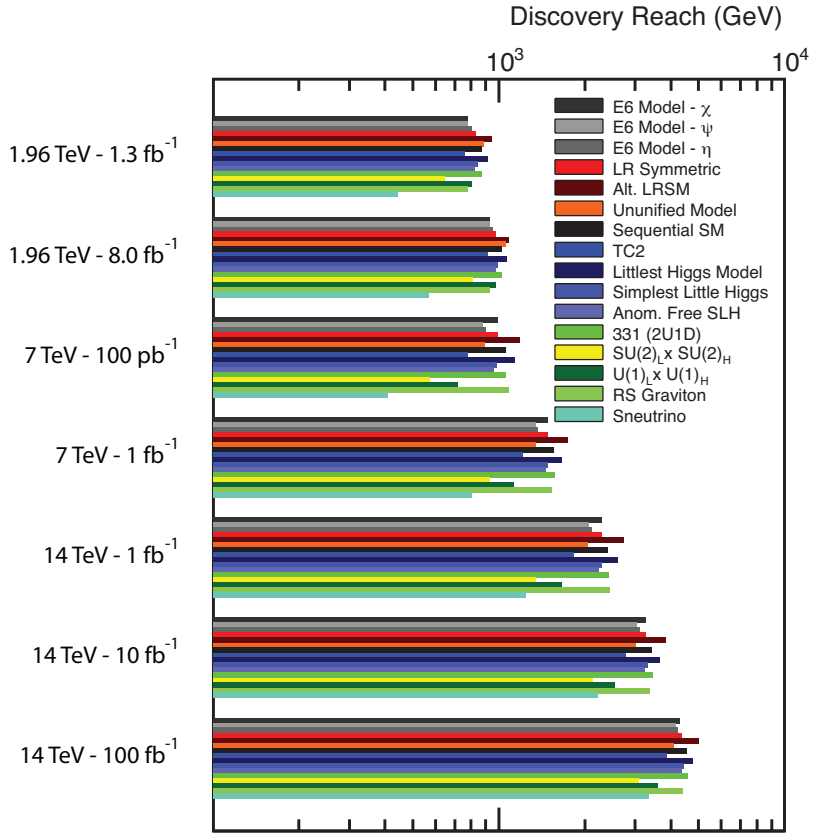
Z' Physics



- Motivations
- Basics
- The standard TeV scale case
- Nonstandard cases
- Experimental constraints and prospects
- Implications

Reviews: *The Physics of Heavy Z' Gauge Bosons*, **RMP 81, 1199 [0801.1345]**

The Standard Model and Beyond **(CRC Press)**

Talk at: `www.sns.ias.edu/~pgl/talks/zprime_10.pdf`

Additional References

- *Z' Physics at the LHC*, from P. Nath *et al.*, *The Hunt for New Physics at the Large Hadron Collider*, Nucl. Phys. Proc. Suppl. 200-202, 185 (2010) [arXiv:1001.2693 [hep-ph]]

- *The Physics of New $U(1)'$ Gauge Bosons*, SUSY09, AIP Conf. Proc. 1200, 55 (2010) [arXiv:0909.3260 [hep-ph]]

- J. Erler, PL, S. Munir and E. Rojas, *Z' Searches: From Tevatron to LHC*, arXiv:1010.3097 [hep-ph]

- J. Erler, PL, S. Munir and E. R. Pena, *Improved Constraints on Z' Bosons from Electroweak Precision Data*, JHEP 0908, 017 (2009) [arXiv:0906.2435 [hep-ph]]

Motivations

- **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'**

Standard Model Neutral Current

$$-L_{\rm NC}^{\rm SM} = g J_3^\mu W_{3\mu} + g' J_Y^\mu B_\mu = e J_{em}^\mu A_\mu + g_1 J_1^\mu Z_{1\mu}^0$$

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

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

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

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

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

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

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

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

$Q_{1u} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W$ 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** $\phi_u = \begin{pmatrix} \phi^0_u \\ \phi^-_u \end{pmatrix}$, $\phi_d = \begin{pmatrix} \phi^+_d \\ \phi^0_d \end{pmatrix}$

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

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

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

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

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

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

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

Kinetic Mixing

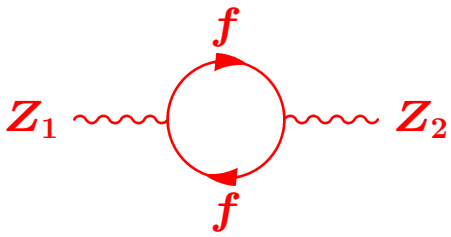
- General kinetic energy term allowed by gauge invariance

$$L_{kin} \to -\frac{1}{4}F_1^{0\mu\nu}F^0_{1\mu\nu} - \frac{1}{4}F_2^{0\mu\nu}F^0_{2\mu\nu} - \frac{\sin\chi}{2}F_1^{0\mu\nu}F^0_{2\mu\nu}$$

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

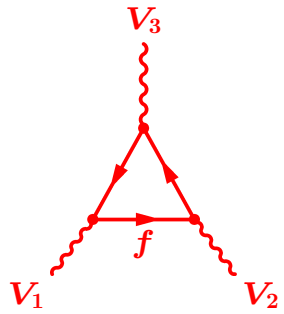
$$-L \to g_1 J_1^\mu Z_{1\mu} + (g_2 J_2^\mu - g_1 \chi J_1^\mu) Z_{2\mu}$$

- Usually absent initially but induced by loops, e.g., nondegenerate heavy particles, 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 $Q_{Hu} + Q_{H_d} \neq 0$)
- 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, 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

Sequential Z_{SM}

- **Same couplings to fermions as the SM Z boson**
  - **Reference model**
  - **Hard to obtain in gauge theory unless complicated exotic sector**
    [e.g., "diagonal" embedding of $SU(2) \subset SU(2)_1 \times SU(2)_2$]
  - **Kaluza-Klein excitations with TeV extra dimensions**

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

- **Motivated by minimal fermions** (only ν_L^c needed for anomalies), $SO(10)$, 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 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

- **General:** $Q_2 = \cos\theta_{E_6} Q_\chi + \sin\theta_{E_6} Q_\psi$

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

$SO(10)$	$SU(5)$	$2Q_I$	$2\sqrt{10}Q_N$	$2\sqrt{15}Q_S$
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 $H_u + H_u^*$**
- **Can add kinetic term $-\epsilon Y$ ($Q_\chi - \epsilon Y \Rightarrow Q^{YBL}$)**

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/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

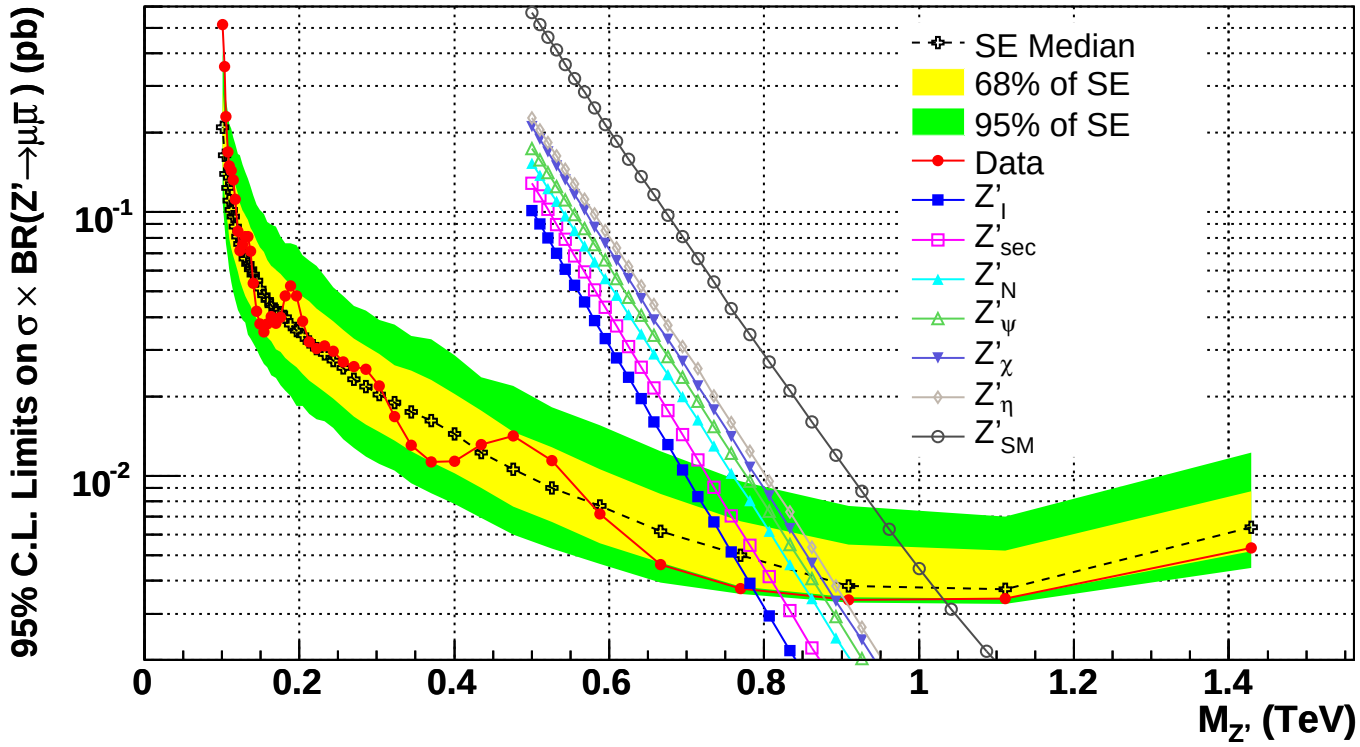
- **Tevatron (CDF, D0): resonance in $\bar{p}p \to e^+e^-, \mu^+\mu^-, \cdots$**

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

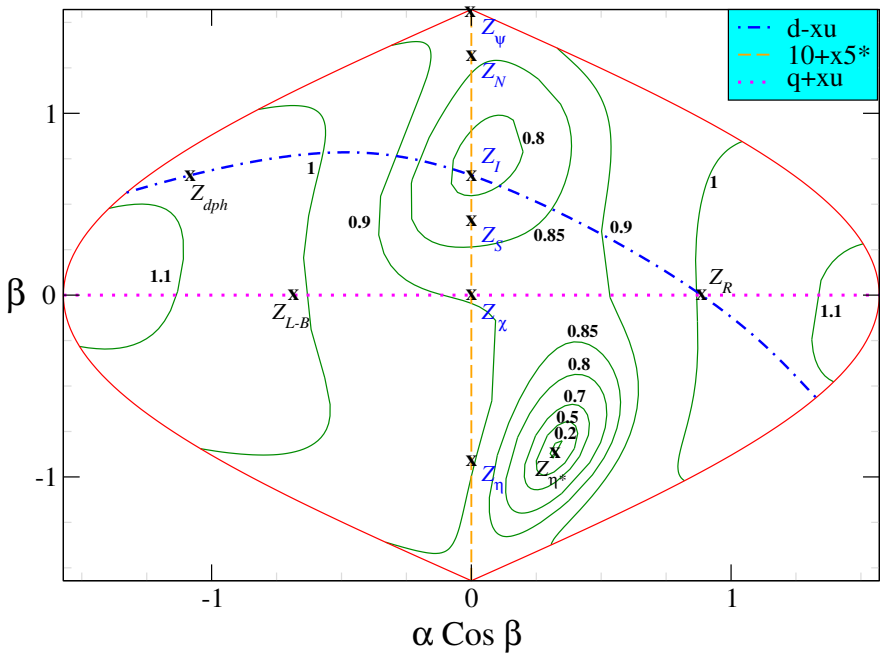
$$\frac{d\sigma}{dy} = \frac{4\pi^2 x_1 x_2}{3M_\alpha^3} \sum_i (f^A_{q_i}(x_1) f^B_{\bar{q}_i}(x_2) + f^A_{\bar{q}_i}(x_1) f^B_{q_i}(x_2)) \Gamma(Z_\alpha \to q_i \bar{q}_i)$$

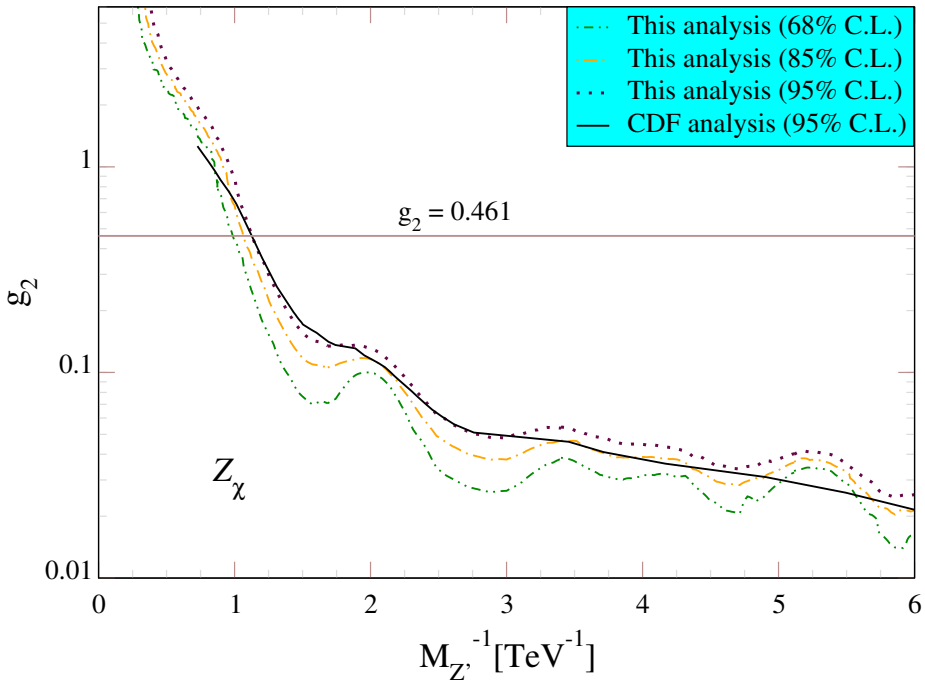
$$\Gamma^\alpha_{f_i} \equiv \Gamma(Z_\alpha \to f_i \bar{f}_i) = \frac{g^2_\alpha C_{f_i} M_\alpha}{24\pi} \left(\epsilon^\alpha_L(i)^2 + \epsilon^\alpha_R(i)^2\right)$$

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



(CDF dimuons: PRL 102, 0918905)





- **From 1010.3097 [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)

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

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

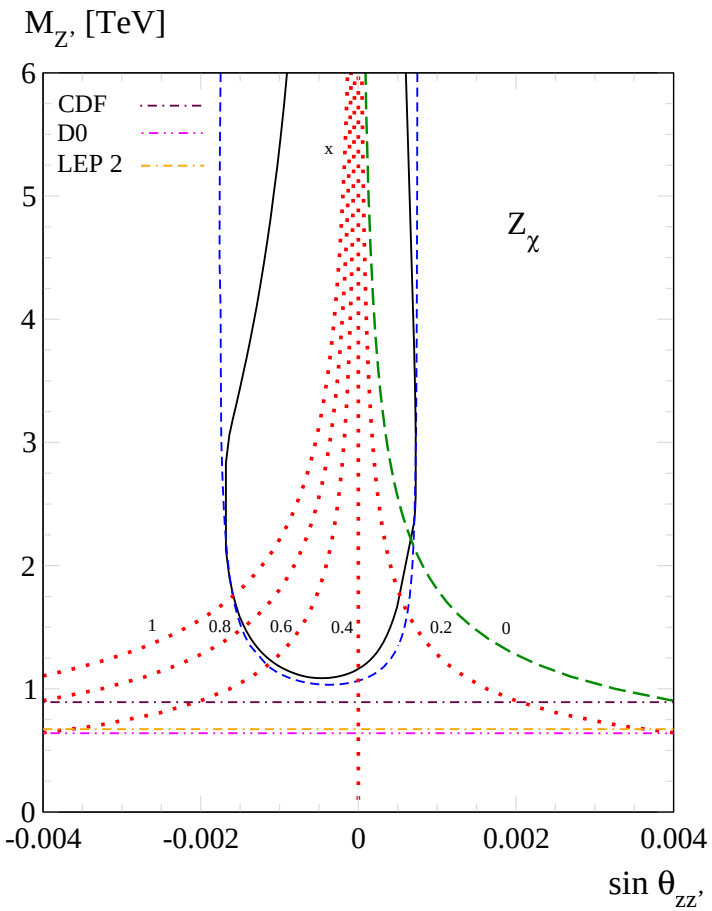
$$y = \left(\frac{g_2}{g_1}\right)^2 (\rho_1 \sin^2\theta + \rho_2 \cos^2\theta) \qquad \rho_\alpha \equiv M_W^2/(M_\alpha^2 \cos^2\theta_W)$$

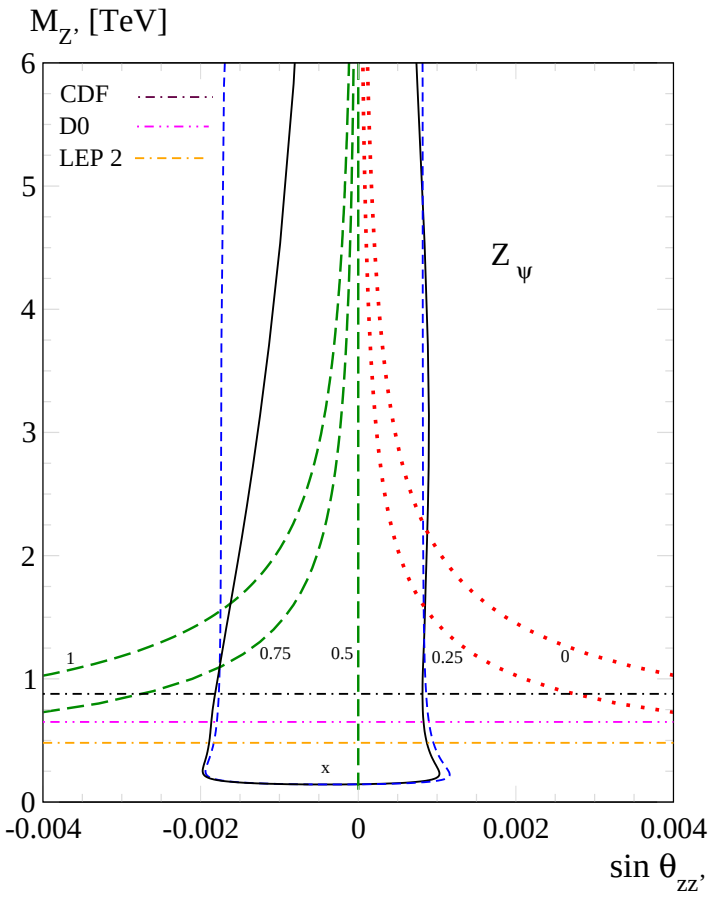
- **Z-pole (LEP, SLC): $Z - Z'$ mixing** (vertices; shift in M_1)

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

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

- **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'

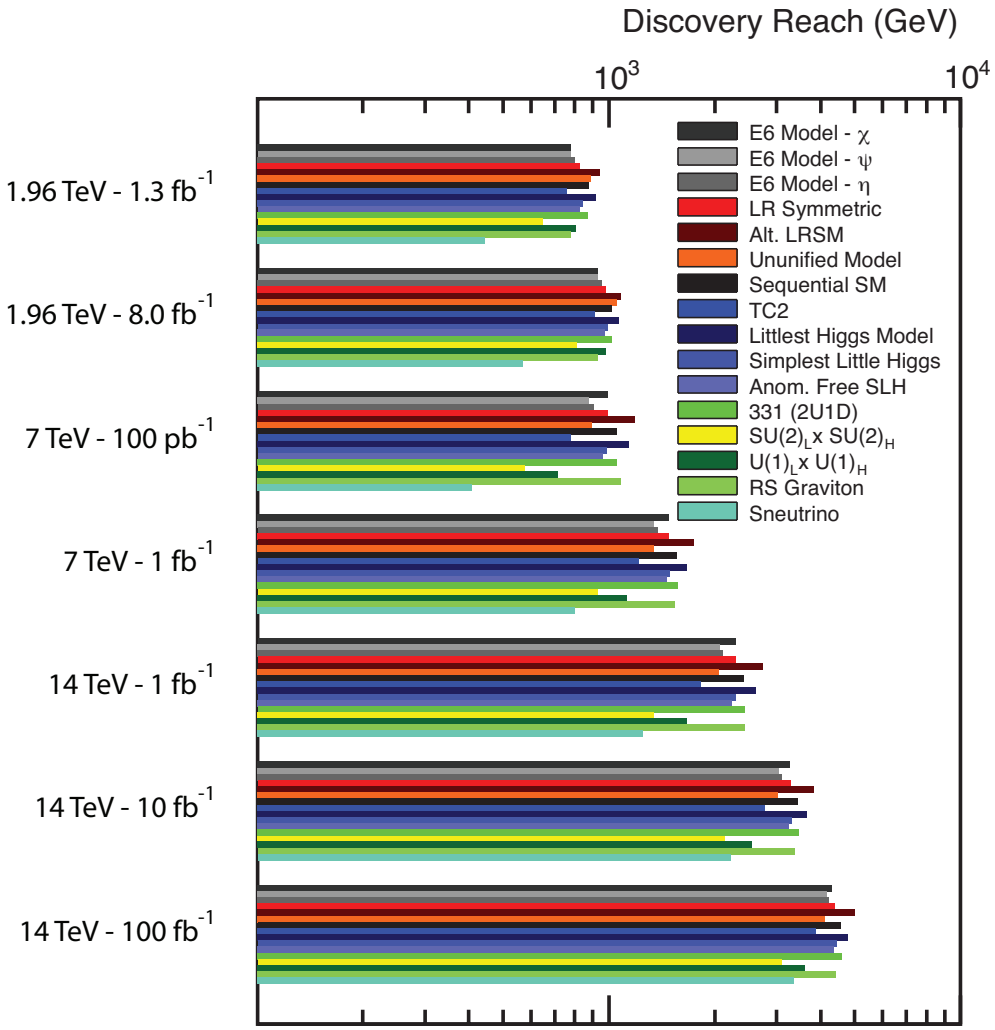
Z'	$M_{Z'}$ [GeV]				$\sin\theta_{ZZ'}$			$\chi^2_{\rm min}$
	EW	CDF	DØ	LEP 2	$\sin\theta_{ZZ'}$	$\sin\theta^{\rm min}_{ZZ'}$	$\sin\theta^{\rm max}_{ZZ'}$	
Z_χ	1,141	892	640	673	-0.0004	-0.0016	0.0006	47.3
Z_ψ	147	878	650	481	-0.0005	-0.0018	0.0009	46.5
Z_η	427	982	680	434	-0.0015	-0.0047	0.0021	47.7
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

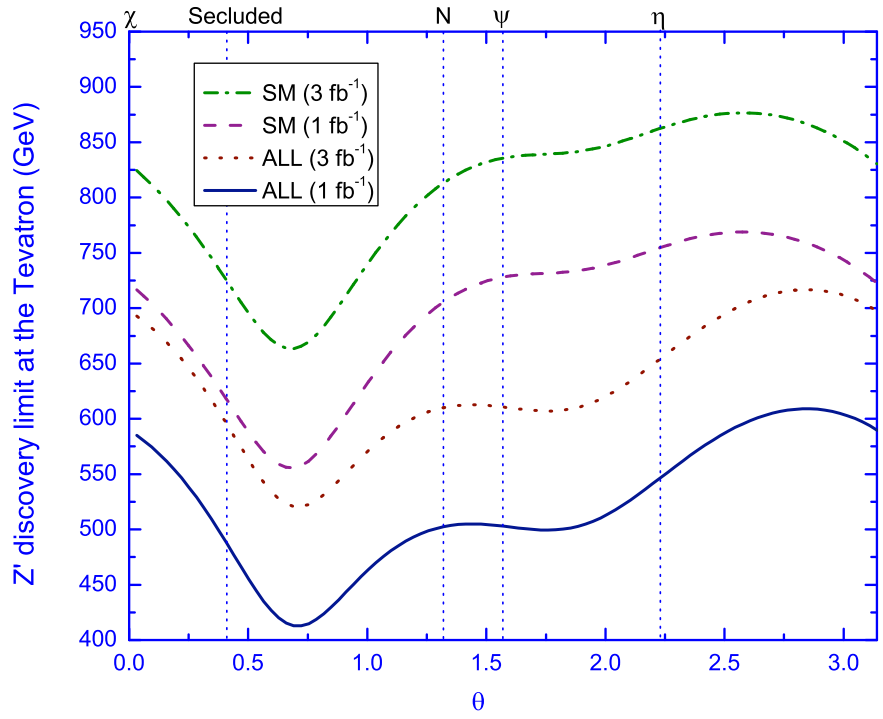
- **Tevatron and LHC:** $pp(\bar{p}p) \to Z' \to e^+e^-, \mu^+\mu^-, jj, \bar{b}b, \bar{t}t, e\mu, \tau^+\tau^-$
- **Rates (total width) dependent on whether sparticle and exotic channels open** ($\Gamma_{Z'}/M_{Z'} \sim 0.01 \to 0.05$ **for** E_6)
- **LHC discovery to** $\sim 4-5$ **TeV**
  - **Spin-0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

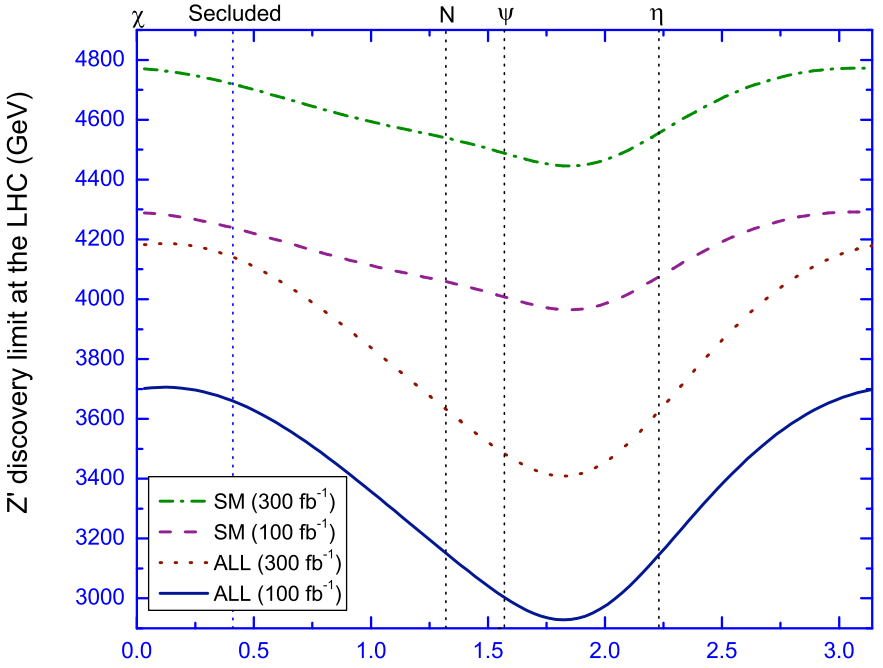
$$\frac{d\sigma^f_{Z'}}{d\cos\theta^*} \propto \frac{3}{8}(1+\cos^2\theta^*) + A^f_{FB}\cos\theta^* \quad \textbf{[for spin-1]}$$

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



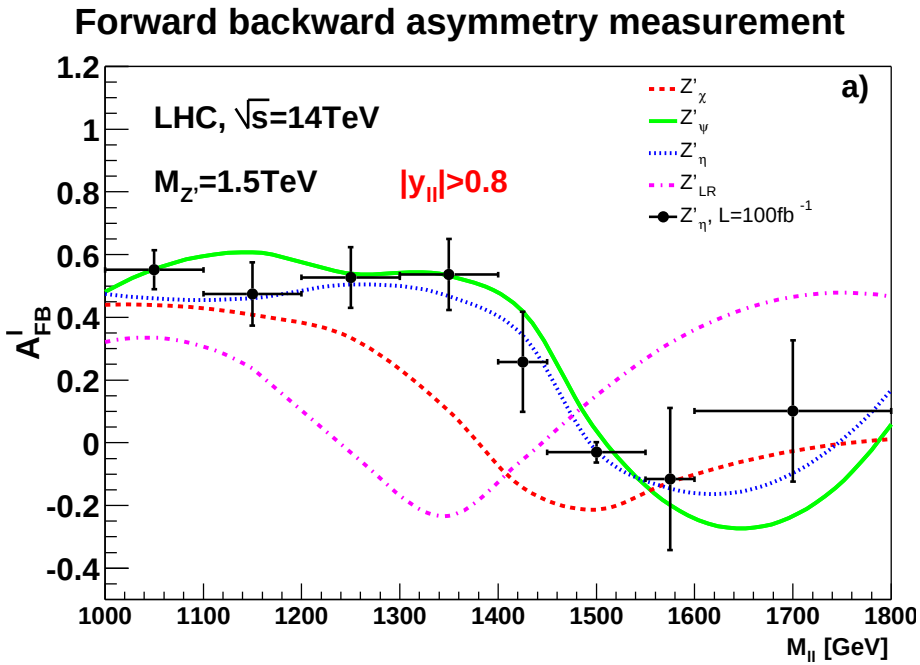
(Courtesy: Steve Godfrey)

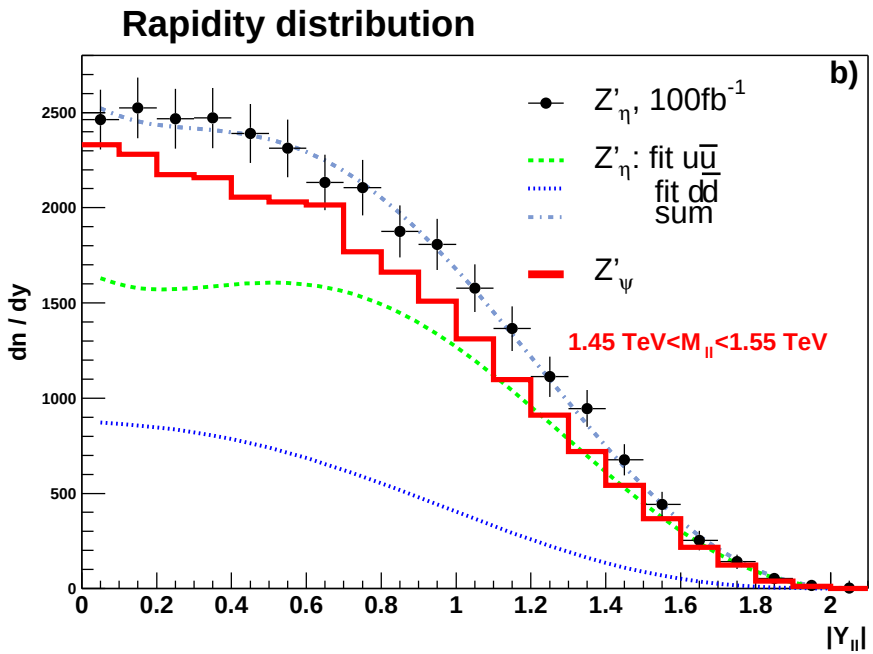




Diagnostics of Z' Couplings

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





(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**

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)

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)