Multi Gauge Bosons at the LHC

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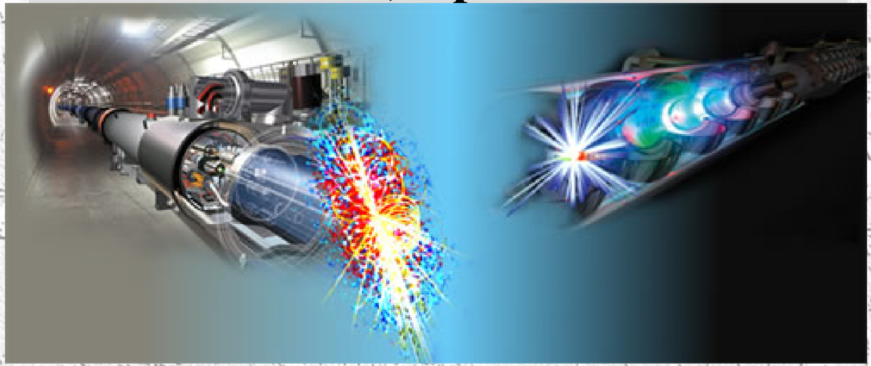
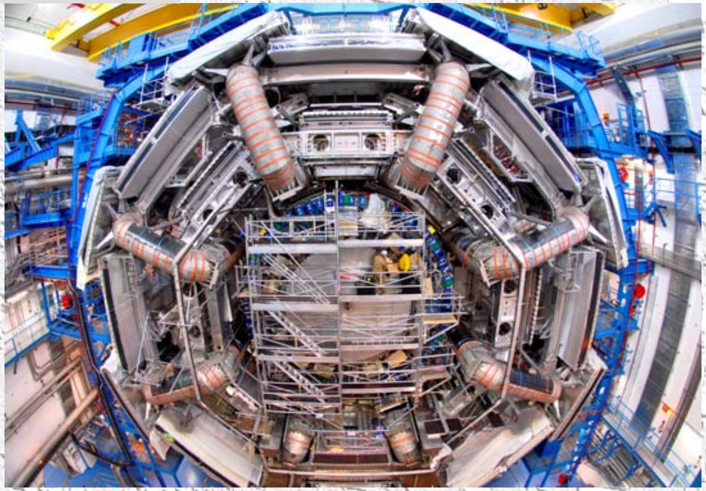
The LHC Early Phase for the ILC
Fermilab, April 12 - 14



Outline

- Introduction LHC physics
- W and Z production
- Di-boson production
- Triple Gauge Couplings



Cross Section of SM Processes

- Cross section of SM processes (W,Z, top etc.) at the LHC are much higher than at the Tevatron

- Low luminosity phase

  $10^{33}/cm^2/s = 1/nb/s$

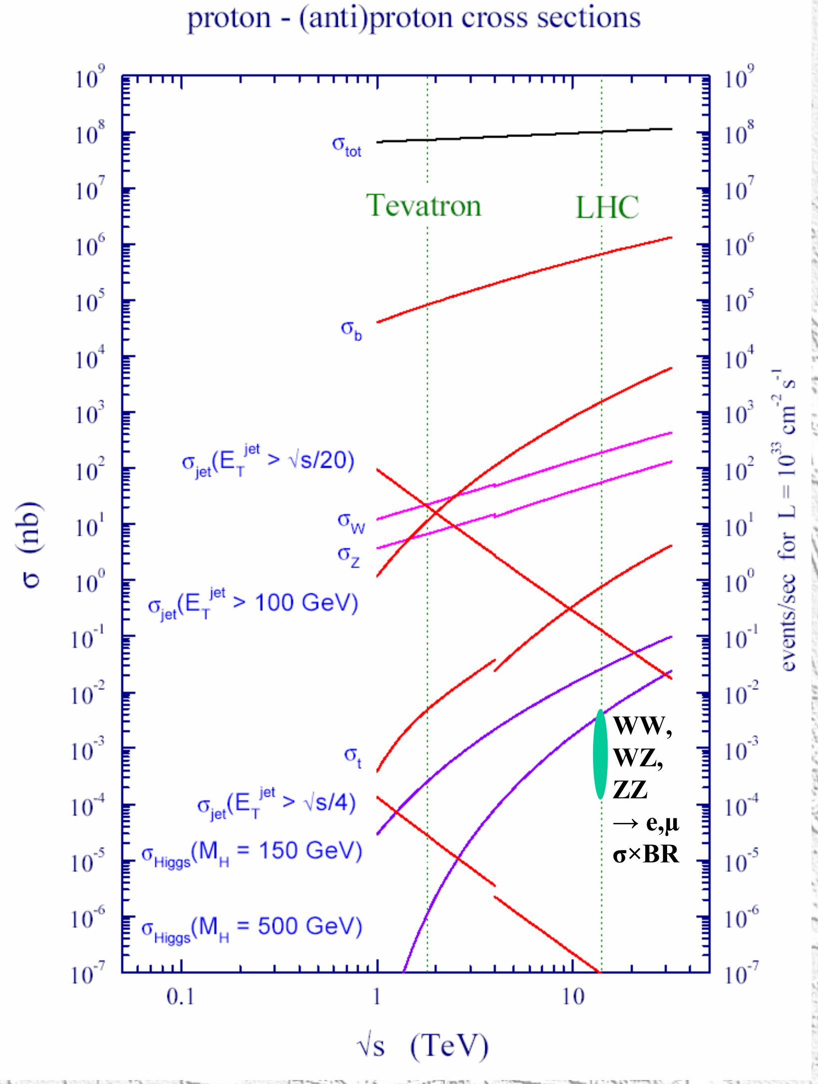
approximately

- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

will be produced per second and

- 1 light Higgs

per minute!



- Most of the precision W,Z,top etc. measurements can be done with $O(10\ fb^{-1})$
- However, requires well understood detector and data

Multi Gauge Bosons at the LHC

At the LHC:

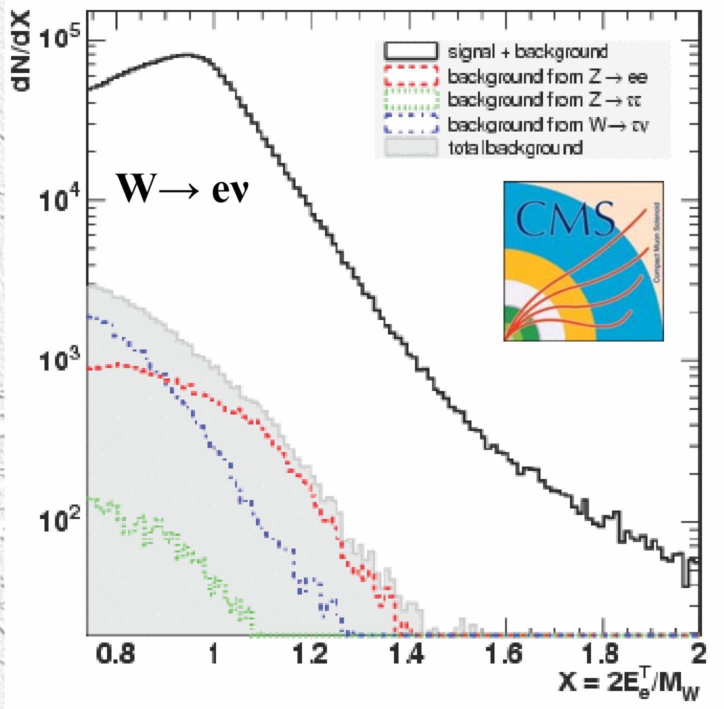
- High cross section and rates for W and Z bosons
- Enormous QCD background

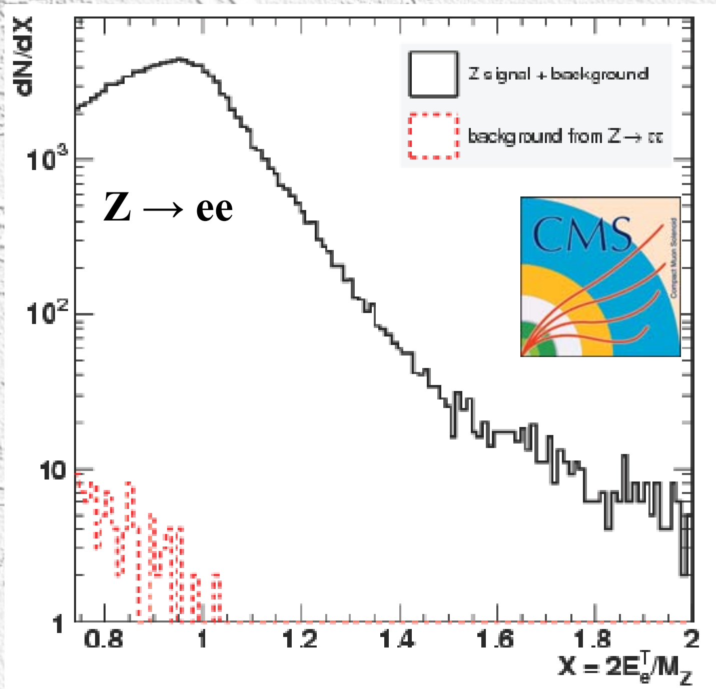
→ go for leptonic decay modes
$W \to e\nu, \mu\nu$ and $Z \to e^+e^-, \mu^+\mu^-$

- Several studies of ATLAS and CMS using complete detector simulation & reconstruction:
  - ATLAS
    SM notes at
    https://twiki.cern.ch/twiki/bin/view/Atlas/StandardModelNotes
  - CMS
    Physics TDR http://cmsdoc.cern.ch/cms/cpt/tdr/
    Plots http://cmsdoc.cern.ch/cms/PRS/results/sm/EWphysics.html

Single W and Z Production

- **Very clean selection of W and Z boson possible e.g. CMS study of W→ eν and Z → ee**





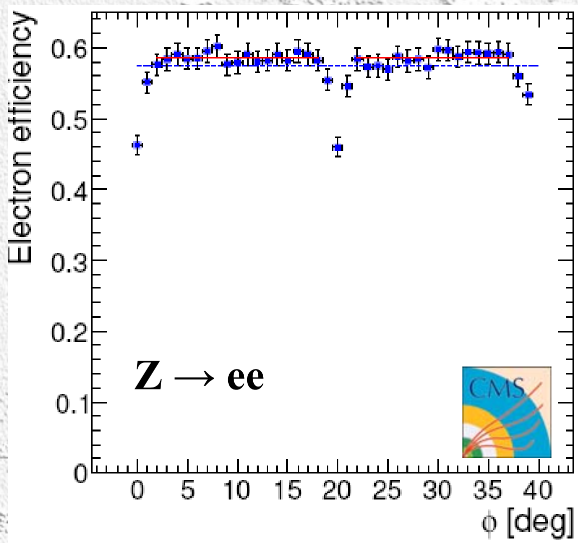
- **QCD background estimated < 1%**

- **Recall rates (initial phase 10^{33}/cm²/s):**
  ≈ 200 W/s → ≈ 20 W→eν /s
  ≈ 50 Z/s → ≈ 1.5 Z → ee /s
  plus the same rates for muon decays!

- **W and Z events will provide an excellent tool for detector calibration**

W and Z Production

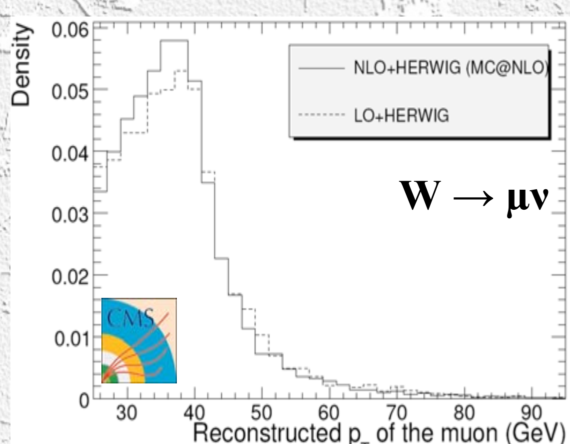
- **Robust selection of W and Z events electron and muon channels for first 1 fb^{-1}**



- **Studies of sys. errors, e.g. $Z \rightarrow \mu\mu$ and $W \rightarrow e\nu$**

Source	Uncertainty (%)
Tracker efficiency	1
Magnetic field knowledge	0.03
Tracker alignment	0.14
Trigger efficiency	0.2
Jet energy scale uncertainties	0.35
Pile-up effects	0.30
Underlying event	0.21
Total exp.	1.1
PDF choice (CTEQ61 sets)	0.7
ISR treatment	0.18
p_T effects (LO to NLO)	1.83
Total PDF/ISR/NLO	2.0
Total	2.3

Source	Uncertainty (%)
Tracker efficiency	0.5
Muon efficiency	1
Magnetic field knowledge	0.05
Tracker alignment	0.84
Trigger efficiency	1.0
Transverse missing energy	1.33
Pile-up effects	0.32
Underlying event	0.24
Total exp.	2.2
PDF choice (CTEQ61 sets)	0.9
ISR treatment	0.24
p_T effects (LO to NLO)	2.29
Total PDF/ISR/NLO	2.5
Total	3.3



Precision of the cross section for the first 1 fb^{-1}:

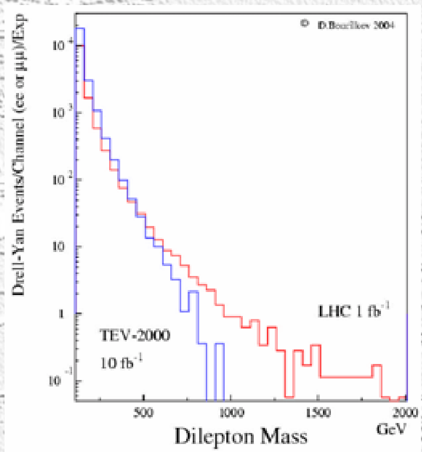
$\Delta\sigma/\sigma(pp \rightarrow Z+X \rightarrow \mu+\mu-+X) = 0.13\%(stat) \pm 2.3\%(syst) \pm 10\%(lumi)$

$\Delta\sigma/\sigma(pp \rightarrow W+X \rightarrow \mu\nu+X) = 0.04\%(stat) \pm 3.3\%(syst) \pm 10\%(lumi)$

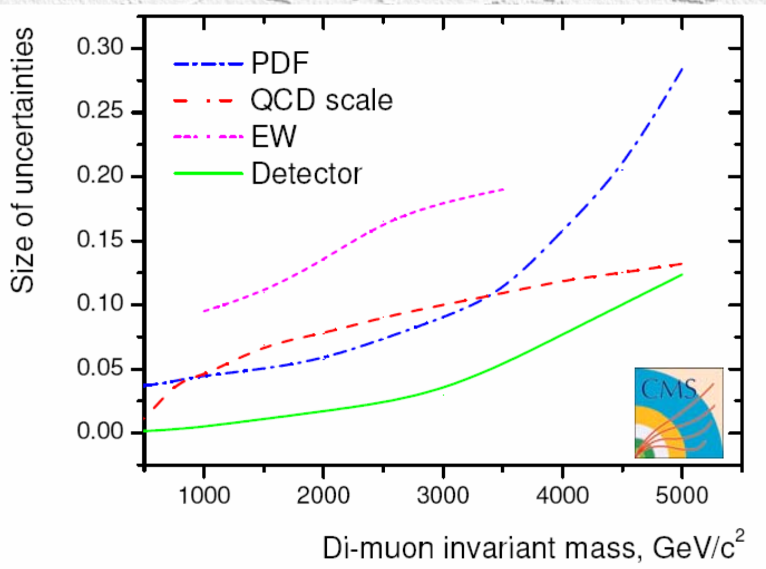
- **measurements of W/Z rates (except lumi) in fiducial volume to % level**
- **parton luminosity**

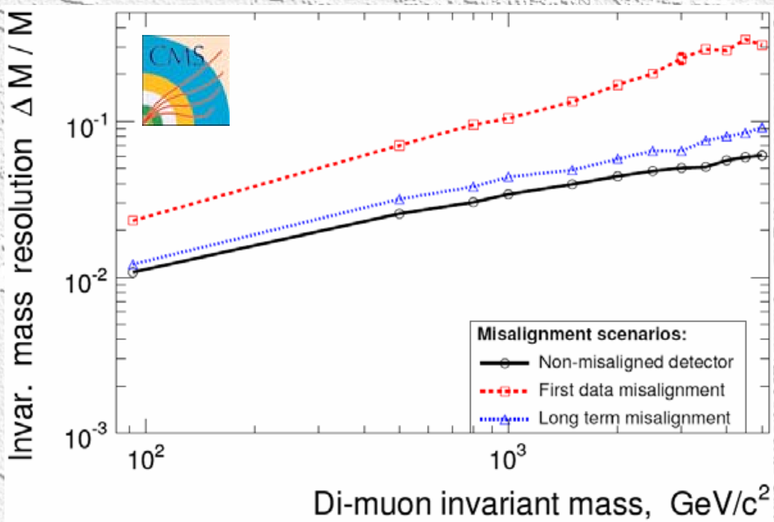
Drell-Yan Muon Pairs

Goal:
- **measurement of μμ cross section from Z to multi-TeV region**
- **asymmetry**
- **constrain PDFs**



Systematic errors:





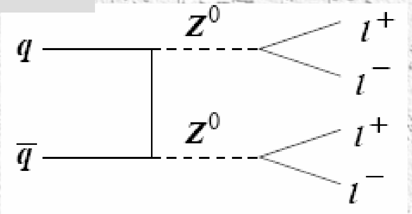
$M_{\mu^+\mu^-}$, TeV/c^2	Detector smearing	Statistical 1 fb^{-1}	Statistical 10 fb^{-1}	Statistical 100 fb^{-1}	Theor. Syst.
≥ 0.2	$8 \cdot 10^{-4}$	0.025	0.008	0.0026	0.058
≥ 0.5	0.0014	0.11	0.035	0.011	0.037
≥ 1.0	0.0049	0.37	0.11	0.037	0.063
≥ 2.0	0.017		0.56	0.18	0.097
≥ 3.0	0.029			0.64	0.134

Detector systematics small wrt to statistics!

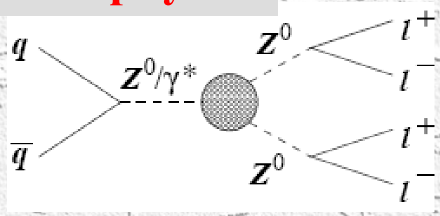
Di-Boson Production

- Very interesting:
  WW,WZ,ZZ final states (some not yet observed at the Tevatron)
- Test triple gauge boson couplings (TGC)
  - γWW and ZWW precisely fixed in SM
  - γZZ and ZZZ do not exist in SM!

SM



New physics



- deviations from SM are amplified with energy
- All di-boson final states contribute WW,WZ,ZZ, Wγ and Zγ

- Production of pairs of heavy gauge bosons
  (l = e, μ)

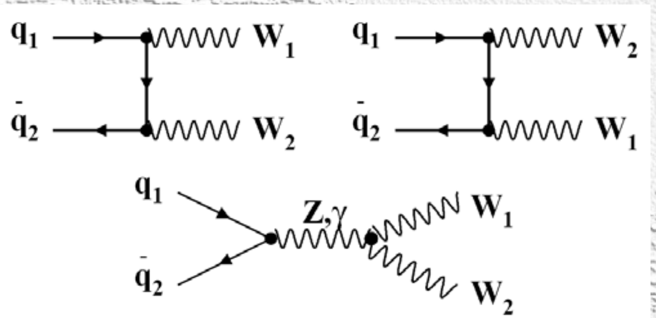
Process		$\sigma_{NLO}\times BR$
WW	→ 2l	5.4 pb
WZ	→ 3l	1.6 pb
ZZ	→ 4l	0.1 pb

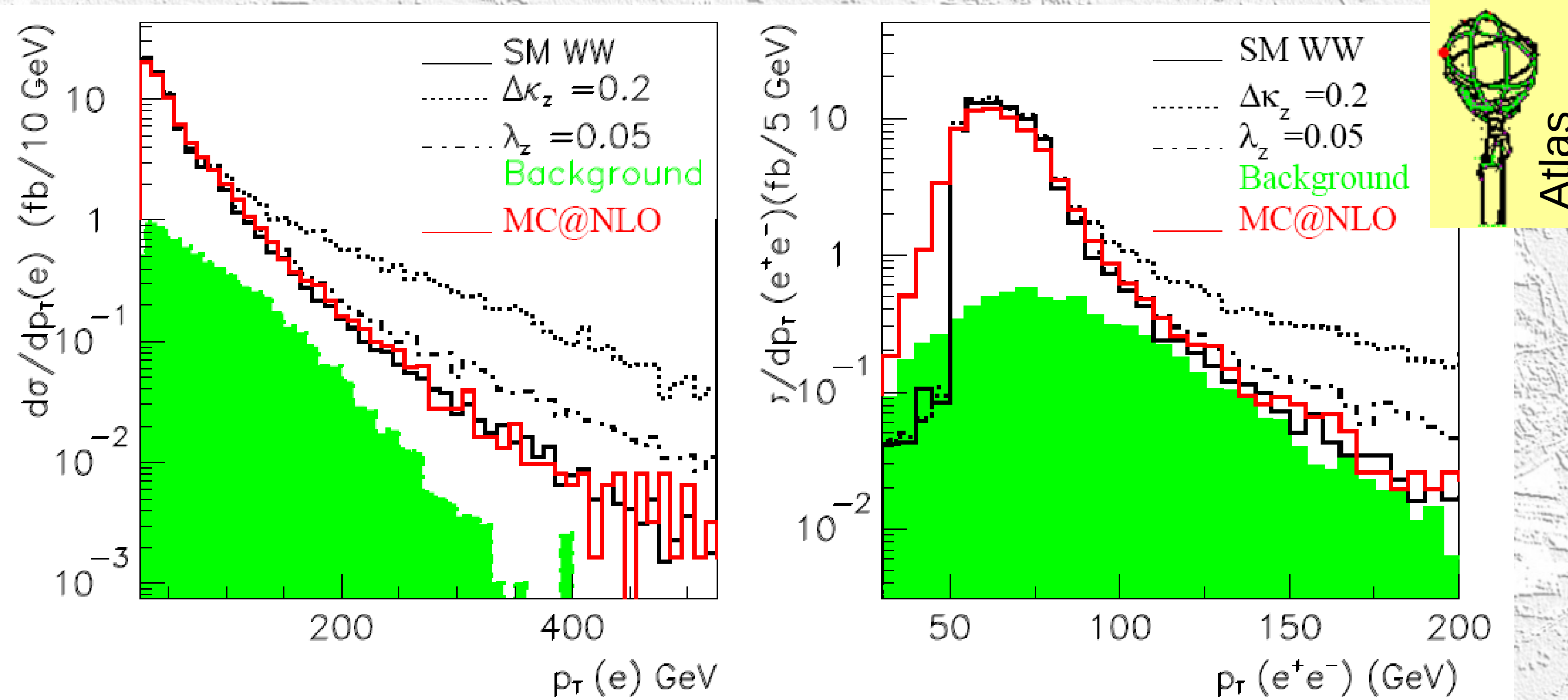
WW

- **WW final states**

  ATLAS study for 30 fb^{-1}
  - **5000 signal events**
  - **1000 bkgd (mainly top pairs)**

Establish signal with < 1fb^{-1}

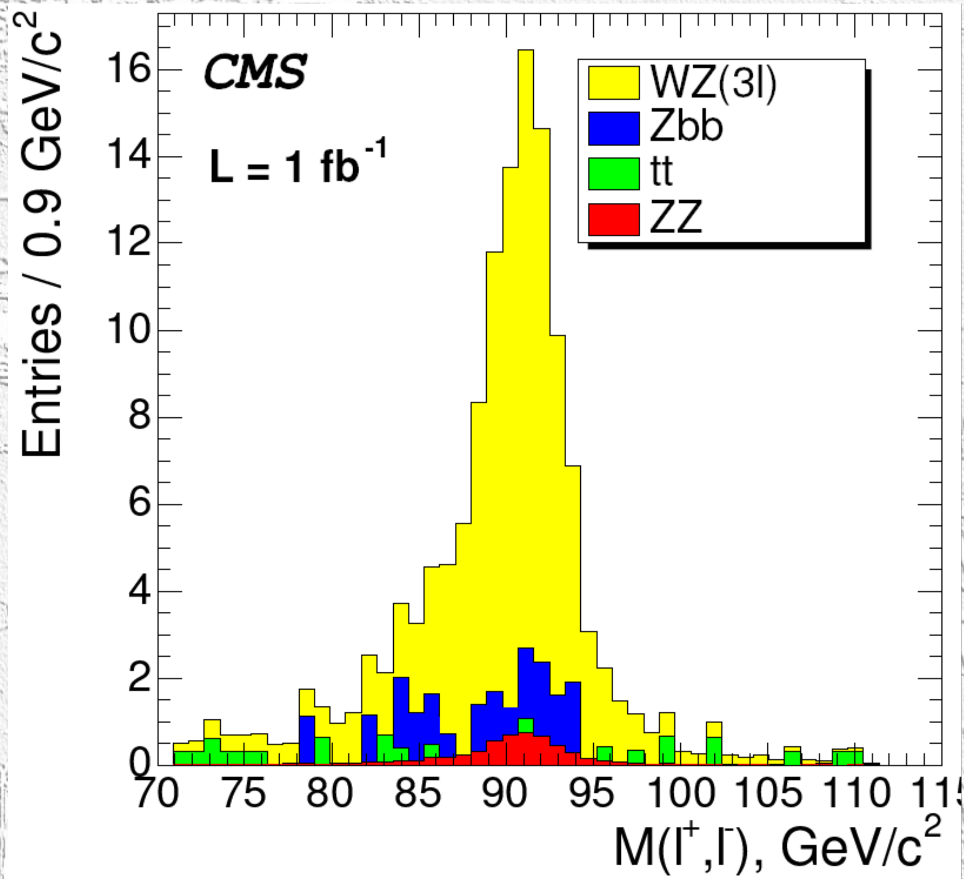




WZ

- **CMS PTDR: WZ and ZZ production investigated**

- **WZ → 3l + ν clear signal with 1 fb^{-1}**
  - **≈ 100 signal events**
  - **≈ 22 background**

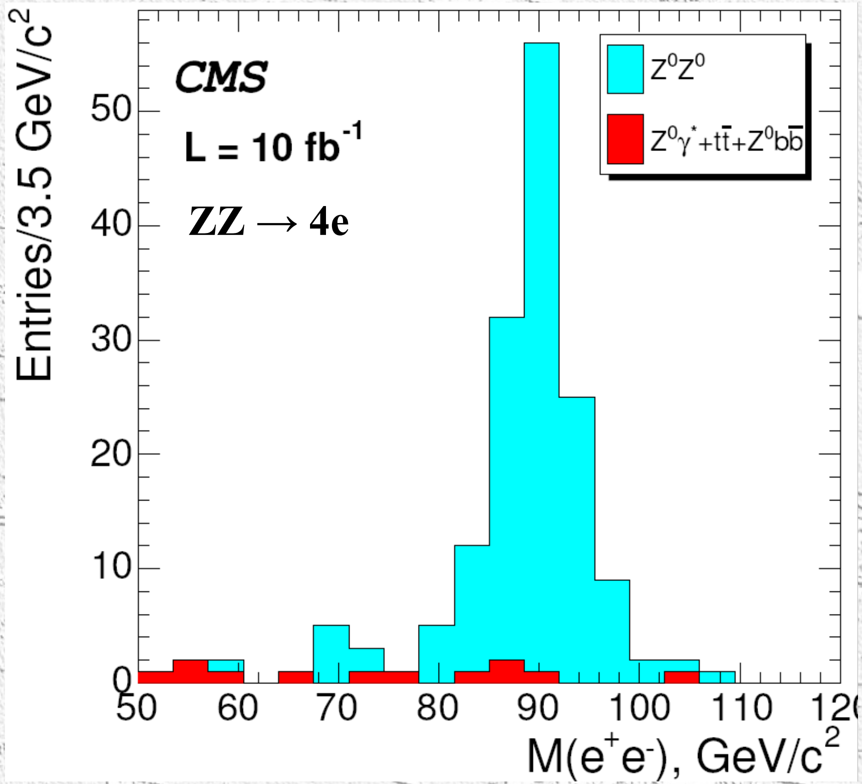


	$e^\pm e^+ e^-$	$\mu^\pm e^+ e^-$	$e^\pm \mu^+ \mu^-$	$\mu^\pm \mu^+ \mu^-$	Total	Efficiency
$W^\pm Z^0 \to \ell^\pm \ell^+ \ell^-$	14.8	26.9	28.1	27.0	96.8	6.1%
$Z^0 Z^0$	0.63	1.54	1.50	1.51	5.18	4.7%
$t\bar{t}$	0.93	1.55	–	0.31	2.79	0.02%
$\mu^+\mu^- b\bar{b}$	–	–	6.54	4.9	11.4	0.005%
$e^+e^- b\bar{b}$	1.21	1.82	–	–	3.03	0.005%

ZZ

- Study of ZZ → 4e
- essentially background free
- adding muons increases statistics by 4

	Efficiency	$N_{events}/1\ fb^{-1}$	$N_{events}/10\ fb^{-1}$
$Z^0\ Z^0$	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
S_L		4.8	13.1

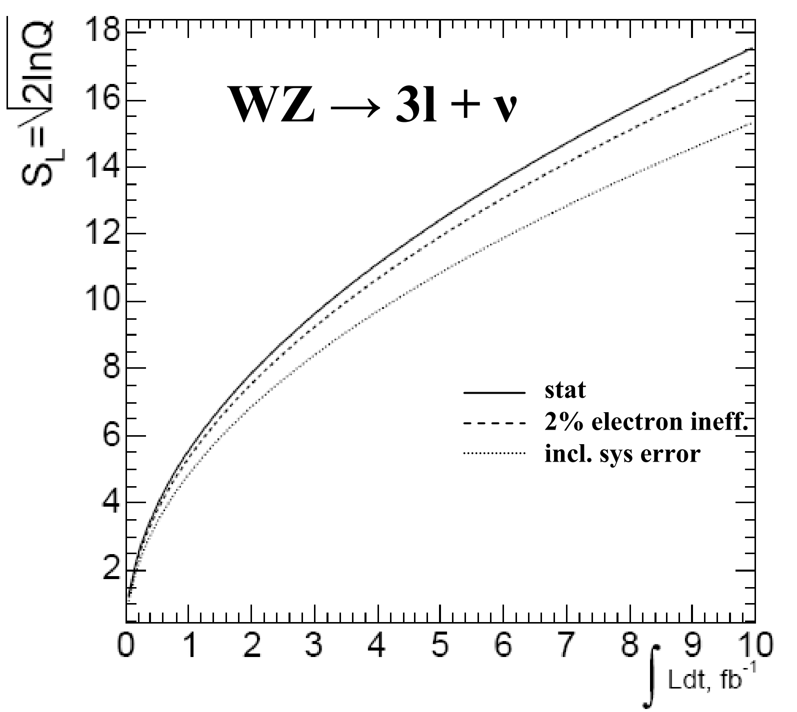


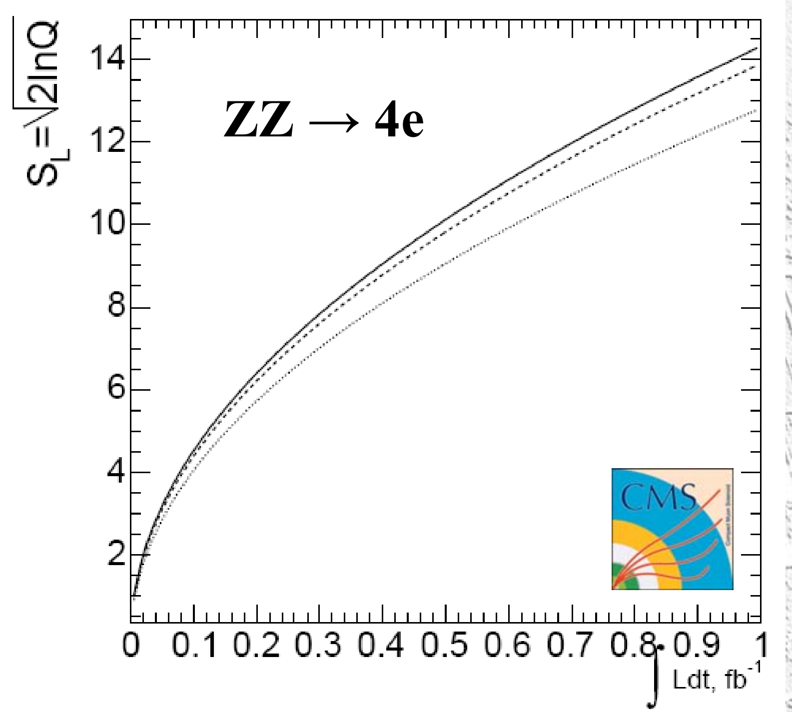
Also observation of ZZ possible with $\leq 1\ fb^{-1}$

- WW, WZ, ZZ prospects:
- $< 1\ fb^{-1}$:
  establish signals
- $O(10\ fb^{-1})$:
  measure total cross section to few %
  in particular ratios, e.g. σ_{WW}/σ_W
  differential cross section → TGC

Significance for WZ and ZZ

- **Significance for WZ → 3l + ν and ZZ → 4e**

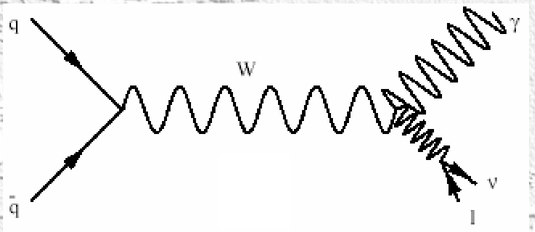




$$S_L = \sqrt{2\ln Q},\ Q = \left(1 + \frac{N_S}{N_B}\right)^{N_S+N_B} e^{-N_S}$$

Wγ Final States

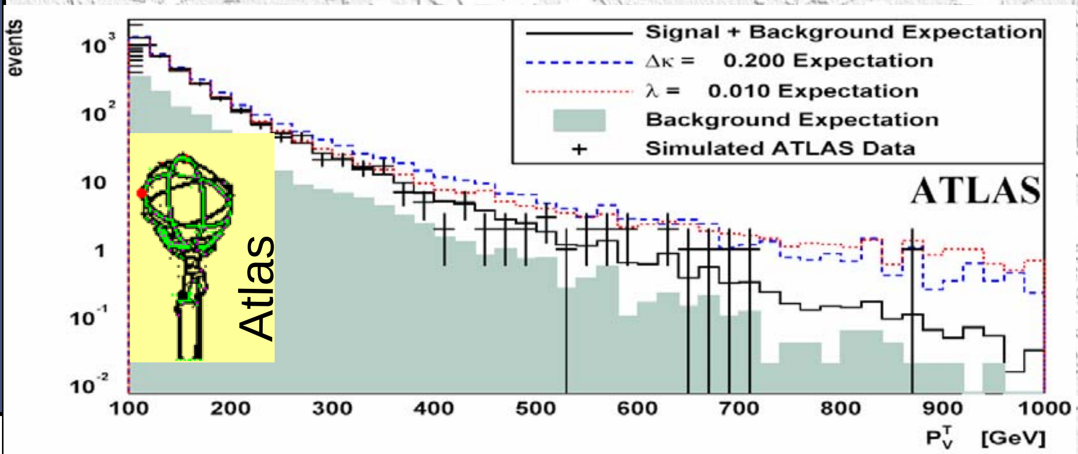
- Wγ final states
- W → eν and μν
- p_T spectrum of bosons

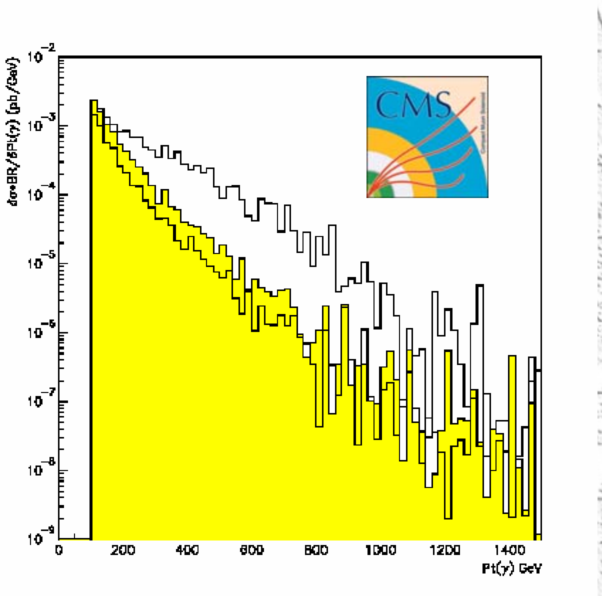


Test CP conserving anomalous couplings at the WWγ vertex Δκ and λ

$p_T(\gamma)$ spectrum for SM couplings & current limits Δκ, λ

Sensitivity to anomalous couplings from high end of the p_T spectrum

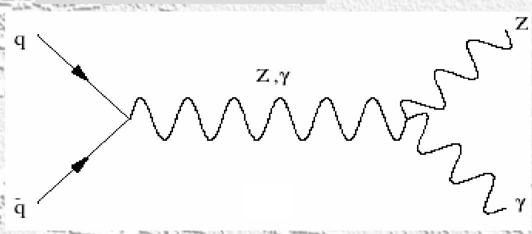




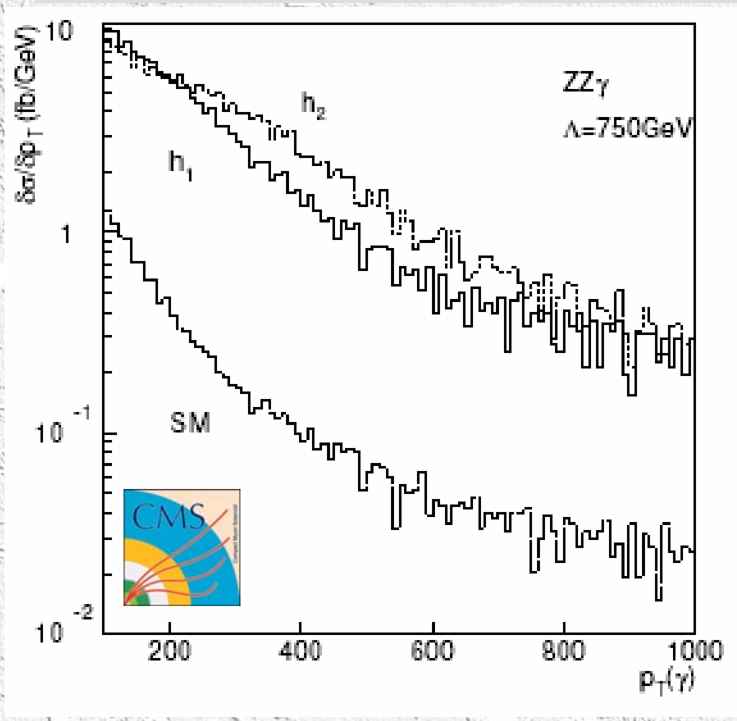
Zγ Final States

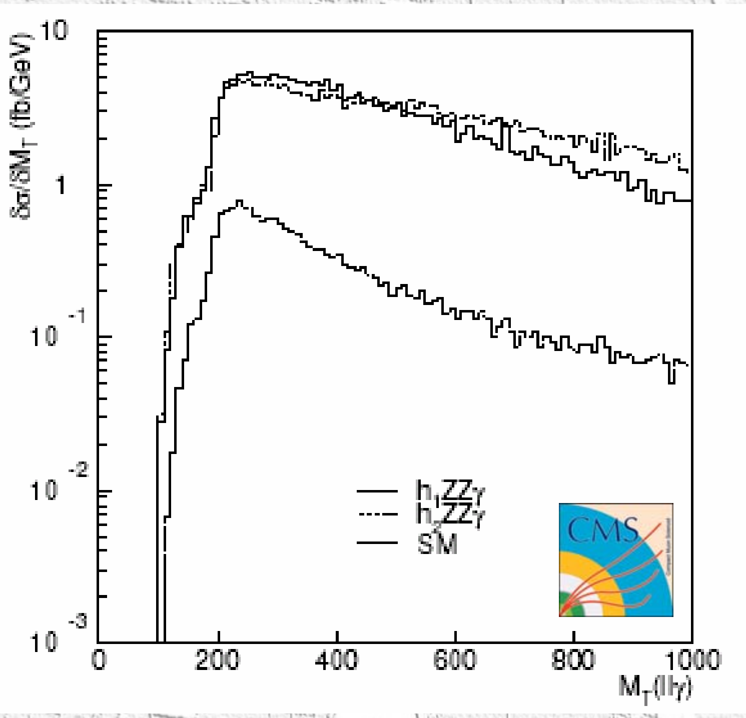
- Zγ final states
- $Z \rightarrow e^+e^-$ and $\mu^+\mu^-$
- p_T spectrum of photons and $m_T(ll\gamma)$

Search for



Spectra for SM couplings compared to current limits on anomalous couplings

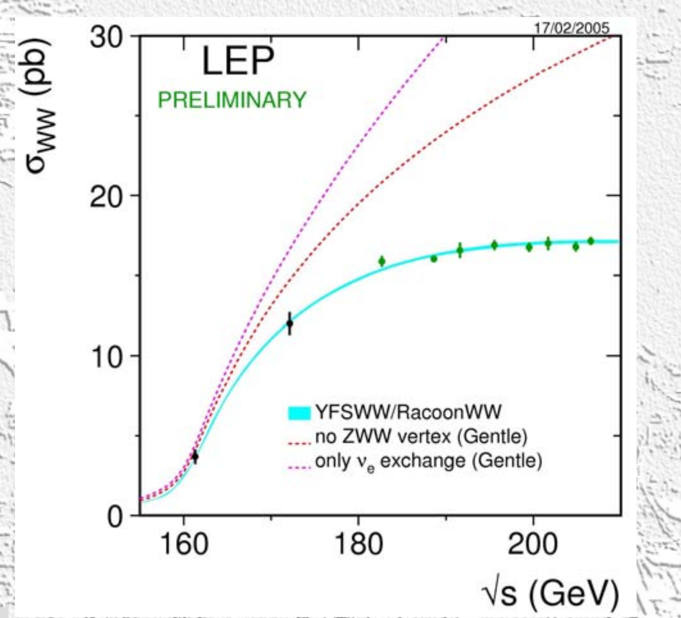




Triple Gauge Couplings at LEP

- Triple Gauge Couplings confirmed at LEP to percent level (WWγ and WWZ vertices)

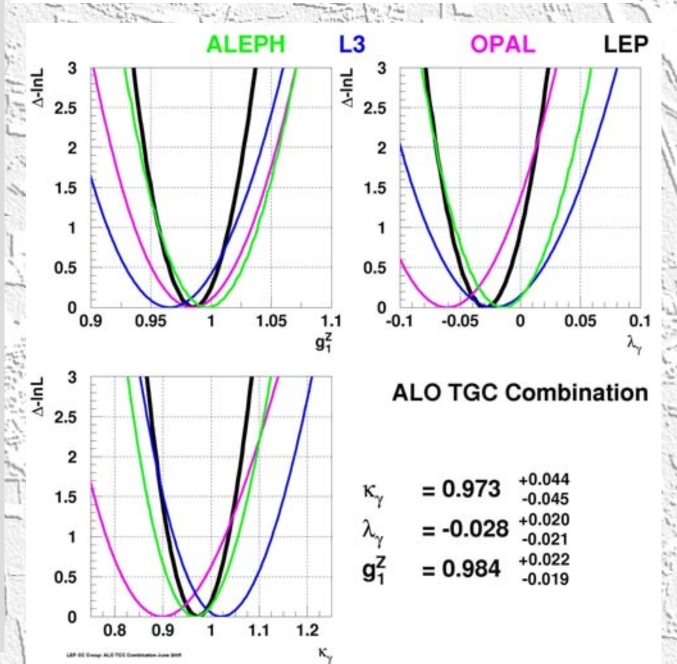
Parameter	68% C.L.
g_1^Z	$0.984^{+0.022}_{-0.019}$
κ_γ	$0.973^{+0.044}_{-0.045}$
λ_γ	$-0.028^{+0.020}_{-0.021}$



- Most general Lorentz invariant Lagrangian imposing charge conservation and C and P invariance
- Leads to five independent couplings

$$g_1^Z,\ \kappa_Z,\ \kappa_\gamma,\ \lambda_Z,\ \lambda_\gamma$$

- Deviation from SM value 1 denoted by Δ
- At LEP additional gauge constraints are imposed reducing the parameters to 3



The LHC Early Phase for the ILC

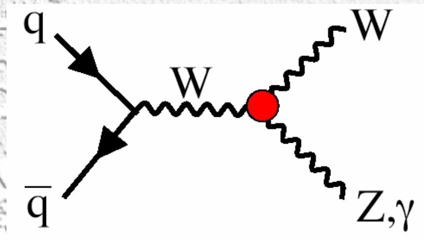
Triple Gauge Couplings at the LHC

- **WWγ and WWZ vertices do exist in the SM**

Requiring C,P and elm. gauge invariance

⇒ 5 coupling parameters

$\kappa_{\gamma,Z}$	1	Dim4, $\propto \sqrt{s}$
$\lambda_{\gamma,Z}$	0	Dim6, $\propto s$
g_1^Z	1	Dim4, $\propto \sqrt{s}$



- **ZZγ and ZZZ vertices do NOT exist in the SM**

Requiring Lorentz & elm. gauge invariance & Bose symmetry

⇒ 12 coupling parameters

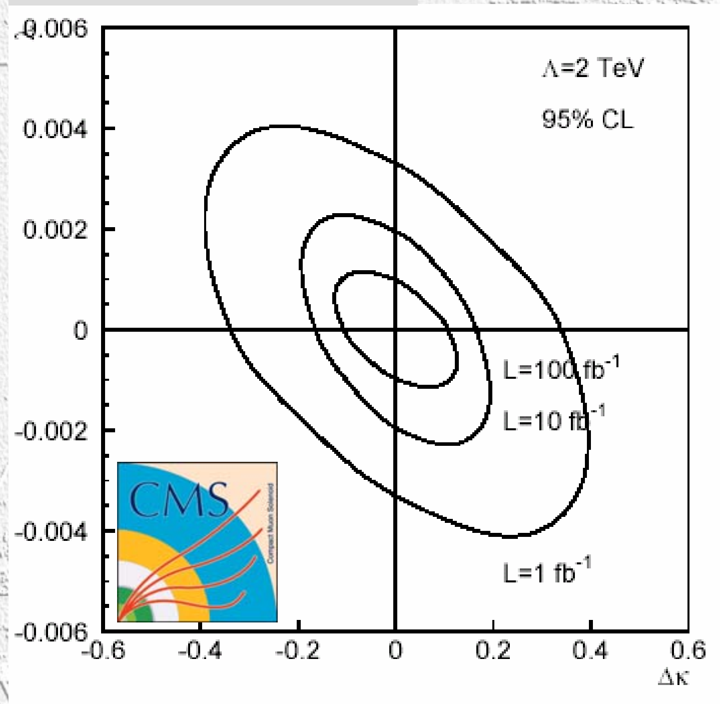
h_i^V, f_i^V (V= γ,Z)

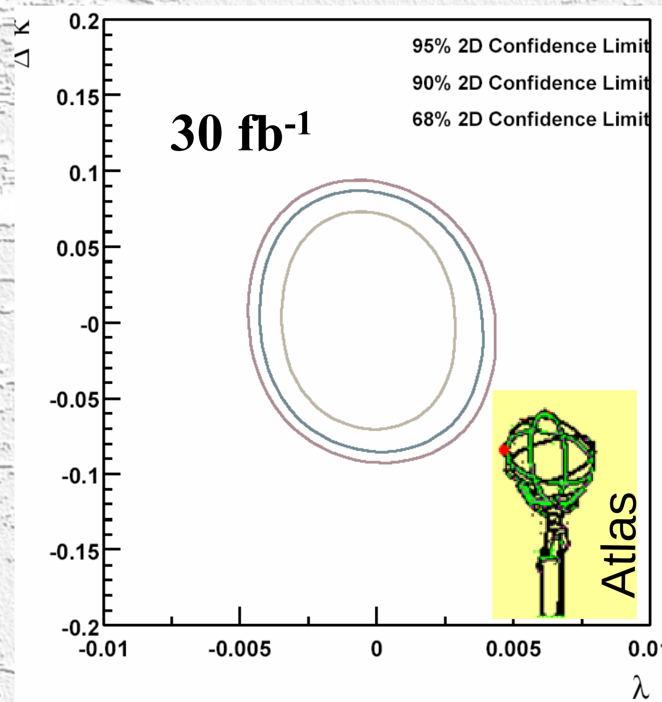
h_1	dim6, $\propto s^{3/2}$	~~CP~~
h_2	dim8, $\propto s^{5/2}$	~~CP~~
h_3	dim6, $\propto s^{3/2}$	CP
h_4	dim8, $\propto s^{5/2}$	CP
f_4	dim6, $\propto s^{3/2}$	~~CP~~
f_5	dim6, $\propto s^{3/2}$	CP

Deviations from SM amplified by high energies!

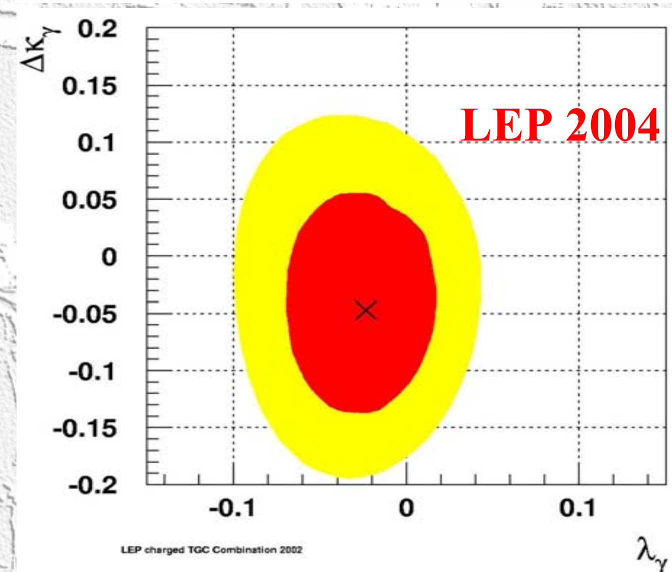
Triple Gauge Couplings at the LHC

- **Wγ final states**



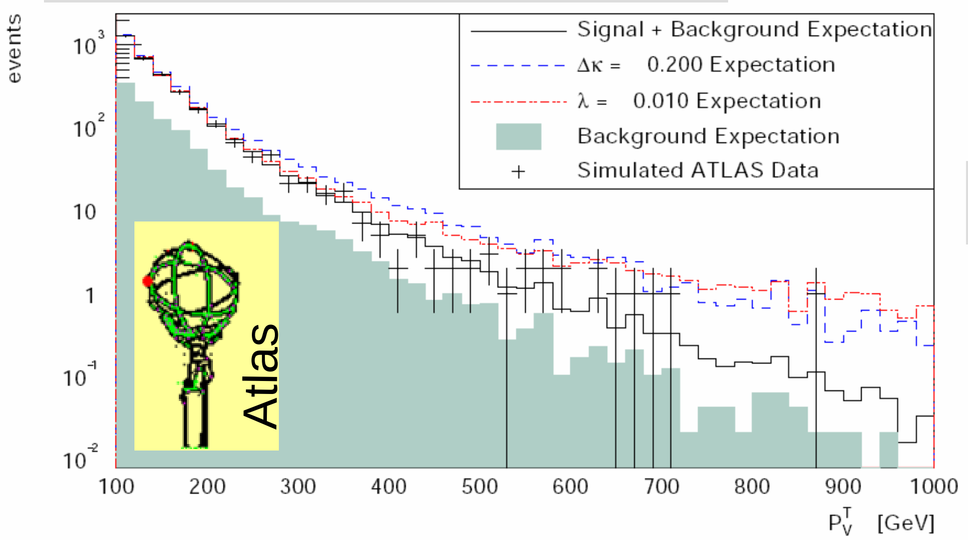


- **Large improvement wrt LEP in particular on λ due to higher energy**

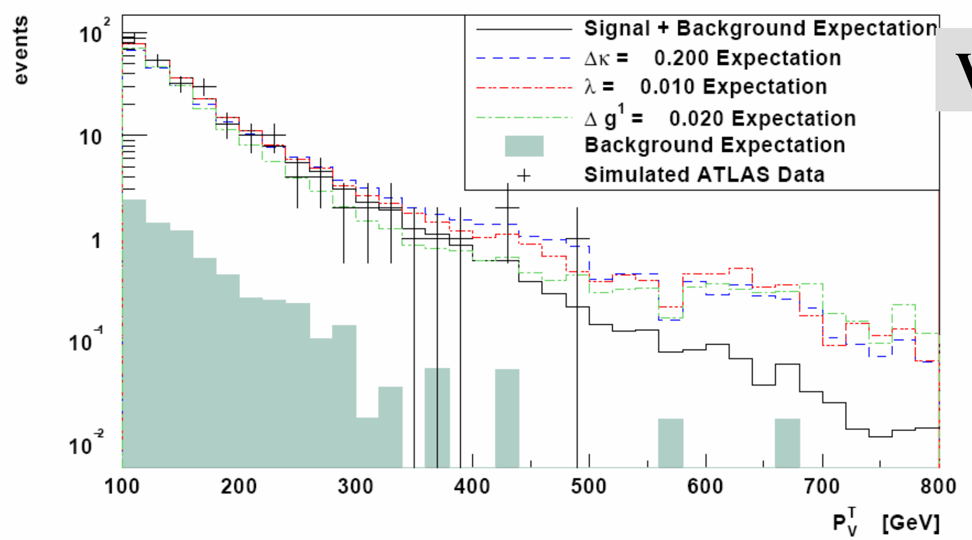


Cross Section of SM Processes

p_T of neutral boson (30 fb^{-1}):



Wγ



WZ

Cross Section of SM Processes

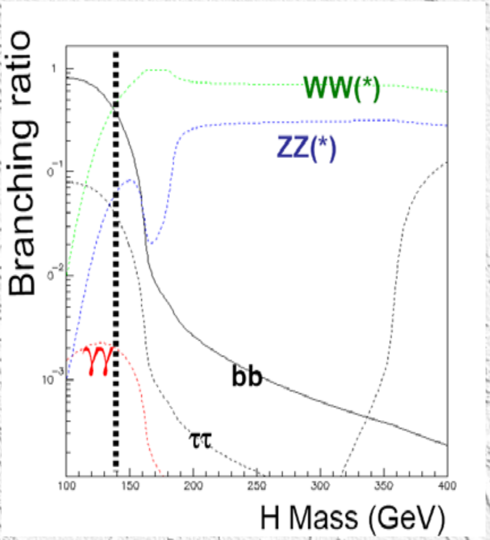
- **ATLAS study combining all di –boson final states**
  - **for 30 fb^{-1}**
  - **compared to LEP**

ATGC Parameter	95% CL LEP2	95% CL 30 fb^{-1} ATLAS
$\Delta\kappa_\gamma$	-0.105, +0.069	-0.075, +0.076
λ_γ	-0.059, +0.026	-0.0035, +0.0035
Δg_1^Z	-0.051,+0.034	-0.0086, +0.011
$\Delta\kappa_Z$		-0.11, +0.12
λ_Z		-0.0072, +0.0072

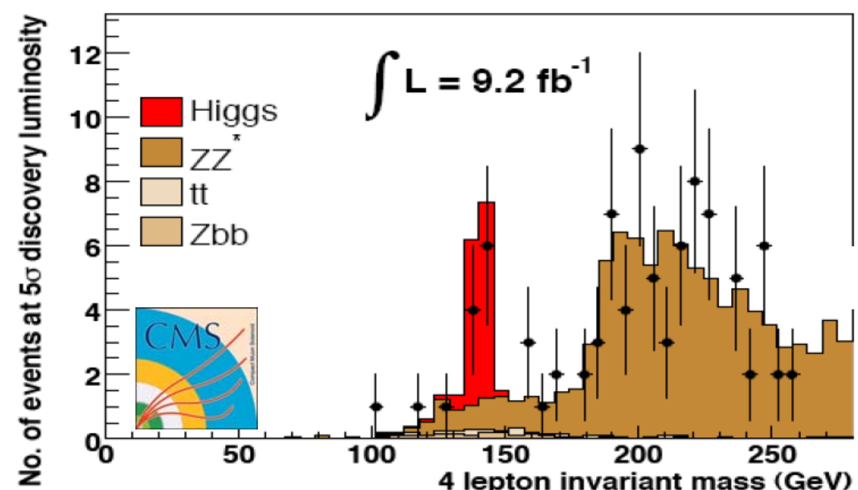
- **Largest improvement in λ as sensitivity is grows with s**

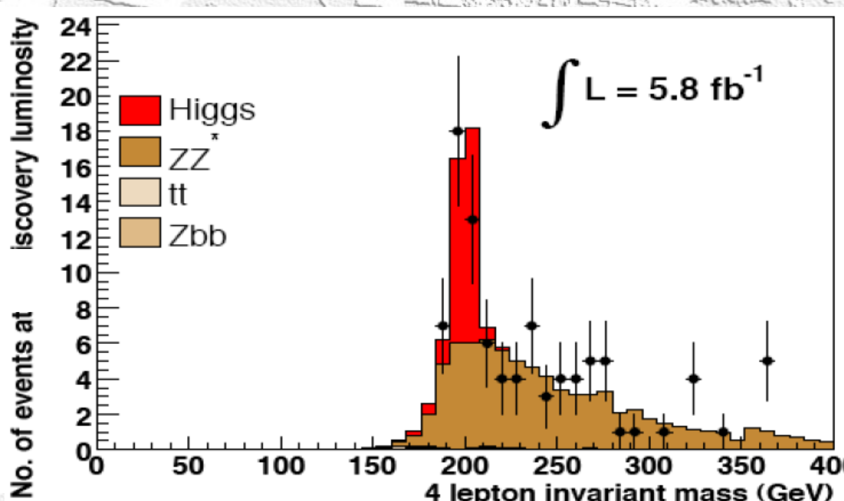
WW and ZZ from Higgs Boson

- Higgs production is other (potential) source of WW and ZZ final states:
- Standard Model Higgs
  $H \rightarrow WW$ and $H \rightarrow ZZ$
  dominant decay modes for m_H > 140 GeV
- Cross section: similar to WW/ZZ continuum



- Mass peak for ZZ
- Luminosity needed for 5 sigma signal:



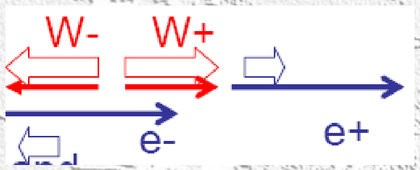


WW and ZZ from Higgs Boson

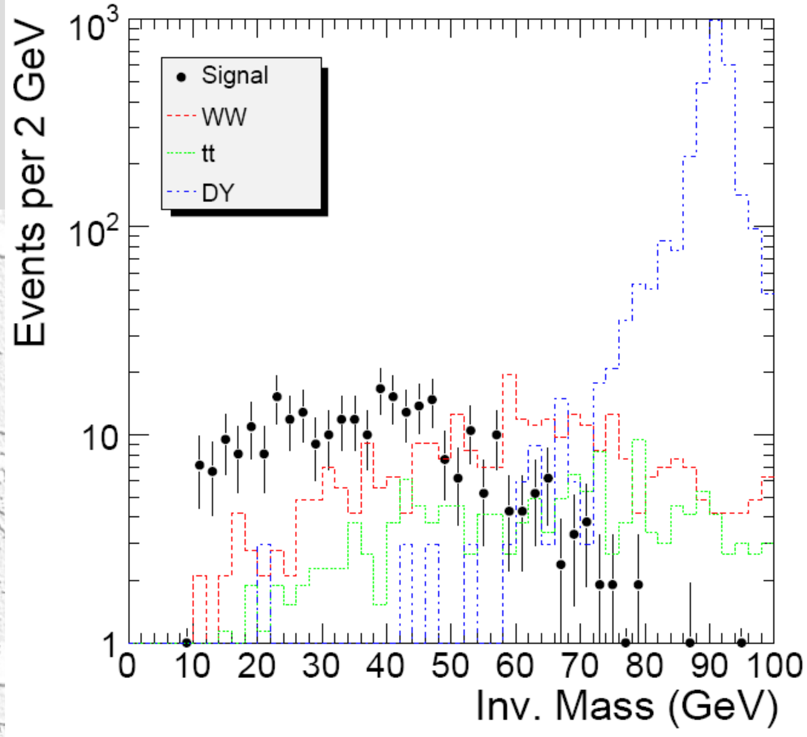
H →WW:

- **main interest around $m_H \approx 160$ GeV to bridge gap between H → γγ and H → ZZ**

- **Separation from WW continuum more difficult as Higgs mass information is washed out**
  - **Higgs events from gg-fusion more central than WW continuum (mainly qq)**
  - **Spin correlation: Higgs is scalar → smaller angle between leptons, i.e. smaller invariant mass**

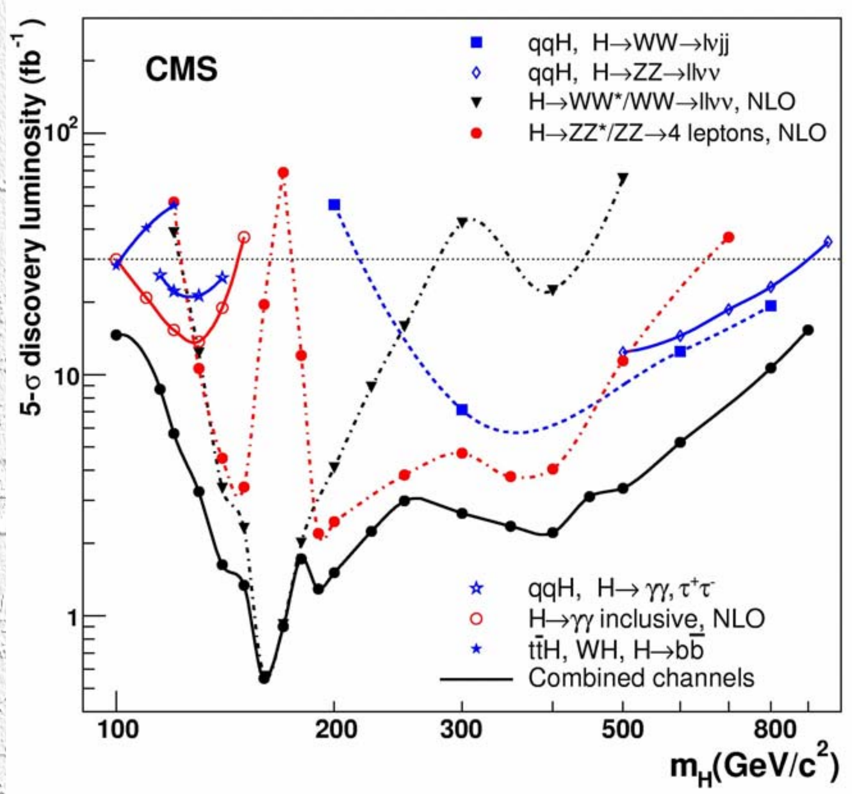


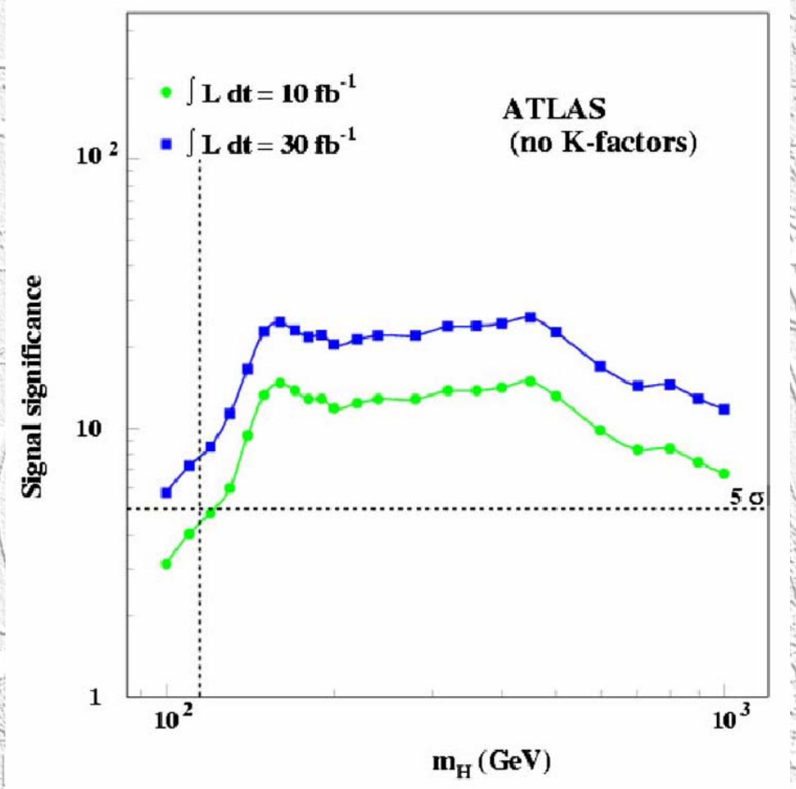
- **H → WW → 2μ + 2ν for 10 fb^{-1}**



SM Higgs Significance

- Significance for SM Higgs di-bosons play important role

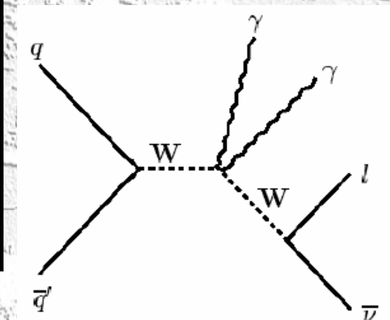




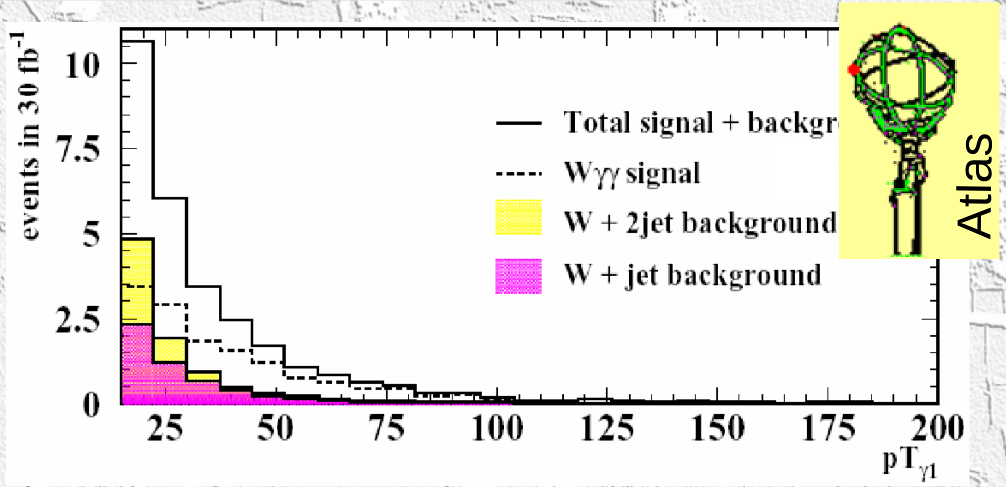
Triple Boson Production

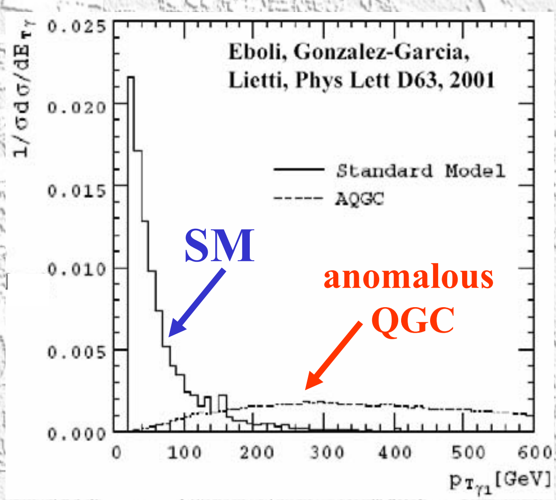
- **Sensitivity to quartic gauge boson couplings (QGC)**

Events for 100 fb^{-1} (m_H = 200 GeV)	Produced (no cuts, no BR)	Selected (leptons, p_T > 20 GeV, $\|\eta\|$ < 3)
pp → WWW (3 ν´s)	31925	180
pp → WWZ (2 ν´s)	20915	32
pp → ZZW	6378	2.7
pp → ZZZ	4883	0.6
pp → Wγγ	best channel for analysis	



- **30 Wγγ signal events in 30 fb^{-1}**





Summary

- Di-boson production at the LHC
  - relatively large cross section
  - allows use of leptonic decays

- 1 fb^{-1}
  - sufficient to establish WW, WZ, ZZ production
- O(10 fb^{-1}) or less:
  - measure cross sections to few percent (e.g. σ_{WW}/σ_W)

- TGC:
  - large improvements possible
  - in particular for couplings sensitive to s (e.g. λ)

- Background to New Physics, e.g. Higgs
  requires good understanding