Determination of the Spin of New Resonances in Electroweak Gauge Boson Pair Production at the LHC

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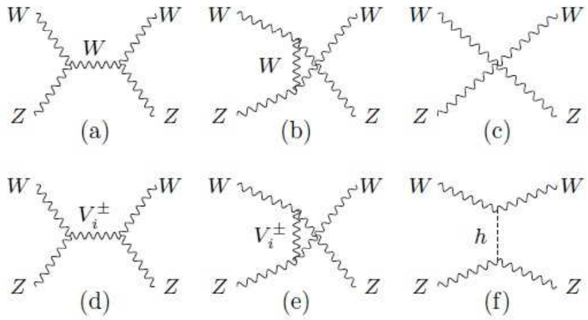
Motivation

- CERN LHC is starting to probe the TeV scale → EWSB sector at center stage (no direct experimental signal yet).
- Partial wave unitarity of longitudinal weak boson scattering → there should exist a new state at the TeV scale (the EWSB precise mechanism is not predicted).



Models

- **SM** $\rightarrow$ Higgs boson **(scalar field)** responsible for cutting off the growth of this scattering amplitude.
- **New strongly interacting sector** $\rightarrow$ new spin–1 states that unitarize the weak gauge boson scattering.[1]
- **Higgsless models** with extra dimensions $\rightarrow$ unitarity restoration through the exchange of an infinite tower of spin–1 K-K excitations of EW gauge bosons (first one may be observable at the LHC)[2]

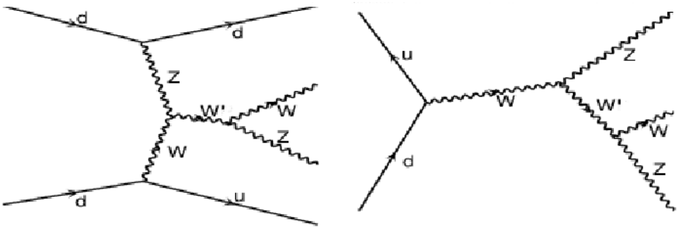
Thus, a common feature of many EWSB scenarios is the existence of new vector resonances, Z' and W', that couple to W^+W^- and $W^{\pm}Z$ pairs respectively

[1] S. Dimodopoulos and L. Susskind (1979), S. Weinberg (1979), C. T. Hill and E. H. Simmons (2003).

[2] C. Csaki, C. Grojean, H. Murayama, L. Pilo, G. Cacciapaglia, J. Terning, G. Marandella (2004), Y. Nomura (2003), R. S. Chivukula, D. A. Dicus and H.-J. He (2002).

Previous model independent analysis

Model independent: Weak Boson Fusion (WBF) or associated production with EW gauge boson



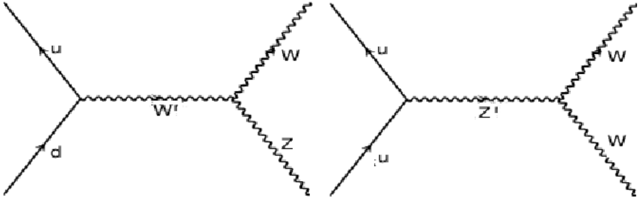
Unfortunately[3]:

- Z' signals unobservable even for increased luminosity.
- W' observable with modest luminosities → but spin determination only for light resonances and with assumption of increased luminosity

[3] A. Birkedal, K. Matchev and M. Perelstein (2005), A. Alves, O. J. P. Eboli, M.C. Gonzalez-Garcia *et al* (2009), M. Asano and Y. Shimizu (2011).

Alternative

Direct production via the V' coupling to light quarks [4]



Study of the processes:

$$\begin{aligned} pp &\to Z' &&\to W^+W^- \to \ell^+\ell^{(\prime)-} \not{E}_T \\ pp &\to W' &&\to W^\pm Z \to \ell^+\ell^-\ell^{(\prime)\pm} \not{E}_T \end{aligned}$$

- **Model independent spirit**: relevant couplings of V', width and mass.
- **Spin assignment**: from final state leptons spin correlations and angular distributions of the produced EW gauge bosons.

[4] A. Alves, O. J. P. Eboli, D. Goncalves Netto, M. C. Gonzalez-Garcia *et al* (2009).

Couplings

- **Model independent spirit:**
  Free parameters:
  $$\left(\frac{g_{V'q\bar{q}}}{g_{Vq\bar{q}}}\,\frac{g_{V'WV}}{g_{V'WV\,max}}\right),\quad \Gamma_{V'}\quad \text{and}\quad M_{V'}$$
  where
  $$g_{Z'WW\,max} = g_{ZWW}\,\frac{M_Z}{\sqrt{3}M_{Z'}}\quad \text{and}\quad g_{W'WZ\,max} = g_{ZWW}\,\frac{M_Z^2}{\sqrt{3}M_{W'}M_W}$$
  One constraint:
  $$\begin{aligned}\Gamma_{Z'} &> 0.27\,\mathrm{GeV}\left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\right)\left(\frac{g_{Z'WW}}{g_{Z'WW\,max}}\right)\left(\frac{M_{Z'}}{M_Z}\right)^2\\ \Gamma_{W'} &> 0.40\,\mathrm{GeV}\left(\frac{g_{W'q\bar{q}}}{g_{Wq\bar{q}}}\right)\left(\frac{g_{W'WZ}}{g_{W'WZ\,max}}\right)\left(\frac{M_{W'}}{M_W}\right)^2\end{aligned}$$
- Concreteness $\Rightarrow$ couplings with **same Lorentz structure as SM** ones but arbitrary strengh. (Higgsless models)
- $Z'ZZ$ coupling vetoed. (Higgsless models)

Cross Sections

$$\sigma_{\text{tot}} = \sigma_{SM} + \left(\frac{g_{V'q\bar{q}}}{g_{Vq\bar{q}}}\frac{g_{V'WV}}{g_{V'WV\,max}}\right)\sigma_{int}(M_{V'},\Gamma_{V'}) + \left(\frac{g_{V'q\bar{q}}}{g_{Vq\bar{q}}}\frac{g_{V'WV}}{g_{V'WV\,max}}\right)^2\sigma_{V'}(M_{V'},\Gamma_{V'})$$

$\Rightarrow$Study as a function of $\left(\frac{g_{V'q\bar{q}}}{g_{Vq\bar{q}}}\frac{g_{V'WV}}{g_{V'WV\,max}}\right)$, $\Gamma_{V'}$ and $M_{V'}$

- Template $\rightarrow$ model with a new scalar (Higgs inspired couplings) with a coupling strenght such that scalar production cross section is equal to the V' after all the cuts. (same mass and width)
- Parton level study keeping the full helicity structure of the amplitude (MadGraph) including experimental resolutions and detection efficiencies.

Cuts

$$pp \to W' \to ZW^{\pm} \to \ell^+\ell^-\ell'^{\pm}\not{E}_T$$

- Main SM backgrounds:

$$pp \to W^{\pm}Z \to \ell^{\pm}\ell'^{+}\ell'^{-}\not{E}_T$$
$$pp \to ZZ \to \ell^+\ell^-\ell'^{\pm}[\ell'^{\mp}]$$
$$pp \to t\bar{t} \to bW^+\bar{b}W^- \to jW^-W^+\bar{b}W^- + bW^+\bar{j}W^+W^- \to \ell^+\ell'^-\ell''^{\pm}\not{E}_T$$

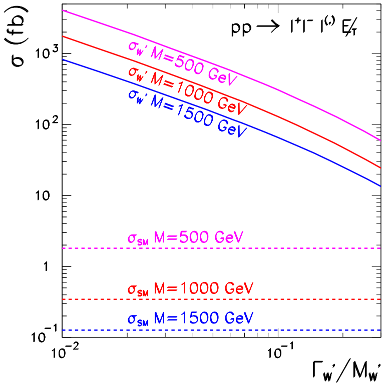
- Starting cuts $\to |\eta_\ell| < 2.5$, $\Delta R_{\ell\ell} > 0.2$, $p_T^\ell > 10$ GeV and $\not{E}_T > 10$ GeV
- SFOC leptons $\to |M_{\ell^+\ell^-} - M_Z| < 20$ GeV.
- Leading lepton $\to p_t > 120$ GeV
- ν reconstruction:
  Imposing $(p^\nu + p^\ell)^2 = M_W^2 \Rightarrow$ twofold ambiguity

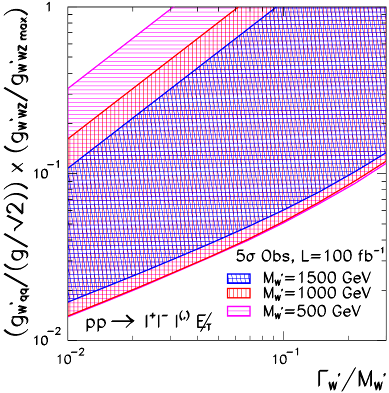
$$|M_{\text{rec}}^{\text{min}} - M_{W'}| < \delta\ .$$

with

$$M_{W'} = 500 \text{ GeV} \to \delta = 50 \text{ GeV}$$
$$M_{W'} = 1000 \text{ GeV} \to \delta = 100 \text{ GeV}$$
$$M_{W'} = 1500 \text{ GeV} \to \delta = 200 \text{ GeV}$$

Cross sections and 5σ signal observation





Final state leptons and angular correlations in WZ COM

- A convenient variable for contrasting the production of particles with different spin[5] :

$$\cos\theta^*_{\ell\ell} \equiv \tanh\left(\frac{\Delta\eta_{\ell\ell}}{2}\right)$$

  $\Delta\eta_{\ell\ell}$ is the rapidity difference between the same charge leptons $\rightarrow$ is invariant under longitudinal boosts.
- Using the neutrino reconstruction $\rightarrow$ Z polar angle in the WZ COM frame:

$$\cos\theta_{WZave}$$

- Expected behaviour:

$$\begin{array}{lcl} \text{spin}-1 & \rightarrow & \text{peaked at } \cos\theta^*_{\ell\ell} = 0 \\ \text{spin}-0 & \rightarrow & \text{flat} \end{array}$$

However, with the cuts...

[5] J. M. Smillie and B. R. Webber (2005), A. Alves, O. Éboli and T. Plehn (2006), A. Alves and O. Éboli (2007).

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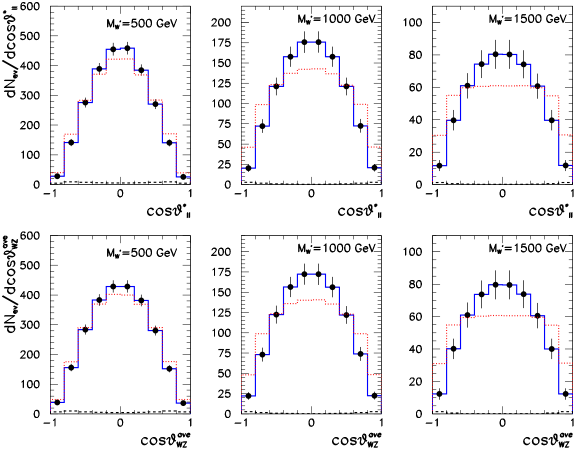
$\cos\theta^*_{\ell\ell}$ and $\cos\theta_{WZave}$



W' (solid blue line with error bars) and charged scalar resonance (dotted red line).

$$(\Gamma_{W'} = 0.05 M_{W'} \text{ and } \left(\frac{g_{W'q\bar{q}'}}{g_{Wq\bar{q}'}} \frac{g_{W'WZ}}{g_{W'WZ\,max}}\right) = 0.3)$$

Discrimination between spin–0 and spin–1

Both variables with comparable discrimination power → $\cos\theta_{WZave}$ larger uncertainties

Construction of asymmetry:

$$A_{\ell\ell} = \frac{\sigma(|\cos\theta^*_{\ell\ell}| < 0.5) - \sigma(|\cos\theta^*_{\ell\ell}| > 0.5)}{\sigma(|\cos\theta^*_{\ell\ell}| < 0.5) + \sigma(|\cos\theta^*_{\ell\ell}| > 0.5)} \, .$$

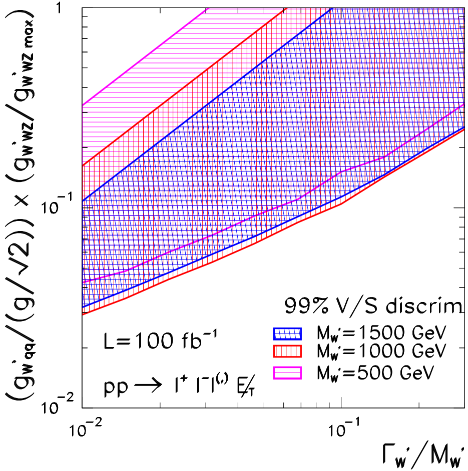
(eliminates normalization systematics)

99% CL spin determination for a given $\mathcal{L}$ (assuming vector distributions):

$$|A^V_{\ell\ell} - A^S_{\ell\ell}| \geq 2.58\, \sigma_{A^V_{\ell\ell}} = 2.58\, \frac{\sqrt{1 - {A^V_{\ell\ell}}^2}}{\sqrt{N_{\rm tot}}}$$

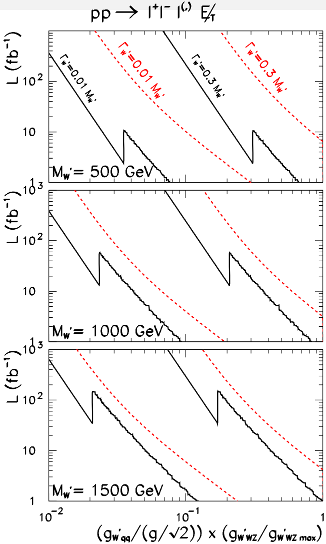
where $N_{\rm tot} = \mathcal{L} \times \sigma_{\rm tot} \times (\epsilon^\ell)^3$

99% CL spin discrimination



W' spin determination at 99% CL for 100 fb^{-1} using the asymmetry $A_{\ell\ell}$.

Luminosity requirement



Solid black (dashed red) → integrated luminosity required for discovery (99% CL spin determination)

Cuts

$$pp \to Z' \to W^+W^- \to \ell^+\ell^{(\prime)-}\not{E}_T$$

- Main SM backgrounds:

$$pp \to W^+W^- \to \ell^+\ell'^-\not{E}_T$$
$$pp \to ZZ \to \ell^+\ell^-\not{E}_T$$
$$pp \to t\bar{t} \to bW^+\bar{b}W^- \to \ell^+\ell'^-\not{E}_T$$
$$pp \to \tau\bar{\tau} \to \ell^+\ell'^-\not{E}_T$$

- Starting cuts$\to |\eta_\ell| < 2.5$, $\Delta R_{\ell\ell} > 0.2$ and $p_T^\ell > 50$ GeV
- Jet veto $\to |\eta_j| < 3$ and $p_T^j > 20$ GeV.
- SF leptons $\to \not{E}_T > 50$ GeV and $m_{\ell^+\ell^-} > 100$ GeV.
- 2ν in final state $\Rightarrow$ Complete reconstruction of the event is impossible

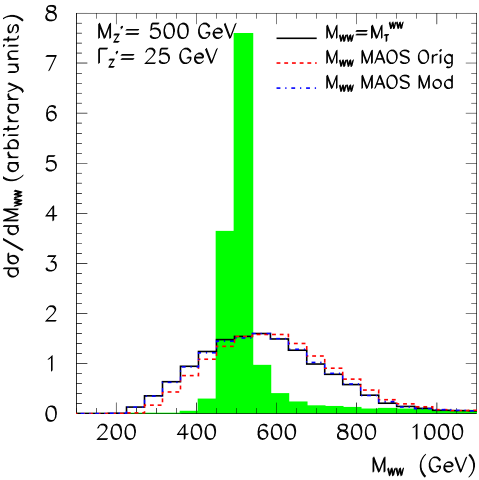
$$M_T^{WW}$$

M_{T2} Assisted on-Shell (MAOS)[6] original or modified[7]

[6] W. S. Cho, K. Choi, Y. G. Kim *et al* (2009), C. G. Lester and D.J. Summers (1999)

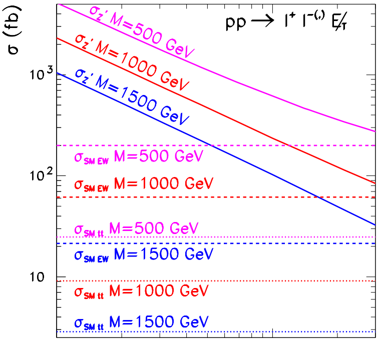
[7] K. Choi, S. Choi and J. S. Lee (2009).

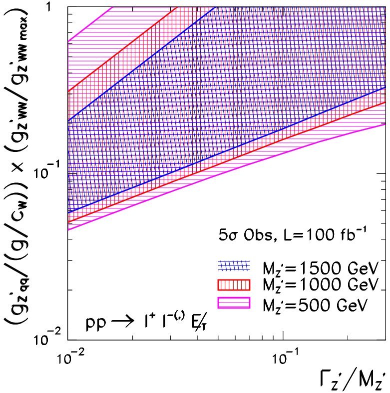
WW invariant mass



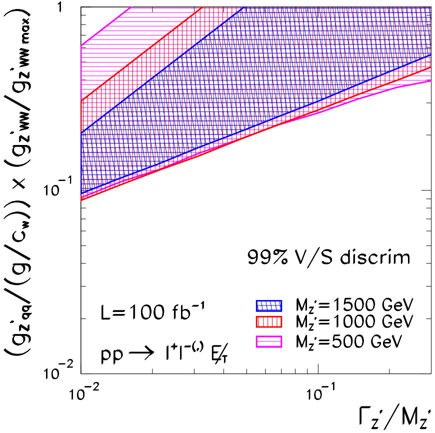
$$M_T^{WW} > \frac{M_{Z'}}{2}$$

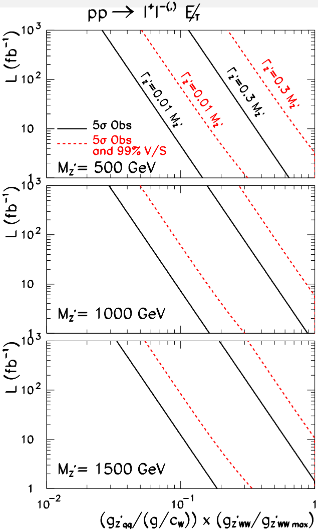
Cross Sections and 5σ signal observation





99% CL spin discrimination





ATLAS and CMS Combined exclusion limits on the production of a Z'

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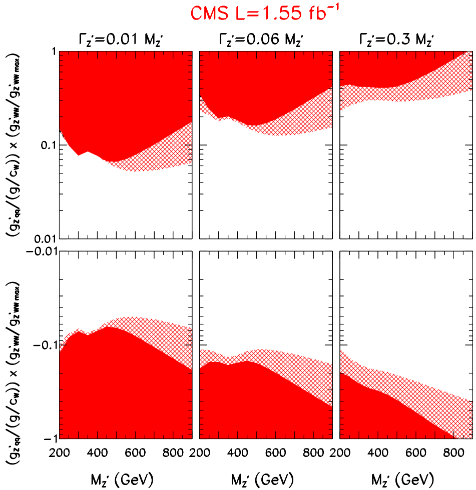
Using

$$2010/11 \text{ collected data} \rightarrow \begin{array}{c} \text{ATLAS} \rightarrow 1.02\ \text{fb}^{-1} \\ \text{CMS} \rightarrow 1.55\ \text{fb}^{-1} \end{array}$$

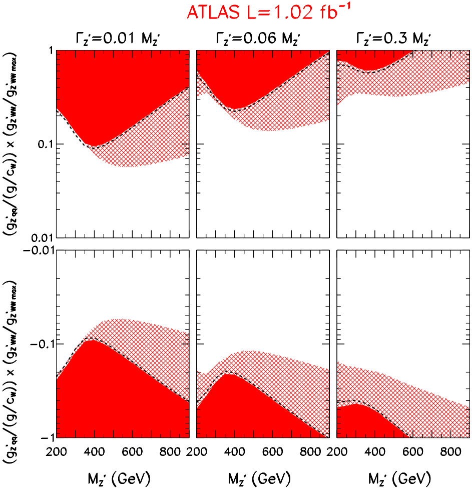
Analysis of $pp \rightarrow \ell^+ \ell^{(\prime)-} \not{E}_T$:

- Complete simulation of the signal and background required.
- Using the same Model independent framework.
- No positive signal observed $\rightarrow$ Exclusion limits on the production of a Z'.

ATLAS and CMS combined exclusion limits on the production of a Z'



ATLAS and CMS combined exclusion limits on the production of a Z'



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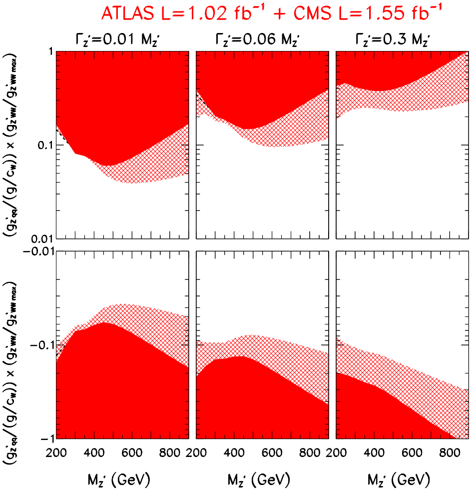


Conclusions

- (W') $\cos\theta^*_{\ell\ell}$ and $\cos\theta_{WZ}$ and (Z') $\cos\theta^*_{\ell\ell}$ and $\cos\theta_{WW}$ similar discriminating power $\rightarrow$ no need of COM reconstruction
- Z': M_T^{WW} and MAOS similar power.
- 99% CL determination of the spin $\rightarrow$ large fraction of the parameter space where W' and Z' can be observed for 100 fb^{-1}(14 TeV).
  Early (10 fb^{-1}) discovery possible for weakly coupled W'.

Ex.: W' in Higgsless models:

$$\overset{M_{W'} < 1 \text{ TeV}}{\left(\frac{g_{W'q\bar{q}}}{g_{Wq\bar{q}}}\frac{g_{W'WZ}}{g_{W'WZ\,max}}\right)} \simeq \mathcal{O}(0.07) \quad \rightarrow \quad \begin{array}{c}\text{Observation} \sim 10\text{fb}^{-1}\\ \text{Spin determination } O(10)\text{fb}^{-1}\end{array}$$

Ex.: Z' in Higgsless models:

$$\overset{M_{Z'} < 1 \text{ TeV}}{\left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\frac{g_{Z'WW}}{g_{Z'WW\,max}}\right)} \simeq \mathcal{O}(0.1) \quad \rightarrow \text{Observation and Spin determination} \sim 100\text{fb}^{-1}$$

7 TeV LHC run is already scrutinizing the lighest masses $\rightarrow$ First exclusion limits almost/already avaliable

Widths

Couplings, width (Γ_V) and mass (M_V) as free parameters, only one constraint:

$$\Gamma_{Z'} \geq \sum_{q=u,d} \Gamma\left(Z' \to q\bar{q}\right) + \Gamma\left(Z' \to W^+W^-\right)$$

$$\Gamma_{W'^+} \geq \Gamma\left(W'^+ \to u\bar{d}\right) + \Gamma\left(W'^+ \to W^+Z\right)$$

Using

$$\Gamma\left(Z' \to u\bar{u}\right) = 0.3\left(\frac{M_{Z'}}{M_Z}\right)\left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\right)^2 \quad \Gamma\left(Z' \to d\bar{d}\right) = 0.38\left(\frac{M_{Z'}}{M_Z}\right)\left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\right)^2$$

$$\Gamma\left(Z' \to W^+W^-\right) = 0.028\left(\frac{M_{Z'}}{M_Z}\right)^3\left(\frac{g_{Z'WW}}{g_{Z'WW\,max}}\right)^2$$

$$\Gamma\left(W'^+ \to q'\bar{q}\right) = 0.68\left(\frac{M_{W'}}{M_W}\right)\left(\frac{g_{W'q\bar{q}}}{g_{Wq\bar{q}}}\right)^2$$

$$\Gamma\left(W'^+ \to W^+Z\right) = 0.019\left(\frac{M_{W'}}{M_W}\right)^3\left(\frac{g_{W'WZ}}{g_{W'WZ\,max}}\right)^2$$

We get

$$\Gamma_{Z'} > 0.27\,\text{GeV}\left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\right)\left(\frac{g_{Z'WW}}{g_{Z'WW\,max}}\right)\left(\frac{M_{Z'}}{M_Z}\right)^2$$

$$\Gamma_{W'} > 0.40\,\text{GeV}\left(\frac{g_{W'q\bar{q}}}{g_{Wq\bar{q}}}\right)\left(\frac{g_{W'WZ}}{g_{W'WZ\,max}}\right)\left(\frac{M_{W'}}{M_W}\right)^2$$

ν reconstruction (W')

Reconstruction imposing $(p^{\nu} + p^{\ell})^2 = M_W^2 \Rightarrow$ twofold ambiguity:

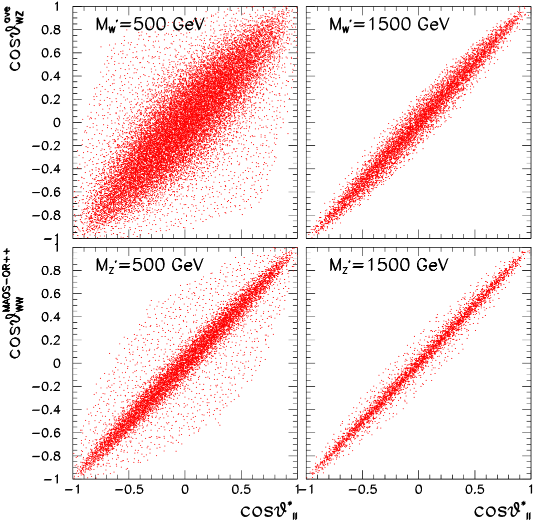
$$p_L^{\nu} = \frac{1}{2{p_T^l}^2}\left\{\left[M_W^2 + 2(\vec{p_T^l}\cdot\vec{\not{p}_T})\right]p_L^l \pm\sqrt{\left[M_W^2 + 2(\vec{p_T^l}\cdot\vec{\not{p}_T})\right]^2|\vec{p}^l|^2 - 4(p_T^l E^l \not{E}_T)^2}\right\}$$

- $$|M_{\mathrm{rec}}^{\min} - M_{W'}| < \delta\ .$$

  with

$$M_{W'} = 500\ \mathrm{GeV} \rightarrow \delta = 50\ \mathrm{GeV}$$
$$M_{W'} = 1000\ \mathrm{GeV} \rightarrow \delta = 100\ \mathrm{GeV}$$
$$M_{W'} = 1500\ \mathrm{GeV} \rightarrow \delta = 200\ \mathrm{GeV}$$

$\cos\theta^*_{\ell\ell}$ vrs $\cos\theta_{WZave}$



Up: $\cos\theta^*_{ll} \otimes \cos\theta^{ave}_{WZ}$ spectrum for W' and $M_{W'} = 0.5$ TeV (left panel) and 1.5 TeV (right panel) where $\cos\theta^{ave}_{WZ}$ is the average of the two possible solutions.

ν reconstruction (Z')

2ν in final state $\Rightarrow$ Complete reconstruction of the event is impossible

- Transverse mass:

$$M_T^{WW} = \left[\left(\sqrt{(p_T^{\ell^+\ell'^-})^2 + m^2_{\ell^+\ell'^-}} + \sqrt{\not{p}_T^2 + m^2_{\ell^+\ell'^-}}\right)^2 - (\vec{p}_T^{\,\ell^+\ell'^-} + \vec{\not{p}}_T)^2\right]^{1/2}$$

- M_{T2} Assisted on-Shell (MAOS)[8] reconstruction.
  For $W^+(p_1+p_2)W^-(k_1+k_2) \to \ell^+(p_1)\nu(p_2)\ell^-(k_1)\nu(k_2)$:

$$M_{T2} \equiv \min_{\mathbf{p_2}_T + \mathbf{k_2}_T = \not{p}_T} \left[\max\left\{M_T(\mathbf{p_1}_T, \mathbf{p_2}_T), M_T(\mathbf{k_1}_T, \mathbf{k_2}_T)\right\}\right]$$

$$M_T^2(\mathbf{p_1}_T, \mathbf{p_2}_T) = 2(|\mathbf{p_1}_T||\mathbf{p_2}_T| - \mathbf{p_1}_T \cdot \mathbf{p_2}_T)\ .$$

Without initial state radiation:

$$\mathbf{p_2}_T^{\mathrm{maos}} = -\mathbf{k_1}_T, \quad \mathbf{k_2}_T^{\mathrm{maos}} = -\mathbf{p_1}_T.$$

[8] W. S. Cho, K. Choi, Y. G. Kim *et al* (2009), C. G. Lester and D.J. Summers (1999)

MAOS original vrs modified

- MAOS-original:

$$p_{2\,L}^{\mathrm{maos}}(\pm) = \frac{1}{|\mathbf{p_1}_T|^2}\Big[p_{1L}\, A \pm \sqrt{|\mathbf{p_1}_T|^2 + p_{1L}^2}\,\sqrt{A^2 - |\mathbf{p_1}_T|^2|\mathbf{p_2}_T^{\mathrm{maos}}|^2}\Big],$$

$$k_{2\,L}^{\mathrm{maos}}(\pm) = \frac{1}{|\mathbf{k_1}_T|^2}\Big[k_{1L}\, B \pm \sqrt{|\mathbf{k_1}_T|^2 + k_{1L}^2}\,\sqrt{B^2 - |\mathbf{k_1}_T|^2|\mathbf{k_2}_T^{\mathrm{maos}}|^2}\Big]$$

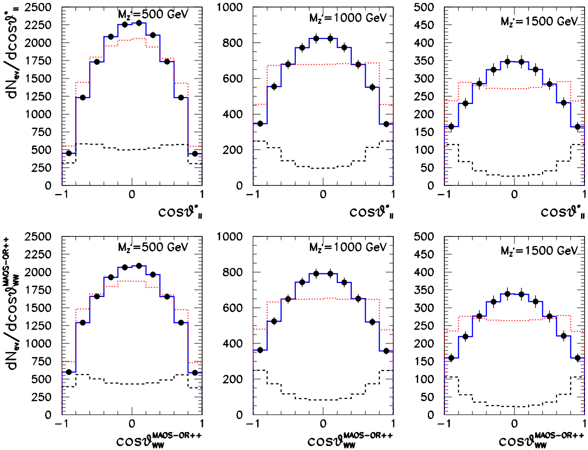
where $A \equiv M_W^2/2 + \mathbf{p_1}_T \cdot \mathbf{p_2}_T^{\mathrm{maos}}$ and $B \equiv M_W^2/2 + \mathbf{k_1}_T \cdot \mathbf{k_2}_T^{\mathrm{maos}}$.

- MAOS-modified[9]:

$$p_{2\,L}^{\mathrm{maos}} = \frac{|\mathbf{p_2}_T^{\mathrm{maos}}|}{|\mathbf{p_1}_T|}p_{1L}, \quad k_{2\,L}^{\mathrm{maos}} = \frac{|\mathbf{k_2}_T^{\mathrm{maos}}|}{|\mathbf{k_1}_T|}k_{1L}.$$

[9] K. Choi, S. Choi and J. S. Lee (2009).

$\cos\theta^*_{\ell\ell}$ and $\cos\theta^{MAOS-OR++}_{WW}$



$\cos\theta^*_{ll}$ (up) and $\cos\theta^{\mathrm{MAOS-OR++}}_{WW}$ (down).

($\Gamma_{Z'} = 0.01 M_{Z'}$ and $\left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\frac{g_{Z'WW}}{g_{Z'WW\,max}}\right) = 0.3$). We assumed an integrated luminosity of 100 fb^{-1}.