WW scattering at the LHC
Part 2 – simulations

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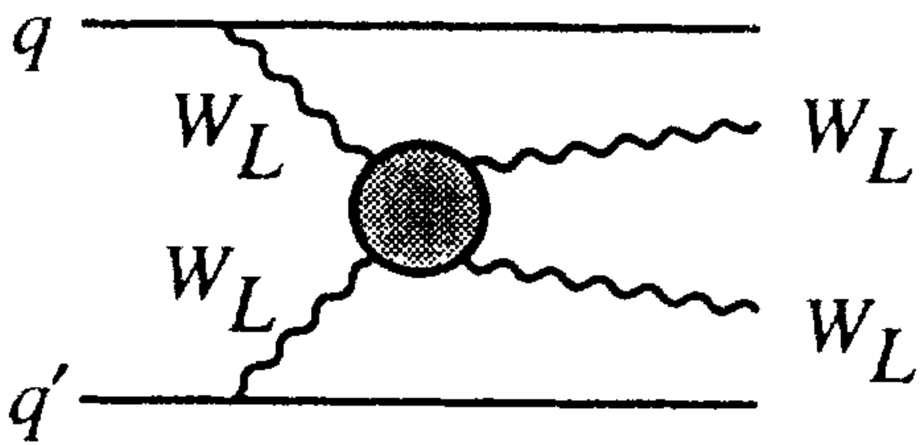
Cracow – Warsaw LHC Workshop
Warsaw, March 26, 2010

"*W stands for Wrong*"
John Kerry
(and he had to lose)

Signal definition

The key process:

p p → V V j j,
with V = W, Z



Experimental point of view:

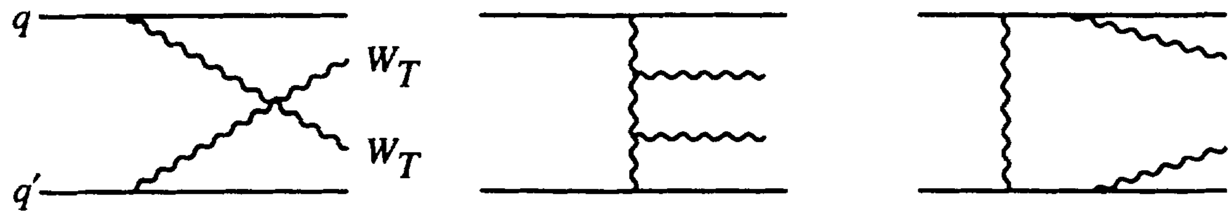
Strong VV scattering = excess of V_L V_L production wrt. the SM with a light higgs

4 scattering processes: **W+W-** **W+W+** **W Z** **Z Z**	**X**	**3 decay modes:** **purely leptonic** **semi-leptonic** **purely hadronic**	**=**	**Potentially at least 12 analyses to do!**

Physics backgrounds

*** Irreducible (SM contributions):**

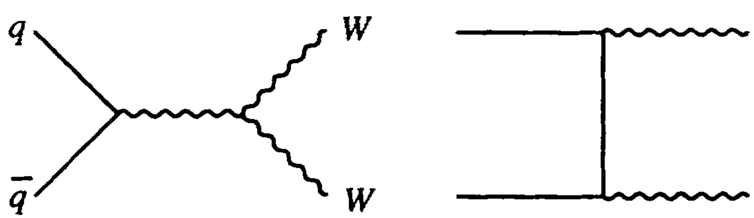
A)



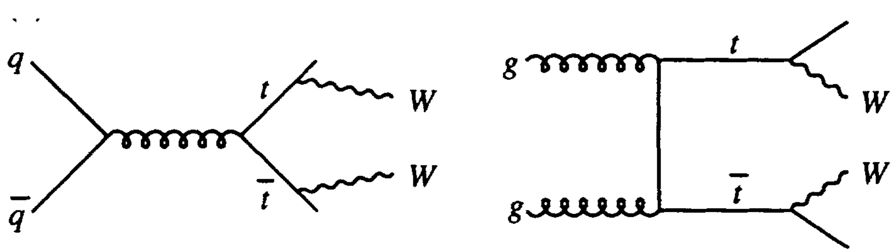
includes scattering diagrams and non-scattering diagrams (EW and QCD)

*** Reducible, depends on process and selected decay mode**

B) qq annihilation



C) top production



D) gluon-gluon fusion

E) additional background from multi-jet processes for semi-leptonic decay modes (Wj, Wjjj)

F) additional background from multi-jet processes for purely hadronic decay modes (jj, jjjj)

The choice of the most promising channel to look at...

l=e,mu

Process	Decay mode	BR	Types of physics backgrounds
W+ W-	$l\nu l\nu$	0.046	A B* C D* WZ, ZZ
	$l\nu qq$	0.292	A B* C D* E WZ
	qqqq	0.457	A B C D E F W+W+, WZ, ZZ
W+ W+	$l\nu l\nu$	0.046	A WZ
	$l\nu qq$	0.292	A E WZ, ZZ
	qqqq	0.457	A B E F W+W-,WZ, ZZ
W Z	$l\nu ll$	0.015	A B* ZZ
	$l\nu qq$	0.151	A B* E WW,ZZ
	llqq	0.045	A B* E ZZ
	qqqq	0.473	A B E F WW, ZZ
Z Z	llll	0.005	A B* D*
	$ll\nu\nu$	0.027	A B* D* W+W-
	llqq	0.094	A B* D* E WZ
	$qq\nu\nu$	0.280	A B* D* E WW
	qqqq	0.489	A B D E F WW, WZ

*) suppressable by requiring tag jets

...is far from obvious

Selective literature on the subject

*** A nice starter**

* Chanowitz, hep-ph/0412203, Proceedings of “Physics at LHC”, Vienna, July 2004.

*** Canonical papers, analyses done at the phenomenological (parton) level**

* Bagger et al., Phys. Rev. D 49 (1994) 1246, Phys. Rev. D 52 (1995) 3878,
* Dobado, Herrero et al., Phys. Lett. B 352 (1995) 400, Phys. Rev. D 62 (2000) 055011
* Butterworth et al., Phys. Rev. D 65 (2002) 996014
* Ballestrero et al., JHEP 05 (2009) 015, JHEP 11 (2009) 126.

*** Analyses including detector simulation**

* CMS: Riccardo Bellan, "Study and Development of the CMS High Level Trigger and Muon Reconstruction Algorithms and Their Effects on the pp$\rightarrow\mu^+\mu^-$jjjj Vector Boson Fusion Process”, CERN-THESIS-2009-139,
* CMS: Paweł Zych, “Observation of the strongly-coupled Higgs sector in the CMS detector at the LHC” - PhD thesis, U of Warsaw, 2007,
* ATLAS: arXiv: 0901.0512v4

Previous analyses and studies

*** Parton level studies:**

- Typically, we need **~200 /fb** of data at nominal LHC energy to observe signal.
- Which is the best process to look at (W+W-, W+W+, WZ, ZZ) depends on the physics scenario. **We really need to study all 4 processes!**

*** PhD Thesis of Paweł Zych:**

- Focus on W+W- in semi-leptonic decay mode.
- Signal calculation in Pythia 6.146 – a modified version to compute the WL WL strong scattering in the Effective W Approximation and in different scenarios.
- **Important improvement of the background treatment** compared to previous analyses:
  - **tt production:** with new pT-ordered parton shower (Pythia 6.3), or ttj (CompHEP) with old parton shower development done in Pythia 6.1,
  - **Wjjj -** explicitly require additional jets at generation level (CompHEP) instead of at parton shower level only (Pythia),
- **Realistic CMS detector simulation** including underlying event, detector geometry, trigger, reconstruction efficiencies, etc. (ORCA),
- Conclusion: need **~300-700 /fb** to observe signal, depending on the scenario. Best for a 800 GeV scalar resonance (S4).

*** Recent studies by ATLAS:**

- WW, WZ and ZZ processes, leptonic and semi-leptonic decay modes considered.

The conclusions that can be drawn so far:

1. Background estimates are difficult, especially in the hadronic modes, some results barely agree. More studies are required.
2. There are many theoretical issues concerning the formal definition and calculation of the signal.
3. This is clearly not physics of the first of the LHC. Full nominal energy and luminosity is necessary. Therefore, there is still time to do things better.

Our goals:

1. There may be ways to enhance the signal significance and most studies indicate this is a worthwhile task:
   - to enhance the flux of W_L relative to W_T,
   - to distinguish W_L from W_T in the final sample,
   - other means?

   This defines our present plan of action.
2. In all the studies done so far, leptonic channels look at least reasonably promising in a ~2 years timescale and are never less promising than semi-leptonic,
3. Good electron and muon reconstruction is the advantage of CMS.

   This defines our choice of the purely leptonic mode as our main topic of interest.

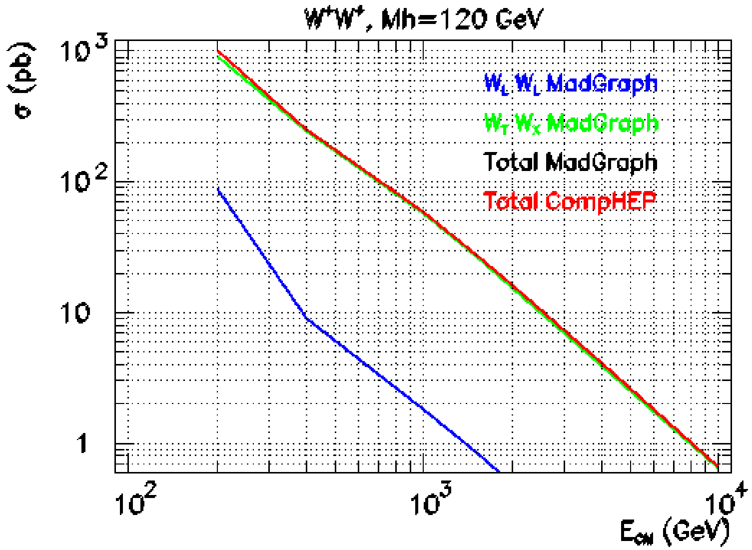
Comparative study of the process generators

* **Pythia** – commonly used to generate signal in the Effective W Approximation - scenarios with different resonances are available by choice of input *a4*, *a5* parameters,
  - very fast,
  - handles only 2→2 processes + decays, so the only backgrounds available are:
    qq→WW (relevant only if no tag jets required),
    qq→tt (relevant for W+W-),
  - does **parton showering, hadronization and vector boson decay.**

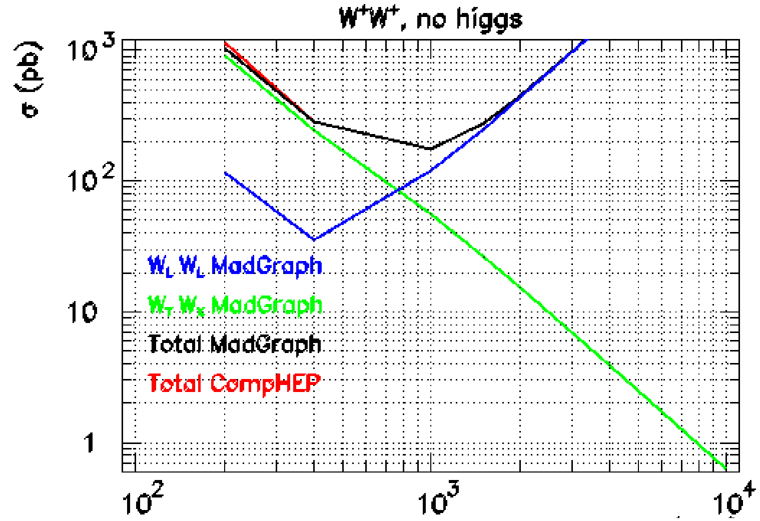
* **MadGraph** – **the best program to generate backgrounds**
  - handles all processes of up to 6 particles in the final state,
  - user friendly interface,
  - no strong WW scattering model with amplitude unitarization is available,
  - possibility to modify the source code, e.g. separate different W polarizations, or exclude unwanted diagrams (e.g. Higgs), **in the following studies we will be using the no-higgs case (without amplitude unitarization) as the formal definition of signal.**
  - interfaced with Pythia to do parton showering, hadronization and vector boson decay.

* **CompHEP** – **the best program for background cross checks**
  - handles all processes of up to 6 particles in the final state,
  - very reliable numerically,
  - not possible to disentagle different polarizations, hard to manipulate the code,
  - complicated user interface – a lot of fingering needed.

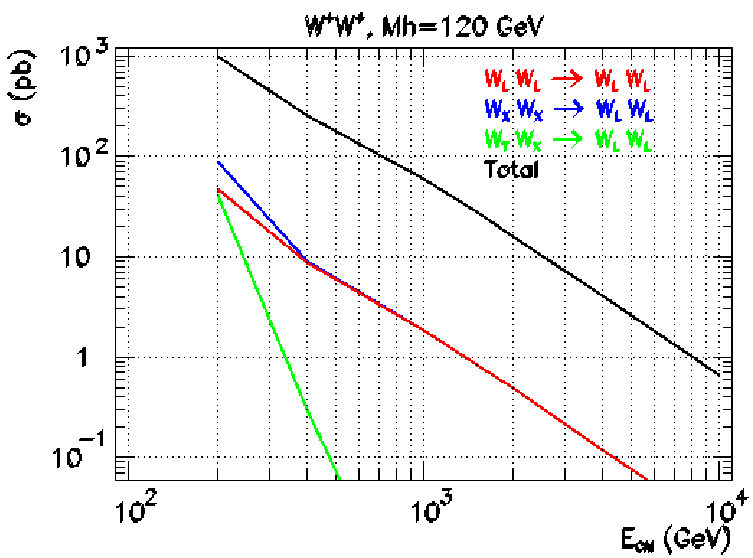
Step 1: basics of WW→WW scattering revisited
Total cross sections for |η|< 1.5



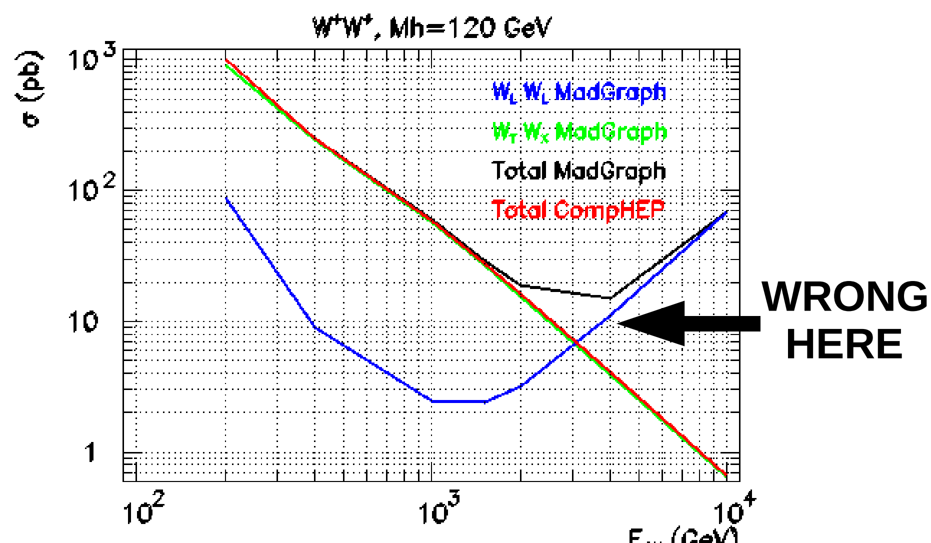
Light SM higgs case: WT by far dominates



No-higgs limit: WL rises with energy

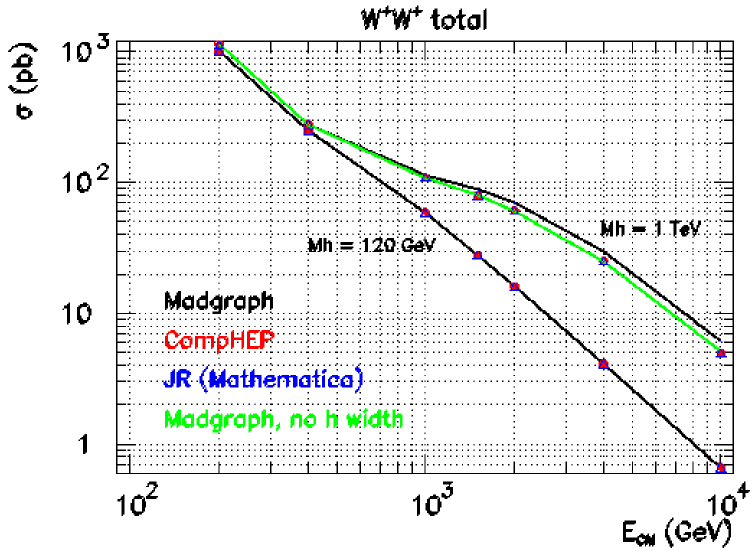


Final state polarization = initial state polarization

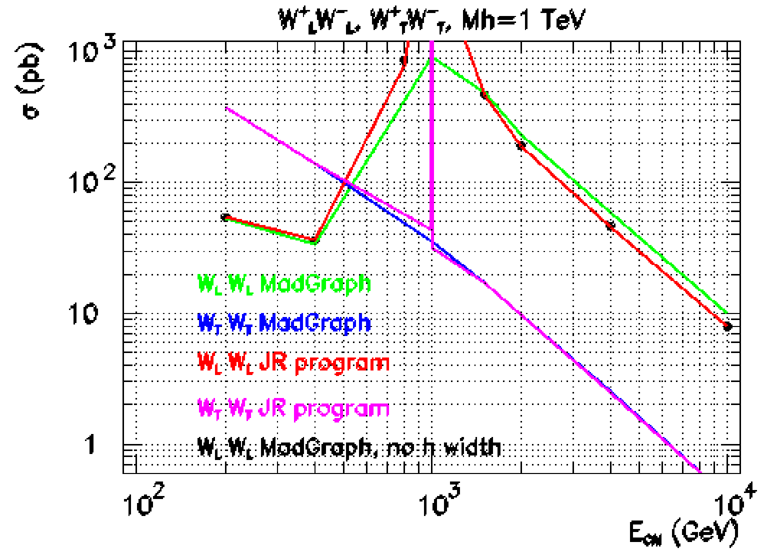


Beware of Z width in tree level calculations!

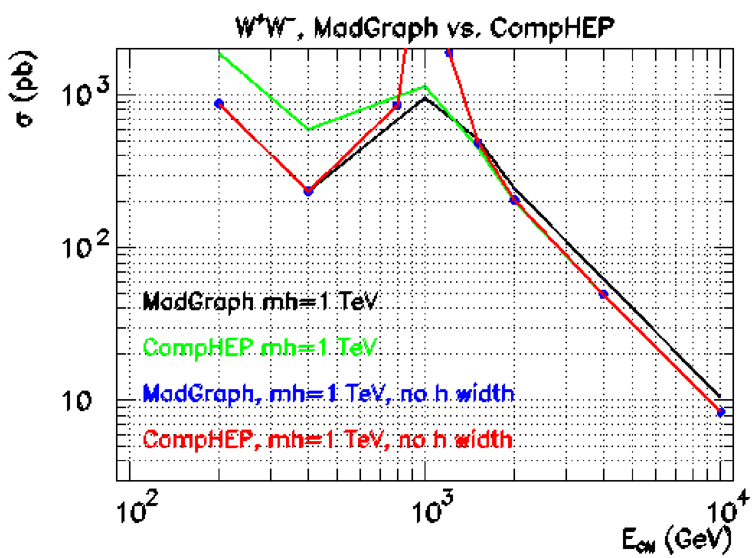
Some computational issues in MadGraph: higgs width



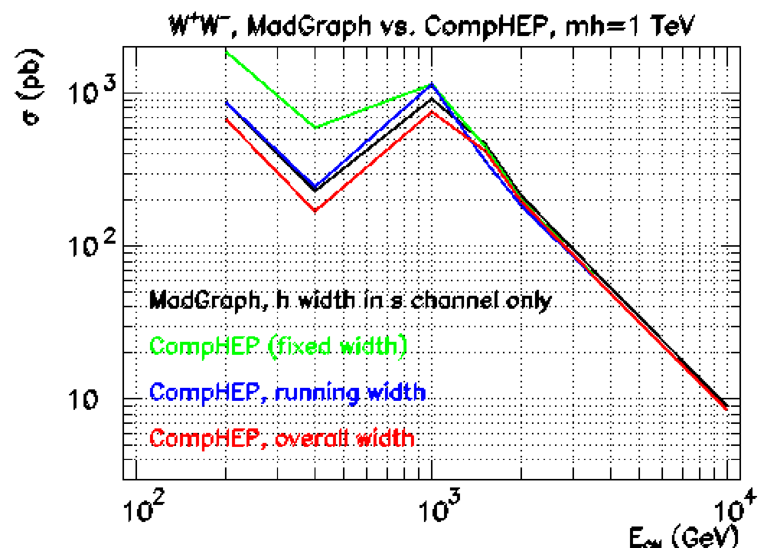
Large higgs width (heavy higgs) can bias tree level calculations



... but also is needed to avoid poles

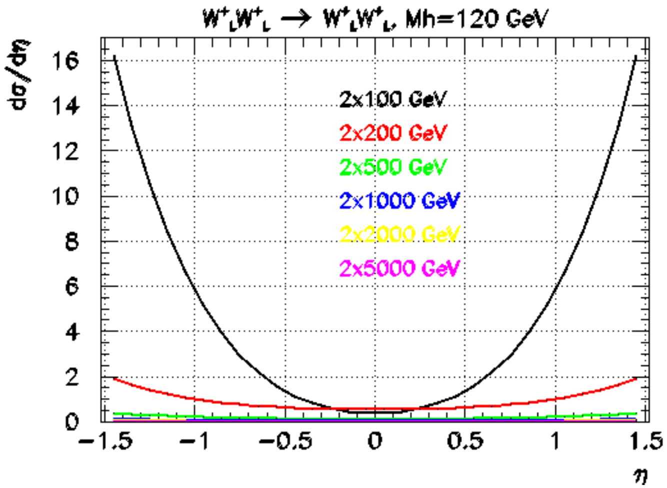


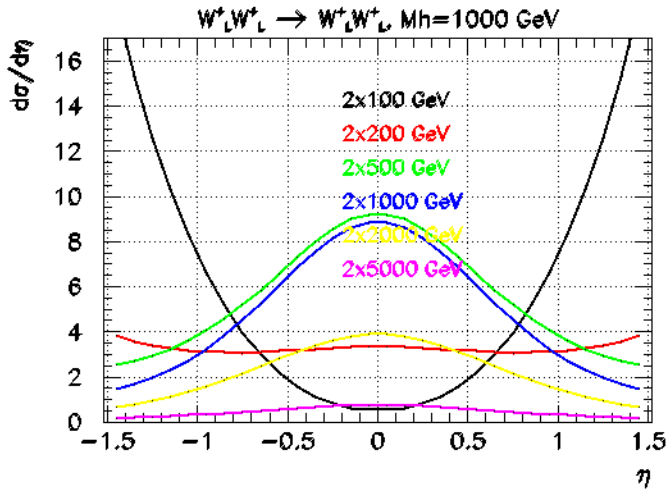
Use a finite higgs width in the s-channel only

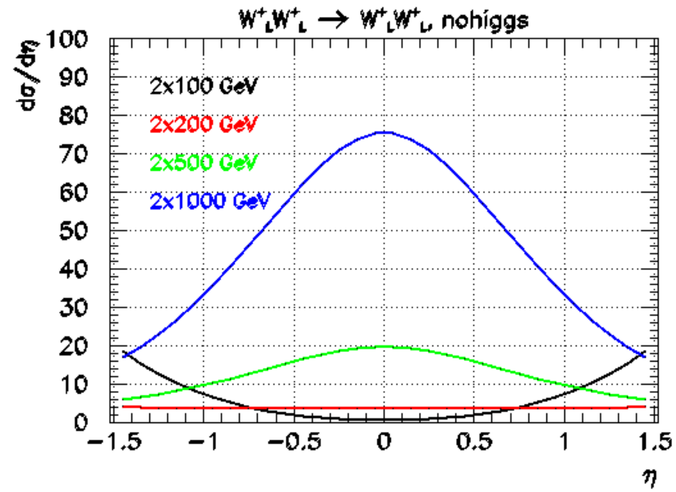


The uncertainty related to higgs width implementation

Angular distributions
Pseudorapidity wrt. initial W direction



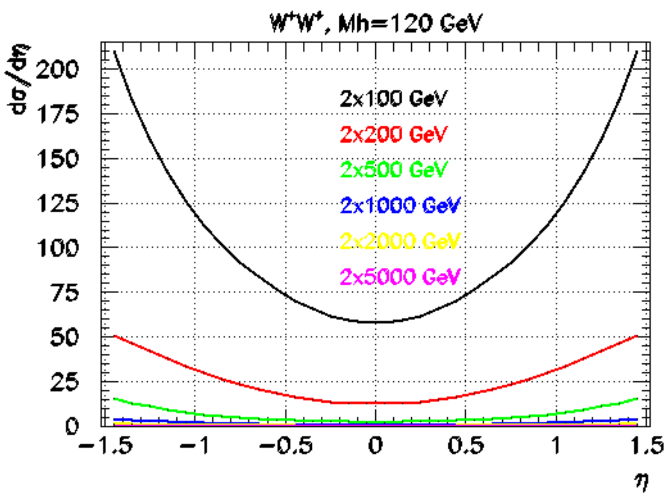


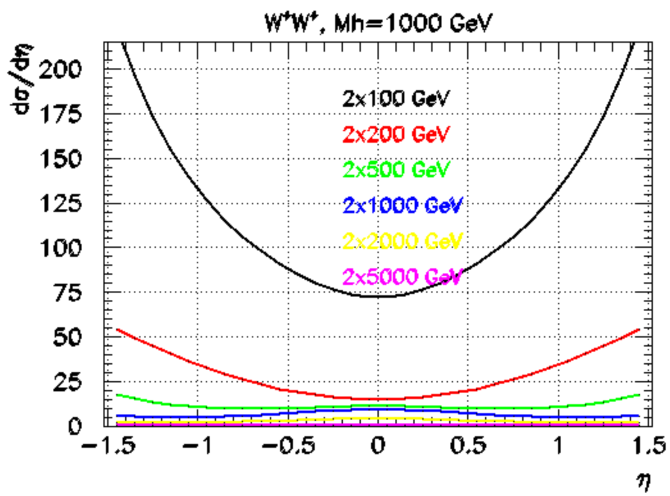


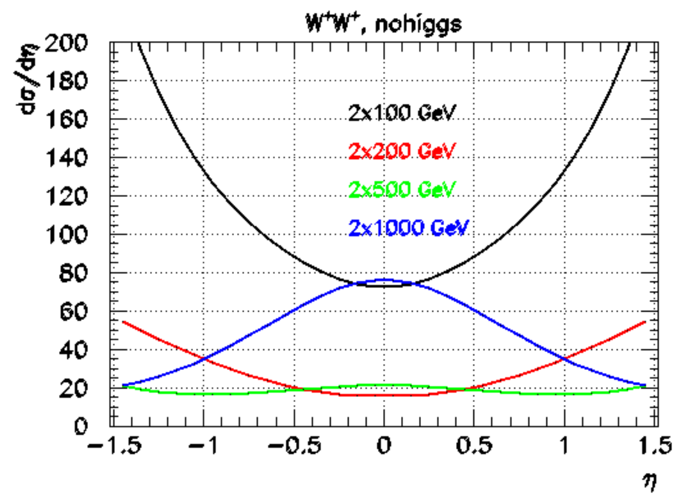
Light higgs: W in forward region, dominated by W_T

Heavy higgs: visible W_L component in central region

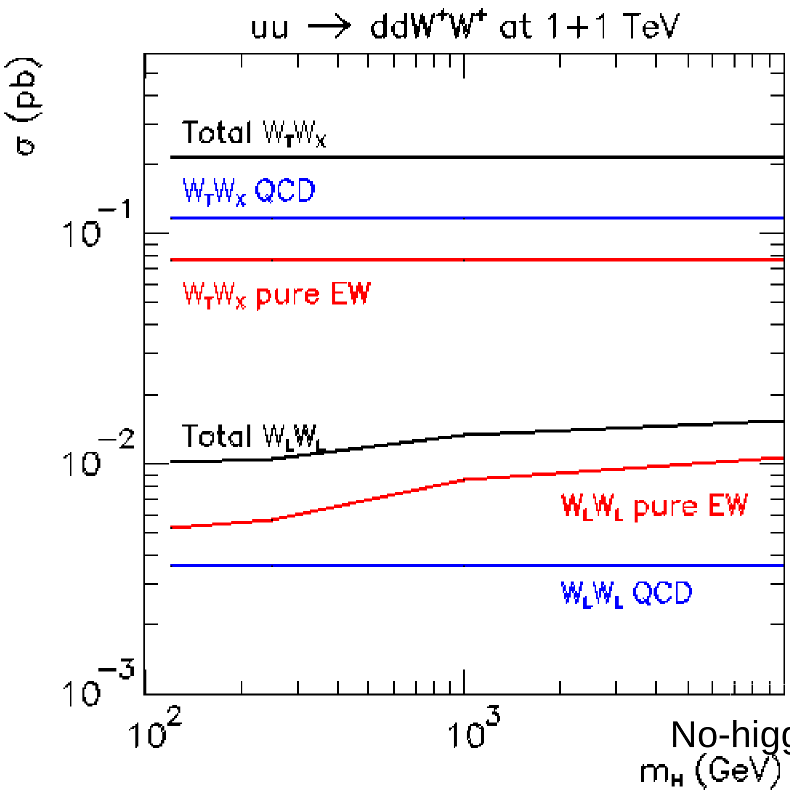
No higgs: W_L in central region dominates







Step 2: consider uu $\rightarrow$ dd W+ W+ at 2 TeV
(the dominant subprocess in the W+W+ channel)



This is our signal

No-higgs limit

CKM matrix not included
alpha_s at MZ taken

Diagrams	MadGraph	CompHEP Feynman gauge	CompHEP Unitary gauge
With WW scattering	12.29 +- 0.014 pb	0.0282 +- 0.7% pb	10.98 +- 0.2% pb
Non-scattering	12.36 +- 0.02 pb	0.132 +- 0.8% pb	11.01 +- 0.3% pb
Total	0.170 +- 0.001 pb	0.170 +- 0.4% pb	0.169 +- 1.1% pb

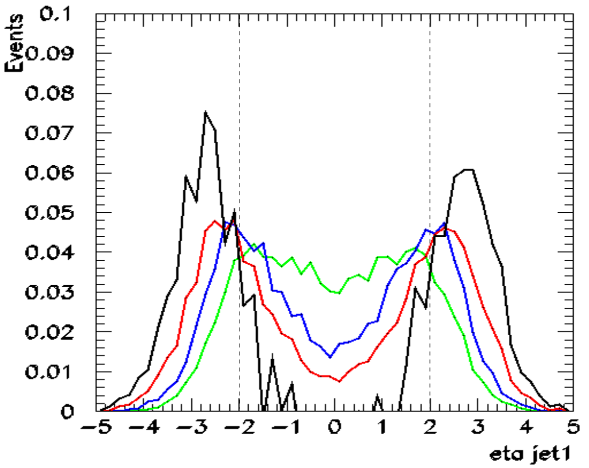
* Contributions from scattering and non-scattering diagrams cannot be separated,

* Good agreement between the two generators,

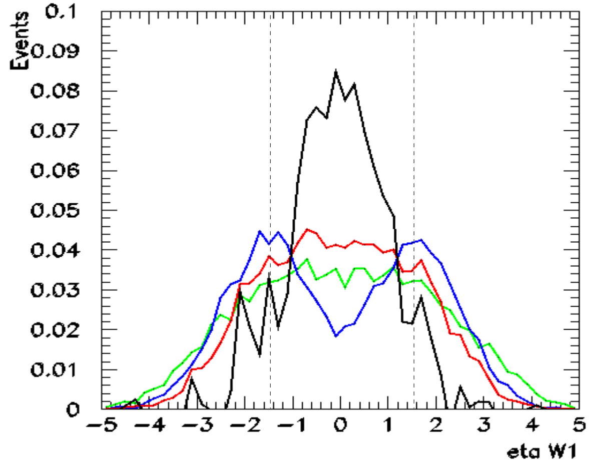
* WL contribution before selection cuts is <5%, which is consistent with the ratio of interaction cross sections for on shell $W_L W_L$ and $W_T W_X$,

Results for uu → dd W+ W+ at 2 TeV

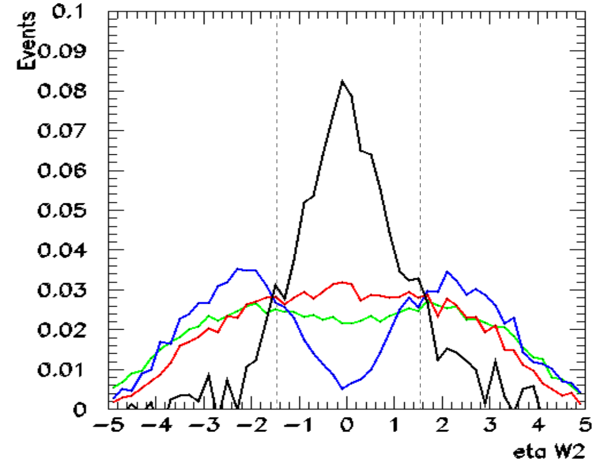
Backgrounds: **SM $W_T W_X$**, **SM $W_L W_L$**, **Signal** = **No-higgs $W_L W_L$** – **SM $W_L W_L$**,
each distribution is normalized to 1



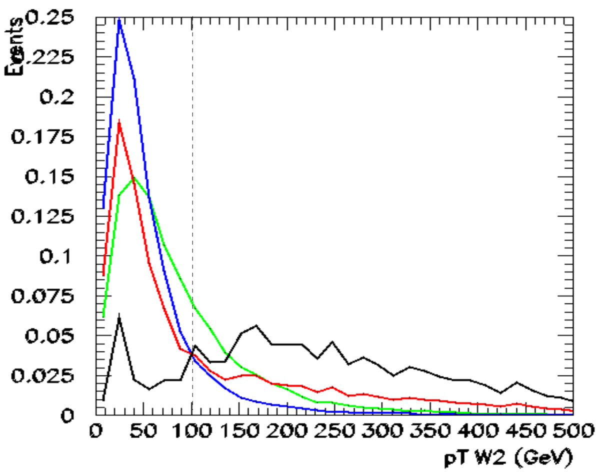
2 < |η_j| < 5



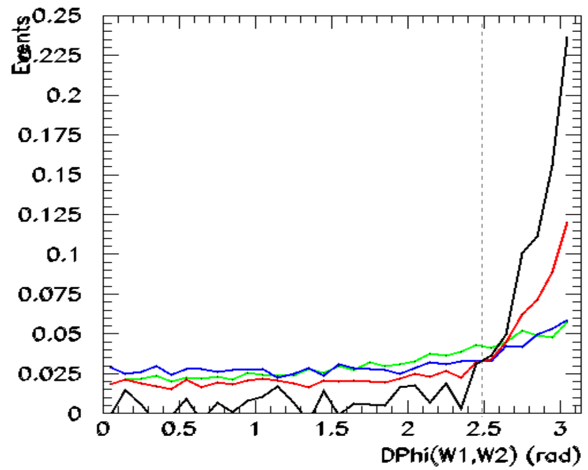
|η_W| < 1.5



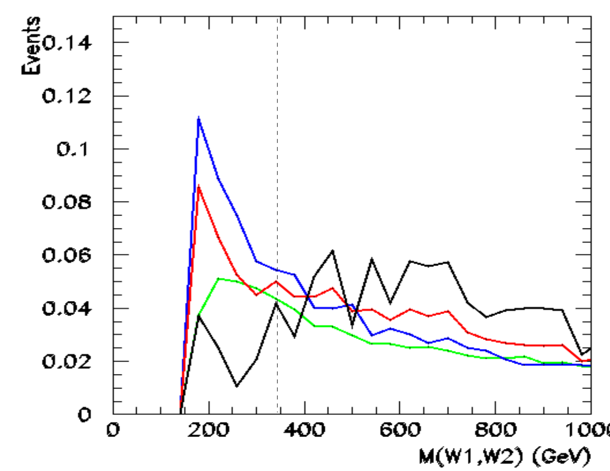
|η_W| < 1.5



pT_W > 100 GeV



Δϕ_WW > 2.5 rad



M_WW > 350 GeV

Proof of principle: a 0^{th} order analysis

Samples\Events	Cross section	Initial sample	Final sample	Reduction factor	Final X-sect
WT WX	0.2122 pb	13617	164	0.012	0.0025 pb
WL WL SM	0.0101 pb	7973	87	0.011	0.0001 pb
WL WL No Higgs	0.0154 pb	6796	1210	0.178	0.0027 pb
Signal	**0.0053 pb**	**-**	**-**	**0.497**	**0.0026 pb**
Background	**0.2223 pb**	**-**	**-**	**0.012**	**0.0026 pb**
Signal / Background	**0.024**	**-**	**-**	**41.5**	**0.987**

MadGraph: signal in pp $\rightarrow$ jjW+W+ at 14 TeV after jet cuts = 8.7 fb
signal in uu $\rightarrow$ ddW+W+ at 2 TeV after jet cuts = 5.3 fb

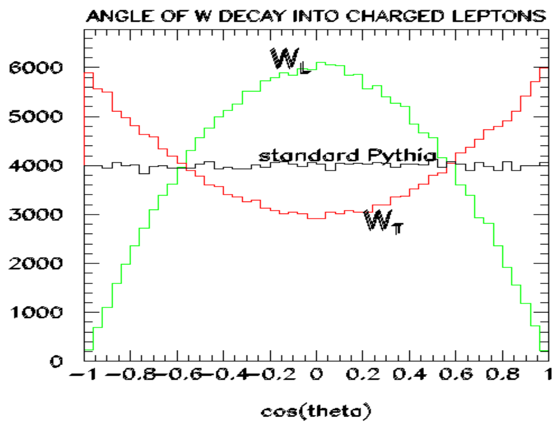
Assuming that uu at 2 TeV is a fair 0^{th} approximation of pp at 14 TeV in terms of kinematics, this means **we could have** 8.7/5.3*S*BR*L = **19 W+W+ signal events in the purely leptonic mode per 100 /fb of data.**

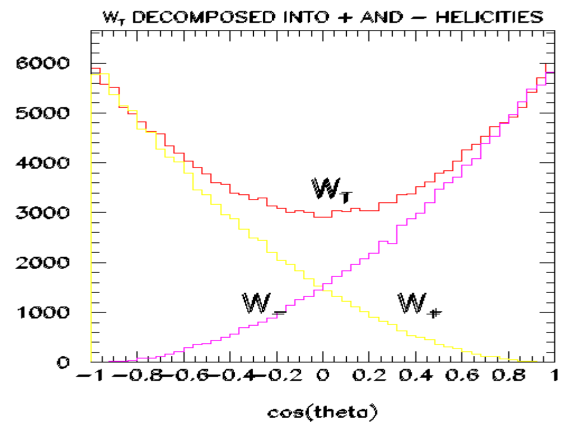
This is only an order of magnitude estimate

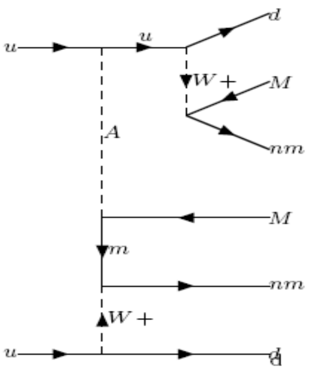
W decay and polarization

* Angular distribution of W decay can discriminate W_L from W_T in a model-independent way.

* Correct angular distributions for W_L and W_T decays are now available in Pythia (ask me).





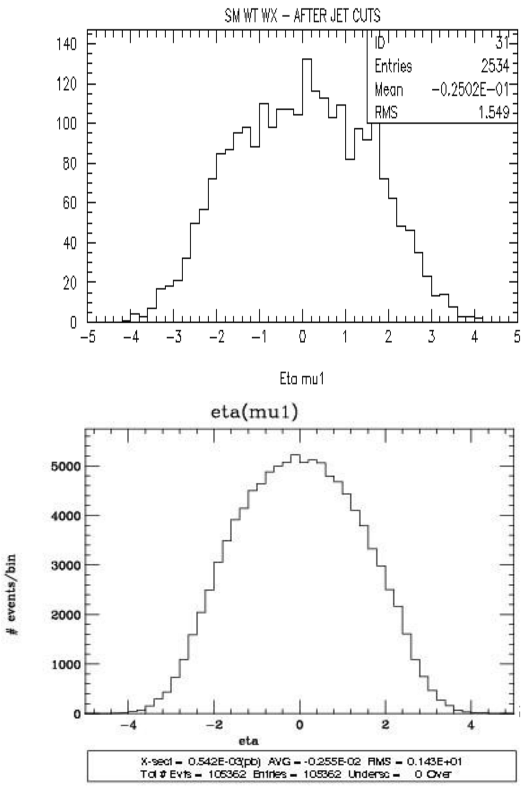


* The possibility to measure W polarization in CMS is already under investigation. It can help us in the WZ process and WW in semi-leptonic mode. The purely leptonic WW will be a bigger challenge.

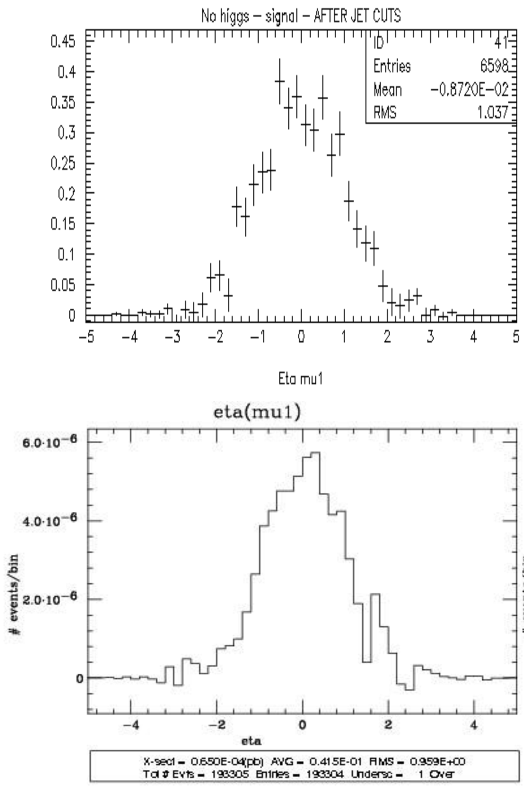
*** Two possible paths:**

- generate uu→ddW+W+ in MadGraph, decay W in Pythia (along with jet hadronization)
    - caveat: this excludes l+ l+ ν ν diagrams without W+W+ as intermediate state,
- generate directly uu→dd l+ l+ ν ν in MadGraph
    - caveat: too many single diagrams to handle,
    - caveat: information about W polarization is not available.

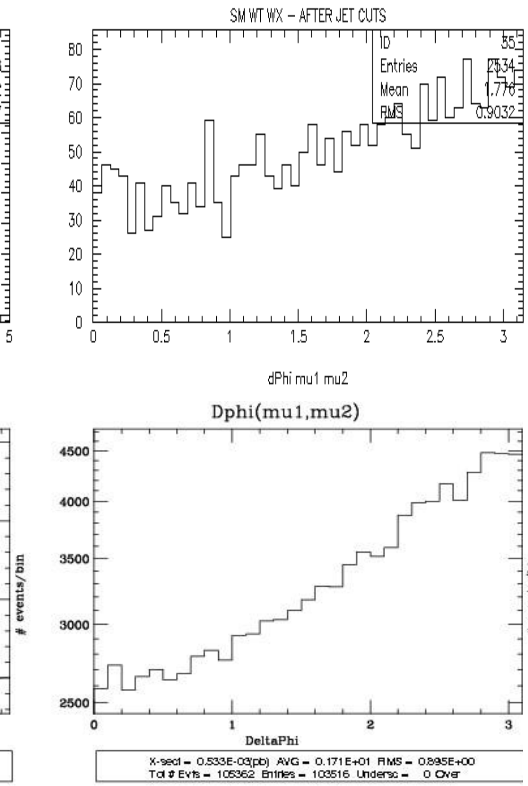
The process uu→dd μ+μ+νν
Example of kinematic distributions of final state muons



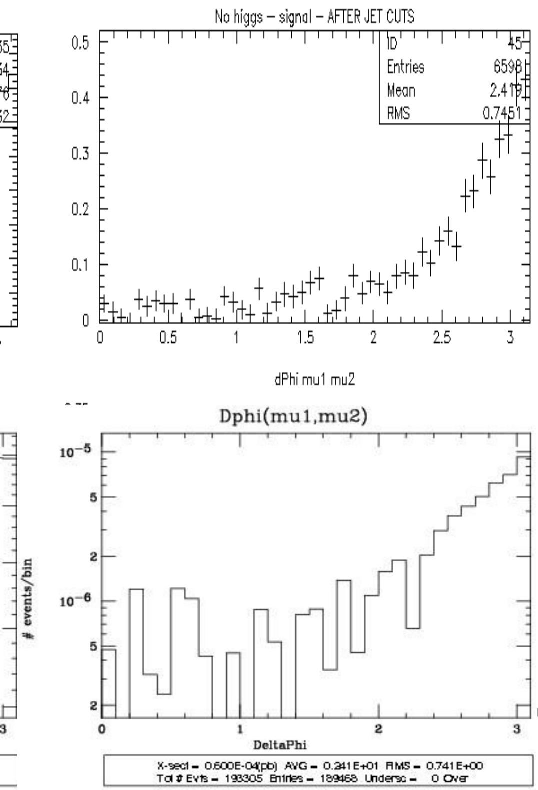
η_μ - background



η_μ - signal



Δϕ_μμ - background



Δϕ_μμ - signal

Upper row: W+W+ generation in MadGraph, W decay in Pythia, Signal = No-higgs LL – SM LL
Lower row: full process in MadGraph, Signal = No-higgs total – SM total

Agreement of the two is important!

Conclusion and plans

* We are getting impetum and things start looking promising and exciting.

*** Plans on the theory/phenomenology side:**

- compare standalone $W \to Wq$ calculations using EWA with results obtained using the "subtraction method",
- see how to enhance $W \to W_L\, q$ relative to $W \to W_T\, q$,
- implement "No-higgs" models with amplitude unitarization in MadGraph?
- extend analysis to other interesting processes, e.g. qq annihilation for WZ.

*** Plans on the experimental side:**

- how to maximize the efficiency of W, Z identification (can the next speaker teach us something here?) using leptons,
- continue work on how to determine W polarization from decay products,
- find the jet reconstruction algorithm that best fits our needs (Zych's work already sheds some light on it, but only for the semi-leptonic modes).

* Clearly, there is a lot of work to be done. Collaborators are most welcome!

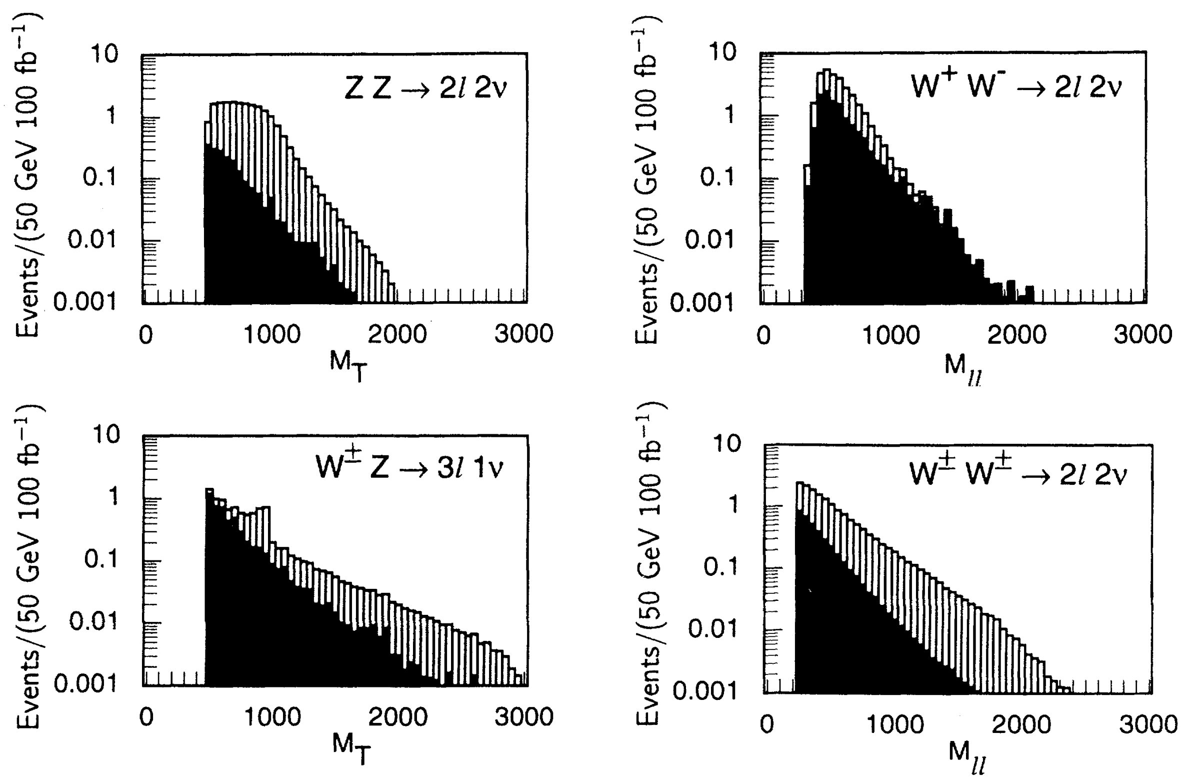
Backup I: the study of Bagger et al.

* Original calculations, physics backgrounds: A, B, C + detector acceptance backgrounds

* Several models considered, with scalar and/or vector resonances

Scalar Model
Ms = 1 TeV

Vector Model
Mv = 1 TeV



* Conclusions
  - generally, we need ~2 years of LHC running at nominal parameters to observe the signal at 99% CL in any of the considered scenarios,
  - the choice of the best process to look at depends on the nature of the resonances. We really need to study all 4 processes!

Backup II: results of Bagger et al. (leptonic mode)

Number of selected signal events per LHC year

	Bkgd.	SM	Scalar	$O(2N)$	Vec 1.0	Vec 2.5	LET-CG	LET-K	Delay-K
$ZZ(4\ell)$	0.7	9	4.6	4.0	1.4	1.3	1.5	1.4	1.1
$ZZ(2\ell 2\nu)$	1.8	29	17	14	4.7	4.4	5.0	4.5	3.6
W^+W^-	12	27	18	13	6.2	5.5	5.8	4.6	3.9
$W^\pm Z$	4.9	1.2	1.5	1.2	4.5	3.3	3.2	3.0	2.9
$W^\pm Z(M_T^{\rm cut})$	0.82				2.3				
$W^\pm W^\pm$	3.7	5.6	7.0	5.8	12	11	13	13	8.4

Number of LHC years needed to observe a 99% CL signal

	Model							
Channel	SM	Scalar	$O(2N)$	Vec 1.0	Vec 2.5	LET-CG	LET-K	Delay-K
$ZZ(4\ell)$	1.0	2.5	3.2					
$ZZ(2\ell 2\nu)$	0.5	0.75	1.0	3.7	4.2	3.5	4.0	5.7
W^+W^-	0.75	1.5	2.5	8.5		9.5		
$W^\pm Z$				7.5				
$W^\pm W^\pm$	4.5	3.0	4.2	1.5	1.5	1.2	1.2	2.2

Backup III:
recent ATLAS studies for leptonic and semi-leptonic modes

- Signal calculations in Pythia (using EWA, the same code as previous analyses),
- Physics backgrounds - generated in MadGraph with W,Z decayed in Pythia:
  A (SM irreducible), C (top), E (W/Zjjj or W/Zjjjj, depending on resonance mass),
- Realistic simulation of the ATLAS detector
- Results:

Process	Cross section (fb)		Luminosity (fb^{-1})		Significance
	signal	background	for 3σ	for 5σ	for 100 fb^{-1}
$WW/WZ \to \ell\nu\, jj$, $m = 500$ GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \to \ell\nu\, jj$, $m = 800$ GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \to \ell\nu\, jj$, $m = 1.1$ TeV	0.24 ± 0.03	0.46 ± 0.25	85	230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, $m = 500$ GeV	0.28 ± 0.04	0.20 ± 0.18	30	90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV	0.24 ± 0.02	0.30 ± 0.22	60	160	3.9 ± 1.2
$W_{j}Z_{\ell\ell}$, $m = 800$ GeV	$0.27 \pm 0.02 \pm 0.05$	$0.23 \pm 0.07 \pm 0.05$	38	105	4.9 ± 1.1
$W_{j}Z_{\ell\ell}$, $m = 1.1$ TeV	$0.19 \pm 0.01 \pm 0.04$	$0.22 \pm 0.07 \pm 0.05$	68	191	3.6 ± 1.0
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

Generally more optimistic by at least a factor ~3 than Zych's.