Nouveau Naturalness at the LHC

Kavli-IPMU-Durham-KIAS Workshop

Sep 11th 2015

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CERN

What I will try to cover:

- Recent ideas in BSM on a central puzzle in fundamental physics:

Hierarchy Problem

with a view towards novel LHC signatures.

- Focus on two topics taking up a lot of coffee time bandwidth:

Twin Higgs

Relaxion

- For other ideas see e.g. V. Khoze talk.

Hierarchy Problem

- If new physics sets in at the weak scale then no problem:

SUSY

Large Extra Dimensions

Technicolor

Little Higgs

Warped Extra Dimensions

Composite Higgs

- LHC has explored weak scale and so far nothing (i.e. stop squarks) has shown up.

- So… What is going on?

- Perhaps hierarchy problem resolved by something that looks very different at the LHC.

Hierarchy Problem

- This workshop:

"New Particle Searches Confronting the First Run-II Data"

- This talk:

"BSM Theorists Confronting the Run-I Data"

- LHC results are driving the development of new theory ideas, in some cases radical: Indicative of healthy state of field.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

Total shift symmetry.

$$\phi \to \phi + \alpha$$

$$\mathcal{L} \sim M^2|H|^2$$

Write down an EFT consistent with all symmetries and valid at the cutoff scale "M". Throughout assume that "M" is very far above the weak scale.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

Discrete shift symmetry.

$$\phi \to \phi + 2\pi f$$

$$\mathcal{L} \sim M^2 |H|^2$$

Anomaly coupling breaks shift symmetry to discrete shift symmetry

$$+ \frac{\phi}{32\pi^2 f} \widetilde{G} G$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

No shift symmetry.

$$\cancel{\phi} \rightarrow \cancel{\phi}$$

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

$$+\frac{\phi}{32\pi^2 f}\widetilde{G}G$$

"g" parameter controls the explicit and complete breaking of shift symmetry

Anomaly coupling breaks shift symmetry to discrete shift symmetry

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

Relaxion "scans" Higgs mass

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

Higgs mass takes large value M >> 125 GeV

$$-gM^2\phi$$

Relaxion couples to QCD like the axion

Relaxion wants to roll due to small terms in potential

$$+\frac{\phi}{32\pi^2 f}\widetilde{G}G$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

Axion-like coupling leads to usual axion potential

$$+f_\pi^2 m_\pi^2 \cos\left(\frac{\phi}{f}\right)$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

Which in terms of light quark masses scales like

$$+f_\pi^3 m_q \cos\left(\frac{\phi}{f}\right)$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

Thus in terms of the Higgs vacuum expectation value the potential is

$$+f_\pi^3 \lambda_q \langle h \rangle \cos\left(\frac{\phi}{f}\right)$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

Once it has rolled far enough, Higgs will develop a small VEV.

Then axion potential turns on and Relaxion stops rolling

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

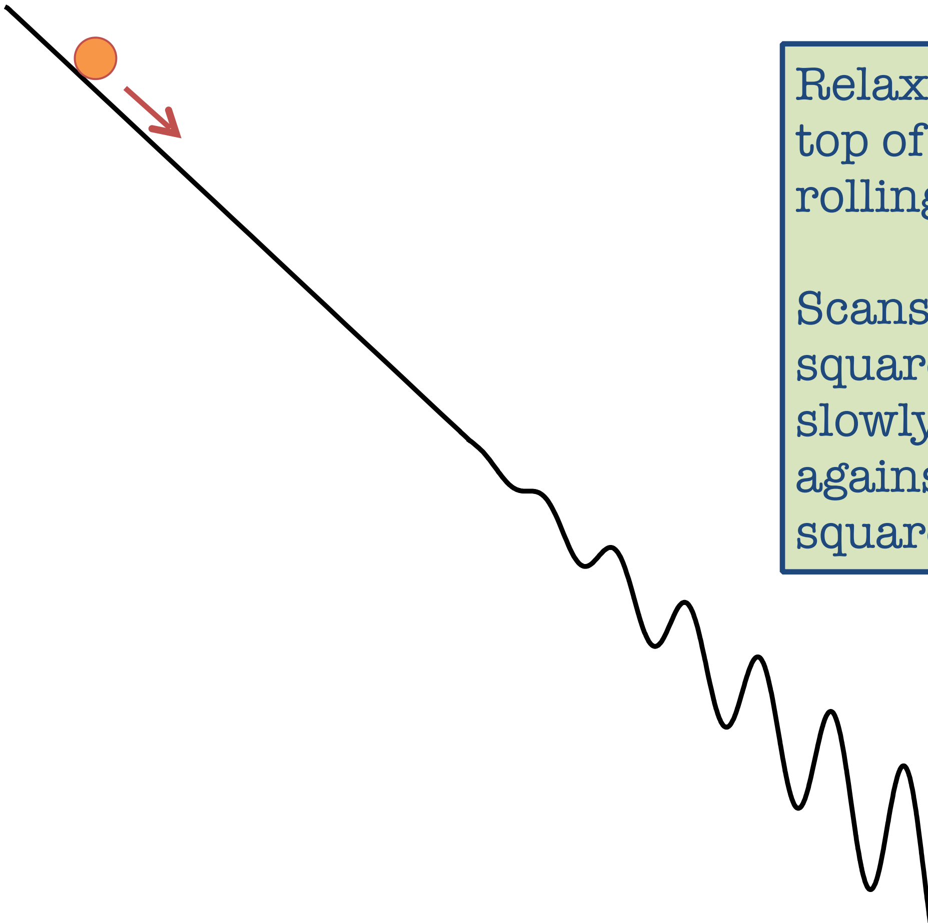
In early Universe Relaxion rolls

$$+f_\pi^3 \lambda_q \langle h \rangle \cos\left(\frac{\phi}{f}\right)$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution



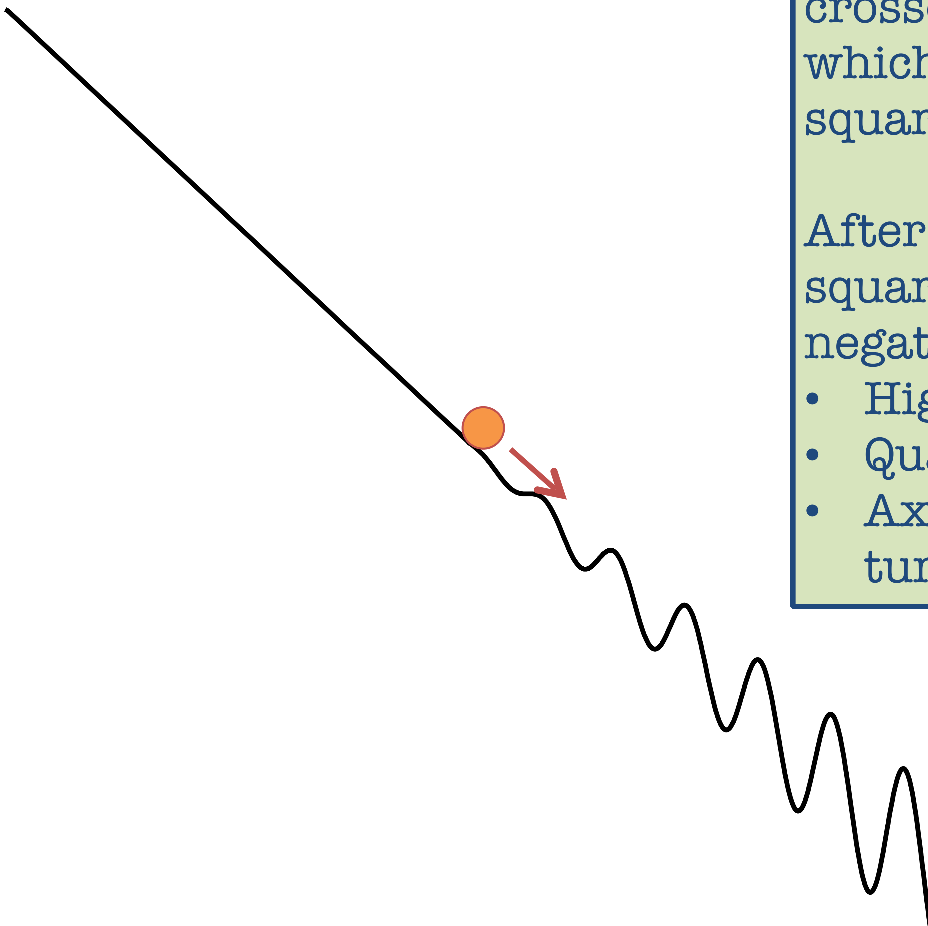
Relaxion starts at the top of potential. Starts rolling down.

Scans Higgs mass-squared while it rolls, slowly cancelling against large mass-squared.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution



At some point relaxion crosses critical value at which Higgs mass-squared becomes zero.

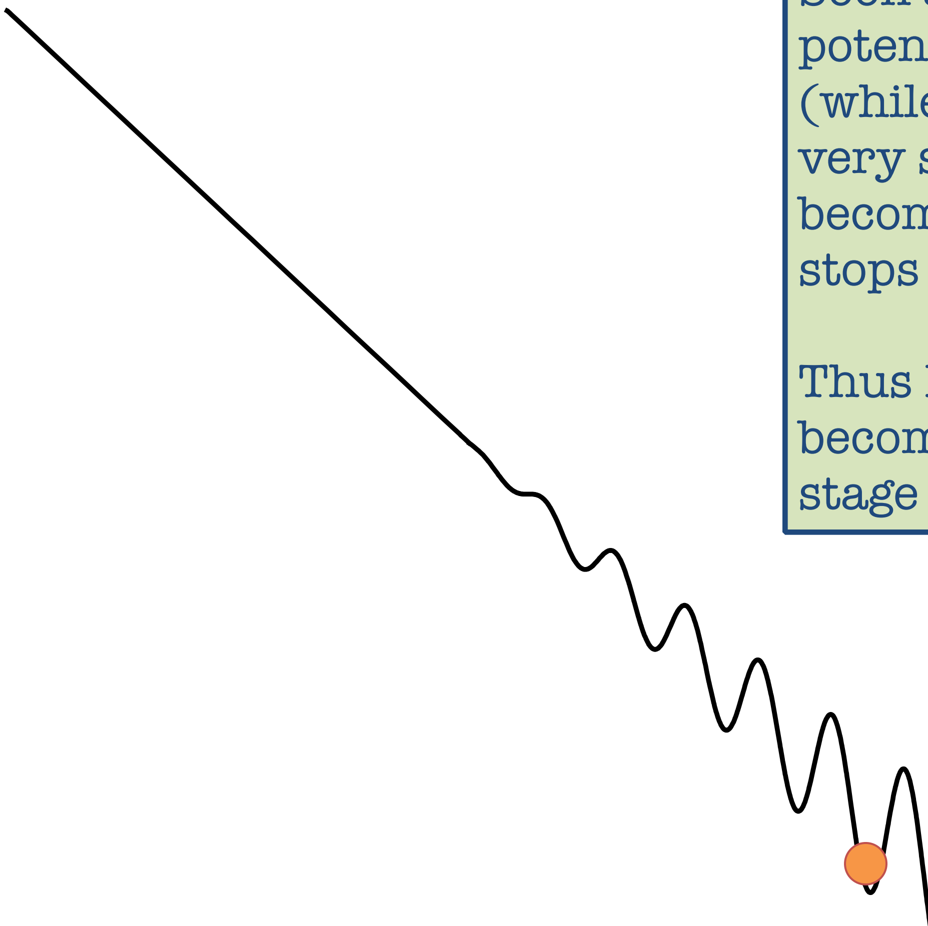
After this mass-squared becomes negative:

- Higgs gets a vev
- Quarks get mass
- Axion potential turns on

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution



Soon after axion potential turns on (while Higgs vev is still very small), relaxion becomes trapped and stops rolling.

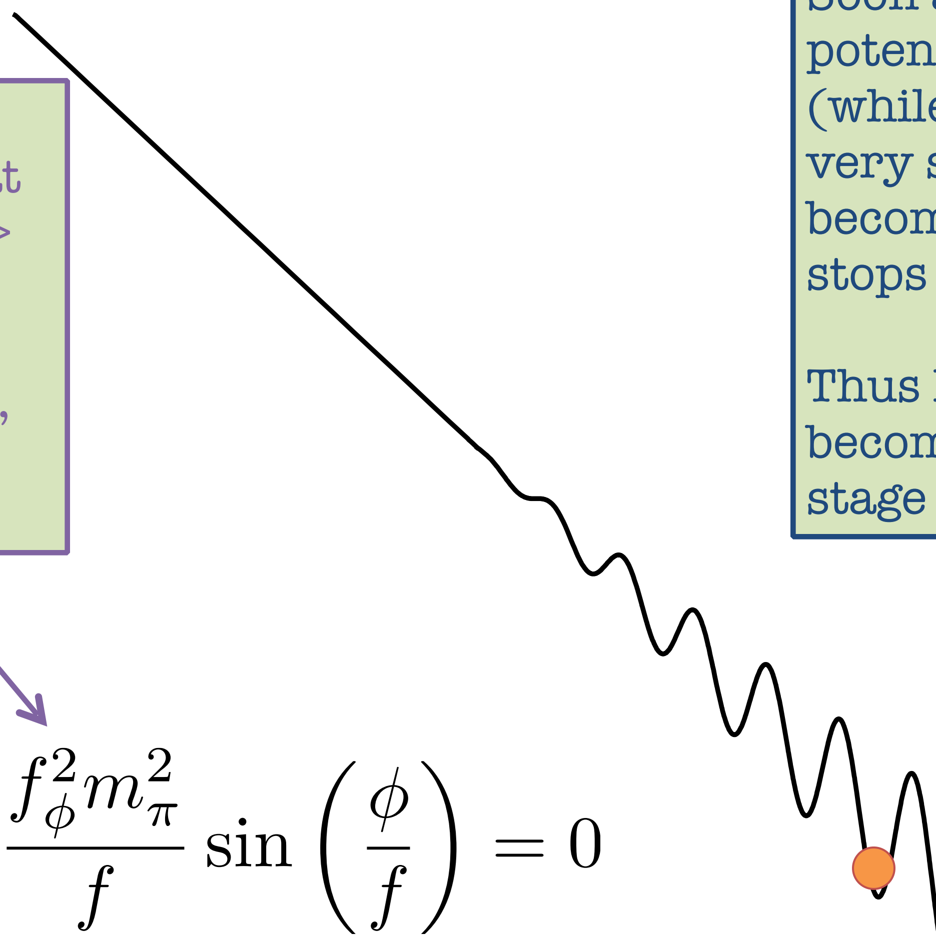
Thus Higgs vev becomes stuck at this stage too.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution

Can choose “g” parameter such that field stops when <h> is still very small. This is a parameter choice, not a tuning, since radiatively stable.



Soon after axion potential turns on (while Higgs vev is still very small), relaxion becomes trapped and stops rolling.

Thus Higgs vev becomes stuck at this stage too.

$$\frac{\partial V}{\partial \phi} \sim gM^2 - \frac{f_\phi^2 m_\pi^2}{f} \sin\left(\frac{\phi}{f}\right) = 0$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Problem. At min of potential, where relaxion comes to rest

$$\frac{\partial V}{\partial \phi} \sim gM^2 - \frac{f_\phi^2 m_\pi^2}{f} \sin\left(\frac{\phi}{f}\right) = 0$$

- Thus we have strong CP angle $\phi \neq 0$!
- To resolve this use a hidden sector QCD'

$$\frac{\phi}{32\pi^2 f} \widetilde{Q}' Q'$$

… with hidden sector quarks coupled to Higgs.

See also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant. 2015

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Hubble scale is during inflation is...

$$H < \Lambda_{QCD}$$

- Field excursion is...

$$\delta\phi \sim 10^{41} \text{ GeV}$$

- Number of e-foldings is...

$$N \gtrsim 10^{45}$$

- "g" parameter is...

$$g \sim 10^{-27} \text{ GeV}$$

- Maximum cutoff scale is

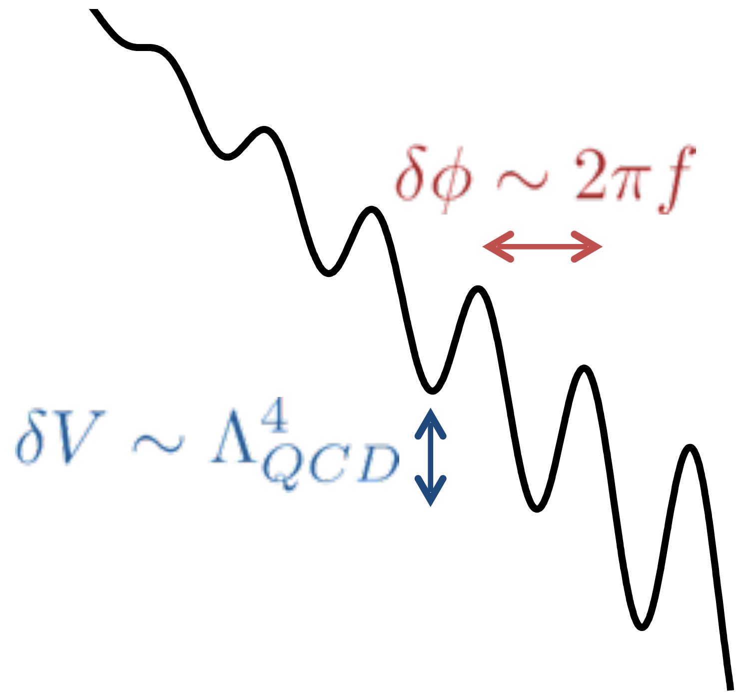
$$M \sim 10^{7} \text{ GeV}$$

...for typical axion parameters, variations possible.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- And the cosmological constant?



- Thus there are many aspects that are unfamiliar, but basic idea shows promise and a dynamical approach has never been constructed before!

The Relaxion

- Returning to the cutoff:

$$M \sim 10^7 \text{ GeV}$$

- If new physics above this scale, as expected, the mechanism isn't enough: dominant Higgs mass contributions can't be relaxed away.

- Relaxation must be part of a bigger picture, otherwise mechanism has a **UV issue**.

- So why bother, we have good old SUSY?

Supersymmetry

- SUSY solves hierarchy problem for all scalars and will get us all the way to:

$$M \sim M_P$$

- However, crudely speaking, SUSY predicted
  - $m_h \sim M_Z$
  - $m_{\tilde{q}} \sim m_h$

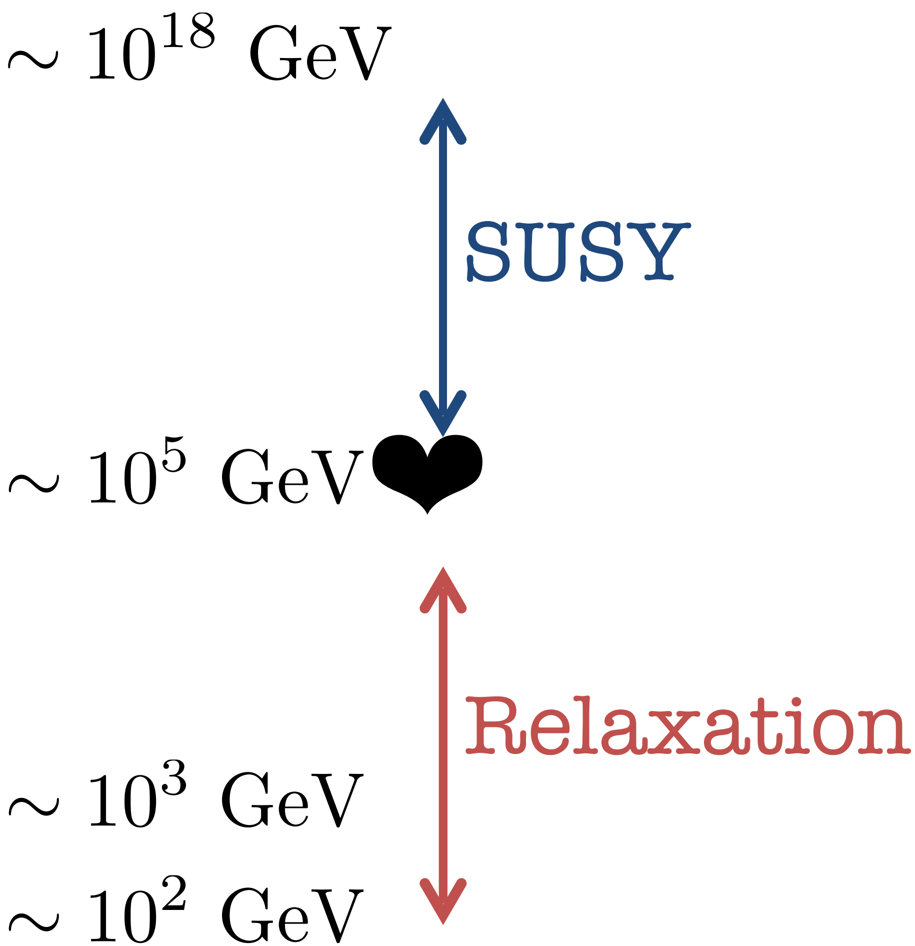
in contradiction with experiment.

- Perhaps in post-LHC era SUSY has an **IR issue**?

> - Caveat: there are still ways in which SUSY could still be natural. Dirac Gauginos my absolute favorite (see Alves, Galloway, MM, Weiner for a UV-natural theory), but other mechanisms possible too.

Natural Heavy Supersymmetry

- Perhaps they are made for one other?



- Battell, Giudice, MM, 2015

Natural Heavy Supersymmetry

- Perhaps they are made for one other?

$\sim 10^{18}$ GeV Stringy?

SUSY

$\sim 10^{5}$ GeV

Relaxation

LHC

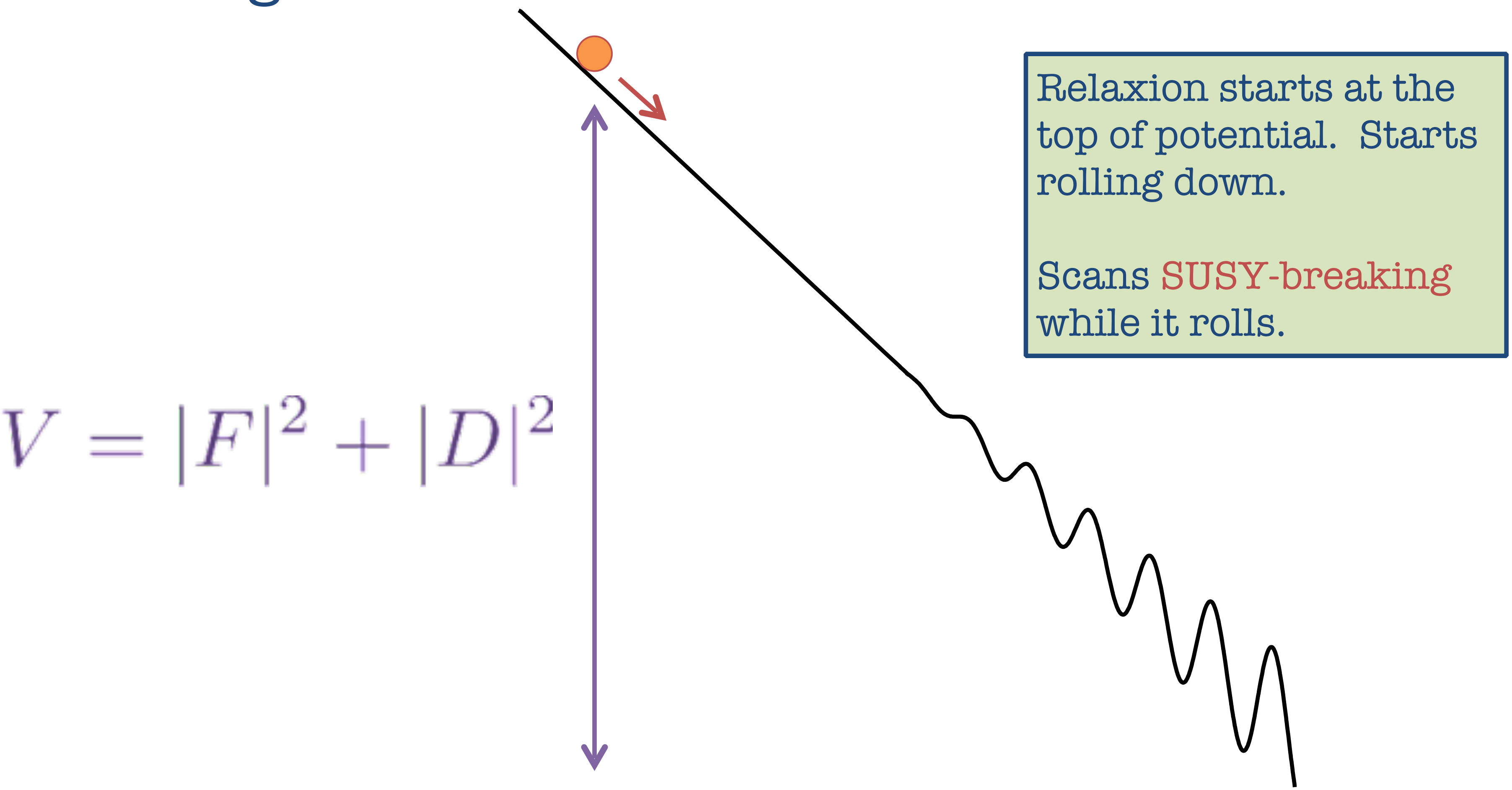
$\sim 10^{3}$ GeV

$\sim 10^{2}$ GeV

- Battell, Giudice, MM, 2015

Natural Heavy Supersymmetry

- In SUSY, scanning implies scanning of SUSY breaking



Natural Heavy Supersymmetry

- Relaxation requires axion-like coupling

$$\mathcal{L} \supset \frac{\phi}{16\pi^2 f} G\widetilde{G}$$

Note loop factor

- In SUSY this requires generation of soft masses!

$$W = \frac{S}{16\pi^2} \mathcal{W}\mathcal{W}$$

- Where the relaxion superfield is

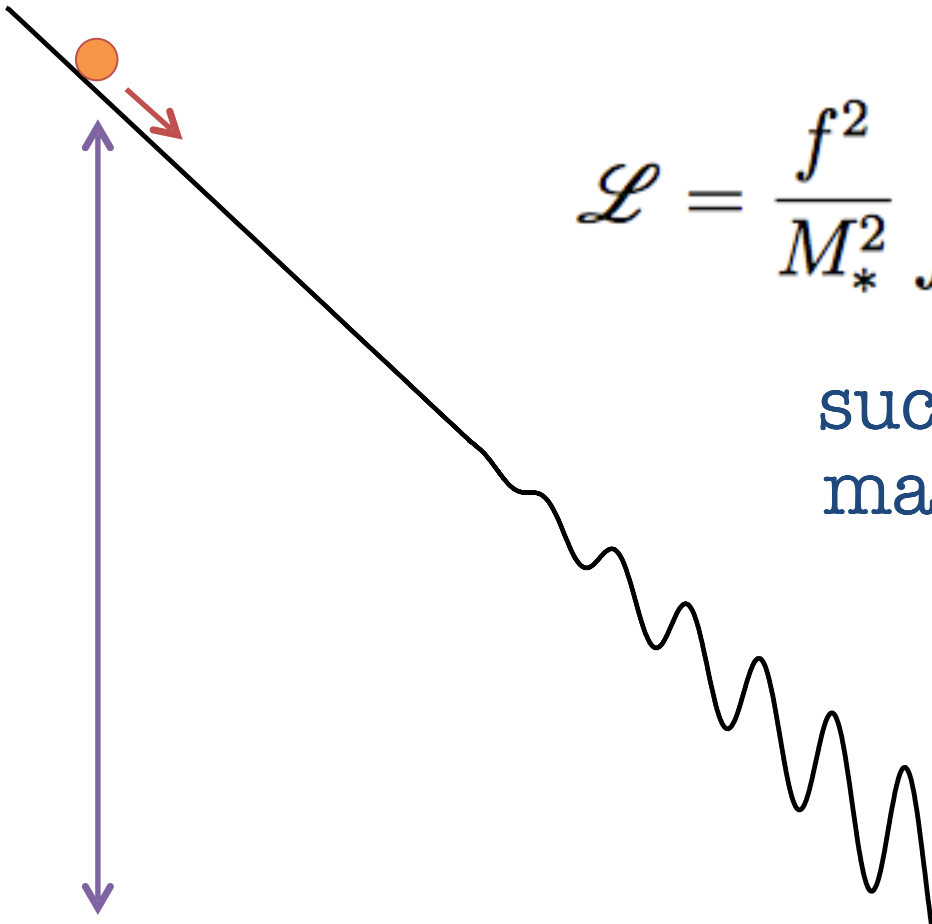
srelaxion relaxion relaxino SUSY-breaking

$$S = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\theta\tilde{a} + \theta^2 F$$

- Note field not canonically normalised.

Natural Heavy Supersymmetry

- Typically also have Kahler interactions:



Note no loop factor

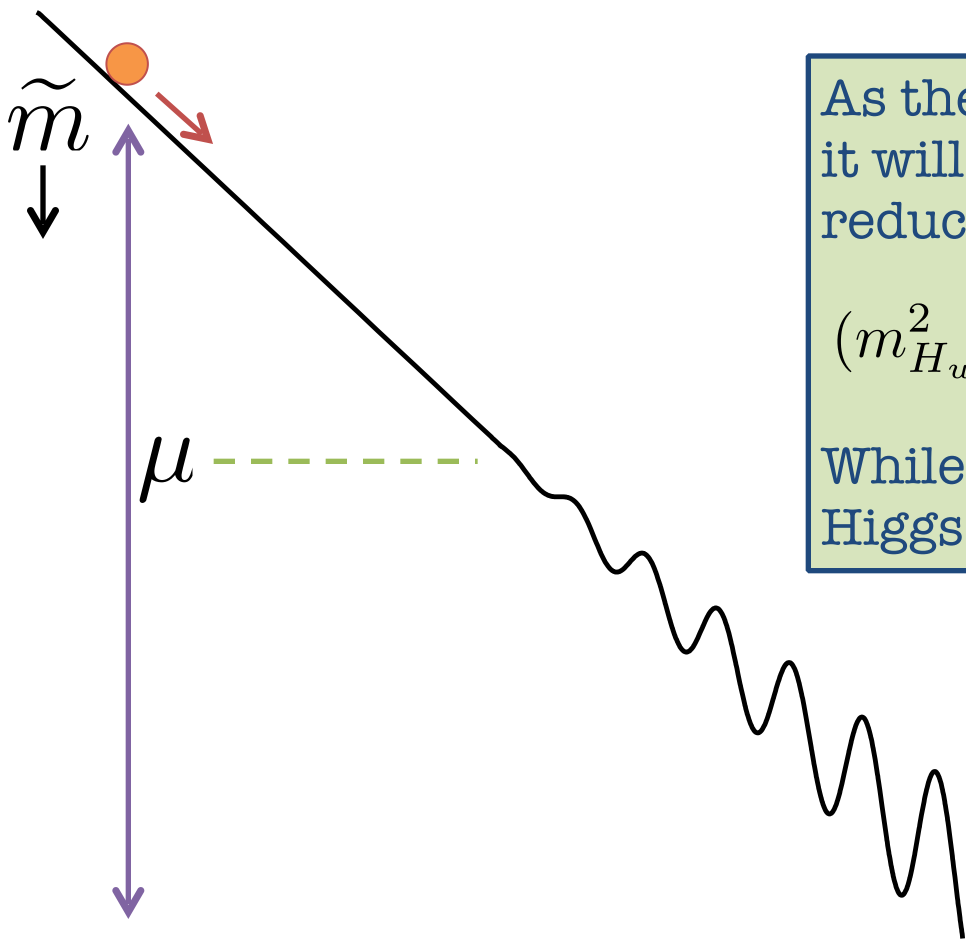
$$\mathcal{L} = \frac{f^2}{M_*^2} \int d^4\theta \, (S + S^\dagger)^2 \Phi_i^\dagger \Phi_i \, .$$

Higgs/Squarks/..

such that scalar soft masses will also scan.

Natural Heavy Supersymmetry

- Supersymmetric Higgs mass is crucial:



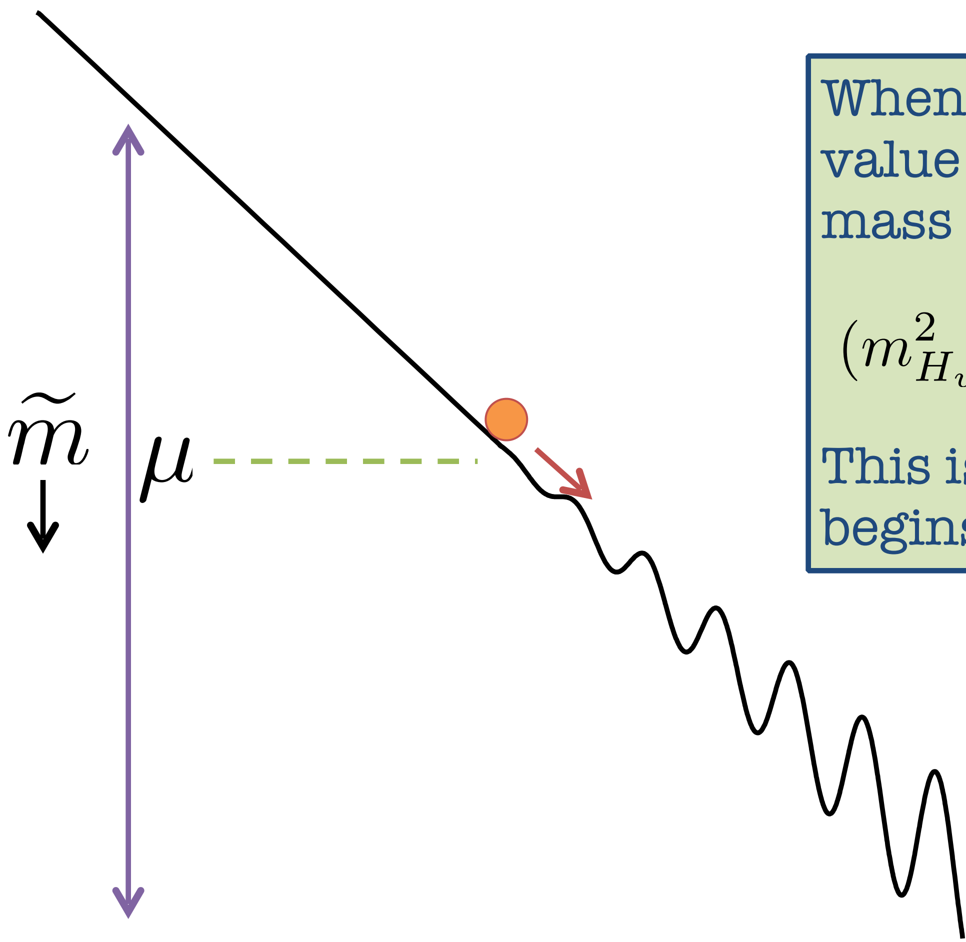
As the relaxion rolls down the potential it will scan the Higgs soft masses, reducing them as they relaxion rolls…

$$(m_{H_u}^2 + |\mu|^2)(m_{H_d}^2 + |\mu|^2) - |B_\mu|^2 > 0$$

While the soft masses are large the Higgs does not get a vev.

Natural Heavy Supersymmetry

- Supersymmetric Higgs mass is crucial:



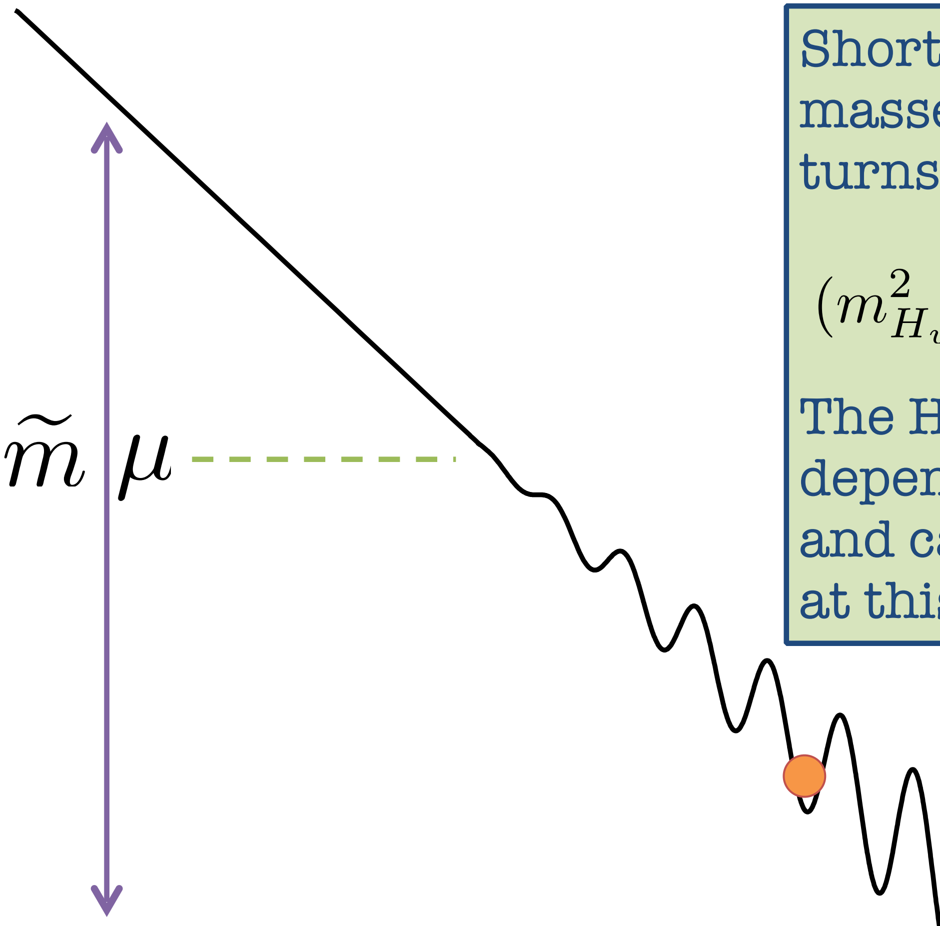
When the soft masses pass a critical value the determinant of Higgs sector mass matrix crosses zero:

$$(m_{H_u}^2 + |\mu|^2)(m_{H_d}^2 + |\mu|^2) - |B_\mu|^2 \sim 0$$

This is the critical point at which vev begins to turn on.

Natural Heavy Supersymmetry

- Supersymmetric Higgs mass is crucial:



Shortly after Higgs vev turns on quark masses also turn on, axion potential turns on, relaxion gets stuck.

$$(m_{H_u}^2 + |\mu|^2)(m_{H_d}^2 + |\mu|^2) - |B_\mu|^2 < 0$$

The Higgs vev at the stopping point depends on the slope of the potential, and can be much lower than soft masses at this point.

Natural Heavy Supersymmetry

- General shift-symmetric Lagrangian:

Daft field normalization

Scalar soft terms

Higgs Soft terms

$$\mathcal{L} = \int d^4\theta \left[f^2 K(S+S^\dagger) + Z_i(S+S^\dagger)\,\Phi_i^\dagger e^V \Phi_i + U(S+S^\dagger)\,e^{-qS} H_u H_d \right]$$

$$+ \int d^2\theta \left[C_a(S)\,\mathrm{Tr}\mathcal{W}_a\mathcal{W}_a + \mu_0\, e^{-qS} H_u H_d + \mathrm{Yukawas} \right) \Big] + \mathrm{h.c.}$$

Axion couplings and gaugino mass

SUSY Higgs mass

General form of SUSY Axion couplings. With SUSY breaking: "Axion Mediation" Baryakhtar, Hardy, March-Russell. 2013.

- And a tiny superpotential term breaks shift:

$$W/f^2 = \frac{m}{2} S^2 \qquad F = -m \left(\frac{s - i\,a}{\sqrt{2}} \right) \kappa(s)$$

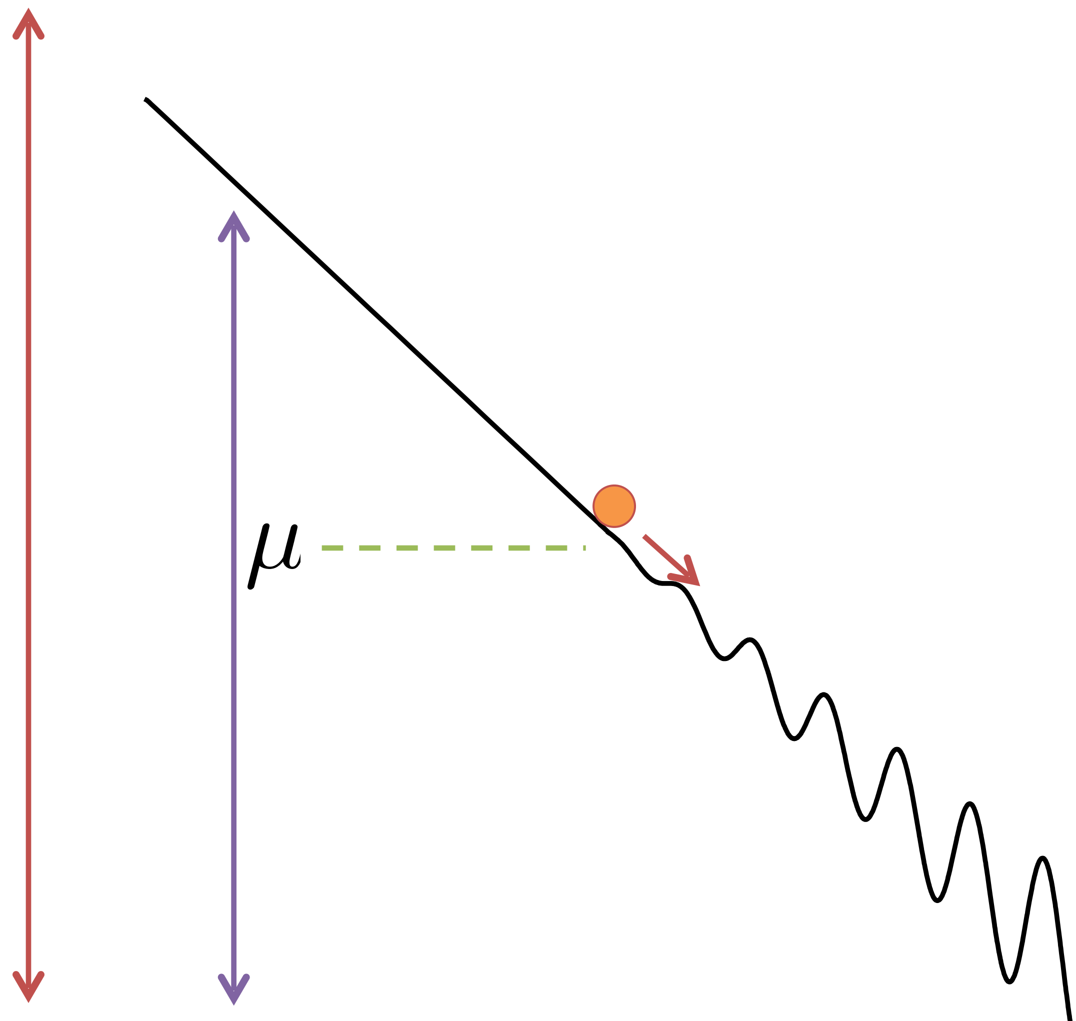
Controls SUSY breaking

Natural Heavy Supersymmetry

- Inflationary constraints

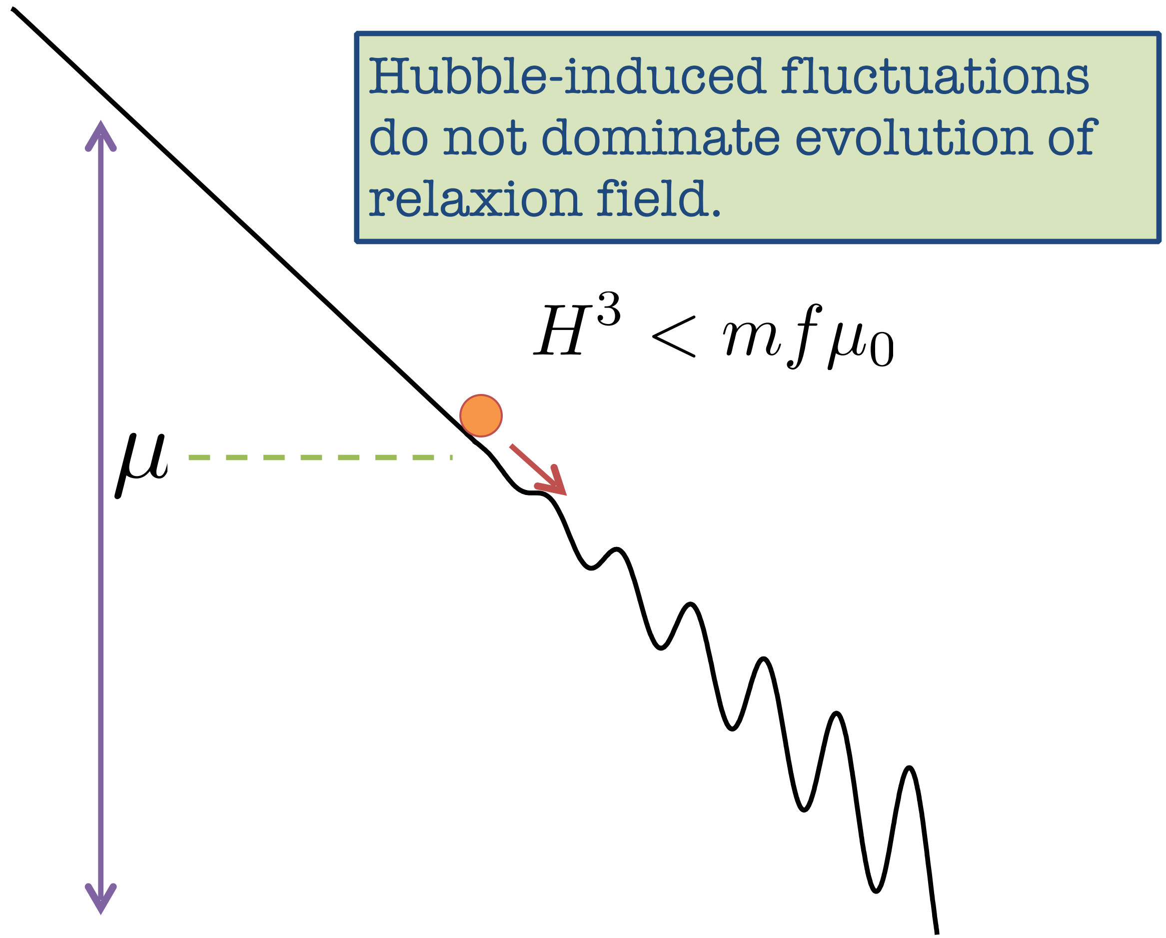
Inflation dominates vacuum energy.

$$H > \frac{\mu f}{M_P}$$



Natural Heavy Supersymmetry

- Inflationary constraints



Natural Heavy Supersymmetry

- Combining these constraints we get

$$\mu_0 < \left(\frac{\Lambda}{300\ \mathrm{MeV}}\right)^{4/3} \left(\frac{10^9\ \mathrm{GeV}}{f}\right)^{4/3} 5\times 10^5\ \mathrm{GeV}$$

which is equivalent to an upper bound on scalar soft masses. Soft masses < 1000 TeV a prediction!

- Other parameters still odd...

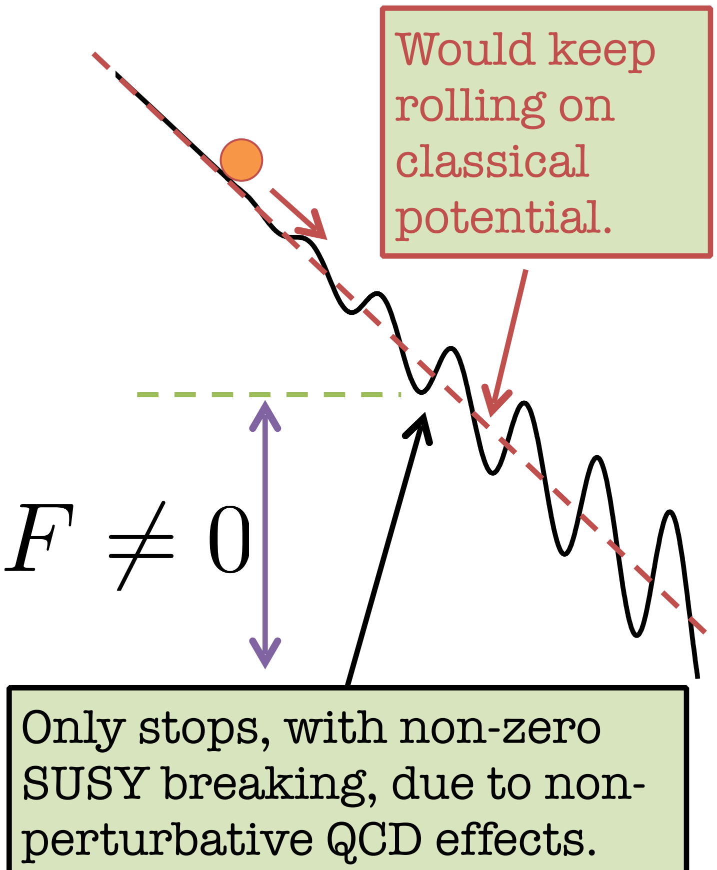
$$\Delta a > a_* = \left(\frac{300\ \mathrm{MeV}}{\Lambda}\right)^4 \left(\frac{f}{10^9\ \mathrm{GeV}}\right)^2 \left(\frac{\mu_0}{10^5\ \mathrm{GeV}}\right)^2 10^{30}$$

$$N > \left(\frac{300\ \mathrm{MeV}}{\Lambda}\right)^8 \left(\frac{f}{10^9\ \mathrm{GeV}}\right)^6 \left(\frac{\mu_0}{10^5\ \mathrm{GeV}}\right)^4 10^{42}$$

Supersymmetry Breaking

The Relaxion

$$V(a) = \frac{m^2}{2} f^2 a^2 + \Lambda^4 \cos \frac{a}{\sqrt{2}}$$

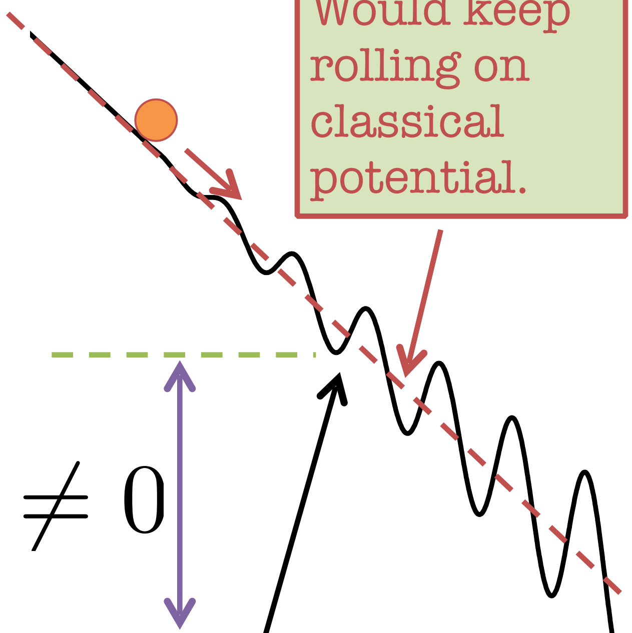


Supersymmetry Breaking

The Relaxion

$$V(a) = \frac{m^2}{2} f^2 a^2 + \Lambda^4 \cos \frac{a}{\sqrt{2}}$$

Would keep rolling on classical potential.



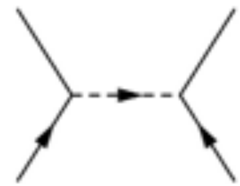
$F \neq 0$

Only stops, with non-zero SUSY breaking, due to non-perturbative QCD effects.

The Relaxino

$$m_{\tilde{a}} = m$$

If SUSY spontaneously broken have massless Goldstino?



Integrating out heavy scalars:

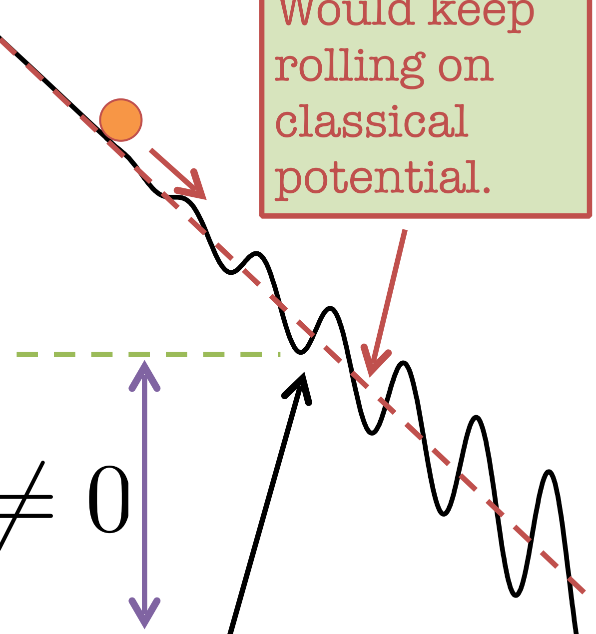
$$\delta m_{\tilde{a}} = -\frac{1}{2\sqrt{2}am}\left(im_q e^{ia/\sqrt{2}} q^c q + h.c.\right)$$

Supersymmetry Breaking

The Relaxion

$$V(a) = \frac{m^2}{2} f^2 a^2 + \Lambda^4 \cos \frac{a}{\sqrt{2}}$$

Would keep rolling on classical potential.



$$F \neq 0$$

Only stops, with non-zero SUSY breaking, due to non-perturbative QCD effects.

The Relaxino

$$m_{\tilde{a}}(a) = m - \frac{\Lambda^4 \sin \frac{a}{\sqrt{2}}}{\sqrt{2}\, a m f^2}$$

From chiral condensate.

$$m^2 f^2 \langle a \rangle = \frac{\Lambda^4}{\sqrt{2}} \sin \frac{\langle a \rangle}{\sqrt{2}}$$

At minimum of relaxion potential. Thus:

$$m_{\tilde{a}}(a) \to 0$$

The Goldstino!

Particle Spectrum

R-Even States

$\boxed{\text{SM}}$

a $\ll$ eV

R-Odd States

$\boxed{\tilde{q},\ \tilde{l},\ \widetilde{H}}$ $\lesssim 100$ TeV

$\boxed{\tilde{g},\ \widetilde{B},\ \widetilde{W}}$ ~ 1 TeV

$\tilde{a} = \widetilde{G}_L$ 1 keV $\leftrightarrow$ GeV

Particle Spectrum

$\tilde{q},\ \tilde{l},\ \widetilde{H}$ $\lesssim 100$ TeV

$\tilde{g},\ \widetilde{B},\ \widetilde{W}$ ~ 1 TeV

SM

$\tilde{a} = \widetilde{G}_L$ 1 keV $\leftrightarrow$ GeV

a $\ll$ eV

This is a natural theory of Mini-Split SUSY!

Big hierarchy: SUSY. Little hierarchy: relaxation.

New Deep IR – Far UV Connections

R-Even States

SM

a

R-Odd States

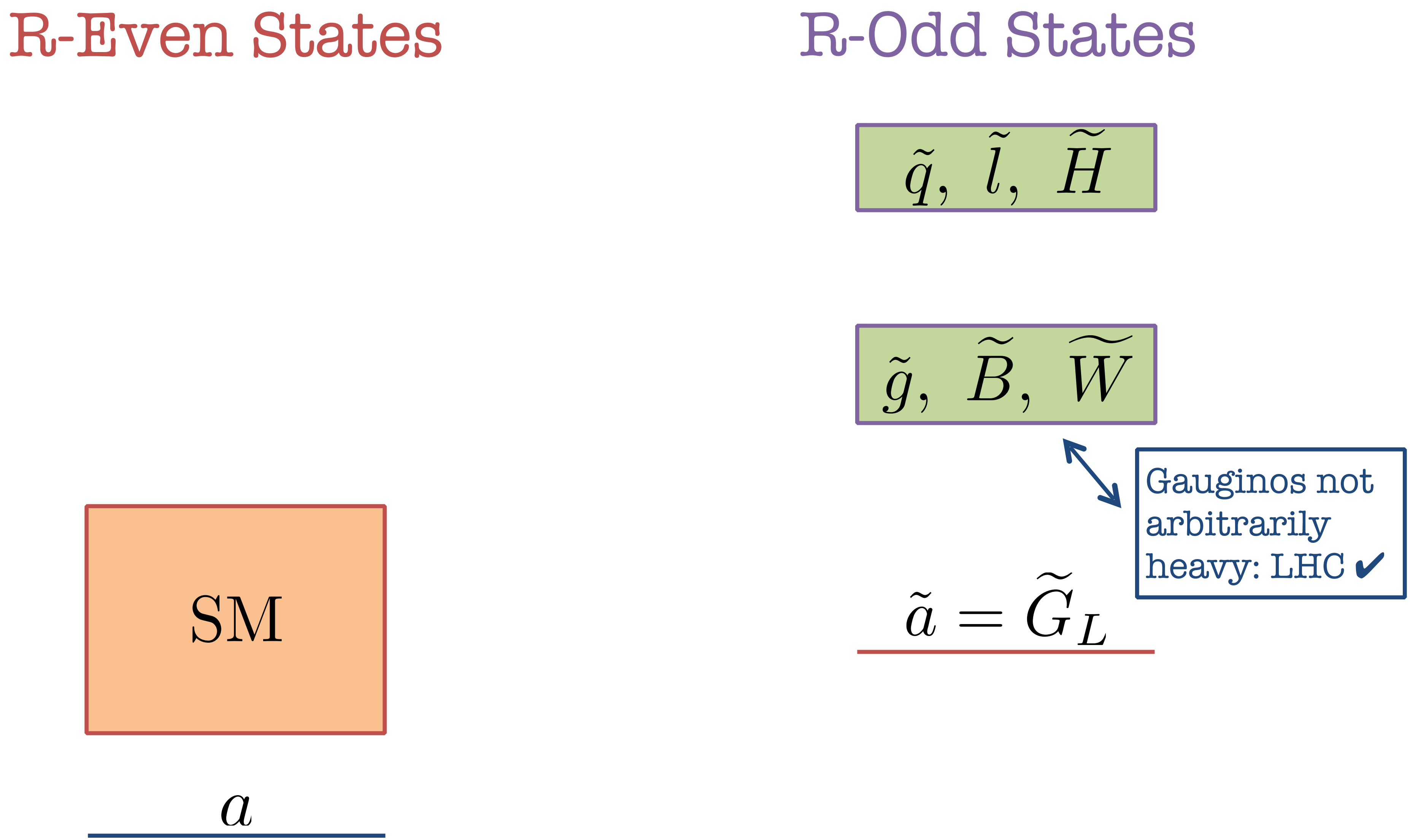
$\tilde{q}, \ \tilde{l}, \ \widetilde{H}$

Loop factor a prediction.

$\tilde{g}, \ \widetilde{B}, \ \widetilde{W}$

$\tilde{a} = \widetilde{G}_L$

New Deep IR – Far UV Connections



New Deep IR – Far UV Connections

R-Even States

R-Odd States

$\tilde{q},\ \tilde{l},\ \widetilde{H}$

$\tilde{g},\ \widetilde{B},\ \widetilde{W}$

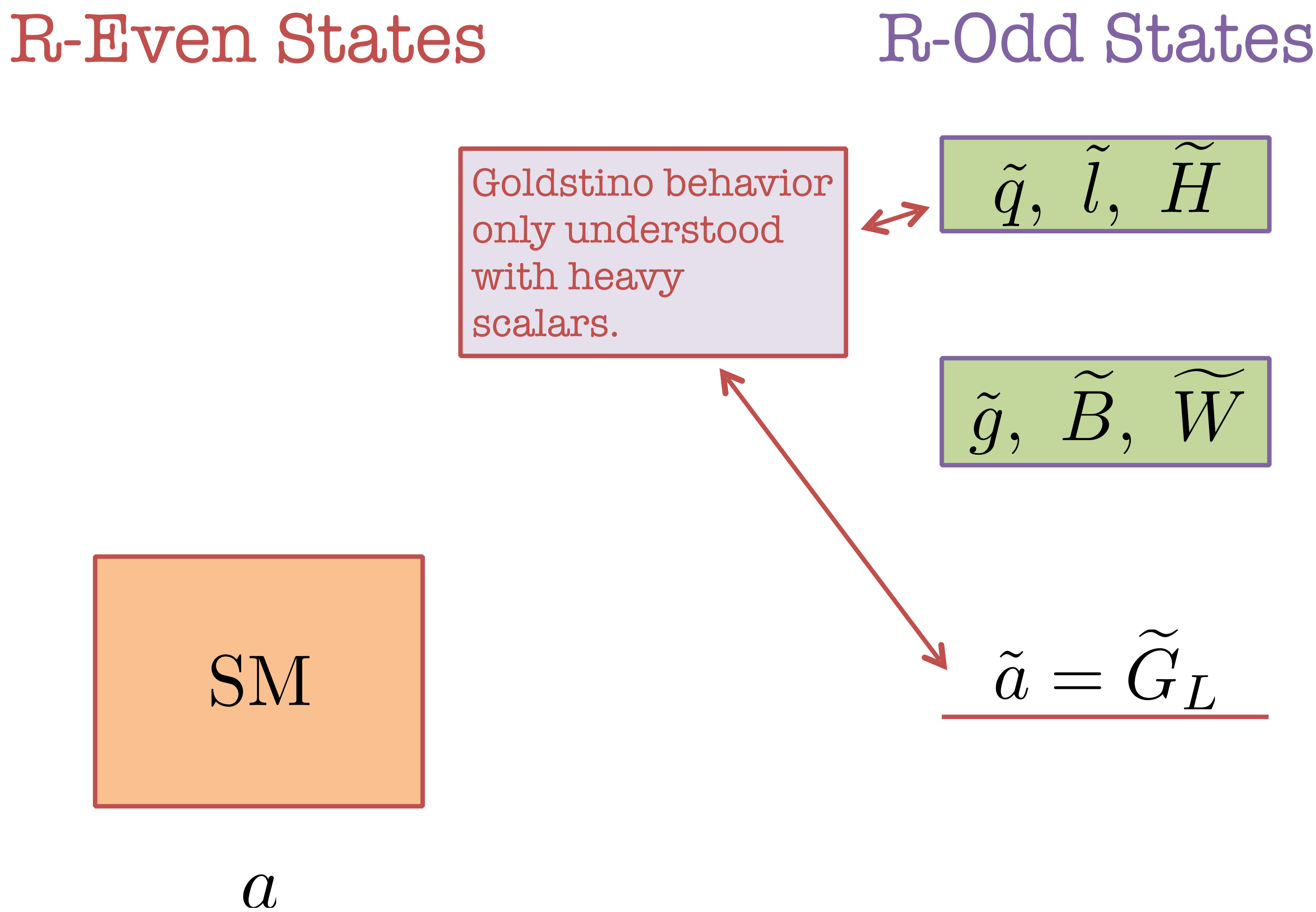
SM

$\tilde{a} = \widetilde{G}_L$

a

SUSY partner of relaxion must be lightest in SUSY tower of states.

New Deep IR – Far UV Connections



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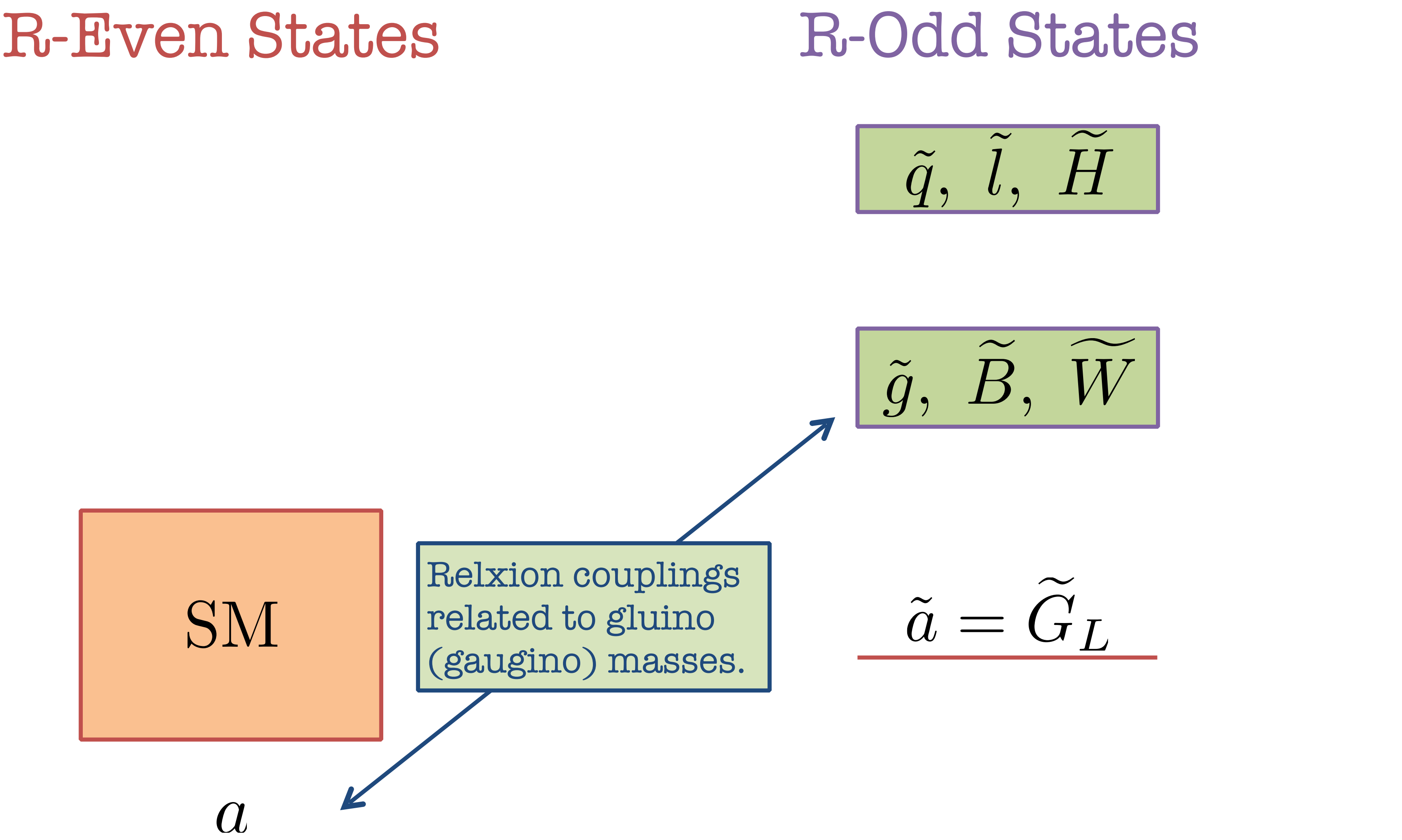

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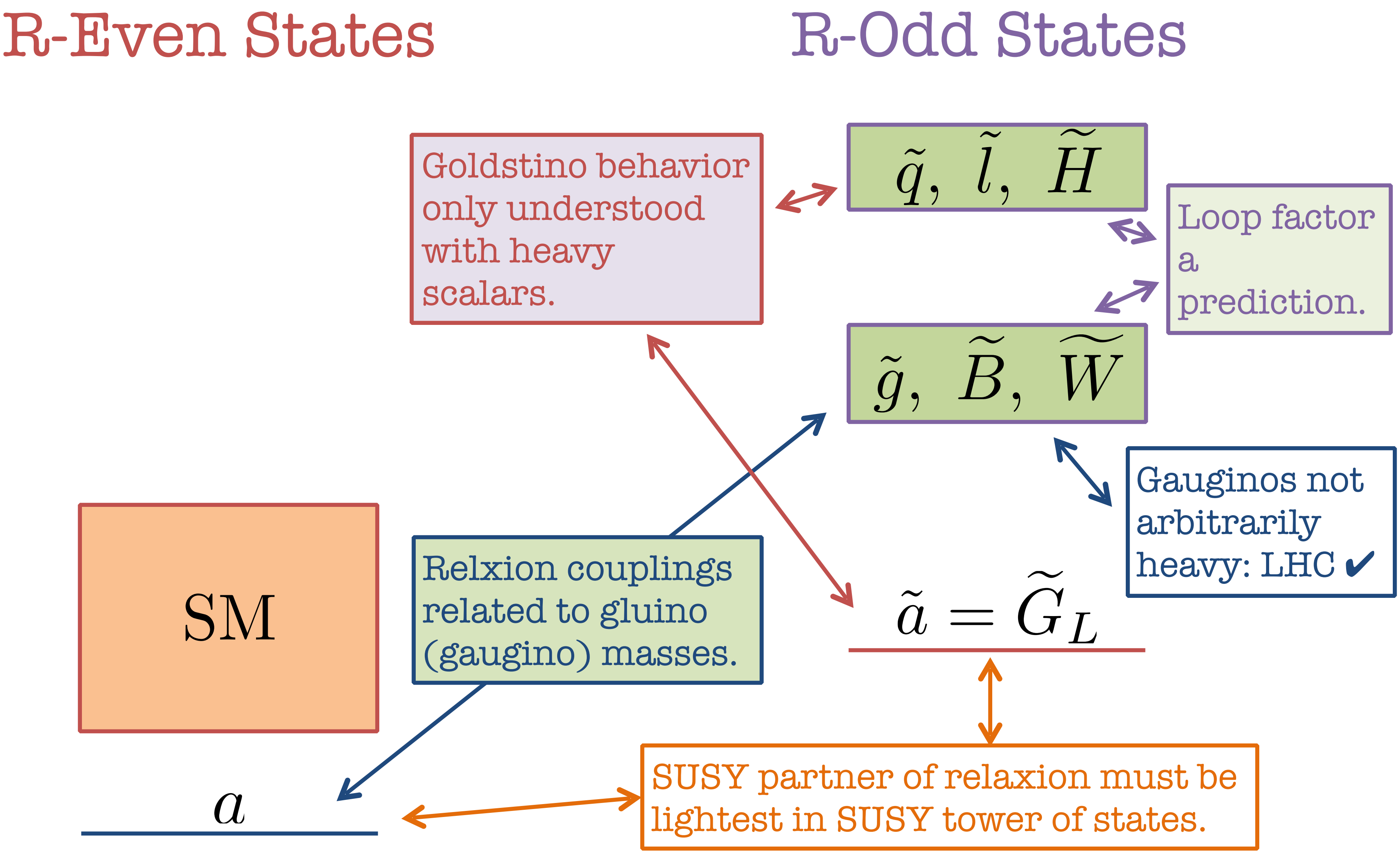
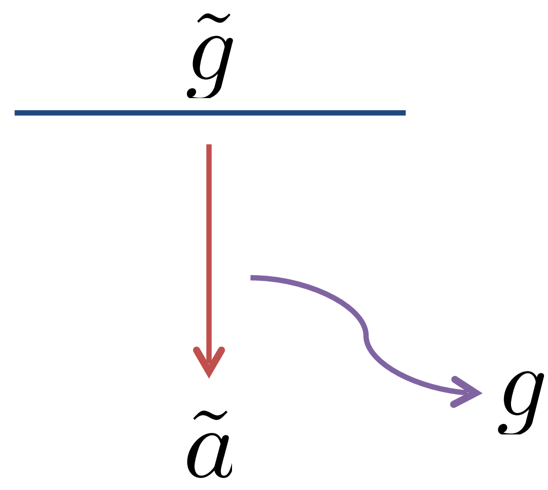


LHC Phenomenology

- Scalars and Higgsinos likely to be out of reach.

- Gauginos possibly within LHC reach. Heavy Higgsinos: all gauginos pure gauge eigenstates.

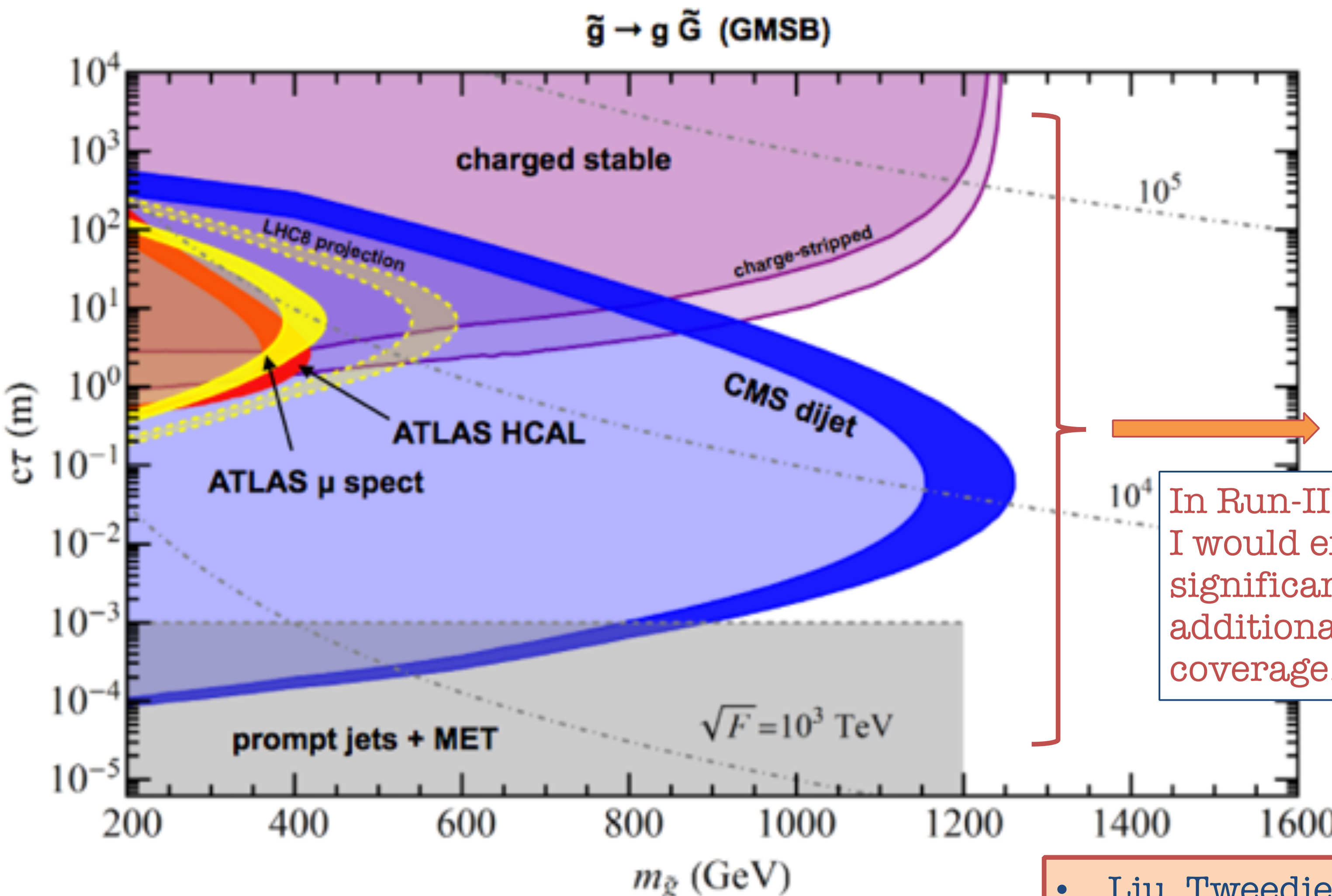
“Decay between 100 microns and a journey to the moon.” (Giudice)



$$\tau_{\mathrm{NLSP}} = \left(\frac{m_{3/2}}{1\ \mathrm{MeV}}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{NLSP}}}\right)^5 1.7 \times 10^2\ \mathrm{m}/c$$

LHC Phenomenology

- Displaced gluino decay limits:



In Run-II
I would expect
significant
additional
coverage.

- Liu, Tweedie, 2015

LHC Phenomenology

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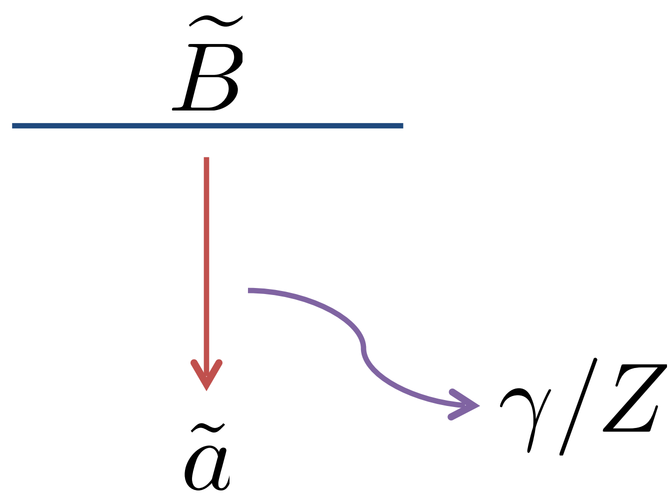

"Decay between 100 microns and a journey to the moon." (Giudice)

Ratio: $\sim \cot^2 \theta_W$

$$\tau_{\mathrm{NLSP}} = \left(\frac{m_{3/2}}{1\ \mathrm{MeV}}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{NLSP}}}\right)^5 1.7 \times 10^2\ \mathrm{m}/c$$

LHC Phenomenology

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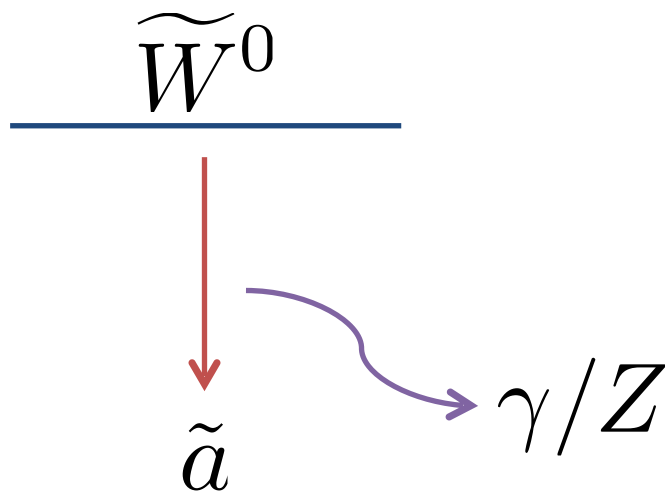


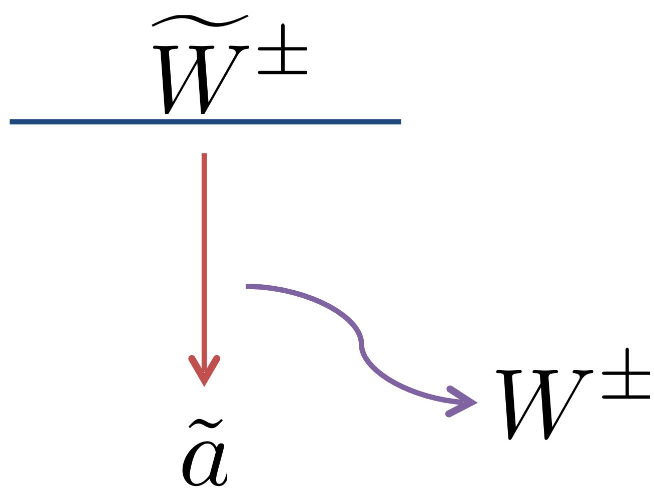
"Decay between 100 microns and a journey to the moon." (Giudice)

Ratio: $\sim \tan^2\theta_W$

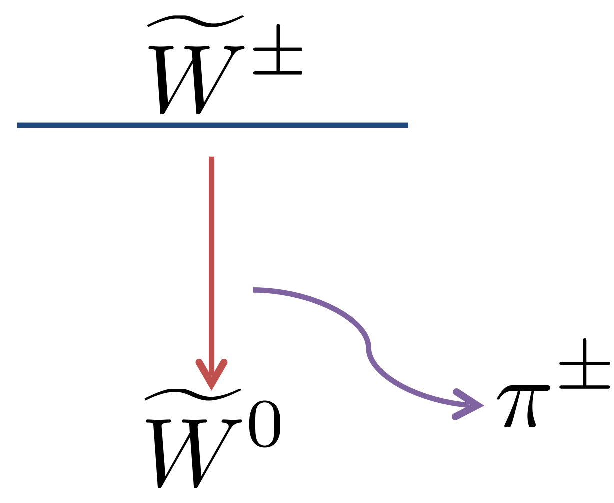
$$\tau_{\mathrm{NLSP}} = \left(\frac{m_{3/2}}{1\ \mathrm{MeV}}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{NLSP}}}\right)^5 1.7\times 10^2\ \mathrm{m}/c$$

LHC Phenomenology

- Wino mass splitting small $M_{\tilde{W}^{\pm}} - M_{\tilde{W}^{0}} \approx 165 \text{ MeV}$
- May have W-bosons, or disappearing tracks.



$100\mu\text{m/c} < \tau_{\tilde{W}^{\pm}\to W^{\pm}+\tilde{a}} < \text{ moon/c}$



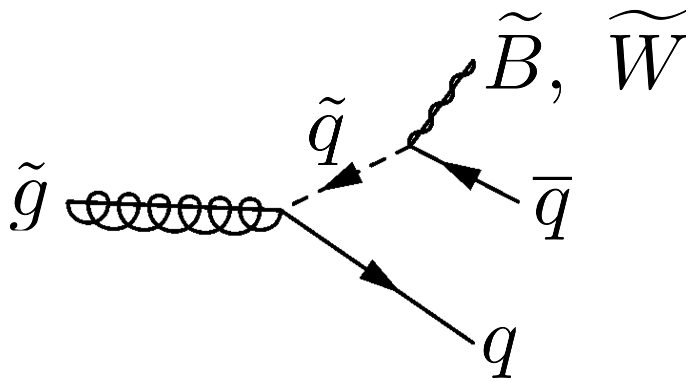
$\tau_{\tilde{W}^{\pm}\to\pi^{\pm}+\tilde{W}^{0}} = 6 \text{ cm/c}$

- Final state depends on SUSY-breaking scale.

LHC Phenomenology

- Dominant production will come from gluino pair production.

- Bino or Wino NLSP produced from gluino decays:



$$\tau_{\tilde{g}\to q\bar{q}\tilde{B}/\tilde{W}} \approx \left(\frac{\tilde{m}}{10^5\ \mathrm{GeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{M_{\tilde{g}}}\right)^5\ 10^{-1}\ \mu\mathrm{m}/c$$

- Gluino NLSP will decay directly to relaxino.

LHC Phenomenology

- Relaxino predicted to be NLSP:
  - Looks like Mini-Split with gauge mediation.

- Typical signatures (decay in detector):
  - MET: relaxino very light and neutral
  - Two displaced vertices
    - A jet at each for gluino NLSP
    - A weak gauge boson at each for bino/wino NLSP
  - Jets (2 for gluino NLSP, 4 otherwise)

- Typical signatures (decay outside detector):
  - R-hadron for gluino NLSP
  - Jets+MET for bino/wino NLSP

LHC Phenomenology

- Relaxino predicted to be NLSP:
  - Looks like Mini-Split with gauge mediation.

- Typical signatures (decay in detector):
  - MET: relaxino very light and neutral
  - Two displaced vertices
    - A jet at each for gluino NLSP
    - A weak gauge boson at each for bino/wino NLSP
  - Jets (2 for gluino NLSP, 4 otherwise)

- Typical signatures (decay outside detector):
  - R-hadron for gluino NLSP
  - Jets+MET for bino/wino NLSP

Twin Higgs

Chacko, Goh, Harnik 2005

- Take two identical copies of the Standard Model:

$$\mathrm{SM}_A \xleftrightarrow{A \leftrightarrow B} \mathrm{SM}_B$$

- Enhance symmetry structure to global SU(4):

Quartic cross-couplings dictated by symmetry

$$V_{\text{Higgs}} = \lambda \left(|H_A|^2 + |H_B|^2\right)^2 - \Lambda^2 \left(|H_A|^2 + |H_B|^2\right)$$

Exchange enforces equal quadratic corrections for each Higgs. Thus masses still respect SU(4) symmetry.

Twin Higgs

Chacko, Goh, Harnik 2005

- Total symmetry-breaking pattern is: $\mathrm{SU}(4) \rightarrow \mathrm{SU}(3)$

- Thus 7 Goldstone bosons:

$$\mathrm{SU}(4) \rightarrow \mathrm{SU}(3) \Rightarrow 7 \times \pi$$

$$7 \times \pi \rightarrow 3 \times \pi \Rightarrow W_B, Z_B$$

$$7 \times \pi \rightarrow 4 \times \pi \Rightarrow \begin{pmatrix} H^{\pm} \\ H^{0} \end{pmatrix}$$

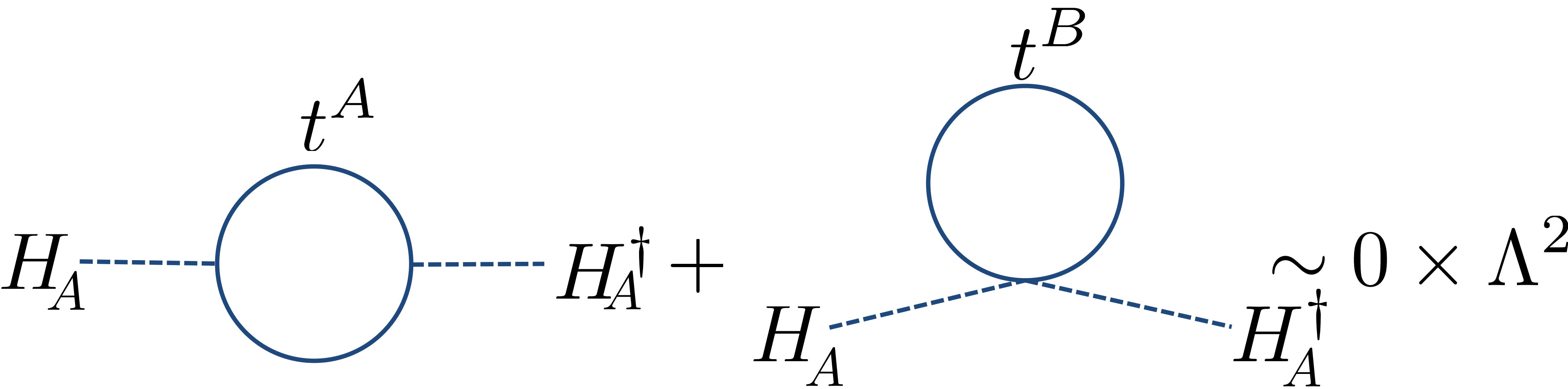
- The SM Higgs light because of the symmetry-breaking pattern!

- Hierarchy problem solved all the way up to the scale: Λ

Twin Higgs

Chacko, Goh, Harnik 2005

- In usual "quadratic divergences" parlay:



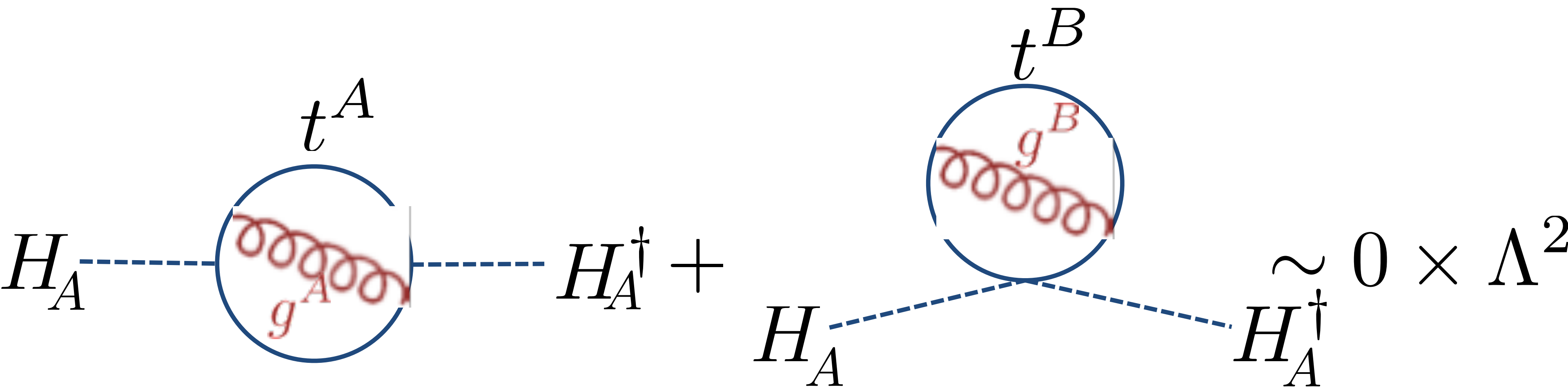
Quadratic divergences from SM top quark loops cancelled by loops of "Twin" top quarks.

- Cancellation persists for all Twin particles: Twin W-bosons, Twin gluons, etc.

Twin Higgs

Chacko, Goh, Harnik 2005

- In usual "quadratic divergences" parlay:



Quadratic divergences from SM top quark loops cancelled by loops of "Twin" top quarks.

- Cancellation persists for all Twin particles: Twin W-bosons, Twin gluons, etc.

Standard Model

"Twin" Standard Model

$g \quad Z$

$q \quad \gamma \quad h_A$

$l \quad W$

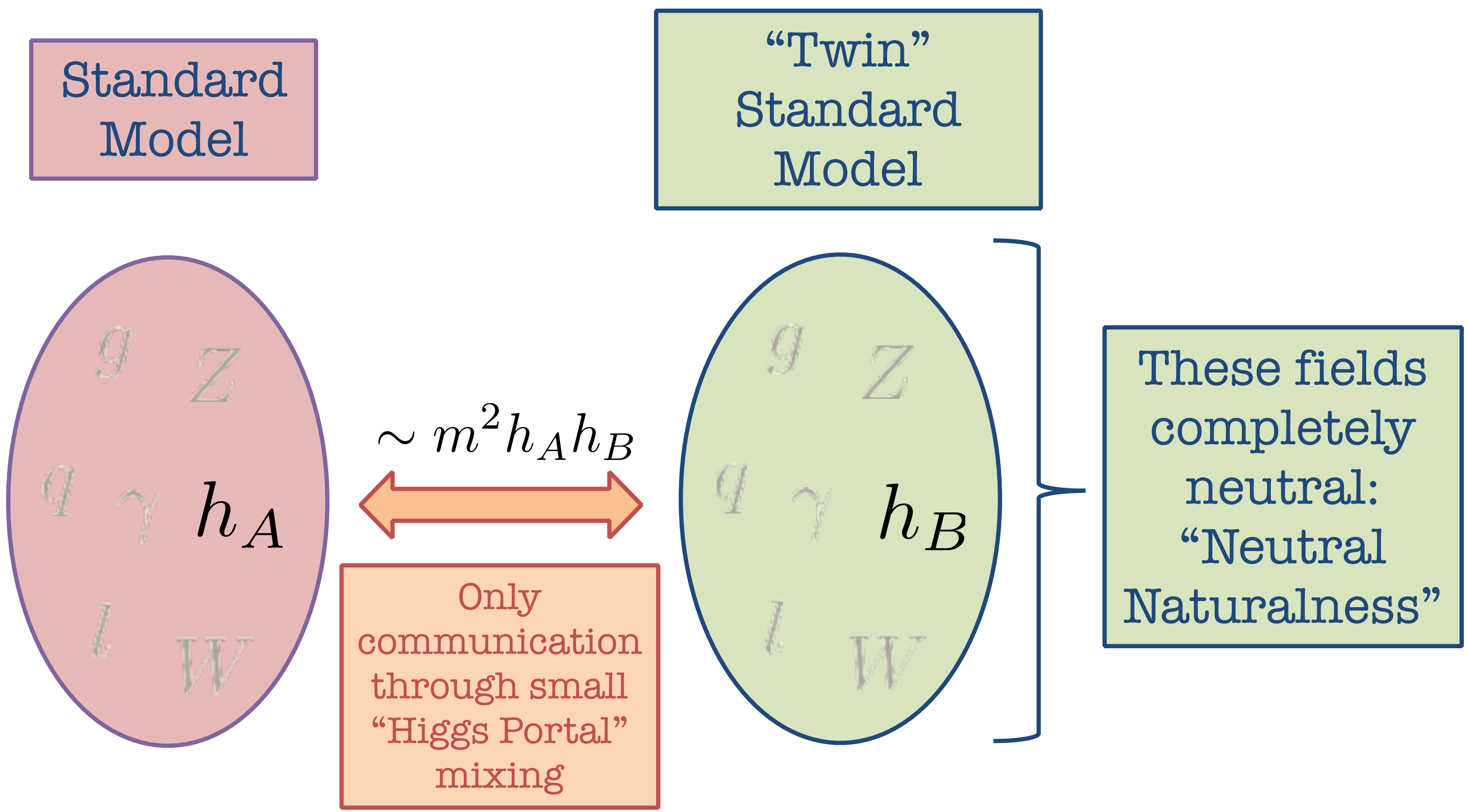
$g \quad Z$

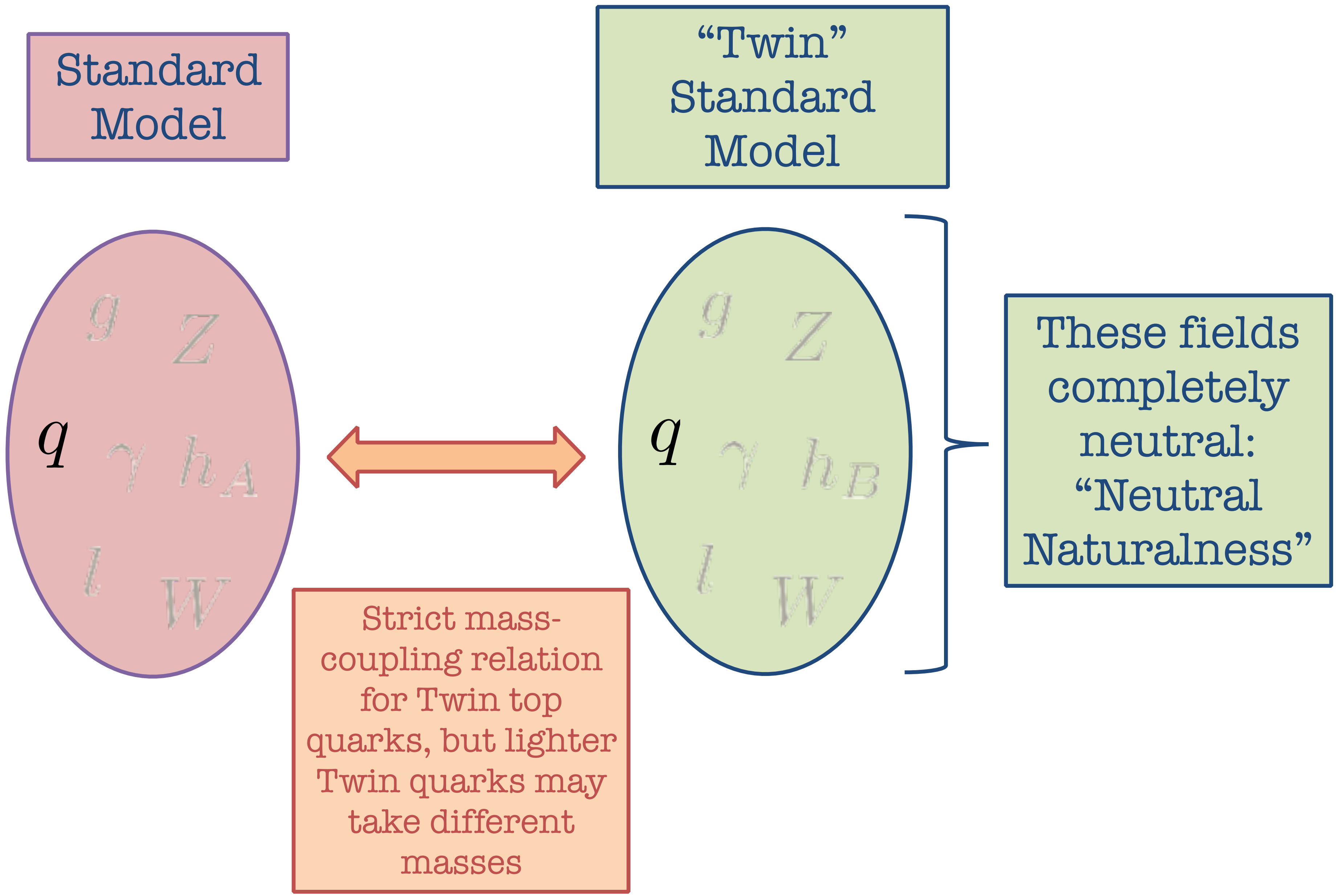
$q \quad \gamma \quad h_B$

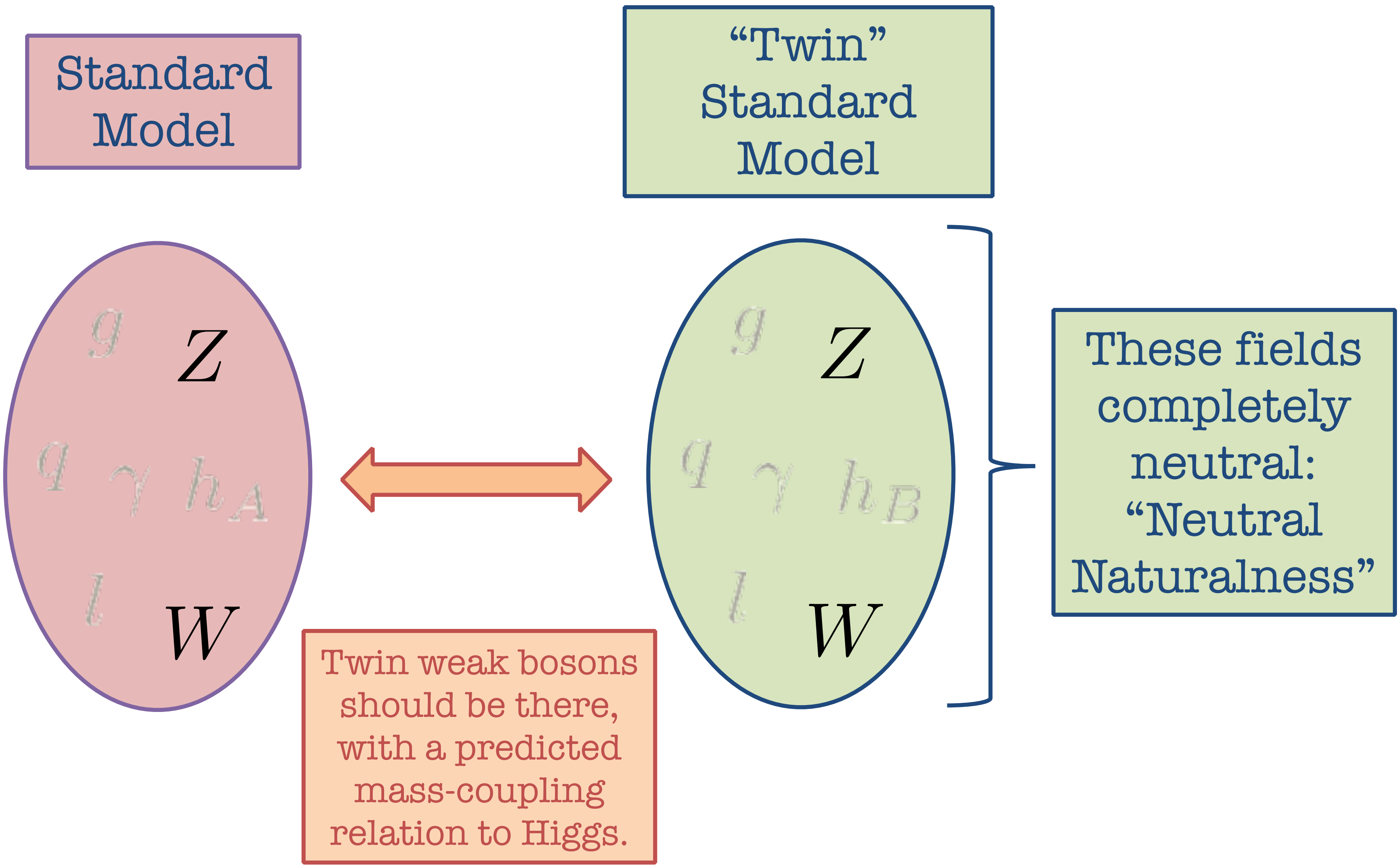
$l \quad W$

These fields completely neutral: "Neutral Naturalness"

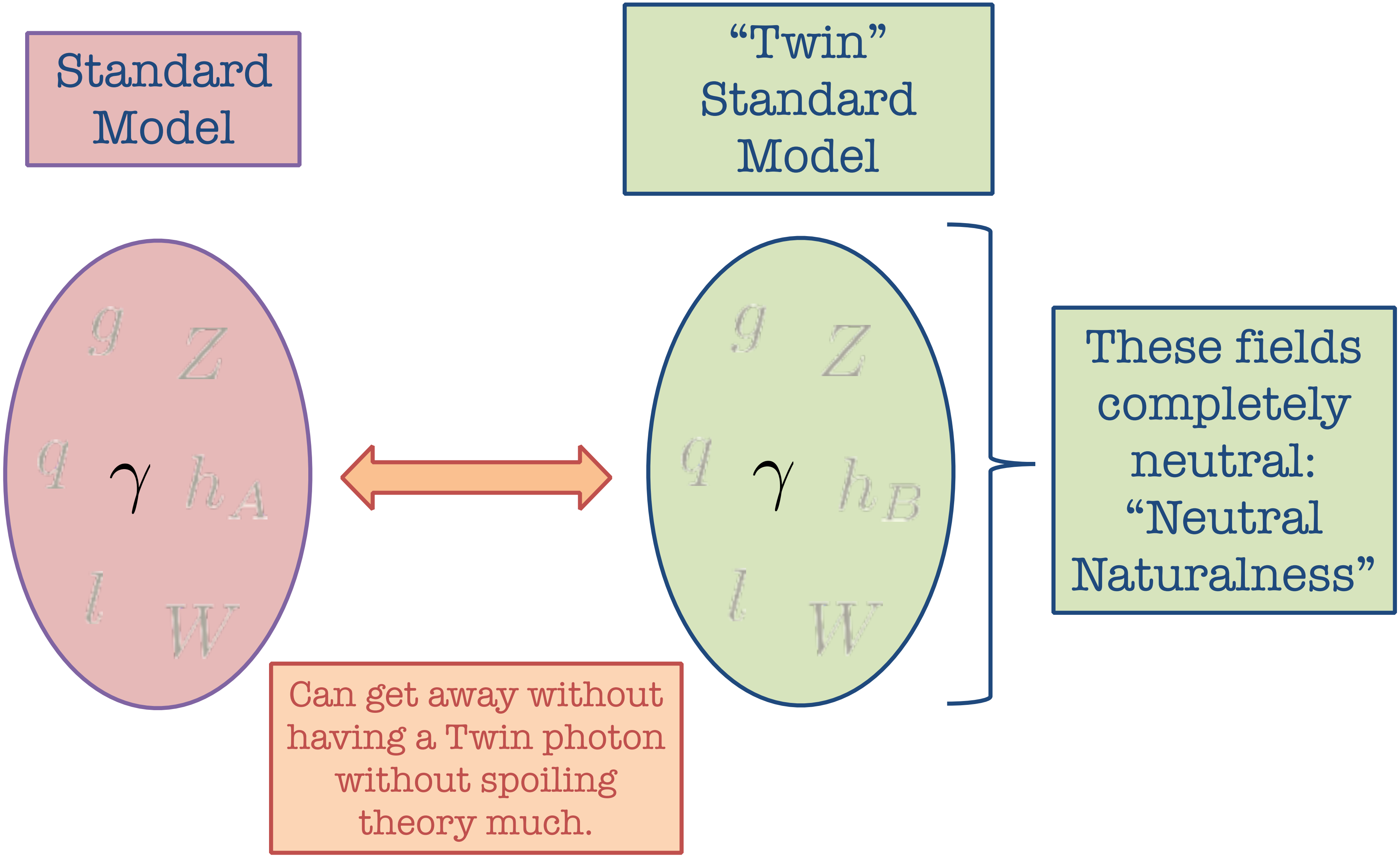
Predictions for Twin sector most robust for the Twins of the SM fields that couple most strongly to Higgs.

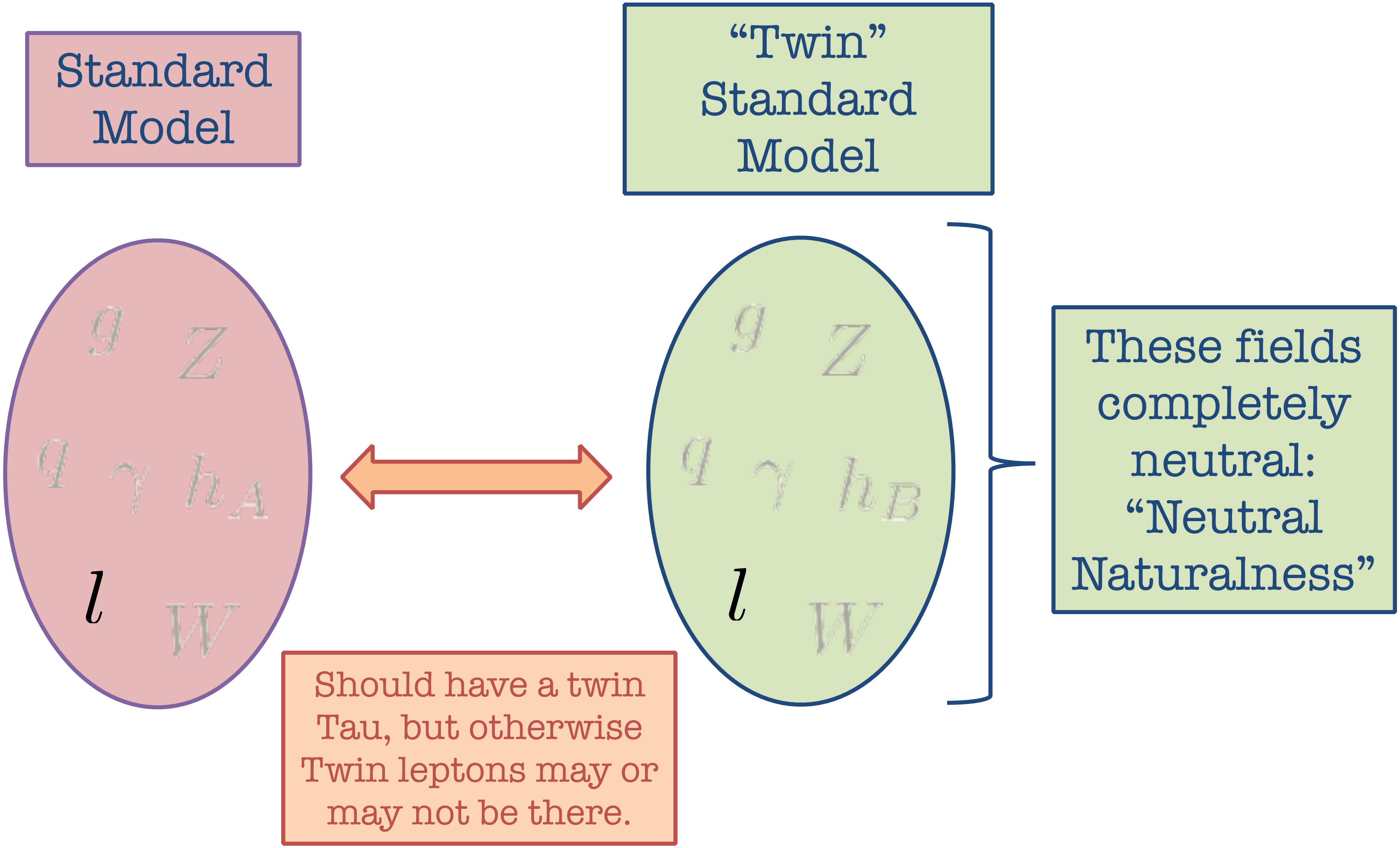

Standard Model
"Twin" Standard Model
g Z q γ h_A l W
$\sim m^2 h_A h_B$
Only communication through small "Higgs Portal" mixing
g Z q γ h_B l W
These fields completely neutral: "Neutral Naturalness"

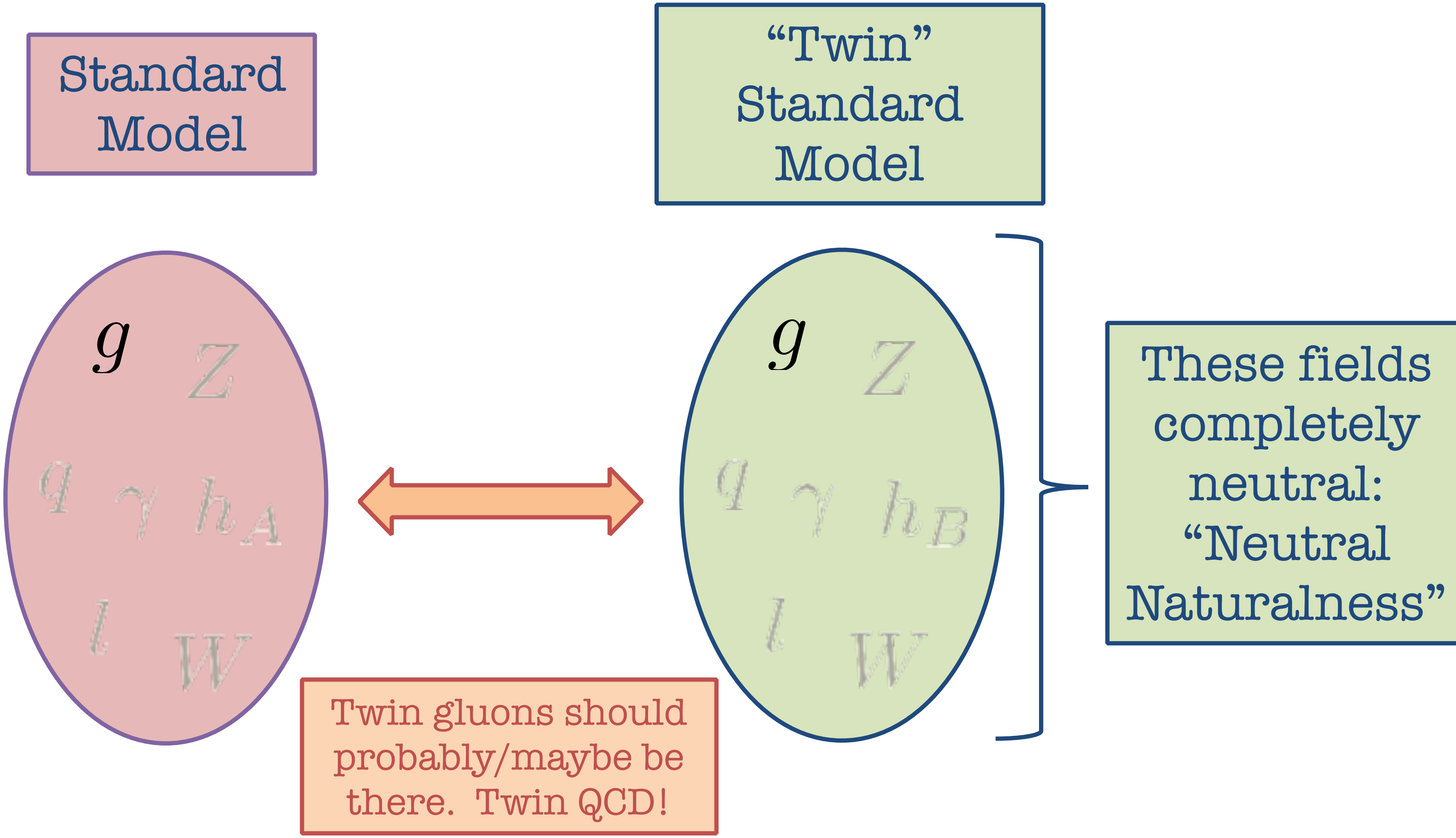

Standard Model
"Twin" Standard Model
g Z q γ h_A l W
g Z q γ h_B l W
These fields completely neutral: "Neutral Naturalness"
Strict mass-coupling relation for Twin top quarks, but lighter Twin quarks may take different masses



Standard Model
"Twin" Standard Model
g Z q γ h_A l W
g Z q γ h_B l W
These fields completely neutral: "Neutral Naturalness"
Twin weak bosons should be there, with a predicted mass-coupling relation to Higgs.


Standard Model
"Twin" Standard Model
g Z q γ h_A l W
g Z q γ h_B l W
These fields completely neutral: "Neutral Naturalness"
Can get away without having a Twin photon without spoiling theory much.


Standard Model
"Twin" Standard Model
g Z q γ h_A l W
g Z q γ h_B l W
These fields completely neutral: "Neutral Naturalness"
Should have a twin Tau, but otherwise Twin leptons may or may not be there.



Standard Model
"Twin" Standard Model
g
Z
q
γ
h_A
l
W
g
Z
q
γ
h_B
l
W
These fields completely neutral: "Neutral Naturalness"
Twin gluons should probably/maybe be there. Twin QCD!

Twin Higgs - Pheno

- Collider phenomenology is very diverse…

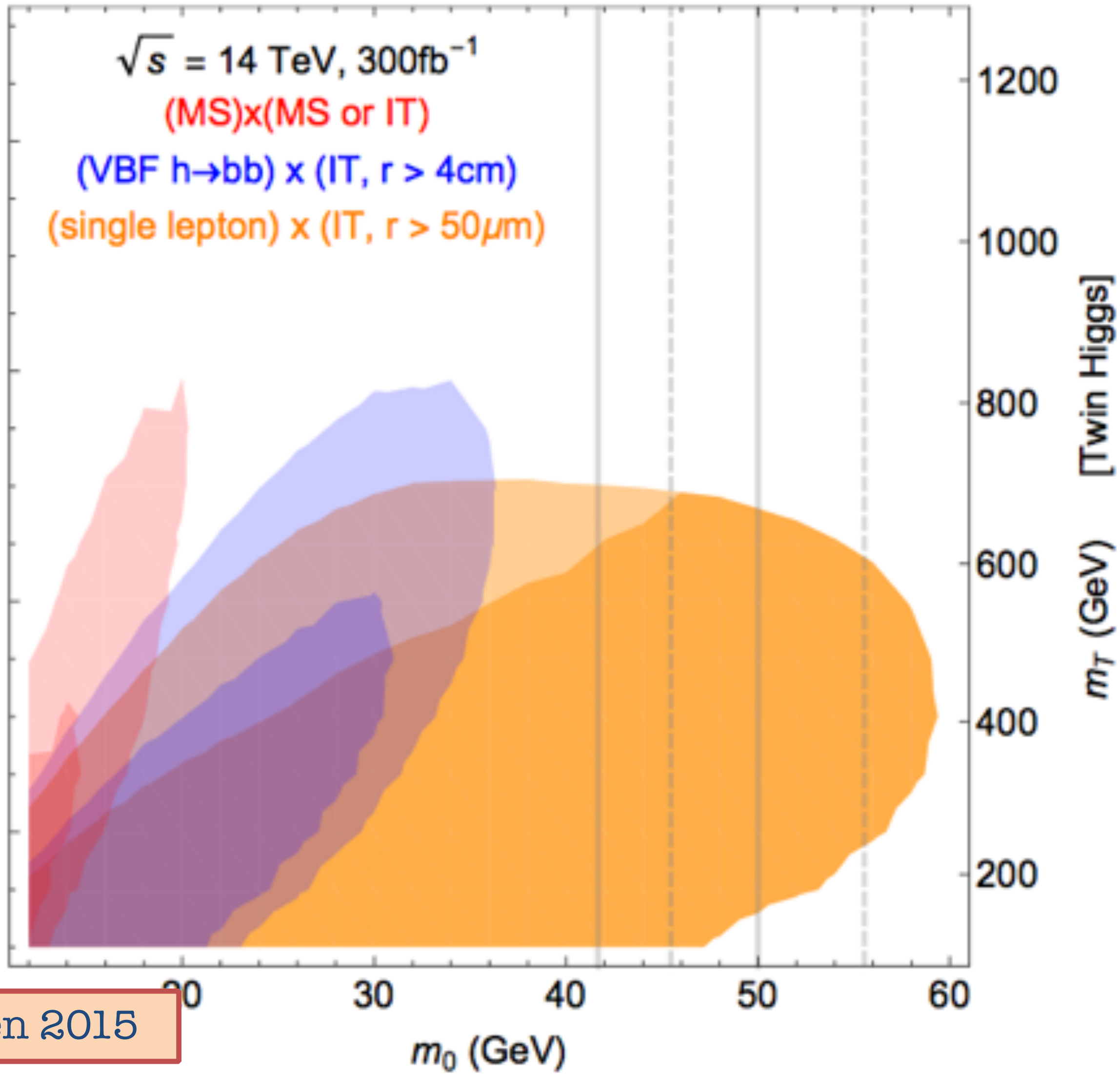
Exotic Higgs Decays to
"Twin Glueballs"

Craig, Katz, Strassler, Sundrum 2015

- LHC pheno driven by Twin QCD + Higgs Portal + displaced vertices.

Twin Higgs - Pheno

- Twin glueballs discoverable at LHC:

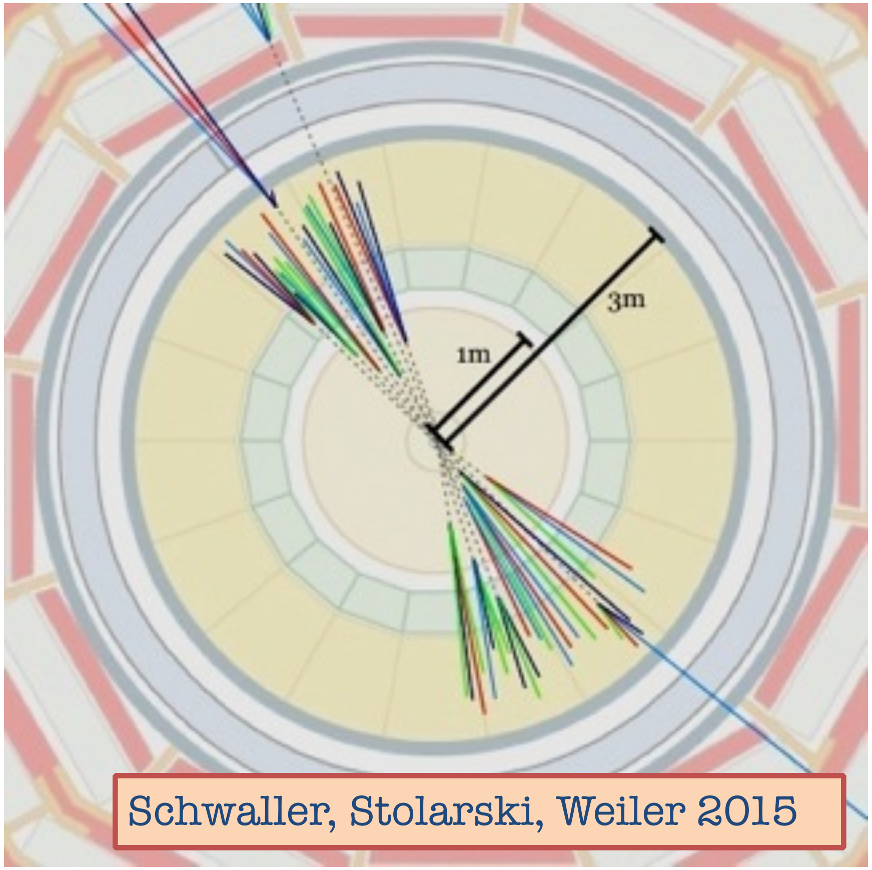


Curtin, Verhaaren 2015

Twin Higgs - Pheno

- Collider phenomenology is very diverse and radically different to usual signatures.

“Emerging Jets” a potential feature of hidden dark QCD sector.



Schwaller, Stolarski, Weiler 2015

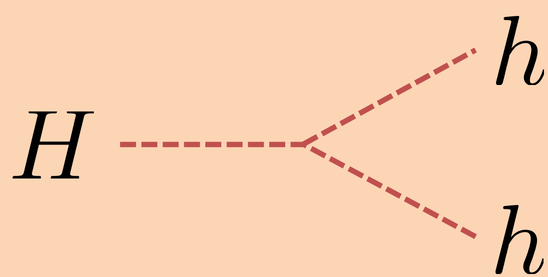
- LHC pheno driven by Twin QCD + Higgs Portal and often displaced vertices.

Twin Higgs - Pheno

- Collider phenomenology may also exhibit more standard BSM signatures.

Precision Higgs: "Higgs Portal" type mixing between heavier Twin Higgs and SM Higgs. All couplings modified by: $c_h \longrightarrow \cos\theta$

Heavy Higgs Decays could lead to Di-Higgs resonances:

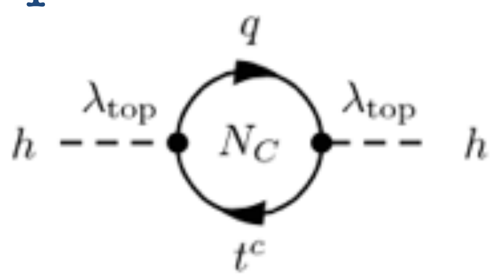


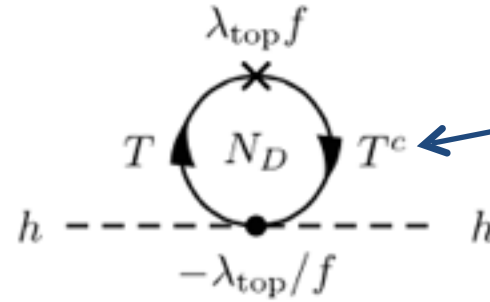
- LHC pheno driven by Twin QCD + Higgs Portal and often displaced vertices.

Variations

- Poland, Thaler, 2008

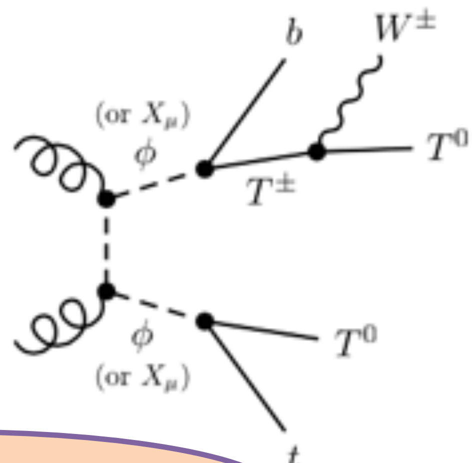
- What if there is no Twin QCD?
  - "Dark Top"



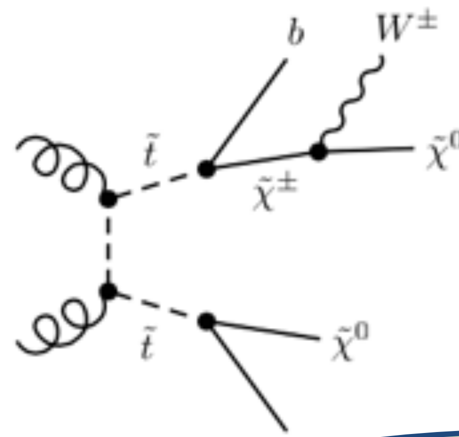


This guy is the dark matter!

  - Collider signatures difficult unless produced in cascade after coloured resonance production.



vs.



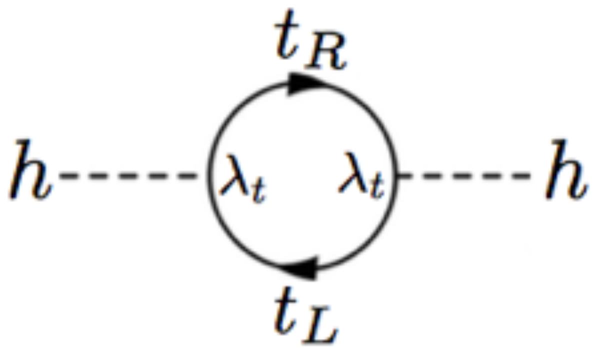
Dark Top

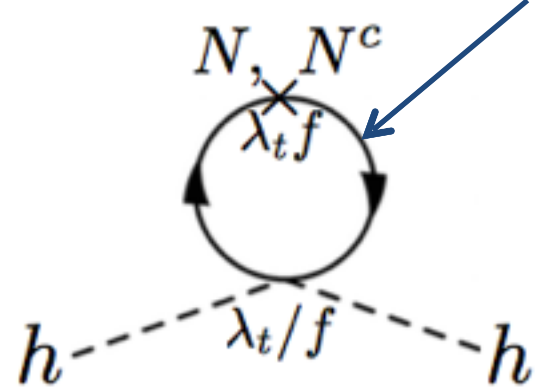
SUSY Analogue

Variations

- Batell, McCullough, 2015

- What if there is no Twin QCD?
  - “Natural Neutrinos”





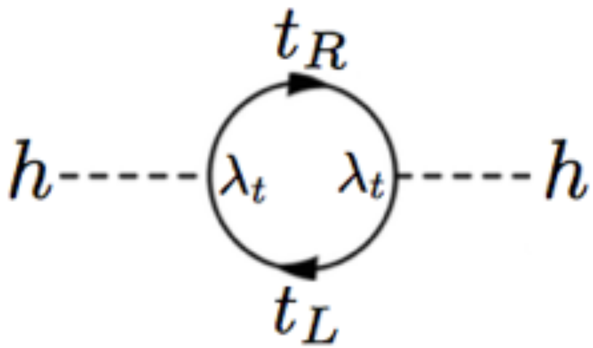
This guy is the RHN!

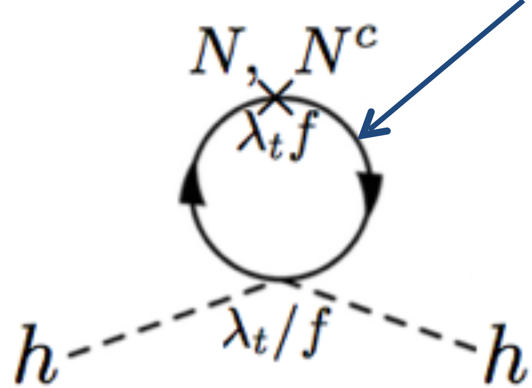
- Low energy experiment:
  - Vector-like RHN means non-unitarity of PMNS
  - Lepton flavor violation
  - Neutrinoless double beta decay
- Realizes “Inverse” or “Linear” SeeSaw.

Variations

- Batell, McCullough, 2015

- What if there is no Twin QCD?
  - "Natural Neutrinos"





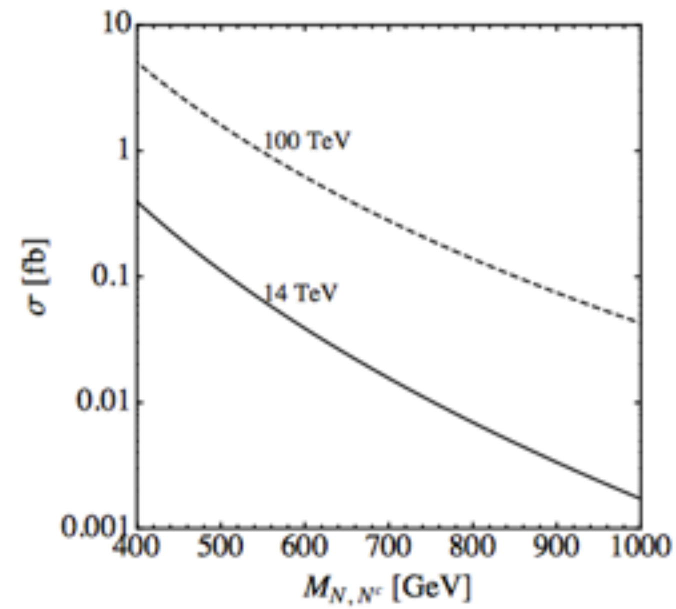
This guy is the RHN!

- At LHC:

Mixing enables associated production.

$$Z^* \to \nu N \to h\nu\nu$$
$$Z^* \to \nu N \to Z\nu\nu$$
$$Z^* \to \nu N \to Wl\nu$$
$$W^* \to lN \to hl\nu$$
$$W^* \to lN \to Zl\nu$$
$$W^* \to lN \to Wll$$

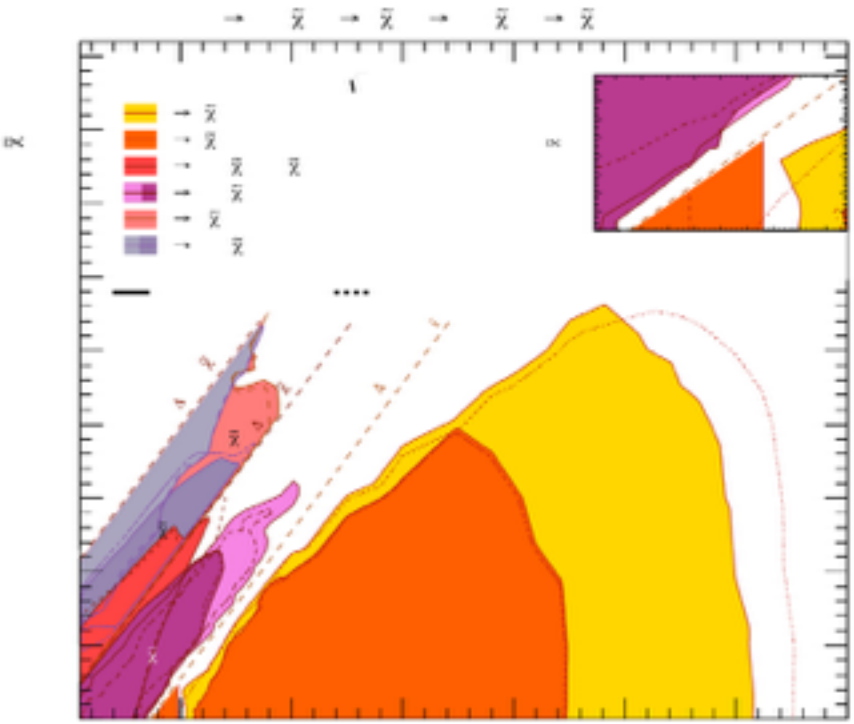
But cross sections are small...

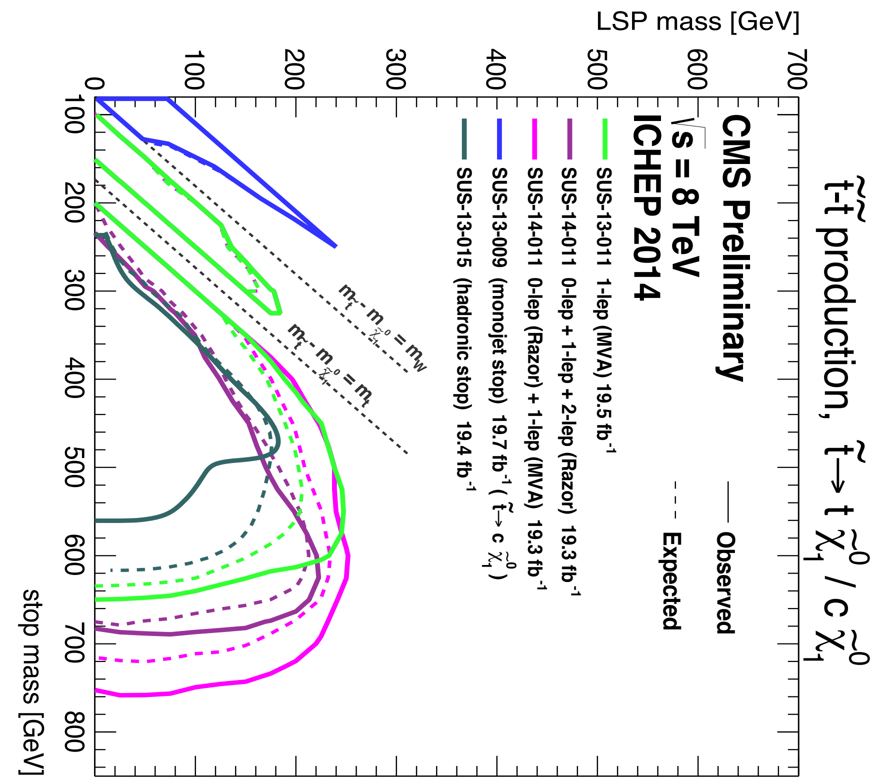


See yesterday talk by Weiland!

Summary

- Hierarchy problem more puzzling than ever.





- Experimental progress has been game changing for BSM theory.

To The Future

- LHC Run I has fundamentally changed our perspective on the hierarchy problem.

- **Twin Higgs** is difficult to test. However, by looking in new places LHC Run-II and future colliders could answer many questions.

- Radical new idea has emerged: "**Relaxation**". Initially looks difficult to test. However, addressing strong-CP issues may lead to promising Run II possibilities.

- When SUSY and relaxation are married, to realize **Natural Heavy SUSY**, cosmological constraints point towards gauginos with displaced decays at LHC Run II or future colliders.