First Results from CMS

XXXVIII SLAC Summer Institute
“Neutrinos”
August 2nd, 2010
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The CMS collaboration:
3170 scientists and engineers (including 800 students) from 169 institutes and 39 countries
CMS Detector

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

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- ~76k scintillating PbWO₄ crystals

**PRESHOWER**
- 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
7 TeV operations since March 30th

346 nb\(^{-1}\) delivered by LHC
303 nb\(^{-1}\) collected by CMS (88% efficient)
  – Most of the data taken in 2 last weeks
  – Fast turnaround: 254 nb\(^{-1}\) validated for analysis
LHC operations: the future

Short term: at least 1 fb\(^{-1}\) delivered by end of 2011
- We have 0.03\% so far
- Must reach \(1 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}\) this year

Longer Term: 3000 fb\(^{-1}\) collected by end of LHC life
- Must reach peak \(1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}\) during 2021-2030

From S. Meyers, ICHEP
Expected cross sections at 7 TeV

\[ \sqrt{s} = 2 \quad 7 \quad 14 \text{ TeV} \]

\[ \sigma(pp \to X) \quad [\text{mb}] \]

\[ \sigma(\text{jets}) \quad p_T > 0.01 E_{cm} \quad y_j < 2 \]

\[ \sigma(b \bar{b}) \quad p_T > 30 \text{ GeV} \]

\[ W^\pm \to l\nu \]

\[ t\bar{t} \]

\[ W^+ W^- \]

\[ gg \to h \]

\[ VV \to h \quad (120 \text{ GeV}) \]
Outline of the talk

1. The basic objects, and CMS reconstruction performance with the early data
   • Tracks, Jets, b-tags
   • Missing energy “$\text{MET}$”
   • Muons, electrons and photons

2. Standard Candles and Early Physics results
   • Jet production
   • Early searches
   • $\psi$, Y, W, Z
   • Top quarks

3. Outlook
   • Higgs
   • New Physics (NP): SUSY,..
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Tracks

- Central region of detector (r=2.4-110cm) instrumented with silicon strip and silicon pixel detectors for 3D tracking of charged particles
  - Coverage: pseudo-rapidity $|\eta|=0$ to 2.5

Side view of tracker quadrant:

Cosmic muon:
Jet reconstruction

Quarks and gluons initiate jet production, detected through had/em showers.

4 jet reconstruction algorithms:

1. Calorimeter only
2. Calorimeter, corrected using associated track measurements
3. Particle flow: reconstruct all particles using all sub-detectors prior to jet clustering
4. Track jets (independent)
Jet Energy Calibration

Calorimeter response is non-linear and non-uniform, so observed energy needs to be corrected:
- depending on algorithm, jet $p_T$ and $\eta$..: correction up to factor 2!
- Correction done using MC so far, but checked in data, e.g. with energy balance in $\gamma$+jet events

MC/data agree within ~5-10% (=systematic uncertainty for jet energy measurement)
B tagging of jets

- Identify jets originating from b quark by long lifetime of B hadrons
  - causes a decay vertex clearly separated from the interaction point
- Example algorithms:
  - Reconstruct secondary vertices based on track impact parameter
  - Select jets with leptons from semileptonic decay of B

*Discovered at SLAC/PEP!*
B tagging: 3D impact parameter

Measure the 3D impact parameter of tracks within jets:
- Large impact parameter value: track points to secondary vertex
- Need excellent alignment and general tracking performance

For tracks with $p_T > 1$ GeV belonging to central jets with $p_T > 40$ GeV:

![Graph showing 3D impact parameter distribution](image)
**Missing Transverse Energy ME$_T$**

- **Missing transverse momentum** is defined as the apparent imbalance of the component of the momentum in the plane perpendicular to the beam direction
  - Note: we only have handle in transverse direction since “boost” of initial quark/gluon is unknown

- magnitude is referred to as **missing transverse energy ME$_T$**

- Allows for (indirect) detection of neutrinos, WIMPS,.. which cause imbalance in the transverse vector sum
  - E.g. most SUSY models predict ME$_T$>150 GeV
ME$_T$: Experimental Challenge

ME$_T$ reconstruction with 3 algorithms: “calo ME$_T$”, track-corrected ME$_T$, “Particle flow ME$_T$”.

Reconstructed ME$_T$ has to be cleaned of effects due to:
- instrumental noise
- cosmics, beam halo,..

*Beam halo tagged events at high ME$_T$:*
$\text{ME}_T$ resolution

$\text{ME}_T$ resolution due to noise, calorimeter response etc strongly depends on the associated sum of transverse energy, $\Sigma \text{E}_T$

Very good (5-10 %) $\text{ME}_T$ resolution, esp. for particle flow and track-corrected $\text{ME}_T$, as measured in minimum-bias data
Simulation of $\mathcal{M}_T$ over 7 orders of magnitude

- Minimum Bias events:
  - Calo jets
  - PF jets

- Di-jet events:
Muons: the “M” in CMS

• Hits in muon detectors, matched up with tracks
• CMS trigger flexible: can use very loose muon triggers
  – 50k J/ψ per pb$^{-1}$ down to 0 p$_T$ in forward direction!
• Muon identification studied using minimum bias events and dimuon resonances

Min bias data, compared to simulation.
Error bars stat. only
Muon momentum resolution

- Excellent momentum resolution ~1% for $|\eta|<0.7$, as determined by fits to the J/\(\psi\) line shape
- Uncertainty dominated by statistics, will improve with more data from Y resonance
Electrons and Photons

- Reconstructed using ECAL clusters
  - Detector Material causes conversions and bremsstrahlung, energy flow spreads due to magnetic field
  - Superclusters formed to collect the total energy

*Supercluster pseudorapidity, Minimum Bias data*
Electrons and Photons

- Photons selected using ECAL and tracking isolation
- Electrons selected using ECAL and track matching

Central photon candidates in Min.bias data

Electron candidates: reconstructed transverse mass
Triggers

- Reducing data stream with fast online decision
- Two levels: “L1” (hardware) and “HLT” (software)
- HLT trigger menu: 150 triggers (jet, $\text{ME}_T$, muon,...)
- Current total trigger processing time per event: <50 ms
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   • New Physics (NP): SUSY,..
Inclusive jet cross section

- Basic measurement at hadron collider- very high rate of jet production
- Good test of jet reconstruction- see good agreement with NLO theory
- Jet $p_T$ spectra produced for all jet rec. approaches
  - Extending distributions to low $p_T$ using “Particle Flow”

![CMS preliminary, 60 nb⁻¹, $\sqrt{s} = 7$ TeV graph showing jet $p_T$ spectra for different $|y|$ ranges and NLO pQCD+NP compared to EXP. uncertainty and Anti-$k_T$, R=0.5 PF]
Incl. b-jet cross section

- Sizable theoretical uncertainties, interesting to verify results at high energy
  - Reasonable agreement with NLO
- Important background to NP searches

Common syst. cancel out in ratio

B-jet/incl. jet:
Search for narrow resonance in dijets

- Measure differential cross section for centrally produced jets

- Many NP models predict new massive objects coupling to q, g, resulting in resonances

- Starting to exclude certain NP ranges, e.g.
  - string resonances with $m < 1.6$ TeV,
  - excited quark mass $m < 0.59$ TeV
  - axigluon mass $m < 0.52$ TeV

8/2/2010
Starting to reach beyond Tevatron:

- Highest di-jet mass in first 120nb\(^{-1}\) of data: m_{jj}=2.13 TeV
Stopped Gluinos and Heavy Stable Charged Particles

- Search for long lived particles decaying in the detector after end of each LHC fill
  - No signal observed during search intervals, can be interpreted as exclusion limit on gluino masses: $<229\text{GeV} \ (t=200\text{ns})$ and $<225\text{GeV} \ (t=2.6\mu\text{s})$.

- Search for anomalous signals from heavy particles
  - Interpret in context of (quasi-)stable stau, gluino, scalar top as limits on cross section
**J/ψ → µ⁺µ⁻ differential and total cross section**

Total cross section for incl. J/ψ production in the di-muon decay channel (4 ≤ p_T ≤ 30 GeV/c and |y| < 2.4):

\[
\text{BR}(J/ψ → µ⁺µ⁻) \cdot \sigma(pp → J/ψ + X) = (289.1 ± 16.7\text{(stat)} ± 60.1\text{(syst)}) \text{ nb}
\]

- Syst. dominated by the stat. precision of the muon efficiency determination from data

**Differential cross section**

*(null polarization scenario)*

![Differential cross section graph](image)
Fraction of J/Ψ from B Hadron decay

- Use transverse decay length to separate prompt from non-prompt component

**Forward: 1.4<|y|<2.4**

**Central: |y|<1.4**

**Prompt diff. cross section:**

- Forward: 1.4<|y|<2.4
- Central: |y|<1.4
Y(1s, 2s and 3s) → μ+μ− measured the Y(1s) cross section x BR in dimuons and the corresponding differential cross section

$$\sigma(pp \rightarrow \Upsilon(1S)X) \cdot B(\Upsilon(1S) \rightarrow \mu^+ \mu^-) = (8.3 \pm 0.5 \pm 0.9 \pm 1.0) \text{nb}$$
W and Z production cross sections

- Precision test for pert. QCD (NNLO) and proton PDFs
  - First ewk process in pp collisions at 7TeV!

- Benchmark point for lepton reconstruction and identification, $M_{E_T}$

- Important related measurements:
  - Ratio W/Z cross section; uncertainty on luminosity cancels
  - Forward backward asymmetry of lepton pairs sensitive to NP (e.g. extra neutral gauge bosons)
  - $W$+jets production: test of pert. QCD and one of most important background processes!
Extraction of the $W(Z)\rightarrow \mu \nu (\mu \mu)$ signal

- Trigger HLT path: $\mu + X (p_T > 9 \text{ GeV/c}) \, |\eta| < 2$.
- QCD background shapes from data, others from MC

![Graph 1](image1.png)

$N_Z = 77$

![Graph 2](image2.png)

$N_w = 818 \pm 27$
Extraction of the $W(Z)\rightarrow e\nu (ee)$ signal

- Trigger HLT path: $e/\gamma + X (E_T > 15 \text{ GeV/c})$
- Yield of $W$ bosons determined using simultaneous fits to background and signal contributions

$N_Z = 61$

$N_w = 800 \pm 30$
W and Z: cross section results

Important test of many analysis components:

- Lumi, $e, \mu$ efficiency, $M_{E_T}$ resolution, background systematics,…

8/2/2010
lepton charge asymmetry and W+jets

- $W^+$ and $W^-$ produced at different rates in pp collisions
  - More $u$ than $d$ quarks
  - Charge asymmetry measurement useful constraint for PDFs

- $W + \text{jets}$ production:
  - Important background to (single) top, Higgs, NP searches
Putting it all together: top quarks

So far only produced at Tevatron, discovery in 1995

Top physics tests all aspects of the reconstruction:
\( M_{E_T}, \) leptons, jets, b-tagging.

Extremely interesting as place for NP discovery-
massive \( X \rightarrow \) \( tt \), top decay,…

2 main channels:

- **“lepton+jets”:** 4 jets (2 from b), and missing \( E_T \) from \( \nu \)
  - BF=24/81, but significant background

- **“dilepton”:** 2 jets and missing \( E_T \) from \( \nu \)
  - Clean, but low stat. BF=4/81
lepton+jets channel

- Pretag event selection:
  - Exactly one good isolated and central muon (electron) with \( p_T > 20(30) \) GeV, at least 4 central jets \( p_T > 30 \) GeV, no MET requirement

- In the presence of at least 1 b-tagged jet to suppress background:

plots are “out of the box”, i.e. no syst., no data-driven background estimation, etc etc.
lepton+jets channel: combined

Observed: 4 events
Expected: 3.3 top events

CMS Preliminary
0.25 pb$^{-1}$ at $\sqrt{s} = 7$ TeV

Jet multiplicity

Top signal region
Event display of a “golden” $\mu$+jets event

Event passes all selection cuts
1 high-momentum muon
significant MET > 100 GeV
$m_T(W) = 104$ GeV/$c^2$
4 high-$p_T$ jets,
one of which with good $b$-tag

reconst. top mass around 210 GeV/$c^2$
masses of 2 untagged jets (3 possible comb.): 104, 105, 151 GeV/$c^2$
Dilepton Channel

• Event selection:
  – 2 isolated, prompt, oppositely charged, central muons or electrons $p_T>20$ GeV, $M_{E_T}>30$ GeV, at least 2 central jets $p_T>20$ GeV, Z veto

![Histogram chart showing events with ee/μμ/eμ]
Event display of “golden” $\mu\mu$+jets event

July 18th
Golden $\mu\mu+$jets event...cont’d

Multiple primary vertices $\rightarrow$ multiple $pp$ collisions (“pile-up”)

Jets & muons originate from same primary vertex

$y$ [cm]

$\mathbf{m}(\mu\mu) = 26 \text{ GeV/c}^2$

Preliminarily reconstr. mass is in the range $160–220 \text{ GeV/c}^2$ (consistent with $m_{\text{top}}$)
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   - QCD processes
   - Top
   - Early searches

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   - New Physics: SUSY,..
Outlook

• **Higgs detection**
  – SM $H \rightarrow \gamma \gamma$, WW, ZZ
  – Higgs production associated with b or t quarks

• **New Physics**
  – SUSY, UED, LH,… detected in signatures with jets, leptons, photons and $\text{MET}_T$
    • $\text{MET}_T$ from undetected lightest new particle, the dark matter candidate
  – Many other channels, e.g. resonances, $W'Z'$, top, QCD sector, $B_s$…

• Have shown performance and calibration of the important ingredients for the CMS discovery program: jets, MET, leptons, btags
SM Higgs Prospects

- SM Higgs: combination of $\gamma\gamma + WW + ZZ$ search channels
- With 7TeV, 100pb$^{-1}$ by Nov and 1fb$^{-1}$ by end of 2011
  - expected 95% CL exclusion range: 145-190 GeV
  - Conservative estimate, based on $\gamma\gamma + WW + ZZ$ channels only
Preparing for SUSY search

- Example: jets+\(\text{ME}_T\) signature ("hadronic search")
- Typically require \(\text{ME}_T > 150\) GeV
  - QCD multijet + mismeasured MET is not main background, but poorly known (and large) cross section needs to be estimated from data
- With current data set don’t expect to have any sensitivity to SUSY, used for bkg testing
Example: $\text{MET}_T$ shape prediction with templates

Form templates from data to model (true and fake) $\text{MET}_T$, using Jet and $\gamma+\text{jet}$ triggers

- Test template prediction in region relevant for SUSY searches
Summary

• CMS is taking and analyzing data at 7 TeV
  – 9 years after CMS construction began
  – Combined effort of thousands of people

• First results with up to 0.25pb\(^{-1}\) show good performance of all sub-detectors, good control over standard candle processes and the first European top quarks!
  – Impressive turn around- data was taken only few weeks ago

• Ready for our discovery program!
• Backup Material
Tracker Performance

- $p_T$ spectrum
- $\eta$ distribution
- $\phi$ distribution
- Transverse impact parameter
Impact parameter Resolution

- Good agreement between data and MC for wide range of track $p_T$
B tag performance: mistag

- Mistag rate estimated from data using “negative tags”
- Examine jets that have a secondary vertex reconstructed behind the IP
  - Indicates rate of misreconstructed b-jets
B-tag purity for incl b-jet study

![Graph showing b-tagged sample purity vs. p_T (GeV) with CMS preliminary, 60 nb^{-1} at \sqrt{s} = 7 TeV. The graph compares Data and MC, with Data/MC = 0.976 ± 0.022 and \chi^2/NDF = 1.2/3.]
Exclusive B physics

- First candidates for $B_s \rightarrow J/\psi \phi$

![Graphs and diagrams showing particle decay distributions and event plots for $D^0 \rightarrow K\pi$, $D^{**} \rightarrow D^0(K\pi)\pi^+$, and $D^+ \rightarrow K\pi^+\pi^+$ (and $c\bar{c}$) decays.](image)
Tau identification

[Graph showing event distributions and analysis results related to tau identification.]
Charged track multiplicity

CMS preliminary

- Data 7 TeV
- PYTHIA-6 D6T
- PYTHIA-6 DW
- PYTHIA-6 P0
- PYTHIA-6 CW
- PYTHIA-8

leading track-jet $p_T > 3$ GeV/c
charged particles ($p_T > 0.5$ GeV/c)

leading track-jet $p_T > 20$ GeV/c
charged particles ($p_T > 0.5$ GeV/c)

8/2/2010 SSI
Jet $p_T$ resolution

- Measure $p_T$ asymmetry of the two leading jets in back-to-back dijet events
open b prod cross section

• Require presence of a muon from semileptonic B decay
• See discrepancy with MC@NLO in pseudorapidity distribution
MSSM Higgs pp--->bbΦ, Φ-->ττ
B tag performance: efficiency

- efficiency is estimated from data using events with jets containing a muon
- Examine momentum of muon transverse to jet, $p_{t}^{\text{rel}}$
  - Muons from B have large $p_{t}^{\text{rel}}$
  - B fraction determined with template fits
  - Tagging efficiency calculated using b fraction and number of tagged

![Graph showing muons from jets that pass B-tag](image1)

![Graph showing muons from jets that fail B-tag](image2)
Trigger Performance

- Rates within 20% of expectation, smooth running and data delivery
- Optimal efficiency as measured with data

Example: Photon trigger
L1 & HLT Photon efficiency wrt
RECO SuperCluster:
Barrel & Endcaps
nearly 100% efficient.