Z’ VBF at the LHC

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Z’

- Are there any new gauge bosons beyond the ones associated with the $SU(3)\times SU(2)\times U(1)$ gauge group?
- In many beyond standard model theories, new gauge bosons are predicted.
- simplest way, include a second $U(1)$ group. new gauge boson $Z’$
- $Z’$ mixes with the $Z$ boson, $Z’WW$ coupling $\sim \sin\phi$
- $Z’$ also couples to fermions,

$$\mathcal{L} = \sum_f z_f g_Z Z'_{\mu} \bar{f} \gamma^\mu f$$

fermion charges coupling
current LHC Z’ searches

• qq ->Z’-> l+l−

2.7 fb⁻¹ (13 TeV, ee) + 2.9 fb⁻¹ (13 TeV, ϒυ)

$E_6 \rightarrow SO(10) \otimes U(1)_\psi$

$\rightarrow SU(5) \otimes U(1)_\chi \otimes U(1)_\psi$

sequential SM:
Z’ has SM Z couplings.

easy to compare
not gauge invariant

Only sensitive to Z’ff couplings
VBF is sensitive to $Z'WW$ coupling.

VBF process has distinctive kinematics -- easy to suppress backgrounds

- energetic jets in the forward direction, because of the t-channel kinematics
- large rapidity separation and large invariant mass of the two jets
VBF $Z'$ cross section

For a 1 TeV $Z'$, assuming its coupling to a pair of $W$ is the same as a $Z$ boson,

$$\sigma_{pp \rightarrow WWjj \rightarrow Z'jj} = 6.8 \text{ pb}$$  \hspace{1cm} \text{MadGraph}$$

Very different from a heavy Higgs

$$\sigma_{pp \rightarrow WWjj \rightarrow Hjj} = 62 \text{ fb}$$  \hspace{1cm} \text{MadGraph}$$

full NNLO calculation, VBFNNLO

$$\sigma_{pp \rightarrow WWjj \rightarrow Hjj} = 87 \text{ fb}$$

Both have weak coupling, why $Z'$ cross section so much larger?
Zprime VBF cross section, effective W approximation

• At the LHC, $\sqrt{s} \gg m_W$, one can consider the initial beams of quarks as sources which emit $W$s. Then $W$ interact to produce new states. Or equivalently, giving $W$s structure function. (Kane, Repko, and Rolnick, 1984. Dawson 1985)

• When using the effective $W$ approximation,

  • First calculate $\hat{\sigma}(W^+W^- \rightarrow Z')$

  • Then calculate the $W$ luminosity $L_{W^+W^-|pp}(\hat{s})$
\[ \hat{\sigma}(W^+W^- \rightarrow Z') \]

Assume Z'WW coupling is the same as ZWW

\[
\hat{\sigma}(W^+W^- \rightarrow Z' \rightarrow W^+W-) = \frac{16\pi}{3} \frac{m_{Z'}^2}{m_{Z'}^2 - 4m_W^2} \frac{(\Gamma(Z' \rightarrow WW))^2}{((\hat{s}_{WW} - m_{Z'}^2)^2 + \Gamma_{tot}^2 m_{Z'}^2)}
\]

\[ \Gamma(Z' \rightarrow WW) = \frac{g^2 \cos^2 \theta_w}{192\pi} \frac{m_{Z'}^5}{m_W^4} \]  

\[ \Gamma(Z' \rightarrow ff) = \frac{5}{8} \frac{\alpha m_{Z'}^2}{\cos^2 \theta_w} \]  

large enhancement factor for heavy Z'  

Dutta and Nandi, 1993

Small, compared to Z' \rightarrow WW  

Rizzo, 1995

\[ \hat{\sigma}(W^+W^- \rightarrow Z') \simeq \hat{\sigma}(W^+W^- \rightarrow Z' \rightarrow W^+W^-) \]
Effective $W$ approximation

Distribution of a $W$ inside a quark is given by

$$dF(x, k) = \frac{(E + E' + \omega)^2}{(64\pi^3 EE'\omega)} \frac{\langle |M|^2 \rangle}{(2p \cdot k - m_W^2)^2} |P| dx dk d\phi$$

Kane, Repko, and Rolnick, 1984. Dawson 1985

$$M = \bar{u}(p') \gamma(g_V + g_A \gamma_5) u(p)$$

$$dF(x)dx = \frac{1}{12\pi^2 (g_V^2 + g_A^2)} \{1 + \frac{(1 - x)^2}{x} \log(p^2 + (1 - x)m_W^2)\} \frac{1}{(1 - x)m_W^2} + \frac{(1 - x)p^2}{x(p^2 + (1 - x)m_W^2)} \} dx$$

transverse

Longitudinal
Effective W approximation

WW luminosity in a two-quark system

\[ \left. \frac{dL}{d\tau} \right|_{qq/WW}^{\tau} = \int_{\tau}^{1} f(q/W)(x) f(\tau/x) \frac{dx}{x} \]

WW luminosity in a proton-proton system

\[ \left. \frac{dL}{d\tau} \right|_{pp/WW}^{\tau} = \int_{\tau}^{1} \frac{d\tau'}{\tau} \int_{\tau}^{1} \frac{dx}{x} f_i(x) f_j(1) d\xi \left. \frac{dL}{d\xi} \right|_{qq/WW} \]

Z' production cross section through VBF

\[ \sigma = \int_{m_{Z'}}^{1} \frac{d\tau}{d\tau} \left. \frac{dL}{d\tau} \right|_{pp/WW} \sigma_{WW \rightarrow Z'} \]
VBF $Z'$ vs Higgs

For the Higgs, only longitudinal mode contributes

$$\frac{dL}{d\tau}|_{qq/V^tV^t} = \left(\frac{g_V^2 + g_A^2}{4\pi^2}\right)^2 \frac{1}{\tau} [(1 + \tau)\log(1/\tau) + 2(\tau - 1)]$$

For a $Z'$, transverse mode, longitudinal mode, and transverse-longitudinal mode contribute. The transverse mode dominates.

$$\frac{dL}{d\tau}|_{qq/V^tV^t} = \left(\frac{g_V^2 + g_A^2}{8\pi^2}\right)^2 \frac{1}{\tau} \log\left(\frac{\hat{s}}{m_W^2}\right)^2 [(2 + \tau)^2 \log(1/\tau) - 2(1 - \tau)(3 + \tau)]$$

Large enhancement factor when the $Z'$ is heavy
VBF Z’ cross section

For a 1 TeV Z’, assuming its coupling to a pair of W is the same as a Z boson

Using effective W approximation,  \( \sigma_{pp\rightarrow WWjj\rightarrow Z'jj} = 5.3\text{pb} \)

Corrections of effective W approximation are \( O(m_W^2/m_{Z'}^2) \), and \( O(m_{Z'}^2/s) \)

For a 1 TeV heavy Higgs

Using effective W approximation,  \( \sigma_{pp\rightarrow WWjj\rightarrow Hjj} = 50\text{fb} \)

In models where Z’WW is generated through Z-Z’ mixing, the cross section scales as

\( \sim g_{WWZ'}^2 \sim \sin^2 \theta_{Z-Z} \)
Constraints on Z-Z’ mixing

- A Z’ mixes with SM Z distorts the Z properties.
- Strong constraints from LEP, from $e^+e^- \rightarrow ff$ measurements.
- In canonical models, VBF Z’ cross section is small, not the most sensitive channel.
- In case of discovery (from Drell-Yan process), VBF is important to establish models, and couplings.

![Graph showing constraints on the mass and mixing angle for the Z and Z’ from [17]. The solid lines show the regions allowed by precision electroweak data at 95% C.L. assuming Higgs doublets and singlets, while the dashed regions allow arbitrary Higgs. The labeled curves assume specific ratios of Higgs doublet VEVs.](image_url)
fermiophobic $Z'$

• All constraints (direct searches, electroweak precisions) are strongly weakened for fermiophobic models, where there is no direct coupling of $Z'$ to SM fermions. (The constraints are also weak for leptophobic $Z'$, or $Z'$ does not couple to first generation leptons)

• One example, consider a hidden $U(1)$, which can only couple to SM through a mixed anomaly. The gauge anomaly is cancelled by Green-Schwarz mechanism.  
  
  Kumar, Rajaraman and Wells, 2007.

• In fermiophobic models, $Z'$ can only be produced through VBF.

• possible decay modes, $Z' \rightarrow WW, ZZ, Z\gamma$
fermiophobic Z’

![Graph showing the cross section as a function of M_X for various values of M_Z']

- Z’ -> ZZ->4l
- Cross section can be sizable
- Worth studying other channels

Kumar, Rajaraman and Wells, 2007.
$Z'\rightarrow WW$

This year data, exclude $\sim 1.4 - 1.6$ TeV
Long term, exclude up to 3 TeV
Conclusion

• A new gauge boson is predicted in many beyond Standard Model theories.
• Current LHC searches are focused on Drell-Yan mode.
• For canonical models (E6, B-L), VBF process is important for establishing models.
• For fermiophobic models (and baryophobic models), Z’ can only be produced through VBF, and decay to two bosons (not a pair of photons).
• with this years data at CMS (~ 40^{-1} fb), emu can exclude up to ~ 1.6 TeV. Similarly, mumu can exclude up to ~ 1.4 TeV. with this year's data.
• Long term --> exclusions can be closer to 3 TeV.