FRATERNAL TWIN HIGGS

arXiv:1501.05310 w. N. Craig, M.Strassler and R.Sundrum
work in progress w. N. Craig

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CERN-CKC Institute on Neutral Naturalness,
April 23-26, 2015

Why Fraternal Twin Higgs?

~~Neutral naturalness is about seeing nothing at the LHC~~

~~Is this true?~~

Neutral naturalness can be about seeing something (pretty unusual) at the LHC

Twin Higgs: What Do We Find In the Hidden Sector?

Bottom-up approach:

The original paper (*Chacko, Goh, Harnik; 2005*) doubled the full
SM in the twin sector
Original twin Higgs

A different approach: keep only the particles which a necessary for naturalness. Do to demand approximate symmetry to be more precise than the naturalness requires
Fraternal twin Higgs

What Do We Need to Preserve Naturalness?

- Three species of twin tops with a coupling to the twin Higgs. The Z_2 should be respected to precision of 1% in this sector.
- Twin W to cancel the W-loop → gauged twin SU(2) embedded into the global SU(4). The Z_2 should hold to the level of 10%.
- Claim: although there is no one-loop divergence involving a gluon, the *global SU(3) that the twin tops are charged under must be gauged*.

Why?

Technically — 2-loop correction to the Higgs mass

$$\delta m_h^2 \approx \frac{3 y_t^2 \Lambda^2}{4\pi^4}(g_3^2 - \hat{g}_3^2)$$

Need the visible and twin color couplings to agree within 30%.

New UV-free force in the twin sector.

What Do We Need for Naturalness?

- Twin RH bottom to cancel SU(3) anomaly. Twin bottom Yukawa is allowed by symmetries but its values is a free parameter, as long as $\hat{y}_b \lesssim 5 y_b$
- Twin LH tau should cancel SU(2) anomaly
- We introduce RH tau (singlet fermion) in order to give mass to taus. It is not necessary. If RH tau not introduced, massless twin taus are similar to twin neutrinos.
- One generation of twin neutrinos must be present. Twin tau and twin neutrino masses are almost free parameters

Not needed:

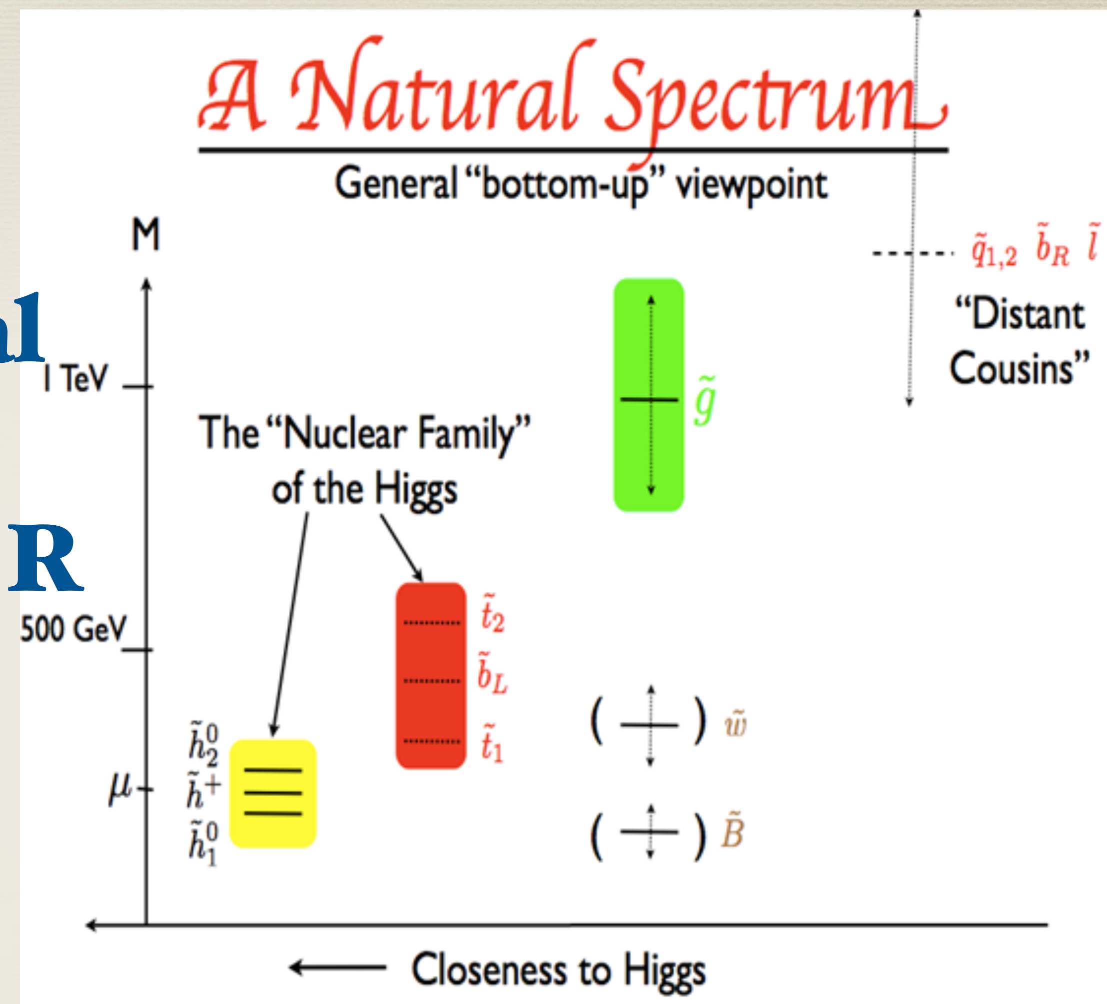
- Twin light generations (Natural SUSY — no light flavor sfermions).
- Twin U(1) (Natural SUSY — bino can easily be heavy). No twin photon.

Much smaller field content than in the SM. No cosmological problem.

Minimal Or Non-Minimal?

This approach is in lots of senses similar to the “Natural SUSY”:

- **naively look minimal from IR**
- **very non-minimal from UV**



$$SU(6) \times SU(4)$$
$$\downarrow$$
$$\left[SU(3) \times SU(2)\right] \times \left[SU(3) \times SU(2)\right]$$

UV completion of “Fraternal Twin”?

Use the tools from GUT model building

example:

$$SU(5)/\mathbb{Z}_2 \to SU(3) \times SU(2) \times U(1)$$

Orbifolds are a clean way of reducing symmetries

See talk by Simon Knapen for more ideas and details.

Fraternal Color

Fraternal color should be gauged, because without it top Yukawas would run differently.*

Threshold corrections

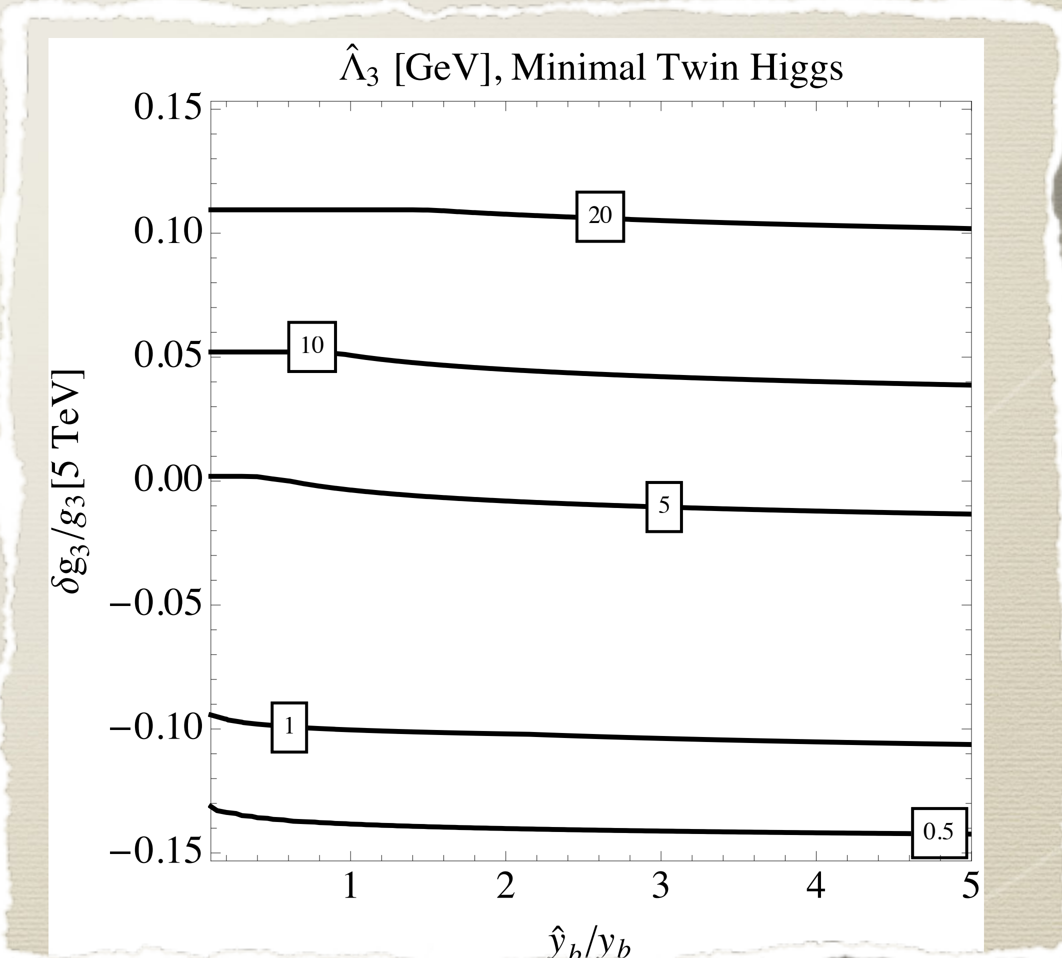
No fraternal color → FT < 10%

How precise should Z_2 be? 15% if we demand that FT>30%.

New confining force in the twin sector

Where is the confining scale?

Depending on the goodness of Z_2 the confinement scale can vary from less than 1 GeV to more than 20 GeV. Typically — slightly heavier than QCD scale.



*see talk by Brian Batell for not gauged SU(3).

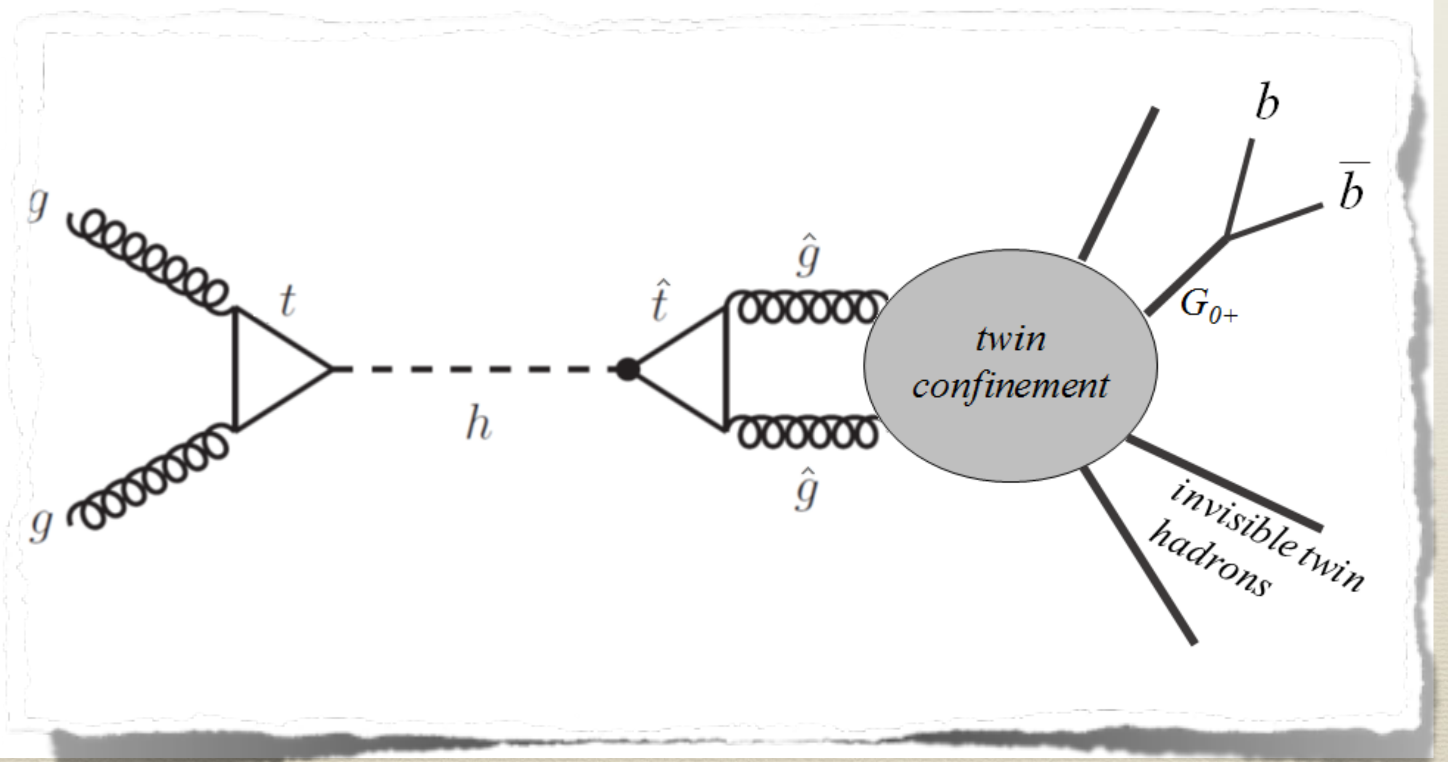
Higgs Portal and Hidden Valley Phenomenology

Mixing between the visible and the twin Higgs produces a coupling:

$$\mathcal{L} \supset -\frac{\hat{\alpha}_3}{6\pi}\frac{v}{f}\frac{h}{f}\hat{G}^a_{\mu\nu}\hat{G}^{\mu\nu}_a$$

The SM-like Higgs decays into the twin sector.
The BR is close to 0.1%.
The couplings are suppressed relative to the SM by $\frac{v}{f}$

How will these events look like?



Some hidden sector hadrons
can produce
interesting signatures
at the LHC.

Twin Sector Spectrum — Glueballs

Consider first limit $m_{\hat{b}} \gg \hat{\Lambda}_{QCD}$

Below the scale of the twin bottom mass we get a pure glue.

Spectrum of Glueballs:

Lattice calculations: Morningstar et. al., Lucini et al....

- For a tower of states with different spin, P and C
- The lowest state is 0^{++}
- Heavy states decay fast enough into the light glueballs, if kinematically allowed
- The lightest states has a mass $m_{0^{++}} \approx 6.8\hat{\Lambda}_{QCD}$
- 0^{++} decays to the SM via its mixing with the higgs
- Other states, which cannot decay to other glueballs have very long lifetime ⟶ MET at the LHC

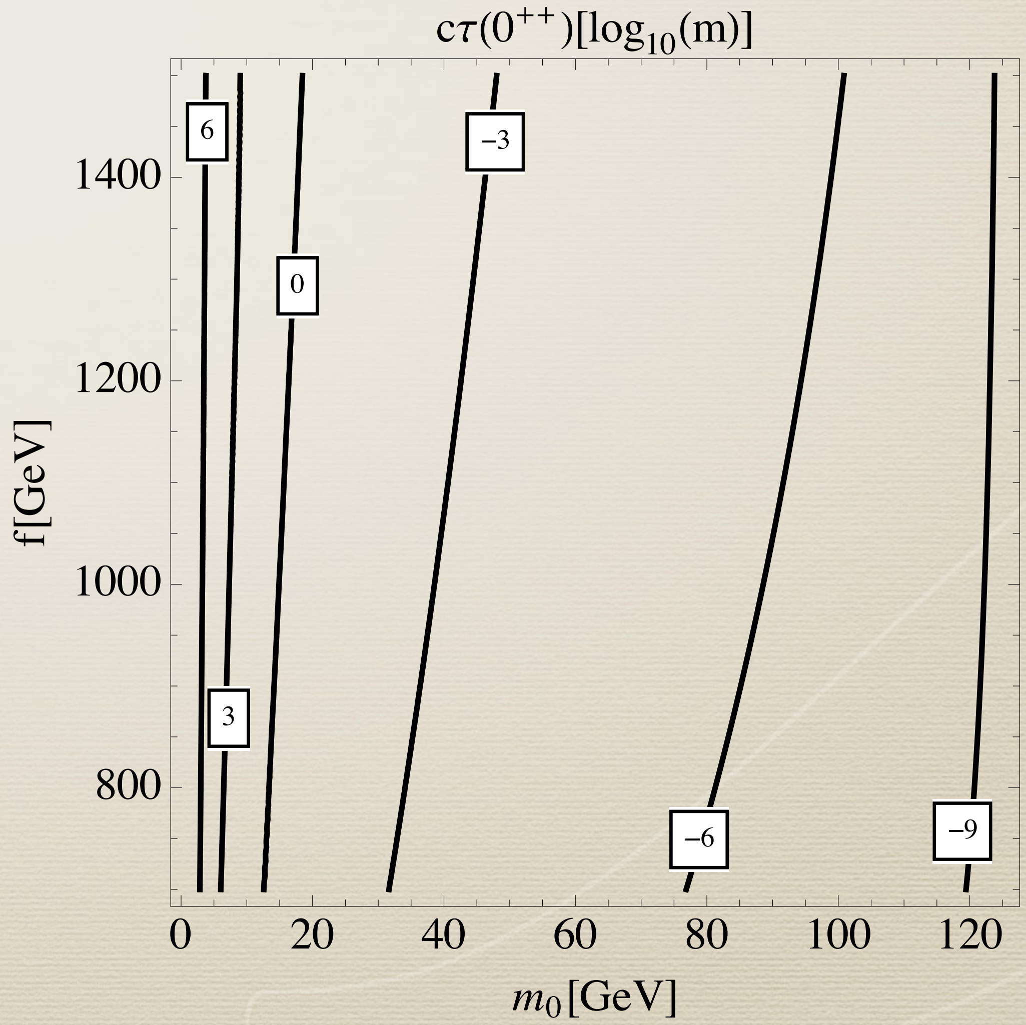
Glueball Lifetime

0^{++} mixes with the higgs and decays to the same final states, as the higgs

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

decay constant, known from lattice $\propto m_0^3$

Decay goes as 7th power of the glueball mass



Signal: displaced vertices. Displacement can be plausible as big as 1...10 meters.

More Complicated Story — Quarkonium

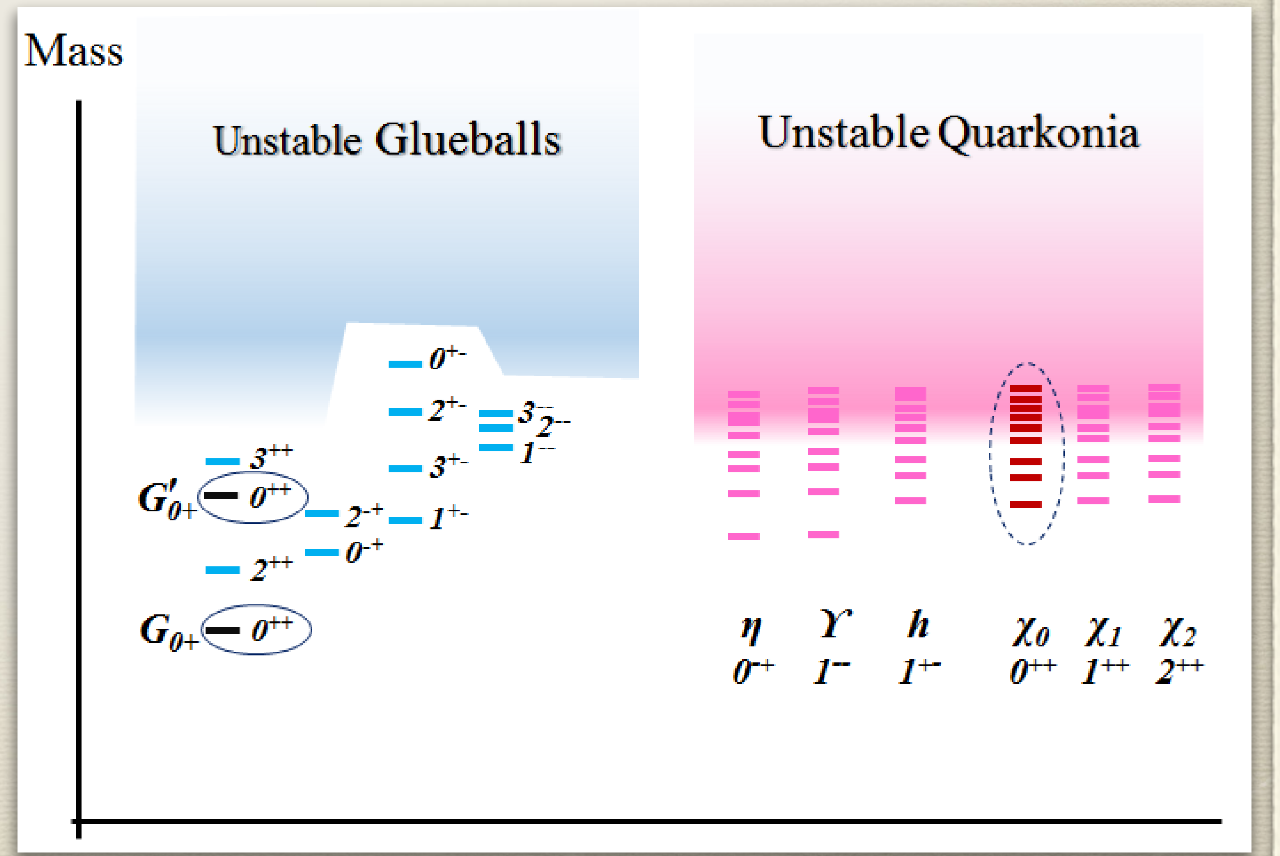
Twin bottom quarks should be in the spectrum because of anomaly cancellations. Its mass is a free parameter as long as it does not cause a new naturalness problem.

$$m_{\hat{b}} \lesssim 70 \text{ GeV}$$

Twin bottoms form high towers of quarkonium states.

Both glueballs and quarkonia can decay to the SM states.

Both can result in displaced vertices at the LHC.

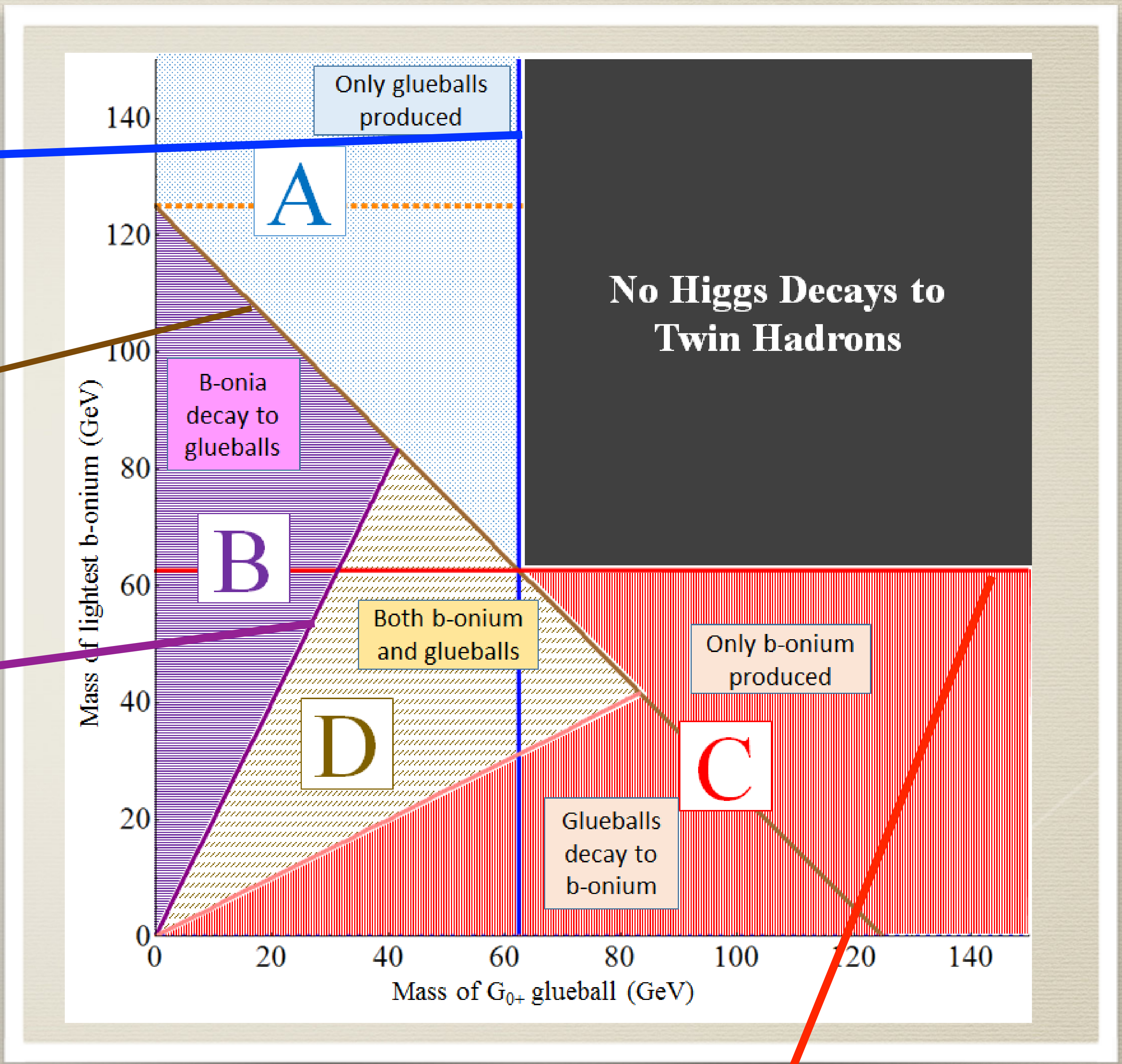


Full Parameter Space of the Model

Two glueball production is kinematically allowed

Decay into one glueball and one bottomonium is allowed

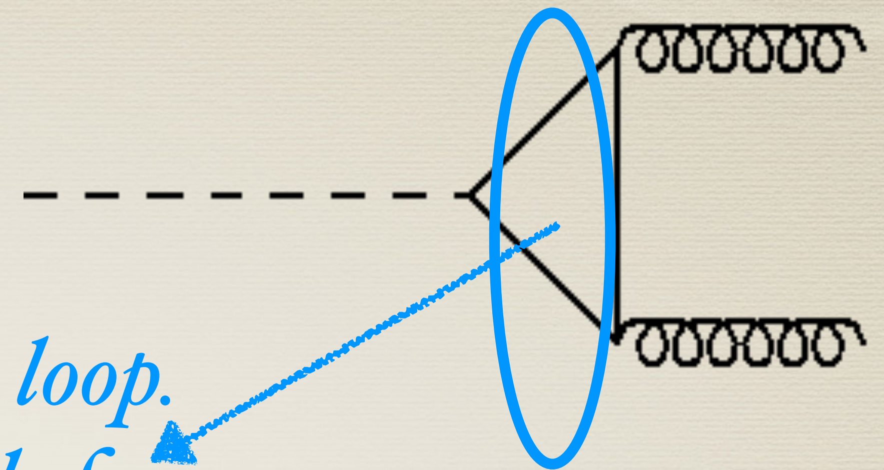
Quarkonia can decay to glueballs



Two quarkonia production is kinematically allowed

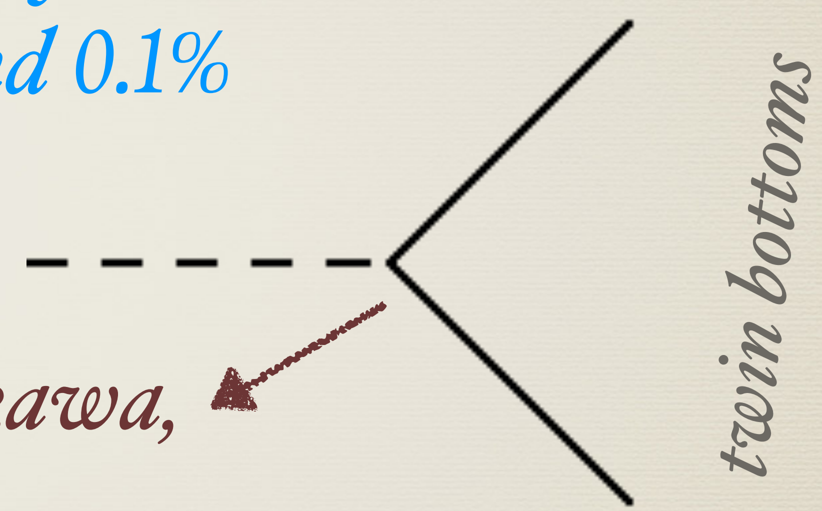
Production of Twin Hadrons

Irreducible rate:



Twin stops running in the loop.
Depends only on the scale f.
Perturbatively BR — around 0.1%

Reducible rate:



BR is proportional to twin bottom Yukawa,
we do not know this value

For sufficiently high twin bottom Yukawa (twin bottom mass beyond 19 GeV) the model would already be excluded by excessive invisible Higgs rate.

Can we always rely on perturbative rate in this case?

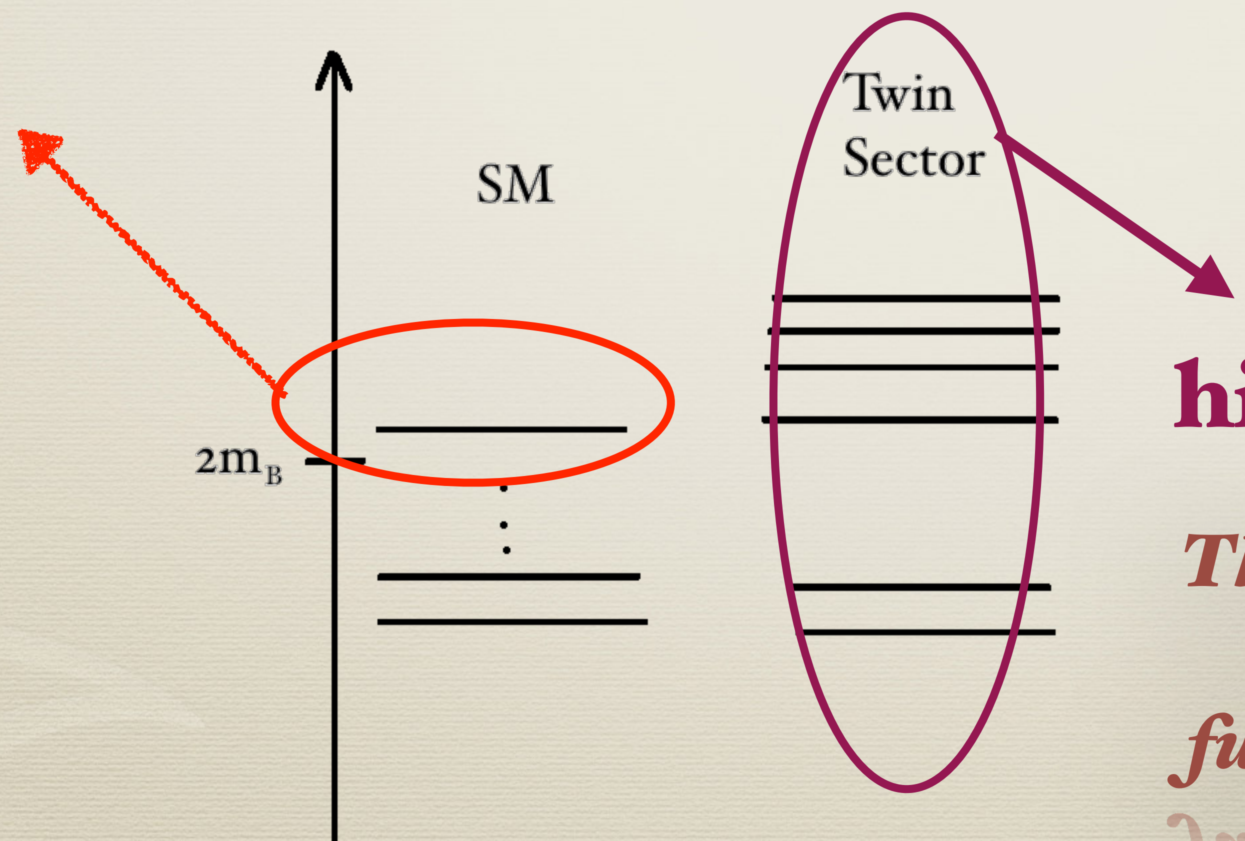
Beyond the Perturbation Theory

If $\hat{y}_b \gtrsim 1.25 y_b$, the model is perturbatively excluded

higgs invisible rate would be too high

Why we cannot always rely on perturbation theory?

promptly decays to B-mesons



No light quarks
No decays into B's
The towers are higher than in the SM

The resonance structure of 2-point function can modify the BRs

Beyond the Perturbation Theory

The maximal possible suppression compared to the perturbative rate is Γ/Δ

width of the state

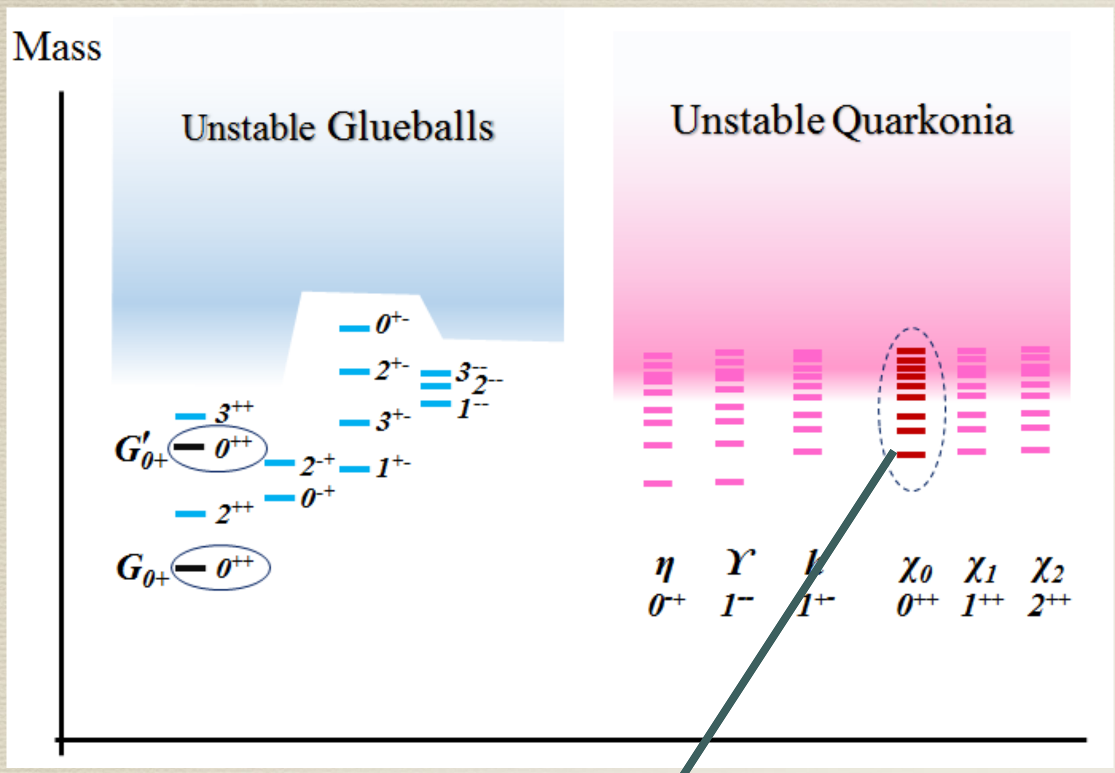
splitting between the states

Suppression is roughly $\hat{\alpha}_3^2 (E_n/m_{\hat{\chi}})^{3/2}$

Enough to render the BR < 10% in the entire parameter space. But does not take into account important effects

Similar effects can reduce the decay rate to gg by no more than factor of 10. The exotic BR cannot fall below 0.01%, and can be significantly enhanced

Decays of Twin Bottomonium



phenomenologically relevant states can mix with the higgs and decay to the SM

Decay length:

$$\Gamma_{\chi\to YY} \sim 2\times 10^{-3}\left(\frac{v}{f}\right)^4 \frac{m_\chi^{11/3} m_0^{10/3}}{v^2 m_h (m_h^2 - m_\chi^2)^2}\Gamma_{h\to YY}(m_h)$$

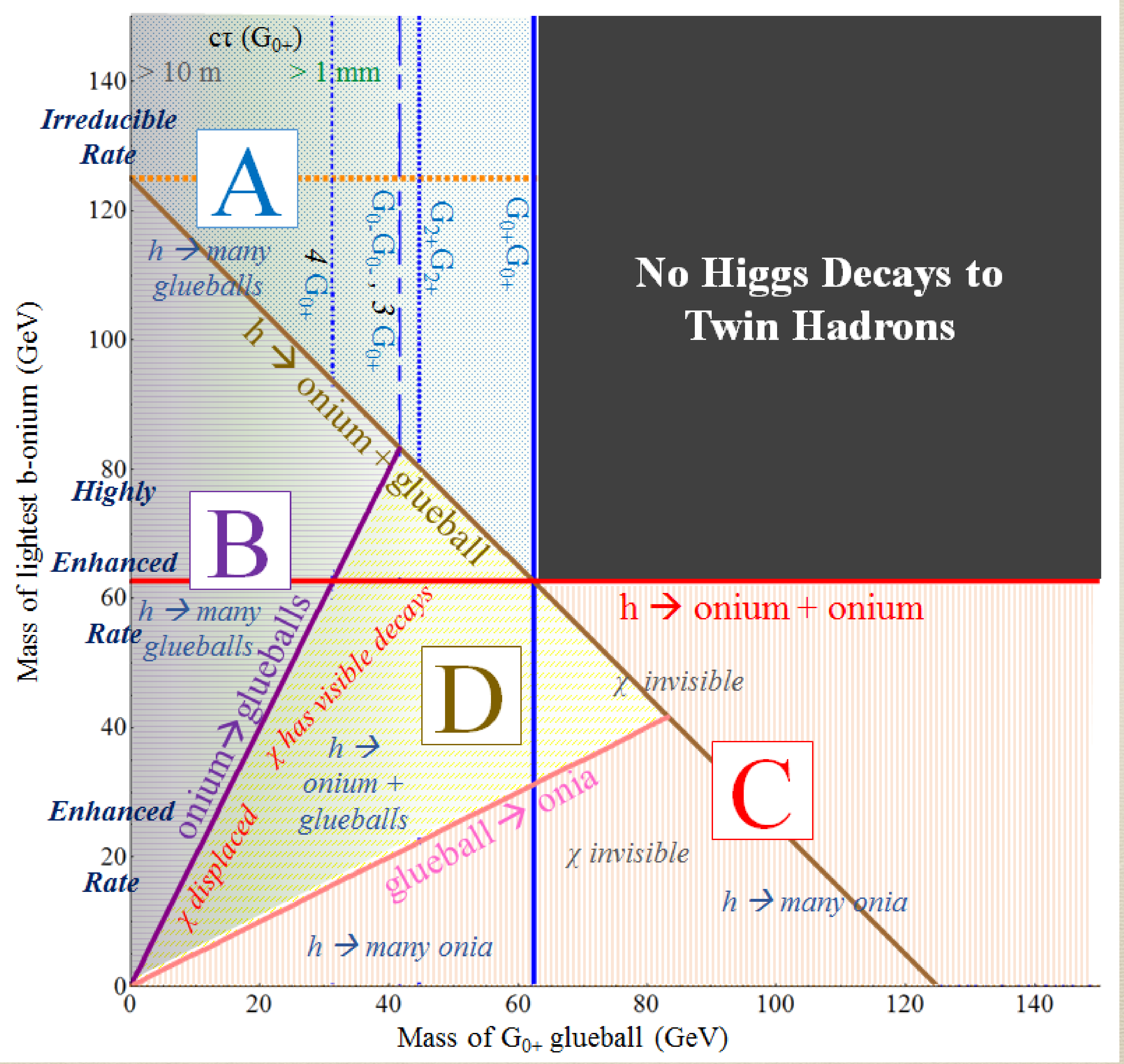
linear potential approximation + string tension from lattice

Competing process: de-excitation to Υ via twin Z off shell → twin neutrinos

sensitive to the mass splitting between qaurkonia to the 7th power, hard to model

If glueballs are sufficiently light, visible decay to the SM are possible, lifetime is shorter than that of glueballs

LHC Signals



cτ (G0+)
> 10 m
> 1 mm
Irreducible Rate
Highly Enhanced Rate
Enhanced Rate
A
B
C
D
h → many glueballs
4 G0+
G0-G0-, 3 G0+
G2+G2+
G0+G0+
No Higgs Decays to Twin Hadrons
h → onium + glueball
h → onium + onium
h → many glueballs
onium → glueballs
χ has visible decays
χ displaced
h → onium + glueballs
χ invisible
glueball → onia
χ invisible
h → many onia
h → many onia
Mass of lightest b-onium (GeV)
Mass of G0+ glueball (GeV)
0
20
40
60
80
100
120
140

Proposed Searches for the LHC

- Exclusive double displaced vertex search (heart of region A) with higgs invariant mass reconstruction
- Single displaced vertex (usually hard due to unknown and hard-to-estimate backgrounds). Use associated production & VBF
- Inclusive double displaced vertex (can come with missing energy and/or other particles)

Beyond LHC:
if glueballs are heavier than 40 GeV, the decays are prompt. The generic rate is too small for the LHC (0.1%), but $h \to 4b$ with this rate is a reasonable target for future lepton colliders. If there is resonant enhancement, the BR can be as big as 10%, exotic Higgs decays are measurable at the LHC

Signals Beyond the LHC?

There are many variations on how the twin sector can look like.
Fraternal twin, beyond fraternal, exact mirror symmetry...

It must have a DM candidate

Much more on DM: talk by J. March-Russel. On asymmetric DM in twin higgs — "hidden talk" by M. Farina

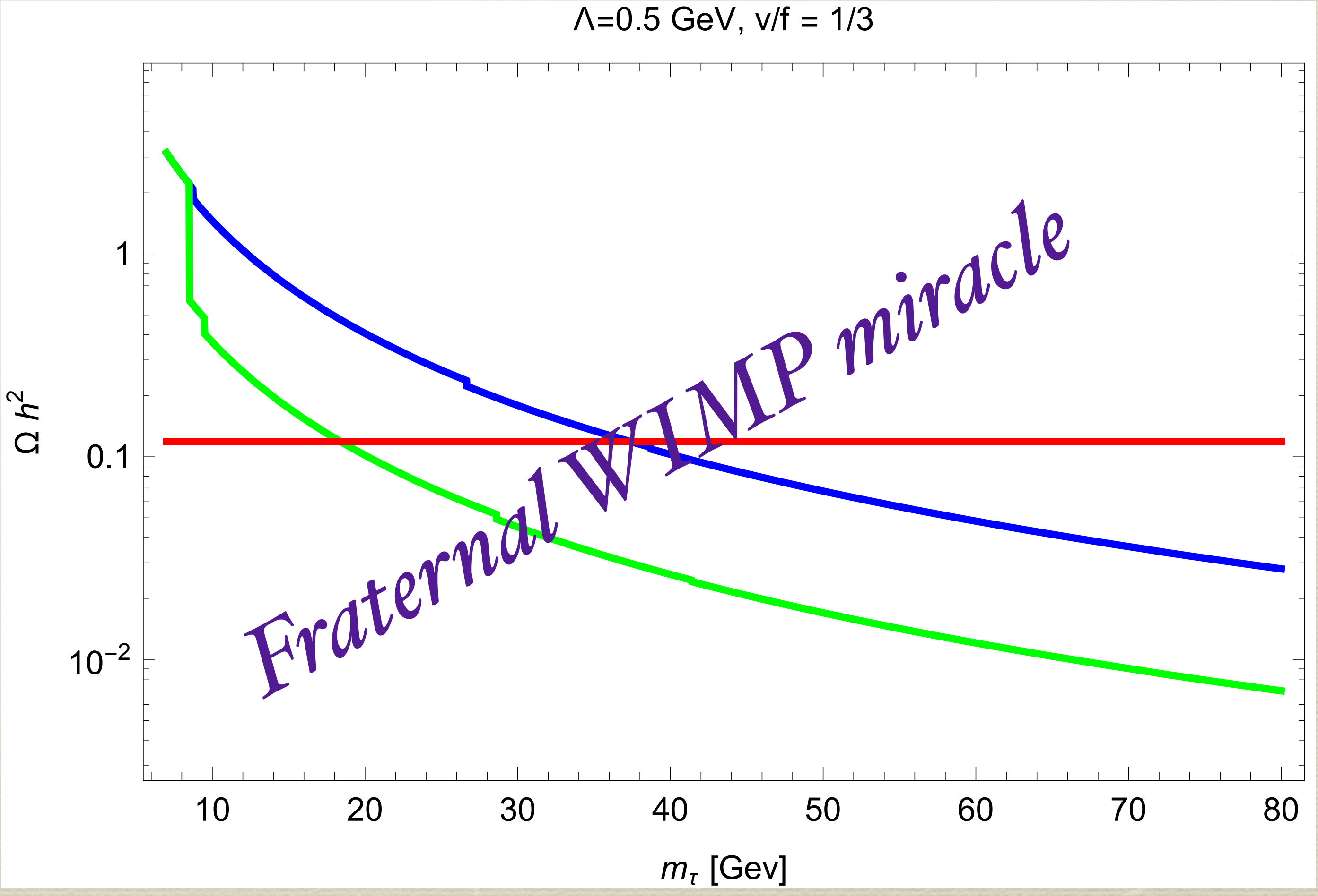
- Does Fraternal Twin Higgs has a built in DM candidate?
- Thermal relic abundance?
- Signatures at direct detections experiments?
- Asymmetric DM?
- From asymmetric DM to Darkogenesis/Xogenesis/Cogenesis?

Twin Tau as a Thermal Relic

In the Fraternal Twin Higgs the Twin Tau is the lightest particle, which is charged under twin EM ⟶ can be stable.

Dominant annihilation — twin neutrinos

The strength of annihilation — WIMP-like. Guaranteed by naturalness



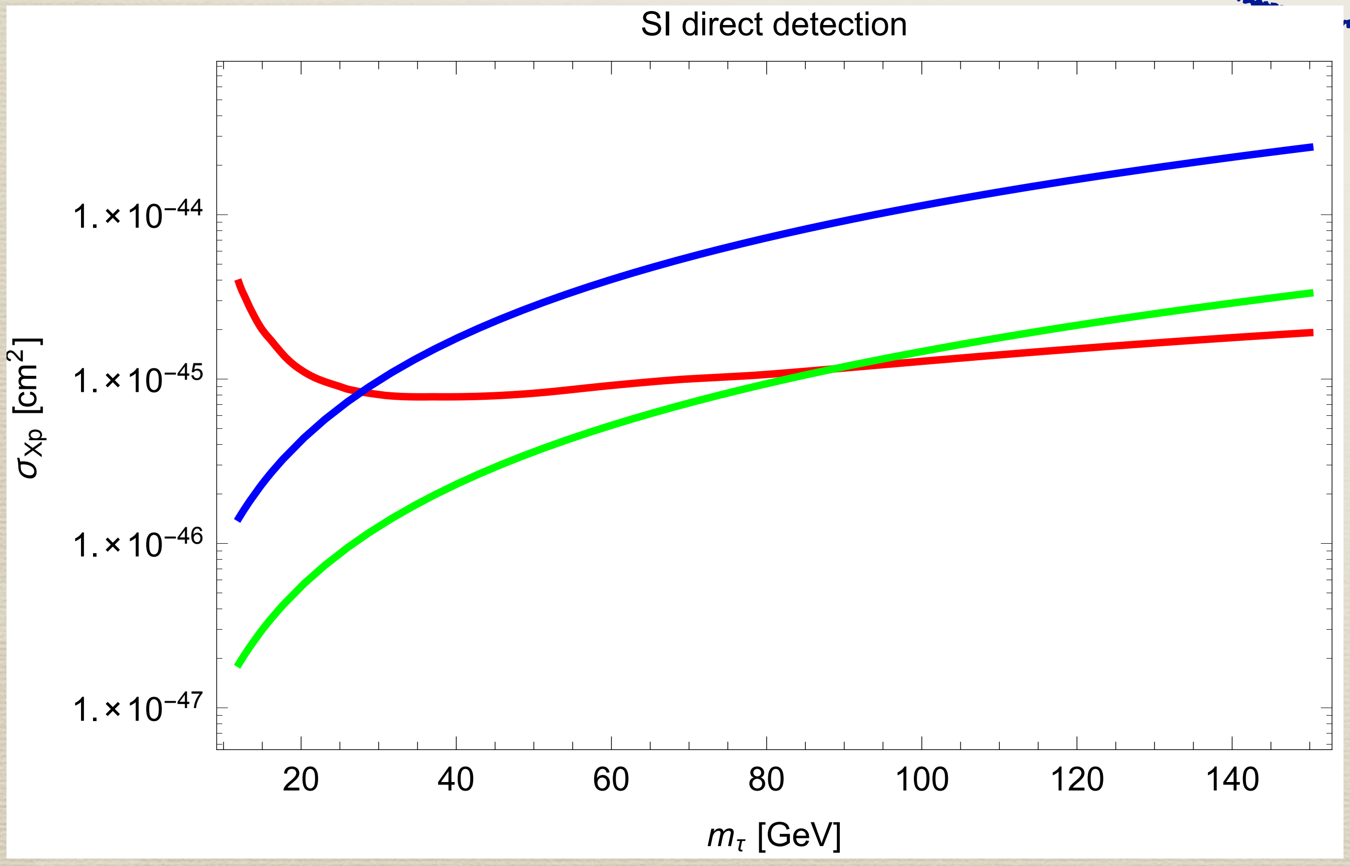
LUX and Beyond

The twin W and Z do not mix with the visible gauge boson: interaction with the visible sector via fermionic Higgs portal:

free parameter, constrained by naturalness and invisible higgs decay

$$\mathcal{L} \supset -\hat{y}_\tau \frac{|H|^2 \hat{\tau}^+ \hat{\tau}^-}{\sqrt{2} f}$$

constrained by naturalness



LUX

v/f = 1/3

v/f = 1/5

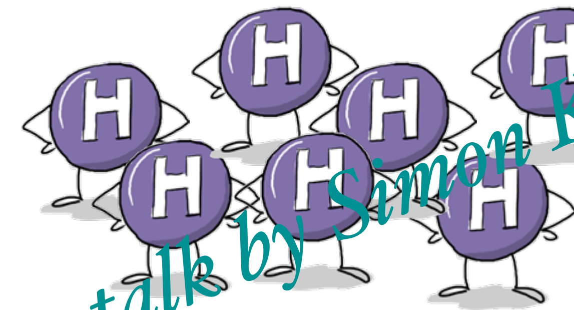
Big portion is already excluded, a lot will be probed soon

Twin Tau — Generalization

For abelian groups, all irreps are dimension one $d_l = 1 \quad \forall l$

$$[SU(3\Gamma) \times SU(2\Gamma)]/Z_\Gamma \to [SU(3) \times SU(2)]^\Gamma \times U(1)^{\Gamma-1} \times S_\Gamma$$

$$g^{(1)} = g^{(2)} = \cdots g^{(\Gamma)}$$

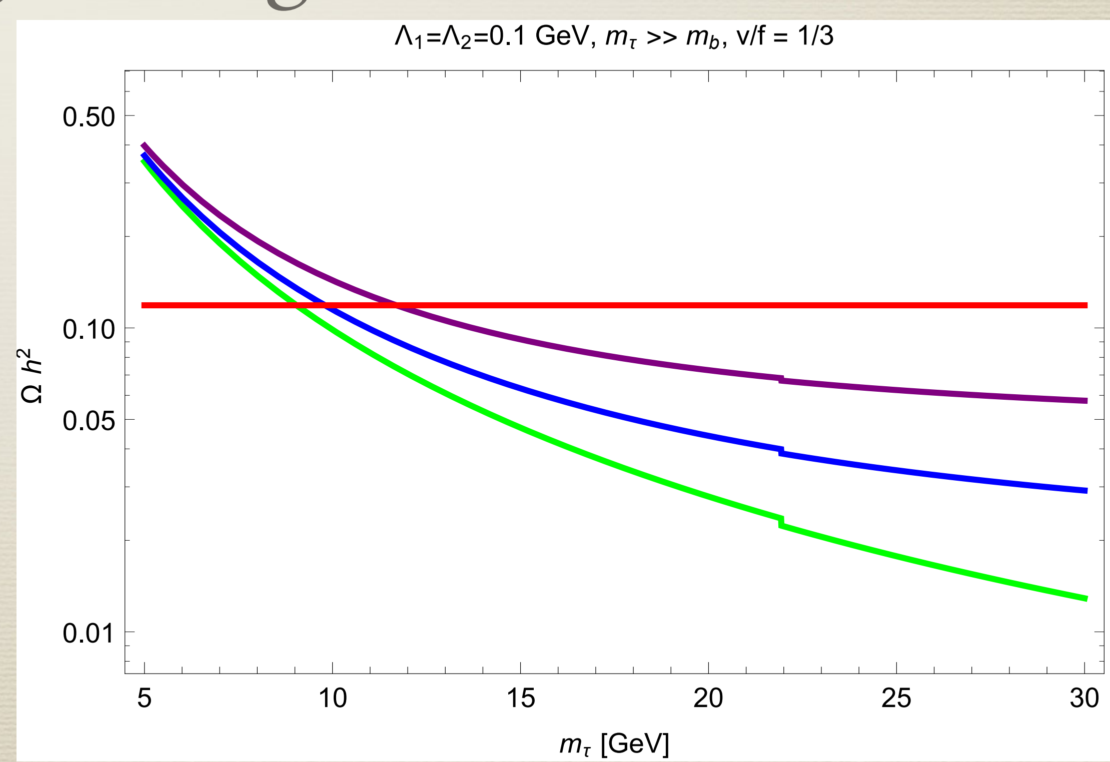


From a talk by Simon Knapen

Fraternal WIMP miracle easily generalizes to Z_N theories: coexistent DM in different sector, even lighter DM is favored

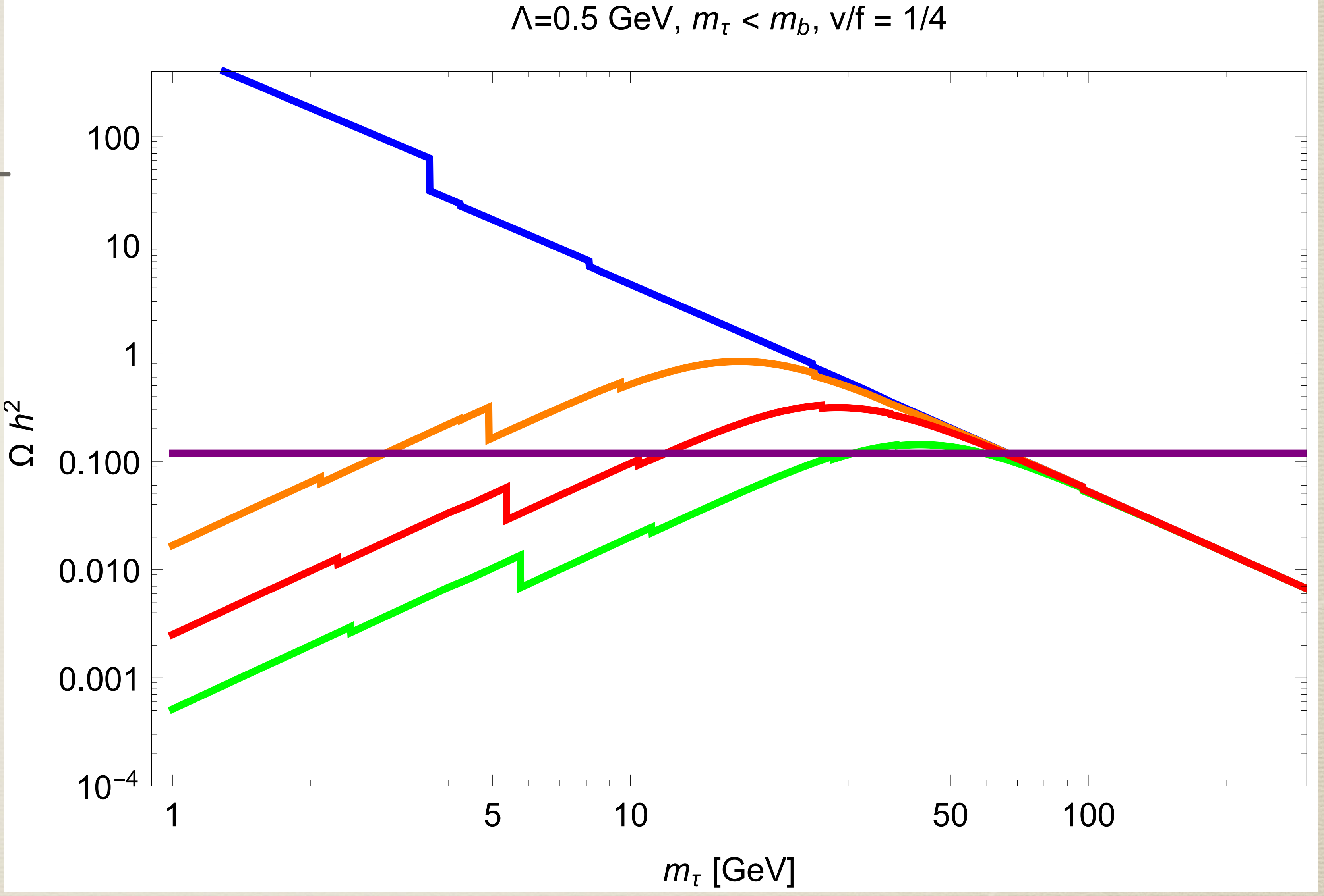
Heavy twin tau: 100, 25 and 15 GeV.

The lightest tau has the biggest abundance



Gauging the Twin Hypercharge

Gauged twin EM — even lighter candidates are possible:



Worry: a-priori kinetic mixing is a free parameter. In the effective theory cannot form at less than 4 loops.

Kinetic mixing usually dominates the direct detection for very light DM O(1 GeV).

Conclusions and Outlook

- Twin Higgs models, built on assumptions of IR minimality, are not necessarily “invisible”.
- Searches for displaced vertices (“hidden valley signatures”) are motivated naturalness
- New motivation for exotic higgs decays at the LHC and future lepton colliders
- Twin tau is a natural thermal relic candidate in fraternal twin higgs
- Most of the parameter space is on the edge of current LUX bounds, next generation of direct detection results should probe almost the entire parameter space