Studies of Diboson Production and Triple Gauge Coupling at LHC

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Outline

- Introduction
 - Diboson production at LHC
 - Triple gauge boson couplings
- Studies with full simulation data
 - WZ, ZZ from CMS
 - WZ, WW and ZZ from ATLAS
- Summary

Diboson Production at Hadron Machine

- LO Feynman diagram, $V_1, V_2, V_3 = Z, W, \gamma \rightarrow WW, ZW, ZZ, W\gamma$.
- Only **s** channel has three boson vertex
- Diboson final states have predictable $\sigma_{\text{production}}$ and **manifest the gauge boson coupling**

SM:

- **Pure neutral** vertexes $ZZZ, ZZ\gamma$ are **forbidden** (Z/γ carry no charge and weak isospin that needed for gauge bosons couple)
- Only charged couplings **$WW\gamma, WWZ$** are allowed

Study of WZ, WW and ZZ at LHC

- s-channel dominates, $\sigma(\text{SM}) = 57.7 \text{ pb}$
- Sensitive only to **WWZ** coupling
- Clean signal **eee**, **ee μ** , **$\mu\mu e$** , **$\mu\mu\mu$**
- 3 isolated high p_T leptons with large $E_T(\text{miss})$

- $\sigma(\text{SM}) = 127.5 \text{ pb}$
- Sensitive to **WWZ** and **WW γ**
- Clean signal **ee**, **$\mu\mu$** , **$e\mu$**
- 2 isolated high p_T leptons with opposite charge and large missing E_T

- s channel suppressed by $O(10^{-4})$
- Only t-channel at tree level, $\sigma(\text{SM}) = 16.8 \text{ pb}$
- 4 isolated high p_T leptons from the Z pair decays
- Clean signal **eeee**, **ee $\mu\mu$** , **$\mu\mu\mu\mu$** , almost bkg free

Triple Gauge Boson Couplings

- Characterized by an effective Lagrangian, parameterized in terms of coupling parameters for new physics

$$\begin{aligned}
 L_{WWW} / g_{WWW} = & ig_1^V (W_{\mu\nu}^+ W^{\mu\nu} V^\nu - W_\mu^+ V_\nu W^{\mu\nu}) \\
 & + i\kappa_V W_\mu^+ W_\nu V^{\mu\nu} + i \frac{\lambda_V}{M_W^2} W_{\lambda\mu}^+ W_\nu^\mu V^{\nu\lambda} \\
 & - g_4^V W_\mu^+ W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
 & + g_5^V \varepsilon^{\mu\nu\rho\alpha} (W_{\mu\nu}^+ \vec{\partial}_\rho W_\nu) V_\alpha \\
 & + i\tilde{\kappa}_V W_\mu^+ W_\nu \tilde{V}^{\mu\nu} + i \frac{i\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^+ W_\nu^\mu \tilde{V}^{\nu\lambda}
 \end{aligned}$$

- C , P and CP symmetry conservation, **5** free parameters:
 - $\lambda_\gamma, \lambda_Z$: grow with s , big advantage for LHC
 - $\Delta\kappa_\gamma = \kappa_\gamma - 1$, $\Delta g_1^Z = g_1^Z - 1$, $\Delta\kappa_Z = \kappa_Z - 1$: grow with $\sqrt{s}$
- Tree level SM: $\lambda_\gamma = \lambda_Z = \Delta\kappa_\gamma = \Delta g_1^Z = \Delta\kappa_Z = 0$

Anomalous Coupling and Form Factor

- Cross section increase for coupling with non-SM values, yielding large cross section at high energies that violating tree level unitarity $\rightarrow$ form factor scale

$$a(s) = \frac{a_0}{(1 + s / \Lambda_{FF}^2)^2}$$

s : subprocess CM energy. Λ : form factor scale

- **TGCs** manifest in
 - cross section enhancement
 - high $p_T(V=Z,W,\gamma)$
 - production angle

LHC Expectations for the TGCs

LHC

- High CM energy $\rightarrow$ larger σ
 - High luminosity $\rightarrow$ high statistics
 - High sensitivity
- $\rightarrow$ Expected to be $\sim \times 10$ improvement on LEP/Tevatron

Predictions for TGCs at 95% C.L. for $L=30 \text{ fb}^{-1}$ (inc syst)

$$-0.0035 < \lambda_\gamma < +0.0035$$

$$-0.0073 < \lambda_Z < +0.0073$$

$$-0.075 < \Delta\kappa_\gamma < +0.076$$

$$-0.11 < \Delta\kappa_Z < +0.12$$

$$-0.86 < \Delta g_Z^1 < +0.011$$

Motivations

- Measure dibson production σ and **TGCs**
- **Explore** none-Abelian $SU(2) \times U(1)$ gauge structure of **SM** and test the central part of the SM
- **Probe new physics** if production cross section, or TGCs deviate from SM prediction $\rightarrow$ complementary to direct search for new physics
- **Understand the backgrounds of many important physics** analyses
Search for Higgs, SUSY, graviton and study of $t\bar{t}b\bar{a}$

Diboson as Background

Signal and Background Samples (CMS)

		$\sigma \times \text{Br}$	k-factor
Signal	$ZZ(4e)$	18.7 fb	1.3
	$WZ(3l, l=e, \mu, \tau)$	1.6 pb	1.92
Main bkg	$t\bar{t}(2l)$	62.3 pb	1.6
	$Z(ee)b\bar{b}$	60.3 pb	2.4
	$Z(\mu\mu)b\bar{b}$	60.3 pb	2.4
	$t\bar{t}(4e)$	194 fb	1.6
	$ZZ(2e2\mu)$	32.3 fb	1.35

$t\bar{t}(2l)$ generated with TopReX, $Zb\bar{b}$ with CompHEP, all others with Pythia

WZ→3l Expected Signal & Background

- M(l+l-) after all cuts 4 channels combined (3e,2e1μ,2μ1e,3μ)
- Presence of peaking backgrounds
 - Zbb
 - ZZ (irreducible)
- High significance in the first 1 fb⁻¹

Expected signal and background yields for 1 fb⁻¹

	$e^{\pm}e^{+}e^{-}$	$\mu^{\pm}e^{+}e^{-}$	$e^{\pm}\mu^{+}\mu^{-}$	$\mu^{\pm}\mu^{+}\mu^{-}$	Total	Efficiency, %
$W^{\pm}Z^0 \rightarrow \ell^{\pm}\ell^{+}\ell^{-}$	14.8	26.9	28.1	27.0	96.8	6.1
Z^0Z^0	0.63	1.54	1.50	1.51	5.19	4.7
$t\bar{t}$	0.93	1.55	–	0.31	2.79	0.02
$\mu^{+}\mu^{-}b\bar{b}$	–	–	6.54	4.9	11.4	0.005
$e^{+}e^{-}b\bar{b}$	1.21	1.82	–	–	3.03	0.005
Total background	2.8	4.9	8.0	6.7	22.5	–
S_L	5.3	7.3	6.5	6.6	12.8	–

$ZZ \rightarrow 4e$ Expected Signal & Background

$M(e^+e^-)$ after all cuts
(2 entries per event)

Nearly background free!

Expected signal and background yields for 1 and 10 fb⁻¹

	Efficiency, %	$N_{\text{events}}/1\text{fb}^{-1}$	$N_{\text{events}}/10\text{fb}^{-1}$
$Z^0 Z^0$	38	7.1	71.1
$Z^0 \gamma^*$	4.5	0.16	1.60
$Z^0 b\bar{b}$	0.07	0.08	0.84
$t\bar{t}$	0.06	0.12	1.22
Total background	—	0.36	3.66
S_L	—	4.8	13.1

WZ and ZZ Discovery Potential (CMS)

ZZ → 4e signal significance

WZ → 3l signal significance

5 σ discovery at:

- **ZZ : $\sim 1 \text{ fb}^{-1}$**
- **WZ : $\sim 150 \text{ pb}^{-1}$**

$$S_L = \sqrt{2 \ln Q}, \quad Q = \left(1 + \frac{N_S}{N_B}\right)^{N_S + N_B} e^{-N_S}$$

MC Data for Diboson Studies(ATLAS)

Process	MC data	Process	MC data
$ZW^+ \rightarrow 2e/2\mu + X$	26033	$t\bar{t} \rightarrow \ell + X$	1.96×10^5
$ZW^- \rightarrow 2e/2\mu + X$	29085	$Z(@Peak) \rightarrow ee/\mu\mu/\tau\tau$	2.30×10^6
$ZZ \rightarrow 4e, 4\mu, 2e2\mu$	19933	$W \rightarrow e/\mu/\tau + \nu$	1.61×10^6
$WW \rightarrow \ell\nu + X$	32056	$W+jet \rightarrow \ell\nu + X$	1.59×10^6
$ZZ(pythia) \rightarrow 4\ell (e,\mu)$	4.66×10^4	$Z+jet \rightarrow ee/\mu\mu/\tau\tau$	5.80×10^6
$Zbb \rightarrow 4\ell$	4.99×10^4	$DY \ Z/\gamma \rightarrow \ell^+ \ell^- (e, \mu, \tau)$	1.67×10^7
$Z\gamma \rightarrow \ell\ell (e,\mu)$	2.50×10^4		

- Data produced in ATLAS GRID, and Michigan ATLAS computer cluster
- Background (pythia 6.2), $10^6 \sim 10^7$ for Z+jet, W+jet, DY, W+jet and W→lepton
- Signal events produced by MC@NLO (v2.3)-Jimmy, **W/Z width effect is not included** (v3.1 has included width)

WZ

WW

ZW Signal and Backgrounds (ATLAS)

(for 1 fb⁻¹ data)

	N_{eee}	$N_{ee\mu}$	$N_{\mu\mu e}$	$N_{\mu\mu\mu}$	$N_{\text{total}}(1\text{fb}^{-1})$
N_{signal}	16.9	17.1	21.9	19.8	75.7
N_{bkg}	1.71	0.88	1.73	2.00	6.32
S/B	9.84	19.4	12.7	9.92	12.0
$S/\sqrt{B}$	12.9	18.2	16.7	14.0	30.1

WW Signal and Background (ATLAS)

(for 1 fb⁻¹ data)

<i>Process</i>	N_{ee}	$N_{\mu\mu}$	$N_{e\mu}$	N_{total}
$WW \rightarrow l\nu + X$ ($l=e,\mu$)	36.7	37.6	284.4	358.7
Total background	188.6	112.1	59.4	360.1
S/B	0.19	0.34	4.79	1.0
$S/\sqrt{B}$	2.67	3.55	36.9	18.9

Invariant Mass and Pt Distributions for ZZ

For 1 fb^{-1} data at ATLAS

- 13 events candidates
- Background **free** with current statistics

Boosted Decision Trees (BDT) and Artificial Neural Network (ANN)

—signal —background

ATLAS

e-boost

ANN

Comparison of the efficiencies of BDT/ANN

Summary

- ZZ, WZ and WW signals are expected to be **established** at CMS and ATLAS with $100\text{pb}^{-1}\sim 1\text{fb}^{-1}$

Expected signal and background with 1fb^{-1} data at CMS/ATLAS

	CMS (N_s/N_b)	ATLAS (N_s/N_b)
WW	$\times$	284.4/59.4 ($e\mu$)
ZZ	7.1/0.4 ($4e$)	13/0 ($4e, 4\mu, 2e2\mu$)
WZ($3l, l=e, \mu$)	97/23	75.7/6.3

- Anonymous gauge boson coupling can be probed with a few fb^{-1} data
- To improve the TGC's with LHC data, it's **crucial** to build the TGCs into **MC@NLO** event generator

Backup Slides

Length: ~ 46 m
 Radius : ~ 12 m
 Weight : ~ 7000 tons
 Channels: $\sim 10^8$
 $L_{\text{cable}}: \sim 3000$ km

ATLAS

EM Calorimetry

- $\sigma/E \sim 10\%/\sqrt{E(\text{GeV})} \oplus 1\%$
- $|\eta| < 3.2, |\eta| < 2.5$ (fine granularity)

Solenoid

Forward Calorimeters

End Cap Toroid

Muon spectrometer

- $\sigma/p_T \sim 2-7\%$
- $|\eta| < 2.7, |\eta| < 2.5$ (precision phys.)

Central solenoid

- 2 T

Inner detector

- $\sigma/p_T \sim 0.05\% p_T(\text{GeV}) \oplus 0.1\%$
- $|\eta| < 2.5$

Hadron Calorimeter

- $\sigma/E \sim 50\%/\sqrt{E(\text{GeV})} \oplus 3\%$
- $|\eta| < 3$

Shielding

EM calorimeter:

- Lead tungstate
- $\sigma/E = 5\% / \sqrt{E} \text{ (GeV)} \oplus 2\%$

Magnet solenoid

- 4 T

Muon spectrometer

- DT+CSA+RPC

Hadron Calorimeters

- Barrel & Endcap:
- Cu/Scintillating sheets
- $s/E = 65\% / \sqrt{E} \text{ (GeV)} \oplus 5\%$

Inner Detector:

- Silicon pixels and strips

magnet
yoke

Triple Gauge Boson Couplings

non-abelian $SU(2)_L \times U(1)_Y$
gauge group (foundation of SM!)

Open window to electroweak
symmetry breaking mechanism

LHC: orders of magnitude
Improvement over LEP/Tevatron

Expected 95% C.L. constraints contours (outer $\rightarrow$ inside):
(14 TeV, 100 fb $^{-1}$), (28 TeV, 100 fb $^{-1}$), (14 TeV, 1000 fb $^{-1}$), (28 TeV, 1000 fb $^{-1}$)

Quartic Gauge Boson Couplings

100fb⁻¹

6000fb⁻¹

100fb⁻¹

6000fb⁻¹

Systematic Uncertainties (CMS)

WZ

Systematic source	Cross section	Significance
Luminosity	10.0	—
Trigger efficiency	1.0	1.0
Electron identification	2.6	5.2
Muon identification	3.4	6.8
Jet energy scale	5.0	5.0
$Z^0 b\bar{b}$ subtraction	12.0	12.0
$Z^0 Z^0 \rightarrow 4l$ subtraction	4.0	4.0
PDF uncertainty	—	3.5
Total	17.4	20.8

ZZ

Systematic uncertainties on cross section

Source of systematic uncertainty	$\int Ldt = 1 \text{ fb}^{-1}$	$\int Ldt = 10 \text{ fb}^{-1}$
Luminosity	10.0	5.0
Trigger efficiency	1.0	1.0
Background subtraction	0.6	0.6
$Z^0 \gamma^*$ subtraction	1.2	1.2
Electron identification	4×2.0	4×1.5
Total	12.9	7.9

Systematic uncertainties on significance

Source	$\int Ldt = 1 \text{ fb}^{-1}$	$\int Ldt = 10 \text{ fb}^{-1}$
Trigger efficiency	1.0	1.0
Background subtraction	0.6	0.6
$Z^0 \gamma^*$ subtraction	1.2	1.2
Electron identification	4×2.0	4×1.5
PDF and QCD scale factor	6.4	6.4
Total	18.4	14.9