Z' indication from APV data and searches at future LC

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Summary

- Discussion of the latest determination of Q_W of atomic cesium (2.5σ away from the SM)

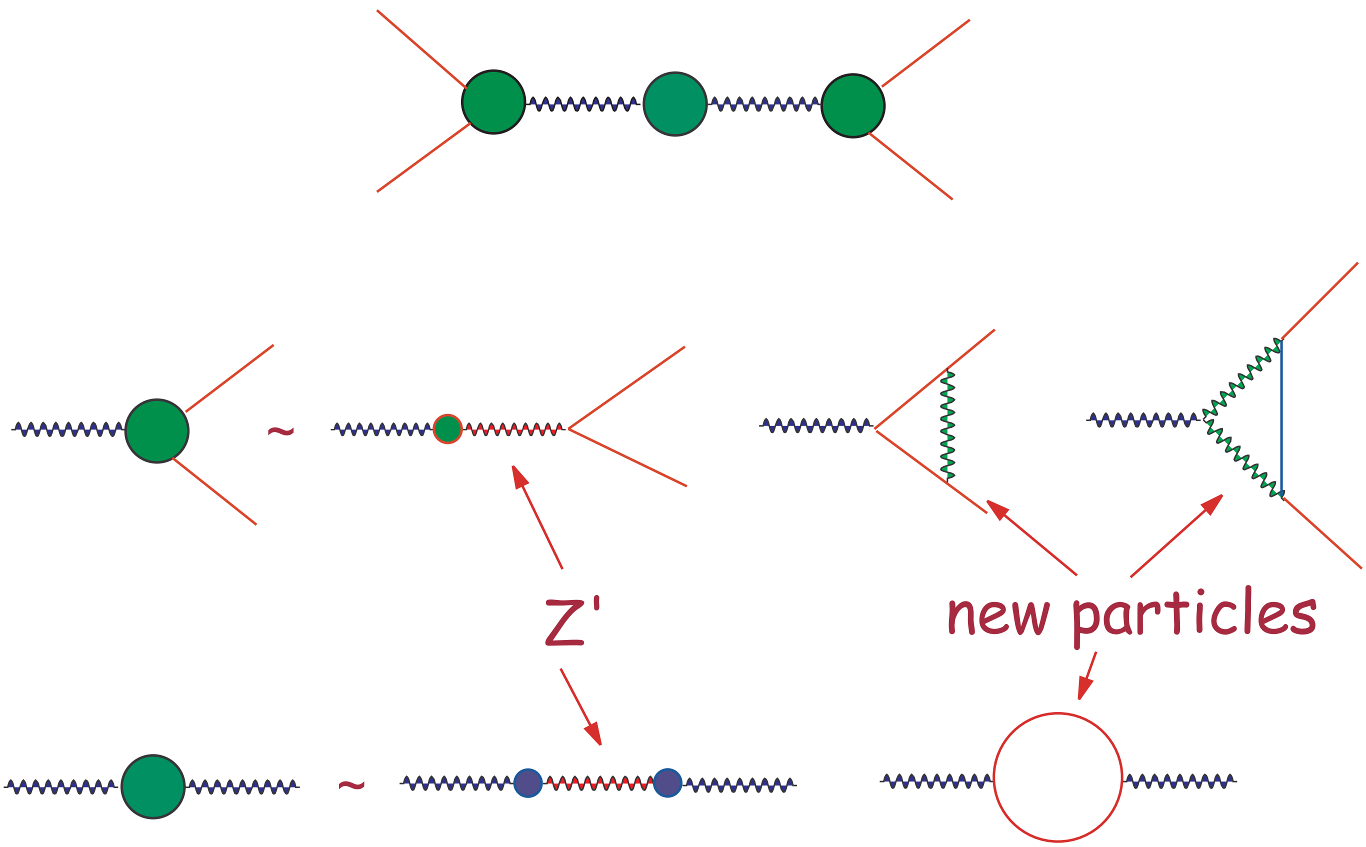
- Implications of APV for new physics
  - Composite Models, Lepto-quarks
  - Extra-dimension models
  - New Vector Bosons from E_6 and LR models

- An extra-Z' could explain the discrepancy for Q_W

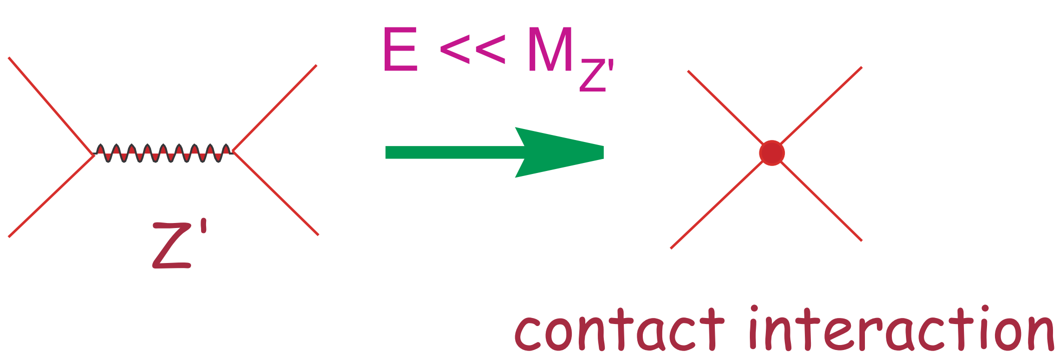
- Searches of Z' at future colliders

- Conclusions

LEP physics puts heavy constraints on new physics. But which kind of new physics is detectable at LEP?



New physics invisible at LEP may come from new 4-fermi interactions



Low-energy experiments complementary to LEP

- they probe different energy scale

- they probe a different set of model-independent electron-quark couplings

A good possibility are experiments in

Atomic Parity Violation

Measure the combinations $v_e a_q$, $a_e v_q$.
From Q_W in atomic cesium one gets

$$c_{1u,1d} = -8\, a_e\, v_{1u,1d}$$

Atomic Parity Violation

Within the SM the relevant 4-fermi PV interaction between charged leptons and quarks is given by

$$\mathcal{L}_{\text{eff}}^{PV} = \frac{G_F}{\sqrt{2}}\Big[(\bar{\ell}\gamma_\mu\gamma_5\ell)\sum_{q=u,d} c_{1q}\bar{q}\gamma^\mu q +$$

$$+(\bar{\ell}\gamma_\mu\ell)\sum_{q=u,d} c_{2q}\bar{q}\gamma^\mu\gamma_5 q\Big]$$

where

$$c_{1q} = -8a_\ell v_q \qquad c_{2q} = -8v_\ell a_q$$

In terms of nucleons

$$\mathcal{L}_{\text{eff}}^{PV} = -\frac{G_F}{\sqrt{2}}\Big[(\bar{\ell}\gamma_\mu\gamma_5\ell)\sum_{N=p,n} c_{1N}\bar{N}\gamma^\mu N +$$

$$+(\bar{\ell}\gamma_\mu\ell)\sum_{N=p,n} c_{2N}\bar{N}\gamma^\mu\gamma_5 N\Big]$$

where

$$c_{ip} = -2c_{iu} - c_{id}, \quad c_{in} = -c_{iu} - 2c_{id}, \qquad i = 1,2$$

In the SM:

$$a_f = -1/2T_{3L}^f, \qquad v_f = 1/2(T_{3L}^f - 2s_\theta^2 Q^f)$$

$$c_{1q} = -8a_\ell v_q = -(T_3^q - 2s_\theta^2 Q^q)$$

$$c_{2q} = -8v_\ell a_q = -T_3^q(1 - 4s_\theta^2)$$

In the non-relativistic limit, for a point-like nucleus with Z protons and N neutrons

$$H_{PV} = \frac{G_F}{4\sqrt{2}m_\ell}\Big[Q_W(Z,N)\vec{\sigma}_\ell \cdot [\vec{p},\delta^3(\vec{r})]_+ +$$

$$+2(c_{2p}\vec{S}_p + c_{2n}\vec{S}_n) \cdot [\vec{p},\delta^3(\vec{r})]_+$$

$$-2i\vec{\sigma}_\ell \wedge (c_{2p}\vec{S}_p + c_{2n}\vec{S}_n) \cdot [\vec{p},\delta^3(\vec{r})]_+\Big]$$

The weak charge of the nucleus is defined as

$$Q_W(Z,N) = 2\left[c_{1p}Z + c_{1n}N\right]$$

For large values of Z, the term in Q_W is dominant (coherence effect) whereas spin terms tend to cancel (Bouchiat and Bouchiat 1974-75)

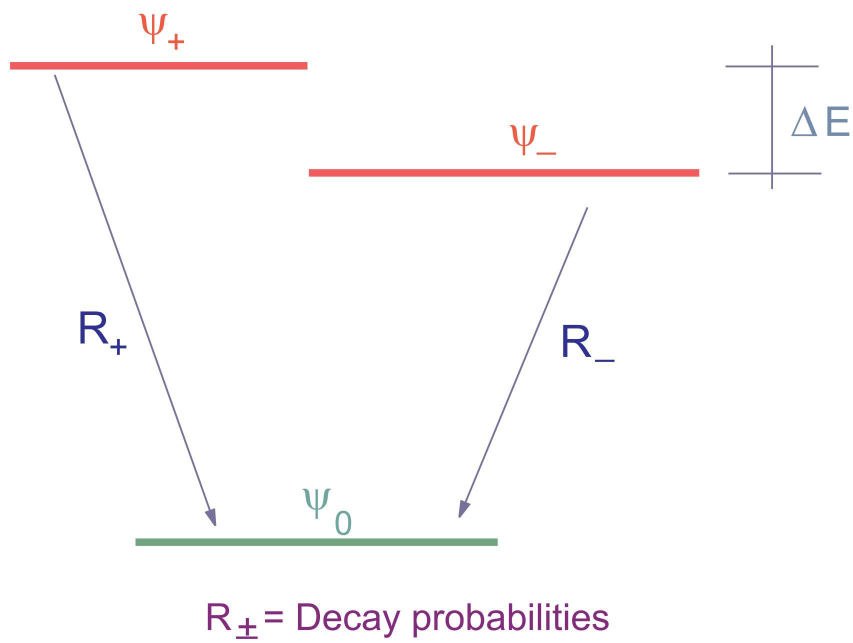
$$\langle H_{PV}\rangle \propto Z^2 Q_W(Z,N) \propto Z^3$$

One Z from the electron momentum $\vec{p}$, one Z from the wave function at the origin and one Z from Q_W

For Cesium $Z = 55$ and $Z^3 \approx 2 \cdot 10^5$

In APV one observes an optical transition between a pair of states $\psi_\pm$ mixed by H_{PV}, and ψ_0, with ψ_+ of the same nominal parity as ψ_0

$$|\psi_+\rangle \to |\psi_+\rangle + \eta|\psi_-\rangle \qquad \eta = \frac{\langle\psi_-|H_{PV}|\psi_+\rangle}{\Delta E}$$



$$R_+ = |M_1|^2, \qquad R_- = |E_1^{pv}|^2$$

The total transition probability

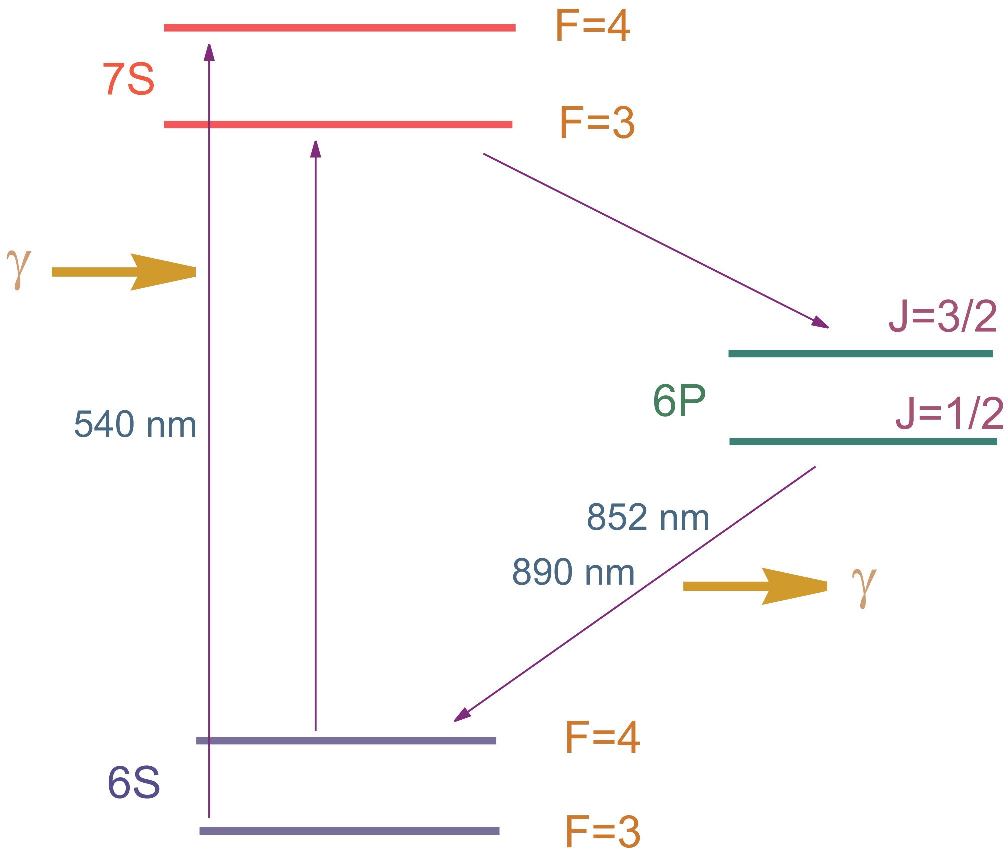
$$W \sim M_1^2 + |E_1^{pv}|^2 \pm 2Im(E_1^{pv})M_1$$

$\pm$ depending on the helicity of the absorbed (emitted) photon.
Measure the circular dichroism

$$\delta = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \sim 2Im(E_1^{pv})/M_1$$

PV effect proportional to $Im(E_1^{pv})/M_1$ (bigger if R_+ suppressed transition)

Last technique used for the $6S \to 7S$ in atomic ${}^{133}_{55}Cs$ giving rise to $\delta \approx 10^{-4} \div 10^{-3}$, in Paris (1982,1984) and in Boulder (1985,1988,1997).



To overcome the background the interference with a large electro-induced (Stark) transition has been used

$$\text{Experiment} \longrightarrow \langle H_{PV} \rangle \approx Q_W \, \kappa_{PV}$$

The atomic form-factor κ_{PV} must be evaluated theoretically.

High-precision measurements must be coupled with calculations of similar accuracy for a precise determination of Q_W.

Theoretical evaluation of κ_{PV}

Blundell et al., Dzuba et al.

κ_{PV} from many-body perturbative theory with Hartree-Fock potential

The error on k_{PV} estimated from the discrepancies with experimental values of PC observables (energy levels, hyperfine splittings etc.) and by requiring stability against variation of the parameters

(1992) $\Delta\kappa_{PV}/\kappa_{PV} \sim 1\%$

(Taken into account: nuclear distribution, nuclear spin-dependent effects, Z-exchange among the electrons)

In 1999 $\Delta\kappa_{PV}/\kappa_{PV}$ **down to** 0.4%

(Bennett and Wieman)

- new measurements of relevant quantities in cesium are in better agreement with the theoretical calculation
- a problem of the previous calculations, when applied to sodium and lithium, leading to 1% discrepancy in the lifetimes, it has now disappeared after new experiments

Calculations must be extended to higher orders in many-body perturbation theory to confirm the small theoretical error

Possible experimental improvements

Figure of merit for the Boulder experiment:

$$\left|\frac{Q_W^{\text{exp}} - Q_W^{\text{SM}}}{Q_W^{\text{exp}}}\right| = 0.016 \pm (0.0038)_{\text{exp}} \pm (0.005)_{\text{th}}$$

The prospective isotope ratio limits for APV studies in Seattle and Berkeley give

$$\left|\frac{\mathcal{R}^{\text{exp}} - \mathcal{R}^{\text{SM}}}{\mathcal{R}^{\text{exp}}}\right| = \ ? \ \pm (0.001)_{\text{exp}} \pm (0.004)_{\text{th}}$$

where, (A_{PV} is a PV observable)

$$\mathcal{R} = \frac{A_{PV}(N') - A_{PV}(N)}{A_{PV}(N') + A_{PV}(N)}$$

and it can be expressed as

$$\mathcal{R} = \mathcal{R}^{\text{SM}}(1 + \delta_{\mathcal{R}})$$

$\delta_{\mathcal{R}}$ contains new physics and depends on the variation of the neutron density along the isotope chaine. In a simple model of constant neutron and proton density ($\Delta N = N' - N$)

$$\delta_{\mathcal{R}}(\text{radius}) = -\frac{3}{7}\frac{N'}{\Delta N}(Z\alpha)^2 \delta\left(\frac{R_{N'} - R_N}{R_p}\right)$$

For Cesium and Barium, nuclear theory is a factor two away from the required experimental sensitivity (Pollock (1992), Chen and Vogel (1994))

The data on APV

Experimental result in 1988 (Boulder group) and theoretical evaluation of k_{PV} in 1991 (Blundell et al., Dzuba et al.) get Q_W at a level of 2.5%

$$Q_W\left({}^{133}_{55}Cs\right) = -71.04 \pm (1.58)_{\text{exp}} \pm (0.88)_{\text{theor}}$$

In 1999, the same group (Bennett,Wieman) with uncertainty 0.6%

$$\boxed{Q_W\left({}^{133}_{55}Cs\right) = -72.06 \pm (0.28)_{\text{exp}} \pm (0.34)_{\text{theor}}}$$

to be compared with the SM result

$$Q_W^{\text{SM}}\left({}^{133}_{55}Cs\right) = -73.24 \pm 0.13 \qquad (m_H = 100\ GeV)$$

↑ from hadronic loops

$$\boxed{Q_W^{\text{exp}} - Q_W^{\text{theor}} = 1.18 \pm 0.46, \quad (2.57\ SD)}$$

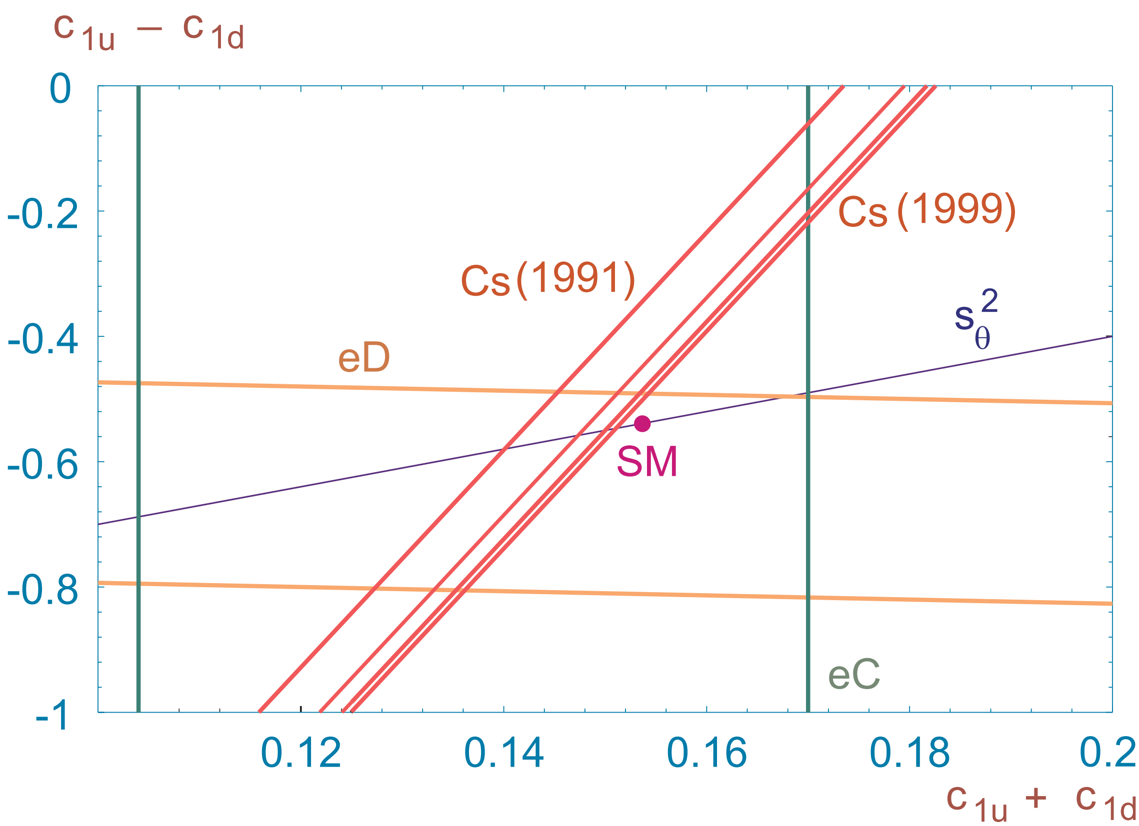
If this difference is not due to an experimental error, or a statistical fluctuation, or an error in the theoretical calculations, or some over-looked contributions in the SM, then

SM disfavored at 99%CL

For increasing m_H, Q_W decreases and the discrepancy increases

$$Q_W = -2[(2Z+N)c_{1u} + (Z+2N)c_{1d}]$$

$$\text{Cs}(1991) \longrightarrow Q_W = -71.08 \pm 1.81$$
$$\text{Cs}(1999) \longrightarrow Q_W = -72.06 \pm 0.44$$



$$\text{eD[SLAC](1995)} \longrightarrow 2c_{1u} - c_{1d} = 0.94 \pm 0.26$$
$$\text{eC[Bates](1990)} \longrightarrow c_{1u} + c_{1d} = 0.137 \pm 0.033$$

The new Cesium result deviates of $\approx 2.5\sigma$ from the SM prediction

Let us parameterize: (Altarelli,Barbieri,Caravaglios)

$$Q_W = -72.72 \pm 0.13 - 102\epsilon_3^{\text{rad}} + \delta_N Q_W$$

For $m_t = 175\ GeV$, $m_H = 100(300)\ GeV$

$$\epsilon_3^{\text{rad}} = 5.110(6.115) \times 10^{-3}$$

For instance, new physics contributing to the Z self-energy (oblique corrections) gives

$$\delta_N Q_W(\text{oblique}) = -102\,\epsilon_{3N}$$

To compensate the discrepancy on Q_W one would need

$$\epsilon_{3N} = (-11.6 \pm 4.5) \times 10^{-3}$$

LEP and SLC physics constrain strongly deviations from the SM:

$$\epsilon_3^{\text{exp}} = \epsilon_3^{\text{rad}} + \epsilon_{3N} = (4.19 \pm 1) \times 10^{-3}$$

then $\epsilon_{3N} \sim 10^{-3}$ (for a light Higgs)

almost an order of magnitude too small

We need new physics not constrained by LEP

One possible neglected contribution to Q_W is the difference between neutron and proton spatial distributions in the nucleus. It is small ($Q_W^{n-p} \approx 0.1$) but largely model-dependent.
Even with a conservative error estimate

$$\Delta Q_W^{n-p} = \pm 0.3$$ (Pollock,Welliver)

the deviation with respect to SM remains $\approx 2\sigma$
The following analysis is based on the result by Bennett and Wieman

Bounds on $\delta_N Q_W$

$$Q_W^{\rm exp} - Q_W^{\rm SM}(m_H) = 0.66 + 102\epsilon_3^{\rm rad}(m_H) - \delta_N Q_W \pm 0.46$$

For a light Higgs ($m_H = 100\ GeV$)

$$\boxed{95\%\text{CL}, \quad 0.28 \le \delta_N Q_W \le 2.08}$$

The positive lower bound implies strong restrictions on new physics.
All the models leading to $\delta_N Q_W \le 0$ are excluded. For increasing m_H both bounds increase.

Bounds on New Physics

The relevant parity violating effective lagrangian within the SM is

$$\mathcal{L}^{\mathrm{PV}}_{\mathrm{SM}} = \frac{G_F}{\sqrt{2}} \left[\bar{e}\gamma_\mu\gamma_5 e \sum_{q=u,d} c_{1q}\bar{q}\gamma^\mu q \right]$$

The typical low-energy contribution of new physics is a similar 4-fermi interaction

$$\mathcal{L}^{\mathrm{PV}}_{\mathrm{NP}} = \frac{4\pi g_{NP}}{\Lambda^2} \left[\bar{e}\gamma_\mu\gamma_5 e \sum_{q=u,d} h_{1q}\bar{q}\gamma^\mu q \right]$$

An experimental sensitivity to

$$\frac{\Delta Q_W}{Q_W} \approx 1\% \longrightarrow \Lambda \approx 17\, g_{NP}\, TeV$$

strong NP, $\quad g^2_{NP} \approx 1 \mapsto \Lambda \approx 17\ TeV$

weak NP, $\quad g^2_{NP} \approx \alpha \mapsto \Lambda \approx 1.5\ TeV$

Q_W probes NP at $\Lambda \gtrsim 1\ TeV$

Models of New Physics

Contact Interactions from Compositeness

A typical example operator: (Langacker)

$$\mathcal{L} = \pm \frac{g^2}{\Lambda^2} \bar{e}\, \Gamma_\mu\, e\, \bar{q}\, \Gamma^\mu\, q$$

with $\Gamma_\mu = \gamma_\mu \frac{1-\gamma_5}{2}$, Λ the compositeness scale, and g^2 the strength of the interaction (we expect $g^2 \sim 4\pi$).
Using

$$Q_W = -2\left[(2Z+N)c_{1u} + (Z+2N)c_{1d}\right]$$

The contact interactions modify the coefficients

$$c_{1u,1d} \to c_{1u,1d} + \Delta C_{1u,1d}$$

In this example: $\Delta C_{1u} = \Delta C_{1d} = \Delta C$

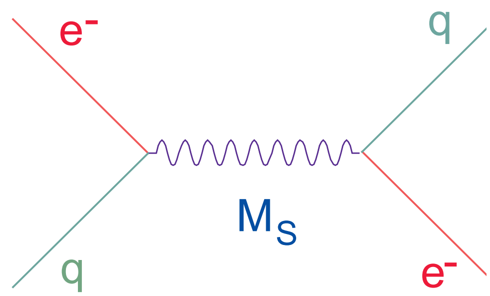
$$\Delta C = \mp \frac{\sqrt{2}\pi}{G_F \Lambda^2}$$

The negative sign in $\mathcal{L}$ is excluded, whereas for the positive sign we have the 95%CL bound

$$12.1 \leq \Lambda(TeV) \leq 32.9$$

to be compared with PDG limit, $\Lambda \geq 3.5\ TeV$

Lepto-quarks



A typical example: $SU(5)$ inspired lepto-quark

(Langacker)

$$\mathcal{L} = \frac{\eta_L^2}{2M_S^2} \bar{e}_L \gamma_\mu e_L \bar{u}_L \gamma^\mu u_L + (L \to R)$$

$$c_{1u} \to c_{1u} + \Delta C, \qquad \Delta C = \mp \frac{\sqrt{2}\eta_{L,R}^2}{8G_F M_S^2}$$

From $\pi^0 \to \ell^+\ell^- \longrightarrow \eta_L \sim 0$ or $\eta_R \sim 0$.

If $\eta_R \neq 0$, $\Delta C > 0 \longrightarrow \delta_N Q_W < 0$ (excluded).

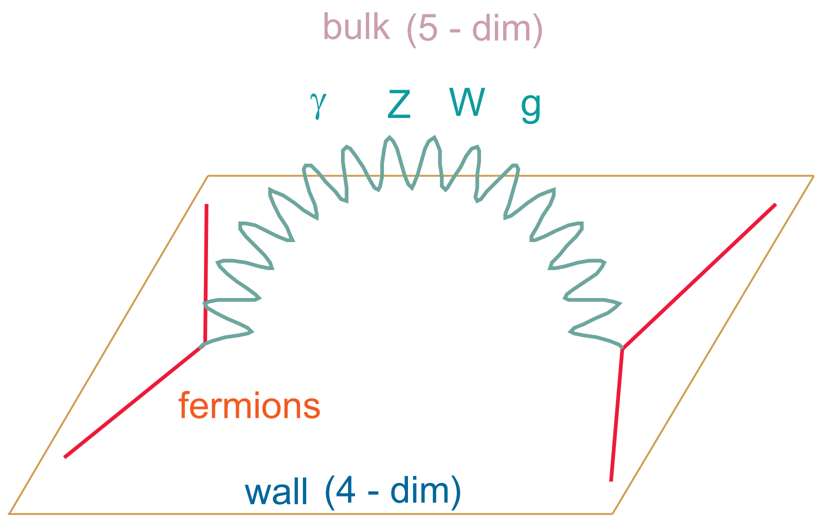
If $\eta_R = 0$ $(\eta_L \neq 0)$ the 95%CL bound is

$$1.7 \leq \frac{M_S(TeV)}{\eta_L} \leq 4.5$$

or, assuming a weak interaction, $\eta_L^2 \sim 4\pi\alpha_{\text{em}}$

$$0.5 \leq M_S(TeV) \leq 1.4$$

Extra-dimension Models



Theories with extra compact dimensions involve KK excitations of the SM gauge bosons with mass

$$M_{KK}^2 = \frac{n^2}{R^2}$$

and couplings to fermions

$$\text{KK couplings} = \sqrt{2}\ \text{SM couplings}$$

with R the compactification radius

The corrections to Q_W (Casalbuoni, De Curtis, Dominici, Gatto) come from

- from Z-like KK modes
- from the W-like KK modes (they give a correction to G_F)
- a change of s_θ^{eff}

The first two contributions give (for zero mixing)

$$\delta_N Q_W \sim (\sqrt{2})^2 \sum_{n=1}^{\infty} (M_Z^2 - M_W^2) \frac{R^2}{n^2} Q_W^{SM} < 0$$

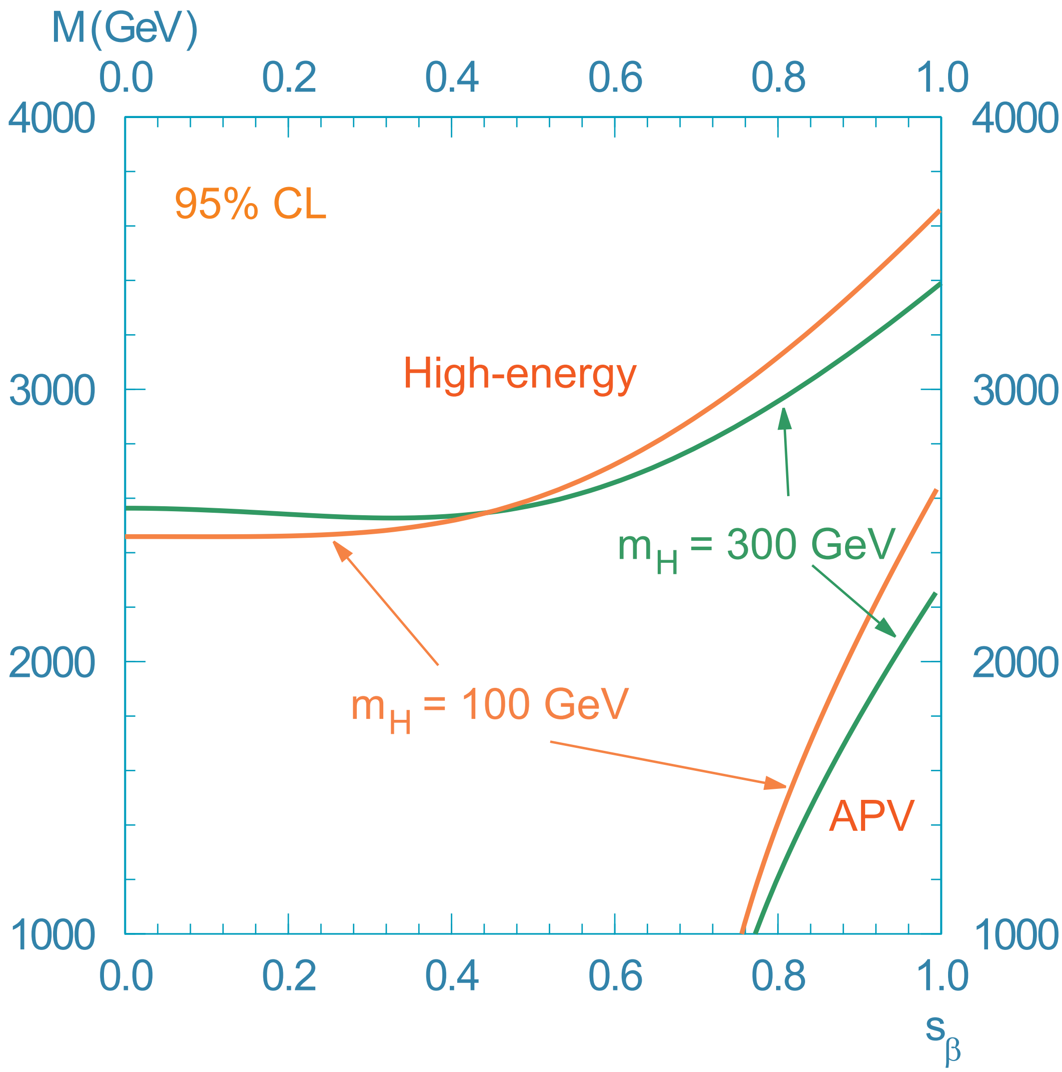
The change of s_θ^{eff} also gives $\delta_N Q_W < 0$

Extra-dimension models (with Higgs in the bulk) are disfavored at more than 99%CL for any compactification radius

The result does not substantially change in presence of mixing terms (tan $\beta = \frac{<\phi_2>}{<\phi_1>}$ with ϕ_1=Higgs in the bulk and ϕ_2=Higgs in the 4D wall)

As long as $\sin\beta < 0.707$ the new physics contribution is $\delta_N Q_W < 0$

95%CL Bounds on the compactification scale $M = 1/R$ for given s_β from the high-energy precision measurements (ϵ parameters) and from APV data (Casalbuoni,De Curtis,Dominici,Gatto)

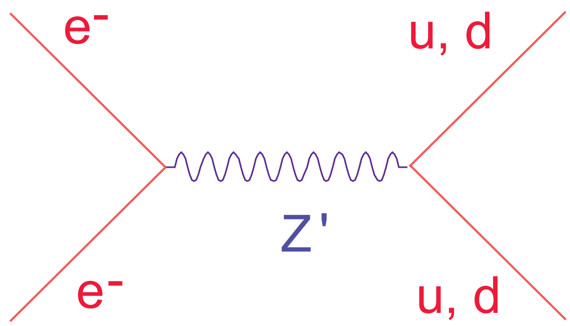


The two regions are incompatible at 95%CL

A global fit to all data is possible but the $\chi^2_{\rm min}$/d.o.f is unpleasantly large

Extra-U(1) Models from E_6

$$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$$
$$\to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$$



Models with a further massive neutral vector boson, Z' coupled to ordinary fermions

$$\begin{aligned} J^f_{Z'\mu} &= J^f_{\chi\mu} \cos\theta_6 + J^f_{\psi\mu} \sin\theta_6 \\ &= \bar{f}\left[\gamma_\mu v'_f + \gamma_\mu\gamma_5 a'_f\right] f \end{aligned}$$

The couplings v'_f, a'_f depend on the angle θ_6 (defining the embedding of $U(1)'$ in E_6)

Model	χ	ψ	η
$\theta_6(deg)$	0	90	$-\tan^{-1}\sqrt{5/3} \approx -52$

The $Z - Z'$ mixing angle θ_M is very much constrained by Z-pole observables ($\theta_M > 4$ mrad excluded for most models)

Both $Z - Z'$ mixing and the direct Z' contribution affect the NC experiments off the Z-pole

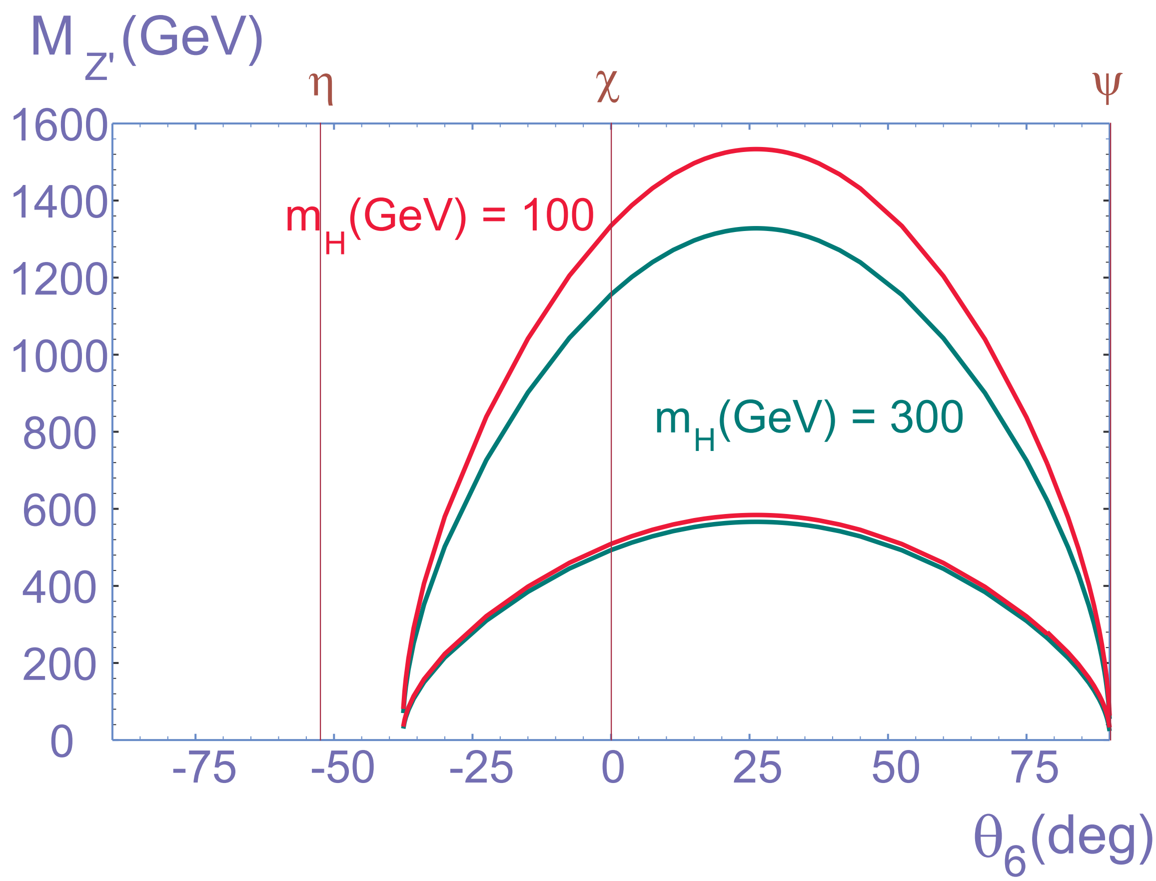
Bounds on Extra Z' from Q_W

Casalbuoni, De Curtis, Dominici, Gatto

The correction at Q_W, for $\theta_M = 0$, is

$$\delta_N Q_W = 16 a'_e \left[(2Z+N)v'_u + (Z+2N)v'_d\right] \frac{M_Z^2}{M_{Z'}^2}$$

Bounds on $\delta_N Q_W \to$ 95%CL bounds on $M_{Z'}$



Lower positive bound on $\delta_N Q_W \longrightarrow$ upper bound on $M_{Z'}$.

Excluded region $\longrightarrow \delta_N Q_W \leq 0$ (η and ψ models are excluded).

Direct search at Tevatron $\longrightarrow$ gives approximately $M_{Z'}(GeV) \geq 600$.

LR models

$$SO(10) \to SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

The further massive neutral vector boson, Z'_{LR} is coupled to the current

$$J^\mu_{Z'} = \alpha_{LR} J^\mu_{3R} - \frac{1}{2\alpha_{LR}} J^\mu_{B-L}$$

with $\alpha_{LR} = \sqrt{g_R^2/g_L^2 \cot^2\theta_W - 1}$.
In the L-R symmetric model (LR) one has $g_R = g_L$ and the fermionic couplings

$$a'_e v'_{u,d} = -a_e^{SM} v_{u,d}^{SM}$$

giving

$$\delta_N Q_W = -\frac{M_Z^2}{M_{Z'}^2} Q_W^{SM} > 0$$

The 95%CL bound is (for light Higgs)

$$\boxed{540 \leq M_{Z'}(GeV) \leq 1470}$$

The limit from Tevatron is $M_{Z'} \geq 630\ GeV$

Sequential Standard Model

A simple scaled Z' (with the same couplings to fermions as the SM) would give

$$\delta_N Q_W = \frac{M_Z^2}{M_{Z'}^2} Q_W^{SM} < 0$$

Excluded at more than 99%CL

Present bounds on Z'

Indirect bounds: recent fits (Cho,Hagiwara,Umeda; Erler,Langacker) to all the high-energy and the low-energy observables including Q_W (not the latest measurement). The best fit value for θ_M is ~ 0.

χ	ψ	η	LR	SSM
545	146	365	564	809

95%CL mass limits in GeV (Erler,Langacker (1999))

An update of this analysis (including the latest Q_W) gives a very good fit for the χ model with $M_{Z'_\chi} = 812^{+339}_{-152}$ GeV, $\sin\theta_M = (-1.12 \pm 0.80) \times 10^{-3}$, ($M_H = 145^{+103}_{-61}$ GeV, $\alpha_s = 0.1233 \pm 0.0039$)

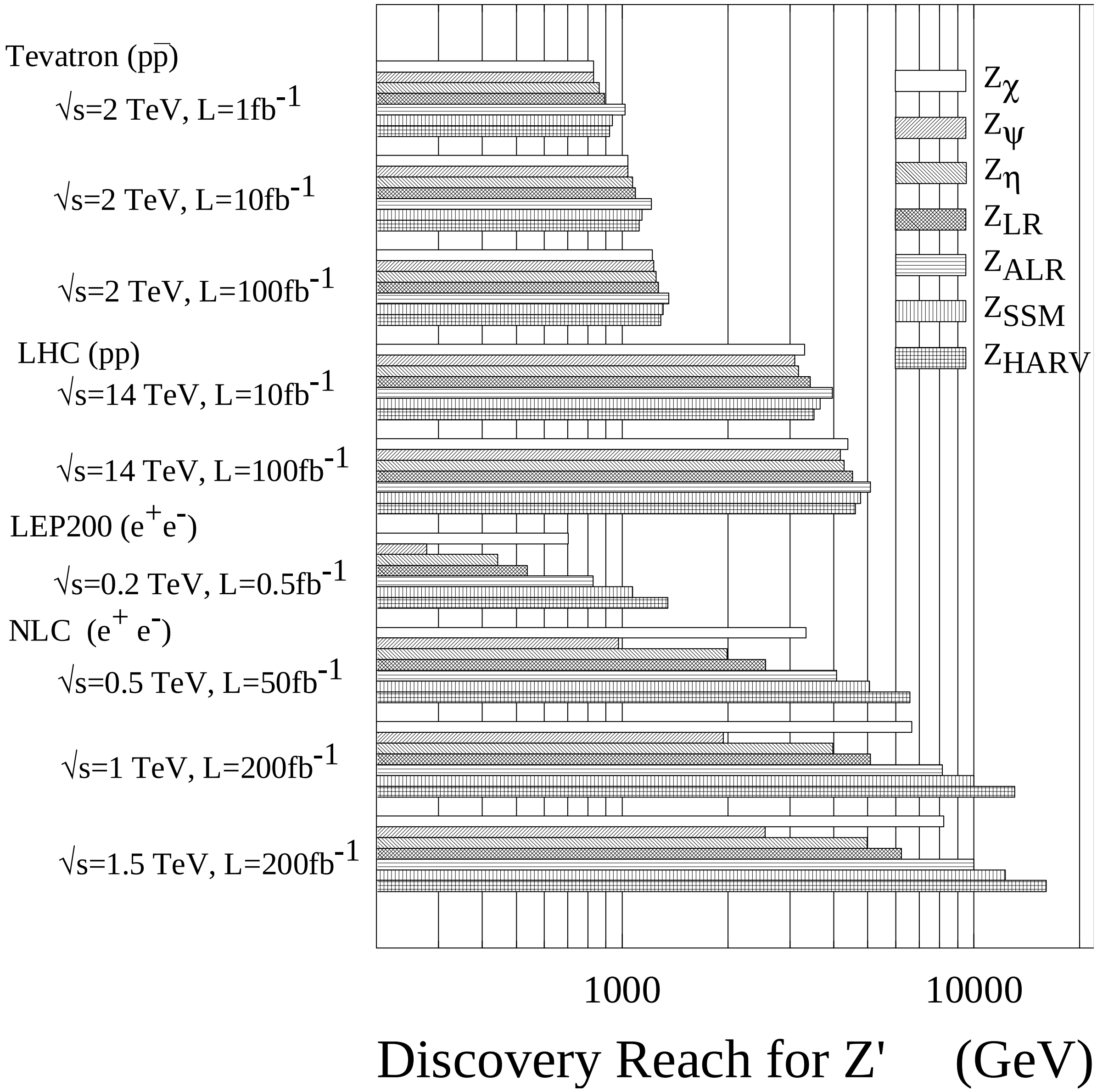
Direct search: from Tevatron, 95%CL limit on $M_{Z'}(GeV)$ from $\sigma(pp \to Z')B(Z' \to ll)$ (CDF coll. (1997))

χ	ψ	η	LR	SSM
595	590	620	630	690

From LEP2 (sensitive to $M_{Z'}$) and LEP1 (Γ_Z), the average of the 4 expts gives (for $\theta_M = 0$)
$M_{Z'_{\chi,\psi,\eta}}(GeV) > 464, 298, 323$ (E.Gross, Tampere 1999)

Discovery reach for Extra Z'

Cvetic, Godfrey; Rizzo



At hadron colliders from DY production of lepton pairs (e, μ). Bounds are relatively insensitive to the specific models.

Discovery limit at Tevatron Upgrade:

$M_{Z'} = 900(1000) GeV$ for $L = 1(10) fb^{-1}$

Discovery limit at LHC:

$M_{Z'} = 3.5(4.5) TeV$ for $L = 10(100) fb^{-1}$

Z' at future LC

Casalbuoni,De Curtis,Dominici,Gatto,Riemann

From $e^+e^- \to \gamma, Z, Z' \to f\bar{f}$ below threshold $\longrightarrow$ informations about the nature of Z'

LC scenarios:

$$\textbf{LC300} : \sqrt{s}(GeV) = 300,\ L(fb^{-1}) = 300$$
$$\textbf{LC500} : \sqrt{s}(GeV) = 500,\ L(fb^{-1}) = 500$$
$$P(e^-) = 0.9,\ P(e^+) = 0.6$$

Observables:

σ_t^l, σ_t^{had}, A_{FB}^l, A_{FB}^{had}, A_{FB}^b, A_{FB}^c, A_{LR}^l, A_{LR}^{had}, A_{LR}^b, A_{LR}^c, $R_t^b = \sigma_t^b/\sigma_t^{had}$, $R_t^c = \sigma_t^c/\sigma_t^{had}$

Efficiencies:

$\epsilon_l = 95\%$, $\epsilon_b = 60\%$, $\epsilon_c = 40\%$

Systematic errors:

$\Delta\epsilon_l/\epsilon_l = 0.5\%$, $\Delta\epsilon_b/\epsilon_b = 1\%$, $\Delta\epsilon_c/\epsilon_c = 1.5\%$, $\Delta L/L = 0.5\%$, $\Delta P/P = 1\%$

Cuts:

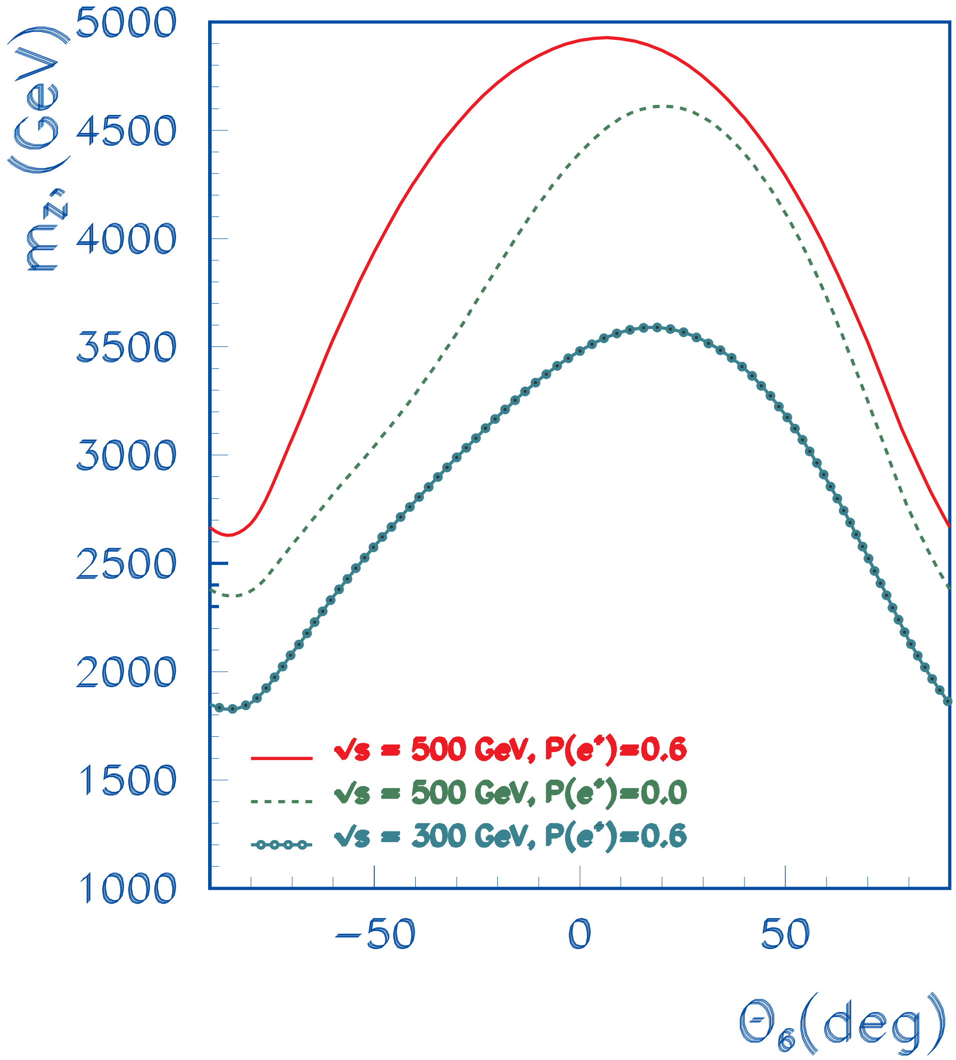
angular acceptance cut of 20^o to final state leptons,

cut on the energy of radiated photons:

$$\sqrt{s'/s} = (1 - E_\gamma/E_{beam})^{1/2} > 0.9$$

Use of full one-loop EW corrections, QCD corrections, ISR at two loops (Leike,Riemann)

95%CL lower bounds for $M_{Z'}$ in E_6



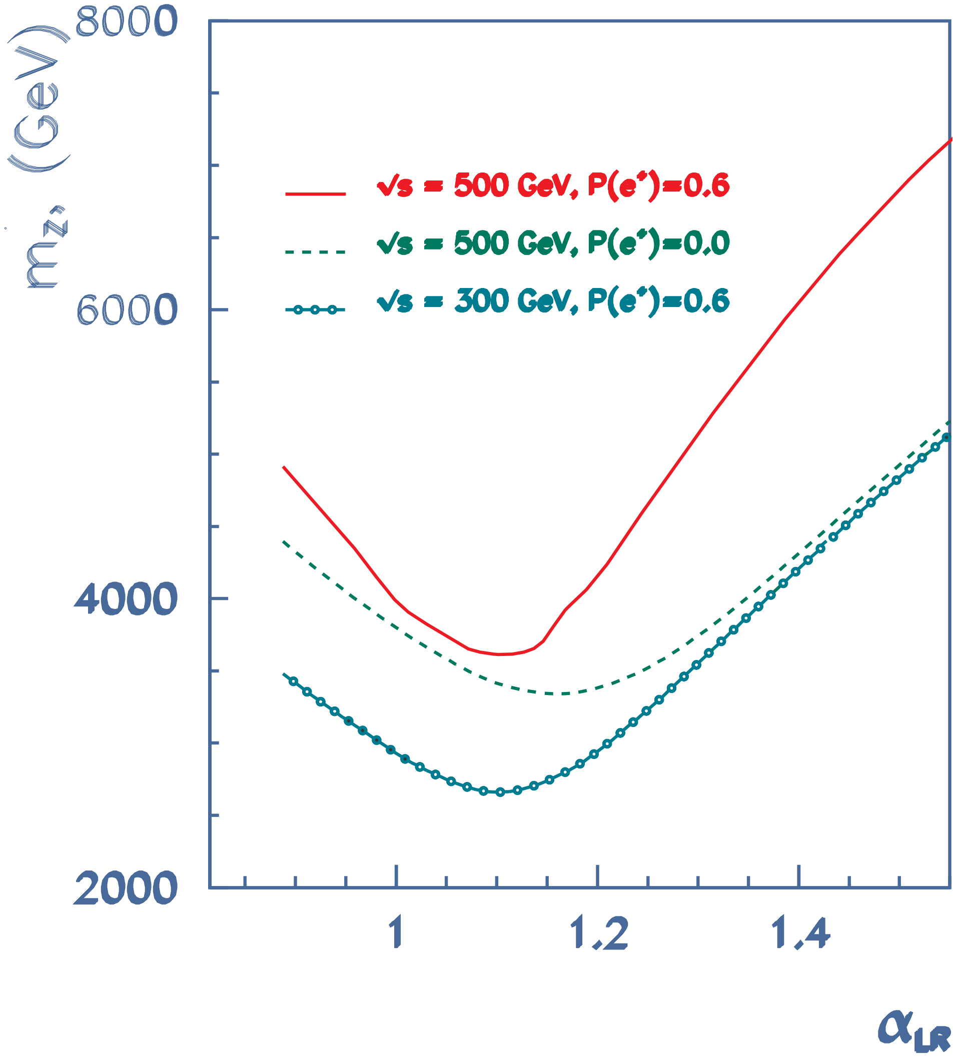
In the LC configurations considered the search reach is $5-10\sqrt{s}$

Both high-luminosity and e^+-polarization are effective in increasing the reach:

$L(fb^{-1})=50$ $P(e^+)=0$	$L(fb^{-1})=500$ $P(e^+)=0$	$L(fb^{-1})=500$ $P(e^+)=0.6$
3.5	4.4	4.9

95%CL $M_{Z'_\chi}^{lim}(TeV)$ @ LC500

95%CL lower bounds for $M_{Z'_{LR}}$

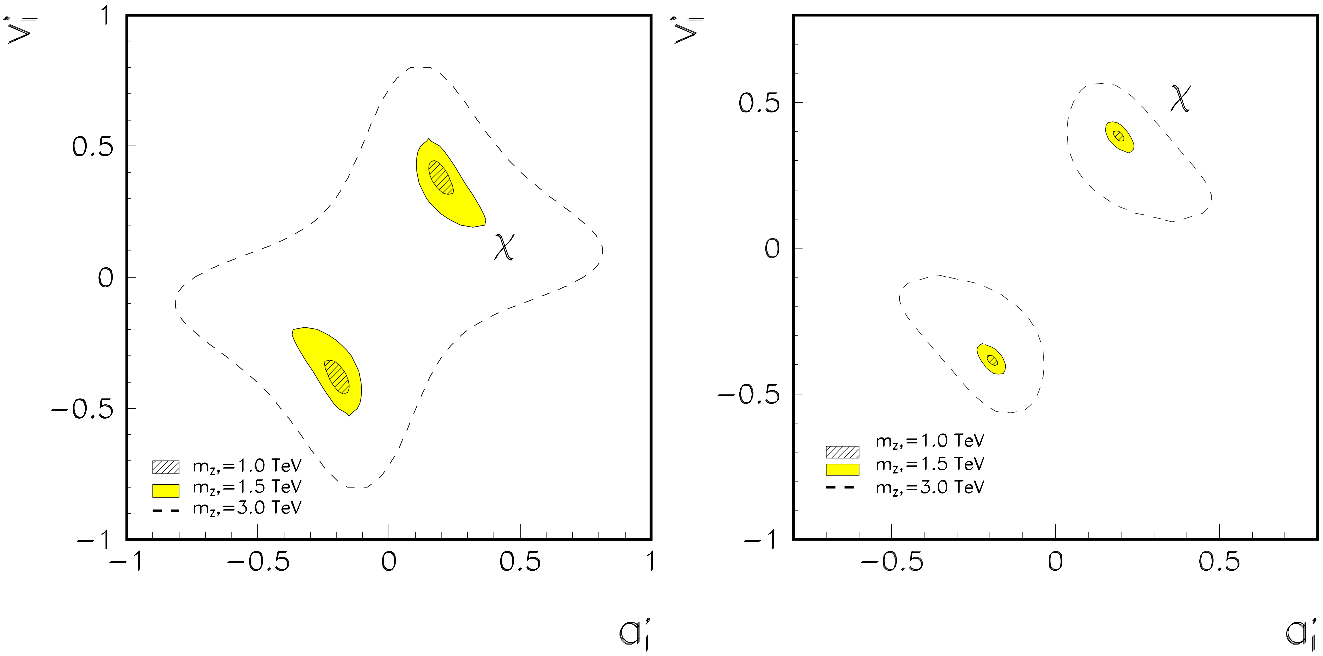


Z' couplings to leptons

Assume the knowledge on $M_{Z'}$ (from LHC) $\longrightarrow$ extract v_l' and a_l' from σ_t^l, A_{FB}^l, A_{LR}^l

95%CL Contours

$\sqrt{s} = 300\ GeV,\ L = 300\ fb^{-1}$ $\quad$ $\sqrt{s} = 500\ GeV,\ L = 500\ fb^{-1}$

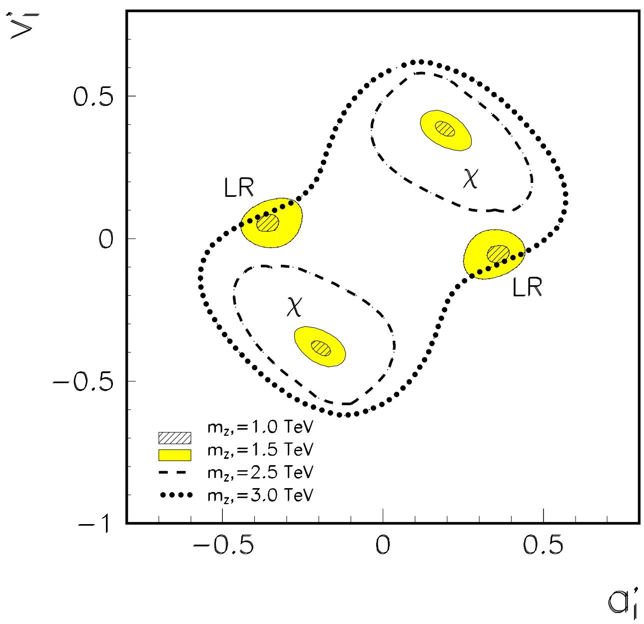


For $M_{Z'_\chi} = 1\ TeV$ the v_l' and a_l' couplings could be determined at LC300(LC500) within $10 \div 20\%$ $(5 \div 10\%)$ unless a sign ambiguity

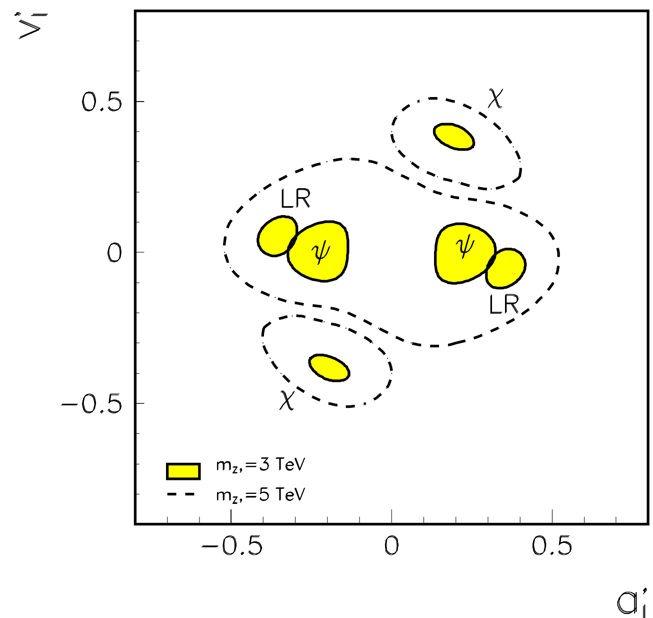
- $P(e^+) \neq 0$ does not help for the leptonic observables
- The sensitivity is weakened by decreasing luminosity, especially with increasing $M_{Z'}$

Assume a Z' either in the χ model or in the LR model, and derive 95%CL bounds on $Z'l\bar{l}$ couplings for different LC scenarios and various Z' masses (S. Riemann)

$\sqrt{s} = 500\ GeV,\ L = 50\ fb^{-1}$



$\sqrt{s} = 1.5\ TeV,\ L = 100\ fb^{-1}$



($M_{Z'} = 2.5, 3\ TeV$ for χ model)

The sensitivity is weakened with increasing $M_{Z'}$

$$\frac{\Delta a'_1}{\Delta a'_2}, \frac{\Delta v'_1}{\Delta v'_2} \sim \left(\frac{M^2_{Z'_1} - s}{M^2_{Z'_2} - s} \right)^{1/2}$$

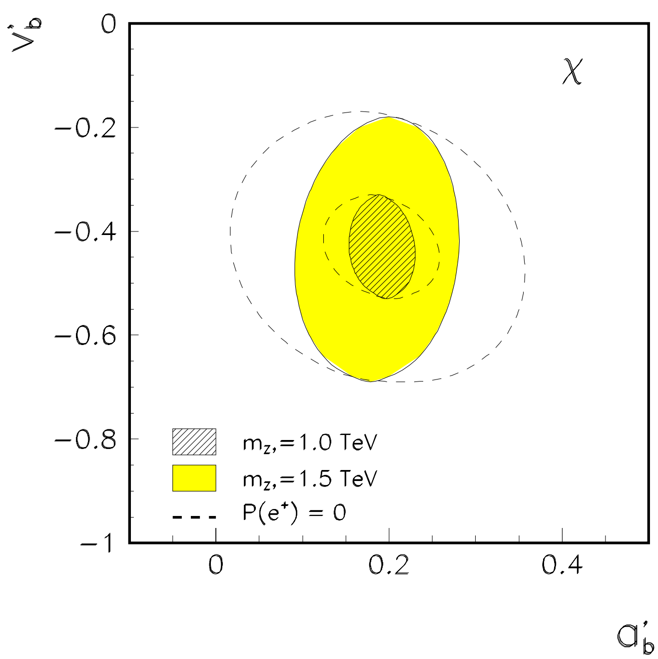
and with decreasing luminosity

$$\frac{\Delta a'_1}{\Delta a'_2}, \frac{\Delta v'_1}{\Delta v'_2} \sim \left(\frac{\mathcal{L}_2}{\mathcal{L}_1} \right)^{1/4}$$

A LC at $\sqrt{s} = 1.5\ TeV$ with $L = 100\ fb^{-1}$ allows a clear distintion between Z' models up to $M_{Z'} = 3\ TeV$ analyzing leptonic observables. In general a good separation is possible for $M_{Z'} < 3 \times \sqrt{s}$

95%CL contour for $(a'_b,\ v'_b)$

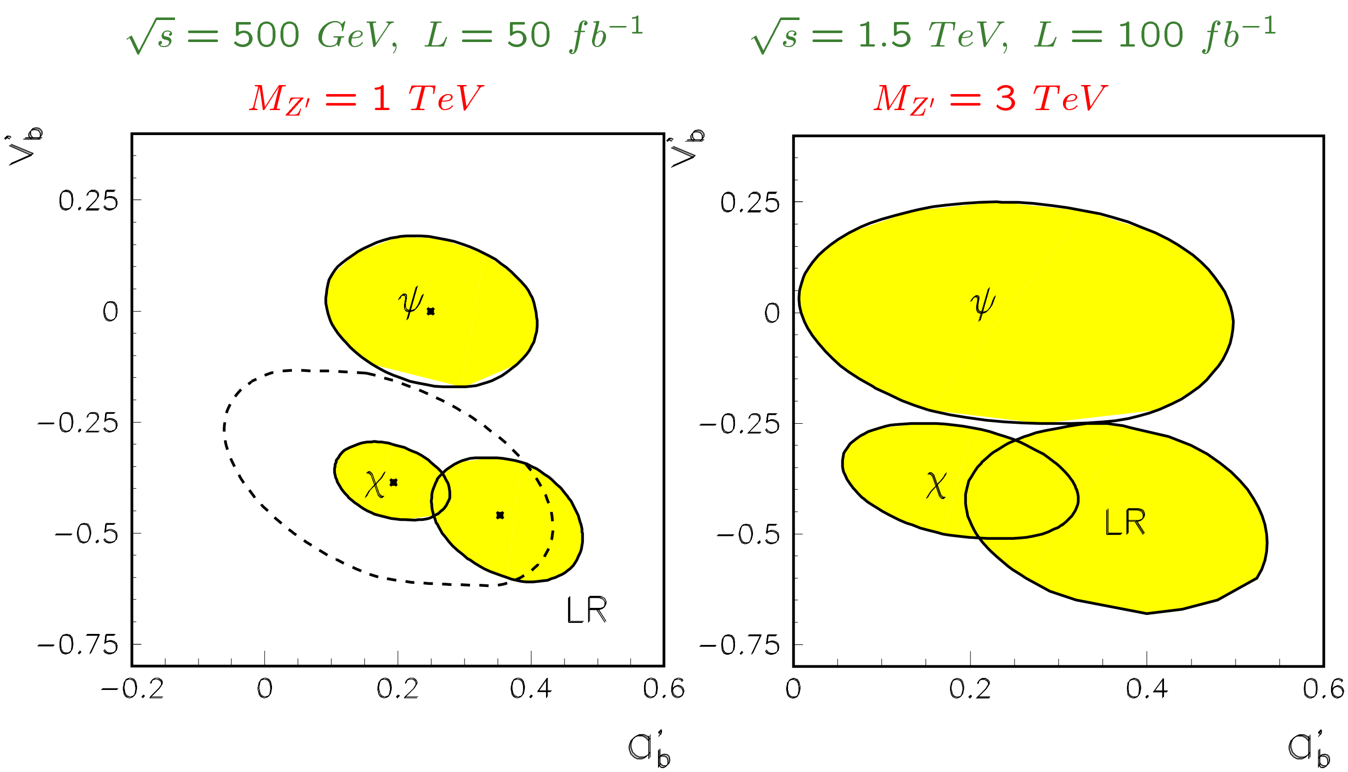
Using $\sigma_t^b,\ A^b_{FB},\ A^b_{LR}$ $\longrightarrow$ extract $a'_b,\ v'_b$
at **LC500**, $P(e^-) = 0.9,\ P(e^+) = 0.6$
Systematic errors limit the accuracy of $a'_b,\ v'_b$ determination



For $M_{Z'_\chi} = 1\ TeV$ the v'_b and a'_b couplings could be determined at LC500 within 10÷20% unless a sign ambiguity BUT this depends critically on the systematics assumed

- $P(e^+) \neq 0$ gives improvements due to the large deviations in the χ model for A^b_{LR}
- Systematics dominates statistics and almost remove the improvements due to high-luminosity

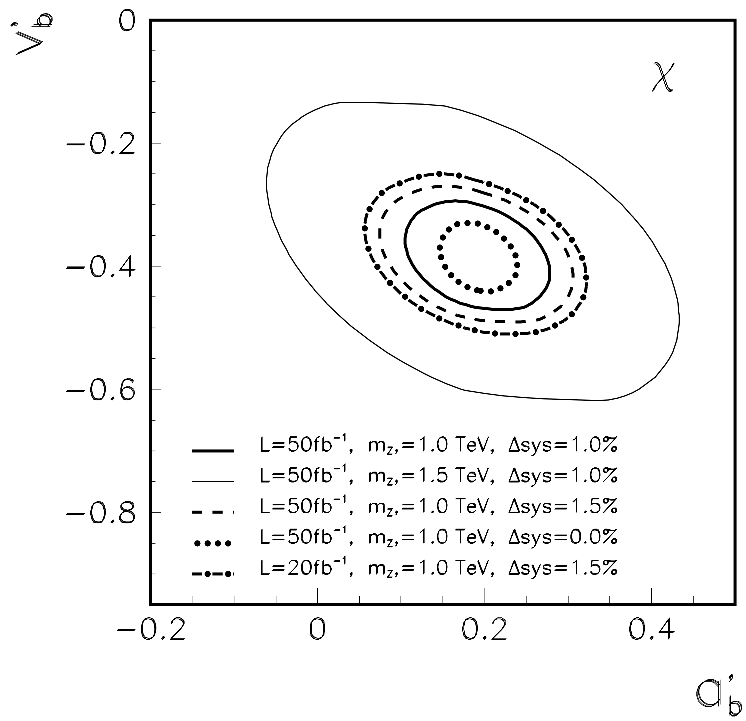
95%CL bounds on $Z'b\bar{b}$ couplings for different LC scenarios and various Z' masses (S. Riemann)



$(\cdots\cdots \quad M_{Z'} = 1.5\ TeV$ for $\chi)$

If $M_{Z'}/\sqrt{s} > 2$ the distinction between models becomes nearly impossible. An increase of luminosity cannot substantially improve the result (systematics dominates statistics)

Influence of luminosity, Z' mass and systematic errors on contours of $Z'b\bar{b}$ couplings.
A Z' in the χ model is assumed.



$\sqrt{s} = 500\ GeV$

(S. Riemann)

Conclusions

The new determination of Q_W could be affected by several errors BUT, taking the result as it is $\longrightarrow$

$$\textit{clear indication of new physics}$$

Our main conclusions are:

- Only new physics with no measurable effects at LEP is possible

- Q_W puts lower and upper bound on new scales
  - Composite models, $12 \leq \Lambda(TeV) \leq 33$
  - Lepto-quarks, $0.5 \leq M_S(TeV) \leq 1.4$
  - Extra-dimension disfavored at more than 99%CL ($\sin\beta < 0.707$)
  - Extra-$U(1)$, the region $-90^o \leq \theta_6 \leq -38^o$ is excluded, upper bounds on $M_{Z'} \approx 1 \div 1.5\ TeV$ (similar for LR)

- In particular a χ model describing a Z'_χ with mass in the TeV range improves the fit to the EW data with respect to the SM

- A Z' with a mass $\leq 1\ TeV$ may be directly observable at the upgrading of Tevatron and certainly at LHC

- For this mass range a future LC could be able to do a variety of diagnostics of the Z' couplings to fermions

Quantity measured	Calculation tested	Difference ($\times 10^3$) Dzuba, *et al.*	Difference ($\times 10^3$) Blundell *et al.*	σ_{Expt}
6S→7S dc Stark shift	$\langle 7P \mid\mid D \mid\mid 7S \rangle$	−3.4[19]	−0.7[22]	1.0[4]
$6P_{1/2}$ lifetime	$\langle 6S \mid\mid D \mid\mid 6P_{1/2} \rangle$	−4.2[−8]	4.3[1]	1.0[43]
$6P_{3/2}$ lifetime	$\langle 6S \mid\mid D \mid\mid 6P_{3/2} \rangle$	−2.6[−41]	7.9[−31]	2.3[22]
α	$\langle 7S \mid\mid D \mid\mid 6P_{1/2} \rangle$, and $\langle 7S \mid\mid D \mid\mid 6P_{3/2} \rangle$	–	−1.4	3.2
β	same as α	–	−0.8	3.0
6S HFS	$\psi_{6S}(r=0)$	1.8	−3.1	–
7S HFS	$\psi_{7S}(r=0)$	−6.0	−3.4	0.2
$6P_{1/2}$ HFS	$\langle 1/r^3 \rangle_{6P}$	−6.1	2.6	0.2
$7P_{1/2}$ HFS	$\langle 1/r^3 \rangle_{7P}$	−7.1	−1.5	0.5

Vector and axial-vector couplings for the extra-$U(1)$ and the LR models.
Here $c_2 = \cos\theta_2$ with $\theta_2 = \theta_6 + \tan^{-1}\sqrt{5/3}$

Extra-U(1)	LR
$a'_e = \frac{1}{4}s_\theta\left(-\frac{1}{3}c_2 + \sqrt{\frac{5}{3}}s_2\right)$	$a'_e = -\frac{1}{4}\sqrt{c_{2\theta}}$
$v'_u = 0$	$v'_u = \left(\frac{1}{4} - \frac{2}{3}s_\theta^2\right)/\sqrt{c_{2\theta}}$
$v'_d = \frac{1}{4}s_\theta\left(c_2 + \sqrt{\frac{5}{3}}s_2\right)$	$v'_d = \left(-\frac{1}{4} + \frac{1}{3}s_\theta^2\right)/\sqrt{c_{2\theta}}$

The corrections to Q_W are given by

$$\delta_N Q_W = 16\Big\{\frac{1}{16}\left[\left(1+4\frac{s_\theta^4}{c_{2\theta}}\right)Z - N\right]\Delta\rho_M$$
$$+\left[(2Z+N)\left(a_e v'_u + a'_e v_u\right) + (Z+2N)\left(a_e v'_d + a'_e v_d\right)\right]\theta_M$$
$$+\left[(2Z+N)\,a'_e v'_u + (Z+2N)\,a'_e v'_d\right]\frac{M_Z^2}{M_{Z'}^2}\Big\}$$

where θ_M is the mixing angle, a_f, v_f, a'_f, v'_f are the couplings of Z and Z' to fermions, and $\Delta\rho_M$ is an additional contribution to the ρ parameter arising from the mixing

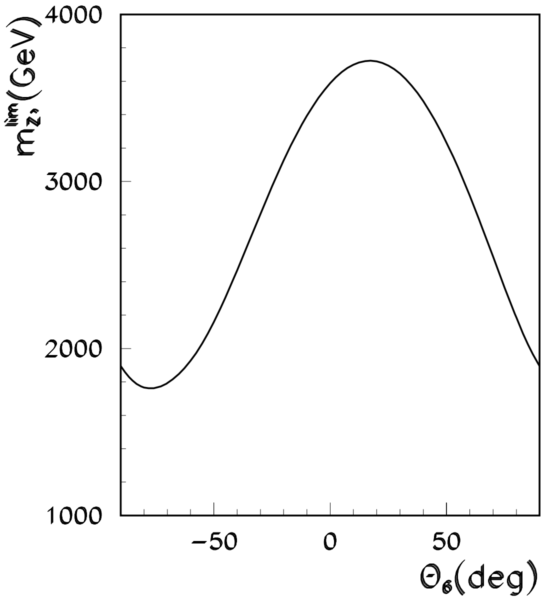
$$\Delta\rho_M = \sin^2\theta_M\left(\frac{M_{Z'}^2}{M_Z^2} - 1\right)$$

95%CL Bounds on Z' mass

S. Riemann

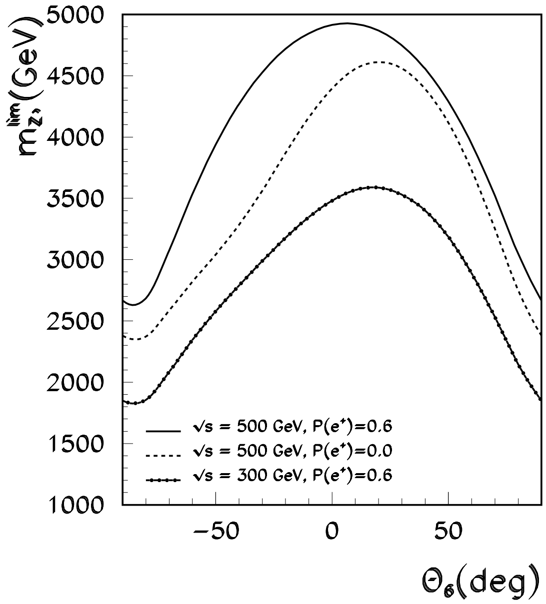
E_6 models

$\sqrt{s} = 500\ GeV,\ L = 50\ fb^{-1}$



$P(e^-) = 0.8,\ P(e^+) = 0$

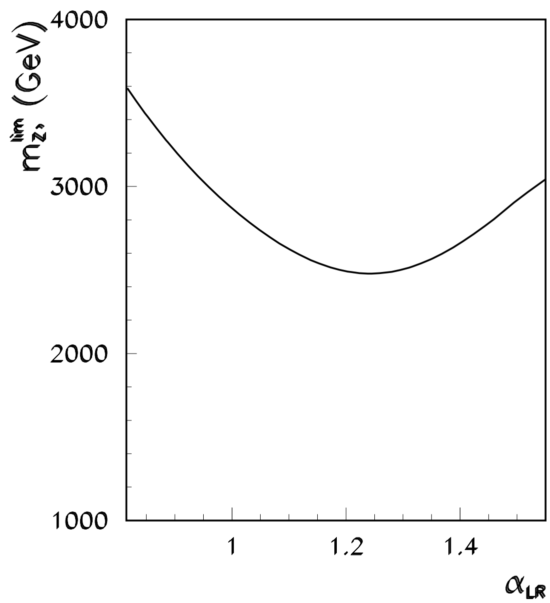
$\sqrt{s} = 300(500)\ GeV,\ L = 300(500)\ fb^{-1}$



$P(e^-) = 0.9,\ P(e^+) = 0, 0.6$

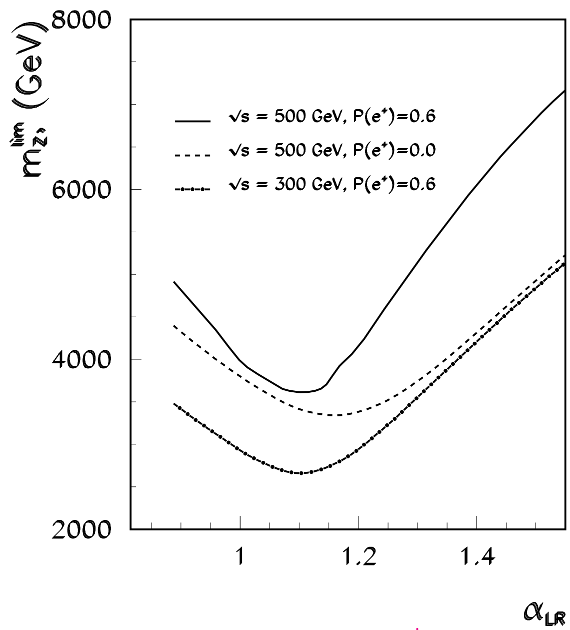
LR models

$\sqrt{s} = 500\ GeV,\ L = 50\ fb^{-1}$



$P(e^-) = 0.8,\ P(e^+) = 0$

$\sqrt{s} = 300(500)\ GeV,\ L = 300(500)\ fb^{-1}$



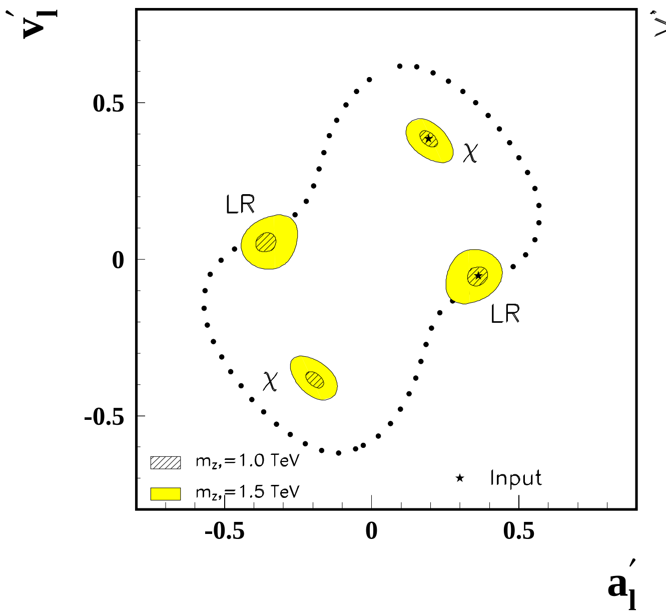
$P(e^-) = 0.9,\ P(e^+) = 0, 0.6$

95%CL contours for a'_f and v'_f

S. Riemann

leptons

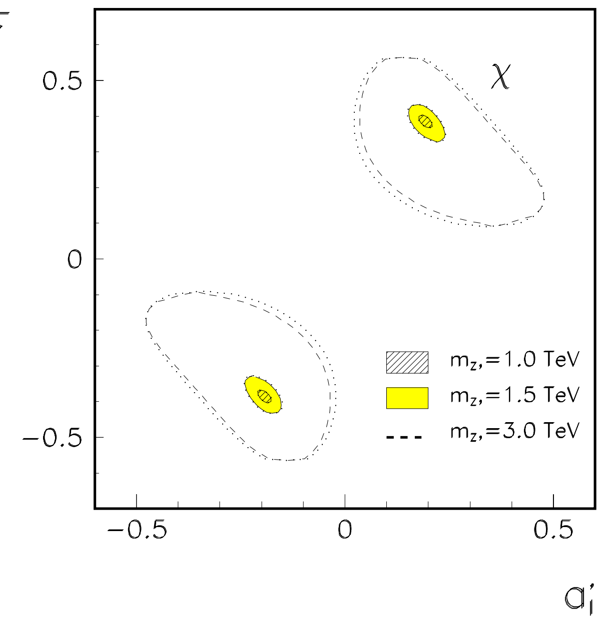
$\sqrt{s} = 500\ GeV,\ L = 50\ fb^{-1}$



$P(e^-) = 0.8,\ P(e^+) = 0$

$\cdots\cdots\quad M_{Z'} = 3\ TeV$

$\sqrt{s} = 500\ GeV,\ L = 500\ fb^{-1}$

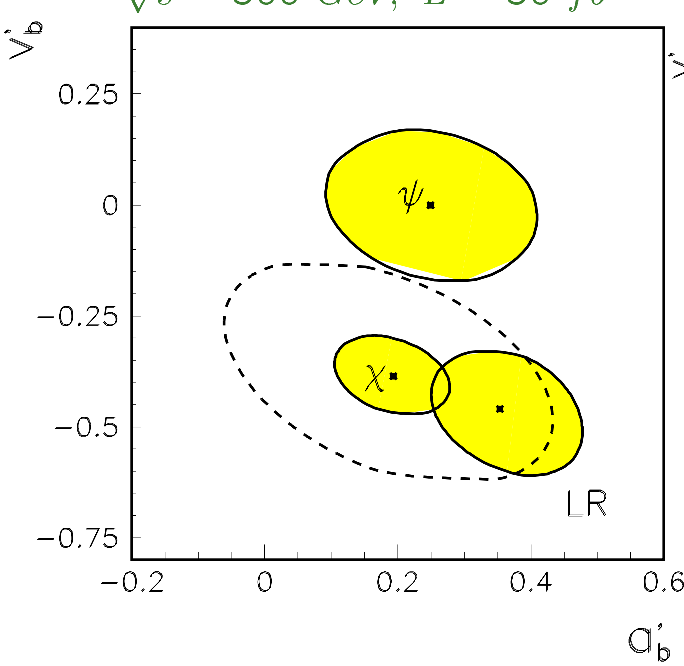


$P(e^-) = 0.9,\ P(e^+) = 0.6$

$\cdots\cdots\quad P(e^+) = 0.6$

b-quark

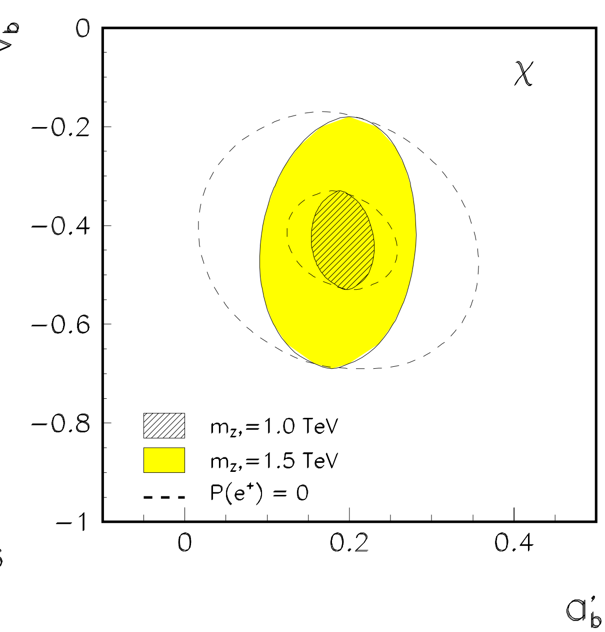
$\sqrt{s} = 500\ GeV,\ L = 50\ fb^{-1}$



$P(e^-) = 0.8,\ P(e^+) = 0$

$\cdots\cdots\quad M_{Z'} = 1.5\ TeV$

$\sqrt{s} = 500\ GeV,\ L = 500\ fb^{-1}$



$P(e^-) = 0.9,\ P(e^+) = 0, 0.6$