How do we achieve our goal?

Beyond SM:
- Supersymmetry? Composite models? …

Higgs:
- CP, $\kappa_{V,f}$, flavour violation, …

Electroweak:
- $\sin^2\theta$, TGCs, …

Standard Model

QCD

Flavour:
- Top, CKM, …

New Accelerators:
- HL-LHC, ILC, FCC CLIC, CEPC, SppC …

Cosmology & Astrophysics:
- inflation, dark matter, cosmic rays, grav. waves, …
• « Empty » space is unstable
• Hierarchy problem
• Dark matter
• Origin of matter
• Masses of neutrinos
• Inflation
• Quantum gravity
• ...

The Standard Model
Higgs Mass Measurements

- ATLAS + CMS ZZ* and γγ final states

- Run 1: $125.09 \pm 0.21\,\text{(stat)} \pm 0.11\,\text{(syst)}$ GeV
- CMS Run 2: $125.26 \pm 0.20\,(\text{stat.}) \pm 0.08\,(\text{sys.})$ GeV
- ATLAS Run 2: $124.98 \pm 0.28$ GeV

Naïve combination $125.13 \pm 0.14$ GeV

Crucial for stability of Electroweak vacuum
Theoretical Constraints on Higgs Mass

- Large $M_h \rightarrow$ large self-coupling $\rightarrow$ blow up at low energy scale $\Lambda$ due to renormalization.

\[ \lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2v^4} \log \frac{Q}{v} \]

- Small: renormalization due to t quark drives quartic coupling $< 0$ at some scale $\Lambda \rightarrow$ vacuum unstable.

- Vacuum could be stabilized by Supersymmetry.

Instability @ $10^{11.4 \pm 0.8}$ GeV

**Vacuum Instability in the Standard Model**

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

Andreassen, Frost & Schwartz, arXiv:1707.08124

- Instability scale:

\[
\log_{10} \frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0 \left( \frac{M_h}{\text{GeV}} - 125.66 \right) - 1.2 \left( \frac{M_t}{\text{GeV}} - 173.10 \right) + 0.4 \frac{\alpha_3(M_Z) - 0.1184}{0.0007}
\]

- Naïve combination of recent ATLAS/CMS data:

\[m_t = 172.47 \pm 0.35 \text{ GeV} \Rightarrow \log_{10}(\Lambda/\text{GeV}) = 11.4 \pm 0.8\]

- Sensitive to \(\alpha_s\) as well as \(m_t\) and \(M_h\).
Instability during Inflation?

- Do inflation fluctuations drive us over the hill?

- Then Fokker-Planck evolution

- Do AdS regions eat us?
  - Disaster if so
  - Mitigate with more inflation?

Stabilize vacuum with some physics beyond the SM?

Elementary Higgs or Composite?

- Higgs field: \( \langle 0 | H | 0 \rangle \neq 0 \)
- Quantum loop problems

\[ m_h^2 \sim (200 \text{ GeV})^2 \]

Cutoff
\( \Lambda = 10 \text{ TeV} \)

Cut-off \( \Lambda \sim 1 \text{ TeV} \) with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- New ‘technicolour’ force?
  - Heavy scalar resonance?
  - Problems with precision electroweak data
  - Pseudo-Nambu-Goldstone boson?
Standard Model Effective Field Theory

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6:

\[ \mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n \]

- Operators constrained by SU(2) × U(1) symmetry:

\[
\mathcal{L} \supset \frac{\bar{c}_H}{2v^2} \partial^\mu [\Phi^\dagger \Phi] \partial_\mu [\Phi^\dagger \Phi] + \frac{g^2}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + \frac{g_s^2}{m_W^2} \Phi^\dagger \Phi G^a_{\mu\nu} G^{\mu\nu}_a \\
+ \frac{2ig}{m_W^2} \bar{c}_{HW} \left[ D^\mu \Phi^\dagger T_{2k} D^\nu \Phi \right] W^k_{\mu\nu} + \frac{ig'}{m_W^2} \bar{c}_{HB} \left[ D^\mu \Phi^\dagger D^\nu \Phi \right] B_{\mu\nu} \\
+ \frac{ig}{m_W^2} \bar{c}_W \left[ \Phi^\dagger T_{2k} \not{D}_\mu \Phi \right] D^\nu W^k_{\mu\nu} + \frac{ig'}{2m_W^2} \bar{c}_B \left[ \Phi^\dagger \not{D}_\mu \Phi \right] D^\nu B_{\mu\nu} \\
+ \frac{\bar{c}_t}{v^2 y_t} \Phi^\dagger \Phi \Phi^\dagger \cdot \bar{Q} L t_R + \frac{\bar{c}_b}{v^2 y_b} \Phi^\dagger \Phi \Phi^\dagger \cdot \bar{Q} L b_R + \frac{\bar{c}_\tau}{v^2 y_\tau} \Phi^\dagger \Phi \Phi^\dagger \cdot \bar{L} L \tau_R
\]

- Constrain with precision EW, Higgs data, TGCs ...
Electroweak Precision Data

- Operators affecting oblique parameters

\[ \mathcal{L}_{\text{dim-6}} \subset \frac{c_{WB}}{m_W^2} \mathcal{O}_{WB} + \frac{c_W}{m_W^2} \mathcal{O}_W + \frac{c_B}{m_W^2} \mathcal{O}_B + \frac{c_T}{v^2} \mathcal{O}_T + \frac{c_{2W}}{m_W^2} \mathcal{O}_{2W} + \frac{c_{2B}}{m_W^2} \mathcal{O}_{2B} \]

- Also other electroweak tests

- Constraints from LEP et al. data

Fits to individual dimension-6 operators

Global fit to dimension-6 operators

Global Fits to LHC Data

- Associated H production rates & kinematics
- LHC Triple-gauge couplings
- Global combination
- Individual operators

Preferred framework for analyzing Run 2


Complementary!
ATLAS Higgs EFT Analysis

**Diagram:**

- **ggF**
  - 0-jet
  - 1-jet
  - ≥ 2-jet
    - VH
      - qq → VH
        - W → ℓν
          - Z → ℓℓ + ν̄ν
    - ZH
      - gg → ZH

- **VBF**
  - EW qqH incl. VH → qqH

**Operators:**

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expression</th>
<th>HEL Coefficient</th>
<th>Vertices</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_g$</td>
<td>$</td>
<td>H</td>
<td>^2 G^A_{μν} G^{Aμν}$</td>
</tr>
<tr>
<td>$O_γ$</td>
<td>$</td>
<td>H</td>
<td>^2 B^μν B^{μν}$</td>
</tr>
<tr>
<td>$O_μ$</td>
<td>$y_μ</td>
<td>H</td>
<td>^2 \bar{u}_H u_R + \text{h.c.}$</td>
</tr>
<tr>
<td>$O_{HW}$</td>
<td>$i (D^μH)^+ σ^{a H} (D^νH) W^{a μν}$</td>
<td>$c_{HW} = \frac{m_W^2}{g} \tilde{c}_{HW}$</td>
<td>HWW, HZZ</td>
</tr>
<tr>
<td>$O_{HB}$</td>
<td>$i (D^μH)^+ (D^νH) B^{μν}$</td>
<td>$c_{HB} = \frac{m_W^2}{g} \tilde{c}_{HB}$</td>
<td>HZZ</td>
</tr>
<tr>
<td>$O_W$</td>
<td>$i (H^+ σ^{a H} D^μH) D^ν W^{a μν}$</td>
<td>$c_{WW} = \frac{m_W^2}{g} \tilde{c}_W$</td>
<td>HWW, HZZ</td>
</tr>
<tr>
<td>$O_B$</td>
<td>$i (H^+ D^μH) δ^{μν} B_{μν}$</td>
<td>$c_B = \frac{m_W^2}{g} \tilde{c}_B$</td>
<td>HZZ</td>
</tr>
</tbody>
</table>
Sensitivities to Operators

- Rate relative to SM with different operators

Higher sensitivity at higher $p_T$
Δχ^2 Distributions for Higgs EFT Coefficients

- SM (coefficient = 0) always allowed at Δχ^2 < 4 level (< 2 σ)

- **Next steps:**
  - Combine with TGCs
  - Combine with precision EW
What lies beyond the Standard Model?

**Supersymmetry**

- Stabilize electroweak vacuum
- Successful prediction for Higgs mass
  - Should be $< 130$ GeV in simple models
- Successful predictions for couplings
  - Should be within few % of SM values
- Naturalness, GUTs, string, …, dark matter

New motivations
From LHC Run 1
## Inputs to Global Fits for New Physics

### Electroweak observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Source Th./Ex.</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_W$ [GeV]</td>
<td>[33] / [57, 58]</td>
<td>$20.079 \pm 0.012 \pm 0.010_{\text{MSSM}}$</td>
</tr>
<tr>
<td>$\Delta_m^\text{EXP} - \Delta_m^\text{SM}$</td>
<td>[59] / [60]</td>
<td>$(30.2 \pm 8.8 \pm 2.0_{\text{MSSM}}) \times 10^{-16}$</td>
</tr>
<tr>
<td>$R_{\mu\mu}$</td>
<td>[61-63]</td>
<td>2D likelihood, MFV</td>
</tr>
<tr>
<td>$\tau(B_s \to \mu^+ \mu^-)$</td>
<td>[63]</td>
<td>$2.04 \pm 0.44_{\text{stat.}} \pm 0.05_{\text{syst.}} \text{ ps}$</td>
</tr>
<tr>
<td>$\text{BR}_{b \to s}^{\text{EXP/SM}}$</td>
<td>[65] / [66]</td>
<td>$0.988 \pm 0.045_{\text{EXP}} \pm 0.068_{\text{TH,SM}} \pm 0.050_{\text{TH,SUSY}}$</td>
</tr>
<tr>
<td>$\Delta M_{B_d}^{\text{EXP/SM}}$</td>
<td>[34, 69] / [66]</td>
<td>$0.966 \pm 0.278_{\text{EXP}} \pm 0.037_{\text{SM}}$</td>
</tr>
<tr>
<td>$\Delta M_{B_u}^{\text{EXP/SM}}$</td>
<td>[34, 69] / [66]</td>
<td>$0.968 \pm 0.60_{\text{EXP}} \pm 0.078_{\text{SM}}$</td>
</tr>
<tr>
<td>$\text{BR}_{B \to X_s \ell\ell}^{\text{EXP/SM}}$</td>
<td>[68] / [66]</td>
<td>$2.01 \pm 1.30_{\text{EXP}} \pm 0.18_{\text{SM}}$</td>
</tr>
<tr>
<td>$\text{BR}_{K \to \mu\mu}$</td>
<td>[72] / [73]</td>
<td>$1.0005 \pm 0.0017_{\text{EXP}} \pm 0.0093_{\text{TH}}$</td>
</tr>
</tbody>
</table>

### Flavour observables:

### Interpretation requires lattice inputs

### Dark Matter

- $\sigma_p$ [3, 5, 6] Combined likelihood in the $(m_{\tilde{g}}, \sigma_p)$ plane
- $\sigma_{SD}$ [4] Likelihood in the $(m_{\tilde{g}}, \sigma_{SD})$ plane

### LHC observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Source</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g \to q\bar{q}\chi_1, bb\chi_1, tt\chi_1$</td>
<td>[16, 17]</td>
<td>Combined likelihood in the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ plane</td>
</tr>
<tr>
<td>$\tilde{q} \to q\chi_1^0$</td>
<td>[16]</td>
<td>Likelihood in the $(m_{\tilde{q}}, m_{\tilde{\chi}_1^0})$ plane</td>
</tr>
<tr>
<td>$\tilde{b} \to b\chi_1^0$</td>
<td>[16]</td>
<td>Likelihood in the $(m_{\tilde{b}}, m_{\tilde{\chi}_1^0})$ plane</td>
</tr>
<tr>
<td>$\tilde{t}_1 \to t\chi_1^0, c\chi_1, b\chi_1^\pm$</td>
<td>[16]</td>
<td>Likelihood in the $(m_{\tilde{t}<em>1}, m</em>{\tilde{\chi}_1^0})$ plane</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^\pm \to \nu\ell\tilde{\chi}_1^0, \nu\tau\tilde{\chi}_1^0, W^\pm \tilde{\chi}_1^0$</td>
<td>[18]</td>
<td>Likelihood in the $(m_{\tilde{\chi}<em>1^\pm}, m</em>{\tilde{\chi}_1^0})$ plane</td>
</tr>
<tr>
<td>$\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0, \tau^+\tau^-\tilde{\chi}_1^0, Z\tilde{\chi}_1^0$</td>
<td>[18]</td>
<td>Likelihood in the $(m_{\tilde{\chi}<em>2^0}, m</em>{\tilde{\chi}_1^0})$ plane</td>
</tr>
<tr>
<td>Heavy stable charged particles</td>
<td>[74]</td>
<td>Fast simulation based on [74, 75]</td>
</tr>
<tr>
<td>$H/A \to \tau^+\tau^-$</td>
<td>[28, 29, 76, 77]</td>
<td>Likelihood in the $(M_A, \tan \beta)$ plane</td>
</tr>
</tbody>
</table>
Best-Fit Sparticle Spectrum

Phenomenological MSSM

Fit excluding $g_\mu - 2$

Accessible to LHC?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091
Squark & Gluino Mass Planes

Phenomenological MSSM

Fit including $g_\mu - 2$

Fit excluding $g_\mu - 2$

‘Nose’ regions where LHC sensitivity reduced because of compressed spectrum

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091
How Light can Squarks & Gluinos be?

Phenomenological MSSM

Squarks, gluinos could weigh ~ 1 TeV if drop $g_{\mu}-2$

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091
Decay Pattern at ‘Nose’ Point

Phenomenological MSSM

‘Nose’ point excluding $g_{\mu-2}$

LHC sensitivity reduced because of compressed spectrum, multiple decay modes

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091
Sparticle Masses in the pMSSM

- 68 & 95% CL ranges
- Best-fit values
- Accessible in pair production at ILC500, ILC1000, CLIC

Bagnaschi, Sakurai, JE et al,
- No issue with measured Higgs mass
- Central values of decay BRs similar to SM
- Substantial deviations possible

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091
Direct Dark Matter Searches

- Compilation of present and future sensitivities
Direct Dark Matter Searches

Spin-independent scattering cross-section close to PandaX upper limit?

Spin-dependent scattering: Strongest limit from PICO experiment

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091
Simplified Dark Matter Models

• Present sensitivities for different mediator bosons

• Complementarity between LHC and direct searches

Model dependence
Simplified Dark Matter Models

- Involve bosonic mediator particles of spin 0 or 1
- The latter are gauge bosons of some U(1)' with vector and/or axial-vector couplings
- Consistency of theory requires cancellation of anomalous triangle diagrams
- Standard Model has quark-lepton cancellation
- Should be re-examined in models with extra fermions and/or gauge bosons

JE, Fairbairn & Tunney, arXiv:1704.03850
Anomaly Cancellation Conditions

- Colour/U(1)':

- SU(2)_W/U(1)'

- U(1)_{Y^2}/U(1)'

- U(1)_{Y}/U(1)''

- U(1)'''

- Gravity/U(1)'

- Non-trivial set of constraints

(a) $[SU(3)_C^2] \times [U(1)']$, which implies $\text{Tr}[[T^i, T^j]Y'] = 0$,

(b) $[SU(2)_W^2] \times [U(1)']$, which implies $\text{Tr}[[T^i, T^j]Y'] = 0$,

(c) $[U(1)_Y^2] \times [U(1)']$, which implies $\text{Tr}[Y^2Y'] = 0$,

(d) $[U(1)_Y] \times [U(1)'^2]$, which implies $\text{Tr}[YY'^2] = 0$,

(e) $[U(1)'^3]$, which implies $\text{Tr}[Y'^3] = 0$,

(f) Gauge-gravity, which implies $\text{Tr}[Y'] = 0$.

JE, Fairbairn & Tunney, arXiv:1704.03850, 1705.03447
Simplified Dark Matter Models

- Mass of Z’ boson > about 3 TeV if produced by 1st generation quarks and decays to leptons
- Impact reduced if leptophobic
- Impact of direct DM searches reduced if
  - DM particle has axial Z’ coupling
  - DM particle has axial nuclear coupling
  - DM particle decouples from 1st/2nd generation
- What anomaly-free U(1)’ models compatible with these desiderata?
Anomaly-Free Dark Matter Models are not so Simple

- If a single DM fermion and generation-independent U(1)’ charges for SM particles:
  - The SM leptons must have non-zero U(1)’ charges
  - The DM particle has vector U(1)’ coupling
- If DM fermion has axial coupling:
  - Must have 2\textsuperscript{nd} ‘dark’ fermion
  - Z’ still leptophilic
- Leptophobic models need DM particle + ≥ 2 other dark particles with different U(1)’ charges
- Interesting experimental signatures?

JE, Fairbairn & Tunney, arXiv:1704.03850
Experimental Constraints on Anomaly-Free Dark Matter Models

- Excluded by LHC dilepton searches
- **Excluded** by direct dark matter searches

JE, Fairbairn & Tunney, arXiv:1704.03850
H- and Z-Portal Models are not dead yet

Consider spin-0, -1/2, -1 DM coupled to Standard Model via Higgs or Z boson
All available collider, DM search constraints
Bayesian & frequentist statistical analyses

JE, Fowlie, Marzola & Raidal, arXiv:1711.09912
Higgs coupled to Spin-0 DM

- **Red** = 1-, 2-σ regions
- **Grey** = relic density
- **On- and off-shell cases both allowed**

Relic density + collider

Also indirect DM search

Also direct DM search

Possible future direct DM search

JE, Fowlie, Marzola & Raidal, arXiv:1711.09912
Higgs coupled to Spin-$\frac{1}{2}$ DM

- **Red** = 1-, 2-\(\sigma\) regions
- **Grey** = relic density
- **On- and off-shell cases both allowed**
Z Boson coupled to Spin-$\frac{1}{2}$ DM

- Red = 1-, 2-$\sigma$ regions
- Grey = relic density
- On- and off-shell cases both allowed

Dirac fermion
Vector coupling

Dirac fermion
Axial coupling

Majorana fermion
Axial coupling
<table>
<thead>
<tr>
<th>Model</th>
<th>Bayes factor</th>
<th>$\min \chi^2$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real scalar $h$-portal</td>
<td>0.55</td>
<td>2.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Complex scalar $h$-portal</td>
<td>0.28</td>
<td>2.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Real vector $h$-portal</td>
<td>0.23</td>
<td>2.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Complex vector $h$-portal</td>
<td>0.059</td>
<td>2.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Majorana $h$-portal</td>
<td>0.59</td>
<td>2.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Dirac $h$-portal</td>
<td>0.71</td>
<td>2.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Scalar $Z$-portal</td>
<td>$3 \times 10^{-14}$</td>
<td>55</td>
<td>$1.4 \times 10^{-12}$</td>
</tr>
<tr>
<td>Vector $Z$-portal</td>
<td>$6.8 \times 10^{-10}$</td>
<td>35</td>
<td>$2.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>Majorana $Z$-portal</td>
<td>1</td>
<td>2.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Dirac $Z$-portal</td>
<td>0.24</td>
<td>2.6</td>
<td>0.27</td>
</tr>
</tbody>
</table>

JE, Fowlie, Marzola & Raidal, arXiv:1711.09912
The LHC in Future Years

- **LS1**: Splices fixed
- **LS2**: Injectors upgrade
- **LS3**: New Low-β* quads

**Year**

- 2010
- 2015
- 2020
- 2025
- 2030
- 2035
- 2040

**Luminosity [cm^{-2}s^{-1}]**

- 30 fb^{-1}
- 300 fb^{-1}
- 3000 fb^{-1}

**Integrated luminosity [fb^{-1}]**

- 0
- 500
- 1000
- 1500
- 2000
- 2500
- 3000
- 3500
Present & Future Constraints on D=6 Operators

### Operators

<table>
<thead>
<tr>
<th>Bosonic CP-even</th>
<th>Constraints from rates</th>
<th>Constraints including kinematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_H$</td>
<td>$\frac{1}{2v^2} \left[ \partial_\mu (H^\dagger H) \right]^2$</td>
<td>$\bar{c}_g (\times 1000)$</td>
</tr>
<tr>
<td>$O_T$</td>
<td>$\frac{1}{2v^2} \left( H^\dagger D_\mu H \right)^2$</td>
<td>$\bar{c}_g (\times 1000)$</td>
</tr>
<tr>
<td>$O_6$</td>
<td>$-\frac{\lambda}{v^2} (H^\dagger H)^3$</td>
<td>$\bar{c}_g (\times 100)$</td>
</tr>
<tr>
<td>$O_g$</td>
<td>$\frac{g^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^a_{\mu\nu}$</td>
<td>$\bar{c}_w$</td>
</tr>
<tr>
<td>$O_\gamma$</td>
<td>$\frac{g}{m_W^2} H^\dagger H B_{\mu\nu} B_{\mu\nu}$</td>
<td>$\bar{c}_g (\times 100)$</td>
</tr>
<tr>
<td>$O_W$</td>
<td>$\frac{ig}{2m_W} \left( H^\dagger \sigma^i D_\mu H \right) D_\nu W^i_{\mu\nu}$</td>
<td>$\bar{c}_H$</td>
</tr>
<tr>
<td>$O_B$</td>
<td>$\frac{ig'}{2m_W} \left( H^\dagger D_\mu H \right) \partial_\nu B_{\mu\nu}$</td>
<td>$\bar{c}_{HW}$</td>
</tr>
<tr>
<td>$O_{HW}$</td>
<td>$\frac{ig}{2m_W} \left( D_\mu H^\dagger \sigma^i D_\nu H \right) W^i_{\mu\nu}$</td>
<td>$\bar{c}_{HB}$</td>
</tr>
<tr>
<td>$O_{HB}$</td>
<td>$\frac{ig'}{2m_W} \left( D_\mu H^\dagger D_\nu H \right) B_{\mu\nu}$</td>
<td>$\bar{c}_{d3}$</td>
</tr>
<tr>
<td>$O_{2W}$</td>
<td>$\frac{1}{2m_W} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$</td>
<td>$\bar{c}_{u3}$</td>
</tr>
<tr>
<td>$O_{2B}$</td>
<td>$\frac{1}{m_W} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$</td>
<td>$\bar{c}_{d3}$</td>
</tr>
<tr>
<td>$O_{2G}$</td>
<td>$\frac{1}{2m_W} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$</td>
<td>$\bar{c}_{u3}$</td>
</tr>
<tr>
<td>$O_{3W}$</td>
<td>$\frac{g^3}{3m_W^3} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$</td>
<td>$\bar{c}_{d3}$</td>
</tr>
<tr>
<td>$O_{3G}$</td>
<td>$\frac{g^3}{4m_W^3} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$</td>
<td>$\bar{c}_{d3}$</td>
</tr>
</tbody>
</table>

Englert, Kogler, Schulz & Spannowsky, arXiv:1511.05170

Current: 300/fb  
Future: 3000/fb
Projected $\text{e}^+\text{e}^-$ Colliders: Luminosity vs Energy
Future Circular Colliders

The vision:

explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)
• LHC constraints

• **FCC-ee** constraints: see $\Lambda \sim 10$ TeV?

JE & Tevong You, arXiv:1510.04561
**FCC-ee Higgs & TGC Measurements**

**EWPTs and Higgs**

- **Shadings:**
  - With/without theoretical EWPT uncertainties

Should extend to include prospective FCC-hh measurements of TGCs, …
Precision FCC-ee Measurements

Precision Electroweak

- $M_Z$
- $\Gamma_Z$
- $R_\ell^0$
- $R_b^0$
- $M_W$
- $m_t$

Precision Higgs

- $h \rightarrow \gamma\gamma$
- $h \rightarrow ZZ$
- $h \rightarrow WW$
- $h \rightarrow gg$

- cmssm low mass
- cmssm high mass
- nuhm1 low mass
- nuhm1 high mass

- FCC-ee
- SM unc. Higgs WG

Sensitivity enhanced by higher center-of-mass energy

CLIC Sensitivities to Dimension-6 Operators

Global fit
Individual operators
Omitting $W^+W^-$

JE, Roloff, Sanz & Tevong You, arXiv:1701.04804
CLIC Sensitivities to Dimension-6 Operators

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Higgs Cross Sections

- At the LHC and beyond:
Squark-Gluino Plane

Discover 12 TeV squark, 16 TeV gluino @ 5σ
Summary

• The discovery of the Higgs boson at the LHC is a big challenge for theoretical physics!
• The LHC may yet discover physics beyond the SM at ~ 13 TeV
• If it does, priority will be to study it
• If it does not, natural to focus on the Higgs
• In either case, a large circular collider offers the best prospects for future discoveries