

NATURALNESS IN THE DARK AT THE LHC

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hep-ph/1501.05310

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Matt Strassler

BSM Strategic Situation

THEORETICAL DRIVERS

Naturalness
(vs. Anthropic Principle)

Dark Matter WIMP miracle

Baryogenesis + WIMP miracle

(Cui, Sundrum '12
Cui, Shuve '14)

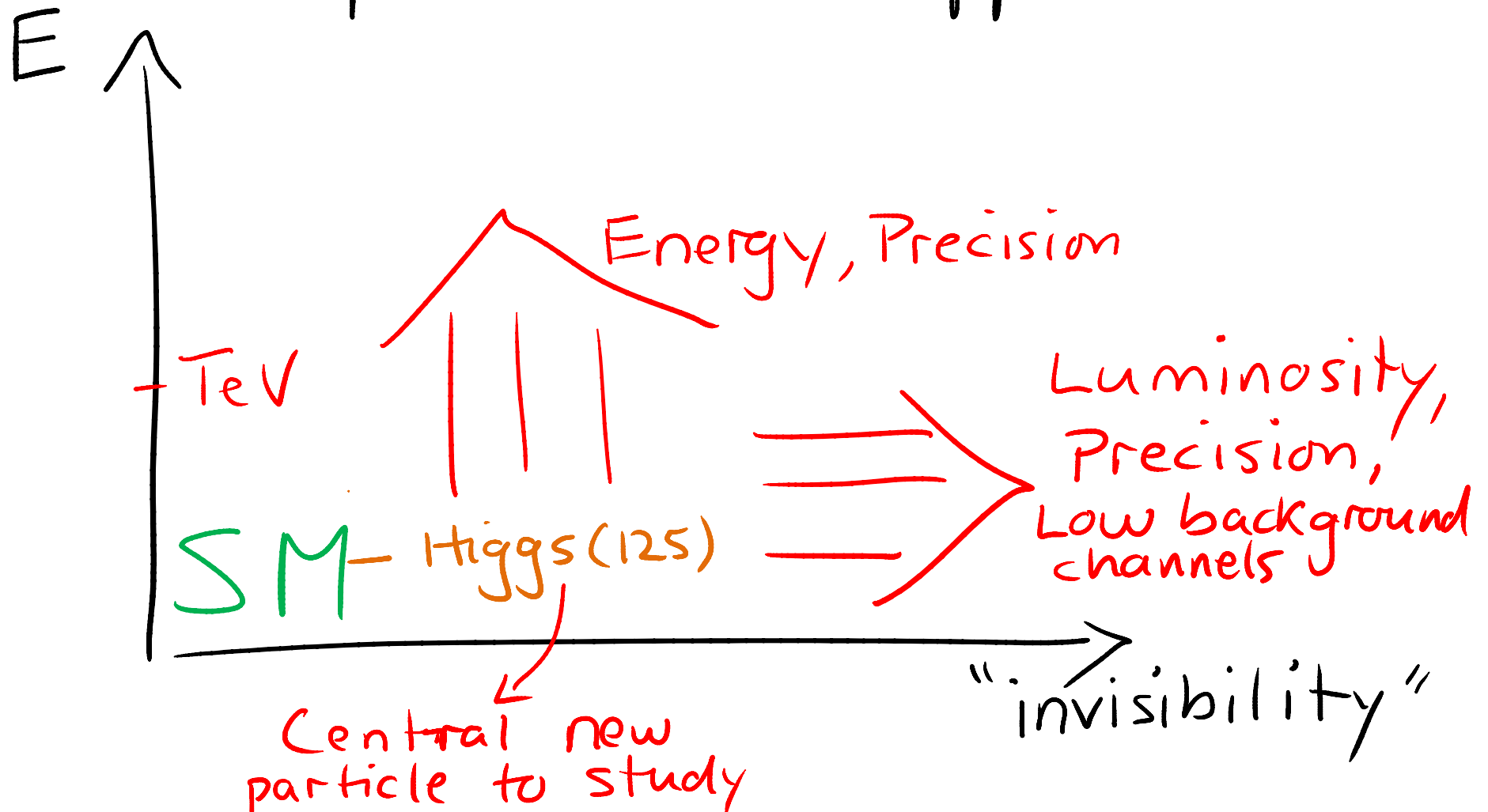
Flavor/~~CP~~ Origins Constraints



EXAMPLES

BSM Strategic Situation

Experimental Opportunities



SM Portals

Low-dimension gauge-invariants
that dark sectors (SM-sterile)
can couple to with minimal
suppression:

$$\mathcal{L} \sim B_{\mu\nu} \mathcal{O}_{\text{dark}}^{\mu\nu} + |H|^2 \mathcal{O}_{\text{dark}}$$

↙ hypercharge field strength ↗ Higgs doublet

Can dominate production
& decays back to SM

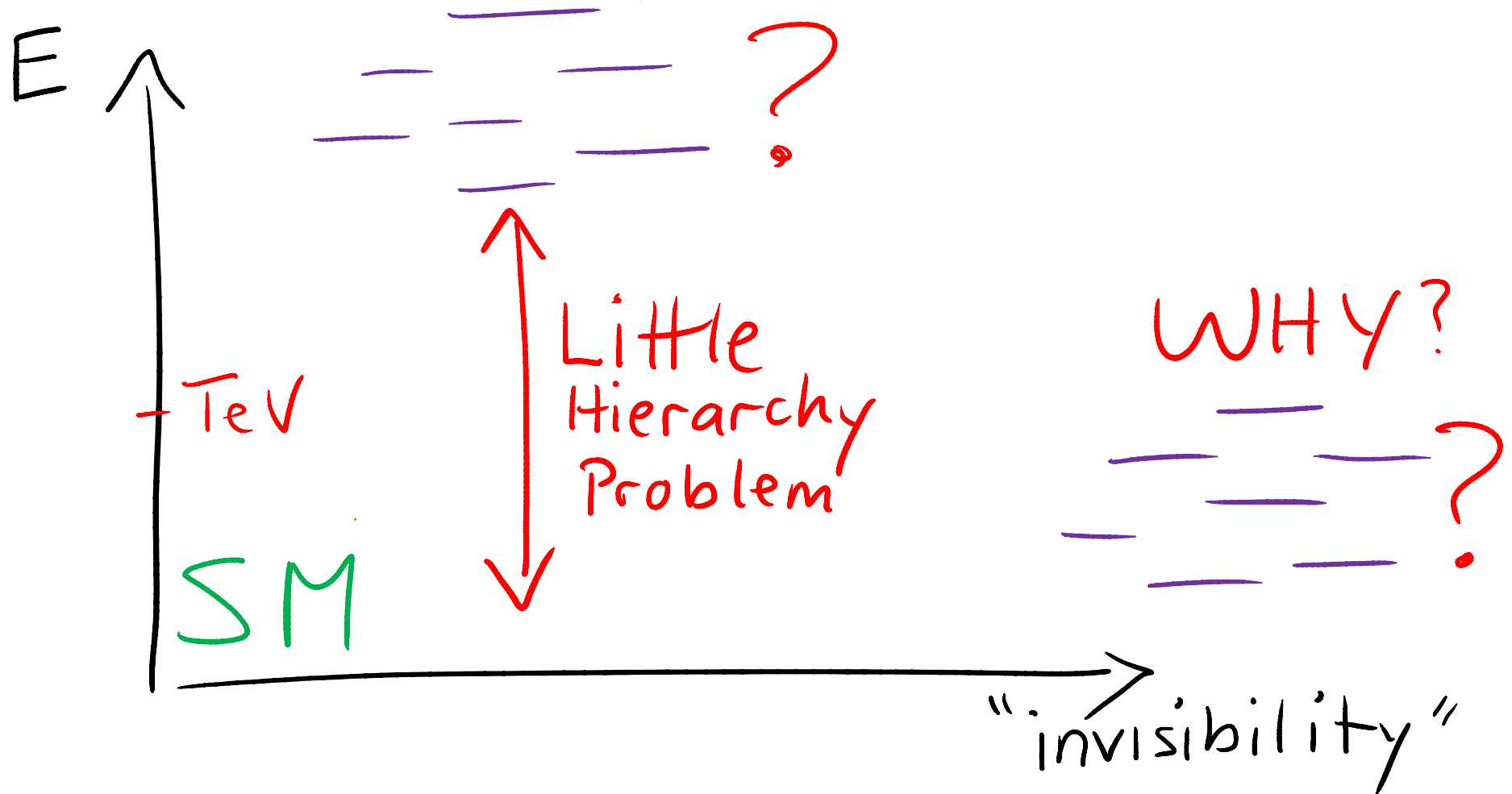
BSM Strategic Situation

NATURALNESS
EXPECTATIONS

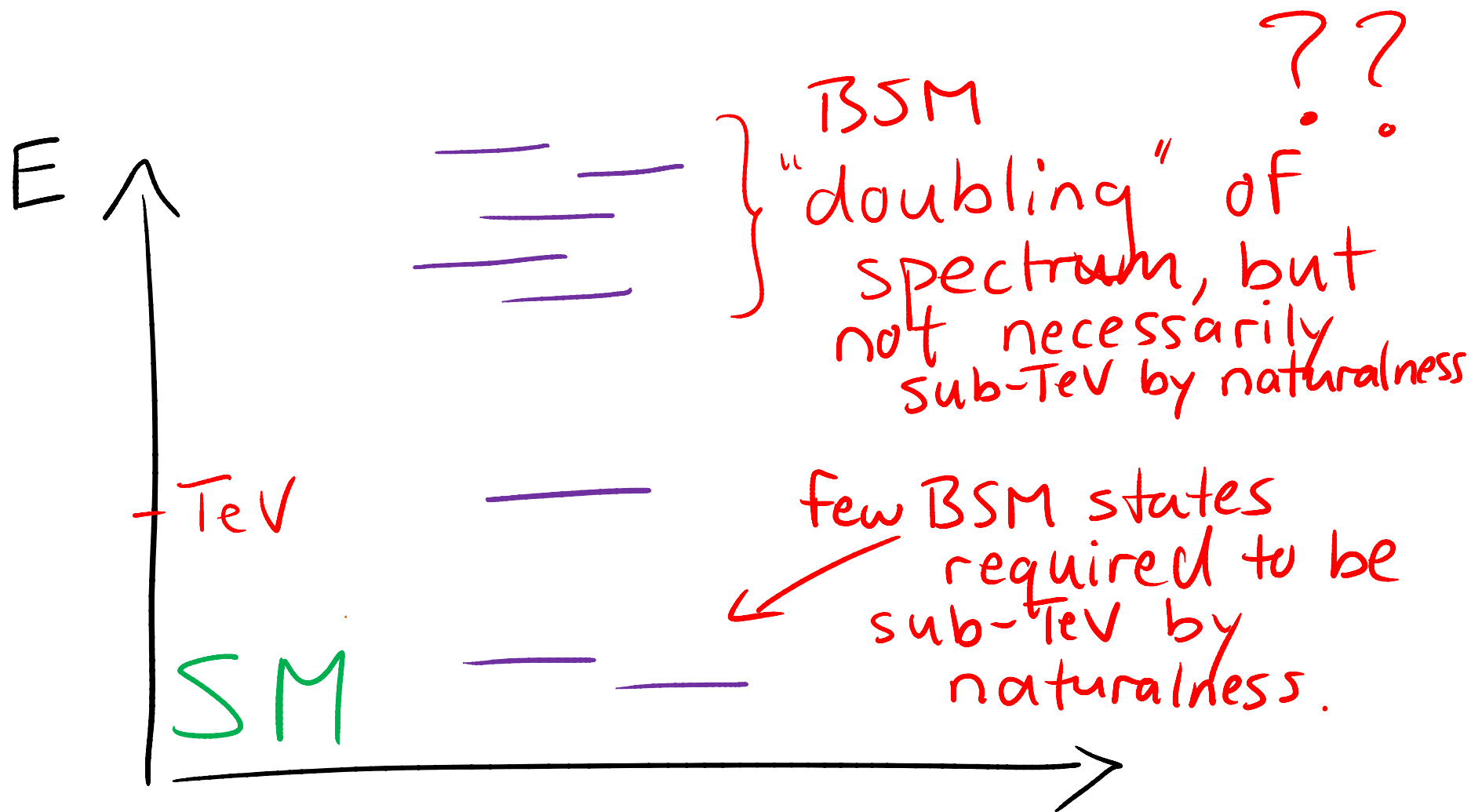


DESPERATE Situation

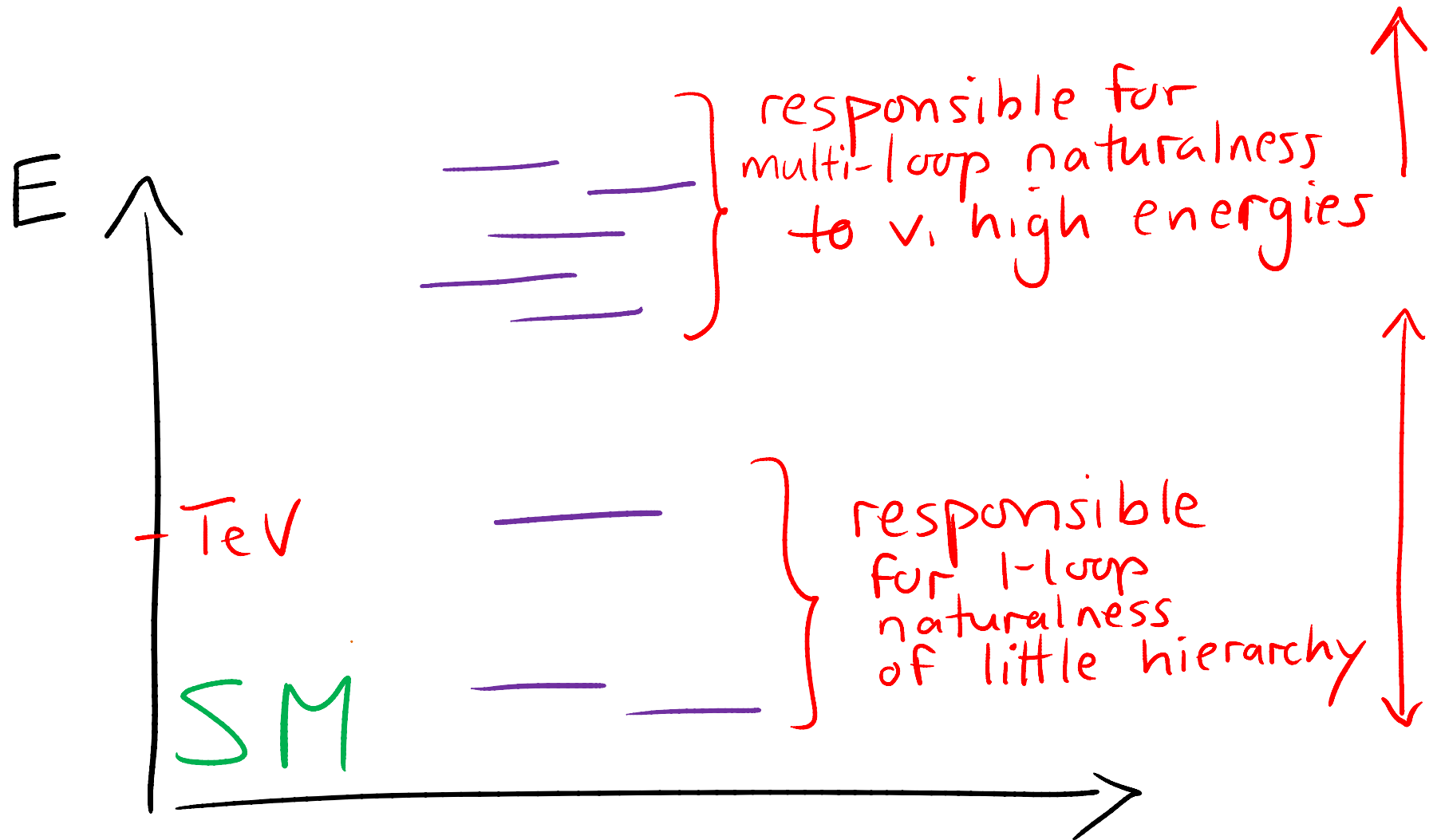
Nothing BSM seen!



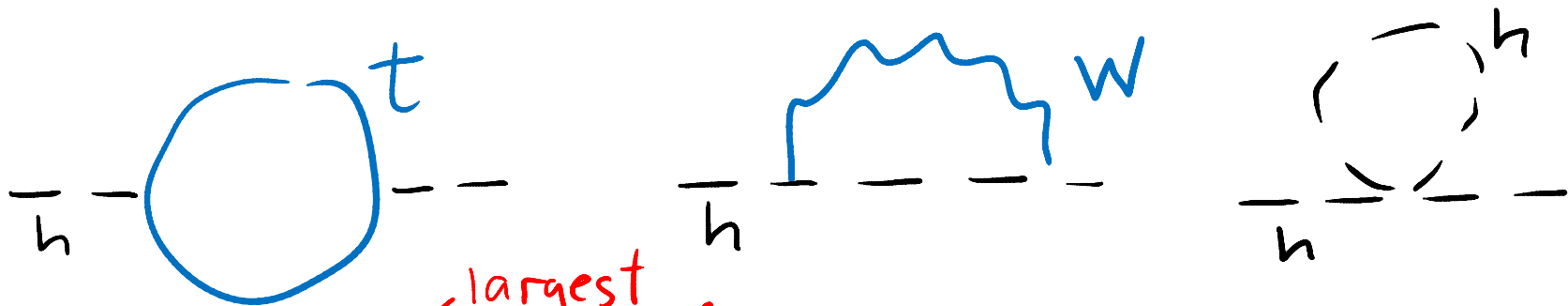
SPARSE SPECTRUM



NATURALLY SPARSE



Largest contributions to Hierarchy Problem from heaviest SM particles



$\sim \frac{O(1)}{16\pi^2} \Lambda_{UV}^2$
largest couplings
at one-loop

naturalness
 $m_h^2 \Rightarrow \text{Related BSM states} \lesssim \text{TeV}$

DOMINANT PARADIGMS

SUSY, Higgs Compositeness
||| AdS/CFT duality

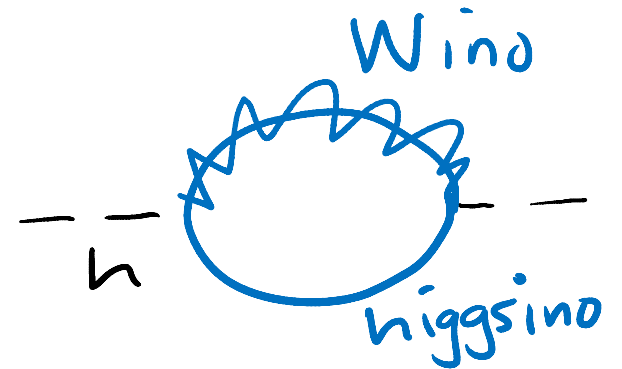
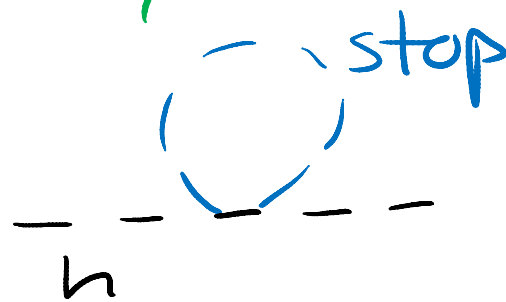
RS1 warped dimensions

include sparse spectrum
possibility in their parameter
spaces:

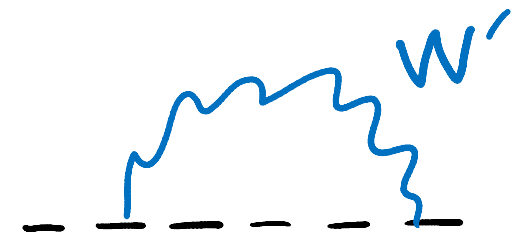
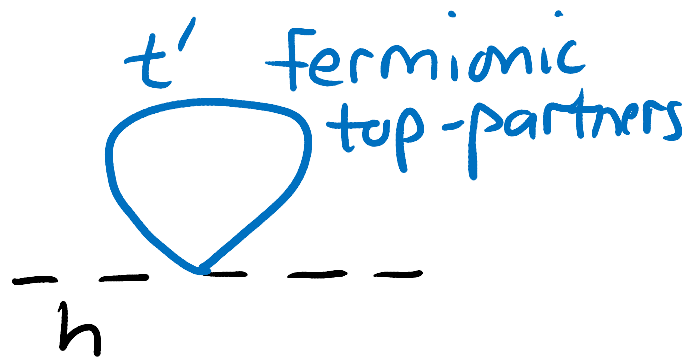
- SUSY soft parameters
- Extra-dimensional "deconstruction"
- Extra-dimensional boundary conditions
- Little Higgs PGB structure

Little Hierarchy Protected by Few BSM "Partners" & Symmetry Cancellations

Superpartners:



Ordinary
Continuous
Symmetries



(PGIB symmetries, e.g. Little Higgs)

BOTTOM-UP APPROACH

$$\Lambda_{UV} \sim 5-10 \text{ TeV}$$

describe minimal solutions to
little hierarchy problem,
with few particles $\lesssim$ LHC
reach.

defer UV completions to
v. high energies.

NATURAL SUSY

Dimopoulos, Giudice '95
Cohen, Kaplan, Nelson '96
...

Bottom-up structure
Brust, Katz, Lawrence,
Sundrum '11

super-partners of light SM

responsible for
multi-loop naturalness
to v. high energies
INTEGRATED OUT



Incomplete (super-)multiplets OK for light SM,
viewed as integrated out.

Top - Partners / Stops

Especially important: $\frac{3}{4\pi^2} y_{\text{top}}^2 \Lambda_{UV}^2$
 $\lesssim 500 \text{ GeV}$ by NATURALNESS

Significant colored cross-sections

Typically visible decays
(including $\cancel{e}$)

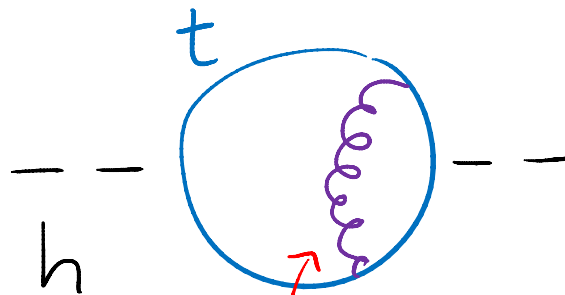
Roughly, $\gtrsim 700 \text{ GeV}$ LHC bounds

HAS THEORY LED
US ASTRAY?

LOOKING IN THE
WRONG PLACE?

TRY TO OPEN
THEORY/PHENO APERTURE

MUST TOP-PARTNERS BE COLORED?

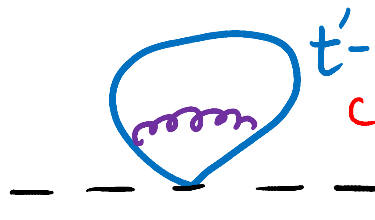


A Feynman diagram showing a top quark loop. A horizontal dashed line labeled 'h' (Higgs boson) enters a circular loop from the left. The top quark line is labeled 't'. Inside the loop, a gluon (represented by a curly line) is emitted from the top quark line. The loop exits to the right as another dashed line.

$$\sim \frac{3}{4\pi^2} y_t^2 \Lambda_{UV}^2$$

exception
to "1-loop rule"
for little hierarchy problem

runs significantly
due to QCD

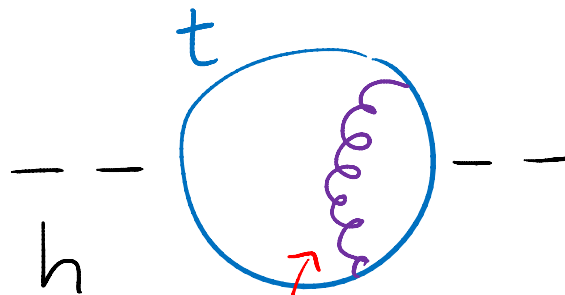


A Feynman diagram showing a top-partner loop. A horizontal dashed line enters a teardrop-shaped loop from the left. The top-partner line is labeled 't'-partner'. Inside the loop, a gluon (represented by a curly line) is emitted from the top-partner line. The loop exits to the right as another dashed line.

colored to "know"
about y_t -running

$$\Rightarrow [SU(3)_{QCD}, \text{Protective symmetry}] = 0$$

MUST TOP-PARTNERS BE COLORED?



A Feynman diagram showing a top quark (t) loop. A dashed line labeled h (Higgs boson) enters from the left and exits to the right. Inside the loop, there is a gluon loop (represented by a curly line) connecting two vertices on the top quark line.

$$\sim \frac{3}{4\pi^2} y_t^2 \Lambda_{UV}^2$$

exception
to "1-loop rule"
for little hierarchy problem

runs significantly
due to QCD

~~FALSE "THEOREM"~~

$[SU(3)_{QCD} / \text{protective symmetry}] = 0$

t' -partner colored (to "know" about y_t -running)

TWIN HIGGS

Chacko, Goh, Harnik '05

SM states: $SU(2)_{EW}$ doublets $H, Q \equiv (t_L, b_L)$
+ singlet t_R

"Twin" states: $SU(2)_{twin}$ doublets H, Q
+ singlet t_R

$SU(4)$ -symmetric potential

$$V = \lambda (|\mathcal{H}|^2 - f^2)^2, \quad \mathcal{H} \equiv \begin{pmatrix} H \\ H \end{pmatrix} \equiv 4$$

SSB $\rightarrow SU(3)$.

Want SM-like Higgs among PGBs,
naturally light on scale $f > v_{weak}$

Explicit ~~SU(4)~~ by

$$\mathcal{L} = y_t \bar{Q} H t_R$$

But including

$$\mathcal{L} = y_t \bar{Q} H t_R,$$

$$16\pi^2 V_{1\text{-loop}} = -6y_t^2 |H|^2 \Lambda_{uv}^2 - 6y_t^2 |H|^2 \Lambda_{uv}^2 \\ + 3y_t^4 |H|^4 \ln\left(\frac{\Lambda_{uv}^2}{y_t^2 |H|^2}\right) \\ + 3y_t^4 |H|^4 \ln\left(\frac{\Lambda_{uv}^2}{y_t^2 |H|^2}\right)$$

TWIN $\mathbb{Z}_2$ SYMMETRY

$$H, Q, t \longleftrightarrow H, Q, t$$

$$\Rightarrow y_t = y_t \equiv y_t$$

$$16\pi^2 V_{1\text{-loop}} = -6 y_t^2 |H|^2 \Lambda_{uv}^2 \\ + \text{log-divergent} + \text{finite}$$

$\Rightarrow$ Accidental $SU(4)$ symmetry
of quadratic divergence.

If SM-like Higgs $\equiv$ PGB of $SU(4) \rightarrow SU(3)$,
not destabilized by this divergence!

Vacuum Alignment

$$f^2 = |\langle H \rangle|^2 + |\langle H \rangle|^2$$

7 Goldstone bosons:

3 eaten by $SU(2)_{EW} \times U(1)_Y$

3 eaten if $SU(2)_{\text{twin}}$ gauged

1 light PGB Higgs scalar,

mostly SM-like only if $|\langle H \rangle| \ll |\langle H \rangle|$

But exact $\mathbb{Z}_2$ favors $|\langle H \rangle| = |\langle H \rangle|$

$\therefore$ some EXPLICIT ~~$\mathbb{Z}_2$~~ REQUIRED

Need for gauged $SU(2)_{\text{twin}}$ W

$$\delta m_h^2 \sim \frac{9 \Lambda_{uv}^2}{32\pi^2} (g_2^2 - g_2^2)$$

Naturalness up to $\Lambda_{uv} \sim 5 \text{ TeV}$

$$\Rightarrow g_2 \approx g_2 \pm 10\%$$

By comparison, $U(1)_{\text{twin hypercharge}}$
not required by naturalness

TWIN COLOR: QCD

$$\delta m_h^2 \approx \frac{3\Lambda_{uv}^2}{4\pi^2} (y_t^2 - \bar{y}_t^2)^2$$

Naturalness up to $\Lambda_{uv} \sim 5 \text{ TeV}$
requires $y_t = \bar{y}_t \pm 1\%$

But if only y_t runs, naturally

$$y_t \sim \bar{y}_t \pm \frac{g_{QCD}^2}{2\pi^2} y_t$$

← running over e-folding

$$\Rightarrow SU(3): g_3(\Lambda_{uv}) \sim g_3(\Lambda_{uv}) \pm 20\%$$

$\sim 10\%$

TWIN GAUGE

ANOMALY-CANCELLATION

$$\Rightarrow b_R, (\nu_L, \tau_L) \equiv 1$$

MASS $\forall$ TWIN MATTER

if include τ_R, ν_R :

$$\mathcal{L} = y_b \bar{Q} \tilde{H} b_R + y_\tau \bar{\ell} \tilde{H} \tau_R + y_\nu \bar{\ell} H \nu_R$$

$$y_{b,\tau,\nu} \ll 1 \text{ but } \neq y_{b,\tau,\nu}$$

HIGGS DYNAMICS

$$V_{\text{eff}} = \lambda (|H|^2 + |H|^2 - F^2)^2 + \kappa (|H|^4 + |H|^4) + \rho |H|^4 + \sigma f^2 |H|^2$$

} $\mathbb{Z}_2$ -symmetric

} $\mathbb{Z}_2$ -breaking

$$+ \frac{3y_t^4}{16\pi^2} \left(|H|^4 \ln \frac{\Lambda_{UV}^2}{y_t^2 |H|^2} + |H|^4 \ln \frac{\Lambda_{UV}^2}{y_t^2 |H|^2} \right)$$

$\mathbb{Z}_2$ -symmetric
(twin) top-loop.

Taking λ dominant,

$\langle H \rangle \sim \text{few } \langle H \rangle \Rightarrow H \equiv \text{light (P)GBs}.$

Heavy Exotic Higgs h'

$$\text{Mass} \sim \sqrt{\lambda} f$$

below which effectively

$$|H|^2 = f^2 - |H|^2$$

$$\Rightarrow V_{\text{eff}}(H) \approx \left[2\sigma - 2\kappa - \frac{3y_t^4}{4\pi^2} \ln \frac{\Lambda_{UV}}{m_{t'}} \right] \frac{m_{t'}^2}{y_t^2} |H|^2 \\ + \left[2\kappa + \frac{3y_t^4}{4\pi^2} \ln \frac{\Lambda_{UV}}{m_{t'}} + \frac{3y_t^4}{8\pi^2} \ln \frac{m_{t'}}{m_t} \right] |H|^4$$

where top-partner: $m_{t'} = y_t \langle B \rangle$, $m_t = y_t \langle A \rangle$

Matching to SM

$$\lambda_{SM} \approx 2K + \frac{3y_t^4}{4\pi^2} \ln \frac{\Lambda_{UV}}{m_{t'}}$$

comparable naturally
& can fit data, $\lambda_{SM} \approx 1/8$

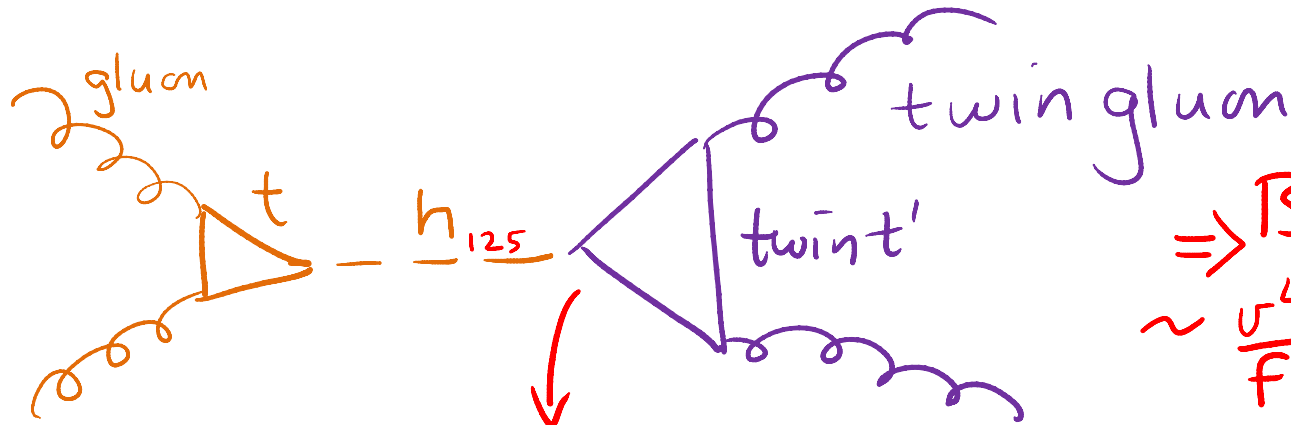
$$\lambda_{SM} v_{weak}^2 \approx (\lambda_{SM} - 25) \frac{m_{t'}^2}{y_t^2}$$

$\Rightarrow$ Electroweak Tuning

$$= 2m_t^2 / m_{t'}^2 = 2v^2 / f^2 \sim 20\% \text{ for } f \sim 3v$$

$$\frac{\lambda_{SM} v_{weak}^2}{\lambda_{SM} (m_{t'}^2 / y_t^2)}$$

(Perturbative) TWIN PRODUCTION

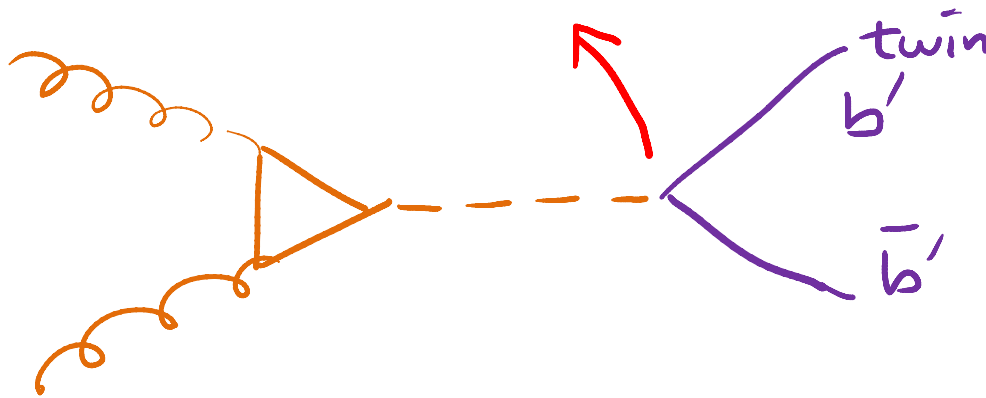


$$\Rightarrow \text{Br}(h_{125} \rightarrow \text{twin gluons})$$

$$\sim \frac{v^4}{f^4} \text{Br}(h_{125} \rightarrow \text{gluons})$$

$$\sim 10^{-4}$$

$$H \sim \sqrt{f^2 - H'^2} \sim f \left(1 - \frac{v}{f^2} H'\right) \quad \text{"irreducible"}$$



$$\text{Br}(h \rightarrow \text{twin } b' \bar{b}')$$

$$\sim \frac{y_{b'}^2}{y_b^2} \frac{v^2}{f^2} \text{Br}(h \rightarrow b \bar{b})$$

can be several % !
if $2m_{b'} < m_h$

≡ Rare, Exotic Higgs (125 GeV) decays
into MISSING ENERGY??

Barbieri, Gregoire, Hall '05

TWIN CONFINEMENT

Minimal twin sector $\Rightarrow$
twin QCD confinement scale
 $\gg$ QCD confinement scale

despite $g_{\text{QCD}}(\Lambda_{\text{UV}}) \approx g_{\text{QCD}}(\Lambda_{\text{W}}) \pm 20\%$
 $\Lambda_{\text{QCD}}^{\overline{\text{MS}}} = 1 - 20 \text{ GeV}$

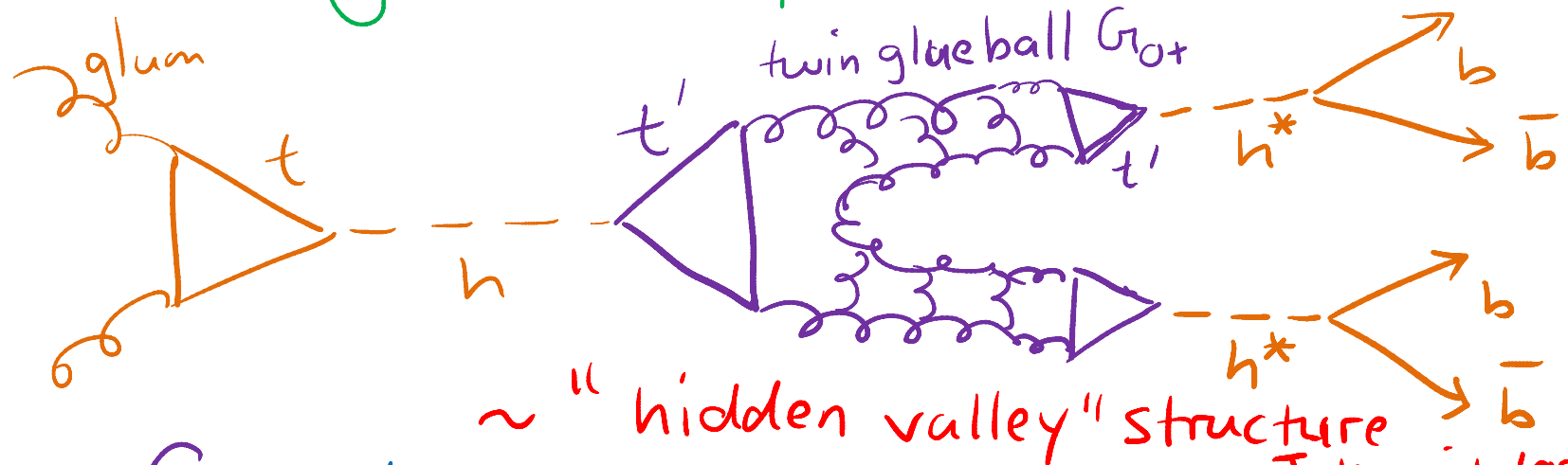
Massive twin fermions $\Rightarrow$

Bottom of Twin Spectrum
 $\equiv$ Twin Glueballs

lightest G_{0+} $J^{PC} = 0^{++}$ $m_{G_{0+}} = 6.8 \Lambda_{\text{QCD}}^{\overline{\text{MS}}} \sim 10 - 100 \text{ GeV}$

Lattice:
Morningstar et al
Chen et al
Gockeler et al
Lucini et al
 $\overline{\text{MS}}$

Through the portal and back



~ "hidden valley" structure
Juknevich '09

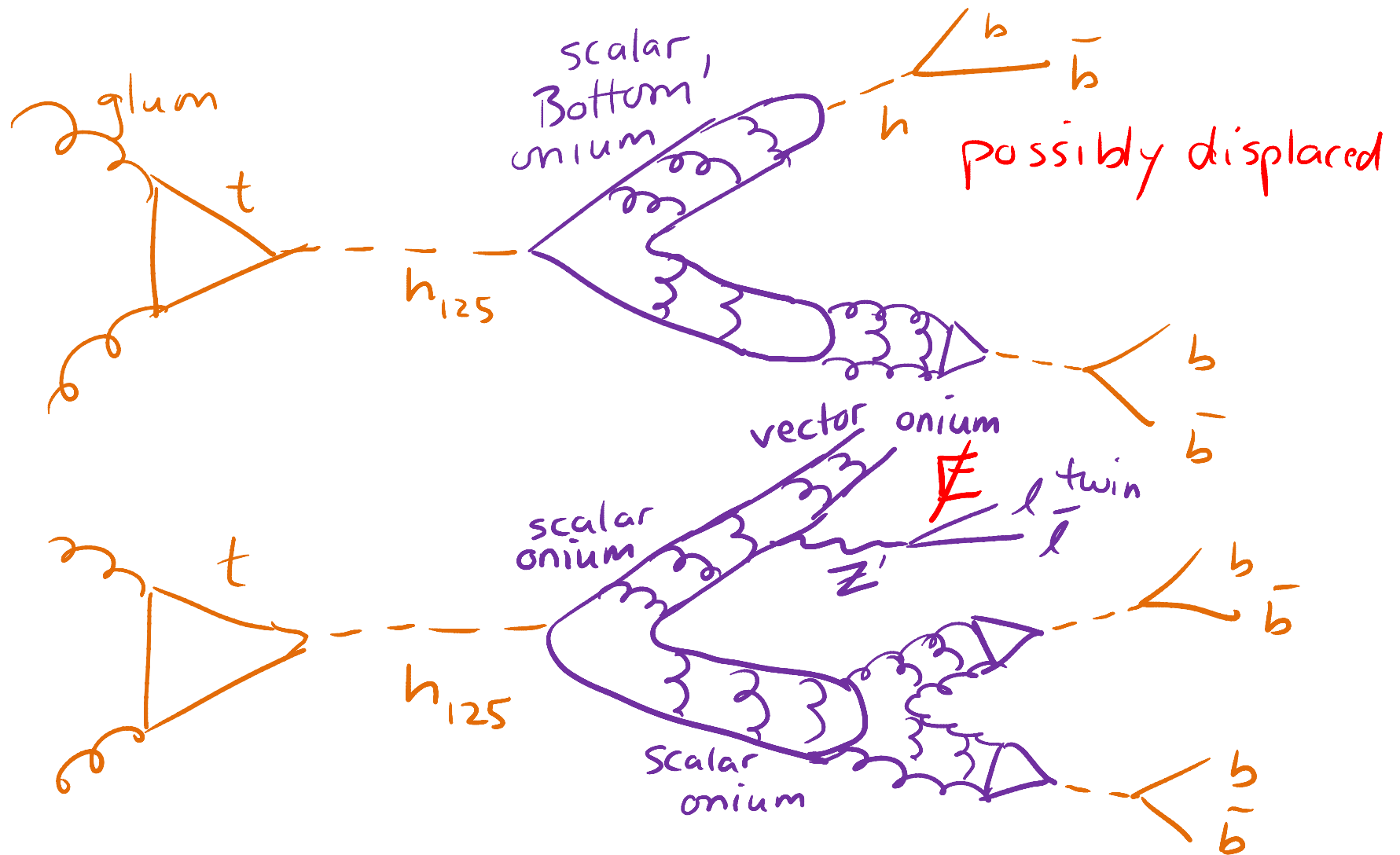
G_{0+} has quantum numbers
to mix with h_{125} & decay to SM

$$\Gamma_{G_{0+} \rightarrow b\bar{b}} \approx \left[\frac{m_{0+}^3}{24\pi f^2 (m_h^2 - m_{0+}^2)} \right]^2 \Gamma_{h^* \rightarrow b\bar{b}}^{\text{"SM"}}$$

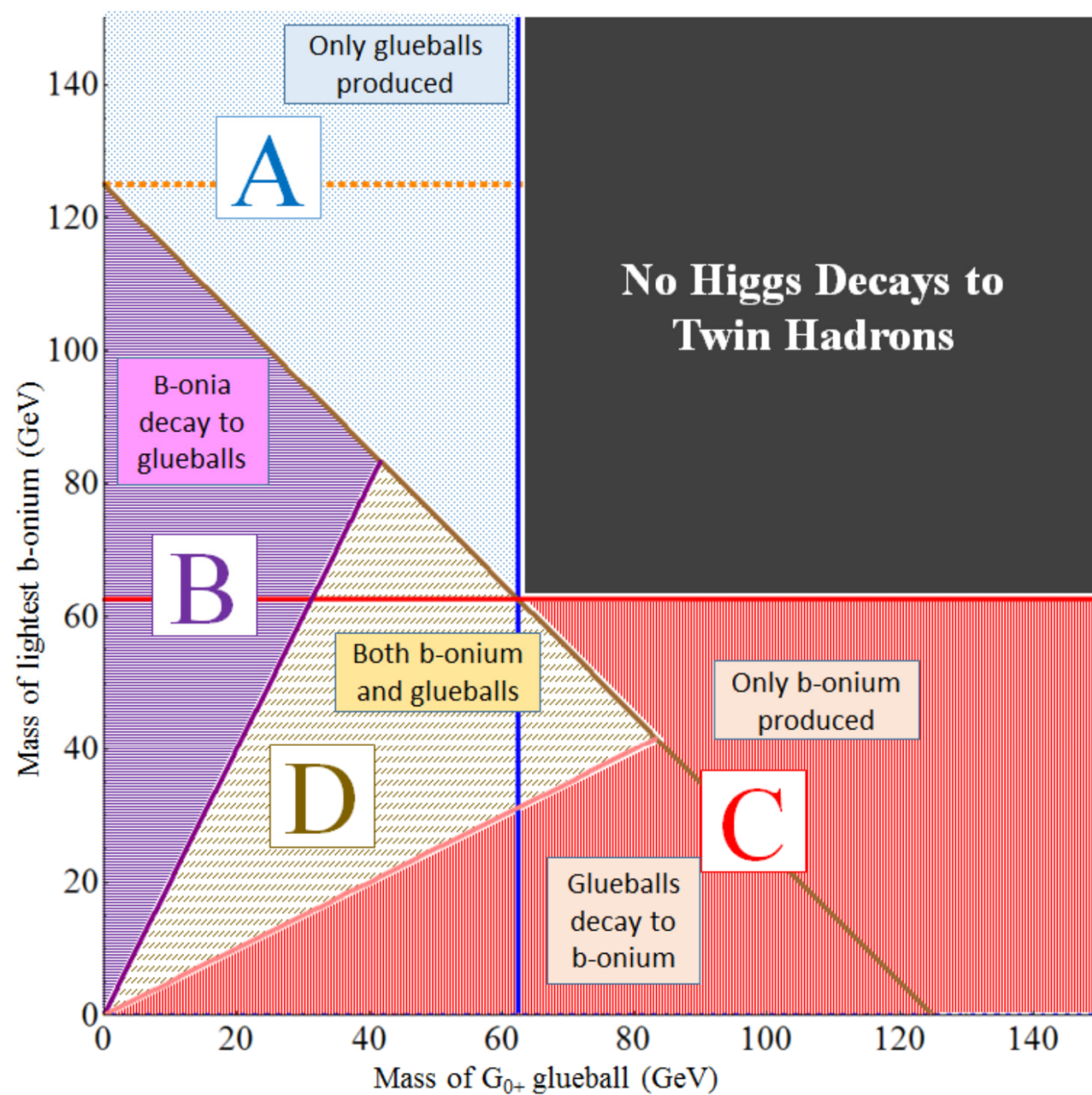
$$\equiv c\tau_{G_{0+}} \sim 20 \text{ m} \cdot \left(\frac{10 \text{ GeV}}{m_{0+}} \right)^7 \cdot \left(\frac{f}{750 \text{ GeV}} \right)^4$$

DISPLACED DECAYS

Twin Bottom-Onium



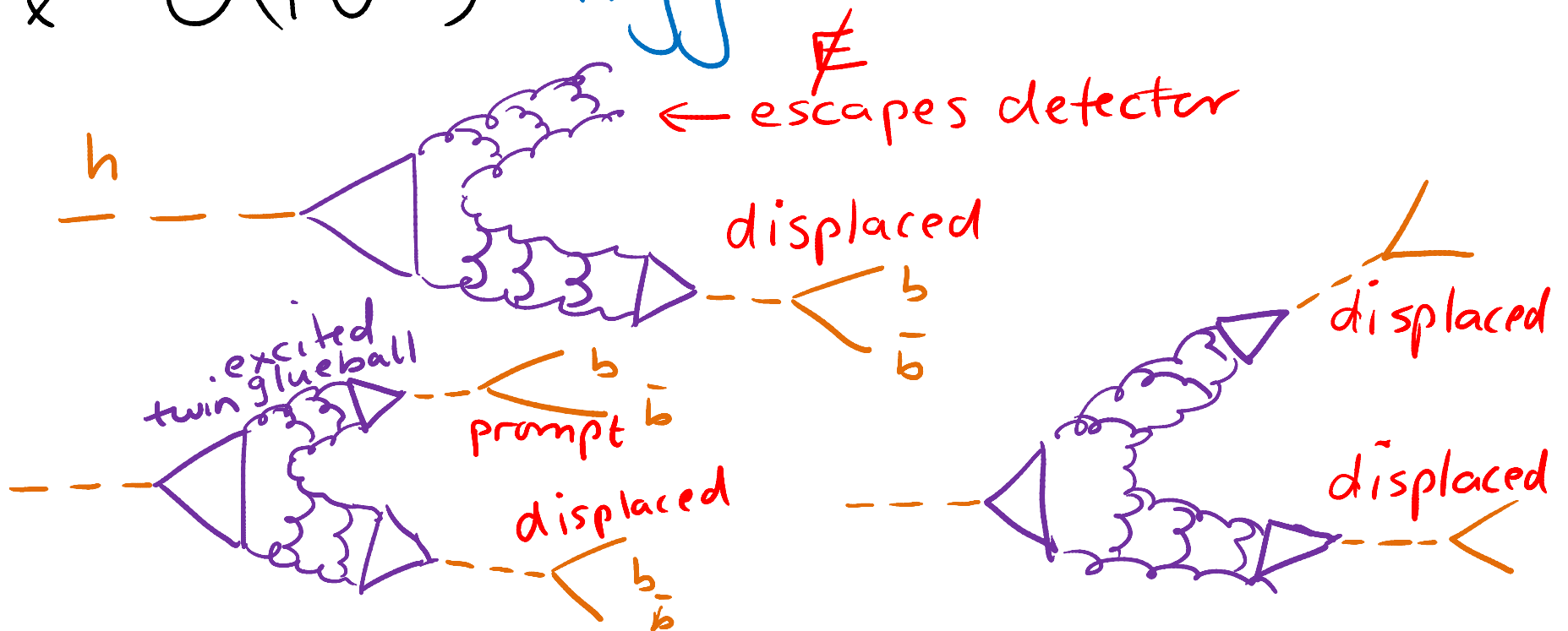
is complicated, highly spectrum-dependent if $b'\bar{b}' < m_h$, & non-perturbative



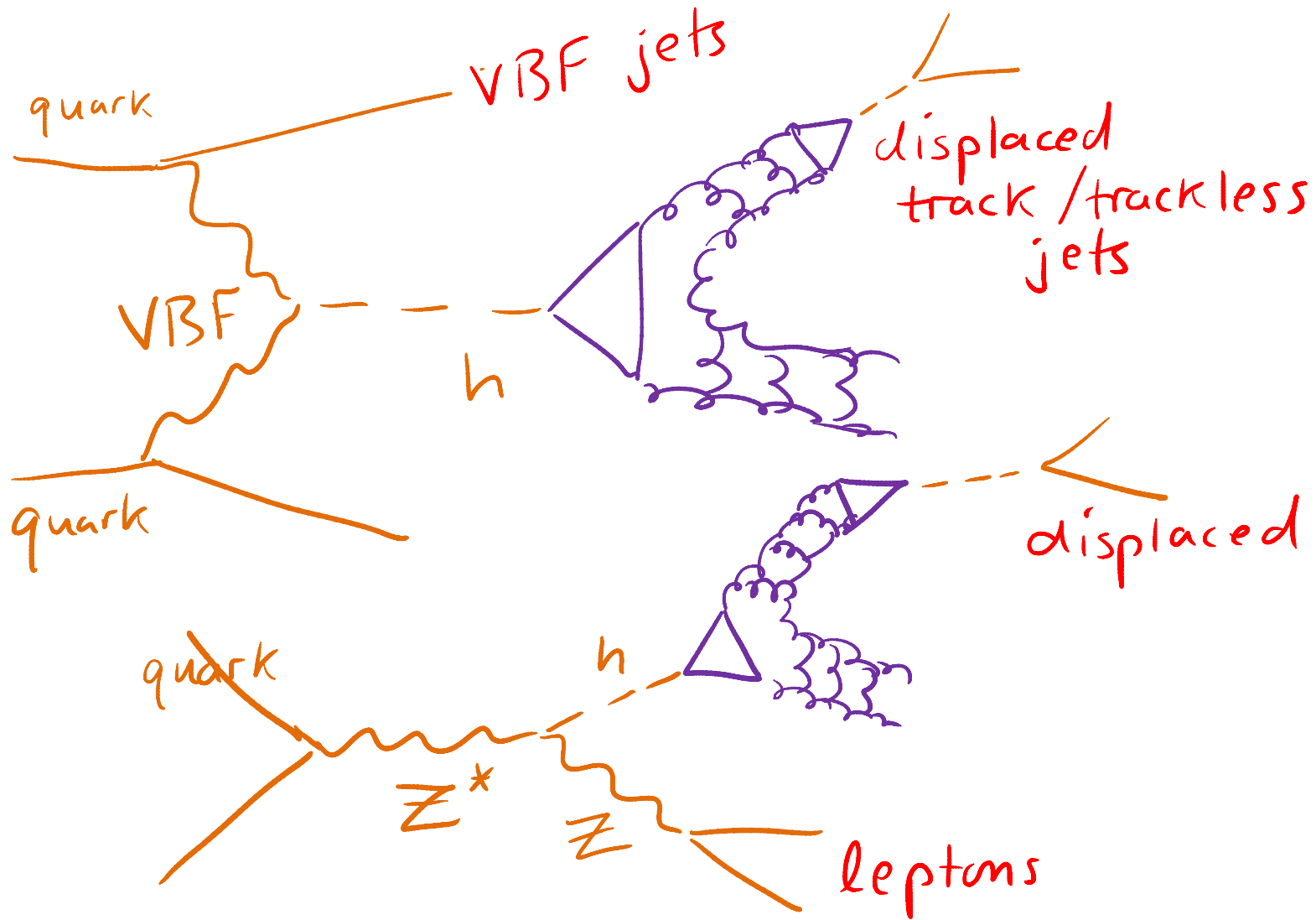
LHC II Pheno

Assuming "irreducible" $\text{Br} \sim 10^{-4}$
(for decoupled twin b)

$\times O(10^7)$ higgs events



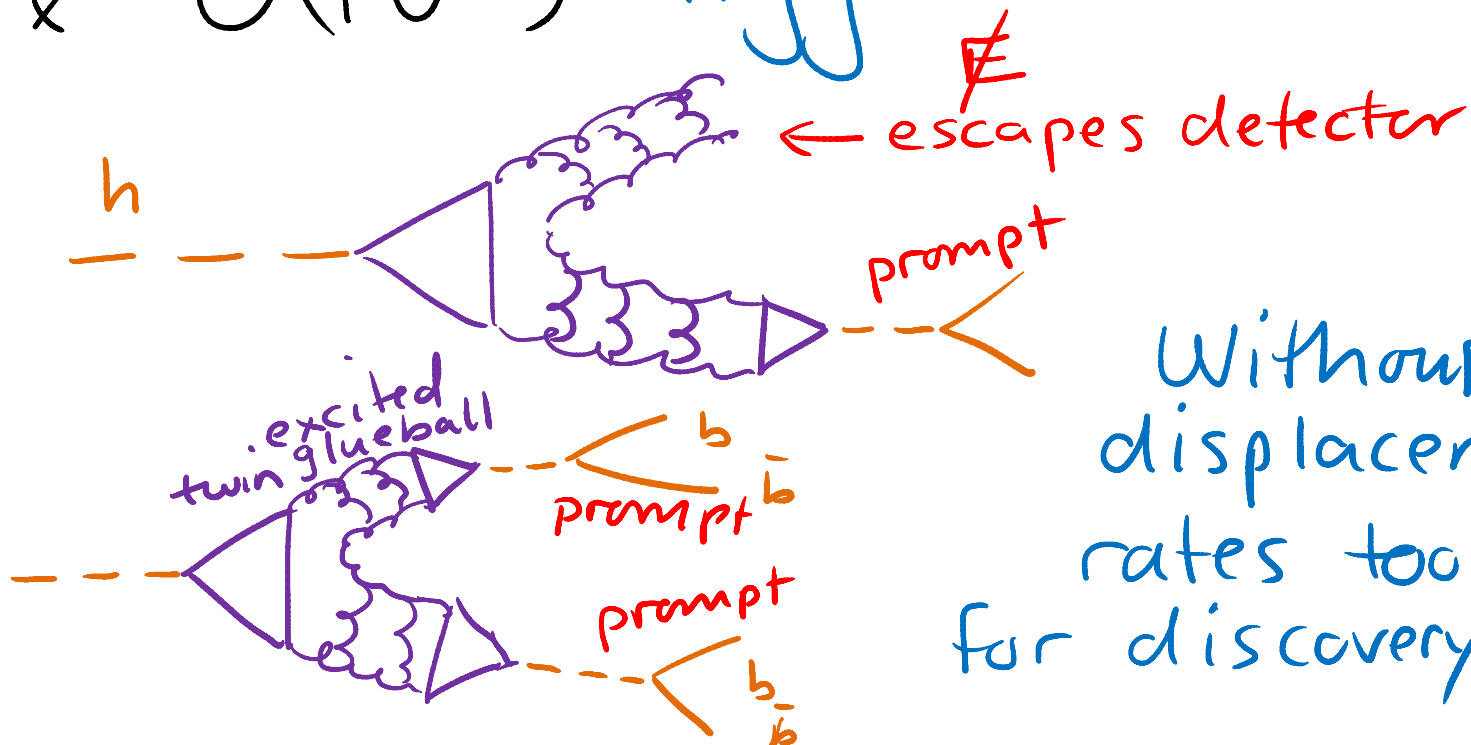
Triggering



LHC II Pheno

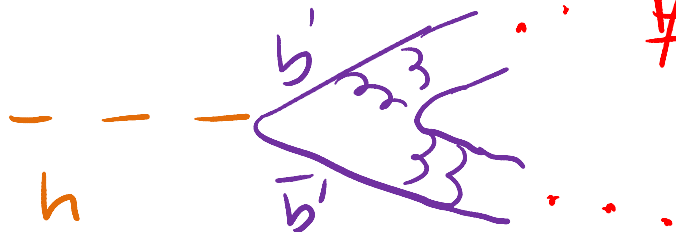
Assuming "irreducible" $\text{Br} \sim 10^{-4}$
(for decoupled twin b)

$\times O(10^7)$ higgs events



Without
displacement
rates too low
for discovery

LHC II Pheno

But  $\neq$, prompt, displaced

The diagram shows a horizontal orange line labeled 'h' entering a vertex. From this vertex, two purple lines labeled 'b'' emerge, one upwards and one downwards. From each 'b' line, three wavy purple lines (gluons) branch out to the right. Red dots are placed along the continuation of the b' lines and near the gluon branches.

may all be observable
if $y_{b'}$ large enough.

Precision Higgs Measurements

$$\ominus_{\text{SM twin}}^{\text{higgs}} \sim \frac{v}{f} \Rightarrow \left(1 - \frac{v^2}{f^2}\right) \text{ reduction} \\ \text{in SM Br's}$$

on cusp of LHC precision for
 $f/v \sim \text{few}$

(but within grasp of a lepton
collider)

EW Precision Tests

S, T have mild sensitivity
to higgs mass $\propto \ln\left(\frac{m_h}{m_Z}\right)$

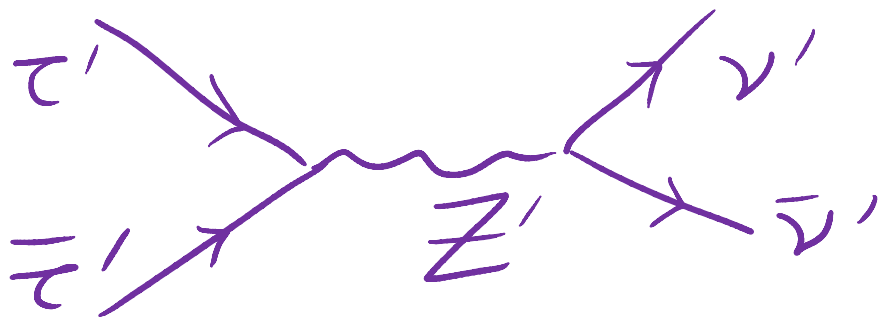
$\xrightarrow{\text{Twin Higgs}}$ $\ln\left(\frac{m_h}{m_Z}\right) + \frac{v^2}{f^2} \ln\left(\frac{m_{h'}}{m_Z}\right)$

only mildly constrains
(@ 1-2 σ) heavy exotic higgs
 $\lesssim \text{TeV}$

Dark Matter

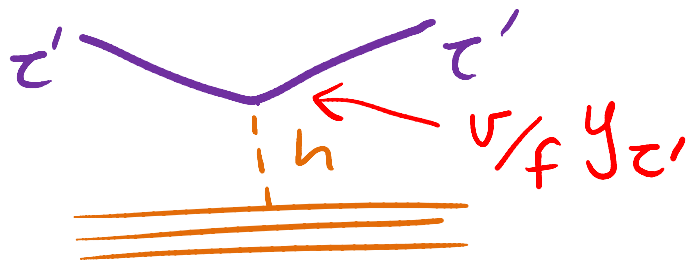
Craig, A. Katz (to appear)

τ' attractive DM candidate



WIMP miracle
for freezeout
density over large
 $m_{\tau'}$ range.

Direct detection interactions with matter
are mediated by Higgs Portal:



Suppressed interactions still
strongly constrained by LUX
will be covered by future
direct detection

Conclusions

- Bottom-up minimal Twin-Higgs model solving Little Hierarchy Problem
 - Novel, striking displaced vertex signatures + precision Higgs ^{corrections}
- Ideas for UV completion of Twin Higgs exist in recent literature, suggest visible SM + twin charges $\gtrsim 5 \text{ TeV}$
- Important case study in program of excluding or discovering naturalness.