Title: What Can We Learn from Precision Higgs

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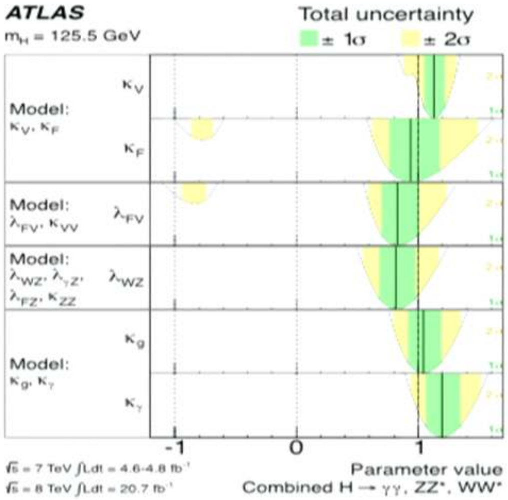
Abstract: In the coming years, LHC experiments will measure Higgs properties, such as its couplings, with increasing precision. Electron-positron Higgs factories, such as the ILC or TLEP, would be able to achieve even better precision. In this talk, I will discuss some of the physics questions that can be addressed by a precision Higgs coupling measurement program. First, the issue of naturalness of the electroweak scale can be addressed in a robust, model-independent manner. Second, the possibility of a first-order electroweak phase transition can be definitively probed, testing one of the necessary conditions of electroweak baryogenesis scenario.

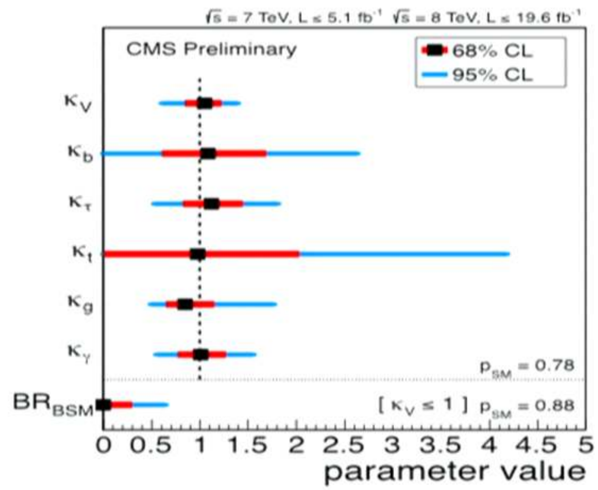
What Can We Learn from Precision Higgs

Maxim Perelstein, Cornell

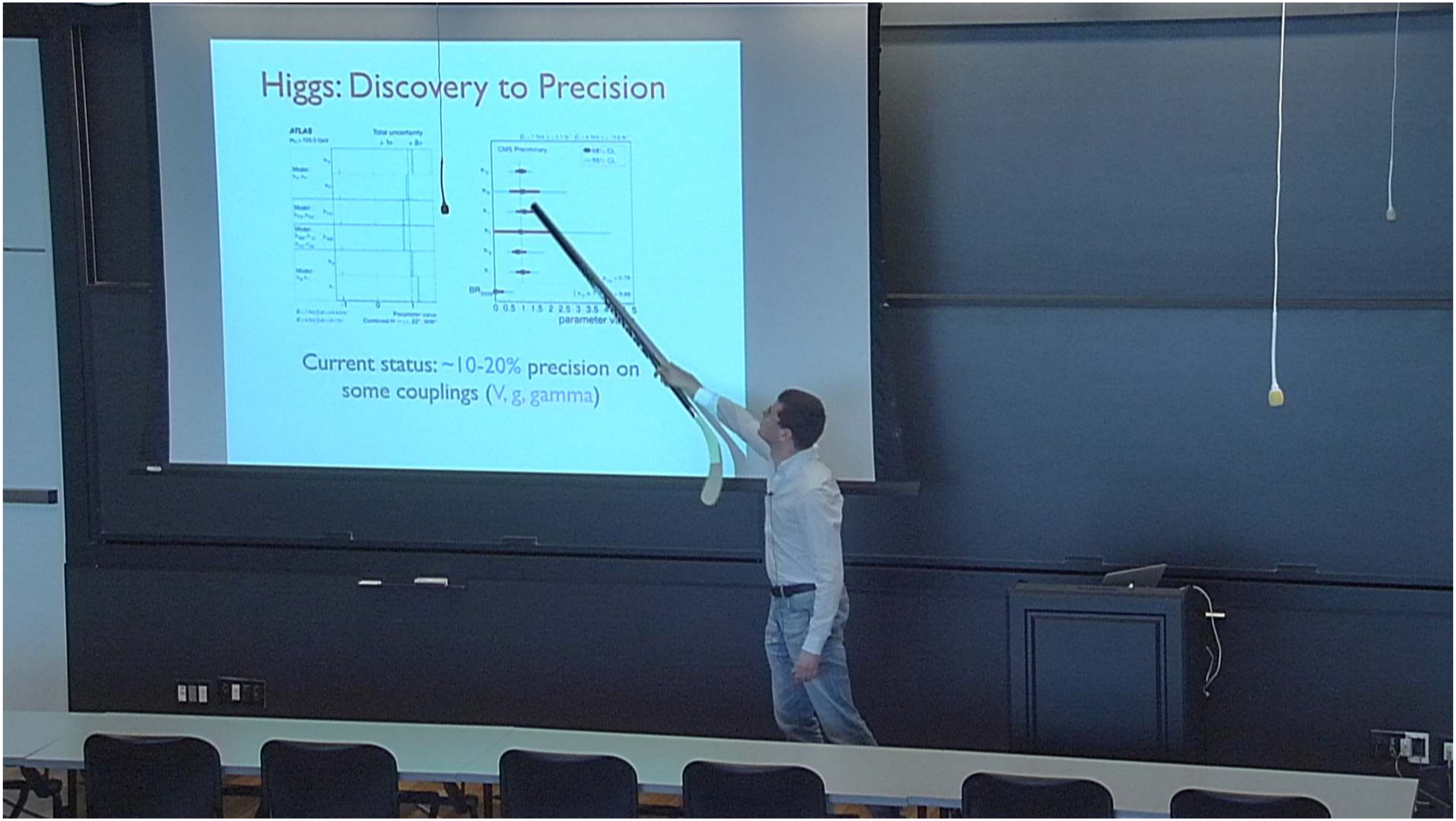
Perimeter Institute Seminar, June 13, 2014

Higgs: Discovery to Precision





Current status: ~10-20% precision on some couplings (V, g, gamma)


Higgs: Discovery to Precision
ATLAS
CMS Preliminary
parameter value
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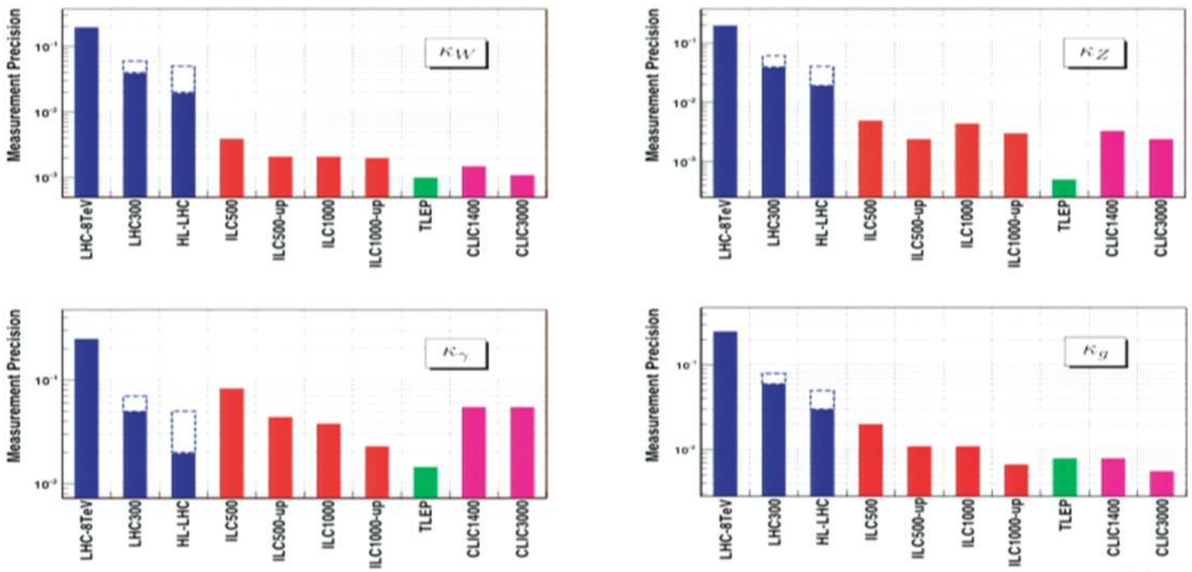
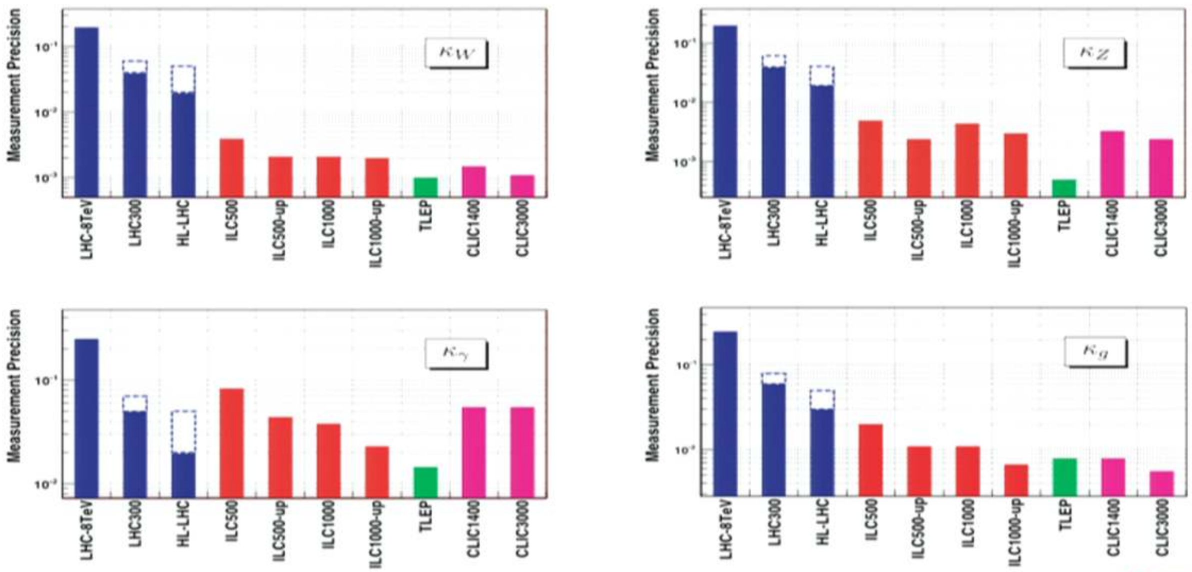
Future: Higgs Precision Program



Snowmass Higgs Report

- 2-5% precision achievable at the HL-LHC
- 0.1% precision on V, 1% on g and gamma at e+e- Higgs factories
- At or almost at precision electroweak levels!

Future: Higgs Precision Program



Snowmass Higgs Report

- 2-5% precision achievable at the HL-LHC
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Outline

- This talk is about potential physics implications of Higgs Coupling (HC) measurements at this level of precision

- Two parts:

  - HC and Naturalness: a model-independent connection [Farina, MP, Rey-Le Lorier, 1305.6068]

  - HC and Electroweak Phase Transition dynamics [A. Katz, MP, 1401.1827]

Intro: Minimalist BSM

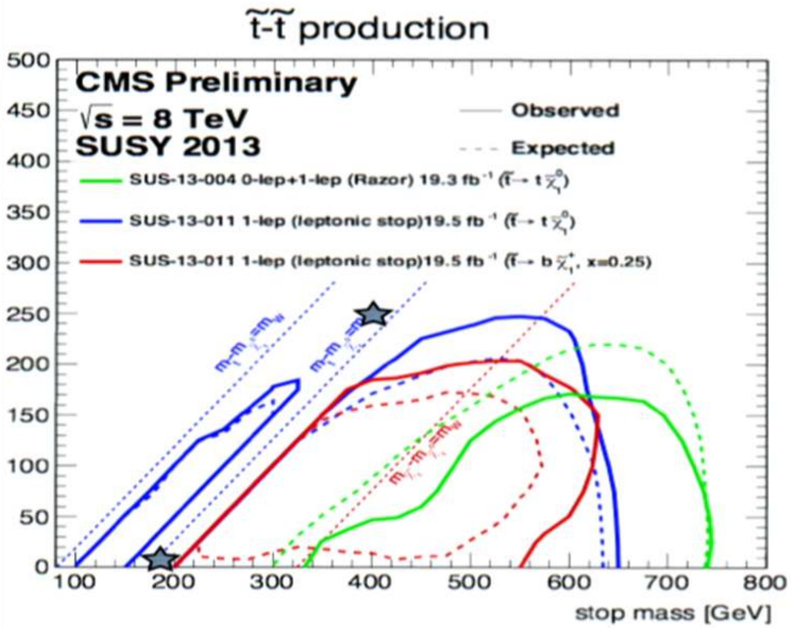
- Precision electroweak tests strongly suggest that physics remains weakly coupled until (at least) ~10 TeV scale
- In this talk, I will take a modest attitude and only think about physics below 10 TeV (do not insist on perturbative gauge coupling unification etc.)
- If only SM until 10 TeV, the Higgs mass parameter needs to be fine tuned:

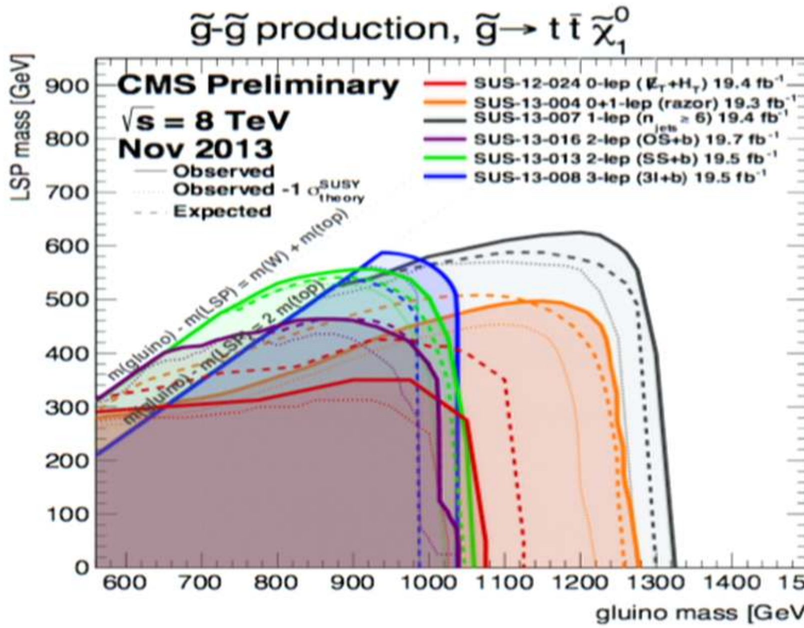
$$-m^2 = -m^2_{\rm tree} + \frac{c}{16\pi^2}\Lambda^2 \qquad \Delta = \frac{\delta m^2}{m^2}$$

$$(v, m_h) \Rightarrow m \approx 90 \text{ GeV} \qquad \delta m^2 \sim \frac{3y_t^2\Lambda^2}{8\pi^2} \Rightarrow \Delta_{\rm SM} \gtrsim 500$$

- Note: this assumes that the SM is an effective theory and new propagating d.o.f.'s coupled to the Higgs appear at some scale, possibly >>10 TeV
- Avoiding this fine-tuning is the (only) motivation for new physics at the energy scale accessible to the LHC. Only a few mechanisms for doing so in a weakly-coupled theory are known (SUSY, Little Higgs, Gauge-Higgs Unification).

Naturalness: Not Dead Yet





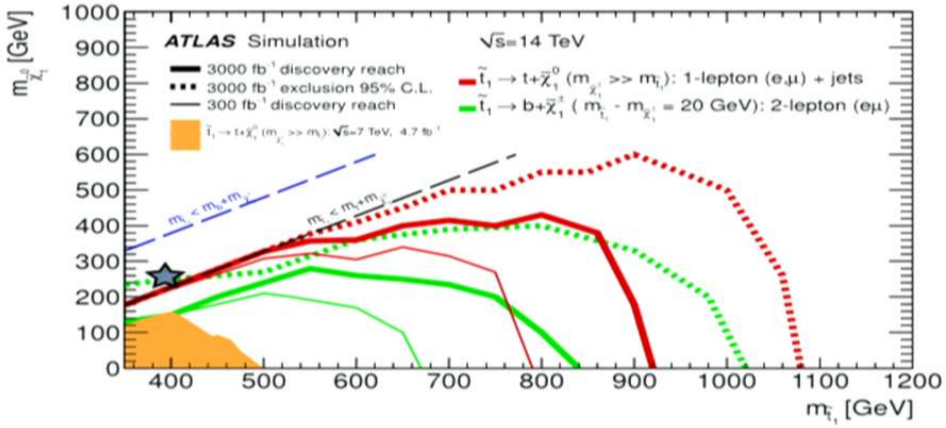
- Direct stop searches currently do not exclude big regions of parameter space with $\Delta_{\rm EFT} \sim 1/4$ or even ~1 in the "stealthy" region $m_{\tilde t} \approx m_t, m_\chi \approx 0$
- Gluino bounds OK too for now: $m_{\tilde g} < 4 m_{\tilde t}$ is 100% natural if gluino is Dirac

Minimalist SUSY

- Consider an "effective" SUSY theory with a 10 TeV cutoff [e.g. Brust, Katz, Lawrence, Sundrum, 1110.6670]
- Only superpartners canceling the largest contributions to m^2 must appear. Stops and gluinos are especially important at the LHC.
- One-loop fine-tuning estimate in the effective theory is simply

$$\Delta \approx \frac{3y_t^2 m_{\tilde{t}}^2}{8\pi^2} \log \frac{\Lambda^2}{m_{\tilde{t}}^2} \approx \left(\frac{m_{\tilde{t}}}{200\ \mathrm{GeV}}\right)^2$$

- In SUSY literature, fine-tuning is typically quantified by measuring the dependence of the Higgs mass on input parameters, usually at a high (GUT) scale
- The above estimate, "EFT FT", should be thought of as a rough model-independent lower bound on FT
- Can physics at >10 TeV reduce tuning? Logically possible, but no concrete convincing example so far.



- Even at 14 TeV, probing compressed spectra, as well as stealthy and RPV scenarios, will remain non-trivial in direct searches based on current strategies
- Taylor-made searches for these regions (e.g. ISR-tags to search for compressed spectra) may be developed
- An alternative approach: indirect search by measuring Higgs couplings

1. Higgs and Naturalness: General Argument

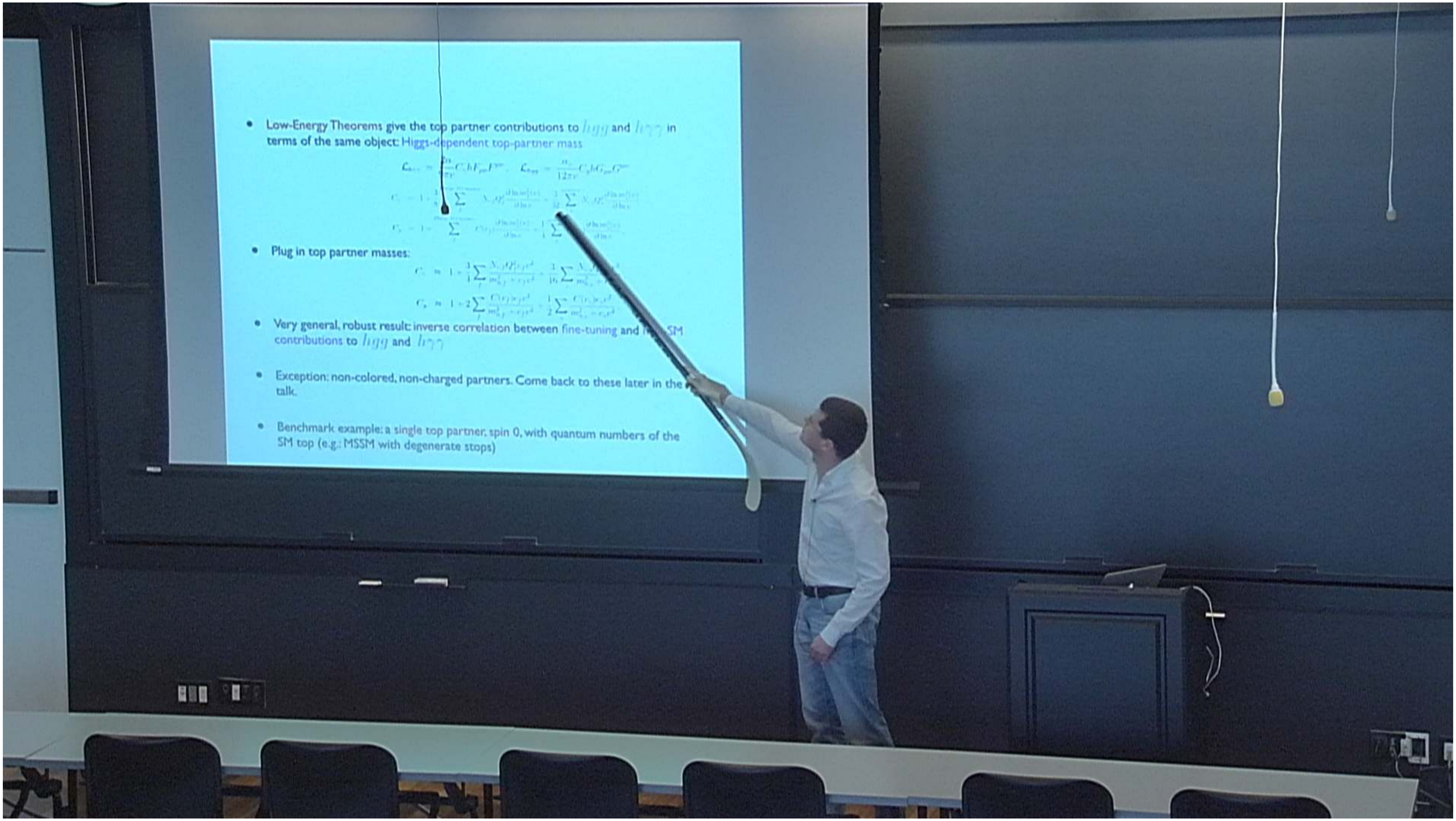
[Farina, MP, Rey Le-Lorier, 1305.6068]

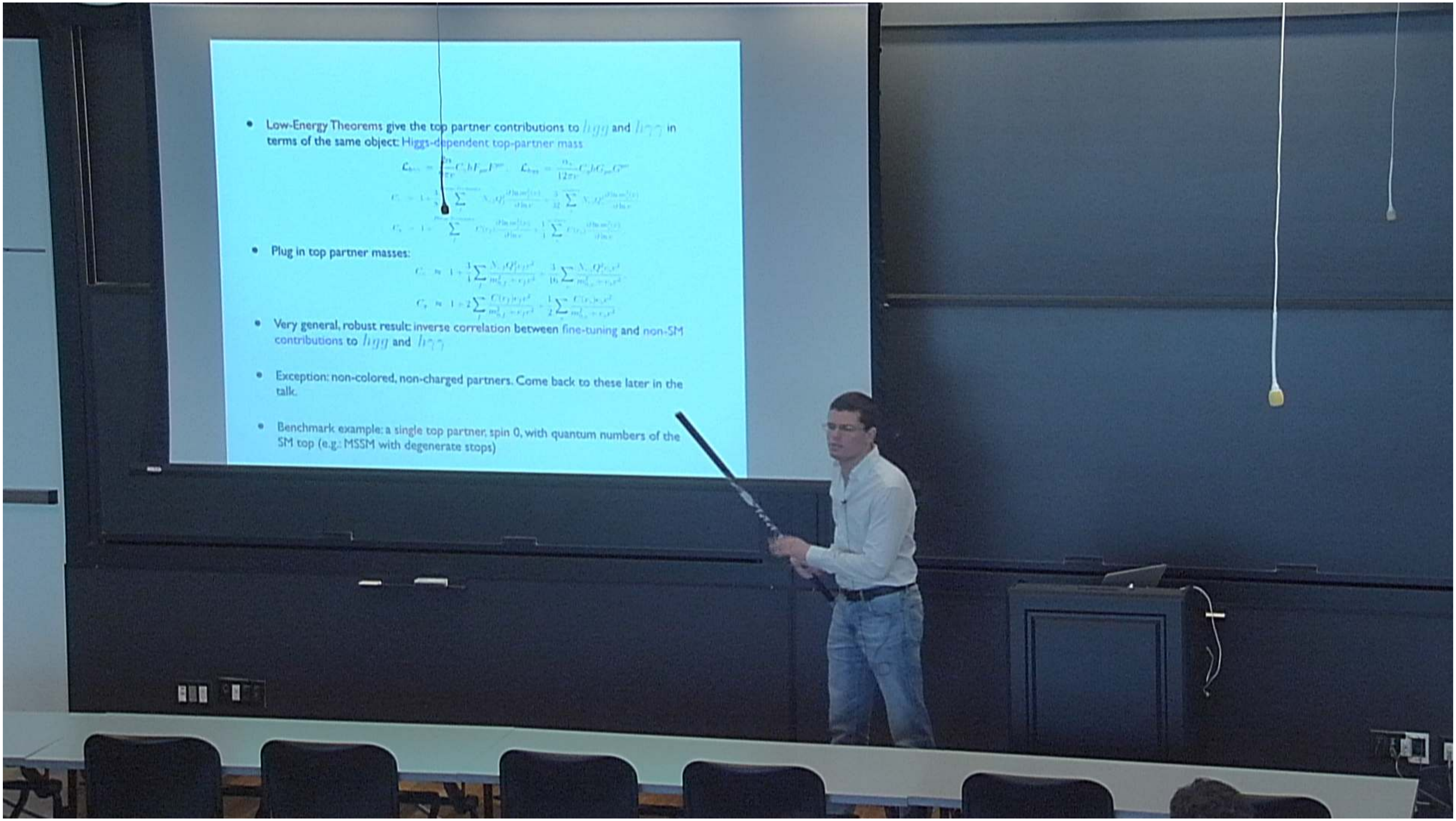
- One-loop quantum corrections to Higgs potential are given by the Coleman-Weinberg formula:

$$V_{\rm CW}(h) \;=\; \frac{1}{2}\sum_k g_k(-1)^{F_k}\int \frac{d^4\ell}{(2\pi)^4}\,\log\left(\ell^2+m_k^2(h)\right)$$

- The only input is Higgs-dependent masses of all particles; focus on tops
- The famous mass renormalization is just $\delta\mu^2 \equiv \frac{\delta^2 V_{\rm CW}}{\delta h^2}|_{h=0}$.
- Top partner mass is $m^2(T_i) = m_{0,i}^2 + c_i h^2 + \cdots$
- Cancellation of quadratic divergence gives a sum rule: $6y_t^2 = \sum_i g_i(-1)^{F_i}c_i$
- Potential fine-tuning comes from the next (log-divergent) term:

$$\Delta = \frac{\delta\mu^2}{\mu^2} \approx 0.78\left(\sum_i g_i(-1)^{F_i}c_i\left(\frac{m_{0,i}}{1\ \rm TeV}\right)^2\log\frac{\Lambda^2}{m_{0,i}^2} - 6y_t^2\left(\frac{m_t}{1\ \rm TeV}\right)^2\log\frac{\Lambda^2}{m_t^2}\right)$$


Low-Energy Theorems give the top partner contributions to hgg and hγγ in terms of the same object: Higgs-dependent top-partner mass
Plug in top partner masses:
Very general, robust result: inverse correlation between fine-tuning and
SM
contributions to hgg and hγγ
Exception: non-colored, non-charged partners. Come back to these later in the
talk.
Benchmark example: a single top partner, spin 0, with quantum numbers of the SM top (e.g.: MSSM with degenerate stops)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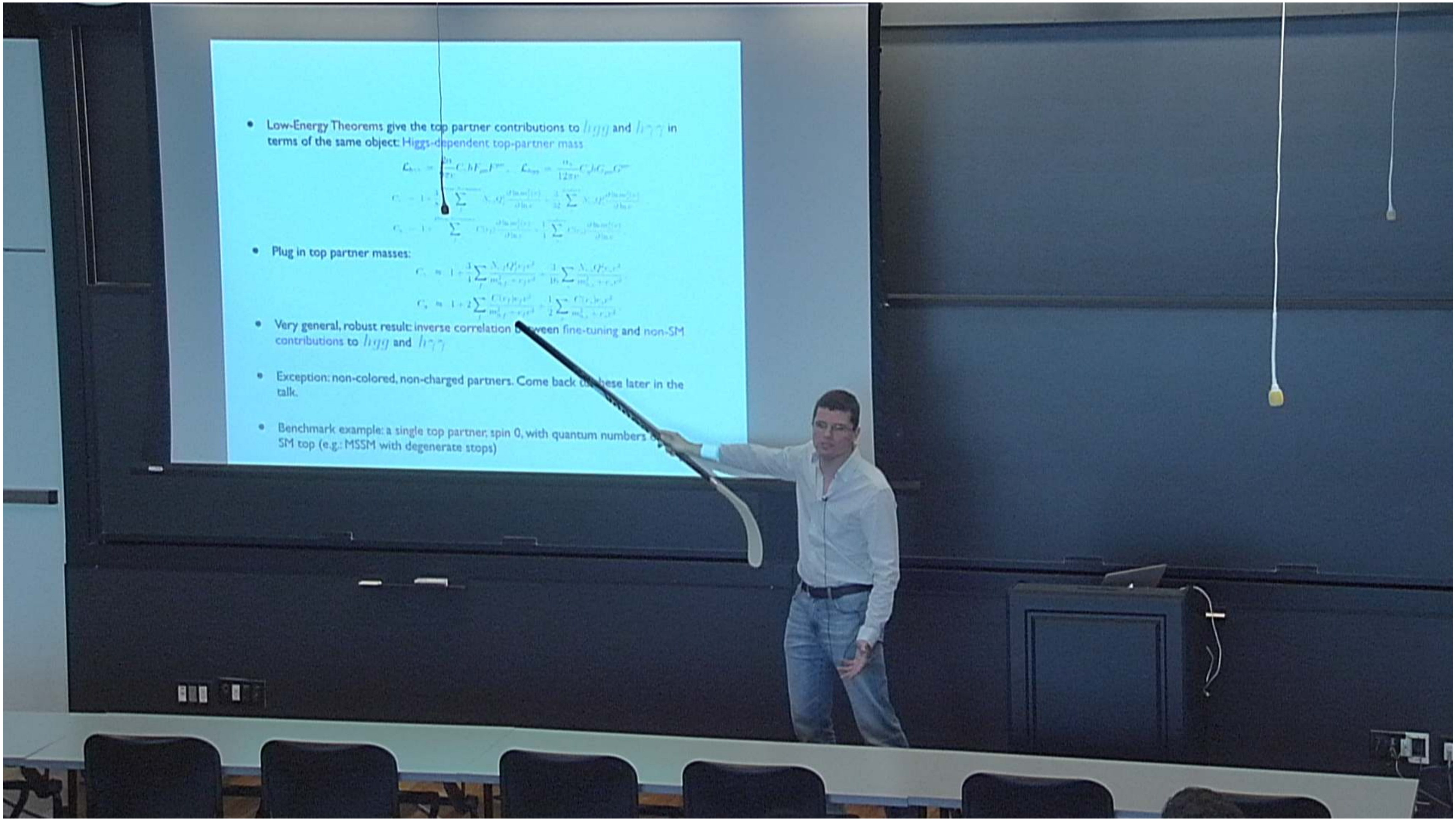

Low-Energy Theorems give the top partner contributions to hgg and $h\gamma\gamma$ in terms of the same object: Higgs-dependent top-partner mass
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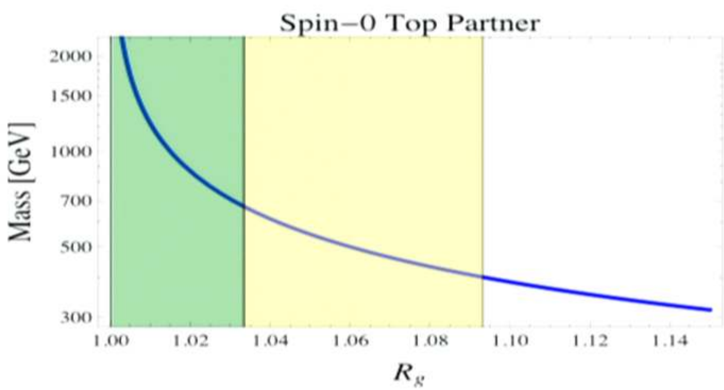

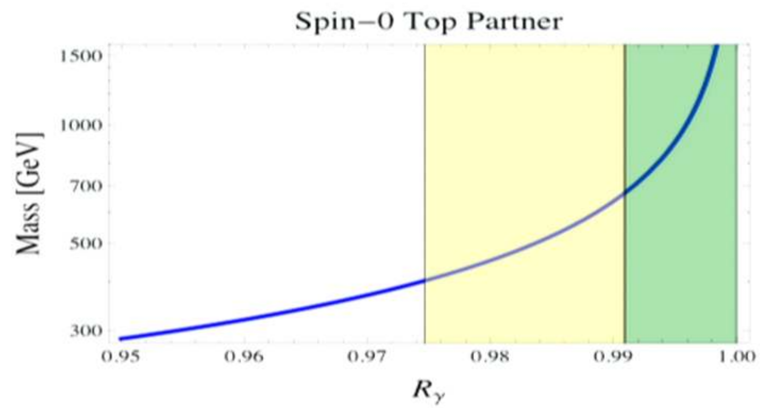

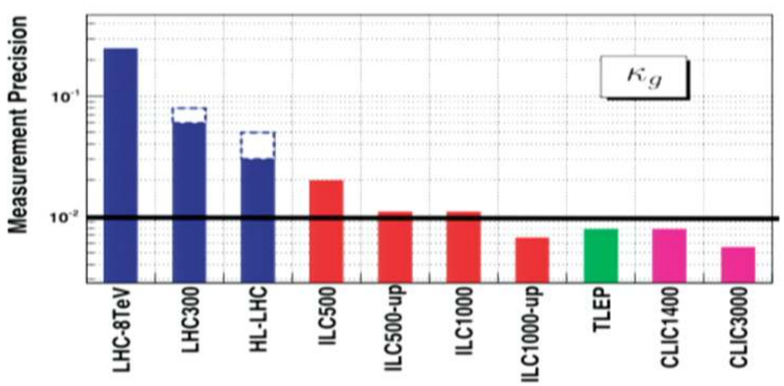

A 1% measurement of R_g would probe the top partner mass of ~1.2 TeV...

* assuming that a ~1% direct measurement of tth coupling is available! This needs e+e- @ 500 GeV

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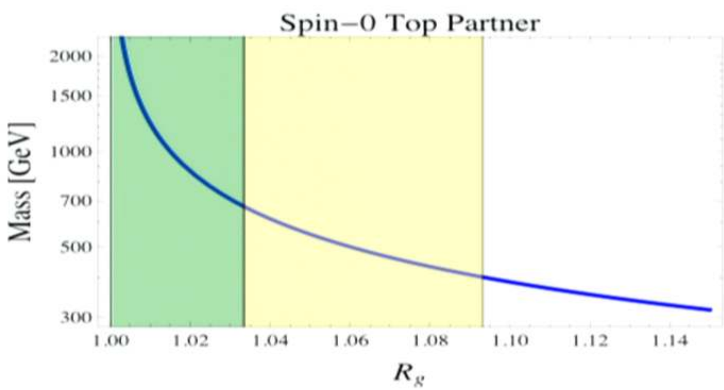

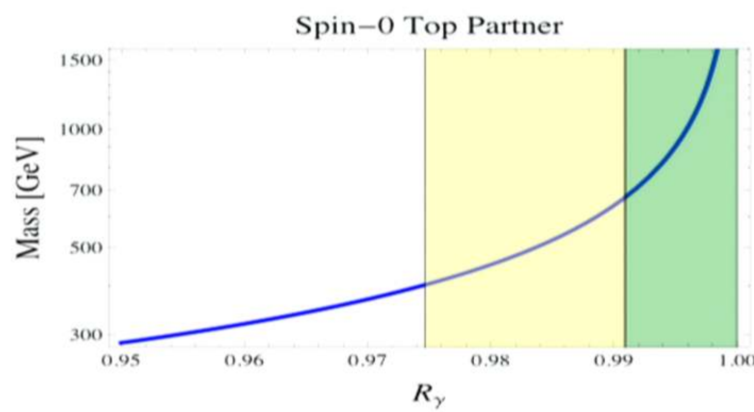

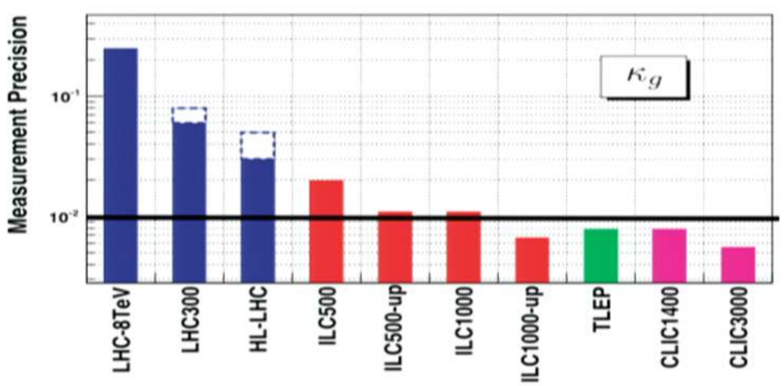

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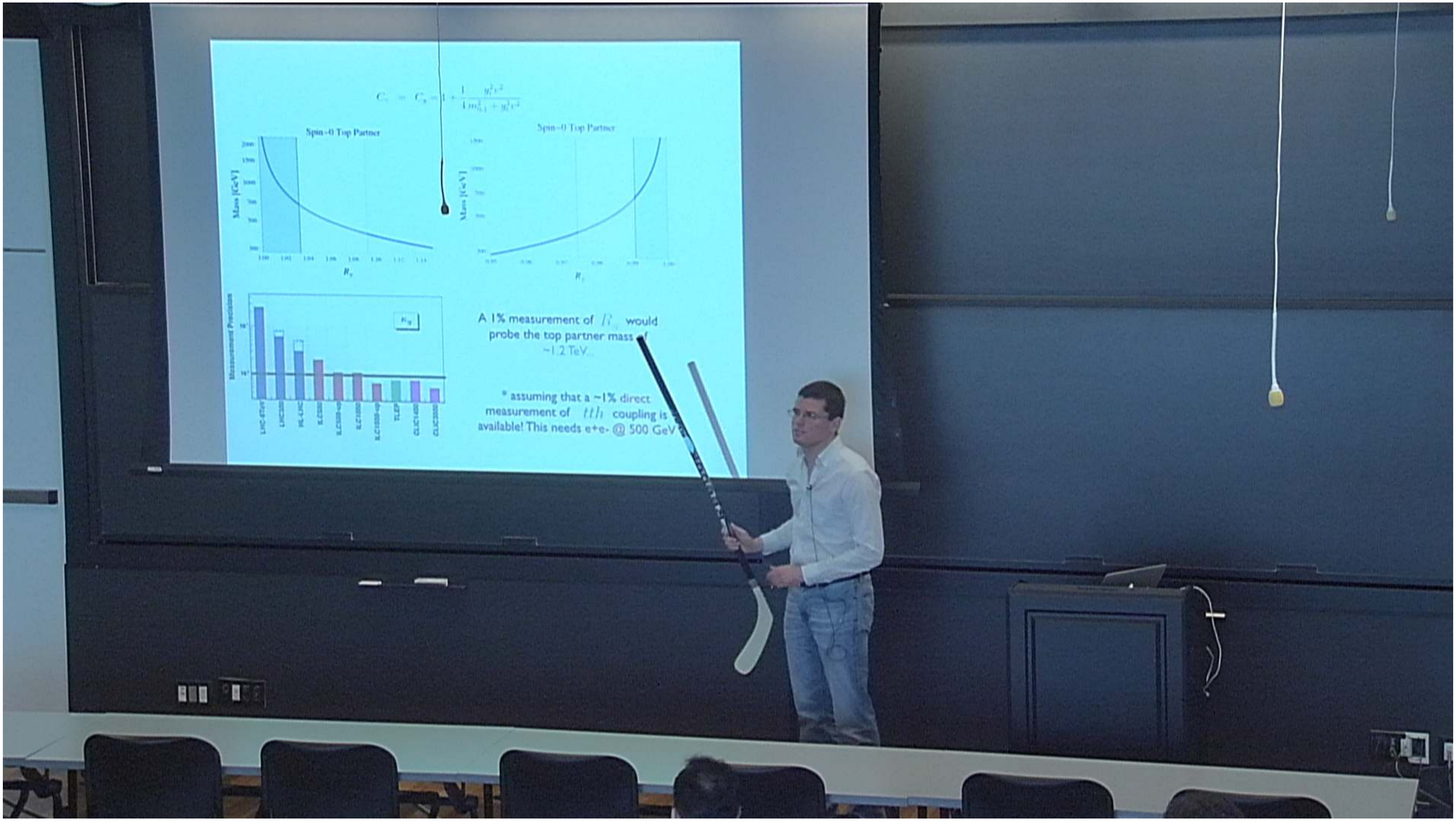
Spin-0 Top Partner
Mass [GeV]
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Mass [GeV]
Measurement Precision
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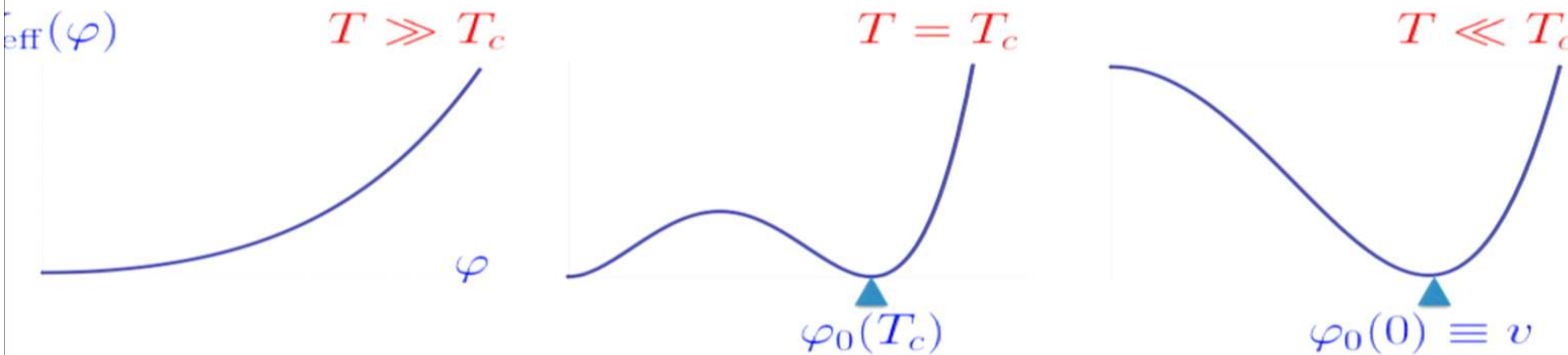
First-Order EWPT in Cartoons



- "Transition strength" ~ entropy release $\xi = \varphi_0(T_c)/T_c$
- Numerical studies: EW Baryogenesis possible if $\xi \geq 0.9$

HC and EWPT

- No possibility of producing "plasma" with restored EW symmetry (T-RHIC?) so no direct experimental probe
- However, hard to induce large modifications of the finite-T potential without also modifying T=0 Higgs potential and couplings
- Can precise measurements of Higgs couplings conclusively probe the nature of EWPT?
- Two basic mechanisms for first-order EWPT: tree-level mixing with other scalars; and loop-induced corrections (the famous Th^3 term)
- We will focus on loop-y models since they seem harder to probe

HC and EWPT: Setup

- The cubic term at high-T is induced by loops of scalars, not fermions
- Add a single complex scalar Φ, with $V_\Phi = m_0^2|\Phi|^2 + \kappa|\Phi|^2|H|^2 + \eta|\Phi|^4.$
- One-loop corrections to the potential at both T=0 and finite-T are well known:

$$V_1(\varphi) = \frac{g_i(-1)^{F_i}}{64\pi^2}\left[m_i^4(\varphi)\log\frac{m_i^2(\varphi)}{m_i^2(v)} - \frac{3}{2}m_i^4(\varphi) + 2m_i^2(\varphi)m_i^2(v)\right];$$

$$V_T(\varphi;T) = \frac{g_i T^4(-1)^{F_i}}{2\pi^2}\int_0^\infty dx\, x^2 \log\left[1-(-1)^{F_i}\exp\left(\sqrt{x^2+\frac{m_i^2(\varphi)}{T^2}}\right)\right],$$

- Again, the key object is the Higgs-dependent Φ mass! But recall:

$$\mathcal{L}_{h\gamma\gamma} = \frac{2\alpha}{9\pi v}C_\gamma h F_{\mu\nu}F^{\mu\nu}, \quad \mathcal{L}_{hgg} = \frac{\alpha_s}{12\pi v}C_g h G_{\mu\nu}G^{\mu\nu}$$

$$C_\gamma = 1 + \frac{3}{8}\sum_f^{Dirac\ fermions} N_{c,f}Q_f^2\frac{\partial \ln m_f^2(v)}{\partial \ln v} + \frac{3}{32}\sum_s^{scalars} N_{c,s}Q_s^2\frac{\partial \ln m_s^2(v)}{\partial \ln v}$$

$$C_g = 1 + \sum_f^{Dirac\ fermions} C(r_f)\frac{\partial \ln m_f^2(v)}{\partial \ln v} + \frac{1}{4}\sum_s^{scalars} C(r_s)\frac{\partial \ln m_s^2(v)}{\partial \ln v},$$

- Expect direct correlation between the size of the cubic coupling induced at finite-T and non-SM contributions to hgg and $h\gamma\gamma$ (unless Φ is color and EM-neutral)

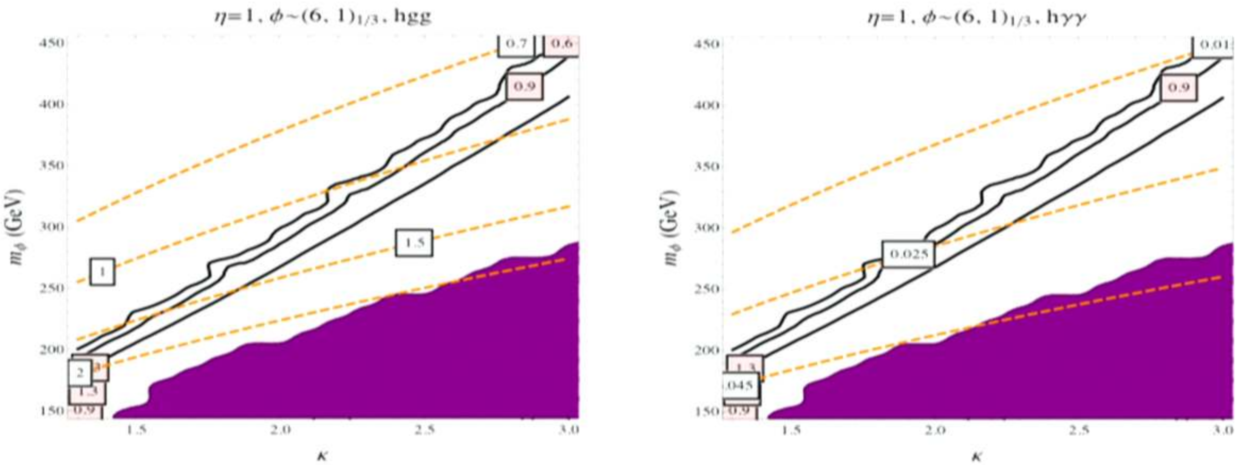
Analytic Example

- A special case can be studied analytically*: $m_0 = 0$
- High-temperature expansion of the thermal potential:

$$V_{\rm eff}(\varphi;T) = V_0(\varphi) + V_T(\varphi;T) \approx \frac{1}{2}\left(-\mu^2 + \frac{g_\Phi \kappa T^2}{24}\right)\varphi^2 - \frac{g_\Phi \kappa^{3/2} T}{24\sqrt{2}\pi}\varphi^3 + \frac{\lambda}{4}\varphi^4$$

- Location of the broken-symmetry minimum at finite T: $\frac{\partial V_{\rm eff}}{\partial \varphi} = 0$ ➡ $\varphi_0(T)$
- Critical temperature: $V_{\rm eff}(0, T_c) = V_{\rm eff}(\varphi_0(T_c), T_c)$
- Solve together: $T_c^2 = \frac{24\mu^2}{g_\Phi \kappa \left(1 - \frac{g_\Phi \kappa^2}{24\pi^2\lambda}\right)}, \quad \varphi_+(T_c) = \frac{g_\Phi \kappa^{3/2} T_c}{12\sqrt{2}\pi\lambda}.$
- Strongly 1-st order if $\kappa > 3.6\, g_\Phi^{-2/3}$
- Gluon-Higgs coupling: $R_g = \frac{1}{8}\frac{\kappa v^2}{m_0^2 + \kappa v^2} \approx 0.12$

Results: "Sextet"

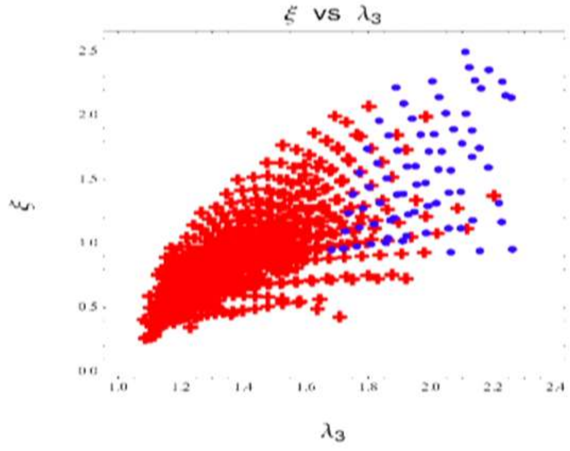


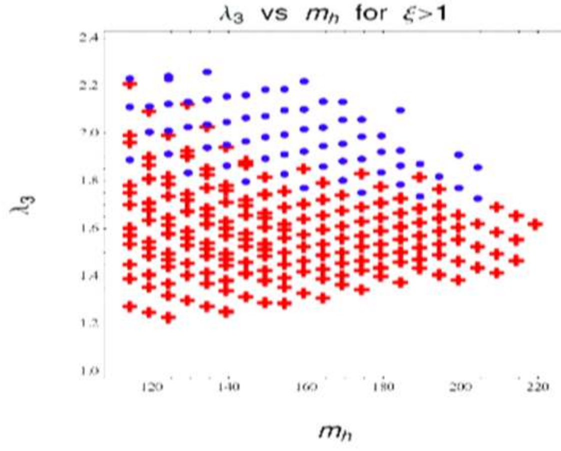
ATLAS: $R_g = 1.08 \pm 0.14,$ $R_\gamma = 1.23^{+0.16}_{-0.13}.$ → ruled out!*

[* usual caveat: SM total width assumed]

Higgs Self-Coupling

[Noble, MP, 0711.3018]





same correlation for Higgs self-coupling: deviations of 20% or more in a broad range of models with first-order EWPT

Measure it at a 100 TeV collider?

Conclusions: EWPT

- Strongly first-order EWPT, and with it Electroweak Baryogenesis, remains a viable possibility in a general BSM context
- We focused on the models where first-order EWPT is induced by loops of a BSM scalar, with various SM quantum numbers
- In the case of colored scalar, LHC-14 measurement of hgg will be able to conclusively probe the full parameter space with 1-sf order EWPT
- For non-colored scalars, e+e- Higgs factories will be necessary
- TLEP would be able to conclusively probe the full parameter space with 1-st order EWPT in all models, even if induced by a SM-singlet scalar