Precision Electroweak Measurements at the Energy Frontier - Determining the next Energy Scale

Ashutosh Kotwal
Duke University

(Summary of Snowmass 2013 Studies)

Center for Future High Energy Physics
IHEP Beijing, 16 July 2013

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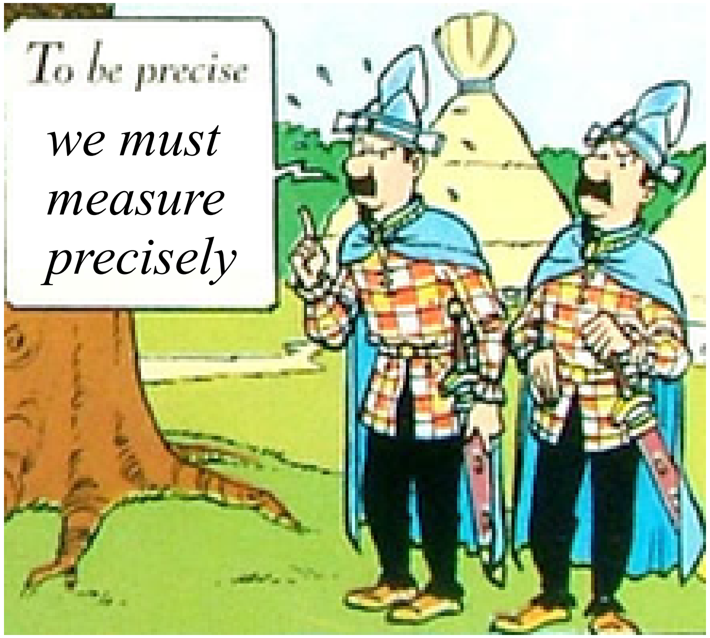

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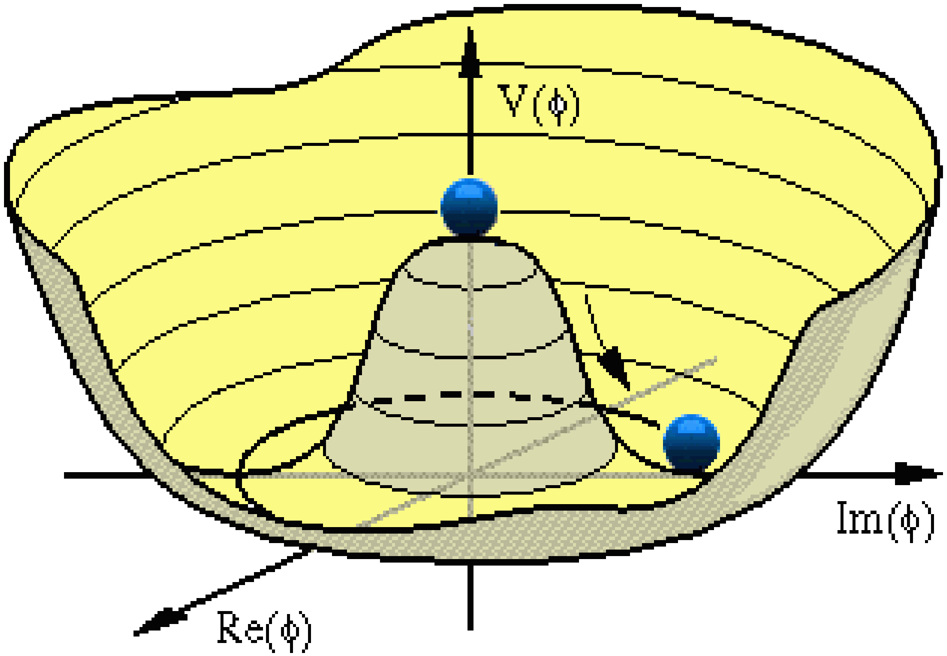
Spontaneous Symmetry Breaking

- 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

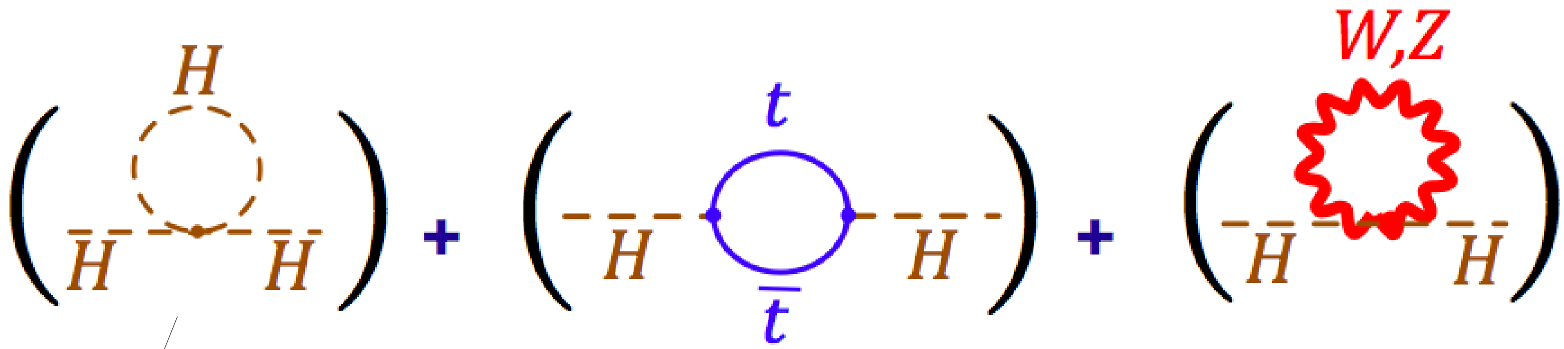


- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state

- 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?

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



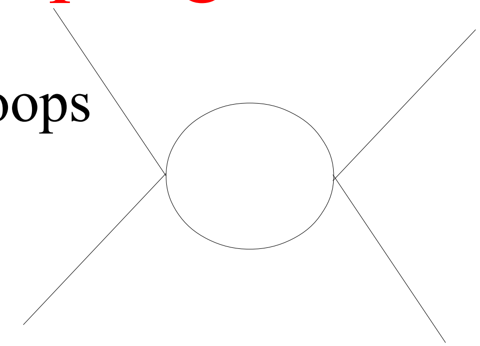
$$\lambda \int^{\Lambda} \mathrm{d}^4 k\, (k^2 - m_H{}^2)^{-1} \sim \Lambda^2 \lambda$$

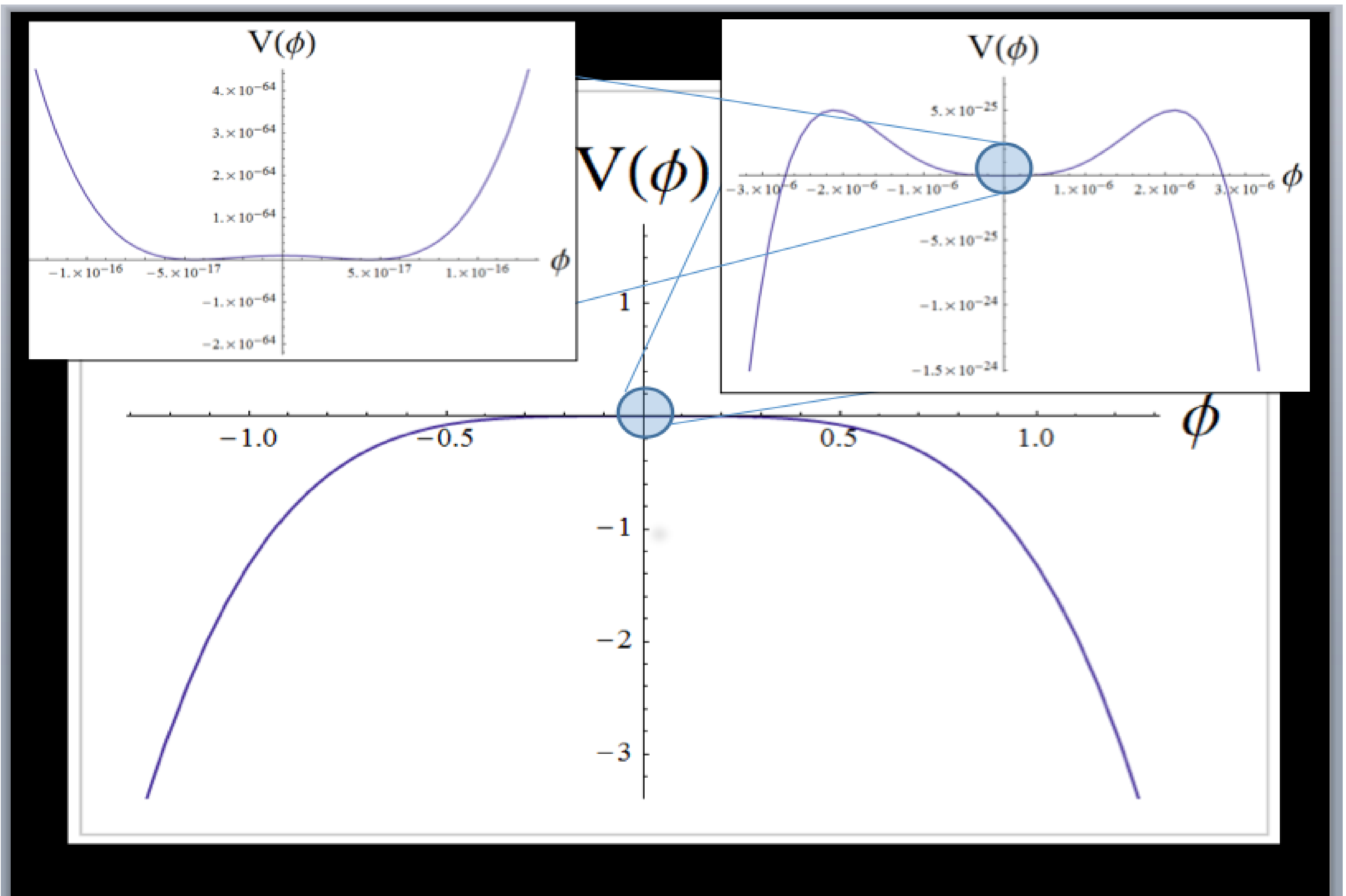
The Higgs boson ought to be a very heavy particle, naturally

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

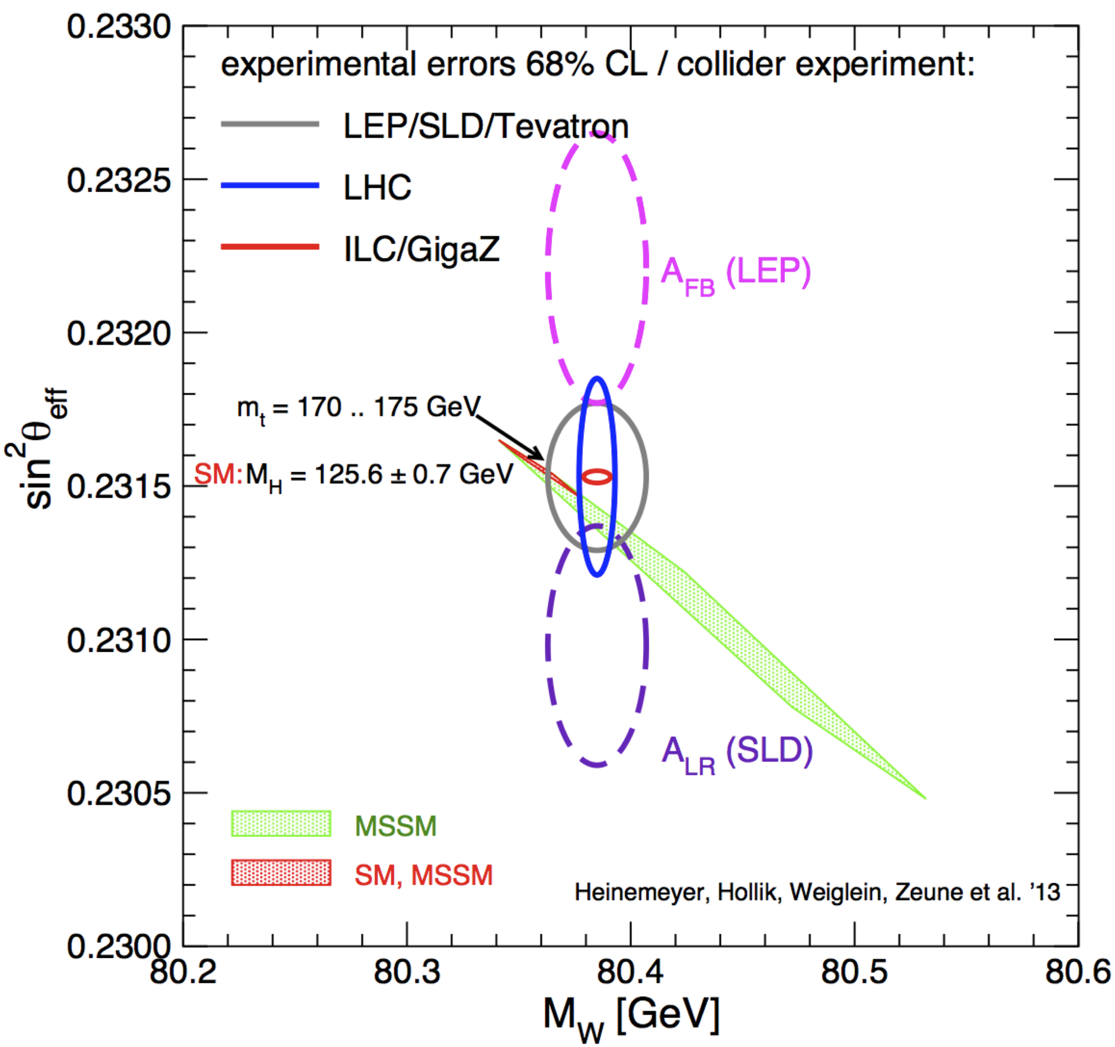
Next Steps for Electroweak Measurements

- Electroweak observables access all the mechanisms that can stabilize / explain the light Higgs mass
  - Is it stabilized by a symmetry such as SuperSymmetry ?
  - Is 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 $\sin^2\theta_{eff}$
  - Vector boson scattering and tri-boson production

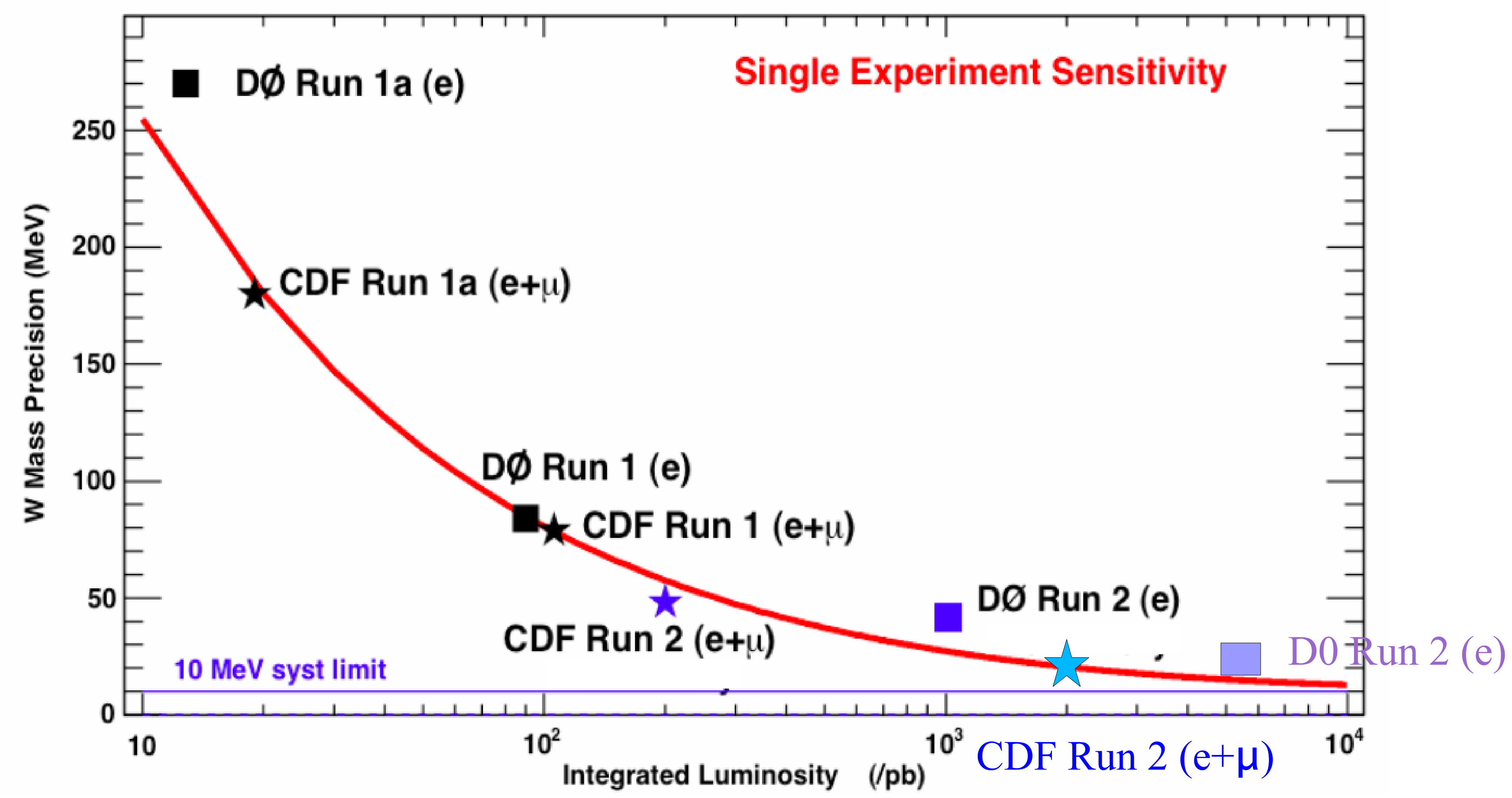
$\sin^2\theta_{eff}$ and M_W

- 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
$\mathcal{L}[\,\text{fb}^{-1}]$	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 ?

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

- Tevatron projection: ~40 × 10^{-5}

$\Delta\sin^2\theta^l_{\text{eff}}$ $[10^{-5}]$ final state	CDF e^+e^-	D0 e^+e^-	final CDF $\mu^+\mu^-$	final CDF e^+e^-	final CDF combined
$\mathcal{L}[\text{fb}^{-1}]$	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 $\Delta\sin^2\theta^l_{\text{eff}}$	**92**	**101**	**82**	**44**	**41**

(from Arie Bodek)

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

$\Delta\sin^2\theta^l_{\text{eff}}$ $[10^{-5}]$	ATLAS	CMS	LHC/per experiment		
$\sqrt{s}$ [TeV]	7	7	8	14	14
$\mathcal{L}[\text{fb}^{-1}]$	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* $\sin^2\theta^l_{\text{eff}}$ *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

$\sin^2\theta_{eff}$ 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/CEPC has further statistical potential: 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	$\Delta(\Delta\alpha_{\mathrm{had}}) = 1.38(1.0) \cdot 10^{-4}$	$\Delta M_Z = 2.1$ MeV	missing h.o.	total
ΔM_W [MeV]	5.4	2.5(1.8)	2.6	4.0	7.6(7.4)
$\Delta \sin^2\theta^{\ell}_{\mathrm{eff}} [10^{-5}]$	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 $\sin^2\theta^{\ell}_{\mathrm{eff}}$.*

	$\Delta m_t = 0.6(0.1)$ GeV	$\Delta(\Delta\alpha_{\mathrm{had}}) = 5 \times 10^{-5}$	$\Delta M_Z = 2.1$ MeV	missing h.o.	total
ΔM_W [MeV]	3.6(0.6)	1.0	2.6	1.0	4.7(3.0)
$\Delta \sin^2\theta^{\ell}_{\mathrm{eff}} [10^{-5}]$	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

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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.*

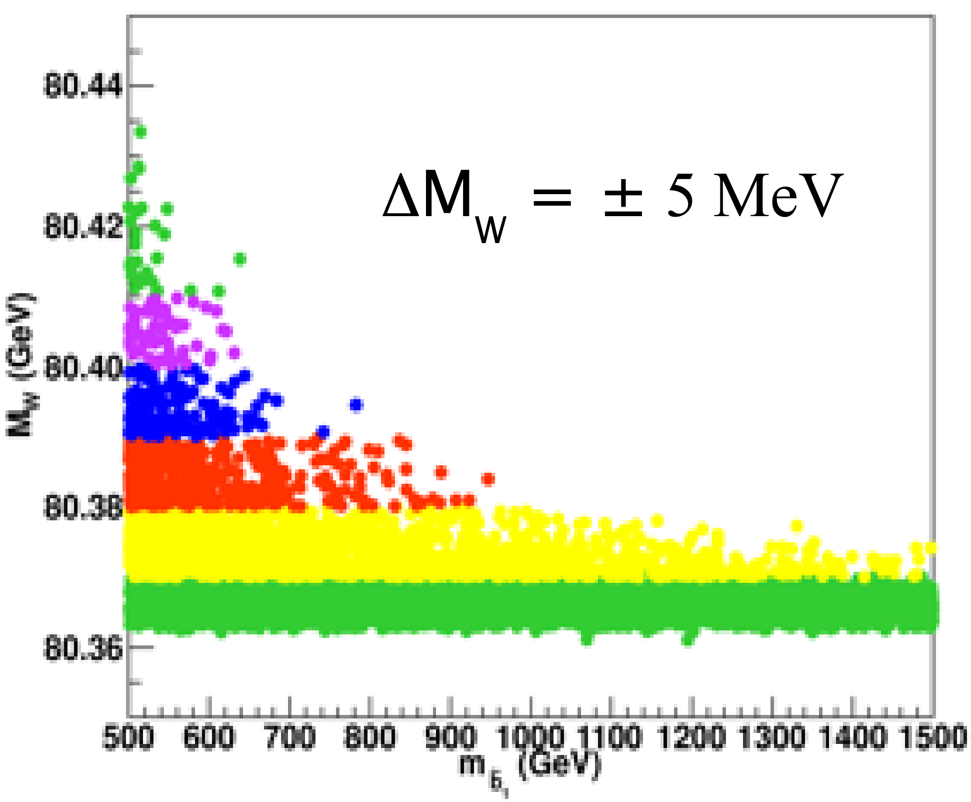
- Desirable to improve m_{top} precision below 0.5 GeV

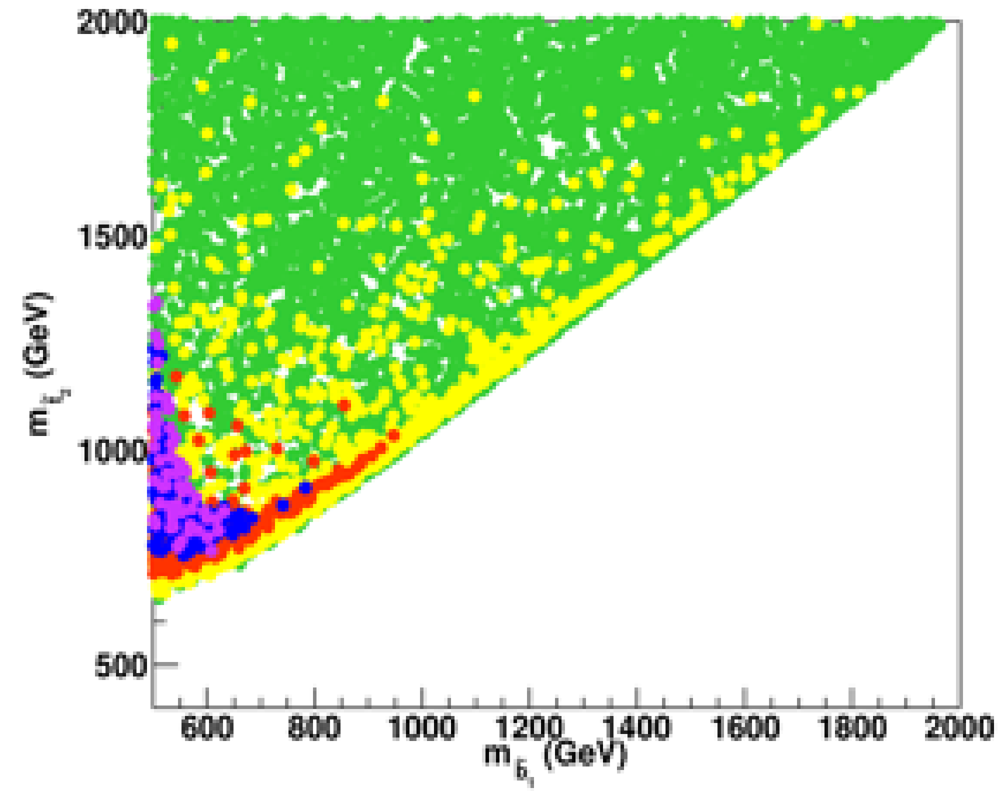
  Non-perturbative QCD effects in connecting reconstructed and pole mass

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

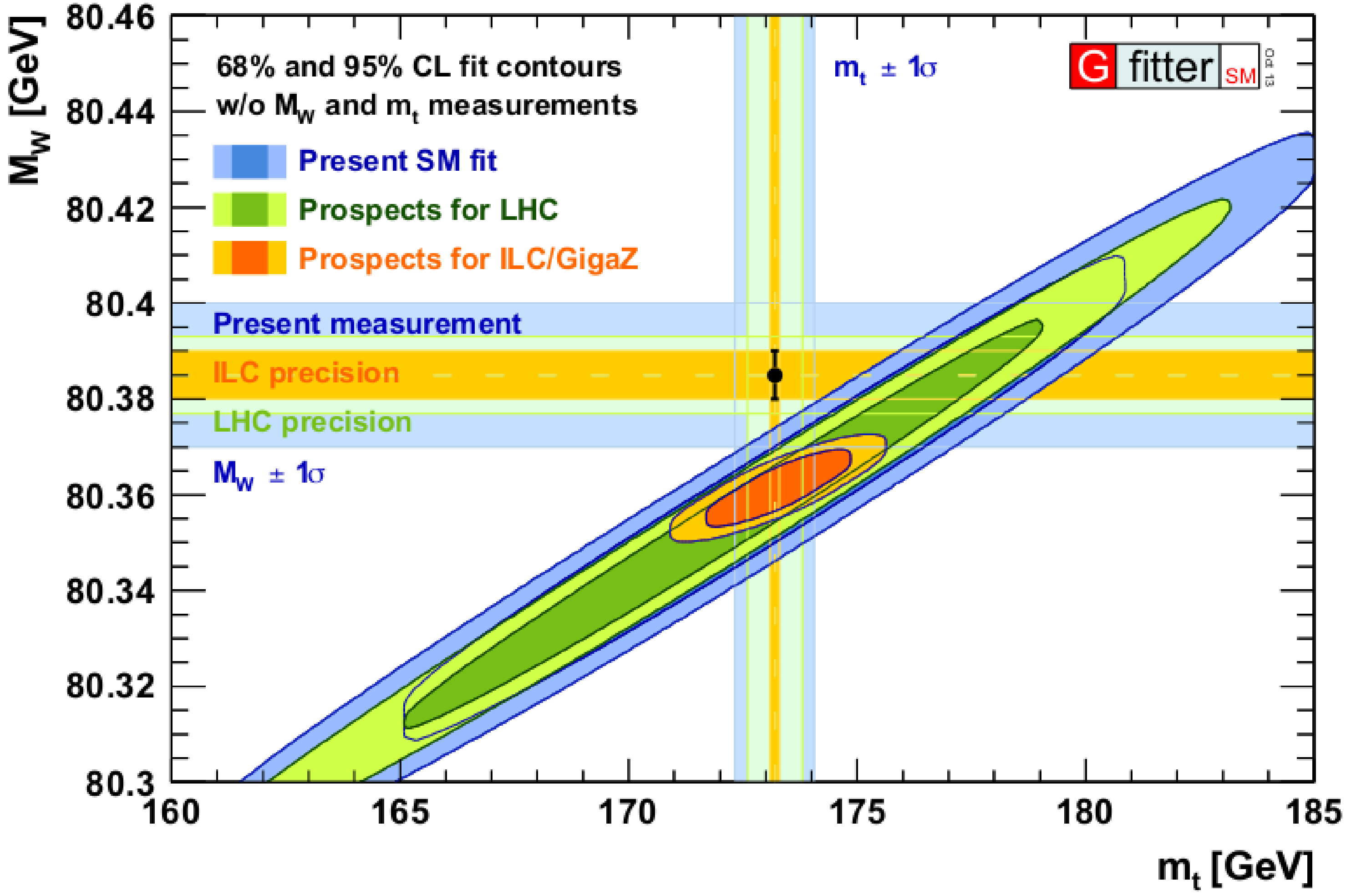
What could we learn ?

- 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



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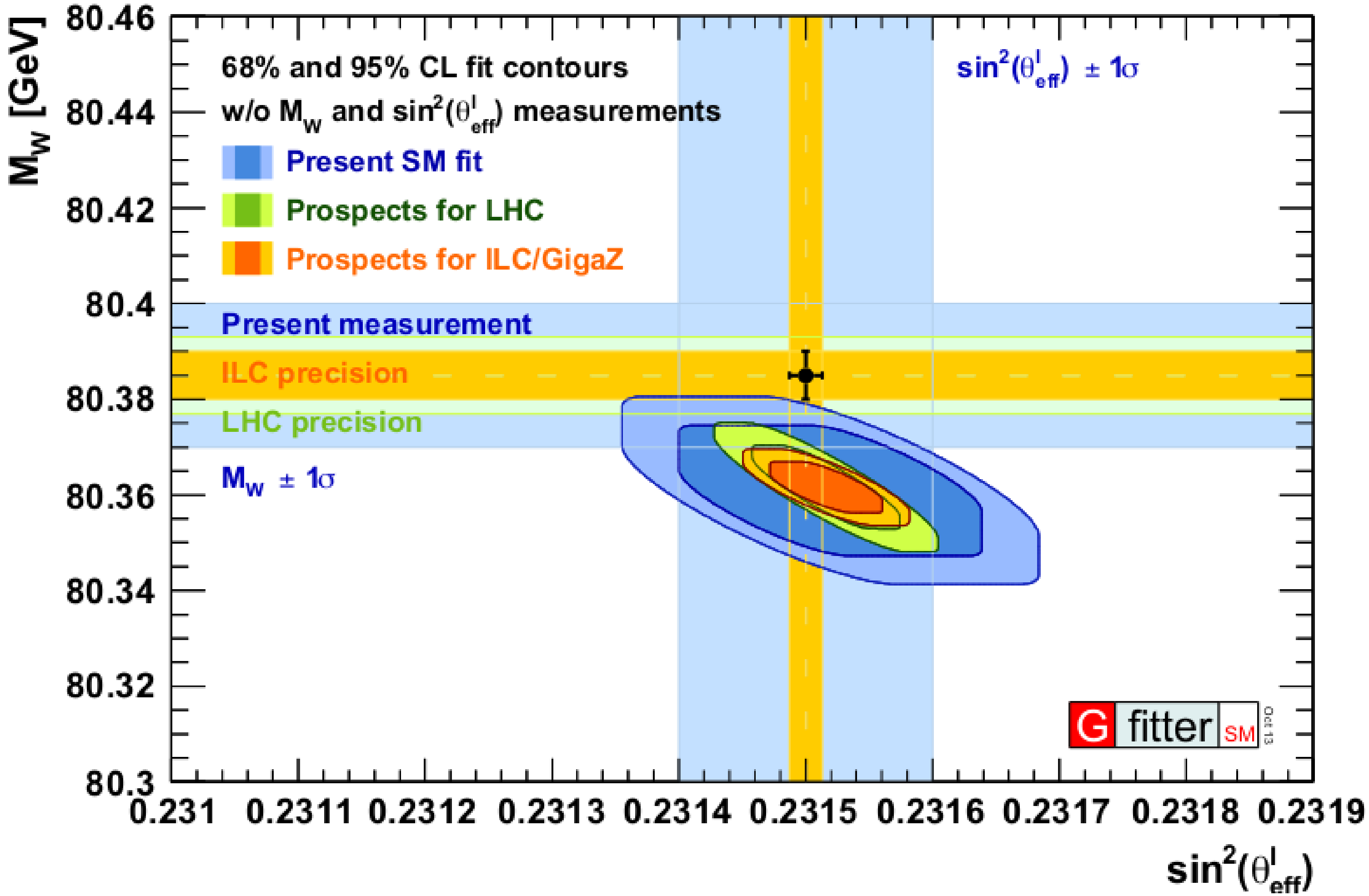
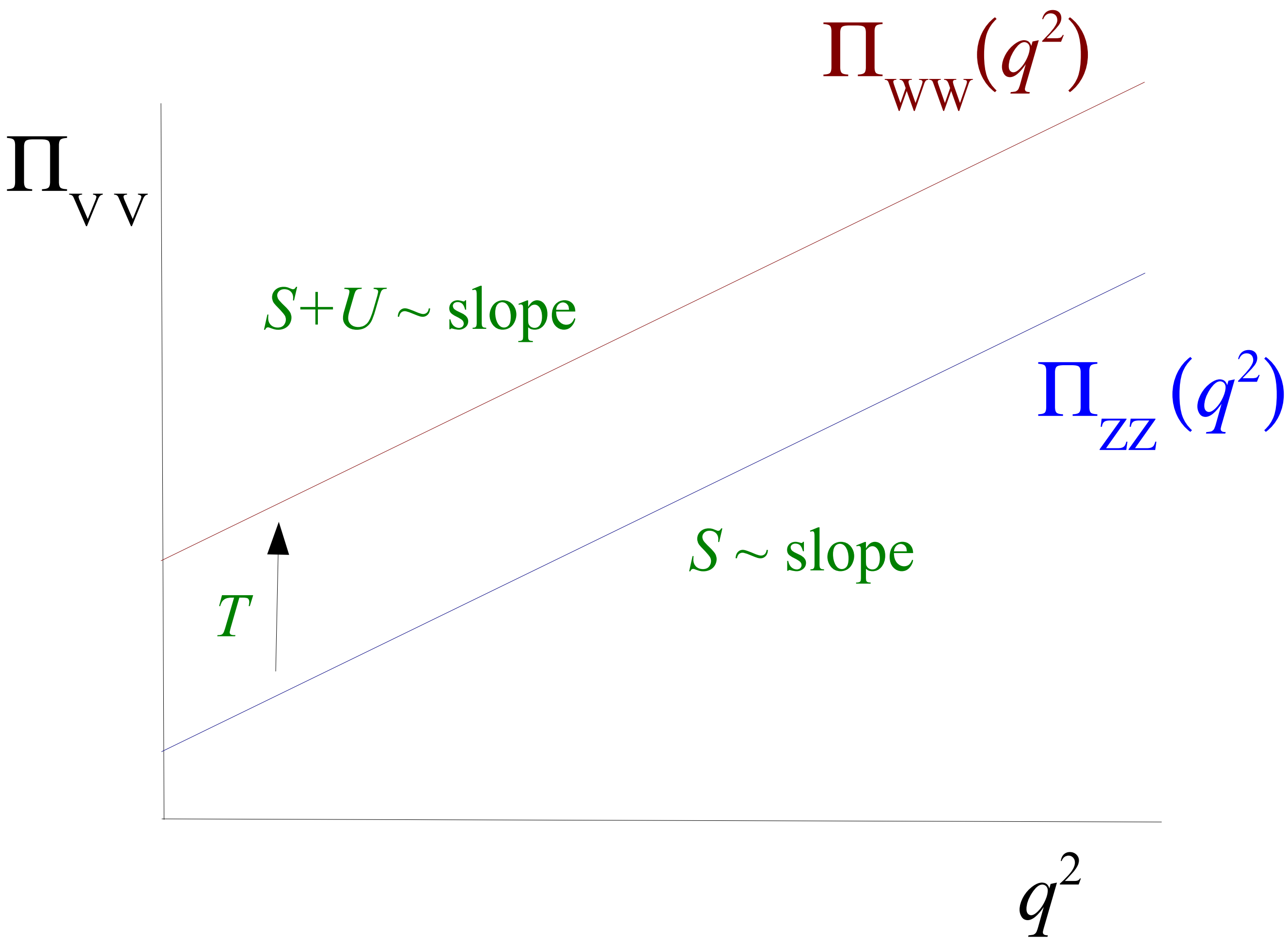
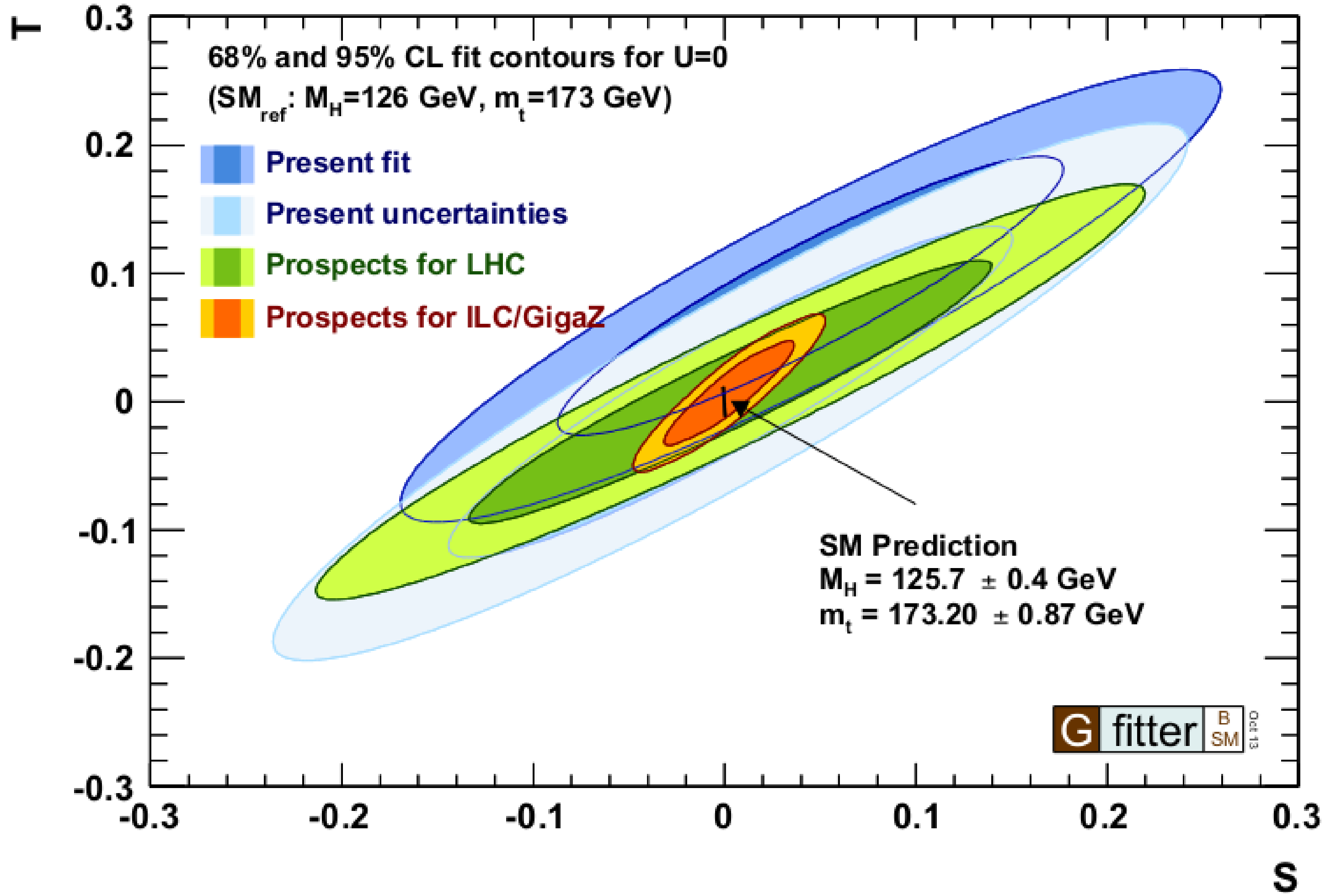


STU Parameterization

- 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, $\Delta\sin^2\Theta = 8 \times 10^{-5}$

What Can We Learn About New-Physics Scale?

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

$$\mathcal{L}_{\rm SILH} = \boxed{\frac{c_H}{2f^2}\partial^\mu \left(H^\dagger H\right) \partial_\mu \left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)}$$

$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right)$$

$$\boxed{+\frac{ic_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})}$$

$$+\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$+\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}. \qquad (15)$$

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

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

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

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

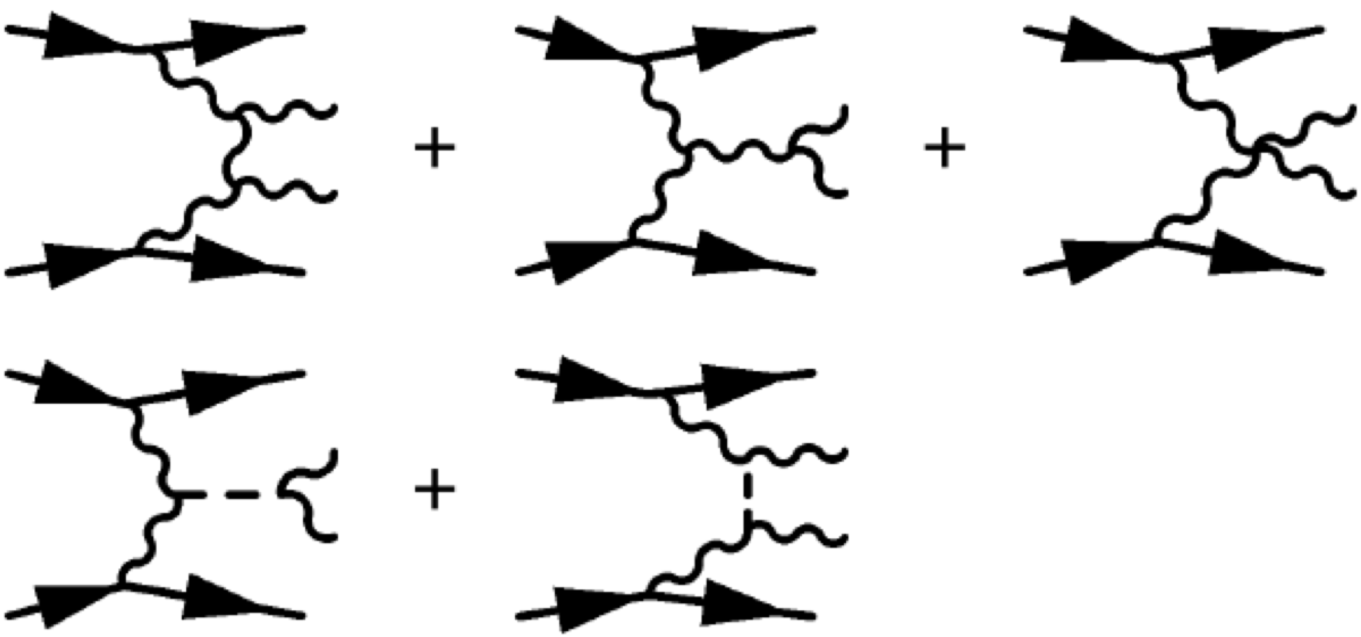
Conclusion: interpreted in a dimension-6 operator framework, EWPOs are already probing multi-TeV scale

Equivalent to Higgs coupling change of order few %

(caveat: different operators, different coefficients)

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

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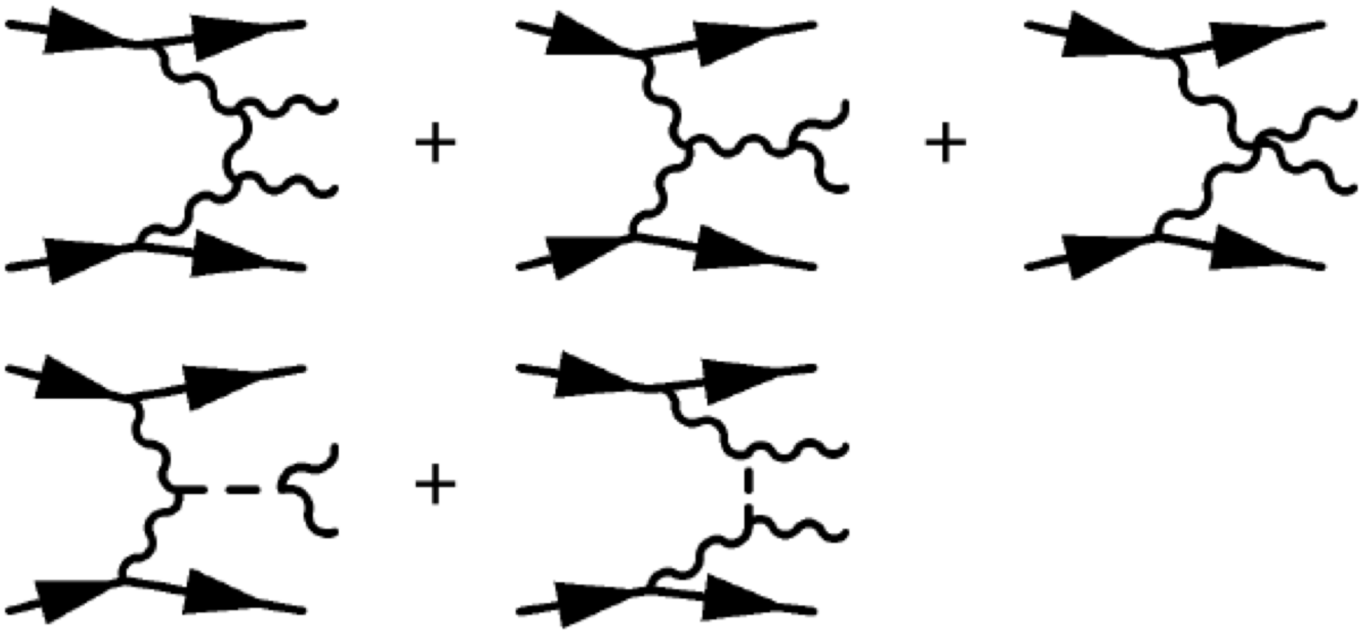
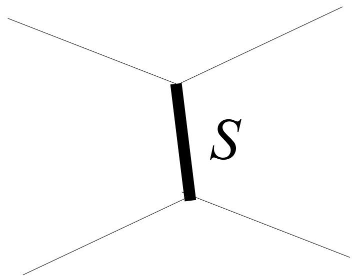
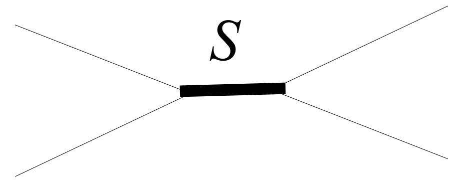


We still have to demonstrate experimentally that unitarizing mechanism is working, and how it is working

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: $\phi\phi \rightarrow \phi\phi$





$[\Box - m_S^{\,2}]^{-1} \sim m_S^{\,-2}[1 + \Box/m_S^{\,2}]$

- For energies << m_S, induces effective field theory operators:
  - Dimension-4: $(f/m_S)^2\,(\phi^\dagger\phi)^2$
  - Dimension-6: $O_{\phi d} = (f^2/m_S^{\,4})\ \partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$
  - 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

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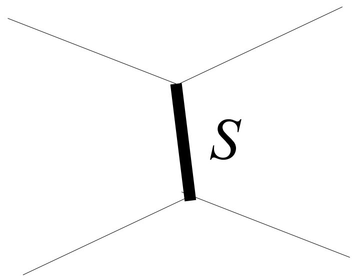

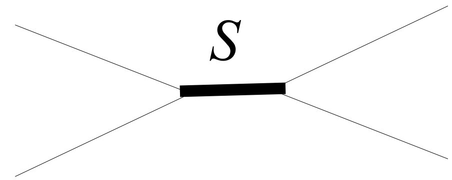

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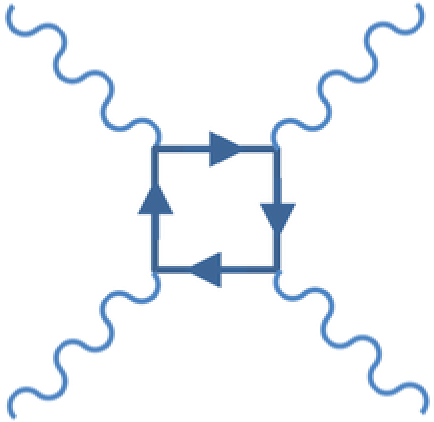
  - This is one of the operators predicted in strongly-interacting light Higgs models
  - Observing a deviation in VBS consistent with this model would immediately point to model parameter values

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

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

Another Toy Model

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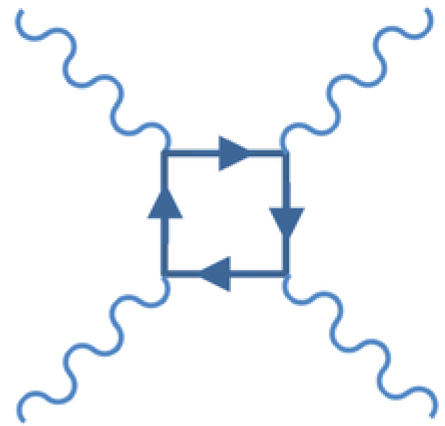

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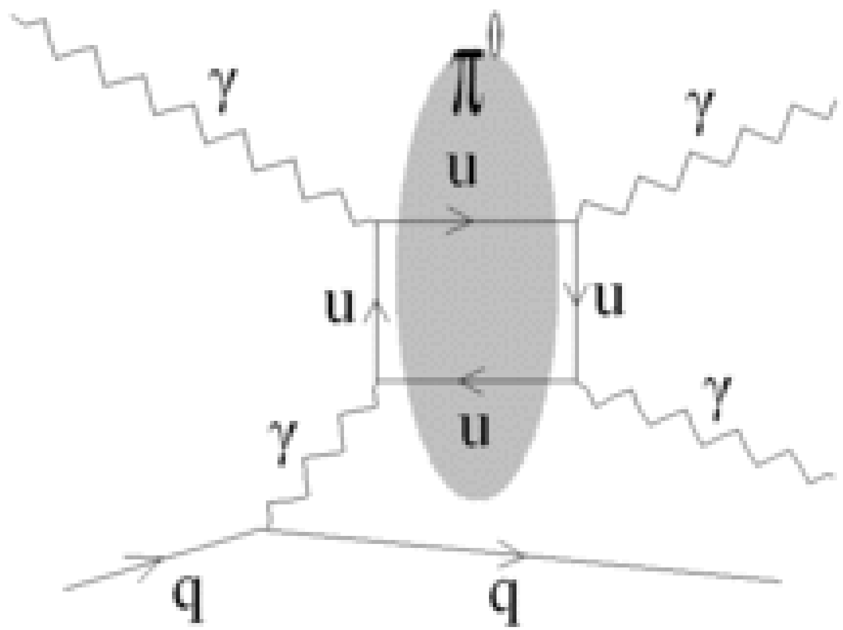
  - Second term can be re-written in terms of

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

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

Another Analogy – Primakoff Production of π^0

- Primakoff production by photon interacting with strong nuclear EM field



  - Therefore following operators can describe scalar resonance production in VBS

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

Operator coefficients contain information on mass and coupling of new scalar resonance

Effective Field Theory Operators

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

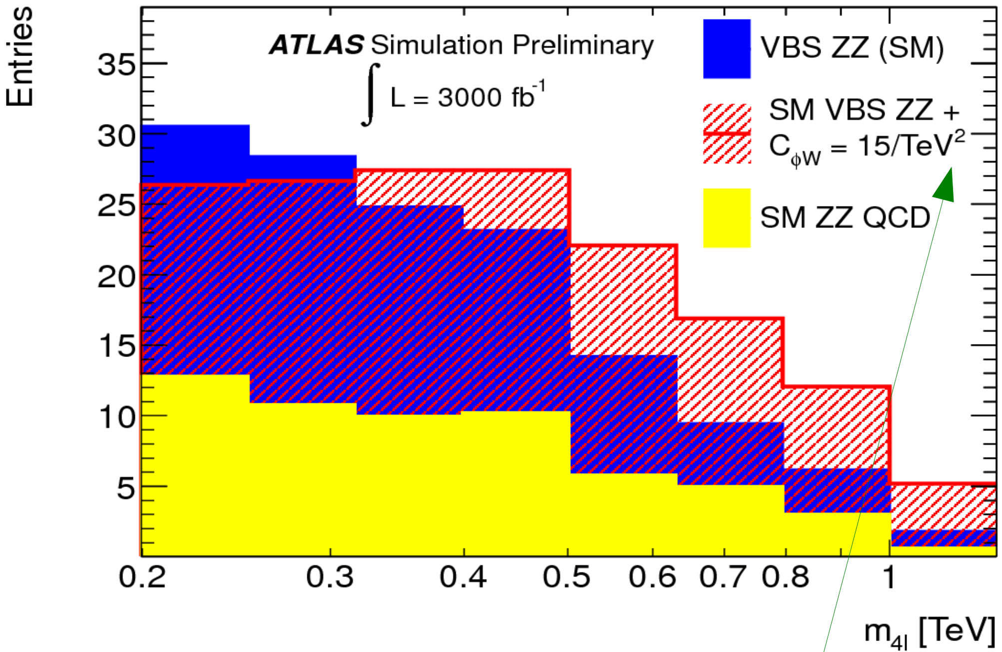
$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j$$

- 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
  - Dimension-8 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

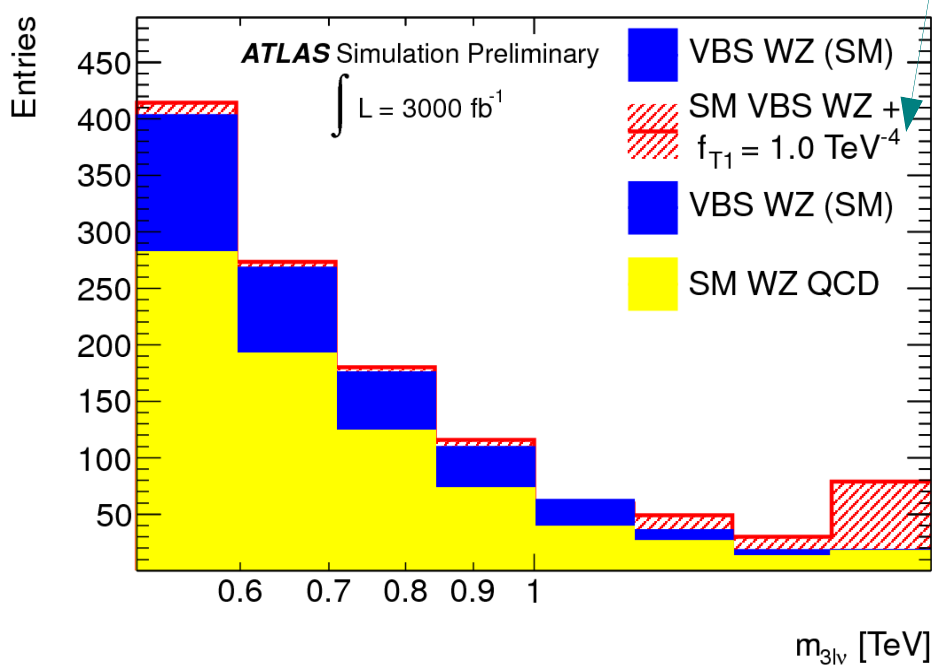
ZZ → leptons



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

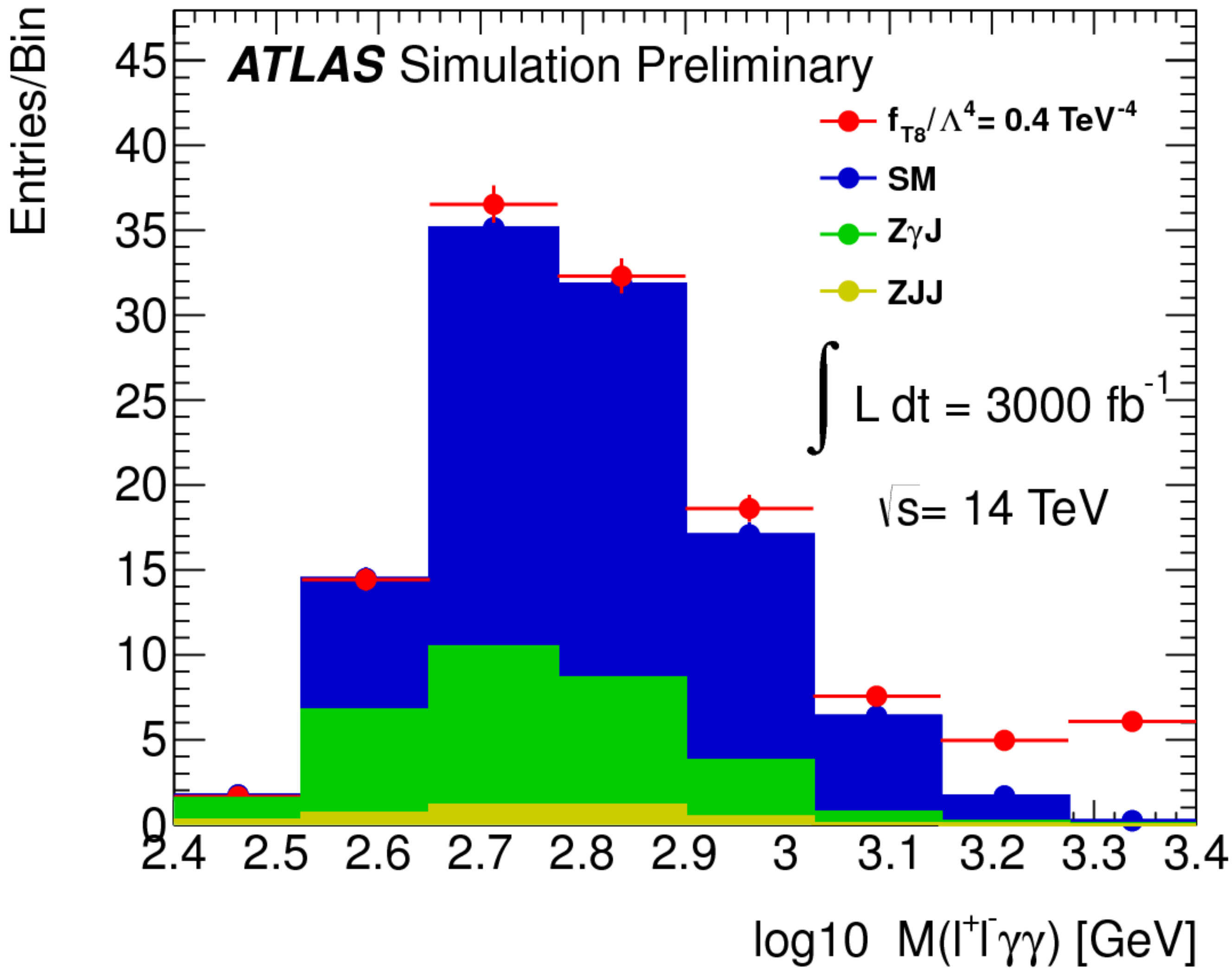
dim-8 operator coefficient implies sensitivity to strong dynamics at TeV-scale

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 HL-LHC upgrade

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}

$$O_{\phi d} = \frac{c_{\phi d}}{M_S^2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)$$

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

VBS and Tribosons at 100 TeV pp Collider

Parameter	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	pileup	5σ [TeV^{-4}]	95% CL [TeV^{-4}]
$f_{T,1}/\Lambda^4$	14	300	50	0.2 (0.4)	0.1 (0.2)
$f_{T,1}/\Lambda^4$	14	3000	140	0.1 (0.2)	0.06 (0.1)
$f_{T,1}/\Lambda^4$	14	3000	0	0.1 (0.2)	0.06 (0.1)
$f_{T,1}/\Lambda^4$	100	1000	40	0.001 (0.001)	0.0004 (0.0004)
$f_{T,1}/\Lambda^4$	100	3000	263	0.001 (0.001)	0.0008 (0.0008)
$f_{T,1}/\Lambda^4$	100	3000	0	0.001 (0.001)	0.0008 (0.0008)

Table 1-25. *In $pp \to W^{\pm}W^{\pm} + 2j \to \ell\nu\ell\nu + 2j$ processes, 5σ-significance discovery values and 95% CL limits are shown for coefficients the higher-dimension operator, $f_{T,1}/\Lambda^4$, for different machine scenarios without the UV cut and with the UV cut in parenthesis. Pileup refers to the number of pp interactions per crossing.*

Parameter	dim.	Luminosity [fb^{-1}]	14 TeV	33 TeV	100 TeV
c_{WWW}/Λ^2 [TeV^{-2}]	6	300	4.8 (8)	-	-
		1000	-	-	1.3 (1.5)
		3000	2.3 (2.5)	1.7 (2.0)	0.9 (1.0)
$f_{T,0}/\Lambda^4$ [TeV^{-4}]	8	300	1.2	-	-
		1000	-	-	0.004
		3000	0.6	0.05	0.002

Table 1-26. *In the $pp \to WWW \to 3\ell + 3\nu$ process, the 5σ-significance discovery values are shown for the coefficients of higher order operators. The values in parentheses are obtained with the UV bound applied. pp colliders at $\sqrt{s} = 14$, 33 and 100 TeV are studied.*

VBS and Tribosons at 100 TeV *pp* Collider

Conclusion:

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

Dimension-8 operators are probed much more strongly than dimension-6 operators (due to stronger growth of amplitude with energy)

For dimension-8 operator coefficients of order ~ 1:

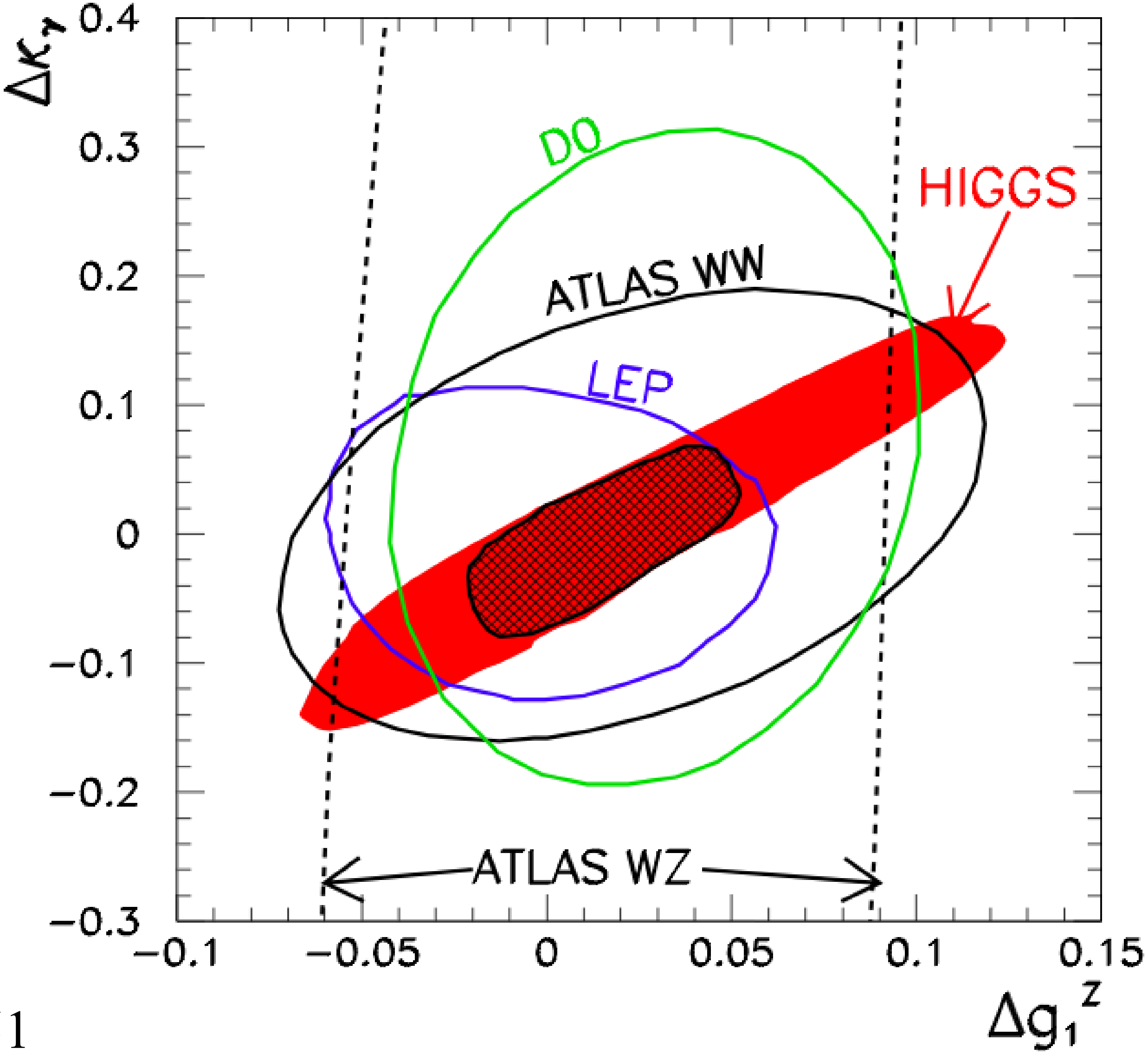
LHC probes energy scale $\Lambda \sim 1.6$ TeV

VLHC probes $\Lambda \sim 6$ TeV (with 3/ab)

LHC probes dimension-8 operators much more sensitively than ILC

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

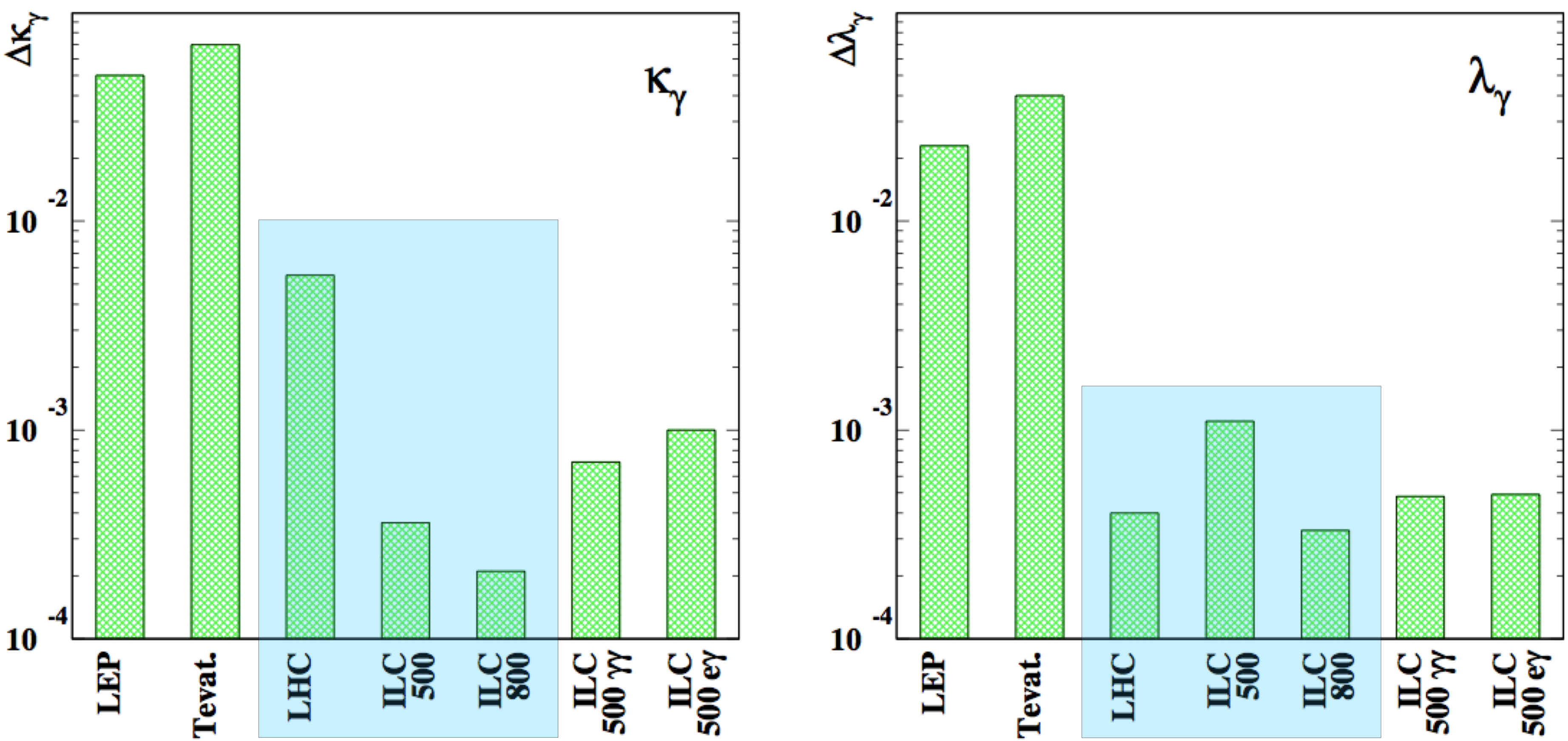


Figure 1-22. *Comparison of $\Delta\kappa_\gamma$ and $\Delta\lambda_\gamma$ at different machines. For LHC and ILC three years of running are assumed (LHC: 300 fb^{-1}, ILC $\sqrt{s}$ = 500 GeV: 500 fb^{-1}, ILC $\sqrt{s}$ = 800 GeV: 1000 fb^{-1}). If available the results from multi-parameter fits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

Generally, ILC 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 3-4 higher precision than ILC/GigaZ possible including systematics
  - Near-term: Tevatron and LHC pushing towards ΔM_W ~ 10 MeV and 5 MeV respectively

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.

Conclusions

- 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
- ILC1000 vs LHC sensitivity to higher-dimension operators in VBS and multi-boson production
  - ILC more sensitive to dimension-6 operators through diboson production (clean environment, sensitivity through interference with SM)
  - LHC more sensitive (by 1-2 orders of magnitude) to dimension-8 operators compared to ILC1000, as probed by VBS and triboson production

Conclusions

- For the next decade, the LHC will continue to be the facility to explore these processes at higher levels of precision.
- The LHC will improve the sensitivity to anomalous trilinear gauge couplings by 1-2 orders of magnitude beyond LEP and the Tevatron.
- The HL-LHC is needed to demonstrate that the Higgs couplings to the electroweak vector bosons is an essential component of the unitarization mechanism for vector boson scattering. An integrated luminosity of 300 fb^{-1} is not enough.
- The sensitivity to higher-dimension operators improves by a factor of 2-3 with the HL-LHC, in comparison with the 300 fb^{-1} at the LHC.
- Triboson production and vector boson scattering are sensitive and complementary probes of dimension-8 operators. These processes becomes rapidly more sensitive with increasing beam energy, providing strong motivation for a 100 TeV pp collider.
- Anomalous trilinear gauge couplings, which are induced by dimension-6 operators, are significantly better probed by the high-energy ILC options compared to the LHC. On the other hand, anomalous quartic gauge couplings, which are induced by dimension-8 operators, are significantly better probed (by 1-2 orders of magnitude) by the LHC, due to the stronger growth of the anomalous cross section with energy. Interpreting the latter as being induced by electroweak resonances, the LHC is sensitive to resonance masses that are higher by more than a factor of two, as compared to ILC1000.

THANK YOU

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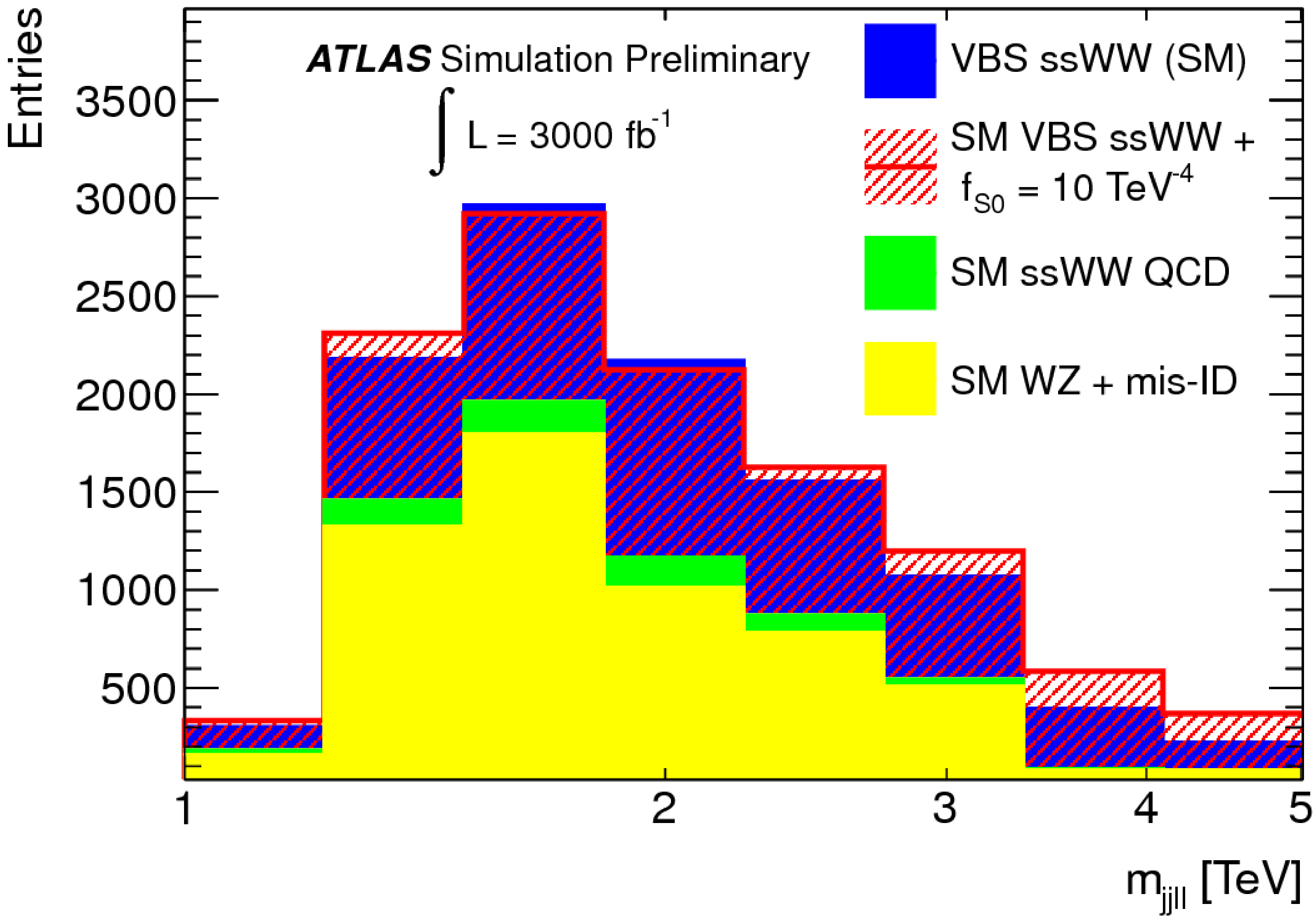
Electroweak Report posted at:

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

and arXiv:1310.6708

VBS Study using same-sign WW → leptons



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