Studies of Diboson Production and Triple Gauge Coupling at LHC

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On behalf of ATLAS and CMS

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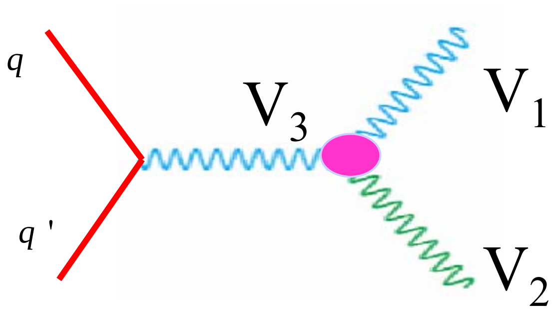
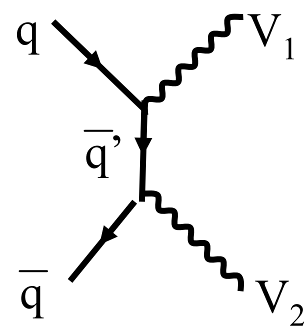
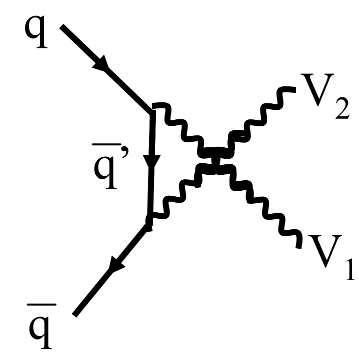
Outline

- 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





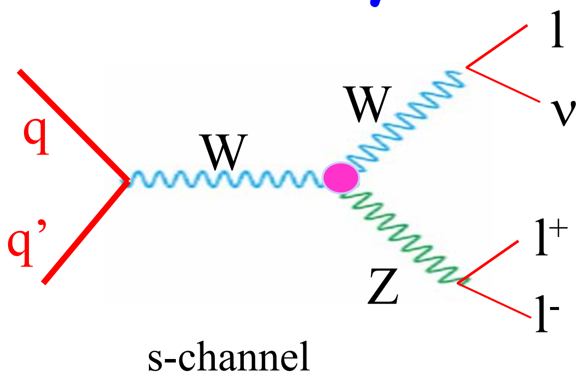


- LO Feynman diagram, V_1, V_2, V_3 = Z, W, $\gamma \rightarrow$ WW, ZW, ZZ, Wγ.
- Only s channel has three boson vertex
- Diboson final states have predictable $\sigma_{production}$ and manifest the gauge boson coupling

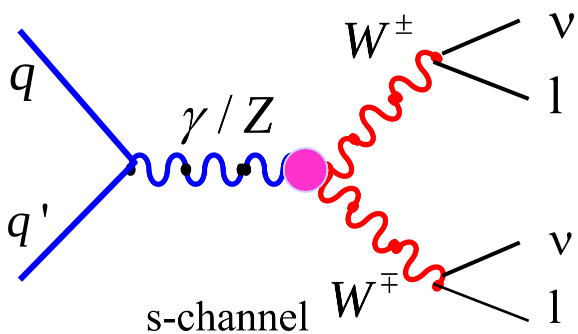
SM:

- Pure neutral vertexes ZZZ, ZZγ are forbidden (Z/γ carry no charge and weak isospin that needed for gauge bosons couple)
- Only charged couplings WWγ, WWZ are allowed

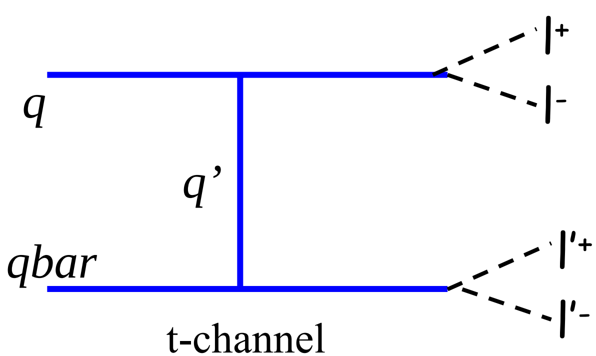
Study of WZ, WW and ZZ at LHC



- s-channel dominates, σ(SM) = 57.7 pb
- Sensitive only to WWZ coupling
- Clean signal eee, eeμ, $\mu\mu$e, $\mu\mu\mu$
- 3 isolated high p_T leptons with large E_T(miss)

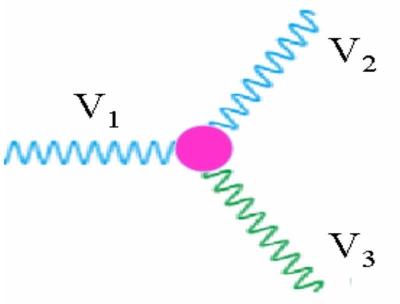


- σ(SM) = 127.5 pb
- Sensitive to WWZ and WWγ
- Clean signal ee, $\mu\mu$, eμ
- 2 isolated high p_T leptons with opposite charge and large missing E_T



- s channel suppressed by O(10^{-4})
- Only t-channel at tree level, σ(SM) = 16.8 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



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

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

- C, P and CP symmetry conservation, 5 free parameters:
  - λ_γ ,λ_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 ✸ form factor scale

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

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 ✹ larger σ
- High luminosity ✹ high statistics
- High sensitivity

✹ Expected to be ~×10 improvement on LEP/Tevatron

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

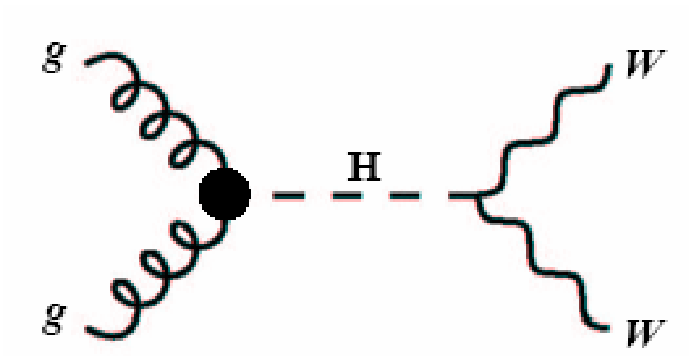
$-0.0035 < \lambda_\gamma < +0.0035$
$-0.0073 < \lambda_Z < +0.0073$
$-0.075 < \Delta\kappa_\gamma < +0.076$
$-0.11 < \Delta\kappa_Z < +0.12$
$-0..86 < \Delta g^1_Z < +0.011$

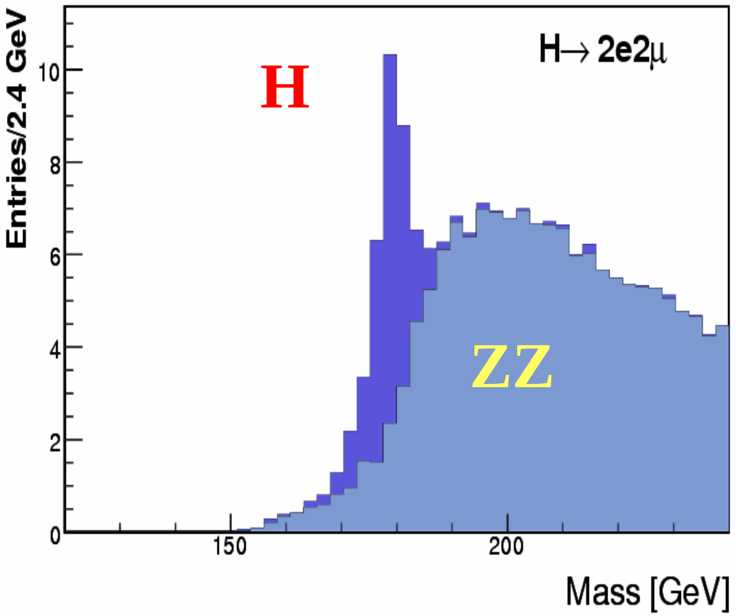
Motivations

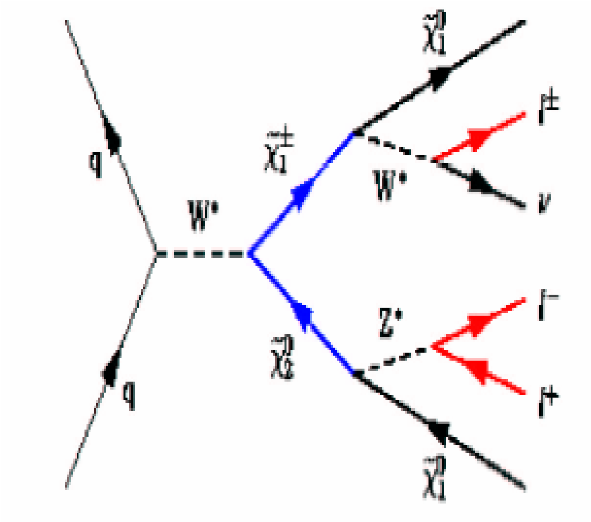
- Measure dibson production σ and TGCs
- Explore none-Abelian $SU(2)\otimes U(1)$ gauge structure of SM and test the central part of the SM
- Probe new physics if production cross section, or TGCs deviate from SM prediction $\rightarrow$ complementary to direct search for new physics
- Understand the backgrounds of many important physics analyses

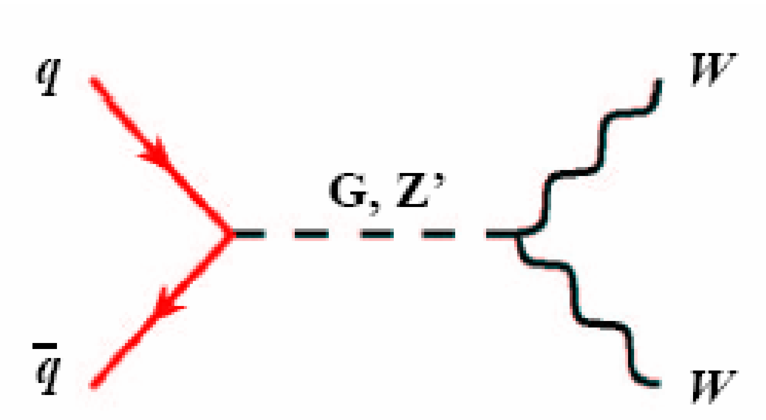
  Search for Higgs, SUSY, graviton and study of ttbar

Diboson as Background







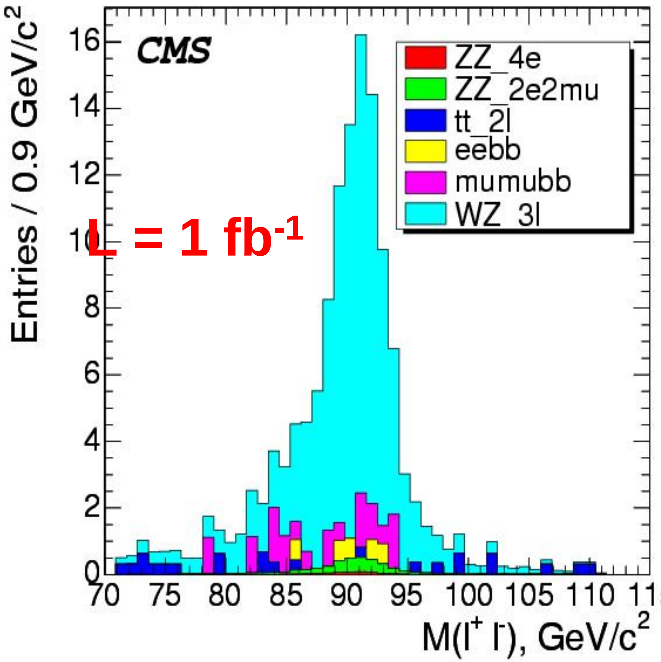


Signal and Background Samples (CMS)

		$\sigma\times Br$	k-factor
Signal	ZZ(4e)	18.7 fb	1.3
Signal	WZ(3l, l=e,μ,τ)	1.6 pb	1.92
Main bkg	ttbar(2l)	62.3 pb	1.6
Main bkg	Z(ee)bb	60.3 pb	2.4
Main bkg	Z($\mu\mu$)bb	60.3 pb	2.4
Main bkg	ttbar(4e)	194 fb	1.6
Main bkg	ZZ(2e2μ)	32.3 fb	1.35

tt(2l) generated with TopReX, Zbb 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}

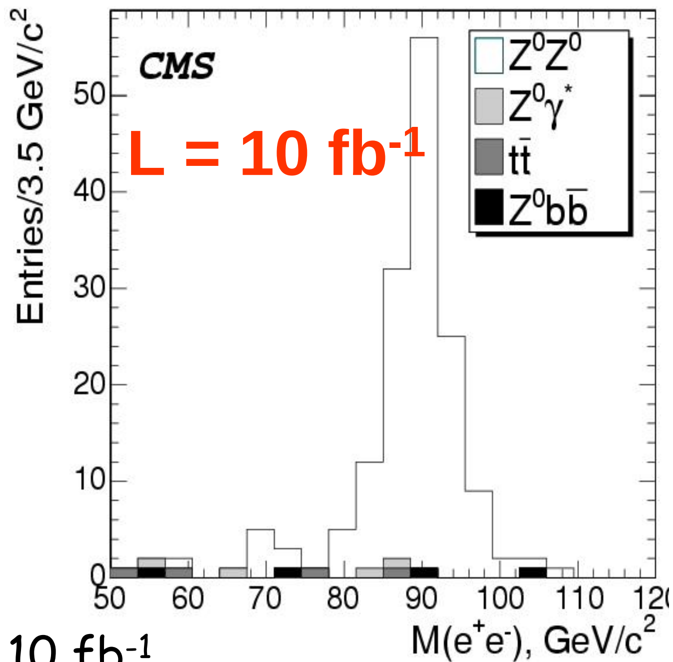
Expected signal and background yields for 1 fb^{-1}

	$e^\pm e^+ e^-$	$\mu^\pm e^+ e^-$	$e^\pm \mu^+ \mu^-$	$\mu^\pm \mu^+ \mu^-$	Total	Efficiency, %
$W^\pm Z^0 \to \ell^\pm \ell^+ \ell^-$	14.8	26.9	28.1	27.0	96.8	6.1
$Z^0 Z^0$	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!

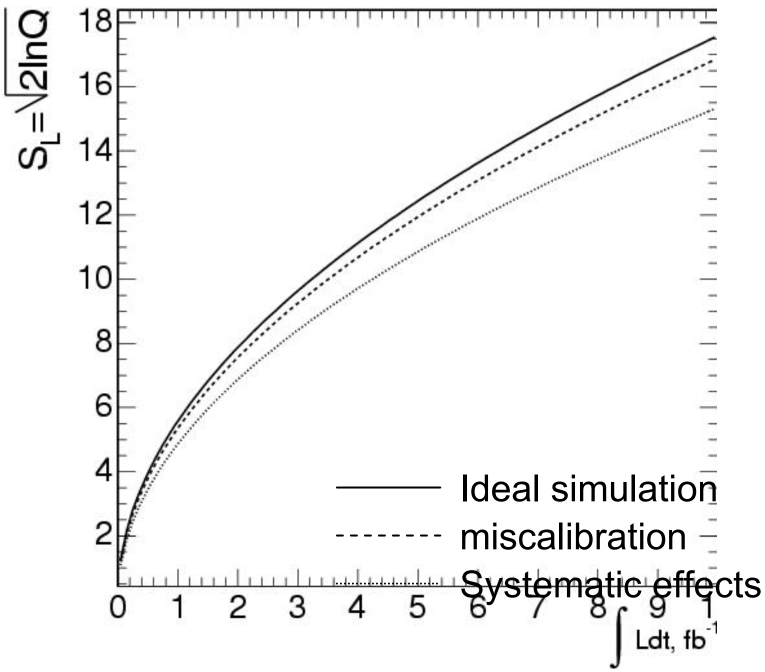


Expected signal and background yields for 1 and 10 fb^{-1}

	Efficiency, %	$N_{events}/1fb^{-1}$	$N_{events}/10fb^{-1}$
Z^0Z^0	38	7.1	71.1
$Z^0\gamma^*$	4.5	0.16	1.60
$Z^0b\bar{b}$	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

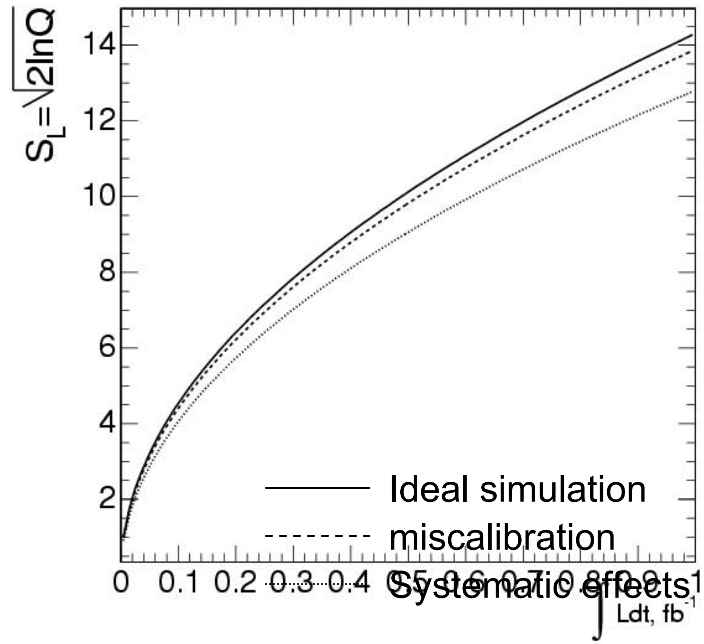
WZ and ZZ Discovery Potential (CMS)

ZZ→4e signal significance



0

WZ →3l signal significance



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

5 σ discovery at:

- **ZZ : ~1 fb^{-1}**
- **WZ : ~150 pb^{-1}**

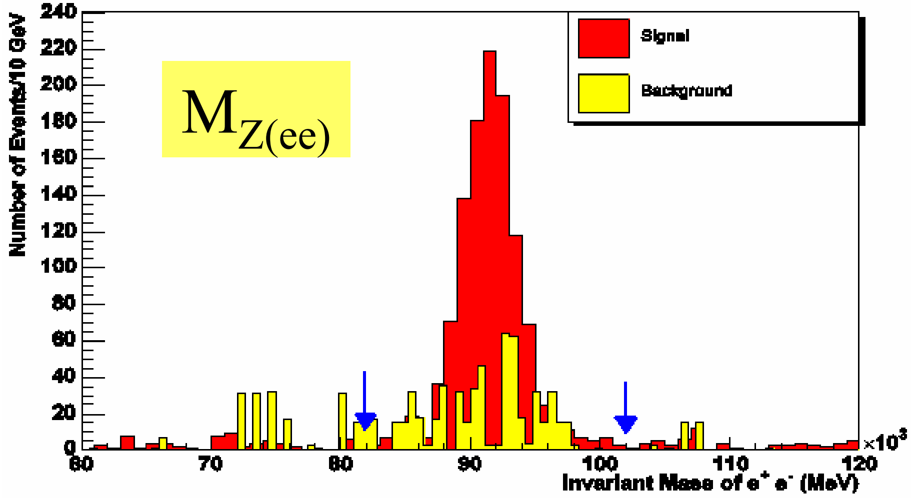
MC Data for Diboson Studies(ATLAS)

Process	MC data	Process	MC data
$ZW^+ \rightarrow 2e/2\mu + X$	26033	ttbar $\rightarrow \ell + x$	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	$W \rightarrow e/\mu/t + \nu$	1.61×10^6
$WW \rightarrow \ell\nu + x$	32056	W+jets $\rightarrow \ell\nu + x$	1.59×10^6
ZZ(pythia) $\rightarrow 4\ell$ (e,μ)	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, μ, τ)	1.67×10^7
$Z\gamma \rightarrow \ell\ell$ (e,μ)	2.50×10^4		

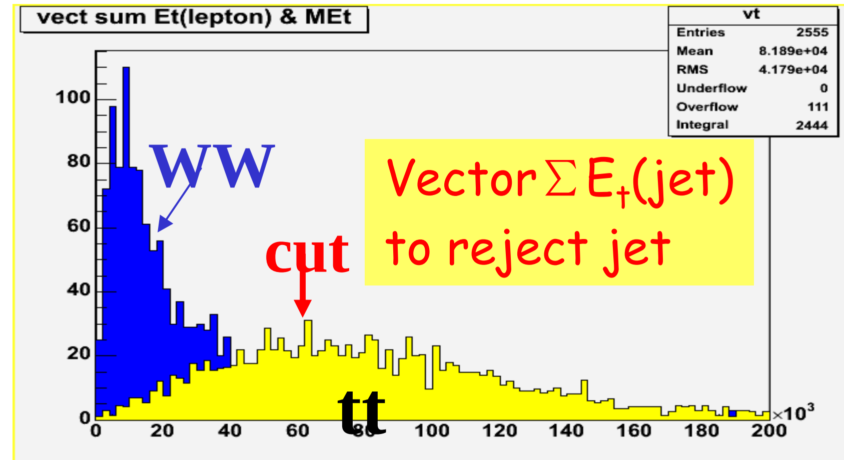
- Data produced in ATLAS GRID, and Michigan ATLAS computer cluster
- Background (pythia 6.2), $10^6 \sim 10^7$ for Z+jet, W+jet, DY, W+jet and W✸lepton
- Signal events produced by MC@NLO (v2.3)–Jimmy, W/Z width effect is not included (v3.1 has included width)

WZ

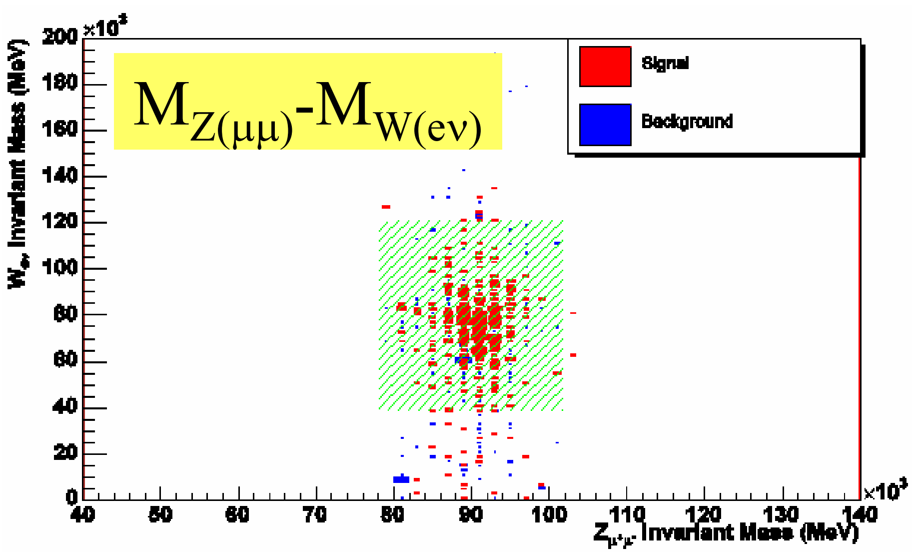
WW



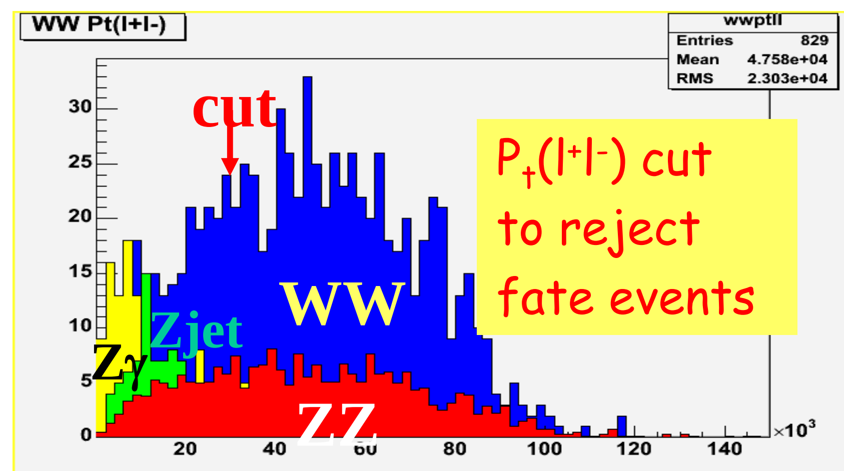
Number of Events/10 GeV
Signal
Background
$M_{Z(ee)}$
Invariant Mass of e⁺ e⁻ (MeV)
×10³



vect sum Et(lepton) & MEt
vt
Entries 2555
Mean 8.189e+04
RMS 4.179e+04
Underflow 0
Overflow 111
Integral 2444
WW
cut
tt
Vector ΣE_t(jet)
to reject jet
×10³



$W_{e\nu}$ Invariant Mass (MeV)
Signal
Background
$M_{Z(\mu\mu)}$-$M_{W(e\nu)}$
$Z_{\mu^+\mu^-}$ Invariant Mass (MeV)
×10³

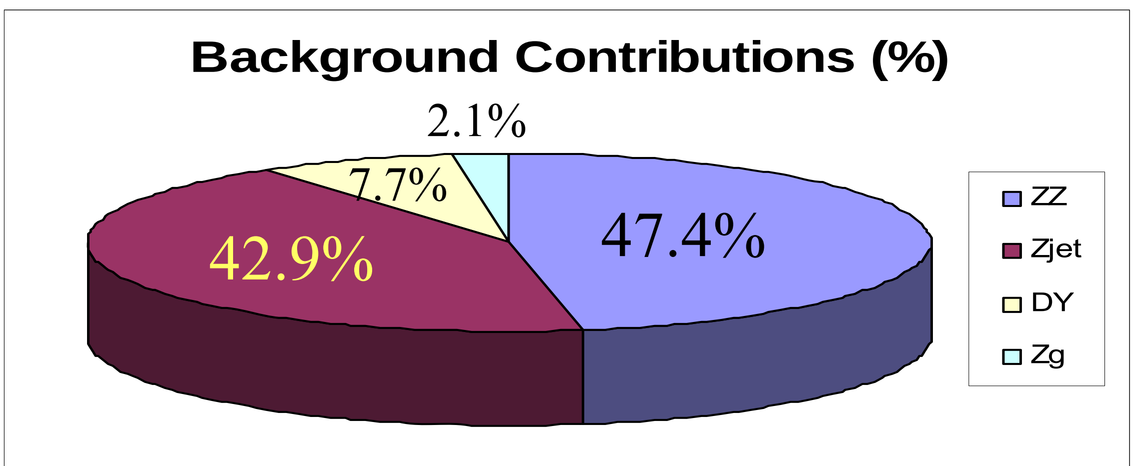


WW Pt(l+l-)
wwptll
Entries 829
Mean 4.758e+04
RMS 2.303e+04
cut
$P_t(l^+l^-)$ cut
to reject
fate events
WW
Zjet
Zγ
ZZ
×10³

ZW Signal and Backgrounds (ATLAS)

(for 1 fb^{-1} data)

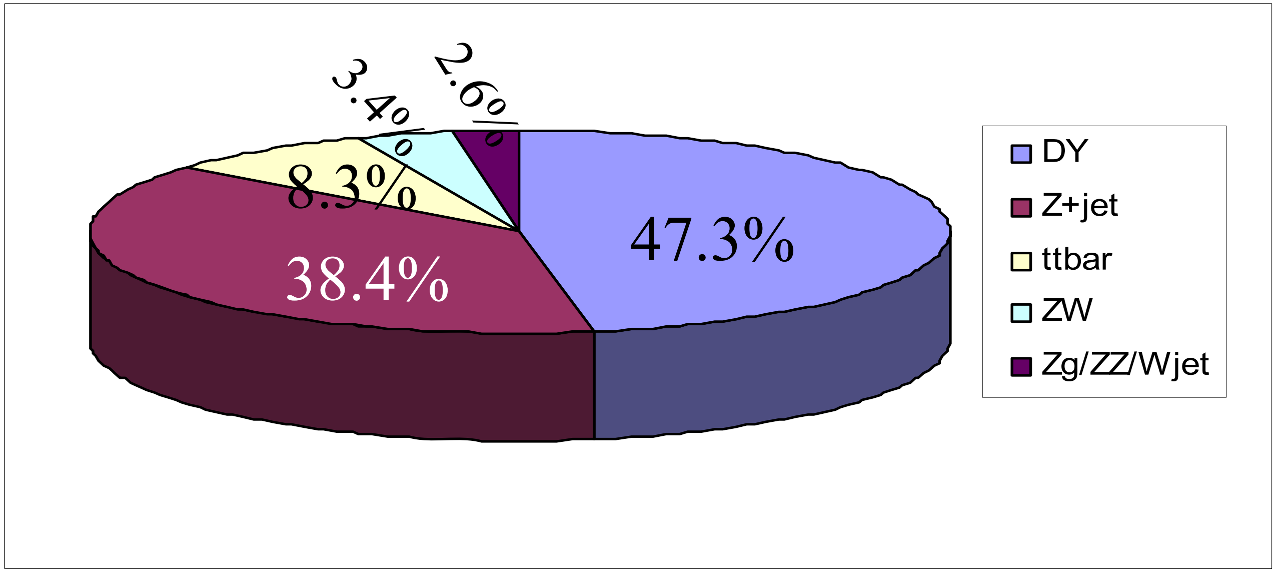
	N_{eee}	$N_{ee\mu}$	$N_{\mu\mu e}$	$N_{\mu\mu\mu}$	$N_{total}(1fb^{-1})$
N_{signal}	16.9	17.1	21.9	19.8	75.7
N_{bkg}	1.71	0.88	1.73	2.00	6.32
S/B	9.84	19.4	12.7	9.92	12.0
S/⌧B	12.9	18.2	16.7	14.0	30.1



WW Signal and Background (ATLAS)

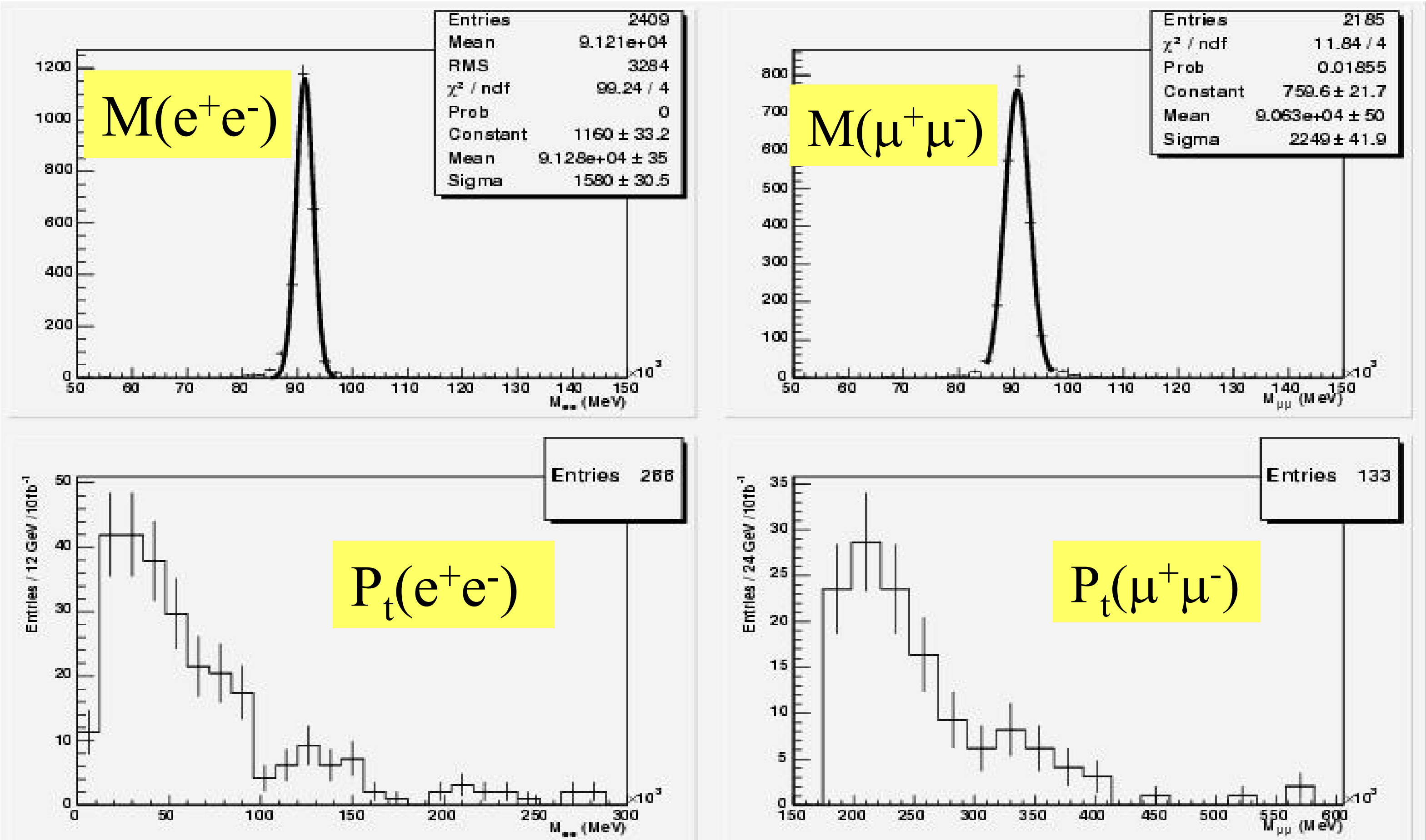
(for 1 fb^{-1} data)

Process	N_{ee}	$N_{\mu\mu}$	$N_{e\mu}$	N_{total}
WW✸lν+X (l=e,μ)	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/⌧B	2.67	3.55	36.9	18.9



Invariant Mass and Pt Distributions for ZZ

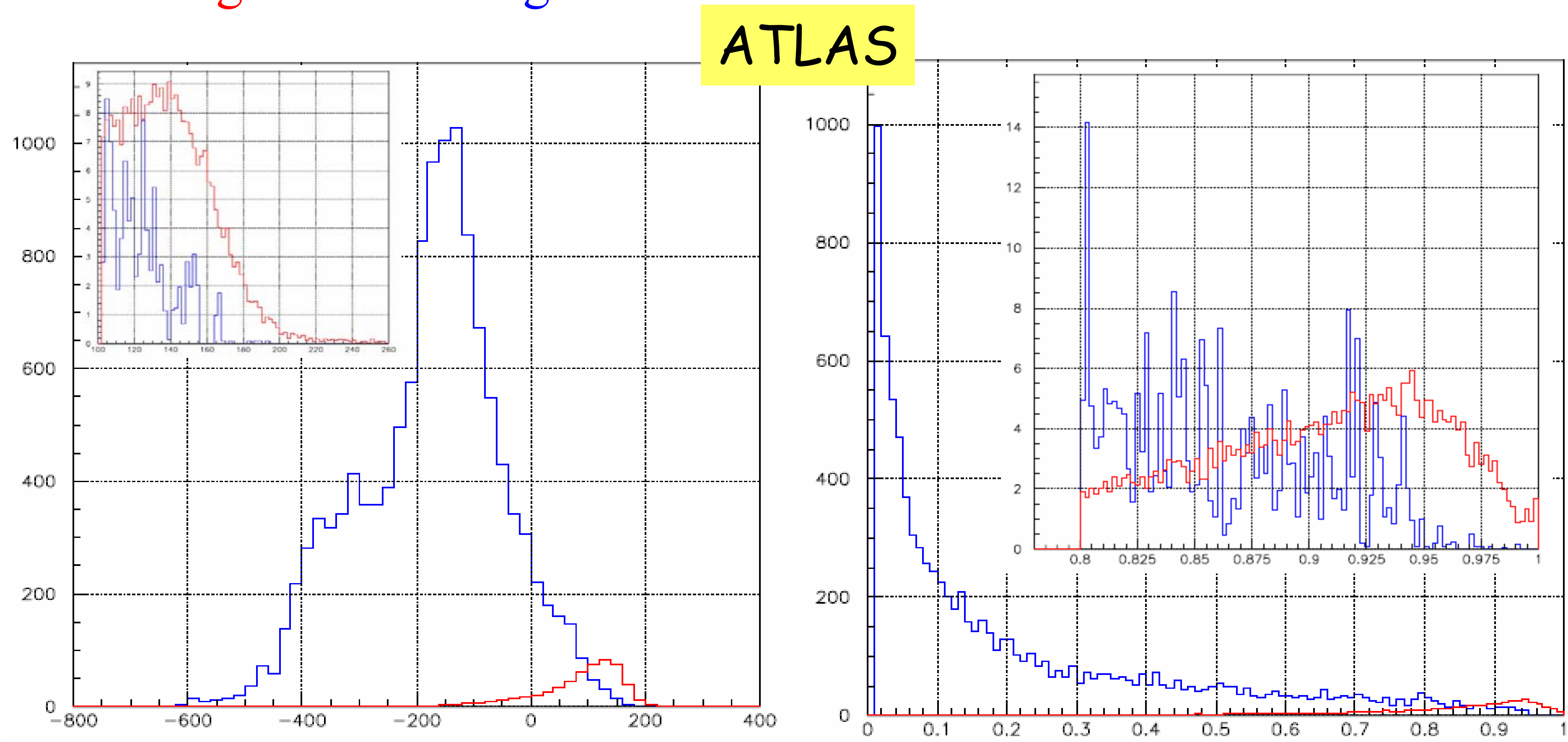
For 1 fb^{-1} data at ATLAS



- 13 events candidates
- Background free with current statistics

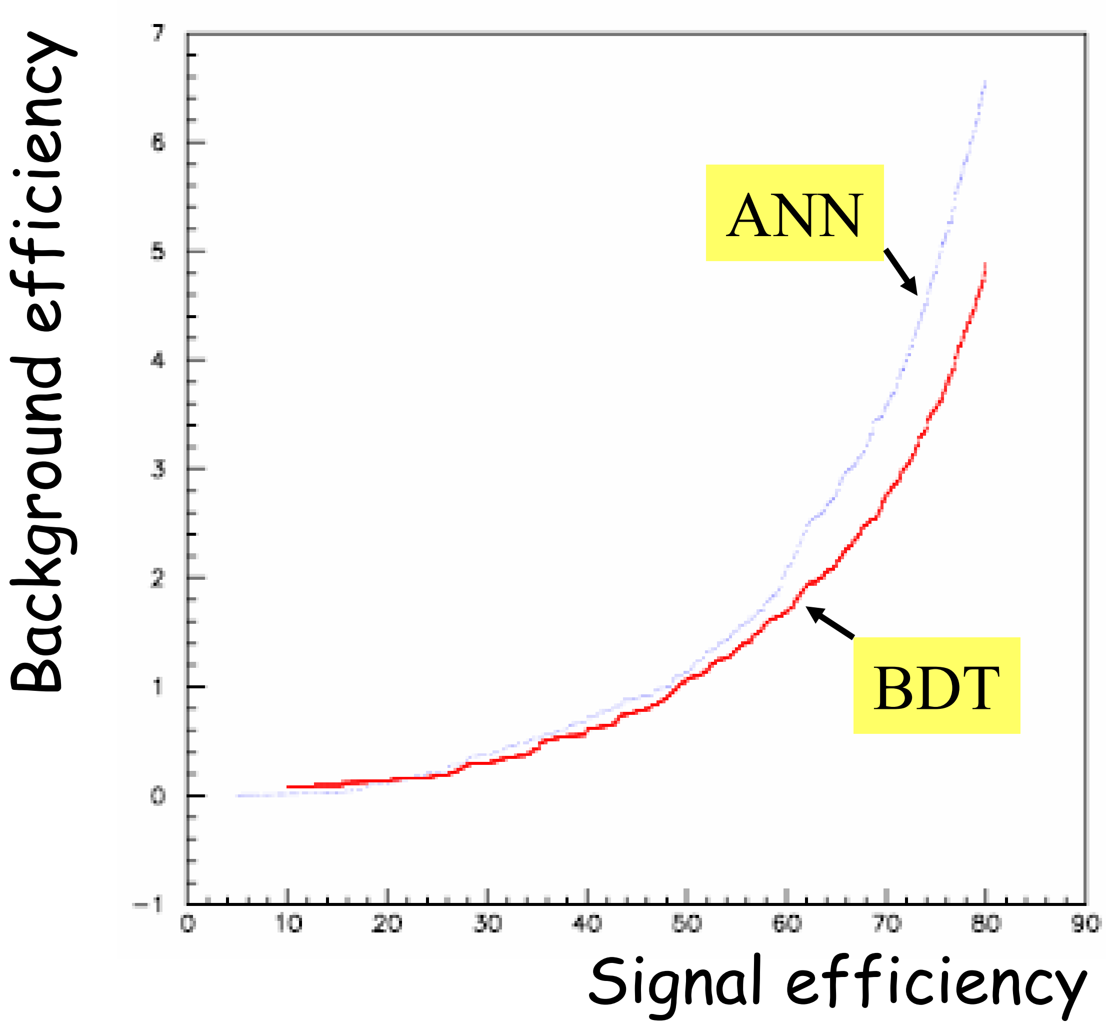
Boosted Decision Trees (BDT) and Artificial Neural Network (ANN)

—signal —background



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 $100pb^{-1}$~$1fb^{-1}$

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

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

- Anomalous 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

Muon spectrometer

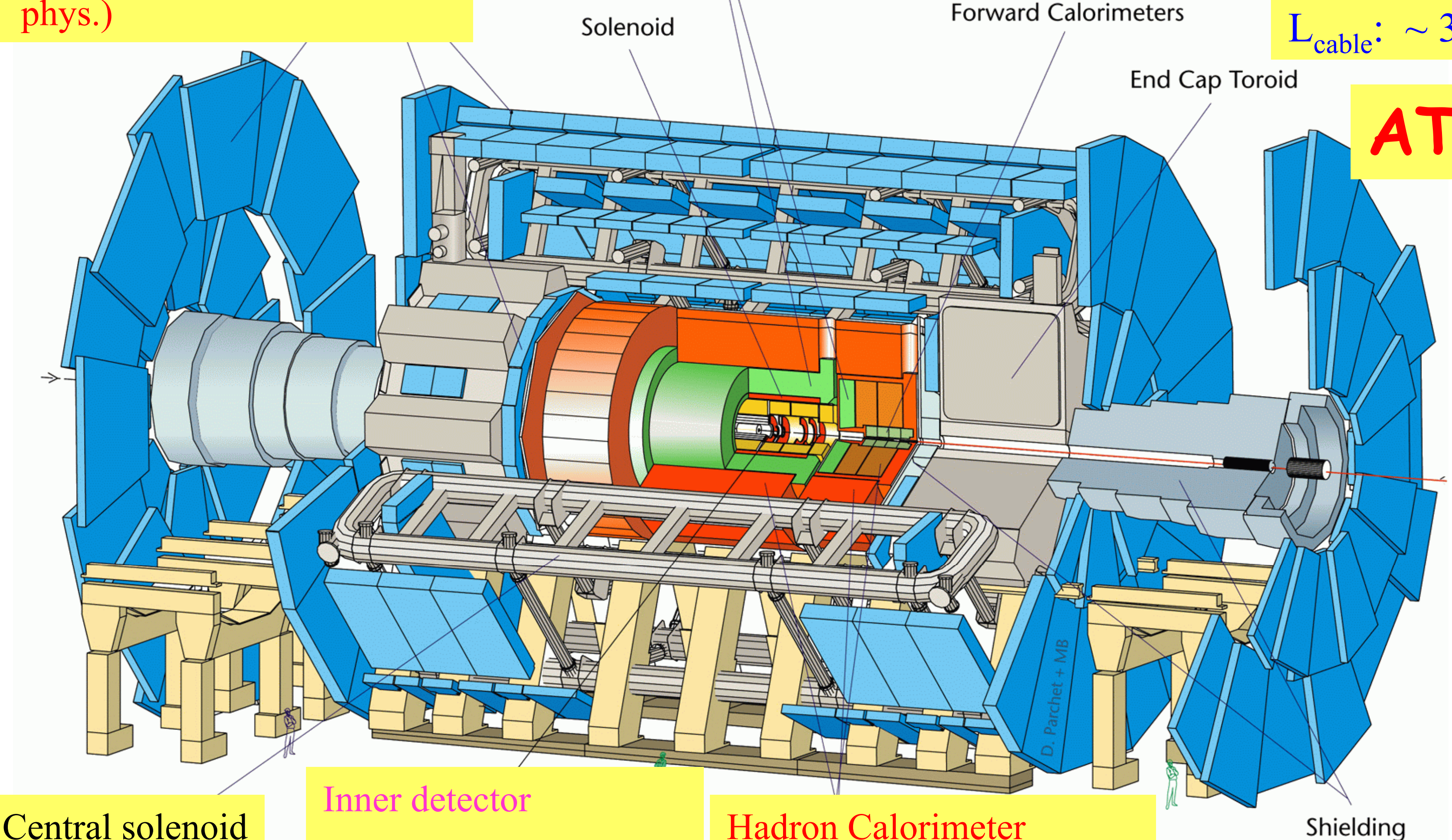
- $\sigma/p_T \sim 2\text{-}7\ \%$
- $|\eta| < 2.7$, $|\eta| < 2.5$ (precision phys.)

EM Calorimetry

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

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

ATLAS



Central solenoid

- 2 T

Inner detector

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

Hadron Calorimeter

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

EM calorimeter:

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

Magnet solenoid

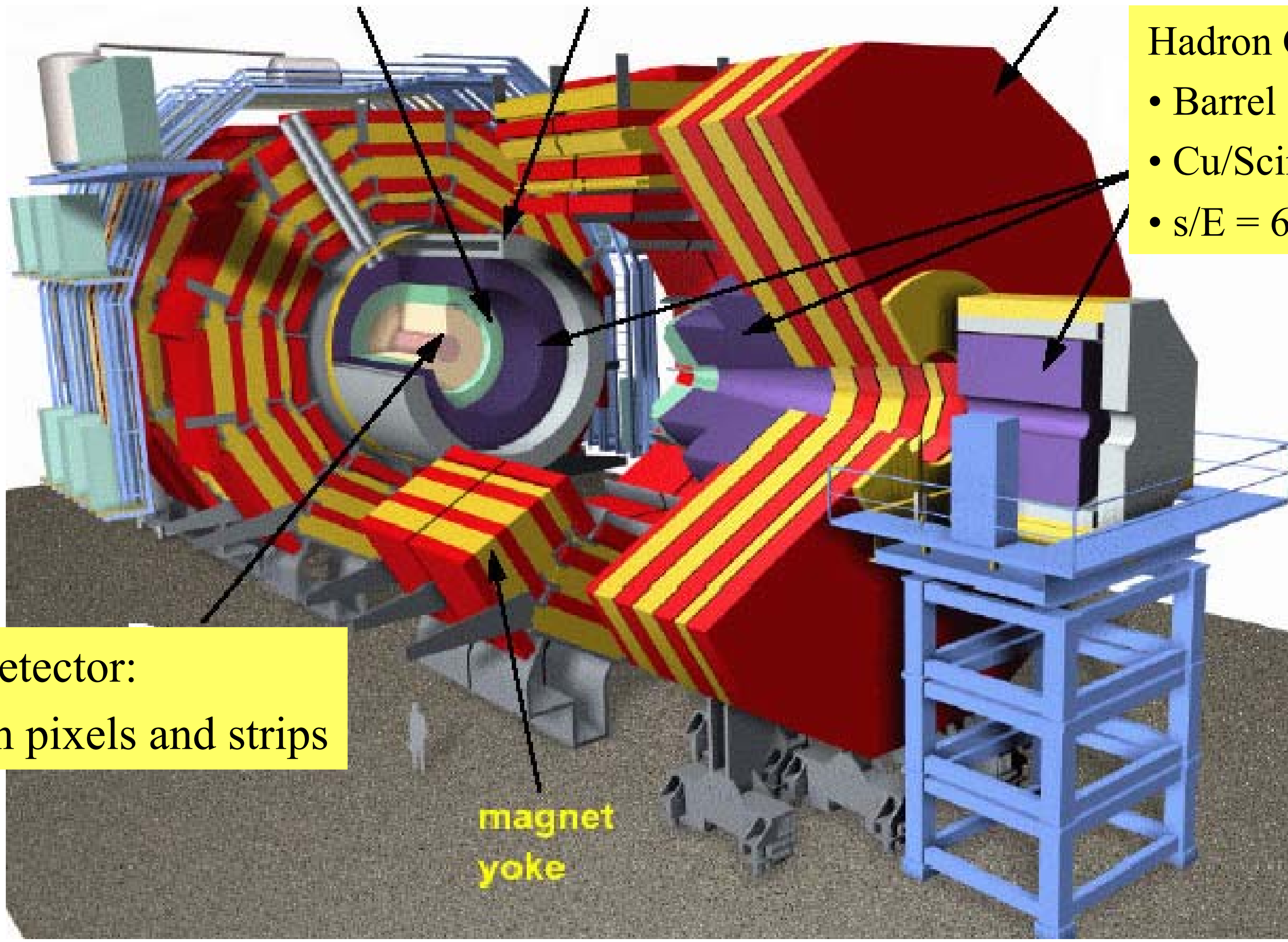
- 4 T

Muon spectrometer

- DT+CSA+RPC

Hadron Calorimeters

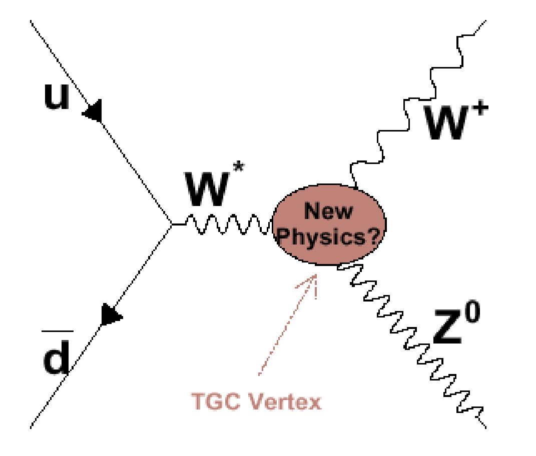
- Barrel & Endcap:
- Cu/Scintillating sheets
- $s/E = 65\% / \sqrt{E}\ (\mathrm{GeV}) \oplus 5\%$



Inner Detector:

- Silicon pixels and strips

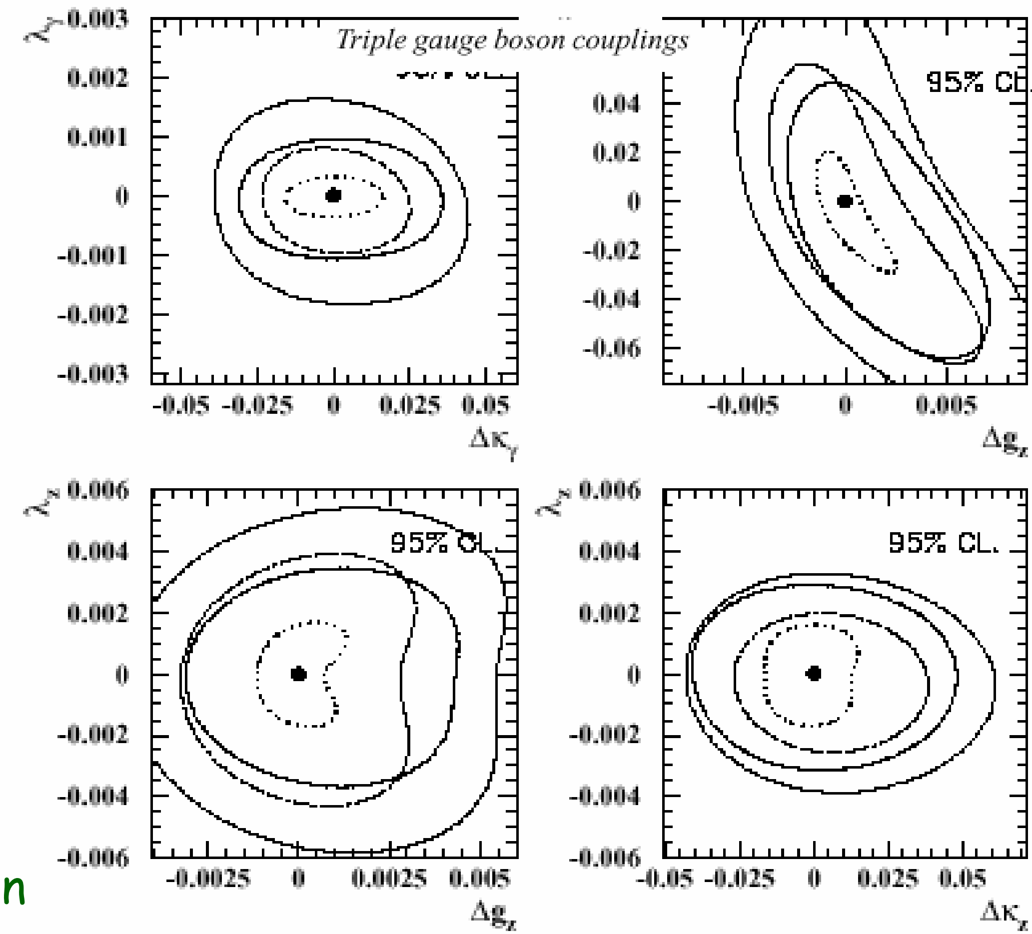
Triple Gauge Boson Couplings



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

Open window to electroweak symmetry breaking mechanism

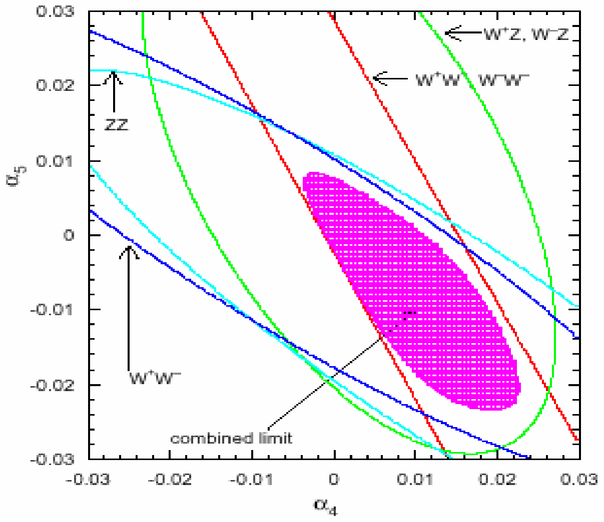
LHC: orders of magnitude Improvement over LEP/Tevatron



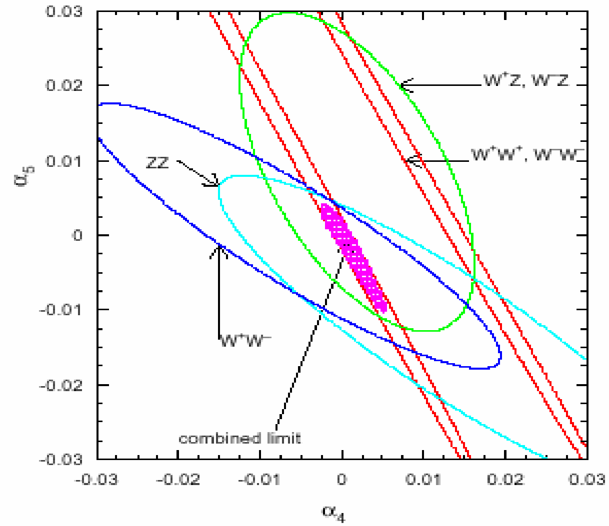
Expected 95% C.L. constrains contours (outer-> inside): $(14TeV, 100fb^{-1})$, $(28TeV, 100fb^{-1})$, $(14TeV, 1000fb^{-1})$, $(28TeV, 1000fb^{-1})$

Quartic Gauge Boson Couplings

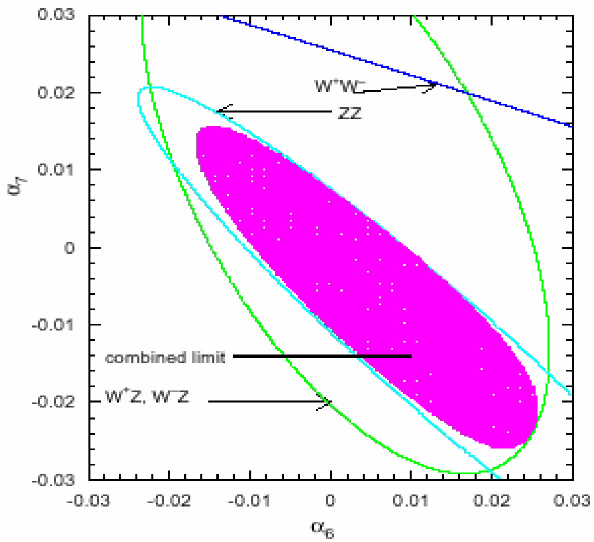
100fb^{-1}



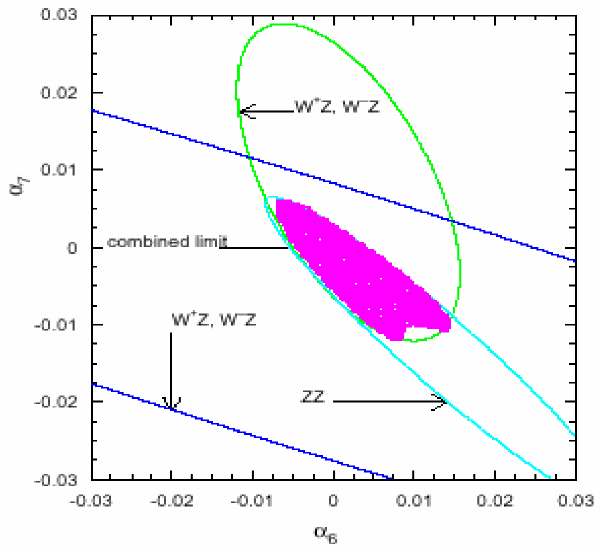
6000fb^{-1}



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	$\int L dt = 1\,\mathrm{fb}^{-1}$	$\int L dt = 10\,\mathrm{fb}^{-1}$
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	$\int L dt = 1\,\mathrm{fb}^{-1}$	$\int L dt = 10\,\mathrm{fb}^{-1}$
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