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Di-Boson Production at the LHC

Chia Ming, Kuo
National Central University, Taiwan

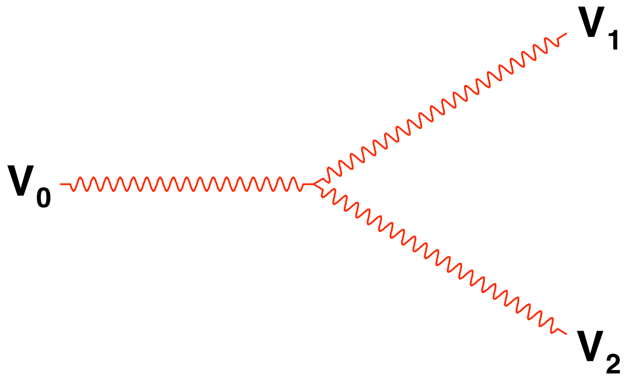
On behalf of
Atlas & CMS

Motivation

The consequence of the non-Abelian structure of the SM

➡ self-couplings of gauge bosons

Triple Gauge Coupling

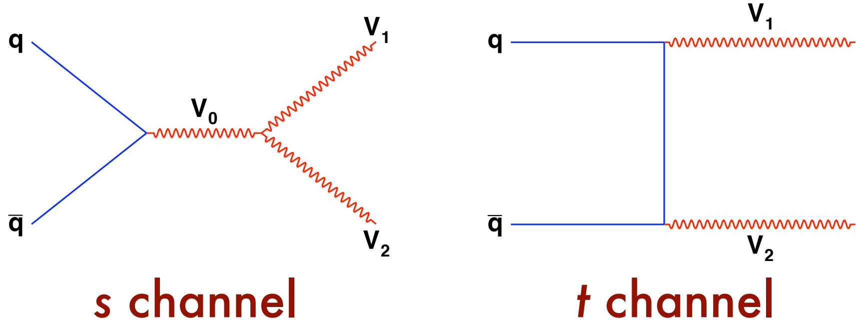


- charged TGC : WWZ, WWγ
  - allowed in SM
- neutral TGC : ZZZ, ZZγ, Zγγ
  - forbidden in SM

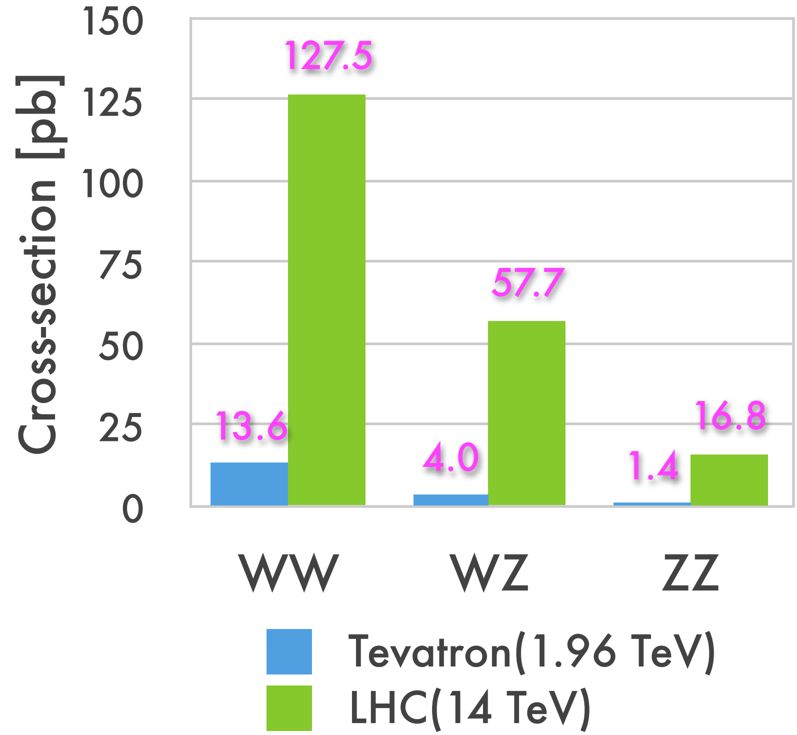
- Probing the coupling between gauge bosons tests the core of the SM
- Deviations from SM would indicate the presence of new physics
- An important, often irreducible, background in the search for new physics

WW, WZ, ZZ Production @ LHC

Di-boson production at collider



- WW
  - σ_{SM} = 127.5 pb
  - sensitive to WWZ and WWγ coupling
- WZ
  - σ_{SM} = 57.7 pb
  - *s* channel dominates
  - only sensitive to WWZ coupling
- ZZ
  - σ_{SM} = 16.8 pb
  - only *t* channel at tree level
  - *s* channel is strongly suppressed at $O(10^{-4})$ level



Triple Gauge-boson Couplings

- Most general description of the TGC vertex by an Lorentz invariant effective Lagrangian

$$
\begin{aligned}
L_{WWV}/g_{WWV} = & \, i g_1^V (W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\
& + i\frac{\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
& + g_5^V \epsilon^{\mu\nu\lambda\rho} (W^\dagger_\mu \partial_\lambda W_\nu - \partial_\lambda W^\dagger_\mu W_\nu) V_\rho \\
& + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda}
\end{aligned}
$$

V=Z,γ

	g_1^V	κ_V	λ_V	g_4^V	g_5^V	$\tilde{\kappa}_V$	$\tilde{\lambda}_V$
C	even	even	even	odd	odd	even	even
P	even	even	even	even	odd	odd	odd
CP	even	even	even	odd	even	odd	odd
SM	1	1	0	0	0	0	0

K. Hagiwara et al. PRD 41, 2113

Triple Gauge-boson Couplings

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& + i \frac{\lambda_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda} - g_4^V W_\mu^\dagger W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
& + g_5^V \epsilon^{\mu\nu\lambda\rho} (W_\mu^\dagger \partial_\lambda W_\nu - \partial_\lambda W_\mu^\dagger W_\nu) V_\rho \\
& + i\tilde{\kappa}_V W_\mu^\dagger W_\nu \tilde{V}^{\mu\nu} + i \frac{\tilde{\lambda}_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu \tilde{V}^{\nu\lambda}
\end{aligned}
$$

V=Z,γ

	g_1^V	κ_V	λ_V	g_4^V	g_5^V	$\tilde{\kappa}_V$	$\tilde{\lambda}_V$
C	even	even	even	odd	odd	even	even
P	even	even	even	even	odd	odd	odd
CP	even	even	even	odd	even	odd	odd
SM	1	1	0	0	0	0	0

K. Hagiwara et al. PRD 41, 2113

$\Delta\kappa = \kappa - 1 \quad \Delta g_1^Z = g_1^Z - 1$

WWZ : $\Delta g_1^Z \ \Delta\kappa_Z \ \lambda_Z$

WWγ : $\Delta\kappa_\gamma \ \lambda_\gamma$

($g_1^\gamma = 1$: EM gauge invariance)

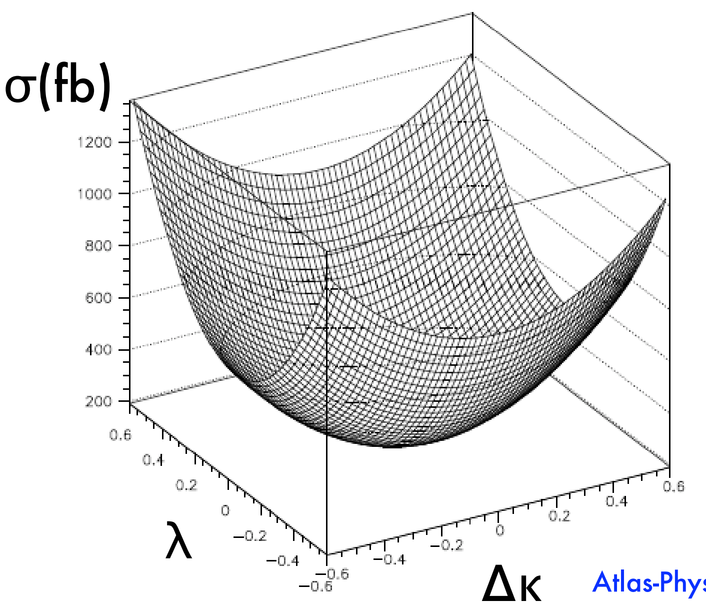
Anomalous TGC

- A form factor is introduced to avoid unitarity violation at high energies

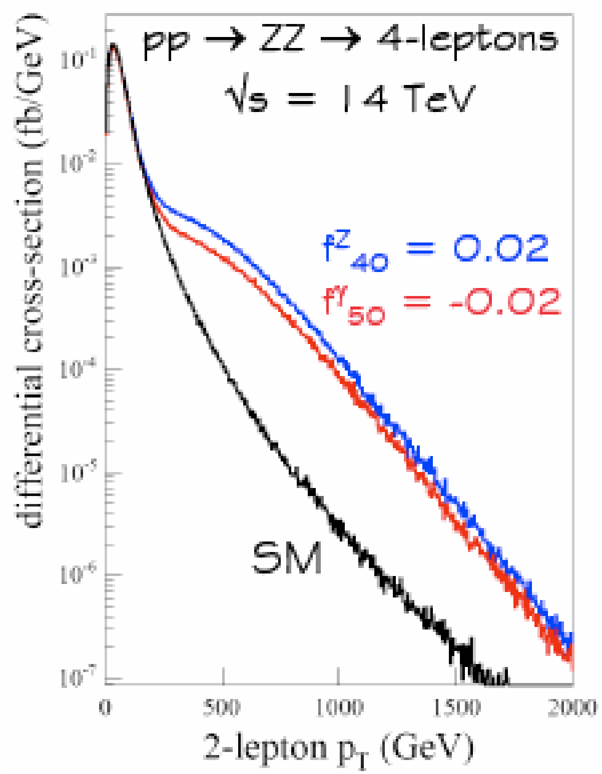
$$\lambda(s) = \frac{\lambda}{\left(1+\frac{s}{\Lambda_{FF}^2}\right)^2} \qquad \Delta\kappa(s) = \frac{\Delta\kappa}{\left(1+\frac{s}{\Lambda_{FF}^2}\right)^2} \qquad \Delta g_1^Z(s) = \frac{\Delta g_1^Z}{\left(1+\frac{s}{\Lambda_{FF}^2}\right)^2}$$

Signatures of anomalous couplings

- enhancement of cross section
- large scattering angle → small rapidity region
- enhancement at high P_T



Atlas-Phys-Pub-2006-011



TGC limits from Atlas

- Using fast simulated WZ, Wγ and background samples
- λ_Z, $\Delta\kappa_\gamma$, λ_γ : a maximum likelihood fit to one dimensional $P_T(V)$ distribution
- $\Delta\kappa_Z$, Δg^1_Z : fit to two dimensional $P_T(Z)$ vs. $P_T(l_W)$ distribution

95%C.L. incl. syst.

	Atlas	CDF (WW+WZ)	CDF(Wγ+WW+WZ)
L	30 fb^{-1}	350 pb^{-1}	Wγ : 200 pb^{-1} WW+WZ : 350 pb^{-1}
λ_Z	(-0.0073, 0.0073)	(-0.28, 0.28)	(-0.18, 0.17)
λ_γ	(-0.0035, 0.0035)		
$\Delta\kappa_Z$	(-0.11, 0.12)	(-0.50, 0.43)	(-0.46, 0.39)
$\Delta\kappa_\gamma$	(-0.075, 0.076)		
Δg^1_Z	(-0.0086, 0.011)		

(CDF results : hep-ex/0705.2247, assuming equal WWZ and WWγ coupling)

LHC : orders of magnitude improvement over Tevatron
Neutral TGC still needs to be explored at the LHC

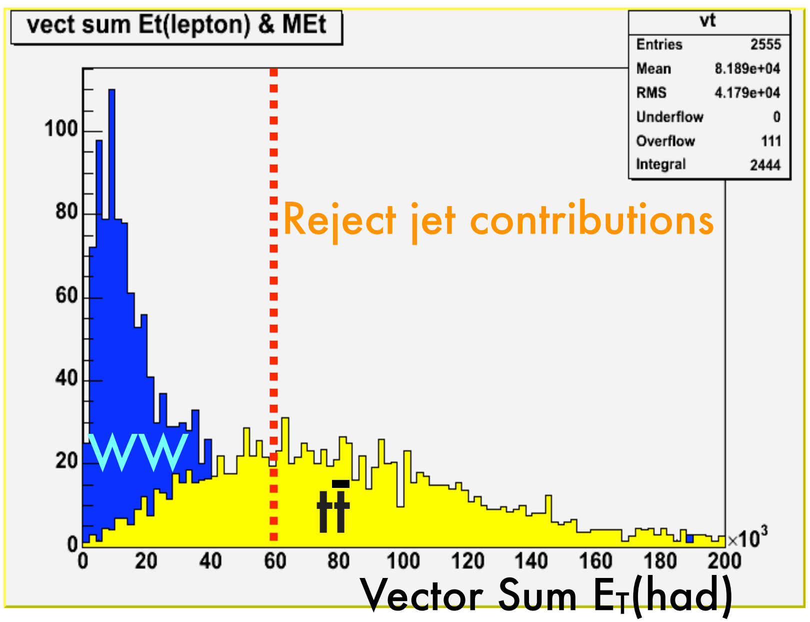
MC samples for studies @ Atlas

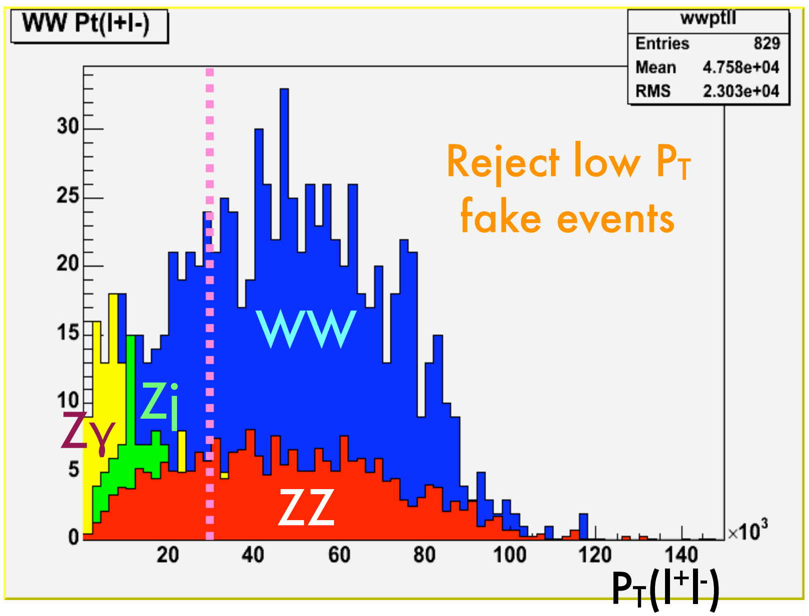
Process	MC data	Process	MC data
$ZW^+ \rightarrow 2e/2\mu + X$	26033	ttbar $\rightarrow \ell + x$	1.96×10^5
$ZW^- \rightarrow 2e/2\mu + X$	29085	Z(@Peak) $\rightarrow ee/\mu\mu/\ \tau\tau$	2.30×10^6
$ZZ \rightarrow 4e, 4\mu, 2e2\mu$	19933	$W \rightarrow e/\mu/t + \nu$	1.61×10^6
$WW \rightarrow \ell\nu + x$	32056	W+jets $\rightarrow \ell\nu + x$	1.59×10^6
ZZ(pythia) $\rightarrow 4\ell\ (e,\mu)$	$4.66\ \times10^4$	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		

- Signal samples were produced with MC@NLO(v2.3)-Jimmy
  - W/Z width effect is not included
- Background samples were produced with PYTHIA 6.2
- No pile-up effect included

$WW \to l\nu l\nu$ @ Atlas

- Select two isolated leptons with $P_T > 25, 20$ GeV
- MET > 30, 35, 40 GeV for e^+e^-, $e\mu$ and $\mu^+\mu^-$
- M_{ee} & $M_{\mu\mu} > 50$ GeV; $M_{e\mu} > 30$GeV; Veto $M_Z(ee,\mu\mu)$
- $M_T(W^+W^-) < 500$ GeV
- Vector sum of E_T(had) < 60 GeV; Scalar sum of E_T(had) < 45 GeV
- $P_T(l^+l^-) > 30$ GeV





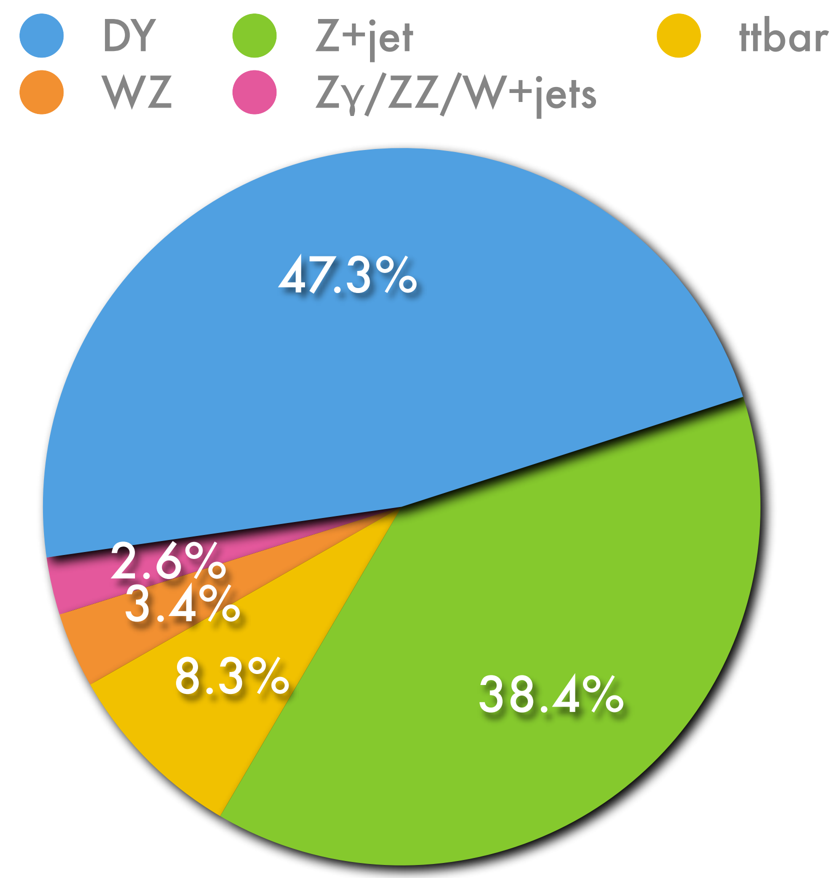
WW→lνlν @ Atlas

	ee	μ μ	eμ	Tot./fb^{-1}
N_S	36.7	37.6	284.4	358.7
N_B	188.6	112.1	59.4	360.1
S_L	2.6	3.4	25.3	16.6
$N_S/\sqrt{N_B}$	2.7	3.6	36.9	18.9

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

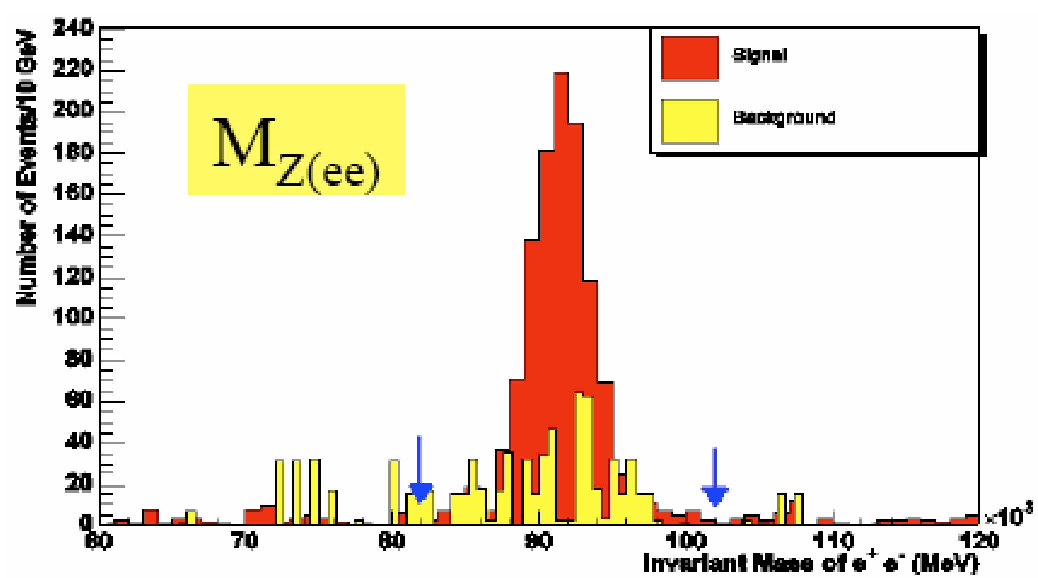
(CDF prel. result with 825 pb^{-1} : 95 observed events expected signal : 52.4(4.4), bkg : 37.8(4.8))

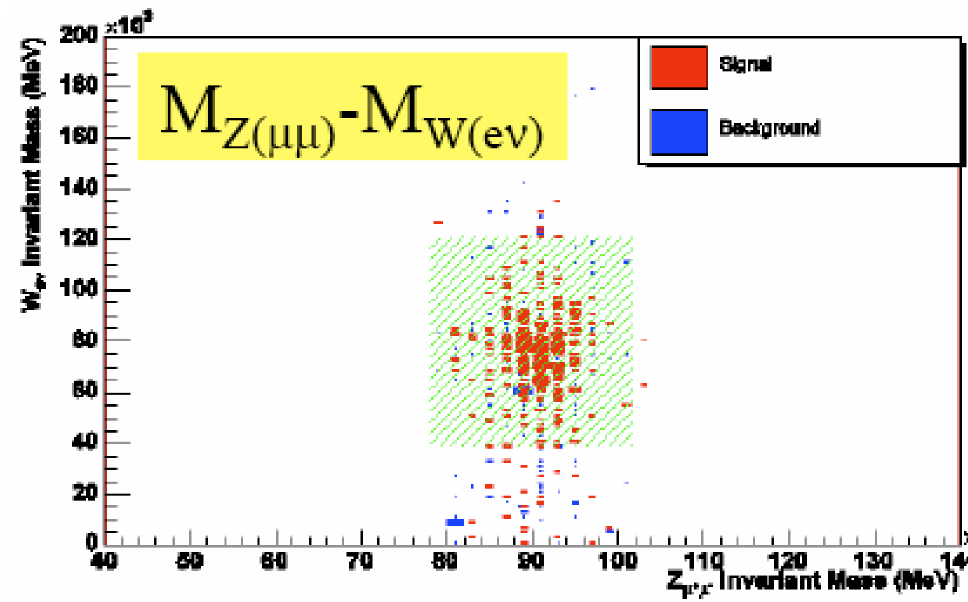
Background contributions



WZ→lllν @ Atlas

- Select three isolated electrons or muons with P_T > 10 GeV
- Z candidates are formed by the combination of the same-flavour opposite-charge pairs
    - the mass is within 10 GeV of the nominal Z mass
- The third high P_T electron or muon with MET > 25 GeV
- No more than one jet with energy greater than 30 GeV in $|\eta|<3$
- Vector sum of E_T < 100 GeV; Scalar sum of E_T < 200 GeV

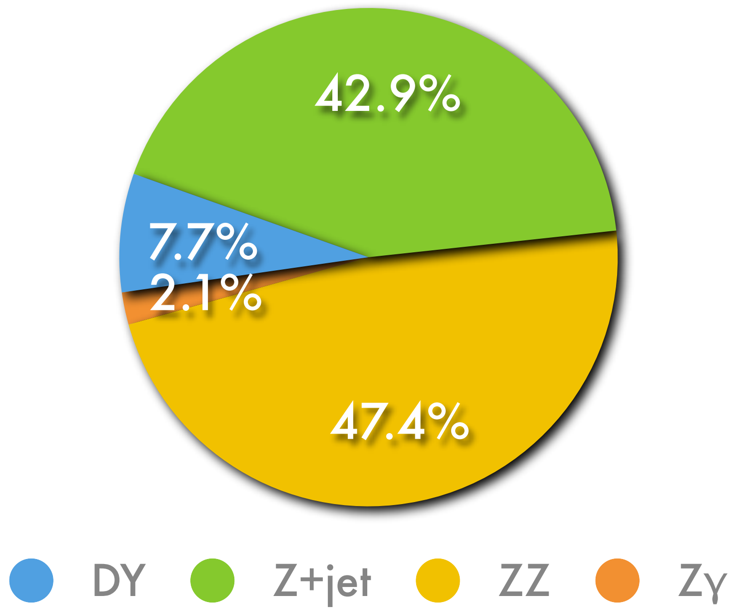




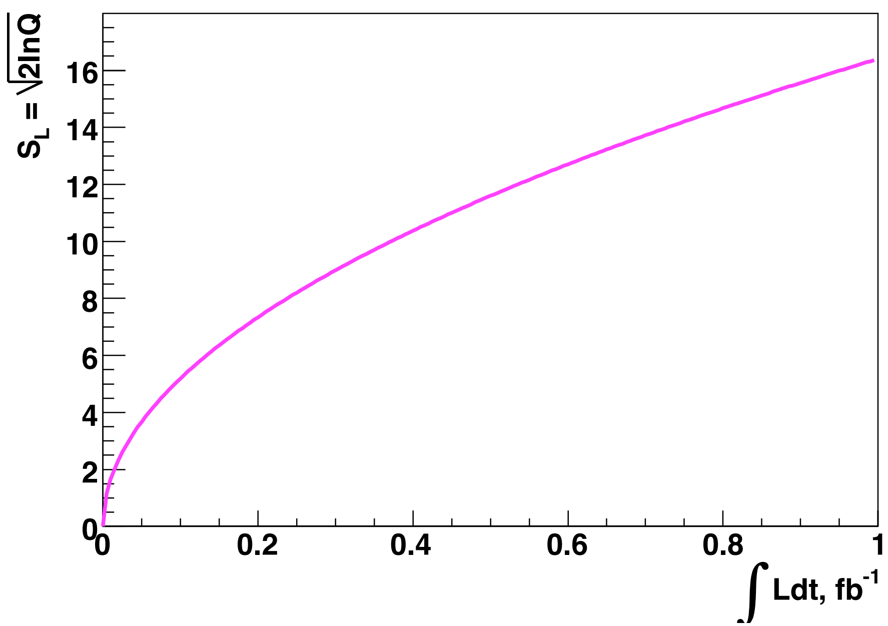
WZ→lllν @ Atlas

	3e	2e1 μ	1e2μ	3μ	Tot./fb^{-1}
N_S	16.9	17.1	21.9	19.8	75.7
N_B	1.7	0.9	1.7	2.0	6.3
S_L	7.4	8.6	8.9	8.0	16.4

Background contributions



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



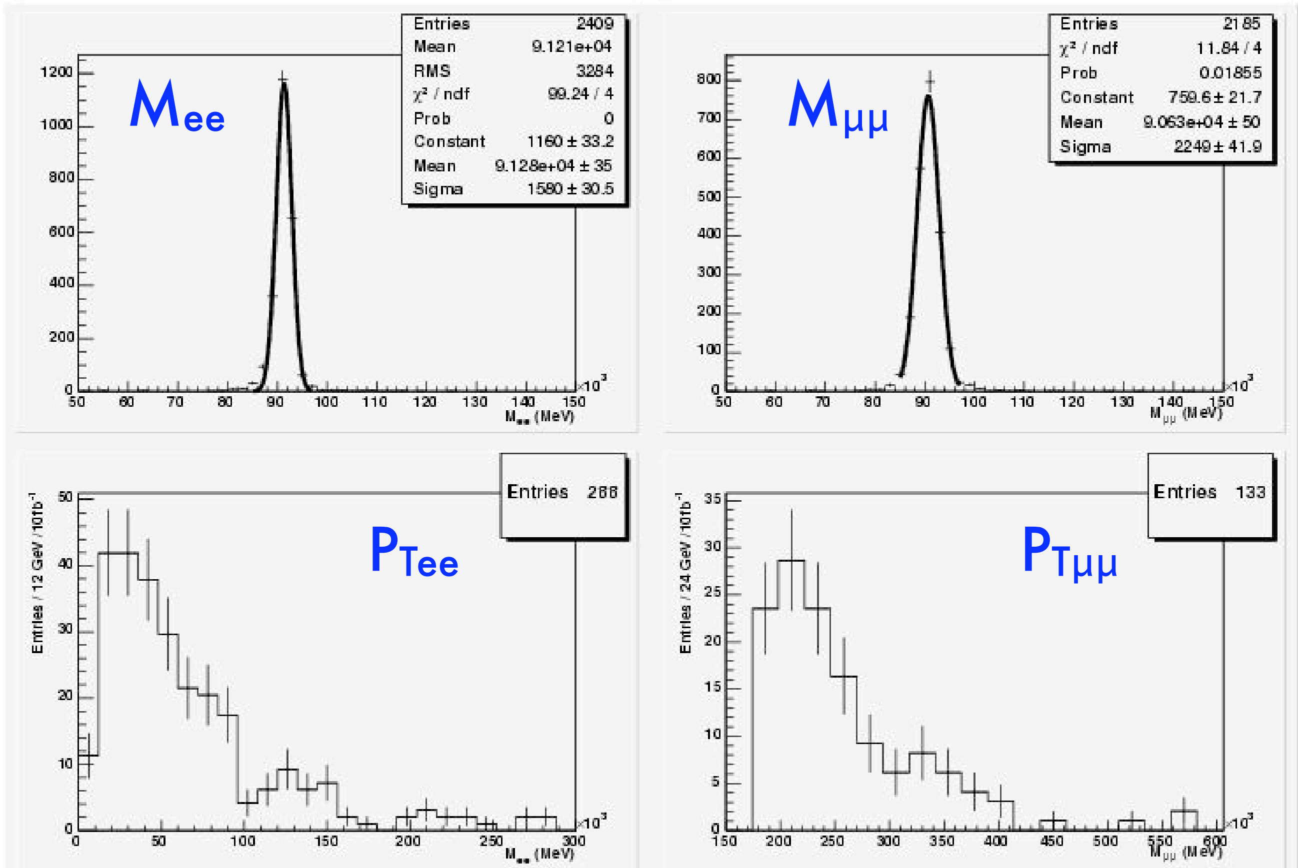
5σ discovery at ~ 100 pb^{-1}

ZZ→llll @ Atlas

- Two-lepton pairs with at least one lepton $P_T > 25$ GeV
- $\Delta R(l^+l^-) = \sqrt{(\Delta\eta^2+\Delta\Phi^2)} > 0.2$
- $|M_{ll} - M_Z| < 12$ GeV

13.4 candidate events are expected at 1 fb^{-1}

Almost background free !



134 selected events for 10 fb^{-1}

MC samples for studies @ CMS

Signal

Data sample	Generator	N_{events}	$\int L\,dt$, fb^{-1}
Z^0Z^0/γ^*	PYTHIA	21 560	827
Z^0Z^0		15 467(72%)	
$Z^0\gamma^*$		5634(26%)	
$\gamma^*\gamma^*$		459(2%)	
$W^\pm Z^0/\gamma^*$	PYTHIA	91 181	54.7
$W^\pm Z^0$		87 078(95.5%)	
$W^\pm\gamma^*$		4103(4.5%)	

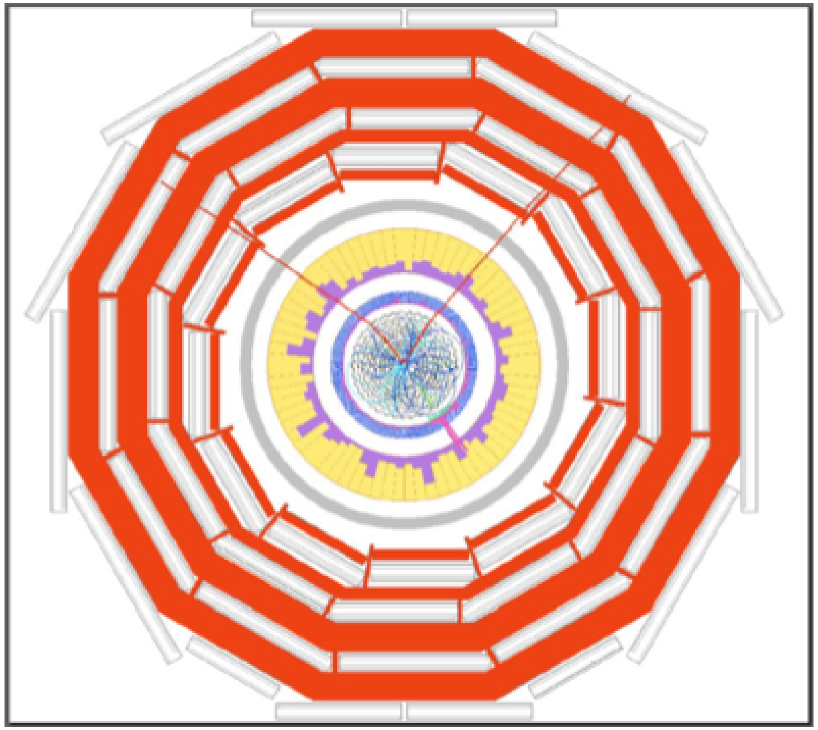
- Pile-up is included
- $<N_{PU}> = 5$
- $L = 2\times10^{33}$ cm^{-2}s^{-1}

Background

Data sample	Generator	N_{events}	Pre-selection	$\int L\,dt$, fb^{-1}
$Z^0b\bar{b}(e^+e^-b\bar{b})$	CompHEP	290 823	$Z^0 \to e^+e^-, b \to X$, $60 < M(e^+e^-) < 100\,\mathrm{GeV}/c^2$	4.8
$Z^0b\bar{b}(\mu^+\mu^-b\bar{b})$	CompHEP	110 148	$Z^0 \to \mu^+\mu^-, b \to X$, $60 < M(\mu^+\mu^-) < 100\,\mathrm{GeV}/c^2$	1.8
$Z^0/\gamma^*b\bar{b}(4e)$	CompHEP	81 000	$Z^0/\gamma^* \to e^+e^-$, at least $4e$, $M(e^+e^-) > 5\,\mathrm{GeV}/c^2$	673
$t\bar{t}(2\ell)$	TopRex	378 000	$W \to e/\mu/\tau$	6
$t\bar{t}(4e)$	PYTHIA	79 000	$W \to e/\mu/\tau, \tau \to e/\mu$, at least $4e$	413
$Z^0/\gamma^*Z^0/\gamma^*(4e)$	PYTHIA	250 000	$Z^0/\gamma^* \to e^+e^-$	9615
$Z^0/\gamma^*Z^0/\gamma^*(4\mu)$	PYTHIA	8241	$Z^0/\gamma^* \to \mu^+\mu^-$	317
$Z^0/\gamma^*Z^0/\gamma^*(2e2\mu)$	PYTHIA	10 000	$Z^0/\gamma^* \to 2\ell, \ell = e/\mu$	310

$WZ \to ll l\nu$ @ CMS

$W \to e\nu$ $Z \to \mu\mu$



Signal definition

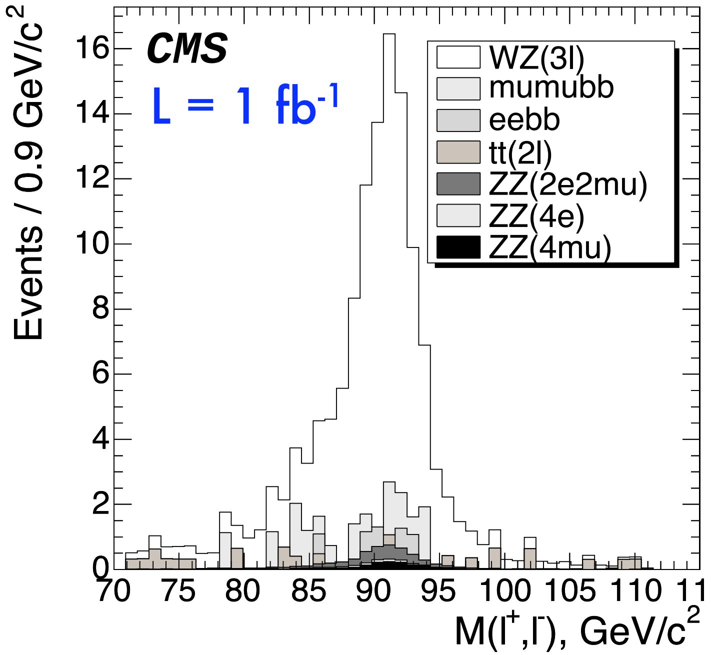
- Restrict to on-shell Z : $|M_{l+l-} - M_Z| < 20$ GeV
- Implicitly force W to be on-shell

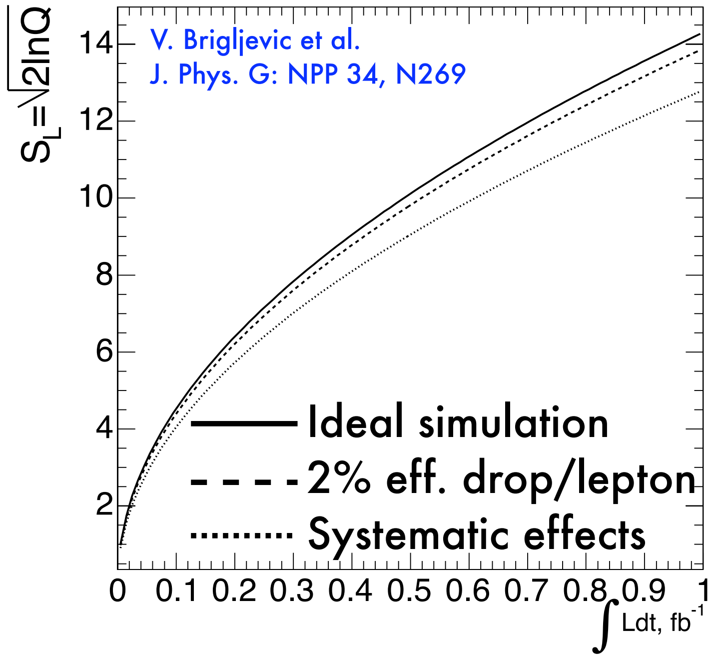
σ_{NLO} from MCFM

- σ_{NLO} ($pp \to W^+Z \to 3l$, $l=e,\mu,\tau$) = 1034 fb
- σ_{NLO} ($pp \to W^-Z \to 3l$, $l=e,\mu,\tau$) = 630 fb

- Select three isolated electrons or muons with $P_T > 10$ GeV and $|\eta|<2.5$
- Z candidates are formed by the combination of the same-flavor opposite-charge pairs
  - the mass is within 20 GeV of the nominal Z mass
  - veto event if more than one Z candidate
- Find third lepton from W with $P_T > 20$ GeV
  - If more than one candidate, select the one with the highest P_T
- Jets with $\Delta R(\text{jet}, l)<0.3$ are not considered

WZ→lllν @ CMS



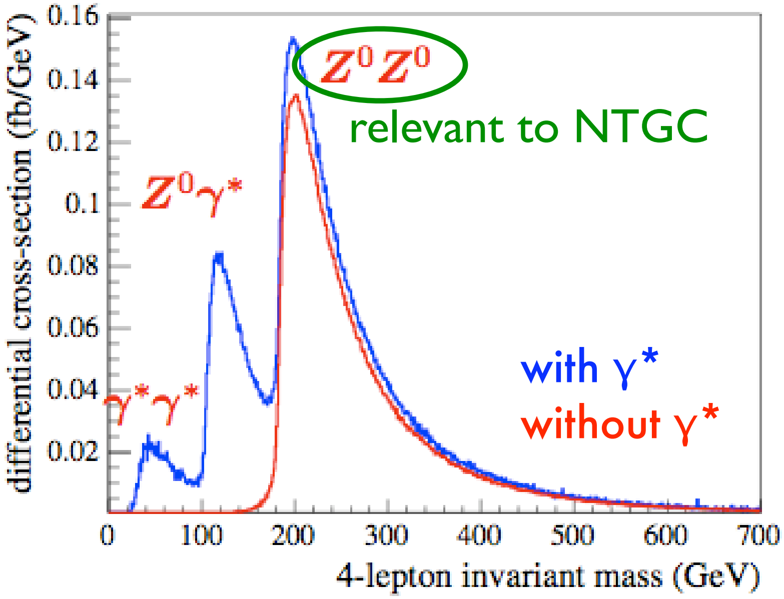


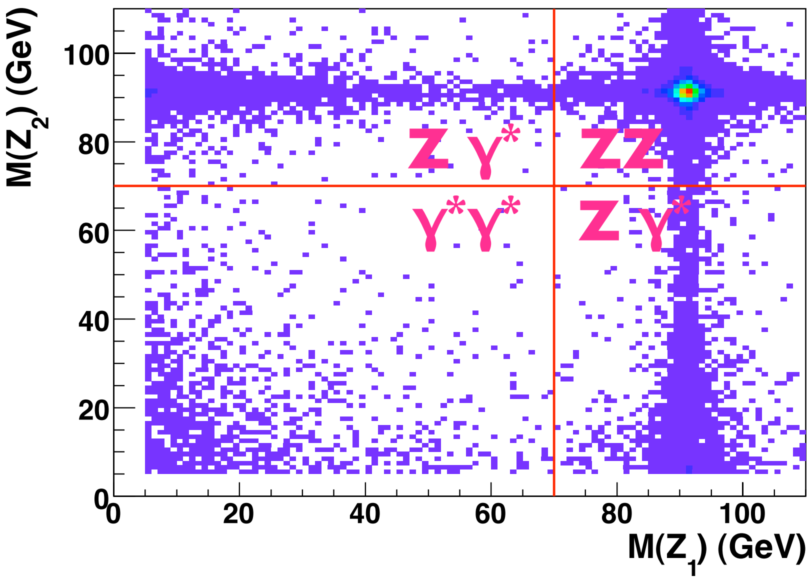
	3e	2e1μ	1e2μ	3μ	Total
WZ	14.8	26.9	28.1	27.0	96.8
ZZ	0.63	1.54	1.50	1.51	5.19
$t\bar{t}$	0.93	1.55		0.31	2.79
$\mu\mu b\bar{b}$			6.54	4.9	11.4
$eeb\bar{b}$	1.21	1.82			3.03
Tot. background	2.8	4.9	8.0	6.7	22.5
S_L	5.3	7.3	6.5	6.6	12.8

High significance at the first fb^{-1}
5σ discovery (including systematic uncertainties) at ~ 150 pb^{-1}

(D0 prel. result from 760-860 pb^{-1} : 12 observed events with an estimated 3.61(0.2) background)

ZZ→4e @ CMS

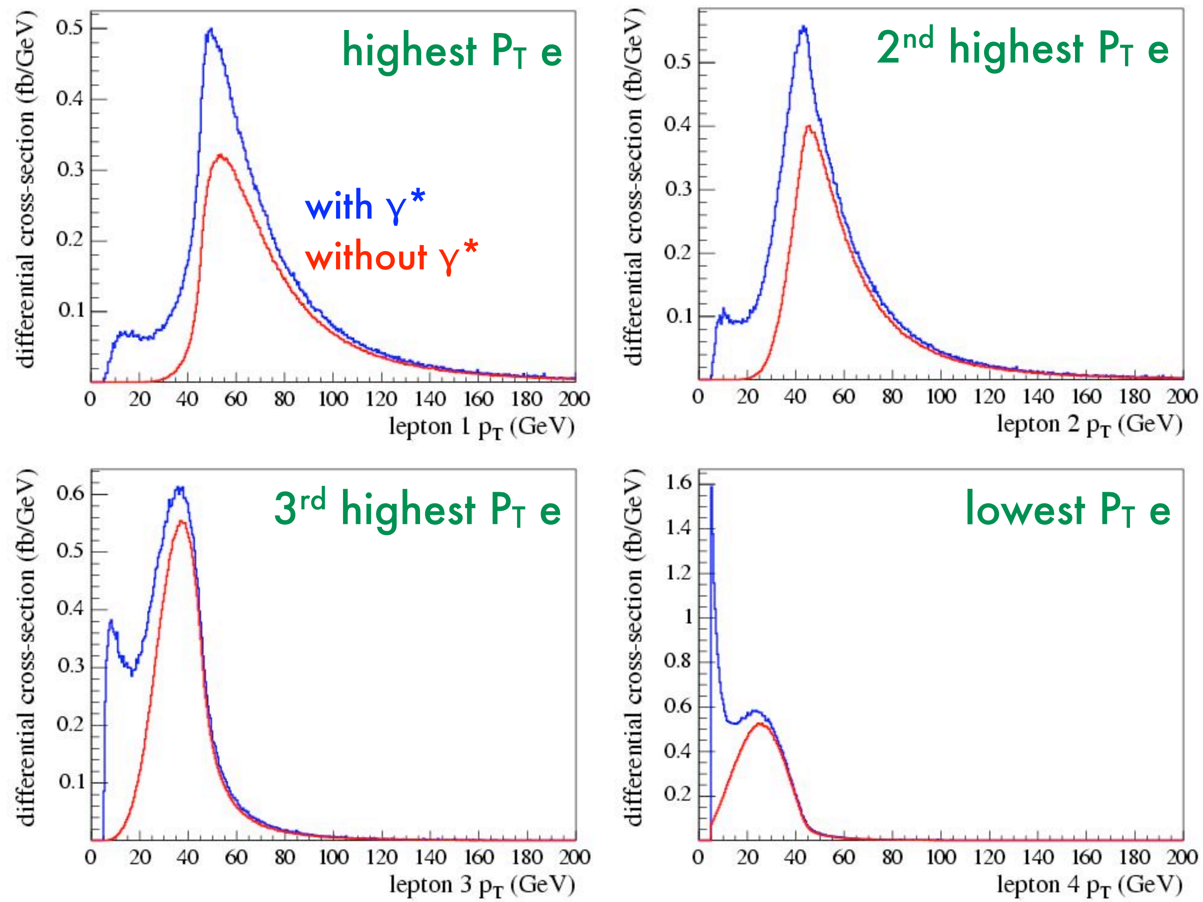




Signal is defined as events with two Z bosons on shell : $70 < M_Z < 110$ GeV ($\sigma_{NLO} = 9.35$ fb)

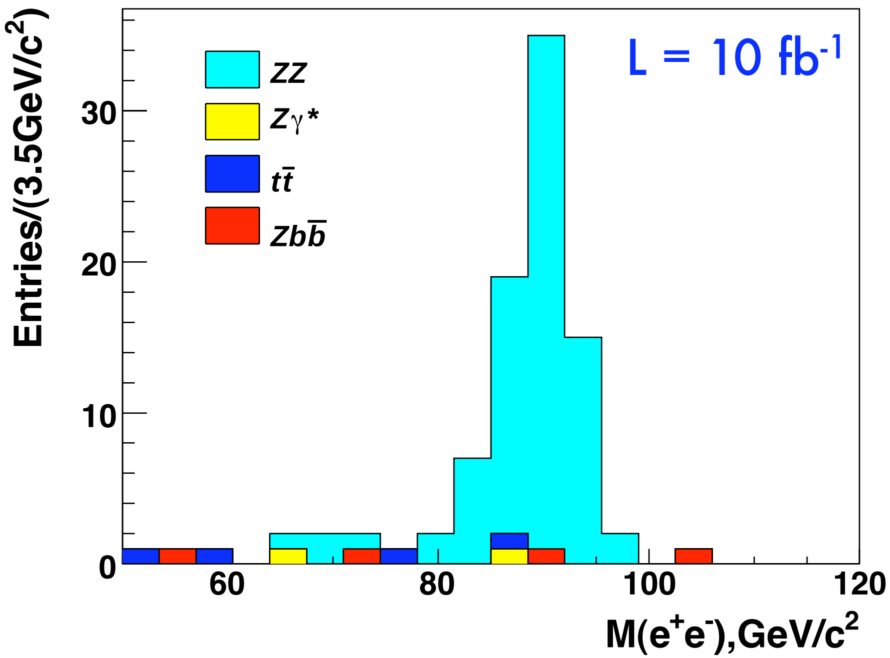
Level-1 and High Level Trigger			
Sample	Single Ele.	Double Ele.	Single OR Double Ele.
ZZ	97.3 %	98.4%	99.5%
$Zb\bar{b}$(2ebb)	85.5 %	77.6%	92.1%
$Zb\bar{b}$(4e)	87.7%	81.1%	93.9%
$t\bar{t}$(2l)	82.0%	70.3%	89.6%
$t\bar{t}$(4e)	78.2%	68.9%	86.9%

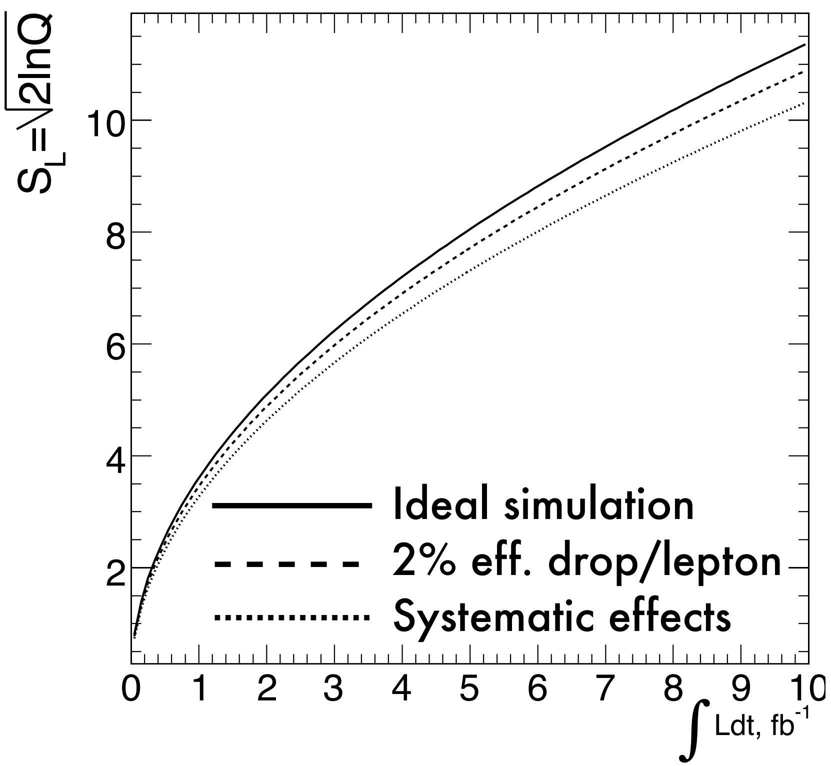
ZZ→4e @ CMS



- Select four isolated electrons with P_T>30, 20, 15, 10 GeV
- Z candidates are formed from electron pairs with opposite charge and $50 < M(e^+e^-) < 120$ GeV
- Select the "best" combination of the Z candidates
  - the one for which one of the Z candidates has the mass closest to the nominal Z mass
- If there are more than 4 electrons, select only one ZZ combination (based on electron P_T)

ZZ→4e @ CMS





	Events / 1 fb^{-1}	Events / 10 fb^{-1}
ZZ	3.6 (0.05)	35.6
$Z\gamma^*$	0.08 (0.01)	0.8
$Zb\bar{b}$	0.08 (0.01)	0.84
$t\bar{t}$	0.12 (0.02)	1.22
Total background	0.28	2.86

Almost background free !
5σ discovery (including systematic uncertainties) at ∼ 2 fb^{-1}

Summary

- WW, WZ, ZZ production are expected to be observed with the early LHC data (100 pb^{-1} ~ 1 fb^{-1})

Expected event yields at the first fb^{-1} at the LHC

	Atlas (S/B)	CMS (S/B)
$WW \rightarrow e\mu$	284.4/59.4	
$WZ \rightarrow 3l$	75.7/6.3	96.8/22.5
ZZ	13.4/0 (4l)	3.6/0.28 (4e)

- The probe of triple gauge-boson couplings will be possible with the first few fb^{-1} data

- In perspective, the study of di-boson production will be extended to include WW, Wγ and Zγ in CMS, and Wγ and Zγ in Atlas

Backup

Systematic Uncertainties (CMS)

WZ

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
$Z^0Z^0 \to 4l$ subtraction	4.0	4.0
PDF uncertainty	–	3.5
Total	17.4	20.8

ZZ - cross section

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

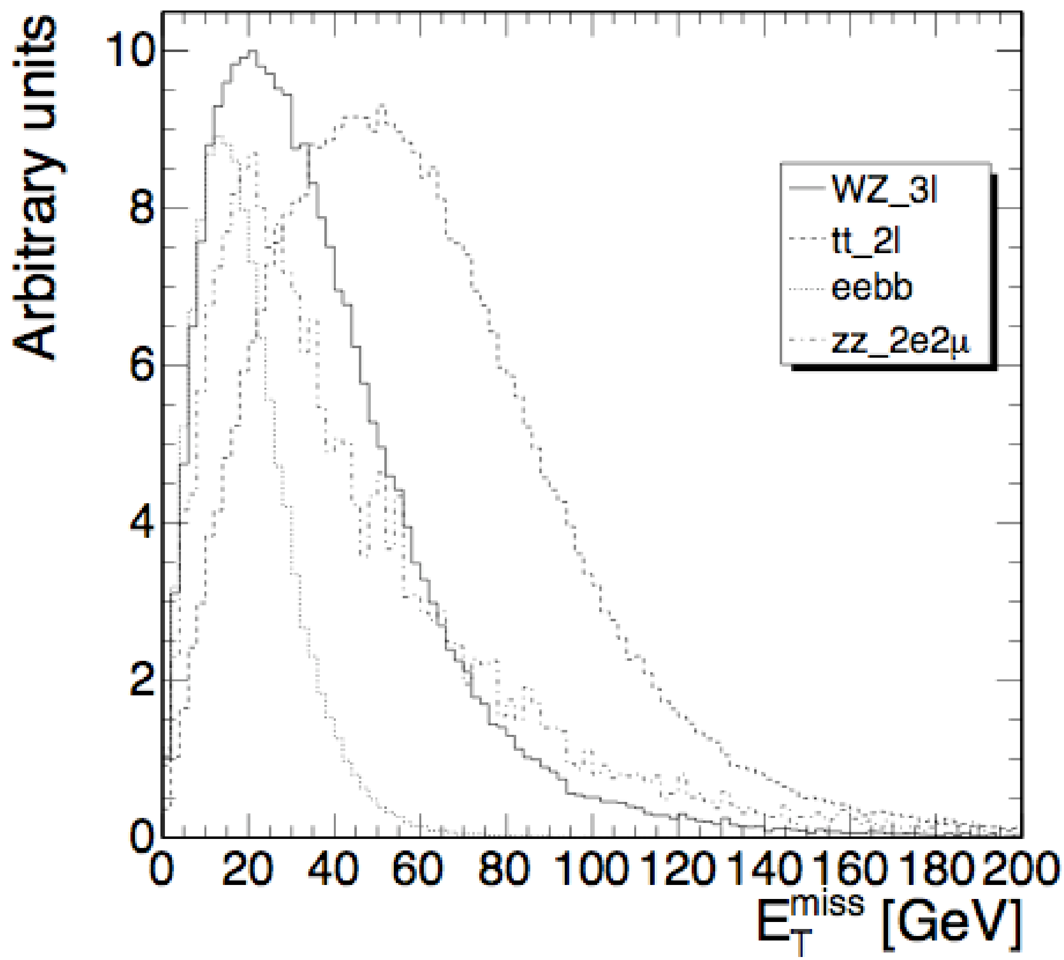
ZZ - significance

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

Atlas Fast Simulation : WZ, Wγ

	$Z\gamma$	W+jet	Z+jet	$t\bar{t}(\gamma)$	$W\gamma \to \tau\nu\gamma$	all Backgrd	$W\gamma$ Signal
$P^T_\gamma > 100$ GeV	1277	2097	2101	945	665	8153	10638
$P^T_{1\pm} > 25$ GeV	1196	1938	1800	837	586	7098	10066
$P^T_{\text{miss}} > 25$ GeV	377	1557	215	689	574	3511	7311
$\Delta R(\gamma, 1^\pm) > 1$	376	1543	183	611	574	3385	6791
$\sum_{\text{jets}} \vec{P}^T_{\text{jet}_i} < 100$ GeV	341	1280	133	286	534	2623	4262

	Z+jet	ZZ	$t\bar{t}$	All Backgrd	WZ Signal
3 leptons, $P^T_{1\pm} > 25$ GeV	398	500	461	1359	3285
$P^T_{\text{miss}} > 25$ GeV	3.2	90	357	450	2453
$\lvert M_{1^+1^-} - M_Z \rvert < 10$ GeV	2.8	76	65	144	2331
$\sum_{\text{jets}} \vec{P}^T_{\text{jet}_i} < 100$ GeV	2.5	72	44	119	1987


Arbitrary units
10
8
6
4
2
0
0 20 40 60 80 100 120 140 160 180 200
E_T^{miss} [GeV]
WZ_3l
tt_2l
eebb
zz_2e2μ