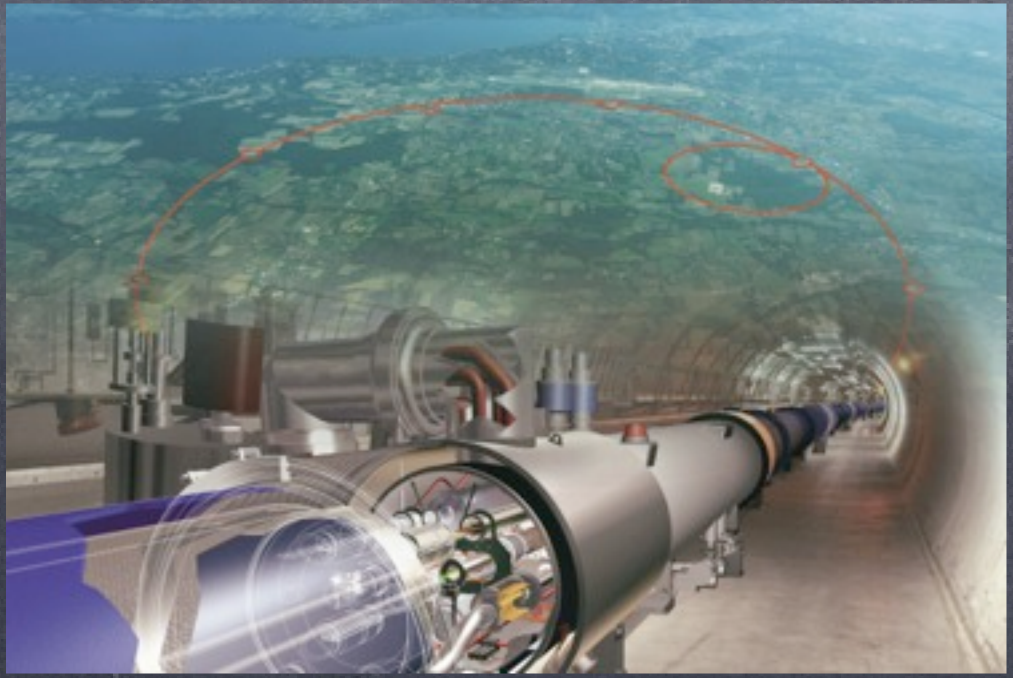
Adam Falkowski

Introduction to Physics beyond the Standard Model

Part 5: LHC Searches for Physics Beyond the Standard Model

Osaka, 22 May 2014



Phenomenological Reasons
For Physics Beyond the Standard Model

- Neutrino Oscillations
- Dark Matter ?
- Inflation
- Baryon Asymmetry

No direct connection between new physics and LHC

Esthetic Reasons
For Physics Beyond the Standard Model

- Fermion generation structure and mass/mixing hierarchies
- Vacuum metastability
- Gauge coupling unification
- Strong CP problem
- Naturalness problem

Only argument directly connecting NP to LHC

… 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

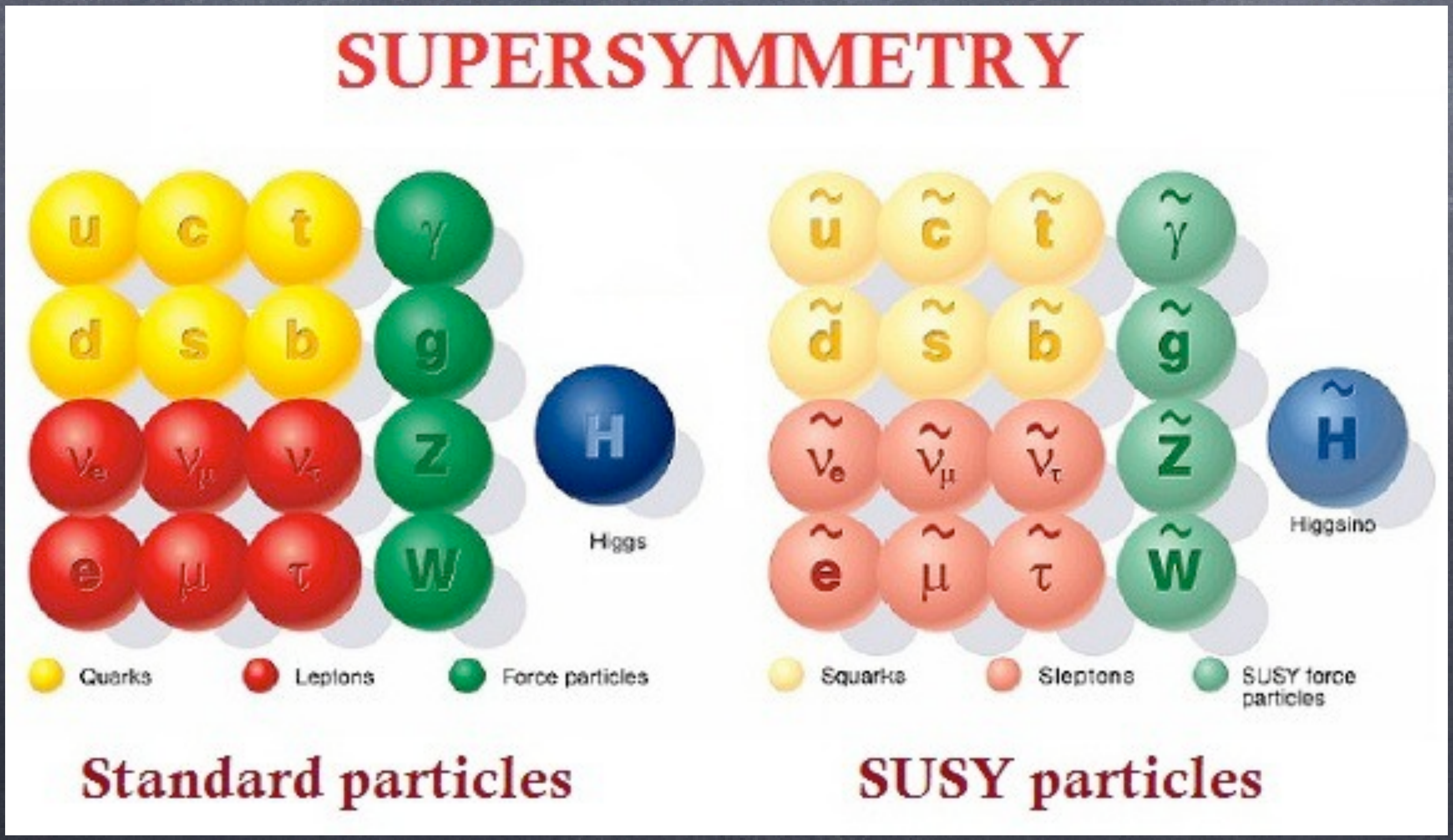
From Colin Bernet

- 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

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

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

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

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

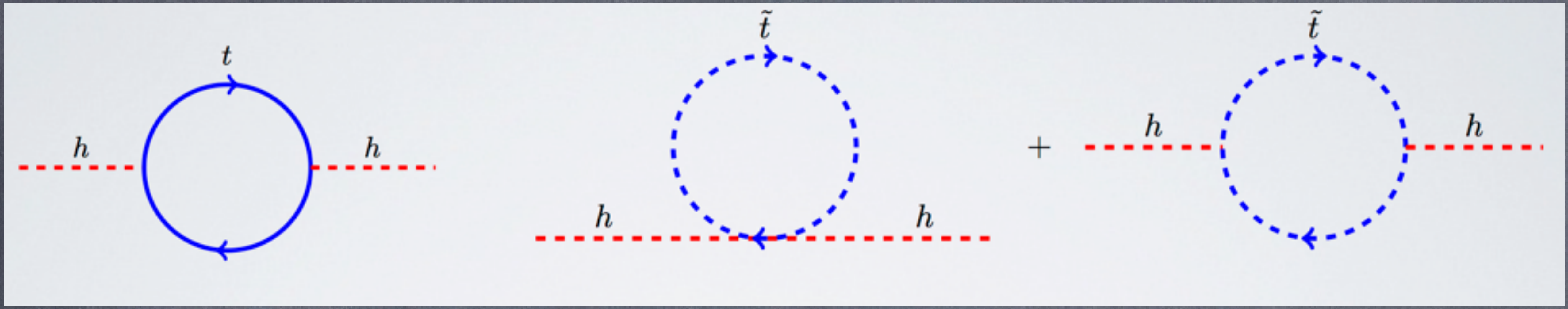
Independent of |H|, irrelevant for Higgs potential
thus no quadratically divergent corrections to Higgs mass

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

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

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

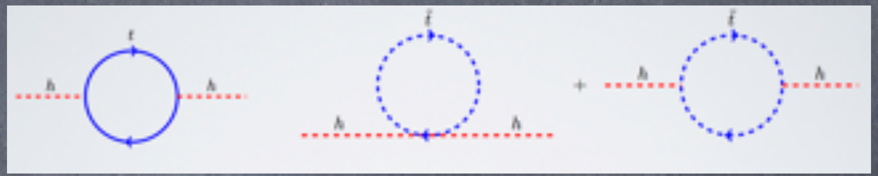
The Higgs mass in minimal supersymmetry

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



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

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

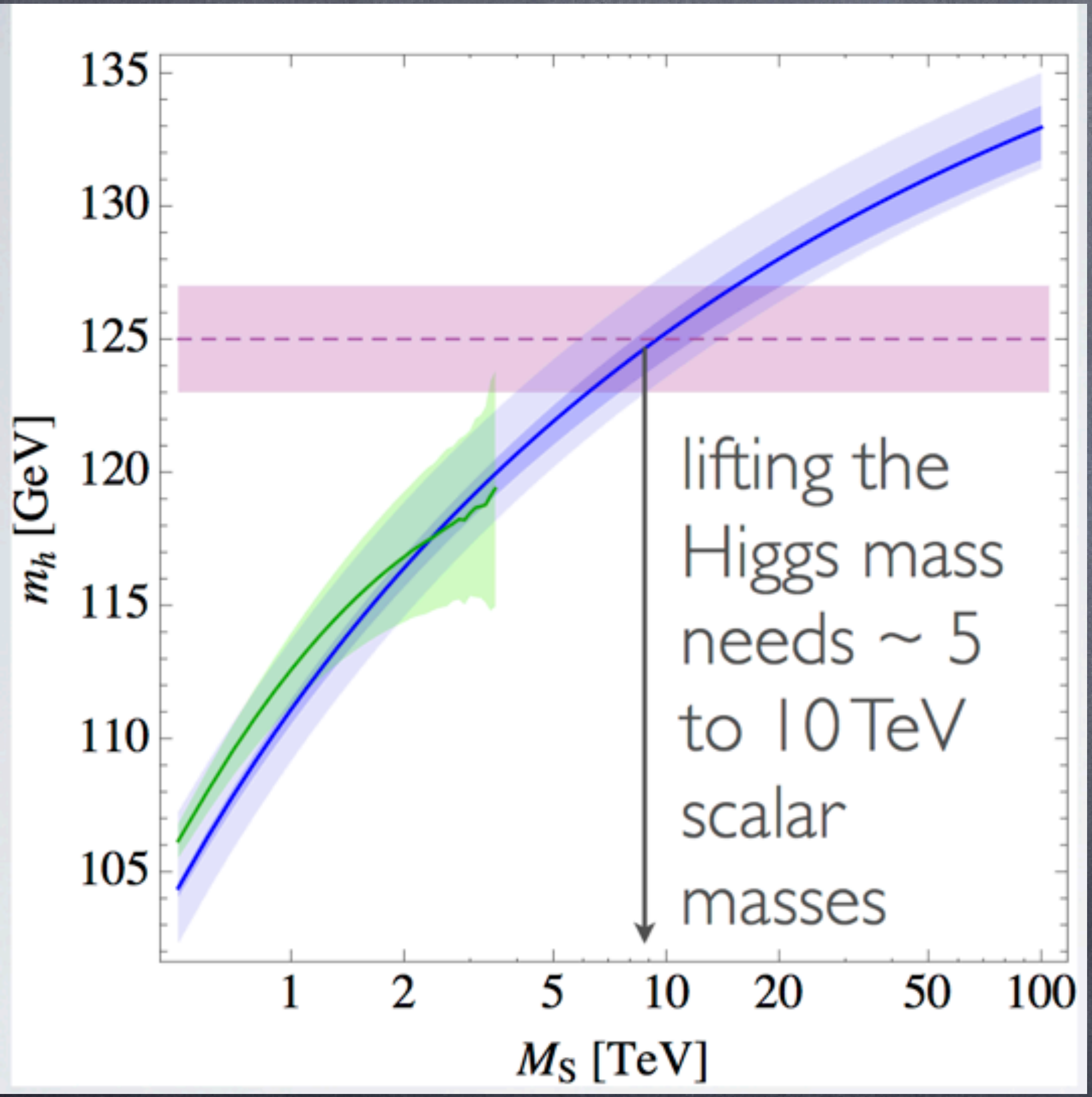
In reality, 2-loop corrections are sizable and negative, and make things even worse: for zero A-term one needs the stop soft mass to be at 10 TeV

This implies a huge fine-tuning of order 0.01%

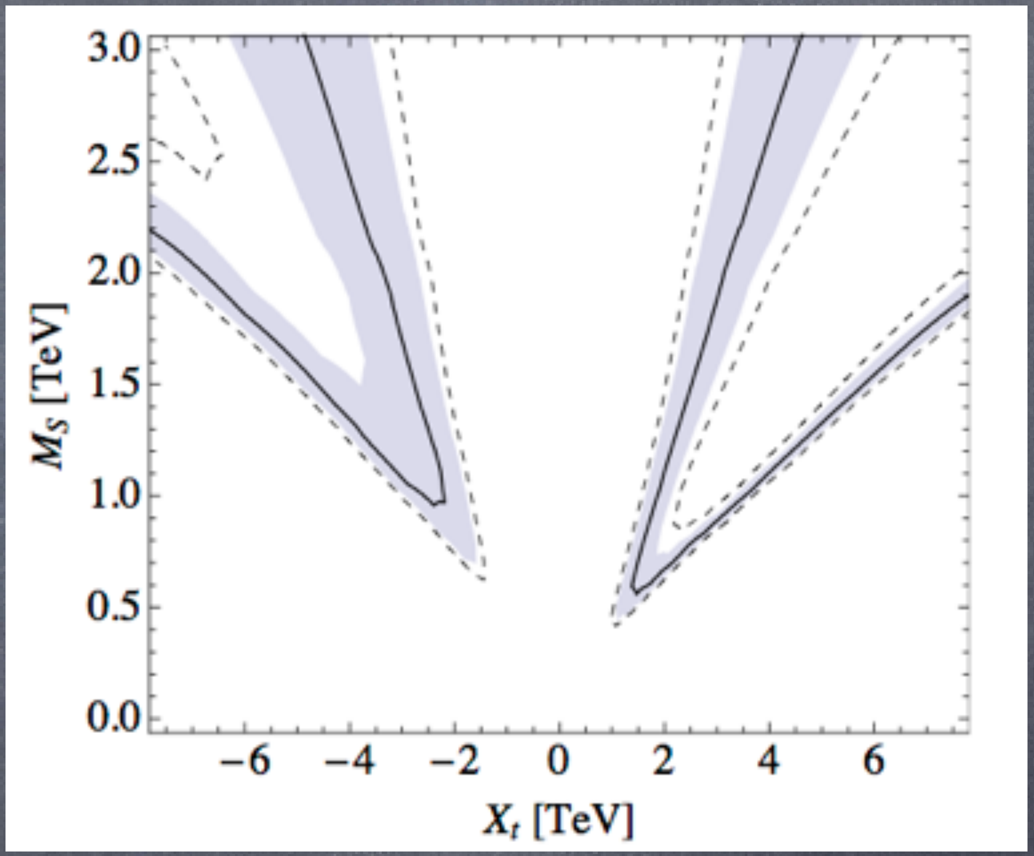
Smaller stop masses are possible for sizable A-terms, but that also implies fine-tuning (at least 1%)

Supersymmetry

The Higgs mass in minimal supersymmetry



From Draper et al. 1112.3068

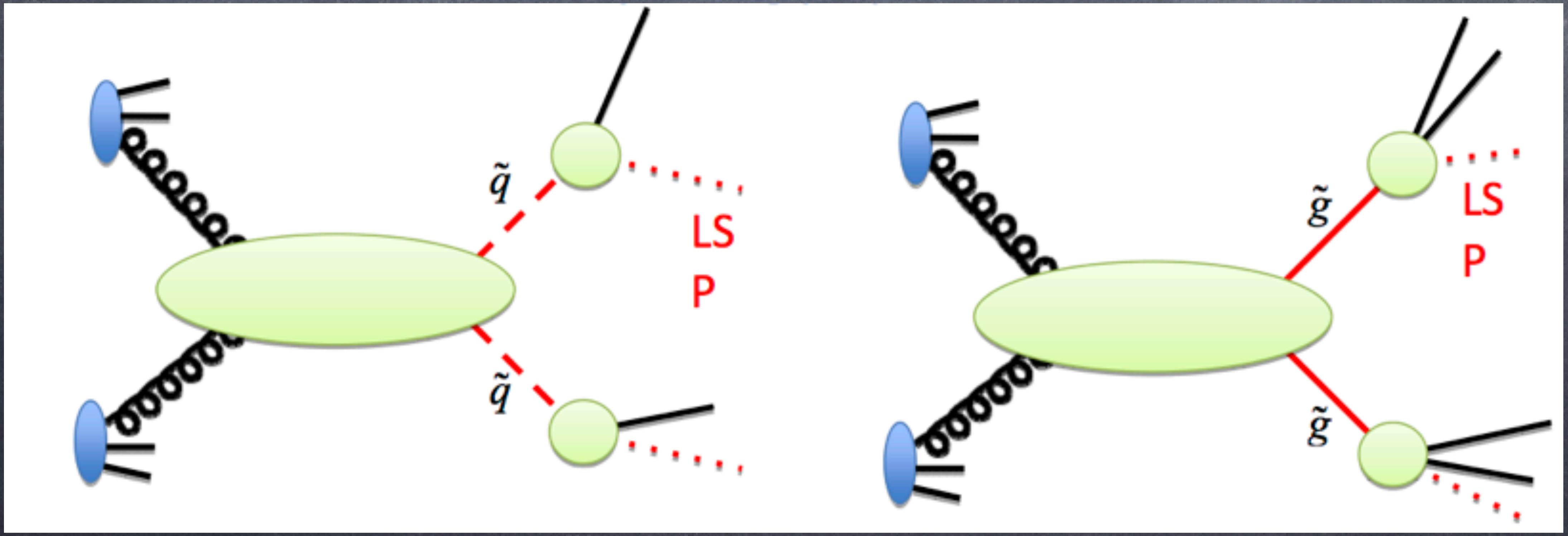


Supersymmetry

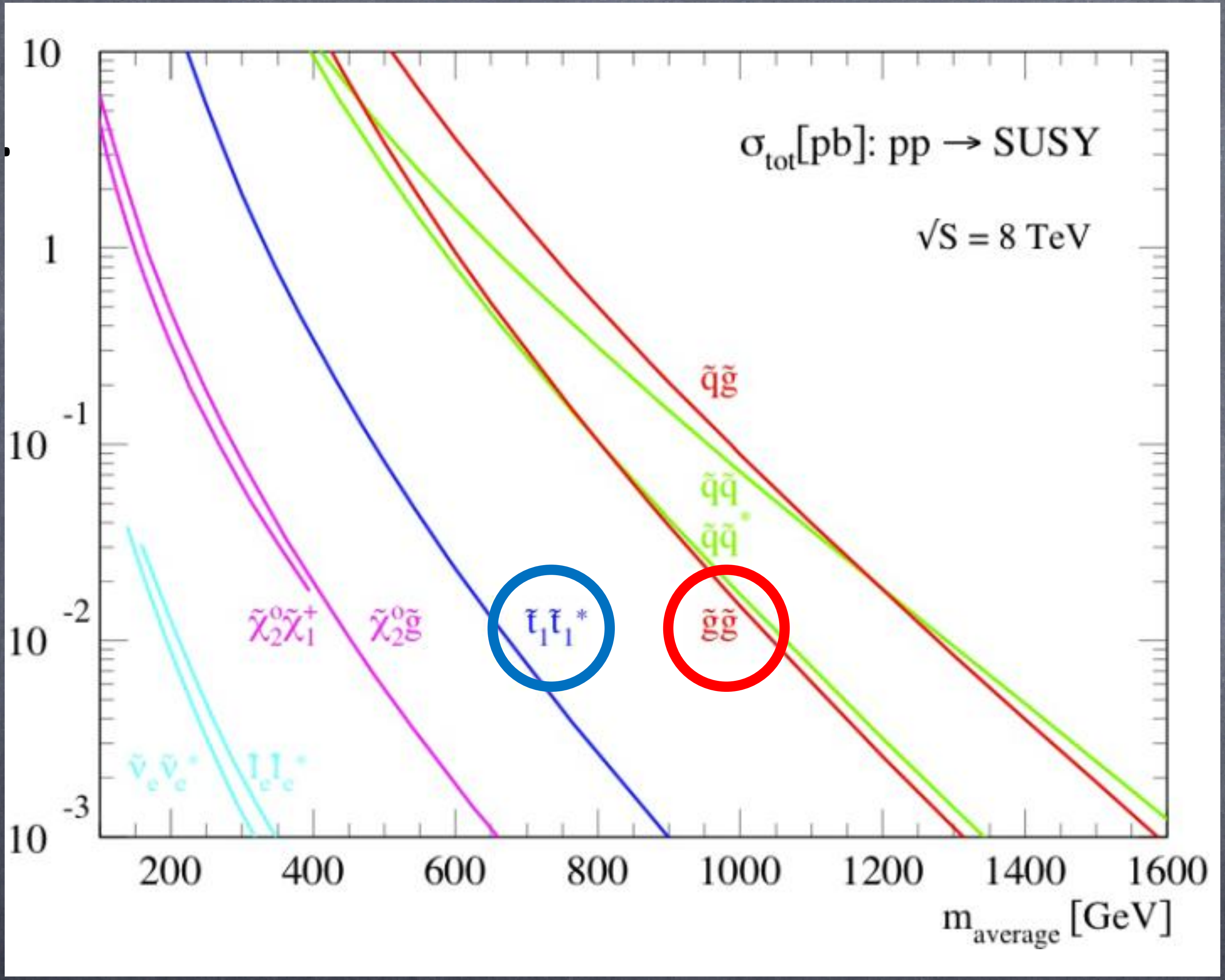
Predictions on natural supersymmetry

- 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)

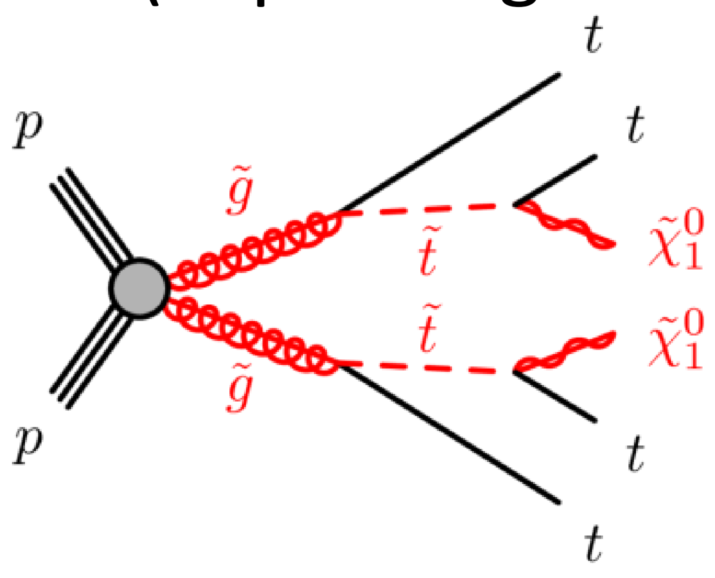
- At least, superpartners of the top quark and electroweak gauginos and Higgsinos not heavier than ~300 GeV, while gluino should not be heavier than ~1.5 TeV



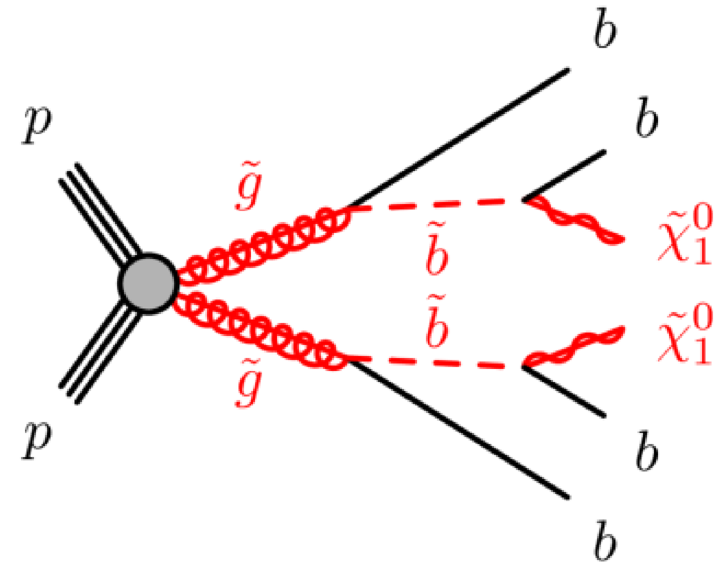
Supersymmetry - Cross Sections



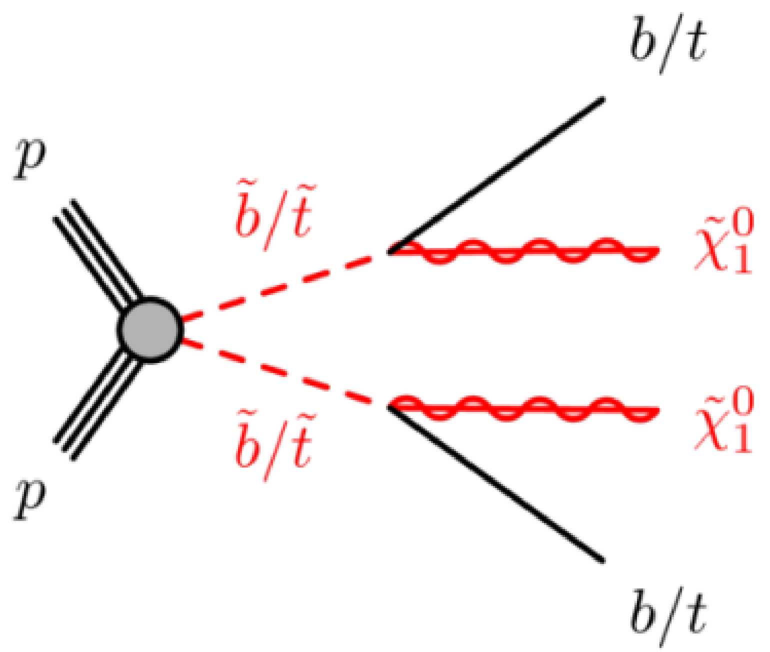
Supersymmetry - 3rd generation



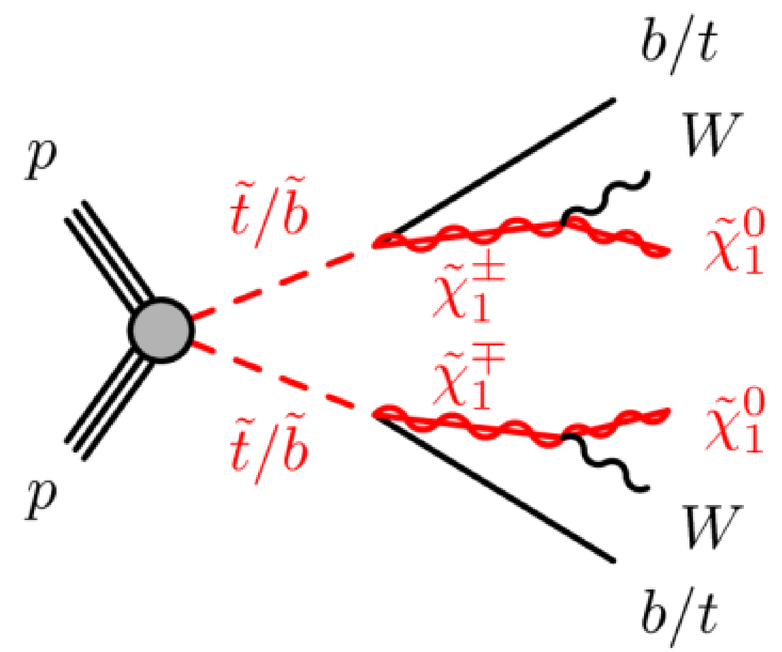
$$\tilde{g} \rightarrow t\tilde{t}^{(*)} \rightarrow t\bar{t}\tilde{\chi}_1^0$$



$$\tilde{g} \rightarrow b\tilde{b}^{(*)} \rightarrow b\bar{b}\tilde{\chi}_1^0$$



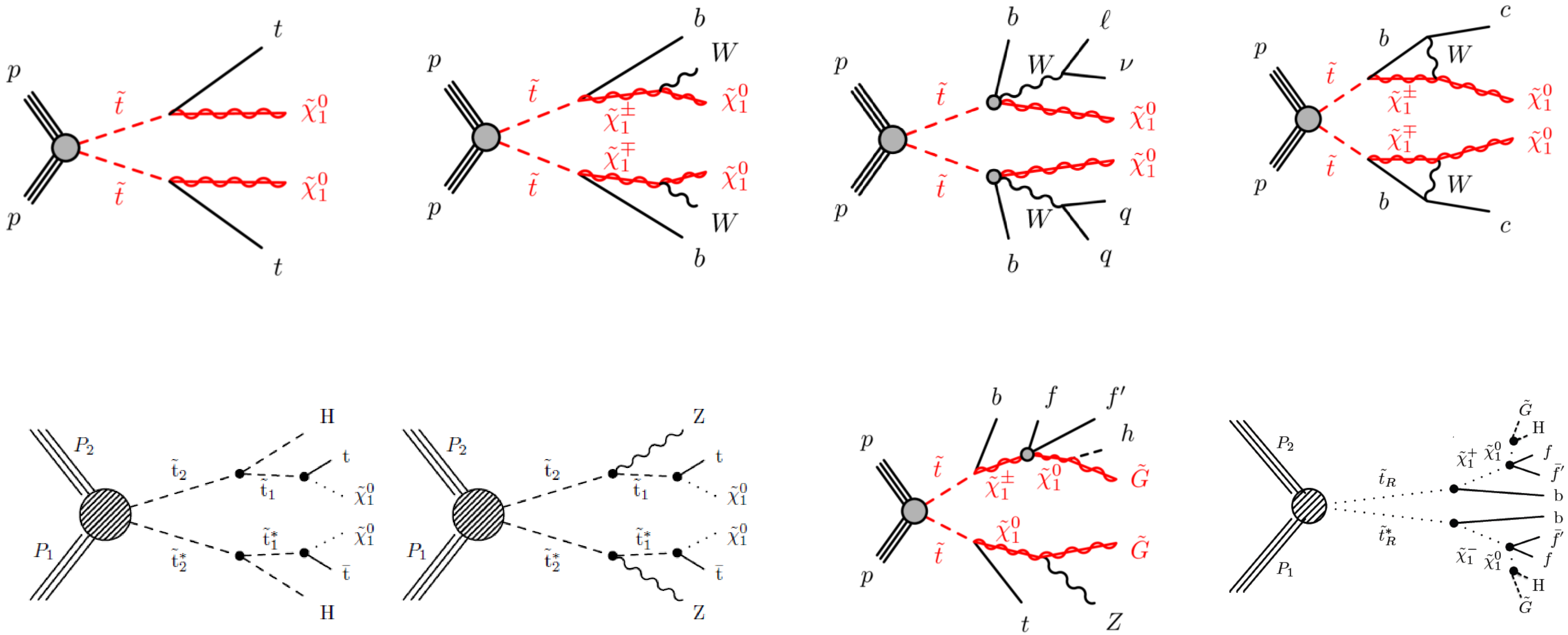
$$\tilde{b} \rightarrow b\tilde{\chi}_1^0 \,/\, \tilde{t} \rightarrow t\tilde{\chi}_1^0$$



$$\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \,/\, \tilde{b} \rightarrow t\tilde{\chi}_1^0$$

Slide from talk of T. Yamanaka in Moriond

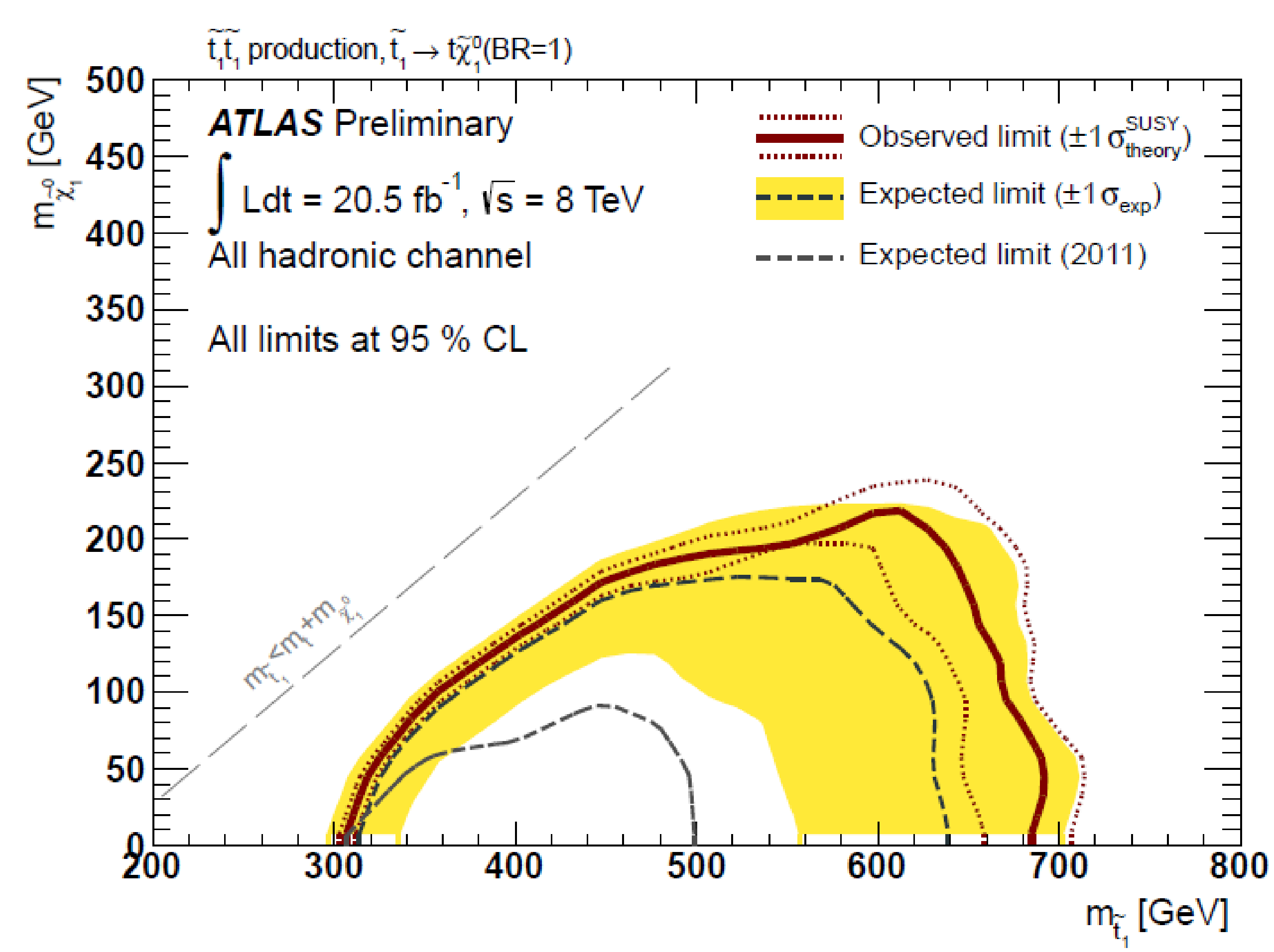
Direct Stop Pair Production

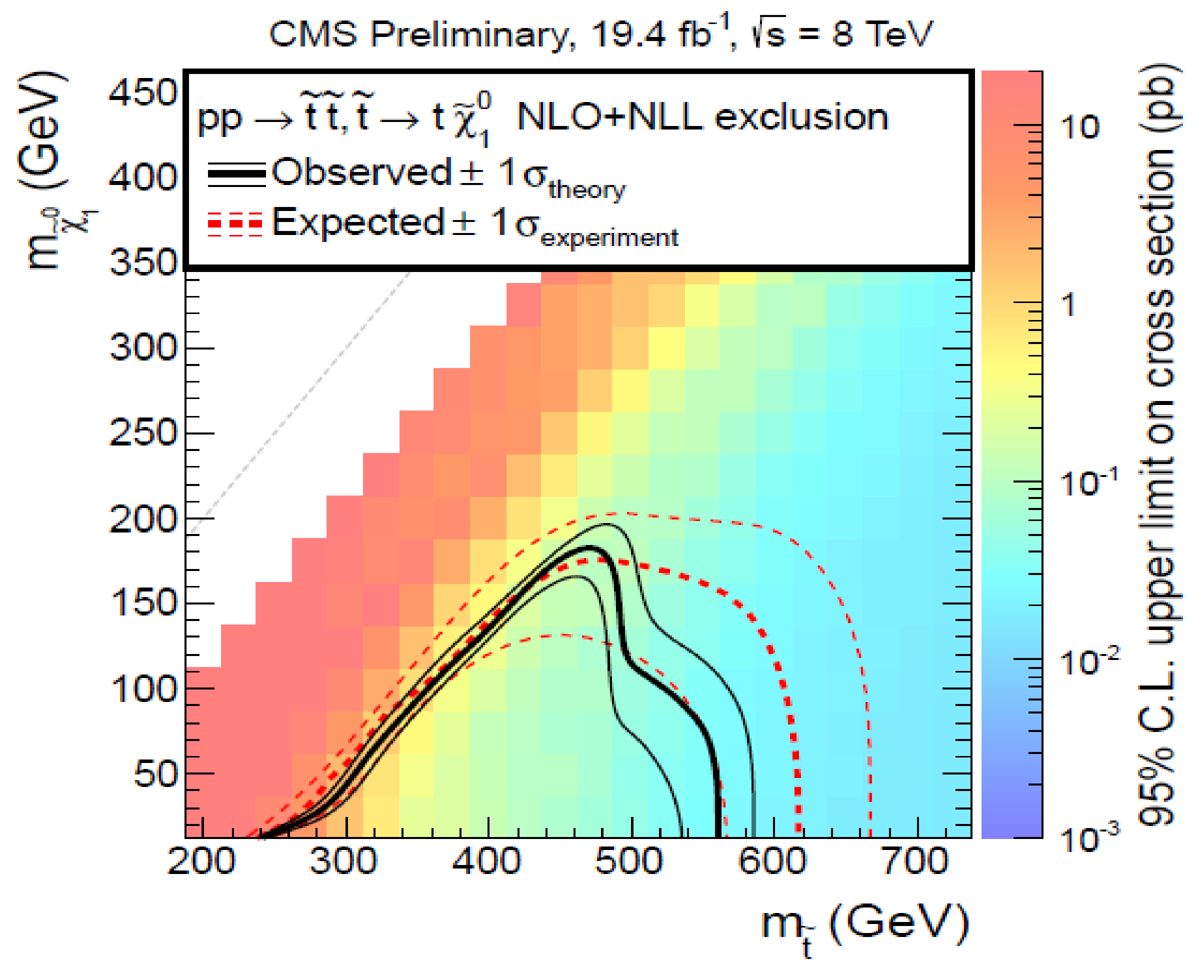


Slide from talk of T. Yamanaka in Moriond

Supersymmetry - 3rd generation

Direct limits on stops



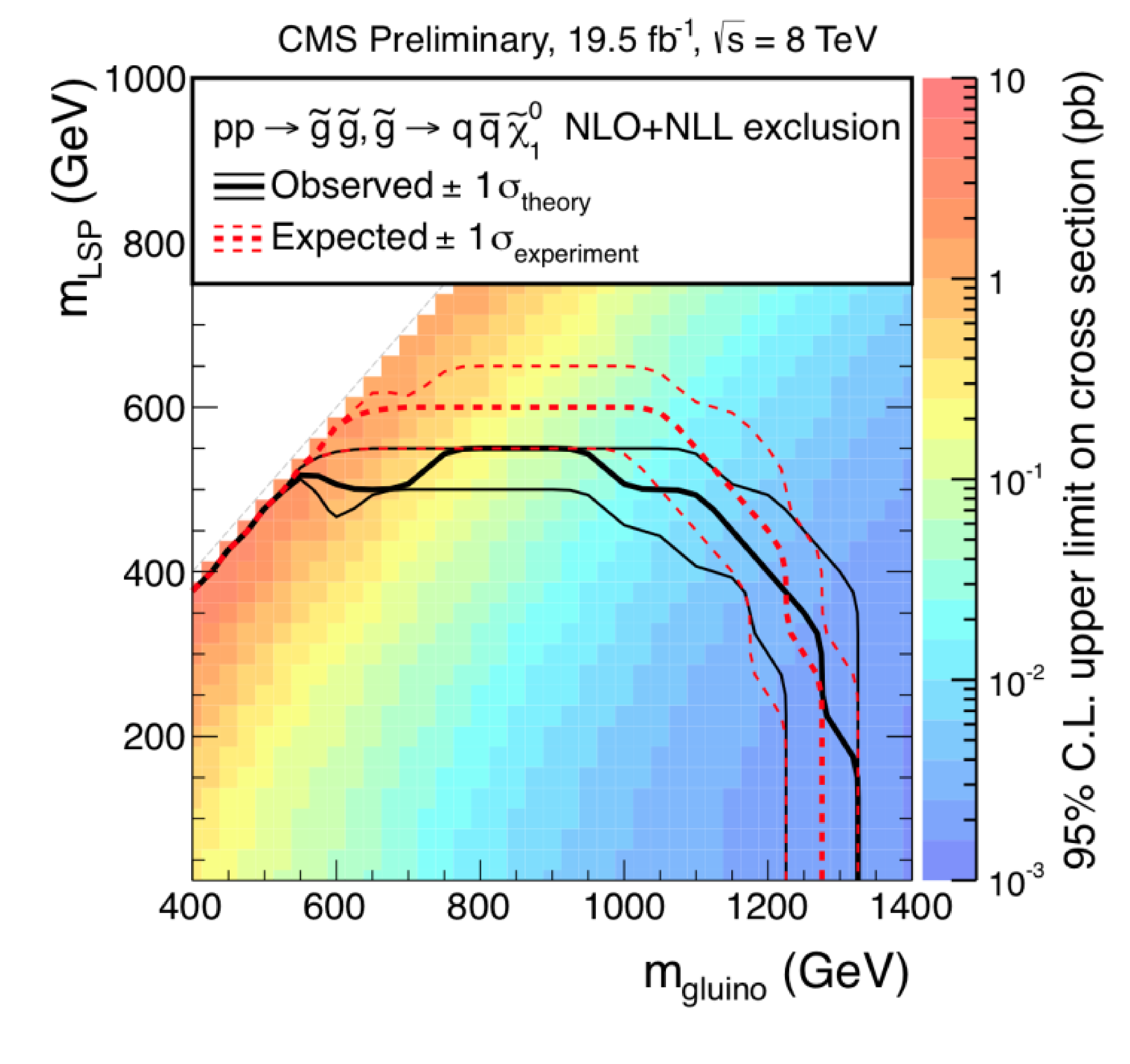


However, some hope remains in "difficult" regions where no limits exist

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

Supersymmetry

Direct limits on gluinos



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

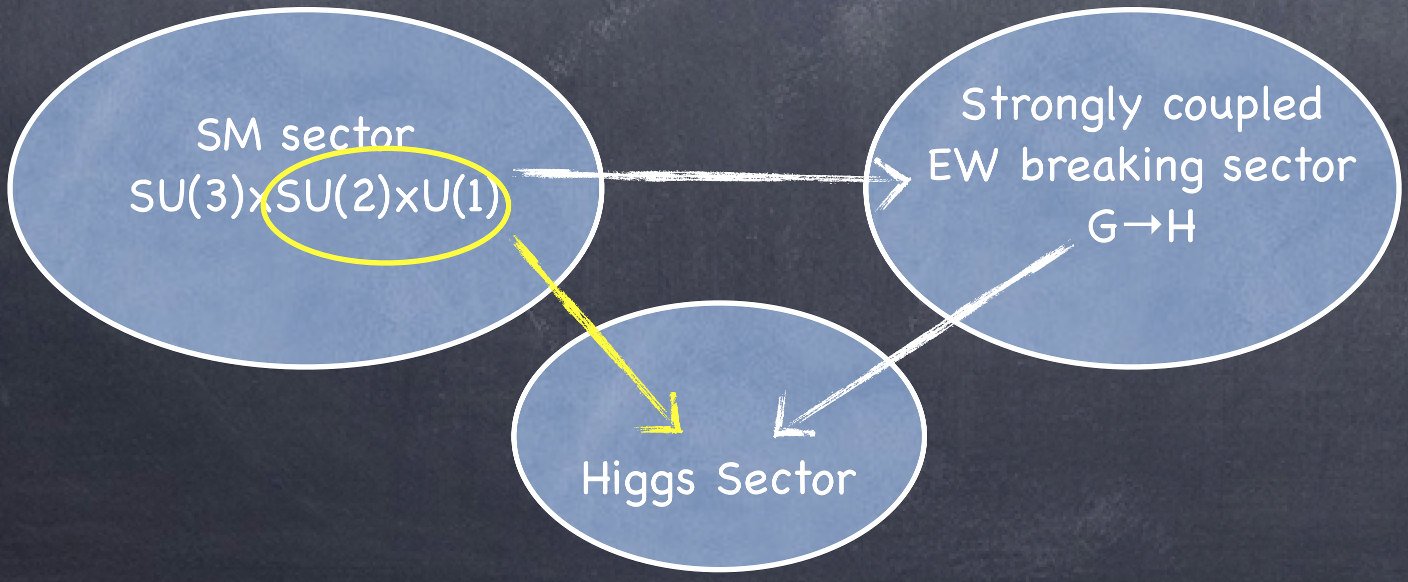
= composite pseudo-Goldstone-boson Higgs

- 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



Minimal Composite Higgs Model

Like QCD: (techni)quarks, strong dynamics, global symmetry

M_{PL}

New "quarks"

Hierarchy

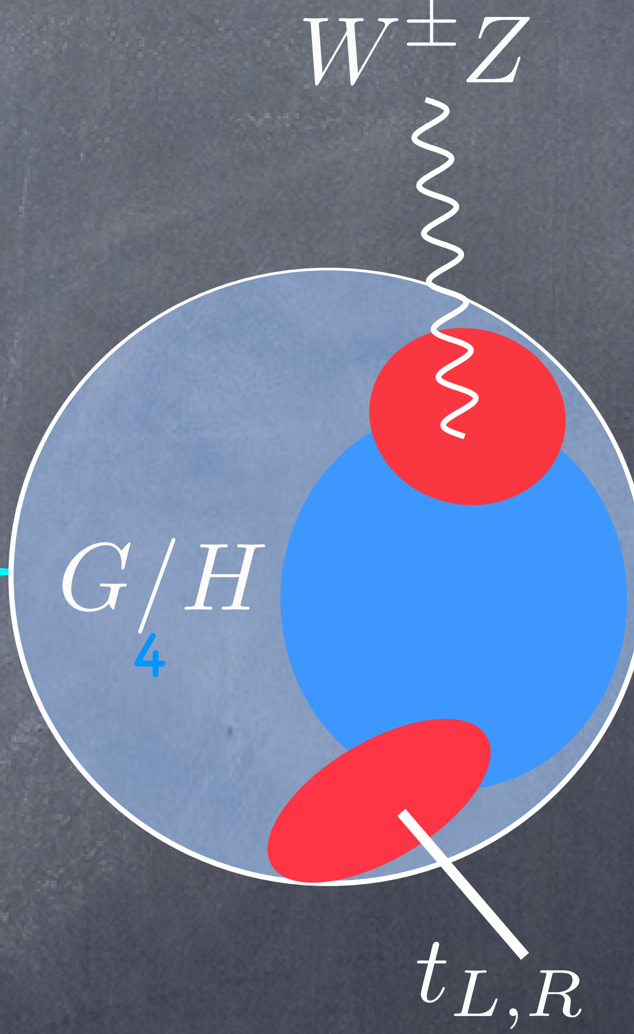
Global symmetry
$G = SO(5)$ 10

dynamically generated

f=TeV

Composite states
(incl. scalars)

$H = SO(4)$ 6



4 naturally light

composite PseudoGoldstone bosons = Higgs doublet

Kaplan,Georgi,Dimopoulos,Dugan,Galison '84; Agashe,Contino,DaRold,Pomarol '05 -'07

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

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

SU(3) preserving   SU(3) breaking

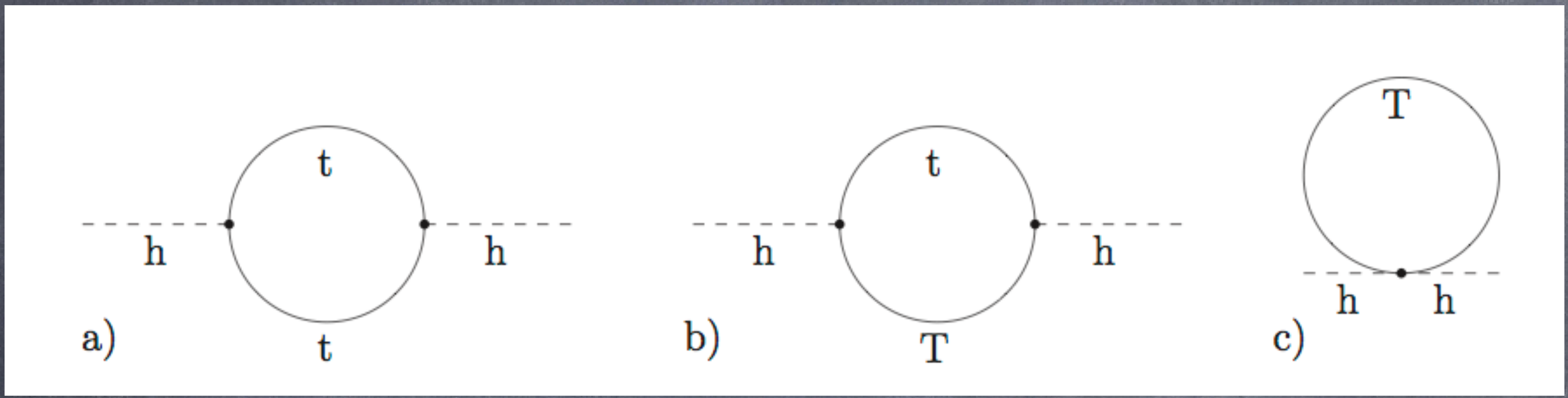
$$V_{\text{CW}} = \frac{1}{32\pi^2} \text{Str} \left\{ M^2(|H|)\Lambda^2 - \frac{1}{2} M^4(|H|) \left(\log[\Lambda^2/M^2(|H|)] - \frac{1}{2} \right) \right\}$$

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

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

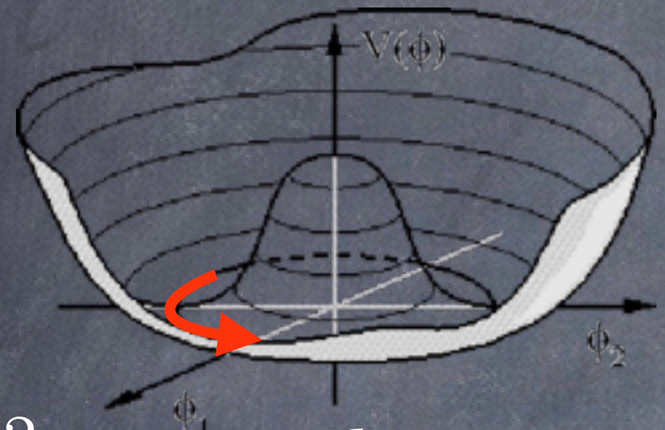
Composite Higgs

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

NGBHiggs couplings to SM fields

Higgs = Goldstone Boson of SO(5)/SO(4)



described by angular variable $\sin\frac{h}{f}$

$$\frac{g^2}{4}f^2\sin^2\frac{h}{f}W_\mu W^\mu \overset{h\to\langle h\rangle + h}{=} \frac{g^2}{4}\underbrace{f^2\sin\frac{\langle h\rangle}{f}^2}_{v^2}W_\mu W^\mu$$

$$+\frac{g^2}{2}f\sin\frac{\langle h\rangle}{f}\sqrt{1-\sin^2\frac{\langle h\rangle}{f}}\;hW_\mu W^\mu+..$$

$$c_V=\sqrt{1-\frac{v^2}{f^2}}$$

Coupling to W and model independent

$$c_f=\frac{1+2m-(1+2m+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

Coupling to fermions model dependent $m_t\sim\sin^{2m+1}\left(\frac{h}{f}\right)\cos^n\left(\frac{h}{f}\right)$

Pomarol,Riva,'12

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

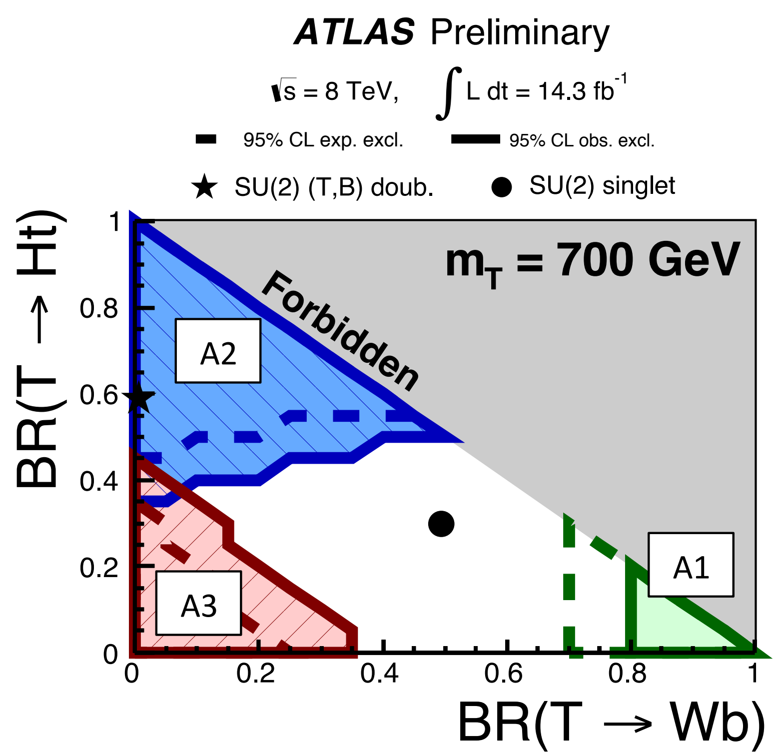
Composite Higgs

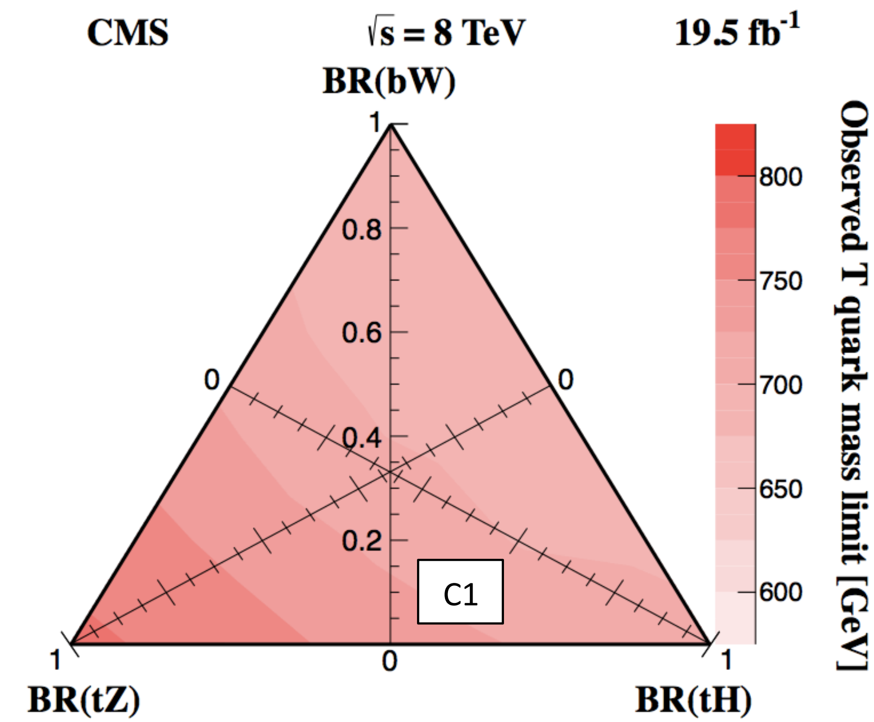
Predictions of natural composite Higgs

- 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 - Top Partners

Vector-like Top Summary





Vector-like top masses below 700 GeV are excluded for a large fraction of possible BR sets.

Vector-like T BR Hypothesis	ATLAS Limit on m_T [GeV]: obs (exp) ref	CMS Limit on m_T [GeV]: obs (exp) ref
100% Wb (chiral, Y)	**740** (770) A1	**700** (790) C1
100% Zt	**750** (750) A3	**780** (810) C1
100% Ht	**850** (850) A2	**710** (770) C1
SU(2) singlet T	**670** (680) A1 (comb w/ A2)	**700** (770) C1
T in a (T,B) doublet	**790** (750) A2	**730** (780) C1

Slide borrowed from M. Cooke talk in Moriond

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

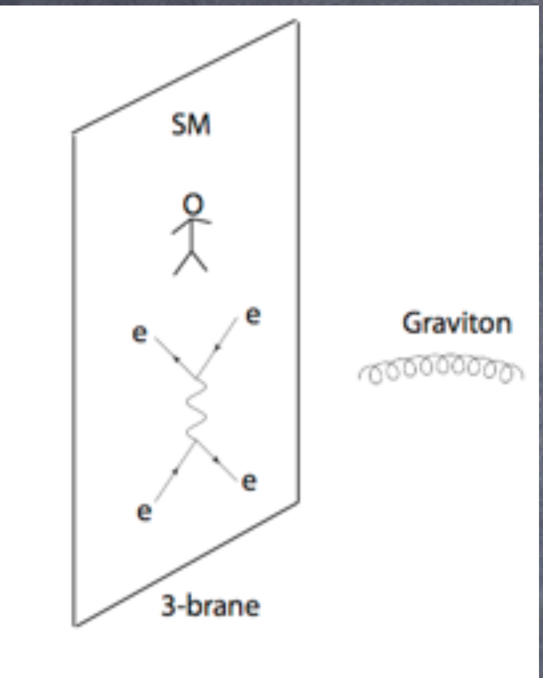
- Little Higgs is a cousin of composite Higgs. It is also a pseudo-Goldstone boson of an approximate global symmetries, and the cancellation of quadratic divergences works the similar way
- The main difference is that the scale of the strongly coupled sector is pushed higher, to about 10 TeV, and the 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

from Hsin-Chia Cheng
1003.1162

Low quantum-gravity scale (ADD)



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

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

ADD scenario very unlikely:

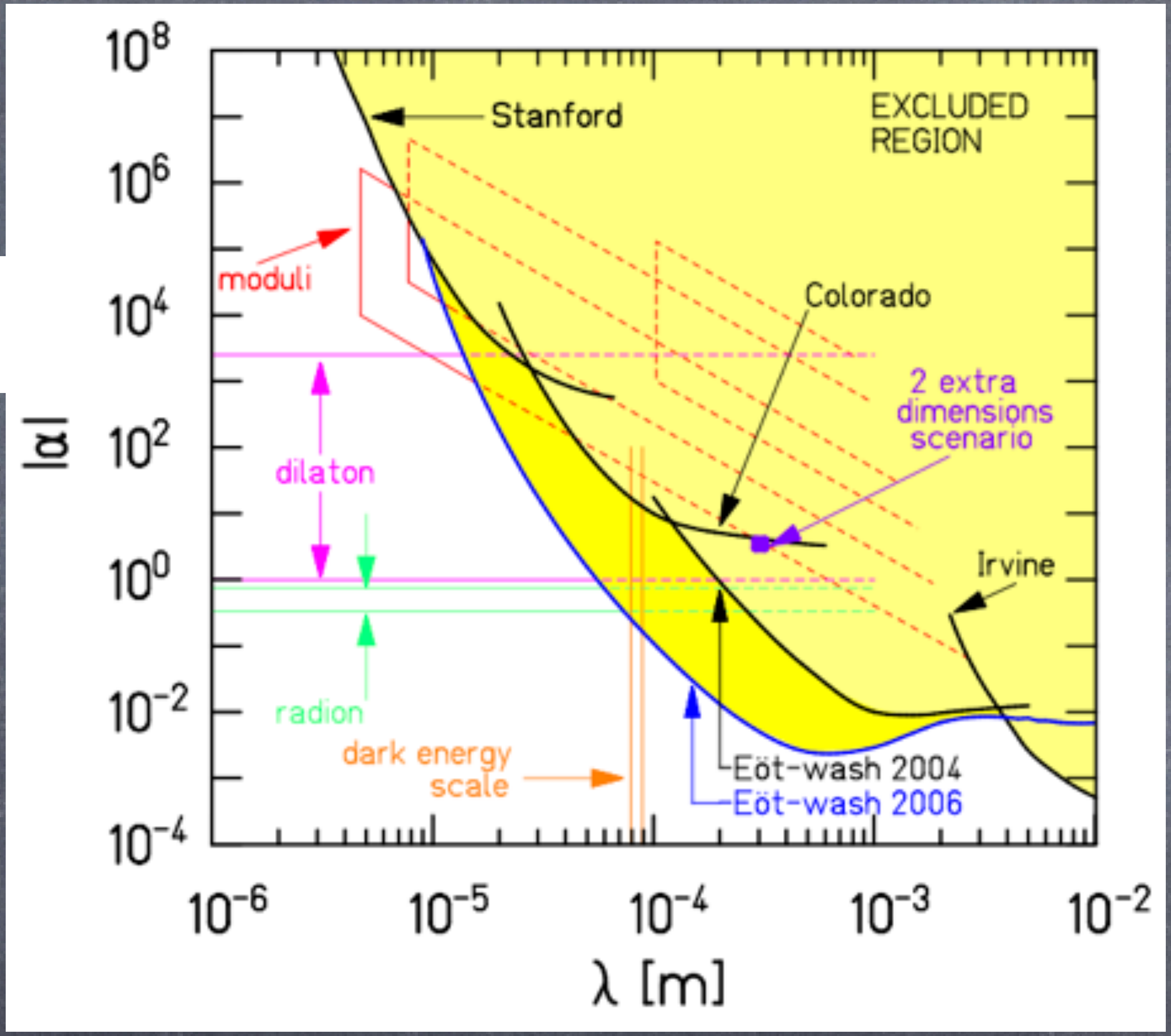
- One expects SM accompanied by all sorts of higher-dimensional operators suppressed by the low quantum gravity scale, but none has been seen
- By itself does not explain why the Higgs boson is light (mh << M*)
- No "black holes" seen at the LHC

Other solutions to naturalness problem

Low quantum-gravity scale (ADD)

Kapner et al
hep-ph/0611184

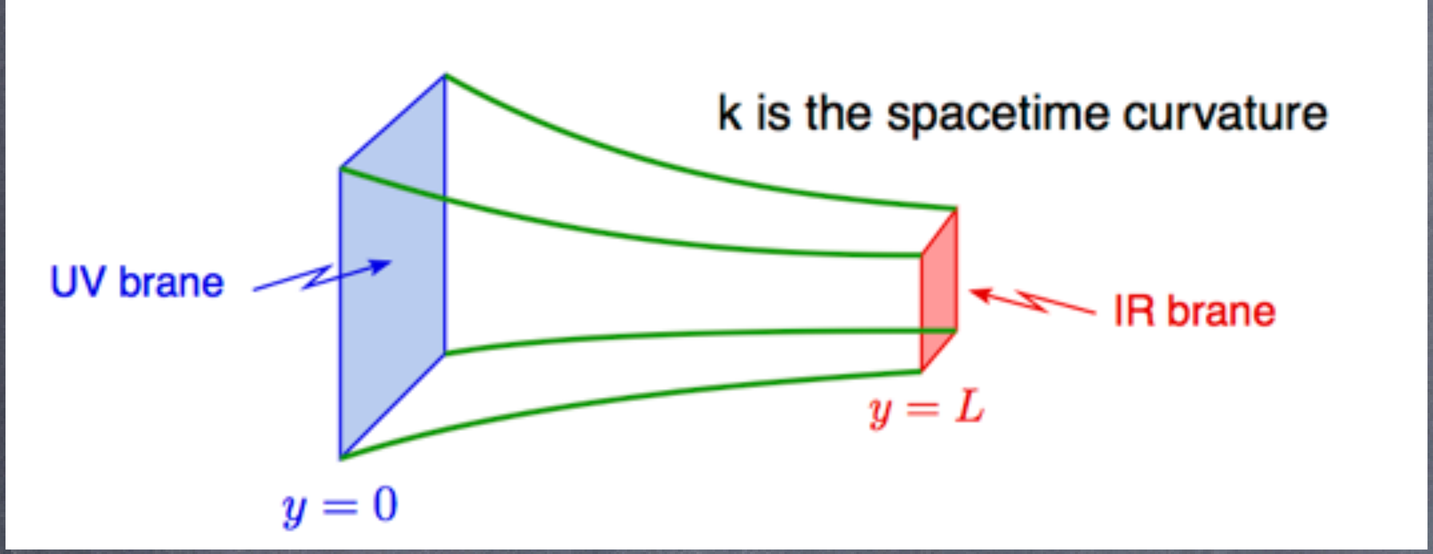
$$V(r) = -G_N \frac{m_1 m_2}{r} \left(1 + \alpha e^{-r/\lambda}\right)$$



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

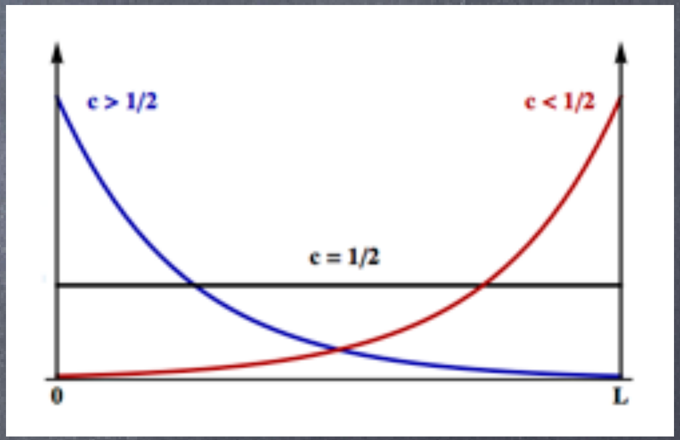
- For a warped (curved) extra dimension the cut-off scale is different, depending on the position along the extra dimension.Typically, the UV brane is assumed to have a cut-off at the 4D Planck scale, while the IR brane has a cut-off at TeV

- 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

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

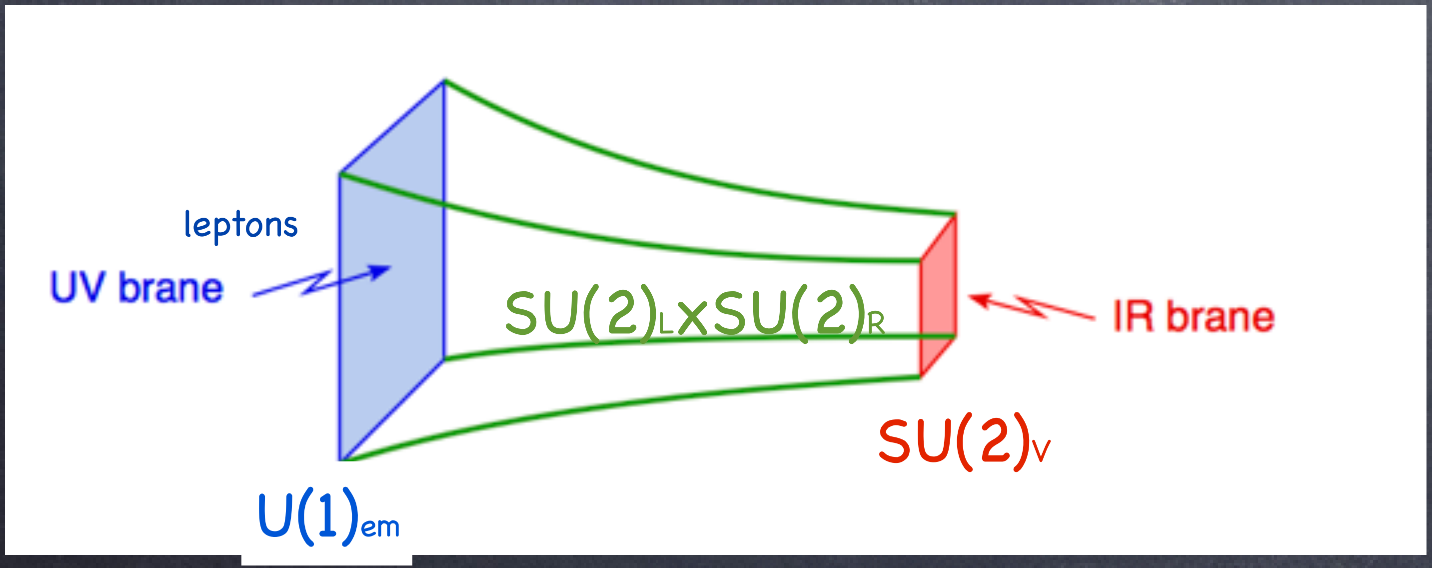


Other solutions to naturalness problem

Warped Extra Dimension (Randall-Sundrum)

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

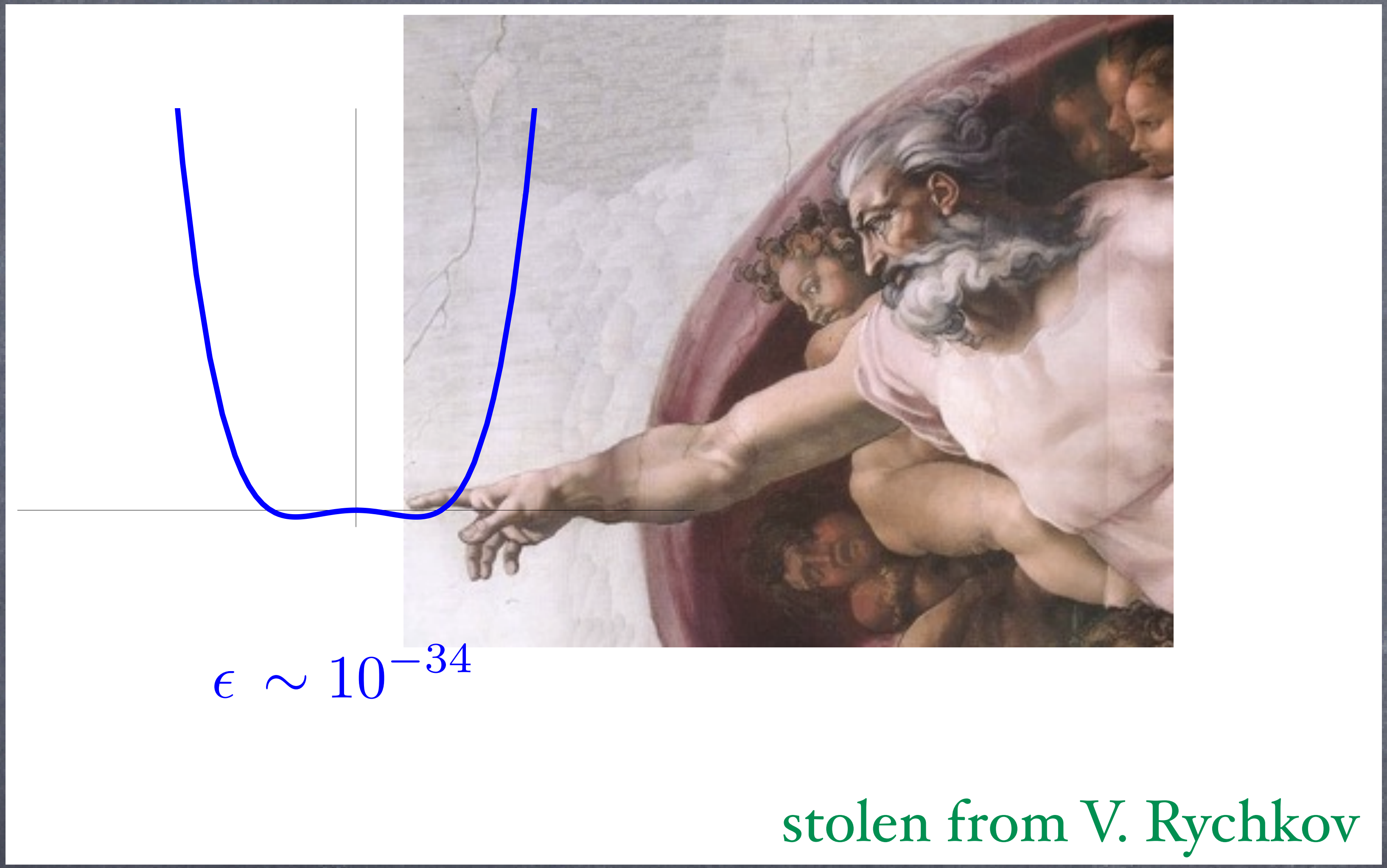
- Bulk gauge symmetry translates to global symmetry of the strongly coupled sector
- IR localized fields correspond to composite states of the strongly coupled sector
- UV localized fields corresponds to weakly coupled fundamental fields probing the strongly coupled sector
- Models of gauge-Higgs unification 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



Arigato

Backup

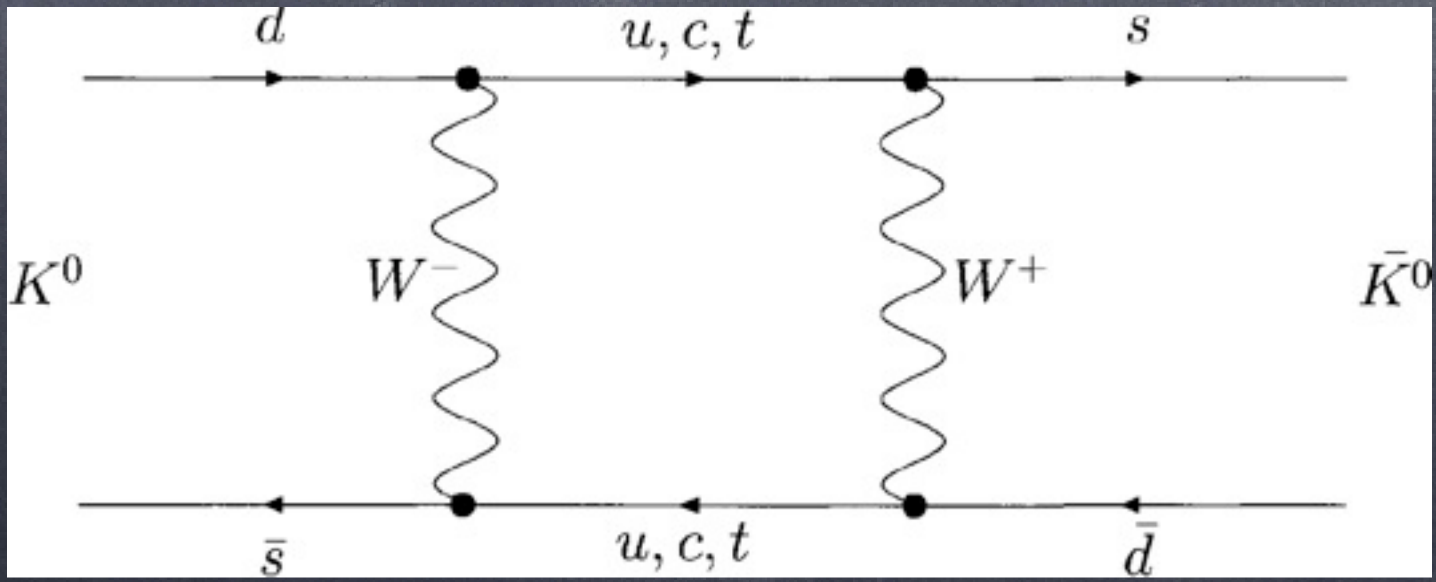
Do fine-tuning arguments work?

- 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
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