CMS: Muon System and Physics performance

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on behalf of the CMS collaboration
Outline

- Introduction,
- Muon detectors,
- Muon reconstruction,
  - High Level Trigger,
  - Local reconstruction,
  - Global reconstruction,
  - Muon isolation,
- Physics performance,
- Summary
Introduction

- Results presented for two LHC instantaneous luminosities:
  - Low luminosity (LL) first 3 year of data taking:
    \[ \mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} = 2 \text{ nb}^{-1} \text{s}^{-1} \]
  - High luminosity (HL) after:
    \[ \mathcal{L} = 10^{34} \text{ cm}^{-2} \text{s}^{-1} = 10 \text{ nb}^{-1} \text{s}^{-1} \]

- All results presented with full CMS simulation (GEANT 3)
- Pile up included for both luminosities,
- OO-reconstruction ORCA (Object-oriented Reconstruction for CMS Analysis)
Muon Detectors in CMS
Three type of gaseous detectors:

- **Drift Tubes** in barrel region,

- **Cathode Strips Chambers** in endcap regions,
  - DT’s and CSC’s provide precise position measurements, \( \rightarrow p_t^{\mu} \),

- **Resistive Plate Chambers** in both barrel and endcaps.
  - RPC provide precise bunch crossing (bx) id.
  - all the 3 sub-sistem contribute to the L1-trigger.
4 stations of DT’s, interleaved with the iron of magnet yoke, self triggering and bx identification,

4 stations of CSC’s with same capabilities, interleaved with iron disk yoke, up to $|\eta| < 2.4$,

6 –Barrel– or 4 –Endcaps– station of RPC’s up to $|\eta| < 2.1$,

L1 trigger up to $|\eta| < 2.1$

Start-up staged detector: no ME4 and RPC $|\eta| < 1.6$
**Drift Tube chambers**

- Made of 3 SuperLayers, 2 in $r - \phi$ and 1 in $r - z$ (not in the 4th station) separated by honeycomb spacer
- Each SL made of 4 layers of staggered 4.2 cm wide cells,
- $E$-field shaped to give maximum linearity,
- Gas mixture: $Ar - CO_2$ 85 – 15%,
- Single point resolution: $\sim 200 \mu m$,
- Chamber resolution:
  - pos $\sim 100 \mu m$, dir $\sim 1 \text{ mrad}$,
- Total 250 chambers,
  - $\sim 190k$ wires.
Cathode Strip Chambers

- Arranged in 4 disks,
- Inner ring have 18 CSCs each covering 20°, outer 36 covering 10°,
- Made of 6 Layers, trapezoidal shape,
- Radial strips measure precise bending coordinate by interpolation of induced charge $\sigma \sim 100 \div 240 \mu m$,
- Orthogonal anode wires readout $\sigma \sim cm$, 3d points,
- Gas mixture: $Ar - CO_2 - CF_4 30 - 50 - 20\%$,
- Total 540 chambers, $\sim 0.5 M$ channels.
**Resistive Plate Chambers**

- Double gap, single readout (strips),
- Dedicated trigger detectors,
- Fast timing response, precise identification of $b_x \sigma_t \sim 1 \, ns$,
- Coarse $\sim cm$ position resolution,
- $p_t^\mu$ assignment via Pattern Comparator Trigger,
- Help in identification of $\mu$ tracks,
- Total 612 chambers, $\sim 160 \, k$ channels.
Muon Reconstruction

In CMS the High Level Trigger is performed on a commercial processor farm (Filter Unit) running software algorithm on raw data,

- Software used will be as much as possible the same used in offline reconstruction
- Offline reconstruction will make full use of complete calibration, alignment, etc...

Robust, high quality reconstruction software

- Use of a common framework
- Object-oriented Reconstruction for CMS Analisys: ORCA

Basic principle: regional reconstruction

- Reconstruction performed in region only,
- Need seed to start: for HLT is Level-1 trigger object

Working prototype of full HLT reconstruction and selection already developed: DAQ & HLT TDR, CERN/LHCC 2002/26, 15 december 2002
Local Pattern Recognition

DT’s and CSC’s are multi-layers detectors:

first step of muon reconstruction is local, i.e. inside chambers

Barrel

- Reconstruct $r - \phi$ SL hits (time-space conversion), hit error $\equiv$ resolution,
- $v_{drift}$ depends on $\vec{B}$ field and impact angle $\theta$,
  first approx.: $\vec{B}$ @ center of wire, $\theta = 0$,
- Build segments $2D$ –linear fit–,
- Solve L/R ambiguity by best $\chi^2$ criterion,
- Apply impact angle correction to hits and refit,

- Build segment in $r - \varpi$ SL (where present): initial $\theta$ assuming $\mu$ from I.P.,
- Associate two projections (if present) to build a $3D$ segment,
Local Pattern Recognition: Barrel (2)

- Apply further correction for $\vec{B}$, using knowledge of hit position along the wire ($\vec{B}$ varies!) and do final refit.
- Position and direction of segment and corresponding error matrices from linear fit,
- Hits error (used in the fit) depends on $\vec{B}$ and $\theta$, apply proper corrections,
- Resolution: $\sigma_{pos} \sim 100 \mu m$ for bending coordinate, $\sigma_{dir} \sim 1 mrad$.
**Local Pattern Recognition (2)**

**Endcap**

- Reconstruct 3D hits,
- Fit (“Gatti” function) charge distribution on nearby strips to get cluster centroid,
- Use discriminated wire-group signal to get non-bending coordinate,
- Associate two projection by time coincidence,
- Fit 3D segment using 3D hits, linear fit,
- Resolution: $\sigma_{pos} \sim 100 \div 250 \mu m$ for bending coordinate, depending on chamber,
Local Pattern Recognition: Endcap(2)

Residuals ME1/1

$\chi^2 / \text{ndf} = 1173 / 97$

Constant: 1302
Mean: 0.0009831
Sigma: 0.01096

Residuals ME2/1, ME3/1, ME4/1

$\chi^2 / \text{ndf} = 324.2 / 97$

Constant: 1494
Mean: 0.0002587
Sigma: 0.02013

Residuals ME1/2, ME2/1, ME3/1, ME4/1

$\chi^2 / \text{ndf} = 175.6 / 97$

Constant: 489.5
Mean: 0.0001817
Sigma: 0.01843

Residuals ME2/2, ME3/2, ME4/2

$\chi^2 / \text{ndf} = 210.7 / 97$

Constant: 1149
Mean: 0.0001227
Sigma: 0.02356
Standalone Muon Reconstruction (1)
Based only on Muon detectors: DT, CSC and RPC,

Seed generation:
- L1-output for L2 trigger or
- From track segments from local reconstruction,
Search of detectors compatible with seed,
Search of detectors compatible with seed,

- Local pattern reconstruction performed **only** in those detectors: regional reconstruction on demand,

- Use **DT** 3D segments, **CSC** 3D hits constituents of segments, and **RPC** hits,
Standalone Muon Reconstruction (2)

- Trajectory building inside-out to collect hits,
- Kalman filter technique to grow trajectory, $\chi^2$ cuts to reject bad hits,
- State propagation across iron with non-const $B$ field: CPU time consuming!
- Track fitting works outside-in,
- Extrapolation to nominal I.P. and refit
Standalone Muon Reconstruction (6)

Resolution at L2: \( \frac{1/P_{t,\text{rec}} - 1/P_{t,\text{gen}}}{1/P_{t,\text{gen}}} \)

a) Barrel \((|\eta| < 0.8)\)

reso \(\sim 10\%\)

b) Overlap \((0.8 < |\eta| < 1.2)\)

reso \(\sim 15\%\)

c) Endcap \((1.2 < |\eta| < 2.1)\)

reso \(\sim 16\%\)
Global Muon Reconstruction (1)

- Inclusion of inner Tracker hits:
- Use L2 reconstructed muons as seed for tracker reconstruction,
- Get muon state at outermost tracker surface and at interaction point,
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- Define region of interest in the tracker,
Global Muon Reconstruction (1)

- Inclusion of inner Tracker hits:
  - Use L2 reconstructed muons as seed for tracker reconstruction,
  - Get muon state at outermost tracker surface and at interaction point,
  - Define *region of interest* in the tracker,
  - Create one or more seeds from pairs of reconstructed hits in different tracker layers,
Global Muon Reconstruction (1)

For a given seed build trajectory:

- Building inside-out,
- Kalman filter applied,
- Uniform $B$, few material: propagation is much simpler and faster than in the muon system,

Trajectory cleaning and final fit:

- Solve ambiguities,
- Ghosts suppression (# hits and $\chi^2$),
- Use tracker and muon hits for final fit,
- Reject bad tracks.
Global Muon Reconstruction (2)

Resolution with Tracker: \( \frac{1/P_t^{\text{rec}} - 1/P_t^{\text{gen}}}{1/P_t^{\text{gen}}} \)

a) Barrel \(|\eta| < 0.8\)  

reso \(\sim\) 1.0\%  

b) Overlap \((0.8 < |\eta| < 1.3)\)  

reso \(\sim\) 1.4\%  

c) Endcap \((1.3 < |\eta| < 2.1)\)  

reso \(\sim\) 1.7\%
Global Muon Reconstruction (3)

L1, L2, L3 efficiency vs $|\eta|$
Global Muon Reconstruction (4)

L1, L2, L3 efficiency vs $|p_T^\mu|$
**Muon Isolation (1)**

- Based on \( \sum E_t \) or \( \sum p_t \) in cones around reconstructed muons,
  - Cones sizes and thresholds are optimized to get maximum rejection for minimum bias events above trigger \( p_t \) threshold for a fixed efficiency on reference signal \((W \rightarrow \mu\nu)\)
  - Flat \( \epsilon(\eta) \) by construction,

- Calorimeter isolation, @ L2
  - \( \sum E_t \) from ECAL & HCAL towers: sensitive to PileUp,

- Pixel isolation, @ L2.5
  - \( \sum p_t \) from 3—hit tracks in the pixel detector,
  - Need 3 layers, no with pixel staging, problem if pixel inefficiencies,
  - Take tracks from the same vertex as \( \mu \), reduce PU,

- Tracker isolation, @ L3
  - \( \sum p_t \) from tracker tracks, regional reconstruction around muon,
Muon Isolation (2)

$\epsilon_{MB}$ vs $p_t^{gen}$ for $\epsilon_W \geq 97\%$

- Calorimetry isolation
- Pixel isolation
- Tracker isolation

- High lumi
- $|\eta|<2.4$
- Eff(W)>97%

Efficiency MB vs Efficiency W

- Pt(gen)>22 GeV
- $|\eta|<2.4$

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Physics Performance

From here...

to here!

- $p p \rightarrow H^0 \rightarrow ZZ$
  - $\mu^+ \mu^-$
  - $\mu^+ \mu^-$

- $H \rightarrow ZZ^* \rightarrow 4 \ell^\pm$
- $130 < M_H < 170$ GeV
- $E_T > 20, 10, 10$ GeV;
- $p_T^{e, \mu} > 20, 10, 5, 5$ GeV;
- $|\eta^{e, \mu}| < 2.5, 2.4$

$t\bar{t} + Zb\bar{b} + ZZ^*$

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Physics Performance (1)

Single muon rate Low (a) and High (b) lumi:

- **threshold [GeV/c]**
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60

- **Rate [Hz]**
  - $1 \times 10^2$
  - $1 \times 10^3$
  - $1 \times 10^4$
  - $1 \times 10^5$

**Legend**
- **generator**
- L1
- L2
- L2 + isolation (calo)
- L3
- L3 + isolation (calo + tracker)
**Physics Performance (2)**

Contribution to single $\mu$ rate High Lumi before and after isolation:

- $K^+ / \pi^+ \rightarrow \mu \nu$ suppressed!
- $c/b \rightarrow \mu + X$ suppressed!
- $\tau \rightarrow \mu + X$ suppressed!
- $W^\pm \rightarrow \mu \nu$ suppressed!
- $Z^0 / \gamma^* \rightarrow \mu^+ \mu^-$ suppressed!

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Di-muon rate (symmetric $p_T$ thr.) Low (a) and High (b) lumi:
Combined signal and di-muon rate Low (a) and High (b) lumi:

(a)

(b)
Physics Performance (5)

Efficiency for $W \rightarrow \mu \nu$ and $t\bar{t} \rightarrow \mu + X$:

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Physics Performance (6)

Efficiency for $W \rightarrow \mu \nu$ and $Z \rightarrow \mu \mu$:
Physics Performance (7)

Efficiency for $H^0 \rightarrow WW \rightarrow 2\mu 2\nu$ vs single and di-$\mu$ thr.:

L3 Single$_{\mu}$ after Iso

L3 isolated Di$_{\mu}$
Possible Working Point at Low and High Lumi

<table>
<thead>
<tr>
<th>Lumi</th>
<th>1 $\mu$ thr.</th>
<th>di $\mu$ thr.</th>
<th>total rate ($\pi K/bcT/W/Z$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1-HLT GeV</td>
<td>L1-HLT GeV</td>
<td>$Hz$ (~frac)</td>
</tr>
<tr>
<td>LL</td>
<td>14-19</td>
<td>3-7</td>
<td>29 (3.4/8.7/14.5/2.4)</td>
</tr>
<tr>
<td>HL</td>
<td>20-31</td>
<td>5-10</td>
<td>55 (0.8/2/42/7.6)</td>
</tr>
</tbody>
</table>

- Different threshold for L1 and HLT, room for more exclusive HLT selection at lower threshold (correlation, topological trigger, $m_{\mu\mu}$ selection, ...),
- $b$ physics contents is relevant at low lumi, and can be enhanced with dedicated trigger below HLT threshold,
- e.g. $B_s \rightarrow J/\psi\phi$: trigger at L1 di-$\mu$ + regional tracker reco + $J/\psi$ mass reconstruction ($\delta m \sim 55$ MeV, $\sim 30$ MeV with full reco) can give $\epsilon \sim 5\%$ for signal $\rightarrow \sim 10^5$ ev/yr (20 $fb^{-1}$)
- total rate is dominated (especially at High Lumi) by $W$, to lower the threshold must reject part of these events, without losing efficiency,
### Signal Efficiency at Nominal Threshold

<table>
<thead>
<tr>
<th>Signal</th>
<th>$\epsilon_{LL}$</th>
<th>$\epsilon_{HL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>69%</td>
<td>42%</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>92%</td>
<td>86%</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow \mu + X$</td>
<td>72%</td>
<td>58%</td>
</tr>
<tr>
<td>$H_{120} \rightarrow WW \rightarrow 2\mu2\nu$</td>
<td>87%</td>
<td>64%</td>
</tr>
<tr>
<td>$H_{160} \rightarrow WW \rightarrow 2\mu2\nu$</td>
<td>92%</td>
<td>77%</td>
</tr>
<tr>
<td>$H_{150} \rightarrow ZZ^* \rightarrow 4\mu$</td>
<td>98%</td>
<td>97%</td>
</tr>
<tr>
<td>$H_{200} \rightarrow ZZ \rightarrow 4\mu$</td>
<td>99%</td>
<td>99%</td>
</tr>
</tbody>
</table>

- $W$, $Z$, $t\bar{t}$ efficiency relative events with at least one muon in $|\eta| < 2.1$,
- Higgs efficiency relative to events with $n_\mu \geq 1$ within $|\eta| < 2.1$, and all within $|\eta| < 2.4$. 
Summary

- CMS muon system has been designed with high redundancy for selection and reconstruction,
- High Level Trigger reconstruction already developed, will be very close to the offline reco,
- Fully exploit muon and tracker detectors to give excellent performance in term of resolution and efficiency,
- Still room for further optimization and development,
- Physics performance very promising,

(eagerly) Waiting for first $p+p$ collision!!
Backup Slide
Muon Alignment Issue

- Rate of $\mu$ usable for alignment ($p_t > 50$ GeV from L1 trigger): $0.2 \div 1 \text{ Hz} \approx \mu/$sector
- With perfect knowledge of $B$—field, $\sim 4$ days even at Low luminosity to reach $\sim 200 \, \mu$m precision,
- But with $\Delta B/B \sim 0.1\%$ need several months,
- to achieve $\sim 100 \, \mu$m precision (i.e. better than chamber resolution) years!!
- must have external alignment for $\sim 100 \, \mu$m precision
- web of laser and optical link to align muon detectors also with inner tracker will be present in CMS
- in the endcaps might use halo muons, need special trigger
## Muon Reconstruction Timing

<table>
<thead>
<tr>
<th>algorithm</th>
<th>mean CPU time (ms/event)</th>
<th>mean CPU time (ms/event)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Lumi total</td>
<td>High Lumi total</td>
</tr>
<tr>
<td>L2</td>
<td>640</td>
<td>580</td>
</tr>
<tr>
<td>Calo iso</td>
<td>100</td>
<td>90</td>
</tr>
<tr>
<td>L3</td>
<td>420</td>
<td>590</td>
</tr>
<tr>
<td>Pixel iso</td>
<td>65</td>
<td>320</td>
</tr>
<tr>
<td>Tk iso</td>
<td>190</td>
<td>370</td>
</tr>
<tr>
<td>Total</td>
<td>710</td>
<td>660</td>
</tr>
</tbody>
</table>

- Average CPU time (on **INTEL PIII 1 GHz**) for 1 event passing previous selection,
- expect a factor $2 \times 2 \times 2$ from Moore’s law in 2007,
- most of time spent in propagation in iron with GEANE,
- work in progress to replace it with a fully customizable and optimized propagator, expected major improvement.