IPMU seminar, 19th July 2018

# The SM EFT framework and Cosmological Relaxation

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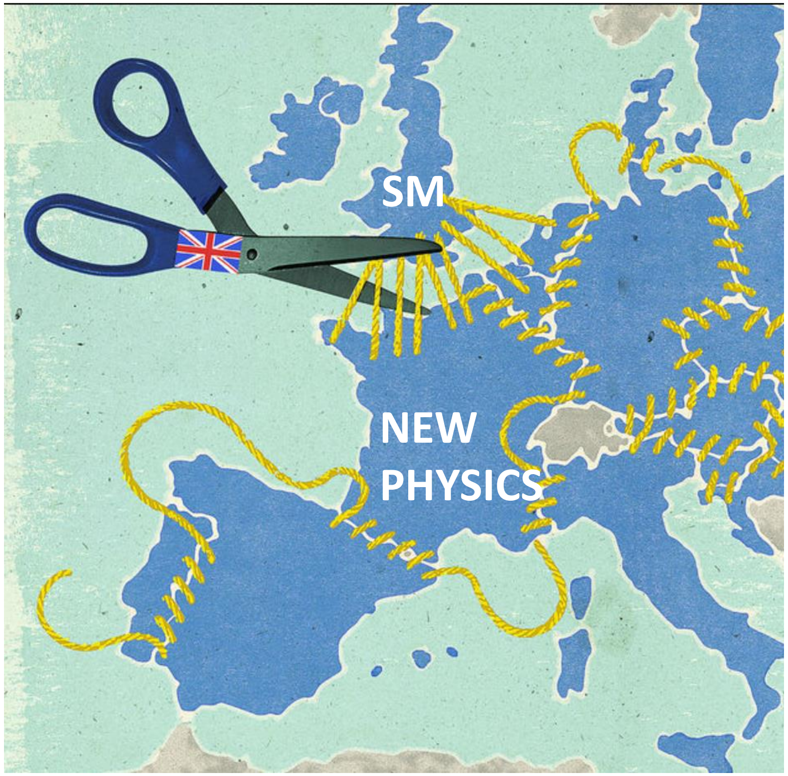
# SMEXIT

## Implications of decoupling new physics



# Introduction

- **Soft** exit from the SM: New physics around the corner

  - Usual *low-scale SUSY/compositeness/extra-dimensions*… just a bit more fine-tuned

  - *Neutral naturalness/Twin Higgs*… hidden naturalising sector

- **Hard** exit from the SM: New physics decoupled

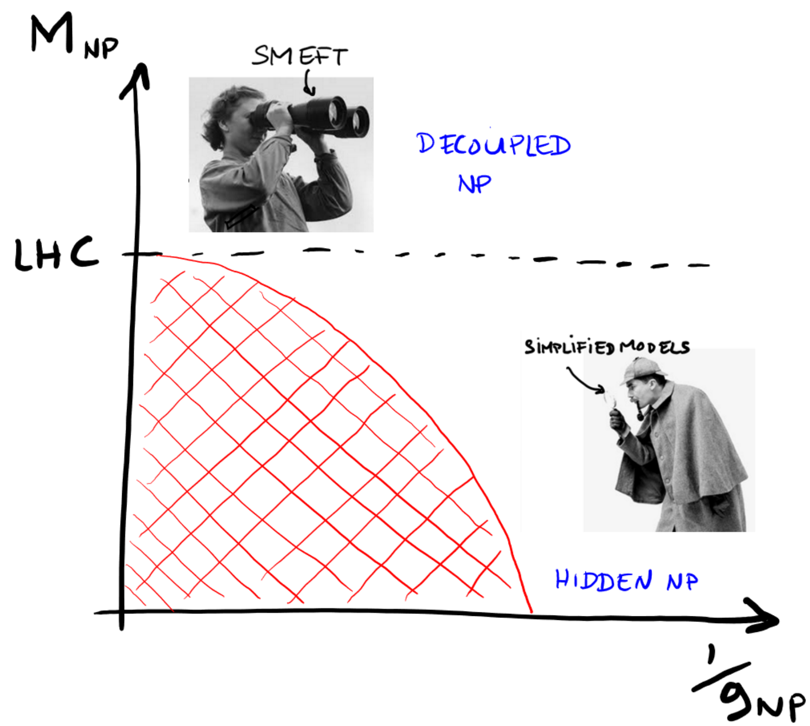
  - Accept fine-tuning while *SUSY/compositeness/extra-dimensions* resolve other problems at heavier scales

  - *Anthropic landscape, censorship-type approaches…*

  - *Cosmological relaxation, clockwork…*

  - Phenomenological framework: **SM EFT**

# Introduction




Spotted at CERN:

Free yourself from negative emotions with EFT (Emotional Freedom Techniques)

Find peace with high energies


- SM EFT a systematic approach to decoupled new physics
- Job is now to classify phenomenology, from bottom-up and top-down
- Precision experimental measurements may find a pattern of deviations

# Outline

- **Part I: SM EFT**
  - A phenomenological framework for decoupled new physics
- **Part 2: B Anomalies**
  - Signs of a non-zero Wilson coefficient?
- **Part 3: Cosmological Relaxation**
  - A new approach to decoupling new physics without fine-tuning

# References


**SM EFT:**

*-Updated Global SMEFT Fit to Higgs, Diboson and Electroweak Data*
**John Ellis, Christopher W. Murphy, Veronica Sanz** and **TY**
[arXiv:1803.03252]

*-Dimension-6 operator analysis of the CLIC sensitivity to new physics*
**John Ellis, Philipp Roloff, Veronica Sanz** and **TY**
**JHEP** 05 (2017) 096 [arXiv:1701.04804]

*-Sensitivities of Prospective Future e+e− Colliders to Decoupled New Physics*,
**John Ellis** and **TY**
**JHEP** 03 (2016) 089 [arXiv:1510.04561]

*-Comparing EFT and Exact One-Loop Analyses of Non-Degenerate Stops*,
**Aleksandra Drozd**, **John Ellis, Jeremie Quevillon** and **TY**
**JHEP** 06 (2015) 028 [arXiv:1504.02409]

*-The Effective Standard Model after LHC Run I*,
**John Ellis**, **Veronica Sanz** and **TY**
**JHEP** 29 (2015) 007 [arXiv:1410.7703]

**Cosmological Relaxation:**

*-A Dynamical Weak Scale From Inflation*,
**TY**
**JCAP** 1709 (2017) 09, 019 [arXiv:1701.09167]

*-Leptogenesis in Cosmological Relaxation with Particle Production*
**Minho Son, Fang Ye, TY**
1804.06599

**B anomalies:**

*-The Case for Future Colliders from B decays,*
**Ben Allanach, Ben Gripaios** and **TY**
**JHEP** 03 (2018) 021 [arXiv:1710.06363]

- **Part I: SM EFT**
- Part 2: B Anomalies
- Part 3: Cosmological Relaxation

# Why SM EFT?

Include only experimentally discovered degrees of freedom in our theory

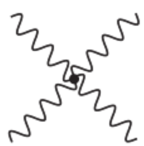
## The TeV Scale

What effective theory captures everything we know experimentally about weak interactions?

1933–1982 4-fermion interactions

$\sim G_F E^2 \qquad \Rightarrow \; \Lambda \sim \text{TeV}$

1982–2011 SM without Higgs



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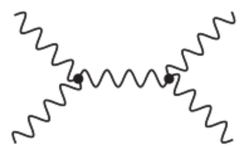


$\sim \dfrac{g^2 E^2}{m_W^2} \quad \Rightarrow \; \Lambda \sim \text{TeV}$

2012-now SM + higher-dimension operators?

$\Rightarrow \Lambda \lesssim M_P?$

Markus Luty PASCOS 2015 slide

# Why SM EFT?

Take a step back: recall the situation before 2012

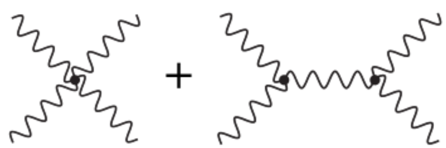
## The TeV Scale

What effective theory captures everything we know experimentally about weak interactions?

1933–1982 4-fermion interactions

$\sim G_F E^2 \quad \Rightarrow \Lambda \sim \text{TeV}$

1982–2011 SM without Higgs



$\sim \dfrac{g^2 E^2}{m_W^2} \quad \Rightarrow \Lambda \sim \text{TeV}$

2012-now SM + higher-dimension operators?

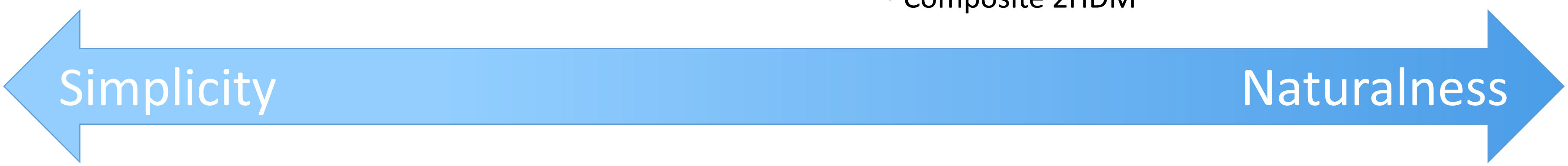
$\Rightarrow \Lambda \lesssim M_P?$

Markus Luty PASCOS 2015 slide

# Beyond the Standard Model?

- A priori many ways to break electroweak symmetry!

- Technicolor
- 2HDM
- Higgs + SUSY
- NMSSM
- Composite 2HDM




- Fundamental Scalar (SM Higgs)
- Composite Higgs
- Extra Dimensions
- Walking Technicolor
- Little Higgs

- But tension between simplicity and naturalness

# EFT for weak bosons

- 1980s-2012: Discovery of weak bosons. Non-linear effective Lagrangian for spontaneously-broken global symmetry (breaking mechanism unknown!)

- **Global** symmetry-breaking pattern gives low-energy effective theory regardless of UV mechanism responsible for it

$$SU(2) \times SU(2) \to SU(2)_V \qquad (\rho \equiv M_W / M_Z \cos\theta_w \sim 1)$$

$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma - m_i \bar{\psi}^i_L \Sigma \psi^i_R + \mathrm{h.c.}$$

$$\Sigma = \exp\left( i \frac{\sigma^a \pi^a}{v} \right)$$

# EFT for weak bosons + scalar

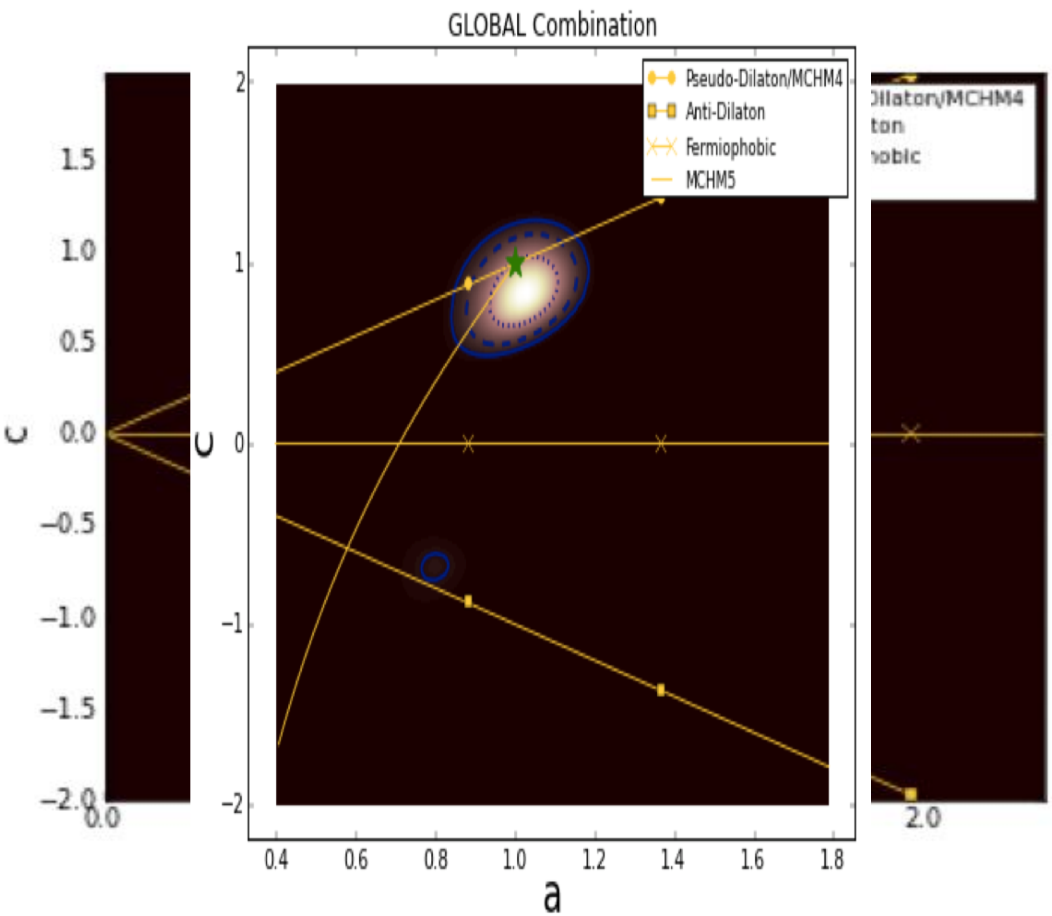
- 2012: Non-linear electroweak Lagrangian + general couplings to singlet scalar

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) - m_i \bar{\psi}^i_L \Sigma \left(1 + c\frac{h}{v} + \ldots\right)\psi^i_R + \mathrm{h.c.}$$
$$+ \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \quad ,$$

$$\Sigma = \exp\left(i\frac{\sigma^a \pi^a}{v}\right)$$

# Fit experimental data to couplings

- Could have had very different coupling patterns than SM!




July 2012 post-discovery

J. Ellis and T.Y. [arXiv:1207.1693]

# Why SM EFT?

Assuming a SM Higgs and decoupled new physics at higher energies, the SM EFT is the next phenomenological framework

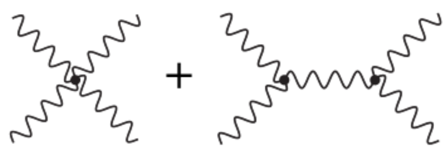
## The TeV Scale

What effective theory captures everything we know experimentally about weak interactions?

1933–1982 4-fermion interactions

$\sim G_F E^2 \quad \Rightarrow \Lambda \sim \text{TeV}$

1982–2011 SM without Higgs



$\sim \dfrac{g^2 E^2}{m_W^2} \quad \Rightarrow \Lambda \sim \text{TeV}$

2012-now SM + higher-dimension operators?

$\Rightarrow \Lambda \lesssim M_P?$

Markus Luty PASCOS 2015 slide

# Dimension-6 Operators

| | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|
| $Q_L$ | **3** | **2** | $\frac{1}{6}$ |
| $q_R^u$ | **3** | **1** | $\frac{2}{3}$ |
| $q_R^d$ | **3** | **1** | $-\frac{1}{3}$ |
| $L_L$ | **1** | **2** | $-\frac{1}{2}$ |
| $l_R$ | **1** | **1** | $-1$ |
| $\phi$ | **1** | **2** | $\frac{1}{2}$ |

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad + \quad \boxed{\mathcal{L}_{\rm SM}^{\rm dim\text{-}6} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i}$$

(+ dim-5 Weinberg operator)

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D_\mu^L Q_L + \bar{q}_R i\gamma^\mu D_\mu^R q_R + \bar{L}_L i\gamma^\mu D_\mu^L L_L + \bar{l}_R i\gamma^\mu D_\mu^R l_R$$
$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu}$$
$$\mathcal{L}_H = (D_\mu^L\phi)^\dagger(D^{L\mu}\phi) - V(\phi)$$
$$\mathcal{L}_Y = y_d\bar{Q}_L\phi q_R^d + y_u\bar{Q}_L\phi^c q_R^u + y_L\bar{L}_L\phi l_R + \text{h.c.} \quad ,$$

- First classified systematically by Buchmuller and Wyler (Nucl. Phys. B 268 (1986) 621)
- 59 dim-6 CP-even operators in a **non-redundant** basis, assuming minimal flavor structure (Gradkowski et al [arXiv:1008.4884])

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu|H|^2)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda|H|^6$$
$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2|H|^2 B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2|H|^2 G^A_{\mu\nu}G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon_{abc}W^{a\,\nu}_\mu W^b_{\nu\rho}W^{c\,\rho\mu}$$

Basis adopted from Pomarol and Riva 1308.1426

(SILH basis Giudice et al. hep-ph/0703164)

| | | |
|---|---|---|
| $\mathcal{O}_{y_u} = y_u\vert H\vert^2\bar{Q}_L\widetilde{H}u_R + \text{h.c.}$ | $\mathcal{O}_{y_d} = y_d\vert H\vert^2\bar{Q}_L H d_R + \text{h.c.}$ | $\mathcal{O}_{y_e} = y_e\vert H\vert^2\bar{L}_L H e_R + \text{h.c.}$ |
| $\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$<br>$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$<br>$\mathcal{O}_L^{(3)\,q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$ | $\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$ | $\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$ |
| $\mathcal{O}_{LL}^{(3)\,ql} = (\bar{Q}_L\sigma^a\gamma_\mu Q_L)(\bar{L}_L\sigma^a\gamma^\mu L_L)$ | | $\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L\sigma^a\gamma^\mu L_L)(\bar{L}_L\sigma^a\gamma_\mu L_L)$ |

+ four-fermion operators

# Modifications of EWPO from dim-6 Operators

- (Pseudo-)Observables

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_\ell + 3\Gamma_\nu \qquad R_\ell = \frac{\Gamma_{had}}{\Gamma_\ell} \qquad \sigma_{had} = 12\pi \frac{\Gamma_e \Gamma_{had}}{\hat{m}_Z^2 \Gamma_Z^2} \qquad A_{FB}^f = \frac{3}{4} A_e A_f \qquad M_W = c_W M_Z$$

$$R_q = \frac{\Gamma_q}{\Gamma_{had}}$$

- Depends on

$$\Gamma_f = \frac{\sqrt{2} G_F M_Z^2 \hat{M}_Z}{6\pi}\left[(g_L^f)^2 + (g_R^f)^2\right] \qquad A_f = \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}$$

$$g^f = T_f^3 - Q_f s_W^2 \qquad s_W^2 = \frac{1}{2} - \frac{1}{2}\sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_F m_Z^2}}$$

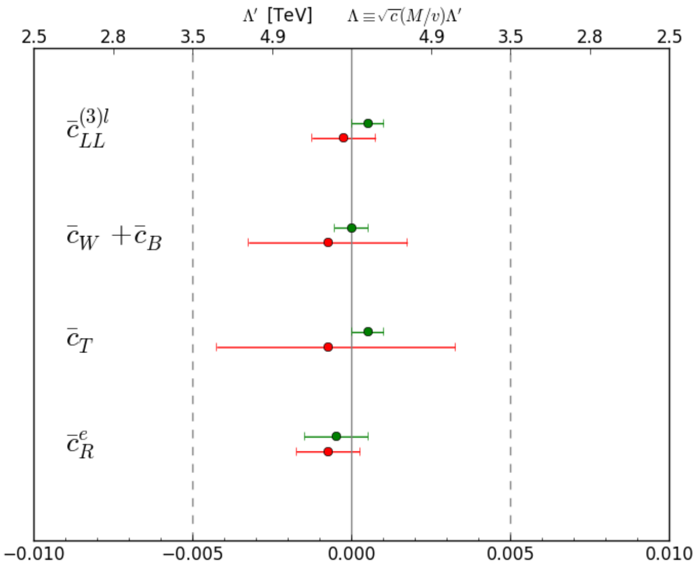
- Dim-6 operators can modify observables directly through Zff couplings contributions or indirectly through redefinitions of input observables

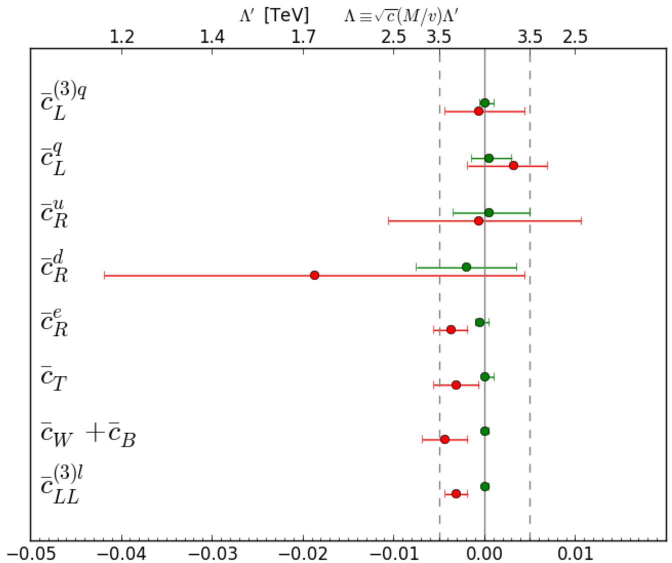
$$m_Z^2 = (m_Z^2)^0 (1 + \Pi_{ZZ}) \qquad G_F = G_F^0 (1 - \Pi_{WW}^0) \qquad \alpha(m_Z) = \alpha^0(m_Z)(1 + \Pi'_{\gamma\gamma})$$

# SM EFT Present Constraints

- Marginalized constraints on a complete non-redundant basis of dim-6 operators affecting EWPTs

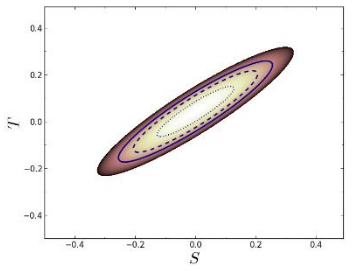
Ellis, Sanz and T.Y. 1410.7703



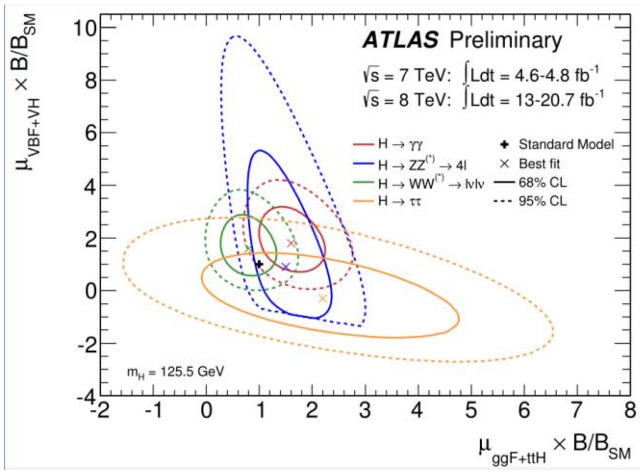

- S,T parameter corresponds to $(c_W + c_B)$, $c_T$ subset

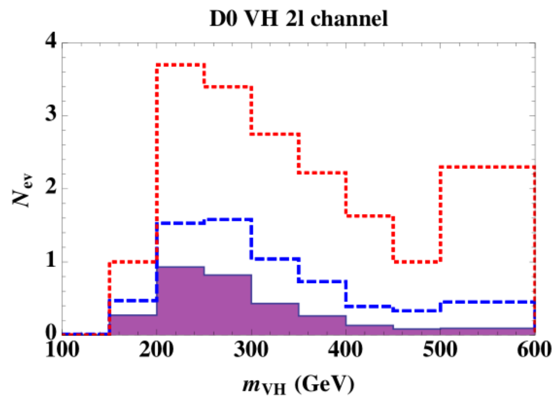
$$S = \frac{4\sin^2\theta_W}{\alpha(m_Z)}(\bar{c}_W + \bar{c}_B) \approx 119(\bar{c}_W + \bar{c}_B)$$
$$T = \frac{1}{\alpha(m_Z)}\bar{c}_T \approx 129\bar{c}_T\,.$$

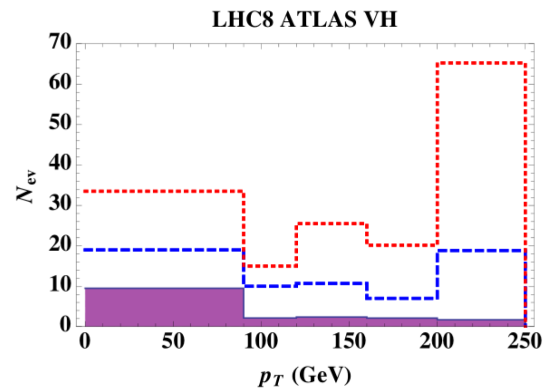


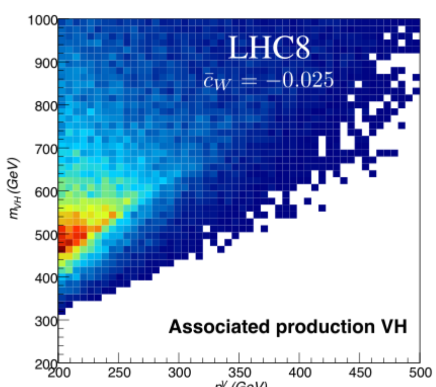
# Higgs constraints on dim-6 operators

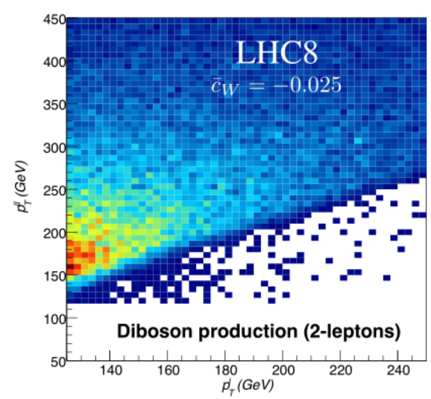
- Operators affect Higgs signal strength measurements, differential distributions



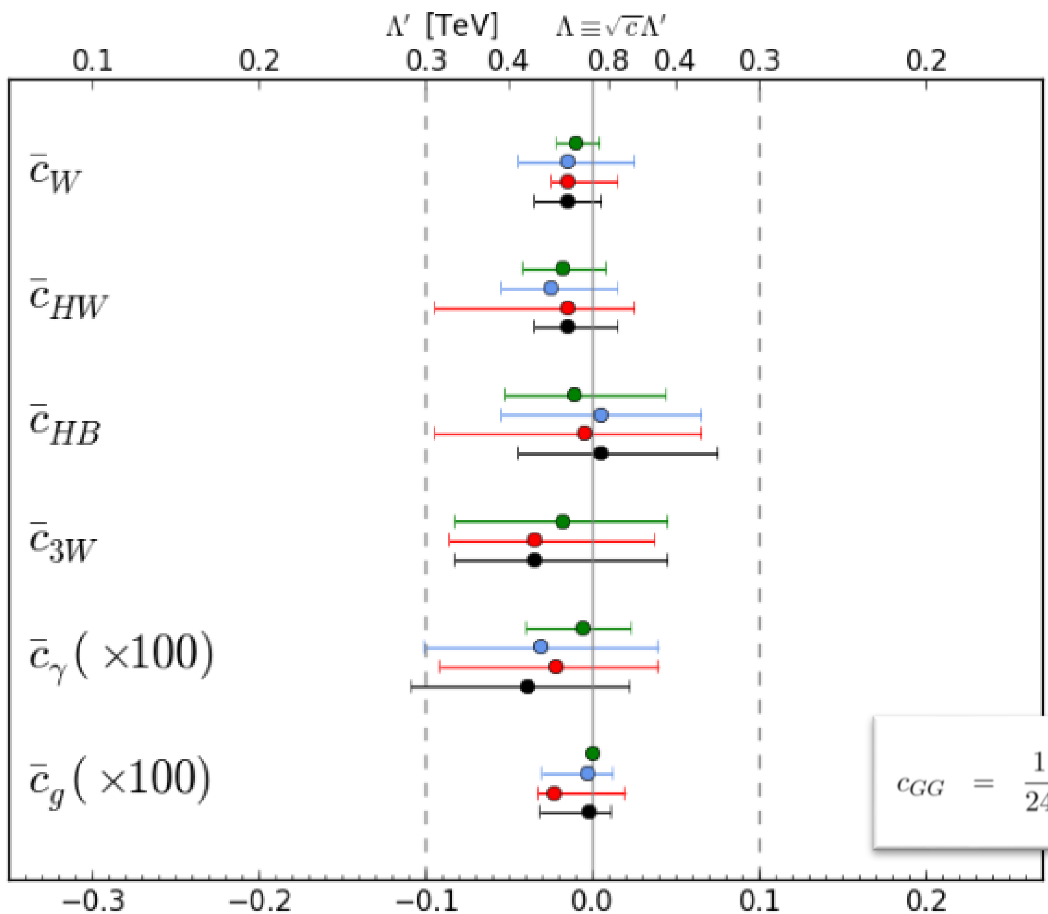




Ellis, Sanz and T.Y. 1410.7703

# SM EFT Present Constraints

- Constraints from LHC triple-gauge coupling measurements and Higgs physics

x 10 TeV




e.g. stops

$$\mathcal{O}_{GG} \;=\; g_s^2\,|H|^2\,G^a_{\mu\nu}G^{a,\mu\nu}$$

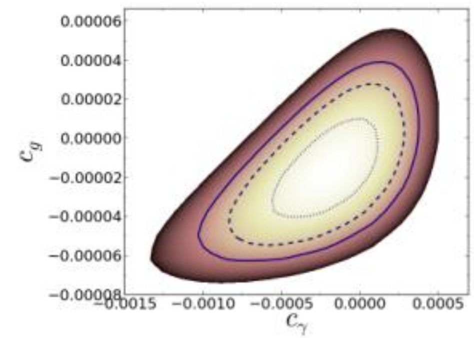
$$c_{GG} \;=\; \frac{1}{24}\left(\frac{h_t^2 - \frac{1}{6}g_1^2 c_{2\beta}}{m_{\tilde{Q}}^2} + \frac{h_t^2 + \frac{1}{3}g_1^2 c_{2\beta}}{m_{\tilde{t}_R}^2} - \frac{\tilde{X}_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2}\right)$$

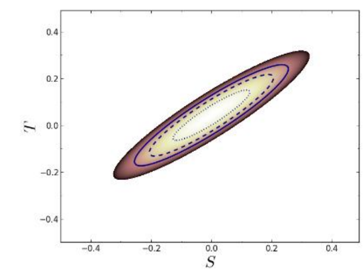
Ellis, Sanz and T.Y. 1410.7703

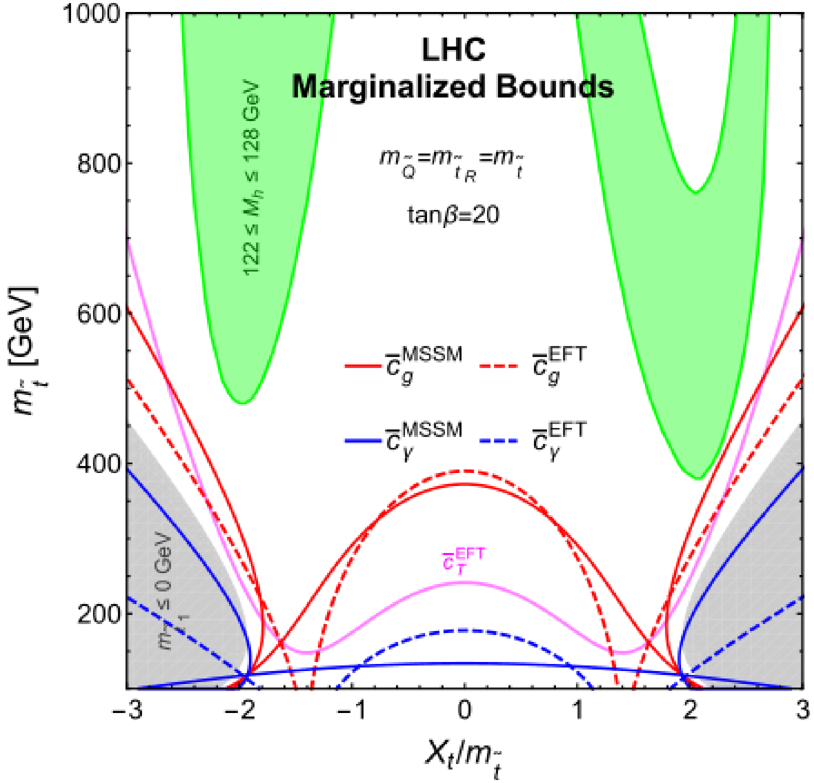
Tevong You

# Translating EFT Constraints to MSSM Stops

| Coeff. | Experimental constraints | | 95 % CL limit | deg. $m_{\tilde{t}_1}$, $X_t = 0$ |
|---|---|---|---|---|
| $\bar{c}_g$ | LHC | marginalized | $[-4.5, 2.2] \times 10^{-5}$ | $\sim 410$ GeV |
| | | individual | $[-3.0, 2.5] \times 10^{-5}$ | $\sim 390$ GeV |
| $\bar{c}_\gamma$ | LHC | marginalized | $[-6.5, 2.7] \times 10^{-4}$ | $\sim 215$ GeV |
| | | individual | $[-4.0, 2.3] \times 10^{-4}$ | $\sim 230$ GeV |
| $\bar{c}_T$ | LEP | marginalized | $[-10, 10] \times 10^{-4}$ | $\sim 290$ GeV |
| | | individual | $[-5, 5] \times 10^{-4}$ | $\sim 380$ GeV |
| $\bar{c}_W + \bar{c}_B$ | LEP | marginalized | $[-7, 7] \times 10^{-4}$ | $\sim 185$ GeV |
| | | individual | $[-5, 5] \times 10^{-4}$ | $\sim 195$ GeV |



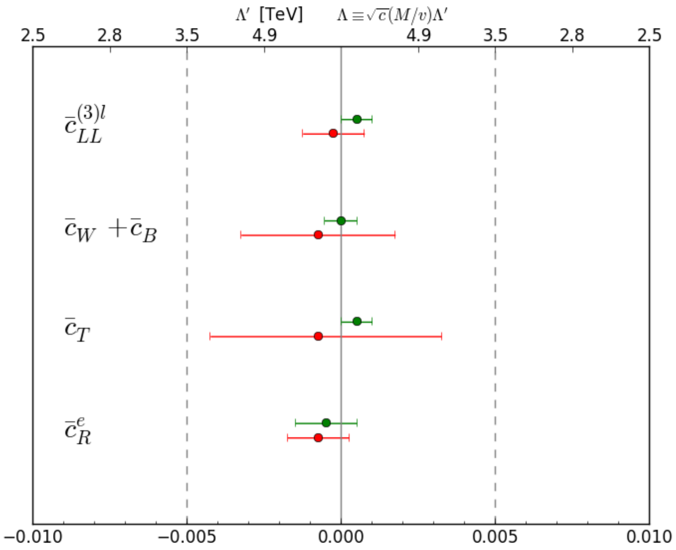




Drozd, Ellis, Quevillon and T.Y.
1504.02409

# FCC-ee EWPT Constraints

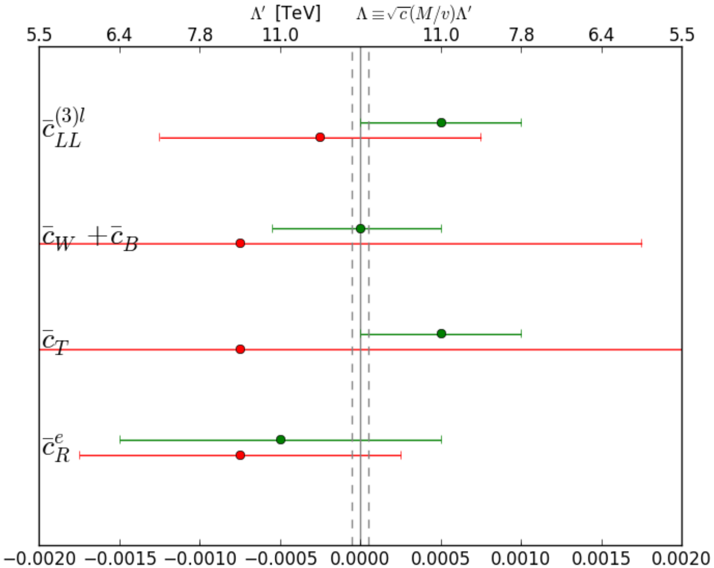
Tevong You




LEP

# FCC-ee EWPT Constraints

Tevong You

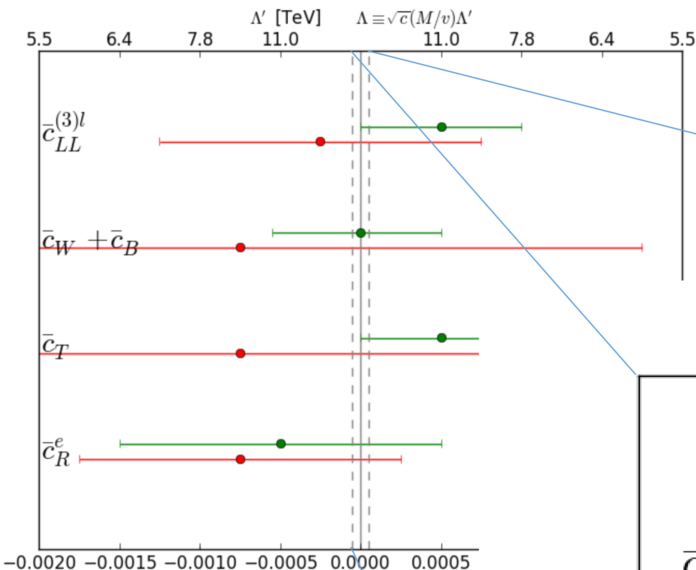



LEP

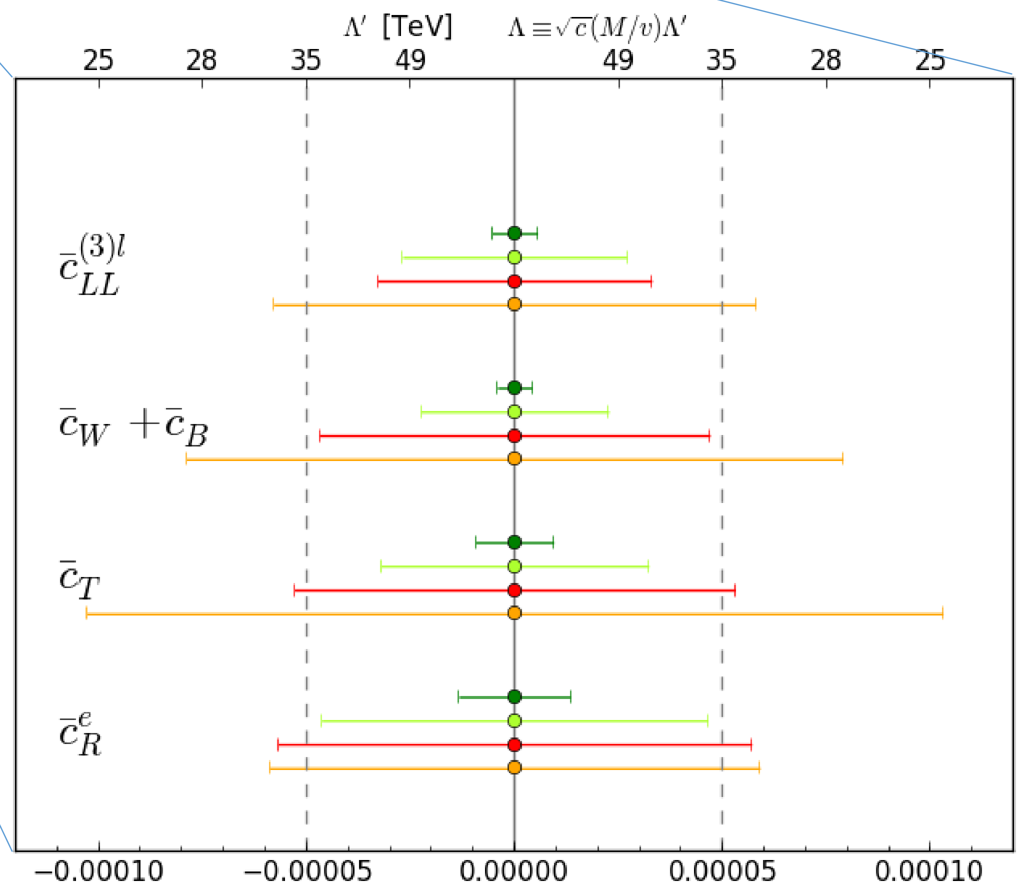
Tevong You

# FCC-ee EWPT Constraints

J. Ellis and T.Y. [arXiv:1510:04561]




LEP




FCC-ee

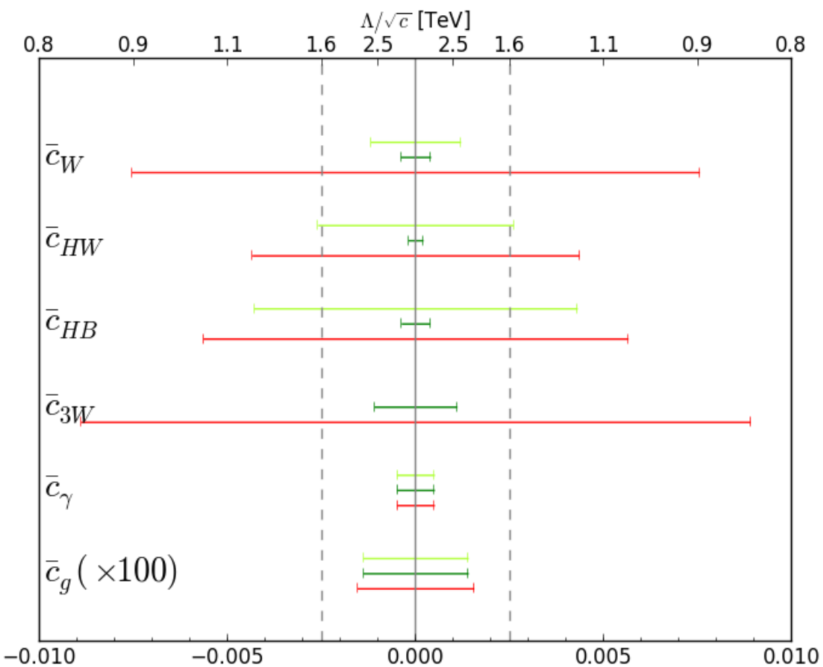
-Dark green: One-by-one (exp. uncertainty only)

-Light green: One-by-one (exp + TH uncertainty)

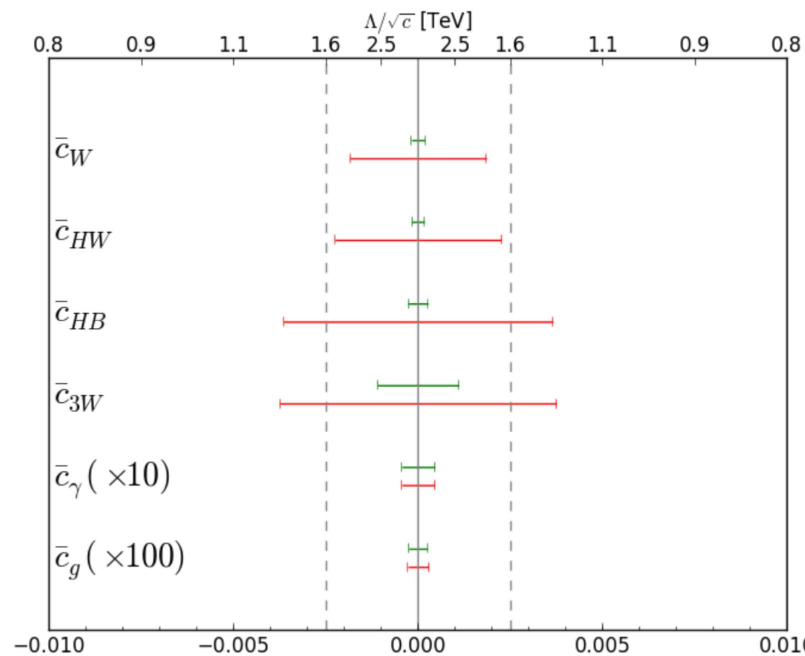
-Red: Marginalised (exp. uncertainty only)

-Orange: Marginalised (exp + TH uncertainty

# Future Higgs Constraints




**ILC**




**FCC-ee**

- Similar precision to current EWPT

# Future Constraints to MSSM Stops

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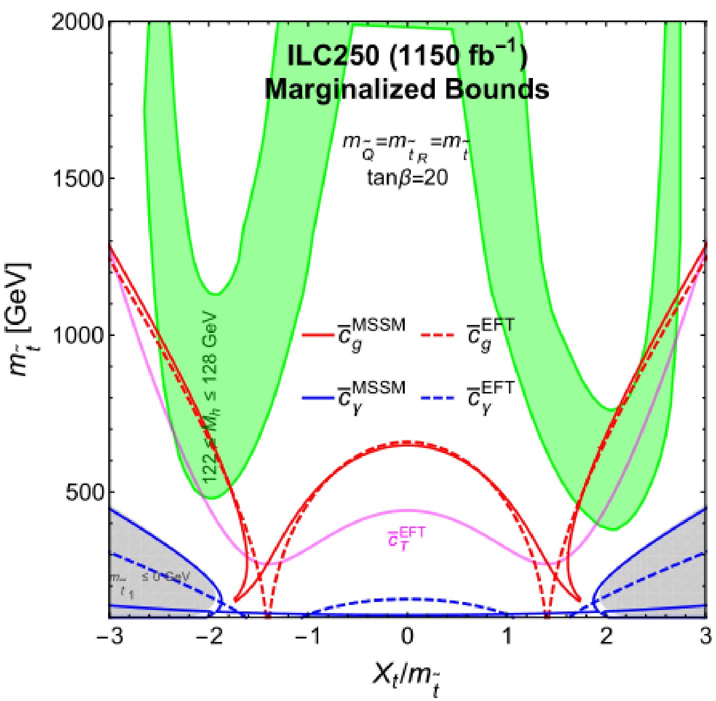
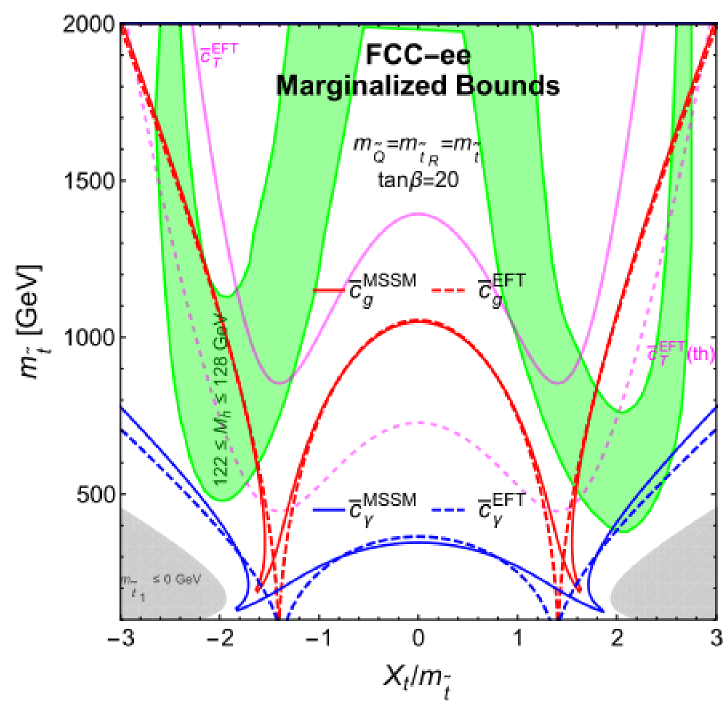
| Coeff. | Experimental constraints | | 95 % CL limit | deg. $m_{\tilde{t}_1}$ $X_t = 0$ | deg. $m_{\tilde{t}_1}$ $X_t = m_{\tilde{t}}/2$ |
|---|---|---|---|---|---|
| $\bar{c}_g$ | $\mathrm{ILC}^{1150\mathrm{fb}^{-1}}_{250\mathrm{GeV}}$ | marginalized | $[-7.7, 7.7] \times 10^{-6}$ | $\sim 675$ GeV | $\sim 520$ GeV |
| | | individual | $[-7.5, 7.5] \times 10^{-6}$ | $\sim 680$ GeV | $\sim 545$ GeV |
| | FCC-ee | marginalized | $[-3.0, 3.0] \times 10^{-6}$ | $\sim 1065$ GeV | $\sim 920$ GeV |
| | | individual | $[-3.0, 3.0] \times 10^{-6}$ | $\sim 1065$ GeV | $\sim 915$ GeV |
| $\bar{c}_\gamma$ | $\mathrm{ILC}^{1150\mathrm{fb}^{-1}}_{250\mathrm{GeV}}$ | marginalized | $[-3.4, 3.4] \times 10^{-4}$ | $\sim 200$ GeV | $\sim 40$ GeV |
| | | individual | $[-3.3, 3.3] \times 10^{-4}$ | $\sim 200$ GeV | $\sim 35$ GeV |
| | FCC-ee | marginalized | $[-6.4, 6.4] \times 10^{-5}$ | $\sim 385$ GeV | $\sim 250$ GeV |
| | | individual | $[-6.3, 6.3] \times 10^{-5}$ | $\sim 390$ GeV | $\sim 260$ GeV |
| $\bar{c}_T$ | $\mathrm{ILC}^{1150\mathrm{fb}^{-1}}_{250\mathrm{GeV}}$ | marginalized | $[-3, 3] \times 10^{-4}$ | $\sim 480$ GeV | $\sim 285$ GeV |
| | | individual | $[-7, 7] \times 10^{-5}$ | $\sim 930$ GeV | $\sim 780$ GeV |
| | FCC-ee | marginalized | $[-3, 3] \times 10^{-5}$ | $\sim 1410$ GeV | $\sim 1285$ GeV |
| | | individual | $[-0.9, 0.9] \times 10^{-5}$ | $\sim 2555$ GeV | $\sim 2460$ GeV |
| $\bar{c}_W + \bar{c}_B$ | $\mathrm{ILC}^{1150\mathrm{fb}^{-1}}_{250\mathrm{GeV}}$ | marginalized | $[-2, 2] \times 10^{-4}$ | $\sim 230$ GeV | $\sim 170$ GeV |
| | | individual | $[-6, 6] \times 10^{-5}$ | $\sim 340$ GeV | $\sim 470$ GeV |
| | FCC-ee | marginalized | $[-2, 2] \times 10^{-5}$ | $\sim 545$ GeV | $\sim 960$ GeV |
| | | individual | $[-0.8, 0.8] \times 10^{-5}$ | $\sim 830$ GeV | $\sim 1590$ GeV |

Drozd, Ellis, Quevillon and T.Y.
1504.02409

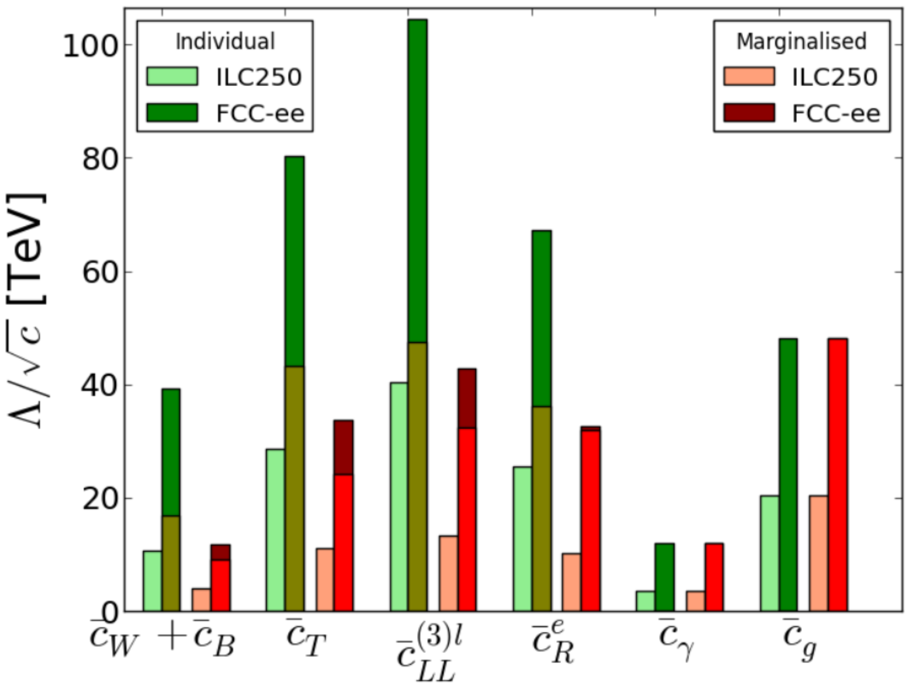


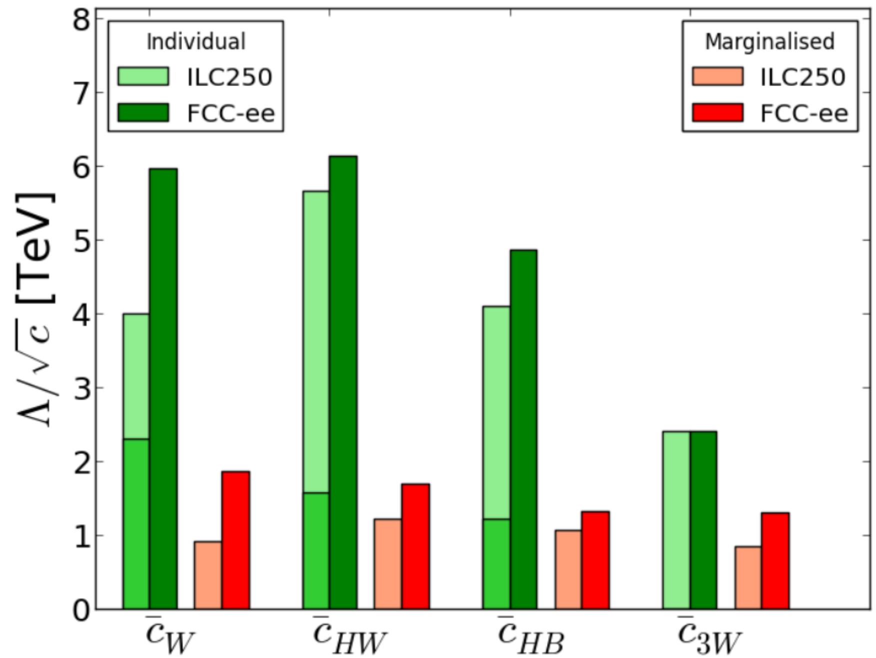



# Future e+e- Constraints

J. Ellis and T.Y. [arXiv:1510:04561]

## ILC and FCC-ee




- Future precision sensitive to TeV scale, even for loop-induced operators

- One-loop matching simplified by a **Universal One-Loop Effective Action**

*Henning, Lu, Murayama, 1412.1837;*
*Drozd, J. Ellis, Quevillon, TY, 1512.03003;*
*S.A.R. Ellis, Quevillon, TY, Z. Zhang, 1604.02445, 1706.07765.*

- Part I: SM EFT
- **Part 2: B Anomalies**
- Part 3: Cosmological Relaxation

# B anomalies

$$\mathcal{O}^l_{ij} = (\bar{s}\gamma^\mu P_i b)(\bar{l}\gamma_\mu P_j l)$$

- Anomalies in processes involving $\mathrm{b} \to s\, \mu^+\mu^-$ transitions:

- LHCb 3.4 σ in P5' angular distribution of $\mathrm{B} \to K^*\, \mu^+\mu^-$ (2 σ for Belle)
- Various other kinematic observables in $\mathrm{b} \to s\, \mu^+\mu^-$
- 3.2 σ in $B_s \to \varphi\, \mu^+\mu^-$
- ~4 σ non-zero Wilson coefficient in global fit to these "messy" observables

- 2.5 σ in "clean" observable $R_K$
- 2.5 σ in "clean" observable $R_K^*$
- ~4 σ non-zero Wilson coefficient in combined fit to just these two clean observables

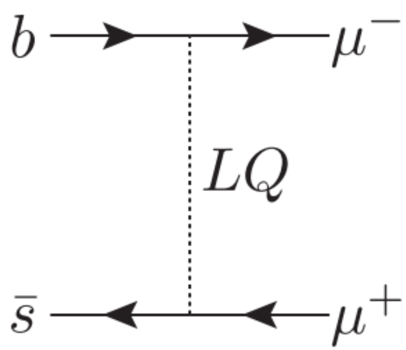
- *Consistency* of all these various anomalies is non-trivial

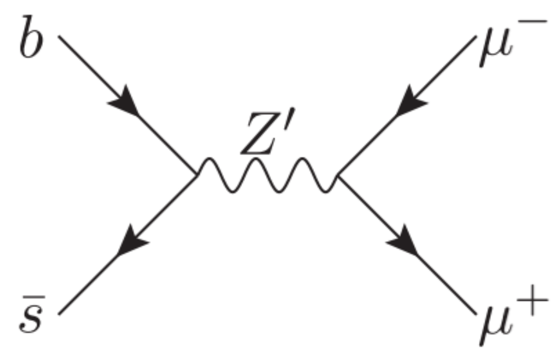
# Motivation for future colliders

- If $b \to s\mu^+\mu^-$ anomalies are confirmed, can we *definitely* discover directly the source (i.e. LQ/Z′) at higher energies? (80 TeV unitarity limit = **no general no-lose theorem** at FCC-hh)

Di Luzio, Nardecchia [1706.01868]

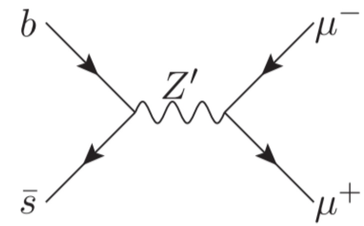
- Consider sensitivity to most **pessimistic** scenario: only include minimal couplings required to explain $b \to s\mu^+\mu^-$ anomalies



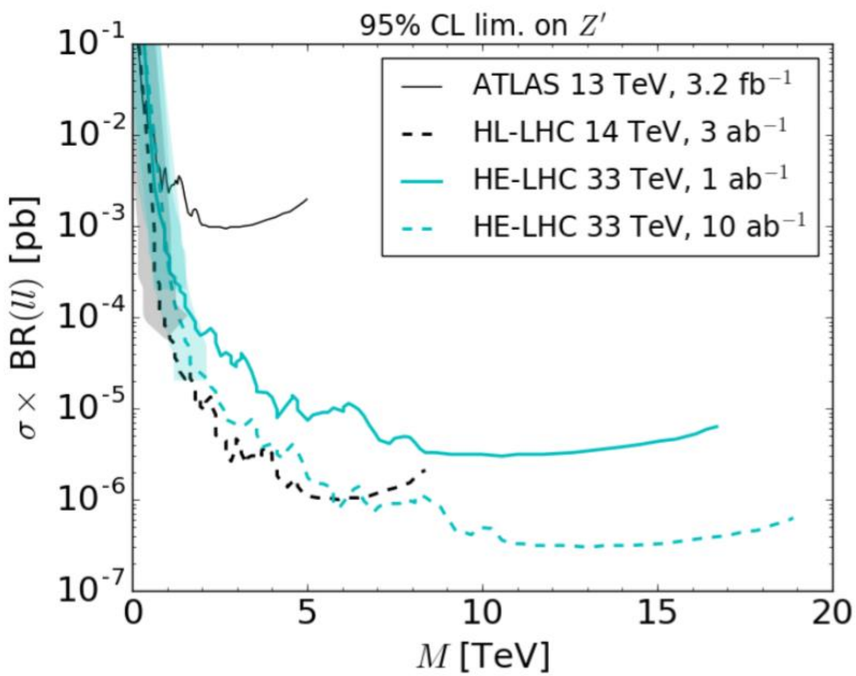



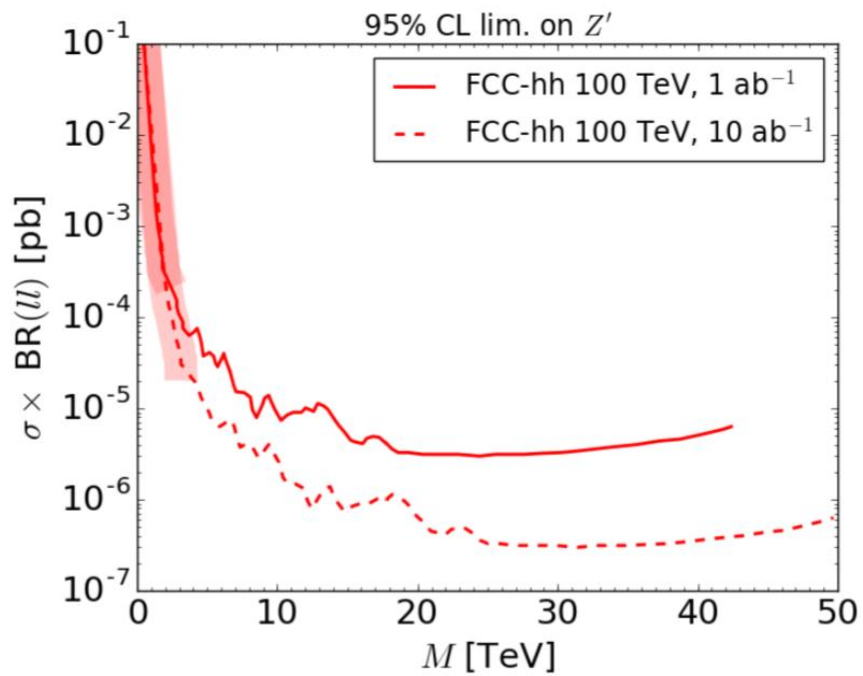

- More realistic models will only be *easier* to discover

# Z′ Sensitivity



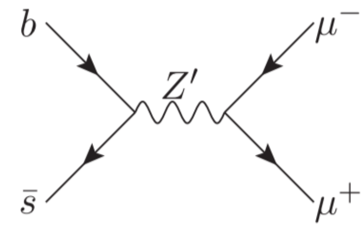

- Extrapolate current 13 TeV di-muon search:




- Actual limits depend on $Z'$ couplings in signal x-section

# Z′ Sensitivity

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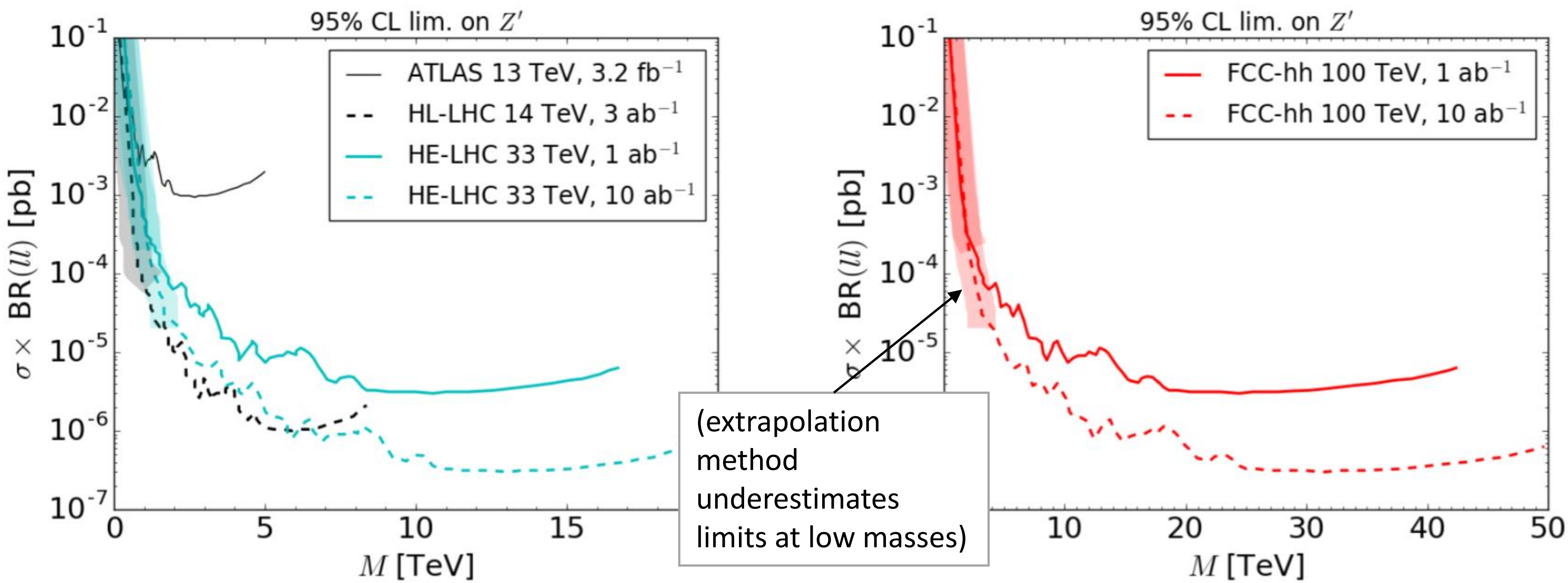


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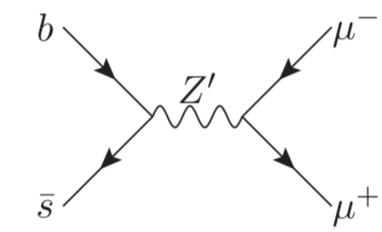


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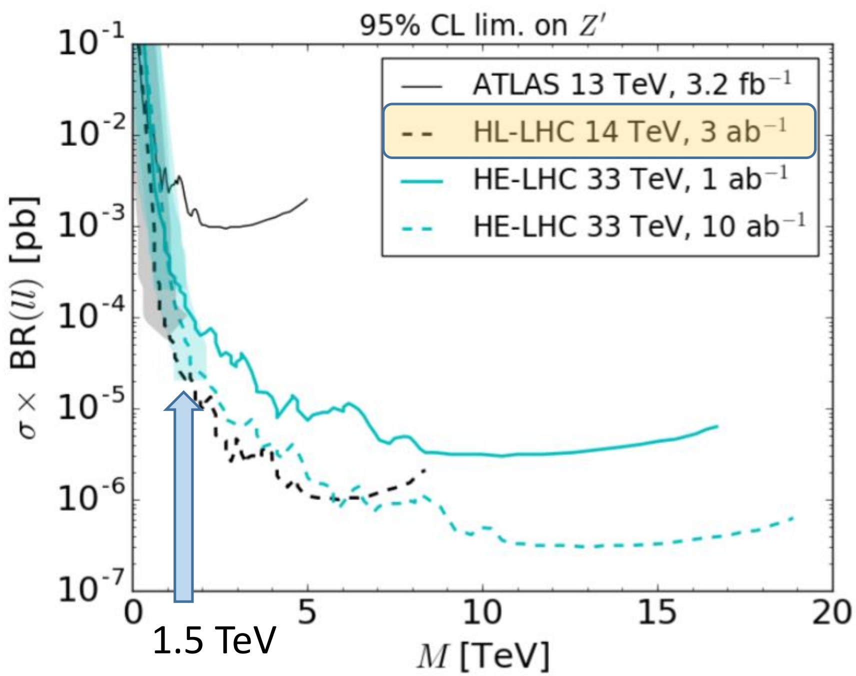


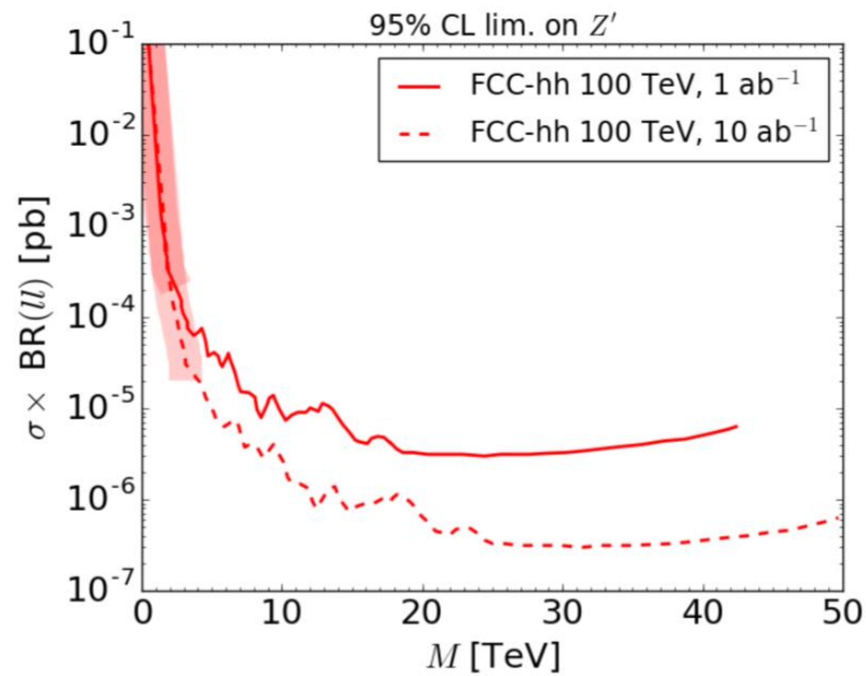


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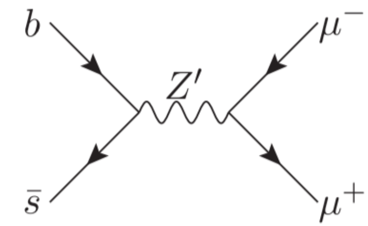
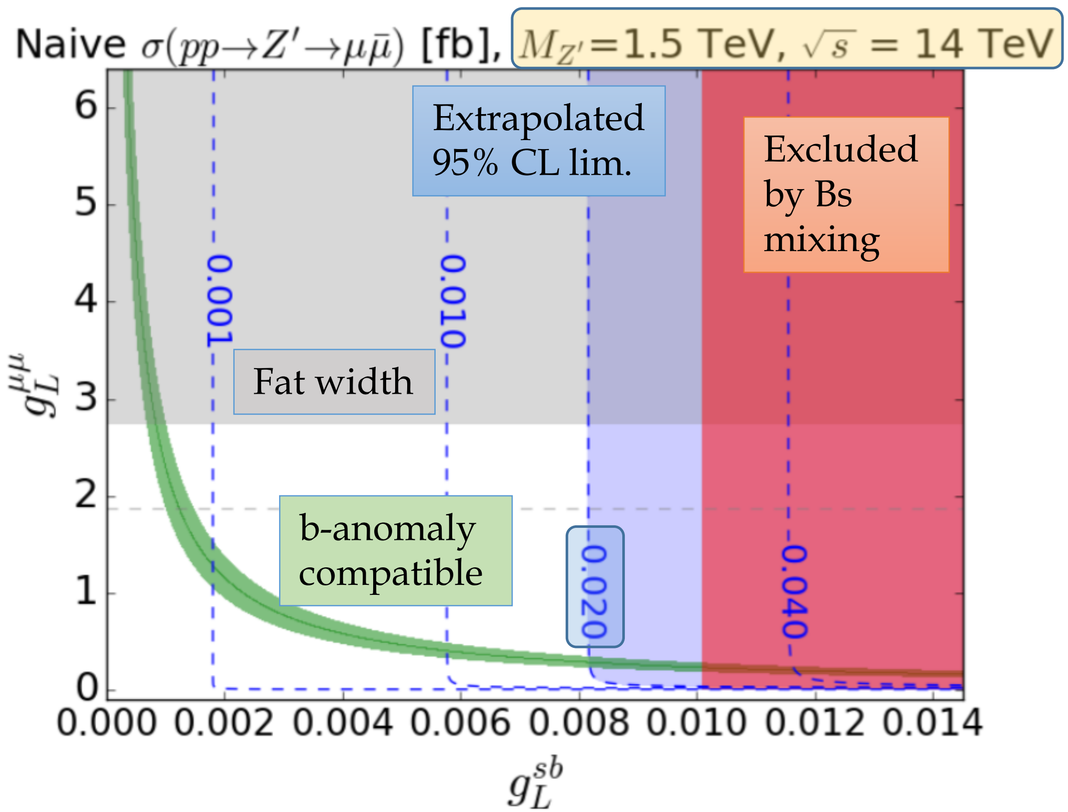
# Z′ Sensitivity




- Extrapolate current 13 TeV di-muon search:

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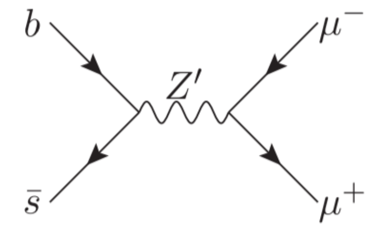
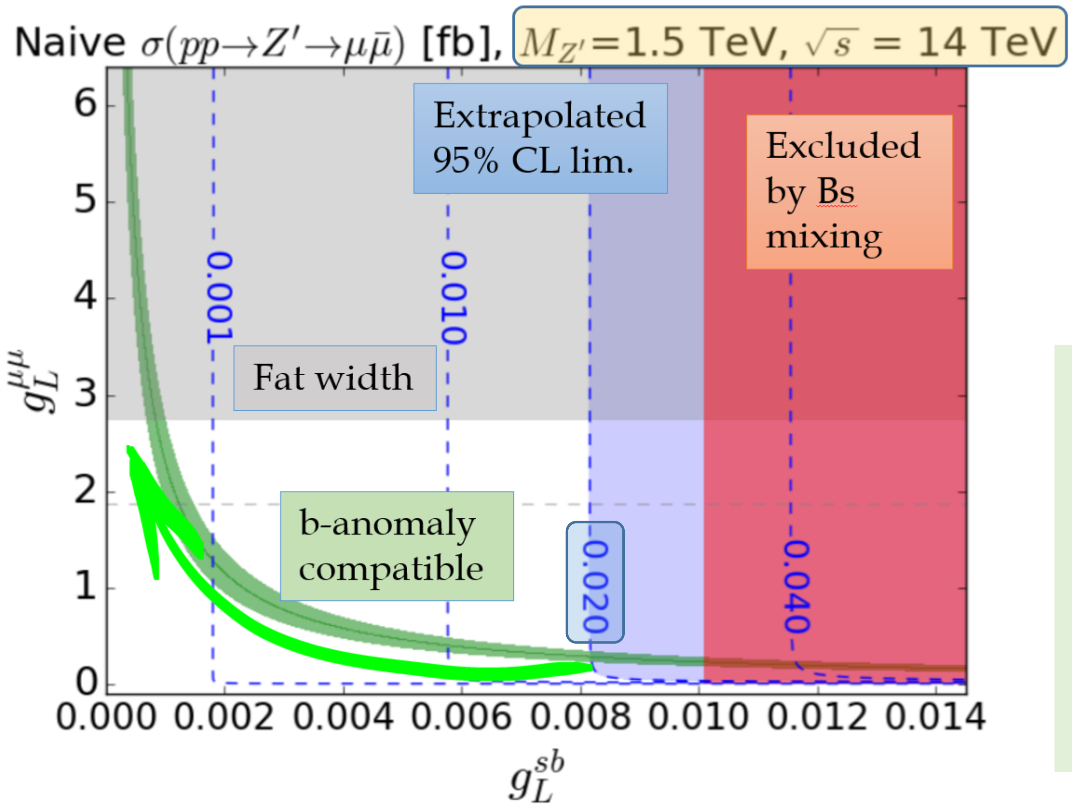
# Z′ Sensitivity



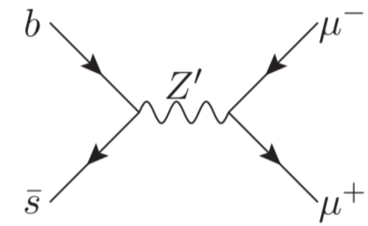

- Extrapolate current 13 TeV di-muon search:



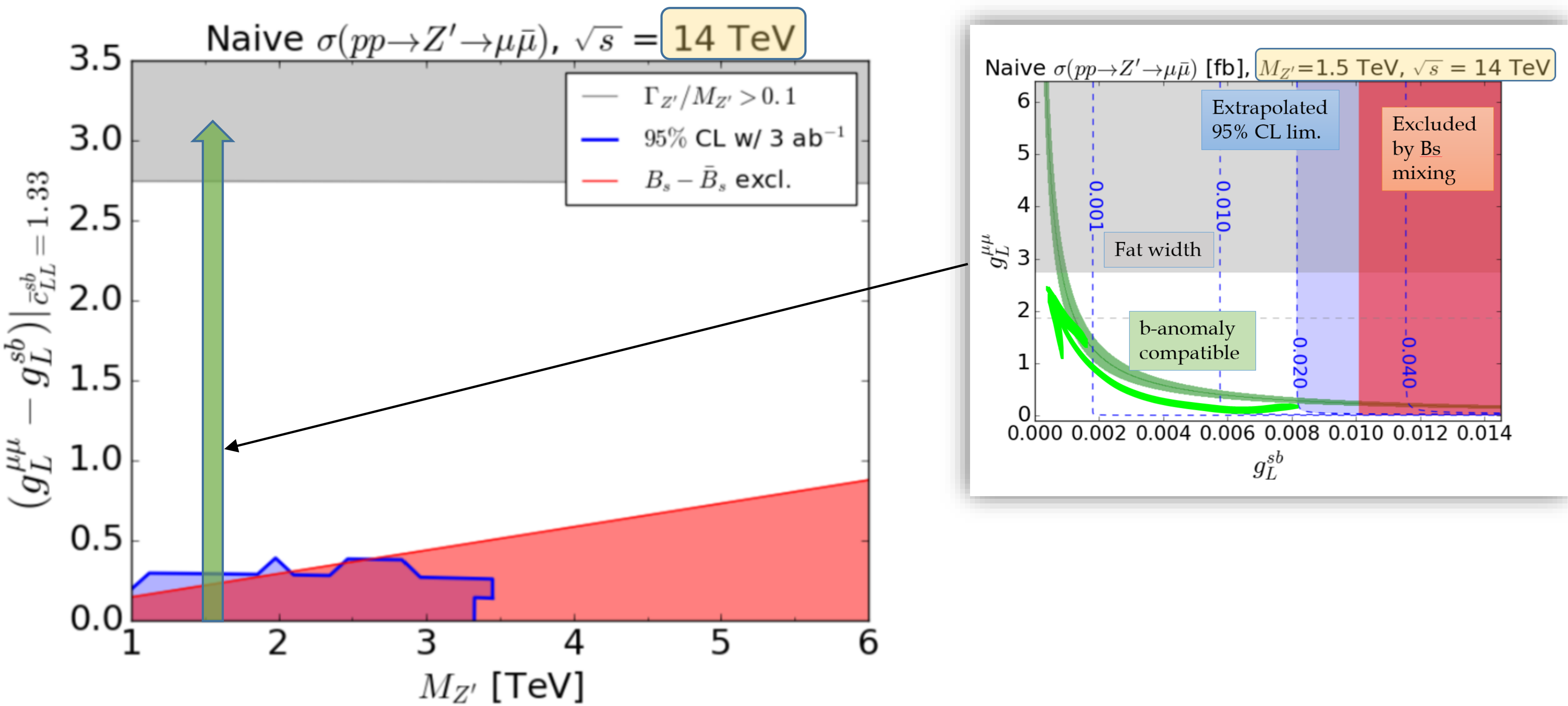

Summary of Z′ coverage: For each $M_{Z'}$, plot vertically the anomaly-compatible region

- Actual limits depend on Z′ couplings in signal x-section

# Z′ Sensitivity

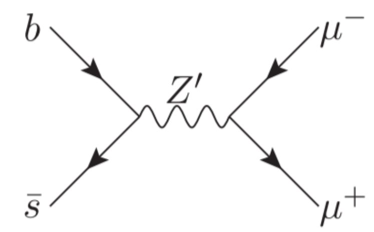



- Extrapolate current 13 TeV di-muon search:




- Actual limits depend on Z′ couplings in signal x-section

# Z′ Sensitivity

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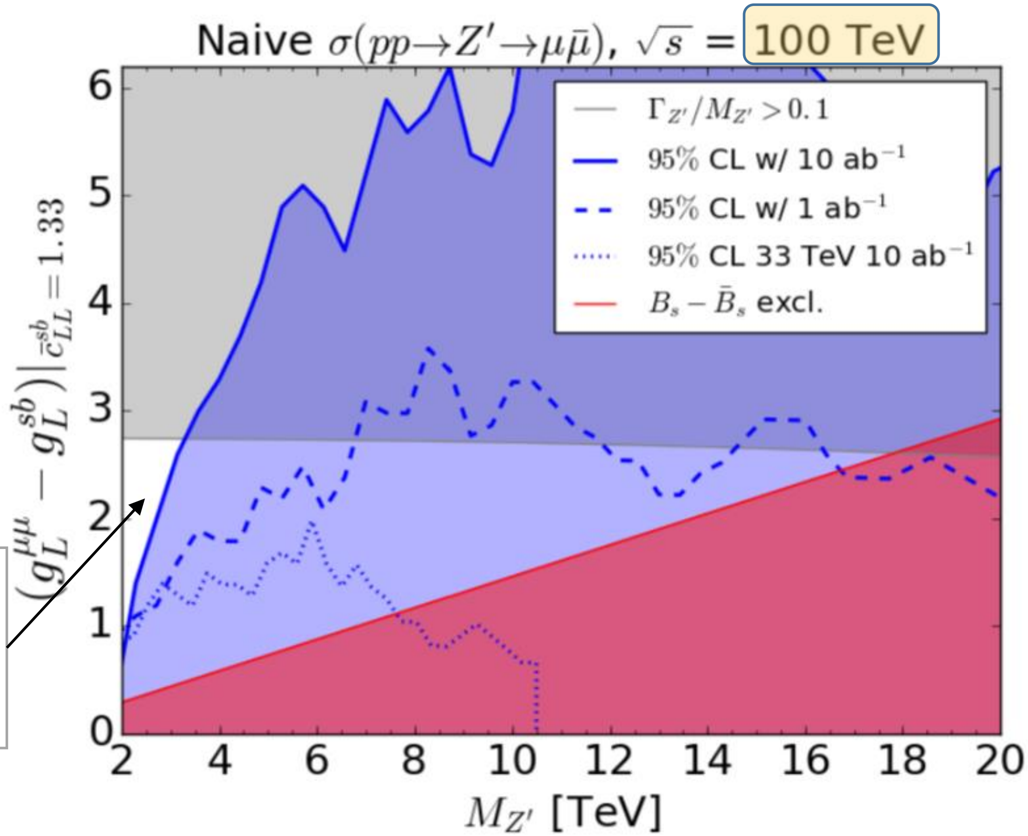
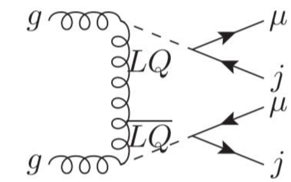


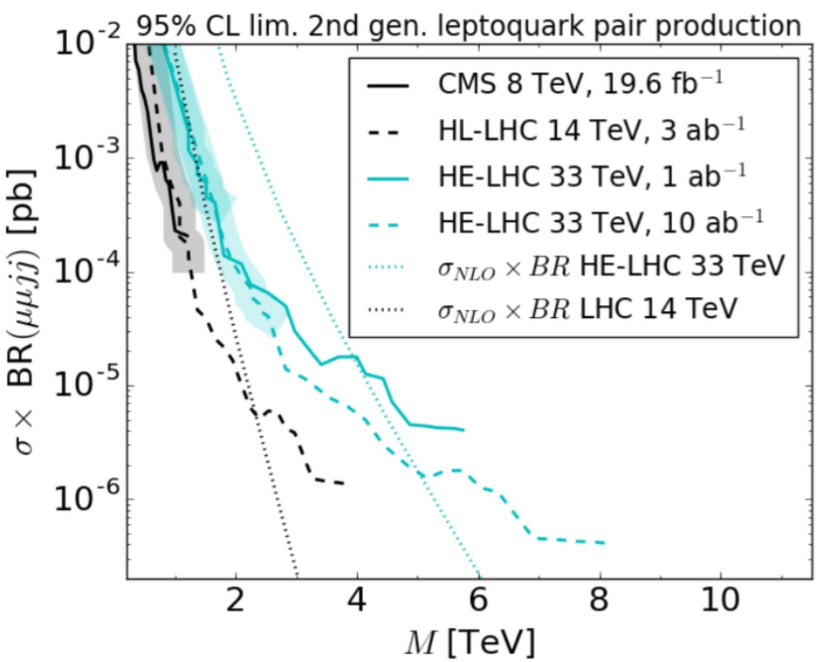

(extrapolation method underestimates limits at low masses)

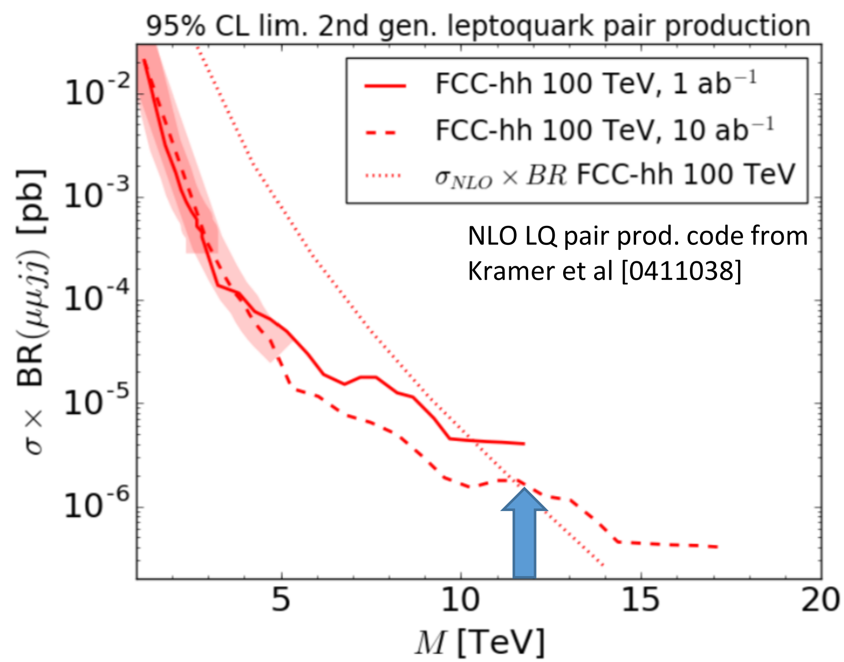
- 100 TeV can cover **all** parameter space of most *pessimistic* scenario

# Leptoquark Sensitivity

- Extrapolate current 8 TeV LQ di-muon+di-jet search:

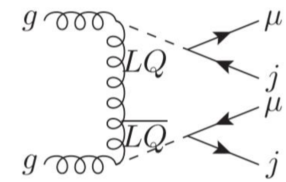


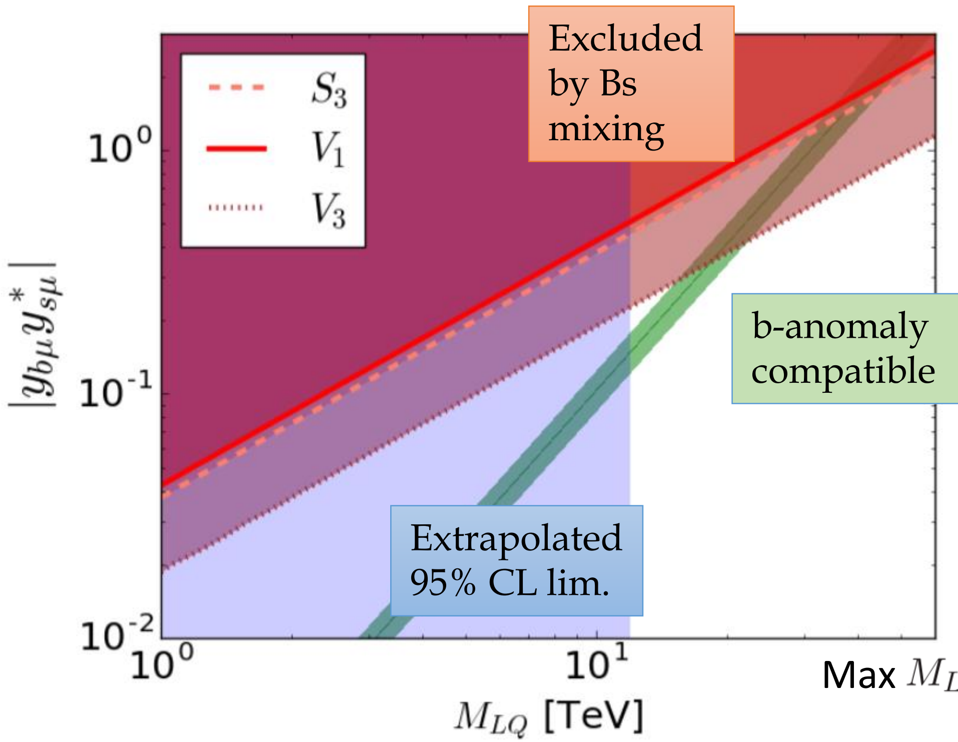




- Pair production for scalar LQ depends only on QCD coupling
- Upper limit from Bs mixing constraint

# Leptoquark Sensitivity




- Extrapolate current 8 TeV LQ di-muon+di-jet search:




Max $M_{LQ} = 37, 41, 18$ TeV for $S_3, V_1, V_3$

- Pair production for scalar LQ depends only on QCD coupling
- Upper limit from Bs mixing constraint

# Take-home message

- Complete coverage of Z′ models at 100 TeV FCC-hh

- Contrived LQ models may still survive FCC-hh

- Future studies: consider backgrounds, other channels, more realistic benchmark models, etc.

- Even if anomalies vanish, motivates **direct** discovery potential of future hadron colliders and interplay with **indirect** sensitivity from B physics

- Part I: SM EFT
- Part 2: B Anomalies
- **Part 3: Cosmological Relaxation**

# Beyond the Standard Model?

- Hierarchy problem is still a problem: $(m_h)^2_{tree} + (m_h)^2_{radiative} = (m_h)^2_v$

$$\delta m_\phi^2 \propto m_{\rm heavy}^2, \quad \delta m_\psi \propto m_\psi \log\left(\frac{m_{\rm heavy}}{\mu}\right)$$

- Earliest example of an unnatural, arbitrary feature of a fundamental theory:

$$m_{inertial} = q_{gravity}$$

- Classical electromagnetism fine-tuning:

$$(m_e c^2)_{\rm obs} = (m_e c^2)_{\rm bare} + \Delta E_{\rm coulomb}, \qquad \Delta E_{\rm coulomb} = \frac{e^2}{4\pi\epsilon_0 r_e}$$

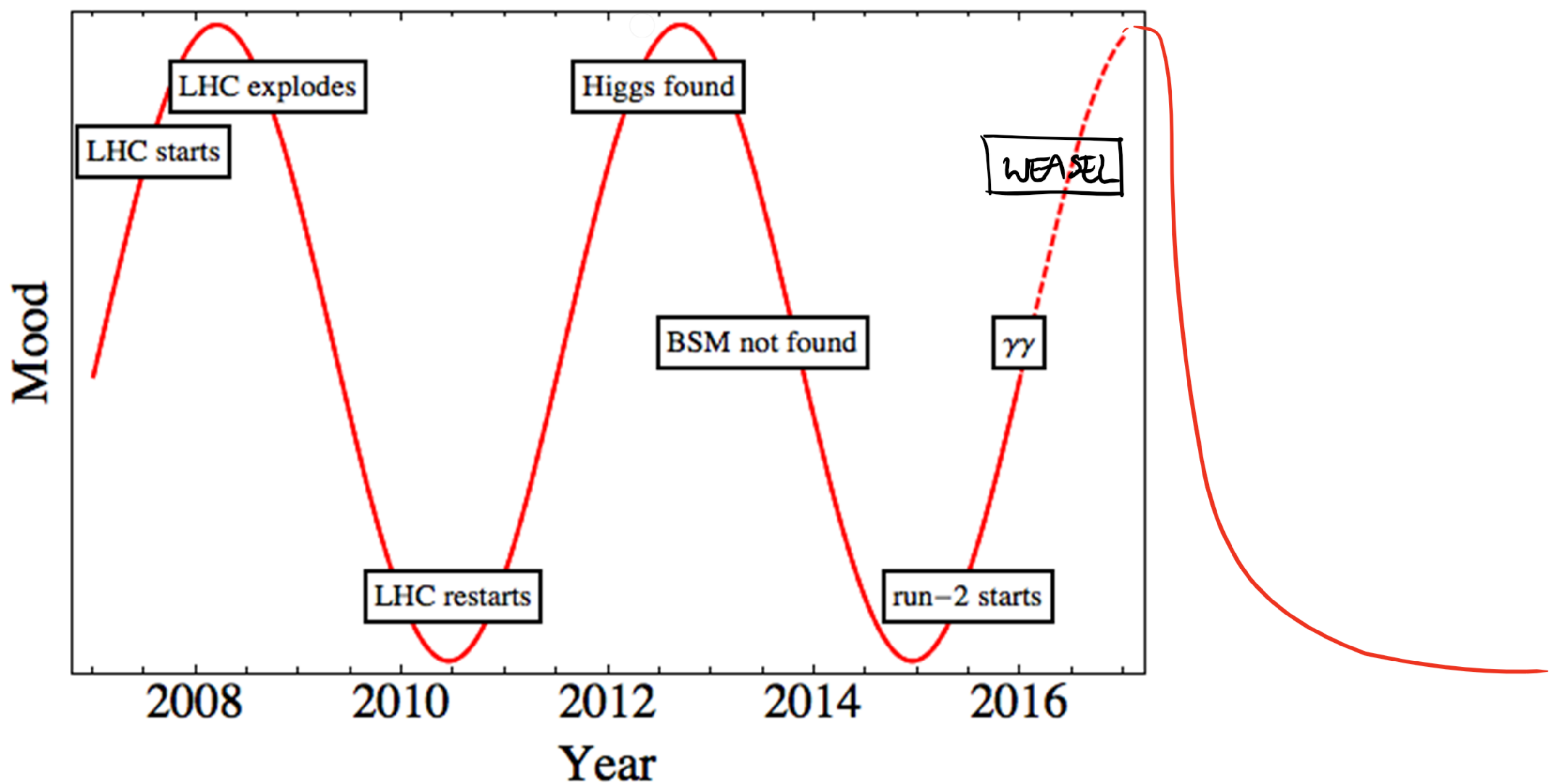
- Pions, cut-off also at natural scale

- Higgs? Expect new physics close to weak scale

# Understanding the origin of EWSB

- The SM has many *arbitrary* features put in by hand which hint at **underlying structure**
  - *Pattern of Yukawa couplings*
  - *QCD Theta term*
  - *Neutrino mass*
  - *Higgs potential*
- Maybe it just is what it is ¯_(ツ)_/¯
- but we would like a **deeper understanding**
  - *e.g. PQ axion for Theta term, see-saw for neutrino mass, Froggat-Nielsen for Yukawas…*
- In SM, **no understanding** of Higgs sector: Higgs potential and couplings *put in by hand*
- Just like in condensed matter systems, we feel there must be some underlying structure that **explains the origin of EWSB**
- In any such theory in which the Higgs potential is *calculable*, there is a **UV sensitivity** to the Higgs mass (that is no longer a free parameter) which requires fine-tuned cancellations
- Unlike solutions to other arbitrary features, this one points to **weak-scale new physics**

# Beyond the Standard Model?




http://resonaances.blogspot.com.es/2016/01/do-or-die-year.html

- Maybe Nature is trying to tell us we are missing something in the way we think about the hierarchy problem

# Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

L. F. Abbott, Phys. Lett. B 150 (1985) 427

- Higgs mass is naturally at large cut-off M

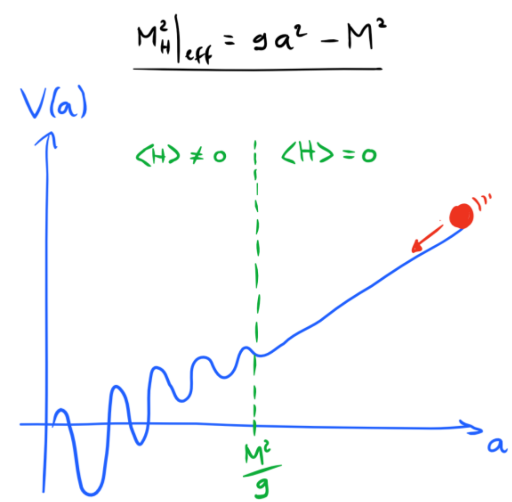
$$V_{\text{soft}}(a) \simeq (ga - M^2)|h|^2 + gM^2 a + \ldots$$

- Axion-like particle *a* protected by shift symmetry, explicitly broken through technically-small parameter *g*

- Scans an effective Higgs mass

- Barriers switch on after EWSB

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n$$



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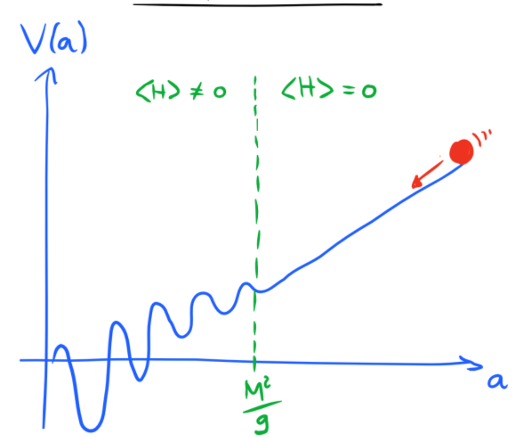
$$M_H^2\big|_{\text{eff}} = g a^2 - M^2$$



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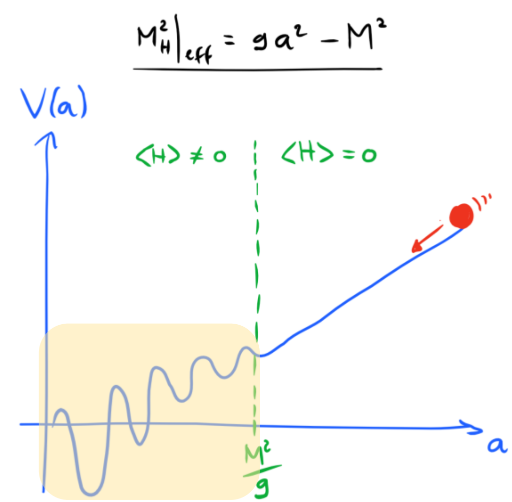

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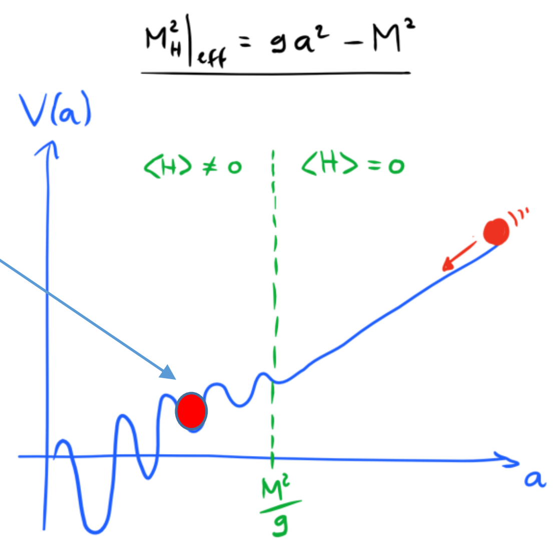
- Trapped when barrier height = slow-roll slope

$$gM^2 \sim \frac{\Lambda_G^{4-n} v^n}{f_\phi}$$




- Technically-natural for v << M

# Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

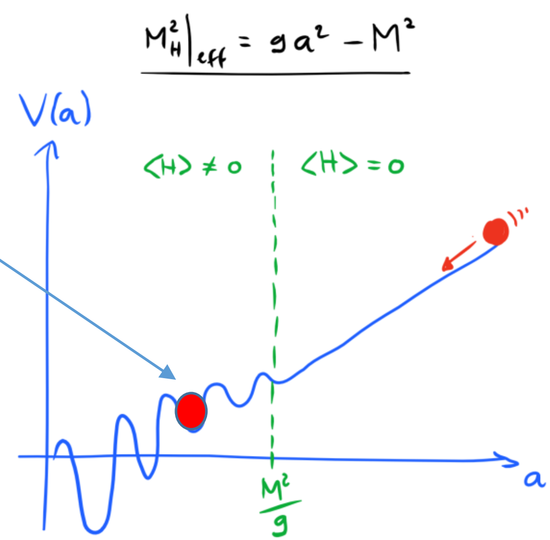
L. F. Abbott, Phys. Lett. B 150 (1985) 427

Constraints: H < v, classical rolling vs quantum, inflaton energy density dominates relaxion, etc.

Very small *g* and natural scanning range lead to super-planckian field excursions, exponential e-foldings…

- Trapped when barrier height = slow-roll slope

$$gM^2 \sim \frac{\Lambda_G^{4-n} v^n}{f_\phi}$$




- Technically-natural for v << M

# Relaxation Models (apologies for lack of references)

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n \qquad gM^2 \sim \frac{\Lambda_G^{4-n} v^n}{f_\phi}$$

- **n=1 models** Graham et al [arXiv:1504.07551]
  - G=QCD: Need additional ingredients to overcome strong-CP problem
  - New gauge group G: new physics at weak scale + coincidence problem
- **n=2 models** Espinosa et al [arXiv:1506.09217]
  - G can be at higher scales, raises M cut-off too
  - Requires second scalar to relax relaxion barriers: double-scanning mechanism
- **n=0 models** Hook and Marques-Tavares [arXiv:1607.01786], **TY** [arXiv:1701.09167]
  - More promising, make use of axial gauge coupling $\mathcal{L} = \frac{1}{32\pi^2}\frac{a}{f}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}G_{\mu\nu}G_{\rho\sigma}$

# Relaxation backreaction on inflation

**TY** [arXiv:1701.09167]

- Minimal relaxion setup, **no v-dependence in relaxion sector**

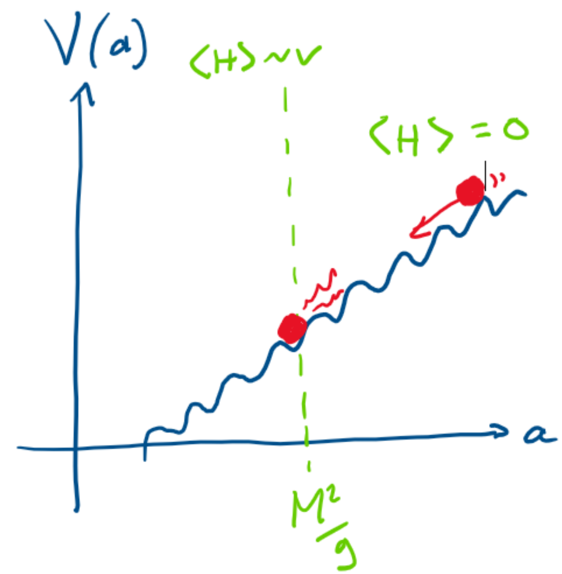
$$\mathcal{L} \supset \left(M^2 - g\phi\right)|h|^2 + gM^2\phi + ... + \Lambda_G^4 \cos\left(\frac{\phi}{f_\phi}\right) - \frac{\alpha_D}{f_D}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} ,$$

- Backreaction instead ends inflation
  - e.g. Inflation supported by electroweak dissipation $\mathcal{L} \supset -\frac{\alpha}{f}\sigma F_{\mu\nu}\tilde{F}^{\mu\nu}$

$$\ddot{\sigma} + 3H\dot{\sigma} + V'_\sigma(\sigma) = -I\frac{\alpha}{f}\left(\frac{H}{\xi}\right)^4 e^{2\pi\xi} , \qquad \xi \equiv \frac{\alpha}{2f}\frac{\dot{\sigma}}{H}$$

See e.g. Anber and Sorbo 0908.4089

- Hubble falls
- Dark dissipation increases
- Relaxion loses KE and is trapped




| | $M$ | $g$ | $H_I$ | $H_c$ | $N_e$ | $\Lambda_G$ | $f_\phi$ | $f_D/\alpha_D$ |
|---|---|---|---|---|---|---|---|---|
| $\sim$ [GeV] | $10^8$ | $10^{-11}$ | $10^{-2}$ | $10^{-5}$ | $10^{18}$ | $10^{3.5}$ | $10^9$ | $10^{15}$ |

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| | $M$ | $g$ | $H_I$ | $H_c$ | $N_e$ | $\Lambda_G$ | $f_\phi$ | $f_D/\alpha_D$ |
|---|---|---|---|---|---|---|---|---|
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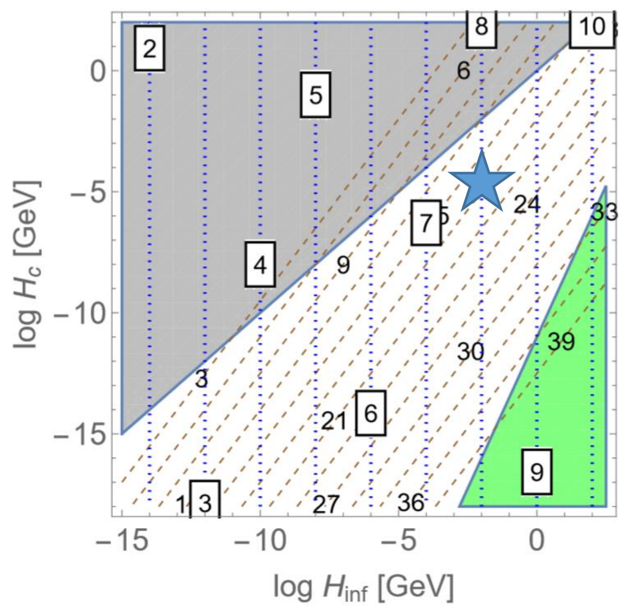
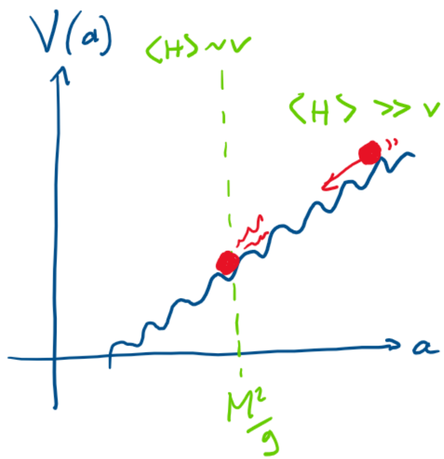


# Relaxation backreaction on particle production

Hook and Marques-Tavares [arXiv:1607.01786]

- v-dependence in gauge particle production

$$\mathcal{L} \supset \left(M^2 - g\phi\right)|h|^2 + gM^2\phi + \ldots + \Lambda_G^4 \cos\left(\frac{\phi}{f_\phi}\right) - \frac{\alpha_D}{f_D}\phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$




- For M ~ 10-100 TeV sub-Planckian field excursions, no tiny parameters
- Model can be realised before, during, or after inflation

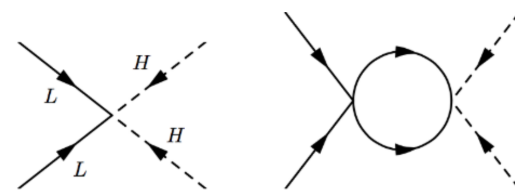
# Relaxation backreaction on particle production

Hook and Marques-Tavares [arXiv:1607.01786]

- Relaxation after inflation: relaxion can reheat universe

- Leptogenesis during reheating: L and CP violation by higher-dimensional operators parametrising decoupled new physics

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\lambda_{1,ij} HH\bar{L}_j^c L_i + \frac{1}{\Lambda_2^2}\lambda_{2,ijkl}(\bar{L}_i\gamma^\mu L_j)(\bar{L}_k\gamma_\mu L_l)$$
$$+ \frac{1}{\Lambda_3^2}\lambda_{3,ijkl}(\bar{L}_i\gamma^\mu L_j)(\bar{E}_k\gamma_\mu E_l) + h.c.$$




Hamada & Kawana [arXiv:1510.05186]

- Attractive features in leptogenesis for cosmological relaxation with particle production

Minho Son, Fang Ye, TY [1804.06599]

- Minimal EFT setup for naturally decoupled new physics

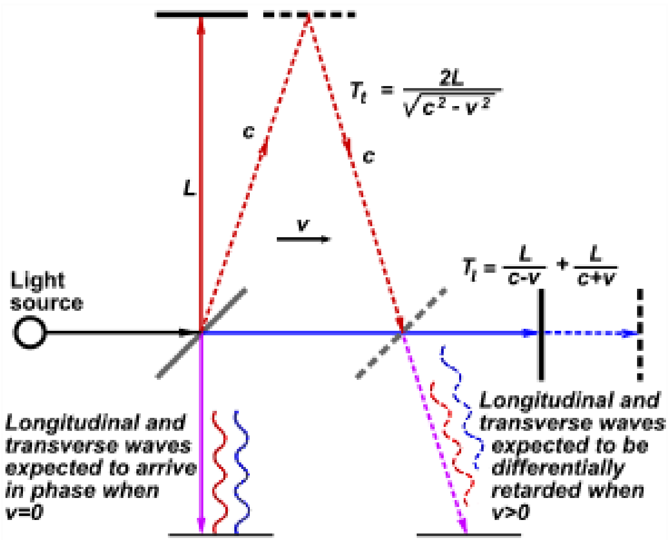
# Conclusion

- Decoupled new physics motivates an SM EFT approach to phenomenology
- Future precision may probe even loop-induced operators at the TeV scale
- B anomalies could be the first indirect signs of new physics at accessible energy scales
- A desert above the weak scale has interesting implications for naturalness and model-building
- Cosmological relaxation mechanisms one possible avenue to explore

# Conclusion

- A SM-like Higgs boson and no direct signs of new physics may turn out to be a significant experimental null result

- Null results may still lead to **deeper understanding**




- *No new physics at the TeV scale could be our "Michelson-Morley" moment*