Collider Physics III: Beyond the Higgs Boson

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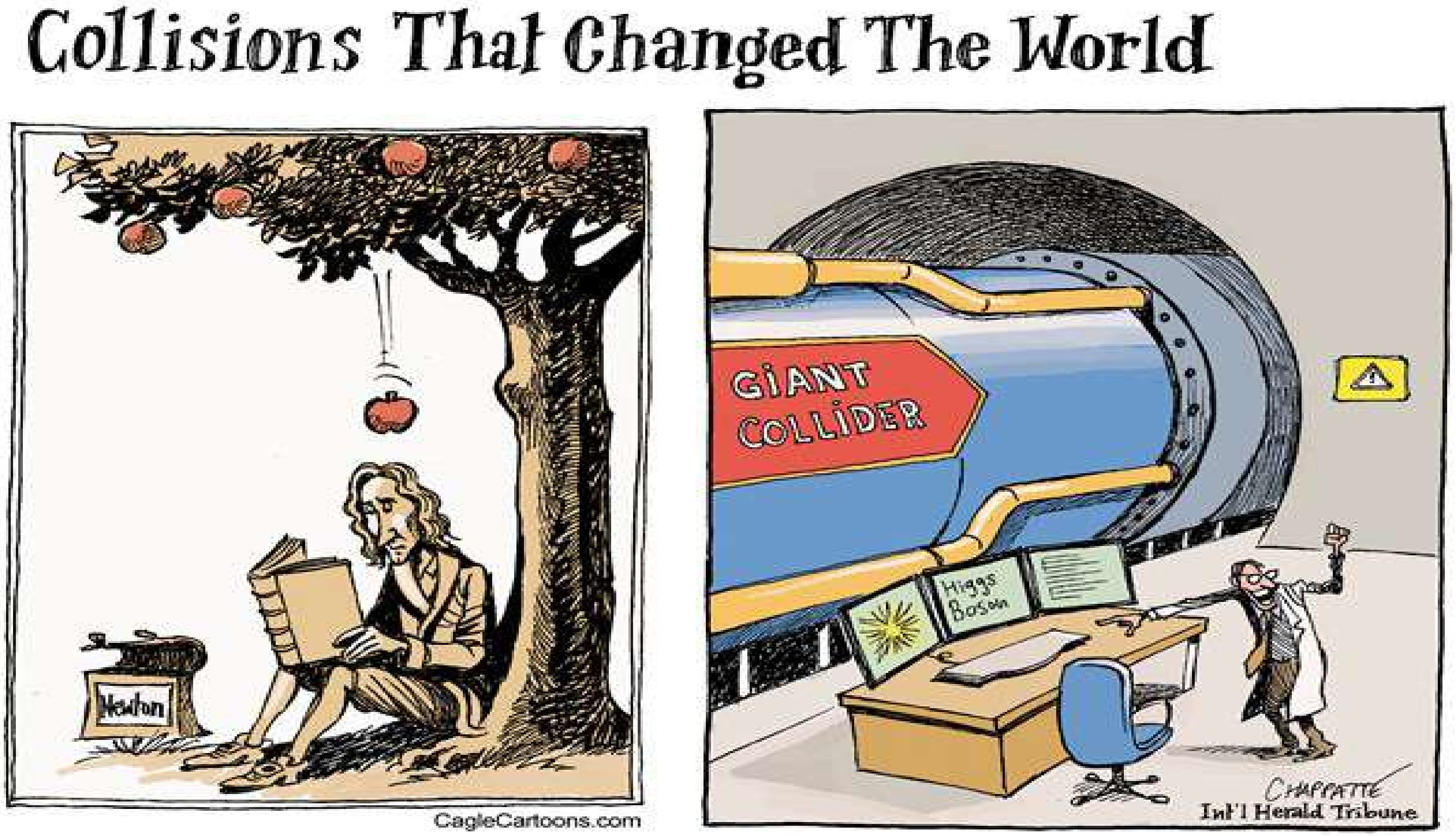


TIFR
September 26, 2023

Spontaneous Symmetry Breaking

- 2008 Nobel Prize in Physics

  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

Yoichiro Nambu

- How to think of the vacuum as an “electroweak condensed state” ?

Spontaneous Symmetry Breaking

- Is the mechanism of Electroweak Symmetry Breaking, the Standard Model Higgs mechanism?

Origin of the Higgs Concept

- Prediction of “forces” based on the idea of gauge invariance in Quantum Field Theory
  - Ψ → ∫$^{EB\xi(Y)}$ Ψ (B∈PB∫ IΞKOΛΞ ∈IΞΛK ΛΛ∫Ξ ΕΛK €∫Θ∫)
- ∂KIΞΛ∫PUIΞΛK ΛΛ∈Σ∫ UΛΞMΛΠ∫ KIΞΘA_μ (∈.H.∈. B∈PB∫ €∫Θ∫)
  - $\partial_\mu \Psi \rightarrow D_\mu \Psi = (\partial_\mu - i\, g\, A_\mu)\, \Psi$
  - $A_\mu \rightarrow A_\mu + \partial_\mu \xi$
- Gauge-invariant Field Strength tensor $F_{\mu\nu}$
  - $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
  - For gauge transformation in the internal space described by the (Abelian) U(1) group
- Kinetic energy associated with e.g. “electromagnetic field”
  - $F_{\mu\nu} F^{\mu\nu}$

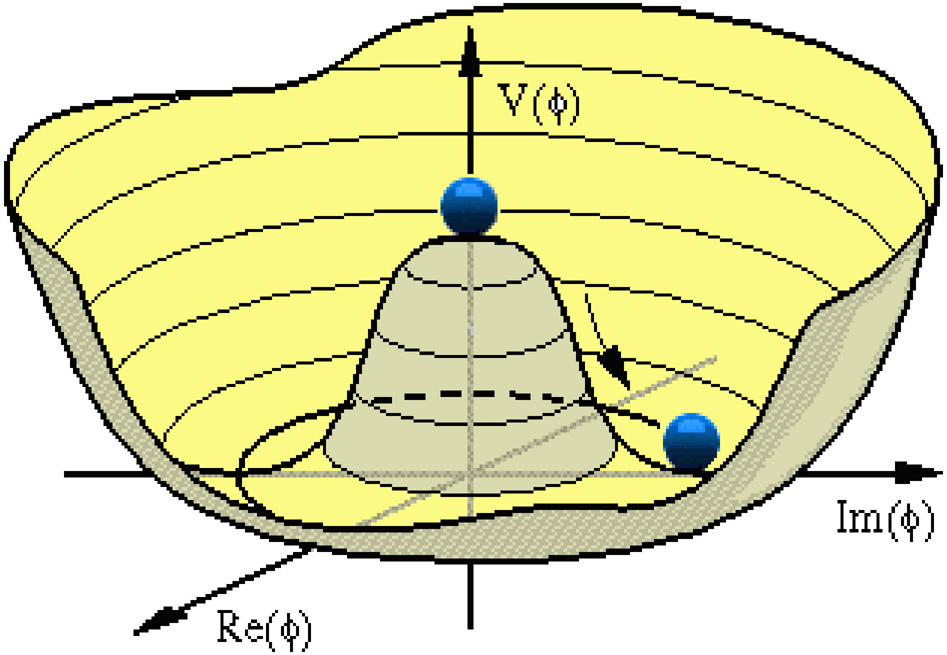
Origin of the Higgs Concept

- Quantum of gauge field must remain massless to preserve gauge invariance
  - – ∫ ∈ΟΟΙΠϑΞ $I^{2} A_{\mu} A^{\mu}$ ΜΕΛΓΕΠΕϑ ⌠
- ΔΙΞΕΛΚΒ ΜΕϑ ⌠ΕΙΙΕΛΚ ∪ΛΚ∈Ξ ϑ ⌠ ϑΥΜϑΞΕ ϑΚΙΘΦΛΞϑΘ∪ΞΛΙ ∈ΒΚϑΙΞΙ
- But fails spectacularly for the weak force mediated by *W* and *Z* bosons, which have masses of ~80 GeV and ~90 GeV respectively

- Ideas from Laudau, Ginzburg, Anderson, Nambu, Goldstone, Englert, Brout, Higgs, Kibble, Guralnik, Hagan, Salam, Weinberg, Glashow...
  - Introduce a new scalar field ϕ (ΙΙΓϑ |μΕΒΒΟ|∈ϑΘ⌠) with appropriate quantum numbers under the $SU(2)_L$ and $U(1)_Y$ gauge groups
  - Introduce an ad-hoc non-linear potential $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$

Spontaneous Symmetry Breaking of Gauge Symmetry

- postulate of scalar Higgs field which develops a vacuum expectation value via spontaneous symmetry breaking (SSB)



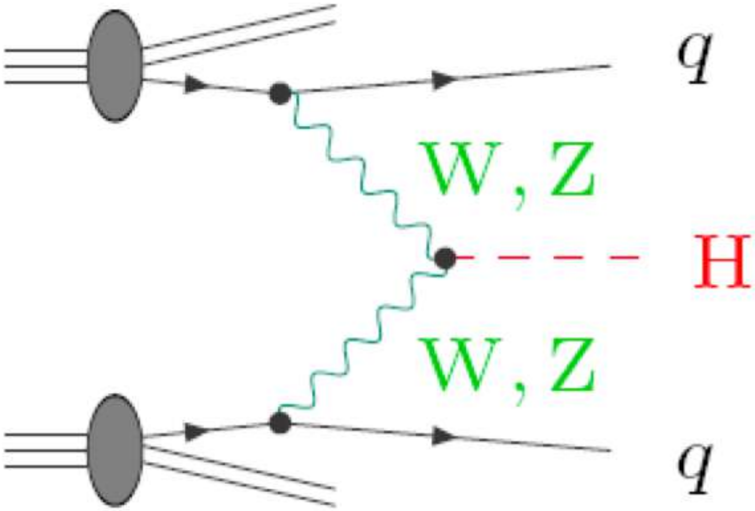
- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state
- Renormalizability of QFT with SSB of non-Abelian Gauge Symmetry proven by 't Hooft and Veltman

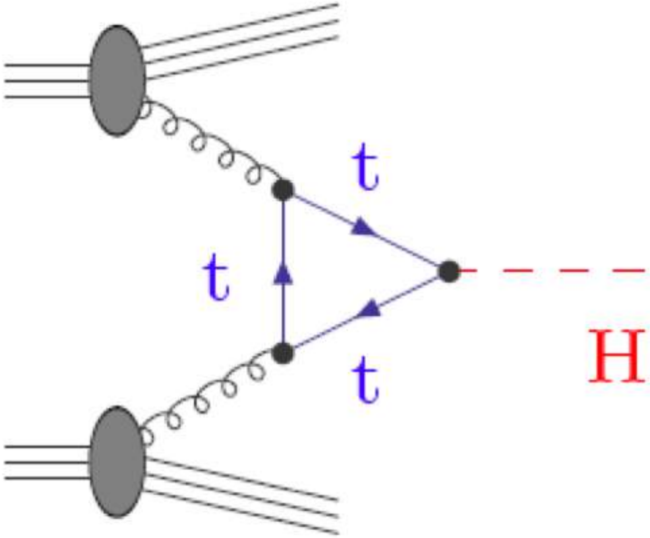
Some Key Features of Electroweak Standard Model

- Gauge groups are $SU(2)_L$ and $U(1)_Y$ (Glashow)
- Fermions are in the fundamental representations of these groups
- Higgs vacuum expectation value (v) breaks $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$ (Weinberg, Salam)
- Efficient solution for generating mass terms for electroweak gauge bosons ...
  - Higgs kinetic energy term $(D_\mu \varphi)^2$ contains $g^2 W_\mu W^\mu \varphi^2$ term
  - After SSB, $W_\mu W^\mu \varphi^2 \rightarrow W_\mu W^\mu v^2 + \ldots$ generating gauge boson mass terms with mass $\sim gv$
- …AND fermions
  - $y \varphi \Psi_L \Psi_R \rightarrow y v \Psi_L \Psi_R + \ldots$ after SSB, where y is an ad-hoc "Yukawa" dimensionless parameter and $yv \sim$ fermion mass

Some Key Properties of Electroweak Standard Model

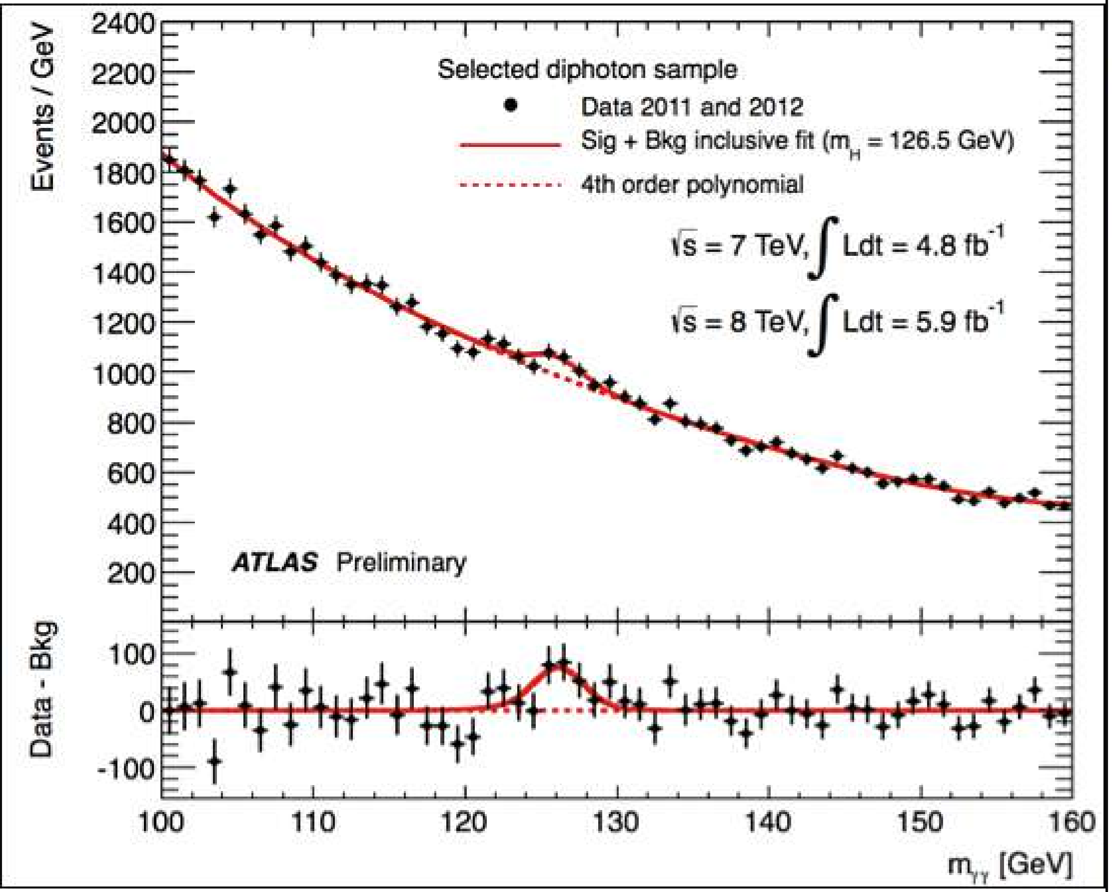
- Electroweak boson couplings to the Higgs field excitations are specified:
  - eg. $(D_\mu \varphi)^2$ contains $g^2\, W_\mu W^\mu \varphi^2$ term → $g^2\, W_\mu W^\mu (v+h)^2$
  - Quanta of the "radial" excitation *h* are the Higgs bosons



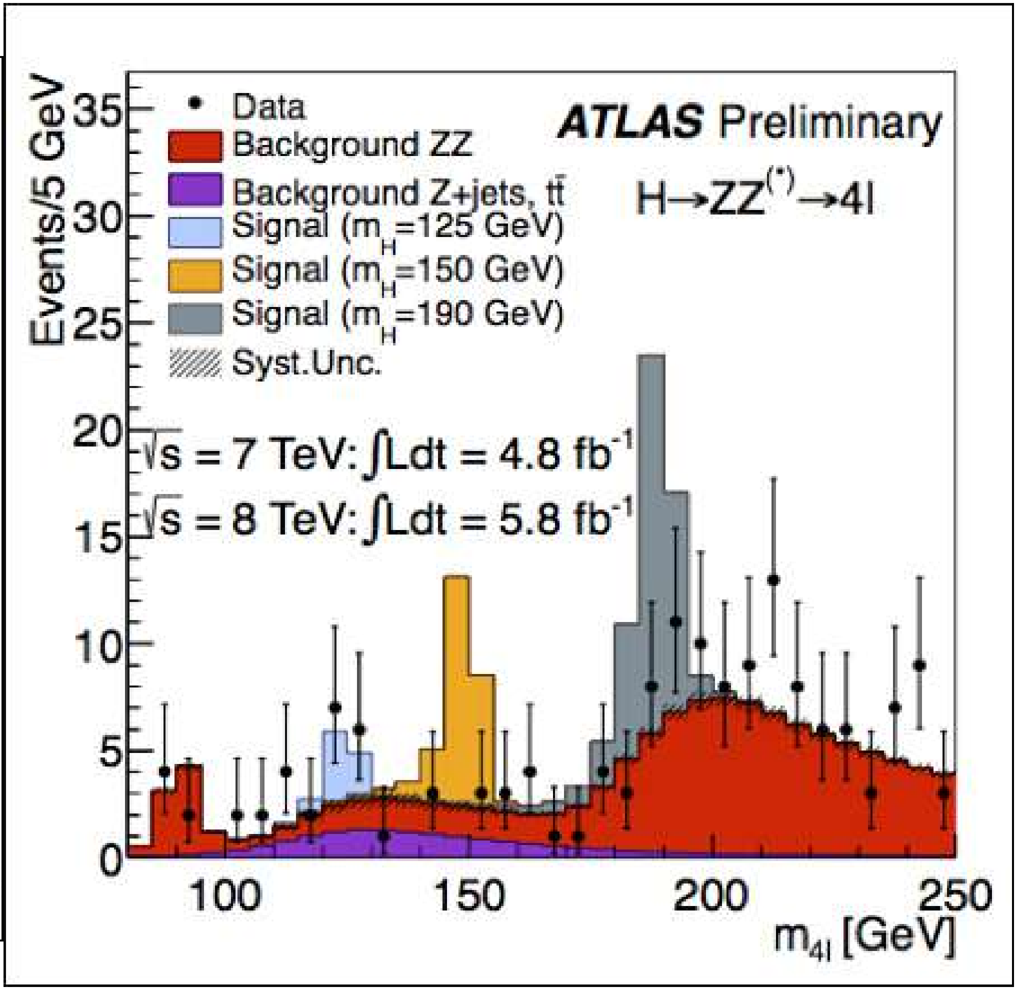


- Fermions' Yukawa couplings to Higgs boson *h* are proportional to fermion mass
  - $y\, \varphi\, \Psi_L \Psi_R \rightarrow y\, v\, \Psi_L \Psi_R + y\, h\, \Psi_L \Psi_R$

Higgs Discovery Plots from ATLAS

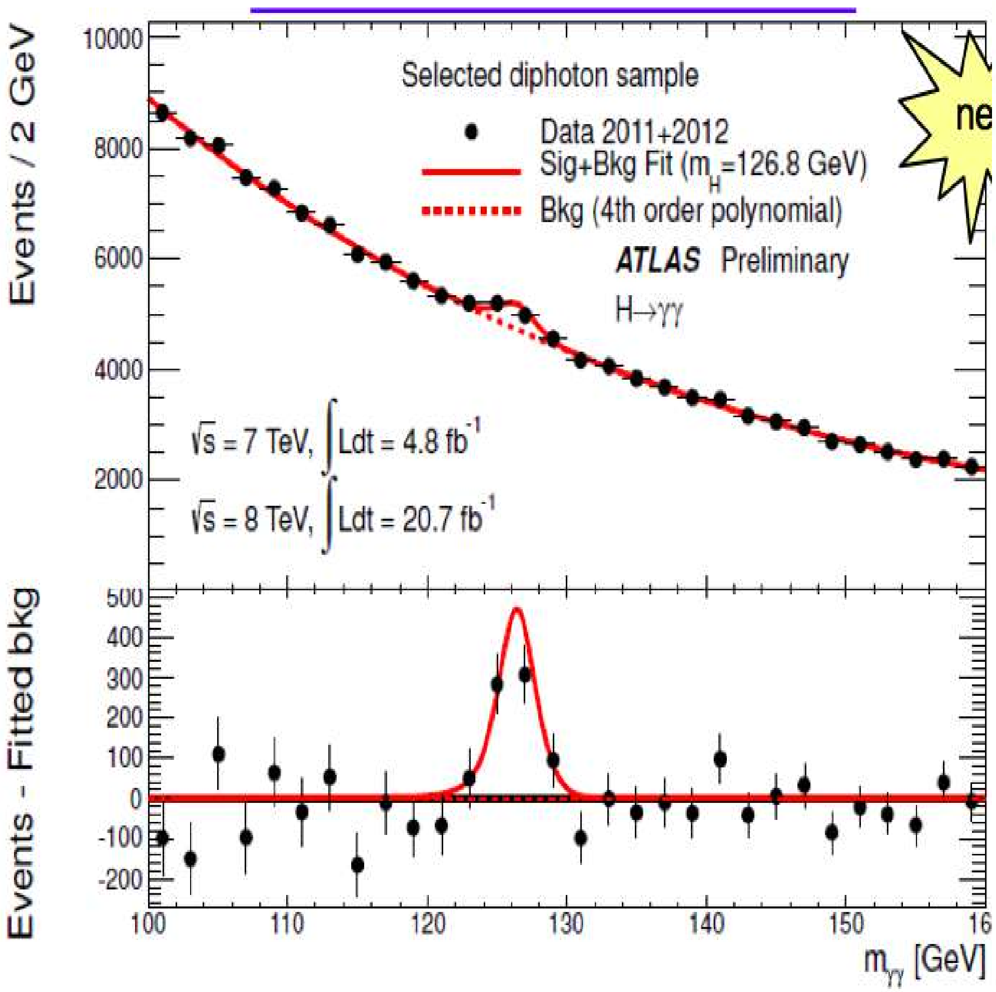


Higgs → γγ

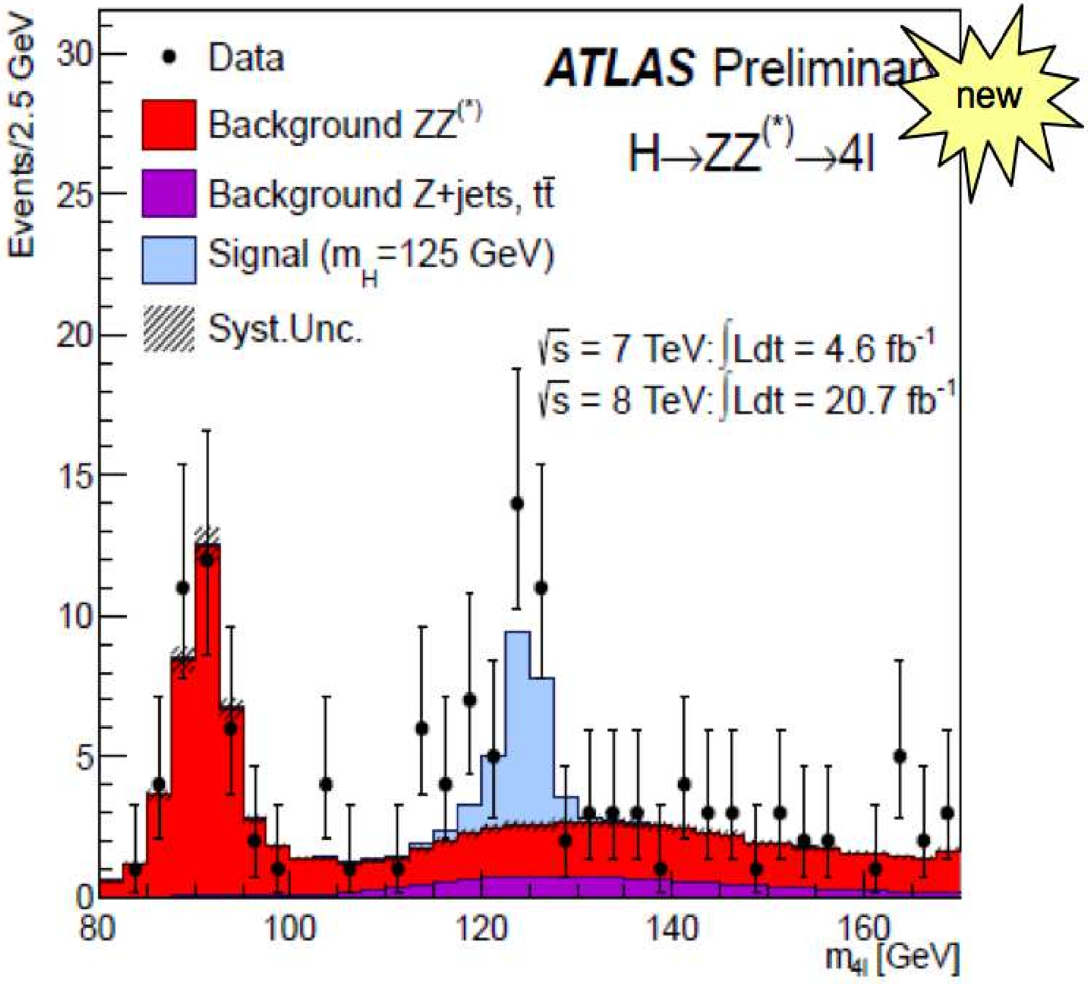


Higgs → *ZZ*

Higher-Significance Higgs Signal Plots from ATLAS



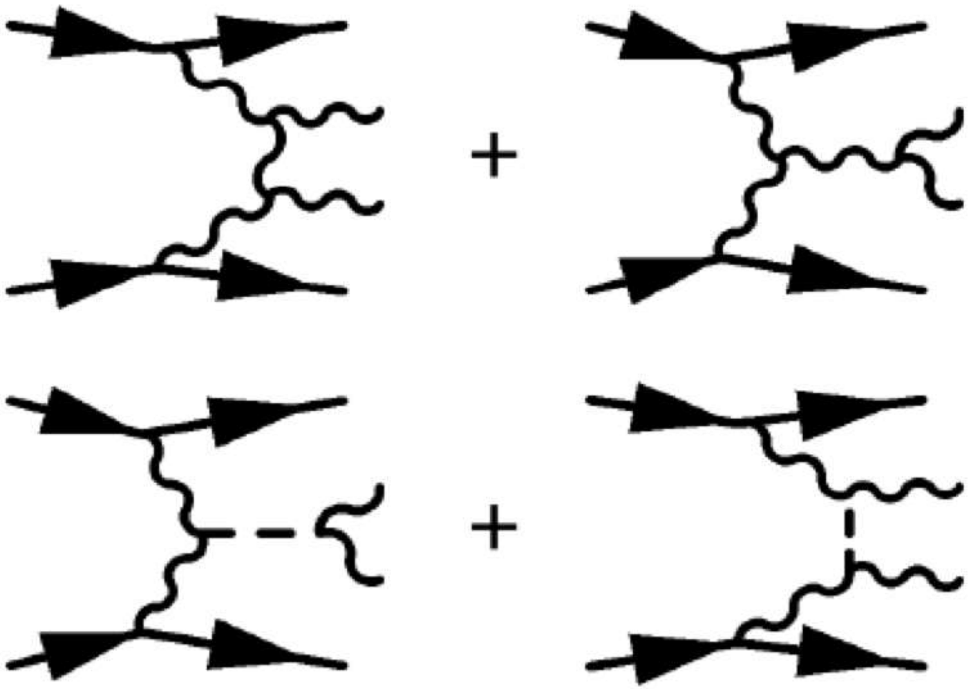
Higgs → γγ



Higgs → *ZZ*

Higgs Boson Properties to be Measured (Precisely)

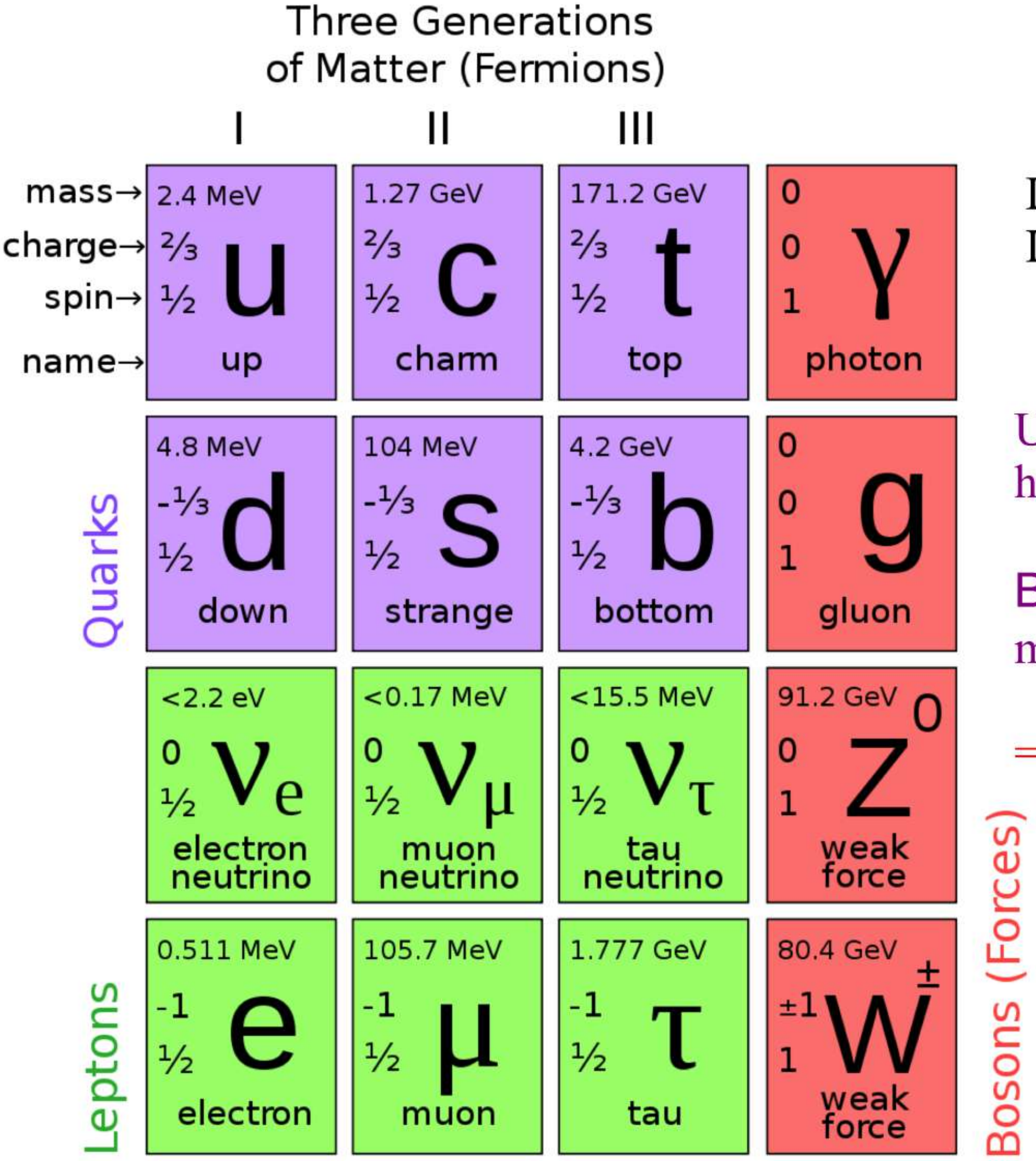
- Higgs boson spin & parity $J^P = 0^+$ by measuring decay angular distributions
- Measure all couplings as precisely as possible to test Standard Model
- To be confirmed that longitudinally-polarized vector boson scattering amplitudes do not violate tree-level unitarity



Without diagrams involving Higgs Bosons, tree-level unitary violated above ~1 TeV in vector-boson center-of-mass energy

Is SM Higgs enough?

Some open questions



Three Generations of Matter (Fermions)

	I	II	III	
mass→ charge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon
Quarks	4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon
	<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
Leptons	0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^{\pm}$ weak force

Bosons (Forces)

Large range of fermion masses →
Large range of Yukawa couplings

Up-type and down-type fermions have different quantum numbers...

But ϕ and $\phi^\dagger$ have the appropriately matching quantum numbers

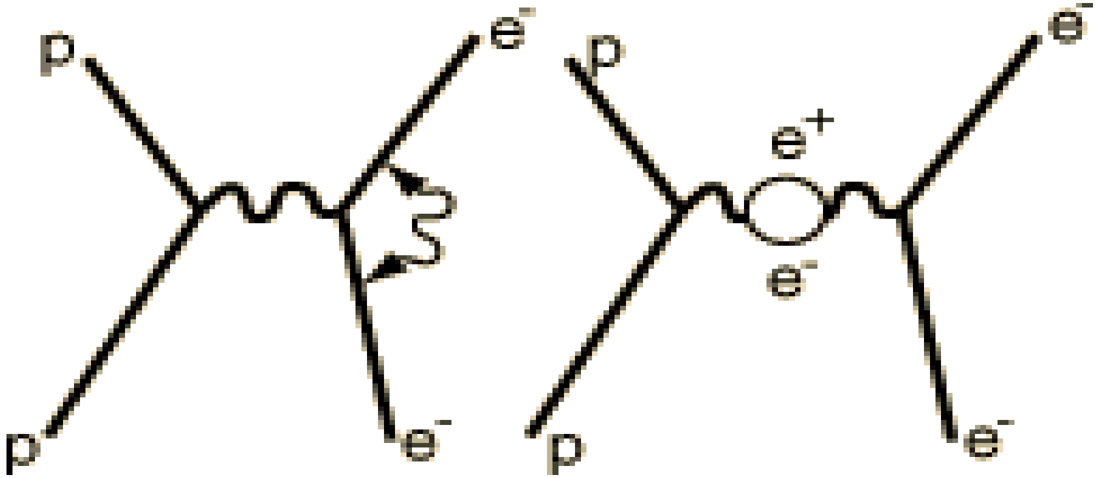
=> single Higgs field suffices in SM

What if two separate Higgs fields were used for up-type and down-type fermions ?

Ratio of vacuum expectation Values ~ *t*/*b*, *c*/*s* mass ratio
=> Two-Higgs Doublet Model

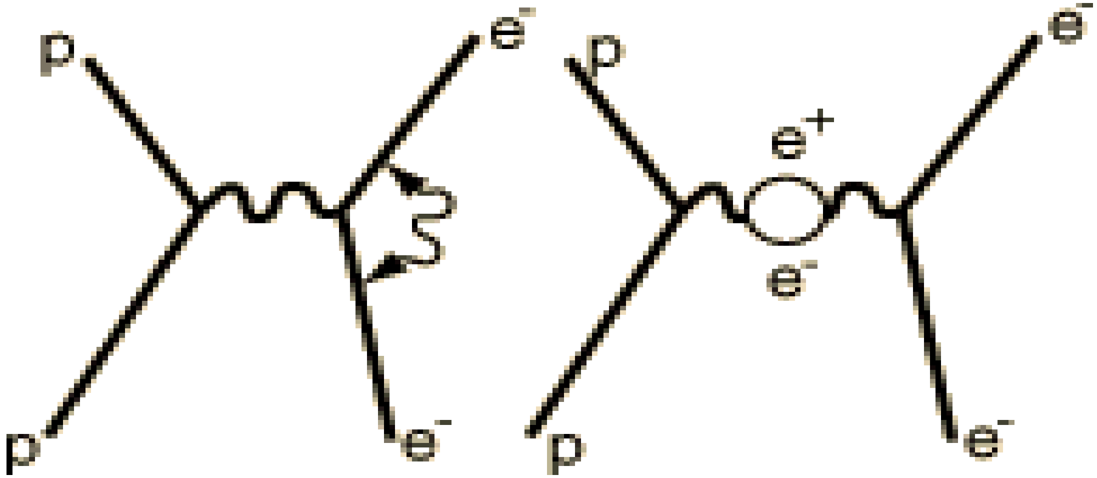
Importance of Quantum Loops

Importance of Quantum Loops – Example I



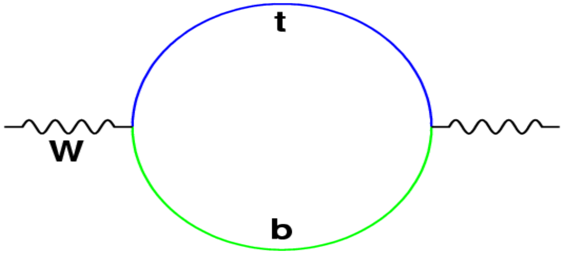
Importance of Quantum Loops – Example I

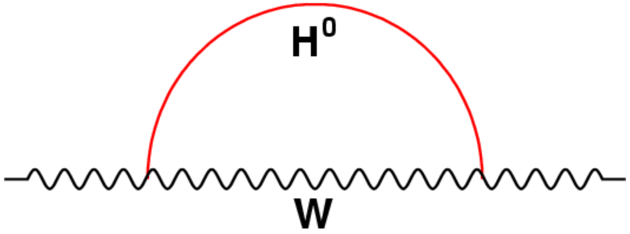
- Willis Lamb (Nobel Prize 1955) measured the difference between energies of $^2S_{1/2}$ and $^2P_{1/2}$ states of hydrogen atom
  - 4 micro electron volts difference compared to few electron volts binding energy
  - States should be degenerate in energy according to tree-level calculation
- Harbinger of vacuum fluctuations to be calculated by Feynman diagrams containing quantum loops
  - Modern quantum field theory of electrodynamics followed (Nobel Prize 1965 for Schwinger, Feynman, Tomonaga)

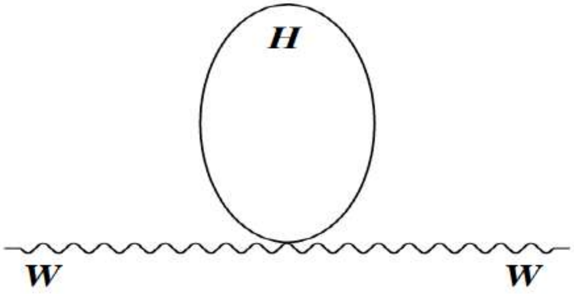


Test of Quantum Loops at High Energy – Example II

- W boson mass: radiative corrections due to heavy quark and Higgs loops







Motivate the introduction of the ρ parameter: $M_W^2 = \rho\ [M_W(\text{tree})]^2$

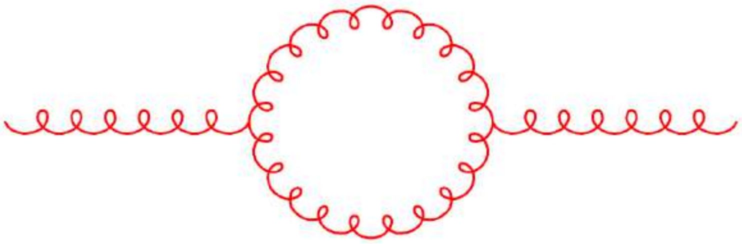
with the predictions $\Delta\rho = (\rho 21)\ \gamma \int\ _{\text{top}}^{2}$ and $\Delta\rho\ \gamma\ \ln M_H$

- The top quark mass, the W boson mass and the mass of the Higgs boson provides a stringent test of the standard model at loop level

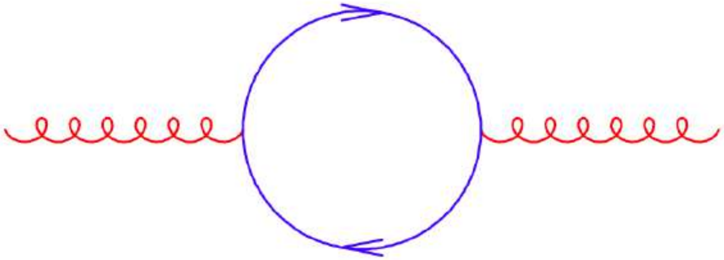
Example III - Asymptotic Freedom in QCD

QCD Lagrangian with no dimensionful parameters should be scale-invariant

BUT quantum loops induce a distance (or momentum) scale dependence !



Color-charge *anti-screening* due to quark loops



Color-charge screening due to quark loops

Running of coupling constant induces an energy scale Λ ~ 0.2 GeV where coupling becomes large

$$\alpha_s = \frac{6\pi}{(33 - 2N_f)\ln(\mu/\Lambda)}$$

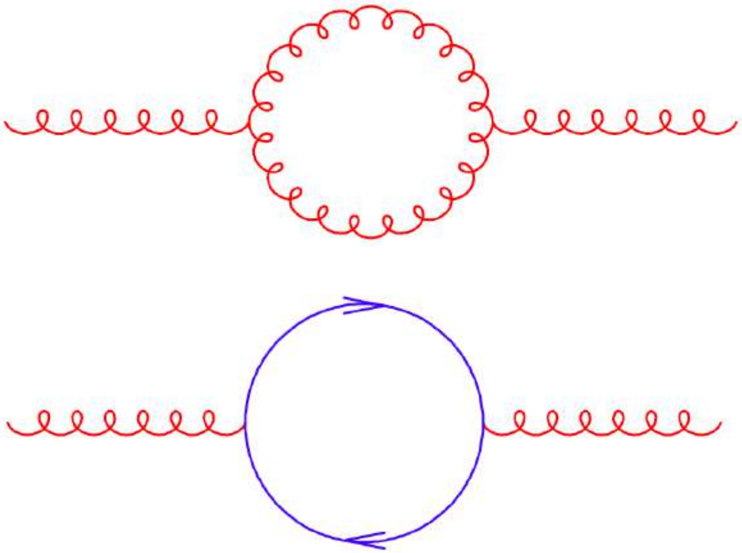
N_f = Number of quark flavors

$\alpha_\Delta \rightarrow 0$ as $\mu \rightarrow \infty$: asymptotic freedom

(2004 Nobel Prize for Gross, Wilczek, Politzer)

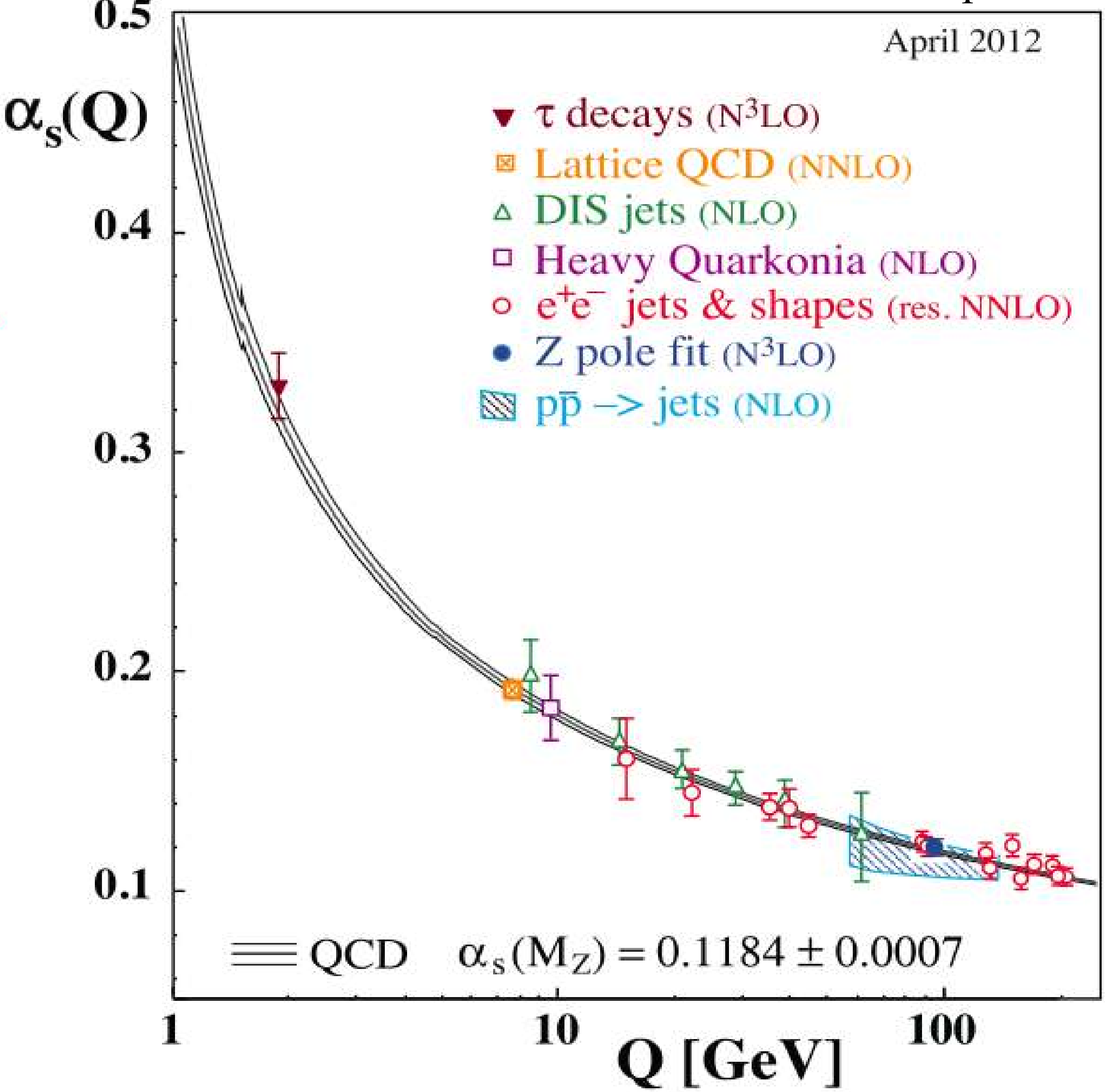
Example III - Test of QCD Quantum Loops at High Energy

QCD Lagrangian with no dimensionful parameters



Running of strong coupling has been confirmed experimentally

From Particle Data Group review

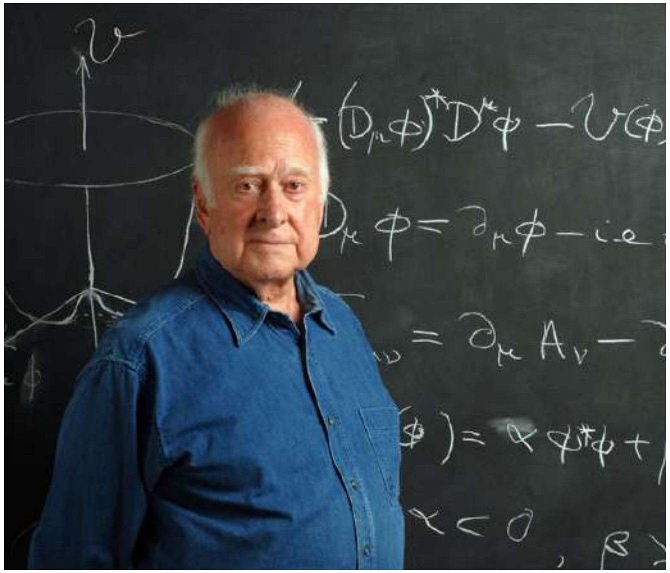


Particle Physics after Higgs Boson – Higgs loops

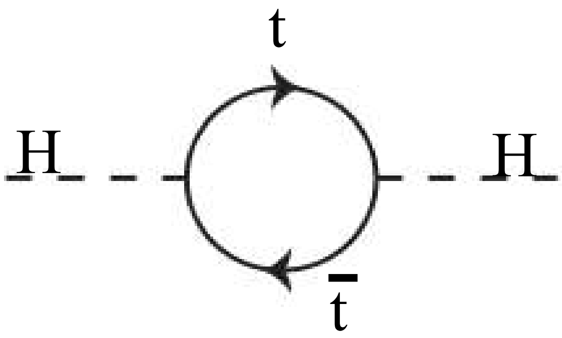
- What does the discovery of the Higgs boson imply for the next big questions in particle physics?

- Higgs mechanism solves the problem of electroweak symmetry breaking in a self-consistent and efficient manner.....

- But it creates a new problem
  - Quantum radiative corrections to the Higgs boson mass are very large and uncontrolled....
  - a worrisome side-effect that cannot be resolved within the quantum field theory containing only the Higgs field

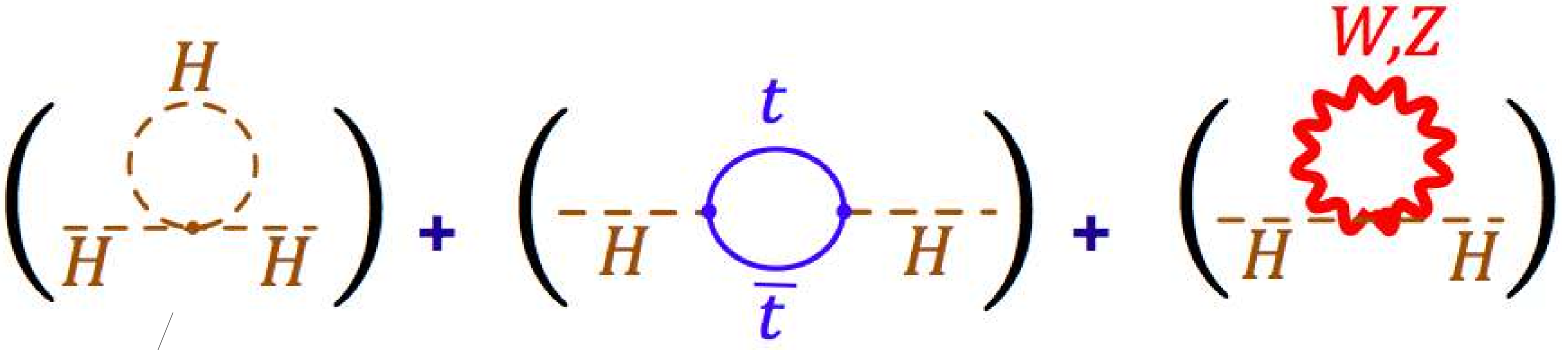


Peter Higgs



Why is the Higgs Boson so Light?

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



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

For the first time, we have additive corrections to parameters which are quadratically divergent

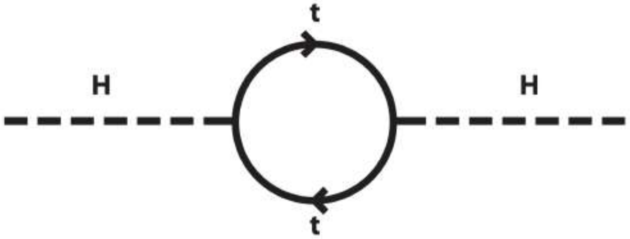
The Higgs boson ought to be a very heavy particle, naturally

However, observed $m_H << \Lambda$

Fine-tuning Problem of Higgs Boson Mass

- The divergent integral in this quantum loop must be regulated by a high-momentum cutoff, Λ, which could be the gravitational Planck energy scale $M_{planck} \sim 10^{19}$ GeV
  - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop

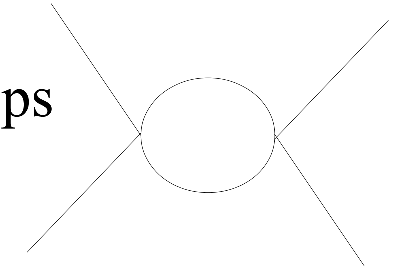


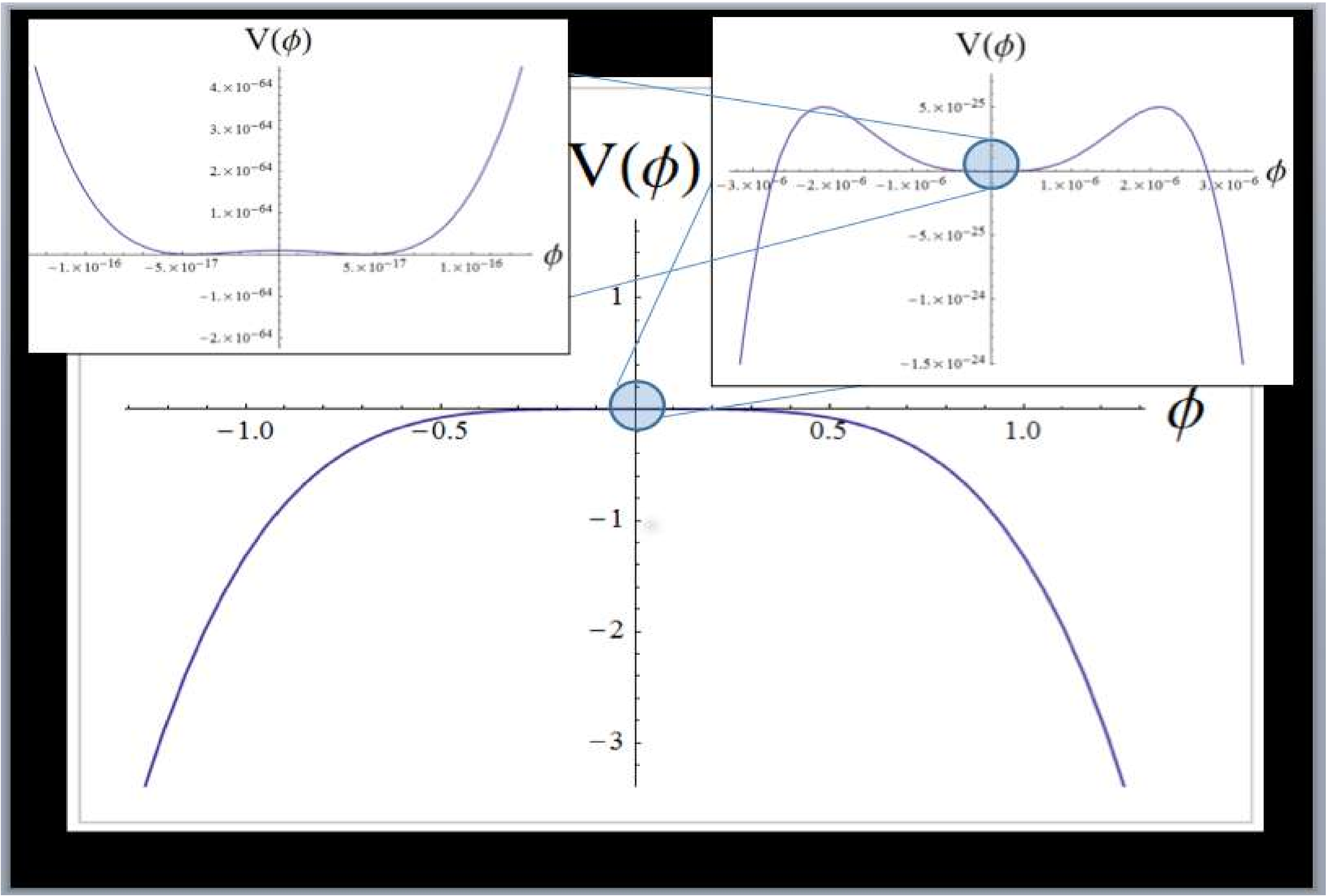
- physical Higgs boson mass ~ 125 GeV

- Therefore need extreme "fine-tuning" of bare lagrangian parameters at high energy

Radiative Corrections to Higgs Self-Coupling

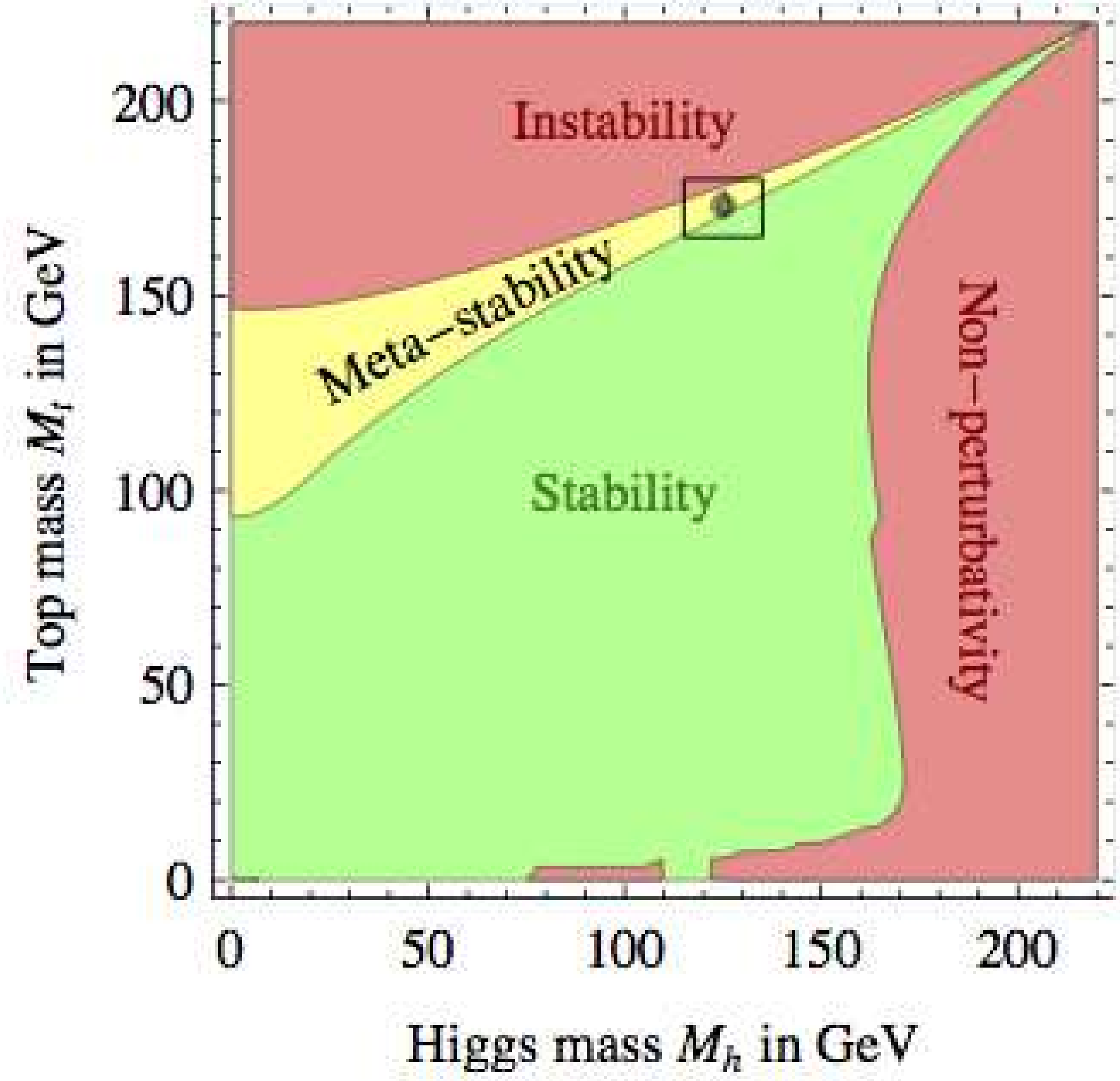
- $\lambda|\phi|^4$ receives radiative corrections from Higgs and top-quark loops





(from Paul Steinhardt)

Stability of Electroweak Vacuum



Higgs boson puzzles

- First fundamental (?) scalar field to be discovered
- Spontaneous symmetry breaking by development of a VeV
  - But VeV is induced parametrically by ad-hoc Higgs potential, no dynamics
- Parameters of Higgs potential are not stable under radiative corrections
  - First time that the radiative correction to a particle mass is additive and quadratically divergent
  - Gauge boson masses are protected by gauge invariance
  - Fermion masses are protected by chiral symmetry of massless fermions

- Single scalar Higgs field is a strange beast, compared to fermions and gauge bosons
- Additional symmetries and/or dynamics strongly motivated by Higgs discovery

SuperSymmetry

- SuperSymmetry is a space-time symmetry introduced in particle physics in the 1970's

  A SuperSymmetry (SUSY) operator Q is defined by

  $$Q\,|\,j> \;=\; |\,j \pm \tfrac{1}{2}>$$

  ie. angular momentum of a quantum state is changed by ½ unit

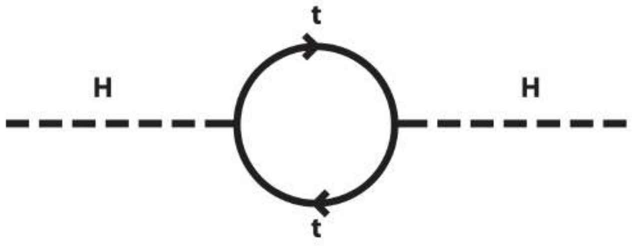
  - A (symmetry) operator linking fermions and bosons

- A minimal supersymmetric extension of the Standard Model (MSSM) has been constructed some time ago

SUSY to the Rescue

- The divergent integral in this quantum loop must be regulated by a high-momentum cutoff, Λ, which could be the gravitational Planck energy scale $M_{planck} \sim 10^{19}$ GeV
    - Loop calculation gives Higgs boson mass correction ~ M^2_{planck}

Top quark loop



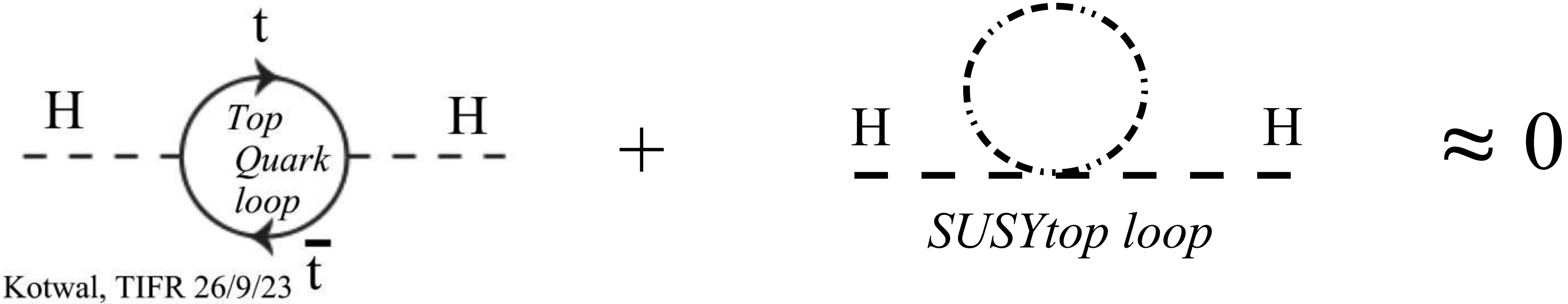
- physical Higgs boson mass ~ 125 GeV
- Therefore need extreme "fine-tuning" through renormalization

SUSY top loop

- SUSY vastly reduces fine-tuning requirement by introducing additional amplitudes containing fermion → boson loops and boson → fermion loops

SUSY to the Rescue

- SUSY adds bosonic (scalar) partners to fermions and fermionic partners to scalar and vector bosons
  - Higgs bosons ↔ Higgsino fermions
  - Top quark fermions ↔ supersymmetric top bosons
  - *W* and *Z* bosons ↔ Wino and Zino fermions
- By construction, all properties other than spin identical between super-partners
- Fermion loop with negative sign relative to boson loop, cancels exactly if SUSY was a exact symmetry
  - Eliminates uncontrolled radiative corrections in the Higgs sector

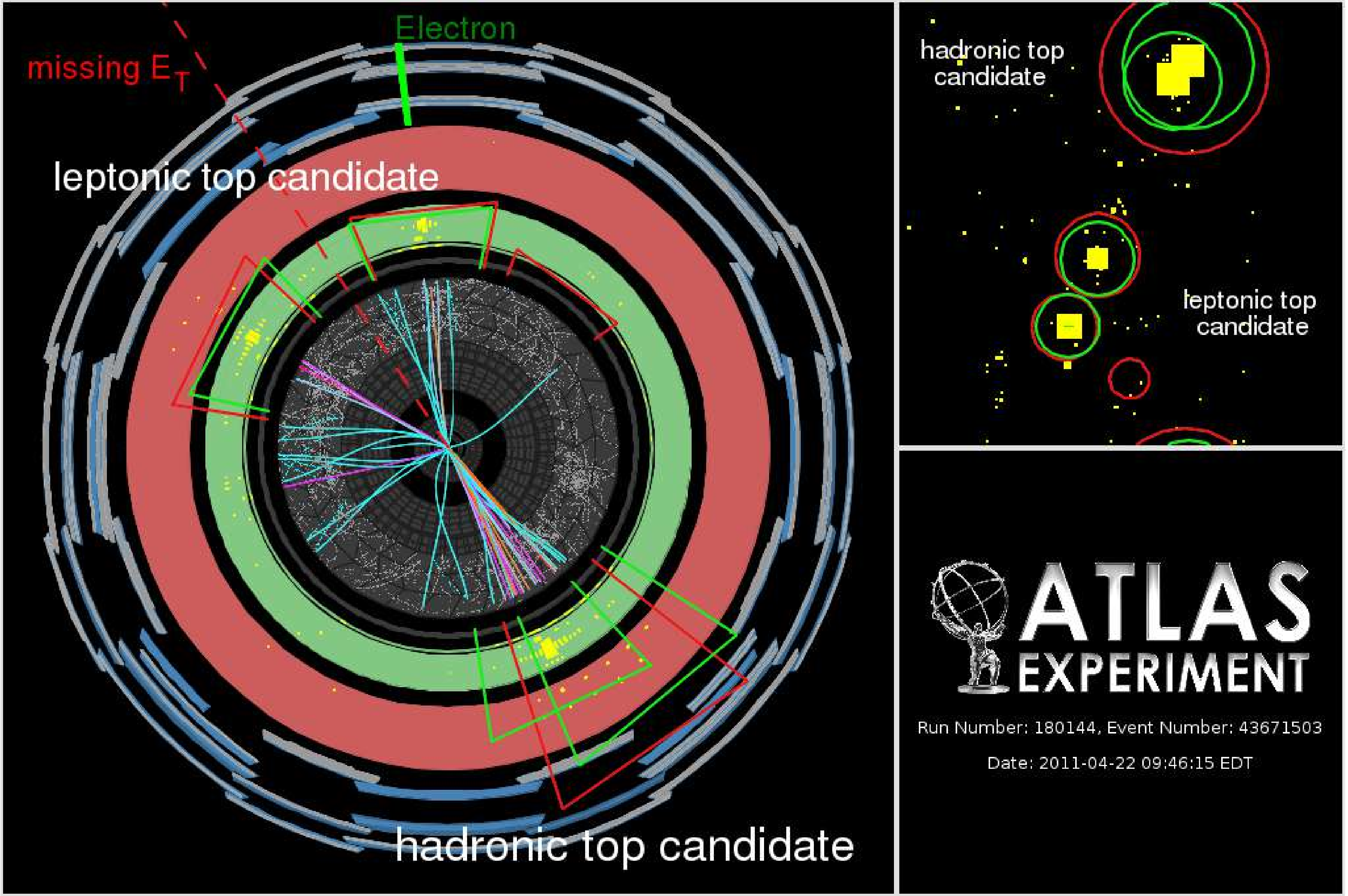


Higgs Sector of SUSY

- Standard Model trick of using ϕ and $\phi^\dagger$ to couple to up-type and down-type quarks respectively, no longer works
  - Terms containing $\phi^\dagger$ cannot respect SUSY-invariance

- MSSM is forced to introduce second Higgs field with the same quantum numbers as $\phi^\dagger$
  - Two-Higgs Doublet Model with H_u and H_d is required to build the Higgs sector in MSSM
  - Pattern of fermion masses is a mystery – may be partially explained by ratio of vacuum expectation values of H_u and H_d
  - Motivates search for additional Higgs bosons
    - $H_2 \rightarrow t\bar{t},\ b\bar{b},\ \tau\tau,\ \mu\mu$

search for heavy particles decaying to top quark pairs

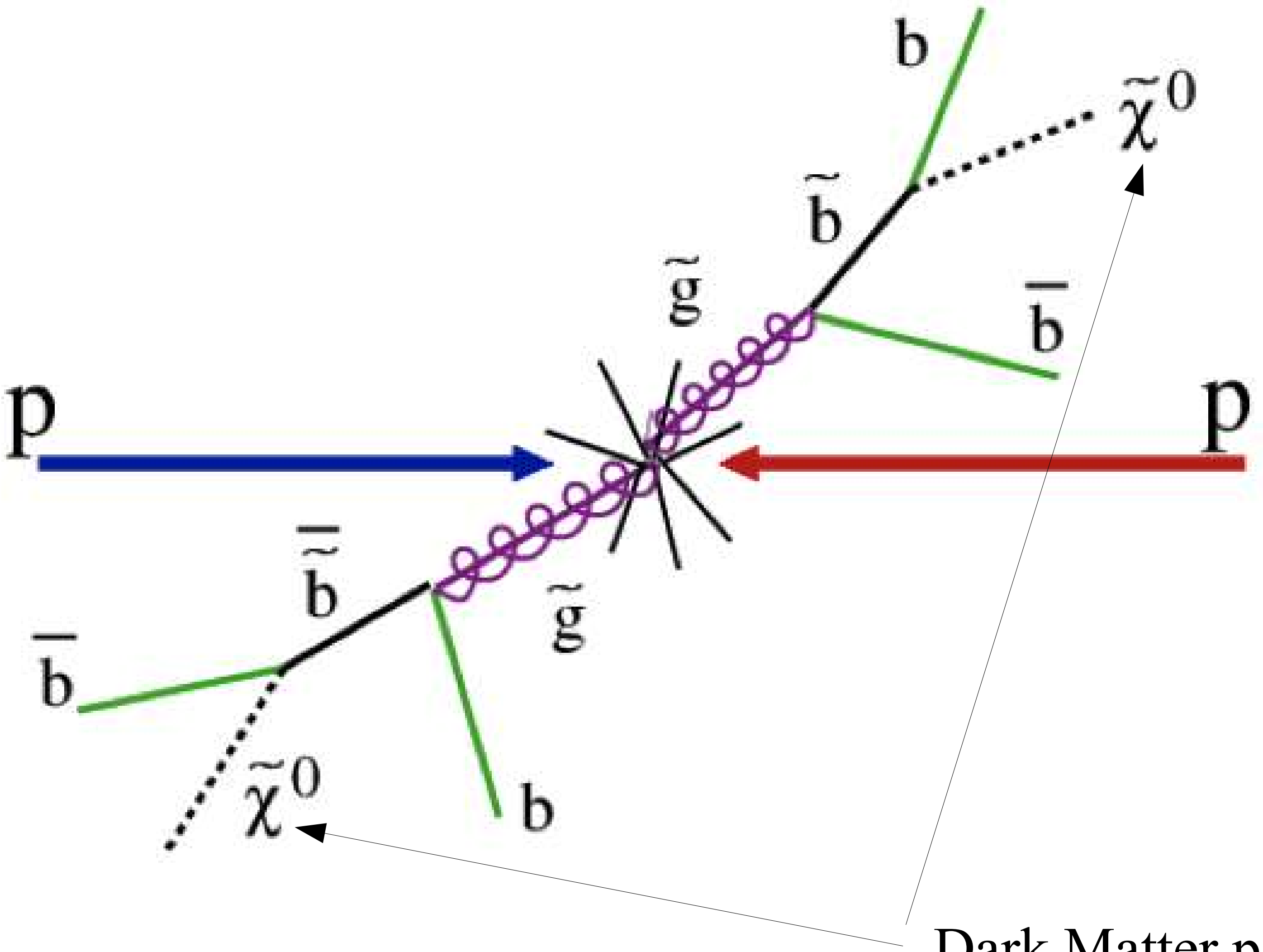


Higgs Sector of SUSY

- Standard Model trick of using ϕ and $\phi^\dagger$ to couple to up-type and down-type quarks respectively, does not work in SUSY
    - Lagrangian terms containing $\phi^\dagger$ cannot respect SUSY-invariance

- MSSM is forced to introduce second Higgs field with the same quantum numbers as $\phi^\dagger$
    - Two-Higgs Doublet Model with H_u and H_d is required to build the Higgs sector in MSSM
    - Pattern of fermion masses is a mystery – may be partially explained by ratio of vacuum expectation values of H_u and H_d
    - Motivates search for additional Higgs bosons, e.g. $H_2 \to t\overline{t}$
    - Observed Higgs would be mixture of H_u and H_d => Partial unitarization of vector boson scattering by the light Higgs
        - Search for anomalous vector boson scattering

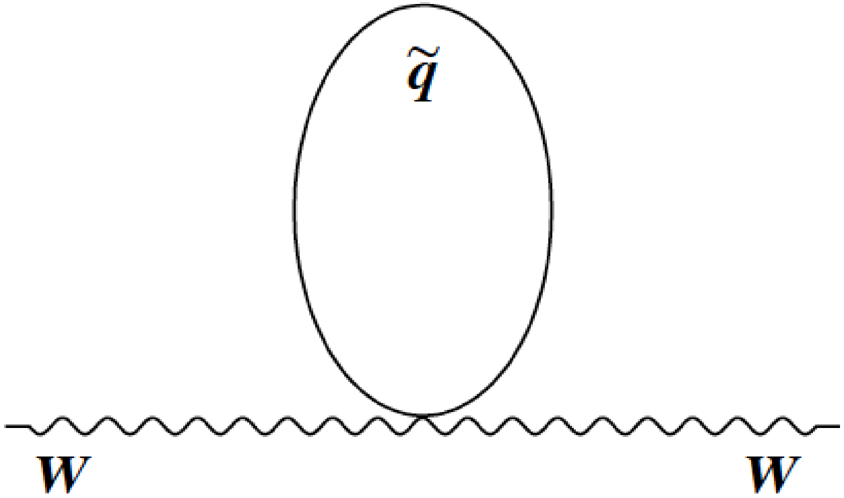
Production of SUSY Particles at LHC

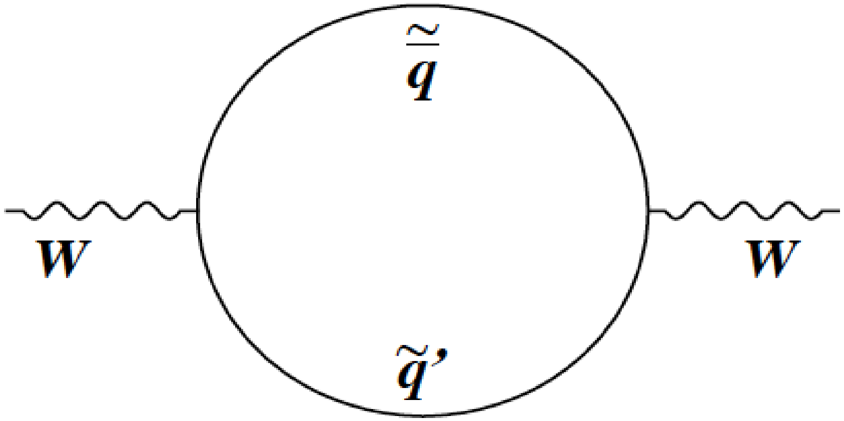


Dark Matter particles?

New Physics through Quantum Loops

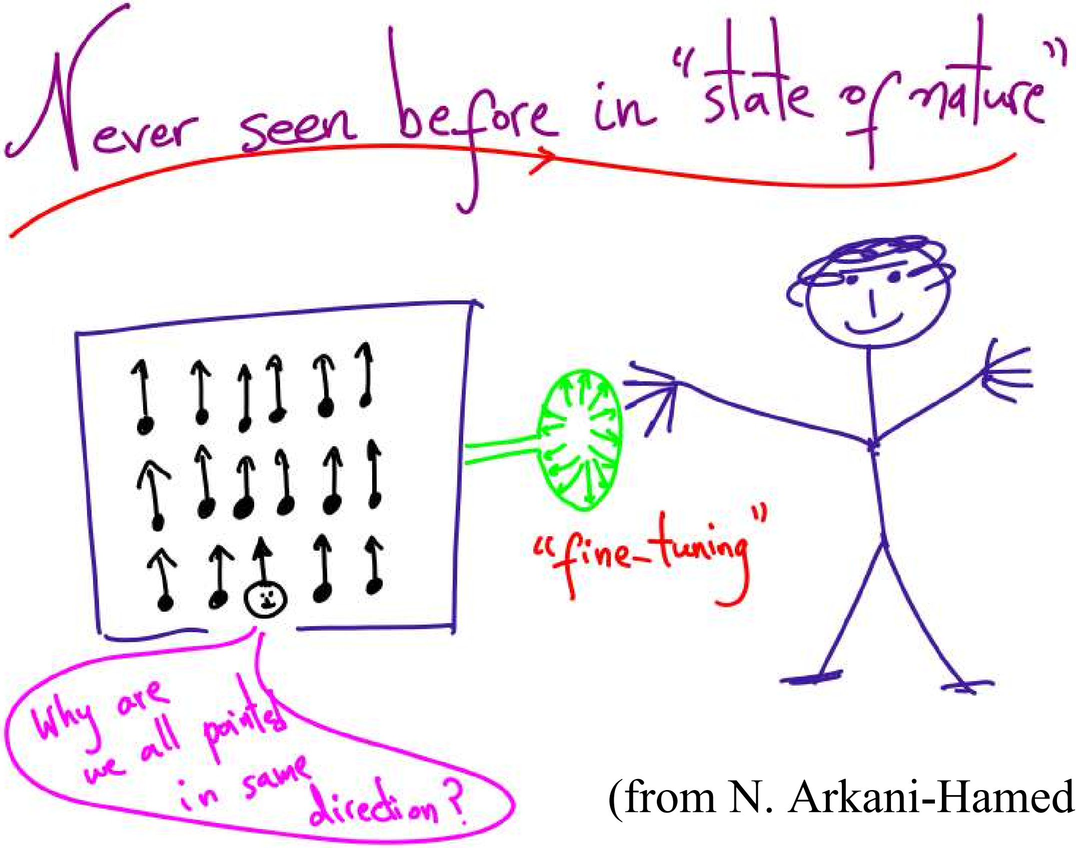
W Mass Corrections from Supersymmetric Particles





Summary of Fine-tuning

- Higgs boson completes the Standard Model
- Guiding principle for expecting physics beyond Standard Model is the need for a "natural" theory
    - Solving the "fine-tuning" problem of the Standard Model



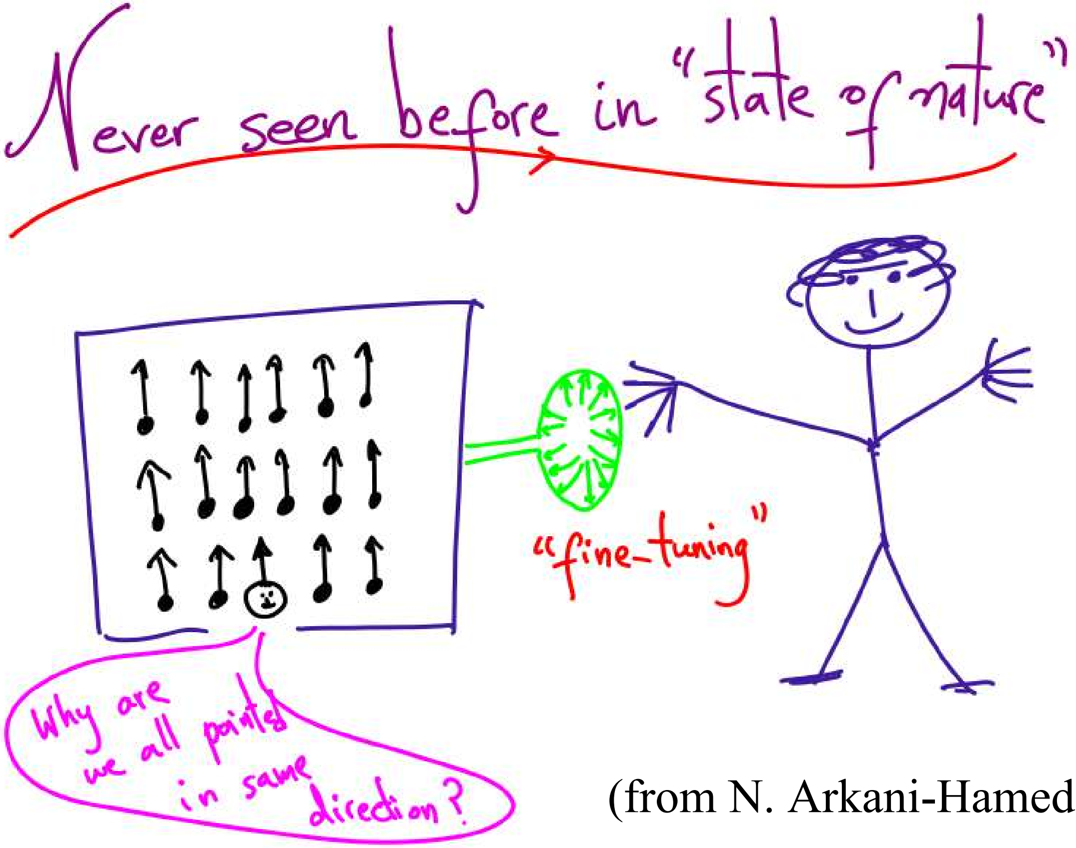
(from N. Arkani-Hamed)

Spontaneous Symmetry Breaking

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

Summary of Fine-tuning

- Higgs boson completes the Standard Model
- Guiding principle for expecting physics beyond Standard Model is the need for a “natural” theory
    - Solving the “fine-tuning” problem of the Standard Model with a fundamental scalar field



(from N. Arkani-Hamed)

Existence of weakly-interacting Dark Matter particles also requires physics beyond Standard Model

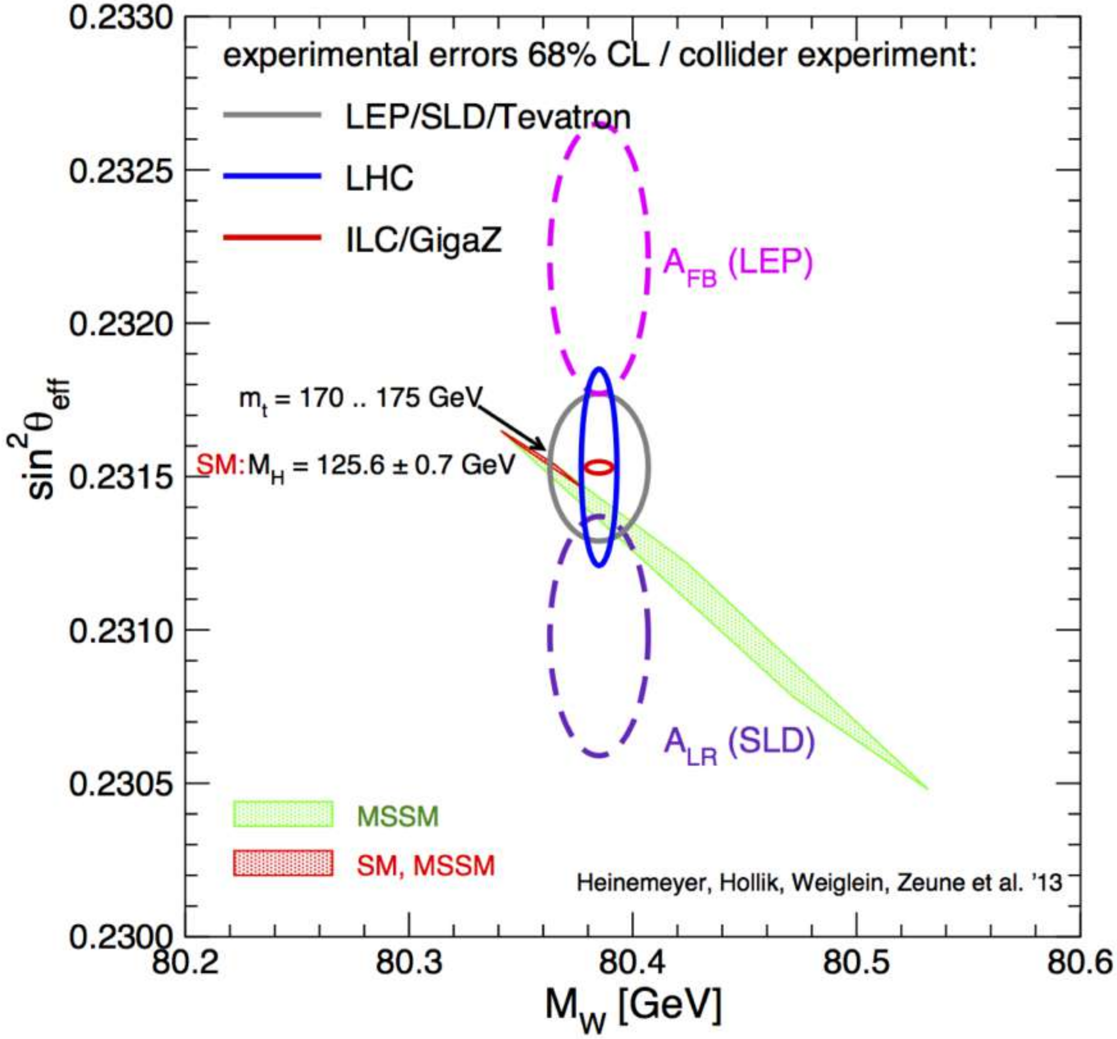
Next Steps for Electroweak Measurements

- 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?

- two areas of electroweak physics
  - Electroweak precision observables (EWPOs) : M_W and $\sin^2\theta_{\text{⌡ΑΑ}}$
  - ◊ ∫∪∆Ξ∩ΛΟΛΚ Ο∪∈ΙΙ∫ΞΚΒ ∈Κ⌠ ΙΞ2∩ΛΟΛΚ ΜΞΛ⌠Ρ∪ΙΞΛΚ

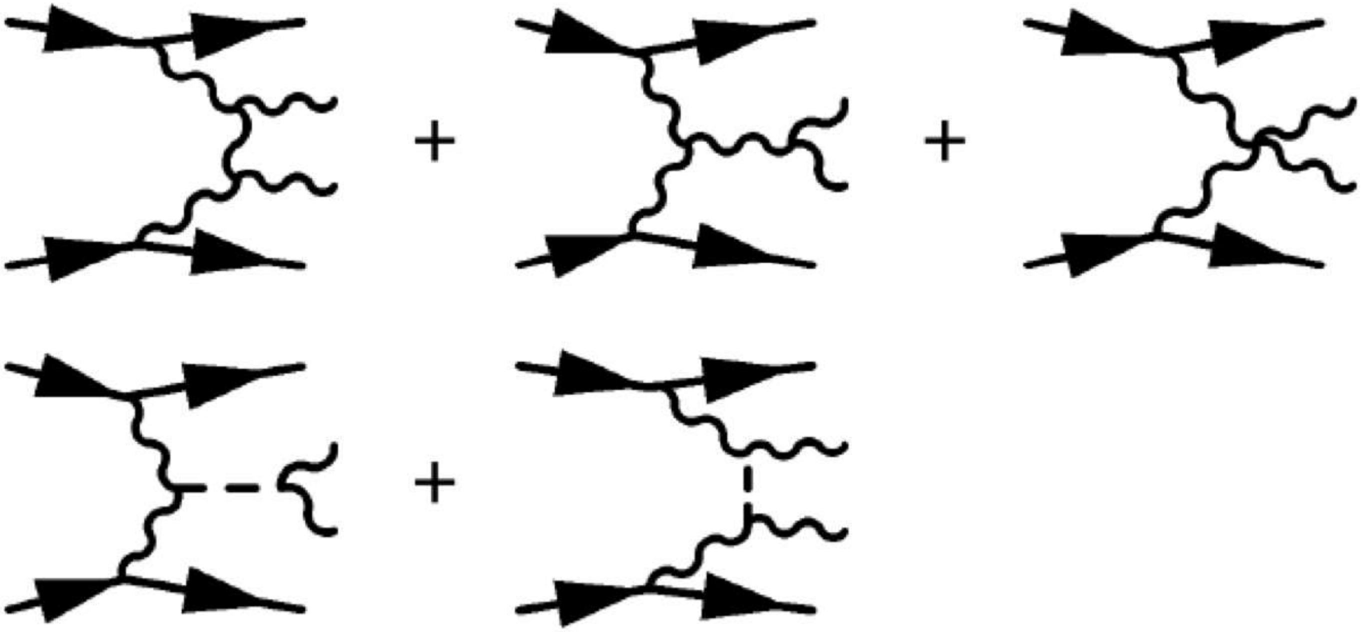
$\mathrm{Sin}^2\theta_{\mathrm{eff}}$ and M_W

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



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

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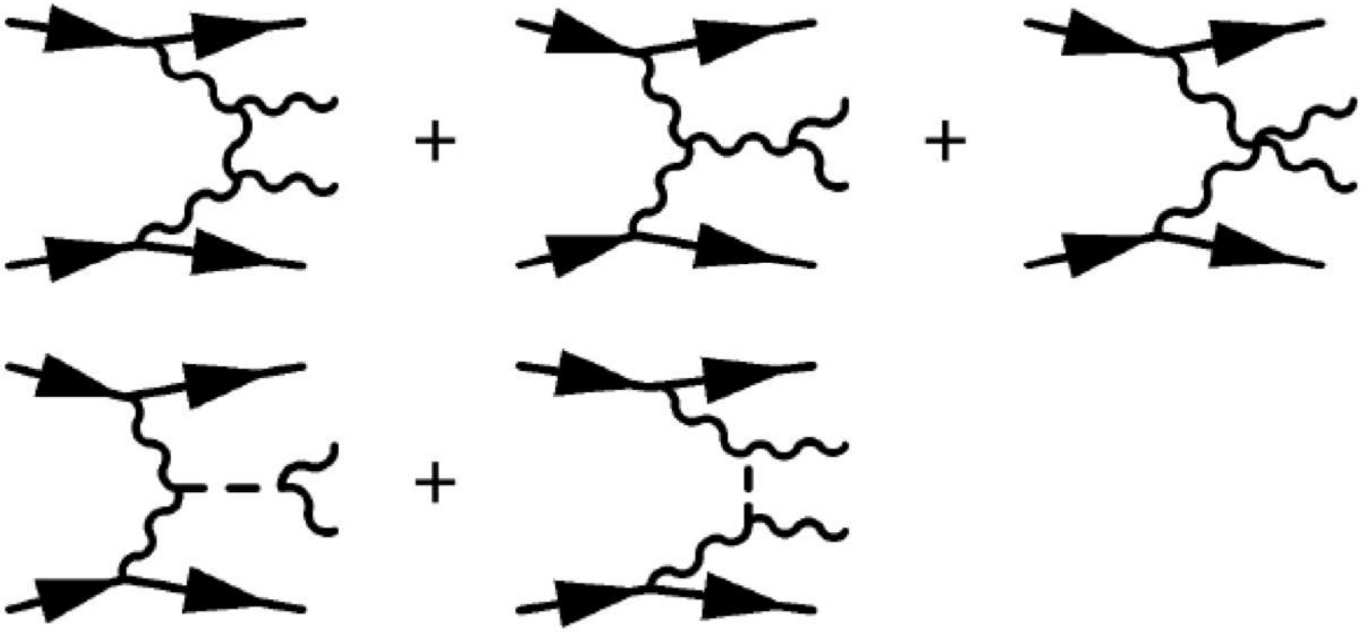
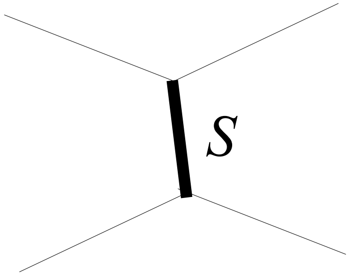
- This is a key process accessible for the first time at LHC
- A prime motivator for LHC/SSC: without Higgs (or some other) mechanism, longitudinally-polarized vector boson scattering amplitudes would violate tree-level unitarity above ~ 1 TeV

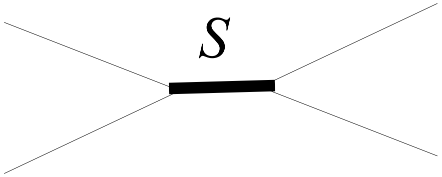


We still have to demonstrate experimentally that unitarizing mechanism is working, and how it is working

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





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

- 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

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: $\phi\phi \to \phi\phi$

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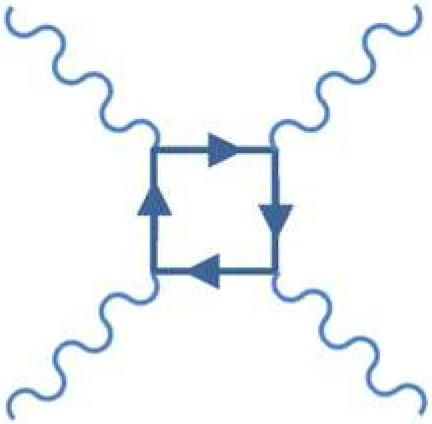
  - This is one of the operators predicted in strongly-interacting light Higgs models
  - Observing a deviation in VBS consistent with this model would immediately point to model parameter values

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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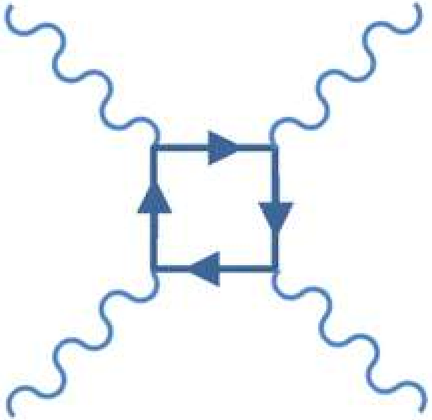

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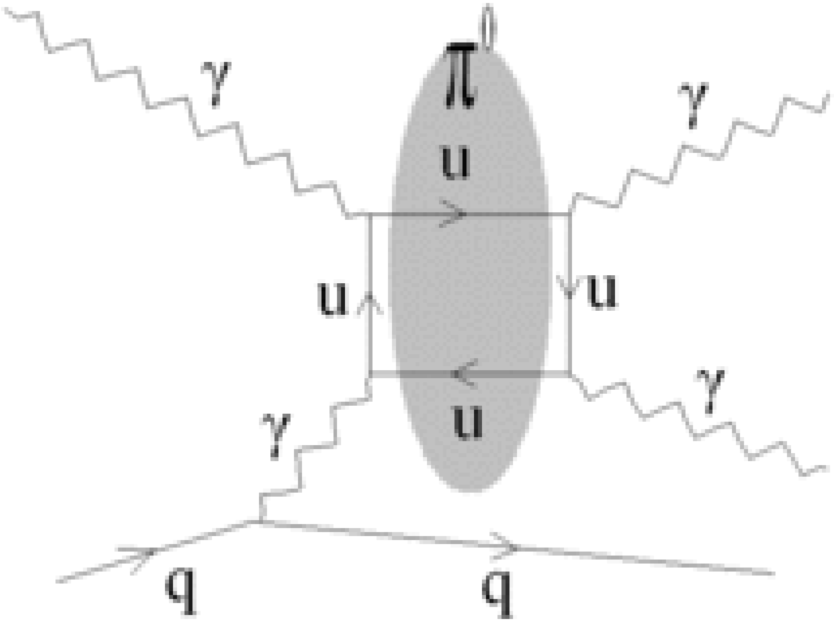
Operator coefficients contain information on mass and coupling of new dynamical degrees of freedom

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

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

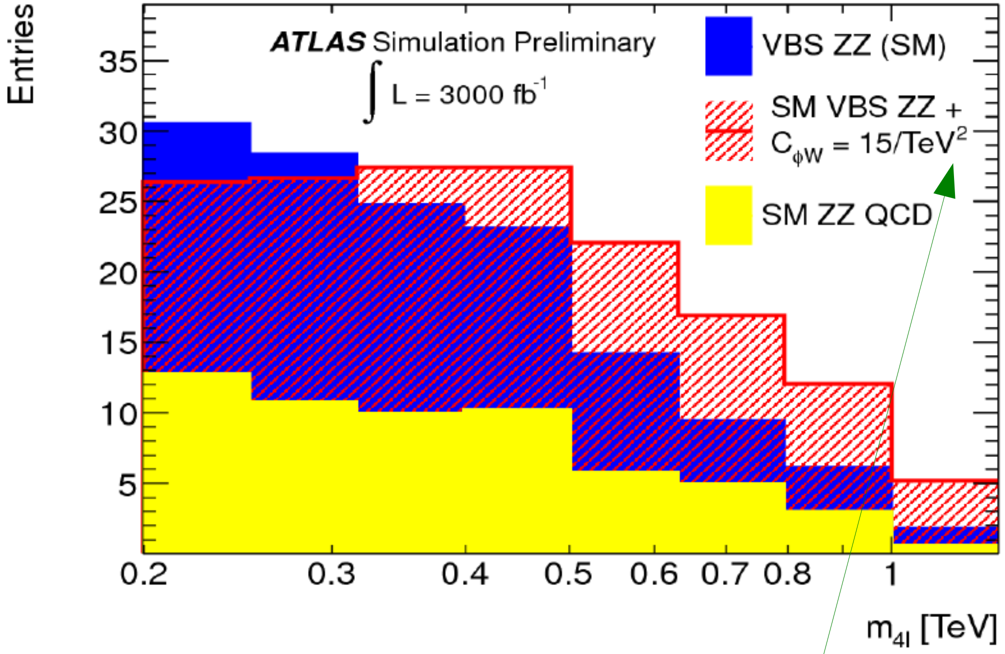
- LHC has shown the potential for
  - measuring new physics parameterized by higher-dimension operators
  - Differentiating between different operators using
    - Direct measurement of energy-dependence
    - different channels

  - 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

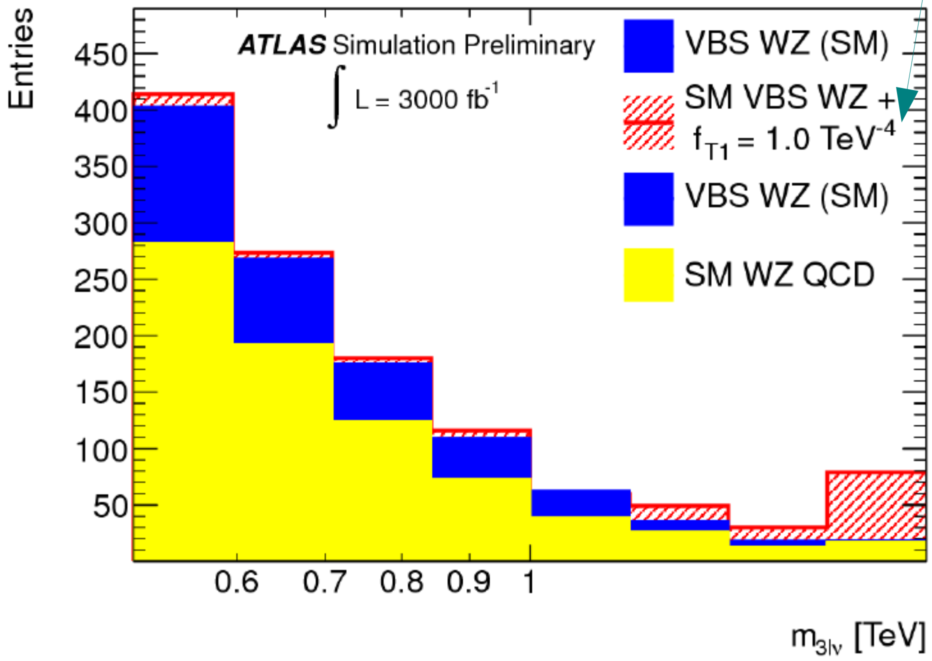
ZZ → leptons



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

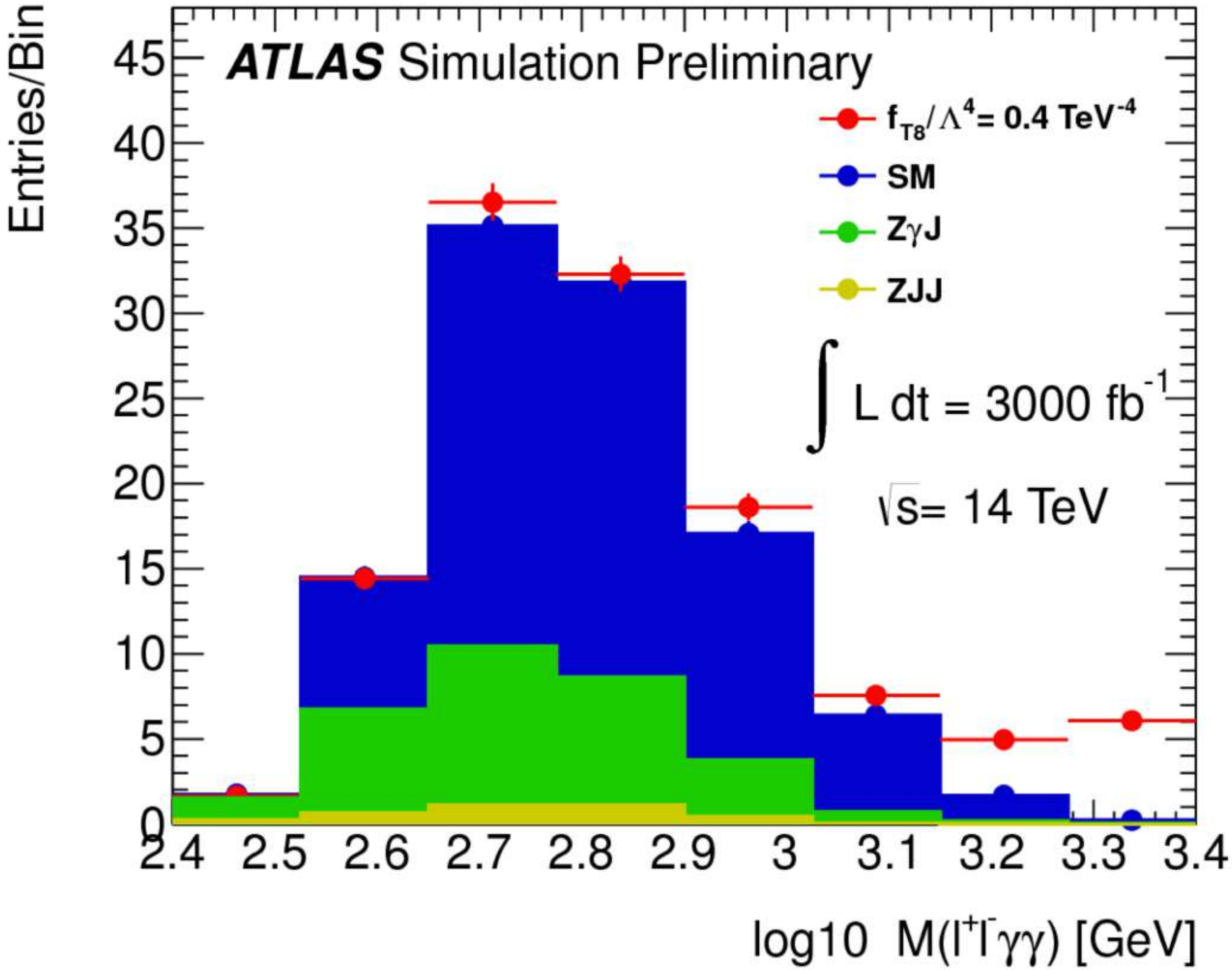
dim-8 operator coefficient implies sensitivity to strong dynamics at TeV-scale

WZ → leptons



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

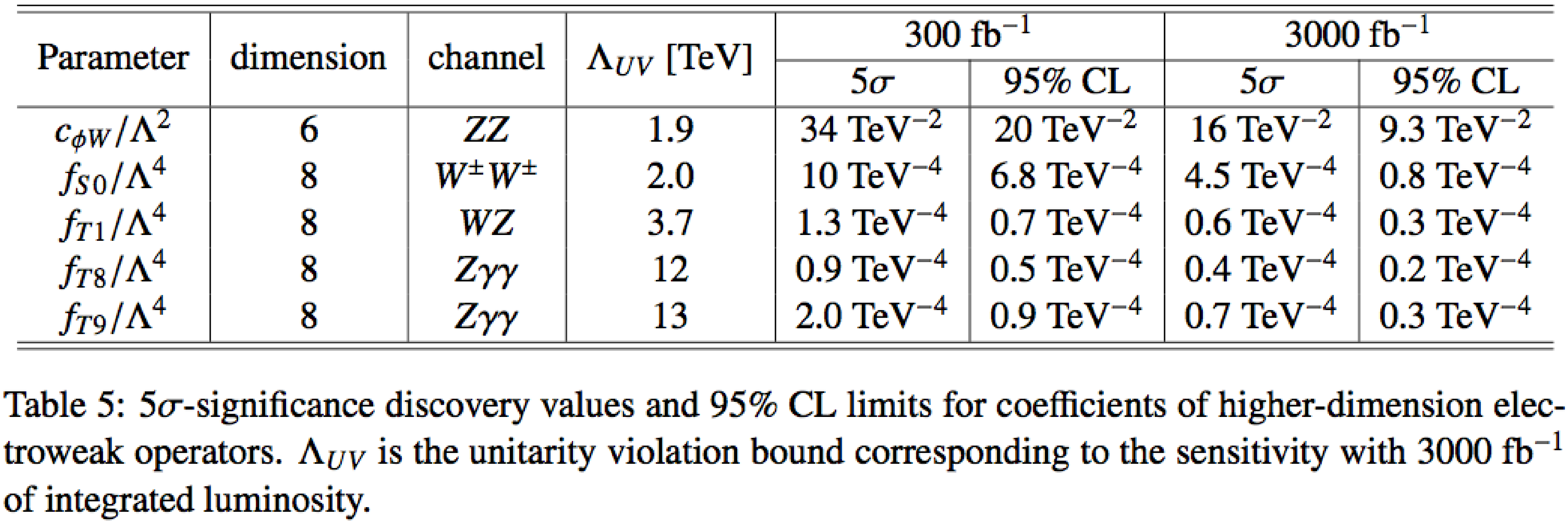
Complementarity of VBS and Triboson production



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:

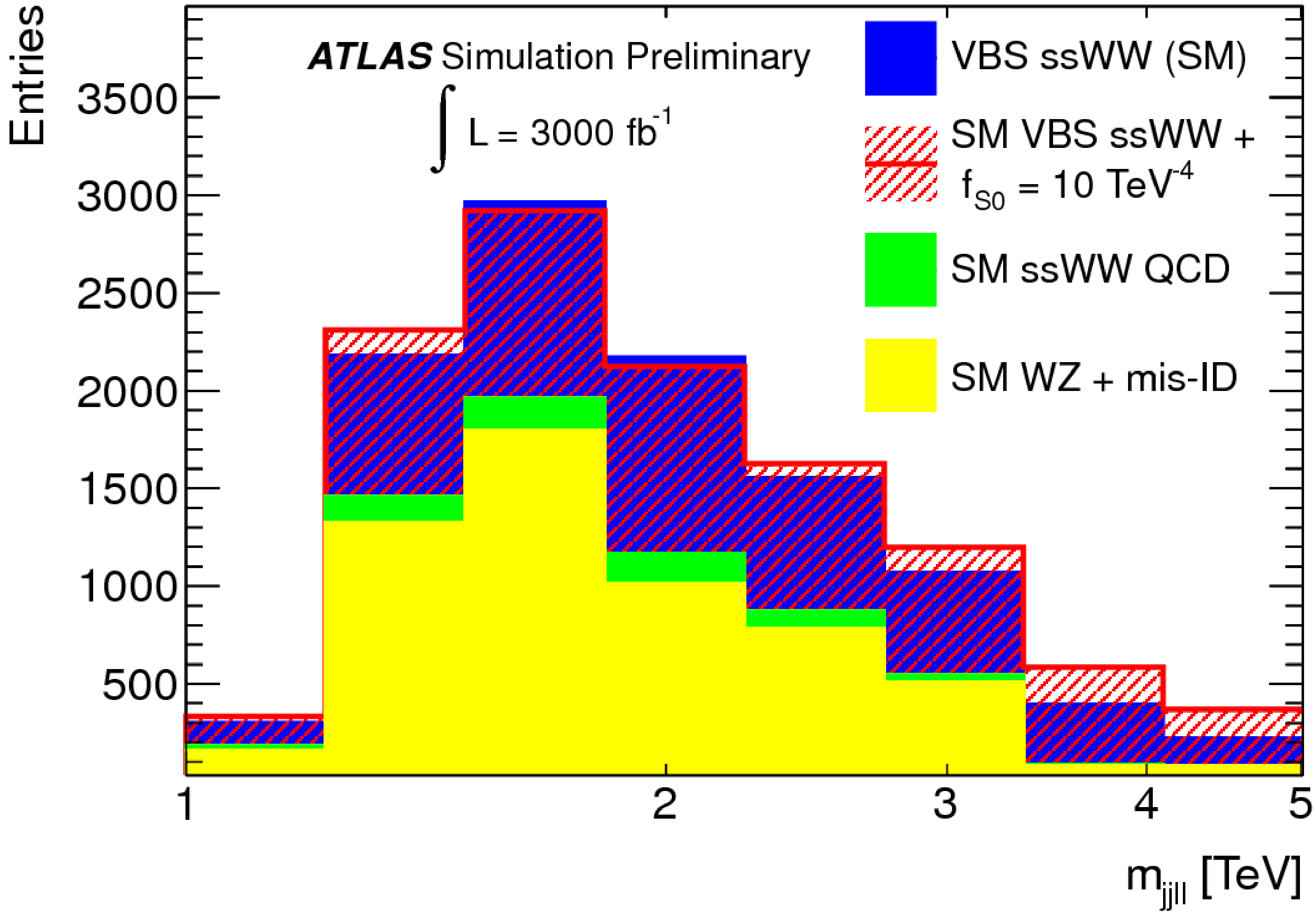
1) factor of 2-3 improvement in sensitivity with Phase II

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

VBS Study using same-sign WW → leptons



Stronger SM interference for "S_0" operator → different kinematic dependence