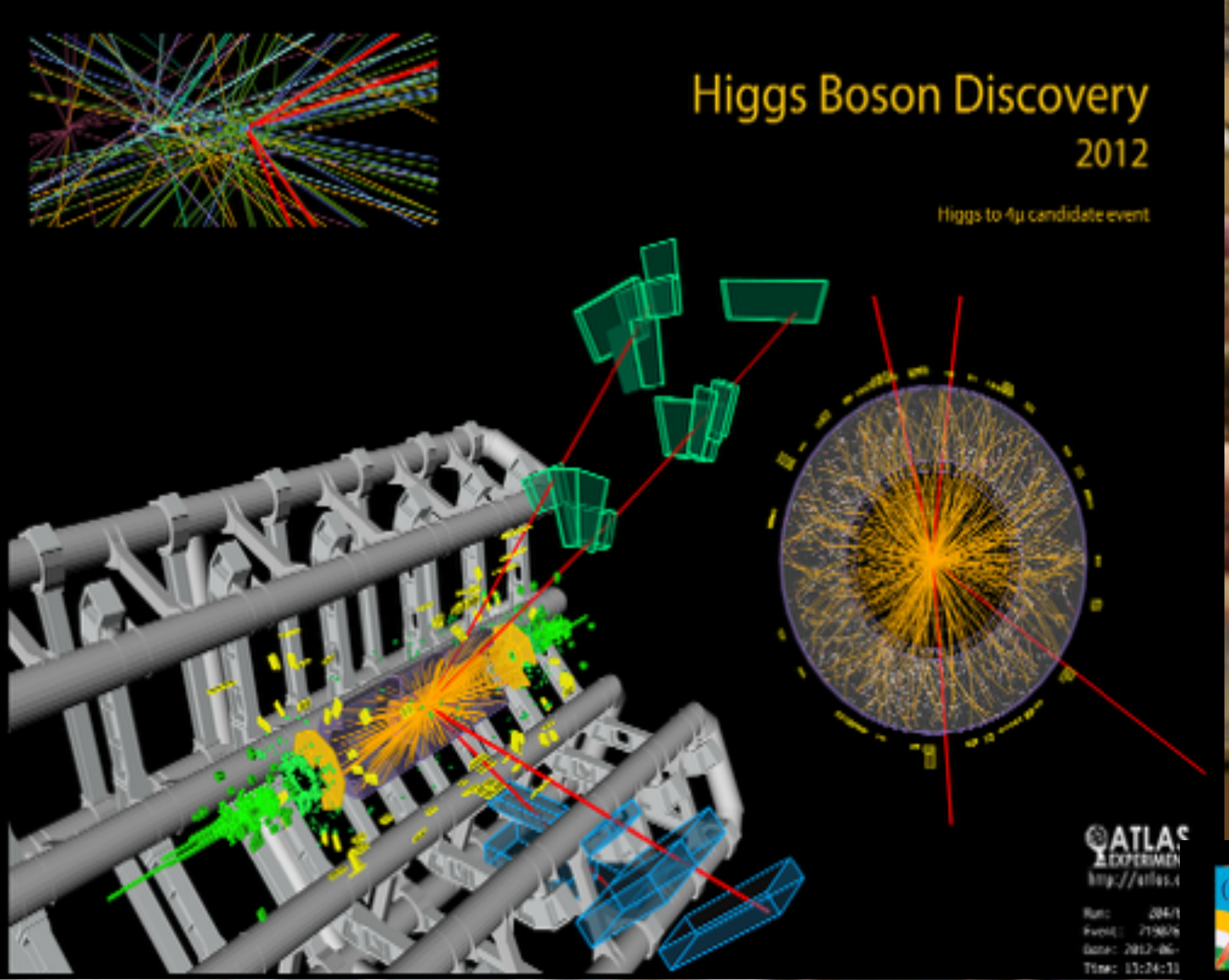
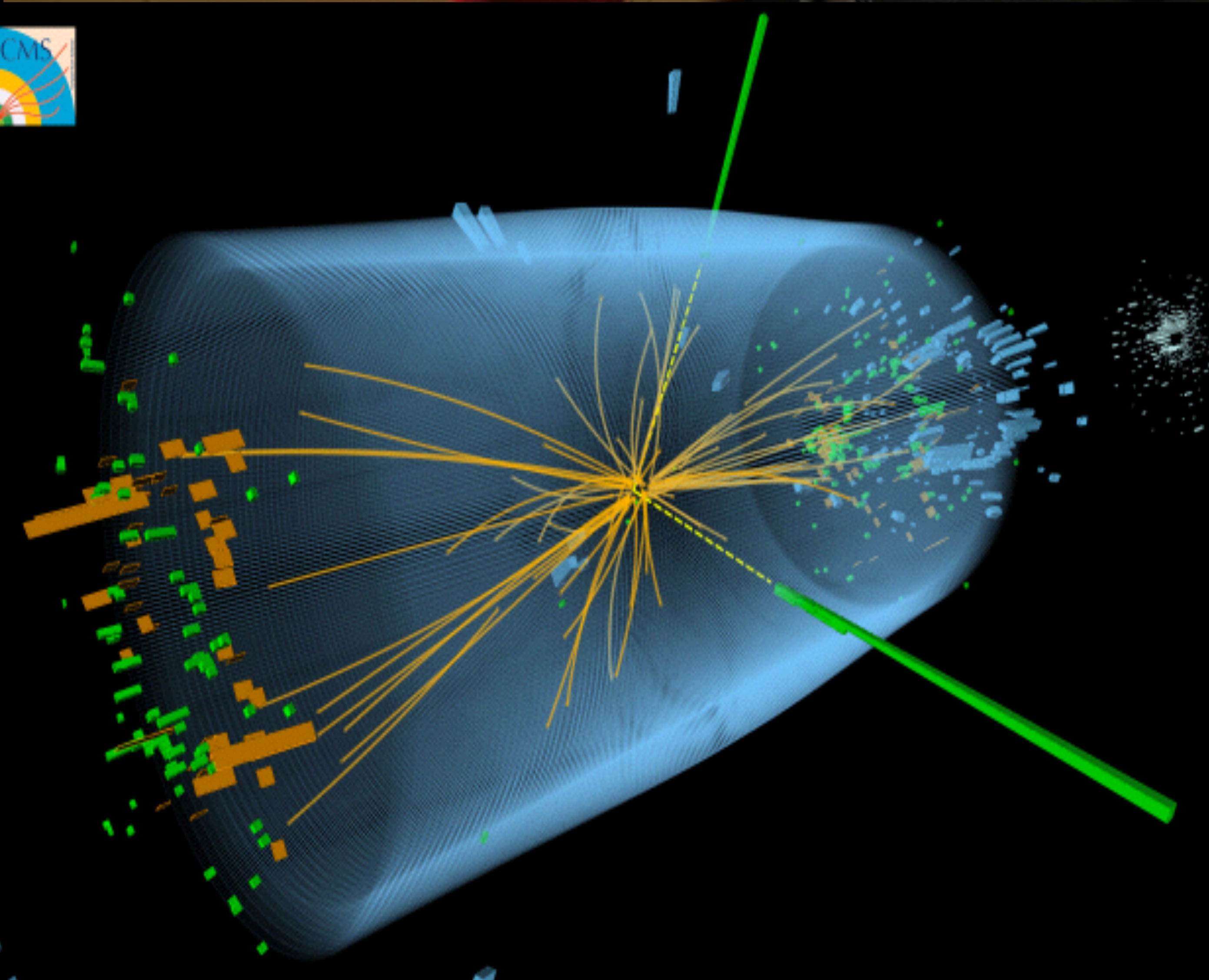
HIGGS AND DARK SECTOR

JiJi Fan
Syracuse University

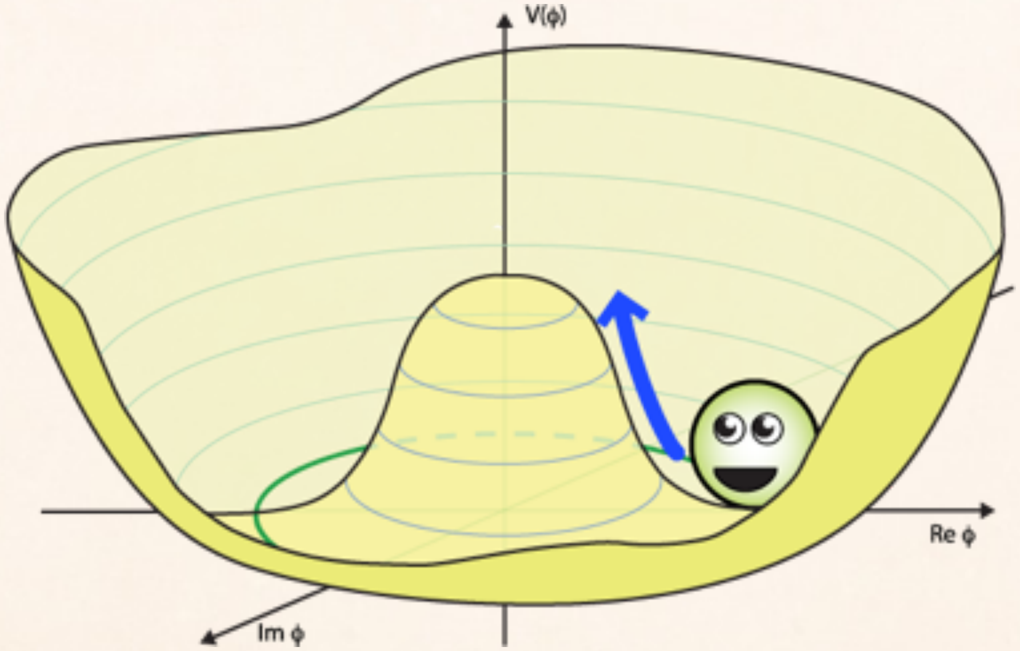
Argonne, US LUA meeting, 11/13/14


Higgs Boson Discovery
2012
Higgs to 4μ candidate event
ATLAS
EXPERIMENT
Run:
Event:
Date: 2012-06-
Time: 15:24:51


CMS

Now we finally confirm the Higgs mechanism for the electroweak symmetry breaking.

$$V(\phi) = -\frac{1}{2}m_0^2|\phi|^2 + \frac{1}{4}\lambda|\phi|^4$$



This is only a low-energy effective description.

We don’t know:

Why the Higgs potential is like this?

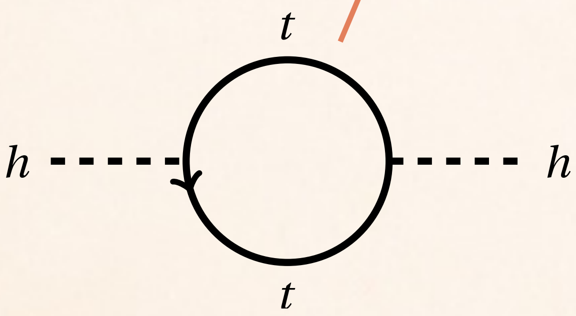
What are the values of the parameters in the potential?

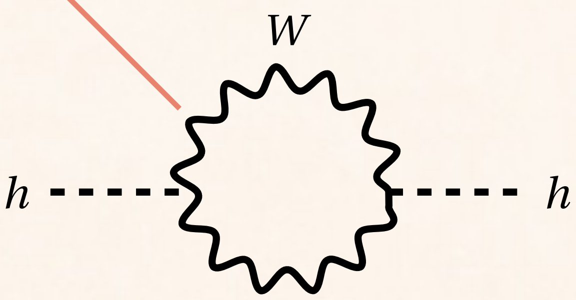
Naturalness Puzzle of a Fundamental Scalar (Hierarchy Problem)

Physical mass
125 GeV

Bare mass,
parameter in the Lagrangian

$$m_h^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_h^2\right)\Lambda^2 \sim m_0^2 - (115\,\mathrm{GeV})^2\left(\frac{\Lambda}{400\,\mathrm{GeV}}\right)^2$$





Λ: scale up to which SM is valid

Natural electroweak symmetry breaking means that no large cancellations among terms on the right-hand side to get the correct physical Higgs mass.

SM only up to the Planck scale is very fine-tuned.

No fine-tuning is also one (implicit) principle of interpreting experimental data

Constrain new physics

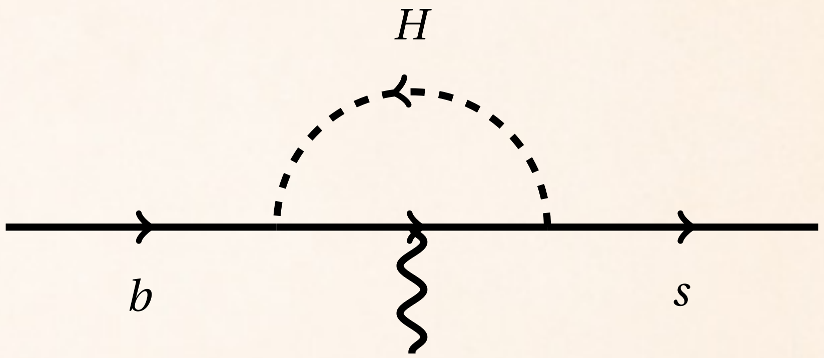
$$\mathrm{BR}(B \to X_s \gamma)^{\mathrm{exp}} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$$

Heavy-flavor average group

agrees very well

$$BR(B \to X_s \gamma)^{\mathrm{SM}} = (2.98 \pm 0.26) \times 10^{-4}.$$

Becher & Neubert



charged Higgs below ~350 GeV is ruled out

No fine-tuning is also the (implicit) principle behind interpreting experimental data

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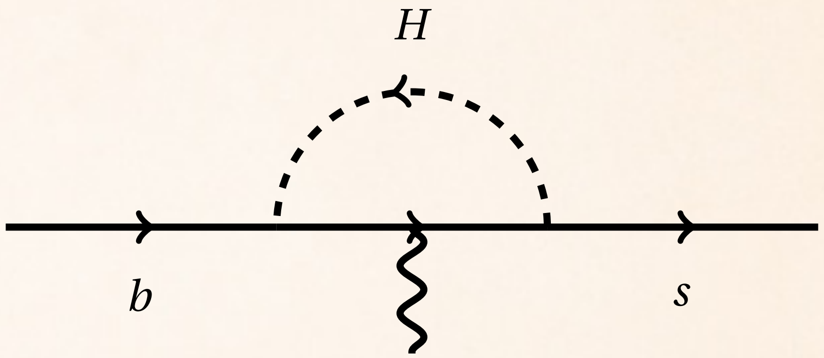
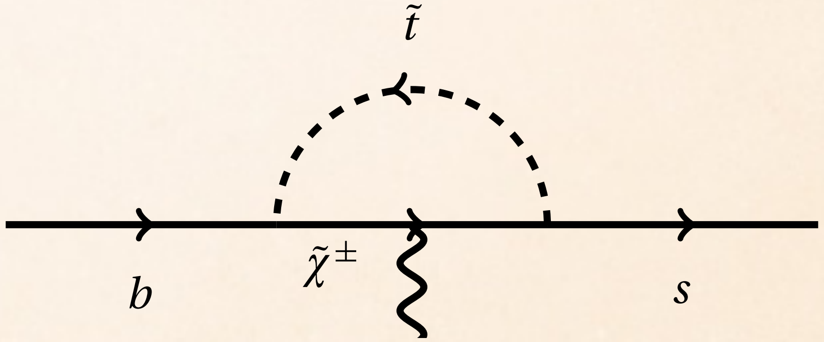
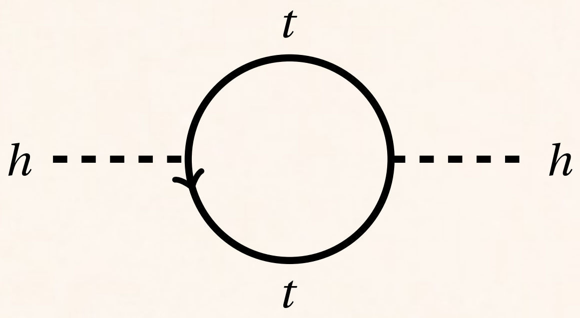


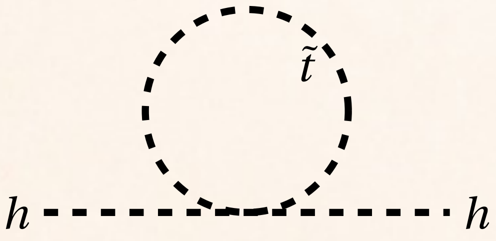
fine-tune to evade the constraint

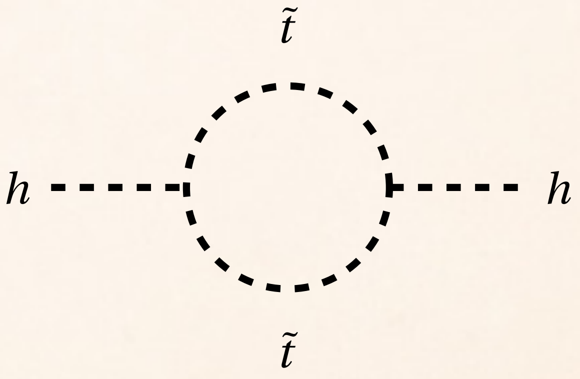


The naturalness puzzle reflects the extreme sensitivity of the Higgs potential to high energy physics.

This puzzle motivates studies of beyond SM physics, for example, supersymmetry.







When stops are much heavier compared to the tops, in other words, if SUSY is badly broken in the low energy theory, we will introduce the fine-tuning problem again.

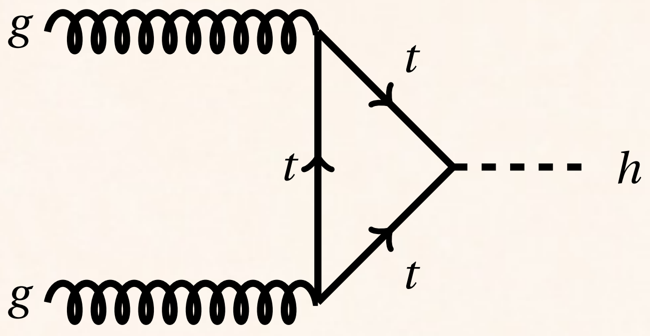
To avoid more than 10 % fine-tuning, we want light stops with mass $\lesssim$ 700 GeV Papucci, Ruderman and Weiler 2011

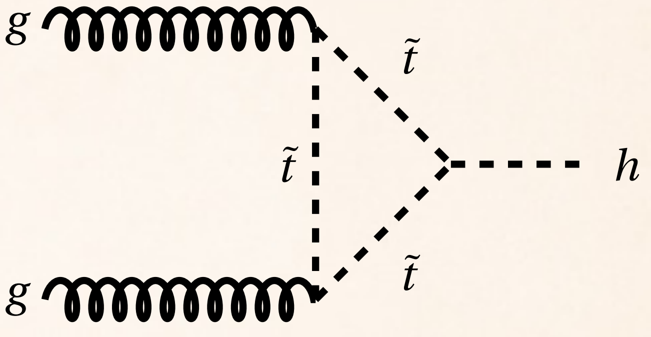
Higgs couplings to SM fields could be sensitive to new physics

SM

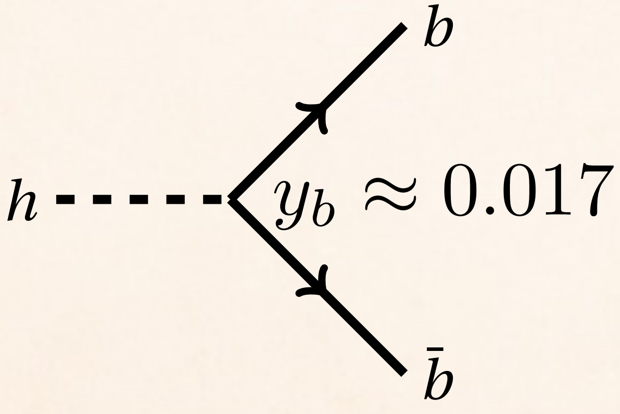
BSM

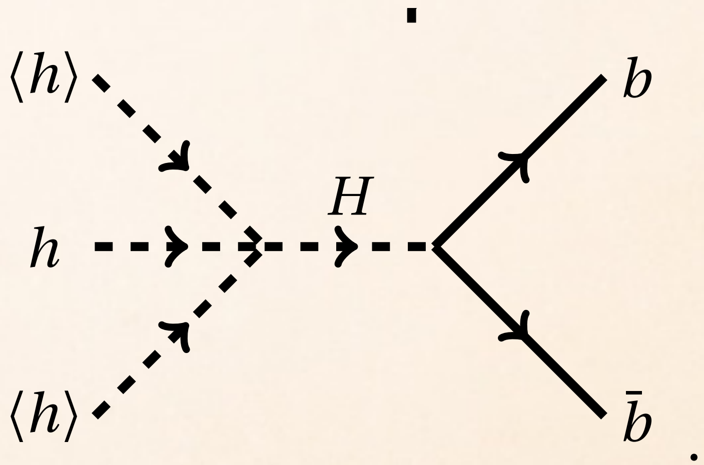
Production





Decay





SM values could be small

Size of modifications are determined by the scale of new physics

Higgs boson provides a lamp post for our search of new physics beyond the Standard Model.

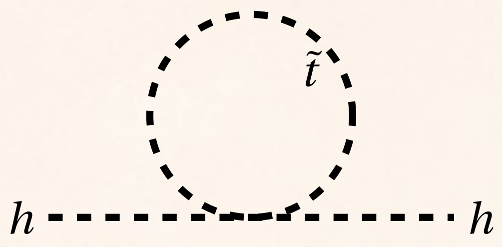
The precision measurement of Higgs sector might tell us the next energy scale we should be after.

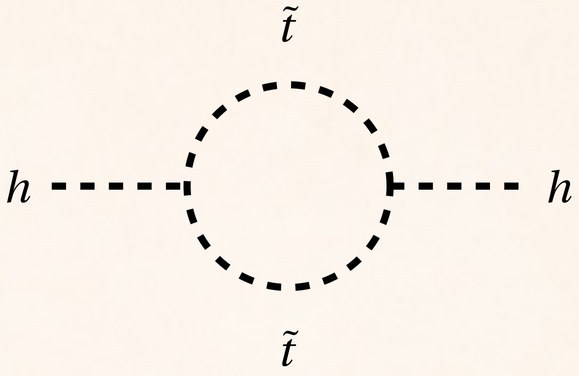
In this talk, I’m not going to exhaust every aspect of Higgs physics.

I’ll focus on two implications of current and upcoming Higgs data for the mass scale of possible new physics.

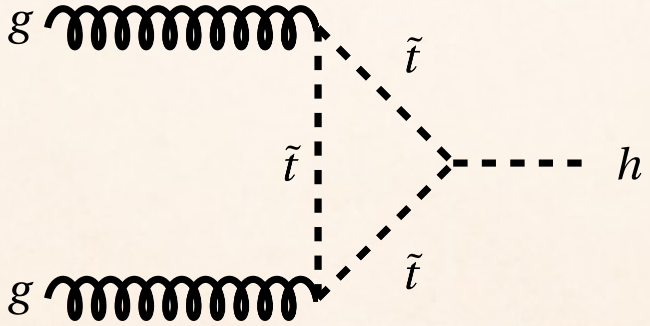
Higgs Coupling Implications for natural SUSY

Stop sector: As reviewed, stops have an effect on the Higgs mass and fine-tuning:



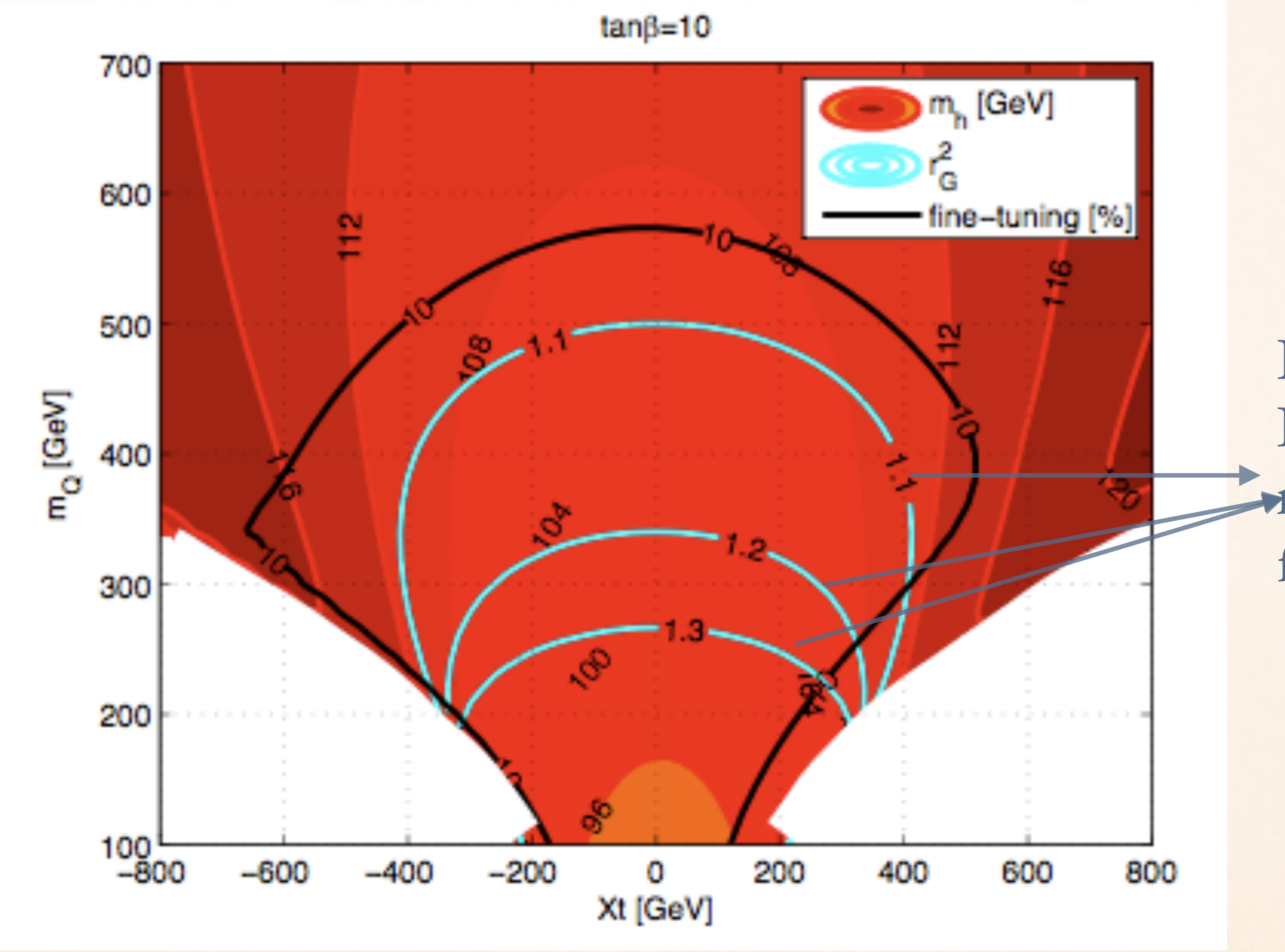


Effect on Higgs couplings:
modify the most important Higgs production channel at a hadron collider



Natural Higgs is not a SM-like Higgs!

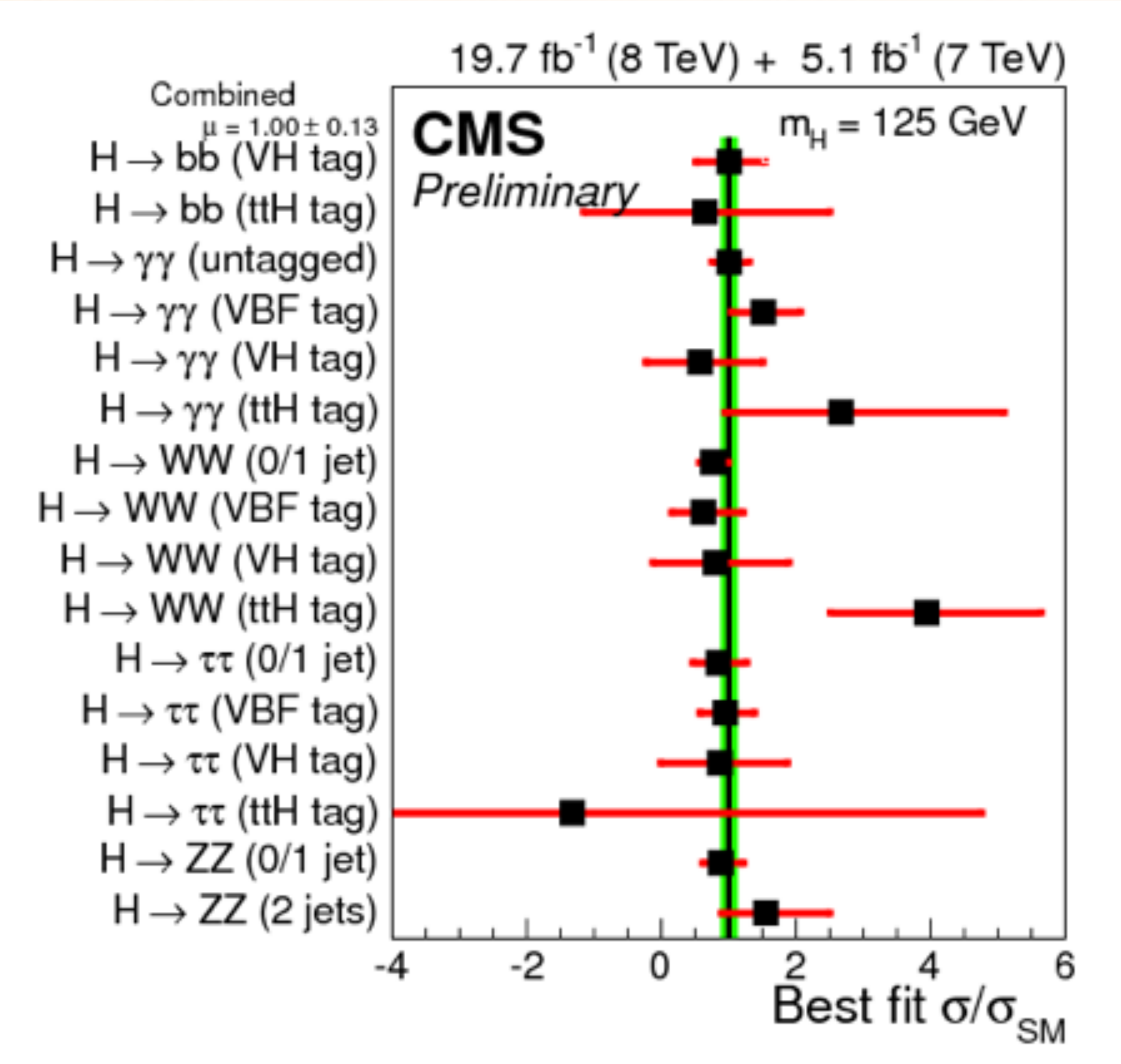
The smaller the stop contribution to fine-tuning is,
the bigger its contribution to Higgs coupling modification is.

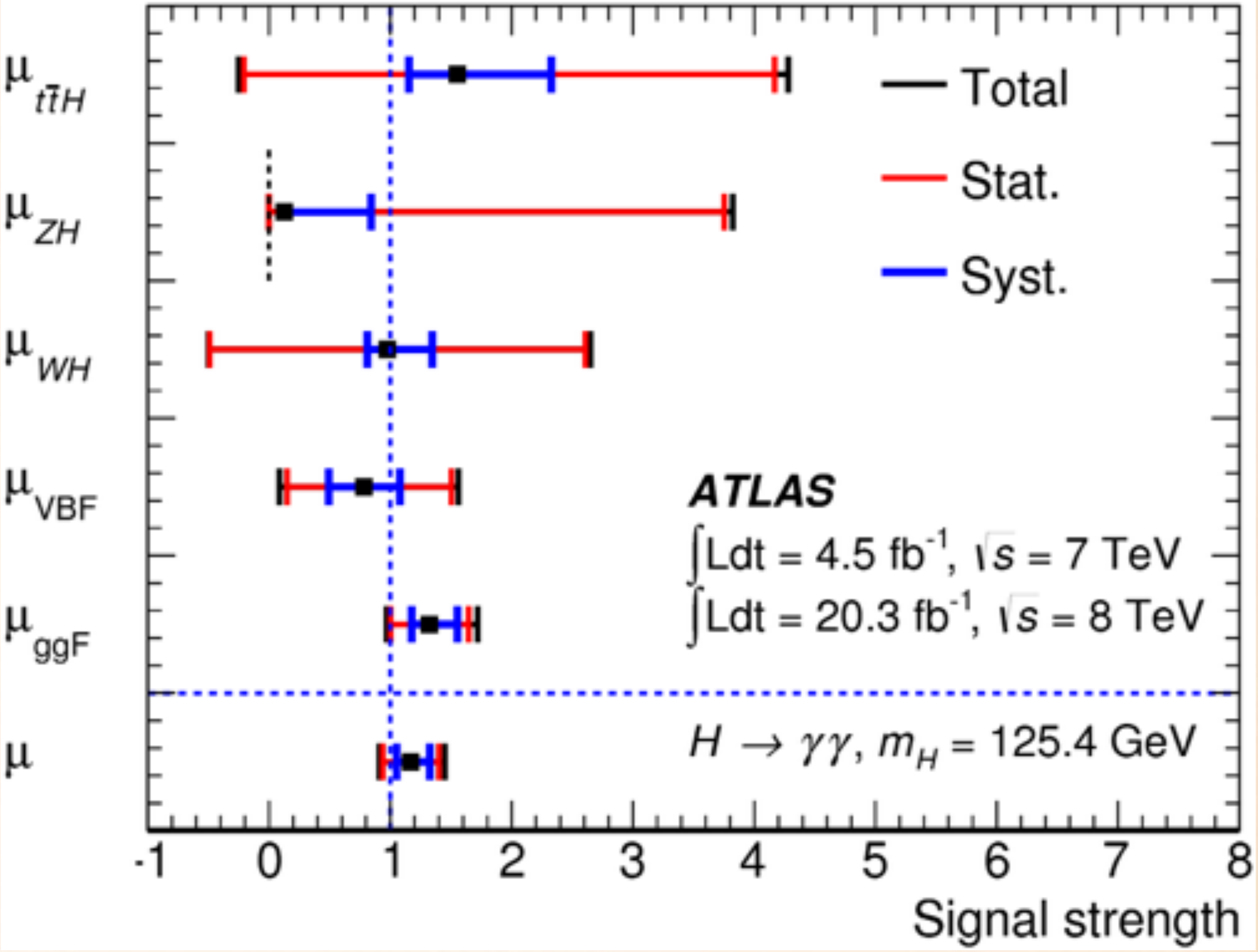


Enhancement of Higgs production rate in the gluon fusion channel

Blum, D’Agnolo, JF , 2012

I don’t require the stop sector only to be responsible for the observed Higgs mass





The data is consistent with the SM so far;
but still has room for deviations.

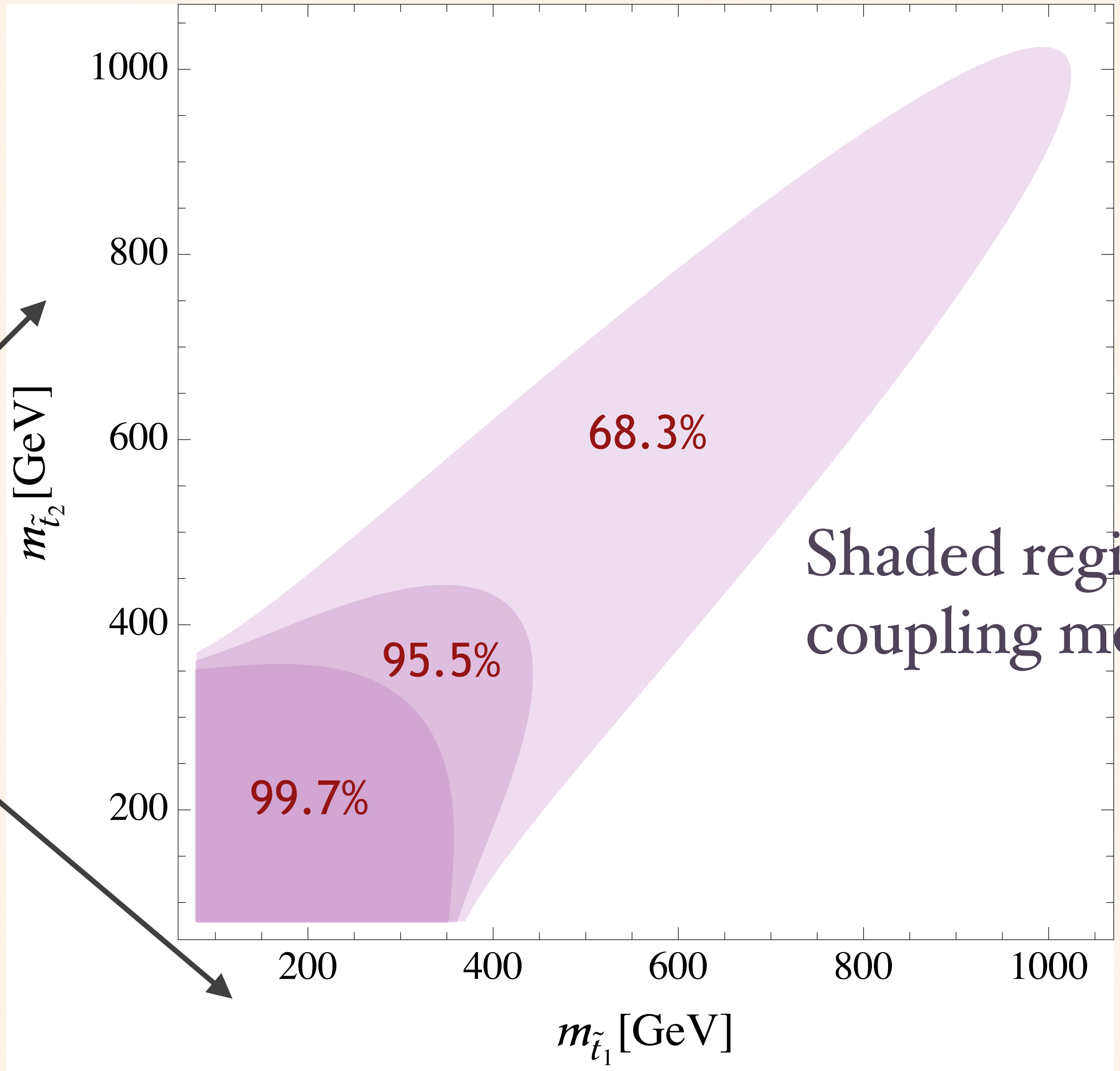
We want to extract from the data:

What do measured Higgs properties tell us about allowed stop masses and the degree of electroweak fine-tuning ?

JF and Reece 2014

Assume only stops modify Higgs coupling

Physical stop masses



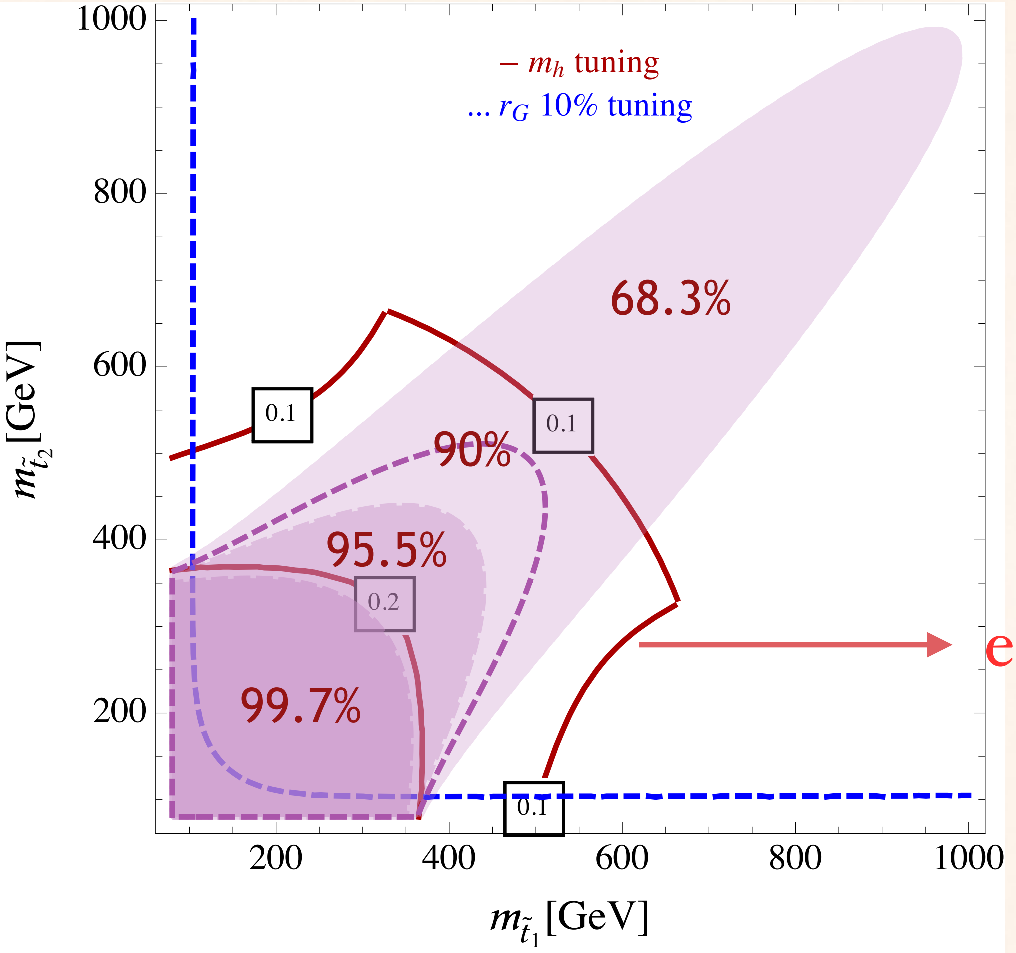
Shaded region inconsistent with Higgs coupling measurements

JF and Reece 2014

Higgs coupling measurements rules out that **both stops with mass below 400 GeV** at 2σ level in the case when stops are the only contribution to the Higgs coupling modification.

The bound is **independent of stop mixing.**

Assume only stops modify Higgs coupling (assuming Yukawa couplings are not modified)



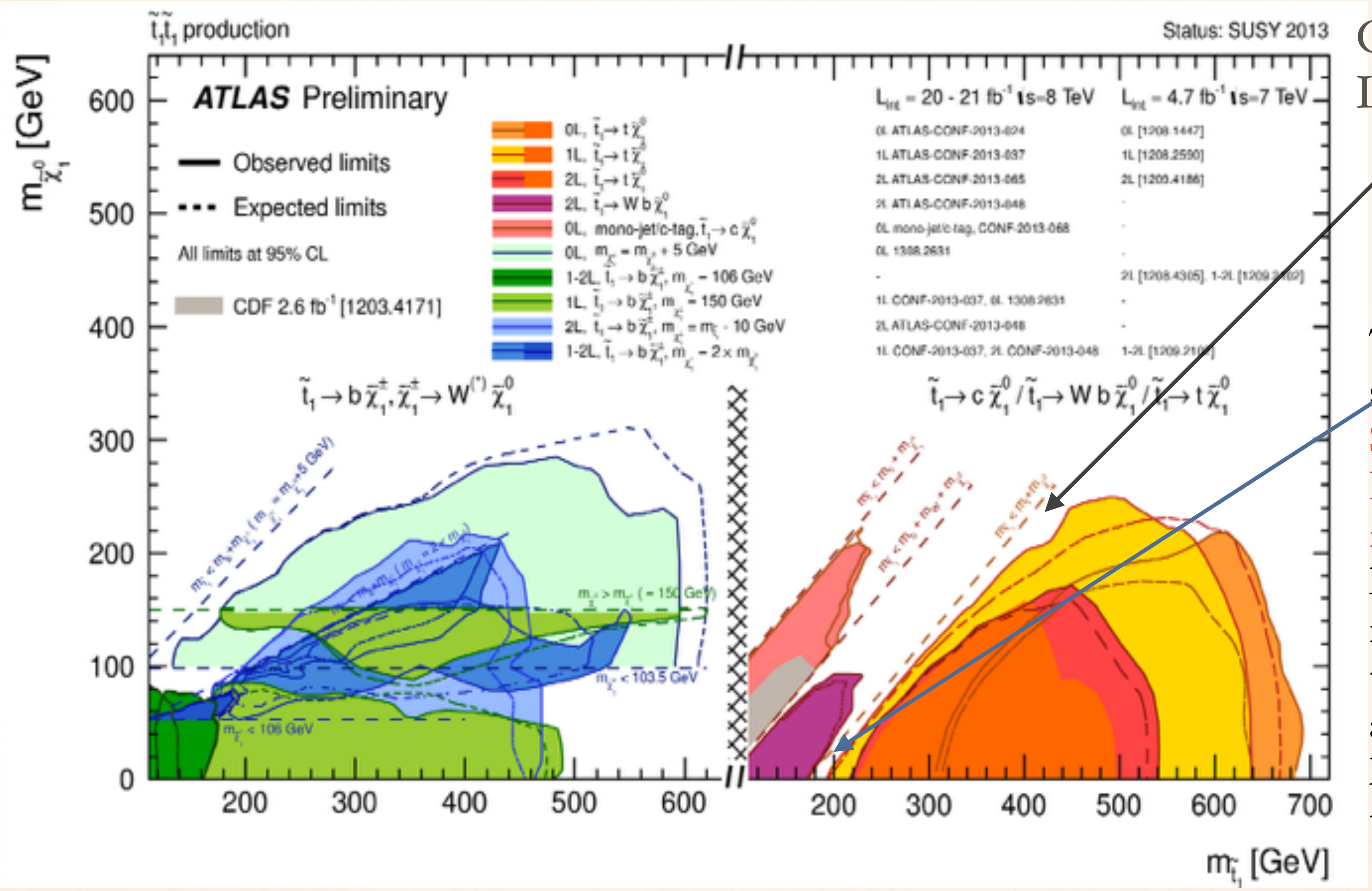
JF and Reece 2014

electroweak fine-tuning

Higgs coupling measurements rules out that **both stops with mass below 400 GeV** in the case when stops are the only contribution to the Higgs coupling modification.

These constraints suggest **a minimum electroweak fine-tuning of between a factor of 5 and 10**.

Direct collider bounds of stops: current bounds close to 500 - 700 GeV but with loopholes

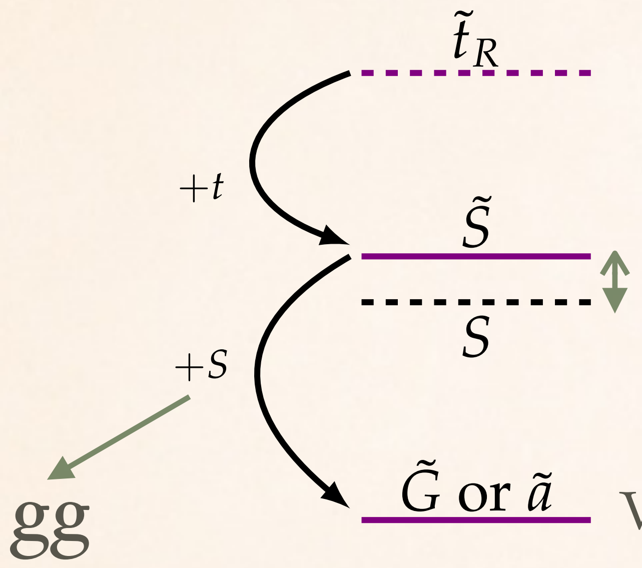


Compressed region: LeCompte, Martin

Tricky Regions such as Stealth Stops (JF, Reece, Ruderman, 2011, 2012) : light stops with masses close to the top mass and could be hidden in the top background

Bounds could also be relaxed (considerably) in cases with more complicated decay chains.

Bounds could also be relaxed (considerably) in cases with more complicated decay chains. For example, MSSM + singlet



m_S ~ 100 GeV

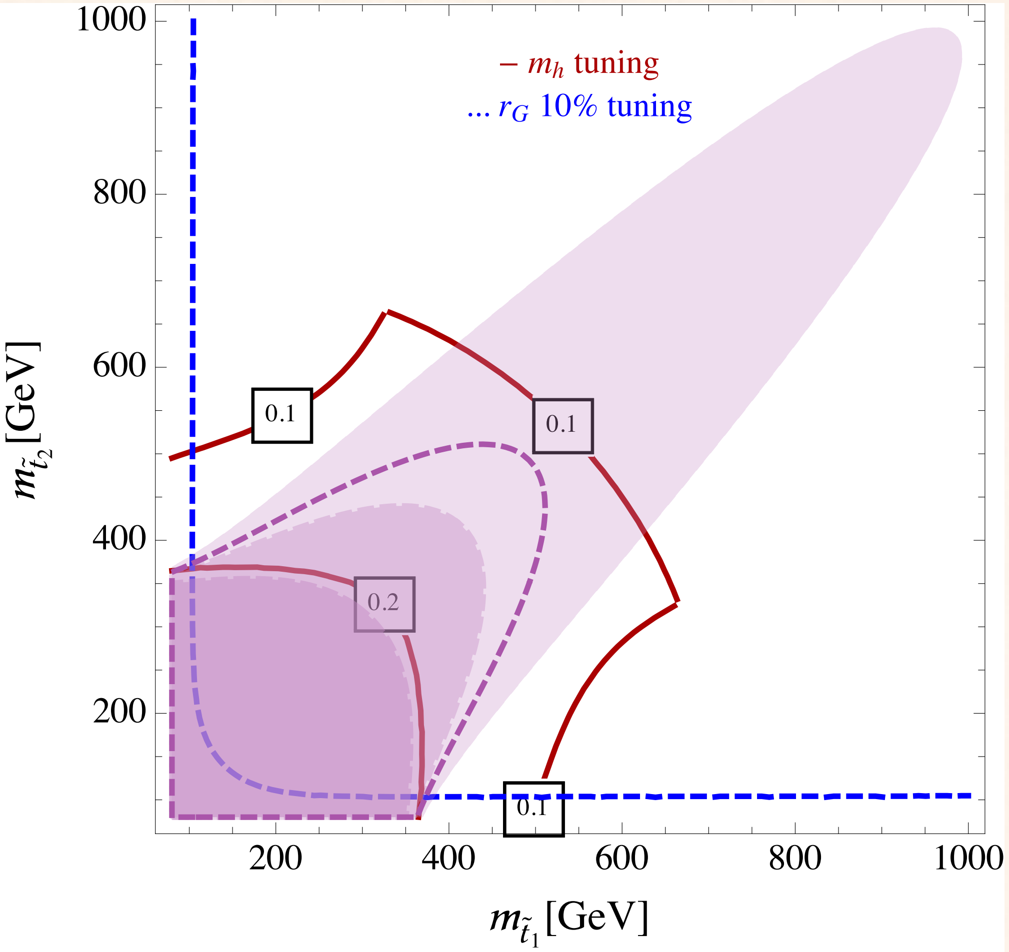
Δm ~ 10 GeV

final state: tops + additional jets

Very light fermion that carries away little missing energy

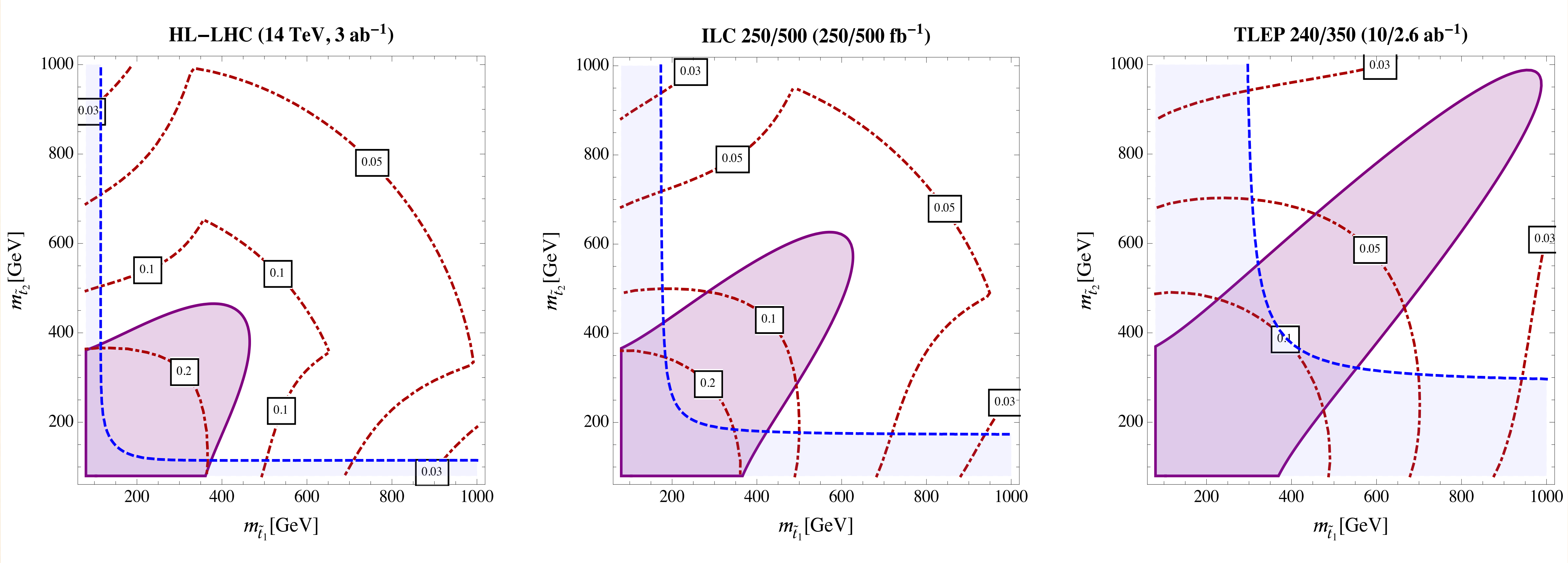
Stealth SUSY:
Fan, Reece, Ruderman 2011, 2012

Potential observable:
jet multiplicity distribution of top pair production



Higgs coupling bounds are independent of how stops decay .
It is complementary to direct searches !

Sensitivities of future experiments



Purple: Higgs coupling 2σ sensitive region;

Blue: Higgs coupling fine-tuning worse than 10%;

Red: Higgs mass fine-tuning contours.

So far, we have discussed in the SUSY context, the implications of Higgs coupling measurements for the mass scales of beyond SM bosons (for example, stops).

In general, the scale at which the new bosonic states appear marks the cut-off of the quadratic divergence in the quantum corrections to the Higgs mass.

Measuring deviations in Higgs couplings at the LHC could indirectly but quite generally, establish the presence of new bosonic scale beyond the weak scale even in case where the deviations arise from Higgs interacting with new fermonic states.

Higgs coupling deviations and a new bosonic scale

Arkani-Hamed, Blum, D'Agnolo and JF 2012;
Blum, D'Agnolo and JF, work to appear in 2014;

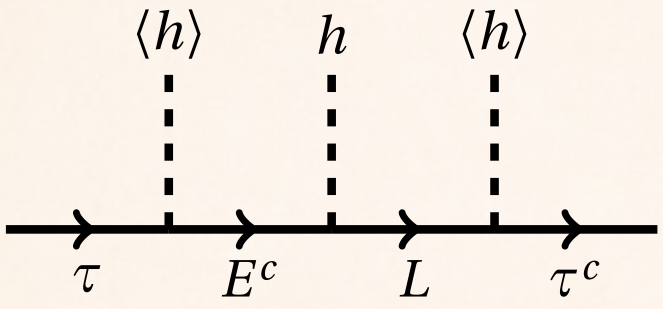
Suppose that we find evidence for deviation in one/more Higgs couplings in the upcoming Higgs coupling measurements. Assume that there is no other light scalar (and associated gauge bosons) in the low energy spectrum and the deviations purely come from new fermions beyond the SM which couples to the SM Higgs.

The new Yukawa couplings will push Higgs quartic coupling to large negative values in the UV, triggering an unacceptable vacuum instability at a scale Λ_{UV} .

Beneath $\Lambda_{UV,}$ bosonic degrees of freedom must kick in to rescue the vacuum instability.

Example: Higgs-tau-tau coupling
new vector-like fermions mixing with the SM tau's.

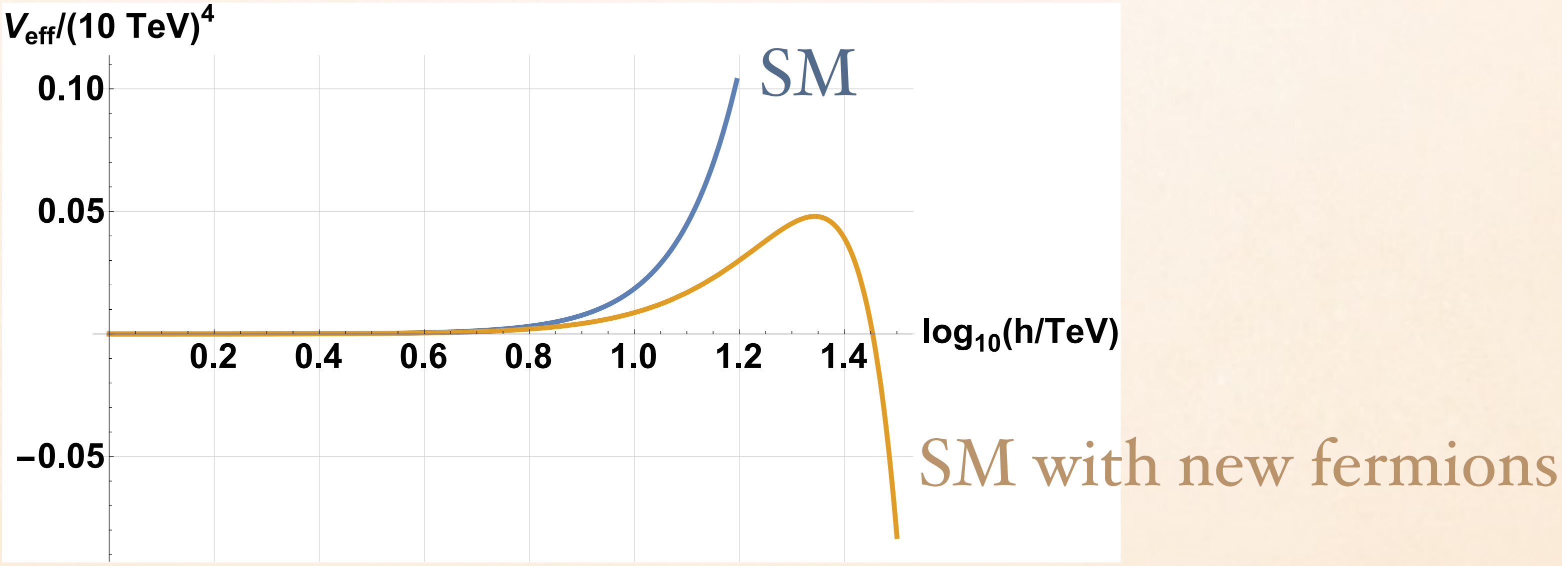
$$-\mathscr{L}_{NP} = Y_{Le^c} H^\dagger L e^c + Y_{lE^c} H^\dagger l E^c + Y_{LE^c} H^\dagger L E^c + Y_{L^c E} H^T \epsilon L^c E + M_L L^T \epsilon L^c + M_E E E^c + cc.$$



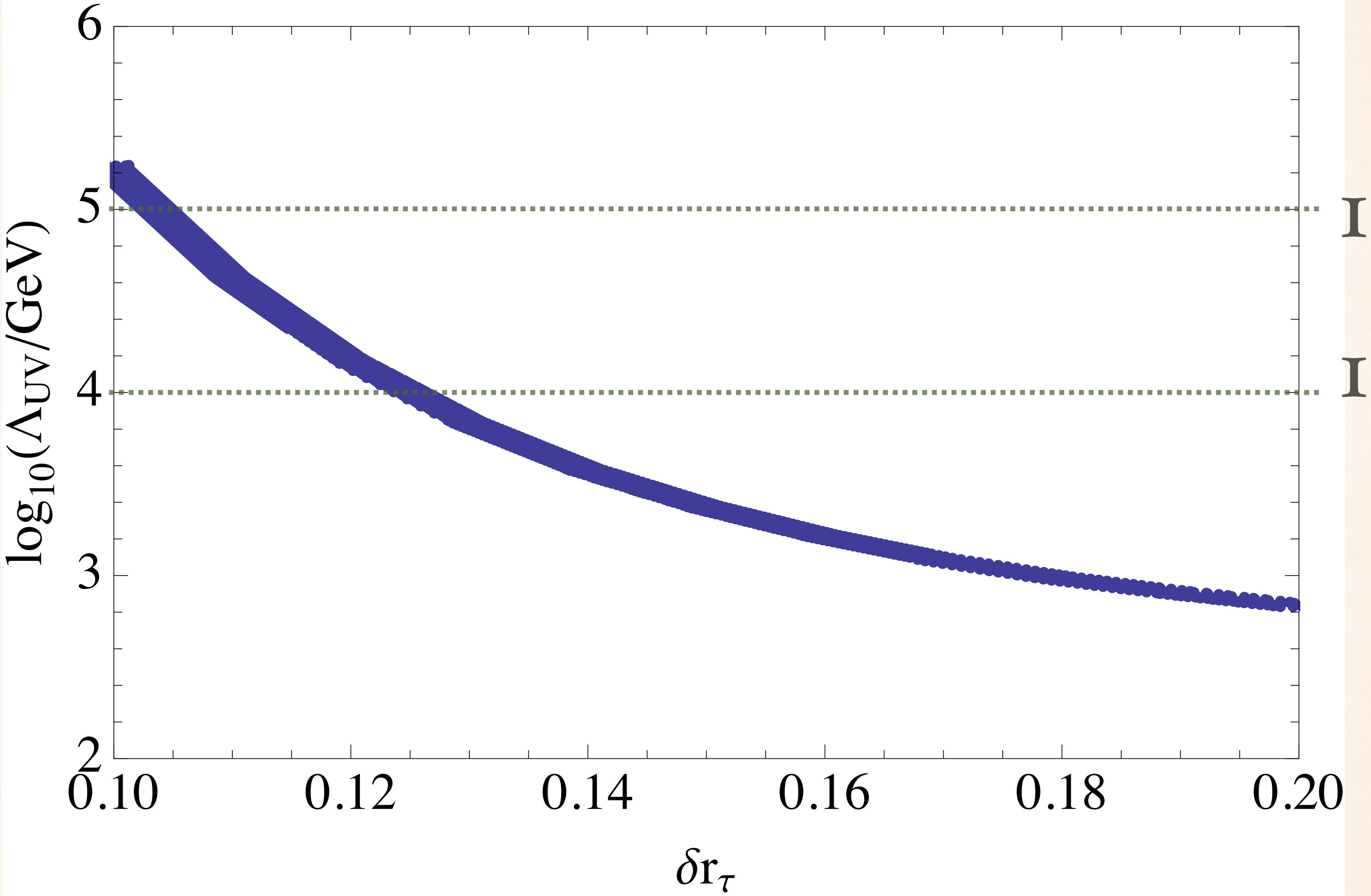
$$r_\tau = \frac{y_{h\tau\tau}}{y_{h\tau\tau}^{\rm SM}} \approx 1 + \frac{Y_{Le^c} Y_{lE^c} Y_{L^c E}}{M_L M_E}$$

Higgs quartic coupling running

$$16\pi^2 \frac{d\lambda}{dt} \sim -2Y^4 \qquad \lambda(\Lambda_{\rm UV}) \approx -0.06$$



Upper bound
on $\Lambda_{\text{UV,}}$
the scale where
new bosons
must appear



100 TeV

10 TeV

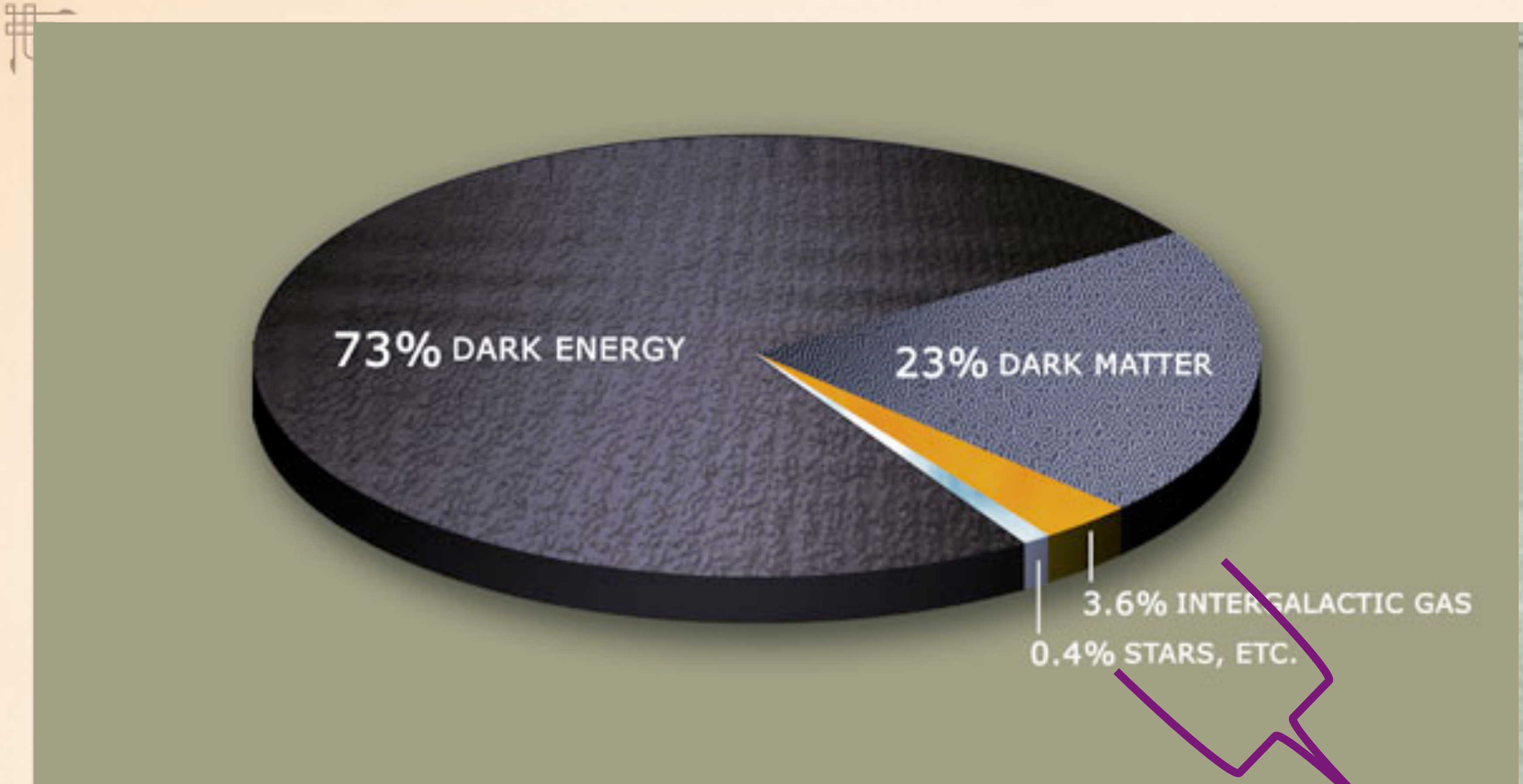
Deviation in h$\tau\tau$ coupling $$\delta r_\tau \equiv \frac{g_{h\tau\tau} - g^{\text{SM}}_{h\tau\tau}}{g^{\text{SM}}_{h\tau\tau}}$$

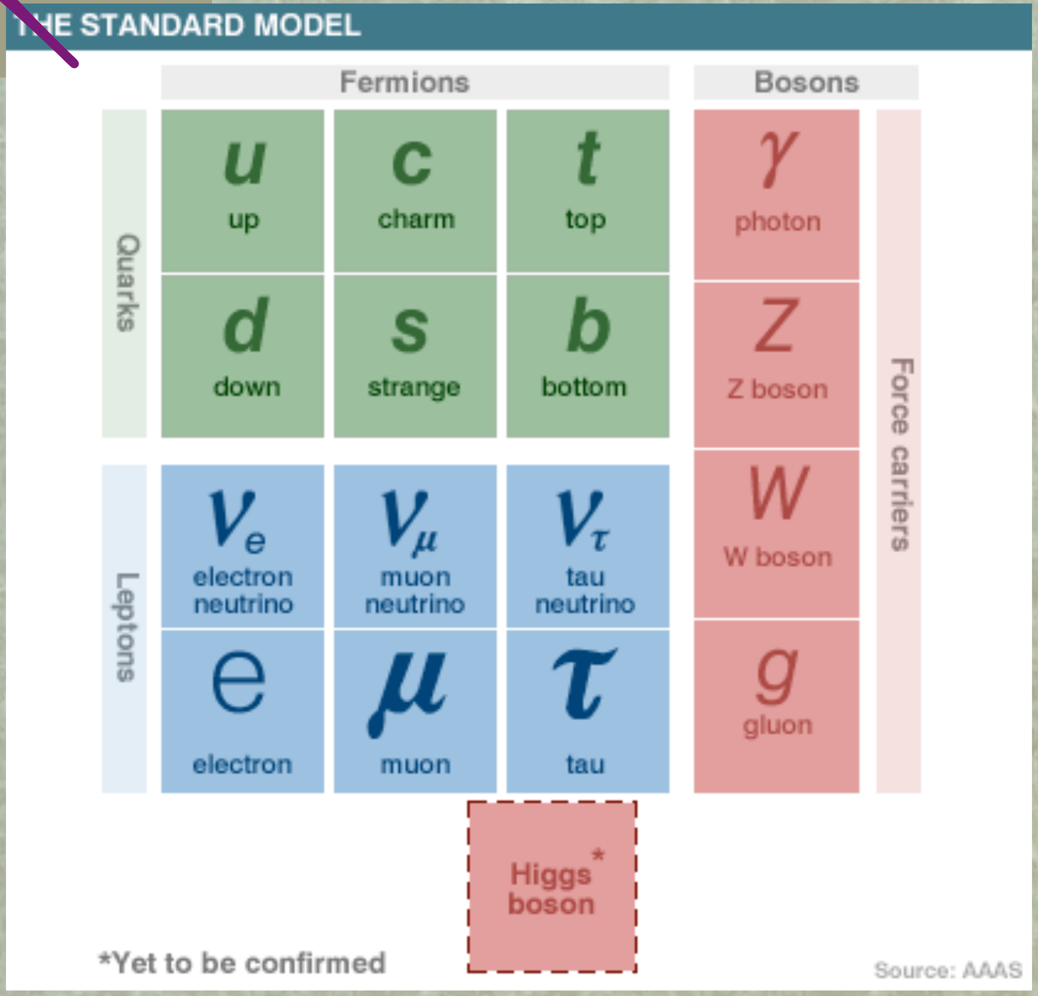
Blum, D'Agnolo and JF, work to appear in 2014

O(10%) deviation in Hbb, $H\tau\tau$, $H\gamma\gamma$, HGG, and much smaller deviation in Htt, HZZ, HWW, would imply new bosonic states at scales of order 10-100 TeV or below.

Blum, D'Agnolo and JF, work to appear in 2014

Dark Sector





THE STANDARD MODEL

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	

Higgs boson*

*Yet to be confirmed

Source: AAAS

15% of the total matter comes from a very complicated model: the Standard Model!

Our visible world deviates markedly from any principle of minimality!!

In visible sector, we have several stable particles: electron, neutrinos, proton.

In sharp contrast, when we usually talk of dark sector, our default is a single component cold collisionless DM with a thermal history.

It is important to explore non-minimal possibilities to find unexplored or less explored experimental signatures which might lead to unexpected discoveries!

Zoo of DM models

Multi-component DM

Minimal models:
thermal WIMP, axion

Partially Interacting DM:
double disk DM...
(Fan, Katz, Randall, Reece, 2013)

Self-interacting DM:
dark atom, mirror matter,
hidden charged DM...

Very light axion
with GUT scale
decay constant

DM with a non-thermal history:
asymmetric DM,
WIMP from moduli decays....

Topogical DM: Q-ball..

Decaying DM

Recent DM anomalies: a diffuse gamma-ray excess in the galactic center in Fermi-LAT data with a spectrum that peaks in the GeV range

Goodenough, Hooper 2009; Boyarsky, Malyshev, Ruchayskiy 2011; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Gordon Macias 2013; Hooper, Slatyer 2013; Daylan, Finkbeiner, Hooper, Linden, Portillo, Slayter 2014 ....

see also Simona Murgia's talk on behalf of the Fermi-LAT collaboration at Fermi symposium

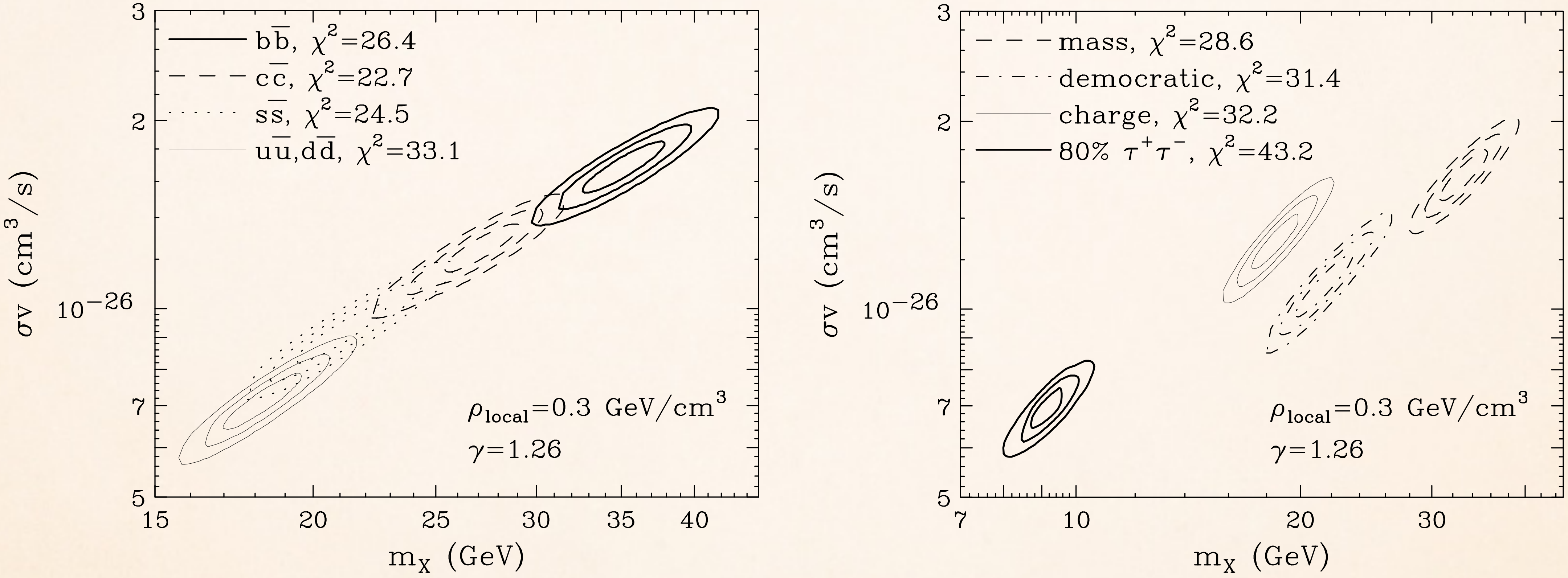
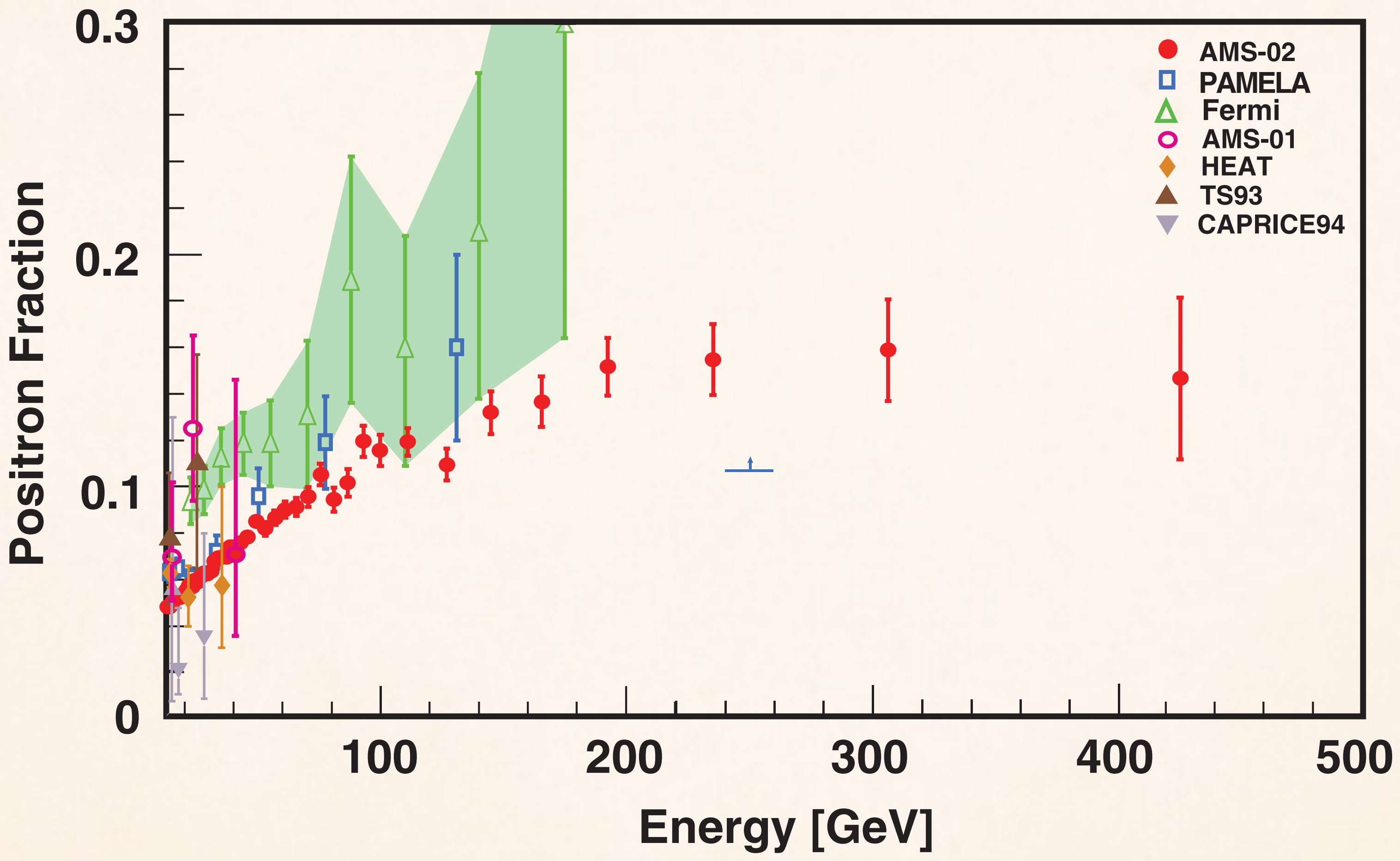


FIG. 15: The range of the dark matter mass and annihilation cross section required to fit the gamma-ray spectrum observed from the Inner Galaxy, for a variety of annihilation channels or combination of channels (see Fig. 14). The observed gamma-ray spectrum is generally best fit by dark matter particles with a mass of ∼20-40 GeV and that annihilate to quarks with a cross section of $\sigma v \sim (1-2) \times 10^{-26}$ cm^3/s.

Daylan, Finkbeiner, Hooper, Linden, Portillo, Slayter 2014

PAMELA, AMS-02: rise of positron fraction



AMS-02, PRL, 2014

There are other astrophysical anomalies such as observation of a 3.5 keV X-ray line in the galaxy clusters.

All these astrophysical observations are highly interesting.

Each of them has a large astrophysical uncertainty which requires a lot more work to do to reach a final conclusion.

I’ll just discuss briefly their particle physics implications assuming that they are DM signals.

Different observations point towards different DM interpretations.
I’ll focus on the GeV excess.

A module to explain every anomaly and to be less constrained by direct detection and collider searches

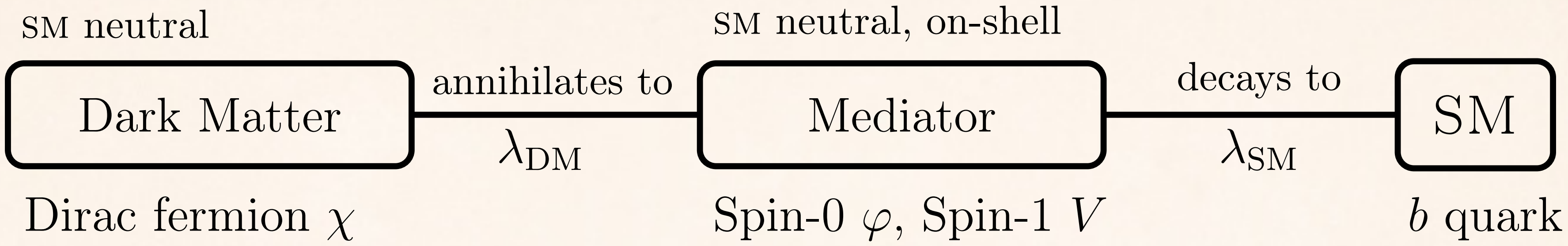
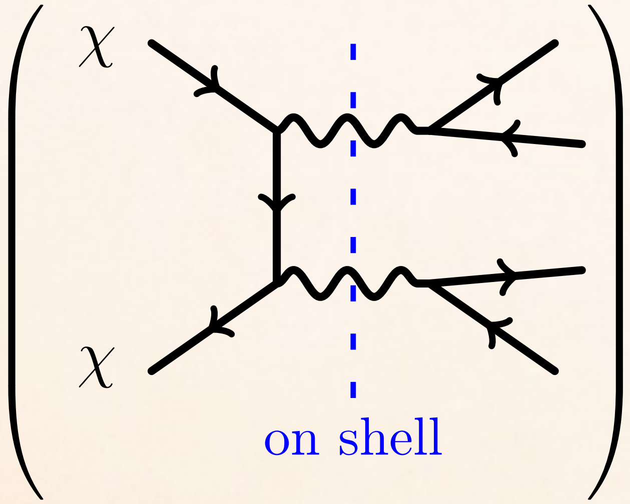


Illustration taken from paper by
Abdullah, DiFranzo, Rajaraman, Tait, Tanedo, Wijangco 2014

For PAMELA/AMS,
e+e- final state

Rate ~



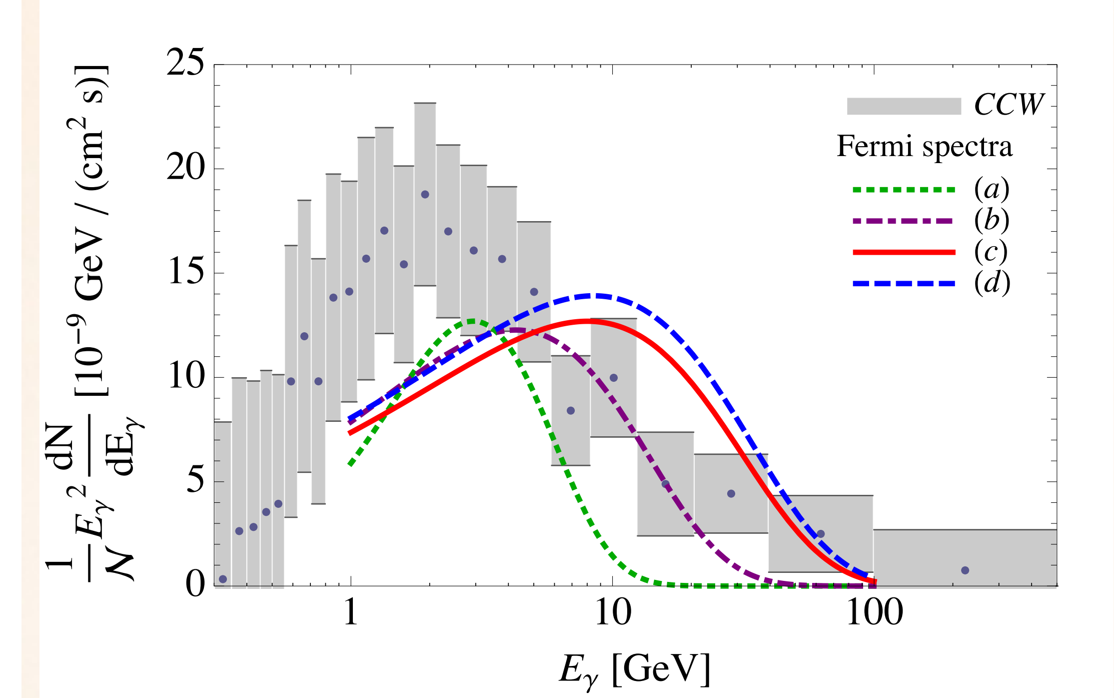
$\sim \lambda_{\mathrm{DM}}^2$

Basic idea:
the signal rate is determined
by the coupling in the dark sector
while direct coupling between the
dark sector and visible sector
could be small and less constrained

mediators: dark photon (fixed-target) searches

A' experiment (APEX), Heavy Photon Search (HPS), Dark Light ...

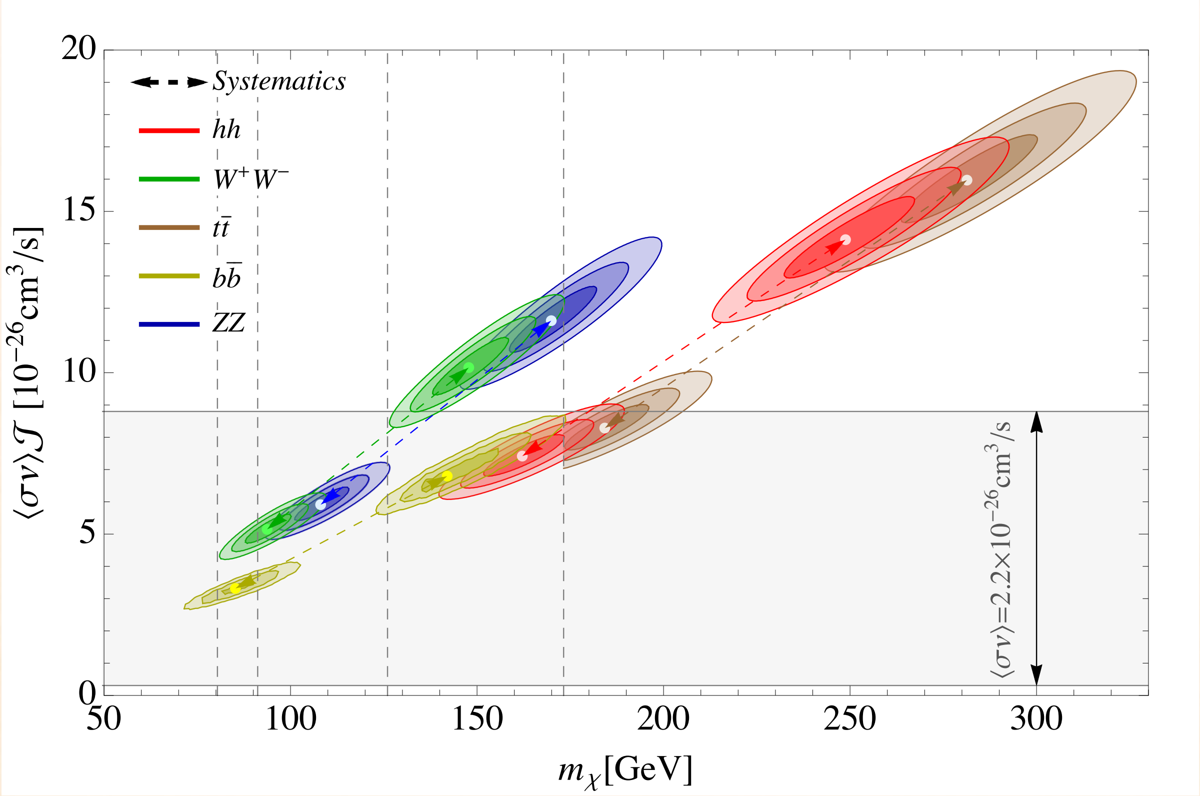
A new twist of GeV excess:
heavier DM with mass ~ (100 - 300) GeV annihilating into WW/ZZ/tt



Agrawal, Batell, Fox, Harnik 2014

Then the excess could be explained by simple WIMP models such as MSSM neutralinos!

This explanation could be tested at collider!



Conclusion

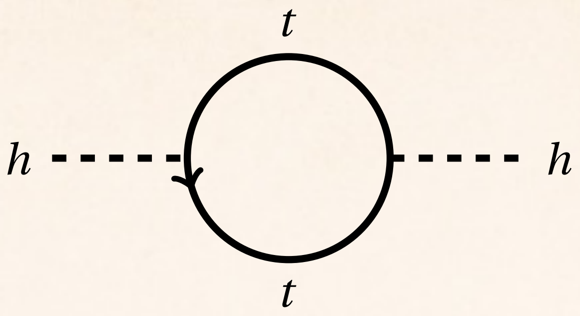
We live in a exciting era of data.

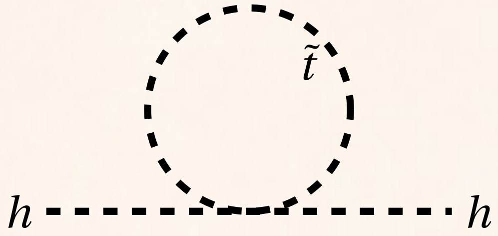
We must keep exploring new possibilities both theoretically and experimentally. It might be unlikely we'll stumble upon exactly the right theory without an experimental clue. But we could stumble upon that experimental clue by exploring a broader range of theories.

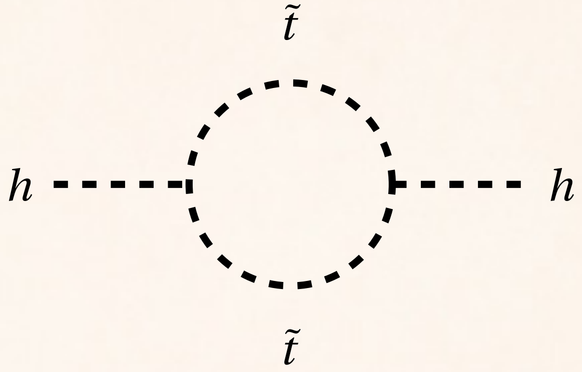
Between the LHC (Higgs measurements, direct searches...), dark matter searches and other experiments, our discovery prospects remain bright!

Thank you !

Backup







Quantum correction to Higgs mass $\sim \frac{3m_t^4}{4\pi^2 v^2} \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$

An analogy: introduce positron $\delta m_e = \frac{3\alpha}{2\pi} m_e \log \frac{\Lambda_{\mathrm{UV}}}{m_e}$

HIGGS MASS IN SUSY

Let's start with minimal supersymmetric standard model: at tree-level

$$V = |F|^2 + |D|^2,$$

$$V \supset \frac{1}{8}(g^2 + g'^2)(h_u^{02} - h_d^{02})^2$$

$$m_h < m_Z |\cos(2\beta)| \qquad \tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

To get a 125 GeV Higgs, one needs a large quantum correction or to go beyond MSSM.

For moderately large tan β, tan β > 2,

Physical Higgs mass

$$m_h^2 = -2\left(|\mu|^2 + m_{H_u}^2|_{\text{tree}} + m_{H_u}^2|_{\text{rad}}\right)$$

$W \supset \mu H_u H_d$

Soft mass of Hu at tree level and loop level

Natural EWSB means that no large cancellations among terms on the right-hand side to get the correct physical Higgs mass.

For moderately large tan β, tan β > 2,

$$m_h^2 = -2\left(|\mu|^2 + m_{H_u}^2|_{\rm tree} + m_{H_u}^2|_{\rm rad}\right)$$

Natural EWSB means that no large cancellations among terms on the right-hand side to get the correct physical Higgs mass.

This leads to naturalness requirements:

At tree-level: light Higgsinos: $|\mu| \sim m_h$

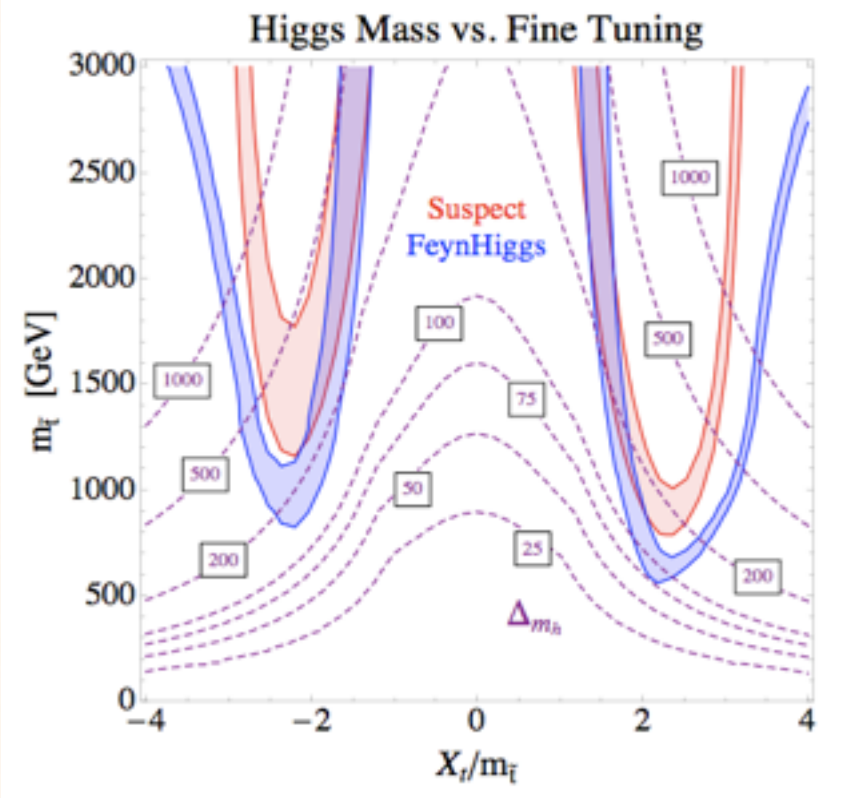
At one-loop level: light stops (with mass ≲ 700 GeV to avoid more than 10 % fine-tuning Papucci, Ruderman and Weiler 2011)

SUSY breaking mediation scale

$$(\Delta^{-1})_{\tilde t} = \left|\frac{2\delta m_{H_u}^2}{m_h^2}\right|, \quad \delta m_{H_u}^2|_{\rm stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + A_t^2\right) \log\left(\frac{\boxed{\Lambda}}{\rm TeV}\right)$$

Kitano, Nomura 2006

$$(\Delta^{-1})_{\tilde{t}} = \left|\frac{2\delta m^2_{H_u}}{m_h^2}\right|, \quad \delta m^2_{H_u}|_{\text{stop}} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{Q_3} + m^2_{u_3} + A_t^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$



Hall, Pinner, Ruderman 2011

In MSSM, to get the Higgs mass to be 125 GeV, a large quantum correction must be introduced with multi-TeV SUSY breaking parameters;
the fine-tuning is worse than a few percent.

$$|X_t| \gtrsim 1000 \text{ GeV}, \quad M_S \gtrsim 500 \text{ GeV}.$$

$$M_S \equiv (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}$$

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

$$\gtrsim (85\text{GeV})^2$$

Alternative Routes for SUSY

Keep naturalness: go beyond MSSM: NMSSM, λSUSY...
Alleviate collider constraints: RPV, compressed SUSY, folded SUSY, Stealth SUSY (JF, Ruderman, Reece 2012, 2013) ...

125 GeV Higgs boson

Give up strict naturalness: high-scale supersymmetry
SUSY still stabilizes most of the hierarchy, preserves gauge coupling unification, provides DM candidate. Ameliorates flavor and CP problem

STOP EFFECT

Stop sector:

$$\mathcal{L}_{\text{stop masses}} = -\left(\tilde{t}_L^* \ \tilde{t}_R^*\right) m_{\tilde{t}}^2 \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

Soft mass of left-handed stop

Mixing between left and right-handed stop

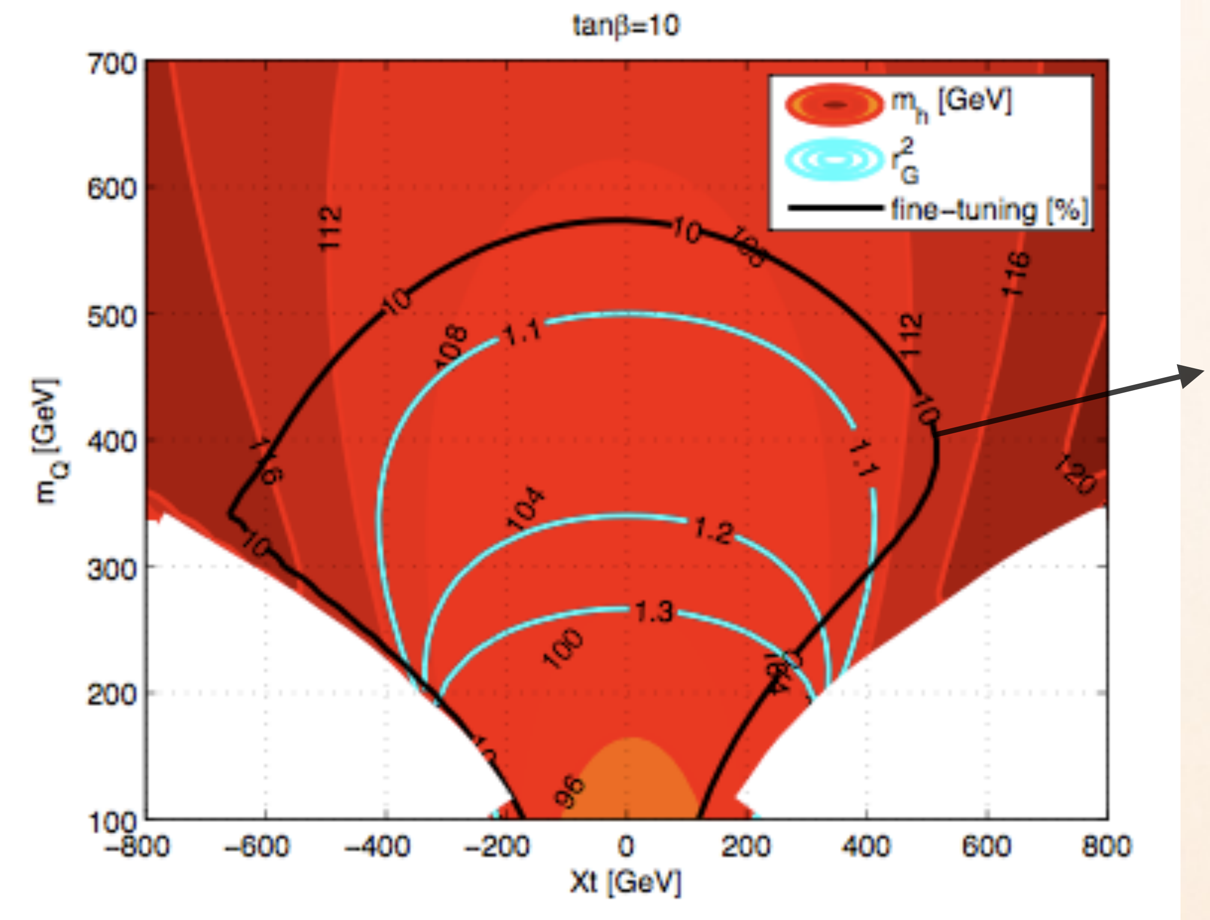
$$m_{\tilde{t}}^2 = \begin{pmatrix} \boxed{m_{Q_3}^2} + m_t^2 + \Delta_{\tilde{u}_L} & m_t \boxed{X_t} \\ m_t X_t^* & \boxed{m_{U_3}^2} + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix},$$

Soft mass of right-handed stop

Stop sector: $$m_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} & m_t X_t \\ m_t X_t^* & m_{U_3}^2 + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix},$$

Stops have an effect on Higgs mass and fine-tuning:

$$(\Delta^{-1})_{\tilde{t}} = \left| \frac{2\delta m_{H_u}^2}{m_h^2} \right|, \quad \delta m_{H_u}^2|_{\text{stop}} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + A_t^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$



Higgs mass 10% fine-tuning

Blum, D’Agnolo, JF , 2012

Low energy Higgs theorem

Ellis, Gaillard, Nanopoulos 1976; Shifman, Vainshtein, Voloshin, Zakharov 1979

hgg, h***γγ*** couplings are related to the beta function coefficients

Gauge kinetic term $\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu}$

Run the gauge coupling from Λ to μ with an intermediate scale M, at which the beta function coefficient changes from b to b + Δb

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2} \log \frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2} \log \frac{\Lambda}{M}$$

Suppose the intermediate scale M is a function of Higgs field h, M = M(h). Expanding around the Higgs VEV, one obtains the Higgs coupling

$$\frac{\Delta b}{32\pi^2} \frac{h}{v} G^a_{\mu\nu} G^{a\mu\nu} \frac{\partial \log M(v)}{\partial \log v}$$

We want to extract the bottom line from the data:

what do measured Higgs properties tell us about allowed stop masses?

Since there are three parameters in the stop mass squared matrix, usually people made a variety of choices, e.g., fix X_t or the mixing angle and plot in the physical mass plane.

What I am going to present next is a new way of extracting the Higgs coupling constraints on the stop sector. (I will assume that the Higgs mass comes from some additional physics beyond MSSM).

JF and Reece 2014

three free parameters

$$m^2_{\tilde{t}} = \begin{pmatrix} \boxed{m^2_{Q_3}} + m_t^2 + \Delta_{\tilde{u}_L} & m_t \boxed{X_t} \\ m_t X_t^* & \boxed{m^2_{U_3}} + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix},$$

diagonal mass splitting   off-diagonal splitting

$$\left| m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2} \right| = \sqrt{\boxed{(m^2_{Q_3} + \Delta_{\tilde{u}_L} - m^2_{U_3} - \Delta_{\tilde{u}_R})^2} + \boxed{4 m_t^2 X_t^2}}$$

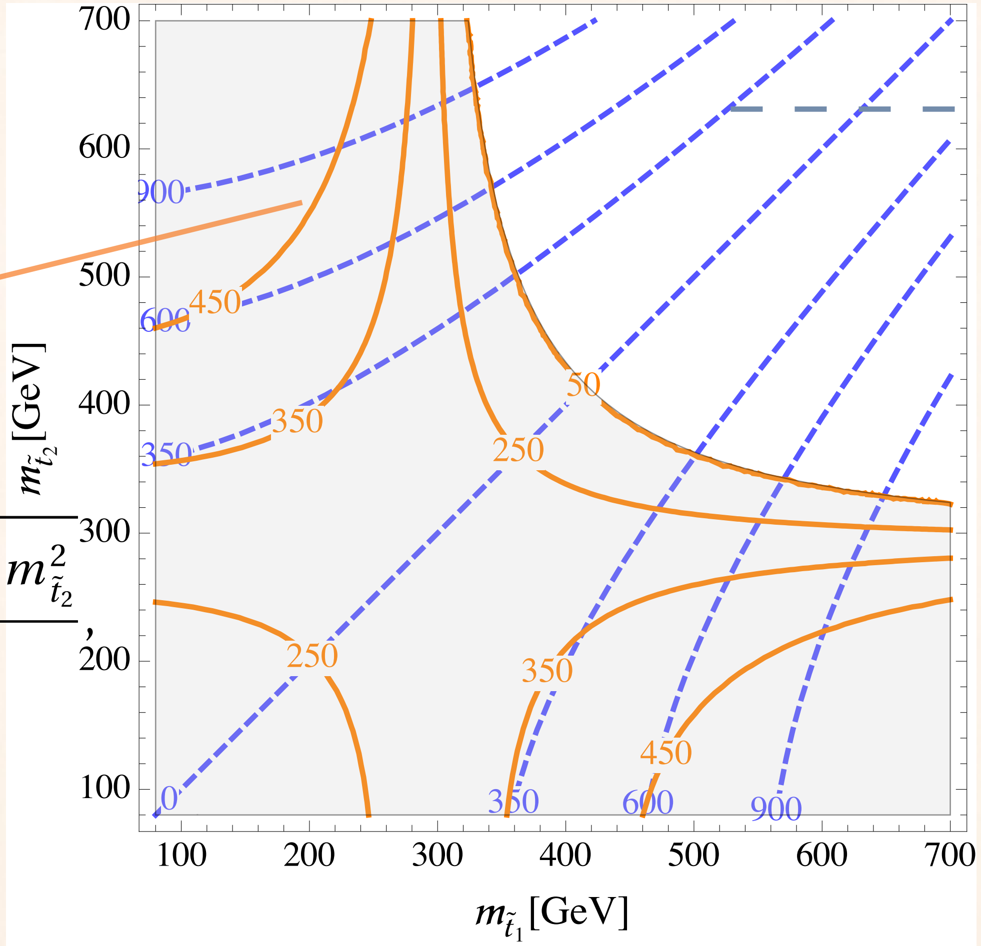
For fixed physical stop masses,

$$\left| X_t^{\max} \right| = \frac{\left| m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2} \right|}{2 m_t},$$

$$r_G^{\tilde{t}} \equiv \frac{c^{\tilde{t}}_{hgg}}{c^{\mathrm{SM}}_{hgg}} \approx \frac{1}{4} \left(\frac{m_t^2}{m^2_{\tilde{t}_1}} + \frac{m_t^2}{m^2_{\tilde{t}_2}} - \frac{m_t^2 X_t^2}{m^2_{\tilde{t}_1} m^2_{\tilde{t}_2}} \right), \quad \text{stop contribution},$$

The maximal deviation in Higgs-digluon coupling allowed by the data (from the fit)

$$\left| X_t^{\min} \right| = \frac{\sqrt{m_t^2 (m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}) - 4 \boxed{\left(r_G^{\tilde{t}} \right)^{\text{fit;max}}} m^2_{\tilde{t}_1} m^2_{\tilde{t}_2}}}{m_t},$$



$|X_{t;\text{max}}|$

$$\left|X_t^{\max}\right| = \frac{\left|m_{\tilde t_1}^2 - m_{\tilde t_2}^2\right|}{2m_t},$$

$|X_{t;\text{min}}|$

$$\left|X_t^{\min}\right| = \frac{\sqrt{m_t^2(m_{\tilde t_1}^2 + m_{\tilde t_2}^2) - 4\left(r_G^{\tilde t}\right)^{\text{fit;max}} m_{\tilde t_1}^2\, m_{\tilde t_2}^2}}{m_t},$$

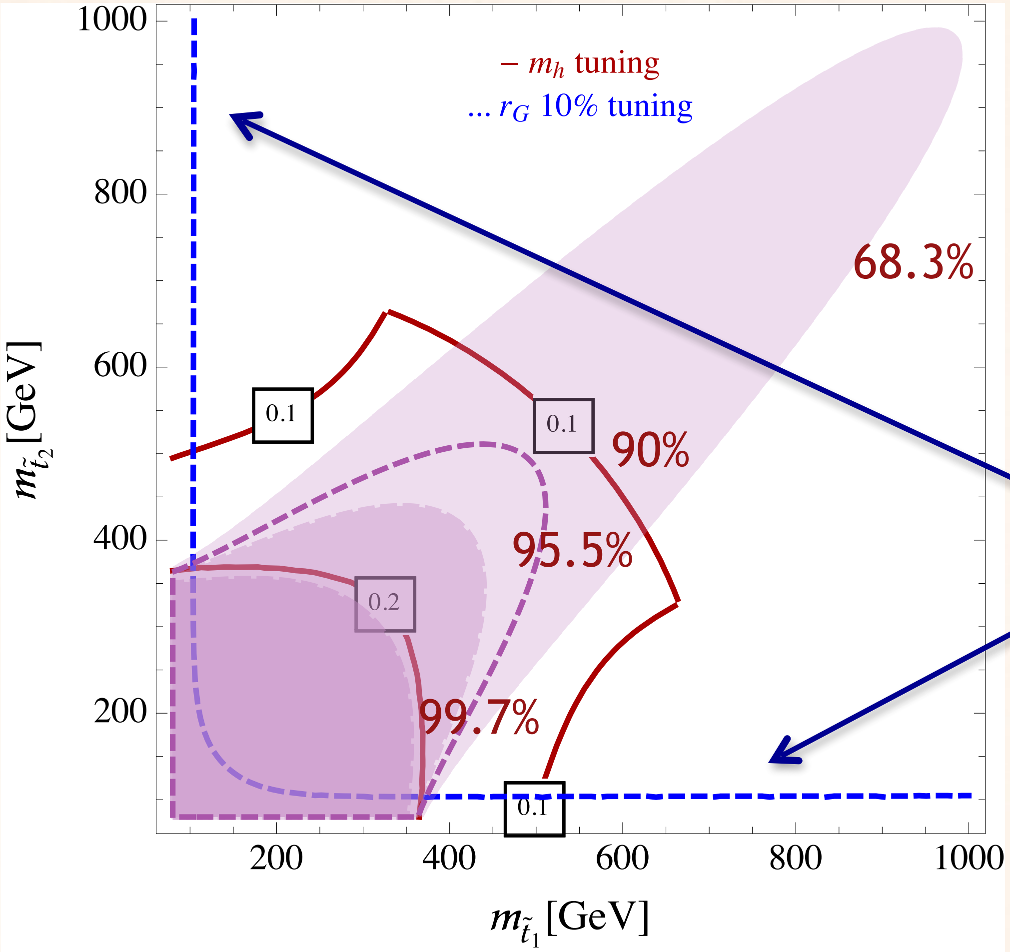
Fine-tuning associated with Higgs coupling:

$$r_G^{\tilde{t}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right), \quad \text{stop contribution,}$$

$$\text{Higgs coupling fine} - \text{tuning} \sim \left| \frac{\frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}}{\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}} \right|$$

More formally,

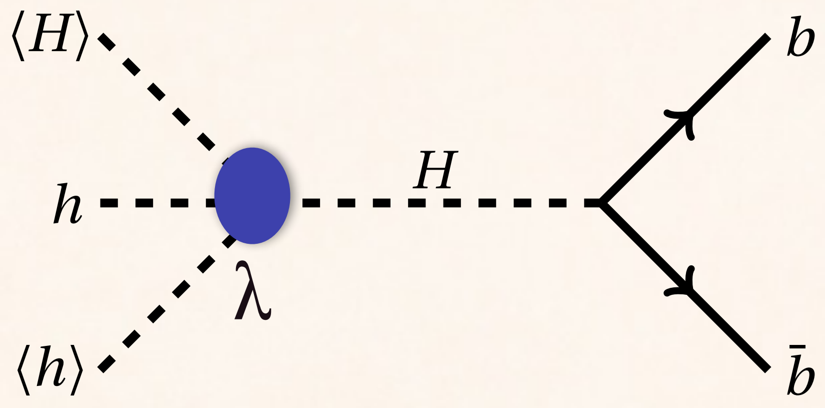
$$\left(\Delta_G^{-1}\right)_{\tilde{t}} = \left|\sum_i \left(\frac{\partial \log r_G^{\tilde{t}}}{\partial \log p_i}\right)^2\right|^{1/2} \qquad p = (m_{Q_3}^2, m_{U_3}^2, X_t)$$



10% Higgs coupling fine-tuning constrains even one stop below 100 GeV

This is in tension with electroweak baryogenesis with light stops. One could relieve the tension by increasing the Higgs invisible decay to light neutralinos. Carena, Nardini, Quiros and Wagner; Cohen, Morrissey and Pierce; Curtin, Jaiswal, Meade 2012

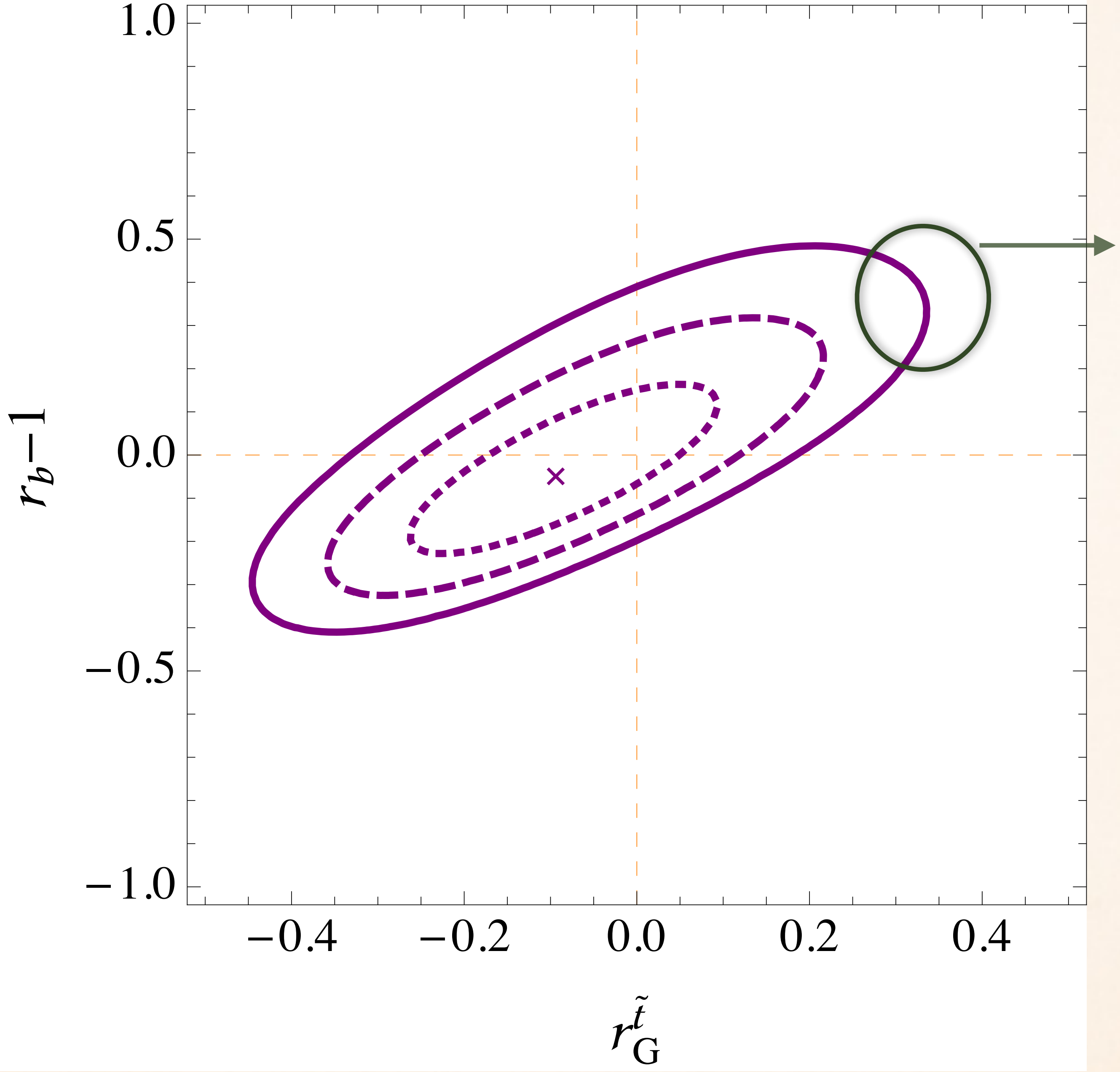
In SUSY, there could be another source of Higgs coupling modification, which comes from Higgs mixings as SUSY requires more than one Higgs doublet. They may modify Higgs coupling to massive SM fields, such as the bottom Yukawa. This could affect the Higgs decays significantly (the dominant Higgs decay channel is h to b quarks).



$$r_b \equiv \frac{v c^{\rm SUSY}_{hb\bar{b}}}{m_b} \sim 1 - \frac{\lambda v^2}{\boxed{m_H^2}}$$

Heavy CP-even Higgs mass

Global fit with 2 parameters



When bottom Yukawa is enhanced, the reduction in branching ratios of most channels compensate the increase in gluon fusion rate due to an enhanced Higgs digluon rate

In certain natural SUSY models, such as vector-like D-term models, the bottom Yukawa could be enhanced

$$r_b = \frac{y_{hb\bar{b}}}{y^{\rm SM}_{hb\bar{b}}} \approx \left(1 - \frac{m_h^2}{m_H^2}\right)^{-2}$$

$$\approx 1 + 0.22 \left(\frac{400\,\mathrm{GeV}}{\boxed{m_H}}\right)^2$$

Blum, D’Agnolo, JF , 2012

Heavy CP-even Higgs mass

The Higgs coupling bound on the stops could be relaxed if the bottom Yukawa is enhanced but only when the heavy Higgs is lighter than 500 GeV.

JF, Reece 2014

Currently, both ATLAS and CMS perform neutral heavy Higgs search in the $\tau\tau$ final state (the bound is model dependent);
ATLAS also looks for heavy Higgs in leptonic WW channel and WWbb channel.

It would be interesting to look for heavy Higgs to ZZ.

In this case, direct searches and Higgs coupling measurements are complimentary as well !

Example 1:
Higgs-diphoton coupling

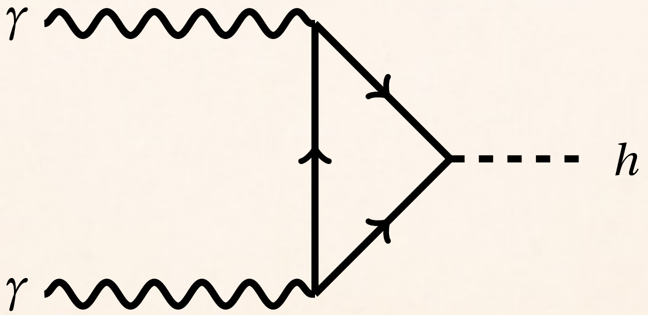
$$\psi, \psi^c \sim (1,2)_{\pm\frac{1}{2}}, \quad \chi, \chi^c \sim (1,1)_{\mp 1}.$$

new Yukawa interactions

$$\mathcal{L}_M = -\left(\psi^{+Q}\ \chi^{+Q}\right)\begin{pmatrix} m_\psi & yH \\ y^c H & m_\chi \end{pmatrix}\begin{pmatrix} \psi^{-Q} \\ \chi^{-Q} \end{pmatrix} + cc,$$

$$\mu_{\gamma\gamma} = \frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{\rm SM}} \approx \left|1 + 0.2Q^2\frac{yy^cv^2}{m_1^2}\right|^2$$

Lightest new lepton mass



Joglekar, Schwaller and Wagner; Arkani-Hamed, Blum, D'Agnolo and JF 2012

Example 1:
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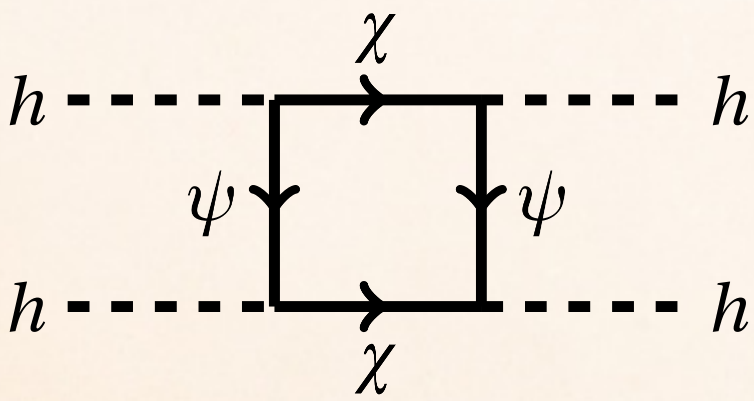
Lightest new lepton mass

Higgs quartic coupling

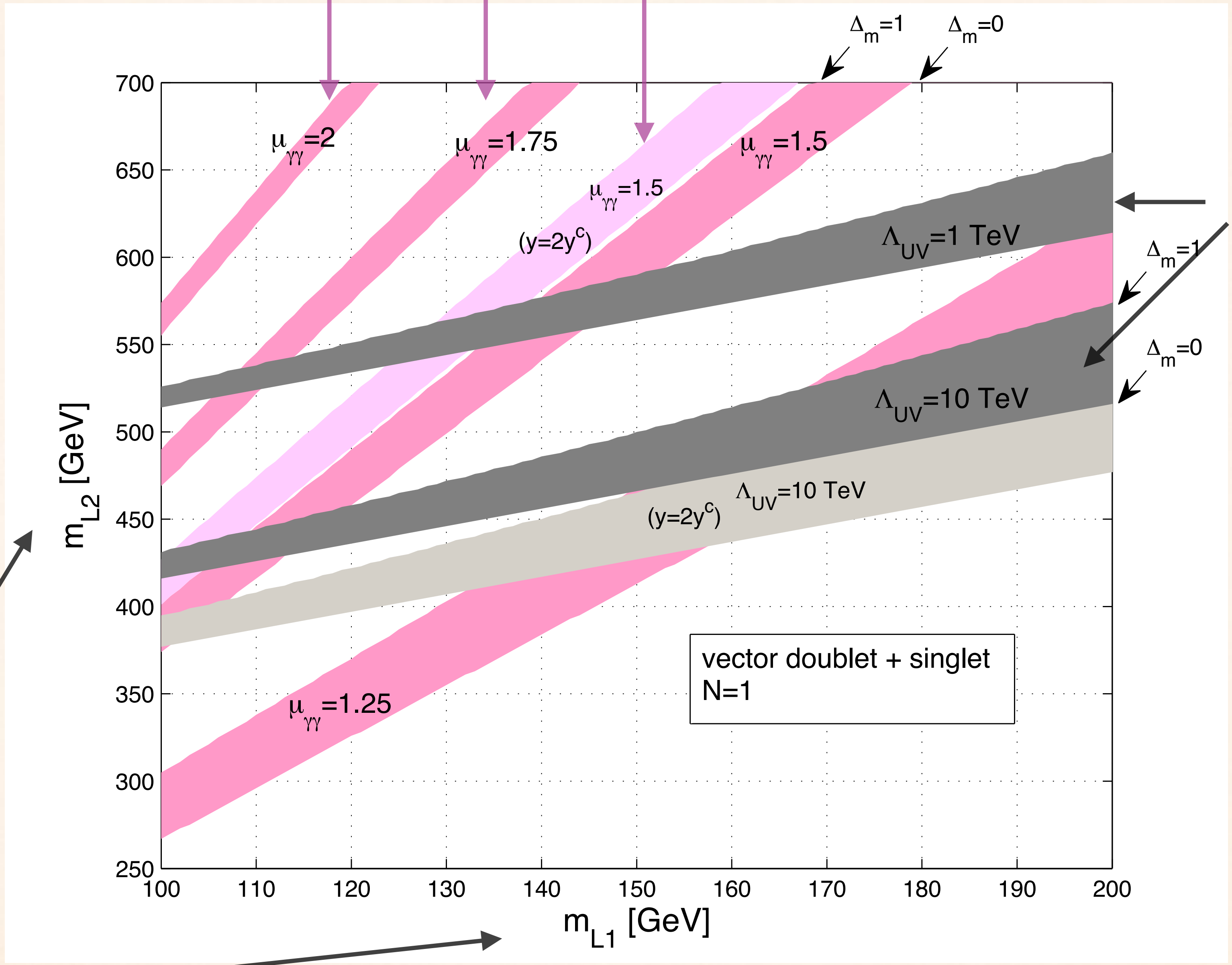


$$16\pi^2 \frac{d\lambda}{dt} \sim -2y^4 - 2y^{c4}$$

$$\lambda(\Lambda_{\text{UV}}) \approx -0.06$$

Joglekar, Schwaller and Wagner; Arkani-Hamed, Blum, D'Agnolo and JF 2012

Enhancement of the Higgs decaying to diphoton rate



the scale where new bosons must appear

Physical masses of the new leptons

Arkani-Hamed, Blum, D'Agnolo and JF 2012

In the future, beyond HL-LHC,

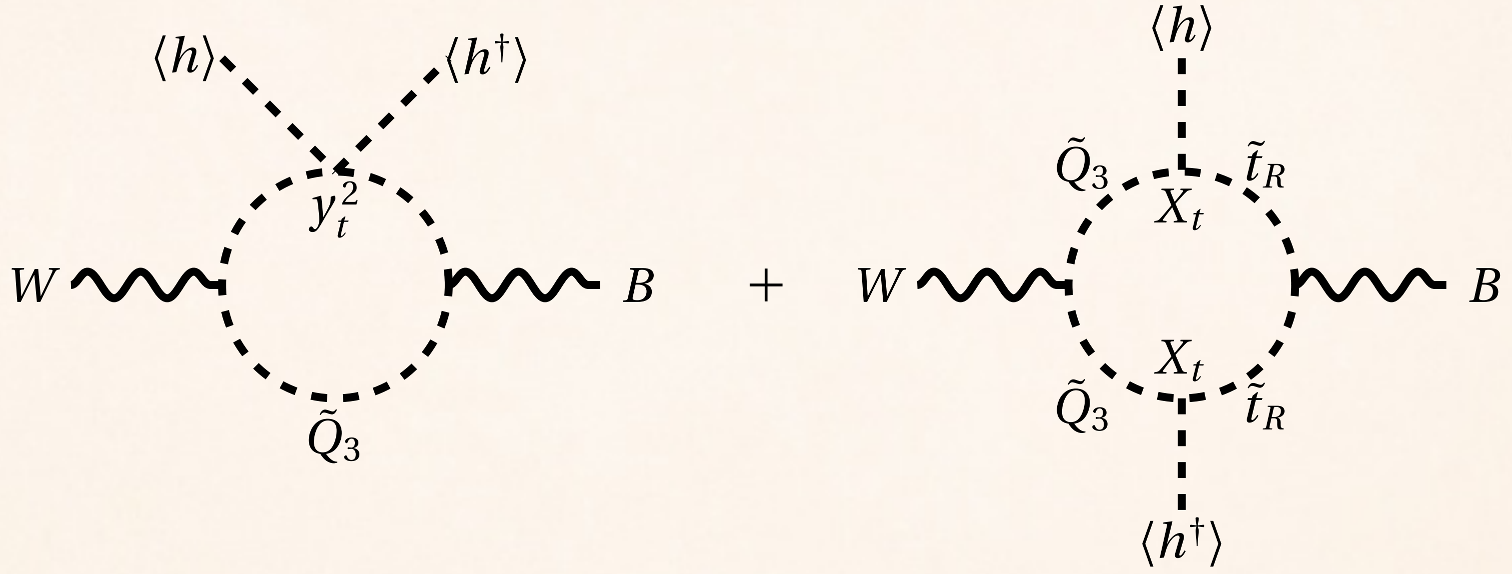
International Linear Collider (ILC)

Future Circular Collider (FCC-ee, formerly known as TLEP)

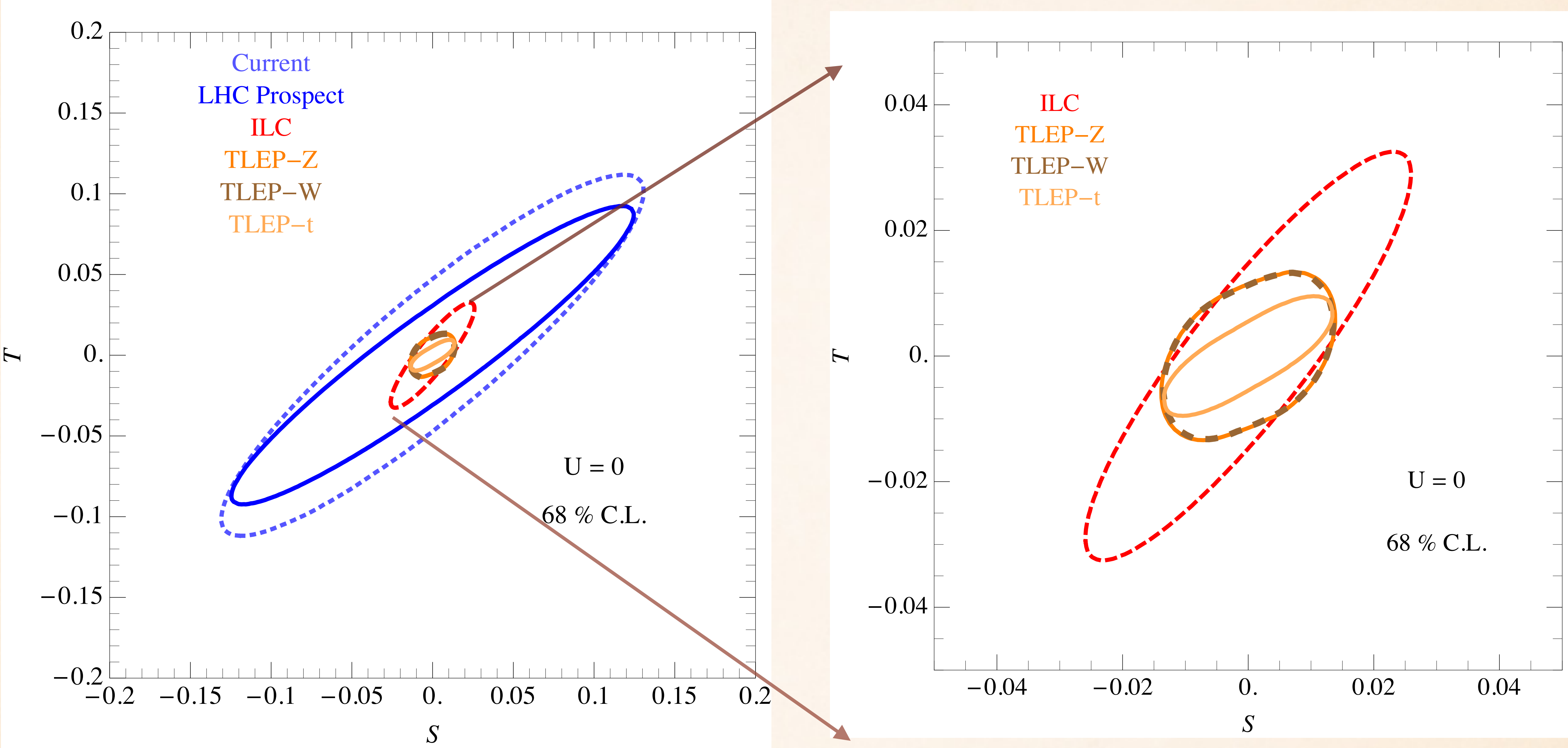
Circular Electron Positron Collider (CEPC)...

They could measure Higgs properties very well as well as other electroweak observables.

Electroweak Precision Test:
Another Potentially Powerful Probe



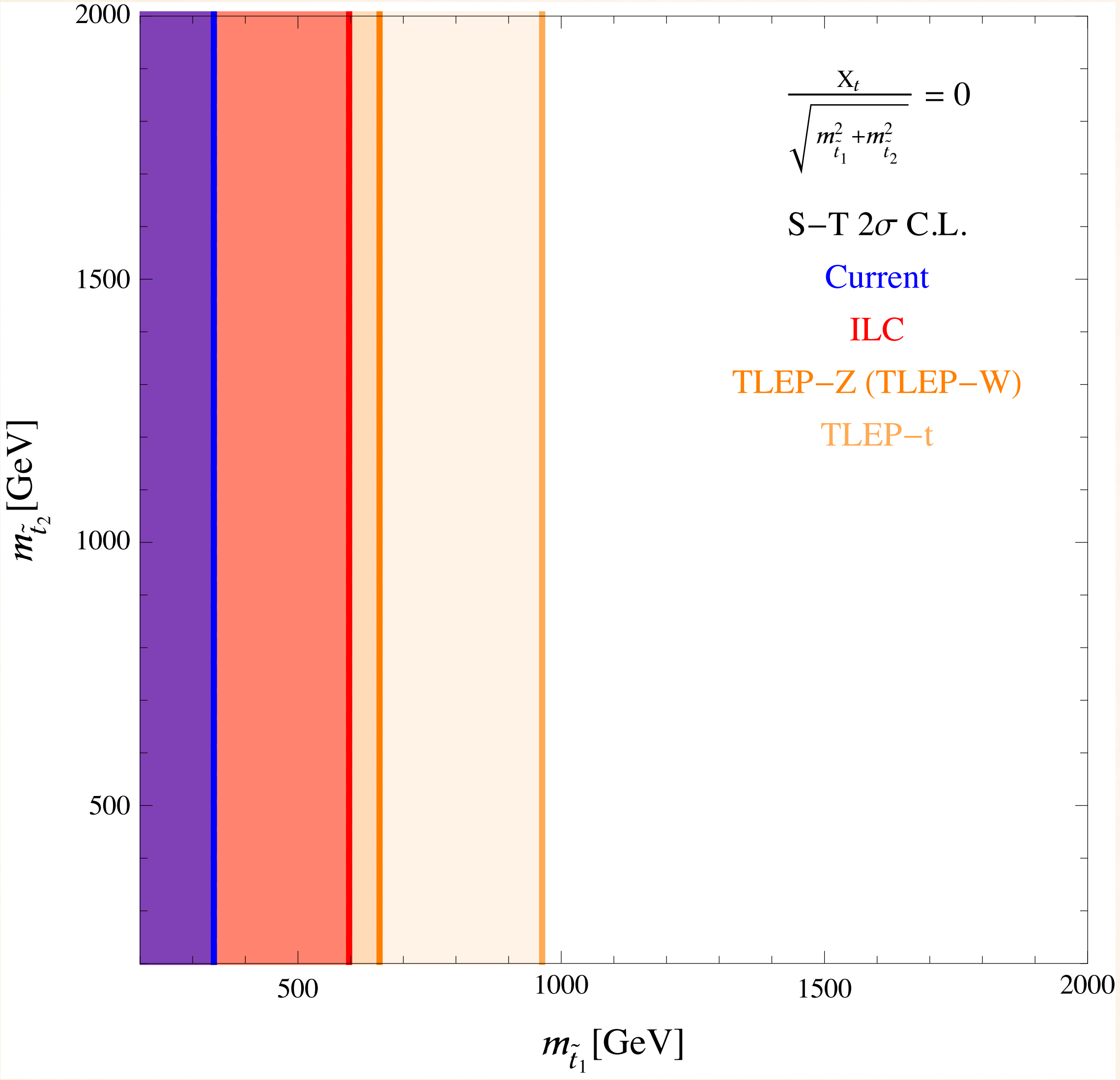
BSM particles could modify vacuum polarizations and electroweak observables such as W boson mass and weak mixing angle

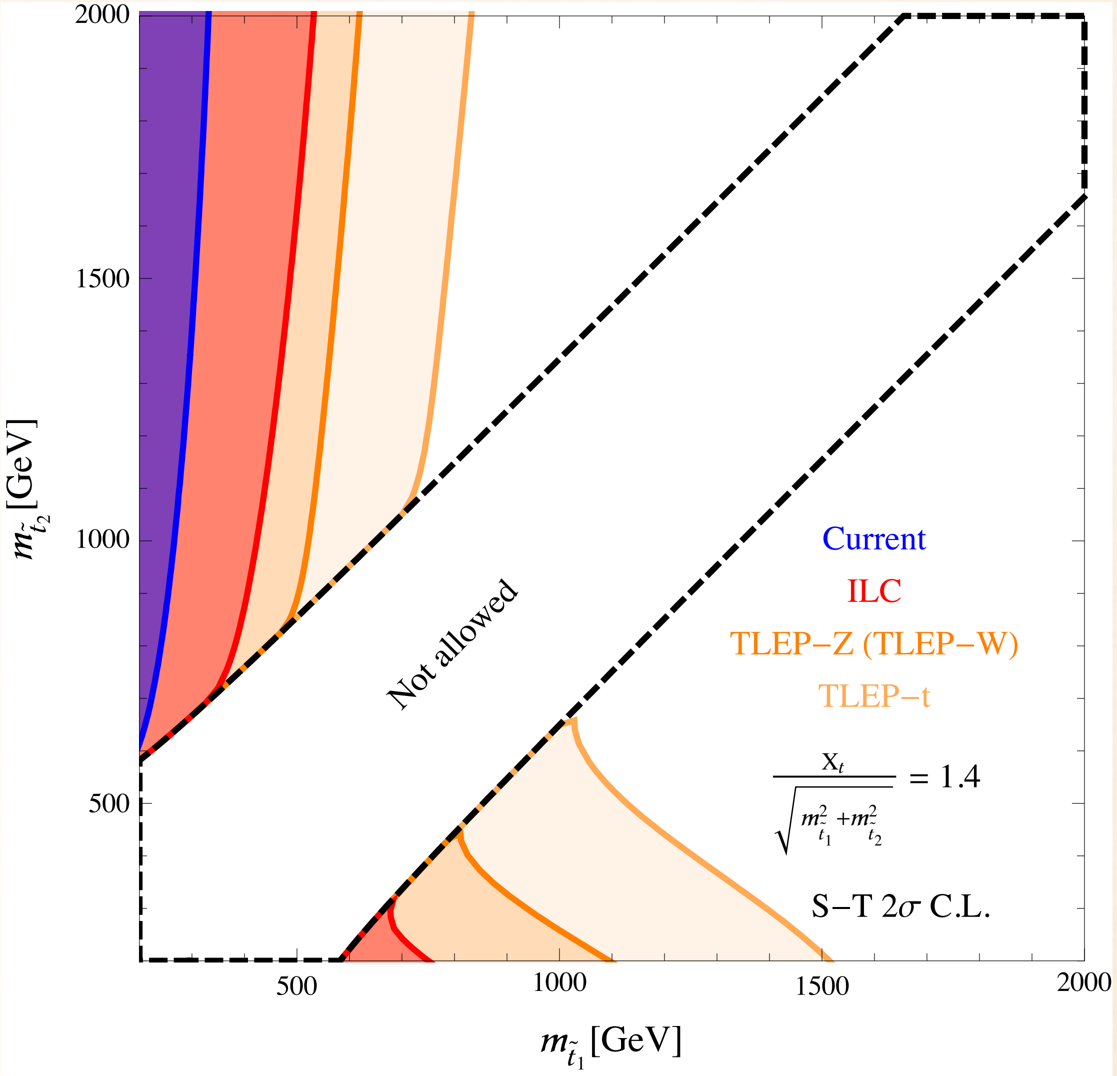


JF, Reece and Wang, work to appear

Constraints on new physics: for example, stops

The EWPT probe is comparable to the Higgs probe



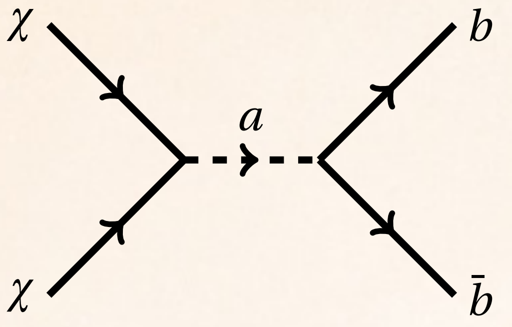


JF, Reece and Wang, work to appear

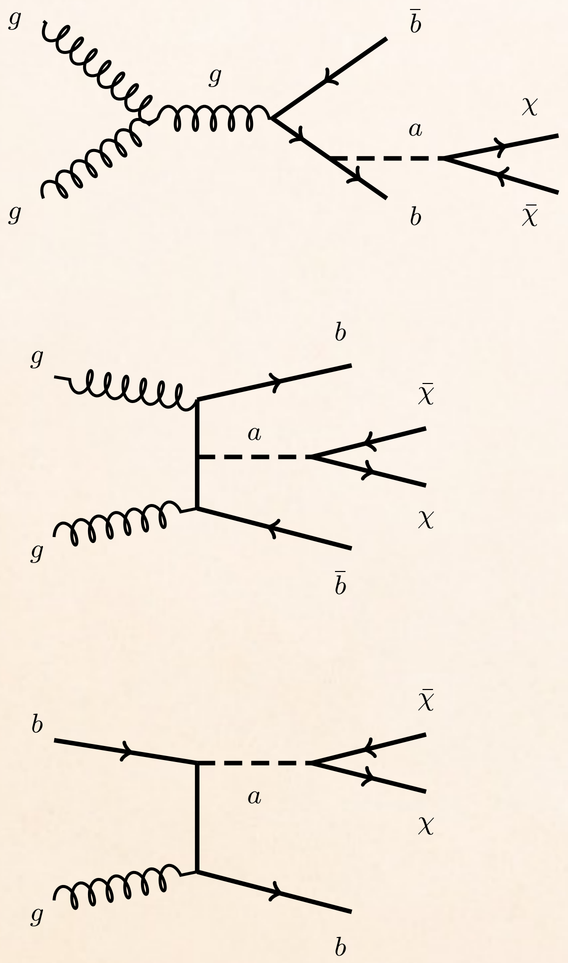
It is not difficult to write down a model though

not hard to make models ≠ not baroque

Neal Weiner, talk at Harvard 2014



Izaguirre, Krnjaic and Shuve; Ipek, McKeen, Nelson 2014



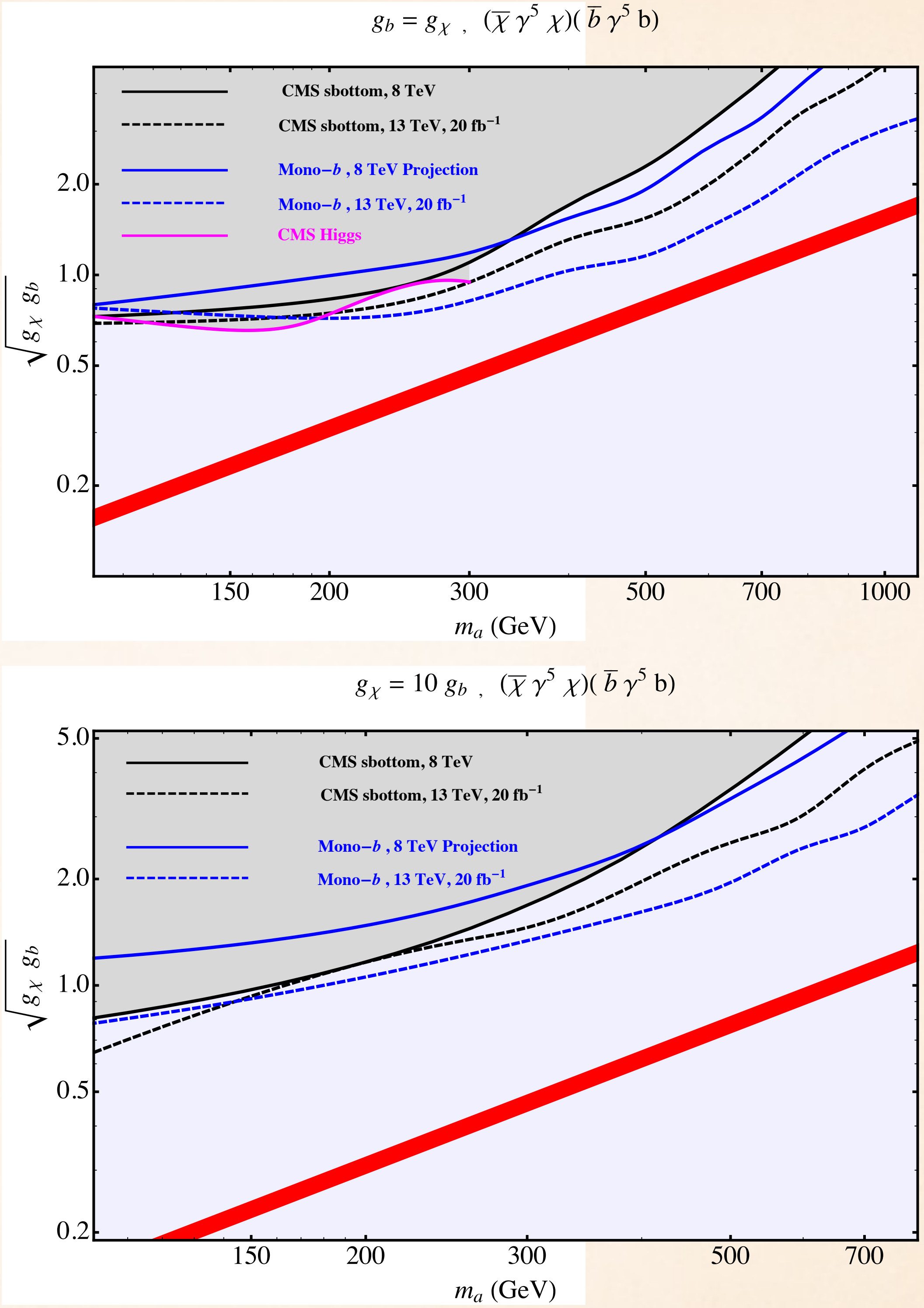


FIG. 5: Parameter space for the pseudoscalar-mediated scenario with constraints from the same searches and simulation details described in Fig. 3. As with the axial-vector mediator, scattering at direct-detection experiments through a b loop is not constraining as the leading interaction is spin-dependent. Here we also include a constraint from the CMS Higgs search from [25]