Precision Electroweak Measurements at the Energy Frontier

Ashutosh Kotwal
Duke University

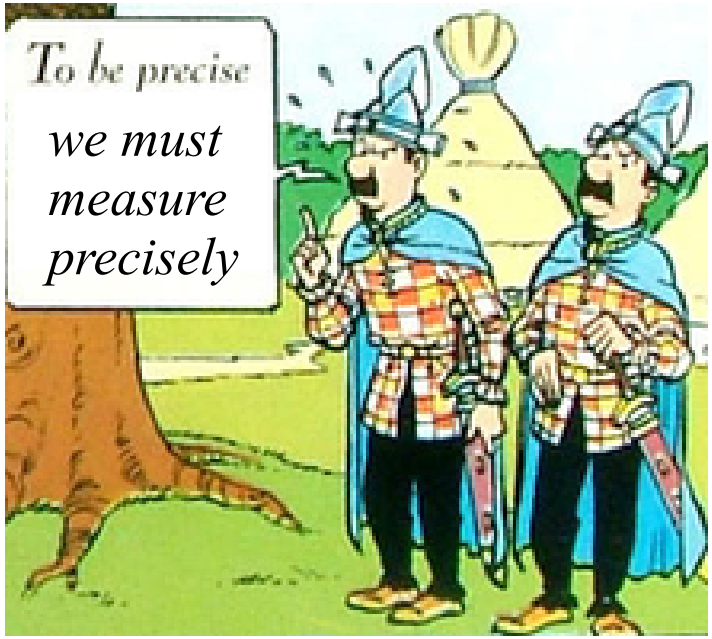
for the Electroweak Physics Sub-Group

Snowmass Workshop
Minneapolis - July 30, 2013

Precision Electroweak Measurements at the Energy Frontier

Ashutosh Kotwal
Duke University

for the Electroweak Physics Sub-Group



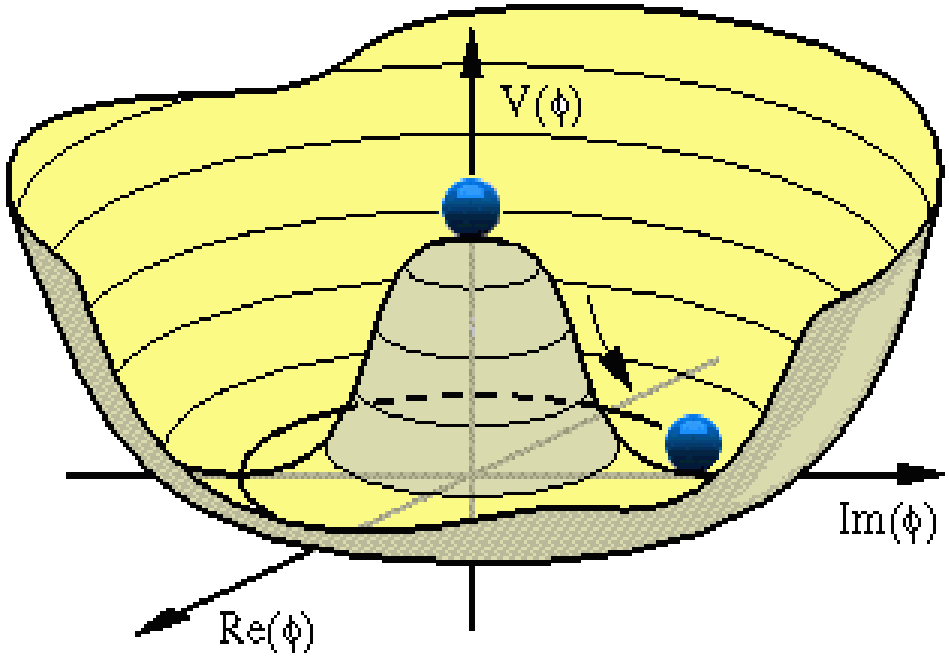
Snowmass Workshop
Minneapolis - July 30, 2013

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

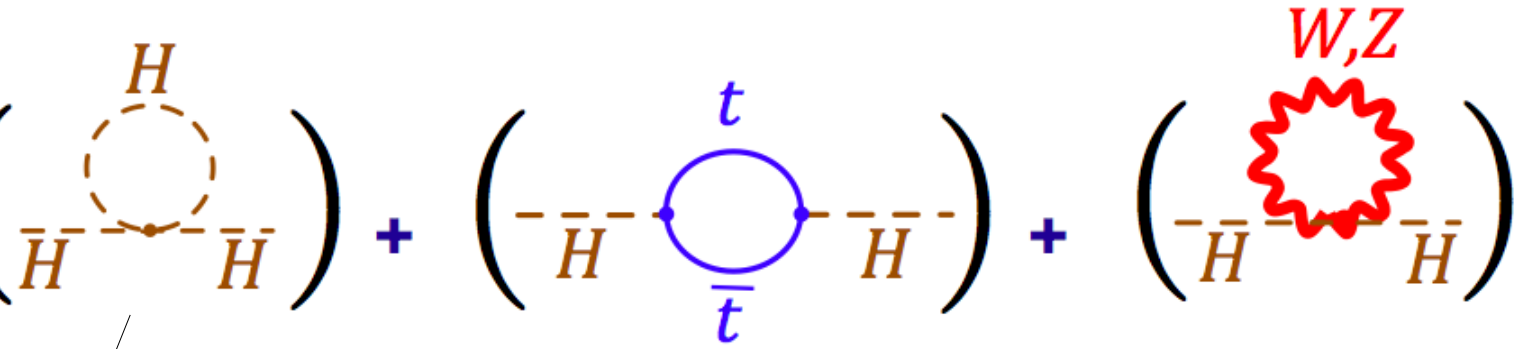


- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state

- 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?

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



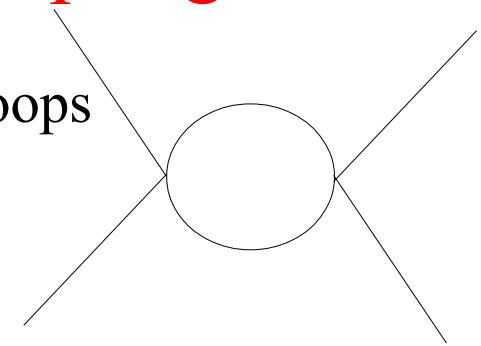
$$\lambda \int^{\Lambda} d^4k \, (k^2 - m_H^2)^{-1} \sim \Lambda^2 \lambda$$

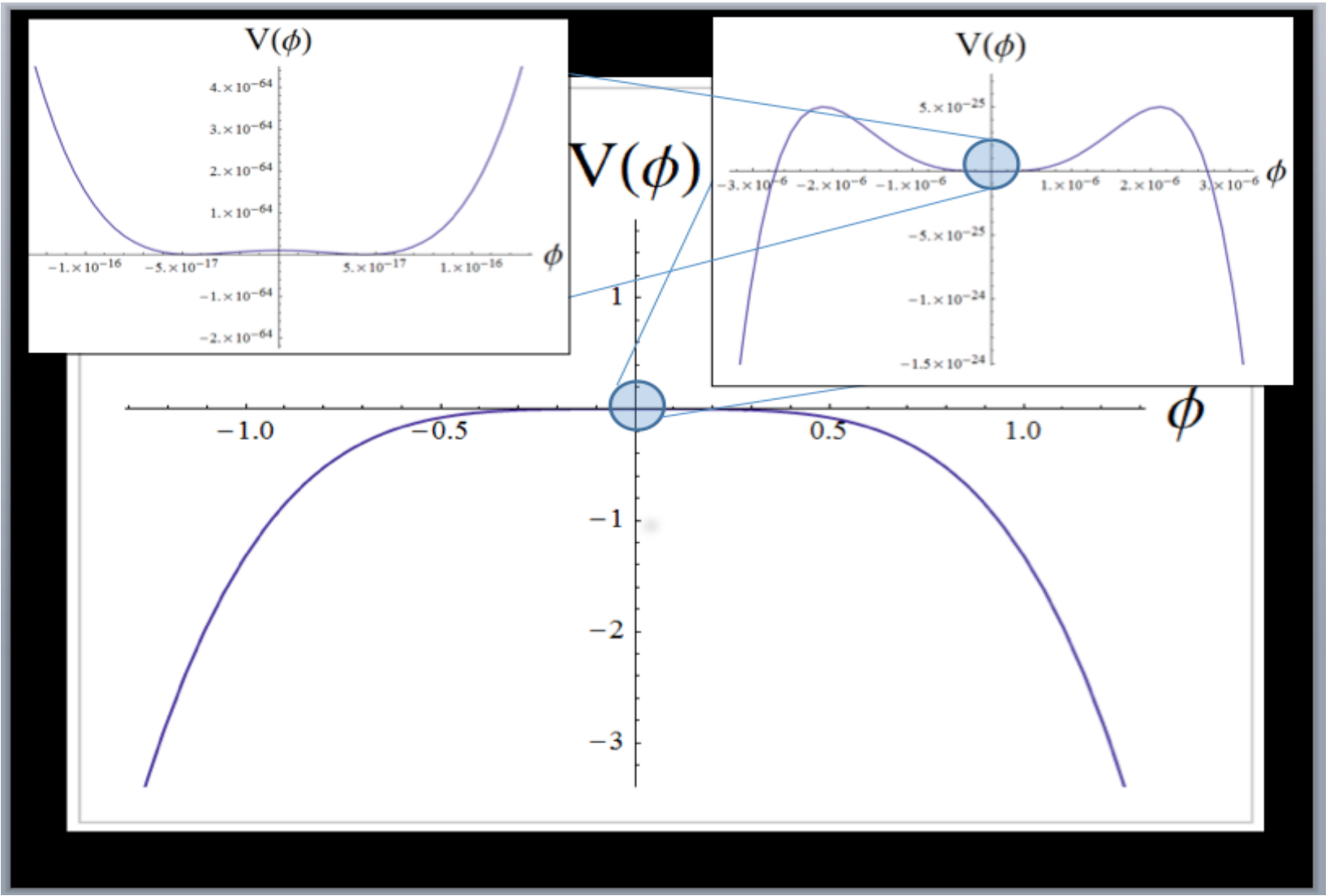
The Higgs boson ought to be a very heavy particle, naturally

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

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

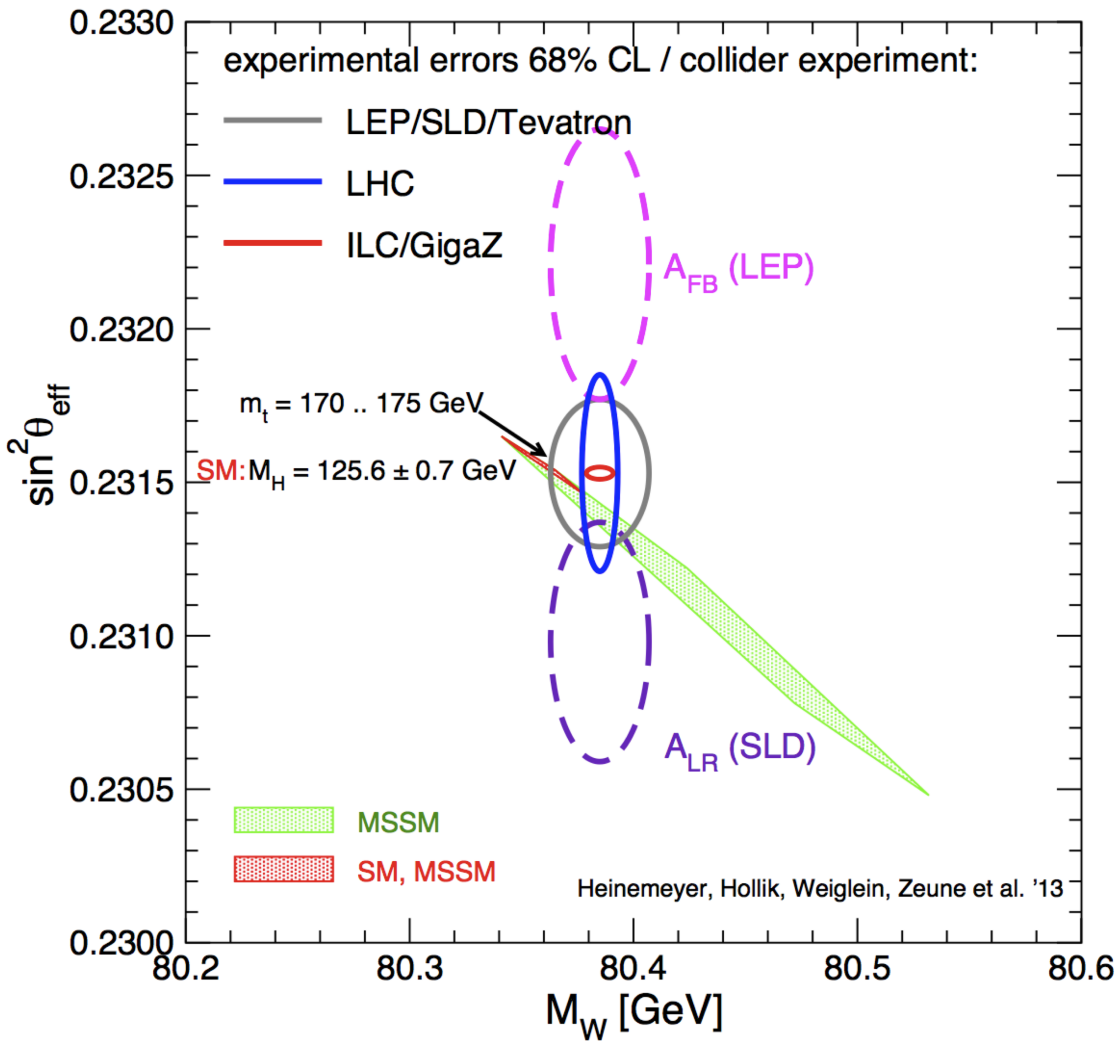
Next Steps for Electroweak Measurements

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

- Our report discusses two areas of electroweak physics
  - Electroweak precision observables (EWPOs) : M_W and $\sin^2\theta_{eff}$
  - Vector boson scattering and multi-boson production (focusing on triboson producton)

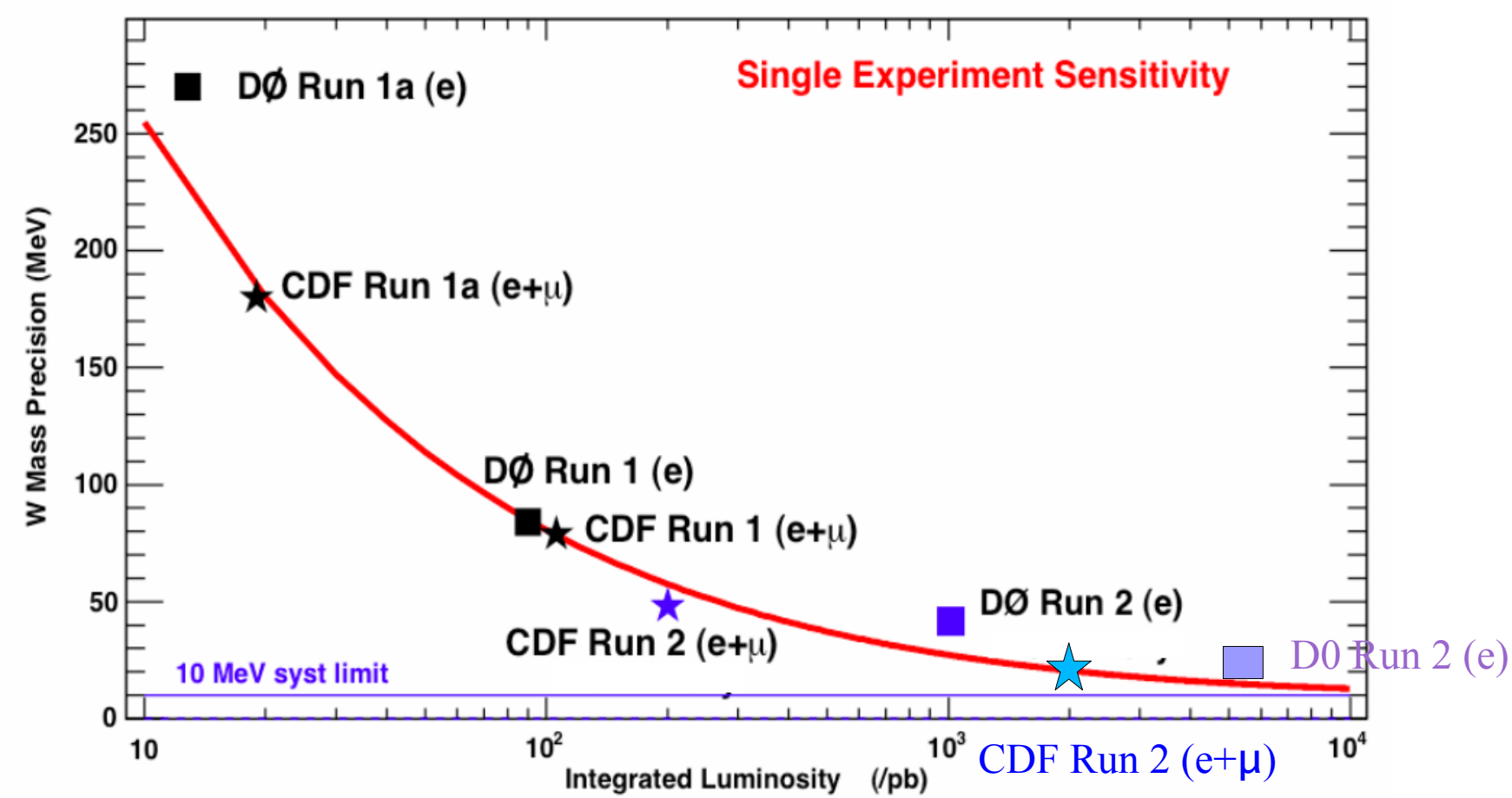
$\sin^2\theta_{eff}$ and M_W

- 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
$\mathcal{L}[\mathrm{fb}^{-1}]$	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
$\mathcal{L}[\mathrm{fb}^{-1}]$	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)

- TLEP promises even higher statistics

  Warrants detailed investigation of systematics and beam polarization

Lepton colliders heading towards ~2 MeV measurement of M_W ? or better ?

$\sin^2\theta_{eff}$ 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
$\mathcal{L}[\mathrm{fb}^{-1}]$	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
$\mathcal{L}[\mathrm{fb}^{-1}]$	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

(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
- Interesting to compare LEP, SLC precision ~ 27 × 10^{-5} each with 3σ difference

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

- ILC/GigaZ projection: ~1.3×10^{-5}

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

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

- TLEP has further statistical potential
  polarization to be investigated

- More than factor of 10 improvement over LEP, SLC precision

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)
$\Delta \sin^2\theta^\ell_{\rm eff}[10^{-5}]$	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.*

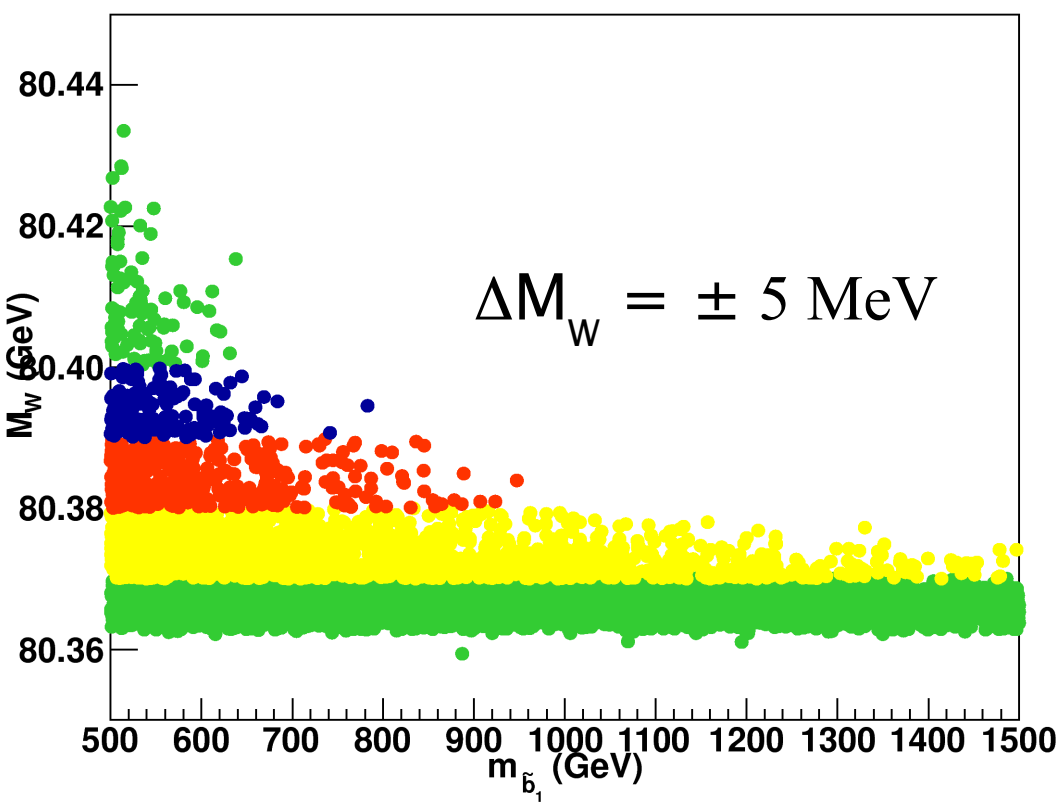
- Desirable to improve m_{top} precision below 0.5 GeV

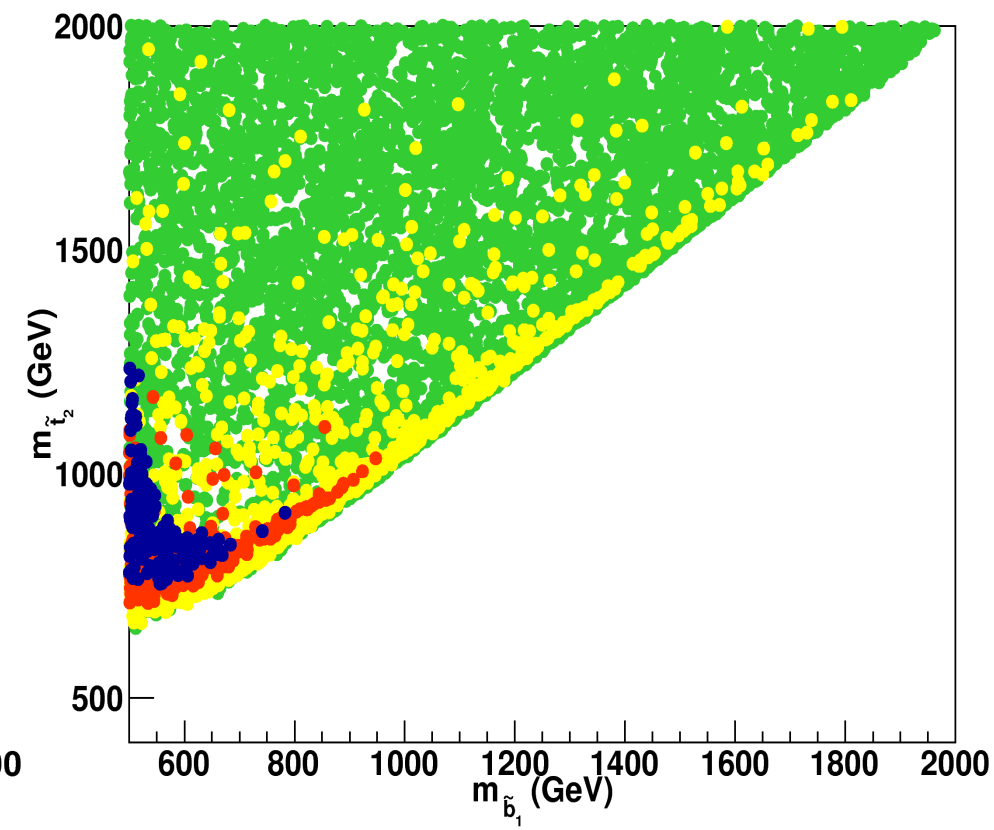
  Non-perturbative QCD effects in connecting reconstructed and pole mass

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

What could we learn ?

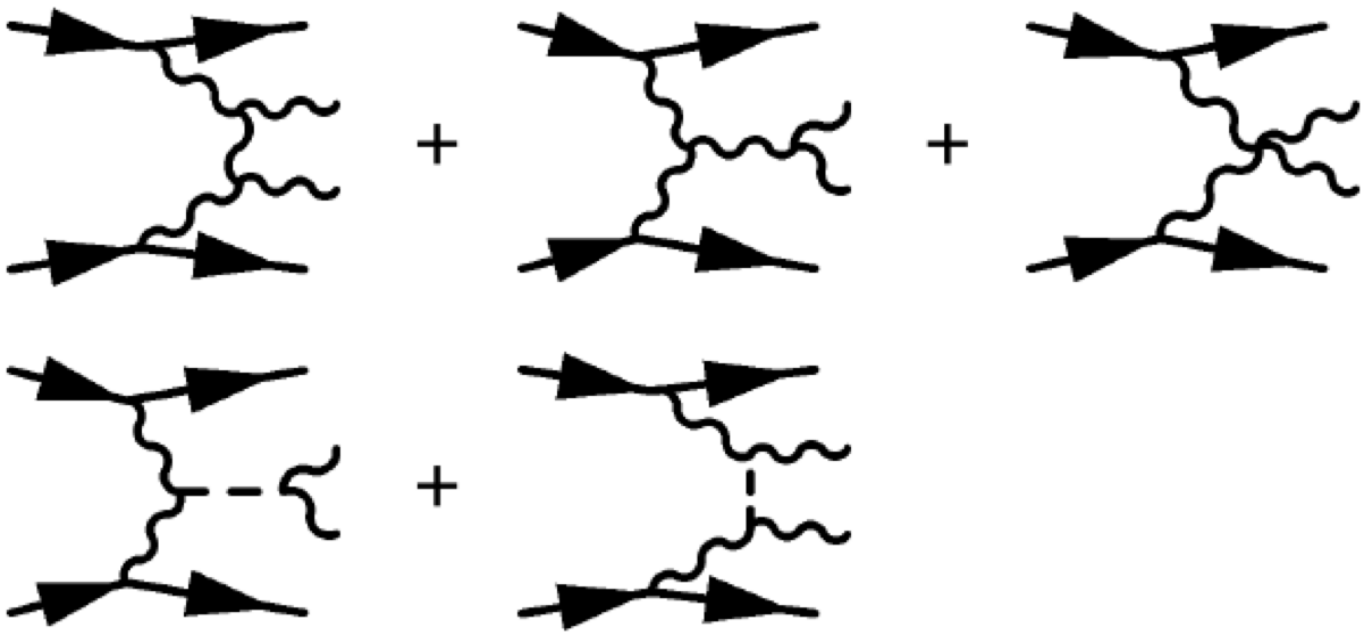
- SUSY-breaking parameter space is large
- Consider scenario after light stop discovery with mass = (400 ± 40) GeV
- MW predicts correlation with sbottom mass and heavy stop mass in MSSM
    - Parameter space shrinks rapidly depending on value and precision of M_W





Vector Boson Scattering

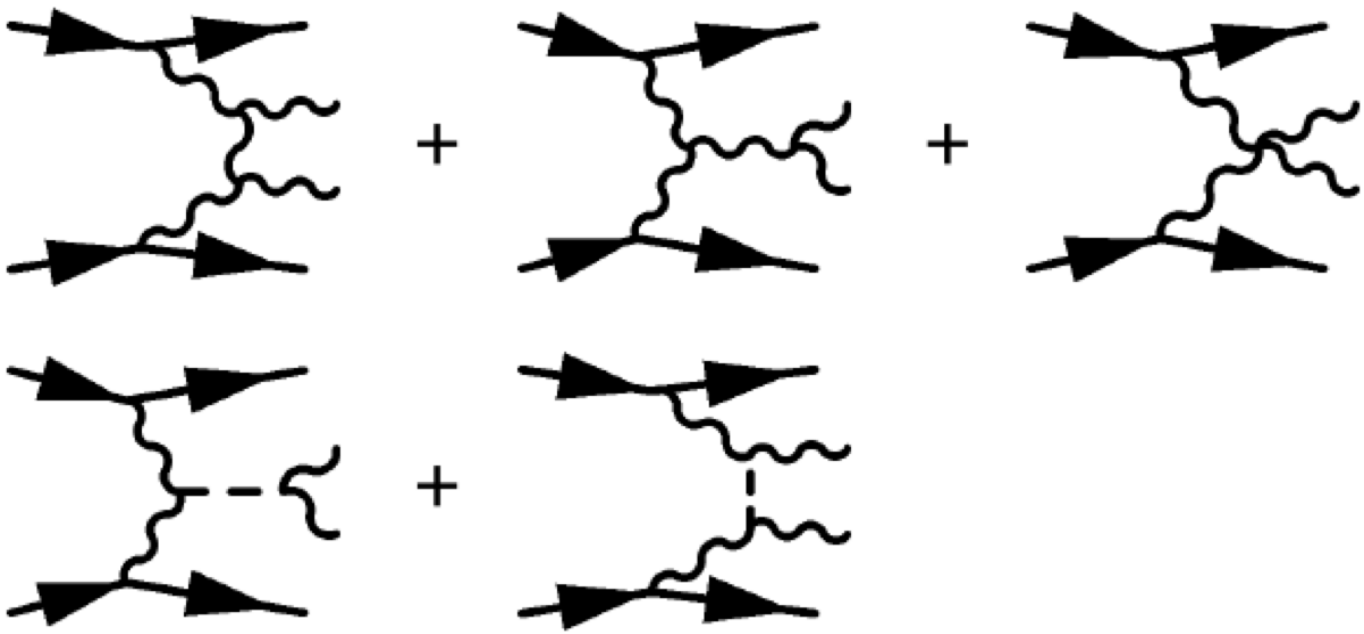
- This is a key process accessible for the first time at LHC
- A prime motivator for LHC/SSC: without Higgs (or some other) mechanism, longitudinally-polarized vector boson scattering amplitudes would violate tree-level unitarity above ~ 1 TeV



Vector Boson Scattering is intimately connected with EWSB

Vector Boson Scattering

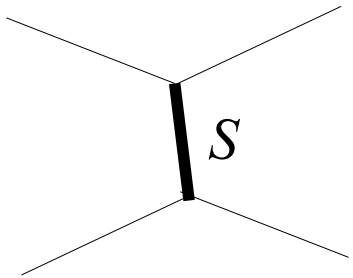
- This is a key process accessible for the first time at LHC
- A prime motivator for LHC/SSC: without Higgs (or some other) mechanism, longitudinally-polarized vector boson scattering amplitudes would violate tree-level unitarity above ~ 1 TeV

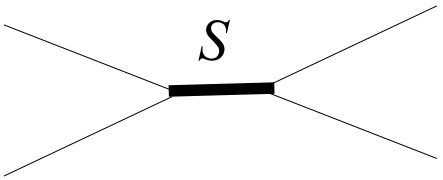


We still have to demonstrate experimentally that unitarizing mechanism is working, and how it is working

A Toy Model for BSM extension

- Consider a term coupling the Higgs to a singlet scaler *S*: $f\,\phi^\dagger\phi S$
- Via *S* exchange, can mediate scattering process: $\phi\phi \rightarrow \phi\phi$

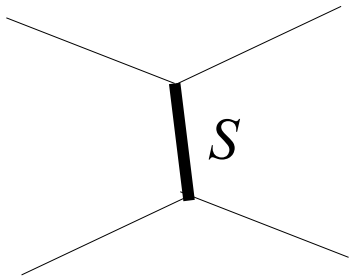


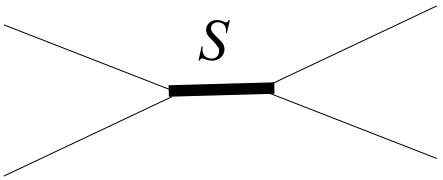


- For energies << m_S, induces effective field theory operators:
  - Dimension-4: $(f/m_S)^2\left(\phi^\dagger\phi\right)^2$
  - Dimension-6: $O_{\phi d} = (f^2/m_S^4)\ \left|\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)\right.$
  - This is one of the operators predicted in strongly-interacting light Higgs models
    - Alternate mechanism to SUSY for ensuring light Higgs boson
  - alters VBS compared to SM

A Toy Model for BSM extension

- Consider a term coupling the Higgs to a singlet scaler S: $f\,\phi^\dagger\phi S$
- Via S exchange, can mediate scattering process: $\phi\phi \rightarrow \phi\phi$

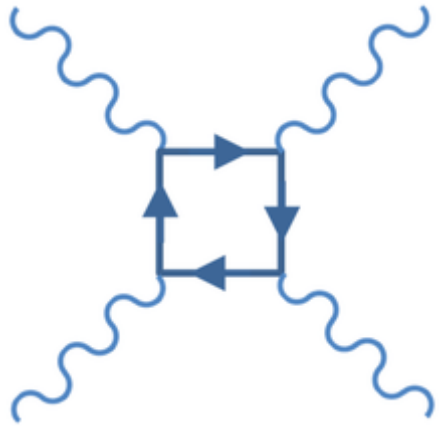




- For energies << m_S, induces effective field theory operators:
  - Dimension-4: $(f/m_S)^2\left(\phi^\dagger\phi\right)^2$
  - Dimension-6: $O_{\phi d} = (f^2/m_S^4)\ \left|\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)\right.$
  - This is one of the operators predicted in strongly-interacting light Higgs models
  - Observing a deviation in VBS consistent with this model would immediately point to model parameter values

Another Toy Model

- Consider the analogy with light-by-light scattering via electron loop



- Euler-Heisenberg effective lagrangian at low energies

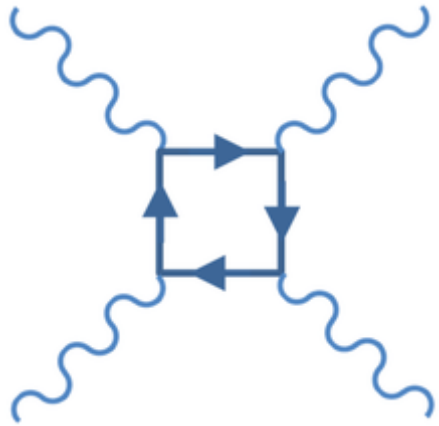
$$\mathcal{L} = \frac{1}{2}\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{2\alpha^2}{45m^4}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + 7\left(\mathbf{E}\cdot\mathbf{B}\right)^2\right]$$

  - Second term can be re-written in terms of

$$F_{\mu\rho}F^{\mu\sigma}F^{\nu\rho}F_{\nu\sigma} \qquad\qquad \left(F_{\mu\nu}F^{\mu\nu}\right)^2$$

Another Toy Model

- Consider the analogy with light-by-light scattering via electron loop



- Euler-Heisenberg effective lagrangian at low energies

$$\mathcal{L} = \frac{1}{2}\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{2\alpha^2}{45m^4}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + 7\left(\mathbf{E}\cdot\mathbf{B}\right)^2\right]$$

  - Second term can be re-written in terms of

$$F_{\mu\rho}F^{\mu\sigma}F^{\nu\rho}F_{\nu\sigma} \qquad\qquad \left(F_{\mu\nu}F^{\mu\nu}\right)^2$$

Operator coefficients contain information on mass and coupling of new dynamical degrees of freedom

Effective Field Theory Operators

- All dimension-6 and dimension-8 operators have been catalogued

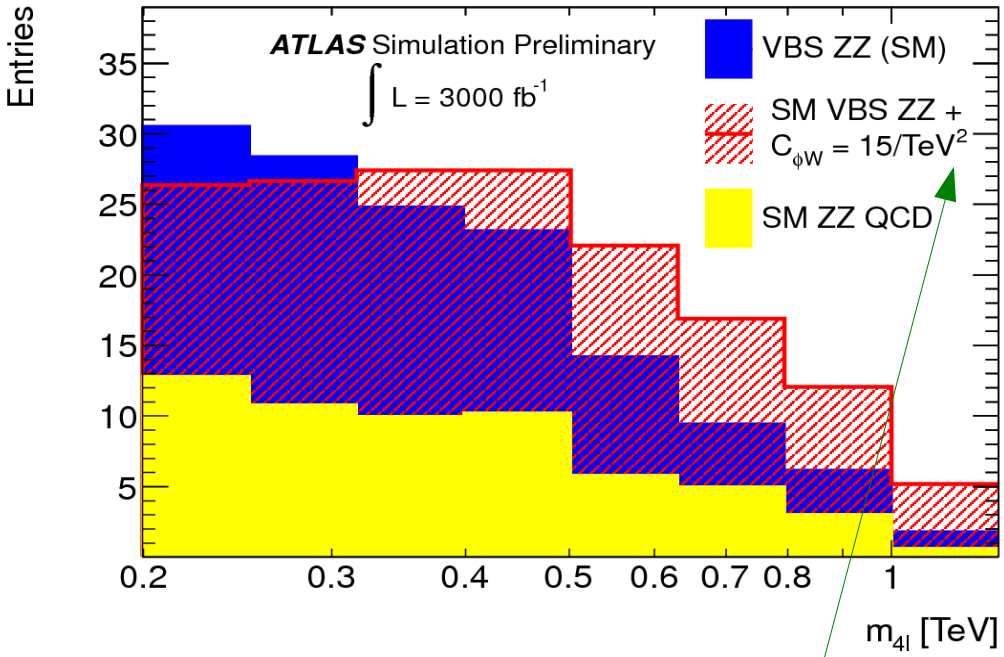
$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j$$

- LHC has shown the potential for
  - measuring new physics parameterized by higher-dimension operators
  - Differentiating between different operators using
    - Direct measurement of energy-dependence
    - different channels
  - Operators tested:

$$\begin{aligned}
\mathcal{O}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{O}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{O}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{O}_{T,1} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]
\end{aligned}$$

VBS Studies using Forward Tagged Jets

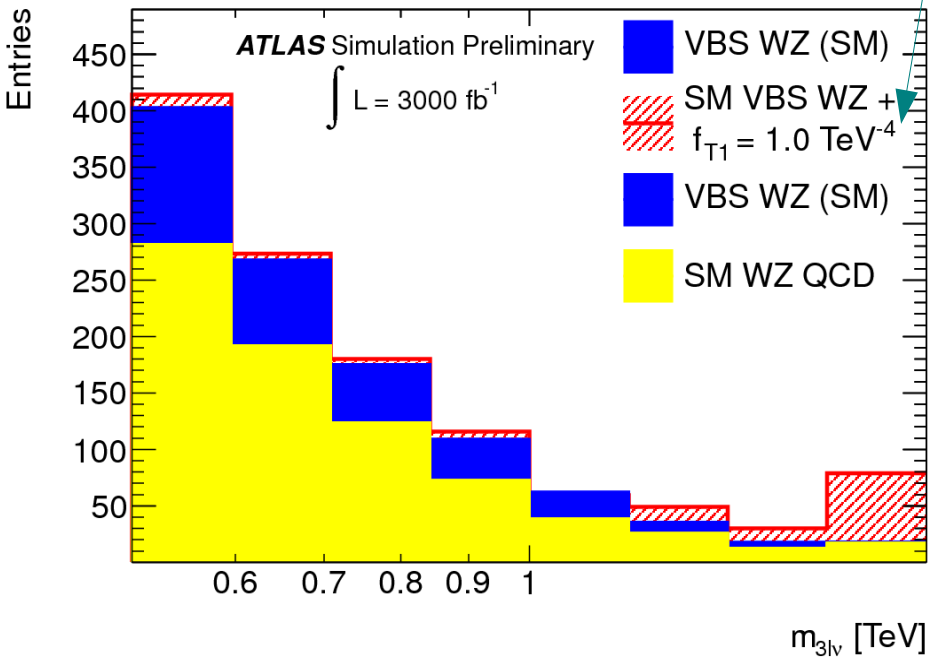
ZZ → leptons



dim-8 operator coefficient implies sensitivity to strong dynamics at TeV-scale

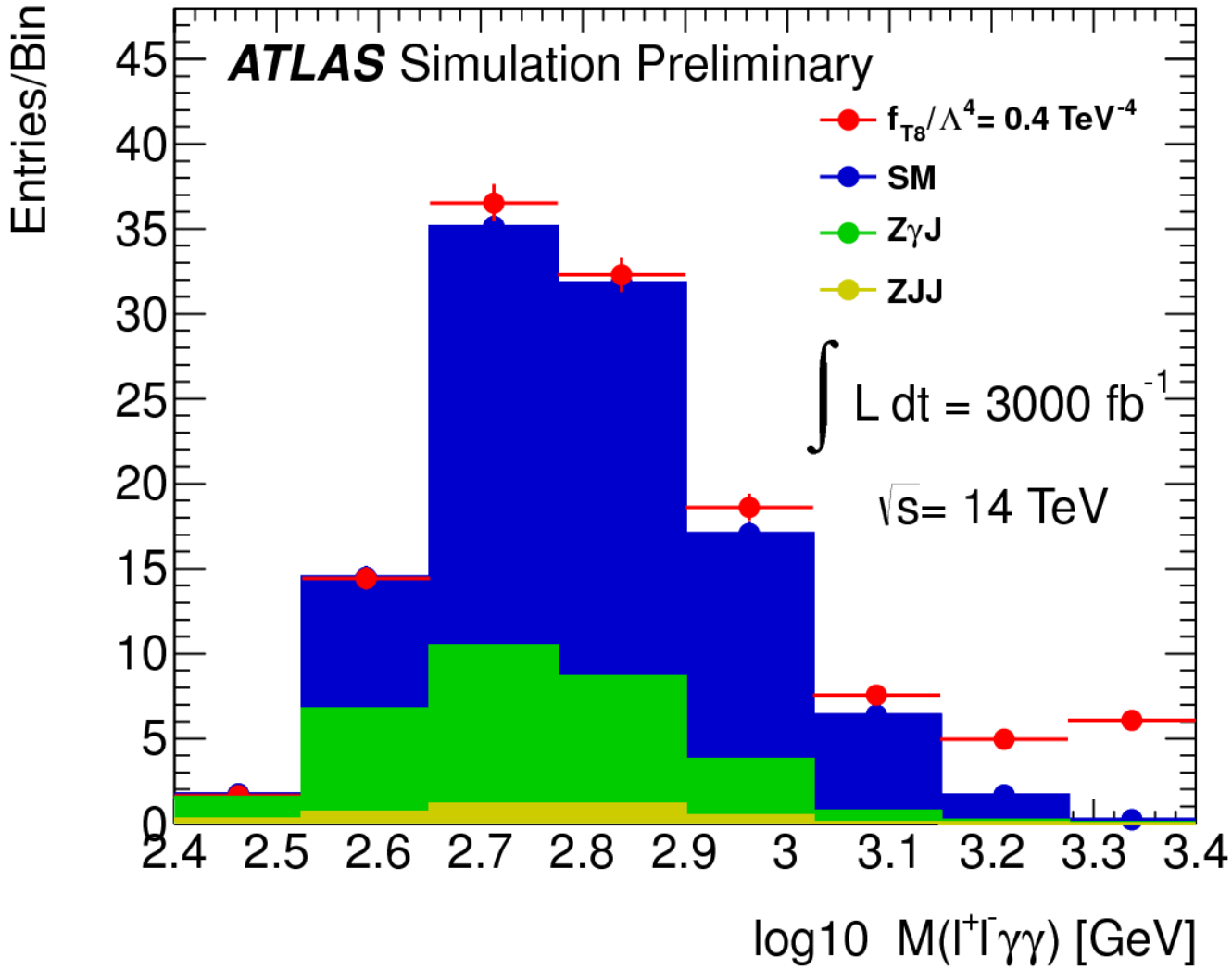
Threshold of interest for dim-6 operator coefficient $< v^{-2} \sim 16\ \mathrm{TeV}^{-2}$

WZ → leptons



(ATLAS Public Document ATL-PHYS-PUB-2013-006)

Complementarity of VBS and Triboson production



Anomalous Zγγ production at high mass also very sensitive to "T" operators

=> Comparison of VBS and triboson production is another powerful capability for characterizing the new physics

Program of VBS and Triboson Measurements

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Table 5: 5σ-significance discovery values and 95% CL limits for coefficients of higher-dimension electroweak operators. Λ_{UV} is the unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1} of integrated luminosity.

Conclusions:

1) factor of 2-3 improvement in sensitivity with Phase II

2) single-channel sensitivities pushed into the TeV-scale if new dynamics is strongly-coupled to Higgs and vector bosons

3) a powerful method of probing models of strongly-interacting light Higgs

4) model-independent tests of BSM dynamics

Example Test of Unitarization by Higgs

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi d}/\Lambda^2$ at 14 TeV	6	WZ	1.9	29 TeV^{-2}	17 TeV^{-2}	15 TeV^{-2}	8.7 TeV^{-2}

Conclusion:

We are not really testing unitarization by SM Higgs until operator < 16 TeV^{-2}

Example Test of Unitarization by Higgs

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi d}/\Lambda^2$ at 14 TeV	6	WZ	1.9	29 TeV^{-2}	17 TeV^{-2}	15 TeV^{-2}	8.7 TeV^{-2}

Conclusion:

We are not really testing unitarization by SM Higgs until operator < 16 TeV^{-2}

Single-channel tests of unitarization achievable with HL-LHC

VBS and Multi-Bosons at 33 TeV *pp* Collider

Parameter	channel	300 fb^{-1} at 14 TeV	3000 fb^{-1} at 14 TeV	3000 fb^{-1} at 33 TeV
$c_{\phi W}/\Lambda^2$	$ZZjj$	34 TeV^{-2}	16 TeV^{-2}	12 TeV^{-2}
f_{T1}/Λ^4	$WZjj$	1.3 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T0}/Λ^4	WWW	1.2 TeV^{-4}	0.5 TeV^{-4} →	0.05 TeV^{-4}

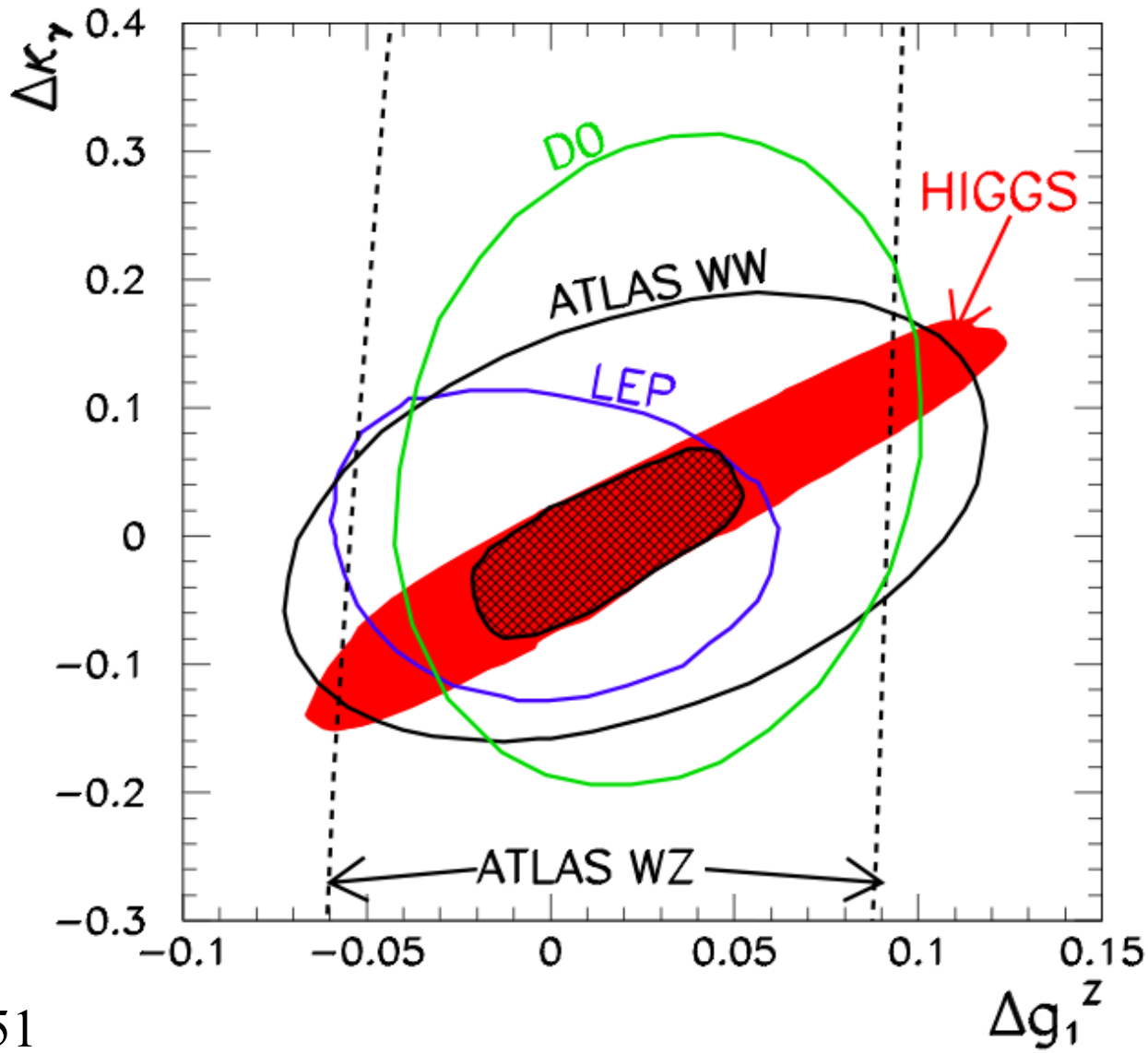
Table 1-23. *5σ-significance discovery values for coefficients of higher-dimension operators.*

Conclusion:

triboson production is dramatically more sensitive to new physics at higher beam energy

Combined Fit to Higgs and Anomalous Gauge Couplings

- Illustrates the complementary of approaches to new physics via coupling deviations



Corbett *et al.*, arXiv:1304.1151

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
  - TLEP also worth investigating given high statistics potential
  - Near-term: Tevatron and LHC pushing towards ΔM_W ~ 10 MeV and 5 MeV respectively

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
  - TLEP also worth investigating given high statistics potential
  - Near-term: Tevatron and LHC pushing towards ΔM_W ~ 10 MeV and 5 MeV respectively
- LHC opens up new and important area of vector boson scattering (VBS) and triboson production
  - single-channel tests of unitarization of VBS achievable with HL-LHC
  - Significantly extended sensitivity to new dynamics in the Higgs sector using VBS and multi-boson production
  - We are working on comparisons between LHC and ILC sensitivity to these observables

THANK YOU

- Thanks to the working group members !

M. Baak, A. Bodek, R. Caputo, T. Corbett, C. Degrande, O. Eboli, J. Erler, B. Feigl, A. Freitas, J. Gonzalez Fraile, C. Gonzalez-Garcia, J. Han, S. Heinemeyer, J. L. Holzbauer, S.-C. Hsu, W. Kilian, S. Li, M. Marx, O. Mattelaer, J. Metcalfe, M.-A. Pleier, C. Pollard, M. Rauch, J. Reuter, M. Rominsky, J. Rojo, W. Sakumoto, C. Schwinn, R. Sekulla, A. Vicini, G. Weiglein, G. Wilson, L. Zeune

Electroweak Report draft posted at:

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

Electroweak parallel sessions:

Wed, 8:30-10:00

- joint session with Higgs, Higgs coupling discussion - 1.5h

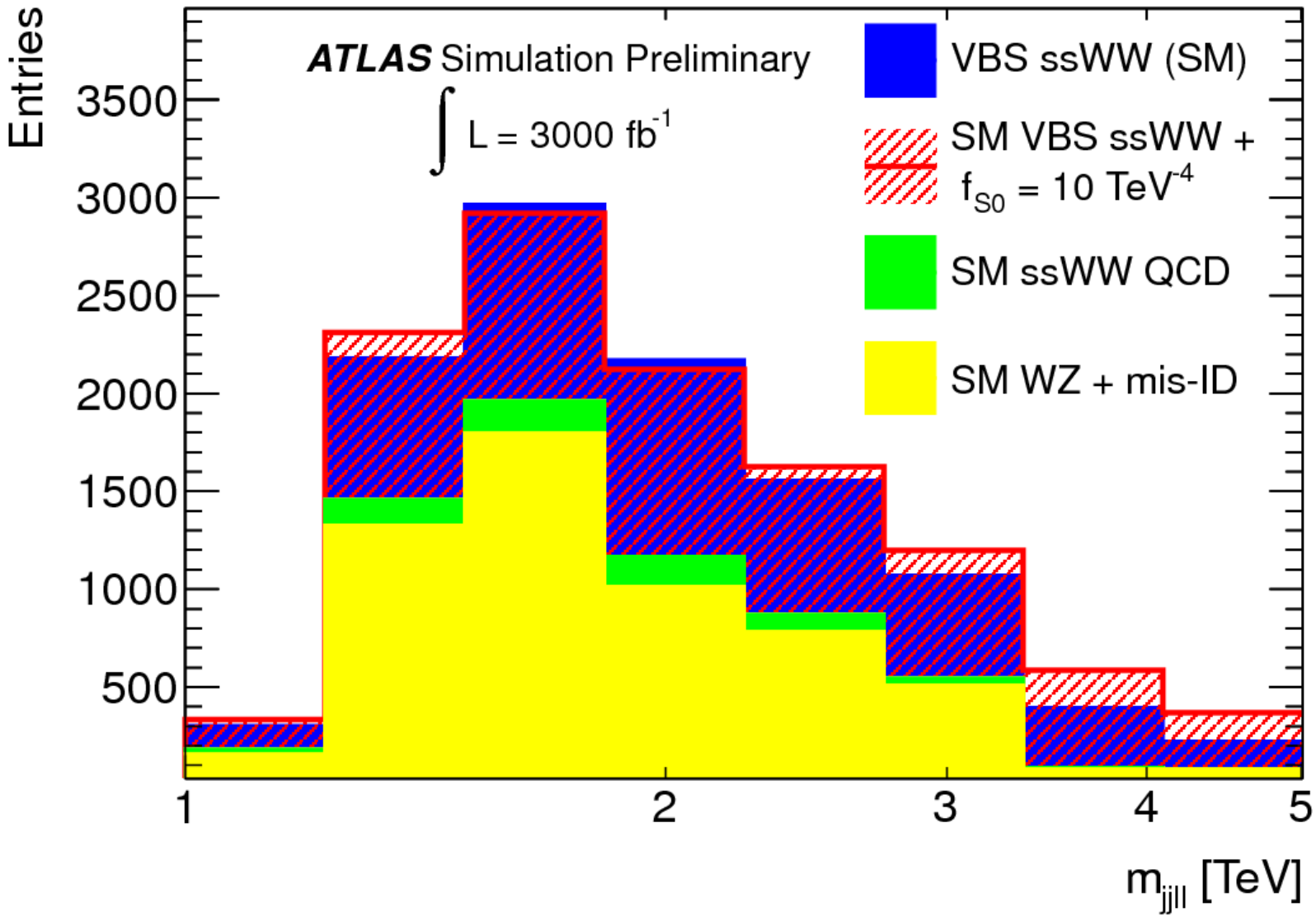
Friday, 8:30-12:00

- Multi-boson processes 1.5h-
- Precision Observables 1.5h-

Saturday, 8:30-12:00

- 08:30-11:00 - group work and QCD discussion

VBS Study using same-sign WW → leptons



Stronger SM interference for "S0" operator → different kinematic dependence