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Diboson physics with the ATLAS detector

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Presented results based on the following documents

- *“Diboson Physics with the ATLAS Detector” (B. Zhou), CSC Note SM6*
- *“Diboson Physics with the ATLAS Detector”, ATL-PHYS-INT-2008, April 2008*
- *“QCD Corrections to Vector Boson Pair Production”, N. Kauer, talk at DIS2008, UCL, London*

Outline

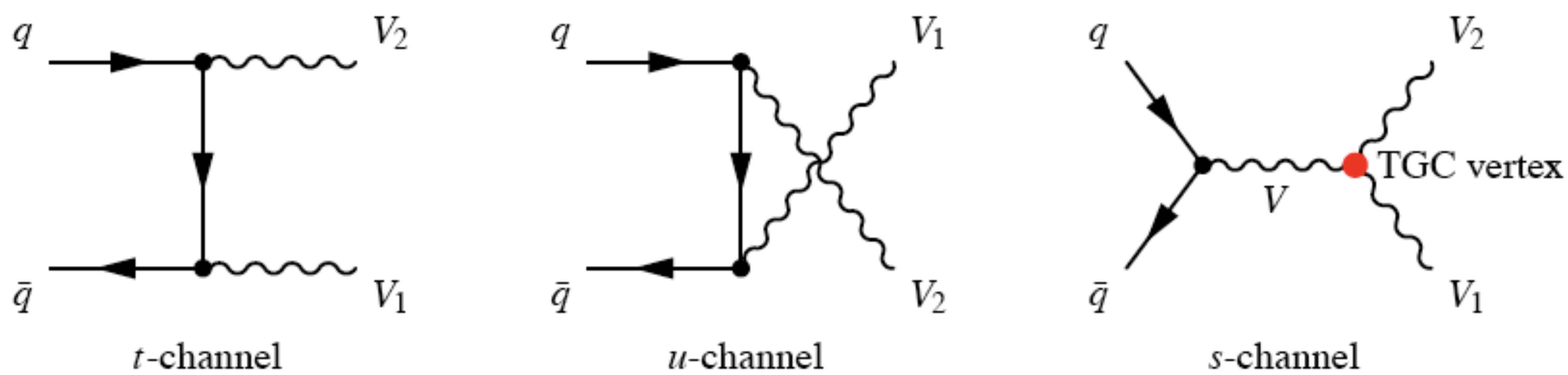
- ATLAS sensitivity to SM diboson production (W^+W^-, $W^\pm Z$, ZZ, $W^\pm\gamma$ and $Z\gamma$), using *final states containing electrons, muons and photons*
  - cross section measurements uncertainties estimated for integrated luminosities from 0.1 to 30 fb^{-1}
  - significance for a 5σ discovery evaluated
- sensitivity to anomalous triple gauge boson couplings (TGC) estimated

- studies include trigger information, detector calibration and alignment corrections
- analysis done over over 30 million fully simulated and reconstructed events
- *Boosted Decision Tree* applied to select channels
- focus on the results of the early running of LHC

Motivation for diboson studies:

- important test of the high energy behavior of EW interactions
- vector boson self-couplings related to the non-Abelian nature of the $SU(2)_L \times U(1)_Y$ symmetry group
- important backgrounds for the main LHC discoveries

Diboson final states



- tree level Feynman diagrams for electroweak diboson production at hadron colliders
- *LHC diboson production rate exceed that of Tevatron by at least a factor 100* (10 time higher cross-section and at least 10 times higher in luminosity)
- cross-sections known (for any channel) at least at NLO

Diboson mode	Conditions	$\sqrt{s} = 1.96$ TeV $\sigma[pb]$	$\sqrt{s} = 14$ TeV $\sigma[pb]$
W^+W^- [14]	W-boson width included	12.4	111.6
$W^\pm Z$ [14]	Z and W on mass shell	3.7	47.8
ZZ [14]	Z's on mass shell	1.43	14.8
$W^\pm\gamma$ [15]	$E_T^\gamma > 7$ GeV, $\Delta R(\ell,\gamma) > 0.7$	19.3	451
$Z\gamma$ [16]	$E_T^\gamma > 7$ GeV, $\Delta R(\ell,\gamma) > 0.7$	4.74	219

Theoretical predictions for VB pair production

- $e^+e^-, pp, p\bar{p} \to W^+W^-, ZZ$ at LO (and decays)
Brown, Mikaelian (1979); Stirling, Kleiss, S. Ellis (1985); Gunion, Kunszt (1986); Muta, Najima, Wakaizumi (1986); Berends, Kleiss, Pittau (1994) [$e^+e^- \to f_1\bar{f}_2f_3\bar{f}_4$ at LO]

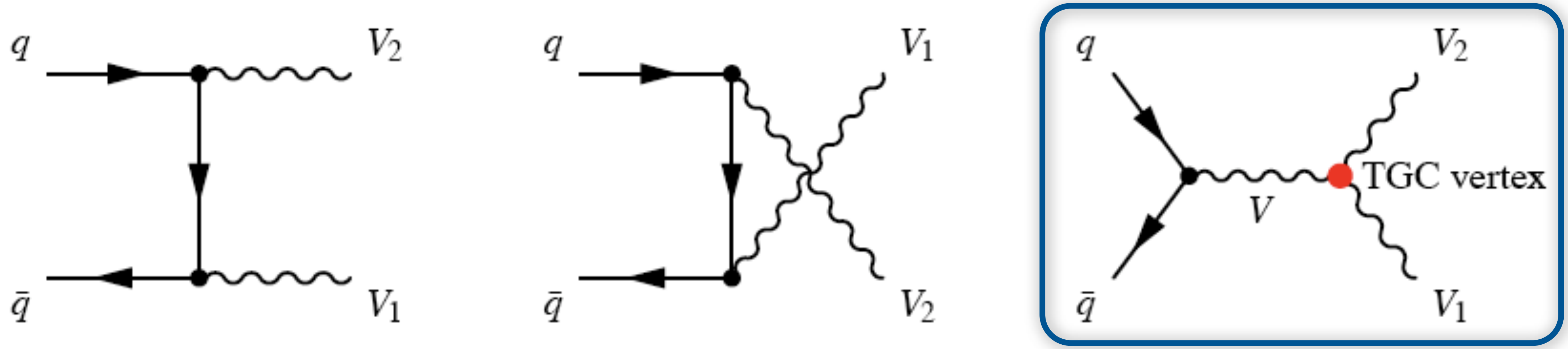
- $pp, p\bar{p} \to W^+W^-, ZZ, W^\pm Z$ at NLO QCD (with leptonic decays)
Ohnemus (1991); Mele, Nason, Ridolfi (1991); Ohnemus, Owens (1991); Frixione (1993); Ohnemus (1994); Dixon, Kunszt, Signer (1998,1999); Campbell, K. Ellis (1999) [$pp, p\bar{p} \to \ell\bar{\ell}\ell'\bar{\ell}'$ at NLO QCD]

- $gg \to W^+W^-, ZZ$ (with leptonic decays), (1-loop)^2 NNLO QCD correction
Dicus, Kao, Repko (1987); Glover, van der Bij (1989); Kao, Dicus (1991); Matsuura, v.d. Bij (1991); Zecher, Matsuura, v.d. Bij (1994); Dührssen, Jakobs, v.d. Bij, Marquard (2005); Binoth, Ciccolini, NK, Krämer (2005,2006)

- 2-loop-virtual–Born interference for $q\bar{q} \to W^+W^-$ (all kin. inv. $\gg M_W$) $\to$ NNLO QCD correction
Chachamis, Czakon, Eiras (2007)

from N. Kauer's talk - DIS2008, UCL, April 2008

Triple gauge boson couplings



t-channel *u*-channel *s*-channel

- triple and quartic gauge boson couplings arise in the SM due to the non-Abelian nature of the theory
  - non-zero value couplings predicted at tree level for *charged sector* (WWγ, WWZ), absence of couplings in the *neutral sector* (ZZZ, ZZγ and Zγγ)
- any theory predicting physics beyond the SM introduces deviations in the gauge couplings at some high energy scale
  - many models predict deviation from SM at the level of 10^{-3} - 10^{-4}

- *signature*: enhanced diboson production cross-sections, especially at high p_T or M_T
- *experimental limits* on non-SM TGC can be obtained by comparing the shape of the measured p_T or mass distribution (or transverse mass for W related final states) with predictions

Charged and Neutral TGC

Charged sector (WWγ, WWZ)

- Lagrangian conserving C and P separately (leads to a reduction of unknown parameters)

$$\mathcal{L}/g_{WWV} = ig_1^V(W^*_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{*\mu}V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2}W^*_{\rho\mu}W^\mu_\nu V^{\nu\rho}$$

- SM triple gauge vertices $g_1^V = \kappa^V = 1,\ \lambda^V = 0 \text{ with } V = \gamma, Z$

- model-independent parameterization of the non-SM physics - *anomalous couplings*

$$\mathbf{\Delta g_1^Z} \equiv g_1^Z - 1,\ \mathbf{\Delta}\kappa^\gamma \equiv \kappa^\gamma - 1,\ \mathbf{\Delta}\kappa^{\mathbf{Z}} \equiv \kappa^Z - 1,\ \lambda^\gamma,\ \lambda^{\mathbf{Z}}$$

- with non-SM coupling parameters, amplitude for gauge boson pair production grow, eventually violating the tree-level unitarity - violation avoided by an effective cutoff scale Λ

$$\Delta\kappa(\hat{s}) = \frac{\Delta\kappa}{(1+\hat{s}/\Lambda^2)^n}$$

$$n = 2 \text{ charged TGC},\ n = 3 \text{ neutral TGC}$$

new physics, responsible for anomalous couplings, at a scale Λ

Neutral sector (ZZγ, ZZZ -and Zγγ-)

- effective Lagrangian (case of on-shell Z bosons only)

$$\mathcal{L} = -\frac{e}{M_Z^2}[\mathbf{f_4}^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + \mathbf{f_5^V}(\partial^\sigma V_{\sigma\mu})\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}Z^{\rho\sigma}Z_\beta]$$

SM couplings f^V_i (i=4,5) are zero at tree level

Current status from Tevatron

- *diboson cross-section measurements* using up to 2 fb^{-1} of integrated luminosity

Process	Source	L fb^{-1}	observed events	background events	σ(data) [pb] $\pm$ (stat)$\pm$(sys)$\pm$(lum)	σ(theory) [pb]
W^+W^-	CDF [20]	0.83	95	38$\pm$5	13.6$\pm$2.3$\pm$1.6 $\pm$ 1.2	12.4$\pm$0.8
$(ee, \mu\mu, e\mu)$	D0 [21]	0.25	25	8.1$\pm$.5	13.8$\pm$4.1$\pm$1.1 $\pm$ 0.9	"
$W^\pm Z$	CDF [22]	1.1	16	2.7$\pm$0.4	$5.0^{+1.8}_{-1.4} \pm 0.4$	3.7$\pm$0.3
$(\ell^\pm \nu \ell^+ \ell^-)$	D0 [23]	1.0	13	4.5$\pm$0.6	2.7 +1.7−1.3 (total)	"
$Z\gamma$	CDF [24]	0.2	72	4.9$\pm$1.1	4.6 $\pm$0.6 (sta+sys) $\pm$ 0.3	4.5$\pm$0.3
$(\ell^+\ell^-\gamma)$	D0 [25]	1.0	968	117$\pm$12	4.96 $\pm$0.3 (sta+sys) $\pm$ 0.3	4.7$\pm$0.2
$W^\pm\gamma$	CDF [24]	0.2	323	114$\pm$21	18.1 $\pm$3.1 (sta+sys) $\pm$ 1.2	19.3$\pm$1.4
$(\ell^\pm \nu\gamma)$	D0 [26]	0.16	273	132$\pm$7	14.8 $\pm$1.9 (sta+sys) $\pm$ 1.0	16.0$\pm$0.4
ZZ	CDF [27]	1.9	2	0.014	$1.4^{+0.7}_{-0.6} \pm 0.6$	1.5$\pm$0.2
$(\ell^+\ell^-\ell^+\ell^-)$	D0 [28]	1.0	1	0.13	< 4.4	"

all results consistent with SM predictions, based upon NLO matrix element calculations

- *charged triboson vertex measurements* for $W^+W^-\gamma$ and W^+W^-Z ($W^\pm Z$ and $W^\pm\gamma$ channels)

Coupling	Source	L (fb^{-1})	λ_Z	$\Delta\kappa_Z$	$\Delta\kappa_\gamma$	λ_γ
$WW\gamma$ from $W^\pm\gamma$	D0 [26]	0.16			[-0.88, 0.96]	[-0.2, 0.2]
WWZ from $W^\pm Z$	D0 [23]	1.0	[-0.17, 0.21]	[-0.12, 0.29]		
WWZ from $W^\pm Z$	CDF	1.9	[-0.13, 0.14]	[-0.82, 1.27]		
$WWZ = WW\gamma$						
from W^+W^-	D0 [29]	0.25	[-0.31, 0.33]	[-0.36, 0.33]		
from W^+W^-, $W^\pm Z$	CDF [30]	0.35	[-0.18, 0.17]	[-0.46, 0.39]		

95% CL on the anomalous gauge couplings (Λ=2TeV)

Data samples

Process	cross-section (fb)	ε_{filter}	N_{MC}	Generator
$q\bar{q}' \to W^+W^- \to \ell^+\nu\ell^-\nu$	11718	1.0	180,000	MC@NLO
$gg \to W^+W^- \to \ell^+\nu\ell^-\nu$	540.0	0.96	180,000	gg2ww
$(\ell = e,\ \mu,\ \tau)$				
$q\bar{q}' \to W^+Z \to \ell^+\nu\ell^+\ell^-$	441.7	1.0	50,000	MC@NLO
$q\bar{q}' \to W^-Z \to \ell^-\nu\ell^+\ell^-$	276.4	1.0	50,000	MC@NLO
$(\ell = e,\ \mu;\ Z$ on mass shell)				
$q\bar{q}' \to ZZ \to \ell^+\ell^-\ell^+\ell^-$	66.8	1.0	49,250	MC@NLO
$q\bar{q}' \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$	397	1.0	118,000	MC@NLO
$(\ell = e,\ \mu;\ Z$ on mass shell)				
$q\bar{q}' \to ZZ \to \ell^+\ell^-\ell^+\ell^-$	159	0.219	43,000	PYTHIA
$(\ell = e,\ \mu,\ \tau;\ M_{Z/\gamma^*} > 12$ GeV)				
(4 leptons $(e,\ \mu)$, $p_T^\ell > 5$ GeV, $\lvert\eta^\ell\rvert < 2.7$)				
$q\bar{q}' \to W^+\gamma \to \ell^+\nu\gamma$	10220	1.0	38,400	PYTHIA
$q\bar{q}' \to W^-\gamma \to \ell^-\nu\gamma$	6820	1.0	25,600	PYTHIA
$(\ell = e,\ \mu;\ E_T^\gamma > 10$ GeV)				
$q\bar{q}' \to Z\gamma \to \ell^+\ell^-\gamma$	5280	1.0	66,000	PYTHIA
$(\ell = e,\ \mu;\ E_T^\gamma > 10$ GeV)				

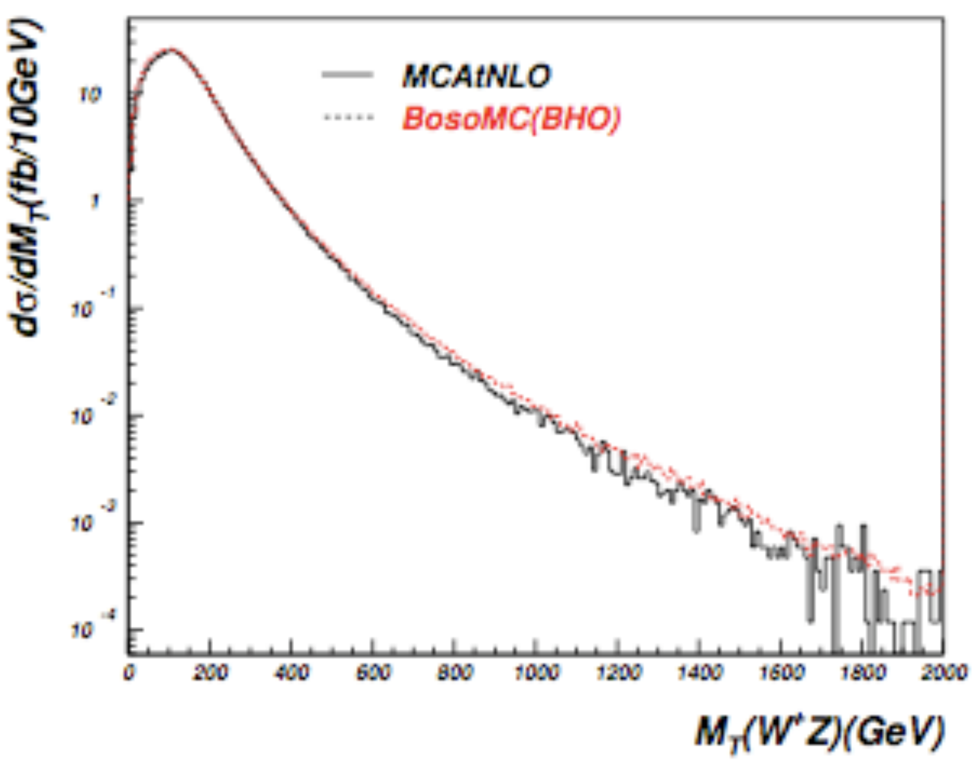
- gauge-boson decays into τ included (with τ decaying to all)
- W- boson width and spin-spin correlation included
- 'zero-width' approximation used in $W^\pm Z$ and ZZ calculations (no Z/γ^* interference)
- LO cross-sections rescaled to NLO by using K-factors from NLO ME calculation

Main backgrounds	N_{MC}	Generator
tt→l + X	700,000	MC@NLO
Z + X and W + X (X = jets or γ)	30M 1.1 M	PYTHIA AcerMC

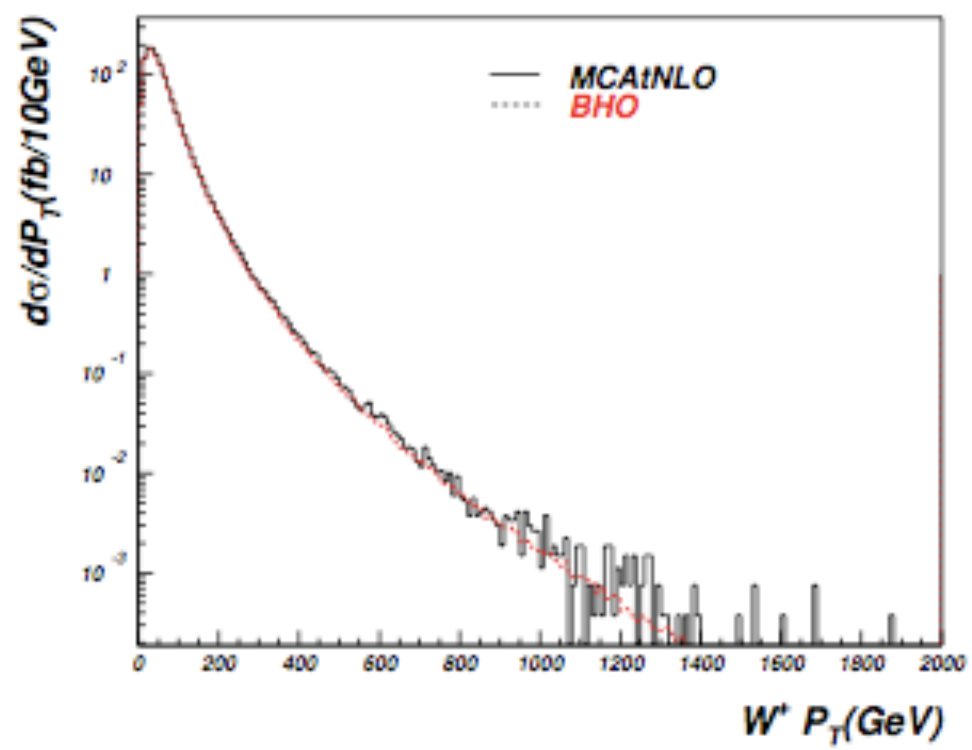
Generators for TGC studies

- No anomalous triple gauge boson coupling implemented in MC@NLO and PYTHIA
- BosoMC and BHO used to calculate LO and NLO cross-sections for all five diboson final states (BHO models ZZ, W^+W^- and Zγ, BosoMC $W^\pm Z$, $W^\pm\gamma$)
  - parton level generators, no parton shower
- ZZ, W^+W^- and $W^\pm Z$ cross sections and distributions at NLO *with SM couplings* compared to MC@NLO ones (using CTEQ6M pdf set) - *agreement within 2%*

$W^\pm Z$ production - $M_T(W^+Z)$
histograms normalized to cross-section

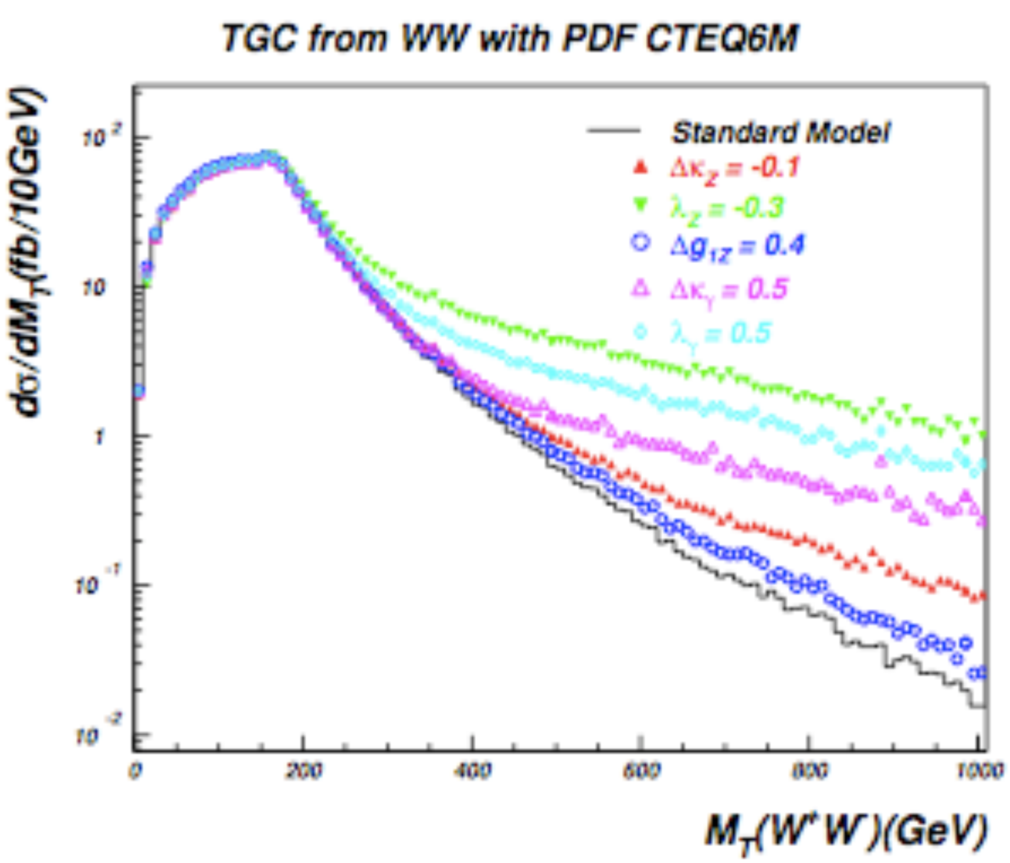


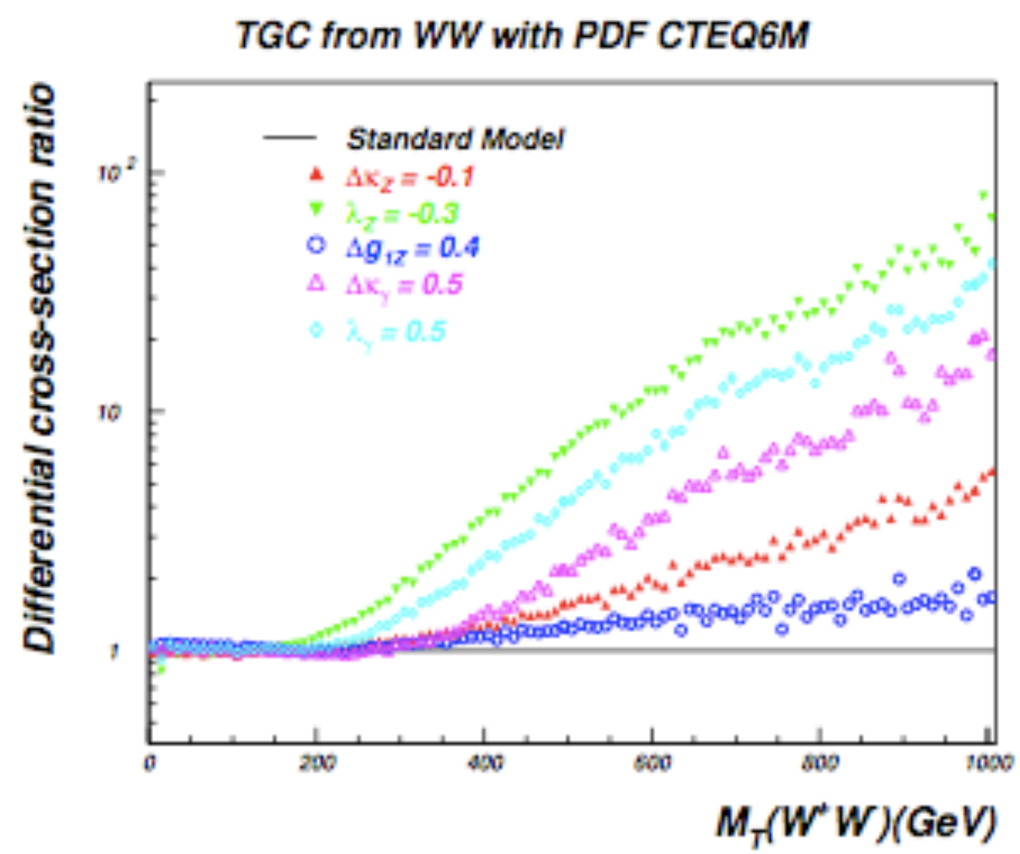
W^+W^- production - $p_T(W)$
histograms normalized to cross-section



Reweighing the fully simulated samples

- BHO and BosoMC calculations with different anomalous coupling parameters used to *re-weight* the fully simulated events generated with MC@NLO
  - weighing applied after passing the event selection cuts
- *weights* generated in one-dimensional and two-dimensional anomalous coupling space according to parton level kinematics
  - 5M events for each coupling parameter space point
  - step size ranges from 0.1×10^{-3} to 1.0×10^{-3}
- *fully simulated events weighed equivalent then to fully simulated events with the corresponding anomalous couplings*





Diboson event selection

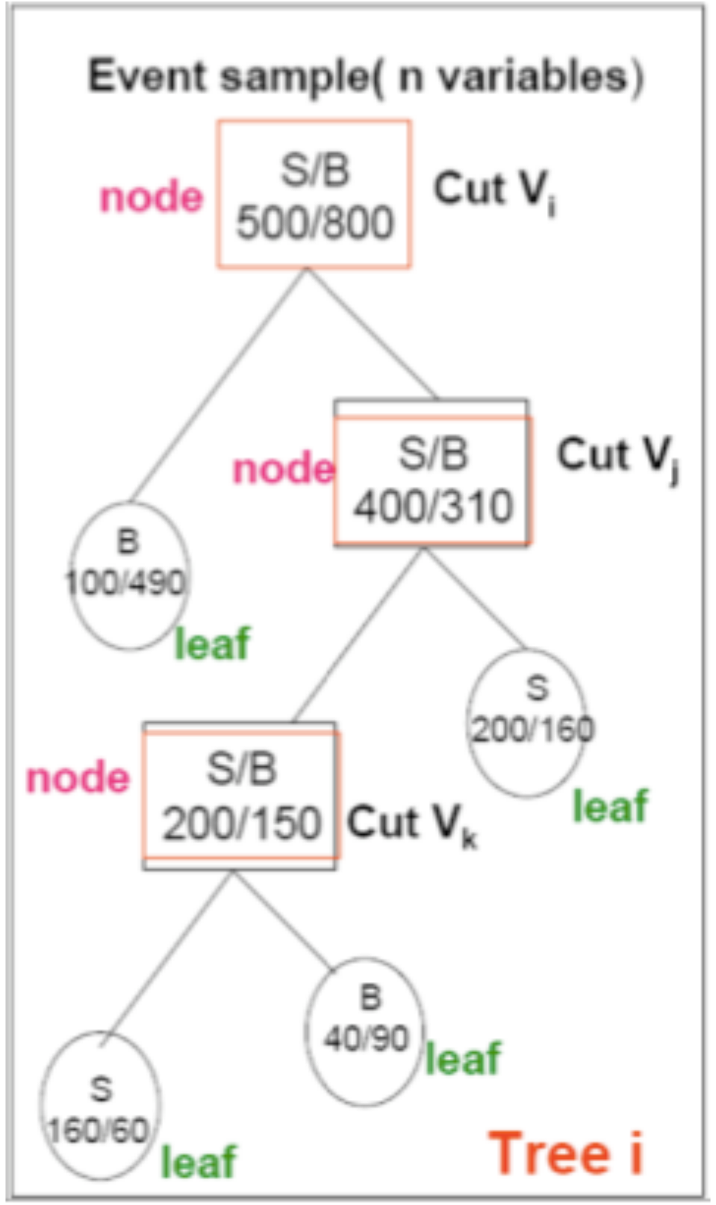
- *Physics objects*: electrons, photons, muons, missing ET, and hadronic jets

Object	Identification	η-φ Coverage	Efficiency/ Resolution
electrons	all cuts but the TRT passed additional ID isolation + E/p	$\lvert\eta\rvert < 2.5$ (excluded region $1.35 < \lvert\eta\rvert < 1.57$) $E_T > 25$ GeV (or two e with $E_T > 10$ GeV)	75% barrel, 60% endcap
muons	combined tracks (STACO) isolated (E_T(cone0.45) < 5GeV)	$\lvert\eta\rvert < 2.5$, $p_T > 5$ GeV	94.9% (88.3 ± 0.2)% after the isolation
hadronic jets	0.7 cone, $E_T > 20$ GeV	$\lvert\eta\rvert < 3.0$	-
missing ET	energy deposited in all calo cells and from the muons	-	Resolution (on W^+W^- events) 6.5 GeV
photons	as electrons in the EM calo but no charged track in the ID		

- trigger menus: single muon, single electron, dielectron and dimuon
  - efficiency 95-100% (with the exception of Wγ events, 80%)
- two analysis approaches: *cut based* and *Boosted Decision Tree* (preselection cuts common to both approaches)

Boosted Decision Trees (BDT)

- advanced data analysis technique developed for MiniBooNE and BaBar
- BDT program works with a set of data including *both signal and background*
- data presented by a set of physics variable distributions

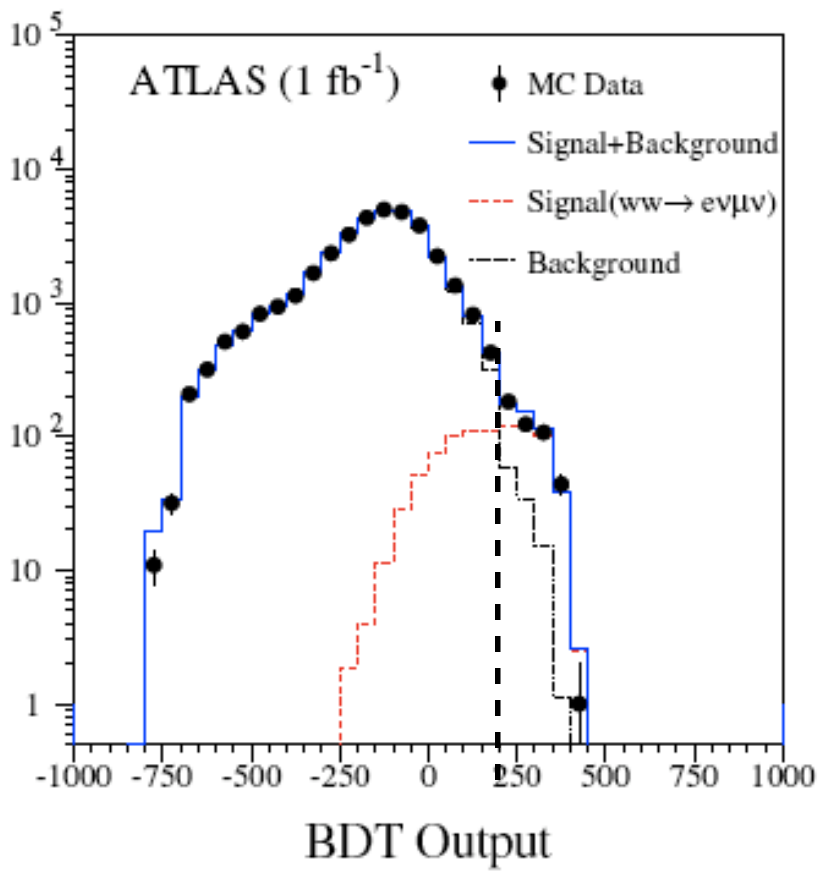


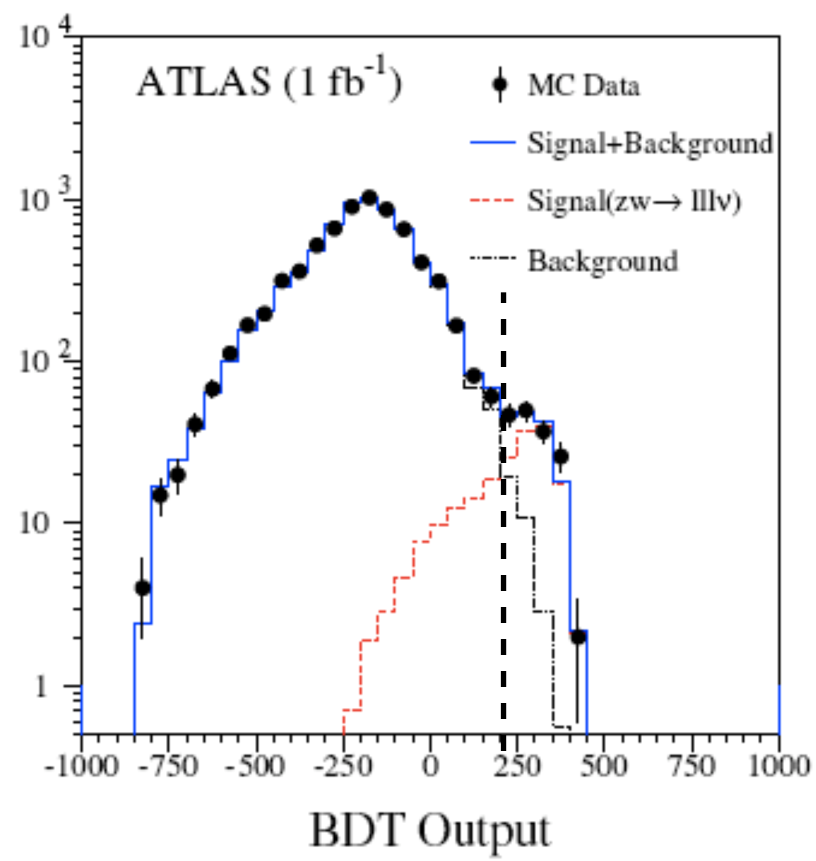
BDT training procedure

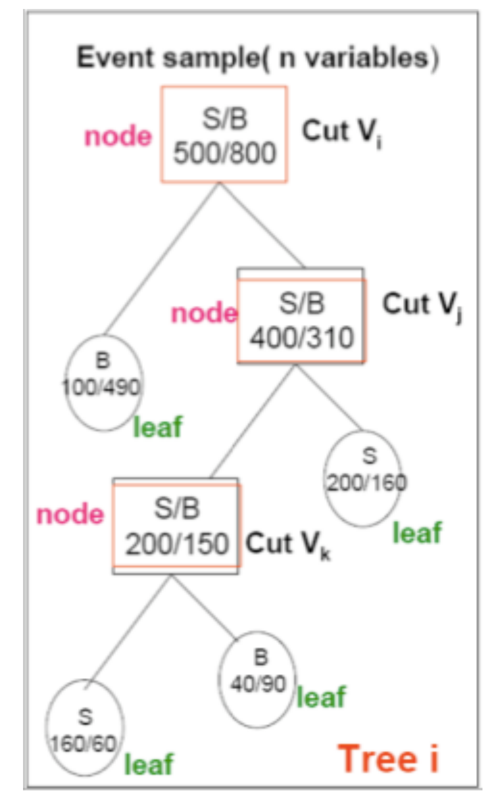
- a *decision tree* split data recursively basing on cuts on the input variables, until a stopping criterion is reached (i.e. too few events, purity, etc.)
- every event ends up in a *signal or background leaf* of the decision tree
  - *event in the signal leaf score 1, otherwise -1*
- *"boosted"* = misclassified events will be given a larger weight in the following tree
- procedure repeated several hundreds to thousand times until the performance reaches optimal
- *discriminator: sum of weighted scores from all trees is the final score of the event (BDT output)*

Boosted Decision Trees

- measure of BDT performance with statistically independent *test* samples
- high score for a given test event means that it is most likely a *signal event*, low score, a *background event*
- *by choosing a particular value of the score on which to cut, one can select a desired fraction of the signal or a desired signal over background ratio*







BDT-output spectra from MC experiments for W^+W^- (left) and $W^{\pm}Z$ (right)
MC data ("mock data") = sample of simulated events with appropriate statistics according to the luminosity and the SM

$W^{\pm}Z \rightarrow l^{\pm}\nu\ l^{+}l^{-}$ selection

Signature	σ×BR	Trigger eff	Backgrounds	TGC
3 charged isolated leptons	442 fb for $W^{+}Z$ 276 fb for $W^{-}Z$	98.9 ± 1.0 % (single or dilepton triggers)	$ZZ \rightarrow 4l$ with one l undetected $Z+X \rightarrow 2l +X$ (X = jets or photons faking leptons) $tt \rightarrow W^{+}W^{-}bb\sim \rightarrow 3l + X$	WWZ

- *event preselection*: 3 leptons (at least one with p_T > 25 GeV) and miss-E_T > 15 GeV consistent with Z dilepton decays (M_{ll} = 91.18 ± 20 GeV) and W leptonic decay (10 GeV < M_T(l, miss-E_T) < 400 GeV)
  - efficiency: on $W^{+}Z$ 26% - on $W^{-}Z$ 29%
- *event selection:*
  - miss-E_T > 25GeV and isolated tracks originating from the same collision point
  - no more than one hadronic jet with E_T> 30 GeV and $|\eta|$< 3.0
  - $p_T(3l)$ + E_T < 120 GeV and ∑had-E_T < 200 GeV (against tt and hadronic jet events)
  - p_T(3rd lepton) > 20 GeV (25 GeV) for muons (electrons) and ΔR(leptons) > 0.2 (against Z +X background)
  - $|M_Z - M_{\mu\mu}|$ < 12 GeV or $|M_Z - M_{ee}|$ < 9 GeV
  - 40 GeV < M_T(3rd l, miss-E_T) < 120 GeV

$W^{\pm}Z \rightarrow l^{\pm}\nu\ l^{+}l^{-}$ selection

cut-based analysis: number of selected events at 1 fb^{-1} of integrated luminosity

	WZ	ZZ	$t\bar{t}$	$Z+$jet	$Z+\gamma$	Drell-Yan	Total bkg	N_{WZ}/N_B
N events	**53**	2.7	.023	1.9	0.18	2.5	**7.3**	7.3
% of background	-	37	.32	26	2.5	35	-	-

- for 100 pb^{-1} only 5 signal events and 0.7 background events expected → *significance* (= Poisson probability with mean N_B to observe ≥ N_S + N_B events) *only* ***3.6 σ***
- *improvement through BDT analysis*
  - 1000 trees with 20 tree-split nodes
  - 22 kinematics and topology variables
  - 50% of signal and background events for the training (total: 12k signal - 18k background)

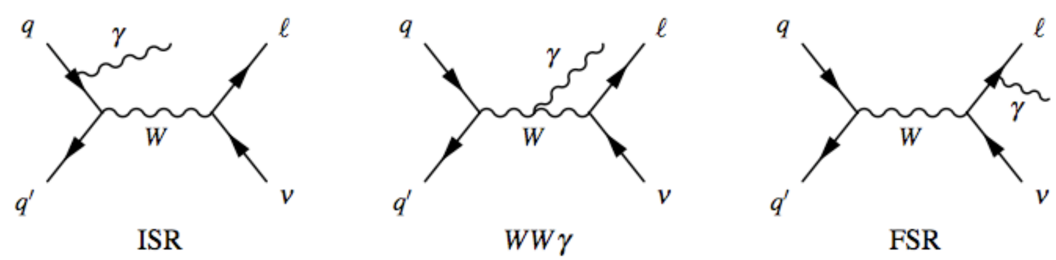
BDT analysis (BDT cut > 200): number of selected events at 1 fb^{-1} of integrated luminosity

	WZ	ZZ	$t\bar{t}$	$Z+$jet	$Z+\gamma$	Other	Total bkg	N_{WZ}/N_B
N events	**128**	7.7	2.8	2.5	2.0	1.1	**16**	7.9
% of background		48	17	16	12	7.0	-	-

- for 100 pb^{-1} 12.8 signal events and 1.6 background events expected → *significance* (including both statistics and 20% systematic uncertainties) **= *5.9 σ***

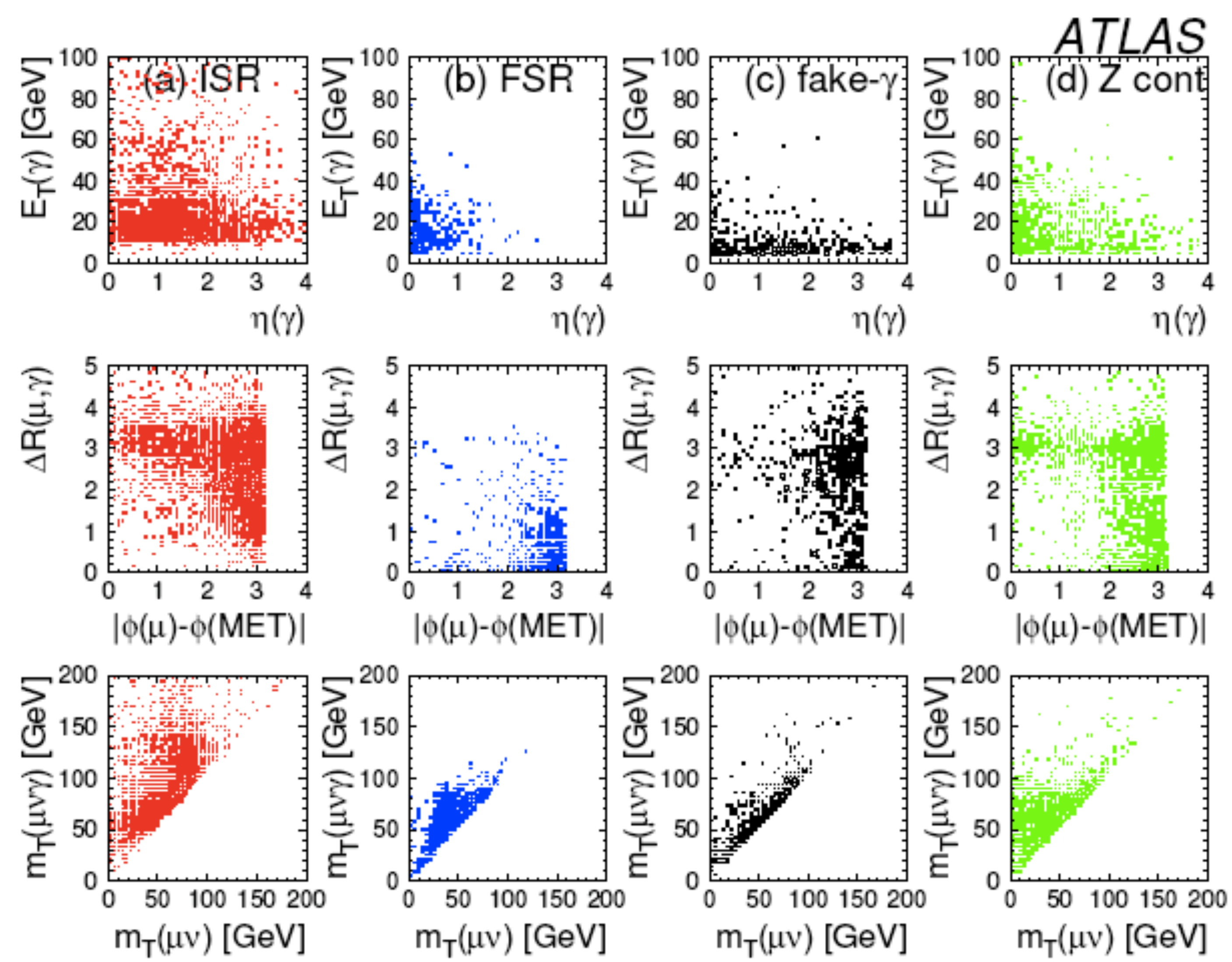
$W^{\pm}\gamma \rightarrow l^{\pm}\nu\ \gamma$ selection

Signature	σ[pb]	Trigger eff	Backgrounds	TGC
one high-p_T e or μ (in absence of the OSSF one), one high-p_T photon and miss-E_T	19.26 for $W^+\gamma$ 8.15 for $W^-\gamma$ from BHO NLO and E_T^{γ} > 10 GeV	~80% (μ20, e22i, γ55)	inclusive W+X→ lγν +X with γ from FSR inclusive W+X → lν +X with X = jet faking a γ inclusive Z + X → ll + X with one l undetected and X = γ or jet faking a γ	WWγ



background

- *preselection:* one isolated lepton and one isolated photon with $p_T^{l,\gamma}$ > 10 GeV
- most energetic photon of the event selected



W±(μ±ν) events variables, from signal (ISR) and backgrounds (FSR, fake γ and inclusive Z contamination)

BDT method to select $W^{\pm}\gamma$ events

- three separate trainings:
  1. $l\gamma\nu$ events with FSR photons from other sources
  2. $W^{\pm}\gamma$ signal photons from fake photons
  3. signal photons from contamination of Z inclusive events
- 19 variables used
- $W^{\pm}\gamma$ selection efficiency 65% with S/B = 0.95 (0.98) for electron (muon) final states

number of events after several cuts for 1 fb^{-1} of integrated luminosity

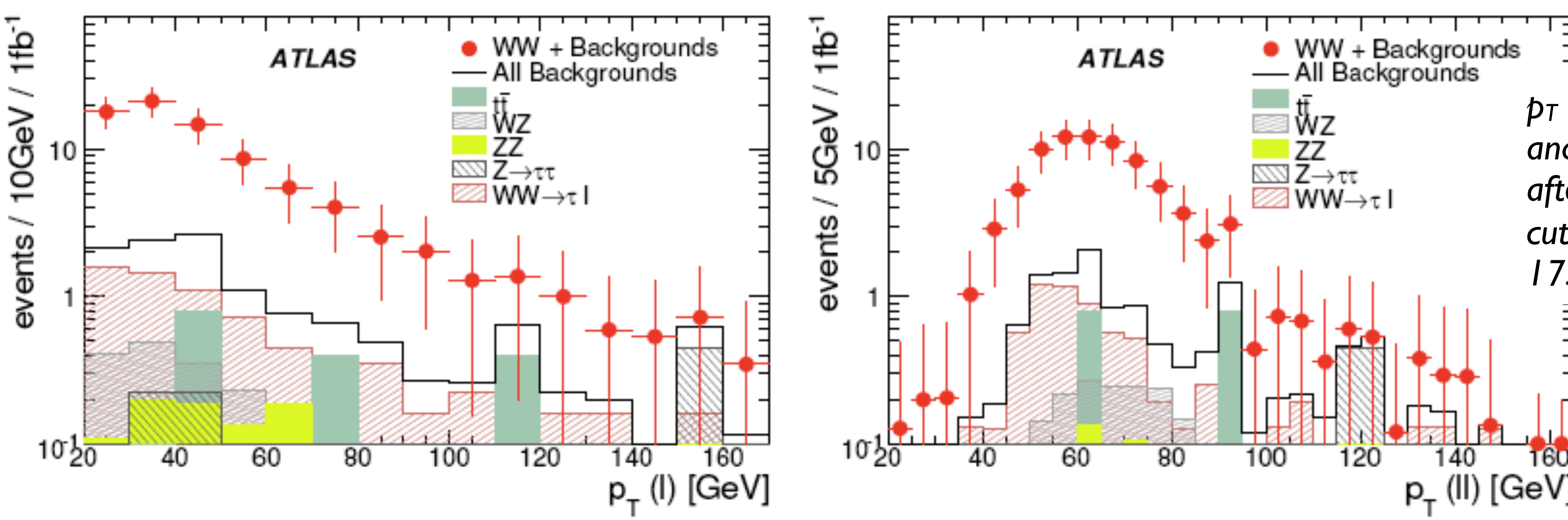
		Signal	Background			
		$W^{\pm}\gamma$	W+FSR_γ	W+fake_γ	$Z(\ell\ell)\gamma$	Total
$\ell = e$	Pre-selected	1710	11440	7890	32480	
	BDT selection	1145	242	791	101	
	Triggered	966	188	628	93	
	NLO scaled	1604 (k=1.66)				1183 (k=1.3)
$\ell = \mu$	Pre-selected	2680	28410	10250	3950	
	BDT selection	1793	413	961	409	
	Triggered	1305	177	595	260	
	NLO scaled	2166 (k=1.66)				1342 (k=1.3)

- BDT effective against FSR and fake photons

$W^+W^- \rightarrow l^+\nu\ l^-\nu$ selection

Signature	σ×BR	Trigger eff	Backgrounds	TGC
two high-p_T e or μ OSSF one) with high miss-E_T	1302 ± 65 fb (qq) 60 ± 3 fb (gg)	98.2% (ee), 95.9% (μμ) and 97.4% (eμ) dilepton e25i or μ20 or 2e10 or 2μ6	tt, inclusive Z and W and Drell-Yan with mis-measured miss-E_T	WWZ, WWγ

- *preselection:* two high-pT leptons (p_T > 10 GeV) and miss-E_T >15 GeV
- *event selection:* conventional cuts or BDT selection cuts
  - two isolated leptons with OS and p_T > 20 GeV and |η| < 2.5
  - jet veto for any jet with p_T > 20 GeV in |η| < 3 (against tt)
  - miss-ET < 50 GeV (against pileup and Z/γ* in DY)
  - Z mass veto (against inclusive Z background)
  - angular variable cuts: ϕ_{ll} < 2 rad (high signal detection eff) or $\phi(p_T^{ll}, p_T^{miss})$ >175 deg (for TGC studies)



p_T distributions of lepton and lepton pairs for 1 fb^{-1} after applying kinematic cuts and $\phi(p_T^{ll}, p_T^{miss})$ > 175 deg selection

$W^+W^- \rightarrow l^+\nu\ l^-\nu$ selection

- WW overall signal detection efficiency 1.4-3% - for 100 pb^{-1} *significance* ***4.7 σ*** (ϕ_{ll} < 2 rad cut)

improvement through BDT analysis

- 1000 decision trees with 20 tree-split nodes
- 22 kinematics and topology variables
- input data for BDT analysis after the pre-selection cuts
- 50% preselected simulated events for the training, 50% to test event selection performance

WW → leptons detection sensitivities of accepted signal and background events for 1 fb^{-1}
BDT selection efficiencies including the trigger requirements based on pre-selected events

				Background fraction			
Modes	$\varepsilon_{WW}(\%)$	N_{WW}	N_{bkg}	$t\bar{t}$	$W^{\pm}Z$	$Z+X$	N_{WW}/N_{bkg}
$e\nu\mu\nu$	32.7	347± 3	64± 5	47.7%	27.8%	21.8%	5.4
$\mu\nu\mu\nu$	12.1	70± 2	17± 2	54.1%	34.6%	11.3%	4.1
$e\nu e\nu$	13.7	52± 1	11± 1	81.4%	7.2%	11.4%	4.7

- for measurements with 100 pb^{-1}, application of BDT is compelling (47 signal events against 10 events using cut-based analysis)
- *BDT significance =* ***10 σ*** (including 20% systematic uncertainties - background events 9.2)

$Z\gamma \to l^+l^-\gamma$ selection

Signature	σ[pb]	Trigger eff	Backgrounds	TGC
two high-p_T e or μ + isolated high-pT photon (from ISR)	5.44 from BHO NLO and E_T^γ > 10 GeV	single or dilepton trigger ~98% (~90%) for electrons (muons)	Z + FSR γ (from leptons from Z decay), Z + fake γ from jets, W + X reconstructed as llγ	ZZZ, ZZγ (Zγγ)

forbidden in the SM!

- *preselection:* two leptons and one photon with E_T^γ > 10 GeV
- *event selection:* BDT analysis
  - two stages:
    1. identify FRS photon background
    2. distinguish signal from Z events with fake γ
  - separate training for electron and muon Z decay with 19 variables in total
  - input data for BDT analysis after the pre-selection cuts

		Signal	Background			
		$Z\gamma$	Z+FSR_γ	Z+fake_γ	$W(l\nu)\gamma$	Total
$\ell = e$	Pre-selected	430	2760	490	44	
	BDT selection	288	70	74	0	
	Triggered	282	65	79	0	
	NLO scaled	367 (k=1.3)				187 (k=1.3)
$\ell = \mu$	Pre-selected	950	7500	790	930	
	BDT selection	636	173	186	0	
	Triggered	578	164	165	0	
	NLO scaled	751 (k=1.3)				429 (k=1.3)

number of Zγ signal and background events after pre-selection, BDT and trigger selections for 1 fb^{-1}

signal efficiency 67%
S/B = 2.0 (1.8) for electron (muon) Z decay

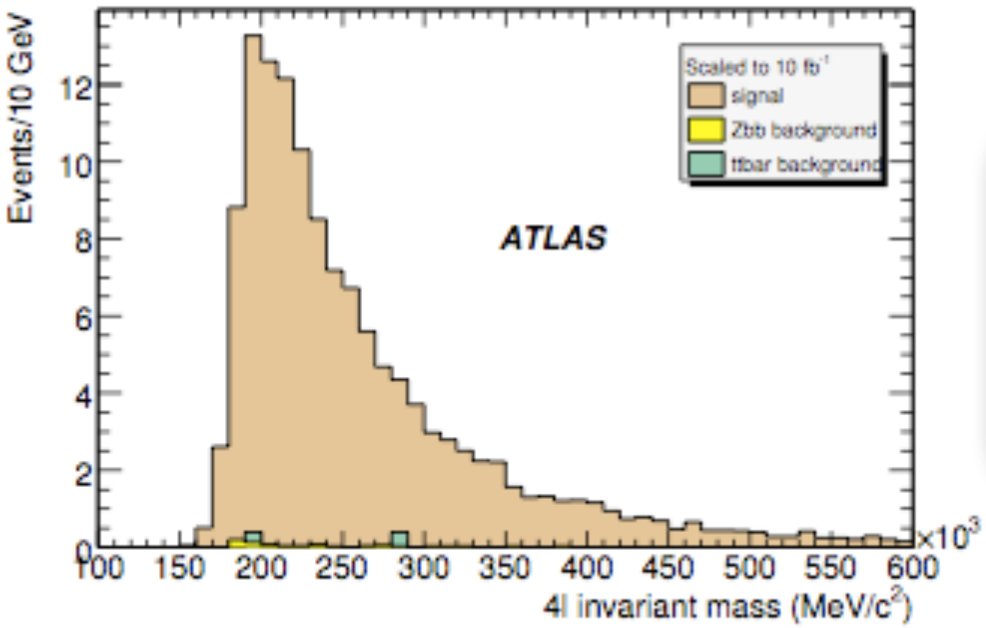
$ZZ \rightarrow l^+l^- \, l^+l^-$ selection

Signature	σ	Trigger eff	Backgrounds	TGC
four high-p_T isolated leptons	σ×BR =159 fb (PYTHIA) 17.75 pb (MC@NLO, pure on-shell ZZ)	single or dilepton trigger ~100%	tt → WWbb → 4l + X Zbb →4l + X	ZZZ, ZZγ (Zγγ)

- *l* = e μ or τ - τ contribution to the four lepton channels less than 4%
- PYTHIA cross section including four leptons BR and filter rescaled with k = 1.35
- *preselection:* electrons p_T > 5 GeV and $|\eta|$ < 2.5, 0.5 < E/P < 3.0 - muons p_T > 5 GeV and $|\eta|$ < 2.7 + χ^2 <15 (match between MS and ID tracks and track fit)
- *event selection:*
  - isolation ($E_{0.2}/E_T^{\mu} < 0.2$)
  - lepton separation $\Delta R(l^+l^-) > 0.2$
  - *loose Z mass cut:* one lepton with p_T > 20 GeV + one lepton pair with 70 < M_{ll} < 110 GeV
  - *tight Z mass cut:* both lepton pairs with 70 < M_{ll} < 110 GeV

	4μ [%]		4e [%]		2e2μ [%]	
	tight	loose	tight	loose	tight	loose
Signal	41.4 ± 0.6	52.4 ± 0.7	24.4 ± 0.5	30.0 ± 0.6	28.1 ± 0.4	34.3 ± 0.4
Zbb	0.13 ± 0.06		0.61 ± 0.14		0.51 ± 0.13	
tt	0.07 ± 0.07		0.07 ± 0.07		0.07 ± 0.07	

ZZ→$l^+l^- l^+l^-$ selection



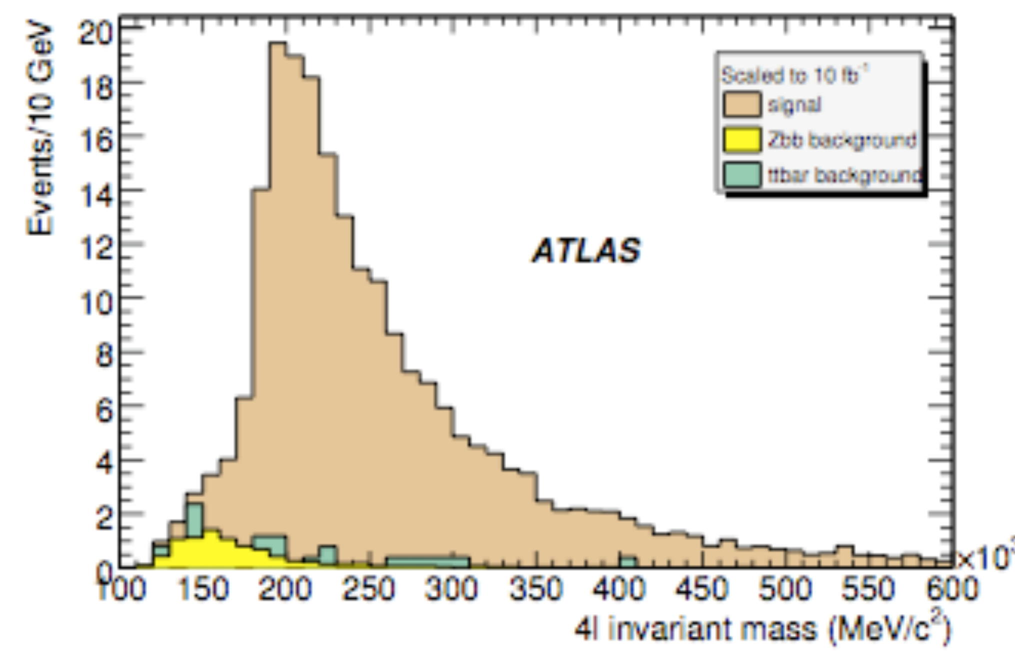
expected number of events for L = 1 fb^{-1}

tight Z mass cut

	4μ events	$4e$ events	$2\mu 2e$ events	Total
Signal	4.5±0.05	2.6±0.04	6.2±0.06	13.3 ±0.09
$Zb\bar{b}$	0.01±0.003	0.04±0.01	0.04±0.01	0.08±0.01
$t\bar{t}$	0.04±0.04	0.04±0.04	0.04±0.04	0.12±0.07
Total background	0.05±0.04	0.08±0.04	0.08±0.04	0.20±0.07

loose Z mass cut

	4μ events	$4e$ events	$2\mu 2e$ events	Total
Signal	5.7±0.06	3.2±0.04	7.6±0.07	16.5±0.1
$Zb\bar{b}$	0.1±0.01	0.5±0.02	0.3±0.02	0.9±0.1
$t\bar{t}$	0.1±0.06	0.5±0.14	0.4±0.13	1.0±0.2
Total background	0.2±0.06	1.0±0.14	0.7±0.13	1.9±0.2

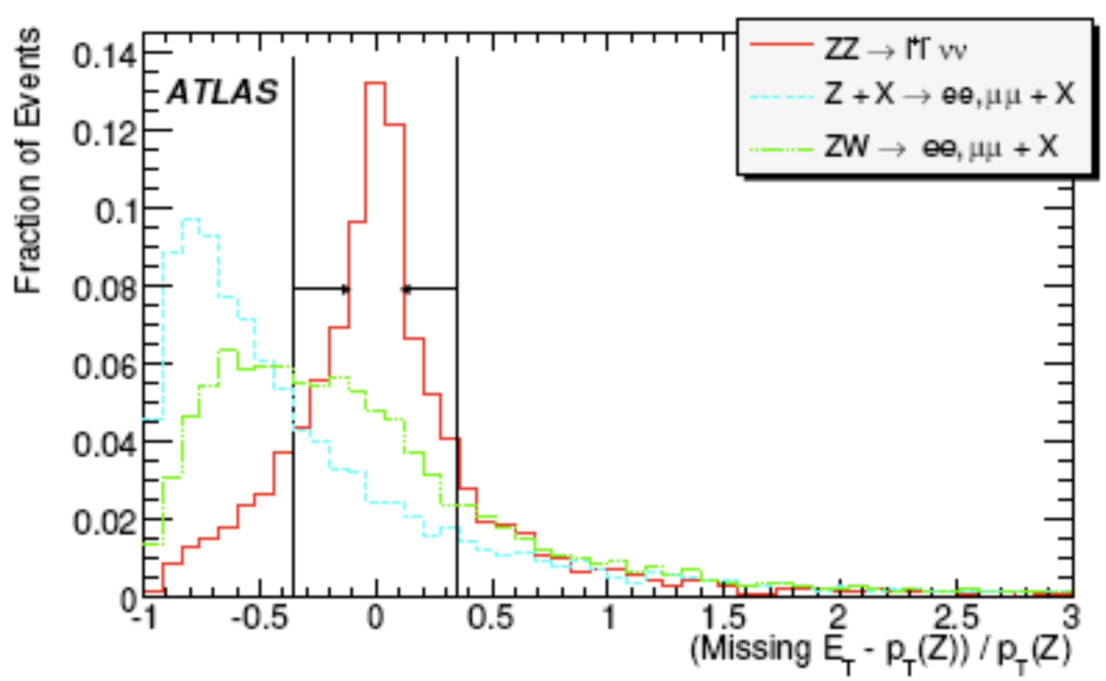


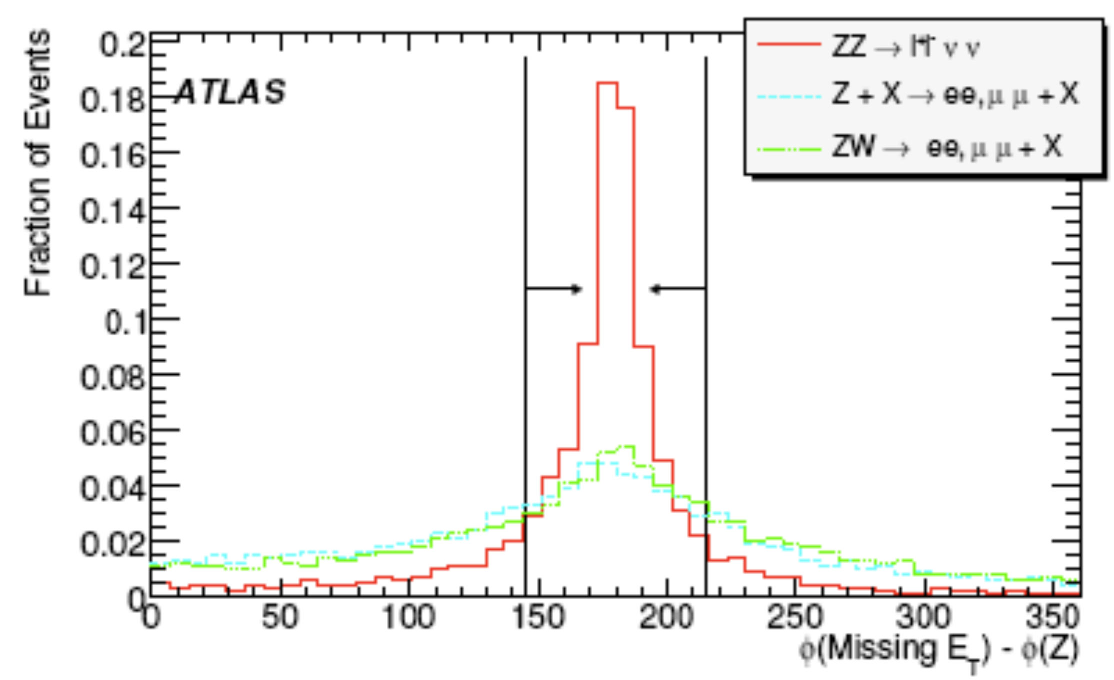
- ATLAS *significance* to the ZZ → 4l signal for 1 fb^{-1} (20% systematic uncertainties) ***= 6.8 σ*** (loose Z mass cut and BDT selections)

ZZ→l⁺l⁻ νν selection

Signature	σ×BR	Trigger eff	Backgrounds	TGC
two high-p_T charged leptons + large miss-E_T	300 fb (PYTHIA rescaled)	efficiency ~ 97% e22i or μ20	tt, Z→ ll Drell-Yan with not reconstructed jets, $W^{\pm}Z, W^+W^-$, ZZ	ZZZ, ZZγ (Zγγ)

- *preselection:* two high-pT leptons and miss-ET
- *event selection* (each cut effective mostly against a given background):
  - two OS good quality leptons with p_T > 20 GeV and $|\eta|$ < 2.5 (against tt and Z→ττ)
  - $|M_{ll}$ - 91.2 GeV$|$ < 10 GeV (against background with leptons not from Z)
  - hadronic jet veto (events with p_{Tjet} > 30 GeV and $|\eta_{jet}|$ < 3.0) (against tt, t→Wb)
  - third-lepton veto and angular matching $\phi_{miss-ET} - \phi_Z$ (against $W^{\pm}Z$)
  - miss-E_T > 50 GeV (against ZZ Drell-Yan + jets)
  - $p_T(Z)$ > 100 GeV (against single Z channel)





$ZZ \to l^+l^- \nu\nu$ selection

Cut	$ZZ \to \ell\ell\nu\nu$	$ZZ \to 4l$	$Z \to ll$	$t\bar{t}$	$W^{\pm}Z$	W^+W^-	$Z \to \tau\tau$
Leptons	130.1	54.3	13100	4530	271.2	491.1	2170
Third-lepton veto	101.9	3.1	1900	428.9	52.9	375.6	1690
	(78.3%)	(5.7%)	(14.5%)	(9.5%)	(19.5%)	(76.5%)	(77.9%)
Dilepton mass	100.2	2.7	1740	110.2	45.3	83.8	40.1
	(98.3%)	(87.1%)	(91.6%)	(25.7%)	(85.6%)	(22.3%)	(3.4%)
Missing E_T	38.0	0.34	3.8	17.9	9.4	18.3	0
	(39.9%)	(12.6%)	(0.2%)	(16.2%)	(20.8%)	(21.8%)	(0.0%)
Jet veto	34.4	0.30	0.44	6.0	7.6	16.7	0
	(90.5%)	(88.2%)	(11.6%)	(33.5%)	(80.9%)	(91.3%)	(0.0%)
p_T^Z	**10.2**	**0.08**	**0.4**	**3.0**	**1.7**	**0.02**	**0**
	(29.7%)	(26.7%)	(90.9%)	(50.0%)	(22.4%)	(0.1%)	(0.0%)
Stat. Error [90%CL]	0.2	0.01	0.2	2.1	0.1	0.22	[1.6]

- expected *signal yields* to $ZZ \to 2l2\nu$ for 1 fb^{-1} (error statistical only)

N_{signal}	Signal efficiency	$N_{background}$	N_S/N_B
10.2 ± 0.2	2.6%	5.2 ± 2.6	2.0 ± 0.8

Cross section measurements

- *binned likelihood method* used to determine the most likely cross sections and to extract sensitivities to the anomalous TGCs
- *expected events* determined from high statistics MC simulation - *observed events* include statistical fluctuation according to the luminosity
- events binned by one or more observable - for each bin expected signal and background events compared to the observed number of events (n in each bin) with a likelihood
- likelihood based on a Poisson statistics convoluted with Gaussian probabilities to model signal and background uncertainties

$$L = \int_{1-3\sigma_b}^{1+3\sigma_b} \int_{1-3\sigma_s}^{1+3\sigma_s} g_s g_b \frac{(f_s\nu_s + f_b\nu_b)^n e^{-(f_s\nu_s+f_b\nu_b)}}{n!} df_s df_b, \;\; g_i = \frac{e^{(1-f_i)^2/\sigma_i^2}}{\int_0^\infty e^{(1-f_i)^2/\sigma_i^2} df_i} (i = s, b)$$

- a *total log-likelihood* is formed from all the bin likelihood
- statistic test used $-2\ln L = -2 \sum_{k=channels} \sum_{i=bins} \log(L_i^k)$
- *the minimum of the negative log-likelihood determines the most likely cross-section (or anomalous TGC)*
  - 68% CL (± 1σ)= minimum ± 1.0
  - 95% CL = minimum ± 1.92 (one parameter) - minimum ± 2.99 (two parameters)

Systematic uncertainties

- *theoretical uncertainties*: PDF errors and QCD scales
  - from 3.4% to 6.2%
- *experimental uncertainties:*
  - *luminosity determination:* using Z and W production (leptonic decays) this can be controlled to 5%
  - *lepton identification efficiencies:* lepton acceptance uncertainty about 2-3% - lepton trigger
  - *energy/momentum resolution:* 3% uncertainty
  - *jet energy scale and resolution:* 10% uncertainty
  - *background model and estimate:* uncertainties of 15-20% for all channels but $ZZ \to 4l$ (less than 2%)
    - Tevatron reaches 10% with 1 fb^{-1}, ATLAS should reach the same results with 100 pb^{-1}

Study done on $W^{\pm}Z$: a 3.4-6.7% background contribution uncertainty would produce additional cross-section measurement errors of 2-3%

Signal significances and stat uncertainties

- *all diboson final states - 1 fb-1 - 20% systematic uncertainties of the background estimation*

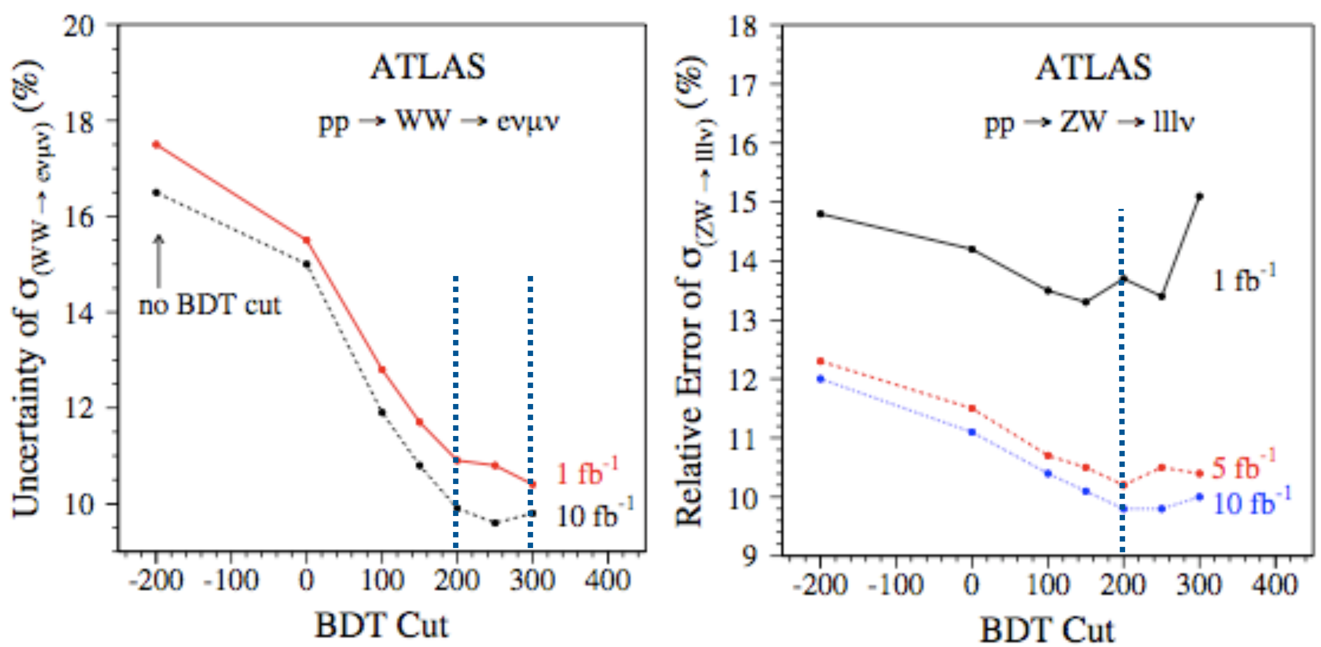
probability of the background fluctuating w.r.t the expected total observation, assuming 20% systematic uncertainties

Diboson mode	Signal	Background	Signal eff.	σ_{stat}^{signal}	p-value	Sig.	100 pb^{-1}
$W^+W^- \rightarrow e^\pm \nu \mu^\mp \nu$	347±3	64±5	12.6% (BDT)	5.4%	3.6×10^{-166}	27.4	
$W^+W^- \rightarrow \mu^+ \nu \mu^- \nu$	70±1	17±2	5.2% (BDT)	12.0%	8.8×10^{-30}	11.3	9.9 σ
$W^+W^- \rightarrow e^+ \nu e^- \nu$	52±1	11±2	4.9% (BDT)	13.9%	1.9×10^{-24}	10.1	
$W^+W^- \rightarrow \ell^+ \nu \ell^- \nu$	103±3	17±2	2.0% (cuts)	9.9%	1.4×10^{-54}	15.5	
$W^\pm Z \rightarrow \ell^\pm \nu \ell^+ \ell^-$	128±2	16±3	15.2% (BDT)	8.8%	3.0×10^{-76}	18.4	5.9 σ
	53±2	8±1	6.3% (cuts)	13.7%	3.1×10^{-30}	11.4	
$ZZ \rightarrow 4\ell$	17±0.5	2±0.2	7.7% (cuts)	24.6%	6.0×10^{-12}	6.8	
$ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$	10±0.2	5±2	2.6% (cuts)	31.3%	7.7×10^{-4}	3.2	
$W\gamma \rightarrow e \nu \gamma$	1604±65	1180±120	5.7% (BDT)	2.5%	significance > 30		>10 σ
$W\gamma \rightarrow \mu \nu \gamma$	2166±88	1340±130	7.6% (BDT)	2.1%	significance > 30		
$Z\gamma \rightarrow e^+ e^- \gamma$	367±12	187±19	5.4% (BDT)	5.2%	1.2×10^{-91}	20.3	>10 σ
$Z\gamma \rightarrow \mu^+ \mu^- \gamma$	751±23	429±43	11% (BDT)	3.6%	5.9×10^{-171}	27.8	

- for 100 pb^{-1}, statistical uncertainties are large but still good significance
  - signal detection significances listed right to the table (including 20% systematic error)

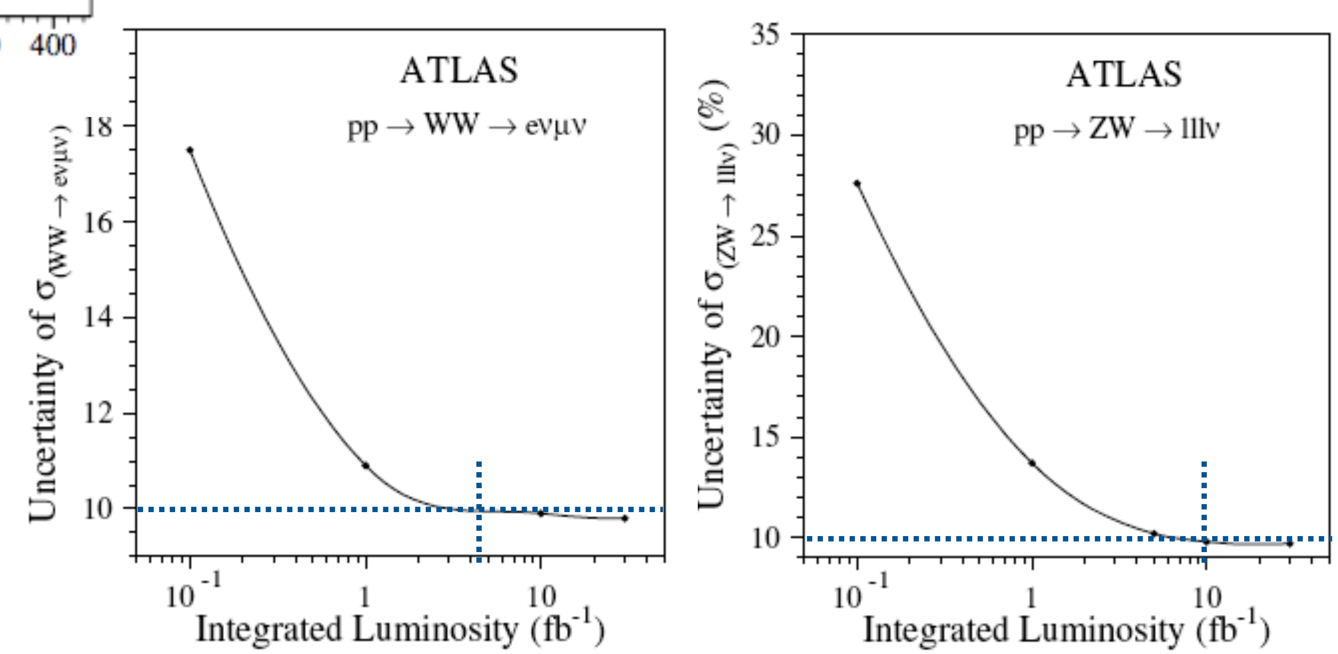
Measurements errors

- cross-section measurement errors estimated for various event selection cuts and integrated luminosities in the W^+W^- and $W^\pm Z$ BDT based analysis
  - cuts on the BDT spectra varied and cross section measurements repeated
  - a total 9.2% systematic uncertainties included in the fitting process



cross-section measurement errors as a function of the BDT cut for different integrated luminosities

relative cross-section errors as a function of the integrated luminosity (BDT cut at 200)

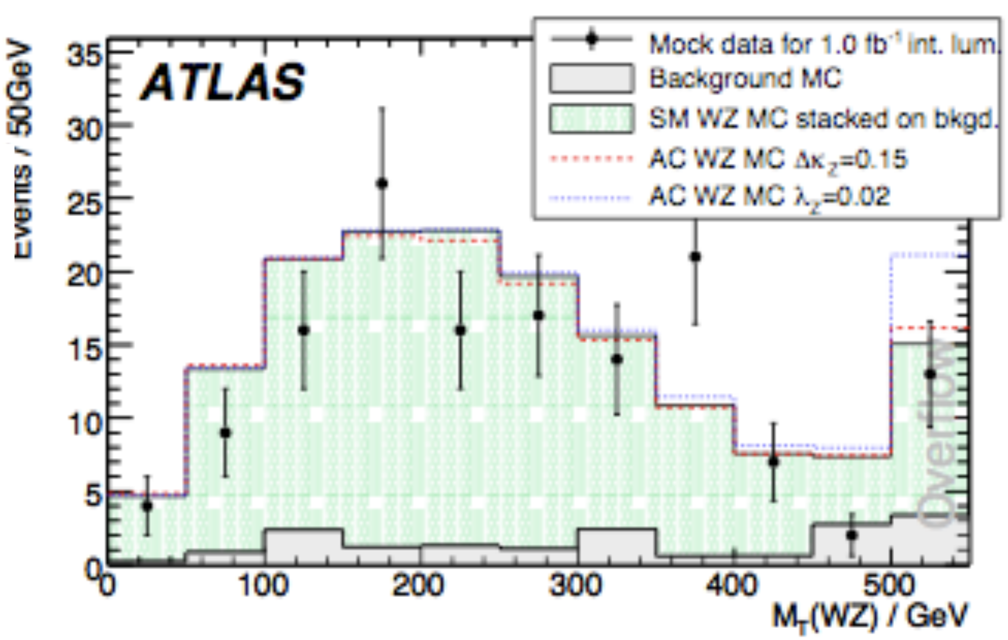


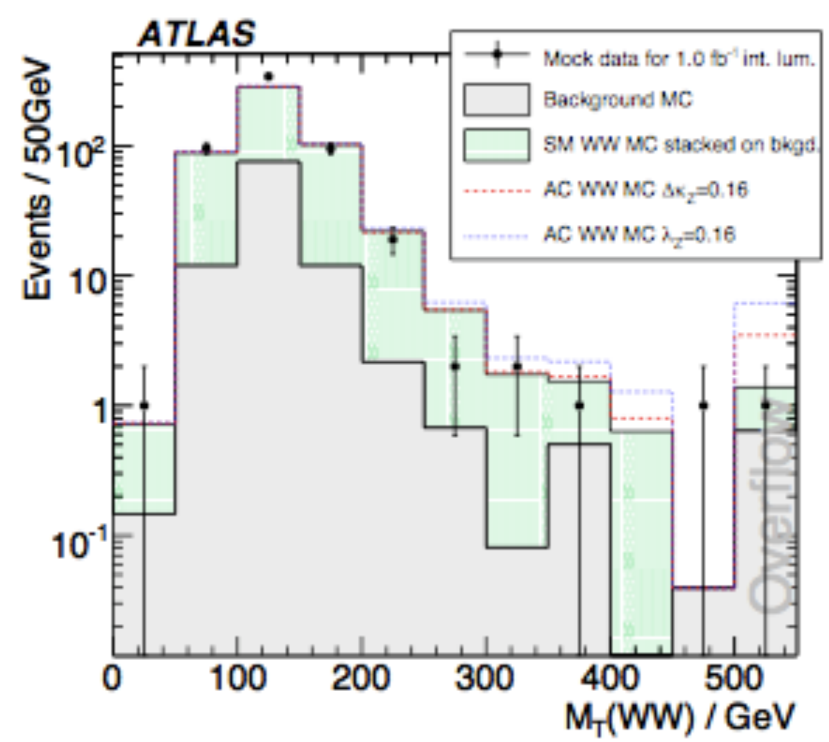
- BDT output spectra used to build the log-likelihood by using *mock data*
- systematic error starts to dominate after 5 fb^{-1} of integrated luminosity for W^+W^- cross-section measurements, and after 10fb^{-1} for $W^\pm Z$

Sensitivity to anomalous couplings

- *signature:* increase in the cross-section at high values of gauge boson p_T and M_T
- *procedure*: comparing the "measured" cross section or p_T/M_T distributions to models with anomalous TGCs
- binned likelihood fitting procedure, using M_T or p_T spectrum for each channel, used to extract the 95% CL intervals of anomalous coupling parameters
  - one- and two-dimensional limits set on charged CP conserving coupling parameters from WW, WZ and Wγ final states
  - ZZ final state used to probe the neutral anomalous TGC sensitivity
- Λ form factor scale chosen so that the TGC limit is less than the unitarity limit (Λ = 2-3 TeV in the CSC analysis)

$W^{\pm}Z$ analysis for 1 fb^{-1} last bins are "overflow" bins





W^+W^- analysis for 1 fb^{-1} last bins are "overflow" bins

Sensitivity to anomalous couplings

- *95% CL interval on the anomalous TGC couplings in the effective Lagrangian for 10 fb^{-1} and Λ = 2 TeV (in brackets variables used in the fit to set the sensitivity interval)*

Charged sector

Diboson, (fit spectra)	λ_Z	$\Delta\kappa_Z$	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
WZ, (M_T)	[-0.015, 0.013]	[-0.095, 0.222]	[-0.011, 0.034]		
$W\gamma$, (p_T^γ)				[-0.26, 0.07]	[-0.05, 0.02]
WW, (M_T)	[-0.040, 0.038]	[-0.035, 0.073]	[-0.149, 0.309]	[-0.088, 0.089]	[-0.074, 0.165]
WZ, (D0) (1.0 fb^{-1})	[-0.17, 0.21]	[-0.12, 0.29] ($\Delta g_1^Z = \Delta\kappa_Z$)			
$W^\pm\gamma$ (D0), (0.16 fb^{-1})				[-0.88,0.96]	[-0.2,0.2]
WW, (LEP) ($\lambda_\gamma = \lambda_Z, \Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$)			[-0.051,0.034]	[-0.105,0.069]	[-0.059,0.026]

Neutral sector

	f_4^Z	f_5^Z	f_4^γ	f_5^γ
$ZZ \to \ell\ell\ell\ell$	[−0.010, 0.010]	[−0.010, 0.010]	[−0.012, 0.012]	[−0.013, 0.012]
$ZZ \to \ell\ell\nu\nu$	[−0.012, 0.012]	[−0.012, 0.012]	[−0.014, 0.014]	[−0.015, 0.014]
Combined	[−0.009, 0.009]	[−0.009, 0.009]	[−0.010, 0.010]	[−0.011, 0.010]
LEP Limit	[−0.30, 0.30]	[−0.34, 0.38]	[−0.17, 0.19]	[−0.32, 0.36]

Summary

- CSC studies performed on large data samples and using advanced analysis technicques
  - *BDT improves sensitivities significantly*
- focus on the results achievable in the early running of LHC

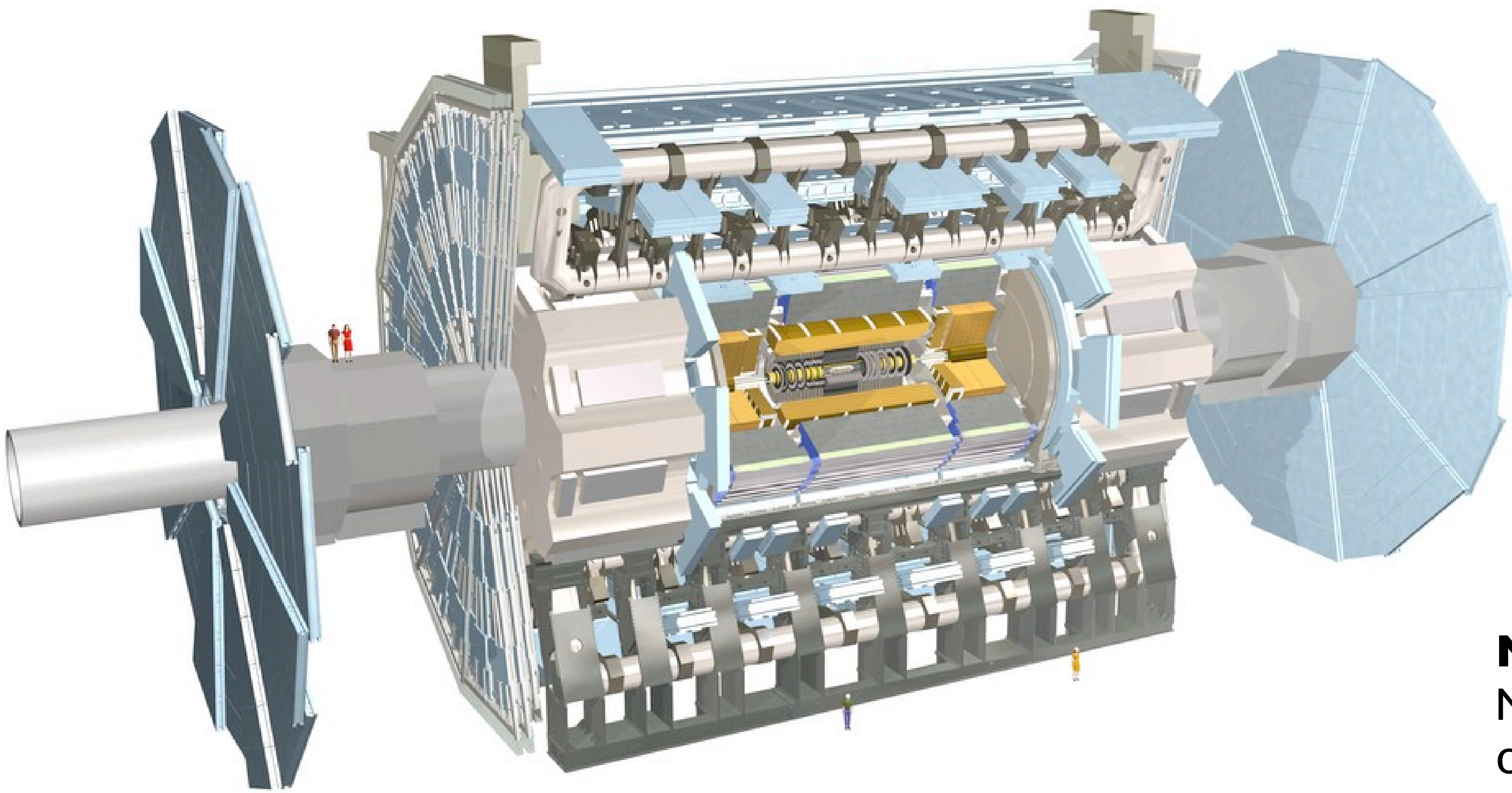
- with 100 pb^{-1} of integrated luminosity, the *SM signals of W^+W^-, $W^\pm Z$ and $W^\pm\gamma$ can be established with significance better than 5σ assuming 20% of systematic uncertainties*
- *ZZ production can be established with 1 fb^{-1} of data using the four-lepton decay channels*
  - only ZZ pairs used so far, study on Zγ in progress

- systematic uncertainties dominated the cross-section measurement errors starting from 5-30 fb^{-1} of data

- *anomalous TGC sensitivities can be significantly improved, starting from 100 pb^{-1} of data, over the results from Tevatron*

Backup Slides

ATLAS Detector



TRACKER (ID)
Si pixels + strips TRT → particle identification
$\sigma/p_T = 5\times10^{-4}\, p_T \oplus 0.01$
$|\eta| < 2.5$

EM CALO
Pb-liquid argon - uniform longitudinal segmentation
$\sigma/E = 10\%/\sqrt{E} \oplus 0.07$
$|\eta| < 3.2$

HAD CALO
Fe-scint. + Cu-liquid argon
($\geq$ 10 λ)
$\sigma/E = 50\%/\sqrt{E} \oplus 0.03$ $|\eta| < 3.2$
$\sigma/E = 100\%/\sqrt{E} \oplus 0.1$ $3.1 < |\eta| < 4.9$

MUON SYSTEM
MDT, CSC, RPC, TGC
$\sigma/p_T = 10\%/p_T$ at p_T = 1 TeV/c
$|\eta| < 2.7$

Cross Sections for dibosons → 4l

Process	Generator	$\sigma \cdot BR$ [fb]	Corrections	FA	Events (K)
$qq \to ZZ \to 4l$	PYTHIA6.3	158.8	+47.64	[4l] 0.219	100
$qq \to WZ$	HERWIG/Jimmy	26500		[3l] 0.0143	70

$qq \to ZZ^{(*)}$

$\sigma_{eff} = \sigma_{LO} \cdot [BR(Z \to ee, \mu\mu, \tau\tau)]^2 \cdot EF \cdot (K + 0.3) = 34.82 \cdot [K(M_{ZZ}) + 0.3]$ fb

$qq \to WZ$

$\sigma_{eff} = \sigma_{NLO}(W^+Z + W^-Z) \cdot EF = 807$ fb

M_{ZZ} [GeV/c^2]	K factor
[115, 125]	1.15
[125, 135]	1.21
[135, 145]	1.25
[155, 165]	1.34
[175, 185]	1.31
[195, 205]	1.32
[295, 305]	1.40
[395, 405]	1.52
[495, 505]	1.84
[595, 605]	1.81