WW scattering studies at a Future Linear Collider

A presentation given at the University of Edinburgh - High Energy Physics Group.

Andres F. Osorio-Oliveros

andres@hep.man.ac.uk

High Energy Physics Group

The University of Manchester

< ↑ ↓ >

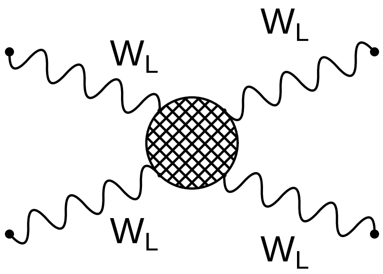
Outline

- Motivations
  - Physics (why WW scattering?)
  - Why a FLC?
- Plans for a Future Linear Collider
- WW Scattering Analysis
- Z and W reconstruction
- Results
- Sensitivities
- Conclusions

< ↑ ↓ >

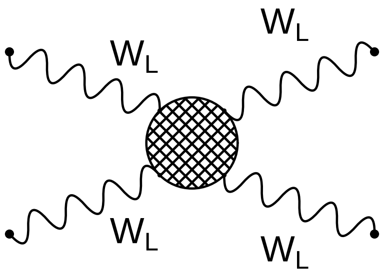
Motivations

- The mechanism describing how Nature gives mass to particles remains one of the open questions in particle physics today.
- The Higgs Mechanism is the answer in the Standard Model
- If there is no a Higgs, new physics is needed at the TeV scale to restore unitarity
- It is in this context, that the strong scattering of $W_L W_L$ bosons provides a window to look for information about the underlying symmetry.



Motivations

- The mechanism describing how Nature gives mass to particles remains one of the open questions in particle physics today.
- The Higgs Mechanism is the answer in the Standard Model
- If there is no a Higgs, new physics is needed at the TeV scale to restore unitarity
- It is in this context, that the strong scattering of $W_L W_L$ bosons provides a window to look for information about the underlying symmetry.



- The EW can be described by the EW Chiral Lagrangian.
- This is an effective theory which:
  - has operators of higher dimensions
  - introduces anomalous couplings
- In particular there are two 4D operators:

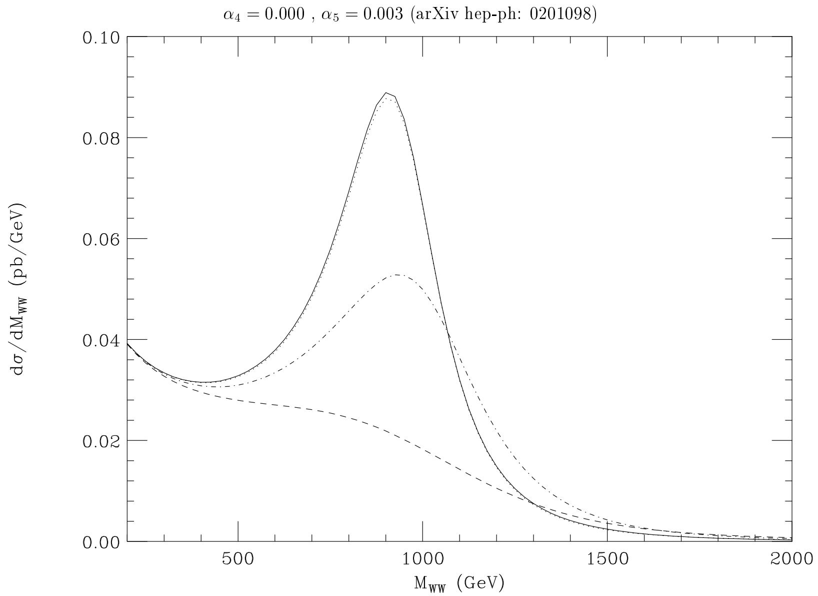
$$L_4 = \frac{\alpha_4}{16\pi^2} tr(V_\mu V_\nu) tr(V^\mu V^\nu)$$
$$L_5 = \frac{\alpha_5}{16\pi^2} tr(V_\mu V^\mu) tr(V_\nu V^\nu)$$

- The coefficients α_4 and α_5 are related to the scale of the new physics (in the SM these parameters are 0)

Motivations

- From WW scattering studies at LHC (Butterworth,et.al-Phys.Rev.D65:096014):
  - EW Chiral Lagrangian
  - Unitarisation protocols

  ▷ Prediction of resonances depending on the values of the α_4 and α_5 parameters
- As an example:



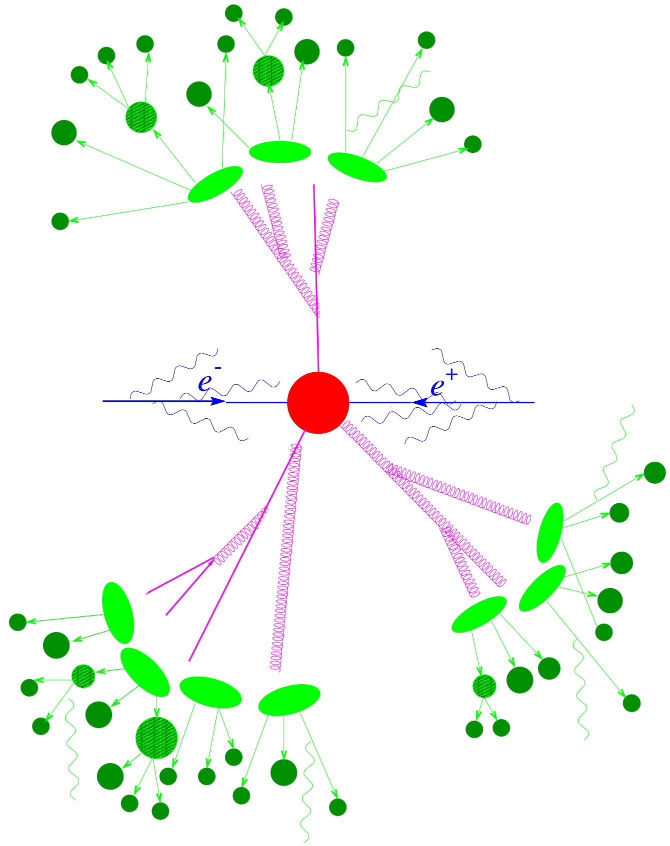
To sum up:

- What's the sensitivity to the α_4 and α_5 that can be reached at a Future Linear Collider? Can I improve previous analysis on the subject?
  (Ref: Chierici, et al - LC-PHSM-2001-038)
- Given that these parameters can be measured, what can we learn about new physics at higher energies?
  (LHC - LC complementarity)

< ↑ ↓ >

Motivations

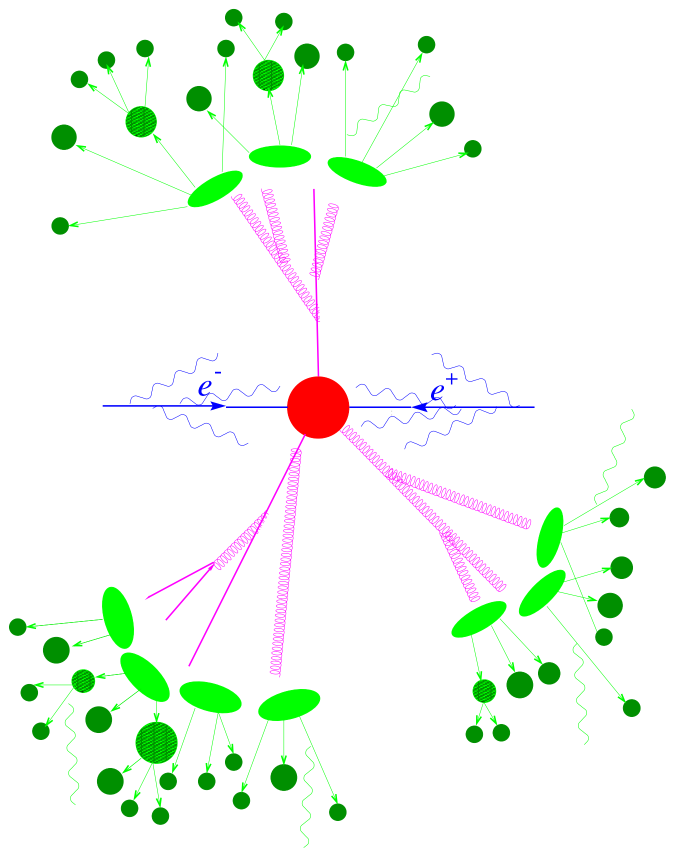
The LC scenario



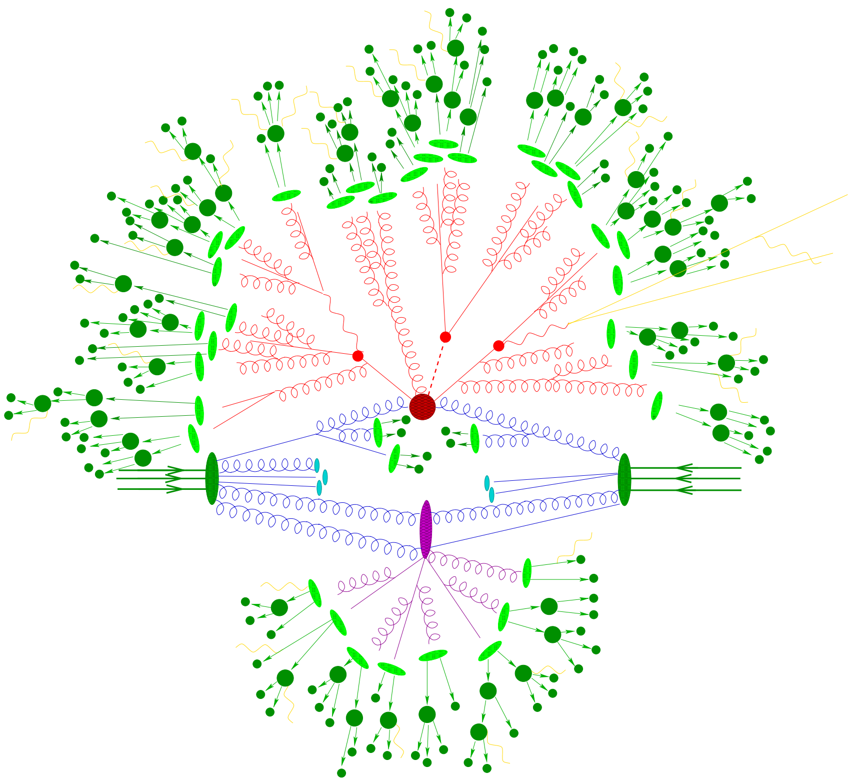
< ↑ ↓ >

Motivations

The LC scenario

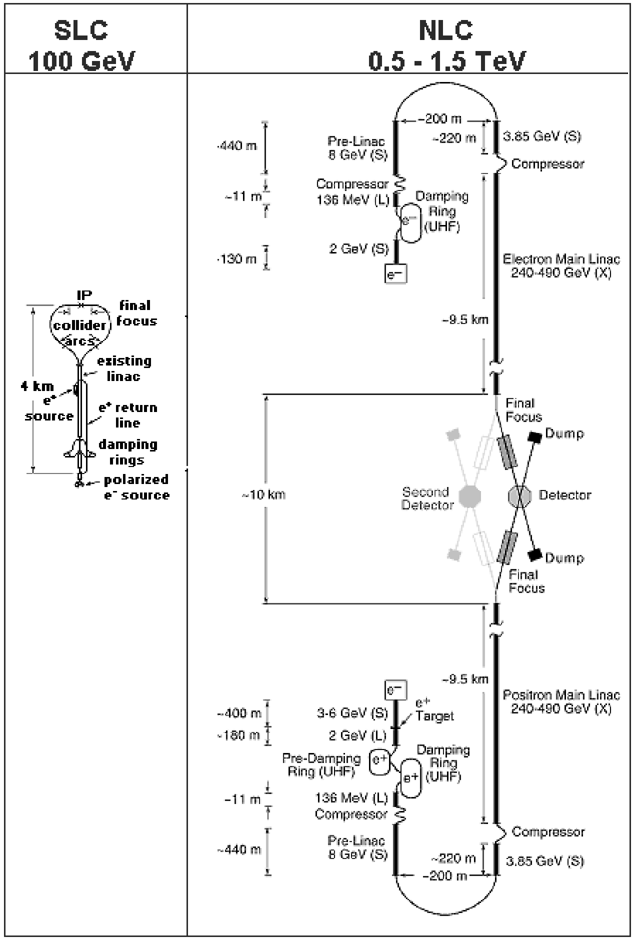


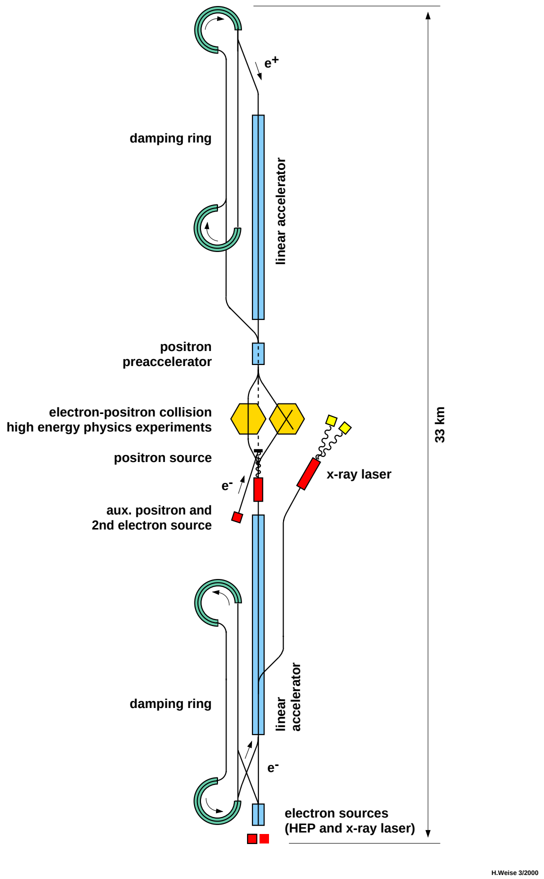
The LHC scenario



A Future Linear Collider

A global collaboration and project (ILC home page http://www.linearcollider.org)

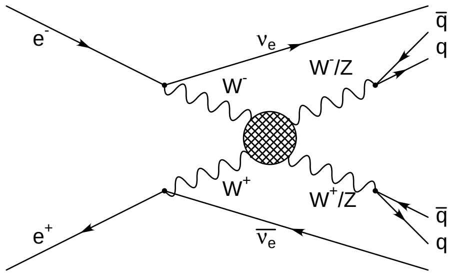




WW Scattering Analysis

Signal consists of the following processes:

$$e^+e^- \to \nu\bar{\nu}W^+W^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$$
$$e^+e^- \to \nu\bar{\nu}ZZ \to \nu\bar{\nu}q\bar{q}q\bar{q}$$



- Scenario: $\alpha_4 = \alpha_5 = 0.0$ (SM) Higgs $\to \infty$
- Backgrounds:

  $e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$ (non-res.)

  $e^+e^- \to e^+e^-W^+W^-$

  $e^+e^- \to e^+\nu W^-Z$

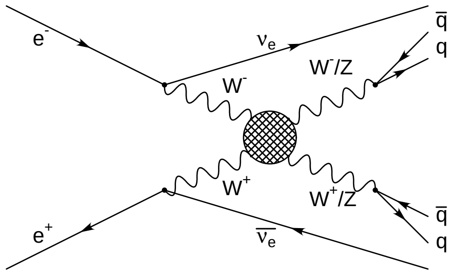
  $e^+e^- \to W^+W^-(ZZ)$

  $e^+e^- \to q\bar{q}$

WW Scattering Analysis

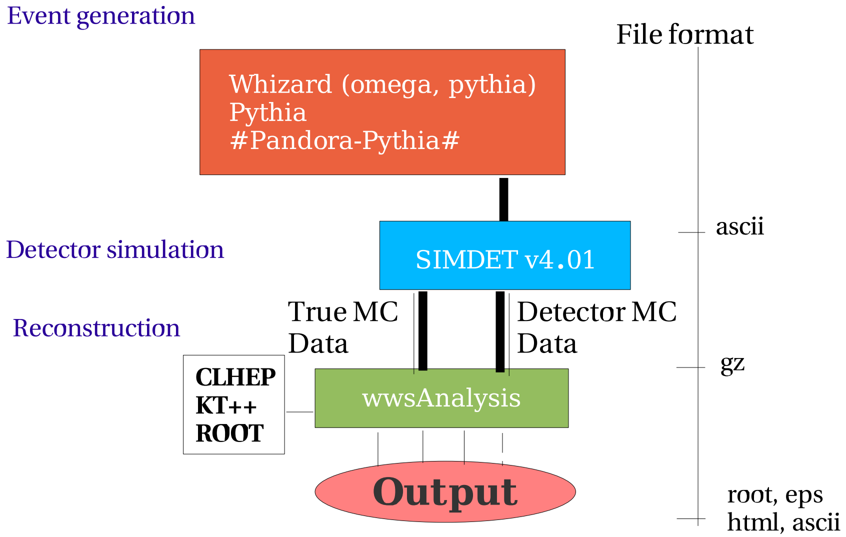
Signal consists of the following processes:

$$e^+e^- \to \nu\bar{\nu}W^+W^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$$
$$e^+e^- \to \nu\bar{\nu}ZZ \to \nu\bar{\nu}q\bar{q}q\bar{q}$$



- Scenario: $\alpha_4 = \alpha_5 = 0.0$ (SM) Higgs $\to \infty$
- Backgrounds:
  $e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$ (non-res.)
  $e^+e^- \to e^+e^-W^+W^-$
  $e^+e^- \to e^+\nu W^-Z$
  $e^+e^- \to W^+W^-(ZZ)$
  $e^+e^- \to q\bar{q}$

- Framework:



- WHiZard 1.29 is the main event generator:
  - 6 fermions final states
  - all possible quark final states were generated
  - need to apply cuts to separate signals from other processes
  - the anomalous α_4 and α_5 quartic couplings are included
  - beam polarisation

WW Scattering Analysis

- We followed TESLA project specifications:
  (TeV Energy Super-conducting
  Linear Collider Accelerator)
  - C.M.E.: $\sqrt{s} = 800$ GeV
  - Polarised beams:
  0.80 e^-, 0.40 e^+ (PoWER Group)
  - Luminosity: $\mathcal{L} = 1000\ fb^{-1}$
  > L(10^{34} cm^{-2}s^{-1})=5.8
- Both ISR and FSR are turned On
- Summary of the cross sections obtained from our study:

Type	Generated process: $e^+e^- \rightarrow$	Cross Sect. [fb]	Generator
6 fermions	$W^+W^-\nu\bar{\nu} \rightarrow q\bar{q}q\bar{q}\nu\bar{\nu}$	9.21	Whizard
	$ZZ\nu\bar{\nu} \rightarrow q\bar{q}q\bar{q}\nu\bar{\nu}$	4.05	Whizard
	$q\bar{q}q\bar{q}\nu\bar{\nu}$ (backgrounds)	6.55	Whizard
	$WZe\nu \rightarrow q\bar{q}q\bar{q}e\nu$	38.50	Whizard
	$e^+e^-W^+W^- \rightarrow e^+e^-q\bar{q}q\bar{q}$	234.80	Pythia*
4 fermions	$W^+W^- \rightarrow q\bar{q}q\bar{q}$	1948.10	Pythia*
	$ZZ \rightarrow q\bar{q}q\bar{q}$	142.90	Pythia*
	$e^+e^-t\bar{t}$	1.30	Pythia*
2 fermions	$t\bar{t} \rightarrow X$	136.90	Pythia *
	$q\bar{q}$	4464.60	Pythia*

* Pythia does not include a e^+e^- polarised beams option during integration

WW Scattering Analysis

- We followed TESLA project specifications: (TeV Energy Super-conducting Linear Collider Accelerator)
  - C.M.E.: $\sqrt{s} = 800$ GeV
  - Polarised beams: 0.80 e^-, 0.40 e^+ (PoWER Group)
  - Luminosity: $\mathcal{L} = 1000\ fb^{-1}$
  > L(10^{34} cm^{-2}s^{-1})=5.8
- Both ISR and FSR are turned On
- Summary of the cross sections obtained from our study:

Type	Generated process: $e^+e^- \rightarrow$	Cross Sect. [fb]	Generator
6 fermions	$W^+W^-\nu\bar{\nu} \rightarrow q\bar{q}q\bar{q}\nu\bar{\nu}$	9.21	Whizard
	$ZZ\nu\bar{\nu} \rightarrow q\bar{q}q\bar{q}\nu\bar{\nu}$	4.05	Whizard
	$q\bar{q}q\bar{q}\nu\bar{\nu}$ (backgrounds)	6.55	Whizard
	$WZe\nu \rightarrow q\bar{q}q\bar{q}e\nu$	38.50	Whizard
	$e^+e^-W^+W^- \rightarrow e^+e^-q\bar{q}q\bar{q}$	234.80	Pythia*
4 fermions	$W^+W^- \rightarrow q\bar{q}q\bar{q}$	1948.10	Pythia*
	$ZZ \rightarrow q\bar{q}q\bar{q}$	142.90	Pythia*
	$e^+e^-t\bar{t}$	1.30	Pythia*
2 fermions	$t\bar{t} \rightarrow X$	136.90	Pythia *
	$q\bar{q}$	4464.60	Pythia*

* Pythia does not include a e^+e^- polarised beams option during integration

- We used the fast Detector Simulation SIMDET (v.4.01):
  - Tracking system: CCD vertex detector (1.5cm) + Forward Tracker
  - Magnetic field: 4 T
- Calorimetry:
  - ECal resolution: $\Delta E/E = 0.2/\sqrt{E}$
  - HCal resolution: $\Delta E/E = 0.5/\sqrt{E}$
- 3D cells - good granularity -> Energy Flow concept.

Z and W reconstruction

Main problem is to reconstruct Z and W pairs

- Objects from the detector simulation are forced into 4 jets using the K_T jet algorithm - exclusive mode, E recomb. scheme
- If succeed, we then have 3 possible combinations
- Use a 1C Kinematic Fit to find the best pair option
  $Q(\vec{x},\vec{\lambda}) = (\vec{x}-\vec{x}_0)V^{-1}(\vec{x}-\vec{x}_0) + 2\vec{\lambda}\vec{f}(\vec{x})$
- Where: $\vec{f}(\vec{x})$: constraints
  $\vec{x}$: jet parameters (P_{tot},θ,ϕ)
  $\vec{\lambda}$: Lagrange multipliers
  $\vec{V}$: error matrix
  Error matrix: resolution functions
  $\sigma_{Ptot}(p_q)$, $\sigma_\theta(p_q)$, $\sigma_\phi(p_q,\theta_q)$
- 1c : $M_{jet_1 jet_2} = M_{jet_3 jet4}$

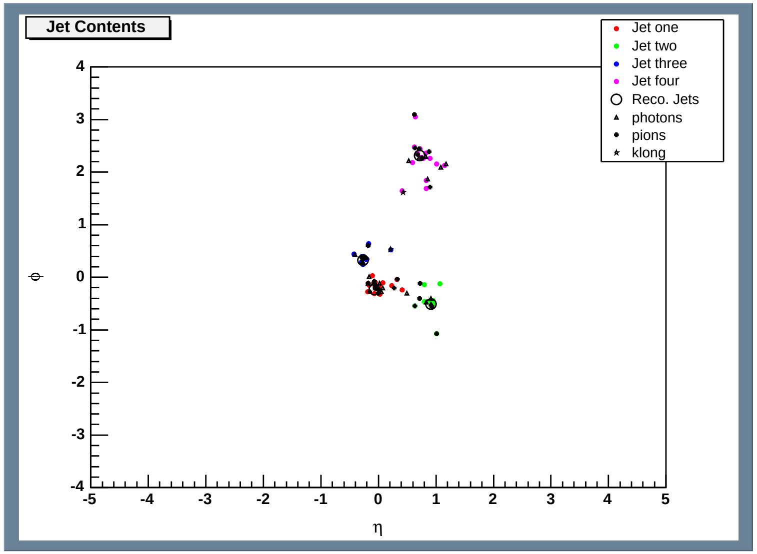
< ↑ ↓ >

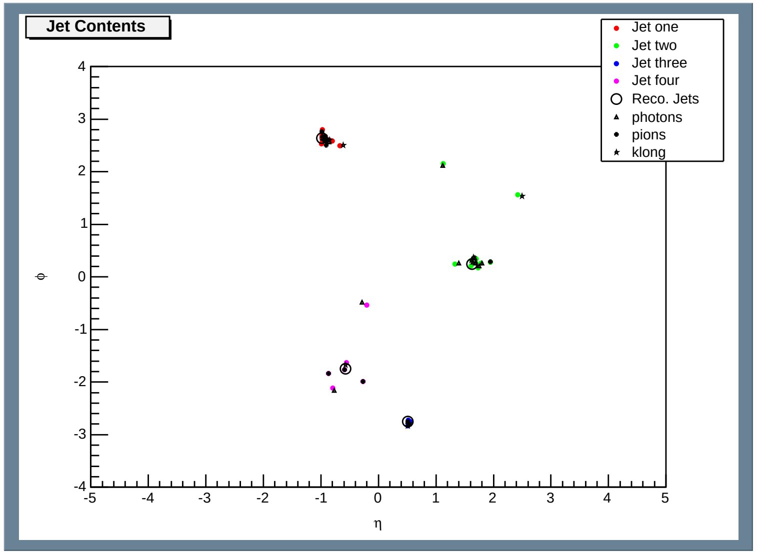
Z and W reconstruction

Main problem is to reconstruct Z and W pairs

- Objects from the detector simulation are forced into 4 jets using the K_T jet algorithm - exclusive mode, E recomb. scheme
- If succeed, we then have 3 possible combinations
- Use a 1C Kinematic Fit to find the best pair option
  $Q(\vec{x},\vec{\lambda}) = (\vec{x}-\vec{x}_0)V^{-1}(\vec{x}-\vec{x}_0) + 2\vec{\lambda}\vec{f}(\vec{x})$
- Where: $\vec{f}(\vec{x})$: constraints
  $\vec{x}$: jet parameters (P_{tot},θ,ϕ)
  $\vec{\lambda}$: Lagrange multipliers
  $\vec{V}$: error matrix
  Error matrix: resolution functions
  $\sigma_{Ptot}(p_q)$, $\sigma_\theta(p_q)$, $\sigma_\phi(p_q,\theta_q)$
- 1c : $M_{jet_1 jet_2} = M_{jet_3 jet4}$

- Jet configurations



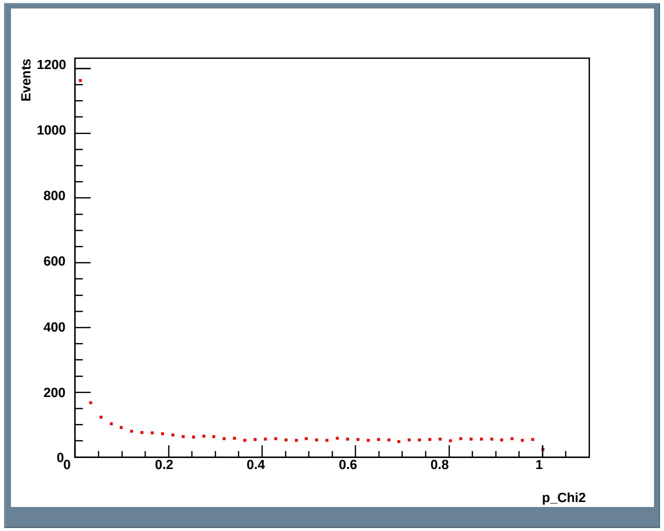


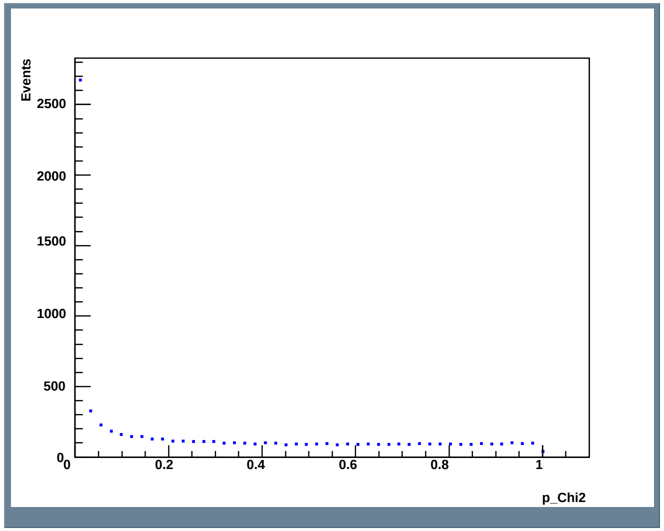
Z and W reconstruction

Main problem is to reconstruct Z and W pairs

- Objects from the detector simulation are forced into 4 jets using the K_T jet algorithm - exclusive mode, E recomb. scheme
- If succeed, we then have 3 possible combinations
- Use a 1C Kinematic Fit to find the best pair option
  $Q(\vec{x},\vec{\lambda}) = (\vec{x}-\vec{x}_0)V^{-1}(\vec{x}-\vec{x}_0) + 2\vec{\lambda}\vec{f}(\vec{x})$
- Where: $\vec{f}(\vec{x})$: constraints
  $\vec{x}$: jet parameters (P_{tot},θ,ϕ)
  $\vec{\lambda}$: Lagrange multipliers
  $\vec{V}$: error matrix
  Error matrix: resolution functions
  $\sigma_{Ptot}(p_q)$, $\sigma_\theta(p_q)$, $\sigma_\phi(p_q,\theta_q)$
- 1c : $M_{jet_1 jet_2} = M_{jet_3 jet4}$

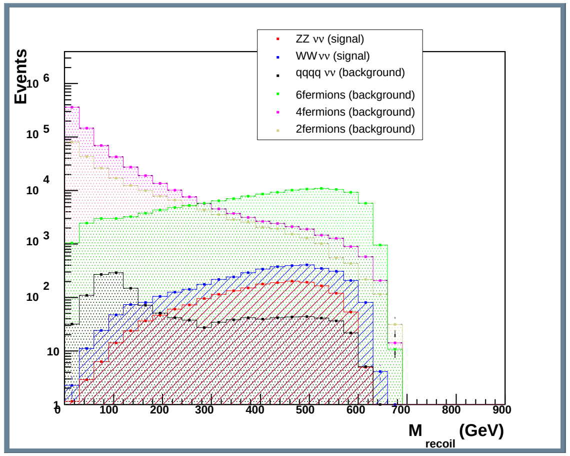
- Kinematic Fit results



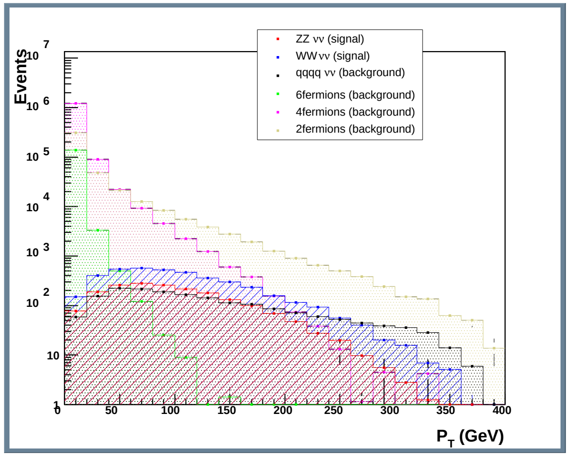


Z and W reconstruction

- Recoil Mass distribution



- Transverse momentum distribution



more...

- General selection cuts
  - Recoil mass: $M_{recoil} \geq 200$ GeV
  - $P_T \geq 20$ GeV
  - $E_{trans} \geq 150$ GeV
  - Scaled ycut parameter $4.0 \leq ln\sqrt{ycut_{1,2} * s} \leq 7.2$
  - Total missing momentum$|\cos\theta_{P_{miss}}| < 0.99$
  - Most energetic track $|\cos\theta_{P_{Emax}}| < 0.99$
  - Charged tracks in each jet $nTracks \geq 2$
  - Probability (χ^2) > 0.005
  - Ask for energy around highest track ≥ 2 GeV $5\,\deg$ cone

- ZZ selection

  $85 < M_{1C} < 100$ GeV

- WW selection

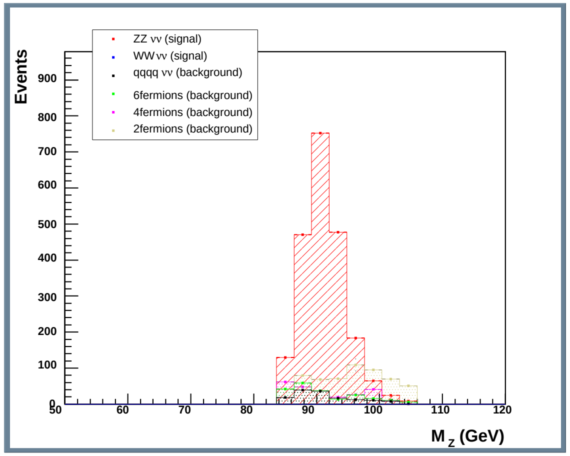
  $75 < M_{1C} < 85$ GeV

Results

- Cut flow summary

Cut flow	Signals		Backgrounds		
	$\nu\bar{\nu}WW$	$\nu\bar{\nu}ZZ$	$q\bar{q}q\bar{q}$	$WZ\nu e$	Other
none	9210	4050	6550	38500	6928600
M_{recoil}	7128	3825	1935	49	32815
P_T	6863	3664	1860	49	3450
E_T	6347	3562	1688	42	2439
y_{cut}	6141	3497	1601	42	1890
$\cos\theta_{P_{emax}}$	6133	3493	1595	42	1886
$\cos\theta_{P_{miss}}$	6086	3470	1580	42	1778
Charged tracks	6086	3028	1490	21	1505
E_{cone}	5971	2981	1468	9	1244
$P(\chi^2)$	**5971**	**2295**	**1139**	**negl.**	**1047**

- $\nu\bar{\nu}ZZ$ selection

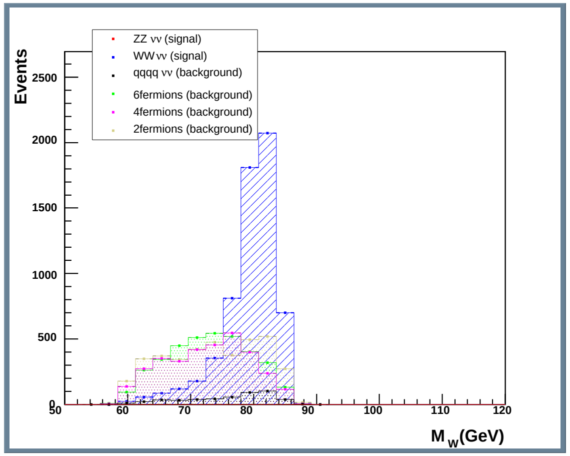


Results

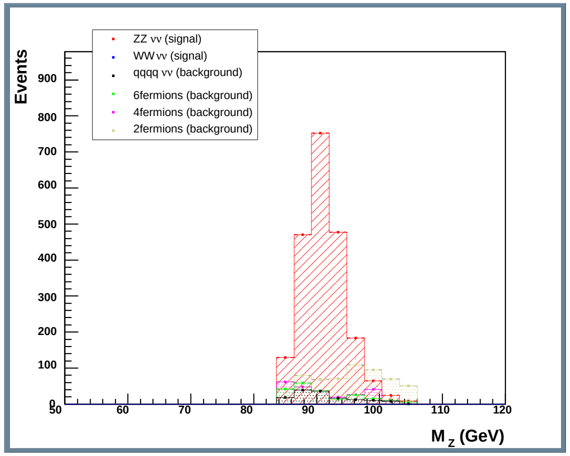
- Cut flow summary

Cut flow	Signals		Backgrounds		
	$\nu\bar{\nu}WW$	$\nu\bar{\nu}ZZ$	$q\bar{q}q\bar{q}$	$WZ\nu e$	Other
none	9210	4050	6550	38500	6928600
M_{recoil}	7128	3825	1935	49	32815
P_T	6863	3664	1860	49	3450
E_T	6347	3562	1688	42	2439
y_{cut}	6141	3497	1601	42	1890
$\cos\theta_{P_{emax}}$	6133	3493	1595	42	1886
$\cos\theta_{P_{miss}}$	6086	3470	1580	42	1778
Charged tracks	6086	3028	1490	21	1505
E_{cone}	5971	2981	1468	9	1244
$P(\chi^2)$	**5971**	**2295**	**1139**	**negl.**	**1047**

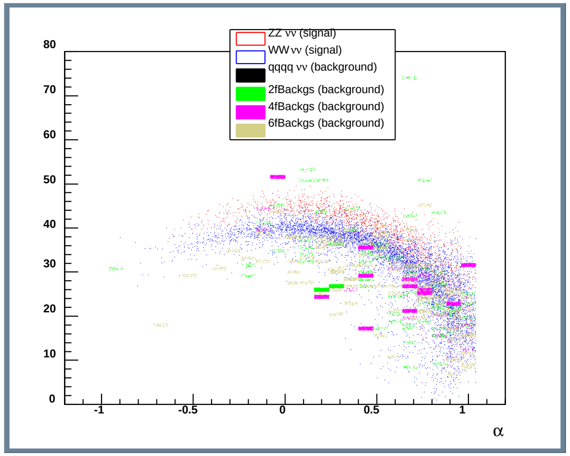
- $\nu\bar{\nu}WW$ selection



- $\nu\bar{\nu}ZZ$ selection



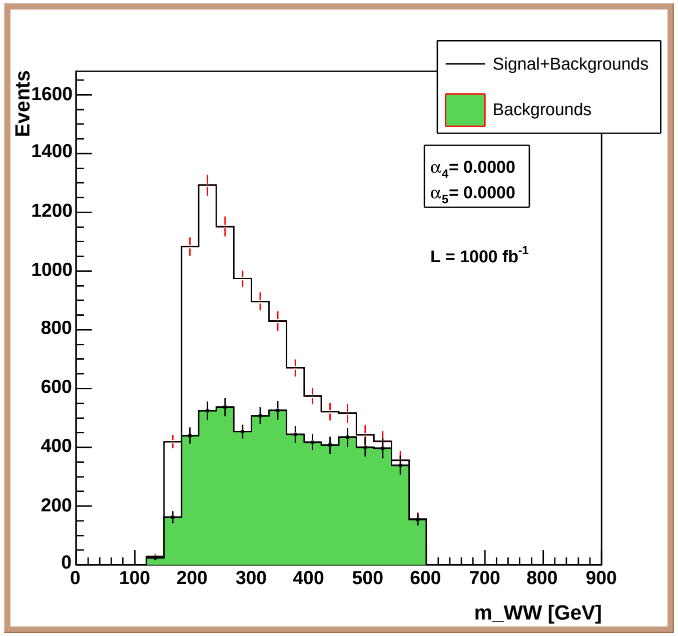
- Armentero-Podolanski plot

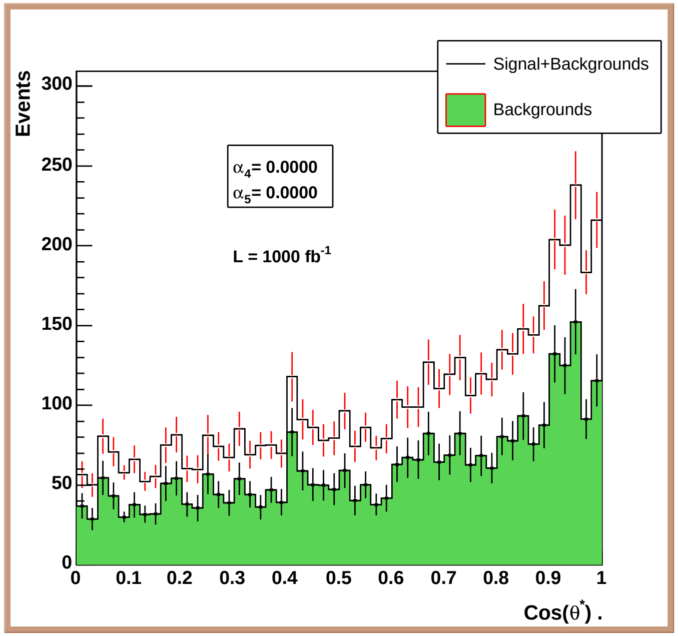


Sensitivity study

Now I have Z and W candidates and a working analysis system.
I combined the pairs of Z and W and make some distributions:

- M_{WW} and $|\cos\theta^*|$ distribution for $\alpha_4 = \alpha_5 = 0.0$





What happens when α_4 and α_5 are different from zero?

Expected rate change in the end results and therefore deviations from SM predictions

Sensitivity study

- I generated 20 scenarios, varying one of the a.c. at a time (10 for $\alpha_5 = 0.0$ and 10 for $\alpha_4 = 0.0$)

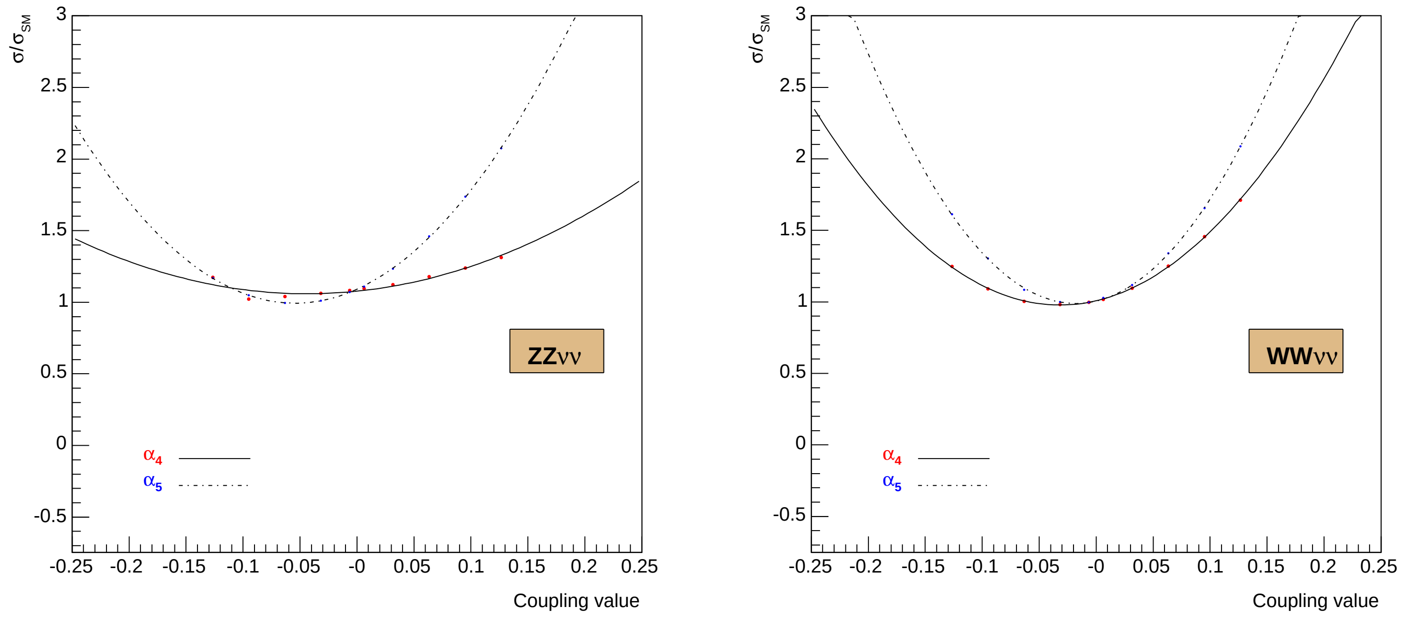
< ↑ ↓ >

Sensitivity study

- I generated 20 scenarios, varying one of the a.c. at a time (10 for $\alpha_5 = 0.0$ and 10 for $\alpha_4 = 0.0$)
- Looked at the cross section for each and compare it to SM

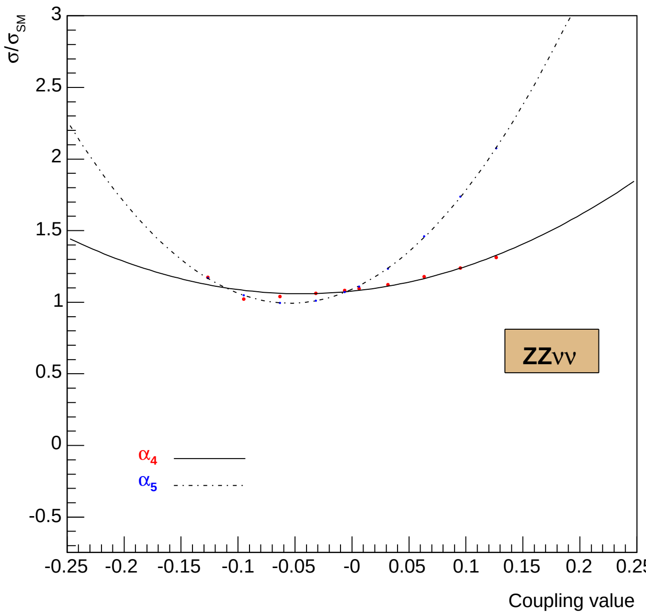
Sensitivity study

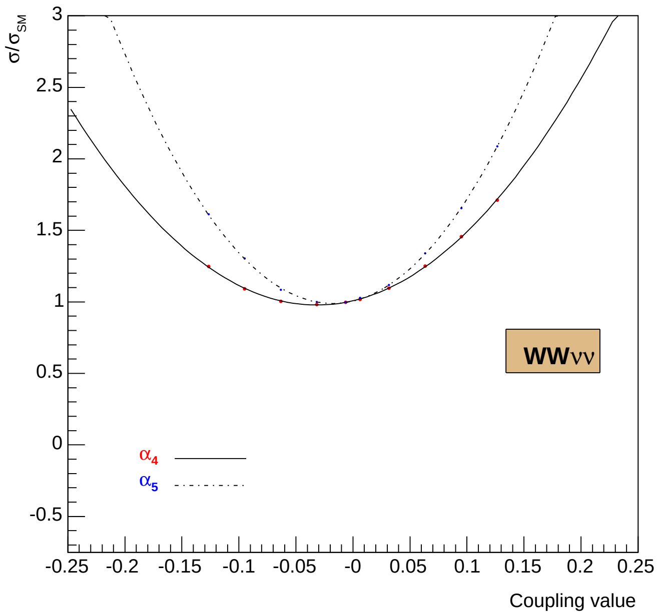
- I generated 20 scenarios, varying one of the a.c. at a time (10 for $\alpha_5 = 0.0$ and 10 for $\alpha_4 = 0.0$)
- Looked at the cross section for each and compare it to SM



Sensitivity study

- I generated 20 scenarios, varying one of the a.c. at a time (10 for $\alpha_5 = 0.0$ and 10 for $\alpha_4 = 0.0$)
- Looked at the cross section for each and compare it to SM





- We expect better sensitivity to α_5 than α_4 in particular when looking at the $\nu\bar{\nu}WW$ channel

Sensitivity study

- Generated 12 extra scenarios with both α_5 and α_4 diff. from zero (each scenario had 400,000 events, enough statistics)

Sensitivity study

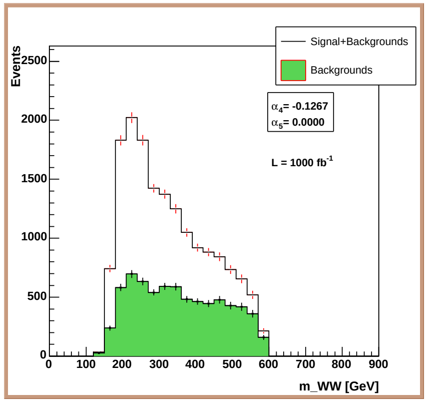
- Generated 12 extra scenarios with both α_5 and α_4 diff. from zero (each scenario had 400,000 events, enough statistics)
- Rerun the whole analysis

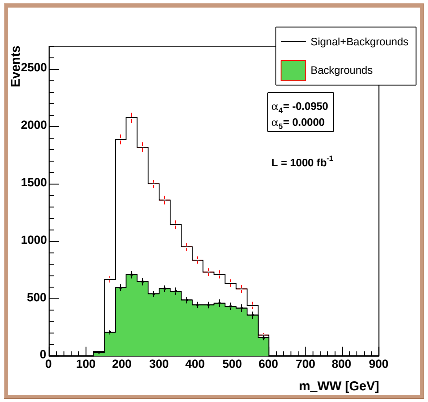
Sensitivity study

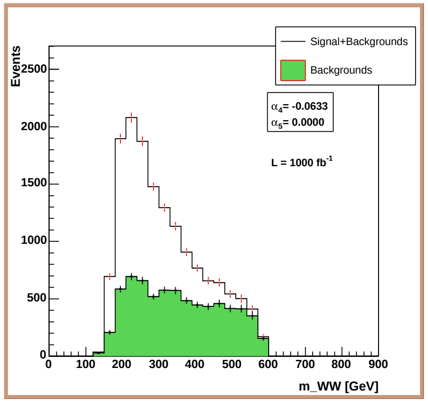
- Generated 12 extra scenarios with both α_5 and α_4 diff. from zero (each scenario had 400,000 events, enough statistics)
- Rerun the whole analysis
- Examples of the new M_{WW} distributions:

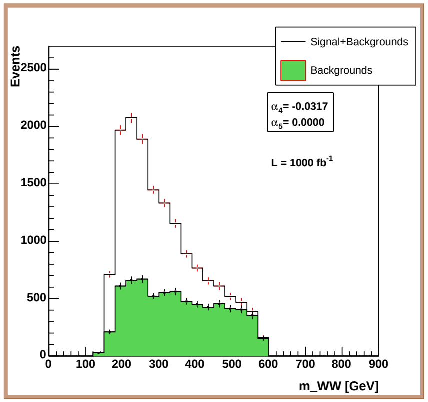
Sensitivity study

- Generated 12 extra scenarios with both α_5 and α_4 diff. from zero (each scenario had 400,000 events, enough statistics)
- Rerun the whole analysis
- Examples of the new M_{WW} distributions:



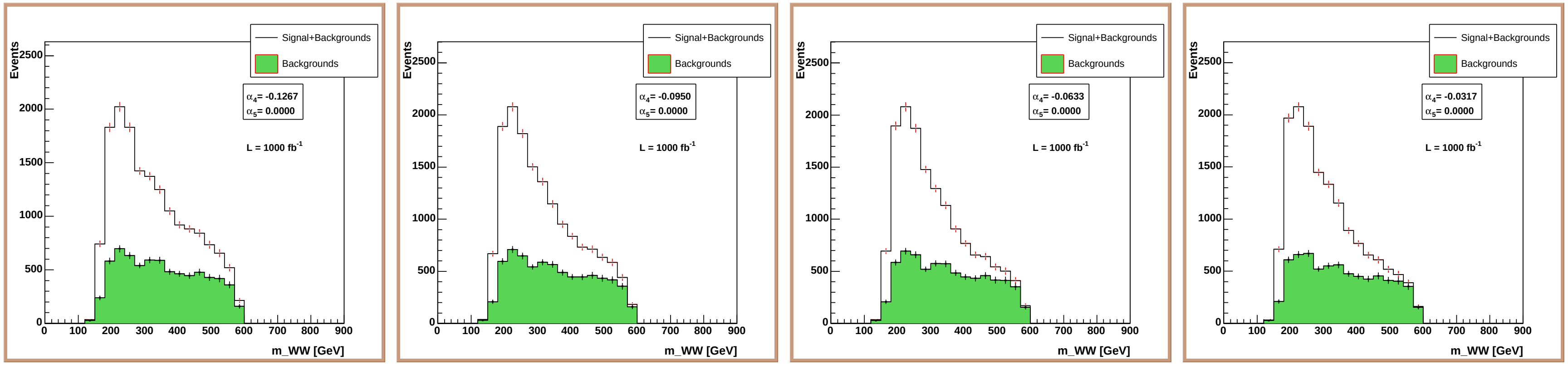






Sensitivity study

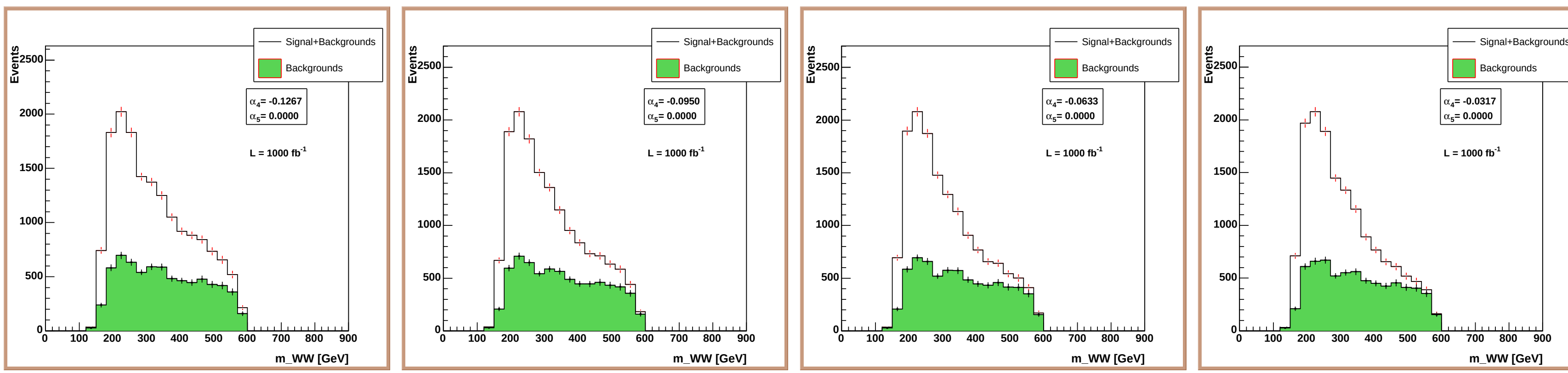
- Generated 12 extra scenarios with both α_5 and α_4 diff. from zero (each scenario had 400,000 events, enough statistics)
- Rerun the whole analysis
- Examples of the new M_{WW} distributions:



- In order to study the sensitivity I used a Binned Maximum Log Likelihood applied to both M_{WW} and $|\cos\theta^*|$ distributions for each scenario

Sensitivity study

- Generated 12 extra scenarios with both α_5 and α_4 diff. from zero (each scenario had 400,000 events, enough statistics)
- Rerun the whole analysis
- Examples of the new M_{WW} distributions:



- In order to study the sensitivity I used a Binned Maximum Log Likelihood applied to both M_{WW} and $|\cos\theta^*|$ distributions for each scenario
- BLLH takes as input: SM predicted signal, "observed" events, expected BKG and uncertainties in selection efficiencies, backgrounds and luminosity (not really needed ; = 0.001)

Sensitivity study

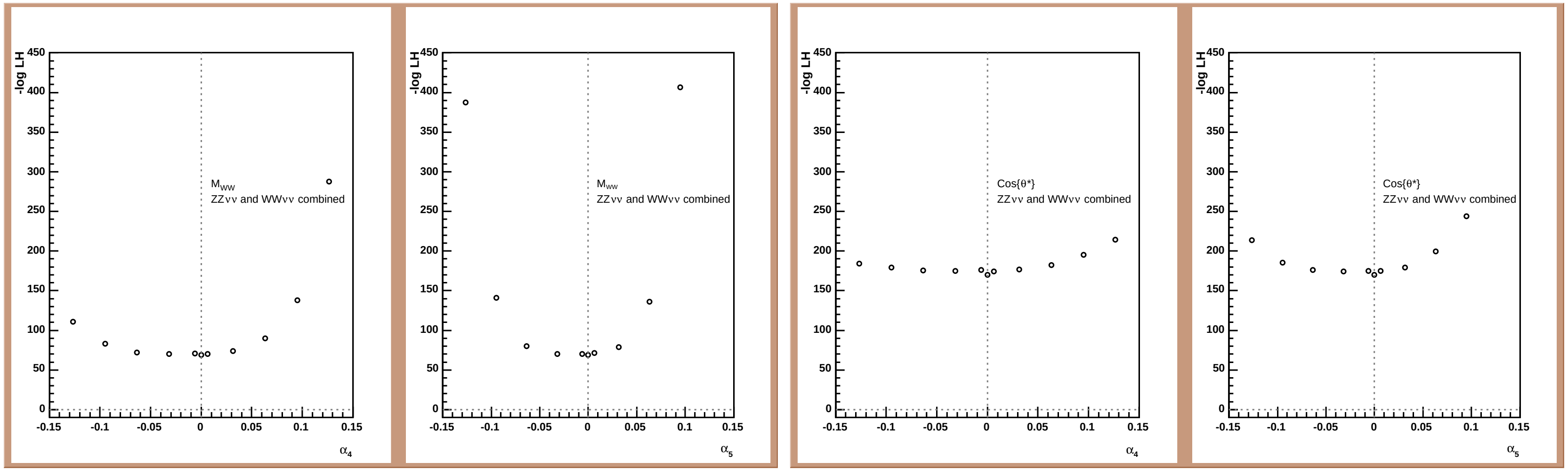
- I end up with 32 LLH values for every scenario and each distribution

Sensitivity study

- I end up with 32 LLH values for every scenario and each distribution
- These are the results for those 20 scenarios mentioned before:

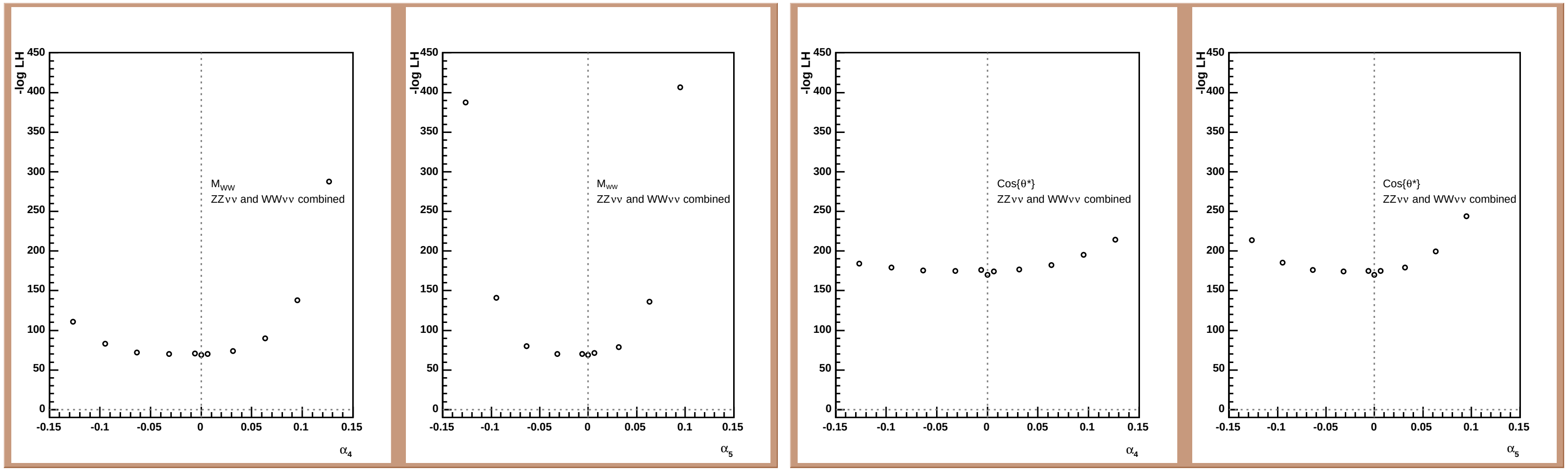
Sensitivity study

- I end up with 32 LLH values for every scenario and each distribution
- These are the results for those 20 scenarios mentioned before:



Sensitivity study

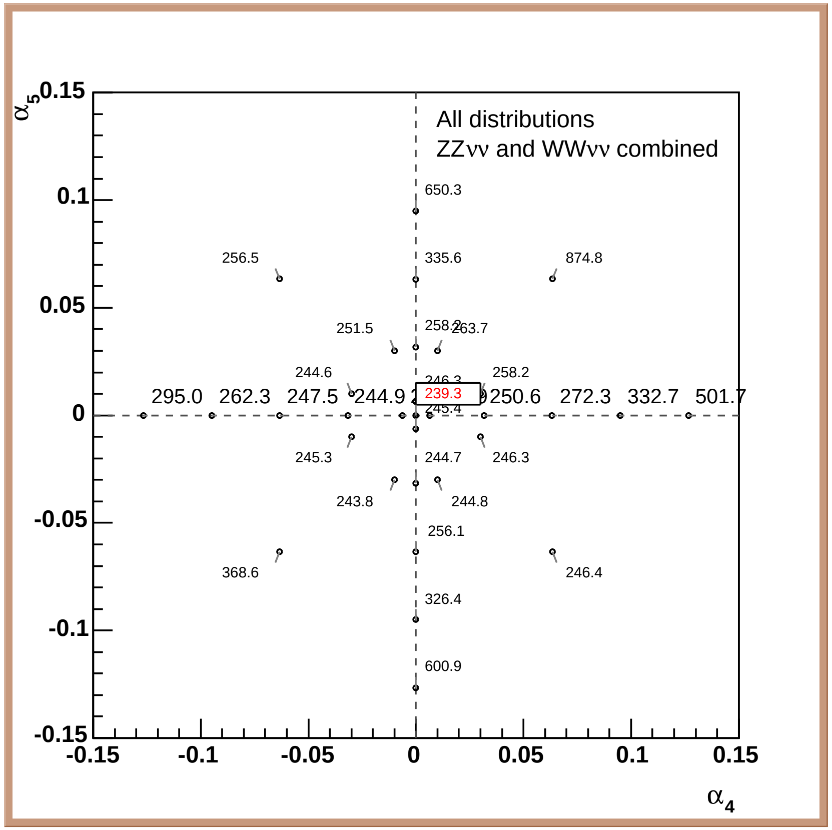
- I end up with 32 LLH values for every scenario and each distribution
- These are the results for those 20 scenarios mentioned before:



- Observation: no symmetric behaviour of those LLH points with respect to the minimum (SM scenario)

Sensitivity study

- The combined results for those two distributions are



Sensitivity study

- Under construction!
- The fit of those LLH values has been more complicated than expected
- At the moment, I'm using S-plines to get a nice fit to those points and extract the limits that I want (and desperately need :))
- What are the estimated values?

Conclusions

- The hadronic decays of processes

$$e^+e^- \rightarrow \nu\bar{\nu}W^+W^-$$
$$e^+e^- \rightarrow \nu\bar{\nu}ZZ$$

can be exploited to find new physics provided LHC does not find a Higgs boson

- If our ignorance about new physics is parametrised in term of the α_4 and α_5 anomalous couplings, they could be measure at the ILC
- I achieved to write an analysis framework to study hadronic and leptonic decays
  ▷ It is OO and it would be interesting to see what can do with semi-leptonic decays
- I applied very useful analysis techniques (jet reconstruction, kinematic fit, binned log likelihoods)
- There is progress done on extracting the sensitivity to those anomalous couplings and therefore provide 68/90 percent Confidence Levels

Conclusions

If you can look into the seeds of time,
And say which grain will grow and which will not
Speak to me.

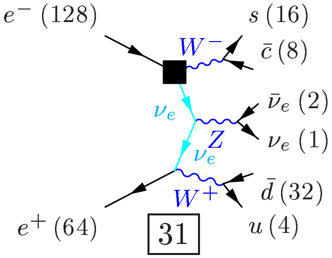
Macbeth, William Shakespeare

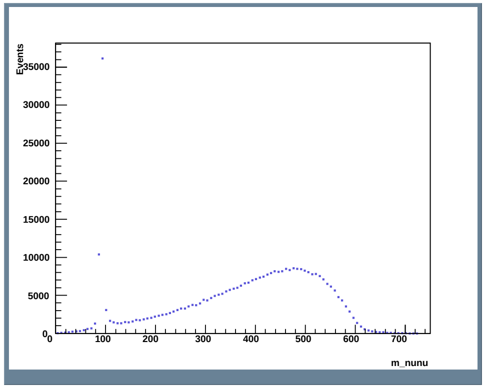
Extra slide 1

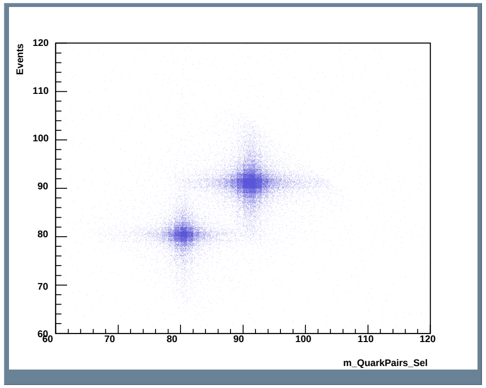
Signal preparation using the following cuts in phase space:

$$147.0\,\text{GeV} \leq m^1_{q\bar{q}} + m^2_{q\bar{q}} \leq 171.0\,\text{GeV} \;: W$$
$$171.0\,\text{GeV} \leq m^1_{q\bar{q}} + m^2_{q\bar{q}} \leq 195.0\,\text{GeV} \;: Z$$
$$|m^1_{q\bar{q}} + m^2_{q\bar{q}}| \leq 20.0\,\text{GeV}$$
$$m_{\nu\bar{\nu}} \geq 100.0\,\text{GeV}$$

Multiplicity: 3
Resonances: 3
Log-enhanced: 2
t-channel: 2

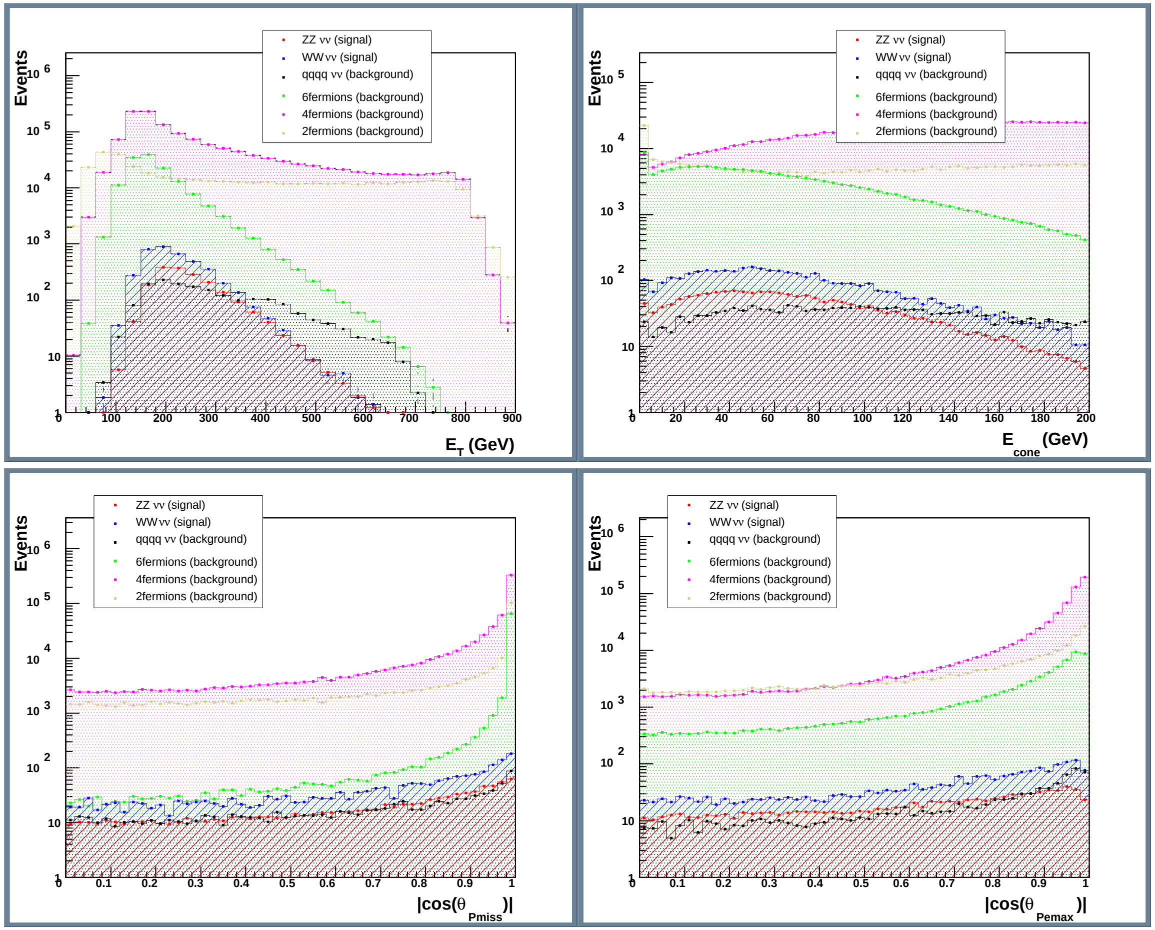






Extra slide 2

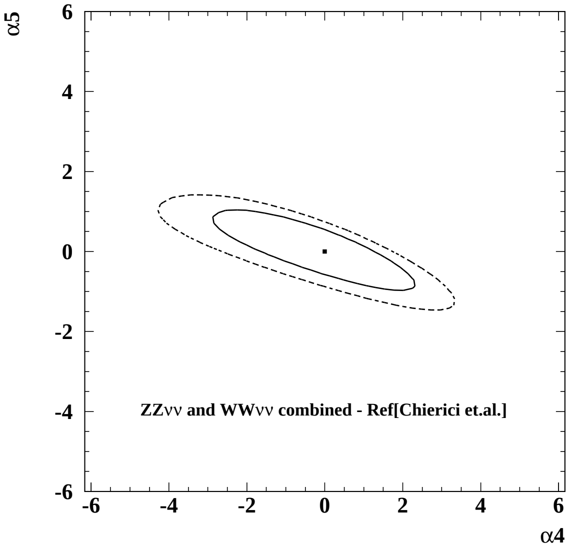
More distributions:



Chierici et al results

Previous results:

- Confidence Levels contours



- Sensitivities (1 dimensional limits)

1 DIM analysis	68% C.L. (TESLA 1000 fb^{-1} 800 GeV and polarisation)	
α_4	$\sigma_- = -1.1$	$\sigma_+ = 0.8$
α_5	$\sigma_- = -0.4$	$\sigma_+ = 0.3$

- My preliminary results
  ▷ using a polynomial fit
- Sensitivities (2 dimensional limits)

2 DIM analysis	68% C.L. (TESLA 1000 fb^{-1} 800 GeV and polarisation)	
α_4	$\sigma_- = -1.18$	$\sigma_+ = 1.24$
α_5	$\sigma_- = -0.95$	$\sigma_+ = 0.96$