Studies of Diboson Production and Triple Gauge Boson Couplings

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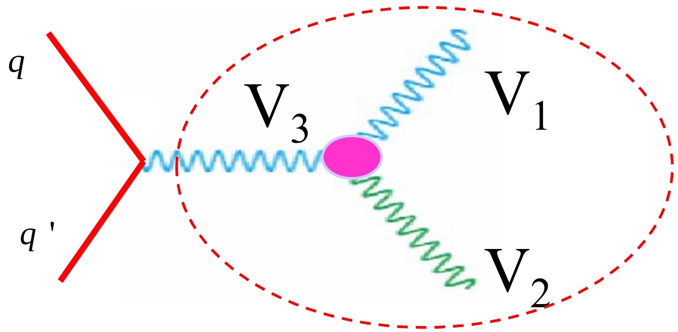
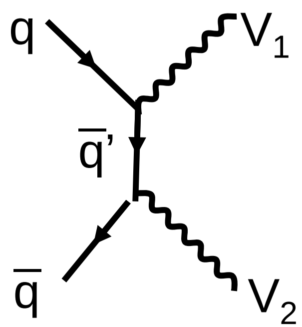
Outline

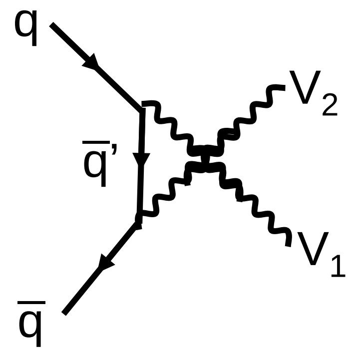
- Introduction
- Recent Tevatron results
- Effort from ATLAS/CMS
- Summary

Introduction

Diboson Production at Hadron Collider





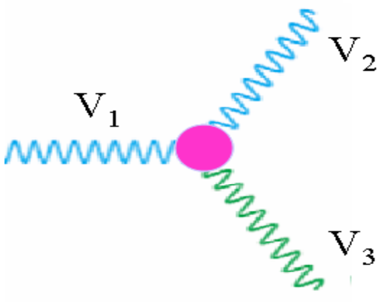


- LO Feynman diagram, V_1, V_2, V_3 = Z, W, $\gamma \rightarrow$ WW, ZW, ZZ, Wγ.
- Production cross section predictable
- Only s channel has three boson vertex, which manifest the gauge boson coupling

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

Triple Gauge Boson Couplings



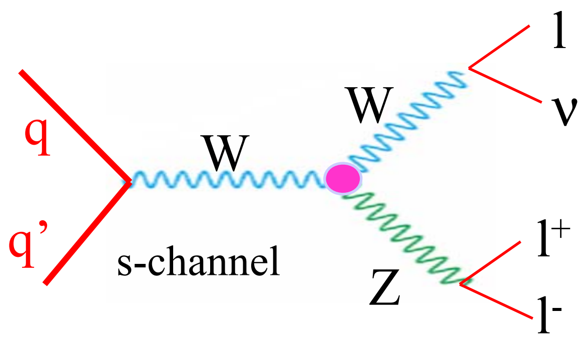
$$
\begin{aligned}
L_{WWV}/g_{WWV} =& ig_1^V (W_{\mu\nu}^+ W^\mu V^\nu - W_\mu^+ V_\nu W^{\mu\nu}) \\
&+ i\kappa_V W_\mu^+ W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda\mu}^+ W_\nu^\mu V^{\nu\lambda} \\
&- g_4^V W_\mu^+ W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
&+ g_5^V \varepsilon^{\mu\nu\rho\alpha}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

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

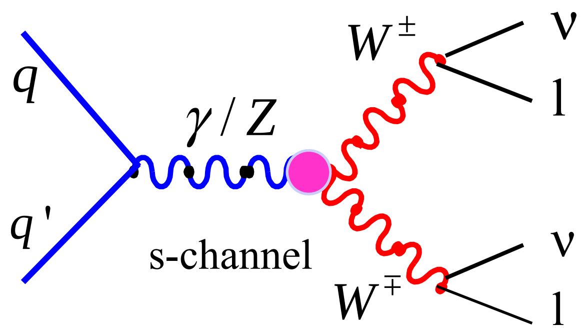
- C, P and CP symmetry conservation, 5 free parameters:
  - λ_γ , λ_Z: grow with s, big advantage for LHC
  - $\Delta\kappa_\gamma = \kappa_\gamma - 1$, $\Delta g_1{}^Z = g_1{}^Z - 1$, $\Delta\kappa_Z = \kappa_Z - 1$: grow with √s

- Tree level SM: $\lambda_\gamma = \lambda_Z = \Delta\kappa_\gamma = \Delta g_1{}^Z = \Delta\kappa_Z = 0$

Production of WZ, WW



- s-channel dominates,
- Sensitive only to WWZ coupling
- Clean signal eee, eeμ, μμe, μμμ
- 3 isolated high p_T leptons with large E_T(miss)

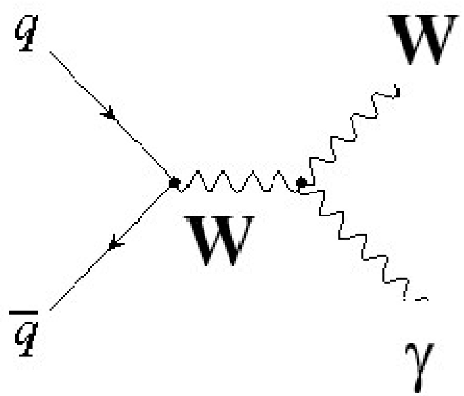


Sensitive to WWZ and WWγ

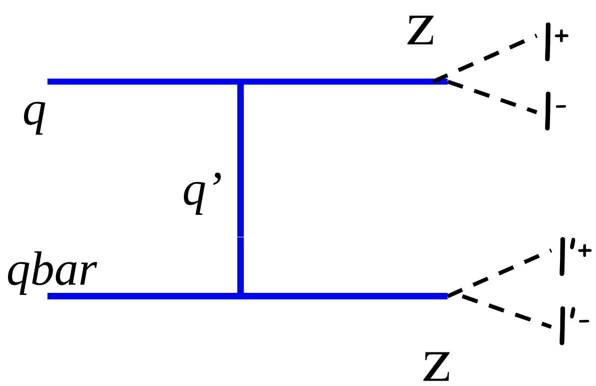
- Clean signal ee, μμ, eμ
- 2 isolated high p_T leptons with opposite charge and large missing E_T

t-channel

Production of Wγ, ZZ

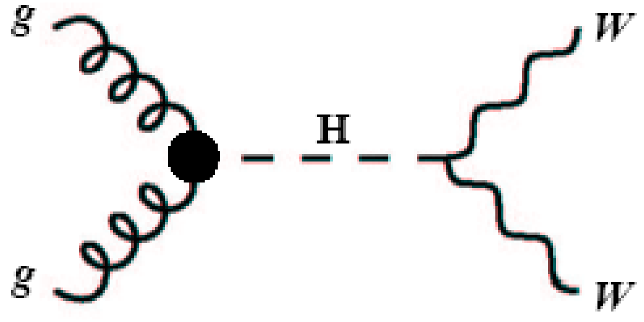


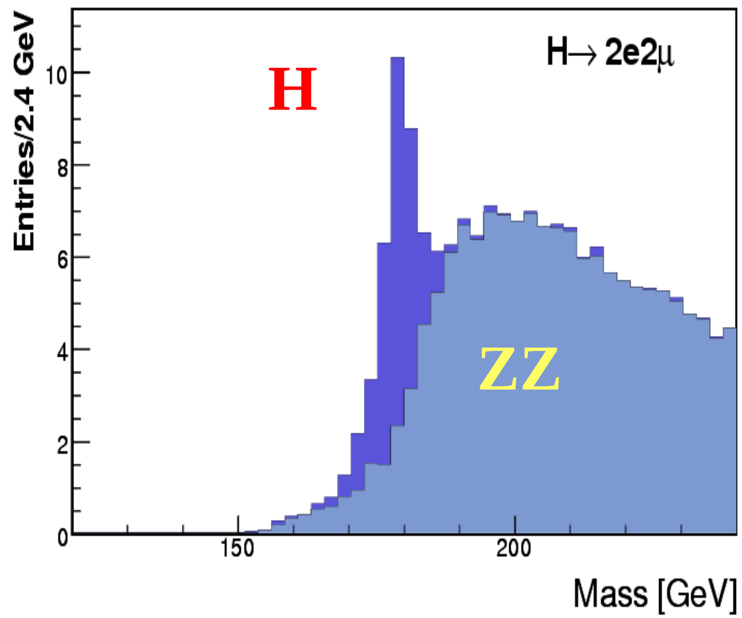
- Isolated high p_T lepton (e, μ) large missing E_T
- Isolated γ
- Main bkg: W+jet, Z+ γ

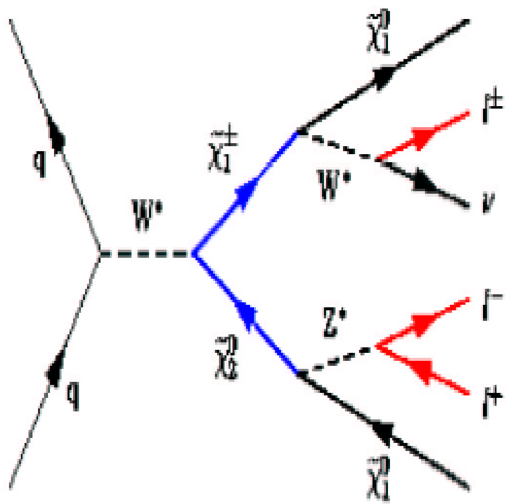


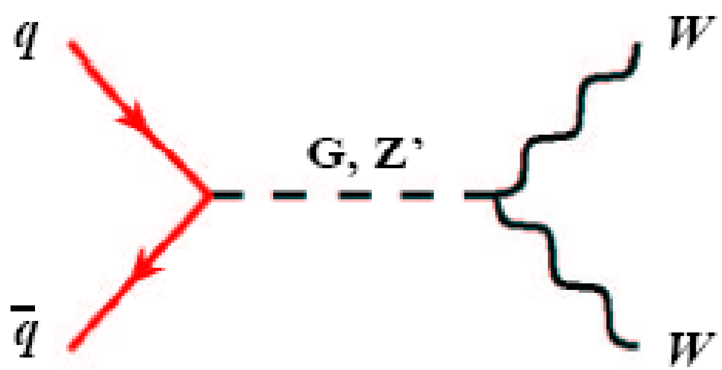
- s channel suppressed by $O(10^{-4})$
- Only t-channel at tree level,
- 4 isolated high p_T leptons from the Z pair decays
- Clean signal eeee, eeμμ, μμμμ, almost bkg free

Diboson as background for searches









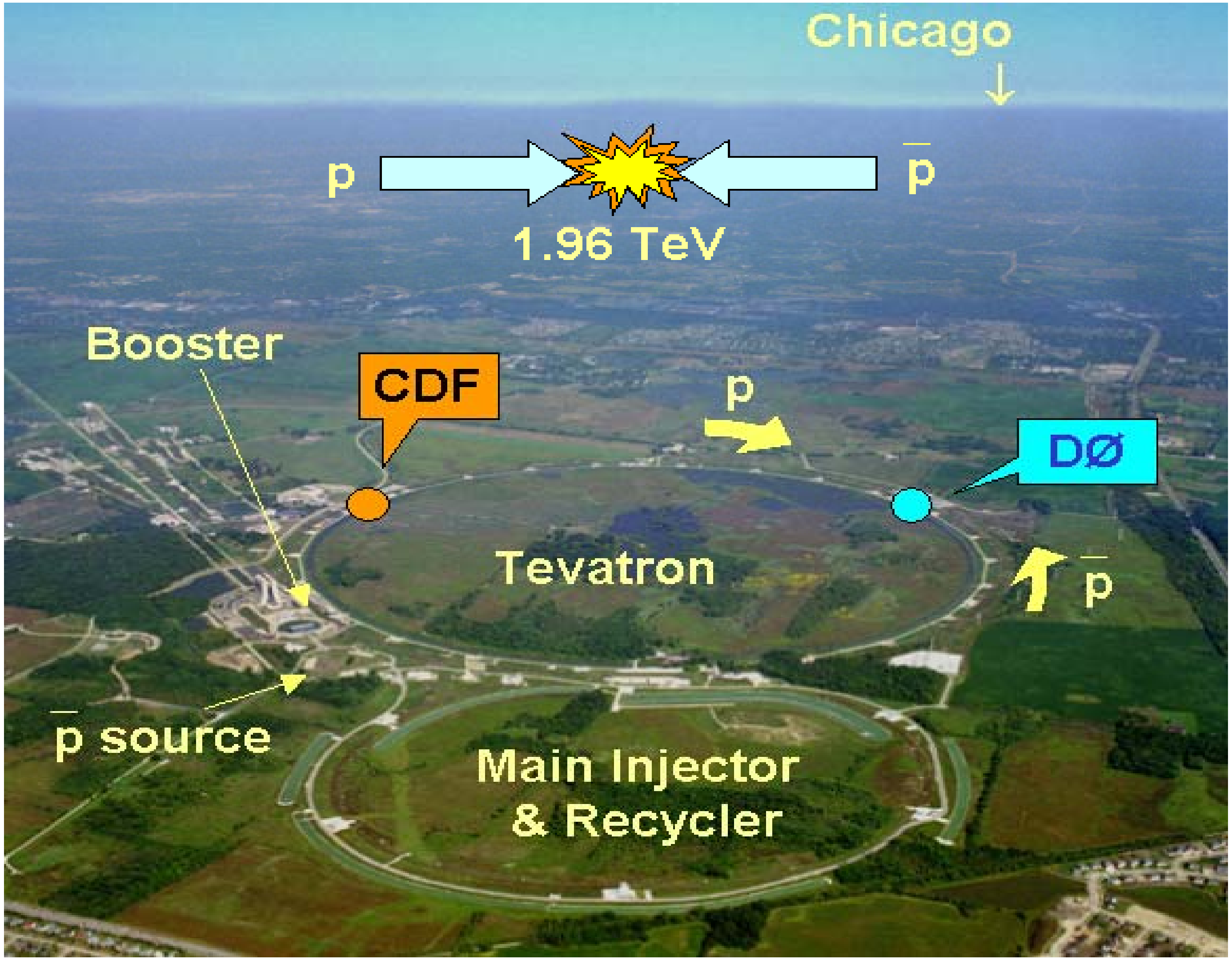
Motivations

- Measure diboson production σ and TGCs
- Explore none-Abelian $SU(2)\times U(1)$ gauge structure of 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

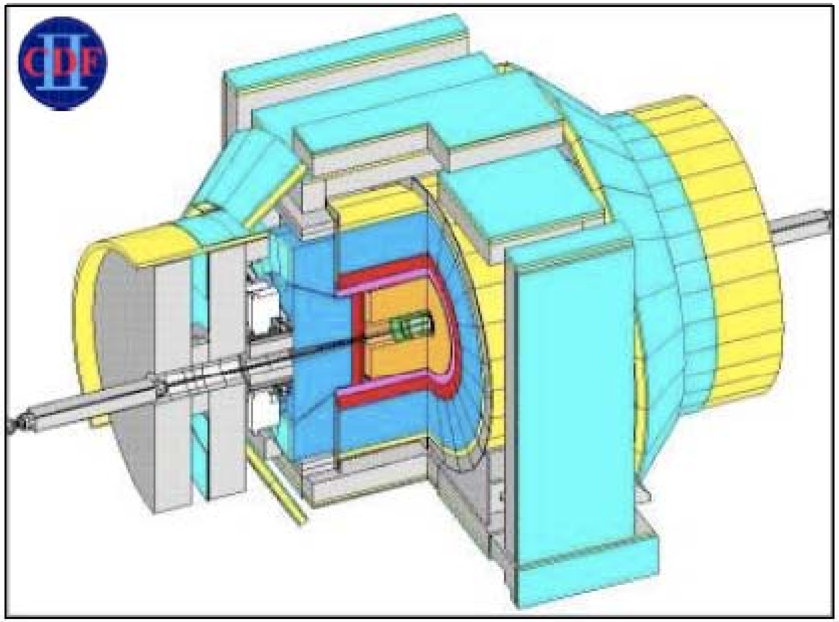
  Search for Higgs, SUSY, graviton and study of ttbar

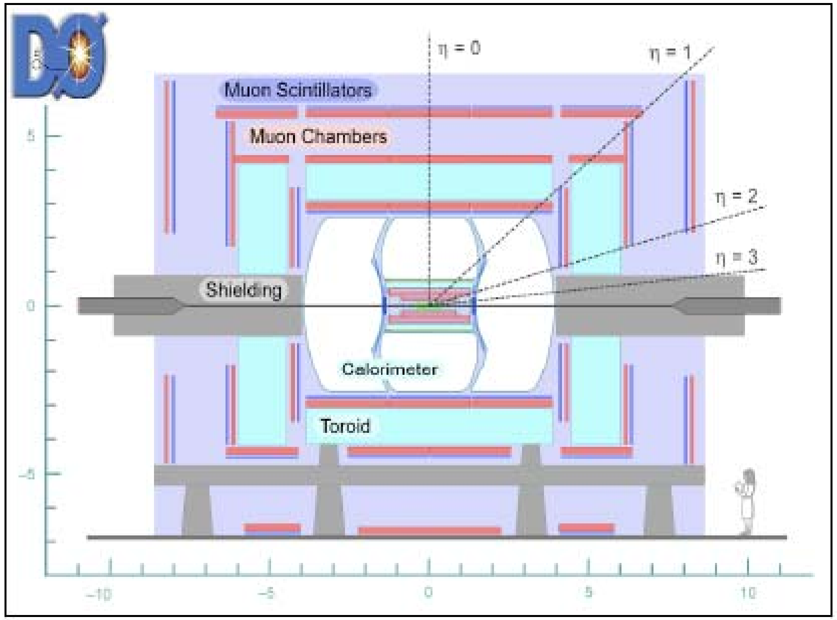
Recent Results from Tevatron

Experiments at Tevatron



CDF & D0 Detectors

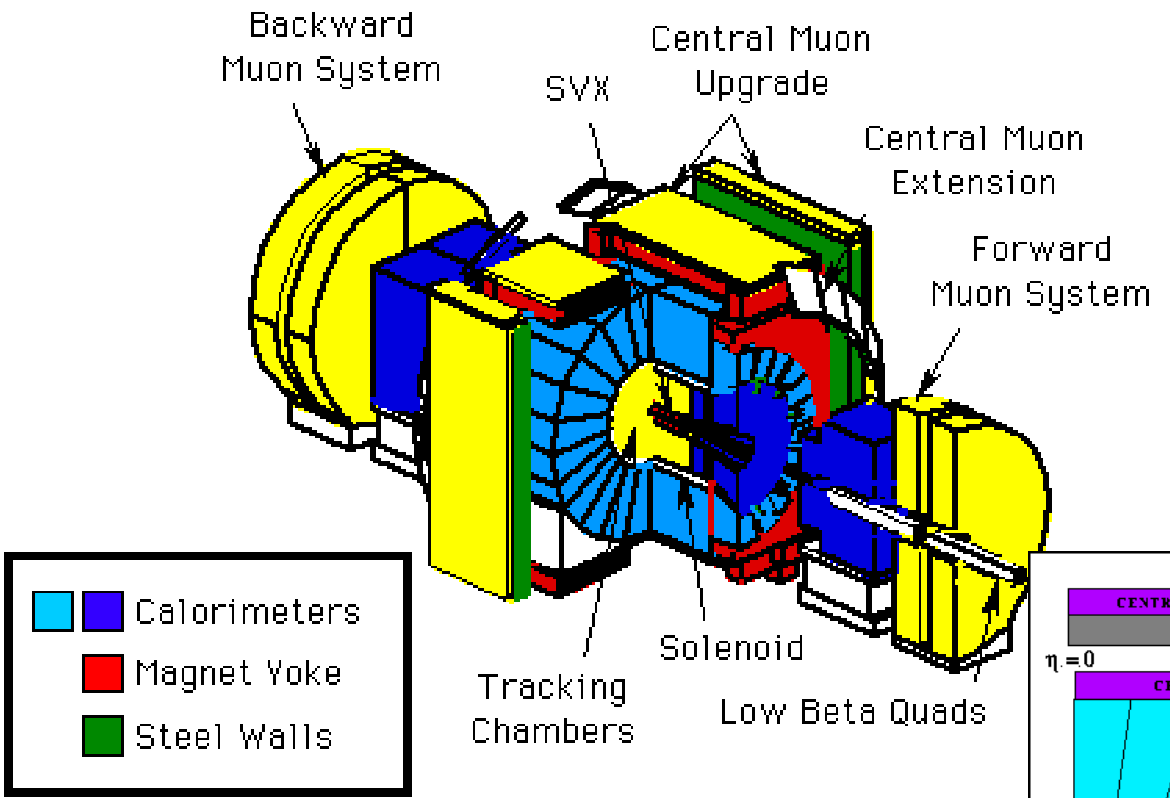


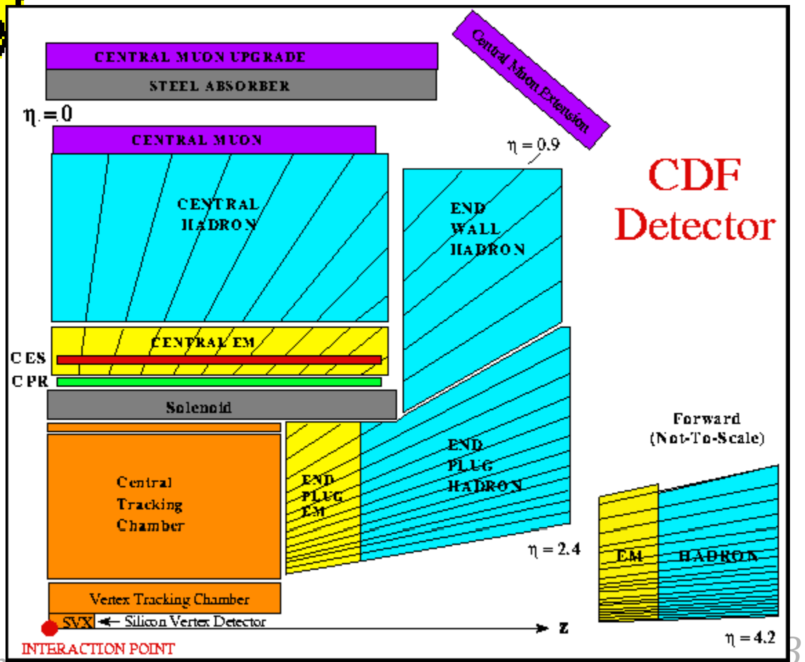


- **CDF Run II Upgrades:**
- New Silicon Vertex Detector (SVX) and
- faster tracking drift chamber (COT)
- New scinitllating-tile end-plug
- calorimeters
- Increased ηφ coverage for muon
- detectors
- New Scintillator Time-Of-Flight system

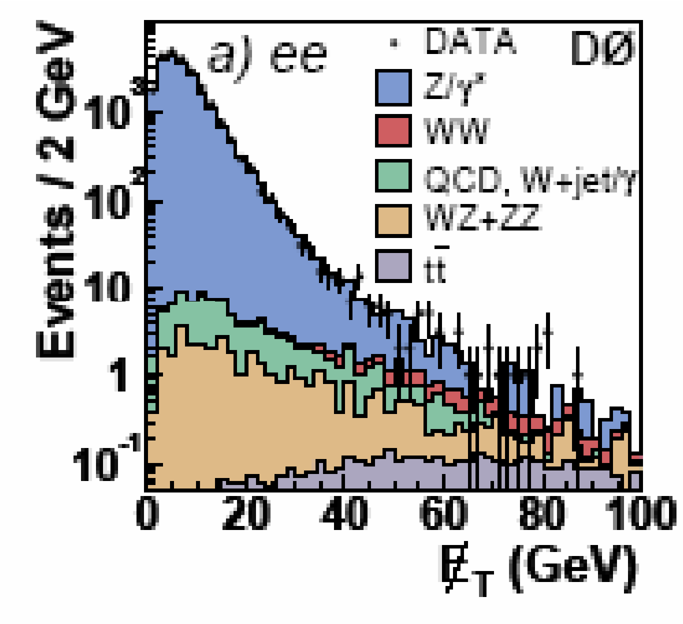
- **D0 Run II Upgrades:**
- New silicon (SMT) and Fiber (CFT)
- trackers, placed in new 2T Solenoid
- Calorimeters supplemented with
- Preshower detectors
- Significantly improved Muon System

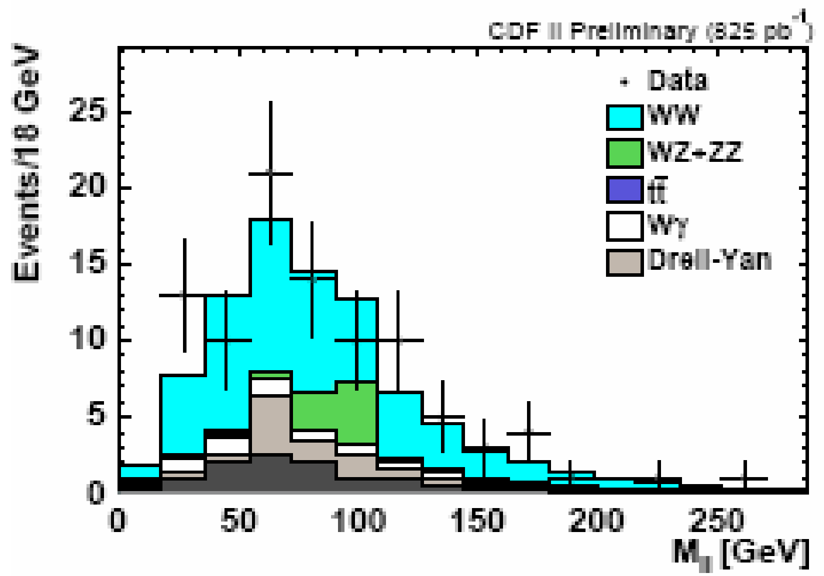
CDF Detector





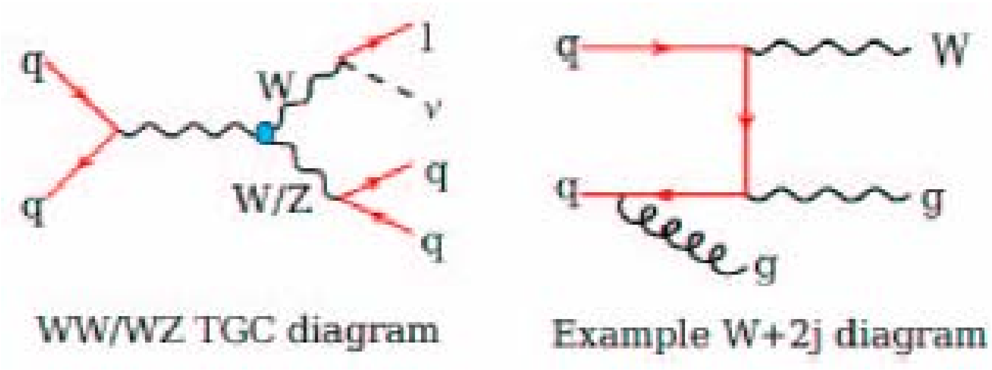
WW Production at Tevatron

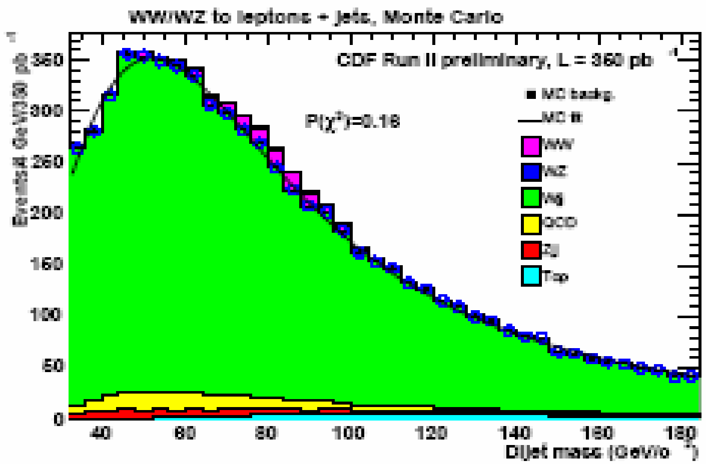




	$L(pb^{-1})$	N_{obs}/N_b	$\sigma(pb)$
D0	224-252	25/9.8	$13.8^{+4.3}_{-3.8}(stat)^{+1.2}_{-0.9}(sys) \pm 0.9(lum)$
CDF	825	95/43.4	$13.6 \pm 2.3(stat) \pm 1.6(sys) \pm 0.9(lum)$
NLO			12 ± 0.8

WW+WZ→lνjj

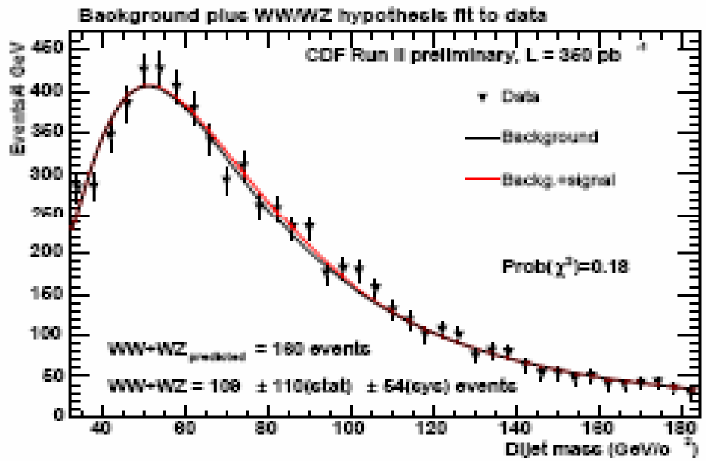




Monte Carlo

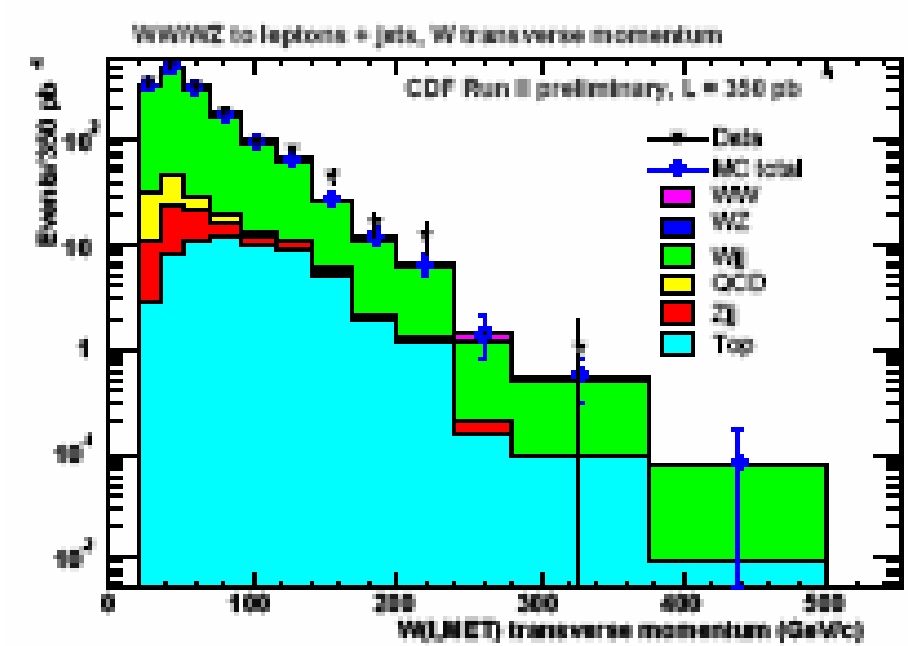
- 1 lepton with p_T>25GeV, $\not{E}_T$>25 GeV
- ≥2 jets with p_T > 15 GeV

σ(WW+WZ) < 36 pb @ 95% CL



Data

WW+WZ→lνjj anomalous coupling from CDF

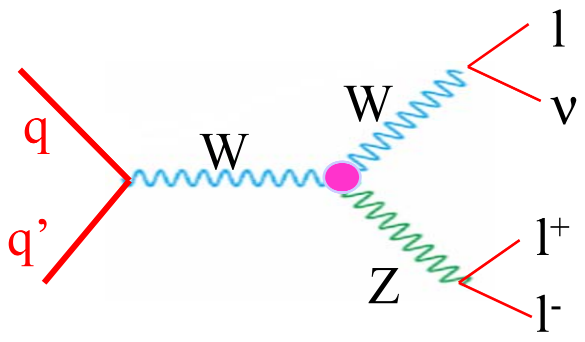


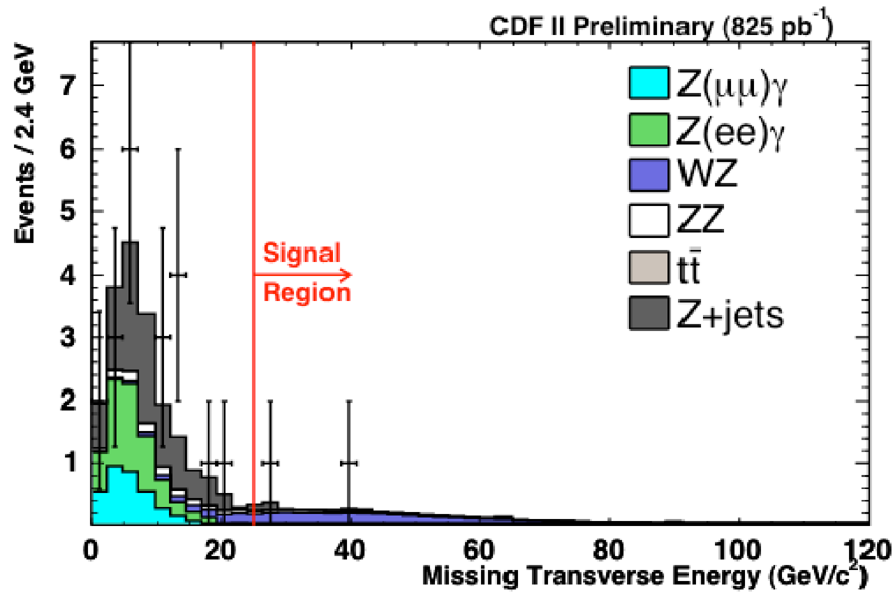
$W(l, \not{E}_T)\ p_T$

- Select 56 < m_{jj} < 112 peak region
- Minimize likelihood for p_T of $W(l,E_T)$

$-0.51 < \Delta\kappa < 0.44, \quad -0.28 < \lambda < 0.28$

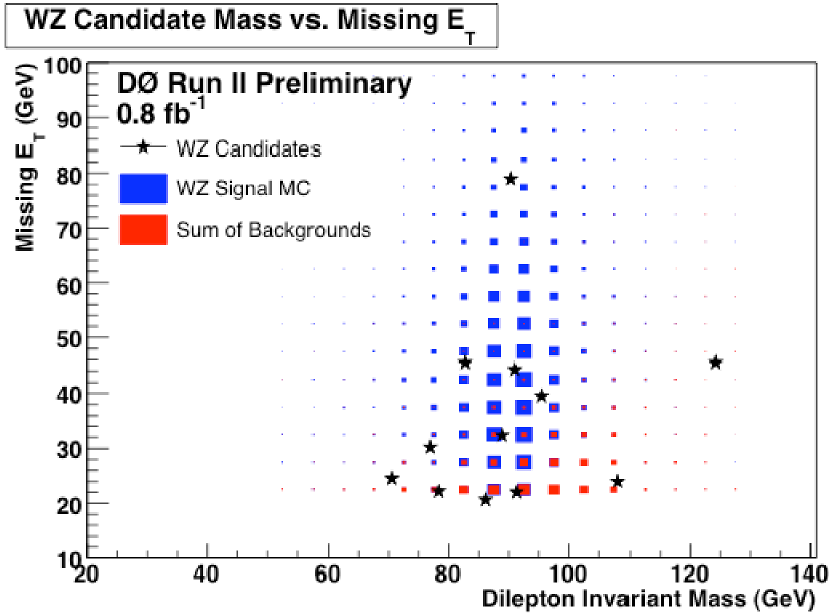
WZ → lνll

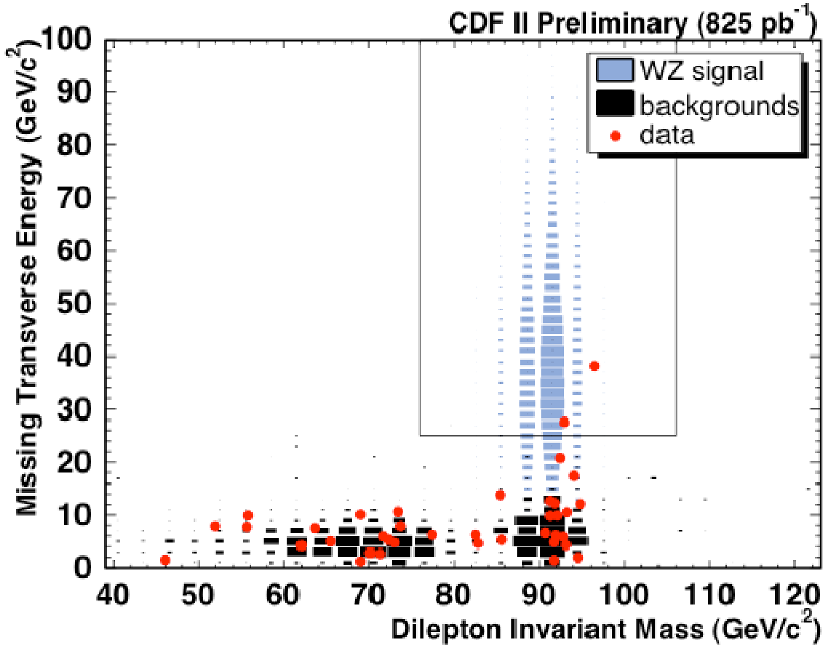




- 3 leptons (e, μ)
  - CDF: p_T(leading) >20 GeV, p_T(others) > 10 GeV
  - D0: p_T(all) > 15 GeV
- $m(l^+l^-)$ within m_Z window
- $\not{E}_T$ is used to suppress the bkg of Z+jet/γ

WZ → lνll results

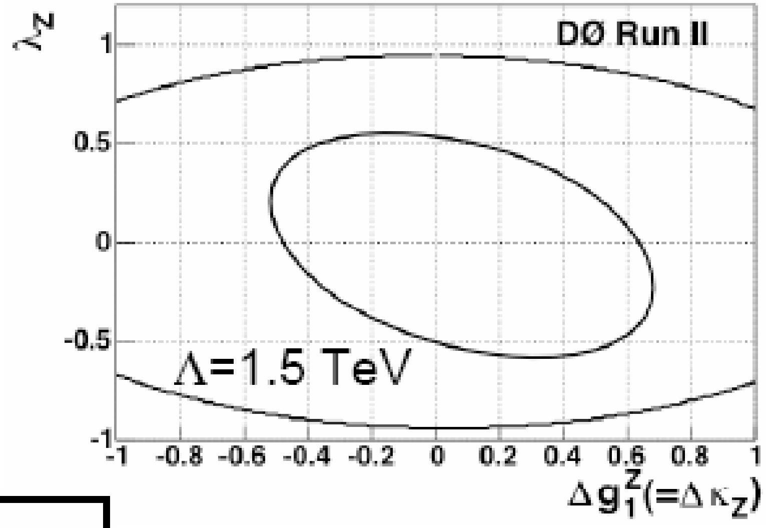




	L(pb^{-1})	N_{obs}	$N^{signal}_{expected}$	$N^{bkg}_{expected}$	σ(pb)
D0	760-860	12	7.5 ± 1.2	3.6 ± 0.2	$3.98^{+1.91}_{-1.53}$
CDF	825	2	3.7 ± 0.3	0.9 ± 0.2	< 6.3 (95% CL)
NLO					3.7 ± 0.1

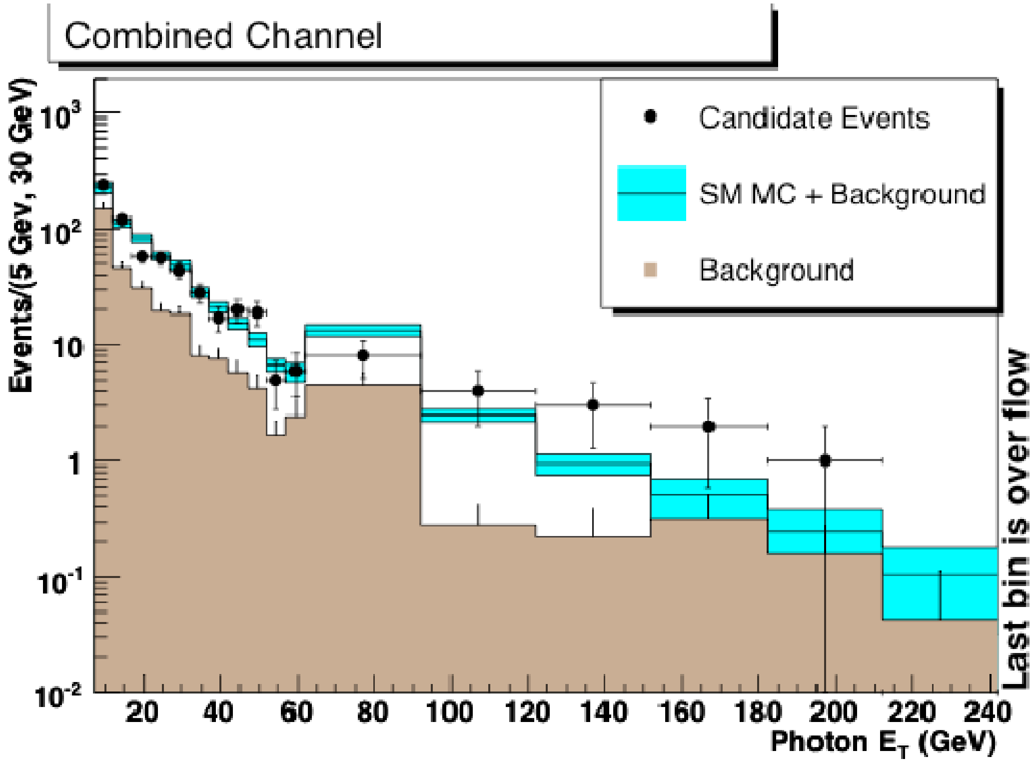
WWZ Anomalous Coupling

For L = 300 pb^{-1} data, expect 2 signal and 1 background events. Observed 3 events. TGCs are determined to be



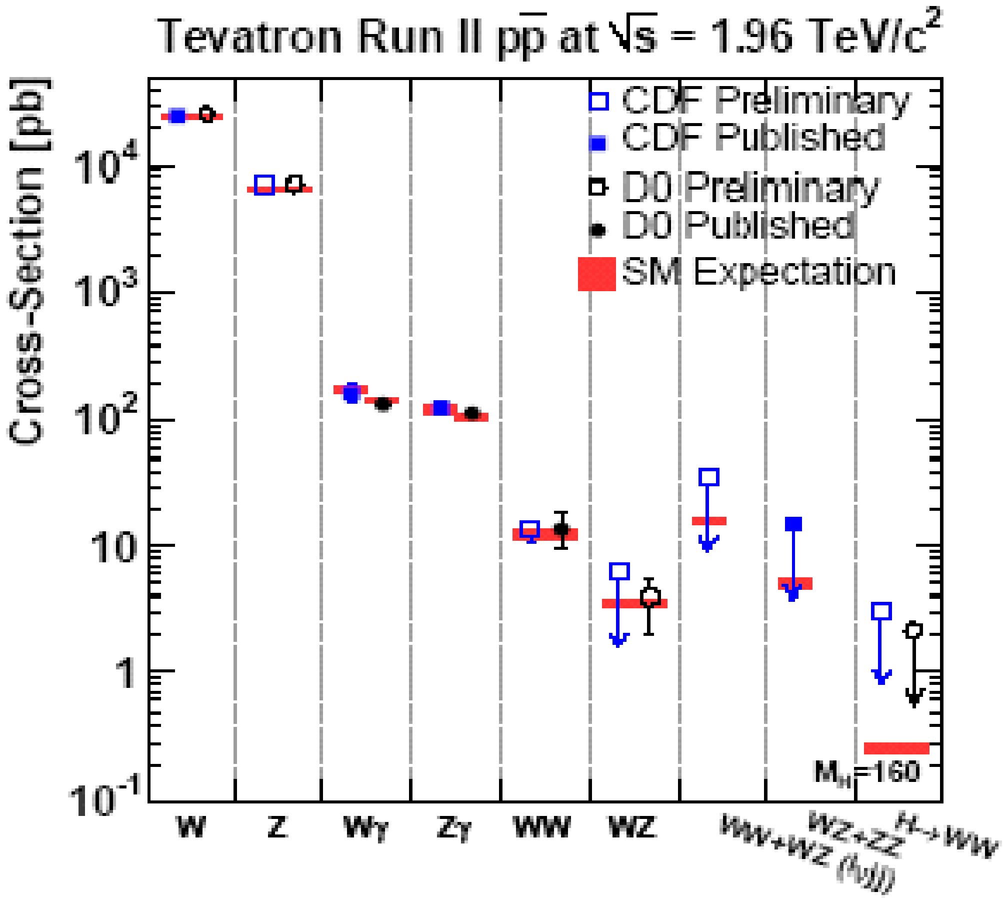
Condition	Λ=1.0 TeV	Λ=1.5 TeV
$\Delta g^Z_1=\Delta\kappa_Z=0$	$-0.53<\lambda_Z<0.56$	$-0.48<\lambda_Z<0.48$
$\lambda_Z=\Delta\kappa_Z=0$	$-0.57<\Delta g^Z_1<0.76$	$-0.49<\Delta g^Z_1<0.66$
$\lambda_Z=0$	$-0.49<\Delta g^Z_1=\Delta\kappa_Z<0.66$	$-0.43<\Delta g^Z_1=\Delta\kappa_Z<0.57$
$\lambda_Z=\Delta g^Z_1=0$	$-2.0<\Delta\kappa_Z<2.4$	-

$\sigma(W\gamma \rightarrow l\nu\gamma)$ from D0



Channel	$L(pb^{-1})$	$\sigma(pb)$
$W\gamma \rightarrow e\nu\gamma$	933	$3.12 \pm 0.49 \pm 0.19$
$W\gamma \rightarrow \mu\nu\gamma$	878	$3.21 \pm 0.49 \pm 0.2$
SM		3.21 ± 0.08

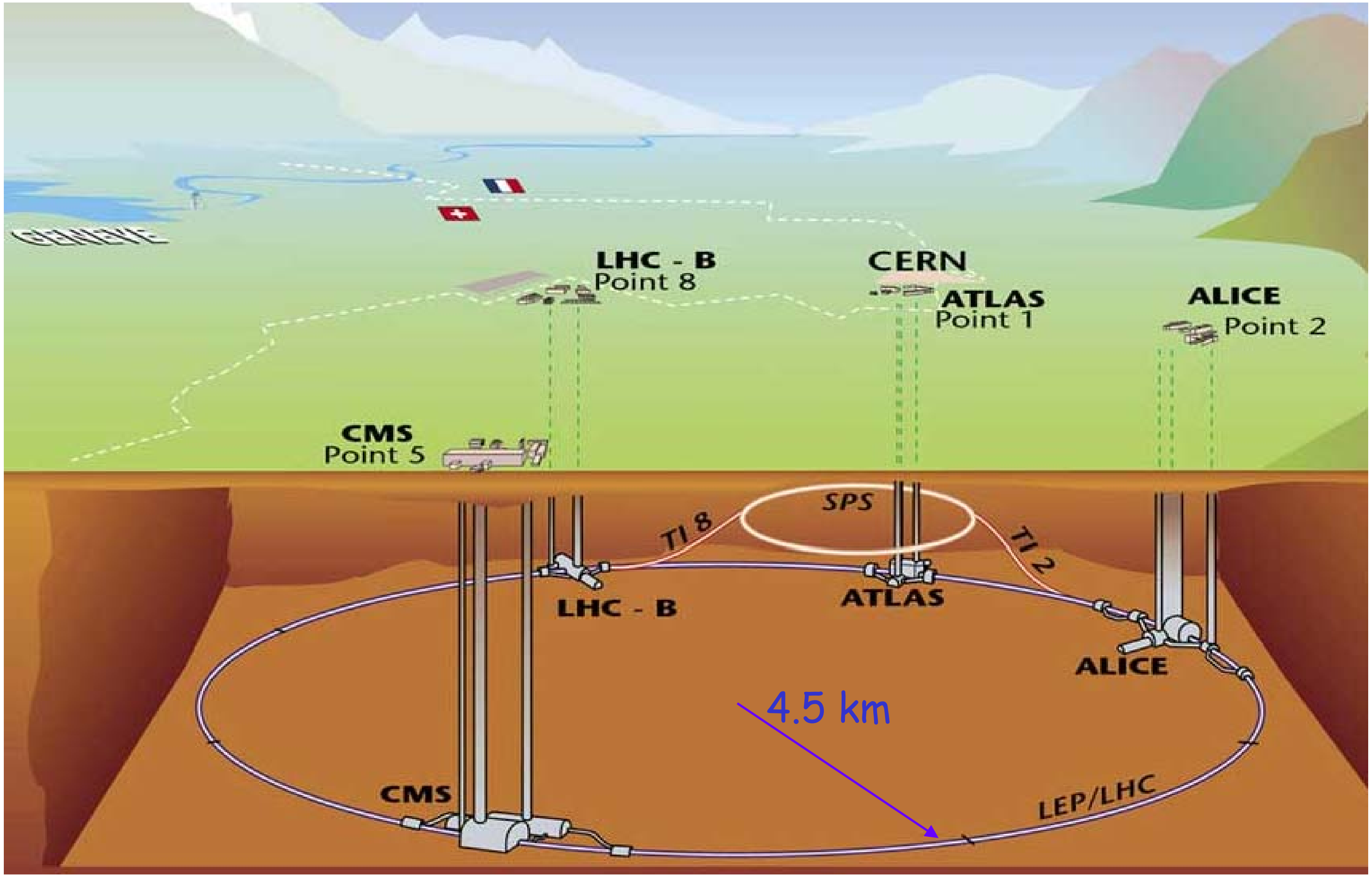
Tevatron Results on Dibson Studies



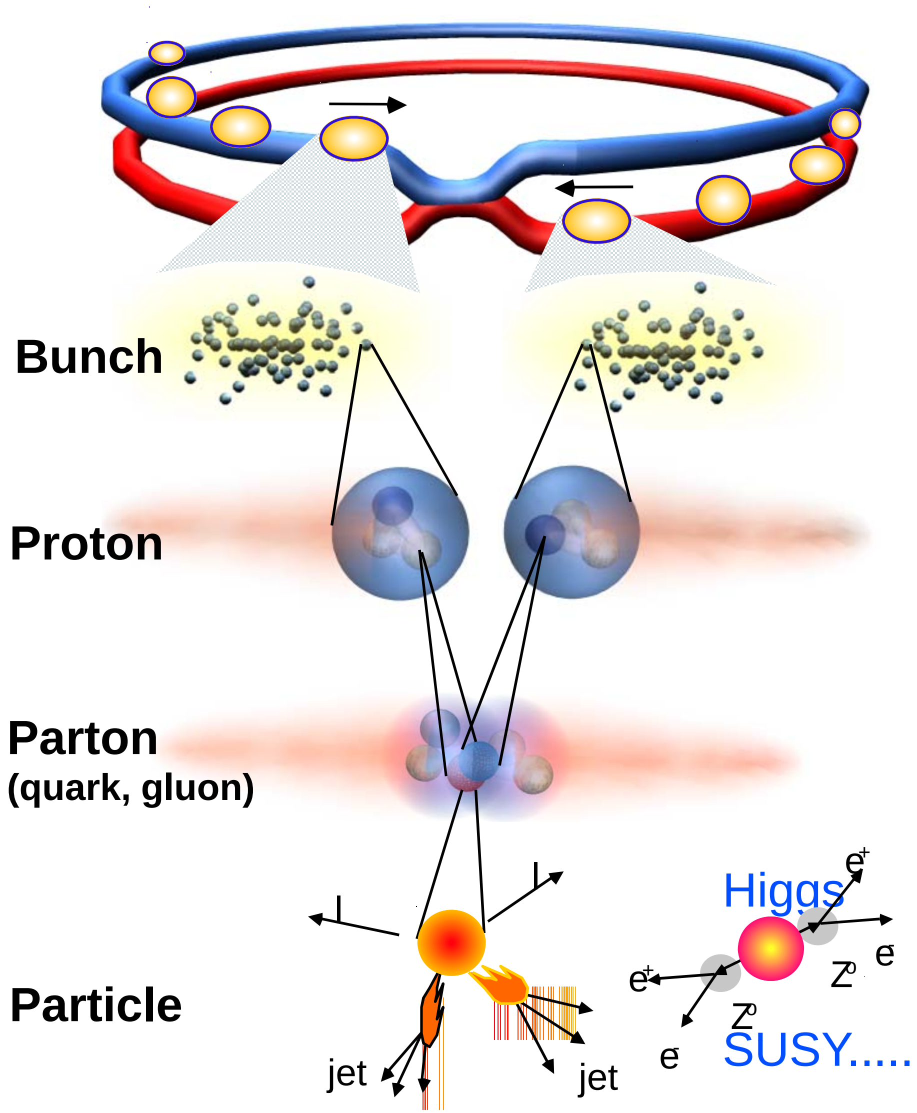
Tevatron results consistent with SM prediction

Diboson Studies from ATLAS and CMS

The LHC Experiments



Collisions at the LHC



2804 bunch/beam
7 + 7 TeV
separation: 7.5 m (25 ns)
40 MHz crossing rate
10^{11} proton / bunch
10^{9} pp collision/s
(superposition of 23 pp interactions per bunch crossing: pile-up)

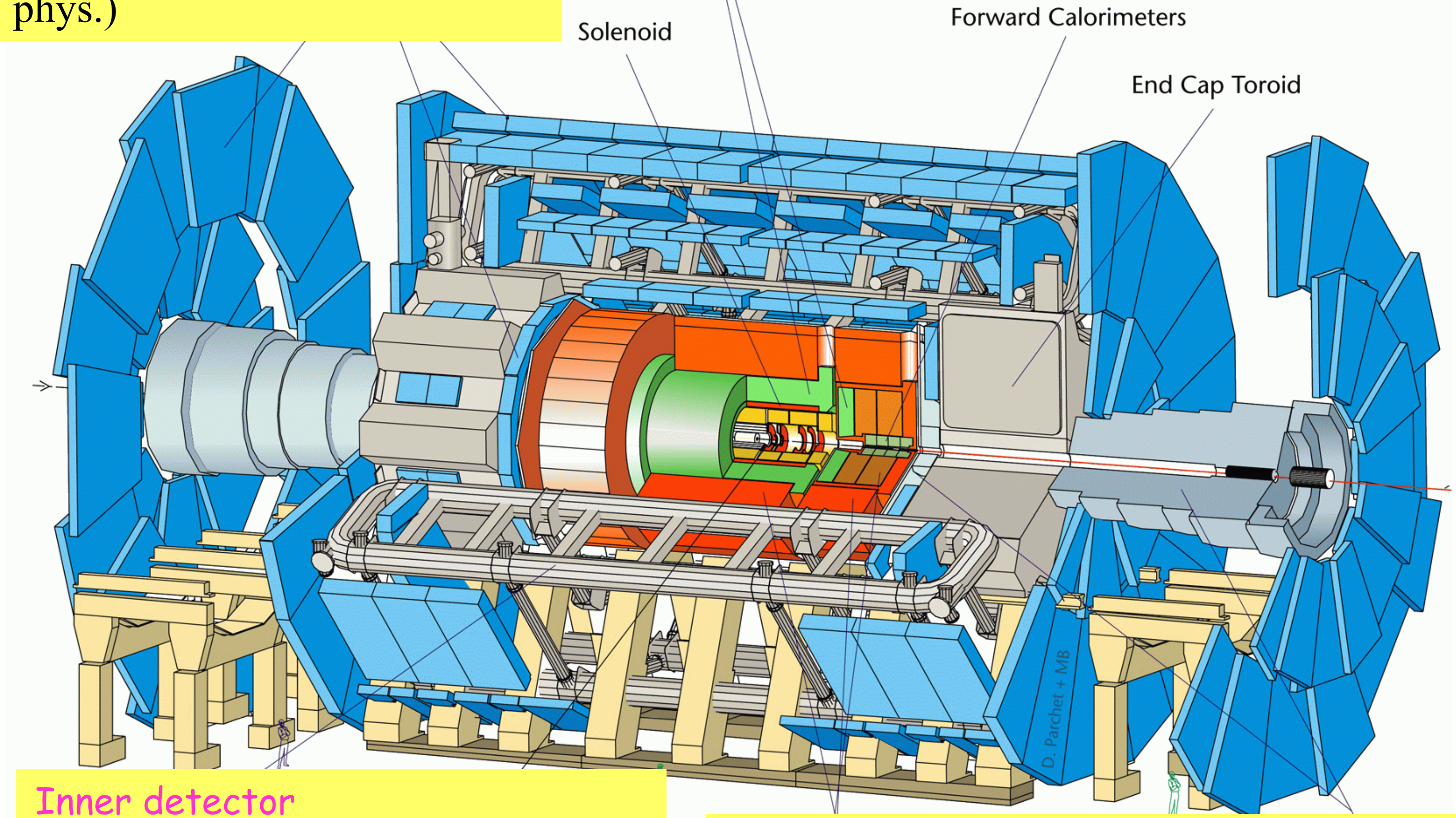
$N = L \times \sigma(pp) = 10^9$

- Mostly low p_t events (soft) events
- Interesting high p_t events are rare
- New physics rate ~ 0.00001 Hz
  → event selection:
  1 in 10,000,000,000,000

Muon spectrometer
- air-core toroids, MDT+RPC+TGC
- $\sigma/p_T \sim 2\text{-}7\ \%$
- $|\eta| < 2.7$, $|\eta|<2.5$ (precision phys.)

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

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



Inner detector
- Si pixels and strips
- Transition Radiation Detector (e/π separation)
- $\sigma/p_T \sim 0.05\%\ p_T(GeV) \oplus 0.1\%$;
- $|\eta| < 2.5$, B=2 T(central solenoid)

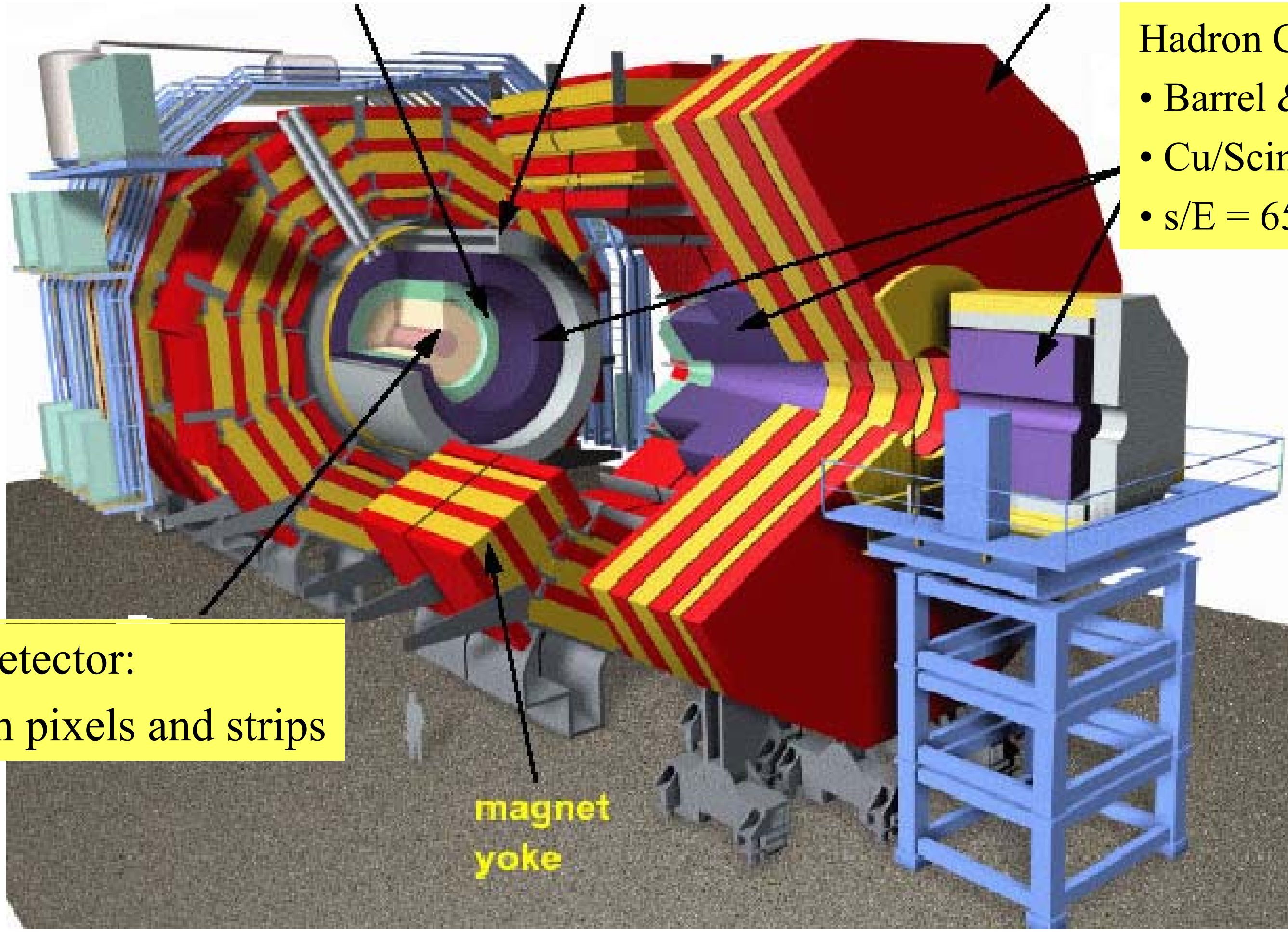
Hadron Calorimeter
- Fe/scintillator (central), Cu/W-LAr (fwd)
- $\sigma/E \sim 50\%/\sqrt{E(GeV)} \oplus 3\%$
- $|\eta|<3$

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

LHC Expectations for the TGCs

LHC

- High CM energy $\rightarrow$ larger σ
- High luminosity $\rightarrow$ 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)

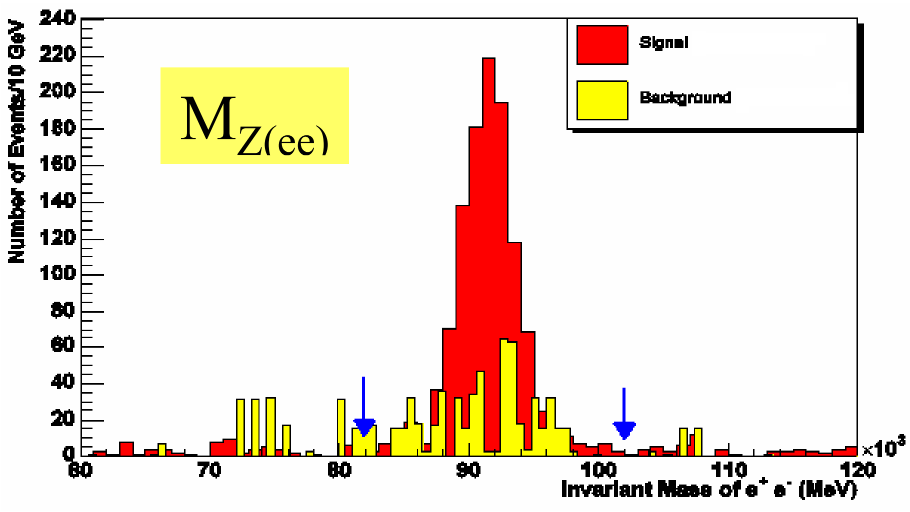
$-0.0035 < \lambda_\gamma < +0.0035$
$-0.0073 < \lambda_Z < +0.0073$
$-0.075 < \Delta\kappa_\gamma < +0.076$
$-0.11 < \Delta\kappa_Z < +0.12$
$-0..86 < \Delta g^1{}_Z < +0.011$

MC Data for Diboson Studies(ATLAS)

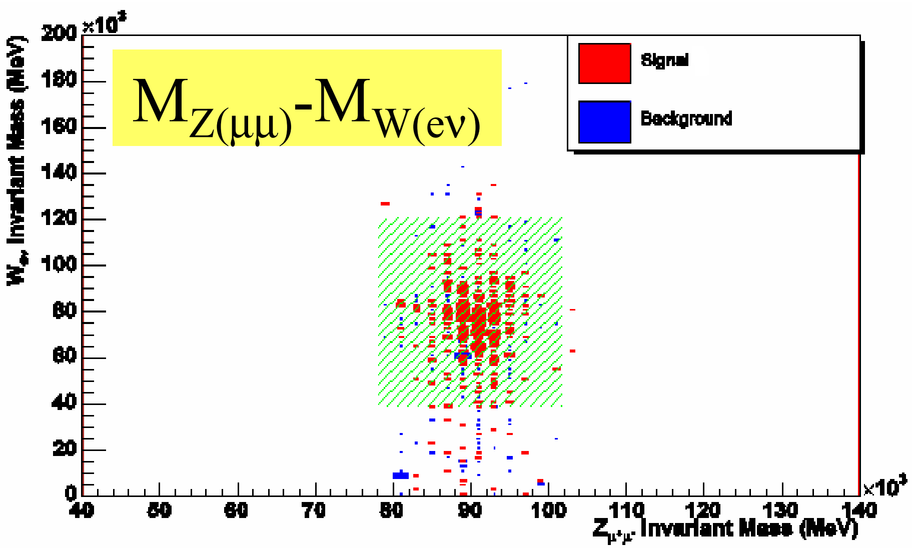
Process	MC data	Process	MC data
$ZW^+ \rightarrow 2e/2\mu + X$	26033	ttbar$\rightarrow \ell + x$	1.96×10^5
$ZW^- \rightarrow 2e/2\mu + X$	29085	Z(@Peak) $\rightarrow ee/\mu\mu/\tau\tau$	2.30×10^6
$ZZ \rightarrow 4e, 4\mu, 2e2\mu$	19933	$W\rightarrow e/\mu/t + \nu$	1.61×10^6
$WW\rightarrow \ell\nu + x$	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$\rightarrow$lepton
- Signal events produced by MC@NLO (v2.3)-Jimmy, W/Z width effect is not included (v3.1 has included width)

WZ

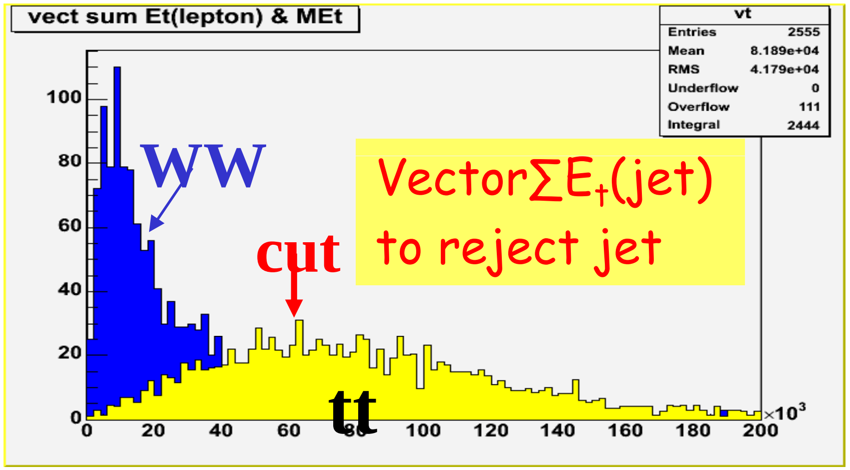


$M_{Z(ee)}$
Signal
Background
Number of Events/10 GeV
Invariant Mass of e^+e^- (MeV)
$\times10^3$

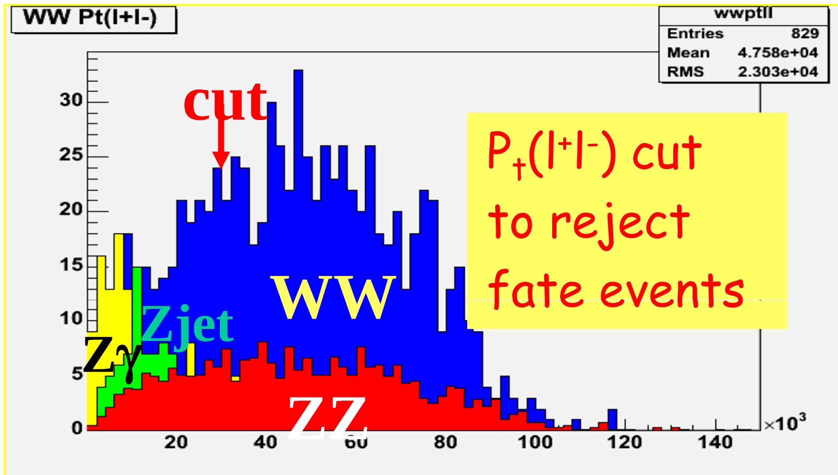


$M_{Z(\mu\mu)}$-$M_{W(e\nu)}$
Signal
Background
$W_{e\nu}$ Invariant Mass (MeV)
$Z_{\mu^+\mu^-}$ Invariant Mass (MeV)
$\times10^3$

WW



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
VectorΣE_t(jet)
to reject jet
$\times10^3$

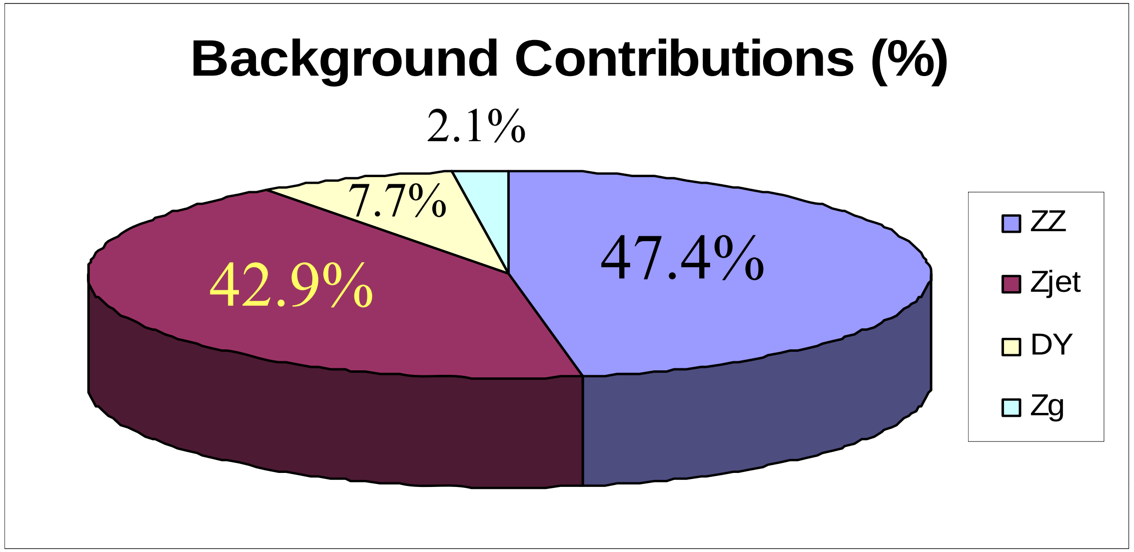


WW Pt(l+l-)
wwptll
Entries 829
Mean 4.758e+04
RMS 2.303e+04
cut
$P_t(l^+l^-)$ cut
to reject
fate events
WW
Zjet
$Z\gamma$
ZZ
$\times10^3$

ZW Signal and Backgrounds(ATLAS)

(for 1 fb^{-1} data)

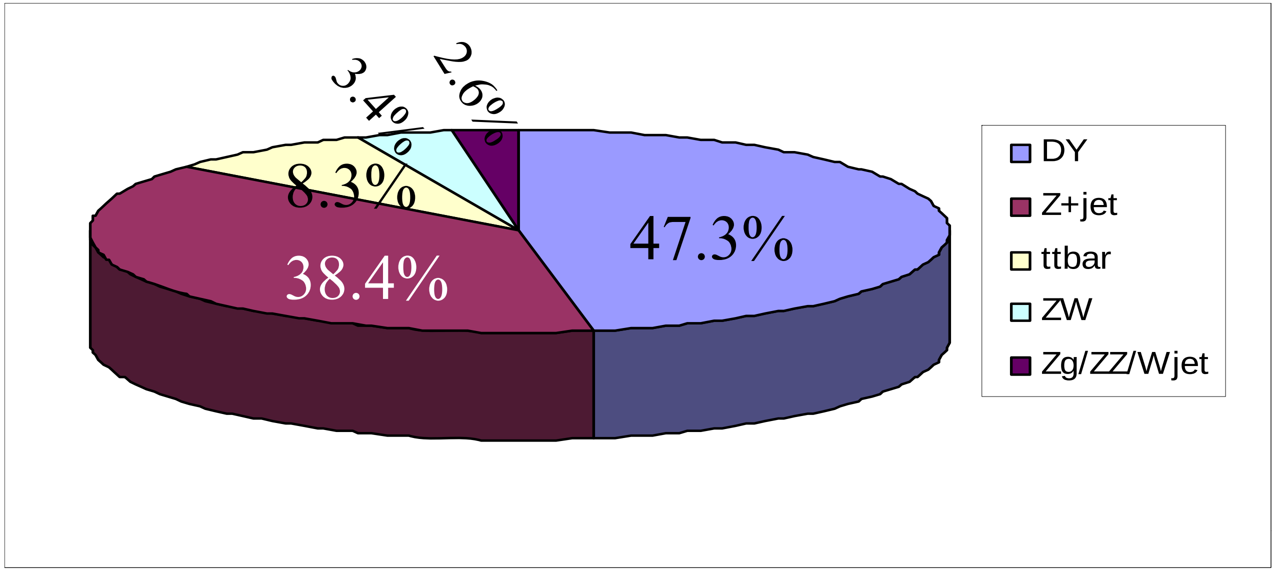
	N_{eee}	$N_{ee\mu}$	$N_{\mu\mu e}$	$N_{\mu\mu\mu}$	$N_{total}(1fb^{-1})$
N_{signal}	16.9	17.1	21.9	19.8	75.7
N_{bkg}	1.71	0.88	1.73	2.00	6.32
S/B	9.84	19.4	12.7	9.92	12.0



WW Signal and Background (ATLAS)

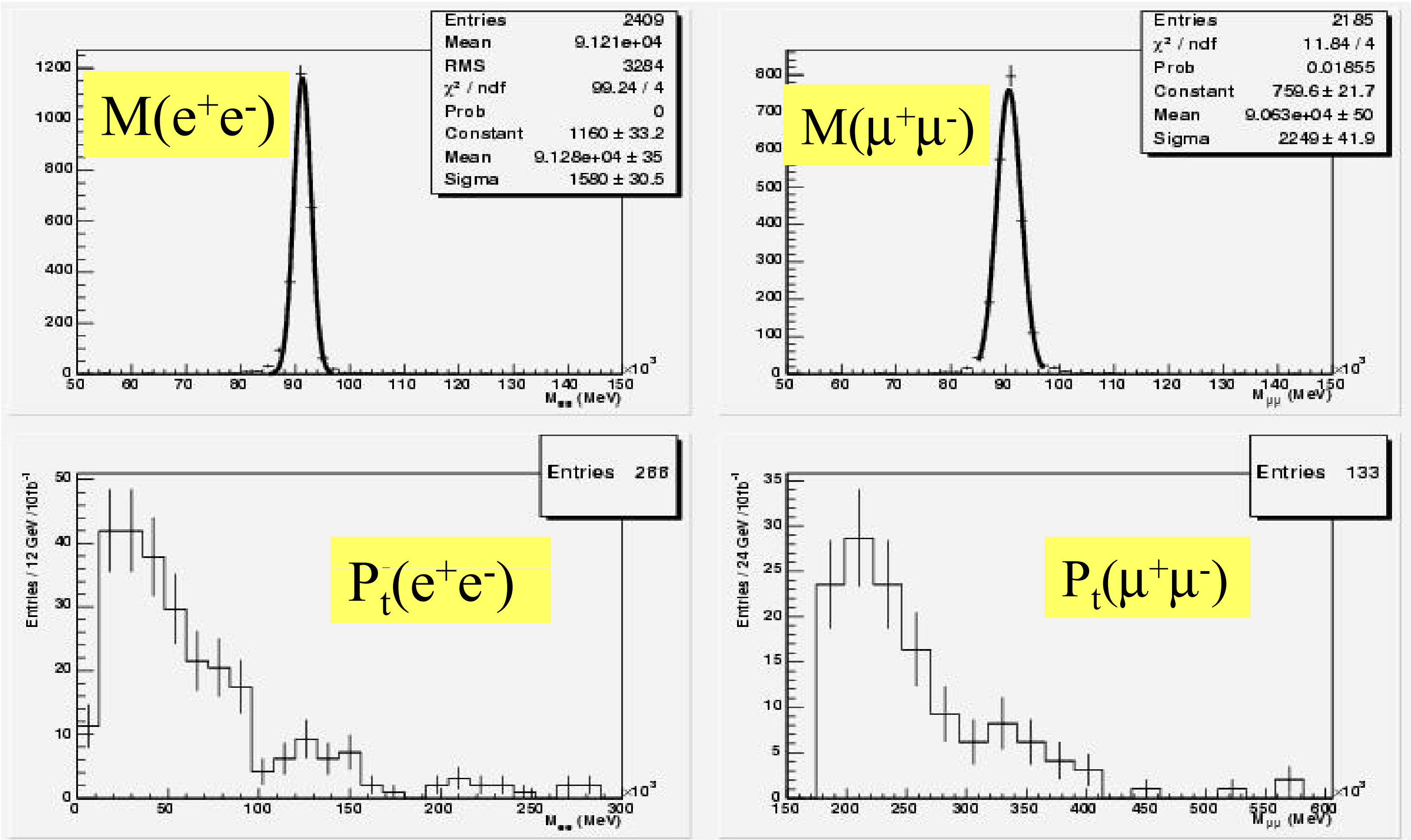
(for 1 fb^{-1} data)

Process	N_{ee}	$N_{\mu\mu}$	$N_{e\mu}$	N_{total}
$WW \to l\nu + X$ ($l = e, \mu$)	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



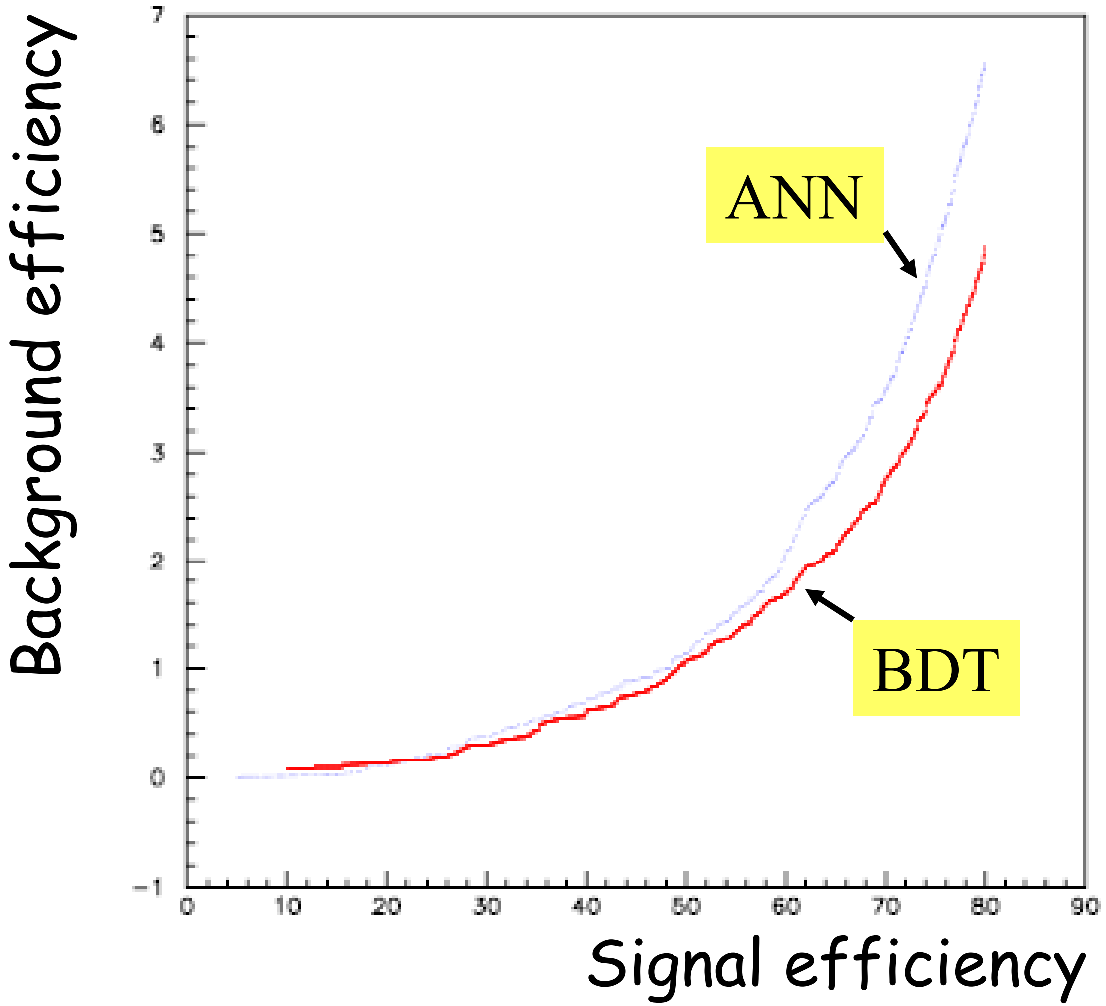
Invariant Mass and Pt Distributions for ZZ

For 1 fb^{-1} data at ATLAS



- 13 events candidates
- Background free with current statistics

Comparison of the efficiencies of BDT/ANN

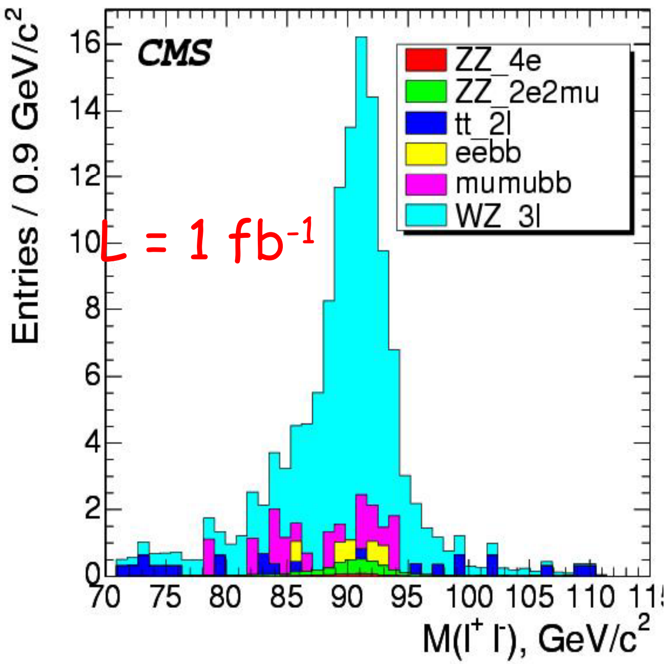


Signal and Background Samples (CMS)

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

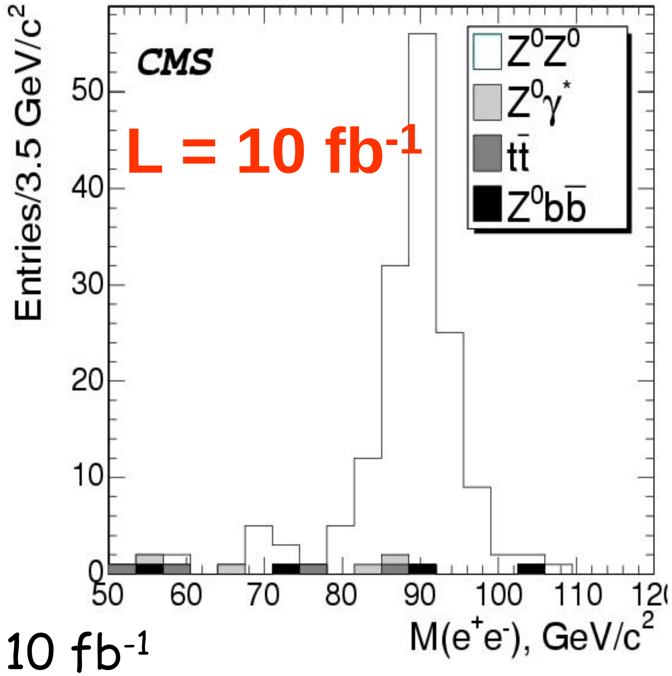
Expected signal and background yields for 1 fb^{-1}

	$e^\pm e^+ e^-$	$\mu^\pm e^+ e^-$	$e^\pm \mu^+ \mu^-$	$\mu^\pm \mu^+ \mu^-$	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	–

$ZZ \to 4e$ Expected Signal & Background

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

Nearly background free!

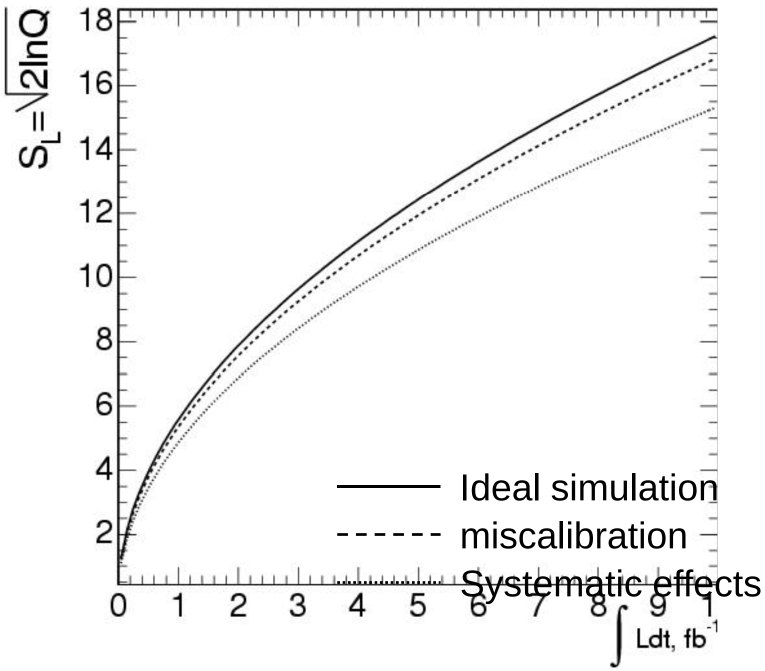


Expected signal and background yields for 1 and 10 fb^{-1}

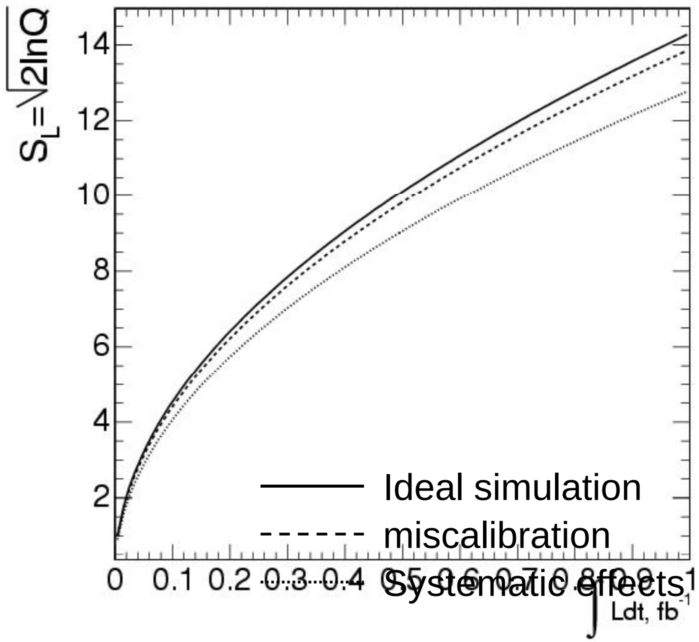
	Efficiency, %	$N_{events}/1fb^{-1}$	$N_{events}/10fb^{-1}$
Z^0Z^0	38	7.1	71.1
$Z^0\gamma^*$	4.5	0.16	1.60
$Z^0b\bar{b}$	0.07	0.08	0.84
$t\bar{t}$	0.06	0.12	1.22
Total background	–	0.36	3.66
S_L	–	4.8	13.1

WZ and ZZ Discovery Potential (CMS)

ZZ→4e signal significance



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

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

Summary

- D0 and CDF have been actively studies diboson production and the corresponding TGCs. The results so far are consistent with SM predictions.
- WZ, WW and ZZ signals are expected to be established at CMS and ATLAS with $100pb^{-1}$~$1fb^{-1}$
- Anomalous gauge boson coupling can be probed with a few fb^{-1} data
- Advanced techniques (BDT, ANN) can significantly improve the S/B.
- To improve the TGCs with LHC data, it's crucial to correctly build the TGCs into MC@NLO event generators

Anomalous Coupling and Form Factor

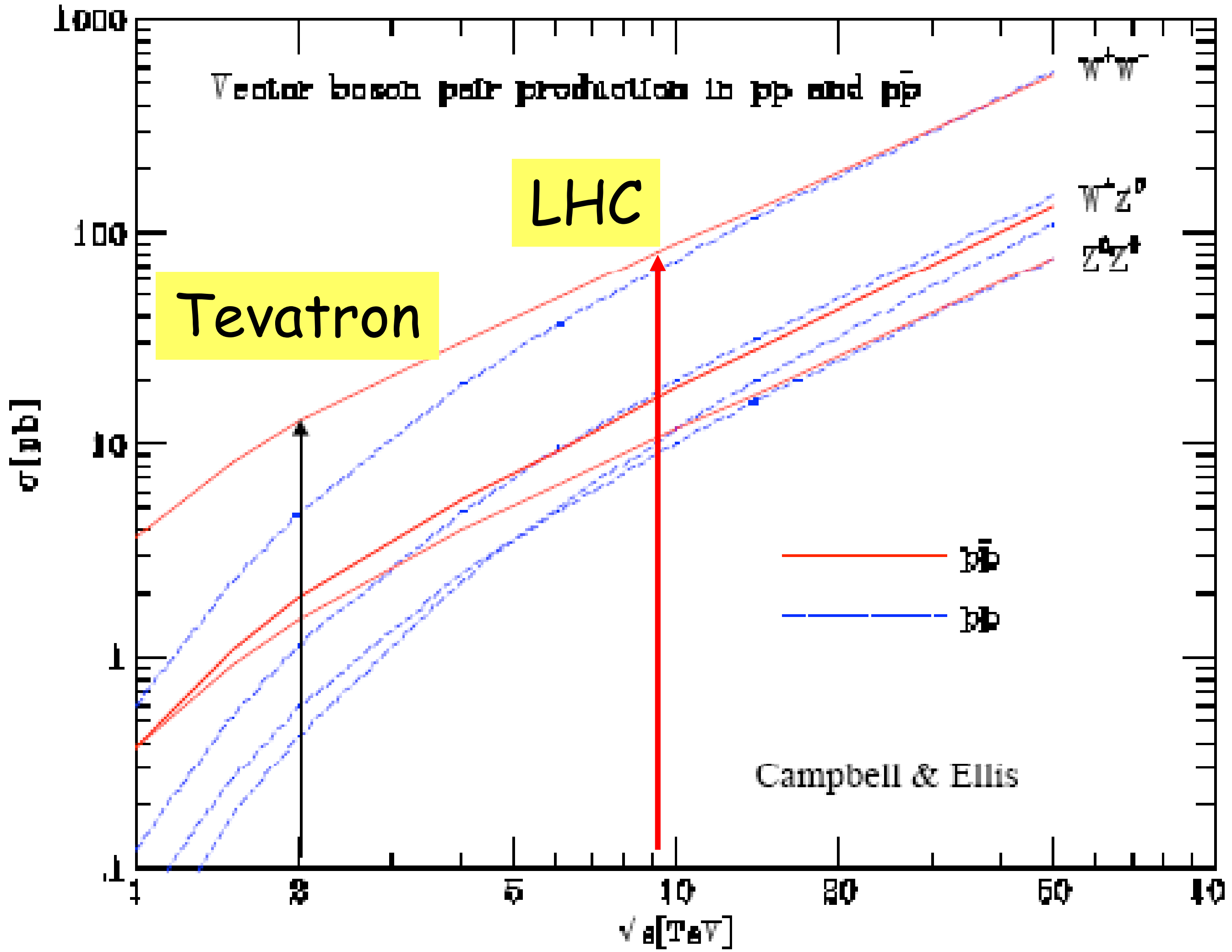
- Cross section increase for coupling with non-SM values, yielding large cross section at high energies that violating tree level unitarity $\rightarrow$ form factor scale

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

s: subprocess CM energy. Λ: form factor scale

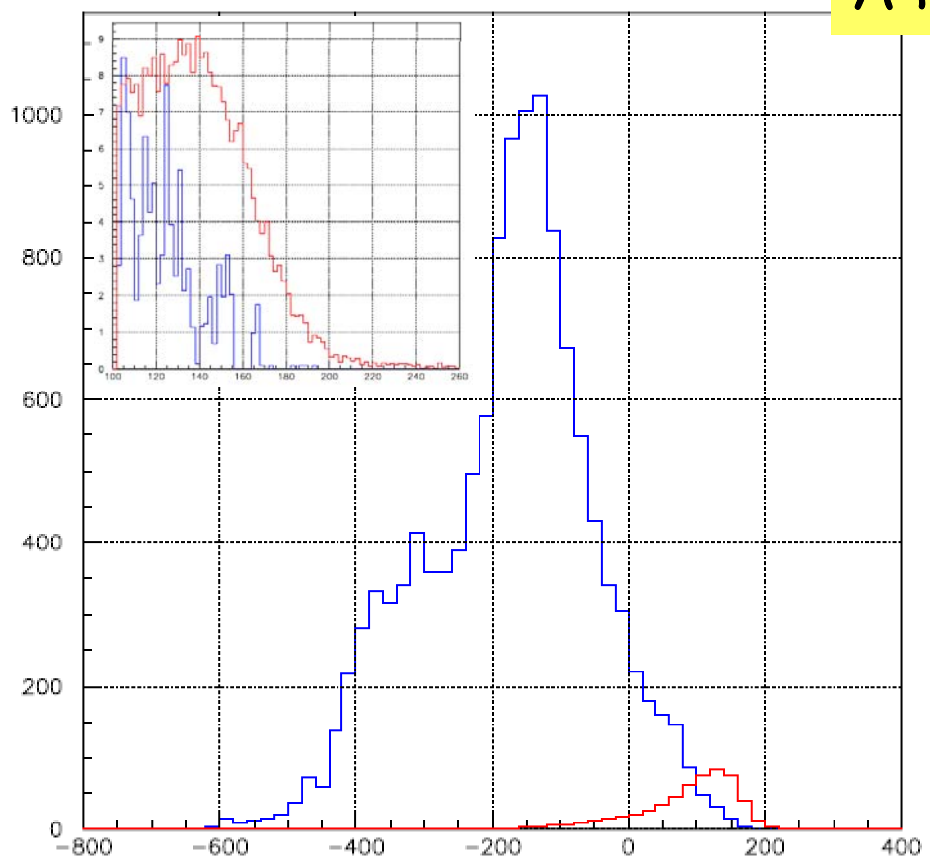
- TGCs manifest in
  - cross section enhancement
  - high $p_T(V=Z,W,\gamma)$
  - production angle

Diboson Production Cross Section

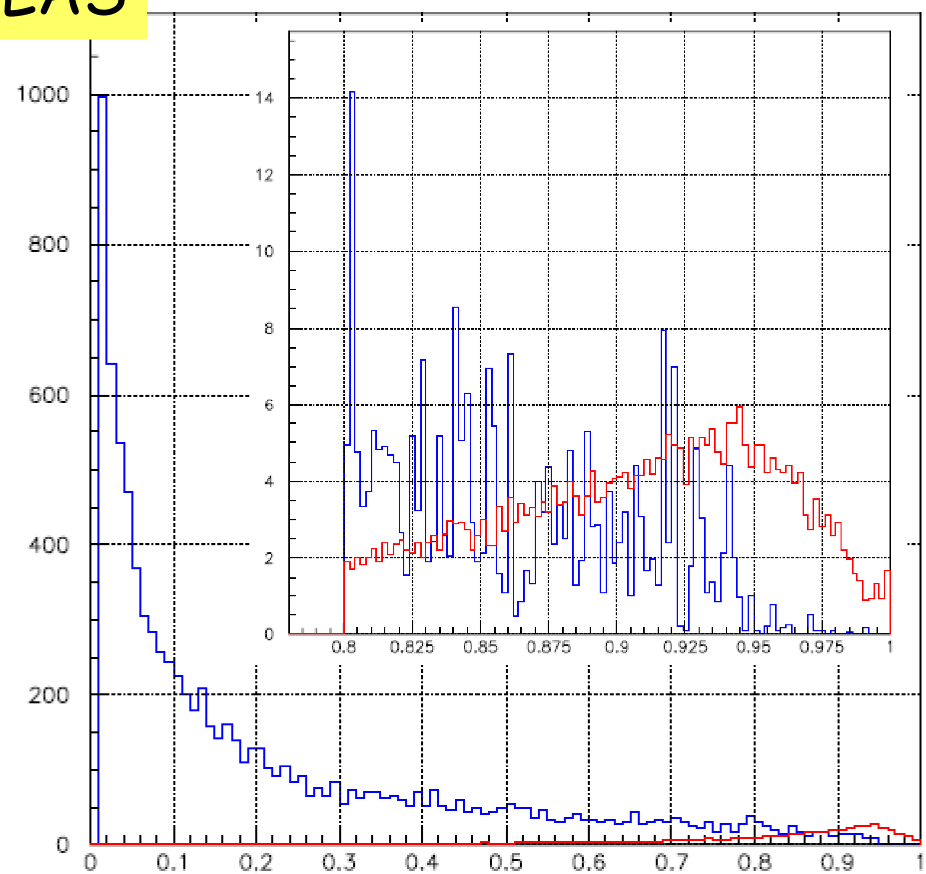


Boosted Decision Trees (BDT) and Artificial Neural Network (ANN)

ATLAS



e-boost



ANN