Precision Electroweak Measurements at e^+e^- colliders - Determining the Next Energy Scale

Ashutosh Kotwal
Duke University

(Summary of Snowmass 2013 Studies)

Beijing-Chicago Workshop
14-15 September 2015

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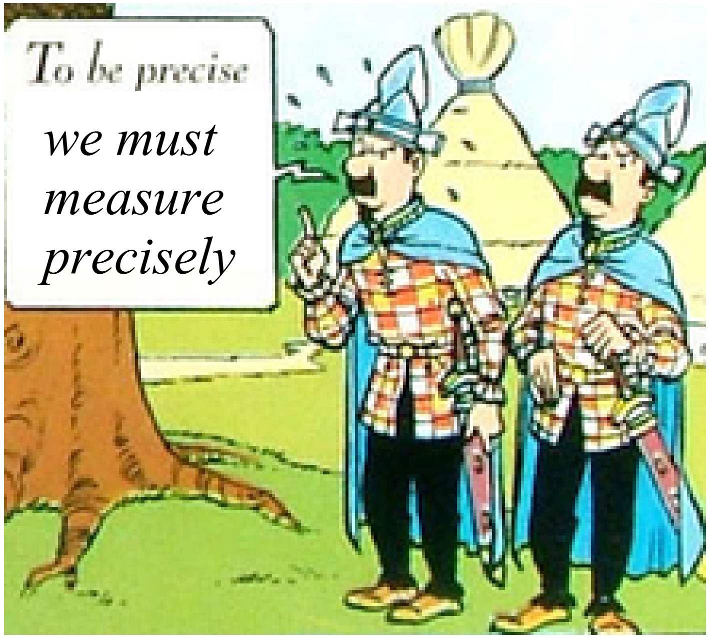

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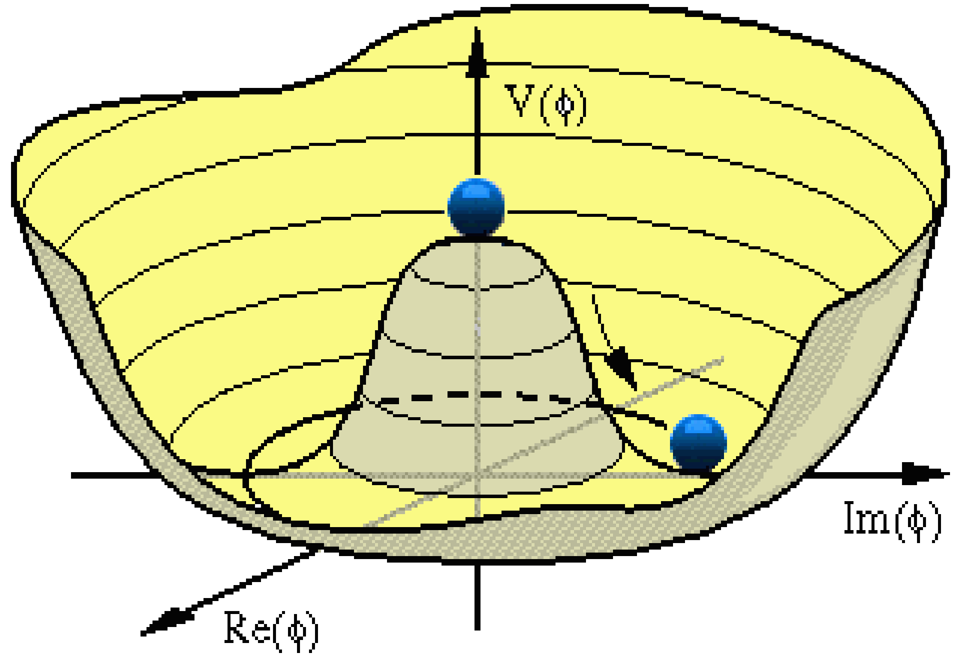
Spontaneous Symmetry Breaking

- Is the mechanism of Electroweak Symmetry Breaking, the Standard Model Higgs mechanism? Or is there more to it ??

Spontaneous Symmetry Breaking of Gauge Symmetry

- The Higgs potential in the SM is a parameterization that respects certain rules of QFT

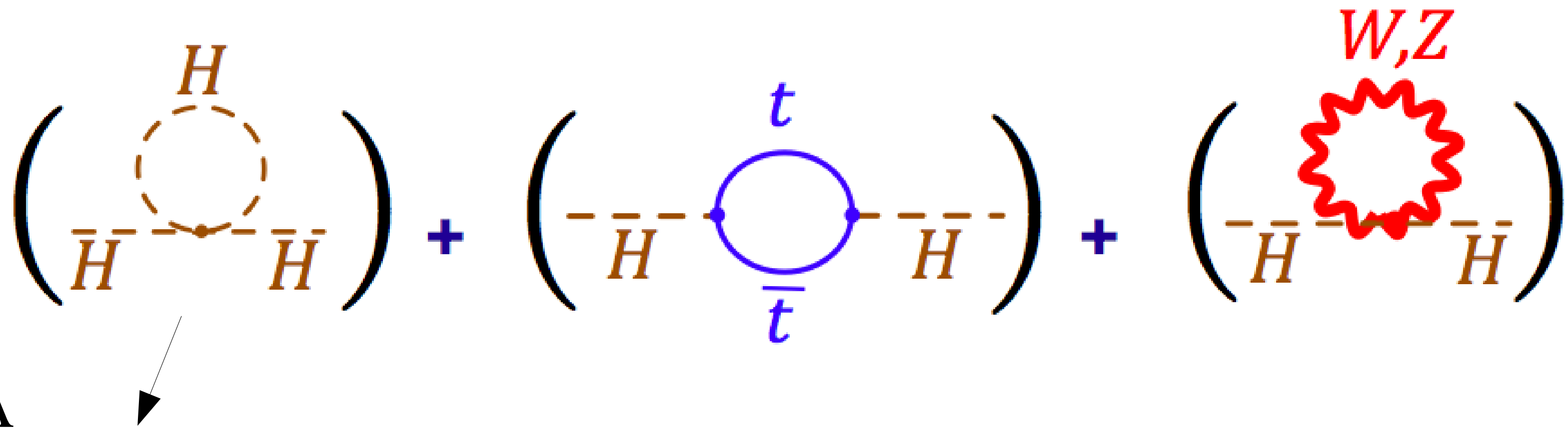


- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state

- Discovery of the "radial excitation" a.k.a the Higgs boson means that we have taken the first, big step in establishing the properties of this potential

Next Big Question: Why is the Higgs Boson so Light?

$$m_H^2 - m_{\text{bare}}^2 =$$



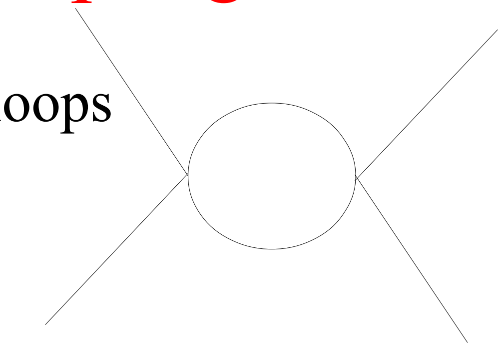
$$\lambda \int^{\Lambda} d^4k \, (k^2 - m_H^{\;2})^{-1} \sim \Lambda^2 \lambda$$

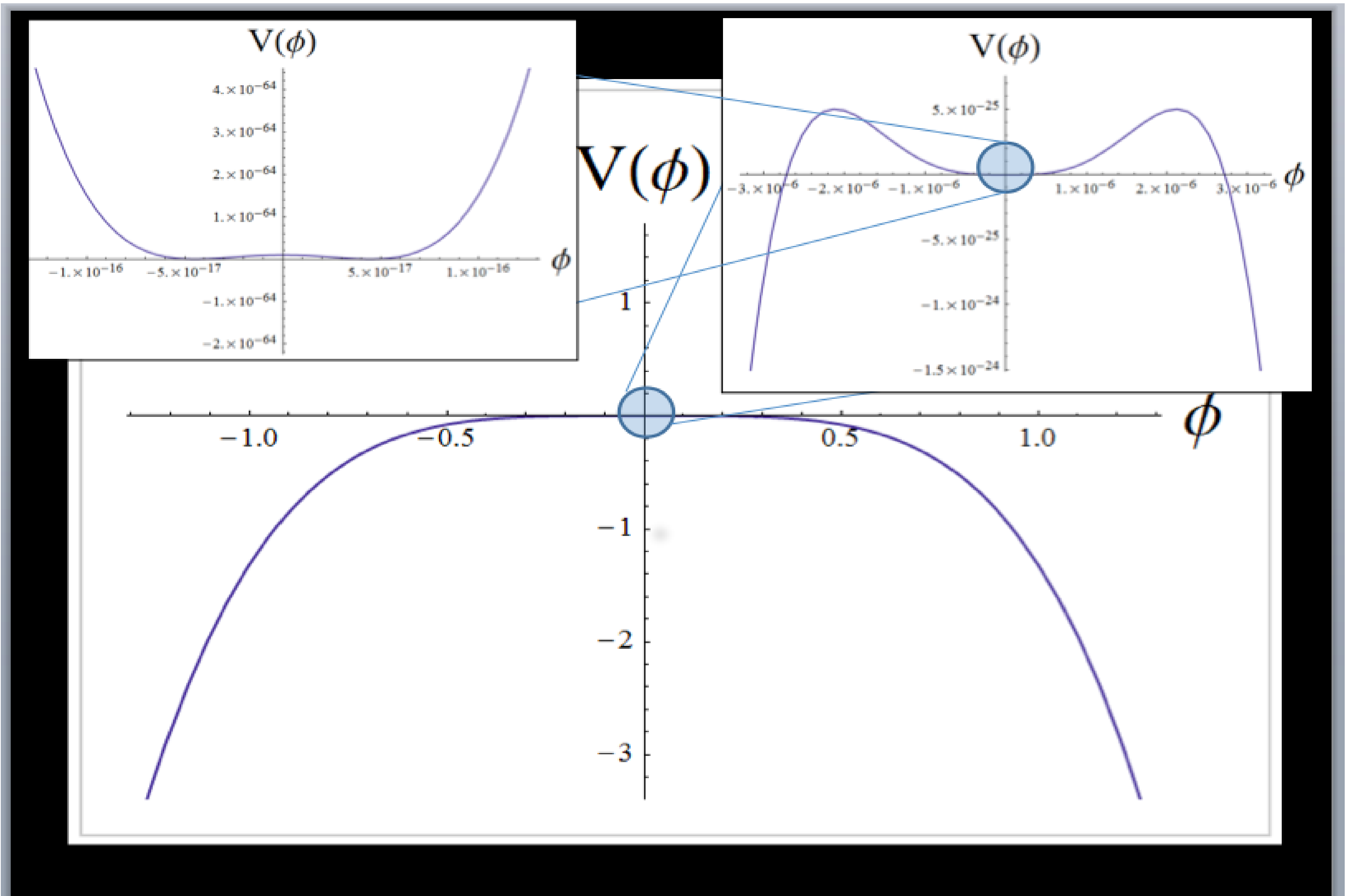
The Higgs boson ought to be a very heavy particle, naturally

However, observed $m_H << \Lambda$

Radiative Corrections to Higgs Self-Coupling

- $\lambda|\phi|^4$ receives radiative corrections from Higgs and top loops

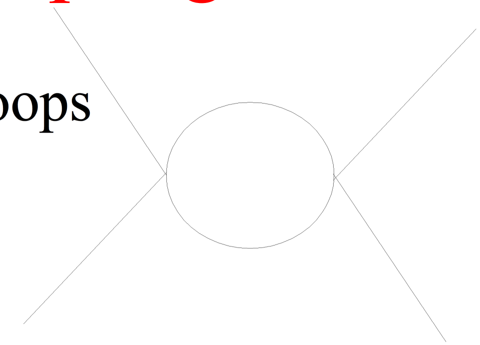


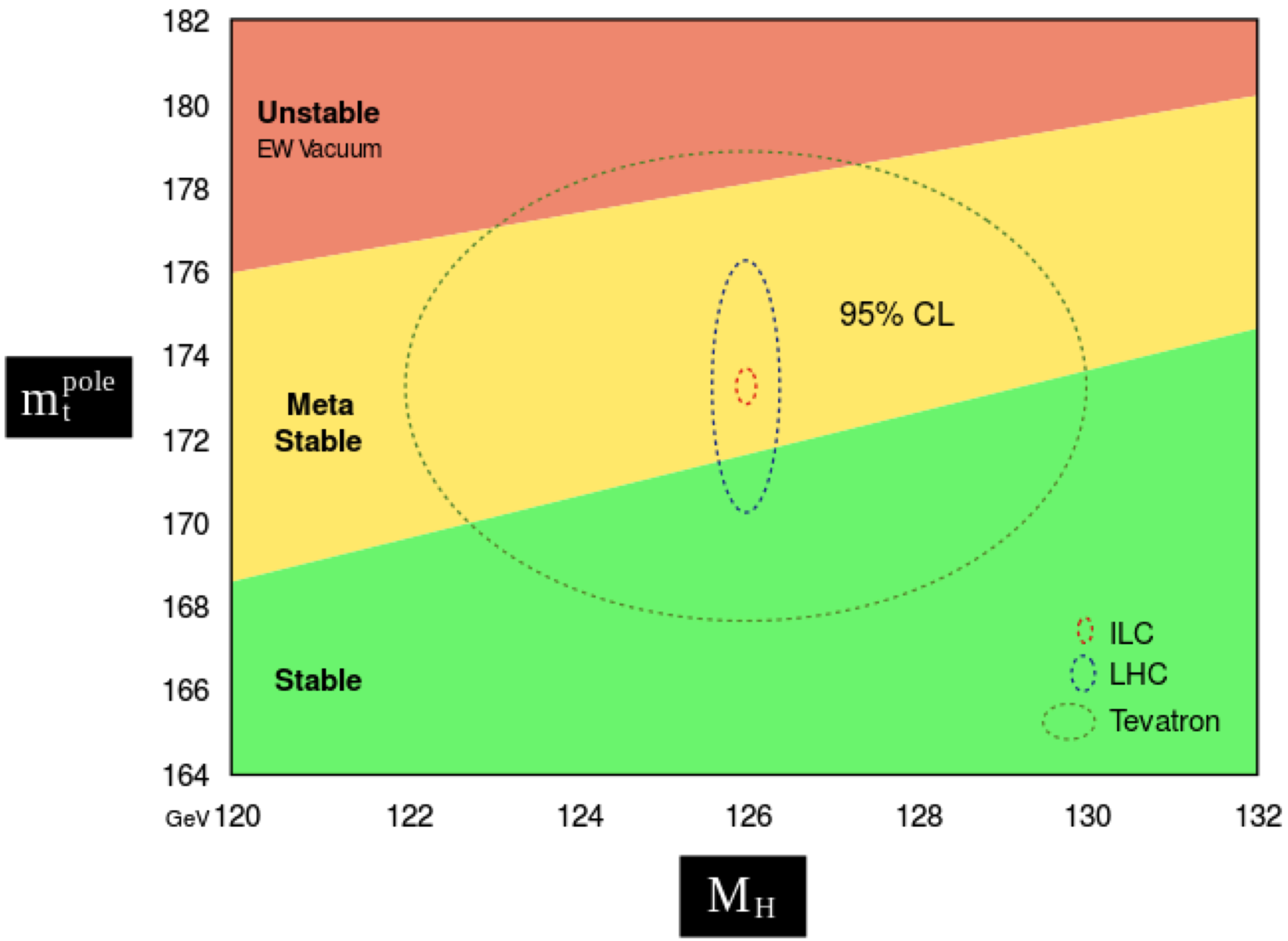


Paul Steinhardt's talk on 7/15/2013 at Argonne USATLAS Workshop

Radiative Corrections to Higgs Self-Coupling

- $\lambda|\phi|^4$ receives radiative corrections from Higgs and top loops





Next Steps for Electroweak Measurements

- For the first time: All SM fields in the Electroweak sector are detected and parameters are measured
    - Since Higgs boson mass is measured to ~1 GeV
- We must over-constrain SM by measuring electroweak observables as precisely as possible
    - Complementary to direct searches for new particles
    - New physics may be revealed through precision measurements of W and Z bosons

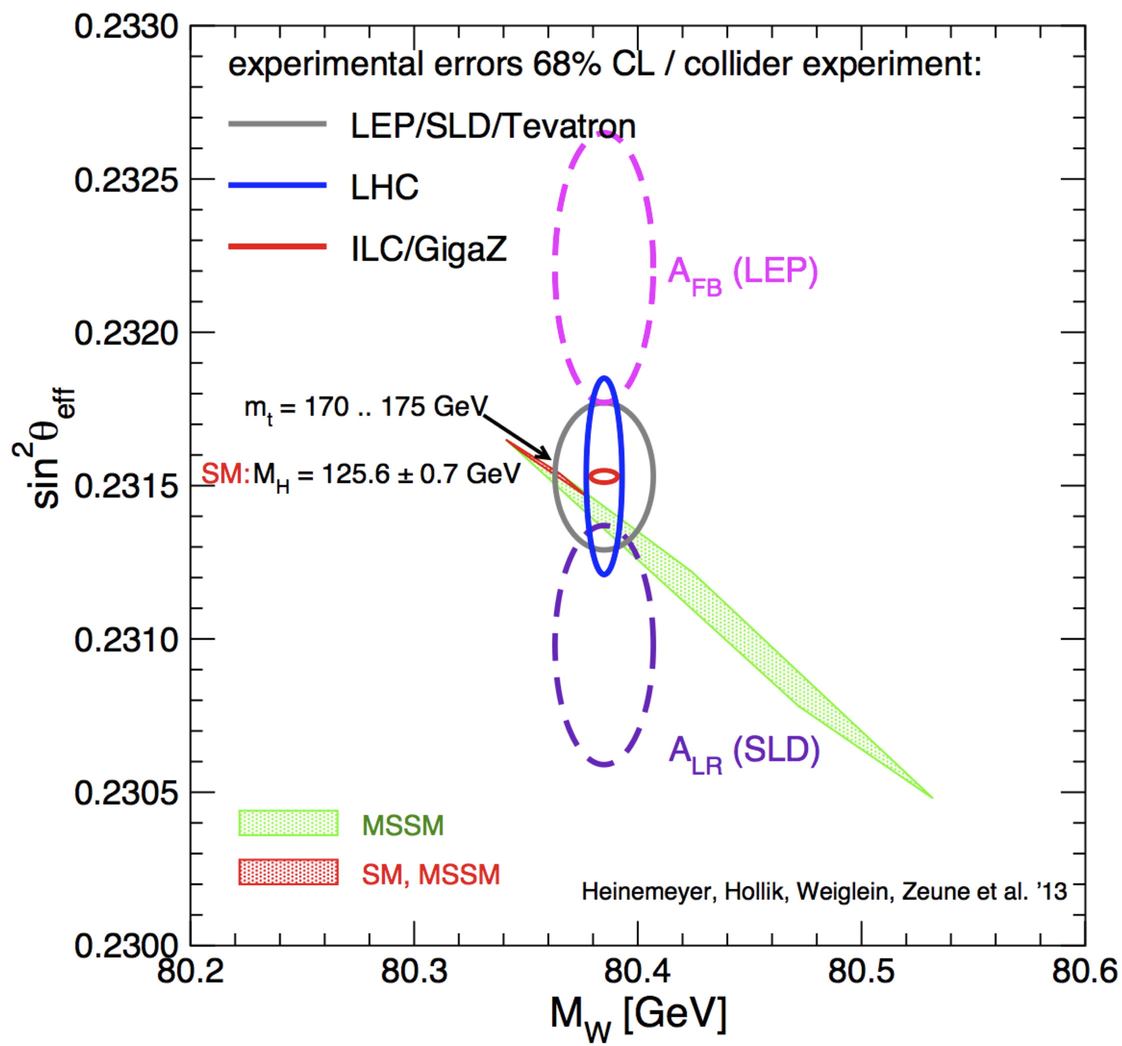
Next Steps for Electroweak Measurements

- Electroweak observables access all the mechanisms that can stabilize / explain the light Higgs mass
  - Is it stabilized by a symmetry such as SuperSymmetry ?
  - Is the Higgs boson a pseudo Nambu-Goldstone Boson?
  - Is there new strong dynamics ?
  - Do extra-dimensional models bring the Planck scale close to Electroweak scale?

- Our Snowmass report discusses two areas of electroweak physics
  - Electroweak precision observables (EWPOs) : M_W and $\sin^2\theta_{J\square}$
  - ◊ ∫∪∏Λ∃∩ΛΟΛΚ Ο∪∈∏∫∃ΚΒ ∈Κ∫ Ι∃∃2∩ΛΟΛΚ Μ∃Λ∫Ρ∪∏∃ΛΚ

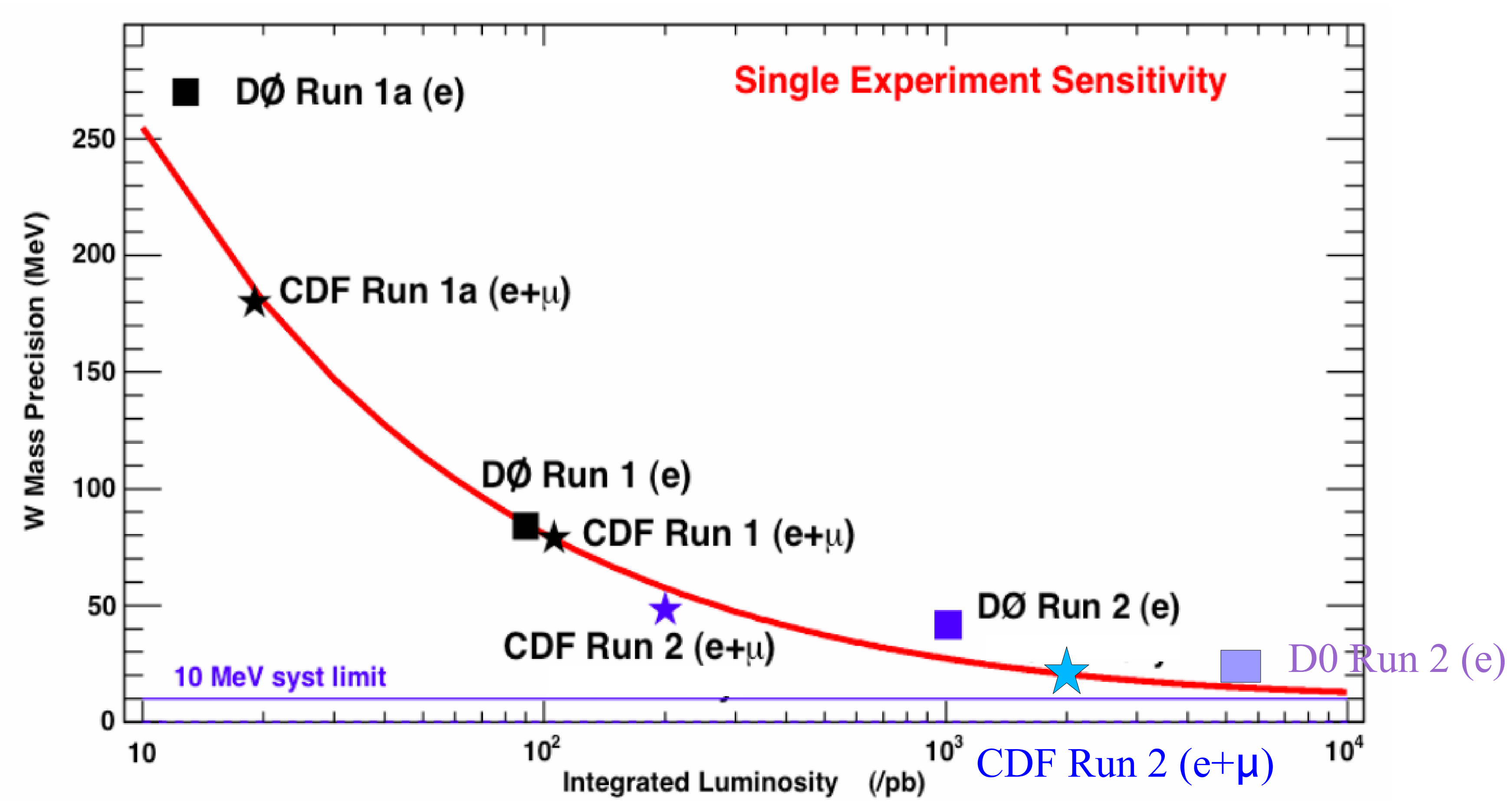
$\mathrm{Sin}^2\theta_{eff}$ and M_W

- Both EWPOs are now precisely predicted in the SM
  - And correlated range predicted in beyond-SM models such as MSSM



Projecting the M_W Precision

- Tevatron experience:
  - Larger calibration and control samples of data + increasing experience



Projecting the M_W Precision at Tevatron

- Tevatron experience:
    - Larger calibration and control samples of data + increasing experience

ΔM_W [MeV]	CDF	D0	combined	final CDF	final D0	combined
$\mathcal{L}[\text{fb}^{-1}]$	2.2	4.3(+1.1)	7.6	10	10	20
PDF	10	11	10	5	5	5
QED rad.	4	7	4	4	3	3
$p_T(W)$ model	5	2	2	2	2	2
other systematics	10	18	9	4	11	4
W statistics	12	13	9	6	8	5
Total	19	26(23)	16	10	15	9

Table 1-4. *Current and projected uncertainties in the measurement of M_W at the Tevatron.*

- Tevatron final uncertainty of 9-10 MeV

  Assuming factor of two improvement in PDF uncertainty (possible with LHC measurements of boson distributions)

LHC Target for M_W Precision

- Larger PDF sensitivity than Tevatron by factor of ~2

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}$[fb^{-1}]	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

- Target LHC uncertainty of 5 MeV
  requires further factor of ~3 improvement in PDFs
  improved generators and radiative corrections

M_W Precision at Lepton Colliders

- WW threshold scan being revisited at ILC: new estimates in progress
  - 3-4 MeV complementary measurements possible with kinematic fitting and final-state reconstruction

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
systematics	70		
statistics	200		
experimental total	210	3.9	1.9
beam energy	13	0.8	0.8
theory	-	1.0	1.0
total	210	4.1	2.3

Work in progress

(from Graham Wilson)

- CEPC/TLEP promises higher statistics: 25 million *WW* pairs at threshold

  Warrants detailed investigation of systematics, beam energy calibration and polarization: could deliver ~1 MeV measurement of M_W
- Lepton colliders heading towards ~2 MeV measurement of M_W ? or better ?

$\sin^2\theta_{J\Box}$ Precision at Hadron Colliders

- Tevatron projection: ~40 × 10^{-5}

$\Delta \sin^2 \theta^l_{\rm eff}$ [10^{-5}] final state	CDF e^+e^-	D0 e^+e^-	final CDF $\mu^+\mu^-$	final CDF e^+e^-	final CDF combined
$\mathcal{L}$[fb^{-1}]	2.1	5.0	9.0	9.0	9.0 $\mu\mu$ + 9 e^+e^-
PDF	12	48	12	12	12
higher order corr.	13	8	13	13	13
other systematics	5	38	5	5	5
statistical	90	80	80	40	40
total $\Delta \sin^2 \theta^l_{\rm eff}$	**92**	**101**	**82**	**44**	**41**

(from Arie Bodek)

Table 1-6. *Current and target uncertainties in the measurement of* $\sin^2 \theta^l_{\rm eff}$ *at the Tevatron.*

$\Delta \sin^2 \theta^l_{\rm eff}$ [10^{-5}]	ATLAS	CMS	LHC/per experiment		
$\sqrt{s}$ [TeV]	7	7	8	14	14
$\mathcal{L}$[fb^{-1}]	4.8	1.1	20	300	3000
PDF	70	130	35	25	10
higher order corr.	20	110	20	15	10
other systematics	70	181	60(35)	20	15
statistical	40	200	20	5	2
Total	108	319	75(57)	36	21

(ATLAS preliminary from Regino Caputo)

Table 1-7. *Current and target uncertainties in the measurement of* $\sin^2 \theta^l_{\rm eff}$ *at the LHC.*

- LHC may reach ~ 20 × 10^{-5} if current PDF uncertainties reduced by factor ~ 7
- Moller Experiment (polarized *ee* scattering) at JLAB also targets ~ 20 × 10^{-5}
- Interesting to compare LEP, SLC precision ~ 27 × 10^{-5} with 3σ difference

$\sin^2\theta_{J\square}$ Precision at Lepton Colliders

- ILC/GigaZ projection: ~1.3 × 10^{-5}

$\Delta \sin^2 \theta^l_{\rm eff}$ $[10^{-5}]$	ILC/GigaZ	TLEP(Z)
systematics	1.2	
statistical	0.5	0.2
total	1.3	

Table 1-11. *Projected uncertainties in the measurement of* $\sin^2 \theta^l_{\rm eff}$ *at lepton colliders.*

- CEPC/TLEP has further statistical potential: 100B to trillion *Z* bosons

  polarization to be investigated: could achieve precision ~ 1 to 3 x 10^{-6}

- More than factor of 10 improvement over LEP, SLC precision with ILC/GigaZ
- Factor of 50 with CEPC/TLEP

Parametric and Theoretical Uncertainties

- Anticipate missing higher-order corrections will be calculated

	$\Delta m_t = 0.9$ GeV	$\Delta(\Delta\alpha_{\rm had}) = 1.38(1.0)\cdot 10^{-4}$	$\Delta M_Z = 2.1$ MeV	missing h.o.	total
ΔM_W [MeV]	5.4	2.5(1.8)	2.6	4.0	7.6(7.4)
$\Delta\sin^2\theta^\ell_{\rm eff}[10^{-5}]$	2.8	4.8(3.5)	1.5	4.5	7.3(6.5)

Table 1-2. *Current parametric and theory uncertainties of SM predictions of M_W and $\sin^2\theta^\ell_{\rm eff}$.*

	$\Delta m_t = 0.6(0.1)$ GeV	$\Delta(\Delta\alpha_{\rm had}) = 5\times 10^{-5}$	$\Delta M_Z = 2.1$ MeV	missing h.o.	total
ΔM_W [MeV]	3.6(0.6)	1.0	2.6	1.0	4.7(3.0)
$\Delta\sin^2\theta^\ell_{\rm eff}[10^{-5}]$	1.9(0.3)	1.8	1.5	1.0	3.2(2.6)

Table 1-3. *Anticipated parametric and theory uncertainties of SM predictions.*

Parametric and Theoretical Uncertainties

- Anticipate missing higher-order corrections will be calculated

	$\Delta m_t = 0.9$ GeV	$\Delta(\Delta\alpha_{\rm had}) = 1.38(1.0)\cdot 10^{-4}$	$\Delta M_Z = 2.1$ MeV	missing h.o.	total
ΔM_W [MeV]	5.4	2.5(1.8)	2.6	4.0	7.6(7.4)
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ΔM_W [MeV]	3.6(0.6)	1.0	2.6	1.0	4.7(3.0)
$\Delta \sin^2\theta^\ell_{\rm eff}[10^{-5}]$	1.9(0.3)	1.8	1.5	1.0	3.2(2.6)

Table 1-3. *Anticipated parametric and theory uncertainties of SM predictions.*

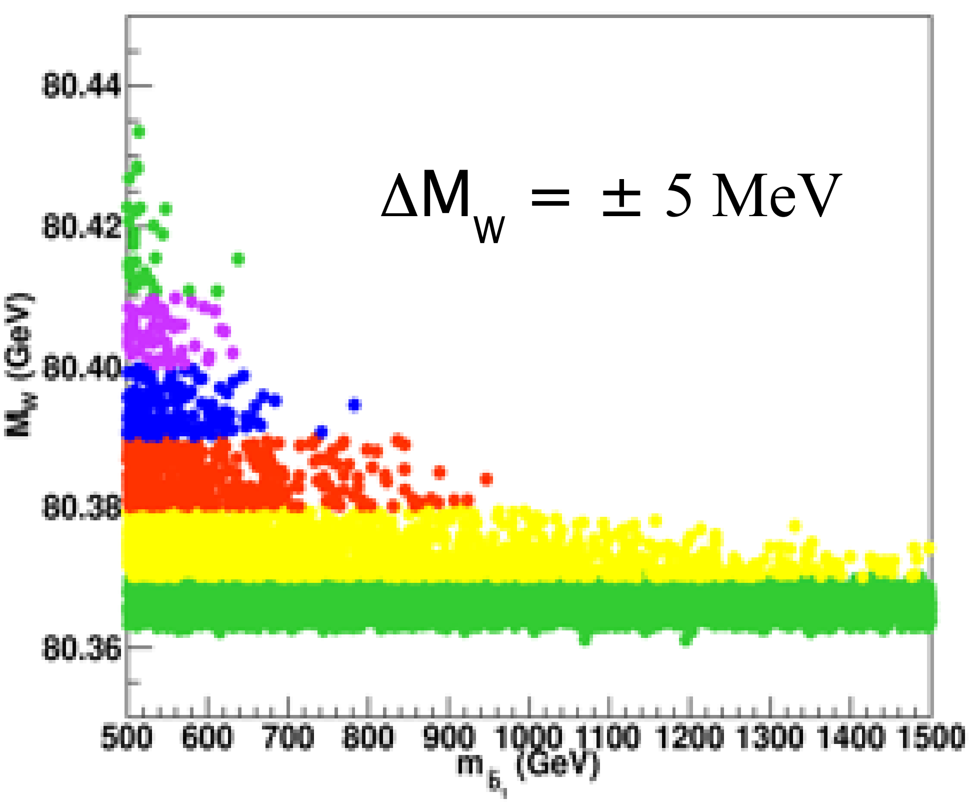
- Desirable to improve m_{top} precision below 0.5 GeV

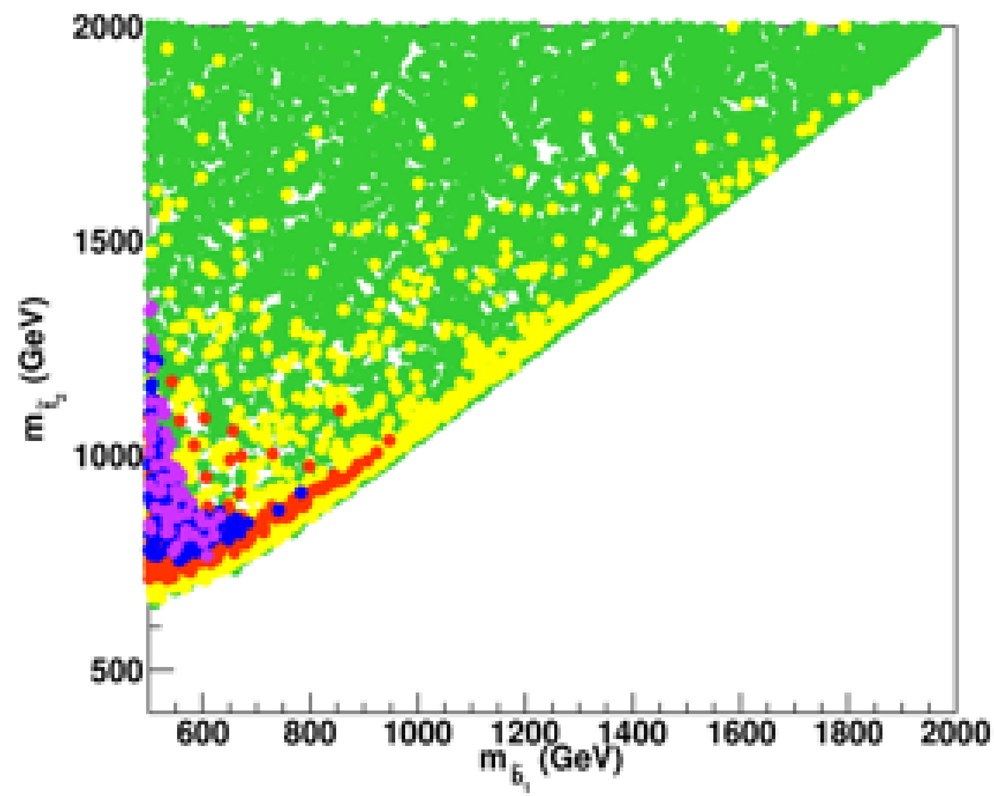
  Non-perturbative QCD effects in connecting reconstructed and pole mass

- Hadronic loops in running α_{EM} → need factor 2-3 improvement (lattice?)

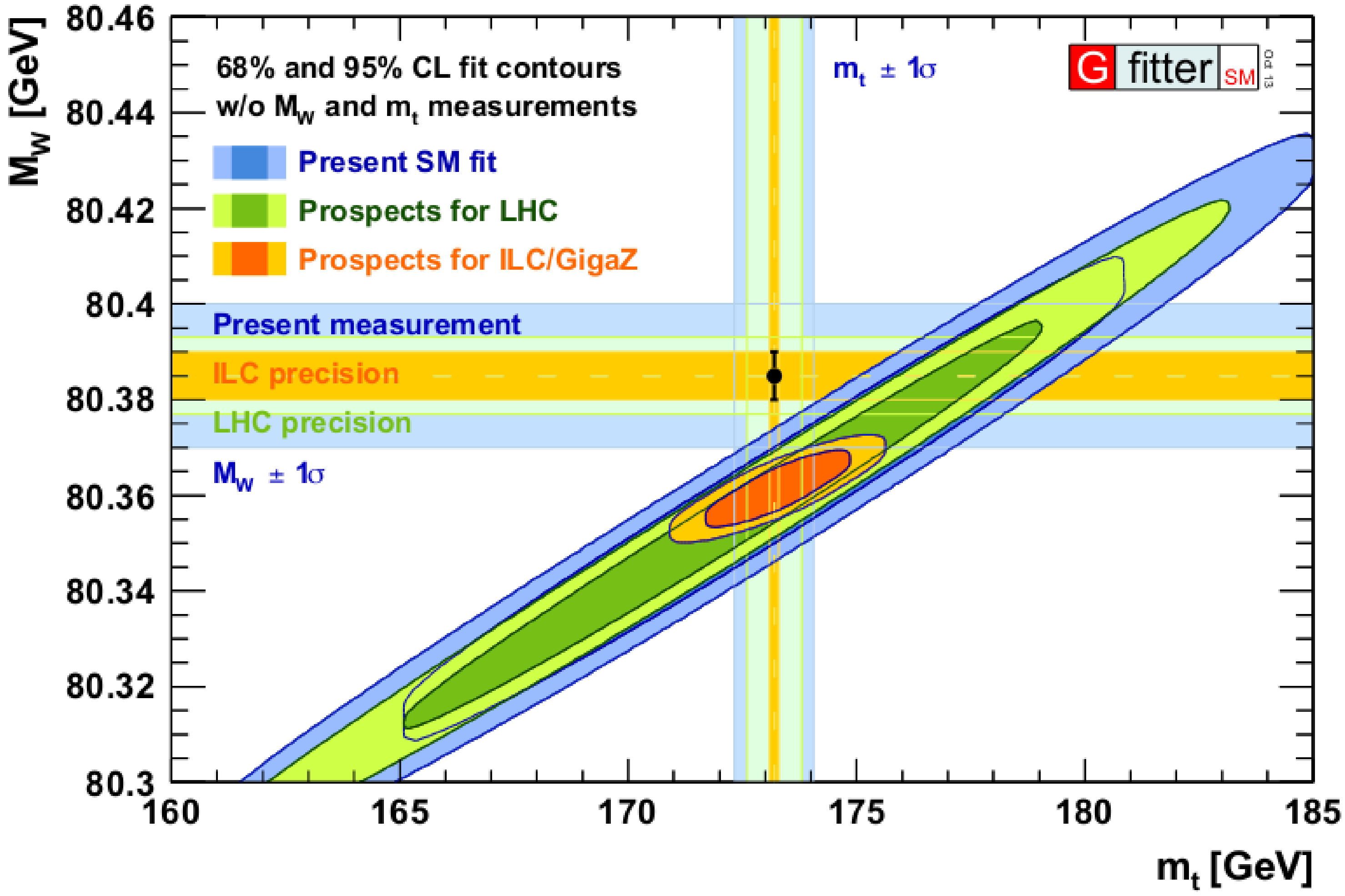
What could we learn ?

- SUSY-breaking parameter space is large
- Consider scenario after light stop discovery with mass = (400 ± 40) GeV
- MW predicts correlation with sbottom mass and heavy stop mass in MSSM
    - Parameter space shrinks rapidly depending on value and precision of M_W

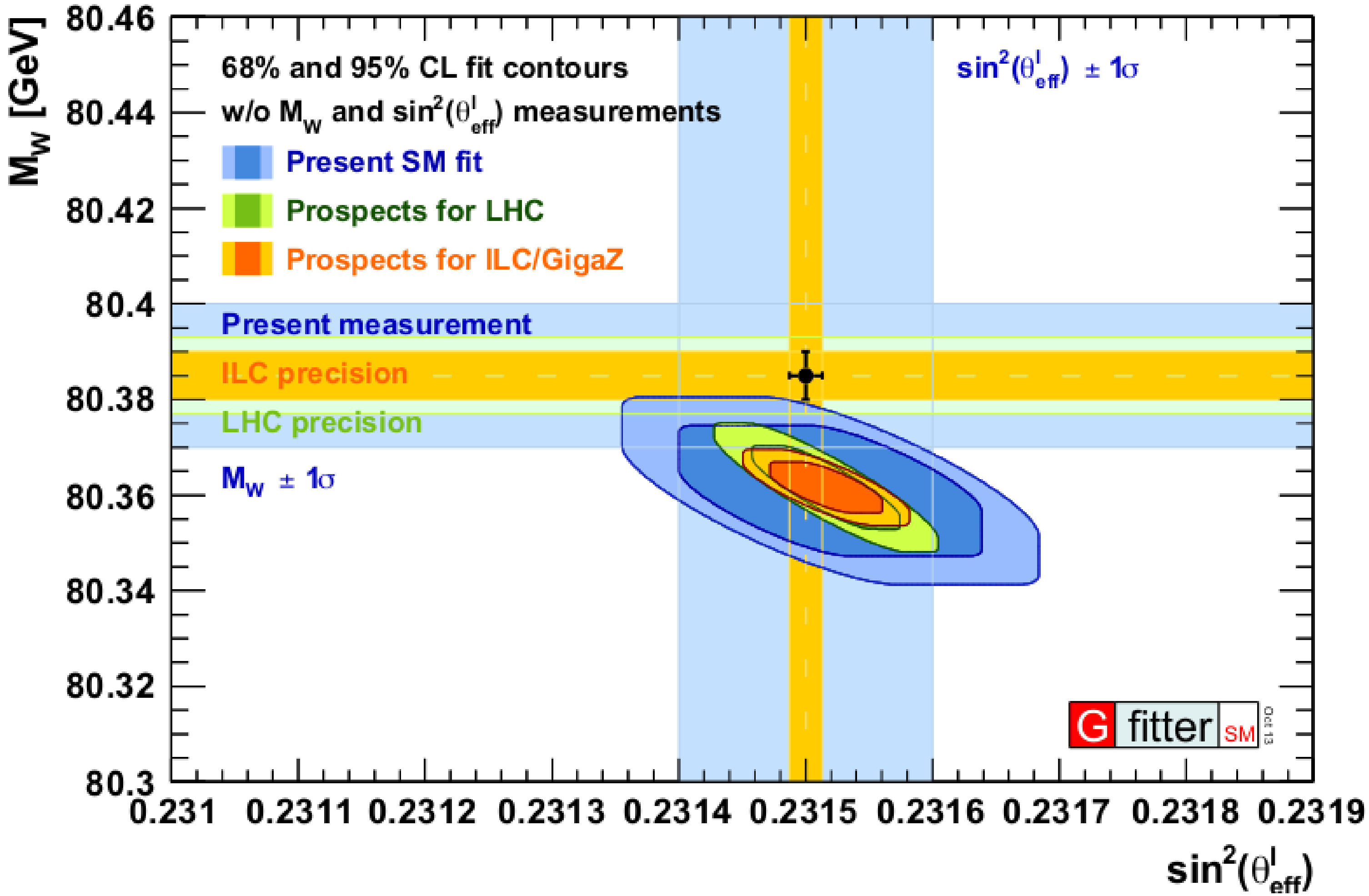




Summary - EWPOs

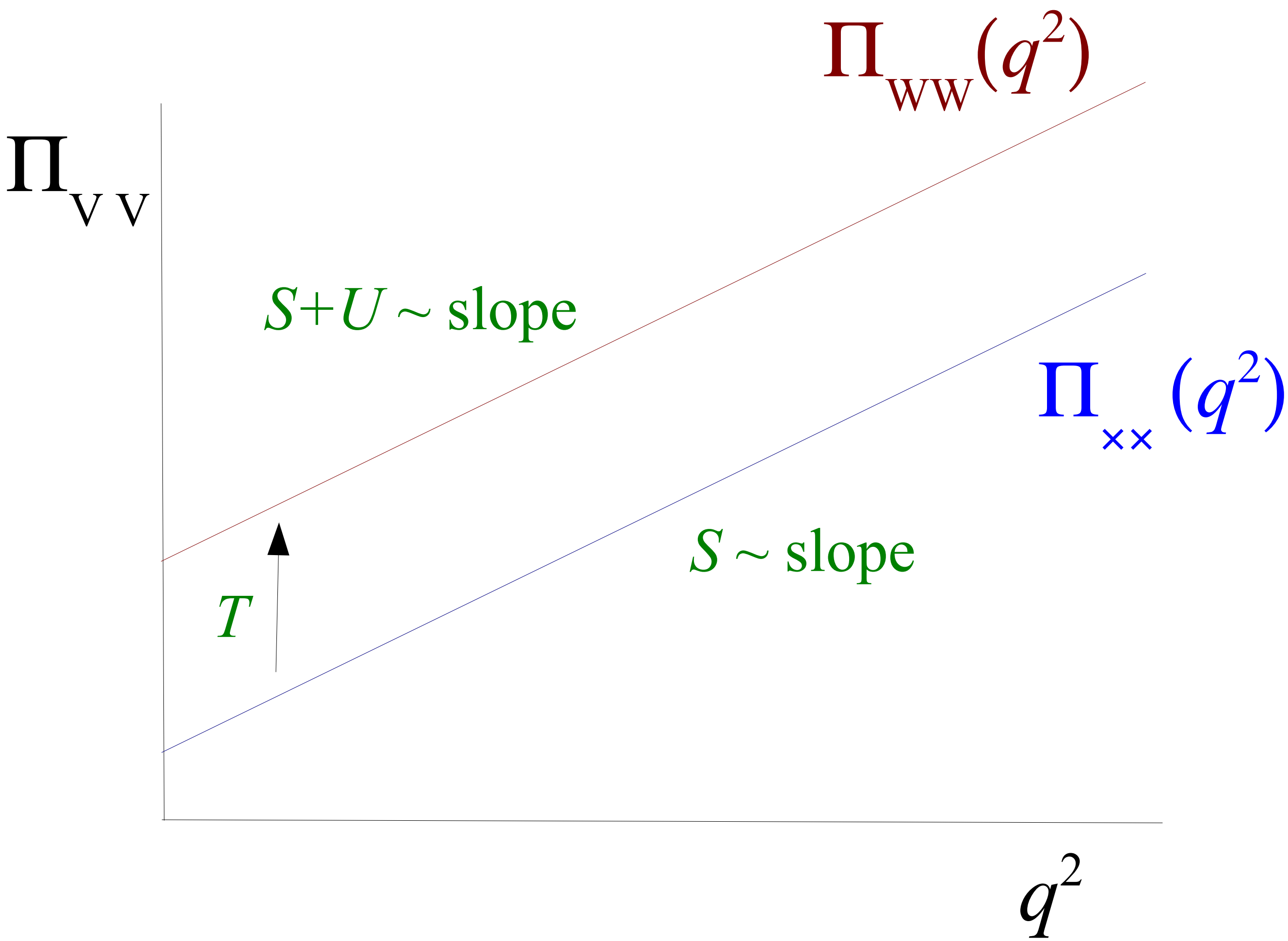


Summary - EWPOs

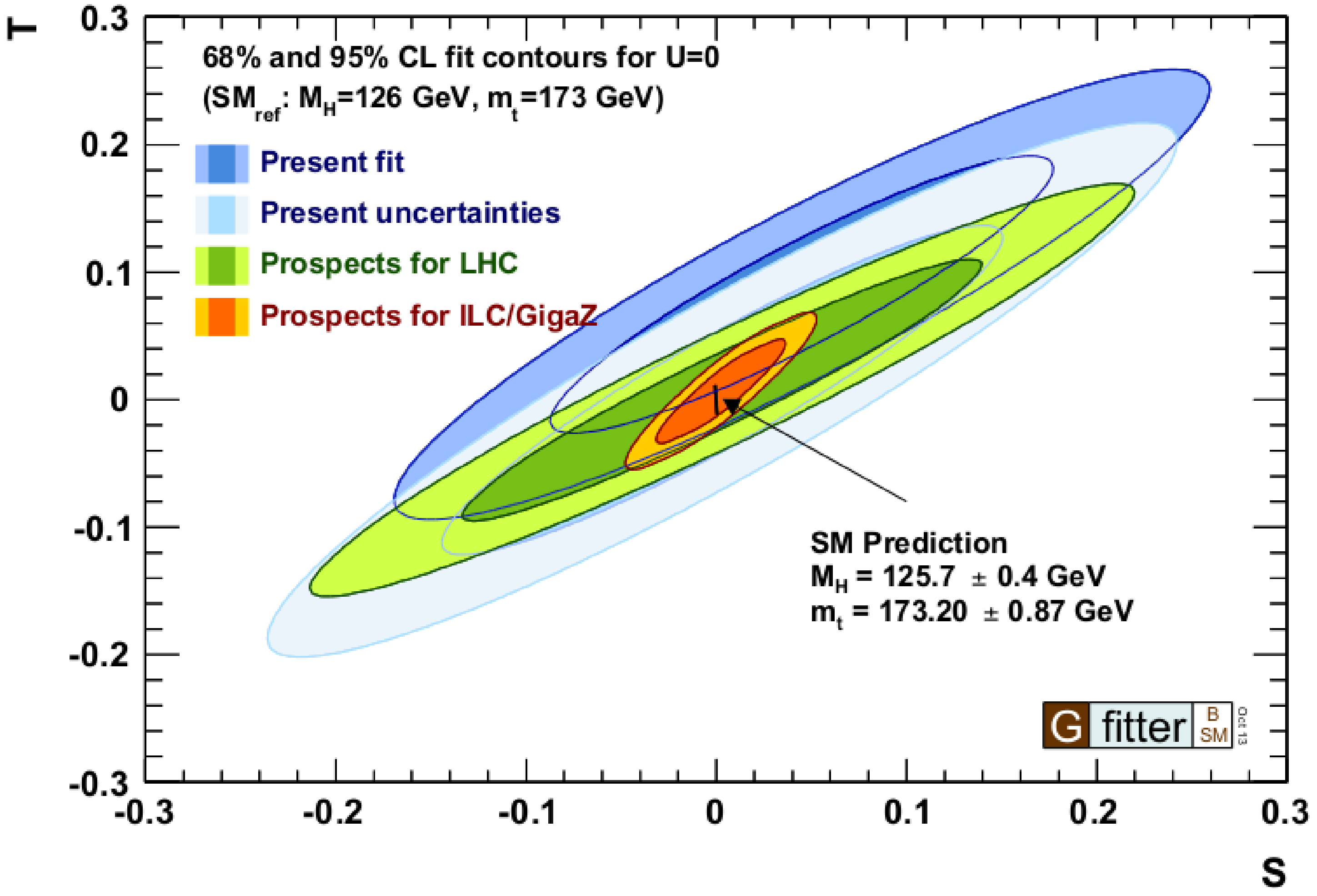


STU Parameterization

- Generic parameterization of new physics contributing to W and Z boson self-energies through radiative corrections in propagators
  - *S, T, U* parameters (Peskin & Takeuchi, Marciano & Rosner, Kennedy & Langacker, Kennedy & Lynn)



Summary - EWPOs



What Can We Learn About New-Physics Scale?

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha M_Z^2}{2M_W^2(M_Z^2 - M_W^2)}(1+\Delta r)$$

$$\Delta r \approx \Delta r^{\rm SM} + \frac{\alpha}{2s_W^2}\Delta S - \frac{\alpha c_W^2}{s_W^2}\Delta T + \frac{s_W^2 - c_W^2}{4s_W^4}\Delta U,$$

$$\sin^2\theta_{\rm eff}^\ell \approx (\sin^2\theta_{\rm eff}^\ell)^{\rm SM} + \frac{\alpha}{4(c_W^2 - s_W^2)}\Delta S - \frac{\alpha s_W^2 c_W^2}{c_W^2 - s_W^2}\Delta T,$$

$\Delta S = 0.04$, $\Delta T = 0$ => $\Delta M_W = 27$ MeV, $\Delta \sin^2\Theta = 14 \times 10^{-5}$

(1-2 sigma of current uncertainties)

$\Delta S = 0$, $\Delta T = 0.03$ => $\Delta M_W = 32$ MeV, $\Delta \sin^2\Theta = 8 \times 10^{-5}$

Note: world average measurement: $\Delta M_W = 15$ MeV

What Can We Learn About New-Physics Scale?

(from Giudice *et al*, "The Strongly-Interacting Light Higgs", hep-ph/0703164)

$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right)$$
$$+\frac{ic_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$
$$+\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$+\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}. \qquad (15)$$

$$\Delta\rho \equiv \widehat{T} = c_T \xi,$$

$$\widehat{S} = (c_W + c_B)\frac{m_W^2}{m_\rho^2}$$

$$\xi \equiv \frac{v^2}{f^2}, \quad v = \left(\sqrt{2} G_F\right)^{-1/2} = 246\ \text{GeV}$$

Higgs couplings change by factor
$1 - \xi c_H/2$

What Can We Learn About New-Physics Scale?

$\Delta S = 0.04, \Delta T = 0$ => if $C_W + C_B = 1$, $m_\rho = 4.5$ TeV

$\Delta S = 0, \Delta T = 0.03$ => if $c_T = 1$, $f = 15$ TeV

Higgs coupling change by 6% (1.5%)
<=> if $c_H = 1$, $f = 1$ (2) TeV

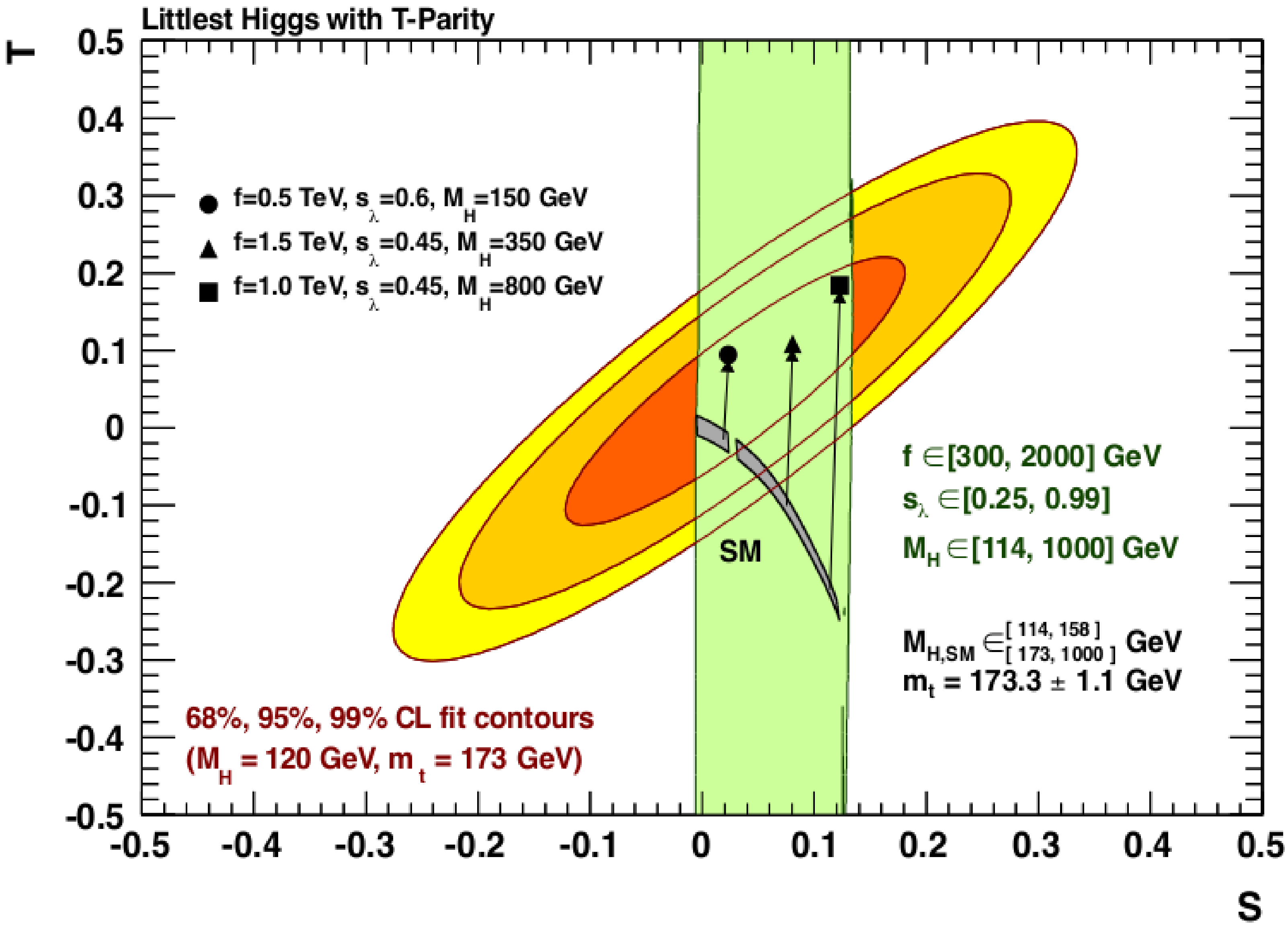
Conclusion: interpreted in a dimension-6 operator framework, EWPOs are already probing multi-TeV scale

Equivalent to Higgs coupling change of order 0.5 %

(caveat: different operators, different coefficients)

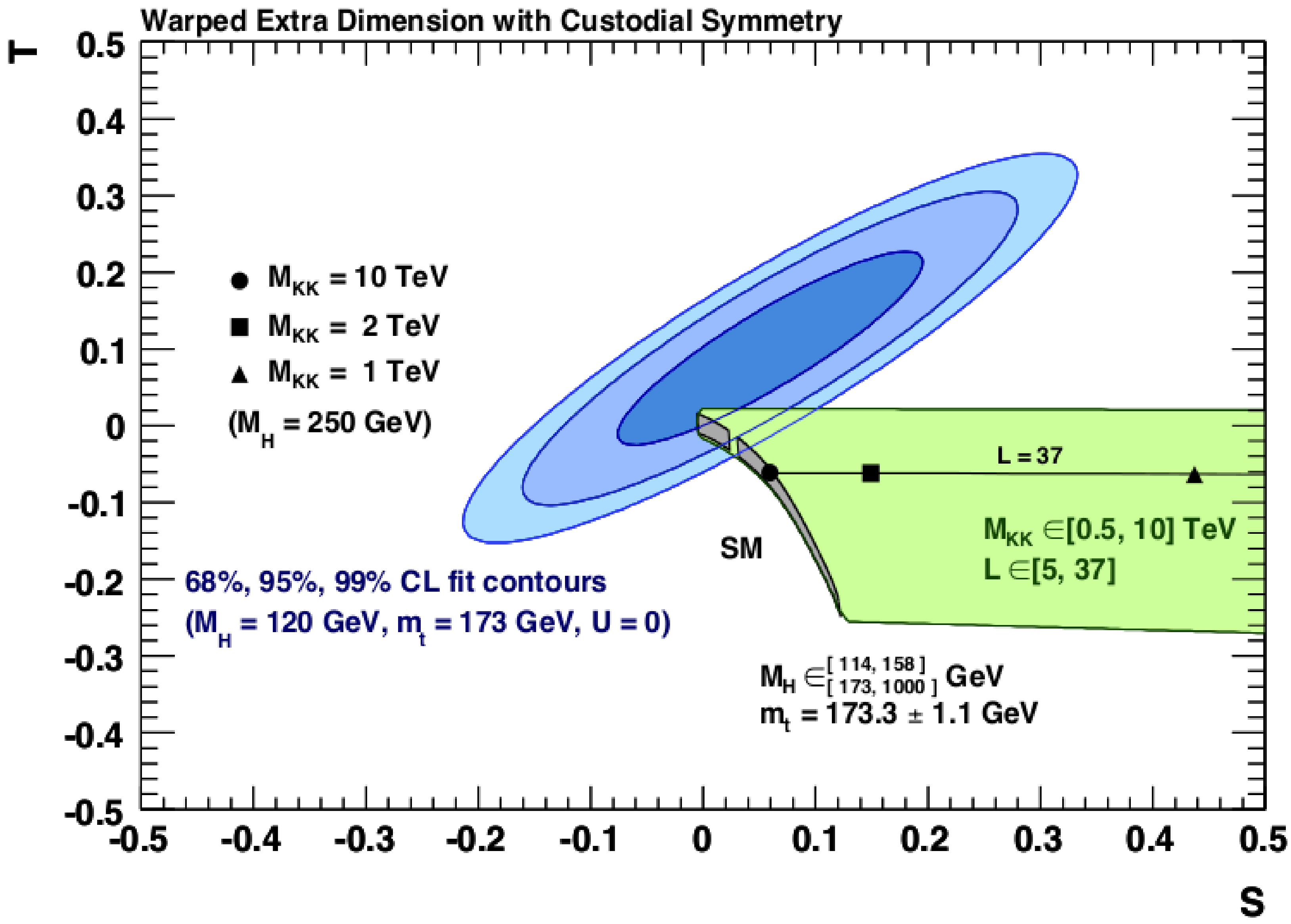
10,000 times the LEP statistics → EWPO improved by ~100 (statistical error)
→ new physics energy scale probed factor of 10 higher → 50-100 TeV

What Can We Learn About New-Physics Scale?



Gfitter Group

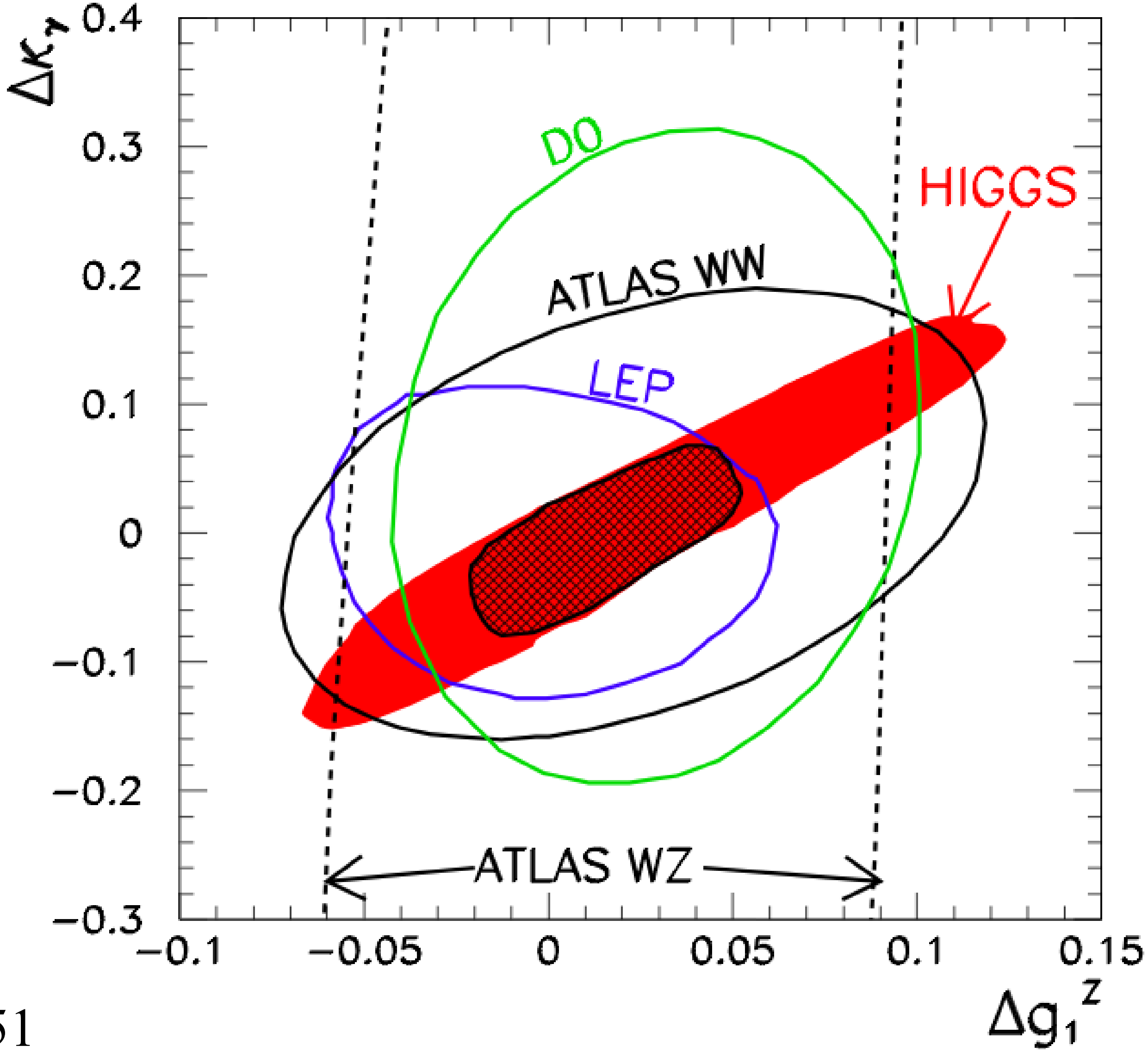
What Can We Learn About New-Physics Scale?



Gfitter Group

Combined Fit to Higgs and Anomalous Trilinear Gauge Couplings

- Illustrates the complementary of approaches to new physics via coupling deviations (equivalent to dimension-6 operators)



Corbett *et al.*,
arXiv:1304.1151

LHC and ILC Comparison for Anomalous Trilinear Gauge Couplings

- equivalent to dimension-6 operator coefficients

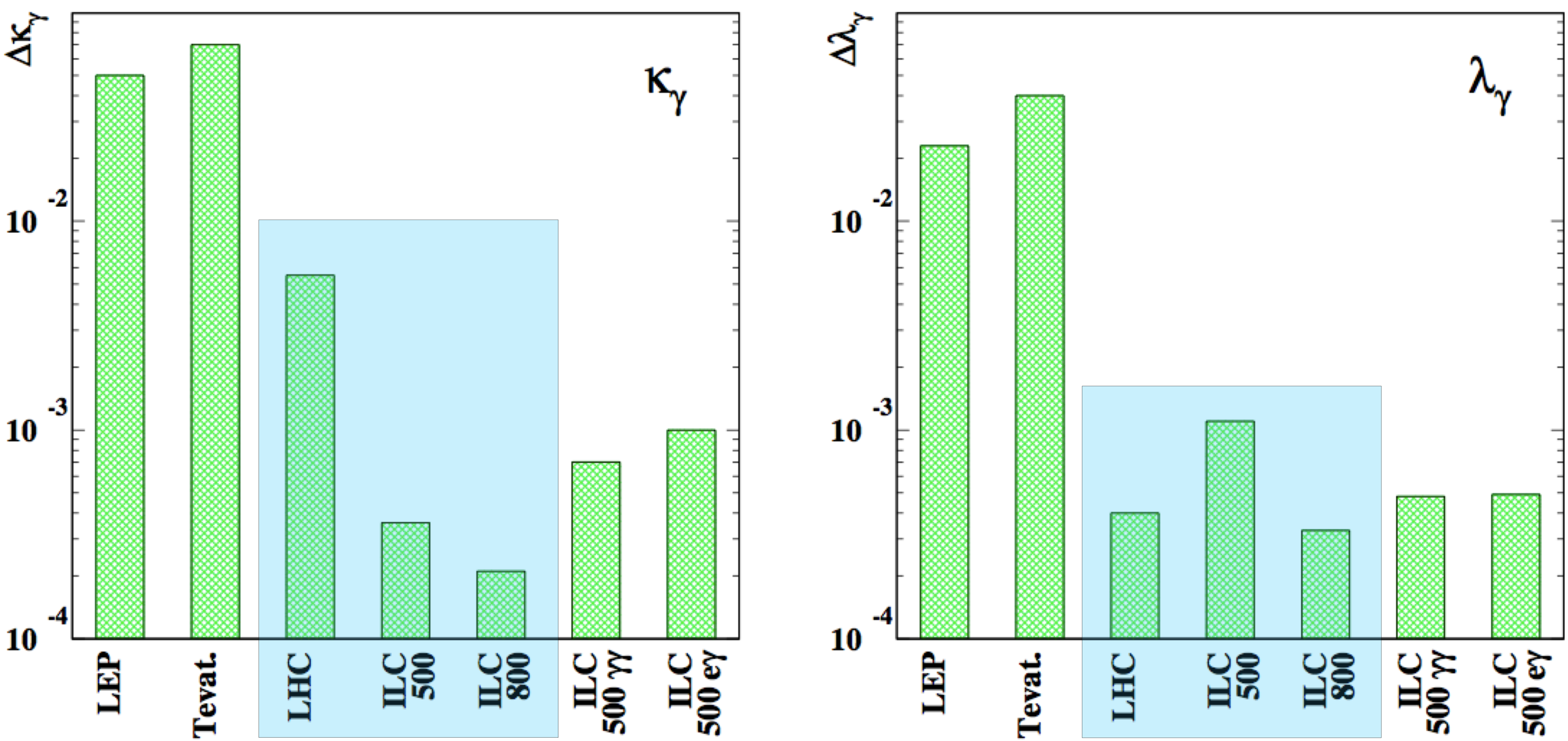


Figure 1-22. *Comparison of $\Delta\kappa_\gamma$ and $\Delta\lambda_\gamma$ at different machines. For LHC and ILC three years of running are assumed (LHC: 300 fb^{-1}, ILC $\sqrt{s} = 500$ GeV: 500 fb^{-1}, ILC $\sqrt{s} = 800$ GeV: 1000 fb^{-1}). If available the results from multi-parameter fits have been used. Taken from Ref. [193, 194].*

Generally, electron-positron collider probes dimension-6 operators, through diboson production, much better than LHC

Conclusions

- Electroweak physics is directly connected with the next big question after Higgs discovery: the mechanism for stabilizing the Higgs potential

- Electroweak Precision Measurements can test SM and probe BSM parameter space

  - High precision measurements of M_W (factor of 5 improvement → ~3 MeV) and $\sin^2\theta_{eff}$ (factor of 10 improvement → ~1.3 x 10^{-5}) are good goals for ILC/GigaZ

  - CEPC/TLEP gives high statistics potential: factor 3-10 higher precision than ILC/GigaZ possible including systematics
    - < 1 MeV precision on M_W
    - 1-3 x 10^{-6} precision on $\sin^2\theta_{eff}$

Conclusions

- Complementary approaches to precision measurements for estimating the energy scale of new physics
  - Higgs branching ratios
  - Z-pole measurements
  - W mass measurement at WW threshold
  - Diboson measurements and anomalous couplings

- Precision measurements can probe energy scales of many TeV to many 10's of TeV

Conclusions – parametric uncertainties

Measurements of M_W at the few MeV level, and $\sin^2\theta^{\ell}_{\rm eff}$ at the level of 10^{-5}, require that the parametric uncertainties from m_{top}, M_Z, and $\Delta\alpha_{had}$ (the contribution to the running of α_{EM} from hadronic loops) as well as the missing higher order calculations be addressed. Parametric uncertainties from m_{top} and $\Delta\alpha_{had}$, if reduced by a factor of 2 compared to current uncertainties, will prevent them from exceeding the anticipated total precision on M_W at the LHC. At the ILC and TLEP a factor of 5 and 10 improvement, respectively, in the parametric uncertainties is needed, which is only achievable if the precision on M_Z is considerably improved as well. TLEP can improve the M_Z precision by a factor of at least 10. It is anticipated that calculations in the coming years will reduce the effect of missing higher-order calculations by a factor of 4 which is sufficient for the LHC and ILC target uncertainties, but further effort will be needed for TLEP.

THANK YOU

- Thanks to the Snowmass Energy Frontier Electroweak working group members !

Conveners: A. Kotwal and D. Wackeroth

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Electroweak Report posted at:

http://snowmass2013.org/tiki-index.php?page=Precision+Study+of+Electroweak+Interactions

and arXiv:1310.6708