Constraints from m_W in an EFT and in the pMSSM

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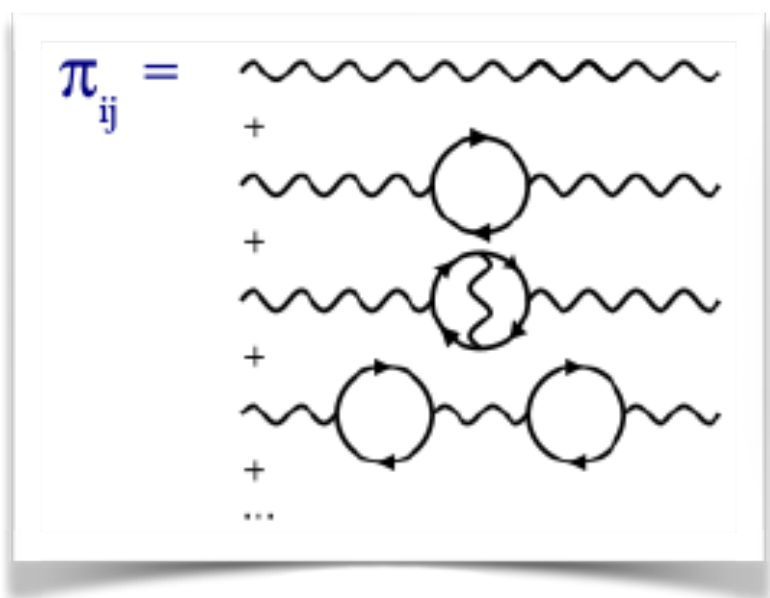
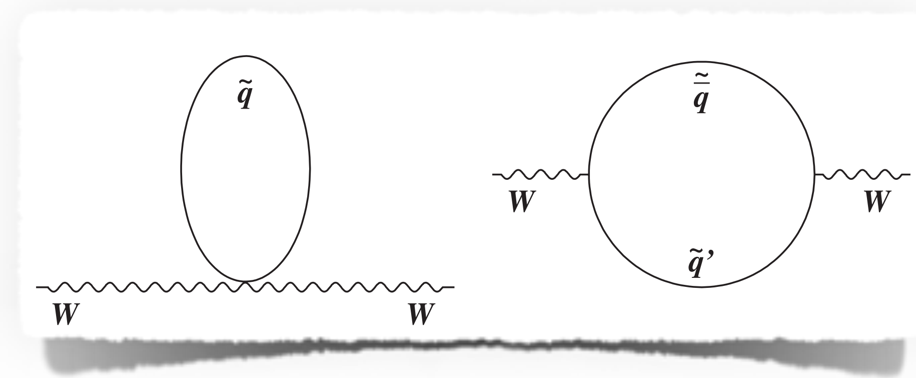
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{em}}{\sqrt{2}G_F}\frac{1}{1-\Delta r}$$



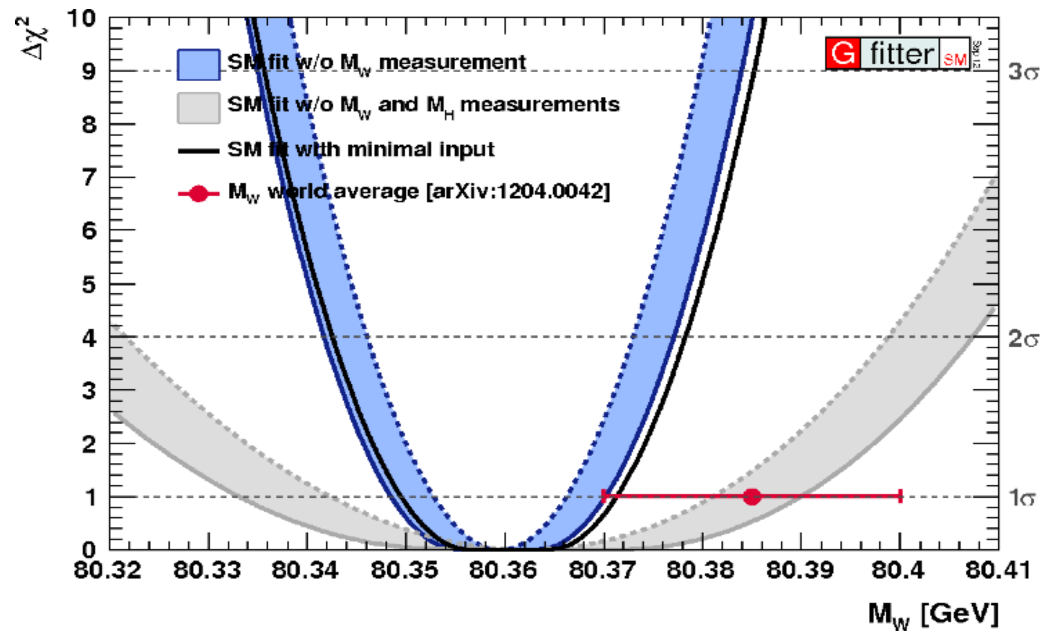


W mass workshop
Mainz, Germany
9 February 2017

Overview

First priority: measure and calculate m_W in the SM to <5 MeV

Second priority: study implications for physics beyond the SM



Discuss here two cases:
an effective field theory (EFT) and the phenomenological MSSM (pMSSM)

EFT: general framework for describing perturbative physics at a high scale

pMSSM: well-motivated class of models with TeV-scale particles

SM effective field theory

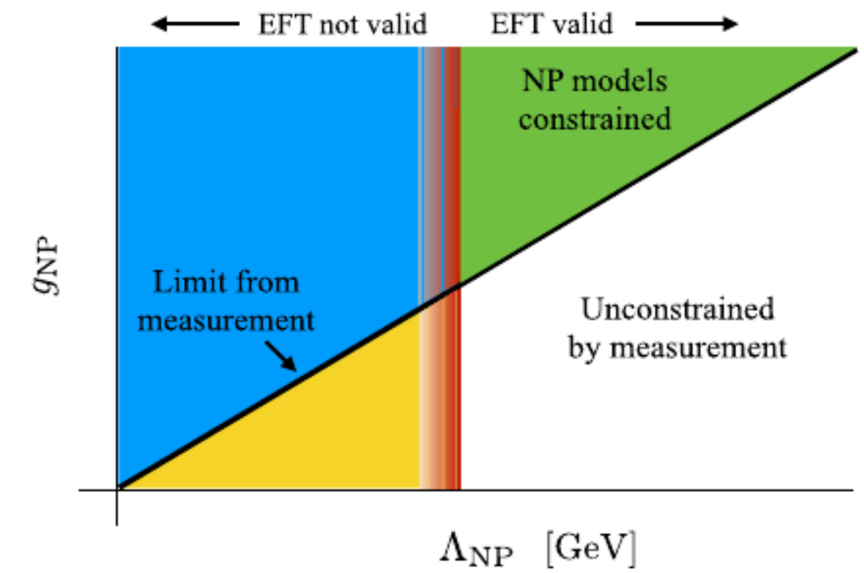
Parametrize high-scale physics in powers of inverse scale of effective operators

For example: $c_{WWZ}\,(v^2/\Lambda_{NP}^2)(W_{\mu\nu}\,W^{\nu\rho}\,Z_\rho{}^\mu)$

Dimensionless effective coupling

Suppression from scale hierarchy

Dimension-6 operator



PLB 740 (2015) 8

1610.07922, Sec. II.2.3

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \mathcal{L}_8 + \cdots$$

One operator violating lepton number conservation

76 operators conserving baryon number (one generation)
2499 operators for three generations
4 operators violating baryon number conservation

Equations of motion reduce number of dimension-6 operators from 76 to 59

Dimension-6 SM EFT

Operators fall into categories:

1. Four-fermion operators: 21
2. Gluon self-interaction operators: 3
3. Higgs and electroweak operators: 35

(SILH basis)

Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2} \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Yukawa and Dipole	
$[O_e]_{ij}$	$\frac{\sqrt{2m_{e_i} m_{e_j}}}{v^3} H^\dagger H \bar{\ell}_i H e_j$
$[O_u]_{ij}$	$\frac{\sqrt{2m_{u_i} m_{u_j}}}{v^3} H^\dagger H \bar{q}_i \widetilde{H} u_j$
$[O_d]_{ij}$	$\frac{\sqrt{2m_{d_i} m_{d_j}}}{v^3} H^\dagger H \bar{q}_i H d_j$
$[O_{eW}]_{ij}$	$\frac{g}{m_W^2} \frac{\sqrt{2m_{e_i} m_{e_j}}}{v} \bar{\ell}_i \sigma^k H \sigma_{\mu\nu} e_j W^k_{\mu\nu}$
$[O_{eB}]_{ij}$	$\frac{g'}{m_W^2} \frac{\sqrt{2m_{e_i} m_{e_j}}}{v} \bar{\ell}_i H \sigma_{\mu\nu} e_j B_{\mu\nu}$
$[O_{uG}]_{ij}$	$\frac{g_s}{m_W^2} \frac{\sqrt{2m_{u_i} m_{u_j}}}{v} \bar{q}_i \tilde{H} \sigma_{\mu\nu} T^a u_j G^a_{\mu\nu}$
$[O_{uW}]_{ij}$	$\frac{g}{m_W^2} \frac{\sqrt{2m_{u_i} m_{u_j}}}{v} \bar{q}_i \sigma^k \tilde{H} \sigma_{\mu\nu} u_j W^k_{\mu\nu}$
$[O_{uB}]_{ij}$	$\frac{g'}{m_W^2} \frac{\sqrt{2m_{u_i} m_{u_j}}}{v} \bar{q}_i \tilde{H} \sigma_{\mu\nu} u_j B_{\mu\nu}$
$[O_{dG}]_{ij}$	$\frac{g_s}{m_W^2} \frac{\sqrt{2m_{d_i} m_{d_j}}}{v} \bar{q}_i H \sigma_{\mu\nu} T^a d_j G^a_{\mu\nu}$
$[O_{dW}]_{ij}$	$\frac{g}{m_W^2} \frac{\sqrt{2m_{d_i} m_{d_j}}}{v} \bar{q}_i \sigma^k H \sigma_{\mu\nu} d_j W^k_{\mu\nu}$
$[O_{dB}]_{ij}$	$\frac{g'}{m_W^2} \frac{\sqrt{2m_{d_i} m_{d_j}}}{v} \bar{q}_i H \sigma_{\mu\nu} d_j B_{\mu\nu}$

Vertex	
$[O_{He}]_{ij}$	$\frac{i}{v^2} \bar{e}_i \gamma_\mu \bar{e}_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hq}]_{ij}$	$\frac{i}{v^2} \bar{q}_i \gamma_\mu q_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{Hq}]_{ij}$	$\frac{i}{v^2} \bar{q}_i \sigma^k \gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{ij}$	$\frac{i}{v^2} \bar{u}_i \gamma_\mu u_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{ij}$	$\frac{i}{v^2} \bar{d}_i \gamma_\mu d_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{ij}$	$\frac{i}{v^2} \bar{u}_i \gamma_\mu d_j \tilde{H}^\dagger D_\mu H$

1610.07922,
Sec. III.2.1

Oblique corrections and EFT

Historical parametrization of new physics in electroweak propagators: S, T, U

S, T related to dimension-6 operators; U related to dimension-8 operator

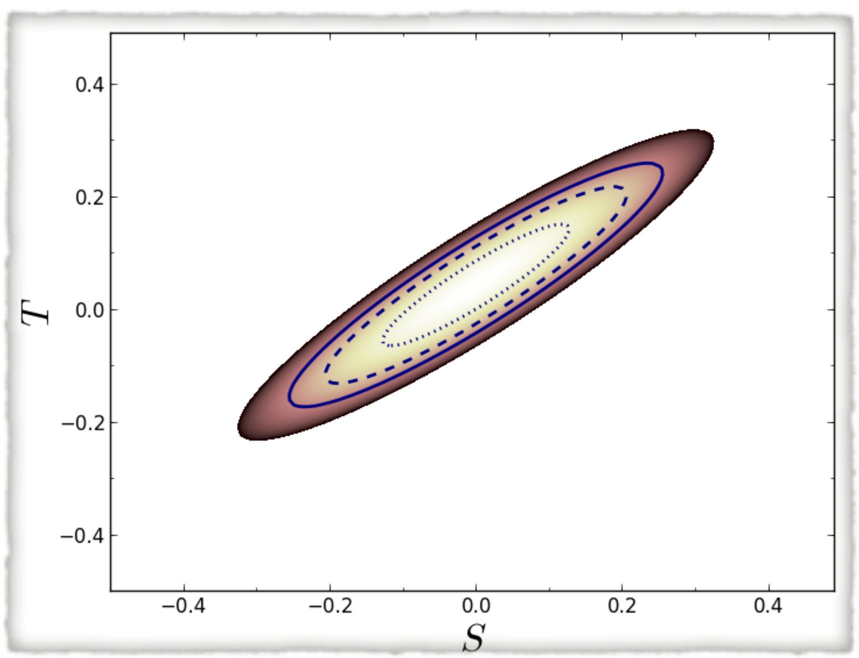
$$\mathcal{L}_{\rm VV} = -W^{+\mu}\pi_{+-}\left(p^2\right)W^-_\mu - \frac{1}{2}W^{3\mu}\pi_{33}\left(p^2\right)W^3_\mu - W^{3\mu}\pi_{3B}\left(p^2\right)B_\mu - \frac{1}{2}B^\mu\pi_{BB}\left(p^2\right)B_\mu$$

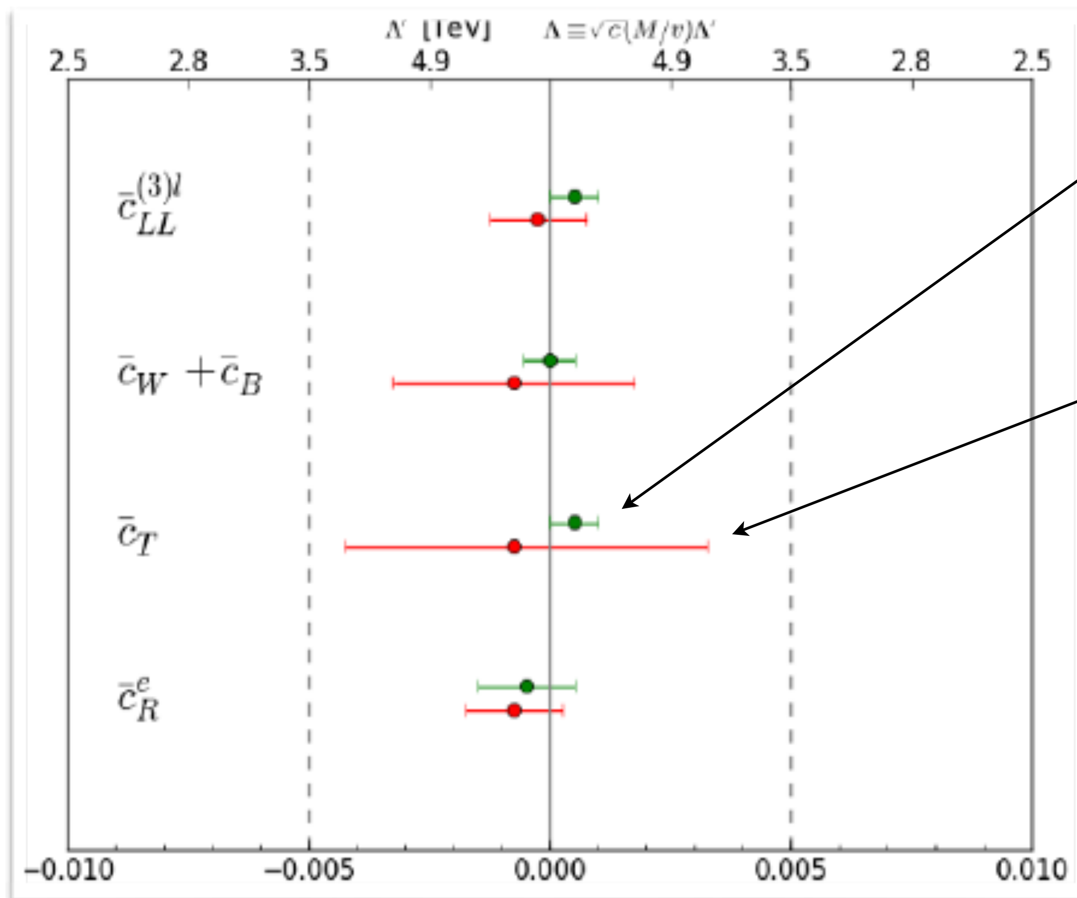
$$\mathcal{L}_{\text{dim-6}} \supset \frac{\bar{c}_{WB}}{m_W^2}\mathcal{O}_{WB} + \frac{\bar{c}_W}{m_W^2}\mathcal{O}_W + \frac{\bar{c}_B}{m_W^2}\mathcal{O}_B + \frac{\bar{c}_T}{v^2}\mathcal{O}_T + \frac{\bar{c}_{2W}}{m_W^2}\mathcal{O}_{2W} + \frac{\bar{c}_{2B}}{m_W^2}\mathcal{O}_{2B}$$

Traditional constraints from m_Z (S), Γ_Z (T), m_W (U)

$$\hat{S} \equiv \frac{g}{g'}\frac{\pi'_{3B}(0)}{\pi'_{+-}(0)} \qquad \hat{T} \equiv \frac{\pi_{+-}(0) - \pi_{33}(0)}{\pi_{+-}(0)}$$

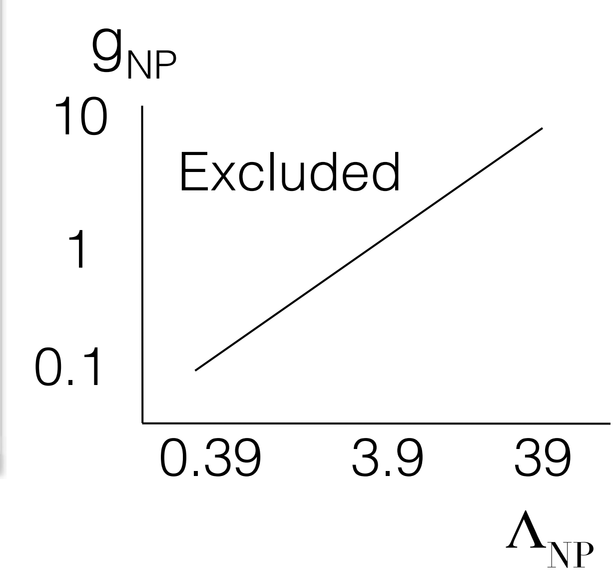
$$\hat{S} = \bar{c}_W + \bar{c}_B \qquad \hat{T} = \bar{c}_T$$





Individual constraint: $0 < c_T < 0.002$

Global fit constraint: $|c_T| < 0.004$



Use m_Z as an input:
Individual impact of m_W not clear

JHEP 03 (2015) 157

Phenomenological MSSM

Supersymmetry the best motivated model for TeV-scale physics
Must search systematically and exhaustively

Phenomenological MSSM defines free parameters broadly consistent with existing constraints
A number of dedicated studies probe the available parameter space

ATLAS combined Run 1 direct searches with Higgs measurements to exclude models defined by scanning 19 parameters up to mass scales of 4 TeV

Parameter	**Minimum value**	**Maximum value**
$\Delta\rho$	-0.0005	0.0017
$\Delta(g-2)_\mu$	-17.7×10^{-10}	43.8×10^{-10}
$\mathrm{BR}(b \to s\gamma)$	2.69×10^{-4}	3.87×10^{-4}
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	1.6×10^{-9}	4.2×10^{-9}
$\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$	66×10^{-6}	161×10^{-6}
$\Omega_{\tilde{\chi}_1^0} h^2$	—	0.1208
$\Gamma_{\mathrm{invisible(SUSY)}}(Z)$	—	2 MeV
Masses of charged sparticles	100 GeV	—
$m(\tilde{\chi}_1^\pm)$	103 GeV	—
$m(\tilde{u}_{1,2}, \tilde{d}_{1,2}, \tilde{c}_{1,2}, \tilde{s}_{1,2})$	200 GeV	—
$m(h)$	124 GeV	128 GeV

Parameter	**Min value**	**Max value**	**Note**
$m_{\tilde{L}_1}(= m_{\tilde{L}_2})$	90 GeV	4 TeV	Left-handed slepton (first two gens.) mass
$m_{\tilde{e}_1}(= m_{\tilde{e}_2})$	90 GeV	4 TeV	Right-handed slepton (first two gens.) mass
$m_{\tilde{L}_3}$	90 GeV	4 TeV	Left-handed stau doublet mass
$m_{\tilde{e}_3}$	90 GeV	4 TeV	Right-handed stau mass
$m_{\tilde{Q}_1}(= m_{\tilde{Q}_2})$	200 GeV	4 TeV	Left-handed squark (first two gens.) mass
$m_{\tilde{u}_1}(= m_{\tilde{u}_2})$	200 GeV	4 TeV	Right-handed up-type squark (first two gens.) mass
$m_{\tilde{d}_1}(= m_{\tilde{d}_2})$	200 GeV	4 TeV	Right-handed down-type squark (first two gens.) mass
$m_{\tilde{Q}_3}$	100 GeV	4 TeV	Left-handed squark (third gen.) mass
$m_{\tilde{u}_3}$	100 GeV	4 TeV	Right-handed top squark mass
$m_{\tilde{d}_3}$	100 GeV	4 TeV	Right-handed bottom squark mass
$\|M_1\|$	0 GeV	4 TeV	Bino mass parameter
$\|M_2\|$	70 GeV	4 TeV	Wino mass parameter
$\|\mu\|$	80 GeV	4 TeV	Bilinear Higgs mass parameter
M_3	200 GeV	4 TeV	Gluino mass parameter
$\|A_t\|$	0 GeV	8 TeV	Trilinear top coupling
$\|A_b\|$	0 GeV	4 TeV	Trilinear bottom coupling
$\|A_\tau\|$	0 GeV	4 TeV	Trilinear τ lepton coupling
M_A	100 GeV	4 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

JHEP 10 (2015) 134

m_W and pMSSM scan

Ideally incorporate m_W measurement into pMSSM constraints
Existing scan uses an m_W window of 80340 - 80428 MeV
ATLAS measurement would lower upper bound to 80408 MeV at 95% CL

Can use existing scan to find relative reduction of parameter space, but not total reduction of parameter space, from the W mass constraint

Dominant contribution to m_W is from stop and sbottom quarks:

arXiv:hep-ph/0412214

$$\Delta\rho_0^{\mathrm{SUSY}} = \frac{3G_\mu}{8\sqrt{2}\pi^2}\Big[-\sin^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{t}}\mathrm{F}_0\left(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}\right) - \sin^2\theta_{\tilde{b}}\cos^2\theta_{\tilde{b}}\mathrm{F}_0\left(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}\right)$$
$$+\cos^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{b}}\mathrm{F}_0\left(m^2_{\tilde{t}_1}, m^2_{\tilde{b}_1}\right) + \cos^2\theta_{\tilde{t}}\sin^2\theta_{\tilde{b}}\mathrm{F}_0\left(m^2_{\tilde{t}_1}, m^2_{\tilde{b}_2}\right)$$
$$+\sin^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{b}}\mathrm{F}_0\left(m^2_{\tilde{t}_2}, m^2_{\tilde{b}_1}\right) + \sin^2\theta_{\tilde{t}}\sin^2\theta_{\tilde{b}}\mathrm{F}_0\left(m^2_{\tilde{t}_2}, m^2_{\tilde{b}_2}\right)\Big]$$

$$\rho = \frac{M_W^2}{M_Z^2\cos^2\theta_W} = \frac{1}{1-\Delta\rho}$$

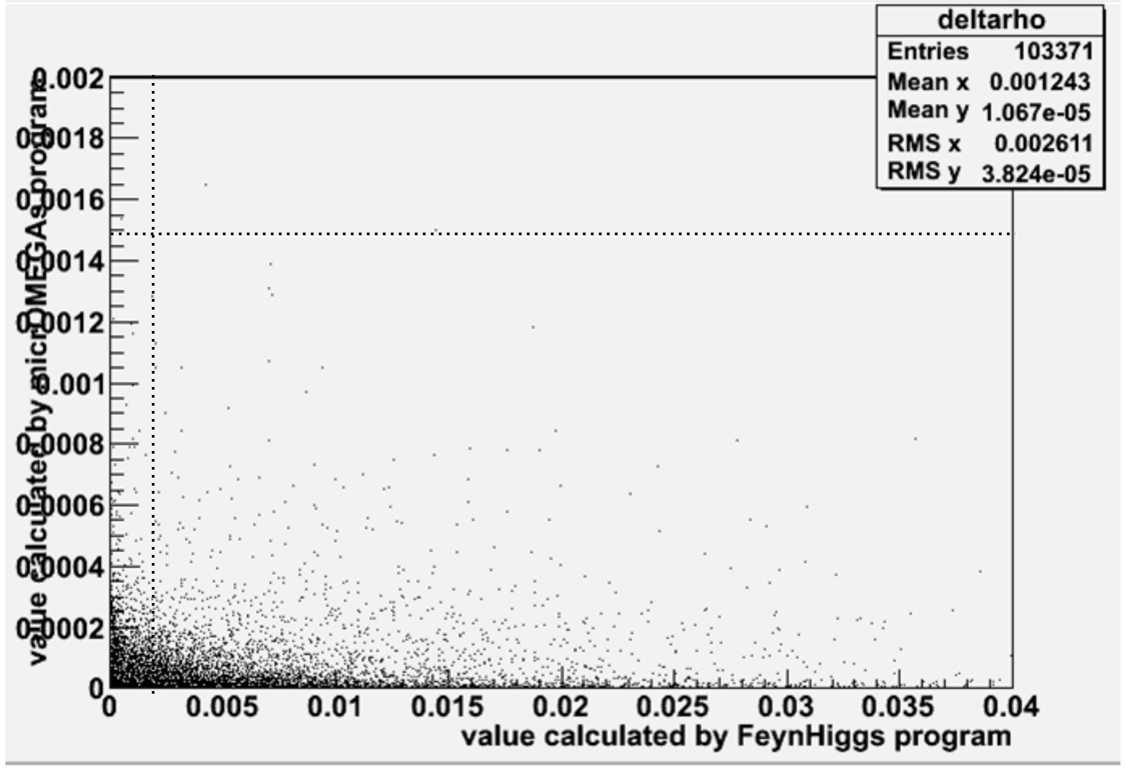
$$\mathrm{F}_0(x,y) = x + y - \frac{2xy}{x-y}\ln\left(\frac{x}{y}\right).$$

← 0 for x=y

m_W and pMSSM scan

Initial study: calculated m_W using model parameters and FeynHiggs 2.11.2
Includes QCD corrections to the sbottom mass that affect it by up to 100 GeV
Corrections are not in FeynHiggs 2.3.2 or micrOMEGAs
  micrOMEGAs used to constrain the model points in the ATLAS scan

In probing fractional reduction of parameter space need to use micrOMEGAs for consistency
After discovering SUSY we will need corrections when mapping measurements to parameters
  Will be a source of parameter uncertainty



Summary

W mass measurement significantly constrains new physics

Effects that contribute differently to m_W and m_Z
E.g. squarks with non-universal masses

Investigating impact of m_W measurements on EFT and pMSSM

Ideally produce new propaganda plots in these frameworks