M_W at hadron colliders in light of the CDF measurement: Theoretical considerations

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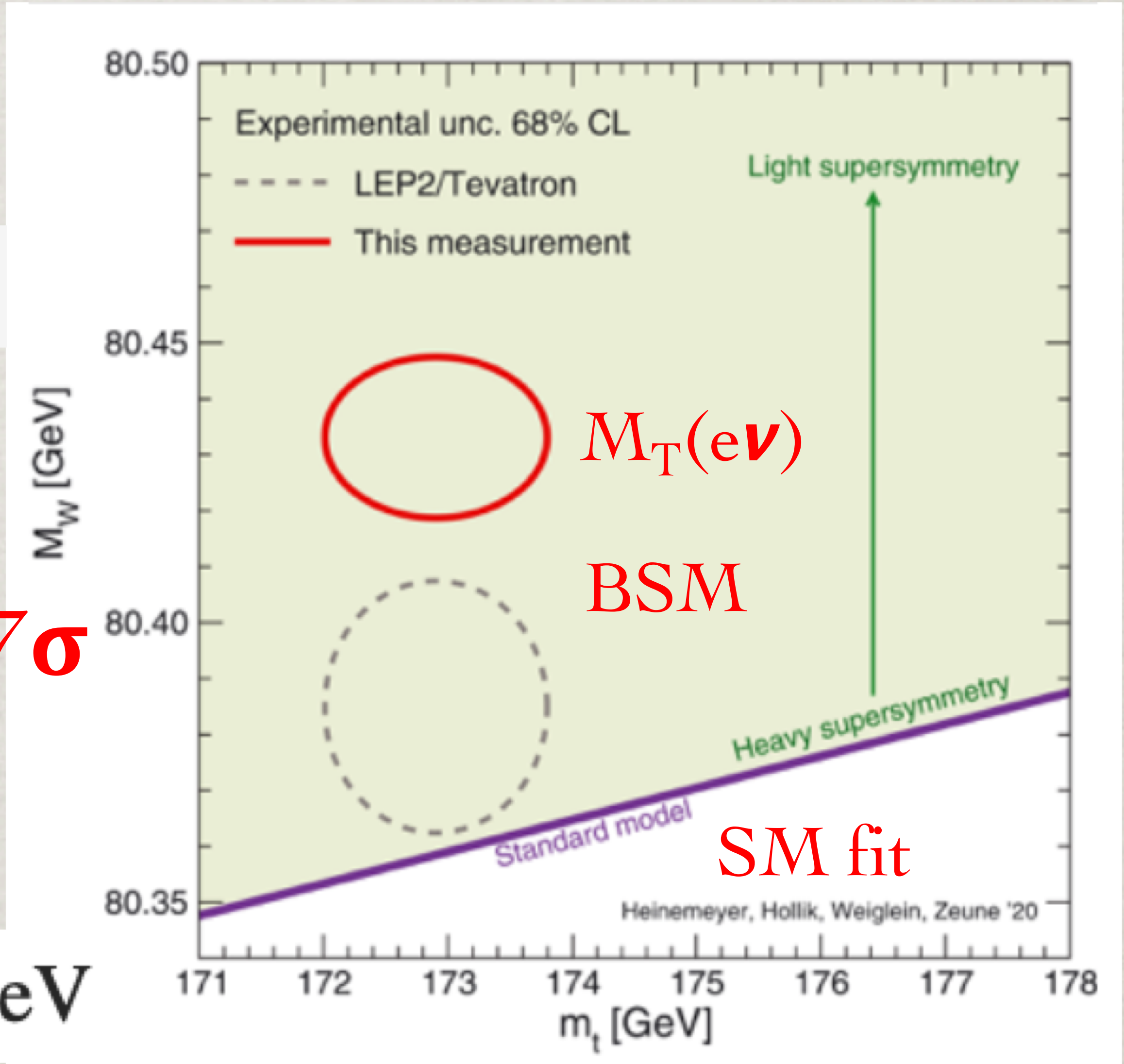
A. EW global fit
B. $M_T(e\nu)$ variable
C. BSM Physics

CDF new Measurement very exciting!

$$M_W = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}}$$
$$= 80,433.5 \pm 9.4 \text{ MeV}/c^2,$$

7σ



SM global fit:

$$M_W = 80,357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}} \text{ MeV}$$

Today, I will only make theoretical remarks.

A. The Standard Model (SM) is specified by a gauge theory

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

$$\begin{array}{cccc} & g_2 & g_1 & g_3 \\ \rightarrow & \sin\theta_w & \alpha & \alpha_s \end{array}$$

+ **VEV**: $G_F = \frac{1}{\sqrt{2}\, v^2} = \frac{g^2}{4\sqrt{2}\, M_W^2}$

+ (independent) fermion masses & mixings

Three accurately measured independent parameters:

$$G_F = 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

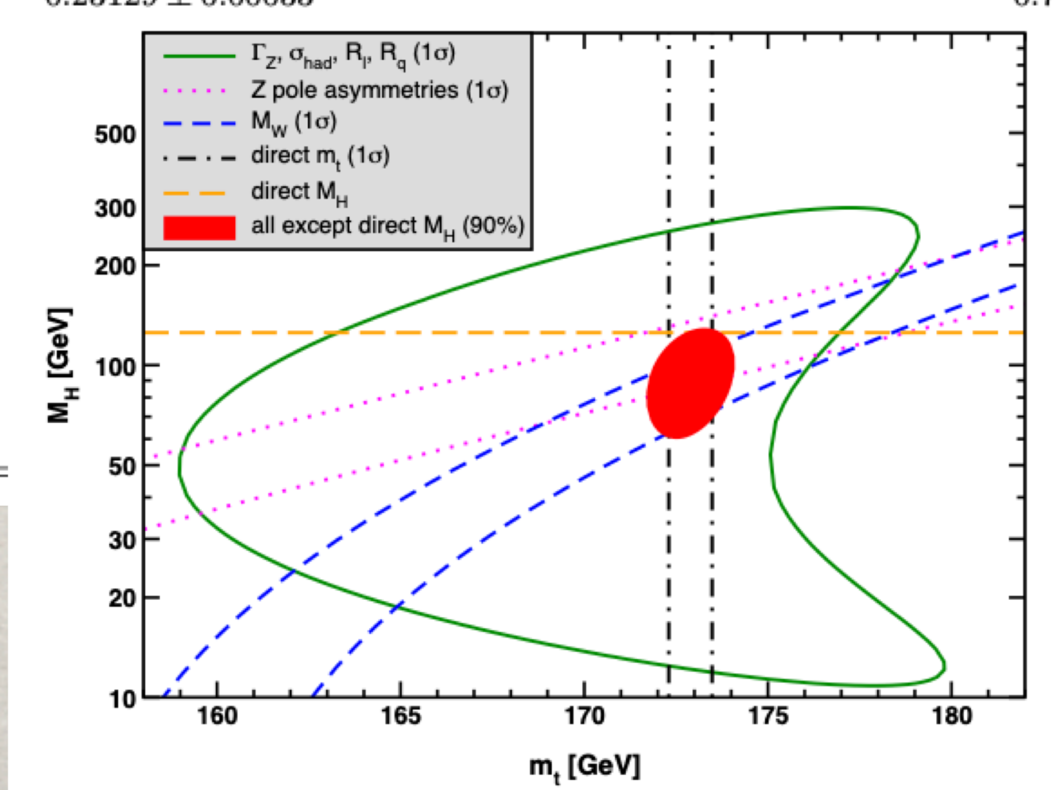
$$\alpha^{-1} = 137.035999150(33) \qquad M_Z = (91.1876 \pm 0.0021)\ \mathrm{GeV}$$

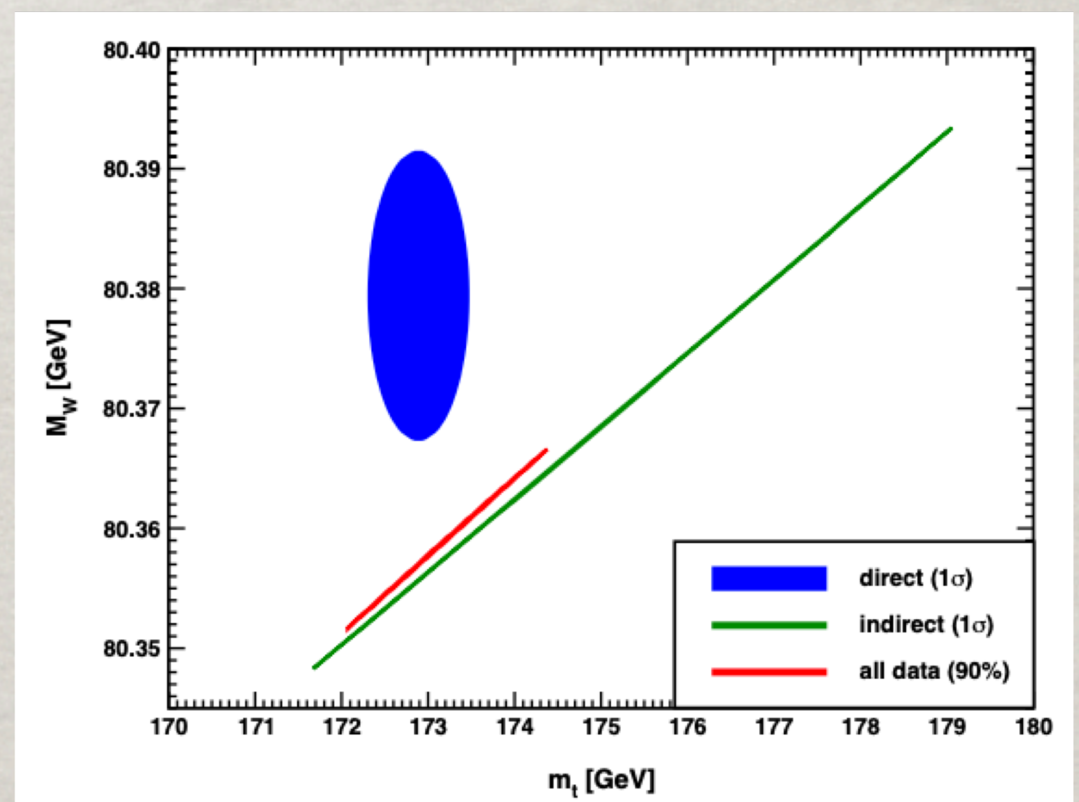
Although all EW parameters/observables can be expressed by these three, the modern approach is to perform a **global fit** for all observables with proper experimental error bars.

EW global fit (PDG) :

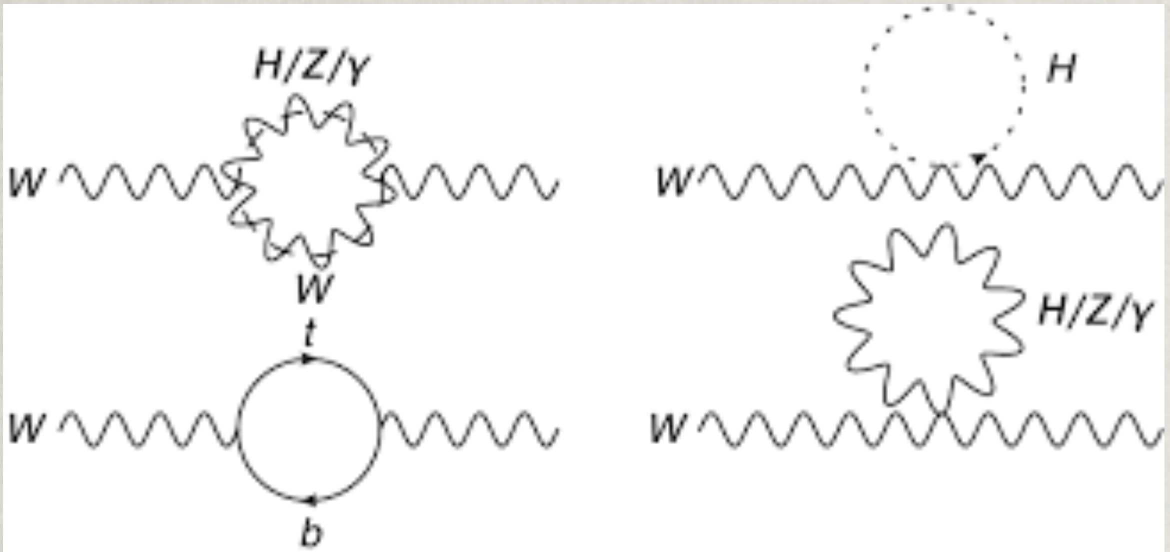
Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1882 ± 0.0020	-0.3
Γ_Z [GeV]	2.4955 ± 0.0023	2.4942 ± 0.0009	0.6
$\sigma_{\rm had}$ [nb]	41.481 ± 0.033	41.482 ± 0.008	0.0
R_e	20.804 ± 0.050	20.736 ± 0.010	1.4
R_μ	20.784 ± 0.034	20.735 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.781 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21581 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01619 ± 0.00007	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0996 ± 0.0016	0.1030 ± 0.0002	-2.1
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0736 ± 0.0002	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1031 ± 0.0002	-0.5
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23153 ± 0.00004	0.7
	0.23148 ± 0.00033		-0.2
	0.23129 ± 0.00033		-0.7
A_e			
A_μ			
A_τ			
A_b			
A_c			
A_s			

Quantity	Value	Standard Model	Pull
m_t [GeV]	172.89 ± 0.59	173.19 ± 0.55	-0.5
M_H [GeV]	125.30 ± 0.13	125.30 ± 0.13	0.0
M_W [GeV]	80.387 ± 0.016	80.361 ± 0.006	1.6
	80.376 ± 0.033		0.5
	80.370 ± 0.019		0.5
Γ_W [GeV]	2.046 ± 0.049	2.090 ± 0.001	-0.9
	2.195 ± 0.083		1.3
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0001	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0476 ± 0.0002	1.4
$Q_W(p)$	0.0719 ± 0.0045	0.0711 ± 0.0002	0.2
$Q_W(\mathrm{Cs})$	-72.82 ± 0.42	-73.23 ± 0.01	1.0
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.88 ± 0.02	0.1
$\hat{s}_Z^2(\mathrm{eDIS})$	0.2299 ± 0.0043	0.23121 ± 0.00004	-0.3
τ_τ [fs]	290.75 ± 0.36	288.90 ± 2.24	0.8
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.18 \pm 0.78) \times 10^{-9}$	$(4508.74 \pm 0.03) \times 10^{-9}$	3.1





The “oblique corrections” S-T-U:



$$\widehat{\alpha}(M_Z)T \equiv \frac{\Pi^{\rm new}_{WW}(0)}{M_W^2} - \frac{\Pi^{\rm new}_{ZZ}(0)}{M_Z^2} \,,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}_Z^2\widehat{c}_Z^2} S \equiv \frac{\Pi^{\rm new}_{ZZ}(M_Z^2) - \Pi^{\rm new}_{ZZ}(0)}{M_Z^2} - \frac{\widehat{c}_Z^2 - \widehat{s}_Z^2}{\widehat{c}_Z\widehat{s}_Z}\frac{\Pi^{\rm new}_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi^{\rm new}_{\gamma\gamma}(M_Z^2)}{M_Z^2} \,,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}_Z^2}(S+U) \equiv \frac{\Pi^{\rm new}_{WW}(M_W^2) - \Pi^{\rm new}_{WW}(0)}{M_W^2} - \frac{\widehat{c}_Z}{\widehat{s}_Z}\frac{\Pi^{\rm new}_{Z\gamma}(M_Z^2}{M_Z^2} - \frac{\Pi^{\rm new}_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$

$$M_Z^2 = M_{Z0}^2 \frac{1-\widehat{\alpha}(M_Z)T}{1-G_F M_{Z0}^2 S/2\sqrt{2}\pi} \,,$$

$$M_W^2 = M_{W0}^2 \frac{1}{1-G_F M_{W0}^2 (S+U)/2\sqrt{2}\pi}$$

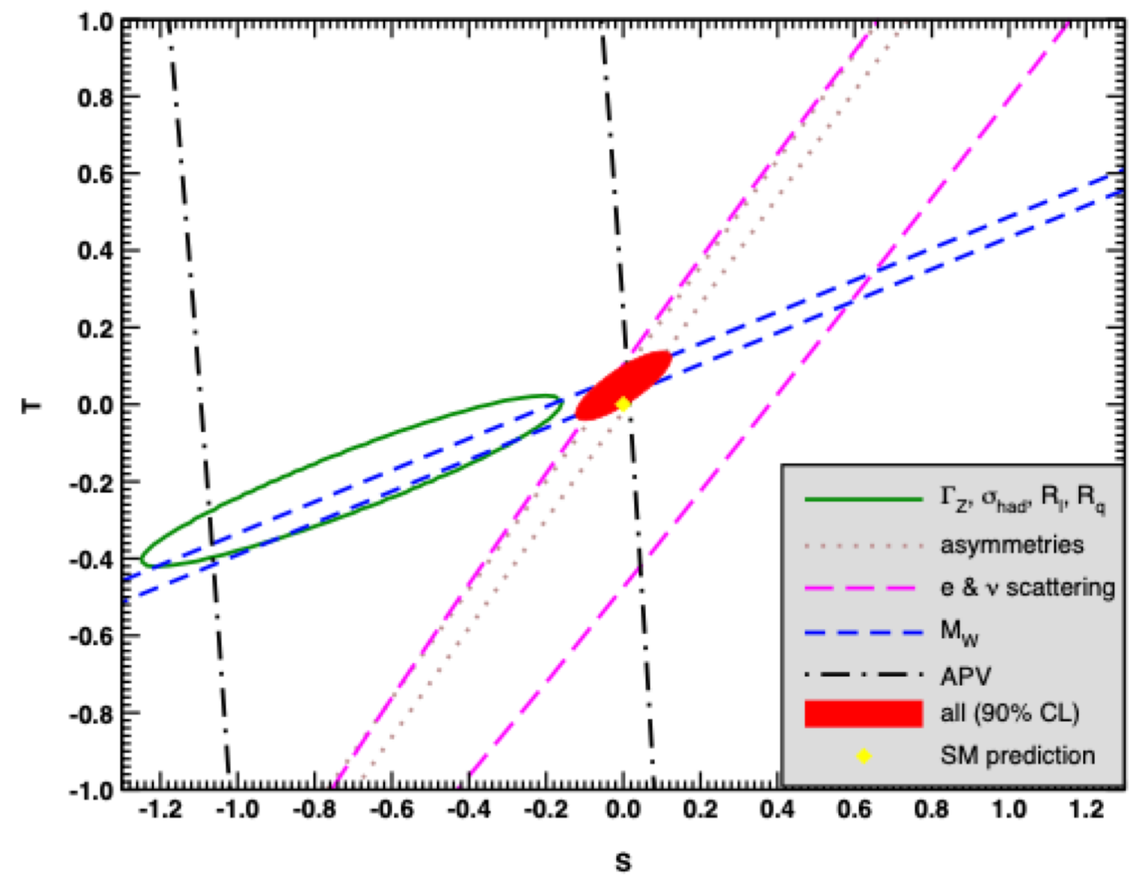


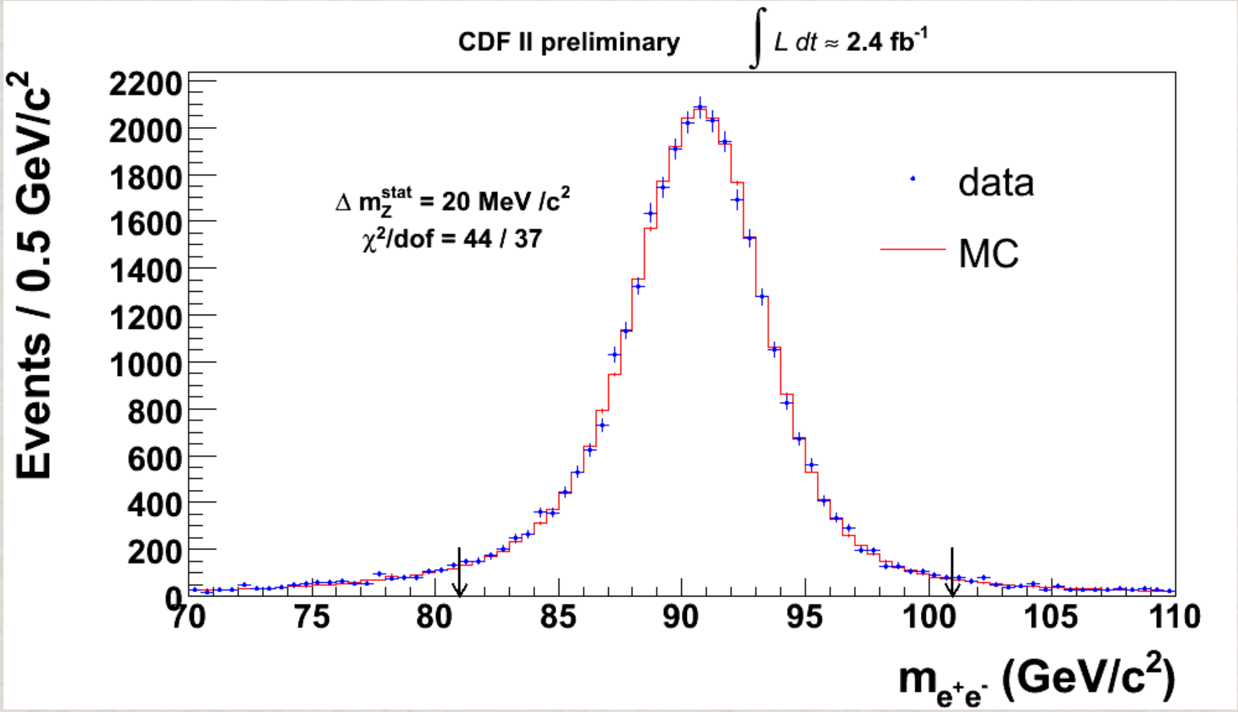
Figure 10.6: 1 σ constraints (39.35% for the closed contours and 68% for the others) on S and T (for $U=0$) from various inputs combined with M_Z. S and T represent the contributions of new physics only. Data sets not involving M_W or Γ_W are insensitive to U. With the exception of the fit to all data, we fix $\alpha_s = 0.1185$. The black dot indicates the Standard Model values $S = T = 0$.

With such an accuracy of a part per mille, there is little room to wiggle!

B. On M_W & $M_T(e\nu)$

First recall $M_Z(e^+e^-)$: $m_{ee}^2 = (p_{e^+} + p_{e^-})^2 \approx 2p_{e^+} \cdot p_{e^-} \approx 2E_{e^+}E_{e^-}(1 - \cos\theta_{e^+e^-})$

$$\frac{d\hat{\sigma}}{dm_{ee}^2} \propto \frac{\Gamma_Z M_Z}{(m_{ee}^2 - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \frac{d\hat{\sigma}}{d\cos\theta}$$



- In QFT, the pole in $s=m_{ee}^2$ is defined to be the pole mass; and off-shell correction may be included $\Gamma_Z \rightarrow \Gamma_Z(s/M_z^2)$
- Only depending on measurements of E_{e+}, E_{e-} & $\cos_{e+e-}$; Map out M_Z & Γ_Z in the Breit-Wigner resonance, Errors determined by experimental resolutions.
- This is equally applicable to $M_W(jj)$!

B. On M_W & $M_T(e\nu)$

For the leptonic decays at hadron colliders: $W \to e\nu, \mu\nu$:

$$m_{e\nu}^2 = (E_e + E_\nu)^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 - (p_{ez} + p_{\nu z})^2$$

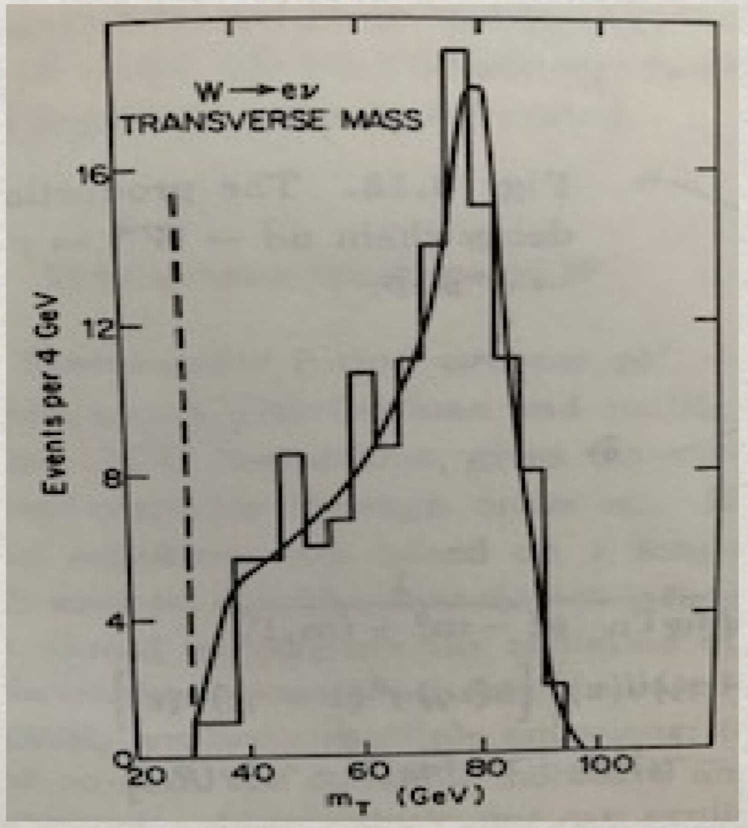
$$\begin{aligned} m_{e\nu T}^2 &= (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 \\ &\approx 2\vec{p}_{eT} \cdot \vec{p}_{\nu T} \approx 2E_{eT}\not{E}_T\ (1 - \cos\phi_{e\nu}) \end{aligned}$$

$$E_T = \sqrt{m^2 + p_T^2} \approx p_T$$

$$\vec{\not{p}}_T = -\sum \vec{p_T}(observed)$$

- Kinematically, $0 < m_{e\nu T}^2 < m_{e\nu}^2$
  🙁 it is NOT Lorentz invariant, only boost invariant; broad range.
- 😀 Mathematically related to M_W

History: 40 years ago,
UA1 with ~ 40 events
$M_W = 83 \pm 4$ GeV,
$\Gamma_W < 6.5$ GeV
Two parameters!



(1). W Width effect:

$$\frac{d\hat{\sigma}}{dm^2_{e\nu}dm^2_{e\nu,T}} \propto \frac{\Gamma_W M_W}{(m^2_{e\nu} - M^2_W)^2 + \Gamma^2_W M^2_W} \frac{1}{m_{e\nu}\sqrt{m^2_{e\nu} - m^2_{e\nu,T}}}$$

Convoluted relation between M_W & M_T !

Narrow Width Approx. $\boldsymbol{\Gamma_W} \rightarrow 0$:

$$\frac{d\hat{\sigma}}{dm^2_{e\nu}dm^2_{e\nu,T}} \propto \delta(m^2_{e\nu} - M^2_W) \frac{1}{m_{e\nu}\sqrt{m^2_{e\nu} - m^2_{e\nu,T}}} \rightarrow \frac{1}{m_{e\nu}\sqrt{M^2_W - m^2_{e\nu,T}}}$$

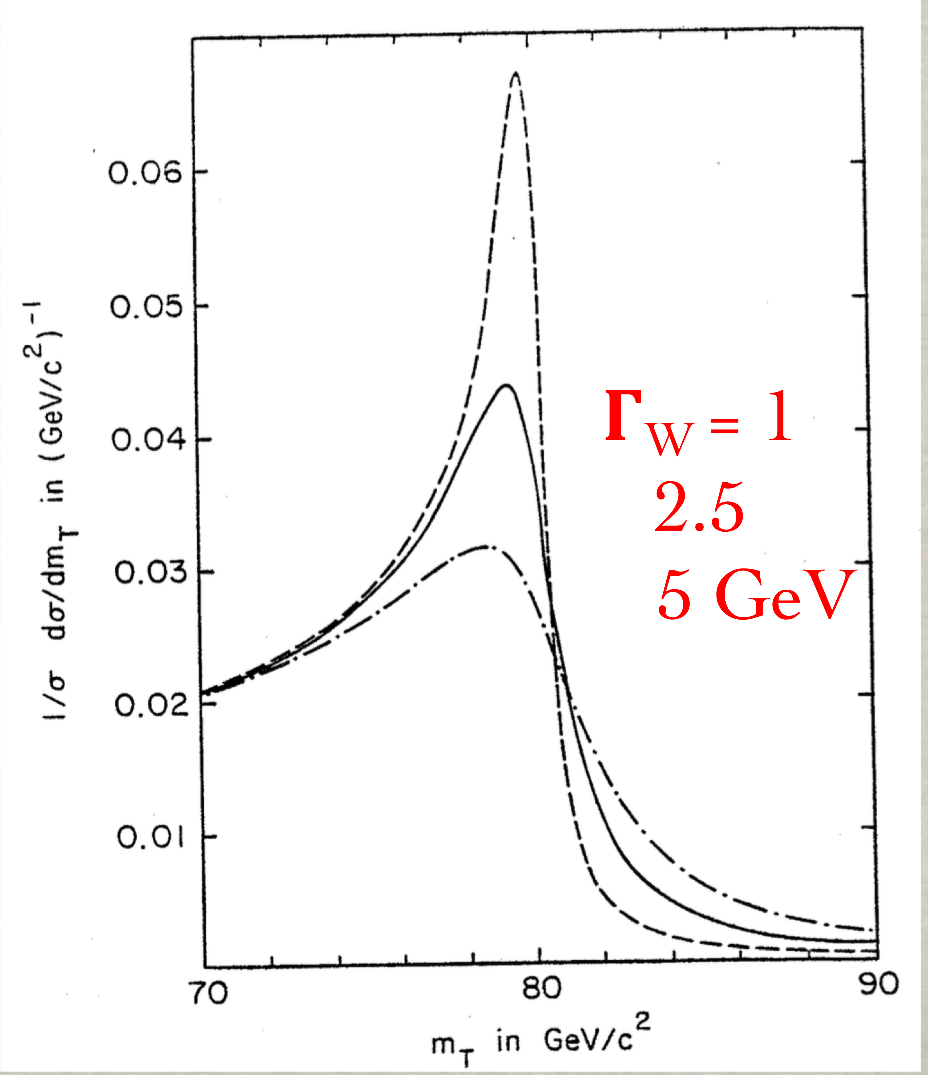
This is an "edge" search on $M_T \leq M_W$

not a bump search, sensitive to $\boldsymbol{\Gamma_W}$!

Edge is lower, shape changed!

Current accuracy on $\boldsymbol{\Gamma_W}$:

Full width $\Gamma = 2.085 \pm 0.042$ GeV



(2). W transverse motion: $p_T(W)$

$$\frac{d\hat{\sigma}}{dm_{e\nu}^2 dm_{e\nu,T}^2} \propto \frac{\Gamma_W M_W}{(m_{e\nu}^2 - M_W^2)^2 + \Gamma_W^2 M_W^2} \frac{1}{m_{e\nu}\sqrt{m_{e\nu}^2 - m_{e\nu,T}^2}}$$

If W has a transverse motion (must!), say $p_X(W)$:

$\boldsymbol{\beta}_W = p_X(W)/M_W$

$$m_{e\nu,T}^2(\beta_W) = m_{e\nu,T}^2 - \frac{4\beta_W^2 p_x^2 p_z^2}{{p_T}^2} + O(\beta_W^4)$$

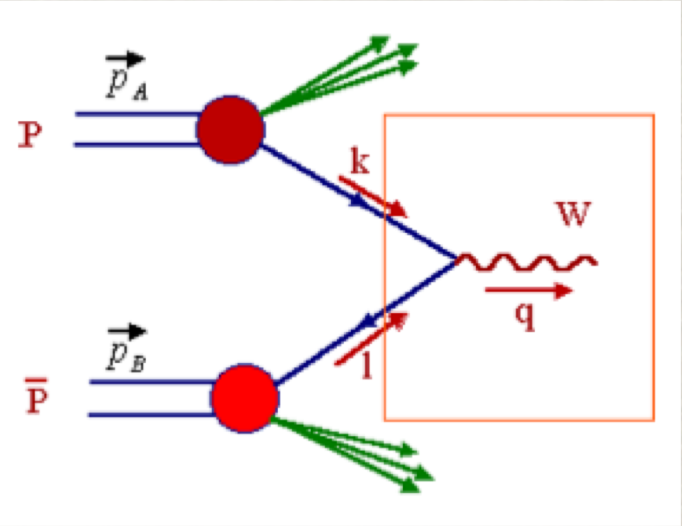
The measured $M_T(e\boldsymbol{\nu})$ in the lab frame is shifted downward w.r.t. that of $p_T(W) = 0$.

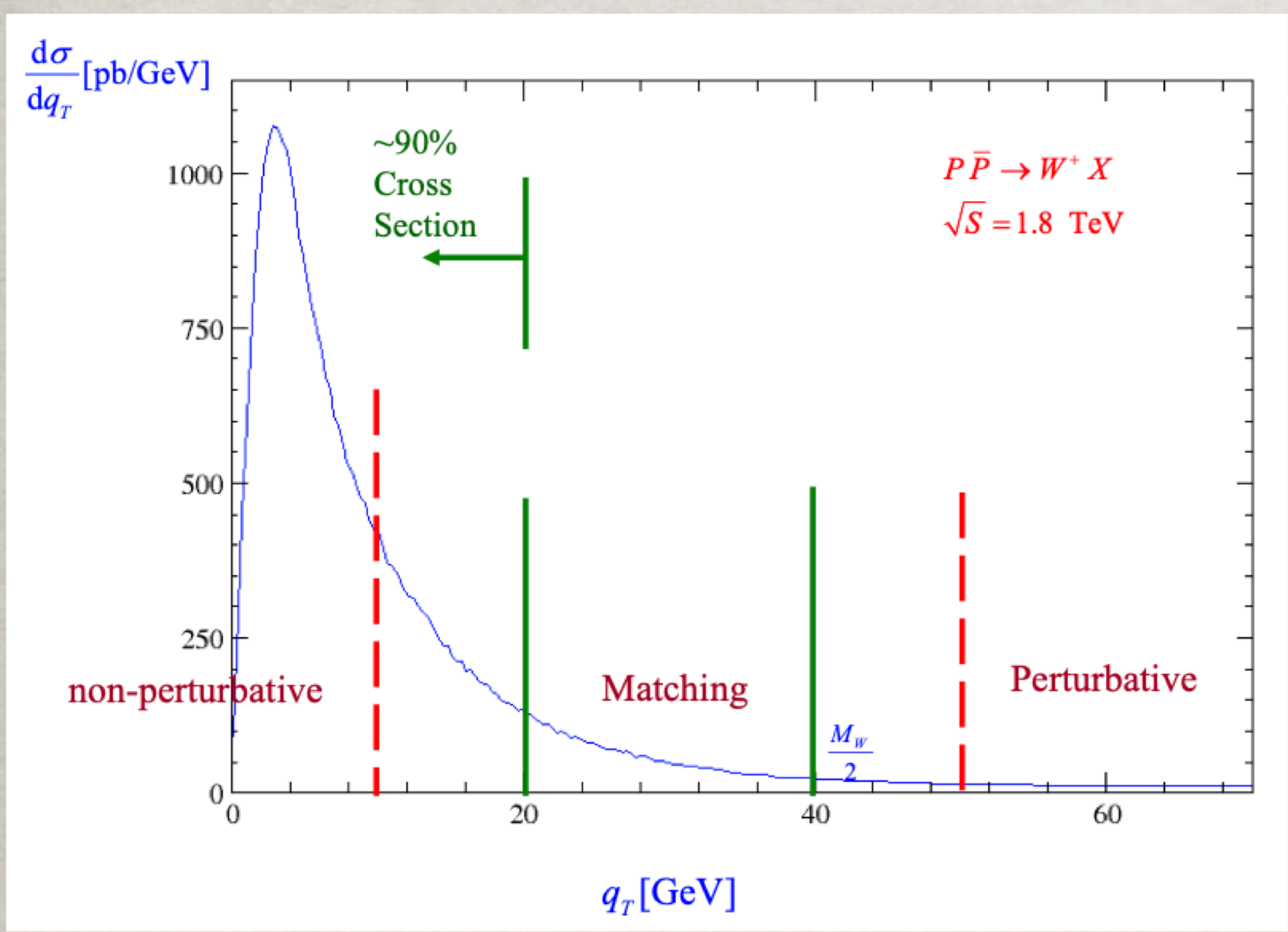
Need to model $p_T(W)$ well!

(2). W transverse motion: $p_T(W)$

At the leading order, $p_T(W) = 0$

With higher order corrections, peak at $p_T(W) \approx 2 - 3$ GeV





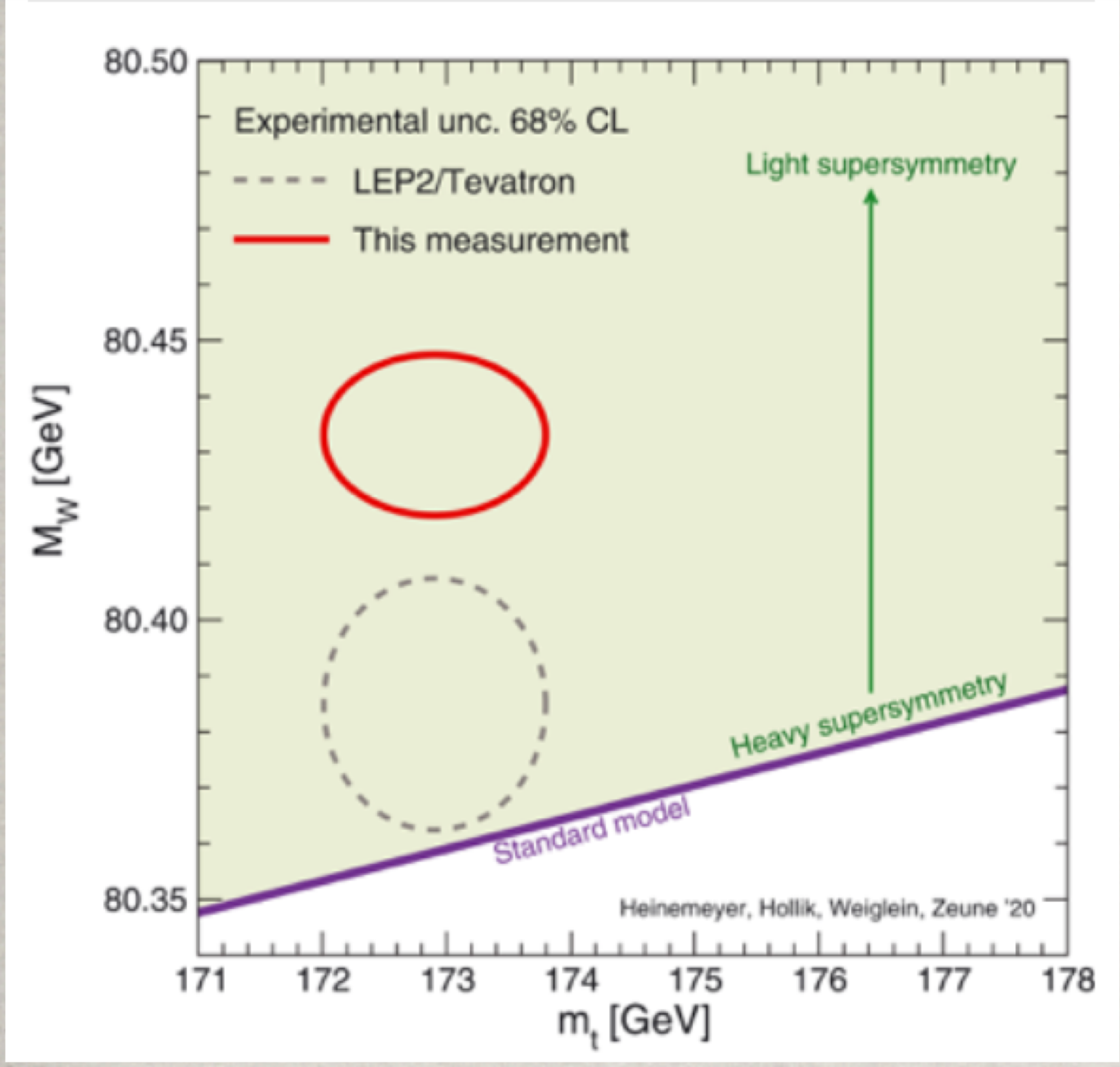
"ResBos": C.-P. Yuan et al. Phys. Rev. D56, 5558 (1997)

ResBos: NNLL resummation; match $p_T(W)$; off-shell width …

Theory uncertainty ~ Λ_{QCD}

CDF data driven approach: modeled $p_T(W)$ w.r.t. $p_T(Z)$

C. BSM Physics?



Observations:

- Keep everything else the same, only lift up M_W :

- U-parameter alone: custodial viol but dim-8, may not be large.

- GF via 4-lepton operator:
  → change M_W?

- Global effects (minimally?):
  $\Delta(M_W/M_Z) \sim -3.15S + 4.86T + 2.54U$
  S-T and S-T-G_F (J. Gu et al. below)
- Many models to accommodate it!

Lots of theoretical activities and fast increasing:

Y.-Z. Fan, T.-P. Tang, Y. Tsai, L. Wu: 2204.03693 (DM); C. Lu, L. Wu, Y. Wu, B. Zhu: 2204.03996 (g-2); G.-W. Yuan, L. Zu, L. Feng, Y.-F. Cai: 2204.04183 (axion); Strumia: 2204.04191 (Z', T); J.M. Yang & Y. Zhang: 2204.04202 (SUSY) J. Blas, et al.: 2204.04204 (EFT, top fit); J. Gu, Z. Liu, T. Ma, J. Shu; arXiv:2204.05296; (W',Z',SUSY); M. Endo, S. Mishima: 2204.05965; T. Biekottrt, S. Heinemetre, G. Weiglain: 2204.05975 (Higgs); … …

Summary

- The new CDF result on M_W is outstanding!
- Precision EW fit cannot accommodate the difference.
- Many new physics scenarios can explain the difference:
  W', Z', 2HDM, SUSY, DM, axion, string states … …
- Theoretical systematics should be scrutinized:
  M_T is not invariant! Need knowledge of $p_T(W)$ & Γ_W
  $p_T(W)$ in low and high (√);
  Floating W-width & error bar (SM input?)
  Others: & PDF (valence quarks, flavor? √);
  QED photon radiation in ISR and FSR (√ ?)
  ... (?)
- Look forward to the news from CMS, LHCb …

More excitement to come !