Results from the CMS Experiment
The March Meeting Attack

Albert De Roeck
CERN, Geneva, Switzerland and
University of Antwerp & UC Davis & IPPP Durham UK

UC Davis
Physics
Outline

• Introduction
• LHC & CMS Operations
• New Physics results at 7 TeV
• Summary & outlook for 2011
With LHC we are entering a New Era in Fundamental Science

The Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is a turning point in modern physics.

The exploration of a new energy frontier just started

**pp collisions at a centre of mass energy of 7 TeV**
The Origin of Particle Masses

A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery could be solved with the ‘Higgs mechanism’ which predicts the existence of a new elementary particle, the ‘Higgs’ particle (theory 1964, P. Higgs, R. Brout and F. Englert)

The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

The LHC will have sufficient energy to produce it for sure, if it exists
Astronomers say that most of the matter in the Universe is invisible Dark Matter.

‘Supersymmetric’ particles?

We shall look for them with the LHC.

F. Zwicky 1898-1974
Beyond the SM? Ask a Theorist

Or maybe not…😊

During the last 2-3 years we –LHC experimentalists- got more models to deal with than we needed… Some theorists found it a challenge to invent a model with signatures difficult for the experiments: heavy stable charged particles, hidden valley models, Quirks…
The CMS Collaboration: >3170 scientists and engineers, >800 students from 182 Institutions in 39 countries.

~ 1/4 of the people who made CMS possible
CMS Detector

Compact Muon Solenoid

- **SILICON TRACKER**
  - Pixels (100 x 150 μm²)
    - ~1m² ~66M channels
  - Microstrips (80-180μm)
    - ~200m² ~9.6M channels

- **CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
  - ~78k scintillating PbWO₄ crystals

- **PRESHOOWER**
  - Silicon strips
    - ~16m² ~137k channels

- **STEEL RETURN YOKE**
  - ~13000 tonnes

- **SUPERCONDUCTING SOLENOID**
  - Niobium-titanium coil
    - carrying ~18000 A

- **HADRON CALORIMETER (HCAL)**
  - Brass + plastic scintillator
    - ~7k channels

- **FORWARD CALORIMETER**
  - Steel + quartz fibres
    - ~2k channels

- **MUON CHAMBERS**
  - Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
  - Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers

**Technical Specifications**

- Total weight: 14000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T
Great Moments

Sep 10, 2008
Circulating beam...

Mar 30, 2010
First 7 TeV collisions

00:37 Nov 7, 2010
First Heavy Ion Collisions

22:00 Mar 13, 2011
First 2011 collisions

Some of the key moments the last years
Candidate Event for Top Production

Missing $E_T$

Top Di-Muon Candidate Event
Excellent operation of the accelerator and CMS 8.7 $\mu$b$^{-1}$ of data collected
2010: Luminosity and Operation

- ~47 pb⁻¹ delivered by LHC and ~43 pb⁻¹ collected by CMS (ε~92%)
- Average fraction of operational channels per CMS sub-system >99%
- Good performance, handled increase of more than 5 orders of magnitude in instantaneous luminosity over 7 months!

Max instantaneous luminosity now ~ 2.04 × 10³² cm⁻² s⁻¹
The aim for this year was 10³² cm⁻² s⁻¹...
LHC Start-up in 2011

• LHC teams worked very efficiently from 20th Feb until 13th March on commissioning the LHC for the new settings

• Main changes with respect to last year:
  – Beta*=1.5m (instead of 3.5m) → pile up will be more than twice
  – Will operate with 75 ns (or 50ns) spacing between the bunches → last year 150 ns
    • Max: 936 bunches (75ns) or 1400 bunches (50ns)
  – Optimization of the turnaround time: aim for ~2h between two stable beams
    • Ramp up/down ~20min, squeeze in 10 min
LHC 2011 Operation so far

936 bunches/$10^{33}$ cm$^{-2}$s$^{-1}$ by end of April? ➞ 1 fb$^{-1}$ already by this summer!!
Expected Performance

Intensity ramp-up

- 32 bunches \( \mathcal{L} \approx 0.35 \times 10^{32} \text{cm}^{-2}\text{s}^{-1} \)
- 64 bunches \( \mathcal{L} \approx 0.7 \times 10^{32} \text{cm}^{-2}\text{s}^{-1} \)
- 136 bunches \( \mathcal{L} \approx 1.6 \times 10^{32} \text{cm}^{-2}\text{s}^{-1} \)
- 200 bunches \( \mathcal{L} \approx 2.5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1} \)

If we extrapolate up to 936 bunches \( \mathcal{L} > 1 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} \) in April?!

but scrubbing, SEU, unknowns etc

If \( 10^{33} \) achieved by the end of April \( \sim 1 \text{fb}^{-1} \) before the end of June becomes a realistic goal.
Delivered so far in 2011

\( \sim 26 \text{pb}^{-1} \) delivered by LHC at 7 TeV and \( \sim 23 \text{pb}^{-1} \) collected by CMS. Overall data taking efficiency \( \sim 89\% \). Many calibration and timing runs

\( \sim 345 \text{nb}^{-1} \) delivered at low energy (2.76 TeV) \( \sim 330 \text{nb}^{-1} \) recorded by CMS
The experiment is alive and well!!
The New Challenge

Pile-up!!!
Detector Performance: Tracks & Jets

**Charm production**

\[ \text{Charm production} \]

\[ \text{CMS Preliminary} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

**p_T spectrum**

\[ \text{p}_T \text{ spectrum} \]

**de/dx**

**B-tagging**

**Dijet mass**

**Missing E_T Cleanup**

**Events/GeV**

**Calo E_T [GeV]**

**m_{h_1h_2} [GeV]**
The CMS detector works beautifully!!!
Physics Results

- Studies of general characteristics of minimum bias events (our future pile-up)
- Study of the underlying event in collisions with a hard scattering
- Resonances/known particles
- Jet physics & QCD
- B-physics
- W,Z boson production at 7 TeV
- Top at 7 TeV
- Searches for new physics
- New: Heavy Ion collisions at 2.76 TeV
- …
Physics Results

83 analyses approved
35 submitted/published
12 PAS
13 in CWR
23 finalizing the draft
29 in pipeline

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

28/3/2011
Standard Model
Jet Production at 7 TeV

ICHEP 2010
Higher Statistics and reduced systematics
Inclusive Jet Cross Sections

![Graph showing data and theoretical predictions for inclusive jet cross sections.](chart)
B-physics Results

Extensive studies of $b$/$B$ production. Consistent picture in all channels:
- Data between predictions of MC@NLO and Pythia;
- Differences in shape, both for $p_T$ and rapidity distributions.
B-jets: Two Bs in one jet

New: Secondary vertex finder seeded with high IP tracks, jet independent

Sizable fraction of total BB cross section from collinear B-hadron pairs
Fraction of collinear BB production increases with leading jet $p_T$

Extremely important groundwork for upcoming searches with (boosted) bb final states. In particular: low-mass Higgs!
Top Cross Sections

New Analysis: Lepton+jets, b-tagged

- divide sample into distinct categories: Nr. jets, Nr. of b-tags, electrons, muons
- fit the secondary vertex mass distribution, using templates, simultaneously in all categories
- let also data/MC scale factors (JES, b-tag eff, W+j Q^2-scale) float in the fit

Result:
- top cross section, with overall 11% syst. uncert.
- scale factors consistent with 1, within the fit error

A fantastic proof of the excellent understanding of all relevant physics objects, and of their outstanding MC description.
Top Production Cross Sections

- CMS Preliminary, $\sqrt{s} = 7$ TeV
- CMS combined (prelim.)
  - TOP-11-001
- CMS dilepton (prelim.)
  - TOP-10-006
- CMS dijet (prelim.)
  - TOP-10-002
- ATLAS combined (prelim.)
  - ATLAS-COM-2011-000
- ATLAS dilepton (prelim.)
  - ATLAS-COM-2011-004
- ATLAS dijet (prelim.)
  - ATLAS-COM-2011-033
- ATLAS dijet (prelim.)
  - ATLAS-COM-2011-033

Top Pair Production Cross Section [pb]

- Top mass:
  - dilepton
  - TOP-10-006

<table>
<thead>
<tr>
<th>Method</th>
<th>Measured $m_{top}$ (in GeV/c^2)</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMWT</td>
<td>173.8 ± 4.9 (stat.) ± 4.3 (syst.)</td>
<td>0.65</td>
</tr>
<tr>
<td>KINb</td>
<td>174.8 ± 5.5 (stat.) ± 5.5 (syst.)</td>
<td>0.35</td>
</tr>
<tr>
<td>combined</td>
<td>175.5 ± 4.6 (stat.) ± 4.6 (syst.)</td>
<td></td>
</tr>
</tbody>
</table>

Syst. uncertainty dominated by:
- JES (3.1 GeV)
- b-JES (2.5 GeV)
Single Top Production

Two methods employed:
- Cut based using angular info
- BDT, based on kinematic observables

In-channel single top quark production

$\sigma = 83.0 \pm 29.6 \pm 9.1 \text{(lumi)} \text{ pb}$

An example of finding tiny signals with leptons, MET, b-tag & jets

Showing the readiness for challenging searches such as low-mass Higgs
3 pb⁻¹ results published, JHEP01(2011)080
new prelim. results for 36 pb⁻¹
Z important tool: data-driven methods for controlling lepton eff., scale, resolution, E_Tmiss (hadronic recoil).
In general excellent data-MC agreement

Amazing precision reached (~1% experimental !) 
Start to put important constraints on theory (NNLO, PDFs)
Vector Boson Production

Improvement in CMS Tau Identification Performance
due to reconstruction of individual decay modes
(vector meson resonances), based on Particle Flow
for same efficiency, fake rate reduced by factor of 3
for the Z analysis included:
mu+had, e+had, e+mu, mu+mu (~55% of total BR)
had-tau eff. constrained by ratio lept/semi-lept channels
W charge asymmetry and Polarization

W asymmetry and $W^+$ over $W^-$ ratio: Challenging PDF predictions!

$W ightarrow \nu \bar{\nu}$
$1.418 \pm 0.006_{\text{stat}} \pm 0.036_{\text{syst}}$

$W ightarrow jj$ (dijet, $p_T > 50$ GeV)
$1.423 \pm 0.006_{\text{stat}} \pm 0.036_{\text{syst}}$

$W ightarrow j$ (single jet, $p_T > 50$ GeV)
$1.421 \pm 0.007_{\text{stat}} \pm 0.033_{\text{syst}}$

$W$ (combined)
$1.421 \pm 0.006_{\text{stat}} \pm 0.033_{\text{syst}}$

First measurement of W polarization: both $W^+$ and $W^-$ preferred left-handed

$$LP = \frac{p_T(\ell) \cdot \vec{p}_T(W)}{\vec{p}_T(W)^2}$$

**Measurement**
- Lepton
- Possible polarization
- Recoil
- MET($\nu$)

$|p_T(W)| > 50$ GeV
Preparing for Searches: W+ Jets

- simultaneous extraction of W signal and top background
- 2D fit to $M_T$ and $N_{b\text{jets}}$ distributions
- final distributions: unfolded to particle level
- presented for experimental lepton and jet acceptance, e.g. $p_{T\text{jet}} > 30$ GeV

Excellent agreement with ME+PS matched Monte Carlo model.
Also tested: Berends-Giele scaling
Di-Boson Production

**WW**
- same pre-selection as for HWW search, including a jet veto
- WW cross section and WW/W ratio in agreement with SM exp.
- limits on TGC from fit to leading lepton $p_T$
  - consistent with LEP results and similar sensitivity as Tevatron

**$W_\gamma$ and $Z_\gamma$**
- cross sections measured for $E_{T\gamma} > 10$ GeV and $dR(\text{lept},\gamma) > 0.7$
- cross sections in agreement with SM predictions
- first limits on $WW_\gamma, ZZ_\gamma, Z\gamma_\gamma$ TGC at 7 TeV

**Figure:** Events / (bin width/10 GeV) vs $E_{T\gamma}$ [GeV]
- CMS 2010, 36 pb$^{-1}$
- $\sqrt{s} = 7$ TeV

Measurements of Di-Boson production established.
First limits on TGCs
Groundwork for HWW search!
Note: the luminosity uncertainty is now 4%
Searches for New Physics

Can LHC compete with the Tevatron? Yes we can!

- The LHC at $\sqrt{s} = 7$ TeV offers
  (with respect to Tevatron):
  - Higher center-of-mass energy → access to new physics scales, even with very low luminosities
  - $\sim$ 10 times more gluon-gluon initial state → top factory, more Higgs cross section, also larger QCD backgrounds
  - $\sim$ 3 times more $q\bar{q}'$ initial state → larger W/Z production in general (inclusive or associated)
Higgs
same pre-selection as for WW analysis, including a jet veto

Then: 2 analyses

- cut-based (lepton $\Delta \Phi$, lepton mom.)
- Boosted Decision Tree with 15% higher eff. for same bkgrd

**Progression of Cuts: data vs MC**

<table>
<thead>
<tr>
<th>CMS, $\sqrt{s}$ = 7 TeV, $L_{\text{int}} = 36 \text{ pb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
</tr>
</tbody>
</table>

![Graph showing the progression of cuts for data vs MC.](image)

**Limit ($\sigma_{H}\rightarrow WW/\sigma_{SM}$)**

<table>
<thead>
<tr>
<th>$\tau_{\text{SM}}$</th>
<th>$\tau_{\text{SM}}$</th>
<th>$\tau_{\text{SM}}$</th>
<th>$\tau_{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper limit, Observed</td>
<td>upper limit, Expected $= 1\times$</td>
<td>upper limit, Expected $= 2\times$</td>
<td></td>
</tr>
</tbody>
</table>

**SM-like Higgs in 4-gen model excluded for (144 < $M_H$ < 207) GeV**

<table>
<thead>
<tr>
<th>95% CL Limit for $MH=160$ GeV</th>
<th>CMS (Bayesian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td>3 x SM</td>
</tr>
<tr>
<td>Observed</td>
<td>2.1 x SM</td>
</tr>
</tbody>
</table>
Search for Higgs Decaying to TauTau

Channels used: e-mu, e-had, mu-had
improved mass reconstruction (better resolution) using likelihood, based on tau decay kinematics of visible decay products and $E_T^{miss}$

first limits on MSSM Higgs production, already improving on the Tevatron results

The hunt for MSSM Higgs(es) is open. Tau channel will play prominent role.

Beautiful analysis... Strong involvement of the UC-Davis group
These first results already triggered quite a bit of discussion eg arXiv:1103.6247 (A Djouadi et al.)

- Competitiveness & robustness
- Model parameter independence
- Usefulness for the SM Higgs search
**More Higgs Searches**

Search for charged Higgs boson in $e\tau$ and $\mu\tau$ dilepton channels of Top quark pair decays in pp collisions at $s^{1/2}=7$ TeV

Inclusive search for $\Phi^{\pm\pm}$ in leptonic final states at $\sqrt{s}=7$ TeV in 2010
Physics Beyond the Standard Model

New Gauge Bosons?  Supersymmetry  ZZ/WW resonances?  Leptoquarks?
Extra Dimensions?  Black Holes???  Long lived particles?  Compositness?

We do not know what is out there for us...
A large variety of possible signals. We have to be ready for that
Exotica
We do not know what is out there for us... A large variety of possible signals. We have to be ready for that.
Exclude a new gauge bosons up to 1.58 TeV (W’) and 1.1 TeV (Z’) @ 95% CL
This goes beyond the Tevatron limits of ~ 1.1 (W’) and 1.0 (Z’) TeV
Highest $M_T$ Candidates

- Muon event
  - $M_T = 487$ GeV candidate event

- Electron event
  - $M_T = 493$ GeV candidate event
Di-Electron Event Candidates

$M_{ee} = 419$ GeV
• Expressed in terms of couplings to up and down quarks: $c_u$, $c_d$
Searches: Leptoquarks

GUT inspired models predict new particles with lepton and quark properties
*Some excitement at HERA in '97 (M~ 200 GeV)

Search in muon or electron + jet final states
95% CL limit: 394 GeV (muon) / 384 GeV (electron)

CMS limit improves the Tevatron bounds already by about 70-80 GeV
Searches: Leptoquarks

\[ S_T = p_T^{\beta} + \text{MET} + p_T^{\beta_1} + p_T^{\beta_2} \]

1st gen LQs - ee\(jj\)+ev\(jj\) channels

\[ M_{\text{LQ}} > 340, 384 \text{ GeV for } \beta = 0.5, 1 \]
A Fourth Quark Flavor Generation?

We can’t be sure that there are only 3 generations (u,d) (s,c) (b,t). A possible new generation should be heavy!

Look for b’ and t’ quarks
This channel:  b’→ tW decays
Hence we have b’→ tW→ WWb

Utilize the W leptonic decays
Search for same sign di-lepton (+4 jets) for or tri-lepton (+2 jets) events
No events found/background of 0.32 expected from SM processes

CMS limit: M(b’) > 357 GeV 95% CL
Tevatron M(b’) > 338 (372) GeV 95% CL
Searches for Top Resonances

- Bump hunt in $M(t\bar{t})$ spectrum
- Lepton+jets channels ($e$ and $\mu$)
- No bump seen in data
- Set limits, competitive with Tevatron

[CMS Preliminary plots showing distributions and limits]
Searches with Jets

1) Di-jet mass spectrum (→ narrow resonances)
2) Di-jet angular distributions (→ contact interactions)

\[ \chi = e^{2\eta^2} = \frac{1 + \cos \theta'}{1 - \cos \theta'} \]

\[ R_\eta \equiv \frac{N_{2j}(|\eta| < 0.7)}{N_{2j}(0.7 < |\eta| < 1.3)} \]

\[ M_{\text{String}} > 2.5 \text{ TeV} \quad M_{q^*} > 1.58 \text{ TeV} \]

\[ \Lambda > 4 \text{ TeV} \quad (\text{expected } \Lambda > 2.9 \text{ TeV}) \]

\[ \Lambda > 5.6 \text{ TeV} \quad (\text{expected } \Lambda > 5 \text{ TeV}) \]
Search for Extra Dimensions

Are there extra space dimensions that open at higher energies?

Example: Experimental signature affects the di-fermion production
Study here: di- photon production

Results

| $n_{ED}$ | 1.88 | 2.29 | 1.93 | 1.74 | 1.62 | 1.53 |

New mass scale larger than 1.5-2.3 TeV depending on the number of extra Dimensions (similar in the $\mu \mu$ channel)
Tighter limits than at the Tevatron
Same analysis can be reinterpreted as search for resonances decaying into pair of photons (e.g., GKK).

Just shy of the Tevatron limits (expect to exceed in combination).

\[ M(\gamma\gamma) > 952 \text{ GeV}, \quad k/M_{\text{Pl}} = 0.1 \]

\[ M(e^+e^-\mu^+\mu^-) > 1079 \text{ GeV}, \quad k/M_{\text{Pl}} = 0.1 \]
Searches for Extra Dimensions

Mono-jet final states

- One high $p_T$ jet + large MET + no leptons
- Suppress cosmic/beam halo/instrumental backgrounds
- Data-driven estimate for $Z \rightarrow \nu \bar{\nu} +$ jets background
- Data consistent with SM, set limits on $M_D$ vs $\delta$

| $N_{DATA}$ | 275 |
| $N_{BKG}$ (data-driven) | 297 +/- 45 |
| $N_{SIGNAL}(M_D=2,\delta=2)$ | 115.2 |

$M_D$ = “True” Planck scale
$\delta$ = number of extra dimensions

CMS limits on $M_D$ (36 pb$^{-1}$)
Search for Micro-Black Holes

Extra Dimensions!

Planck scale a few TeV?

Evaporates in $10^{-27}$ sec

Look for the decay products of an evaporating black hole (lifetime $\sim 10^{-27}$ sec)

- Define $S_T$ to be the scalar sum of all high $p_T$ objects found in the event
- Look for deviations at high $S_T$

Black hole masses excluded in range 3-4.5 TeV depending on assumptions

arXiv:1012.3375
Quark Compositness ($q^* \rightarrow qZ$)

- Complementary to $q^* \rightarrow jj$ decay channel
- Search for bump/deviations in $Z$ $p_T$ spectrum
- No deviation from SM prediction, set limits

Gauge Interactions

$M_{q^*} = \Lambda, \ f = f^* = f_S = 1$

$M_{q^*} > 0.91$ TeV

Contact Interactions

$M_{q^*} = \Lambda, \ f = f^* = 1, f_S = 0$

$M_{q^*} > 1.17$ TeV

(H1 limit, 475 pb$^{-1}$, gauge int., $f_S = 0$, $M_{q^*} > 252$ GeV)
Also excited quarks in q*-> qZ channel ⇒ m_{q*} > 1.17 TeV
Lepton Jets (Hidden Valleys)

- Hidden sector contains a new low mass particle ($m_1 \sim $ few GeV)
- It decays into SM pairs (i.e. $\mu \mu$)
- Collimated groups of di-muons $[\mu \mu]$
  * opposite charge, $m_{\mu \mu} < 9$ GeV, consistent vertex
- Search for new $\mu \mu$ resonances in various event topologies: $[\mu \mu]$, $[\mu \mu][\mu \mu]$, etc.

Simulation 1 (CMS)

- No new $\mu \mu$ resonance seen
- Set model independent upper limits on $\sigma \times BR \times \alpha$ ($\sim 0.1 - 0.5$ pb)
- Verified sensitivity in various benchmark models (ex. NMSSM Higgs, MSSM + $\gamma_{\text{DARK}}$)

CMS Preliminary 2010 - $\sqrt{s}$ = 7 TeV, $l = 35$ pb$^{-1}$
Long Lived Particles in Supersymmetry

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

Gravitino Dark Matter and GMSB
- In some models/phase space the gravitino is the LSP
- $\Rightarrow$ NLSP (neutralino, stau lepton) can live ‘long’
- $\Rightarrow$ non-pointing photons

$\Rightarrow$ Challenge to the experiments!

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

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

- Basic idea: R-hadrons can lose enough energy in the detector to stop somewhere inside (usually calorimeters)
- Sooner or later they must decay
- Trigger: \((\text{jet}) \&\& !\text{(beam)}\)
- Only possible backgrounds: cosmics and noise
  - Being already studied with CRAFT data

Eg when there is no beam!
Searches: Stopped Gluinos

Search for Heavy Stable Charged Particles that stop in the detectors and decay a long time afterwards (nsec, sec, hrs...)

Gluino masses are excluded:
- Time profile analysis (10 µs) exclude $m_{\tilde{g}} < 382$ GeV
- Counting experiment (10 µs - 1000s) exclude $m_{\tilde{g}} < 370$ GeV

Heavy Stable Charged Particles

Stable particles that traverse the detector

Eg heavy stable gluino (R-hadron) or stop/stau

First search limits using tracker $\text{d}E/\text{d}x$ and muon identification

Result for $3.1 \text{ pb}^{-1}$

0 events after cuts

95% CL limits on production cross sections of a few 100 pb in the 300-400 GeV mass range

Eg. Gluinos $> 398$ GeV
Reach Overview

Summary of mass limits

- Z' SSM II
- Z'ψ II
- GKK II k/M = 0.1
- W' IV
- GKK γγ k/M = 0.1
- Ms, γγ, GRW
- Ms, μμ, GRW
- MD, monojet, nED = 2
- LQ1, β=0.5
- LQ1, β=1.0
- LQ2, β=0.5
- Me* with Λ = 2 TeV
- Mu* with Λ = 2 TeV
- Mq*, boosted Z
- Mq*, jj mass (3 pb^{-1})
- b' → tW
- gluino mass (3 pb^{-1})
- stopped gluino mass

As broad a spectrum as possible:
- new heavy resonances,
- leptoquarks, excited fermions,
- composition, extra dimensions,
- hidden valleys...

Big effort into development of data-driven background estimations:
- sharp tools established

- 29 searches with 2010 data!
- most of them published or submitted for publication;
- with few exceptions, all of them provide world's best limits so far

CMS is well prepared for new data
Supersymmetry
Supersymmetry: a new symmetry of Nature?

Candidate particles for Dark Matter ⇒ Produce Dark Matter in the lab

SUSY particle production at the LHC

+ Z b-jets
+ 4 jets
**Searches for SUSY**

<table>
<thead>
<tr>
<th>0-leptons</th>
<th>1-lepton</th>
<th>OSDL</th>
<th>SSDL</th>
<th>≥3 leptons</th>
<th>2-photons</th>
<th>γ+lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets + MET</td>
<td>Single lepton + Jets + MET</td>
<td>Opposite-sign dilepton + jets + MET</td>
<td>Same-sign di-lepton + jets + MET</td>
<td>Multi-lepton</td>
<td>Di-photon + jet + MET</td>
<td>Photon + lepton + MET</td>
</tr>
</tbody>
</table>

*Large* → *SM backgrounds* → *Low*

Sensitivity to strongly produced SUSY

Sensitivity to gauge-mediated SUSY

- **Focus on signatures (topologies), use different approaches/observables**
  - \(\alpha_T\), "Razor", HT, MHT, ...

- Established many different **data-driven techniques** to derive backgrounds
  - jet smearing and re-balancing, ABCD, fakeable-object technique to estimate fake lepton rates, generic properties of lepton \(p_T\) spectra, generic properties of falling SM spectra

- Different trigger paths (all hadronic HT-based, leptonic)

- Not necessarily optimized for best excl. limits, but sharpened tools for discovery!

- cross check, cross check, cross check....

---

70
Search for SUSY

All Hadronic Channel: Jets + Missing Transverse Energy

\[ \alpha_T = \frac{E_{T_{j2}}}{M_{T_{j1,j2}}} = \frac{\sqrt{E_{T_{j2}} / E_{T_{j1}}}}{\sqrt{2(1 - \cos \Delta \varphi)}} \]

Control QCD with the \( \alpha_T \) variable
No QCD expected for \( \alpha_T > 0.5 \)

Control EWK backgrounds from data itself using
\( W \rightarrow \mu \nu, \gamma + \text{jet} \) and other control samples

arXiv:1101.1628
-All 2010 data included: ~10-12 Events expected/ 13 observed

No discovery of supersymmetry yet… Stronger exclusion limits

Masses of squarks/gluinos > ~600 GeV!!! (in the CMSSM)

$m_0$ and $m_{1/2}$ are universal scalar and gaugino masses at the GUT scale
Where do we expect SUSY?

O. Buchmuller et al
arXiv:0808.4128

Precision measurements
Heavy flavour observables

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

Many other groups attempt to make similar predictions
Add the new CMS/ATLAS results to the constraints.
## Changes in for the « Best Point »

<table>
<thead>
<tr>
<th>Model</th>
<th>Minimum $\chi^2$</th>
<th>Probability</th>
<th>$m_{1/2}$ (GeV)</th>
<th>$m_0$ (GeV)</th>
<th>$A_0$ (GeV)</th>
<th>$\tan \beta$</th>
<th>$M_h$ (no LEP) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMSSM with CMS</td>
<td>22.0</td>
<td>29%</td>
<td>370</td>
<td>80</td>
<td>-340</td>
<td>14</td>
<td>112.6</td>
</tr>
<tr>
<td>CMSSM with ATLAS</td>
<td>24.9</td>
<td>16%</td>
<td>400</td>
<td>100</td>
<td>-430</td>
<td>16</td>
<td>112.8</td>
</tr>
<tr>
<td>NUHM1 with CMS</td>
<td>(19.3)</td>
<td>31%</td>
<td>(260)</td>
<td>(110)</td>
<td>(1010)</td>
<td>(8)</td>
<td>(121.9)</td>
</tr>
<tr>
<td>NUHM1 with ATLAS</td>
<td>20.9</td>
<td>28%</td>
<td>380</td>
<td>90</td>
<td>70</td>
<td>14</td>
<td>113.5</td>
</tr>
<tr>
<td>NUHM1 with ATLAS</td>
<td>23.3</td>
<td>18%</td>
<td>490</td>
<td>110</td>
<td>-630</td>
<td>25</td>
<td>116.5</td>
</tr>
<tr>
<td>VCMSSM with CMS</td>
<td>(22.5)</td>
<td>(31%)</td>
<td>(300)</td>
<td>(60)</td>
<td>(30)</td>
<td>(9)</td>
<td>(109.3)</td>
</tr>
<tr>
<td>VCMSSM with ATLAS</td>
<td>23.8</td>
<td>25%</td>
<td>340</td>
<td>70</td>
<td>50</td>
<td>9</td>
<td>115.5</td>
</tr>
<tr>
<td>VCMSSM with ATLAS</td>
<td>27.1</td>
<td>13%</td>
<td>390</td>
<td>90</td>
<td>70</td>
<td>11</td>
<td>117.0</td>
</tr>
<tr>
<td>mSUGRA with CMS</td>
<td>(29.4)</td>
<td>(6.1%)</td>
<td>(550)</td>
<td>(230)</td>
<td>(430)</td>
<td>(28)</td>
<td>(107.8)</td>
</tr>
<tr>
<td>mSUGRA with ATLAS</td>
<td>29.4</td>
<td>6.1%</td>
<td>550</td>
<td>230</td>
<td>430</td>
<td>28</td>
<td>121.2</td>
</tr>
<tr>
<td>mSUGRA with ATLAS</td>
<td>30.9</td>
<td>5.7%</td>
<td>550</td>
<td>230</td>
<td>430</td>
<td>28</td>
<td>121.2</td>
</tr>
</tbody>
</table>
Search using B-jets + MET

- Extension of the $\alpha_T$ analysis to b-jets
- Improved sensitivity at large $\tan\beta$ and $m_0$ ($\tan\beta > 50$)

[Graphs showing efficiency and mass distributions]
SUSY: OS Di-Leptons + jets + MET

- Two opposite-sign leptons (e^+e^−, μ^+μ^−, e^±μ^±)
- Dominant background: top-pair production
- Estimated via matrix method: 1.4 ± 0.8 events predicted, 1 observed
SUSY: SS Di-Leptons + jets + MET

- Two same-sign leptons ($e^+e^-, \mu^+\mu^-, e^+\mu^-, e^+\tau^-, \mu^+\tau^-, \tau^+\tau^-$)
- Dominant background: misidentified leptons
- Similar sensitivity as in the OS channel for small $\tan\beta$
- Tau channels are not yet included in the limit; will be for large $\tan\beta$

![Graph showing CMS Preliminary results with $\sqrt{s} = 7$ TeV and $L = 35$ pb$^{-1}$]
SUSY: Multiple leptons

- Chargino mass > 170 GeV/c² for this particular value of m₀, tanβ
- Gluino mass > 690 for m₀ = 100 GeV/c²
GMSB SUSY Searches

Gauge Mediated SUSY breaking: LSP is the Gravitino

Phenomenology depends on NLSP
  - if neutralino, decays into gravitino and $\gamma$, $Z^0$, or $h^0$
    (depending on neutralino mixing)

Here analyse collisions with:
  two hard photons (30 GeV), missing transverse momentum and jets

For equal squark and gluino masses the limits are 740, 800 GeV, and 780 GeV
Summary of Search Channels

Channels with
- Jets only
- Single leptons
- Di-leptons
- Photons

In this model the squarks/gluinos get excluded for masses below 600-700 GeV.
Results as Simplified Models

Models proposed at: http://www.lhcnwnewphysics.org

- CMS Preliminary $\sqrt{s} = 7$ TeV $L = 36$ pb$^{-1}$
- $A \to 4\text{jets} + \text{LSPs}$
- High $H_t$ selection

Example:
Efficiency plot for MHT-based all-hadronic analysis

- CMS Preliminary $L_{int} = 35$ pb$^{-1}$ $\sqrt{s} = 7$ TeV

- $\rho_{\text{prod}} = 3\text{LO-QCD}$
- $\rho_{\text{prod}} = 3\text{LO-QCD}$
- $\rho_{\text{prod}} = 3\text{LO-QCD}$

Hadronic Searches
Most sensitive analysis per point

- Jets + $H_t$ miss
- Razor

Shows complementarity of hadronic analyses.
CMS will provide these results electronically.
Feedback is welcome.
The fine-tuning price of the early LHC
Alessandro Strumia

LHC already probed and excluded half of the parameter space of the Constrained Minimal Supersymmetric Standard Model allowed by previous experiments. Only about 0.7% of the CMSSM parameter space survives. This fraction rises to about 2% if the bound on the Higgs mass can be circumvented.

A slight wave of panic???
Panic for a 500GeV Linear Collider?

H. Weerts
ALCPG Meeting
Summary talk
last March
Panic for a 500GeV Linear Collider?

Expectation: If no signal @ 7 TeV w/ >1 fb⁻¹, then LC500 is not a good place to study mSUGRA/CMSSM

But there are other of course SUSY scenarios.
New proposal for a CMS postcard:
Total $H_T = 1132$ GeV  Missing $H_T = 693$ GeV
Be prepared for discoveries...
The Future: 2011-2012 Run

- The Machine is back for the 2011 run since March 13
- Run both years 2011 and 2012
  - Higher energy in 2012?
  - Long shutdown after 2012 run
- Minimal promised scenario: 7 TeV and 1 fb$^{-1}$ of data by end of 2011, but:
  - Very likely to get more
    - More bunches (up to 900/1400?)
    - Beta* (squeeze) from 3.5 m to 1.5 m already operational
- $\Rightarrow$ A few fb$^{-1}$, perhaps 5 fb$^{-1}$/exp not excluded!

GOOD NEWS FOR HIGGS HUNTERS

But: no higher beam energy in 2011.
2011: Project Higgs!

New studies including more Higgs decay channels and for several machine scenarios

The hunt for the elusive Higgs boson has definitely started in 2011 at the LHC!!
Summary: It’s been a Great Year

• CMS is very well advanced with the detector commissioning and calibration
• Physics papers being completed on the 2010 7 TeV collisions. Lots of results on QCD, EWK, B-physics, and the top. Many searches for new physics have been made, and most go already beyond the reach of the Tevatron.
• Search papers are now published on full 2010 statistics. No sign of new physics yet - but still looking…
• CMS is ready for the ‘real game’ ie searches for new physics, and for the Higgs…. Possibly already in 2011
• The LHC is doing its part with a great start-up!!!