Combining Searches of Z' and W' Bosons

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arXiv: 1211:2229

November, 2012

Introduction

- Z' and W' i.e. massive vector bosons (neutral or charged) at the TeV scale are common predictions of theories beyond the SM.

- Several direct searches of these particles are done by ATLAS and CMS: through leptonic decays, hadronic decays, dibosons...

- We analyze in a model-independent way the possible scenarios where TeV vector bosons can appear, focusing in those with sizable leptonic signals at LHC.

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New Vector Bosons

- Gauge Symmetry: The origin of the interactions.
- It allows to keep the SM unitary and renormalizable.

$$SU(3)_c \times SU(2)_L \times U(1)_Y \xrightarrow{EWSB} SU(3)_c \times U(1)_{EM}$$

- **New Physics furnish complete representations of the SM gauge group.**

Vector	$\mathcal{B}_\mu$	$\mathcal{B}^1_\mu$	$\mathcal{W}_\mu$	$\mathcal{W}^1_\mu$	$\mathcal{G}_\mu$	$\mathcal{G}^1_\mu$	$\mathcal{H}_\mu$	$\mathcal{L}_\mu$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,\mathrm{Adj})_0$	$(1,\mathrm{Adj})_1$	$(\mathrm{Adj},1)_0$	$(\mathrm{Adj},1)_1$	$(\mathrm{Adj},\mathrm{Adj})_0$	$(1,2)_{-\frac{3}{2}}$

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$$\{\mathcal{W},\mathcal{B}\} = \{(\underbrace{\mathcal{W}^-,\mathcal{W}^+}_{\text{Charged}},\underbrace{\mathcal{W}^0),\mathcal{B}}_{\text{Neutral}}\}$$

SM+$\mathcal{W}$+$\mathcal{B}$

The most general 4-dimensional lagrangian with couplings with the currents of the SM:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\left[D_\mu \mathcal{B}_\nu D^\nu \mathcal{B}^\mu - D_\mu \mathcal{B}^\nu D^\mu \mathcal{B}_\nu\right] + \frac{\mu_{\mathcal{B}}^2}{2}\mathcal{B}_\mu \mathcal{B}^\mu$$
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$$+ g_{\mathcal{B}\mathcal{B}}\mathcal{B}_\mu \mathcal{B}^\mu \phi^\dagger \phi + g_{\mathcal{W}\mathcal{W}}\mathcal{W}_\mu^a \mathcal{W}_a^\mu \phi^\dagger \phi + g_{\mathcal{W}\mathcal{B}}\mathcal{W}_\mu^a \mathcal{B}^\mu \phi^\dagger \frac{\sigma_a}{2}\phi$$
$$- \left(g_{\mathcal{B}}^\phi \mathcal{B}^\mu \phi^\dagger i D_\mu \phi + g_{\mathcal{W}}^\phi \mathcal{W}_a^\mu \phi^\dagger \frac{\sigma^a}{2} i D_\mu \phi + \mathrm{h.c.}\right) - \left(\mathcal{B}^\mu J_{\mathcal{B}\mu} + \mathcal{W}_a^\mu J_{\mathcal{W}\mu}^a\right)$$

The SM currents can be

$$J_{\mathcal{B}}^\mu = \sum_{\text{fermions}} g_{\mathcal{B}}^f \left[\bar{f} \otimes f\right]_{\text{singlet}}^\mu$$
$$J_{\mathcal{W}}^{a,\mu} = \sum_{\text{fermions}} g_{\mathcal{W}}^f \left[\bar{f} \otimes f\right]_{\text{triplet}}^{a,\mu}$$

We will focus on Drell-Yan production (non mixing-suppressed).

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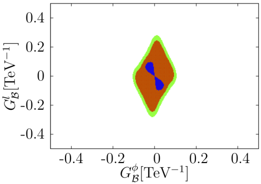

$G_{\mathcal{B}}^{f,\phi} \equiv g_{\mathcal{B}}^{f,\phi} / M_{\mathcal{B}}$

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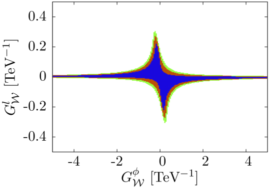

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Corrections due to SM mixing terms (g_V^ϕ):

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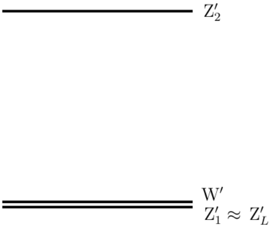
Mass eigenvectors:

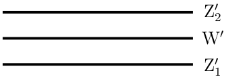
$$Z'_{1\mu} = \cos\theta \mathcal{W}^3_\mu - \sin\theta \mathcal{B}_\mu$$
$$Z'_{2\mu} = \sin\theta \mathcal{W}^3_\mu + \cos\theta \mathcal{B}_\mu$$

$$\sin 2\theta = \frac{g_{\mathcal{WB}} v^2}{2\left(M^2_{Z'_2} - M^2_{Z'_1}\right)}$$

Scenario 1: $|M^2_\mathcal{B} - M^2_\mathcal{W}| \gg v^2$



Scenario 2: $|M^2_\mathcal{B} - M^2_\mathcal{W}| \lesssim v^2$



A triplet plus a singlet at different scales without mixing between them.

Two Z' and a W'nearly degenerate in mass: Important interference effects between Z'.

Triplets

- Drell-Yan production at LHC at LO (NWA) for Z′ (Carena et al. '04):

$$\sigma(pp \to l^+l^-) = \sigma(pp \to Z') \times \Gamma(Z' \to l^+l^-) = \frac{\pi}{6s}\left[c_u \omega_u(s, m_{Z'}^2) + c_d \omega_d(s, m_{Z'}^2)\right]$$

$$c_q = \left(g_R^{q2} + g_L^{q2}\right) \mathrm{Br}(Z' \to l^+l^-)$$

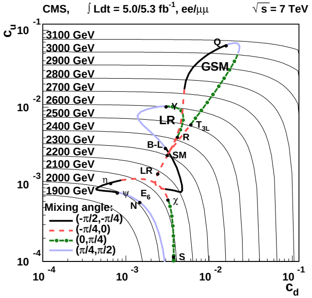
Example: $c_u - c_d$ plane for the triplet $\mathcal{W}_\mu^a$ (scenario 1)

- $W_L' + Z_L'$
- In the NWA and neglecting interference with SM, the limits depend only on

$$\tilde{g}_{\mathcal{W}} = \frac{2 g_{\mathcal{W}}^l g_{\mathcal{W}}^q}{\sqrt{3 g_{\mathcal{W}}^{q2} + g_{\mathcal{W}}^{l2}}}.$$

- Analysis in the neutral channel with the NWA:

$$c_u = c_d = \frac{\tilde{g}_{\mathcal{W}}^2}{96}.$$



S. Chatrchyan et al. '12

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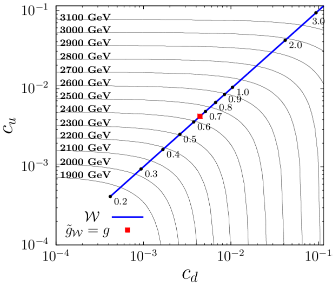


The Generalized Sequential Model (GSM)

- Based on a two-site moose with the SM electroweak group on each site:

$$[SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2 \xrightarrow{\text{broken to}} [SU(2)\times U(1)]_{\text{diag}}$$

(W′,Z'_1,Z'_2) equals to (W,Z,γ), with the replacements:

$$g\to gt,\qquad g'\to g't' \qquad \tan\theta_W \to \tan\theta = \tan\theta_W \frac{t'}{t} \in [0,\infty] \qquad e\to \frac{e}{\sqrt{t'^{-2}+\tan\theta_W t^{-2}}}$$

Same mass matrix as SM, but shifted (splitting $<$ 10 GeV).

Parametrization: $\left(\bar{t}=\frac{t+t'}{2},\theta,M_{\mathcal{W}}\right)$.

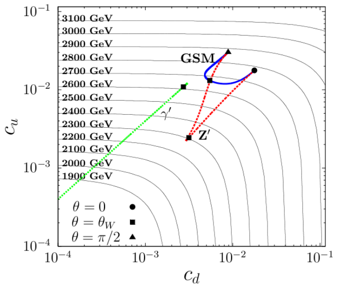
- $\mathbf{c_u - c_d}$ **analysis for** $\boldsymbol{\Delta} < \mathcal{O}(\boldsymbol{\Gamma}) << \mathbf{M_V}$:

$$c_q = \frac{1}{6\pi \mathrm{Tr}\Sigma}\left\{\mathrm{Tr}\left[G_l G_q\right] + \frac{\mathrm{Tr}\left[G_l\tilde{\Sigma}G_q\tilde{\Sigma}\right]}{\det\Sigma}\right\},$$

$$\Sigma_{ij} = \frac{1}{24\pi}\sum_{\text{fermions}}\left[(g_L^f)_i(g_L^f)_j + (g_R^f)_i(g_R^f)_j\right],$$

$$\tilde{\Sigma}_{ij} \equiv \mathrm{adj}(\Sigma)_{ij} = \epsilon_j^m\epsilon_i^n\Sigma_{mn},$$

$$G_{ij}^{q/l} = (g_V^{q/l})_i(g_V^{q/l})_j + (g_A^{q/l})_i(g_A^{q/l})_j.$$



② Direct Searches

- **Exclusion limits**: dileptonic and lepton+$\not{E}_T$ channels independently and combining in the same likelihood both of them (data from CMS collaboration, $L = 5fb^{-1}$, $\sqrt{s} = 7$TeV, 2012).

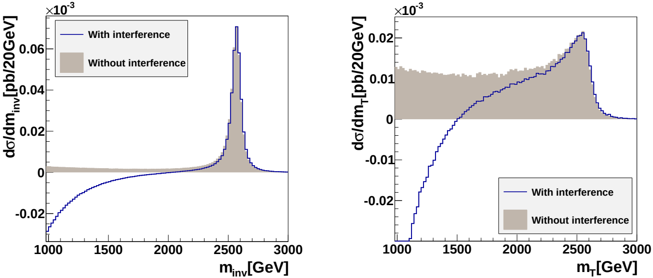
Monte Carlo simulation done with:

- MadGraph/MadEvent 4.5 for signal simulation
- PYTHIA 6.426 for parton showering and hadronization
- PGS 4 for detector simulation

We should take into account non trivial effects due to

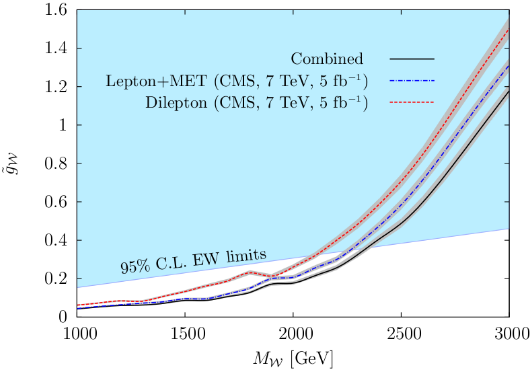
- Systematic errors (estimated on $10\% - 15\%$)
- Interference effects due to nearly degenerate resonances
- Interference with SM process

Simulation at CMS at $\sqrt{s} = 7$TeV, for a GSM ($M_{\mathcal{W}} = 2.6$TeV,$\theta = \theta_W$,$\bar{t}$=1):



Exclusion limits

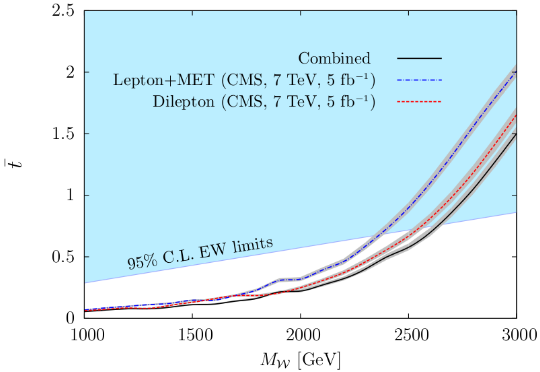
Triplet $(g^q_{\mathcal{W}} = g^l_{\mathcal{W}})$ in the plane $(M_{\mathcal{W}} - \tilde{g}_{\mathcal{W}})$



Exclusion limits at 95%CL

Exclusion limits

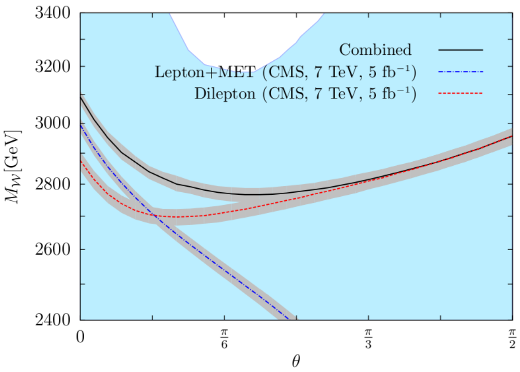
GSM with $\theta = \theta_W$ in the plane $(M_{\mathcal{W}} - \bar{t})$



Exclusion limits at 95%CL

Exclusion limits

GSM with $\bar{t} = 1$ in the plane $(\theta - M_{\mathcal{W}})$



Exclusion limits at 95% CL

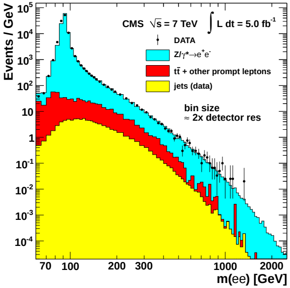
3 Summary and Outlook

Summary and Outlook

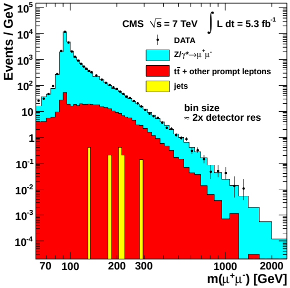
- We have analyzed the different scenarios where sizable leptonic signal from vector resonances at the TeV scale can be observed in LHC:
  - Any W' has to be accompanied with at least one Z' boson nearly degenerate in mass.
  - Any Z' with significant isospin breaking has to be accompanied with a W' boson both nearly degenerate.
  - Any Z' different enough from a $\mathcal{B}$-like boson or a $\mathcal{W}^3$-like boson has to be accompanied with another Z' nearly degenerate.
- We have developed a new effective NWA approximation to describe models with two close Z', and so they can be analyzed with the $c_u - c_d$ plane.
- We have combined the neutral and charged channels in a single likelihood in order to find the exclusion limits for direct searches.
- The EW limits are still competitive and dominate for large couplings and masses.

Thank you!

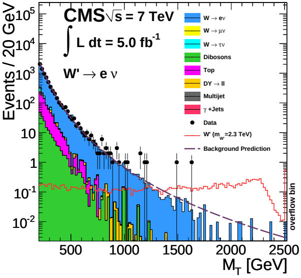
Backup



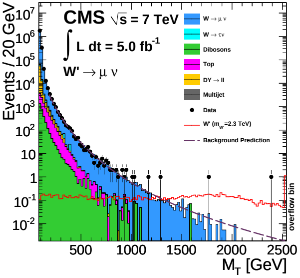
CMS √s = 7 TeV ∫ L dt = 5.0 fb⁻¹
DATA
Z/γ*→e⁺e⁻
tt̄ + other prompt leptons
jets (data)
bin size
≈ 2x detector res
Events / GeV
m(ee) [GeV]



CMS √s = 7 TeV ∫ L dt = 5.3 fb⁻¹
DATA
Z/γ*→μ⁺μ⁻
tt̄ + other prompt leptons
jets
bin size
≈ 2x detector res
Events / GeV
m(μ⁺μ⁻) [GeV]



CMS √s = 7 TeV
∫ L dt = 5.0 fb⁻¹
W' → e ν
W → eν
W → μν
W → τν
Dibosons
Top
DY → ll
Multijet
γ +Jets
Data
W' (m_W'=2.3 TeV)
Background Prediction
overflow bin
Events / 20 GeV
M_T [GeV]

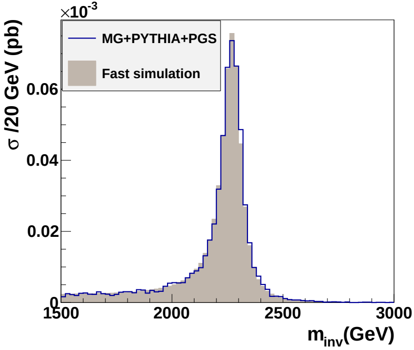


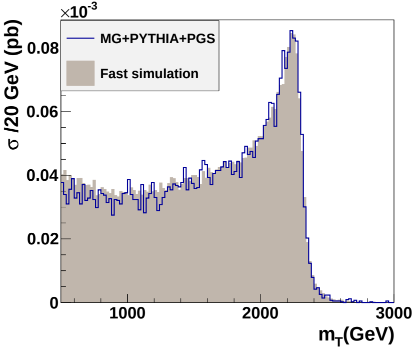
CMS √s = 7 TeV
∫ L dt = 5.0 fb⁻¹
W' → μ ν
W → μ ν
W → τν
Dibosons
Top
DY → ll
Multijet
Data
W' (m_W'=2.3 TeV)
Background Prediction
overflow bin
Events / 20 GeV
M_T [GeV]

Backup

$$J^{f,a}_{\mathcal{W}\mu} = \left[(g^{l}_{\mathcal{W}})_{ij} \bar{l}_i \gamma_\mu \frac{\sigma^a}{2} l_j + (g^{q}_{\mathcal{W}})_{ij} \bar{q}_i \gamma_\mu \frac{\sigma^a}{2} q_j \right]$$

$$J^{f}_{\mathcal{B}\mu} = \left[(g^{l}_{\mathcal{B}})_{ij} \bar{l}_i \gamma_\mu l_j + (g^{e}_{\mathcal{B}})_{ij} \bar{e}_i \gamma_\mu e_j + (g^{q}_{\mathcal{B}})_{ij} \bar{q}_i \gamma_\mu q_j + (g^{u}_{\mathcal{B}})_{ij} \bar{u}_i \gamma_\mu u_j + (g^{d}_{\mathcal{B}})_{ij} \bar{d}_i \gamma_\mu d_j \right]$$

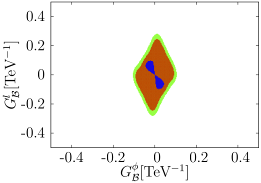


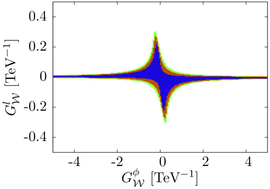


$$\xrightarrow{EWSB} \mathcal{L}_{\rm mass} = \frac{1}{2}\left(Z^\mu\ \mathcal{W}_3^\mu\ \mathcal{B}^\mu\right) \begin{pmatrix} \mu_Z^2 & \frac{g{\rm Re}[g_\mathcal{W}^\phi]v^2}{4\cos\theta_W} & -\frac{g{\rm Re}[g_\mathcal{B}^\phi]v^2}{2\cos\theta_W} \\ \frac{g{\rm Re}[g_\mathcal{W}^\phi]v^2}{4\cos\theta_W} & M_\mathcal{W}^2 & -\frac{g_{\mathcal{W}\mathcal{B}}v^2}{4} \\ -\frac{g{\rm Re}[g_\mathcal{B}^\phi]v^2}{2\cos\theta_W} & -\frac{g_{\mathcal{W}\mathcal{B}}v^2}{4} & M_\mathcal{B}^2 \end{pmatrix} \begin{pmatrix} Z_\mu \\ \mathcal{W}_\mu^3 \\ \mathcal{B}_\mu \end{pmatrix} +$$

$$+\left(W^{\mu\dagger}\ \mathcal{W}^{\mu\dagger}\right) \begin{pmatrix} \mu_W^2 & \frac{gg_\mathcal{W}^\phi v^2}{4} \\ \frac{gg_\mathcal{W}^{\phi *} v^2}{4} & M_\mathcal{W}^2 \end{pmatrix} \begin{pmatrix} W_\mu \\ \mathcal{W}_\mu \end{pmatrix}$$

Perturbativity + Electroweak precision tests ($G_V^{f,\phi} \equiv g_V^{f,\phi}/M_V$):



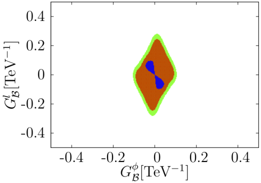


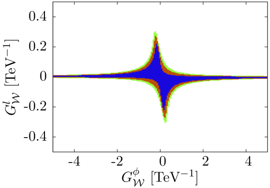
Backup

$$\xrightarrow{EWSB} \mathcal{L}_{\rm mass} = \frac{1}{2}\left(Z^\mu\ \mathcal{W}_3^\mu\ \mathcal{B}^\mu\right)\begin{pmatrix} \mu_Z^2 & \cancel{\frac{g\mathrm{Re}[g_\mathcal{W}^\phi]v^2}{4\cos\theta_W}} & \cancel{-\frac{g\mathrm{Re}[g_\mathcal{B}^\phi]v^2}{2\cos\theta_W}} \\ \cancel{\frac{g\mathrm{Re}[g_\mathcal{W}^\phi]v^2}{4\cos\theta_W}} & M_\mathcal{W}^2 & -\frac{g_{\mathcal{W}\mathcal{B}}v^2}{4} \\ \cancel{-\frac{g\mathrm{Re}[g_\mathcal{B}^\phi]v^2}{2\cos\theta_W}} & -\frac{g_{\mathcal{W}\mathcal{B}}v^2}{4} & M_\mathcal{B}^2 \end{pmatrix}\begin{pmatrix} Z_\mu \\ \mathcal{W}_\mu^3 \\ \mathcal{B}_\mu \end{pmatrix} +$$

$$+\left(W^{\mu\dagger}\ \mathcal{W}^{\mu\dagger}\right)\begin{pmatrix} \mu_W^2 & \cancel{\frac{gg_\mathcal{W}^\phi v^2}{4}} \\ \cancel{\frac{gg_\mathcal{W}^{\phi *} v^2}{4}} & M_\mathcal{W}^2 \end{pmatrix}\begin{pmatrix} W_\mu \\ \mathcal{W}_\mu \end{pmatrix}$$

Perturbativity + Electroweak precision tests ($G_V^{f,\phi} \equiv g_V^{f,\phi}/M_V$):



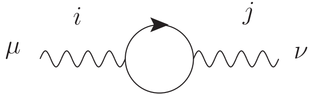


$$V_\mu = V_\mu^0 + \mathcal{O}(v^4/M_V^4), \quad \sin(\alpha) = \mathcal{O}(v^2/M^2) < \mathcal{O}(10^{-2})$$

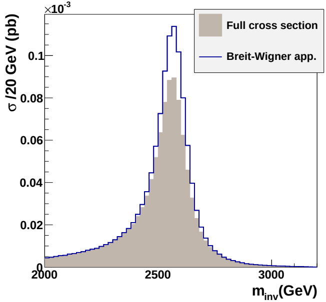
$$M_V^2 = M_{V^0}^2 + \mathcal{O}(v^4/M_V^2) \Rightarrow |M_V - M_V^0| \sim \mathrm{GeV}$$

Backup

- Breit-Wigner approximation breaks down for nearly degenerate resonances
- Imaginary non-diagonal terms of vacuum polarizations become important



$$P_{\mu\nu} = -i\left[p^2\delta_{ij} - M_{ij}^2 - i\mathrm{Im}\Pi_{ij}^T(p^2)\right]^{-1}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right]$$



Simulation at CMS at $\sqrt{s} = 7$TeV, for a GSM ($M_{\mathcal{W}} = 2.6$TeV,$\theta = \pi/4$,t=1)

Backup

Some important consequences:

- Any W′ has to be accompanied with at least one Z′ boson nearly degenerate in mass. For masses of at least $1\mathrm{TeV}$:

$$g_{\mathcal{WB}} \leq 1 \Rightarrow |M_{W'} - M_{Z'_1}| \leq 7.8\mathrm{GeV}$$

$$g_{\mathcal{WB}} \leq 4\pi \Rightarrow |M_{W'} - M_{Z'_1}| \leq 94\mathrm{GeV}$$

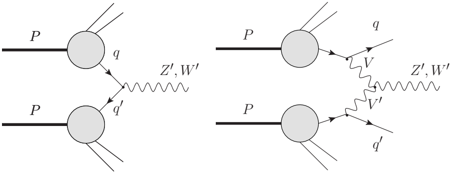
- Any Z′ with significant isospin breaking has to be accompanied with a W′ boson both nearly degenerate.

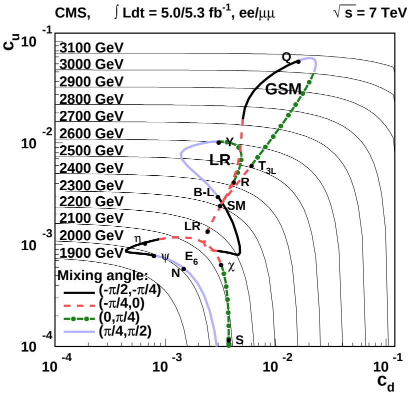
- Any Z′ different enough from a $\mathcal{B}$-like boson or a $\mathcal{W}^3$-like boson has to be accompanied with another Z′ nearly degenerate.

- To obtain a sequential Z′, for masses of at least $1\mathrm{TeV}$:

$$g_{\mathcal{WB}} \leq 1 \Rightarrow |M_{Z'_2} - M_{Z'_1}| \leq 50\mathrm{GeV}$$

- Vector bosons can be produced by Drell-Yan processes or vector boson fusion:





S. Chatrchyan et al. '12

- Drell-Yan production at LHC at LO (NWA) for Z′ (Carena et al. '04):

$$\sigma(pp \to l^+ l^-) = \sigma(pp \to Z') \times \Gamma(Z' \to l^+ l^-)$$

$$= \frac{\pi}{6s}\left[c_u \omega_u(s, m_{Z'}^2) + c_d \omega_d(s, m_{Z'}^2)\right]$$

$$c_q = \left(g_R^{q2} + g_L^{q2}\right) \mathrm{Br}(Z' \to l^+ l^-)$$