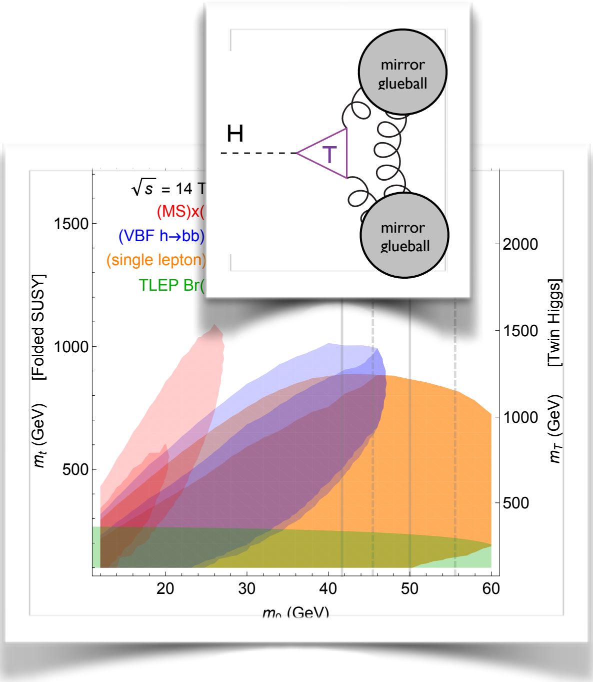
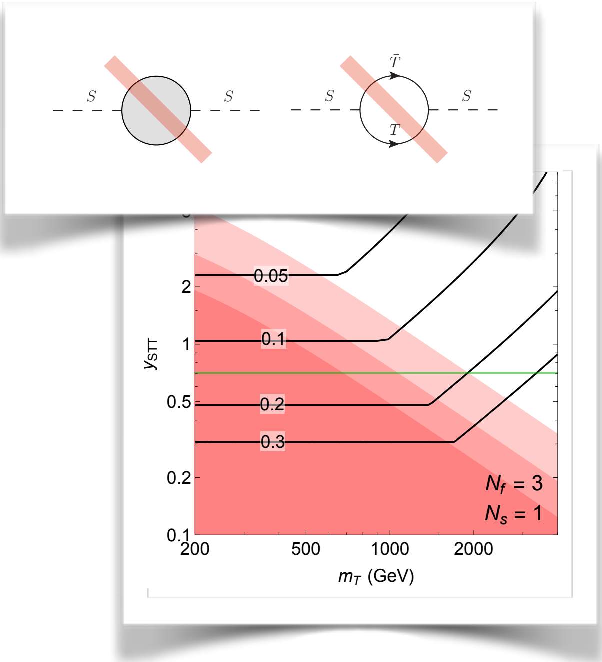
Discovering Neutral Naturalness

Theory Seminar
NHETC
Rutgers University

20. October 2015

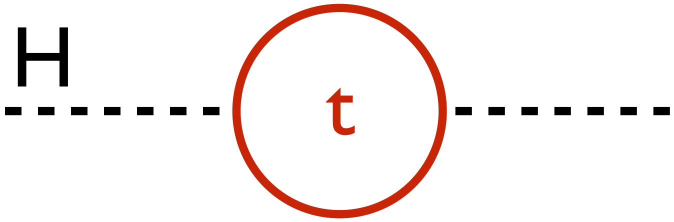




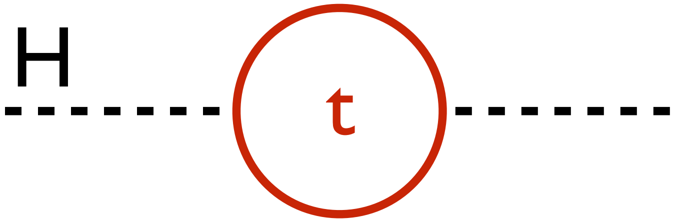
David Curtin
University of Maryland

based on
DC, Verhaaren 1506.06141
DC, Saraswat 1509.04284
Chacko, DC, Verhaaren, 1512.XXXXX

The Hierarchy Problem



The Hierarchy Problem



… can be solved by top partners

The Hierarchy Problem

… can be solved by top partners

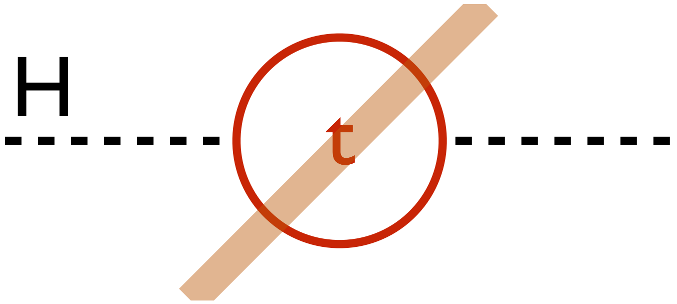
top quark t $\xrightarrow{\text{continuous symmetry}}$ top partner T

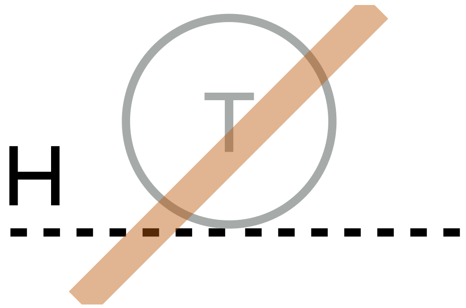
carries color charge

e.g.

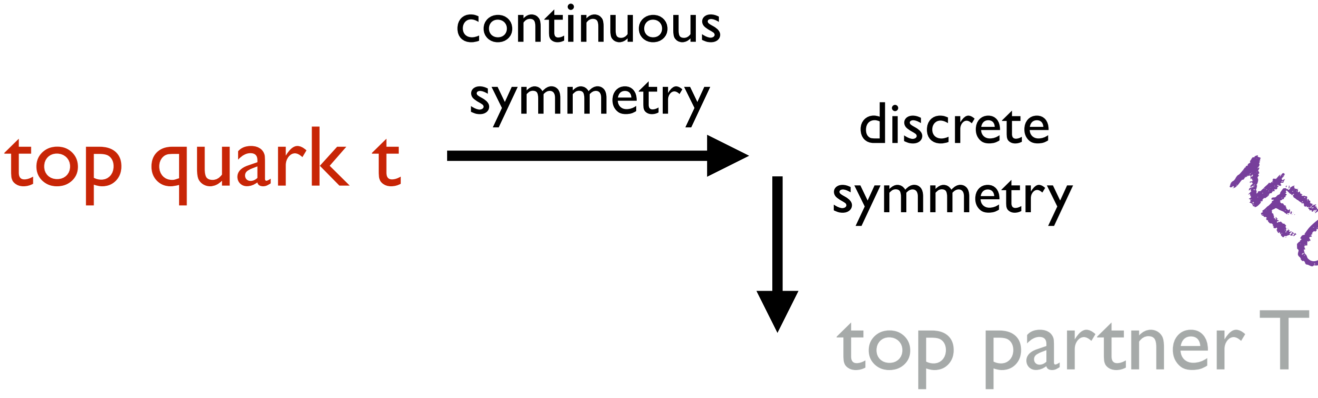
Supersymmetry*, modern* ***composite Higgs*** *models, etc…*

The Hierarchy Problem





The symmetry need not commute with SM color!



top quark t $\xrightarrow{\text{continuous symmetry}}$

discrete symmetry ↓

top partner T

COLOR NEUTRAL!

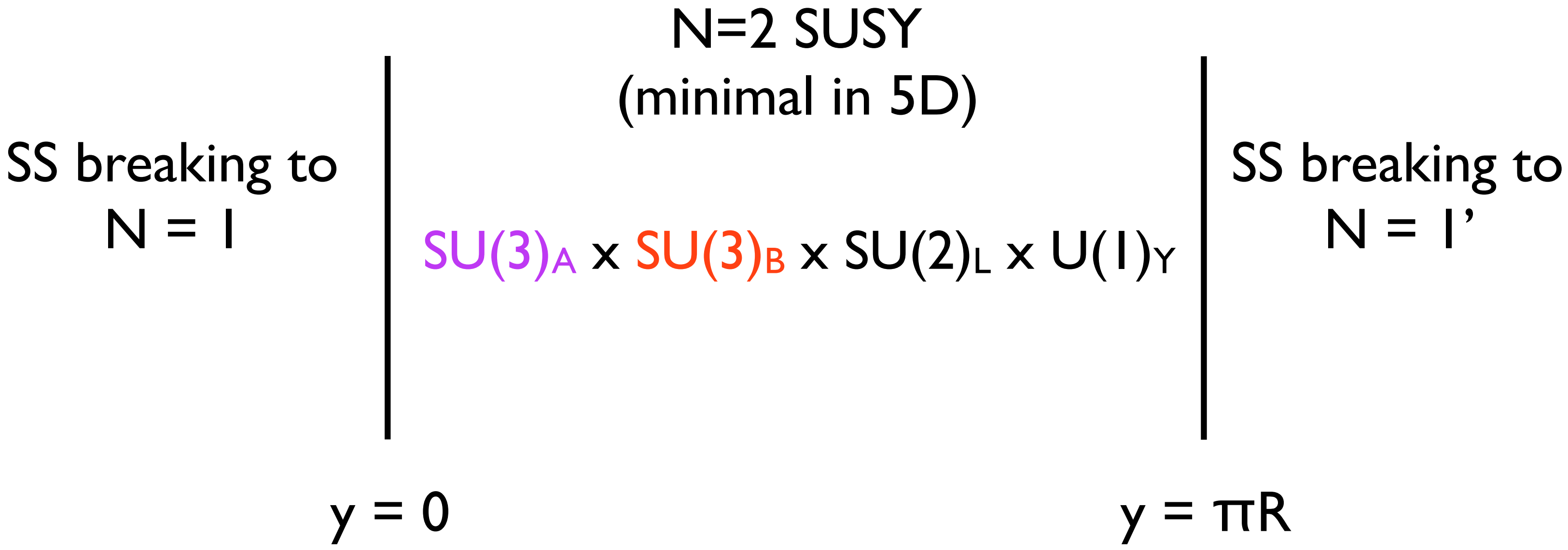
e.g.

Folded SUSY *(EW-charged stops),* ***Twin Higgs*** *(SM singlet T-partners)*

hep-ph/0609152 Burdman, Chacko, Goh, Harnik

hep-ph/0506256 Chacko, Goh, Harnik

Theory Example: Folded SUSY



N=2 SUSY
(minimal in 5D)

SS breaking to
N = 1

$SU(3)_A \times SU(3)_B \times SU(2)_L \times U(1)_Y$

SS breaking to
N = 1'

y = 0

y = πR

Boundary conditions break A↔B symmetry and globally break N=2 to N=0 SUSY.

Normal MSSM EW sector.

SU(3) sectors: only zero modes are A-fermions, B-sfermions.

'Accidental supersymmetry' protects Higgs @ 1-loop with **EW charged top partners.**

hep-ph/0609152
Burdman, Chacko, Goh, Harnik

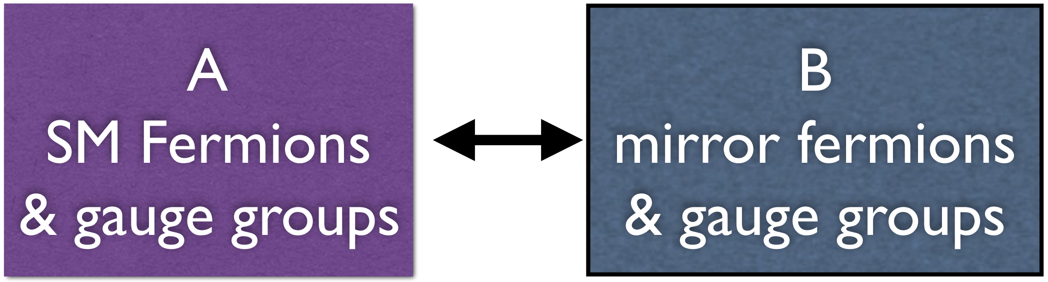
Theory Example: Twin Higgs

SM_A x SM_B (mirror sector) particle content with Z_2 symmetry

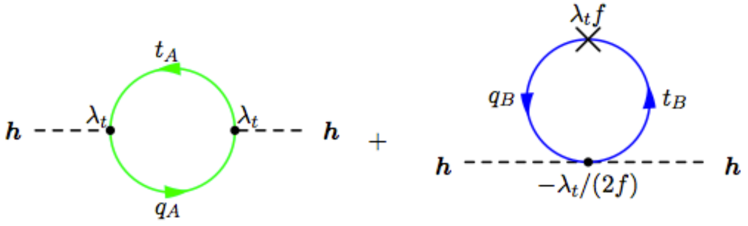
Higgs sector: SU(4), broken by Gauge + Yukawa interactions to $SU(2)_A$ x $SU(2)_B$ x Z_2, which generate mass for goldstone boson.

$$\Delta V = \frac{3}{8\pi^2}\Lambda^2\left(\lambda_A^2 H_A^\dagger H_A + \lambda_B^2 H_B^\dagger H_B\right) \xrightarrow{\lambda_A = \lambda_B \equiv \lambda\,:} \Delta V = \frac{3\lambda^2}{8\pi^2}\Lambda^2\left(H_A^\dagger H_A + H_B^\dagger H_B\right) = \frac{3\lambda^2}{8\pi^2}\Lambda^2 H^\dagger H$$

Z_2 symmetry of quadratically divergent contributions mimics full SU(4) symmetry, *protects pNGB Higgs mass @ 1-loop.*


A
SM Fermions
& gauge groups

B
mirror fermions
& gauge groups

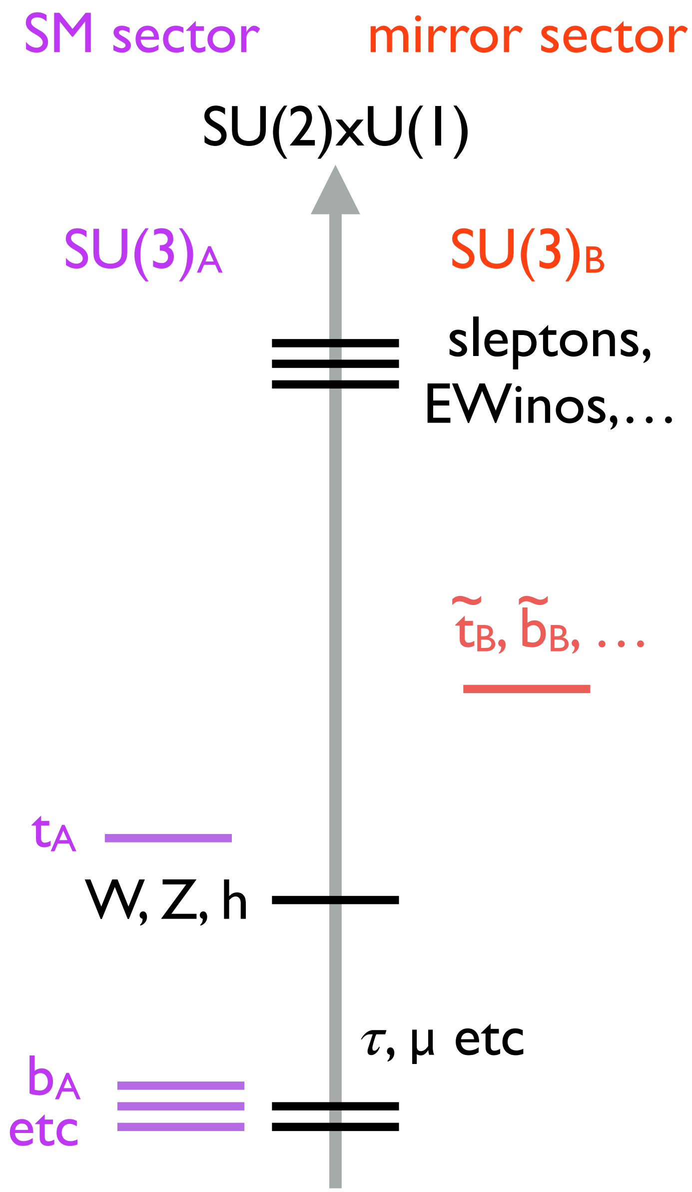


SM singlet top partners.

hep-ph/0506256 Chacko, Goh, Harnik
1411.3310 Burdman, Chacko, Harnik, de Lima, Verhaaren

Typical Low-Energy Spectra

FSUSY (EW charged partners)



SM sector

mirror sector

SU(2)xU(1)

$SU(3)_A$

$SU(3)_B$

sleptons,
EWinos,…

$\tilde{t}_B, \tilde{b}_B, \ldots$

t_A

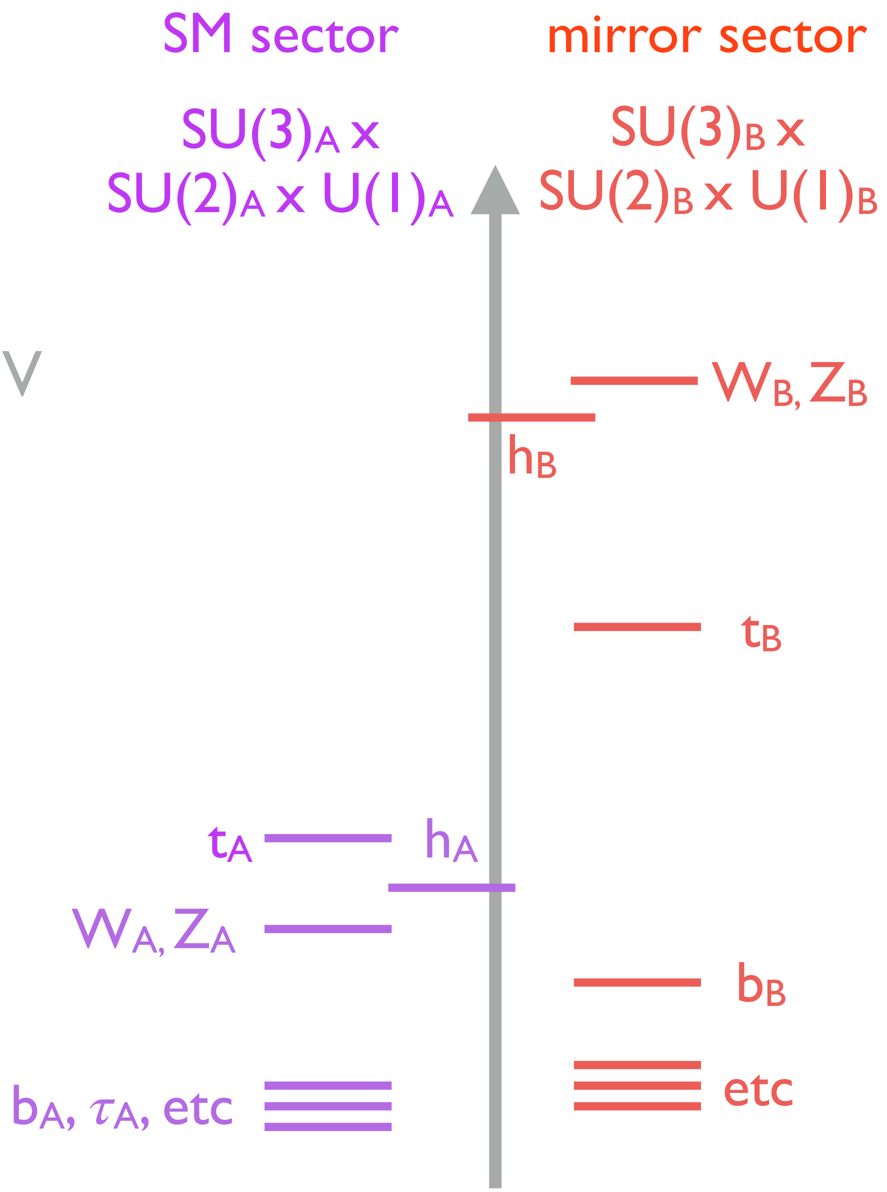
W, Z, h

τ, μ etc

b_A
etc

~ O(1) TeV

Twin Higgs (SM singlet partners)



SM sector

mirror sector

$SU(3)_A \times$
$SU(2)_A \times U(1)_A$

$SU(3)_B \times$
$SU(2)_B \times U(1)_B$

W_B, Z_B

h_B

t_B

t_A

h_A

W_A, Z_A

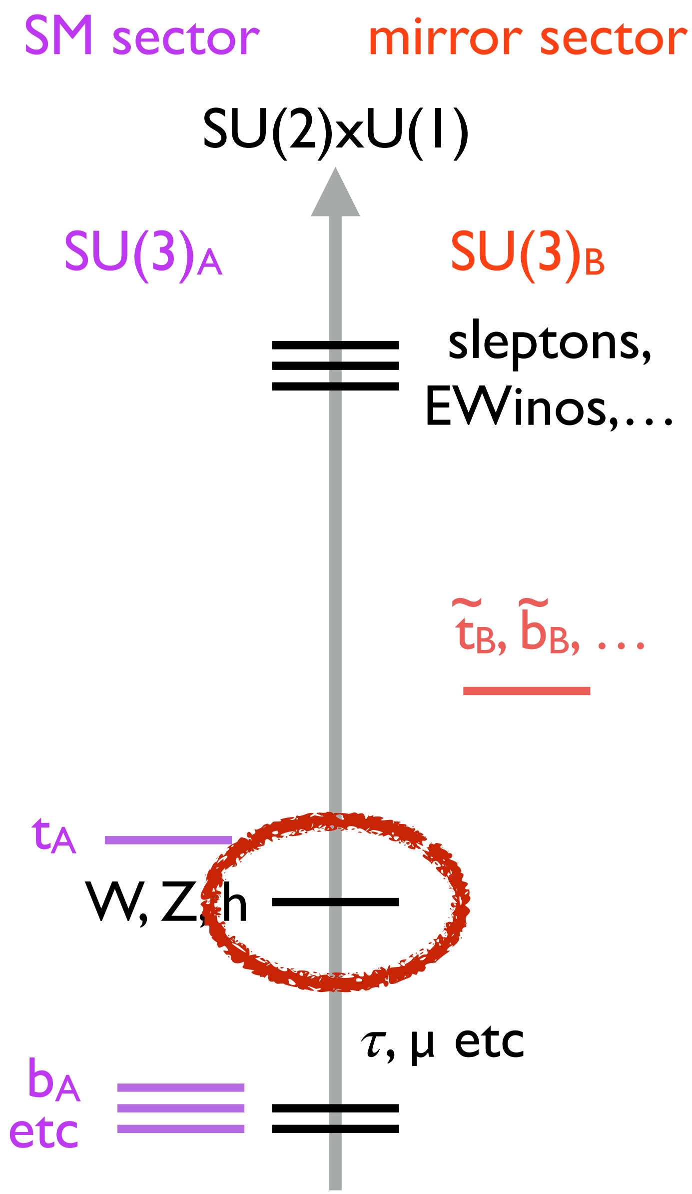
b_B

b_A, τ_A, etc

etc

Typical Low-Energy Spectra

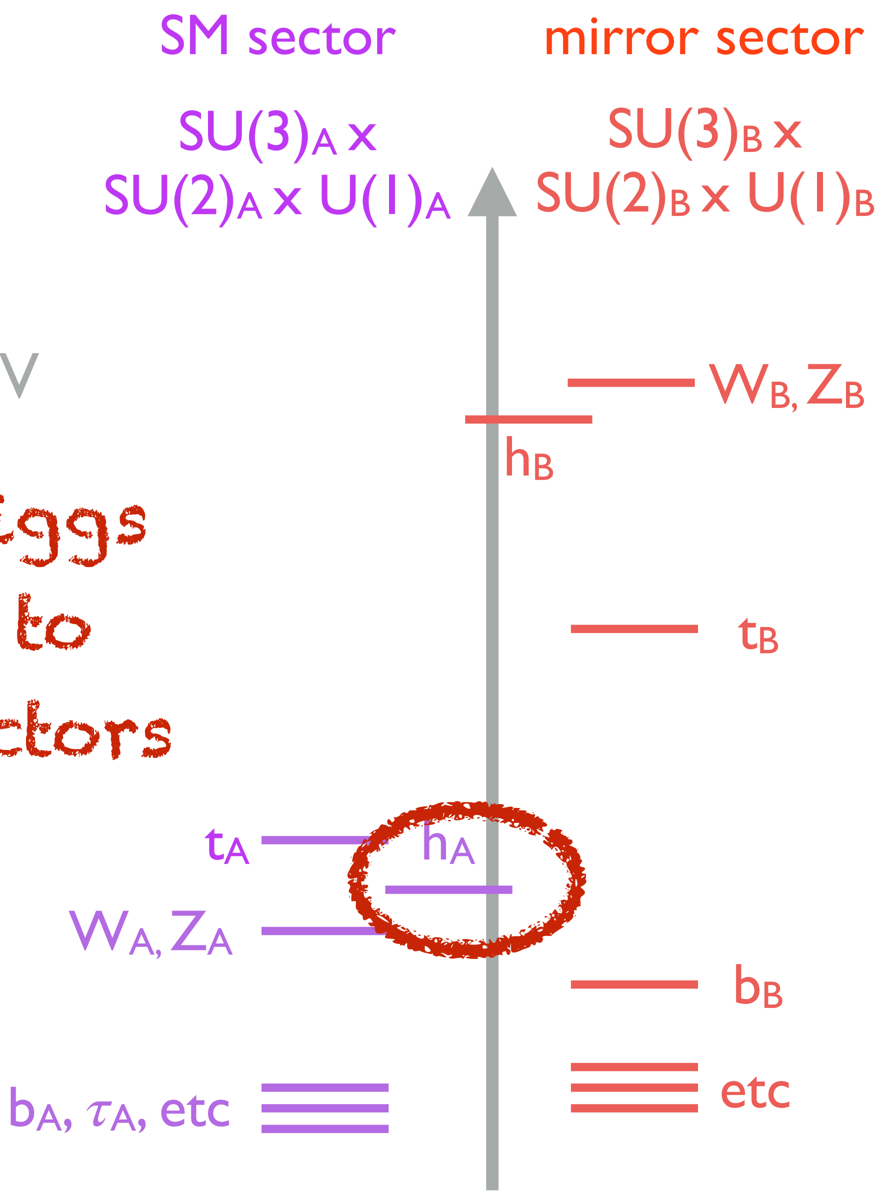
FSUSY (EW charged partners)



~ O(1) TeV

Light Higgs talks to both sectors

Twin Higgs (SM singlet partners)



Neutral Naturalness

Why would we think about this?

1. The LHC is *great* at making colored particles, but so far no top partner discovery…
2. Want to examine naturalness as generally as possible: **test the mechanism, not the model!**

Neutral Naturalness generates radically different phenomenology from colored partners!

What are the most important questions right now?

1. What signals of Neutral Naturalness could we probe **today**?

1. What signals of Neutral Naturalness could we probe **today**?

2. If the signatures are this malleable… will we be able to probe the *general mechanisms* underlying naturalness **tomorrow**?

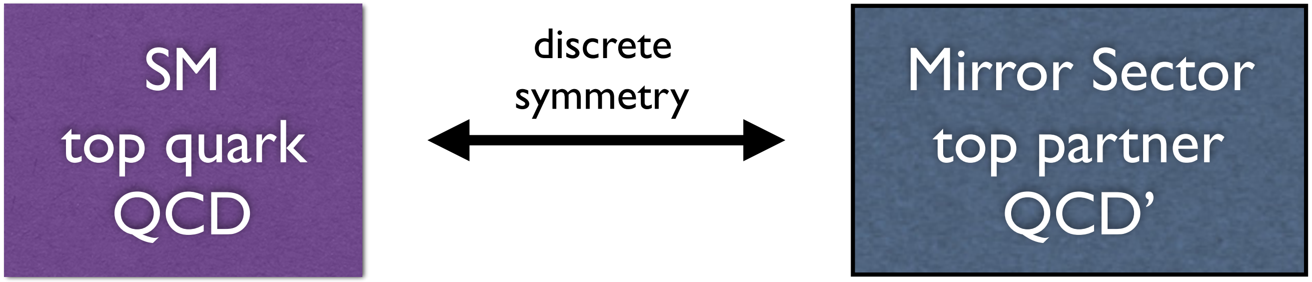
Probing Naturalness today:

Signatures of Neutral Naturalness at the LHC

Hidden Valley Phenomenology

c.f. Strassler, Zurek ’06 etc..

In theories of Neutral Naturalness, the partners in the mirror sector are usually charged under a copy of QCD

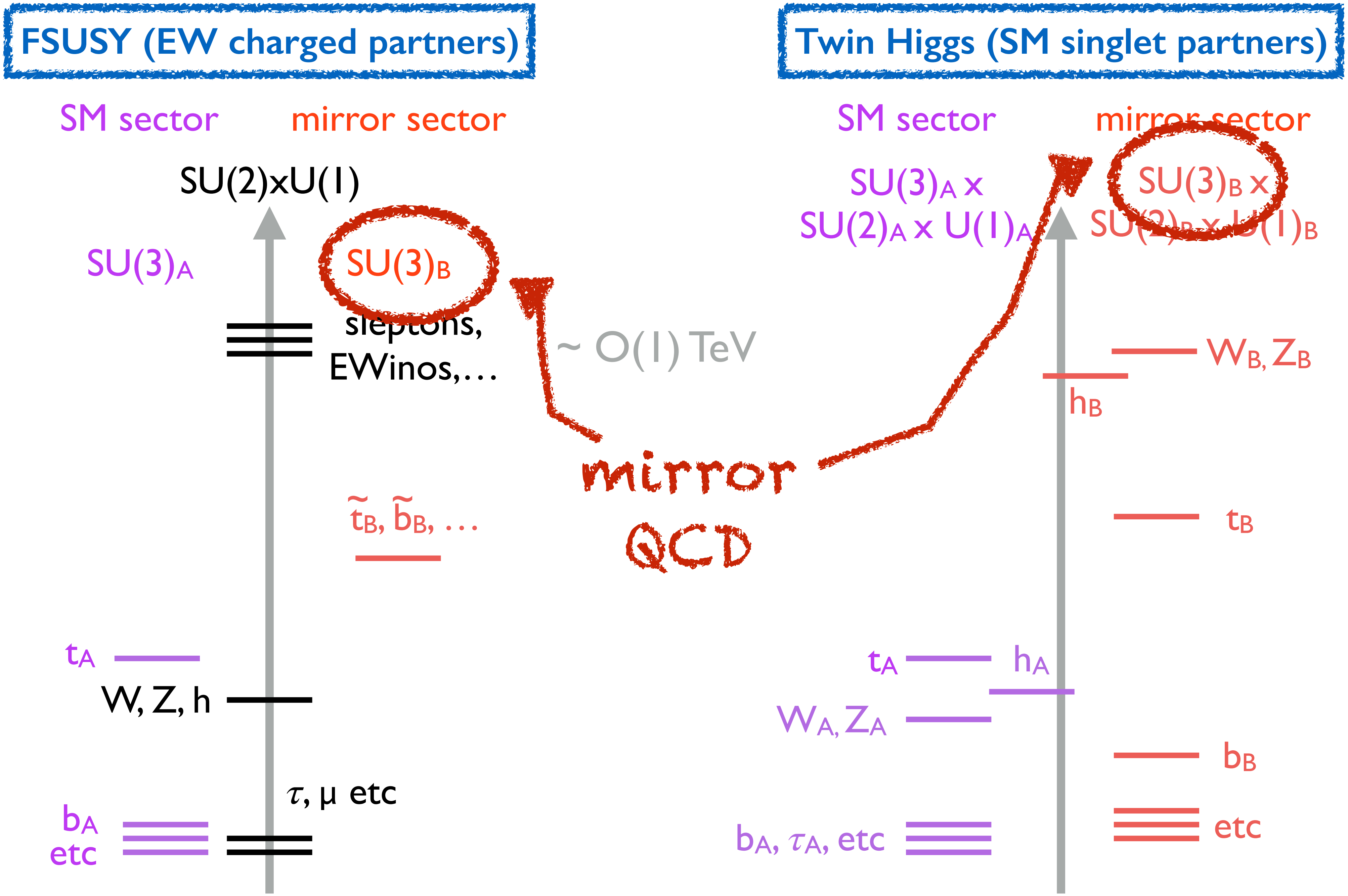


SM
top quark
QCD

discrete
symmetry

Mirror Sector
top partner
QCD’

Typical Low-Energy Spectra



FSUSY (EW charged partners)

SM sector

mirror sector

SU(2)xU(1)

$\mathrm{SU}(3)_A$

$\mathrm{SU}(3)_B$

sleptons,
EWinos,…

~ O(1) TeV

$\tilde{t}_B, \tilde{b}_B, \ldots$

t_A

W, Z, h

τ, μ etc

b_A
etc

mirror
QCD

Twin Higgs (SM singlet partners)

SM sector

mirror sector

$\mathrm{SU}(3)_A \times$
$\mathrm{SU}(2)_A \times \mathrm{U}(1)_A$

$\mathrm{SU}(3)_B \times$
$\mathrm{SU}(2)_B \times \mathrm{U}(1)_B$

W_B, Z_B

h_B

t_B

t_A

h_A

W_A, Z_A

b_B

b_A, τ_A, etc

etc

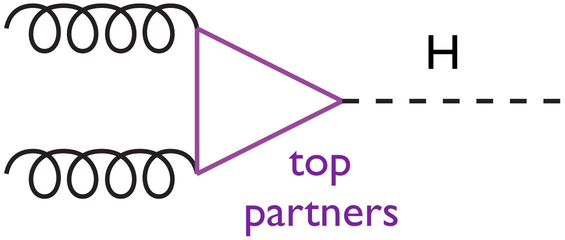
Hidden Valley Phenomenology

c.f. Strassler, Zurek ’06 etc..

Mirror gluons talk to the Higgs via top partner loops!

(just like the top quark connects the Higgs to SM QCD)

$$\mathcal{L}^{(6)} = \frac{\alpha_v\, y^2}{3\pi\, M^2} H^\dagger H \,\mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}$$



The mirror sector contains mirror hadrons.

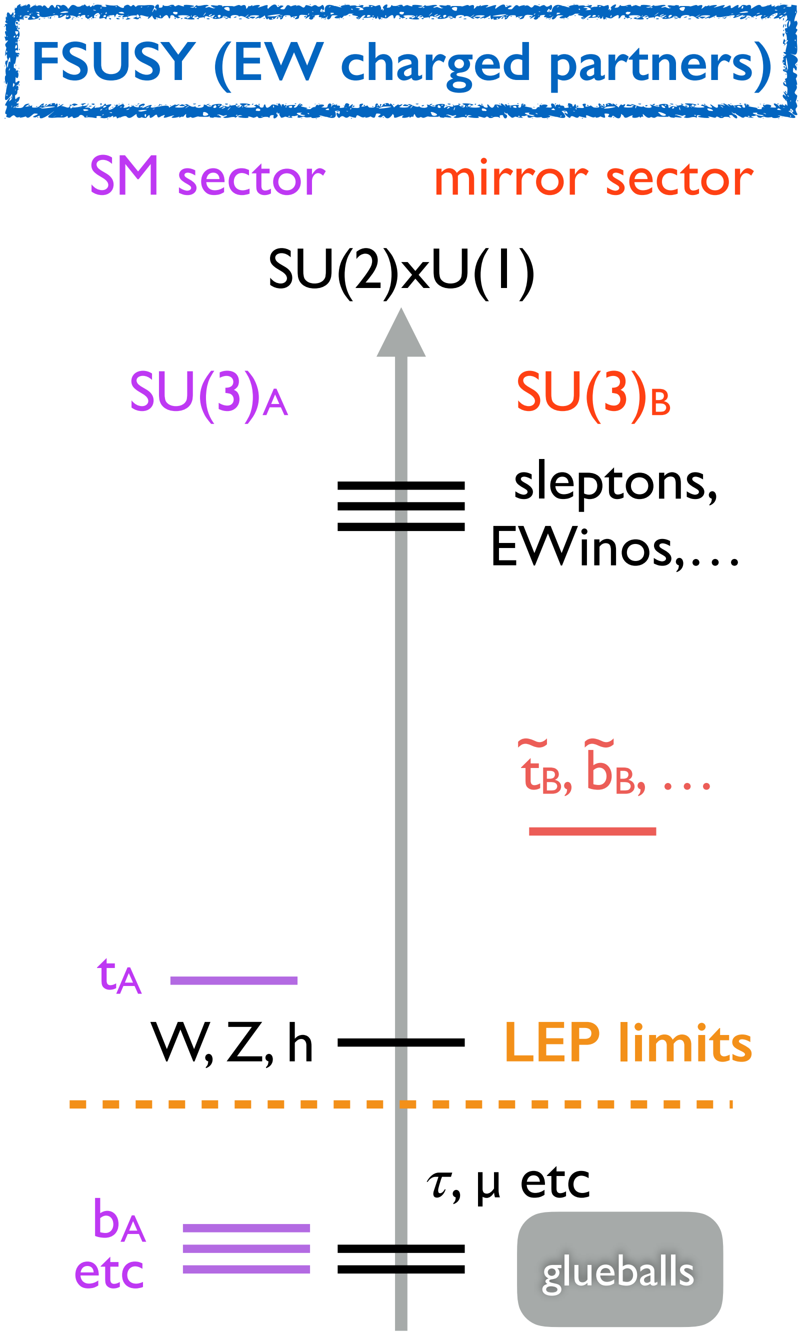
Detailed consequences depend on the mirror spectrum:

pions?

quarkonia?

glueballs?

Typical Low-Energy Spectra



FSUSY (EW charged partners)

SM sector

mirror sector

$SU(2)xU(1)$

$SU(3)_A$

$SU(3)_B$

sleptons,
EWinos,…

$\tilde{t}_B$, $\tilde{b}_B$, …

t_A

W, Z, h

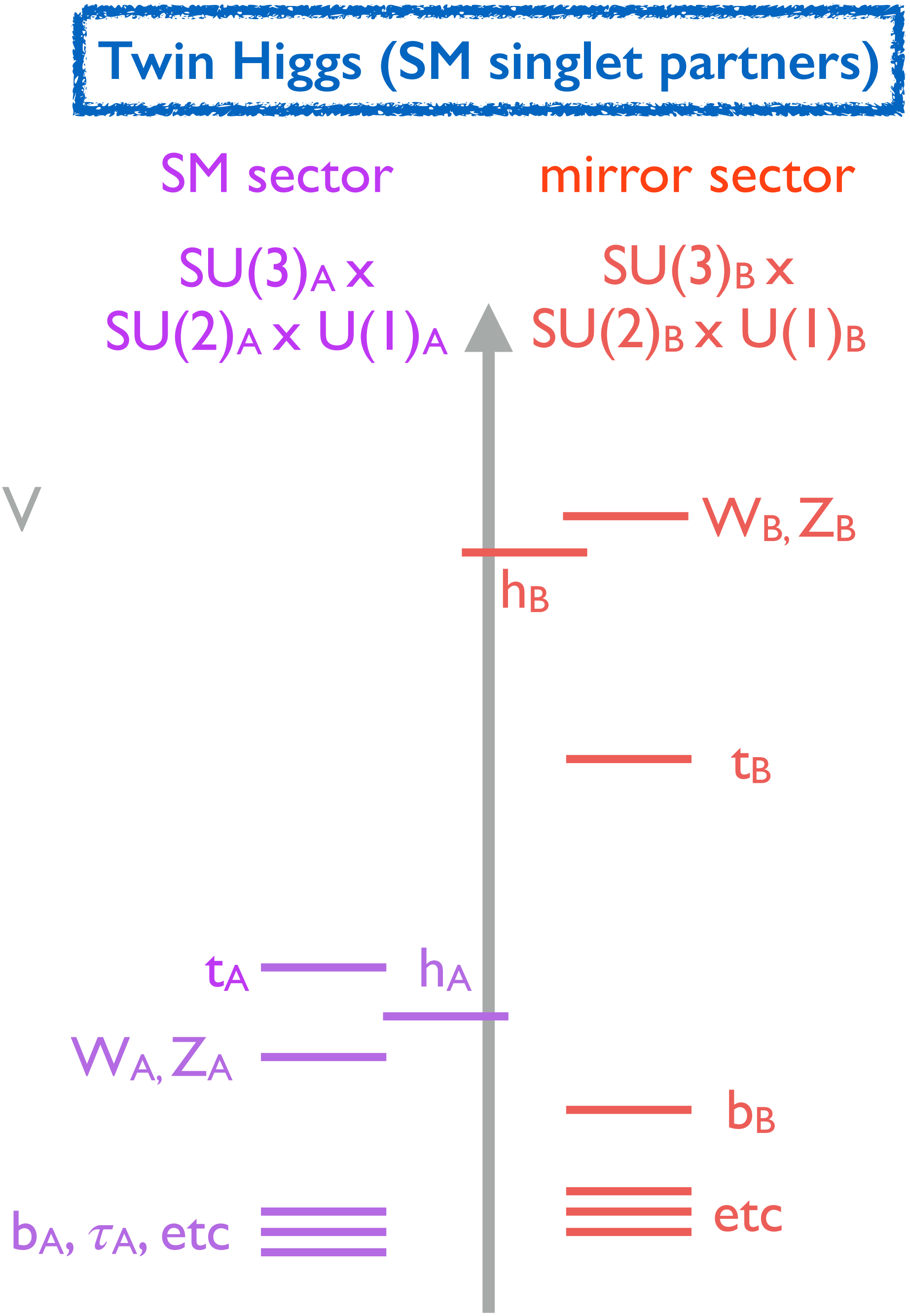
LEP limits

τ, μ etc

b_A
etc

glueballs

~ O(1) TeV



Twin Higgs (SM singlet partners)

SM sector

mirror sector

$SU(3)_A$ x
$SU(2)_A$ x $U(1)_A$

$SU(3)_B$ x
$SU(2)_B$ x $U(1)_B$

W_B, Z_B

h_B

t_B

t_A

h_A

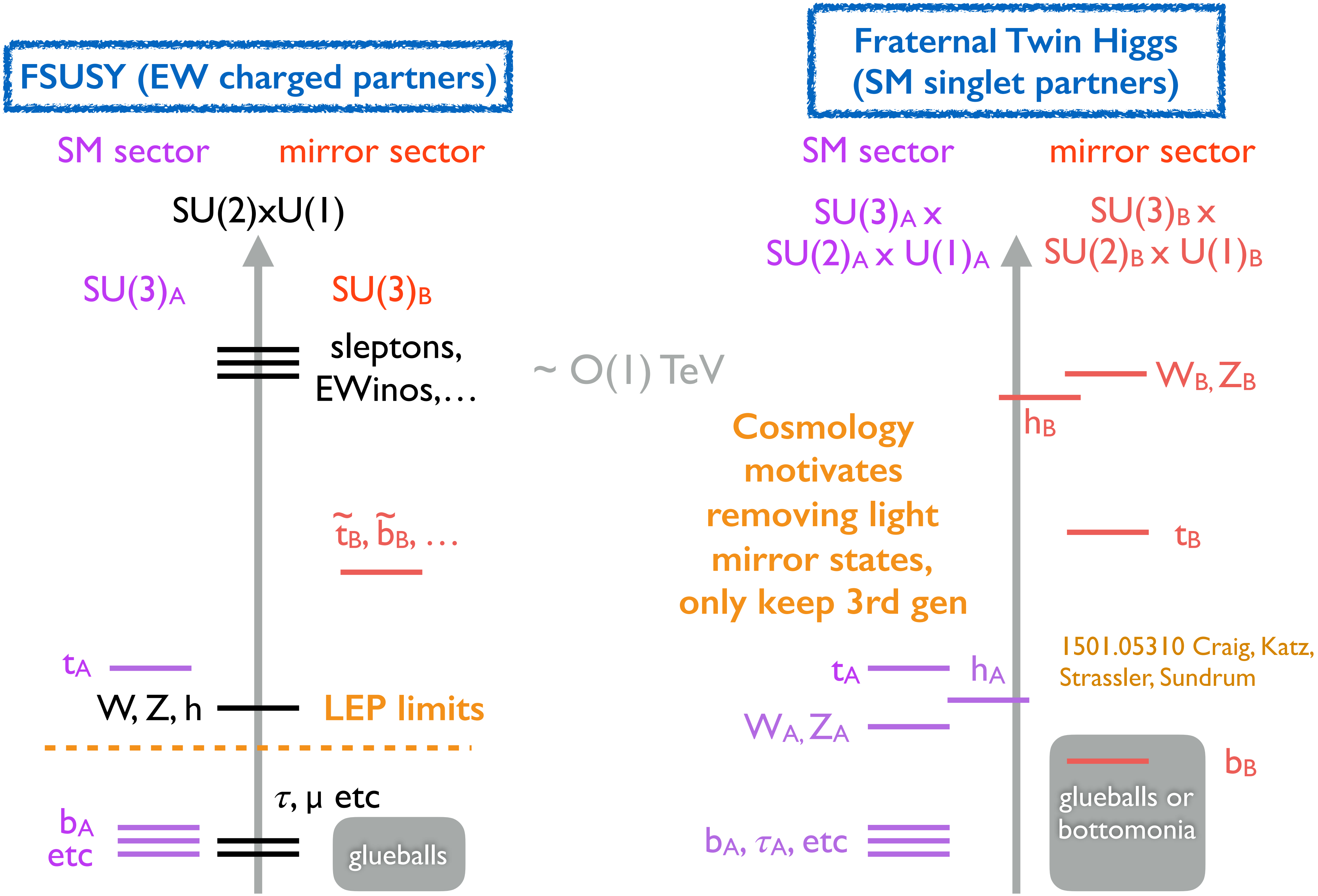
W_A, Z_A

b_B

b_A, τ_A, etc

etc

Typical Low-Energy Spectra



FSUSY (EW charged partners)

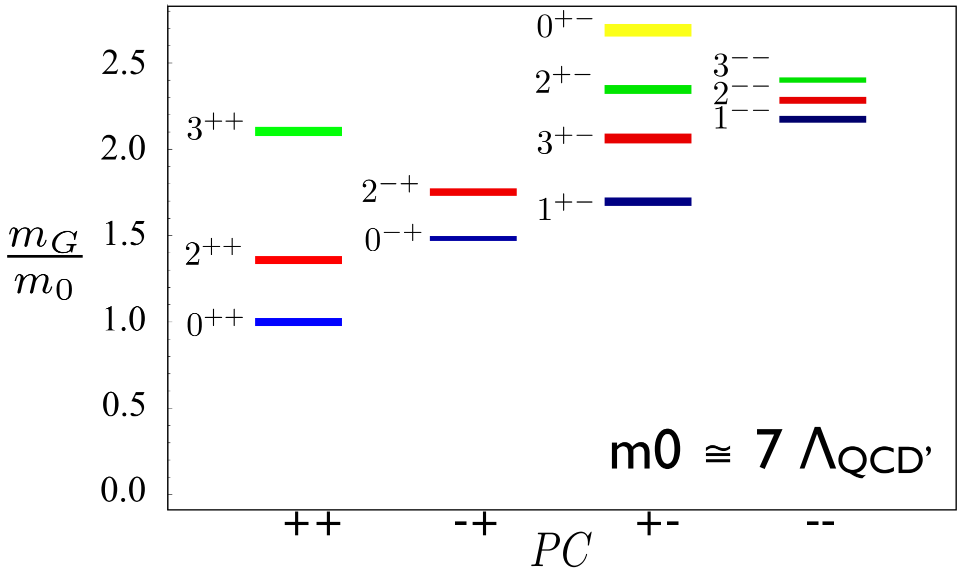
Fraternal Twin Higgs (SM singlet partners)

Cosmology motivates removing light mirror states, only keep 3rd gen

1501.05310 Craig, Katz, Strassler, Sundrum c.f. Strassler, Zurek ’06 etc..

Mirror Glueballs

If the mirror sector has no light matter, the mirror QCD hadrons are **glueballs**.



“Required” for EW charged top partners.

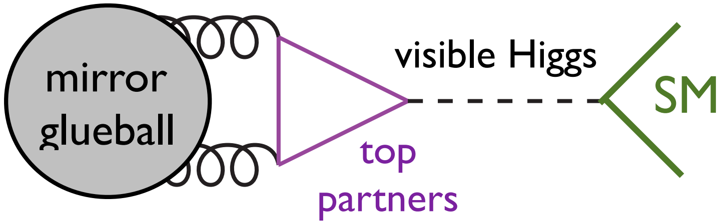
Possible (motivated by cosmology) for SM singlet top partners.

hep-lat/9901004 Morningstar ; 0903.0883 Juknevich, Melnikov, Strassler; 0911.5616 Juknevich

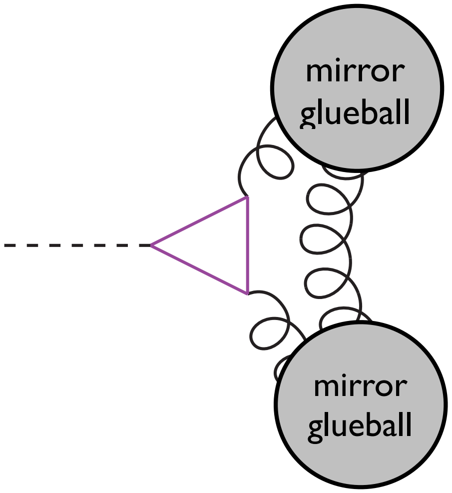
Glueball-Higgs Coupling

0903.0883 Juknevich, Melnikov, Strassler; 0911.5616 Juknevich

Glueballs mix with the Higgs via top partner loop:
0++ would eventually decay back to SM!



The Higgs could also decay to these glueballs:
exotic Higgs decays with displaced vertices!



Key signature of uncolored naturalness!

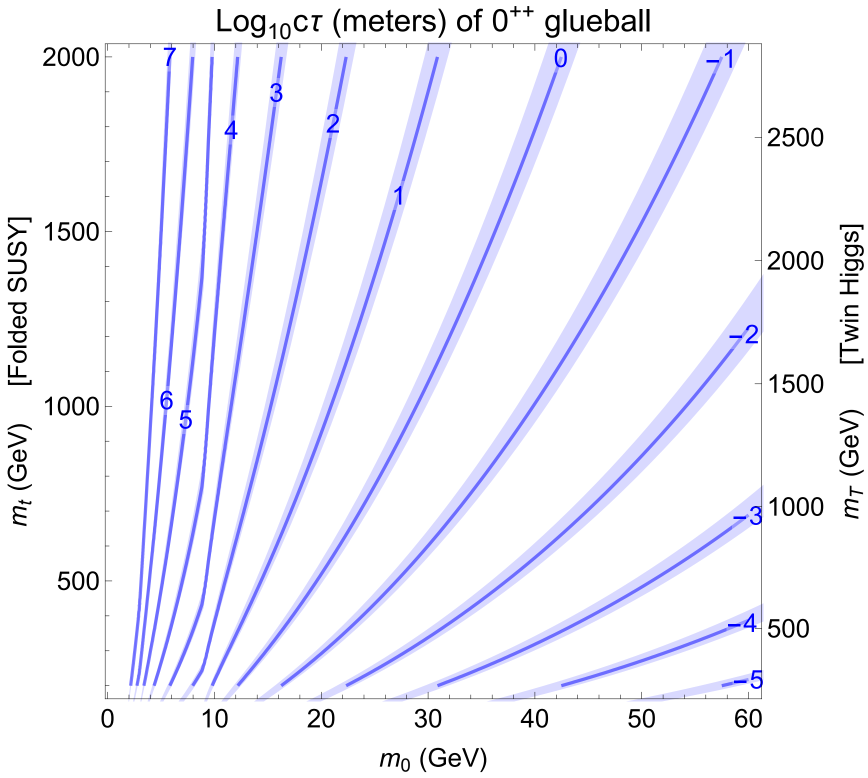
1501.05310 Craig, Katz, Strassler, Sundrum

Is this signature realized?

Mass: $m_0 \sim 7\Lambda_{QCD'} \sim$ 10 - 60 GeV from RG arguments, but can move that around in Twin Higgs theories. DC, Verhaaren 1506.06141

⇒ can be produced in exotic Higgs decays!

Lifetime of 0^{++}: $c\tau \sim$ µm - 1km (using lattice results)



$\text{Log}_{10}c\tau$ (meters) of 0^{++} glueball

$$\Gamma(0^{++} \to \xi\xi) \; = \; \left(\frac{1}{12\pi^2} \left[\frac{y^2}{M^2} \right] \frac{v}{m_h^2 - m_0^2} \right)^2 \left(4\pi\alpha_s^{\mathrm{B}} \mathbf{F}^{\mathbf{S}}_{0^{++}} \right)^2 \Gamma^{\mathrm{SM}}_{h\to\xi\xi}(m_0^2).$$

⇒ displaced decays

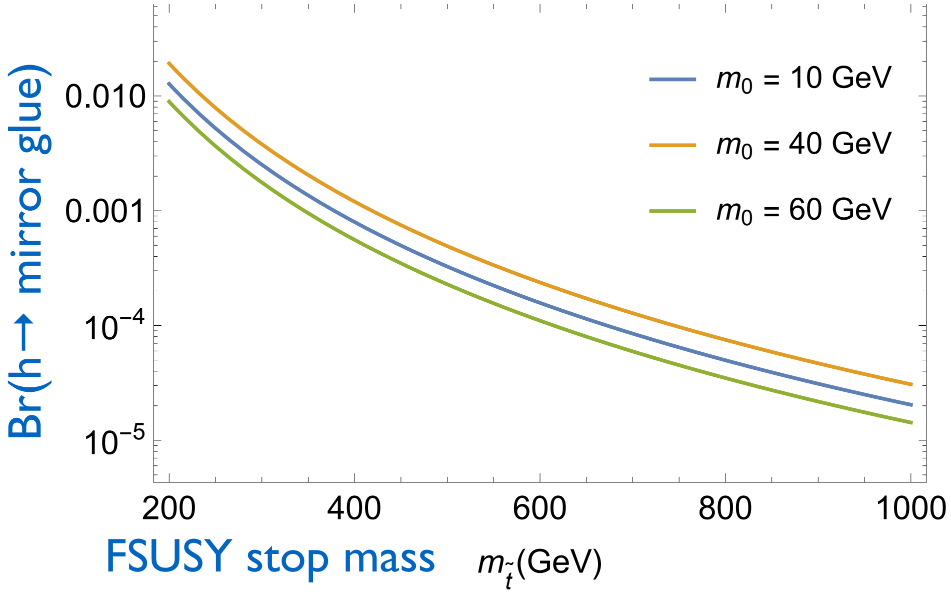
at colliders!

(mostly to bb, $\tau\tau$)

YES!

How many glueballs from Higgs decays?

Estimate inclusive mirror-glue production by rescaling SM Br(h→gg) by top partner loop and mirror α_S' (also from RG arguments).



LHC 14 with 300fb-1 makes O(10 million) higgs bosons.

Could probe TeV-scale top partners if exotic Higgs decays conspicuous enough!

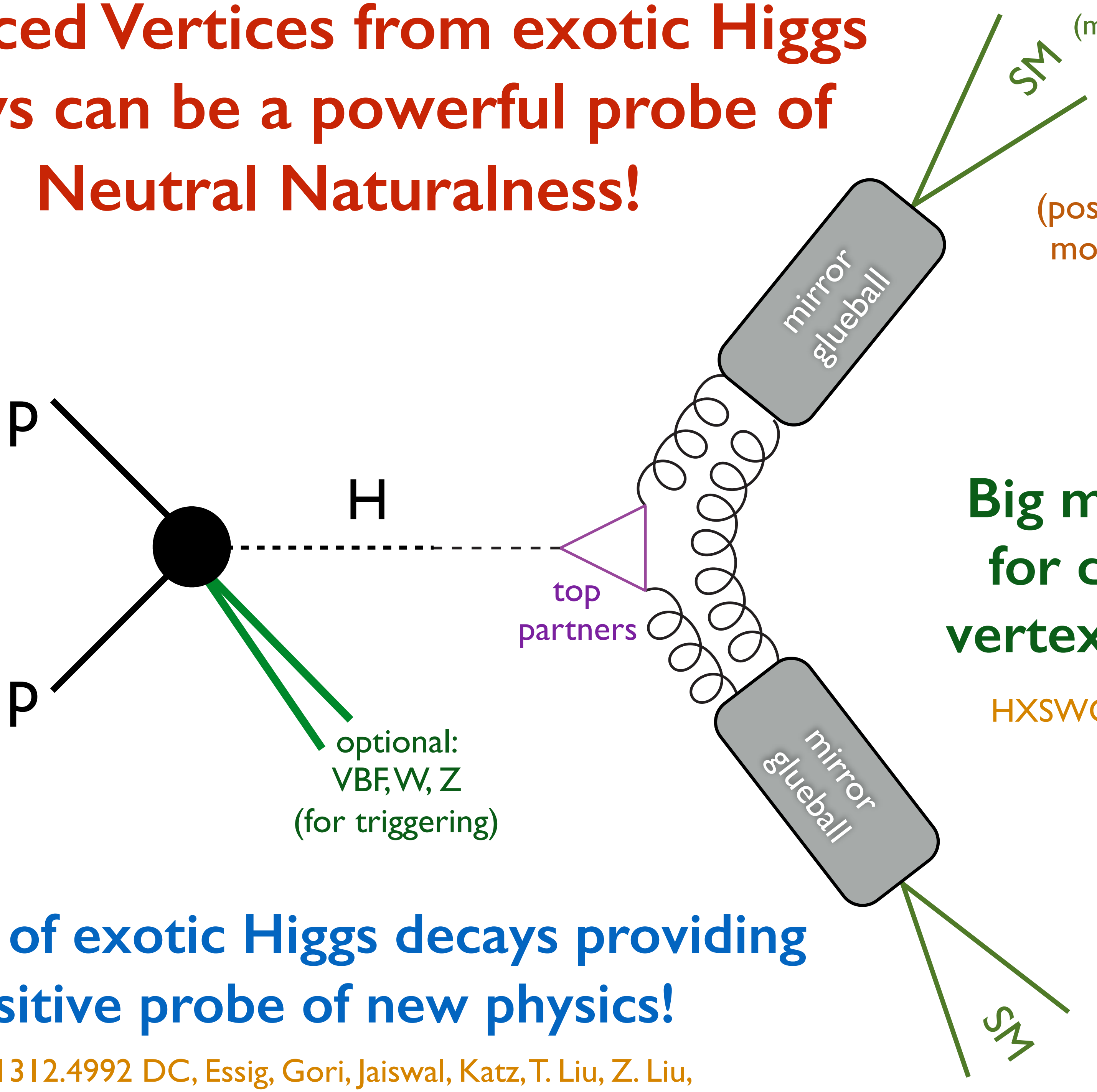
Conservatively estimate exclusive production of **unstable 0++ glueball** by parameterizing our ignorance about mirror hadronization:

$$\mathrm{Br}(h \to 0^{++}0^{++}) = \mathrm{Br}(h \to \text{mirror glue}) \cdot \kappa \cdot \sqrt{1 - \frac{4m_0^2}{m_h^2}}$$

Let κ range from ~ 1/12 (democratic) to ~ 1 (optimistic).

DC, Verhaaren 1506.06141

Displaced Vertices from exotic Higgs decays can be a powerful probe of Neutral Naturalness!



(mostly bb, $\tau\tau$)

(possibile to have more glueballs)

optional:
VBF, W, Z
(for triggering)

Big motivation for displaced vertex searches!

HXSWG yellow report
(soon!)

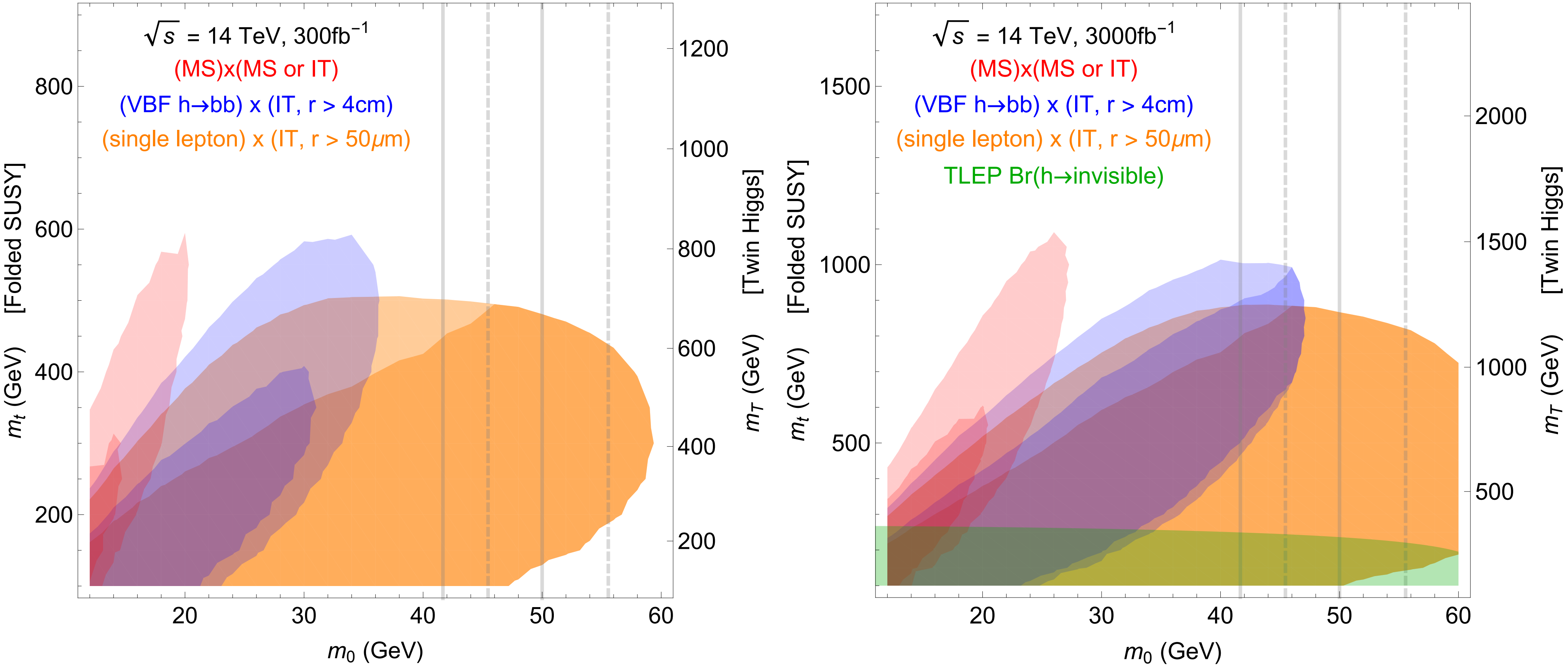
Example of exotic Higgs decays providing sensitive probe of new physics!

Review/Survey: 1312.4992 DC, Essig, Gori, Jaiswal, Katz, T. Liu, Z. Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong

DC, Verhaaren 1506.06141

LHC reach

ATLAS sensitivity projections to LHC14:



Displaced searches probe TeV-scale uncolored top partners!

DC, Verhaaren 1506.06141

LHC reach

ATLAS sensitivity projections to LHC14:

Needs new searches:

one DV + lepton

one DV + VBF

close DV reconstruction

Reach from CMS should be significantly better!

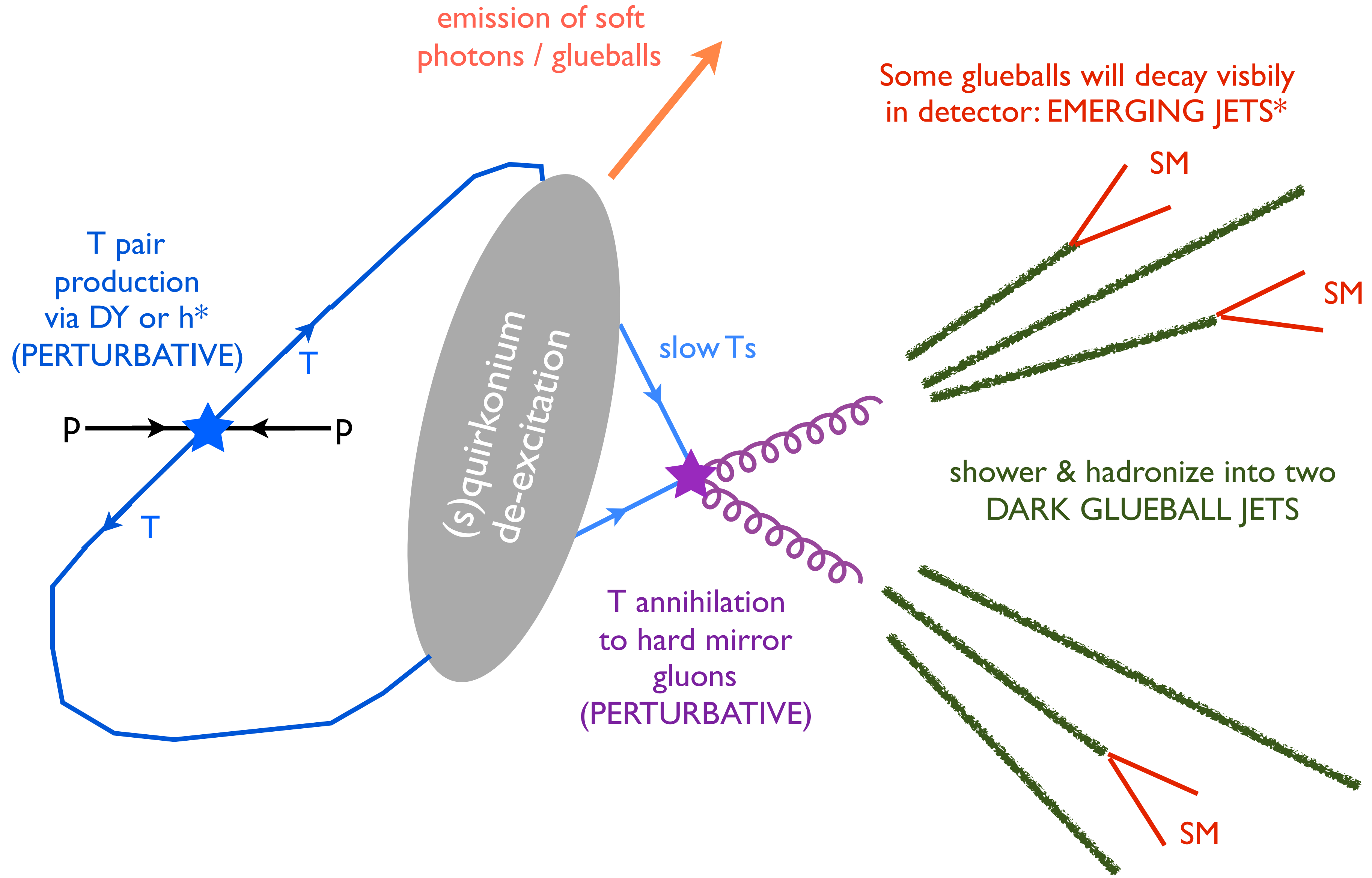
Csaki, Kuflik, Lombardo, Slone 1508.01522

Displaced searches probe TeV-scale uncolored top partners!

DC, Verhaaren 1506.06141

Top partner direct production

Top partner direct production



emission of soft
photons / glueballs

Some glueballs will decay visbily
in detector: EMERGING JETS*

T pair
production
via DY or h*
(PERTURBATIVE)

slow Ts

shower & hadronize into two
DARK GLUEBALL JETS

T annihilation
to hard mirror
gluons
(PERTURBATIVE)

Chacko, DC, Verhaaren, 1512.XXXXX

* see also 1502.05409 Schwaller, Stolarski, Weiler

Top partner direct production

Great opportunity:

- direct evidence of uncolored top partners.
- might have comparable reach to exotic Higgs decays
- could allow measurement of couplings and masses.
- potentiall spectacular signatures: several DVs, or many bb, $\tau\tau$ pairs

Main challenge: how to model mirror hadronization?

Have to parameterize our ignorance again, but this time use DGLAP evolution of hypothetical fragmentation functions to estimate glueball multiplicity and mean p_T.

Chacko, DC, Verhaaren, 1512.XXXXX

Work in progress!

Prospects today

Displaced signatures are a great LHC opportunity, and a **"smoking gun" for most theories with EW top partners (e.g. FSUSY). Can occur in some TH models.**

Many signatures still unexplored, e.g. Flavor….

However: quasi-stable light mirror states are not guaranteed in theories of Neutral Naturalness.

What are the *unavoidable* signatures, at the LHC and at future lepton an 100 TeV colliders?

Probing Naturalness exhaustively:

A No-Lose Theorem for Generalized Top Partners.

Top Partners with SM Charge

Start with TeV-scale top partners that carry SM charge.

If QCD: produce plenty, discover at LHC or 100 TeV.

If partners carry any EW charge, regardless of decay mode etc, will be detectable up to ~ 2+ TeV @ 100 TeV due to RG effects in DY spectrum measurements!

Alves, Galloway, Rudermann, Walsh 1410.6810

TeV-scale SM-charged partners ARE DISCOVERABLE regardless of model details!

Neutral Top Partners

expalin twin higgs signatures
how its tree tuning of soft z2 vs

is that totally model-indep? no

We really only have one class of models for neutral top partners: **Twin Higgs**, which predicts Higgs coupling deviations ~ tuning at lepton colliders.

Is this general? Would like to understand signatures of neutral top partners **model-independently!**

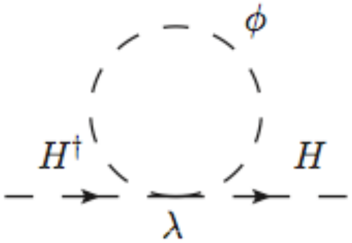
→ **Bottom-Up EFT/Simplified Model Approach!**

DC, Saraswat 1509.04284

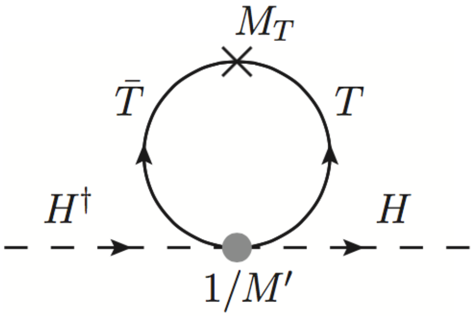
Two distinct low-energy EFTs

Scalar Partners

(Vector partners
"same" as scalars)



Fermion Partners



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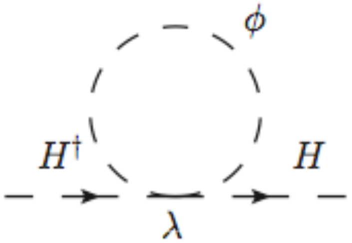
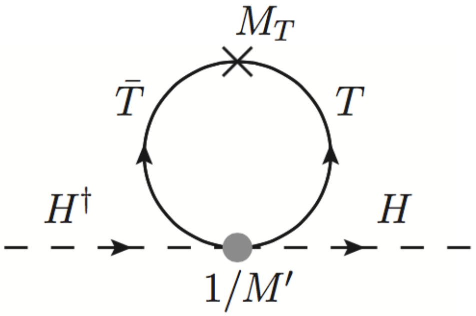
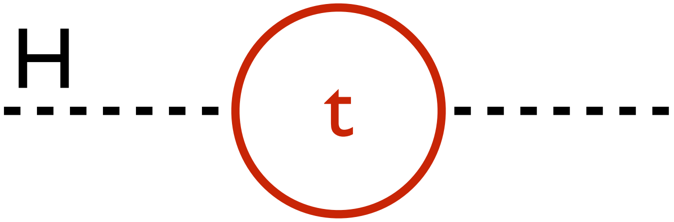


Fermion Partners



Only impose *one* condition on EFT:

cancellation of quadratic divergence from top loop



Two distinct low-energy EFTs

Scalar Partners

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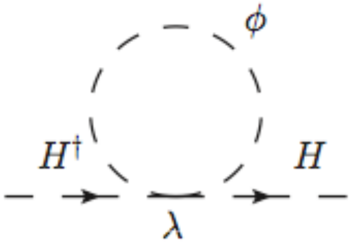
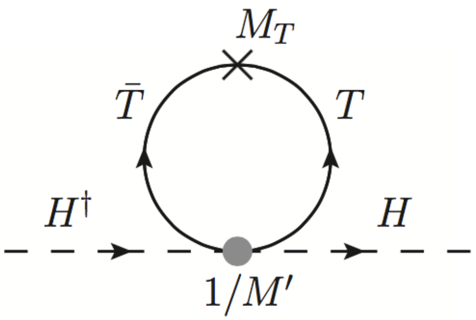


Fermion Partners



Relevant terms in the HEFT expansion:

$$\mathcal{L}_\phi \supset -\sum_i \phi_i^2 \left(\frac{1}{2}\mu_{\phi_i}^2 + \frac{1}{2}\lambda_i |H|^2 \right)$$

$$\mathcal{L}_T \supset \sum_i T_i \bar{T}_i \left(M_{T_i} - \frac{|H|^2}{2M_i'} \right)$$

Condition to cancel one-loop quadratic divergence from top quark:

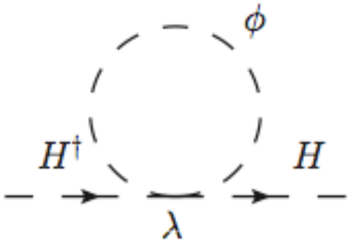
$$\lambda_\phi = \frac{12}{N_r} |y_t|^2$$

$$\frac{M_T}{M'} = \frac{3}{N_f} y_t^2$$

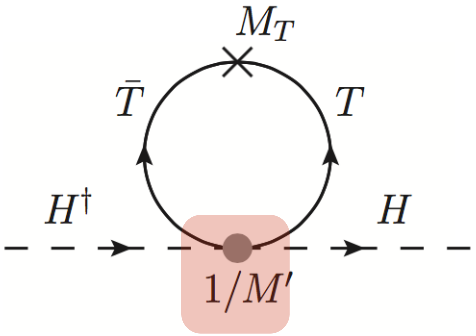
Two distinct low-energy EFTs

Scalar Partners

(Vector partners
"same" as scalars)



Fermion Partners



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Condition to cancel one-loop quadratic divergence from top quark:

$$\lambda_\phi = \frac{12}{N_r}|y_t|^2$$

$$\frac{M_T}{M'} = \frac{3}{N_f} y_t^2$$

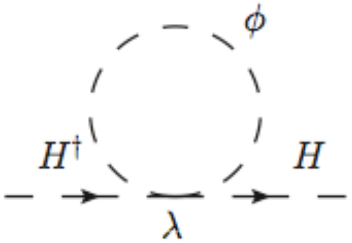
Non-renormalizable term limits what we can compute.
Need partial UV completion for fermion partners!

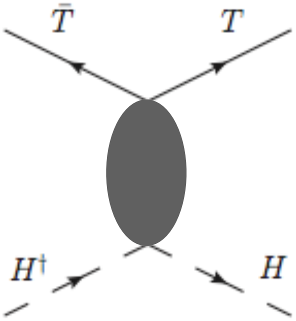
Four possible Neutral Top Partner structures

Scalar Partners

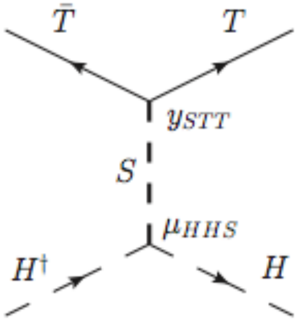
Fermion Partners

For fermion partners, have to distinguish how HHTT operator is generated.

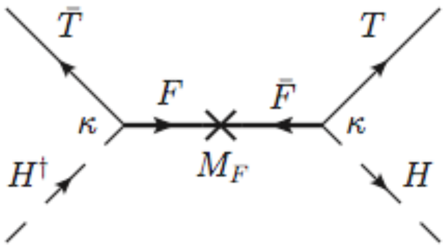




Strong Coupling



Scalar Mediator



Fermion Mediator

Four possible Neutral Top Partner structures

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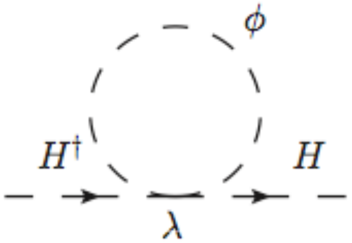
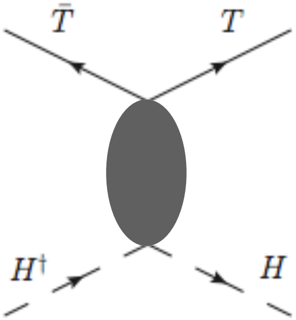
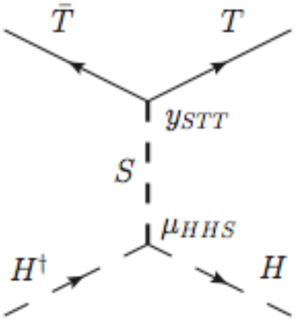
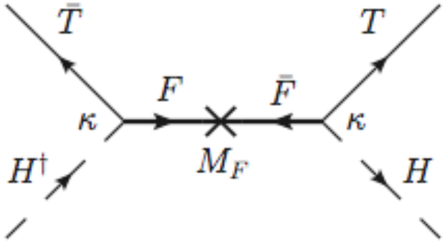




Strong Coupling



Scalar Mediator



Fermion Mediator

↑ ↑ ↑ ↑

?

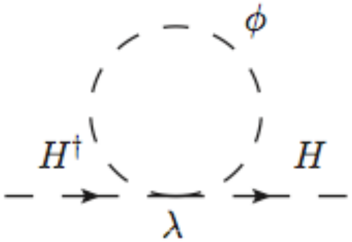
Twin Higgs
with composite/
holographic UV
completion

Twin Higgs
with perturbative
UV completion

?

Four possible Neutral Top Partner structures

Scalar Partners

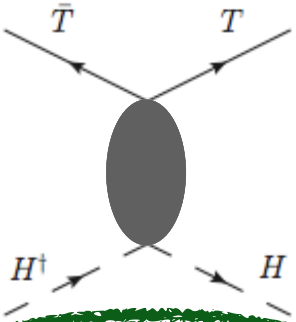


?

Much more general than Twin Higgs!

Fermion Partners

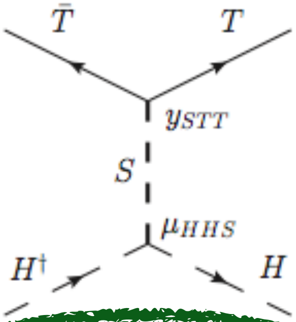
For fermion partners, have to distinguish how HHTT operator is generated.



Strong Coupling

Twin Higgs

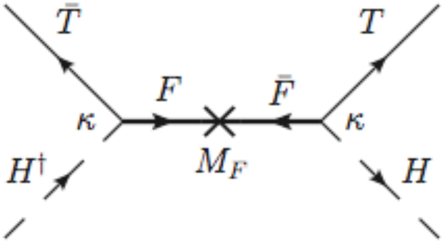
with composite/ holographic UV completion



Scalar Mediator

Twin Higgs

with perturbative UV completion

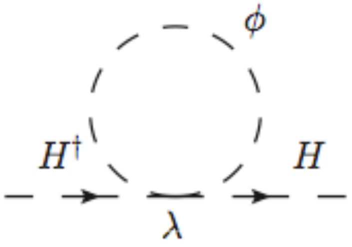


Fermion Mediator

?

Four possible Neutral Top Partner structures

Scalar Partners



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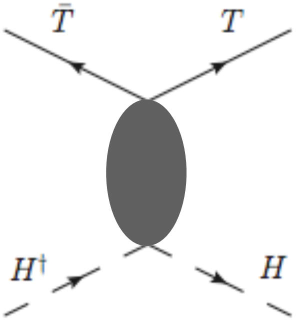

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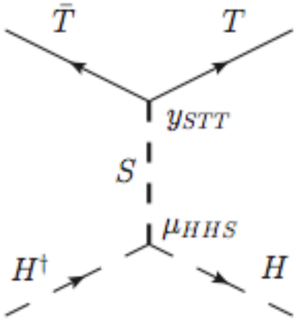

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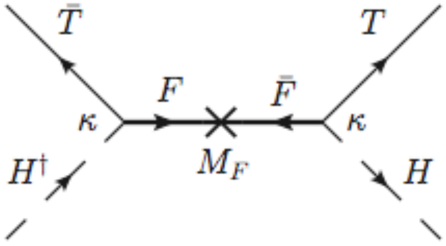


Fermion Mediator

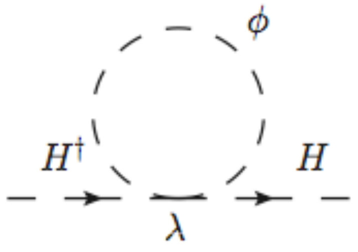
For each scenario, analyze:

Irreducible low-E signatures:

- Zh cross section (lepton collider)
- electroweak precision observables (lepton)
- higgs cubic coupling (100 TeV)
- top partner direct production (100 TeV)

Four possible Neutral Top Partner structures

Scalar Partners



Fermion Partners

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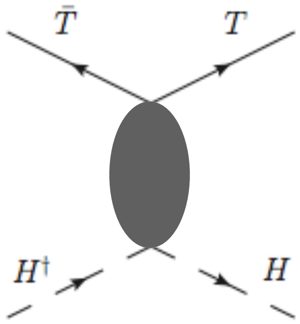
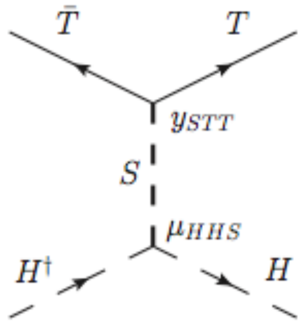
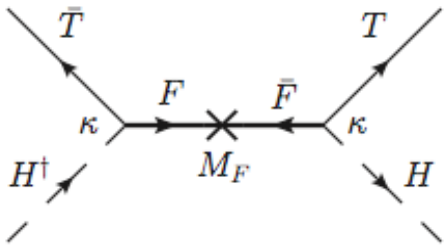


Strong Coupling



Scalar Mediator



Fermion Mediator

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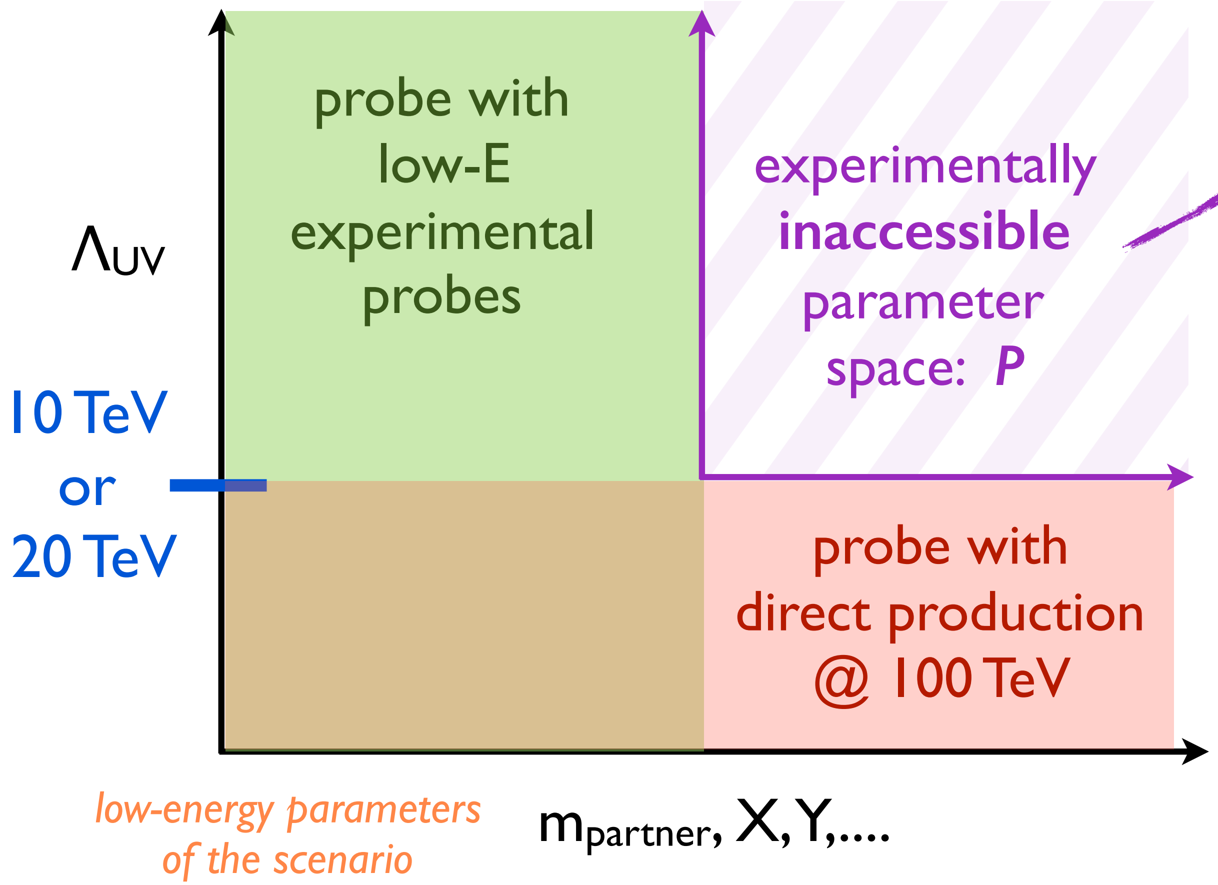
Irreducible tunings $\{\Delta_i\}$ of loop vs tree suffered by scenario ⇛ $\Delta_{tot} = f(\Delta_i)$

These will relate to UV completion scale Λ_{UV}.

Existing UV completions & symmetry arguments suggest **SM-charged BSM** states at this scale → **Assume production at 100 TeV collider!**

Strategy

For each scenario:

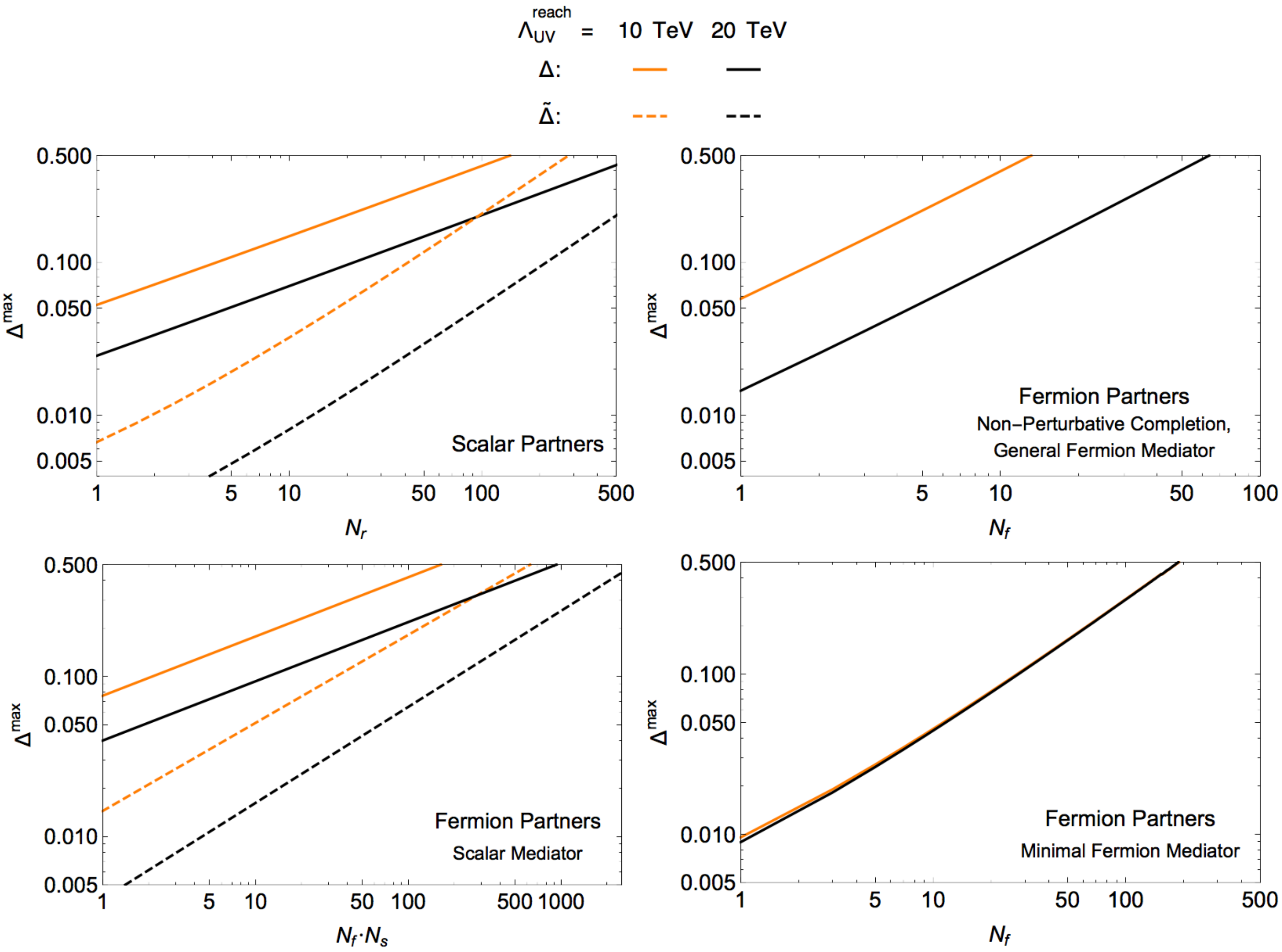


Find the LEAST TUNED the theory can be while escaping experimental detection:

$$\boxed{\Delta^{min}_{tot} = \underset{\{P\}}{\mathrm{Max}}\ f(\Delta_i)}$$

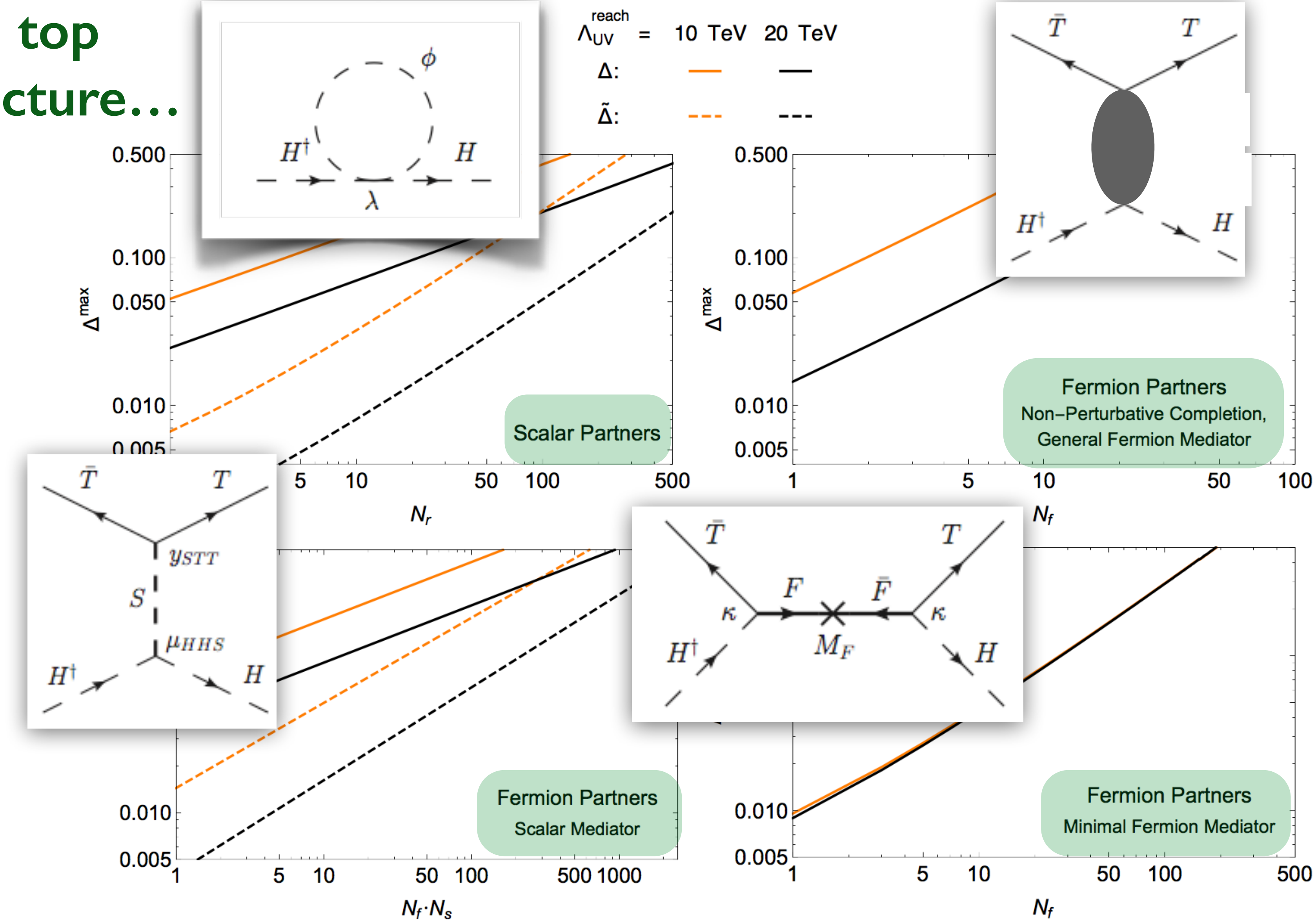
This will allow us to determine how natural an "undiscoverable" theory could be....

Preview of Results



Preview of Results

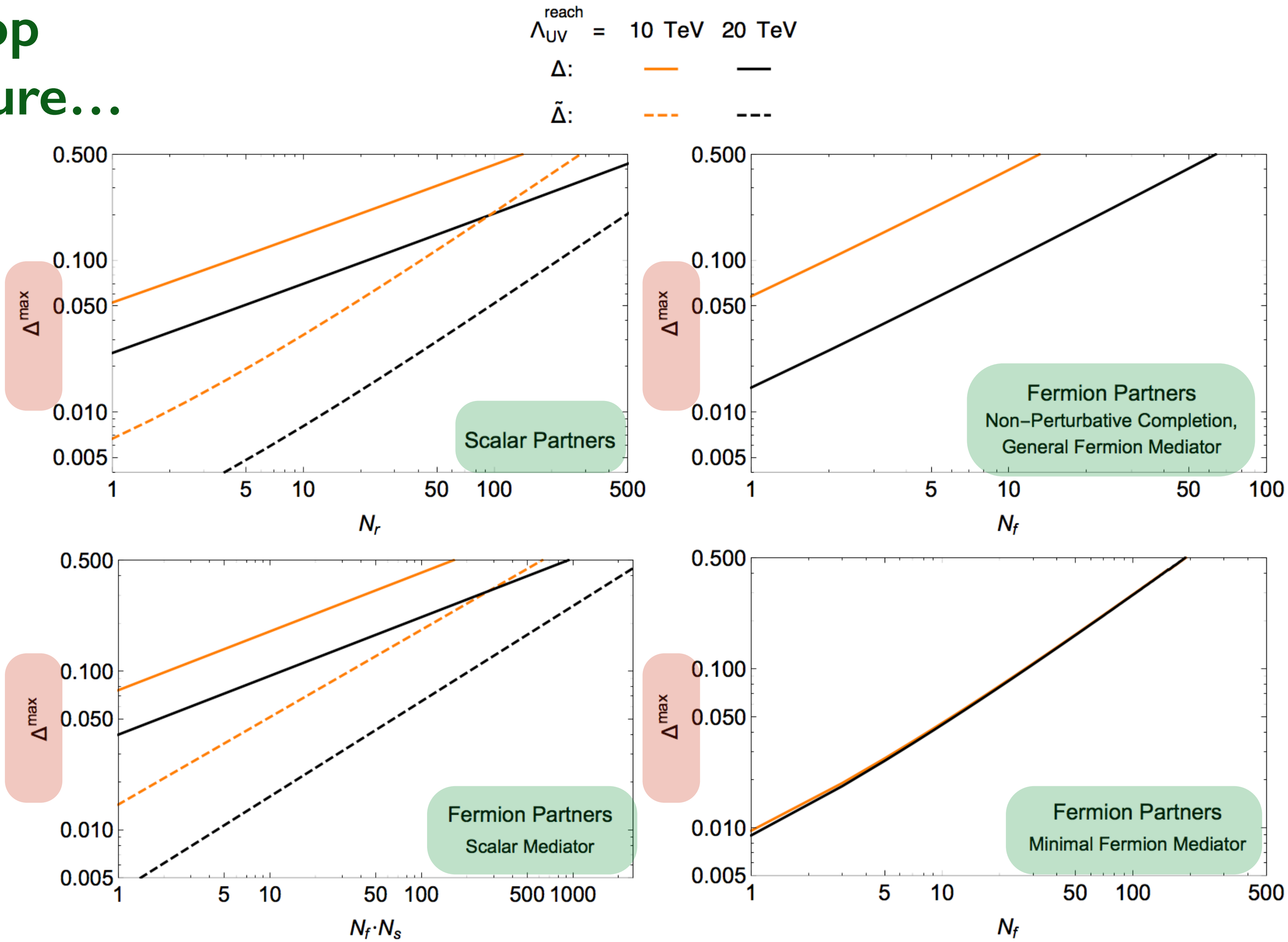
For each top partner structure…



Preview of Results

For each top partner structure…

.. we find the “tuning price” you have to pay to avoid any signatures @ 100 TeV or lepton colliders…



Preview of Results

For each top partner structure…

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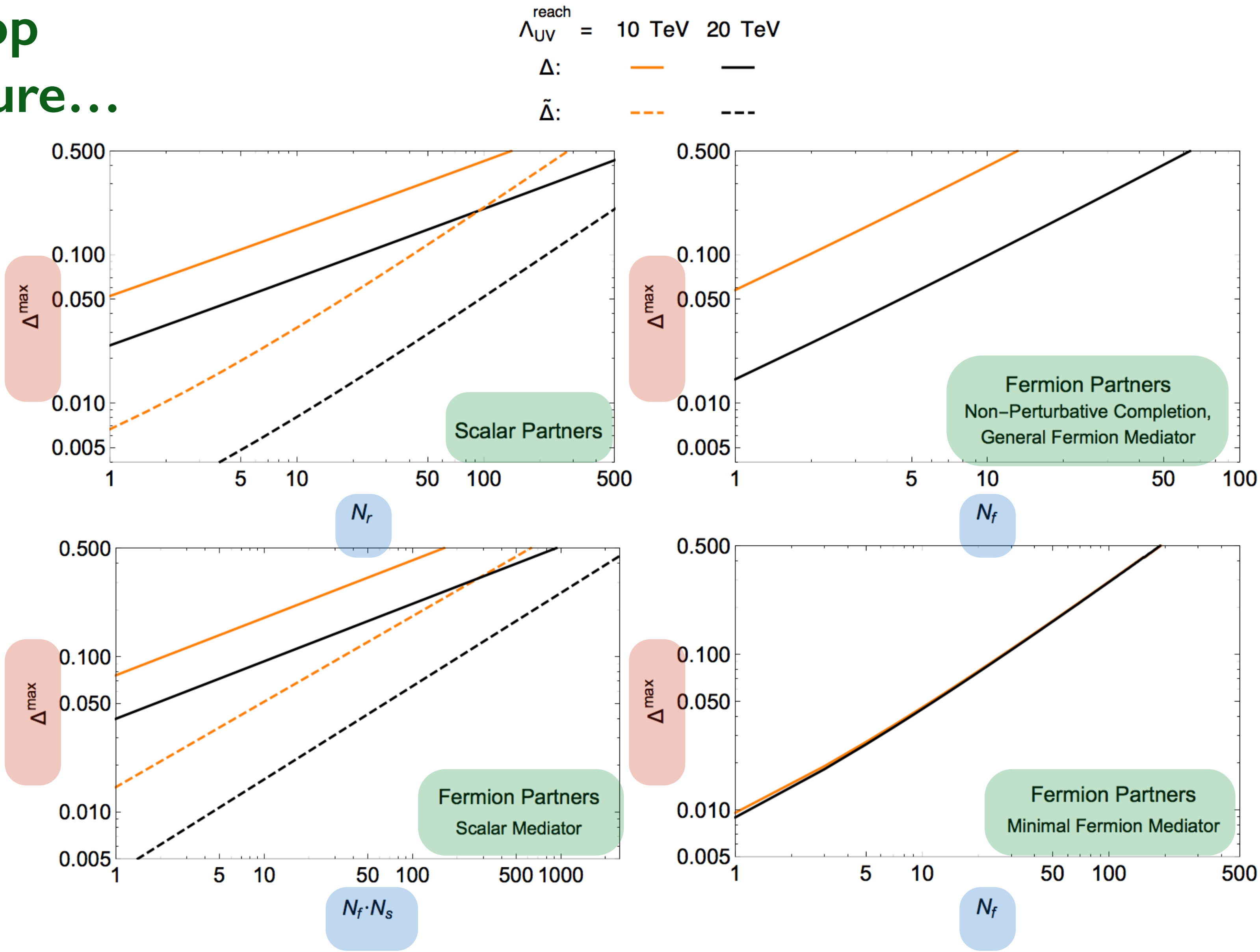


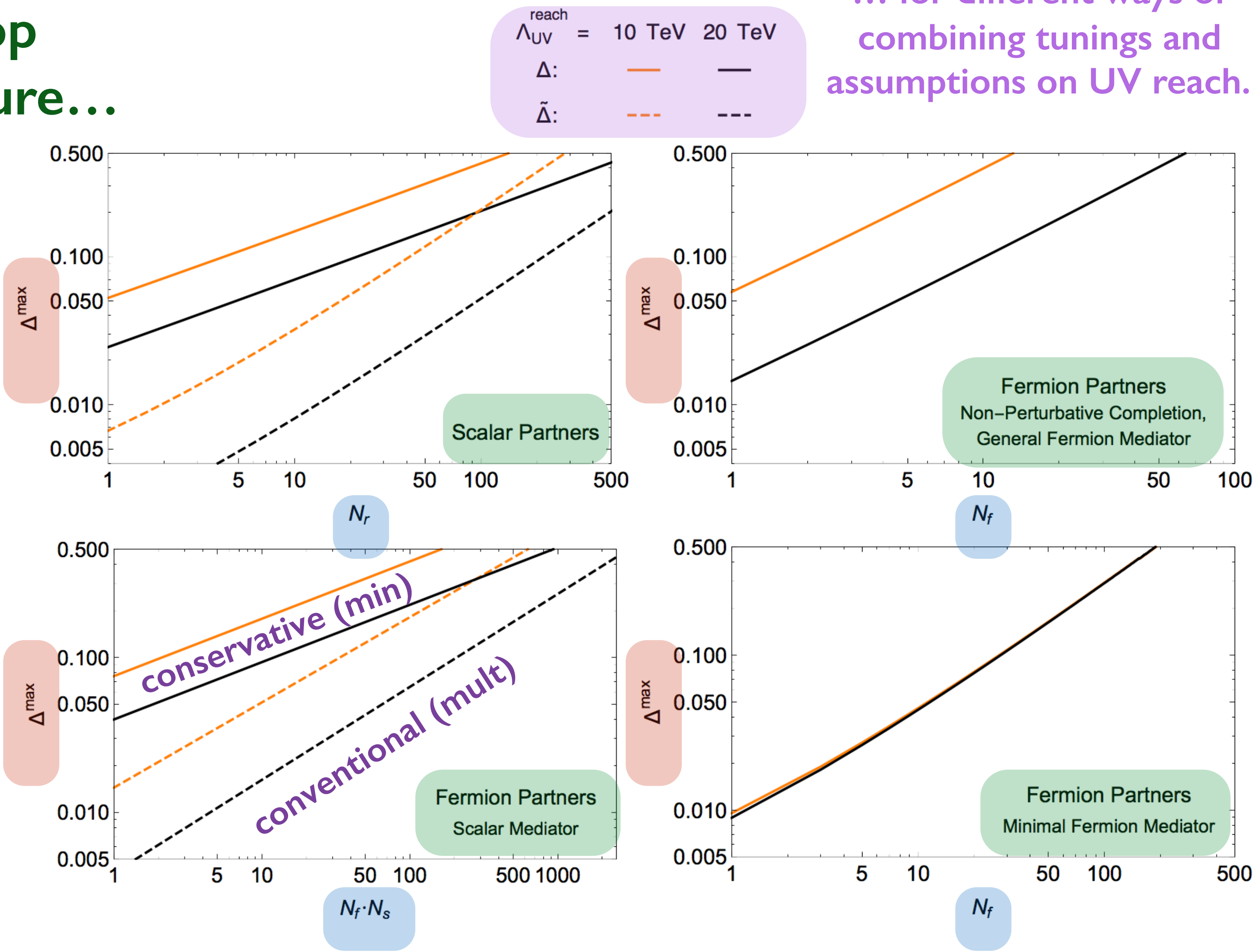
… as a function of the number of top partner dof…

Preview of Results

For each top partner structure…

… for different ways of combining tunings and assumptions on UV reach.

.. we find the "tuning price" you have to pay to avoid any signatures @ 100 TeV or lepton colliders…



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Preview of Results

For each top partner structure…

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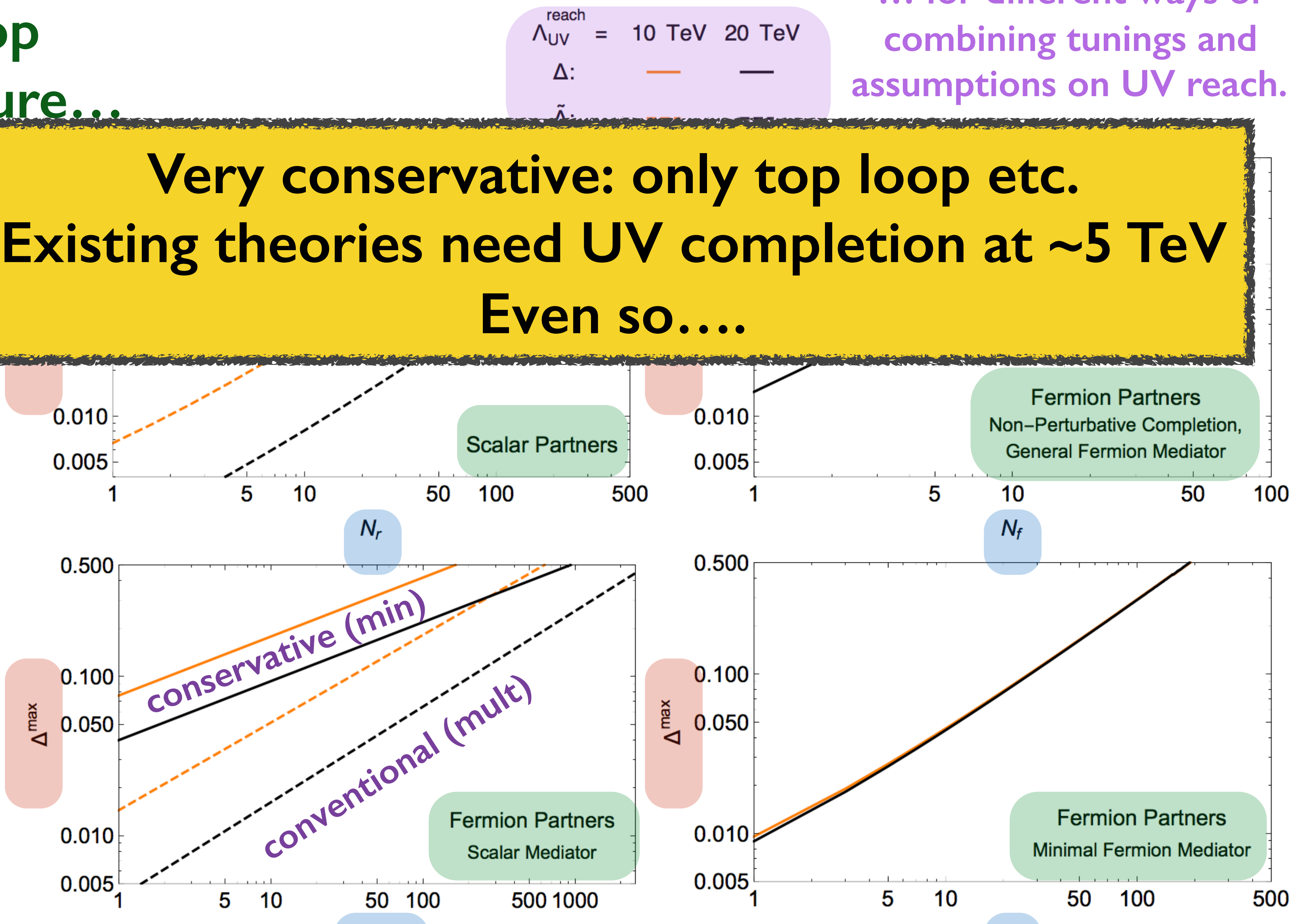


Very conservative: only top loop etc.
Existing theories need UV completion at ~5 TeV
Even so….

.. we find the “tuning price” you have to pay to avoid any signatures @ 100 TeV or lepton colliders…

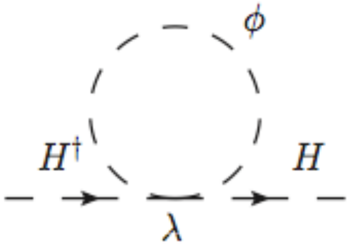
… as a function of number of top partne

→ need many partners to avoid discovery AND tuning!

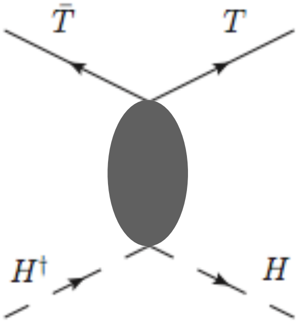
How do we get there?

Neutral Naturalness Scenarios

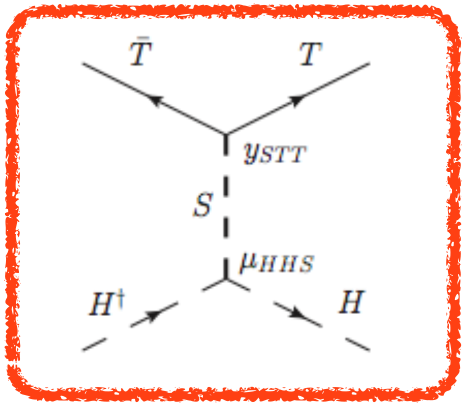
Scalar Partners



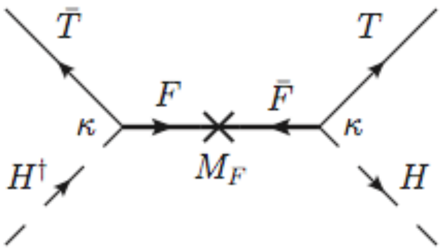
Fermion Partners
(strong coupling)



Fermion Partners
(scalar mediator)



Fermion Partners
(fermion mediator)

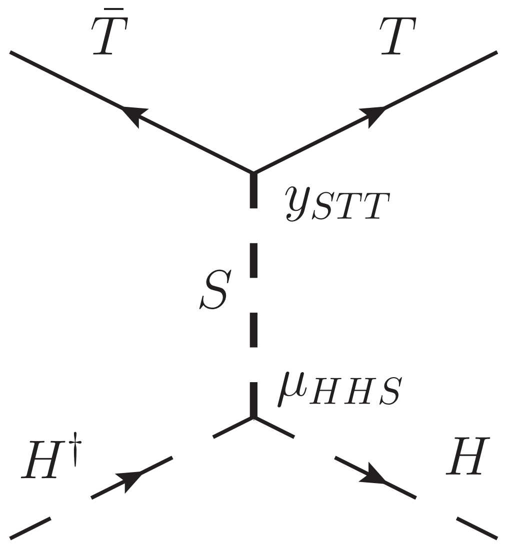


Trickiest/most interesting case
to analyze in complete generality...

Fermion Partner - Scalar Mediator

This is the most complicated and important case.

Contains Twin Higgs & Orbifold generalizations, but is much more general. 1410.6808, 1411.7393 Craig, Knapen, Longhi



Integrate out mediator(s) to match to natural IR theory:

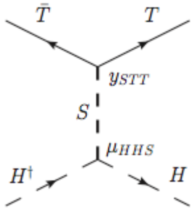
$$\mathcal{L}_T \supset \sum_i T_i \bar{T}_i \left(M_{T_i} - \frac{|H|^2}{2M_i'} \right)$$

low-energy effective Lagrangian to cancel top loop

$$\boxed{N_s \frac{\mu_{HHS} y_{STT}}{m_S^2} = \frac{1}{2M'} = \frac{3}{2N_f} \frac{y_t^2}{M_T}}$$

naturalness matching condition

The Scalar Mediator



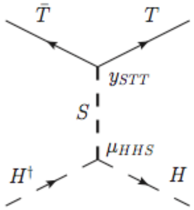
Before we can proceed, we have to know:
How heavy is the scalar mediator?

Naive expectation: new scalars can't be light, otherwise we have another hierarchy problem!
⇛ m_S should be significantly above weak scale!

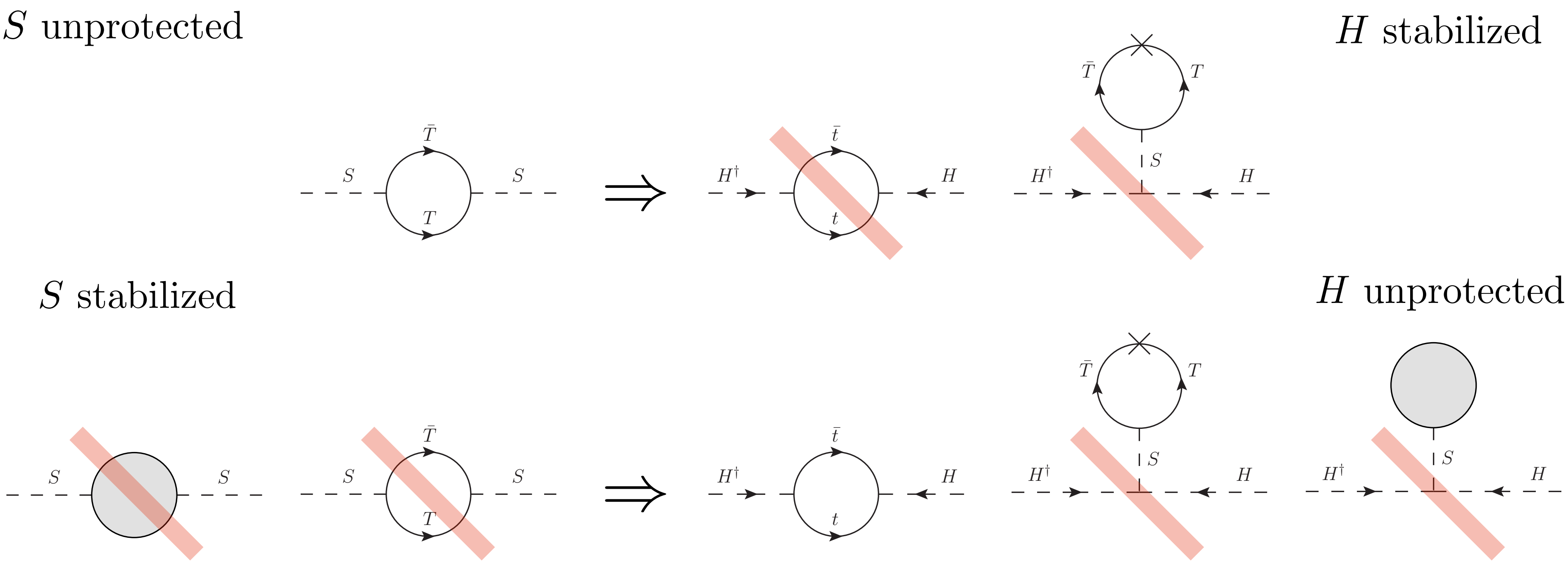
Naive counterargument: we know of many ways to solve the hierarchy problem! Dress up mediator sector with partners etc...

Nope!

The Scalar Mediator



Sacrificial Scalar Mechanism



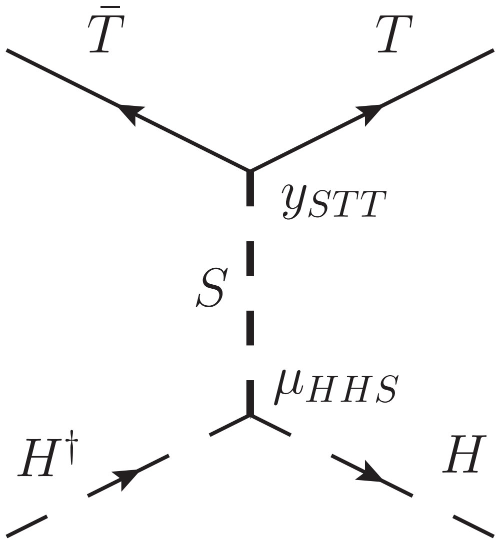
Consequences:

1. Mass of scalar is tied to UV completion scale!
2. $m_S >> m_h$ makes it easy to compute experimental signals.

Higgs Mixing

Take one scalar mediator S

(generalizes simply)



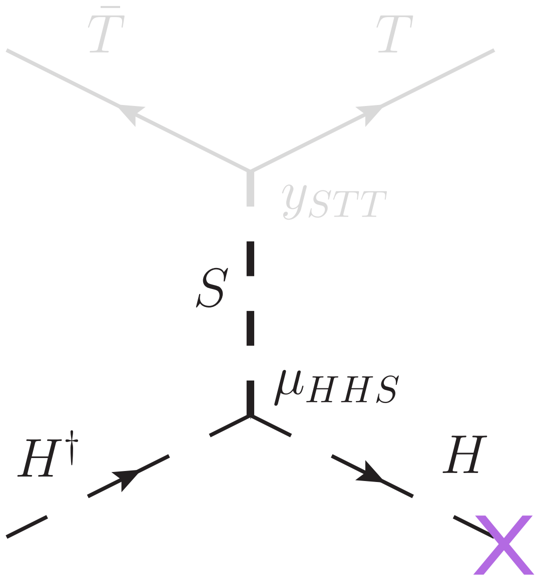
Higgs Mixing

Take one scalar mediator S

(generalizes simply)

In the $m_S >> m_h$ limit, mixing angle is simple:

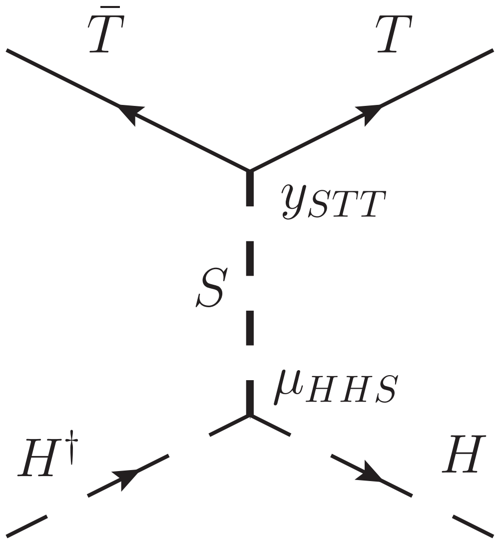
$$s_\theta \approx -\frac{\mu_{HHS}}{m_S^2} v$$



Computing Observables

Take one scalar mediator S

(generalizes simply)



In the $m_S >> m_h$ limit, mixing angle is simple:

$$s_\theta \approx -\frac{\mu_{HHS}}{m_S^2} v$$

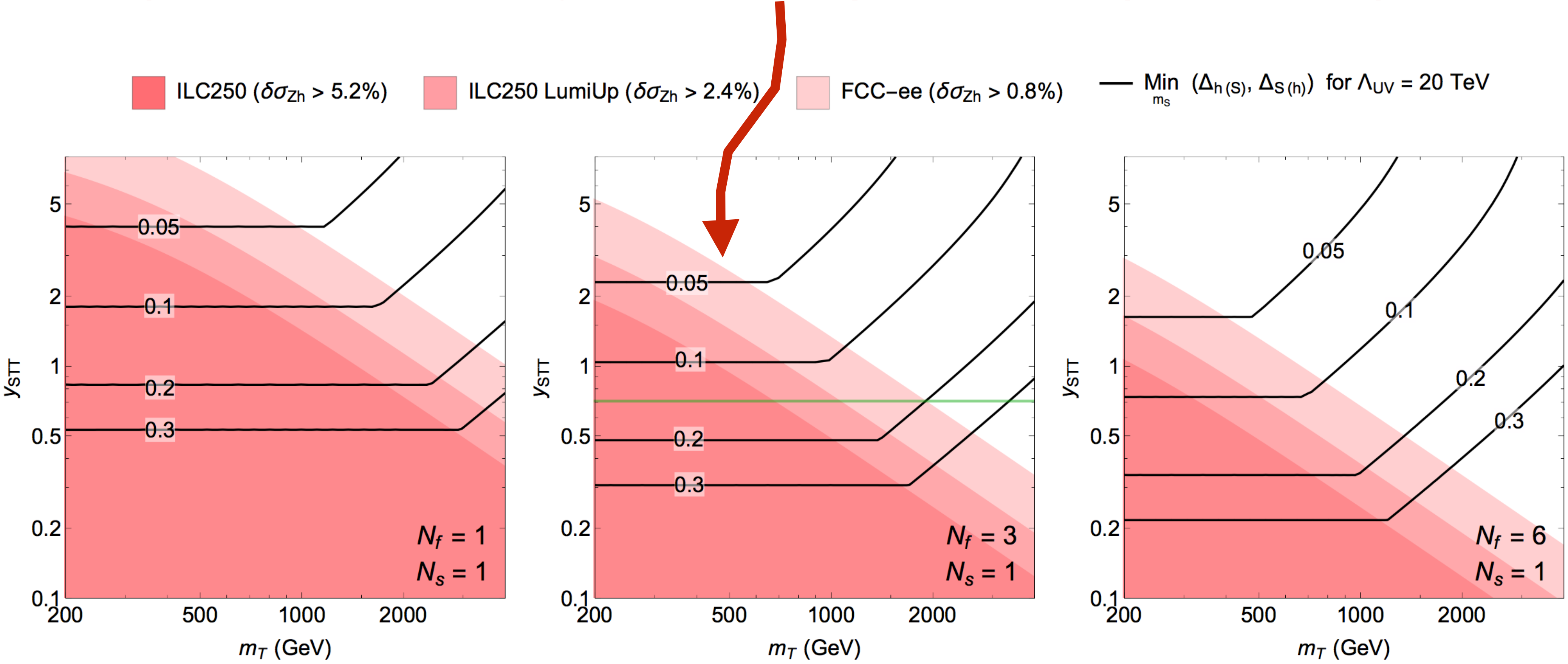
Naturalness condition:

$$\frac{\mu_{HHS} y_{SST}}{m_S^2} = \frac{3}{2N_f} \frac{y_t^2}{M_T} \longrightarrow \boxed{s_\theta \approx -\frac{3}{2N_f} \frac{y_t^2}{y_{SST}} \frac{v}{M_T}}$$

Mediator mass drops out! Only depends on (M_T, y_{SST})

Higgs Mixing in (m_T, y_{STT}) Plane

Lepton colliders have great sensitivity in much of parameter space.



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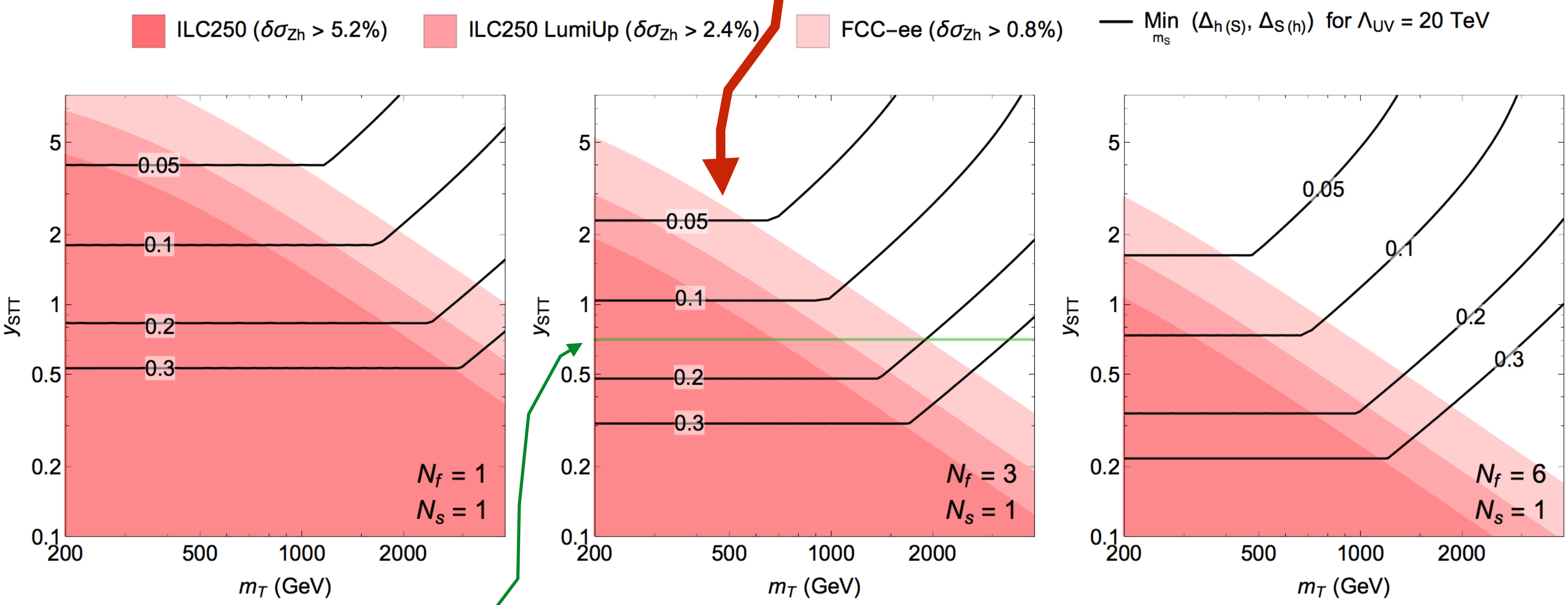

Twin Higgs models are subspaces (lines) in this more general parameter space.

Higgs Mixing in (m_T, y_{STT}) Plane

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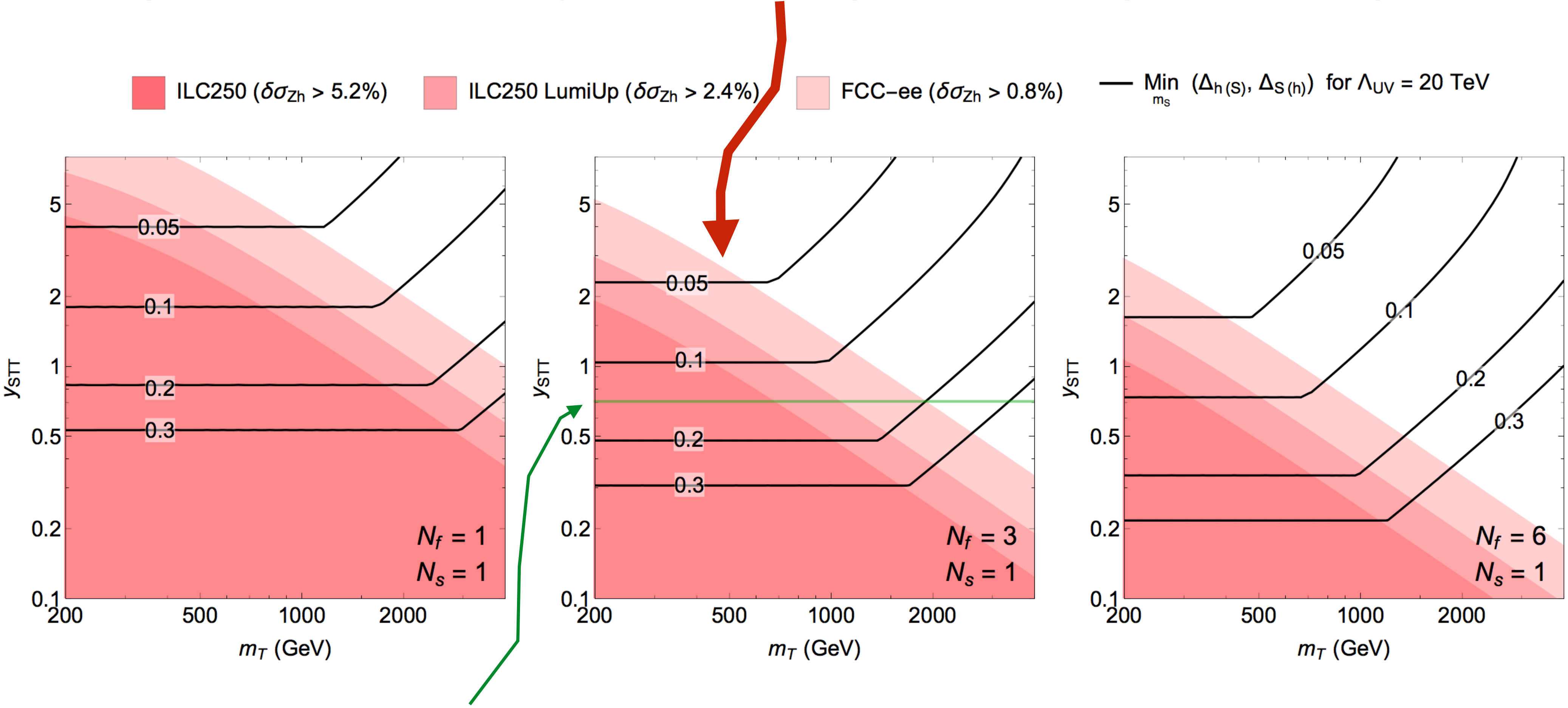
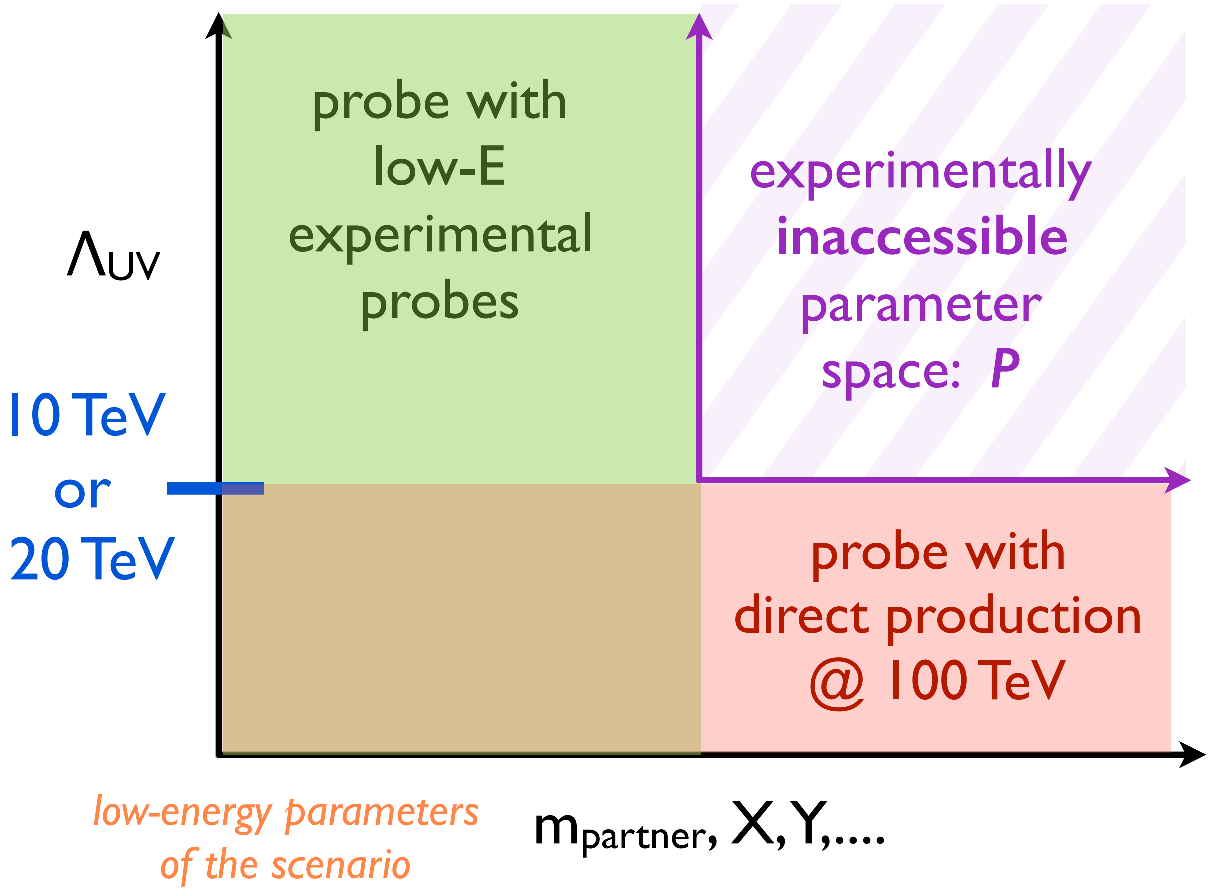


Twin Higgs models are subspaces (lines) in this more general parameter space.

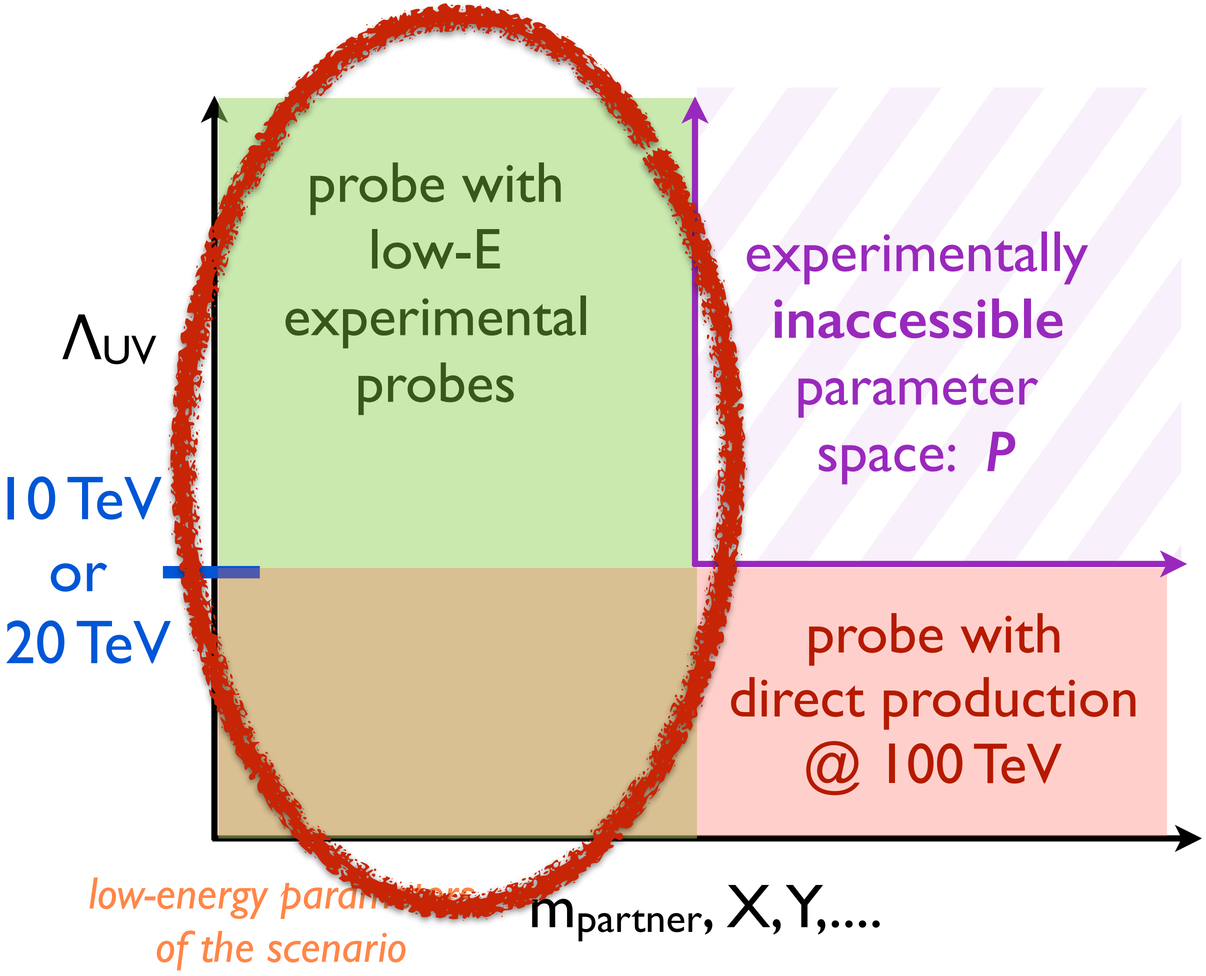
But what if y_{STT} is large??

Recall our main strategy:



Recall our main strategy:

We've determined the reach of low-energy observables (higgs mixing).



probe with low-E experimental probes

experimentally **inaccessible** parameter space: *P*

probe with direct production @ 100 TeV

Λ_{UV}

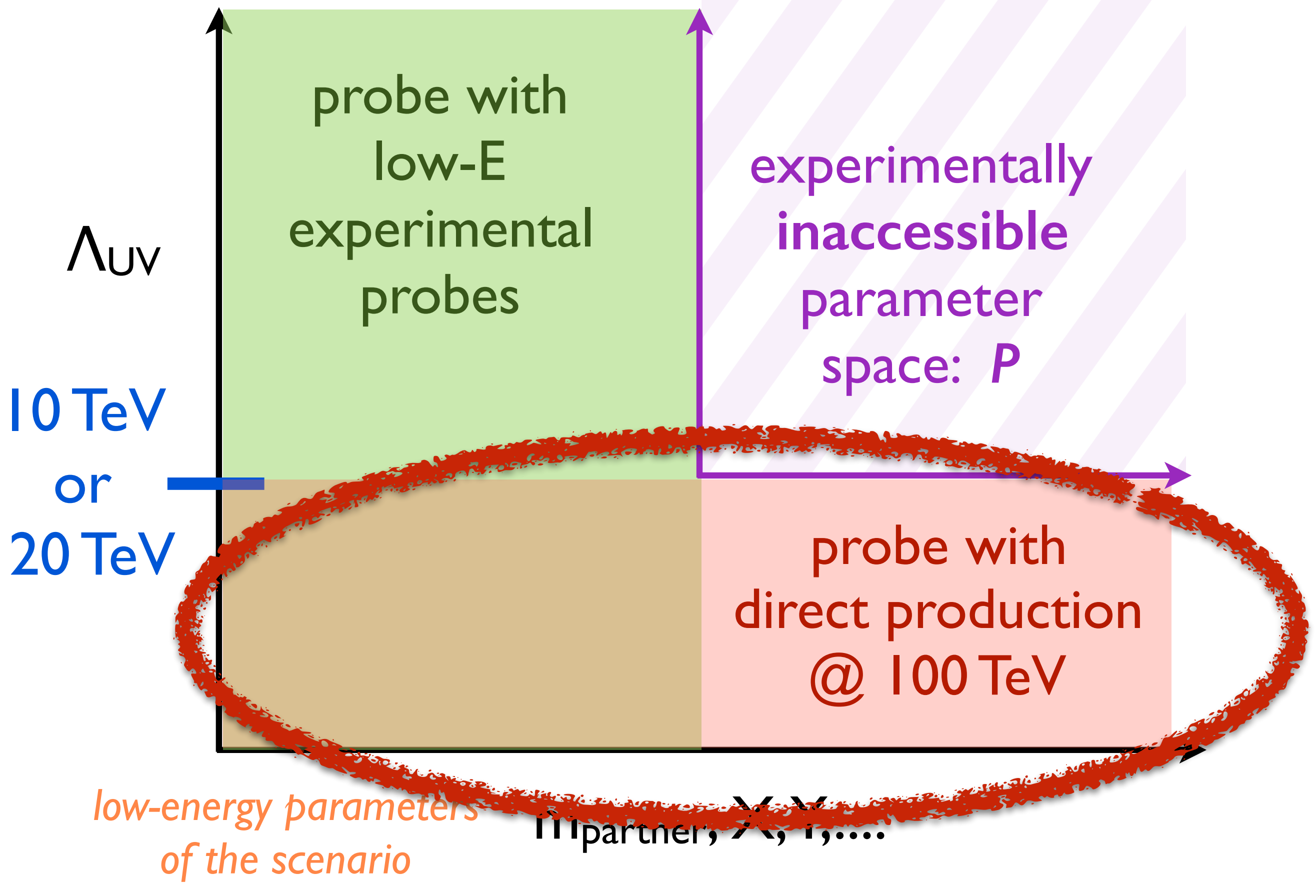
10 TeV or 20 TeV

$m_{partner}$, X, Y,....

low-energy parameters of the scenario

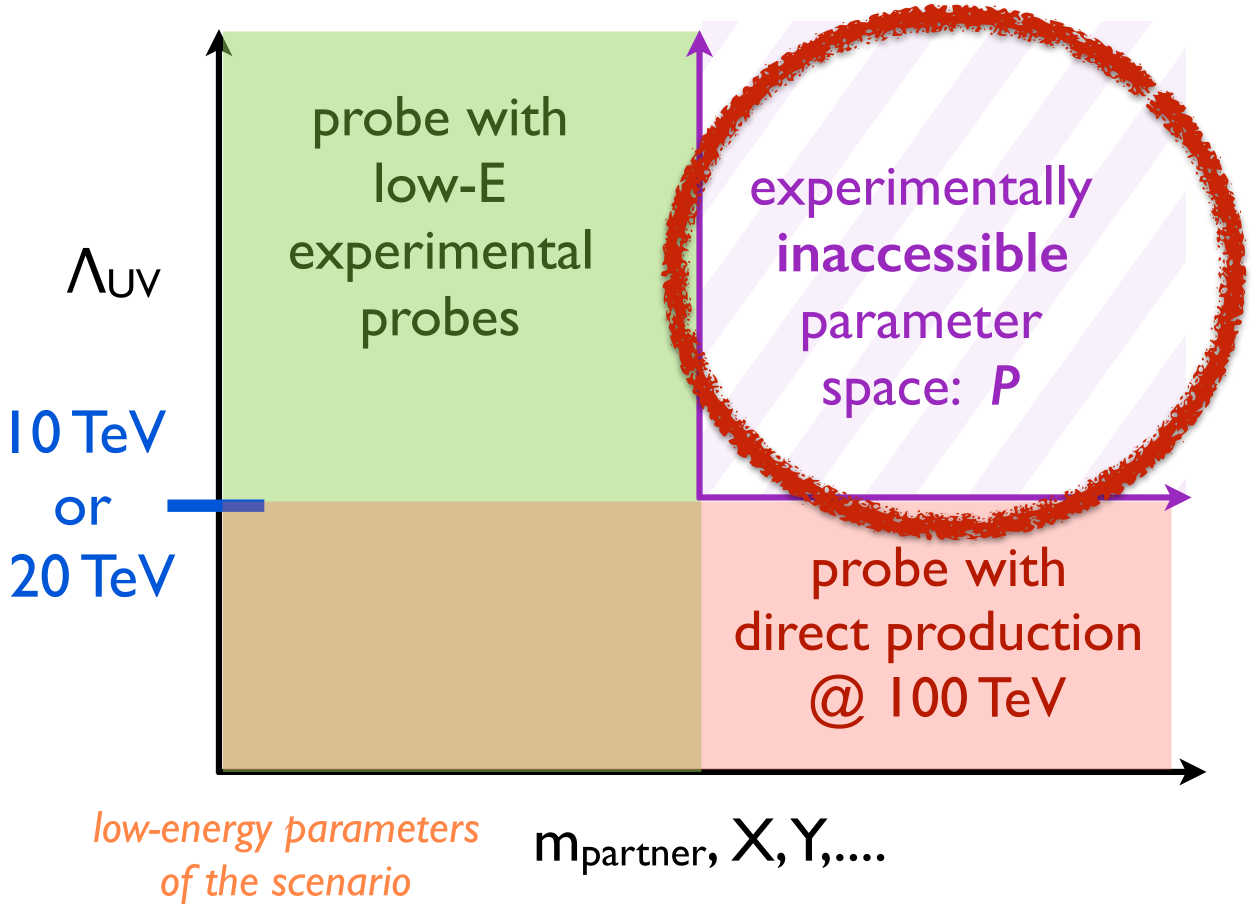
Recall our main strategy:

Now we exploit the 100 TeV collider's ability to probe the UV scale.



Recall our main strategy:

Assuming 10 or 20 TeV can be probed, what unavoidable tuning are we stuck with?



Tunings (1)

$\Delta_{h(S)}$ = log tuning of m_h from mediator loops.

(have to differentiate case where Higgs = PNGB from case without such symmetries....)

Gets worse with large m_S!

$\Delta_{S(T)}$ = tuning from quadratic sensitivity of m_S to T loops (required by Sacrificial Scalar Mechanism!)

Gets better with large m_S!

Can find conservative tuning estimate by maximizing over (unknown) mediator mass!

$$\Rrightarrow \quad \Delta_{H,S} = \underset{m_S}{\mathrm{Max}}\, f(\Delta_{h(S)}, \Delta_{S(T)})$$

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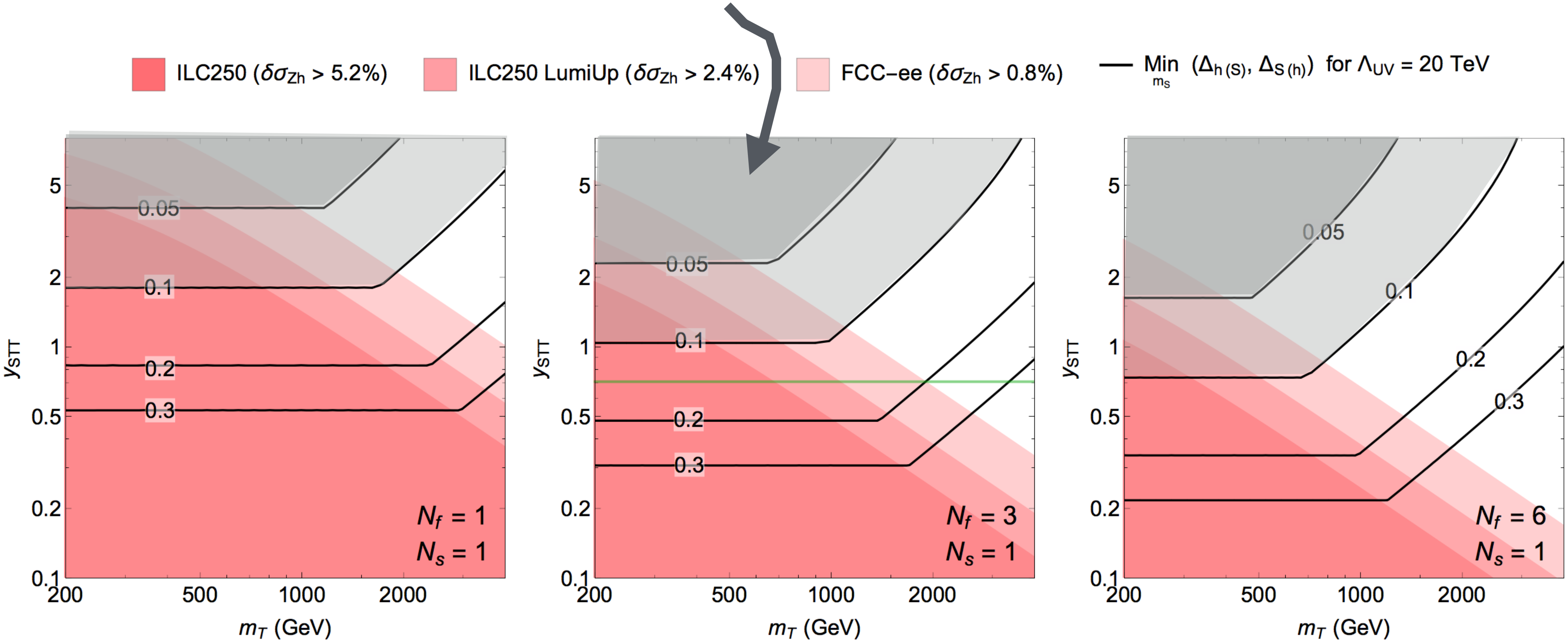
$$\Rrightarrow \quad \Delta_{H,S} = \underset{m_S}{\mathrm{Max}}\ f(\Delta_{h(S)}, \Delta_{S(T)})$$

Since we marginalize over m_S, $\Delta_{H,S}$ is uniquely defined in the (m_T, y_{STT}) plane as the tuning from the mediator sector.

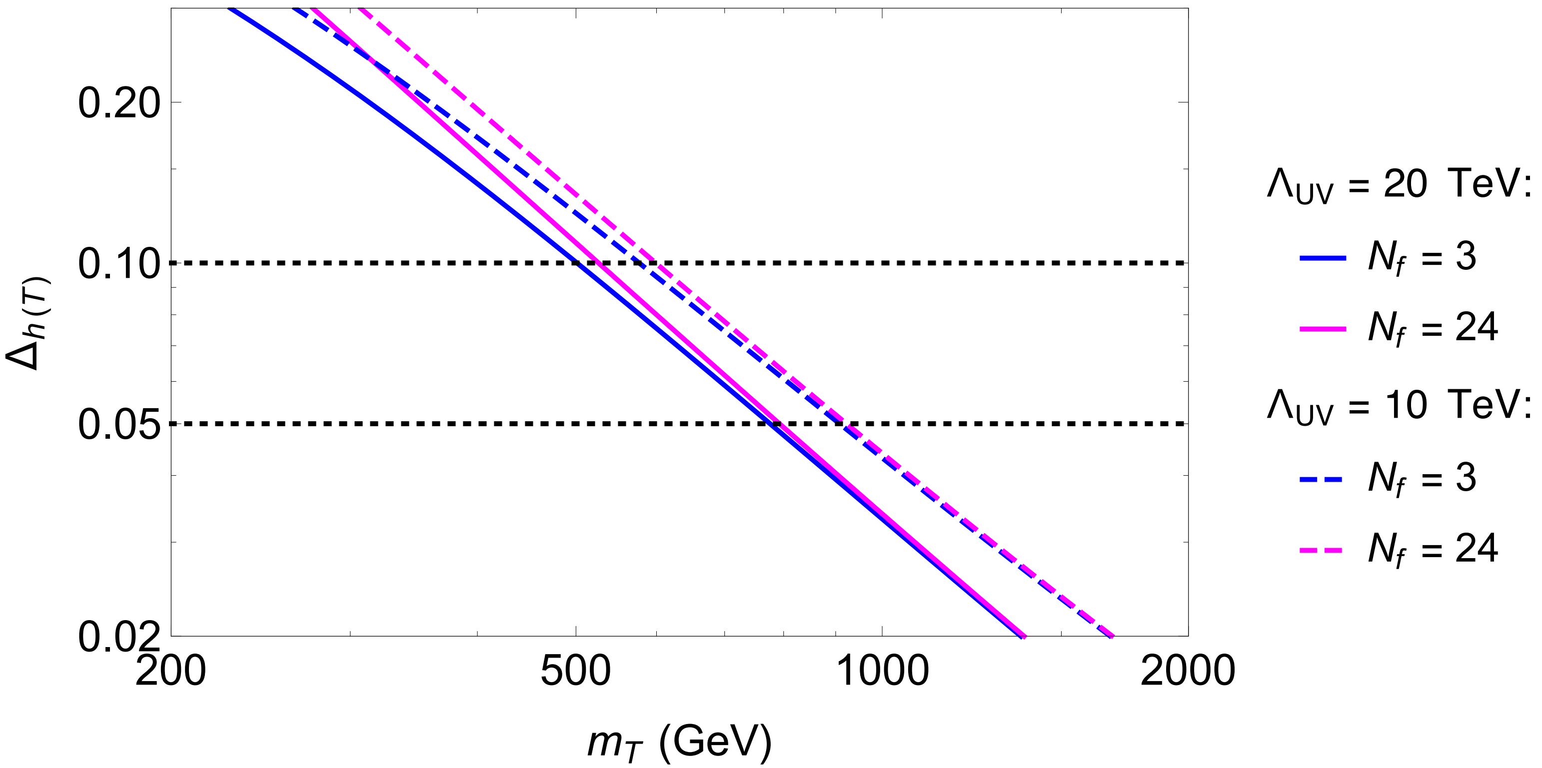
Tuning from Mediator in (m_T, y_{STT}) Plane

For $\Lambda_{UV} \geqq 20$ TeV (*undetectable by 100 TeV*), high y_{STT} is badly tuned!



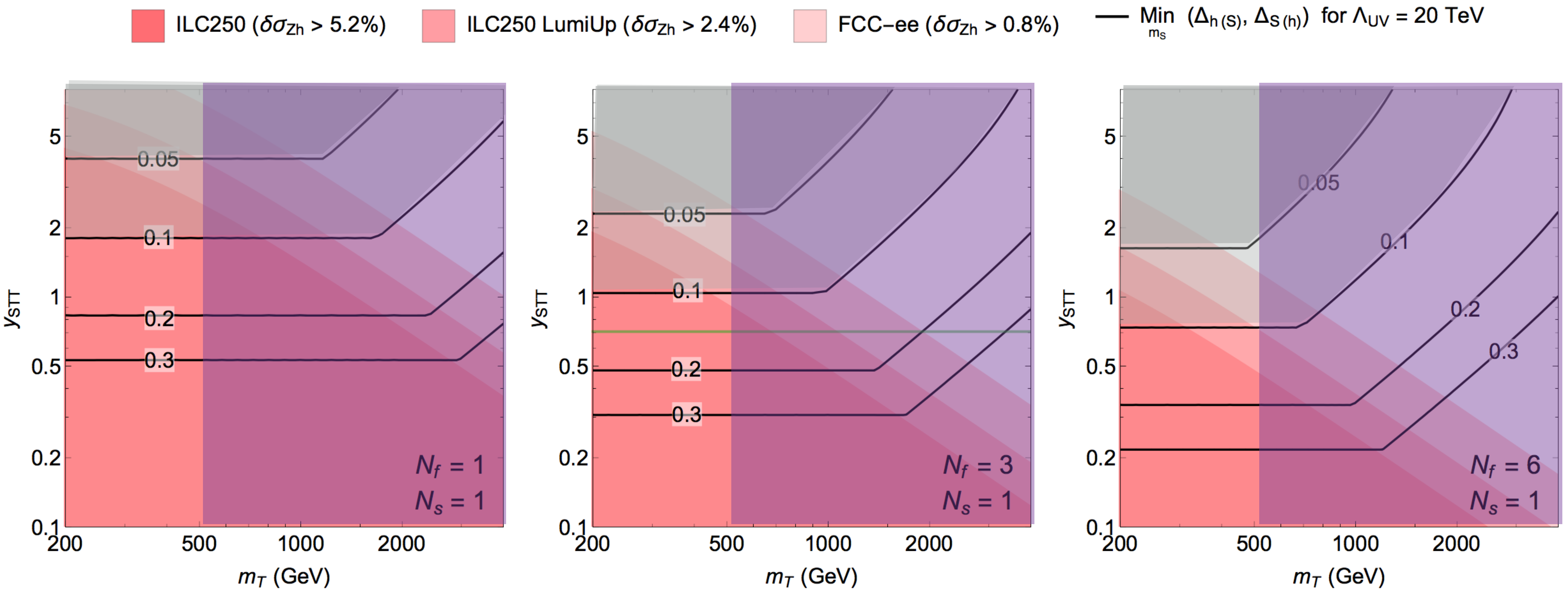
Tunings (2)

For $\Lambda_{UV} \geqq 20$ TeV (*undetectable by 100 TeV*), top partners heavier than ~500 GeV give log-tuning to Higgs mass worse than 10%



Log tuning from t vs T in (m_T, y_{STT}) Plane

For $\Lambda_{UV} \geqq 20$ TeV (*undetectable by 100 TeV*), top partners heavier than ~500 GeV give log-tuning to Higgs mass worse than 10%



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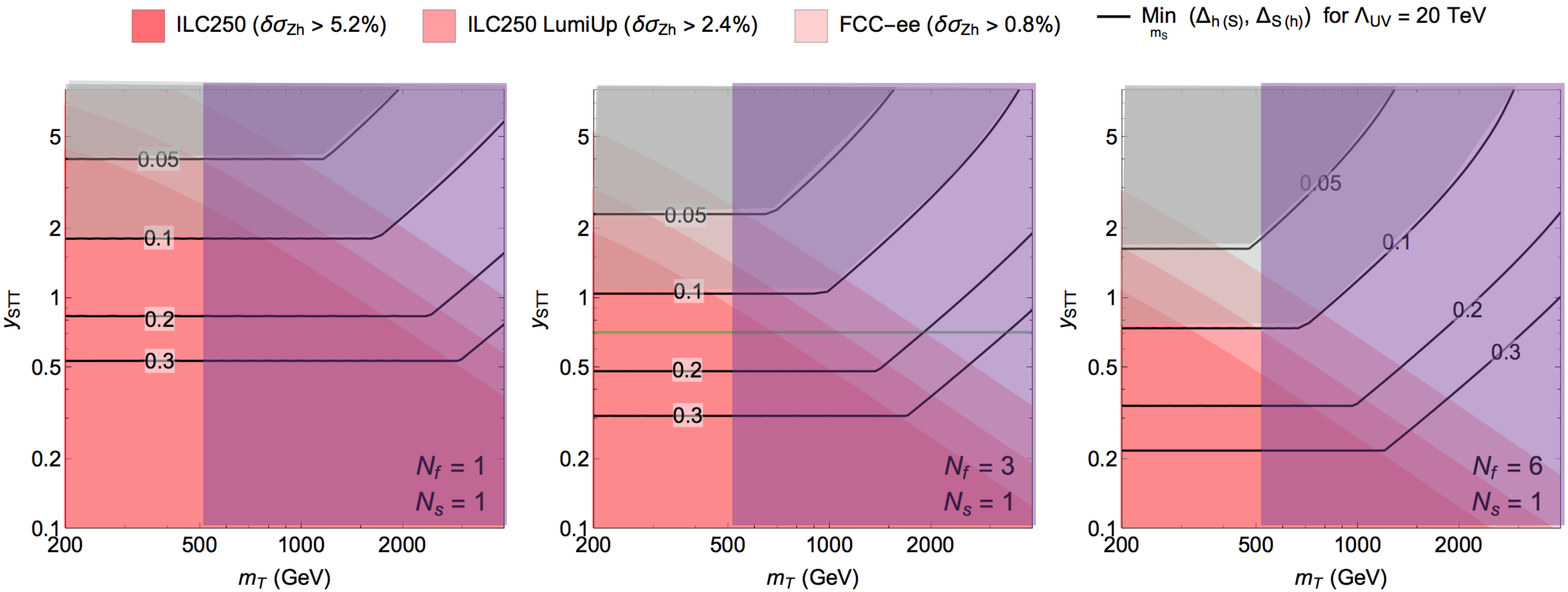
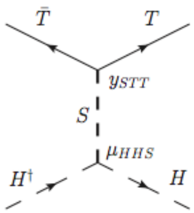
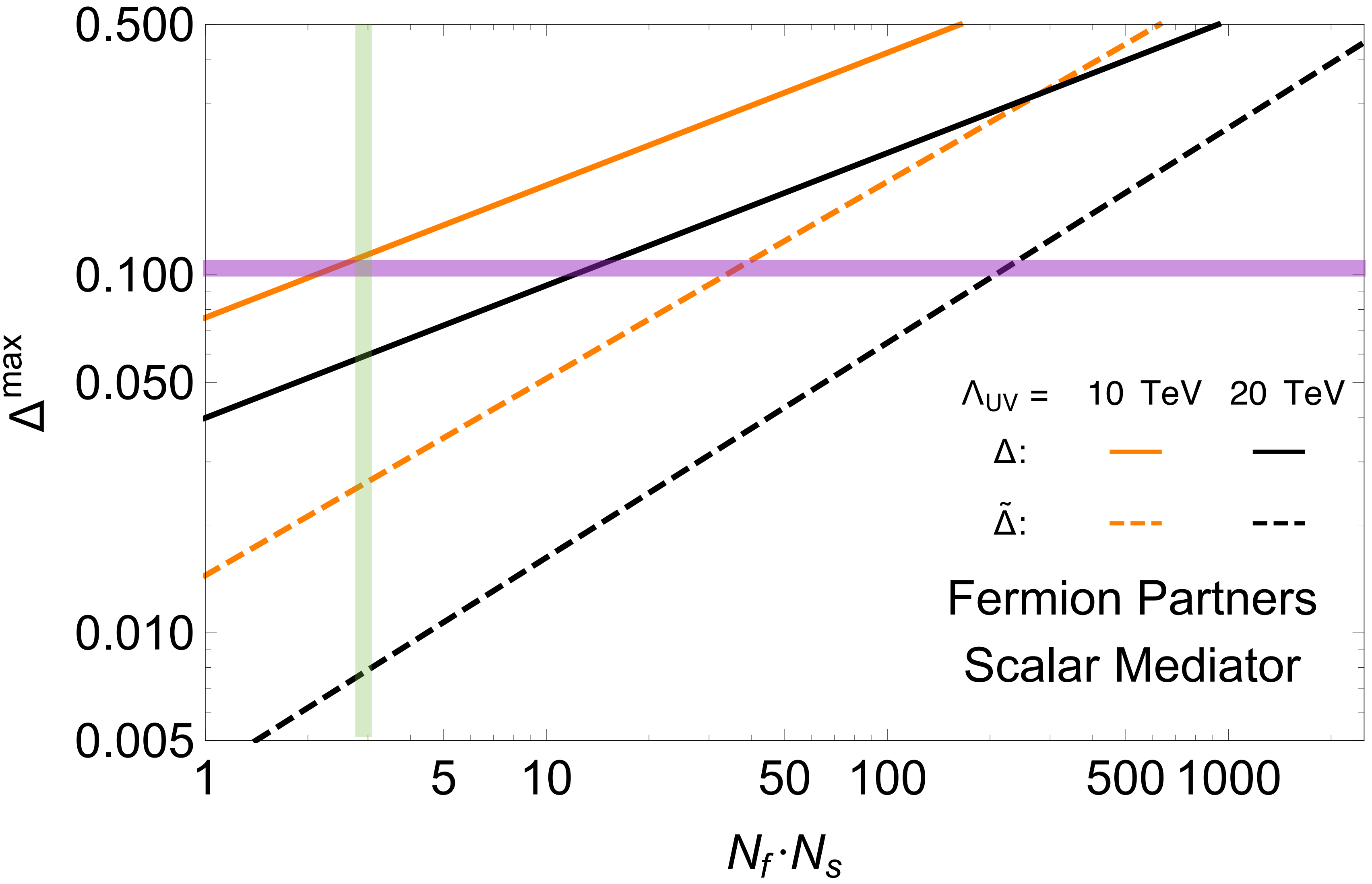


No untuned parameter space left for $N_f \times N_S \sim O(SM)$!

Fermion Partner - Scalar Mediator





A natural theory needs to have VERY MANY fermion partners/scalar mediators to possibly escape detection.

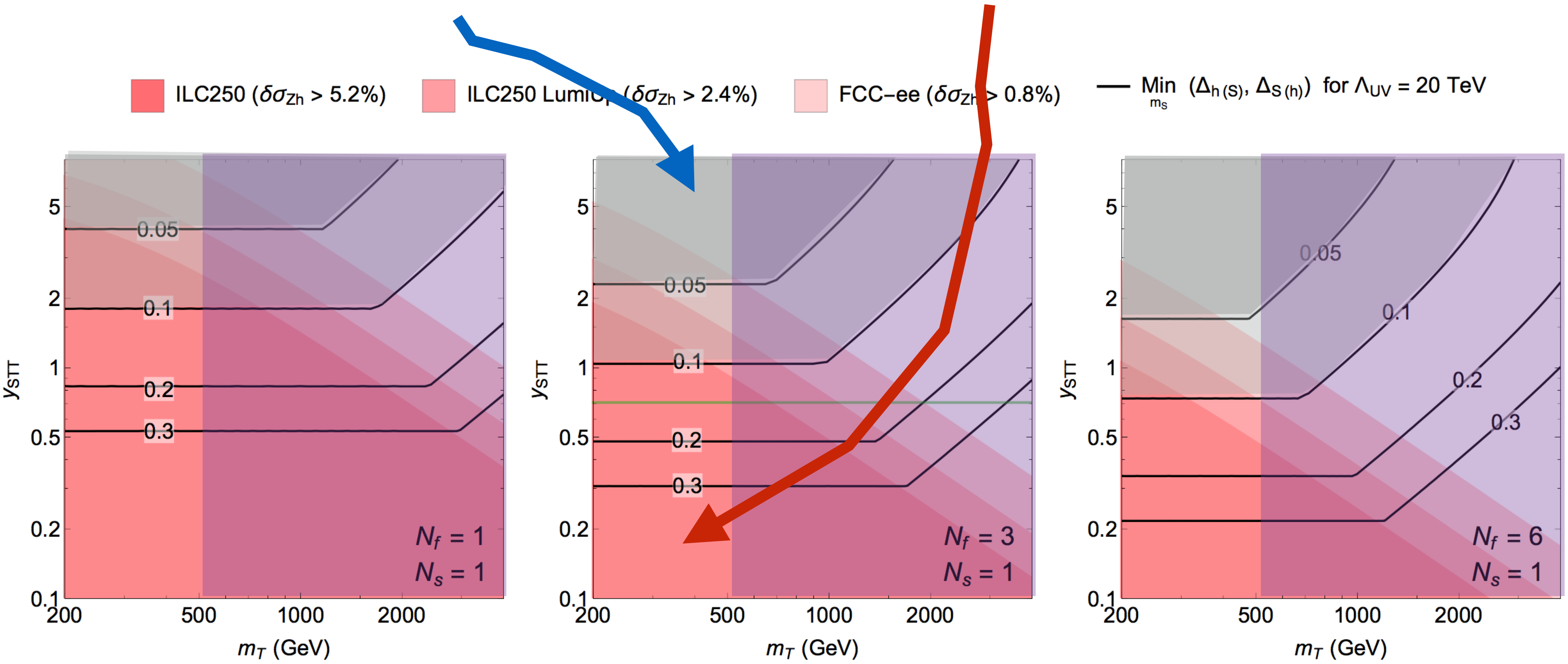
Need both colliders for full coverage!

Large hidden sector coupling:
Higgs mixing is tiny, but need low Λ_{UV}.

No guaranteed signal at lepton collider,
but slam dunk at 100 TeV!

Small hidden sector coupling:
theory can be healthy even for very large Λ_{UV},
but Higgs mixing is large.

No guaranteed 100 TeV signals,
but slam dunk at lepton colliders!



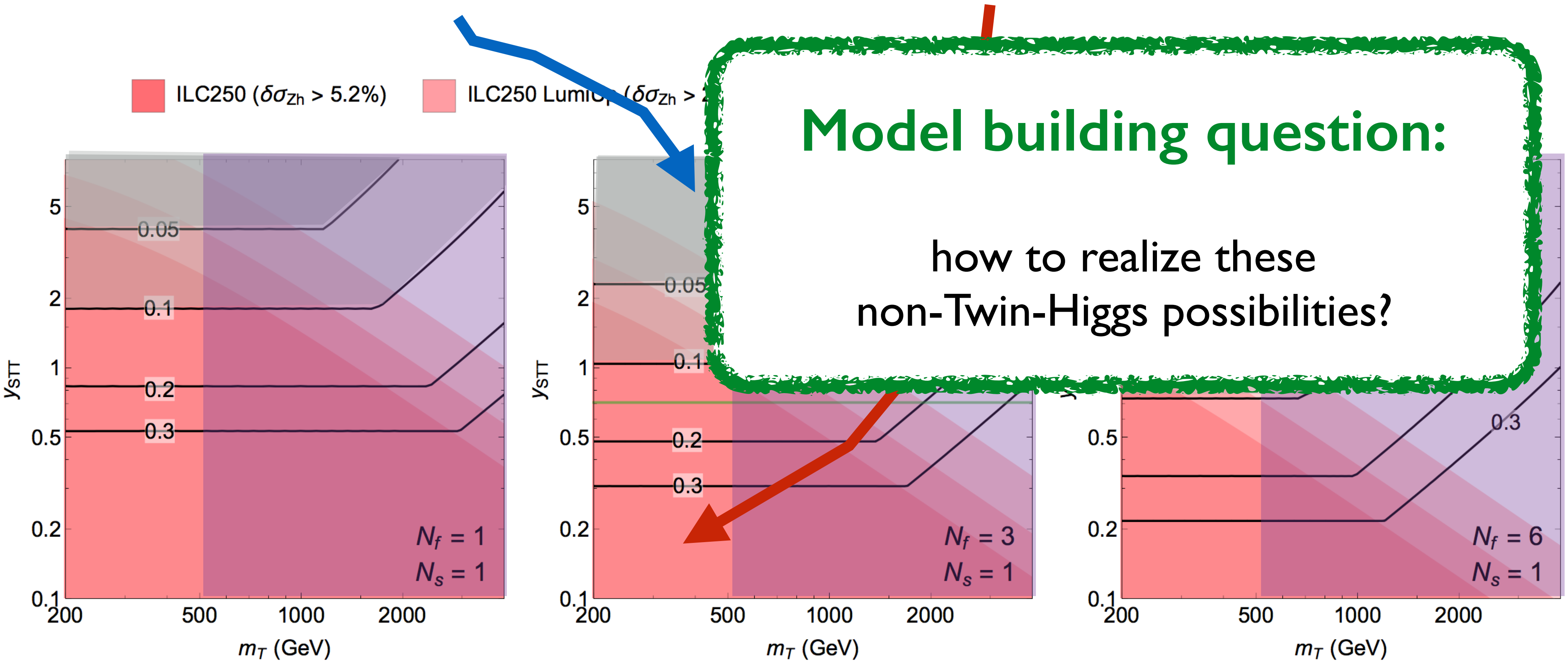
Need both colliders for full coverage!

Large hidden sector coupling:
Higgs mixing is tiny, but need low Λ_{UV}.

No guaranteed signal at lepton collider,
but slam dunk at 100 TeV!

Small hidden sector coupling:
theory can be healthy even for very large Λ_{UV},
but Higgs mixing is large.

No guaranteed 100 TeV signals,
but slam dunk at lepton colliders!



Model building question:

how to realize these
non-Twin-Higgs possibilities?

… go through corresponding derivations for the other scenarios, with similar conclusions….

What’s the upshot?

1. Great discovery potential TODAY

DC, Verhaaren 1506.06141

Chacko, DC, Verhaaren, 1512.XXXXX

Long-lived hidden sector states** (mirror glueballs, quarkonia) generate spectacular displaced signals that allow the **LHC to probe TeV uncolored top partners

2. Implications for LHC searches

*Displaced Vertex searches with just **one DV + VBF or lepton** are required. Also, need **sub-mm decay length** reconstruction.*

HXSWG yellow report (soon!)

DC, Saraswat 1509.04284

3. No-Lose Theorem:

Any theory of ~10% naturalness with O(SM) top partners will be discovered at a planned lepton collider and/or 100 TeV

→ *Model-independent (bottom-up) and very conservative (only top loop etc)*

How to avoid this theorem?

Could have **top partner swarms,** or **neutral top partners without SM charges in UV completion.**

There might also be weird non-perturbative or stringy constructions that don't need top partners?

DC, Saraswat 1509.04284

4. Implications for future colliders

*Both lepton collider **and** 100 TeV have to work **in tandem** for full coverage of **general naturalness***

Without lepton collider:

could miss theory with large-ish Higgs mixing but small hidden sector couplings → very high UV completion scale out of 100 TeV collider reach

Without 100 TeV:

several scenarios give small IR signatures, need to probe UV

DC, Saraswat 1509.04284

5. For full coverage, need to probe UV completion!

Central assumption of SM-charged BSM states at Λ_{UV} allows us to make these very powerful conclusions.

This seems very reasonable, and is certainly the case in all currenty proposed UV completions.

Can we formally prove this always has to be the case, or construct counter-examples?

Summary

1. **Discovery potential TODAY**

   Neutral naturalness motivates spectacular displaced signatures that give the LHC TeV-reach for uncolored top partners.

2. **Implications for LHC searches**

   Need searches with just one DV + lepton or VBF, and sub-mm decay-length reconstruction for full coverage

3. **No-Lose Theorem**

   *Any theory of ~10% naturalness with O(SM) top partners **will be discovered at a planned lepton collider and/or 100 TeV***

4. **Implications for future colliders**

   *Both lepton collider **and** 100 TeV have to work **in tandem** for full coverage of **general naturalness***

5. **Probing UV completion is vital!**

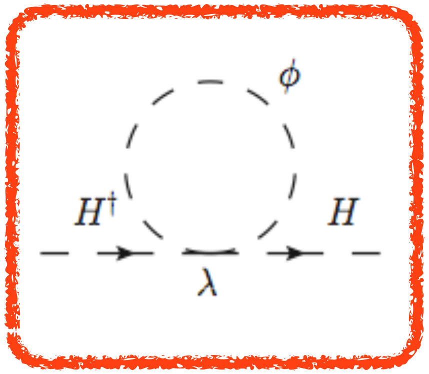
   *Can we **formally** prove that full that SM-charged BSM states appear at Λ_{UV} in full symmetry-based theories?*

Thank you!

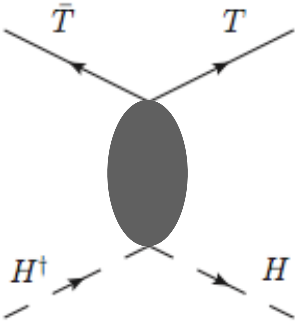
Backup Slides

Neutral Naturalness Scenarios

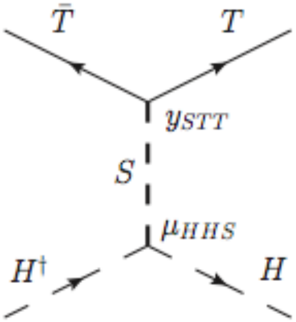
Scalar Partners



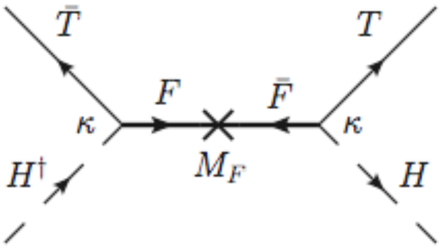
Fermion Partners (strong coupling)



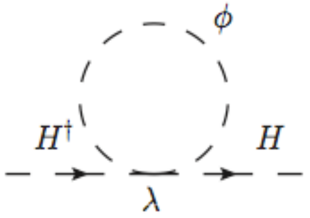
Fermion Partners (scalar mediator)



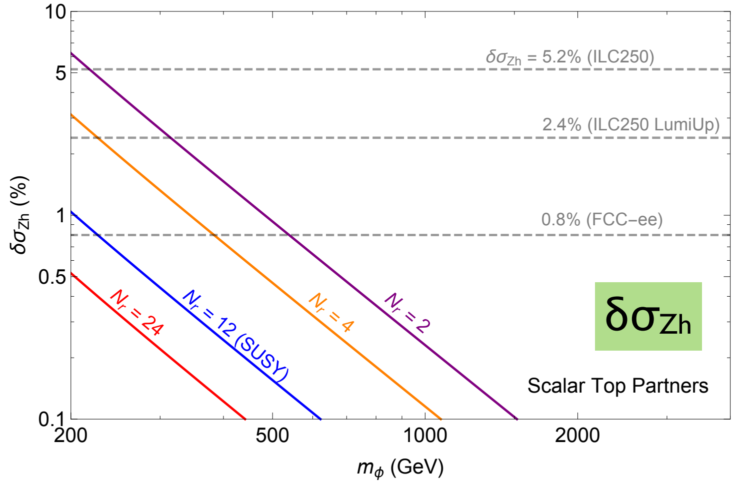
Fermion Partners (fermion mediator)

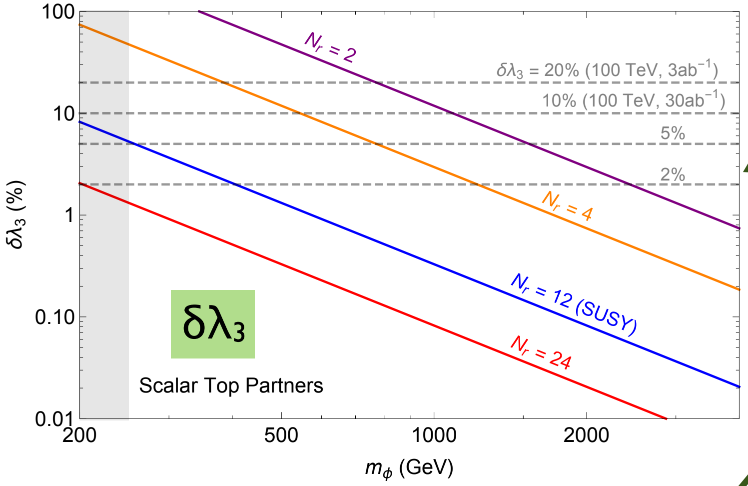


Scalar Partner

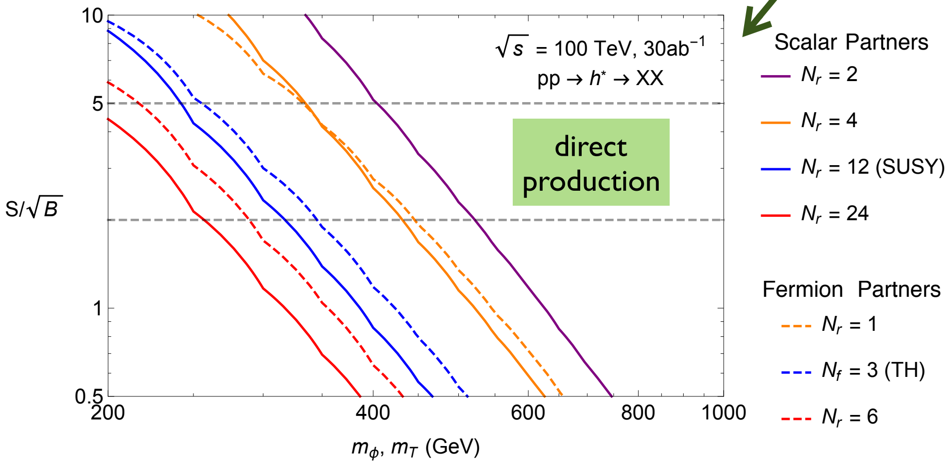


1305.5251 Craig, Englert, McCullough





1409.0005: DC, Meade, Yu
1412.0258 Craig, Lou, McCullough, Thalapillil



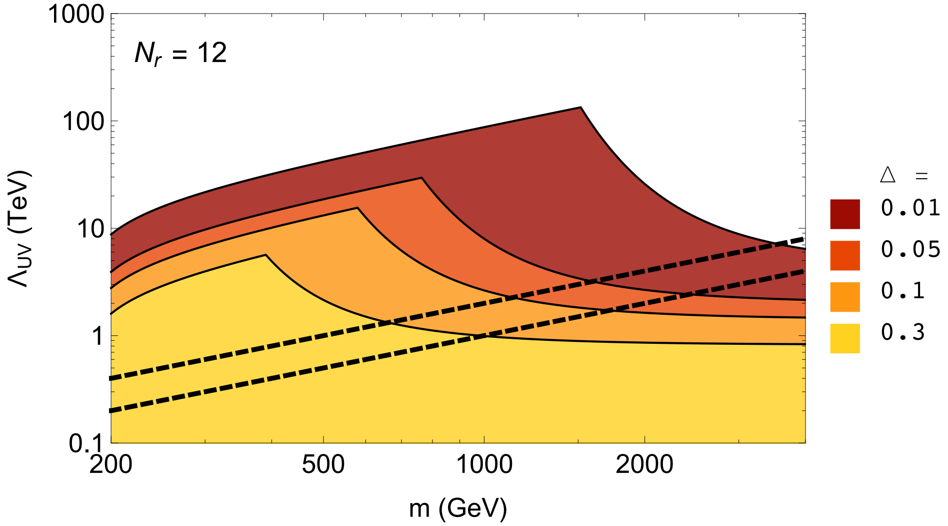
Low-energy probes only have reach of few 100 GeV

Two tunings in theory:

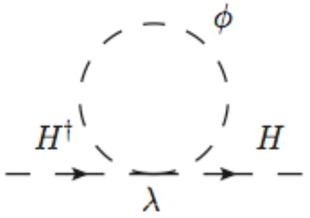
$\Delta_{h(\phi)}$ = log tuning from incomplete t-ϕ cancellation

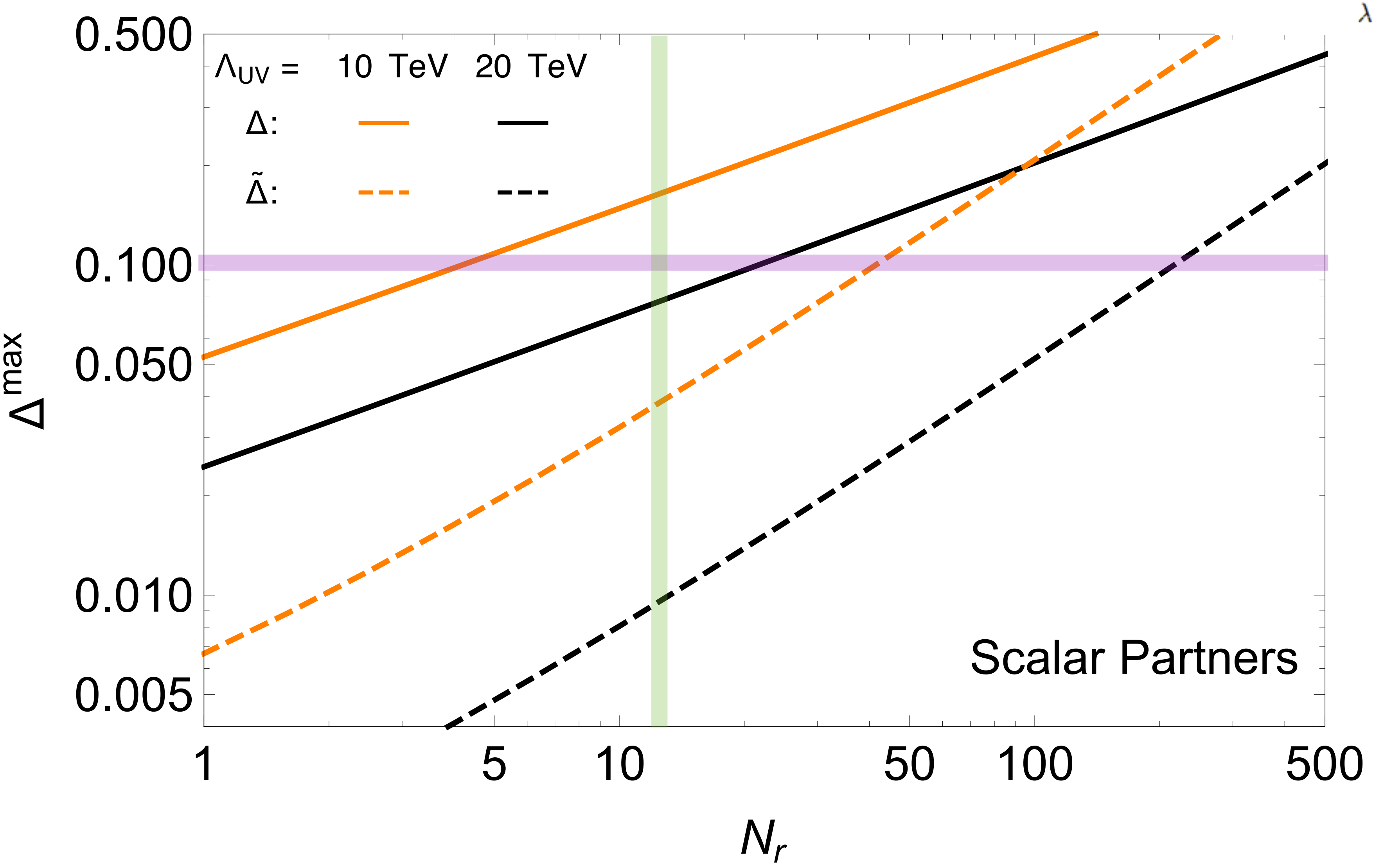
$\Delta_{\phi(h)}$ from quadratically divergent mass contribution due to higgs loops

For given Δ_{tot}, find largest allowed Λ_{UV}:



Scalar Partner

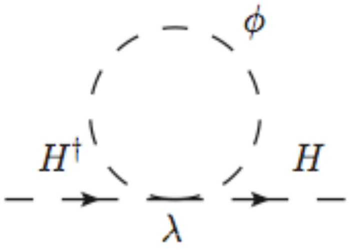




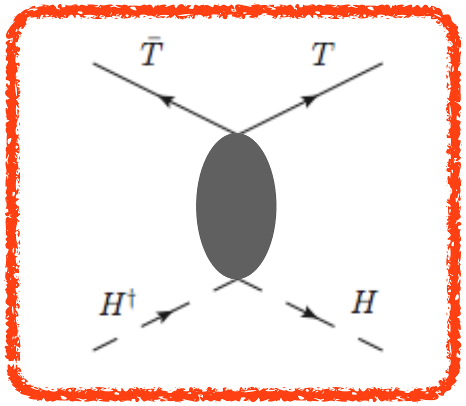
A natural theory needs to have VERY MANY scalar partners to possibly escape detection.

Neutral Naturalness Scenarios

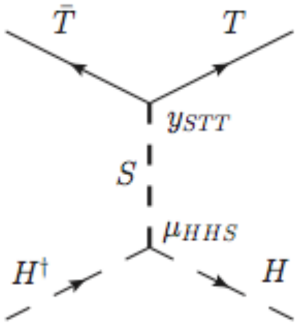
Scalar Partners



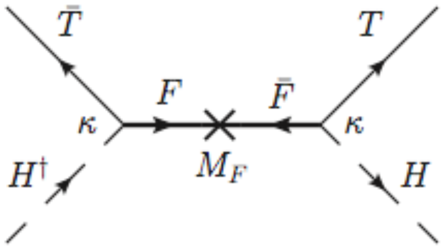
Fermion Partners
(strong coupling)



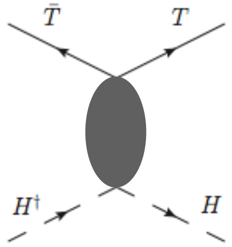
Fermion Partners
(scalar mediator)

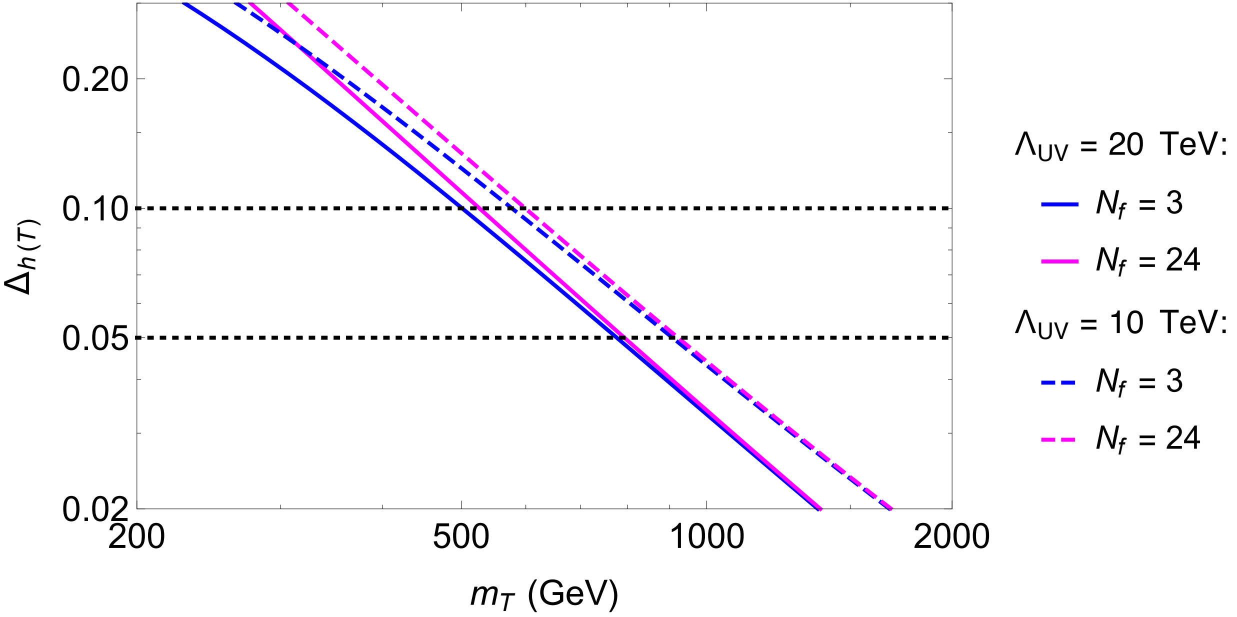


Fermion Partners
(fermion mediator)

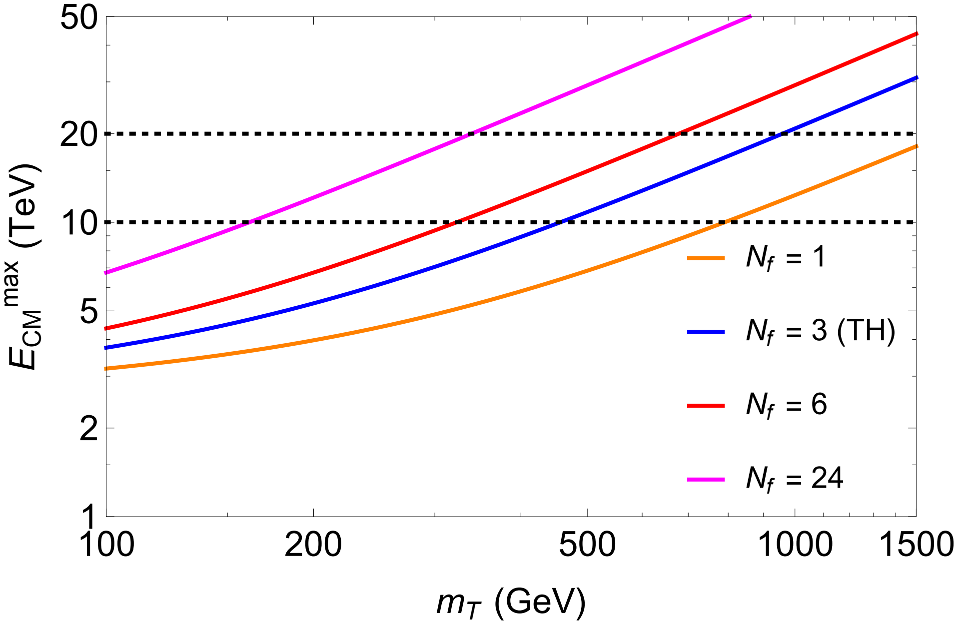


Fermion Partner - Strong Coupling



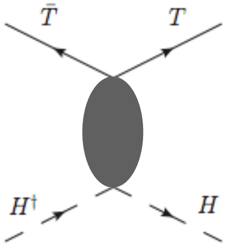


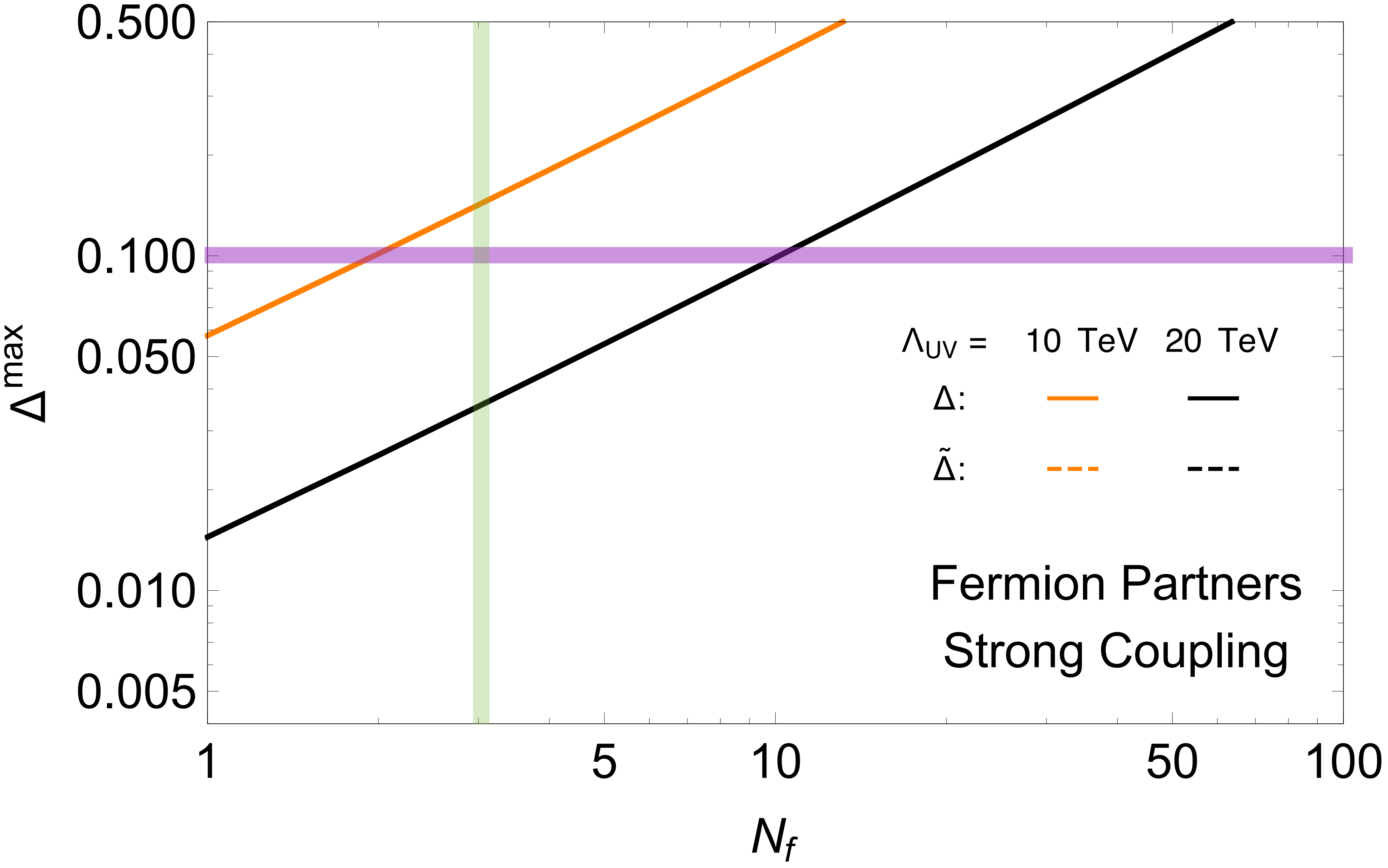
Log tuning of higgs mass:
for Λ_{UV} < 10 - 20 TeV,
$m_T \lesssim$ 500 GeV
OR
tuning worse than 10%.



Unitarity constraints place *strict* upper bound on Λ_{UV} where new physics must get resolved.

Fermion Partner - Strong Coupling





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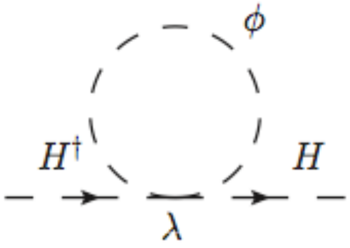
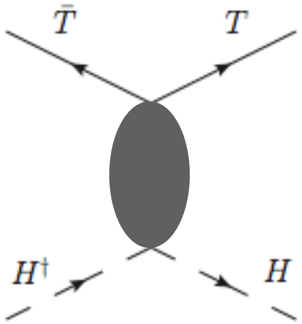
Neutral Naturalness Scenarios

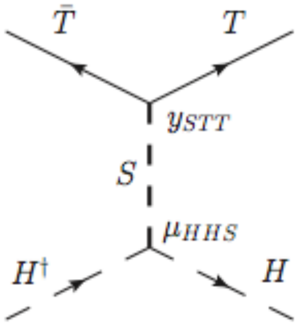
Scalar Partners



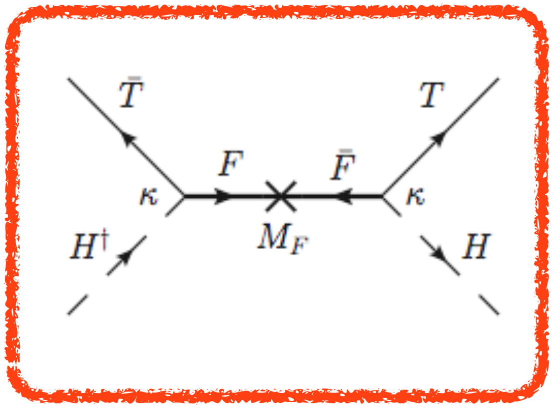
Fermion Partners
(strong coupling)



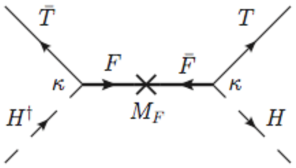
Fermion Partners
(scalar mediator)



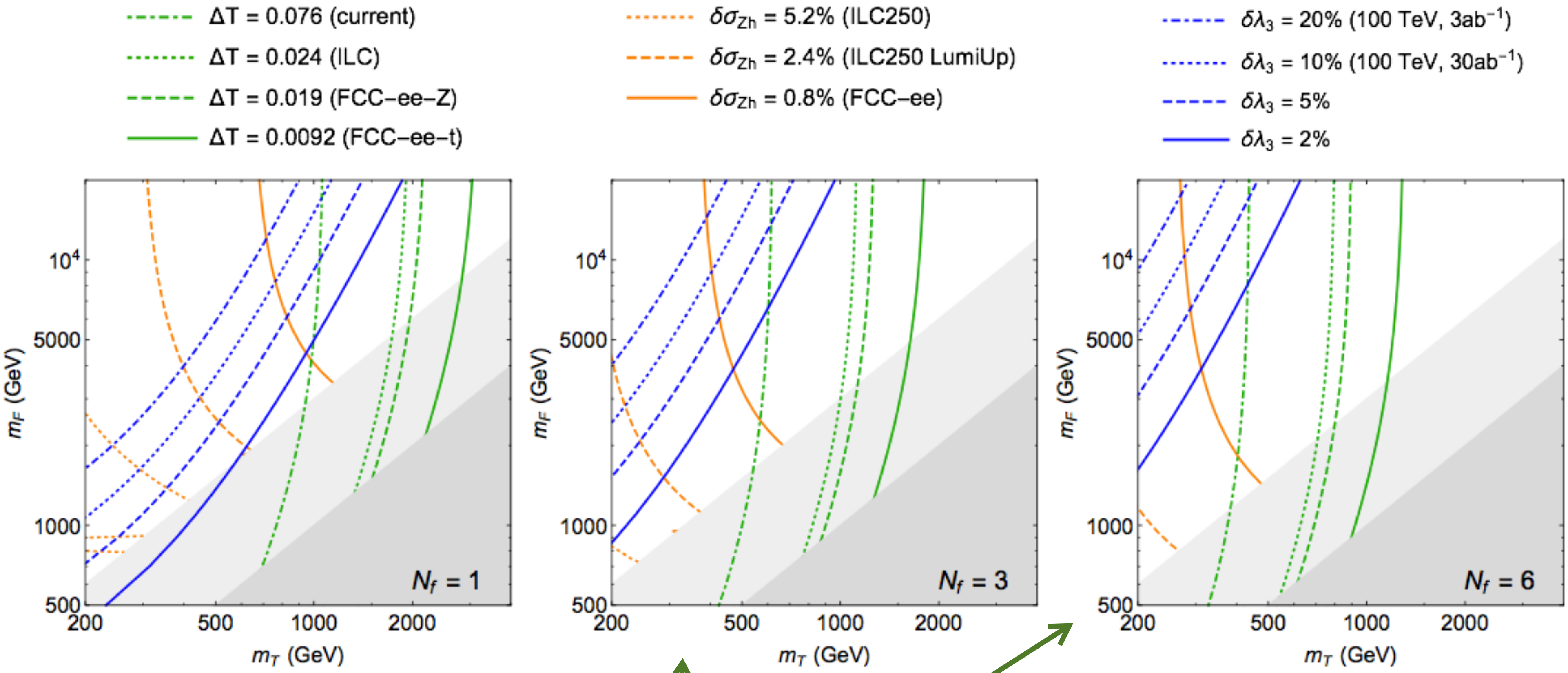
Fermion Partners
(fermion mediator)



Fermion Partner - Fermion Mediator

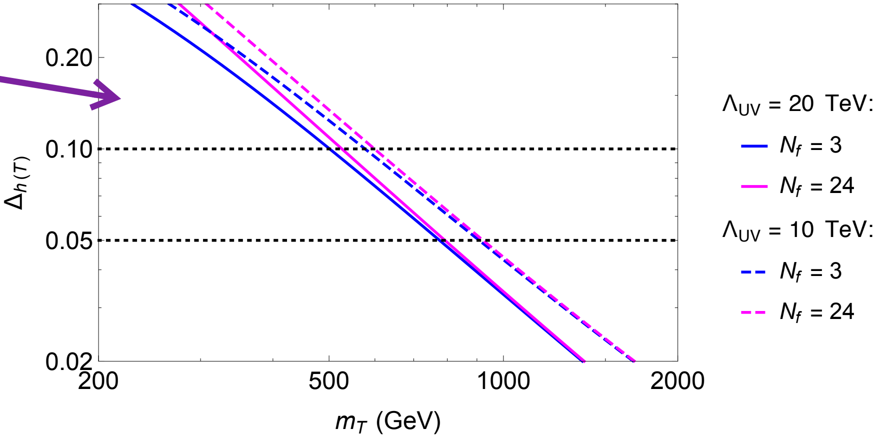


using results from 1506.0546 Fedderke, Lin, Wang

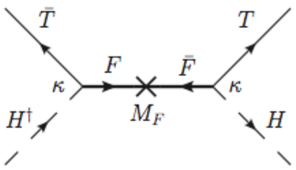


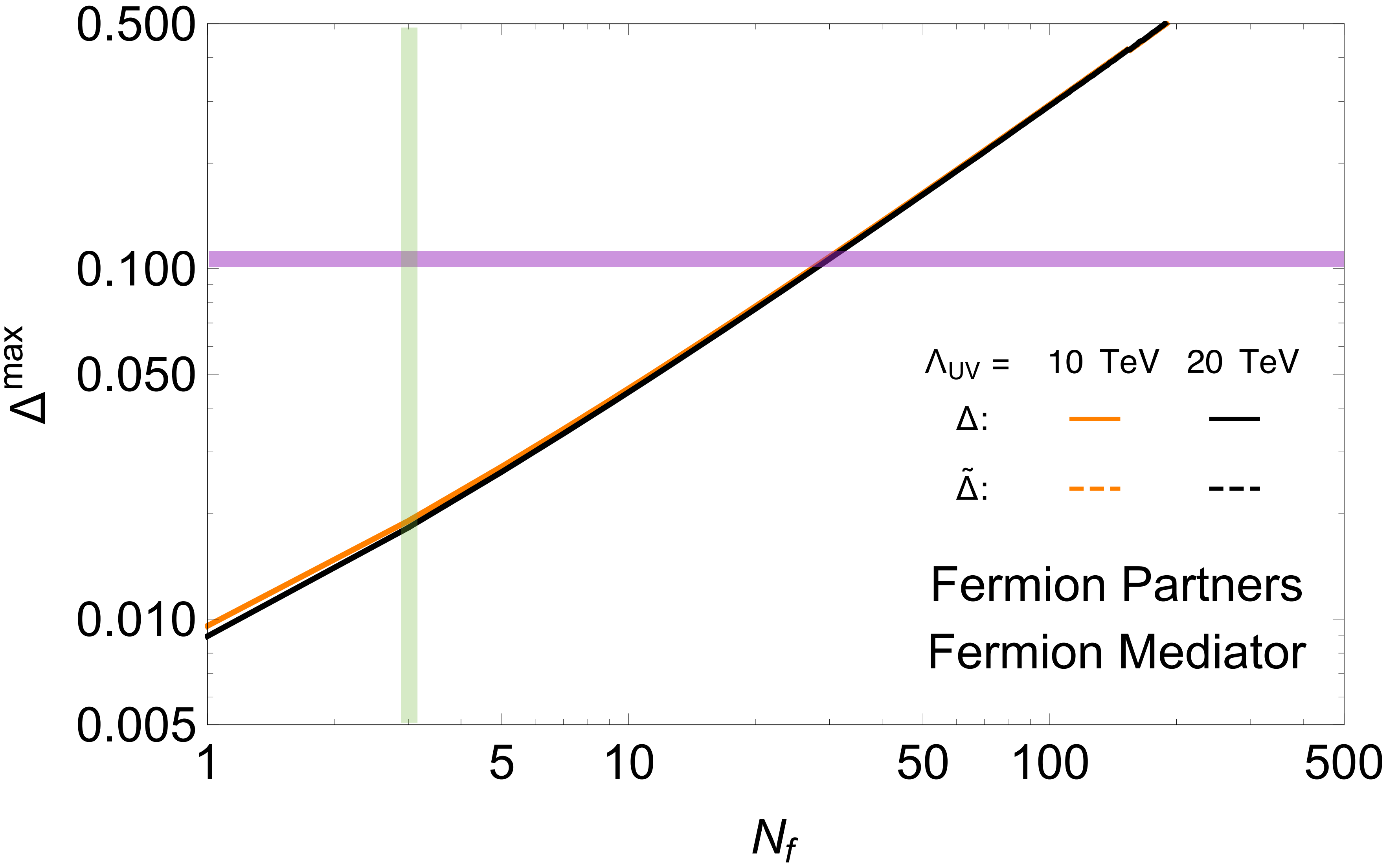
Violation of custodial symmetry → large T parameter deviations!

Again, Higgs log tuning prefers top partners < 500 GeV



Fermion Partner - Fermion Mediator





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