Connection Between Cosmology and HEP: the Hidden Valleys

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SWHEPPS 2016, Unterägeri; June 8, 2016.

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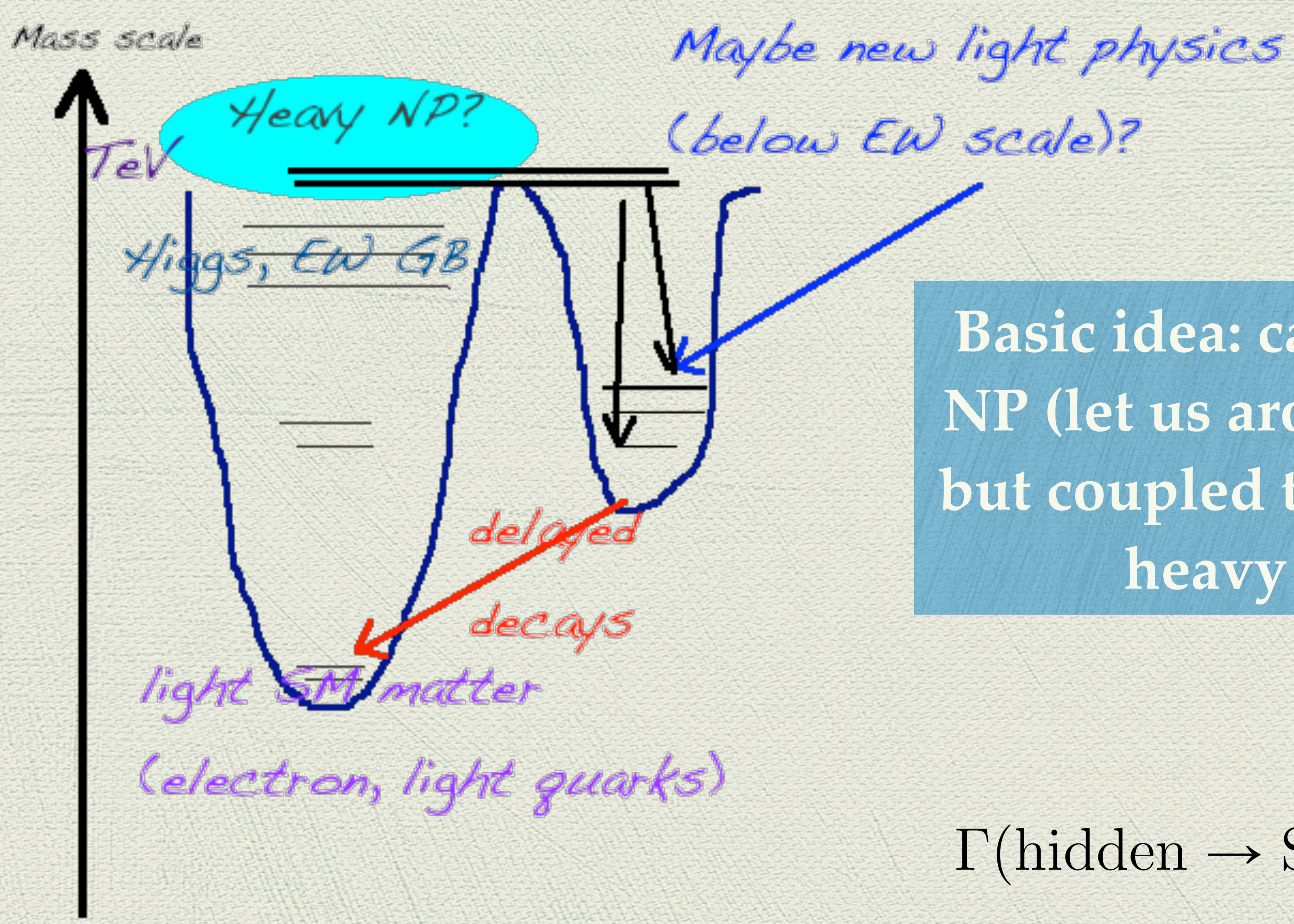
- Neutral Naturalness as the Hidden Valley Example: Cosmology Drives the LHC Searches
- Dark Matter in the Hidden valleys
- Baryogenesis from the Hidden Valleys
- Conclusions and Outlook

What Are Hidden Valleys?

Strassler, Zurek; 2006



Basic idea: can we have low scale NP (let us around 1GeV, or lower) but coupled to the SM directly via heavy O(TeV) states.

$$\Gamma(\text{hidden} \to \text{SM}) \propto \left(\frac{m_{hidden}}{\text{TeV}}\right)^n$$

Why Hidden Valleys?

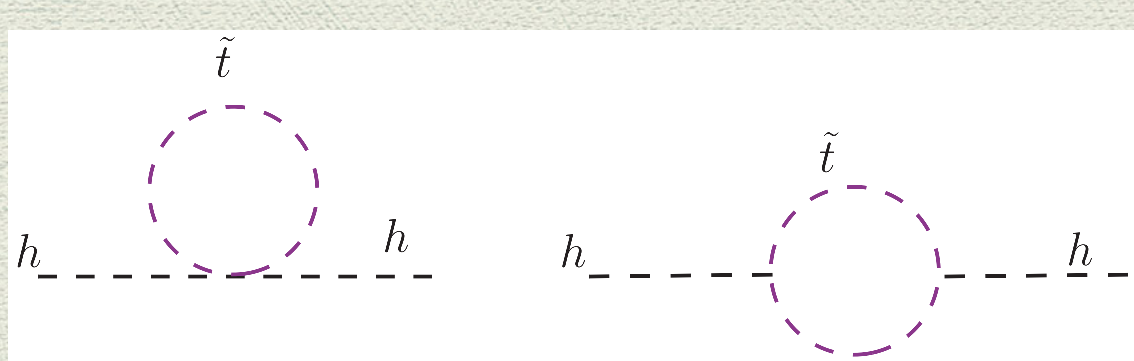
- Can be connected to the Naturalness Problem
- Can accommodate the DM — but cosmological bounds apply. Hidden-valley DM can be symmetric or asymmetric
- Can be a crucial ingredient for producing the visible sector baryon asymmetry

Due to very weak couplings to the visible sector can be tricky to find experimentally — unusual signatures

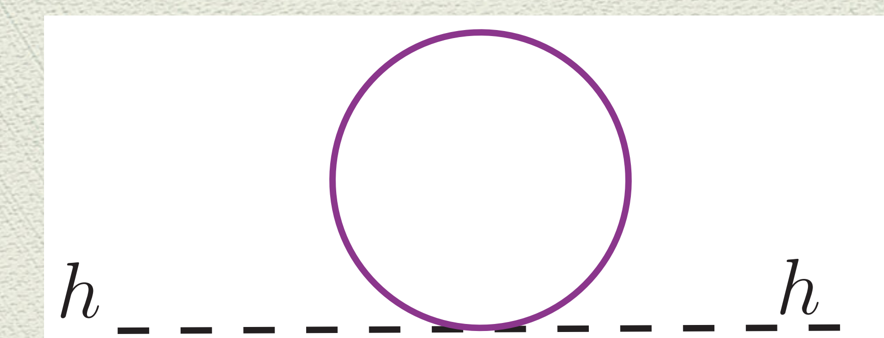
Neutral Naturalness Overview

Where is naturalness? No trace of the top partners of SUSY and composite models. But should they necessarily be colored?

SUSY



pNGB Higgs



In both cases the SM color plays (superficially) no role except the multiplicative factor of 3 ☛ gives way to constructing models with colorless top partners.

Neutral Naturalness Overview

Folded SUSY

Burdman, Chacko, Goh, Harnik; 2006

Scalar quark partners that are sterile under $SU(3)_c$ cancel the top divergencies. The origin — 5…10 TeV scale SUSY orbifold with the honest colored superpartners projected out. Not really SUSY below 5 TeV

Twin Higgs

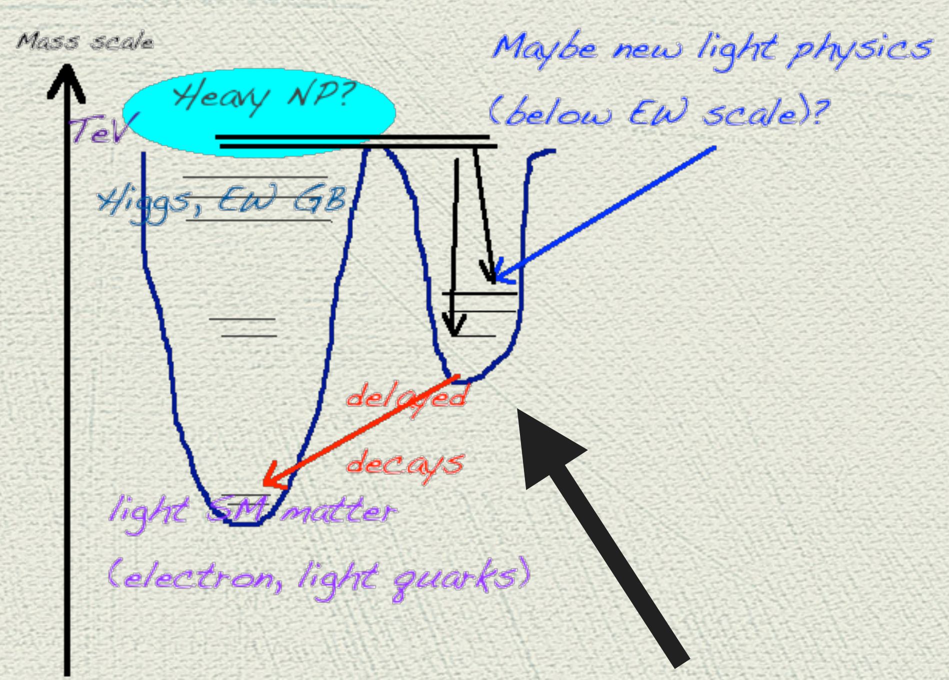
Chacko, Goh, Harnik; 2005

The idea goes along the lines of the little Higgs: the higgs is realized as a pNGB of a large global subgroup, e.g. SU(4) or SO(8). The trick: discrete mirror symmetry is enough to maintain the naturalness up to ~ 5 TeV.

Neutral Naturalness Predicts Hidden Valleys

The SM color is still important for naturalness. SUSY ➟ no naturalness w/o light gluinos due to large 2-loop contributions. We have exactly the same problem in the folded SUSY and a similar problem in the twin Higgs, due contribution of the gluons to the top running.

$$\alpha_3(\Lambda) \approx \hat{\alpha}_3(\Lambda)$$



We have to have 3 "species" of top partners ⇨ need at least global SU(3) in the hidden sector. Naturalness, running due to gluons ⇨ hidden SU(3) must be gauged and have couplings ~ $SU(3)_c$. ☞ Confinement and hidden valley

$$\Lambda_{QCD} \lesssim \hat{\Lambda}_{QCD} \approx 1 \ldots 10 \text{ GeV}$$

Hadrons of the confining SU(3)

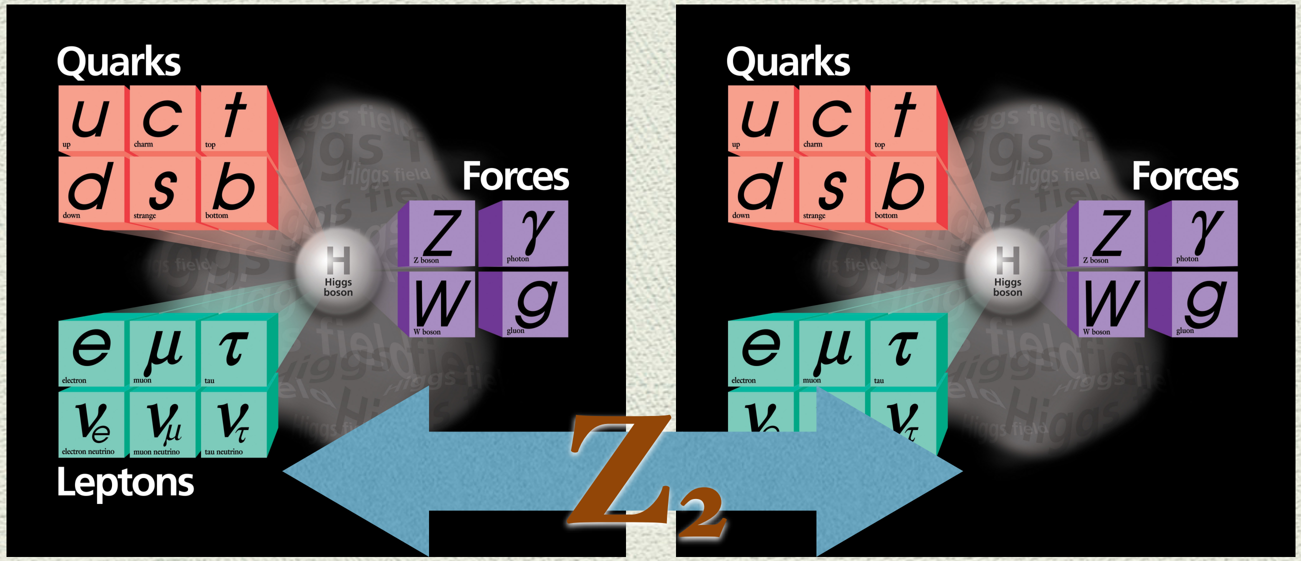
Neutral Naturalness Meets the LHC

General comment: neutral naturalness models were designed to hide naturalness from the LHC, not to promote spectacular signatures. Therefore:

- Twin higgs a-priori does not guarantee any new particles at the LHC
- Generic signatures of both models are deviations of the higgs couplings from the SM predicted values
- Exotic decays of the SM higgs are not guaranteed, but very motivated in the twin higgs
- Exotic higgs decays are guaranteed in the folded SUSY
- New particles might appear: the "radial" higgs in the twin Higgs or the quirks of the folded SUSY (e.g. $W\gamma$ resonances), but this is also not promised

Twin Higgs: Original or Fraternal?

Chacko, Goh, Harnik; 2005



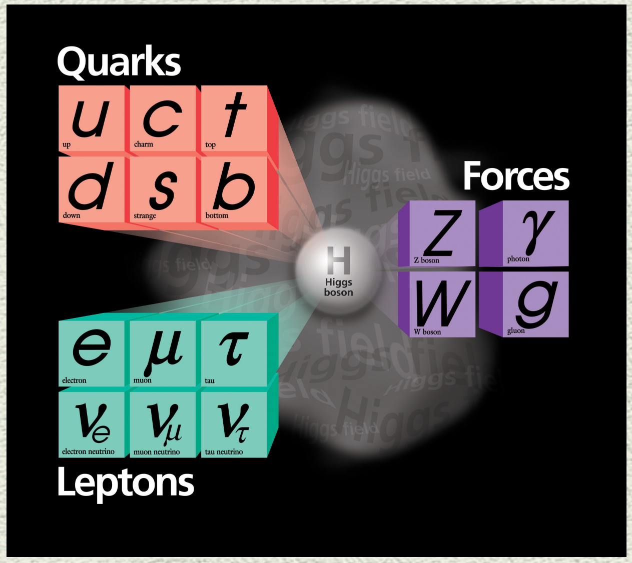
The Z_2 induces an approximate continuous symmetry which protects the EW scale up to ~ 5 TeV

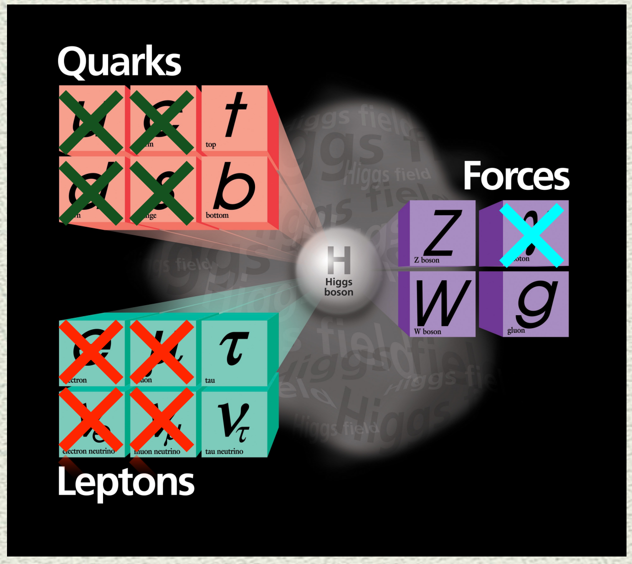
Perfectly preserves the global SU(4) of the Higgs sector, but:

- During the BBN the dark neutrinos, photons, electrons contribute to the radiative degrees of freedom — if $T_{dark} = T_{vis}$ this is completely unacceptable
- The hidden and the visible sector maintain the equilibrium via the Higgses interactions down to < 10 GeV. If we reheat above this temperature, the sector have the same # d.o.f. ☛ same temperature
- Reheating below the equilibration temperature raises very serious questions about the accommodation of the DM and baryogenesis into this mechanism.

Twin Higgs: Original or Fraternal?

Craig, A.K., Strassler, Sundrum; 2015





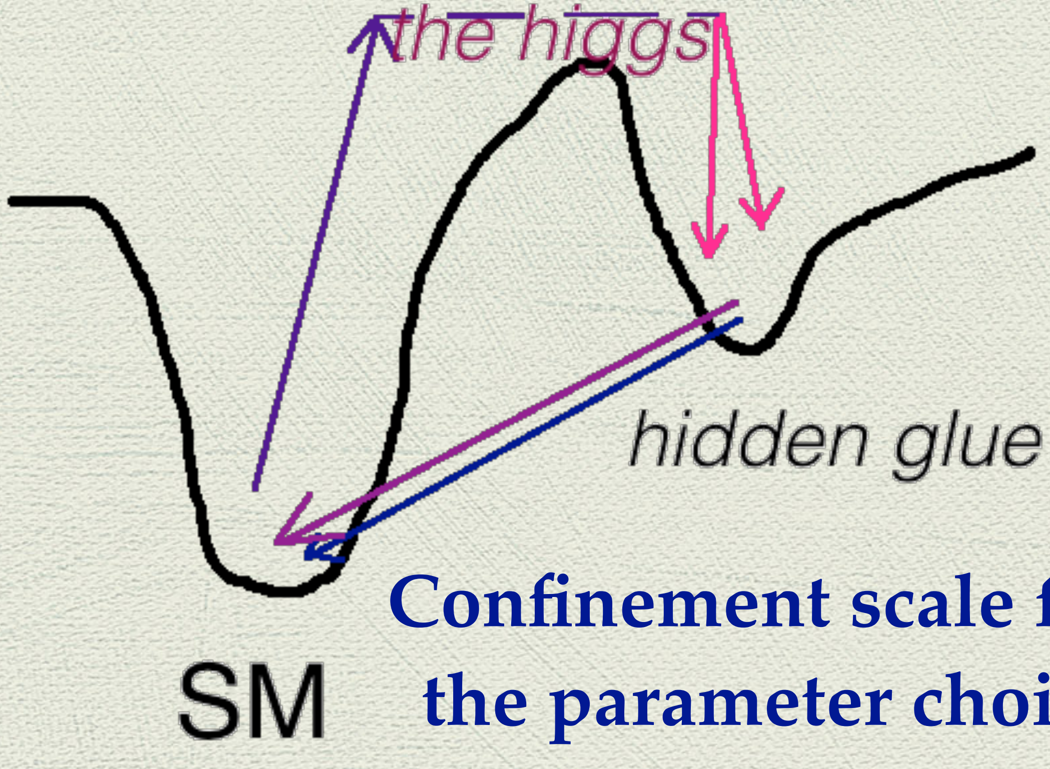
Adopt the logic of the “natural SUSY”. Leave only the states which are necessary for naturalness — the 3rd generation and the hidden glue

Cosmological safety of the fraternal twin higgs:

García-García, Lasenby, March-Russel; 2015; Craig & A.K.; 2015

- Fewer d.o.f in the hidden sector ➛ the hidden sector is naturally colder than the visible one
- The only additional radiative d.o.f are the hidden neutrinos
- Twin QCD PT might produce long-living states out of equilibrium, but usually one can make sure that they decay in time
- **Generally much safer than the original twin higgs**

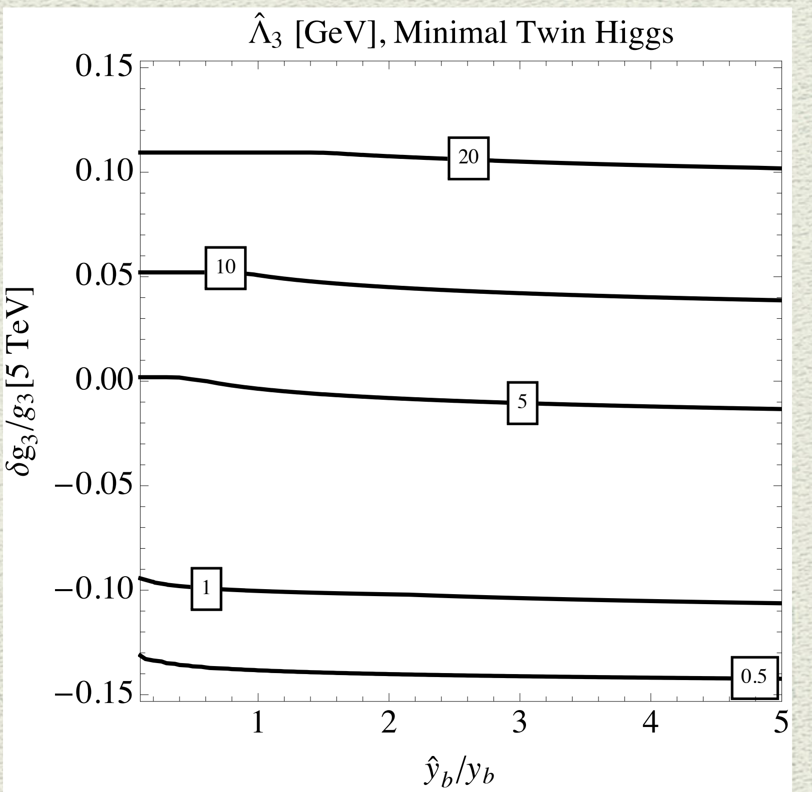
"Fraternal" Signatures at the LHC



Unlike in the original twin Higgs scenario there are no light fermions in the hidden sector and the lightest baryons (glueballs or quarkonia) are the lightest hidden states.

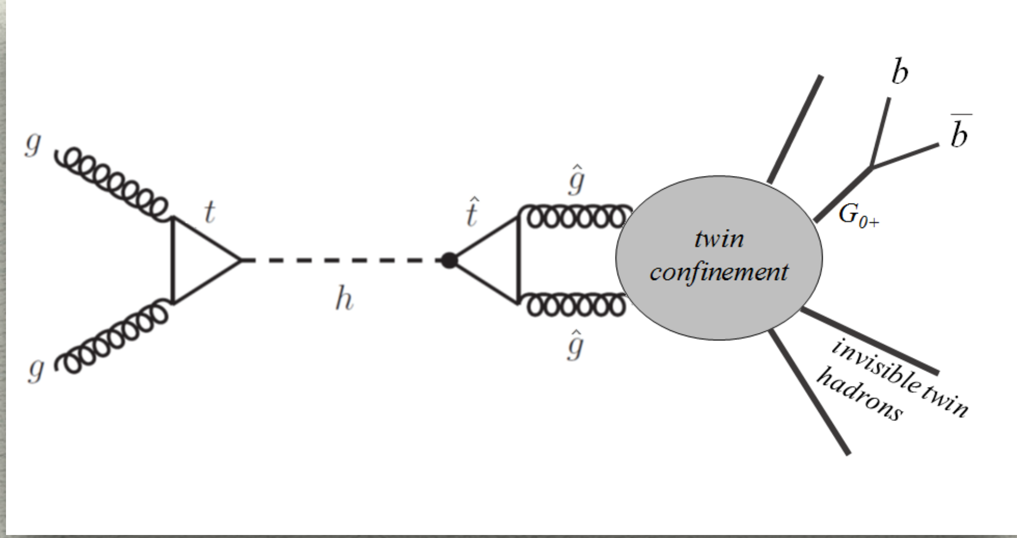
Confinement scale for the most of the parameter choices is around 1… 5 GeV, with the lightest

glueball having a mass ≈ 7Λ.



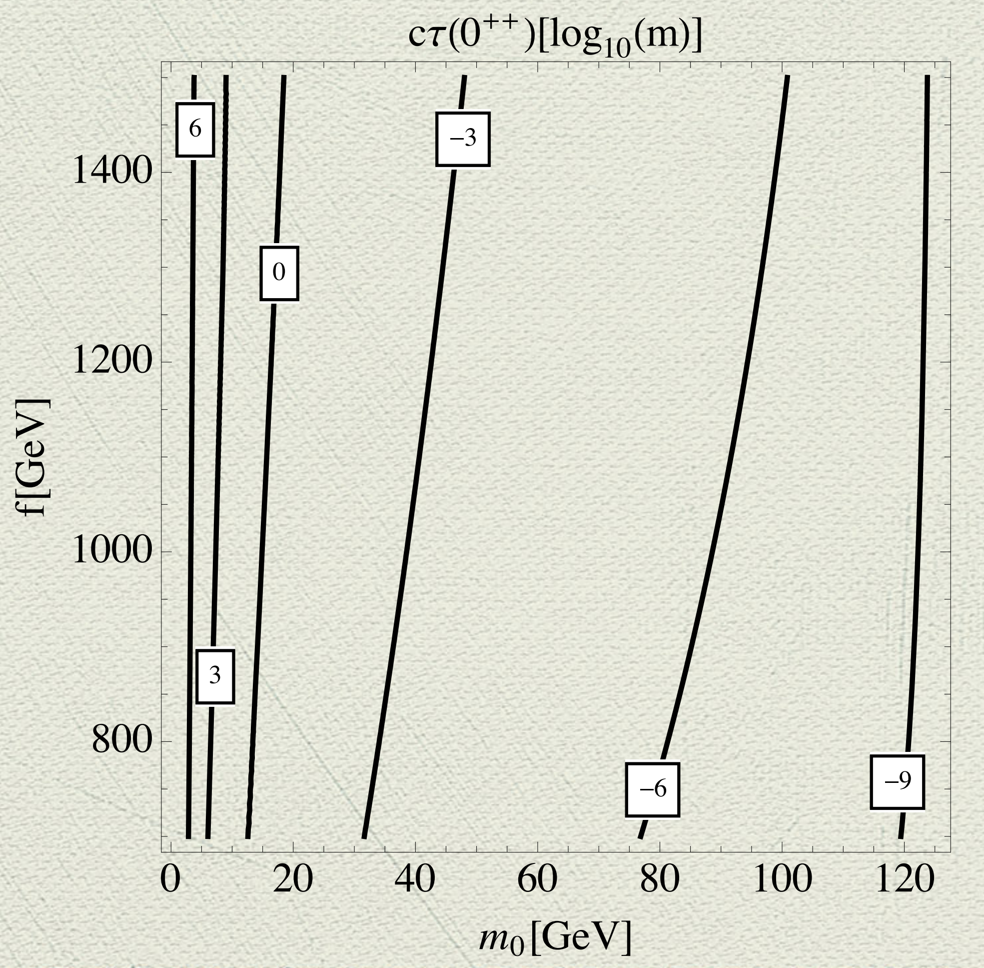
"Fraternal" Signatures at the LHC

Exotic Higgs decays are promised, but the irreducible rate is around 0.1%



Typical signature: higgs decays into light particles, producing displaced vertices, possibly with MET

Lightest glueball decay length



Searches and Signatures

- The parameter space of the possible signatures is practically span by two independent parameters: the dark b-Yukawa and (v/f) — where f is the scale of the global symmetry breaking
- The parameter space is pretty diverse, including displaced vertices ranging from <mm to meters, accompanied by MET and extra jets
- An absolutely universal signature — deviations of the higgs couplings from the SM by $(v/f)^2$ — direct measurement of the FT, can typically be of order 10%.
- In some parts of parameter space decays $h \to (bb)(bb)$ and $h \to (bb)(\tau\tau)$ with displacements O(mm..cm) — relatively easy search for the pair-produced displaced vertices, reconstructing the higgs mass
- Larger displacements ☛ smaller dark confinement scale, dark showering and meta stable glueballs are formed. Typically one displaced vertex, no higgs reconstruction, MET. Problems with triggering and statistic.
- Folded SUSY — similar exotic higgs decays + glueballs emitted from quirk oscillations.

Hidden Valleys DM

- Production of the dark asymmetry in the hidden sector ➪ asymmetric DM: possible direct detection signatures but not annihilation (with or w/o connection with the SM baryogenesis)
- The dark sector can host a thermal relic, which dominantly annihilates into the dark light states, but still has interesting direct detection signatures

The Fraternal WIMP Miracle

Twin higgs is a natural home to accommodate both these DM scenarios. It takes some work to produce the dark baryon asymmetry, but the thermal relic is almost naturally present.

The twin lepton must be in the spectrum, its mass is arbitrary and it predominantly annihilates into the dark neutrinos, which are cosmologically safe.

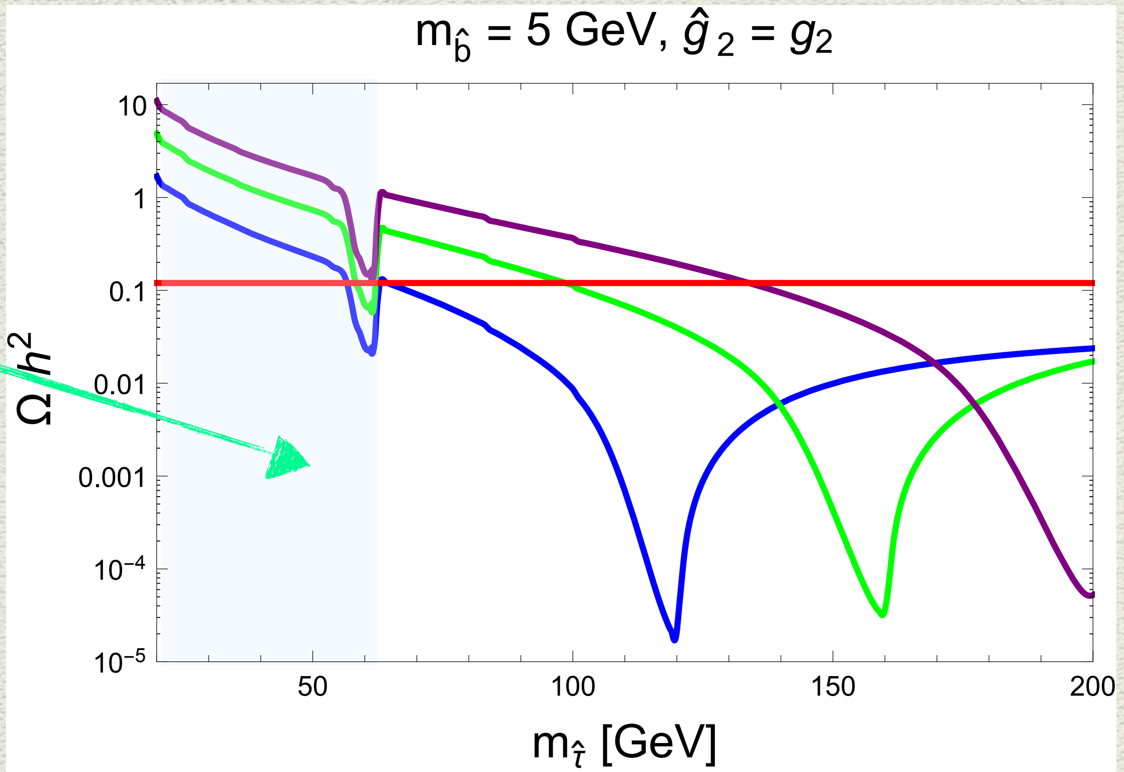
$$[\sigma v]_{\hat{\tau}\hat{\tau}\to\hat{\nu}\hat{\nu}} = \frac{9}{4\pi}\hat{G}_F m_{\hat{\tau}}^2 = \frac{9}{4\pi}\left(\frac{v}{f}\right)^4 G_F m_{\hat{\tau}}^2 \ .$$

Hidden Fermi scale is set by naturalness requirements and force it to be very close to the SM Fermi coupling — WIMP miracle w/o week force

Where is the DM: Higgs Invisible Rate vs Thermal Relic Abundance

Mass of the DM is almost a free parameter, but it also correlates with the coupling of the DM to the SM higgs — constraints on the invisible higgs couplings constraint the parameter space of this scenario

Already excluded by $h \to inv.$ for the "minimal" FT, allowed for $f = (4\dots 5)\, v$

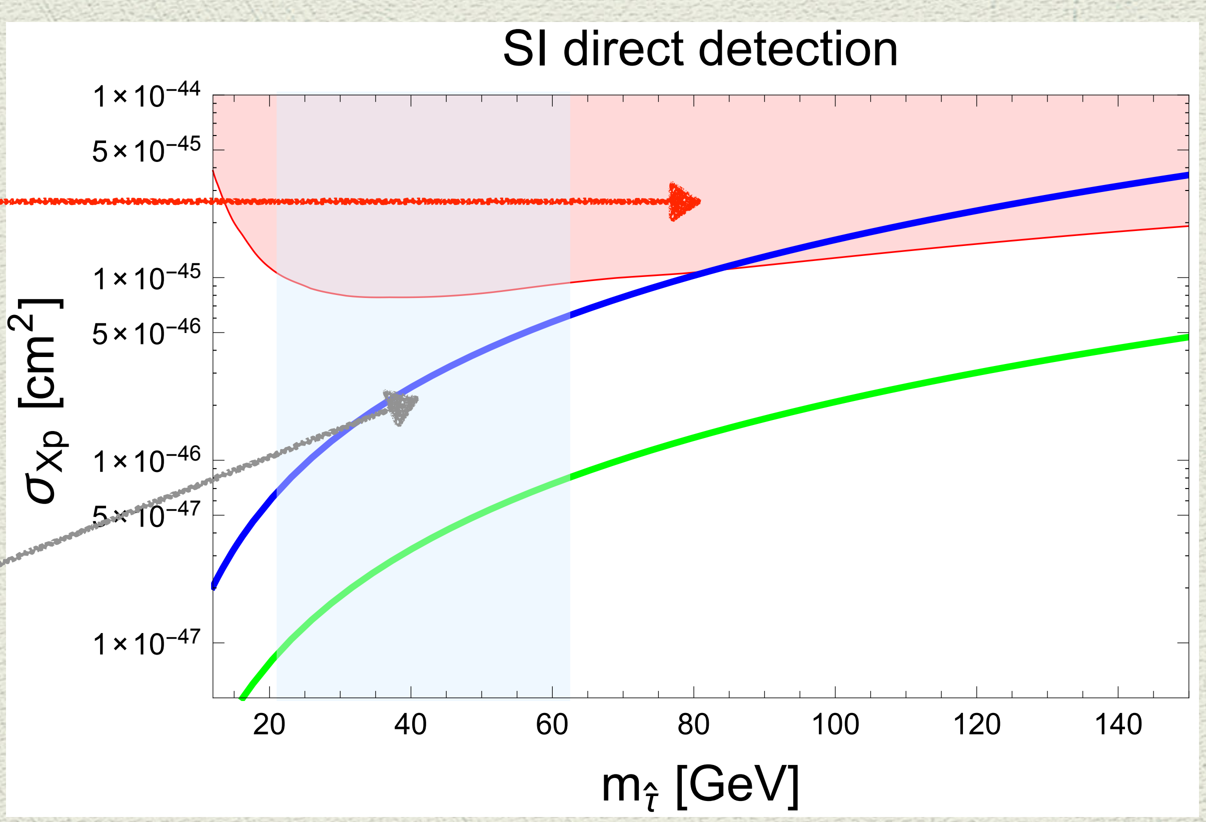


Thermally favored range is between 62 GeV and roughly 130 GeV. Can the progress be made in DD experiments?

Direct Detection Beyond the Corner

Generic direct detection of the DM, harbored by a hidden valley, will proceed via TeV-scale suppressed operators. This generically leads to very small cross sections, well below WIMPs. However, DD already probe cross section much smaller, than naively expected by WIMPs. In particular higgs portal is right on the spot!

LUX exclusions



Partially excluded by higgs invisible decays.

Hidden Valleys and the Baryon Asymmetry

One of the oldest ideas of the particle physics: try to connect the baryonic asymmetry to the DM relic density. Interestingly:

$$\Omega_{DM} \approx 5\ \Omega_{Baryon}$$

Almost natural step: try to produce $n_{DM} \sim n_{B}$. More precisely

$$\Omega_{DM} \sim \frac{m_{DM}}{m_p} \Omega_B$$

Namely this kind of the DM favors the mass range between 5 and 10 GeV, more or less what we expect from the hidden valleys scenarios.

Asymmetric Dark Matter

D. E. Kaplan, Luty, Zyrek; 2009 and many others…

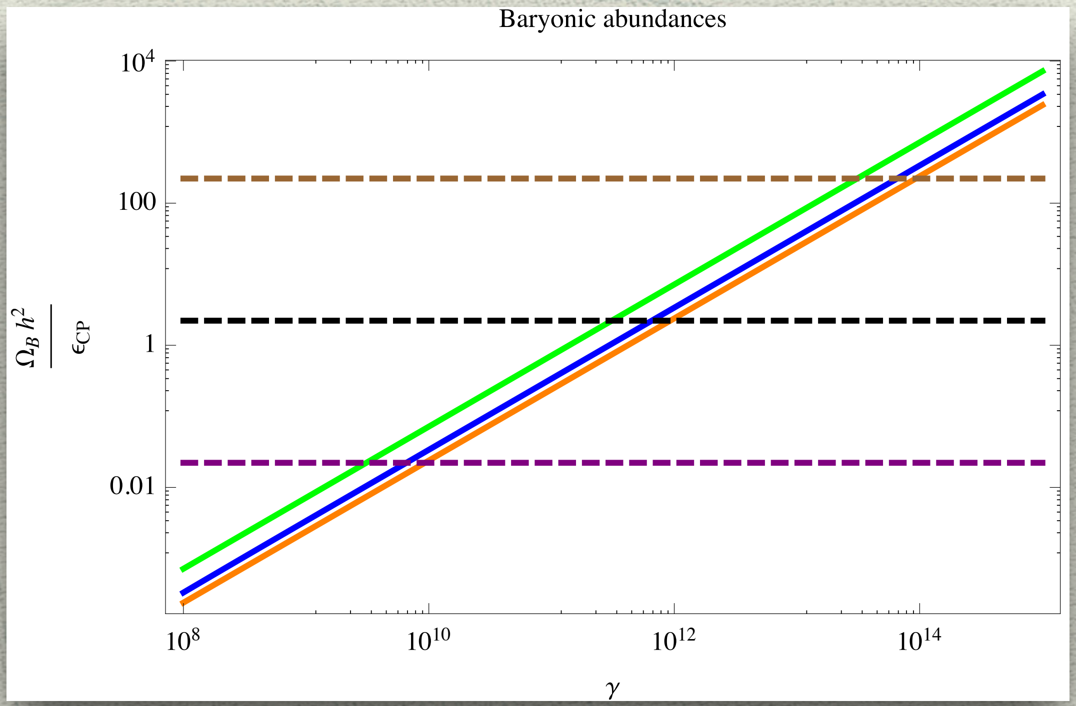
Basic idea:

- Assume that the hidden particle models in the hidden sector also carry B-L charges — it is not difficult to imagine a model where such an assignment is natural
- Produce the B-L asymmetry either via decays of some meta-stable particles out of equilibrium or in one of the possible first order cosmological PT's
- Take care that the contact interactions between the visible sector and the hidden valley are active for long enough time to redistribute the asymmetry between the sector
- Make sure that the symmetric hidden component annihilates fast enough

Low Energy Baryon Asymmetry Production

A.K. & T. Riotto; to appear

Usually it is not easy to produce a baryon asymmetry below the temperature of the EWPT (even EWBG is already on a very shaky ground due to the LHC measurements). Hidden valleys can provide a solution to this problem



Basic idea: the particles which are decaying out of equilibrium and produce the baryon asymmetry can be produced abundantly non-thermally in very strong 1st order PT with runaway bubble. The mass of the particles produced is:

Possible signature are gravity waves, neutron oscillations and higgs exotic decays

$$m \sim \gamma T \quad \text{with} \quad \gamma \gg 1 \; .$$

Conclusions

- Hidden valleys is an excellent example of a well motivated NP scenario, where cosmological observations tell us what are the interesting regions of parameter space and drive the LHC searches
- Hidden Valleys can be a necessary building block of various models, motivated by naturalness, DM and the matter-antimatter asymmetry
- Twin higgs is a particular scenario where cosmological problems of the the original model well motivate alternative scenario with exotic LHC signatures
- Fraternal WIMP miracle is an example of how the DM that is a part of the hidden sector, can follow a logic, very similar to the WIMP miracle. In this case higgs searches at the LHC drive the DD program, which should soon fully explore the parameter space of this model
- Hidden valleys can be a necessary part of intriguing models of baryogenesis, like ADM , low energy baryogenesis from the runaway bubbles and others