CMS Experiment at LHC: Detector Status and Physics Capabilities in Heavy Ion Collisions

Bolek Wyslouch
Massachusetts Institute of Technology
for the CMS Collaboration

Nuclear Physics Seminar
Brookhaven National Laboratory
August 5, 2008

CMS HI groups: Athens, Auckland, Budapest, CERN, Colorado, Cukurova, Ioannina, Iowa, Kansas, Korea, Lisbon, Los Alamos, Lyon, Maryland, Minnesota, MIT, Moscow, Mumbai, Paris, Seoul, Vanderbilt, UC Davis, UI Chicago, Zagreb
Heavy Ion Physics at the LHC

Pb+Pb Collisions at $\sqrt{s_{NN}} \sim 5.5$TeV
Large Cross section for Hard Probes
High luminosity $10^{27}$/cm$^2$s

- Copious production of high $p_T$ particles
  - Nuclear modification factors $R_{AA}$ out to very high $p_T$
- Large cross section for $J/\psi$ and $\Upsilon$ family production
  - $\sigma_{cc}^{LHC} \sim 10 \times \sigma_{cc}^{RHIC}$
  - $\sigma_{bb}^{LHC} \sim 100 \times \sigma_{bb}^{RHIC}$
  - Different “melting” for members of $\Upsilon$ family with temperature
- Large jet cross section
  - Jets directly identifiable
  - Study in medium modifications
Kinematics at the LHC

Access to widest range of $Q^2$ and $x$

$M^2$ (GeV$^2$)

$10^2$ $10^4$ $10^6$ $10^8$

$Z^0$ $\gamma$ $J/\psi$

Saturation

Coverage

Rate/Trigger

$M = 10$ GeV $M = 100$ GeV $M = 1$ TeV

$y = 0$ $y = -2$

$x_{1,2} = (M/\sqrt{s})e^{\pm y}$

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CMS detector at the LHC

- **ECAL**: Scintillating PbWO4 crystals
- **SUPERCONECTING COIL**: Iron Yoke
- **HCAL**: Plastic scintillator/brass sandwich
- **IRON YOKE**: Human scale
- **TRACKER**: Silicon Microstrips, Si Pixels
- **MUON BARREL**: Drift Tube Chambers (DT), Resistive Plate Chambers (RPC)
- **MUON ENDCAPS**: Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC)

**Dimensions**:
- Length: 21.6 m
- Diameter: 15 m
- Weight: ~12500 tons
- Magnetic Field: 4 Tesla
August 1, 2008: CMS is fully installed
This afternoon...
CMS detector will extend deep into LHC

ZDC funded by US DOE NP & NSF

- CMS (+TOTEM):

Largest phase-space coverage ever in a collider.

-420m (FP420)

(CMS detector will extend deep into LHC)
Particle detection layers in CMS
CMS is collecting cosmics..

Global Run July ‘08

Prerequisites: infrastructure, μ-trigger, DAQ integration, r/o synchronization, muon calibration, reconstruction/tracking, etc. ...

Only few hours after first attempt to integrate TK in global running!
CMS is collecting cosmics..

- **Di-muon Trigger:**
  - Drift-Tube coinc. in top+bottom, each ≥ 2 station segments

- **Muon signals traced through**
  - muon system
  - Tracker TOB+TIB
  - ECAL
  - HCAL

- **Global track fit**

- **Excellent data - being used for alignment**
### Physics cases for HI@CMS

<table>
<thead>
<tr>
<th>Case no.</th>
<th>We will look into…</th>
<th>in order to learn about…</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>MB L1 trigger, centrality</td>
<td>Global event characterization</td>
</tr>
<tr>
<td>1</td>
<td>$dN_{\text{ch}}/d\eta$</td>
<td>Color Glass Condensate, $xG_A(x,Q^2)$</td>
</tr>
<tr>
<td>2</td>
<td>Low $p_T$ $\pi/K/p$ spectra</td>
<td>Hydrodynamics, Equation of State</td>
</tr>
<tr>
<td>3</td>
<td>Elliptic Flow</td>
<td>Hydrodynamics, Medium viscosity</td>
</tr>
<tr>
<td>4</td>
<td>Hard-probes (triggering)</td>
<td>Thermodynamics &amp; transport properties</td>
</tr>
<tr>
<td>5</td>
<td>Quarkonia suppression</td>
<td>$\epsilon_{\text{crit}}, T_{\text{crit}}$</td>
</tr>
<tr>
<td>6</td>
<td>Jet “quenching”</td>
<td>Parton density, $\langle q \rangle$ transport coefficient</td>
</tr>
</tbody>
</table>
pp Minimum Bias using Forward HCAL

Min-bias trigger: Number of HF trigger towers over threshold > N: any side (OR), or on both sides (AND) of I.P.

Unfolding the effect of HF min-bias triggering on physical measurements

Re-weighted charged-particle multiplicity per evt.
**Charged Particle Multiplicities**

- Predictions vary by a factor of 4!
- $dN/dy \sim 1500 – 7000$
- (RHIC extrapolation vs. HIJING)

**Hit counting in the first pixel layer**

- Low $p_T$ cutoff $\sim 40$ MeV
- Needs few events $O(1000)$
- Few seconds of data taking
Charged-Hadron Spectra pp

- One of the first measurements to be done: charged-hadron spectrum
  - Important tool for calibration, alignment & understanding of detector response
- Min-bias and/or Zero-bias trigger
  - Statistics: ~ 2 million events
CMS Tracking Performance PbPb

- Occupancy in Pb+Pb
  - $dN/dy = 3500$
  - 1-2% in Pixel Layers
  - < 10% in outer Strip Layers

- Efficiency
  - ~75% above 1 GeV/c

**Occupancy**

- 0.0 < $|\eta| < 0.5$
- Efficiency
- Fake Rate

**Pb+Pb, $dN/dy = 3500$**

- **Efficiency**
  - 0.0 < $|\eta| < 0.5$
  - Transverse
  - Longitudinal

- World’s best momentum resolution
- Excellent impact parameter resolution
• Changes to tracking algorithms allow access to low $p_T$ particles
  • Reconstruct three hit tracks in the pixel system
  • Good efficiency to ~ 300MeV/c in Pb+Pb
  • Particle ID by $dE/dx$ in Silicon
Use the tracker to measure $v_2$ differentially in $p_T$ and $\eta$
- Event plane and $v_2$ determined from independent sub-events
- No non-flow corrections applied
- Compare $v_2$ extracted from simulated particles and reconstructed tracks
- The $p_T$ and $\eta$ dependences of $v_2$ can be reconstructed with high accuracy.
**CMS Trigger and DAQ in p+p**

### Level 1 trigger
- Uses custom hardware
- Muon tracks + calorimeter information
- Decision after ~ 3μsec

<table>
<thead>
<tr>
<th></th>
<th>Level-1</th>
<th>p+p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision rate</td>
<td></td>
<td>1GHz</td>
</tr>
<tr>
<td>Event rate</td>
<td></td>
<td>32MHz</td>
</tr>
<tr>
<td>Output bandwidth</td>
<td></td>
<td>100 GByte/sec</td>
</tr>
<tr>
<td>Rejection</td>
<td></td>
<td>99.7%</td>
</tr>
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</table>

### High level Trigger
- ~1500 Linux servers (~10k CPU cores)
- Full event information available
- Runs “offline” algorithms

<table>
<thead>
<tr>
<th></th>
<th>High Level Trigger</th>
<th>p+p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input event rate</td>
<td></td>
<td>100kHz</td>
</tr>
<tr>
<td>Output bandwidth</td>
<td></td>
<td>225 MByte/sec</td>
</tr>
<tr>
<td>Output rate</td>
<td></td>
<td>150Hz</td>
</tr>
<tr>
<td>Rejection</td>
<td></td>
<td>99.85%</td>
</tr>
</tbody>
</table>
CMS Trigger and DAQ in Pb+Pb vs p+p

**Level 1 trigger**
- Uses custom hardware
- Muon tracks + calorimeter information
- Decision after ~ 3µsec

<table>
<thead>
<tr>
<th>Level-1</th>
<th>Pb+Pb</th>
<th>p+p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision rate</td>
<td>3kHz (8kHz peak)</td>
<td>1GHz</td>
</tr>
<tr>
<td>Event rate</td>
<td>3kHz (8kHz peak)</td>
<td>32MHz</td>
</tr>
<tr>
<td>Output bandwidth</td>
<td>100 GByte/sec</td>
<td>100 GByte/sec</td>
</tr>
<tr>
<td>Rejection</td>
<td>none</td>
<td>99.7%</td>
</tr>
</tbody>
</table>

**High level Trigger**
- ~1500 Linux servers (~10k CPU cores)
- Full event information available
- Runs “offline” algorithms

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<tr>
<td>Input event rate</td>
<td>3kHz (8kHz peak)</td>
<td>100kHz</td>
</tr>
<tr>
<td>Output bandwidth</td>
<td>225 MByte/sec</td>
<td>225 MByte/sec</td>
</tr>
<tr>
<td>Output rate</td>
<td>10-100Hz</td>
<td>150Hz</td>
</tr>
<tr>
<td>Rejection</td>
<td>97-99.7%</td>
<td>99.85%</td>
</tr>
</tbody>
</table>

to be partially funded by US DOE NP

Bolek Wyslouch/MIT
Hard Probes: HLT vs Min Bias

J/ψ, Y and Jet reconstruction available at HLT

Example trigger table:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Threshold</th>
<th>Pre-scale</th>
<th>Bandwidth [MByte/s]</th>
<th>Event size [MByte]</th>
</tr>
</thead>
<tbody>
<tr>
<td>min. bias</td>
<td>–</td>
<td>1</td>
<td>33.75 (15%)</td>
<td>2.5</td>
</tr>
<tr>
<td>jet</td>
<td>100 GeV</td>
<td>1</td>
<td>24.75 (11%)</td>
<td>5.8</td>
</tr>
<tr>
<td>jet</td>
<td>75 GeV</td>
<td>3</td>
<td>27 (12%)</td>
<td>5.7</td>
</tr>
<tr>
<td>jet</td>
<td>50 GeV</td>
<td>25</td>
<td>27 (12%)</td>
<td>5.4</td>
</tr>
<tr>
<td>J/ψ</td>
<td>0 GeV/c</td>
<td>1</td>
<td>67.5 (30%)</td>
<td>4.9</td>
</tr>
<tr>
<td>Y</td>
<td>0 GeV/c</td>
<td>1</td>
<td>2.25 (1%)</td>
<td>4.9</td>
</tr>
<tr>
<td>prompt</td>
<td>10 GeV</td>
<td>1</td>
<td>40.5 (18%)</td>
<td>5.8</td>
</tr>
<tr>
<td>UPC/forward</td>
<td>–</td>
<td>1</td>
<td>2.25 (1%)</td>
<td>1</td>
</tr>
</tbody>
</table>

HLT improves hard probe statistics by more than a factor of 10!
CMS has a very good acceptance in the Upsilon mass region

The dimuon mass resolution allows to separate the three Upsilon states:

- ~54 MeV/c2 within the barrel and
- ~86 MeV/c2 when including the endcaps
mass resolution and acceptance

- Low $p_T$ $J/\psi$ acceptance at forward rapidities.
- The dimuon mass resolution is 35 MeV, full $\eta$ region.

O. Kodolova, M. Bedjidian, CMS note 2006/089
p_T reach of quarkonia (for 0.5 nb^{-1})

- Expected rec. quarkonia yields:
  - J/\psi : \sim 180 000
  - \Upsilon : \sim 26 000

- Detailed studies of Upsilon family feasible with HLT
- Statistical accuracy (with HLT) of expected \Upsilon' / \Upsilon ratio versus p_T \rightarrow model killer...
The Calorimeters: Jet Reconstruction

Jet $E_T \sim 100$GeV, Pb Pb background $dN_{ch}/dy \sim 5000$

Jet in pp  Jet superimposed on Pb Pb background  Jet in Pb-Pb after pileup subtraction
Heavily Ion Jet Finder Performance

High Efficiency

- A modified iterative cone algorithm running on calorimeter data gives good performance in Pb Pb collisions

Good Resolution

- Offline jet finder will run in the HLT

Jet studies from CMS Note 2003/004
HLT impact on the $p_T$ reach of $R_{AA}$

- Jet-trigger allows $R_{AA}$ measurement to $p_T > 200$ GeV/c
- Reach improved by x2 compared to min bias

\[
R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AB}(b) \rangle \cdot d^2\sigma_{pp}/dydp_T}
\]
High $p_T$ Suppression

Clear separation of different energy loss scenarios
Jet $E_T$ reach

- Jet spectra up to $E_T \sim 500$ GeV (Pb-Pb, 0.5 nb$^{-1}$, HLT-triggered)
  - Detailed studies of medium-modified (quenched) jet fragmentation functions
Photon-tagged jet fragmentation functions

DOE Review Driven.

Ingredients:
- Event/Centrality selection
- Reaction plane determination
- Vertex finding
- Track reconstruction
- Jet finding
- Photon identification

Main advantage
- Photon unaffected by the medium
- Avoids measurement of absolute jet energy

All results based on full GEANT-4 simulations using full reconstruction algorithms on expected one run-year statistics

Jet axis provides parton direction

Charged hadron tracks used to calculate $z = p_T/E_T$

Photon energy tags parton energy $E_T$

Multiplicity and flow measurements characterize density, path length

Jet axis

Hadrons

Photon

Measure jet fragmentation function: $dN/d\xi$ with $\xi = -\log z$
In-medium modified fragmentation functions

\[
d\frac{dN}{d\xi} = \log\left(\frac{E_T}{p_T}\right)
\]

Quenching reduces high-\(p_T\) particles
Quenching increases low-\(p_T\) particles

Adapted from hep-ph/0506218

- OPAL, \(\sqrt{s} = 192–209\) GeV
- in vacuum, \(E_{\text{jet}} = 100\) GeV
- in medium, \(E_{\text{jet}} = 100\) GeV

10 GeV/c
1 GeV/c
Photon-tagged fragmentation functions

- Use isolated photons + “back-to-back” cut on azimuthal opening angle between the photon and the jet to suppress NLO and background events.
  - Determines FF with <10% deviation
Event generation

- **Study two scenarios**
  - No quenching: PYTHIA signal and QCD background (p+p) events mixed with central unquenched Pb+Pb HYDJET events
    - No high-\(p_T\) particle suppression
    - Leads to high background rates
  - Quenching: PYQUEN signal and QCD background (p+p) events mixed with central quenched Pb+Pb HYDJET events
    - Suppression of high-\(p_T\) particles
    - Energy loss radiated out of jet cone
    - Challenging for jet finder

HYDJET v1.2: hep-ph/0312204
Signal and background statistics

- **Study for one nominal LHC Pb+Pb run “year”**
  - $10^6$ sec, 0.5nb$^{-1}$, $3.9 \times 10^9$ events
- **Use 0-10% most central Pb+Pb**
  - $dN/d\eta\big|_{\eta=0} \sim 2400$
- **Simulate signal and background QCD (p+p) events**
  - Mix into simulated Pb+Pb events ($\sim 1000$ events)

**Table of Data Set Parameters**

<table>
<thead>
<tr>
<th>Data set</th>
<th>$p_T$ [GeV/c]</th>
<th>signal $\gamma$-jet</th>
<th>$\pi^0$</th>
<th>$\pi^\pm$</th>
<th>$\eta$</th>
<th>$\eta'$</th>
<th>$\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>unquenched</td>
<td>$&gt;70$</td>
<td>4288</td>
<td>23675</td>
<td>47421</td>
<td>12267</td>
<td>8194</td>
<td>30601</td>
</tr>
<tr>
<td>unquenched</td>
<td>$&gt;100$</td>
<td>1216</td>
<td>4422</td>
<td>9103</td>
<td>2357</td>
<td>1567</td>
<td>5975</td>
</tr>
<tr>
<td>quenched</td>
<td>$&gt;70$</td>
<td>4209</td>
<td>7569</td>
<td>14616</td>
<td>3825</td>
<td>2445</td>
<td>9235</td>
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<tr>
<td>quenched</td>
<td>$&gt;100$</td>
<td>1212</td>
<td>1562</td>
<td>3000</td>
<td>829</td>
<td>515</td>
<td>2051</td>
</tr>
</tbody>
</table>
Reconstruction

- **Tracking**
  - Low $p_T$ cutoff at 1GeV/c
  - Efficiency (algorithmic + geometric) ~ 50-60%
  - Fake rate ~ few %

- **Jet finding**
  - Iterative cone algorithm with underlying event subtraction ($R=0.5$)
  - Performance studies on away-side jet finding (see later)

- **Photon ID**
  - Reconstruction of high-$E_T$ isolated photons
  - New for this analysis (see next slides)

Tracking: NIM A566 (2006) 123
ECAL response in p+p and Pb+Pb

ECAL reconstruction chain used with standard p+p settings

NB: The two p+p (QCD) events are not the same.
Photon ID: Isolation and cluster shape cuts

- **Identification**
  - 10 cluster shape variables
    - based on ECAL
  - 10 isolation variables
    - based on ECAL/HCAL
  - Track-based cut

- **Selection**
  - Total of 21 variables grouped into 3 sets
  - Linear discriminant analysis (Fisher) and cut optimization using TMVA

TMVA: [http://tmva.sourceforge.net](http://tmva.sourceforge.net)
Photon identification performance

- Set working point to 60% signal efficiency
- Leads to 96.5% background rejection
- Training is done on unquenched samples only
Photon identification performance

Quenched Pb+Pb

Before cuts: $S/B=0.3$

After cuts: $S/B=4.5$

Photon isolation and shape cuts improve $S/B$ by factor $\sim 15$
Jet finding (away-side)

- **Select** away-side jet with $\Delta \phi(\gamma,\text{jet}) > 172^\circ$, $|\eta| < 2$ and $E_T > 30$ GeV
  - The energy cut reduces the false rate to 10% level
    - Analysis does not use jet energy otherwise
  - **Jet finding efficiency rises sharply between 30-100 GeV MC jet $E_T$**
    - Main source of systematic uncertainty in reconstructed FFs
Fragmentation Functions

- Obtain $dN/d\xi$ using tracks in $R=0.5$ cone around jet axis
- For $\xi>3 (~p_T<4\text{GeV/c})$ $dN/d\xi$ dominated by underlying Pb+Pb event
  - Estimate background using $R=0.5$ cone rotated in $\phi$ by $90^\circ$ relative to jet
  - Sum event-by-event backgrounds and subtract
Reconstructed fragmentation functions

- Major contributions to systematic uncertainty (added in quadrature)
  - Photon selection and background contamination (15%)
  - Track finding efficiency correction (10%)
  - Wrong/fake jet matches (10%)
  - Jet finder bias (largest contribution in quenched case)

\[ \xi = \ln \left( \frac{E_T}{p_T} \right) \]

Unquenched

Quenched

No or small $\xi$ dependence
Medium modification of fragmentation functions can be measured

- High significance for $0.2 < \xi < 5$ for both, $E_T^\gamma > 70$GeV and $E_T^\gamma > 100$GeV
Summary

• The CMS detector has excellent capabilities to study the dense QCD matter produced in very high energy heavy-ion collisions, through the use of hard probes such as high-ET (fully reconstructed) jets and heavy quarkonia.

• With a high granularity inner tracker (full silicon, analog readout), a state-of-the-art crystal ECAL, large acceptance muon stations, and a powerful DAQ & HLT system, CMS has the means to measure charged hadrons, jets, photons, electron pairs, dimuons, quarkonia, Z⁰, etc!

• The CMS Heavy Ion group is busily preparing for the upcoming physics runs in pp and PbPb next year.
• The usual question...
Why CMS?

- **Hermeticity and resolution**
  - largest coverage in $\eta$
  - best in resolution: muons (upsilon), charged tracks
  - fully equipped with all detection layers, including tracker and calorimeters in $2\pi$ and 5 units of $\eta$

- **DAQ and Trigger**
  - Unique arrangement, reliance on HLT
  - EVERY HI collision can be inspected at HLT
  - Transparent switchover from pp to HI

- **Collaboration**
  - Well integrated into CMS, just ask in the CERN cafeteria..
  - CMS HI group at CERN (~20 people) are working full time on preparation for specifics of HI datataking: lots of work

- **Special feature**
  - E.g. analog silicon and pixel readout: there would be no PHOBOS without that..