M_W at hadron colliders --- Theoretical considerations

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Dark Matter & Neutrino Physics 2022

A. EW global fit in the SM
B. $M_T(e\nu)$ variable @ hadron colliders
C. BSM physics interpretations

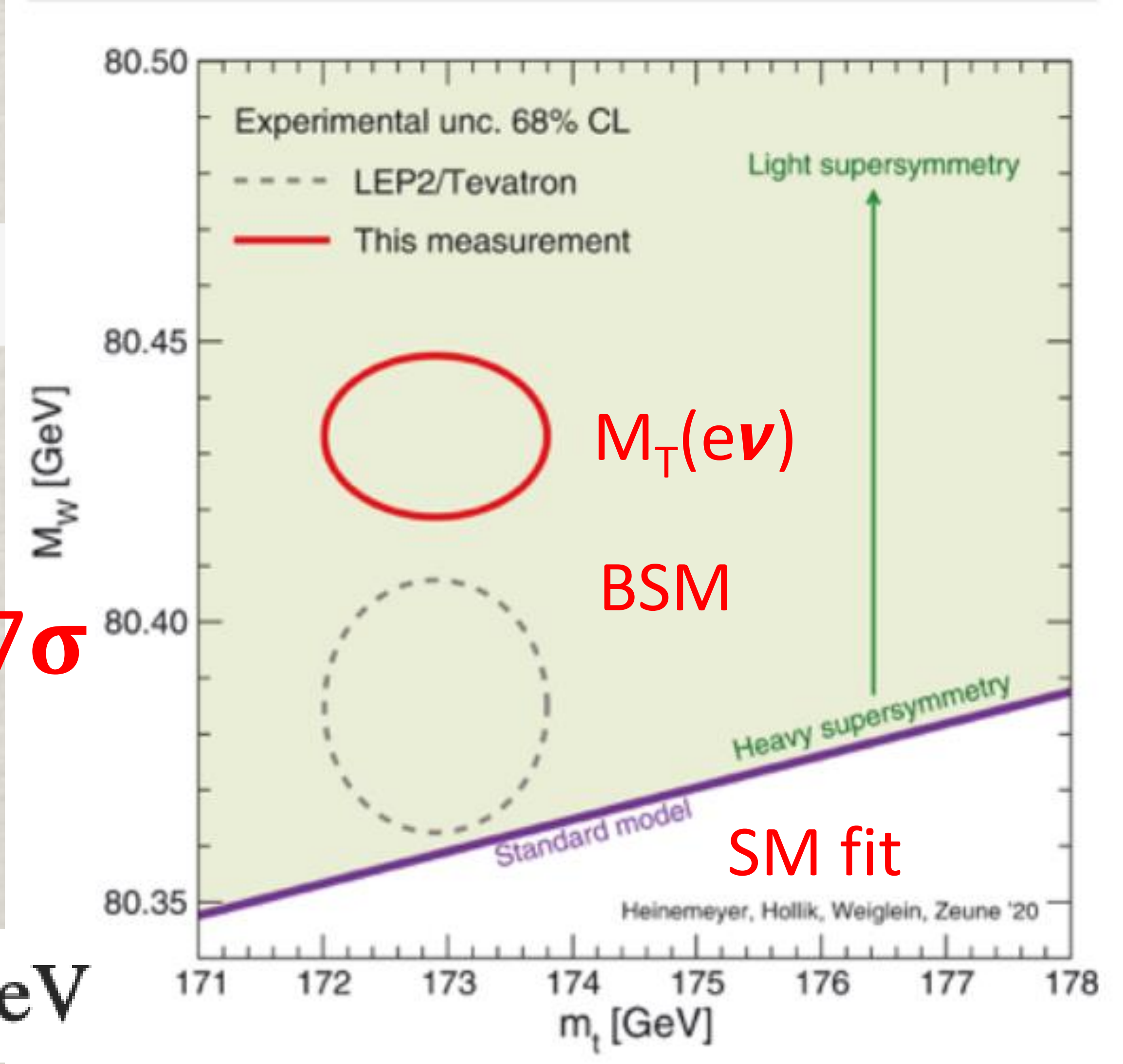
CDF new Measurement very exciting!

$$M_W = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}}$$

$$= 80,433.5 \pm 9.4\ \text{MeV}/c^2,$$

CDF: Science , April 8, 2022

7σ



SM global fit (PDG):

J. Erler & A. Freitas (March, 2020)

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

Today, I will only make theoretical remarks.

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

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

g_2 g_1 g_3

→ $\sin\theta_w$ α α_s

+ the EW scale (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:

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

$\alpha^{-1} = 137.035999150(33)$ (from $(g\text{-}2)_e$)

$M_Z = (91.1876 \pm 0.0021)\ \mathrm{GeV}$ (from LEP-I)

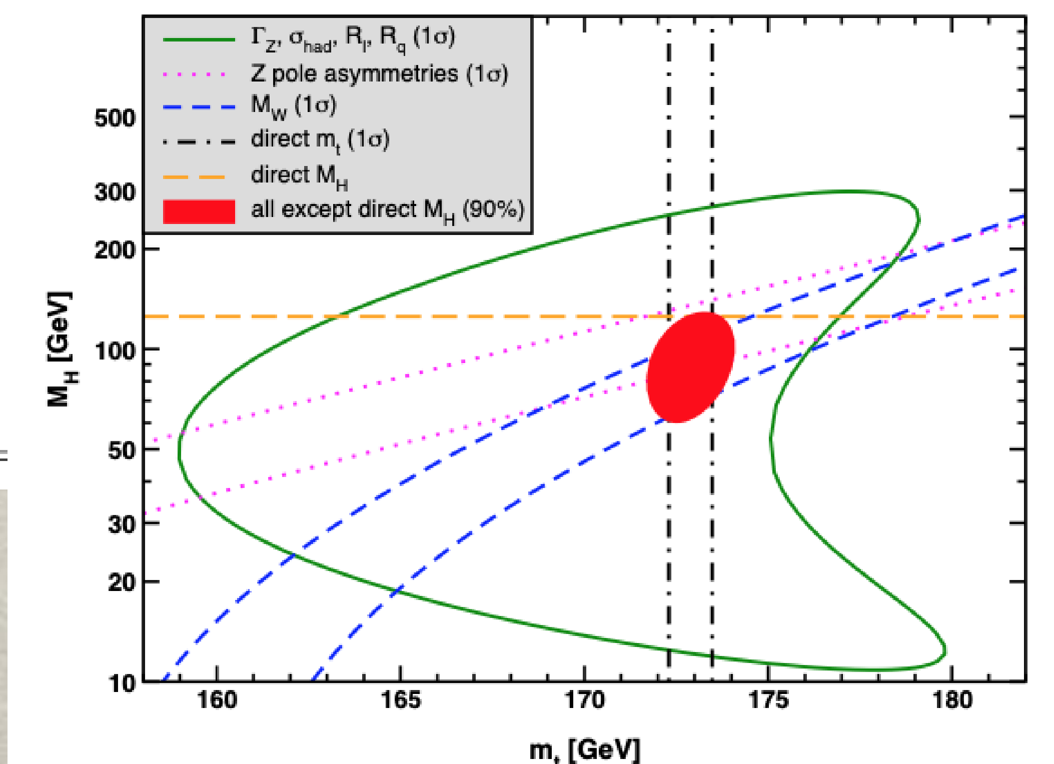
Although all EW observables can be expressed by these three as inputs (at tree-level), others come in at quantum level; the modern approach performs a **global fit** for all observables with proper experimental error bars (e.g. EW@PDG).

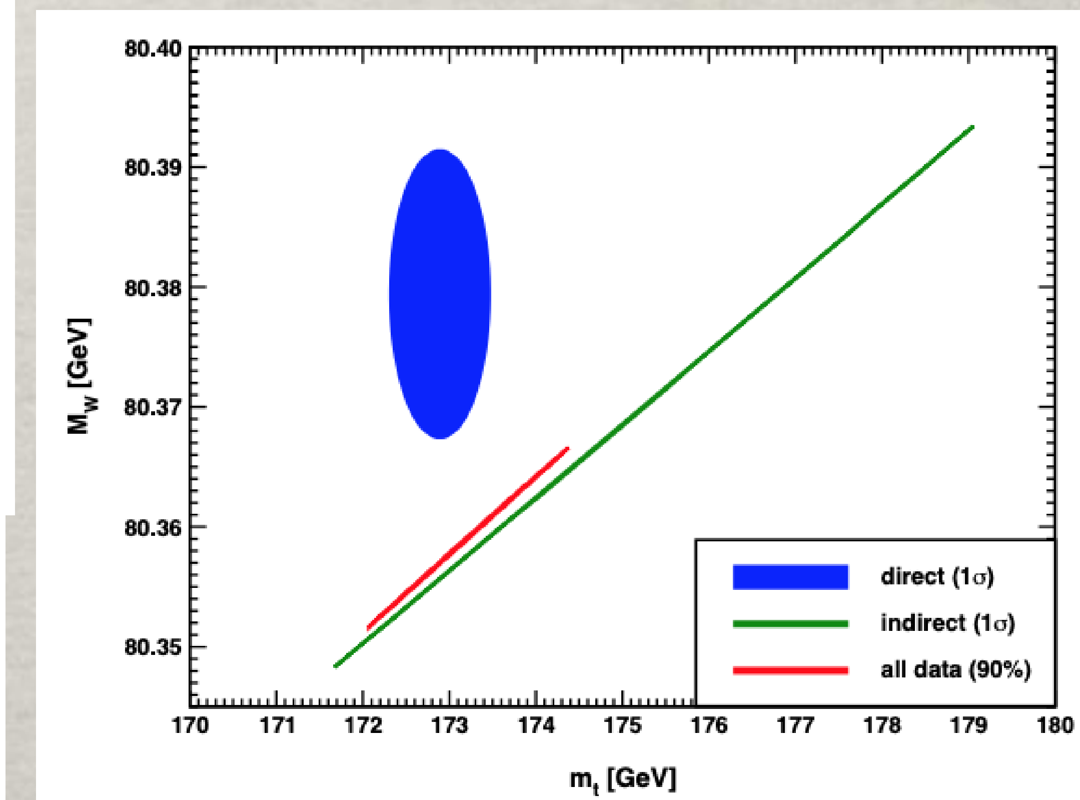
EW global fit with radiative corrections (PDG) :

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
σ_{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			

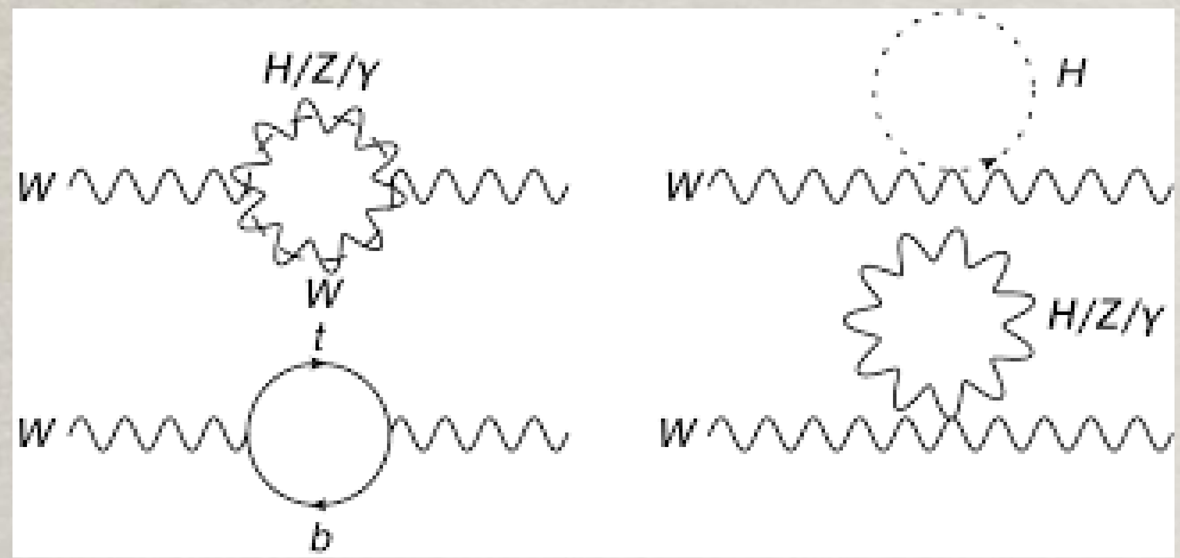
J. Erler & A. Freitas (March, 2020)

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:



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

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

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

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

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

The custodial "symmetry":

$$M_Z = \frac{M_W}{\widehat{\rho}^{1/2}\,\widehat{c}_Z} \qquad \widehat{\rho} = 1.01019 \pm 0.00009.$$

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

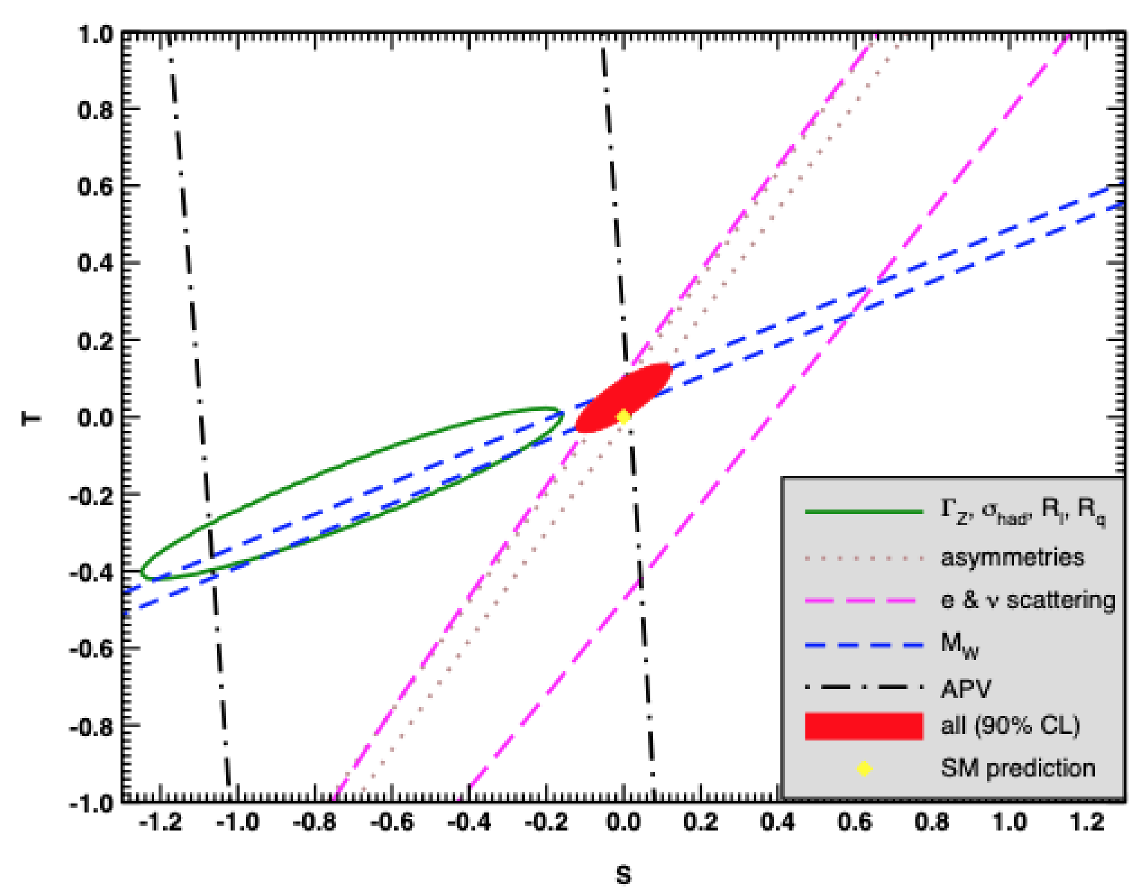


Figure 10.6: 1 σ constraints (39.35% for the closed contours and 68% for the others) on S and T (for $U = 0$) from various inputs combined with M_Z. S and T represent the contributions of new physics only. Data sets not involving M_W or Γ_W are insensitive to U. With the exception of the fit to all data,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

Recent analysis with M_W/m_t measurements;

De Blas, L. Reina et al., arXiv:2204.04204; C.T. Lu et al., 2204.03796

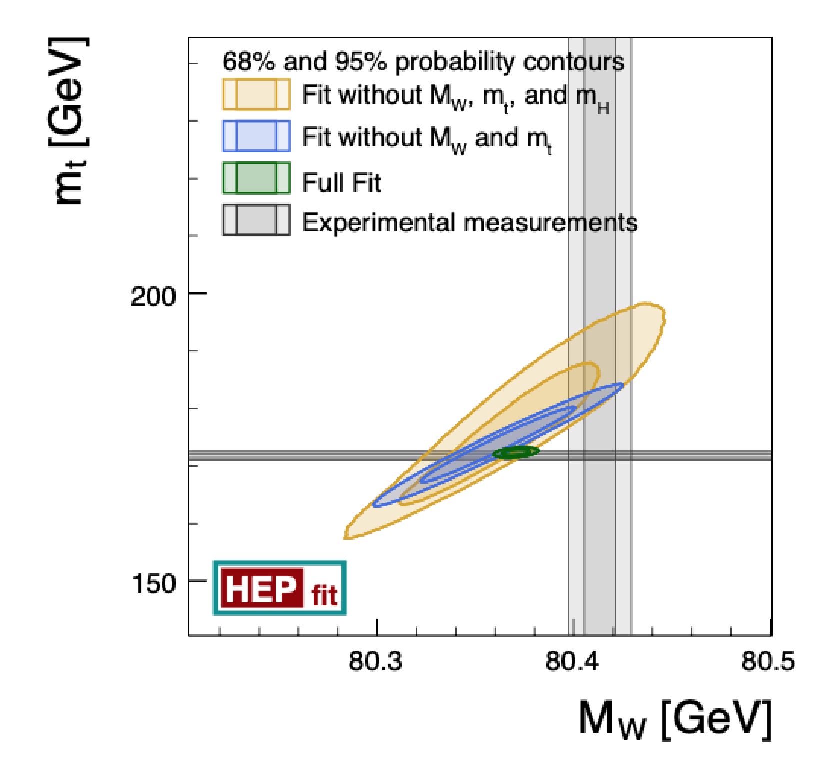
Recent CDF measurement [M_W=(80.4335±0.0094) GeV]

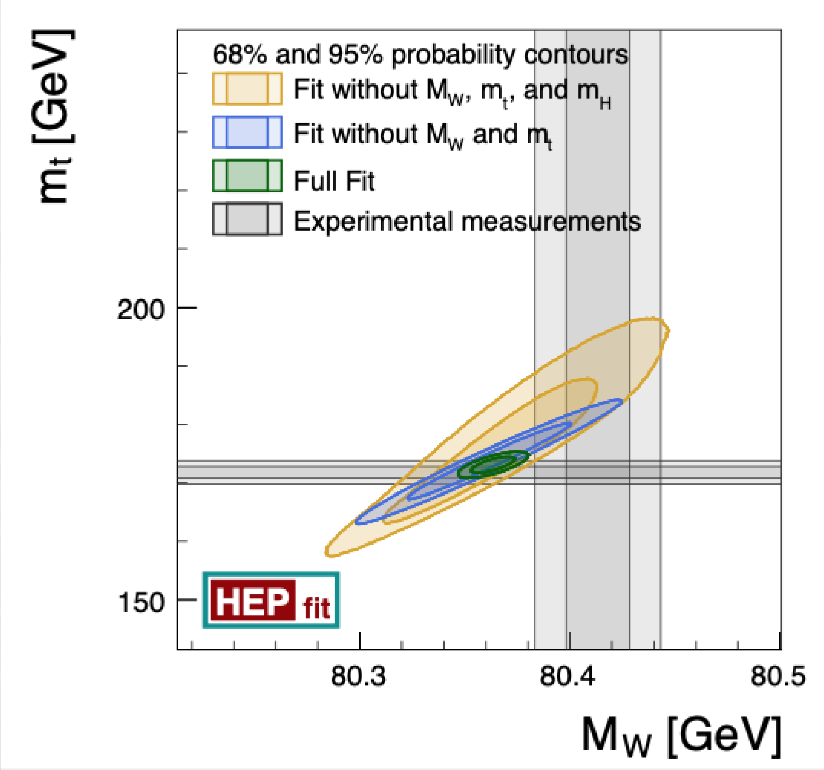
Dominates the M_W average,
but in tension with LEP2, Tevatron & LHC results

previous average		new average	new average
M_W = 80.379 ± 0.012 GeV	→	M_W = 80.4133 ± 0.0088 GeV	M_W = 80.4133 ± 0.015 GeV
		"standard"	*"conservative"*

Model	Pred. M_W [GeV]	Pull	Pred. M_W [GeV]	Pull
	standard average		*conservative average*	
SM	80.3499 ± 0.0056	$6.5\,\sigma$	80.3505 ± 0.0077	$3.7\,\sigma$

Global SM fit:

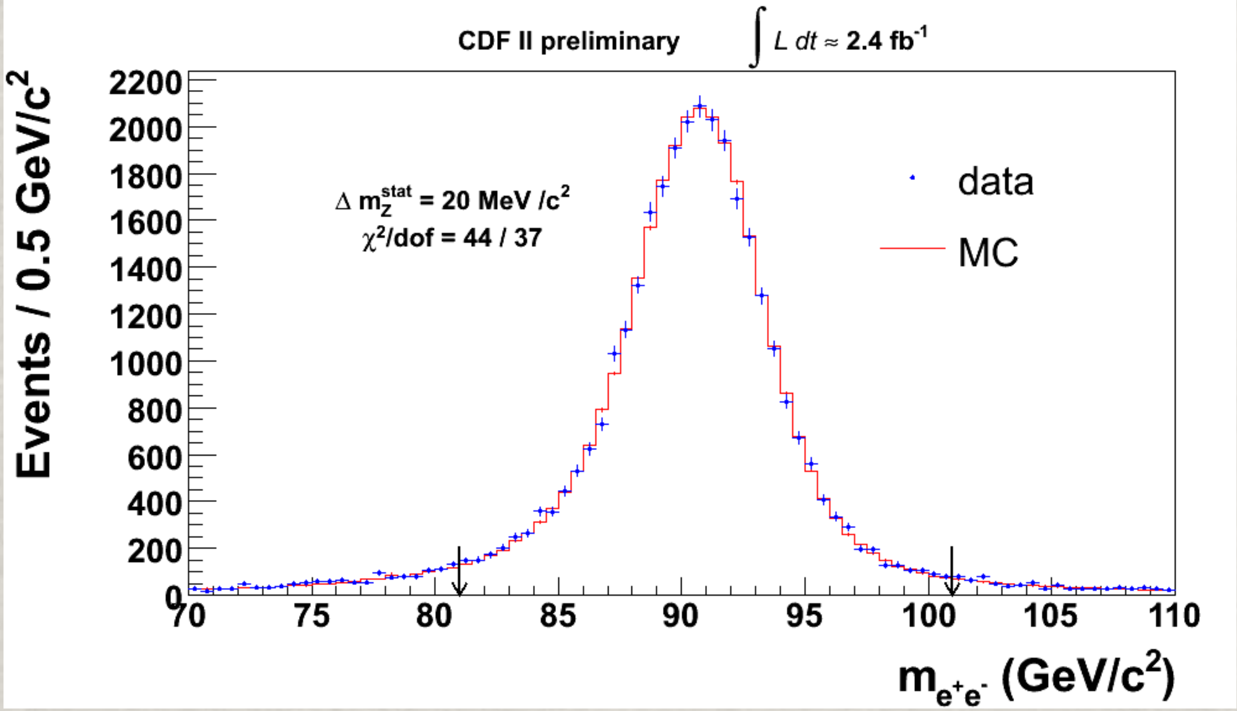




B. On M_W & $M_T(e\nu)$

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: $W \rightarrow e\nu, \mu\nu$:

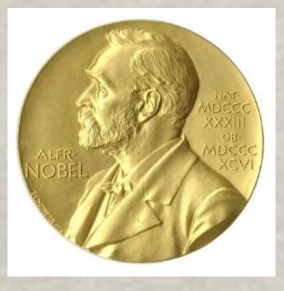
$$m_{e\nu}^2 = (E_e + E_\nu)^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 - (p_{ez} + p_{\nu z})^2$$

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

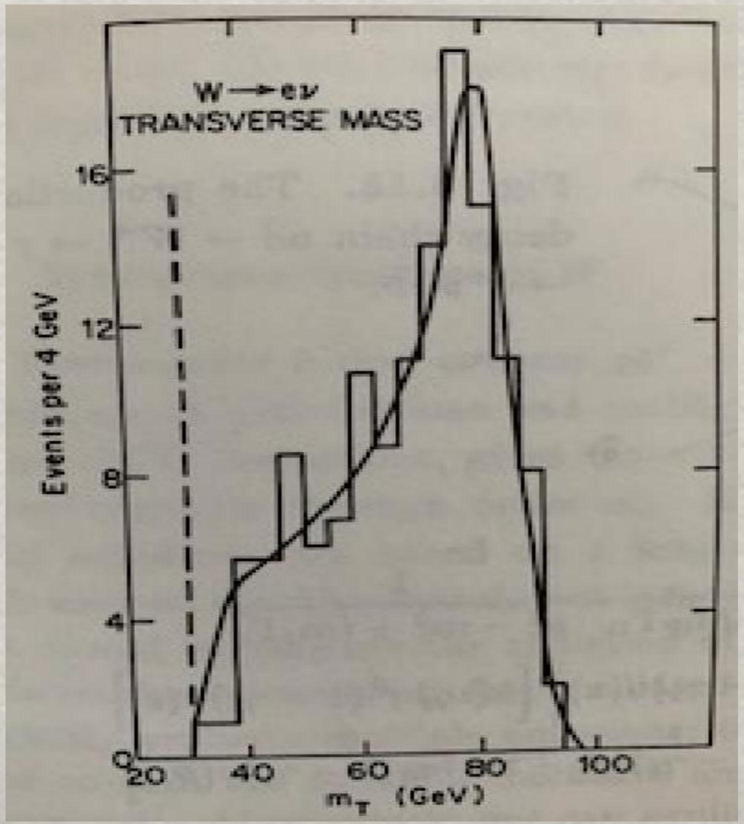
$$E_T = \sqrt{m^2 + p_T^2} \approx p_T$$

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

- Kinematically, $0 \le m_{e\nu T}^2 \le m_{e\nu}^2$
  ☹ 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±4 GeV,
Γ_W < 6.5 GeV
Two parameters!



(1). W Width effect:

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

Convoluted relation between M_W & M_T !

Narrow Width Approx. $\Gamma_W \to 0$:

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

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

not a bump search!

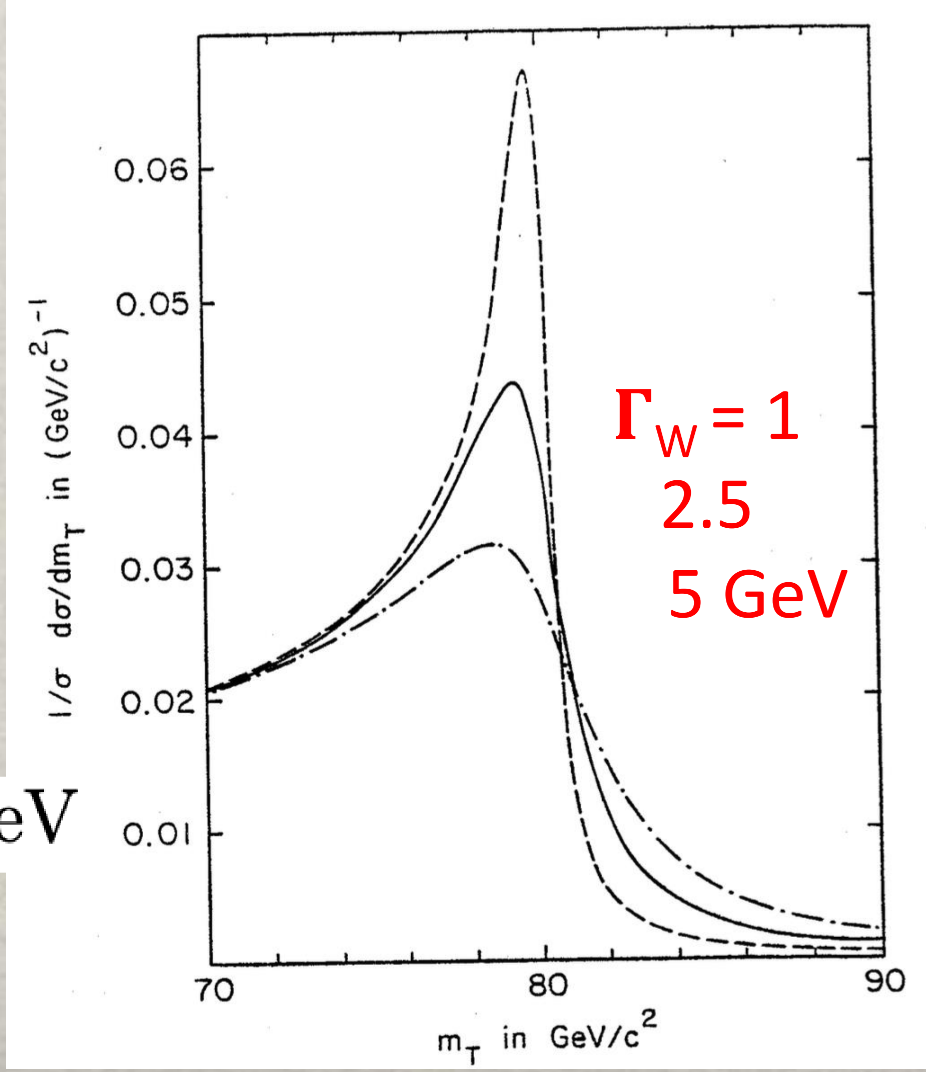
Depending on Γ_W,

edge is lower, shape changed!

Current measurement on Γ_W,

mainly from CDF/D0, fixed M_W

$\Gamma_W = 2{,}085 \pm 42$ MeV at $M_W = 80{,}399 \pm 23$ MeV



J. Smith, van Nerven, J. Vermaseren (1983)

Recent analysis with width errors

J. Isaacson, Yao Fu, C.-P. Yuan, arXiv:2205.02788

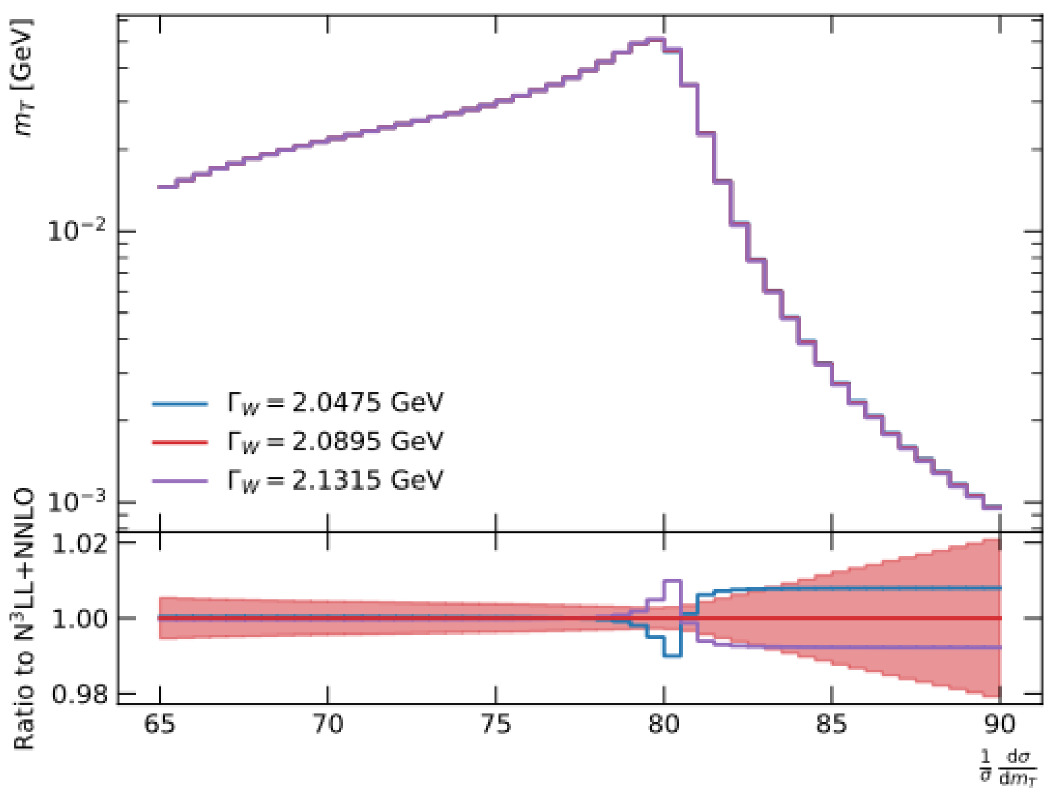


FIG. 9. Comparison of the m_T distribution for various different choices of Γ_W. The width used by CDF was 2.0895 GeV (red curve), and the blue and purple curve represent the shift in the width up and down by one standard deviation of the uncertainty quoted by the PDG [96].

Width	Mass Shift [MeV]
2.0475 GeV	2.0 ± 0.5
2.1315 GeV	0.3 ± 0.5
NLO	1.2 ± 0.5

TABLE V. The shift in M_W due to changing the width. The width is varied by the uncertainty from the PDG [96], with the central value set to 2.0895 GeV used by the CDF collaboration [2]. Additionally, the Standard Model prediction for the width at NLO is considered.

CDF/D0 fitted M_W & Γ_W individually by fixing the other.
Two-parameter fit (M_W, Γ_W) should be advocated!

CDF/D0 combined: arXiv:1003.2826; : arXiv:1307.7627.

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

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

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

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

$$p_{eT}(\beta_W) = p_{eT} - \beta_W \frac{p_x}{p_T} p + O(\beta^2_W)$$

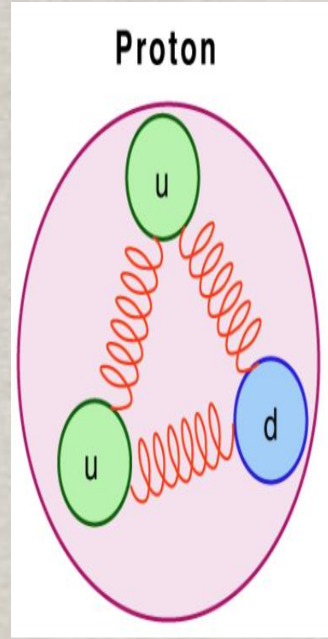
$$m^2_{e\nu,T}(\beta_W) = m^2_{e\nu,T} - \frac{4\beta^2_W p^2_x p^2_z}{{p_T}^2} + O(\beta^4_W)$$

- $M_T(e\boldsymbol{\nu})$ is less sensitive to $p_T(W)$ than p_{eT}
- 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!

V. Barger, A. Martin, and R. Phillips (1983)

(3). Parton transverse motion
TMD (transverse-momentum dependent) DPF



Partons inside the proton (Lorentz contracted) still has transverse motion:

$p_T \approx \alpha_s \Lambda_{QCD}$ ~ O(100 MeV)

UNRAVELLING HIGHER TWISTS

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Received 21 June 1982

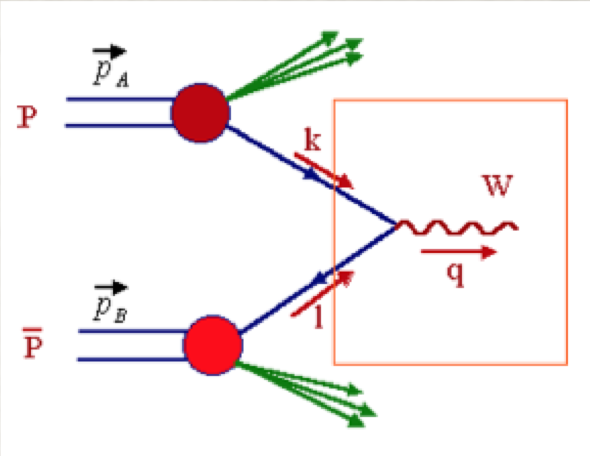
$f_T(x,Q^2) \sim \Lambda^2_{QCD} / Q^2$

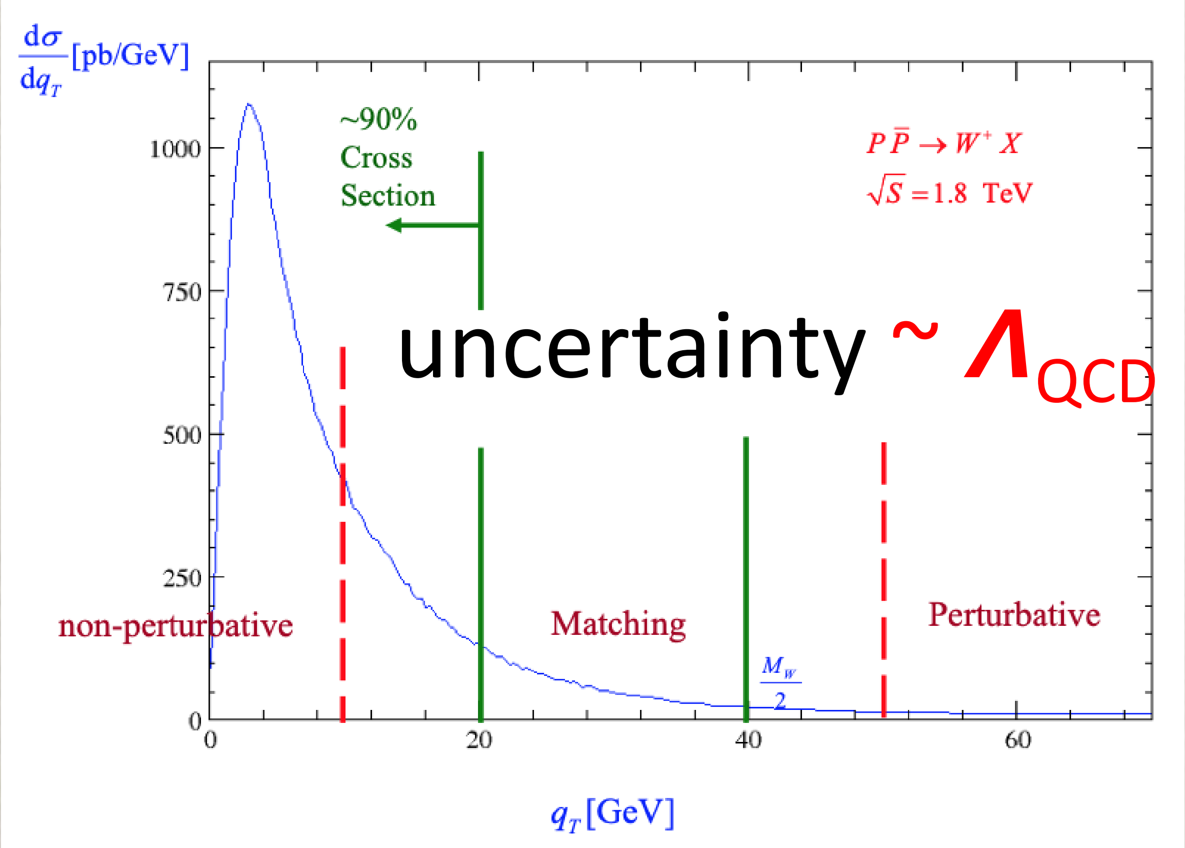
We present a novel method of deriving the first power corrections ($1/Q^2$) to the leptoproduction structure functions. The method is based directly on the manipulation of Feynman diagrams. Correspondence with the operator product expansion approach is established. We find that the transverse components of momenta and the gluon field control both the kinematic and dynamical power corrections. The full QCD result is similar in structure to the naïve parton model with intrinsic transverse momentum. We explain how the concept of parton transverse momentum is generalized in the presence of interaction. In the operator language our method defines a new

R.K. Ellis, et al. , Nucl. Phys. B212, 29 (1983)

(4). Soft gluon resummation & $p_T(W)$

At the leading order, $p_T(W) = 0$
With higher order corrections from soft gluon radiation, peak at $p_T(W) \approx 2 - 3$ GeV



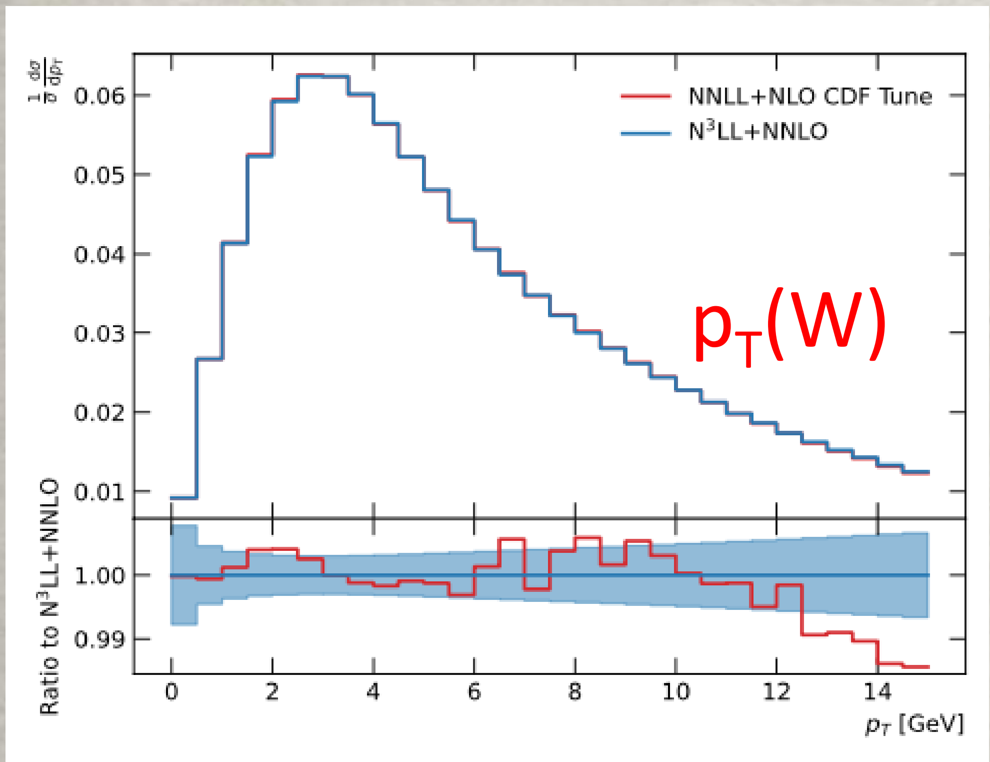


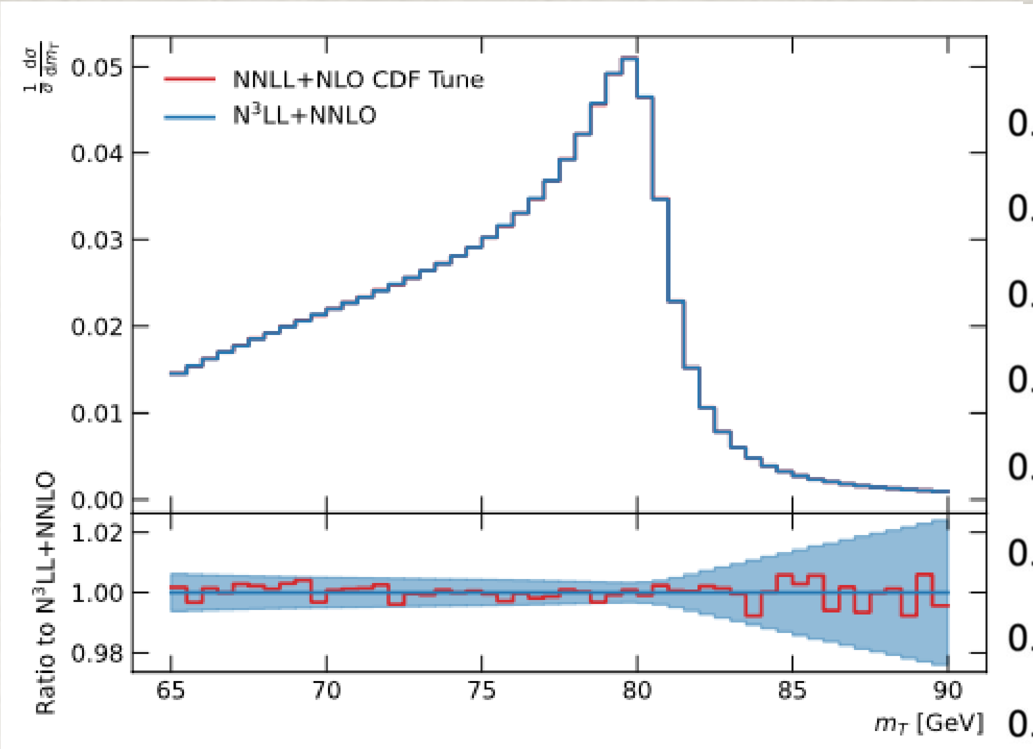
"ResBos": C.-P. Yuan et al. Phys. Rev. D56, 5558 (1997); arXiv:2205.02788.

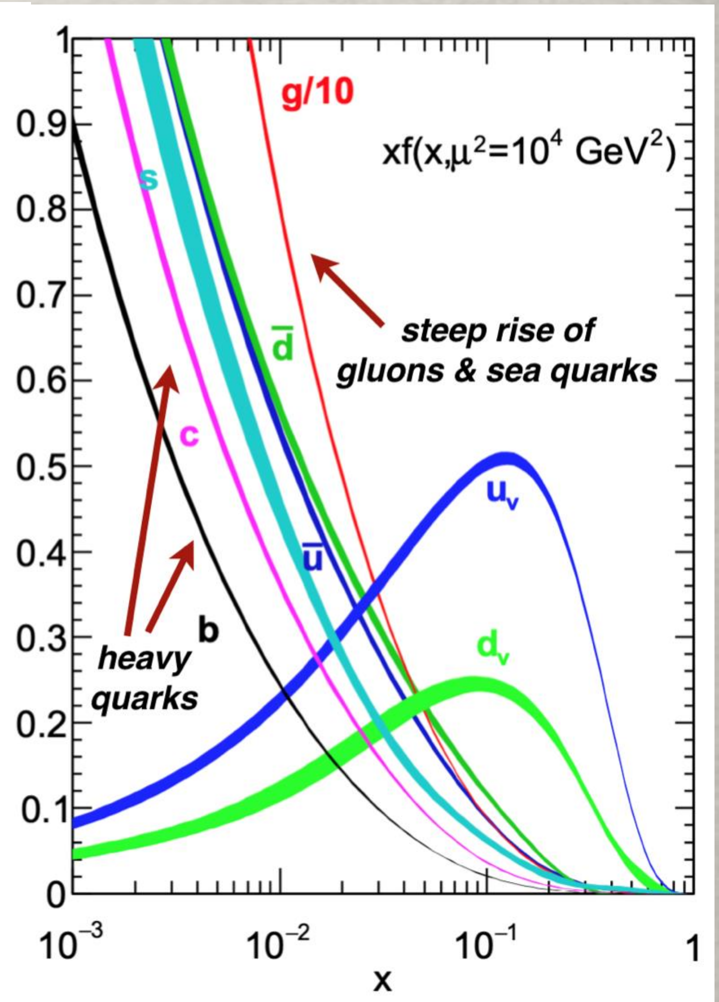
Recent analysis on $p_T(W)$ effects

J. Isaacson, Yao Fu, C.-P. Yuan, arXiv:2205.02788

ResBos: N^3LL + NNLO; matched $p_T(W)$



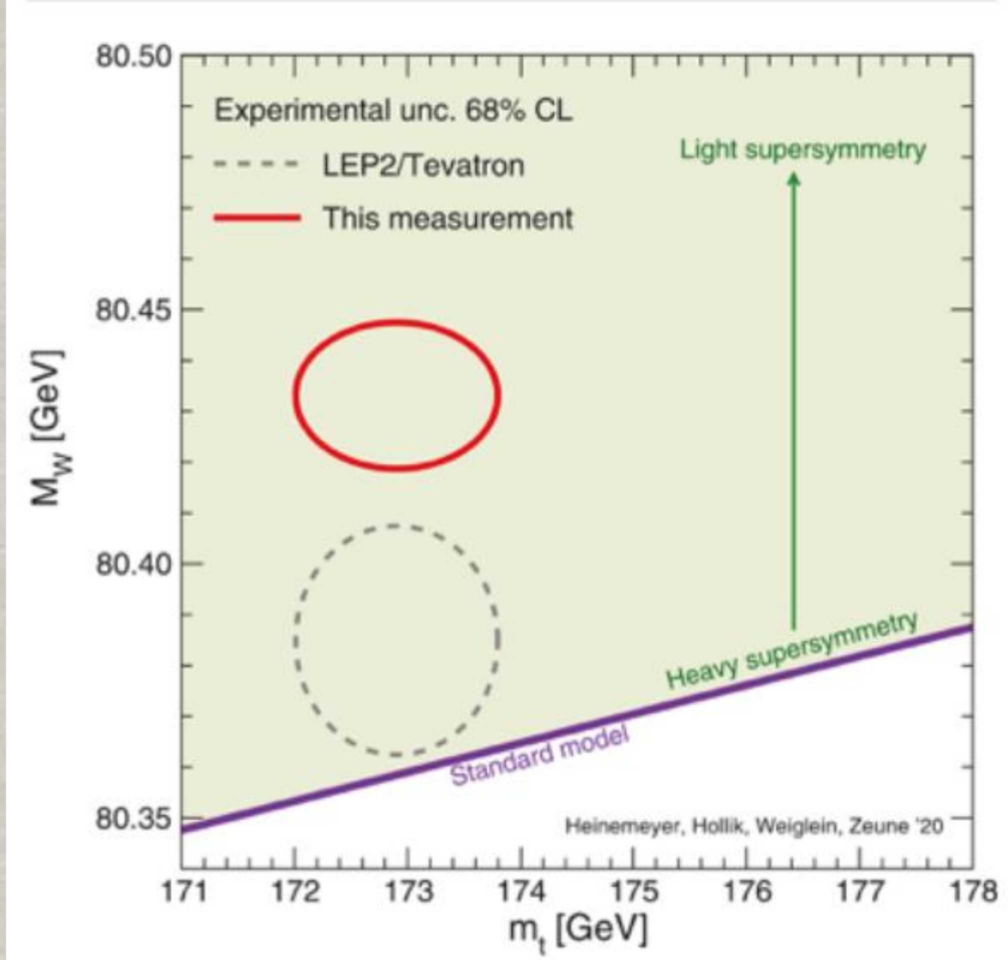




CDF data driven approach:
modeled $p_T(W)$ w.r.t. $p_T(Z)$
perhaps the best one can hope for.

J. Rojo, arXiv:1910.03408
Watch out the difference between u & d

C. BSM Physics?



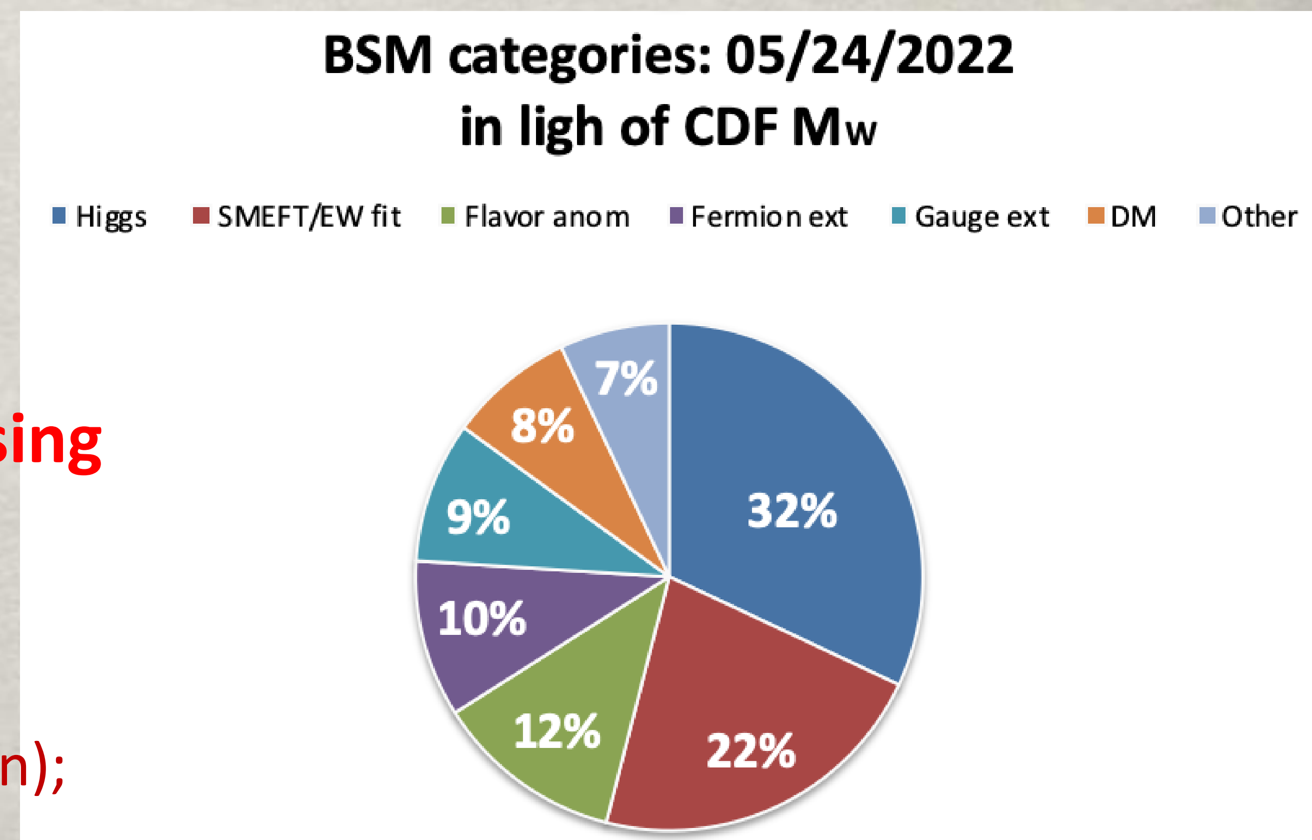
Keep everything else the same, only lift up M_W ?

$$M_Z = \frac{M_W}{\widehat{\rho}^{1/2}\,\widehat{c}_Z}$$

In theory, how easy / hard is it ?

Many models to accommodate it!

Up to date, there > 90 papers!



Lots of theoretical activities and fast increasing (2 weeks after the announcement) :

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); … …

C. BSM Physics?

Observations:

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

1. U-parameter alone: custodial violation, but dim-8 → may not be large enough.
2. G_F via 4-lepton operator → change M_W? but typically has effect on the EW vev / V_{ud} → need some addition.

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

- Global effects (minimally?):

$\Delta(M_W/M_Z) \sim -3.15S + 4.86T + 2.54U$

Multi-variable fit: S-T and S-T-G_F

→ see the previous list.

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 !