Detection of Z' Gauge Bosons in the Di-muon Decay Mode

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Introduction

- \(Z'\) bosons appear in many models beyond SM.
- \(Z' \rightarrow \mu^+\mu^-\) is on list to be studied extensively for Physics TDR:
  - Detailed signal and background studies, with the use of most complex available tools (full simulation, full reconstruction, etc.).
  - As close to reality as possible (background uncertainties, detector misalignment, calibration and B field uncertainties, etc.).
  - Strategy for physics as a function of luminosity.

- Main \(Z'\) physics goals:
  - Understand discovery potential and optimize the search strategy
    • main observable: \(M_{\mu^+\mu^-}\). **This analysis**
  - Work out algorithms to distinguish among models (incl. graviton) and study properties, once discovered **Work in progress**
    • main observables: \(A_{FB}\) on- and off-peak, \(y\), \(\sigma \cdot Br\), \(\Gamma\).
This analysis is discussed in more detail in:

- Analysis note CMS AN 2004/002.
- Talk at PRS meeting, 11 May 2004.

Talks on related subjects by UCLA group (see other references therein):

- A Look at Track Quality Variables Inside Kalman Filter Fits to Tracker and Muon Hits (PRS/$\mu$ meeting, 18 Feb. 2003).
- Status of $Z'$ Background Study for Data Challenge 2004 (PRS/$\mu$ meeting, 1 April 2003).
- Status of a Study of High-Mass Muon Pairs from Drell-Yan, $Z'$, and Gravitons (SUSY/BSM meeting, 7 May 2003).
- Root-Based Muon Analysis - A Users Perspective (Analysis Micro-Workshop, 1 July 2003).
- Progress in Fitting High-Momentum Muons in ORCA (PRS/$\mu$ and SUSY/BSM meetings, 16-17 Sept. 2003).
- Modus Operandi for $Z'$ Analysis (EMU meeting, 10 January 2004).
- Status of a Study of Simulated and Reconstructed $Z'$ Events in CMS (Workshop on Muons at the LHC and Tevatron, 14 April 2004).
Z' → μ⁺μ⁻: signal and backgrounds

- Z's arise in many models:
  - Z_{SSM} in sequential standard model (benchmark toy model);
  - \(Z' = Z_\psi \cos \theta_{E6} + Z_\chi \sin \theta_{E6}\) in E₆ and/or SO(10) models:
    - \(Z_\psi, Z_\chi, Z_\eta (\theta_{E6} = 37.78^\circ)\);
  - \(Z_{LRM}\) and \(Z_{ALRM}\) in left-right symmetric models;
  - etc.

- Limits on the mass:
  - Current: 600-800 GeV;
  - Expected by LHC start-up: \(\leq 1\) TeV.

- Br(Z' → μ⁺μ⁻): 2-8%
  (if no exotic decay channels are open)

- Dominant (and irreducible) background: Drell-Yan production of muon pairs pp → γ/Z⁰ → μ⁺μ⁻.

- Other sources: ZZ, WZ, WW, tt-bar, bb-bar, etc.
  (studied as part of setting up DC04)
Generation and reconstruction

- **Monte Carlo samples:**
  
  *couplings from literature, generated with PYTHIA6.1*
  
  - $Z_{SSM}$, $Z_{\psi}$, $Z_\eta$, $Z_\chi$, $Z_{LRM}$, $Z_{ALRM}$ at 1, 3 and 5 TeV decaying to $\mu^+\mu^-$ (1000 events each);
  
  - Drell-Yan $\mu^+\mu^-$ pairs above 0.2, 0.4, 1, 1.5, 2 and 3 TeV (1000 events each).

- **Simulation and reconstruction:**
  
  *CMSIM 125, ORCA_6_3_0 (no pile-up)*
  
  - apply L1 and HLT requirements ($p_T$ and $\eta$ thresholds et al., except for isolation);
  
  - use MuonAnalysis package as an analysis framework;
  
  - use L1-seeded Global Muon Reconstructor (GMR) for muon identification;
  
  - for off-line reconstruction, refit the GMR-found hits using an optimized combination of tracker-plus-first-muon-station and tracker-only fits (Truncated Muon Reconstructor, TMR) → see three next slides.
Some possible track fitting methods

- Tracker plus full muon system ("Global Muon Reconstructor", GMR)
  - 5 Parameter measurement at inner surface of tracker from backward part of Kalman filter fit to tracker and muon hits (default fitting method).
  - [Link](http://agenda.cern.ch/askArchive.php?base=agenda&categ=a03423&id=a03423s1t0/transparencies) for more information.

- Tracker only
  - Use only tracker hits for Kalman filter. Take measurement from innermost tracker surface.
  - Available as reconstruction option in ORCA (implementation by N. Neumeister).

- Tracker plus first muon station
  - Use tracker and hits from first muon station which contains hits.
Optimization of high-$p_T$ muon track fitting

- Different fitting methods offer certain features:
  - GMR – current default for muons, uses all muon hits.
  - Tracker only – smallest $p_T$-resolution tails, smallest RMS in barrel, and (currently) best pulls.
  - Tracker plus first muon station – best fitted $p_T$-resolution sigma of the 3 methods considered.

- Fits can be compared to choose fit method track-by-track.
  - Kalman filter variables can be used as criteria for replacing bad fits.
  - Currently use tracker-plus-first-muon-station fit, but replace it by tracker-only fit if it has much better probability of $\chi^2$ given N degrees of freedom (about 10% of all tracks).

("Truncated Muon Reconstructor", TMR)

(See J. Mumford’s talks at PRS/μ meetings in February and September 2003 for more details.)
Z_{SSM} (3 TeV) vs Drell-Yan background

TMR has narrower signal, perhaps reduced background tails.

ORCA 6.3.0 Digis
MuonAnalysis package
Note: Optimization algorithm was tuned on different sample.
Event selection

- Both $\mu^+$ and $\mu^-$ should be within $|\eta| < 2.4$ and pass the trigger:
  - Acceptance efficiency: raises from about 80% at 1 TeV to more than 95% at very high $M_{\mu\mu}$ (Figure below);
  - L1/HLT trigger efficiency: about 98% at 1 TeV, about 95% at 5 TeV.

- Require that there are at least two $\mu$’s of opposite charge sign.
- No background-rejection cuts.
- Overall efficiency: 70-75% (1-5 TeV).
Fitting procedure

• Generate ensembles of MC experiments:
  – number of events in each experiment fluctuates according to Poisson distribution with a mean of $\sigma \cdot Br \cdot (\int L dt) \cdot \varepsilon$;
  – appropriately add Drell-Yan contribution from lower masses.

• In each experiment, fit $M_{\mu\mu}$ values using an unbinned maximum likelihood:
  
  $$p(M_{\mu\mu}) = \frac{N_s}{N_{tot}} \cdot p_s(M_{\mu\mu}; m_0, \Gamma) + \left(1 - \frac{N_s}{N_{tot}}\right) \cdot p_b(M_{\mu\mu})$$

  – $p_s$ (signal pdf) is a convolution of a Breit-Wigner with a Gaussian smearing;
  – $p_b$ (background pdf) is an exponential, with the slope parameter determined from fits to Drell-Yan events.

Up to three free parameters: signal fraction ($N_s / N_{tot}$), signal mean ($m_0$), and signal FWHM ($\Gamma$).

No constraints on the absolute background level: fit assumes only background shape is known.
Example: $Z_\psi$ at 1 TeV, $\int L dt = 0.1 \text{ fb}^{-1}$

"Non-fluctuating" mass spectra:
(stat. much larger than expected)
generated and reconstructed

(1 TeV: just above expected
CDF/D0 mass reach;
$\int L dt = 0.1 \text{ fb}^{-1}$: a few days of
LHC low-luminosity running)

Realistic mass spectra:
two typical MC experiments

$S_L = 7.1$

$S_L = 3.6$
Fit results: $m_0$ and $\Gamma$

- **Signal mean mass**: close to true value, small spread. Measured with precision of 4% (at high masses and discovery limit) or better

![Graph 1 TeV Zp, 0.1 fb⁻¹](image1)

1 TeV $Z_p$, $\int L dt = 0.1$ fb⁻¹
Mean mass = 998 GeV; RMS = 19 GeV

![Graph 3 TeV ZSSM, 5 fb⁻¹](image2)

3 TeV $Z_{SSM}$, $\int L dt = 5$ fb⁻¹
Mean mass = 2960 GeV; RMS = 80 GeV

(Still have to account for the radiative tail in the mass distribution in the fits)

- **Signal $\Gamma$**: hard to reconstruct (FWHM dominated by resolution smearing)
Significance estimators (I)

Discussed in detail in V. Bartsch and G. Quast, CMS IN 2003/039

- Use likelihood-ratio estimator $S_L$ to calculate significance of an observed “signal”:

$$S_L = \sqrt{2 \ln \left( \frac{L_{S+B}}{L_B} \right)}, \text{ where}$$

- $L_{S+B}$ is the maximum likelihood from the signal-plus-background fit ($p$),
- $L_B$ is the maximum likelihood from the background-only fit ($p_b$).

Justification:

- In the large-statistics limit, $S_L^2$ is expected to follow a $\chi^2$-distribution with ndof equal to the difference in the number of free parameters between S+B and B-only hypotheses (theorem proved by S.S. Wilks in 1938).
- If ndof is one, then distribution of $S_L$ is a standard Gaussian.
- Therefore, $S_L$ gives the probability (expressed in number of $\sigma$’s) that the pure background fakes a signal (i.e. significance).
Significance estimators (II)

- For comparison with $S_L$, also try a few other commonly used ("counting") estimators:
  
  $$S_{c1} = \frac{N_S}{\sqrt{N_B}},$$
  $$S_{c2} = \frac{N_S}{\sqrt{N_S + N_B}},$$
  $$S_{c12} = 2 \times (\sqrt{N_S + N_B} - \sqrt{N_B}),$$

  (proposed by S. Bityukov and N. Krasnikov)

  $$S_{cL} = \sqrt{2 \ln \left( \frac{1 + N_S/N_B}{N_S + N_B} \exp(-N_S) \right)}.$$ 

  $N_S$ and $N_B$ – number of signal and background events within $m_0 \pm 2\sigma$.

- Usual convention: $S > 5$ is necessary to establish a discovery
  (probability of $2.9 \cdot 10^{-7}$ that the pure background would mimic a signal)
Significance estimators: MC study

- Important caveat: Wilks’ theorem is valid in the large-statistics limit, whereas we are in the small-statistics regime.

Need to check that the tails of $S_L$ distribution for the background-only sample are those of the normal Gaussian.

- Perform a (large) number of background-only MC experiments to obtain the distributions of various definitions of $S$ given above.
- Calculate the probability ($p$-value) of observing a value of $S$ greater than $S_{\text{crit}}$ (how often a false discovery would be claimed for a certain choice of $S_{\text{crit}}$).
- See how well this probability agrees with area in the tail of a Gaussian distribution.
Background to 3 TeV Z' (30 fb$^{-1}$)

1,000,000 MC experiments
$\langle N_{\text{evt}} \rangle$ above 1.5 TeV: 33
$\langle N_{\text{evt}} \rangle$ within $m_0 \pm 2\sigma_m$: 2.3

Fix both $m_0$ and $\Gamma$ to true values
(see Wilks' theorem)

too many events at large $S_{c1}$

Observed:
$S_L > 3$: 1310 events
$S_L > 4$: 38 events
$S_L > 5$: 1 events

Expected for a Gaussian:
Above 3$\sigma$: 1350 events
Above 4$\sigma$: 31.5 events
Above 5$\sigma$: 0.3 events
Significance estimators: MC study

- Check $p$-values for a few other integrated luminosities and signal mass points:
  - in these cases tail of $S_L$ distribution is always consistent with that of a Gaussian;
  - all other $S$ estimators may overestimate or underestimate the probability of a false discovery.

- Also check distributions of $S$ for signal-plus-background fits:
  - $S_{c1} \gg S_L$, $S_{c12} \sim S_L$ for all masses, luminosities, $Z'$ models;
  - $S_L$ is always symmetric and Gaussian-like.

Significance estimator $S_L$ performs as desired for $Z'$ mass reach studies (low background, small statistics regime).

Similarly good performance of $S_L$ was seen by Bartsch and Quast in $H \rightarrow 4\mu$ studies, in a different sig/bknd regime.
$Z_\psi$ at 1 TeV, 0.1 fb$^{-1}$: significance

Fix both $m_0$ and $\Gamma$ to true values to calculate $S_L$

- $S_{c1} >> S_L$
- $S_{c2} < S_L$
- $S_{c12} \leq S_L$

(in agreement with other $Z'$ models, masses, luminosities tried)

- For 0.1 fb$^{-1}$, average $S_L$ is more than 5 for all the $Z'$ models considered.
- TMR reconstruction of high-$p_T$ muons gives $\sim 5\%$ higher $S_L$ (15\% at 3 TeV, 30\% at 5 TeV).
- $S_L$ scales very nicely with $\sqrt{L dt}$. 

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Z' → μ⁺μ⁻: CMS discovery potential

**Z' → μ⁺μ⁻: 5σ significance curves**

**Z' → μ⁺μ⁻ mass reach:**
- > 1 TeV with 0.1 fb⁻¹
- 2.7 – 3.6 TeV with 10 fb⁻¹
- 3.7 – 4.7 TeV with 100 fb⁻¹

(if GMR is used, 100 GeV less with 10 fb⁻¹ and 200 GeV less with 100 fb⁻¹)

**N.B.: no syst. uncertainties**
- Perfect alignment, calibration, B field;
- Background shape, functional forms of pdf’s, mass resolution perfectly known.

ORCA 6.3.0
no pile-up

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A critical look

• Main weak point: systematic uncertainties are not taken into account.
  – Arising from imperfect knowledge of the detector: alignment, magnetic field, calibration, etc.
  – In the fitting procedure: background shape, functional forms of pdf’s, mass resolution, etc.

• Some other items to be improved/checked:
  – Brem photons. Not used in the reconstruction of muon momentum; residual radiative tail not accounted for in the fits.
  – Software. Set of PYTHIA, CMSIM and ORCA is 1.5 years old.
  – Event rates. Given by PYTHIA; need to check $K$-factors.
  – Pile-up. Neglected; effect is expected to be small, but not proven.

_How does this study compare with the previous ones?_
Previous studies of CMS discovery potential (I)

Estimates of the CMS potential to discover $Z'$ were previously reported by four groups/individuals. In chronological order:

- **C.E. Wulz:** *(CMS-TN/93-107 and DPF/DPB Snowmass (1996))*
  - **Tools:** PYTHIA version available at that time; muon momentum smeared using parameterization by W. Ko and J. Rowe *(CMS TN/95-026)*.
  - **Criterion for $Z'$ discovery:** more than 10 signal (di-muon plus di-electron) events in the mass peak.
  - **Conclusion:** it will be possible to discover $Z'$ bosons up to a mass of about 5 TeV with an integrated luminosity of 100 fb$^{-1}$ (in a combined analysis of $Z' \rightarrow \mu^+\mu^-$ and $Z' \rightarrow e^+e^-$ channels).

- **D. Bourilkov:** *(CMS IN-2000/035 and CERN-YR-2000-004)*
  - **Study mainly dedicated to Drell-Yan production of lepton pairs at LHC.**
  - **Tools:** PYTHIA; no further details given.
  - **Conclusion:** “$Z'$ resonances with masses up to ~ 4-5 TeV can be probed at LHC”.
Previous studies of CMS discovery potential (II)

– JINR group (V. Palichik, S. Shmatov et al.):

(hep-ph/0310336, talks at CMS physics (30 April 2002) and SUSY/BSM meetings (7 May 2003); presented at “Physics at LHC”, Prague 2003)

• **Tools:** PYTHIA; muon momentum smeared using parameterization by W. Ko and J. Rowe.

• **Criterion for Z’ discovery:** $S_{c1} > 5$ and at least 10 signal events under the mass peak.

• **Conclusions:** Z’ mass reach is in the range between 2.5 and 3 TeV for an integrated luminosity of 10 fb$^{-1}$, and between 3.5 and 4 TeV for a luminosity of 100 fb$^{-1}$ (for a set of Z’ models similar to one we studied).

– ETH group (M. Dittmar et al.):


• Study focused on observables other than $M_{\mu^+\mu^-}$.

• **Tools:** PYTHIA; no details given on how the stated mass reach was obtained.

• **Conclusion:** “reconfirm the known Z’ boson LHC discovery potential, to reach masses up to about 5 TeV for a luminosity of 100 fb$^{-1}$”.

Previous studies of CMS discovery potential (II)
Comparison with previous studies

This study has two main advantages:

• Full simulation and reconstruction of signal and background; therefore, takes into account:
  – Trigger and track-finding inefficiencies;
  – Charge misassignment;
  – Details of detector acceptance;
  – Momentum and mass resolution, etc.

• Appropriate statistical techniques to quantify the mass reach.

We believe it gives somewhat more justifiable estimates of CMS discovery potential in \( Z' \rightarrow \mu^+\mu^- \) channel, while still suffering from the lack of systematic errors.
Summary

• We have set up a procedure for studying and quantifying the $Z'$ mass reach. Main points:
  – Full simulation (CMSIM) and reconstruction (ORCA6) as input;
  – Unbinned M.L. fits exploring signal and background shapes only;
  – Likelihood-ratio significance estimator, shown to perform as desired.

• We have obtained mass reach estimates in $Z' \rightarrow \mu^+\mu^-$ channel, with systematic uncertainties yet to be accounted for:
  – More than 5$\sigma$ significance above 1 TeV at the earliest stages of data-taking;
  – Average 5$\sigma$ significance at a mass of 3.7-4.7 TeV (depending on the model) with an integrated luminosity of 100 fb$^{-1}$.

• Plan to evaluate systematic uncertainties and their impact, and improve/check other items mentioned earlier.
Acknowledgements

• We would like to thank all the members of CMS who contributed to the software packages used in this study.

• We are particularly grateful to:
  – Norbert Neumeister, for his assistance and numerous useful discussions on reconstruction-related issues.
  – Our referees (Marcos Cerrada, Marcella Diemoz, and Stefano Lacaprara), for careful reading of the note and helpful comments and questions.
Backup slides follow
Background to 5 TeV Z' (300 fb\(^{-1}\))

1,000,000 MC experiments

\( <N_{\text{evt}} > \) above 3 TeV: 7.0
\( <N_{\text{evt}} > \) within \( m_0 \pm 2\sigma_m \): 1.4

too many events in the tails

\( S_L > 3 \): 1343 events
\( S_L > 4 \): 36 events
\( S_L > 5 \): 0 events

Expected for a Gaussian:
Above 3\( \sigma \): 1350 events
Above 4\( \sigma \): 31.5 events
Above 5\( \sigma \): 0.3 events

\( N_S \)/\( \sqrt{N_B} \)
Example at 3 TeV: $Z_{SSM}$ at 10 fb$^{-1}$

"Non-fluctuating" mass spectra: (stat. much larger than expected) generated and reconstructed

Realistic mass spectra: two typical MC experiments

$\sigma_m = 5.7\%$

$S_L = 10.1$

$S_L = 5.6$
Z_{SSM} at 3 TeV, 10 fb^{-1}: significance

- $S_{c1} \gg S_L$
- $S_{c2} < S_L$
- $S_{c12} \sim S_L$

for all $Z'$ models, masses, luminosities tried

Bartsch and Quast also found that $S_{c1}$ badly overestimates true $S$
### Z' at 3 TeV: $S_L$ significance

<table>
<thead>
<tr>
<th>$\int L \cdot dt$</th>
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<th>$Z_{ALRM}$</th>
</tr>
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<tbody>
<tr>
<td>10 fb$^{-1}$ OPT</td>
<td>8.9</td>
<td>3.6</td>
<td>4.3</td>
<td>5.5</td>
<td>6.6</td>
<td>10.6</td>
</tr>
<tr>
<td>10 fb$^{-1}$ GMR</td>
<td>7.7</td>
<td>3.2</td>
<td>3.5</td>
<td>4.7</td>
<td>5.7</td>
<td>9.0</td>
</tr>
<tr>
<td>2 fb$^{-1}$ OPT</td>
<td>3.9</td>
<td>1.5</td>
<td>1.9</td>
<td>2.3</td>
<td>2.9</td>
<td>4.7</td>
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- For 10 fb$^{-1}$, $S$ is more than 5 for most of the Z' models considered;
- For 2 fb$^{-1}$, $S$ is less than 5 for all models;
  - $S_L$ scales nicely with $\sqrt{L_{int}}$
- TMR reconstruction of high-$p_T$ muons helps (~15% gain).
Example at 5 TeV: $Z_\psi$ at 100 fb$^{-1}$

"Non-fluctuating" mass spectra: (stat. much larger than expected) generated and reconstructed

Background flattens out with mass; how well can it be controlled?

Realistic mass spectra: two typical MC experiments

B-only fit

S+B fit

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### Z' at 5 TeV: $S_L$ significance

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<tr>
<td>100 fb$^{-1}$ OPT</td>
<td>2.9</td>
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</tr>
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</table>

- For 100 fb$^{-1}$, $S$ is less than 5 for all Z' models considered;
- For 300 fb$^{-1}$, $S$ is still less than 5 for most of the models;
- Again, TMR reconstruction results in a higher $S$ (by $\sim$ 30%).