Determination of Spin and Present Bounds on New Vector Resonances in Electroweak Gauge Boson Pair Production at the LHC

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Motivation

CERN LHC is probing the TeV scale → EWSB sector at center stage.

Partial wave unitarity of longitudinal weak boson scattering → there should exist a new state at the TeV scale.

Different alternatives:

- **SM** → Higgs boson **(scalar field)**
- **New strongly interacting sector** → new spin–1 states that unitarize the weak gauge boson scattering.[1]
- **Higgsless models** with extra dimensions → 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]

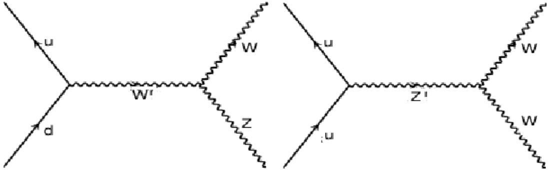
Thus, a common feature of many EWSB scenarios is the existence of new vector resonances, Z' and W', that couple to W^+W^- and $W^\pm Z$ pairs respectively

[1] Dimodopoulos and Susskind (1979), Weinberg (1979), Hill and Simmons (2003).

[2] Csaki, Grojean, Murayama *et al* (2004), Nomura (2003), Chivukula, Dicus, He (2002).

The Channel

Direct production via the V' coupling to light quarks [3]



Study of the processes:

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

- **Model independent spirit**: relevant couplings of V', width and mass.
- Other channels (VBF or associated production)[4]: Z' signals unobservable, W' observable, but spin determination only for light resonances and with increased luminosity

[3] Alves, Eboli, Goncalves Netto, Gonzalez-Garcia *et al* (2009).

[4] Birkedal, Matchev (2005), Alves, Eboli *et al* (2009), Asano, Shimizu (2011).

Couplings

- **Model independent spirit:**
  Free parameters:

$$\left(\frac{g_{V'q\bar{q}}}{g_{Vq\bar{q}}}\frac{g_{V'WV}}{g_{V'WV\,max}}\right) \equiv G, \quad \Gamma_{V'} \quad \text{and} \quad M_{V'}$$

  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:

$$\Gamma_{Z'} \;>\; 0.27\,|G|\,\left(\frac{M_{Z'}}{M_Z}\right)^2 \text{ GeV}$$
$$\Gamma_{W'} \;>\; 0.40\,|G|\,\left(\frac{M_{W'}}{M_W}\right)^2 \text{ GeV}$$

- Concreteness ⇒ couplings with **same Lorentz structure as SM** ones but arbitrary strengh. (Higgsless models)
- $Z'ZZ$ coupling vetoed. (Higgsless models)

Simulation overview

Present bounds on Z' from LHC data (updated from Moriond)

- 4.7 fb^{-1} from ATLAS analysis and 4.6 fb^{-1} from CMS analysis
- Using SM backgrounds carefully evaluated by experimental collaborations, simulating only Z' signal (tuned MC)

Determination of the spin of Z' and W' (prediction for 14 TeV)

- 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)
- **Spin assignment**: from final state leptons spin correlations and angular distributions of the produced EW gauge bosons.
- Parton level study keeping the full helicity structure of the amplitude (MadGraph) including experimental resolutions and detection efficiencies.

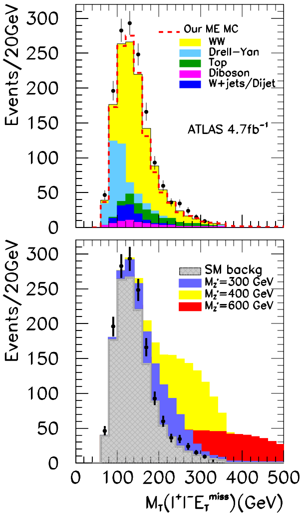
ATLAS analysis

$$pp \to \ell^+\ell^- \not{E}_T$$

- 4.7 fb^{-1} from ATLAS-CONF-2012-025
- Cuts

$$|\eta_e| < 1.37 \text{ or } 1.52 < |\eta_e| < 2.47 \ , \ |\eta_\mu| < 2.4.$$
$$\Delta R_{ee} > 0.3 \ , \ \Delta R_{e\mu,\mu\mu} > 0.2 \ .$$
$$p_T > 25 \ (20) \ \text{GeV},$$
$$M_{\ell\ell} > 15 \ \text{GeV} \ , \quad M_{e\mu} > 10 \ \text{GeV},$$
$$|M_{\ell\ell} - M_Z| > 15 \ \text{GeV},$$
$$E_{T,\ rel}^{miss}(ee) > 50 \ \text{GeV} \ , \quad E_{T,\ rel}^{miss}(\mu\mu) > 55 \ \text{GeV}$$
$$E_{T,\ rel}^{miss}(e\mu) > 25 \ \text{GeV},$$
$$\text{Jet veto } p_T > 30 \text{ GeV and } |\eta_j| < 4.5 \ .$$

- Use W^+W^- to tune MC and simulate Z' signal.
- $Z' \to$ excess of events at higher M_T values $\to$ use transverse mass spectrum to place constraints on Z' properties.



CMS analysis

$$pp \to \ell^+\ell^- \not{E}_T$$

- 4.6 fb^{-1} from arXiv:1202.1489 [hep-ex]
- Cuts

$|\eta_e| < 2.5$ and $|\eta_\mu| < 2.4$.

$\Delta R_{ee} > 0.4$, $\Delta R_{e\mu,\mu\mu} > 0.3$.

$p_T > 20$ (15) GeV,

$M_{\ell\ell} > 20$ GeV , $M_{e\mu} > 12$ GeV,

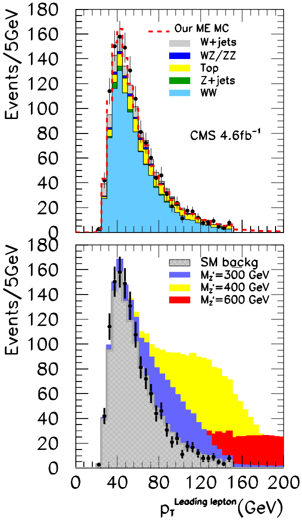
$|M_{\ell\ell} - M_Z| > 15$ GeV,

$E_{T,\ rel}^{miss}(ee,\mu\mu) > 40$ GeV , $E_{T,\ rel}^{miss}(e\mu) > 20$ GeV

$p_T^{\ell\ell} > 45$ GeV,

Jet veto $p_T > 30$ GeV and $|\eta_j| < 5.0$.

- Again W^+W^- to tune MC and simulate Z' signal.
- $Z' \to$ excess of events at higher p_T^{lead} values $\to$ use spectrum to place constraints



Statistical analysis

ATLAS: M_T spectrum

$$-2\ln L_{\mathrm{ATLAS}}(M_{Z'},G,\Gamma_{Z'}) = \underset{\xi_j}{\mathrm{Min}} \left\{ 2\sum_{i=1}^{N_{AT}^{max}} \left[N_B^i + N_S^i - N_d^i + N_d^i \log\frac{N_d^i}{N_B^i + N_S^i} \right] \right.$$
$$\left. + \left(\frac{\xi_b^{st}}{\sigma_b^{st}}\right)^2 + \left(\frac{\xi_b^{sy}}{\sigma_b^{sy}}\right)^2 + \left(\frac{\xi_s^{st}}{\sigma_s^{st}}\right)^2 + \left(\frac{\xi_s^{sy}}{\sigma_s^{sy}}\right)^2 \right\} \equiv \chi^2_{\mathrm{ATLAS}}(M_{Z'},G,\Gamma_{Z'})$$

$$N_B^i = N_b^i\left(1+\xi_b^{st}+\xi_b^{sy}\right) + N_{ww}^i\left(1+\xi_s^{st}+\xi_s^{sy}\right)$$
$$N_S^i = \left(G^2\,N_{Z'}^i + G\,N_{int}^i\right)\left(1+\xi_s^{st}+\xi_s^{sy}\right)$$

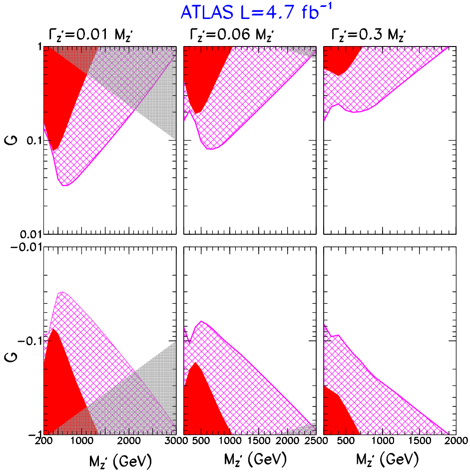
CMS: leading lepton transverse momentum

$$\chi^2_{\mathrm{CMS}}(M_{Z'},G,\Gamma_{Z'})$$

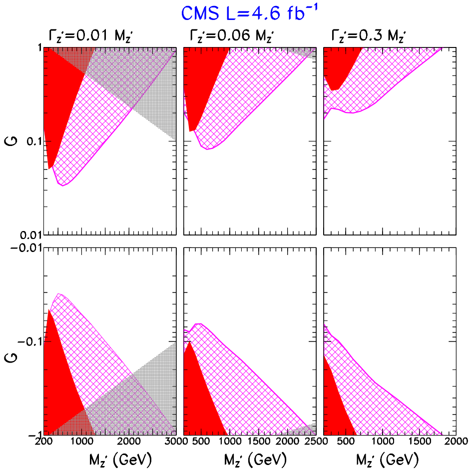
Combination:

$$\chi^2_{\mathrm{comb}}(M_{Z'},G,\Gamma_{Z'}) = \chi^2_{\mathrm{ATLAS}}(M_{Z'},G,\Gamma_{Z'}) + \chi^2_{\mathrm{CMS}}(M_{Z'},G,\Gamma_{Z'})$$

95% exclusion limits on the production of a Z'



95% exclusion limits on the production of a Z'



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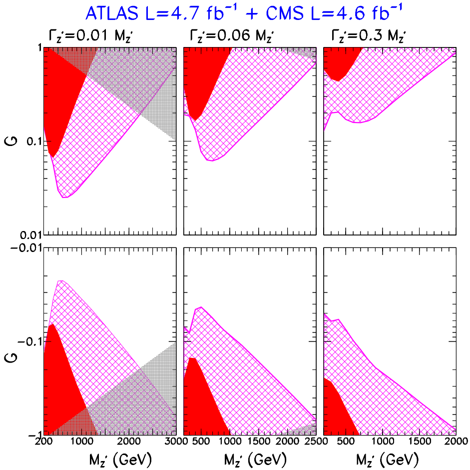

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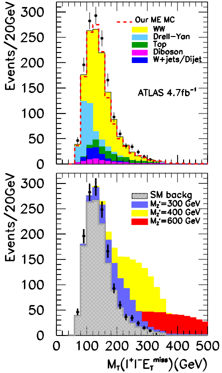

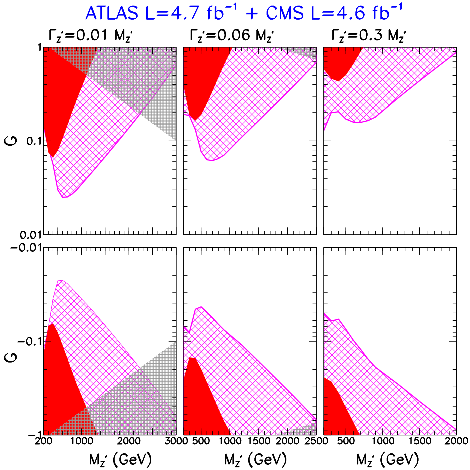

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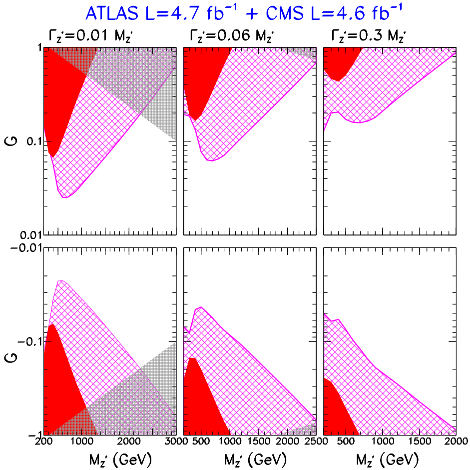


Spin determination

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

- Basic cuts: η_ℓ, $\Delta R_{\ell\ell}$, p_T^ℓ, $\not{E}_T$, $M_{\ell\ell}$, jet veto for Z'

  Invariant mass: W': two fold ambiguity
  Z': M_T or M_{T_2} assisted on-Shell reconstruction (MAOS)

- Contrast the production of particles with different spin[5] :

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

  or using the neutrino reconstruction $\to$ Z polar angle in the WZ COM frame (for Z' use MAOS)

$$\cos\theta_{WZave}$$

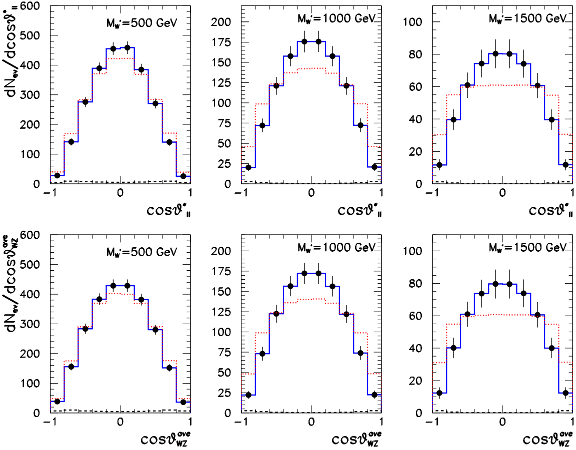
  Expected behaviour:

  spin–1 $\to$ peaked at $\cos\theta^*_{\ell\ell} = 0$
  spin–0 $\to$ flat

However, with the cuts...

[5] Smillie, Webber (2005), Alves, Éboli, Plehn (2006), Alves, Éboli (2007).

$\cos\theta^*_{\ell\ell}$ 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 $\rightarrow \cos\theta_{WZave}$ larger uncertainties

Construction of asymmetry:

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

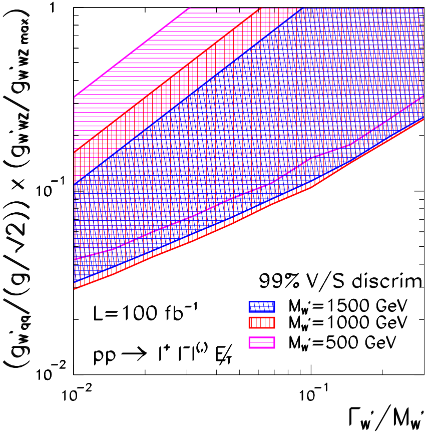
(eliminates normalization systematics)

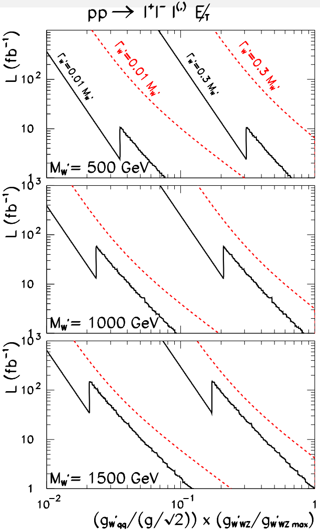
99% CL spin determination for a given $\mathcal{L}$ (assuming vector distributions):

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

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

99% CL spin discrimination





Conclusions

- 7 TeV LHC run (4.7 fb^{-1} ATLAS + 4.6 fb^{-1} CMS) excludes a big region of the parameter space for the production of a Z'.

  Ex.: Z' saturating partial wave amplitude and with SM strength to quarks (*i.e.* $G = 1$) excluded up to 2 TeV.

  Model independent bounds → Adaptable to any model! → **arXiv:1112.0316**

- 99% CL Determination of the spin possible in a sizeable 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'.

  (W') $\cos\theta^*_{\ell\ell}$ and $\cos\theta_{WZ}$ similar power → no need of COM reconstruction

  Ex.: Z' in Higgsless models: → **arXiv:1102.3429**

$$\left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\,\frac{g_{Z'WW}}{g_{Z'WW\,max}}\right)_{M_{Z'}<1\text{ TeV}} \simeq \mathcal{O}(0.1)$$

→ Observation and Spin determination ~ 100fb^{-1}

Conclusions

- 7 TeV LHC run (4.7 fb^{-1} ATLAS + 4.6 fb^{-1} CMS) excludes a big region of the parameter space for the production of a Z'.

  Ex.: Z' saturating partial wave amplitude and with SM strength to quarks (*i.e.* $G = 1$) excluded up to 2 TeV.

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

THANK YOU!

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

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

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

Cuts-W'

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

- Main SM backgrounds:

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

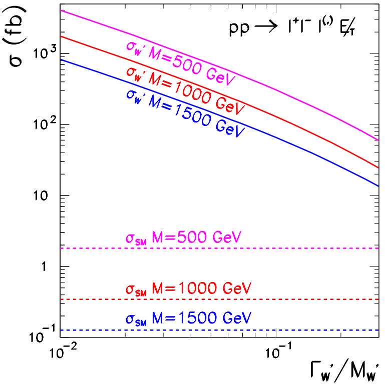
- Starting cuts $\to |\eta_\ell| < 2.5$, $\Delta R_{\ell\ell} > 0.2$, $p_T^\ell > 10$ GeV and $\not{E}_T > 10$ GeV
- SFOC leptons $\to |M_{\ell^+\ell^-} - M_Z| < 20$ GeV.
- Leading lepton $\to p_t > 120$ GeV
- ν reconstruction:
  Imposing $(p^\nu + p^\ell)^2 = M_W^2 \Rightarrow$ twofold ambiguity

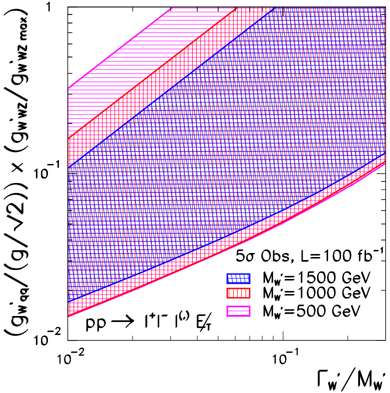
$$|M_{\rm rec}^{\rm min} - M_{W'}| < \delta \ .$$

with

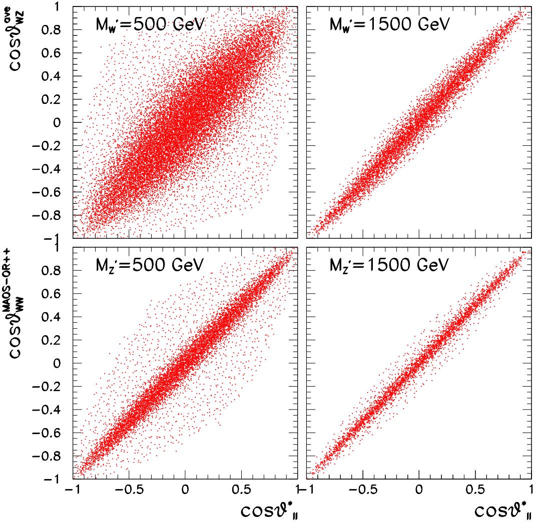
$$M_{W'} = 500 \text{ GeV} \to \delta = 50 \text{ GeV}$$
$$M_{W'} = 1000 \text{ GeV} \to \delta = 100 \text{ GeV}$$
$$M_{W'} = 1500 \text{ GeV} \to \delta = 200 \text{ GeV}$$

Cross sections and 5σ signal observation-W'





$\cos\theta^*_{\ell\ell}$ 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.

Cuts-Z'

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

- 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).

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 $W^+(p_1+p_2)W^-(k_1+k_2) \rightarrow \ell^+(p_1)\nu(p_2)\ell^-(k_1)\nu(k_2)$:

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

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

Without initial state radiation:

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

[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:

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

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

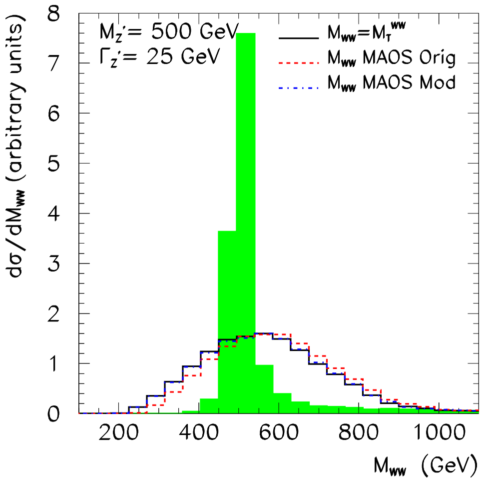
where $A \equiv M_W^2/2 + \mathbf{p_1}_T \cdot \mathbf{p_2}_T^{\text{maos}}$ and $B \equiv M_W^2/2 + \mathbf{k_1}_T \cdot \mathbf{k_2}_T^{\text{maos}}$.

- MAOS-modified[9]:

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

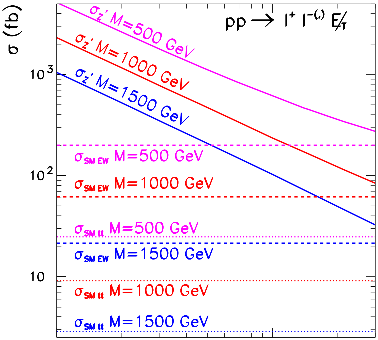
[9] K. Choi, S. Choi and J. S. Lee (2009).

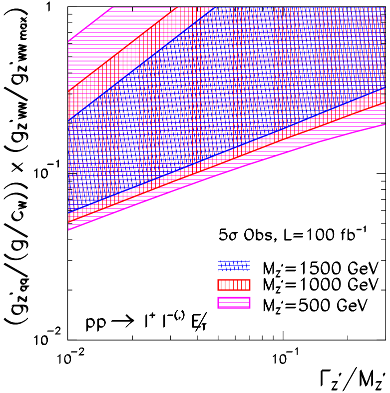
WW invariant mass



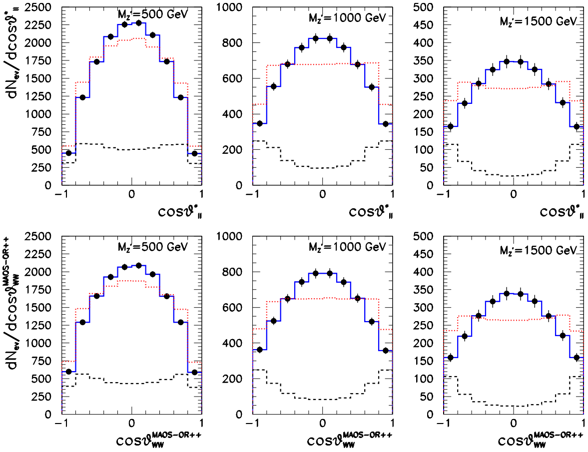
$$M_T^{WW} > \frac{M_{Z'}}{2}$$

Cross Sections and 5σ signal observation





$\cos\theta^*_{\ell\ell}$ 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}.

99% CL spin discrimination