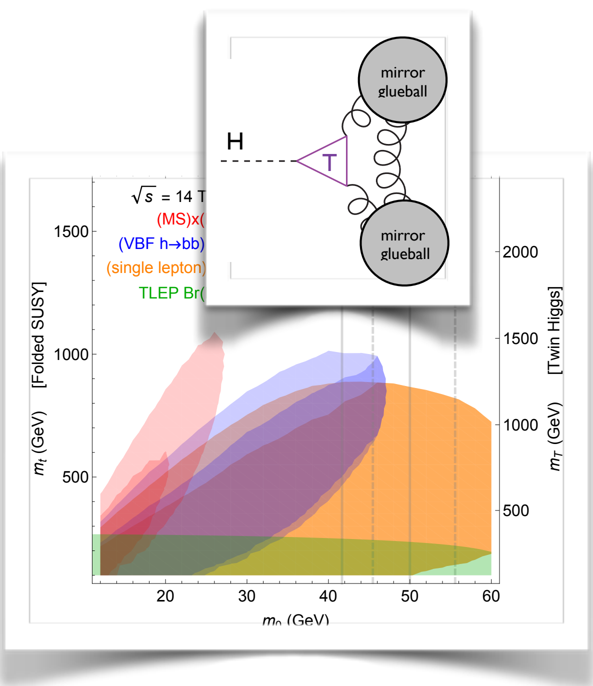
# Neutral Naturalness

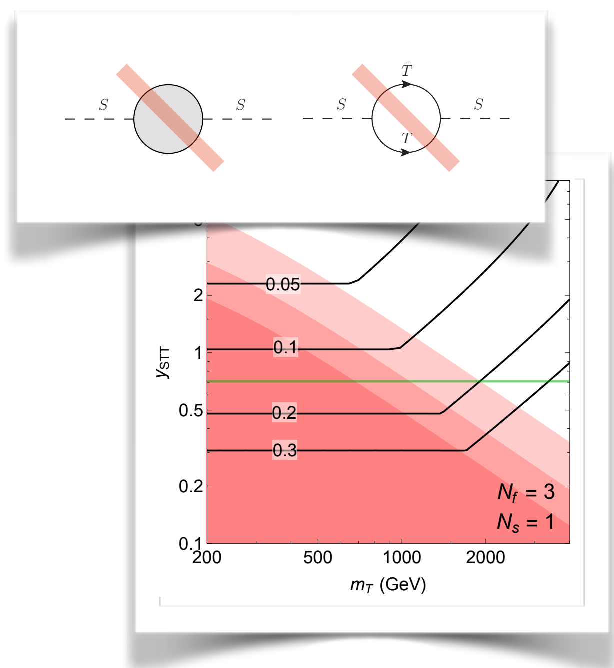
## - Theories and Signatures -



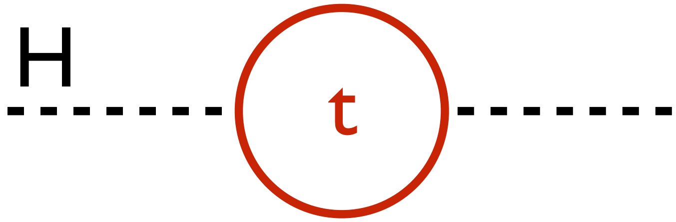

PITT PAC Workshop
Higgs and Beyond
University of Pittsburgh

3 December 2015


David Curtin
University of Maryland

# The Hierarchy Problem



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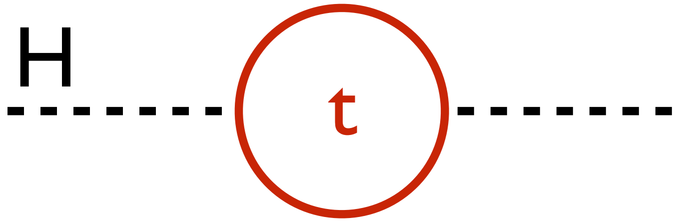
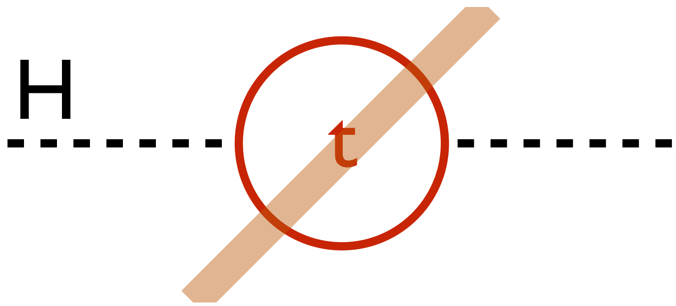
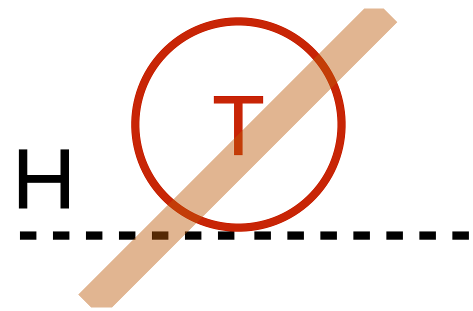



… can be solved by top partners

# The Hierarchy Problem



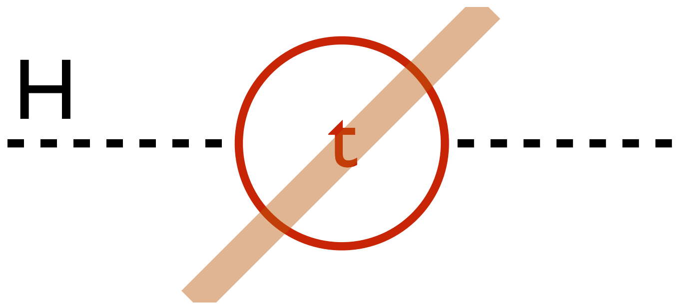

… can be solved by top partners

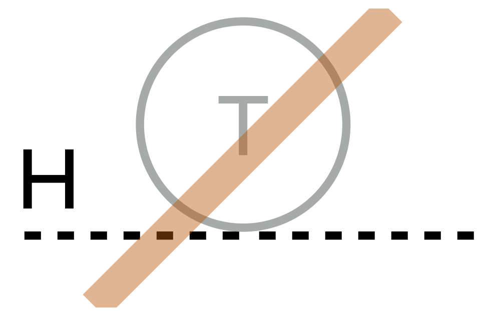
top quark t —continuous symmetry→ top partner T (carries color charge)

e.g.

***Supersymmetry****, modern* ***composite Higgs*** *models (Little Higgs), etc…*

# The Hierarchy Problem




The symmetry need not commute with SM color!

top quark t → (continuous symmetry)

↓ discrete symmetry

top partner T

COLOR NEUTRAL!

e.g.

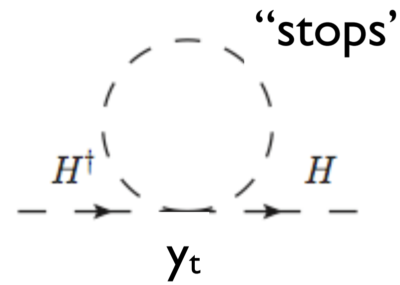
***Folded SUSY*** *(EW-charged stops)*, ***Twin Higgs*** *(SM singlet T-partners)*

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

hep-ph/0506256 Chacko, Goh, Harnik

# Discrete Symmetry Protection

$Z_2$ that ensures scalar coupling = top Yukawa can mimic protection of SUSY at one-loop $O(\Lambda^2)$ level.




→ **Folded SUSY.** hep-ph/0609152 Burdman, Chacko, Goh, Harnik

$Z_2$ that relates two copies of an SU(2) Higgs sector to each other can mimic protection of SU(4) goldstone at one-loop $O(\Lambda^2)$ level.

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

→ **Twin Higgs** hep-ph/0506256 Chacko, Goh, Harnik

Can be generalized to other discrete symmetries. 1411.7393 Craig, Knapen, Longhi

# Concrete

# Theory Examples

# 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

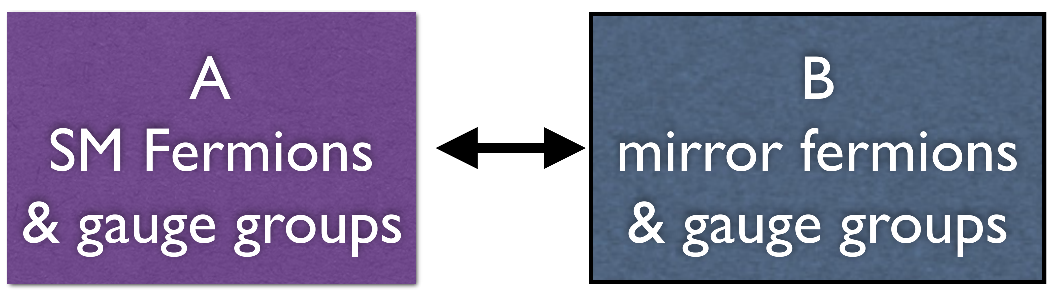
# Theory Example: Twin Higgs

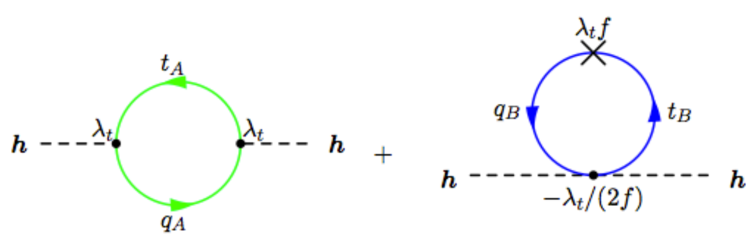
$SM_A$ x $SM_B$ (mirror sector) particle content with $Z_2$ symmetry

Higgs sector: SU(4), broken by Gauge + Yukawa interactions to $SU(2)_A \times SU(2)_B \times Z_2$, 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.*

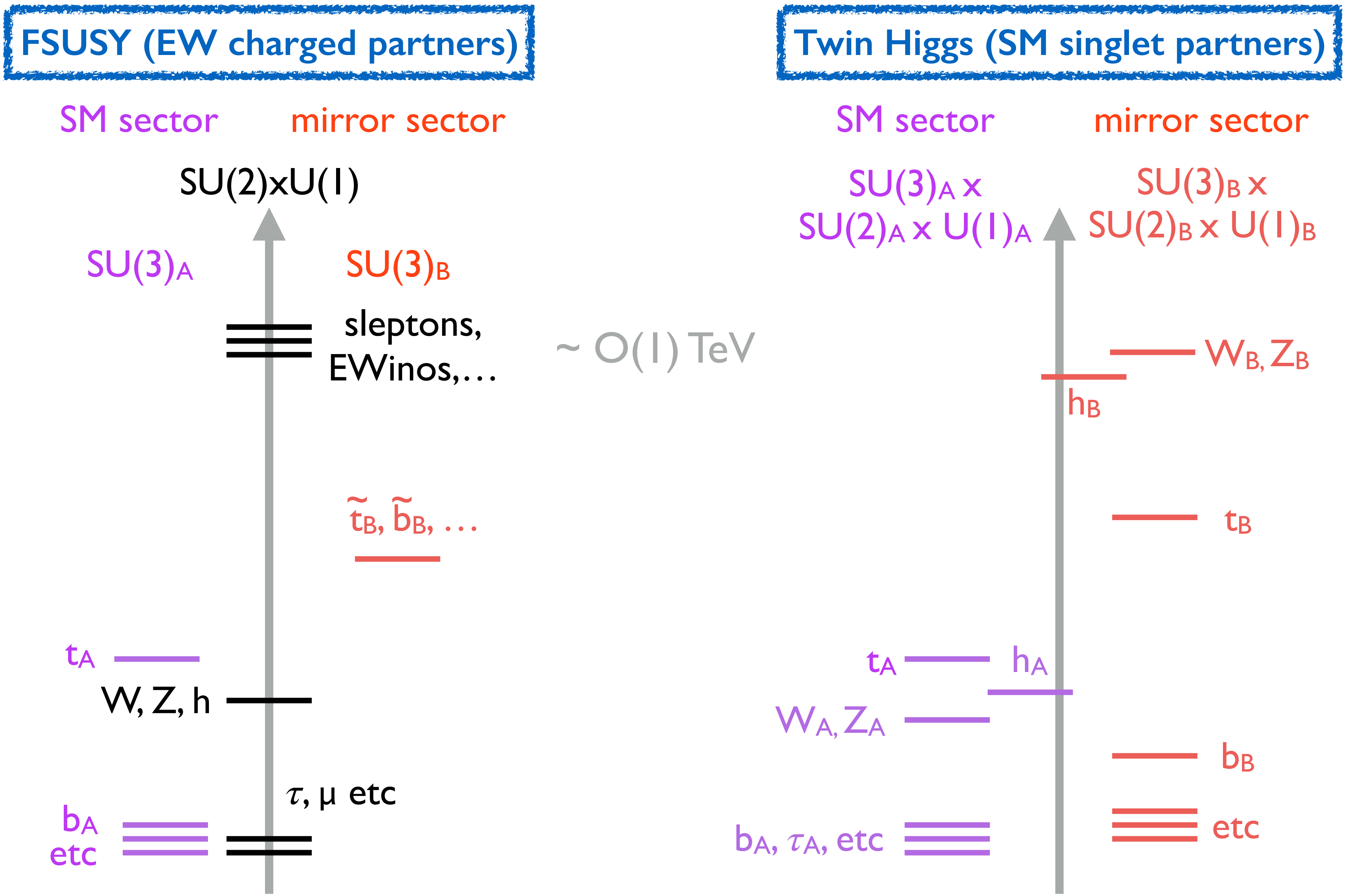



**SM singlet top partners.**

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

# Typical Low-Energy Spectra



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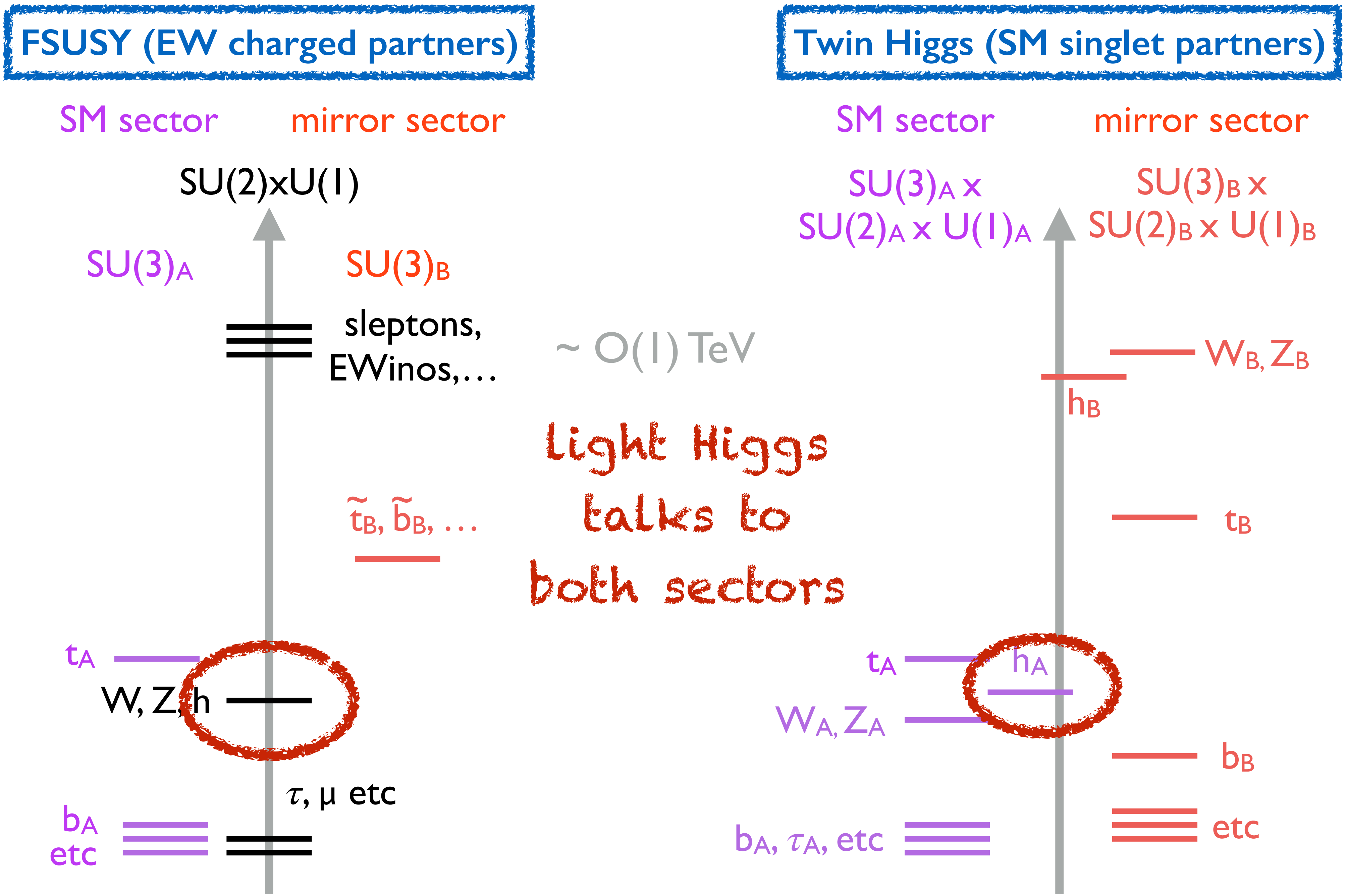


# UV Completions

# UV Completions

Necessary at O(5 TeV) due to incomplete cancellation of quadratic Higgs mass corrections (2-loop / Yukawa RG effects)

At these higher scales, full symmetry of theory becomes apparent:

Higgs and top fall into larger multiplets

New SM-charged matter and Higgs states appear

*This new matter could come from completed multiplets, and also due to peculiarities of the UV completion, e.g. KK-modes*

# UV Completions

Neutral Naturalness solves the Little Hierarchy Problem.

At high scales, one of the 'known' mechanisms kicks in to solve *full* Hierarchy Problem.

## Supersymmetric Twin Higgs

1312.1341 Craig, Howe

## Composite Twin Higgs

0811.0394 Batra, Chacko;
1501.07803 Barbieri, Greco, Rattazzi, Wulzer;
1501.07890 Low, Tesi, Wang

## Holographic (RS) Twin Higgs

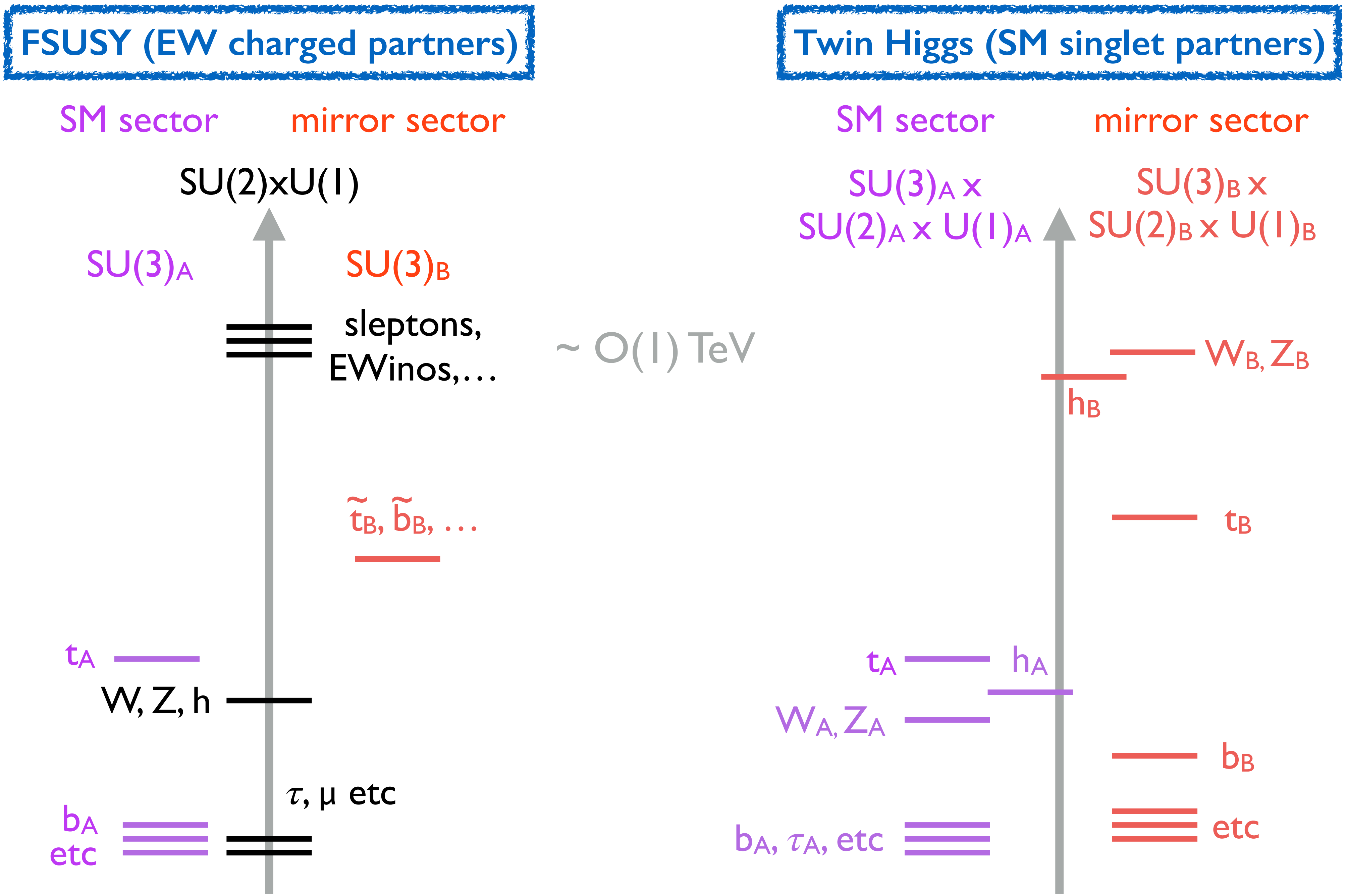
1411.2974 Geller, Telem

*(FSUSY is more challenging… deconstruction? Other approaches….)*

# Collider Signals

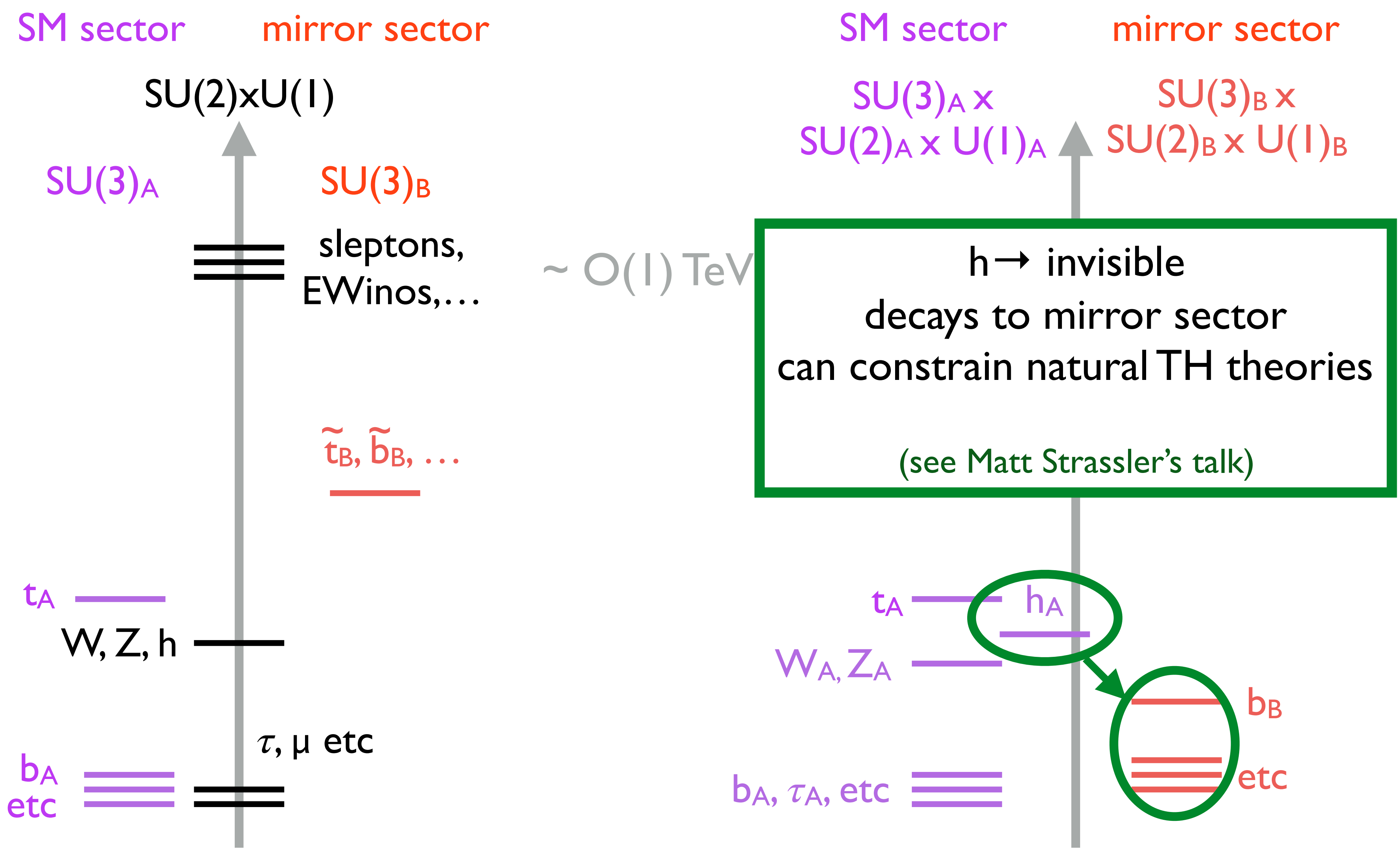
# LHC

# Typical Low-Energy Spectra



# Typical Low-Energy Spectra

**FSUSY (EW charged partners)** | **Twin Higgs (SM singlet partners)**



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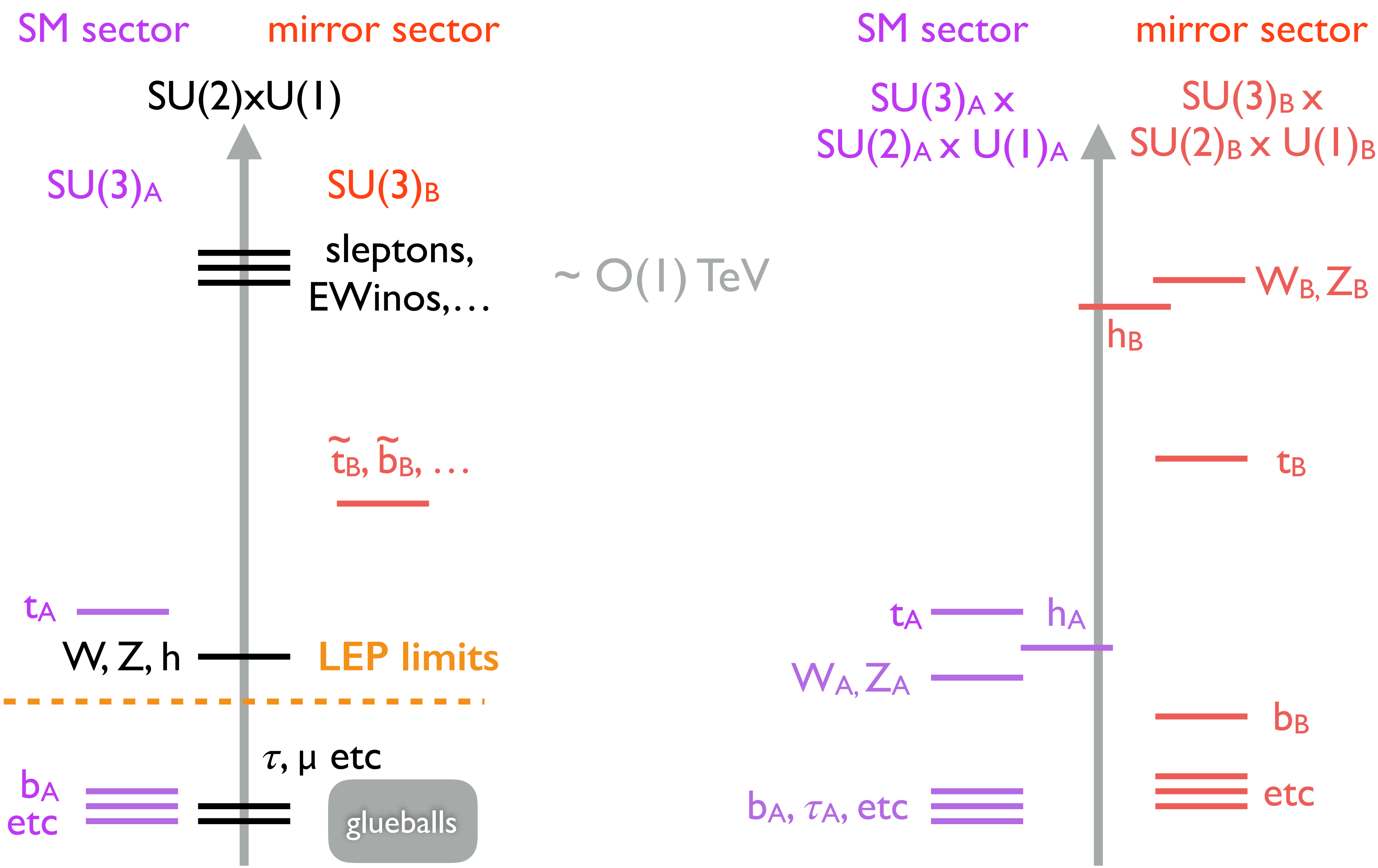

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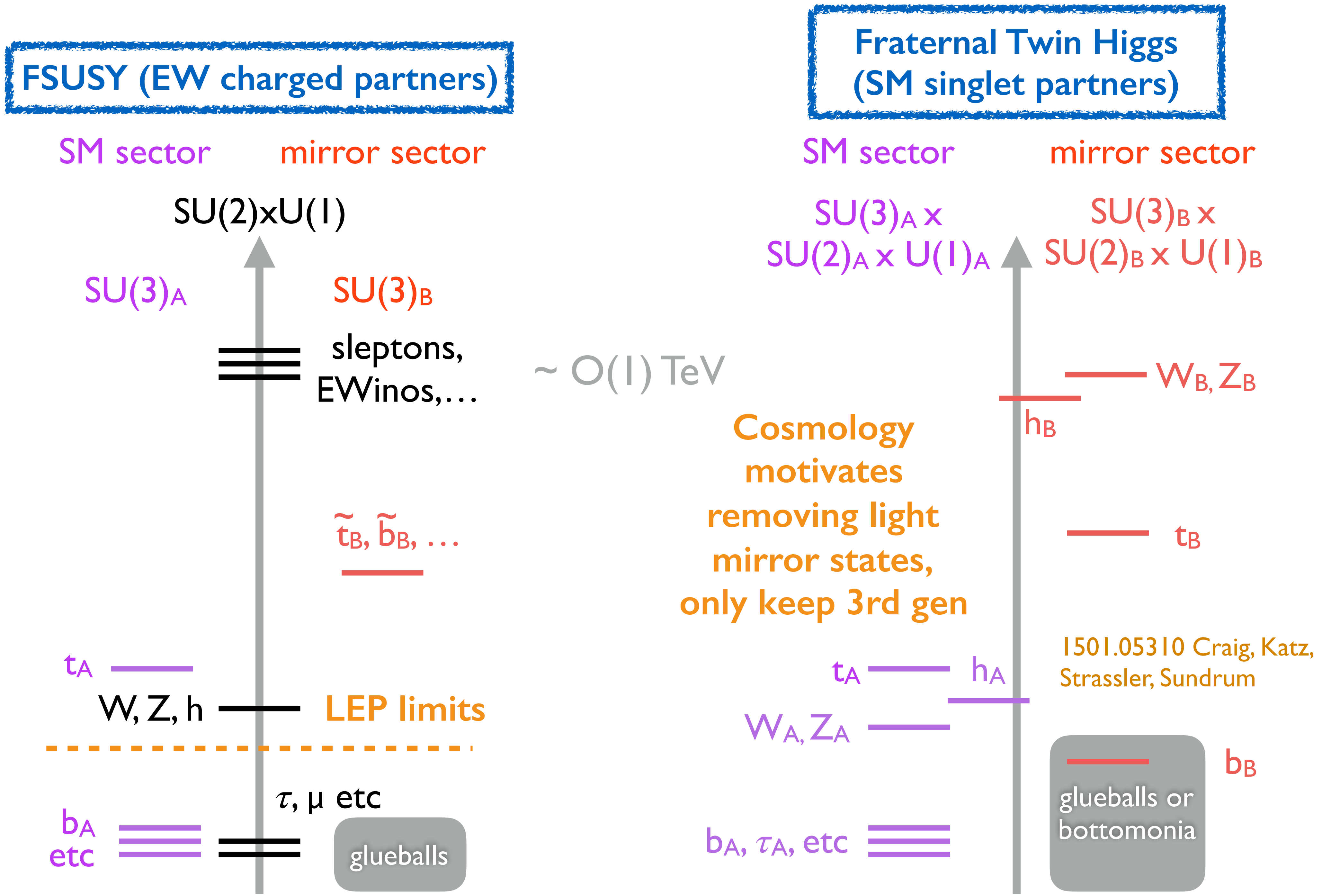
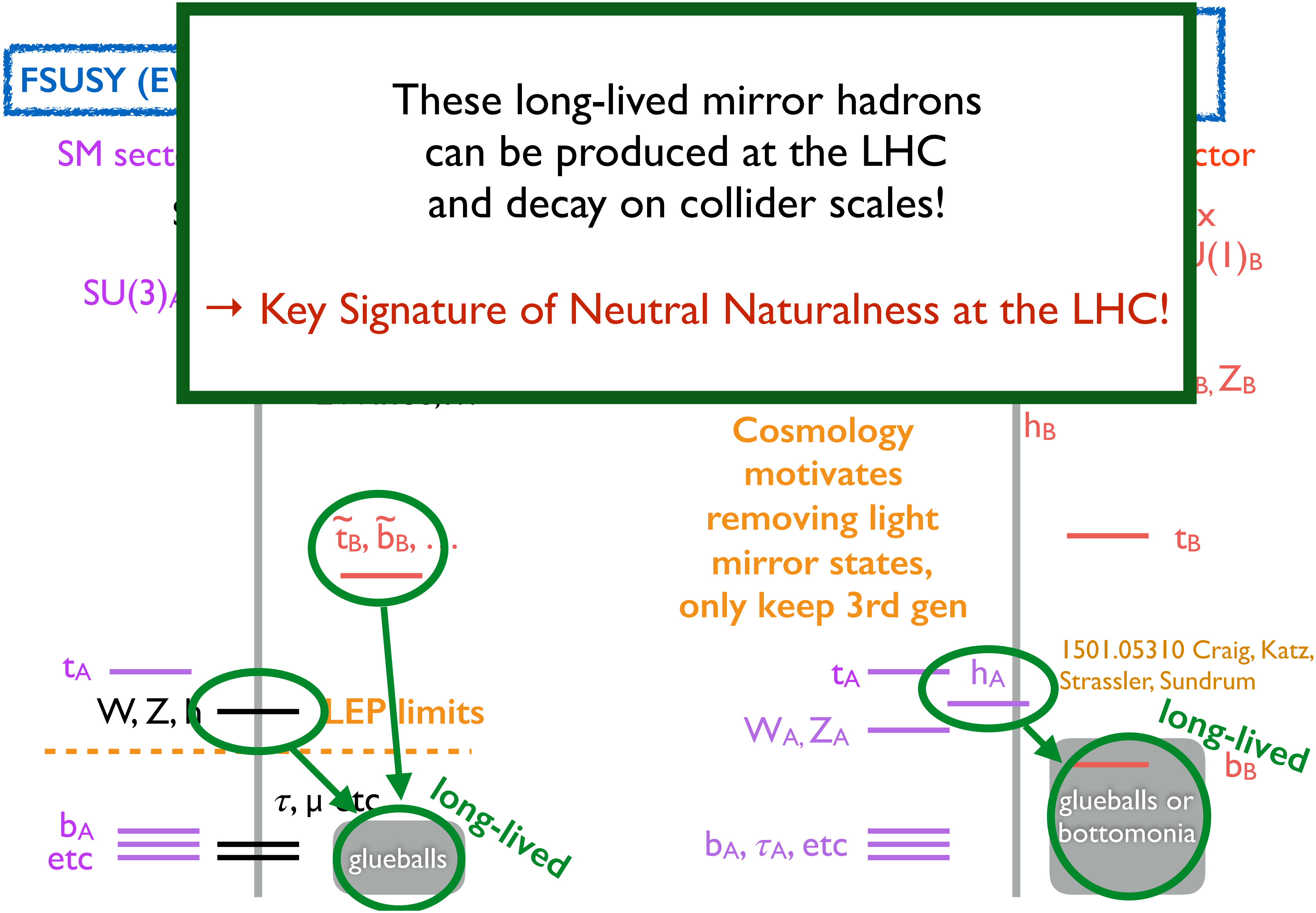


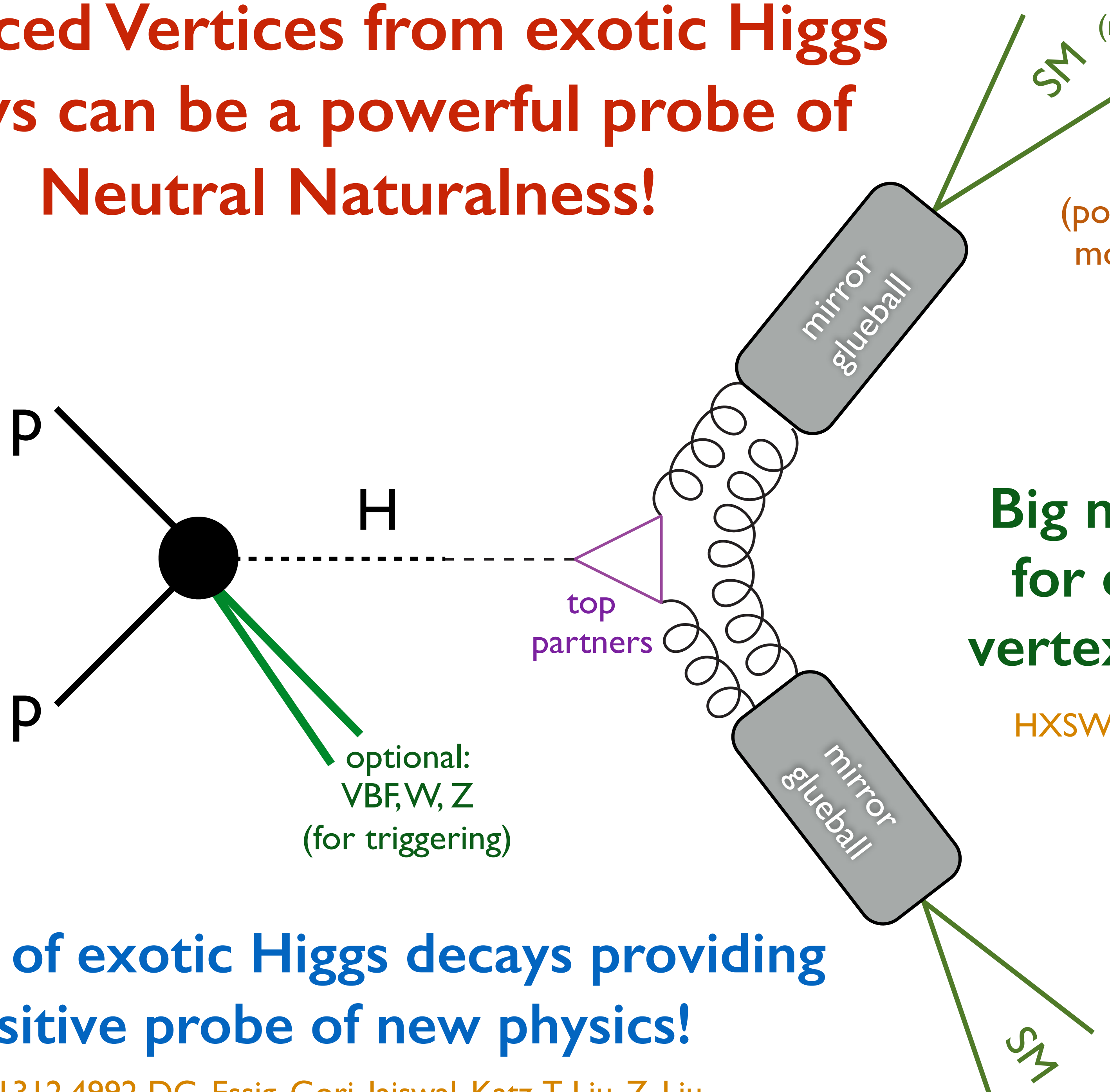
# Typical Low-Energy Spectra

These long-lived mirror hadrons
can be produced at the LHC
and decay on collider scales!

→ Key Signature of Neutral Naturalness at the LHC!



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




**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

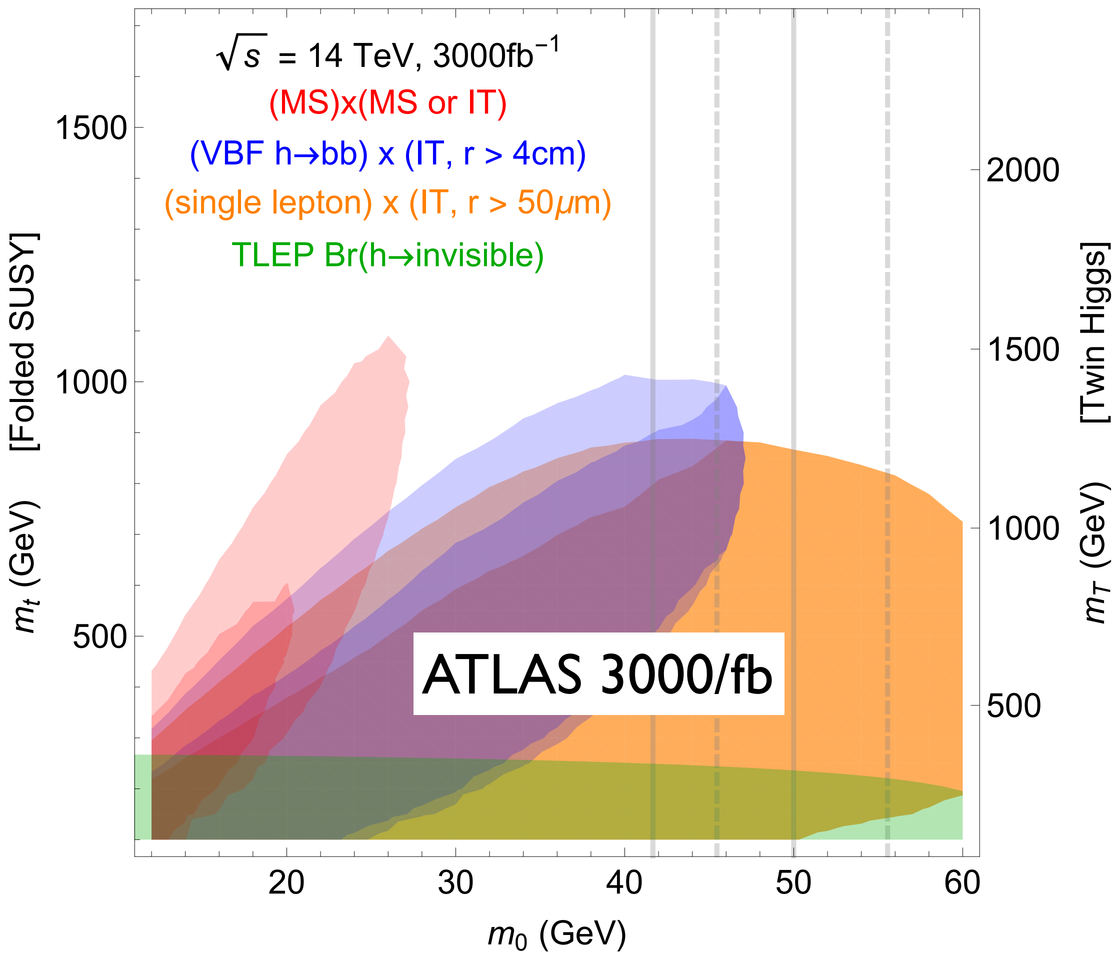
(see Matt Strassler's talk)

1501.05310 Craig, Katz, Strassler, Sundrum

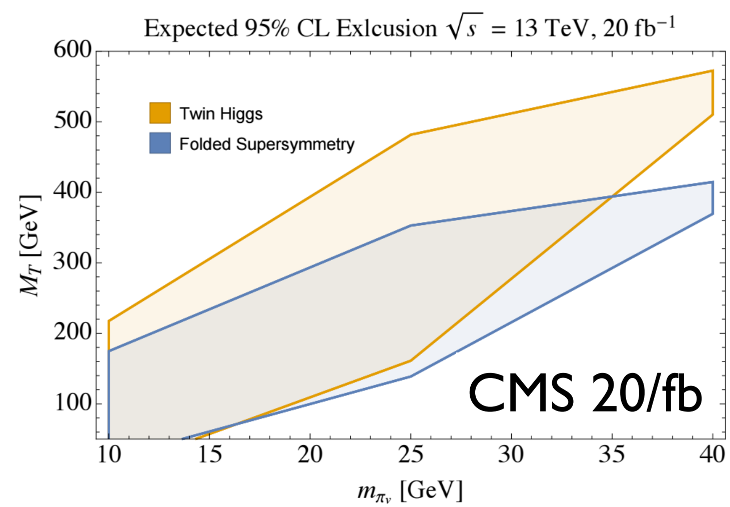
DC, Verhaaren 1506.06141

# Displaced Higgs Decays

## Exotic Higgs decays to **long-lived** mirror glueballs give TeV-scale top partner reach at the LHC!




This signature is "**guaranteed**" for EW-charged top partners (FSUSY), and **possible** for neutral top partners (TH)




DC, Verhaaren 1506.06141

Csaki, Kuflik, Lombardo, Slone 1508.01522

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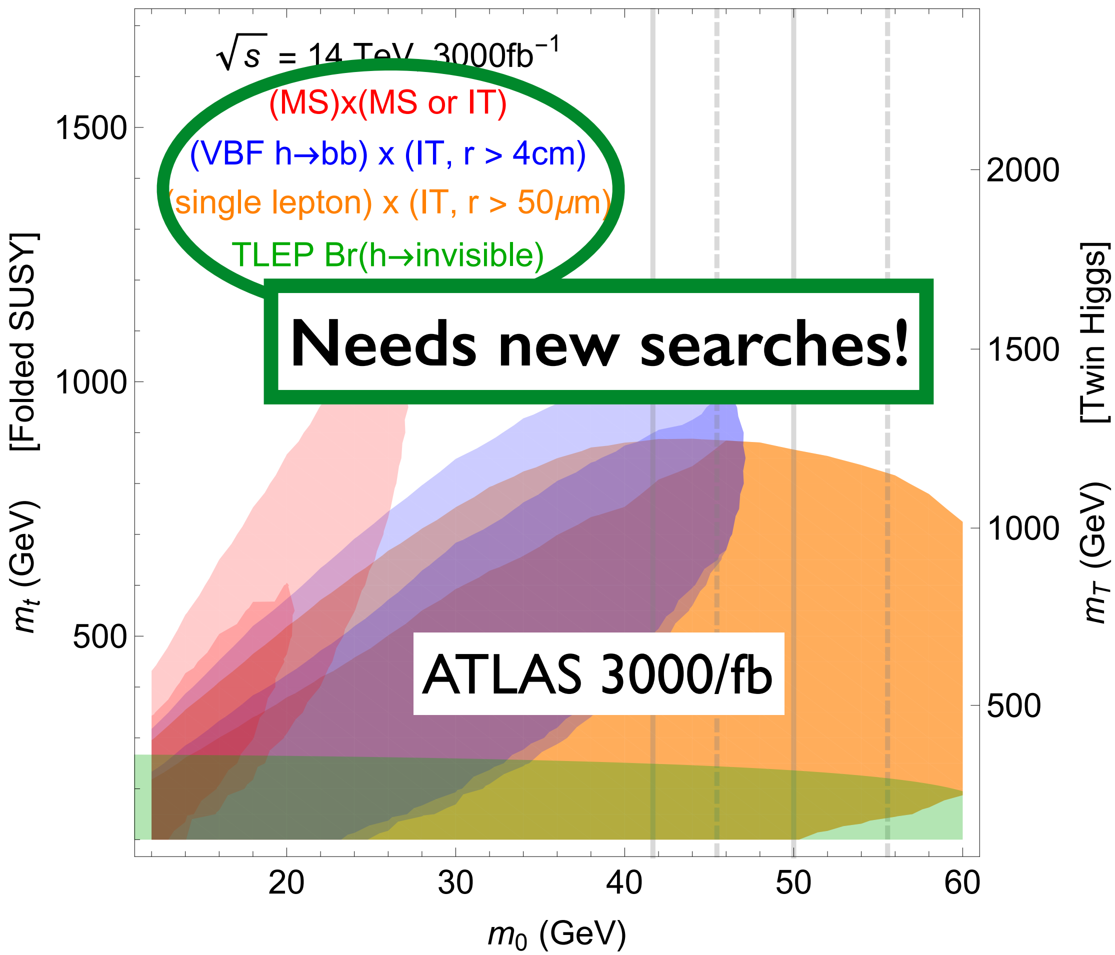


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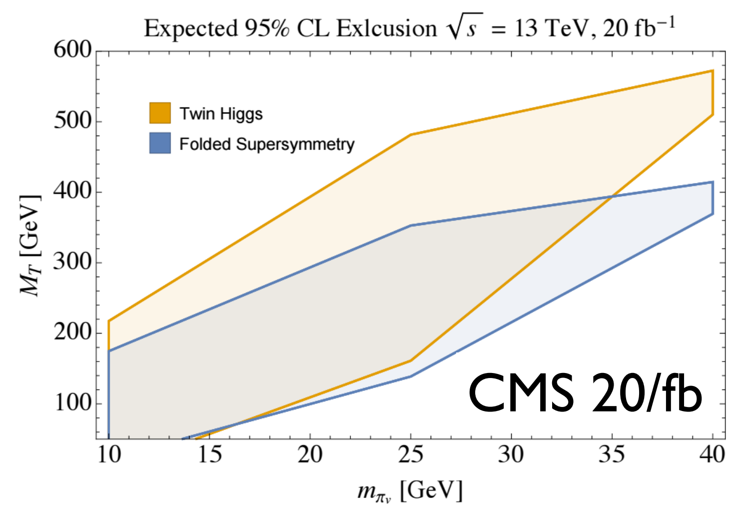
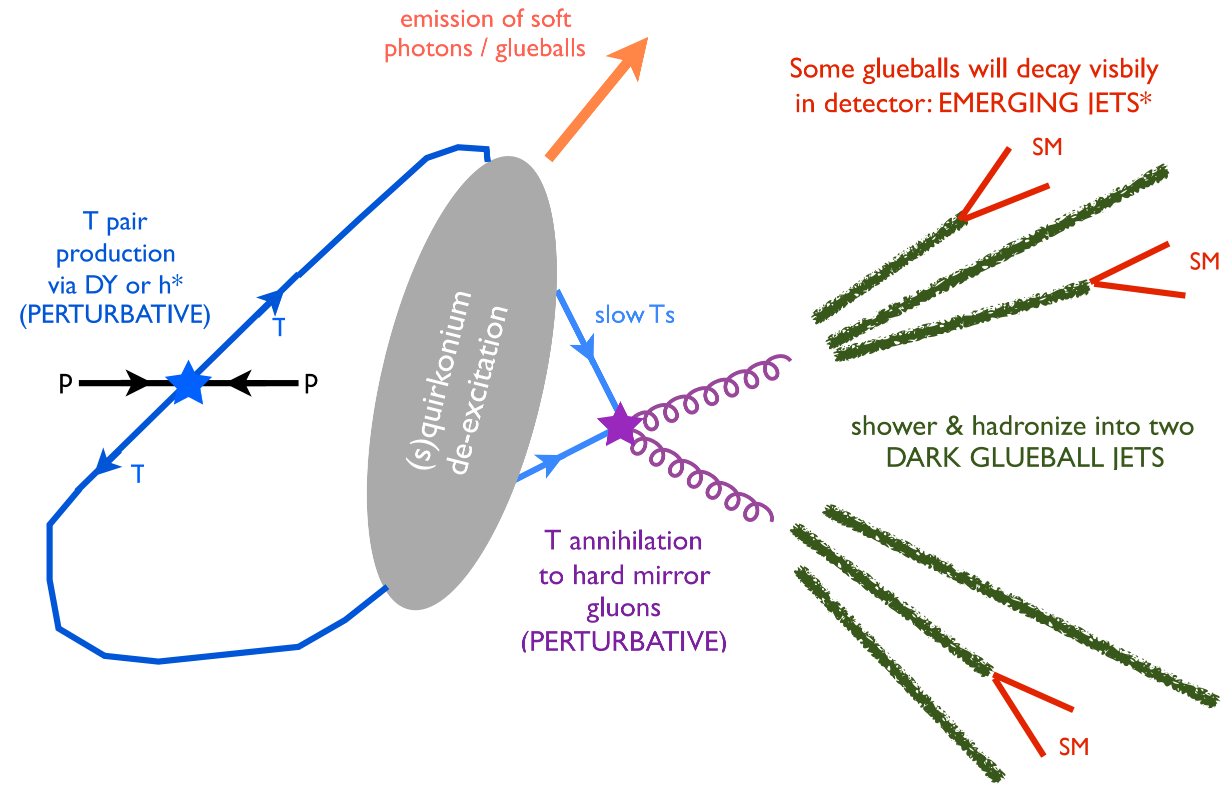



DC, Verhaaren 1506.06141

Csaki, Kuflik, Lombardo, Slone 1508.01522

# Quirky Partner Pair Production




Work in progress!

Chacko, DC, Verhaaren, 1512.XXXXX

- **In some cases, better reach than exotic Higgs decays!**
- direct evidence of uncolored top partners.
- could allow measurement of couplings and masses.
- potentiall spectacular signatures: several DVs, or many bb, $\tau\tau$ pairs
- **CHALLENGE: have to factorize unknown mirror hadronization from "hard" theory parameters.**
  →Use DGLAP-evolved space of of dummy fragmentation functions.

# Future Colliders

# Neutral Naturalness Periodic Table

| | | *scalar* | *fermion* |
|---|---|---|---|
| *strong direct production* { | *QCD* | SUSY | Composite Higgs/ RS |
| *DY direct production* { | *EW* | folded SUSY | Quirky Little Higgs |
| *Higgs portal direct production* { | *singlet* | ? | Twin Higgs |

Mirror Glueballs

Higgs portal observables

Higgs coupling shifts

$\sim$ tuning

# Lepton Colliders

**Twin Higgs** predicts Higgs coupling deviations ~ tuning.

Zh cross section measurements at ILC/TLEP will constrain TeV-scale top partner masses in Twin Higgs type scenarios.

Snowmass Working Group Report: Higgs Boson 1310.0861
TLEP Design Study Working Group 1308.6176

Electroweak Precision Constrains will be complementary in TH models, and vital for model-independent exclusions.

Fan, Reece, Wang 1411.1054

# 100 TeV Collider

In theories with long-lived mirror sector hadrons (glueballs, onia) 100 TeV collider has many-TeV top partner reach.

DC, Verhaaren 1506.06141
Chacko, DC, Verhaaren, 1512.XXXXX

Can probe UV completion directly by directly producing heavy SM-charged states!

$\Rightarrow$ ~ 10 TeV reach for e.g. bifundamentals

in progress: Cheng, Jung, Salvioni, Tsai

100 TeV collider is only way to reach ~5% or better precision on Higgs self coupling. (can be sensitive to neutral top partners)

e.g. Barr, Dolan, Englert, Ferreira, Spannowsky 1412.7154
Azatov, Contino, Panico, Son, 1502.00539
He, Ren, Yao 1506.03302

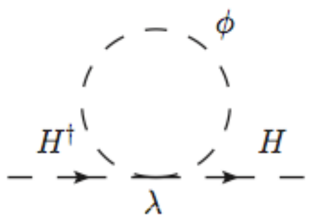
# No-Lose Theorem for Top Partners

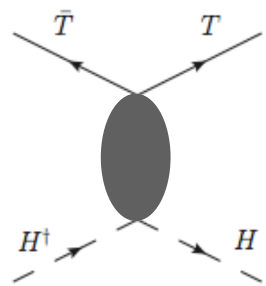
**Bottom-Up EFT/Simplified Model Approach!** DC, Saraswat 1509.04284

Scalar Partners

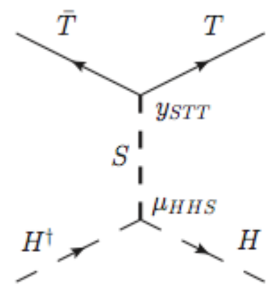
Fermion Partners

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

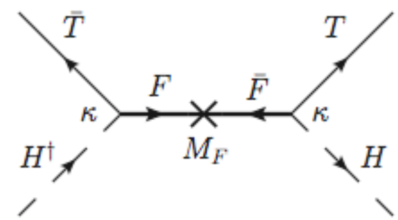



Strong Coupling




Scalar Mediator




Fermion Mediator

Impose top-loop cancellation condition and study irreducible low-energy signatures (at lepton colliders and 100 TeV) and irreducible tunings.

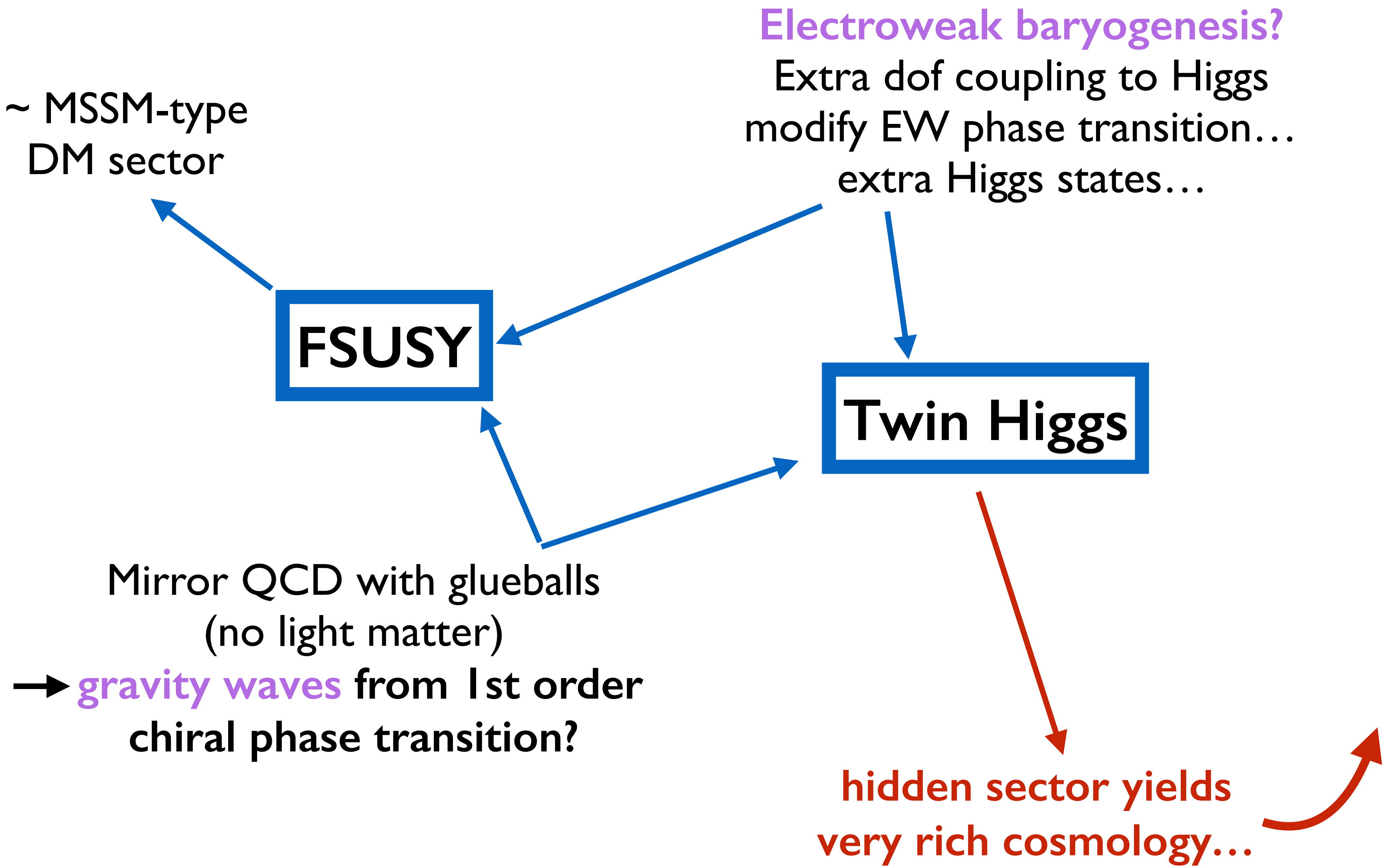
**Model-independent result:**

Natural theories with $N_{partners}$ ~ O(SM) will be discovered at future colliders!

*(Assuming UV completion contains SM charges)*

# Cosmology

# Cosmology and Neutral Naturalness



# Twin Higgs WIMPs

In Mirror TH, light hidden sector dof give large $\Delta N_{eff}$ and overclose.

## Fraternal TH

1505.07109 Garcia Garcia, Lasenby, March-Russell    1505.07113 Craig, Katz

Get rid of all light dof (1,2 gen). Can have "twin-WIMPs" e.g. $\tau'$

Direct detection via Higgs portal: possible in near future

DM annihilates to **light b' and glueballs** to avoid overclosure.

Indirect Detection: WIMPs $\rightarrow b'\bar{b}' \rightarrow b\bar{b} \rightarrow$ detect $\bar{p}$ @ AMS-02?

**IN PROGRESS:** Curtin, Tsai, Verhaaren

## Hadrosymmetric TH

**IN PROGRESS:** Freytsis, Knapen, Robinson, Tsai

Only get rid of light LEPTONS. Still have full mirror copy quarks!

Still have twin-WIMPs. Same Direct Detection as FTH.

DM annihilates to **twin pions** which overclose universe unless we include isospin-violating **vector mediator to mix with SM pions.**

**BBN & dark photon bounds can constrain TH models!**

**Indirect detection: WIMPS $\rightarrow \pi' \rightarrow \pi^* \rightarrow \gamma$ - rays @ FERMI-LAT**

# Twin Higgs Asymmetric DM

Linking visible and hidden sector number densities relies on UV completion

## Fraternal TH

1505.07410 Garcia Garcia, Lasenby, March-Russell

When $m_{b'} < \Lambda_{QCD'}$, $\Delta' \sim b'b'b'$ is stable twin-baryon

Can have $\Delta'$-$\tau'$ bound states (dark atoms) if twin photon light.

Direct detection of $\Delta'$ possible but can be buried under neutrino floor — quite challenging!

## Mirror TH

1506.03520 Farina

Relies on QCD' threshold effects to give twin neutron 5 GeV mass.

Eliminate leptons, relies on UV physics to provide twin pion annihilation channel and avoid overclosure.

# Other Connections

# Flavor

## Composite Twin Higgs:

in progress: Csaki, Geller, Telem, Weiler

KK modes give flavor violation, just like regular Composite Higgs (CH)

$\Rightarrow m_{KK} \gtrsim O(10\text{ TeV})$

crucial difference:

in CH, KK modes regulate Higgs potential, so can't be too heavy.

in CTH, $m_{KK}$ can be much higher $\sim 4\pi f$

$\Rightarrow$ CTH is the only example of an **ANARCHIC FLAVOR MODEL** that can be **ALMOST** natural ($f \gtrsim 3$ TeV)

## More generally:

All Neutral Naturalness Models require some $Z_2$-breaking.
This ultimately has some connection to flavor. Signals? ….

# Repurposing Top Partners

The hidden QCD makes the one-loop cancellation better, which allows the Little Hierarchy Problem to be solved up to scales of ~ 5 TeV.

**You can break the hidden QCD!**

**Need UV completion at ~2 TeV!** **Get some truly neutral particles!**

$\Rightarrow$ Neutral Top Partners could be Dark Matter? 0808.1290 Poland, Thaler

$\Rightarrow$ Neutral Top Partners could be RH Neutrinos? 1504.04016 Batell, McCullough

# Conclusions

# Conclusions

Neutral Naturalness offers generalized perspective on Hierarchy Problem.

⇒ Radically different phenomenology from colored top partners!

Motivates searches for ***displaced decays*** at the LHC to probe TeV-scale!

**Hidden QCD hadrons**, but also e.g. FSUSY sleptons — 1512.00040 Burdman, D'Agnolo

UV completions feature new SM-charges at 5-10 TeV: future opportunity!

Can formulate model-independent **no-lose theorems** for discovery!

Implications for cosmology, flavor physics, neutrinos.... Lots more to do!

Thank you!