CDF W mass anomaly from a dark sector with a Stueckelberg-Higgs portal

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arXiv:2204.09024 [hep-ph], Mingxuan Du, ZL, Pran Nath

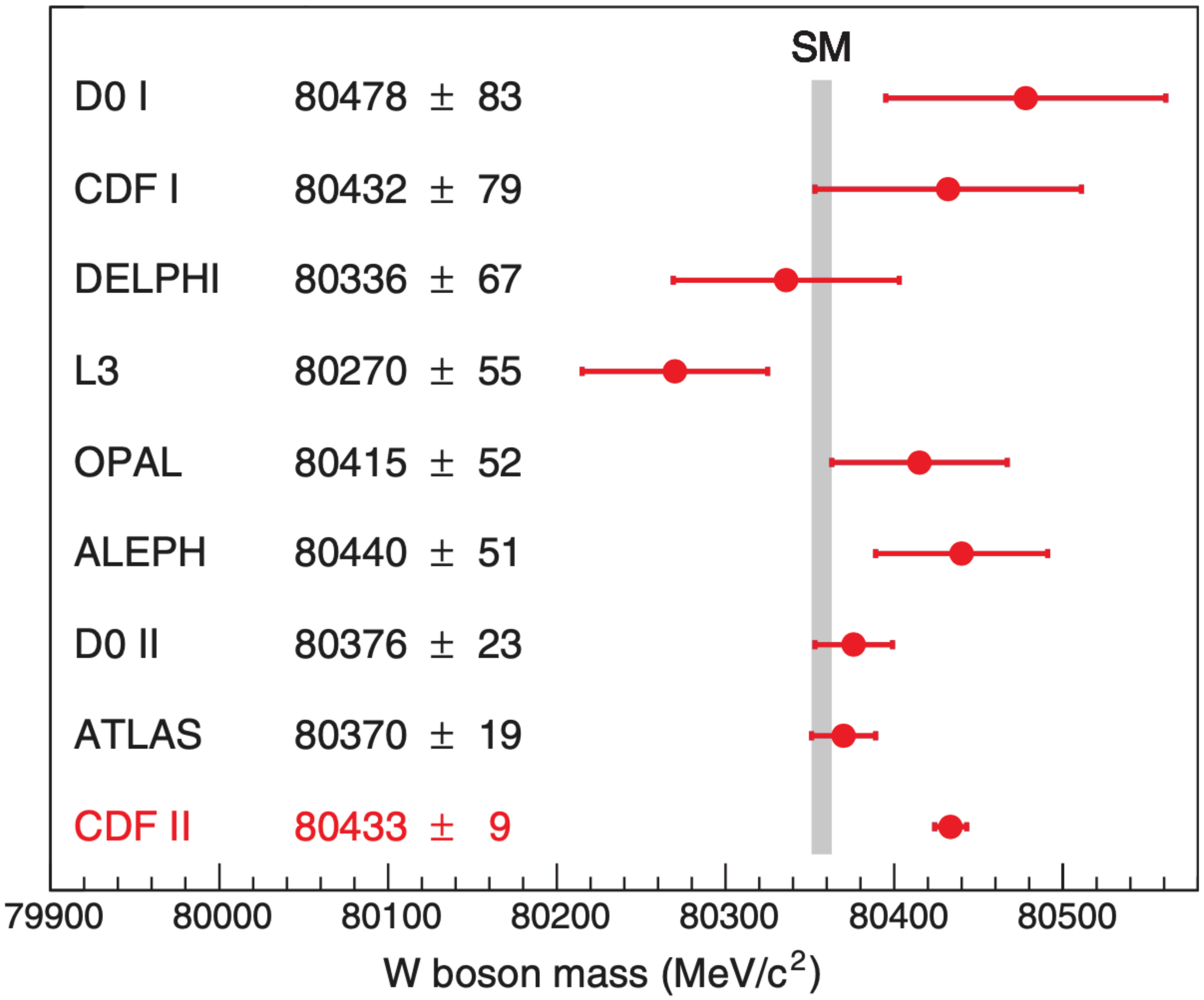
Physics beyond the Standard Model in light of the CDF W boson mass anomaly, KIAS, June 24, 2022

Outline

1. CDF W Mass anomaly
2. Stueckelberg models
3. Stueckelberg-Higgs portal
4. Experimental constraints

1 CDF W Mass Anomaly

[CDF Collaboration et al., Science 376, 170–176 (2022)]



CDF W-Mass Anomaly

W mass is heavier than the SM expectation by 7 σ

Gauge boson-Higgs interaction in the SM

$$\mathscr{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi)$$

$$D_\mu \Phi = \left[\partial_\mu - i \frac{g_Y}{2} B_\mu - i \frac{g_2}{2} \tau^a A_\mu^a \right] \Phi$$

$U(1)_Y$ gauge boson B_μ w/ gauge coupling g_Y

$SU(2)_L$ gauge bosons A_μ^a w/ gauge coupling g_2

Higgs doublet $\Phi = \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \Longrightarrow$ VEV $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

W boson mass in the SM

$$\mathscr{L}_{\text{mass}} = \frac{1}{2}\frac{v^2}{4}\left[g_2^2\left(A_\mu^1\right)^2 + g_2^2\left(A_\mu^2\right)^2 + \left(g_2 A_\mu^3 - g_Y B_\mu\right)^2 \right]$$

charged bosons

neutral bosons

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(A_\mu^1 \mp i A_\mu^2\right) \text{ w/ } M_W = \frac{1}{2} g_2 v$$

Neutral boson masses in the SM

$$\mathscr{L}_{\text{mass}} = \frac{1}{2} V^T M^2 V = \frac{1}{2}\frac{v^2}{4}(B, A^3)\begin{pmatrix} g_Y^2 & -g_Y g_2 \\ -g_Y g_2 & g_2^2 \end{pmatrix}\begin{pmatrix} B \\ A^3 \end{pmatrix}$$

$$\begin{pmatrix} Z_\mu \\ A_\mu^\gamma \end{pmatrix} = \begin{pmatrix} -\sin\theta_W & \cos\theta_W \\ \cos\theta_W & \sin\theta_W \end{pmatrix}\begin{pmatrix} B_\mu \\ A_\mu^3 \end{pmatrix} \longrightarrow M_Z = \frac{1}{2}\sqrt{g_2^2 + g_Y^2}\, v, \quad \longrightarrow M_\gamma = 0$$

$$\cos\theta_W = \frac{g_2}{\sqrt{g_2^2 + g_Y^2}}, \qquad \sin\theta_W = \frac{g_Y}{\sqrt{g_2^2 + g_Y^2}}$$

CDF W Mass Anomaly

$$M_W^{\mathrm{CDF}} = 80{,}433.5 \pm 6.4\,(\mathrm{stat}) \pm 6.9\,(\mathrm{syst})\,\mathrm{MeV}$$

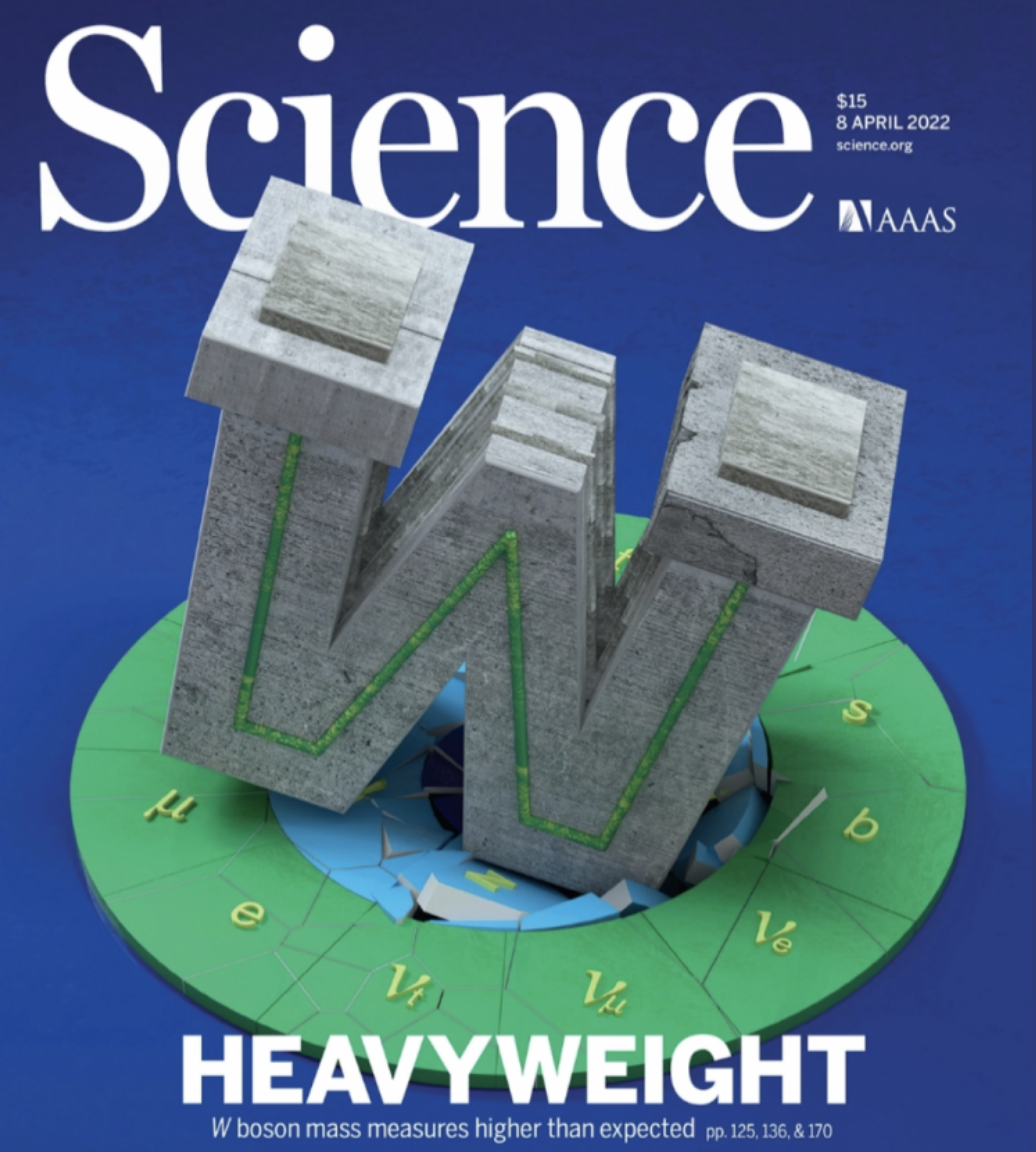
$$= 80{,}433.5 \pm 9.4\,\mathrm{MeV}$$

$$M_W^{\mathrm{SM}} = 80{,}357 \pm 6\,\mathrm{MeV}$$

$$\Delta M_W = M_W^{\mathrm{CDF}} - M_W^{\mathrm{SM}} = +\,76\,\mathrm{MeV}$$

W mass is heavier than the SM expectation by 7 σ

[CDF Collaboration et al., Science 376, 170–176 (2022)]



What are the implications to the SM?

Quantity	SM tree level		Measurement
M_W	$\frac{1}{2} g_2 v$		$M_W^{\text{CDF}} = 80{,}433.5 \pm 9.4\,\text{MeV}$ $\Delta M_W = +76\,\text{MeV}$
M_Z	$\frac{1}{2}\sqrt{g_2^2 + g_Y^2}\, v$	FIXED	$91.1876 \pm 0.0021\,\text{GeV}$
G_F	$\frac{g_2^2}{4\sqrt{2}M_W^2} = \frac{1}{\sqrt{2}\,v}$	FIXED	$1.1663787(6) \times 10^{-5}\,\text{GeV}^{-2}$
$\sin^2\theta_W$	$\frac{g_Y^2}{g_2^2 + g_Y^2} = 1 - \frac{M_W^2}{M_Z^2}$		Z pole asymmetries $\Delta(\sin^2\theta_W) = -0.00147$

Fits to 19 Z-pole observables

[Du, ZL, Nath, 2204.09024]

	PDG-2020	LEP		SM-CDF	
	$O^{\rm exp} \pm \delta O$	$O^{\rm th}$	χ	$O^{\rm th}$	χ
Γ_Z [GeV]	2.4955±0.0023	2.4960	-0.20	2.5000	-1.96
$\sigma_{\rm had}$ [nb]	41.481±0.033	41.470	0.34	41.465	0.50
R_e	20.804±0.05	20.752	1.05	20.778	0.53
R_μ	20.784±0.034	20.752	0.95	20.778	0.18
R_τ	20.764±0.045	20.799	-0.77	20.825	-1.35
R_b	0.21629±0.00066	0.21584	0.68	0.21578	0.77
R_c	0.1721±0.003	0.1711	0.33	0.1712	0.30
$A_{\rm FB}^{(0,e)}$	0.0145±0.0025	0.0163	-0.71	0.0190	-1.81
$A_{\rm FB}^{(0,\mu)}$	0.0169±0.0013	0.0163	0.48	0.0190	-1.64
$A_{\rm FB}^{(0,\tau)}$	0.0188±0.0017	0.0163	1.48	0.0190	-0.13
$A_{\rm FB}^{(0,b)}$	0.0996±0.0016	0.1033	-2.29	0.1118	-7.61
$A_{\rm FB}^{(0,c)}$	0.0707±0.0035	0.0738	-0.89	0.0804	-2.78
$A_{\rm FB}^{(0,s)}$	0.0976±0.0114	0.1034	-0.51	0.1119	-1.25
A_e	0.15138±0.00216	0.14733	1.88	0.15928	-3.66
A_μ	0.142±0.015	0.147	-0.36	0.159	-1.15
A_τ	0.136±0.015	0.147	-0.76	0.159	-1.55
A_b	0.923±0.02	0.935	-0.58	0.936	-0.63
A_c	0.67±0.027	0.67	0.07	0.67	-0.12
A_s	0.895±0.091	0.936	-0.45	0.937	-0.46
χ^2			17.3		97.8

LEP fit [hep-ex/0509008]

SM-CDF fit: same as LEP but w/ $\Delta(\sin^2\theta_W) = -0.00147$

$\Delta\chi^2 \simeq 98 - 17 = 81 \sim 9\sigma$

ballpark agreement w/ 7σ

2 Stueckelberg models

PRL **97,** 021801 (2006) PHYSICAL REVIEW LETTERS week ending 14 JULY 2006

Probing a Very Narrow Z' Boson with CDF and D0 Data

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The CDF and D0 data of nearly 475 pb^{-1} in the dilepton channel is used to probe a recent class of models, Stueckelberg extensions of the standard model (StSM), which predict a Z' boson whose mass is of topological origin with a very narrow decay width. A Drell-Yan analysis for dilepton production via this Z' shows that the current data put constraints on the parameter space of the StSM. With a total integrated luminosity of 8 fb^{-1}, the very narrow Z' can be discovered up to a mass of about 600 GeV. The StSM Z' will be very distinct since it can occur in the region where a Randall-Sundrum graviton is excluded.

Stueckelberg mass for U(1) gauge bosons

$$M^2_{\mathrm{St}} = \begin{pmatrix} M_1^2 & M_1M_2 & 0 \\ M_1M_2 & \frac{1}{4}v^2g_Y^2 + M_2^2 & -\frac{1}{4}v^2g_2g_Y \\ 0 & -\frac{1}{4}v^2g_2g_Y & \frac{1}{4}v^2g_2^2 \end{pmatrix},$$

smaller Z mass if $M_1 > M_Z$

[Feldman, ZL, Nath, PRL 97, 021801 (2006)]

extra dimensions. We begin by recalling that in the on-shell scheme the W boson mass including loop corrections is given by [13]

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W(1-\Delta r)}, \tag{4}$$

$$\sin^2\theta_W = (1 - M_W^2/M_Z^2)$$

$$M_W = 80.425 \pm 0.034 \ \text{GeV}$$

that $\delta \equiv \delta M_Z/M_Z|_{\text{SM}}$ is given by

$$\delta = \sqrt{\left(\frac{1-2\sin^2\theta_W}{\cos^3\theta_W}\frac{\delta M_W}{M_Z}\right)^2 + \frac{\tan^4\theta_W(\delta\Delta r)^2}{4(1-\Delta r)^2}}. \tag{5}$$

Gauge boson mass via the Stueckelberg mechanism

Make massive QED gauge invariant by adding axion **σ**

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{m^2}{2}A_\mu^2 \qquad \Longrightarrow \qquad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(mA_\mu + \partial_\mu \sigma)^2$$

invariant under gauge transformation

$$\delta A_\mu = \partial_\mu \lambda,\ \delta\sigma = -m\lambda$$

σ : longitudinal mode of the vector boson

[E.C.G. Stueckelberg, Helv. Phys. Acta 11, 225 (1938)]

Stueckelberg extensions of the SM (StSM)

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} - \frac{C_{\mu\nu}C^{\mu\nu}}{4} + g_X C_\mu J_X^\mu - \frac{1}{2}\left(\partial_\mu \sigma + M_1 C_\mu + M_2 B_\mu\right)^2$$

invariant under two U(1) gauge transformations

$$U(1)_X \qquad \delta_X C_\mu = \partial_\mu \lambda_X,\ \delta_X \sigma = -M_1 \lambda_X$$

$$U(1)_Y \qquad \delta_Y C_\mu = \partial_\mu \lambda_Y,\ \delta_Y \sigma = -M_2 \lambda_Y$$

[Kors & Nath, hep-ph/0402047 [hep-ph]]

Neutral gauge boson masses in StSM

$$\mathscr{L}_{\text{mass}} = \frac{1}{2} V^T M^2 V = \frac{1}{2} (C\, B\, A^3) \begin{pmatrix} M_1^2 & M_1^2 \epsilon & 0 \\ M_1^2 \epsilon & M_1^2 \epsilon^2 + \frac{v^2}{4} g_Y^2 & -\frac{v^2}{4} g_Y g_2 \\ 0 & -\frac{v^2}{4} g_Y g_2 & \frac{v^2}{4} g_2^2 \end{pmatrix} \begin{pmatrix} C \\ B \\ A^3 \end{pmatrix}$$

$$\epsilon = \frac{M_2}{M_1}$$

3 mass eigenstates: Z', Z, γ

Det = 0 ➡ massless eigenvalue (photon)

$M_1 > M_Z$ ➡ $M_Z(\epsilon) < M_Z(\epsilon = 0)$

Consequences of a ``lighter'' Z

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W(1-\Delta r)} = \frac{\pi\alpha}{\sqrt{2}G_F(1-\Delta r)}\frac{1}{1-M_W^2/M_Z^2}$$

a lighter Z mass ➡ a heavier W mass

However, in the parameter space to interpret the CDF W mass anomaly, the total χ^2 of the StSM fit of the 19 Z pole observables is not better than the SM-CDF fit.

3 Stueckelberg-Higgs portal

Stueckelberg-Higgs portal interaction in StSM

$$\Delta\mathscr{L} = -\frac{C_{\mu\nu}^2}{4} - \frac{1}{2}\left(M_1\bar{C}_\mu + M_2 B_\mu\right)^2 + J_X^\mu C_\mu + \left(i\frac{g_c}{2}\Phi^\dagger D^\mu \Phi \bar{C}_\mu + \mathrm{h.c.}\right) + \frac{g_c^2}{4}\Phi^\dagger\Phi\bar{C}_\mu^2$$

$$D_\mu\Phi = \left[\partial_\mu - i\frac{\bar{g}_Y}{2}B_\mu - i\frac{\bar{g}_2}{2}\tau^a A_\mu^a\right]\Phi \qquad \bar{C}_\mu = C_\mu + \frac{\partial_\mu\sigma}{M_1}$$

$\bar{g}_2$ and $\bar{g}_Y$ do not necessarily take the SM values

gauge invariance ➡ either $g_c = 0$ ⟵ StSM (not working)

or $M_2 = 0$ ⟵ Stueckelberg-Higgs portal

New mass matrix in the neutral gauge boson sector

$$\begin{array}{ccc} C_\mu & B_\mu & A^3_\mu \\ \downarrow & \downarrow & \downarrow \end{array}$$

$$M^2 = \begin{pmatrix} M_1^2 + \frac{v^2}{4} g_c^2 & M_1^2 \epsilon + \frac{v^2}{4} g_c \bar{g}_Y & -\frac{v^2}{4} g_c \bar{g}_2 \\ M_1^2 \epsilon + \frac{v^2}{4} g_c \bar{g}_Y & M_1^2 \epsilon^2 + \frac{v^2}{4} \bar{g}_Y^2 & -\frac{v^2}{4} \bar{g}_Y \bar{g}_2 \\ -\frac{v^2}{4} g_c \bar{g}_2 & -\frac{v^2}{4} \bar{g}_Y \bar{g}_2 & \frac{v^2}{4} \bar{g}_2^2 \end{pmatrix} \begin{array}{l} \leftarrow C_\mu \\ \leftarrow B_\mu \\ \leftarrow A^3_\mu \end{array}$$

$$\epsilon = \frac{M_2}{M_1} = 0$$

$$E_i = (Z', Z, A_\gamma) \qquad E_i = \mathcal{O}_{ji} V_j \qquad \mathcal{O}^T M^2 \mathcal{O} = \mathrm{diag}(M_{Z'}^2, M_Z^2, 0)$$

Neutral gauge bosons souplings to fermions

$$\mathscr{L}_{NC} = \bar{f}\gamma^{\mu}\left[(v_f - \gamma_5 a_f)Z_{\mu} + (v'_f - \gamma_5 a'_f)Z'_{\mu}\right]f + e\bar{f}\gamma^{\mu}Q_f A_{\mu} f,$$

$$a_f = \sqrt{\rho_f}(\bar{g}_Y \mathcal{O}_{22} - \bar{g}_2 \mathcal{O}_{32})T_f^3/2$$

$$v_f = a_f - \sqrt{\rho_f}\kappa_f \bar{g}_Y \mathcal{O}_{22} Q_f$$

ρ_f and κ_f contain radiative corrections

[hep-ex/0509008]

[hep-ph/0407097]

$$a'_f = (\bar{g}_Y \mathcal{O}_{21} - \bar{g}_2 \mathcal{O}_{31})T_f^3/2$$

$$v'_f = a'_f - \bar{g}_Y \mathcal{O}_{21} Q_f$$

Take into account both SM corrections & NP corrections

W mass in the Stueckelberg-Higgs portal model

The W mass is $M_W = \frac{\bar{g}_2 v}{2}$

To explain the larger W mass from CDF we increase the gauge coupling such that

$$\bar{g}_2 = g_2\left(1 + \frac{\Delta M_W}{M_W}\right) \qquad \Delta M_W = +76\,\mathrm{MeV}$$

$\bar{g}_2$ is larger than the canonical SM value g_2 by $\sim 0.1\,\%$

Free parameters in the Stueckelberg-Higgs portal model

We have 3 free parameters

M_1 : Z' mass

g_c : dimensionless Stueckelberg-Higgs coupling

$\bar{g}_Y$: hypercharge gauge coupling

Z mass in the Stueckelberg-Higgs portal model

$$\Delta M_Z^{\text{th}} \simeq -\frac{1}{2} M_Z \frac{M_W^2}{M_1^2 - M_Z^2} \left(\frac{g_c}{g_2} \right)^2$$

$$\Delta M_Z^{\text{exp}} = \frac{\Delta M_W}{\cos \theta_W}$$

$$\Delta M_W = +76\,\text{MeV}$$

$$\Delta M_Z^{\text{exp}} + \Delta M_Z^{\text{th}} \simeq 0 \quad \Rightarrow \quad M_1 > M_Z$$

4 Experimental constraints

Partial decay width of the Z boson

$$\Gamma_{ff} = N_f^c\, \mathcal{R}_f\, \frac{M_Z}{12\pi}\sqrt{1-4\mu_f^2} \times \left[|v_f|^2(1+2\mu_f^2) + |a_f|^2(1-4\mu_f^2) \right]$$

$N_f^c = (1,3)$

$\mu_f = m_f/M_Z$

$$\mathcal{R}_f = \left(1+\delta_f^{\mathrm{QED}}\right)\left(1+\frac{N_f^c-1}{2}\delta_f^{\mathrm{QCD}}\right)$$

$$\delta_f^{\mathrm{QED}} = \frac{3\alpha}{4\pi}Q_f^2$$

$$\delta_f^{\mathrm{QCD}} = \frac{\alpha_s}{\pi} + 1.409\left[\frac{\alpha_s}{\pi}\right]^2 - 12.77\left[\frac{\alpha_s}{\pi}\right]^3 - Q_f^2\frac{\alpha\alpha_s}{4\pi^2}$$

NP & SM radiative corrections

Various Z pole observables

$$\Gamma_Z = \sum_f \Gamma_{ff}$$

$$\sigma_{\text{had}} \equiv \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}}{\Gamma_Z}\sum_{q\neq t}\frac{\Gamma_{qq}}{\Gamma_Z}, \quad R_\ell \equiv \frac{\Gamma_{\text{had}}}{\Gamma_{\ell\ell}}, \quad R_q \equiv \frac{\Gamma_{qq}}{\Gamma_{\text{had}}}$$

$$A_f = \frac{2v_f a_f}{v_f^2 + a_f^2}, \quad A_{\text{FB}}^{(0,f)} = \frac{3}{4}A_e A_f$$

Fits to 19 Z-pole observables

[Du, ZL, Nath, 2204.09024]

		LEP		SM-CDF		St	
	$O^{\rm exp} \pm \delta O$	$O^{\rm th}$	χ	$O^{\rm th}$	χ	$O^{\rm th}$	χ
Γ_Z [GeV]	2.4955±0.0023	2.4960	-0.20	2.5000	-1.96	2.4999	-1.92
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$A_{\rm FB}^{(0,c)}$	0.0707±0.0035	0.0738	-0.89	0.0804	-2.78	0.0737	-0.86
$A_{\rm FB}^{(0,s)}$	0.0976±0.0114	0.1034	-0.51	0.1119	-1.25	0.1033	-0.50
A_e	0.15138±0.00216	0.14733	1.88	0.15928	-3.66	0.14716	1.95
A_μ	0.142±0.015	0.147	-0.36	0.159	-1.15	0.147	-0.34
A_τ	0.136±0.015	0.147	-0.76	0.159	-1.55	0.147	-0.74
A_b	0.923±0.02	0.935	-0.58	0.936	-0.63	0.935	-0.58
A_c	0.67±0.027	0.67	0.07	0.67	-0.12	0.67	0.08
A_s	0.895±0.091	0.936	-0.45	0.937	-0.46	0.936	-0.45
χ^2			17.3		97.8		20.9

LEP Fit [hep-ex/0509008]

SM-CDF Fit

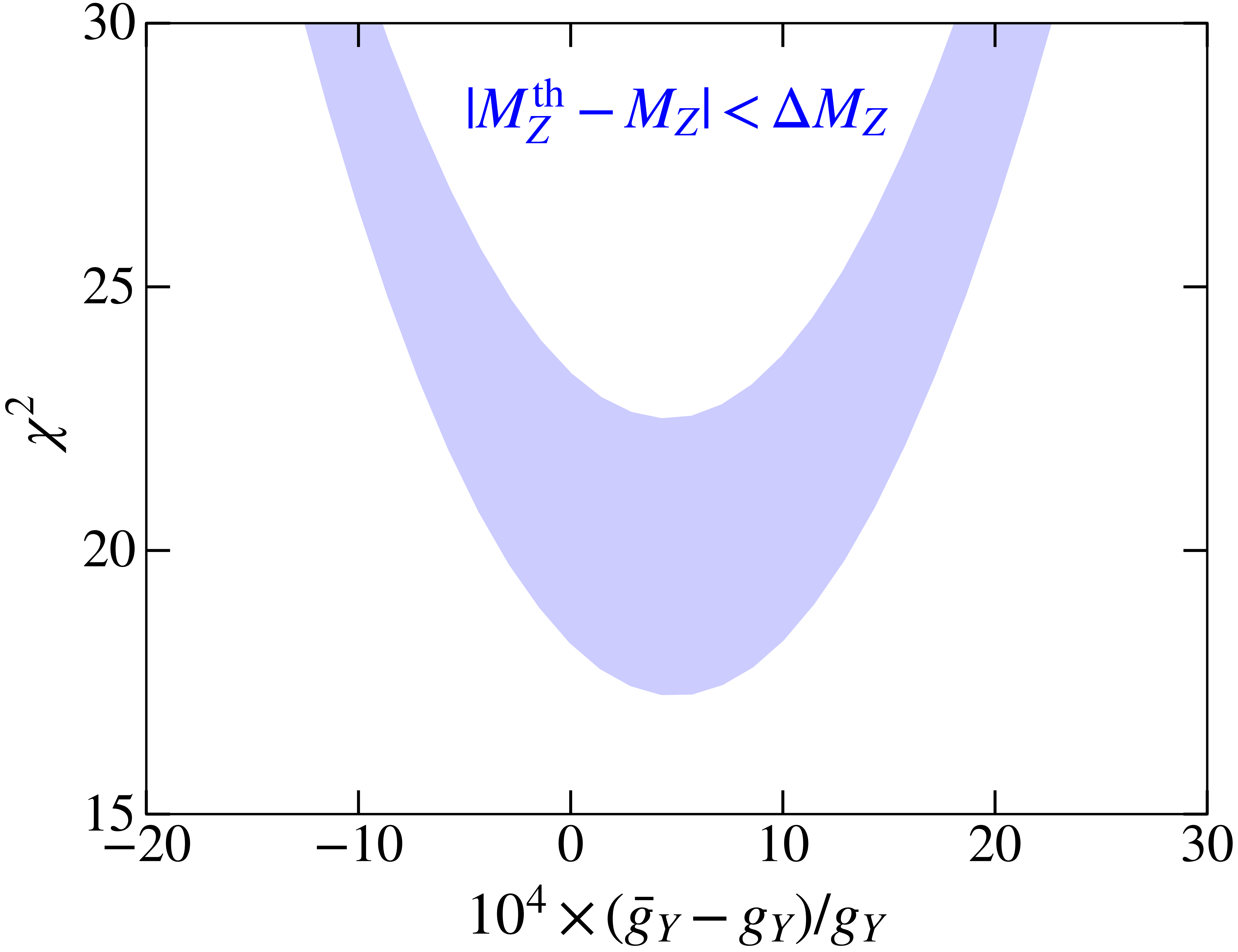
St Fit

$M_1 = 725$ GeV

$g_c = 0.243$

$\bar{g}_Y = g_Y(1 + 0.047\%)$

The χ^2 of 19 Z-pole fits vs. $\bar{g}_Y$



[Du, ZL, Nath, 2204.09024]

MC scan in the space spanned by $(M_1, g_c, \bar{g}_Y)$

Z mass w/ 2 MeV error near the central value

best χ^2:
$\bar{g}_Y \sim 0.047\,\%$ larger than g_Y

(Axial) Vector couplings and asymmetries

SM

$$a_f = \sqrt{\rho_f} T_f^3,$$

$$v_f = a_f - 2\sqrt{\rho_f} \kappa_f \sin^2\theta_W Q_f$$

$$A_f = \frac{2 v_f a_f}{v_f^2 + a_f^2}, \quad A_{\rm FB}^{(0,f)} = \frac{3}{4} A_e A_f$$

$$\Rightarrow \frac{v_f}{a_f}$$

St

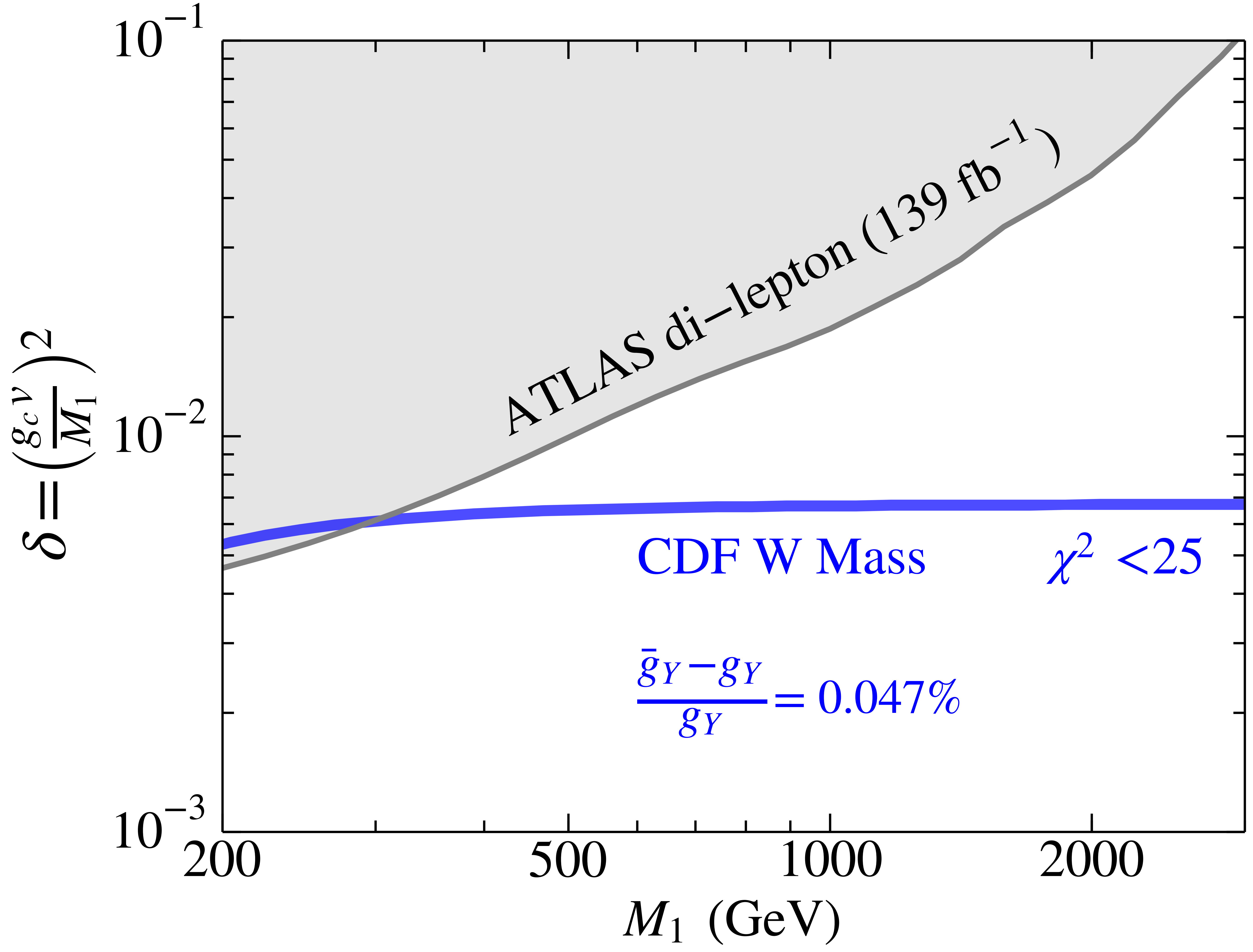
$$a_f = \sqrt{\rho_f} (\bar{g}_Y \mathcal{O}_{22} - \bar{g}_2 \mathcal{O}_{32}) T_f^3 / 2$$

$$v_f = a_f - \sqrt{\rho_f} \kappa_f \bar{g}_Y \mathcal{O}_{22} Q_f$$

$$\frac{\mathcal{O}_{22}}{\mathcal{O}_{32}} = -\frac{\bar{g}_Y}{\bar{g}_2} \equiv -\tan\theta$$

[Du, ZL, Nath, 2204.09024]

Mixing parameter δ vs. M_1



Fix $\bar{g}_Y$

$$\frac{1}{8}\left(\frac{g_c v}{M_1}\right)^2 \simeq \frac{\Delta M_W}{M_W}$$

$M_1 \lesssim 300$ GeV excluded by ATLAS data

Summary

Recently, the W mass measured by CDF is heavier than the SM expectation by 7 σ, which imposes a great challenge to the electroweak sector

Although a heavy boson that mixes with the hypercharge gauge boson (via the mass mixing terms) can explain the W mass anomaly, it leads to a poor fit to the Z-pole observables

A Stueckelberg-Higgs portal interaction can both explain the W mass anomaly and provide an excellent fit to the various Z-pole observables, which can also verified by the coming LHC data at Run 3