Early LHC bound on W'mass in Nonuniversal Gauge Interaction Model

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- Based on

Y. G. Kim, K. Y. Lee, in preparation

K. Y. Lee, Phys. Rev. D 82, 097701 (2011)

K. Y. Lee, Phys. Rev. D 76, 117702 (2007)

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Introduction

- First year of the LHC was successful. ~ 40 pb^{-1}.
- Direct searches for new physics beyond the SM have start ed at the LHC
- Non-universal gauge interaction shows distinctive signals.
    - Violation of the unitarity of the CKM matrix
    - FCNC at tree level
- Early LHC data provides the direct bound on the non-unive rsal gauge model, which is already compatible to the indire ct bounds.

The Model

- $G = SU(2)_l \times SU(2)_h \times U(1)_Y$

$$\Downarrow$$

$$SU(2)_L \times U(1)_Y$$

$$\Downarrow$$

$$U(1)_{EM}$$

Malkawi, Tait, Yuan, PLB 385, 304 (1996)
Muller, Nandi, PLB 383, 345 (1996)
Lee, Lee, Kim, PLB 424, 133 (1998) (EW Precision Test)
Batra, Delgado, Kaplan, Tait, JHEP 0402, 043 (2002) (SUSY)

$$Q_L^{1,2} : (2,1,1/3), \qquad Q_L^3 : (1,2,1/3),$$
$$L_L^{1,2} : (2,1,-1), \qquad L_L^3 : (1,2,-1)$$
$$q_R, l_R : (1,1,2Q),$$

with♪ $Q = T_{3l} + T_{3h} + Y/2.$

The covariant derivative

$$D^\mu = \partial^\mu + i g_l T_l^a W_{l,a}^\mu + i g_h T_h^a W_{h,a}^\mu + i g' \frac{Y}{2} B^\mu,$$

The gauge couplings are parameterized

$$g_l = \frac{e}{\sin\theta \cos\phi}, \qquad g_h = \frac{e}{\sin\theta \sin\phi}, \qquad g' = \frac{e}{\cos\theta}$$

Spontaneous symmetry breaking by

$$\langle\Sigma\rangle = \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix},$$

$$\langle\Phi\rangle = (0, v/\sqrt{2}).$$

with parameterization

$$v^2/u^2 \equiv \lambda \ll 1.$$

Heavy gauge boson masses

$$m^2_{W'^{\pm}} = m^2_{Z'} = \frac{m_0^2}{\lambda \sin^2\phi \cos^2\phi},$$

where $m_0 = ev/(2\sin\theta)$.

LEP electroweak precision test

Corrections to $Z \to l^- l^+$, $Z \to b\bar{b}$ decays♪

$$g_V = T_{3h} + T_{3l} - 2Q\sin^2\theta_W + \lambda\sin^2\phi(T_{3h}\cos^2\phi - T_{3l}\sin^2\phi),$$

$$g_A = T_{3h} + T_{3l} + \lambda\sin^2\phi(T_{3h}\cos^2\phi - T_{3l}\sin^2\phi),$$

	Measurement
m_Z	91.1875 ± 0.0021 GeV
Γ_l	83.984 ± 0.086 MeV
A^l_{FB}	0.0171 ± 0.0010
R_b	0.21638 ± 0.00066
A^b_{FB}	0.0997 ± 0.0016

Low-energy neutral current experiments

νN → νN scattering♪

$$H^{\nu N} = \frac{G_F}{\sqrt{2}} \overline{\nu} \gamma^\mu (1 - \gamma_5) \nu \sum_i [\epsilon_L(i) \overline{q}_i \gamma_\mu (1 - \gamma_5) q_i + \epsilon_R(i) \overline{q}_i \gamma_\mu (1 + \gamma_5) q_i],$$

➡ $$\epsilon_{L,R}(u,d) = \epsilon_{L,R}^{\mathrm{SM}}(u,d)(1 - \lambda \sin^4 \phi).$$

νe → νe scattering ♪

$$H^{\nu e} = \frac{G_F}{\sqrt{2}} \overline{\nu} \gamma^\mu (1 - \gamma_5) \nu \overline{e} \gamma_\mu (g_V^{\nu e} - g_A^{\nu e} \gamma_5) e.$$

➡ $$g_{V(A)}^{\nu e} = g_{V(A)}^{\nu e}|_{\mathrm{SM}}(1 - \lambda \sin^4 \phi).$$

eN → eX scattering

$$H^{eN} = -\frac{G_F}{\sqrt{2}}\sum_i [C_{1i}\bar{e}\gamma^\mu\gamma_5 e\bar{q}_i\gamma_\mu q_i + C_{2i}\bar{e}\gamma^\mu e\bar{q}_i\gamma_\mu\gamma_5 q_i].$$

$$C_{1u,d} = C_{1u,d}^{\mathrm{SM}}(1 - \lambda\sin^4\phi),$$

$$C_{2u} = C_{2u}^{\mathrm{SM}}(1 - \lambda\sin^4\phi) + 2\lambda|V_{31}^U|^2\sin^2\phi\sin^2\theta_W,$$

$$C_{2d} = C_{2d}^{\mathrm{SM}}(1 - \lambda\sin^4\phi) - 2\lambda|V_{31}^D|^2\sin^2\phi\sin^2\theta_W.$$

Atomic Parity Violation

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

$$\Delta Q_W \equiv Q_W - Q_W^{\mathrm{SM}} = -2[\Delta C_{1u}(2Z + N) + \Delta C_{1d}(Z + 2N)] = \Delta Q_W^{\mathrm{SM}}(1 - \lambda\sin^4\phi).$$

Data of low-energy neutral current interactions

	Experiments	SM prediction
$\epsilon_L(u)$	0.326 ± 0.012	0.3460 ± 0.0002
$\epsilon_L(d)$	-0.441 ± 0.010	-0.4292 ± 0.0001
$\epsilon_R(u)$	$-0.175^{+0.013}_{-0.004}$	-0.1551 ± 0.0001
$\epsilon_R(d)$	$-0.022^{+0.072}_{-0.047}$	0.0776
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0003
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5065 ± 0.0001
$C_{1u} + C_{1d}$	0.148 ± 0.004	0.1529 ± 0.0001
$C_{1u} - C_{1d}$	-0.597 ± 0.061	-0.5299 ± 0.0004
$C_{2u} + C_{2d}$	0.62 ± 0.80	-0.0095
$C_{2u} - C_{2d}$	-0.07 ± 0.12	-0.0623 ± 0.0006

$$Q_W = -72.69 \pm 0.48 \quad \text{(Cs)},$$

$$Q_W = -116.6 \pm 3.7 \quad \text{(Tl)},$$

PDG 2010

CKM matrix unitarity

CKM matrix

$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

Unitarity relation

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta,$$

$$|V_{ud}| = 0.97418 \pm 0.00027$$: Beta decay

$$|V_{us}| = 0.2255 \pm 0.0019$$: K decay

$$|V_{ub}| = (3.93 \pm 0.36) \times 10^{-3}$$: B decay

➡ $$\Delta = 0.0009 \pm 0.0010,$$: Unitarity holds.

Non-universal terms in CC interactions separated:

$$\mathcal{L}^{CC} = \mathcal{L}_I^{CC} + \mathcal{L}_3^{CC},$$

where

$$\mathcal{L}_I = \bar{U}_L \gamma_\mu [G_L W^\mu + G_L' W'^\mu](V_U^\dagger V_D) D_L + \text{H.c.},$$

$$\mathcal{L}_3^{CC} = (V_{31}^{U*} \bar{u}_L + V_{32}^{U*} \bar{c}_L + V_{33}^{U*} \bar{t}_L) \times \gamma^\mu (X_L W_\mu^+ + X_L' W_\mu'^+)(V_{31}^D d_L + V_{32}^D s_L + V_{33}^D b_L),$$

with♪

$$G_L = -\frac{g}{\sqrt{2}}(1 - \lambda \sin^4\phi) I$$

$$G_L' = \frac{g}{\sqrt{2}}(\tan\phi + \lambda \sin^3\phi \cos\phi) I$$

$$X_L = -\frac{g}{\sqrt{2}} \lambda \sin^2\phi \cdot,$$

$$X_L' = -\frac{g}{\sqrt{2}}\left(\frac{1}{\sin\phi \cos\phi}\right).$$

‘Observed’ CKM matrix is defined by the effective Hamiltonian

$$\mathcal{H}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} \sum_{q=d,s,b} V_{uq} (\bar{u}\gamma_\mu(1-\gamma_5)q)(\bar{\nu}\gamma^\mu(1-\gamma_5)l)$$

and obtained as (including modified W + W’ effects)

$$V_{CKM} = V^0_{CKM} + \epsilon^c V_U{}^\dagger M V_D + \left(\frac{G'^c_L}{G^c_L}\right)^2 \frac{m^2_W}{m^2_{W'}} \left(V^0_{CKM} + \epsilon'^c V_U{}^\dagger M V_D\right)$$

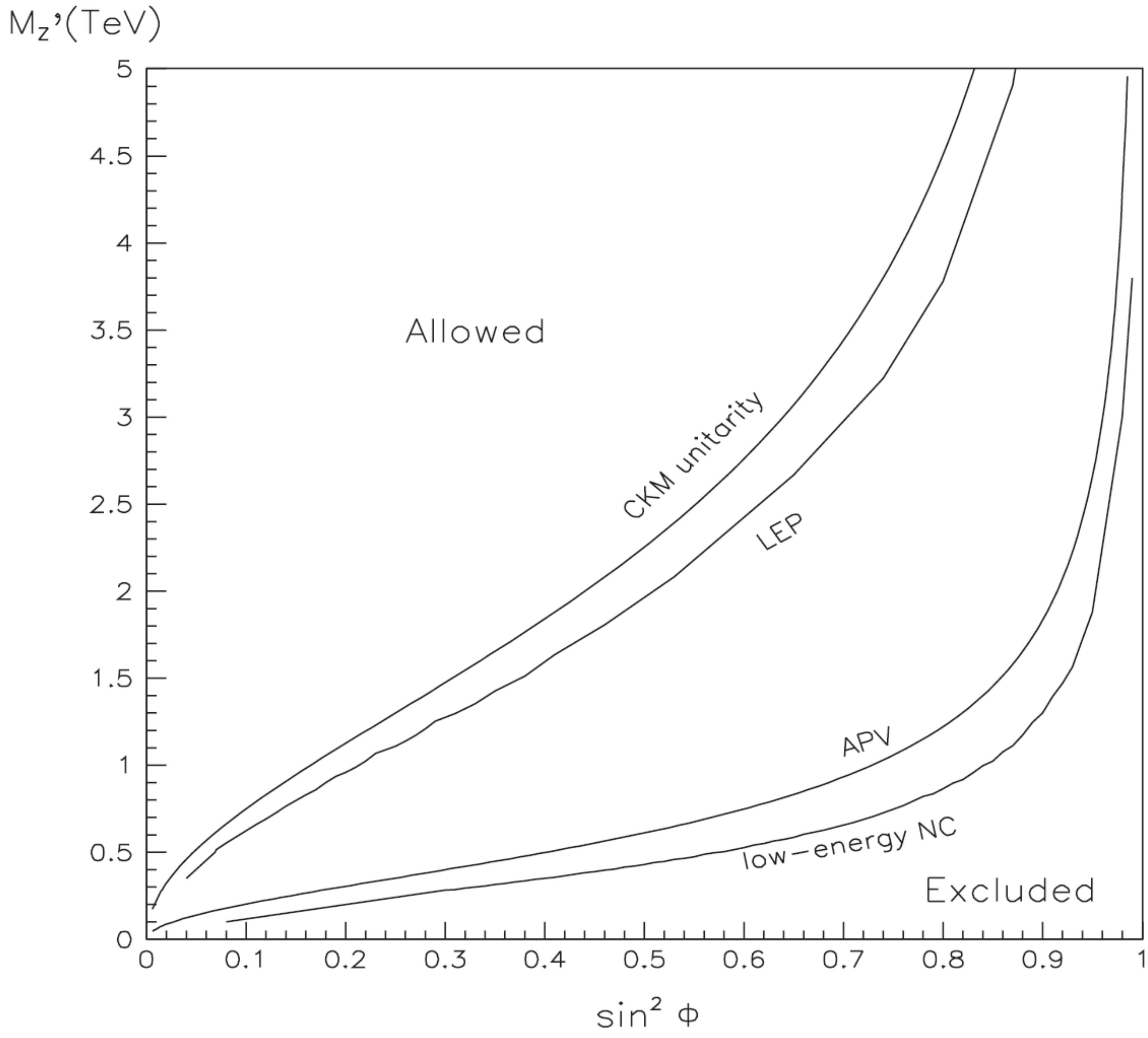
$$\begin{aligned} \epsilon^c &= \lambda \sin^2\phi + \mathcal{O}(\lambda^2) \\ \epsilon'^c &= 1/\sin^2\phi + \mathcal{O}(\lambda), \end{aligned}$$

⇨ $$V_{CKM} = V^0_{CKM}(1 + \lambda \sin^4\phi)$$

Unitarity violating term

➡ $$\Delta = 2\lambda \sin^4\phi$$

Unitarity violated!



M_Z'(TeV)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Allowed
CKM unitarity
LEP
APV
low-energy NC
Excluded
sin² Φ

Lepton Flavour Violation

Non-universal terms in NC interactions separated:

$$\mathcal{L}^{\rm NC} \ = \ \mathcal{L}_I^{\rm NC} + \mathcal{L}_3^{\rm NC} \quad ,$$

Universal terms

$$\mathcal{L}_I^{\rm NC} = \bar{f}_L \gamma_\mu (G_L Z^\mu + G'_L Z'^\mu) f_L + \bar{f}_R \gamma_\mu (G_R Z^\mu + G'_R Z'^\mu) f_R,$$

where

$$\begin{aligned}
G_L &= -\frac{e}{\cos\theta\sin\theta}\left(T_3 - Q\sin^2\theta - \lambda T_3 \sin^4\phi\right) I, \\
G'_L &= \frac{e}{\sin\theta}\left(T_3 \tan\phi + \lambda \frac{\sin^3\phi\cos\phi}{\cos^2\theta}(T_3 - Q\sin^2\theta)\right) I, \\
G_R &= \frac{e}{\cos\theta\sin\theta} Q \sin^2\theta I, \\
G'_R &= -\frac{e}{\sin\theta} \lambda Q \tan^2\theta \sin^3\phi \cos\phi I,
\end{aligned}$$

Non-universal terms

$$\mathcal{L}_3^{\mathrm{NC}} = \bar{f}_L \gamma_\mu (Y_L Z^\mu + Y'_L Z'^\mu) f_L ,$$

where

$$\begin{aligned} Y_L &= -\frac{e}{\cos\theta \sin\theta} \lambda T_3 \sin^2\phi M, \\ Y'_L &= -\frac{e}{\sin\theta} \frac{T_3}{\sin\phi \cos\phi} M, \end{aligned}$$

$$M = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Diagonalization

$$f = V^\dagger f^0$$

$$\begin{aligned}
\mathcal{L}_{NC} &= G_L^{(\prime)} \bar{f}_L \gamma_\mu \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1+\epsilon^{(\prime)} \end{pmatrix} f_L Z^{(\prime)\mu}, \\
&= G_L^{(\prime)} \bar{f}_L^0 \gamma_\mu V^\dagger \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1+\epsilon^{(\prime)} \end{pmatrix} V f_L^0 Z^{(\prime)\mu}, \\
&= G_L^{(\prime)} \bar{f}_L^0 \gamma_\mu \left(I + \epsilon^{(\prime)} V^\dagger M V \right) f_L^0 Z^{(\prime)\mu},
\end{aligned}$$

where

$$(V^\dagger M V)_{ij} = V_{3i}^* V_{3j}$$

$$\begin{aligned}
\epsilon &= \frac{X_L}{G_L} = \frac{\lambda \sin^2\phi}{1 - 2\sin^2\theta} + \mathcal{O}(\lambda^2), \\
\epsilon' &= \frac{X_L'}{G_L'} = -\frac{1}{\sin^2\phi} + \mathcal{O}(\lambda).
\end{aligned}$$

FCNC arise!

Lepton flavour violating processes

$$\begin{aligned}
\mathrm{Br}(\tau^- \to e^- e^+ e^-) &< 3.6 \times 10^{-8},\\
\mathrm{Br}(\tau^- \to e^- \mu^+ \mu^-) &< 3.7 \times 10^{-8},\\
\mathrm{Br}(\tau^- \to e^+ \mu^- \mu^-) &< 2.3 \times 10^{-8},\\
\mathrm{Br}(\tau^- \to \mu^- e^+ e^-) &< 2.7 \times 10^{-8},\\
\mathrm{Br}(\tau^- \to \mu^+ e^- e^-) &< 2.0 \times 10^{-8},\\
\mathrm{Br}(\tau^- \to \mu^- \mu^+ \mu^-) &< 3.2 \times 10^{-8},\\
\mathrm{Br}(\mu^- \to e^- e^+ e^-) &< 1.0 \times 10^{-12}, \qquad \text{at } 90\% \text{ C.L..}
\end{aligned}$$

$$\begin{aligned}
\mathrm{Br}(Z \to e\mu) &< 1.7 \times 10^{-6},\\
\mathrm{Br}(Z \to e\tau) &< 9.8 \times 10^{-6},\\
\mathrm{Br}(Z \to \mu\tau) &< 1.2 \times 10^{-5}, \qquad \text{at } 95\% \text{ C.L..}
\end{aligned}$$

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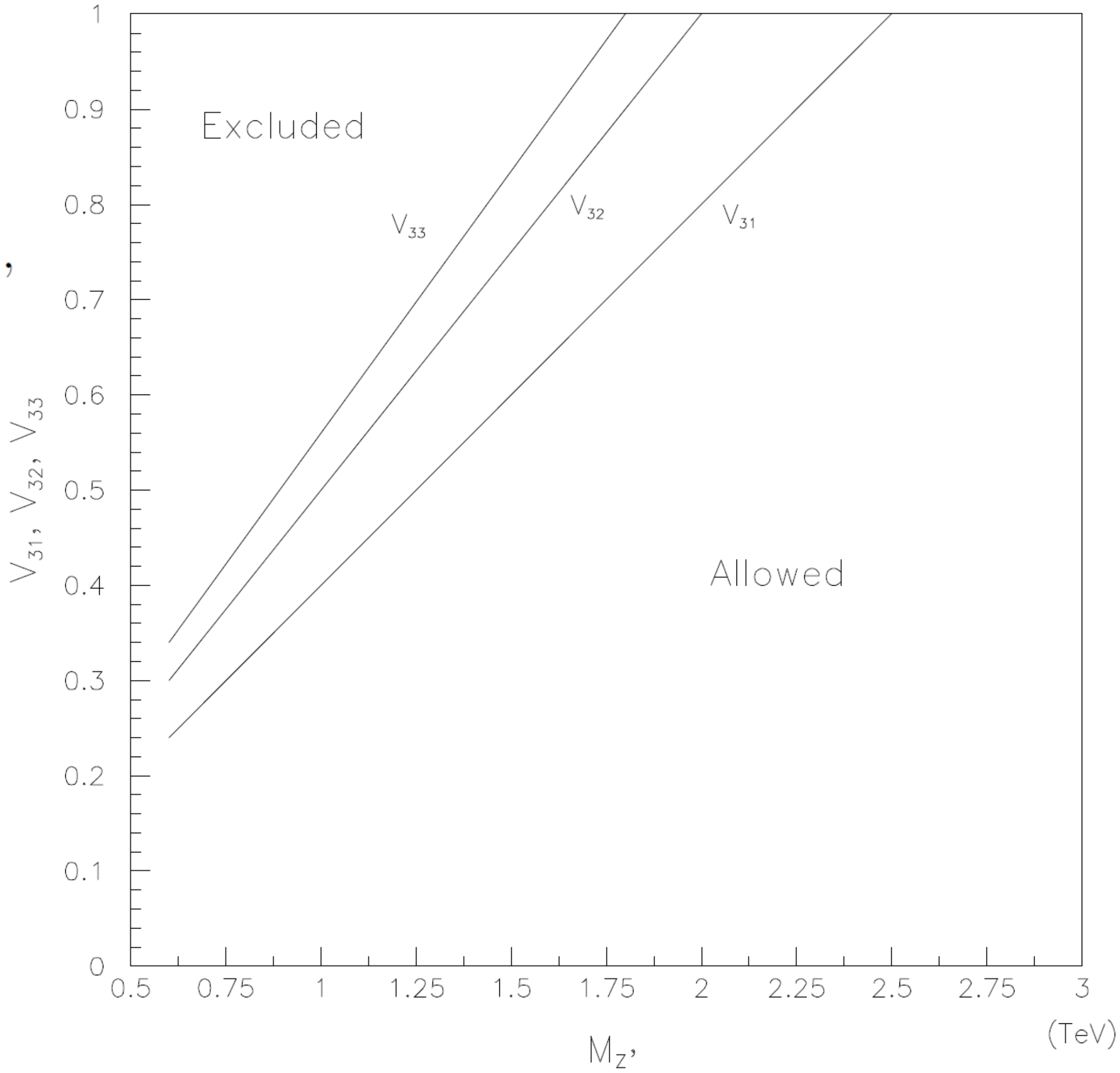
Flavour diagonal corrections

$$\Gamma(Z \to l_i^- l_i^+) = \Gamma_{\rm SM}\left(1 + 2\epsilon |V_{3i}|^2\right) ,$$

Γ_{ll}	Average (MeV)
Γ_{ee}	83.92 ± 0.12
$\Gamma_{\mu\mu}$	83.99 ± 0.18
$\Gamma_{\tau\tau}$	84.08 ± 0.22

LEP EW working group



LFV Z decays

$$\Gamma(Z \to l_i^- l_j^+) = \Gamma(Z \to l_i^+ l_i^-) \cdot \epsilon^2 |V_{3i}|^2 |V_{3j}|^2,$$

LFV τ decays

$$\begin{aligned}\Gamma(\tau^- \to \mu^-(e^-)\mu^+\mu^-) &= \frac{m_\tau^5}{96\pi^3}\left[\left|G_{4LL}^{23(13)} + G'^{23(13)}_{4LL}\right|^2 + \left|G_{4LR}^{23(13)}\right|^2\right], \\ &= \Gamma(\tau^- \to \mu^-(e^-)e^+e^-),\end{aligned}$$

$$G^{(\prime)ij}_{4\alpha\beta} = \left(G_\alpha G_\beta / m^2_{Z^{(\prime)}}\right)\epsilon^{(\prime)} V_{3i}^* V_{3j} \qquad \alpha, \beta = L, R$$

$$\Gamma(\tau^- \to \mu^+ e^- e^-(e^+\mu^-\mu^-)) = \frac{m_\tau^5}{96\pi^3}\left|H_{LL}^{1(2)}\right|^2,$$

$$H_{LL}^k = (G'_L / m_{Z'})^2 \epsilon'^2 V_{32}^* V_{33} V_{31}^* V_{3k}$$

LFV μ decay is given in the similar form.

1) $|V_{33}| \approx 1$

$$|V_{31}|^2 + |V_{32}|^2 + |V_{33}|^2 = 1$$

$$\mathrm{Br}(\tau \to l_i l_j l_k) \propto |V_{33}|^2 |V_{3i}|^2 = \mathcal{O}(10^{-8})$$

➡ $|V_{32}|$, $|V_{31}|$~0

2) $|V_{33}| \approx 0$

$$|V_{31}|^2 + |V_{32}|^2 = 1$$

$$\mathrm{Br}(\mu \to eee) \propto |V_{31}|^2 |V_{32}|^2 < 10^{-12}$$

➡ One of $|V_{32}|$, $|V_{31}|$~1, the other ~0

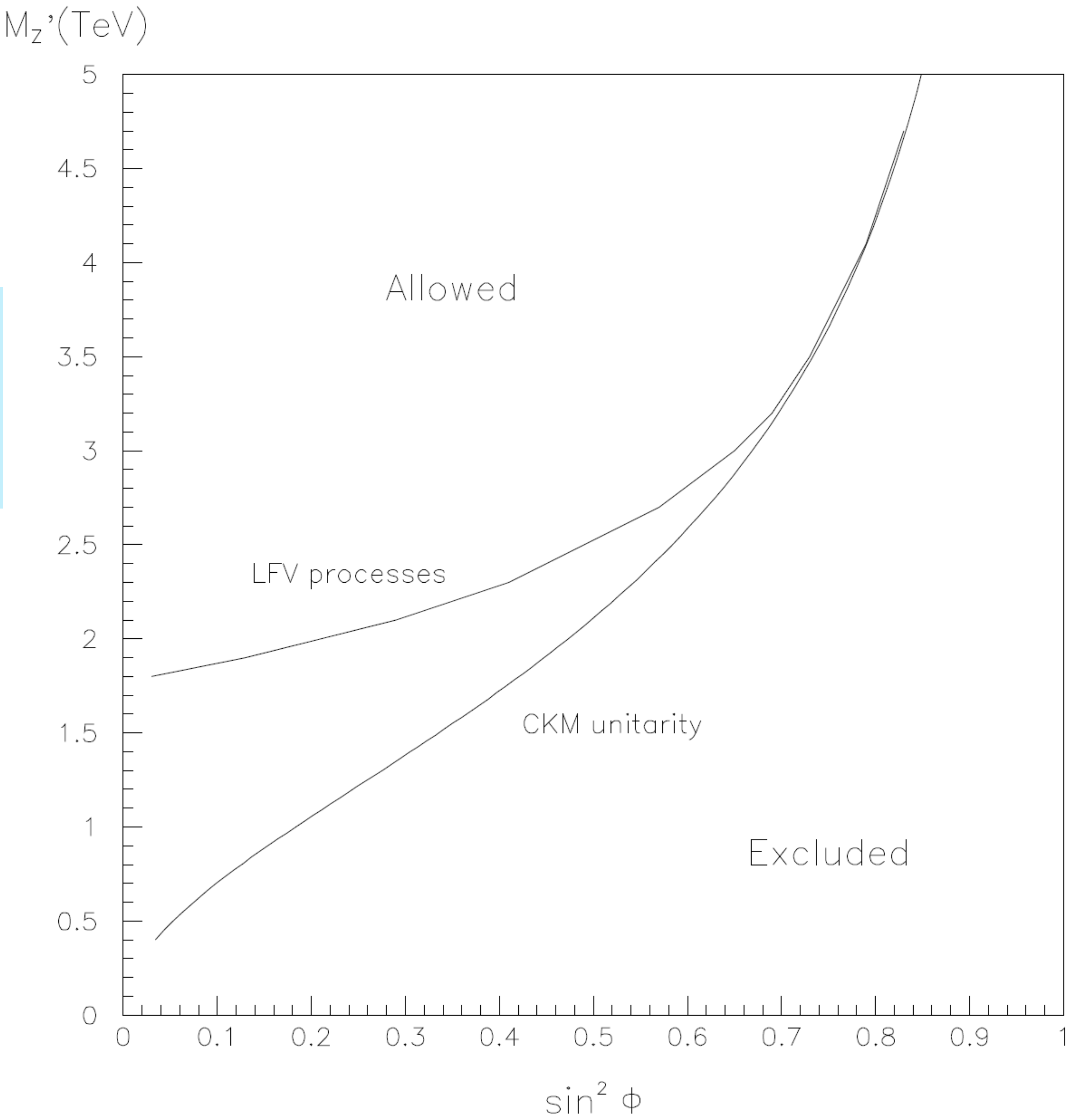
3) $|V_{33}| = \mathcal{O}(0.1)$

Either $|V_{32}|$ or $|V_{31}|$~ $\mathcal{O}(0.1)$ for unitarity.

➡ Corresponding LFV decay exceeds the experimental bound.

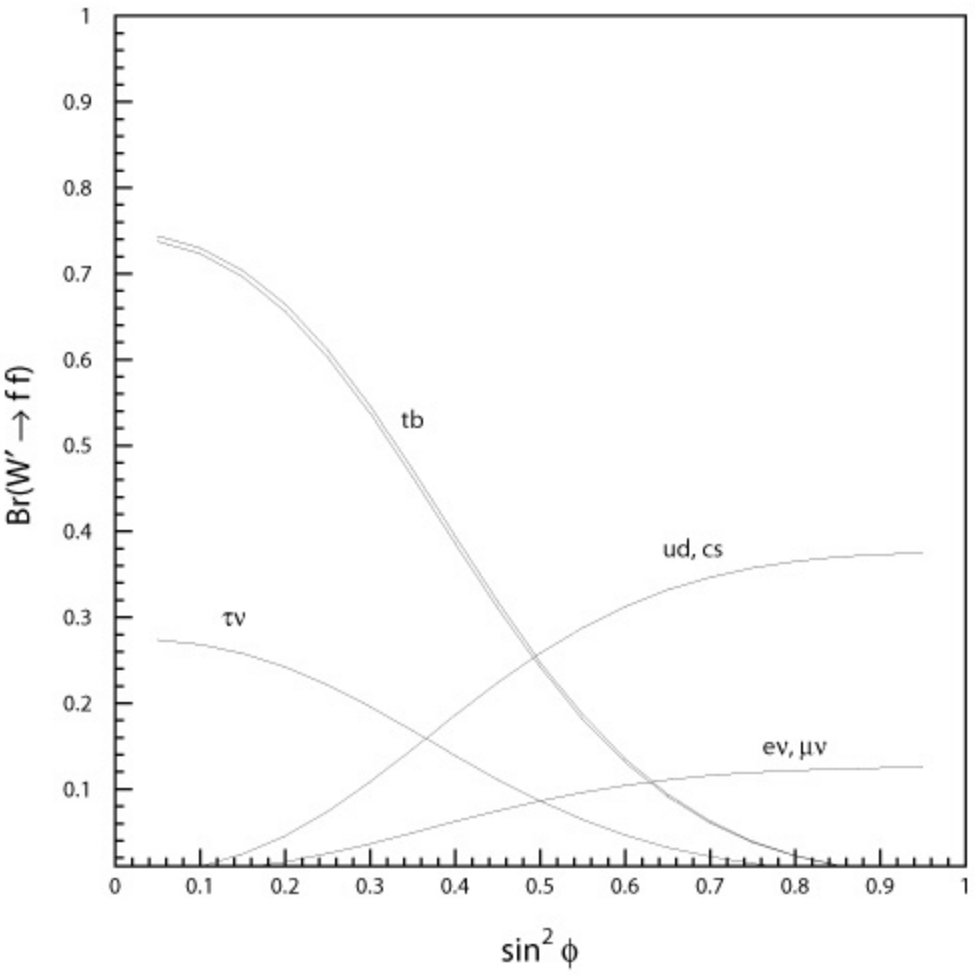
In conclusion, only one $|V_{3i}| \approx 1$ and others are very small.

Combine all parameters and experimental bounds.



Search for W' at the LHC

W' decay width
$$\Gamma(W' \to f\bar{f}') = \frac{1}{24\pi} N_c \, |V_{ff}|^2 \, m_{W'} \left(\frac{g}{\sqrt{2}} X^f(\sin\phi) \right)^2$$



$$X^f(\sin\phi) = \tan\phi,$$ for 1st, 2nd gen.♪

$$= \tan\phi \left(1 - \frac{1}{\sin^2\phi} \right)$$

for 3rd gen.♪

pp → W' → eν / μν

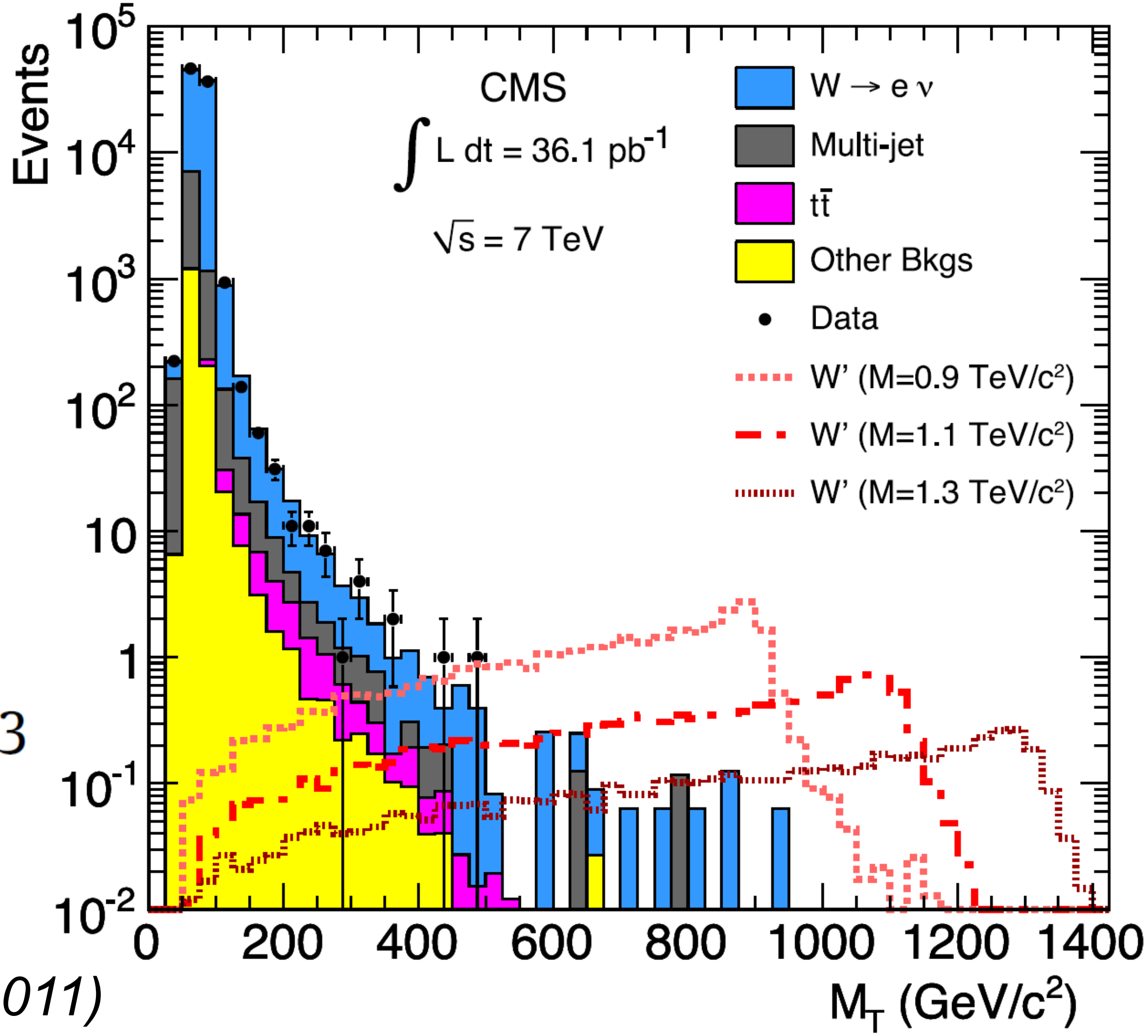
$\sqrt{s} = 7\ \text{TeV}$

$\int L = 36.1 \pm 4.0\ \text{pb}^{-1}$

$E_T > 30$ GeV

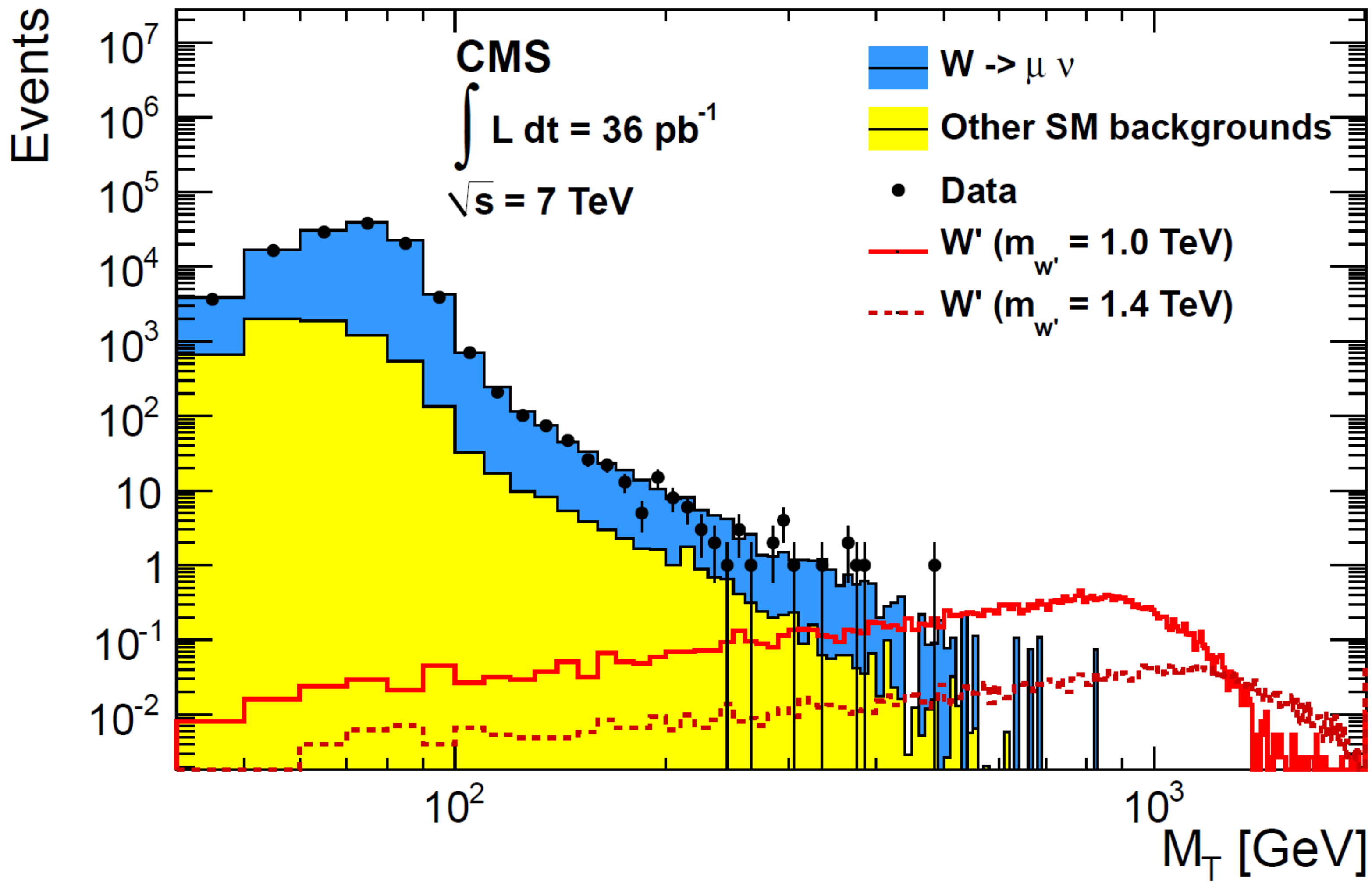
Isolation radius

$$\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$$

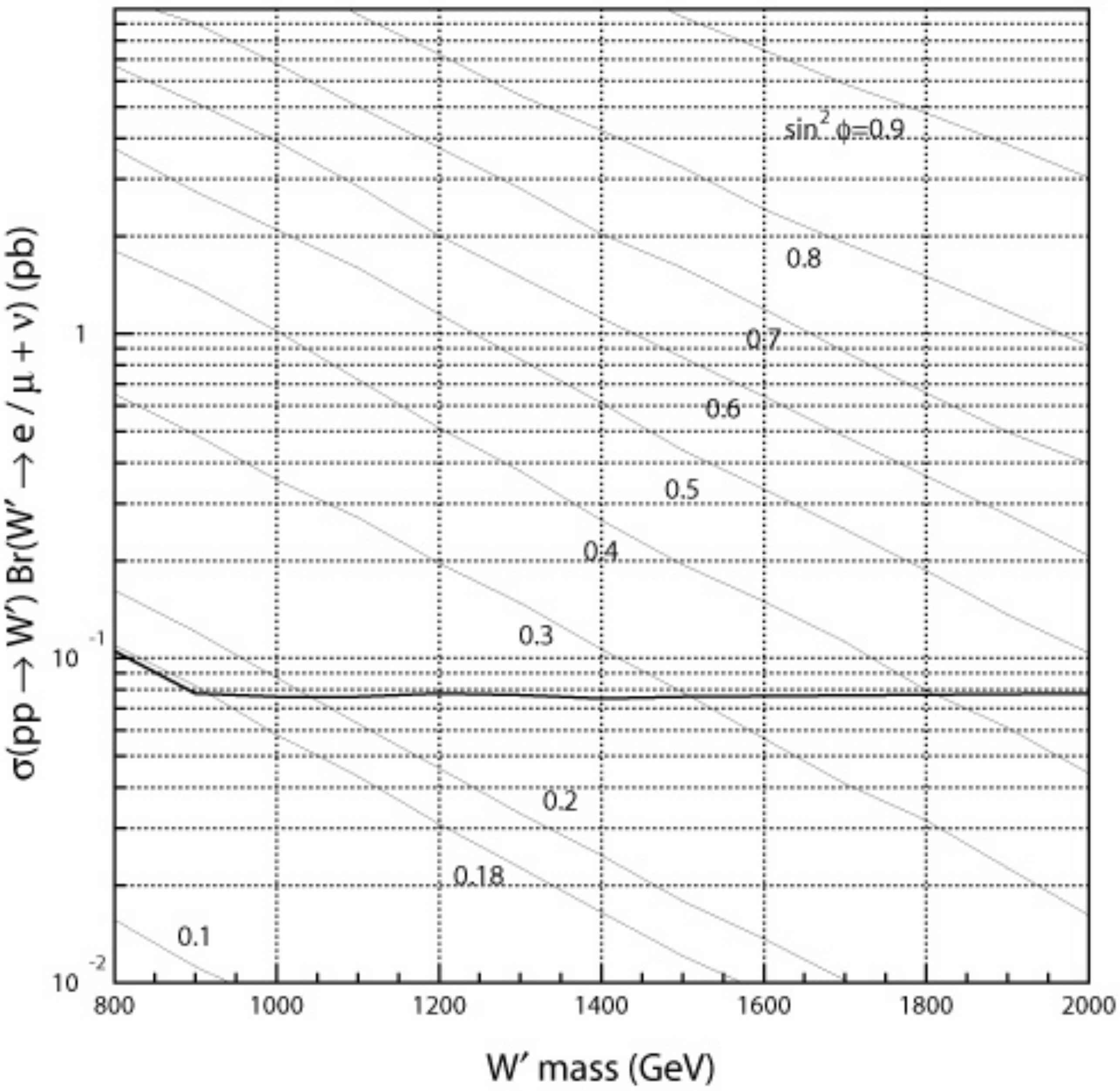


CMS collab., PLB 698, 20 (2011)

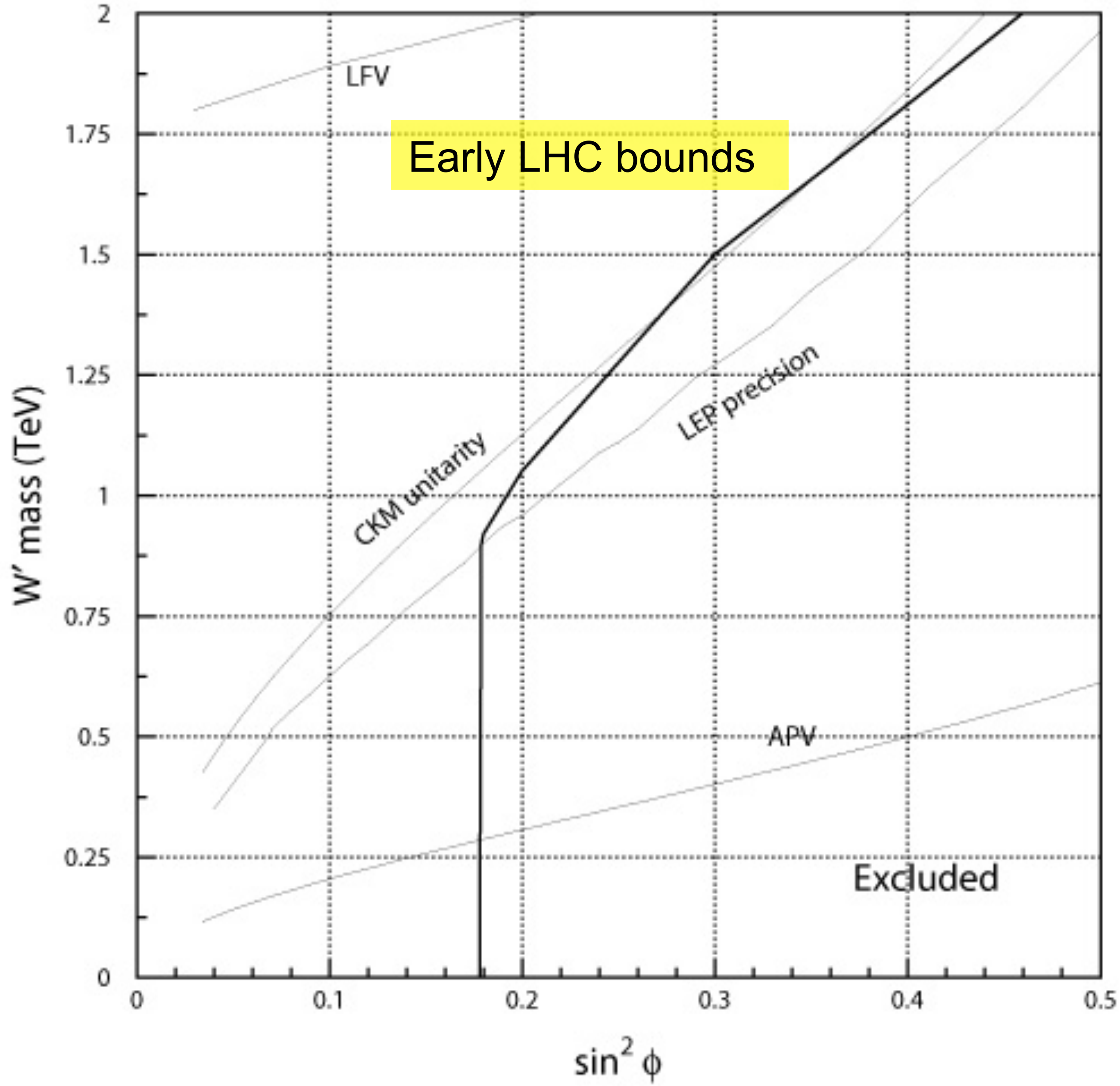
$$M_T = \sqrt{2 \cdot E_T^{ele} \cdot E_T^{miss} \cdot (1 - \cos \Delta\phi_{eE_T^{miss}})}/c^2$$



CMS collab., arXiv:1103.0030 [hep-ex]



sin^2 φ=0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.18
0.1
1
10^{-1}
10^{-2}
800
1000
1200
1400
1600
1800
2000
σ(pp → W') Br(W' → e / μ + ν) (pb)
W' mass (GeV)



Direct bounds are obtained and compatible to the CKM unitarity bounds.

Summary

- The LHC data begin testing the new physics beyond the SM directly.

- The non-universal $SU(2)_l \times SU(2)_h \times U(1)_Y$ model predicts many distinct features and has been constrained by various experiments.

- Early LHC data provides direct bounds on this model which is already compatible to the indirect bounds.