

The LHC precision challenges - the SM perspective

Pietro Slavich

(LPTHE)

Challenges for Precision Physics at the LHC

LPNHE, Paris, 15-18 December 2010

The LHC EW precision challenges - the SM perspective

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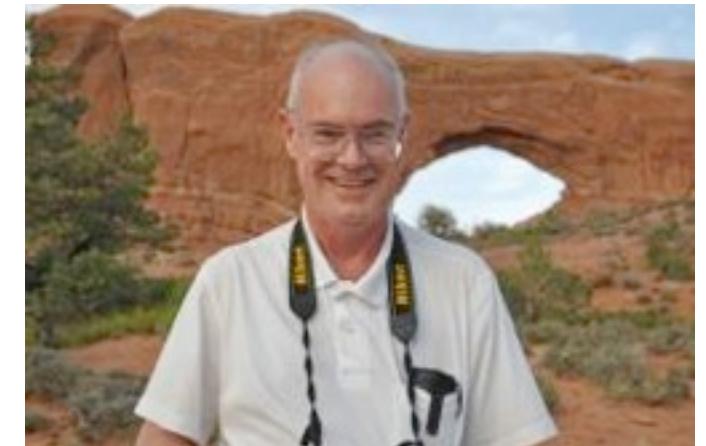
LPNHE, Paris, 15-18 December 2010

Ulrich Baur, 1957 - 2010

Precision Physics at the LHC

1. Motivation
2. Why?
3. W Mass and Width, and $\sin^2 \theta_W$
4. Gauge Boson Self-interactions
5. Higgs Boson Couplings
6. Conclusions

Ulrich Baur
State University of New York at Buffalo



Three meanings of “uncertainty”

- experimental precision of the measurements
 - accumulating statistics
 - understanding beams and detectors
- theoretical precision in extracting “*pseudo-observables*” from measurements
 - modeling signal and background processes (kinematic distributions etc)
 - at hadron colliders: modeling the initial parton-parton state (PDFs)
- theoretical precision in testing the underlying theory (SM, BSM)
 - determining the relations among pseudo-observables

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“Remember that the velocity of the guerrilla band on the march is equal to the velocity of its slowest man”
(Ernesto “Che” Guevara, Guerrilla Warfare, 1961)

Les Houches 2009 “wishlist” for higher-order calculations

Process ($V \in \{Z, W, \gamma\}$)	Comments	Motivation
pre Les Houches 2007	(completed)	
1. $pp \rightarrow VV\text{jet}$ 2. $pp \rightarrow \text{Higgs}+2\text{jets}$ 3. $pp \rightarrow VVV$ 4. $pp \rightarrow t\bar{t}b\bar{b}$ 5. $pp \rightarrow W+3\text{jets}$	$V = Z$ cases missing, W -decays included NLO QCD+EW to VBF γ cases missing $m_b = 0$, no t -decay W -decay included	Higgs background new physics background background for $t\bar{t}H$ new physics background
Les Houches 2007	(in progress)	
6. $pp \rightarrow t\bar{t}+2\text{jets}$ 7. $pp \rightarrow WWb\bar{b}$, 8. $pp \rightarrow VV+2\text{jets}$ 9. $pp \rightarrow b\bar{b}b\bar{b}$	V -decays useful	relevant for $t\bar{t}H$ relevant for $t\bar{t}$ benchmark process $\text{VBF} \rightarrow H \rightarrow VV$ Higgs and new physics signatures
	two-loop observables	
10. $gg \rightarrow W^*W^*$ 11. $pp \rightarrow t\bar{t}$ 12. $pp \rightarrow Z/\gamma+\text{jet}$ 13. $pp \rightarrow W/Z$	NLO QCD NNLO QCD NNLO QCD NNLO QCD \oplus NLO EW	Higgs background benchmark process pdf, jet-energy measurements benchmark process
Les Houches 2009		
14. $pp \rightarrow W+3\text{jets}$ 15. $pp \rightarrow Wb\bar{b}j$ 16. $pp \rightarrow jjjj$ 17. $pp \rightarrow t\bar{t}t\bar{t}$ 18. $pp \rightarrow Wjjjj$ 19. $H \rightarrow f\bar{f}f'\bar{f}'$	W -decay included $m_b = 0$ sufficient (?) leading color sufficient (?) NLO EW+QCD (completed)	new physics background Higgs search new physics background new physics background new physics background Higgs search
	(two-loop)	
20. $gg \rightarrow H$ 21. $pp \rightarrow VV$ 22. $pp \rightarrow Hj$	NLO EW (completed) NNLO NNLO ($m_t \rightarrow \infty$)	Higgs search benchmark process Higgs search

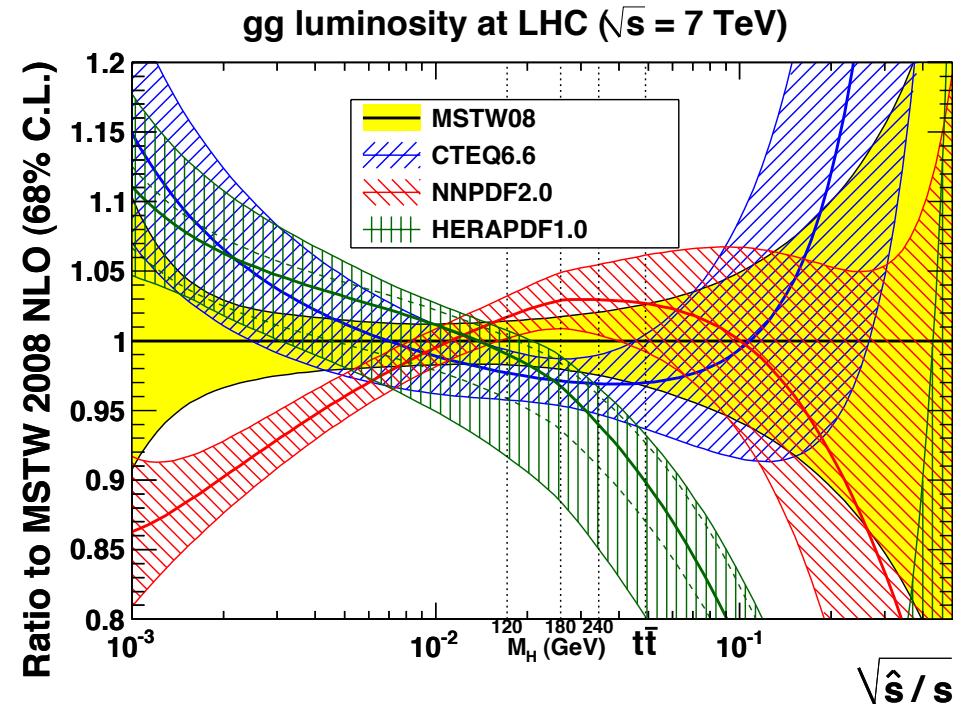
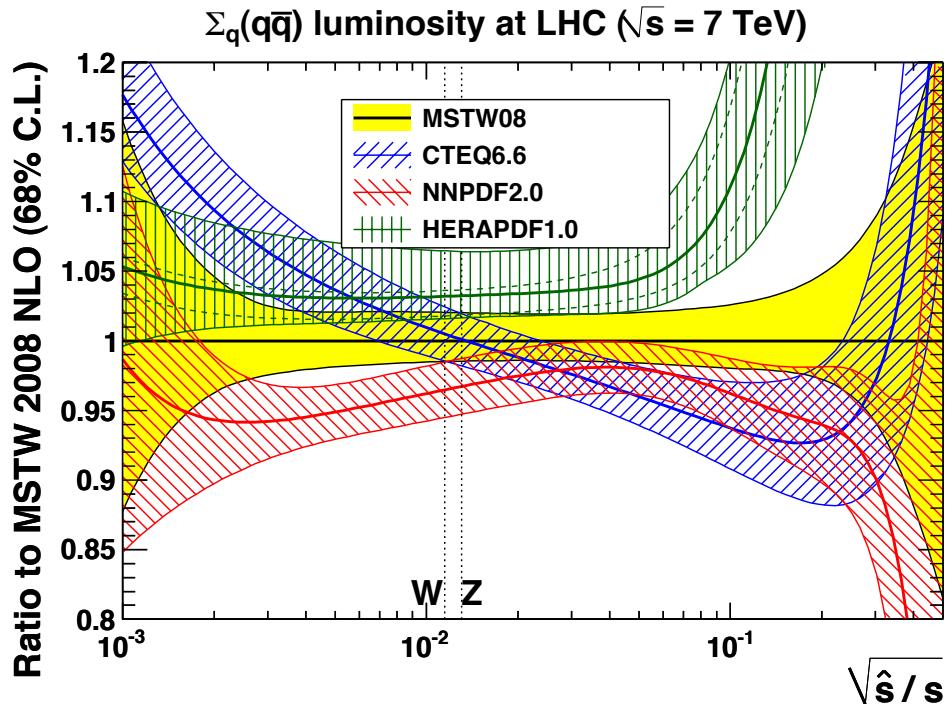
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Experimenter’s wishes for
a precise simulation of
signals and backgrounds

*Slowly but surely
filling up...*

Could be the subject
of a whole other talk (Fawzi’s?)

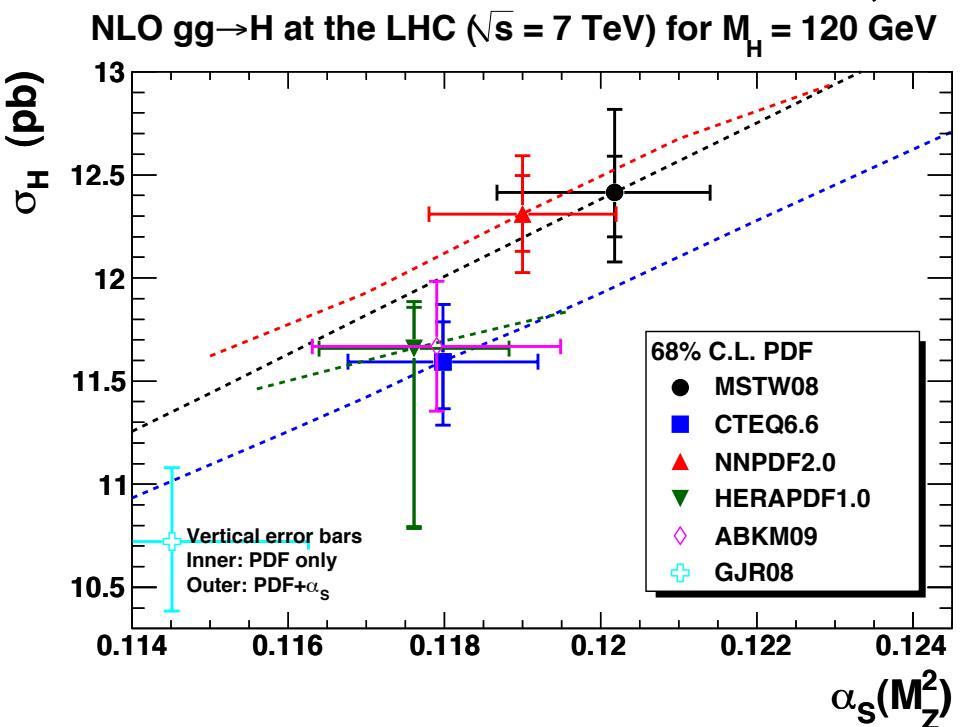
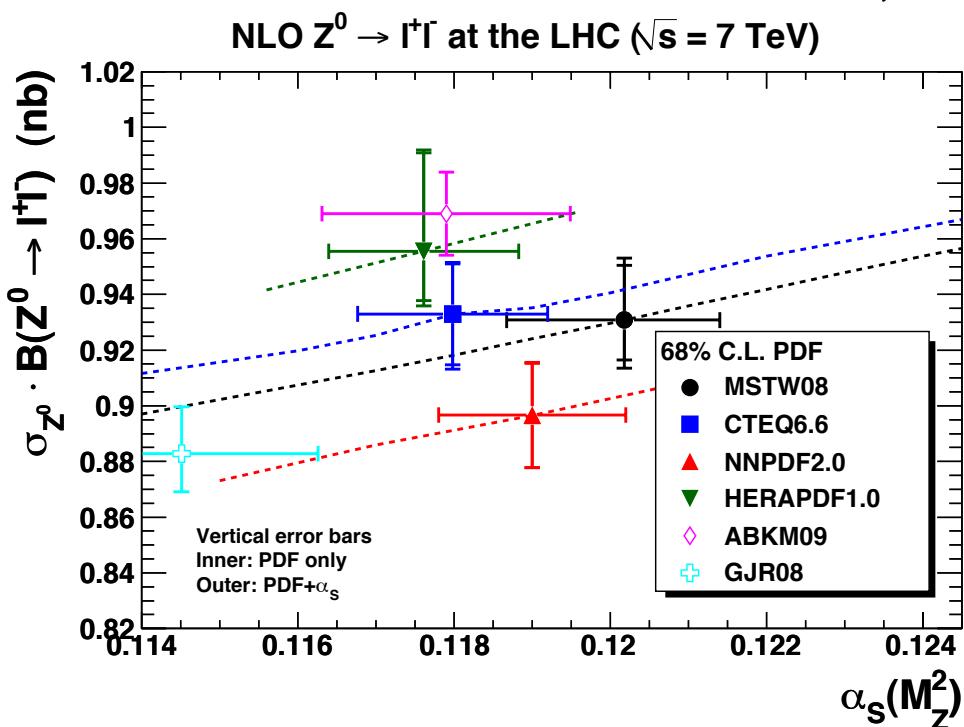
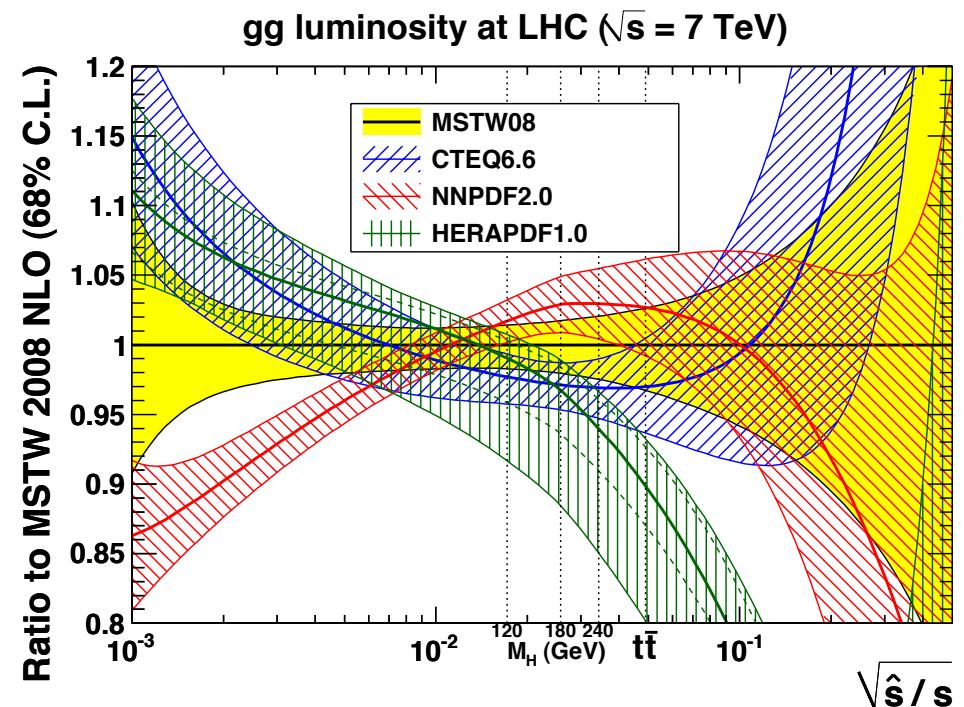
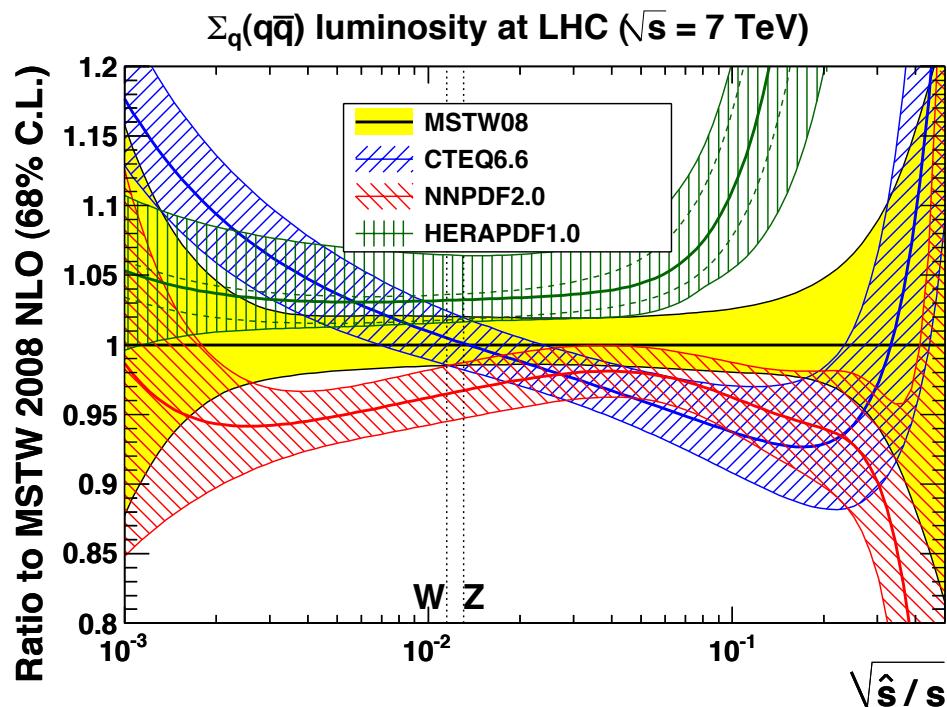
Are the PDFs the slowest guerrilla? (plots by G. Watt of MSTW)



parton luminosities:

$$\frac{\partial \mathcal{L}_{ab}}{\partial(\hat{s}/s)} = \int_0^1 dx_a dx_b f_a(x_a, \hat{s}) f_b(x_b, \hat{s}) \delta(x_a x_b - \hat{s}/s)$$

Are the PDFs the slowest guerrilla? (plots by G. Watt of MSTW)



The differences are due to: choice for $\alpha_s(M_Z)$;
data sets; treatment of errors; treatment of heavy quarks; parametrization at Q_0 ;
theoretical assumptions (flavor symmetries, x -limits); ...

The current recommendation of the PDF4LHC working group:

<< Use the envelope provided by the central values and PDF+as errors from the MSTW08, CTEQ6.6 and NNPDF2.0 PDFs. As a central value, use the midpoint of this envelope >>

Realistic estimate of PDF error in the 5-10% range. What prospects for improvement?

Future

- PDF4LHC generally seen as a very useful discussion forum for PDF questions
- Reaching a level of high sophistication and detailed understanding of PDFs. Clearly not a simple subject
- New data coming, most notably:
 - HERA precision data (High x , Heavy Flavours...)
 - The LHC data.

Future

- Many topics of study to be explored further
 - Heavy flavors (HF data from HERA wanted)
 - α_s studies
 - NNLO
 - Include new data in the fits
 - Benchmark points/TH uncertainties
 - Total uncertainties
 -
- Update recommendation in due time

(two slides by A. DeRoeck, PDF4LHC Meeting, DESY, 29/11/2010)

Precision tests of the SM electroweak sector

An exercise: let's start from a set of well-measured electroweak (*pseudo*)-observables

- fine-structure constant
(from Thomson scattering) $\alpha = 1/137.03599911(46)$
- Fermi coupling constant
(from muon decay) $G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}$
- Z-boson mass
(from LEP data) $m_Z = 91.1876(21) \text{ GeV}$
- leptonic width of the Z
(from LEP data) $\Gamma_{\ell^+\ell^-} = 83.984(86) \text{ MeV}$
- W-boson mass
(from LEP+Tevatron data) $m_W = 80.399(23) \text{ GeV}$
- effective leptonic Weinberg angle (from LEP+SLC data) $s_{\text{eff}}^2 = 0.23153(16)$

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \equiv \frac{(1/2 - s_{\text{eff}}^2)^2 - s_{\text{eff}}^4}{(1/2 - s_{\text{eff}}^2)^2 + s_{\text{eff}}^4}$$

At **tree level**, all of the observables can be expressed in terms of *three* parameters of the SM Lagrangian: v, g, g' or, equivalently, $v, e, s \equiv \sin \theta_W$ (also $c \equiv \cos \theta_W$)

$$\alpha = \frac{e^2}{4\pi}, \quad G_F = \frac{1}{2\sqrt{2}v^2}, \quad m_Z = \frac{ev}{\sqrt{2}sc}, \quad m_W = \frac{ev}{\sqrt{2}s}, \quad s_{\text{eff}}^2 = s^2,$$

$$\Gamma_{\ell^+\ell^-} = \frac{v}{48\sqrt{2}\pi} \frac{e^3}{s^3 c^3} \left[\left(-\frac{1}{2} + 2s^2 \right)^2 + \frac{1}{4} \right]$$

Is this consistent with the experimental data? To check, we compute the three Lagrangian parameters in terms of the best-measured observables α, G_F, m_Z

$$e^2 = 4\pi\alpha, \quad v^2 = \frac{1}{2\sqrt{2}G_F}, \quad s^2 = \frac{1}{2} - \frac{1}{2}\sqrt{1 - \frac{2\sqrt{2}\pi\alpha}{G_F m_Z^2}}$$

and we plug the resulting values of v, e, s in the expressions for $m_W, s_{\text{eff}}^2, \Gamma_{\ell^+\ell^-}$

<i>tree-level predictions</i>	<i>experimental values</i>
$m_W = 80.939 \text{ GeV}$	$80.399 \pm 0.023 \text{ GeV}$
$s_{\text{eff}}^2 = 0.21215$	0.23153 ± 0.00016
$\Gamma_{\ell^+\ell^-} = 80.842 \text{ MeV}$	$83.984 \pm 0.086 \text{ MeV}$

Off by many standard deviations!!!

What happened? We tried to use the SM relations at tree level to predict some observables in terms of other observables, and we failed badly

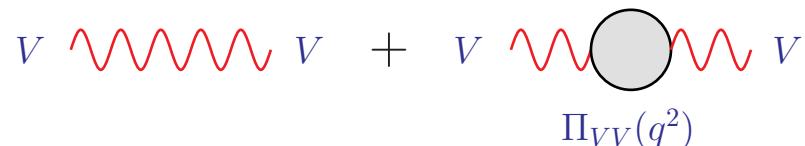


Obviously the tree level is not good enough!

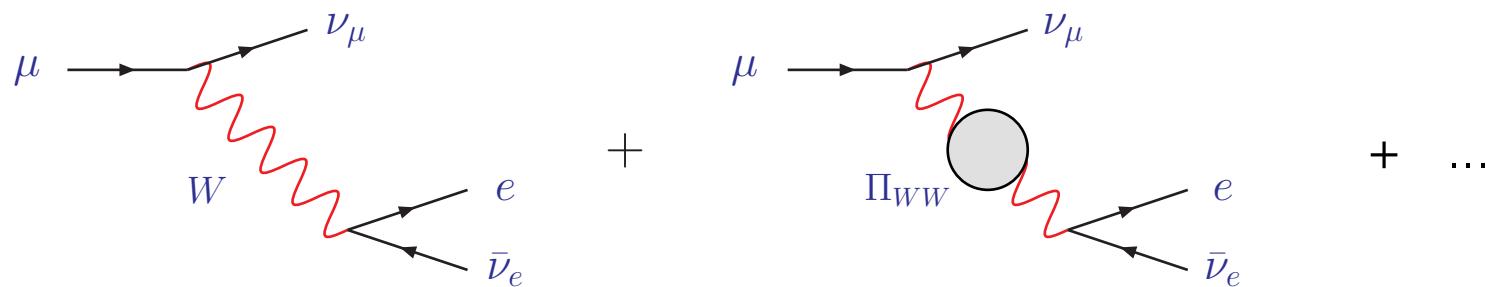
Radiative corrections to the relations between physical observables and Lagrangian params:

$$m_Z^2 = \frac{e^2 v^2}{2 s^2 c^2} + \Pi_{ZZ}(m_Z^2)$$

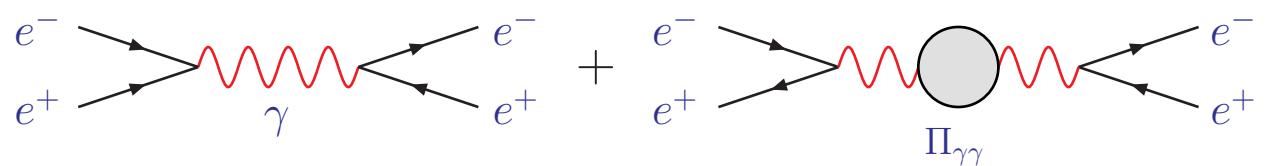
$$m_W^2 = \frac{e^2 v^2}{2 s^2} + \Pi_{WW}(m_W^2)$$



$$G_F = \frac{1}{2\sqrt{2}v^2} \left[1 - \frac{\Pi_{WW}(0)}{m_W^2} + \delta_{VB} \right]$$



$$\alpha = \frac{e^2}{4\pi} \left[1 + \lim_{q^2 \rightarrow 0} \frac{\Pi_{\gamma\gamma}(q^2)}{q^2} \right]$$



this one is tricky: the hadronic contribution to $\Pi'_{\gamma\gamma}(0)$ cannot be computed perturbatively

We can however trade it for another experimental observable: $R_{\text{had}}(q^2) = \frac{\sigma_{\text{had}}(q^2)}{\sigma_{\ell^+\ell^-}(q^2)}$

$$\alpha(m_Z) = \frac{e^2}{4\pi} \left[1 + \frac{\Pi_{\gamma\gamma}(m_Z)}{m_Z} \right] = \frac{\alpha}{1 - \Delta\alpha(m_Z)}$$

$$\Delta\alpha(m_Z) = \underbrace{\Delta\alpha_\ell(m_Z) + \Delta\alpha_{\text{top}}(m_Z) + \Delta\alpha_{\text{had}}^{(5)}(m_Z)}_{\text{calculable}}$$

$$\Delta\alpha_{\text{had}}^{(5)}(m_Z) = -\frac{m_Z^2}{3\pi} \int_{4m_\pi^2}^\infty \frac{R_{\text{had}}(q^2) dq^2}{q^2 (q^2 - m_Z^2)} = 0.02758 \pm 0.00035$$

(This hadronic contribution is one of the biggest sources of uncertainty in EW studies)

All these corrections can be combined into relations among physical observables, e.g.:

$$m_W^2 = m_Z^2 \left[\frac{1}{2} + \frac{1}{2} \sqrt{1 - \frac{2\sqrt{2}\pi\alpha}{G_F m_Z^2} (1 + \Delta r)} \right]$$

Δr can be parametrized in terms of two universal corrections and a remainder:

$$\Delta r = \Delta\alpha(m_Z) - \frac{c^2}{s^2} \Delta\rho + \Delta r_{\text{rem}}$$

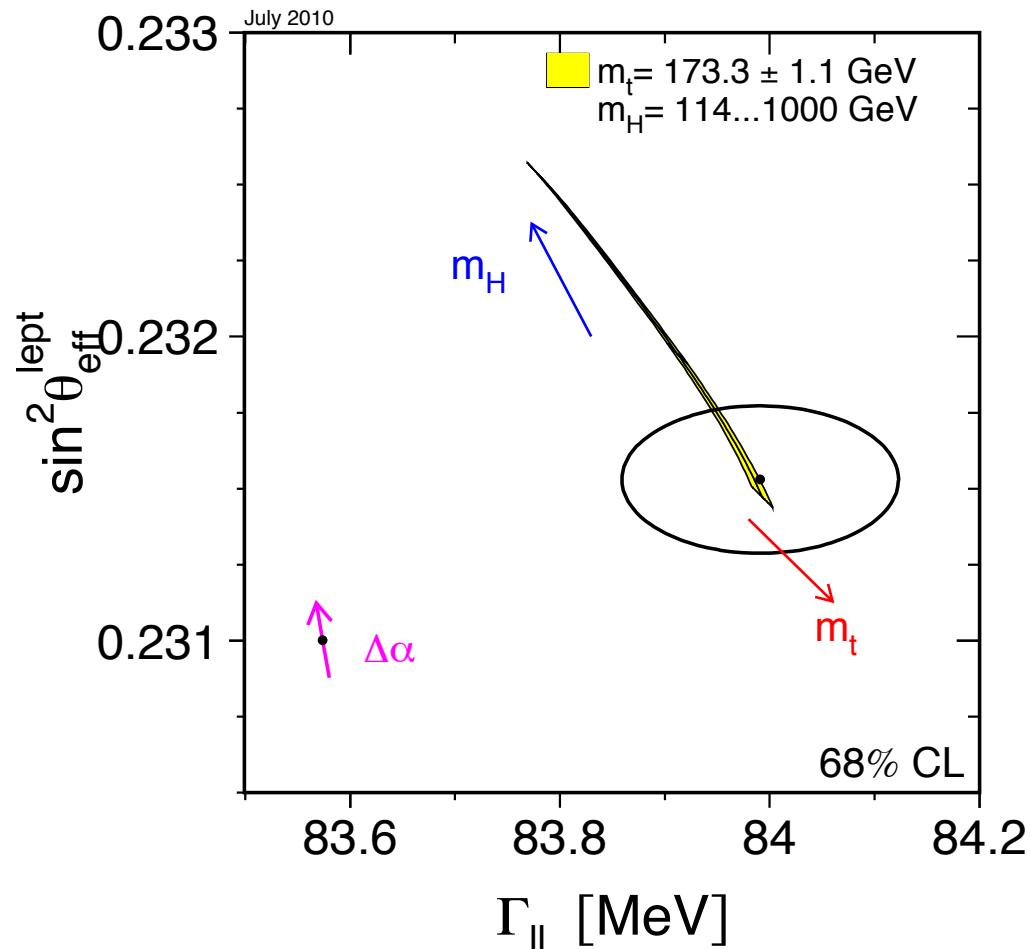
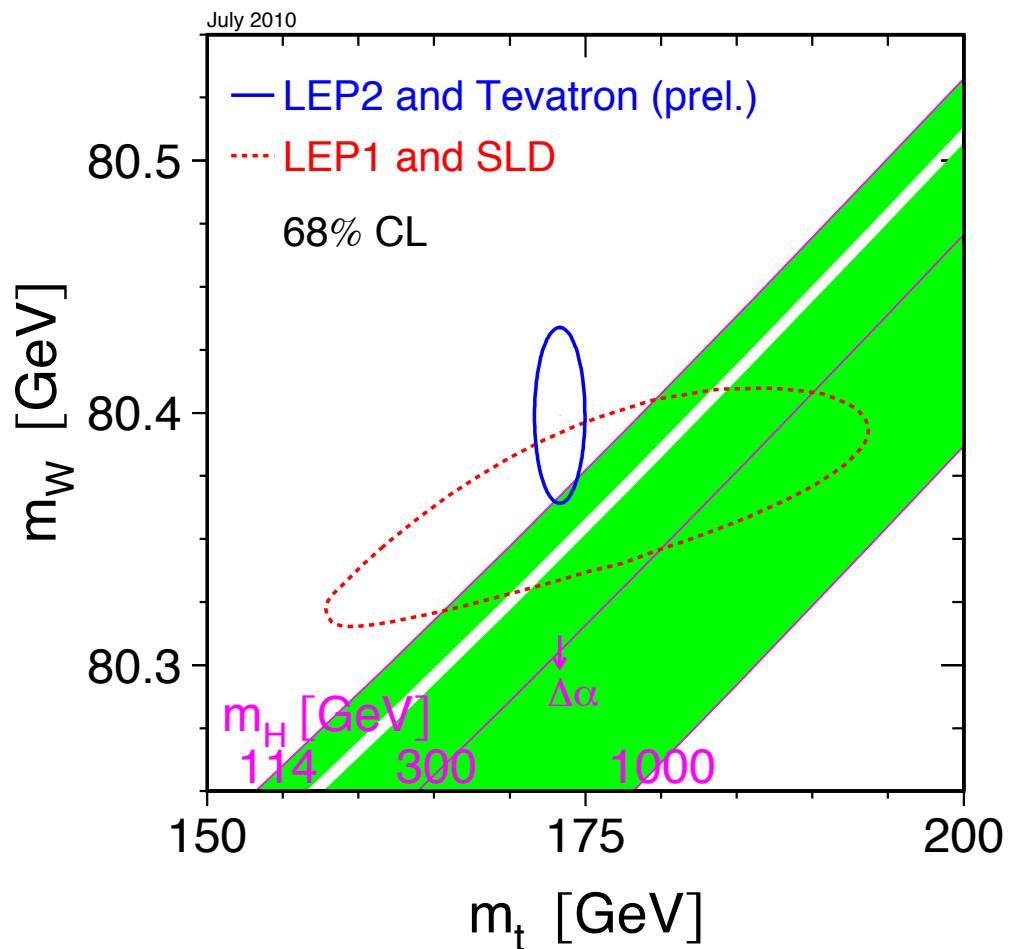
The leading corrections depend quadratically on m_t but only logarithmically on m_H :

$$\Delta\rho = \frac{\Pi_{ZZ}(0)}{m_Z^2} - \frac{\Pi_{WW}(0)}{m_W^2} \approx \frac{3\alpha}{16\pi c^2} \left(\frac{m_t^2}{s^2 m_Z^2} + \log \frac{m_H^2}{m_W^2} + \dots \right)$$

$$\frac{\delta m_W^2}{m_W^2} \approx \frac{c^2}{c^2 - s^2} \Delta\rho, \quad \delta \sin^2 \theta_{\text{eff}} \approx -\frac{c^2 s^2}{c^2 - s^2} \Delta\rho$$

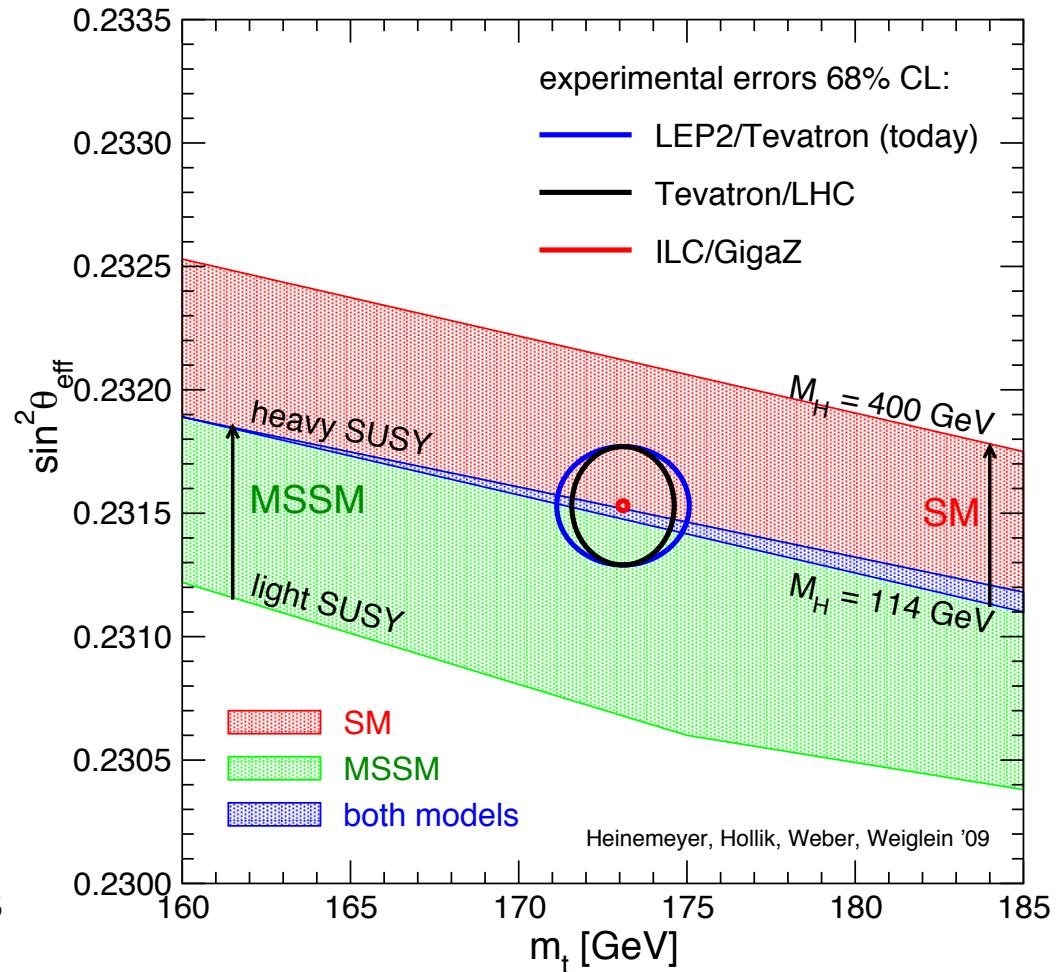
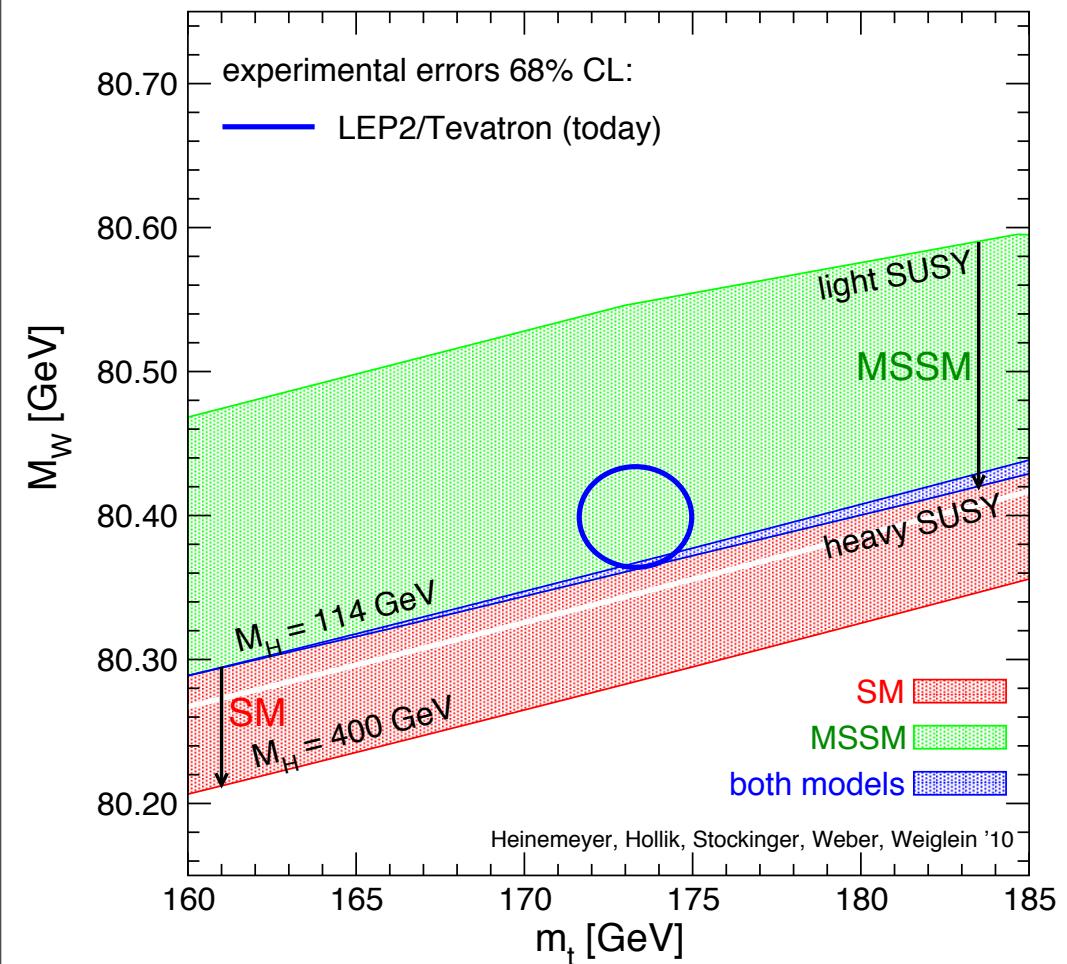
In the SM the predictions for m_W and $\sin^2 \theta_{\text{eff}}$ have been fully computed at the two-loop order, plus some leading (top/strong) corrections at three and four loops

Comparing predictions and experiment (LEP/TEV EWWG 2010)



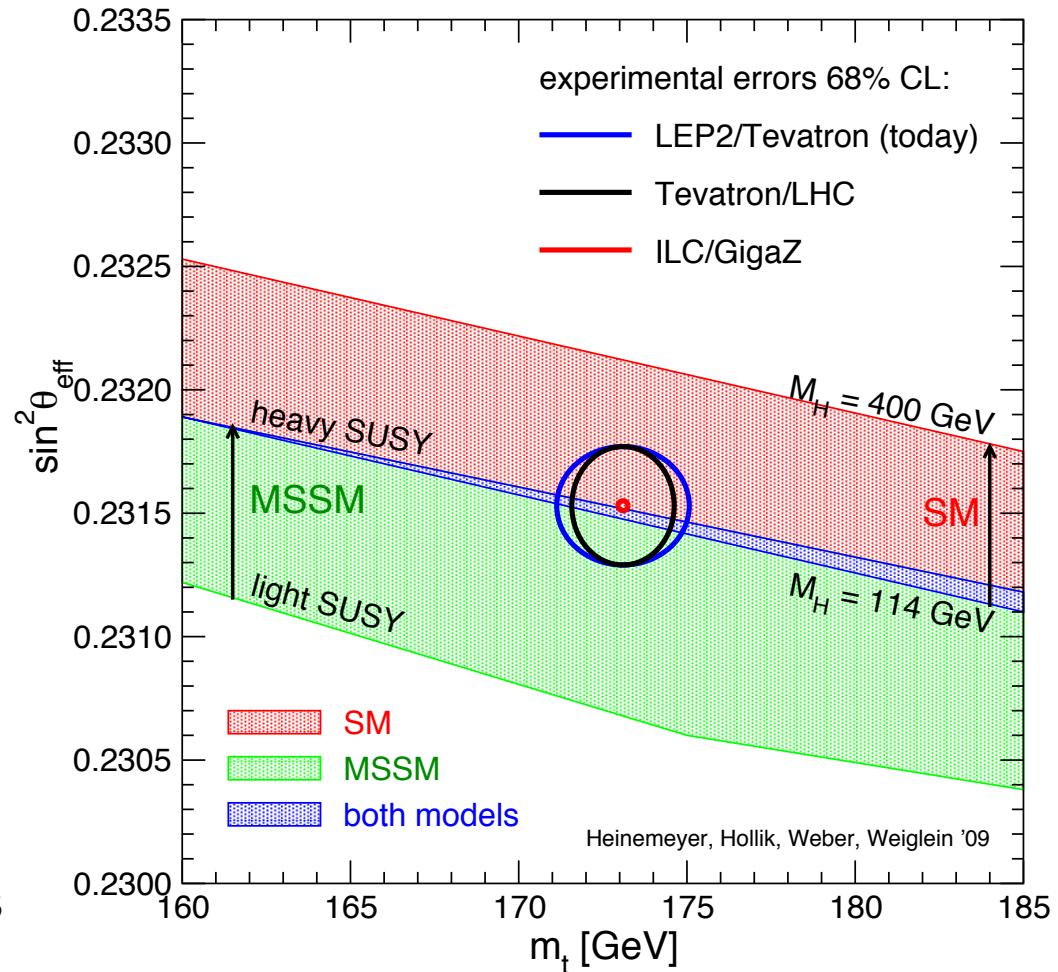
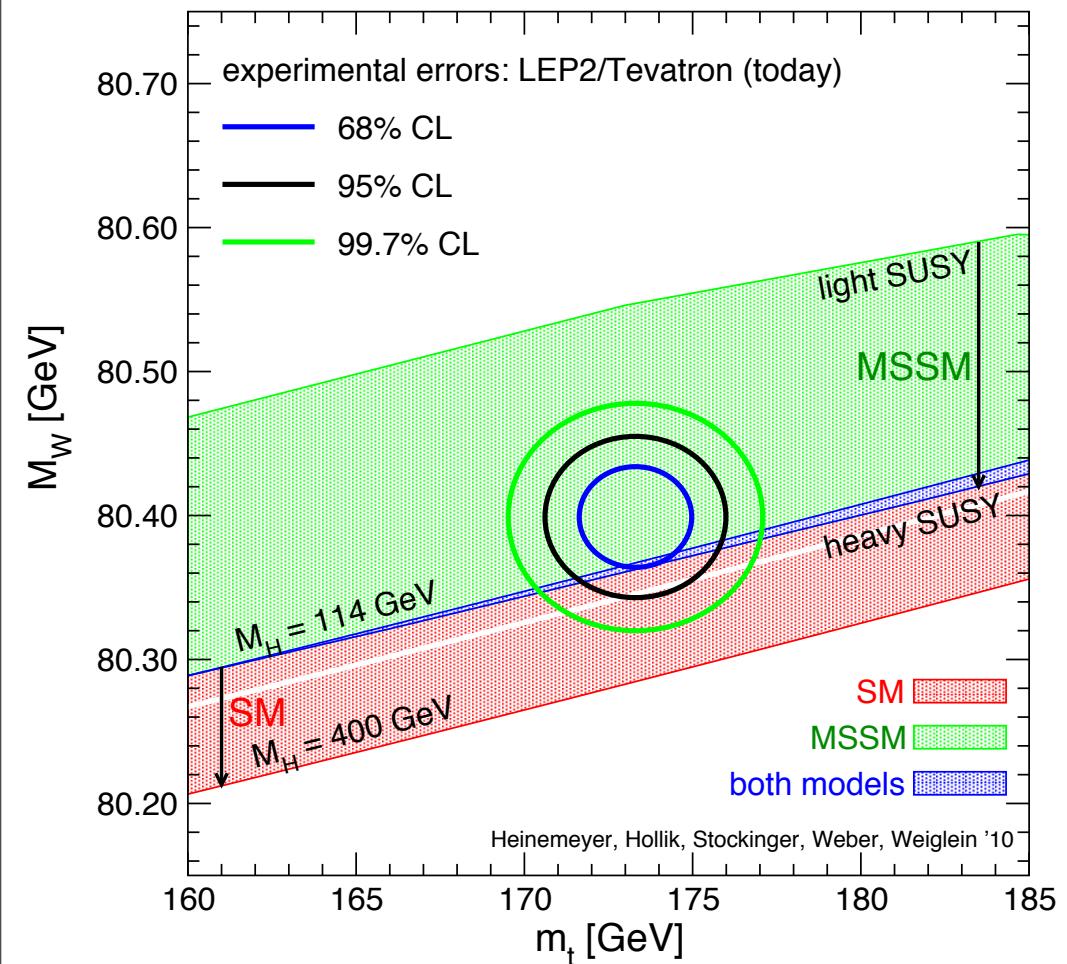
(the LEP/Tevatron results favor a light Higgs boson)

New-Physics contributions (e.g., SUSY) can alter the picture



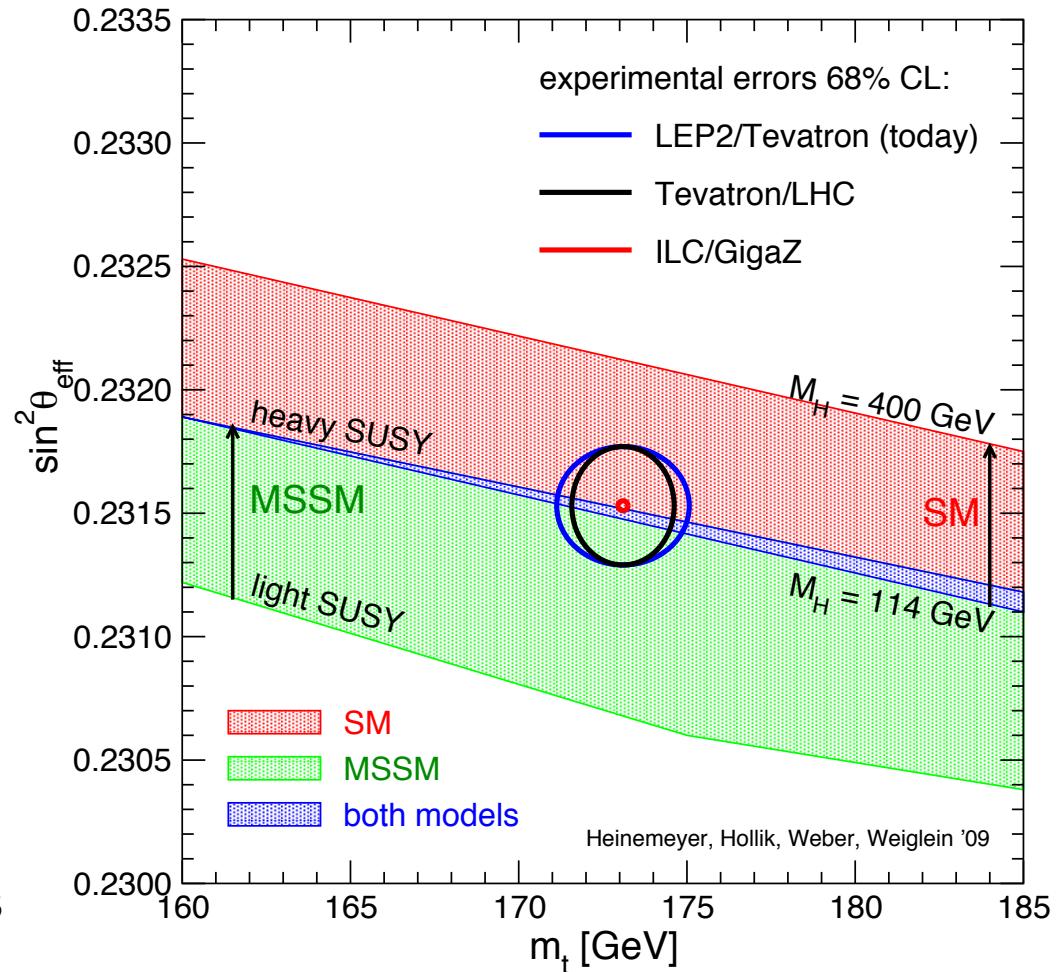
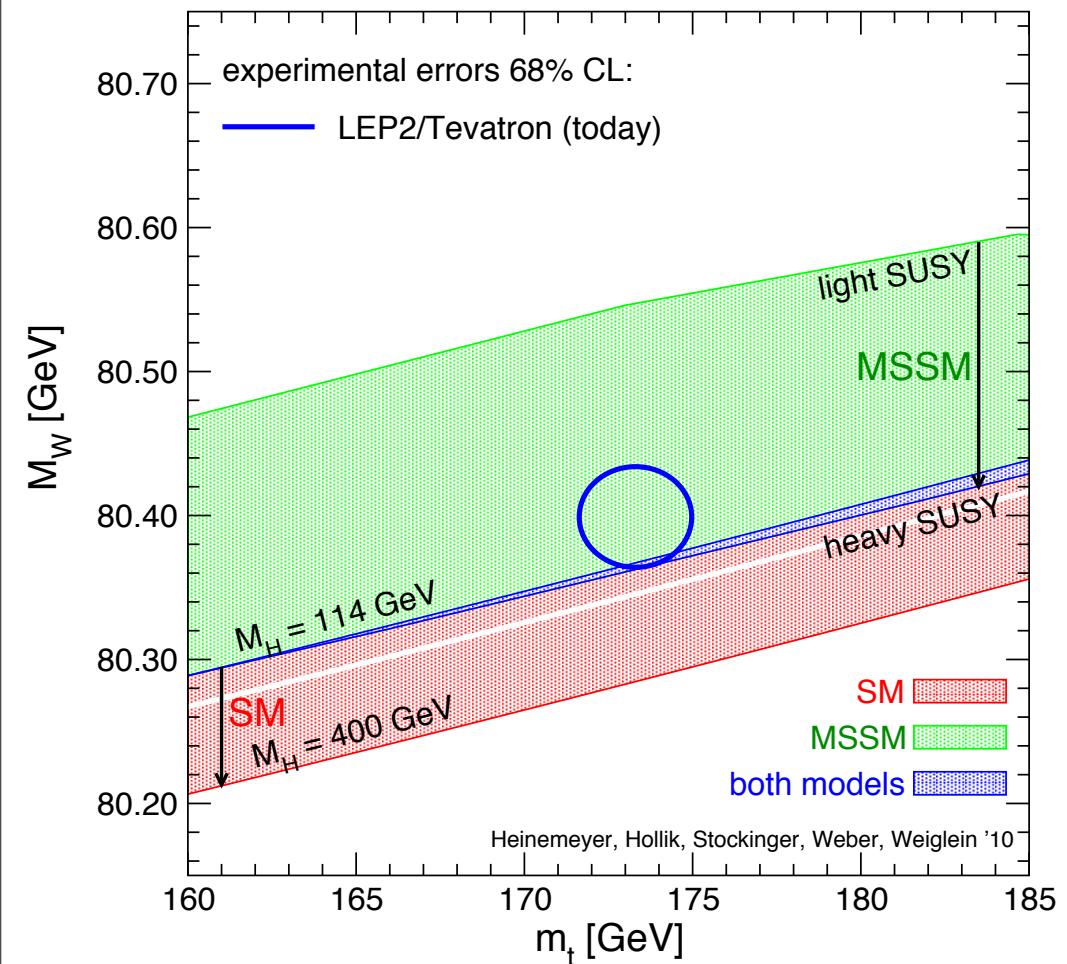
(plots by Sven Heinemeyer *et al.*)

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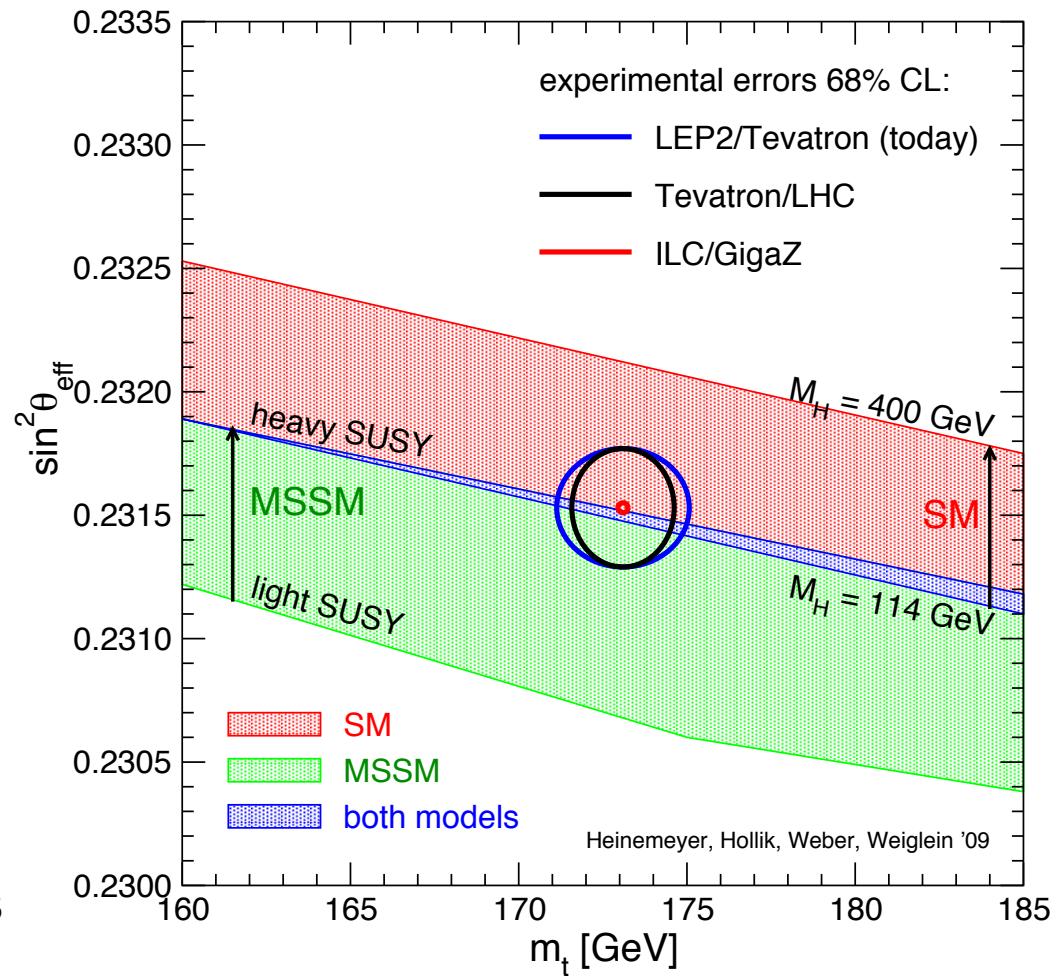
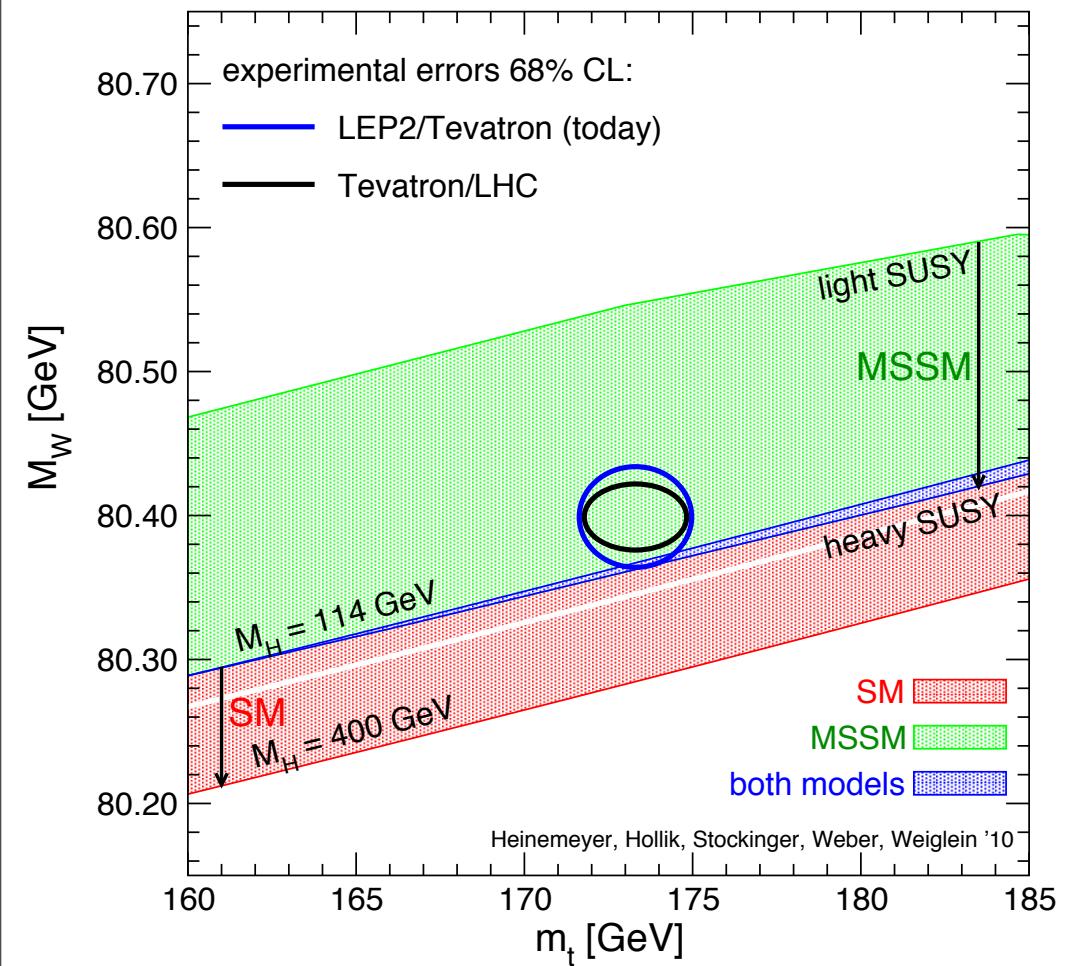
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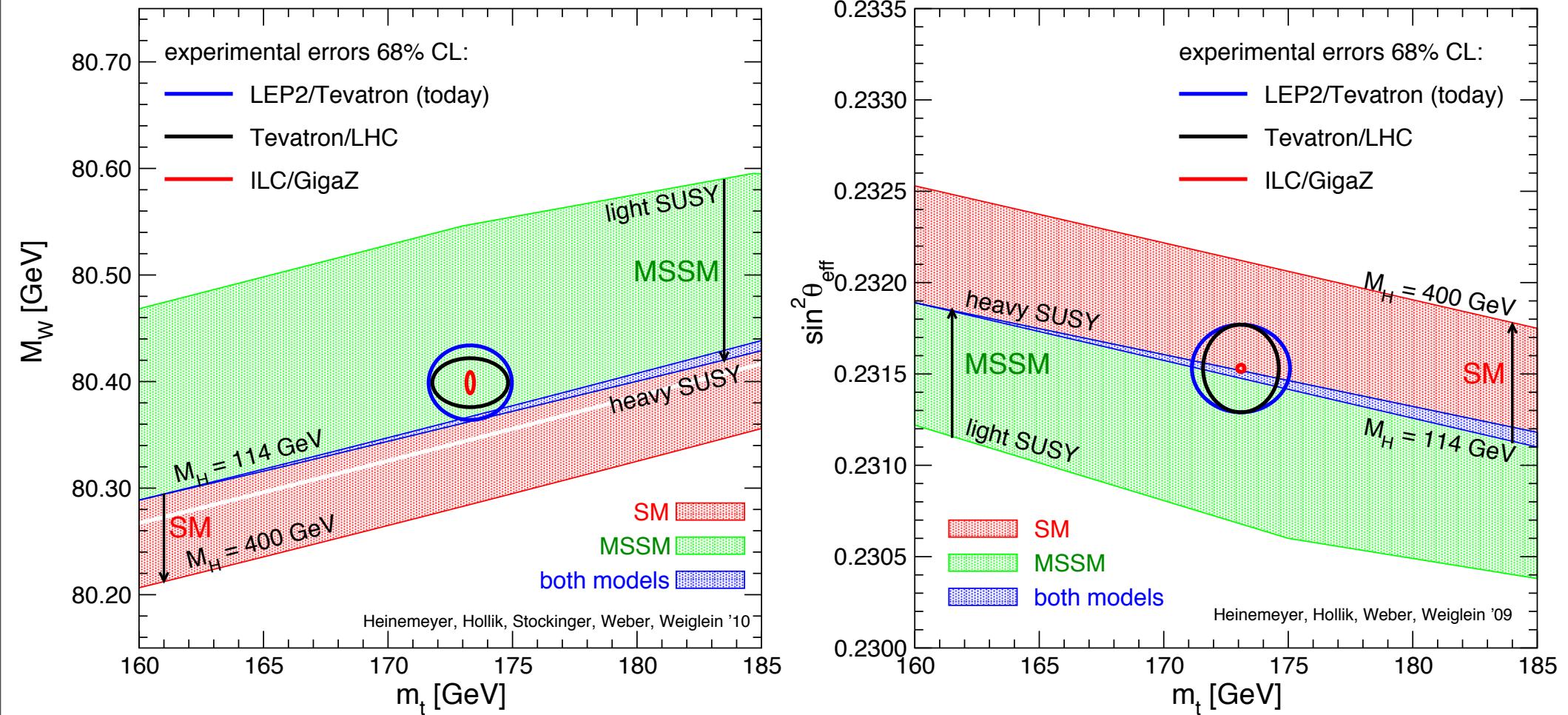
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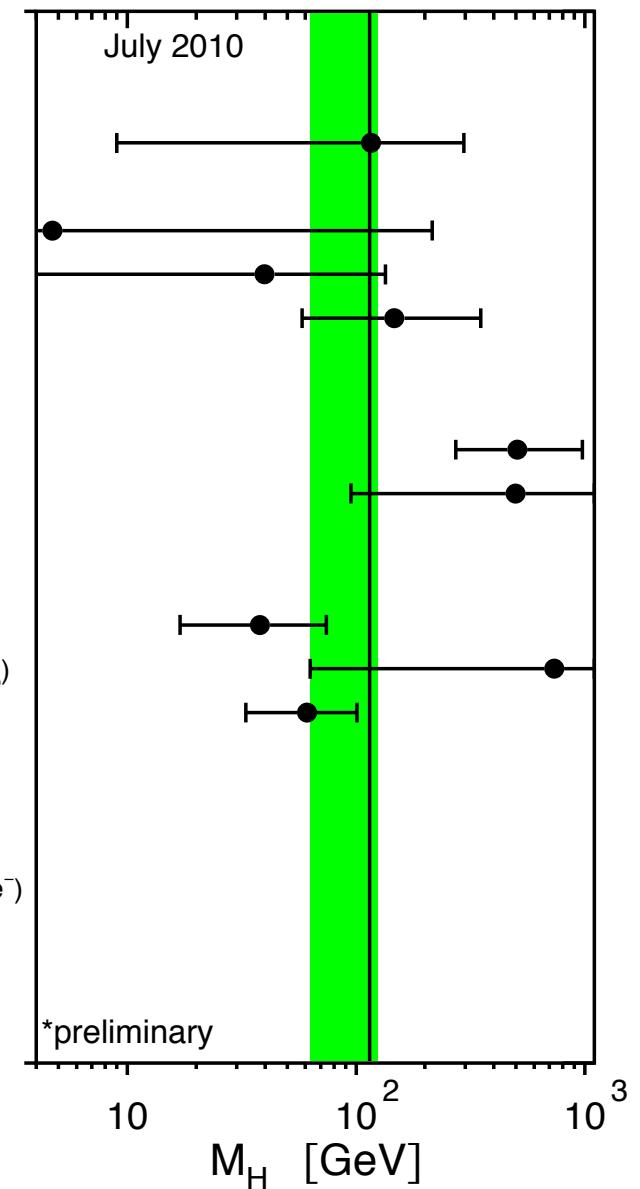
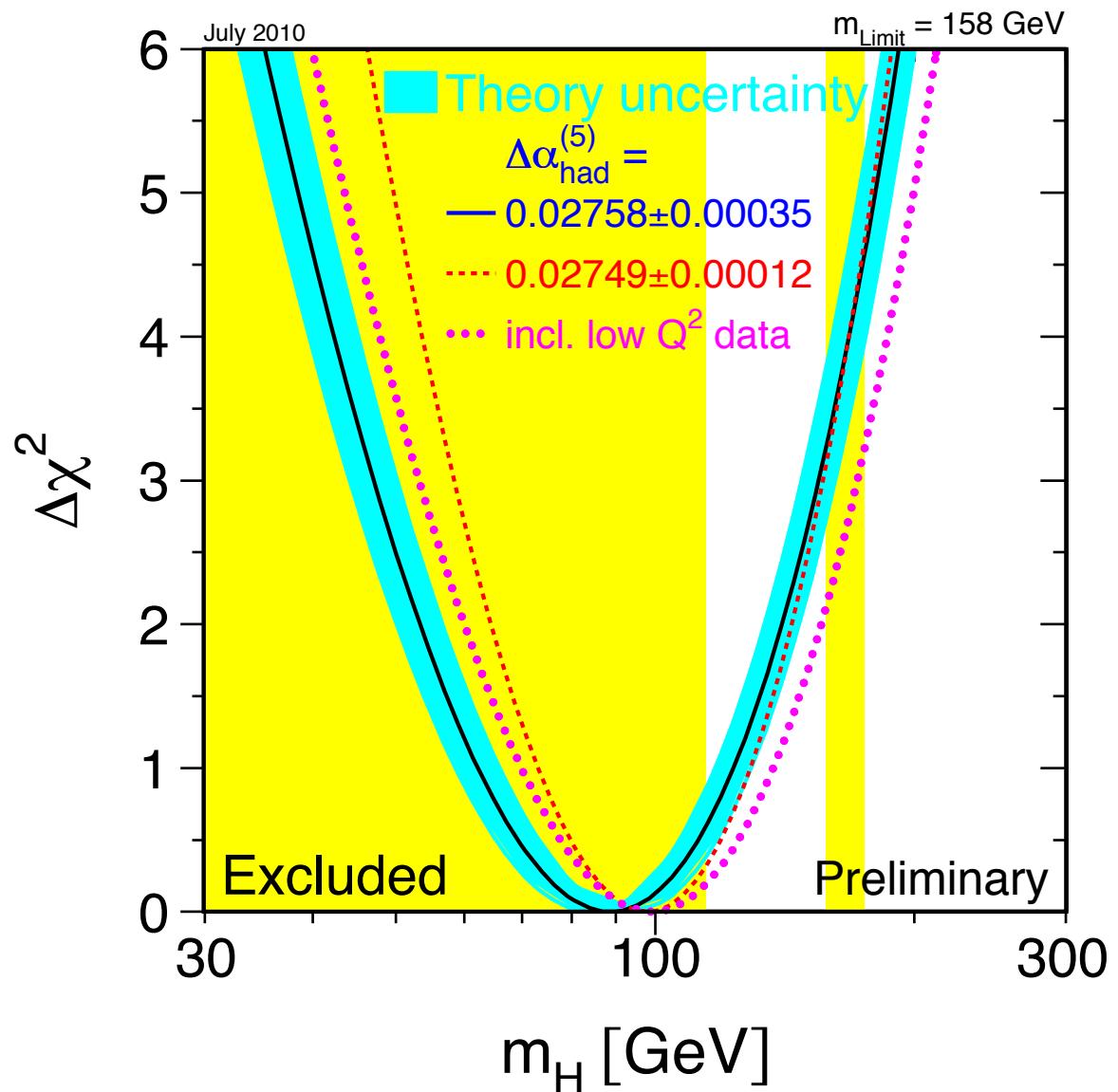
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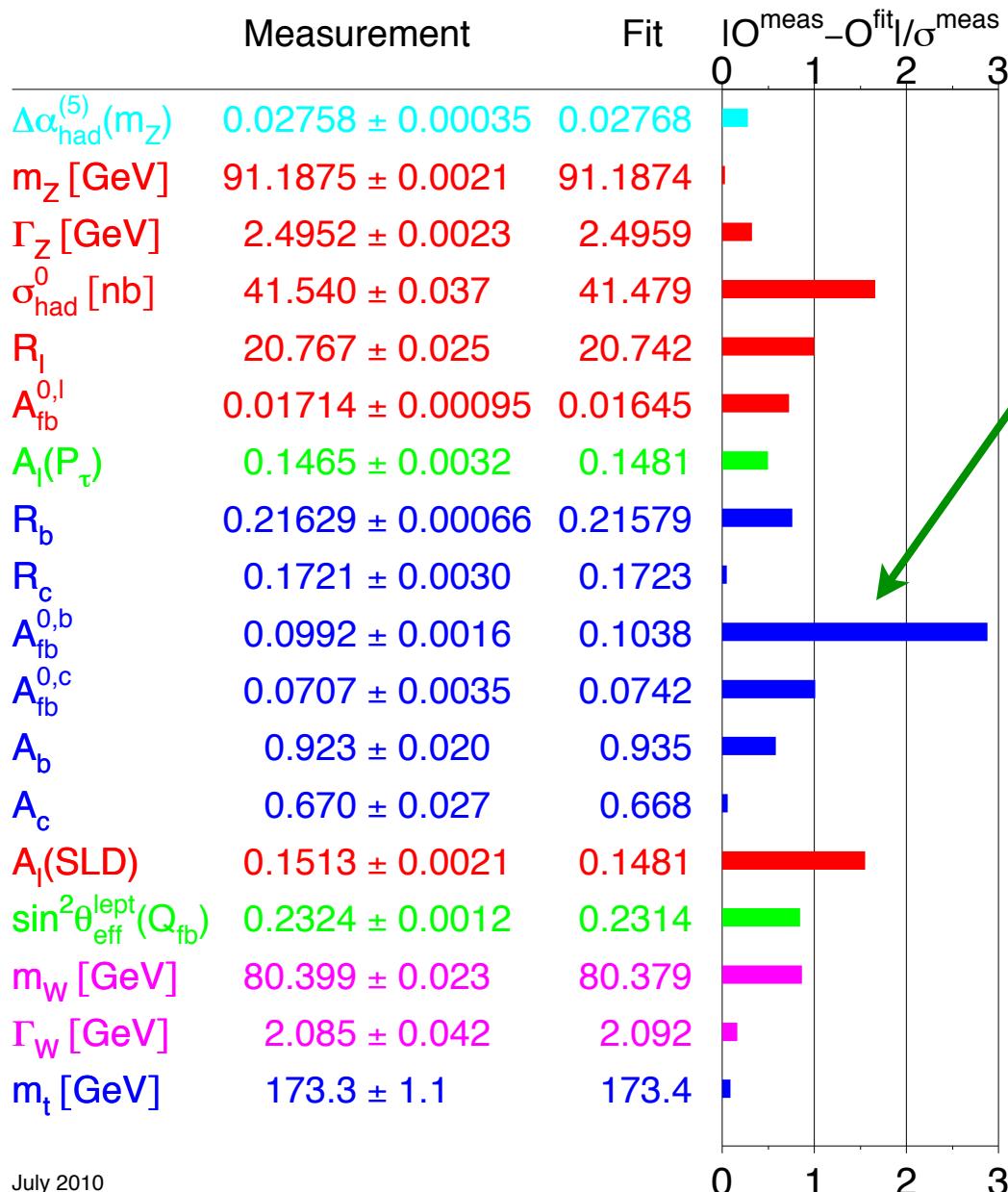


(plots by Sven Heinemeyer *et al.*)

Predicting the SM Higgs mass (LEP/TEV EWWG 2010)



The global fit's dirty secret: $A_{fb}^{0,b}$ from LEP



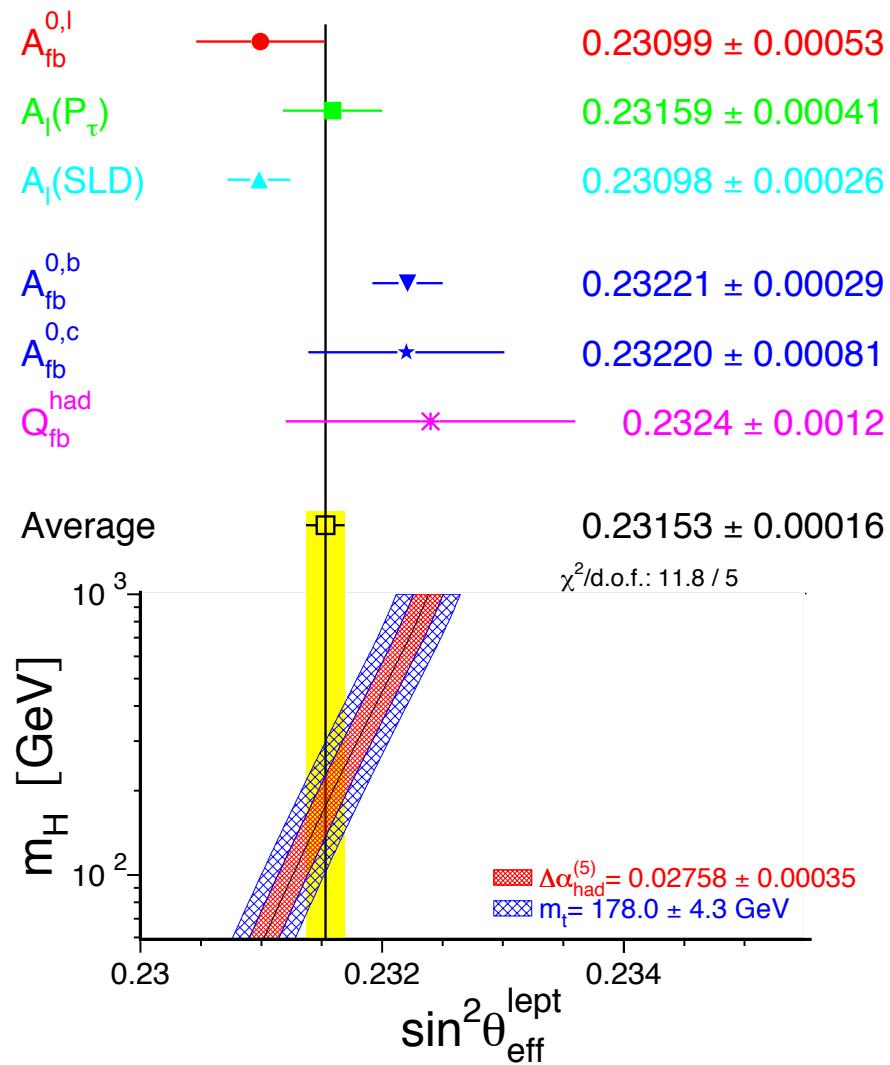
New Physics or just a fluke?

- We can't just throw it away
(see Higgs mass fit)
- But NP would require a large shift to the $Z b_R b_R$ coupling
- Without at the same time upsetting R_b (fine tuning?)
- Popular NP models (THDM, SUSY) shift the wrong way

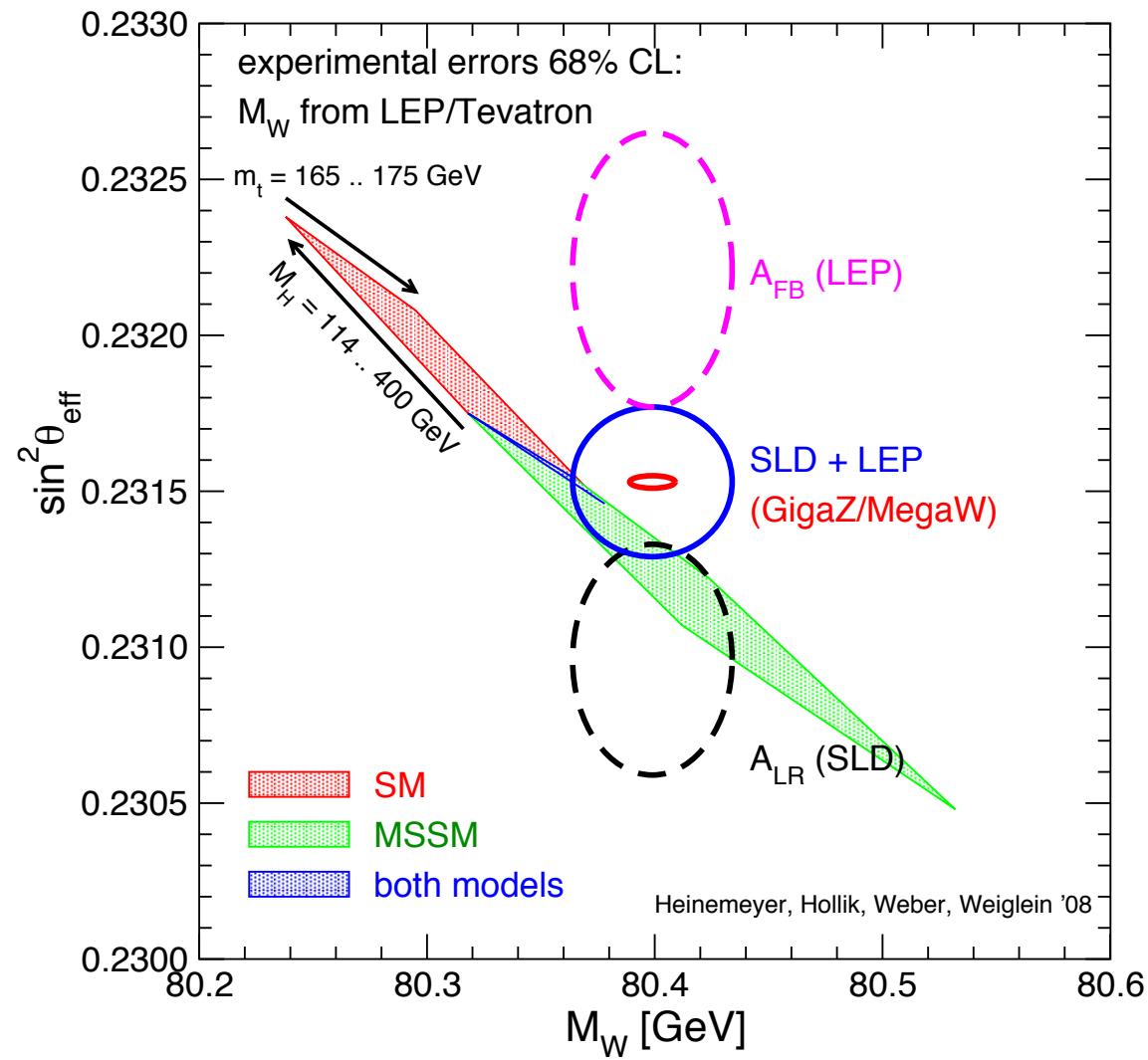
July 2010

(LEP/TEV EWWG 2010)

Determining $\sin^2 \theta_{\text{eff}}^{\text{lept}}$: LEP vs SLD



(LEP EWWG, 2005)



(Sven Heinemeyer et al., 2008)

Prospects for improving the accuracy of $\sin^2 \theta_{\text{eff}}^{\text{lept}}$

LEP & SLD: $\delta \sin^2 \theta_{\text{eff}}^{\text{lept}} \approx 3 \times 10^{-4}$ (but they are 4σ away from each other!)

The accuracy of the theoretical prediction is better: $\delta^{\text{th}} \sin^2 \theta_{\text{eff}}^{\text{lept}} \approx 0.5 \times 10^{-4}$

Full 2-loop (Awramik *et al.*, Hollik *et al.*, 04-06) plus leading $\mathcal{O}(\alpha_s \otimes \alpha_t)$ 3- and 4-loop

Hadron colliders measure A_{FB} in Drell-Yan: $q \bar{q} \rightarrow Z, \gamma^* \rightarrow \ell^+ \ell^-$ (the reverse of LEP)

D0 with 1.1 fb^{-1} : $\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.2327 \pm 0.0019$

TEV:

Expected (per exp and lepton channel) with 10 fb^{-1} : $\delta \sin^2 \theta_{\text{eff}}^{\text{lept}} \approx 6 \times 10^{-4}$

Tagging the direction of the incoming quark: trivial at Tevatron, tricky at LHC!!!
(look for boosted Z's in the forward region)

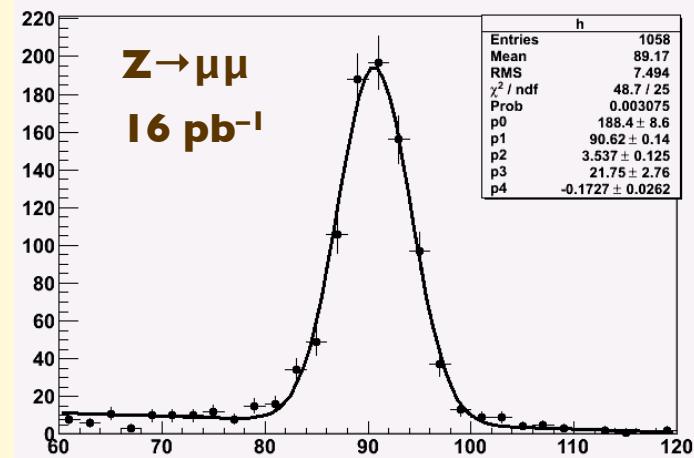
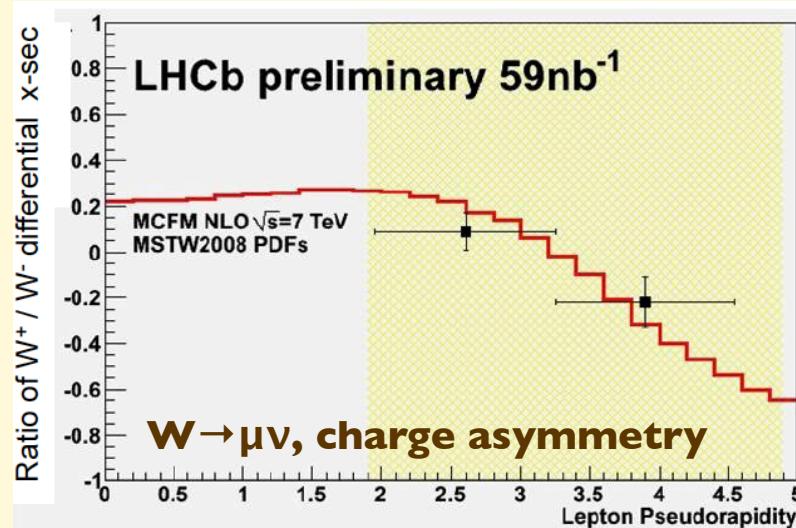
Expected from ATLAS+CMS with 100 fb^{-1} : $\delta \sin^2 \theta_{\text{eff}}^{\text{lept}} \approx 2 \times 10^{-4} \text{ (stat)}$

LHC:

- syst. uncertainty dominated by the PDFs
- stat. could be improved with extended forward acceptance

Could LHCb do MUCH better, by exploiting forward Z's?

EW boson production in the forward region, LHCb



These observations open the way for many interesting new measurements, from PDF constraints, to a determination of A_{FB} and $\sin^2\theta_W$

See S.Stone, for the LHCb collab., 104th LHCC session, <http://indico.cern.ch/conferenceDisplay.py?confId=112439>

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(slide by M. Mangano, HEPTools final meeting in Granada, Nov 2010)

Other precision measurements at hadron colliders

Competitive measurements of (m_W, Γ_W) ? What precision should we aim to?

Concerning m_W : the precision of the theoretical prediction (full 2-loop, leading 3- and 4-loop) is $\delta^{\text{th}} m_W \approx 4 \text{ MeV}$ (Awramik *et al.* 03)

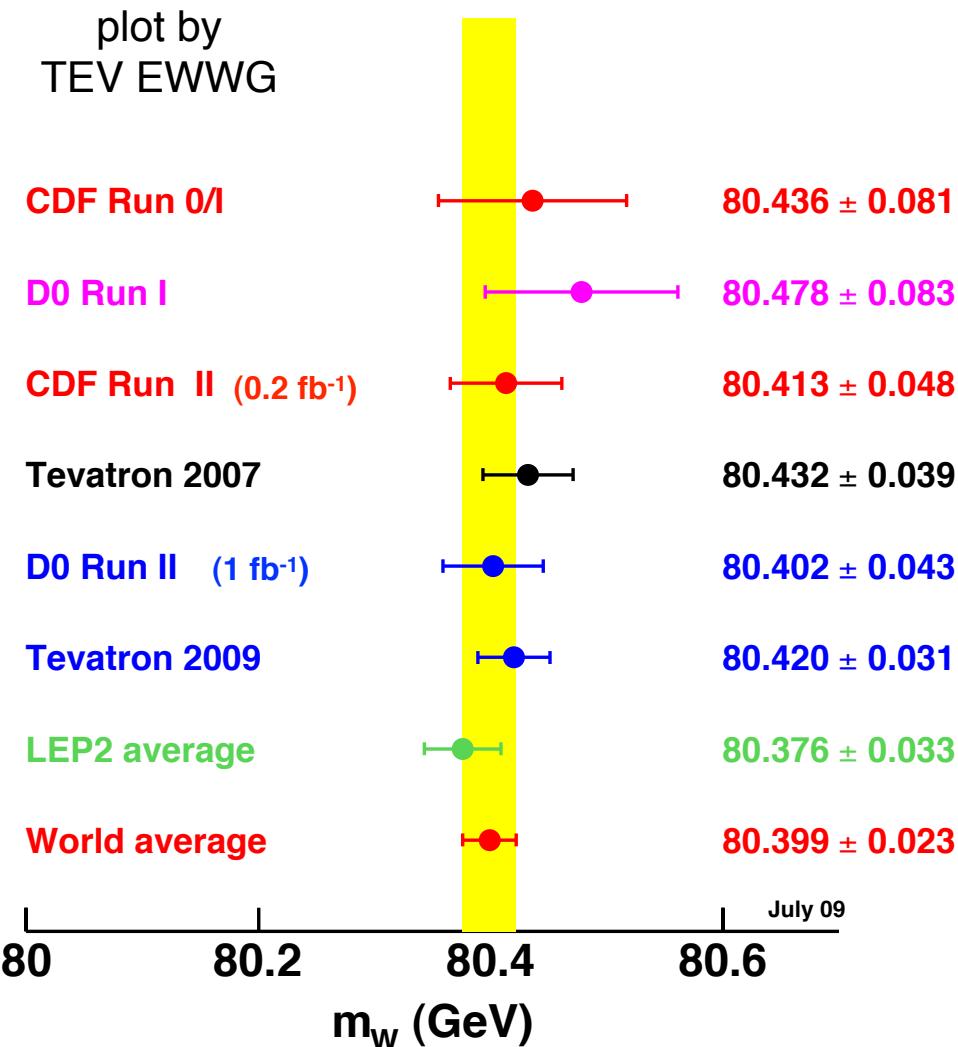
Equal impact on the Higgs-mass fit from m_t and m_W if $\delta m_W = 7 \times 10^{-3} \delta m_t$ (Baur *et al.*)

Tevatron: $\delta m_t = 1.1 \text{ GeV}$ (now),
 $\sim 1 \text{ GeV/experiment}$ (with 10 fb^{-1})
LHC: $\delta m_t \sim 1 \text{ GeV}$

[the accuracy of the pole top mass is anyway limited by non-perturbative effects of $\mathcal{O}(\Lambda_{\text{QCD}})$]

Therefore, the goal should be $\delta m_W < 10 \text{ MeV}$

Current W -mass results



- At Tevatron, m_W extracted from distributions of kinematic variables in leptonic W decays:
 $p_T^\ell, \not{E}_T, M_T \equiv \sqrt{2 p_T^\ell p_T^\nu (1 - \cos \phi_{\ell\nu})}$
- Data fitted with MC templates generated using different values of m_W
- Events from Z decays used for calibration (with LEP inputs for Z mass and width)
- Precise calc. of W, Z production is required
 - QCD: NNLO + NLL
 - EW: not negligible! (Sudakov logs, photon emission in final state)
- Both the statistical error and the calibration (syst.) error will improve with integrated lumi
- Limiting systematic uncertainty expected from PDFs (currently it's 11 MeV)

LHC expectations for W mass

LHC vs Tevatron:

- Larger corrections from thicker detector material
- pp collisions -> no valence antiquarks
- QCD corrections are more important
- ✓ Much bigger W - and Z -production rates!!!

CMS (TDR 2007)
expectation with 10 fb^{-1} :

$\delta m_W \sim 20 \text{ MeV}$ (using “scaled” Z distributions as templates)
[$< 10 \text{ MeV}$ (stat), $< 10 \text{ MeV}$ (syst theo), $< 20 \text{ MeV}$ (syst instr)]

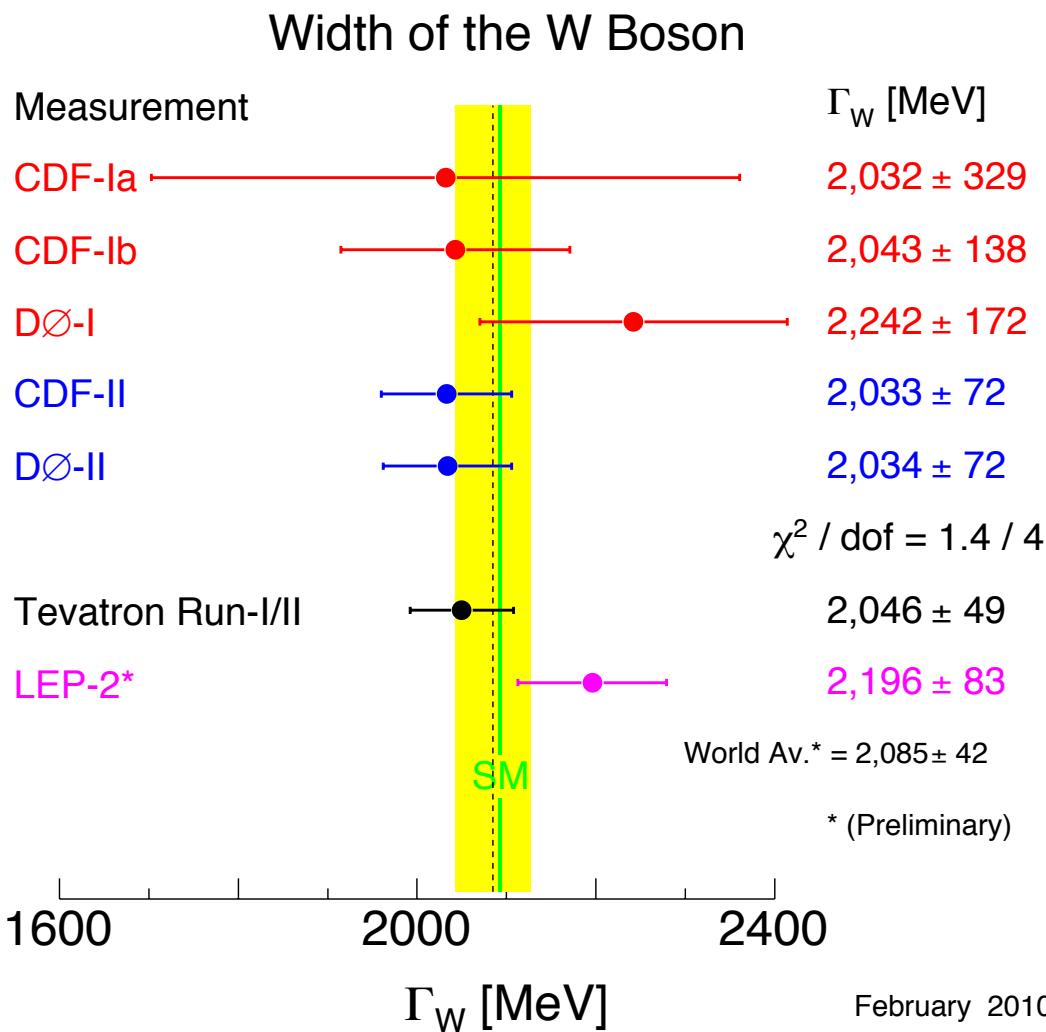
ATLAS (0805.2093) is
much more aggressive:

$\delta m_W \sim 7 \text{ MeV}$ per channel! (using “traditional” MC templates)
[assumes of 1 MeV each for PDF and QED uncertainties]

This expectation was recently criticized in Krasny *et al.*, 1004.2597, on the grounds that it does not take into account PDF uncertainties specific to pp (as opposed to $p\bar{p}$) collisions

(see talk by F. Dyak tomorrow morning)

W width



- Measured by fitting the high-mass tail of the M_T distribution

$$\Gamma_W^{\text{exp}} = 2.085 \pm 0.042 \text{ GeV}$$

$$\Gamma_W^{\text{SM}} = \frac{G_F m_W^3}{6\sqrt{2}\pi} (3 + 2 f_{\text{QCD}}) (1 + \delta_{\text{EW}})$$

$$= 2.0910 \pm 0.0015 \text{ GeV}$$

- Current experimental accuracy far too poor to affect the EW global fit
- However, the width affects the syst. accuracy of the mass measurement (e.g., ATLAS estimate assumes an accuracy improved by a factor 5)

(couldn't find specific studies for the LHC expectations)

Gauge boson self-interactions

Non-abelian SM gauge group \longrightarrow trilinear (TGC) and quartic (QGC) gauge-boson couplings

Will be probed at the LHC thanks to the large di-boson (and tri-boson) samples

E.g., the most general EM- and Lorentz-invariant effective Lagrangian contains 14 independent WWV ($V = Z, \gamma$) couplings. Imposing C and P invariance they reduce to 6:

$$\mathcal{L}_{\text{eff}}^{WWV} = -i g_{WWV} \left[g_1^V (W_{\mu\nu}^\dagger W^\mu - W^{\dagger\mu} W_{\mu\nu}) V^\nu + \kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_{\rho\nu}^\dagger W^{\mu\nu} V^{\nu\rho} \right]$$
$$(g_{WW\gamma} = e, \quad g_{WWZ} = e \cot \theta_W, \quad g_1^\gamma = 1)$$

At tree level the SM predicts $g_1^Z = \kappa_V = 1, \quad \lambda_V = 0$ (with higher-order corrections)

→ Look for deviations from SM in WW (LEP+hadr) and $WZ, W\gamma$ (hadr) production

The couplings of three neutral gauge bosons ($Z\gamma\gamma, ZZ\gamma, ZZZ$) are all zero in the SM

→ Look for deviations from SM in $ZZ, Z\gamma$ production

This requires an accurate determination of the SM prediction for di-boson production
[Currently, NLO QCD (large at the LHC) + 1-loop EW (Sudakov logs)]

Gauge boson self-interactions

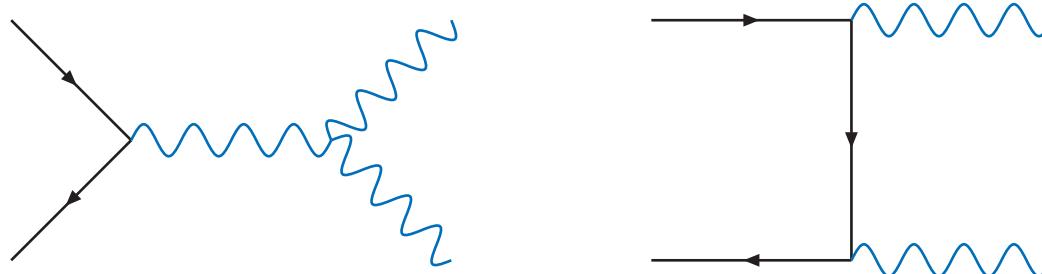
Non-abelian SM gauge group \longrightarrow trilinear (TGC) and quartic (QGC) gauge-boson couplings

Will be probed at the LHC thanks to the large di-boson (and tri-boson) samples

E.g., the most general EM- and Lorentz-invariant effective Lagrangian contains 14 independent WWV ($V = Z, \gamma$) couplings. Imposing C and P invariance they reduce to 6:

$$\mathcal{L}_{\text{eff}}^{WWV} = -i g_{WWV} \left[g_1^V (W_{\mu\nu}^\dagger W^\mu - W^{\dagger\mu} W_{\mu\nu}) V^\nu + \kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_{\rho\nu}^\dagger W^{\mu\nu} V^{\nu\rho} \right]$$
$$(g_{WW\gamma} = e, \quad g_{WWZ} = e \cot \theta_W, \quad g_1^\gamma = 1)$$

At tree level the SM predicts $g_1^Z = \kappa_V = 1, \quad \lambda_V = 0$ (with higher-order corrections)



This requires an accurate determination of the SM prediction for di-boson production
[Currently, NLO QCD (large at the LHC) + 1-loop EW (Sudakov logs)]

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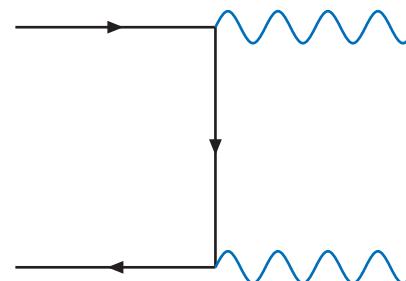
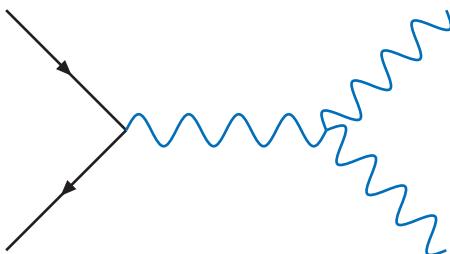
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NOTE: anomalous
TGC violate unitarity!!!



This requires an accurate determination of the SM prediction for di-boson production
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Bounds on anomalous three-gauge-boson couplings

LEP2 results from $e^+e^- \rightarrow W^+W^-$ are consistent with the SM tree-level expectations :

$$\Delta g_1^Z = -0.016^{+0.022}_{-0.019}, \quad \Delta \kappa_\gamma = -0.027^{+0.044}_{-0.045}, \quad \lambda_\gamma = -0.028^{+0.020}_{-0.021}$$

Tevatron experiments have published several bounds on TGC, all in the 10^{-1} range
[worse than LEP2(WW) for charged TGC, better than LEP2(ZZ) for neutral ones]

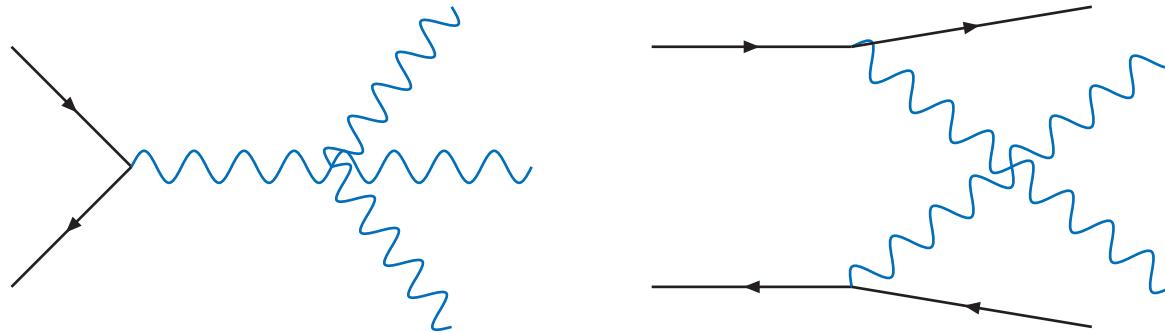
Expectations for LHC: (with 30 fb^{-1})	charged TGC:	$O(10^{-2})$ for $\Delta g_1^Z, \Delta \kappa_V$ (like LEP)
	neutral TGC:	$O(10^{-3})$ for λ_V (better than LEP)
		$O(10^{-3} - 10^{-4})$ (far better than LEP)

(see also Eboli *et al.*, 1006.3562: LHC competitive with LEP already with 1 fb^{-1})

New-Physics contributions scale like $m_W^2/\Lambda_{\text{NP}}^2$. TGC at the LHC are sensitive to the TeV scale

Quartic gauge couplings

They affect three-vector-boson production and diboson + 2 fermions in vector-boson fusion



Direct bounds from LEP in $WW\gamma$, $Z\gamma\gamma$, $ZZ\gamma$, $\nu\bar{\nu}\gamma\gamma$ production

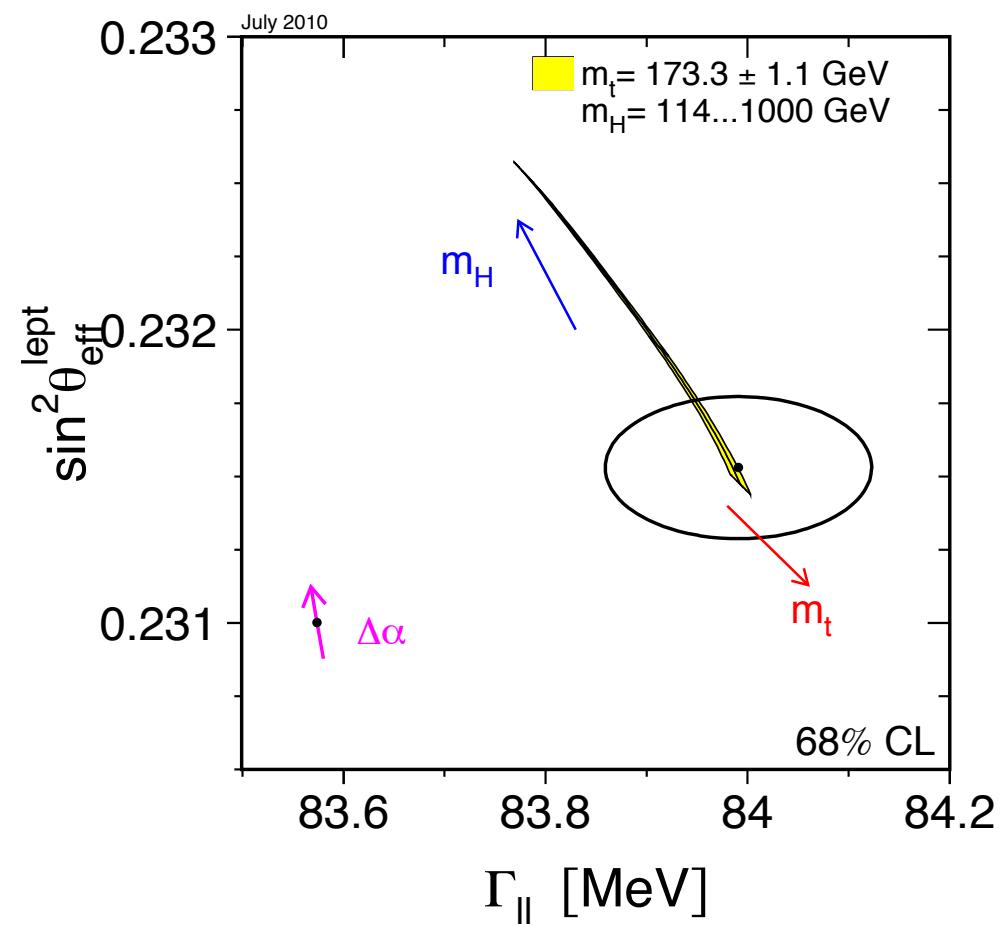
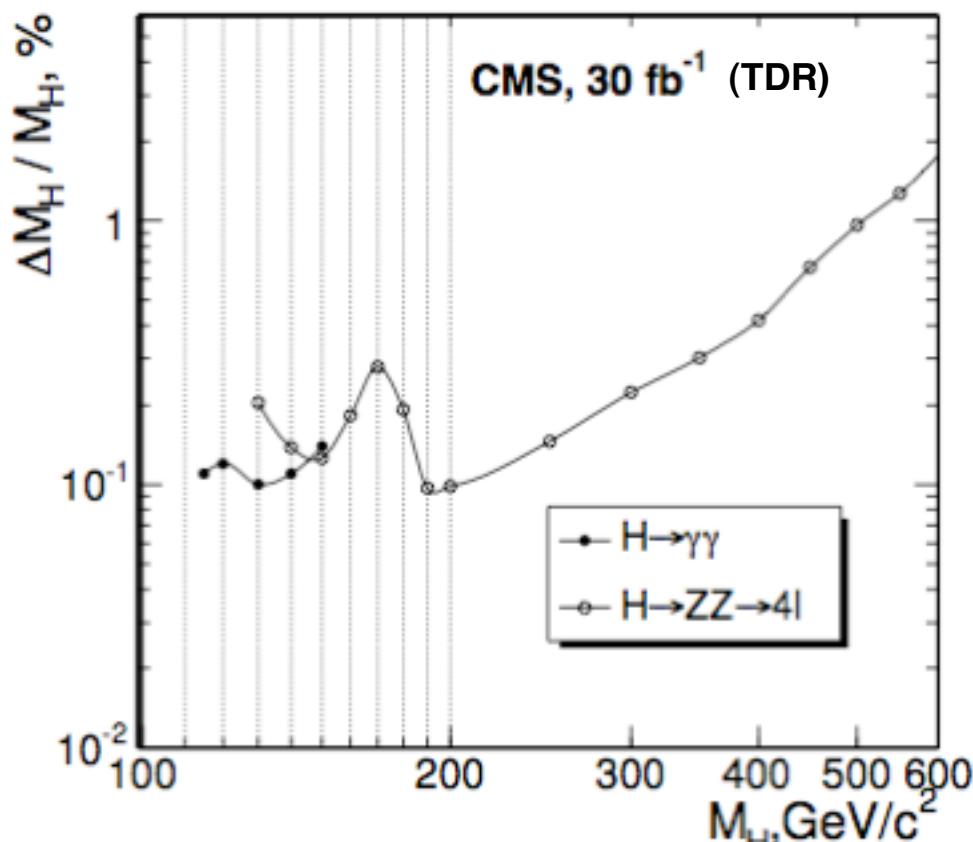
Indirect bounds from S and U parameters are ~ 100 times stronger than LEP bounds

Rates too small to study these processes at the Tevatron

For the LHC, old analysis of di-boson + 2 jets by Eboli *et al.*, hep-ph/0310141:
Indirect bounds can be improved by a factor ~ 100 with 100 fb^{-1} (at 14 TeV)

Precise measurement of the Higgs boson mass

A SM-like Higgs mass will be measured with a precision ranging between 0.1% and 1%



In the SM such accuracy is not too relevant to the EW fit, due to the logarithmic sensitivity to M_H

However, in SUSY extensions of the SM the Higgs mass itself becomes a precision observable!!!

The particle content of the MSSM

Chiral supermultiplets		spin 1/2	spin 0	SU(3)xSU(2)xU(1)
(s)quarks (3 families)	Q	(u_L, d_L)	$(\tilde{u}_L, \tilde{d}_L)$	$(3, 2, \frac{1}{6})$
	U^c	u_R^\dagger	\tilde{u}_R^*	$(\bar{3}, 1, -\frac{2}{3})$
	D^c	d_R^\dagger	\tilde{d}_R^*	$(\bar{3}, 1, \frac{1}{3})$
(s)leptons (3 families)	L	(ν, e_L)	$(\tilde{\nu}, \tilde{e}_L)$	$(1, 2, -\frac{1}{2})$
	E^c	e_R^\dagger	\tilde{e}_R^*	$(1, 1, 1)$
Higgs(inos)	H_1	$(\tilde{h}_1^0, \tilde{h}_1^-)$	(H_1^0, H_1^-)	$(1, 2, -\frac{1}{2})$
	H_2	$(\tilde{h}_2^+, \tilde{h}_2^0)$	(H_2^+, H_2^0)	$(1, 2, +\frac{1}{2})$

Vector supermultiplets		spin 1	spin 1/2	SU(3)xSU(2)xU(1)
gluon, gluino		g	\tilde{g}	$(8, 1, 0)$
W bosons, winos		W^\pm, W^0	$\tilde{w}^\pm, \tilde{w}^0$	$(1, 3, 0)$
B boson, bino		B	\tilde{b}	$(1, 1, 0)$

The Higgs sector of the MSSM

After EWSB we are left with five physical scalars: h, H, A, H^\pm

A SUSY peculiarity: the Higgs quartic coupling is not a free parameter as in the SM

$$V_{\text{SM}} \supset \lambda |H|^4, \quad V_{\text{MSSM}} \supset \frac{1}{8}(g^2 + g'^2) (|H_1^0|^2 - |H_2^0|^2)^2$$

The CP-even scalar masses can be expressed in terms of m_Z, m_A and $\tan \beta \equiv v_2/v_1$

$$m_{h,H}^2 = \frac{1}{2} \left(m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4 m_Z^2 m_A^2 \cos^2 2\beta} \right)$$

For $m_A \gg m_Z$ (decoupling limit) the lightest scalar h has SM-like couplings and the others do not couple to two gauge bosons

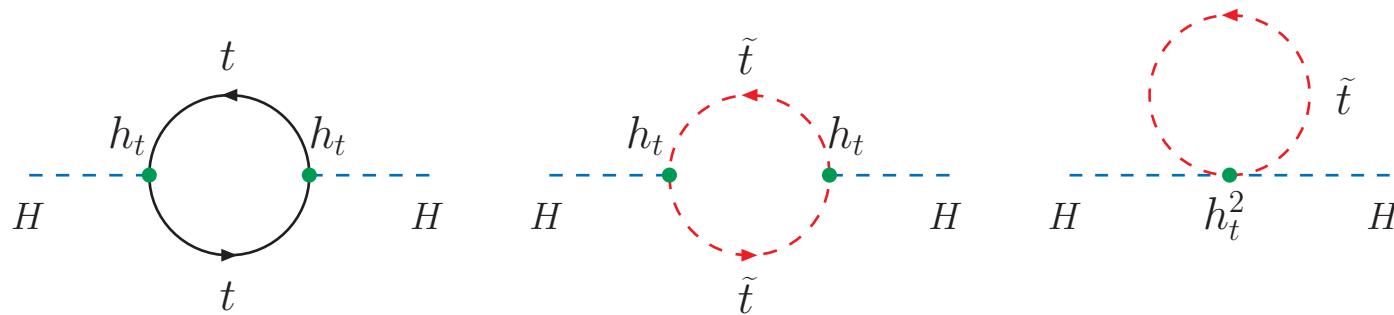
There is a tree-level upper bound on the mass of the lightest CP-even Higgs boson

$$m_h < m_Z \cos 2\beta$$

ruled out by the direct searches at LEP!!! $m_H^{\text{SM}} > 114.4 \text{ GeV}$ (95% C.L.)

The leading one-loop corrections to m_h

- The leading one-loop corrections are due to the particles with the strongest couplings to the Higgs boson: the top quarks and squarks

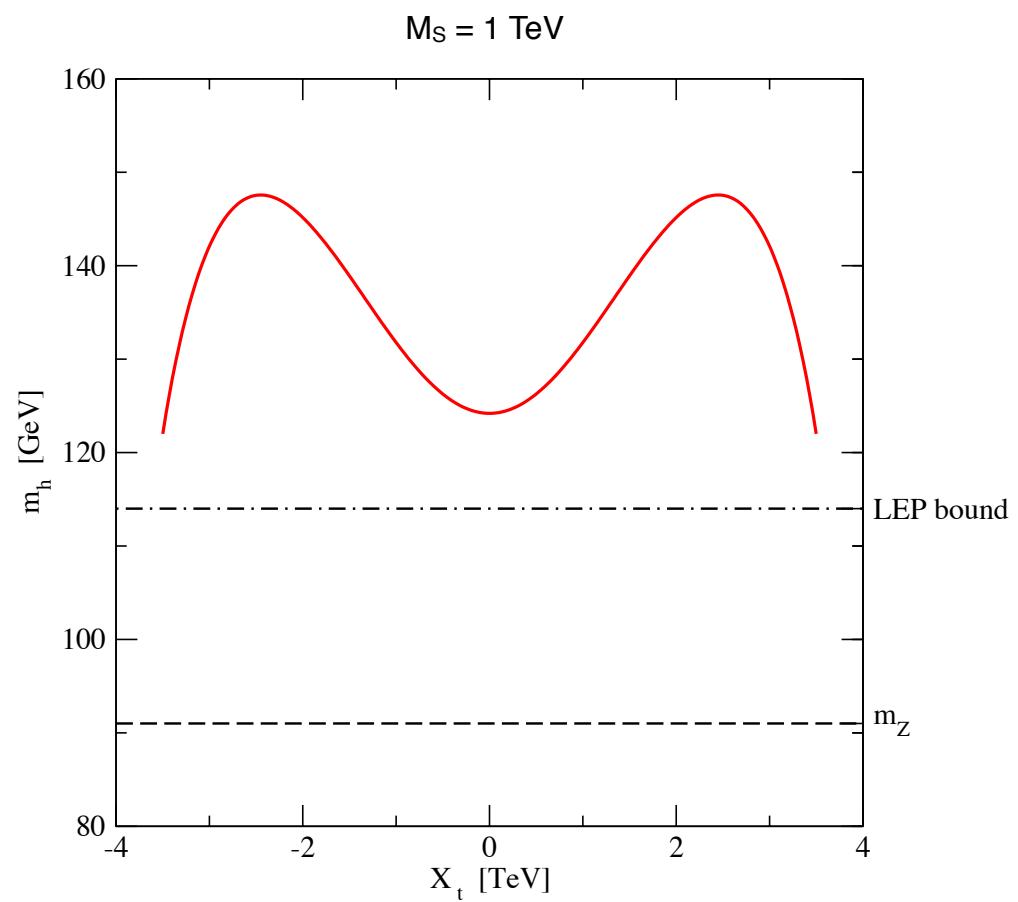
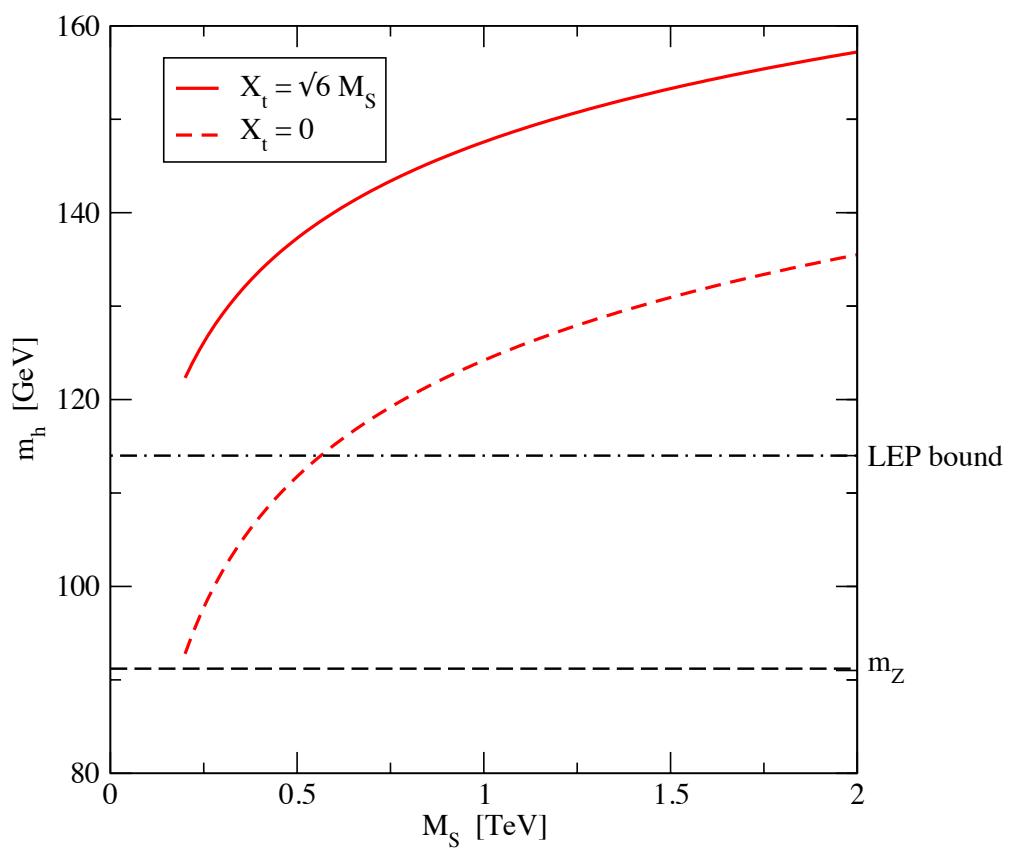


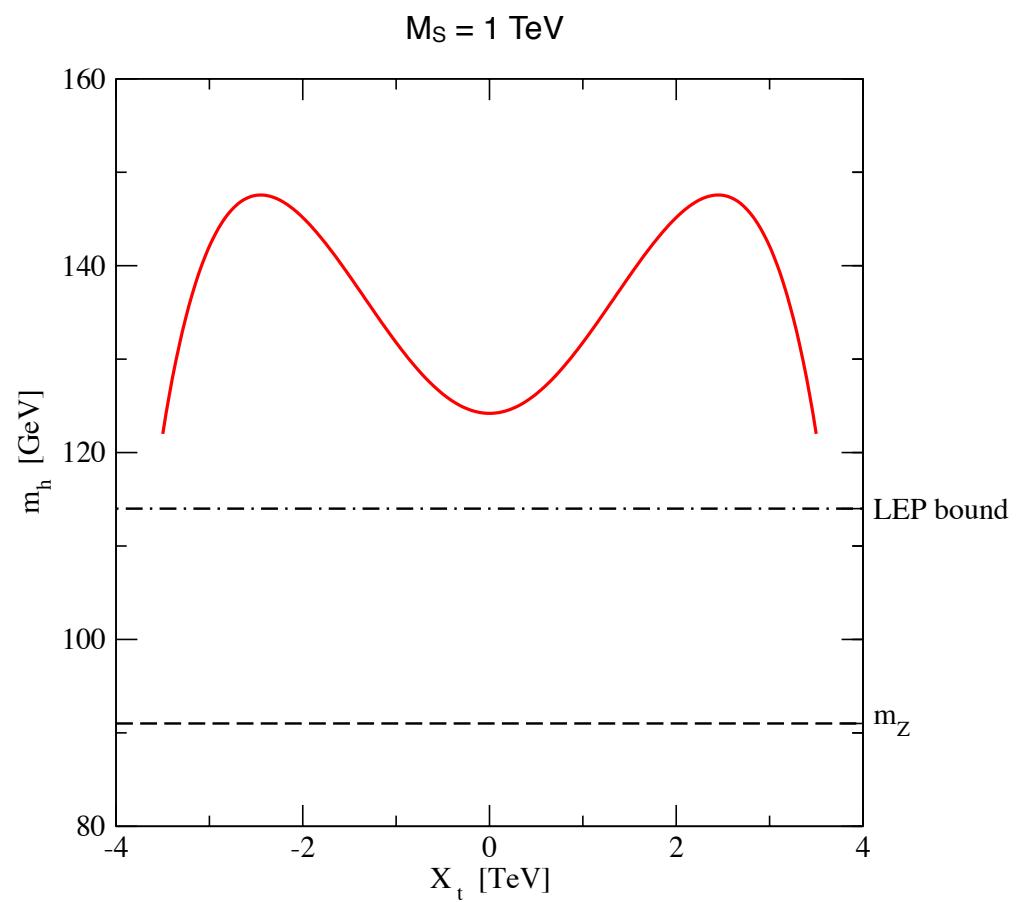
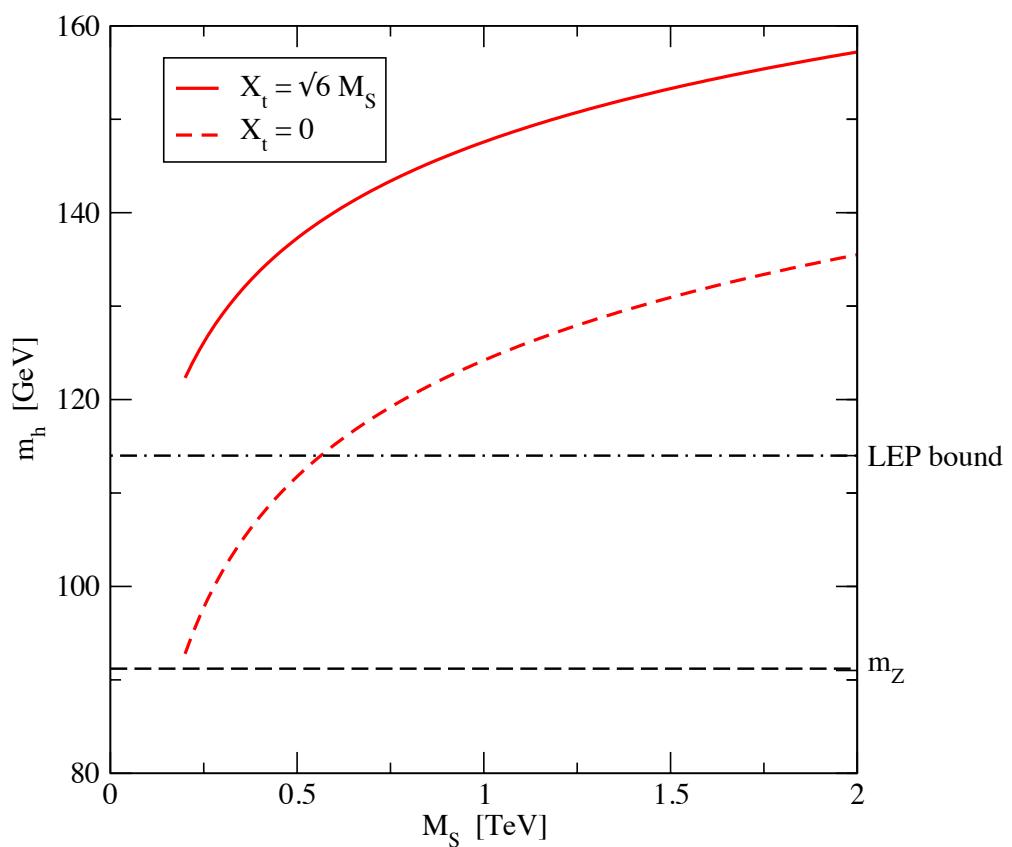
- In the decoupling limit the leading corrections to the light Higgs mass are

$$(\Delta m_h^2)^{\text{1-loop}} \simeq \frac{3 m_t^4}{4 \pi^2 v^2} \left(\ln \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4} \right) - \frac{h_b^4 \mu^4 v^2}{16 \pi^2 M_S^4}$$

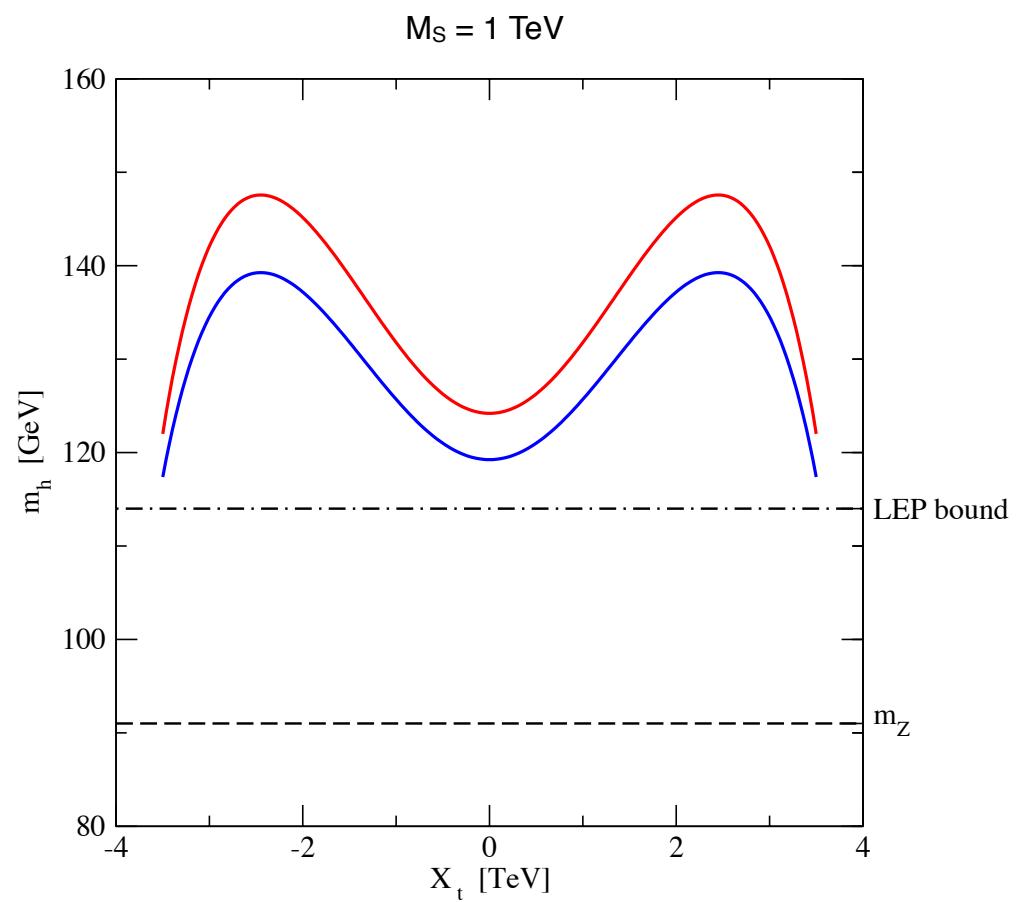
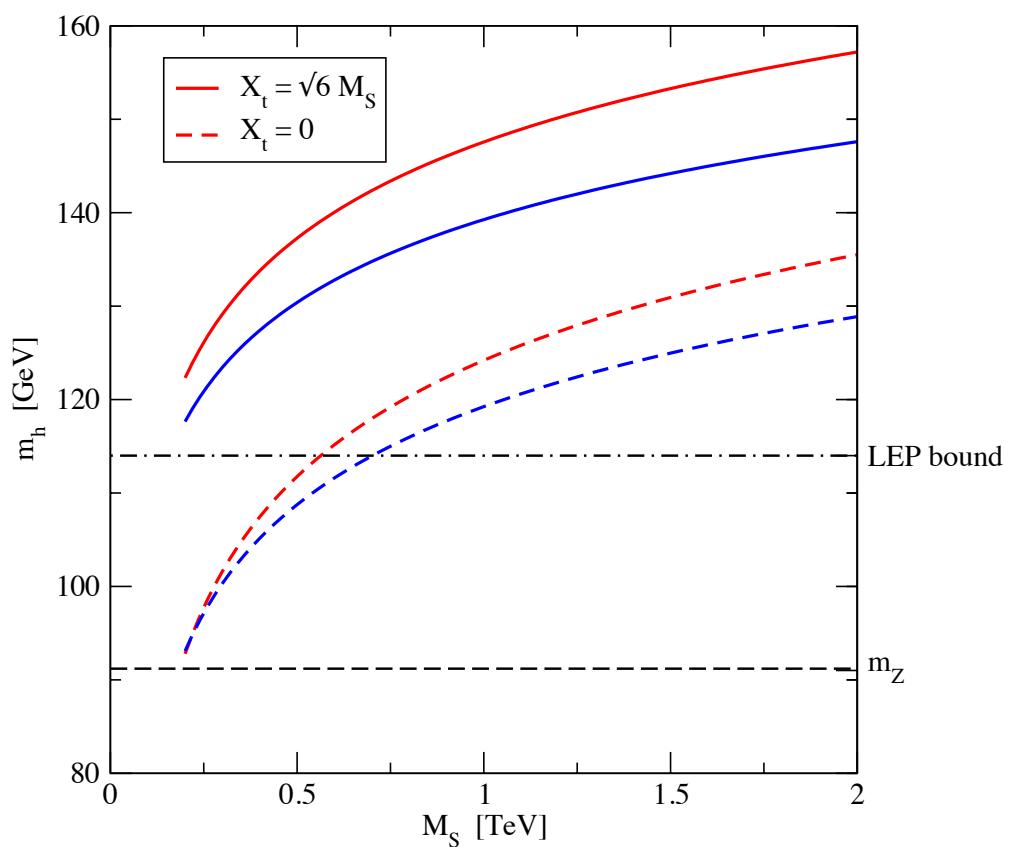
(M_S = average stop mass, $X_t = A_t - \mu \cot \beta$ = L-R stop mixing)

- Δm_h^2 depends on the SUSY-breaking mismatch between top and stop mass
- It is maximized for large stop masses and large stop mixing ($X_t \simeq \sqrt{6} M_S$)
- The corrections controlled by h_b are relevant for large $\tan \beta$ $\left(\frac{h_b}{h_t} = \frac{m_b}{m_t} \tan \beta \right)$

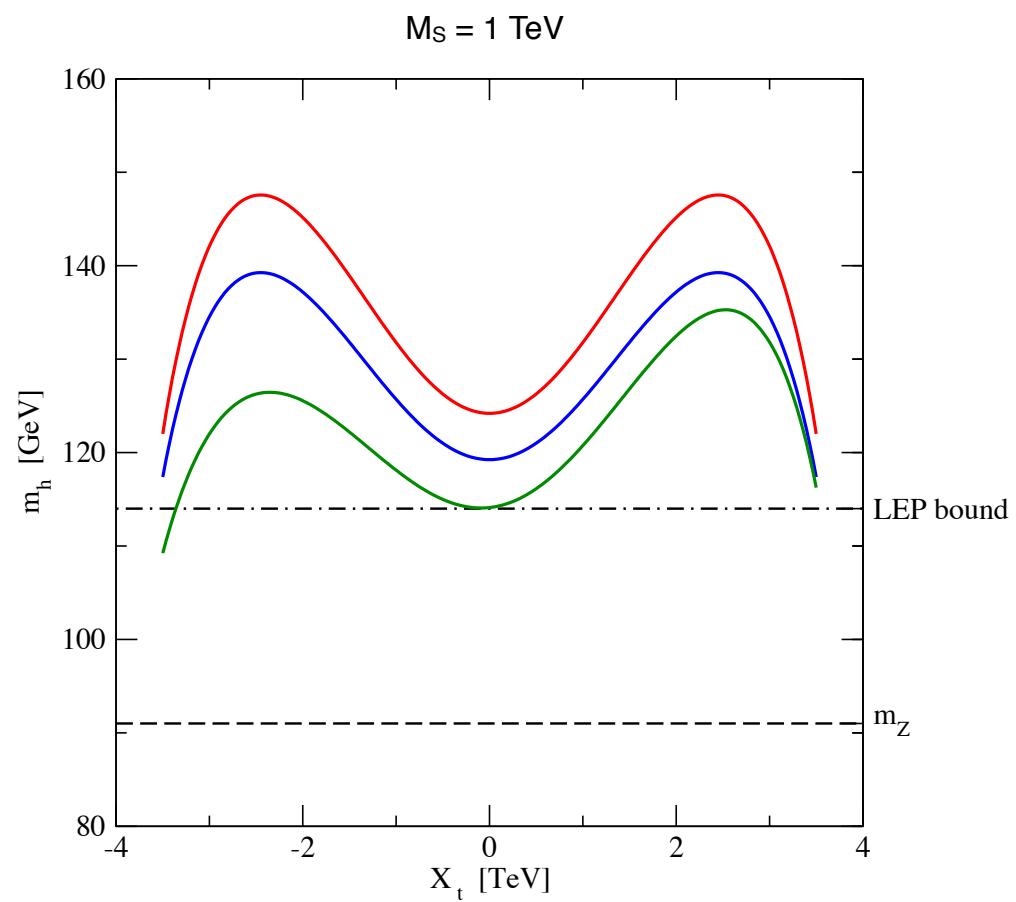
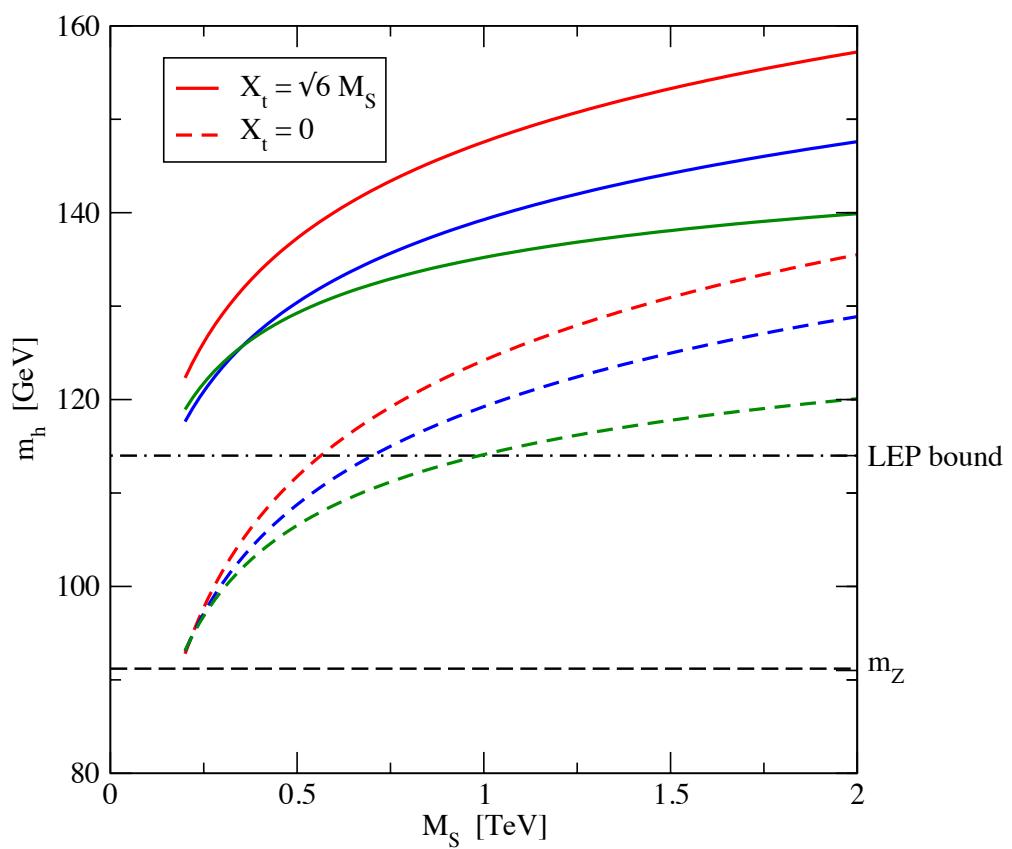




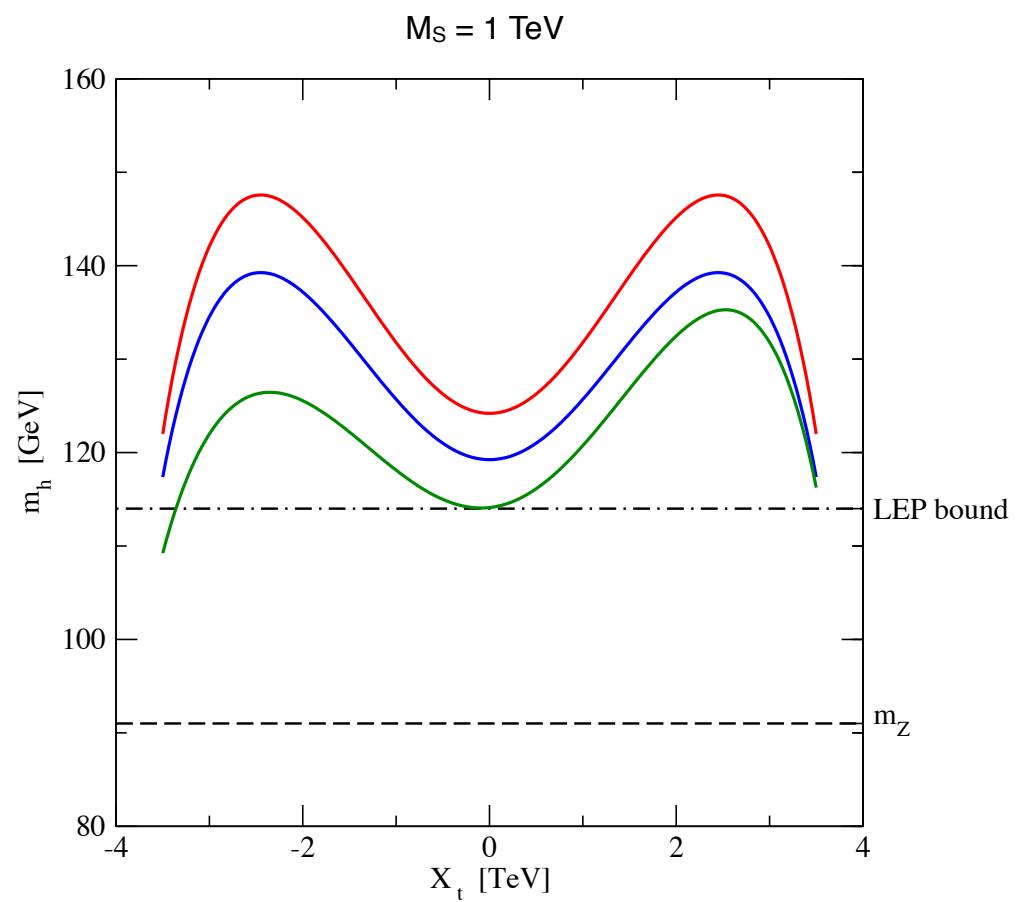
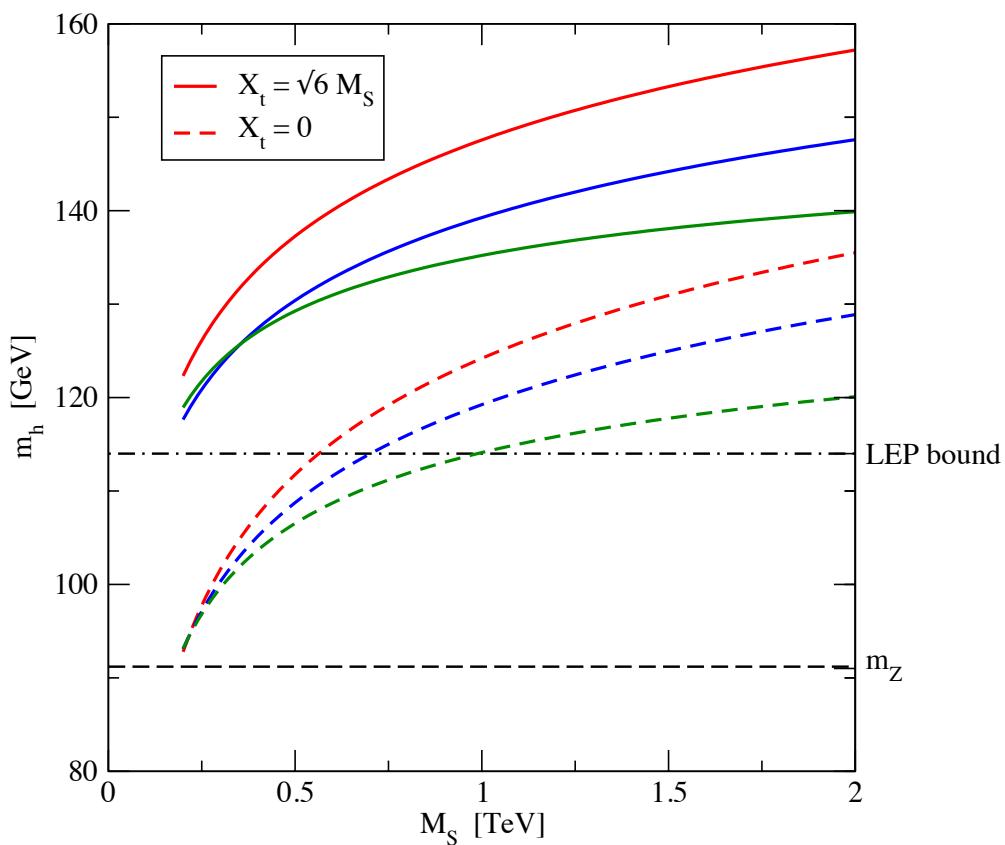
— using the physical top mass in 1-loop



- using the physical top mass in 1-loop
- using the running top mass of the SM



- using the physical top mass in 1-loop
- using the running top mass of the SM
- using the running top mass of the MSSM

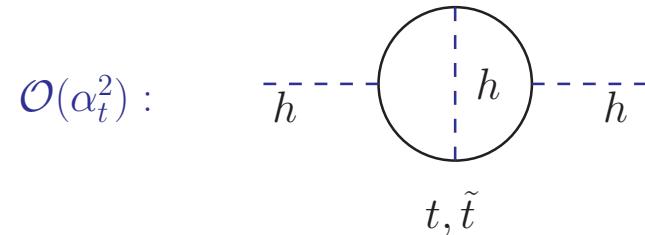
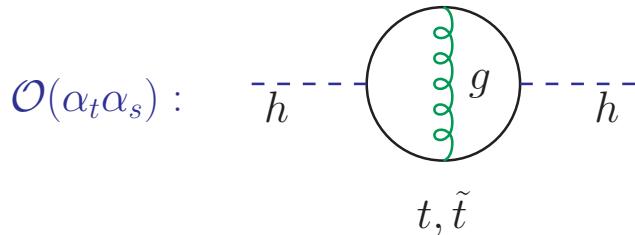


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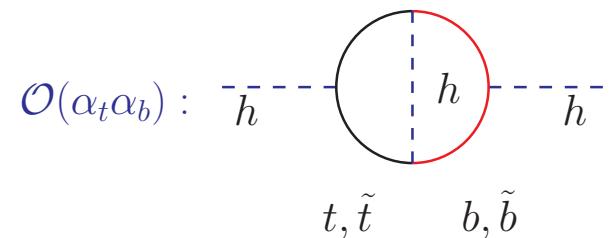
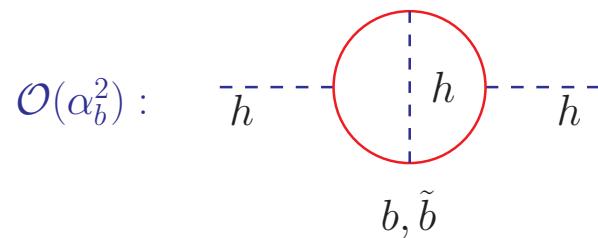
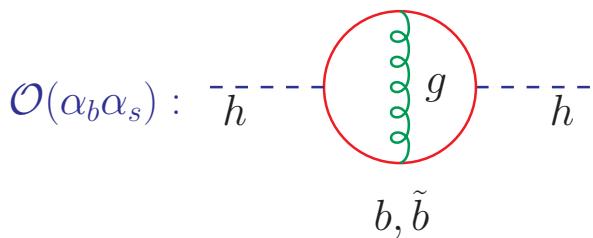
*Higher-order corrections
can be very important!!!*

Two-loop corrections to the Higgs masses

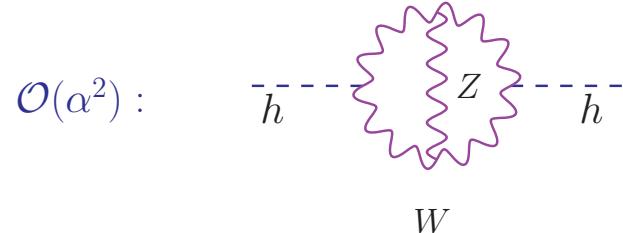
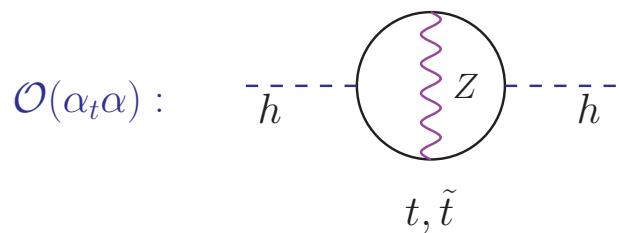
- Top corrections (always important)



- Bottom corrections (relevant only for large $\tan \beta$)



- Electroweak corrections (generally small)



Uncertainties in the MSSM Higgs mass

Public codes for the MSSM mass spectrum (e.g. `FeynHiggs`, `SuSpect`, `SoftSusy`, `SPheno`) currently include full 1-loop plus leading 2-loop top/stop and bottom/sbottom corrections (2-loop part by Heinemeyer *et al.* 98-07; P.S. *et al.* 01-04)

The estimated *theoretical* uncertainty of that prediction is $\Delta^{\text{th}} m_h \approx 3 \text{ GeV}$

A nearly-full 2-loop calculation including EW (Martin 02-04) and even the leading 3-loop terms (Martin 07; Harlander *et al.* 08-10) are now available. Uncertainty should go down to $\leq 1 \text{ GeV}$

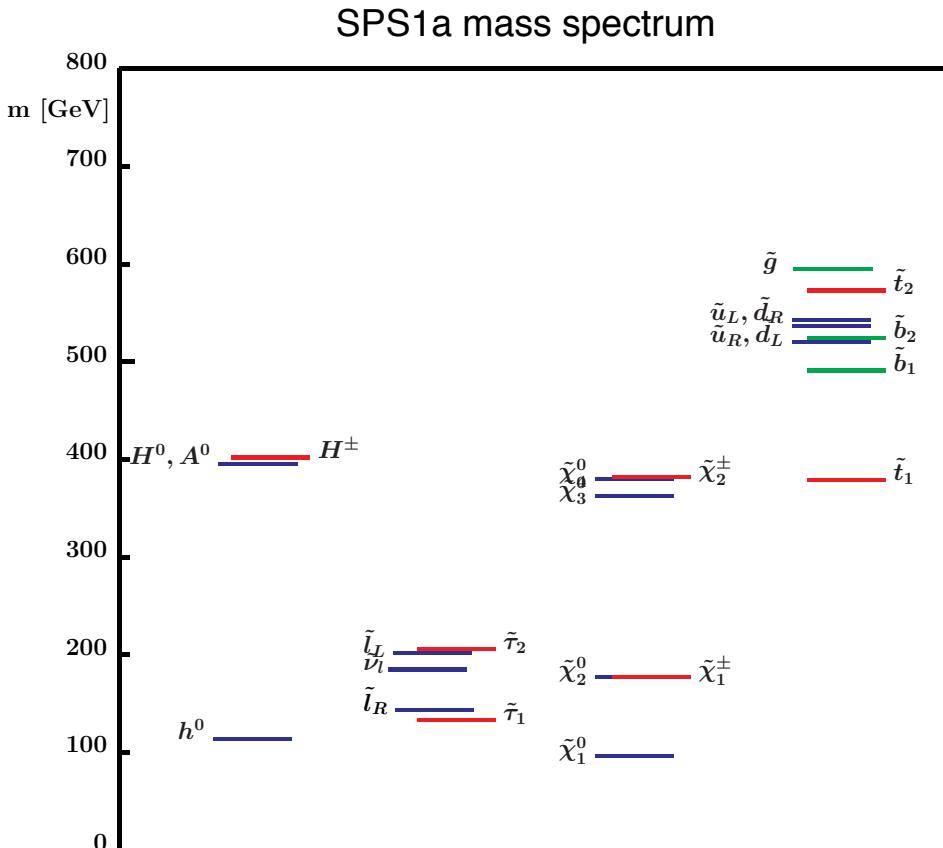
Still largish w.r.t. the expected *experimental* accuracy: $\Delta^{\text{exp}} m_h \approx 100 \text{ MeV}$ (with 30 fb^{-1})

We must also consider the *parametric* uncertainty stemming from the exp. uncertainty of the parameters (e.g. m_t , M_S , X_t , $\tan\beta$, m_g) entering the corrections. That is likely to dominate over the theoretical uncertainty from uncomputed higher-order corrections

However, we can turn the argument around: use precise measurement and precise theoretical prediction for m_h to constrain parameters that are not well measured at the LHC

Example: “Measuring Supersymmetry” with SFitter

(A study of the experimentalists’ most-beloved MSSM benchmark point: [SPS1a](#))



LHC measurements in SPS1a (from 0709.3985)

type of measurement	nominal value	stat.	LES	JES	theo. error
m_h	108.99	0.01	0.25		2.0
m_t	171.40	0.01			1.0
$m_{\tilde{l}_L} - m_{\tilde{\chi}_1^0}$	102.45	2.3	0.1		2.2
$m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$	511.57	2.3		6.0	18.3
$m_{\tilde{q}_R} - m_{\tilde{\chi}_1^0}$	446.62	10.0		4.3	16.3
$m_{\tilde{g}} - m_{\tilde{b}_1}$	88.94	1.5		1.0	24.0
$m_{\tilde{g}} - m_{\tilde{b}_2}$	62.96	2.5		0.7	24.5
m_{ll}^{\max} :	three-particle edge($\tilde{\chi}_2^0, \tilde{l}_R, \tilde{\chi}_1^0$)	80.94	0.042	0.08	2.4
m_{llq}^{\max} :	three-particle edge($\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0$)	449.32	1.4	4.3	15.2
m_{lq}^{low} :	three-particle edge($\tilde{q}_L, \tilde{\chi}_2^0, \tilde{l}_R$)	326.72	1.3		3.0
$m_{ll}^{\max}(\tilde{\chi}_4^0)$:	three-particle edge($\tilde{\chi}_4^0, \tilde{l}_R, \tilde{\chi}_1^0$)	254.29	3.3	0.3	4.1
$m_{\tau\tau}^{\max}$:	three-particle edge($\tilde{\chi}_2^0, \tilde{\tau}_1, \tilde{\chi}_1^0$)	83.27	5.0	0.8	2.1
m_{lq}^{high} :	four-particle edge($\tilde{q}_L, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{\chi}_1^0$)	390.28	1.4	3.8	13.9
m_{llq}^{thres} :	threshold($\tilde{q}_L, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{\chi}_1^0$)	216.22	2.3	2.0	8.7
m_{llb}^{thres} :	threshold($\tilde{b}_1, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{\chi}_1^0$)	198.63	5.1	1.8	8.0

(with 300 fb⁻¹)

Difficult to constrain the stop sector of SPS1a due to large bkgd from sbottom decays
(however, some hope from “fat-jet” analysis – see Gavin’s talk?)

Also, the heavy Higgses cannot be observed, and $\tan\beta$ is not measured directly

The light Higgs mass m_h is the only window on four poorly-constrained parameters:

$$m_A, \tan\beta, M_{\tilde{t}_R}, A_t$$

	LHC	LHC+ILC	SPS1a
$\tan\beta$	13.8 ± 7.4	10.7 ± 3.1	10.0
M_1	105.0 ± 6.9	103.1 ± 0.7	103.1
M_2	194.7 ± 7.3	193.0 ± 1.6	192.9
M_3	568.3 ± 11.6	568.5 ± 7.8	567.7
$M_{\tilde{\tau}_L}$	321.4 ± 248	192.4 ± 4.7	193.5
$M_{\tilde{\tau}_R}$	164.3 ± 120	134.9 ± 5.7	133.4
$M_{\tilde{\mu}_L}$	196.3 ± 7.6	194.4 ± 1.2	194.3
$M_{\tilde{\mu}_R}$	138.0 ± 7.0	135.8 ± 0.6	135.8
$M_{\tilde{e}_L}$	196.4 ± 7.5	194.3 ± 0.8	194.3
$M_{\tilde{e}_R}$	137.9 ± 7.1	135.8 ± 0.6	135.8
$M_{\tilde{q}_3 L}$	491.4 ± 16.2	486.2 ± 11.1	481.1
$M_{\tilde{t}_R}$	483.4 ± 232	409.6 ± 17.1	409.4
$M_{\tilde{b}_R}$	502.6 ± 15.3	499.1 ± 13.1	502.7
$M_{\tilde{q}_L}$	529.6 ± 12.1	526.4 ± 5.3	526.4
$M_{\tilde{q}_R}$	508.9 ± 16.4	507.8 ± 14.4	506.8
A_τ	fixed 0	-102.9 ± 681	-249.3
A_t	-394.4 ± 353	-497.3 ± 74	-496.8
A_b	fixed 0	-274.2 ± 1830	-764.0
m_A	558.2 ± 271.2	394.9 ± 1.5	394.9
μ	353.1 ± 7.7	350.8 ± 2.5	351.0

(table from 1007.2190)

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$M_{\tilde{t}_R}$ comparable with other squarks

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$M_{\tilde{q}_L}$	529.6 ± 12.1	526.4 ± 5.3	526.4
$M_{\tilde{q}_R}$	508.9 ± 16.4	507.8 ± 14.4	506.8
A_-	fixed 0	-102.9 ± 681	-249.3
A_t	-394.4 ± 353	-497.3 ± 74	-496.8
A_b	fixed 0	-274.2 ± 1830	-764.0
m_A	558.2 ± 271.2	394.9 ± 1.5	394.9
μ	353.1 ± 7.7	350.8 ± 2.5	351.0

$\tan\beta$ moderately large

$M_{\tilde{t}_R}$ comparable with other squarks

A_t suffers from sign ambiguity

(table from 1007.2190)

The light Higgs mass m_h is the only window on four poorly-constrained parameters:

$$m_A, \tan\beta, M_{\tilde{t}_R}, A_t$$

	LHC	LHC+ILC	SPS1a
$\tan\beta$	13.8 ± 7.4	10.7 ± 3.1	10.0
M_1	105.0 ± 6.9	103.1 ± 0.7	103.1
M_2	194.7 ± 7.3	193.0 ± 1.6	192.9
M_3	568.3 ± 11.6	568.5 ± 7.8	567.7
$M_{\tilde{\tau}_L}$	321.4 ± 248	192.4 ± 4.7	193.5
$M_{\tilde{\tau}_R}$	164.3 ± 120	134.9 ± 5.7	133.4
$M_{\tilde{\mu}_L}$	196.3 ± 7.6	194.4 ± 1.2	194.3
$M_{\tilde{\mu}_R}$	138.0 ± 7.0	135.8 ± 0.6	135.8
$M_{\tilde{e}_L}$	196.4 ± 7.5	194.3 ± 0.8	194.3
$M_{\tilde{e}_R}$	137.9 ± 7.1	135.8 ± 0.6	135.8
$M_{\tilde{\chi}_L^0}$	491.4 ± 16.2	486.2 ± 11.1	481.1
$M_{\tilde{t}_R}$	483.4 ± 232	409.6 ± 17.1	409.4
$M_{\tilde{b}_R}$	502.6 ± 15.3	499.1 ± 13.1	502.7
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m_A in decoupling limit

(table from 1007.2190)

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$M_{\tilde{t}_R}$ comparable with other squarks

A_t suffers from sign ambiguity

m_A in decoupling limit

The missing information will come from ILC

Summary

- The LHC faces a plethora of “Precision Challenges”. I mostly focused on those that concern the determination of the parameters in the EW sector of the SM
- Despite being principally a discovery machine, the LHC can still improve our knowledge of EW precision observables and solve a few outstanding riddles
- Statistics is rarely the limiting issue, at least in the long term. Understanding of the machine and – especially – PDF uncertainties appear to be more critical
- The EW precision observables (and the Higgs mass) might also constrain the parameter space of BSM models. A true precision analysis will come with ILC
- Apologies for the many challenges I ducked: advanced signal/bkgd calculations, flavor observables, top physics, jets (...) — However, see coming talks

Thank you!!!