Studies on the $e^+e^-$ spectrum with the first data of the CMS experiment at the Large Hadron Collider

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Progetto di Tesi
Dottorato di Ricerca in Fisica XXII ciclo
Fall 2008: LHC starts exploring the TeV region

Essential to do commissioning and early physics at CMS

e+e- spectrum \((p + p \rightarrow e^+ e^- + X)\) allows:

- Calibration of the CMS electromagnetic calorimeter with \(Z \rightarrow e^+ e^-\)
- Early Standard Model physics: \(Z \rightarrow e^+ e^-\) cross-section measurement
- Early Exotic physics: discover/exclude \(Z'\) resonances and investigate the high-mass Drell-Yan spectrum

Up to now: prepared analysis concepts & tools for real data

Plans: develop missing parts, apply to first CMS data
My paper contributions during PhD


2. T. Camporesi et al., “Pre-calibration of the CMS ECAL with cosmic ray muons”, CMS DN-2007/009


4. A. Palma et al., ”Tuning of SuperCluster energy correction for TeV electrons in the ECAL barrel ”, CMS IN-2006/022

5. A. Palma et al.,” Search for Z' gauge bosons in the dielectron channel in CMS “, CMS AN-2006/096

6. J. Brooke et al., ” Search for massive resonance production decaying into an electron or a photon pair”, CMS AN-2007/045

The Large Hadron Collider and CMS
LHC: the physics

- TeV scale can be the realm of a lot of new physics
  - Higgs boson(s), Standard Model–like or not
  - Supersymmetry
  - New gauge bosons: \( W', Z' \)
  - Phenomenology of Extra Dimensions (i.e. mini-Black Holes)
  - Contact interactions

- Crucial to check Standard Model (SM)
  - show that detector behaviour is understood \( \rightarrow \) avoid fake signals
  - Measure SM in unexplored centre-of-mass energy collisions
CERN & LHC: overall views
**LHC: the machine**

- **First collisions:** Fall 08
- **centre-of-mass energy:** 10 TeV in 2008, 14 in 2009

![LHC Diagram]

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Injection</th>
<th>Collisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>TeV</td>
<td>0.45</td>
<td>5.00</td>
</tr>
<tr>
<td>Number of bunches</td>
<td></td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td></td>
<td>4.00E+10</td>
<td>4.00E+10</td>
</tr>
<tr>
<td>RF Voltage</td>
<td>MV</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Longitudinal emittance</td>
<td>eV.s</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Normalised transverse emittance</td>
<td>mum.rad</td>
<td>3.50</td>
<td>3.75</td>
</tr>
</tbody>
</table>

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The CMS detector

Total weight: 12500 T
Overall diameter: 15.0 m
Overall length: 21.5 m
Magnetic field: 4 Tesla
A slice of the CMS detector

Key:
- Muon
- Electron
- Charged Hadron (e.g., Pion)
- Neutral Hadron (e.g., Neutron)
- Photon

Transverse slice through CMS
- Silicon Tracker
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Superconducting Solenoid
- Iron return yoke interspersed with Muon chambers

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CMS electromagnetic calorimeter

- 75,848 PbWO₄ scintillating crystals
- fast response (25 ns between bunches)
- Light Yield (LY): 5 p.e./MeV
- ~0.5% resolution for high energy e/γ

Test beam data: 120 GeV electrons
$e^+e^-$ studies at CMS

$$p + p \rightarrow Z/\gamma^* \rightarrow e^+e^-$$
How to select $Z \rightarrow e^+e^-$ events

- Select events in CMS that:
  1. pass loose electron High Level Trigger (HLT) paths
     - transverse energy deposit in fixed matrices of ECAL crystals ("Towers")
  2. have 2 reconstructed electrons with inv. mass around $Z$ and $p_T > 20$ GeV
     - need to reduce jet contamination from QCD events using i.e. isolation variables

\[ \sum_{\text{track}} \left( \frac{p_T^{\text{track}}}{p_T^{\text{ele}}} \right)^2 < 0.02 \]

$H/E < \sim 0.1$
My PhD project in 1 slide

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Startup calibration of CMS ECAL

- **Barrel** is pre-calibrated using various techniques: cosmic rays (2%), test beam (0.5%), Light Yield (4%)

I have contributed to Barrel calibration [CMS DN-2007/009]

- **Endcaps** are pre-calibrated using LY measurements (~15%)
**In situ Calibration of ECAL with first data**

1. **ϕ-symmetry**
   - Physics (and detector?) is symmetric in azimuthal angle, in each phi-slice energy deposited in ECAL must be the same
   - Use very abundant events: QCD jets and minimum bias
   - With first 10/\( \text{pb} \): brings miscalibration to 8% (useful for Endcaps)

2. **Z→e^+e^-**
   - Ratio of true/measured Z mass gives recalibration coefficient
   - Sets ECAL absolute scale
   - Can be applied to eta-rings or other ECAL regions
   - With first 10/\( \text{pb} \): no improvement if miscalibration is gaussian, but only way to detect local biases and correct for them
Achievable calibration using Z

eta-ring miscalibration

- 3% @ 10/pb
- 1% @ 100/pb
- 0.7% @ 100/pb

\[ p_0 + \frac{p_1}{\sqrt{x}} \]

\[ \chi^2 / \text{ndf} \]

Barrel

Endcaps

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Simulation of calibration with early data

- **CSA08 calibration exercise** (May 2008): 10/pb of data simulated with startup calibration; processed and subdetectors recalibrated (in a few hours)

- **My contribution**: ECAL calibration, successful, results presented to collaboration

http://cms-project-cmsinfo.web.cern.ch/cms-project-cmsinfo/Media/Publications/CMStimes/2008/06_09/index.html
Correct electron response with $Z \rightarrow e^+ e^-$

- Some energy radiated in Bremsstrahlung is not recovered by reconstruction algorithms
- Amount of non-recovered energy depends on Brem. probability (i.e. on material budget of Tracker in front of ECAL) $\rightarrow$ eta-dependence
- Even with perfect ECAL calibration, the Z algorithm allows to correct the energy response of ECAL to electrons
My PhD project in 1 slide

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How to extract a cross-section from CMS

\[
\sigma_s = \frac{N_{tot} - N_b}{A_s \epsilon_s L} = \frac{N_{tot}}{A_s \epsilon_s L} - \frac{A_b \epsilon_b \sigma_b}{A_s \epsilon_s}
\]

- \( N_{tot} \) is the total number of events that pass a certain selection suitable for \( Z \rightarrow e^+e^- \) events
- \( N_b \) is the estimated number of background events in the sample of \( N_{tot} \) events
- \( \epsilon_s (\epsilon_b) \) is the efficiency of the performed selection on signal (background) events
- \( A_s (A_b) \) is the geometrical acceptance of the CMS detector on signal (background) events
- \( \sigma_s (\sigma_b) \) is the cross section of the signal (background)
- \( L \) is the integrated luminosity of the LHC

main systematic uncertainty
5-10% with first data
$Z \rightarrow e^+ e^-$ cross section: simulation

\[\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \rightarrow e^+ e^-) = 1775 \pm 34 \text{ pb}\]

- MC input cross section
- \(~4,000\) evts in 10/pb
- Cross section from analysis

<table>
<thead>
<tr>
<th>$N_{\text{selected}}$</th>
<th>3914 ± 63</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{Background}}$</td>
<td>assumed 0.0</td>
</tr>
<tr>
<td>Tag&amp;Probe $\varepsilon_{\text{total}}$</td>
<td>68.1 ± 0.6 %</td>
</tr>
<tr>
<td>Acceptance</td>
<td>32.39 ± 0.18 %</td>
</tr>
<tr>
<td>Int. Luminosity</td>
<td>10 (pb^{-1})</td>
</tr>
</tbody>
</table>
Optimization of signal selection

- Study w/ all backgrounds, next-to-leading order cross sections
- Work ongoing: plots below just show how important isolation is...

TK iso requested on 2 ele
S/B~170

No track iso requested
S/B~2.5
Fall 2008: LHC starts exploring the TeV region

Essential to do commissioning and early physics at CMS

e⁺e⁻ spectrum allows:

- Calibration of the CMS electromagnetic calorimeter with Z → e⁺e⁻
- Early Standard Model physics: Z → e⁺e⁻ cross-section measurement
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Up to now: prepared analysis concepts & tools for real data

Plans: develop missing parts, apply to first CMS data
What is $Z'$?

- Neutral additional gauge boson
- Predicted in Grand Unified Theories, Dimensional scenarios...
- Various models exist called $Z'\eta$, $Z'\chi$, $Z'\psi$ ...
- Mass is in TeV region, coupling constants are of EW strenght
How should Z' look like?

[A. Palma et al., CMS AN-2006/096]

few evts expected in 10/pb

$M_{Z'} = 1.5$ TeV

VERY low backgd
Signal is outstanding
Search for $Z'\to e^+e^-$: state of the art

CDF Run II Preliminary

Z' masses below 800-950 GeV (model-dep) excluded

NO Z' FOUND YET!
How to look for Z’?

- Look at $e^+e^-$ spectrum at high invariant mass
- Have a pdf that models both SM expected spectrum (bckg only), and a SM+resonance (signal+bckg)
- Build a statistical estimator from ratio of likelihoods

\[
L_f(x_i|\vec{p}) = \prod_{i=1}^{N} f(x_i|\vec{p})
\]

\[
S_L = \sqrt{2\ln(L_{S+B}/L_B)}
\]

this gives evidence for discovery if $>5$, CMS claims Z’ discovery
Conclusions & plans

- LHC scheduled to give collisions in Fall 2008, deliver ~50/pb before 2009
- $e^+e^-$ spectrum allows ECAL calibration and early physics at CMS
- I will apply tools and concepts to real data
- Work ongoing:
  - CALIBRATION: almost done
  - Z CROSS SECTION: optimize event selection (i.e. isolation)
  - Z’ SEARCHES: measure reconstruction efficiencies from data (collaboration with ULB Bruxelles)
Backup slides
ECAL energy resolution

\[ \frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E\, (GeV)}} + \frac{155\, \text{MeV}}{E\, (GeV)} + 0.5\% \]
ECAL calibration

- A hallmark feature of CMS is the high resolution PWO crystal ECAL
  - **Barrel:** $|\eta| < 1.48$
    - 36 Super Modules
    - 61200 crystals (2 x 2 x 23 cm$^3$) – 26$X_0$
  - **Endcaps:** 1.48 < $|\eta|$ < 3.0
    - 4 Dee’s
    - 14648 crystals (3 x 3 x 22 cm$^3$) – 25 $X_0$
  - **Preshower 3$X_0$ (Pb/Si)**

- Calibration aims at the best estimate of the energy of $e/\gamma$’s
  - Achieve/maintain *in situ* the performance measured in test beams

- Energy deposited over different crystals
  \[ E_{e/\gamma} = G F_{e/\gamma} \sum_i c_i E_i \]

  \[ \rightarrow \text{Intercalibration: relative calibration of the channel response} \]
  \[ \rightarrow \text{Particle’s energy reconstruction (geometry and clustering for } e/\gamma \text{’s)} \]
  \[ \rightarrow \text{Global scale calibration} \]

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e+e- events at the LHC

\[ p + p \rightarrow Z/\gamma^* \rightarrow e^+e^- \]

\[ M_{e^+e^-} = \sqrt{(p_{e^+} + p_{e^-})^2} \]
How to calibrate ECAL using $Z \rightarrow e^+ e^-$

- For each event "i":
  - the quantity $\epsilon^i = \frac{1}{2} \left[ \left( \frac{M_{ee}^i}{M_Z} \right)^2 - 1 \right]$ is computed
  - the energy weight of each ECAL region "j" is computed ($w^j$)
  - for each region "j", the quantity $\epsilon^i$ is put in a histogram with weight $w^j$

- After N events, the histogram is fitted with Gaussian and the peak goes in the recalibration coefficient of that region:

$$C_j = \frac{1}{1 + \text{peak}_j}$$

Procedure is iteratively repeated

Elaboration time: ~1min/10K evts/iteration
Convergence of the calibration algorithm

- The algorithm converges when distance between coefficients at iterations “n” and “n-1” gets stable:

\[ d = \frac{1}{N} \sqrt{\sum_{i=1}^{N} (c_n^i - c_{n-1}^i)^2} \]

Energy resolution improves w/ iterations

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Switzerland in 1 slide