Precision measurements and predictions

for M_W, electroweak and top

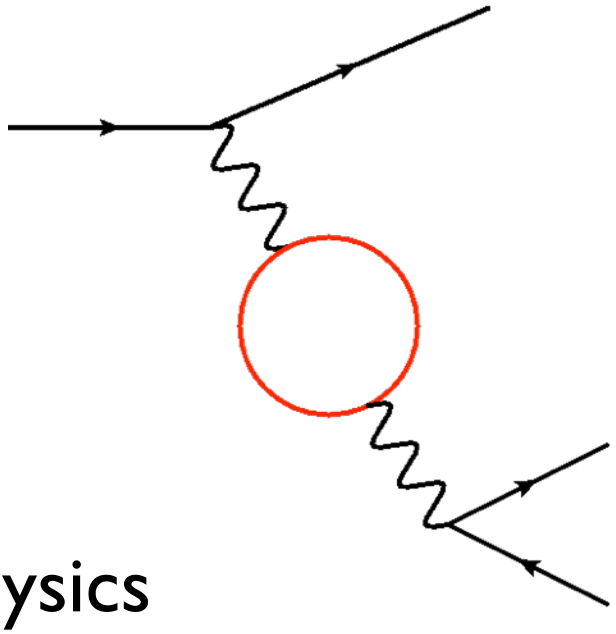
Lisa Zeune

French IRFU Linear Collider Days

27 November 2013

Why do we need precision measurements?

$\sin^2\theta_{\text{eff}}, M_W, \ldots$



- Electroweak precision observables

$$M_W,\quad \sin^2\theta_{\text{eff}},\quad a_\mu\ldots$$

- Highly sensitive to quantum effects of new physics
- Precise theoretical calculation + precise experimental measurement
  - ⟶ Test of theory
  - ⟶ Discrimination between models
  - ⟶ Constraining the parameter space
- Probe of new physics even if BSM particles are out of reach for LHC / ILC

Why do we need precision measurements?

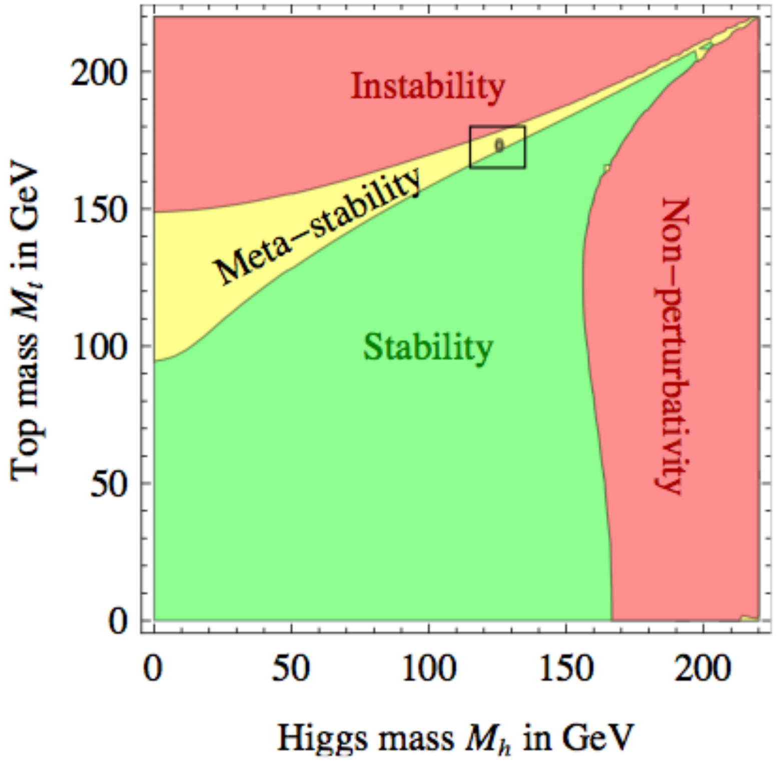
top quark mass

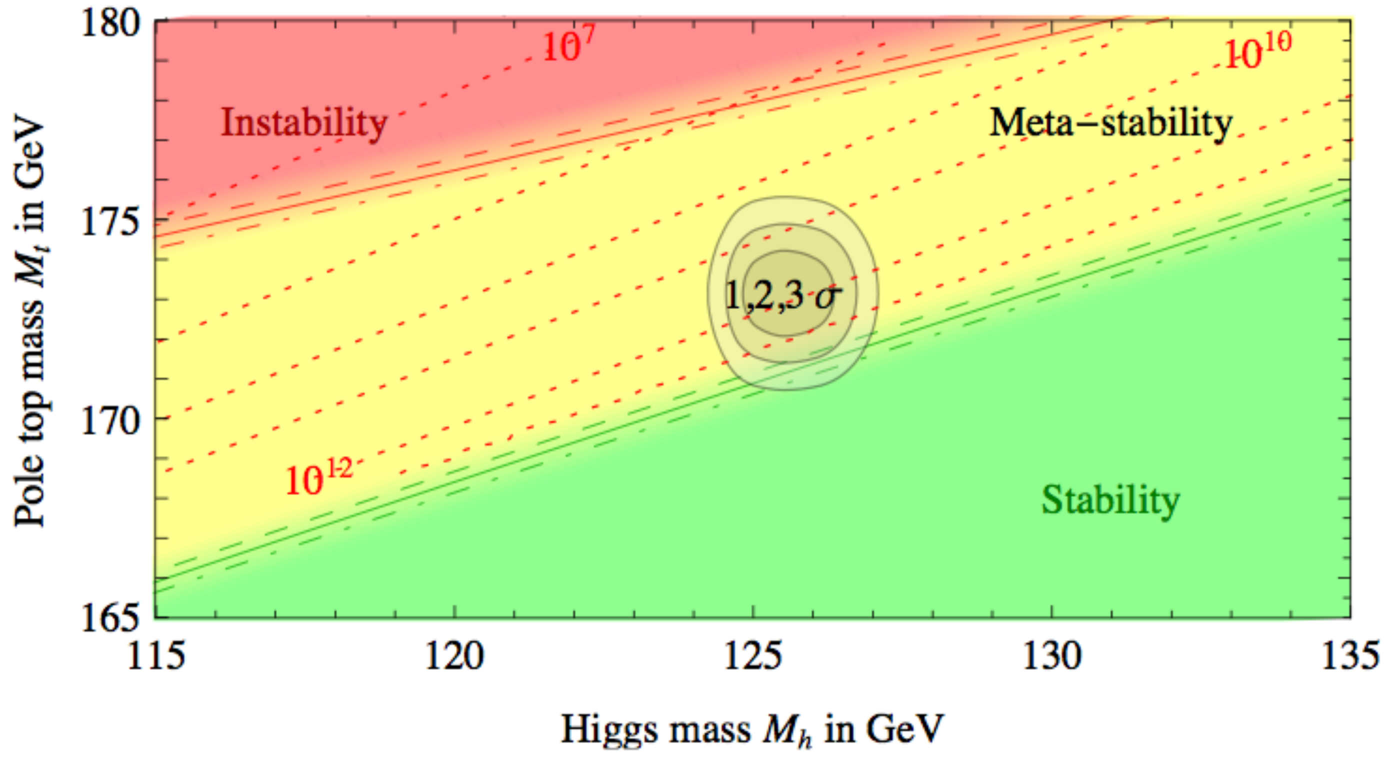
- Heaviest fundamental particles, largest coupling to Higgs

  → window to new physics at TeV scale / is there an underlying theory describing the mass hierarchy in the fermion sector?

- Is the SM Higgs potential stable?

Degrassi et al, ’13

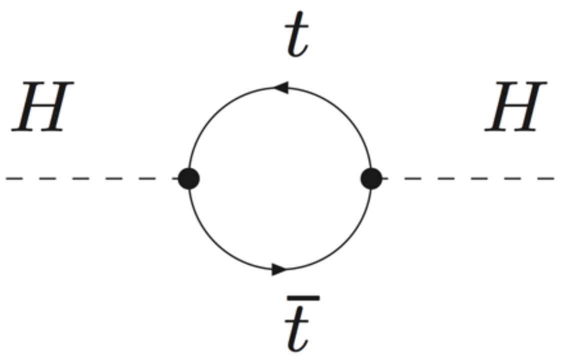




Why do we need precision measurements?

top quark mass

- Radiative corrections:
  - ⟶ Loop contributions proportional to $m_t^2,\ m_t^4$
  - ⟶ Large theory uncertainty in prediction of $M_W,\ \sin^2\theta_{\rm eff}$: parametric uncertainty from m_t
  - ⟶ To have sensitivity to new physics, top mass must be known very precisely
- Close connection to Higgs physics



  - ⟶ Large coupling of the Higgs to the top quark
  - ⟶ One-loop corrections: $\Delta M_h^2 \sim G_\mu C\, m_t^4$
  - ⟶ Higgs mass depends sensitively to m_t in all models where M_h can be predicted, e.g. SUSY (it is a free parameter in the SM)
  - ⟶ Precision Higgs physics needs precision top physics

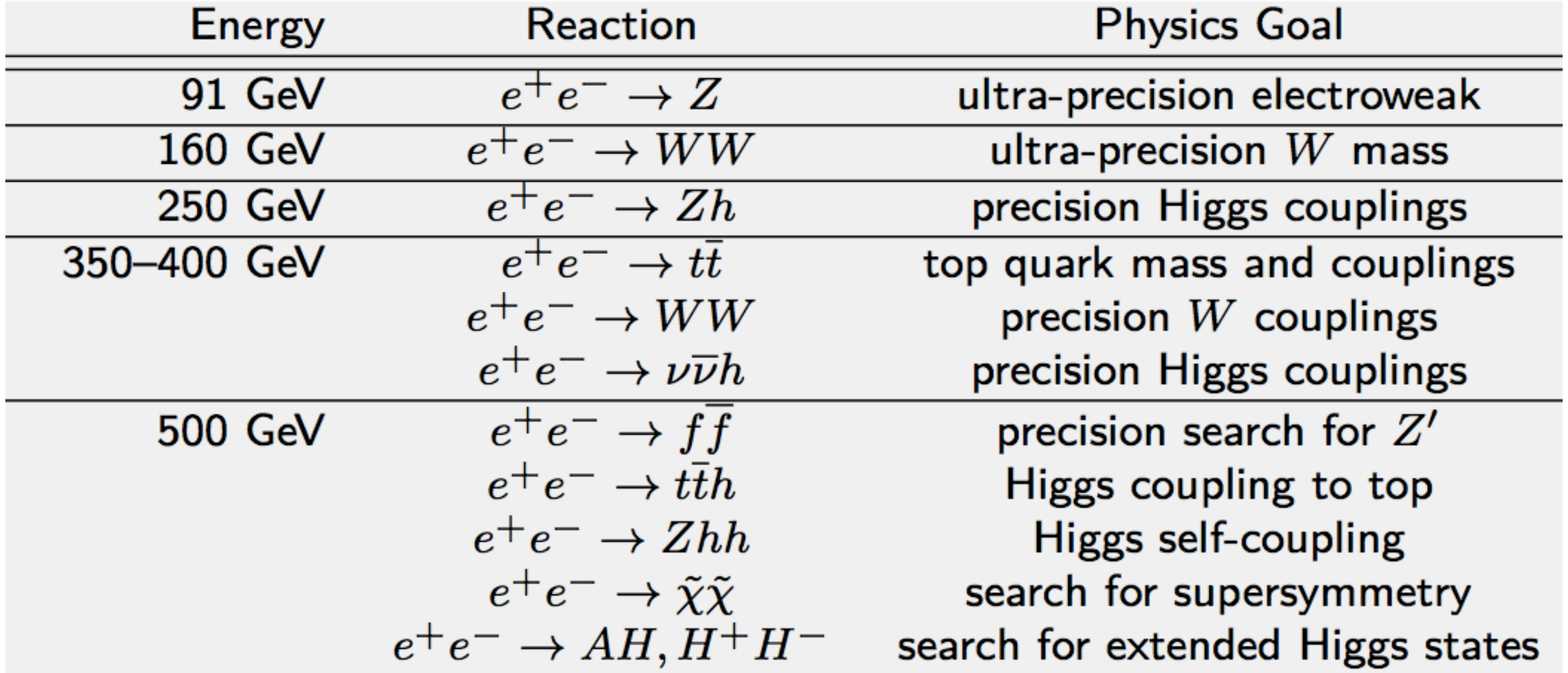
ILC measurements

- Clean experimental environment

- Tunable energy: possibility to carry out measurements at particles production thresholds

  → Possible to run at Z resonance (Giga-Z), WW threshold, top-antitop threshold

ILC, TDR '13



Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states

Approach for ILC in Japan:
start at 250 GeV
(precision Higgs measurements),
upgrade in stages via top-pair
threshold up to 500 GeV
(top quark properties)

- Polarized electron and positron beams

  → method to enhance signal over background

- Possible to perform high precision measurements

What is the top mass?

- What is the mass of an unstable colored particle?
- In theoretical calculations: $\overline{MS}$ mass, pole mass, ...
  well defined in perturbation theory (pole mass not infrared save)

Measurement of the top mass:

- Typically experimentally measured (done at LHC and Tevatron): kinematic reconstruction, fit to invariant mass of decay products
  - + Can be performed at arbitrary energy above threshold
  - \- This is not used in theory
    (Invariant mass believed to be close to pole mass)
  - \- No well defined conversion to $\overline{MS}$ mass

Threshold scan

- At Linear Collider possible to run at top-antitop threshold

  → Very precise measurement of $m_t, \Gamma_t, \alpha_s, \ldots$

- Measurement can be compared with accurate theory prediction

- Threshold mass can be converted to $\overline{MS}$ mass: Conversion formula precisely known and well under control

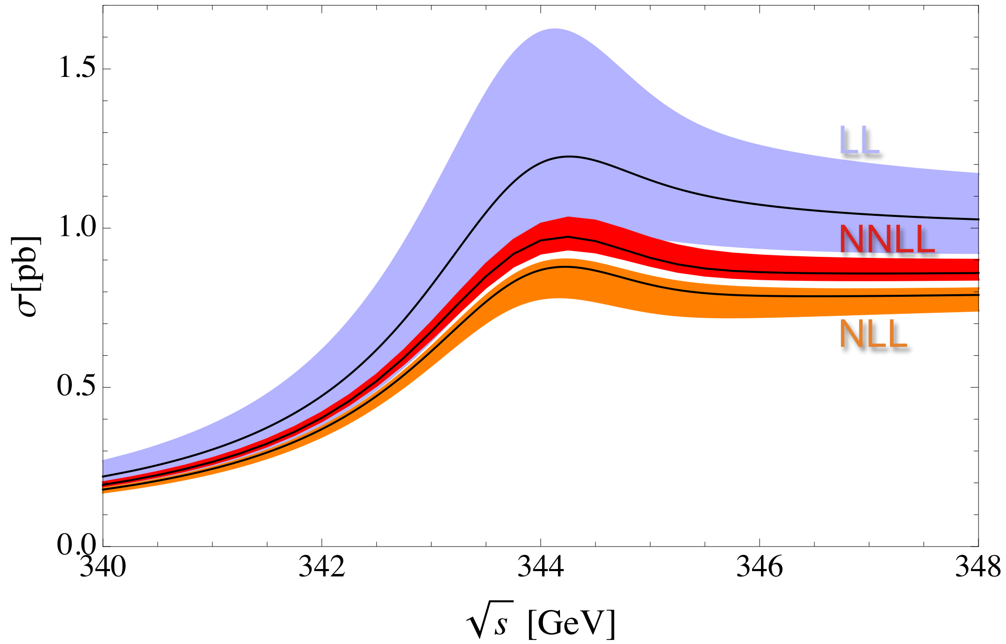
- ILC prediction:

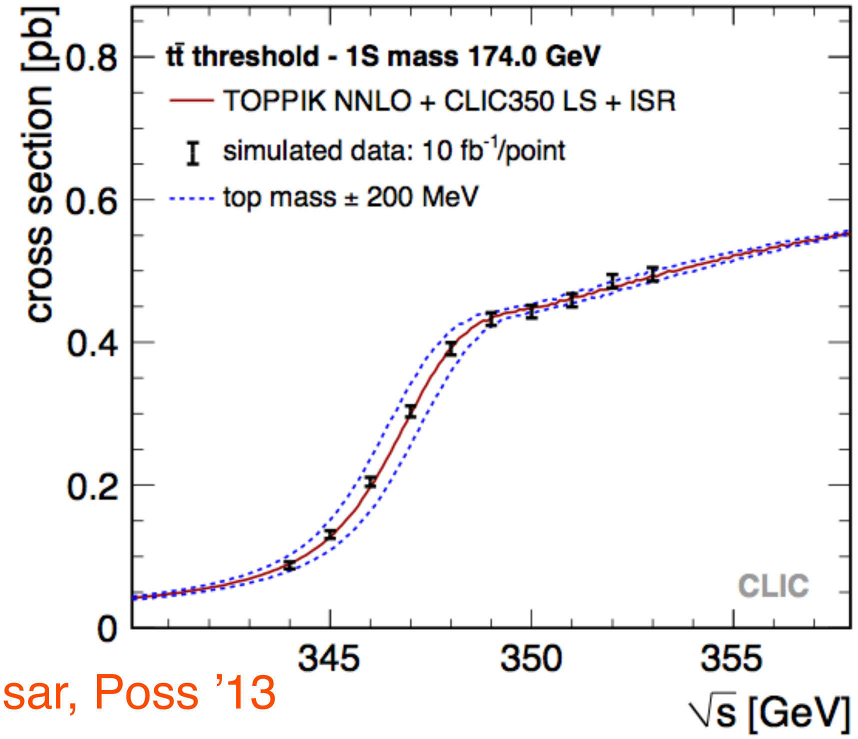
$$\Delta m_t = 0.1 \text{ GeV}$$

  theoretical uncertainty (from conversion formula) dominates

- Qualitative and quantitative improvement in top mass measurement

Hoang, Stahlhofen '13





Seidel, Simon, Tesar, Poss '13

Other top measurements at a LC

- Coupling of top to gauge bosons
  - $\hookrightarrow$ Sensitive to new physics modifying the e.g the $Zt\bar{t}$ vertex
  - $\hookrightarrow$ Sign of coupling, electric charge, spin
- Higgs coupling to top
- Asymmetries, e.g. forward-backward asymmetry A_{FB}
  - $\hookrightarrow$ Tevatron experiments saw possible deviation from the SM
  - $\hookrightarrow$ At LC significant improvement with respect to Tevatron and LHC
- Total width
- Strong coupling constant
- ...

Gauge boson self couplings

- Important test of the SM: precise measurement of pair and triple gauge boson production $e^+e^- \to W^+W^-,\ ZZ,\ W^+W^-Z, \ldots$
- The process of W^+W^- production allows sensitive measurement of triple gauge boson couplings

⟶ New physics can lead to deviations from the SM values

⟶ Possible to experimentally disentangle different types of couplings

$$
\begin{aligned}
L_{\mathrm{WWV}} \quad = \quad & g_{\mathrm{WWV}}[\\
& \underline{\mathrm{i}g_1^{\mathrm{V}}} V_\mu \left(W_\nu^- W_{\mu\nu}^+ - W_{\mu\nu}^- W_\nu^+\right) + \underline{\mathrm{i}\kappa_{\mathrm{V}}} W_\mu^- W_\nu^+ V_{\mu\nu} + \mathrm{i}\,\frac{\lambda^{\mathrm{V}}}{\underline{m_{\mathrm{W}}^2}} W_{\lambda\mu}^- W_{\mu\nu}^+ V_{\nu\lambda} \\
& + \underline{g_4^{\mathrm{V}}} W_\mu^- W_\nu^+ \left(\partial_\mu V_\nu + \partial_\nu V_\mu\right) + \underline{g_5^{\mathrm{V}}} \epsilon_{\mu\nu\lambda\rho} \left(W_\mu^- \partial_\lambda W_\nu^+ - \partial_\lambda W_\mu^- W_\nu^+\right) V_\rho \\
& + \underline{\mathrm{i}\tilde{\kappa}^{\mathrm{V}}} W_\mu^- W_\nu^+ \tilde{V}_{\mu\nu} + \mathrm{i}\,\frac{\tilde{\lambda}^{\mathrm{V}}}{\underline{m_{\mathrm{W}}^2}} W_{\lambda\mu}^- W_{\mu\nu}^+ \tilde{V}_{\nu\lambda}] \, ,
\end{aligned}
$$

In the SM: $\boxed{g_1^{\gamma,Z} = \kappa^{\gamma,Z} = 1,}$ $\boxed{g_4^{\gamma,Z} = g_5^{\gamma,Z} = \tilde{\kappa}^{\gamma,Z} = 0}$ and $\boxed{\lambda^{\gamma,Z} = \tilde{\lambda}^{\gamma,Z} = 0}$

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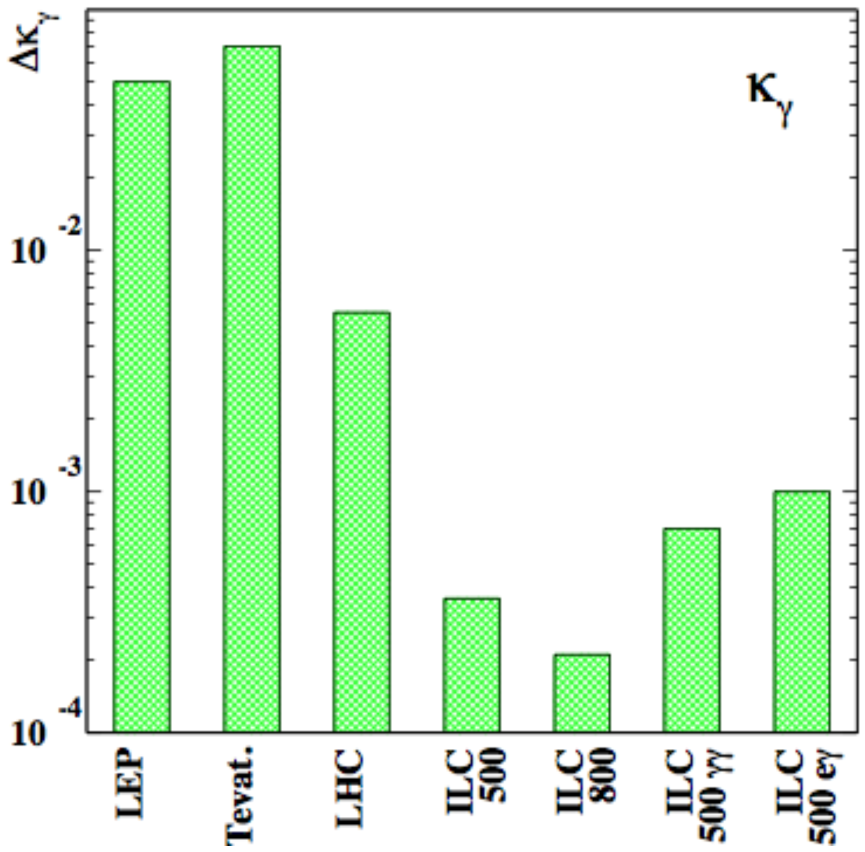
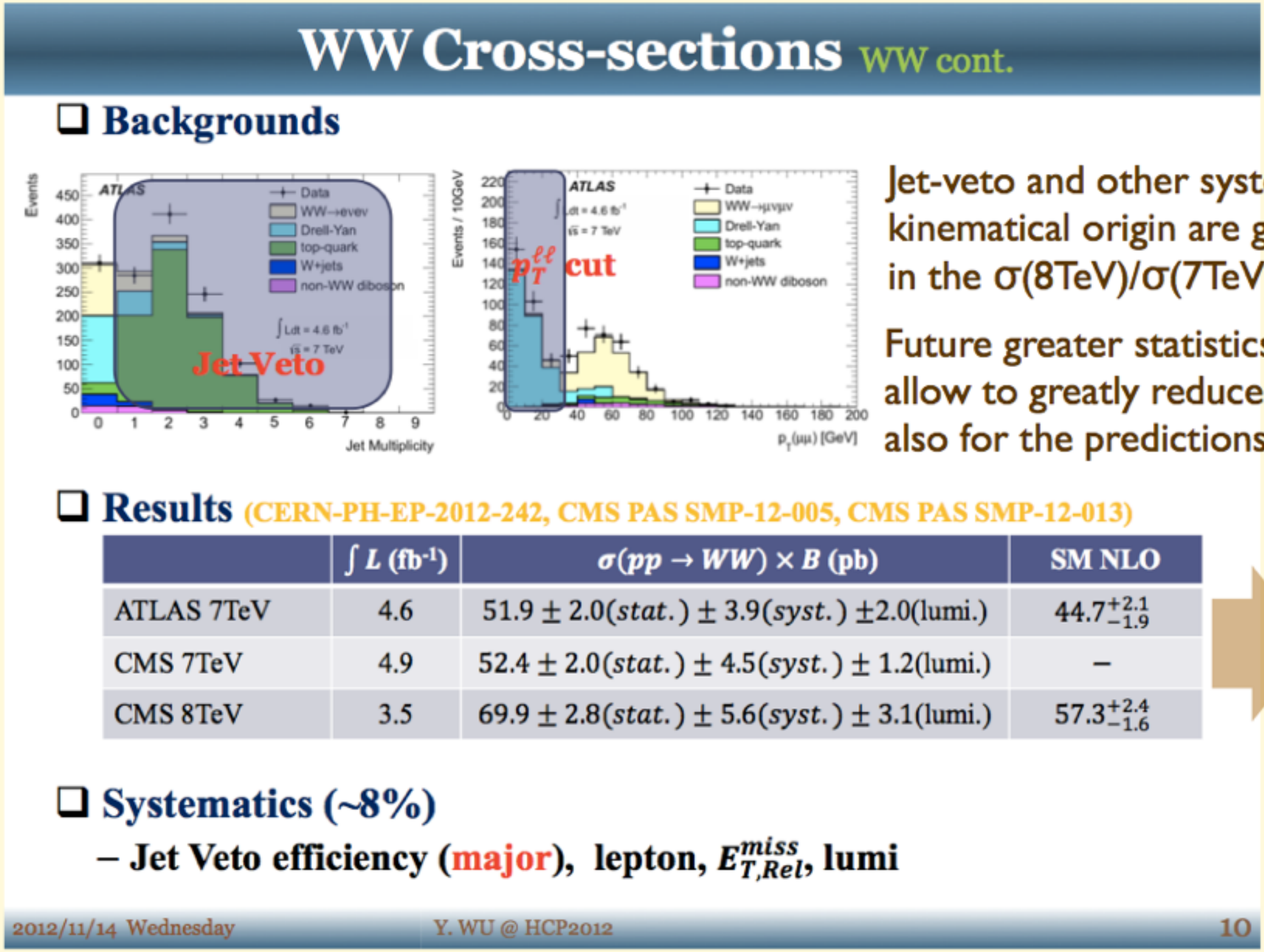


ILC, Reference Design Report '07

WW production at the LHC

Slide from M. Mangano, HCP 2012



WW Cross-sections WW cont.

☐ **Backgrounds**

☐ **Results** (CERN-PH-EP-2012-242, CMS PAS SMP-12-005, CMS PAS SMP-12-013)

	$\int L$ (fb^{-1})	$\sigma(pp \to WW) \times B$ (pb)	SM NLO
ATLAS 7TeV	4.6	$51.9 \pm 2.0(stat.) \pm 3.9(syst.) \pm 2.0$(lumi.)	$44.7^{+2.1}_{-1.9}$
CMS 7TeV	4.9	$52.4 \pm 2.0(stat.) \pm 4.5(syst.) \pm 1.2$(lumi.)	–
CMS 8TeV	3.5	$69.9 \pm 2.8(stat.) \pm 5.6(syst.) \pm 3.1$(lumi.)	$57.3^{+2.4}_{-1.6}$

☐ **Systematics (~8%)**

– **Jet Veto efficiency (major), lepton, $E_{T,Rel}^{miss}$, lumi**

Jet-veto and other systematics of kinematical origin are greatly reduced in the σ(8TeV)/σ(7TeV) ratio

Future greater statistics in pp→ZZ will allow to greatly reduce such systematics also for the predictions at fixed-energy

1.5-2σ off

A proposal for BSM interpretations of this discrepancy:

chargino production and leptonic decay

Feigl, Rzehak, Zeppenfeld, arXiv:1205.3468

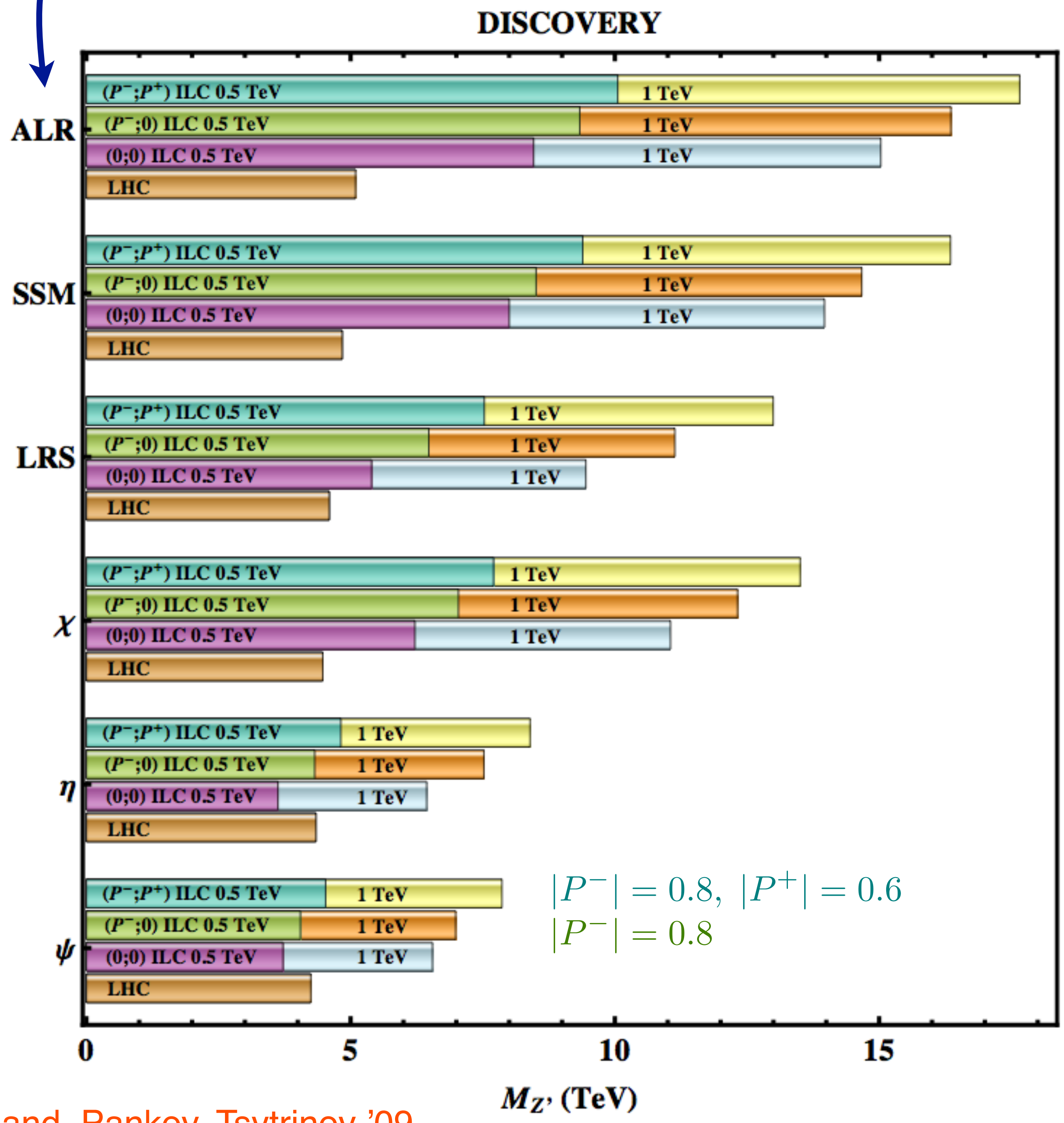
Extra gauge bosons

- Heavy neutral gauge bosons Z' are predicted in many extensions of the SM
- Lower mass limits
  - → EWPO
  - → Direct searches at Tevatron and the LHC
- ILC has potential to see effect of heavy virtual Z' through interference with Z and γ exchange in

$$e^+e^- \to f\bar{f}$$

- Possibility to discriminate between Z' models

Different Z' models



Osland, Pankov, Tsytrinov '09

Effective weak mixing angle: status

$$\boxed{\sin^2\theta^l_{\rm eff} = (1 - M_W^2/M_Z^2)(1 + \Delta\kappa)}$$

- Current most precise single measurements

via forward-backward asymmetry of b quarks

$$A^b_{\rm FB}({\rm LEP}) : \sin^2\theta^{\ell}{}^{\rm exp,LEP}_{\rm eff} = 0.23221 \pm 0.00029$$

$$A^e_{\rm LR}({\rm SLD}) : \sin^2\theta^{\ell}{}^{\rm exp,SLD}_{\rm eff} = 0.23098 \pm 0.00026$$

via left-right asymmetry of electrons

> 3σ difference

- LEP (SLD) measurement prefers SM Higgs mass of 437 (32) GeV

- Precise theoretical calculation, current uncertainties:

$$\Delta\sin^2\theta^l_{\rm eff}{}^{\rm SM,\ theo} = 4.5 \times 10^{-5} \quad \Delta\sin^2\theta^l_{\rm eff}{}^{\rm MSSM,\ theo} = (5-7) \times 10^{-5}$$

- ILC (with Giga-Z option) can significantly improve this measurement

Effective weak mixing angle: measurement

- At LC collider measured in $e^+e^- \to \gamma, Z \to l\bar{l}$ at the Z pole
- With polarized electron beams very precise measurement of the left-right asymmetry

$$A^e_{\mathrm{LR}} = \frac{1}{\mathcal{P}} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{2 g_{V_e} g_{A_e}}{g_{V_e}^2 + g_{A_e}^2}, \qquad \frac{g_{V_e}}{g_{A_e}} = 1 - 4 \sin^2 \theta^l_{\mathrm{eff}}$$

Beam polarization

- With 10^9 Z bosons, electron polarization 80%, no positron polarization: $\Delta \sin^2 \theta^l_{\mathrm{eff}} \sim 5 \times 10^{-5}$
- With additional positron polarization further improvement
- Overall ILC prediction:

$$\Delta \sin^2 \theta^l_{\mathrm{eff}} \lesssim 1.3 \times 10^{-5}$$

- More than factor 10 improvement compared to LEP/SLD
- Also A^b_{FB} can be measured at the LC

W boson mass

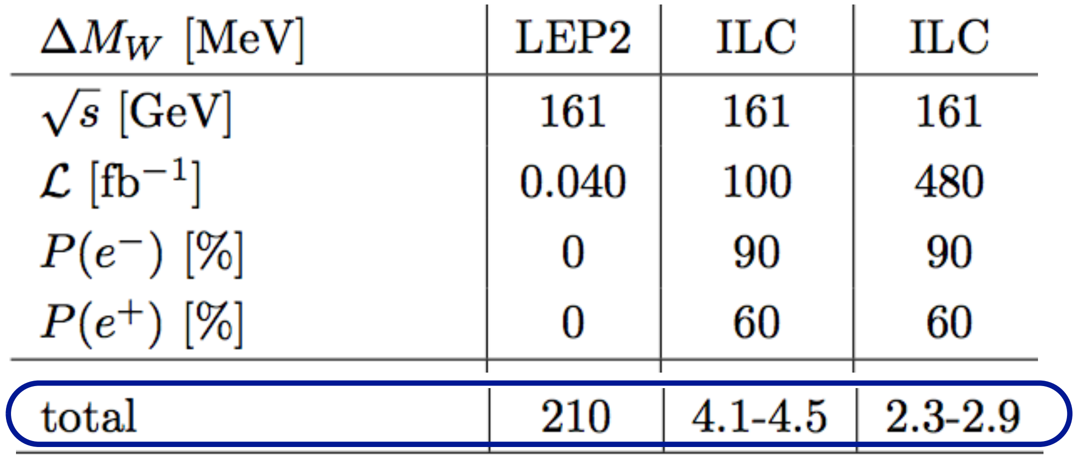
- Experimental precision significantly improved by Tevatron measurements
- World average

$$\boxed{M_W^{\text{exp}} = 80.385 \pm 0.015\ \text{GeV}}$$

Tevatron Electroweak Working Group, April '12

- Improvement at the LHC possible but very challenging
- Significant improvement of M_W possible at a linear collider
- Three uncorrelated methods to measure M_W at the ILC

→ Each has a predicted experimental precision of $\Delta M_W \lesssim 5\ \text{MeV}$



ΔM_W [MeV]	LEP2	ILC	ILC
$\sqrt{s}$ [GeV]	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480
$P(e^-)$ [%]	0	90	90
$P(e^+)$ [%]	0	60	60
total	210	4.1-4.5	2.3-2.9

Run at WW threshold

Wilson at al, Snowmass Study '13

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- Three uncorrelated methods to measure M_W at the ILC

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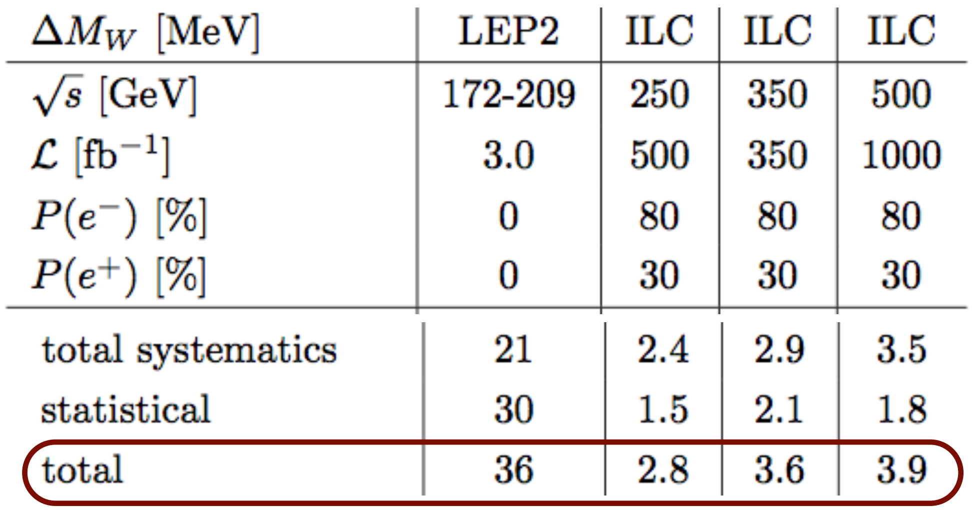
Run at higher energies

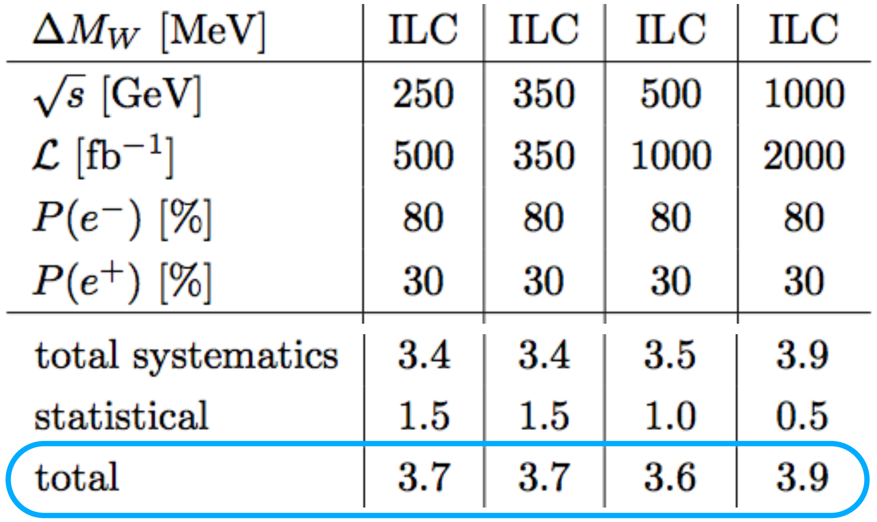
$\sqrt{s} = 250 \ldots 500\ \mathrm{GeV}$

Kinematic reconstruction using semi-leptonic channels



ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	172-209	250	350	500
$\mathcal{L}$ [fb^{-1}]	3.0	500	350	1000
$P(e^-)$ [%]	0	80	80	80
$P(e^+)$ [%]	0	30	30	30
total systematics	21	2.4	2.9	3.5
statistical	30	1.5	2.1	1.8
total	36	2.8	3.6	3.9

Direct reconstruction of the hadronic mass



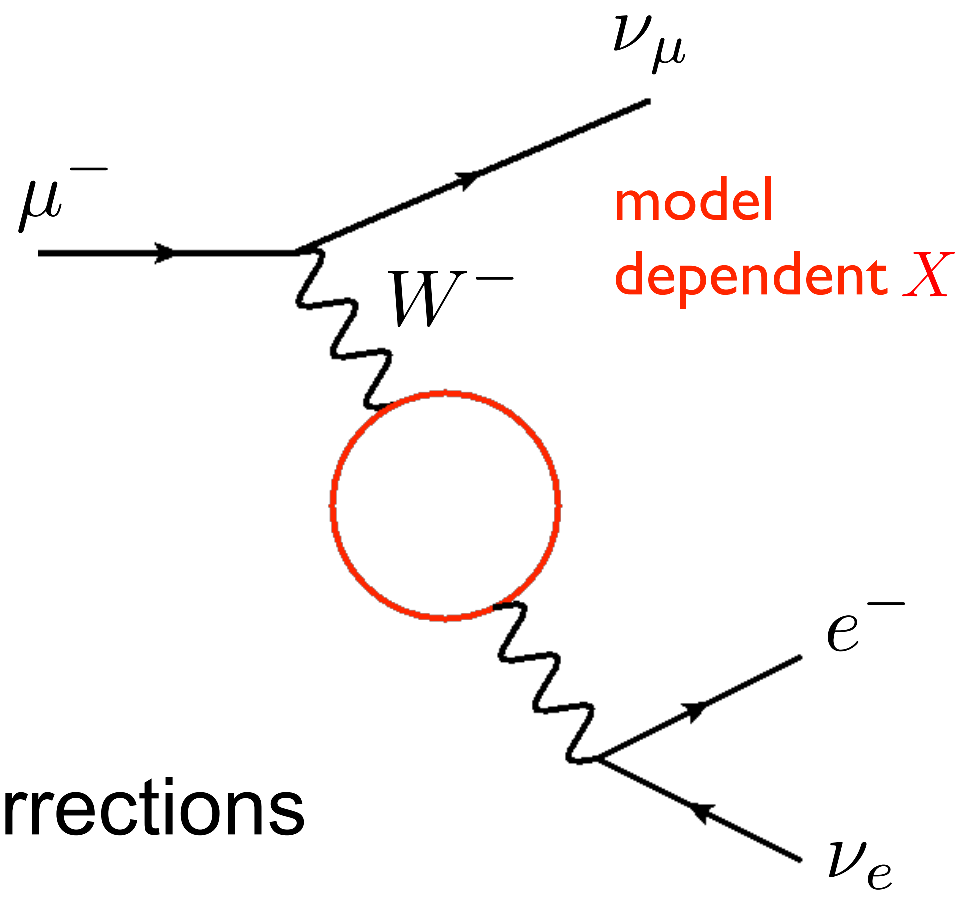
ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5
total	3.7	3.7	3.6	3.9

Wilson at al, Snowmass Study '13

Theoretical determination of the W boson

- Comparison of muon decay in SM and Fermi model gives:

$$\frac{G_\mu}{\sqrt{2}} = \frac{e^2}{8\left(1-\frac{M_W^2}{M_Z^2}\right)M_W^2}\left(1+\Delta r(M_W, M_Z, m_t, \ldots, X)\right)$$



- Model dependent prediction for M_W
- Very precise SM calculation

  (full 2-loop, leading 3- and 4-loop contributions)

- New 1-loop results in MSSM (with complex parameters) and NMSSM
  + inclusion of all available higher-order corrections

$$\Delta r^{(\mathrm{N})\mathrm{MSSM}} = \Delta r^{\mathrm{SM}} + \Delta r^{\mathrm{SUSY}}$$

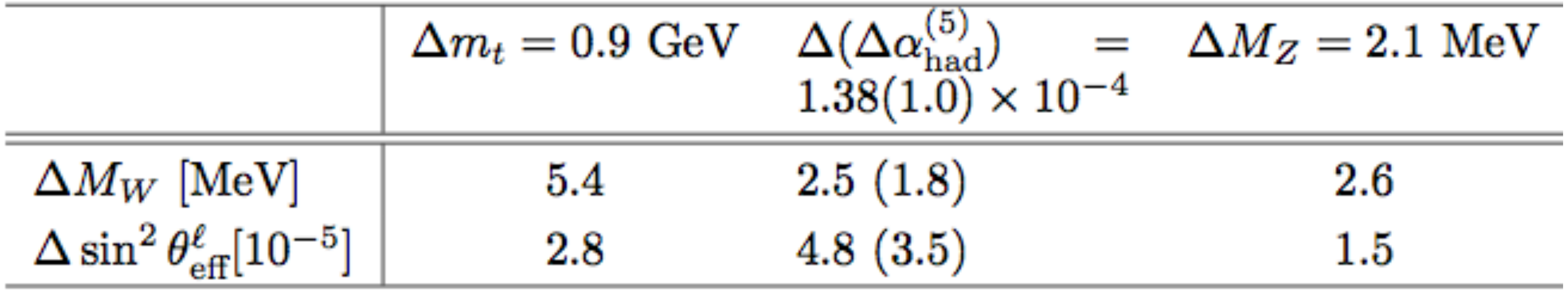
⟶ Most precise W boson mass prediction in MSSM and NMSSM

Heinemeyer, Hollik, Weiglein, LZ '13

Theory uncertainties

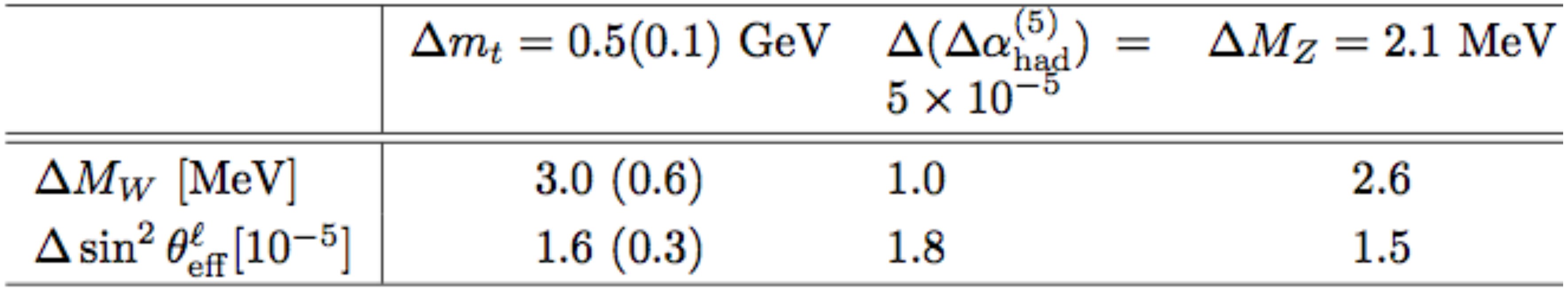
- Current parametric uncertainties

Freitas at al, Snowmass Study '13



	$\Delta m_t = 0.9$ GeV	$\Delta(\Delta\alpha^{(5)}_{\rm had}) = 1.38(1.0) \times 10^{-4}$	$\Delta M_Z = 2.1$ MeV
ΔM_W [MeV]	5.4	2.5 (1.8)	2.6
$\Delta \sin^2\theta^{\ell}_{\rm eff}[10^{-5}]$	2.8	4.8 (3.5)	1.5

- Improved measurements



	$\Delta m_t = 0.5(0.1)$ GeV	$\Delta(\Delta\alpha^{(5)}_{\rm had}) = 5 \times 10^{-5}$	$\Delta M_Z = 2.1$ MeV
ΔM_W [MeV]	3.0 (0.6)	1.0	2.6
$\Delta \sin^2\theta^{\ell}_{\rm eff}[10^{-5}]$	1.6 (0.3)	1.8	1.5

- Uncertainties from missing higher order corrections (current status)

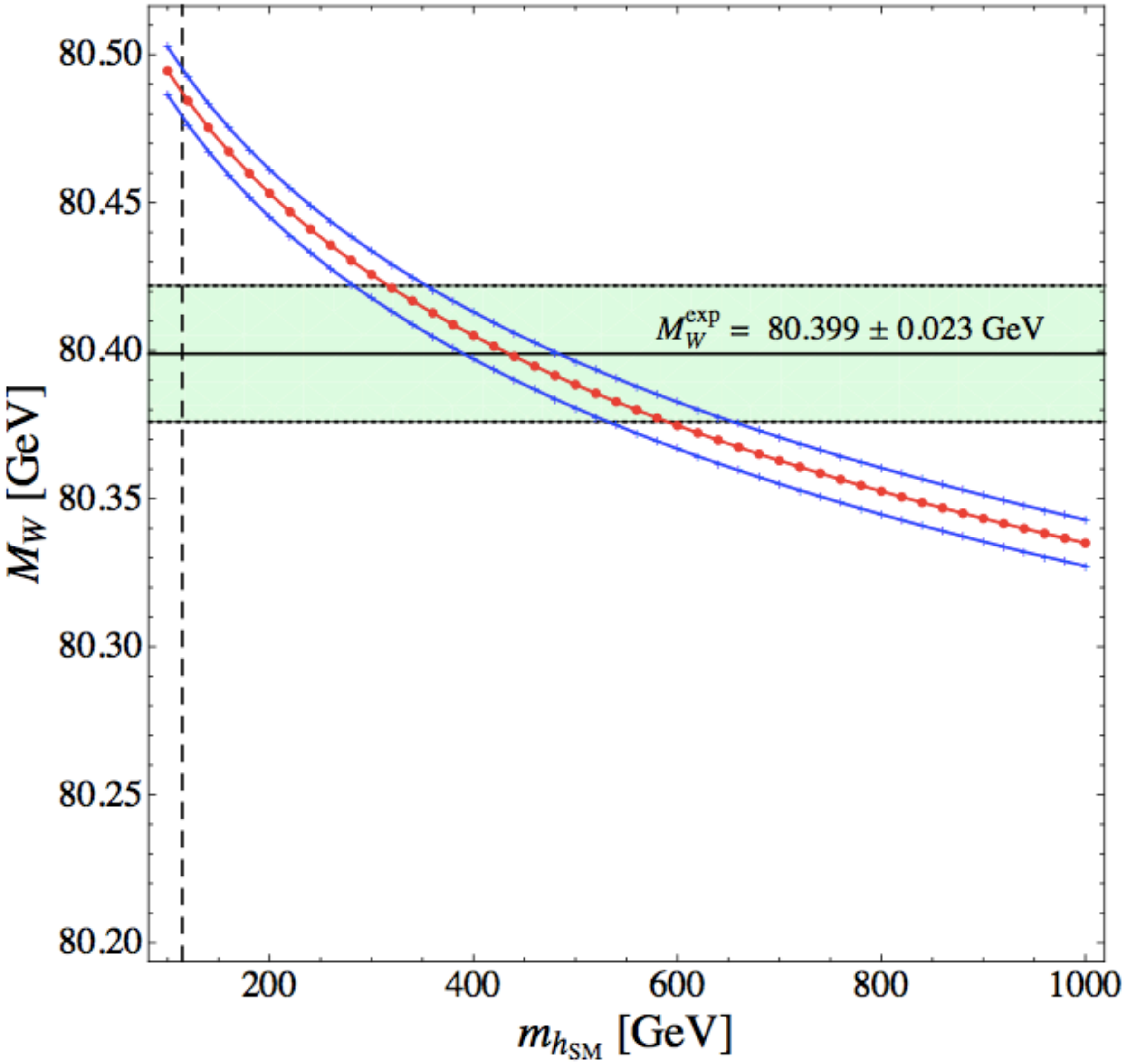
SM: 4 MeV M. Awramik, M. Czakon, A. Freitas and G. Weiglein '03

MSSM: 4 - 9 MeV J. Haestier, S. Heinemeyer, D. Stöckinger, G. Weiglein '05

W boson mass in the SM

Current world average:
$M_W^{\text{exp}} = 80.385 \pm 0.015\ \text{GeV}$

- Tree level prediction differs from SM by more than $30\,\sigma$
- Including all 1-loop contributions:



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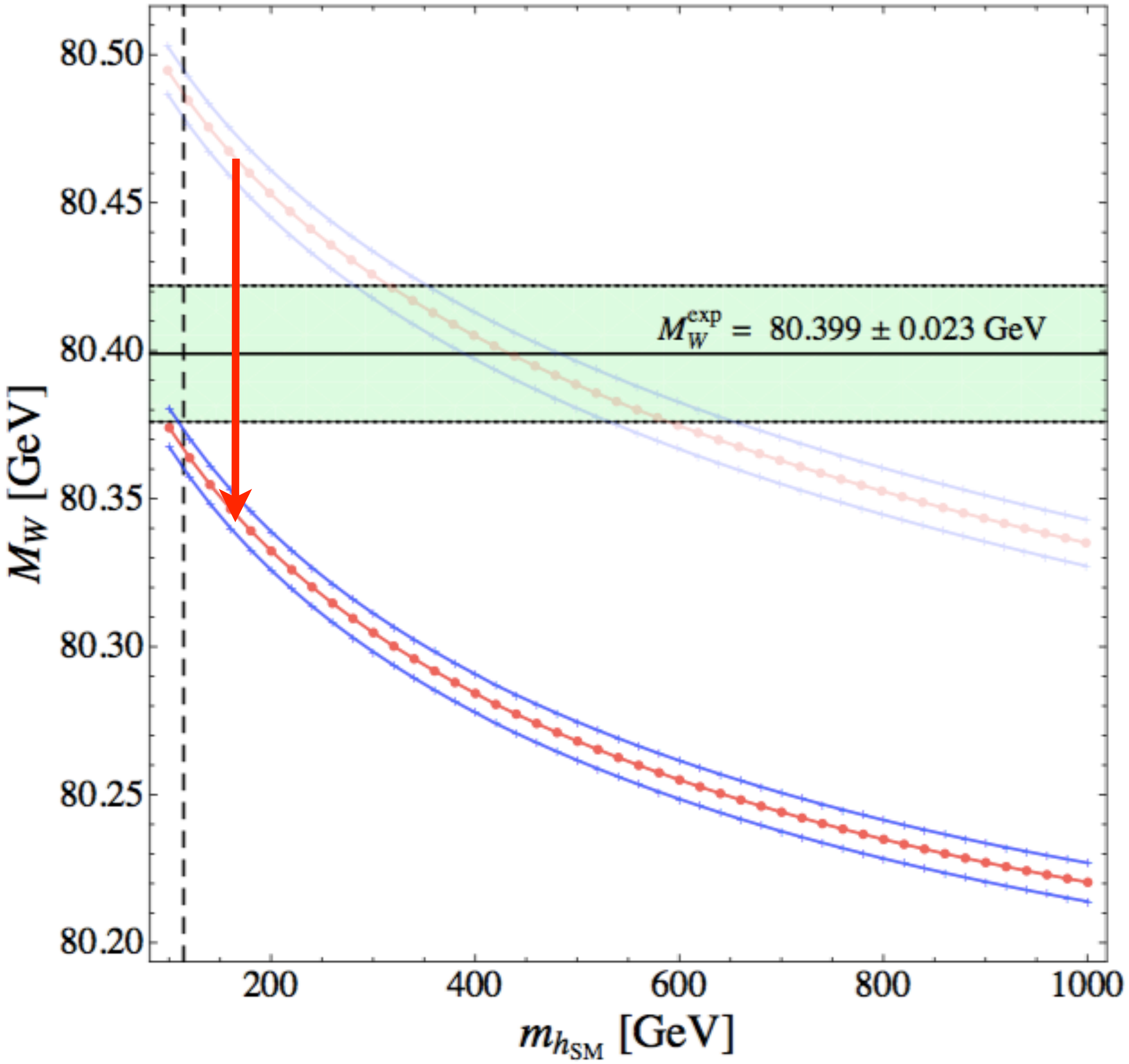
- Tree level prediction differs from SM by more than $30\,\sigma$
- Including all higher order corrections:
- Corrections beyond 1-loop cause a downward shift of more than 100 MeV

⟶ crucial to include higher order corrections



- SM result

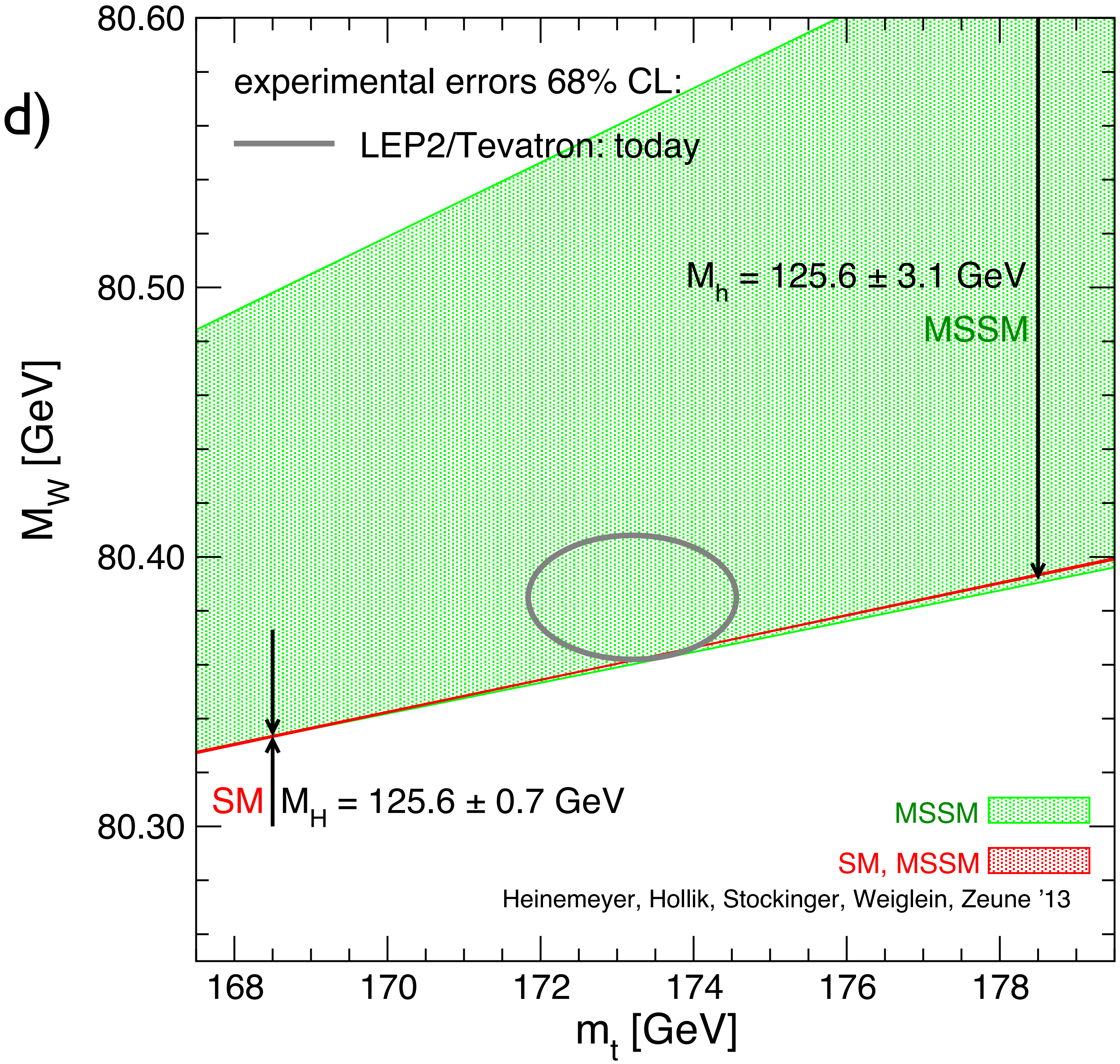
$$M_W^{\text{SM}}(m_t = 173.2 \text{ GeV},\ M_H^{\text{SM}} = 125.64 \text{ GeV}) = 80.361 \text{ GeV}$$

- Deviation from the measurement is $\sim 1.5\,\sigma$

W boson mass prediction in the MSSM

Obtained from parameter scan:

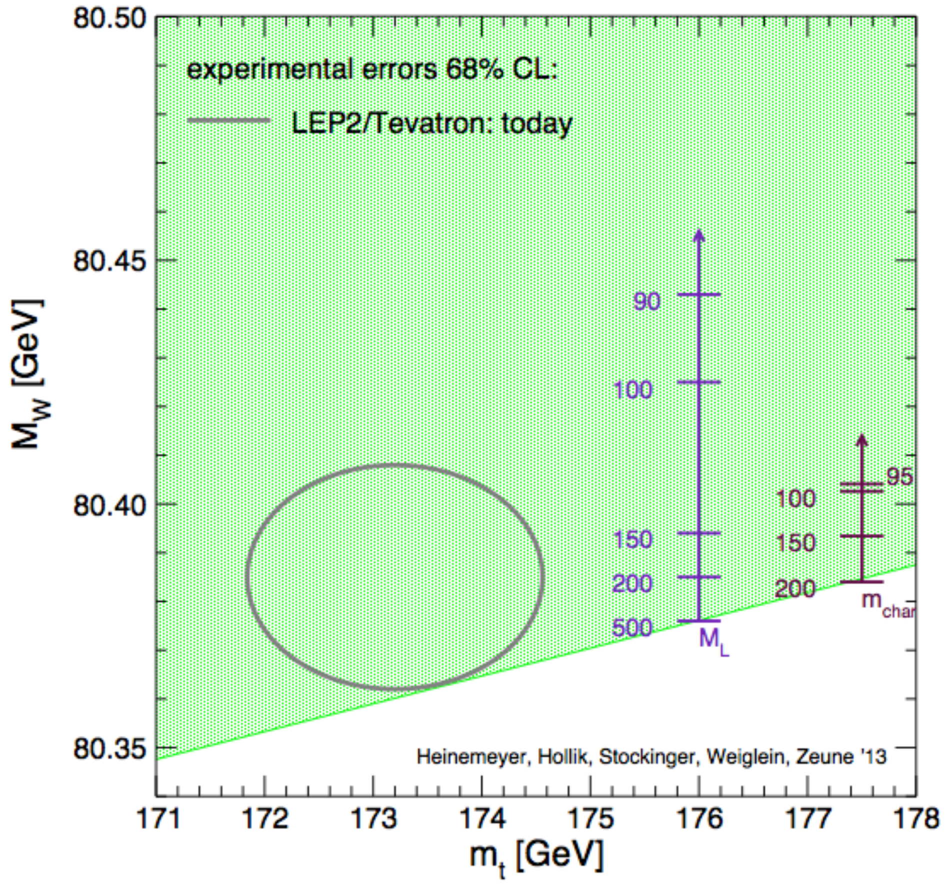
- Allowed MSSM region:
  Discovered Higgs is interpreted as light CP-even MSSM Higgs (3 GeV theory uncertainty added)
- Overlap region - SM and MSSM:
  Observed signal is interpreted as SM Higgs

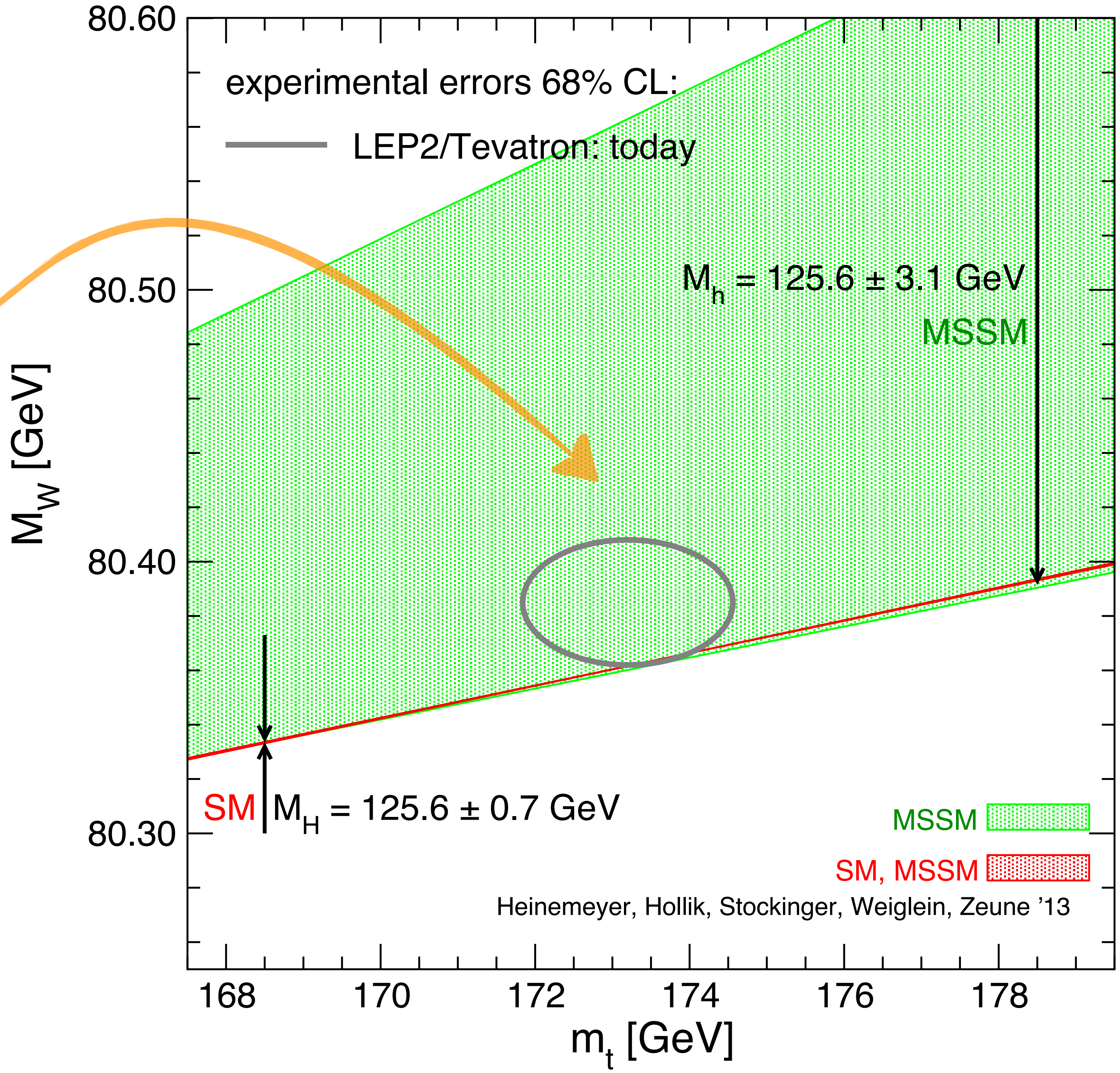


W boson mass prediction in the MSSM

- Largest SUSY contributions from stops and sbottoms (large splitting required)

- Sizable contributions also from light sleptons (~60 MeV) and charginos and neutralinos (~20 MeV)





W boson mass prediction in the MSSM

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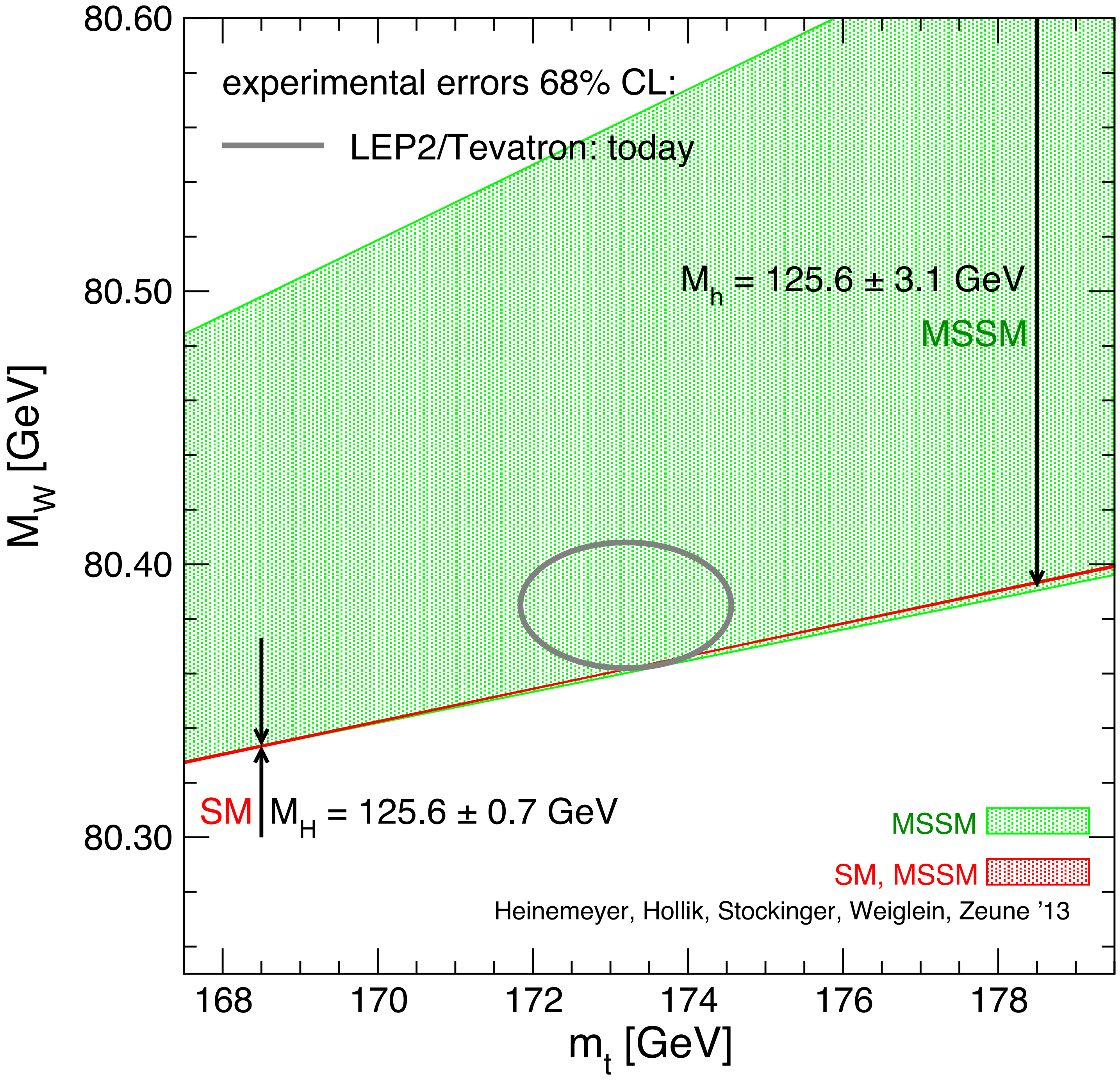
- Slight preference for non zero SUSY contribution

- With current level of precision no clear conclusion can be drawn



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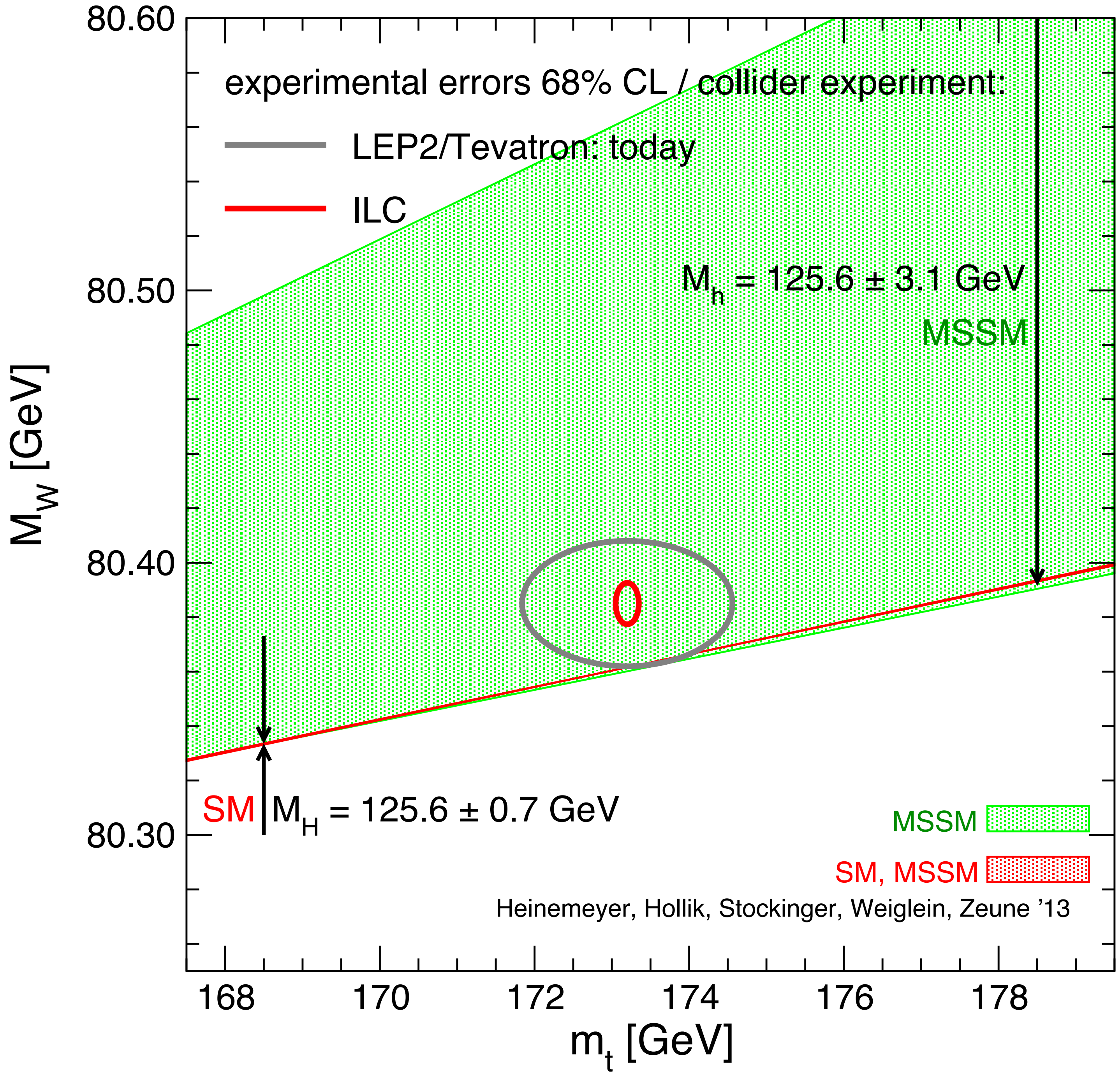
- With current level of precision no clear conclusion can be drawn

- With LC precision it might be possible to discriminate between SM and the MSSM

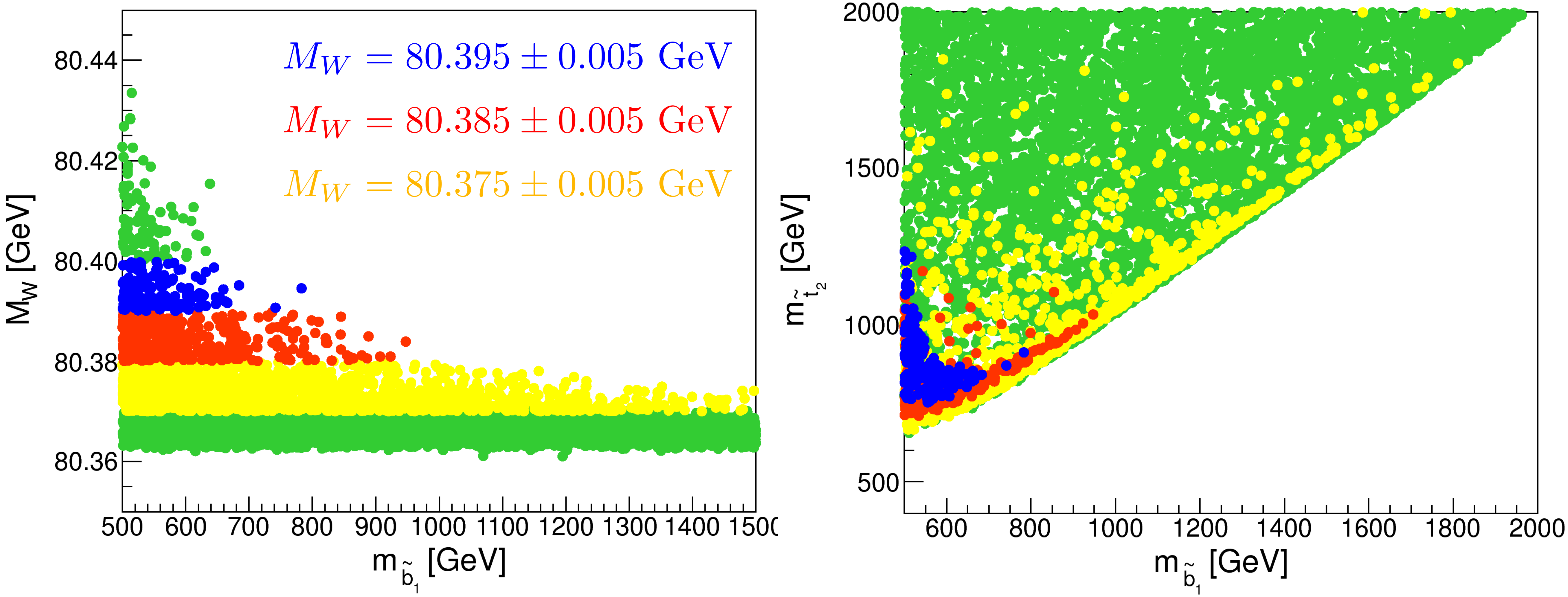


Heinemeyer, Hollik, Stockinger, Weiglein, Zeune '13

Possible future scenario:

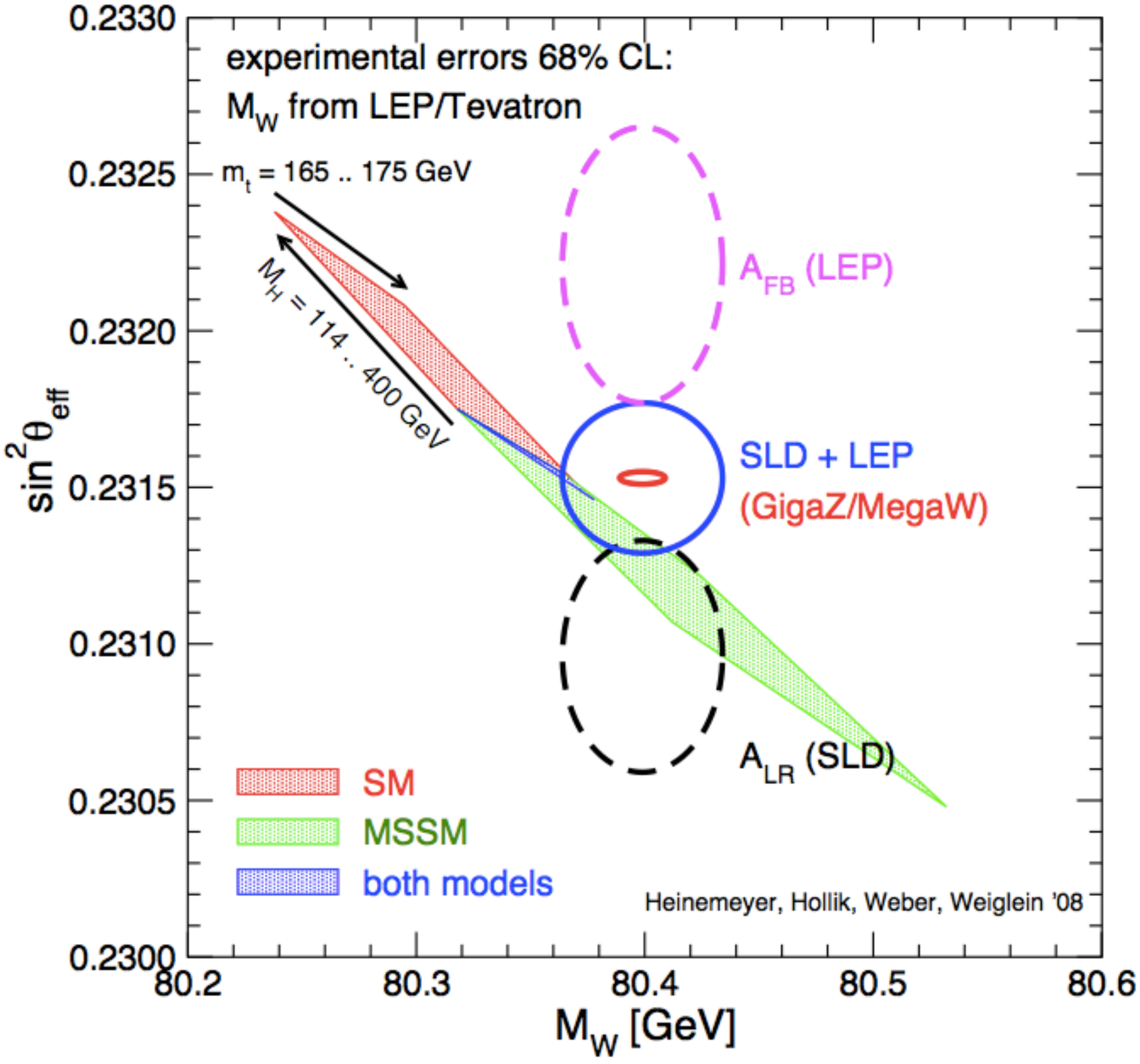
Stop at 400 GeV,
all other SUSY particles heavy,
Higgs at 126 GeV

Heinemeyer, Hollik, Weiglein, LZ '13



- Precise measurement of the W boson mass restricts light sbottom and heavy stop mass ranges to small intervals
- Precision observable provide constraints on undetected particles

SM and MSSM predictions for the W boson mass and the effective mixing angle

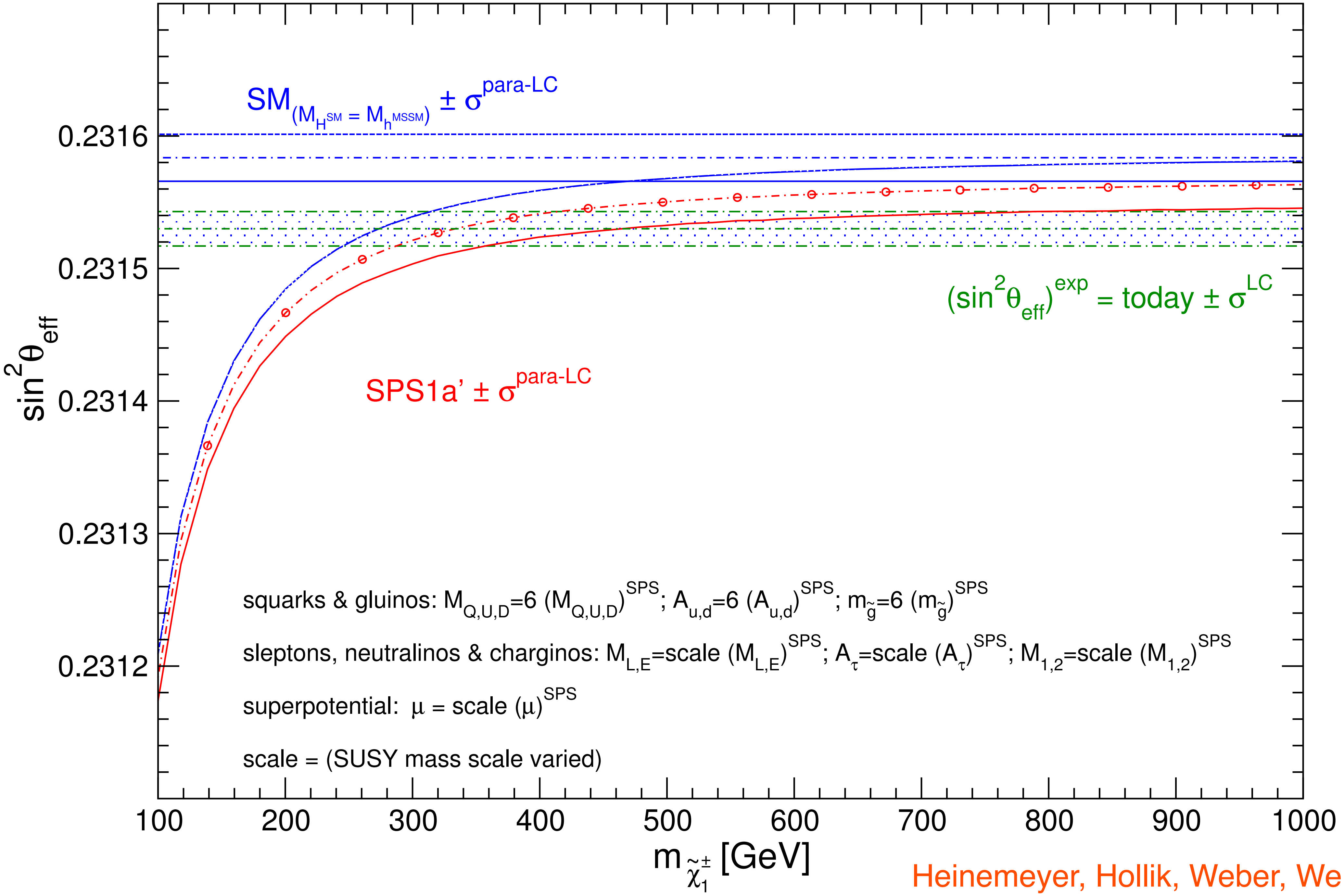


- SLD value favors MSSM
- LEP value inconsistent with both models
- Average of LEP and SLD measurements compatible with SM and MSSM

→ New measurements needed

High precision measurement of $\sin^2\theta^{\mathrm{l}}_{\mathrm{eff}}$

- Sensitivity to SUSY scale in a scenario where no SUSY particles are observed at the LHC



Heinemeyer, Hollik, Weber, Weiglein '07

Conclusions

- Top physics at the linear collider
- Qualitative and quantitative improvement of top mass measurement
- Rich program: precise measurements of top couplings, asymmetries ...
- Electroweak physics at the linear collider
- Precise measurement of processes $e^+e^- \to W^+W^-, ZZ, f\bar{f}, ...$

  ↪ Sensitive to small deviations from SM predictions

- Precise measurement of W boson mass
- Giga-Z: High precision measurement of Z observables

  ↪ New measurement of $\sin\theta^l_{\mathrm{eff}}$

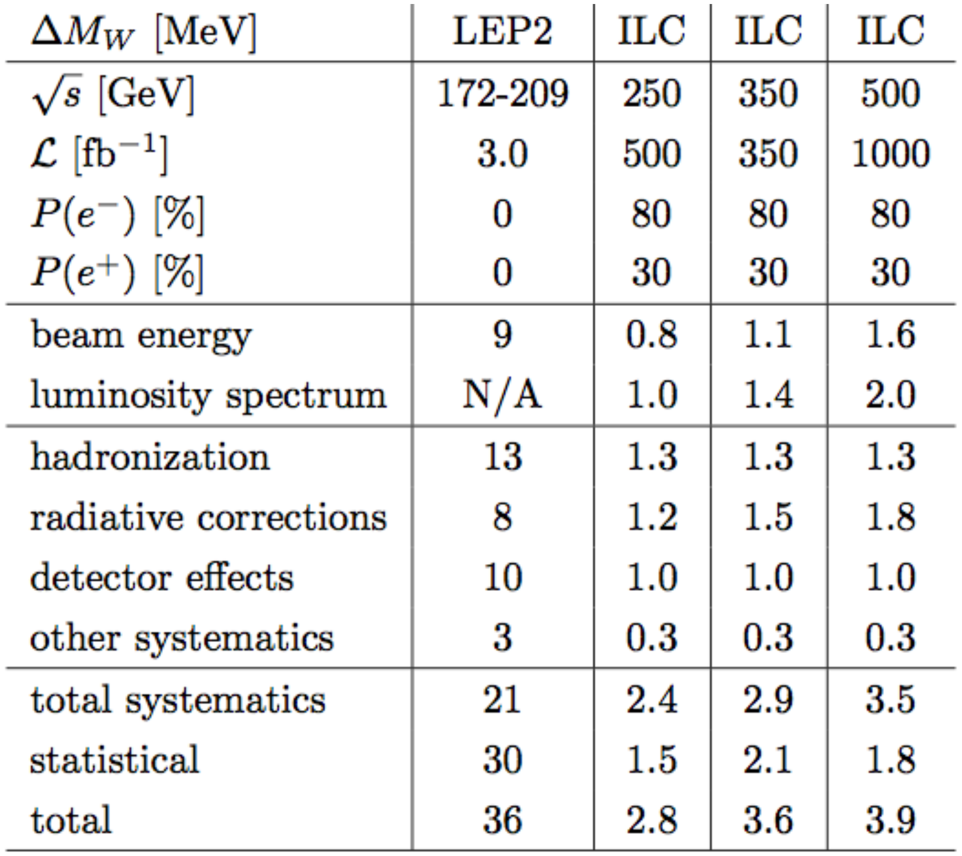
- Sensitivity to new physics effects drastically improves with ILC precision on EWPO and the top mass

  ↪ Sensitive test of any TeV scale new physics model

Back-up

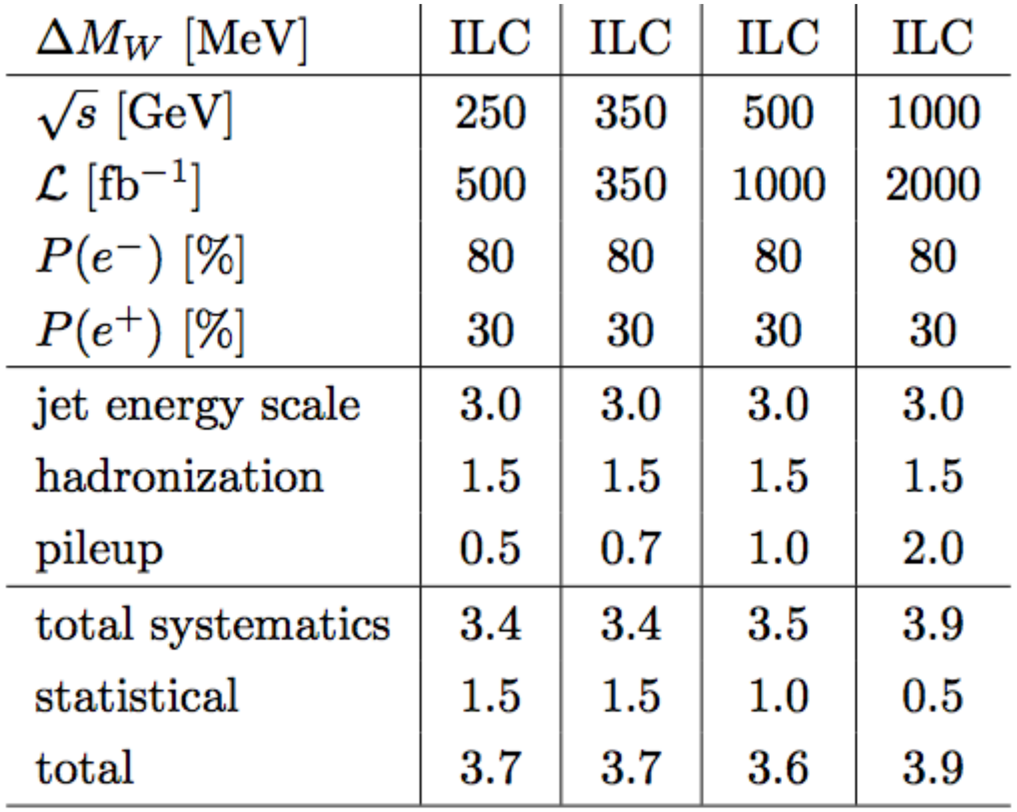
W boson mass at the LC

Kinematic reconstruction using semi-leptonic channels



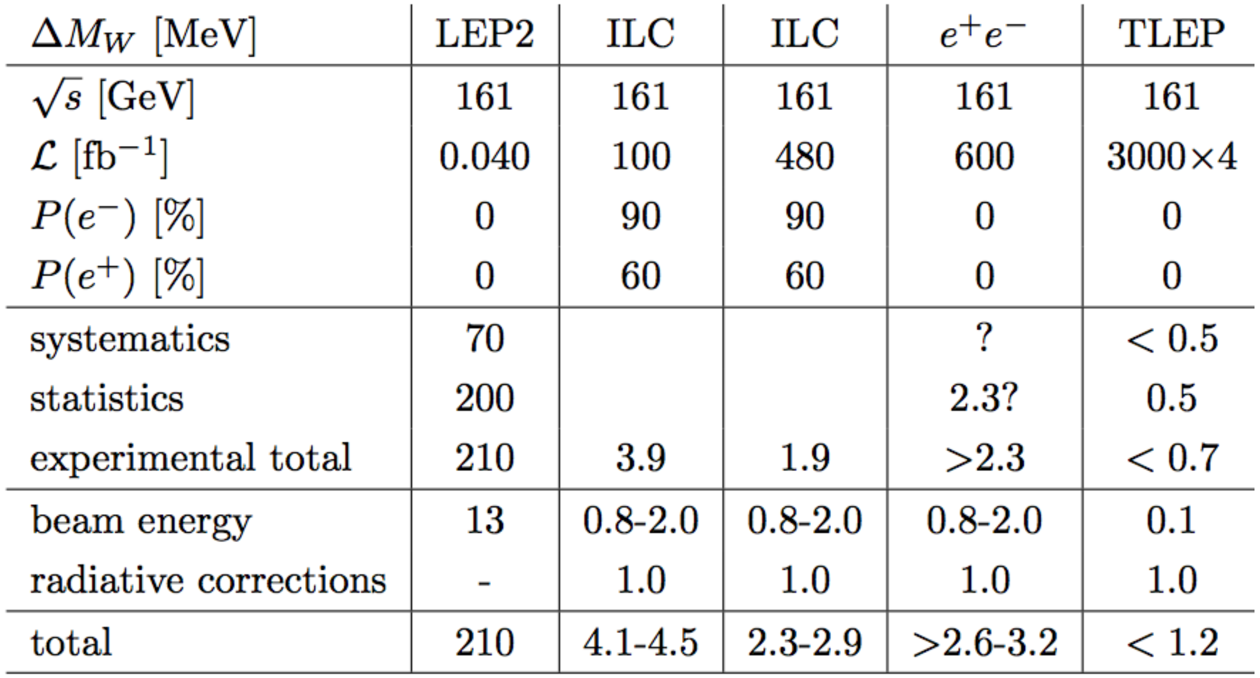
ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	172-209	250	350	500
$\mathcal{L}$ [fb^{-1}]	3.0	500	350	1000
$P(e^-)$ [%]	0	80	80	80
$P(e^+)$ [%]	0	30	30	30
beam energy	9	0.8	1.1	1.6
luminosity spectrum	N/A	1.0	1.4	2.0
hadronization	13	1.3	1.3	1.3
radiative corrections	8	1.2	1.5	1.8
detector effects	10	1.0	1.0	1.0
other systematics	3	0.3	0.3	0.3
total systematics	21	2.4	2.9	3.5
statistical	30	1.5	2.1	1.8
total	36	2.8	3.6	3.9

Direct reconstruction of the hadronic mass



ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5
total	3.7	3.7	3.6	3.9

WW threshold



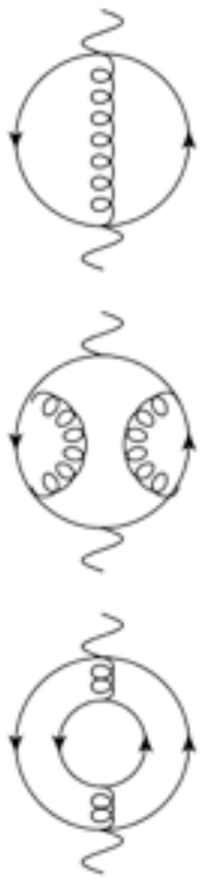
ΔM_W [MeV]	LEP2	ILC	ILC	e^+e^-	TLEP
$\sqrt{s}$ [GeV]	161	161	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480	600	3000×4
$P(e^-)$ [%]	0	90	90	0	0
$P(e^+)$ [%]	0	60	60	0	0
systematics	70			?	< 0.5
statistics	200			2.3?	0.5
experimental total	210	3.9	1.9	>2.3	< 0.7
beam energy	13	0.8-2.0	0.8-2.0	0.8-2.0	0.1
radiative corrections	-	1.0	1.0	1.0	1.0
total	210	4.1-4.5	2.3-2.9	>2.6-3.2	< 1.2

SM model contributions to Δr

$$\Delta r^{\mathrm{SM}} = \Delta r^{(\alpha)} + \Delta r^{(\alpha\alpha_s)} + \Delta r^{(\alpha\alpha_s^2)} + \Delta r^{(\alpha^2)}_{\mathrm{ferm}} + \Delta r^{(\alpha^2)}_{\mathrm{bos}}$$
$$+ \Delta r^{(G_\mu^2 \alpha_s m_t^4)} + \Delta r^{(G_\mu^3 m_t^6)} + \Delta r^{(G_\mu m_t^2 \alpha_s^3)}$$

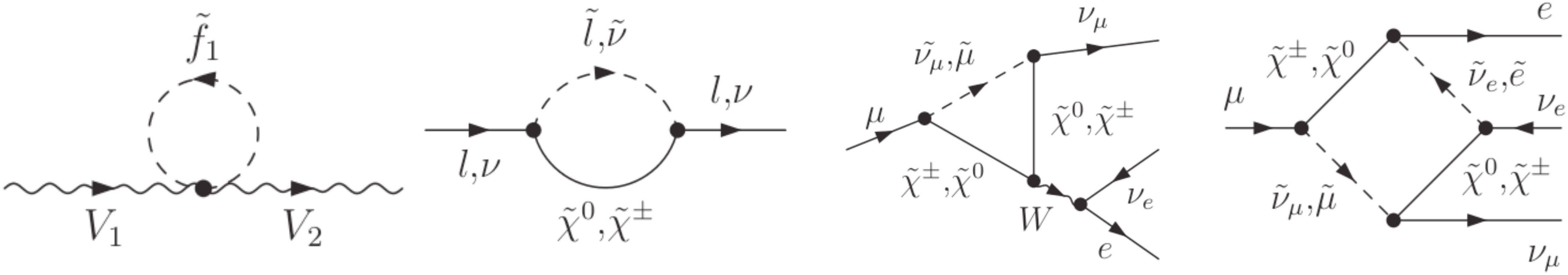
- $\Delta r^{(\alpha)}$: 1-loop contribution
- $\Delta r^{(\alpha\alpha_s)} + \Delta r^{(\alpha\alpha_s^2)}$: 2- and 3-loop QCD corrections
  Chetyrkin, Kuhn, Steinhauser '95, Djouadi, Verzegnassi '88, ...
- $\Delta r^{(\alpha^2)}_{\mathrm{ferm}} + \Delta r^{(\alpha^2)}_{\mathrm{bos}}$: fermionic and bosonic electroweak 2-loop corrections (fitting formula) Awramik, Czakon, Freitas '06, Awramik, Czakon, Freitas, Weiglein '03
- $\Delta r^{(G_\mu^2 \alpha_s m_t^4)} + \Delta r^{(G_\mu^3 m_t^6)}$: 3-loop top quark contribution
  Faisst, Kuhn, Seidensticker, Veretin '03
- $\Delta r^{(G_\mu m_t^2 \alpha_s^3)}$: 4-loop QCD correction
  Boughezal '06
- QCD corrections enter only at 2-loop level

$\longrightarrow$ Large corrections beyond 1-loop level



SUSY contributions to Δr

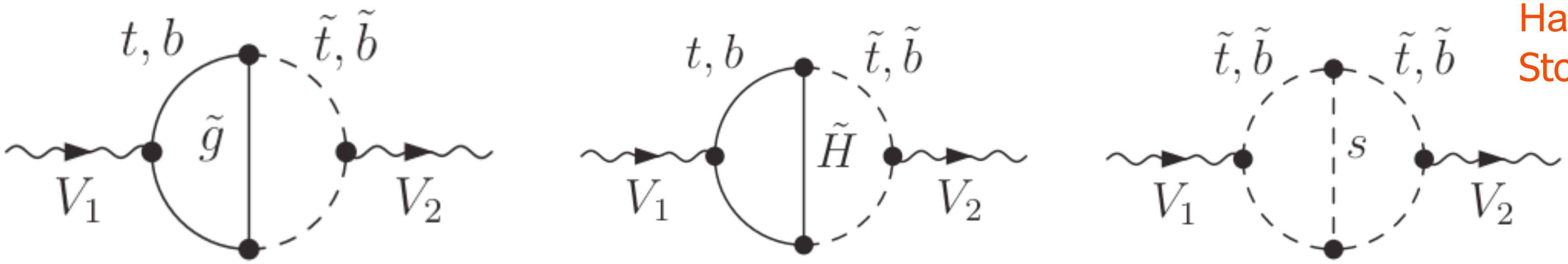
- 1-loop contributions from MSSM Higgs bosons, sfermions, charginos and neutralinos



- Supersymmetric 2-loop contributions
  - SUSY QCD corrections: (S)quark loops with gluon and gluino exchange

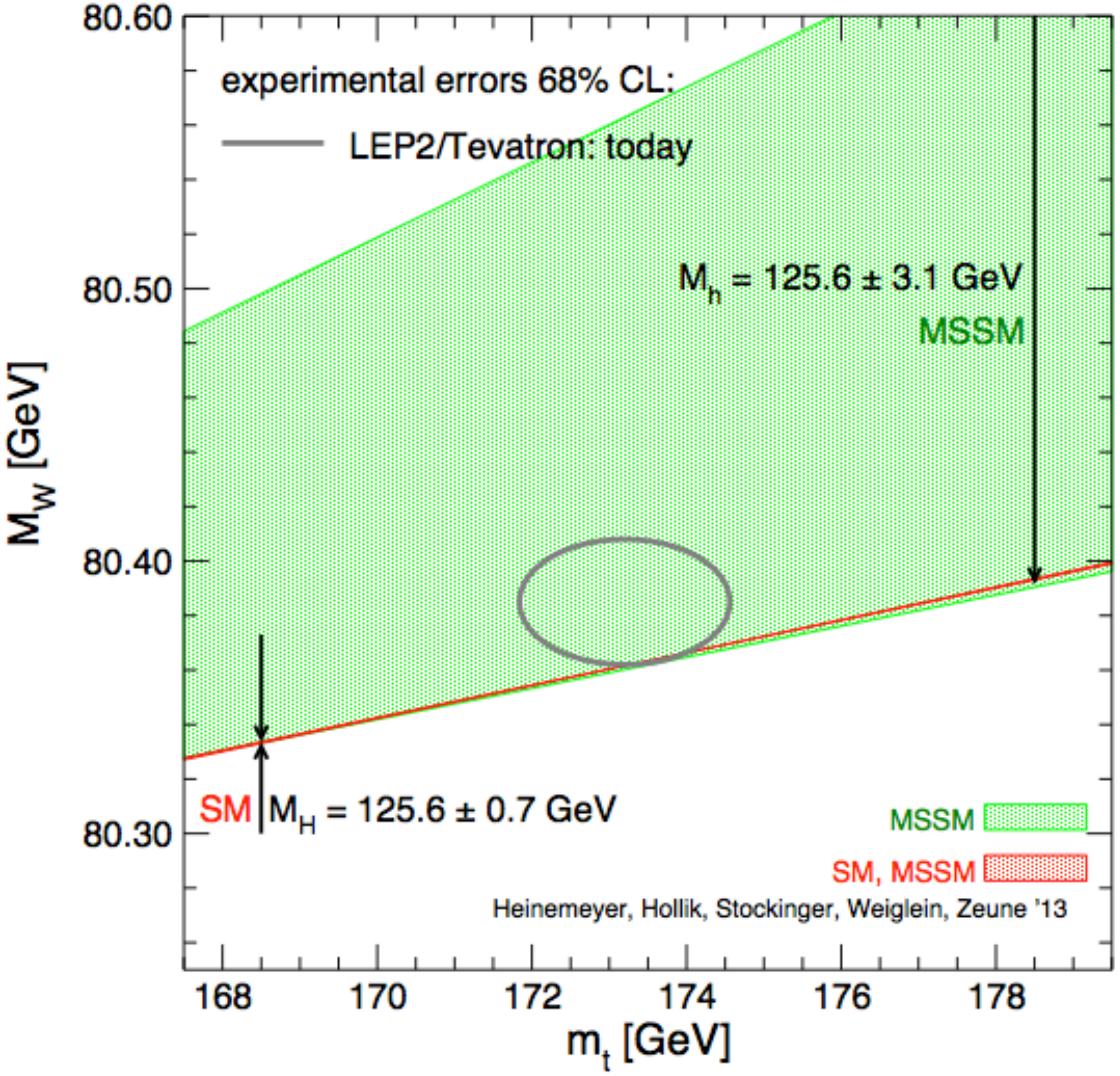
    Djouadi et. al '98
  - Yukawa contributions: (S)quark loops with Higgs and Higgsino exchange

    Haestier, Heinemeyer, Stoeckinger, Weiglein '05



- Leading reducible 2-loop corrections Consoli, Hollik, Jegenlehner '89

Stop and sbottom contribution



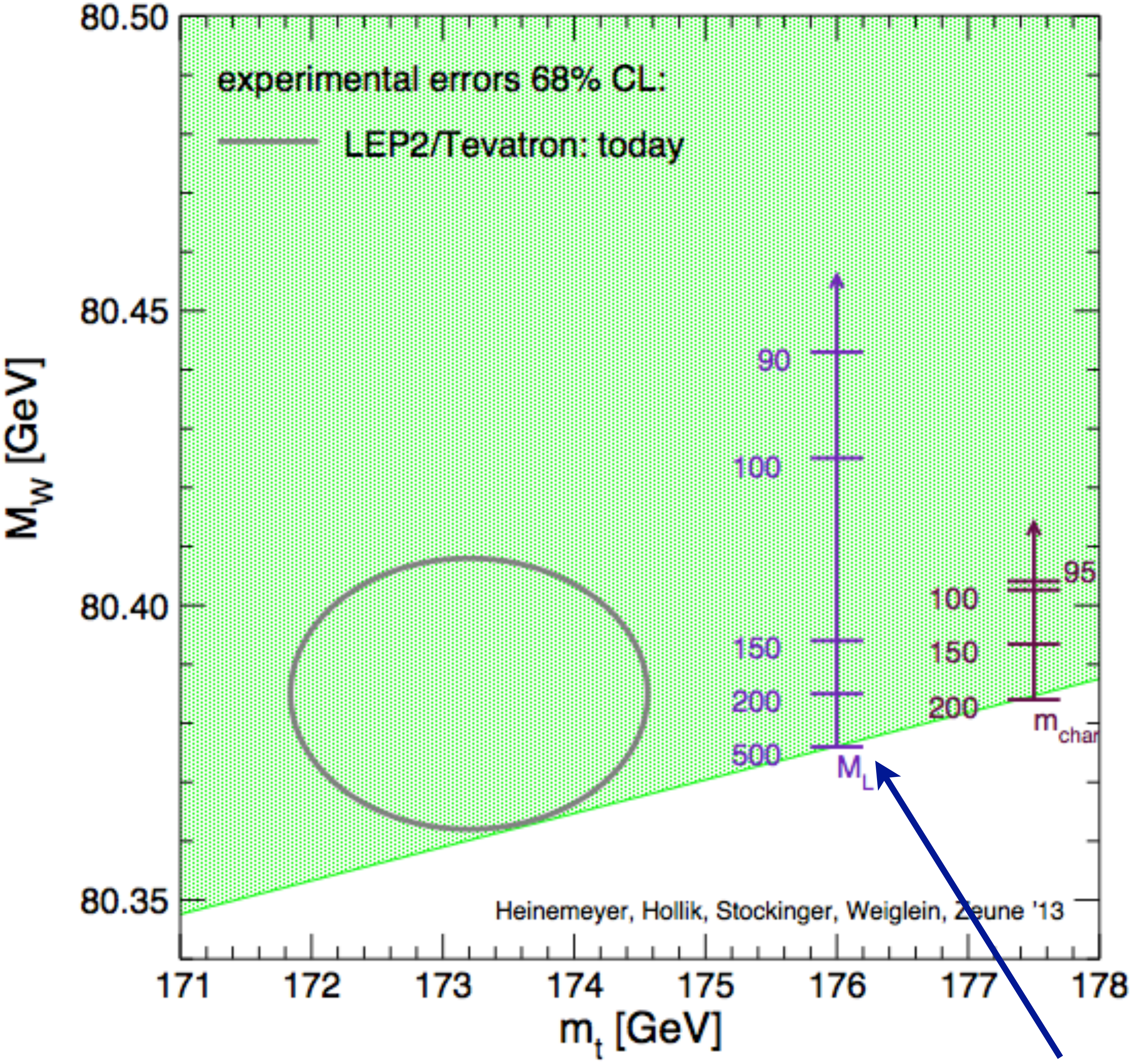
$$\Delta r^{(\alpha)} = \Delta\alpha - \frac{c_w^2}{s_w^2}\Delta\rho + \Delta r_{\rm rem}$$

- Largest SUSY contribution: Stop / sbottom contribution to

$$\Delta\rho = \frac{\Sigma_T^{ZZ}(0)}{M_Z^2} - \frac{\Sigma_T^{WW}(0)}{M_W^2}$$

- Sensitive to the mass splitting between stops and sbottoms
- Very large values for M_W possible for
  - Large mixing between stops and sbottoms
  - Either $\tilde{t}_1$ or $\tilde{b}_1$ is very light (challenged by LHC limits)

Slepton, chargino and neutalino contribution



- Large contribution possible from light sleptons ($\gtrsim$ 60 MeV)
- Contribution from charginos and neutralinos $\approx$ 20 MeV
- Even if light stops and sbottoms would get excluded by negative LHC searches, sizable MSSM M_W contributions are still possible

All other SUSY particles heavy