Z' Bosons On-peak, Off-peak, and Way Off-peak

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Outline

- What is a Z'? How do we see it?
- Why do we care?
- A reasonably general model template: couplings to SM particles—discriminates without reference to a particular model!
- First stab: forming effective couplings from on-peak measurements
- Second stab: measuring Z' interference off-peak
- Finally: adding next-generation low-energy experiments
What is a Z'?  

- A new Drell-Yan resonance (pp→l⁺l⁻)  
- Neutral, colorless  
- Boson, pick your spin:  
  0 (e.g. RP-violating sneutrino)  
  1 (e.g. gauge boson)  
  2 (e.g. KK graviton)
Why do we care?

- Ubiquitous in extensions to SM
- Clean signature at LHC; very small dilepton background
- Good discovery reach
Where we are now

- No $Z'$ yet!
- Tevatron reach ~ 1 TeV; LHC ~ 5 TeV
- PDFs limiting factor at hadron collider
- LEP II, current low-energy experiments similar limits to Tevatron
We find one! What now?

- Locate resonance peak, determine mass
- Measure spin by studying angular distribution; requires few hundred events (~ 30 fb$^{-1}$)

Allanach, et. al
The framework

- We know the mass and spin—start with spin 1
- Goal: accommodate as many models as possible—from favorites to ones nobody's thought of
- What assumptions to make at LHC?
- Need to parametrize model space; will do this in terms of Z' couplings to SM particles
- Too many parameters!
Parameter reduction

- Generation-dependence leads to FCNC; strong limits (at least for first two generations)
- Weak isospin dependence generically leads to Z-Z' mixing—strongly constrained by LEP
- Most likely candidates for parameter reduction:
  1. Make couplings generation-independent
  2. Left-handed doublets have same coupling
Assume spin 1 $Z'$ found. The cross section depends on:

- The mass, $M_{Z'}$
- $Z'$ charges of SM particles (absorb overall coupling):
  $q_L, u_R, d_R, e_L, e_R$
  (couples to fermions as $g_L(1-\gamma_5)/2 + g_R(1+\gamma_5)/2$)
- The width, $\Gamma_{Z'}$
What can we measure?

- Asymmetry ($A_{FB}$): does lepton scatter with quark or against?
- $Z'$ rapidity ($Y$): different u/d PDFs yield different $Z'$ rapidity distributions (more valence u at high x)
Asymmetry

\[ A_{FB} = \frac{F - B}{F + B} \]

- LHC is pp collider—which direction is the quark direction?
- High rapidity Z's tend to come from valence quark (high x) and sea antiquark (low x)
- Higher rapidity, better odds you guess correct quark direction
Putting them together

- Z' Rapidity discriminates relative amount of u vs. d
- Asymmetry gives us parity-symmetric vs. antisymmetric information in couplings, but quark direction correlation depends on rapidity
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- “You got chocolate in my peanut butter!” “You got peanut butter in my chocolate!”
Can we use these observables to extract coupling information?

\[
\frac{d^2 \sigma}{dY \ d\cos \theta} = \sum_{q=u,d} \left[ a'^q_1 (q^2_R + q^2_L) (e^2_R + e^2_L) + a'^q_2 (q^2_R - q^2_L) (e^2_R - e^2_L) + b_1 q_L e_L + b_2 q_L e_R + b^q_3 q_R e_L + b^q_4 q_R e_R \right] + c
\]

- Mass dependence, PDFs, kinematics in a, b, c coefficients of model parameters
- a terms are Z'-only pieces
- b terms are Z' interference with Z, photon
- c is SM background (Z, photon, their interference)
\textbf{Z' cross section, continued}

- Z'-only terms have $1/((M_{Z'}^2 - s)^2 + \Gamma_{Z'}^2 M_{Z'}^2)$ dependence

- In narrow width approximation, this is $\sim \pi \delta(s - M_{Z'}^2)/\Gamma_{Z'} M_{Z'}$ near resonance peak

- $a'$ coefficients scale as $1/\Gamma_{Z'}$ if integrated around resonance peak
b, c not important on-peak

Width dependence of a's known on-peak: absorb into effective couplings

\[
c_q = \frac{M_{Z'}}{24 \pi \Gamma_{Z'}} (q_R^2 + q_L^2) (e_R^2 + e_L^2)
\]

\[
e_q = \frac{M_{Z'}}{24 \pi \Gamma_{Z'}} (q_R^2 - q_L^2) (e_R^2 - e_L^2)
\]

\[
\frac{d^2 \sigma}{dY \, d\cos \theta} = \sum_{q=u,d} \left[ a_1^q c_q + a_2^q e_q \right]
\]
Four measurements

- Four model parameters: $c_u$, $c_d$, $e_u$, $e_d$
- $c_q$ defined and bounded in Tevatron study
  Carena, Daleo, Dobrescu, Tait
- $e_q$ parity antisymmetric: need F/B asymmetry!
- Four measurements for four parameters

Define:

$$F(Y) = \int_0^1 d\cos\theta \frac{d^2\sigma}{dY\,d\cos\theta}$$
$$B(Y) = \int_{-1}^0 d\cos\theta \frac{d^2\sigma}{dY\,d\cos\theta}$$

$$F_> = \left[ \int_{Y_1}^{Y_{\text{max}}} + \int_{-Y_{\text{max}}}^{-Y_1} \right] F(Y)\,dY$$
$$B_> = \left[ \int_{Y_1}^{Y_{\text{max}}} + \int_{-Y_{\text{max}}}^{-Y_1} \right] B(Y)\,dY$$

$$F_< = \int_{-Y_1}^{Y_1} F(Y)\,dY$$
$$B_< = \int_{-Y_1}^{Y_1} B(Y)\,dY$$
Extracting the couplings

- Four measurements related to four parameters linearly:

\[
\begin{pmatrix}
F_- \\
B_- \\
F_+ \\
B_+
\end{pmatrix} =
\begin{pmatrix}
\int a_1^u \\ 
\int a_1^d \\
\int a_2^u \\
\int a_2^d
\end{pmatrix}
\begin{pmatrix}
\int a_1^u \\ 
\int a_1^d \\
\int a_2^u \\
\int a_2^d
\end{pmatrix}
\begin{pmatrix}
c_u \\
c_d \\
e_u \\
e_d
\end{pmatrix}
\]

\[
\vec{m} = M \vec{c}
\]

\[
\vec{c} = M^{-1} \vec{m}
\]
Extracting couplings, cont'd

- Matrix $M$ is model-independent; can be calculated from theory once mass known (width independent)
  1. Calculate $M$ when $Z'$ resonance found
  2. Get $\tilde{m}$ from experimenters in a few years
  3. Hire a high schooler to do matrix algebra (less $\$ than grad student)
  5. PROFIT
As long as M is nonsingular, always works

How well depends on how different rows are

In good shape if “<”, “>” entries very different (separates u vs. d)

Also need F/B entries different ($c_q$ goes like $F+B$, $e_q$ like $F-B$; should be good)

Errors for c/e depend on errors in M
Analysis

- Evaluate entries of matrix M at NLO in QCD (corrections important)
- Generate measurements for test models with full Drell-Yan (+ interference, SM)
- Code includes basic detector cuts ($|\eta| < 2.5$, $p_T > 20$ GeV)
- Include statistical and PDF errors; add in quadrature and diagonalize errors in couplings
- How well are couplings determined if we “find” a particular model?
Model test cases

- Three from $E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\psi \times U(1)_\chi$ : $\psi$, $\chi$, and a mixture $\eta$
- For illustration, overall coupling taken to retain GUT relations to EM coupling
- Also, a left-right symmetric model with gauge group $SU(2)_R$, $g_R = g_L$
- Width chosen to be decay to SM particles; only matters through statistics
Results, 1.5 TeV, 100 fb$^{-1}$

- Errors perpendicular!
- $c_u + c_d$ PDF-limited
- $c_u - c_d$ statistics limited
- Test models discriminated

Dot: PDF error
Dash: Statistical error
Solid: Total error
Dot-dash: $E_6$ family
\( e_u / e_d \) Results, 1.5 TeV, 100 fb\(^{-1}\)

- Statistics more difficult with e's, but still get something
Results, 1.5 TeV, $1 \text{ab}^{-1}$

- Dot: PDF error
- Dash: Statistical error
- Solid: Total error
- Dot-dash: $E_6$ family

- $c$'s PDF-limited only
- $e$'s start to discriminate by themselves
Results, 3 TeV, 1ab$^{-1}$

- Dot: PDF error
- Dash: Statistical error
- Solid: Total error
- Dot-dash: $E_6$ family

- Statistics and PDFs both harder
- Still get some discrimination
Limitations

\[ c_q = \frac{M_{Z'}}{24\pi \Gamma_{Z'}}(q_R^r + q_L^r)(e_R^r + e_L^r) \]

\[ e_q = \frac{M_{Z'}}{\gamma^r \pi \Gamma_{Z'}}(q_R^r - q_L^r)(e_R^r - e_L^r) \]

- Need to know width to get at fundamental model parameters
- A scaling degeneracy is left (only q X e measured)
- A sign degeneracy is left (only squares of couplings measured)
Can we do better?

- Look at cross section again:

\[
\frac{d^2 \sigma}{dY \, d\cos \theta} = \sum_{q=u,d} \left[ a_1^q \left( q_R^2 + q_L^2 \right) (e_R^2 + e_L^2) + a_2^q \left( q_R^2 - q_L^2 \right) (e_R^2 - e_L^2) \right] + \left[ b_1 q_L e_L + b_2 q_L e_R + b_3^q q_R e_L + b_4^q q_R e_R \right] + c
\]

- There's sign information! We should probe a region where this has an effect
Second stab: Off-peak

- Bin in dilepton mass, $M_{ll}$; linear terms important in region between $Z$ and $Z'$ poles, keep on-peak bin
- No easy inversion of cross section; do a brute-force scan of parameter space
- Must fit width to compare on- and off-peak measurements!
- With simple linear relation lost, might as well use more than two $Y$ bins (preliminary result: negligible improvement)
New parameters

- Still have $q_X e$ degeneracy
- This leaves $q_{e_L}, q_{e_R}, u_{e_L}, d_{e_R}$
- Other two combinations are dependent on these four:
  \[
  \frac{q_L e_L}{q_L e_R} = \frac{u_R e_L}{u_R e_R} = \frac{d_R e_L}{d_R e_R}
  \]
- Must fit width, $\Gamma$
Procedure (1.5 TeV)

- Define a set of measurements to distinguish different terms in cross section
- Bin in invariant mass (different weights in linear/quadratic terms): 800-1000 GeV, 1000-1200 GeV, 1200-1400 GeV, 1450-1550 GeV
- Bin in Y (different u/d weights): every 0.4 off-peak, 0.2 on-peak
- Split F/B (different parity weights): as defined previously
Procedure, continued

- Assume we find a particular test model corresponding to a set of measurements
- Determine statistical and PDF errors for the test model
- Scan 5D parameter space: for each test point, construct measurements
- Keep points where $\chi^2$ comparison with model within 5.9 (68% CL)
- This way we see what sections of parameter space are experimentally consistent with test model (illustrated in 2D projections of 5D confidence region)
Fitting the width

- Width determined to a few GeV by comparison of on- and off-peak alone!
- Probably better than experimental resolution of resonance shape
- Tends to correlate with larger coupling

1 ab$^{-1}$, preliminary
Fitting the couplings

- Sign degeneracy from on-peak mostly broken
- Needs both on + off peak to work!
  Degeneracies remain with off-peak only
Anything more?

- Do we need an ILC to get any further?
- What about the q X e degeneracy?
- Can we look in the quark channel?
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Probably not...
Moeller scattering

- New Jlab Moeller experiment measures asymmetry to very high precision, $\delta A \sim 0.6$ ppb
- Leads to error in $\sin^2 \theta_w^{\text{eff}}$ of $0.00025$ ($0.00017$ theory)
- $Z'$ deviation from SM goes like $(e_R^2 - e_L^2)/M_{Z'}^2$—hyperbolic bound in $e_L - e_R$ plane
- Large enough deviation leads to measurement
- We should know $e_L/e_R$ from on-/off-peak analysis—angle in $e_L - e_R$ plane (prelim: $\sim 10^\circ$)

$$\frac{q_L e_L}{q_L e_R} = \frac{e_L}{e_R}$$
Moeller scattering, continued

- Intersection of hyperbolas and lines from other data give us $e_L$ and $e_R$! Breaks degeneracy!

- At 1.5 TeV, test models consistent with Standard Model—we still limit size of $e$ couplings
Moeller scattering, continued

- Increase coupling a little: chi model, $e/\cos \theta_W \rightarrow \frac{1}{2}$

- We can see a deviation in Moeller! Now we get all SM couplings (WIP)
Summary: Z' analysis strategy

- Mostly model-independent procedure
- On-peak bin gives us square couplings with good precision, only PDF limited
- Combining with off-peak bins gives signs, width if poorly measured from resonance shape
- Moeller scattering could break last parameter degeneracy, give us all SM couplings
- Can select high scale theory with these parameters if known well enough