

A Case Study of COVID Mass Gain Phenomenon: W Bosons

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Based on : 2204.05283

With : Cari Cesarotti, Katherine Fraser, Samuel Homiller, Aditya Parikh

Talk Presented @ IPM - School of Particles and Accelerators

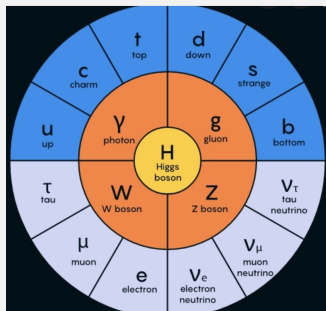
July 27, 2022

Outline

- **Intro.**
- Electroweak Precision Tests
- CDF II Measurement
- Implications for BSM

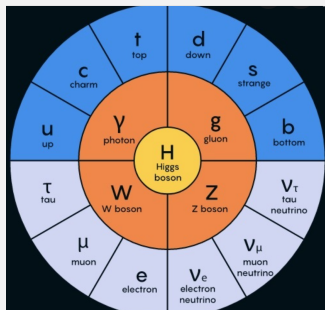
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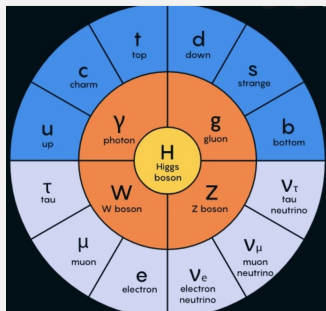
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- Beyond SM (BSM) physics can give rise to detectable signals in electroweak precision tests (EWPTs).



Experimental Efforts

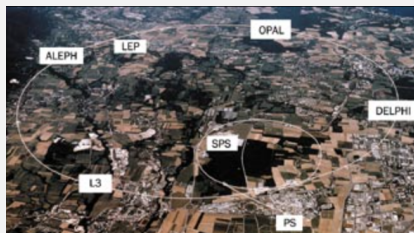
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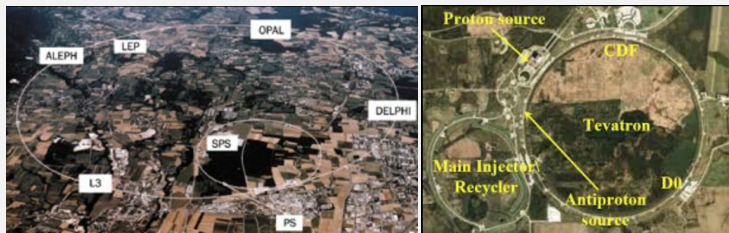
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- Goodness-of-fit of SM is quantified by a χ^2 fit. We use oblique parameters to parametrize deviations from SM.

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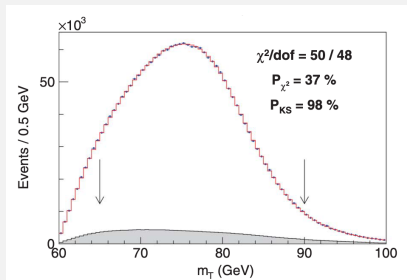
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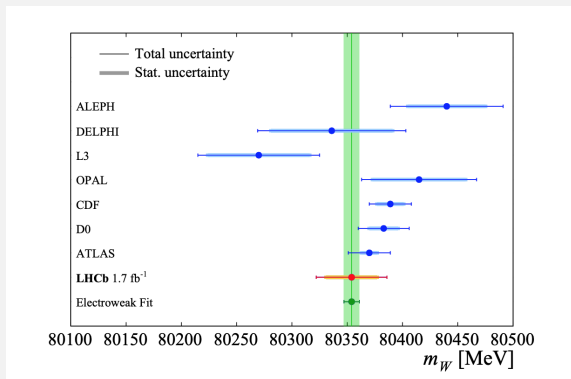
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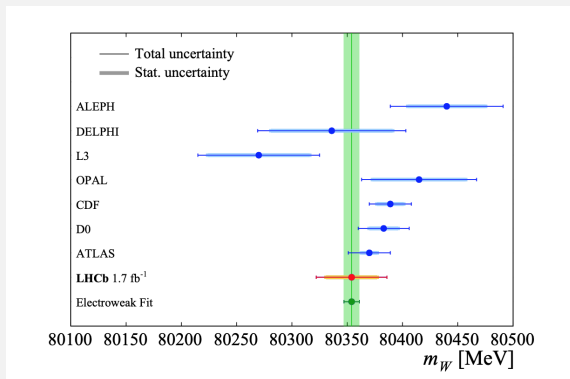
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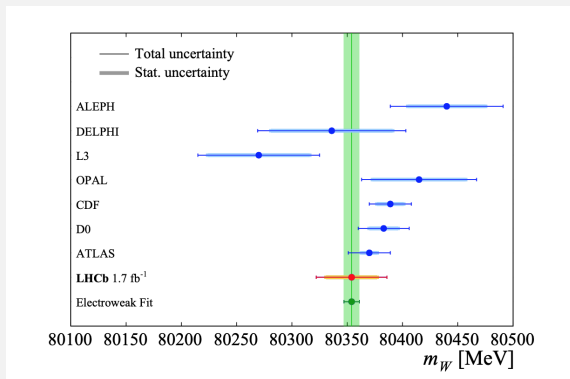


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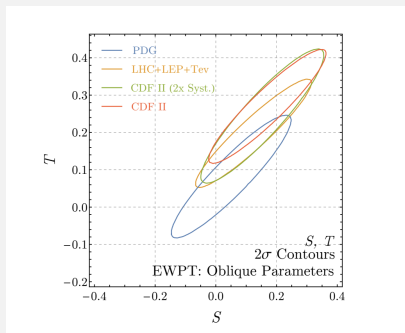
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- **What is the implication of the measurement for BSM?**

Executive Summary

- IF

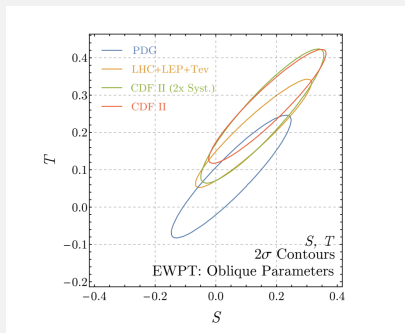
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- A promising BSM explanation: **a scalar triplet with $Y = 0$ and a small vacuum expectation value (vev).**



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- (We use Gfitter set of observables [[1803.01853](#)], which partially overlaps with PDGs.)

EWPTs Observables

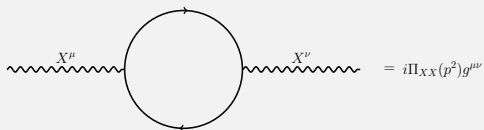
Observable	Measured Value
M_Z [GeV]	91.1876 ± 0.0021
M_h [GeV]	125.25 ± 0.17
M_t [GeV]	172.89 ± 0.59
$\alpha_s(M_Z^2)$	0.1181 ± 0.0011
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	0.02766 ± 0.00007
Γ_Z [GeV]	2.4955 ± 0.0023
Γ_W [GeV]	2.085 ± 0.042
σ_{had}^0 [nb]	41.481 ± 0.033
R_ℓ^0	20.767 ± 0.025
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010
A_ℓ	0.1499 ± 0.0018
$\sin^2 \theta_{\text{eff}}^\ell(Q_{\text{FB}})$	0.2324 ± 0.0012
$\sin^2 \theta_{\text{eff}}^\ell(\text{TeV.})$	0.23148 ± 0.00033
A_b	0.923 ± 0.020
A_c	0.670 ± 0.027
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035
$R^{0,b}$	0.21629 ± 0.00066
$R^{0,c}$	0.1721 ± 0.0030

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The diagram shows a circular loop with two arrows indicating a clockwise flow. Two wavy lines, representing gauge bosons, enter and exit the loop. The left wavy line is labeled X^μ and the right wavy line is labeled X^ν . To the right of the diagram is the mathematical expression $= i\Pi_{XX}(p^2)g^{\mu\nu}$.

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$$S \equiv \frac{4c_W^2 s_W^2}{\alpha} \left[\Pi'_{ZZ}(0) - \frac{c_W^2 - s_W^2}{c_W s_W} \Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0) \right],$$

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$$T \equiv \frac{1}{\alpha} \left[\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2} \right].$$

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- Both are zero in SM. Non-zero S & T affects the electroweak observables.

Oblique Parameters

- In SMEFT:

$$\mathcal{L}_{\text{oblique}} = S \left(\frac{\alpha}{s_W c_W v^2} \right) H^\dagger W_a^{\mu\nu} \sigma^a H B_{\mu\nu} - T \left(\frac{2\alpha}{v^2} \right) |H^\dagger D_\mu H|^2.$$

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$$M_W = M_{W,\text{SM}} \left(1 - \frac{\alpha(M_Z^2)}{4(c_W^2 - s_W^2)} (S - 2c_W^2 T) + \frac{\alpha(M_Z^2)}{8s_W^2} U \right),$$

$$\Gamma_W = \Gamma_{W,\text{SM}} \left(1 - \frac{3\alpha(M_Z^2)}{4(c_W^2 - s_W^2)} (S - 2c_W^2 T) + \frac{3\alpha(M_Z^2)}{8s_W^2} U \right).$$

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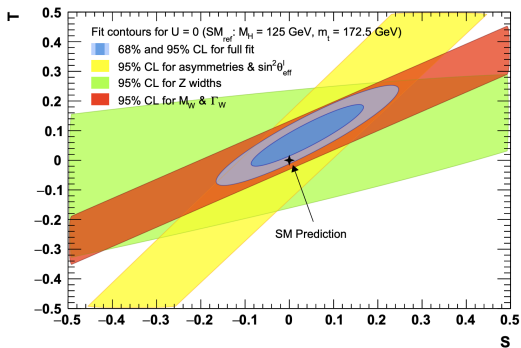
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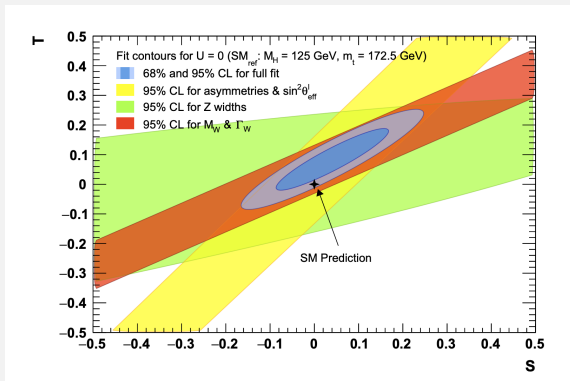
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- On the $S - T$ plane, χ^2 has a chi-square distribution with 2 dofs. We use that to find 2σ ellipses.

$S - T$ Plane

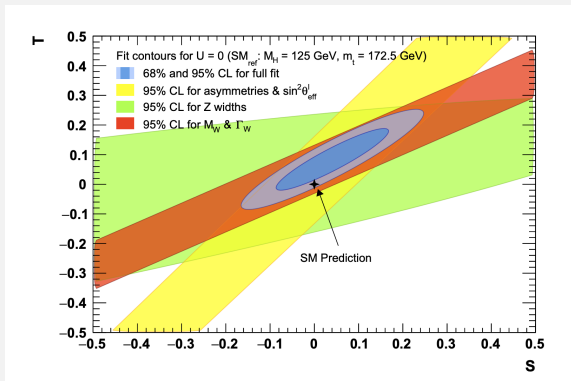


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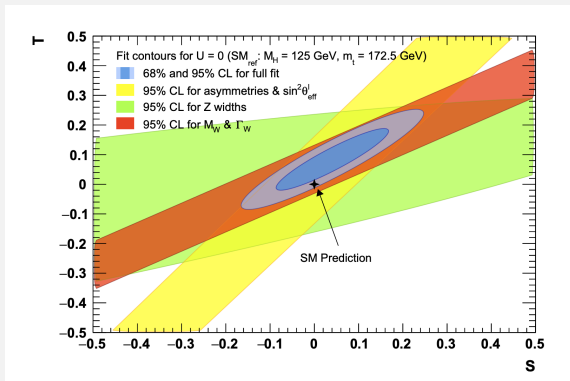
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- Latest measurement was CDF II M_W . We want to see how that affects this ellipse.

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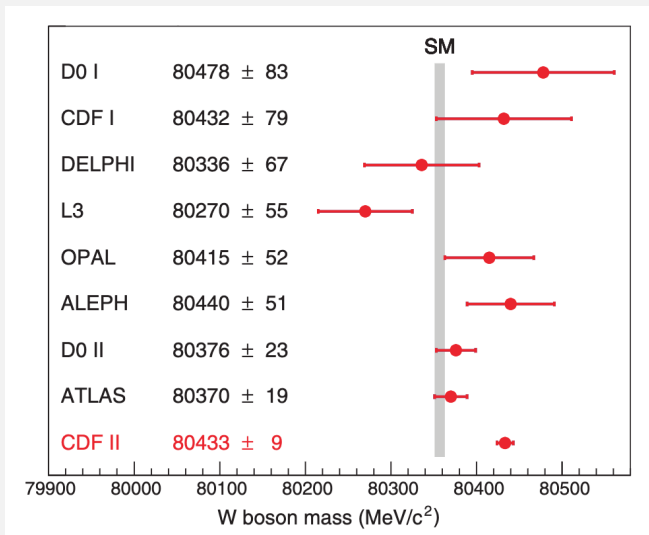
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Distribution	W boson mass (MeV)	χ^2/dof
$m_T(e, \nu)$	$80,429.1 \pm 10.3_{\text{stat}} \pm 8.5_{\text{syst}}$	39/48
$p_T^\ell(e)$	$80,411.4 \pm 10.7_{\text{stat}} \pm 11.8_{\text{syst}}$	83/62
$p_T^\nu(e)$	$80,426.3 \pm 14.5_{\text{stat}} \pm 11.7_{\text{syst}}$	69/62
$m_T(\mu, \nu)$	$80,446.1 \pm 9.2_{\text{stat}} \pm 7.3_{\text{syst}}$	50/48
$p_T^\ell(\mu)$	$80,428.2 \pm 9.6_{\text{stat}} \pm 10.3_{\text{syst}}$	82/62
$p_T^\nu(\mu)$	$80,428.9 \pm 13.1_{\text{stat}} \pm 10.9_{\text{syst}}$	63/62
Combination	$80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}}$	7.4/5

M_W at CDF II



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$$\Gamma_W = 2.0895 \pm 0.0006 \text{ GeV} \quad \text{vs.} \quad \Gamma_W = 2.046 \pm 0.049 \text{ GeV}$$

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- They conclude at most 10 MeV shift in M_W central value.

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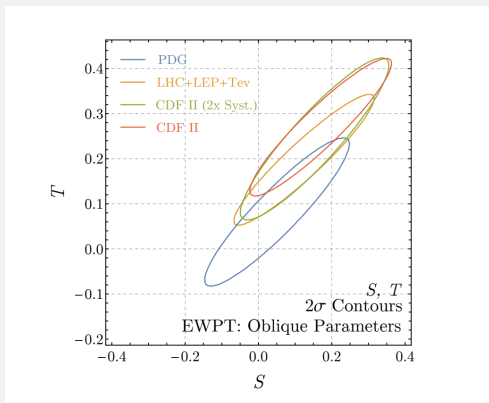
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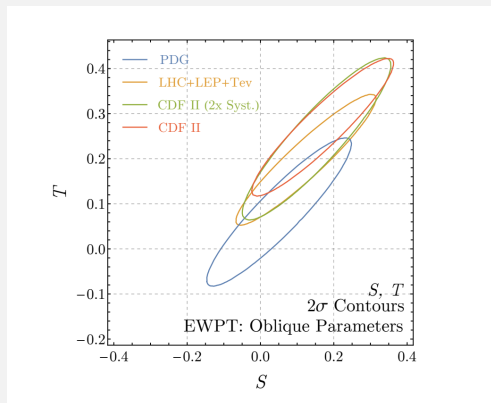
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- Experimental results combined assuming zero correlations. We checked that other correlation values did not change the final deductions.

Oblique Lessons from CDF II

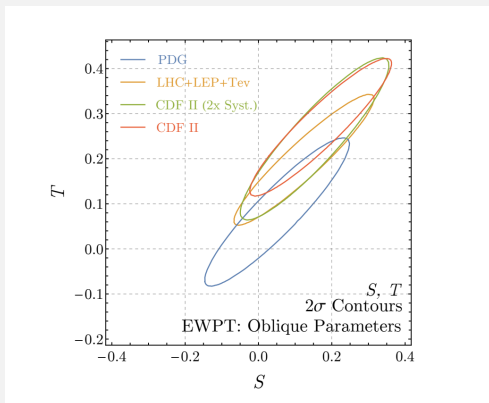


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- Need positive T . What models can give us that?

Outline

- Intro.
- Electroweak Precision Tests
- CDF II Measurement
- Implications for BSM

BSM Explanations

- Many proposals put forward: 2HDM, dark photon, LQ, new fermions, SU(2) triplet, shifting $\Delta\alpha_{\text{had}}$ (related to $g-2$).

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- We focus on the tree level correction. At loop level further corrections appear.

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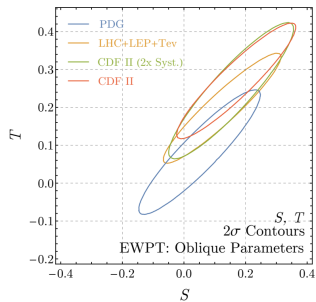
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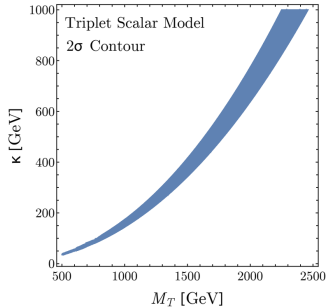
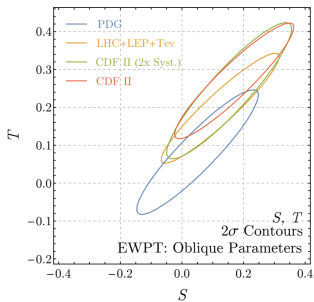
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- The scalar component of the new $SU(2)$ adjoint superfield is a *swino*.

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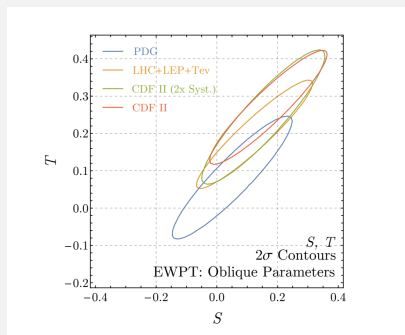
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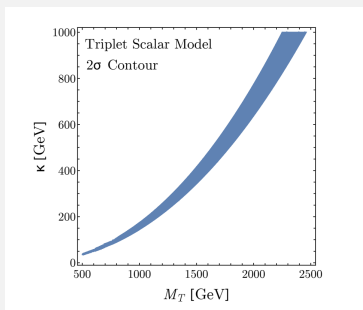


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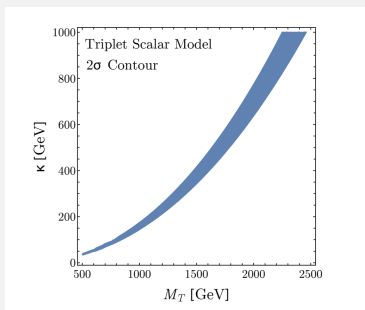
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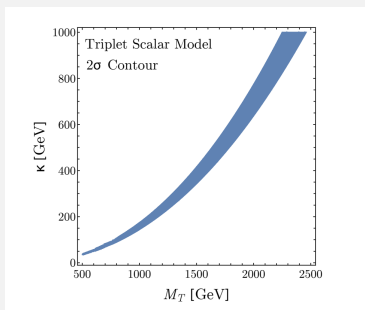
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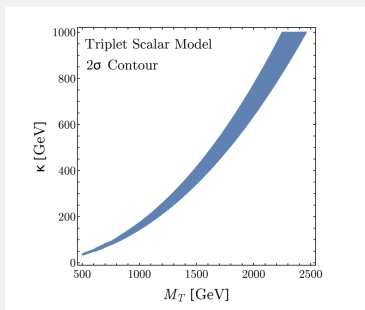
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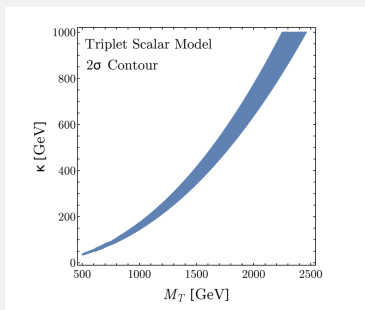
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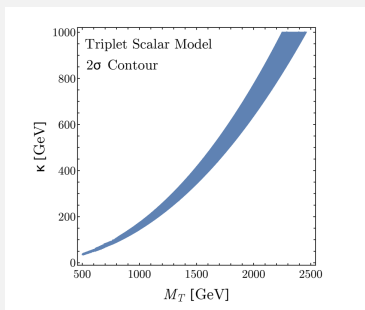
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THANK YOU!

Back up

- When Things are Oblique
- Oblique Contributions
- CDF II Distributions
- CDF II Uncertainties
- RESBOS vs. RESBOS2
- Oblique Parameter U
- Other BSM Models
- More on Swino
- Singlet-Doublet Fermions

When Oblique Parameters Are Useful

See [[hep-ph/9306267](https://arxiv.org/abs/hep-ph/9306267)].

- (1): The electroweak gauge group must be $SU_L(2) \times U_Y(1)$, with no new electroweak gauge bosons apart from the photon, the W^\pm and the Z .
- (2): The couplings of the new physics to light fermions are suppressed compared to its couplings to the gauge bosons.
- (3): The intrinsic scale, M , of the new physics is large in comparison with M_W and M_Z .

$$\alpha V = \delta\Pi'_{ZZ}(M_Z^2) - \left[\frac{\delta\Pi_{ZZ}(M_Z^2) - \delta\Pi_{ZZ}(0)}{M_Z^2} \right],$$

$$\alpha W = \delta\Pi'_{WW}(M_W^2) - \left[\frac{\delta\Pi_{WW}(M_W^2) - \delta\Pi_{WW}(0)}{M_W^2} \right]$$

$$\alpha X = -s_w c_w \left[\frac{\delta\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - \delta\Pi'_{Z\gamma}(0) \right].$$

Oblique Contributions

See [\[1306.4644\]](#).

$$M_W = M_{W,\text{SM}} \left[1 - \frac{\alpha(M_Z^2)}{4(c_W^2 - s_W^2)} \left(S - 2c_W^2 T - \frac{c_W^2 - s_W^2}{2s_W^2} U \right) - \frac{s_W^2}{2(c_W^2 - s_W^2)} \Delta G \right],$$

$$\Gamma_W = \Gamma_{W,\text{SM}} \left[1 - \frac{3\alpha(M_Z^2)}{4(c_W^2 - s_W^2)} \left(S - 2c_W^2 T - \frac{c_W^2 - s_W^2}{2s_W^2} U \right) - \frac{1 + c_W^2}{2(c_W^2 - s_W^2)} \Delta G \right],$$

$$\delta g_V^f = \frac{g_V^f}{2} [\alpha(M_Z^2) T - \Delta G] + \frac{(g_V^f - g_A^f) [\alpha(M_Z^2) (S - 4c_W^2 s_W^2 T) + 4c_W^2 s_W^2 \Delta G]}{4s_W^2 (c_W^2 - s_W^2)},$$

$$\delta g_A^f = \frac{g_A^f}{2} [\alpha(M_Z^2) T - \Delta G],$$

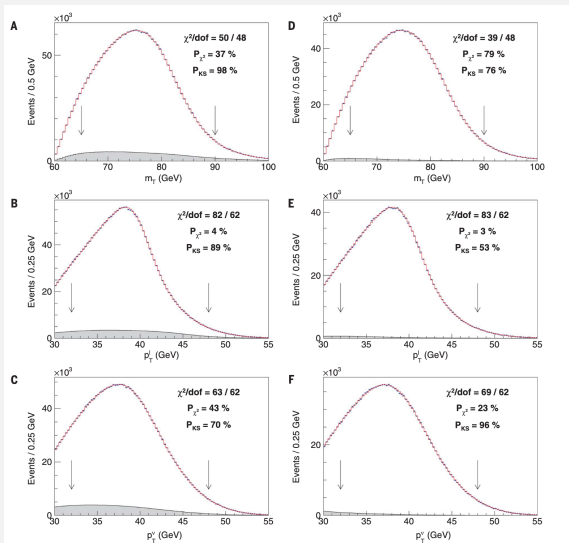
$$G_f \equiv (g_V^f)^2 + (g_A^f)^2, \quad \delta G_f \equiv 2(g_V^f \delta g_V^f + g_A^f \delta g_A^f),$$

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See [\[1306.4644\]](#).

$$\begin{aligned}
 \sin^2 \theta_{\text{eff}}^{\text{lept}} &= \sin^2 \theta_{\text{eff,SM}}^{\text{lept}} - \frac{g_A^e \delta g_V^e - g_V^e \delta g_A^e}{4(g_A^e)^2}, \\
 \mathcal{A}_f &= \mathcal{A}_{f,\text{SM}} - \frac{2[(g_V^f)^2 - (g_A^f)^2]}{G_f^2} (g_A^f \delta g_V^f - g_V^f \delta g_A^f), \\
 A_{\text{FB}}^{0,f} &= A_{\text{FB,SM}}^{0,f} - \left[\frac{3g_V^f g_A^f [(g_V^e)^2 - (g_A^e)^2]}{G_f G_e^2} (g_A^e \delta g_V^e - g_V^e \delta g_A^e) + (e \leftrightarrow f) \right], \\
 \Gamma_Z &= \Gamma_{Z,\text{SM}} + \frac{\alpha(M_Z^2)M_Z}{12s_W^2 c_W^2} \sum_f N_c^f \delta G_f, \\
 \sigma_h^0 &= \sigma_{h,\text{SM}}^0 + \frac{12\pi G_e (\sum_q N_c^q G_q)}{M_Z^2 (\sum_f N_c^f G_f)^2} \left(\frac{\delta G_e}{G_e} + \frac{\sum_q \delta G_q}{\sum_q G_q} - \frac{2 \sum_f N_c^f \delta G_f}{\sum_f N_c^f G_f} \right), \\
 R_\ell^0 &= R_{\ell,\text{SM}}^0 + \frac{\sum_q N_c^q \delta G_q}{G_\ell} - \frac{(\sum_q N_c^q G_q) \delta G_\ell}{G_\ell^2}, \\
 R_c^0 &= R_{c,\text{SM}}^0 + \frac{\delta G_c}{\sum_q G_q} - \frac{G_c \sum_q \delta G_q}{(\sum_q G_q)^2}, \\
 R_b^0 &= R_{b,\text{SM}}^0 + \frac{\delta G_b}{\sum_q G_q} - \frac{G_b \sum_q \delta G_q}{(\sum_q G_q)^2},
 \end{aligned}$$

CDF II Distributions



CDF II Uncertainties

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

RESBOS vs. RESBOS2

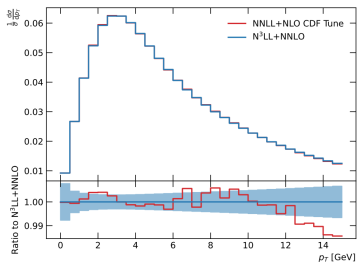


FIG. 2. Comparison of the generated pseudodata for the W transverse momentum for the state-of-the-art RESBOS2 calculation at N³LL+NNLO (blue) accuracy compared to the NNLL+NLO (red) prediction tuned to the Z transverse momentum distribution. The blue band represents the statistical uncertainty of the CDF result.

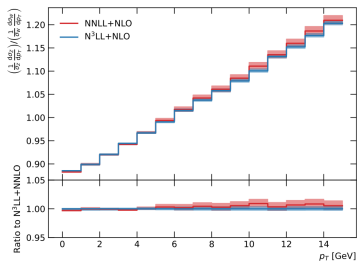


FIG. 3. The ratio for the normalized Z transverse momentum to the normalized W transverse momentum in the region used by the CDF experiment. The NNLL+NLO (red) prediction and the N³LL+NNLO (blue) prediction are consistent with each other over this region. The scale uncertainty is treated in a fully correlated manner.

RESBOS vs. RESBOS2

Observable	Mass Shift [MeV]	
	RESBOS2	+Detector Effect+FSR
m_T	1.5 ± 0.5	$0.2 \pm 1.8 \pm 1.0$
$p_T(\ell)$	3.1 ± 2.1	$4.3 \pm 2.7 \pm 1.3$
$p_T(\nu)$	4.5 ± 2.1	$3.0 \pm 3.4 \pm 2.2$

TABLE II. Summary of the shift in M_W due to higher order corrections. For reference, the CDF result was $80,433 \pm 9$ MeV [2] and the SM predicted value is $80,359.1 \pm 5.2$ MeV [1]. The second column shows the shift in the mass neglecting detector effects and final state radiation (FSR), while the third column includes an estimate for detector effects and FSR in the mass shift. The first uncertainty is the statistical uncertainty induced in the mass extraction due to the number of RESBOS events generated for the pseudoexperiments and the mass templates. The second uncertainty is the detector effect uncertainty calculated by using 100 different smearings of the data to extract the W mass. Additional details on the smearing can be found in Appendix C.

Oblique Parameter U

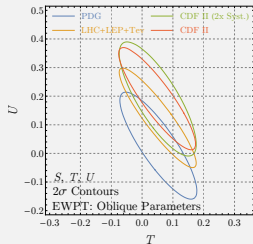
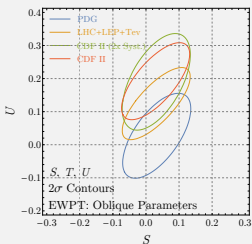
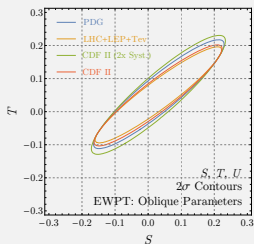
- It is a dim. 8 operator effect. Suppressed in perturbative models.
- Only affects M_W and Γ_W .

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Oblique Parameter U

- None-zero U can explain the anomaly alone.
- Not clear what BSM model can give rise to it.

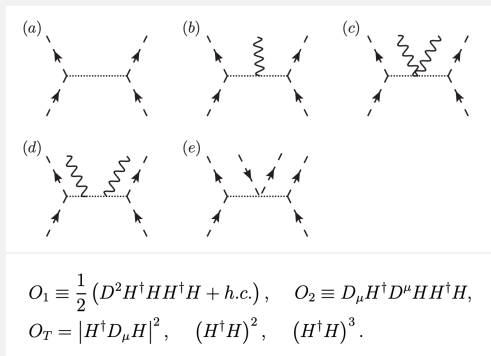


Other BSM Explanations:

- Dark Photon: $T < 0$. Wont work.
- 2HDM: $T \sim \sin^2(\alpha - \beta)$ - a dim. 8 correction.
- $\Delta\alpha_{\text{had}}$: Worsens the $(g - 2)_\mu$ anomaly.
- Leptoquarks: work at loop level; light colored particles.
- New fermions: constrained.

More on Swino

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More on Swino

$$S = \frac{4v^2 \sin \theta_w \cos \theta_w}{\alpha} a_S(\mu = v) + \frac{1}{6\pi} \ln \frac{M_h}{M_{h,ref}},$$

$$T = -\frac{v^2}{2\alpha} a_T(\mu = v) - \frac{3}{8\pi \cos^2 \theta_W} \ln \frac{M_h}{M_{h,ref}},$$

$$a_T^0(v) = \frac{\kappa^2}{M^4} \left[-2 + \frac{1}{(4\pi)^2} \left(-\frac{3}{2}\lambda + 16\eta - \frac{37}{4}g_2^2 + 5\frac{\kappa^2}{M^2} \right) \right. \\ \left. - 2\frac{1}{(4\pi)^2} \left(3\lambda - 3g_1^2 + \frac{9}{2}g_2^2 + 24y_B^2 + 24y_T^2 \right) \ln \left(\frac{v}{M} \right) \right],$$

$$a_S^0(v) = \frac{1}{(4\pi)^2} \frac{g_1 g_2}{M^2} \left[-\frac{1}{120}g_2^2 - \frac{5}{24}\frac{\kappa^2}{M^2} - \frac{1}{6}\frac{\kappa^2}{M^2} \ln \left(\frac{v}{M} \right) \right],$$

Singlet-Doublet Fermions

