FCPPL
France China Particle Physics Laboratory

New Physics at LHC

Z' model independent & dependent Investigation

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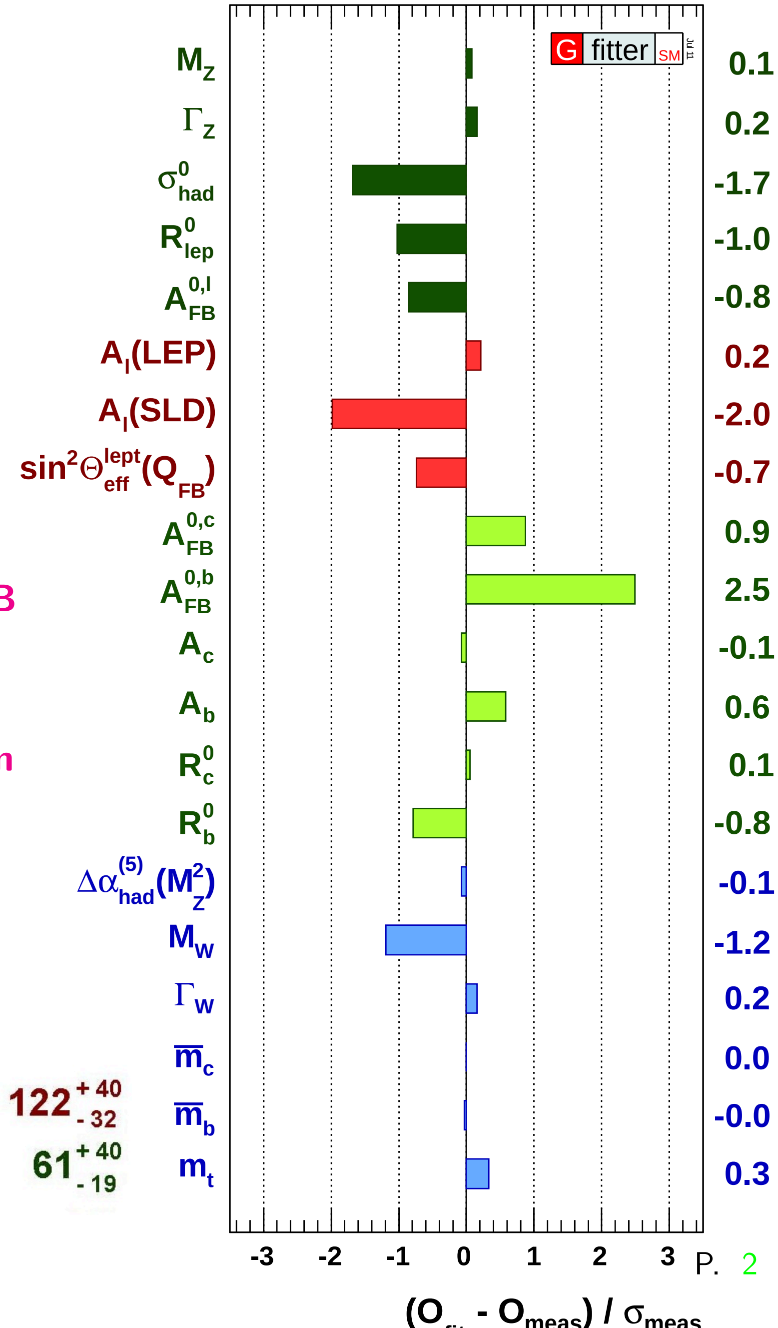
Various New Physics models involving Z' Alternative new particle to higgs

Not only **The simplest New Physics particle**

But also **Reduce the tension of global fit**

SM higgs cannot take this job !

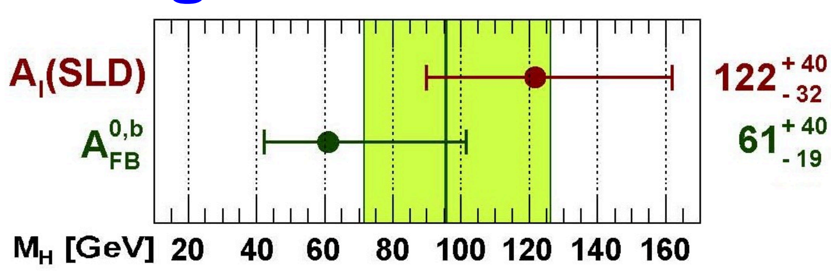


Model independent investigation: avoid detail SSB

EWCL $\subset$ SM$_{\text{particles}}$ $+Z'$ lightest NP particle, $+$Goldstone boson

Model dependent investigation:

TC2 models ......



Bosonic part of EWCL for $W^\pm, Z, Z', \gamma$

$$T=\hat{U}\tau^3\hat{U}^\dagger \qquad \hat{V}_\mu=(D_\mu\hat{U})\hat{U}^\dagger \qquad D_\mu\hat{U}=\partial_\mu\hat{U}+i(gW_\mu-g"X_\mu)\hat{U}-i\hat{U}(\frac{\tau^3}{2}g'+\tilde{g}')B_\mu$$

$$\mathcal{L}^{\rm boson}_{\rm EWCL}=-\frac{f^2}{4}{\rm tr}(\hat{V}_\mu\hat{V}^\mu)+\frac{f^2}{4}\beta_1[{\rm tr}(T\hat{V}_\mu)]^2+\frac{f^2}{4}\beta_2{\rm tr}(\hat{V}_\mu){\rm tr}(T\hat{V}_\mu)+\frac{f^2}{4}\beta_3[{\rm tr}(\hat{V}_\mu)]^2$$

$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}-\frac{1}{2}{\rm tr}[W_{\mu\nu}W^{\mu\nu}]-\frac{1}{4}X_{\mu\nu}X^{\mu\nu}+\frac{1}{2}\alpha_1gg'B_{\mu\nu}{\rm tr}[TW^{\mu\nu}]+\frac{i}{2}\alpha_2g'B_{\mu\nu}{\rm tr}[T[\hat{V}^\mu,\hat{V}^\nu]]+i\alpha_3g{\rm tr}[W^{\mu\nu}[\hat{V}^\mu,\hat{V}^\nu]]$$

$$+\alpha_4{\rm tr}[\hat{V}_\mu\hat{V}_\nu]{\rm tr}[\hat{V}^\mu\hat{V}^\nu]+\alpha_5{\rm tr}[\hat{V}_\mu\hat{V}^\mu]{\rm tr}[\hat{V}^\nu\hat{V}_\nu]+\alpha_6{\rm tr}[\hat{V}_\mu\hat{V}_\nu]{\rm tr}[T\hat{V}^\mu]{\rm tr}[T\hat{V}^\nu]+\alpha_7{\rm tr}[\hat{V}_\mu\hat{V}^\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T\hat{V}^\nu]$$

$$+\frac{1}{4}\alpha_8g^2{\rm tr}[TW_{\mu\nu}]{\rm tr}[TW^{\mu\nu}]+\frac{i}{2}\alpha_9g{\rm tr}[TW^{\mu\nu}]{\rm tr}[T[\hat{V}_\mu,\hat{V}_\nu]]+\frac{1}{2}\alpha_{10}{\rm tr}[T\hat{V}^\mu]{\rm tr}[T\hat{V}^\nu]{\rm tr}[T\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]+\alpha_{11}g\epsilon^{\mu\nu\rho\lambda}{\rm tr}[T\hat{V}_\mu]{\rm tr}[\hat{V}_\nu W$$

$$+\alpha_{12}g{\rm tr}[T\hat{V}^\mu]{\rm tr}[\hat{V}^\nu W_{\mu\nu}]+\alpha_{13}gg'\epsilon^{\mu\nu\rho\lambda}B_{\mu\nu}{\rm tr}[TW_{\rho\lambda}]+\alpha_{14}g^2\epsilon^{\mu\nu\rho\lambda}{\rm tr}[TW_{\mu\nu}]{\rm tr}[TW_{\rho\lambda}]+\alpha_{15}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}^\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T\hat{V}^\nu]$$

$$+\alpha_{16}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}^\mu]{\rm tr}[\hat{V}_\nu\hat{V}^\nu]+\alpha_{17}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[\hat{V}^\mu\hat{V}^\nu]+\alpha_{18}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}_\nu]{\rm tr}[T\hat{V}^\mu]{\rm tr}[T\hat{V}^\nu]+\alpha_{19}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}_\nu]{\rm tr}[\hat{V}^\mu\hat{V}^\nu]$$

$$+\alpha_{20}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}^\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T\hat{V}^\nu]+\alpha_{21}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}^\mu]{\rm tr}[\hat{V}_\nu\hat{V}^\nu]+\alpha_{22}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}^\mu]{\rm tr}[\hat{V}_\nu]{\rm tr}[T\hat{V}^\nu]+\alpha_{23}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}_\nu]{\rm tr}[\hat{V}^\mu]{\rm tr}[\hat{V}^\nu]$$

$$+gg''\alpha_{24}X_{\mu\nu}{\rm tr}[TW^{\mu\nu}]+g'g''\alpha_{25}B_{\mu\nu}X^{\mu\nu}+\alpha_{26}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T[\hat{V}_\rho,\hat{V}_\lambda]]+ig'\alpha_{27}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]B_{\rho\lambda}$$

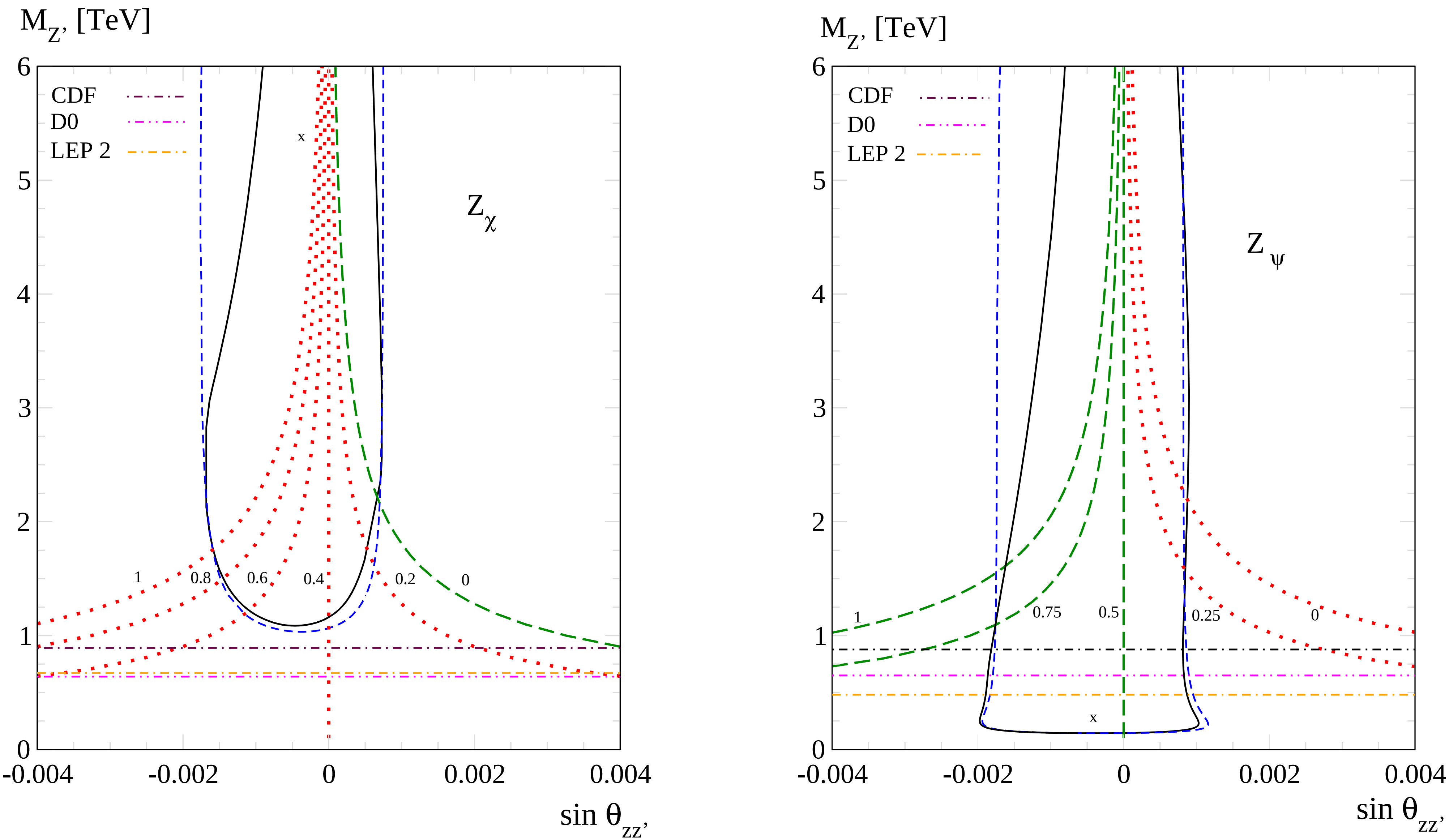
$$+ig\alpha_{28}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[TW_{\rho\lambda}]+g\alpha_{29}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[\hat{V}_\nu W_{\rho\lambda}]+ig''\alpha_{30}\epsilon^{\mu\nu\rho\lambda}X_{\mu\nu}{\rm tr}[T[\hat{V}_\rho,\hat{V}_\lambda]]+ig''\alpha_{31}X_{\mu\nu}{\rm tr}[T[\hat{V}^\mu,\hat{V}^\nu$$

$$+g''\alpha_{32}\epsilon^{\mu\nu\rho\lambda}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]X_{\rho\lambda}+\alpha_{33}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[T[\hat{V}^\mu,\hat{V}^\nu]]+g'g''\alpha_{34}\epsilon^{\mu\nu\rho\lambda}B_{\mu\nu}X_{\rho\lambda}+gg''\alpha_{35}\epsilon^{\mu\nu\rho\lambda}X_{\mu\nu}{\rm tr}[TW_{\rho\lambda}]$$

$$+ig'\alpha_{36}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]B^{\mu\nu}+ig\alpha_{37}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]{\rm tr}[TW^{\mu\nu}]+g\alpha_{38}{\rm tr}[\hat{V}^\mu]{\rm tr}[\hat{V}^\nu W_{\mu\nu}]+g''\alpha_{39}{\rm tr}[\hat{V}_\mu]{\rm tr}[T\hat{V}_\nu]X^{\mu\nu}$$

$$+ig\alpha_{40}{\rm tr}[\hat{V}^\mu]{\rm tr}[T\hat{V}^\nu W_{\mu\nu}]+O(p^6)$$

Y.Zhang, S.Z.Wang and Q.Wang JHEP03(2008)047



Experimental constraints on the mass and mixing angles for the Z_χ and Z_ψ.

The solid lines show the regions allowed by precision electroweak data at 95% C.L. assuming Higgs doublets and singlets,

The dashed regions allow arbitrary Higgs. The labeled curves assume specific ratios of Higgs doublet VEVs–**JHEP08,017(2009)**

$$U_{\text{Minimal } Z'\text{–}Z \text{ mass mixing}} = \begin{pmatrix} c_W & s_W & 0 \\ -s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c' & 0 & s' \\ 0 & 1 & 0 \\ -s' & 0 & c' \end{pmatrix}$$

$$U_{\text{Minimal } Z'\text{–}Z \text{ kinetic mixing}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -\tan\chi \\ 0 & 0 & \frac{1}{\cos\chi} \end{pmatrix} \times U_{\text{Minimal } Z'\text{–}Z \text{ mass mixing}} \qquad \tan\theta_W \equiv \frac{g'}{g} \quad \Downarrow$$

total 8 parameters

$U_{\text{General } Z'-Z \text{ mixing}}$ similar as Minimal Z'–Z kinetic mixing

$$(\mathbf{W}^3_\mu,\ \mathbf{B}_\mu,\ \mathbf{X}_\mu)^{\mathbf{T}} = \mathbf{U}\ (\mathbf{Z}_\mu,\ \mathbf{A}_\mu,\ \mathbf{Z}'_\mu)^{\mathbf{T}}$$

$$U_{Z'\text{–}\gamma \text{ kinetic and } Z'\text{–}Z \text{ mixing}} = \begin{pmatrix} 1 & 0 & -\frac{\sin\overline{\chi}}{\sqrt{1-\sin^2\chi-\sin^2\overline{\chi}}} \\ 0 & 1 & -\frac{\sin\chi}{\sqrt{1-\sin^2\chi-\sin^2\overline{\chi}}} \\ 0 & 0 & \frac{1}{\sqrt{1-\sin^2\chi-\sin^2\overline{\chi}}} \end{pmatrix} \times U_{\text{Minimal } Z'\text{–}Z \text{ mass mixing}}$$

$$U_{\text{Stueckelberg type mixing}} = \begin{pmatrix} c_W & s_W & 0 \\ -s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{g''\sqrt{g^2+g'^2}}{(g^2+g'^2)g''^2+g^2\tilde{g}'^2} & \frac{g\tilde{g}'}{(g^2+g'^2)g''^2+g^2\tilde{g}'^2} \\ 0 & \frac{g\tilde{g}'}{(g^2+g'^2)g''^2+g^2\tilde{g}'^2} & \frac{g''\sqrt{g^2+g'^2}}{(g^2+g'^2)g''^2+g^2\tilde{g}'^2} \end{pmatrix} \begin{pmatrix} c' & 0 & s' \\ 0 & 1 & 0 \\ -s' & 0 & c' \end{pmatrix}$$

Y.Zhang and Q.Wang **JHEP07(2009)012**

General γ-Z-Z' Mixing

$$U = \begin{pmatrix} c_W a & c_W\xi - s_W c_l l & c_W\eta - s_W c_r r \\ s_W a & s_W\xi + c_W c_l l & s_W\eta + c_W c_r r \\ -c_W a\frac{\bar{\tilde{g}}'}{g''} & -c_W\xi\frac{\bar{\tilde{g}}'}{g''} + s_W c_l l\frac{\bar{\tilde{g}}'}{g''} - s_l l & -c_W\eta\frac{\bar{\tilde{g}}'}{g''} + s_W c_r r\frac{\bar{\tilde{g}}'}{g''} + c_r r \end{pmatrix}$$

$$= \begin{pmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ -c_W\frac{\bar{\tilde{g}}'}{g''} & s_W\frac{\bar{\tilde{g}}'}{g''} & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c' & s' \\ 0 & -s' & c' \end{pmatrix} \underbrace{\begin{pmatrix} a & \xi & \eta \\ 0 & l\cos(\theta_l - \theta') & r\sin(\theta_r - \theta') \\ 0 & -l\sin(\theta_l - \theta') & r\cos(\theta_r - \theta') \end{pmatrix}}_{\text{Z-Z' mass mixing} \to \text{I}}$$

depend on $\theta_W, \frac{\bar{\tilde{g}}'}{g''}, \xi, \eta, l, r, \theta_l, \theta_r$ **8 parameters !** **ZHANG Ying** & **WANG Qing**, **Chin Phys C36(4),298(2012)**

$$= \begin{pmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ -c_W\frac{\bar{\tilde{g}}'}{g''} & s_W\frac{\bar{\tilde{g}}'}{g''} & 1 \end{pmatrix} \begin{pmatrix} a & \xi & \eta \\ 0 & l\cos\theta_l & r\sin\theta_r \\ 0 & -l\sin\theta_l & r\cos\theta_r \end{pmatrix} \qquad \begin{pmatrix} B_\mu \\ W^3_\mu \\ X_\mu \end{pmatrix} = U \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

$$= \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} = \begin{pmatrix} c_W + \Delta_{11} & s_W + \Delta_{12} & \Delta_{13} \\ -s_W + \Delta_{21} & c_W + \Delta_{22} & \Delta_{23} \\ \Delta_{31} & \Delta_{32} & 1 + \Delta_{33} \end{pmatrix}$$

Z-Z' mass mxing: $a = l = r = 1 \qquad \bar{\tilde{g}}' = \xi = \eta = 0 \qquad \theta_l = \theta_r = \theta'$

$$U^T \mathcal{M}_0^2 U = \text{diag}(0, M_Z^2, {M'_Z}^2) \qquad U^T \mathcal{K}_0 U = -\frac{1}{4}\text{diag}(1,1,1)$$

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Extra Neutral Current

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$$-\mathcal{L}_{NC} = gW_\mu^3 J^{3,\mu} + g'B_\mu J_Y^\mu + g''X_\mu J_X^\mu = e^* J_{em}^\mu A_\mu + g_Z J_Z^\mu Z_\mu + g'' J_{Z'}^\mu Z'_\mu$$

$$J_3^\mu = \sum_i \bar{f}_i \gamma^\mu t_{3iL} P_L f_i \qquad e^* J_{em}^\mu = e^* \sum_i \bar{f}_i \gamma^\mu q_i f_i$$

$$J_Y^\mu = \sum_i \bar{f}_i \gamma^\mu [y_{iL} P_L + y_{iR} P_R] f_i \qquad J_Z^\mu = \sum_i \bar{f}_i \gamma^\mu (\epsilon_{iL} P_L + \epsilon_{iR} P_R) f_i = \frac{1}{2} \sum_i \bar{f}_i \gamma^\mu (g_{iV} - g_{iA}\gamma_5) f_i$$

$$J_X^\mu = \sum_i \bar{f}_i \gamma^\mu [y'_{iL} P_L + y'_{iR} P_R] f_i \qquad J_{Z'}^\mu = \sum_i \bar{f}_i \gamma^\mu (\epsilon'_{iL} P_L + \epsilon'_{iR} P_R) f_i = \frac{1}{2} \sum_i \bar{f}_i \gamma^\mu (g'_{iV} - g'_{iA}\gamma_5) f_i$$

$$g_{iV,A} = \epsilon_{iL} \pm \epsilon_{iR} \qquad g'_{iV,A} = \epsilon'_{iL} \pm \epsilon'_{iR}$$

$$g_Z J_Z^\mu = gU_{11} J^{3,\mu} + g'U_{21} J_Y^\mu + g''U_{31} J_X^\mu$$

$$e^* J_{em}^\mu = gU_{12} J^{3,\mu} + g'U_{22} J_Y^\mu + g''U_{32} J_X^\mu$$

$$g'' J_{Z'}^\mu = gU_{13} J^{3,\mu} + g'U_{23} J_Y^\mu + g''U_{33} J_X^\mu$$

$$\begin{pmatrix} B_\mu \\ W_\mu^3 \\ X_\mu \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

$$e^* q_i = eq_i + \underbrace{\frac{e}{c_W}\Delta_{22}[y_{iL}P_L + y_{iR}P_R] + \frac{e}{s_W}\Delta_{12} t_{3iL} P_L}_{s_W\Delta_{22} = c_W\Delta_{12}} + \underbrace{g''\Delta_{32}[y'_{iL}P_L + y'_{iR}P_R]}_{\Delta_{32}=0 \text{ or } y'_{iL} = y'_{iR}}$$

Z' Charges to Quark and Leptons

$$\mathcal{L}_{\text{gauge coupling}} = g'' X_\mu J^\mu_X \qquad J^\mu_X = \sum \bar{f}_i \gamma^\mu [y'_{iL} P_L + y'_{iR} P_R] f_i$$

models	Z' EWCL	$U(1)_{B-xL}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$	$U(1)_{q+xu}$
(u_L, d_L)	y'_q	$1/3$	$1/3$	0	$1/3$
u_R	y'_u	$1/3$	$-1/3$	$-x/3$	$x/3$
d_R	y'_d	$1/3$	$-x/3$	$1/3$	$(2-x)/3$
(ν_L, e_L)	y'_l	$-x$	$x/3$	$(x-1)/3$	-1
e_R	y'_e	$-x$	$-1/3$	$x/3$	$-(2+x)/3$
ν_R	y'_{ν_R}	-1	$(x-2)/3$	$-x/3$	$(x-4)/3$

Anomaly cancelation from generation independent charges

$[\mathbf{SU(3)_C}]^2\mathbf{U(1)}'$: $2y'_q - y'_d - y'_u = 0$

$[\mathbf{SU(2)_L}]^2\mathbf{U(1)}'$: $y'_l + 3y'_q = 0$

$\mathbf{U(1)_Y}[\mathbf{U(1)}']^2$: $-y'^2_l + y'^2_q + y'^2_e - 2y'^2_u + y'^2_d = 0$

$[\mathbf{U(1)_Y}]^2\mathbf{U(1)}'$: $3y'_l + y'_q - 6y'_e - 8y'_u - 2y'_d = 0$

$[\mathbf{U(1)}']^3$: $2y'^3_l + 6y'^3_q - y'^3_e - 3y'^3_u - 3y'^3_d - N y'^3_{\nu_R} = 0$

$\mathbf{y}'_{\nu_\mathbf{R}}$: $3y'_q + y'_l - 3y'_u - 3y'_d - y'_e - N y'_{\nu_R} = 0$

$$\begin{cases} y'_l = -3y'_q \\ y'_d = 2y'_q - y'_u \\ y'_e = -2y'_q - y'_u \\ y'_{\nu_R} = -4y'_q + y'_u \\ N_{\nu_R} \text{ No. for each generation} = 1 \end{cases}$$

1. **Fermion decouple:** $y'_u = y'_d = y'_e = y'_{\nu_R} = 0 \;\Rightarrow\; y'_q = y'_l = 0$

2. **Right Handed:** $y'_q = y'_l = 0 \;\Rightarrow\; y'_d = -y'_u = y'_e = -y'_{\nu_R};\ \Delta_{32} = 0$

3. **ν_R decouple:** $y'_{\nu_R} = 0 \;\Rightarrow\; y'_u = 4y'_q,\ y'_e = 2y'_l = 3y'_d = -6y'_q;\ \Delta_{32} = 0$

4. **Left-Right symmetric:** $y'_q = y'_u = y'_d \;\Rightarrow\; y'_l = y'_e = y'_{\nu_R} = -3y'_q$

models	$U(1)_{B-xL_e-yL_\mu}$	$U(1)_{10+x\bar{5}}$ gen−dep	$U(1)_{d-xu}$ gen−dep	$U(1)_{q+xu+yc+zt}$	2+1 leptocratic
$q_{1,L}$	$1/3$	$1/3$	0	$1/3$	$1/3$
u_R	$1/3$	$-1/3$	$-x/3$	$x/3$	$x/3$
d_R	$1/3$	$-x/3$	$1/3$	$(2-x)/3$	$(2-x)/3$
$q_{2,L}$	$1/3$	$1/3$	0	$1/3$	$1/3$
c_R	$1/3$	$-1/3$	$-y/3$	$y/3$	$x/3$
s_R	$1/3$	$-y/3$	$1/3$	$(2-y)/3$	$(2-x)/3$
$q_{3,L}$	$1/3$	$1/3$	0	$1/3$	$1/3$
t_R	$1/3$	$-1/3$	$2-\frac{2}{3}(x+y)\pm\sqrt{3-x^2-y^2}$	$z/3$	$x/3$
b_R	$1/3$	$3+\frac{x+y}{3}$	$1/3$	$(2-z)/3$	$(2-x)/3$
(ν_L^e, e_L)	$-x$	$x/3$	$(x-1)/3$	-1	$-1-2y$
e_R	$-x$	$-1/3$	$x/3$	$-(2+x)/3$	$-(2+x)/3-2y$
(ν_L^μ, μ_L)	$-y$	$y/3$	$(y-1)/3$	-1	$y-1$
μ_R	$-y$	$-1/3$	$y/3$	$-(2+y)/3$	$-(2+x)/3+y$
(ν_L^τ, τ_L)	$x+y-3$	$3+\frac{x+y}{3}$	$\frac{2}{3}-\frac{1}{3}(x+y)$	-1	$y-1$
τ_R	$x+y-3$	$-1/3$	$x+y-3\mp\frac{4}{3}\sqrt{3-x^2-y^2}$	$-(2+z)/3$	$-(2+x)/3+y$

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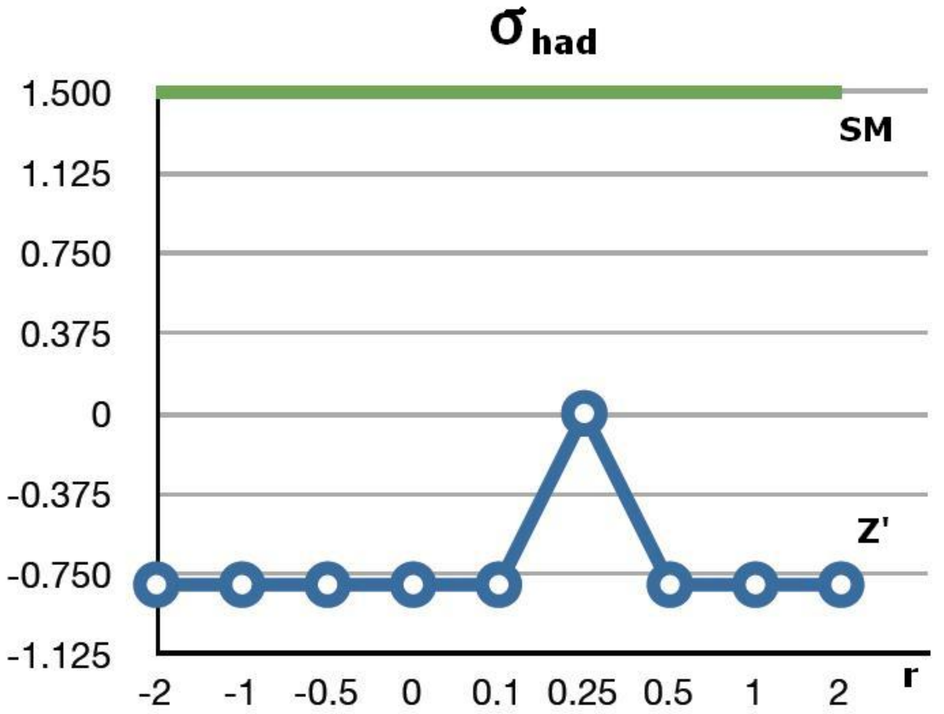
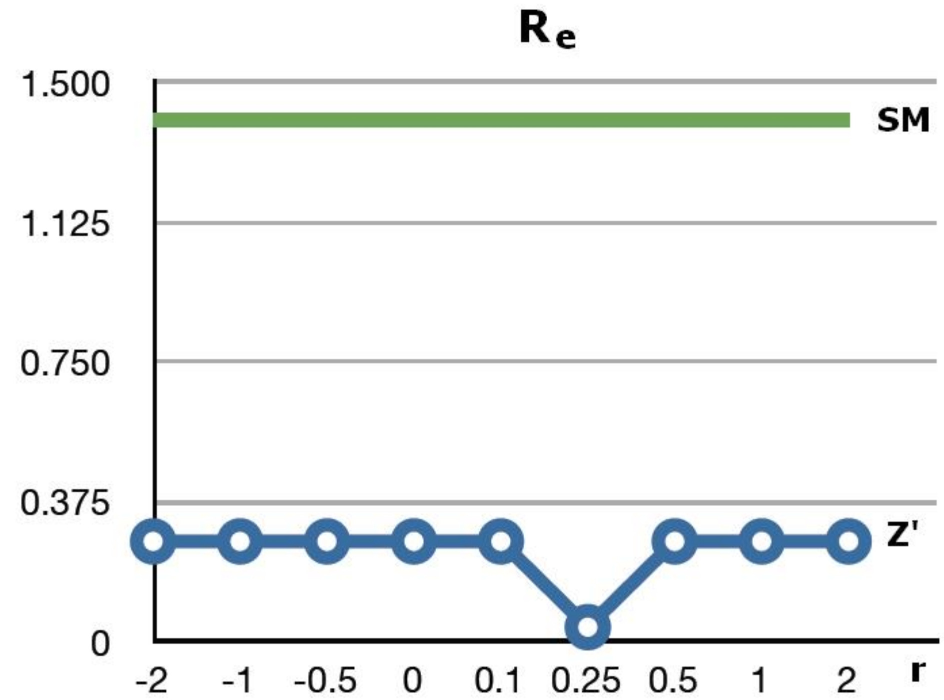
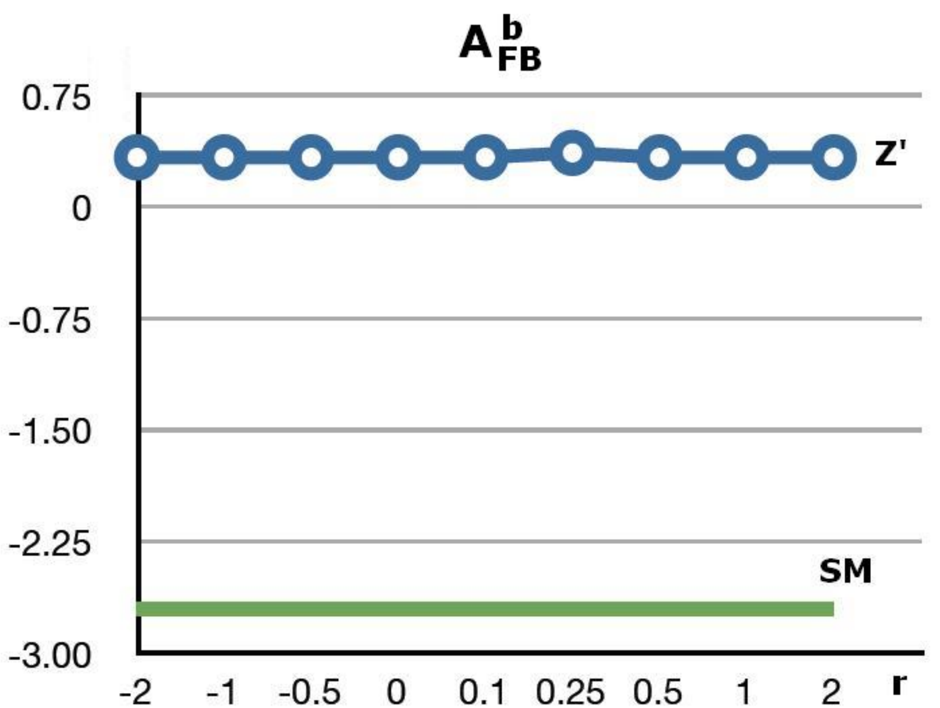
Global Fit

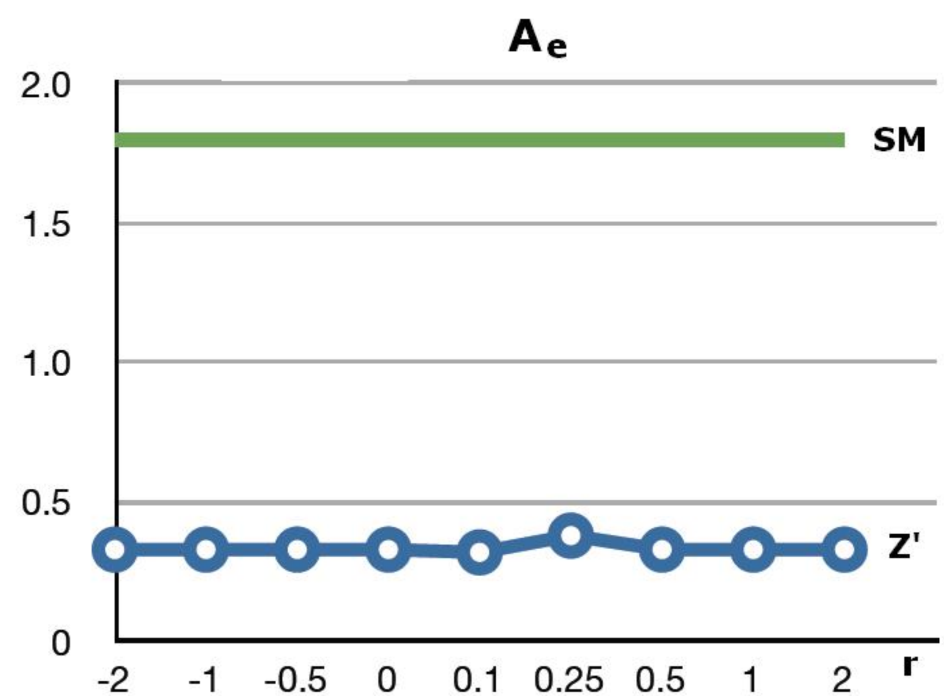
Observable	SM Pull	Z' **Pull at** $r = y'_q/y'_u$								
		-2	-1	-0.5	0	0.1	0.25	0.5	1	2
M_Z [GeV]	0.1	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
Γ_Z [GeV]	-0.1	0.26	0.26	0.26	0.27	0.27	0.05	0.26	0.26	0.26
Γ_{had} [GeV]	-	0.18	0.18	0.18	0.19	0.19	0.07	0.18	0.18	0.18
Γ_{inv} [MeV]	-	0.16	0.16	0.16	0.16	0.16	-0.02	0.16	0.15	0.15
$\Gamma_{l^+l^-}$ [MeV]	-	-0.43	-0.43	-0.43	-0.44	-0.44	-0.01	-0.45	-0.44	-0.44
σ_{had} [nb]	1.5	-0.80	-0.80	-0.81	-0.81	-0.83	-0.01	-0.82	-0.81	-0.81
R_e	1.4	0.27	0.27	0.27	0.28	0.28	0.04	0.28	0.27	0.27
R_b	0.8	0.05	0.05	0.05	0.05	0.05	-0.01	0.05	0.05	0.05
R_c	0.0	-0.02	-0.02	-0.02	-0.02	-0.02	0.00	-0.02	-0.02	-0.02
A^e_{FB}	-0.7	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.06
A^b_{FB}	-2.7	0.34	0.34	0.34	0.34	0.34	0.37	0.34	0.34	0.34
A^c_{FB}	-0.9	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
A^s_{FB}	-0.6	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
A_e	1.8	0.33	0.33	0.33	0.33	0.32	0.38	0.33	0.33	0.33
A_b	-0.6	0.02	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.02
A_c	0.1	0.03	0.03	0.03	0.03	0.03	0.01	0.03	0.03	0.03
A_s	-0.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Y.Zhang ArXiv: 1106.0163 [hep-ph]

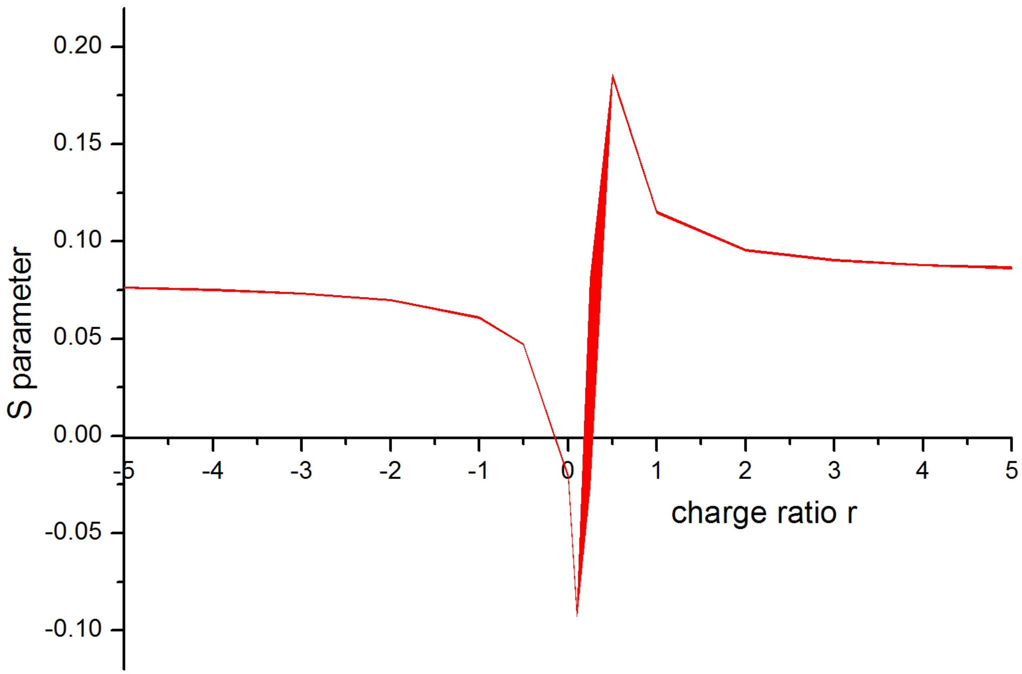

σ_{had}
1.500
1.125
0.750
0.375
0
-0.375
-0.750
-1.125
SM
Z'
-2 -1 -0.5 0 0.1 0.25 0.5 1 2
r

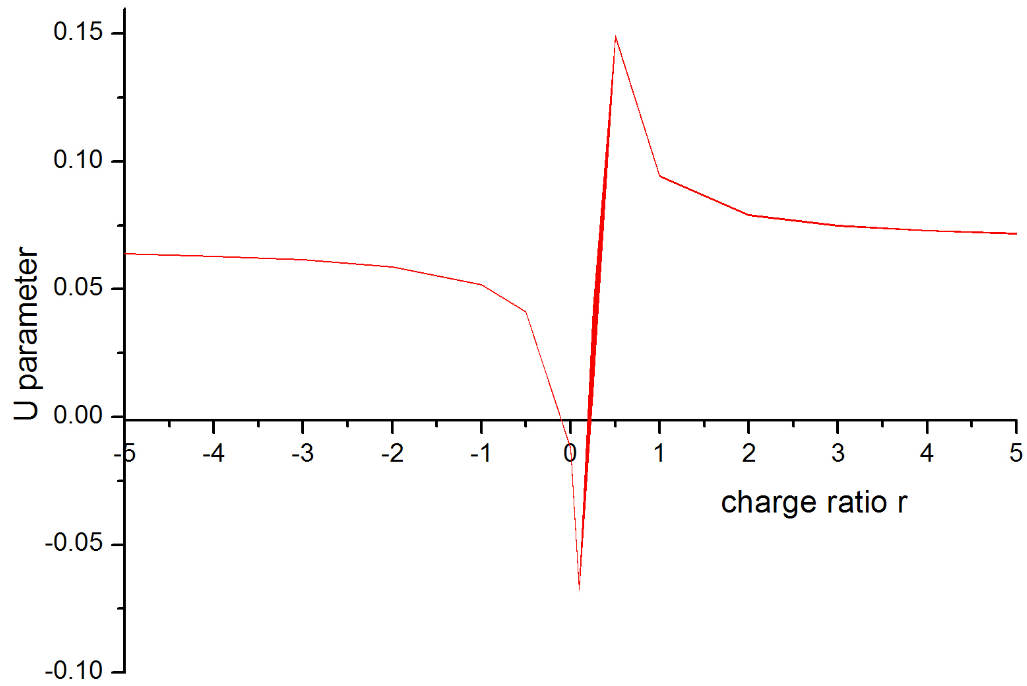

R_e
1.500
1.125
0.750
0.375
0
SM
Z'
-2 -1 -0.5 0 0.1 0.25 0.5 1 2
r


A_{FB}^b
0.75
0
-0.75
-1.50
-2.25
-3.00
Z'
SM
-2 -1 -0.5 0 0.1 0.25 0.5 1 2
r


A_e
2.0
1.5
1.0
0.5
0
SM
Z'
-2 -1 -0.5 0 0.1 0.25 0.5 1 2
r

S, T, U





T parameter almost vanishes

Y.Zhang ArXiv: 1106.0163 [hep-ph]

Z' Decay

$$\Gamma_{Z'}(f\bar{f}) = \frac{N_f G_F M_{Z'}^3}{6\sqrt{2}\pi}(g'^2_{iV} + g'^2_{iA}) = \frac{N_f G_F M_{Z'}^3}{3\sqrt{2}\pi}\left\{y'^2_{iL} + y'^2_{iR}\right\}$$

$$\Gamma_{Z'}(u\bar{u}) = \frac{G_F M_{Z'}^3}{\sqrt{2}\pi}\left\{y'^2_q + y'^2_u\right\}$$

$$\Gamma_{Z'}(d\bar{d}) = \frac{G_F M_{Z'}^3}{\sqrt{2}\pi}\left\{5y'^2_q - 4y'_q y'_u + y'^2_u\right\}$$

$$\Gamma_{Z'}(e\bar{e}) = \frac{G_F M_{Z'}^3}{3\sqrt{2}\pi}\left\{13y'^2_q + 4y'_q y'_u + y'^2_u\right\}$$

$$\Gamma_{Z'}(\nu\bar{\nu}) = \frac{G_F M_{Z'}^3}{3\sqrt{2}\pi}\left\{25y'^2_q - 8y'_q y'_u + y'^2_u\right\}$$

- $\Gamma_{Z'}(u\bar{u}) = \Gamma_{Z'}(d\bar{d}) = \Gamma_{Z'}(e\bar{e}) = \Gamma_{Z'}(\nu\bar{\nu}) = 0$ — **Fermion decouple**
- $\Gamma_{Z'}(u\bar{u}) = \Gamma_{Z'}(d\bar{d}) = 3\Gamma_{Z'}(e\bar{e}) = 3\Gamma_{Z'}(\nu\bar{\nu})$ — **Right Handed**
- $9\Gamma_{Z'}(u\bar{u}) = 9\Gamma_{Z'}(d\bar{d}) = \Gamma_{Z'}(e\bar{e}) = \Gamma_{Z'}(\nu\bar{\nu})$ — **LR symmetric**
- $\frac{\Gamma_{Z'}(u\bar{u})}{17} = \frac{\Gamma_{Z'}(d\bar{d})}{5} = \frac{\Gamma_{Z'}(e\bar{e})}{45} = \frac{\Gamma_{Z'}(\nu\bar{\nu})}{9}$ — **ν_R decouple**

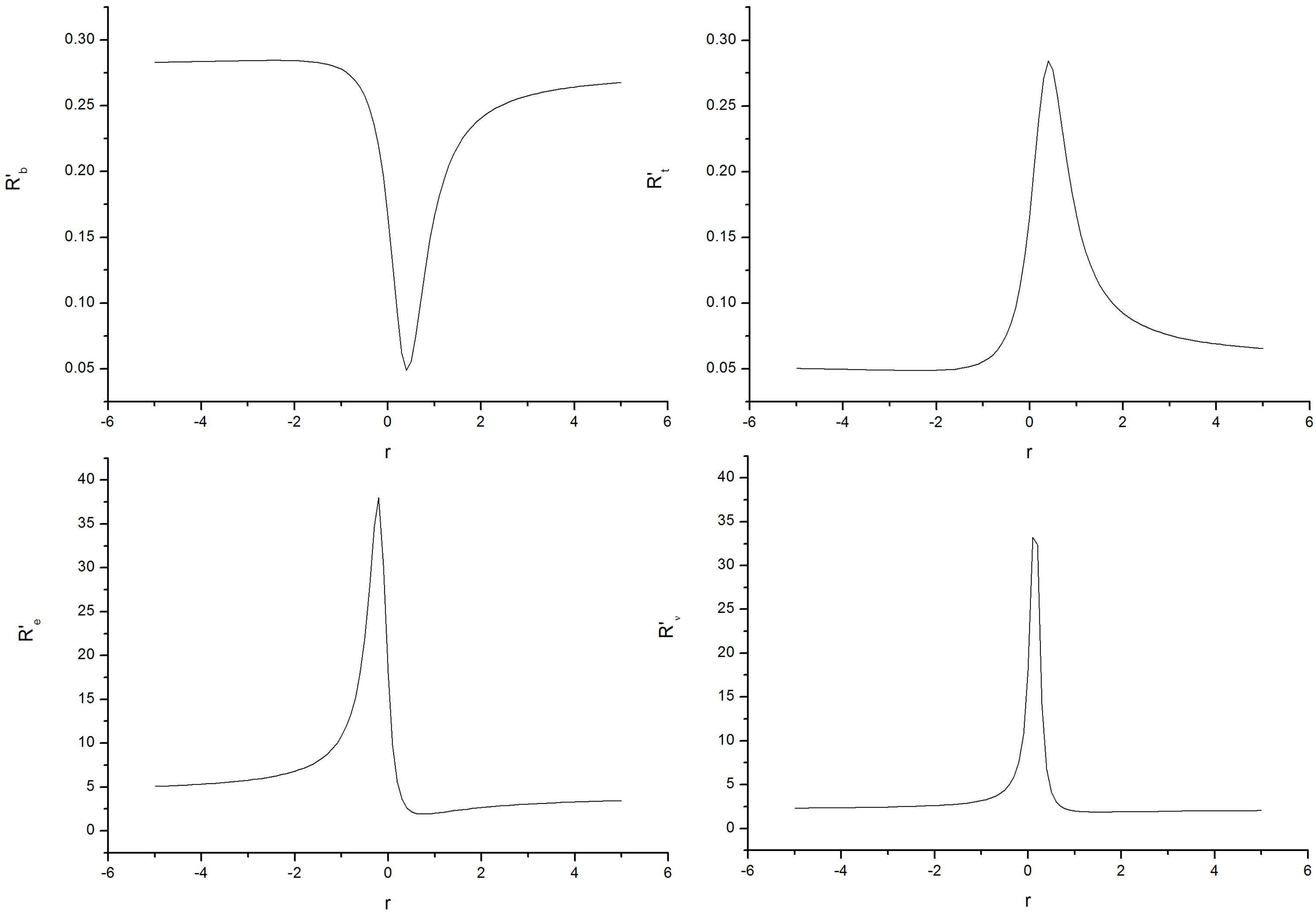
Generation Independent Charges

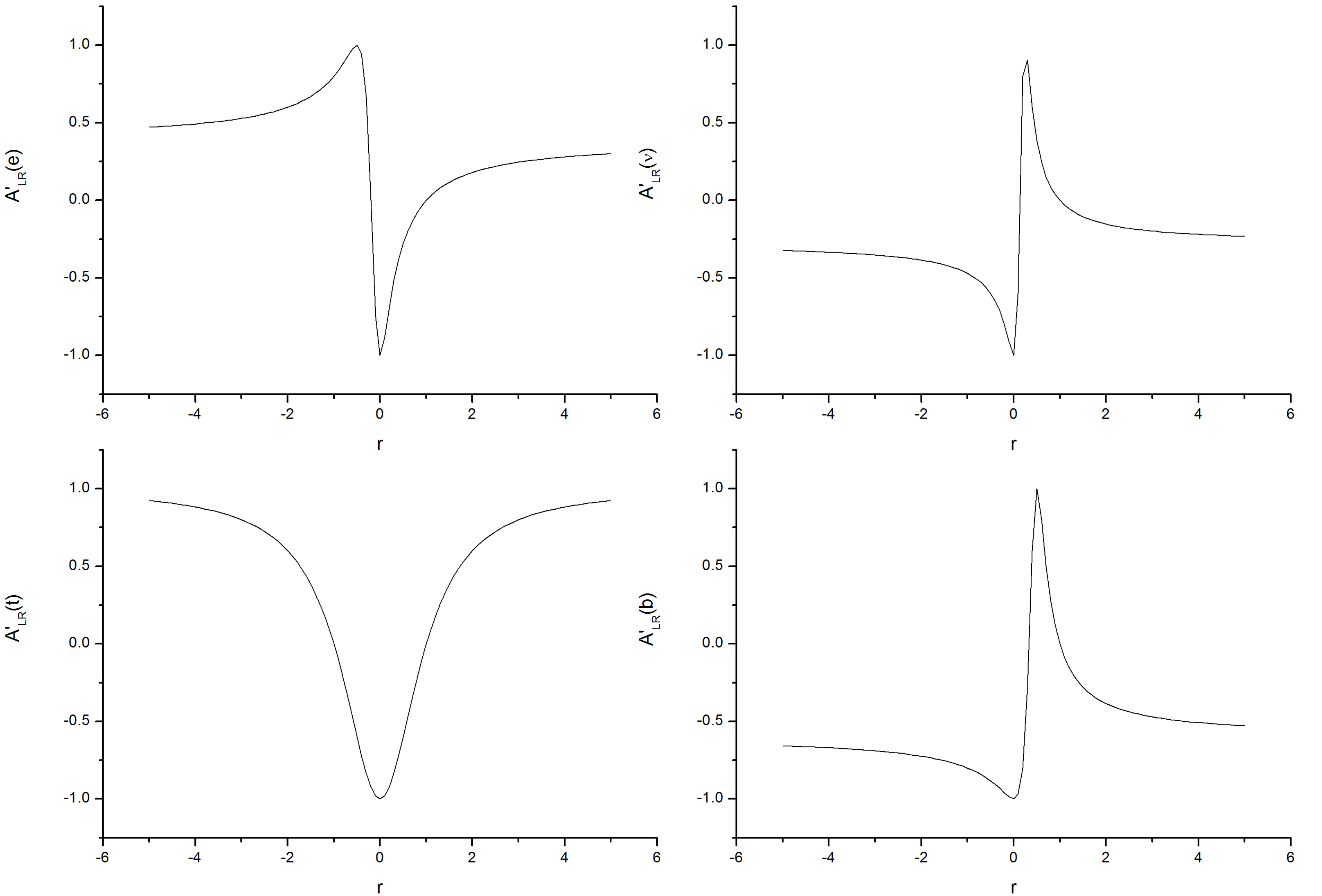
$$R'_e = \frac{\Gamma_{Z'}(\mathrm{had.})}{\Gamma_{Z'}(e\bar{e})} = \frac{54r^2 - 36r + 18}{13r^2 + 4r + 1} \qquad R'_\nu = \frac{\Gamma_{Z'}(\mathrm{had.})}{\Gamma_{Z'}(\nu\bar{\nu})} = \frac{54r^2 - 36r + 18}{25r^2 - 8r + 1}$$

$$R'_b = \frac{\Gamma_{Z'}(b\bar{b})}{\Gamma_{Z'}(\mathrm{had.})} = \frac{5r^2 - 4r + 1}{18r^2 - 12r + 6} \qquad R'_t = \frac{\Gamma_{Z'}(t\bar{t})}{\Gamma_{Z'}(\mathrm{had.})} = \frac{r^2 + 1}{18r^2 - 12r + 6}$$

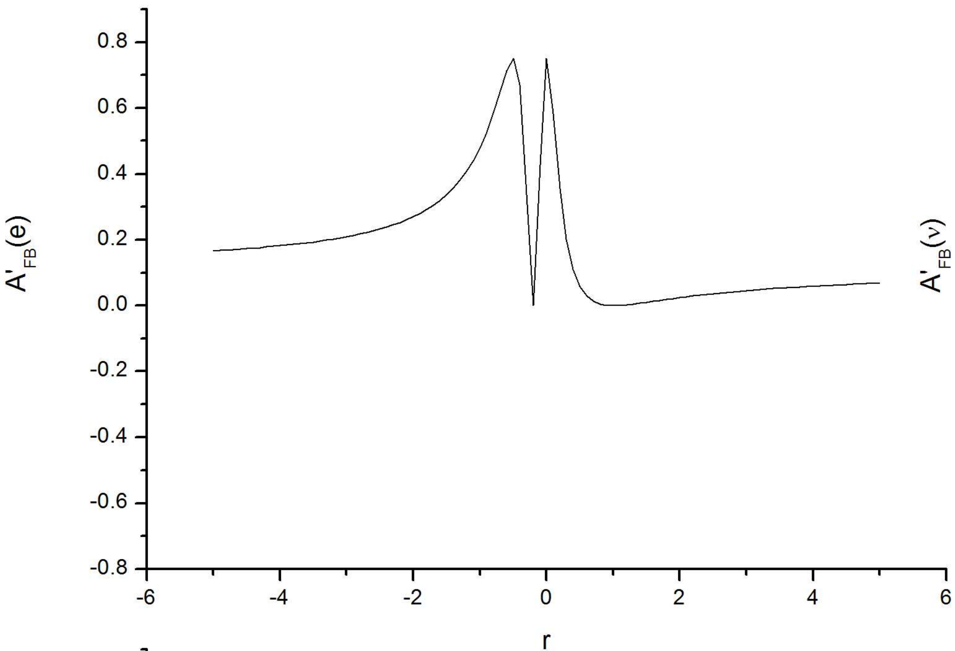
$$r = \frac{y'_q}{y'_u} = \begin{cases} ? & \textbf{Fermion decouple} \\ 0 & \textbf{Right Handed} \\ \frac{1}{4} & \nu_R\ \textbf{decouple} \\ 1 & \textbf{LR symmetric} \end{cases}$$

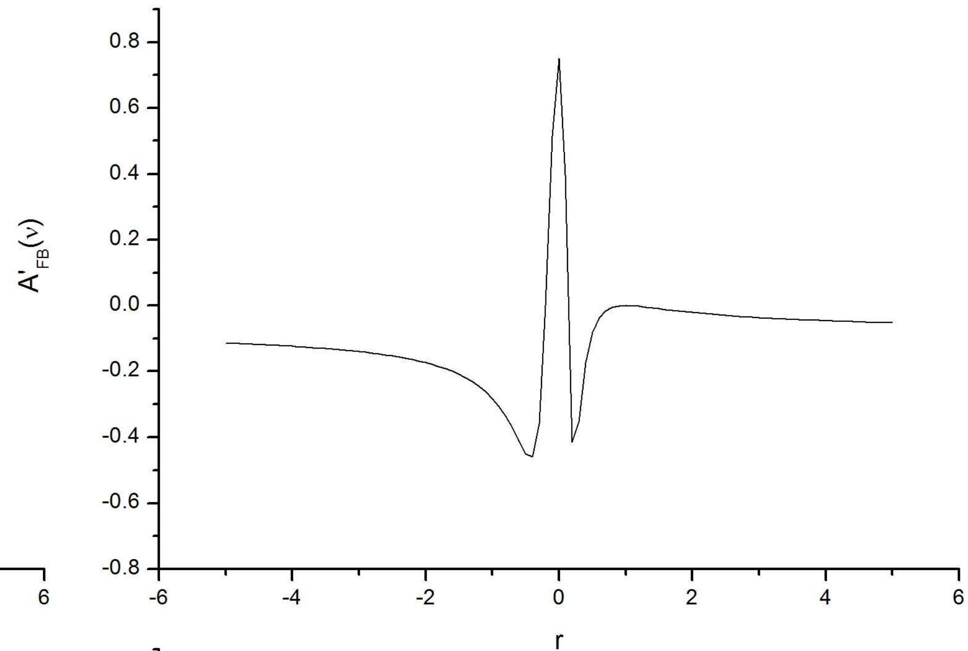
$$\mathbf{A'_{LR}(f)} = \frac{\mathbf{2g'_V g'_A}}{\mathbf{g'^2_V + g'^2_A}} \qquad \mathbf{A'_{FB}(f)} = \frac{\mathbf{3}}{\mathbf{4}}\mathbf{A'_{LR}(e)A'_{LR}(f)}$$

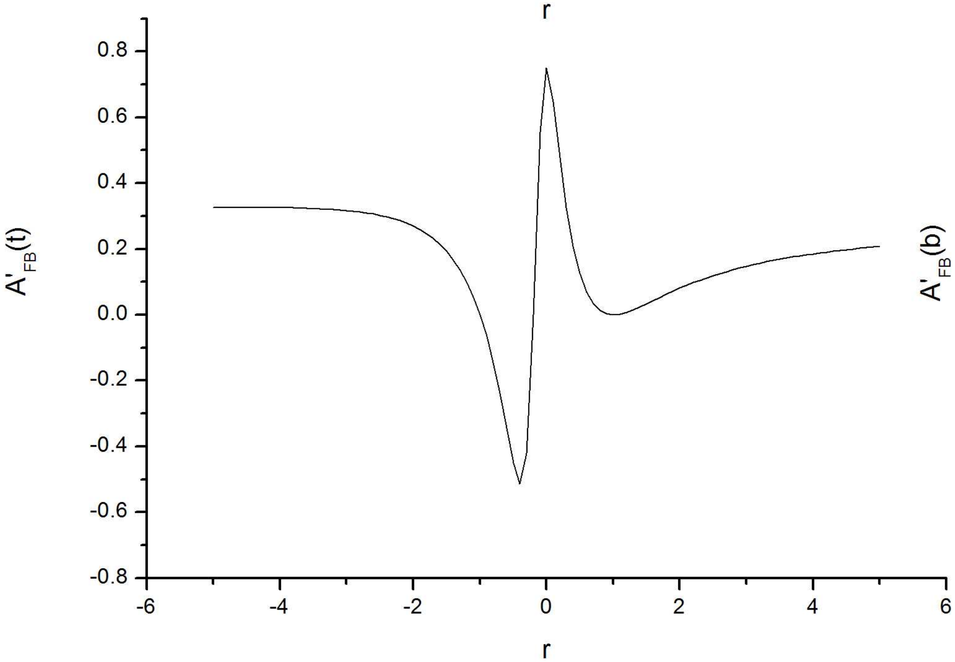

R'b
R't
R'e
R'ν
r
r
r
r
0.30
0.25
0.20
0.15
0.10
0.05
40
35
30
25
20
15
10
5
0
-6
-4
-2
0
2
4
6

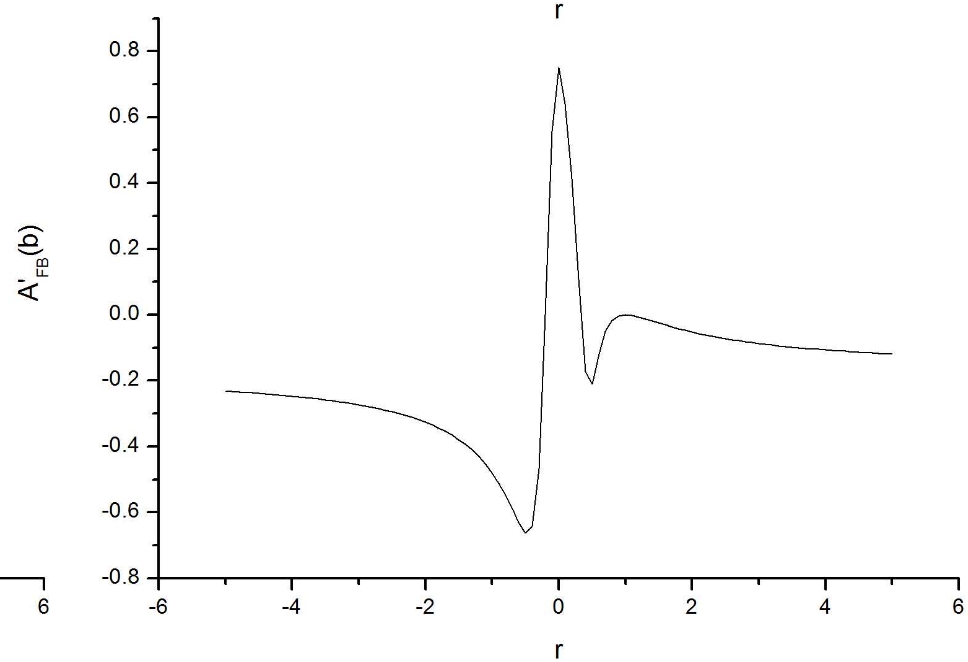


Y.Zhang Mod.Phys.Lett.A26(29),2201(2011)









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Model Dependent Investigation

- **C: Topcolor assisted tecnicolor** C.T.Hill, Phys.Lett.B345(1995)483 formulation
  Zhang,Jiang,Lang,Wang Phys.Rev.D77(2008)055003
- **C: Natural Topcolor-assisted tecnicolor** K.Lane,E.Eichten,Phys.Lett.B352(1995)382 ETC
  Lang,Jiang,Wang Phys.Rev.D79(2009)015002
- **F: New strong interactions at the Tevatron?**
  R.S.Chivukula, A.G.Cohen, E.H.Simmons, Phys.Lett.B380(1996)92
- **C: Symmetry breaking and generational mixing in top-color-assisted technicolor**
  Ge,Jiang,Wang Phys.Rev.D84(2011)015009
  K.Lane, Phys.Rev.D54(1996)2204 Walking effects
- **F: A heavy top quark from flavor-universal colorons**
  M.B.Popovic, E.H.Simmons, Phys.Rev.D58(1998)095007
- **F: A new model of topcolor-assisted technicolor**
  K.Lane, Phys.Lett.B433(1998)96
- **H: Hypercharge-universal topcolor** F.Braam, M.Flossdorf, R.S.Chivukula, S.D.Chiara,E.H.Simmons, Phys.Rev.D77,(2008)055005 Hypercharge effects
  Lang,Jiang,Wang Phys.Lett.B673(2009)63

Classic topcolor

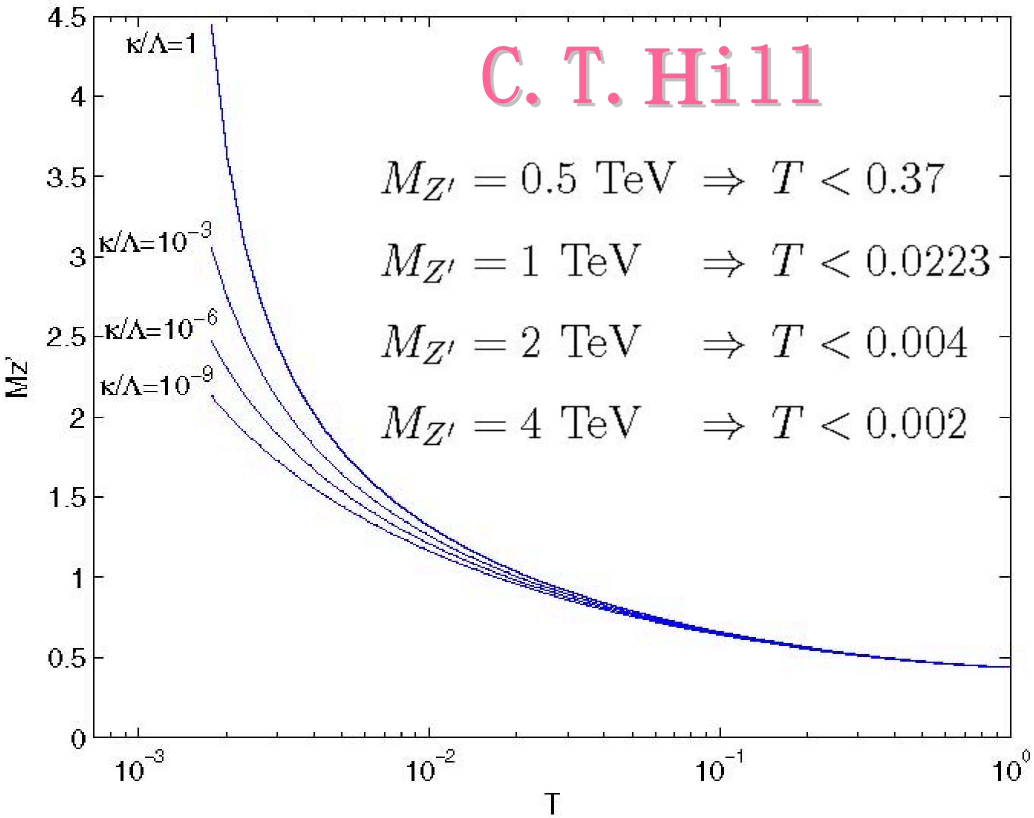
	$SU(3)_1$	$SU(3)_2$	$SU(2)_W$	$U(1)_1$	$U(1)_2$
I	···	SM	SM	···	SM
II	···	SM	SM	···	SM
III	SM	···	SM	SM	···

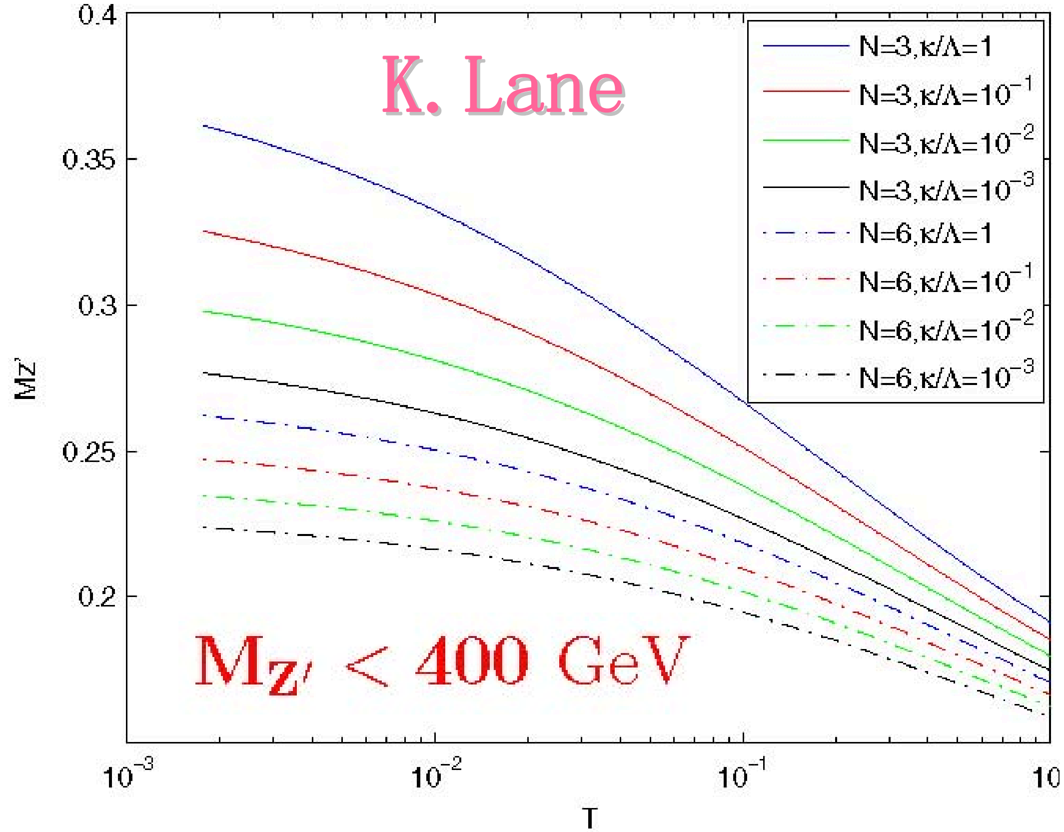
Flavor-universal topcolor

	$SU(3)_1$	$SU(3)_2$	$SU(2)_W$	$U(1)_1$	$U(1)_2$
I	SM	···	SM	···	SM
II	SM	···	SM	···	SM
III	SM	···	SM	SM	···

Hypercharge-universal topcolor

	$SU(3)_1$	$SU(3)_2$	$SU(2)_W$	$U(1)_1$	$U(1)_2$
I	···	SM	SM	SM	···
II	···	SM	SM	SM	···
III	SM	···	SM	SM	···

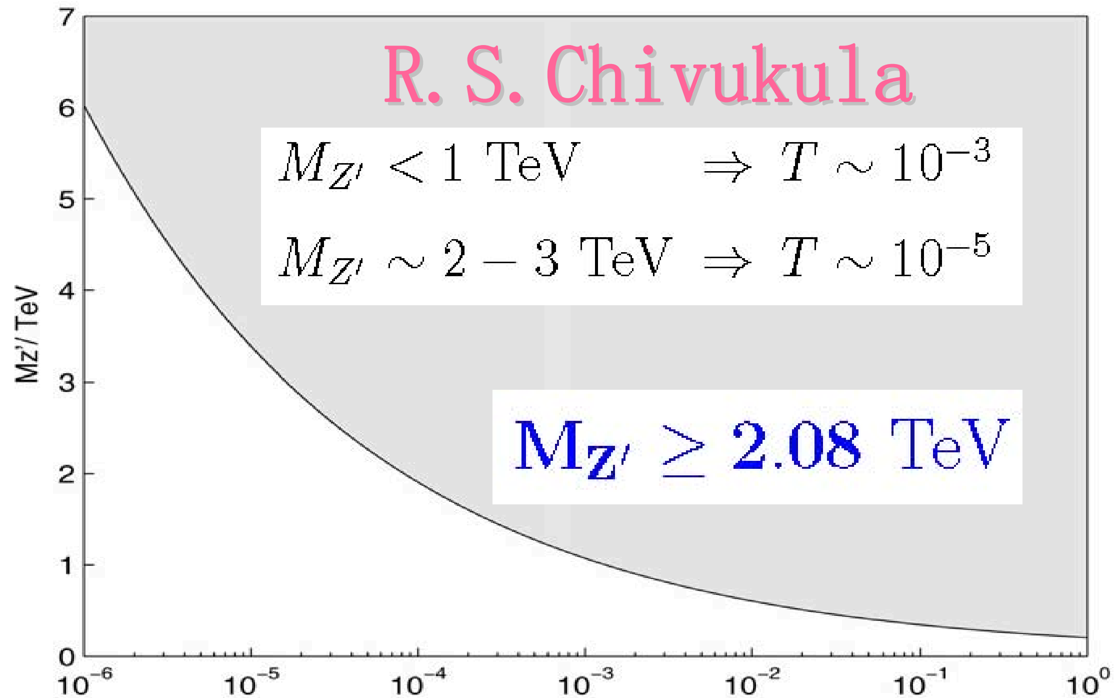




$$M_{Z'} = 0.2 \text{ TeV}, \quad N = 3 \Rightarrow T < 0.74$$

$$M_{Z'} = 0.2 \text{ TeV}, \quad N = 6 \Rightarrow T < 0.25$$

$$M_{Z'} = 0.3 \text{ TeV}, \quad N = 3 \Rightarrow T < 0.0035$$



Three kinds of TopColor-Assisted Technicolor Models

There is <u>no bound</u> for K.Lane's second TC2 model !

Summary

- $\mathbf{Z'}$ not only is the simplest New Physics particle
- but also can improve global fitting result very much in contrast to Higgs

  Even SM higgs is found, Z' is needed in the sense of reducing global fitting result
- We build the most general EWCL for $\mathbf{Z'}$
- Parameterize general & classify $\gamma - \mathbf{Z} - \mathbf{Z'}$ mixing
- Constrain & classify fermion charges to $\mathbf{Z'}$ by anomaly cancelation
- Perform our global fit
- Compute various $\mathbf{R'}, \mathbf{A_{LR}}, \mathbf{A_{FB}}$
- Discuss $\mathbf{M_{Z'}}$ in four TC2 models

清華大學
Tsinghua University

FCPPL

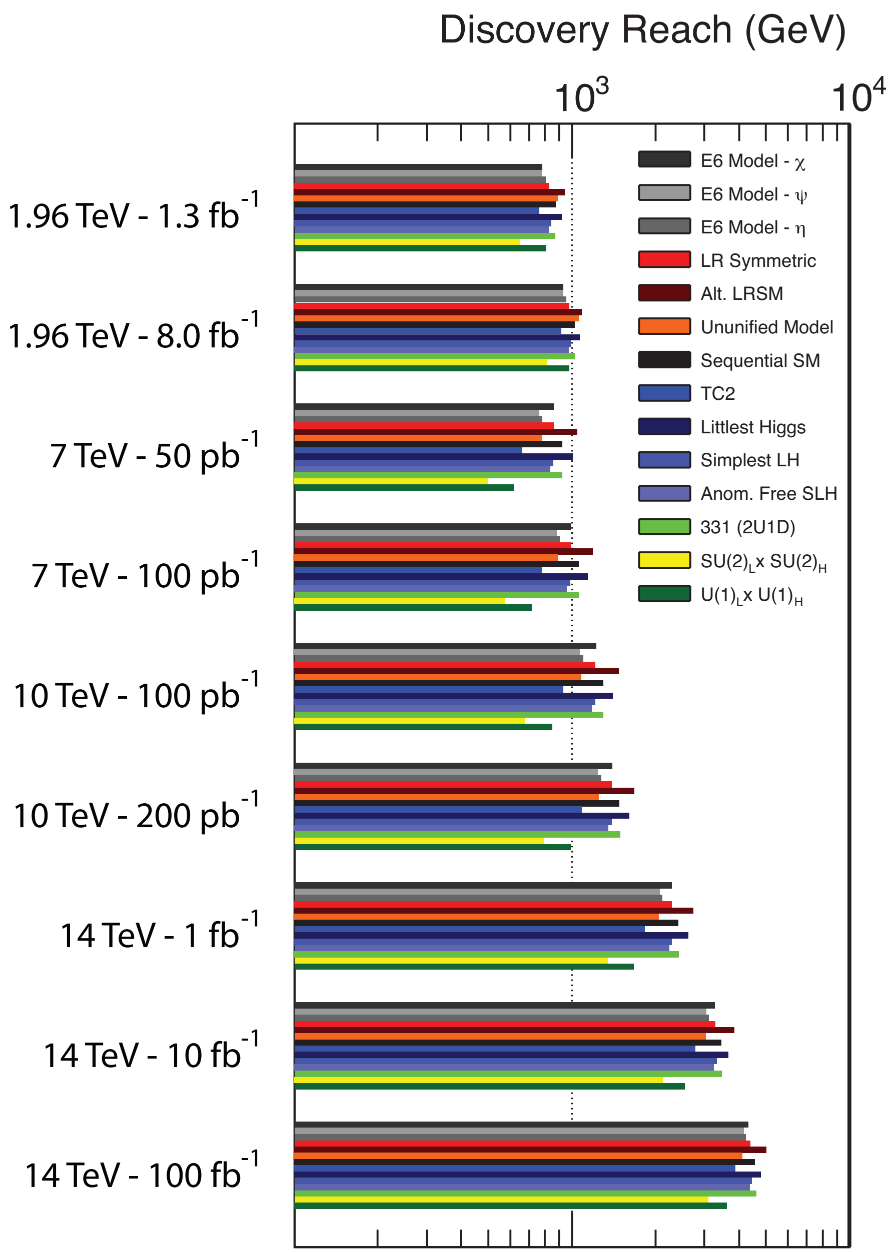
Thanks!

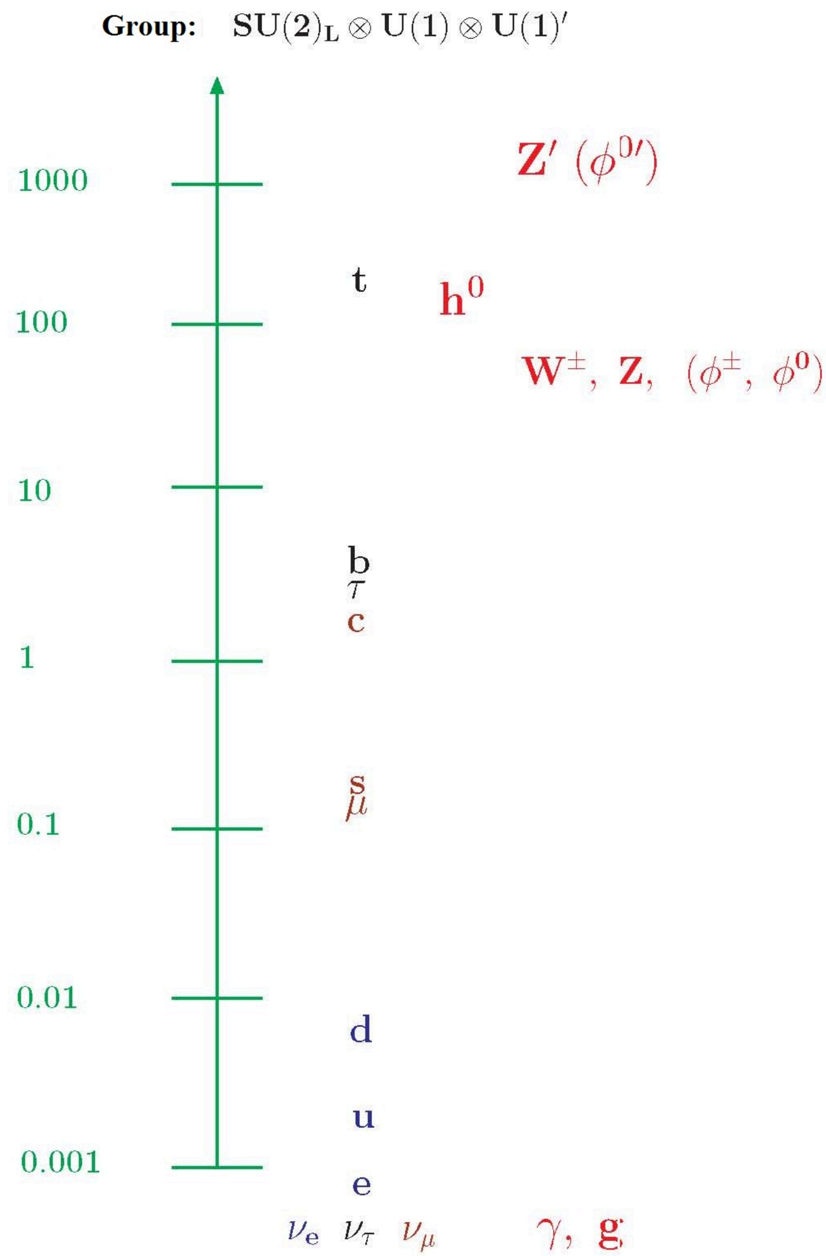
Backup

Tsinghua University

FCPPL France China Particle Physics Laboratory

Masses in units of the proton mass (1GeV)





Atlas: $M_{Z'} > 1.83$TeV for sequential SM at 7TeV in 1.08 e^+e^- (1.21 $\mu^+\mu^-$) fb^{-1} channel–PRL107,272002(2011)

Construct $\mathbf{SU(2)_L \otimes U(1) \otimes U(1)' \to U(1)_{em}}$ Theory

- $\mathbf{SU(2)_L \otimes U(1) \otimes U(1)'}$**trans:** $(e^{i\theta^a t_L^a + i\theta' t'},\ e^{i\theta t})$ $\mathbf{U(1)_{em}}$**trans:** $(e^{i\theta_{em}(t_L^3 + ct')},\ e^{i\theta_{em} t})$

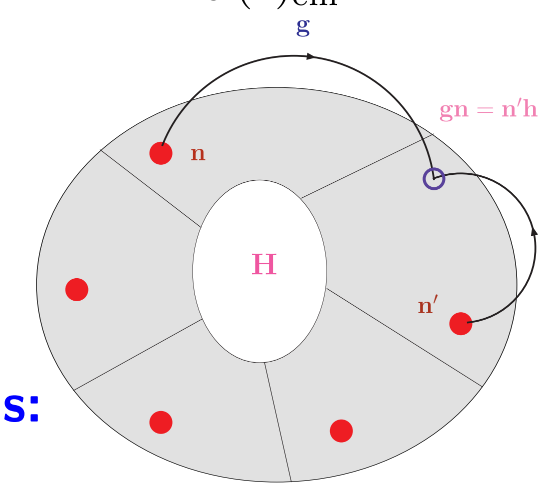
  $\Rightarrow\ t_{em} = t_L^3 + t + ct'$ $[t_L^3, t'] = 0$ $c \neq 0$ **for Stueckelberg** Z'

- **Goldstone: representative coset element** $(U, 1)$ **under** $\mathbf{SU(2)_L \otimes U(1) \otimes U(1)'}$ **trans**

$$(e^{i\theta^a t_L^a + i\theta' t'},\ e^{i\theta t})(\hat{U}, 1) \overset{gn=n'h}{=\!=\!=\!=\!=} (\underbrace{e^{i\theta^a t_L^a + i\theta' t'} \hat{U} e^{-i\theta(t_L^3 + ct')}}_{\hat{U}'},\ 1)\underbrace{(e^{i\theta(t_L^3 + ct')},\ e^{i\theta t})}_{U(1)_{em}}$$

- $\hat{U}$ **transform under** $\mathbf{SU(2)_L \otimes U(1) \otimes U(1)'}$ **as:**

$$\hat{U}' = e^{i\theta^a t_L^a + i\theta' t'}\ \hat{U}\ e^{-i\theta(t_L^3 + ct')}$$



- **Choose** U **as** 2×2 **uni matrix** $t_L^a = \tau^a/2,\ t' = 1$, **covariant der is:**

$$D_\mu \hat{U} = \partial_\mu \hat{U} + i[\underbrace{g_2}_{g} W_\mu + \underbrace{g_1'}_{-g''} X_\mu]\hat{U} - i\hat{U}[\frac{\tau^3}{2}\underbrace{g_1}_{g'} + \underbrace{cg_1}_{\tilde{g}':\ \text{Stueckelberg}}]B_\mu$$

4 couplings !

General γ-Z-Z' Mixing

$$\mathcal{V}_\mu^T \equiv (B_\mu, W_\mu^3, X_\mu)$$

$$\mathcal{L}_M = -\frac{1}{4}f^2\mathrm{tr}[\hat{V}_\mu^2] + \frac{1}{4}\underbrace{\beta_1}_{\text{not ind}} f^2\left(\mathrm{tr}[T\hat{V}_\mu]\right)^2 + \frac{1}{4}\beta_2 f^2\mathrm{tr}[\hat{V}_\mu]\mathrm{tr}[T\hat{V}^\mu] + \frac{1}{4}\underbrace{\beta_3}_{\text{not ind}} f^2\left(\mathrm{tr}[\hat{V}_\mu]\right)^2 \equiv \frac{1}{2}\mathcal{V}_\mu^T\mathcal{M}_0^2\mathcal{V}_\mu$$

$$= \frac{1}{8}(1-2\beta_1)f^2 \underbrace{(gW_\mu^3 - g'B_\mu)}_{g_Z Z_\mu,\ g_Z=\sqrt{g^2+g'^2}}{}^2 + \frac{1}{2}(1-2\beta_3)f^2 \underbrace{(g''X_\mu + \tilde{g}'B_\mu)}_{g''Z'_\mu}{}^2 + \frac{1}{2}\beta_2 f^2 \underbrace{(g''X_\mu + \tilde{g}B_\mu)}_{g''Z'_\mu}{}^2$$

$$\mathcal{L}_K = -\frac{1}{4}B_{\mu\nu}^2 - \frac{1}{2}\mathrm{tr}[W_{\mu\nu}^2] - \frac{1}{4}X_{\mu\nu}^2 + \frac{1}{2}\alpha_1 g g' B_{\mu\nu}\mathrm{tr}[TW^{\mu\nu}] + \frac{1}{4}\alpha_8 g^2\left(\mathrm{tr}[TW_{\mu\nu}]\right)^2$$

$$+gg''\alpha_{24}X_{\mu\nu}\mathrm{tr}[TW^{\mu\nu}] + g'g''\alpha_{25}B_{\mu\nu}X^{\mu\nu} \equiv -\frac{1}{4}\mathcal{V}_{\mu\nu}^T\mathcal{K}_0\mathcal{V}^{\mu\nu}$$

$$\mathcal{V}_{\mu\nu} \equiv \partial_\mu\mathcal{V}_\nu - \partial_\nu\mathcal{V}_\mu$$

$$\mathcal{M}_0^2 = f^2\begin{pmatrix} \frac{\bar{g}'^2}{4} + \bar{\tilde{g}}'^2 & -\frac{\bar{g}\bar{g}'}{4} + \frac{\bar{g}\bar{\tilde{g}}'}{2}\bar{\beta}_2 & -\frac{\bar{g}'\bar{g}''}{2}\bar{\beta}_2 + \bar{g}''\bar{\tilde{g}}' \\ -\frac{\bar{g}\bar{g}'}{4} + \frac{\bar{g}\bar{\tilde{g}}'}{2}\bar{\beta}_2 & \frac{\bar{g}^2}{4} & \frac{\bar{g}\bar{g}''}{2}\bar{\beta}_2 \\ -\frac{\bar{g}'\bar{g}''}{2}\bar{\beta}_2 + \bar{g}''\bar{\tilde{g}}' & \frac{\bar{g}\bar{g}''}{2}\bar{\beta}_2 & \bar{g}''^2 \end{pmatrix}$$

4 independent coefficients: $\frac{g'}{g}, \frac{g'}{g''}, \frac{\tilde{g}}{g''}, \beta_2$

$$\mathcal{K}_0 = -\frac{1}{4}\begin{pmatrix} 1-\alpha_b & -\alpha_a & -2\alpha_c \\ -\alpha_a & 1 & -2\alpha_d \\ -2\alpha_c & -2\alpha_d & 1 \end{pmatrix}$$

4 independent coefficients: $\alpha_a, \alpha_b, \alpha_c, \alpha_d$

Corrections due to Z'

$$M_Z^2 = f^2\left\{\frac{1}{2}\left(\frac{e}{c_W s_W} + (\frac{e}{s_W}\Delta_{11} - \frac{e}{c_W}\Delta_{21})\right)^2 + g''^2\Delta_{31}^2\right\}$$

$$M_{Z'}^2 = f^2\left\{g''^2(1+\Delta_{33})^2 + \frac{1}{4}(g\Delta_{13} - g'\Delta_{23})^2\right\}$$

$$\Delta S = \frac{4s_W c_W}{\alpha}\{(s_W\Delta_{11} - 2s_W c_W(s_W\Delta_{12} + c_W\Delta_{22}) - c_W\Delta_{21})\}$$

$$\Delta T \simeq -\frac{4s_W^2 c_W^2}{\alpha}\frac{g''^2}{e^2}\Delta_{31}^2 \qquad \Delta U = -\frac{8s_W^2}{\alpha}(c_W\Delta_{11} + s_W^3\Delta_{12} + s_W^2 c_W\Delta_{22})$$

$$\delta g_{iV} = c_W\Delta_{11}t_{3iL} + s_W\Delta_{21}(y_{iL} + y_{iR}) + \frac{g'' s_W c_W}{e}\Delta_{31}(y'_{iL} + y'_{iR})$$

$$\delta g_{iA} = c_W\Delta_{11}t_{3iL} + s_W\Delta_{21}(y_{iL} - y_{iR}) + \frac{g'' s_W c_W}{e}\Delta_{31}(y'_{iL} - y'_{iR})$$

$$\delta g'_{iV} = \frac{g}{g''}\Delta_{13}t_{3iL} + \frac{g'}{g''}\Delta_{23}(y_{iL} + y_{iR}) + \Delta_{33}(y'_{iL} + y'_{iR})$$

$$\delta g'_{iA} = \frac{g}{g''}\Delta_{13}t_{3iL} + \frac{g'}{g''}\Delta_{23}(y_{iL} - y_{iR}) + \Delta_{33}(y'_{iL} - y'_{iR})$$

Global Fittings

$$\chi^2 = \sum_i \left(\frac{\mathcal{O}^i_{exp} - \mathcal{O}^i_{th}}{\delta\mathcal{O}^i}\right)^2 = \sum_i \left(\frac{\mathcal{O}^i_{exp} - (\mathcal{O}^i_{SM} + \Delta\mathcal{O}^i_{Z'})}{\delta\mathcal{O}^i}\right)^2 = 20.9 \qquad \frac{\partial}{\partial\Delta_{ij}}\chi^2 = 0$$

r	$\Delta_{11}-0.00017\Delta_{32}$	SD	$\Delta_{12}+1.6\Delta_{32}$	SD	$\Delta_{21}-0.00057\Delta_{32}$	SD	$g''y'_u[\Delta_{31}+0.000014\Delta_{32}]$	SD
-5	-0.00035	0.00029	0.00012	0.00032	-0.00081	0.00092	-0.000010	0.0000074
-4	-0.00035	0.00029	0.00011	0.00032	-0.00079	0.00091	-0.000013	0.0000091
-3	-0.00033	0.00028	0.00010	0.00032	-0.00075	0.00090	-0.000017	0.000012
-2	-0.00031	0.00028	0.000078	0.00032	-0.00067	0.00089	-0.000024	0.000017
-1	-0.00024	0.00026	0.000017	0.00032	-0.00047	0.00086	-0.000043	0.000031
-0.5	-0.00015	0.00025	-0.000073	0.00033	-0.00016	0.00086	-0.000072	0.000051
0	0.00035	0.00042	-0.00054	0.00052	0.0014	0.0015	-0.00022	0.00015
0.1	0.00086	0.00067	-0.0010	0.00073	0.0030	0.0022	-0.00037	0.00024
0.25	-0.00015	0.020	0.000051	0.019	-0.00034	0.062	0	0.0058
0.5	-0.0011	0.00073	0.00085	0.00063	-0.0032	0.0022	0.00022	0.00015
1	0.00063	0.00043	0.00038	0.00040	-0.0017	0.0013	0.000072	0.000051
2	-0.00045	0.00035	0.00025	0.00035	-0.0013	0.0011	0.000031	0.000022
3	-0.00046	0.00034	0.00022	0.00034	-0.0011	0.0010	0.000020	0.000014
4	-0.00044	0.00033	0.00020	0.00034	-0.0011	0.0010	0.000014	0.000010
5	-0.00043	0.00032	0.00019	0.00034	-0.0010	0.0010	0.000011	0.0000081

$\chi^2_{SM} = 259$, $m_H = 90^{+27}_{-22}\text{GeV}$, $m_t = 163.5 \pm 1.3\text{GeV}$ **SD** $\equiv$ **Standard Deviation**

$$\mathbf{SU(N)_{TC}} \otimes \underline{\mathbf{SU(3)_1} \otimes \mathbf{SU(3)_2}} \otimes \mathbf{SU(2)_L} \otimes \underline{\mathbf{U(1)_1} \otimes \mathbf{U(1)_2}}$$

$$\Downarrow \qquad\qquad\qquad\qquad \Downarrow$$

u $\qquad$ colorons $\qquad\qquad$ $\mathbf{Z'}$

$$\searrow \qquad\qquad\qquad\qquad \swarrow$$

$$\mathbf{SU(N)_{TC}} \otimes \mathbf{SU(3)_C} \otimes \underline{\mathbf{SU(2)_L} \otimes \mathbf{U(1)_Y}}$$

$$\Downarrow$$

v $\qquad$ $\mathbf{W^{\pm}},\ \mathbf{Z}$ $\qquad$ **EWCL**

$$\swarrow$$

$$\mathbf{SU(N)_{TC}} \otimes \mathbf{SU(3)_C} \otimes \mathbf{U(1)_{em}}$$