EXOTIC SIGNATURES OF NATURALNESS AT THE HL LHC

Andrey Katz

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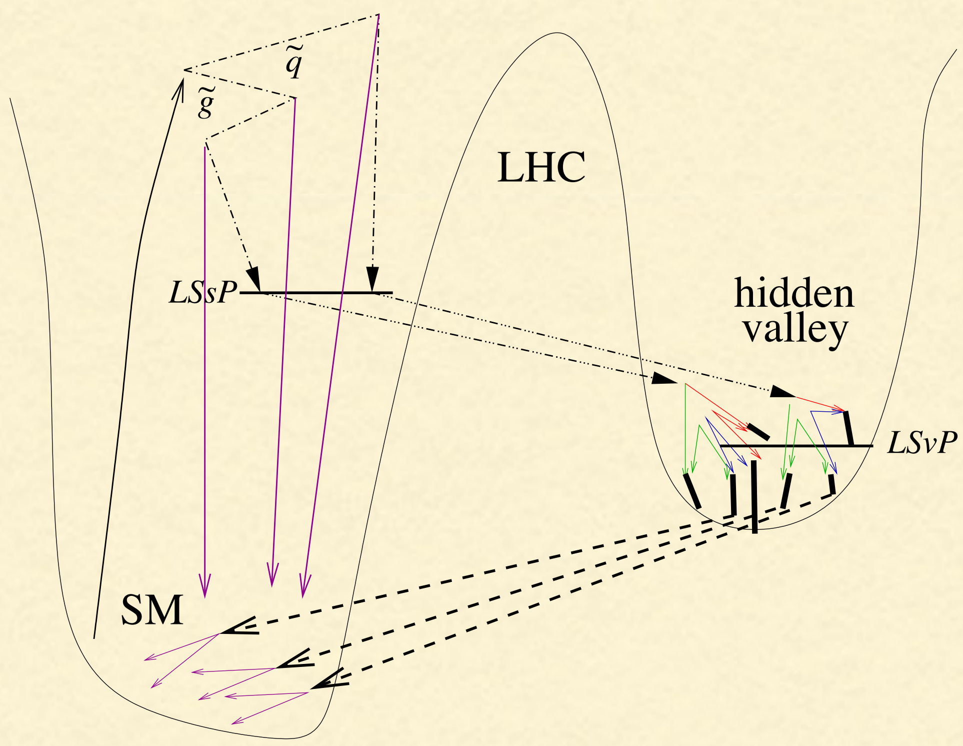
WHY HL LHC?

- Precision measurements
- Very rare processes, e.g. exotic higgs decays

Expect significant gains, for example, in:

"Hidden valleys", Strassler & Zurek, 2006



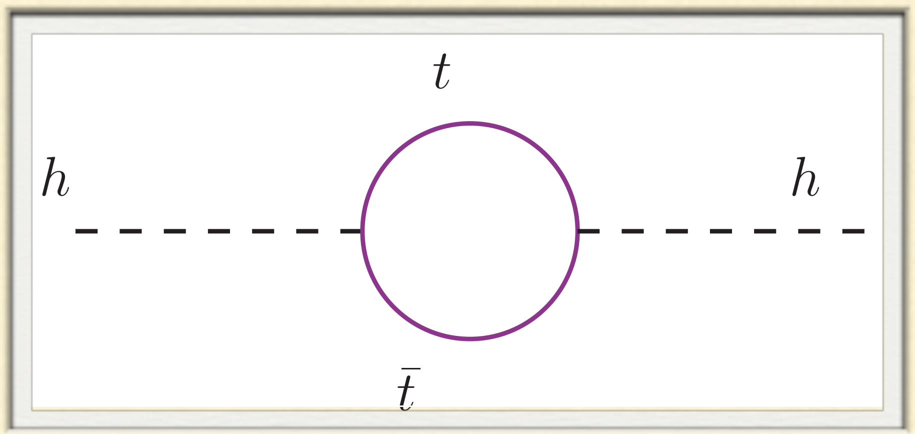
Higgs precision measurements:

- Higgs invisible width [17%, 28%] $\Longrightarrow$ [6%, 17%]
- h $\rightarrow$ bb [11%, 14%] $\Longrightarrow$ [5%, 7%]
- h $\rightarrow$ WW [6%, 11%] $\Longrightarrow$ [4%, 7%]

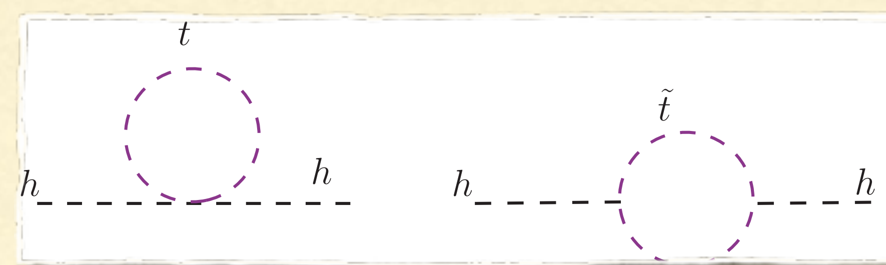
Improvement of more than factor of 2, which can be crucial

TESTING NATURALNESS AT THE LHC

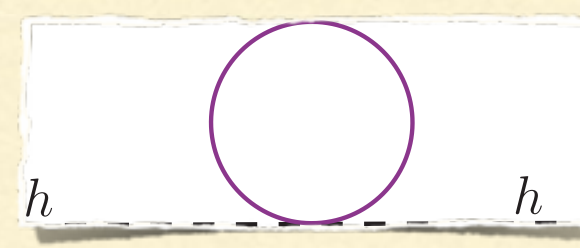
Basic idea behind testing naturalness:
The sensitivity to the high scale at the SM is mostly due to tops
→ expect heavy colored top partners
→ pair production has high cross sections



SUSY — bosonic partners



pNGB Higgs — fermionic partners



This strategy is based on assumption, that we are looking for new heavy particles. The gain by increasing luminosity is expected to be modest.

NEUTRAL NATURALNESS

Basic idea: the top partners are charged under a non-SM SU(3) group. Generically these theories predict no new colored states.

Twin Higgs

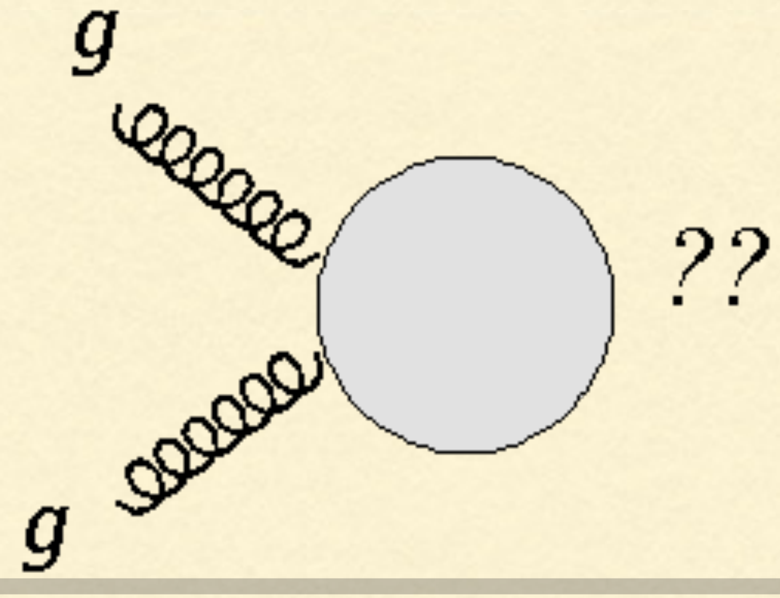
Chacko, Harnik, Goh; 2005

Extension of idea of the Higgs as pNGB. A discrete symmetry in the matter sector protects an accidental continuous symmetry in the Higgs sector.

Folded SUSY

Burdman, Chacko, Harnik, Goh; 2005

Top contribution is canceled by a new scalar particle. Equality of couplings is guaranteed by 5D SUSY



No abundant colored production in both scenarios

UNIVERSAL PREDICTION OF NEUTRAL NATURALNESS

All neutral naturalness scenario predict (small) deviations of the Higgs couplings from the SM values.

- The twin higgs, as all other higgs-pNGB scenario predicts misalignment. All the SM-like higgs couplings are universally suppressed. The suppression rate can be directly related to the degree of fine-tuning in the model.
- Invisible higgs rate is always non-zero in the twin higgs. The higgs is allowed to decay into the "twin sector". The rate is model-dependent.

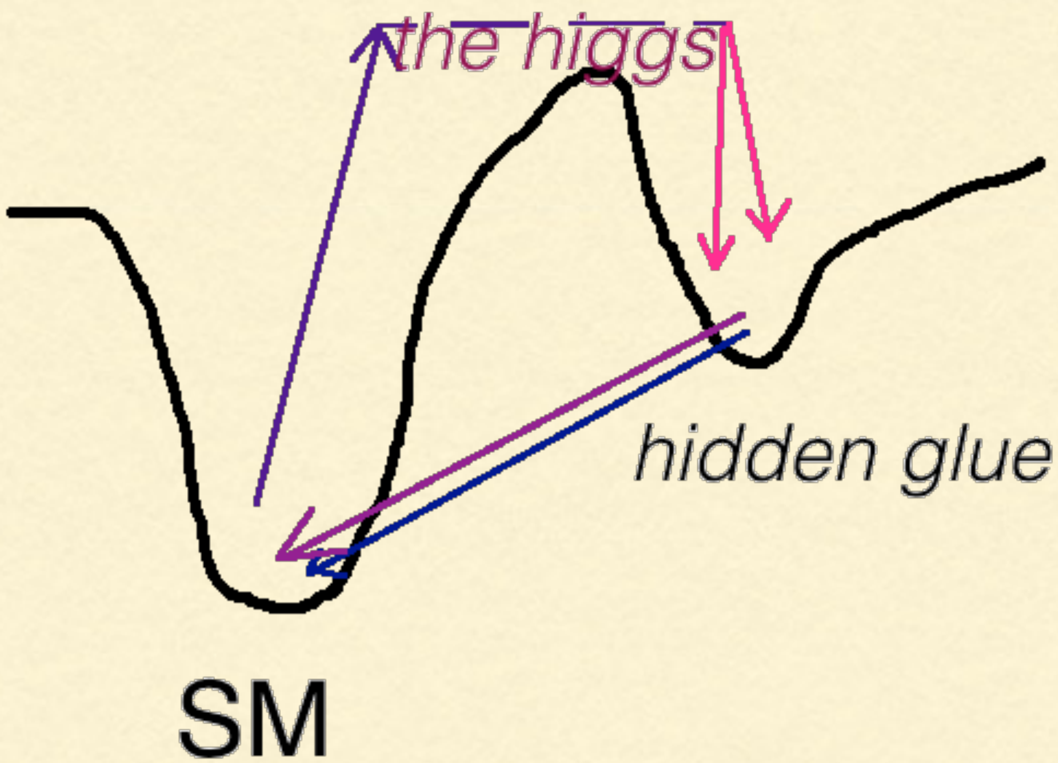
UNIVERSAL PREDICTIONS OF NEUTRAL NATURALNESS

All neutral naturalness scenario predict (small) deviations of the Higgs couplings from the SM values.

- Top partners in folded SUSY have EW charge. We expect deviation of $h\gamma\gamma$ rate from the SM value. In most of the parameter space we expect suppression compared to the SM rate.
- Folded SUSY (like a regular SUSY) implies 2HDM. Expect deviation of the higgs couplings, mostly to the down-type fermions. Slightly model dependent, decoupling or alignment are possible w/o too much fine tuning.

LIKELY PREDICTIONS OF NEUTRAL NATURALNESS

Both twin higgs and folded SUSY predict a new confining force at the twin sector. The confining scale is in most of the cases between 1 GeV to 10 GeV. One can produce the hadrons of the new strong force from Higgs decays (in folded SUSY — also from decays of other particles)



If there are no new light states in the hidden sector, the hadrons of the hidden glue will decay back to the SM. The decay rate

$$\Gamma \propto \left(\frac{\hat{\Lambda}_{QCD}}{m_h}\right)^n$$

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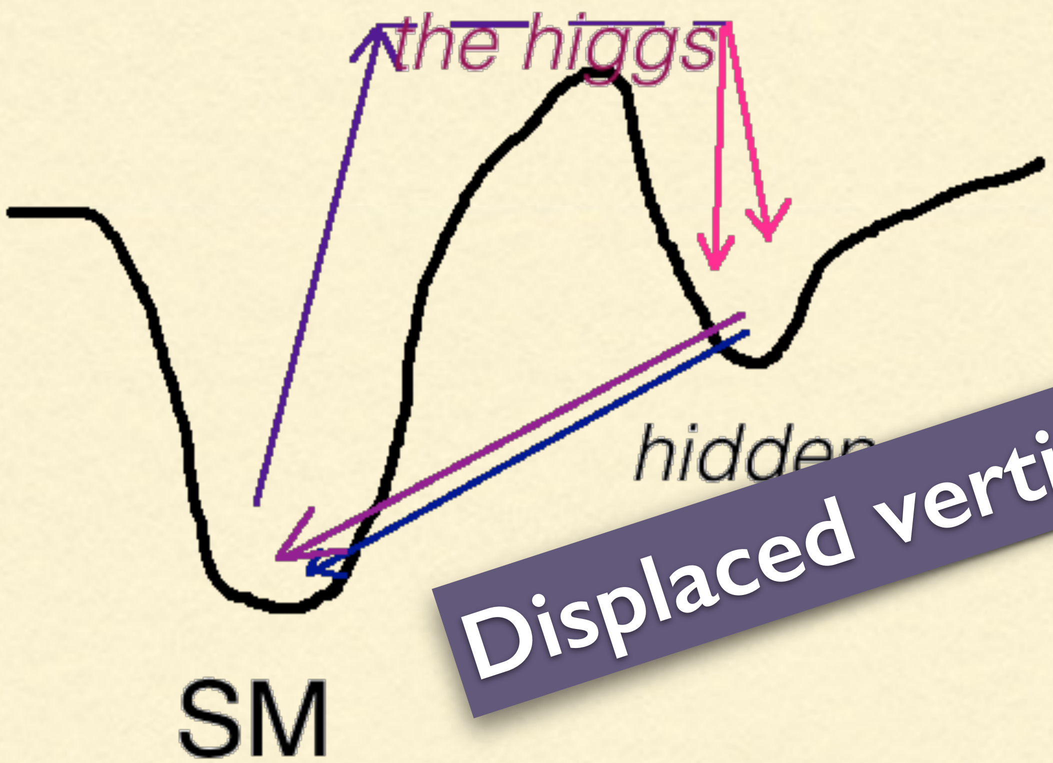

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Displaced vertices from exotic higgs decays

HOW DOES THIS WORK IN THE TWIN HIGGS?

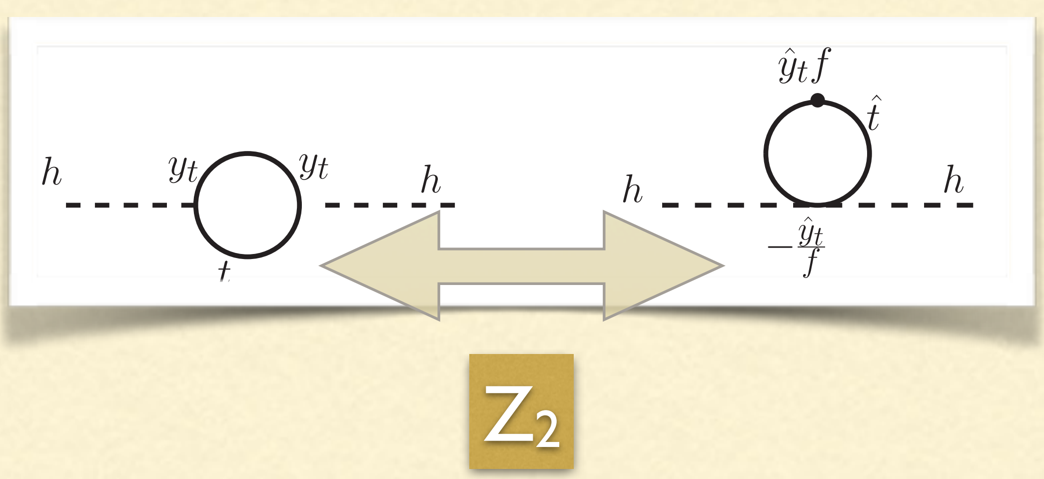
The basic mechanism of the twin higgs:
The full higgs potential has an accidental SU(4) symmetry*.

$$V = \lambda(|\mathcal{H}|^2 - f^2/2)^2$$

full SU(4) doublet

Gauge SU(2)^2 and identify the higgs with the Goldstone boson

In order to get correct vacuum alignment, SU(4) breaking terms should be added.



In order to ensure cancellation of divergencies, we do not need full SU(4) in the quark sector. It is enough to have Z_2 .

**This is a minimal choice, the symmetry can be bigger, e.g. SO(8).*

FRATERNAL TWIN HIGGS

Craig, AK, Strassler, Sundrum; 2015

The original twin higgs idea is based on exact mirror symmetry between the visible and the hidden matter sectors.
The mirror symmetry can be approximate, and we can ask which particles should we keep to get a natural model

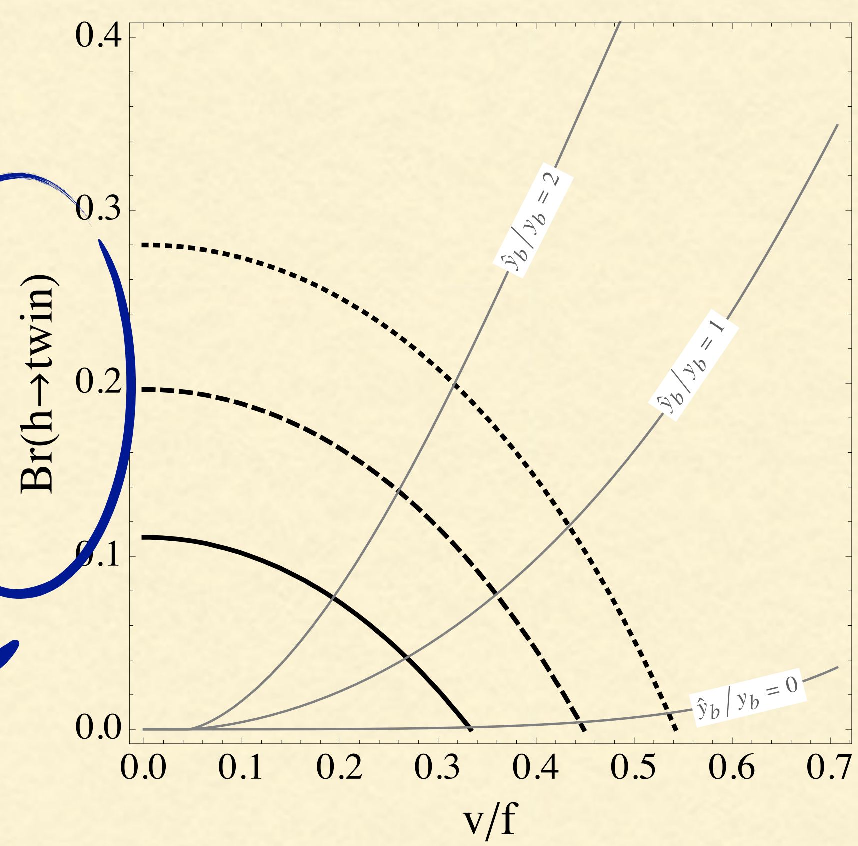
- Mirror top with Yukawa = SM top Yukawa to the level of 1%.
- Mirror W and Z with mirror SU(2) coupling = SM SU(2) to the level of ~ 10%.
- Mirror bottoms and taus for anomaly cancellation (but their Yukawas are almost free parameters)
- Mirror SU(3) with coupling = SM to the level of ~ 25%.
- Light generations are not needed.
- Hypercharge should not necessarily be gauged $\longrightarrow$ no light photon.

TWIN HIGGS — UNIVERSAL SIGNATURES

As in any twin higgs model the couplings to the gauge bosons and fermions are suppressed by $(v/f)^2$ due to misalignment. However, FT ~ $(v/f)^2$.

The higgs couplings fit directly constraints naturalness in any twin higgs model.

Free parameter in fraternal twin higgs, because we do not know what is twin bottom Yukawa



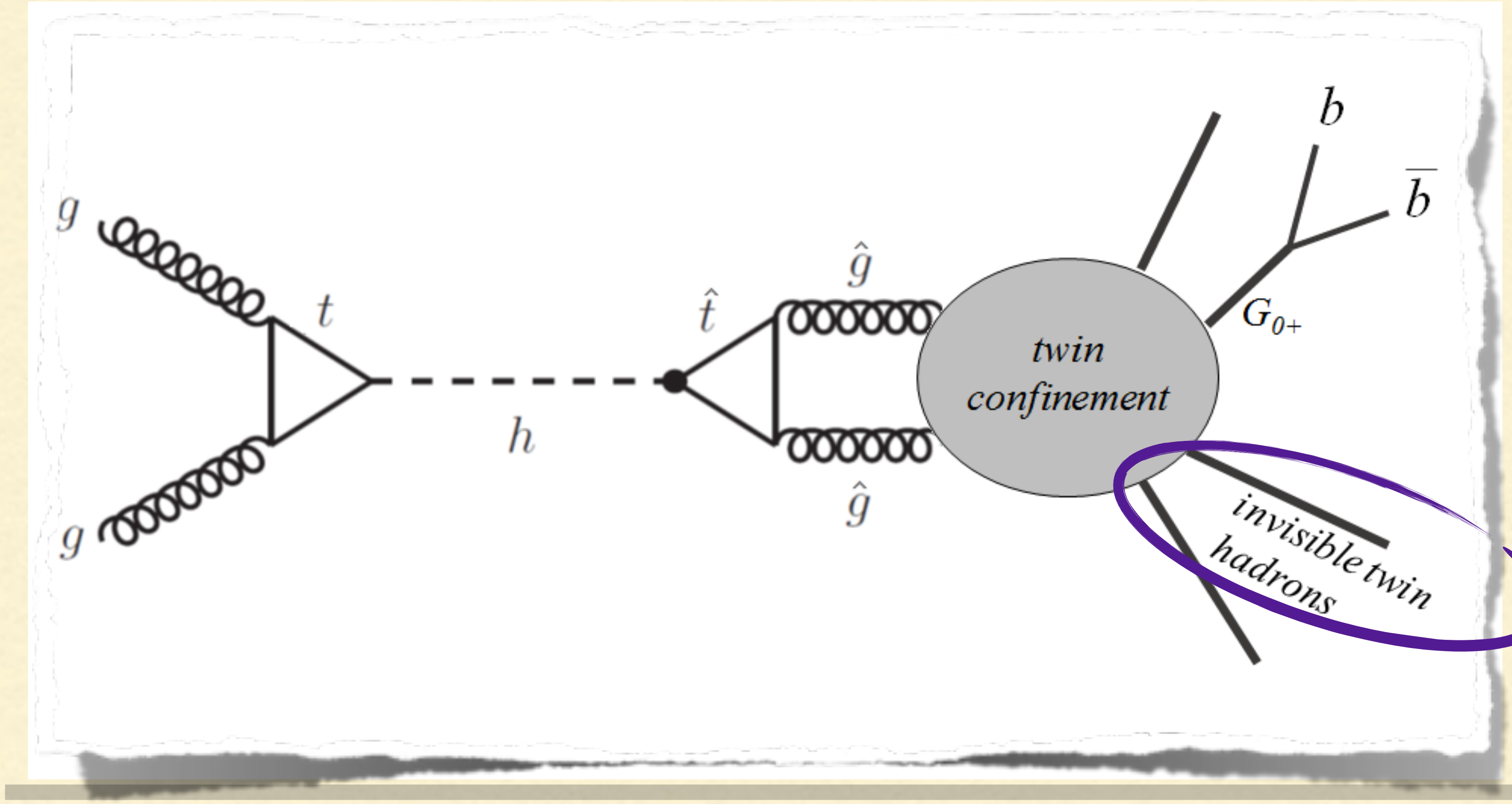
At this point the constraints are mild, and v/f ~ 0.4 are still allowed, corresponding to almost no fine tuning. However, we expect more precise measurements at the LHC13 and especially the HL LHC.

OTHER SIGNATURES OF FRATERNAL TWIN HIGGS

Mixing between the visible and the twin higgs introduces a coupling:

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

Model independent higgs decay rate to the hidden sector for v/f = 1/3 is of order 0.1%. This rate does not depend on the higgs coupling to the twin bottoms and taus!



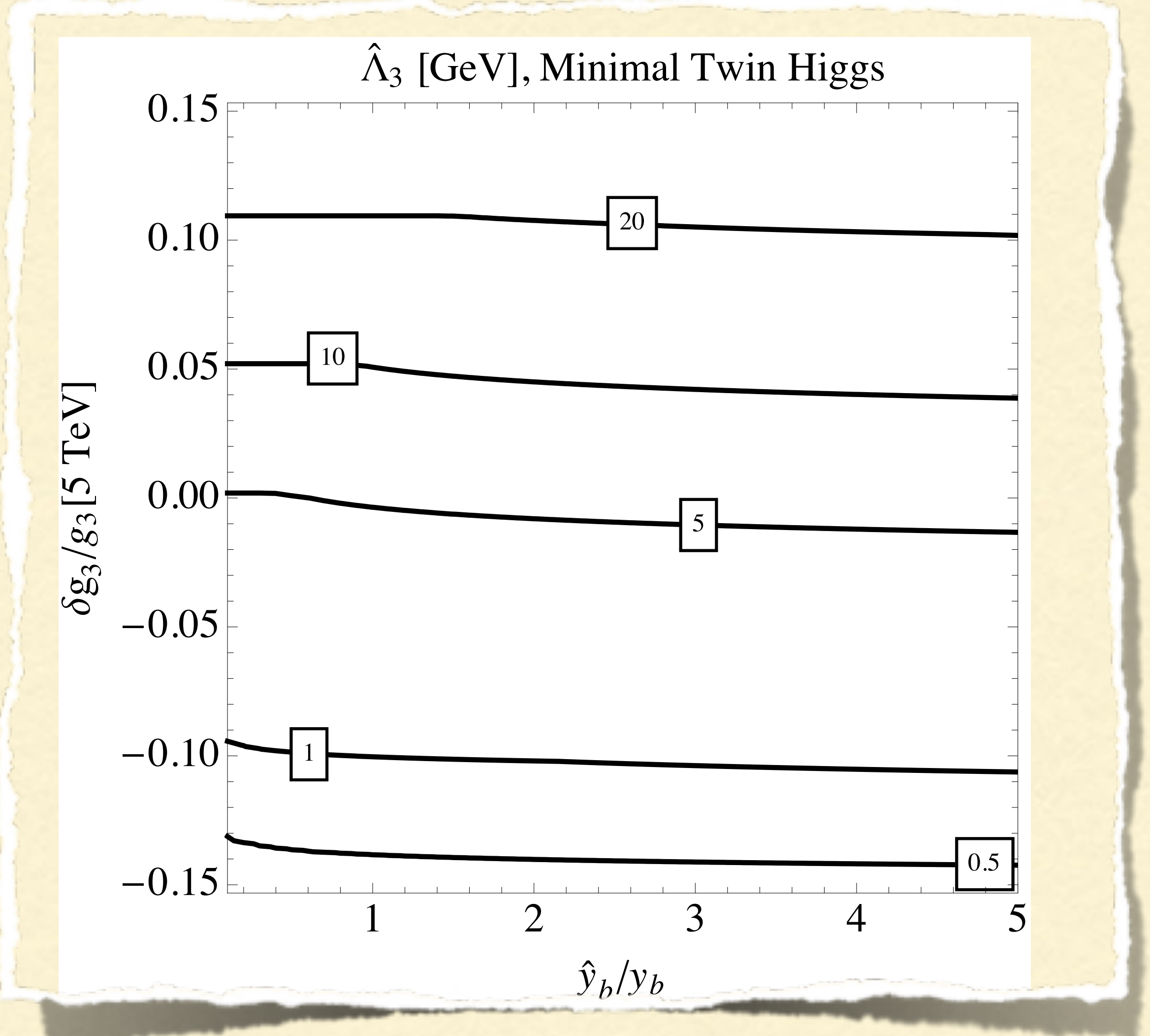
The twin sector does not have light states. We can expect that some of the hidden hadrons will decay to the SM via displaced vertices.

FRATERNAL COLOR

If twin bottom Yukawa is not very small, the spectrum at the of the lightest states in the hidden sector is that of pure glue:

The running to the Landau pole is faster with one generation: the confinement scale is slightly higher than in the SM.

Depending on the precision of the mirror symmetry the confinement scale is between 1 GeV and 20 GeV.



TWIN GLUEBALLS

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

- Tower of states with different spin, P and C.
- The lowest state is 0^{++}
- Heavy states decay very fast into the light ones if allowed
- The lightest state is $m_{0^{++}} \approx 6.8\hat{\Lambda}_{QCD}$
- 0^{++} can decay to the SM via its mixing with the higgs
- other states which do not decay to lighter glueballs have very long lifetimes $\longrightarrow$ MET at the LHC

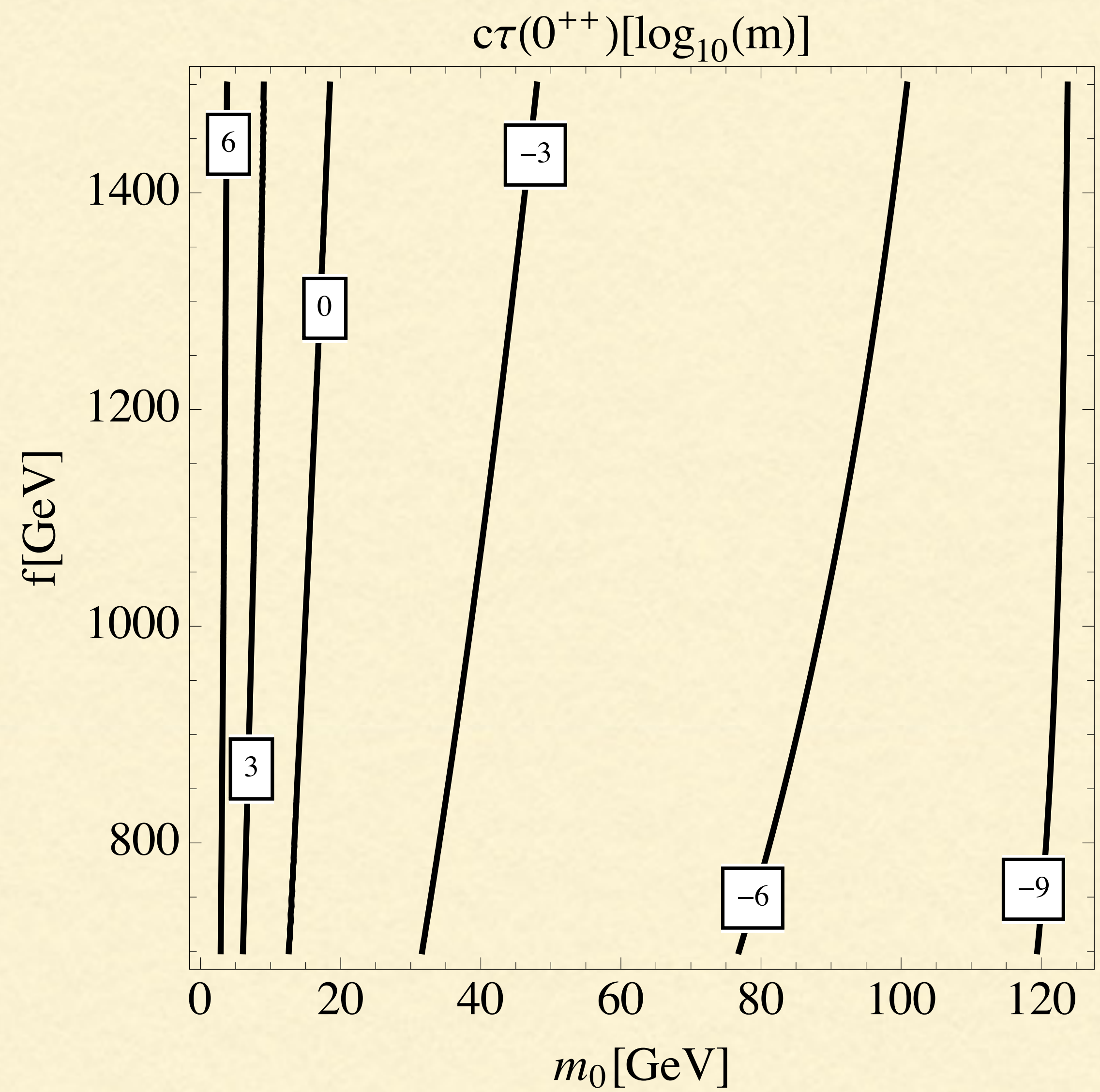
THE LIGHTEST GLUEBALL

Juknevich; 2009

Decay rate:

$$\Gamma_{G_{0+}\to YY} = \left(\frac{\hat{\alpha}_3 v f_0}{6\pi f^2 (m_h^2 - m_0^2)}\right)^2 \Gamma^{SM}_{h\to YY}(m_0^2)$$

decay constant which is known from lattice $\propto m_0^3$



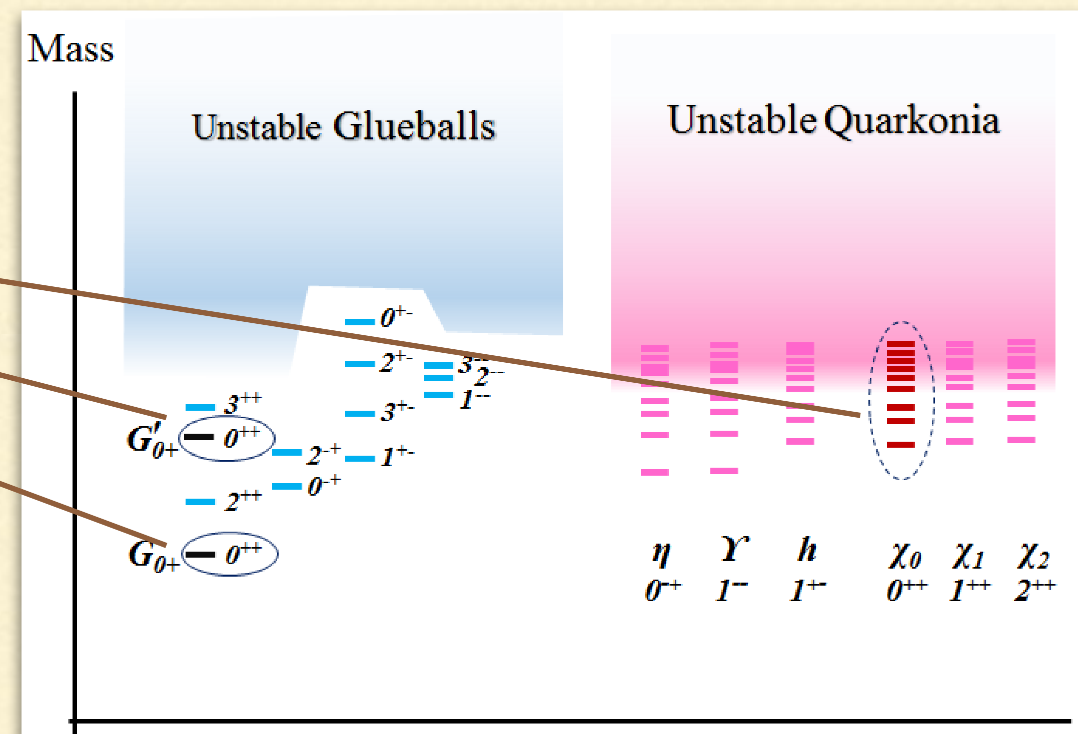
The decay is proportional to the 7th power of glueball mass!
Signal: displaced vertices. Displacement can vary from micrometers to tens or hundreds of meters.

DARK QUARKONIUM STATES

The twin bottom should be in the spectrum due to anomaly cancellation. Its mass is a free parameter, as long as it does not reintroduce the hierarchy problem (~70 GeV)

All these states can decay to the SM via their mixings with the higgs.

In quarkonium spectrum the chi's are not the lightest states, SM decays compete with the dark sector cascades



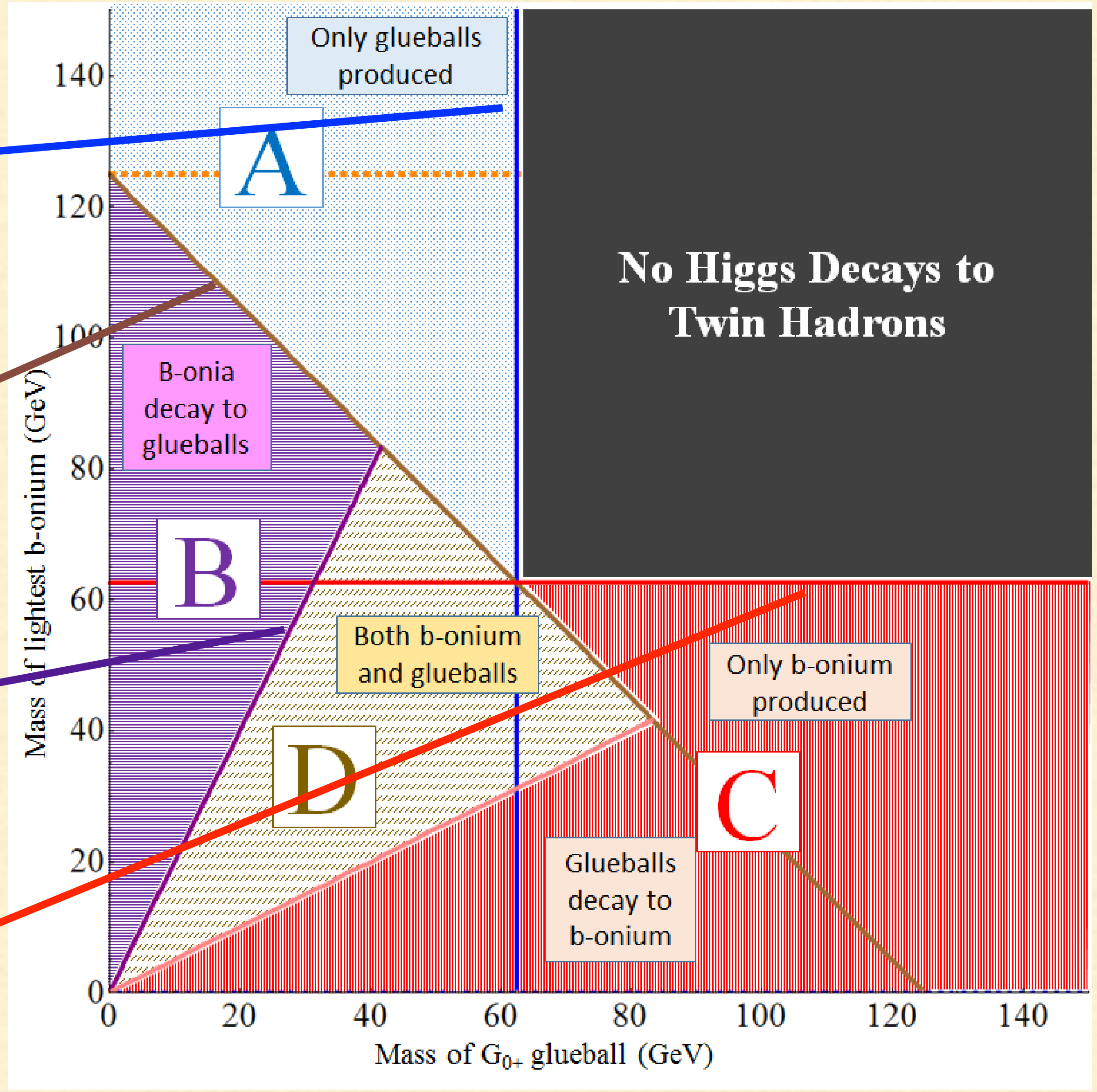
FULL PARAMETER SPACE

Two glueballs production is kinematically allowed

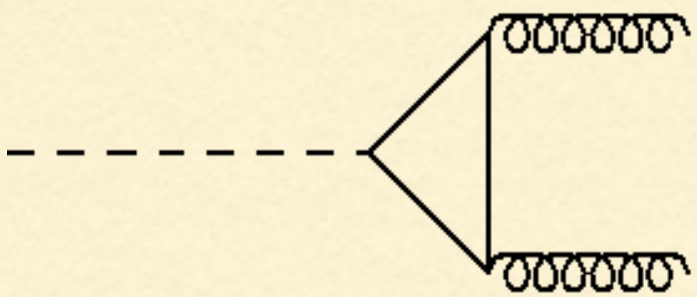
Glueball + bottomonium is kinematically allowed

Qaurkonia can decay to glueballs

Di-quarkonia production is kinematically allowed

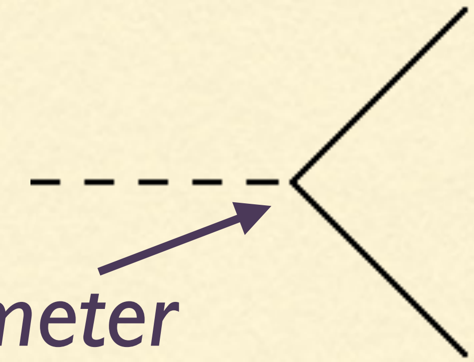


EXPECTED RATES



Irreducible, ~ 0.1%

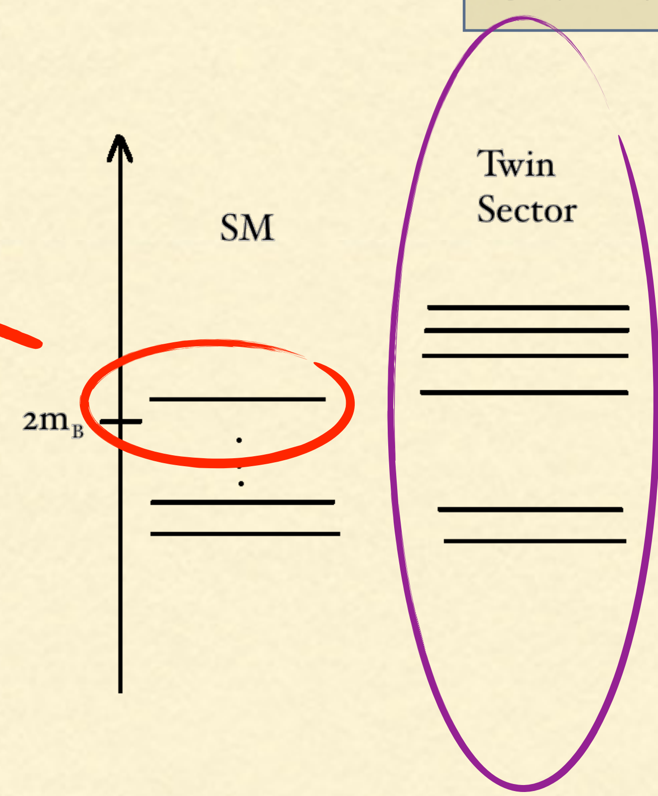
Model dependent:



coupling — free parameter

Can we rely on perturbation theory?

promptly decays to B-mesons



No light quarks, no decays into B-mesons. The towers extend much higher than in the SM

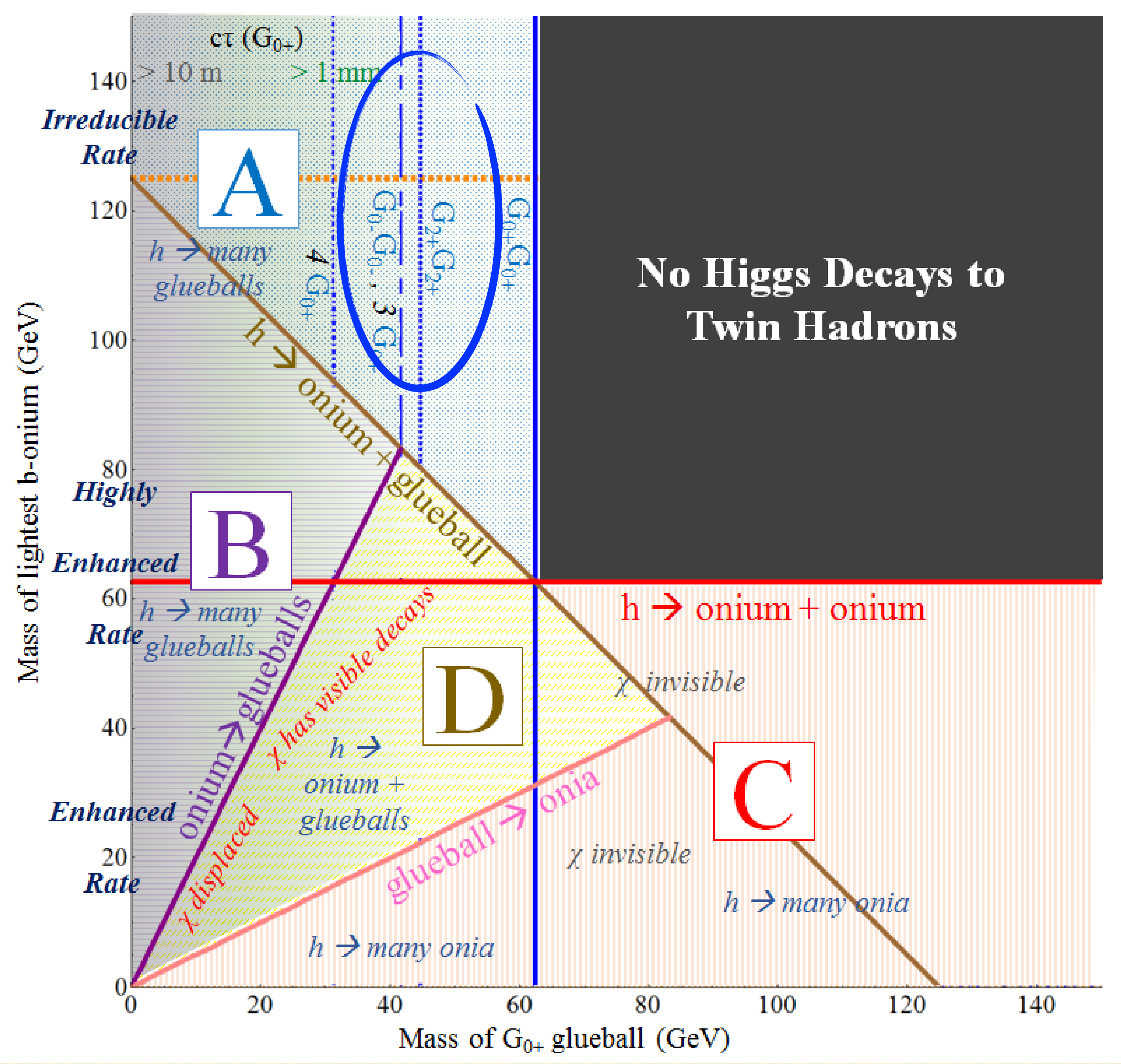
The resonance structure of 2-point function can significantly modify the naive perturbative rates

LHC SIGNALS

Dominated by h → 2 decays with BR ~0.1%

prompt decay — hopeless at the LHC

displacement: h→4b with 2 displaced vertices of order mm



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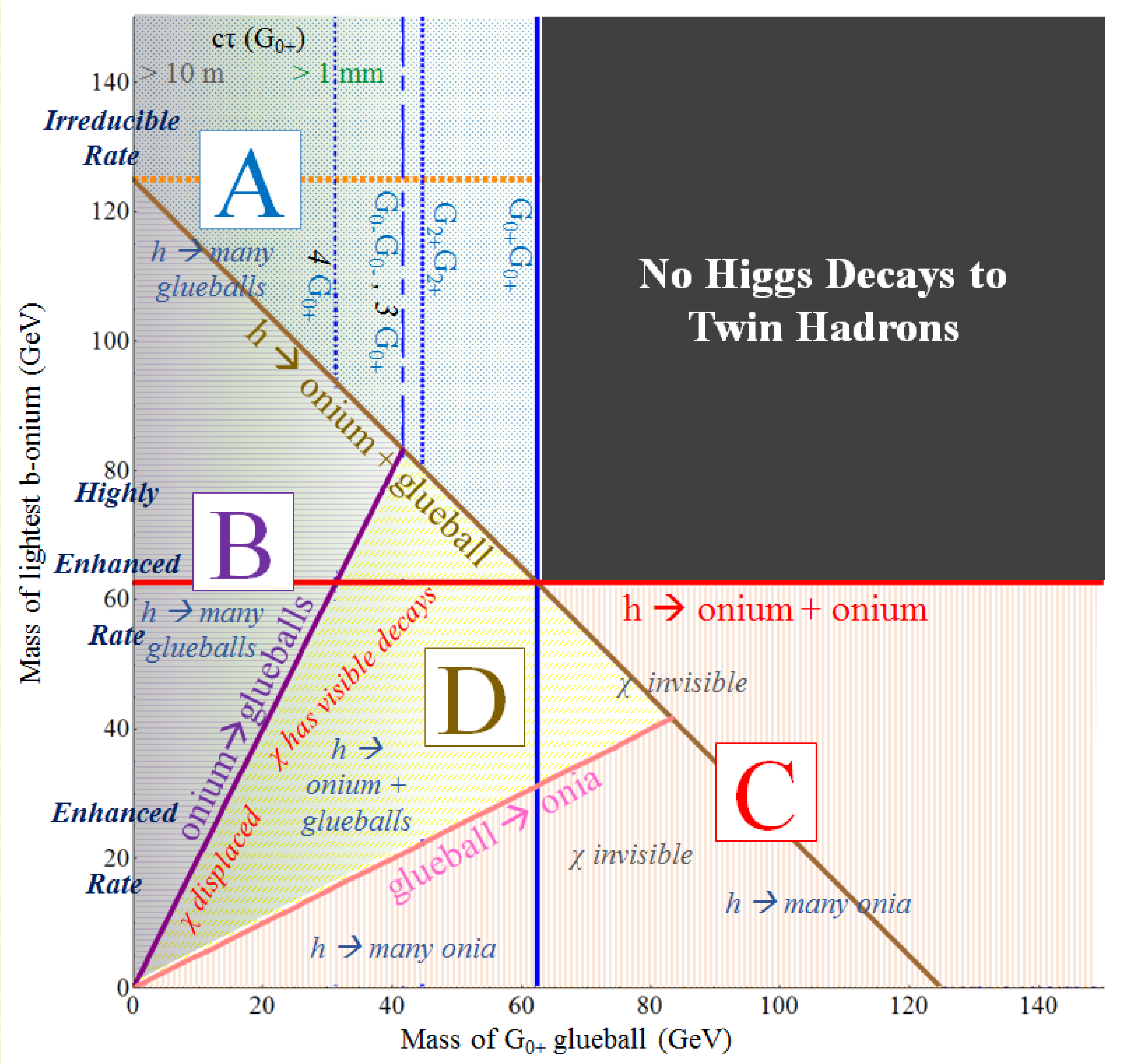

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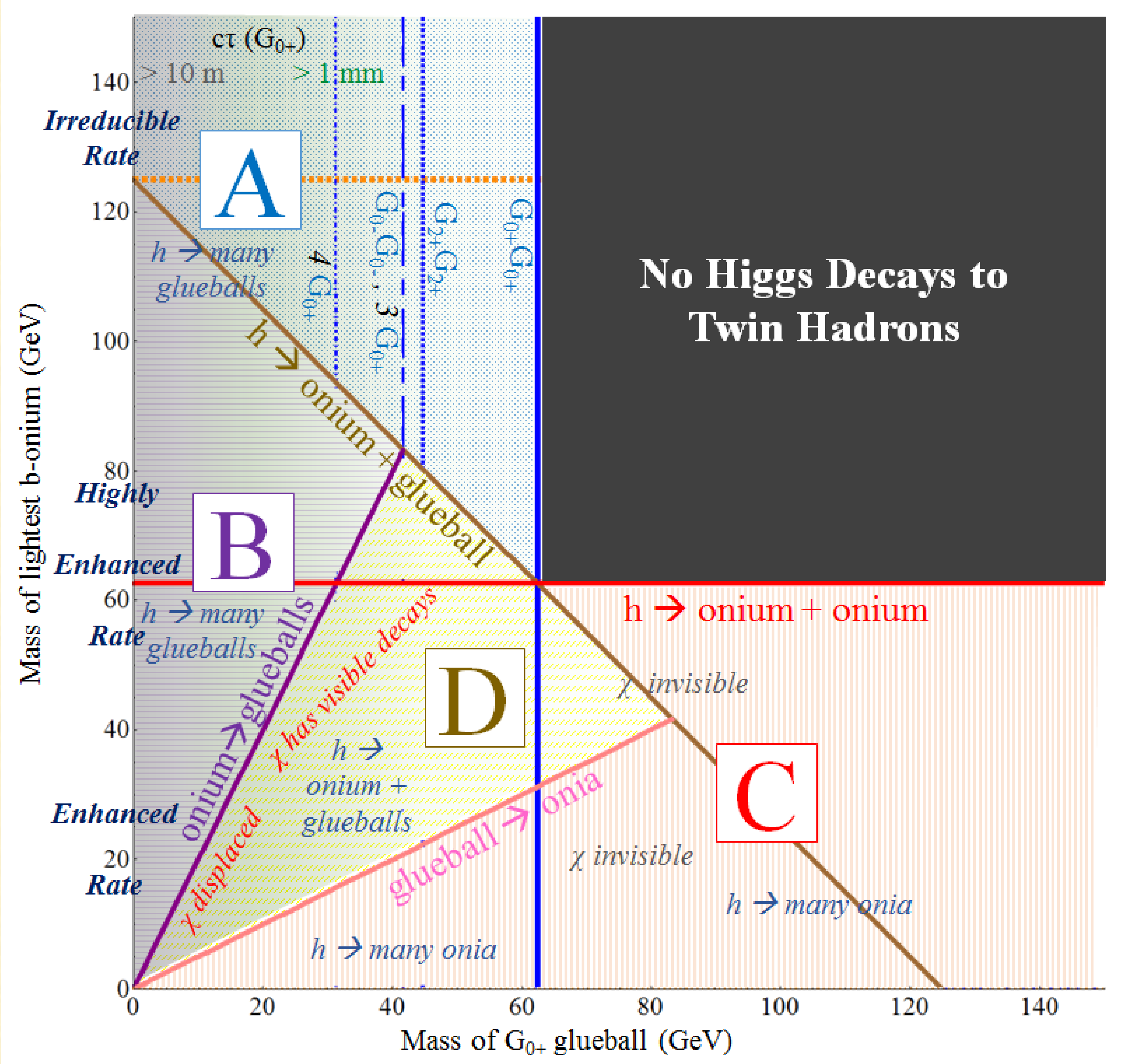

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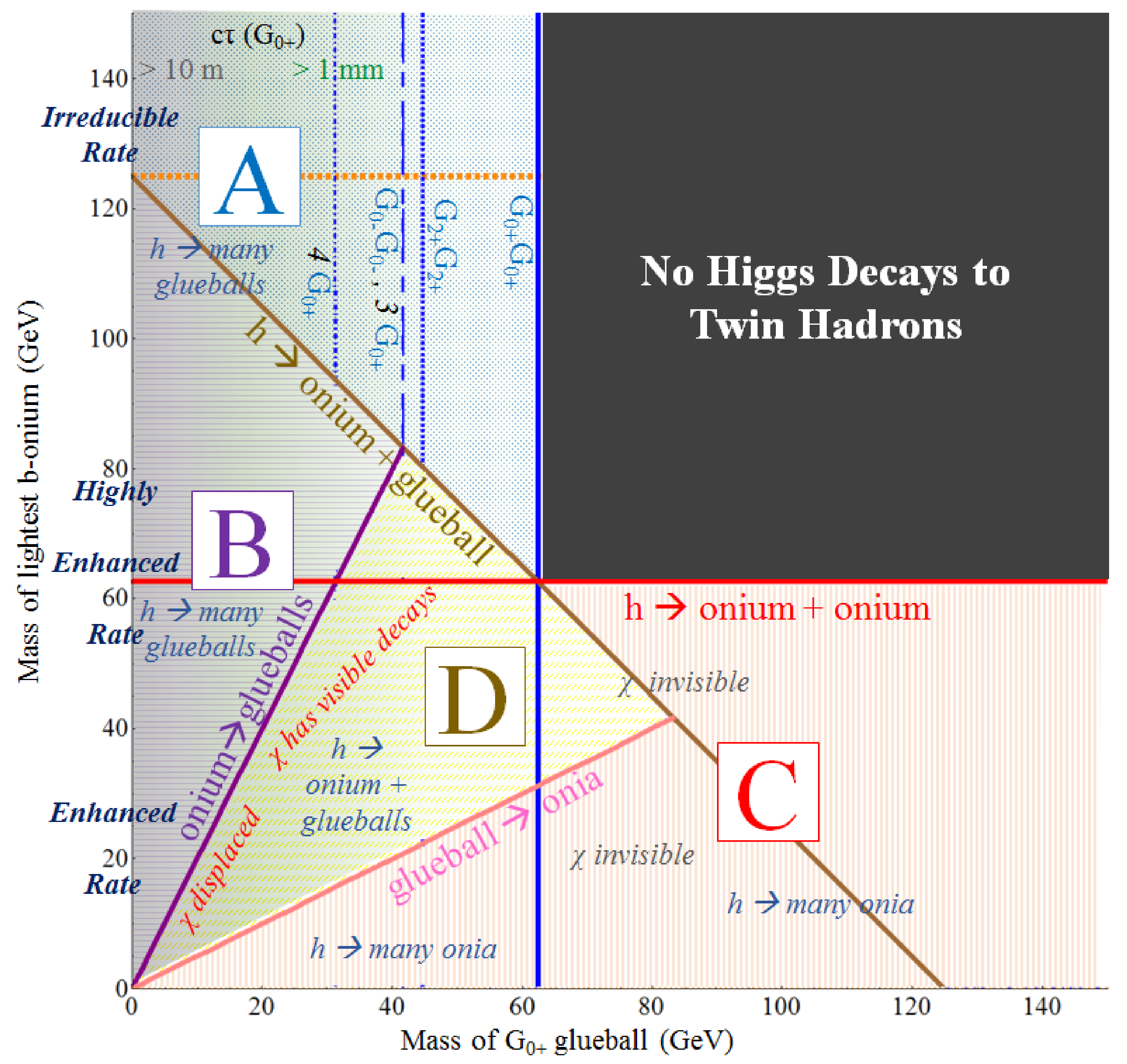

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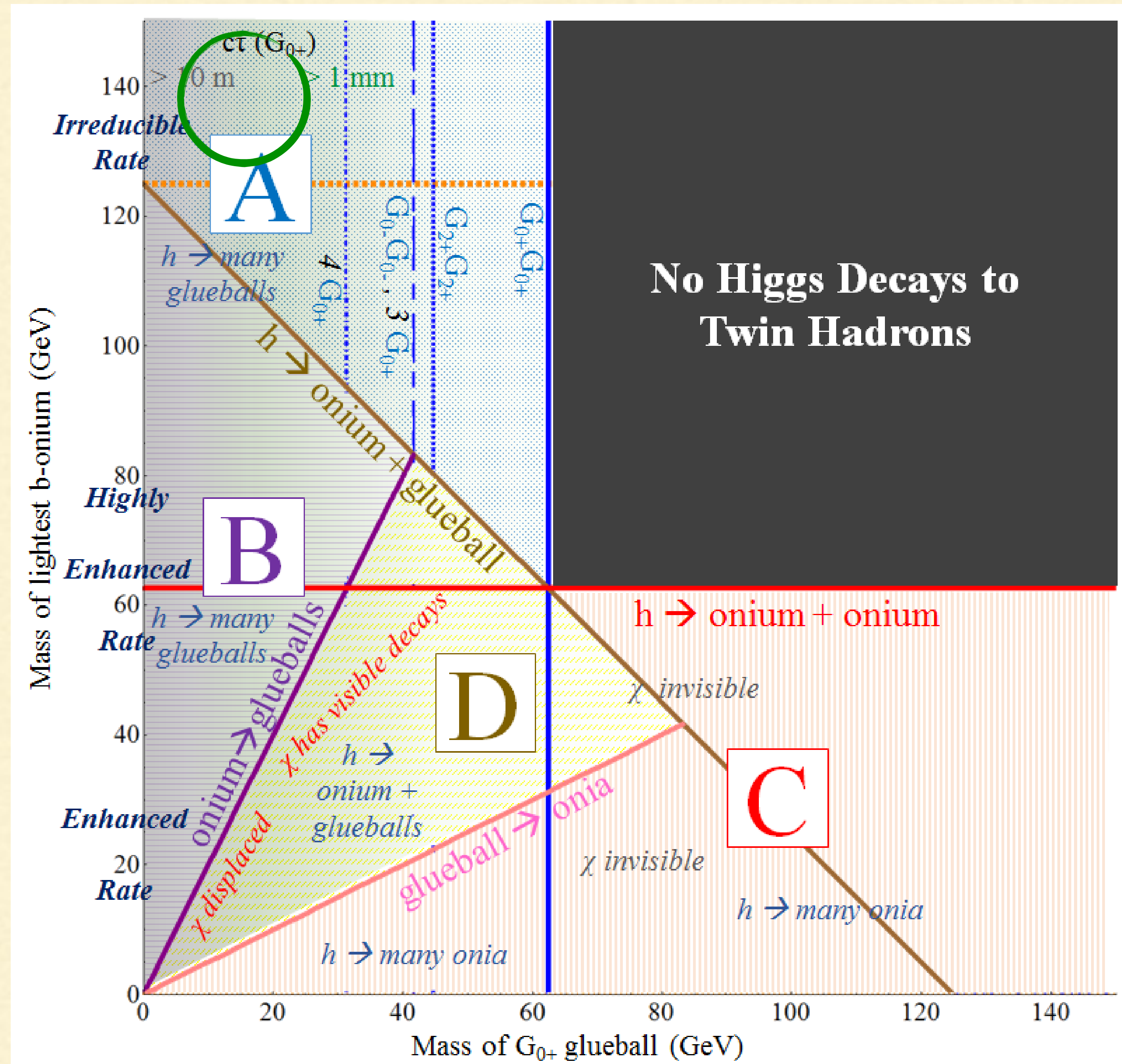

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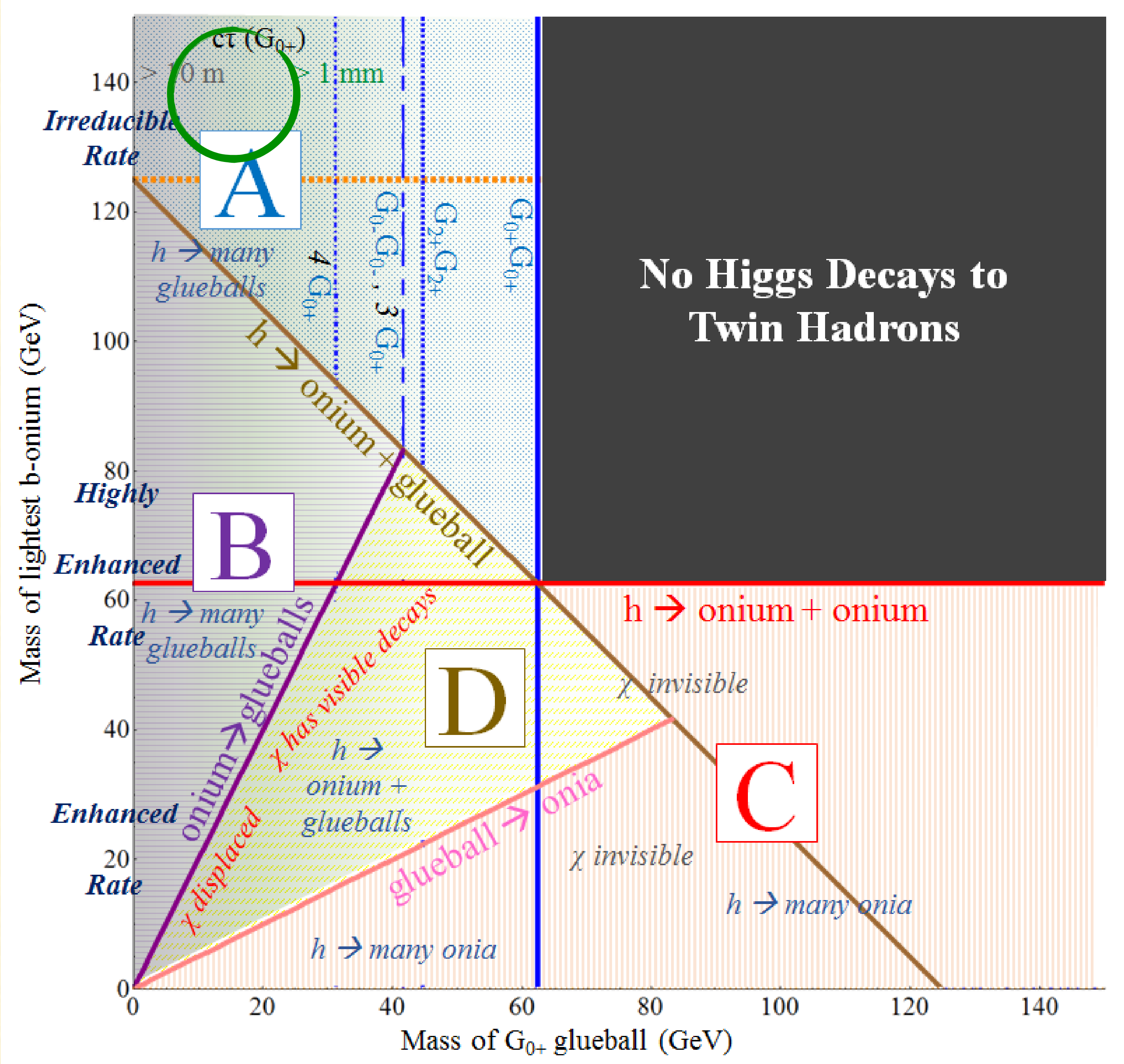

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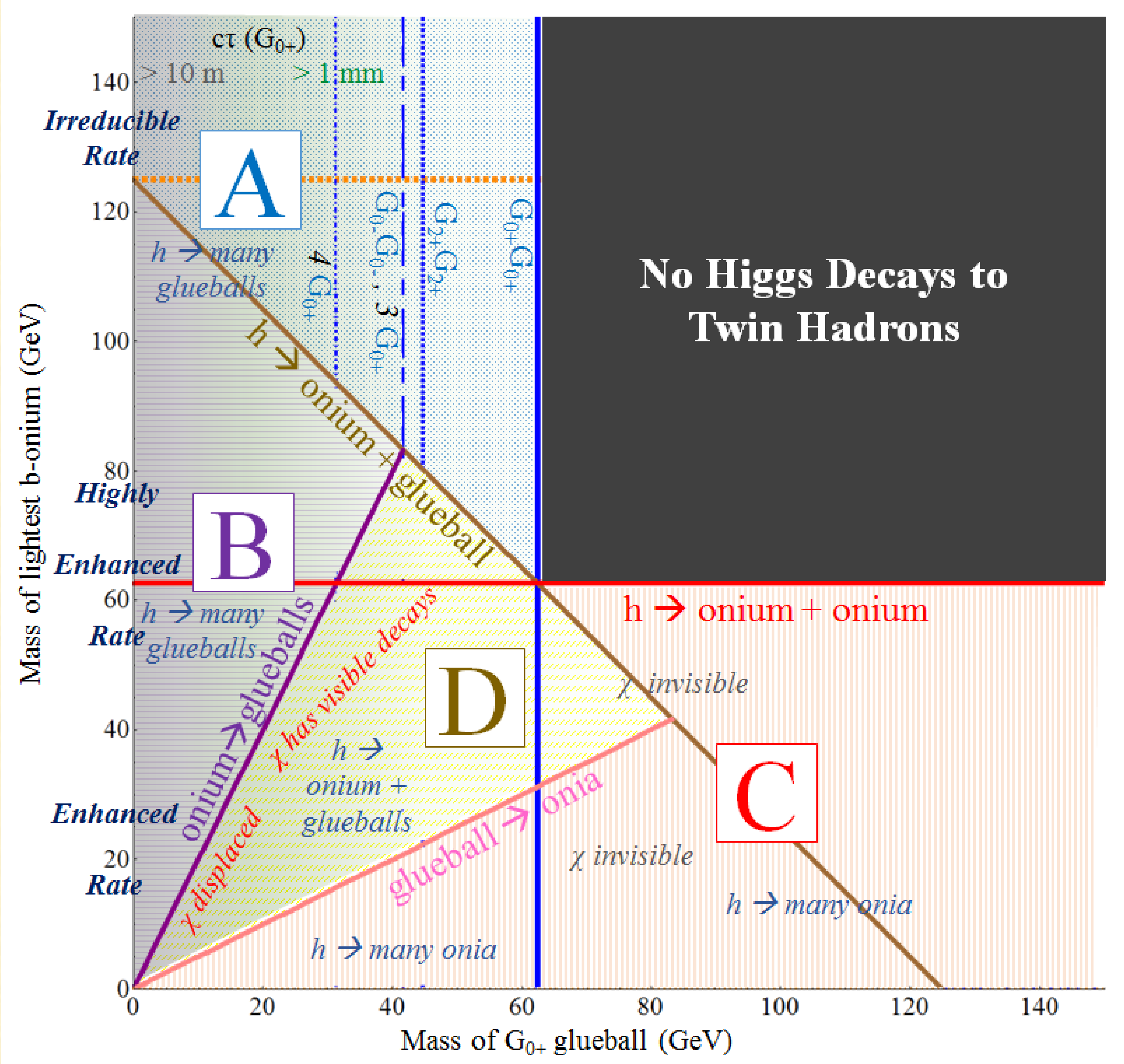

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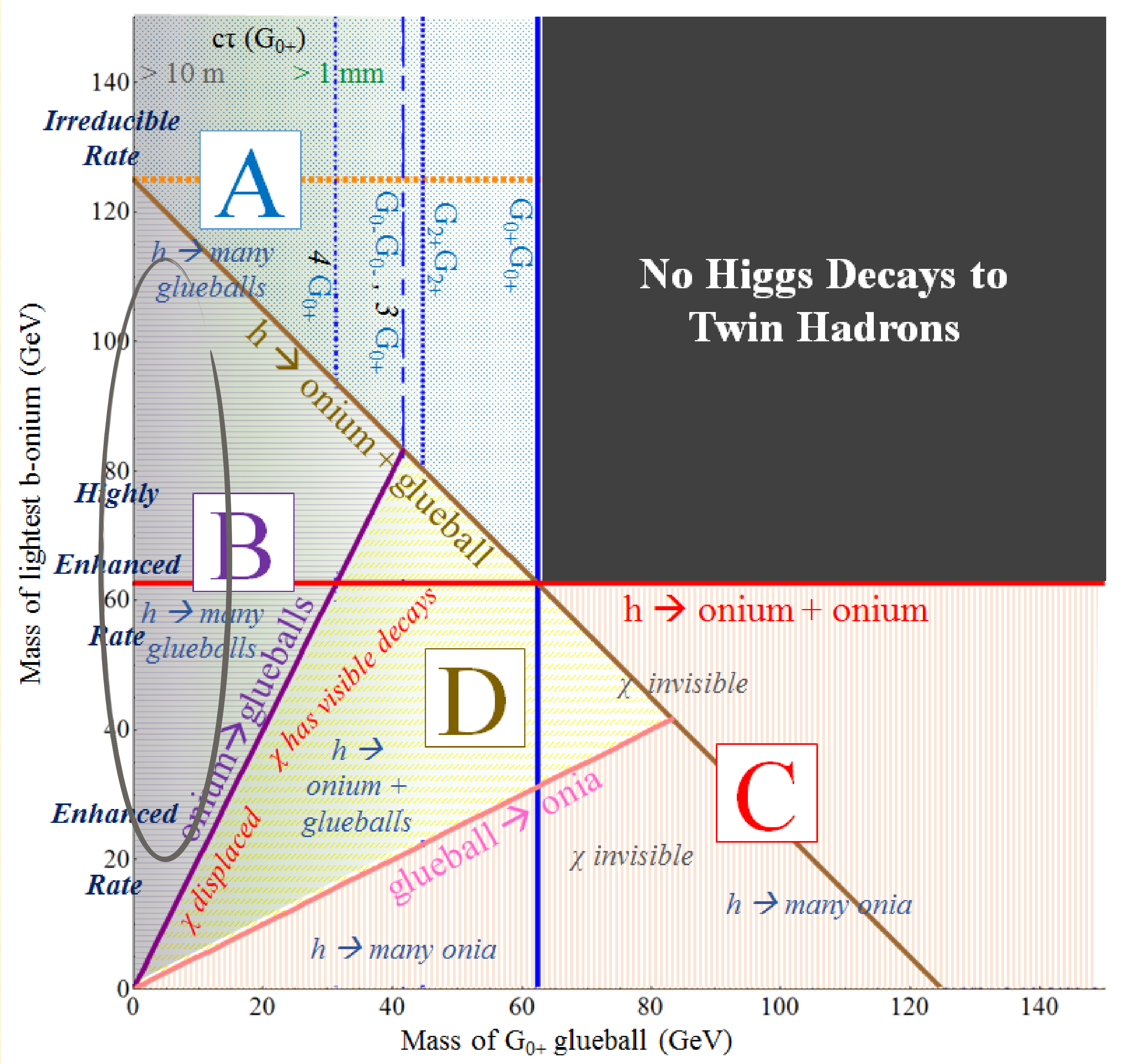

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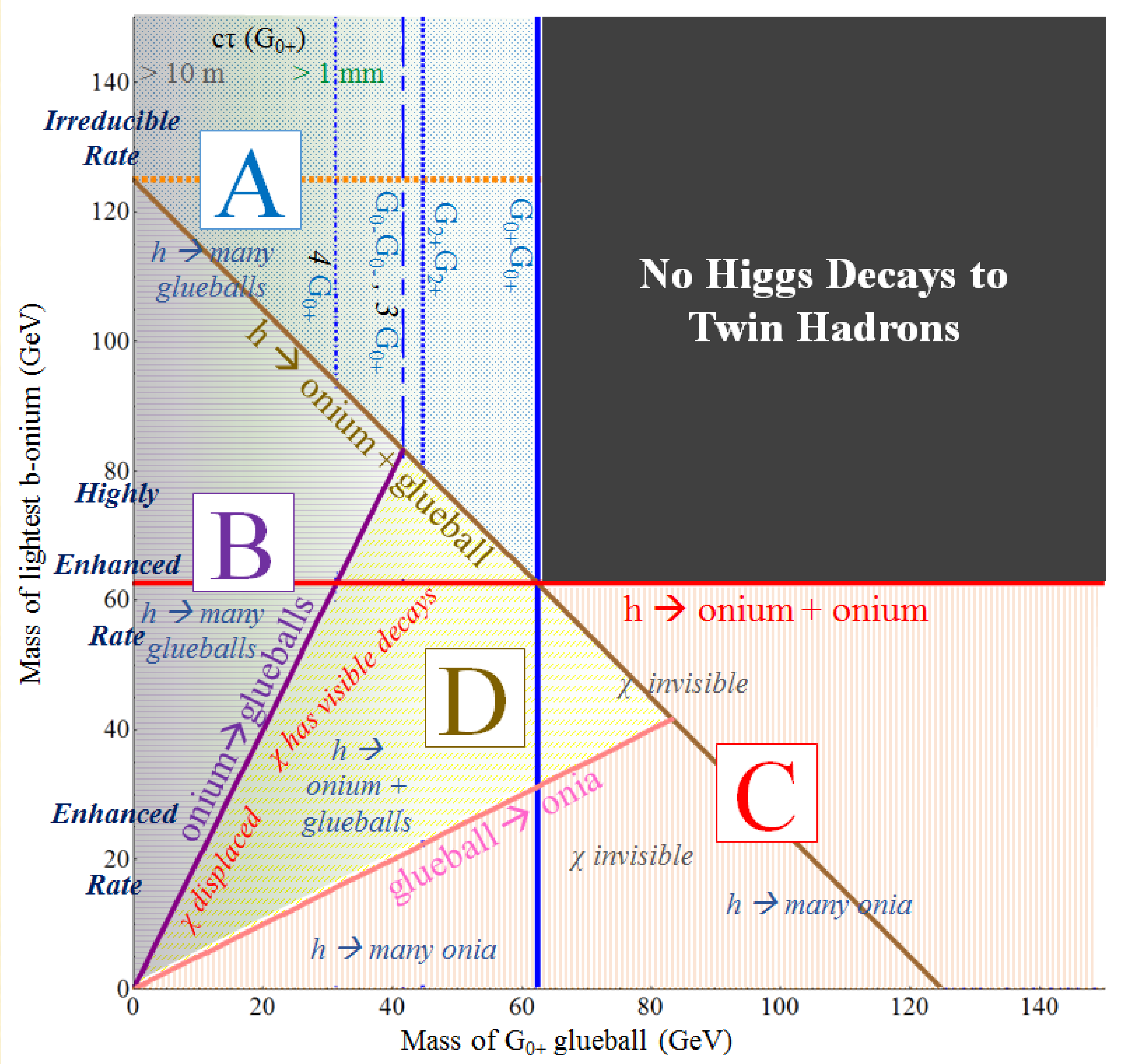

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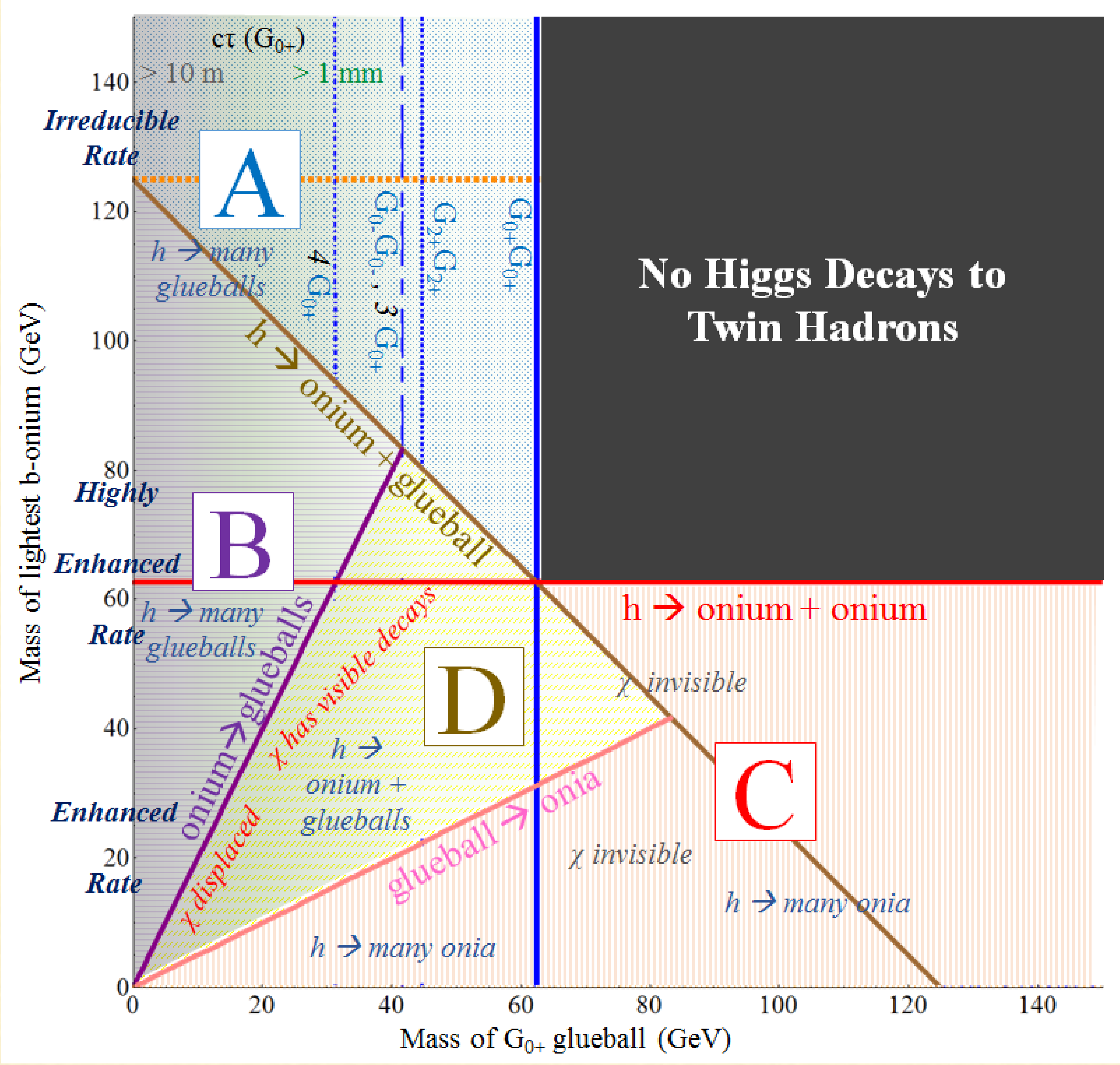
Mostly h→onia+gluballs, onia and glueballs mix



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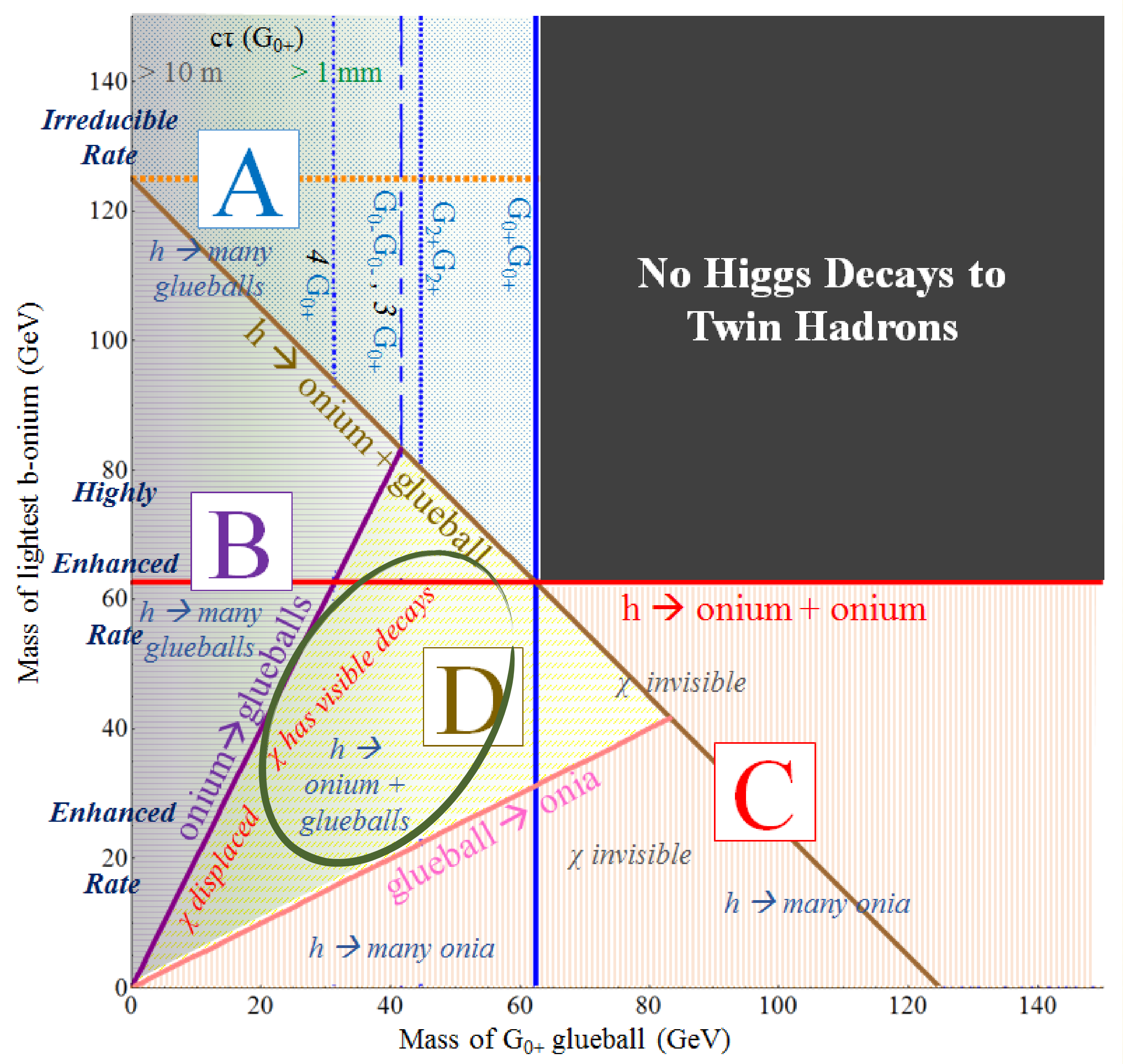

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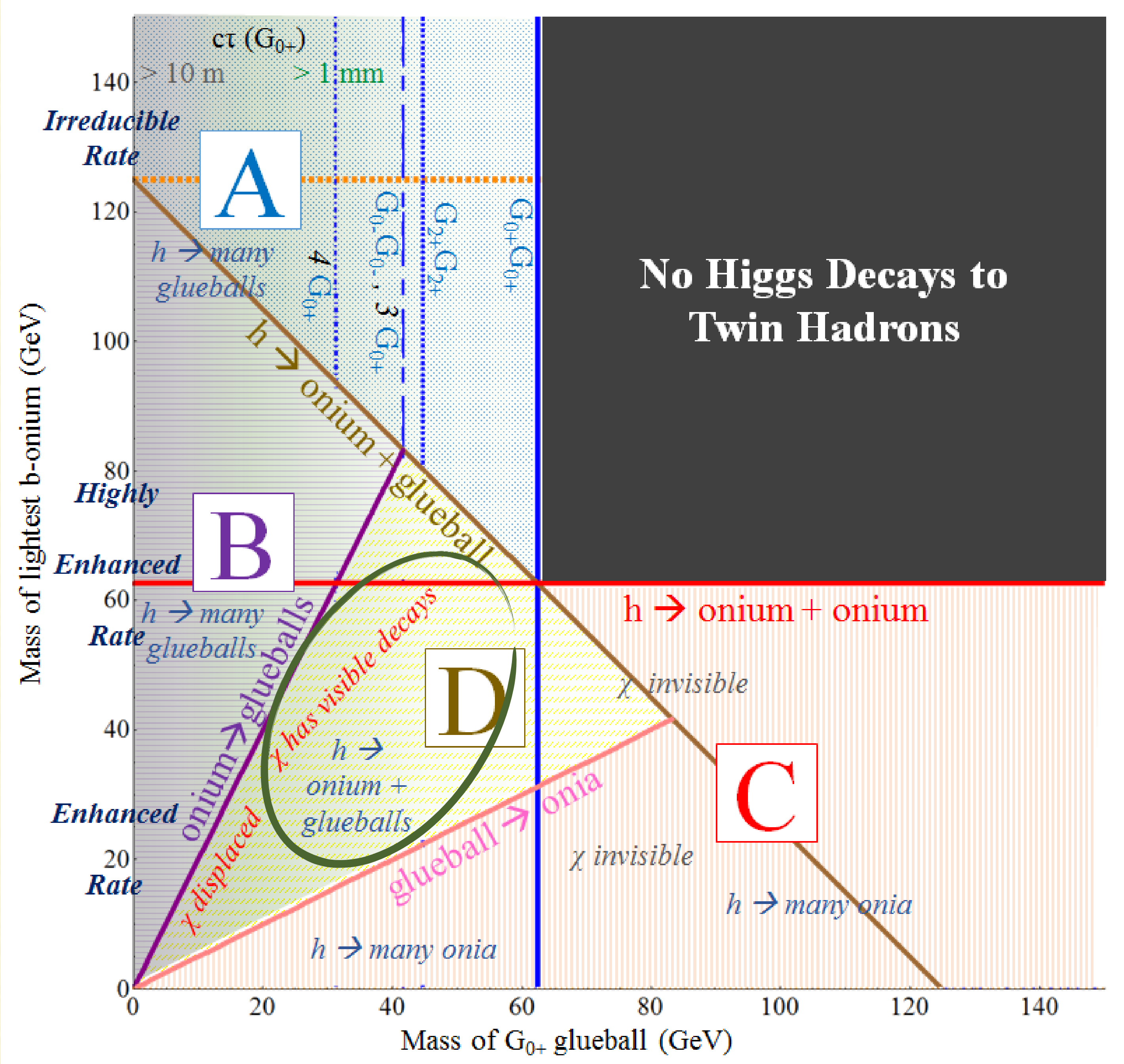

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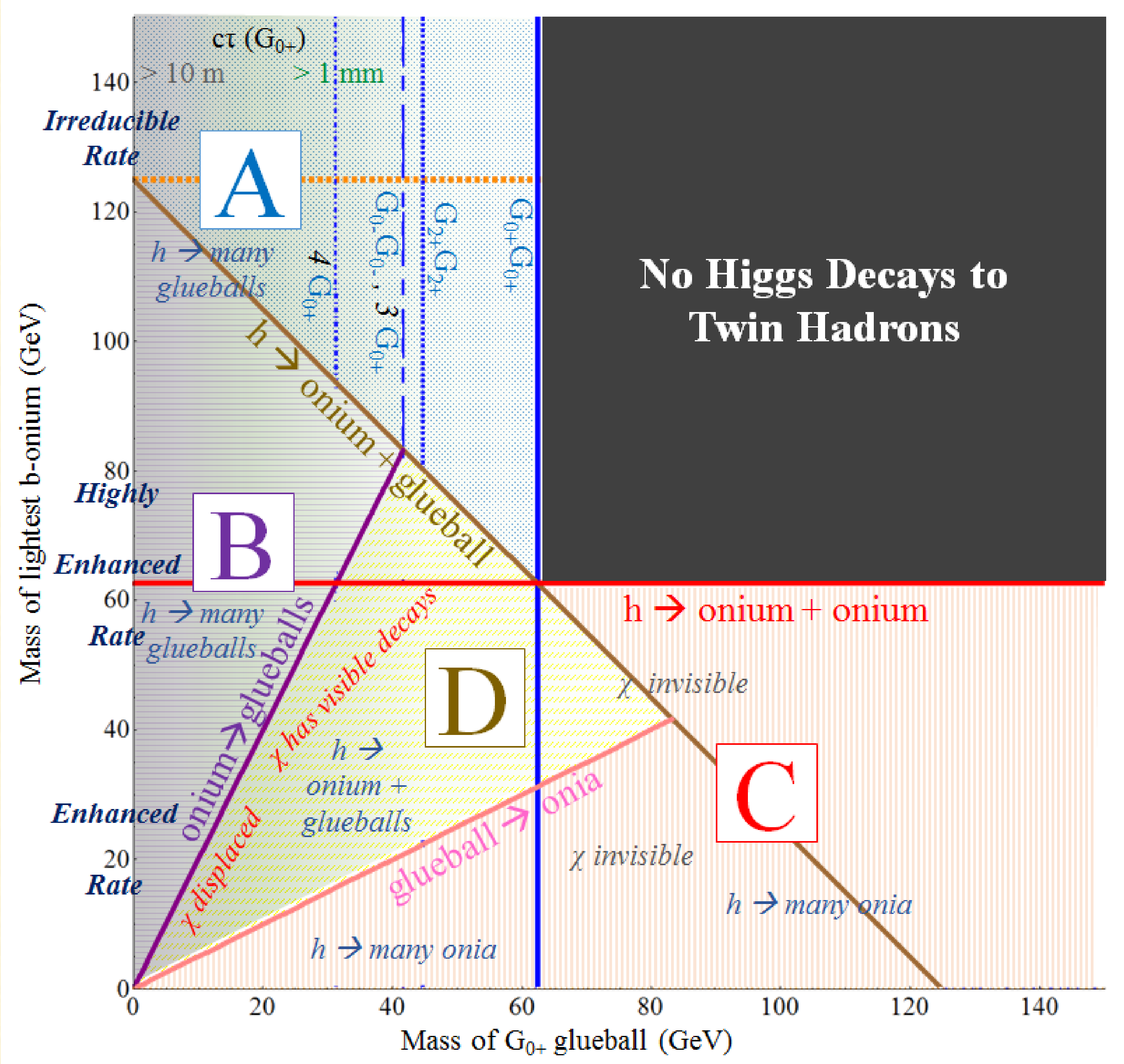

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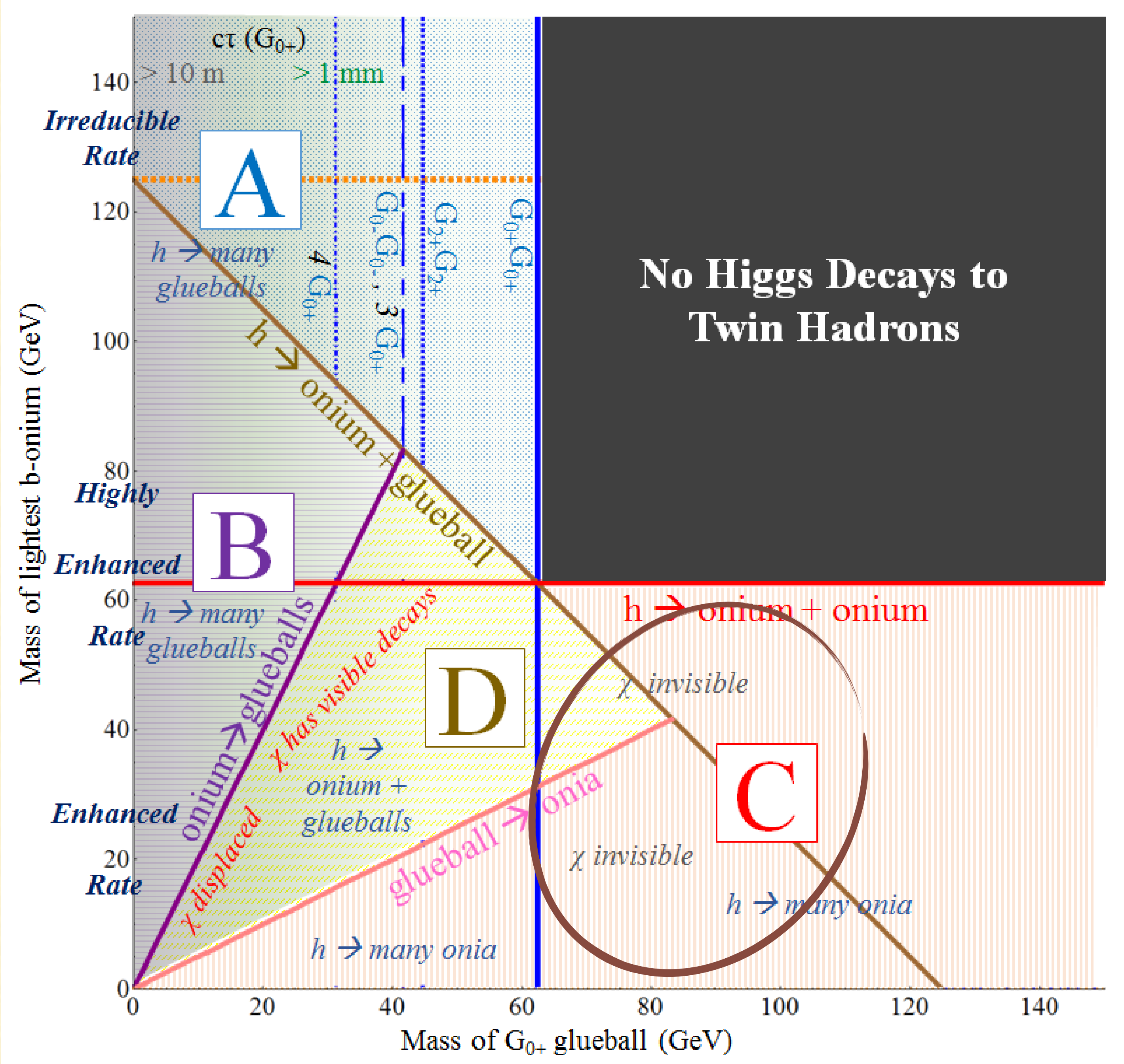

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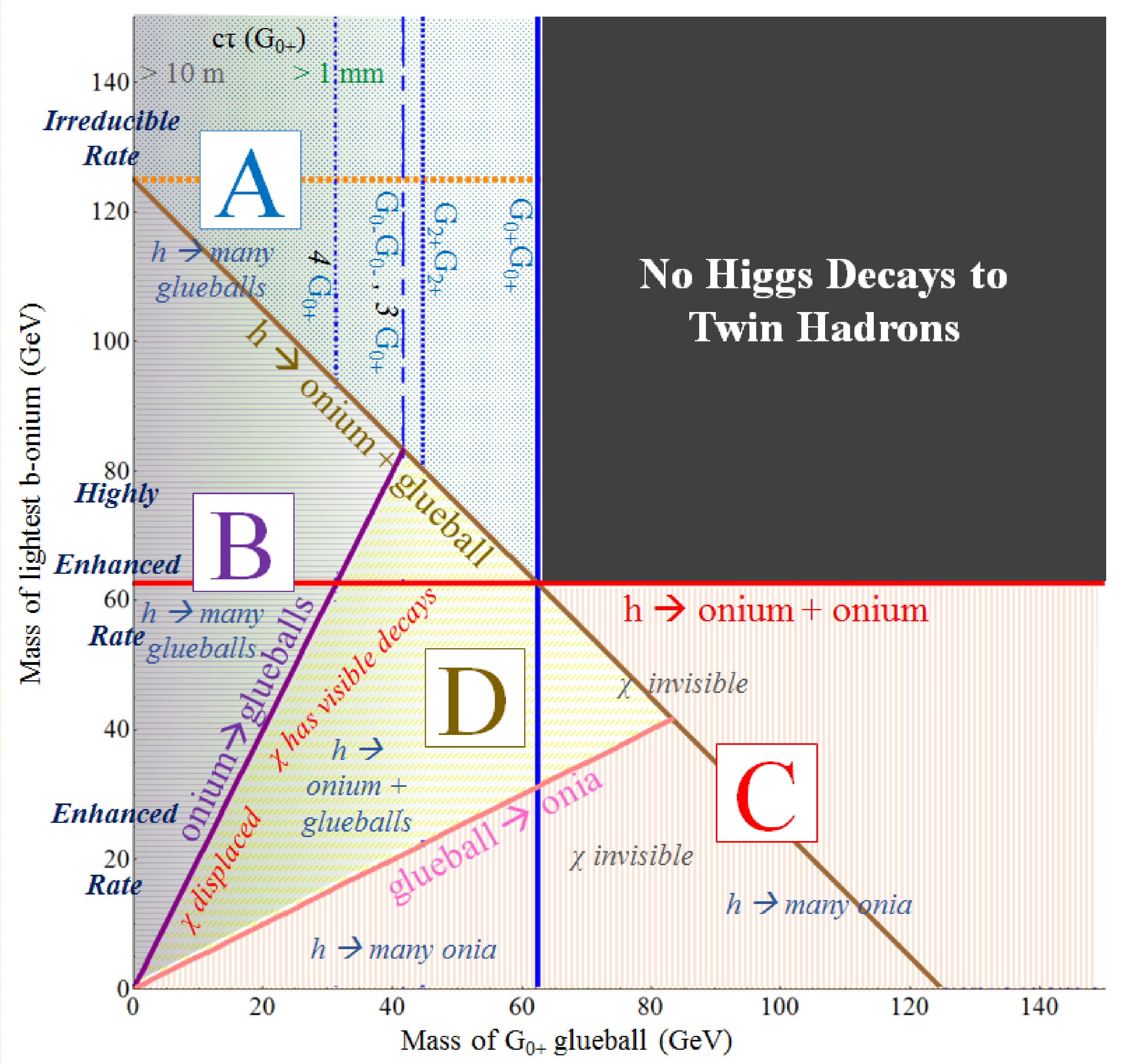

PROPOSED LHC SEARCHES

- Exclusive double displaced vertex (heart of the region A) with full reconstruction of higgs invariant mass
- Single displaced vertex — usually hard due to unknown and hard-to-estimate backgrounds. Use associated production and VBF. Especially relevant for large lifetime (~10 m). Small accpeted rates!
- Inclusive double displaced vertex — relevant for regions dominated by $h \to$ many, may include MET.

LHC AND BEYOND

If glueballs are heavy, around 40 GeV, the displacement is lost. This can happen in fraternal twin higgs (if we are unlucky). This is even more generic in folded SUSY, where we expect somewhat heavier glueballs.

- Dominated to $h \to 2$ glueballs.
- Glueball decay without displacement with the same BR's, as the higgs would decays, if its mass had been equal to the glueball mass
- Irreducible BR — 0.1%. If we are lucky, we can have reducible enhancement up to factor 100.

Decay modes to look at:

$h \to 4b$ (~80%) $h \to 2b2\tau$ (>15%) $h \to 2b2\mu$ (around 0.5%)

HL LHC should have sensitivity ~ 10^{-4}

SUMMARY

- Signatures of "neutral naturalness" are either exotic events (displaced vertices, exotic higgs decays) or small deviations in higgs precision measurements — can be detected only with HL machines
- All neutral naturalness models predict that higgs couplings deviate from the SM values at the level of $\lesssim$ 10%. In some models (twin higgs) higgs couplings fit directly constraints the naturalness of the theory.
- Lots of scenarios predict decays of the higgs with displaced vertices, with the rate at least 0.1%. Very rare, but spectacular events.
- Most of the signatures do not require high energy, but do require high luminosity.