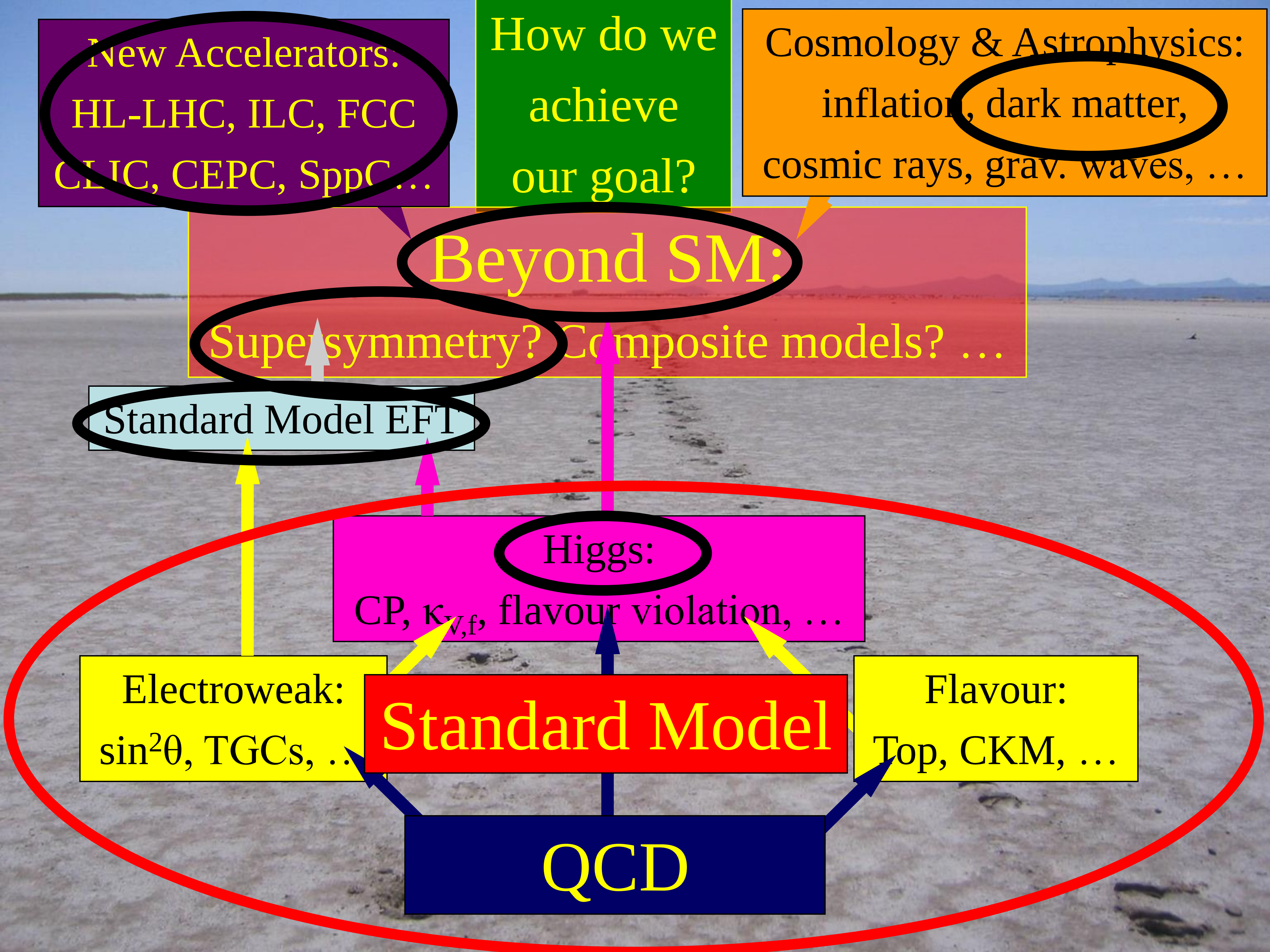
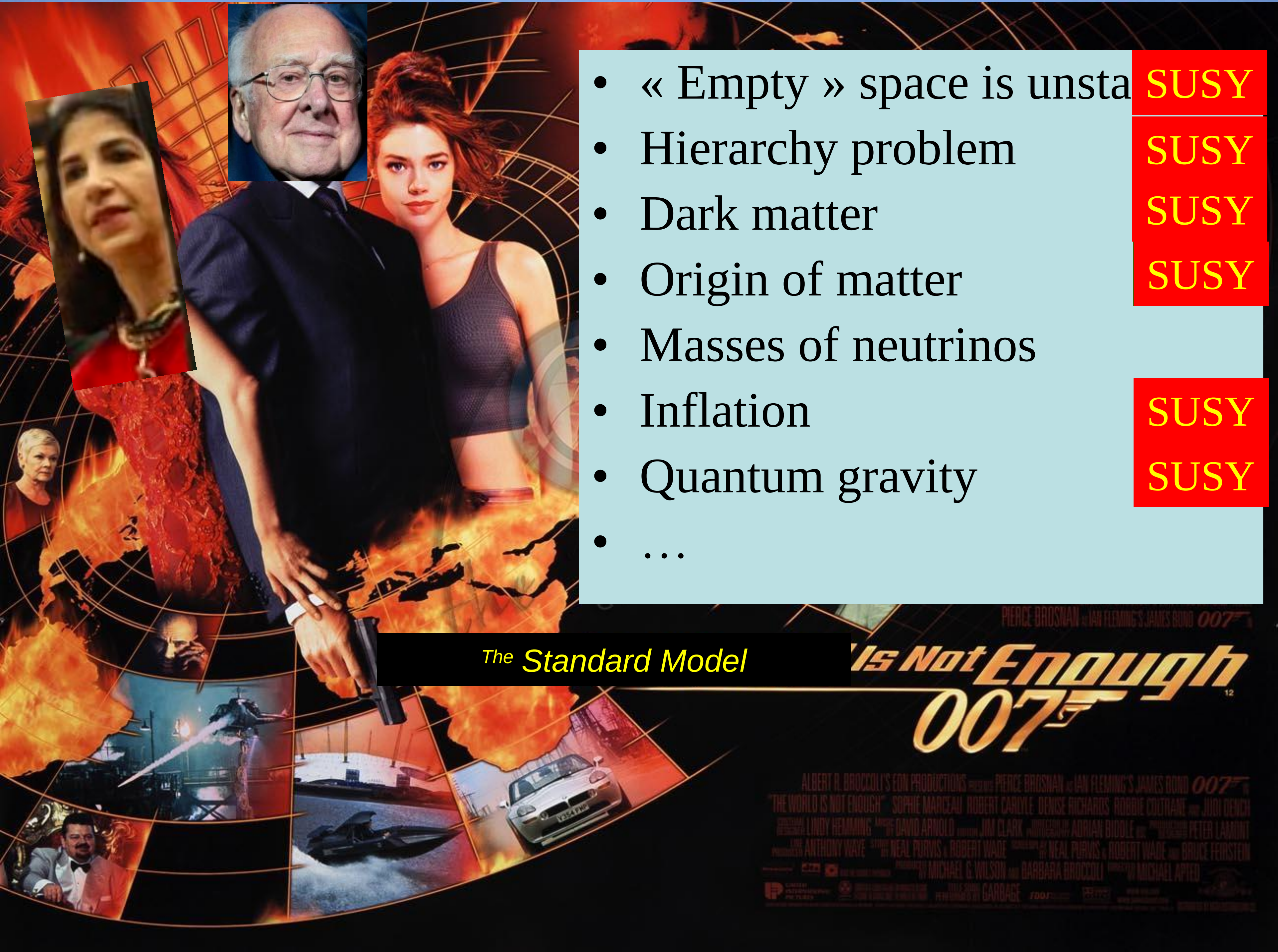
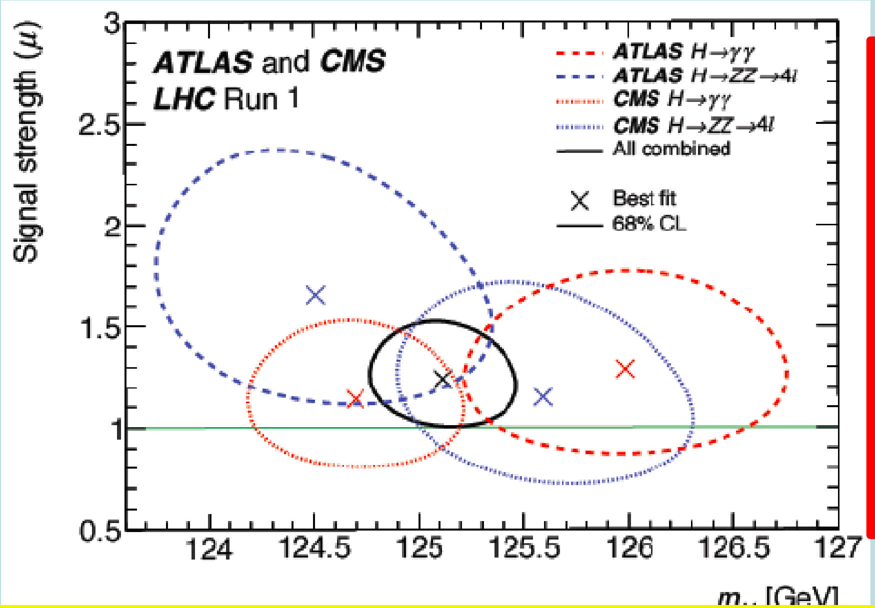

New Accelerators:
HL-LHC, ILC, FCC
CLIC, CEPC, SppC …
How do we
achieve
our goal?
Cosmology & Astrophysics:
inflation, dark matter,
cosmic rays, grav. waves, …
Beyond SM:
Supersymmetry? Composite models? …
Standard Model EFT
Higgs:
CP, κV,f, flavour violation, …
Electroweak:
sin²θ, TGCs, …
Standard Model
Flavour:
Top, CKM, …
QCD

- « Empty » space is unsta SUSY
- Hierarchy problem SUSY
- Dark matter SUSY
- Origin of matter SUSY
- Masses of neutrinos
- Inflation SUSY
- Quantum gravity SUSY
- …



# Higgs Mass Measurements

- ATLAS + CMS ZZ* and γγ final states




Crucial for stability of Electroweak vacuum

- Run 1: $125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$
- 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 ± 0.14 GeV

# Theoretical Constraints on Higgs Mass

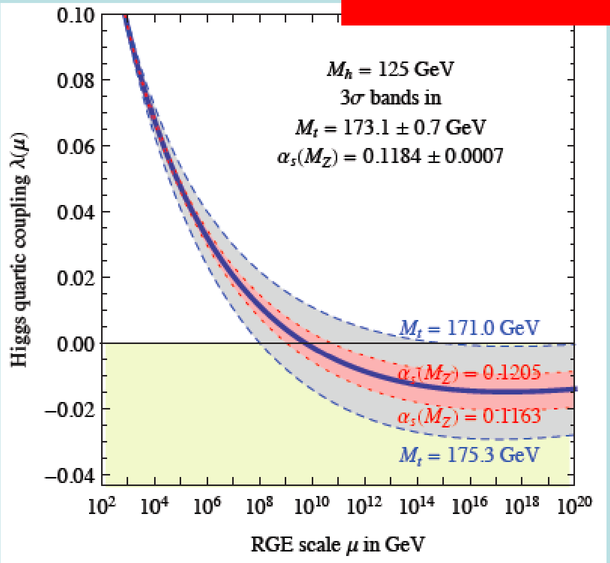
- Large $M_h$ → large self-coupling → blow up at

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

$$\lambda(Q) = \dots$$

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

- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable

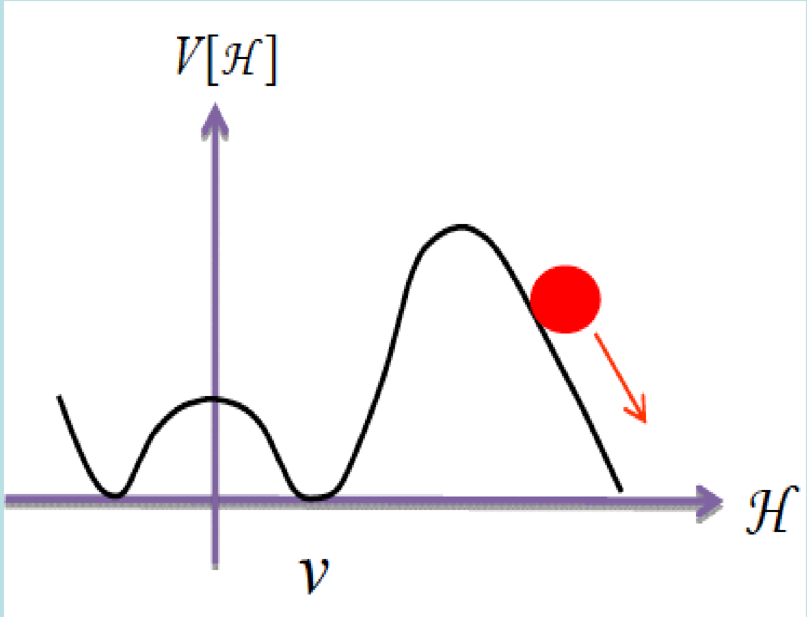


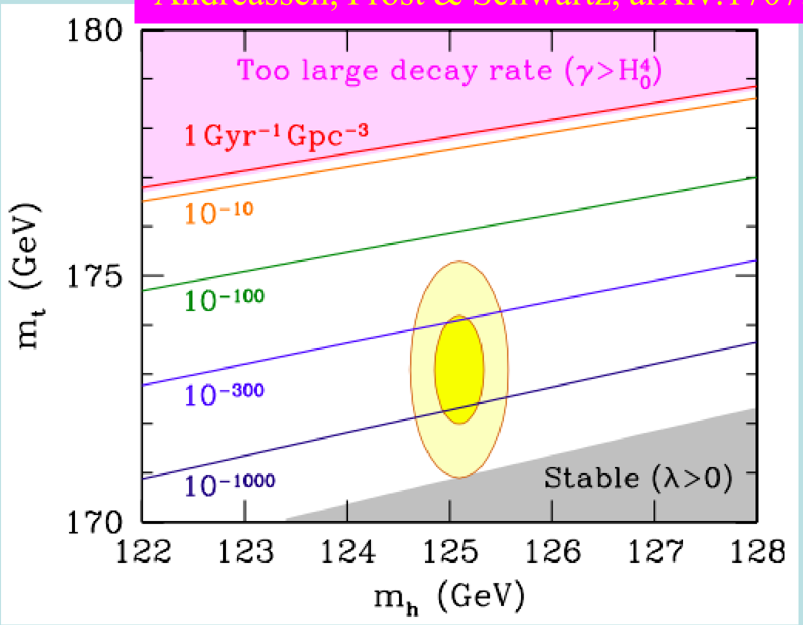

- Vacuum could be stabilized by **Supersymmetry**

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

# Vacuum Instability in the Standard Model

Andreassen, Frost & Schwartz, arXiv:1707.08124




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

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

- Naïve combination of recent ATLAS/CMS data:

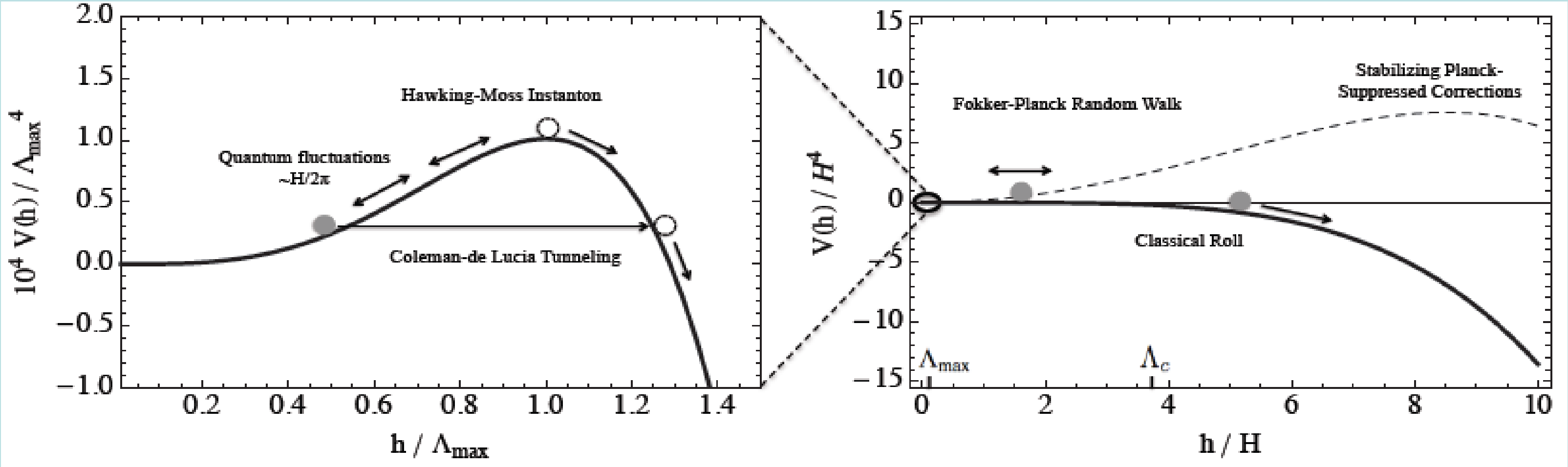
**$m_t = 172.47 \pm 0.35$ GeV ➔ $\log_{10}(\Lambda/\text{GeV}) = 11.4 \pm 0.8$**

- Sensitive to $\alpha_s$ as well as $m_t$ and $M_h$

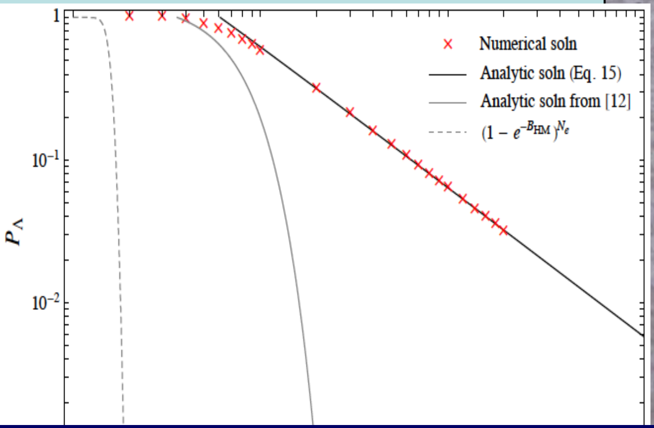
# Instability during Inflation?

Hook, Kearns, Shakya & Zurek: arXiv:1404.5953

- Do inflation fluctuations drive us over the hill?




- Then Fokker-Planck evolution
- Do AdS regions eat us?
  - Disaster if so
  - Mitigate with more inflation?



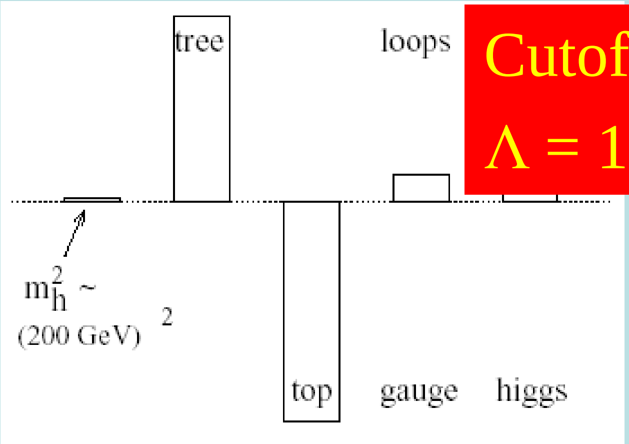

**Stabilize vacuum with some physics beyond the SM?**

# Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- Quantum loop problems




Cutoff

$\Lambda$ = 10 TeV

Cut-off $\Lambda \sim$ 1 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?

Assuming H(125) is SM-like: Model-independent search for new physics

# 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:

$$\begin{aligned}\mathcal{L} \supset\; & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\;\bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\;\bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\ + & \frac{2ig\;\bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\;\bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\ + & \frac{ig\;\bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\;\bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\ + & \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\;\Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\;\Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\;\Phi^\dagger\Phi\;\Phi\cdot\bar{L}_L\tau_R\end{aligned}$$

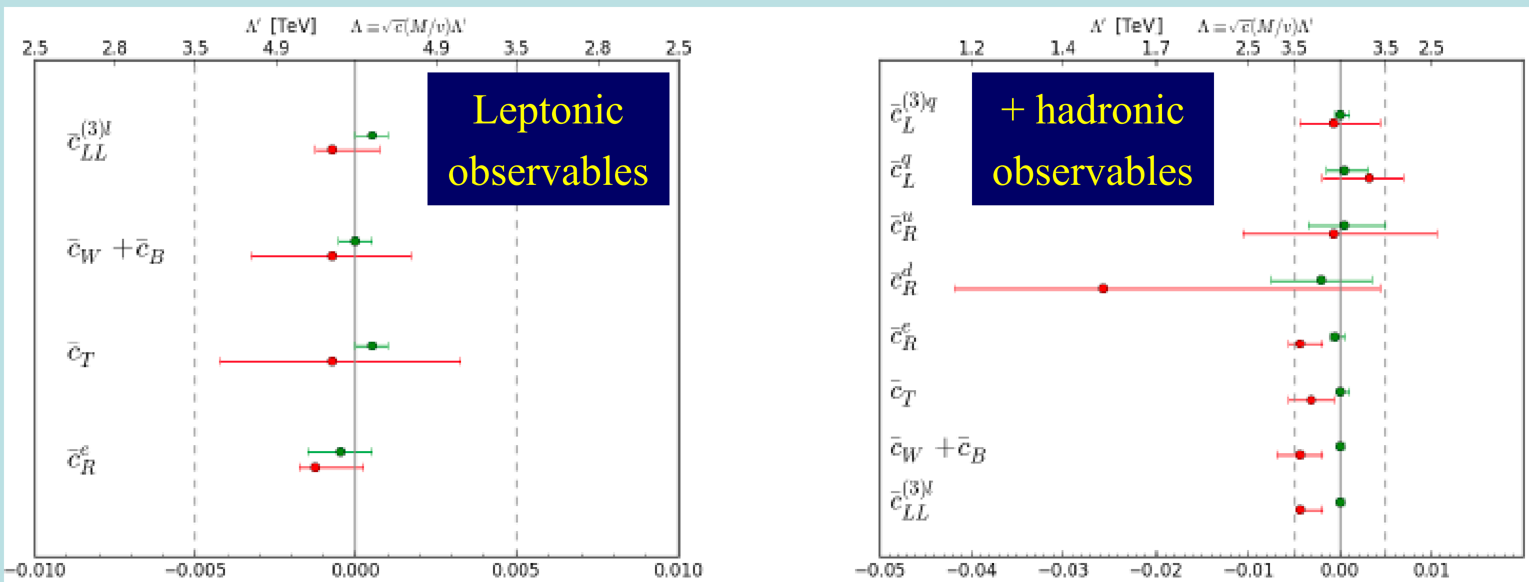
- Constrain with precision EW, Higgs data, TGCs …

# Electroweak Precision Data

- Operators affecting oblique parameters

$$\mathcal{L}_{\text{dim-6}} \subset \frac{\bar{c}_{WB}}{m_W^2}\mathcal{O}_{WB} + \frac{\bar{c}_W}{m_W^2}\mathcal{O}_W + \frac{\bar{c}_B}{m_W^2}\mathcal{O}_B + \frac{\bar{c}_T}{v^2}\mathcal{O}_T + \frac{\bar{c}_{2W}}{m_W^2}\mathcal{O}_{2W} + \frac{\bar{c}_{2B}}{m_W^2}\mathcal{O}_{2B}$$

- Also other electroweak tests
- Constraints from LEP et al. data

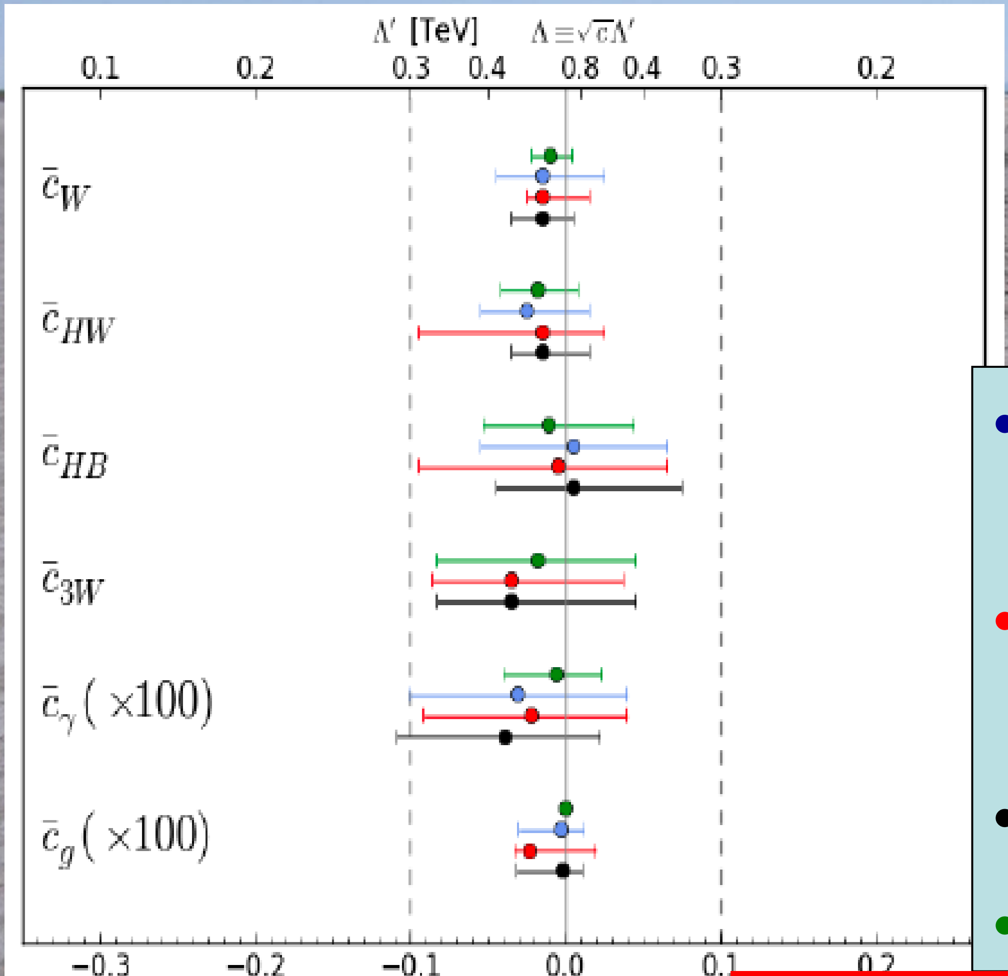



**Fits to individual dimension-6 operators**

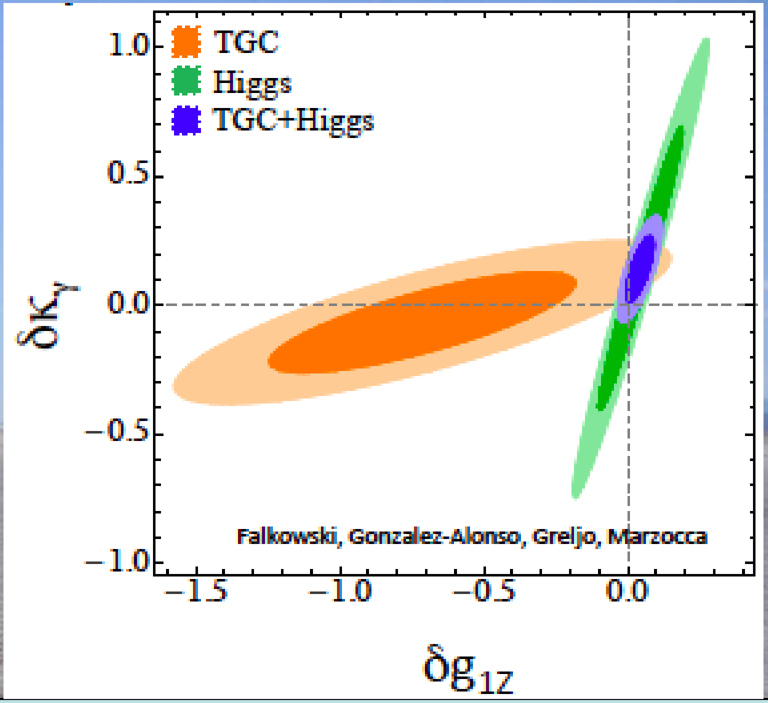
**Global fit to dimension-6 operators**

JE, Sanz & Tevong You, arXiv:1410.7703

# Global Fits to LHC Data



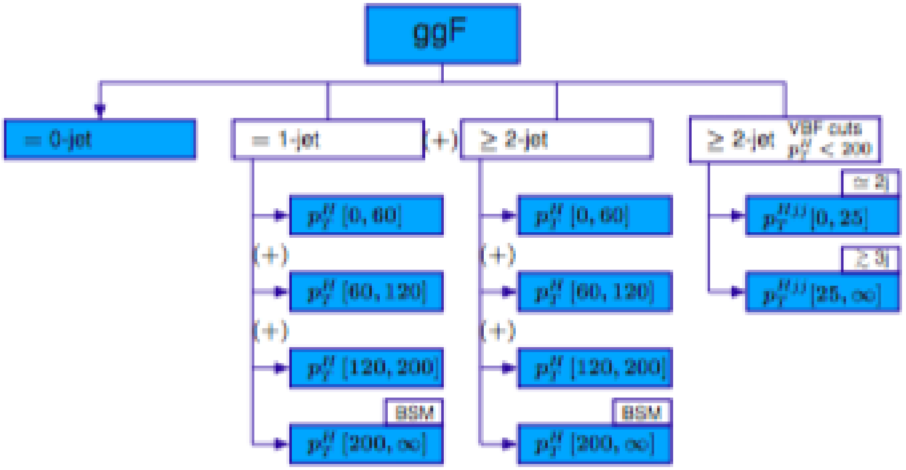

JE, Sanz & Tevong You, arXiv:1410.7703

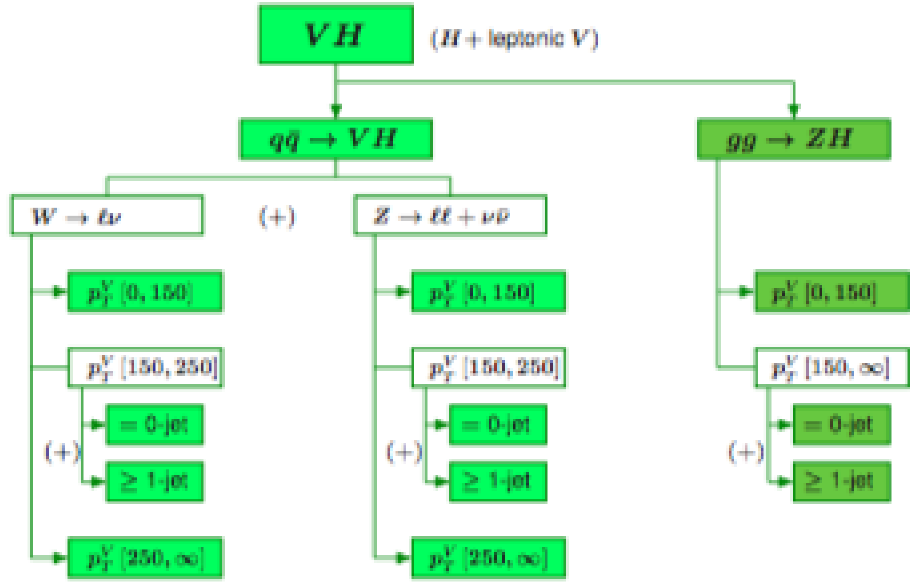


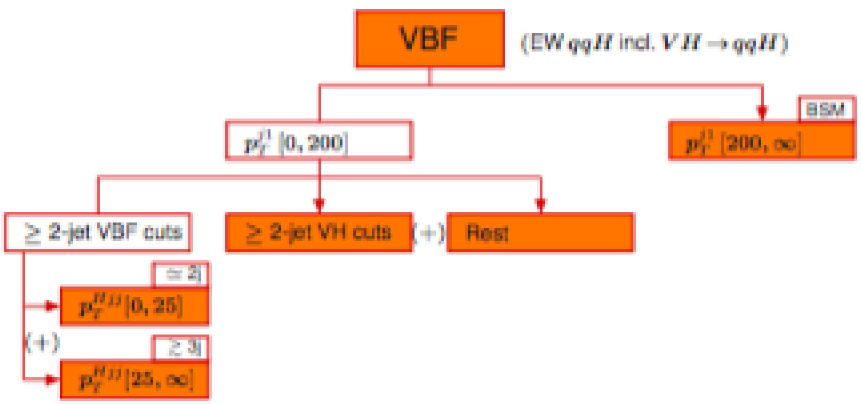

- **Associated H production rates & kinematics**
- **LHC Triple-gauge couplings** Complementary!
- Global combination
- **Individual operators**

Preferred framework for analyzing Run 2

# ATLAS Higgs EFT Analysis



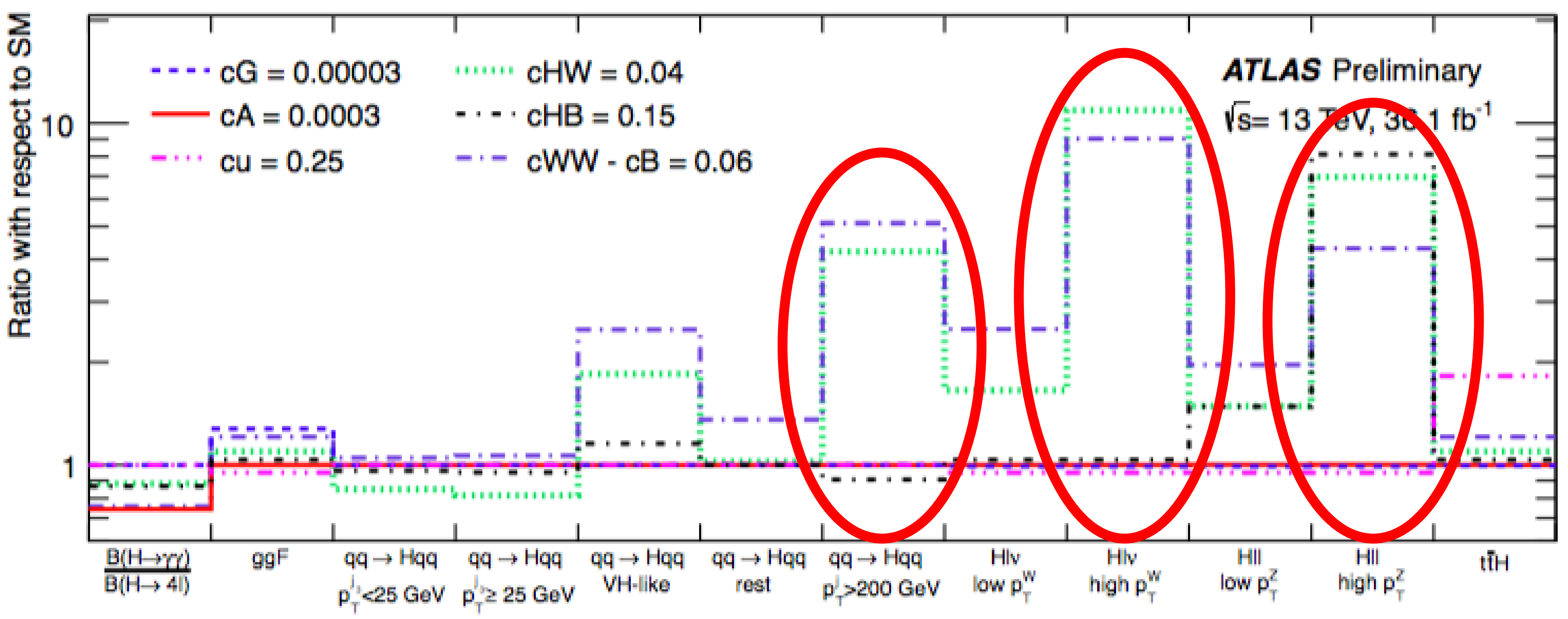





| Operator | Expression | HEL coefficient | Vertices |
|---|---|---|---|
| $O_g$ | $\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ | cG = $\frac{m_W^2}{g_S^2}\bar{c}_g$ | $Hgg$ |
| $O_\gamma$ | $\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ | cA = $\frac{m_W^2}{g'^2}\bar{c}_\gamma$ | $H\gamma\gamma, HZZ$ |
| $O_u$ | $y_u \lvert H\rvert^2 \bar{u}_l H u_R$+ h.c. | cu = $v^2 \bar{c}_u$ | $Ht\bar{t}$ |
| $O_{HW}$ | $i\,(D^\mu H)^\dagger\,\sigma^a\,(D^\nu H)\,W^a_{\mu\nu}$ | cHW = $\frac{m_W^2}{g}\bar{c}_{HW}$ | $HWW, HZZ$ |
| $O_{HB}$ | $i\,(D^\mu H)^\dagger\,(D^\nu H)\,B_{\mu\nu}$ | cHB = $\frac{m_W^2}{g'}\bar{c}_{HB}$ | $HZZ$ |
| $O_W$ | $i\,(H^\dagger \sigma^a D^\mu H)\,D^\nu W^a_{\mu\nu}$ | cWW = $\frac{m_W^2}{g}\bar{c}_W$ | $HWW, HZZ$ |
| $O_B$ | $i\,(H^\dagger D^\mu H)\,\partial^\nu B_{\mu\nu}$ | cB = $\frac{m_W^2}{g'}\bar{c}_B$ | $HZZ$ |

# Sensitivities to Operators

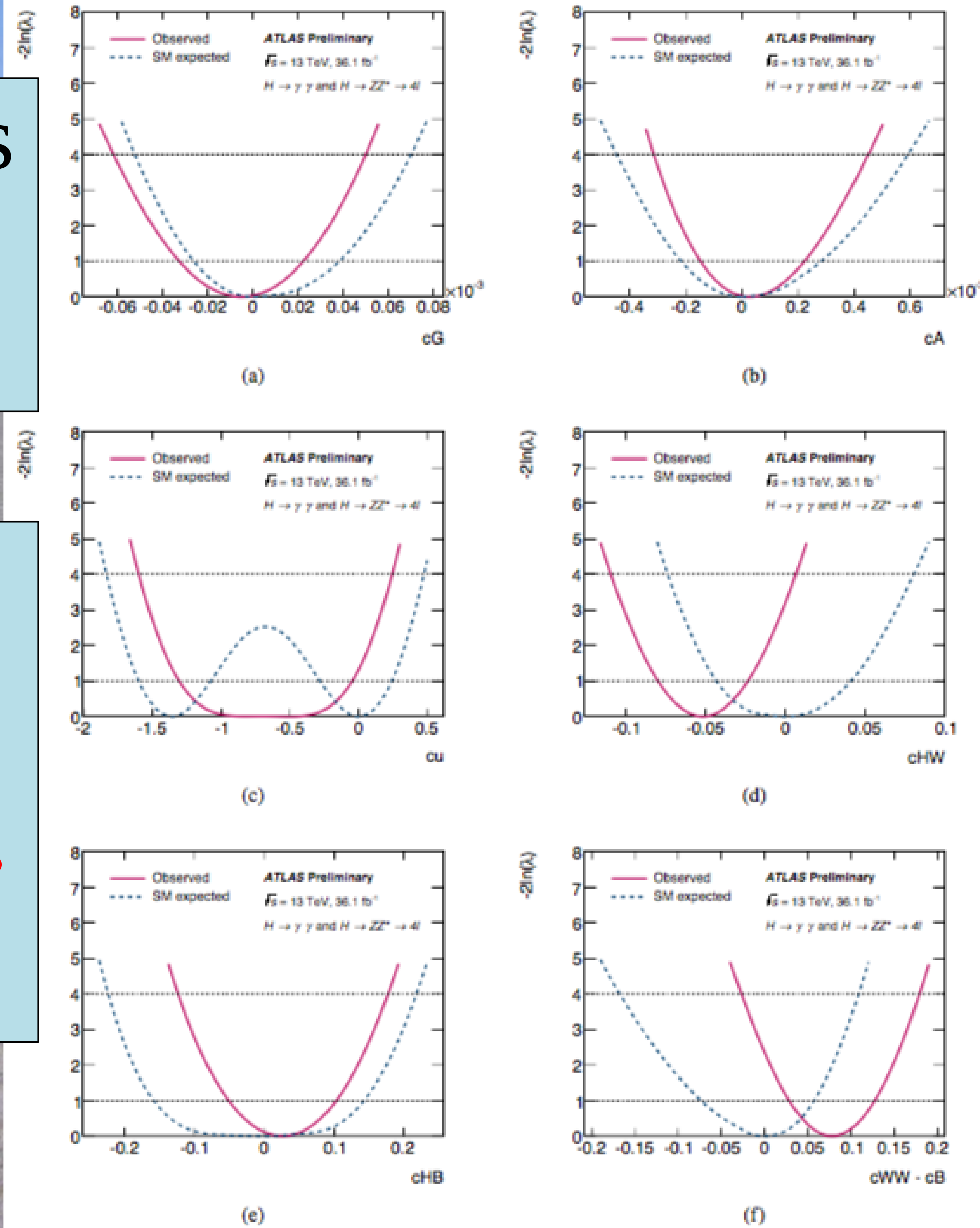
- Rate relative to SM with different operators




- **Higher sensitivity at higher $p_T$**

# $\Delta\chi^2$ Distributions for Higgs EFT Coefficients

- SM (coefficient = 0) always allowed at $\Delta\chi^2 < 4$ level (< 2 $\sigma$)
- **Next steps:**
  - **Combine with TGCs**
  - **Combine with precision EW**



# What lies beyond the Standard Model?

# Supersymmetry

New motivations
From LHC Run 1

- **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**

# Inputs to Global Fits for New Physics

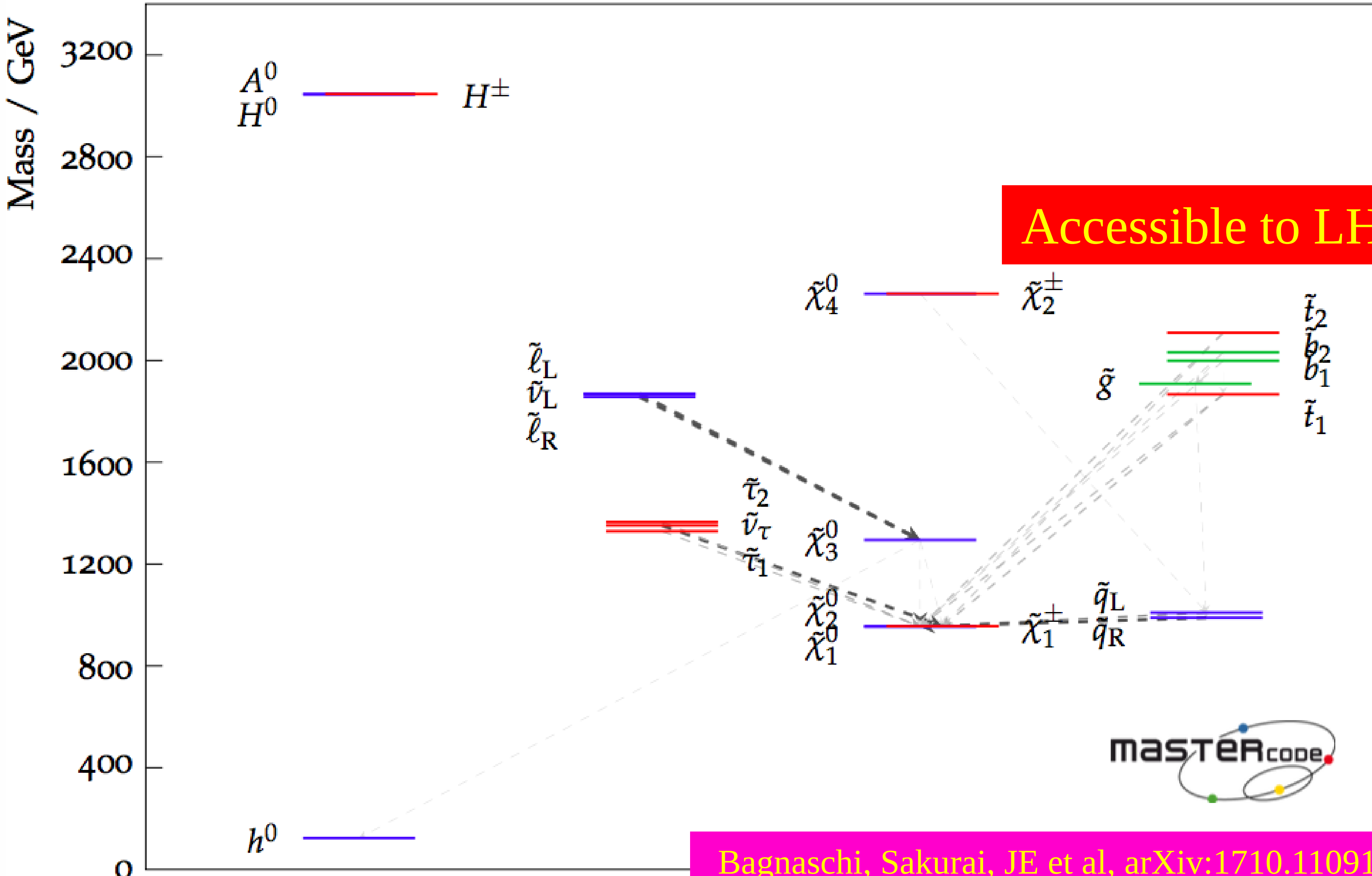
MasterCode

| | Observable | Source Th./Ex. | Constraint |
|---|---|---|---|
| Electroweak observables | $M_W$ [GeV] | [illegible] / [57,58] | [illegible] $\pm 0.012 \pm 0.010_{\rm MSSM}$ |
| | $a_\mu^{\rm EXP} - a_\mu^{\rm SM}$ | [59] / [60] | $(30.2 \pm 8.8 \pm 2.0_{\rm MSSM}) \times 10^{-10}$ |
| Flavour observables: Interpretation requires lattice inputs | $R_{\mu\mu}$ | [61–63] | 2D likelihood, MFV |
| | $\tau(B_s \to \mu^+\mu^-)$ | [63] | $2.04 \pm 0.44(\text{stat.}) \pm 0.05(\text{syst.})$ ps |
| | ${\rm BR}^{\rm EXP/SM}_{b \to s\gamma}$ | [65]/ [66] | $0.988 \pm 0.045_{\rm EXP} \pm 0.068_{\rm TH,SM} \pm 0.050_{\rm TH,SUSY}$ |
| | ${\rm BR}^{\rm EXP/SM}_{B_u \to \tau\nu}$ | [66,67] | [illegible] $\pm 0.096_{\rm SM}$ |
| | $BR^{\rm EXP/SM}_{B \to X_s \ell\ell}$ | [68]/ [66] | $0.966 \pm 0.278_{\rm EXP} \pm 0.037_{\rm SM}$ |
| | $\Delta M^{\rm EXP/SM}_{B_s}$ | [34,69] / [66] | [illegible] $\pm 0.078_{\rm SM}$ |
| | $\dfrac{\Delta M^{\rm EXP/SM}_{B_s}}{\Delta M^{\rm EXP/SM}_{B_d}}$ | [34,69] / [66] | $1.007 \pm 0.004_{\rm EXP} \pm 0.116_{\rm SM}$ |
| | $BR^{\rm EXP/SM}_{K \to \mu\nu}$ | [34,70] / [71] | $1.0005 \pm 0.0017_{\rm EXP} \pm 0.0093_{\rm TH}$ |
| | $BR^{\rm EXP/SM}_{K \to \pi\nu\bar\nu}$ | [72]/ [73] | $2.01 \pm 1.30_{\rm EXP} \pm 0.18_{\rm SM}$ |
| Dark Matter | $\sigma_p^{\rm SI}$ | [3,5,6] | Combined likelihood in the $(m_{\tilde\chi^0_1}, \sigma_p^{\rm SI})$ plane |
| | $\sigma_p^{\rm SD}$ | [4] | Likelihood in the $(m_{\tilde\chi^0_1}, \sigma_p^{\rm SD})$ plane |
| LHC observables | $\tilde g \to q\bar q\tilde\chi^0_1, b\bar b\tilde\chi^0_1, t\bar t\tilde\chi^0_1$ | [16,17] | Combined likelihood in the $(m_{\tilde g}, m_{\tilde\chi^0_1})$ plane |
| | $\tilde q \to q\tilde\chi^0_1$ | [16] | Likelihood in the $(m_{\tilde q}, m_{\tilde\chi^0_1})$ plane |
| | $\tilde b \to b\tilde\chi^0_1$ | [16] | Likelihood in the $(m_{\tilde b}, m_{\tilde\chi^0_1})$, plane |
| | $\tilde t_1 \to t\tilde\chi^0_1, c\tilde\chi^0_1, b\tilde\chi^\pm_1$ | [16] | Likelihood in the $(m_{\tilde t_1}, m_{\tilde\chi^0_1})$, plane |
| | $\tilde\chi^\pm_1 \to \nu\ell^\pm\tilde\chi^0_1, \nu\tau^\pm\tilde\chi^0_1, W^\pm\tilde\chi^0_1$ | [18] | Likelihood in the $(m_{\tilde\chi^\pm_1}, m_{\tilde\chi^0_1})$ plane |
| | $\tilde\chi^0_2 \to \ell^+\ell^-\tilde\chi^0_1, \tau^+\tau^-\tilde\chi^0_1, Z\tilde\chi^0_1$ | [18] | Likelihood in the $(m_{\tilde\chi^0_2}, m_{\tilde\chi^0_1})$ plane |
| | Heavy stable charged particles | [74] | Fast simulation based on [74,75] |
| | $H/A \to \tau^+\tau^-$ | [28,29,76,77] | Likelihood in the $(M_A, \tan\beta)$ plane |

# Best-Fit Sparticle Spectrum

## Phenomenological MSSM

Fit excluding $g_\mu$-2

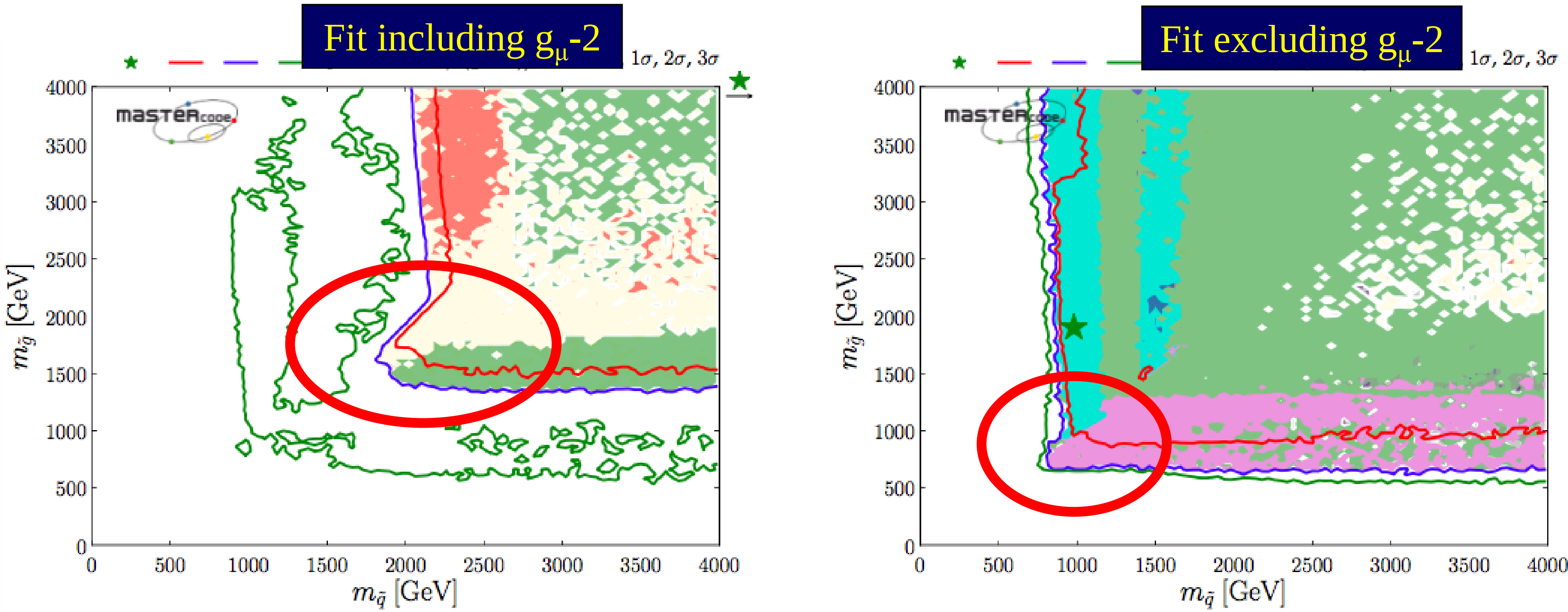



Accessible to LHC?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

# Squark & Gluino Mass Planes

## Phenomenological MSSM

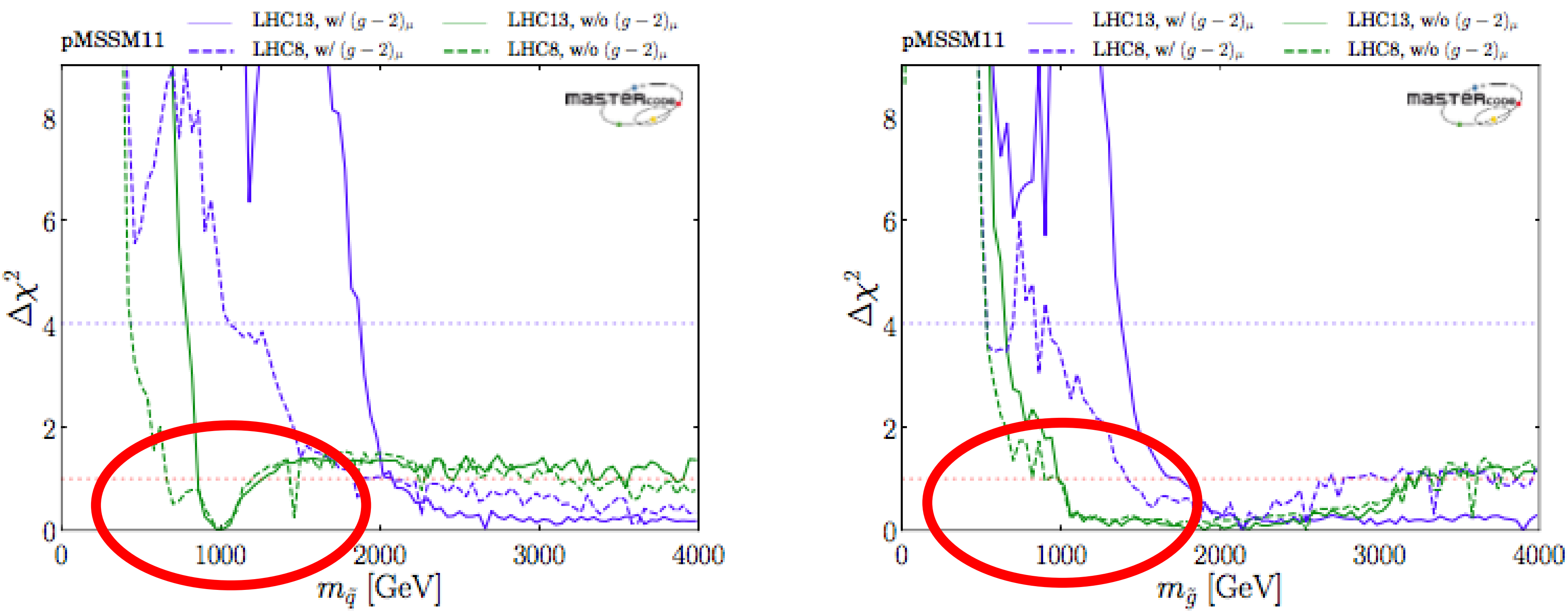



'Nose' regions where LHC sensitivity reduced because of compressed spectrum

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

# How Light can Squarks & Gluinos be?

## Phenomenological MSSM



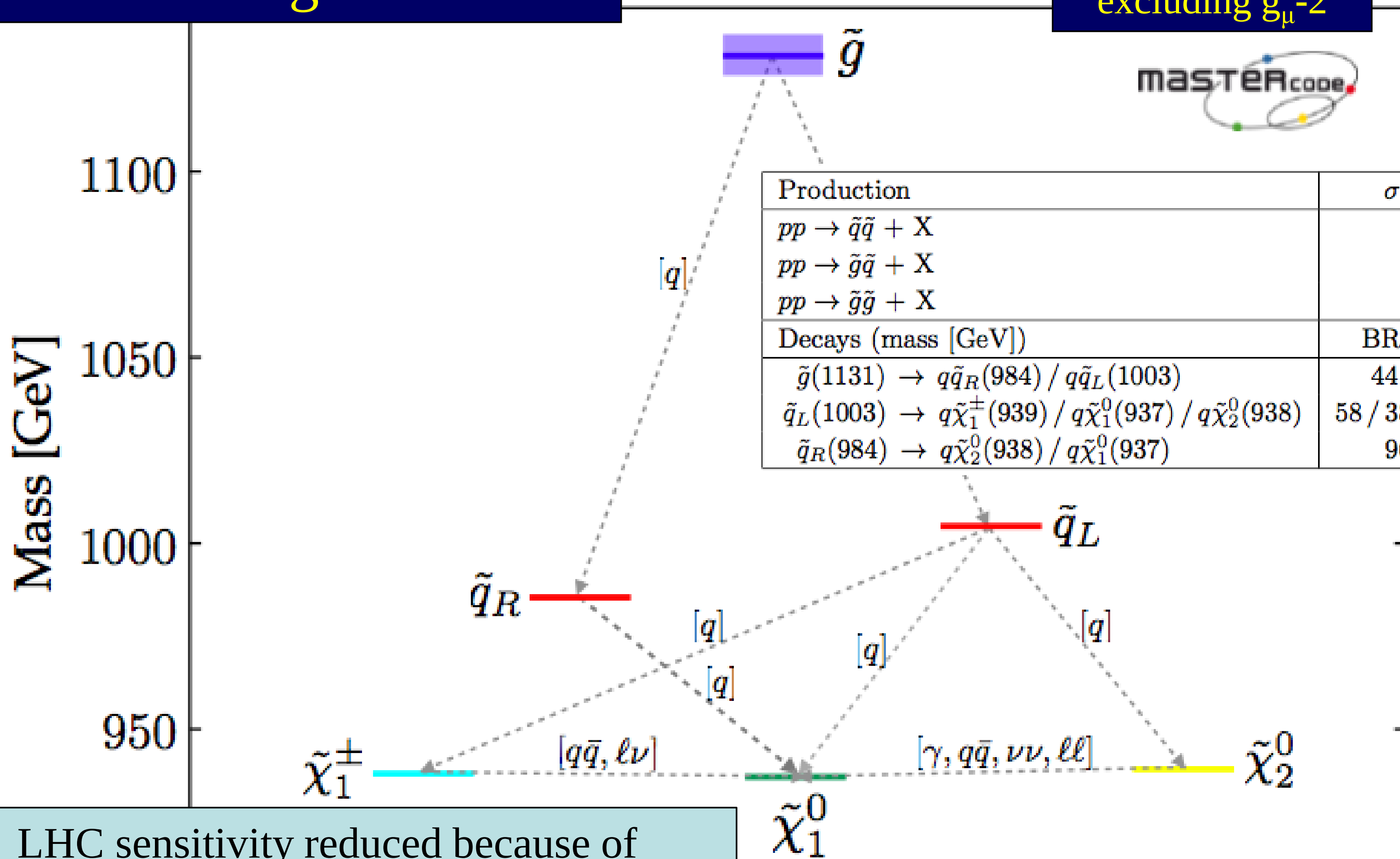

**Squarks, gluinos could weigh ~ 1 TeV if drop $g_\mu$-2**

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

# Decay Pattern at 'Nose' Point

## Phenomenological MSSM

'Nose' point excluding $g_\mu$-2



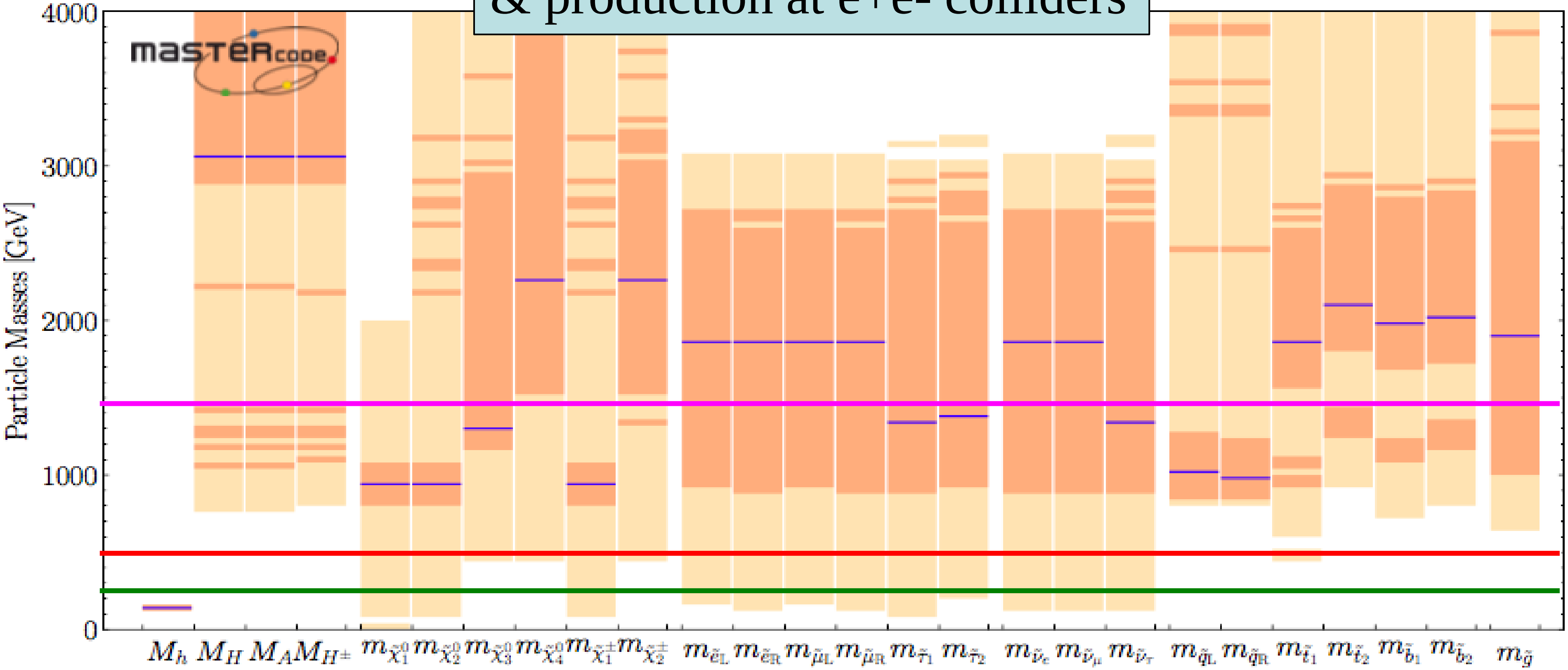

| Production | $\sigma$ [fb] |
|---|---|
| $pp \to \tilde{q}\tilde{q} + X$ | 619 |
| $pp \to \tilde{g}\tilde{q} + X$ | 586 |
| $pp \to \tilde{g}\tilde{g} + X$ | 87 |
| **Decays (mass [GeV])** | **BR [%]** |
| $\tilde{g}(1131) \to q\tilde{q}_R(984)$ / $q\tilde{q}_L(1003)$ | 44 / 56 |
| $\tilde{q}_L(1003) \to q\tilde{\chi}_1^\pm(939)$ / $q\tilde{\chi}_1^0(937)$ / $q\tilde{\chi}_2^0(938)$ | 58 / 38 / 4 |
| $\tilde{q}_R(984) \to q\tilde{\chi}_2^0(938)$ / $q\tilde{\chi}_1^0(937)$ | 96 / 4 |

LHC sensitivity reduced because of compressed spectrum, multiple decay modes

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

# Sparticle Masses in the pMSSM

& production at e+e- colliders



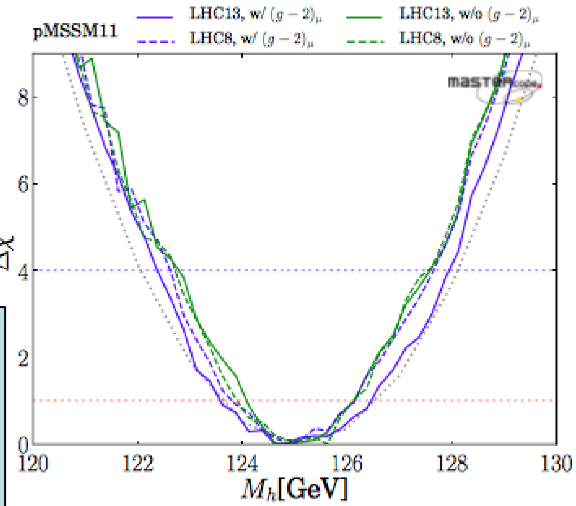

- **68 & 95% CL ranges**
- **Best-fit values**
- **Accessible in pair production at ILC500, ILC1000, CLIC**

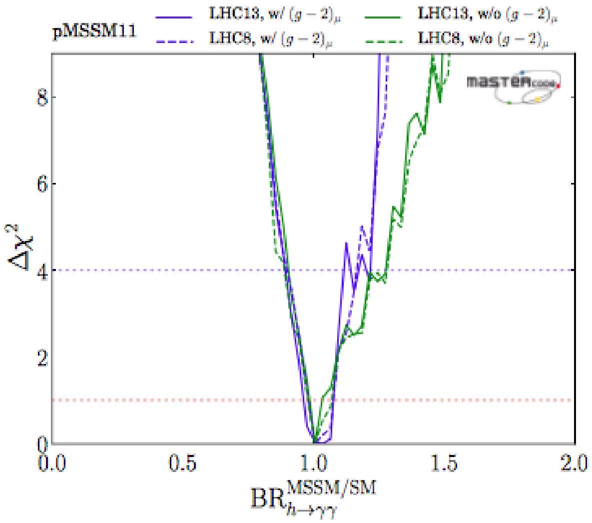
Bagnaschi, Sakurai, JE et al,

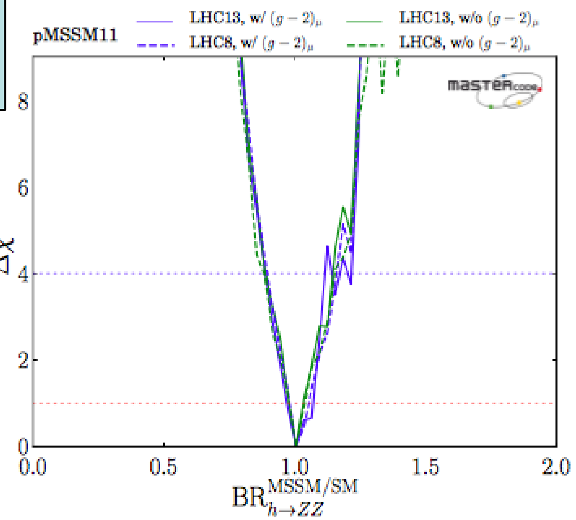
# Higgs properties in the pMSSM

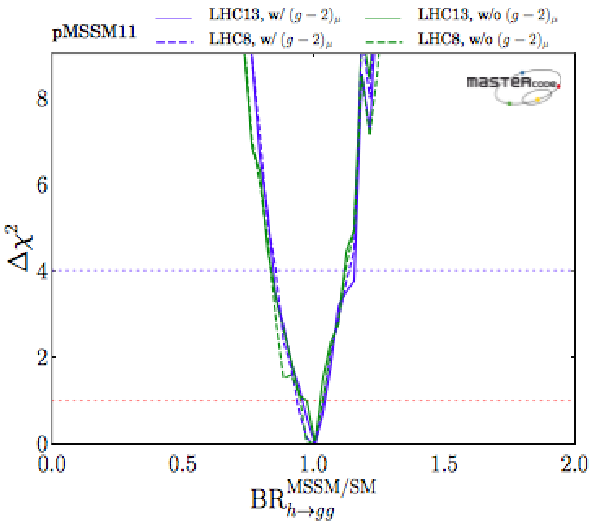
- **No issue with measured Higgs mass**
- Central values of decay BRs similar to SM
- **Substantial deviations possible**

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091



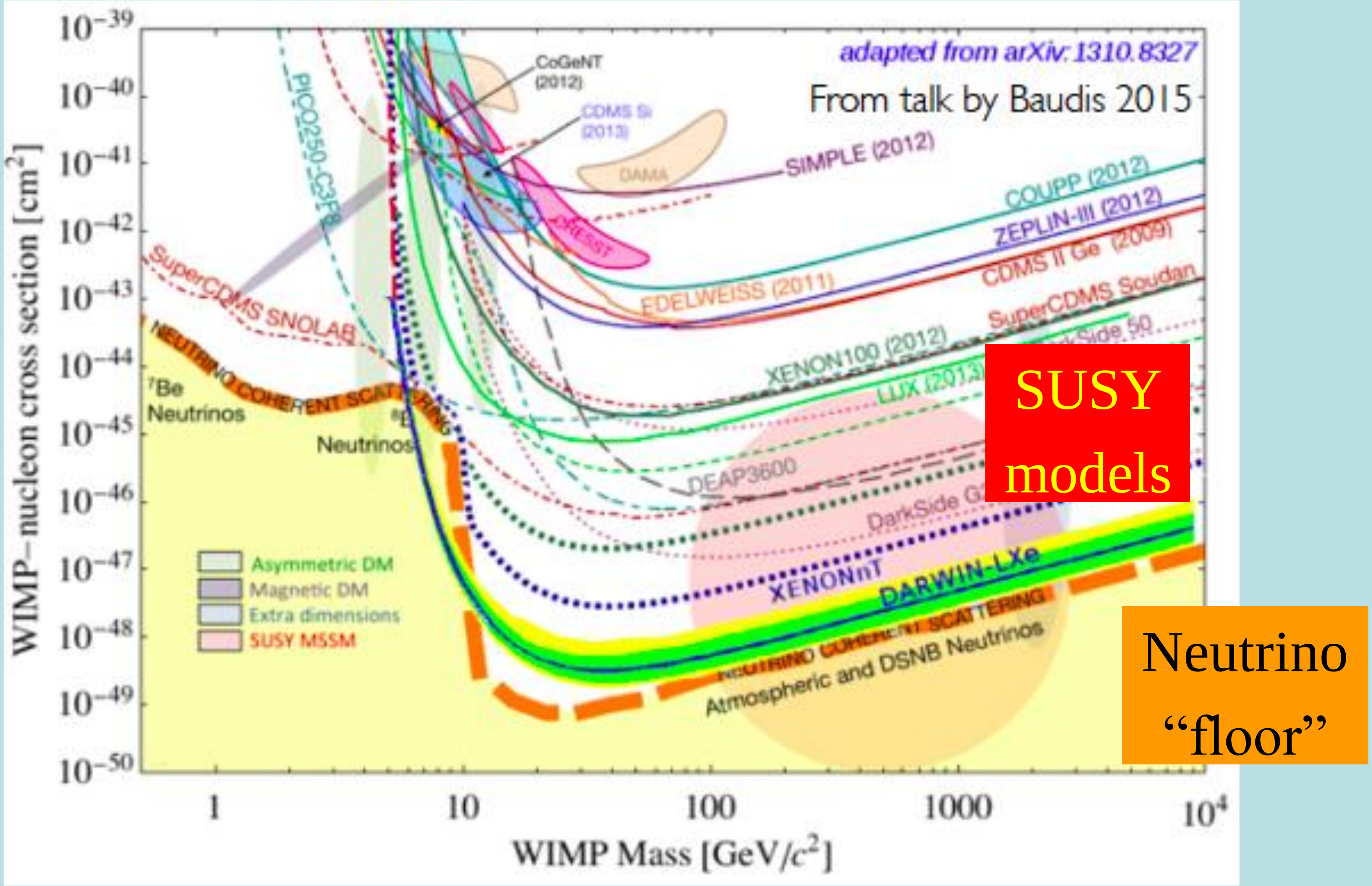



# Direct Dark Matter Searches

- Compilation of present and future sensitivities



# Direct Dark Matter Searches

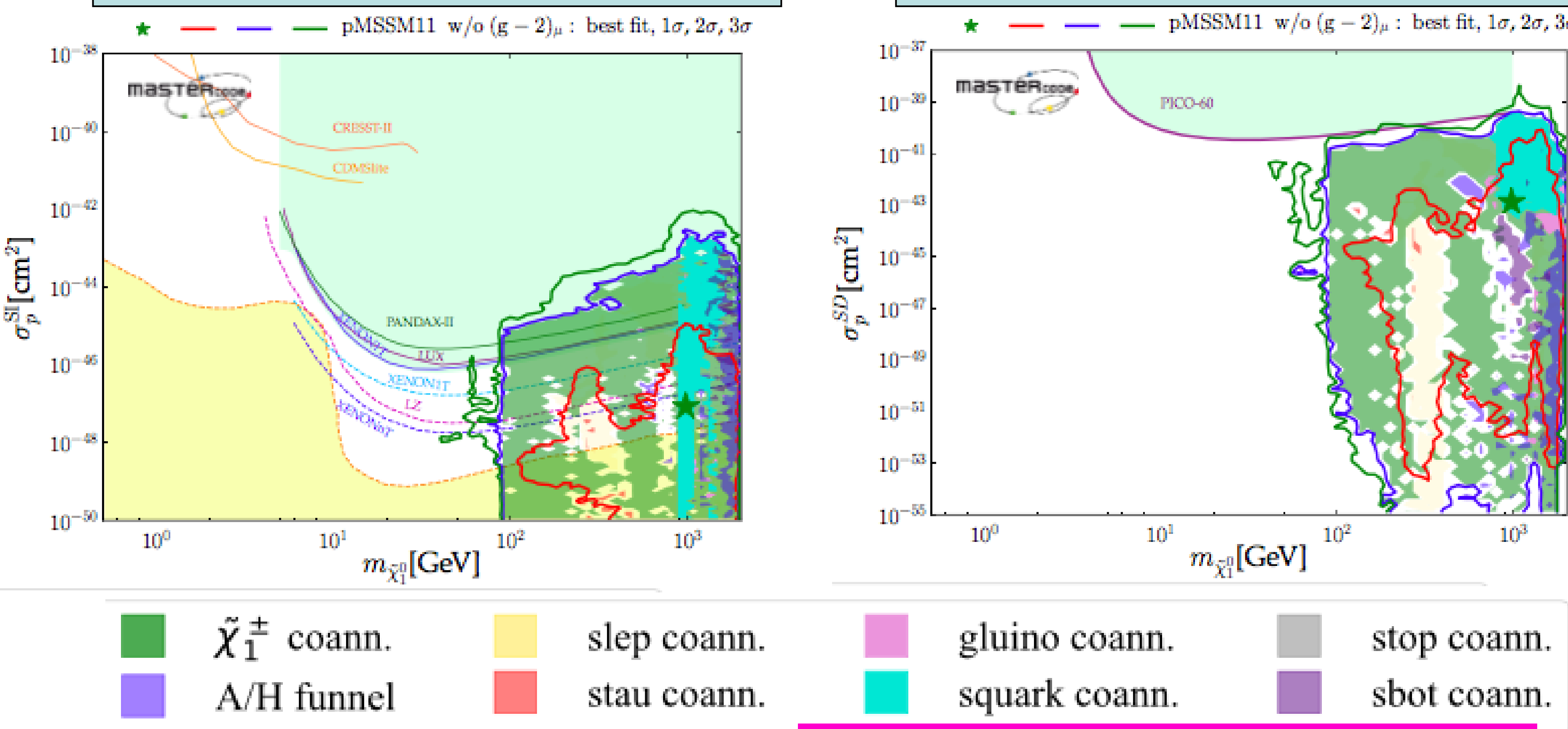
## Phenomenological MSSM

**Spin-independent scattering cross-section**

close to PandaX upper limit?

**Spin-dependent scattering:**

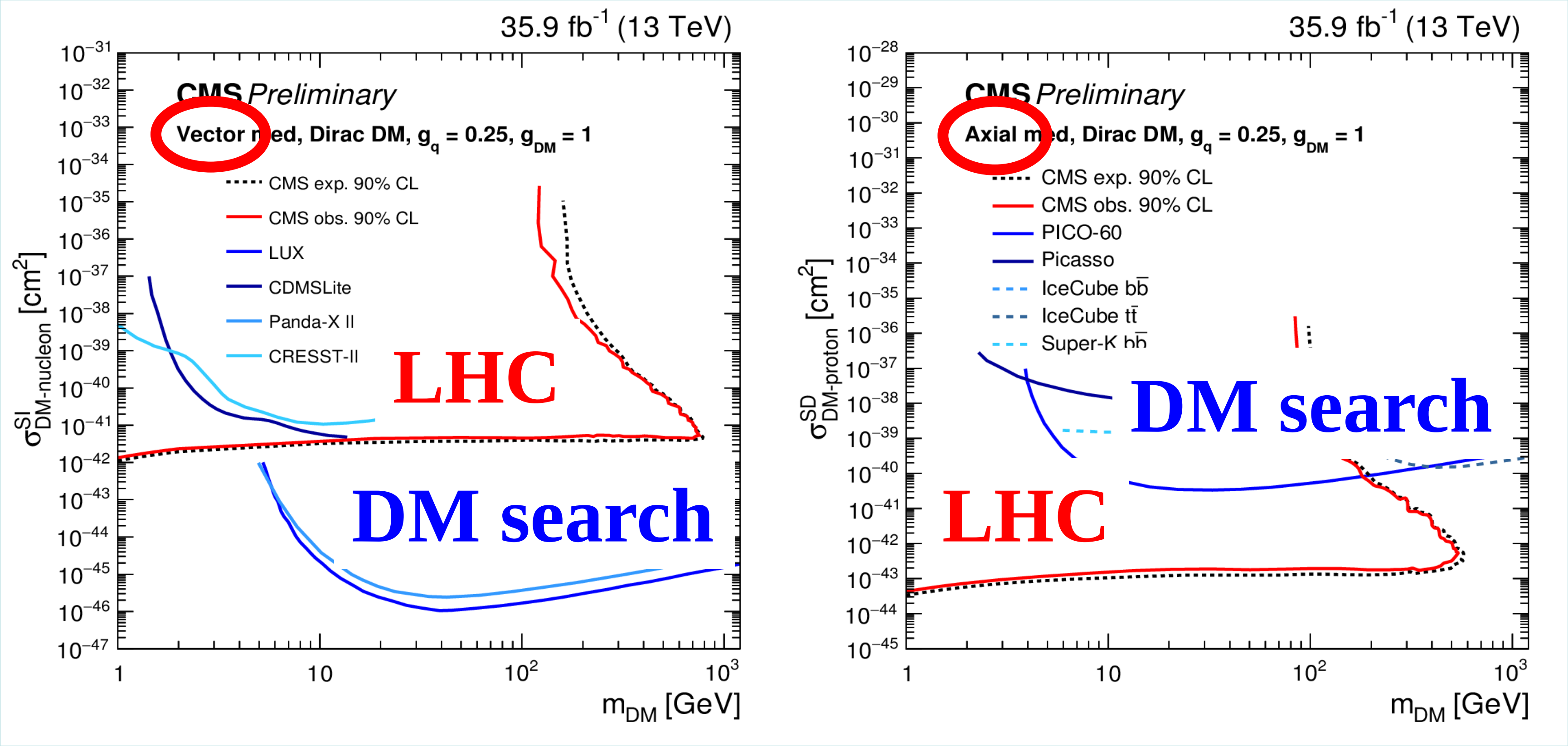
Strongest limit from PICO experiment




Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

# Simplified Dark Matter Models

- Present sensitivities for different mediator bosons



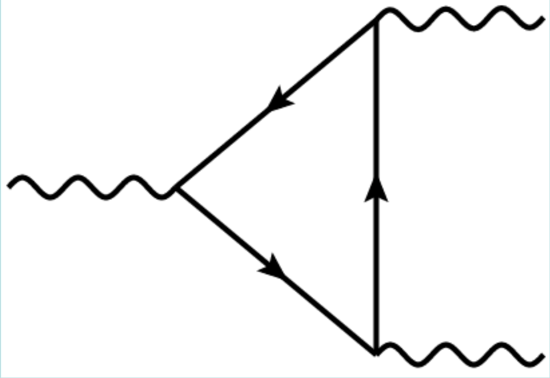

- Complementarity between LHC and direct searches

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

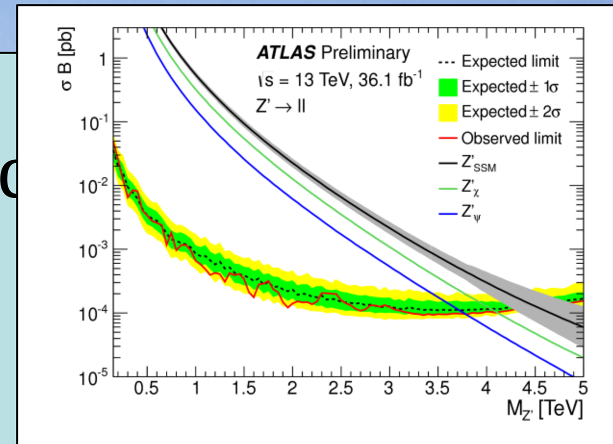
# Anomaly Cancellation Conditions

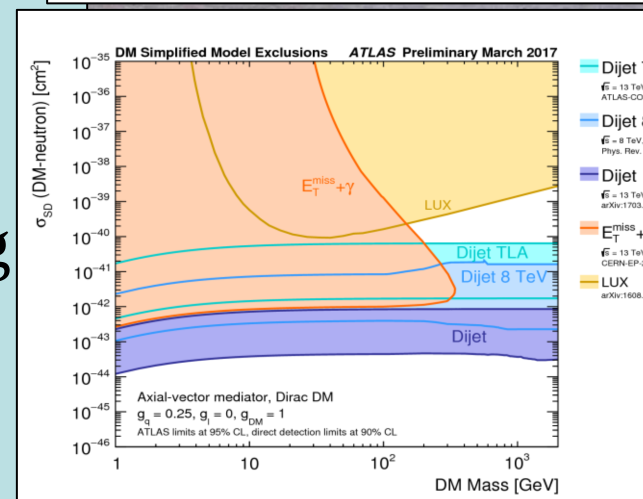
- Colour/U(1)’: (a) $[\mathrm{SU}(3)^2_C]\times[\mathrm{U}(1)']$, which implies $\mathrm{Tr}[\{T^i, T^j\}Y'] = 0$,
- $\mathrm{SU}(2)_W$/U(1)’ (b) $[\mathrm{SU}(2)^2_W]\times[\mathrm{U}(1)']$, which implies $\mathrm{Tr}[\{T^i, T^j\}Y'] = 0$,
- $\mathrm{U}(1)_Y{}^2$/U(1)’: (c) $[\mathrm{U}(1)^2_Y]\times[\mathrm{U}(1)']$, which implies $\mathrm{Tr}[Y^2 Y'] = 0$,
- $\mathrm{U}(1)_Y$/U(1)’$^2$: (d) $[\mathrm{U}(1)_Y]\times[\mathrm{U}(1)'^2]$, which implies $\mathrm{Tr}[Y Y'^2] = 0$,
- U(1)’$^3$: (e) $[\mathrm{U}(1)'^3]$, which implies $\mathrm{Tr}[Y'^3] = 0$,
- Gravity/U(1)’ (f) Gauge-gravity, which implies $\mathrm{Tr}[Y'] = 0$.
- **Non-trivial set of constraints**

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?



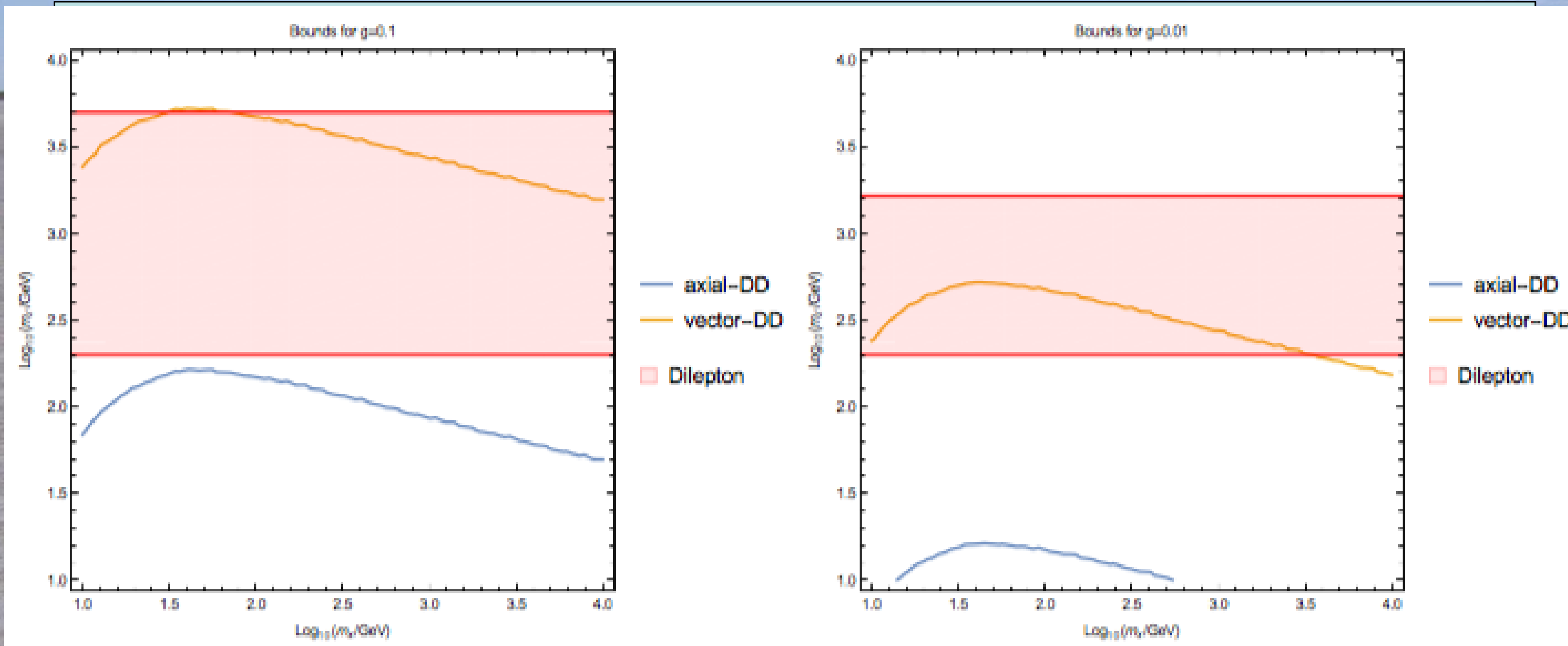



# Anomaly-Free Dark Matter Models are not so Simple

- 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 $2^{nd}$ 'dark' fermion
  - Z' still leptophilic
- Leptophobic models need DM particle + $\geq 2$ 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

## Dropping ideology

# 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

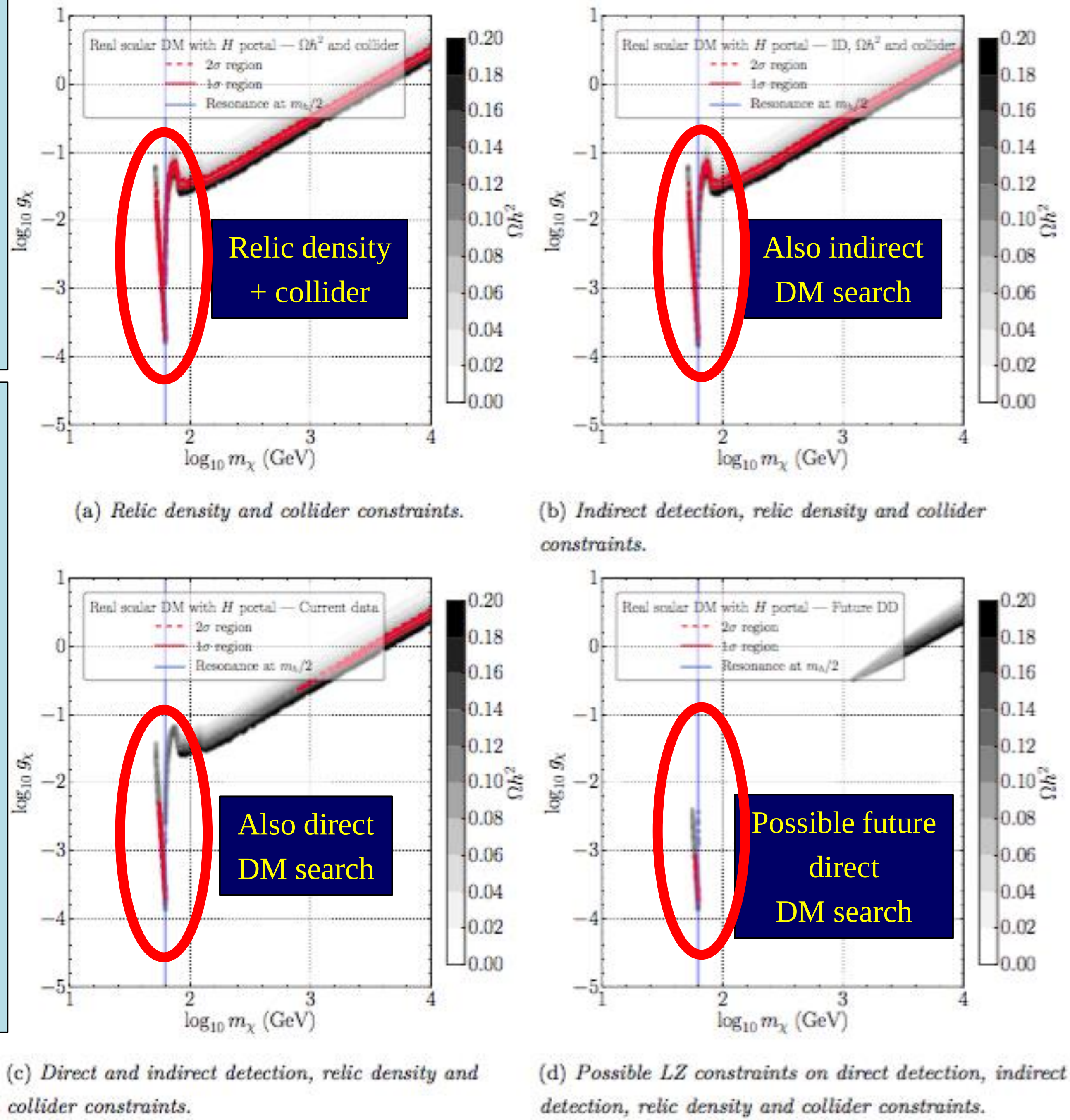
All available collider, DM search constraints

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




(a) *Relic density and collider constraints.*

(b) *Indirect detection, relic density and collider constraints.*

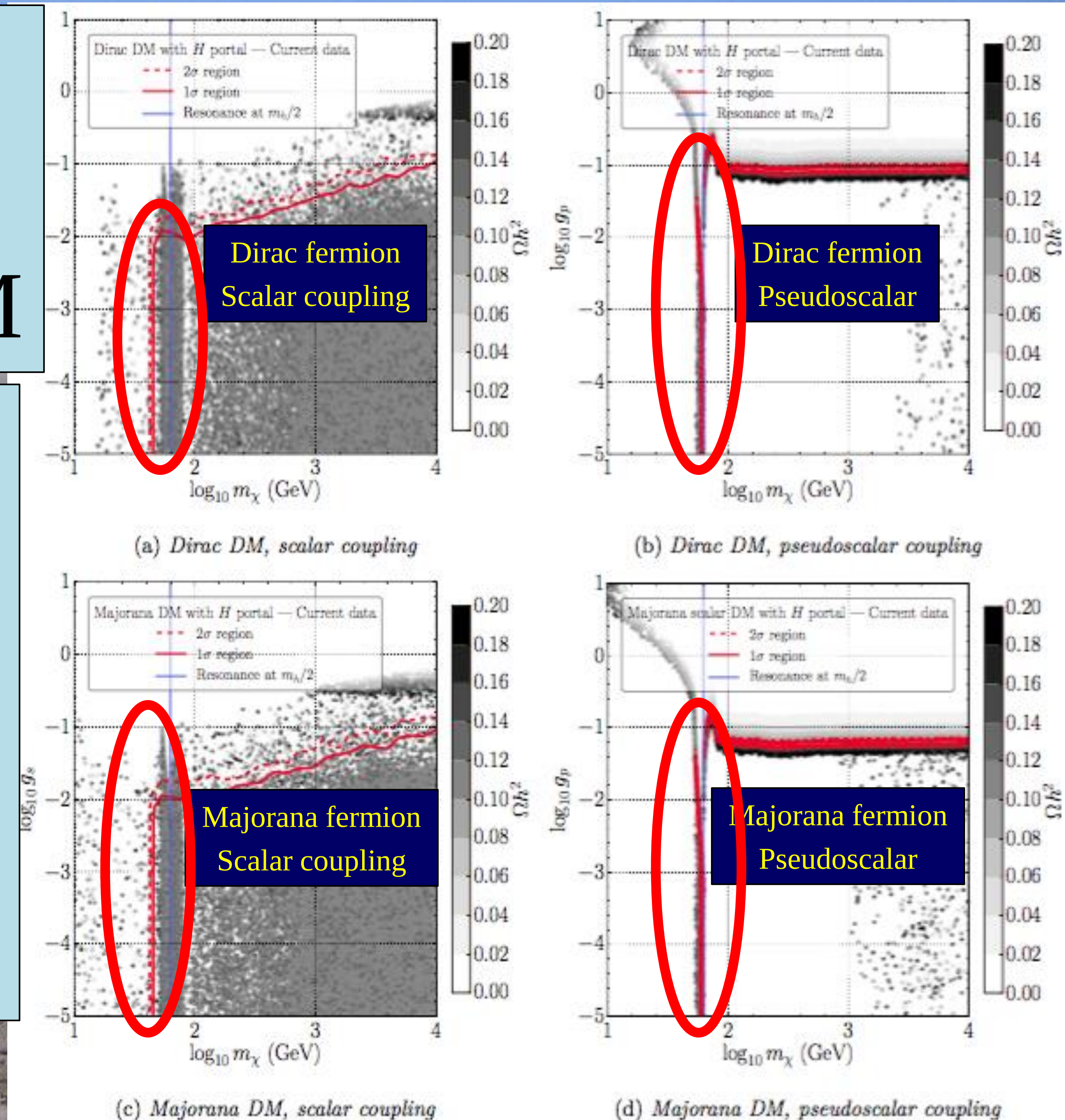
(c) *Direct and indirect detection, relic density and collider constraints.*

(d) *Possible LZ constraints on direct detection, indirect detection, relic density and collider constraints.*

JE, Fowlie, Marzola & Raidal, arXiv:1711.09912

# Higgs coupled to Spin-½ DM

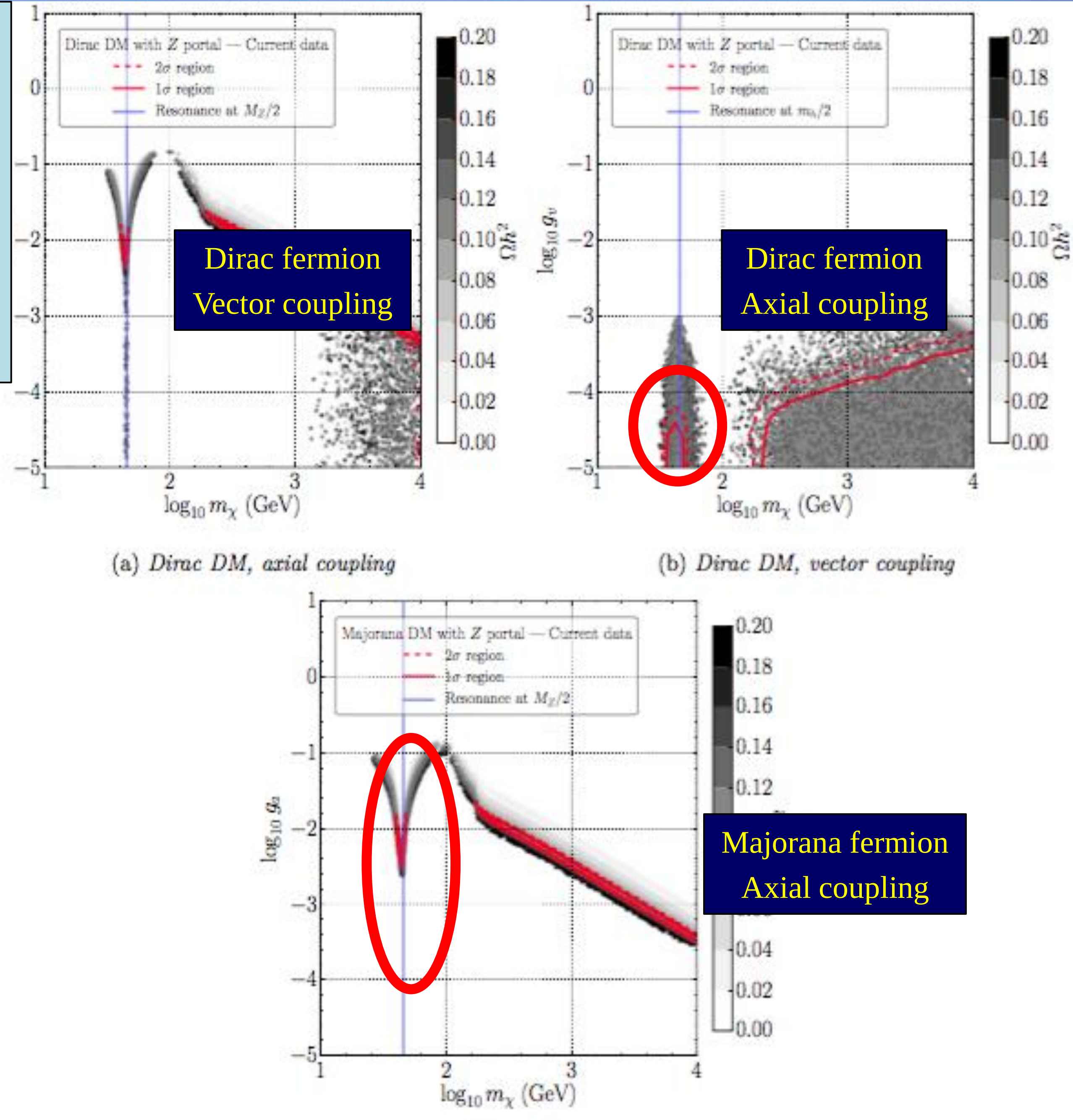
- **Red = 1-, 2-σ regions**
- Grey = relic density
- On- and off-shell cases both allowed




JE, Fowlie, Marzola & Raidal, arXiv:1711.09912

# Z Boson coupled to Spin-½ DM

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




(a) *Dirac DM, axial coupling*

(b) *Dirac DM, vector coupling*

(c) *Majorana DM, axial coupling*

JE, Fowlie, Marzola & Raidal, arXiv:1711.09912

# Summary of Results

| Model | Bayes factor | min $\chi^2$ | $p$-value |
|---|---|---|---|
| Real scalar $h$-portal | 0.55 | 2.6 | 0.27 |
| Complex scalar $h$-portal | 0.28 | 2.6 | 0.27 |
| Real vector $h$-portal | 0.23 | 2.6 | 0.27 |
| Complex vector $h$-portal | 0.059 | 2.6 | 0.27 |
| Majorana $h$-portal | 0.59 | 2.6 | 0.27 |
| Dirac $h$-portal | 0.71 | 2.6 | 0.27 |
| Scalar $Z$-porta | $3 \times 10^{-14}$ | 55 | $1.4 \times 10^{-12}$ |
| Vector $Z$-port | $6.8 \times 10^{-10}$ | 35 | $2.2 \times 10^{-8}$ |
| Majorana $Z$-portal | 1 | 2.6 | 0.27 |
| Dirac $Z$-portal | 0.24 | 2.6 | 0.27 |

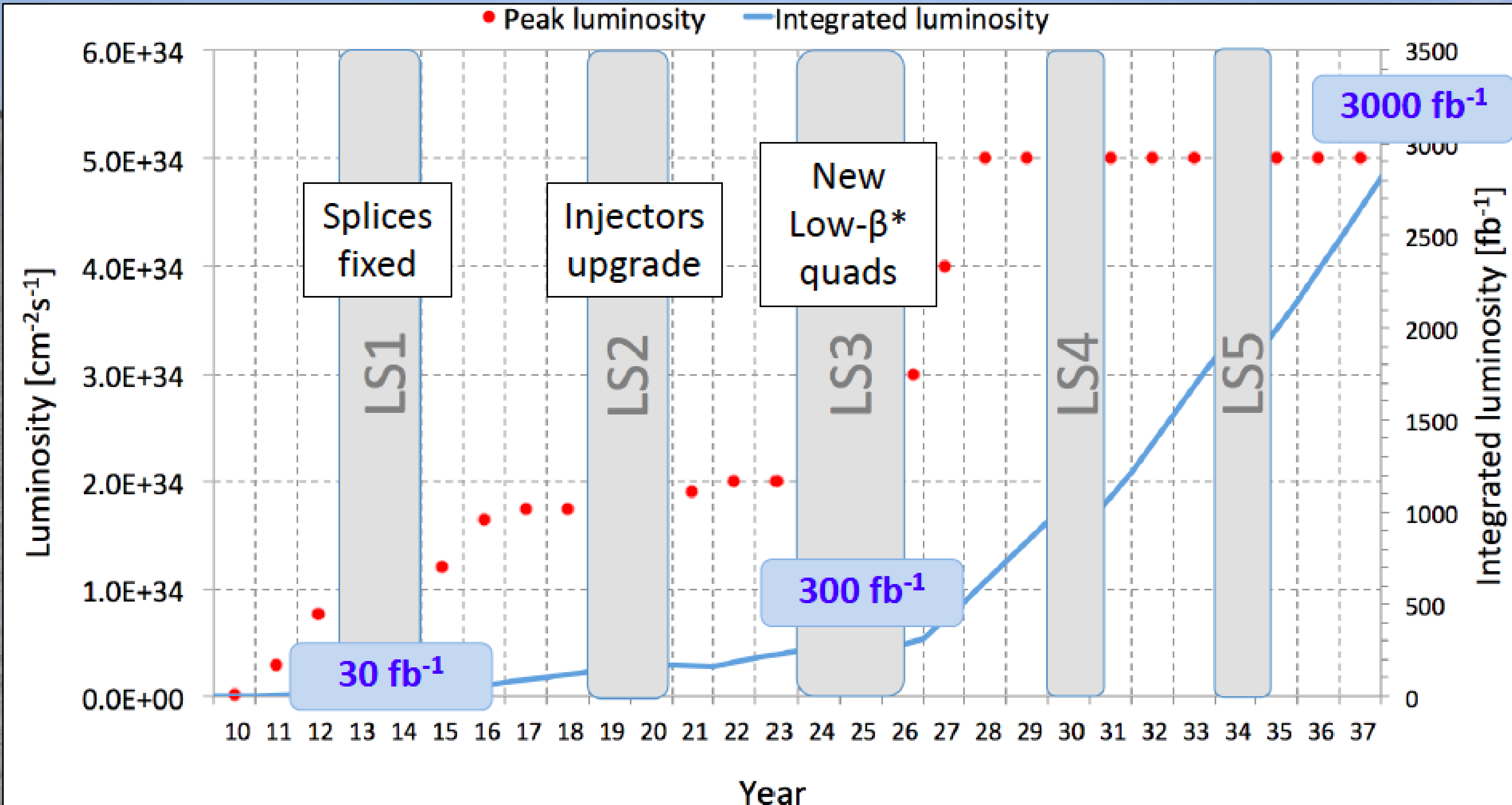
OK

Strongly disfavoured

OK

JE, Fowlie, Marzola & Raidal, arXiv:1711.09912

# The LHC in Future Years

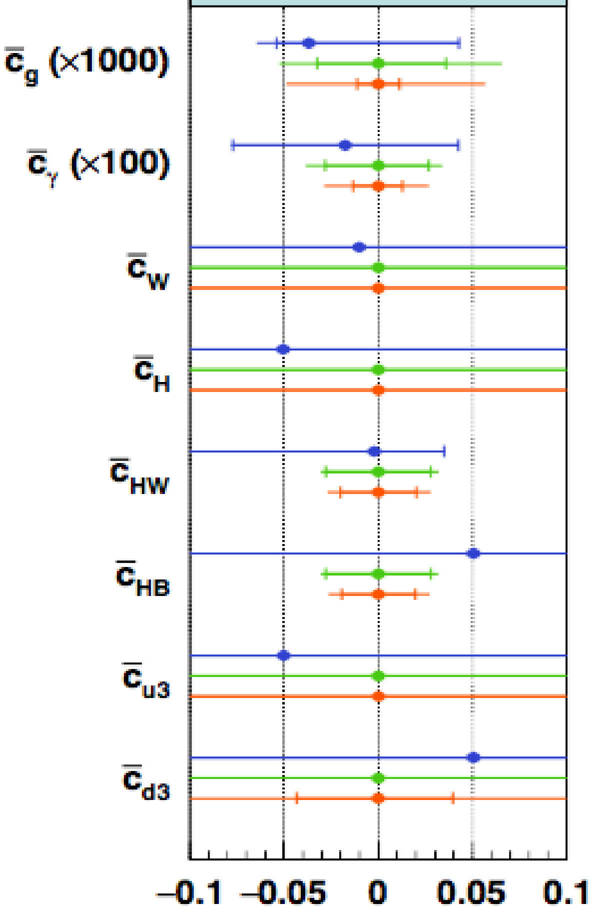


# Present & Future Constraints on D=6 Operators

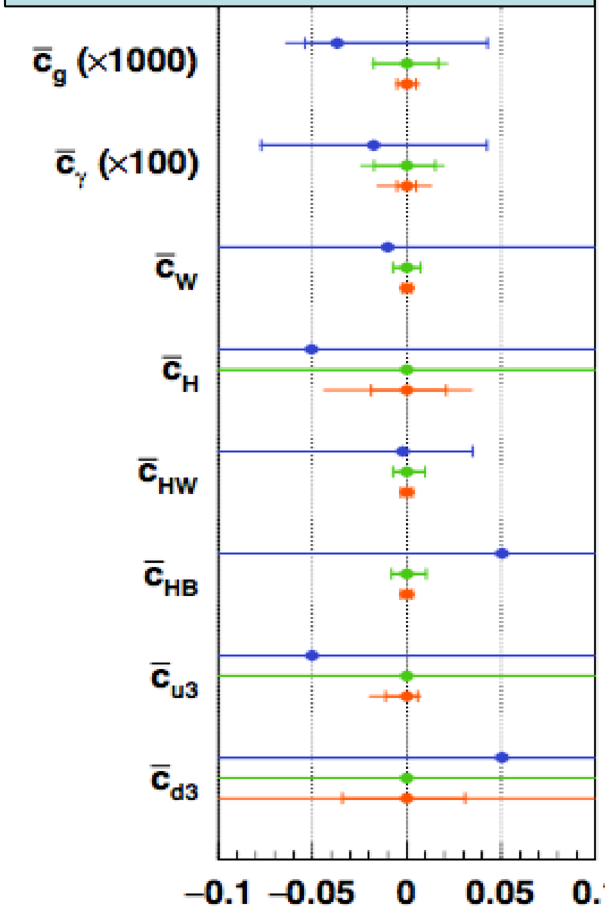
## Operators

| Bosonic CP-even | |
|---|---|
| $O_H$ | $\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$ |
| $O_T$ | $\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$ |
| $O_6$ | $-\frac{\lambda}{v^2}(H^\dagger H)^3$ |
| $O_g$ | $\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$ |
| $O_\gamma$ | $\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$ |
| $O_W$ | $\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$ |
| $O_B$ | $\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$ |
| $O_{HW}$ | $\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$ |
| $O_{HB}$ | $\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$ |
| $O_{2W}$ | $\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$ |
| $O_{2B}$ | $\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$ |
| $O_{2G}$ | $\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$ |
| $O_{3W}$ | $\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$ |
| $O_{3G}$ | $\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$ |

## Constraints from rates



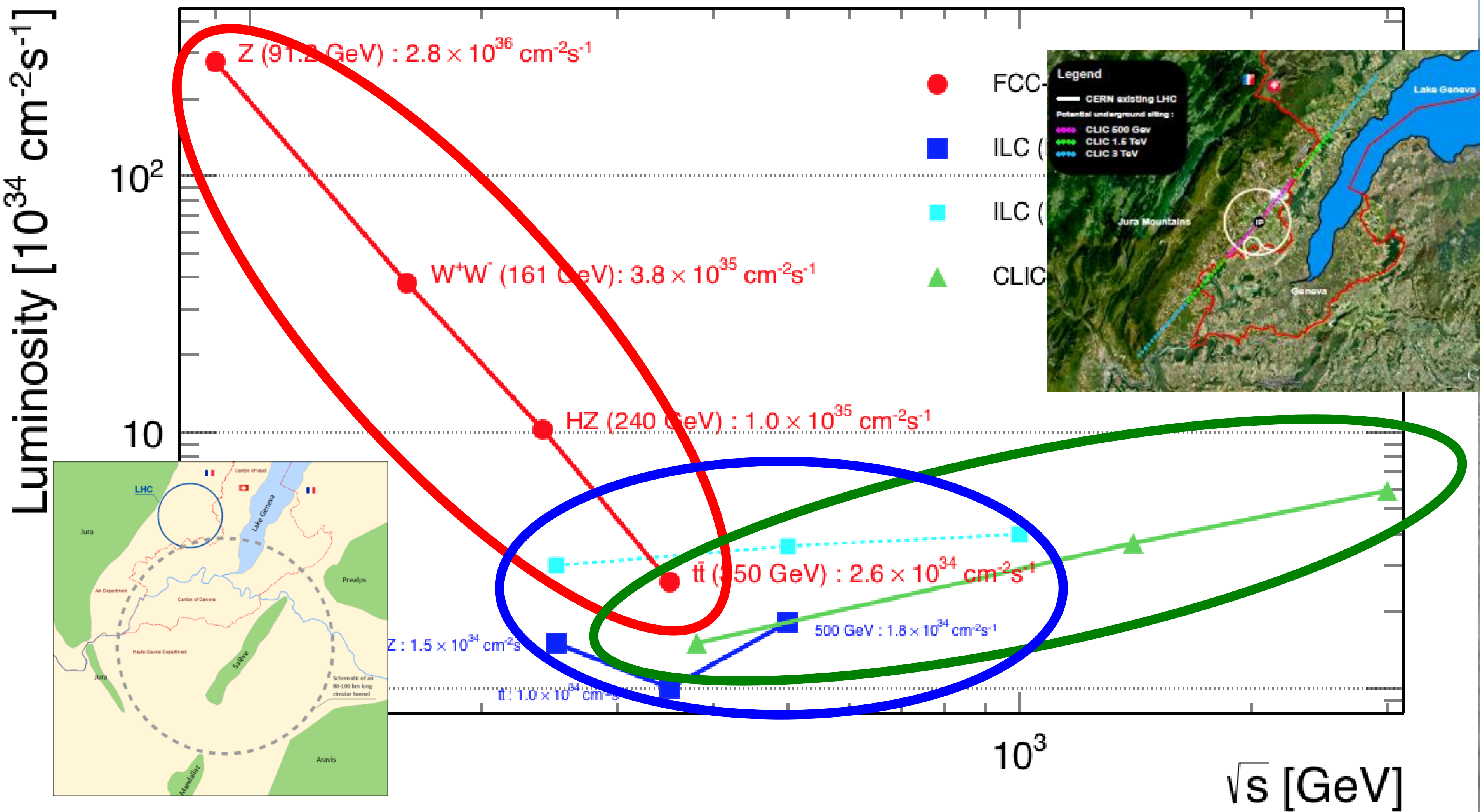

## Constraints including kinematics




**Current** **300/fb** **3000/fb**

Englert, Kogler, Schulz & Spannowsky, arXiv:1511.05170

# Projected $e^+e^-$ Colliders: Luminosity vs Energy



**CEPC-SPPC**

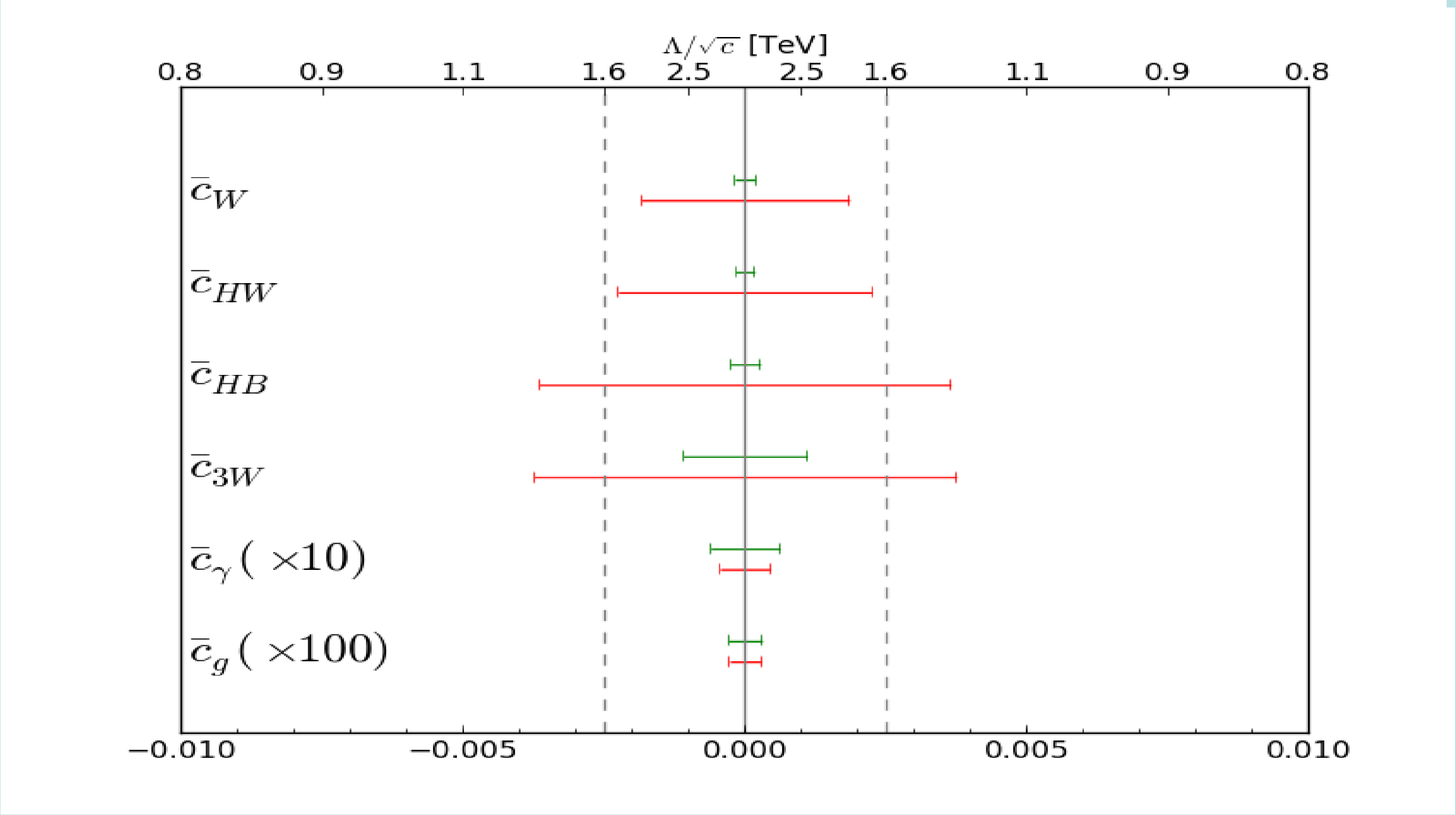
*Preliminary Conceptual Design Report*

# Future Circular Colliders

## The vision:

explore 10 TeV scale directly (100 TeV pp) + indirectly ($e^+e^-$)

# FCC-ee Higgs & TGC Measurements




- LHC constraints

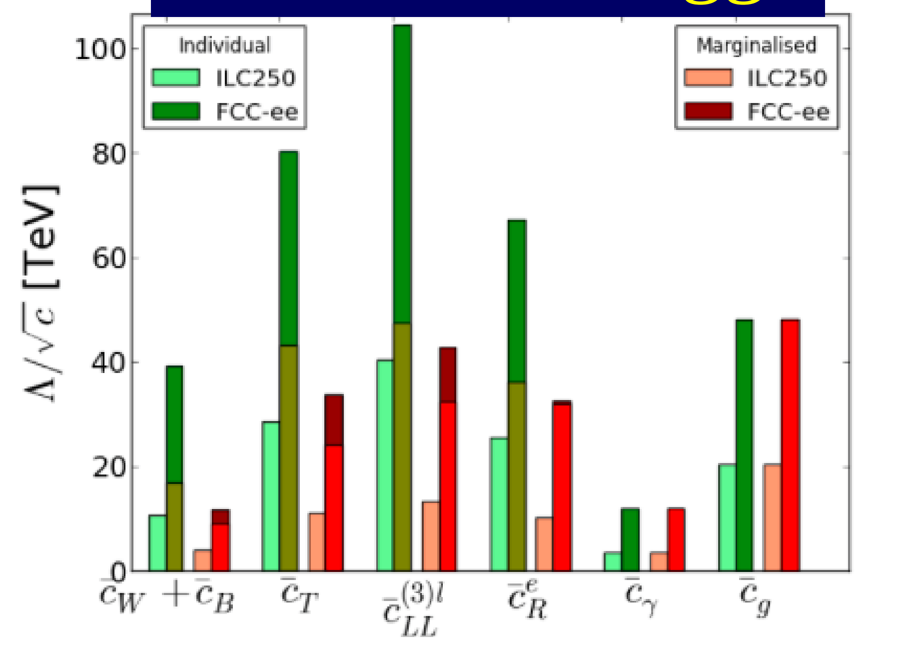
JE & Tevong You, arXiv:1510.04561

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

JE & Tevong You, arXiv:1510.04561

# FCC-ee Higgs & TGC Measurements

## EWPTs and Higgs



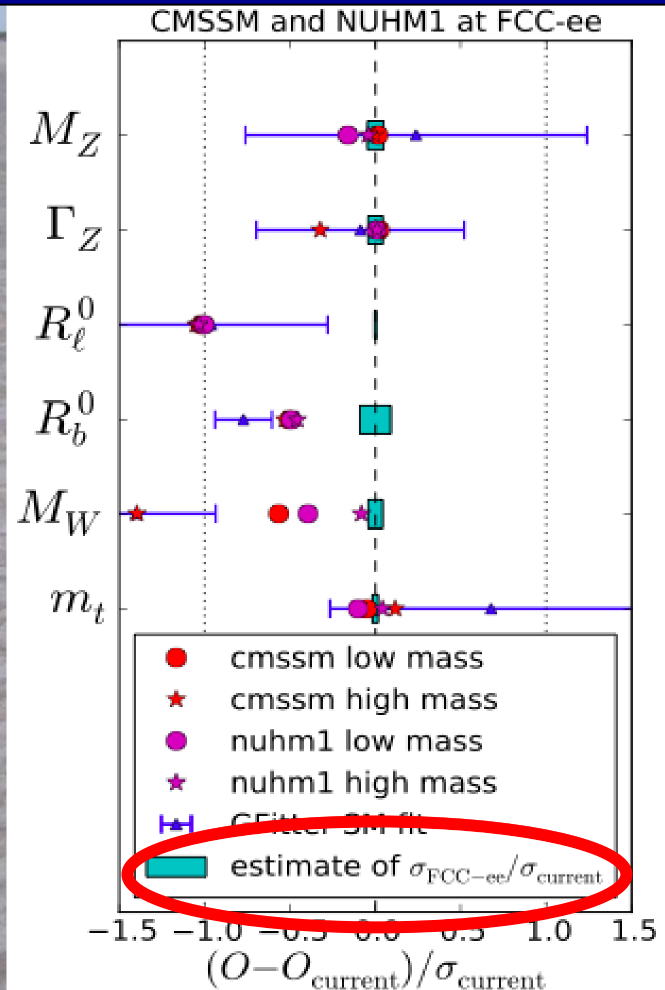

- Shadings:
  - With/without theoretical EWPT uncertainties

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

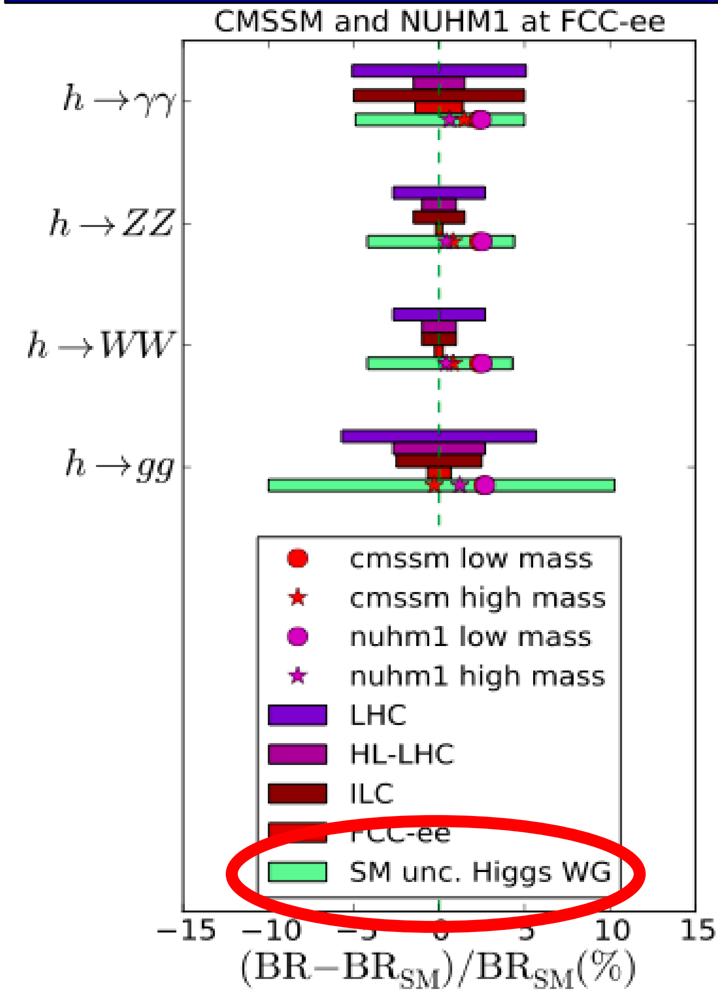
Buchmueller, JE et al: arXiv:1505.04702

# Precision **FCC-ee** Measurements

## Precision Electroweak



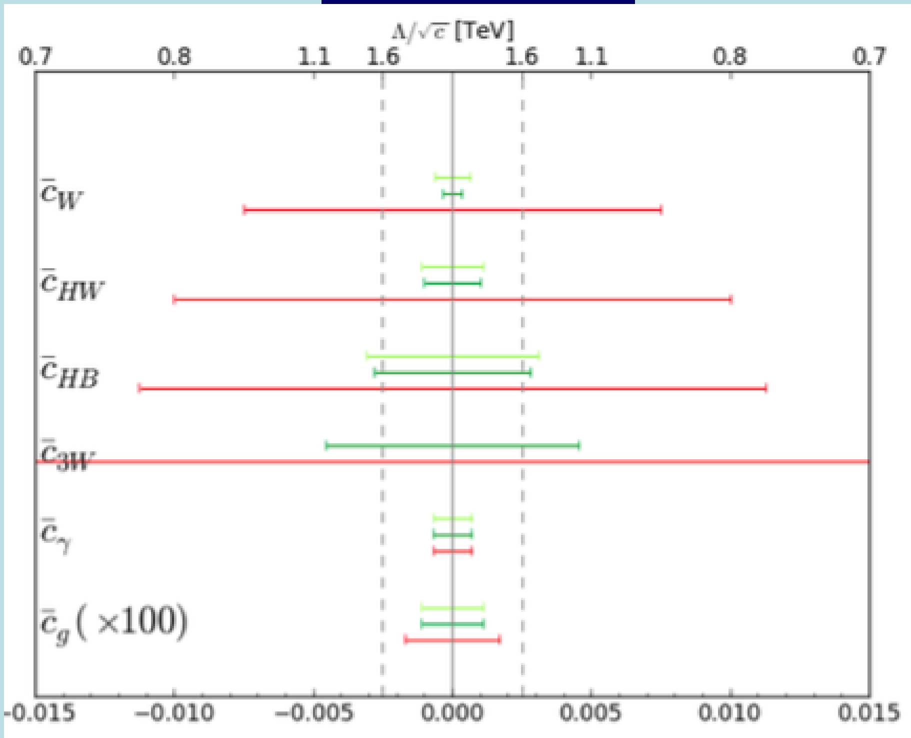

## Precision Higgs

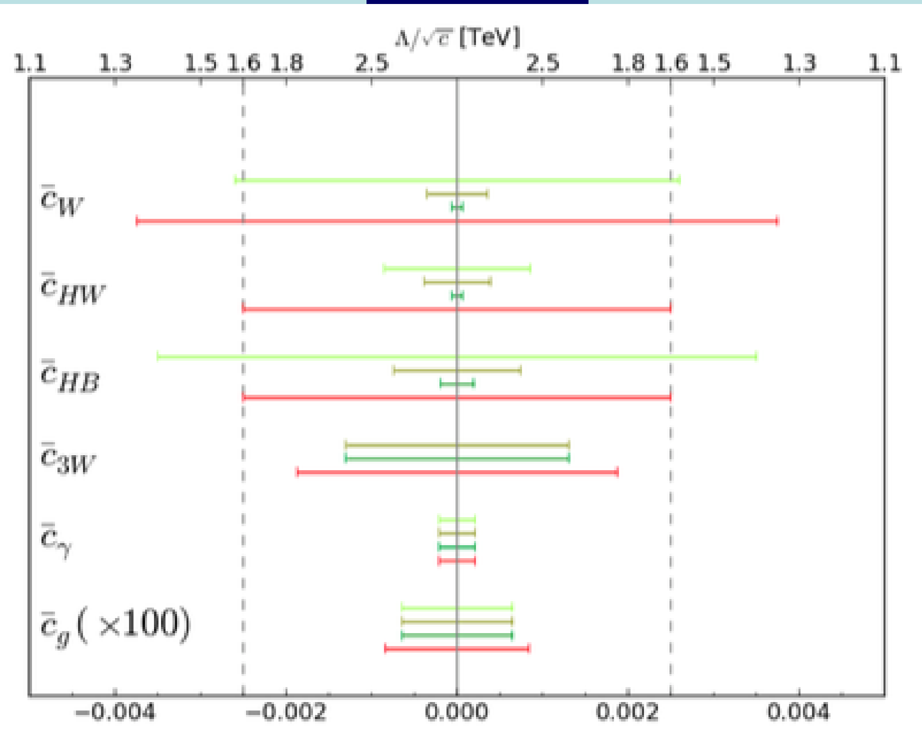


# CLIC Sensitivities to Dimension-6 Operators

350 GeV

3 TeV




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

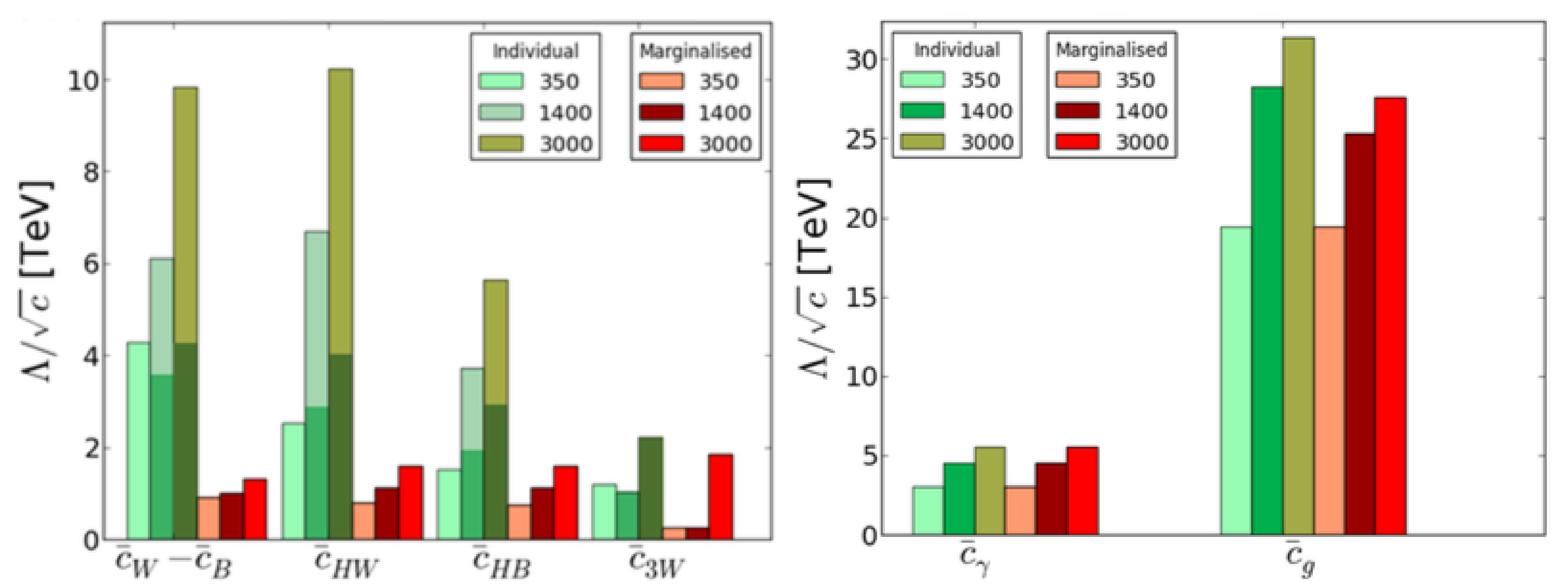
Sensitivity enhanced by higher centre-of-mass energy

JE, Roloff, Sanz & Tevong You, arXiv:1701.04804

# CLIC Sensitivities to Dimension-6 Operators

Individual operators

Global fit

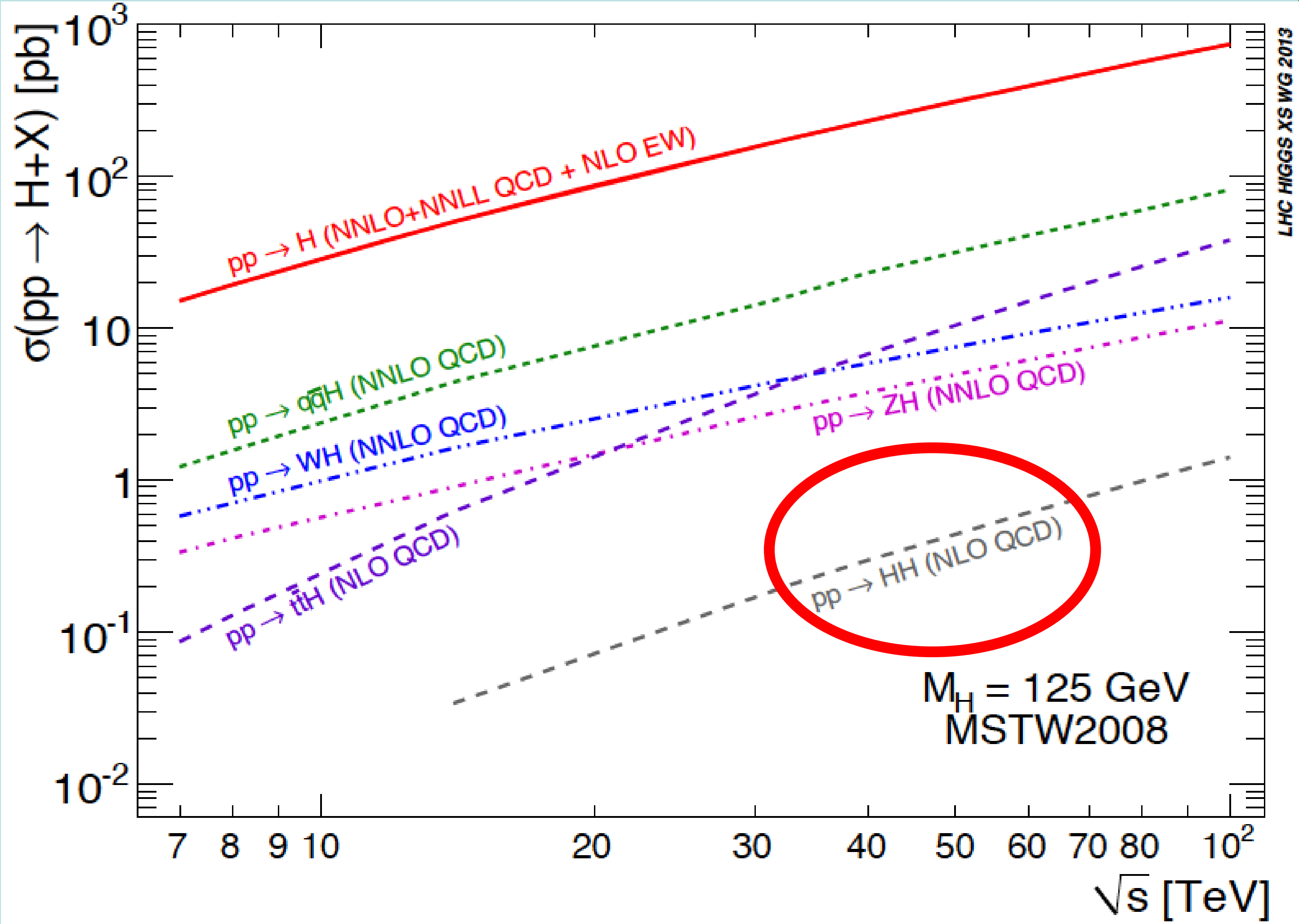



Sensitivity enhanced by higher centre-of-mass energy

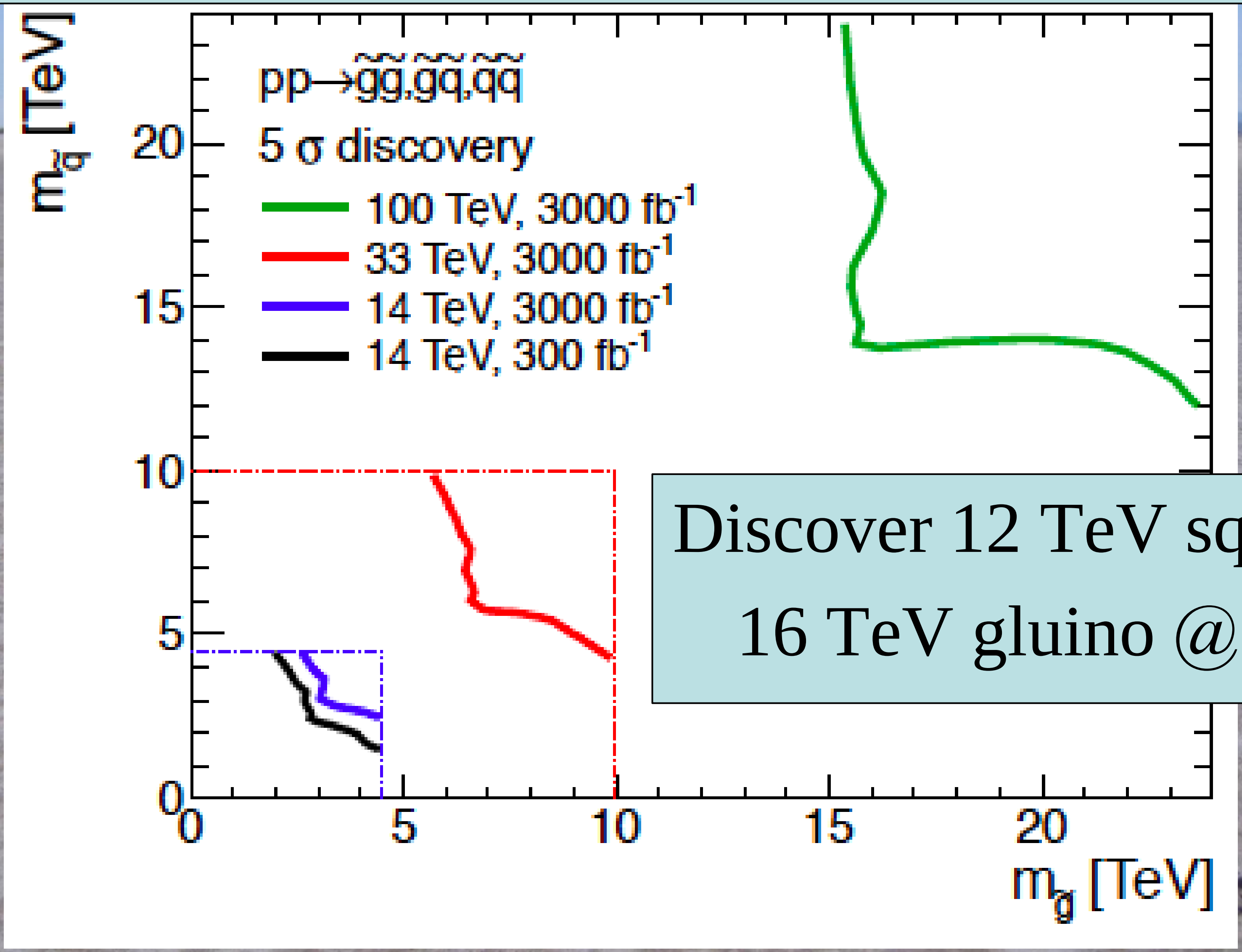
JE, Roloff, Sanz & Tevong You, arXiv:1701.04804

# 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