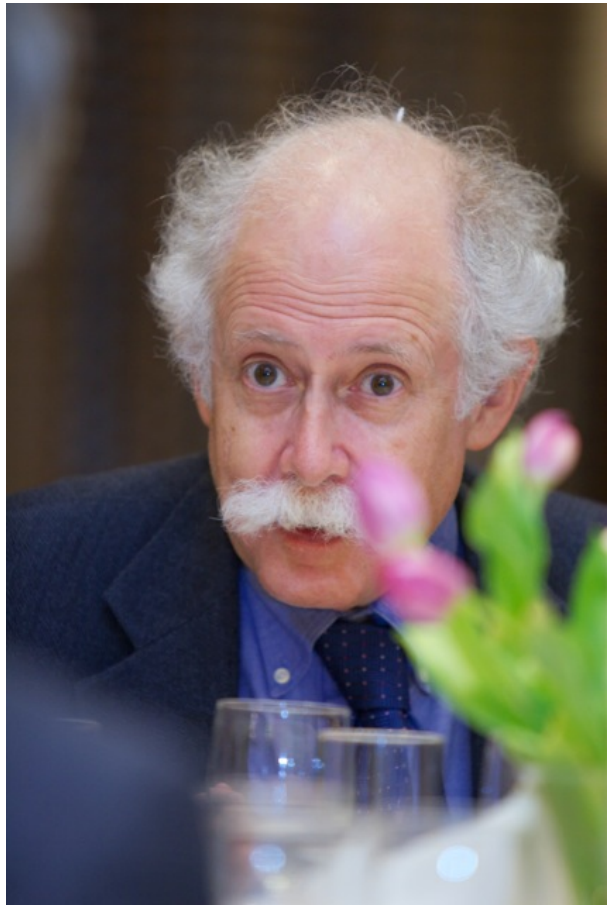
New Heavy Gauge Bosons in pp and $p\bar{p}$ Colliders



- Recollections
- Heavy Gauge Bosons
- Observation and Diagnostics


MOLECULAR MOTIONS –
SELF AND DIRECTED ASSEMBLY
AUDITORIUM
READING ROOM
CONFERENCE ROOM
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Jon Rosner Symposium (4/1/2011) *Paul Langacker (IAS)*

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New heavy gauge bosons in pp and $p\bar{p}$ collisions

Paul Langacker
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
and Institute for Advanced Study, Princeton, New Jersey 08540

Richard W. Robinett
Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003

Jonathan L. Rosner
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637
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Experimental signatures are analyzed for the production of heavy gauge bosons beyond W and Z at pp and $p\bar{p}$ colliders, including the Fermilab Tevatron and proposed multi-TeV machines. Bosons include right-handed W's and various Z's (including the one expected if I_{3R} and $B-L$ are gauged separately, not just in the combination $Y_W=2I_{3R}+B-L$). Signatures include characteristic decay asymmetries, which can occur for both pp and $p\bar{p}$ reactions, and neutral heavy leptons in the final states.

Motivations for a Z'

- **Strings/GUTS** (large underlying groups; $U(n)$ in Type IIa)
  - Harder to break $U(1)'$ factors than non-abelian (remnants)
  - Supersymmetry: $SU(2) \times U(1)$ and $U(1)'$ breaking scales *both* set by SUSY breaking scale (unless flat direction)
  - μ problem

- **Alternative electroweak model/breaking (TeV scale): DSB, Little Higgs, extra dimensions** (Kaluza-Klein excitations, $M \sim R^{-1} \sim 2\ \mathrm{TeV} \times (10^{-17}\mathrm{cm}/R)$), **left-right symmetry**

- **Connection to hidden sector** (weak coupling, SUSY breaking/mediation)

- **Extensive physics implications, especially for TeV scale Z'**

Motivations for a W'

- Less motivated than Z', but possible
- W_L: diagonal $SU(2) \subset SU(2)_1 \times SU(2)_2$ (e.g., Little Higgs); large extra dimensions (Kaluza-Klein excitations)
- W_R: $SU(2)_L \times SU(2)_R \times U(1)$
- Issues
  - Light Dirac or heavy Majorana ν_R
  - U_R (right-handed CKM)

Standard Model with Additional $U(1)'$

$$-L_{\rm NC} = \underbrace{eJ^\mu_{em}A_\mu + g_1 J^\mu_1 Z^0_{1\mu}}_{SM} + \sum_{\alpha=2}^{n+1} g_\alpha J^\mu_\alpha Z^0_{\alpha\mu}$$

$$J^\mu_\alpha = \sum_i \bar{f}_i \gamma^\mu [\epsilon^\alpha_L(i) P_L + \epsilon^\alpha_R(i) P_R] f_i$$

- $\epsilon^\alpha_{L,R}(i)$ are $U(1)_\alpha$ charges of the left and right handed components of fermion f_i (chiral for $\epsilon^\alpha_L(i) \neq \epsilon^\alpha_R(i)$)
- $g^\alpha_{V,A}(i) = \epsilon^\alpha_L(i) \pm \epsilon^\alpha_R(i)$
- May specify left chiral charges for fermion f and antifermion f^c

$$\epsilon^\alpha_L(f) = Q_{\alpha f} \qquad \epsilon^\alpha_R(f) = -Q_{\alpha f^c}$$

$$Q_{1u} = \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W \text{ and } Q_{1u^c} = +\tfrac{2}{3}\sin^2\theta_W$$

Mass and Mixing

- **Mass matrix for single Z'**

$$M^2_{Z-Z'} = \begin{pmatrix} M^2_{Z^0} & \Delta^2 \\ \Delta^2 & M^2_{Z'} \end{pmatrix}$$

- **Eg., $SU(2)$ singlet S; doublets** $\phi_u = \begin{pmatrix} \phi^0_u \\ \phi^-_u \end{pmatrix}$, $\phi_d = \begin{pmatrix} \phi^+_d \\ \phi^0_d \end{pmatrix}$

$$M^2_{Z^0} = \frac{1}{4} g_1^2 (|\nu_u|^2 + |\nu_d|^2)$$

$$\Delta^2 = \frac{1}{2} g_1 g_2 (Q_u |\nu_u|^2 - Q_d |\nu_d|^2)$$

$$M^2_{Z'} = g_2^2 (Q_u^2 |\nu_u|^2 + Q_d^2 |\nu_d|^2 + Q_S^2 |s|^2)$$

$$\nu_{u,d} \equiv \sqrt{2} \langle \phi^0_{u,d} \rangle, \qquad s = \sqrt{2} \langle S \rangle, \qquad \nu^2 = (|\nu_u|^2 + |\nu_d|^2) \sim (246 \text{ GeV})^2$$

- **Eigenvalues $M^2_{1,2}$, mixing angle θ**

$$\tan^2\theta = \frac{M^2_{Z^0} - M^2_1}{M^2_2 - M^2_{Z^0}}$$

- **For $M_{Z'} \gg (M_{Z^0}, |\Delta|)$**

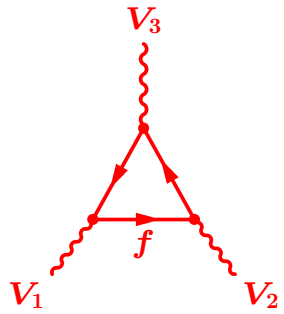
$$M^2_1 \sim M^2_{Z^0} - \frac{\Delta^4}{M^2_{Z'}} \ll M^2_2 \qquad\qquad M^2_2 \sim M^2_{Z'}$$

$$\theta \sim -\frac{\Delta^2}{M^2_{Z'}} \sim C\frac{g_2}{g_1}\frac{M^2_1}{M^2_2} \text{ with } \; C = 2\left[\frac{Q_u|\nu_u|^2 - Q_d|\nu_d|^2}{|\nu_u|^2 + |\nu_d|^2}\right]$$

- **Kinetic mixing also possible**

Anomalies and Exotics

- Must cancel triangle and mixed gravitational anomalies



- No solution except $Q_2 = 0$ for family universal SM fermions
- Must introduce new fermions: SM singlets like ν_L^c or exotic $SU(2)$
  (usually non-chiral under SM)

$$D_L + D_R, \qquad \begin{pmatrix} E^0 \\ E^- \end{pmatrix}_L + \begin{pmatrix} E^0 \\ E^- \end{pmatrix}_R$$

- Supersymmetry: include Higgsinos and singlinos (partners of S)

Models

- Enormous number of models, distinguished by gauge coupling g_2, mass scale, charges Q_2, allowed Yukawas, exotics, kinetic mixing, couplings to hidden sector $\cdots$
- No simple general parametrization
- "Canonical" models: TeV scale $M_{Z'}$ with electroweak strength couplings
  - Sequential Z_{SM}
  - Models based on T_{3R} and $B-L$
  - E_6 models
  - Minimal Gauge Unification Models

The E_6 models

- Example of anomaly free charges and exotics, based on $E_6 \to SO(10) \times U(1)_\psi$ and $SO(10) \to SU(5) \times U(1)_\chi$
- 3×27: 3 S fields, 3 exotic $(D + D^c)$ pairs, 3 Higgs (or exotic lepton) pairs
- Supersymmetric version forbids μ term except χ model $(SO(10))$

$SO(10)$	$SU(5)$	$2\sqrt{10}Q_\chi$	$2\sqrt{6}Q_\psi$	$2\sqrt{15}Q_\eta$
16	$10\ (u, d, u^c, e^+)$	-1	1	-2
	$5^*\ (d^c, \nu, e^-)$	3	1	1
	ν^c	-5	1	-5
10	$5\ (D, H_u)$	2	-2	4
	$5^*\ (D^c, H_d)$	-2	-2	1
1	$1\ S$	0	4	-5

Other Models

- **TeV scale dynamics** (Little Higgs, un-unified, strong $t\bar{t}$ coupling, $\cdots$)
- **Kaluza-Klein excitations** (large dimensions or Randall-Sundrum)
- **Decoupled** (leptophobic, fermiophobic, weak coupling, low scale/massless)
- **Hidden sector "portal"** (e.g., SUSY breaking, dark matter, or "hidden valley") [kinetic or HDO mixing, $\tilde{Z}'$ mediation]
- **Secluded or intermediate scale SUSY** (flat directions, Dirac m_ν)
- **Family nonuniversal couplings** (FCNC, apparent CPT violation)
- **String derived** (may be T_{3R}, T_{BL}, E_6 or "random")
- **Stückelberg** (no Higgs)
- **Anomalous $U(1)'$** (string theories with large dimensions)

Experimental constraints and prospects

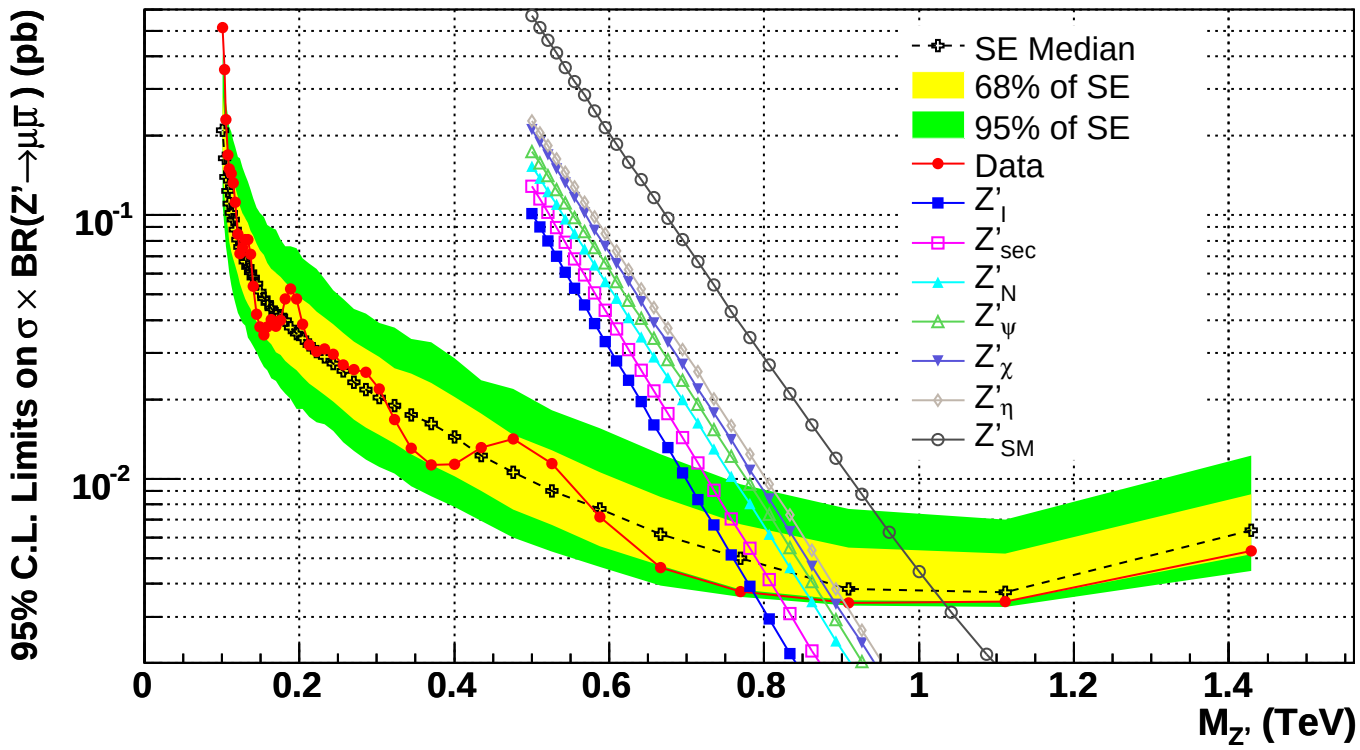
- **Tevatron (CDF, D0): resonance in** $\bar{p}p \to e^+e^-, \mu^+\mu^-, \cdots$
- **LHC (ATLAS, CMS):** $pp \to e^+e^-, \mu^+\mu^-, \cdots$

  $AB \to Z_\alpha$ **in narrow width:**

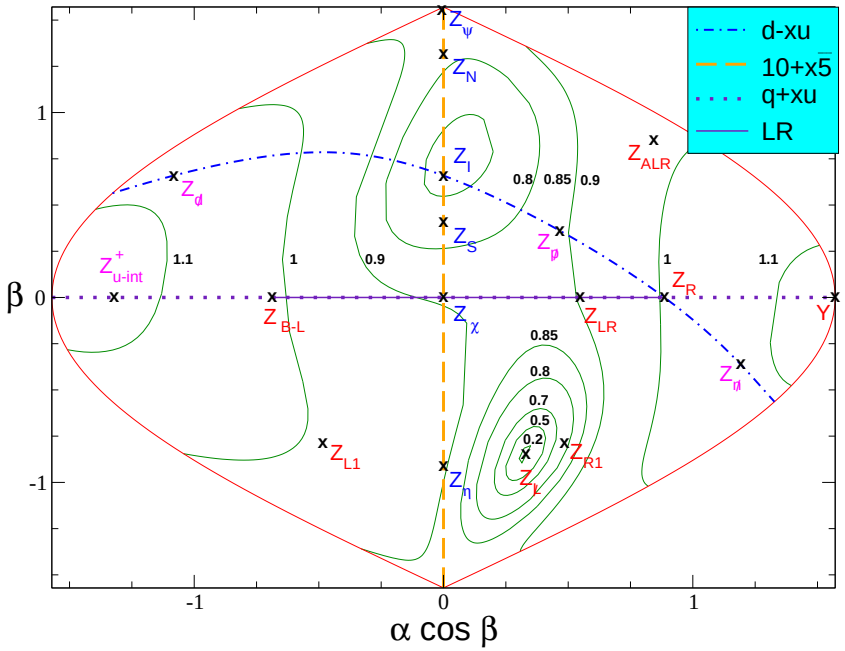
$$\frac{d\sigma}{dy} = \frac{4\pi^2 x_1 x_2}{3M_\alpha^3} \sum_i (f_{q_i}^A(x_1) f_{\bar{q}_i}^B(x_2) + f_{\bar{q}_i}^A(x_1) f_{q_i}^B(x_2)) \Gamma(Z_\alpha \to q_i \bar{q}_i)$$

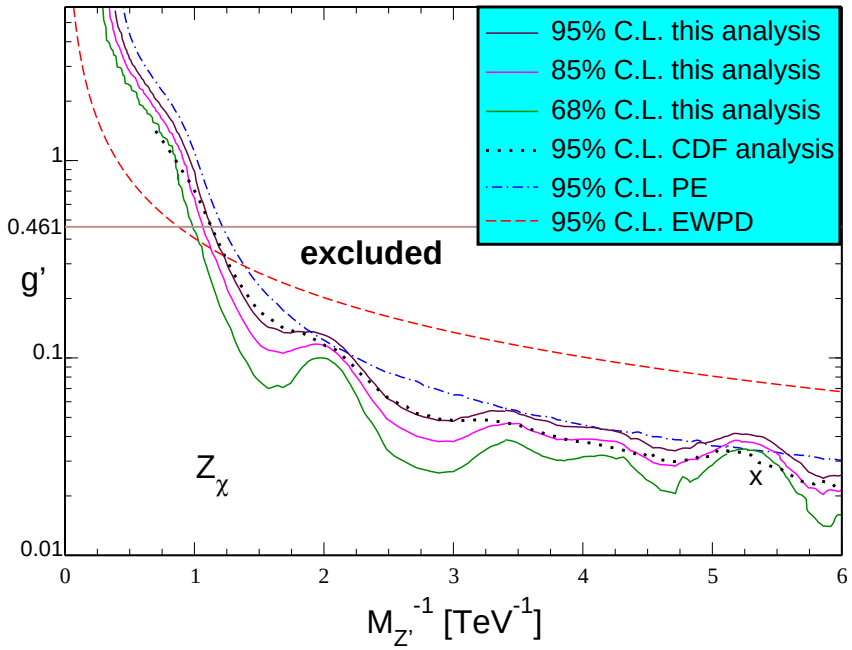
$$\Gamma_{f_i}^\alpha \equiv \Gamma(Z_\alpha \to f_i \bar{f}_i) = \frac{g_\alpha^2 C_{f_i} M_\alpha}{24\pi} \left(\epsilon_L^\alpha(i)^2 + \epsilon_R^\alpha(i)^2\right)$$

$x_{1,2} = (M_\alpha/\sqrt{s})e^{\pm y}$ $\qquad$ $C_{f_i} =$ color factor



(CDF dimuons: PRL 102, 0918905)





- **From 1103.2659 [hep-ph]:**
  $Z' = \cos\alpha\cos\beta Z_\chi + \sin\alpha\cos\beta Z_Y + \sin\beta Z_\psi$

- **Interference with γ, Z included in second plot**

- **Low energy weak neutral current: Z' exchange and $Z - Z'$ mixing** (still very important)

$$-L_{eff} = \frac{4G_F}{\sqrt{2}}(\rho_{eff} J_1^2 + 2w J_1 J_2 + y J_2^2)$$

$$\rho_{eff} = \rho_1 \cos^2\theta + \rho_2 \sin^2\theta \qquad w = \frac{g_2}{g_1}\cos\theta \sin\theta(\rho_1 - \rho_2)$$

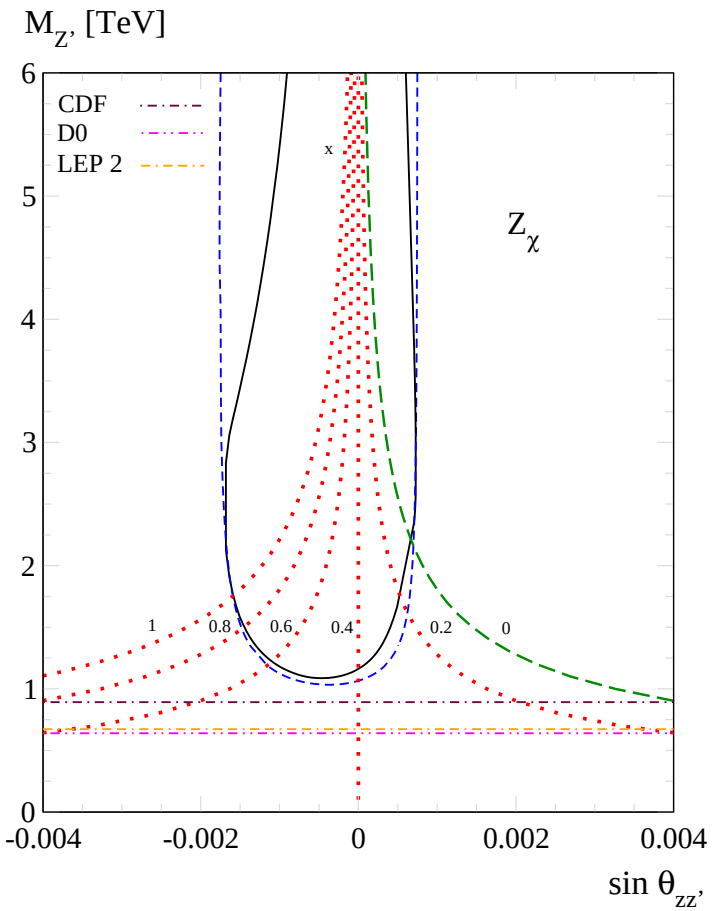
$$y = \left(\frac{g_2}{g_1}\right)^2 (\rho_1 \sin^2\theta + \rho_2 \cos^2\theta) \qquad \rho_\alpha \equiv M_W^2/(M_\alpha^2 \cos^2\theta_W)$$

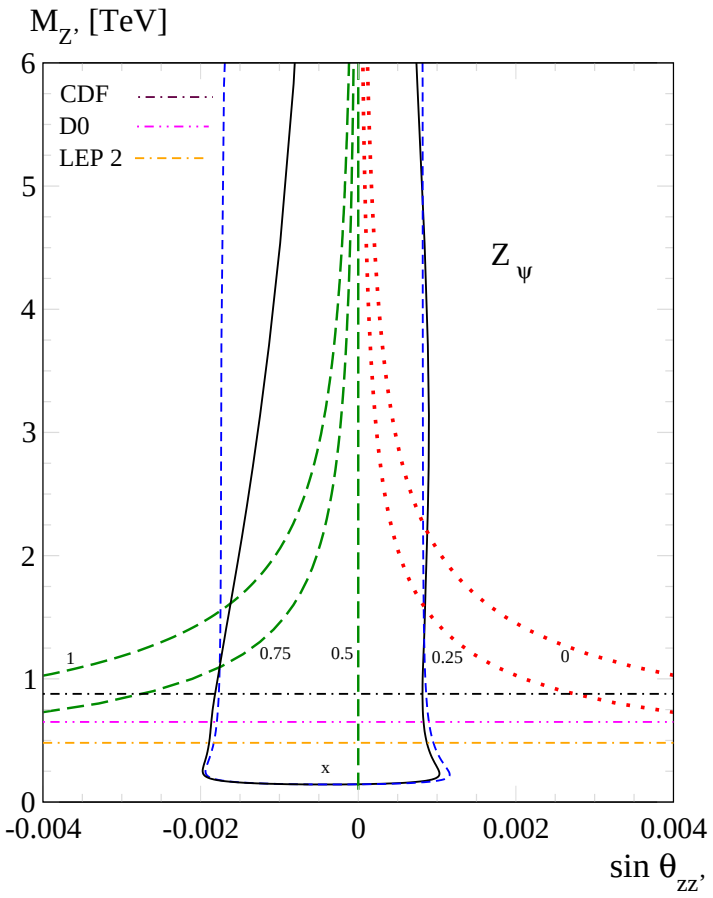
- **Z-pole (LEP, SLC): $Z - Z'$ mixing** (vertices; shift in M_1)

$$V_i = \cos\theta g_V^1(i) + \frac{g_2}{g_1}\sin\theta g_V^2(i)$$

$$A_i = \cos\theta g_A^1(i) + \frac{g_2}{g_1}\sin\theta g_A^2(i)$$

- **LEP2: four-fermi operator interfering with γ, Z**


M_Z' [TeV]
CDF
D0
LEP 2
Z_χ
x
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
-0.004
-0.002
0
0.002
0.004
sin θ_zz'


M_Z' [TeV]
CDF
D0
LEP 2
Z_ψ
1
0.75
0.5
0.25
0
x
0
1
2
3
4
5
6
-0.004
-0.002
0
0.002
0.004
sin θ_zz'

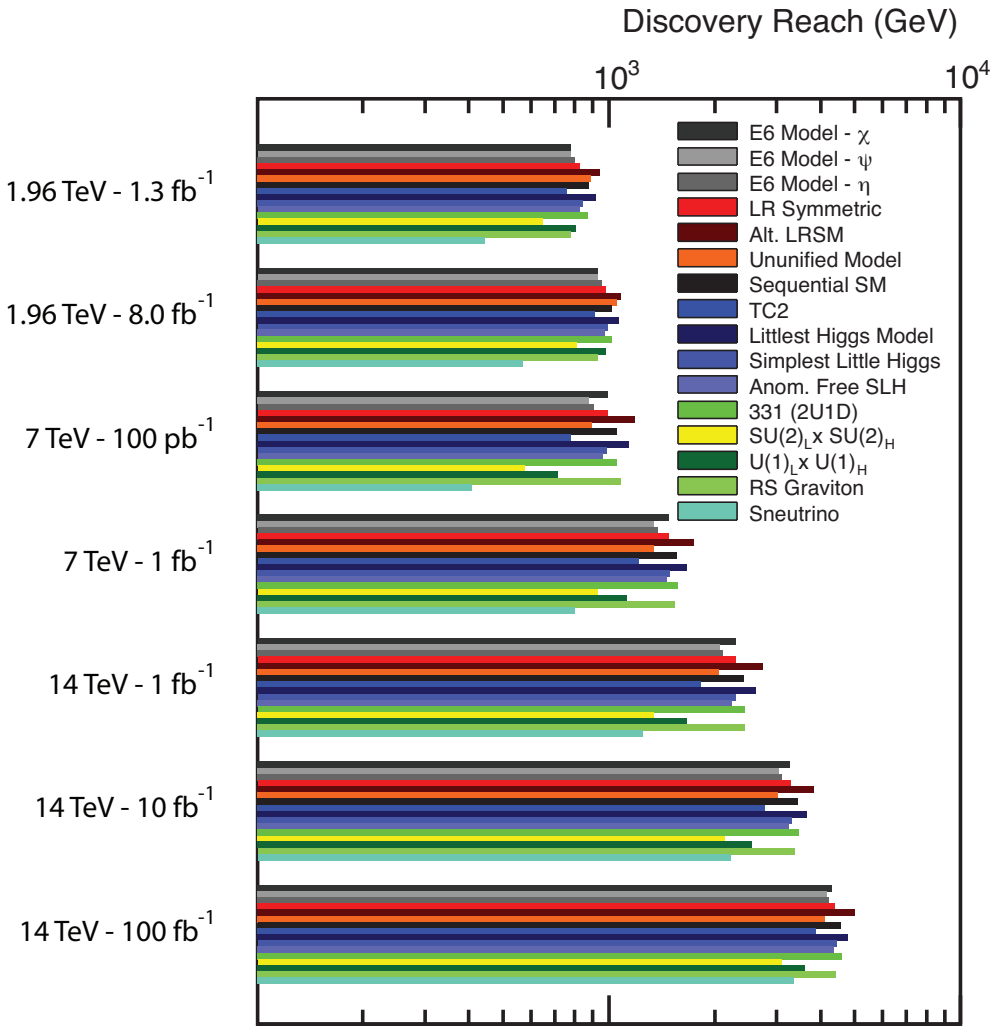
Z'	$M_{Z'}$ [GeV]				$\sin\theta_{ZZ'}$			$\chi^2_{\rm min}$
	EW	CDF	DØ	LEP 2	$\sin\theta_{ZZ'}$	$\sin\theta^{\rm min}_{ZZ'}$	$\sin\theta^{\rm max}_{ZZ'}$	
Z_χ	1,141	892	640	673	-0.0004	-0.0016	0.0006	47.3
Z_ψ	147	878	650	481	-0.0005	-0.0018	0.0009	46.5
Z_η	427	982	680	434	-0.0015	-0.0047	0.0021	47.7
Z_I	1,204	789	575		0.0003	-0.0005	0.0012	47.4
Z_S	1,257	821			0.0003	-0.0005	0.0013	47.3
Z_N	754	861			-0.0005	-0.0020	0.0012	47.5
Z_R	442				0.0003	-0.0009	0.0015	46.1
Z_{LR}	998	630		804	-0.0004	-0.0013	0.0006	47.3
Z_{SM}	1,401	1,030	780	1,787	-0.0008	-0.0026	0.0007	47.2
Z_{string}	1,362				0.0002	-0.0005	0.0009	47.7
SM	∞				0			48.5

Future Prospects

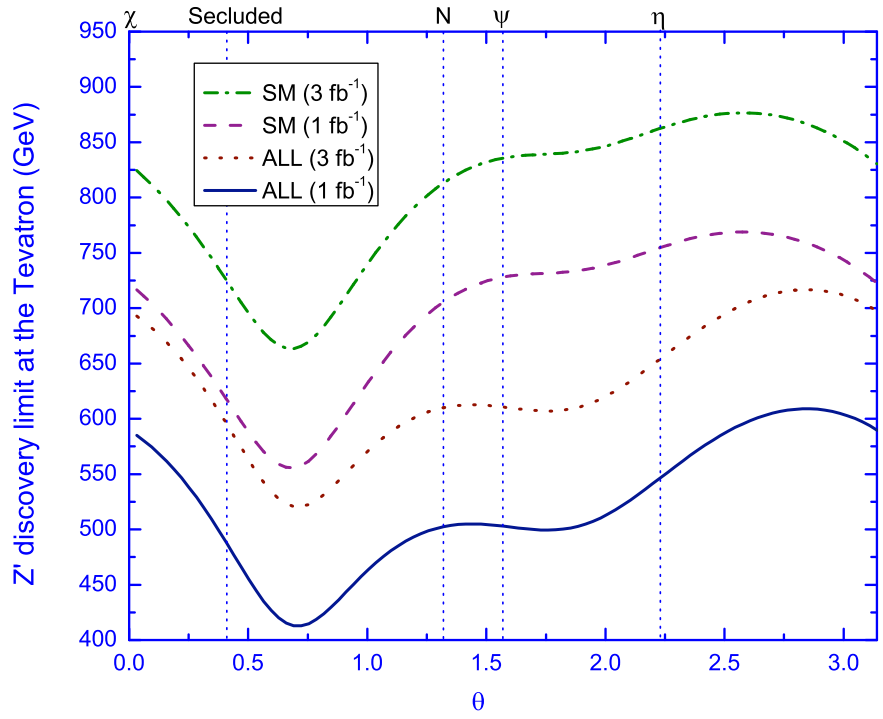
- **Tevatron and LHC:** $pp(\bar{p}p) \to Z' \to e^+e^-, \mu^+\mu^-, jj, \bar{b}b, \bar{t}t, e\mu, \tau^+\tau^-$
- **Rates (total width) dependent on whether sparticle and exotic channels open** ($\Gamma_{Z'}/M_{Z'} \sim 0.01 \to 0.05$ **for** E_6)
- **LHC discovery to** $\sim 4-5$ **TeV**
  - **Spin-0 (Higgs), spin-1 (Z'), spin-2 (Kaluza-Klein graviton) by angular distribution, e.g.,**

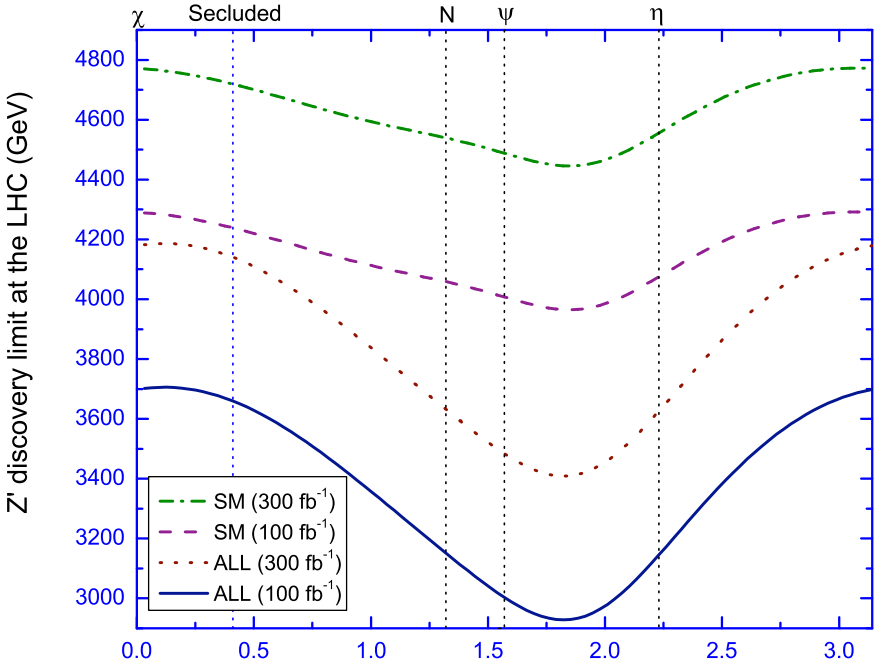
$$\frac{d\sigma^f_{Z'}}{d\cos\theta^*} \propto \frac{3}{8}(1+\cos^2\theta^*) + A^f_{FB}\cos\theta^* \quad \textbf{[for spin-1]}$$

- **ILC: 5σ intererence effects up to ~ 5 TeV**



(Courtesy: Steve Godfrey)





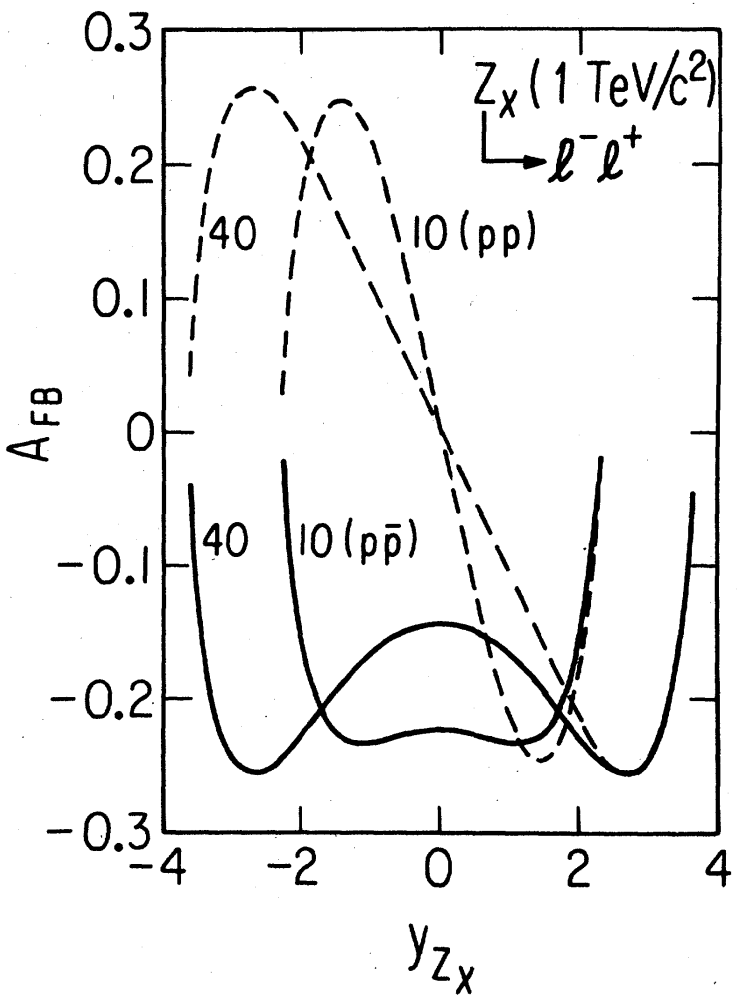
Diagnostics of Z' Couplings

- LHC diagnostics to 2-2.5 TeV
- Forward-backward asymmetries and rapidity distributions in $\ell^+\ell^-$
  - LRR: FB asymmetry in pp for nonzero y
  - For $AB \to Z' \to \bar{f} f$ at fixed y: $A_{FB}^f(y) \equiv (F-B)/(F+B)$

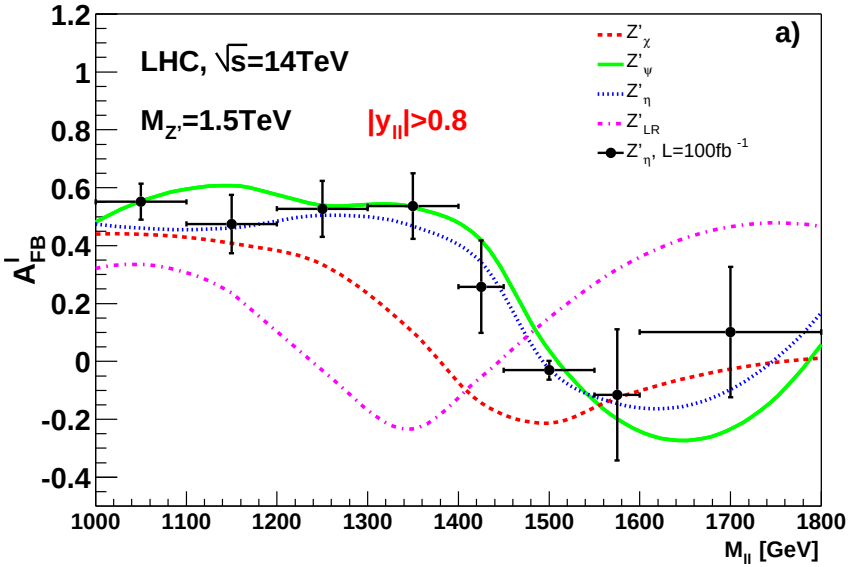
$$F \pm B \sim \left[\begin{array}{c} 4/3 \\ 1 \end{array} \right] \sum_i \left(f_{q_i}^A(x_1) f_{\bar{q}_i}^B(x_2) \pm f_{\bar{q}_i}^A(x_1) f_{q_i}^B(x_2) \right)$$
$$\times \left(\epsilon_L(q_i)^2 \pm \epsilon_R(q_i)^2 \right) \left(\epsilon_L(f)^2 \pm \epsilon_R(f)^2 \right)$$

($x_{1,2} = (M_{Z'}/\sqrt{s}) e^{\pm y}$)

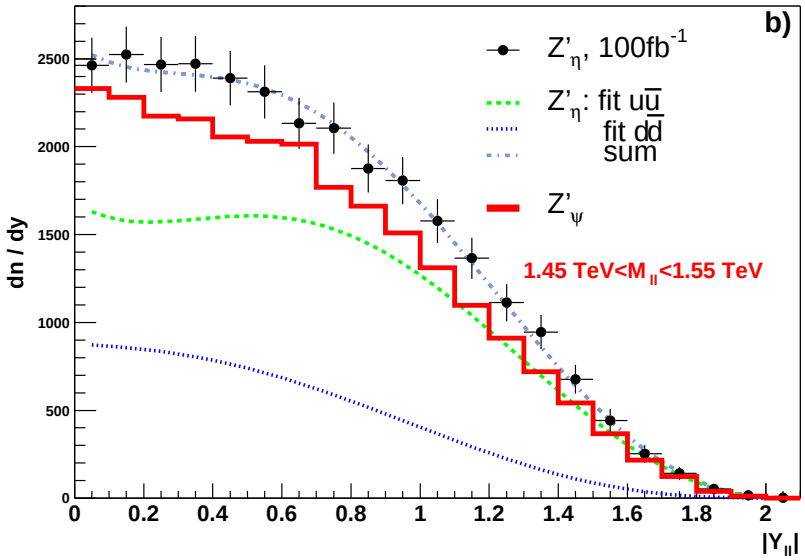
- Additional information from interference off Z' pole



Forward backward asymmetry measurement



Rapidity distribution



(LHC/ILC, hep-ph/0410364)

- Other two body decays (e.g., $t\bar{t}$)
- Lineshape: $\sigma_{Z'} B_\ell$, $\Gamma_{Z'}$
- τ polarization
- Associated production $Z'Z, Z'W, Z'\gamma$
- Rare (but enhanced) decays $Z' \to W \bar{f}_1 f_2$ (radiated W)
- $Z' \to W^+W^-, Zh$, or $W^\pm H^\mp$: small mixing compensated by longitudinal W, Z

$$\Gamma(Z' \to W^+W^-) = \frac{g_1^2 \theta^2 M_{Z'}}{192\pi} \left(\frac{M_{Z'}}{M_Z}\right)^4 = \frac{g_2^2 C^2 M_{Z'}}{192\pi}$$

- LHC/ILC diagnostics complementary

Implications of a TeV-scale $U(1)'$

- **Natural Solution to μ problem** $W \sim hSH_uH_d \rightarrow \ \mu_{eff} = h\langle S\rangle$
  ("stringy version" of NMSSM)

- **Extended Higgs sector**
  - Relaxed mass limits, couplings, parameters (e.g., $\tan\beta \sim 1$)
  - Higgs singlets needed to break $U(1)'$
  - Doublet-singlet mixing, extended neutralino sector
    $\rightarrow$ non-standard collider signatures

- **Extended neutralino sector**
  - Additional neutralinos, non-standard couplings, e.g., light singlino-dominated, extended cascades
  - Enhanced cold dark matter, $g_\mu - 2$ possibilities (even small $\tan\beta$)

- **Exotics (anomaly-cancellation)**
  - **Non-chiral wrt SM but chiral wrt $U(1)'$**
  - **May decay by mixing; by diquark or leptoquark coupling; or be quasi-stable**
- **Z' decays into sparticles/exotics (SUSY factory)**
- **Flavor changing neutral currents (for non-universal $U(1)'$ charges)**
  - **Tree-level effects in B decay competing with SM loops (or with enhanced loops in MSSM with large $\tan\beta$)**
  - **$B_s - \bar{B}_s$ mixing, B_d penguins**
- **Non-universal charges: apparent CPT violation (MINOS)**

- **Constraints on neutrino mass generation**
  - **Various versions allow or exclude Type I or II seesaws, extended seesaw, small Dirac by HDO; small Dirac by non-holomorphic soft terms; stringy Weinberg operator, Majorana seesaw, or small Dirac by string instantons**

- **Large A term and possible tree-level CP violation** (no new EDM constraints) $\rightarrow$ **electroweak baryogenesis**

Conclusions

- New Z' are extremely well motivated
- TeV scale likely, especially in supersymmetry and alternative EWSB
- LHC discovery to 4-5 TeV, diagnostics to 2-2.5 TeV
- Implications profound for particle physics and cosmology
- Possible portal to hidden/dark sector (massless, GeV, TeV)