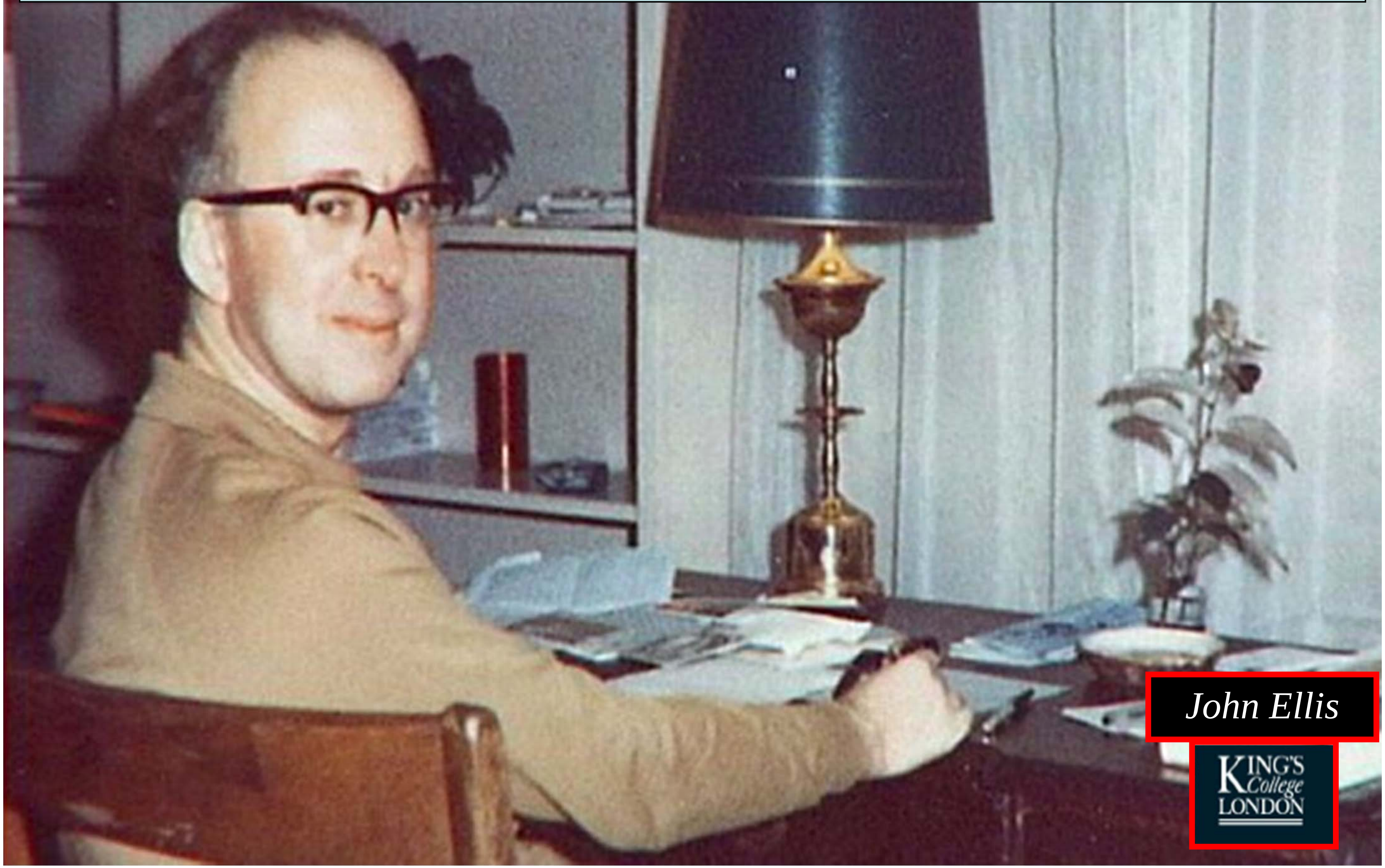
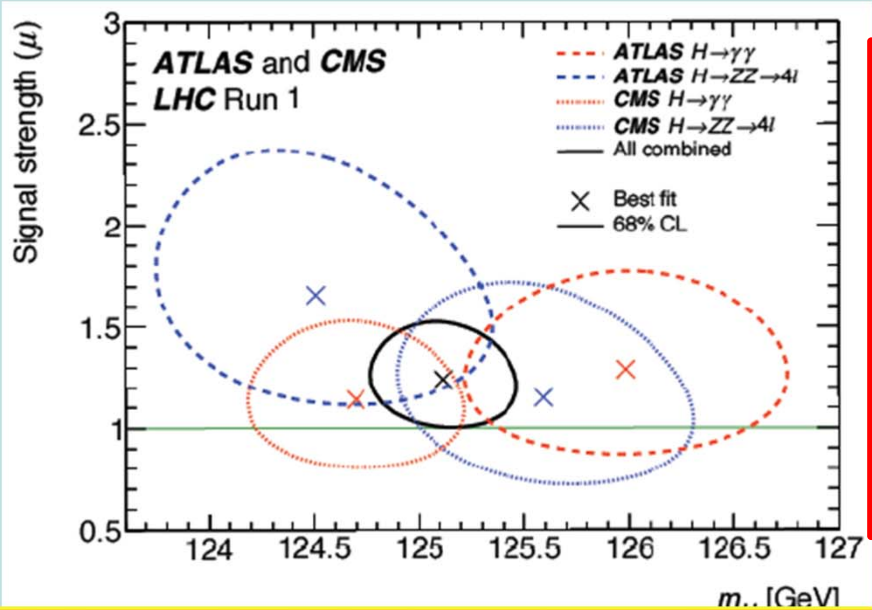
Conclusions/Perspectives



John Ellis

Higgs Mass Measurements

- ATLAS + CMS ZZ* and γγ final states



Crucial for stability of Electroweak vacuum

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

Naïve combination 125.13 ± 0.14 GeV

Theoretical Constraints on Higgs Mass

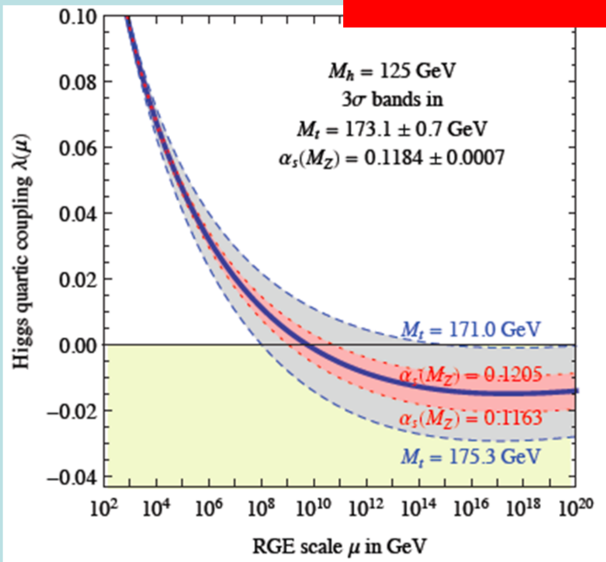
- Large M_h → large self-coupling → blow up at

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

$\lambda(Q) =$

Instability @ $10^{11.4\pm0.8}$ GeV

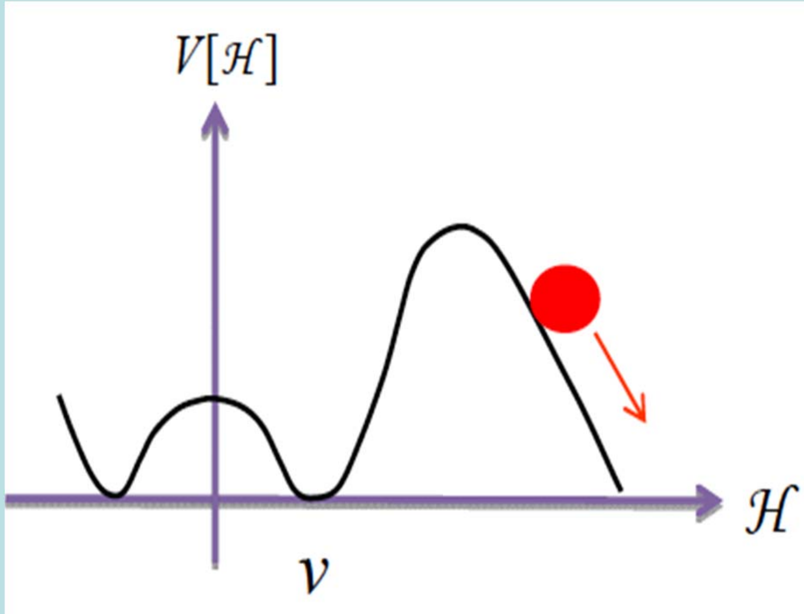
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable



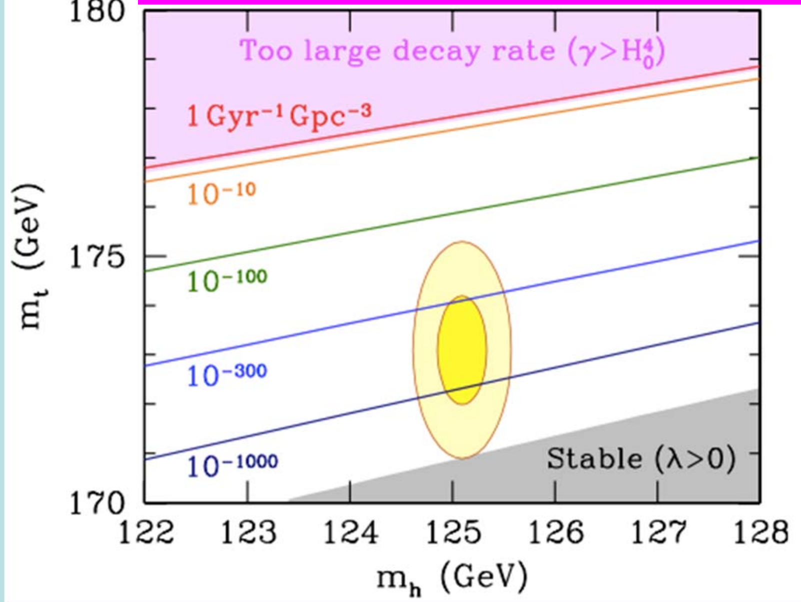
- Vacuum could be stabilized by **Supersymmetry**

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

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

- Naïve combination of recent ATLAS/CMS data:

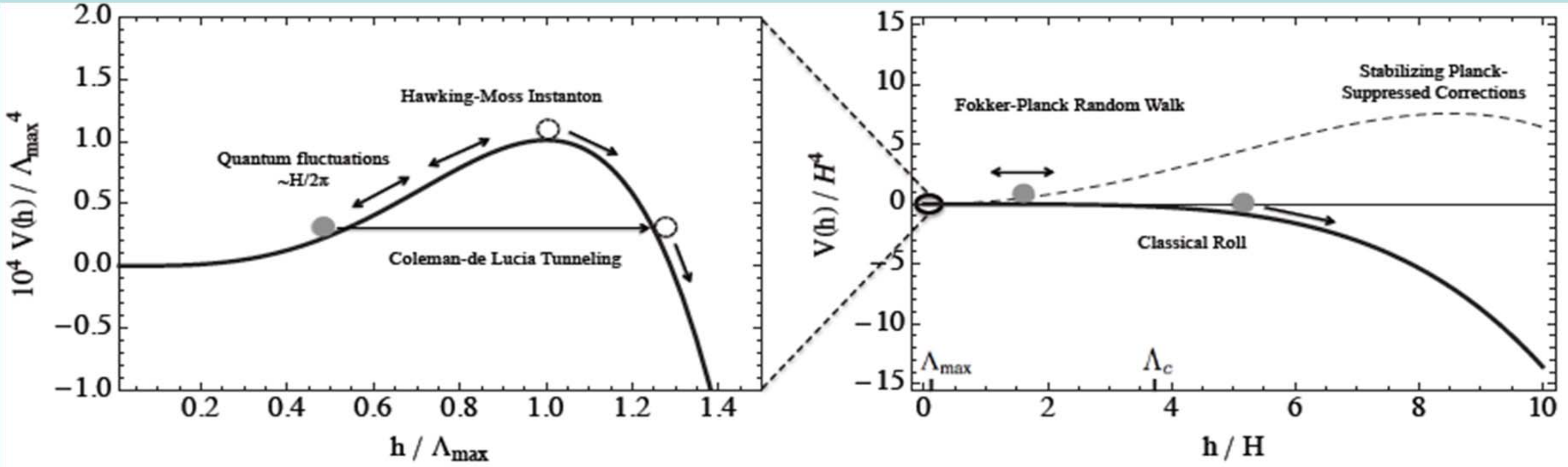
$m_t = 172.47 \pm 0.35$ GeV ➔ $\log_{10}(\Lambda/\mathrm{GeV}) = 11.4 \pm 0.8$

- Sensitive to α_s as well as m_t and M_h

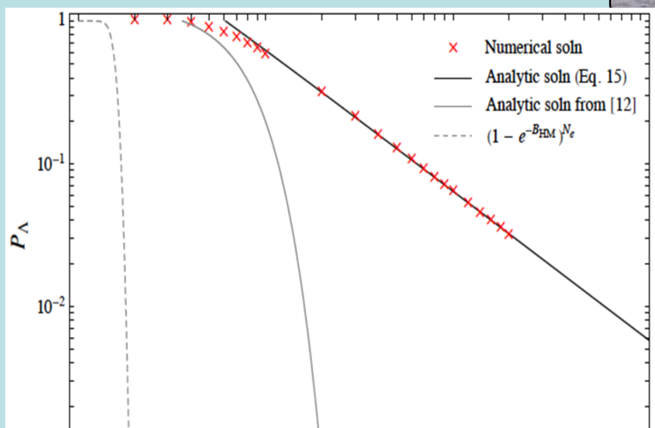
Instability during Inflation?

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?

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:

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

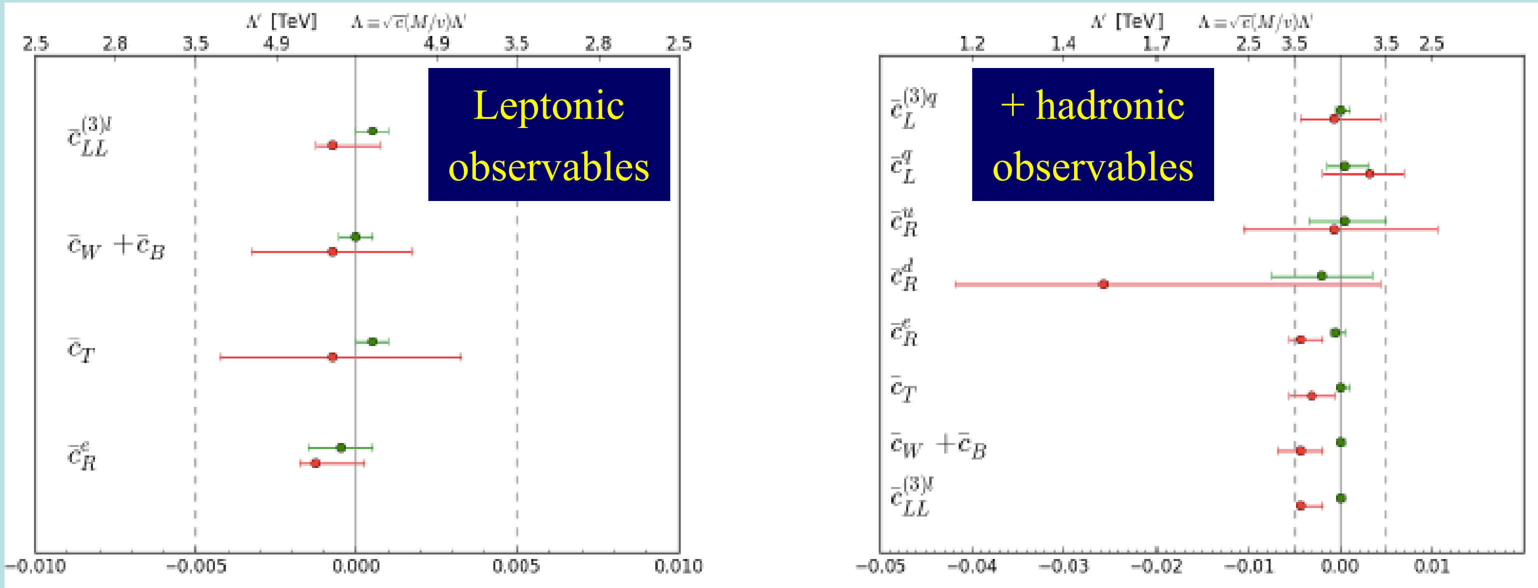
- Constrain with precision EW, Higgs data, TGCs ...

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



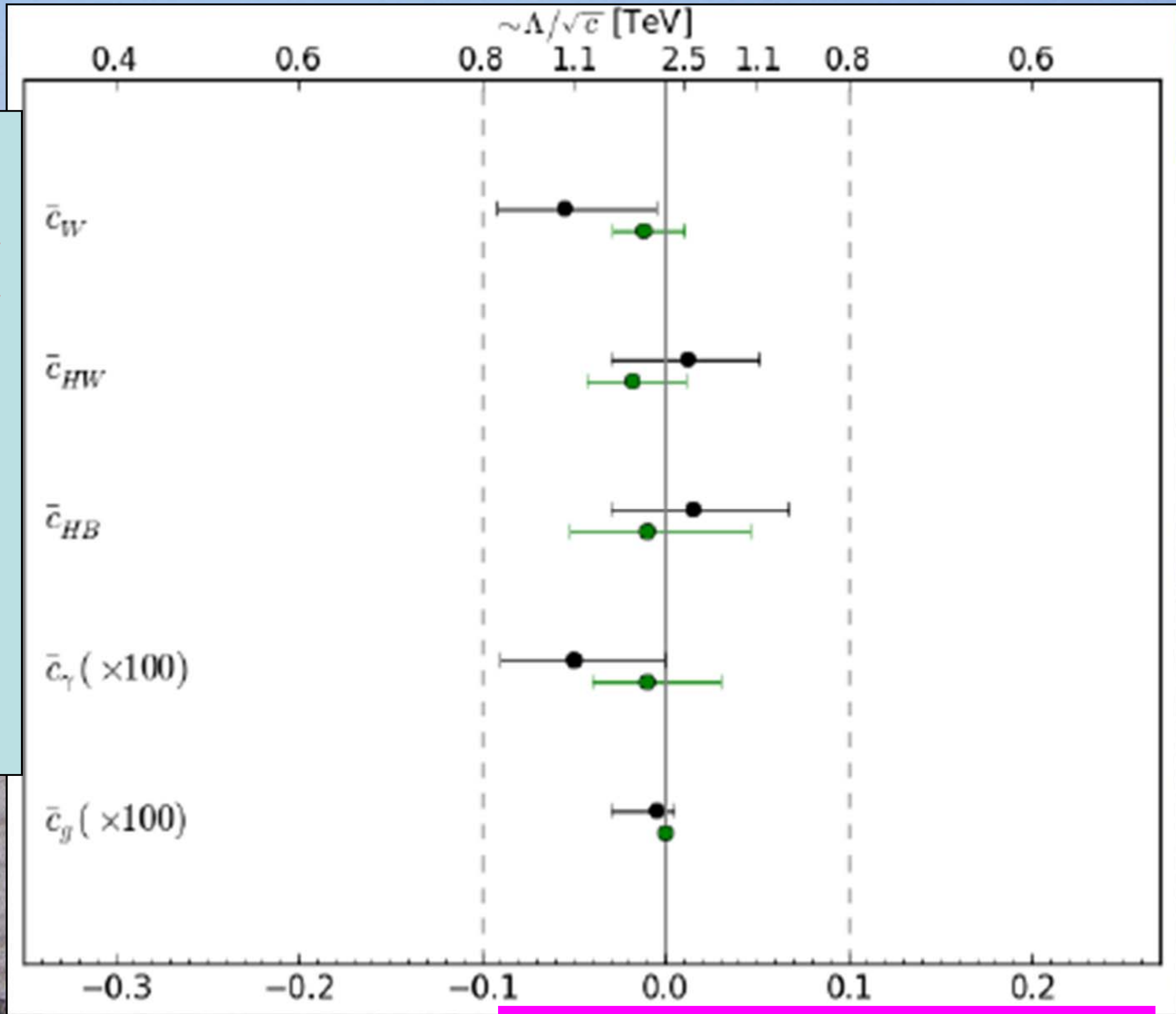
Fits to individual dimension-6 operators

Global fit to dimension-6 operators

JE, Sanz & Tevong You, arXiv:1410.7703

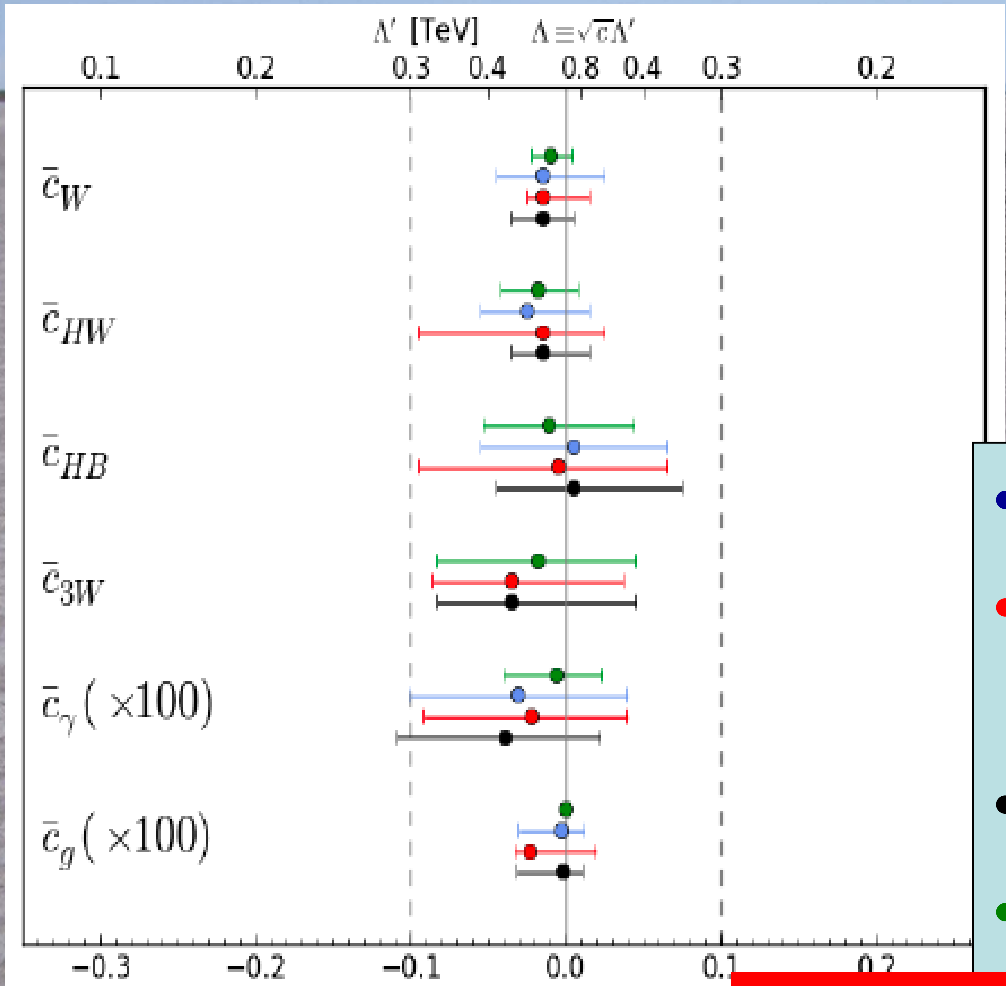
Fits to LHC Higgs Production Data

- Using signal strengths & **VH kinematics** in global fit
- **Single-parameter fits**

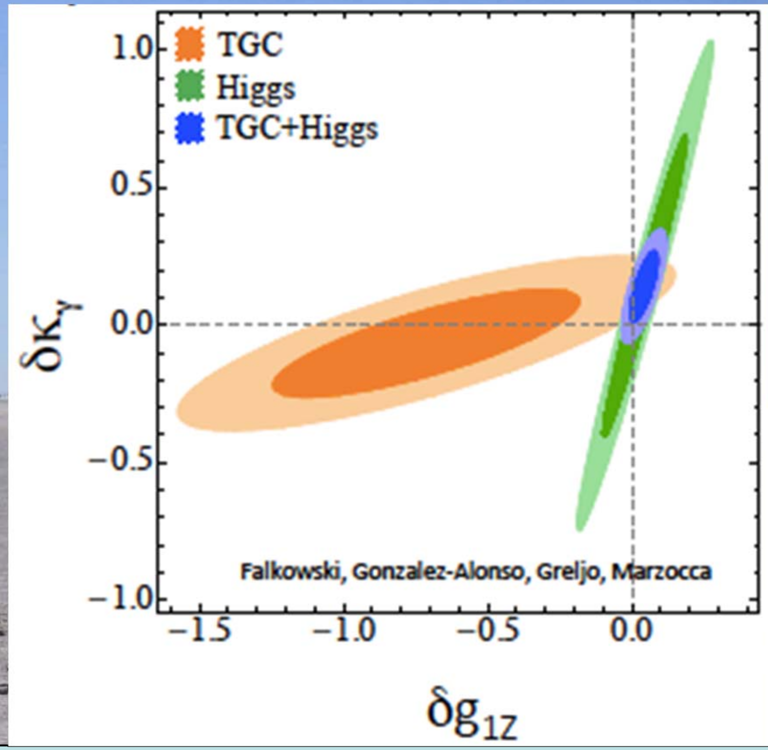


JE, Sanz & Tevong You, arXiv:1404.3667

Global Fits to LHC Data



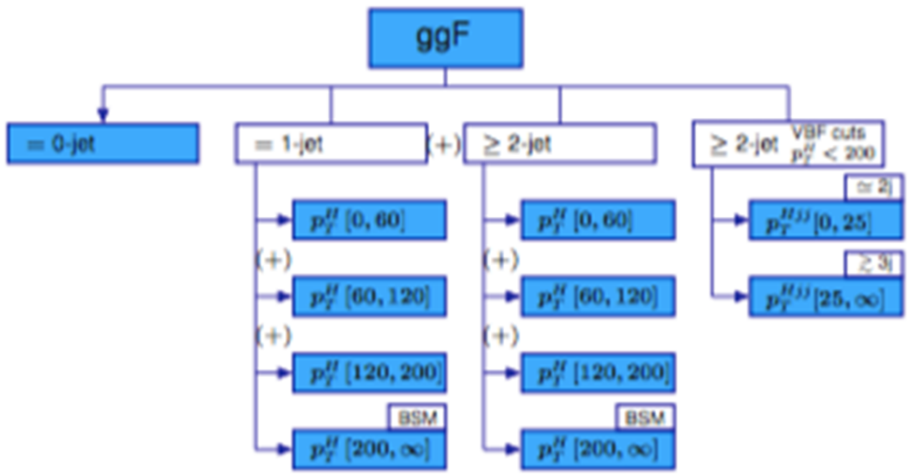
JE, Sanz & Tevong You, arXiv:1410.7703

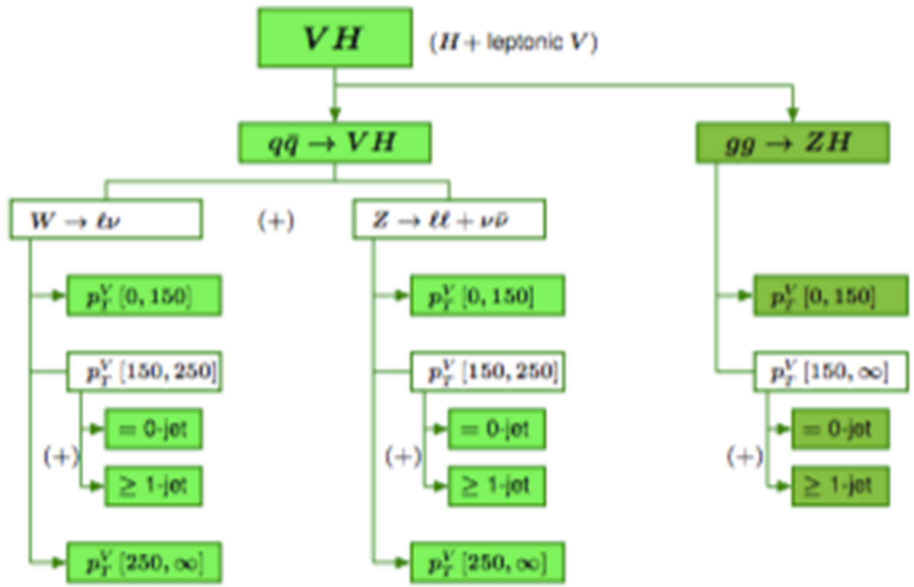


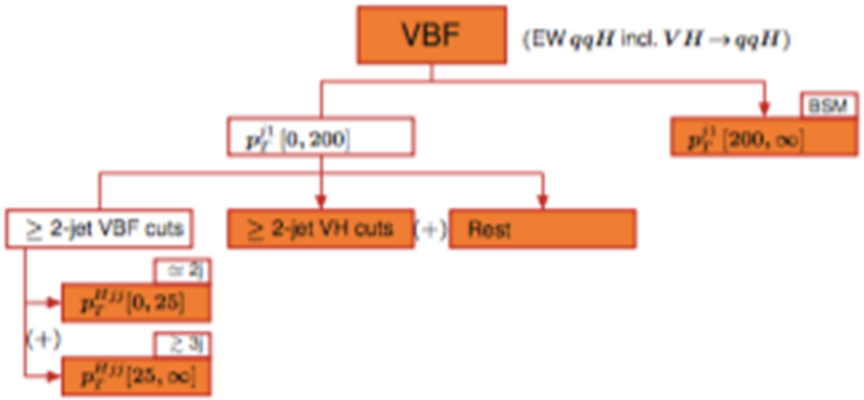
- **Associated H production**
- **LHC Triple-gauge couplings** Complementary!
- Global combination
- **Individual operators**

Preferred framework for analyzing Run 2

ATLAS Higgs EFT Analysis



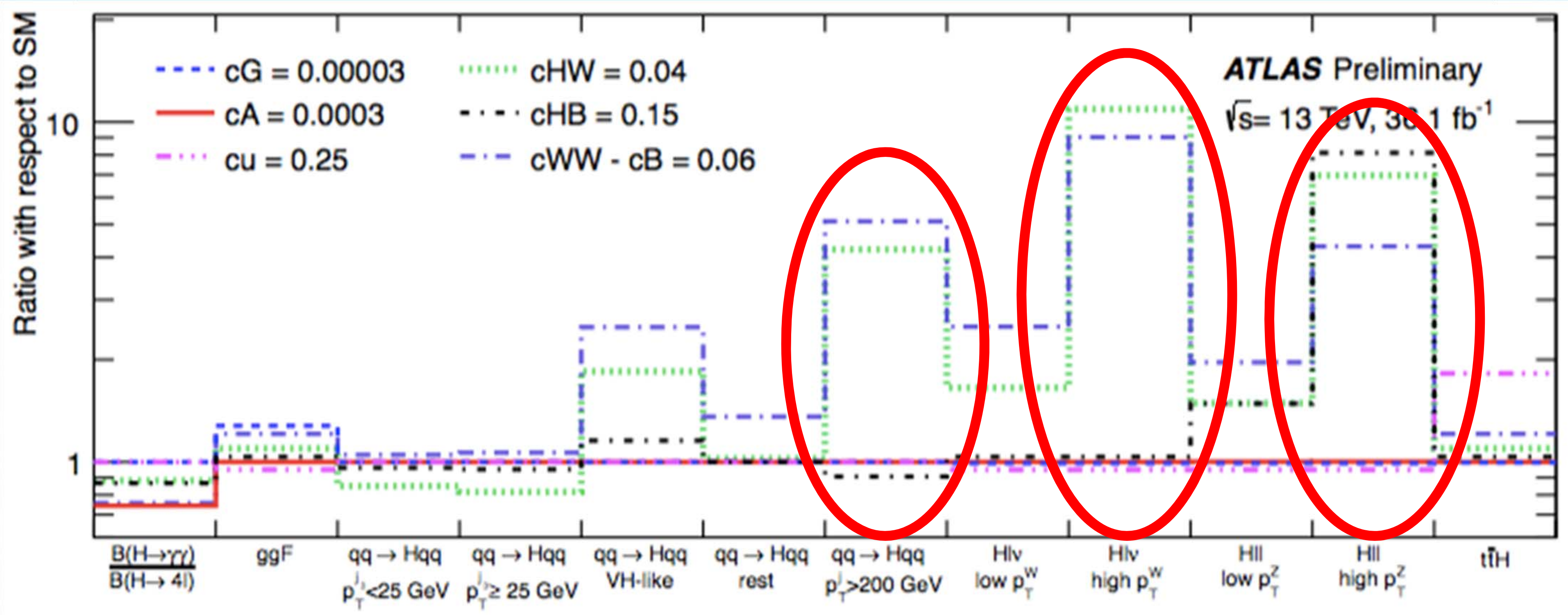




Operator	Expression	HEL coefficient	Vertices
O_g	$\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	cG = $\frac{m_W^2}{g_s^2}\bar{c}_g$	Hgg
O_γ	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	cA = $\frac{m_W^2}{g'^2}\bar{c}_\gamma$	$H\gamma\gamma, HZZ$
O_u	$y_u \lvert H\rvert^2 \bar{u}_l H u_R +$ h.c.	cu = $v^2\bar{c}_u$	$Ht\bar{t}$
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

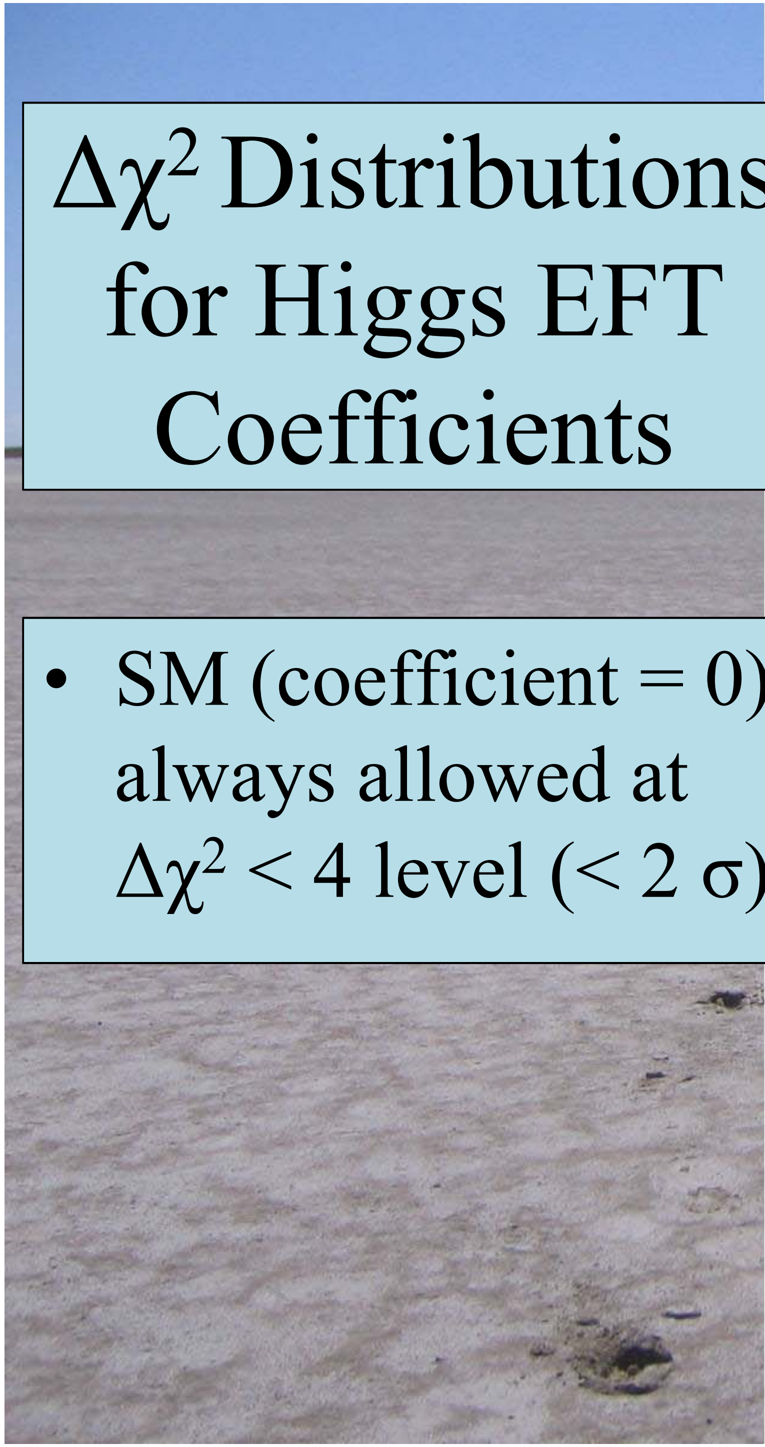
- Rate relative to SM with different operators

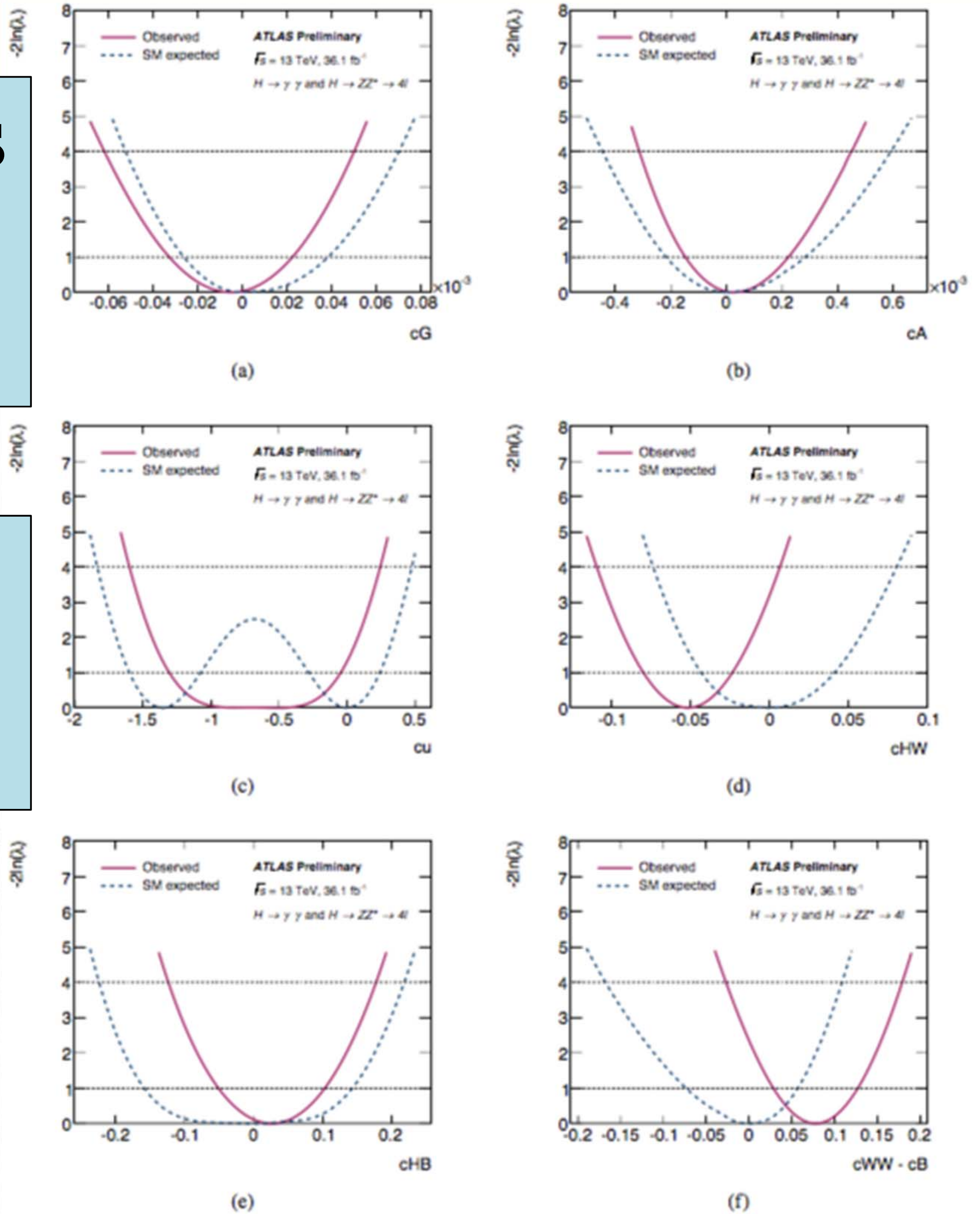


- **Higher sensitivity at higher p_T**

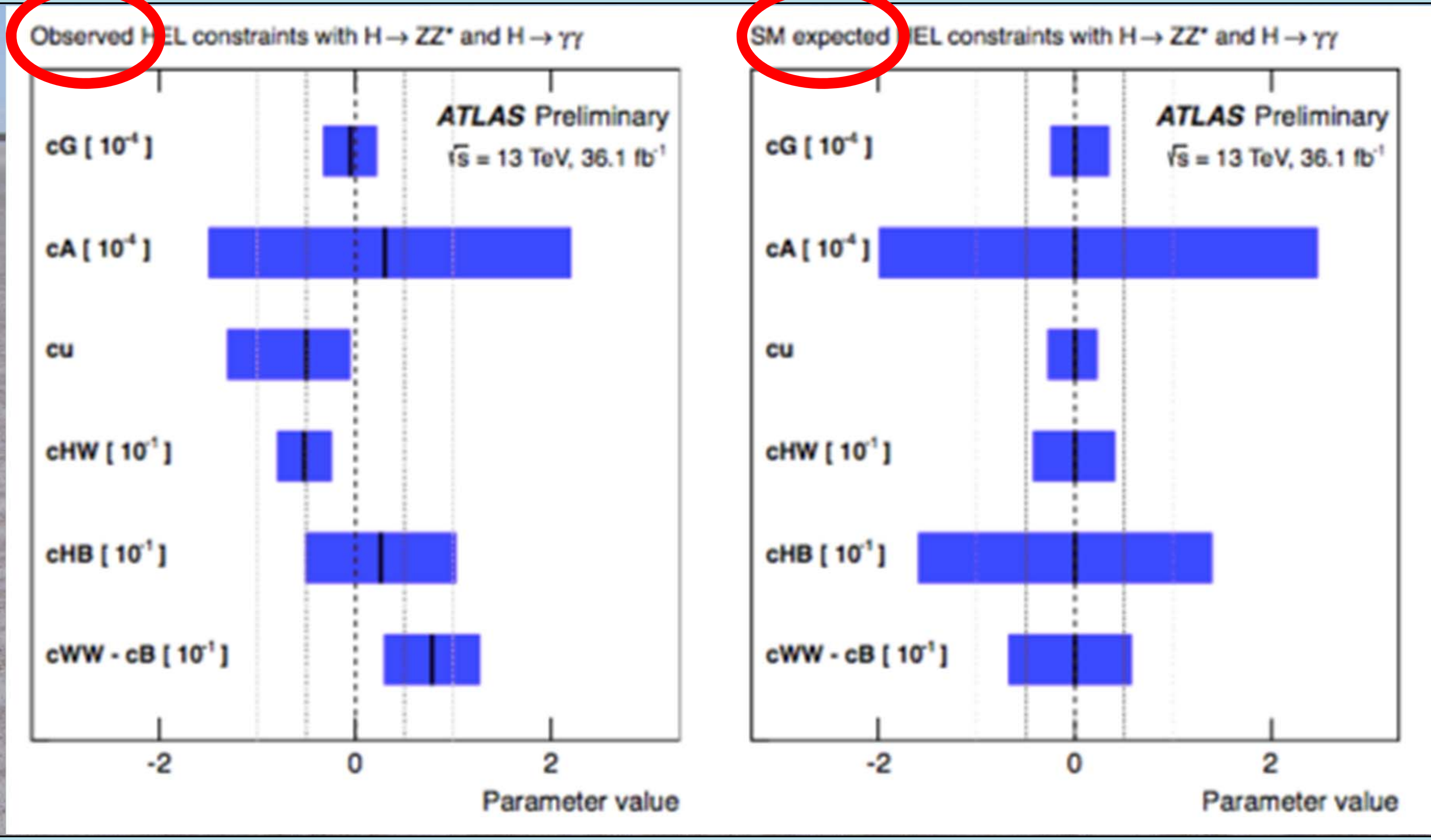
$\Delta\chi^2$ Distributions for Higgs EFT Coefficients

- SM (coefficient = 0) always allowed at $\Delta\chi^2 < 4$ level (< 2 σ)



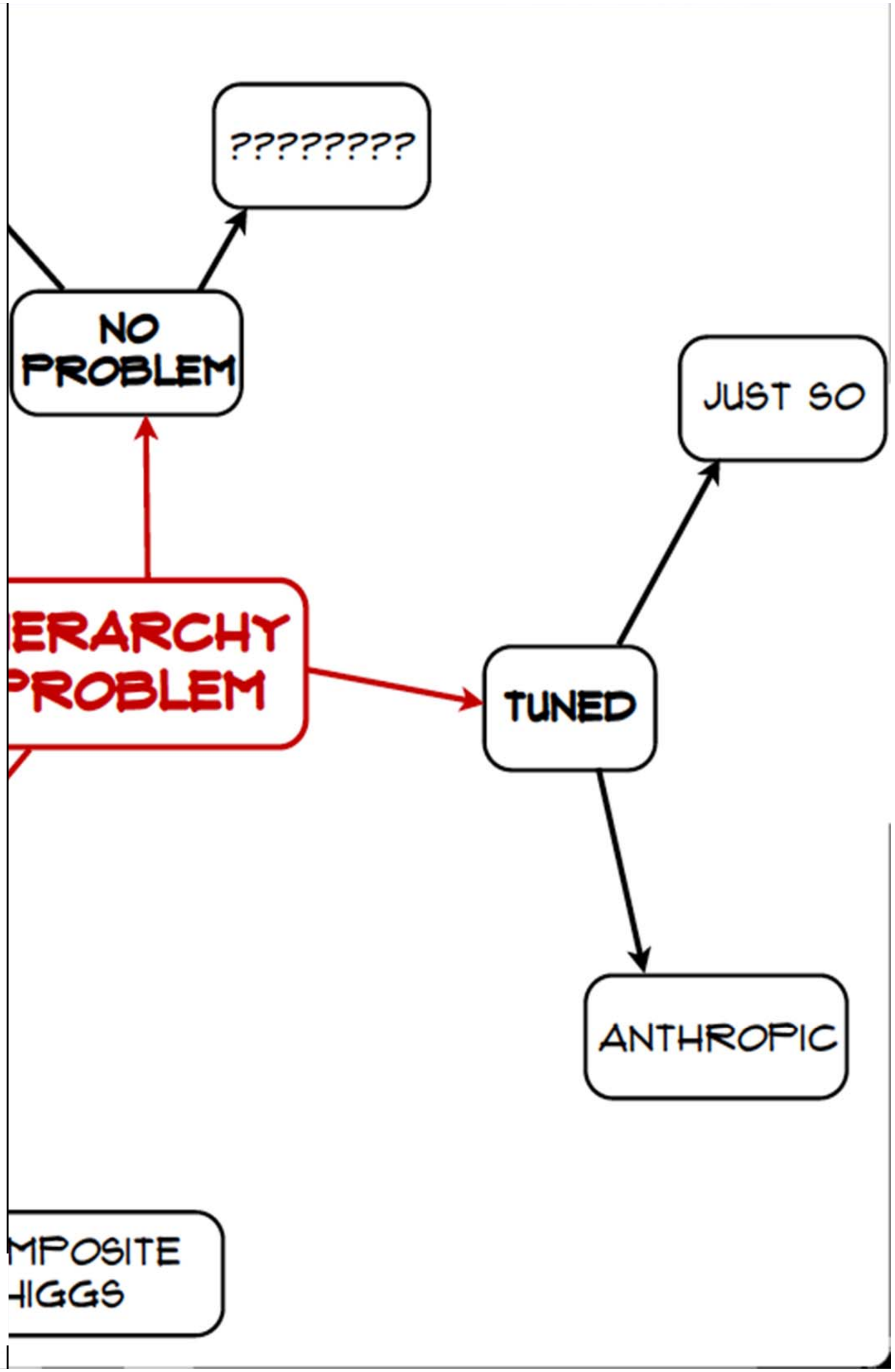


Observed vs Expected Constraints



- No significant deviations from SM
- **Future: combine with precision electroweak and TGC data**

If you know of a better hole, go to it



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**

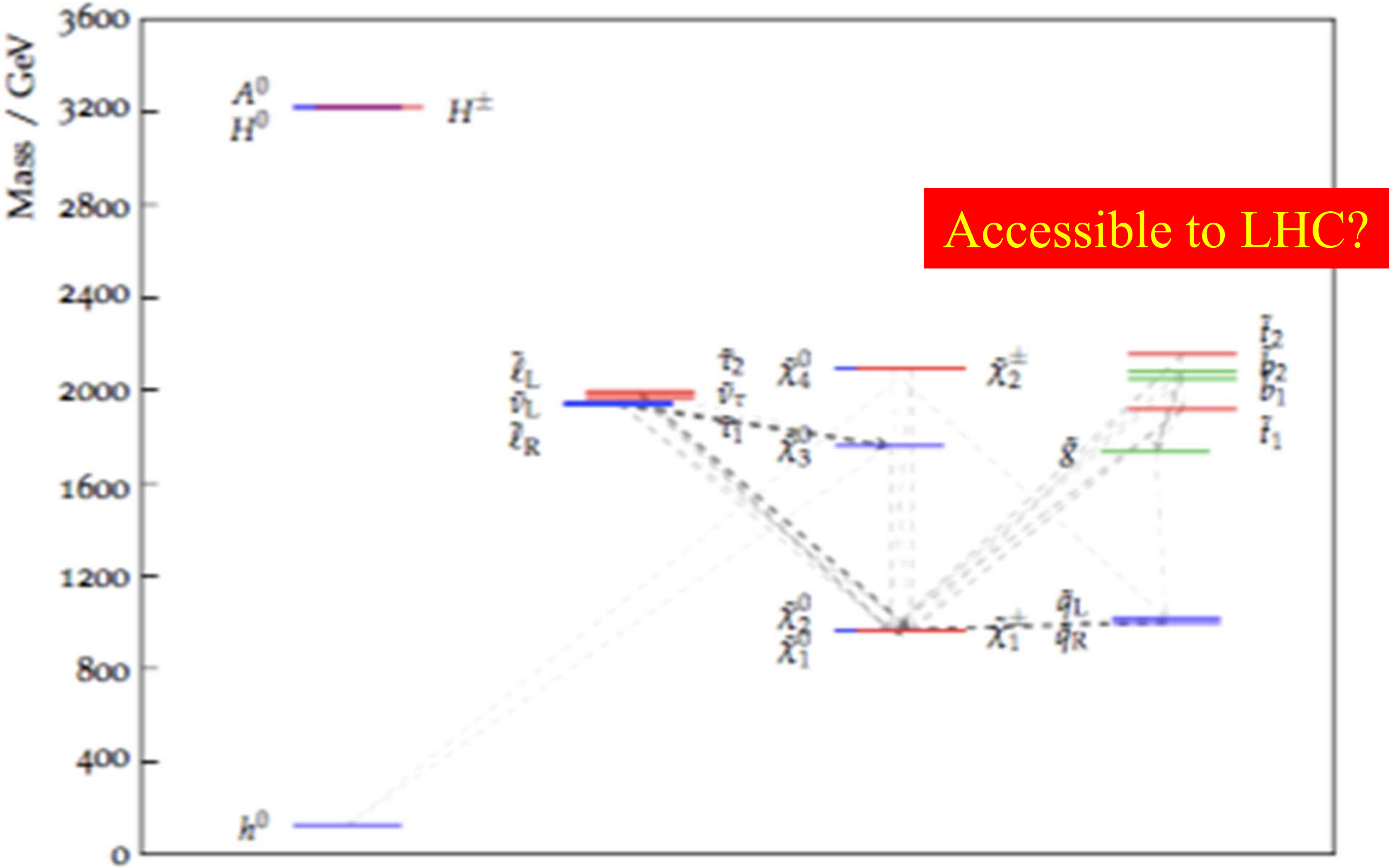
Inputs to Global Fits for New Physics

	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]	$2.04 \pm 0.44({\rm stat.}) \pm 0.05({\rm syst.})$ ps
	${\rm BR}_{b \to s\gamma}^{\rm EXP/SM}$	[65]/ [66]	$0.988 \pm 0.045_{\rm EXP} \pm 0.068_{\rm TH,SM} \pm 0.050_{\rm TH,SUSY}$
	${\rm BR}_{B_u \to \tau\nu}^{\rm EXP/SM}$	[66, 67]	[illegible] $\pm 0.58_{\rm EXP} \pm 0.096_{\rm SM}$
	$BR_{B \to X_s \ell\ell}^{\rm EXP/SM}$	[68]/ [66]	$0.966 \pm 0.278_{\rm EXP} \pm 0.037_{\rm SM}$
	$\Delta M_{B_s}^{\rm EXP/SM}$	[34, 69] / [66]	[illegible] $\pm 0.078_{\rm SM}$
	$\frac{\Delta M_{B_s}^{\rm EXP/SM}}{\Delta M_{B_d}^{\rm EXP/SM}}$	[34, 69] / [66]	$1.007 \pm 0.004_{\rm EXP} \pm 0.116_{\rm SM}$
	$BR_{K \to \mu\nu}^{\rm EXP/SM}$	[34, 70] / [71]	$1.0005 \pm 0.0017_{\rm EXP} \pm 0.0093_{\rm TH}$
	$BR_{K \to \pi\nu\bar\nu}^{\rm EXP/SM}$	[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 $(m_{\tilde\chi_1^0}, \sigma_p^{\rm SI})$ plane
	$\sigma_p^{\rm SD}$	[4]	Likelihood in the $(m_{\tilde\chi_1^0}, \sigma_p^{\rm SD})$ plane
LHC observables	$\tilde g \to q\bar q\tilde\chi_1^0, b\bar b\tilde\chi_1^0, t\bar t\tilde\chi_1^0$	[16, 17]	Combined likelihood in the $(m_{\tilde g}, m_{\tilde\chi_1^0})$ plane
	$\tilde q \to q\tilde\chi_1^0$	[16]	Likelihood in the $(m_{\tilde q}, m_{\tilde\chi_1^0})$ plane
	$\tilde b \to b\tilde\chi_1^0$	[16]	Likelihood in the $(m_{\tilde b}, m_{\tilde\chi_1^0})$, plane
	$\tilde t_1 \to t\tilde\chi_1^0, c\tilde\chi_1^0, b\tilde\chi_1^\pm$	[16]	Likelihood in the $(m_{\tilde t_1}, m_{\tilde\chi_1^0})$, plane
	$\tilde\chi_1^\pm \to \nu\ell^\pm\tilde\chi_1^0, \nu\tau^\pm\tilde\chi_1^0, W^\pm\tilde\chi_1^0$	[18]	Likelihood in the $(m_{\tilde\chi_1^\pm}, m_{\tilde\chi_1^0})$ plane
	$\tilde\chi_2^0 \to \ell^+\ell^-\tilde\chi_1^0, \tau^+\tau^-\tilde\chi_1^0, Z\tilde\chi_1^0$	[18]	Likelihood in the $(m_{\tilde\chi_2^0}, m_{\tilde\chi_1^0})$ 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_μ-2

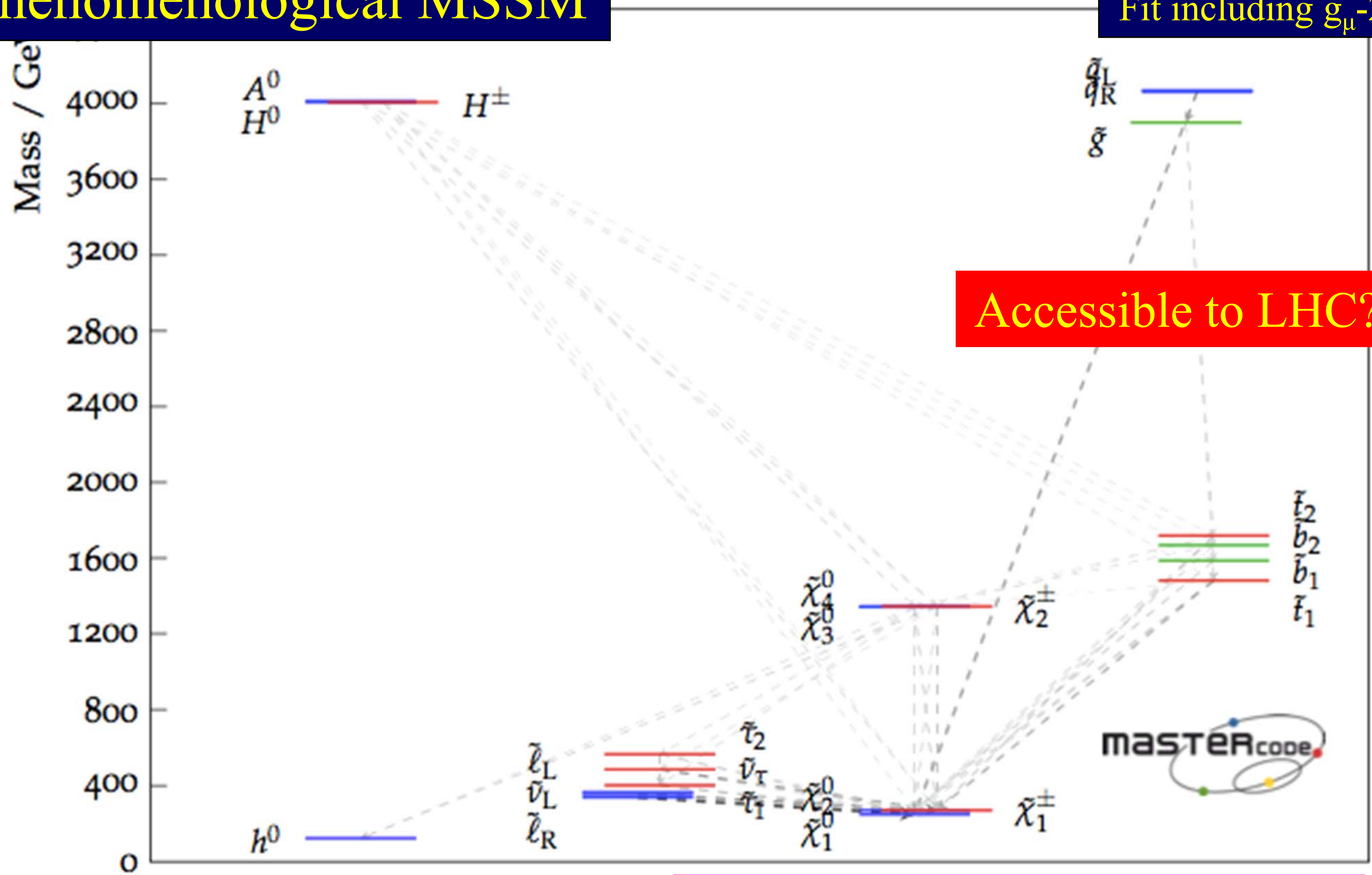


Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Best-Fit Sparticle Spectrum

Phenomenological MSSM

Fit including g_μ-2

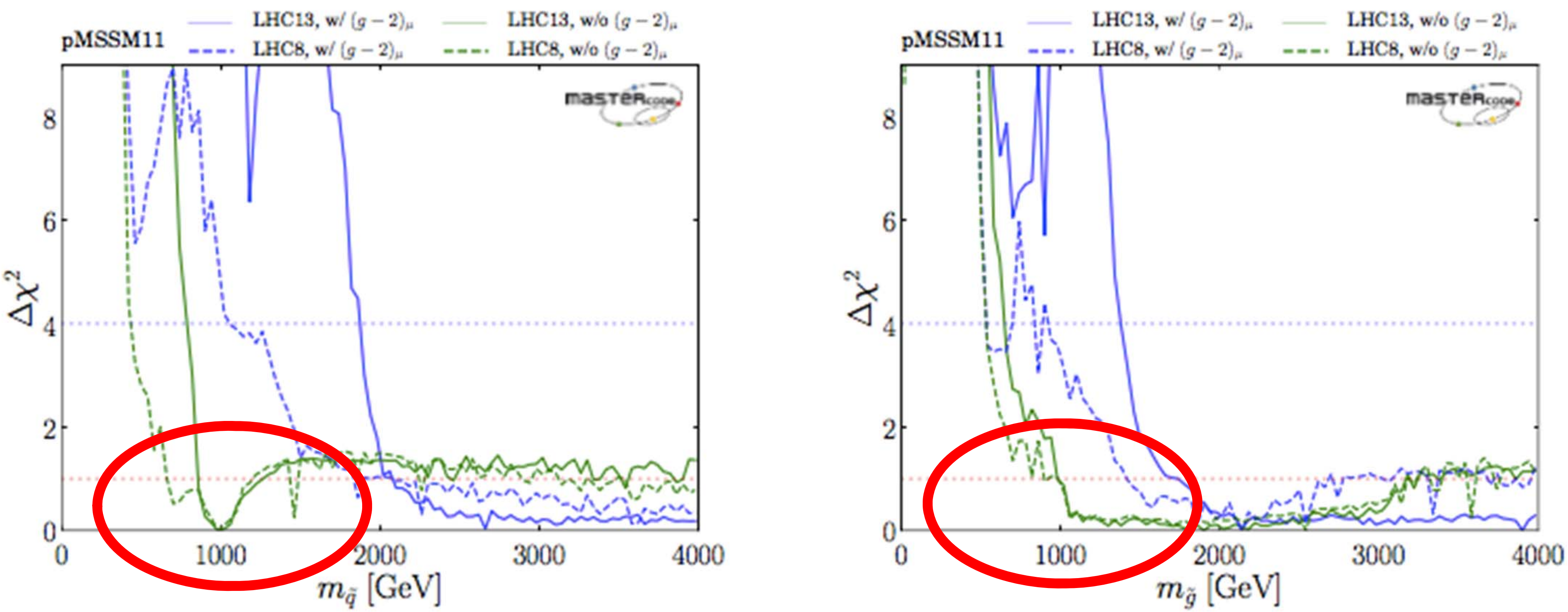


Accessible to LHC?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

How Light can Squarks & Gluinos be?

Phenomenological MSSM

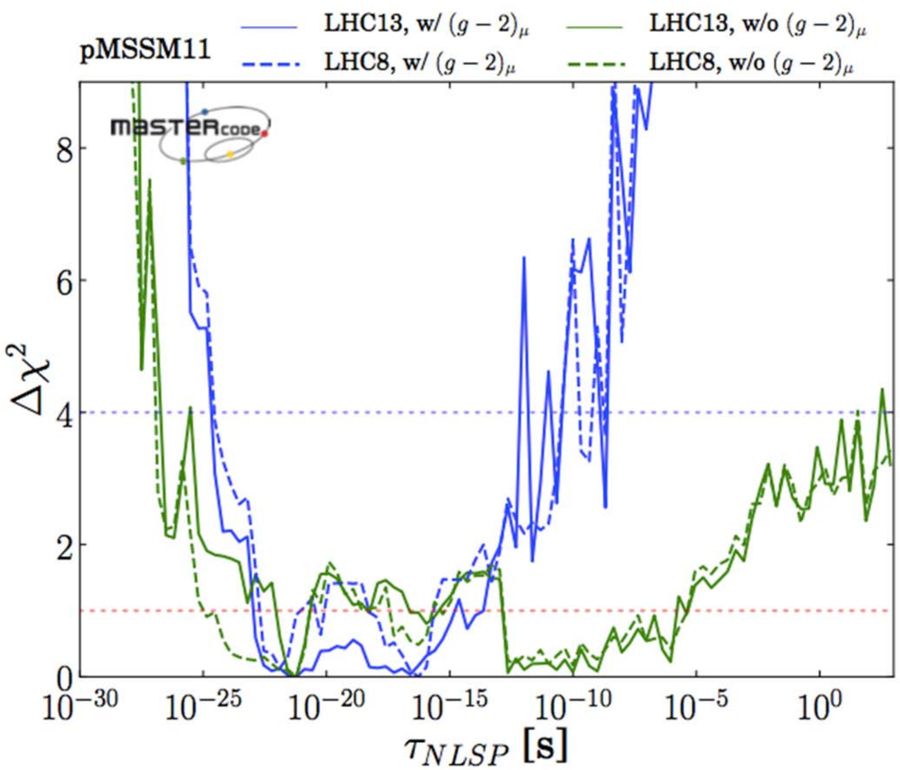


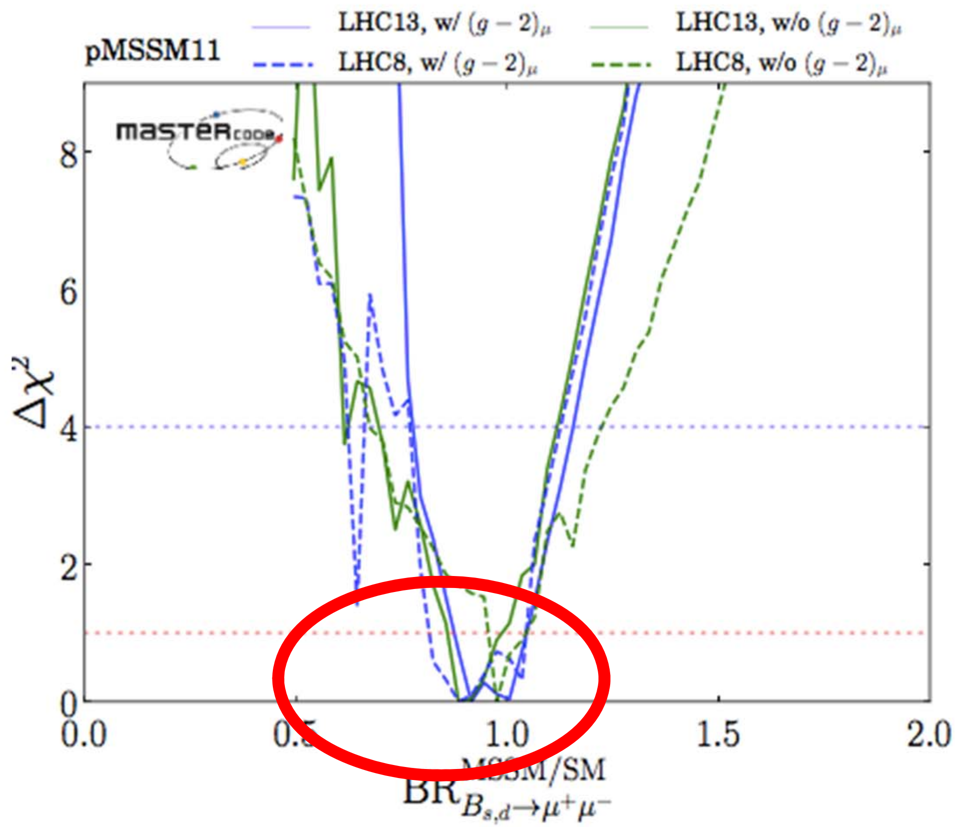
Squarks, gluinos could weigh ~ 1 TeV if drop g_μ-2

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Other Possible LHC Signatures

Phenomenological MSSM



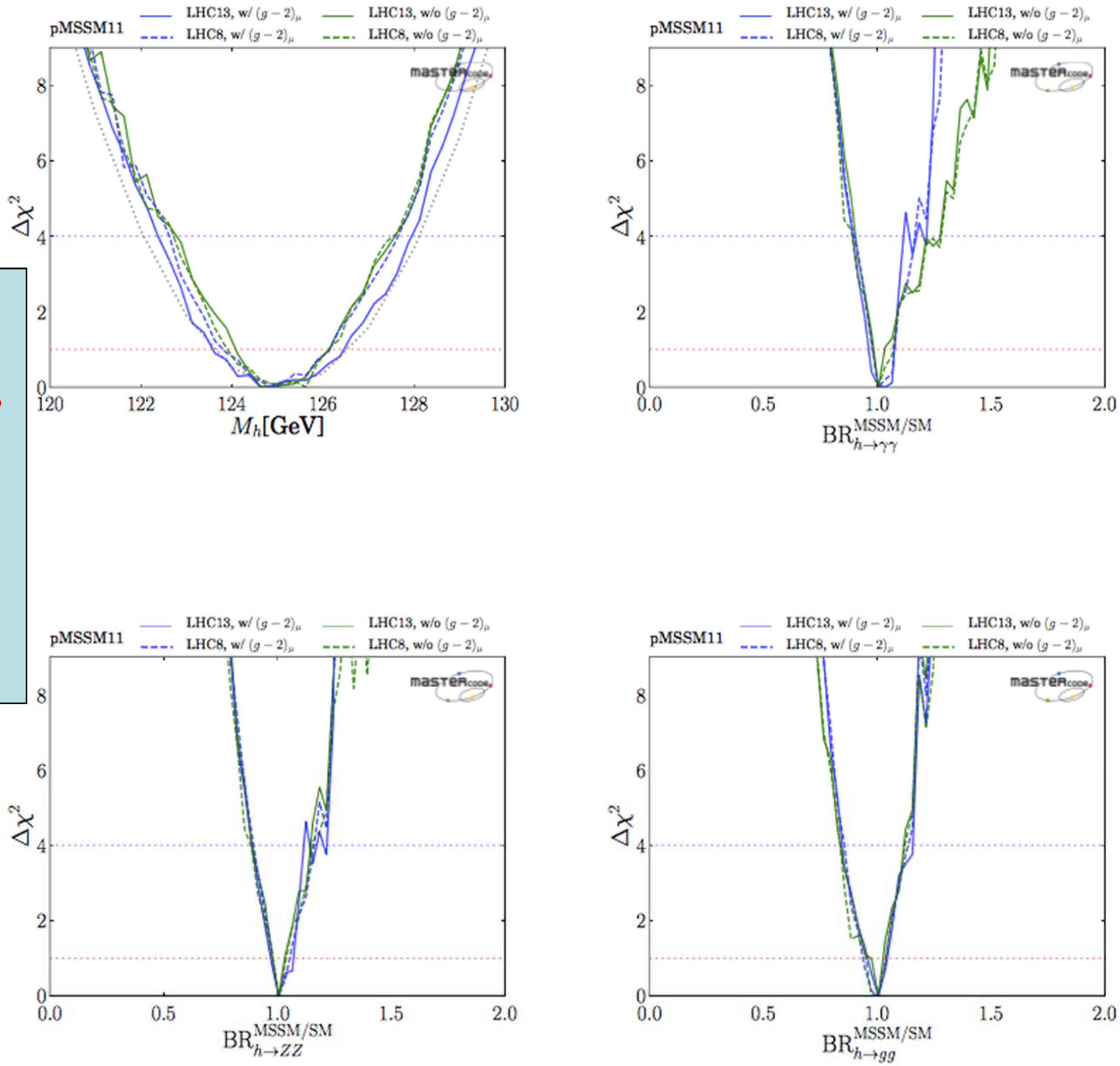


Long-lived sparticle?

$B_{s,d}$ ➔ $\mu^+\mu^-$ decay < SM?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

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

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

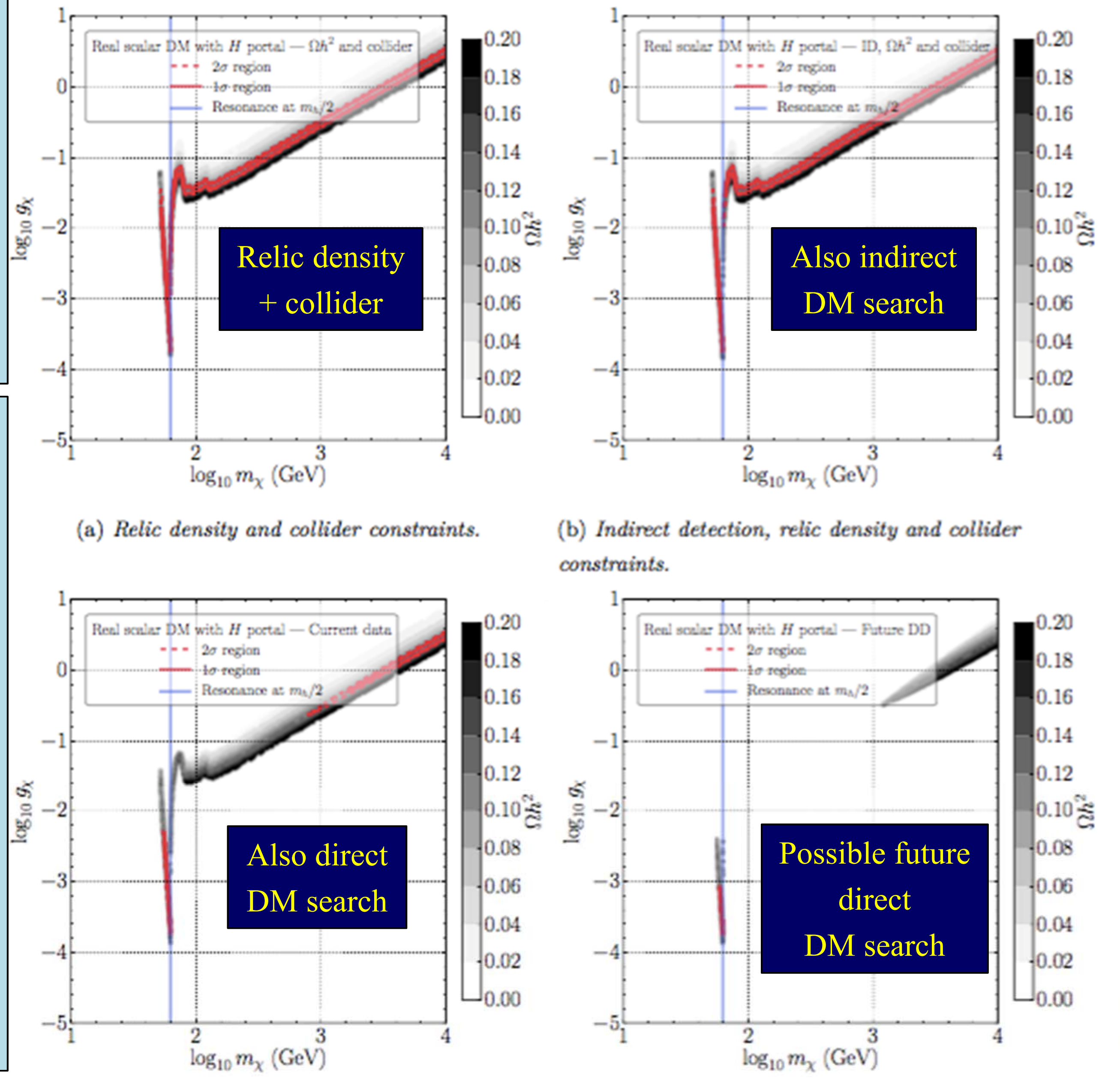
All available collider, DM search constraints

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.*

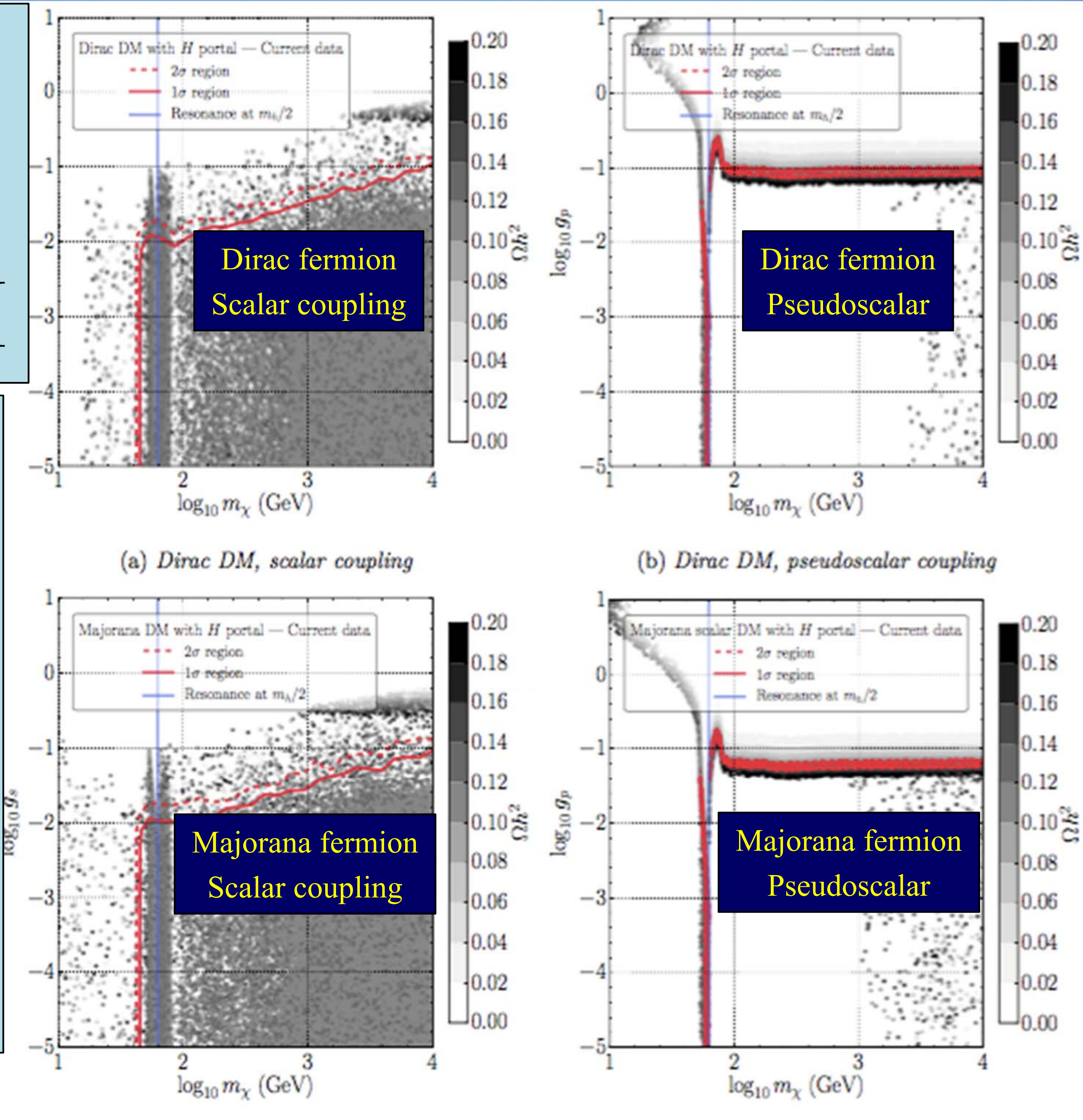
(d) *Possible LZ constraints on direct detection, indirect detection, relic density and collider constraints.*

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



(a) *Dirac DM, scalar coupling*

(b) *Dirac DM, pseudoscalar coupling*

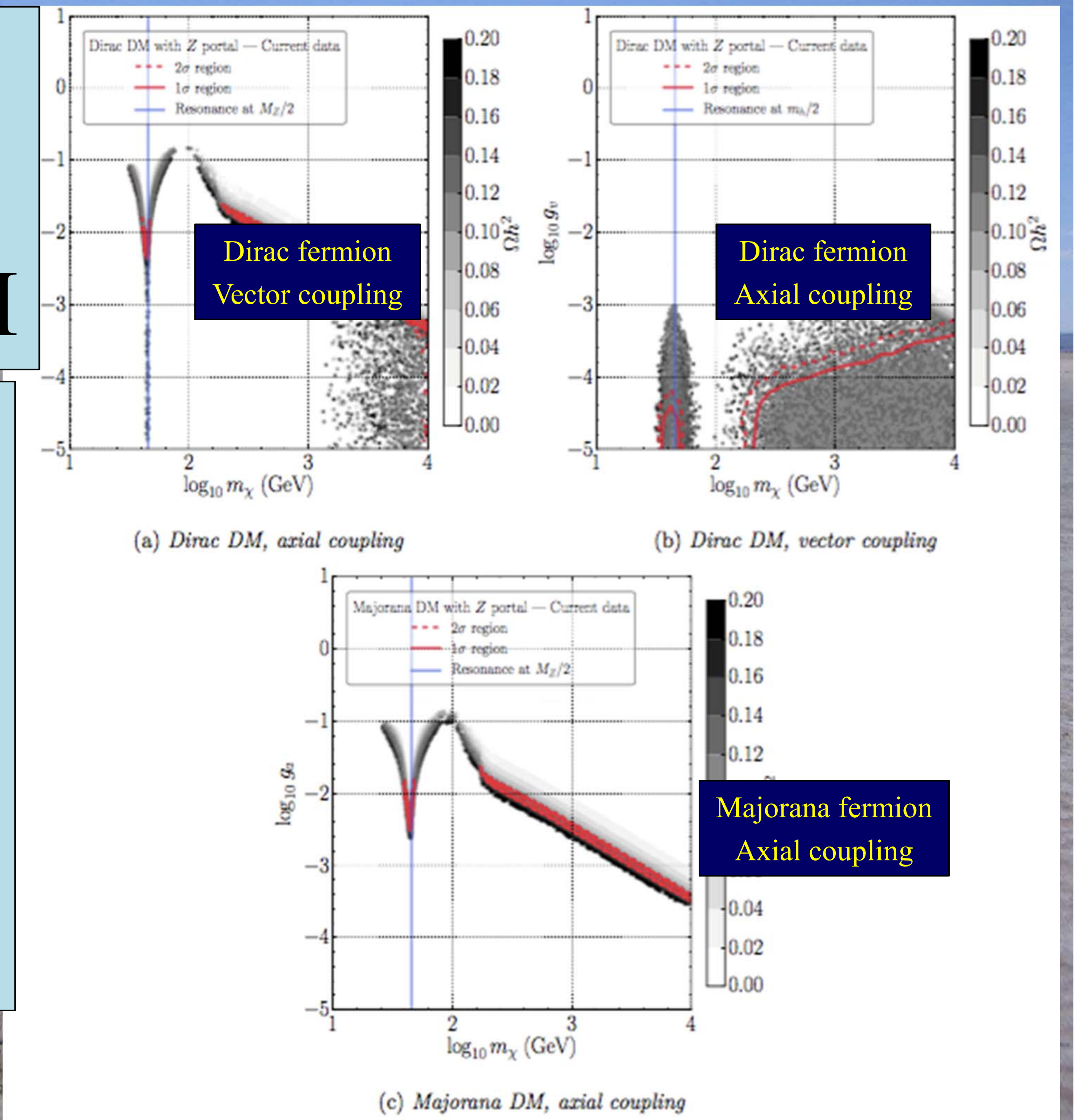
(c) *Majorana DM, scalar coupling*

(d) *Majorana DM, pseudoscalar coupling*

Z Boson 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



(a) *Dirac DM, axial coupling*

(b) *Dirac DM, vector coupling*

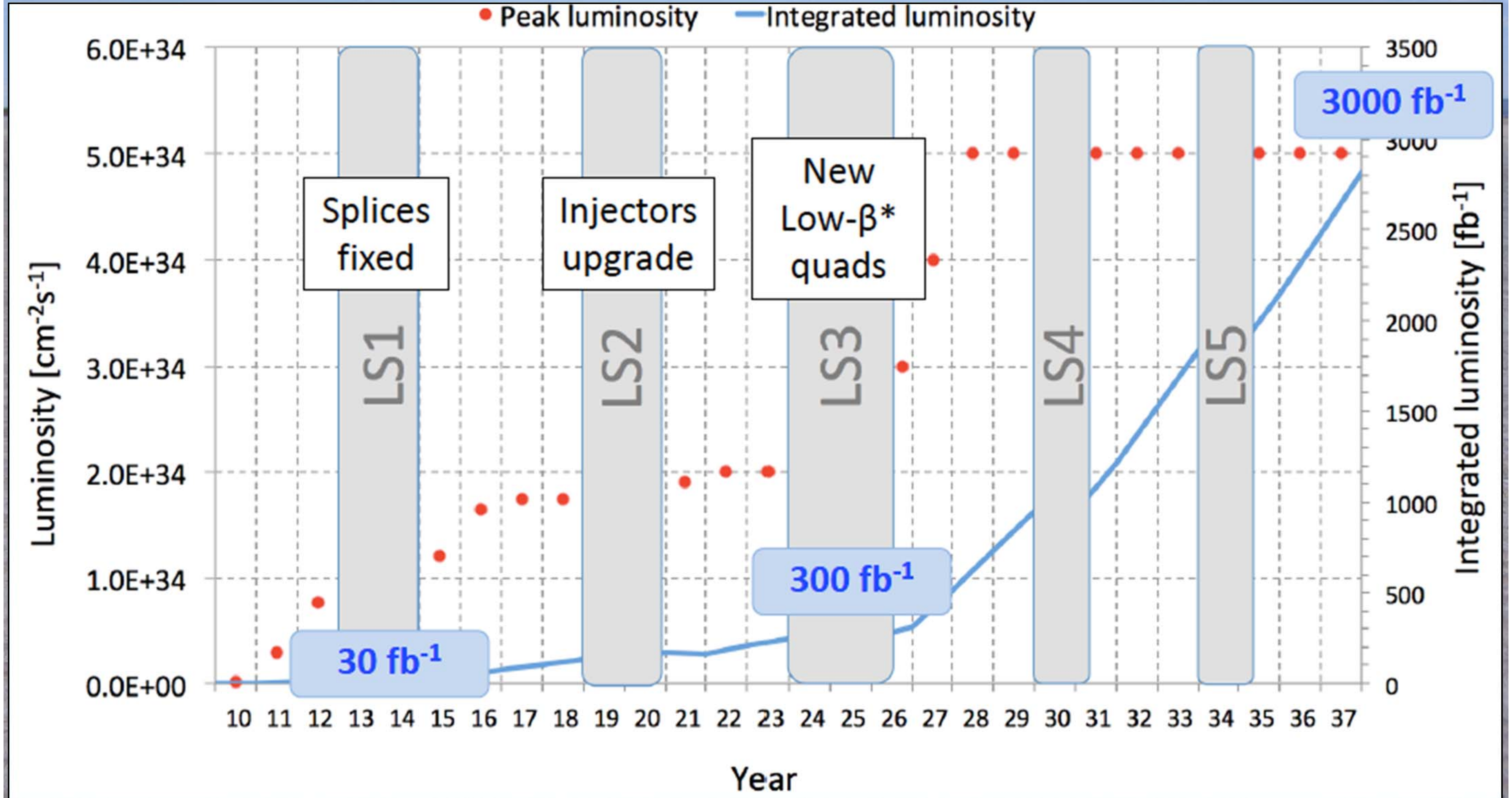
(c) *Majorana DM, axial coupling*

Summary of Results

Model		Bayes factor	min χ^2	p-value
Real scalar h-portal	OK	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-portal	Strongly disfavoured	[illegible] $\times 10^{-14}$	55	1.4×10^{-12}
Vector Z-portal		8×10^{-10}	35	2.2×10^{-8}
Majorana Z-portal	OK	1	2.6	0.27
Dirac Z-portal		0.24	2.6	0.27

JE, Fowlie, Marzola & Raidal, arXiv:1711.09912

The LHC in Future Years

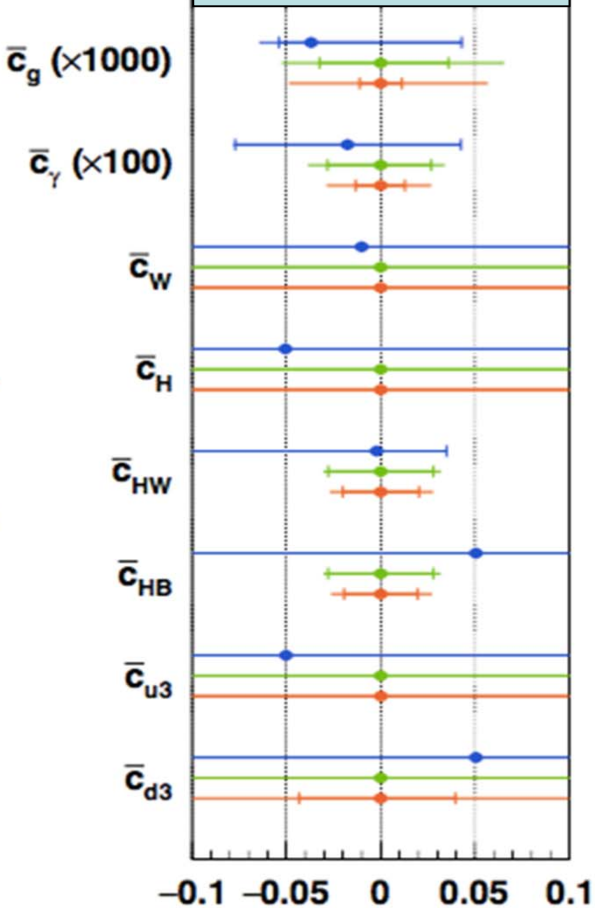


Present & Future Constraints on D=6 Operators

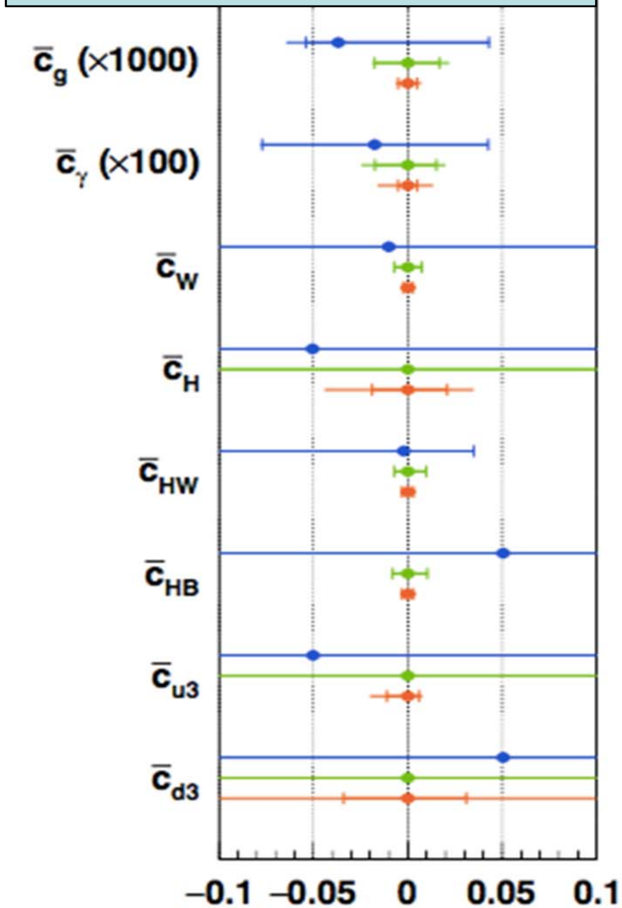
Operators

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_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$
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



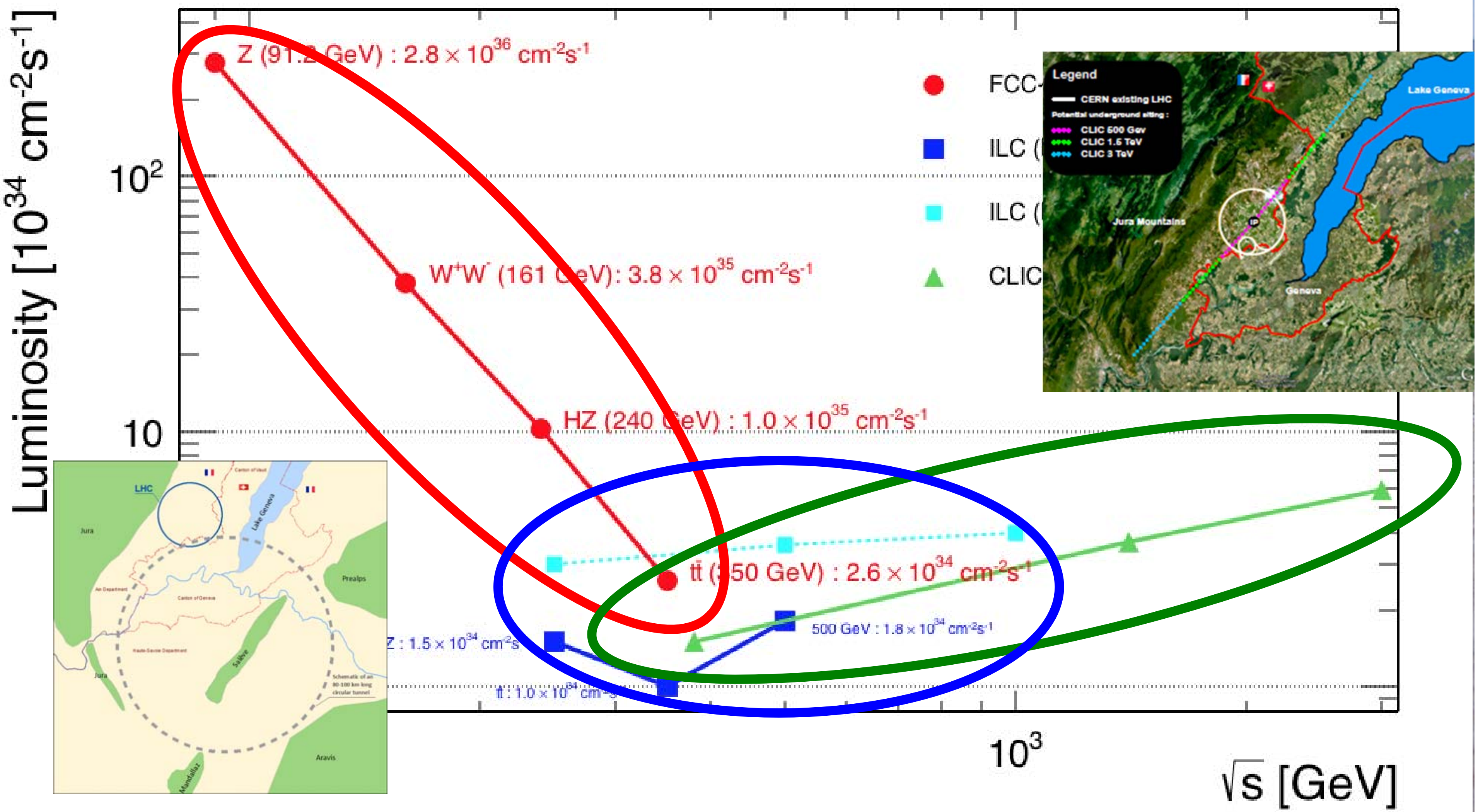
Constraints including kinematics



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

Englert, Kogler, Schulz & Spannowsky, arXiv:1511.05170

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



CEPC-SPPC

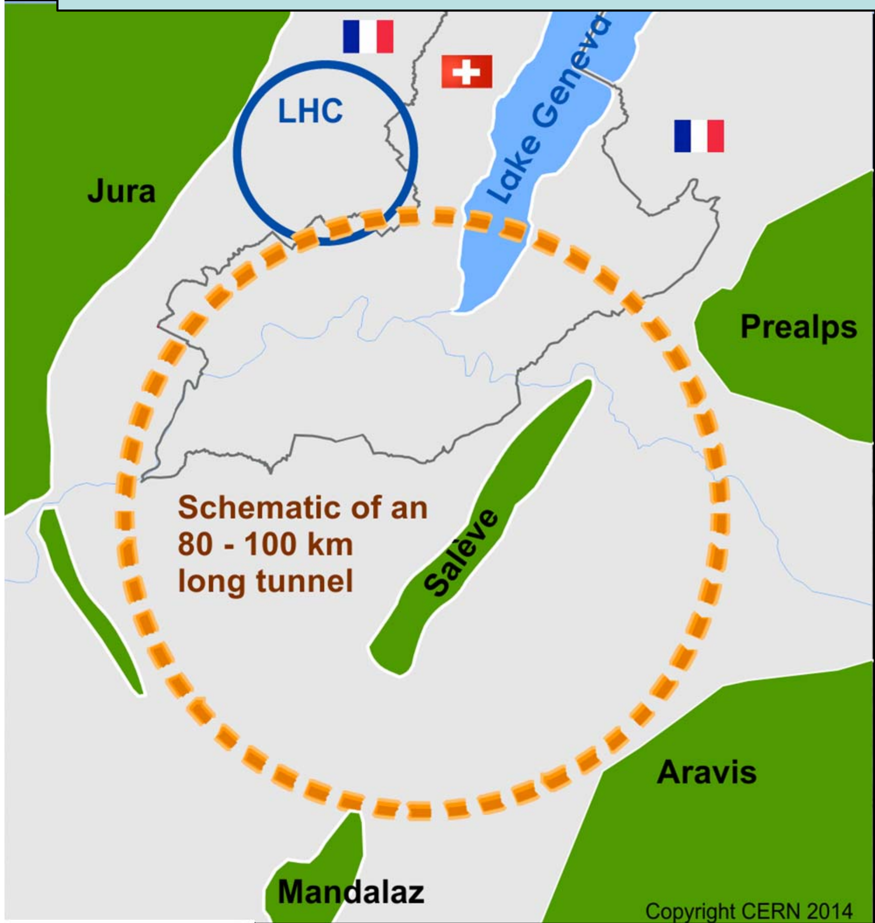
Preliminary Conceptual Design Report

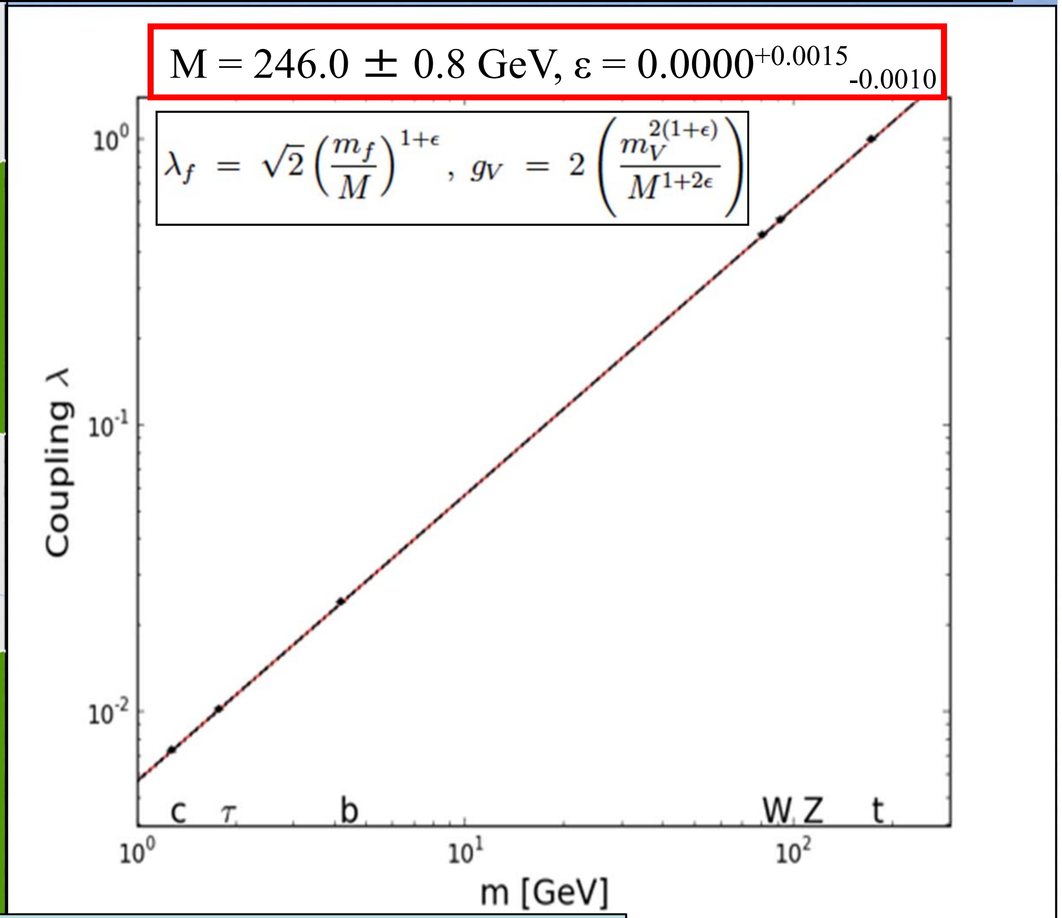
Future Circular Colliders

The vision:

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

Future Circular e^+e^- Collider?





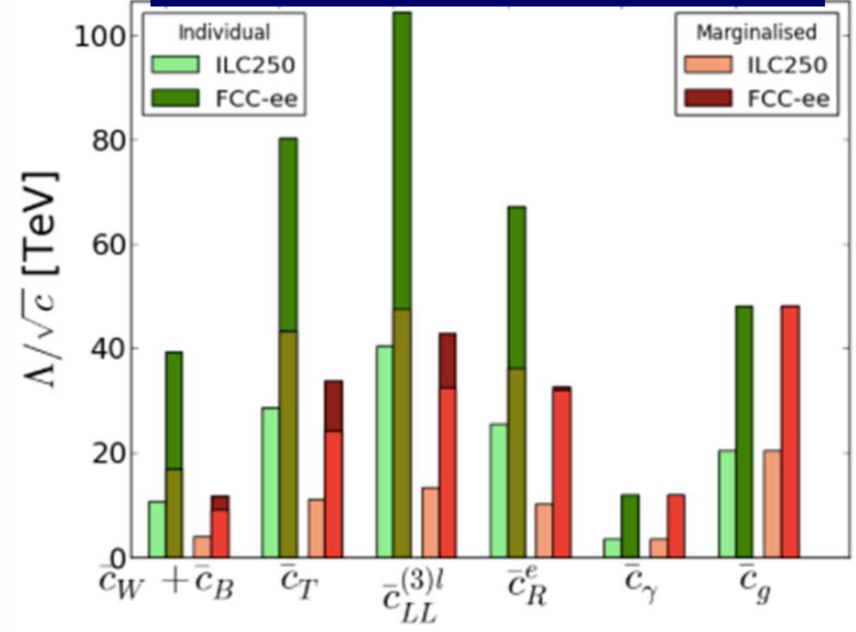
Not just Higgs physics:

Also Tera-Z, Oku-W, Mega-t

JE & Tevong You, arXiv:1510.04561

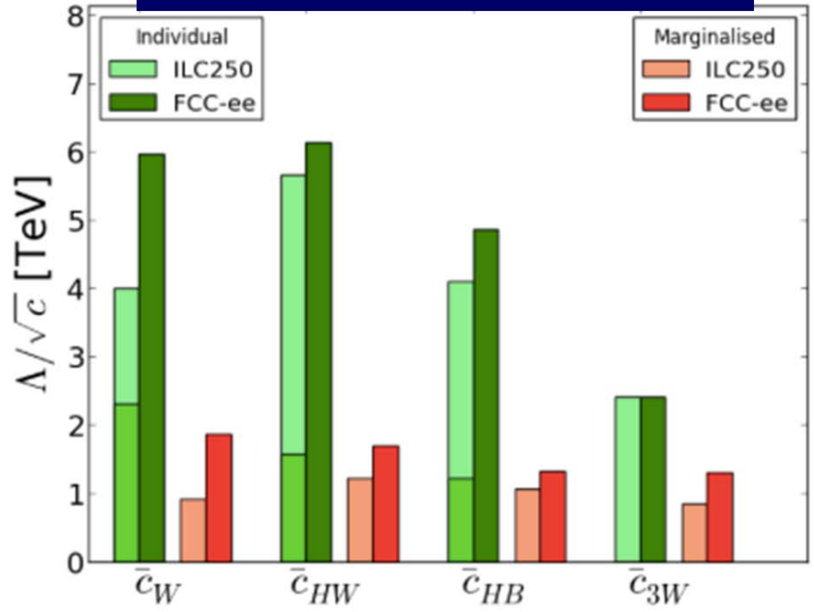
FCC-ee Higgs & TGC Measurements

EWPTs and Higgs



- Shadings:
  - With/without theoretical EWPT uncertainties

Higgs and TGCs

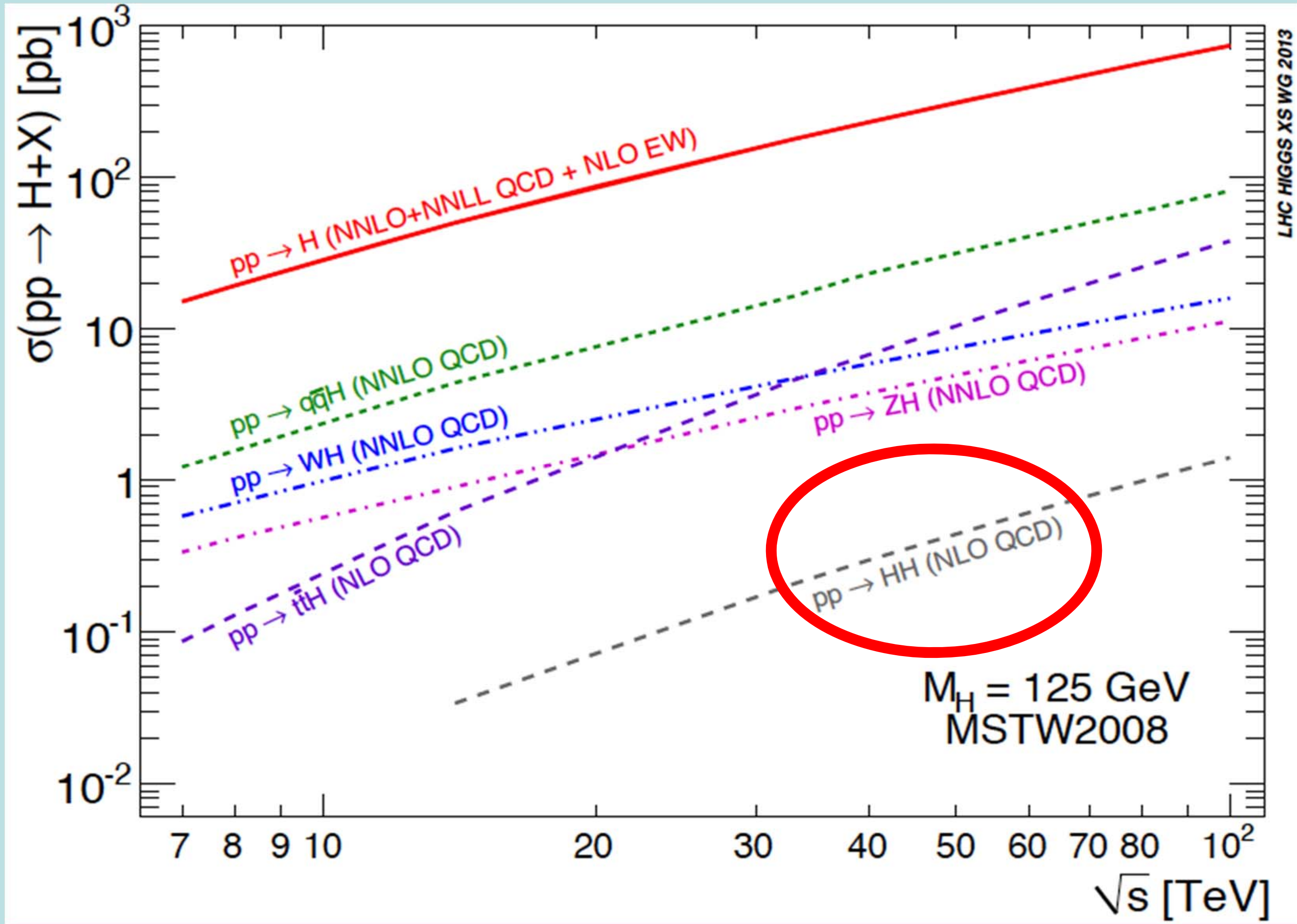


- Shadings of green:
  - Effect of including TGCs at ILC

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

Higgs Cross Sections

- At the LHC and beyond:



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