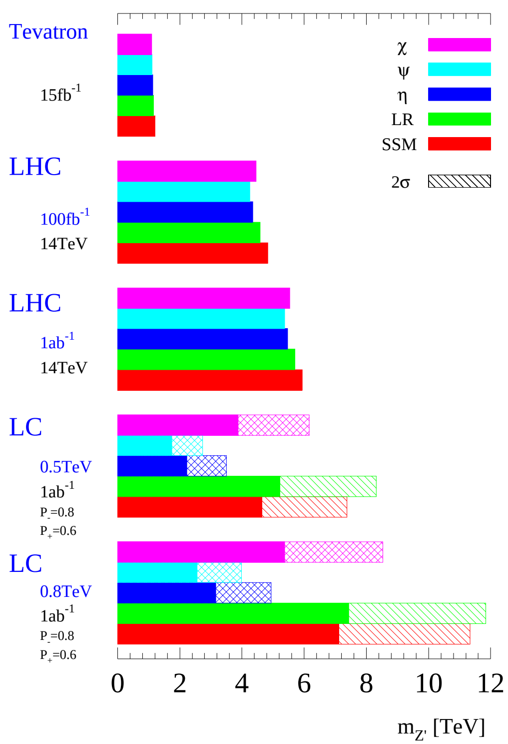
The Physics of Heavy Z-prime Gauge Bosons



- **Motivations**
- **Basics**
- **Models**
- **Experimental constraints and prospects**
- **Implications**

LHC/ILC, hep-ph/0410364

Review: *The Physics of Heavy Z-prime Gauge Bosons*, **0801.1345 [hep-ph].**

Talk at: `www.physics.upenn.edu/~pgl/talks/zprime_08.pdf`

Motivations

- Strings/GUTS
  - Harder to break $U(1)'$ factors than non-abelian
  - Supersymmetry: $SU(2) \times U(1)$ and $U(1)'$ breaking scales *both* set by SUSY breaking scale (unless flat direction)
  - μ problem
- Alternative electroweak breaking (TeV scale): DSB, Little Higgs
- Extra dimensions: Kaluza-Klein excitations
  $(M \sim R^{-1} \sim 2 \text{ TeV} \times (10^{-17}\text{cm}/R))$

Standard Model Neutral Current

$$-L_{\rm NC}^{\rm SM} = gJ_3^\mu W_{3\mu} + g' J_Y^\mu B_\mu = eJ_{em}^\mu A_\mu + g_1 J_1^\mu Z_{1\mu}^0$$

$$A_\mu = \sin\theta_W W_{3\mu} + \cos\theta_W B_\mu$$

$$Z_\mu = \cos\theta_W W_{3\mu} - \sin\theta_W B_\mu$$

$$\theta_W \equiv \tan^{-1}(g'/g) \qquad e = g\sin\theta_W \qquad g_1^2 = g^2/\cos^2\theta_W$$

$$J_1^\mu = \sum_i \bar{f}_i \gamma^\mu [\epsilon_L^1(i) P_L + \epsilon_R^1(i) P_R] f_i \qquad P_{L,R} \equiv \frac{(1 \mp \gamma^5)}{2}$$

$$\epsilon_L^1(i) = t_{3i_L} - \sin^2\theta_W\, q_i \qquad \epsilon_R^1(i) = -\sin^2\theta_W\, q_i$$

$$M_{Z^0}^2 = \frac{1}{4} g_1^2 \nu^2 = \frac{M_W^2}{\cos^2\theta_W} \qquad \nu \sim 246 \text{ GeV}$$

Additional $U(1)'$

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

$$J^{\mu}_{\alpha} = \sum_{i} \bar{f}_i \gamma^{\mu}[\epsilon^{\alpha}_{L}(i)P_L + \epsilon^{\alpha}_{R}(i)P_R]f_i$$

- $\epsilon^{\alpha}_{L,R}(i)$ 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

$$\epsilon^{\alpha}_{L}(f) = Q_{\alpha f} \qquad\qquad \epsilon^{\alpha}_{R}(f) = -Q_{\alpha f^c}$$

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

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 $\phi_u = \begin{pmatrix} \phi^0_u \\ \phi^-_u \end{pmatrix}$, $\phi_d = \begin{pmatrix} \phi^+_d \\ \phi^0_d \end{pmatrix}$

$$\begin{aligned} M^2_{Z^0} &= \frac{1}{4} g_1^2 (|\nu_u|^2 + |\nu_d|^2) \\ \Delta^2 &= \frac{1}{2} g_1 g_2 (Q_u |\nu_u|^2 - Q_d |\nu_d|^2) \\ M^2_{Z'} &= g_2^2 (Q_u^2 |\nu_u|^2 + Q_d^2 |\nu_d|^2 + Q_S^2 |s|^2) \end{aligned}$$

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

- **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

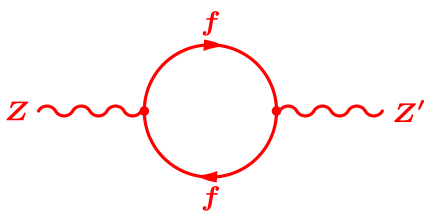
- General kinetic energy term allowed by gauge invariance

$$L_{kin} \rightarrow -\frac{1}{4}F_{\alpha}^{0\mu\nu}F_{\alpha\mu\nu}^{0} - \frac{1}{4}F_{\beta}^{0\mu\nu}F_{\beta\mu\nu}^{0} - \frac{\sin\chi}{2}F_{\alpha}^{0\mu\nu}F_{\beta\mu\nu}^{0}$$

- Negligible effect on masses for $|M_{Z^0}^2| \ll |M_{Z'}^2|$, but

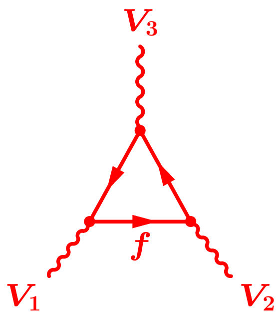
$$-L \rightarrow g_1 J_1^{\mu} Z_{1\mu} + (g_2 J_2^{\mu} - g_1 \chi J_1^{\mu}) Z_{2\mu}$$

- Usually absent initially but induced by loops in running couplings if heavy particles decouple (or by string-level loops) (usually small)



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)

The μ Problem

- In MSSM, introduce Higgsino mass parameter μ: $W_\mu = \mu H_u H_d$
- μ is supersymmetric. Natural scales: 0 or $M_{Planck} \sim 10^{19}$ GeV
- Phenomenologically, need $\mu \sim$ SUSY breaking scale
- In Z' models, $U(1)'$ may forbid elementary μ (if $Q_{H_u} + Q_{H_d} \neq 0$)
- If $W_\mu = \lambda_S S H_u H_d$ is allowed, then $\mu_{eff} \equiv \lambda_S \langle S \rangle$, where $\langle S \rangle$ contributes to $M_{Z'}$
- Can also forbid μ by discrete symmetries (NMSSM, nMSSM, $\cdots$), but simplest forms have domain wall problems
- $U(1)'$ is *stringy* version of NMSSM

Models

- Enormous number of models, distinguished by gauge coupling g_2, mass scale, charges Q_2, exotics, $\cdots$

- No simple general parametrization

- Will focus on TeV scale $M_{Z'}$ with electroweak strength couplings

Sequential Z_{SM}

- Same couplings to fermions as the SM Z boson
  - Reference model
  - Hard to obtain in gauge theory
  - Kaluza-Klein excitations with TeV extra dimensions

Models based on T_{3R} and $B-L$

- Motivated by minimal exotics (only ν_L^c needed), $SO(10)$, and left-right $SU(2)_L \times SU(2)_R \times U(1)_{BL}$

- $T_{BL} \equiv \frac{1}{2}(B-L)$, $\qquad T_{3R} = Y - T_{BL} = \frac{1}{2}\ [u_R, \nu_R],\ -\frac{1}{2}\ [d_R, e_R^-]$

- For non-abelian embedding and no kinetic mixing

$$Q^{LR} = \sqrt{\frac{3}{5}}\left[\alpha T_{3R} - \frac{1}{\alpha} T_{BL}\right]$$

$$\alpha = \frac{g_R}{g_{BL}} = \sqrt{(g_R/g)^2 \cot^2\theta_W - 1} \qquad g_2 = \sqrt{\frac{5}{3}} g \tan\theta_W \sim 0.46$$

- More general: $Q^{YBL} = aY + bT_{BL} \equiv b(zY + T_{BL})$

	T_{3R}	T_{BL}	Y	$\sqrt{\frac{5}{3}}Q^{LR}$	$\frac{1}{b}Q^{YBL}$
Q	0	$\frac{1}{6}$	$\frac{1}{6}$	$-\frac{1}{6\alpha}$	$\frac{1}{6}(z+1)$
u_L^c	$-\frac{1}{2}$	$-\frac{1}{6}$	$-\frac{2}{3}$	$-\frac{\alpha}{2}+\frac{1}{6\alpha}$	$-\frac{2}{3}z-\frac{1}{6}$
d_L^c	$\frac{1}{2}$	$-\frac{1}{6}$	$\frac{1}{3}$	$\frac{\alpha}{2}+\frac{1}{6\alpha}$	$\frac{1}{3}z-\frac{1}{6}$
L_L	0	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2\alpha}$	$-\frac{1}{2}(z+1)$
e_L^+	$\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{\alpha}{2}-\frac{1}{2\alpha}$	$z+\frac{1}{2}$
ν_L^c	$-\frac{1}{2}$	$\frac{1}{2}$	0	$-\frac{\alpha}{2}-\frac{1}{2\alpha}$	$\frac{1}{2}$

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 $(D + D^c)$ 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, ν, 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

- **General:** $Q_2 = \cos\theta_{E_6} Q_\chi + \sin\theta_{E_6} Q_\psi$ (can add kinetic term $-\epsilon Y$)

$$g_2 = \sqrt{\frac{5}{3}} g \tan\theta_W \lambda_g^{1/2}, \qquad \lambda_g = \mathcal{O}(1)$$

$SO(10)$	$SU(5)$	$2Q_I$	$2\sqrt{10}Q_N$	$2\sqrt{15}Q_S$
16	$10\ (u, d, u^c, e^+)$	0	1	$-1/2$
	$5^*\ (d^c, \nu, e^-)$	-1	2	4
	ν^c	1	0	-5
10	$5\ (D, H_u)$	0	-2	1
	$5^*\ (D^c, H_d)$	1	-3	$-7/2$
1	$1\ S$	-1	5	$5/2$

- **GUT Yukawas violated** (proton decay), **e.g., by string rearrangement**

- **Gauge unification requires additional non-chiral** $H_u + H_u^*$

Minimal Gauge Unification Models

- Supersymmetric models with μ_{eff} and MSSM-like gauge unification

- 3 ordinary families (with ν^c), one Higgs pair $H_{u,d}$ and n_{55^*} pairs $(D_i + L_i)$ and $(D_i^c + L_i^c)$

	Q_{55^*}	$Q_{\tilde{\psi}}$		Q_{55^*}	$Q_{\tilde{\psi}}$
Q	y	$1/4$	H_u	x	$-1/2$
u^c	$-x-y$	$1/4$	H_d	$-1-x$	$-1/2$
d^c	$1+x-y$	$1/4$	S_D	$3/n_{55^*}$	$3/2$
L	$1-3y$	$1/4$	D_i	z	$-3/4$
e^+	$x+3y$	$1/4$	D_i^c	$-3/n_{55^*}-z$	$-3/4$
ν^c	$-1-x+3y$	$1/4$	S_L	$2/n_{55^*}$	1
S	1	1	L_i	$\frac{5-n_{55^*}}{4n_{55^*}}+x+3y+3z/2$	$-1/2$
			L_i^c	$-2/n_{55^*}-Q_{L_i}$	$-1/2$

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, hidden sector, $\cdots$)
- **Secluded or intermediate scale SUSY** (flat directions, Dirac m_ν)
- **Family nonuniversal couplings** (FCNC)
- **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

- **Low energy weak neutral current: Z' exchange and $Z-Z'$ mixing**

$$-L_{eff} = \frac{4G_F}{\sqrt{2}}(\rho_{eff}J_1^2 + 2wJ_1J_2 + yJ_2^2)$$

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

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

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

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

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

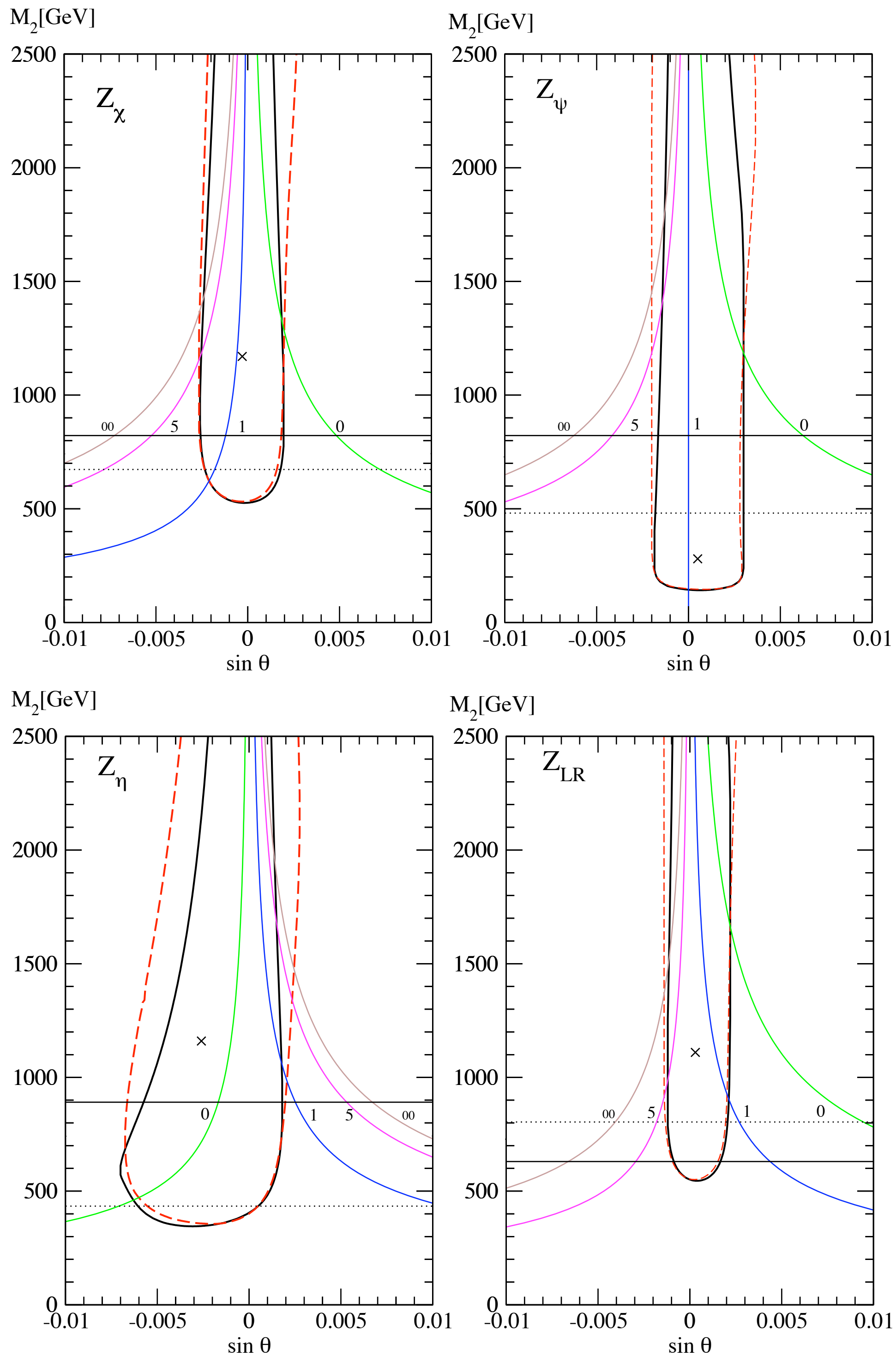
- **LEP2: four-fermi operator interfering with γ, Z**
- **Tevatron (CDF, D0): resonance in $\bar{p}p \to e^+e^-, \mu^+\mu^-, \cdots$**

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

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

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

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



M2[GeV]
Zχ
2500
2000
1500
1000
500
0
-0.01
-0.005
0
0.005
0.01
sin θ
00
5
1
0
Zψ
Zη
ZLR

	ρ_0 free	$\rho_0 = 1$	$\sin\theta$ ($\rho_0 = 1$)	Tevatron	LEP 2
χ	551	545	$(-0.0020) - (+0.0015)$	822	673
ψ	151	146	$(-0.0013) - (+0.0024)$	822	481
η	379	365	$(-0.0062) - (+0.0011)$	891	434
LR	570	564	$(-0.0009) - (+0.0017)$	630	804
sequential	822	809	$(-0.0041) - (+0.0003)$	923	1787

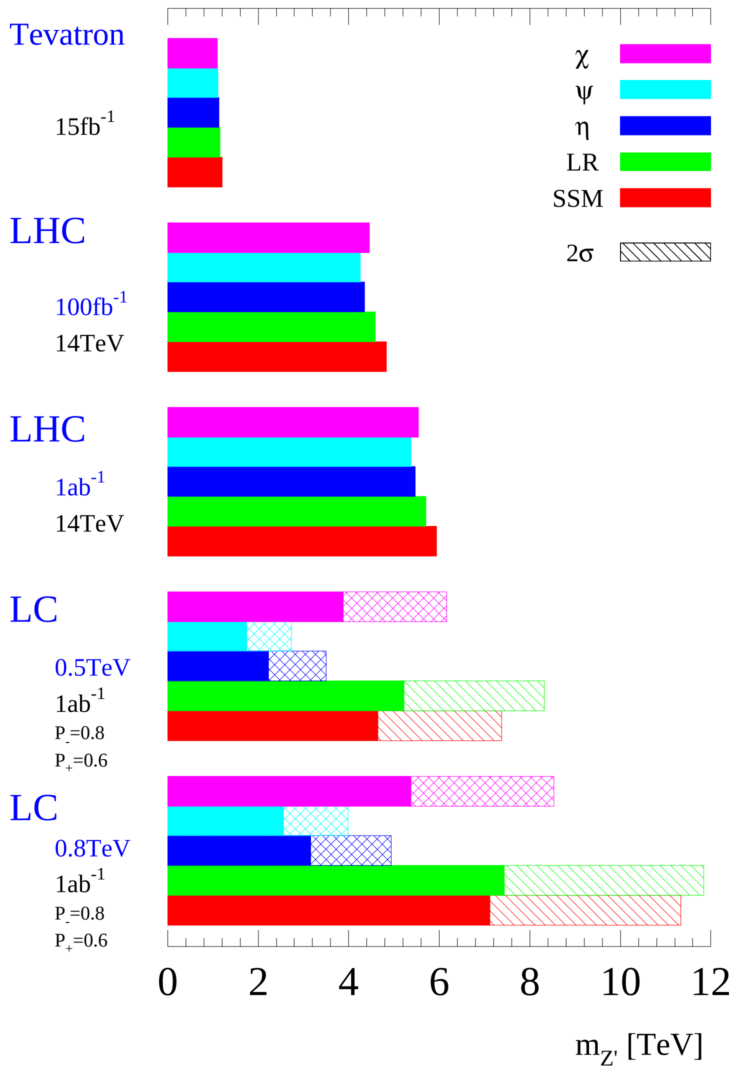
Future Prospects

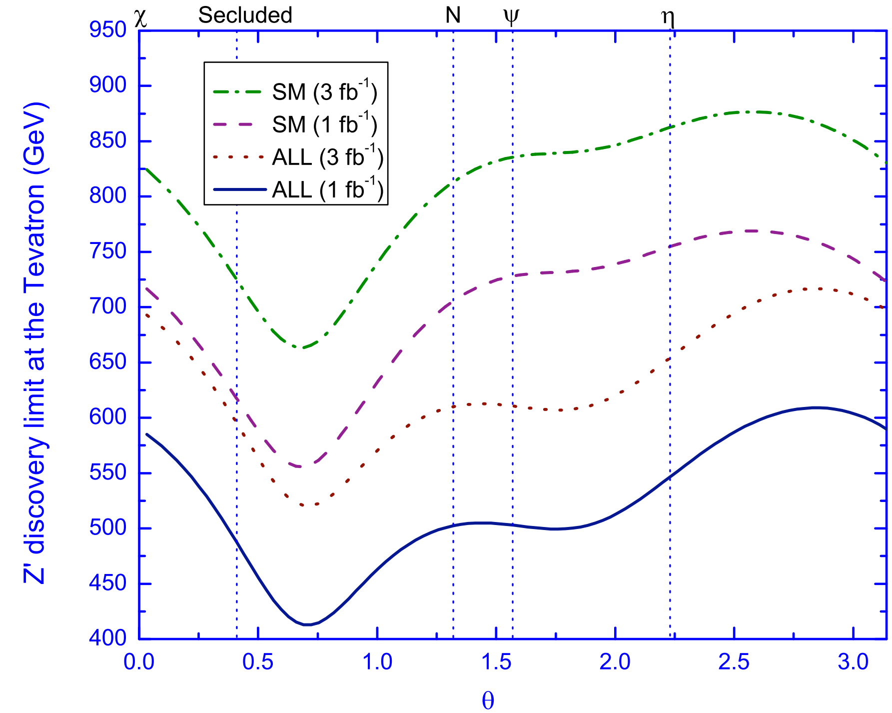
- **Tevatron and LHC:** $pp(\bar{p}p) \rightarrow Z' \rightarrow e^+e^-, \mu^+\mu^-, jj, \bar{t}t, e\mu, \tau^+\tau^-$

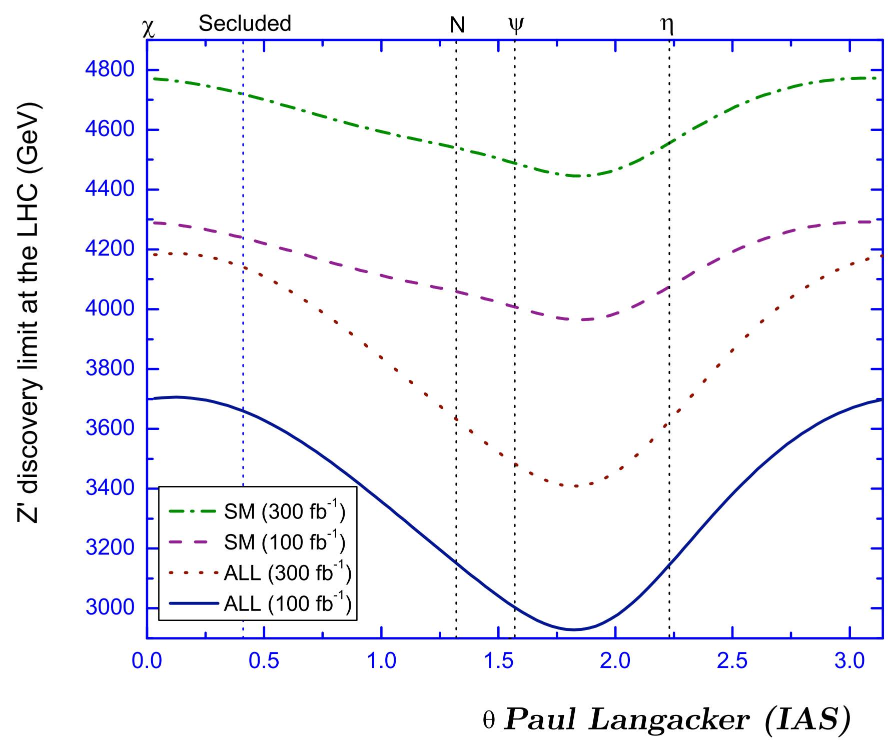
- **Rates (total width) dependent on whether sparticle and exotic channels open** $(\Gamma_{Z'}/M_{Z'} \sim 0.01 \rightarrow 0.05$ **for** $E_6)$

- **LHC discovery to** $\sim 4 - 5$ **TeV**

- **ILC: 5σ intererence effects up to $\sim$ 5 TeV**







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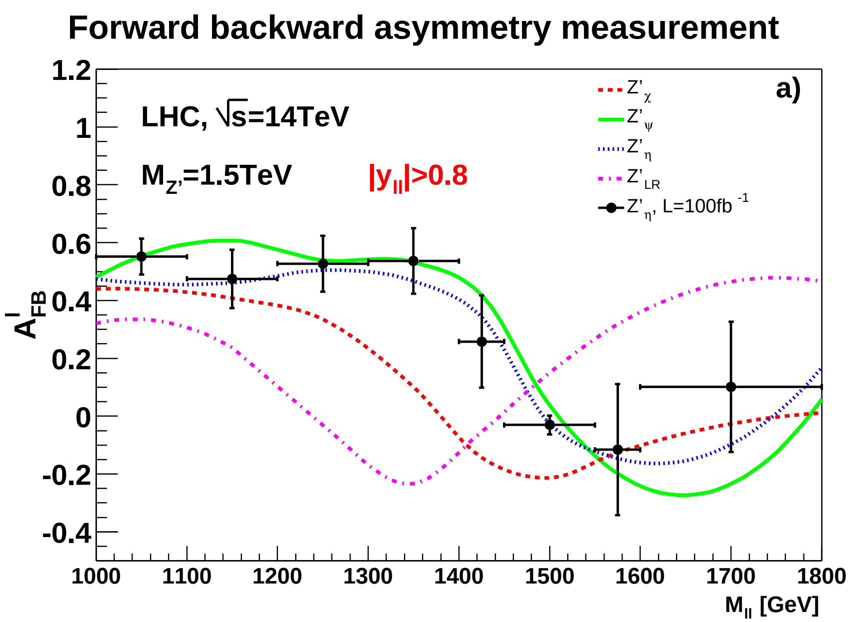
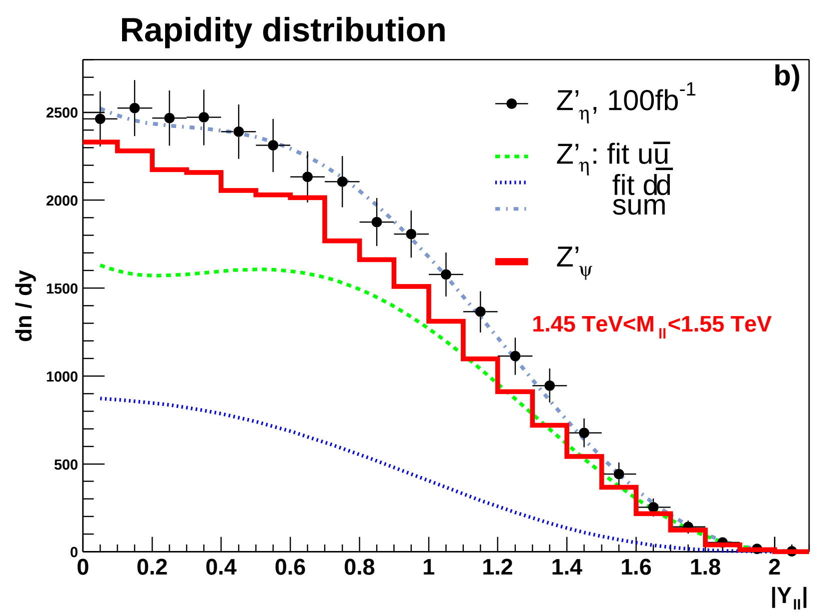
Diagnostics of Z' Couplings

- LHC diagnostics to 2-2.5 TeV
- Forward-backward asymmetries and rapidity distributions in $\ell^+\ell^-$





LHC/ILC, hep-ph/0410364

- Other two body decays
- $\sigma_{Z'} B_\ell \Gamma_{Z'} = \sigma_{Z'} \Gamma_\ell$ (total width cancels)
- 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

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

- Upgrade to hadronic polarization would be useful
- LHC/ILC diagnostics complementary

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

- Natural Solution to μ problem $W \sim hSH_uH_d \rightarrow \ \mu_{eff} = h\langle S \rangle$

- Extended Higgs sector
  - Relaxed mass limits, couplings, parameters (e.g., $\tan\beta \sim 1$)
  - Higgs singlets needed to break $U(1)'$
  - Doublet-singlet mixing $\rightarrow$ highly 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 $\tan\beta$)

- Constraints on neutrino mass generation

- Exotics (anomaly-cancellation)
  - May decay by mixing; by diquark or leptoquark coupling; or be quasi-stable
- Z' decays into sparticles/exotics
- 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 $\tan\beta$)
- $U(1)'$ may couple to both ordinary and (quasi)-hidden sectors
  - $Z' - \tilde{Z}'$ mass difference may communicate SUSY breaking
  - Predictive spectrum with very heavy scalars, light SM gauginos
- Large A term and possible tree-level CP violation (no new EDM constraints) $\longrightarrow$ electroweak baryogenesis

Conclusions

- **Heavy Z' are extremely well motivated**
- **TeV scale likely, especially in supersymmetry and alternative EWSB**
- **Wide variety of models**
- **LHC discovery to 4-5 TeV, diagnostics to 2-2.5 TeV**
- **Implications profound for particle physics and cosmology**