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Physics Beyond The Standard Model

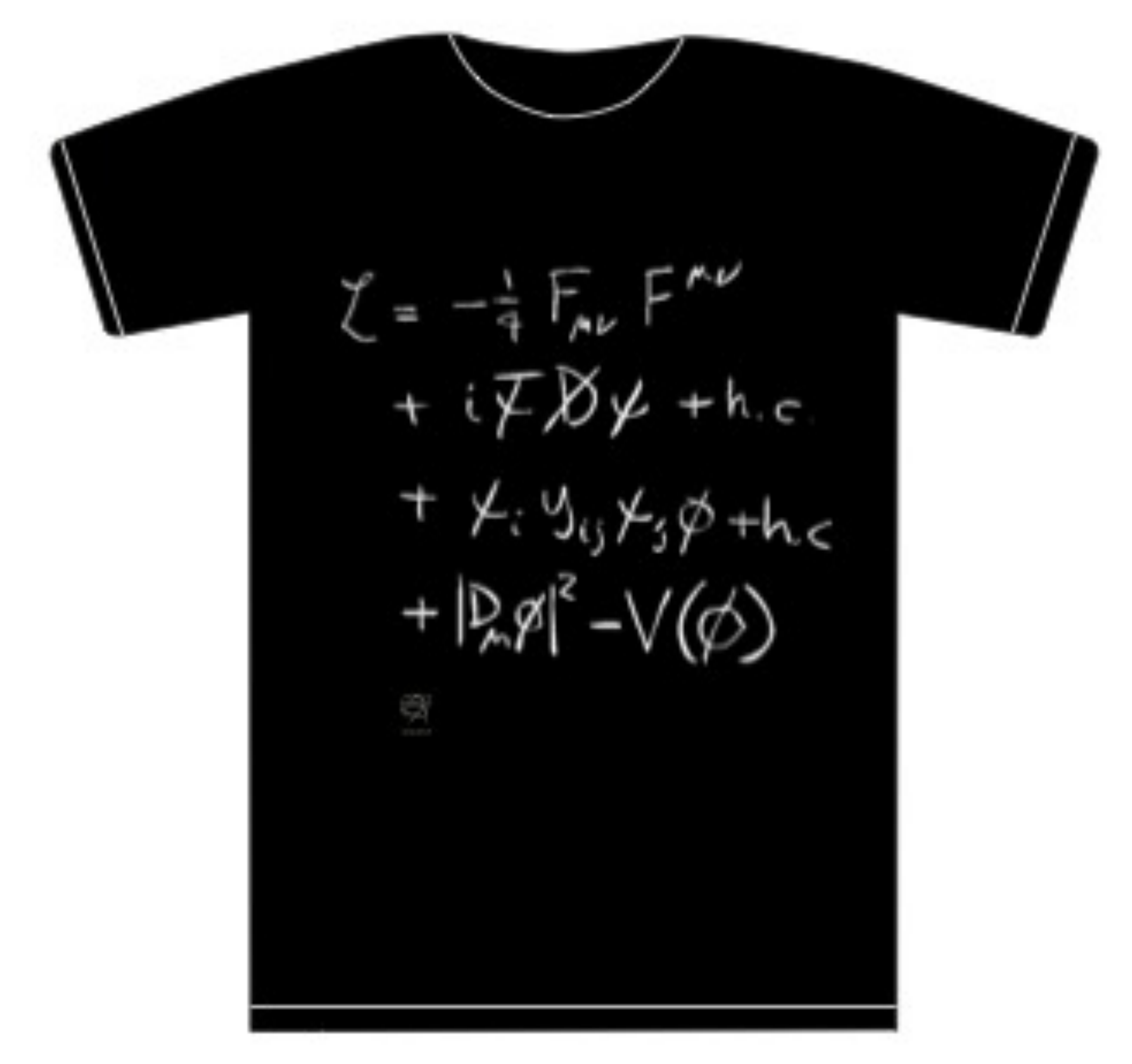
Lectures for *École de Gif'12*

LAL Orsay, 18 Sep 2012

Plan for the next 3 hours

- Intro: why physics beyond the SM
- Models motivated by naturalness of electroweak symmetry breaking
- Models motivated by current experimental data
- Last (?) frontier - the Higgs boson

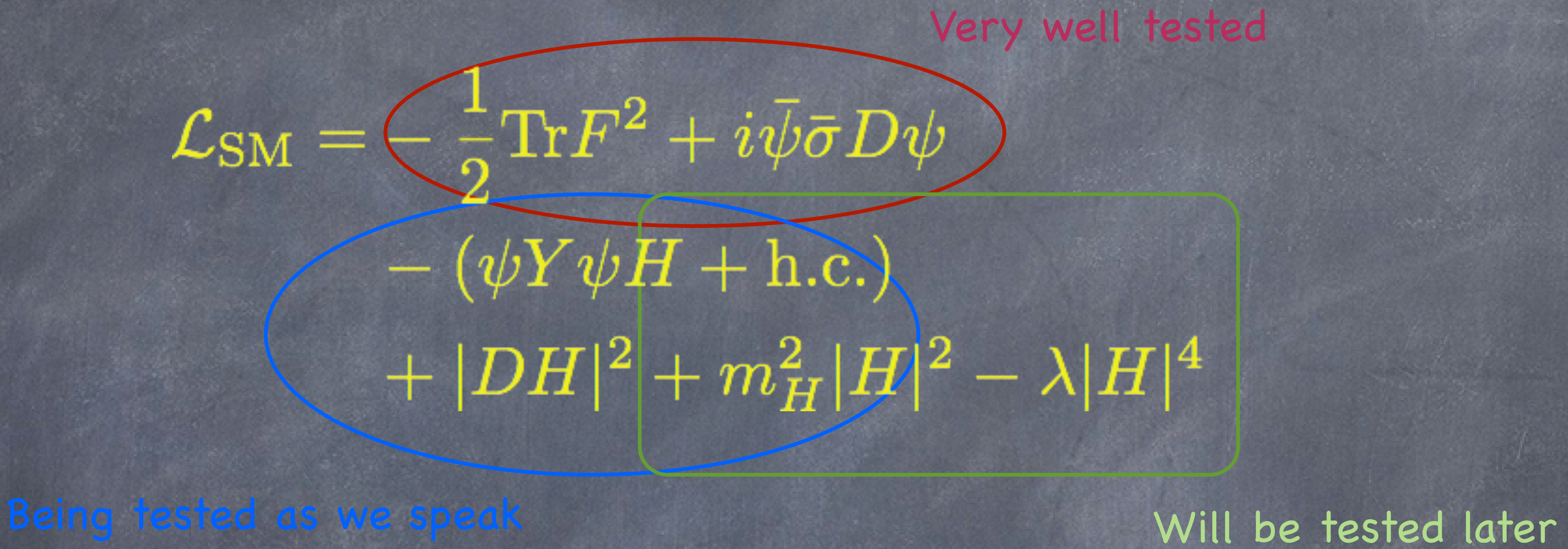
Standard Model



Standard Model

$$\begin{aligned}\mathcal{L}_{\mathrm{SM}} = &-\frac{1}{2}\mathrm{Tr}F^2 + i\bar{\psi}\bar{\sigma}D\psi \\ &-(\psi Y\psi H + \mathrm{h.c.}) \\ &+|DH|^2 + m_H^2|H|^2 - \lambda|H|^4\end{aligned}$$

Standard Model



Very well tested

$$\begin{aligned}\mathcal{L}_{\mathrm{SM}} = &-\frac{1}{2}\mathrm{Tr}F^2 + i\bar{\psi}\bar{\sigma}D\psi \\ &-(\psi Y \psi H + \mathrm{h.c.}) \\ &+ |DH|^2 + m_H^2|H|^2 - \lambda|H|^4\end{aligned}$$

Being tested as we speak

Will be tested later

Now we know all the free parameters of the SM!!!

In particular:

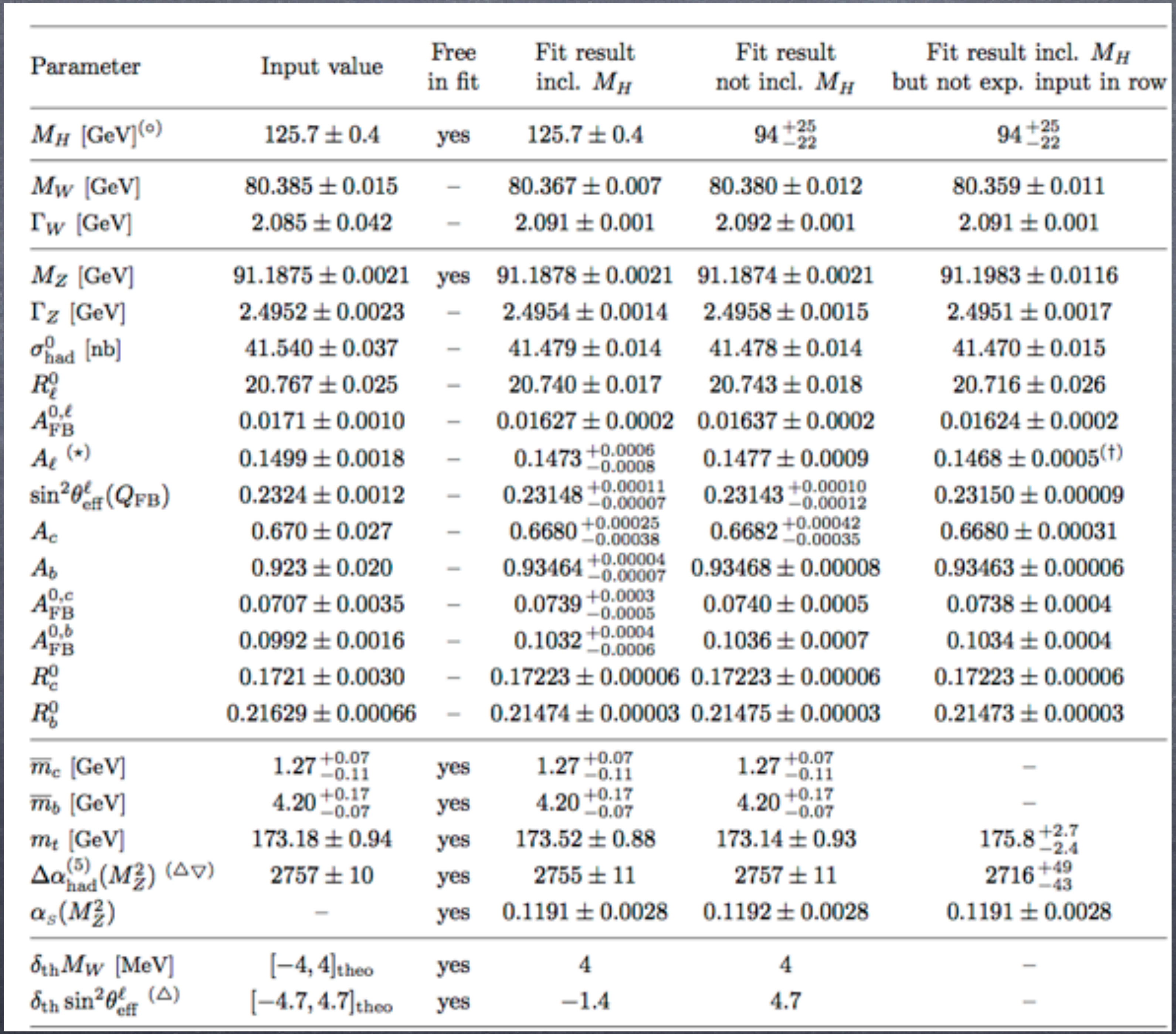
(understood as the "old" SM without neutrino masses)

$$m_H^2 = \frac{m_h^2}{2} \approx (89\mathrm{GeV})^2 \qquad \lambda = \frac{m_h^2}{2v^2} \approx 0.13$$

Standard Model

... and often we know them bloody well!

From Gfitter 1209.2716



Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	94^{+25}_{-22}	94^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0116
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01627 ± 0.0002	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	0.1477 ± 0.0009	$0.1468 \pm 0.0005^{(\dagger)}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23148^{+0.00011}_{-0.00007}$	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6680^{+0.00025}_{-0.00038}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00004}_{-0.00007}$	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	0.0740 ± 0.0005	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	0.1036 ± 0.0007	0.1034 ± 0.0004
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21474 ± 0.00003	0.21475 ± 0.00003	0.21473 ± 0.00003
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\triangledown)}$	2757 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-1.4	4.7	–

Quantum Field Theory works, b!

Beyond the Standard Model a.k.a. New Physics

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{BSM}}$$

............In the first approximation, the SM physics is concerned with (almost) everything that exists, whereas physics beyond the SM is concerned with things that dont exist........................

Millions of possibilities,
so everything below is just
chef's suggestions

Beyond the Standard Model a.k.a. New Physics

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm BSM}$$

Two main possibilities:

Heavy new physics that cannot be produced on-shell
e.g.

$$\mathcal{L}_{\rm BSM} = \frac{c_1}{\Lambda^2}(\bar{\psi}\psi)^2 + \frac{c_2}{\Lambda^2}|H^\dagger D_\mu H|^2 + \dots$$

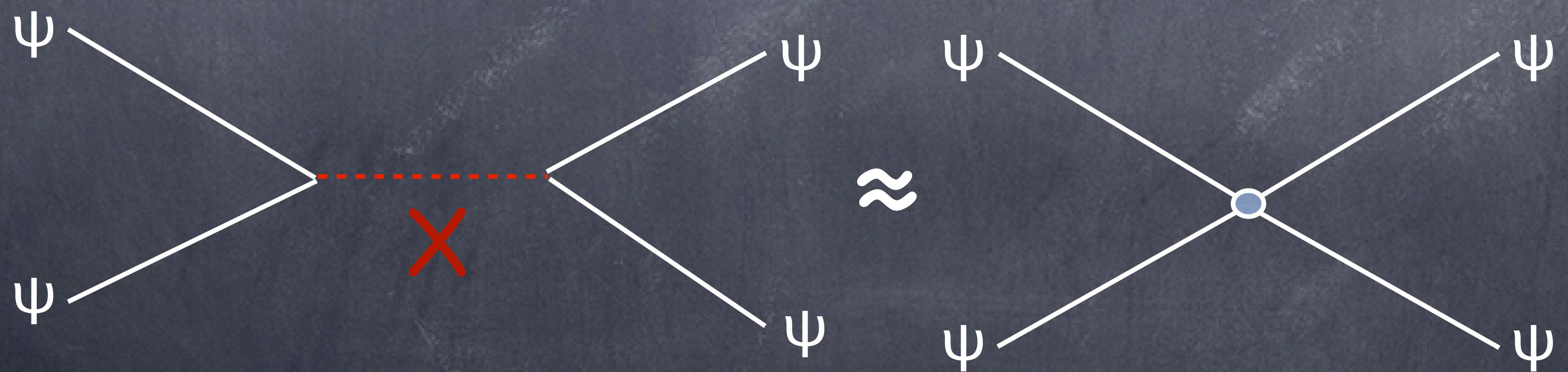
Light new physics that can be produced on-shell
e.g

$$\mathcal{L}_{\rm BSM} = i\bar{X}\bar{\sigma}^\mu D_\mu X + \dots$$

$$\mathcal{L}_{\rm BSM} = X^\dagger X |H|^2 + \dots$$

The case of heavy new physics

- New physics effects can be captured by non-renormalizable higher dimensional operators composed of SM fields that arise when the heavy new particles are integrated out
- Those operators are suppressed by a scale Λ that corresponds to the mass scale of new physics (assuming it couples to the SM with order 1 strength)
- The lowest dimension operators in a given class is the one that matters the most at low energies (so we don't have to consider the infinite series of operators)



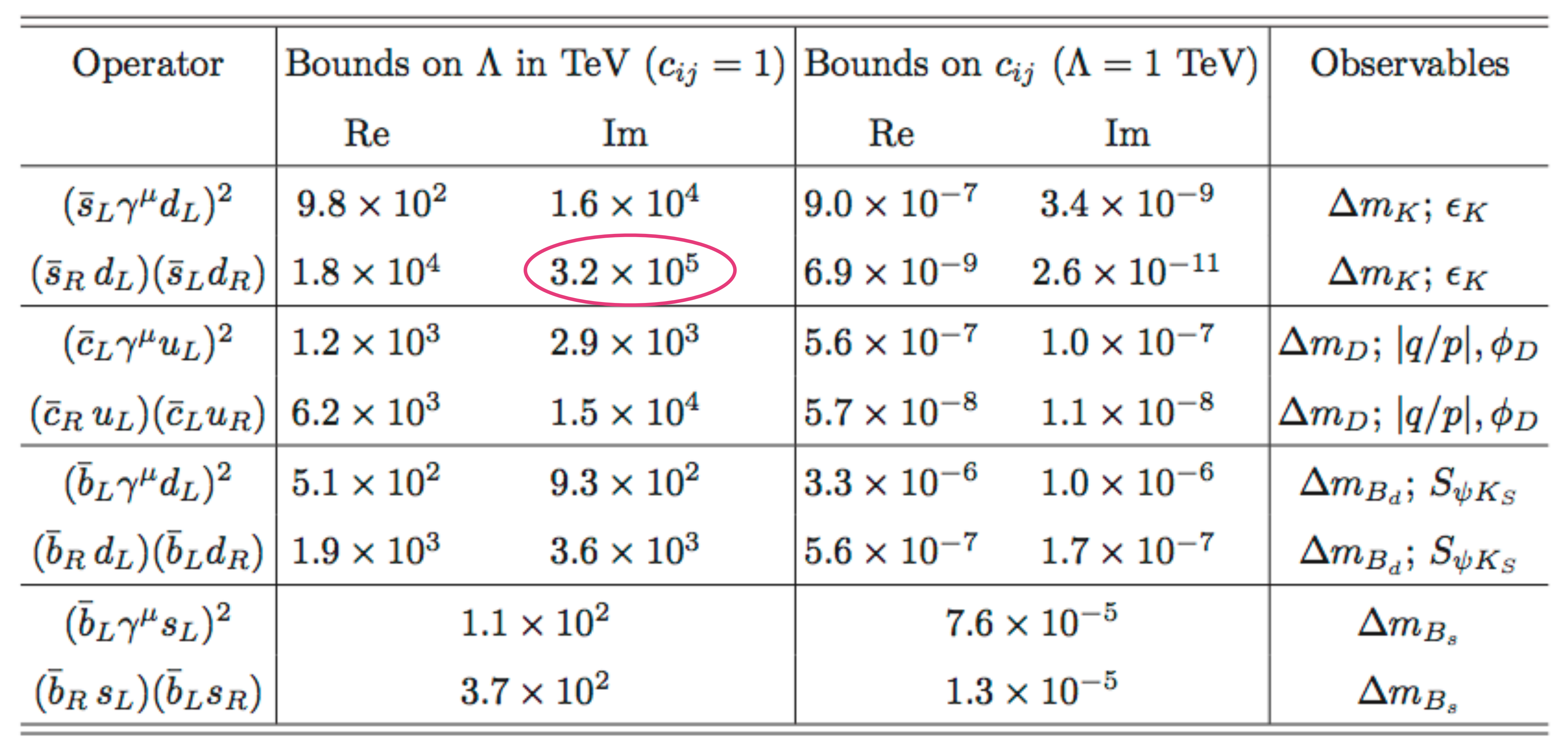
The case of heavy new physics

Strong bounds on some classes of higher-dimensional operators

- For baryon and lepton number violating operators involving like quarks typical bounds Λ≳10^15 GeV
- For flavor violating operators typical bounds Λ≳10-10^5 TeV
- For flavor conserving CP violating operators typical bounds Λ≳100 TeV
- For operators modifying the W and Z boson propagators, typical bounds Λ≳10 TeV

The case of heavy new physics

Strong bounds on flavor violating higher-dimensional operators

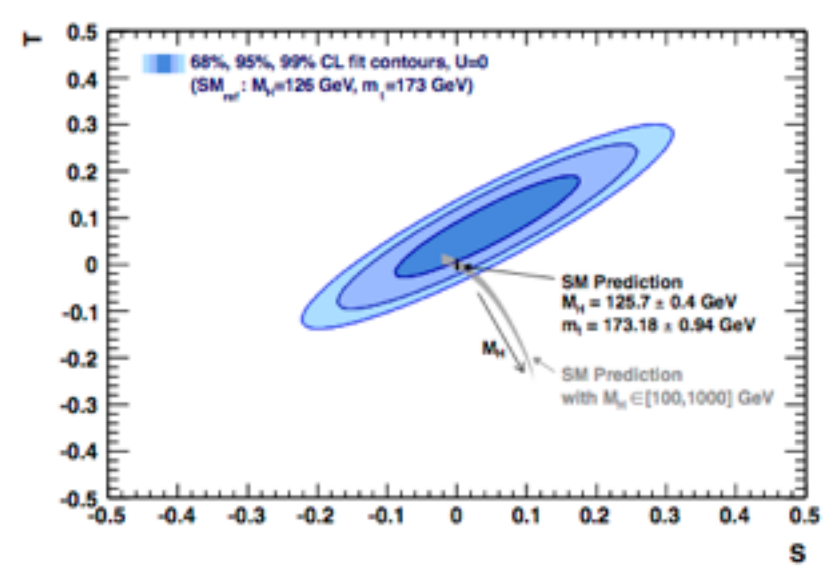


Operator	Bounds on Λ in TeV $(c_{ij}=1)$		Bounds on c_{ij} $(\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert,\phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert,\phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

from Isidori et al. 1002.0900

The case of heavy new physics

The notorious S and T parameters



From Gfitter 1209.2716

$$\mathcal{L}_{\rm BSM} = -\frac{1}{\Lambda_T^2}|H^\dagger D_\mu H|^2 + \frac{1}{\Lambda_S^2}(H^\dagger \sigma^a H) g_L g_Y L^a_{\mu\nu} B_{\mu\nu}$$

$$\to -\frac{1}{\Lambda_T^2}\frac{v^4(g_L^2+g_Y^2)}{8} Z_\mu^2 - \frac{1}{\Lambda_S^2}\frac{v^2 g_L g_Y}{2} L^a_{\mu\nu} B_{\mu\nu}$$

$$T = \alpha_{\rm EM}^{-1}\frac{v^2}{\Lambda_T^2} \qquad S = 16\pi\frac{v^2}{\Lambda_S^2}$$

S,T ≲ 0.1 ⇒ $\Lambda_T \lesssim 8\mathrm{TeV} \qquad \Lambda_S \lesssim 1.5\mathrm{TeV}$

But any new physics relevant for EW symmetry breaking contributes to S and T !

Thus, new physics is constrained as:
- if it enters at the weak scale ~250 GeV, it should contribute to S and T only at the 1-loop level
- if it is heavier than TeV, it should respect the so-called custodial symmetry that ensures ΔT≈0
- be heavier than 10 TeV

The case of light new physics

Gazillions of possibilities, depending on
production, decay, quantum numbers, and so on

Rule of thumb for the limits (very approximate and case dependent!)

- For new colored particles, the limits are in 300 GeV to 2 TeV
- For new particles with weak charges only the limits are around 100 GeV
- For new particles not charged under the SM but coupled via the Higgs portal or the hypercharge portal the limits from high-energy collider are typically weak, and there are often stronger (case-specific) limits from other experiments (e.g. low energy e+e- colliders, direct detection experiments, axion telescopes, etc)

The case of new physics

- The SM is extremely successful
- New physics is extremely constrained
- Then why is there any talk of physics beyond the SM???

Because we know for sure that there is physics beyond the Standard Model

Why New Physics (firm arguments)

- Observed neutrino masses imply new physics (at least, right-handed neutrinos) somewhere between 1 keV and 10^15 GeV

$$\mathcal{L}_\nu = -\frac{1}{\Lambda}(HL)[Y_\nu](HL) \qquad \Lambda \sim 10^{15}\mathrm{GeV}$$

Why New Physics (firm arguments)

- Existence of dark matter requires new physics (at least one new stable particle) somewhere between sub-eV and 10^19 GeV

e.g.

$$\mathcal{L}_{\rm DM} = -m_X^2 X^\dagger X + \lambda_X X^\dagger X |H|^2$$

Why New Physics (firm arguments)

- Domination of matter over anti-matter requires new physics between 100 GeV and 10^16 GeV

e.g.

$$\mathcal{L}_N = -\frac{1}{2} N [M_N] N - N [Y_N] L H + \mathrm{h.c.}$$

Why New Physics (firm arguments)

- Observed neutrino masses imply new physics (at least, right-handed neutrinos) somewhere between 1 keV and 10^15 GeV

- Existence of dark matter requires new physics (at least one new stable particle) somewhere between sub-eV and 10^19 GeV

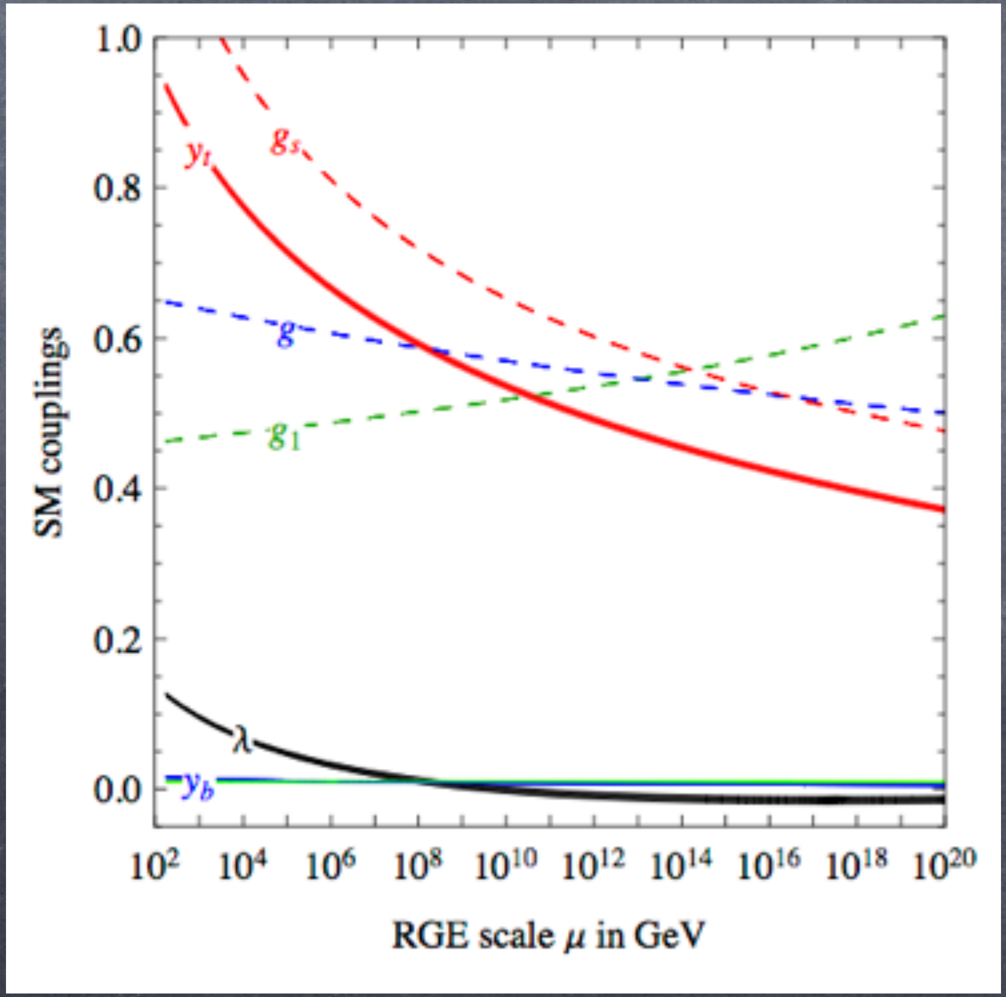
- Domination of matter over anti-matter requires new physics between 100 GeV and 10^16 GeV

:-(unfortunately, none of the above guarantees new physics within the current experimental reach :-(

Why New Physics (esthetic arguments)

- Approximate unification of the SM gauge couplings, together with the quantum numbers of the SM fermions suggest new states at any scale between 100 and 10^14 GeV

Degrassi et al.
1205.6497



but, maybe this is just a red herring, or the truth is more complicated?

Why New Physics (esthetic arguments)

- Fermion masses and mixings suggests another sector generating the observed structures, at any scale above TeV and Planck

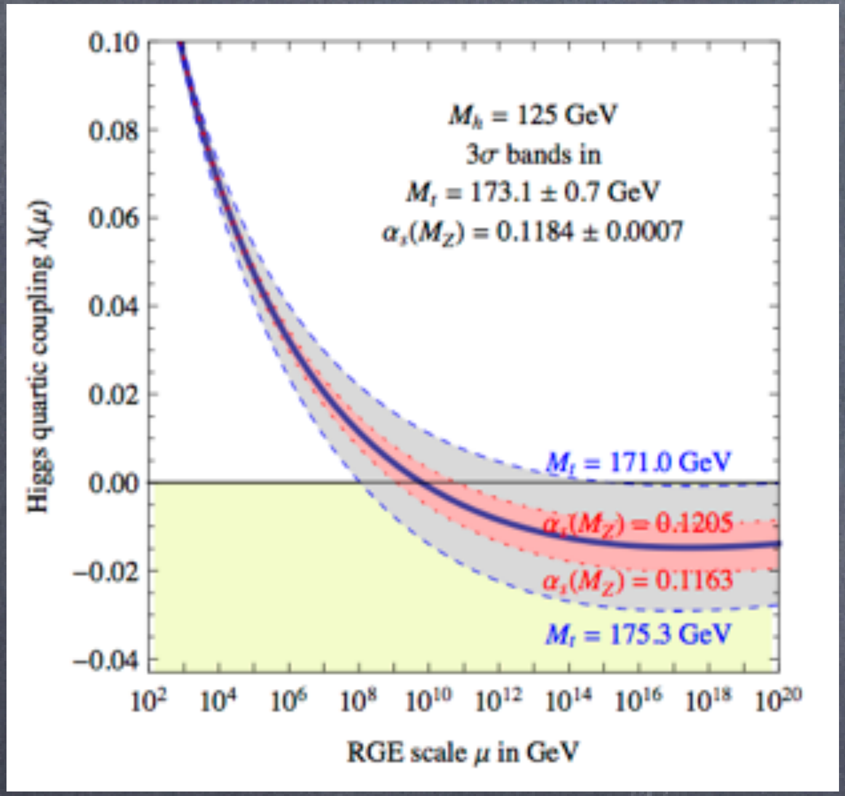
$$V^{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4).$$

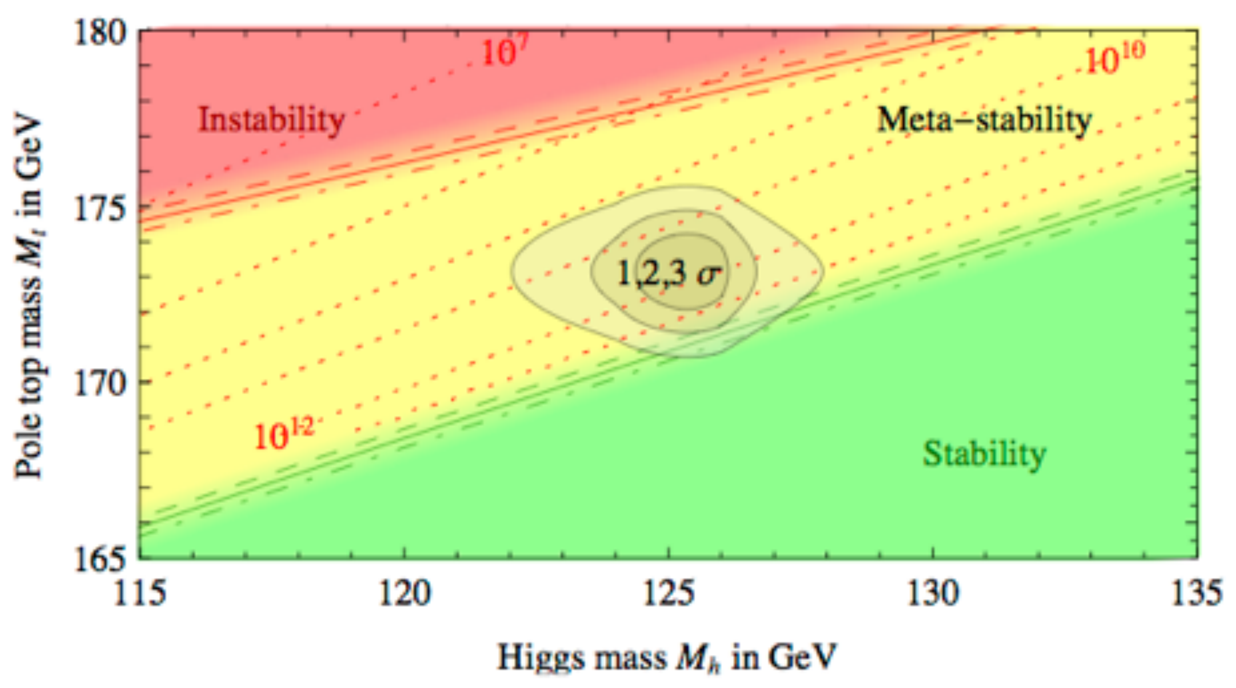
but maybe this is just so?

Why New Physics (esthetic arguments)

- Higgs potential metastability requires new physics between 100 GeV and 10^10 GeV

Degrassi et al.
1205.6497





but, maybe nature does not care about our sense of security?

Why New Physics (esthetic arguments)

- Instability of Higgs mass against radiative corrections suggests new states at 100 GeV

Coleman-Weinberg potential

$$V_{\rm CW} = \frac{1}{32\pi^2}{\rm Str}\left\{M^2(|H|)\Lambda^2 - \frac{1}{2}M^4(|H|)\left(\log[\Lambda^2/M^2(|H|)] - \frac{1}{2}\right)\right\}$$

In particular, the top SM quark contributes:

$$\mathcal{L}_{\rm top} = -\, y_t|H|\bar{t}t \quad \Rightarrow \quad M(|H|) = y_t|H|$$

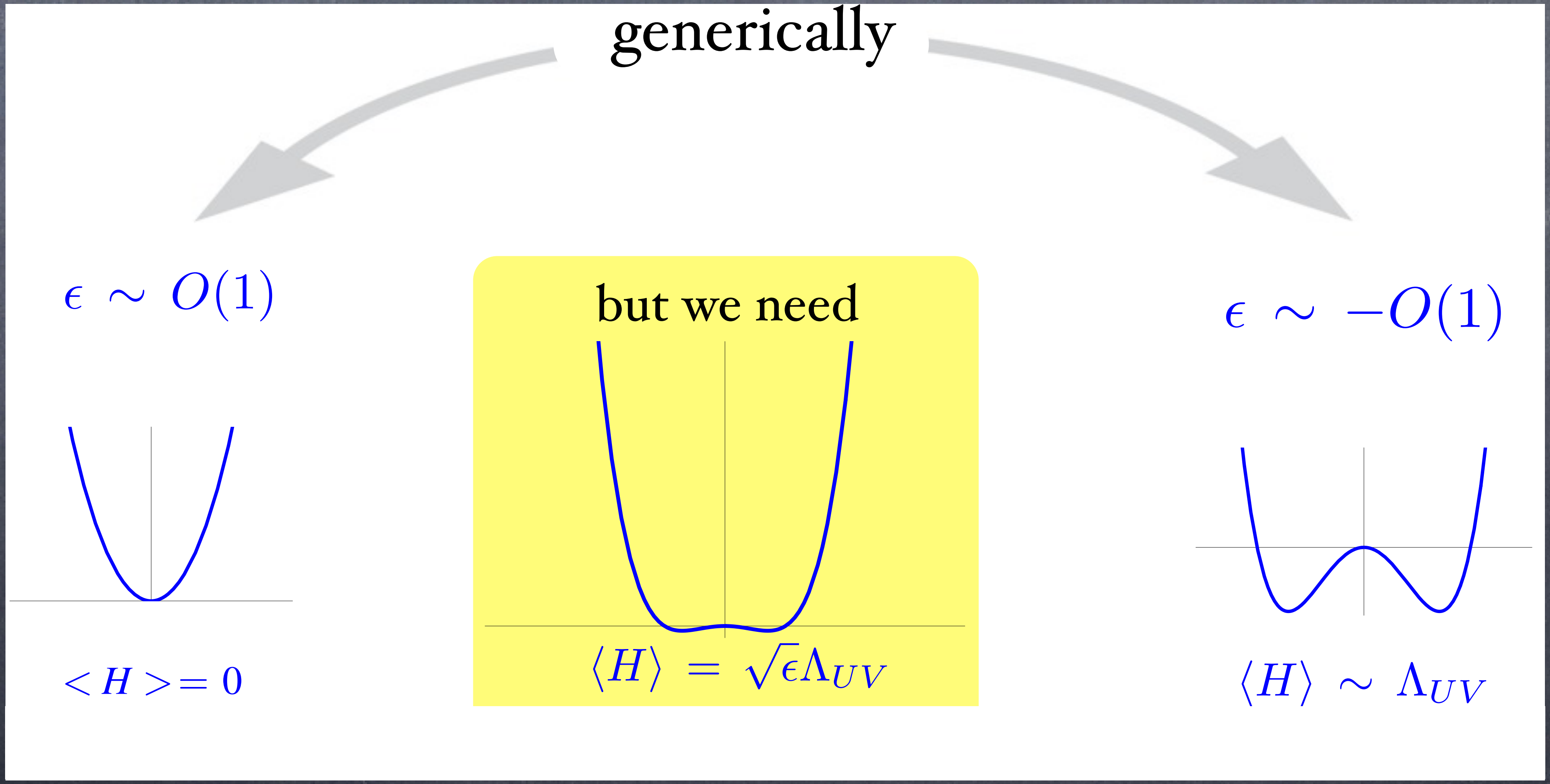
$$V_{\rm CW} = -\,\frac{3\cdot 4}{32\pi^2}y_t^2\Lambda^2|H|^2 + \ldots$$

$$\lambda v^2 \sim \frac{\Lambda^2}{\pi} \quad \Rightarrow \quad v \sim \Lambda$$

Generically, Higgs vev (and Higgs mass) parametrically close to the cut-off of the theory, unless other contributions to Higgs potential approximately cancel the top contributions

Why New Physics (esthetic arguments)

- Instability of Higgs mass against radiative corrections suggests new states at 100 GeV


generically

$\epsilon \sim O(1)$

$< H >= 0$

but we need

$\langle H \rangle = \sqrt{\epsilon}\Lambda_{UV}$

$\epsilon \sim -O(1)$

$\langle H \rangle \sim \Lambda_{UV}$

Why New Physics (esthetic arguments)

- Approximate unification of the SM gauge couplings, together with the quantum numbers of the SM fermions suggest new states at any scale between 100 and 10^14 GeV
- Fermion masses and mixings suggests another sector generating the observed structures, at any scale above TeV and Planck
- Higgs potential metastability requires new physics between 100 GeV and 10^10 GeV
- Instability of Higgs mass against radiative corrections suggests new states at 100 GeV

Only one and rather esthetic argument points unambiguously to new physics at the scales currently explored by the LHC!

Do fine-tuning arguments work?

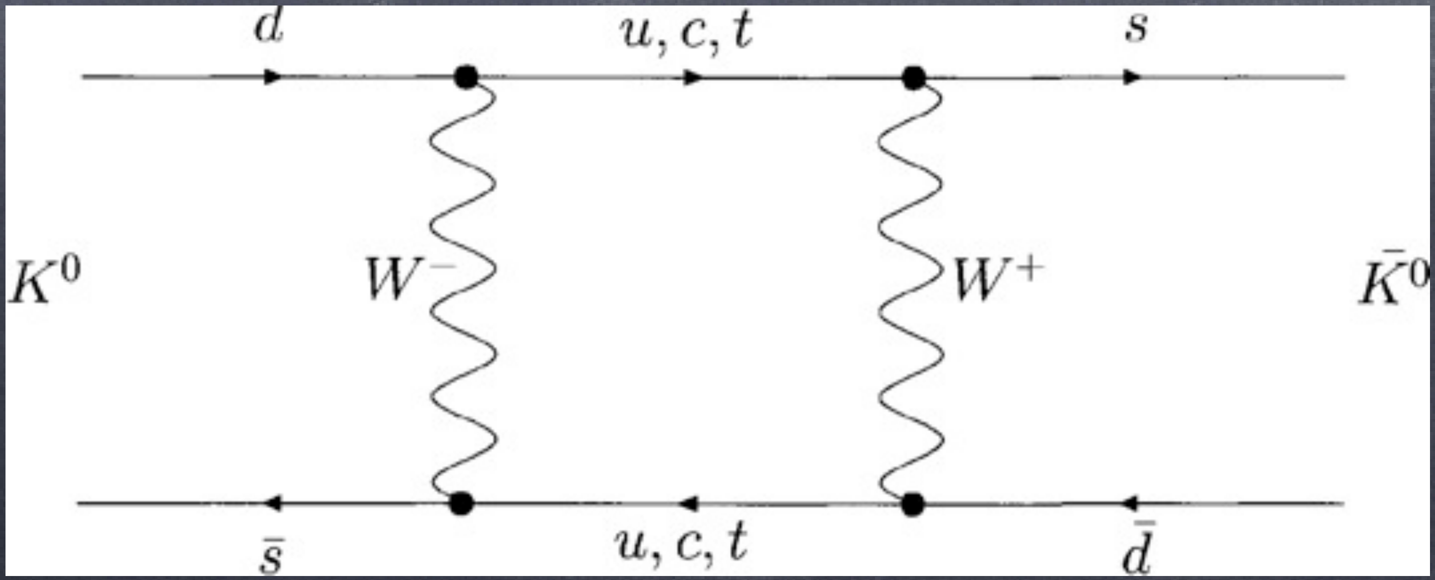
- Our motivations for new physics at the weak scale are almost completely hinged on the Higgs mass fine-tuning problem (a.k.a. naturalness problem)

- Do fine-tuning arguments work in physics? Any precedents?

Do fine-tuning arguments work?

Yes!

- In condensed matter physics, light weakly coupled scalar excitations do not exist unless experimenters carefully fine-tune conditions (e.g. temperature)
- Large, linearly divergent virtual corrections to electron mass (self-energy) unless positrons exists
- (the unique successful prediction of naturalness) large virtual corrections to K-Kbar mixing unless the charm quark exists with the mass on the order of a GeV



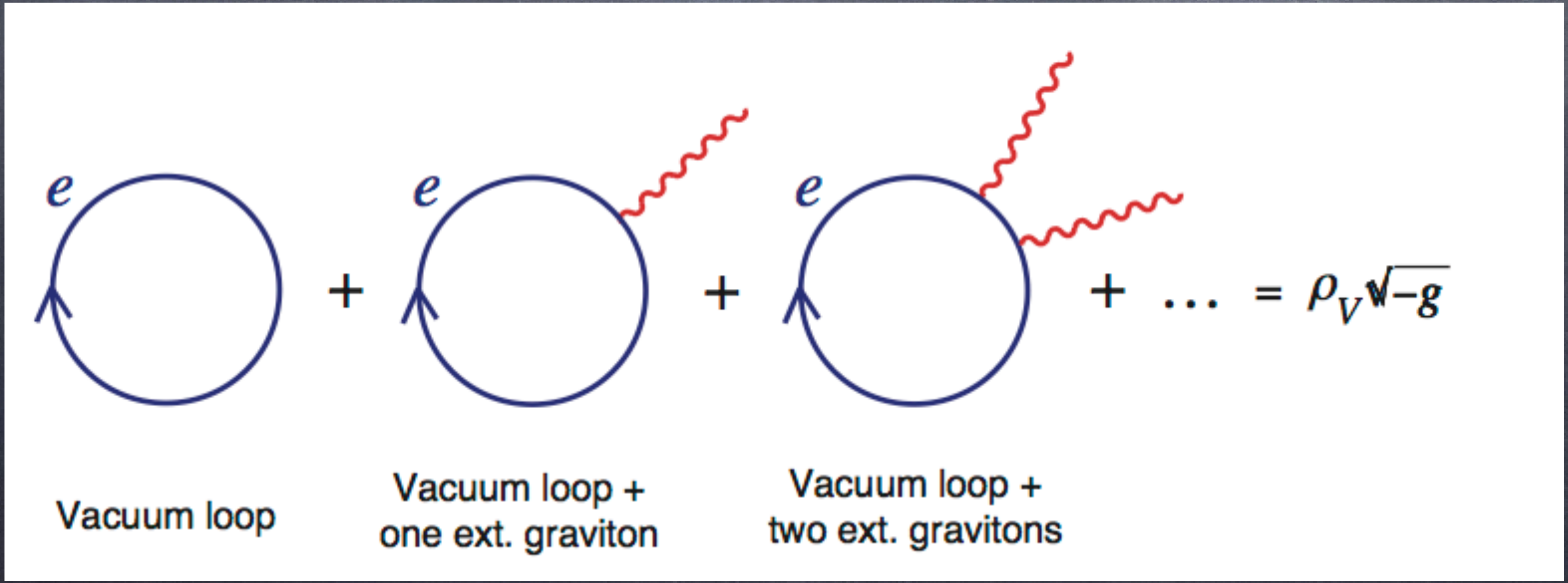
Do fine-tuning arguments work?

No!

- Naturalness expectation violated by some aspects of nuclear physics, for example deuteron binding energy of just 2 MeV, or di-neutron not being bound by 60 keV (vs 100 MeV natural scale)

- Naturalness expectation completely violated by the cosmological constant: SM virtual contributions tens orders of magnitude larger than the observed value

from Polchinski hep-th/0603249



Summary of Introduction

- We know for sure that there is something out there except for the Standard Model
- However, our motivations for new physics at the LHC are almost completely hinged on the Higgs mass fine-tuning problem (a.k.a. naturalness problem)
- It may or may not be a valid argument in the context of electroweak symmetry breaking

… until further notice assume that the naturalness problem is real and that new physics enters near the weak scale to address it

Most important classes of solutions

From Colin Bernet

- Supersymmetry
  (fermion-boson cancellations)

- Composite pGB Higgs
  (fermion-fermion and boson-boson cancellations)

Supersymmetry

- Unbroken supersymmetry marries scalars to fermions of the same mass
- Since fermion masses are protected by chiral symmetry, scalar masses end up being protected as well

Supersymmetry

How does it work in practice? Top sector example...

$$W = y_t t^c Q H_u \Rightarrow$$

large tanβ limit everywhere, for simplicity

$$\mathcal{L}_{\rm SUSY} = -\, y_t t^c t |H| + \text{h.c.} - y_t^2 |H|^2 \left(|\tilde{t}|^2 + |\tilde{t}^c|^2\right)$$

$$\mathcal{L}_{\rm soft} = -\,\tilde{m}^2 |\tilde{t}|^2 - \tilde{m}_c^2 |\tilde{t}^c|^2 - \left(y_t A_t |H| \tilde{t}\tilde{t}^c + \text{h.c.}\right)$$

$$\mathcal{L}_{\rm stop} = -\,(\tilde{t}^\dagger, \tilde{t}^c) \begin{pmatrix} \tilde{m}^2 + y_t^2 |H|^2 & y_t A_t |H| \\ y_t A_t |H| & \tilde{m}_c^2 + y_t^2 |H|^2 \end{pmatrix} \begin{pmatrix} \tilde{t} \\ \tilde{t}^{c\dagger} \end{pmatrix}$$

$$V_{\rm CW} = \frac{1}{32\pi^2} {\rm Str} \left\{ M^2(|H|)\Lambda^2 - \frac{1}{2} M^4(|H|) \left(\log[\Lambda^2/M^2(|H|)] - \frac{1}{2} \right) \right\}$$

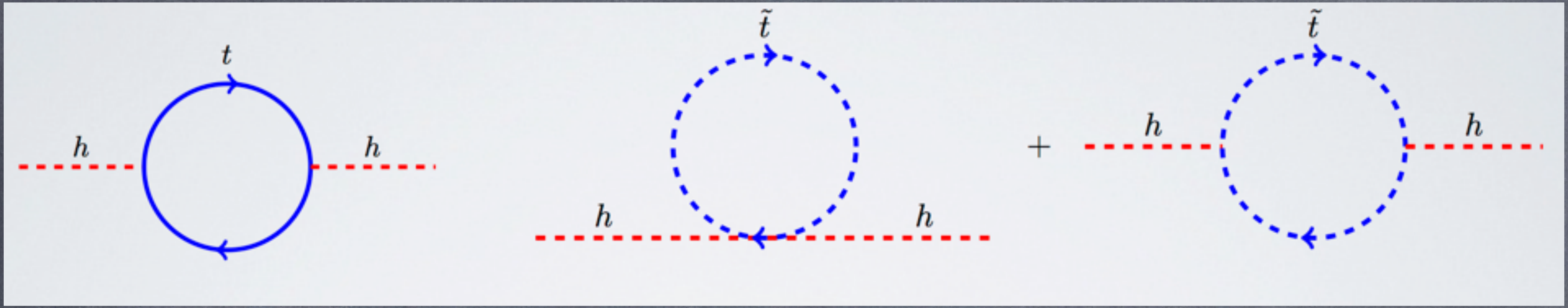
Independent of |H|, irrelevant for Higgs potential
thus no quadratically divergent corrections to Higgs mass

$${\rm Str} M^2(H) = 3\left(2(\tilde{m}^2 + y_t^2|H|^2) + 2(\tilde{m}_c^2 + y_t^2|H|^2) - 4(y_t|H|)^2\right) = 6\left(\tilde{m}^2 + \tilde{m}_c^2\right)$$

$${\rm Str} M^4(H) = 3\left(2(\tilde{m}^2 + y_t^2|H|^2)^2 + 2(\tilde{m}_c^2 + y_t^2|H|^2)^2 + 4y_t^2 A_t^2 |H|^2 - 4(y_t|H|)^4\right) \to 12 y_t^2 |H|^2 \left(\tilde{m}^2 + \tilde{m}_c^2 + A_t^2\right)$$

Dependent on |H|, Higgs mass receives log-divergent corrections proportional to soft susy breaking terms

Supersymmetry



from Matt Reece

$$\delta m_H^2 \approx -\frac{3y_t^2}{8\pi^2}\left(\tilde{m}^2 + \tilde{m}_c^2 + A_t^2\right)\log(\Lambda/\mathrm{TeV})$$

- Higgs mass under control if stop soft mass terms *and* the A-term are of order 100 GeV
- 1% fine-tuning if the soft mass terms *or* the A-term are of order 1 TeV

Supersymmetry

is attractive because

- Gives a solution to fine-tuning problem based on a deep symmetry principle
- Theory can stay perturbative up to very high scales, possibly all the way to the Planck scale
- Electroweak precision observables are affected at 1-loop level, so typically constraints from S and T are not problematic
- Theories with conserved R-symmetry may provide a WIMP dark matter candidate
- The simplest supersymmetric extensions of the SM automatically lead to gauge coupling unification at the scale around 10^16 GeV
- Predicts new colored particles so can be readily tested at the LHC

Supersymmetry

is ugly because

- New degrees of freedom badly violated approximate symmetries of the SM: flavor, CP, baryon and lepton number (if no R-symmetry). Complicated model building required to justify this is not the case

- Simplest extensions of the SM predict Higgs mass close to the Z mass, unless large supersymmetry breaking effects are introduced, which however reintroduce the (little) fine-tuning problem

- Supersymmetry has not been observed at LEP, Tevatron and the LHC, pushing the mass scale of supersymmetric particles to the TeV region, thus reintroducing the (little) fine-tuning problem

Supersymmetry

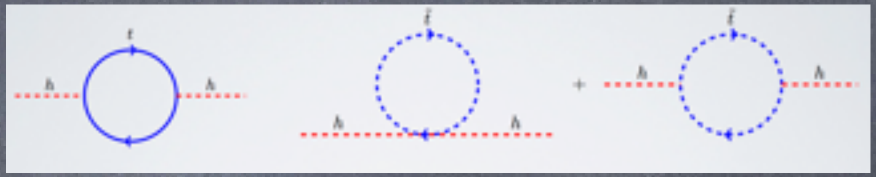
The Higgs mass in minimal supersymmetry

Higgs quartic term by supersymmetry related to electroweak gauge couplings

large tanβ limit everywhere, for simplicity

$$V_D = \frac{g_L^2 + g_Y^2}{8}|H_u|^4 \quad \Rightarrow \quad m_h^2 \approx m_Z^2$$

At 1-loop new contributions to the Higgs quartic due to top and stop loops



$$m_h^2 \approx m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log(\tilde{m}^2/m_t^2) + \frac{A_t^2}{\tilde{m}^2} - \frac{A_t^4}{12\tilde{m}^4}\right) \qquad \tilde{m}_c^2 = \tilde{m}^2$$

To match the observed Higgs mass of 125 GeV, the 1-loop term above has to be as large as the tree-level one! (125^2 = 91^2 +86^2)

For zero A-term, the above formula implies one needs the stop soft mass to be 4 TeV

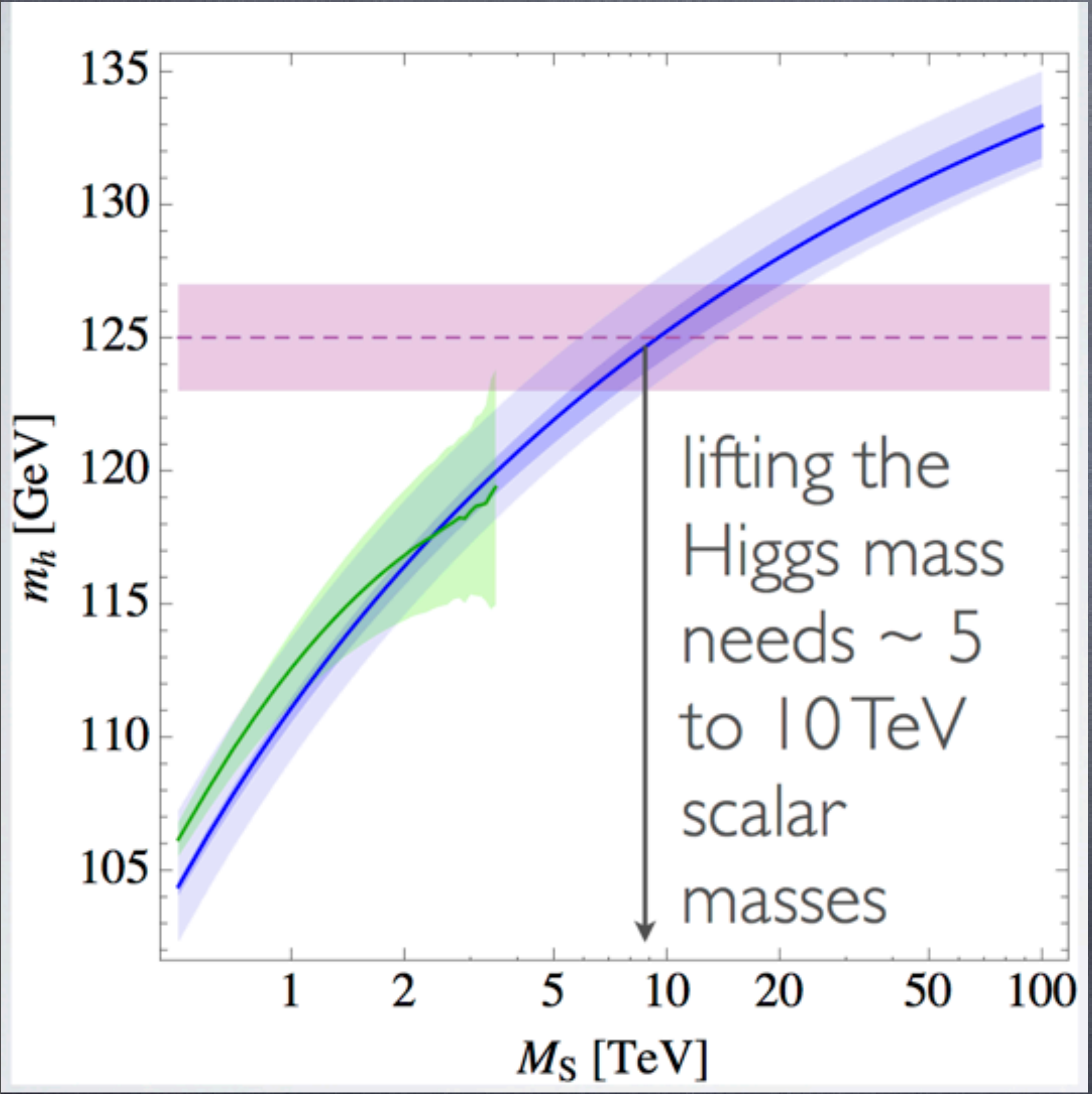
In reality, 2-loop corrections are sizable and negative, and make things even worse: for zero A-term one needs the stop soft mass to be at 10 TeV

This implies a huge fine-tuning of order 0.01%

Smaller stop masses are possible for sizable A-terms, but that also implies fine-tuning (at least 1%)

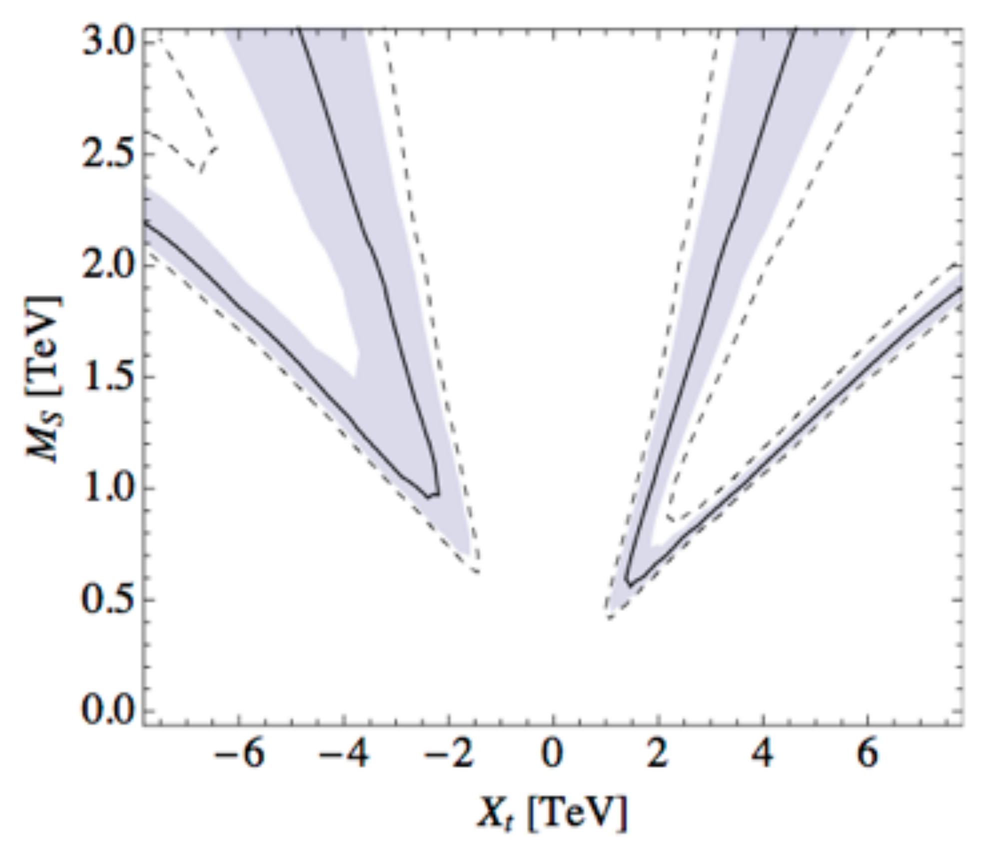
Supersymmetry

The Higgs mass in minimal supersymmetry



lifting the Higgs mass needs ~ 5 to 10 TeV scalar masses

From Draper et al. 1112.3068

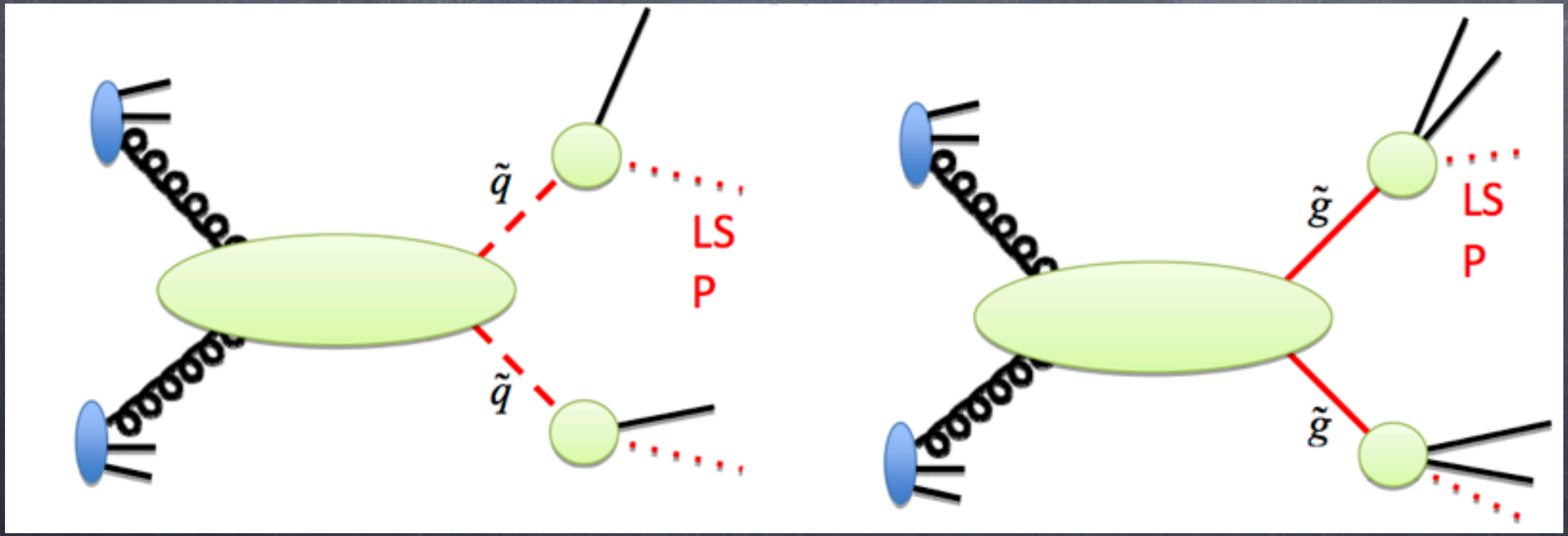


Supersymmetry

Predictions on natural supersymmetry

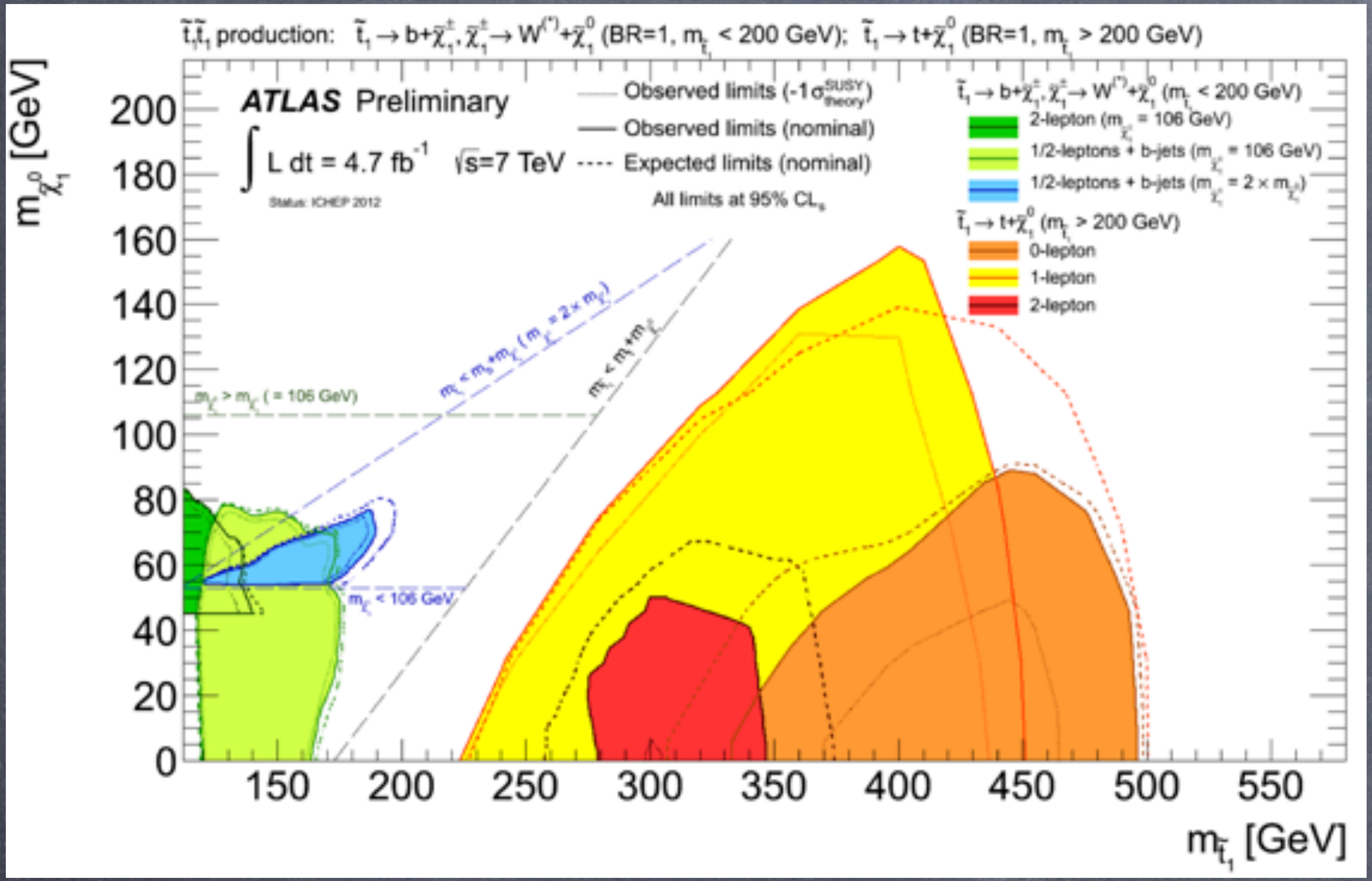
- Generically, most of the superpartners at the weak scale, that is with masses comparable to W and Z masses (we know since LEP it's not true)

- At least, superpartners of the top quark and electroweak gauginos and Higgsinos not heavier than ~300 GeV, while gluino should not be heavier than ~1.5 TeV



Supersymmetry

Direct limits on stops



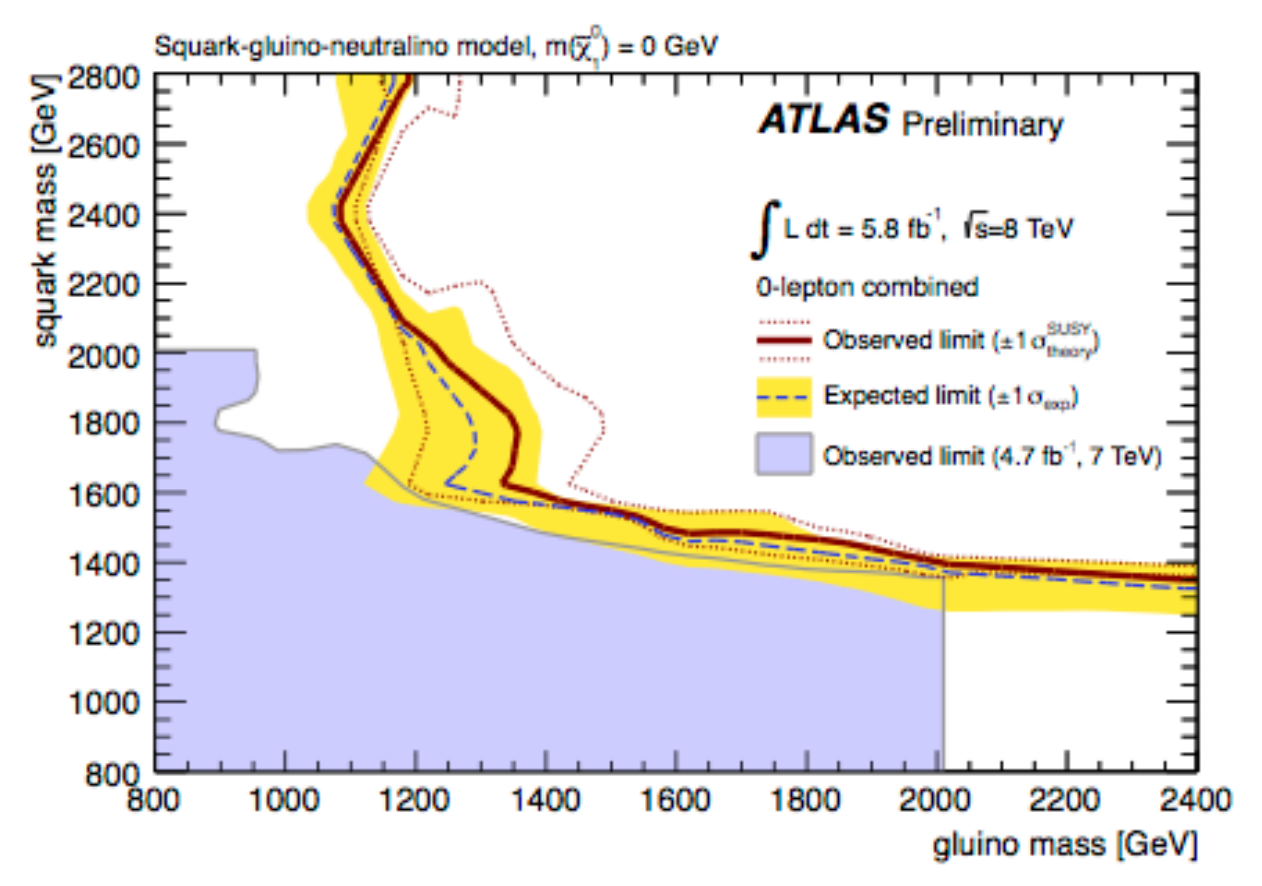
These limits start constraining the possibility of natural supersymmetry in the presence of new beyond-MSSM contributions to the Higgs mass

ATLAS-CONF-2012-070/074

However, some hope remains in "difficult" regions where no limits exist

Supersymmetry

Direct limits on squarks and gluinos



In the most favorable case, limits on superpartners already at 1.5 TeV

ATLAS-CONF-2012-109

But many less favorable scenarios remain to be explored....

Summary of Supersymmetry

- As a solution to the naturalness problem, SUSY is probably not dead....

From Colin Bernet

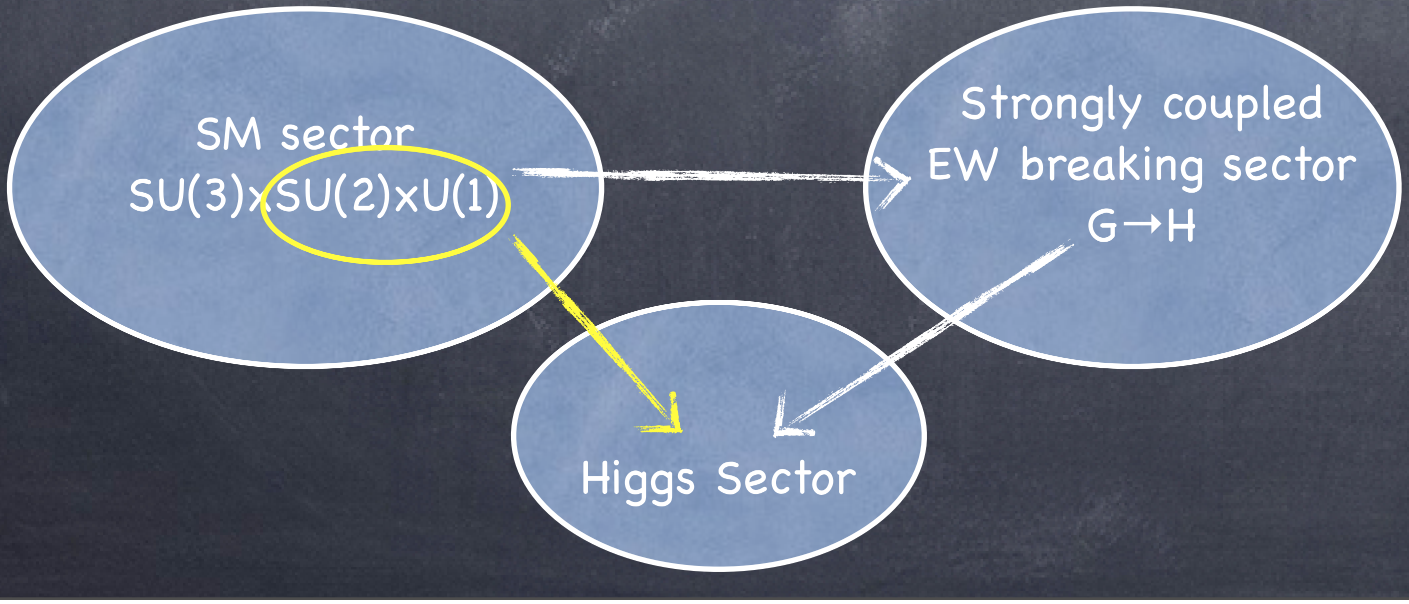
- ...but certainly battered and bruised

- Imo, currently there is no experimental hints or strong theoretical motivation for the existence of SUSY at LHC energies....
- ...which does not mean SUSY searches should not be pursued. On the contrary, SUSY models lead to well-defined experimental signatures that should be explored independently of theoretical motivations

Composite Higgs

= composite pseudo-Goldstone-boson Higgs

- Composite Higgs scenario assumes the existence of a strongly coupled sector charged under the SM gauge group with a global symmetry that is larger than the SM gauge group
- Spontaneous breaking of that global symmetry gives rise to a set of Goldstone boson identified with the SM Higgs doublet
- The global symmetry is softly broken, allowing the Higgs to acquire mass (becoming a pseudo-Goldstone boson) but protecting the Higgs mass from quadratically divergent loop corrections
- Similar in many details to pions in QCD



SM sector

SU(3)xSU(2)xU(1)

Strongly coupled

EW breaking sector

G→H

Higgs Sector

Composite Higgs

Toy model example: Higgs pGB from SU(3)/SU(2) coset

- SU(3) = 8 generators, SU(2) = 3 generators ⇒ 5 Goldstone bosons corresponding to 5 broken generators
- The SM SU(2) identified with the 3 unbroken SU(2) generators
- 4 Goldstones transforming as a doublet under the SM SU(2) identified with the Higgs, the 5th Goldstone ignored here

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} \qquad T^a = \begin{pmatrix} \sigma^a & 0 \\ 0 & 0 \end{pmatrix} \qquad T^{\hat{a}} = \begin{pmatrix} 0 & \cdot \\ \cdot & 0 \end{pmatrix} \qquad \hat{a} = 1 \ldots 4$$

unbroken generators

broken generators

$$\Phi \to e^{iH^{\hat{a}}T^{\hat{a}}/f} \langle \Phi \rangle = \begin{pmatrix} \cdots & H/|H| \sin(|H|/f) \\ H^\dagger/|H| \sin(|H|/f) & \cos(|H|/f) \end{pmatrix} \langle \Phi \rangle = \begin{pmatrix} H \frac{\sin(|H|/f)}{|H|/f} \\ f \cos(|H|/f) \end{pmatrix}$$

- This rewriting isolates the massless Goldstone boson components
- SU(3) invariant |Φ|^2 is independent of H, thus H cannot have non-derivative couplings, thus has no mass or potential as long as the global symmetry is not explicitly broken
- As long as SU(3) is only softly broken H is protected from quadratic divergences at 1 loop

Composite Higgs

How does it work in practice? Top sector example...

Add a vector-like heavy top T, Tc so as to embed the top double into SU(3) representation

$$Q_3 = \begin{pmatrix} Q \\ T \end{pmatrix} \quad t^c \quad T^c$$

Write top Yukawa couplings such that SU(3) is only softly broken

$$\mathcal{L}_{\text{top}} = \underbrace{-y_t \Phi^\dagger Q_3 t^c}_{\text{SU(3) preserving}} \underbrace{- M T T^c}_{\text{SU(3) breaking}} = (t^c, T^c) \begin{pmatrix} y_t f \sin(|H|/f) & y_t f \cos(|H|/f) \\ 0 & M \end{pmatrix} \begin{pmatrix} t \\ T \end{pmatrix}$$

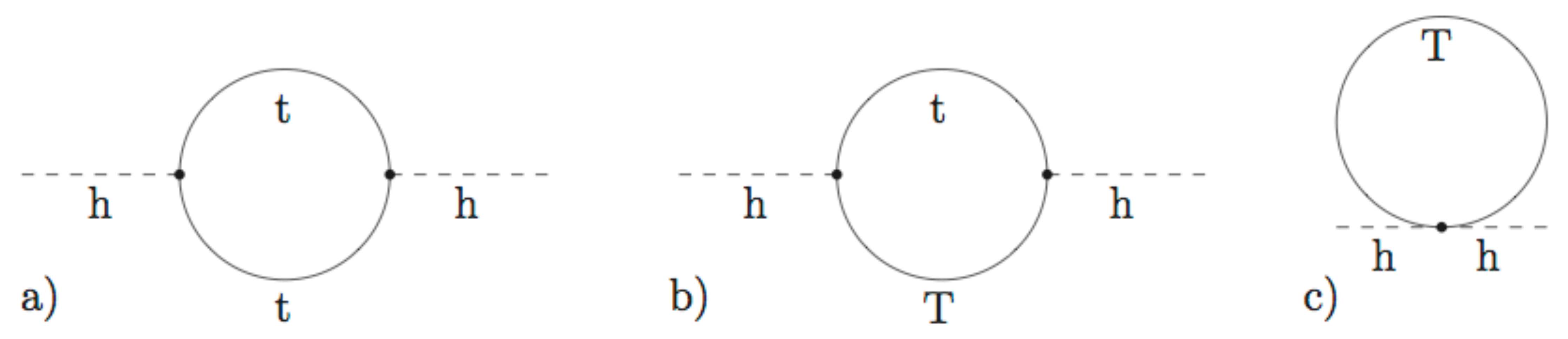
$$V_{\text{CW}} = \frac{1}{32\pi^2} \text{Str} \left\{ M^2(|H|)\Lambda^2 - \frac{1}{2} M^4(|H|) \left(\log[\Lambda^2/M^2(|H|)] - \frac{1}{2} \right) \right\}$$

$$\text{Str} M^2(|H|) = y_t^2 f^2 \sin^2(|H|/f) + y_t^2 f^2 \cos^2(|H|/f) + M^2 = y_t^2 f^2 + M^2$$

Independent of |H|
thus no quadratic divergence
to the Higgs mass

Composite Higgs

How does it work in practice? Top sector example...



from Perelstein, hep-ph/0512128

Quadratic divergences from the top loop canceled thanks to a non-renormalizable vertex h h T T

Composite Higgs

Minimal fully realistic model

- pGB Higgs from SO(5)/SO(4) coset
- SO(5)=10 generators, SO(4)=6 generators, thus 4 Goldstone boson corresponding to 1 Higgs doublet (minimal Higgs sector)
- Unbroken SO(4)=$SU(2)_L \times SU(2)_R$, in which SM electroweak symmetry $SU(2)_L \times U(1)_Y$ can be embedded
- Larger global symmetry $SU(2)_L \times SU(2)_R$ broken to $SU(2)_V$ after EW symmetry breaking implies so-called custodial symmetry - important to keep T parameter under control

Composite Higgs

Minimal fully realistic model - phenomenological properties

Couplings of the Higgs to gauge bosons modified

$$\mathcal{L}_{hVV} = c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu \qquad c_V = \sqrt{1 - v^2/f^2}$$

Elementary fermions mix with composite states, the amount of mixing being proportional to the fermion mass

$$\mathcal{L}_f = \lambda_{q_L} q_L \mathcal{O}_R + \lambda_{q_R} q_R \mathcal{O}_L + y_* \mathcal{O}_L H \mathcal{O}_R \qquad m_q \sim \lambda_{q_L} \lambda_{q_R} v$$

As a result, couplings of heavier SM fermions (top) significantly modified, depending on the representation of composite operators

Heavy resonances of the strong sector coupled most strongly to the 3rd generation quarks, in particular, prediction of a TeV-scale Z′ or G′ decaying to a top quark pair

Top partners coupled to the SM top and Higgs as T′ t H, which implies roughly democratic decays to H t, W±b and Zt

Composite Higgs

is attractive because

- Gives a solution to the fine-tuning problem based on a symmetry principle
- Similar mechanism has been seen at work in high-energy physics (chiral symmetry breaking leading to pions in QCD)
- Compatible with attractive models generating the observable flavor hierarchies and CKM mixing (so-called partial compositeness)
- Predicts new colored particles (in particular, fermionic top partners) so can be readily tested at the LHC

Composite Higgs

is ugly because

- Electroweak precision observables are affected at tree-level by vector resonances in the strong sector mixing with W and Z, pushing the compositeness scale f above TeV and thus reintroducing the fine-tuning
- New degrees of freedom violate approximate symmetries of the SM: especially flavor and CP. Some model building required to justify this is not the case
- Cannot be perturbatively extended far above the TeV scale
- No automatic gauge coupling unification, unless with dedicated model building
- No signs of compositeness or resonances of the electroweak breaking sector have been detected at the LHC

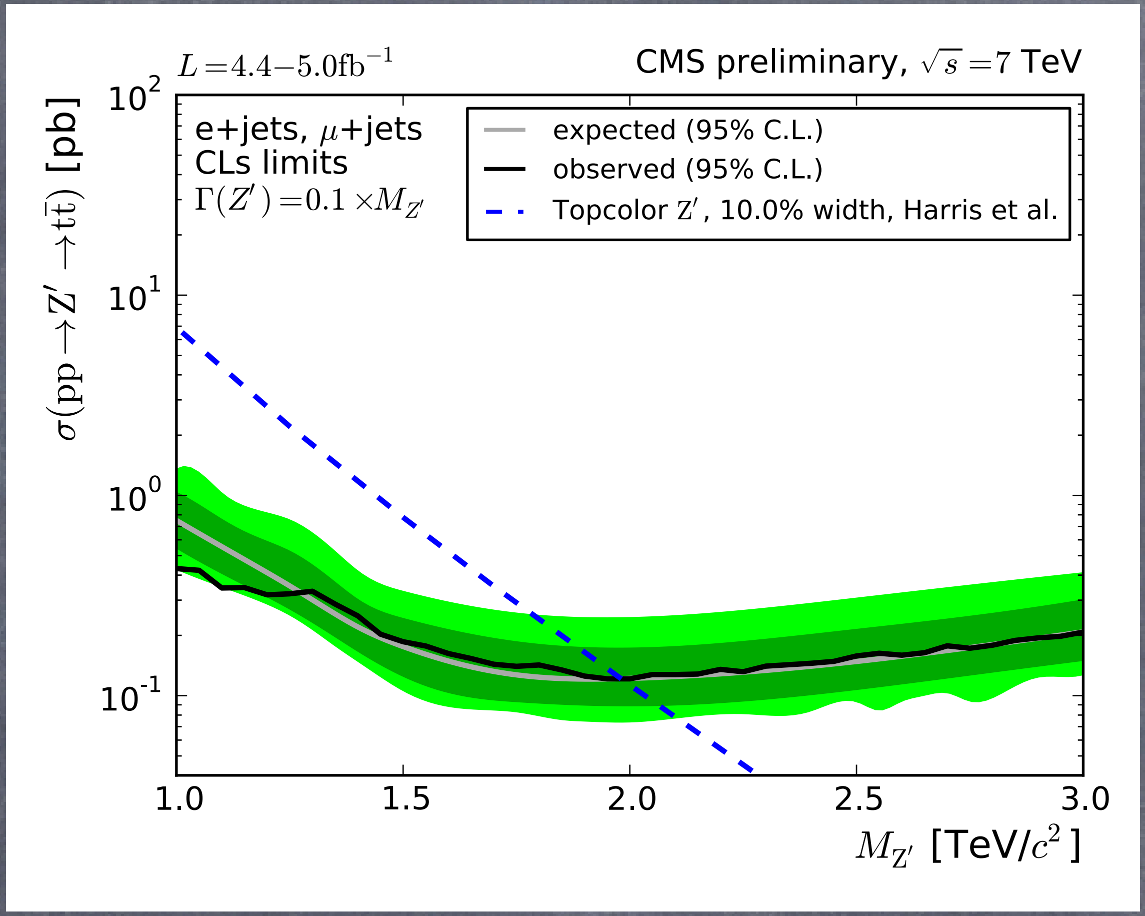
Composite Higgs

Predictions of natural composite Higgs

- Generically, numerous resonances of the EW breaking sector not much above the weak scale (we already know that's not true)
- At least, fermionic partners of the top quark below ~500 GeV, and bosonic partners ofW and Z around ~1-3 TeV
- Couplings of the Higgs boson modified on the order of v^2/f^2

Composite Higgs

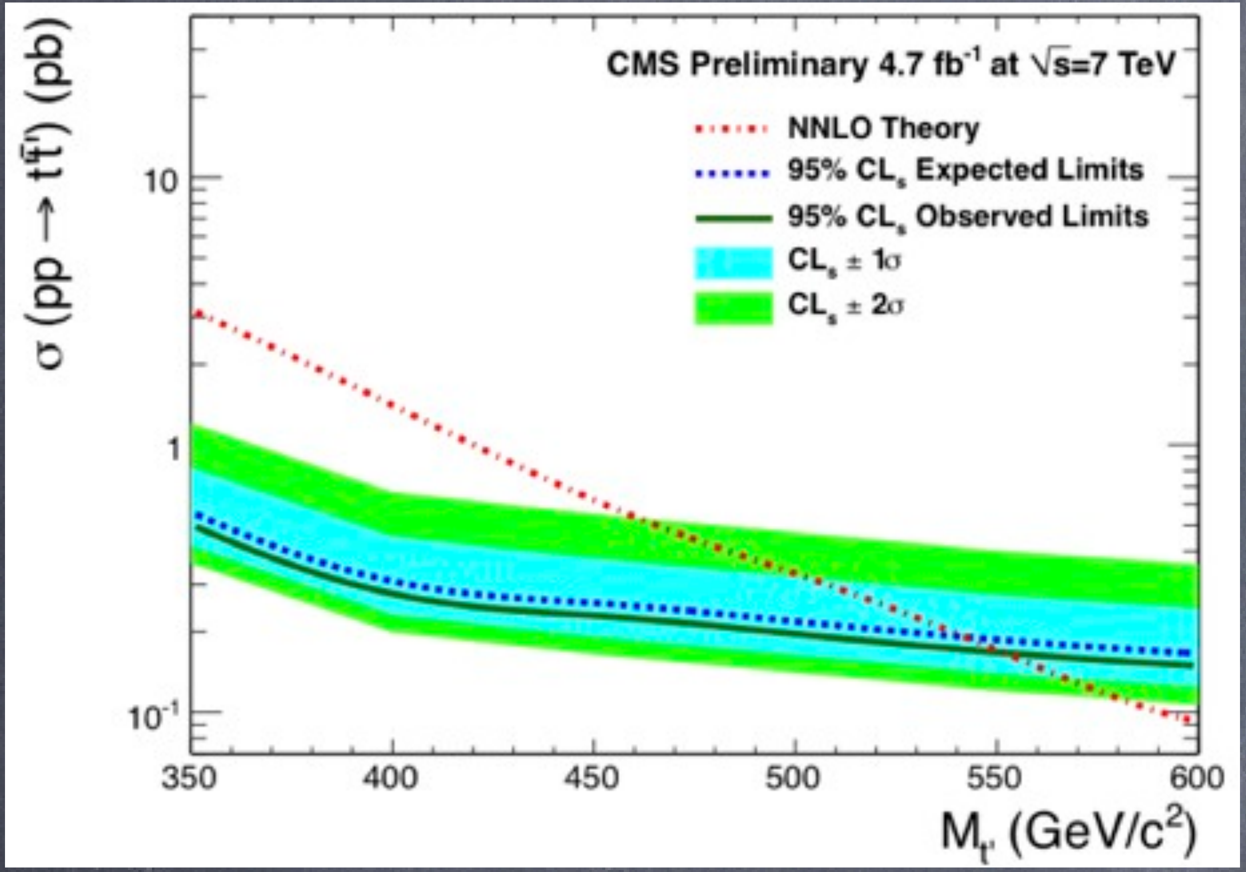
Direct search for ttbar resonances

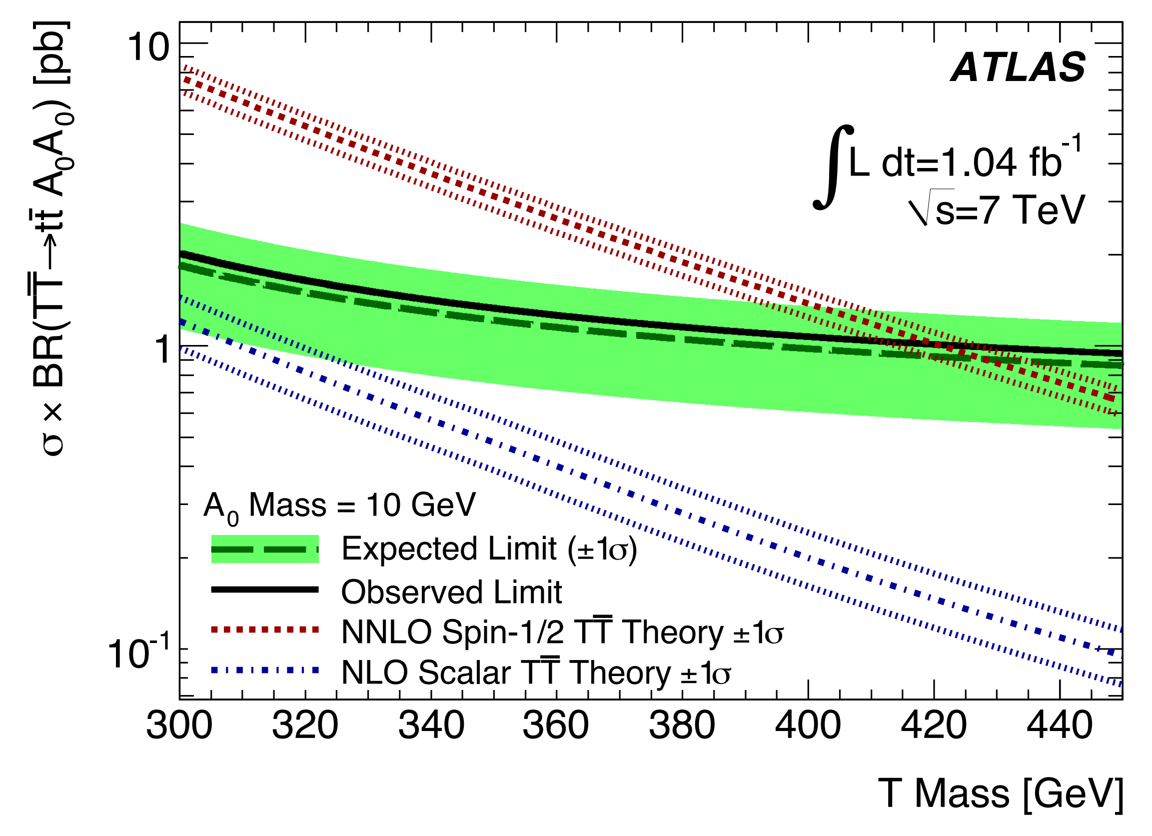


pp→Z′→ t-tbar

Composite Higgs

Direct search for top partners





T→Wb

T→t+MET

Summary of Composite Higgs

- As a solution to the naturalness problem, composite Higgs is probably not dead....

- ...but certainly in an awkward position

- Imo, currently there is no experimental hints or strong theoretical motivation for Higgs compositeness at LHC energies....
- ...which does not mean searches should not be pursued. On the contrary, composite Higgs models lead to well-defined experimental signatures that should be explored independently of theoretical motivations

Other solutions to naturalness problem

Little Higgs

- Little Higgs is a cousin of composite Higgs. It is also a pseudo-Goldstone boson of an approximate global symmetries, and the cancellation of quadratic divergences works the similar way

- The main difference is that the scale of the strongly coupled sector is pushed higher, to about 10 TeV, and the theory is supposed to be weakly coupled up to that scale

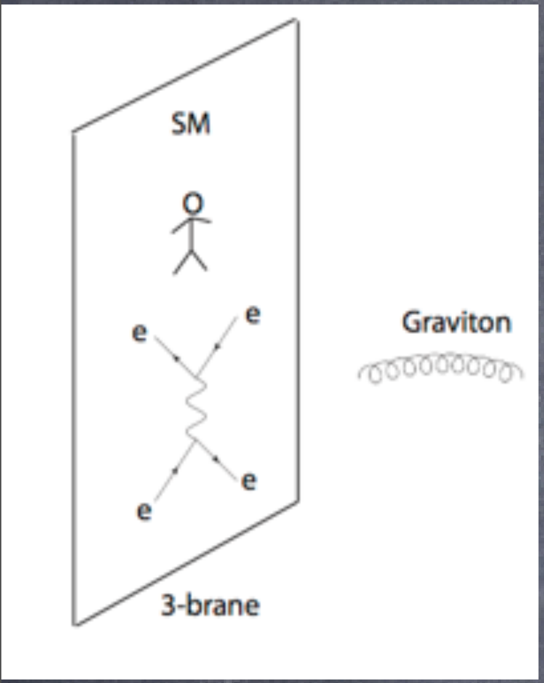
- Due to that, one needs more structure to also control the quadratic divergences to the Higgs mass from the SM gauge bosons, and from the Higgs self-interactions. This is achieved by extending the gauge symmetry, and organizing the breaking of symmetries in the so-called collective fashion (no parameter by itself breaks the symmetries protecting the Higgs, only 2 or more parameters switched on simultaneously)

Little Higgs was good as an example of boson-boson and fermion-fermion cancellation, however explicit examples are typically more complicated, less natural, and more constrained than composite Higgs

Other solutions to naturalness problem

Low quantum-gravity scale (ADD)

from Hsin-Chia Cheng
1003.1162



We are confined to a 4D brane,
while gravity also propagates in n additional dimensions

$$(10^{19}\ \mathrm{GeV})^2 \approx M_{\mathrm{Pl}}^2 = M_*^{n+2} V_n$$

If extra dimensions are sufficiently large, the true quantum gravity scale M* can be as low as TeV

$$\begin{aligned} n &= 1 \Rightarrow L \sim 10^{15}\ \mathrm{cm}\ (> 1\ \mathrm{AU}),\ \text{obviously ruled out,} \\ n &= 2 \Rightarrow L \sim 1\ \mathrm{mm}\ ,\ \text{allowed in 1998, but current bound } L < 200\ \mu\mathrm{m} \\ n &= 3 \Rightarrow L \sim 10^{-6}\ \mathrm{cm}\ . \end{aligned}$$

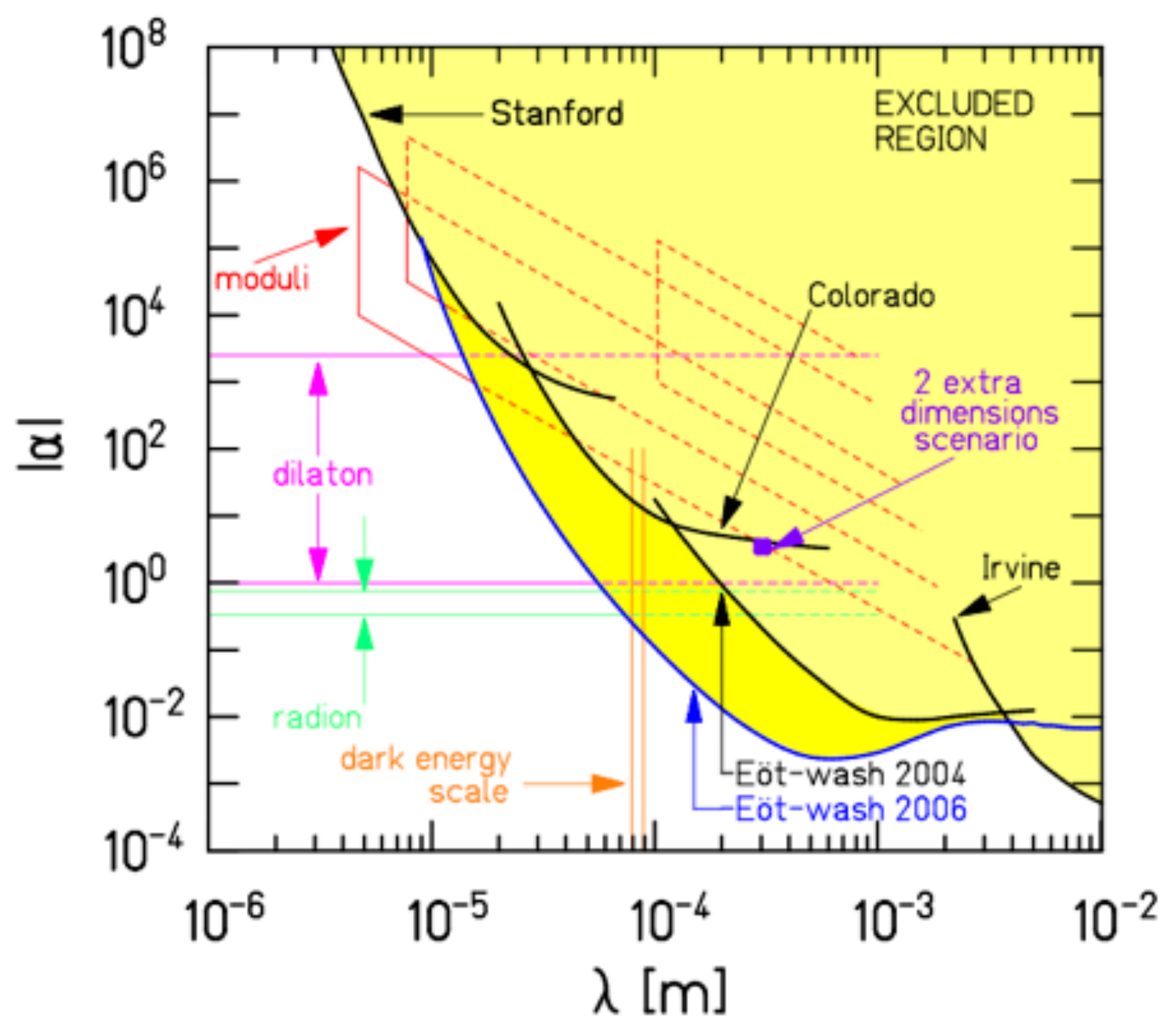
ADD scenario very unlikely:

- One expects SM accompanied by all sorts of higher-dimensional operators suppressed by the low quantum gravity scale, but none has been seen
- By itself does not explain why the Higgs boson is light (mh << M*)
- No "black holes" seen at the LHC

Other solutions to naturalness problem

Low quantum-gravity scale (ADD)

$$V(r) = -G_N \frac{m_1 m_2}{r} \left(1 + \alpha e^{-r/\lambda}\right)$$

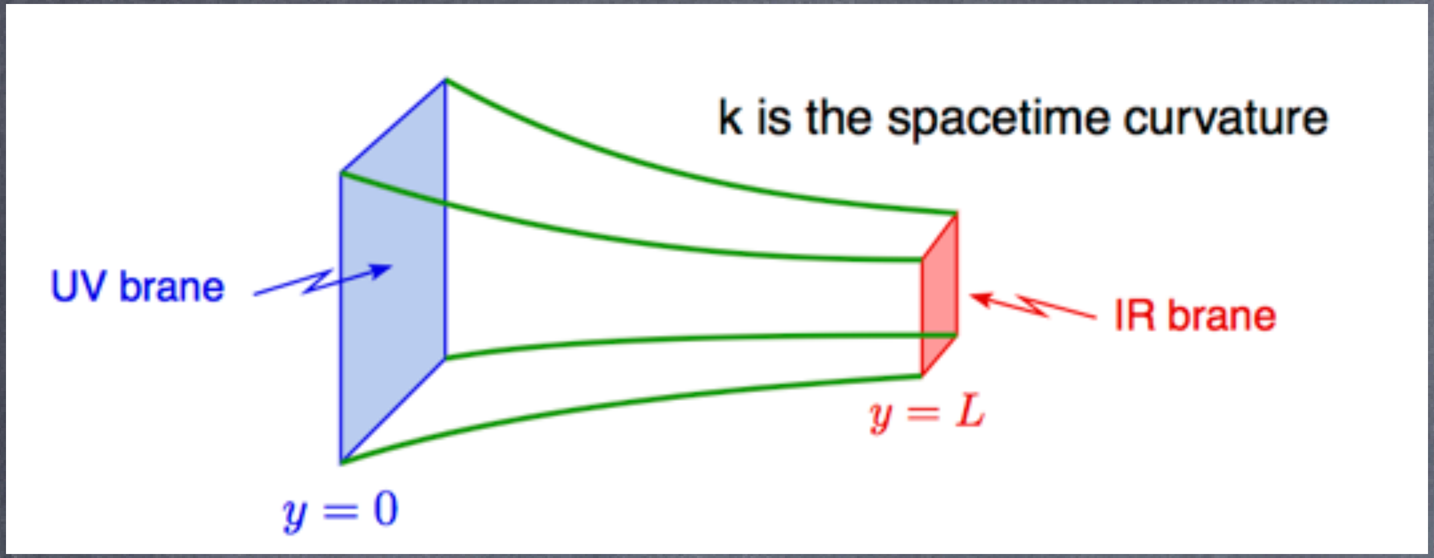


Kapner et al
hep-ph/0611184

ADD was good because it made us realize how poorly we know gravity at sub-millimeter distances, and boosted some experimental progress

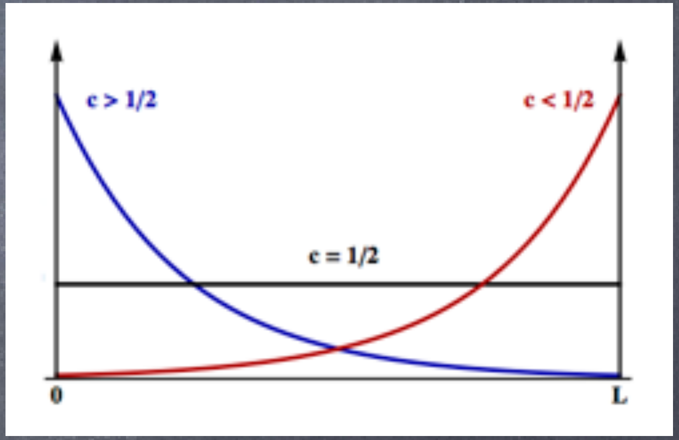
Other solutions to naturalness problem

Warped Extra Dimension (Randall-Sundrum)



from Ponton, 1207.3827

c is 5D fermion mass i
n the units of 5D curvature k



- For a warped (curved) extra dimension the cut-off scale is different, depending on the position along the extra dimension.Typically, the UV brane is assumed to have a cut-off at the 4D Planck scale, while the IR brane has a cut-off at TeV

- In the original RS model, all the SM fields lived on the IR brane, only gravity propagated in the bulk (similar motivation as ADD, but no gravity modification at millimeter distances).

- In the “modern” RS, Higgs remains localized near the IR brane. However, SM gauge fields are flat in the bulk, while most of the SM fermions localized near the UV brane, except for the 3rd generation localized near the IR brane. Small differences in 5D masses of fermions generate sharp localization effects, and provide a model for fermion mass hierarchies

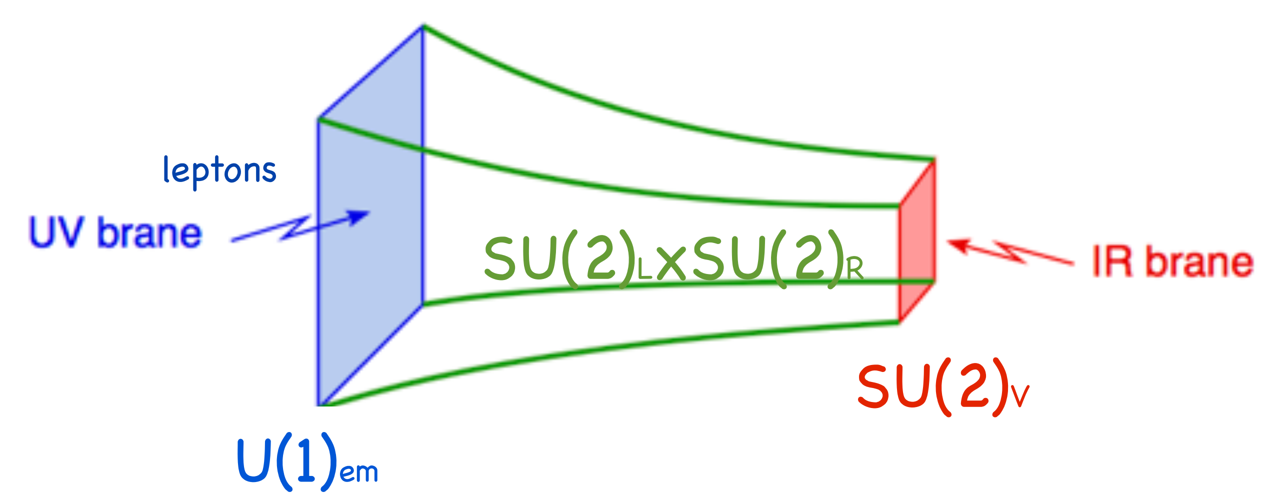
- Higgs can be identified with the 5th component of gauge fields propagating in the bulk, in which case 1-loop corrections to its mass are finite and so the naturalness problem is solved

Other solutions to naturalness problem

Warped Extra Dimension (Randall-Sundrum)

By AdS/CFT conjecture, the Randall-Sundrum set-up provides a perturbative representation of large N strongly coupled sector!

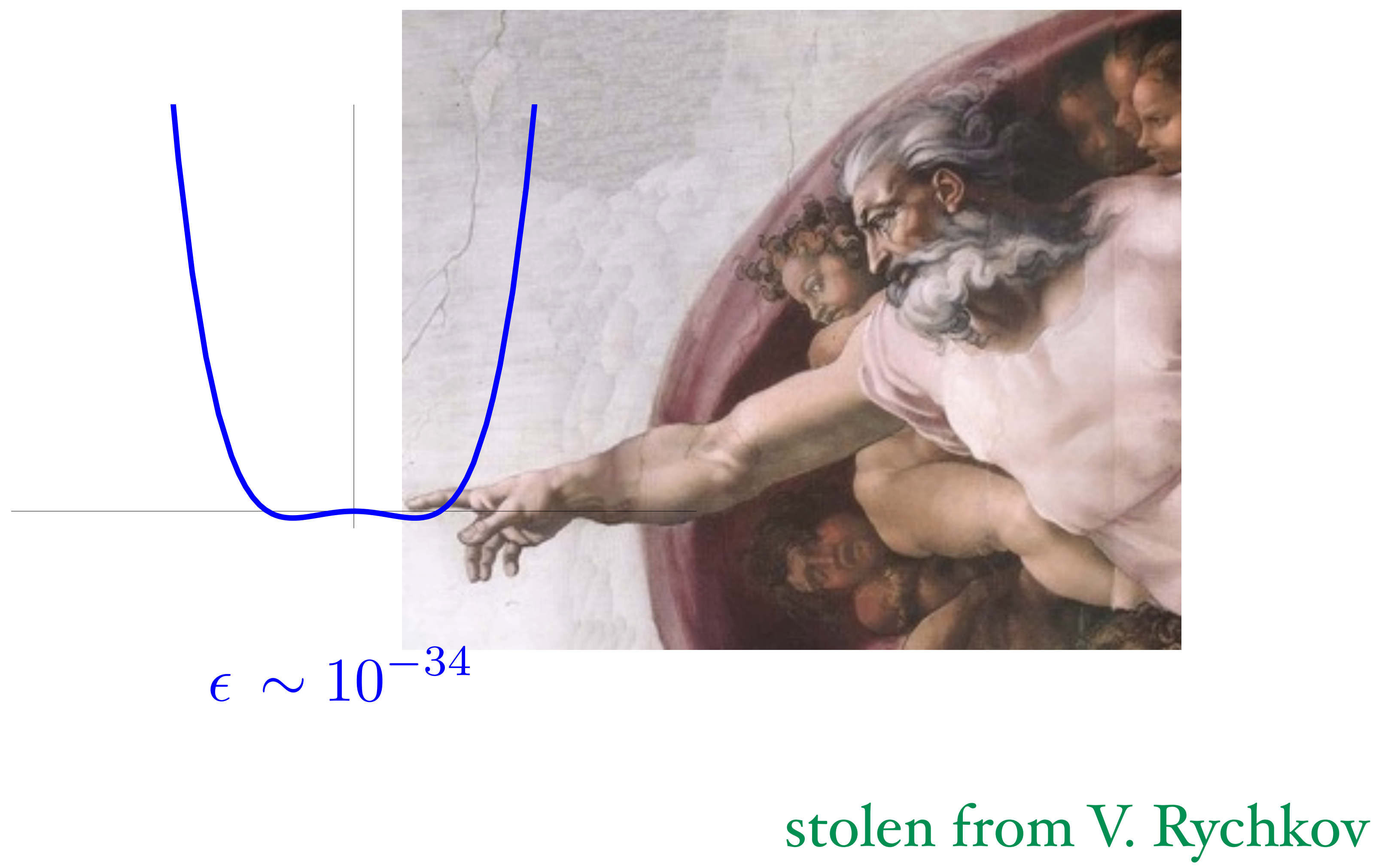
- Bulk gauge symmetry translates to global symmetry of the strongly coupled sector
- IR localized fields correspond to composite states of the strongly coupled sector
- UV localized fields corresponds to weakly coupled fundamental fields probing the strongly coupled sector
- Models of gauge-Higgs unification correspond to pseudo-Goldstone boson composite Higgs
- Even many aspects of low-energy QCD (at large N) can be modeled using the RS set-up



RS was good because
it gave us a nice tool
to study and visualize
strongly coupled sectors

Other solutions to naturalness problem

Divine intervention



stolen from V. Rychkov

Summary of Naturalness

- Naturalness may or may not be relevant to electroweak symmetry breaking
- Currently no serious hints that any of the known mechanisms of ensuring naturalness is operative at the LHC energies
- More Patience? Another mechanism we're not aware of? Multiverse? Divine intervention?

?

Are there are any hints at all of new physics at the weak scale?

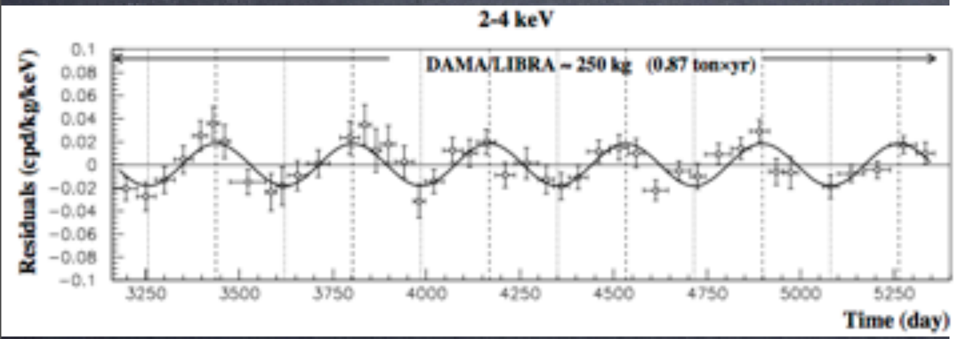
(natural or not)

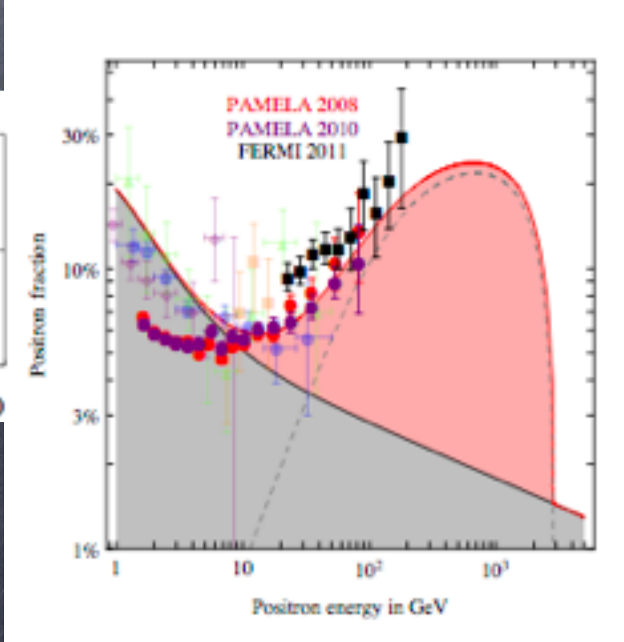
Significant and robust hints of New Physics at the weak scale

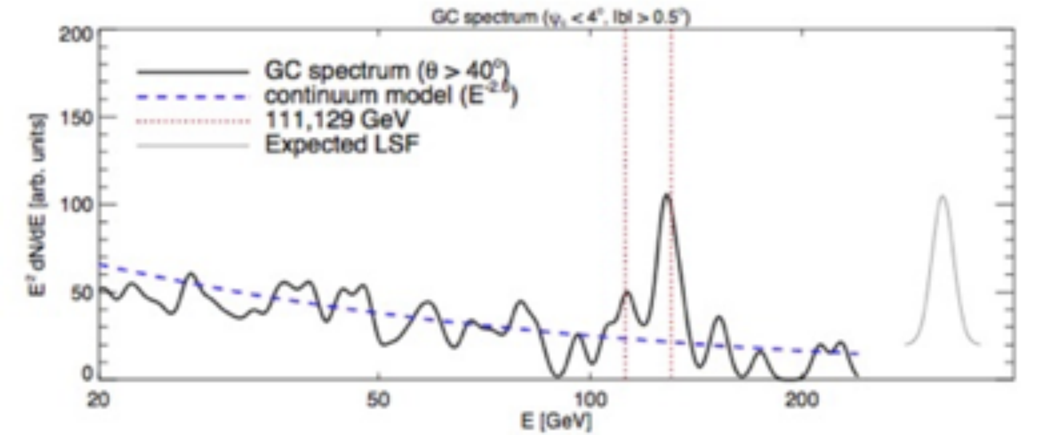
Significant but crazy* hints of new physics at or below the weak scale

Astro

- **DAMA annual modulation:** almost 10σ "evidence" of dark matter with mass in the 5-100 GeV ballpark. Possibly related signal from CoGeNT and CRESST experiments
- **PAMELA and Fermi excess:** raising cosmic-ray positron fraction, interpreted as leptophilic dark matter with mass in the 1 TeV ballpark
- **Fermi line:** a 5σ monochromatic 130 GeV photon emission from the center of galaxy interpreted as evidence of dark matter with mass 130 GeV annihilating to photons







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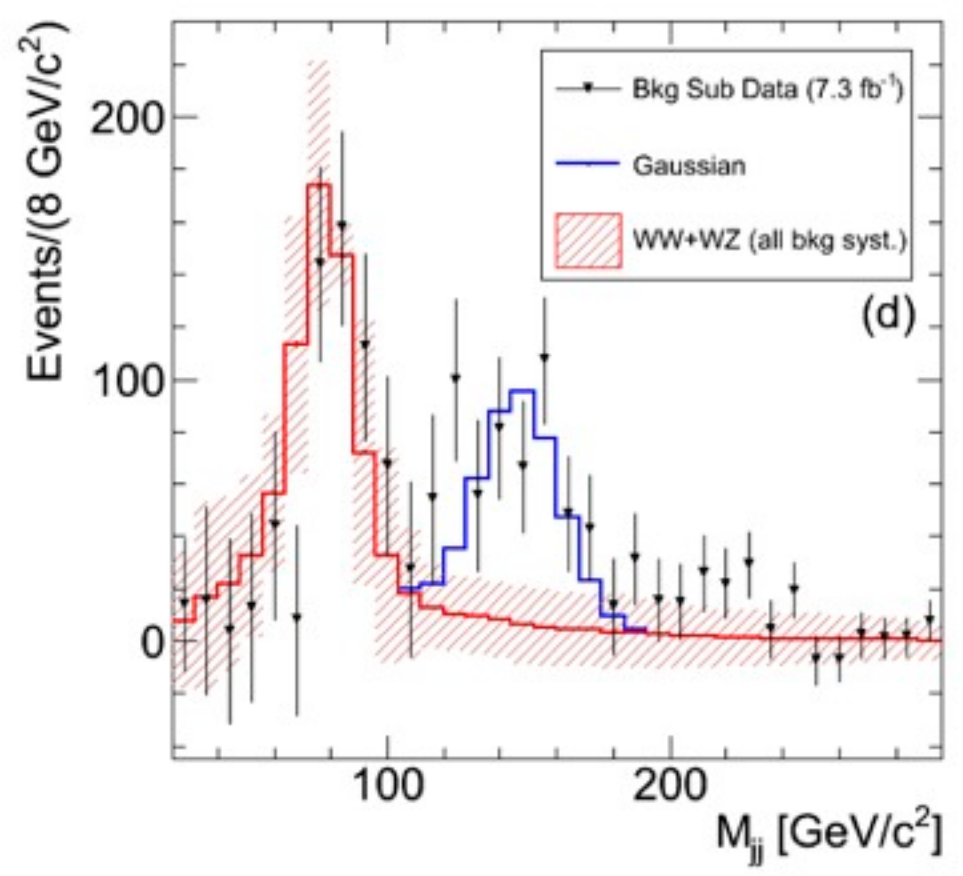
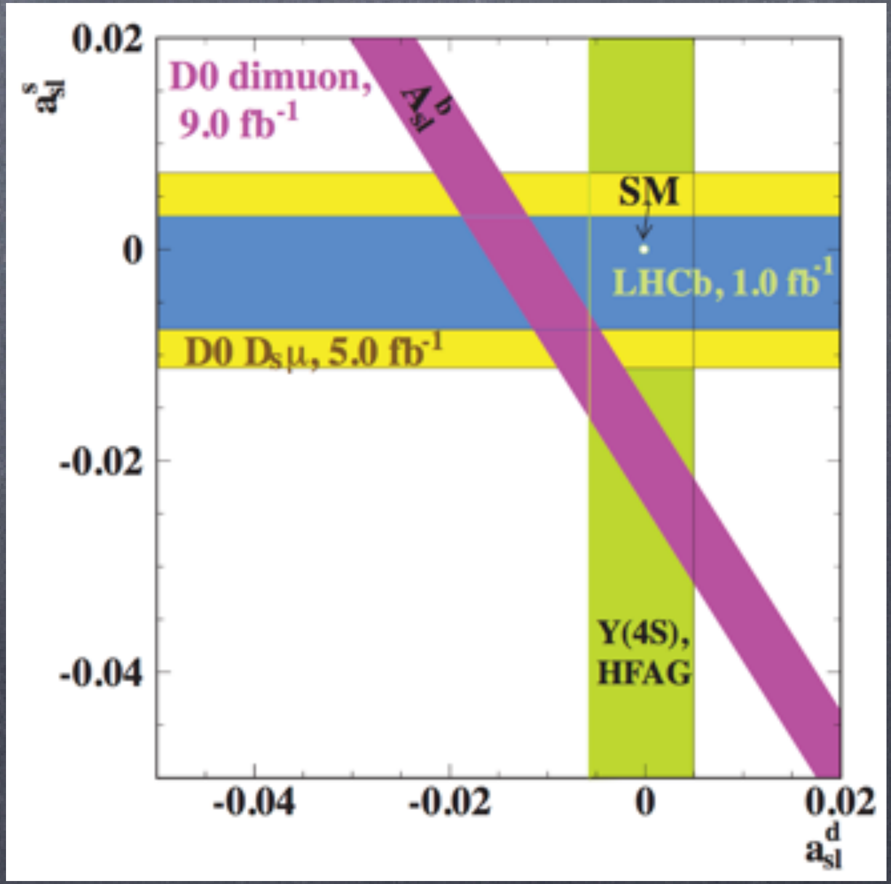
* crazy means that it's not confirmed by other similar experiments, or that theoretical interpretations are crazy, or that it's too good to be true

Significant but crazy* hints of new physics at or below the weak scale

COLLIDERS

- CDF bump: a resonance in the invariant mass spectrum of dijets produced in association with W boson, suggesting a new particle with mass 145 GeV
- D0 dimuon charge asymmetry: 4σ excess of μ+μ+ vs μ-μ- yield, interpreted as anomalous CP violation in B-meson oscillations





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* crazy means that it's not confirmed by other similar experiments, or that theoretical interpretations are crazy, or that it's too good to be true

Most plausible[*] hints of new physics at or below the weak scale

- Muon anomalous magnetic moment
- t-tbar forward-backward asymmetry at the Tevatron

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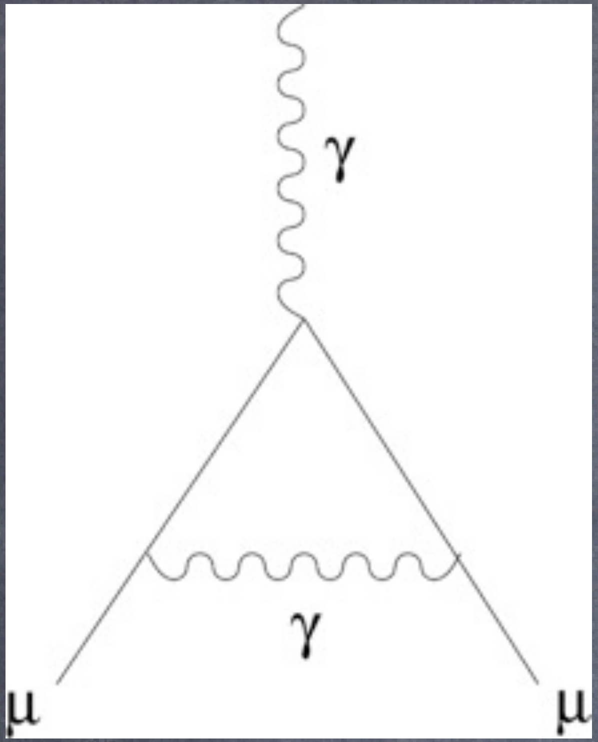
[*] plausible doesn't mean compelling

Muon anomalous magnetic moment

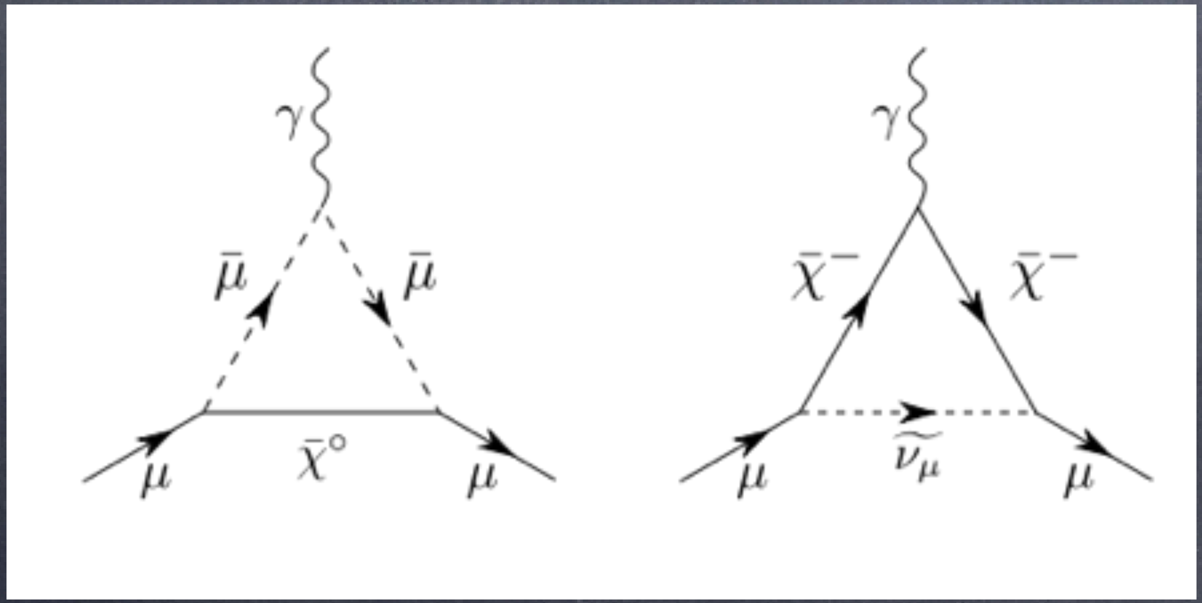
Effective higher-dimensional operator $-\frac{e}{8m} a_\mu F_{\alpha\beta}\bar{\mu}\sigma^{\alpha\beta}\mu$



$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.8 \pm 0.8) \times 10^{-9}.$$

Plausible because it's very natural for weak scale new physics to generate this shift. For example, in SUSY

$$\delta a_\mu \approx 2.8 \times 10^{-9} \frac{\tan\beta}{20} \left(\frac{300\ {\rm GeV}}{\tilde{m}}\right)^2 \left[\frac{1}{8}\frac{10}{\mu/\tilde{m}} + \frac{\mu/\tilde{m}}{10}\right]$$



from Giudice et al. 1207.6393

t-tbar forward-backward asymmetry at the Tevatron

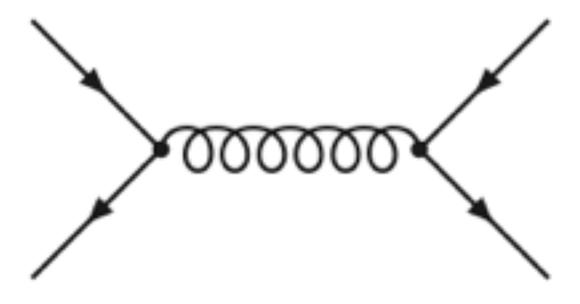
simplest definition:

$$A_{\text{lab}} = \frac{N(y_t > 0) - N(y_t < 0)}{N(y_t > 0) + N(y_t < 0)} = \frac{N(y_t > 0) - N(y_{\bar{t}} > 0)}{N(y_t > 0) + N(y_{\bar{t}} > 0)}$$

better definition:

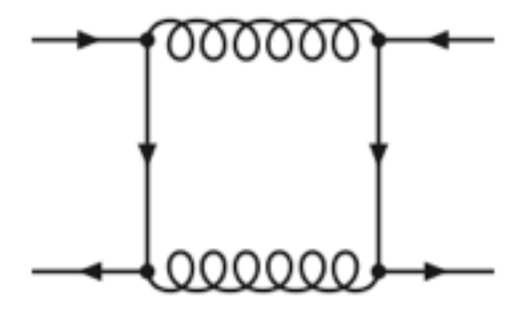
$$A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

- At the Tevatron, forward=proton direction, backward=antiproton-direction

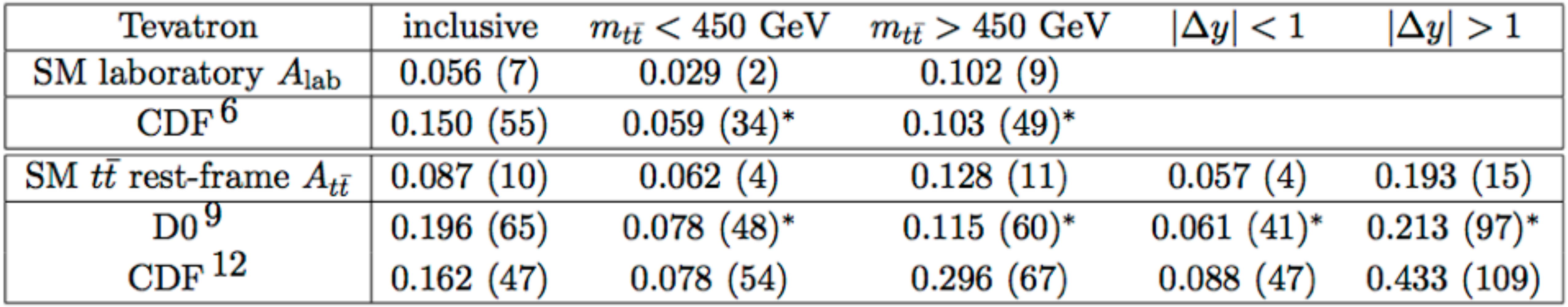


- In leading order QCD no asymmetry is present because gluon couples in vector-like fashion to quarks

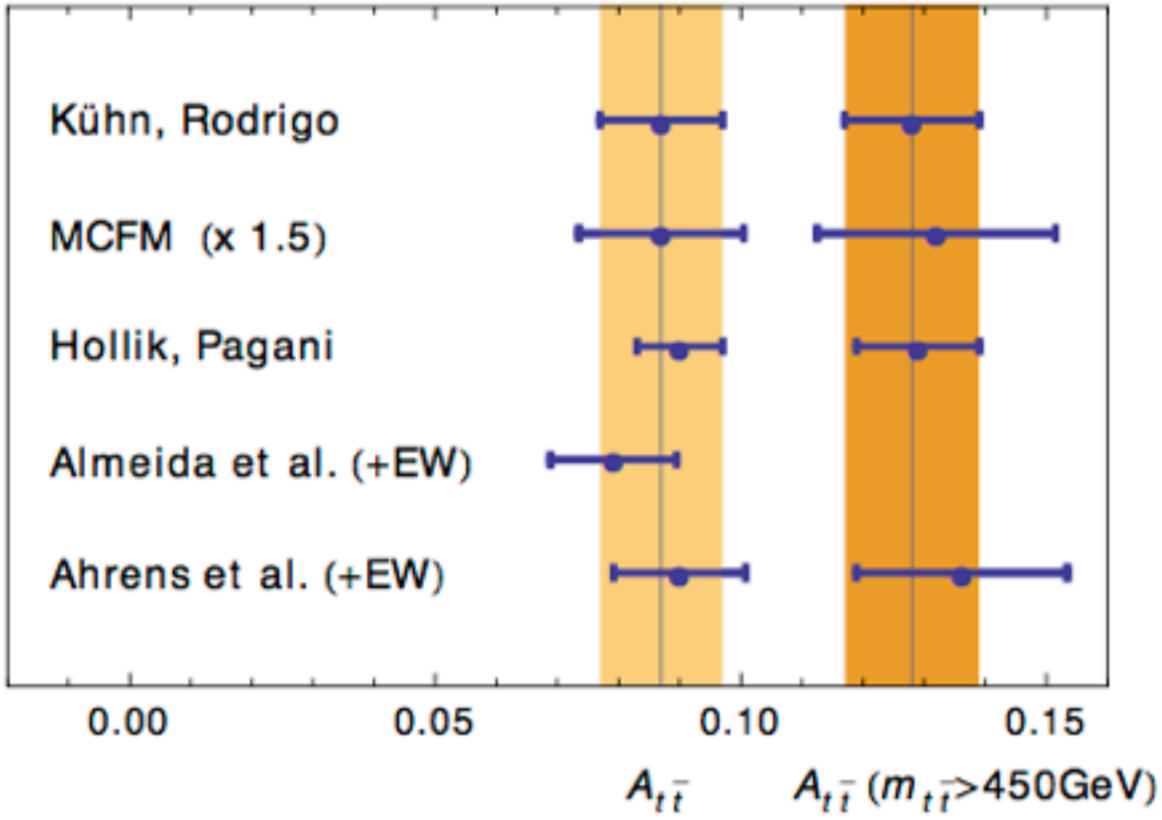
- However asymmetry is generated at 1-loop and can be understood to be due to Coulomb interaction between incoming light quarks and outgoing top quarks



t-tbar forward-backward asymmetry at the Tevatron

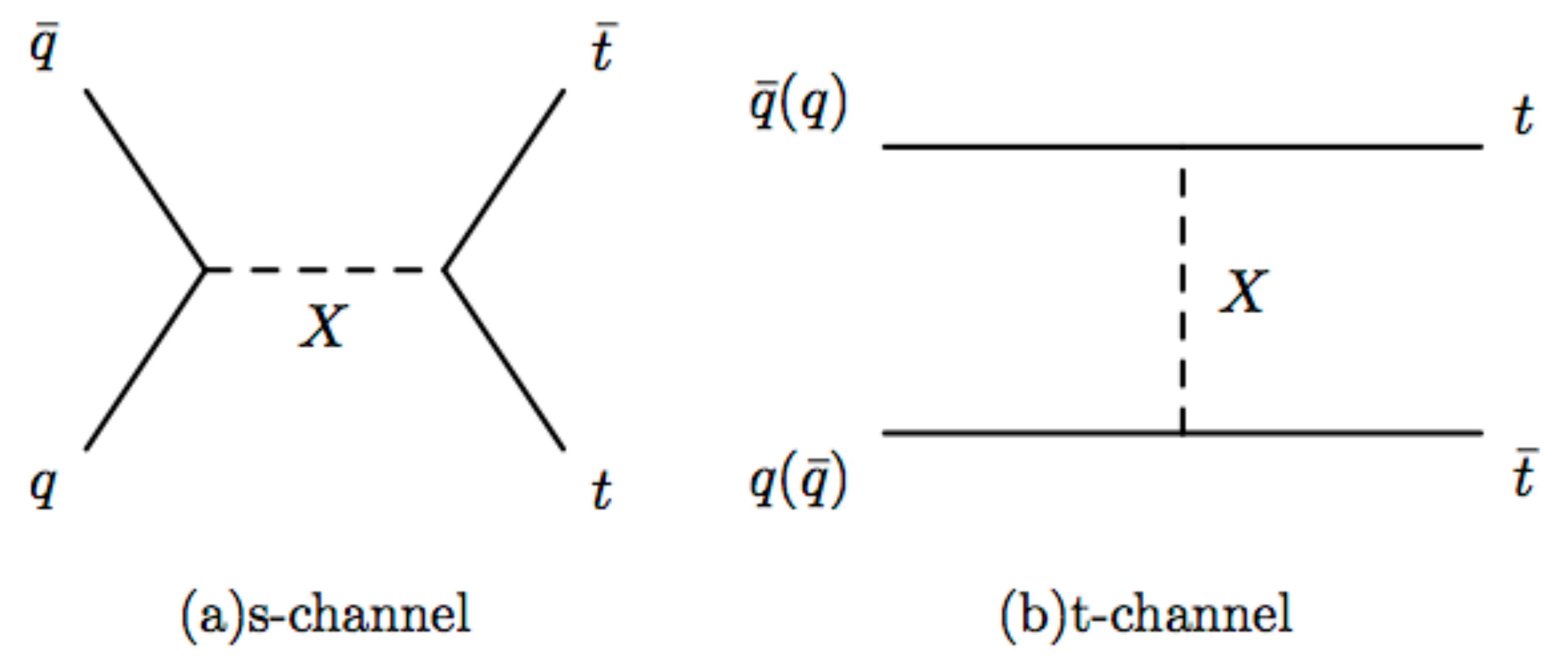


Tevatron	inclusive	$m_{t\bar{t}} < 450$ GeV	$m_{t\bar{t}} > 450$ GeV	$\lvert\Delta y\rvert < 1$	$\lvert\Delta y\rvert > 1$
SM laboratory A_{lab}	0.056 (7)	0.029 (2)	0.102 (9)		
CDF [6]	0.150 (55)	0.059 (34)*	0.103 (49)*		
SM $t\bar{t}$ rest-frame $A_{t\bar{t}}$	0.087 (10)	0.062 (4)	0.128 (11)	0.057 (4)	0.193 (15)
D0 [9]	0.196 (65)	0.078 (48)*	0.115 (60)*	0.061 (41)*	0.213 (97)*
CDF [12]	0.162 (47)	0.078 (54)	0.296 (67)	0.088 (47)	0.433 (109)



from Rodrigo 1207.0331

t-tbar forward-backward asymmetry at the Tevatron

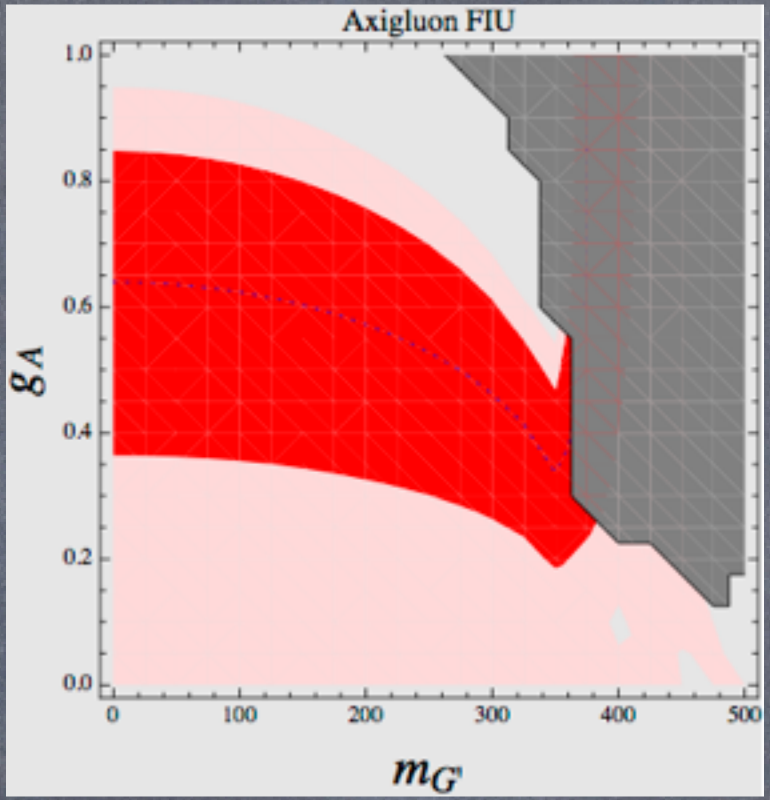


from Knapen et al. 1111.5857

- Asymmetry can be generated by weak scale new physics coupled to quarks in a chiral fashion (different to left- and right-handed quarks)
- 2 main possibilities: flavor conserving s-channel models or flavor violating t-channel models

t-tbar forward-backward asymmetry at the Tevatron

Axigluon example



- The asymmetry measured by CDF and D0 can be fit, for example, by a heavy gluon in the s-channel with an axial flavor-conserving coupling to the up and top quarks.

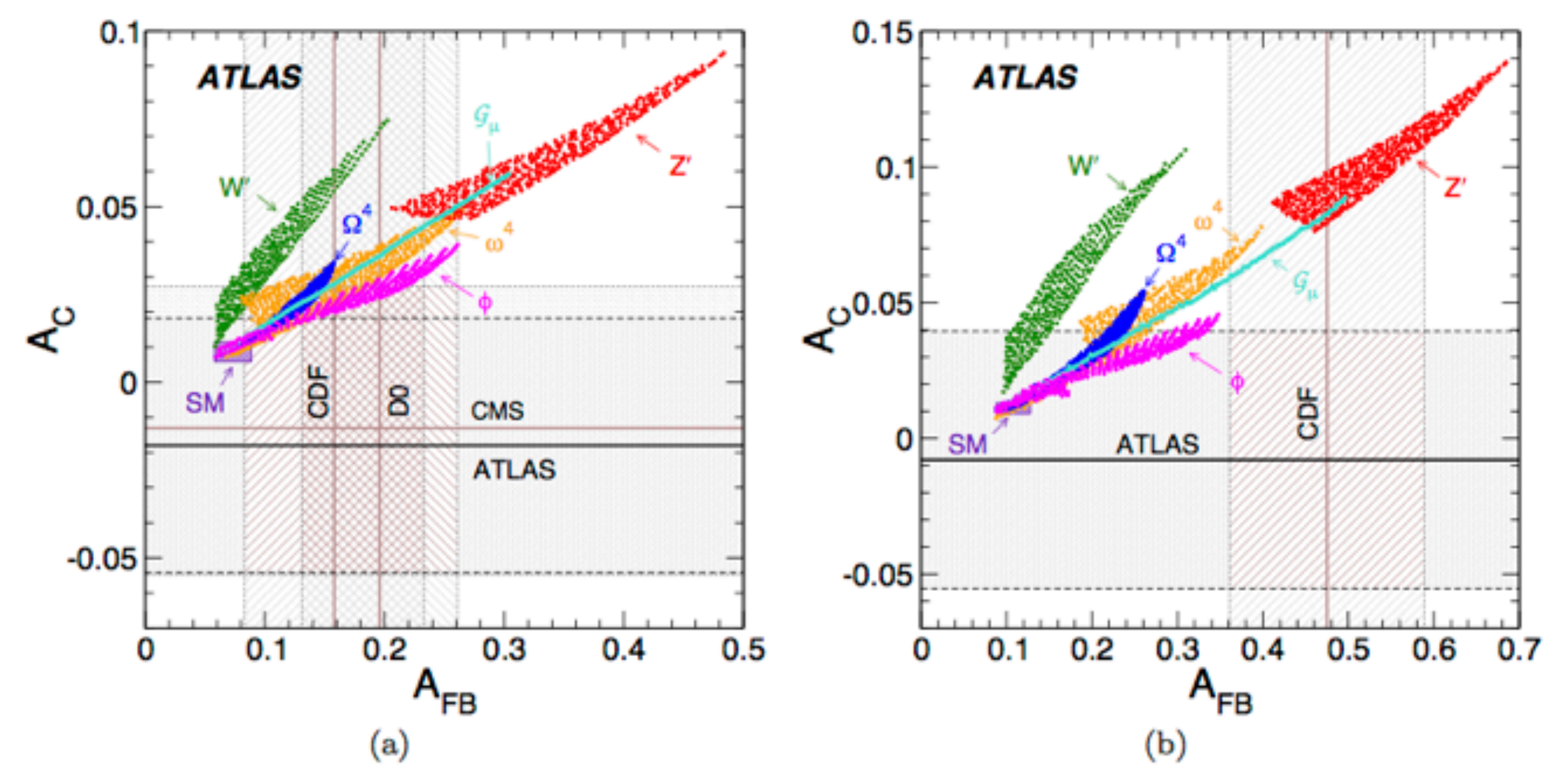
- Parameters allowed by all measurement includes a "light axigluon" region with mass 100-400 GeV and moderate flavor-universal couplings to quarks, or "heavy axigluon" region with mass 2-3 TeV and very large flavor-non-universal couplings to quarks

t-tbar forward-backward asymmetry at the LHC

No obvious forward and backward but one can define the related charge asymmetry

$$A_C^y = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

Unfortunately, no excess at the LHC so far, which constrains all classes of new physics models and excludes some models (especially t-channel Z')



(a)

(b)

t-tbar forward-backward asymmetry at the Tevatron

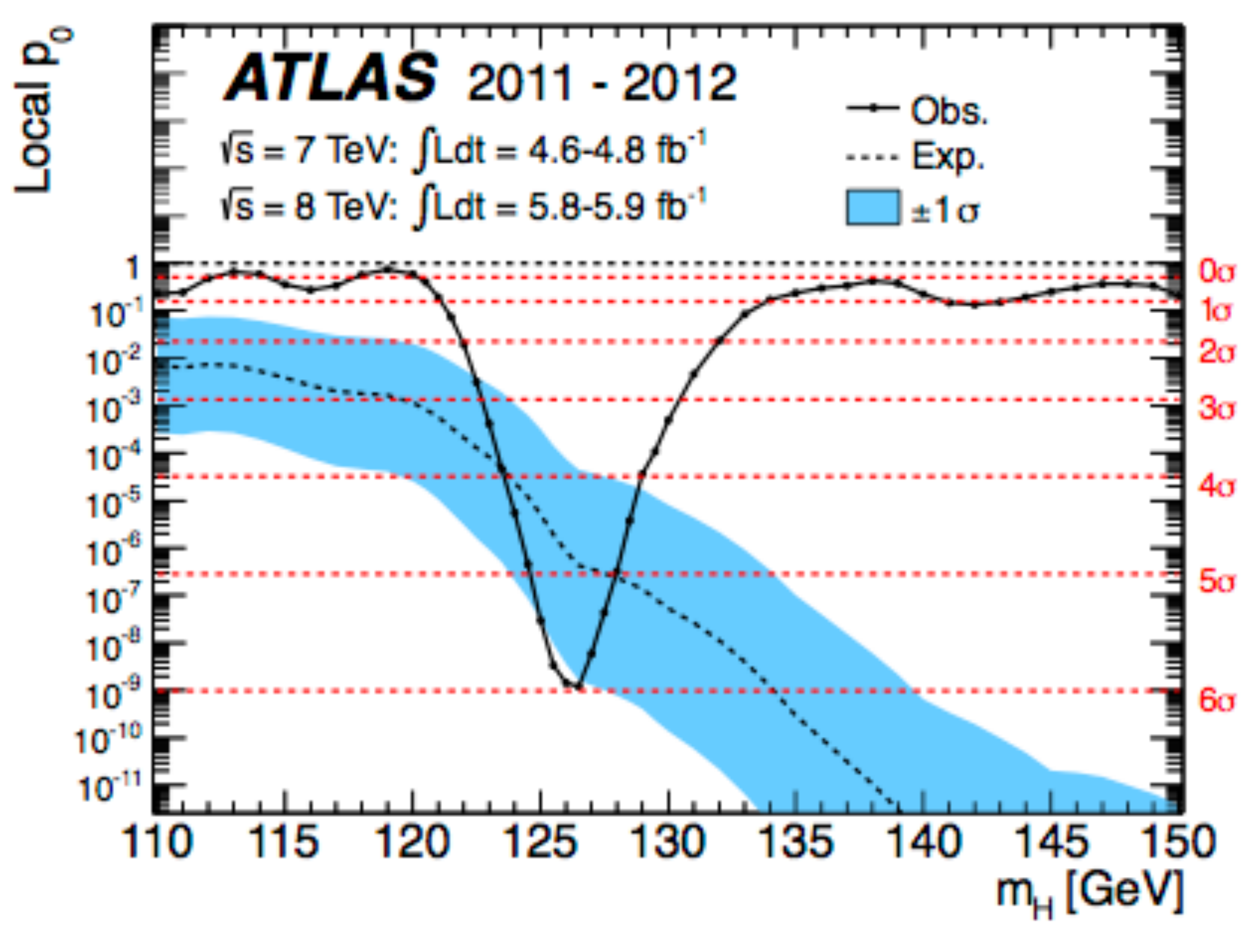
- A fluke?
- A systematic effect?
- Underestimated QCD?
- New physics?

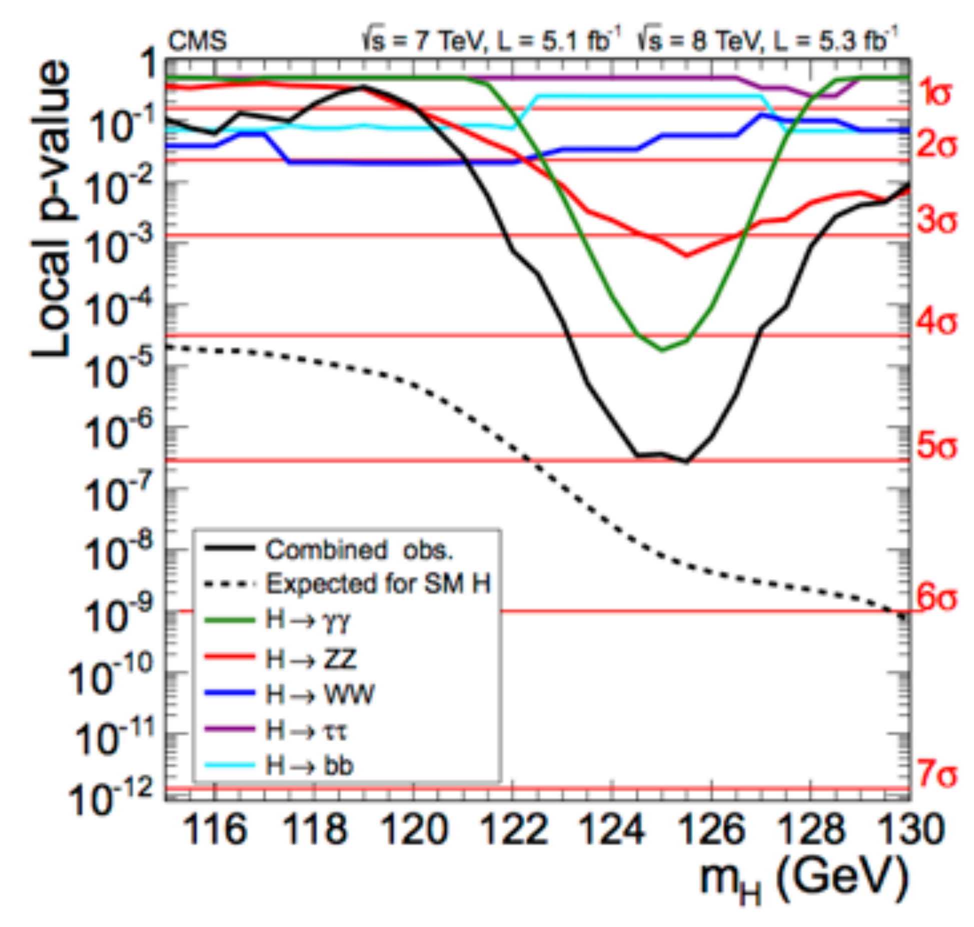
Hopefully, time will tell

Higgs,
the last frontier

Higgs

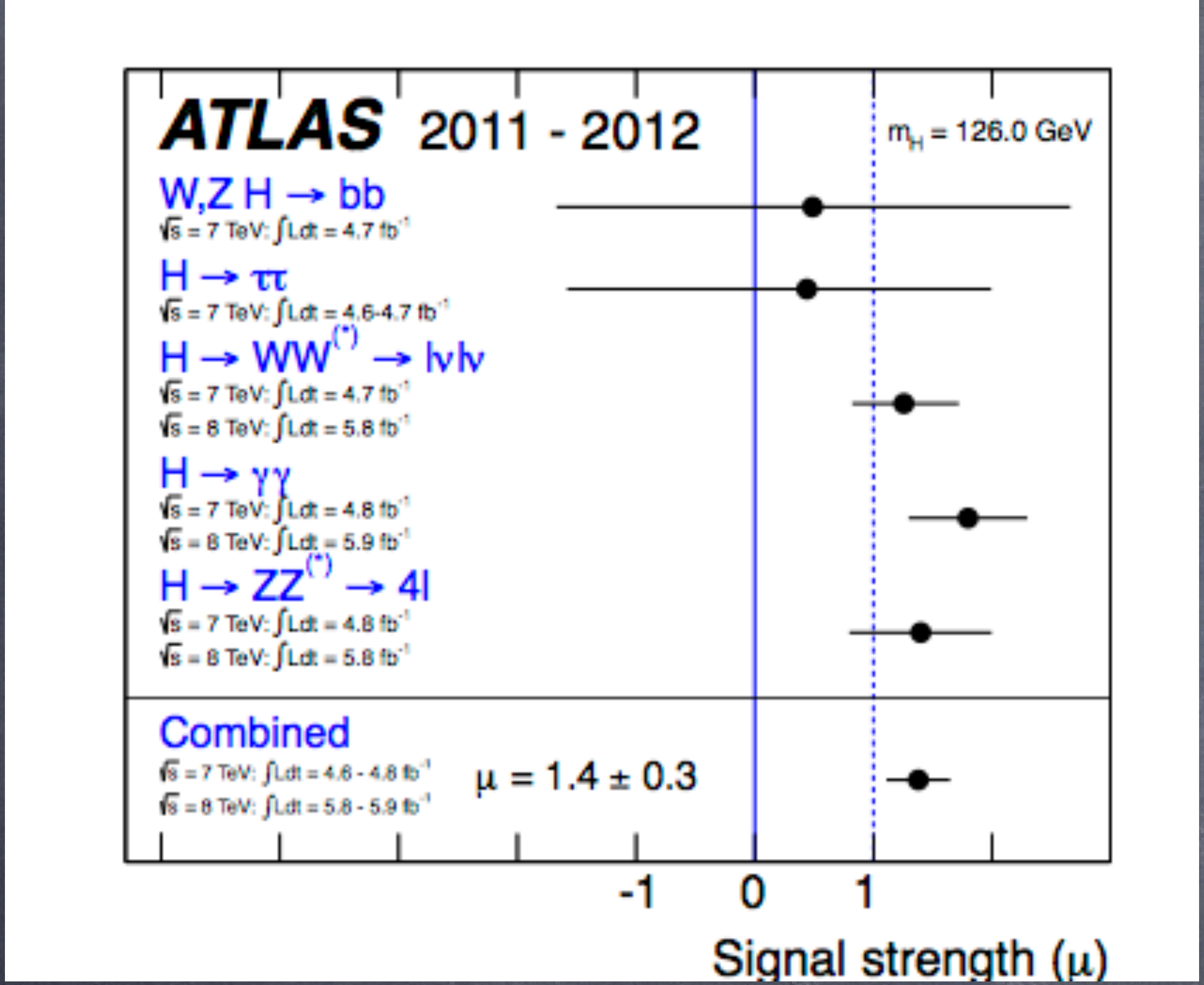
It happened last summer....

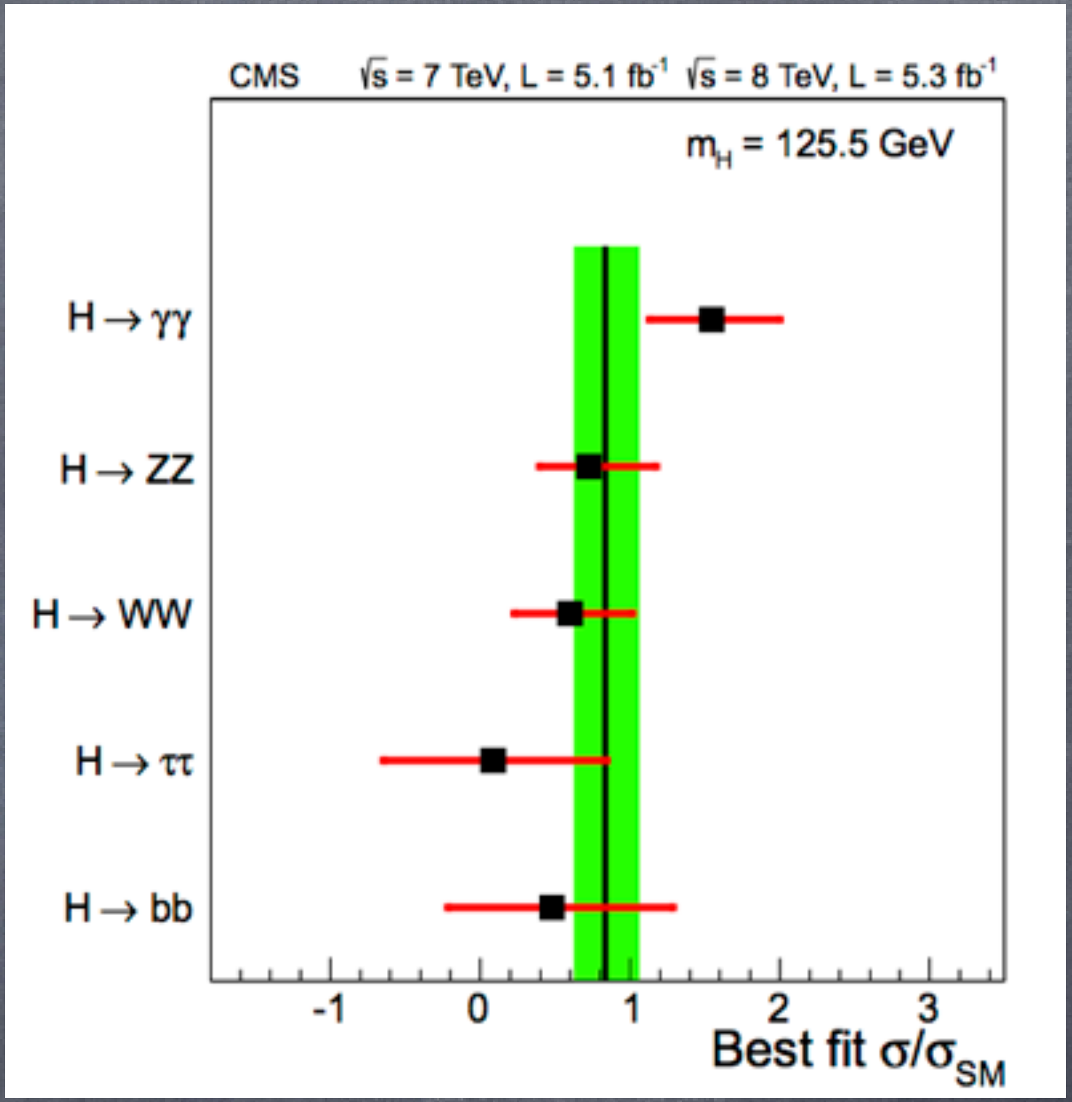




Everyone agrees: Higgs has been discovered

Higgs



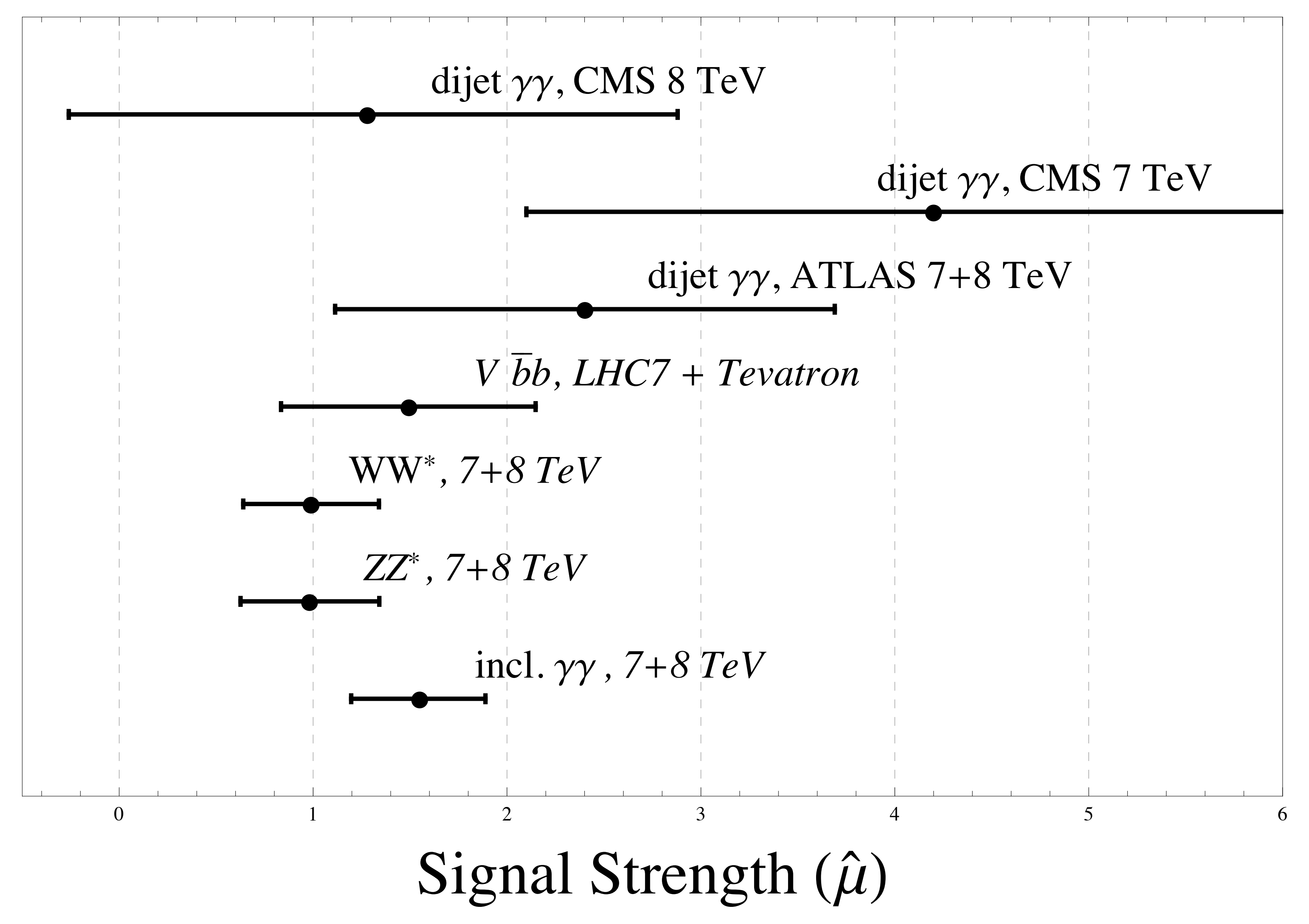


Everyone agrees: Higgs has been discovered

Higgs

Illegal Higgs combination

Carmi et al. 1207.1718



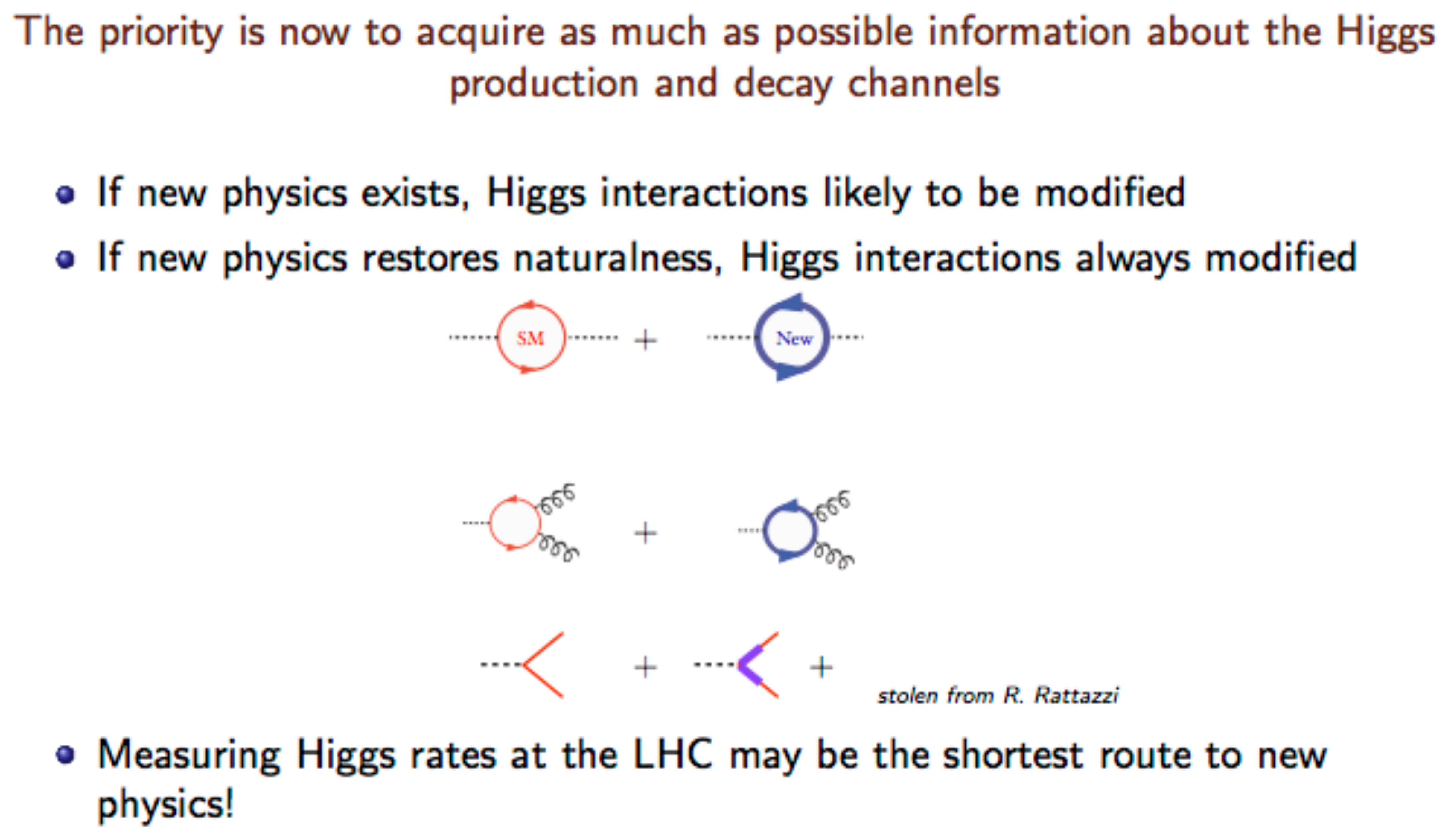
Everyone agrees: Higgs has been discovered

Higgs

Now: is it the SM Higgs?

?

Higgs



The priority is now to acquire as much as possible information about the Higgs production and decay channels

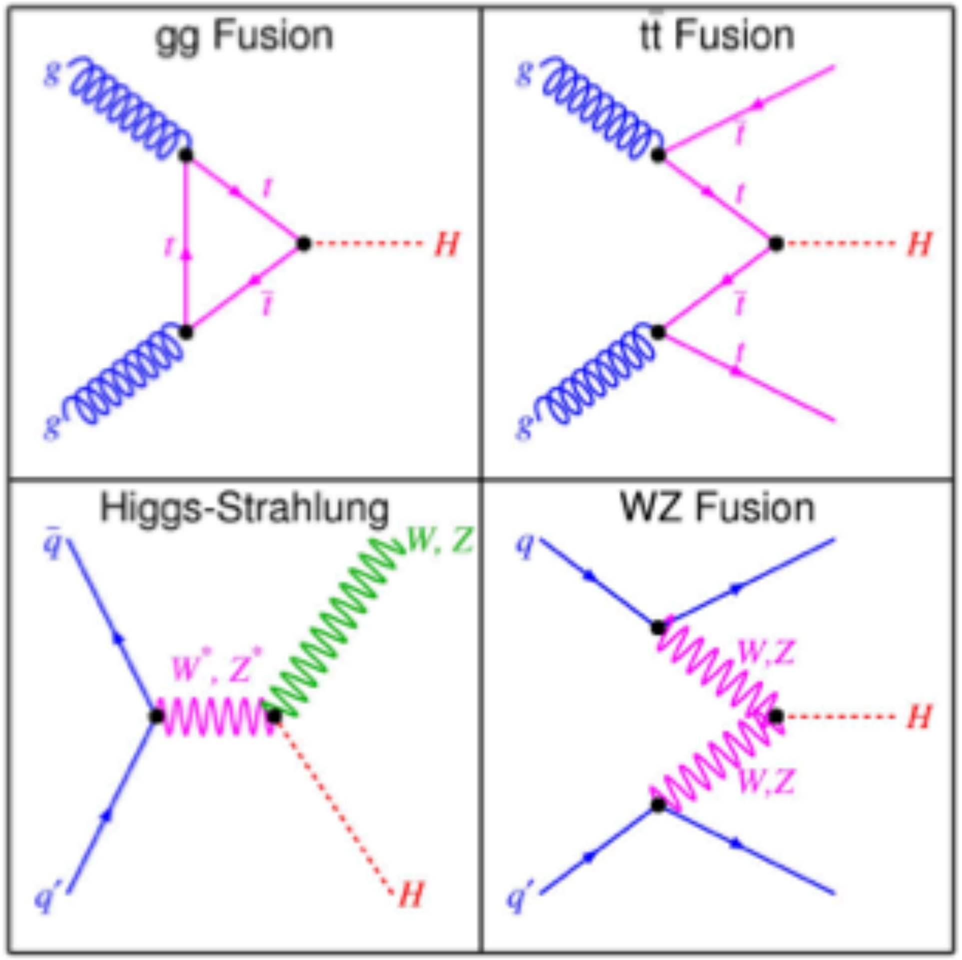
- If new physics exists, Higgs interactions likely to be modified
- If new physics restores naturalness, Higgs interactions always modified

stolen from R. Rattazzi

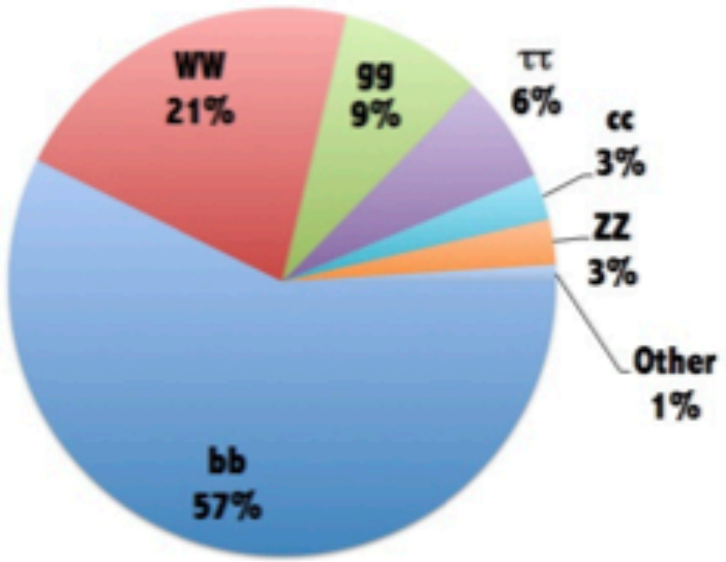
- Measuring Higgs rates at the LHC may be the shortest route to new physics!

Higgs

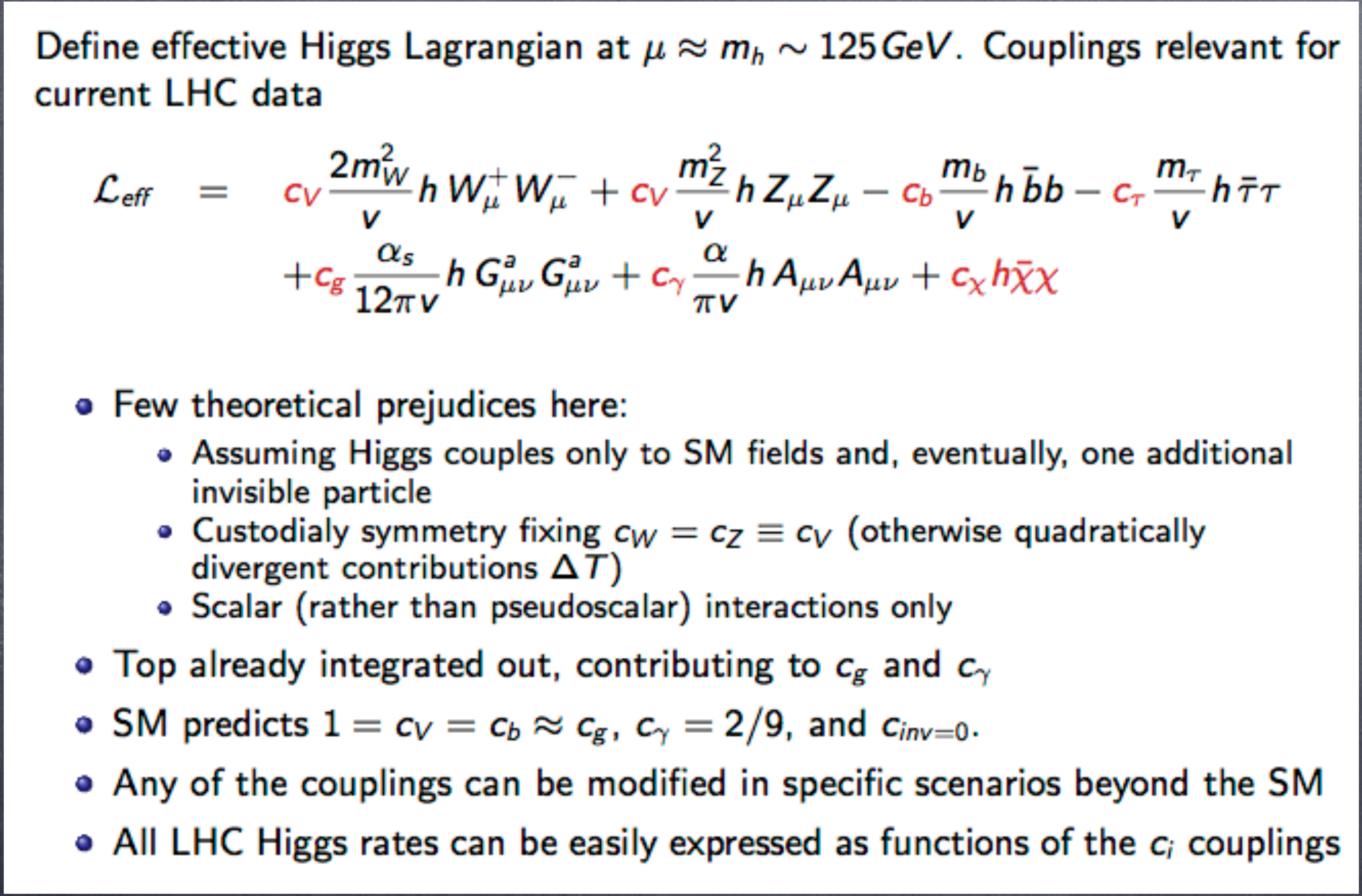
- The SM Higgs with mass $m_h \ll 2m_W$ has many decay channels that are potentially observable at the LHC and Tevatron ($H \to ZZ^*$, $H \to \gamma\gamma$, $H \to b\bar{b}$ $H \to WW^*$, $H \to \tau^+\tau^-$).
- Also different production channels can be isolated (gluon fusion, vector boson fusion, W/Z and $t\bar{t}$ associated production)
- Rich Higgs physics available in near future!



Higgs decays at m_H=125GeV



Higgs

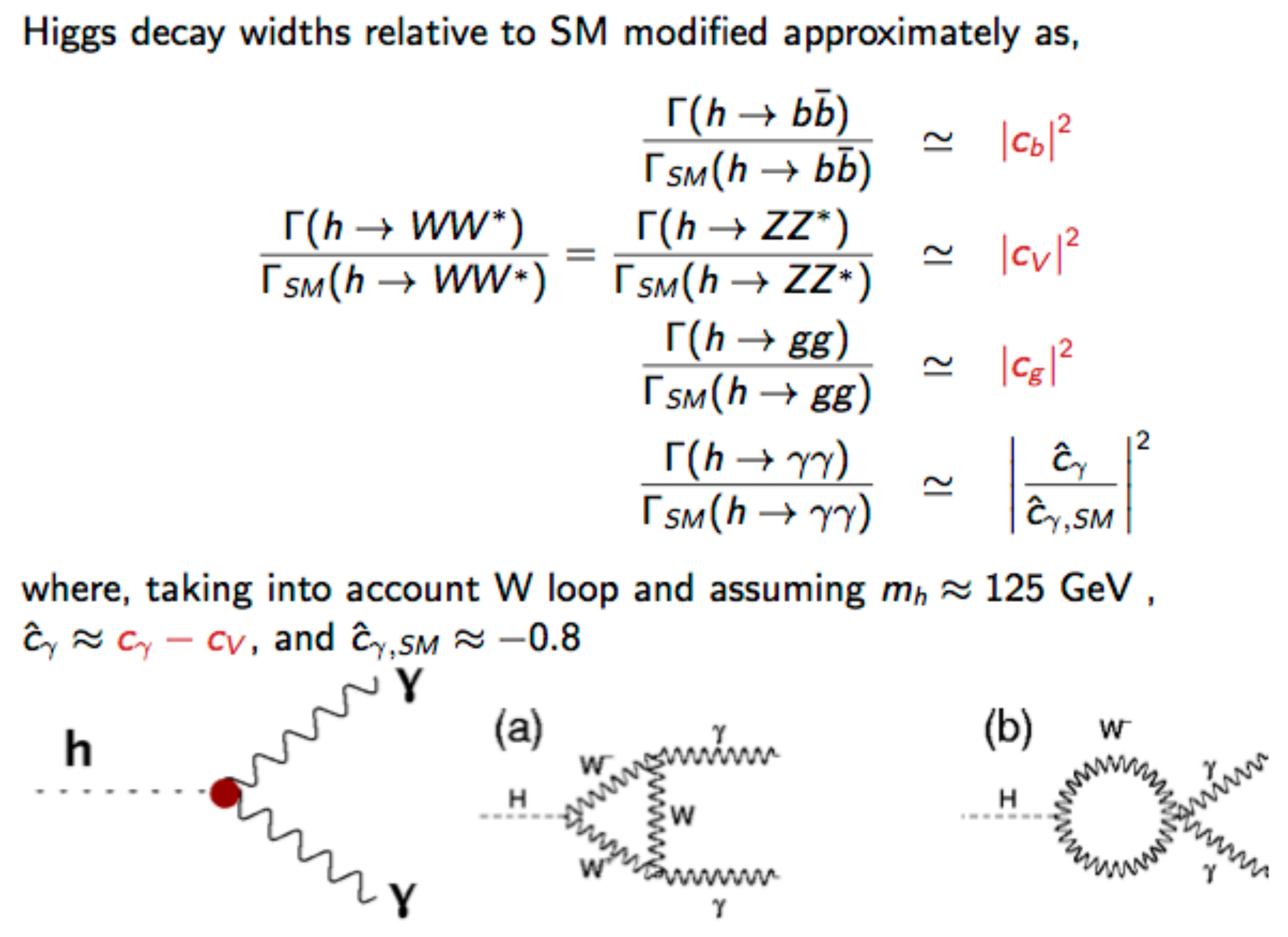


Define effective Higgs Lagrangian at $\mu \approx m_h \sim 125\,GeV$. Couplings relevant for current LHC data

$$\begin{aligned}\mathcal{L}_{eff} \quad = \quad & c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b}b - c_\tau \frac{m_\tau}{v} h\, \bar{\tau}\tau \\ & + c_g \frac{\alpha_s}{12\pi v} h\, G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \frac{\alpha}{\pi v} h\, A_{\mu\nu} A_{\mu\nu} + c_\chi h \bar{\chi}\chi\end{aligned}$$

- Few theoretical prejudices here:
  - Assuming Higgs couples only to SM fields and, eventually, one additional invisible particle
  - Custodialy symmetry fixing $c_W = c_Z \equiv c_V$ (otherwise quadratically divergent contributions ΔT)
  - Scalar (rather than pseudoscalar) interactions only
- Top already integrated out, contributing to c_g and c_γ
- SM predicts $1 = c_V = c_b \approx c_g$, $c_\gamma = 2/9$, and $c_{inv=0}$.
- Any of the couplings can be modified in specific scenarios beyond the SM
- All LHC Higgs rates can be easily expressed as functions of the c_i couplings

Higgs

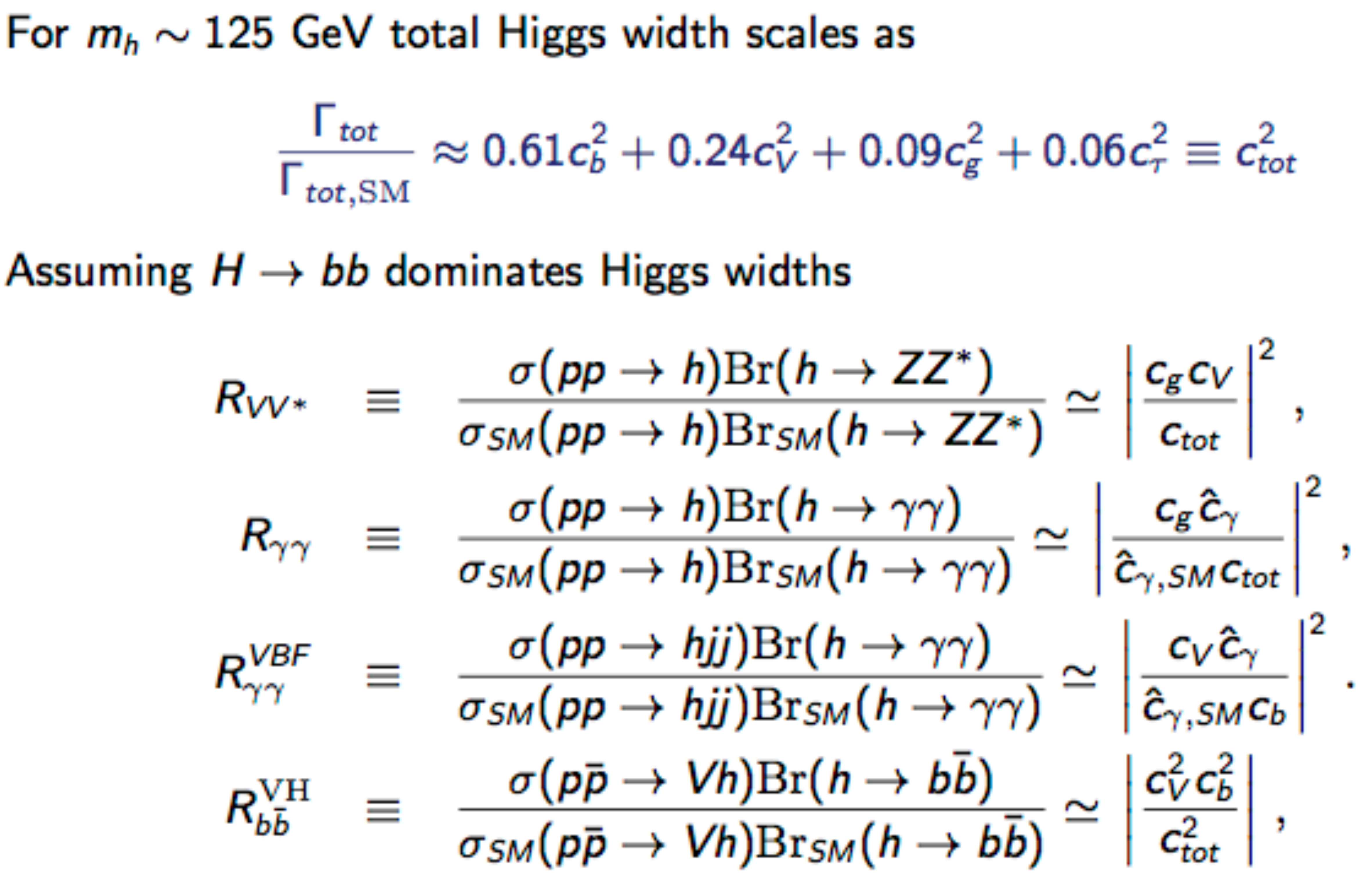


Higgs decay widths relative to SM modified approximately as,

$$\begin{aligned} \frac{\Gamma(h \to b\bar{b})}{\Gamma_{SM}(h \to b\bar{b})} &\simeq |c_b|^2 \\ \frac{\Gamma(h \to WW^*)}{\Gamma_{SM}(h \to WW^*)} = \frac{\Gamma(h \to ZZ^*)}{\Gamma_{SM}(h \to ZZ^*)} &\simeq |c_V|^2 \\ \frac{\Gamma(h \to gg)}{\Gamma_{SM}(h \to gg)} &\simeq |c_g|^2 \\ \frac{\Gamma(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)} &\simeq \left|\frac{\hat{c}_\gamma}{\hat{c}_{\gamma,SM}}\right|^2 \end{aligned}$$

where, taking into account W loop and assuming $m_h \approx 125$ GeV , $\hat{c}_\gamma \approx c_\gamma - c_V$, and $\hat{c}_{\gamma,SM} \approx -0.8$

Higgs



For $m_h \sim 125$ GeV total Higgs width scales as

$$\frac{\Gamma_{tot}}{\Gamma_{tot,\mathrm{SM}}} \approx 0.61c_b^2 + 0.24c_V^2 + 0.09c_g^2 + 0.06c_\tau^2 \equiv c_{tot}^2$$

Assuming $H \to bb$ dominates Higgs widths

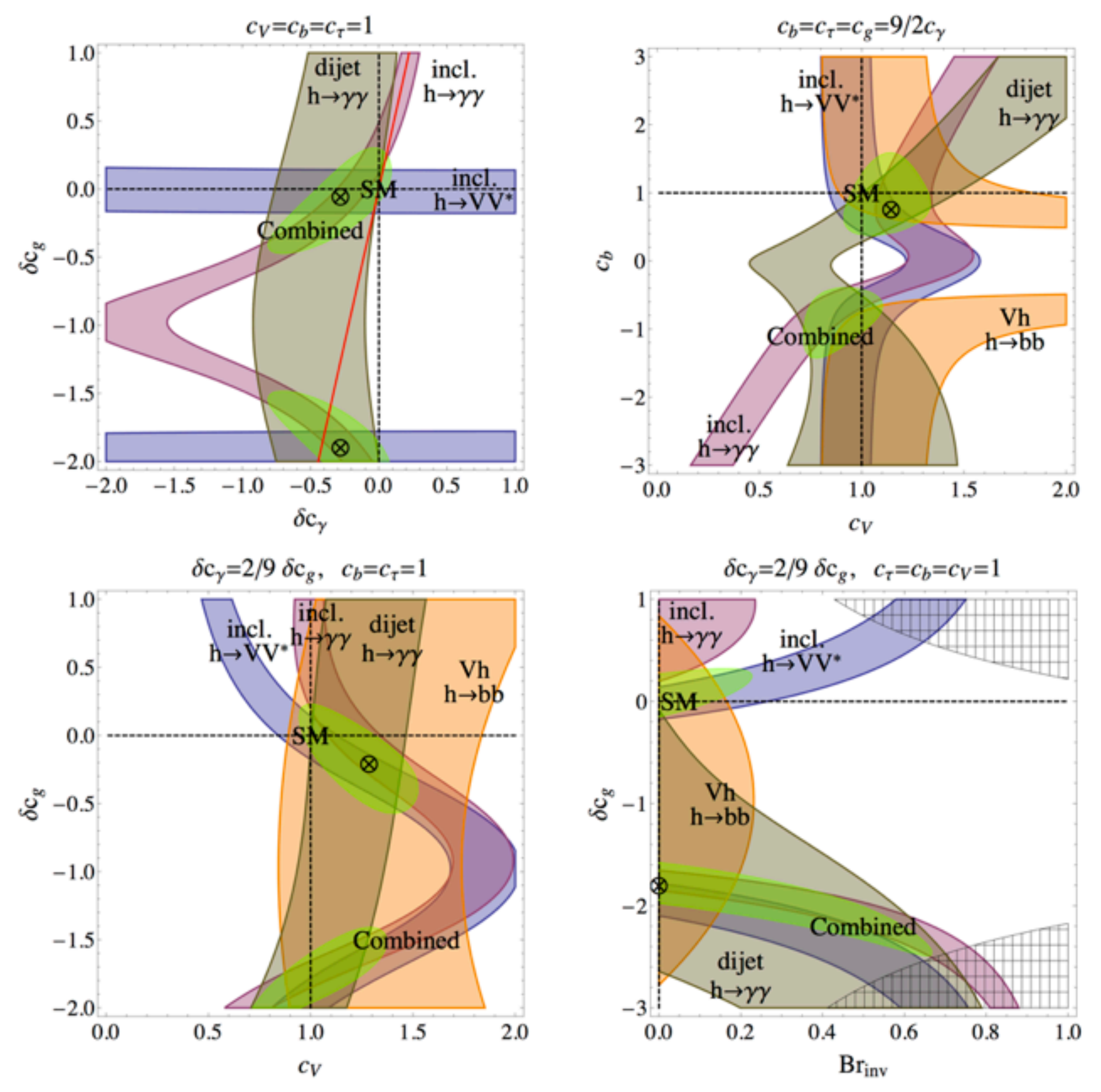
$$\begin{aligned}
R_{VV^*} &\equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to ZZ^*)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to ZZ^*)} \simeq \left|\frac{c_g c_V}{c_{tot}}\right|^2 , \\
R_{\gamma\gamma} &\equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to \gamma\gamma)} \simeq \left|\frac{c_g \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_{tot}}\right|^2 , \\
R_{\gamma\gamma}^{VBF} &\equiv \frac{\sigma(pp \to hjj)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to hjj)\mathrm{Br}_{SM}(h \to \gamma\gamma)} \simeq \left|\frac{c_V \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_b}\right|^2 . \\
R_{b\bar{b}}^{\mathrm{VH}} &\equiv \frac{\sigma(p\bar{p} \to Vh)\mathrm{Br}(h \to b\bar{b})}{\sigma_{SM}(p\bar{p} \to Vh)\mathrm{Br}_{SM}(h \to b\bar{b})} \simeq \left|\frac{c_V^2 c_b^2}{c_{tot}^2}\right| ,
\end{aligned}$$

Higgs

$$\mathcal{L}_{\text{eff}} = c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b} b - c_b \frac{m_\tau}{v} h\, \bar{\tau}\tau$$
$$+ c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^a_{\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h\, A_{\mu\nu} A_{\mu\nu}$$

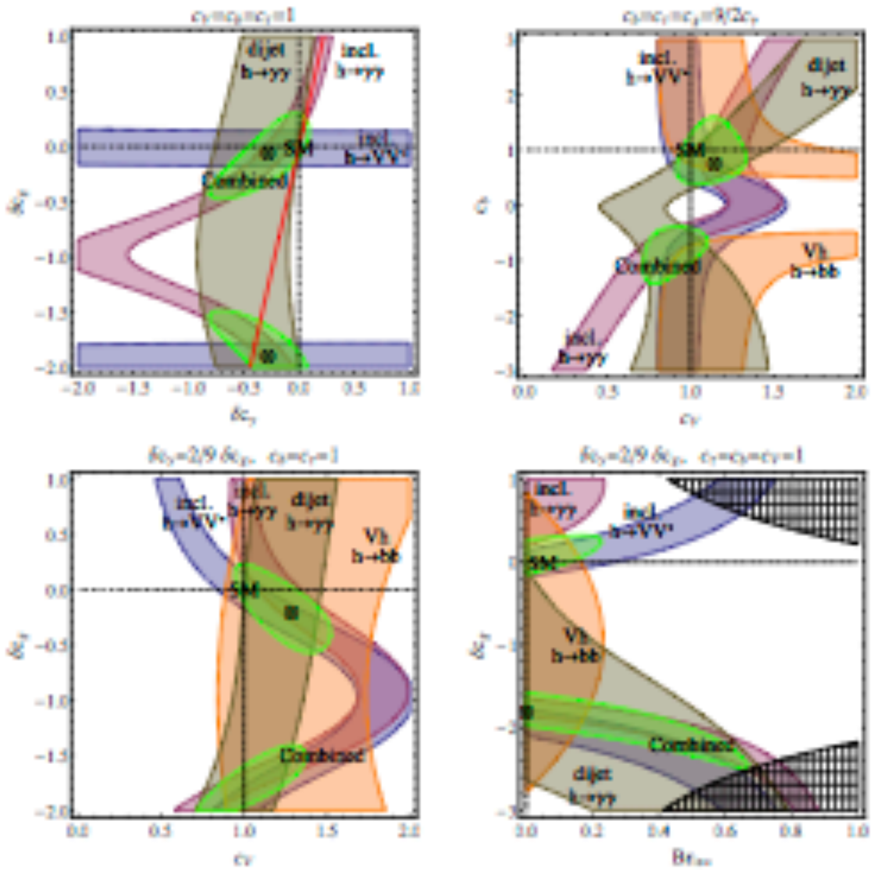
- Carmi+ [1202.3144] : determine the region of effective theory parameter space favored by current Higgs data
- Question whether the current LHC data are consistent with the SM Higgs
- Question whether they favor or disfavor any particular BSM scenario
- Of course at this stage one cannot make very strong statements about Higgs couplings
- Consider it warm-up exercise in preparation for better statistics
- Recently similar approach in Azatov+ [1202.3415] , Espinosa+ [1202.3697] , Giardino+ [1203.4254] , Rauch [1203.6826] , Ellis and You [1204.0464] , Farina+ [1205.0011] , Klute+ [1205.2699]

Higgs



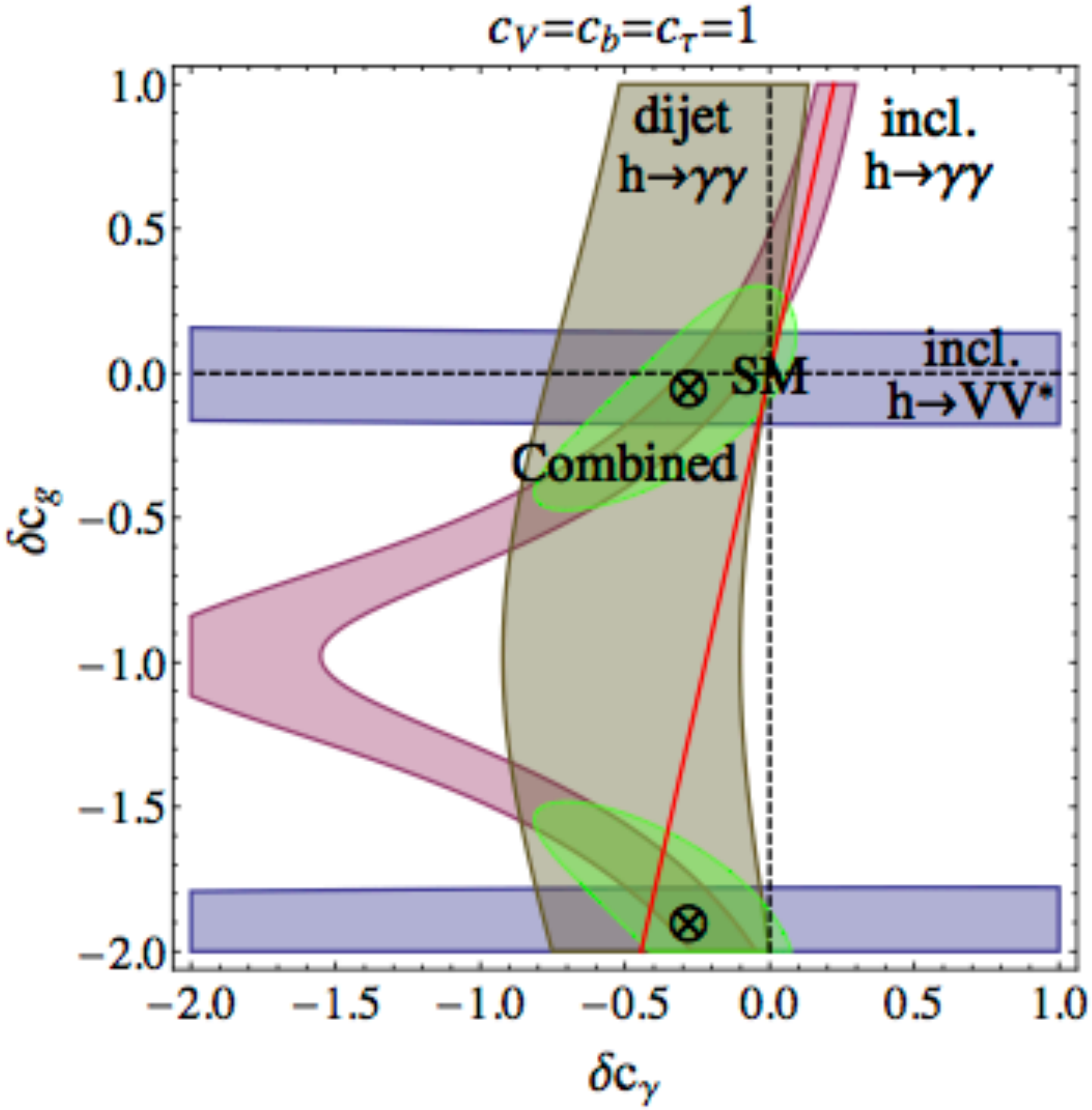
$c_V=c_b=c_\tau=1$
dijet h→γγ
incl. h→γγ
incl. h→VV*
SM
Combined
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0
δc_g
δc_γ
$c_b=c_\tau=c_g=9/2c_\gamma$
incl. h→VV*
dijet h→γγ
SM
Combined
Vh h→bb
incl. h→γγ
3 2 1 0 −1 −2 −3
0.0 0.5 1.0 1.5 2.0
c_b
c_V
$\delta c_\gamma=2/9\ \delta c_g,\ \ c_b=c_\tau=1$
incl. h→VV*
incl. h→γγ
dijet h→γγ
Vh h→bb
SM
Combined
1.0 0.5 0.0 −0.5 −1.0 −1.5 −2.0
0.0 0.5 1.0 1.5 2.0
δc_g
c_V
$\delta c_\gamma=2/9\ \delta c_g,\ \ c_\tau=c_b=c_V=1$
incl. h→γγ
incl. h→VV*
SM
Vh h→bb
Combined
dijet h→γγ
1 0 −1 −2 −3
0.0 0.2 0.4 0.6 0.8 1.0
δc_g
$\mathrm{Br}_{\mathrm{inv}}$

Higgs



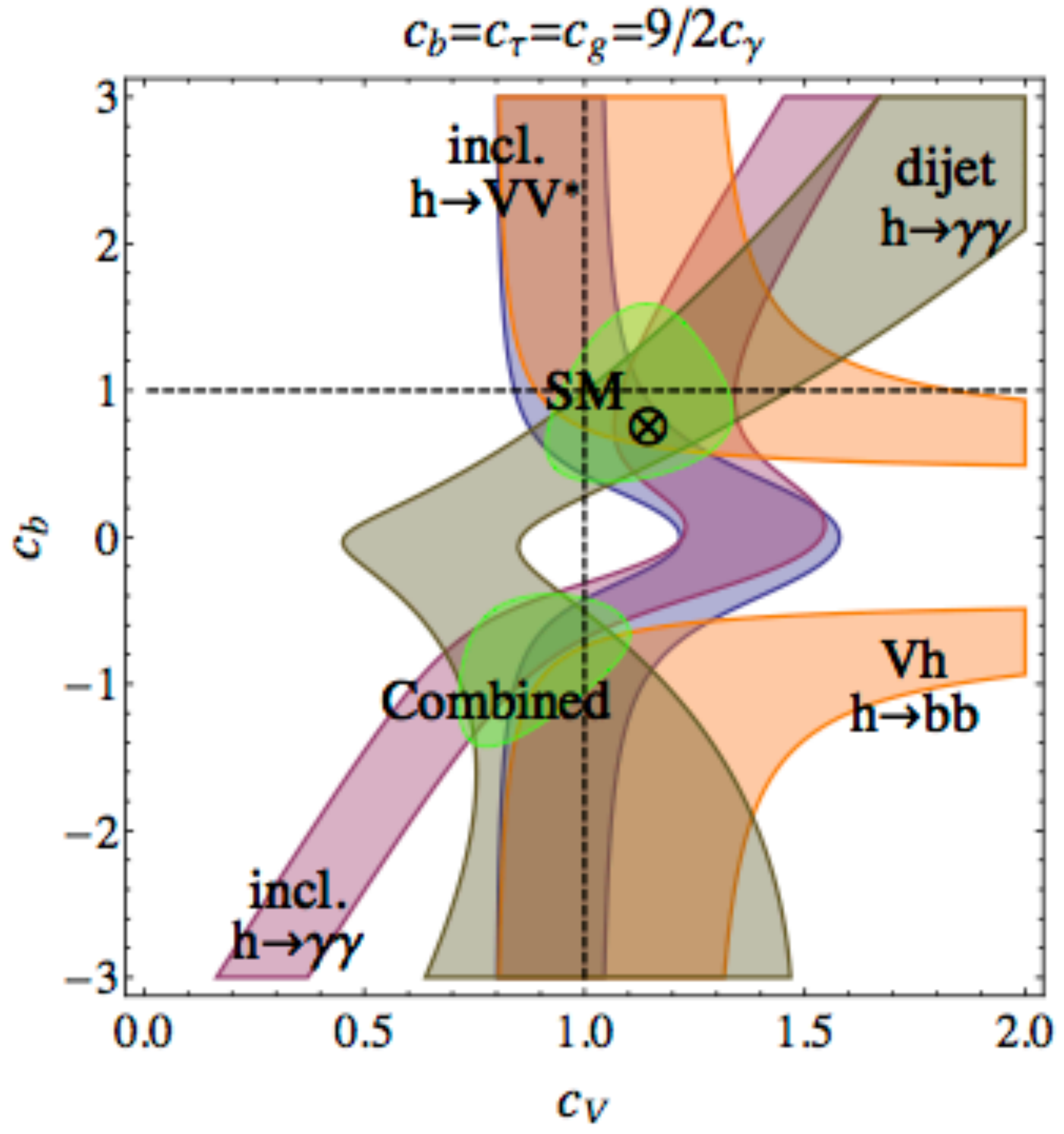
- We consider 2D planes in the parameter space
- Fixing all but 2 parameters (not marginalizing over) and fitting the remaing 2
- 1 sigma bands for 5 most sensitive search channels shown
- Combined = $\Delta\chi^2 < 6$, corresponding to 95% CL for 2 degrees of freedom

Higgs



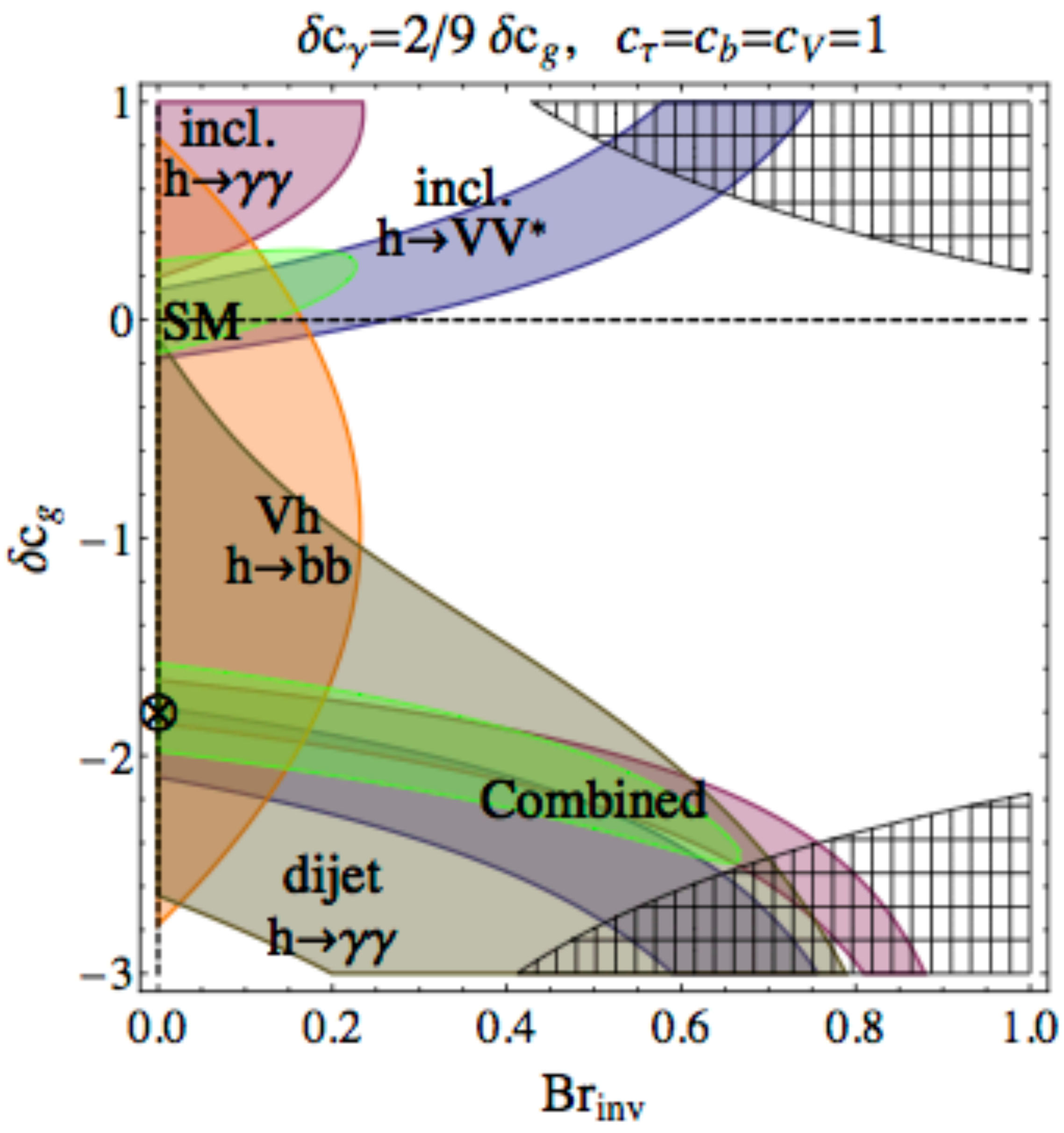
- Only dimension-5 Higgs couplings allowed to vary (motivated if new physics enters only via loops)
- On this plane, no impact on the $VH \to b\bar{b}$
- Good fit if the c_g and c_γ simultaneously lowered

Higgs



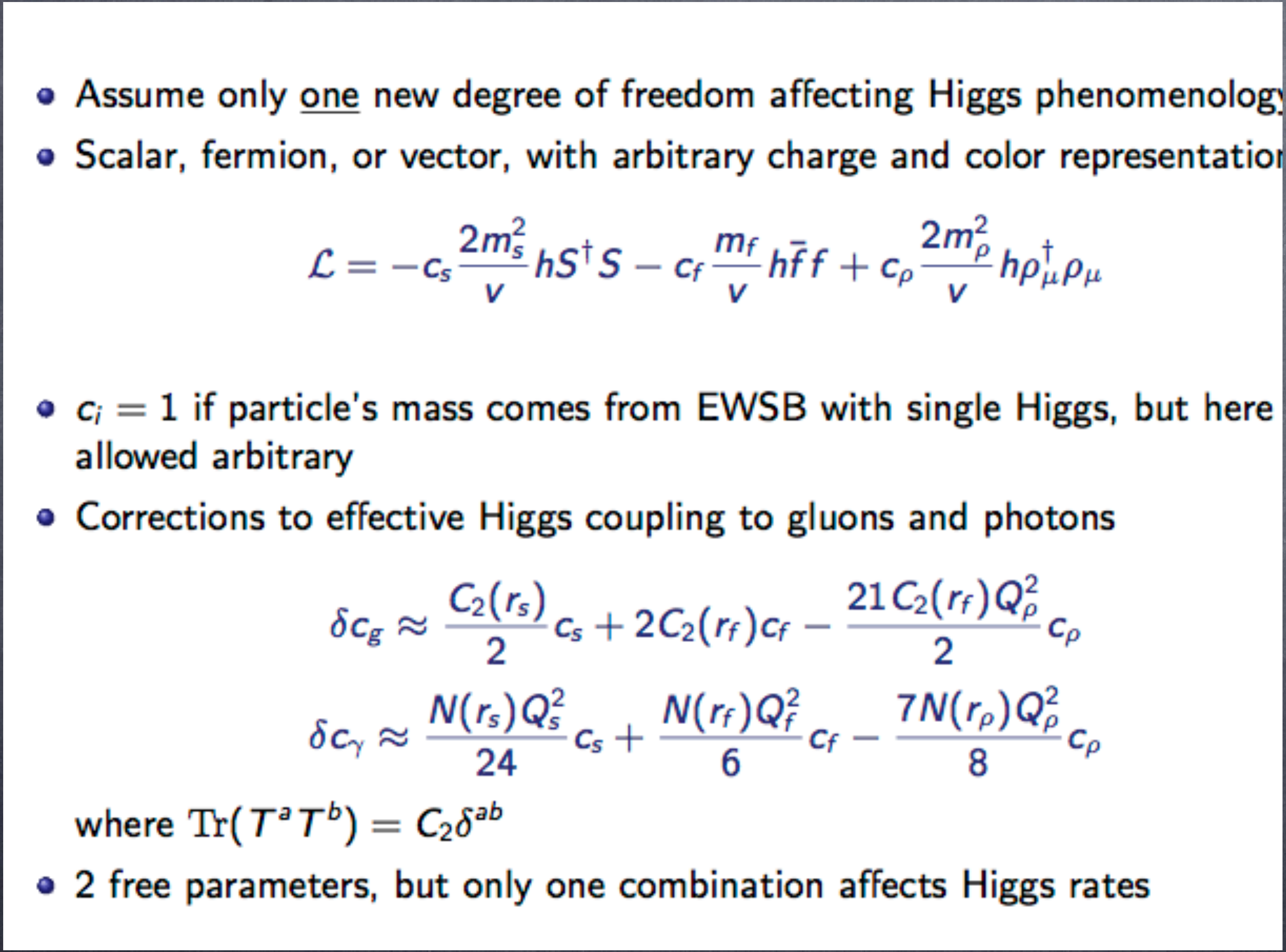
- Composite Higgs inspired parametrization (but couplings to fermions and gauge boson allowed to vary independently)
- Fermiophobic Higgs ($c_b = 0$) disfavored
- Apart from SM-like Higgs, another favored region where sign of Higgs coupling to fermions flipped

Higgs



- Allowing invisible width and simultaneously corrections to effective Higgs couplngs to gluons
- If Higgs coupling to gluons at SM value, $\mathrm{Br}_{inv} > 20\%$ disfavored.
- But a large branching fractions still possible if conspiracy holds (Higgs production increased, but the excess going into invisble, so visible rates not much affected)

Higgs



- Assume only <u>one</u> new degree of freedom affecting Higgs phenomenolog
- Scalar, fermion, or vector, with arbitrary charge and color representatio

$$\mathcal{L} = -c_s \frac{2m_s^2}{v} h S^\dagger S - c_f \frac{m_f}{v} h \bar{f} f + c_\rho \frac{2m_\rho^2}{v} h \rho_\mu^\dagger \rho_\mu$$

- $c_i = 1$ if particle's mass comes from EWSB with single Higgs, but here allowed arbitrary
- Corrections to effective Higgs coupling to gluons and photons

$$\delta c_g \approx \frac{C_2(r_s)}{2} c_s + 2C_2(r_f) c_f - \frac{21 C_2(r_f) Q_\rho^2}{2} c_\rho$$

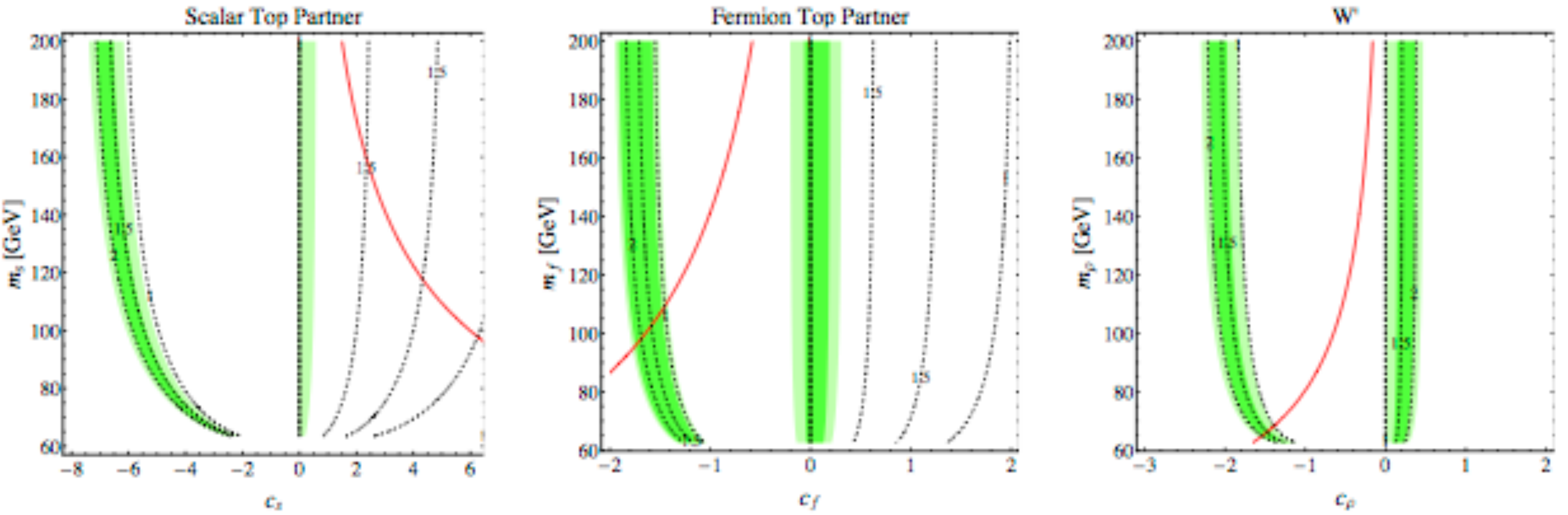
$$\delta c_\gamma \approx \frac{N(r_s) Q_s^2}{24} c_s + \frac{N(r_f) Q_f^2}{6} c_f - \frac{7 N(r_\rho) Q_\rho^2}{8} c_\rho$$

where $\mathrm{Tr}(T^a T^b) = C_2 \delta^{ab}$

- 2 free parameters, but only one combination affects Higgs rates

Higgs

- Best fit regions for scalar top partner, fermionic top partner, and uncharged vector
- Red line is where the new degree of freedom restores naturalness of the SM



Higgs

- Beginning of a beautiful friendship
- More Higgs data from LHC may favor/disfavor particular BSM scenarios...
- ...or just confirm the SM again

That's it

Physics beyond the Standard Model is (mostly) concerned with things that don't exist

Currently there is no serious hints of new physics at the LHC energies

However, we know for sure that there is physics beyond the Standard Model

It's an extremely high-gain game so we need to leave no stone unturned