Recent Results From the LHC

Christian Sander (Universität Hamburg)

SFB Block Meeting – Hamburg – 24th February 2011
Outline

Introduction
Performance of Detectors
Rediscovery of the Standard Model
Beyond the Standard Model
Summary
Outline

Introduction
Performance of Detectors
Rediscovery of the Standard Model
Beyond the Standard Model
Summary
• SM well established except for missing Higgs boson

• New physics expected at TeV scale

• **SM processes:** many orders of magnitude larger cross sections than typical Higgs/BSM cross sections

→ **Searches for Higgs/BSM signatures require a precise understanding of SM processes**
2009: Data taking at $\sqrt{s}=900$ GeV and 2.36 TeV
Since 30th March 10: $\sqrt{s}=7$ TeV
Peak Luminosity: $1.3 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
Plan for 2011: $6.4 \times 10^{32}$ ... $2.2 \times 10^{33}$
Delivered int. Lumi at CMS: 47/pb
Plan for 2011: 2.2/fb ... 7.6/fb
Design: $10^{34}$

+ ~3 weeks of Heavy Ion
(PbPb at $\sqrt{s}=2.76$ TeV/n; int. Lumi ~7/µb)
Data Taking
Outline

Introduction
Performance of Detectors
Rediscovery of the Standard Model
Beyond the Standard Model
Summary
Measurement of strange particle mass resonances:

- **Λ baryon candidate**: Two tracks of opposite charge; assign lower $p_T$ to $m_\pi$; secondary vertex

- **Ξ baryon candidate**: Λ candidate combined with 3rd negative secondary track; SV of Ξ separated from PV; points back to PV

Mass accuracy at the level $10^{-4} \rightarrow$ Very well aligned Si-strip and pixel tracker
Muons

Event display of a $\mu$ candidate: hits in the muon system matched to track

$$p_T = 7.4 \text{ GeV/c}$$

Full invariant mass spectrum of opposite charge muon pairs:

CMS Preliminary

$$\sqrt{s} = 7 \text{ TeV, } L_{\text{int}} = 40 \text{ pb}^{-1}$$
Jet Calibration – Relative Response

- Use diJet balance $B$ from central (barrel) jet and probe jet

$$B = \frac{p_T^{\text{probe}} - p_T^{\text{barrel}}}{p_T^{\text{diJet}}}$$

- Least biased estimator $R$ of relative response $\langle p_T^{\text{probe}} \rangle / \langle p_T^{\text{barrel}} \rangle$

$$R(\eta^{\text{probe}}, p_T^{\text{diJet}}) = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$

- Falling spectrum & finite jet resolution
  → migration to higher $p_T$ bins
  → measured response is systematically biased to higher values
  → binning in diJet $p_T$ minimizes bias

- Residual corrections for MC vs. data difference needed

CMS PAS JME-10/003
Jet Calibration – Absolute Response

Use $\gamma$+jet events for absolute jet energy response; two approaches:

- Transverse momentum balance
- Missing $E_T$ projection fraction (MPF):
  - Only small dependence on jet algorithm
  - Calibration of total recoil → less dependence on further jet activity
- Dominant uncertainties:
  - flavor difference
  - parton corrections
  - QCD bg
  - proton fragments
  - 2nd jet extrapolation

CMS PAS JME-10/010

CMS preliminary, 2.9 pb$^{-1}$ $\sqrt{s} = 7$ TeV

Data / MC

$\gamma > 30$ GeV

$\text{p}_{T}^{\gamma}$ $\text{p}_{T}^{\text{balance}}$

anti-kT 0.5 PF

$\text{p}_{T}^{2\text{nd}} / \text{p}_{T}^{\gamma}$

CMS PAS JME-10/010
• **Missing transverse momentum** is defined as vectorial momentum imbalance in the transverse plain (with magnitude MET)

• Three major algorithms to reconstruct MET at CMS

  - **Calo MET**: based on calorimeter energy deposits
  - **Track corrected MET**: Replacing calorimeter deposits from charged hadrons by matched tracks
  - **Particle Flow MET**: identify stable particles using all subdetectors prior to MET calculation (or jet clustering)

→ Careful noise cleaning of MET tails needed
MET corrections:

- **Type I**: Replace calorimeter deposits clustered in jets by corrected jets; for diJets: introduces bias of \( \text{MET} \parallel \) to jet bisector axis.

- **Type II**: Additional correction from unclustered energy or jets below threshold; determined from MC or from data (e.g. \( Z \rightarrow ll \)).
MET from all PF candidates shows superior resolution with respect to calorimeter MET

CMS PAS JME-10/004 & JME-10/005
Measurement of $W/\ Z$ cross sections important for:

- Calibration of detectors
- Backgrounds for Top/Higgs/BSM analyses
- Precision measurements of SM parameters
Cross section measurements

- Dileptonic channel (CMS)
  \[ \sigma(pp \to t\bar{t} + X) = 194 \pm 72 \text{(stat)} \pm 24 \text{(syst)} \pm 21 \text{(lumi)} \text{ pb} \]

- Semileptonic channel (ATLAS)
  \[ \sigma(pp \to t\bar{t} + X) = 145 \pm 31 \text{(stat)}^{+42}_{-27} \text{(syst)} \text{ pb} \]

- Compared to theory [Langenfeld, Moch, Uwer 09]
  \[ \sigma(pp \to t\bar{t} + X) = 164.6^{+11.4}_{-15.7} \text{ pb} \]
The Ridge

- Angular correlation in pp events at 7 TeV with high track multiplicity
  - $1 \text{ GeV} < \text{track } p_T < 3 \text{ GeV}$
  - $N_{\text{tracks}} > 110$
- Ratio $R$ of signal (same event pairs) and bg (different event pairs)
- Jet peak and back-to-back structure visible

→ Structure at near side long range reassembles Bose-Einstein correlation observed in AuAu collisions at RHIC

JHEP 1009:091 (2010)
Heavy Ions – “Jet Quenching”

- New diJet asymmetry observed (increasing with centrality)
- Not observed in pp collisions

- Possible interpretation:
  
  **Strong jet energy loss in hot dense medium**

CERN-PH-EP-2010-062
**WW / WZ / ZZ or Higgs Physics?**

Integrated Luminosity still small for cross section measurements

However, some exciting candidates!

**Muons (p_T [GeV], η, φ [rad])**

\[
\begin{align*}
\mu_0^- &: (48.1422, -0.412532, -1.92555) \\
\mu_1^+ &: (43.4421, 0.204654, 1.79493) \\
\mu_2^+ &: (25.8769, -0.782084, 0.774588) \\
\mu_3^- &: (19.5646, 2.01112, -0.980597)
\end{align*}
\]

**Invariant Masses**

\[
\begin{align*}
\mu_0 + \mu_1 &: 92.15 \text{ GeV (total } Z \text{ } p_T 26.5 \text{ GeV, } \phi -3.03), \\
\mu_2 + \mu_3 &: 92.24 \text{ GeV (total } Z \text{ } p_T 29.4 \text{ GeV, } \phi +0.6), \\
\mu_0 + \mu_2 &: 70.12 \text{ GeV (total } p_T 27 \text{ GeV),} \\
\mu_3 + \mu_1 &: 83.1 \text{ GeV (total } p_T 26.1 \text{ GeV).}
\end{align*}
\]

**Invariant Mass of 4µ: 201 GeV**

SM expectation im 7/pb: 0.044(3) events
\[
\text{prob}(N \geq 1) \approx 4.2\%
\]

\[pp \rightarrow 4\mu + X\]
Outline

Introduction
Performance of Detectors
Rediscovery of the Standard Model
Beyond the Standard Model
Summary
Many extensions of the SM predict heavy particles coupling to quarks or gluons →
Resonances in diJet invariant mass spectrum

LHC provides better limits than Tevatron with a few pb$^{-1}$
Contact Interactions

- $\chi = \exp (|y_1 - y_2|)$ flat for Rutherford scattering $dN/d\cos \theta \propto 1/\sin^4(\theta/2)$; new physics expected at small $\chi$

- **Centrality ratio $R_c$** of events with both leading jets in central ($|\eta| < 0.7$) and non-central region ($0.7 < |\eta| < 1.3$); new physics expected to produce diJets more central than QCD

→ No significant deviation from QCD prediction

Best fit for $R_c$: $\Lambda = 2.9$ TeV (no trend seen at CMS)
W' Searches

- Extra heavy gauge bosons predicted by left-right symmetric models or supersymmetric Grand Unified Theories

- **Signature**: lepton (here: $e$) and similar MET $0.4 < \frac{E_T^{\text{electron}}}{\text{MET}} < 1.5$ in opposite direction ($\Delta \phi > 2.5$)

→ Better limits on $M_{W'}$ than Tevatron experiments
Leptoquarks

- LQ carry lepton and baryon numbers
- Fractionally charged
- Typically constrained to one lepton/quark generation
- LHC: dominant pair production via $gg$ fusion or $qq$ annihilation

**Signature:** 2 OSSF leptons + 2 jets with high $M_{\mu\mu}$ and $S_T$ ($p_T$ sum of two leading jets and muons)
Leptoquarks

No excess of events observed

→ **Exclusion limits on** $\beta^2 \times \sigma$ ($\beta$: branching ratio of LQ in corresponding lepton, e.g. second generation LQ $\rightarrow q\mu$)

(similar limits for first generation LQ)
Heavy Ionizing Particles

- Search for heavy particles with large electromagnetic charge ($q \gg e$) like Q-balls, magnetic monopoles, micro BH remnants, dyons ...

- **Signature:**
  - Large fraction of high $dE/dx$ hits in tracker $f_{HT}$
  - Small clusters in Ecal layers $w_1 / w_2$

- **Data driven background estimation:**
  - Assume no correlation of $f_{HT}$, $w_1$ and $w_2$
  - Bg dominated: $!f&!w$, $f&!w$ and $!f&w$ → probabilities for bg to pass $f$ or $w$

  $$p_f = \frac{N_{f&!w}}{N_{!w}}, \ (f \leftrightarrow w)$$

  - Estimate: $N_{f&w} = N_{tot} \cdot p_f \cdot p_w$

arXiv:1102.0459v2 [hep-ex]

95% CL XS limit:

| $m$ [GeV] | $|q| = 6e$ | $|q| = 10e$ | $|q| = 17e$ |
|-----------|-----------|-----------|-----------|
| 200       | 1.4       | 1.2       | 2.1       |
| 500       | 1.2       | 1.2       | 1.6       |
| 1000      | 2.2       | 1.2       | 1.5       |

95% CL XS limit (pair production):

| $m$ [GeV] | $|q| = 6e$ | $|q| = 10e$ | $|q| = 17e$ |
|-----------|-----------|-----------|-----------|
| 200       | 11.5      | 5.9       | 9.1       |
| 500       | 7.2       | 4.3       | 5.3       |
| 1000      | 9.3       | 3.4       | 4.3       |
**Heavy Charged Stable Particles**

- (Meta-) stable gluinos or squarks can from neutral bound states ($R$-hadrons) → not visible in muon detectors

- Search based on high $dE/dx$ tracker hits: most probable value of $dE/dx$ estimated by harmonic mean

$$I_h = \left( \frac{1}{N} \sum_i (dE/dx)_i^k \right)^{1/k} \text{ with } k = -2$$

- Relation between $I_h$, mass $m$ and momentum $p$

$$I_h = K \cdot \frac{m^2}{p^2} + C$$

with empirical constants $K$ and $C$ from low energy proton data

**No excess → limits**

[Graphs showing data and theoretical predictions for gluinos and stops at CMS √s = 7 TeV with 3.06 pb⁻¹]

CMS PAS EXO-10-011
Stopped Gluinos

- Probability for $R$-hadron to stop in Hcal: 1% … 20% (model dependent)

  → decay: $\tilde{g} \rightarrow \tilde{\chi}_0 + g$

- Signature: “jets” in triggerable beam gaps

- Backgrounds: beam halo, cosmics, and HCAL noise

- No significant excess → limits on $\sigma \times \text{Br}$ as function of lifetime $\tau$ of gluino

Example: fill with 140 bunches

CMS PAS EXO-10-003
Leptonic SUSY Search

- Cascades with sleptons → more than one lepton, e.g. \( \tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\ell\tilde{\chi}_1^0 \)
- SUSY cascades with charginos → single leptons, e.g. \( \tilde{q} \rightarrow q\tilde{\chi}_1^\pm \rightarrow q\ell\nu\tilde{\chi}_1^0 \)

- **Signature:**
  - exactly one isolated lepton
  - \( \geq 3 \) jets
  - MET > 125 GeV
  - \( M_T(\text{lepton}+\text{MET}) > 115 \) GeV
  - \( M_{\text{eff}}(\text{lepton} + 3 \text{ jets} + \text{MET}) > 500 \) GeV

- QCD background from data; other bgs scaled MC simulation (control regions)

- **Observed:** 2 events
- **Expected:** \( \sim 4 \) events

\[ \text{arXiv:1102.2357v2 [hep-ex]} \]
Hadronic SUSY Search with $\alpha_T$

\[ \alpha_T = \frac{E_{T}^{2nd}}{M_T} = \frac{E_{T}^{2nd}}{\sqrt{2p_T^{1st}p_T^{2nd}(1 - \cos \phi_{12})}} \]

- Perfectly measured diJet events $\alpha_T = 0.5$
- Mismeasurements of $p_T$: $\alpha_T < 0.5$
- **Selection**: 3rd jet $p_T < 50$ GeV & $\alpha_T > 0.55$
- $\alpha_T > 0.5$
  - QCD: jets below threshold
  - Events with genuine MET (Top, $W$, $Z$)
- Possible extension on $N_{\text{jet}} > 2$ by forming two pseudo jets

→ Already with small statistics the LHC experiments are probing new regions of the SUSY parameter space

CMS PAS SUS-10/003
Black Holes

- Models with large flat extra spatial dimensions (e.g. ADD models): Black hole production at the LHC ($\sigma = \pi \cdot R_s^2$)
- Hawking radiation: democratic evaporation (dominantly: quarks and gluons)
- **Signature**: High multiplicity of objects ($p_T > 50$ GeV), high $S_T = \Sigma_i p_{T,i}$
- **Dominant Bg**: QCD; $S_T$ shape independent on object multiplicity

CMS PAS EXO-10-017
No excess at large $S_T$ observed → **Limits:**

- **Model dependent limits** on minimal BH mass $\sim 3.5$ and $\sim 4.5$ TeV
- **Model independent limits** on cross section for New Physics from counting experiments with $S > S_T^{\text{min}}$
Outline

Introduction
Performance of Detectors
Rediscovery of the Standard Model
Beyond the Standard Model
Summary
Summary

- LHC physics program has started successfully
- All **detectors commissioned** and operating with high efficiencies
- The **Standard Model has been rediscovered** → 2011/12 data set will allow precision measurements and has potential to discover (or exclude) the SM Higgs boson over allowed mass region
- Due to higher center of mass energy (compared to Tevatron) the LHC experiments are **exploring new parameter regions of BSM models with the first pb⁻¹**

Very exciting times ahead of us …
Backup
CMS Detector

**Silicon Tracker**
- Pixels: $100 \times 150 \mu m^2$
  - Density: $1 m^2 \approx 66M$ channels
- Microstrips: $80-180 \mu m$
  - Density: $200 m^2 \approx 9.6M$ channels

**Crystal Electromagnetic Calorimeter (ECAL)**
- 76k scintillating PbWO$_4$ crystals

**Preshower**
- Silicon strips
  - Density: $16 m^2 \approx 137k$ channels

**Steel Return Yoke**
- Total weight: 13,000 tonnes

**Superconducting Solenoid**
- Niobium-titanium coil
  - Carrying: $18,000 A$

**Hadron Calorimeter (HCAL)**
- Brass + plastic scintillator
  - Density: $7k$ channels

**Forward Calorimeter**
- Steel + quartz fibres
  - Density: $2k$ channels

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

**Technical Details**
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T
CMS Calorimeter

- **ECal**: Lead-Tungstate PbWo$_4$ crystals
  - Coverage: $|\eta| < 3$
  - High granularity $\Delta \eta \times \Delta \phi = 0.0175 \times 0.0175$ (~80k crystals)
  - $\sim 26 \chi_0$

- **HCal**: Copper (brass) / scintillator sampling calorimeter
  - Coverage: $|\eta| < 5$
  - Granularity (barrel) $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$ (~4k cells)
  - $\sim 7-11 \chi$ (+ 4 $\chi$ from HO in barrel)

- **Calorimeter towers**:
  - One HCal cell and 5$\times$5 crystals
  - Tower thresholds between 0.5 GeV and 0.85 GeV
  - 82 towers in $\eta$ and 72/36/18 towers in $\phi$
- Granularity decreases with increasing $|\eta|$.
- Coverage up to $|\eta| < 5$.
- Most parts inside of magnet except OuterBarell (OB)

from CMS Physics TDR Vol. II
Jet Algorithms

- Jet algorithm should provide good correspondence (multiplicity, position, energy) between
  \[\text{calorimeter jet} \leftrightarrow \text{particle jet / parton}\]

- Jet algorithms should be:
  \[\text{collinear safe, infrared safe, fast ...}\]

- Challenges:
  - Thresholds and zero suppression
  - Noise, pileup, and underlying event
  - Response calibration
  - Out-of-cone showering
Sequential Clustering Algorithms

- For each input object $i$ calculate the "distance to the beam line"
  \[ d_{iB} = p_{T,i}^{2p} \]
- and the "distance" to the other particles $j$
  \[ d_{ij} = \min \left( p_{T,i}^{2p}, p_{T,j}^{2p} \right) \cdot \frac{\Delta R_{i,j}^2}{D^2} \]
  \[ \Delta \phi^2 + \Delta \eta^2 \]
- Find for each $i$ smallest $d_{ij}$
- If $d_{iB} < d_{ij}$ move object $i$ to the list of final jets, else merge $i$ and $j$
- Infrared and collinear safe for $p = -1, 0, +1$
  - $p = +1$ (\(k_T\) algorithm): no fixed cone
  - $p = 0$ (Cambridge-Aachen algorithm): no fixed cone, well suited for subjet structure studies
  - $p = -1$ (anti-\(k_T\) algorithm): almost fixed cone
Jet Calibration

- **Factorization by residual corrections** facilitates use of data driven corrections
  - **L1**: Pile-up and noise measured in zero-bias events
  - **L2**: Jet response vs. $\eta$ relative to barrel using diJet balance
  - **L3**: Jet response vs. $p_T$ found in barrel using $\gamma/Z + \text{jets, top etc.}$

- **With current statistics**: Usage of MC truth with residual corrections from data/MC comparison
- Allows data-driven corrections as they emerge to easily replace MC truth
MC Truth Calibration

Match genJets to reconstructed jets, with \( \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.25 \)

1. Mean of response distribution: \( R(p_T^{true}) = \langle p_T^{reco} / p_T^{true} \rangle \)
   → Fit analytic function

2. Mapping of recoJet \( p_T \) to genJet \( p_T \): \( p_T^{true} \leftrightarrow \langle p_T^{reco} \rangle \)

3. Inversion: \( C(p_T^{reco}) = 1/R(p_T^{true}(p_T^{reco})) \) → \( p_T^{reco,corr} = p_T^{reco} \cdot C(p_T^{reco}) \)
   → Fit analytic function
Identification of all stable particles (electrons, photons, muons, charged and neutral hadrons) **by combination of all subdetectors** prior to jet clustering.
**J/ψ Production**

- **J/ψ reconstruction in µ and e channel**
- Total cross section for inclusive production in µ channel:

  \[ \text{Br}(J/\psi \to \mu^+\mu^-) \cdot \sigma(pp \to J/\psi + X) = (289.1 \pm 16.7\text{(stat)} \pm 60.1\text{(syst)}) \text{ nb} \]

- Unbinned ML fit to transverse decay length to **disentangle prompt** (direct or decay from heavier charmonium states) **and secondary production** (B hadron decays)

- Cross section for non-prompt production in µ channel:

  \[ \text{Br}(J/\psi \to \mu^+\mu^-) \cdot \sigma(pp \to Y \to J/\psi) = (56.1 \pm 5.5\text{(stat)} \pm 7.2\text{(syst)}) \text{ nb} \]

CMS PAS QCD-10/002
Onia – $\Upsilon$ Production

- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ identified and resolved
- Differential cross section measured and compared with theoretical predictions

→ Uncertainties large, but some tension between experimental measurement and different models

![LHCb Preliminary](image)

<table>
<thead>
<tr>
<th>$\sqrt{s} = 7$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int L \sim 4 \text{ pb}^{-1}$</td>
</tr>
</tbody>
</table>
| \begin{align*}
\text{mean (1S)} &= 9455.9 \pm 1.2 \text{ MeV/c}^2 \\
\sigma (1S) &= (46.8 \pm 1.2) \text{ MeV/c}^2 \\
N_{\text{signal}} (1S) &= 3159 \pm 78 \\
N_{\text{signal}} (2S) &= 789 \pm 48 \\
N_{\text{signal}} (3S) &= 405 \pm 39
\end{align*} |

CMS PAS BPH-10-003