM Higgs, e.g.

- $S_H = 0$: $H \rightarrow ZZ$ and $H \rightarrow WW$ angular distribution of decay products
- $H \rightarrow XY...$ cross sections follow the SM predictions
- There is one Higgs boson only (no charged or more neutral ones)
CMS: $H \rightarrow \gamma\gamma$ (VBF)

Vertex for measuring the $\gamma\gamma$ invariant mass:

- two hadron jets from vector boson fusion.

Di-jet event with:
- diphoton mass 121.9 GeV
- dijet mass 1460 GeV
- jet pT: 288.8 and 189.1 GeV
- jet $\eta$: -2.022 and 1.860
Many p-p collisions can be in the same event (same bunch collision). Record: 78 identified vertices. This increases data taking speed and makes life hard.
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

Horváth Dezső: Search for Higgs and SUSY in CMS

ATLAS: 2931 authors, 4 Hungarian

CMS: 2899 authors, 21 Hungarian

ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Observation of a new boson in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is performed. The data used correspond to integrated luminosities of approximately 4.8 fb$^{-1}$ collected at $\sqrt{s}$ = 7 TeV in 2011 and 5.0 fb$^{-1}$ at $\sqrt{s}$ = 8 TeV in 2012. Individual searches in the channels $H \rightarrow Z \gamma$, $W^+W^-$, $H \rightarrow WW^{-}$, $H \rightarrow ZZ^{-}$, and $H \rightarrow ZZ^{-}$ are performed. The measurements of the $H \rightarrow ZZ^{-}$ and $H \rightarrow Z \gamma$ channels in the 7 TeV data are consistent with the Standard Model predictions.

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CMS Collaboration

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

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CMS Collaboration:
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

text: 50%, 2899 authors in 16 pp.
ATLAS: $H \rightarrow \gamma\gamma$ mass distribution

ATLAS Collaboration (2931 authors):

arXiv:1207.7214

CMS: $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$
CMS: $p-$distributions (4 July 2012)

The probability that random fluctuation of the measured background could give the observed excess.

\[ \gamma\gamma \text{ and } ZZ: 5.0\sigma \]
\[ \gamma\gamma, ZZ \text{ and } WW: 5.1\sigma \]
\[ \text{Mind együtt: } 4.9\sigma \]

ATLAS got the same: $\gamma\gamma$ and ZZ: 5.0\sigma

Adding WW increased the ATLAS excess to 6.0\sigma
Doubling 2012 statistics increased CMS excess to 6.9 $\sigma$

Sharp peak, close to SM exp. at 126 GeV, far less elsewhere
CMS, November 2012: mass vs. x-sec

\[ \langle M_X \rangle = 125.8 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \]
CMS data favor + parity for $S_X = 0$
CMS: is it the SM Higgs boson?

Branching ratios of different decay channels as compared to SM predictions for a 126 GeV Higgs boson

\[ \frac{\sigma}{\sigma_{SM}} = 0.88 \pm 0.21 \]

Getting closer to SM, August: \( 0.80 \pm 0.22 \)

ATLAS, November: \( 1.3 \pm 0.3 \)
CMS vs. ATLAS: mass and signal strength

(determined consistently, in various ways)

CMS, November 2012 (updated for HCP-2012)

\[ M_H = 125.8 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV} \]

Local significance of the observation \((M_H = 126 \text{ GeV})\): 6.9\(\sigma\),

\[ \begin{align*}
    \text{H} \to \gamma\gamma: \ & \frac{\sigma}{\sigma\text{(SM)}} = 1.56 \pm 0.43 \\
    \text{H} \to \text{all}: \ & \frac{\sigma}{\sigma\text{(SM)}} = 0.88 \pm 0.21
\end{align*} \]


\[ M_H = 126.0 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV} \]

Local significance of the observation \((M_H = 122 - 131 \text{ GeV})\): 5.9\(\sigma\),

\[ \begin{align*}
    \text{H} \to \gamma\gamma: \ & \frac{\sigma}{\sigma\text{(SM)}} = 1.9 \pm 0.5 \\
    \text{H} \to ZZ \to 4\ell: \ & \frac{\sigma}{\sigma\text{(SM)}} = 1.26 \pm 0.14 \\
    \text{H} \to \text{all}: \ & \frac{\sigma}{\sigma\text{(SM)}} = 1.4 \pm 0.3
\end{align*} \]
Supersymmetry (SUSY)
Problems of the Standard Model – 1

- 3 independent (?) components: 
  \( U(1)_Y \otimes SU(2)_L \otimes SU(3)_C \)

- Gravitation? \( S = 2 \) graviton?

- Asymmetries: right \( \Leftrightarrow \) left World \( \Leftrightarrow \) Antiworld

- Artificial mass creation: Higgs-field \( ad \ hoc \)

- Many fundamental particles:
  \[ 8 + 3 + 1 + 1 = 13 \text{ bosons} \]
  \[ 3 \times 2 \times (2 + 3 \times 2) = 48 \text{ fermions} \]

- Charge quantization: \( Q_e = Q_p, \ Q_d = Q_e/3 \)

- Why the 3 fermion families?
  Originally: Who needs the muon??

- Nucleon spin: how 1/2 produced?
Problems of the Standard Model – 2

- 19 free parameters (too many ??):
  - 3 couplings: $\alpha$, $\Theta_W$, $\Lambda_{QCD}$; 2 Higgs: $M_H$, $\lambda$
  - 9 fermion masses: $3 \times M_\ell$, $6 \times M_q$
  - 4 parameters of the CKM matrix: $\Theta_1$, $\Theta_2$, $\Theta_3$, $\delta$
  - QCD-vacuum: $\Theta$

- $M_\nu > 0 \Rightarrow +3$ masses, $+4$ mixing matrix

- Gravitational mass of the Universe:
  - 4% ordinary matter (stars, gas, dust, $\nu$)
  - 23% invisible dark matter
  - 73% mysterious dark energy

- Naturalness (hierarchy):
  The mass of the Higgs boson quadratically diverges due to radiative corrections. Cancelled if fermions and bosons exist in pairs.
**Coupling constants**

\[ \mu (\log_{10} \mu [\text{GeV}]) \]

\[ \mu (\alpha) \]

\[ \mu (\alpha^2) \]

\[ \mu (\alpha^3) \]

\[ \alpha_i: \text{Local } SU(i) \text{ couplings} \]

They almost meet at \( \mu \sim 10^{13} - 10^{16} \text{ GeV} \)

Do they unite at high energy?
Supersymmetry (SUSY)

**Hypothesis:** Fermions and bosons exist in pairs:

\[ Q|F> = |B>; \quad Q|B> = |F> \quad m_B = m_F \]

Identical particles, just spins different

Broken at low energy, no partners: much larger mass?

---

Almost 50% discovered already!!

We see half (−1) of all SUSY particles!
2 Higgs doublets ⇒ masses to upper and lower fermions
\[ m_L = m_R, \text{ but } \tilde{m}_L \neq \tilde{m}_R \]

8 Higgs fields ⇒ 5 Higgs bosons: \( h^0, H^0, A^0, H^\pm \)

Higgs-parameters: \( \tan \beta = v_1/v_2 \), masses

\textbf{SUSY's quantum number: } R \text{ parity } \quad R = (-1)^{3B-L+2S}

\( R = +1 \) particle, \( R = -1 \) SUSY partner (sparticle)

\textbf{Parity-like: } \( R^2 = +1 \)

If \( R \) conserved, lightest sparticle (LSP) stable

\( R \) parity may not be much violated: we would see

Neutral LSP: excellent dark matter candidate
SUSY: coupling constants

Unification OK!
Bend at low energies: SUSY enters with many new particles ⇒ more loop corrections
CMSSM, mSUGRA

Constrained Minimal Supersymmetric Standard Model

Many simplification constraints (boundary conditions), 105 ⇒ 5 or 6 parameters, e.g. in mSUGRA:

- $m_{1/2}$: fermion masses at the Grand Unification energy (GUE $\sim 10^{14} - 10^{15}$ GeV)
- $m_0$: boson masses at GUE
- $A_0$: SUSY-breaking triple (X–Y–Higgs) couplings at GUE
- $\tan \beta = v_1/v_2$: vacuum exp. values upper/lower Higgs fields
- $m_A$: mass of a Higgs boson (optional)
- $\mu$: mixing parameter of the higgsinos (sign ±)

Really sensitive parameters: $m_0$ and $m_{1/2}$

CMSSM is practically excluded by 2011 LHC data
Many-many alternative models
Experimental limits, constraints

No SUSY phenomenon observed, the data limit the parameter space

- LEP, Tevatron, LHC: Higgs sector
  - Mass of SM Higgs from direct searches $M_H = 125$ GeV (??); $H \sim h^0$
  - Fitting electroweak data
  - Search for neutral Higgs bosons (h and A)

- $BR(b \rightarrow s\gamma)$ measurements at B-factories
- Anomalous magnetic moment of the muon (BNL)
- WMAP (Wilkinson Microwave Anisotropy Probe): density of dark matter (DM), indirect
- Direct searches for DM with $\nu$-detectors
SUSY search

Production in pairs, decay to other SUSY particle
(if $R$ conserved)

Lightest (LSP) stable, neutral, not observable

Signal: missing energy

Typical SUSY decays ($\text{LSP} = \tilde{\chi}_1^0$):

- squark: $\tilde{q} \rightarrow q + \tilde{g}; \quad q + \tilde{\chi}_1^0$
- slepton: $\tilde{\ell} \rightarrow \ell + \tilde{\chi}_1^0$
- gluino: $\tilde{g} \rightarrow q + \bar{q} + \tilde{\chi}_1^0; \quad g + \tilde{\chi}_1^0$
- wino: $\tilde{W} \rightarrow e + \nu_e + \tilde{\chi}_1^0$
What and where to look for?

Even if SUSY is valid, MSSM or cMSSM may not be. If we find new physics, how can we tell it is SUSY? Simplified models $\Rightarrow$ easier interpretation

LHC inverse problem:
Given model and parameters $\Rightarrow$ prediction of reactions
But experiment works the other way around:
We have to tell which model from the data.

SUSY: Cascade decays are model-dependent
Simplified models give reactions with few particles $\Rightarrow$
dependence on few masses and cross sections with relatively wide allowed intervals $\Rightarrow$ characteristic for several models
Simplified Models

Few on-shell particles, simple topology and decays
Not model-independent, but possibly associated with several models.
Possible new physics on well understood SM-base

What can we learn of such analysis?

- Boundaries of search sensitivity, both for data analysis and for new theories.
- Characterizing new physics signals: what models can be associated?
- Limits on more general models: from possible cross-sections.
Topologies of simplified models

Basic topologies with no lepton:

\[ gg \rightarrow \tilde{g}\tilde{g} \rightarrow 2(qq + \text{LSP}) \]

\[ qg \rightarrow \tilde{q}\tilde{g} \rightarrow qqq + 2\text{ LSP} \]

\[ qq \rightarrow \tilde{q}\tilde{q} \rightarrow qq + 2\text{ LSP} \]

and we can add one or more leptons.
Exclusion with simplified models

Search for supersymmetry in events with b-quark jets and missing transverse energy in pp collisions at 7 TeV,


Pure hadronic events: no neutrino, missing momentum from LSP only

\[ \tilde{g} \tilde{g} \to 4 \text{ t-jets} + \text{LSPs} \]

CL 95% exclusion for production of gluino pairs to test models
Conclusion

- We very probably observed the SM Higgs boson or some new boson of spin 0 (or 2), e.g. a Higgs boson of a more general model.

- Let us hope for some deviation from the Standard Model (although none seen yet).

- The simplest SUSY model, mSUGRA does not seem to be supported by experimental data (g-2, LEP, WMAP, LHC, ...)

- Simplified approaches: search for non-SM phenomena in simple reactions with on-shell particles.

- It may help to find new, characteristic reactions.
  If found, identify the new observation with possible models

- Adjust theory to data, not the other way around.
Conclusion–2

- Experimentalist: *What happens to you if we exclude the whole SUSY in 2012?*

- Theorist: *We are far from that, MSSM is not the whole SUSY. And anyways, we are not doing that only ...*
Thank you for your attention
CMS, November 2012: $4\ell$ mass

![Graph showing the distribution of events as a function of $m_{4\ell}$ (GeV) with data points for $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$ and $\sqrt{s} = 8$ TeV, $L = 12.2$ fb$^{-1}$.

- Black dots: Data
- Green filled area: $Z+X$
- Light blue filled area: $Z\gamma^*, ZZ$
- Red line: $m_H = 126$ GeV]
Minimal Supersymmetric SM (MSSM)

Electroweak symmetry breaking

\[ \downarrow \]

MSSM-fermions mix into \[ \Rightarrow \] mass eigenstates

\{Electroweak gauginos + higgsinos\} \[ \Rightarrow \] \{charginos and neutralinos \}

\{\tilde{\gamma}, \tilde{W}^\pm, \tilde{Z}; \tilde{h}^0, \tilde{H}^0, \tilde{H}^\pm\} \[ \Rightarrow \] \{\tilde{\chi}^+_1, \tilde{\chi}^+_2; \tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4\}

mass grows with index

Lightest SUSY particle (LSP) depends on model, e.g.

mSUGRA: \[ \tilde{\chi}^0_1 \] or GMSB: gravitino (\[ \tilde{G} \])

SUSY breaking \[ \Rightarrow \] many (\[ > 100 \]) new parameters

masses, couplings, mixing angles

Lots of model variants, huge parameter space, different constraints.
MSSM mass spectrum: preconceptions

Even if we remain sceptic it is worthwhile to know what do most of the model constructors think (after S.P. Martin)

- R parity is barely violated
- LSP: \( \tilde{\chi}_1^0 \) or gravitino
- Gluino mass \( M_3 \equiv m(\tilde{g}) \gg m(\tilde{\chi}_1^0), m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm) \)
- \( m(\tilde{u}_i) \sim m(\tilde{d}_i) \sim m(\tilde{c}_i) \sim m(\tilde{s}_i) \gg m(\tilde{\ell}_i) \)
- \( m(\tilde{u}_i) \sim m(\tilde{d}_i) \sim m(\tilde{c}_i) \sim m(\tilde{s}_i) > (0, 6_{\text{MSUGRA}} \ldots 0, 8_{\text{GMSB}})m(\tilde{g}) \)
- \( m(\tilde{u}_L) \geq m(\tilde{u}_R) \ldots m(\tilde{s}_L) \geq m(\tilde{s}_R) \) and \( m(\tilde{e}_L) \geq m(\tilde{e}_R), m(\tilde{\mu}_L) \geq m(\tilde{\mu}_R) \) as \( M_L^2 \sim M_R^2 + 0, 5m_{1/2}^2 \).
- \( \tilde{t}_1, \tilde{b}_1 \) lightest squarks and \( \tilde{\tau}_1 \) lightest charged slepton (mixing, Higgs coupling)
- \( m(h^0) \lesssim 150 \text{ GeV} \ll m(A), m(H^\pm), m(H^0) \)
OSET: On-Shell Effective Theory

CMS + theory, 2007–2008

Off-shell particles: hard to identify, missing energy harder to determine

Assume simple production and simple decay of new particle, analyze decay spectra, find corresponding deviations from SM.

LHC phenomena ⇔ Lagrangian of new physics

http://tools.marmoset-mc.net/osetology_wordpress/

Main study: gluino and sqark production and decay
OSET: On-Shell Effective Theory

Monte Carlo

Pair production, 2 decay modes

Amplitudes (cross-sections and branching ratios) free parameters

CMS strategies for discovery

- $\alpha_T$ search for early discovery in (forced) 2-jet events
  ($E_T(J_1) > E_T(J_2)$):
  
  Cut $\alpha_T = \frac{E_T(J_2)}{M_T(J_1, J_2)}$

  $= \frac{E_T(J_2)}{\sqrt{(E_T(J_1) + E_T(J_2))^2 - (p_x(J_1) + p_x(J_2))^2 - (p_y(J_1) + p_y(J_2))^2}}$

  Exclusive 2-jet, inclusive 3-jet search

- Jets + $H_T$ for $> 2$ jets, inclusive
  
  Scalar mom. sum: $H_T = \sum_i |p_T(J_i)|$
  
  Missing transverse mom.: $MHT = H_T = | - \sum_i p_T(J_i)|$

- Razor search: test kinematic consistency for pair production of heavy particles
  Two jets (inv. mass $M_R$) + 0 or 1 lepton
Phenomenological MSSM

Random space points in $(105 \rightarrow) 19$-parameter pMSSM
(1st and 2nd generation sfermions assumed degenerate)

- 10 (real) sfermion masses
- 3 gaugino masses
- 3 trilinear couplings
- $\mu$, $\tan \beta$, $M_A$.

Masses: 50-100 GeV ... 1-3 TeV, $1 < \tan \beta < 60$

Experimental and theoretical constraints applied
So far (mSUGRA, GMSB, ...) overlooked phenomena could emerge

C.F. Berger, J.S. Gainer, J.L. Hewett, T.G. Rizzo:
The missing MSSM menagerie

<table>
<thead>
<tr>
<th>Kind</th>
<th>spin</th>
<th>R parity</th>
<th>gauge eigenstate</th>
<th>mass eigenstate</th>
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<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$H_1^0, H_2^0, H_1^+, H_2^-$</td>
<td>$h^0, H^0, A^0, H^\pm$</td>
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<tr>
<td>squark</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$</td>
<td>same</td>
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<td>$\tilde{s}_L, \tilde{s}_R, \tilde{c}_L, \tilde{c}_R$</td>
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<td>$\tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$</td>
<td>$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$</td>
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<tr>
<td>slepton</td>
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<td>-1</td>
<td>$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e$</td>
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<td>$\tilde{\mu}_L, \tilde{\mu}<em>R, \tilde{\nu}</em>\mu$</td>
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<td>$\tilde{\tau}_L, \tilde{\tau}<em>R, \tilde{\nu}</em>\tau$</td>
<td>$\tilde{\tau}_1, \tilde{\tau}<em>2, \tilde{\nu}</em>\tau$</td>
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<tr>
<td>neutralino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0$</td>
<td>$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$</td>
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<tr>
<td>chargino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{W}^\pm, \tilde{H}_1^+, \tilde{H}_2^-$</td>
<td>$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$</td>
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<tr>
<td>gluino</td>
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<td>-1</td>
<td>$\tilde{g}$</td>
<td>same</td>
</tr>
<tr>
<td>goldstino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{G}$</td>
<td>same</td>
</tr>
<tr>
<td>gravitino</td>
<td>3/2</td>
<td>-1</td>
<td>$\tilde{G}$</td>
<td>same</td>
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</table>
CMS SUSY summary plot

<table>
<thead>
<tr>
<th>CMS preliminary</th>
<th>( m(\text{mother}) - m(\text{LSP}) = 200 \text{ GeV} )</th>
<th>( m(\text{LSP}) = 0 \text{ GeV} )</th>
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<tbody>
<tr>
<td>T1: ( \tilde{g} \rightarrow q\bar{q}\chi^0 )</td>
<td>gluino</td>
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<tr>
<td>T1b: ( \tilde{g} \rightarrow bb\chi^0 )</td>
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<tr>
<td>T1t: ( \tilde{g} \rightarrow tt\chi^0 )</td>
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<td>T2: ( \tilde{q} \rightarrow q\chi^0 )</td>
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<td>T2bb: ( \tilde{b} \rightarrow b\chi^0 )</td>
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<td>T2tt: ( \tilde{t} \rightarrow t\chi^0 )</td>
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<tr>
<td>T3lh: ( \tilde{g} \rightarrow qq(\tilde{\chi}_1^0 \rightarrow l^+ l^- \tilde{\chi}_1^0) )</td>
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<tr>
<td>T3w: ( \tilde{g} \rightarrow qq(\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0 l^\mp) )</td>
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<td>T5lnu: ( \tilde{\chi}_1^\pm \rightarrow l^\pm \nu l )</td>
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<tr>
<td>T5zz: ( \tilde{g} \rightarrow qq(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0) )</td>
<td>gluino</td>
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<tr>
<td>TChislepSlep: ( \tilde{\chi}_1^0 \tilde{\chi}_1^\pm \rightarrow ll\nu l \tilde{\chi}_1^0 )</td>
<td>chargino/neutralino</td>
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<td>TChiwz: ( \tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow WZ\chi^0 \chi^0 )</td>
<td>chargino/neutralino</td>
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</table>

7 TeV, \( \leq 4.98 \text{ fb}^{-1} \)

Mass scales [GeV]