Overview and New(Old) Thoughts

on

Dark[Hidden] Sector{Valleys}

Matt Strassler

Some Comments

~~Overview~~ and New(Old) Thoughts

on

Dark[Hidden] Sector{Valleys}

Bonus: 750 750 750 750 750

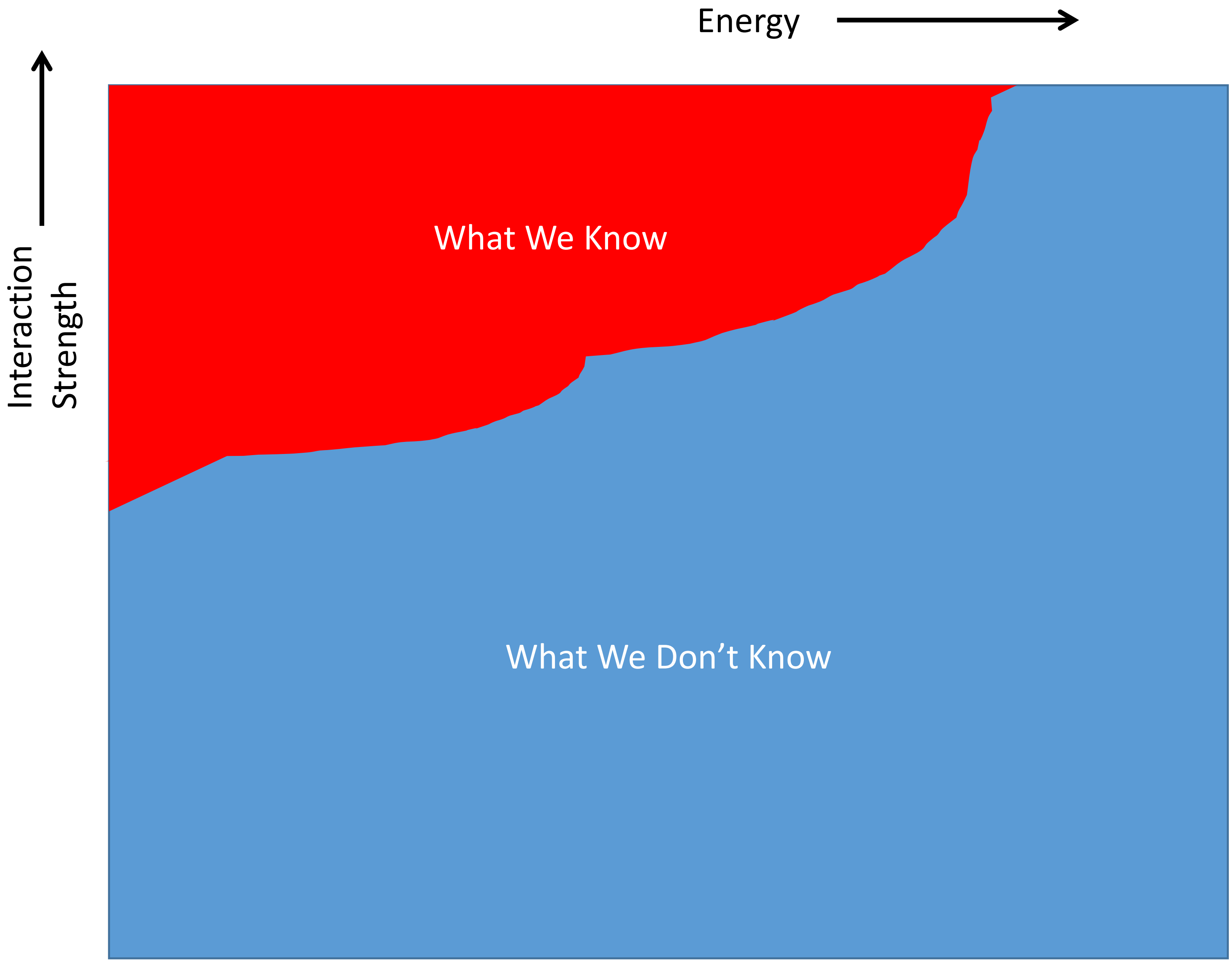
Matt Strassler

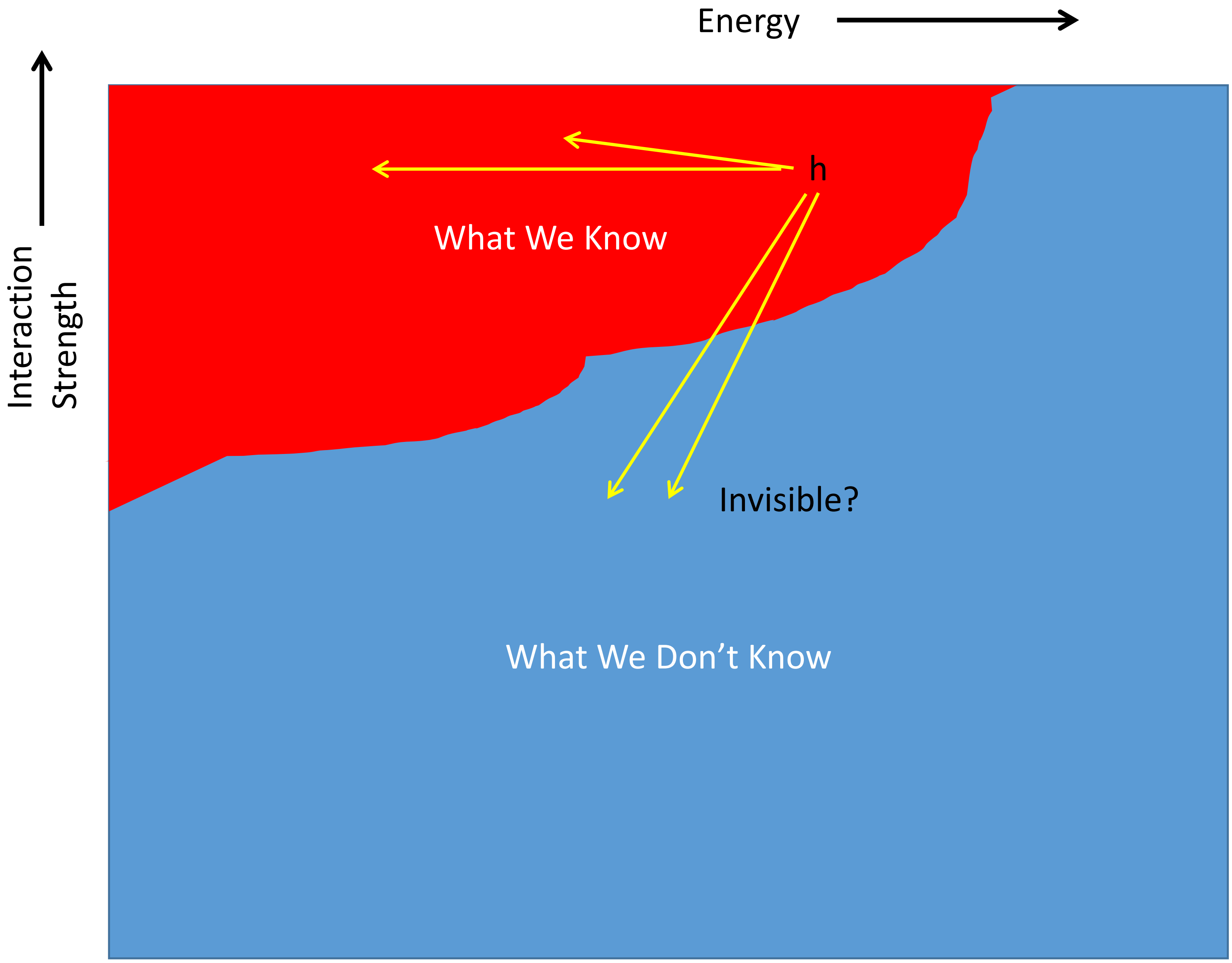
Motivation

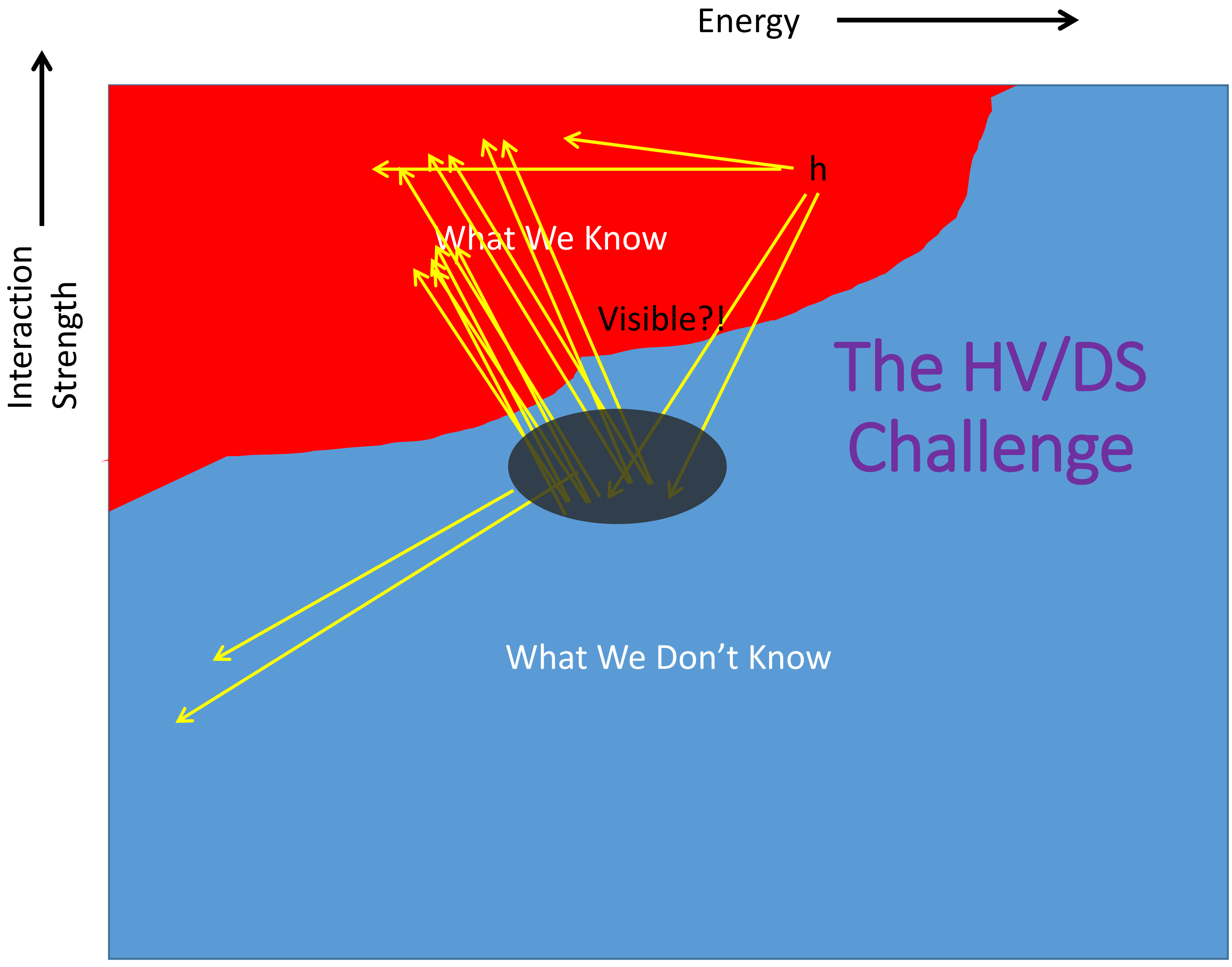
With Higgs, SM now a consistent theory; why look in the dark?

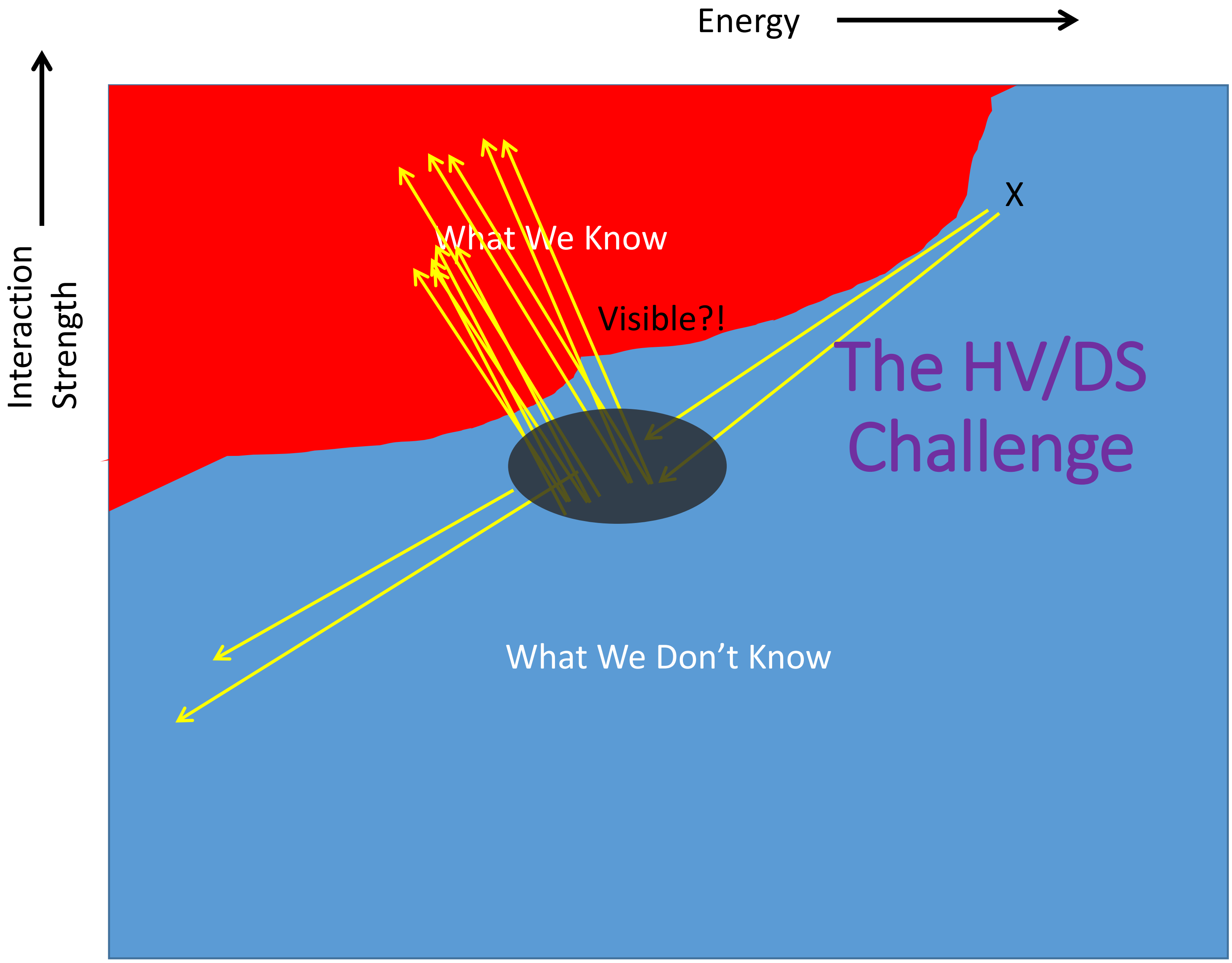
- Dark matter
  - [it exists; but how weakly coupled to SM?]
- Neutrino masses
  - [if RH neutrinos are at the TeV scale]
- Supersymmetry breaking
  - [if SUSY exists!]
- Neutral naturalness
  - [if cancellation of Higgs loops is hidden]

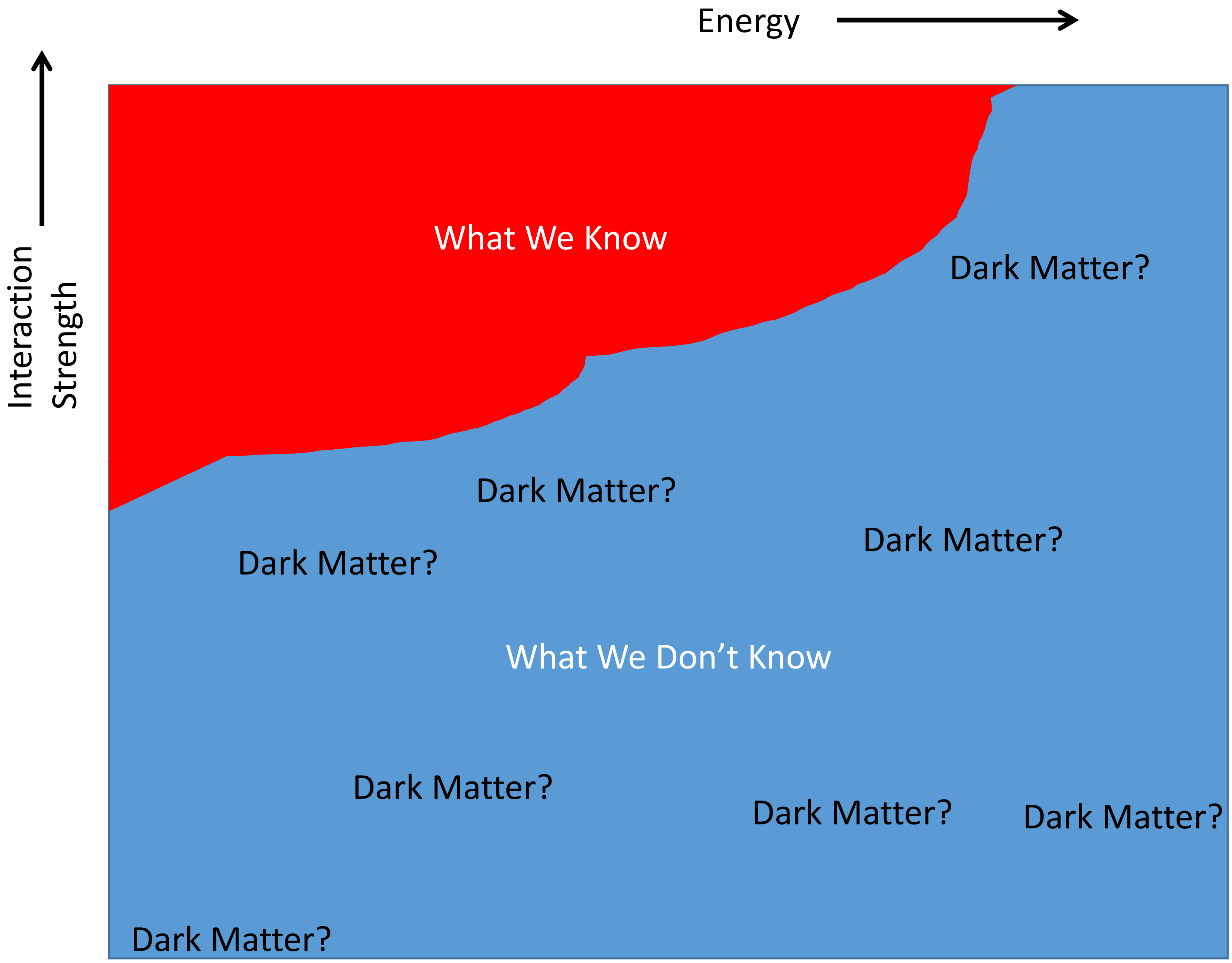
- Caution: true motivation might not yet be known to theorists!
  - Not strongly constrained by experiment
  - Let's not forget the muon, the muon neutrino, the Z boson,…
- And thoroughness is required!
  - Otherwise can't draw any conclusions about SM's completeness at the LHC


Energy
Interaction
Strength
What We Know
What We Don't Know

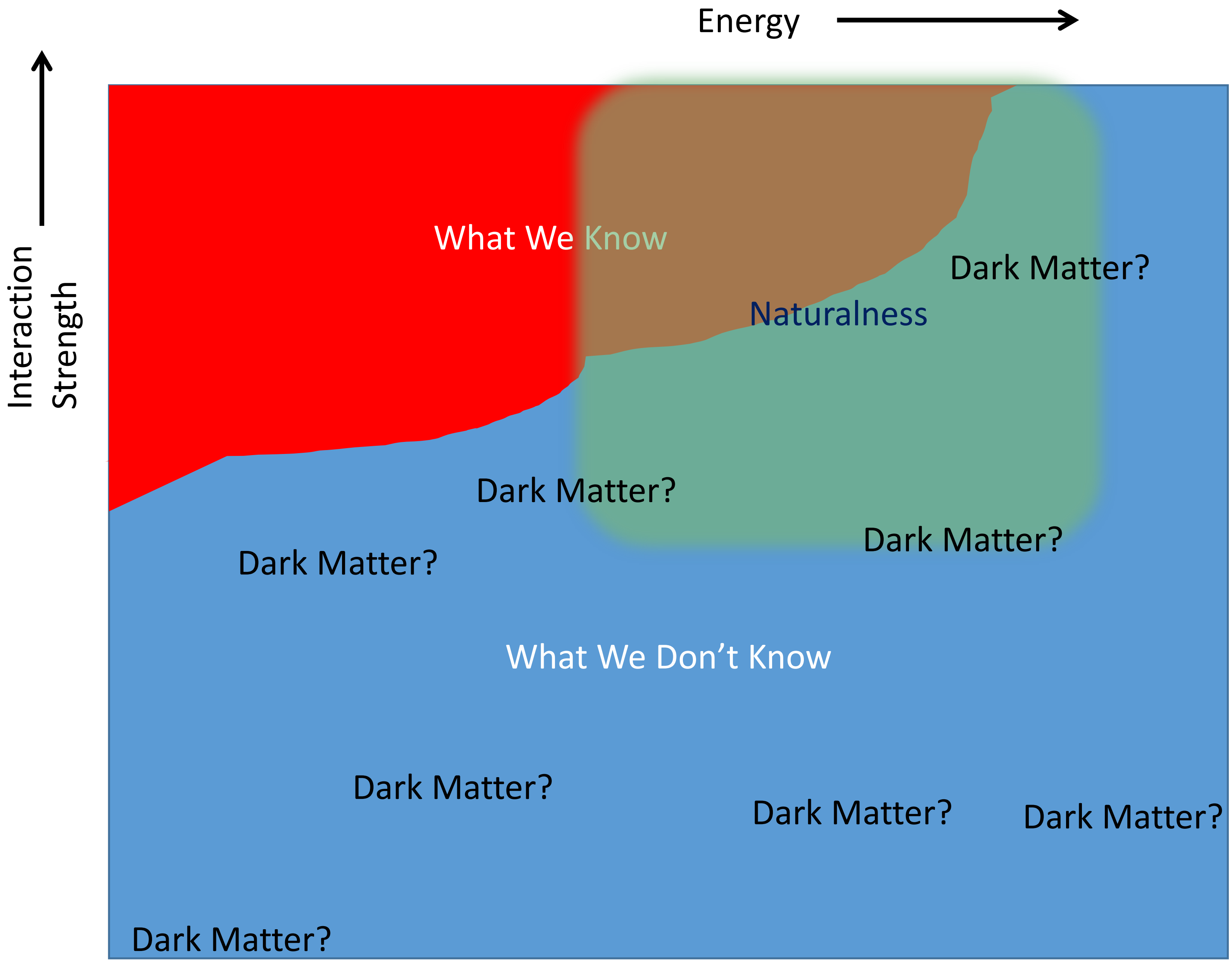

Energy
Interaction Strength
h
What We Know
Invisible?
What We Don't Know


Energy
Interaction Strength
h
What We Know
Visible?!
The HV/DS Challenge
What We Don't Know


Energy
Interaction Strength
What We Know
Visible?!
X
The HV/DS Challenge
What We Don't Know



Energy
Interaction Strength
What We Know
Dark Matter?
Dark Matter?
Dark Matter?
Dark Matter?
What We Don’t Know
Dark Matter?
Dark Matter?
Dark Matter?
Dark Matter?


Energy
Interaction Strength
What We Know
Naturalness
Dark Matter?
Dark Matter?
Dark Matter?
Dark Matter?
What We Don’t Know
Dark Matter?
Dark Matter?
Dark Matter?
Dark Matter?

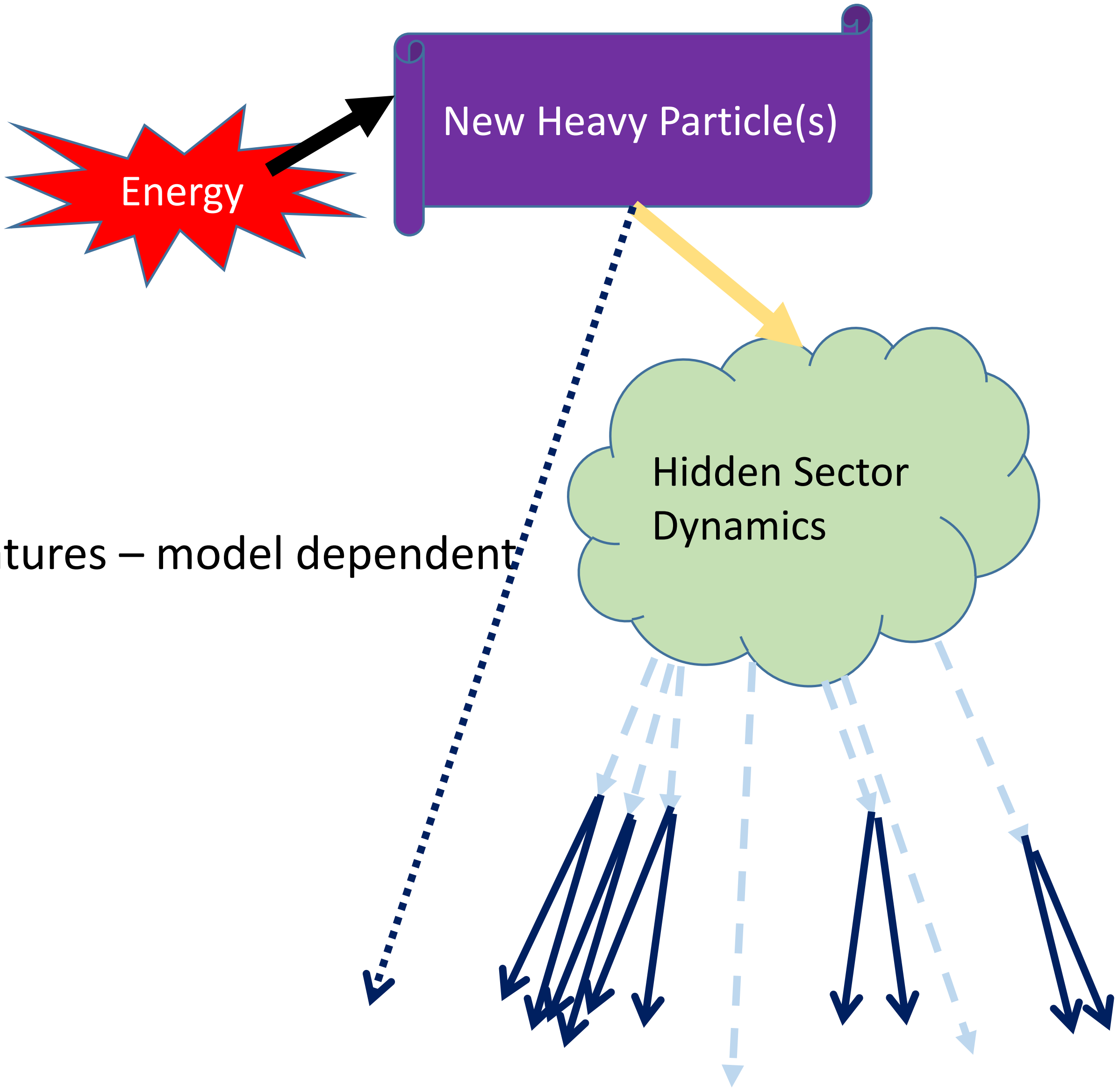
Typical of Hidden Valleys (and not of minimal models)

MJS + Zurek 06

New neutral particles –

- Numerous
  - High diversity
  - High multiplicity
- Boosted
- Clustered
- Displaced

-- May see any/all of these signatures – model dependent



General DS/HV Phenomenology

- New particles can be lighter than LEP limits
- Their self-interactions can be strong and/or unfamiliar
- They may not be stable (or decay invisibly)
- May exhibit hidden valley pheno
  - High diversity, high multiplicity, boosting, clustering, displacement
- Rarely produced directly
  - Usually in decays of heavier particles, known (h,Z,W,t) or unknown

The Scary Truth

- **Huge** range of search strategies needed
  - Given the personnel situation, we must be both efficient and lucky

The Challenge: So Many Variables!!

- Lifetime
  - Prompt vs. slightly displaced vs. mildly displaced vs. highly displaced
- Boost
  - Collimated vs. somewhat collimated vs. not collimated
- Multiplicity/Clustering
  - Single vs. multiple isolated vs. multiple clustered
- Mass scale
  - <1 GeV vs. 1-10 GeV vs. higher mass
- Final State
  - Hadronic vs. photonic vs. taus vs. leptonic
  - Visible vs. partly visible
- Triggering
  - Higgs, Z, W decay vs. higher scale
  - Standard objects vs. non-standard objects

Example of "Easy" Cases Still Open

Dilepton bump in semi-exclusive channels

MJS + Zurek 06

- Lepton pair produced in decay of h, t, new heavy particles
  - Will be drowned in DY background in inclusive search
  - May stand out if cut made on
    - p_T of dilepton pair
    - m(dilepton)/S_T [$S_T = m_{eff}$]
    - MET
    - n_{jets}
  - Better: bin the full DY data in these largely-independent variables

Four-lepton opportunity too!

Search is easy BUT must work out optimal way to bin the data

Do the same for diphotons

Some Easy Cases Closed Run 1
- H → Z Z' or Z' Z' → four leptons
- H → four photons
- Inclusive displaced dilepton pairs
- …

Prioritizing More Challenging Cases

Non-SM Higgs decays: **Very High Priority**

- Theorists: extensive study of **prompt, low multiplicity** decays

Exotic Decays of the 125 GeV Higgs Boson

David Curtin,[1] Rouven Essig,[1] Stefania Gori,[2,3] Prerit Jaiswal,[4] Andrey Katz,[5] Tao Liu,[6] Zhen Liu,[7] David McKeen,[8,9] Jessie Shelton,[5] Matthew Strassler,[1] Ze'ev Surujon,[1] Brock Tweedie,[10] and Yi-Ming Zhong[1,*]

- Some searches complete at ATLAS
  - All-visible with leptons, photons
  - Partly-visible more subtle

- Much more to do on search strategies, triggering, prioritizing

Will leave this for discussion…

Prioritizing More Challenging Cases

SUSY:

- If gluino heavy, rates are not spectacularly high
- RPV, Stealth and HV cases all need more work
  - All have reduced or zero MET
  - Can give LLPs, all-hadronic events, clustered/boosted objects, …
  - Triggering issues?

Fermionic top-partner:

- Similarly, non-minimal top partners need more work (theory!)

Wide/heavy Z’, RS graviton,…

- Rare spectacular events, can they be missed?

Dark matter: (in later talks)

Neutral Naturalness: General Points

If a HV/DS solves naturalness problem, the Higgs must be involved

- To remove t, W effects on H potential…
  - Something new has to couple to Higgs with moderate strength
  - If SM-neutral, almost inevitable that Higgs portal is open
- Furthermore, QCD effects on SM top Yukawa
  - Even if cutoff were 5 TeV these effects would spoil a one-loop cancellation
  - Therefore something has to be able to remove them too
    - If top partner not colored, probably need a hidden QCD-like theory
    - Higgs may then couple to hidden gluons via top partner loop

<u>So if top partner is colorless, expect h portal, often to hidden gluons</u>

- Observable effects?
  - DS/HV pheno depends on the spectrum, dynamics of hidden color
  - Also other light hidden particles, *e.g. light hidden quarks, dark photons, …*

Neutral Naturalness: General Points

If Higgs portal open,

- Small effects on SM Higgs properties (tough at LHC)
- But good chance to get one or more of:

  - Non-SM Decays of 125 GeV Higgs (standard production)
  - HV/DS particles as heavy flavor resonances (or even WW/ZZ)
    - Long lifetime possible
  - Possible emission of on-shell or off-shell Higgs in HV/DS cascades
  - Production of heavier non-SM particles in Higgs sector
    - Additional source of SM resonances and HV/DS particles

Neutral Naturalness: General Points

Common: heavy particles charged under hidden color and SM forces

- Can even be the top partners (Folded SUSY!)
- These can perhaps
  - Decay to SM + HV/DS (Weiler talk)
  - Confine with light hidden quarks to form (meta)stable DS/HV hadrons
  - Confine as quirks (if no light hidden quarks exist) and emit HV/DS hadrons

Some words about quirks later…

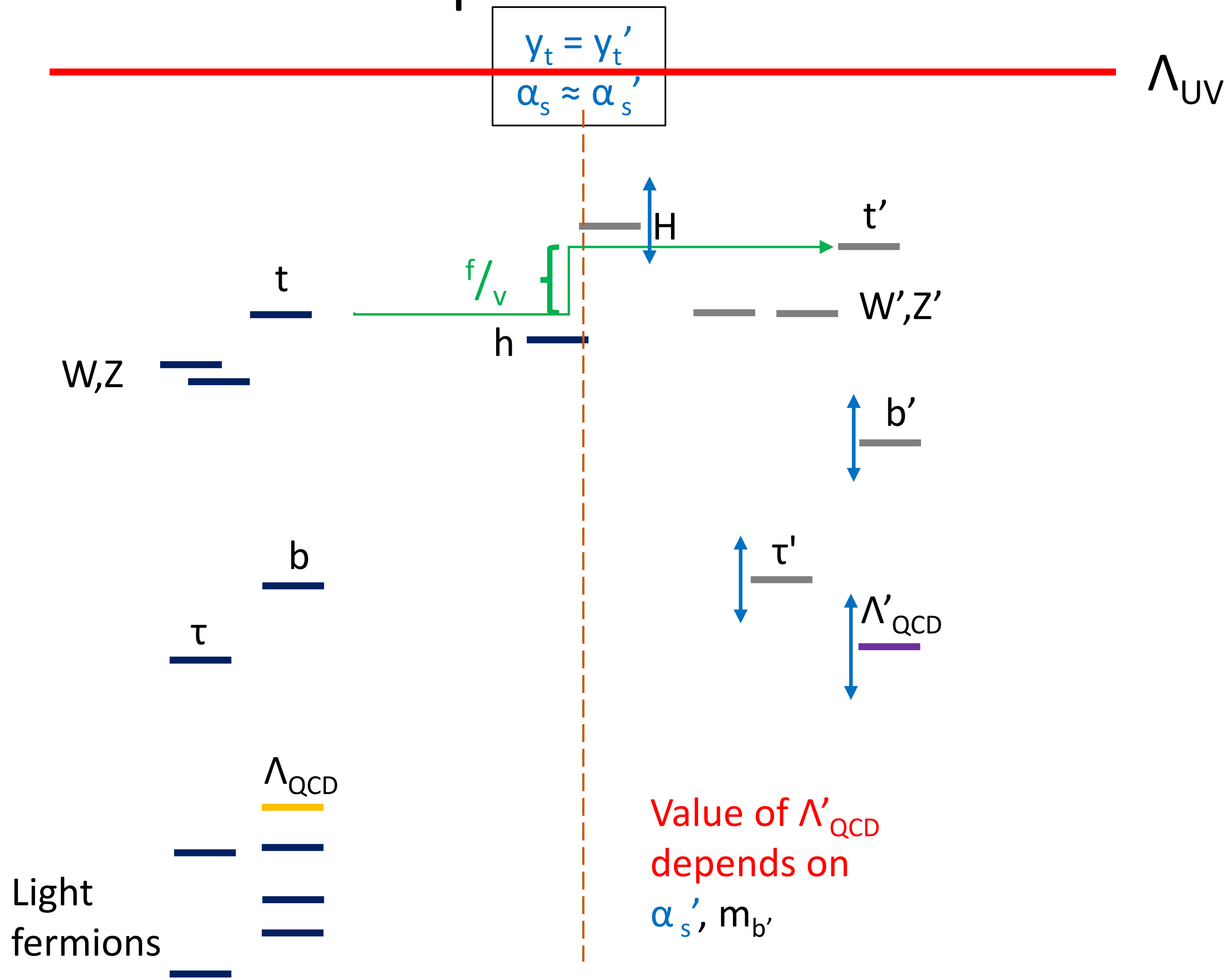
Existence proofs of Neutral Naturalness:

- Twin Higgs and variations hep-ph/0506256 Chacko, Goh & Harnik
  - Example: the "Fraternal" Twin Higgs **arXiv:1501.05310** Craig,Katz,MJS & Sundrum
- Folded SUSY and variations hep-ph/0609152 Burdman, Chacko, Goh & Harnik

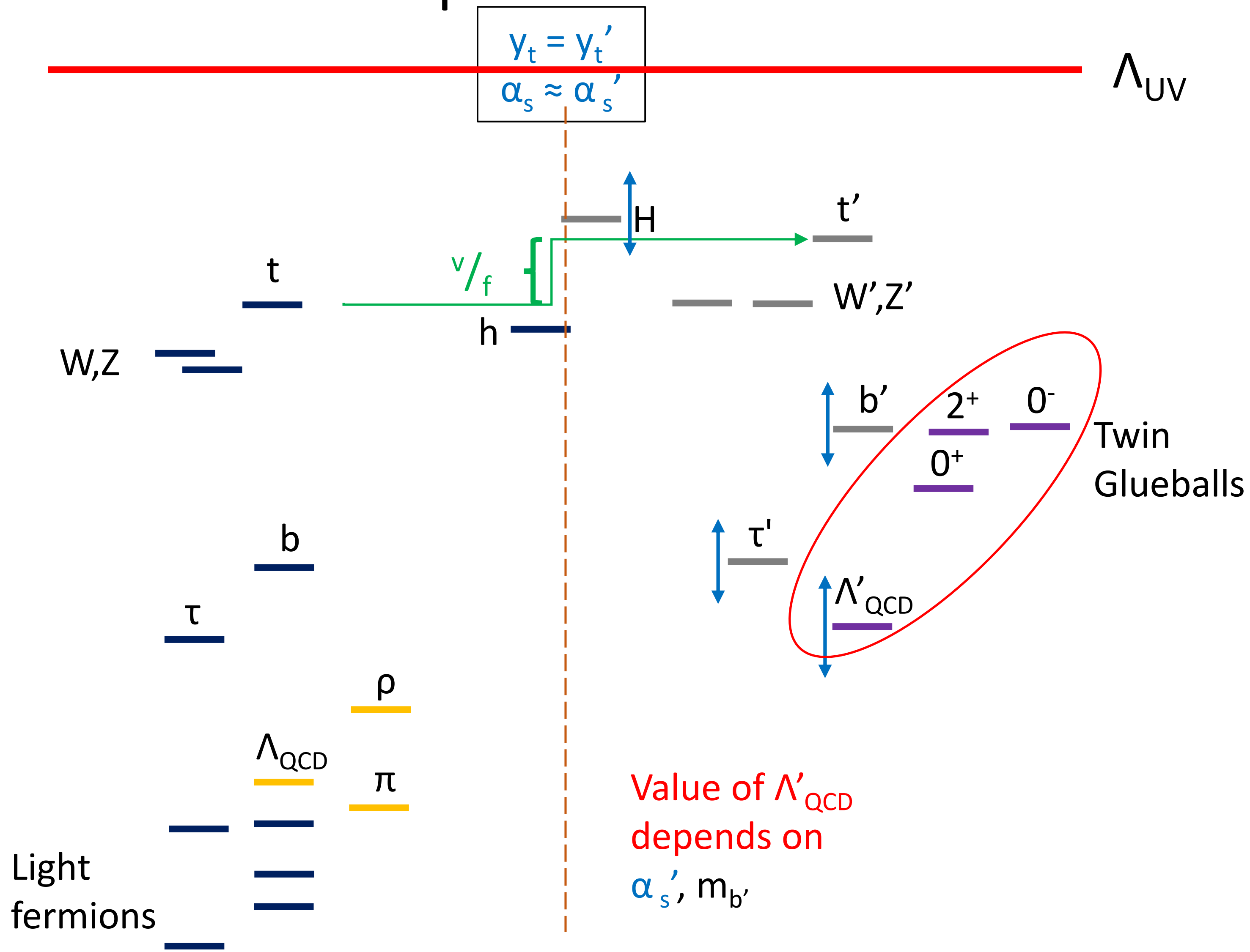
Others?

Spectrum

arXiv:1501.05310 Craig,Katz,MJS & Sundrum

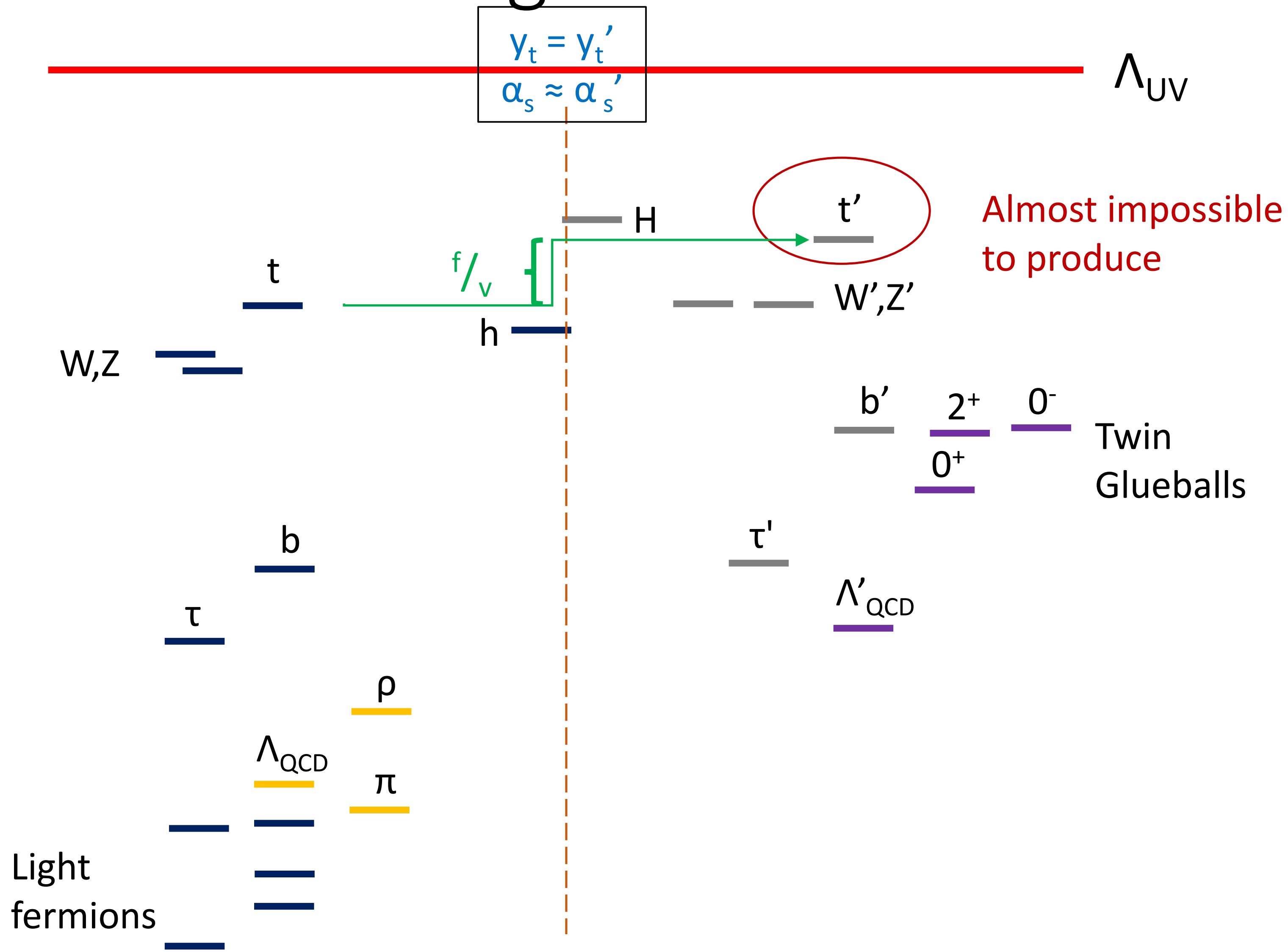


Spectrum



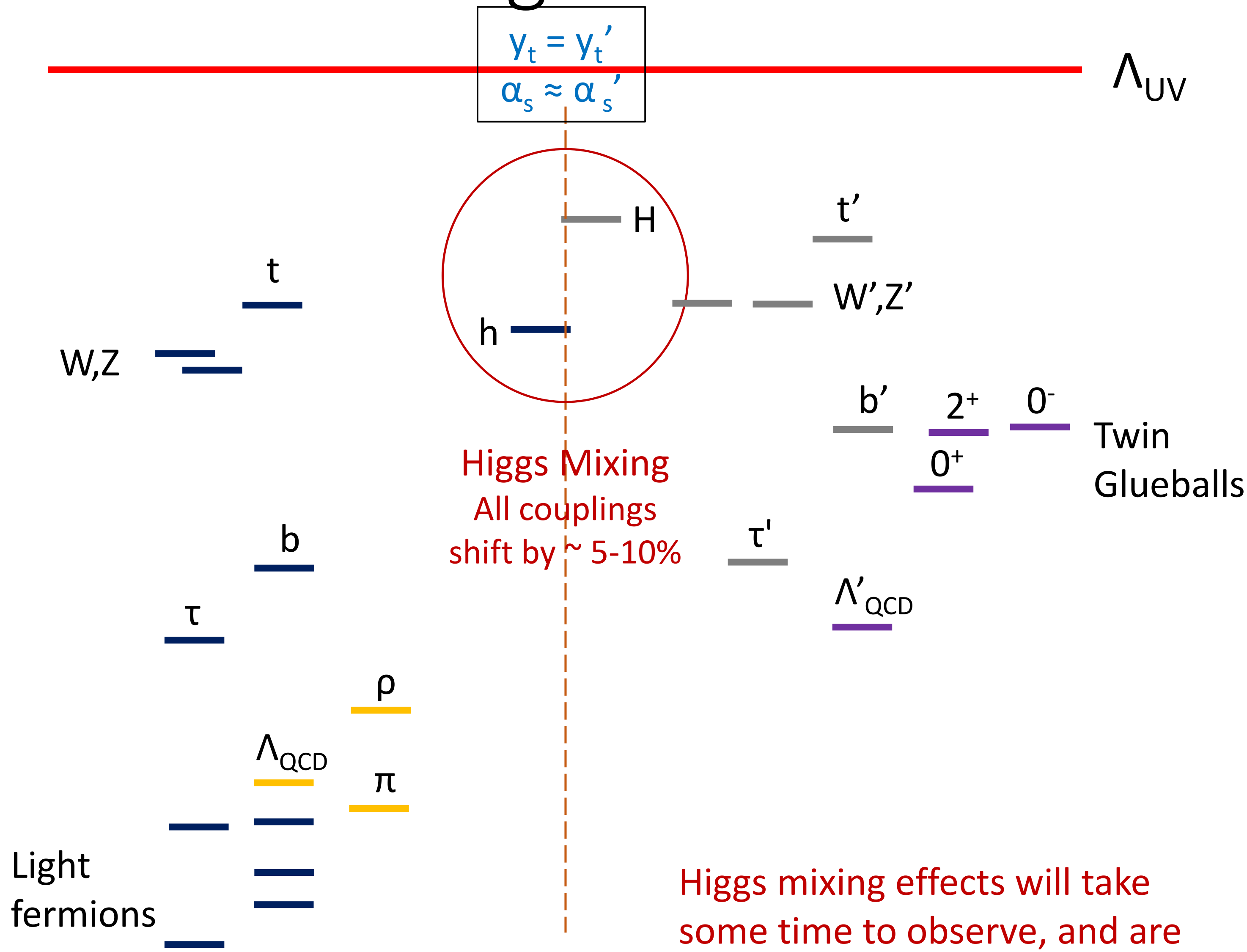
$y_t = y_t'$
$\alpha_s \approx \alpha_s'$
Λ_{UV}
H
t'
v/f
t
W',Z'
h
W,Z
b'
2^+
0^-
Twin
Glueballs
0^+
b
τ'
Λ'_{QCD}
τ
ρ
Λ_{QCD}
π
Value of Λ'_{QCD}
depends on
α_s', $m_{b'}$
Light
fermions

Signals



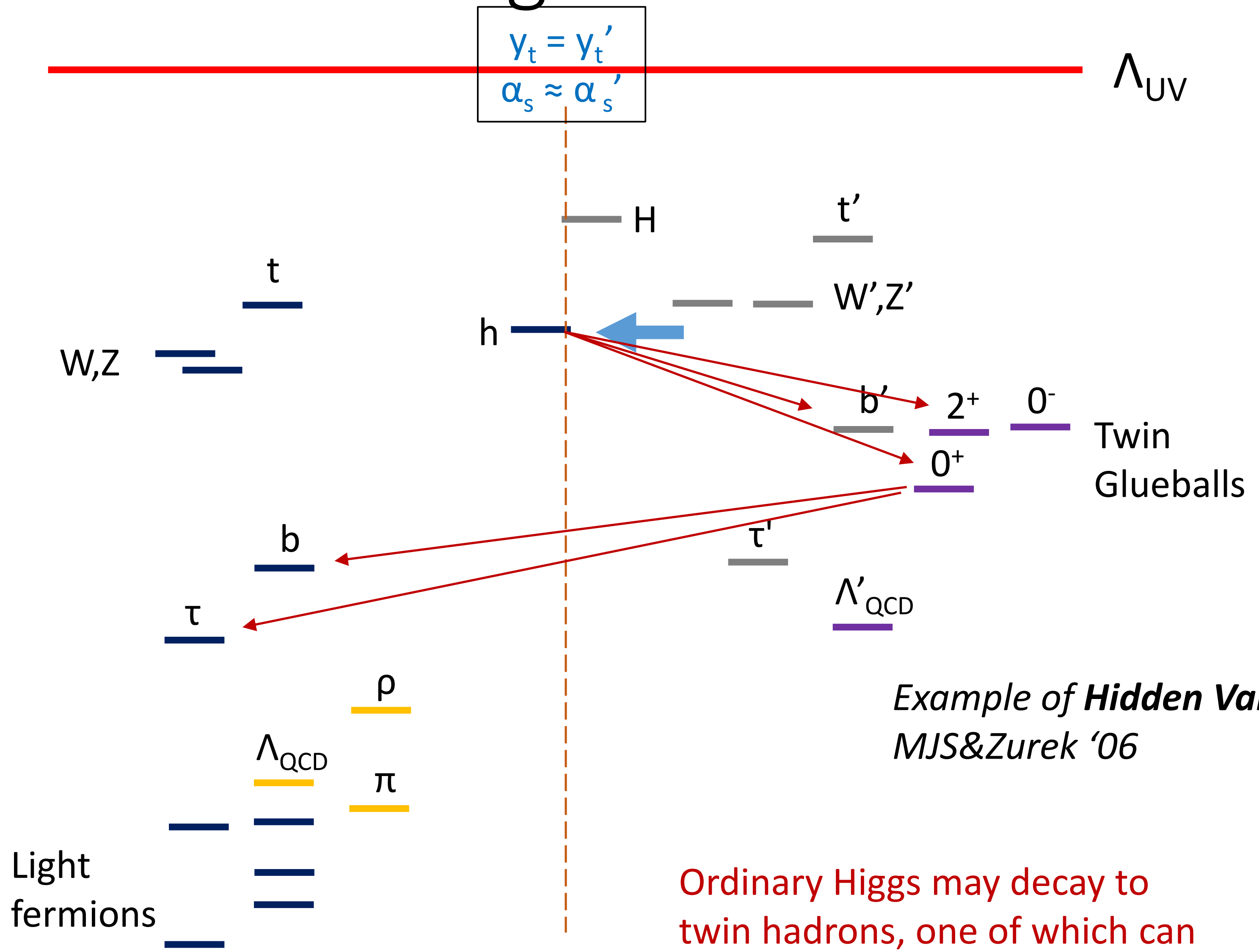
$y_t = y_t'$
$\alpha_s \approx \alpha_s'$
Λ_{UV}
t'
Almost impossible
to produce
H
f/v
t
h
W',Z'
W,Z
b'
2^+
0^-
Twin
Glueballs
0^+
b
τ'
τ
Λ'_{QCD}
ρ
Λ_{QCD}
π
Light
fermions

Signals



Higgs mixing effects will take some time to observe, and are generic to mixing h with a singlet

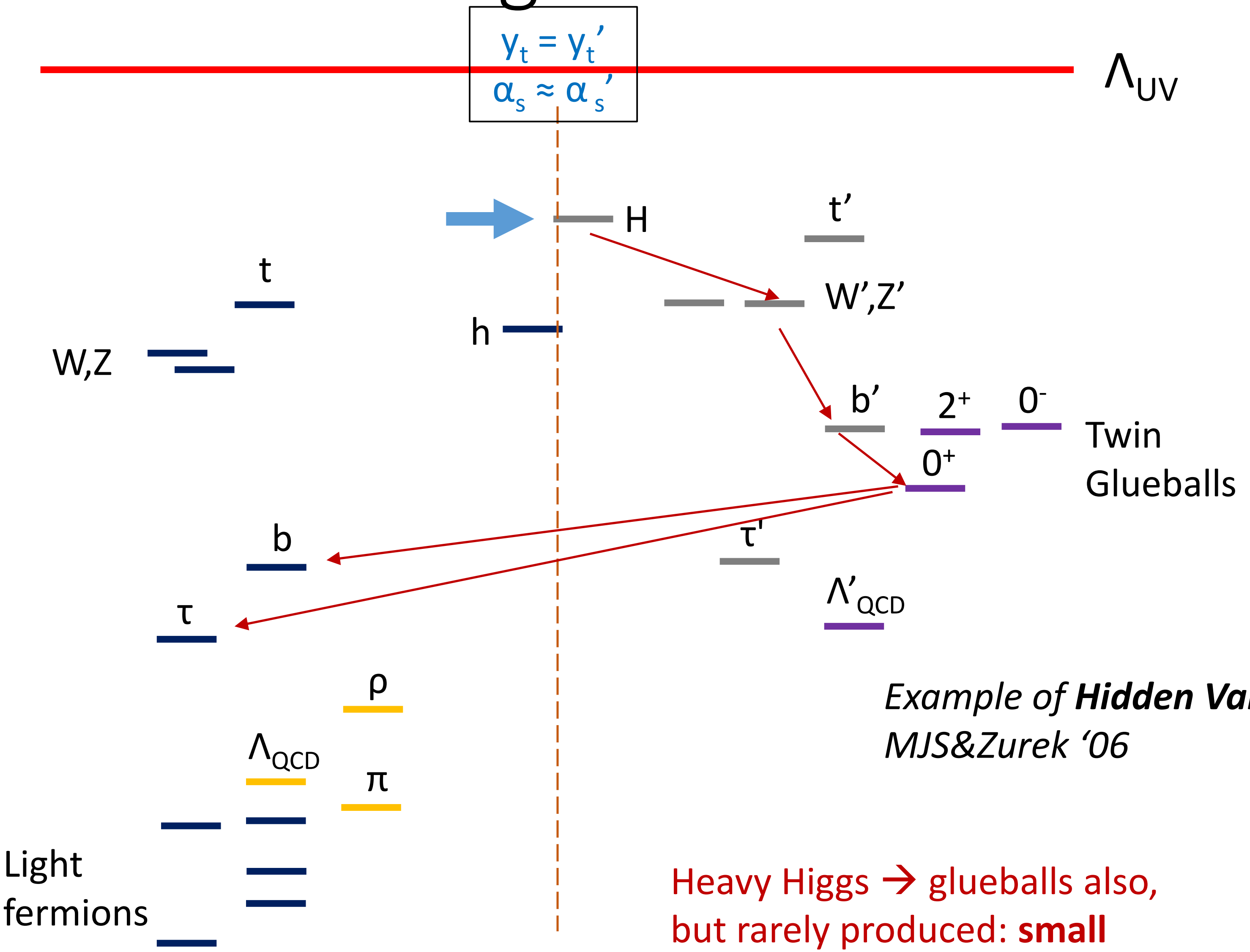
Signals



Example of ***Hidden Valley***
MJS&Zurek '06

Ordinary Higgs may decay to twin hadrons, one of which can produce a visible signal

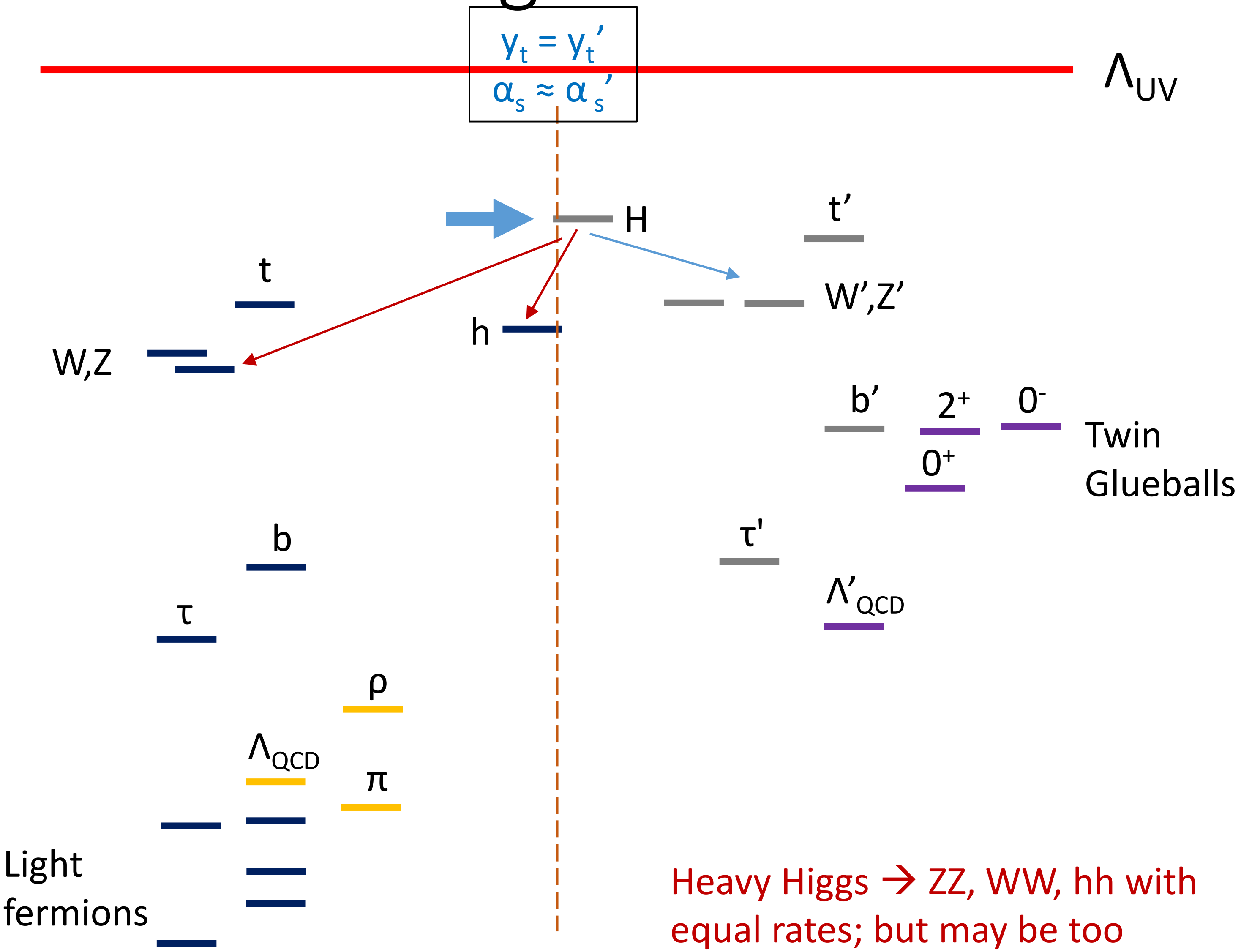
Signals



Example of ***Hidden Valley***
MJS&Zurek '06

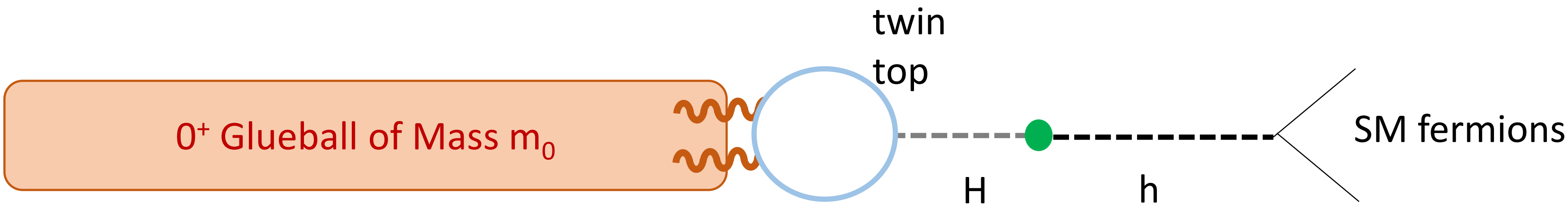
Heavy Higgs → glueballs also, but rarely produced: **small number of spectacular events?**

Signals



Heavy Higgs → ZZ, WW, hh with equal rates; but may be too heavy to discover soon

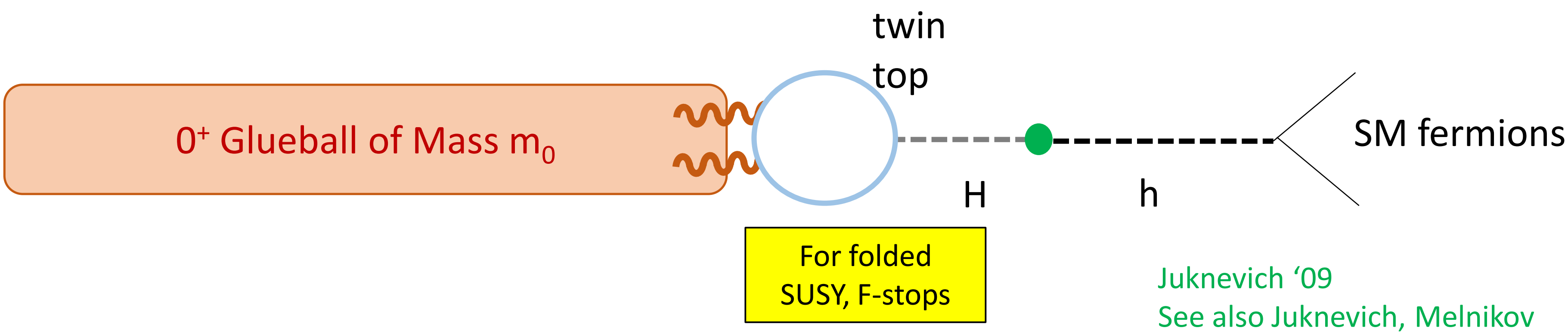
How 0^+ Twin Glueballs Decay



Juknevich '09
See also Juknevich, Melnikov and MJS '09

- 0^+ Glueball mixes with H and therefore with h
- Can decay to anything that a Higgs of mass m_0 would decay to:
  - Mainly heavy flavor fermions
  - Gauge bosons all suppressed at small m_0
- All heavy glueballs decay
  - to light glueballs
  - or twin bottomonium
- All other light glueballs have extremely long lifetimes – invisible

How 0^+ Twin Glueballs Decay



Juknevich '09
See also Juknevich, Melnikov and MJS '09

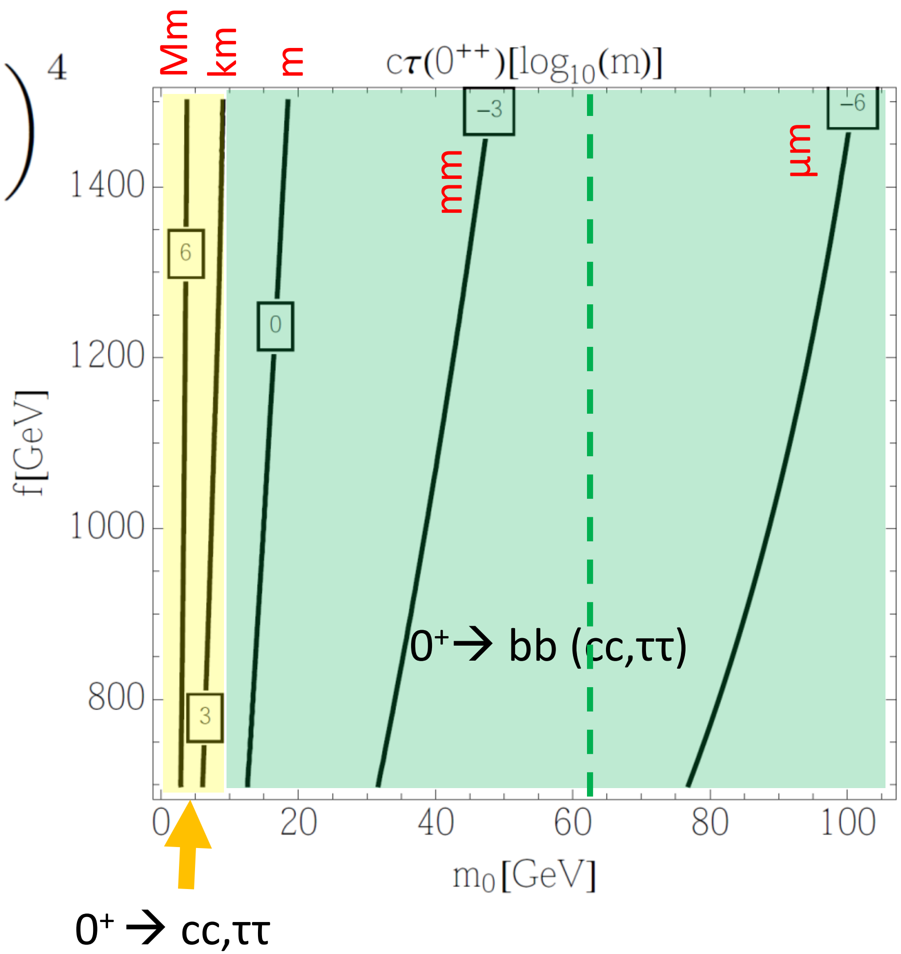
- 0^+ Glueball mixes with H and therefore with h
- Can decay to anything that a Higgs of mass m_0 would decay to:
  - Mainly heavy flavor fermions
  - Gauge bosons all suppressed at small m_0
- All heavy glueballs decay
  - to light glueballs
  - or twin bottomonium
- All other light glueballs have extremely long lifetimes – invisible

Glueball Lifetime

$$\Gamma_{G_{0+}\to YY} = \left(\frac{\hat{\alpha}_3 v \mathfrak{f}_0}{6\pi f^2 (m_h^2 - m_0^2)}\right)^2 \Gamma^{SM}_{h\to YY}(m_0^2)$$

$$c\tau_0 \sim 18\ \mathrm{m}\ \times \left(\frac{10\ \mathrm{GeV}}{m_0}\right)^7 \left(\frac{f}{750\ \mathrm{GeV}}\right)^4$$

- Most glueballs below 40 GeV decay displaced
- For small mass, only a small fraction of glueballs decay in the detector
- Detectable decays tend to be displaced jet pairs or tau pairs



Glueball Lifetime

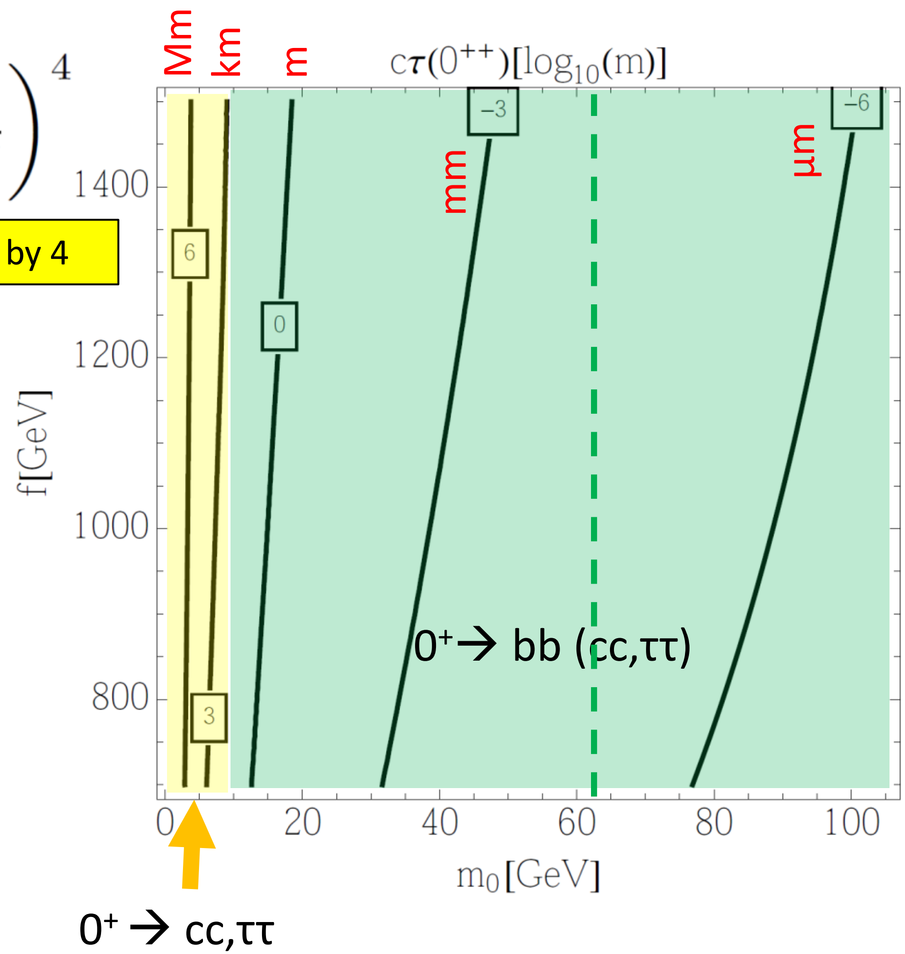
$$\Gamma_{G_{0+}\to YY} = \left(\frac{\hat{\alpha}_3 v \mathfrak{f}_0}{6\pi f^2(m_h^2 - m_0^2)}\right)^2 \Gamma^{SM}_{h\to YY}(m_0^2)$$

For folded SUSY, x ¼

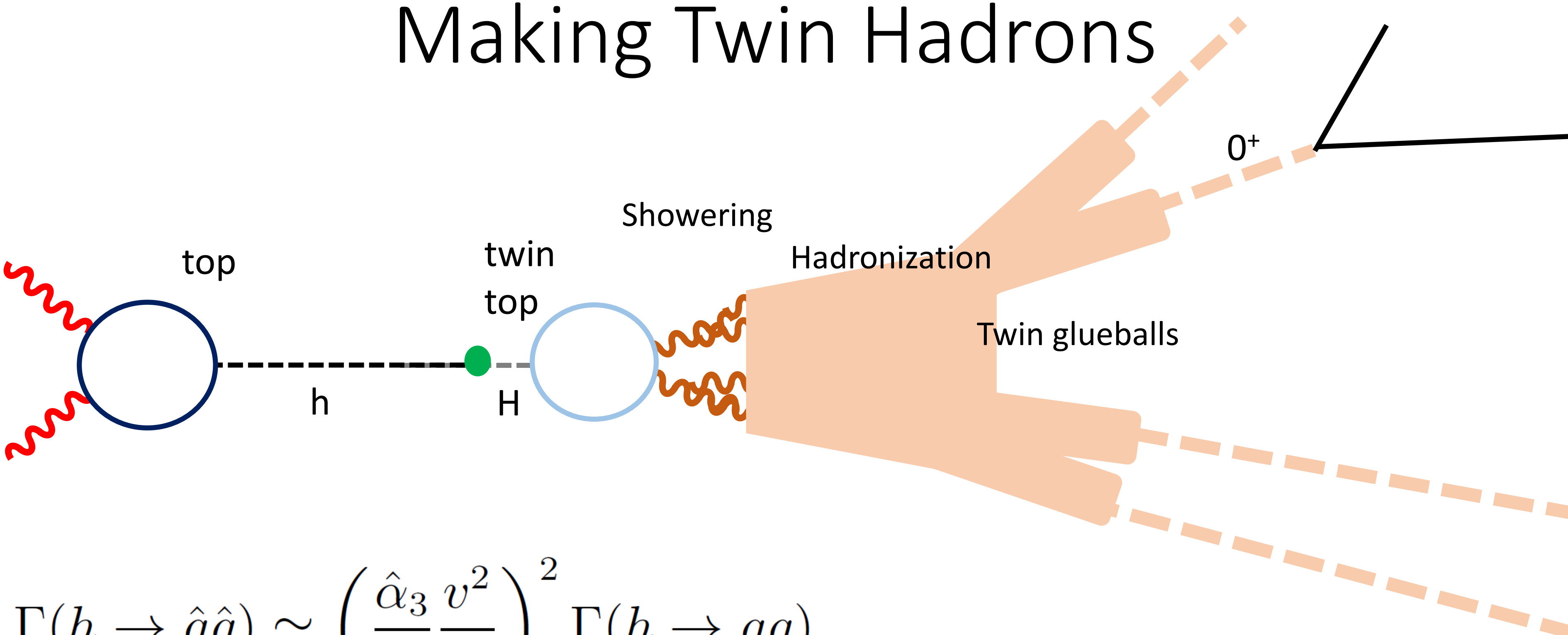
$$c\tau_0 \sim 18\ \mathrm{m}\ \times \left(\frac{10\ \mathrm{GeV}}{m_0}\right)^7 \left(\frac{f}{750\ \mathrm{GeV}}\right)^4$$

For folded SUSY, multiply by 4

- Most glueballs below 40 GeV decay displaced
- For small mass, only a small fraction of glueballs decay in the detector
- Detectable decays tend to be displaced jet pairs or tau pairs



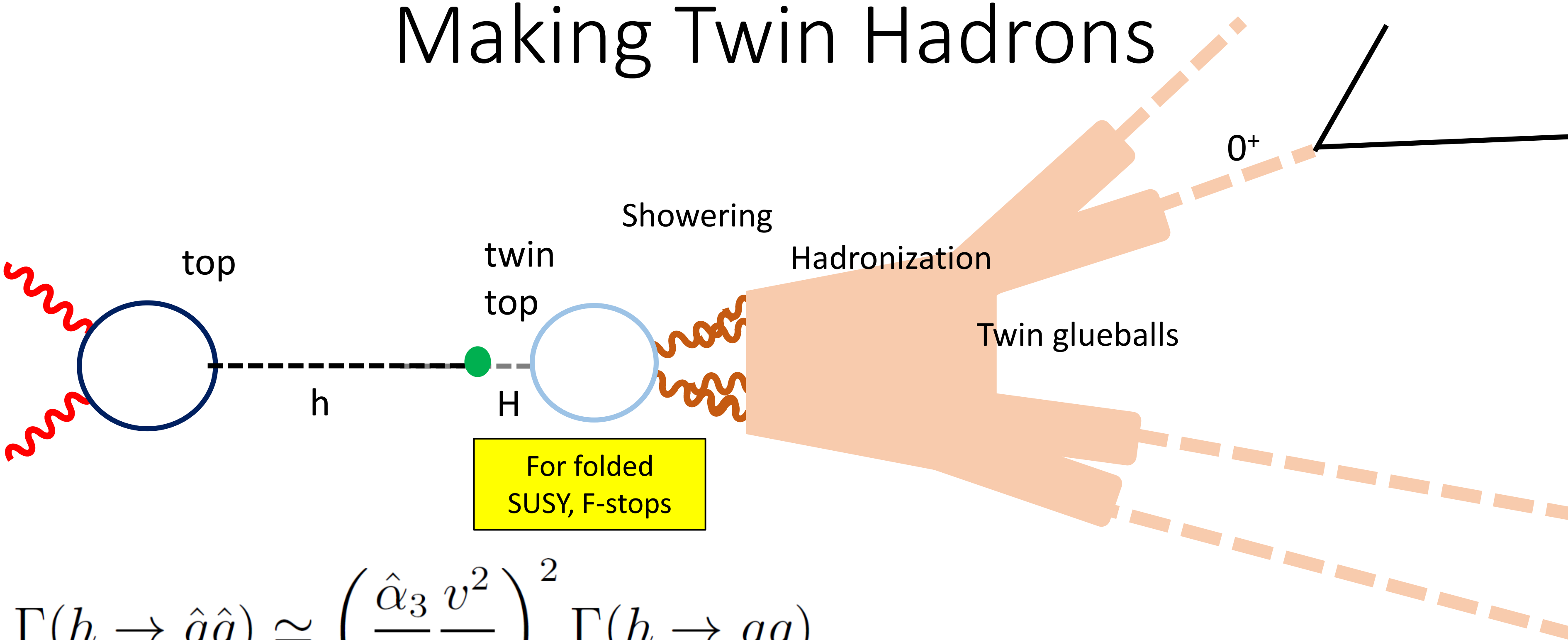
Making Twin Hadrons



$$\Gamma(h \to \hat{g}\hat{g}) \simeq \left(\frac{\hat{\alpha}_3}{\alpha_3}\frac{v^2}{f^2}\right)^2 \Gamma(h \to gg)$$

- Br (h→ twin gluons) ~ 0.1% for f = 3 v
- Enhanced by 60 $(y'_b/y_b)^2$ if h → twin bb

Making Twin Hadrons



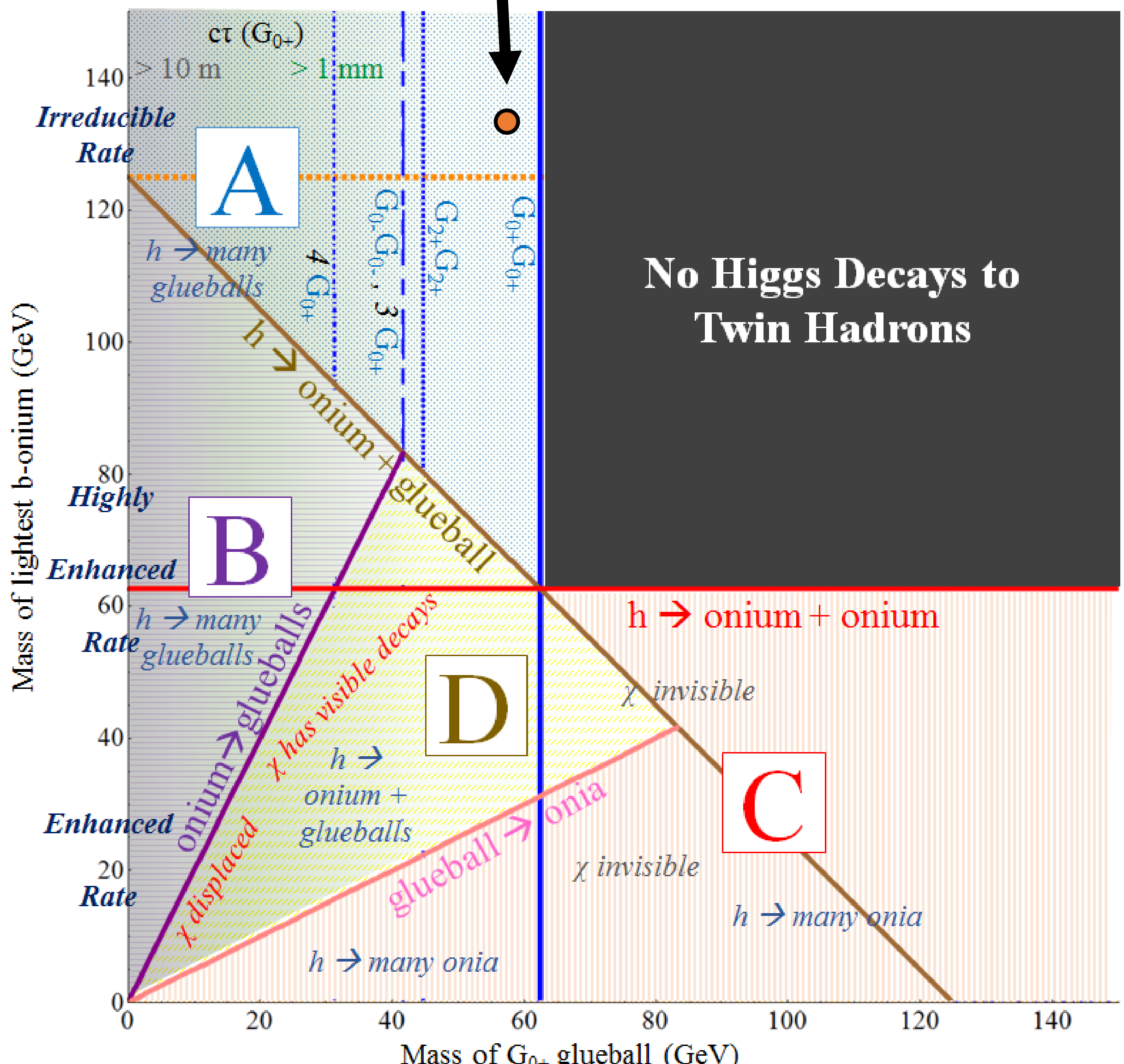
$$\Gamma(h \to \hat{g}\hat{g}) \simeq \left(\frac{\hat{\alpha}_3}{\alpha_3}\frac{v^2}{f^2}\right)^2 \Gamma(h \to gg)$$

For folded SUSY, x ¼

- Br (h→ twin gluons) ~ 0.1% for f = 3 v
- Enhanced by 60 $(y'_b/y_b)^2$ if h → twin bb

Non-SM h decays

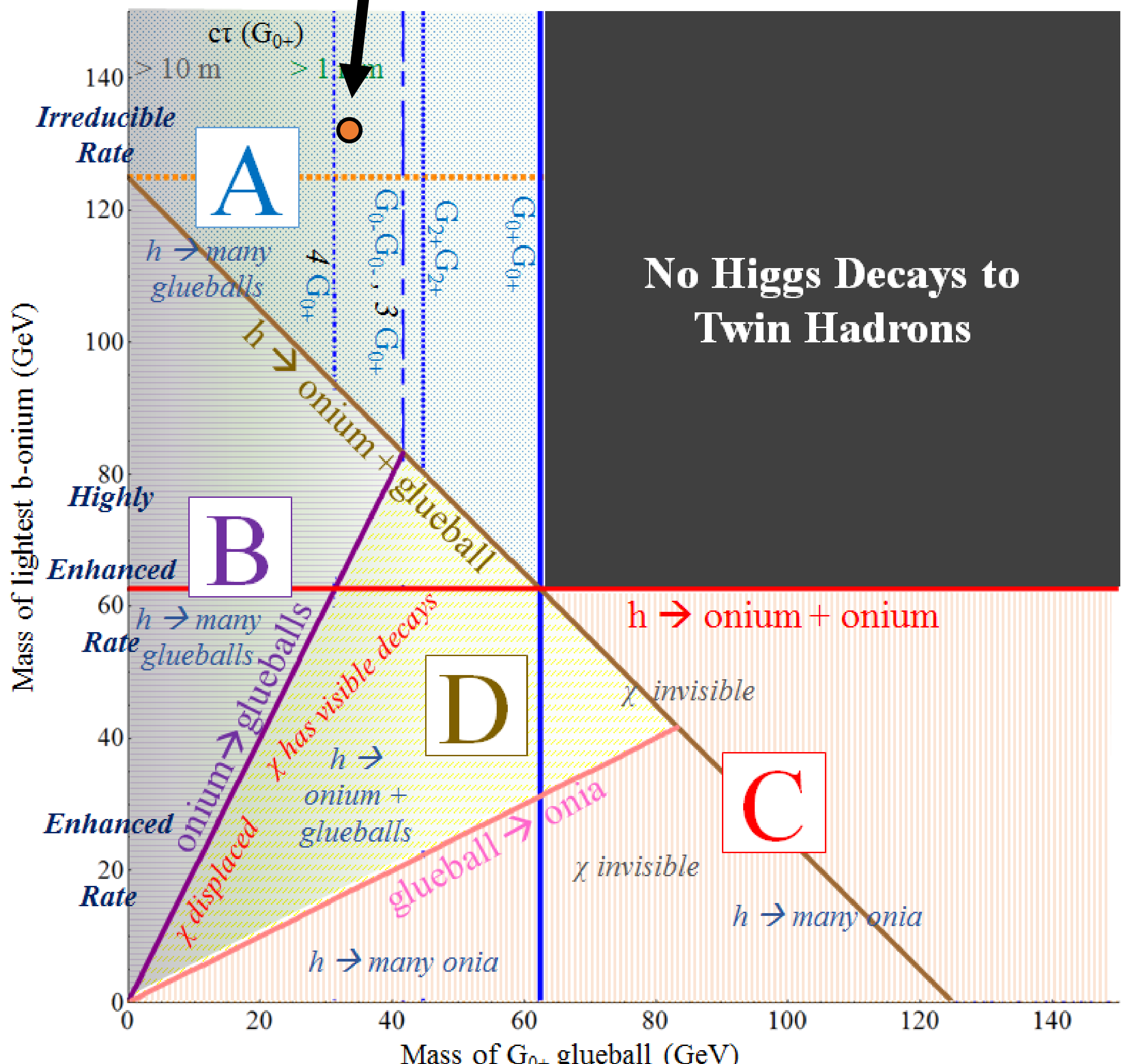
h → G_{0+} G_{0+} → bb bb ~ 10^{-3} level, bbττ ~ 10^{-4}, bbμμ ~ 10^{-6}



Non-SM h decays

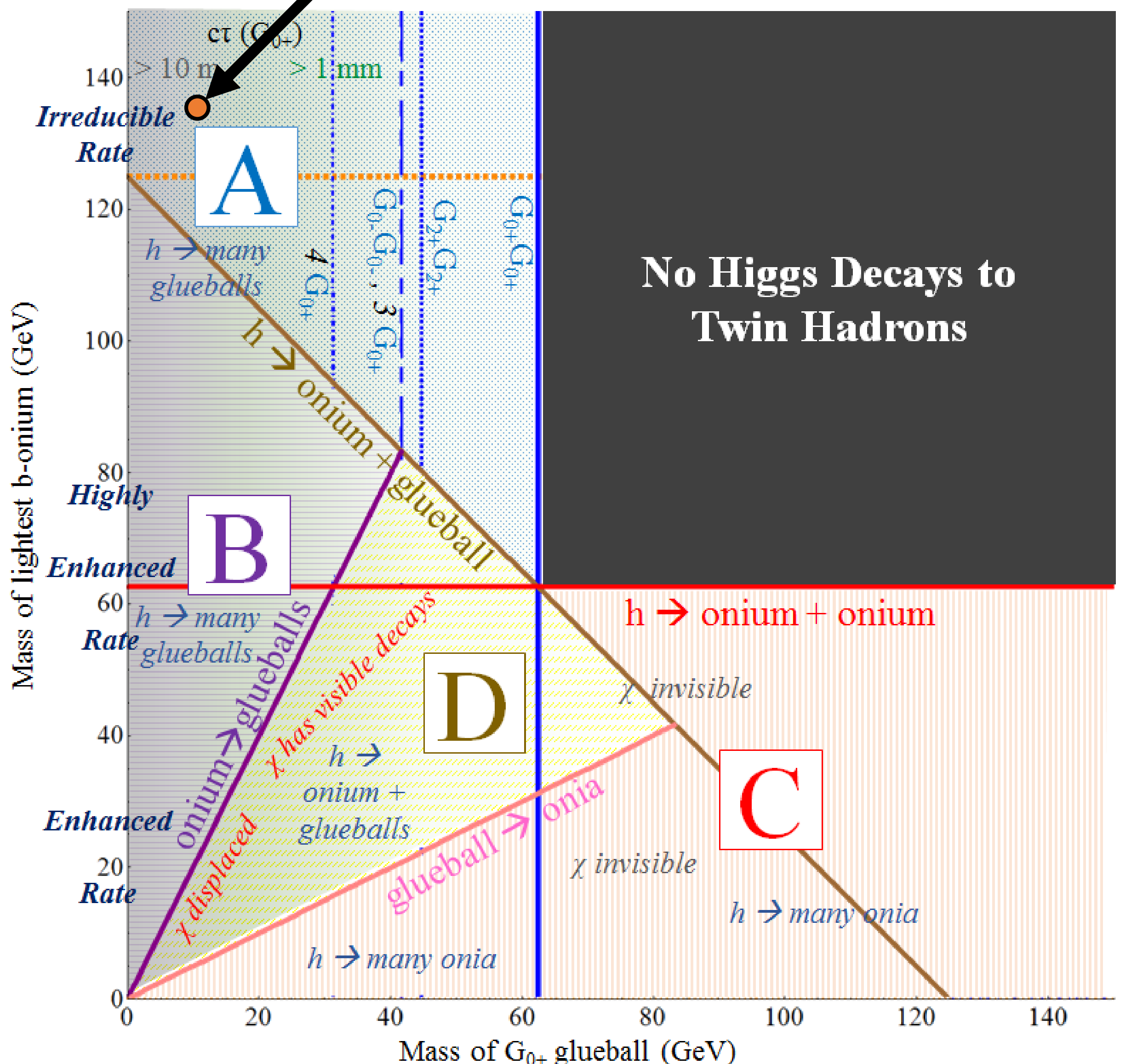
$h \rightarrow G_{0+} G_{0+}$

$\rightarrow$ bb bb ~ 10^{-3} level etc. DISPLACED by cm



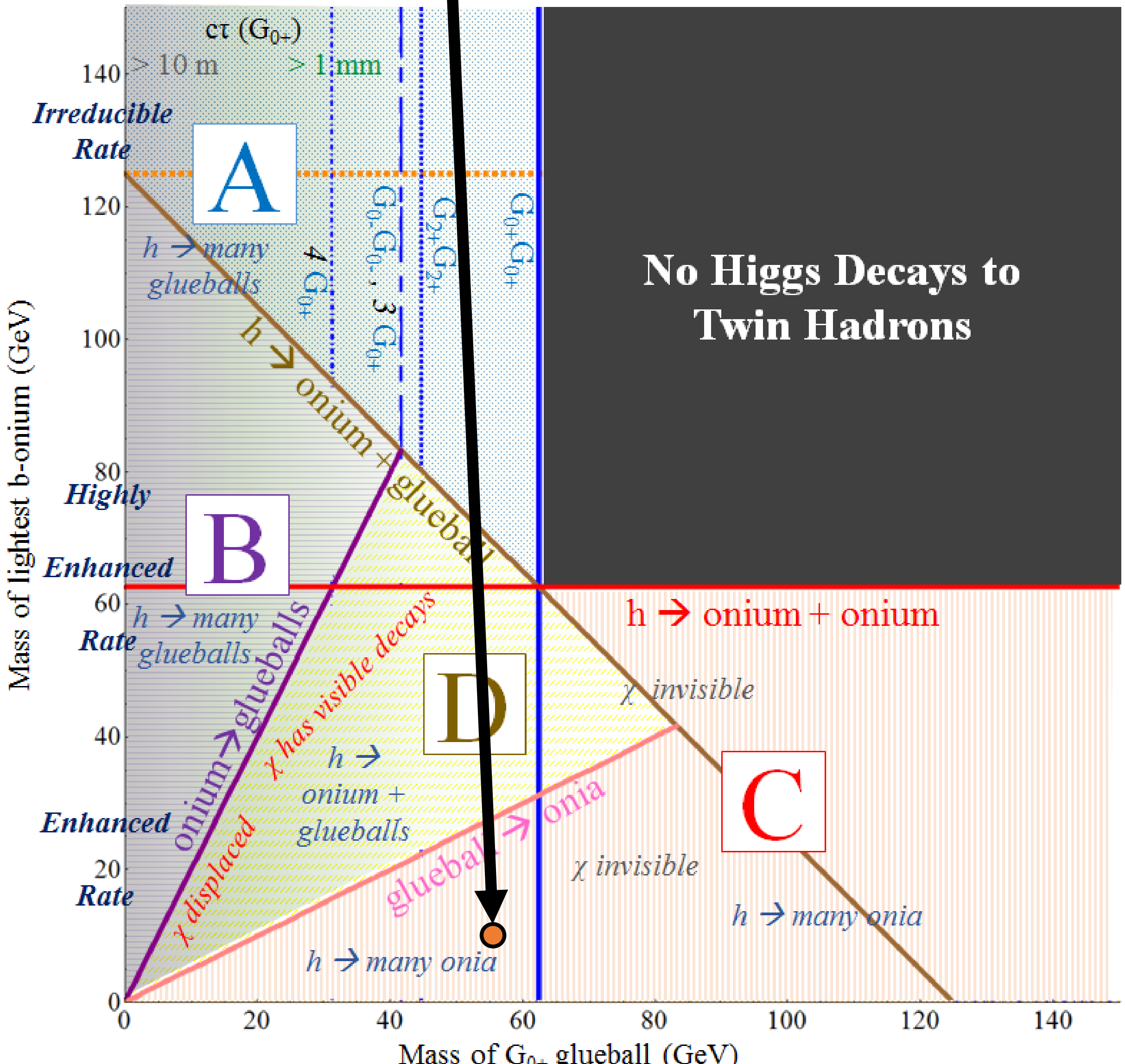
Non-SM h decays

h → many glueballs
→ bb + invisible ~ 10^{-4} (?) DISPLACED by meters



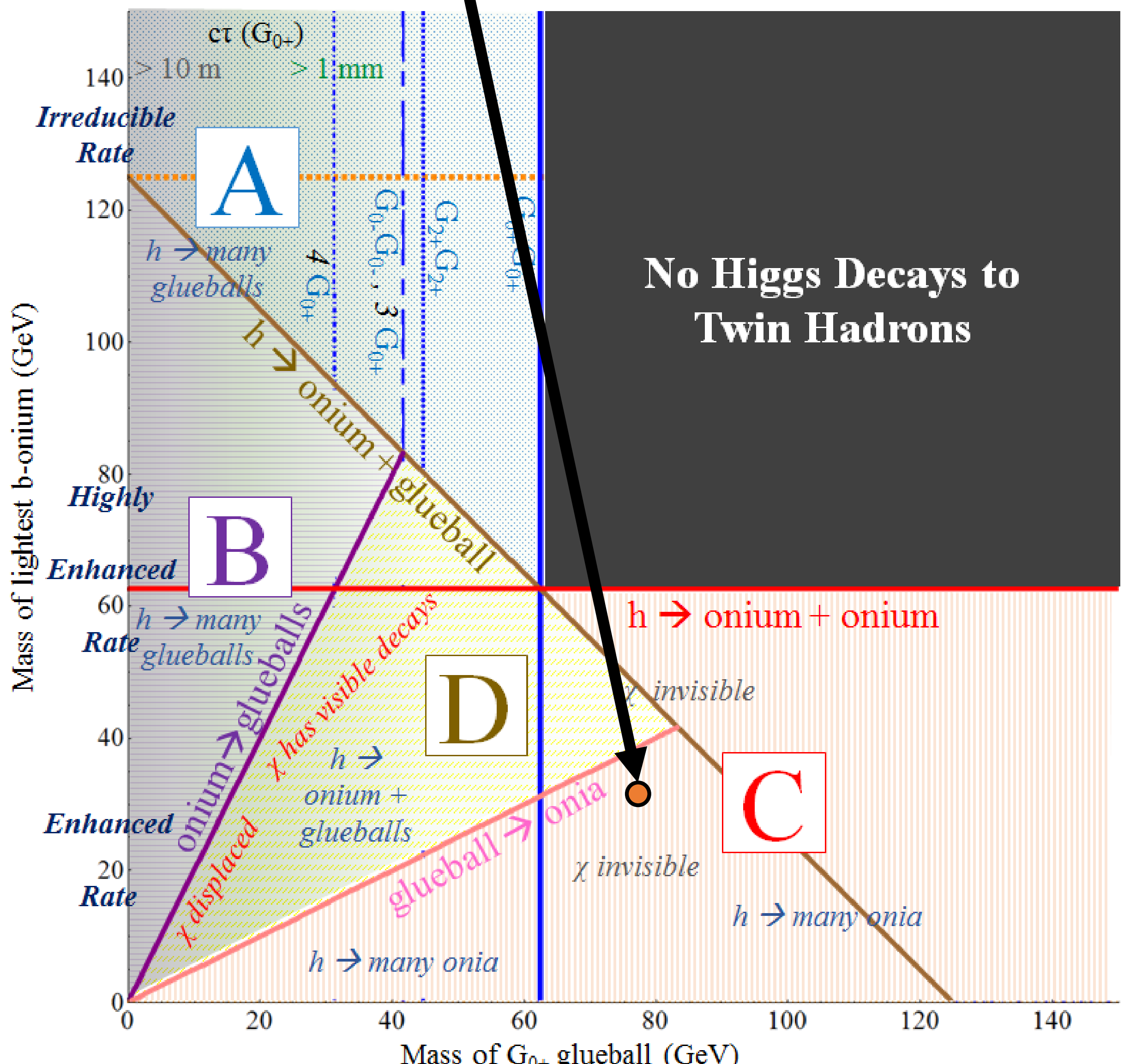
Non-SM h decays

h → twin bottomonia → invisible ~ 1%



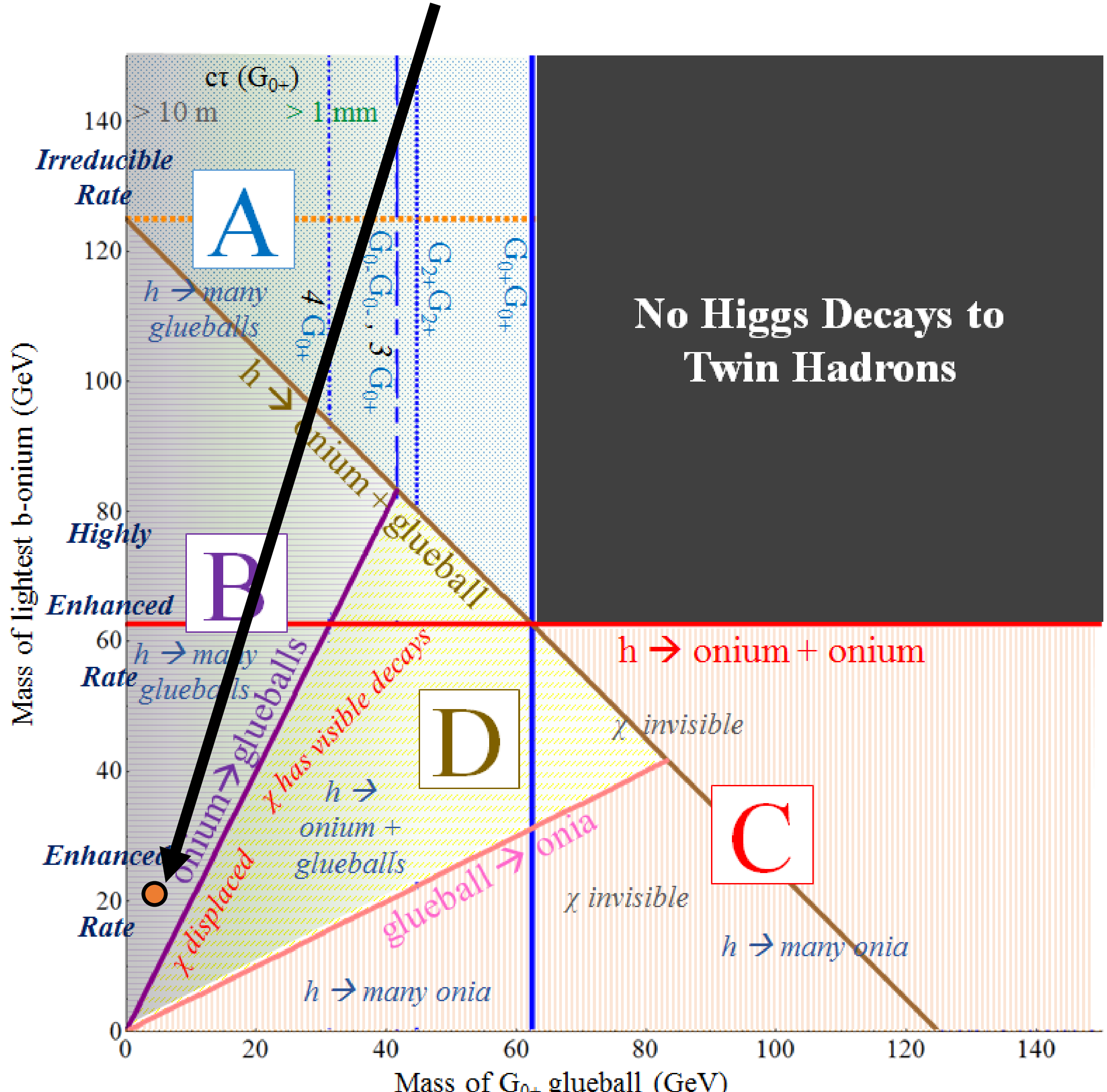
Non-SM h decays

h → twin bottomonia → invisible ~ 10%



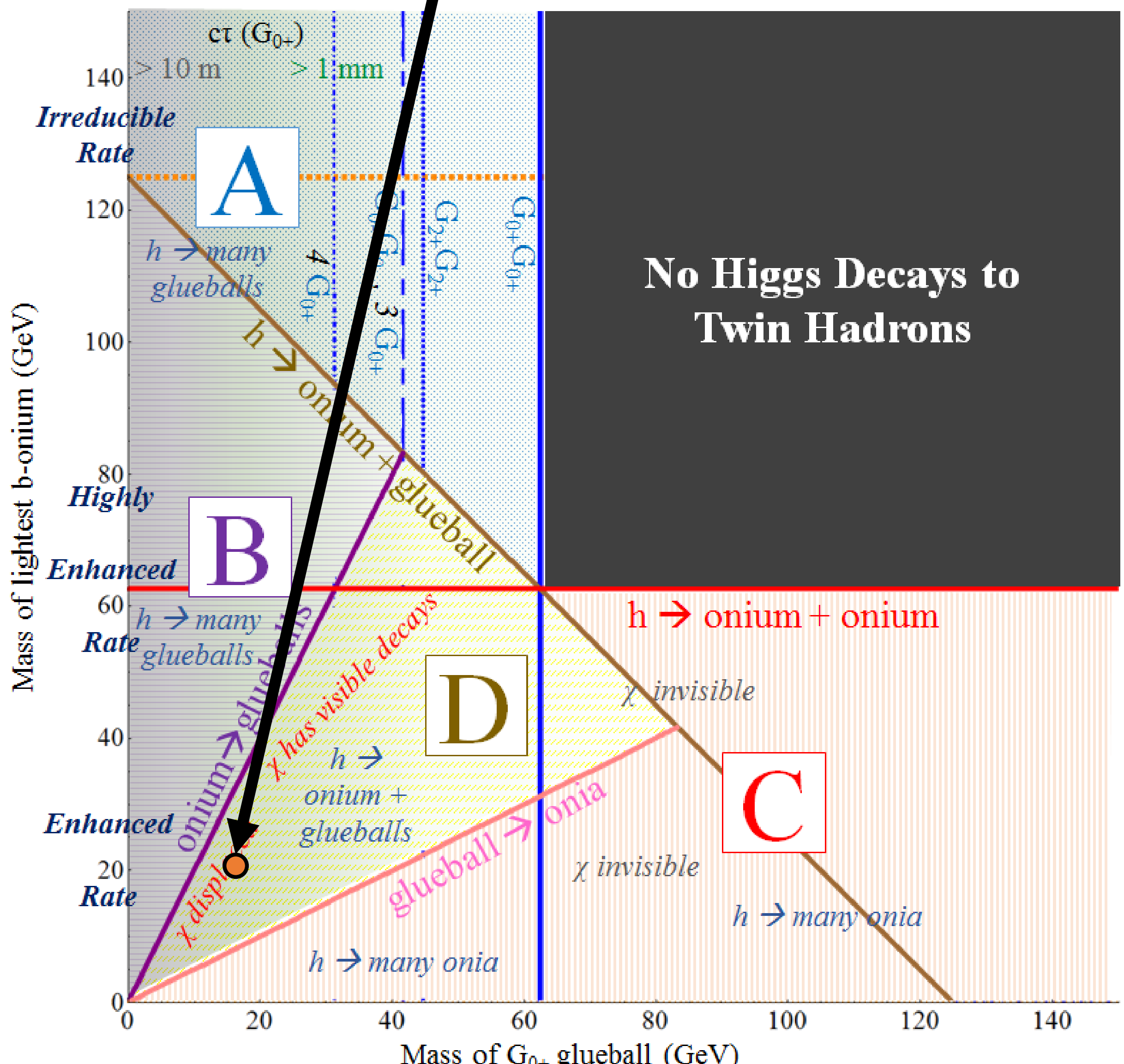
Non-SM h decays

h → many light glueballs, very long lifetimes
→ cc, ττ + invisible ~ 0.1% (?) DISPLACED by meters



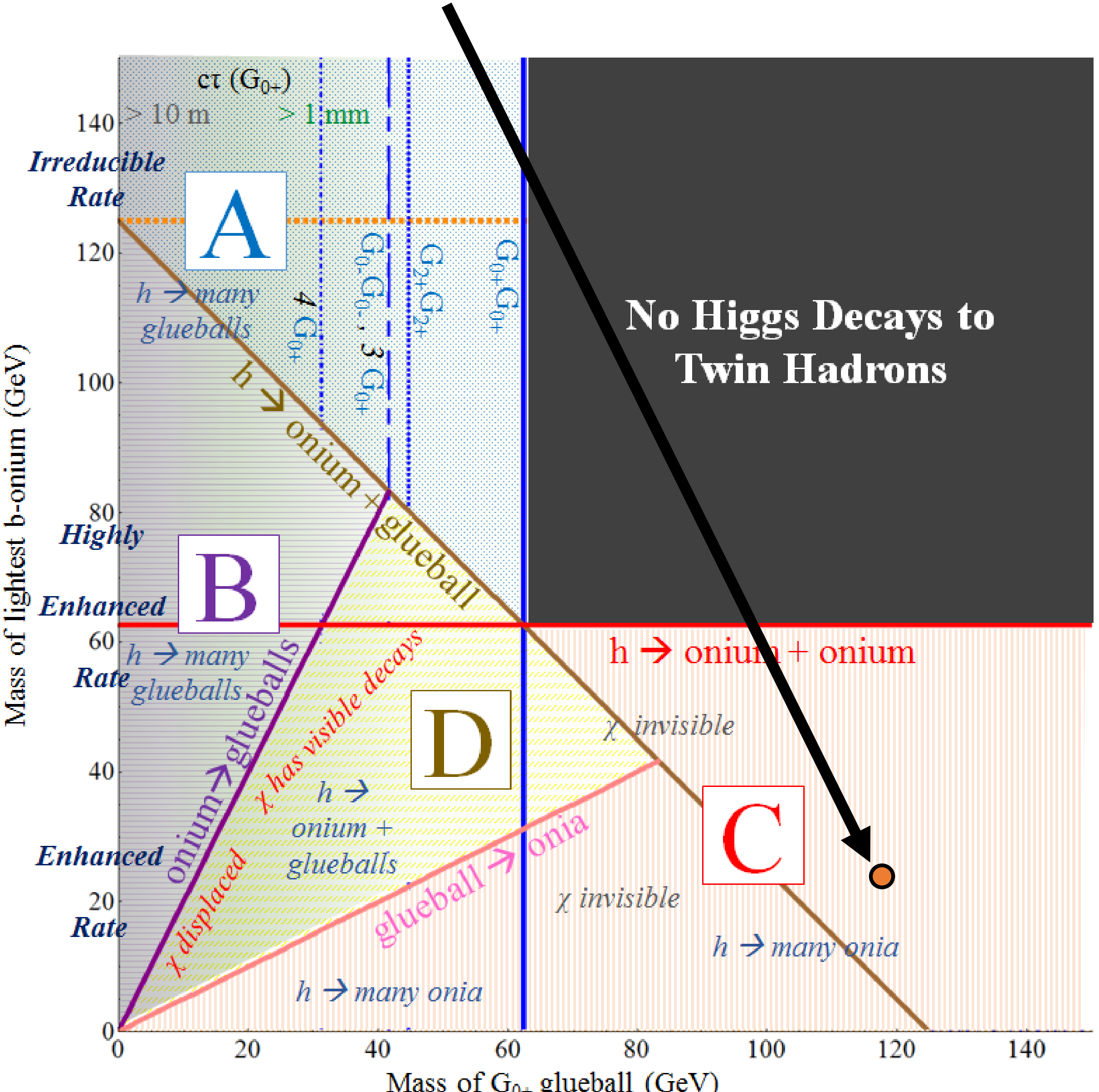
Non-SM h decays

h → G_{0+} + twin bottomonium, long lifetimes
→ bb + invisible ~ few % (?) DISPLACED cm
Rare: 2 displ. vertices with different mass, lifetimes



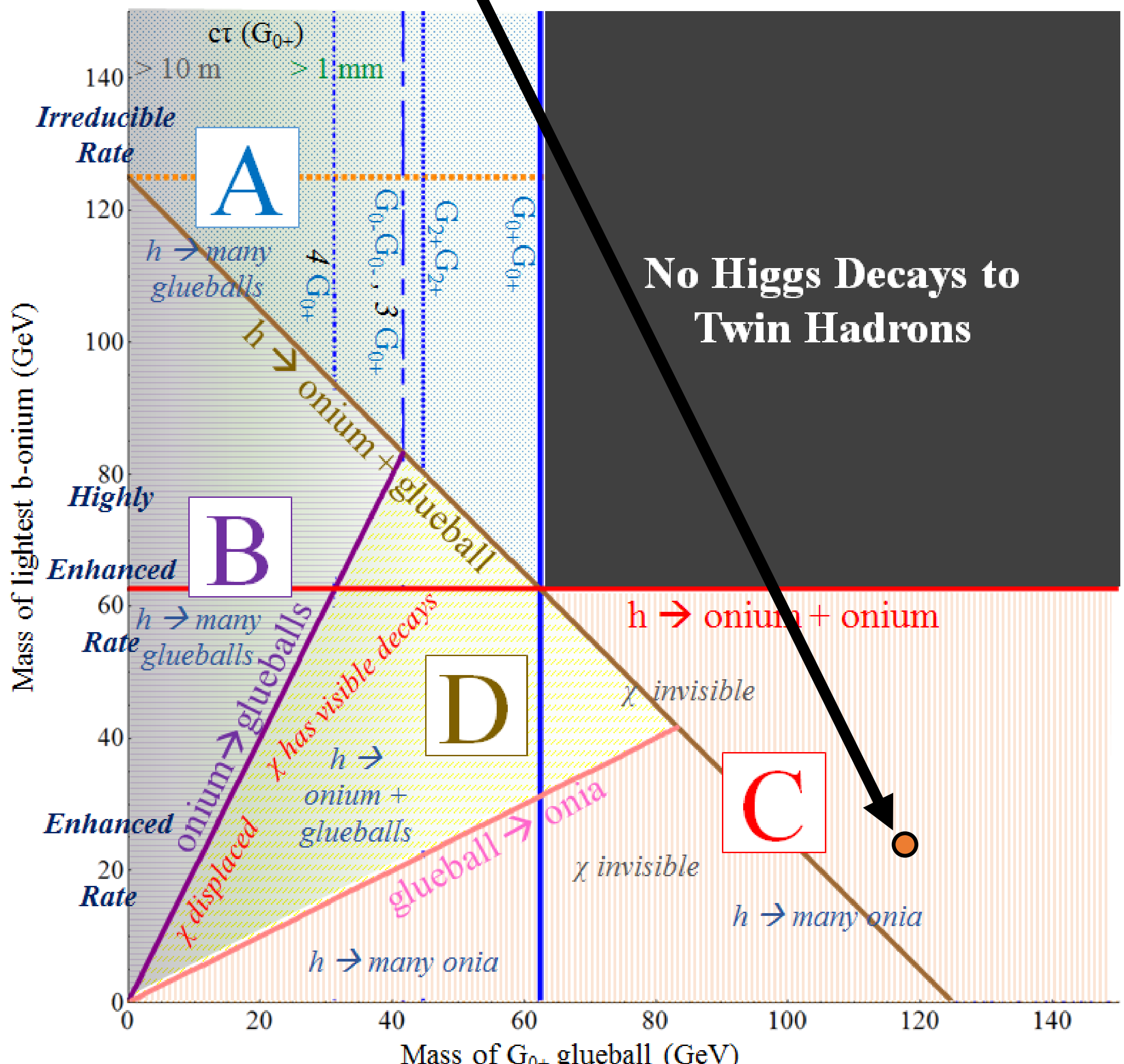
Non-SM h decays

If no light twin neutrinos,
h → twin bottomonia → bb + MET ~ 1% (?)



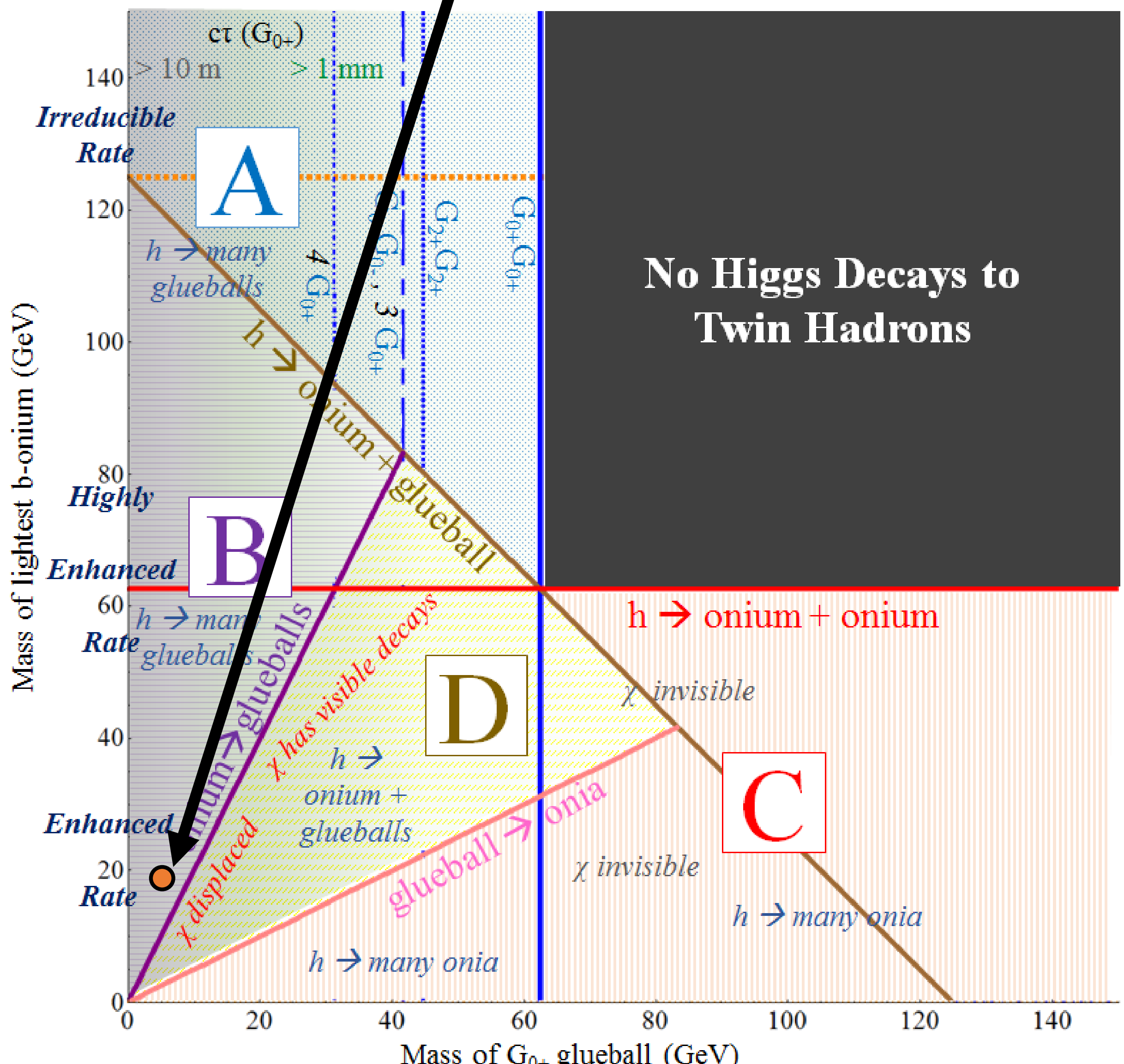
Non-SM h decays

If there's a massless twin photon with kinetic mixing,
h → twin bottomonia → γ + MET < 0.1%

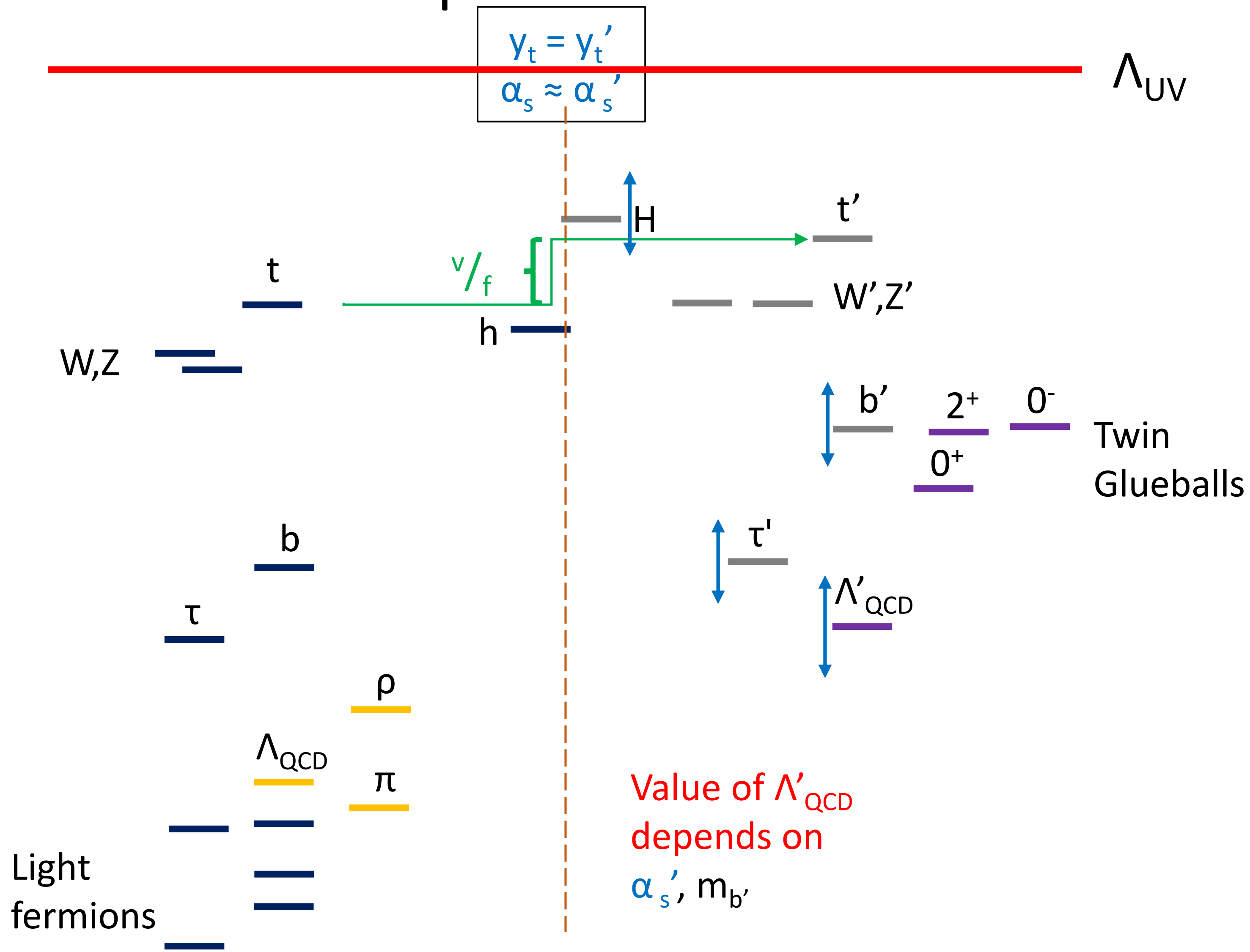


Non-SM h decays

If there's a **massive** twin photon with small kinetic mixing
h → twin glueballs → many twin γ's
→ one or more lepton-jets+ MET ~ 1% DISPLACED



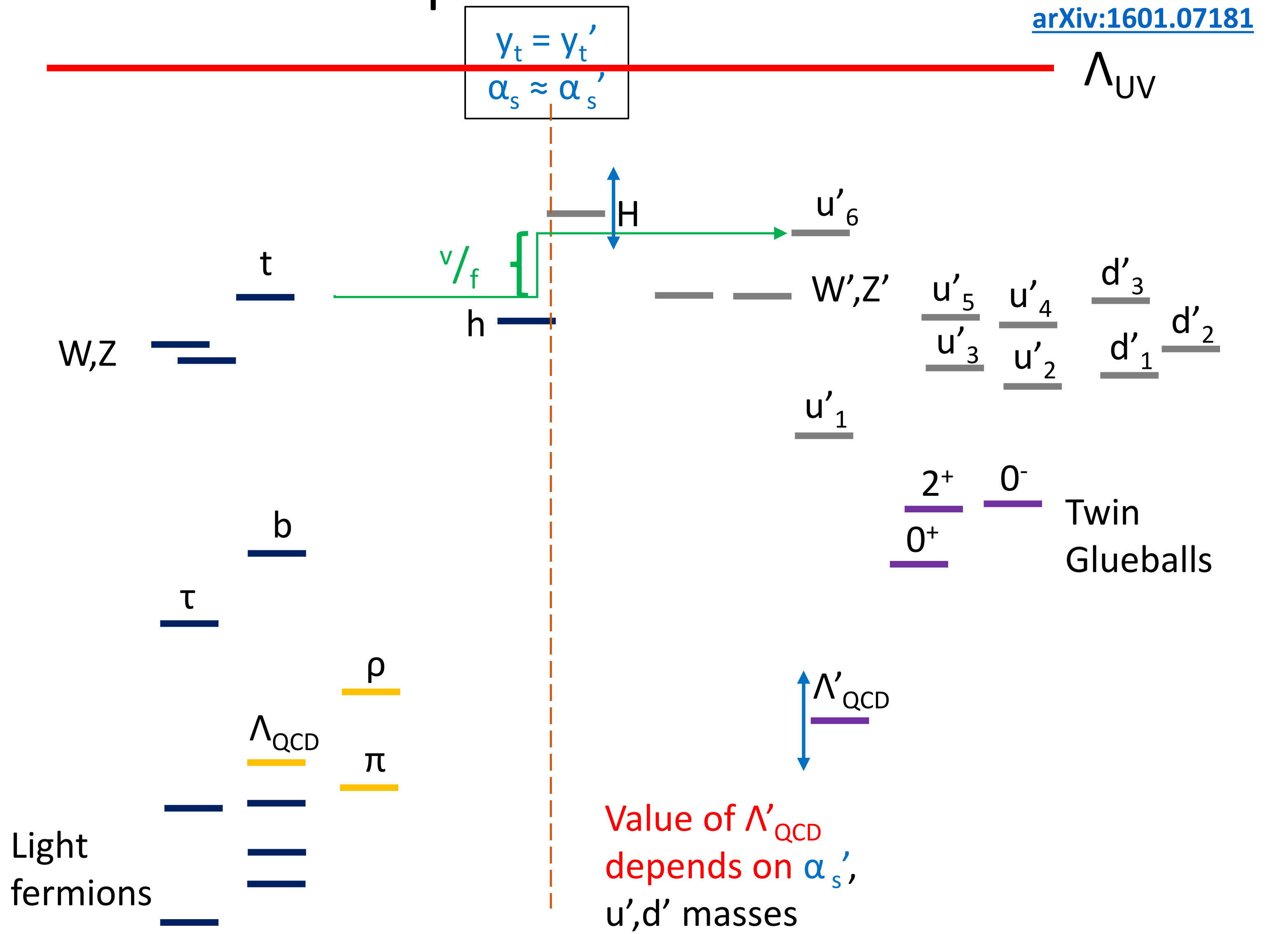
Spectrum



$y_t = y_t'$
$\alpha_s \approx \alpha_s'$
Λ_{UV}
H
t'
$^v/_f$
t
h
W',Z'
W,Z
b'
2^+
0^-
0^+
Twin
Glueballs
b
τ'
τ
Λ'_{QCD}
ρ
Λ_{QCD}
π
Light
fermions
Value of Λ'_{QCD}
depends on
α_s', $m_{b'}$

Spectrum

Craig, Knapen, Longhi & MJS
arXiv:1601.07181



Lower-confinement-scale "quirks":
Kang, Luty, Nasri hep-ph/0611322,
arXiv:0805.4642

Quirks

MJS + Zurek hep-ph/0604261
Juknevich, Melnikov arXiv 0903.0883
Chacko, Curtin, Verhaaren '15

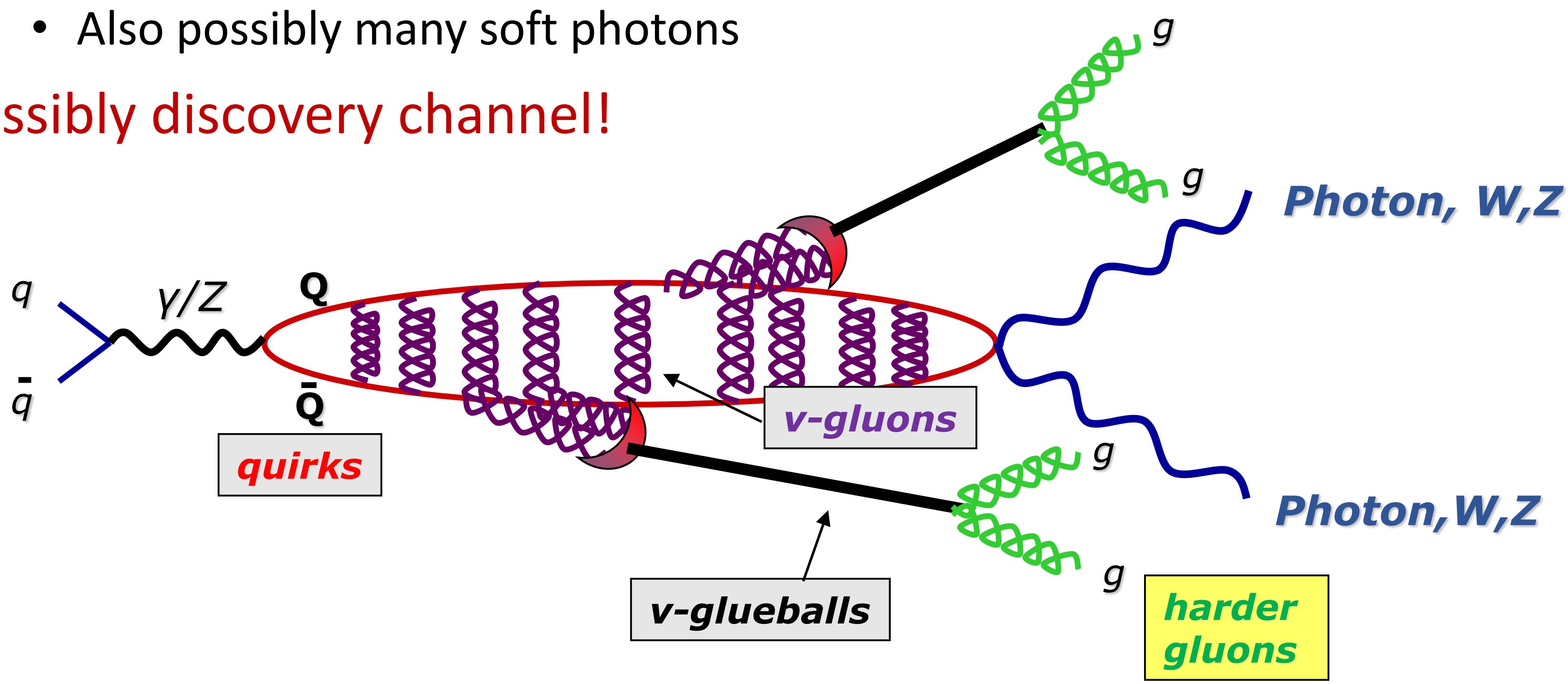
Folded SUSY: top-partners colorless but carry electroweak charges

Burdman, Chacko, Goh, Harnik '06

Production is small but not zero:

- Some glueballs + diboson resonance
- Also possibly many soft photons

Possibly discovery channel!



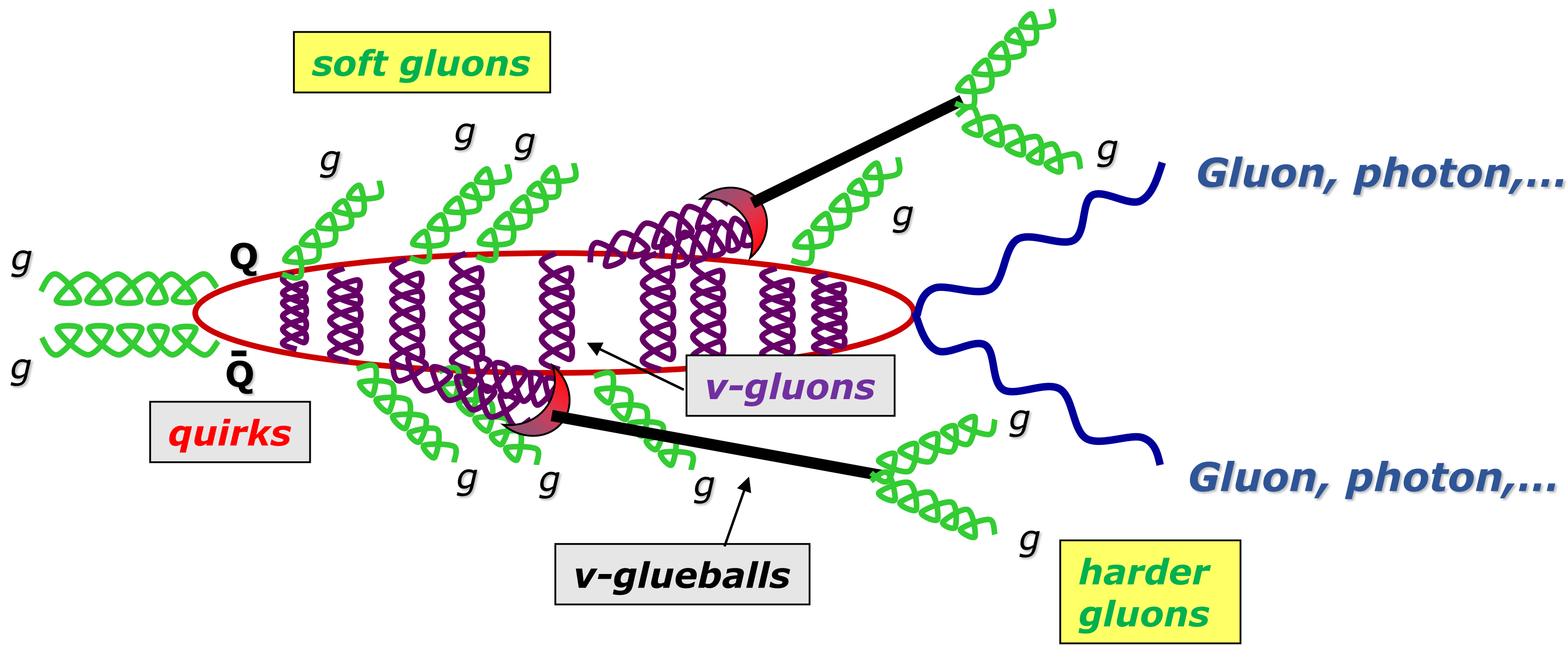
Colored Quirks could arise too

Lower-confinement-scale "quirks":
Kang, Luty, Nasri hep-ph/0611322,
arXiv:0805.4642

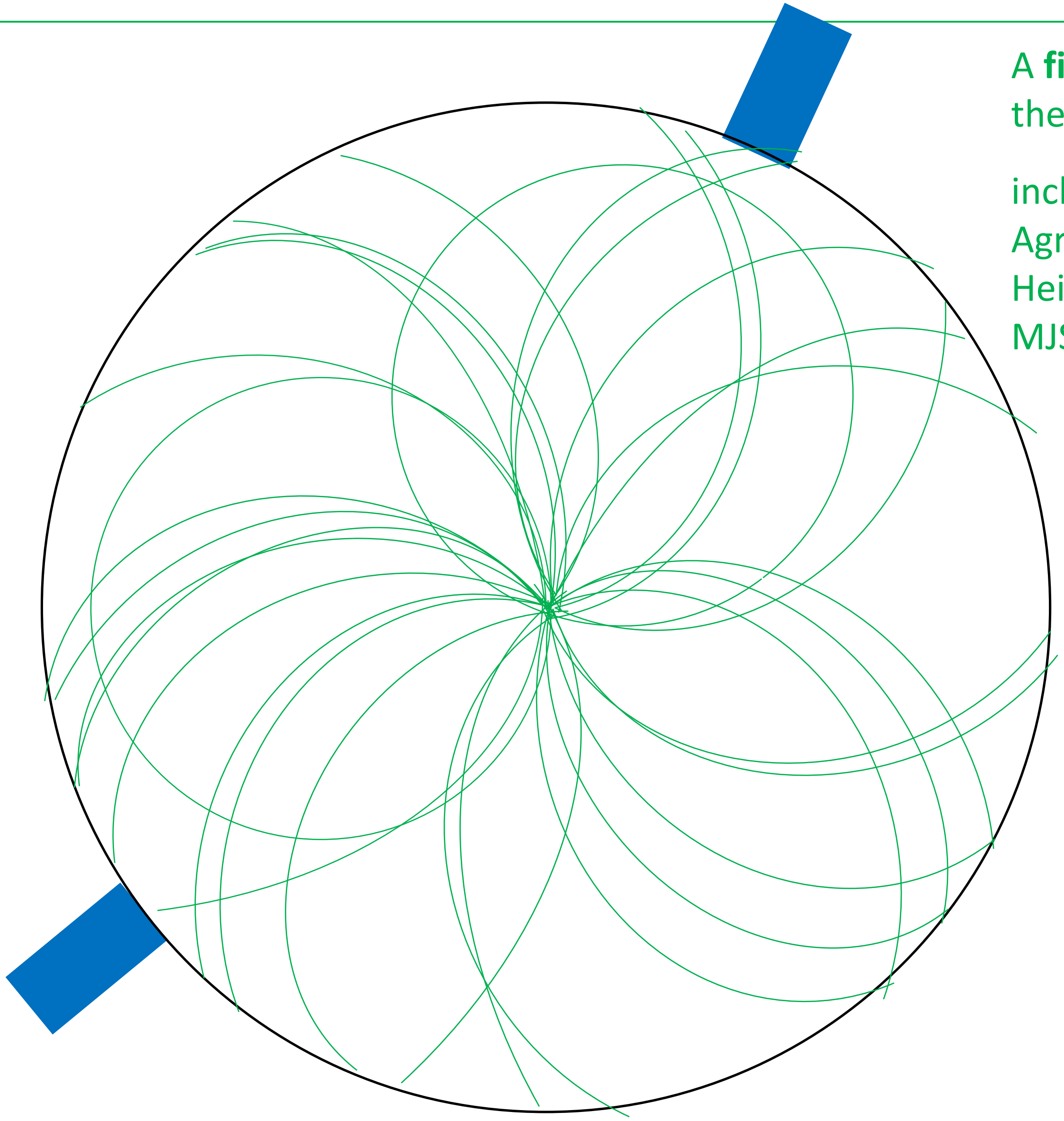
MJS + Zurek hep-ph/0604261
Juknevich, Melnikov arXiv 0903.0883
Chacko, Curtin, Verhaaren '15

Production much larger than electroweak case

Now large number of tracks and/or soft jets from soft gluons



375 GeV Scalar Quirks?



A **finite** set of theory/pheno papers

including Agrawal, Fan, Heidenreich, Reece & MJS **arXiv:1512.05775**

HV/DS and Diphoton bump X_S at 750 GeV?

Statistical fluke or a revolution?

- Why didn't you see something more clearly in Run 1?
- Why didn't CMS see it more clearly in Run 1?

Possible answers:

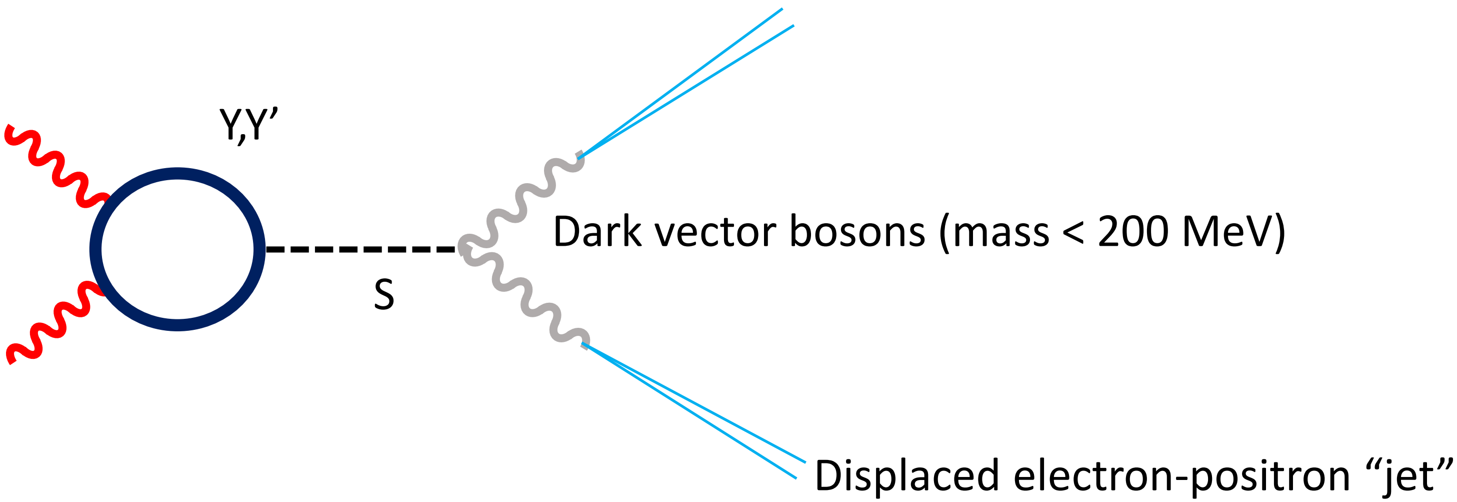
A **infinite** set of theory/pheno papers '16

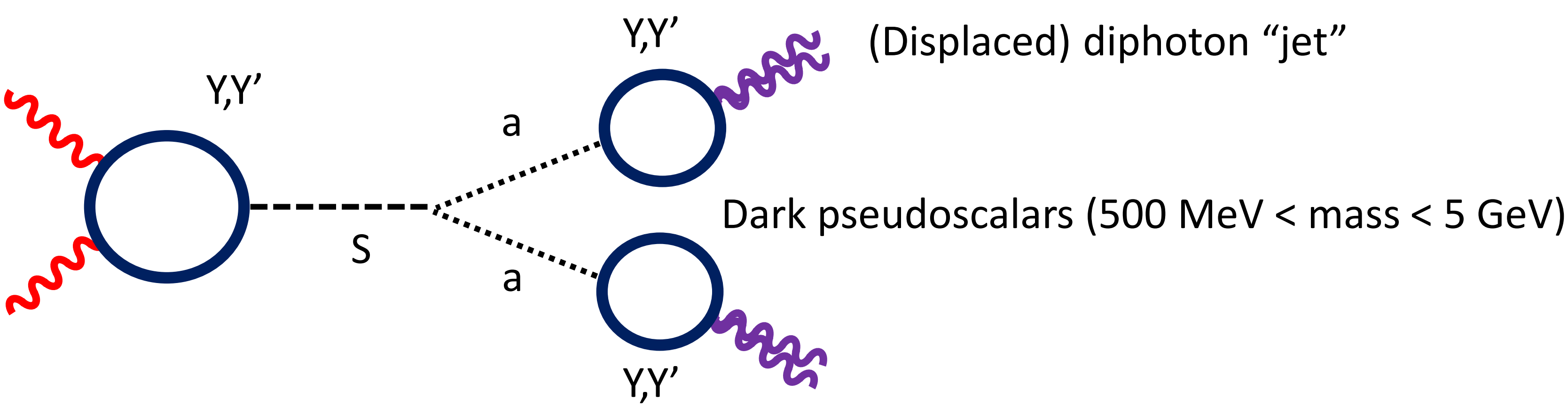
1. It's just a fluctuation.
   - My best guess. But still, lessons worth learning.
2. A signal, but enhanced & distorted by a fluctuation
   - If so, cross-section is smaller, perhaps width as well, than best fit
3. A signal, but the "photons" aren't actually photons
   - Precise definition of photons, choice of isolation, affects results
4. A signal, but the photons are in a cluttered environment
   - Choice of isolation affects results

Signal = two fake photons

A **finite** set of theory/pheno papers

including Agrawal, Fan, Heidenreich, Reece & MJS arXiv:1512.05775





Resonance → fake photons

- Lots of options here:
  - $S \rightarrow aa,\ a \rightarrow \gamma\gamma$ ($m_a \sim 0.1 - 10$ GeV)
  - $S \rightarrow aa,\ a \rightarrow \pi_0\pi_0$ ($m_a \sim 0.3 - 1$ GeV?)
  - $S \rightarrow a\gamma$
  - $S \rightarrow \gamma'\gamma',\ \gamma' \rightarrow ee$ ($m_{\gamma'} < 0.2$ GeV)
  - …

Scholtz talk

Volansky talk

A **finite** set of theory/pheno papers

including Agrawal, Fan, Heidenreich, Reece & MJS **arXiv:1512.05775**

- Typically fakes more convincing if lifetime *x* boost is macroscopic
- Poorer energy resolution ➔ wider than expected for narrow $\gamma\gamma$
- Sensitivity depends strongly on search methods, detector
  - Definition of photon
  - Photon isolation
  - Treatment of conversions
  - ECAL details

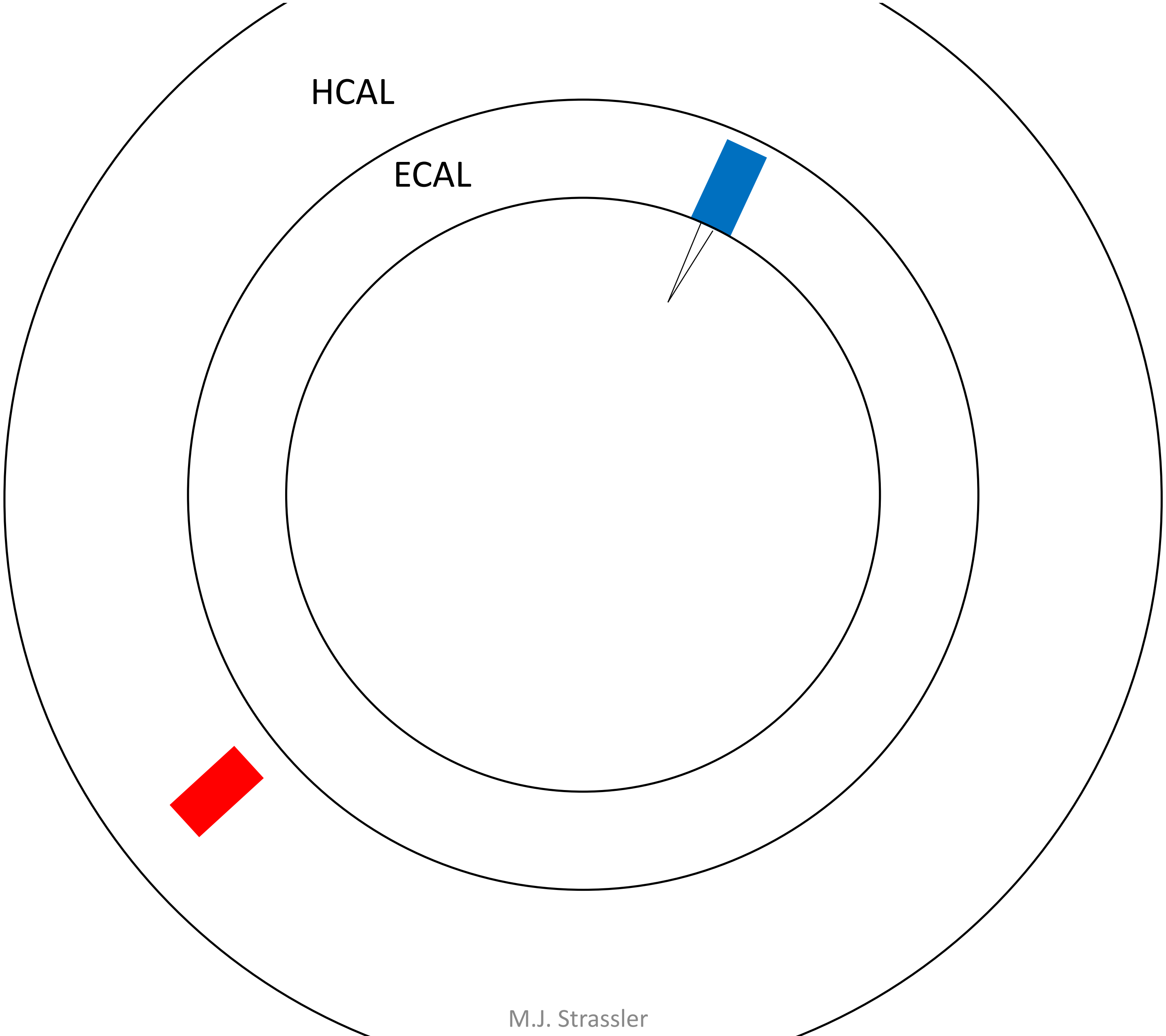
PLAUSIBLE??
Only the ATLAS/CMS photon experts know

Is This Plausible?

Only ATLAS/CMS photon experts know.

- Changes in isolation affect results
- Changes in how conversions are treated affect results
- Very sensitive to details of ECAL
  - CMS vs ATLAS?

An Opportunity?



An Opportunity: Photon + HCAL-only Jet

If mixing with Higgs is small, *a* lifetime can be long

- $c\tau\gamma$ of order meter

And lifetime of dark vector boson can be long at any mass

Then can have one "photon" + one decay of *a* or γ' in HCAL

- Gives narrow HCAL-only jet recoiling against photon
- Invariant mass (once jet energy corrected) of 750 GeV

To my knowledge no existing search for photon + HCAL-only jet

- This is a good idea **independent** of the X_s

Summary

Huge space of signals in DS/HV; lots of great work but **much** more to do

- Easy but not done: general dilepton/diphoton bump hunt
- High priority: Higgs non-SM decays (cf. neutral naturalness)
  - Displaced jet (or jet-pair), tau pairs
    - Possibly only one per event! + MET or + promptPrompt bb bb, ττ ττ and ττμμ (but not just below bb threshold)
  - MET + leptons or photons
- Rare spectacular events related to Higgs portal?

Could 750 excess be related to a HV/DS or something similar?

  - Fake photons from photon-jets or electron-jets
  - Busy events with many tracks from quirks (scalars)
- Could these give strange detector/search-dependence via
  - Photon definitions (unusual EM showers, conversion patterns)
  - Isolation requirements
  - Resolution (i.e. apparent width)

Backup Slides

Motivation

- h decays may serve as window to weakly-interacting unknown particles.
  - e.g. discovery of neutrino in beta decay, other neutrinos in muon, tau decay
  - e.g. non-discovery of 4th neutrino, majorons, others in Z decay

- Dark Matter exists;
  - if it is particles, these particles may not carry SU(2) quantum numbers
  - Therefore these particles may have evaded LEP & have mass < 100 GeV
  - So possible that h → DM → invisible decay
    - Difficult to observe for Br < 10%
  - If DM part of low mass dark **sector** (“*hidden valley*”), then maybe
    - h → dark sector particles → visible particles, with or without MET
      - Much easier to observe! Can sometimes reach Br <<< 10%

- H “Portal” – easy access to dark/hidden sectors/valleys
  - H operator has dimension 1, $|H|^2$ is gauge invariant, dimension 2
  - Coupling to “dark” sector involves low dimension operator

Motivation (2)

- 125 GeV h has very narrow width
  - → small interactions with new sector can generate new decays
  - These decays could have had Br ~ 100%; could still have Br ~ 10%.

- Number of h produced is large, so potential to reach Br ~ 10^{-4} or better
  - 10^6 already produced
  - Approaching 10^8 in foreseeable future
    - But --- trigger and analysis challenges!
    - 2011-2012 data may still be useful!

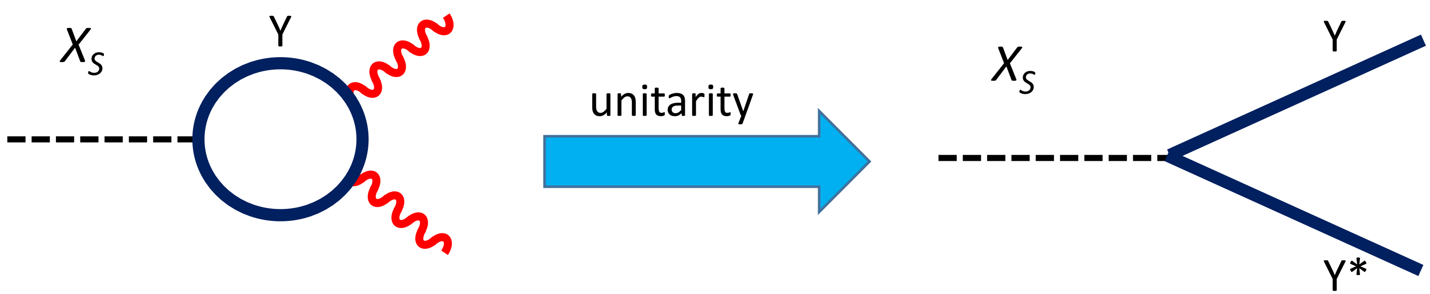
- In some theories,
  - h decays are **first** BSM physics discoverable at LHC
  - Or even the **only** BSM physics discoverable at LHC14!

- Same searches might turn up new members of scalar sector (e.g. heavy H) whose decays are dominated by non-SM final states

Comments

An infinite set of theory/pheno papers

- X_S unlikely to be produced in quark-antiquark collisions
  - Probably gluon-gluon
- X_S unlikely to be produced in the decay of heavier particle
  - Would see excess energy or MET or jets in events
    - Exception (or a sort) later…
- Can't simply be second Higgs
  - It will decay to pairs of known quarks/leptons far more often than photons
  - Coupling to gluons/photons must come from particles with mass > 375 GeV



Resonance → two photons

An infinite set of theory/pheno papers

- Lots of possible models
  - Could be fundamental, could be composite
  - Could be narrow, could be wide (if invisible width)
- No way to distinguish without a second discovery
  - But one will likely follow
- Simplest models: loop generates both gluon, photon couplings
  - $Br\,(X_s \to \gamma\gamma) / Br\,(X_s \to gg) \sim 0.5\%$
- If it's related to naturalness
  - Top partners *t'* , *b'*
  - May decay $t' \to t\,X_s$, $b' \to b\,X_s$
    - *ttjjjj, bbjjjj* – SUSY multijet (+small MET) searches
    - Rare: *ttjjγγ* (at most 1 or 2 events so far)

Agrawal, Fan, Heidenreich, Reece & MJS **arXiv:1512.05775**

Photons in Crazy Environments

A **finite** set of theory/pheno papers

including Agrawal, Fan, Heidenreich, Reece & MJS **arXiv:1512.05775**

X_s can't be heavy quarkonium state

- Very rarely produced

But it could be a heavy colored-quirkonium state

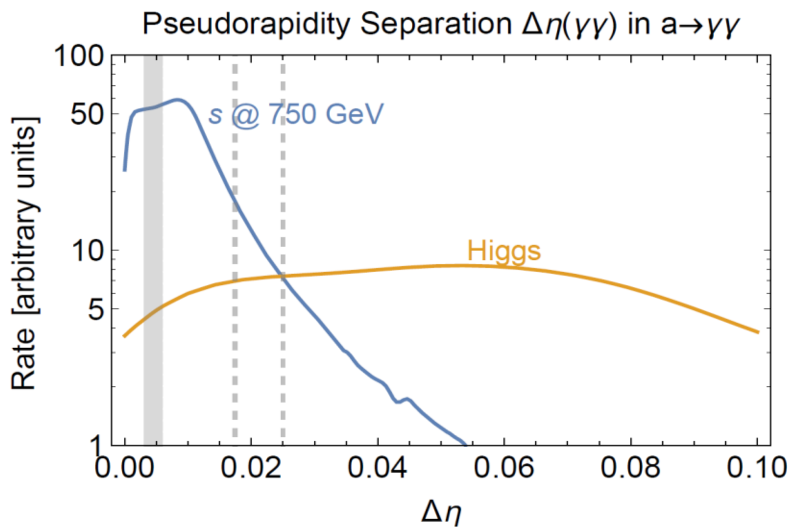
- Fermionic quirks unlikely: leads to large dilepton resonance!
- Scalar seems to be just fine.

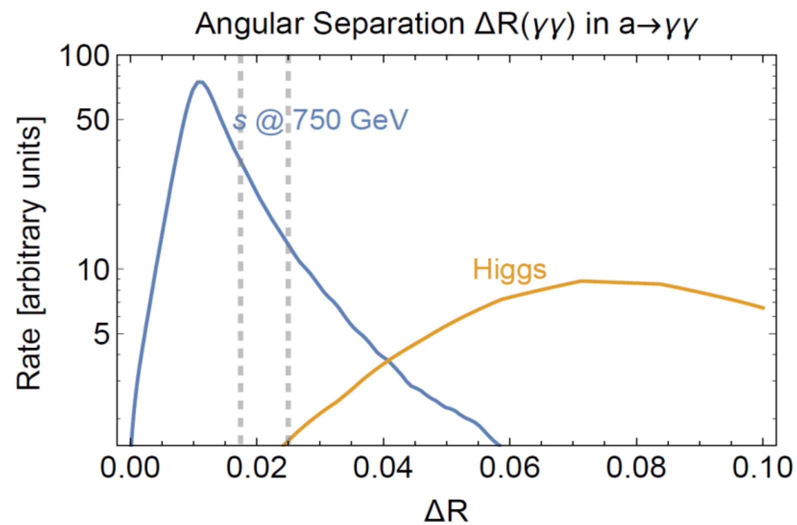
Result:

- (Near-)Ground state sometimes produces two photons
- Decay down to ground state may produce soft particles or soft jets
- Photons may therefore sometimes be lost due to isolation
  - Different isolation requirements lead to very different efficiencies?
- Larger number of tracks/soft jets in 750 GeV bump vs. background

Effect of Boost

m_a = 2 GeV,
$c\tau$ = 1.6 mm



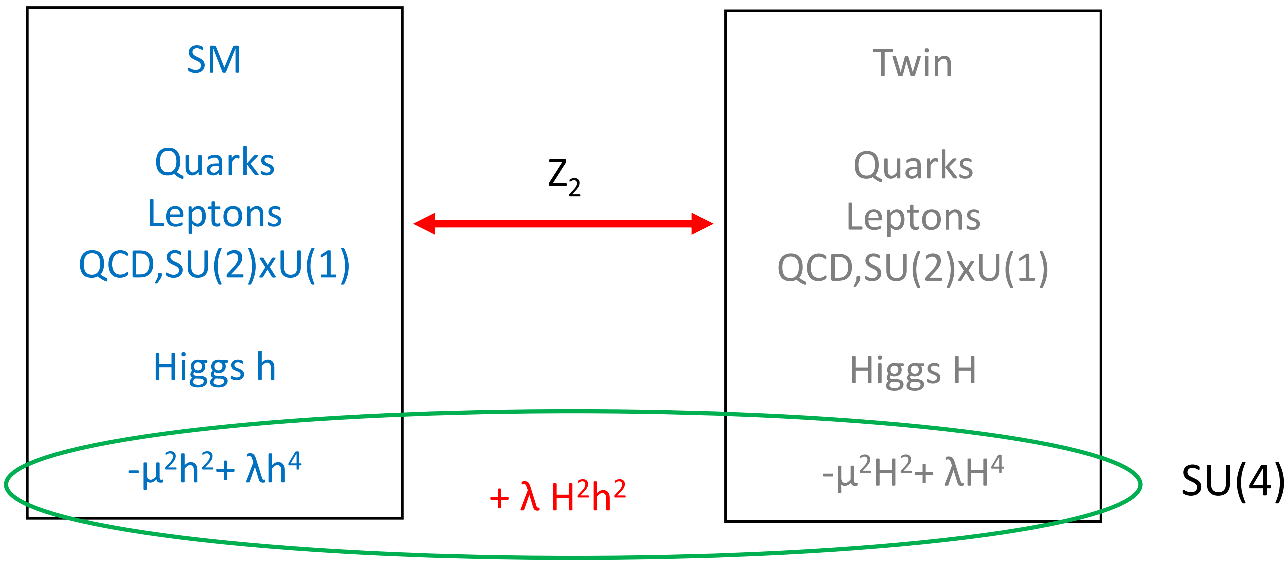


h ➔ *a a*

- Theory can allow as large as 10%, small as 10^{-5}
  - hard to get much below 1% if S produced through mixing
- Photon pairs too often wide for *h* ➔ *a a* to fake *h* ➔ *γ γ*
  - Could shift *h* ➔ *γ γ* upward: search-dependent, detector-dependent
- Limits on *h* ➔ *(γγ) (γγ)* only cover
  - m_a ~ 100 – 400 MeV
  - m_a > 10 GeV

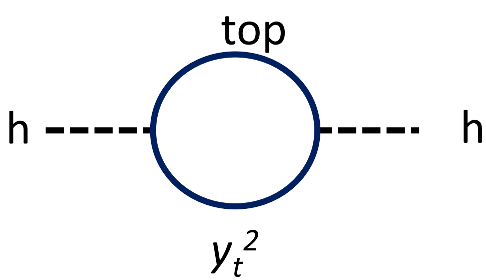
Twin Higgs (original version)

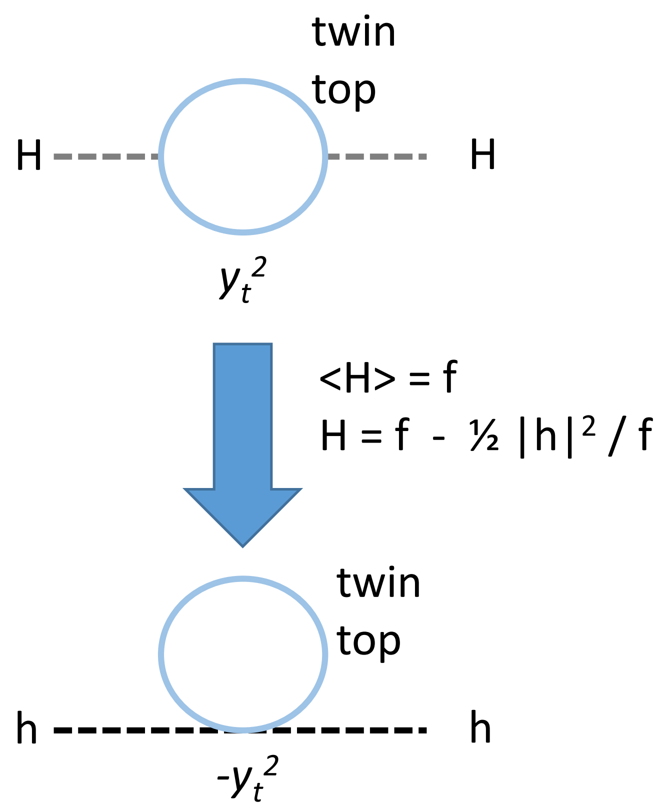
hep-ph/0506256
Chacko, Goh & Harnik



- (h,H) form a quartet of SU(4)
  - H gets a vev f, SU(4)→SU(3) gives 7 Goldstone modes: W, Z, W_{twin}, Z_{twin}, h
- SU(4) is broken to SU(2) x SU(2) by gauge and Yukawa couplings
  - But Z_2 assures that SU(4) in μ,μ is not broken at 1 loop
- Therefore Higgs remains pseudo-Goldstone at one loop
  - Cutoff ~ 5-10 TeV

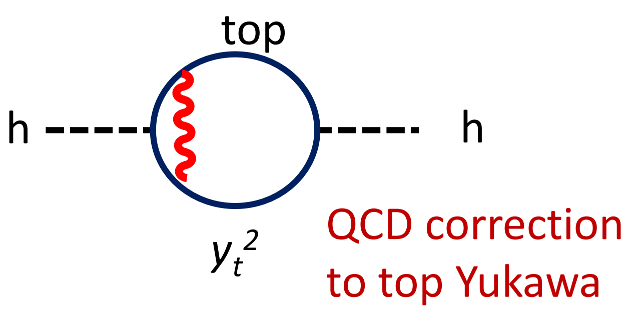
Biggest 1-loop correction

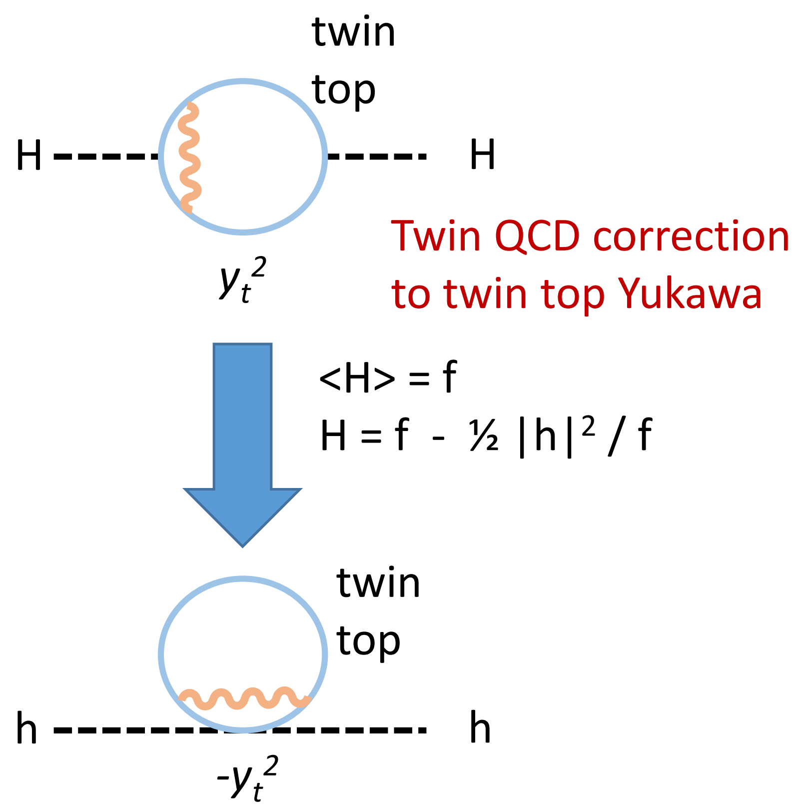




(Similar for W)

Biggest 2-loop correction





QCD coupling makes top Yukawa run significantly

Twin QCD running changes twin top by corresponding amount

So cancellation survives leading-order running

Twin Sector

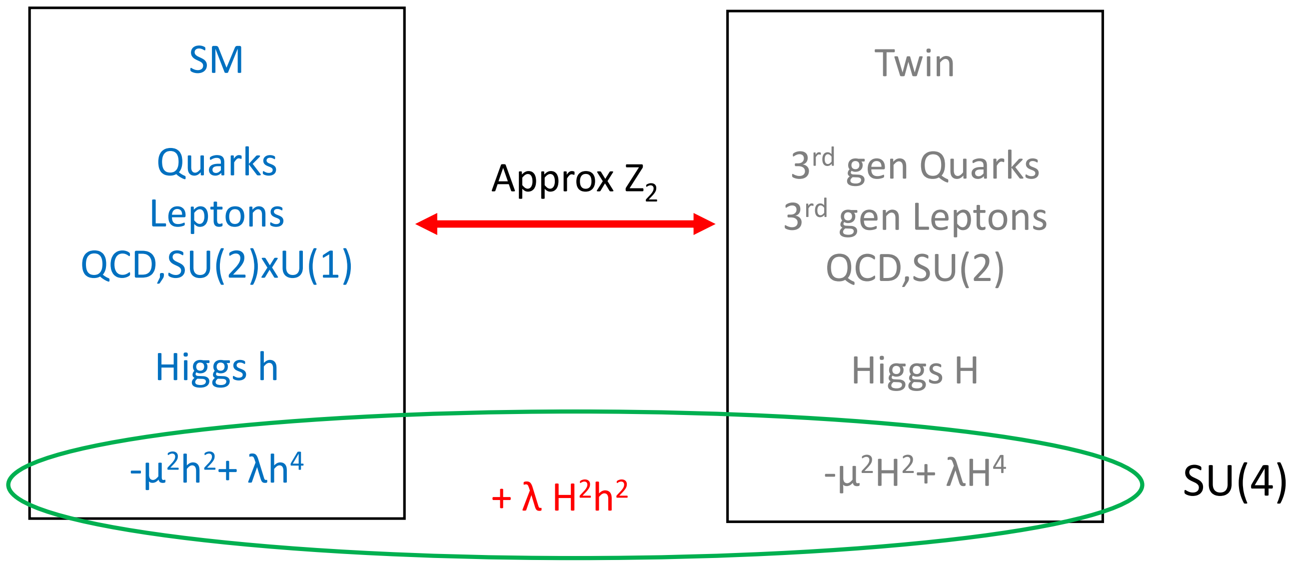
- Turns out f needs to be ~ (3-6) v ~ 750-1500 GeV
  - Too small? Large Higgs-twin Higgs mixing, excluded
  - Too large? Big correction to Higgs mass at two loops

- t'/ t mass ratio = b' / b mass ratio = f/v
  - Twin m_t ~ 525 - 1050 GeV
  - Twin m_b ~ 12 - 24 GeV

- Small tuning (1 in 5 - 10) in Higgs potential to get <H> = f » <h> = v

Twin Higgs (minimal version)

Craig,Katz,MJS & Sundrum
arXiv:1501.05310



- Mechanism is the same
  - Note: top Yukawa couplings must be equal at ~1%
- Z_2 relaxed, unnecessary particles discarded
- Just twin top and bottom, tau and neutrino
  - And twin bottom / bottom Yukawas need not be equal, etc.
  - SU(2), SU(3) couplings equal at ~ 10%
  - No need for twin U(1) hypercharge – drop

Summary

Higgs portal is generic whenever naturalness relies on hidden sector

- We can be unlucky (at least at LHC, though not at e^+e^-)
  - Visible HV signals may be absent – only invisible decays
  - Visible prompt HV signals may be present, but challenging and/or rare
    - e.g. Br ~ 10^{-3} – 10^{-4} and no easy channels
  - **Always** small corrections to SM predictions for h
- Or we can be lucky
  - Visible prompt HV physics may be common and/or spectacular
    - Rates enhanced by twin fermion couplings
    - Leptonic signals
    - Displaced object signals
    - Decays of a heavy Higgs (standard or exotic)

Diversity of possible signals motivates a coherent program of searches at Run 2 for non-SM h (and H) decays

- prompt and non-prompt
- invisible, partly visible and wholly visible
- simple and complex final states

Quirks and Neutral Naturalness?

Fermionic quirks aren't very plausible

- J/Psi-like dilepton resonance should have been observed by now

Scalar quirks: more plausible (but natural?)

- Spin-1 bound state is P-wave, suppressed.

Multiple nearby states affect resonance shape, apparent width?

Neutral Natural?

- Scalar quirks do arise in Folded SUSY
  - Top "squarks" are actually squirks
    - Not colored; confined under a new SU(3) group
    - Not sufficiently produced?
- Quirks in non-minimal models?

Summary

Naturalness remains **the** big question of our time

- Dark matter is **a** big question, but not necessarily of our time

Neutral Naturalness – can hidden sectors hide naturalness?

- Existence Proof: Twin Higgs, Folded SUSY, variations
- Signals: Hidden valley pheno in Higgs sector
  - New resonances, possibly displaced, in Higgs decays
  - Can arise also in rare heavy higgs decays

Who ordered a 750 GeV Boson?

- Is it part of a natural theory? Can top partners decay to it?
- Is it decaying to fake photons (photon-jets or electron-jets, likely displaced?)
  - Can the Higgs decay this way too?
- Is it a bound state, perhaps of permanently bound “quirks”?

- Could the more exotic options help explain
  - the width?
  - the ATLAS/CMS Run 1/Run 2 discrepancies?
  - the variations in 2011/2012 ATLAS/CMS Higgs → photons searches?