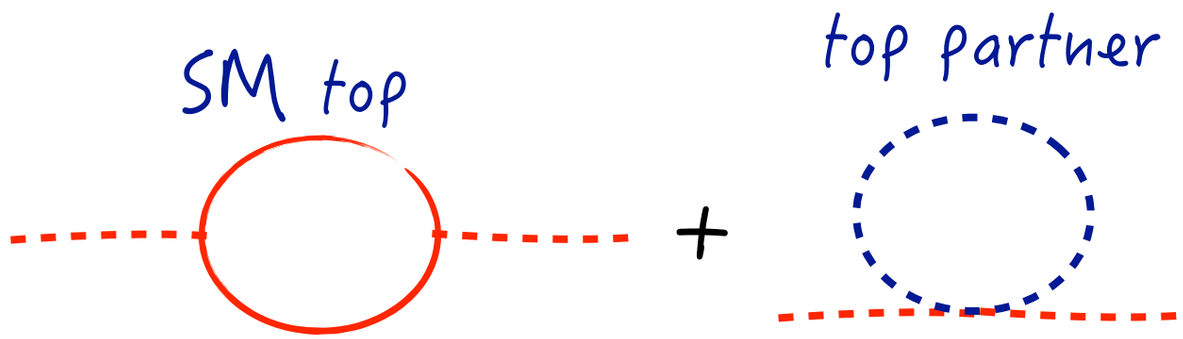
Neutral Naturalness and the Higgs

Roni Harnik
Fermilab

The Tuning Problem

- The weak scale is fine tuned in the SM. a.k.a the **hierarchy problem.**
- This tuning can be removed by invoking a symmetry. e.g. in SUSY:

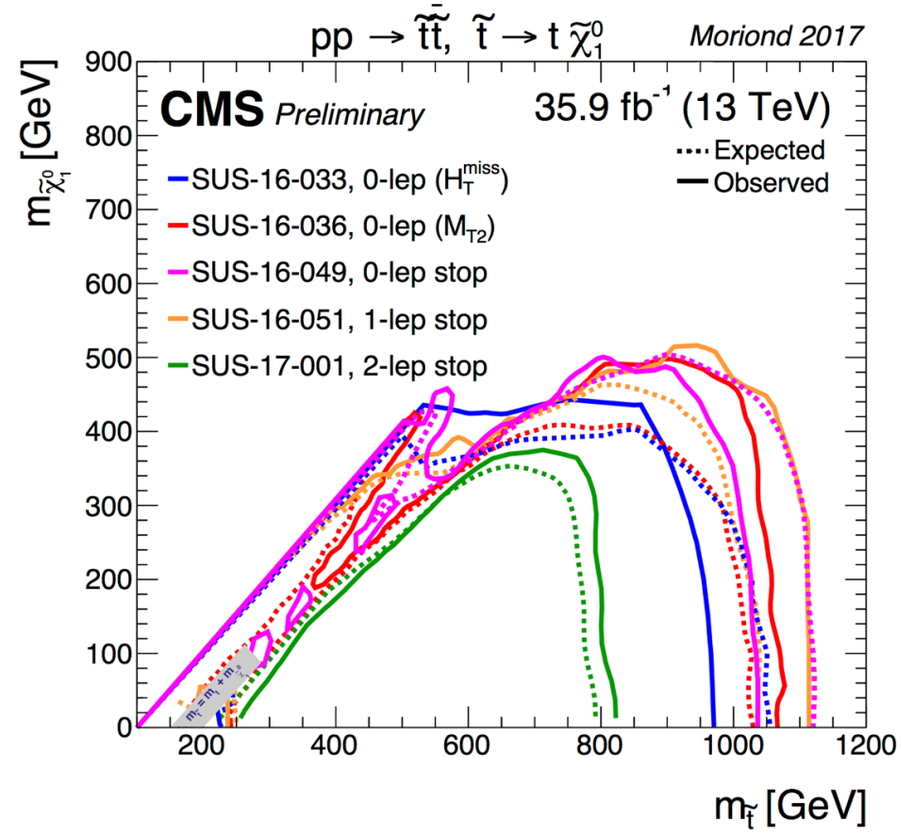
$$\text{top} \xrightarrow[\text{(commutes w/ color)}]{\text{SUSY transformation}} \text{stop}$$



The Tuning Problem

- Naturalness → a **colored** top partner at ≲TeV.
- However, so far the LHC discovered just the Higgs and nothing else new..... (may change soon!)

The current manifestation of the tuning problem:



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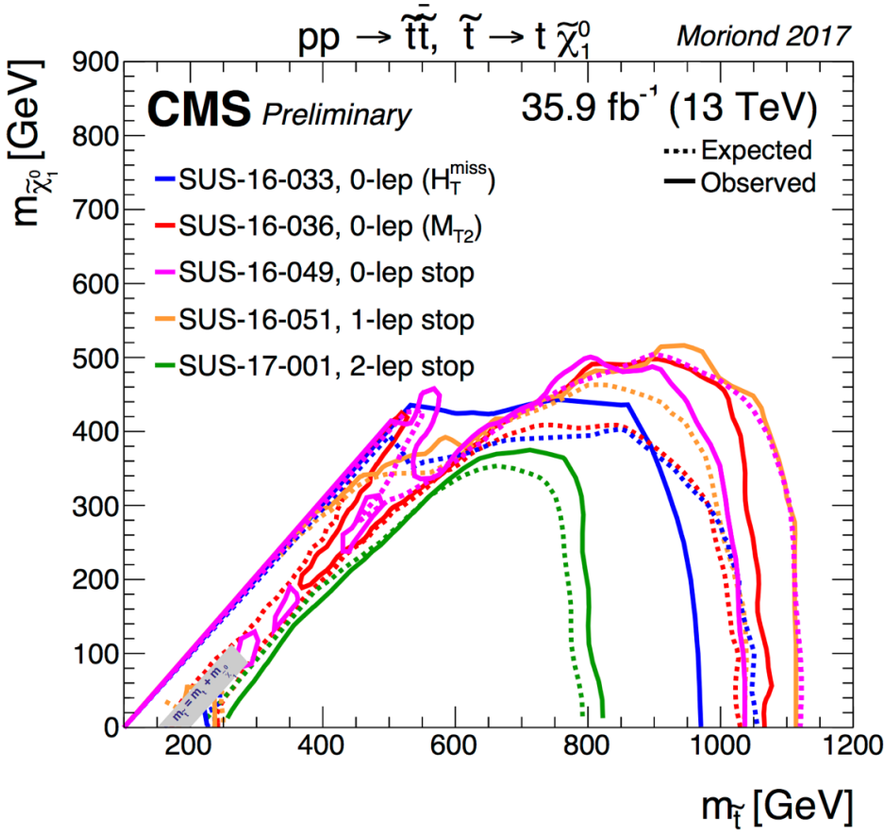
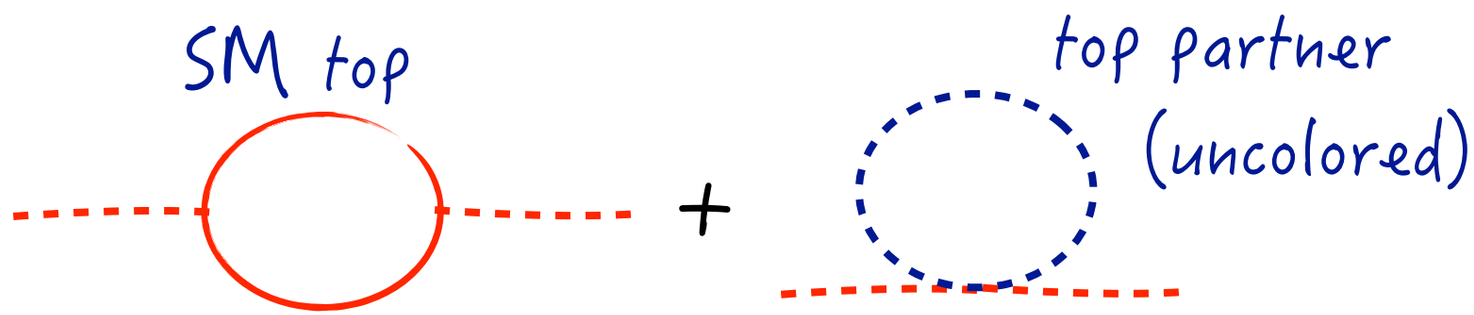
Where the hell is everybody?!



Neutral Naturalness

- Models of Neutral Naturalness address Higgs tuning w/ **uncolored** partners.

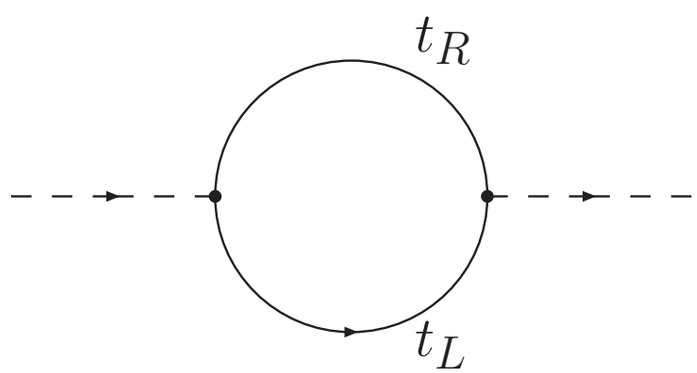


- Higgs Hunters are a good target audience:

Precision and exotic Higgs measurements may be the <u>only</u> LHC discovery channels.

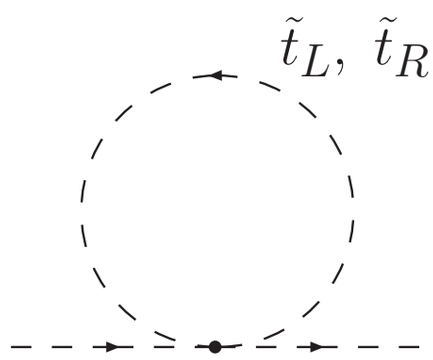
Neutral Naturalness Models

color factor:



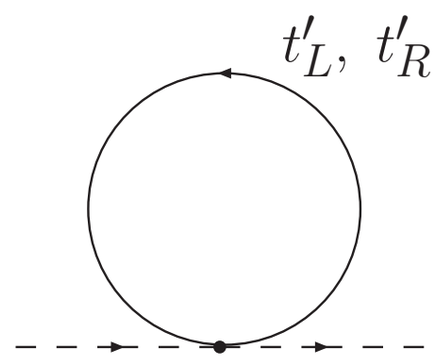
Standard Model

$\times 3$



Supersymmetry

or



Composite Higgs

$\times 3$

Neutral Naturalness Models

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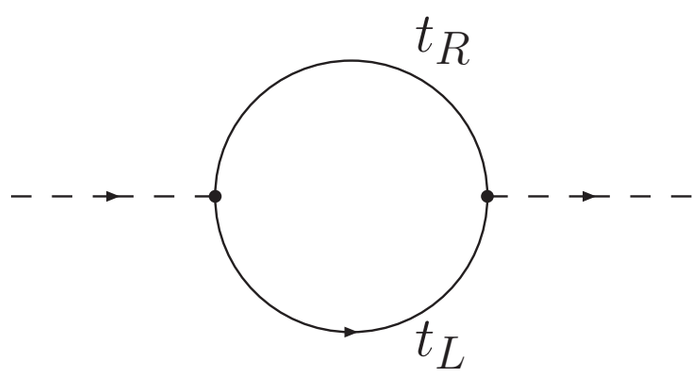

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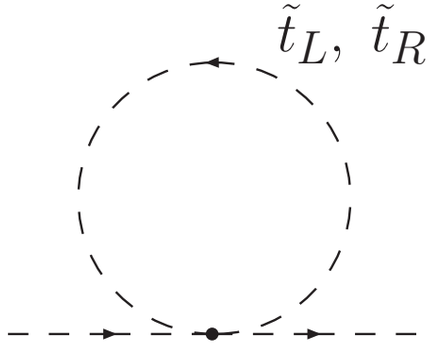

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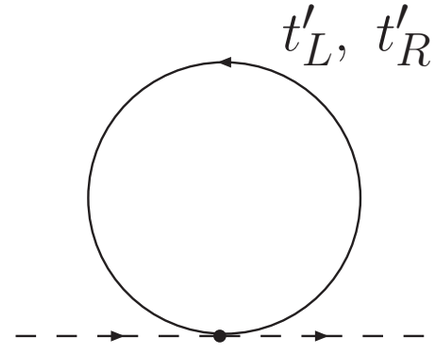
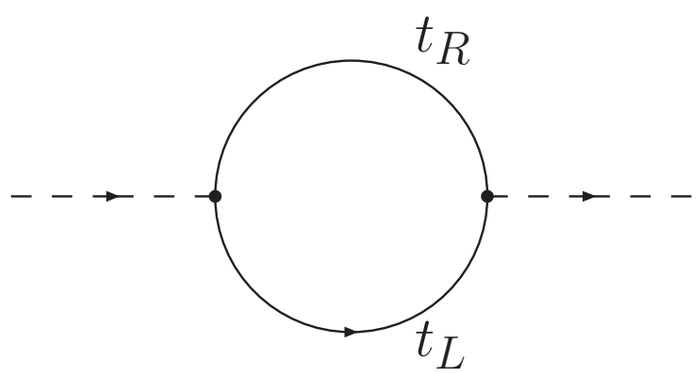


Composite Higgs

$\times \cancel{3}$ 3'

Neutral Naturalness Models

color factor:



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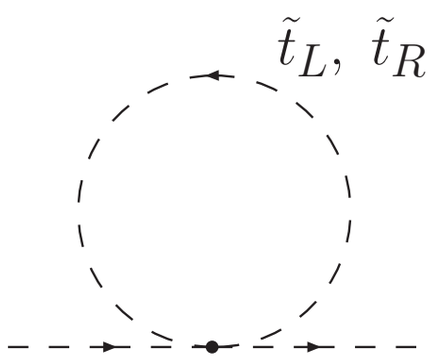

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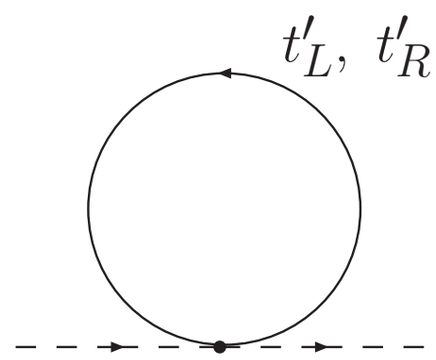

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symmetry does not commute with color.

Neutral Naturalness Models

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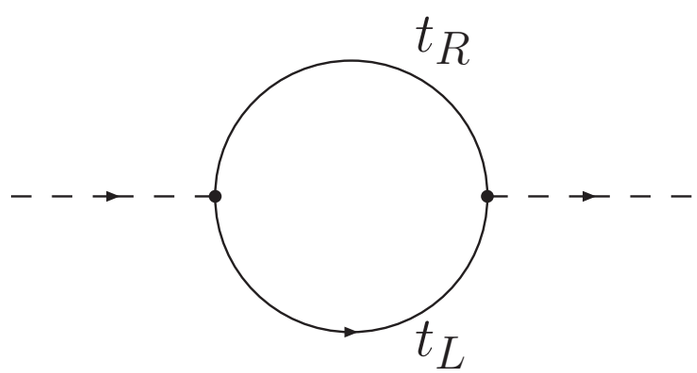

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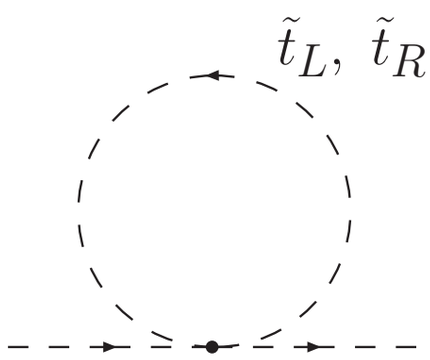

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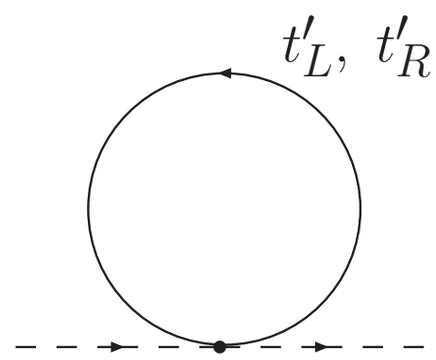

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symmetry does not commute with color.

↓

Folded SUSY

Burdman, Chacko, Goh, RH (06')

↓

Twin Higgs

Chacko, Goh ,RH (05')

Neutral Naturalness Models

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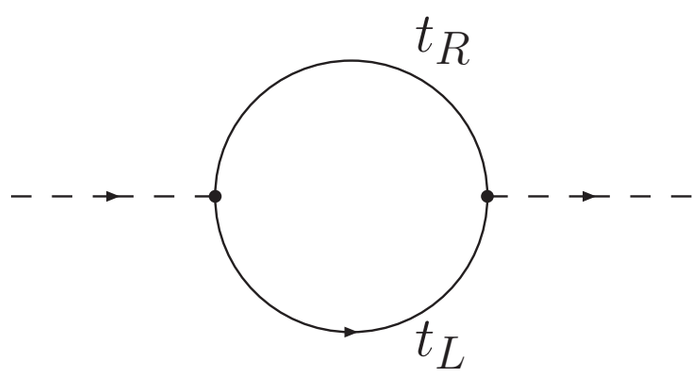

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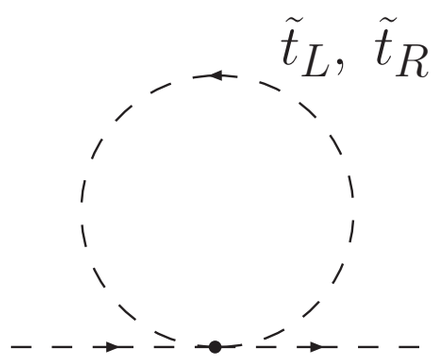

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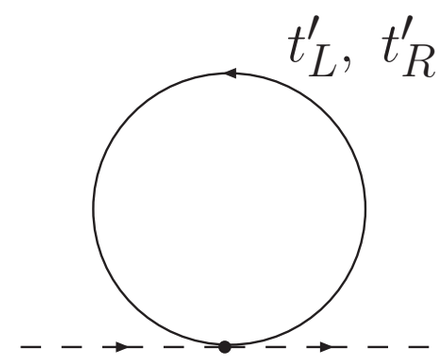

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↓ **Folded SUSY**

Burdman, Chacko, Goh, RH (06')

↓ **Twin Higgs**

Chacko, Goh ,RH (05')

More Example since: Quirky Little Higgs, Dark Top, Top partners as RH Neutrinos, Orbifold Higgs, Fraternal Twin Higgs,

An example:

Twin Higgs

Chacko, Goh, RH (05')

Mirror Symmetry

* Example: Mirror Symmetry

$$(SM_A) \times (SM_B)$$

$$\mathbb{Z}_2$$

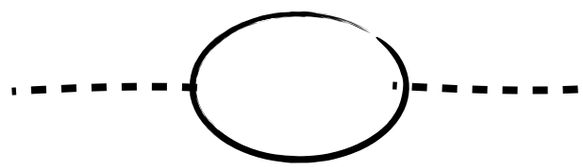
An exchange symmetry. $A \longleftrightarrow B$.

This $\mathbb{Z}_2$ does not commute with $SU(3)_{QCD}$.
Can it play a role in protecting the Higgs? (yes!)

Chacko, Goh, RH (05')

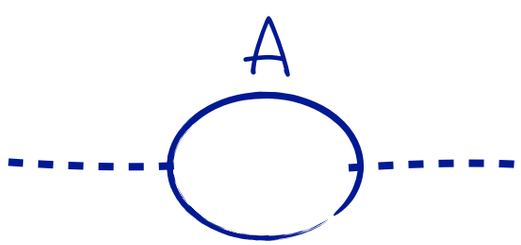
Twin Higgs (the Disney version)

* The Hierarchy problem stems from the mass term in the Higgs potential - a quadratic



$\propto c\Lambda^2 H^2$

* In a mirror model this becomes -



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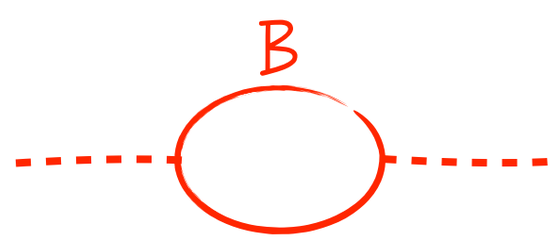
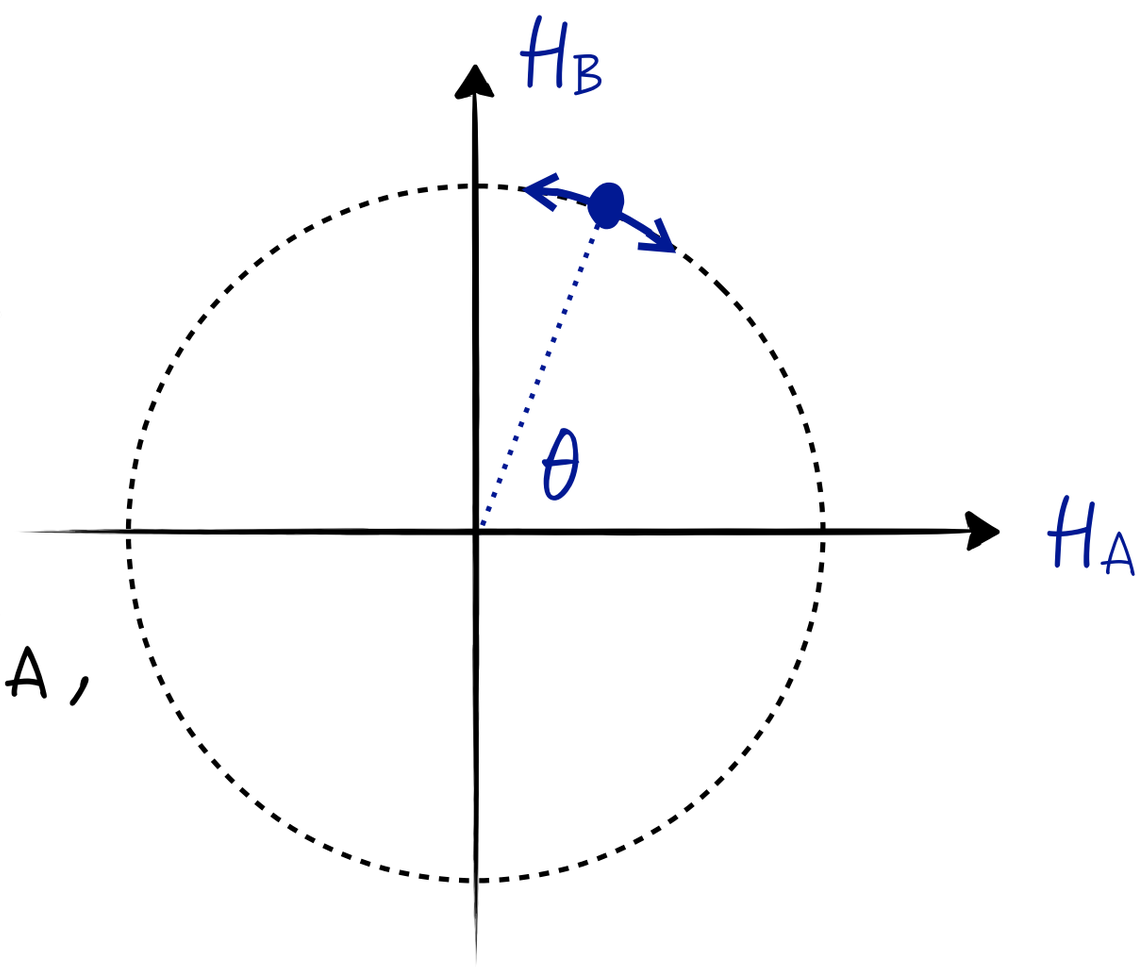


$\propto c\Lambda^2 (H_A^2 + H_B^2)$

Note: $(H_A^2 + H_B^2)$ has a higher symmetry of continuously **rotating** H_A and H_B into one another.

Twin Higgs

* The two Higgs doublets for a 4-plet of a global SU(4) symmetry (or SO(8) in composite models).
* SU(4) is broken spontaneously at a scale f. (mostly by the other Higgs!)
* One Goldstone boson is left uneaten.
* The pNGB is **mostly** H_A, (but a bit H_B too!).



Cancelation

* Z_2 guarantees $(H_A^2+H_B^2)$ structure at quadratic level. SU(4) protects the Higgs!

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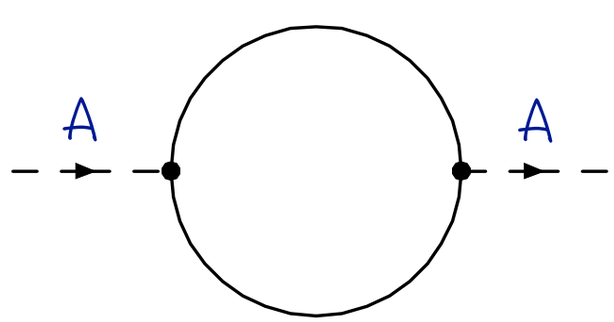
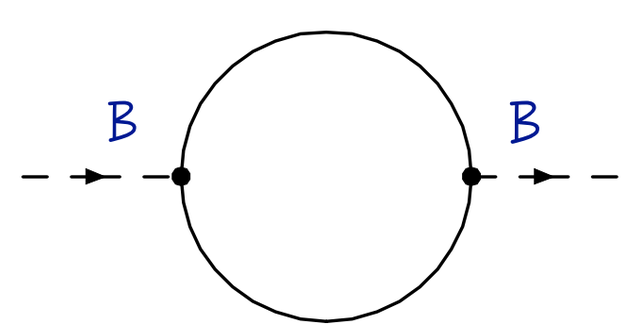
* In diagrams, there is a cancelation between loops.

* Recall 'Higgs portal' coupling SM's - [the Cross term in $\lambda(H_A^2+H_B^2)^2$]





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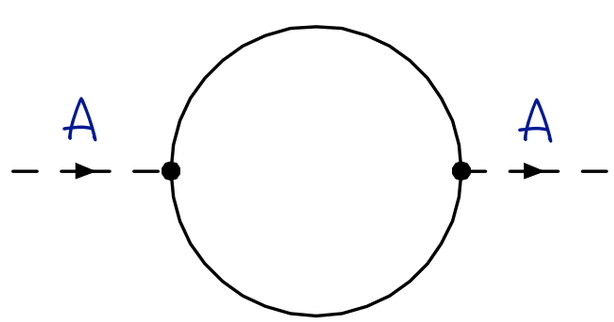

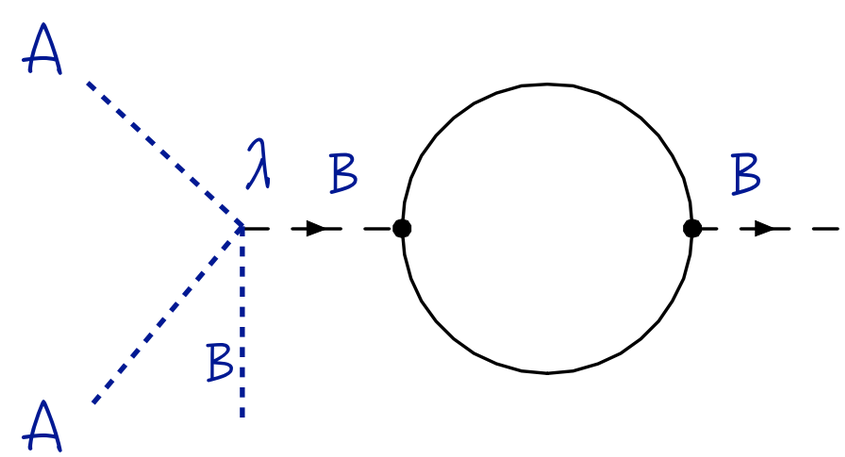

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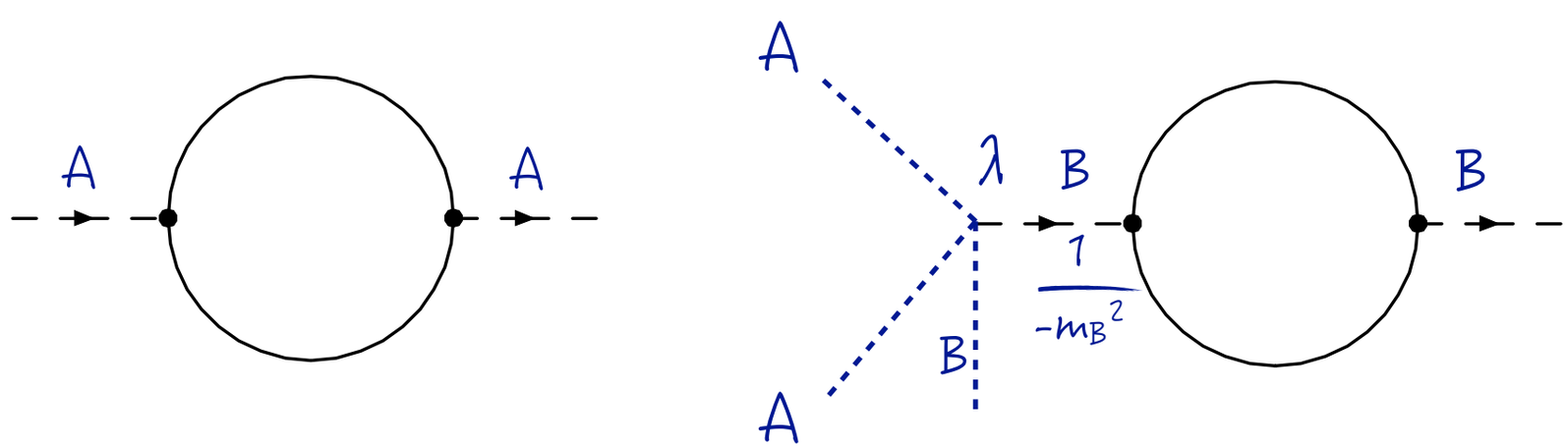

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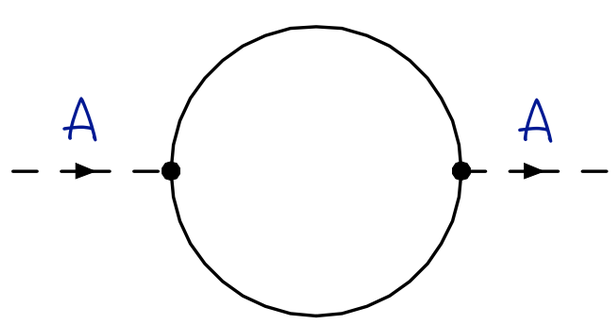

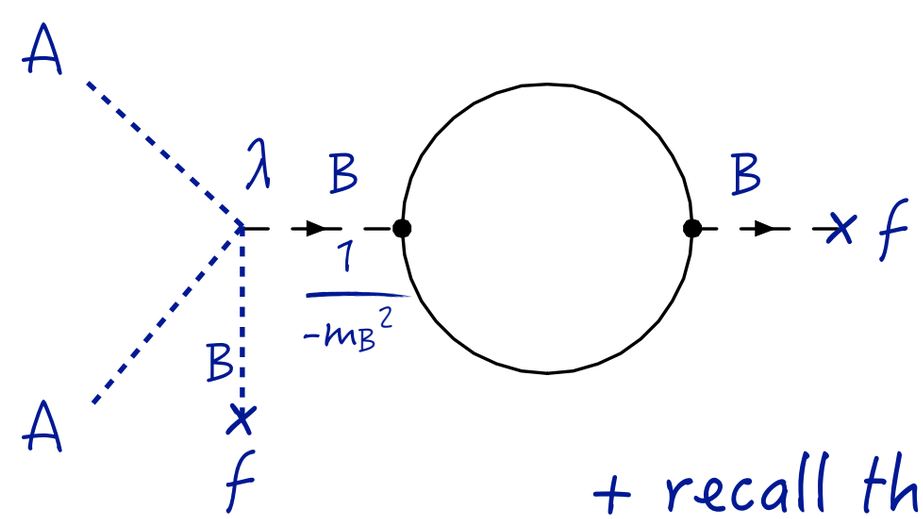

+ recall that $m_B^2=\lambda f^2$

So...

* Let's summarize what we have:
  - Higgs is protected by a symmetry.
  - The model is natural up to Λ beyond LHC scale.
  - All new particles below Λ are <u>complete SM singlets</u>!
* What's the phenomenology?
  - LHC Run 1 finds the Higgs and nothing else! (check).
  - Now what?...

Details:

Interest in Neutral Naturalness is re-kindled.
In recent years many issues are studied-

* UV Completions
  [Craig, Howe][Geller, Telem][Barbieri et al][Low, Wang, Tesi]..
* Dark Matter
  [March-Russell et al][Craig, Katz][Farina]...
* Cosmology
  [Barbieri, Hall][Chacko, Craig, Fox, RH][Csacki, Kuflik,Lombardo]
* Improved Tuning
  [RH, Howe, Kearny][Gregiore et al][Redigolo et al]

* LHC Pheno: Higgs is key! (The rest of this talk)

Twin Higgs Phenomenology

Depends strongly on how strictly we enforce the Z_2:

Craig, Katz, Strassler, Sundrum (15)

Mirror or Fraternal?

* $SM_A \times SM_B$. But what does SM_B really contain?

Mirror Twin Higgs	Fraternal Twin Higgs
Z_2 is nearly exact. SM_B is a **full copy** of our SM, with a slightly higher Higgs vev.	Z2 only acts on the essentials. SM_B contains only the 3rd gen and 3-2 gauge bosons.

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Simple.	Minimal but may be theoretically cumbersome.
Cosmology can be fixed	Cosmology's fine.
LHC elusive (almost)	Displaced decays @ LHC

Identical

Higgs Couplings

* Recall that the pNGB is only **mostly** our Higgs boson, but partially theirs.

* A mixing angle governing this is $\theta \sim \frac{v}{f} = \frac{\text{our vev}}{\text{their vev}}$

* For **both** identical and fraternal models, Higgs couplings to SM states are modified by $\cos(\frac{v}{f})$.

All SM Higgs $\sigma \times BR$'s are modified by $\cos^4(\frac{v}{f})$

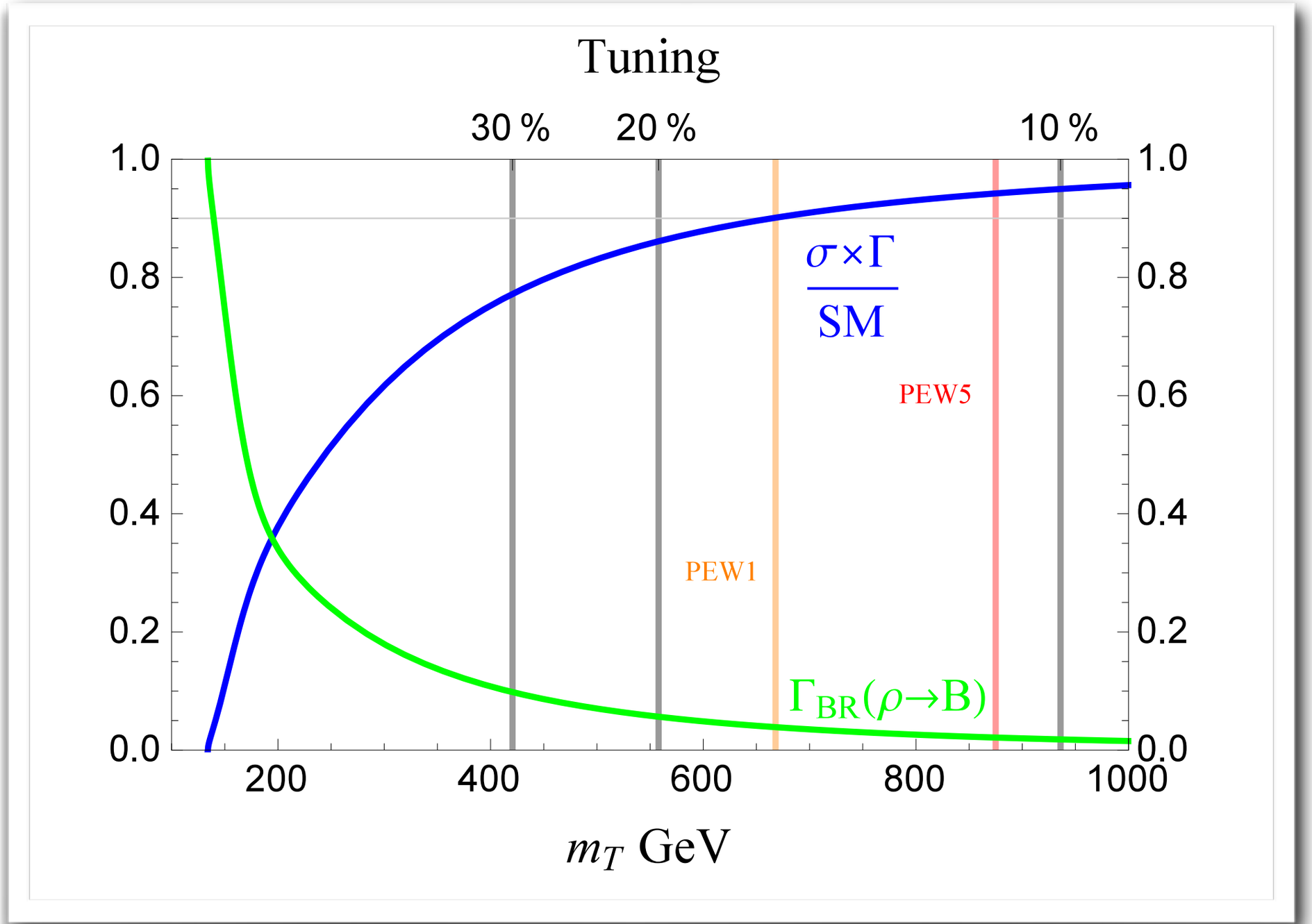
Identical predictions

* In the identical model:
  Roughly $\sin(\frac{v}{f})$ of the pNGB is the other Higgs.
* The 125 GeV Higgs can decay to the other SM.
* Twin bottoms cascade down Invisible states!

$$BR_{(h\to inv)} = \sin^2\left(\frac{v}{f}\right)$$

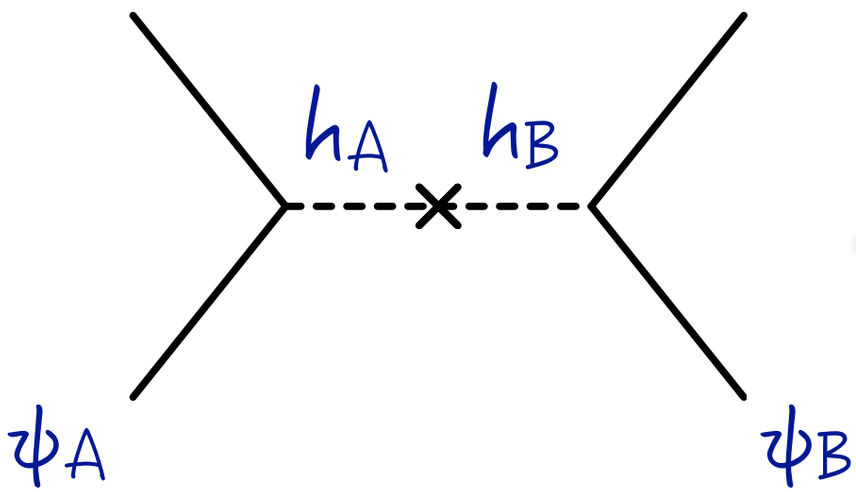
* For identical models, v/f, is setting both Higgs coupling modification and BR_{inv}. A prediction!

Identical prediction



Cosmology

- The Higgs portal keeps the two sectors in thermal eq. down to ~ 3 GeV.



$$n\sigma v \sim \frac{Y_A^2 Y_B^2}{m_h^4} \frac{v^2}{f^2} T^5$$

If the Universe was ever above 3 GeV, we thermalize the twin sector.

$$\Delta N_{eff} \sim 6 \quad :-($$

e.g. [Barbieri, Gregiore, Hall] [Chacko, Craig, Fox, RH]

[Chacko, Craig, Fox, RH] - in prep

Fixing Cosmology

- Easy fix: right handed neutrinos at few GeV.
- The singlet N is:
  - A-B ambivalent
  - Decouples relativistically
  - Decays preferentially to A sector (like f^2/v^2)
- N comes to dominate the Universe, decays, and reheats A sector more.

ΔN_{eff} is set by v/f and N mass & width.
(predictive!)

Fraternal

[see also talk by A. Katz]

* Invisible decay is reduced.

* All SM Higgs $\sigma \times BR$'s are modified by $\cos^2\left(\frac{v}{f}\right)$

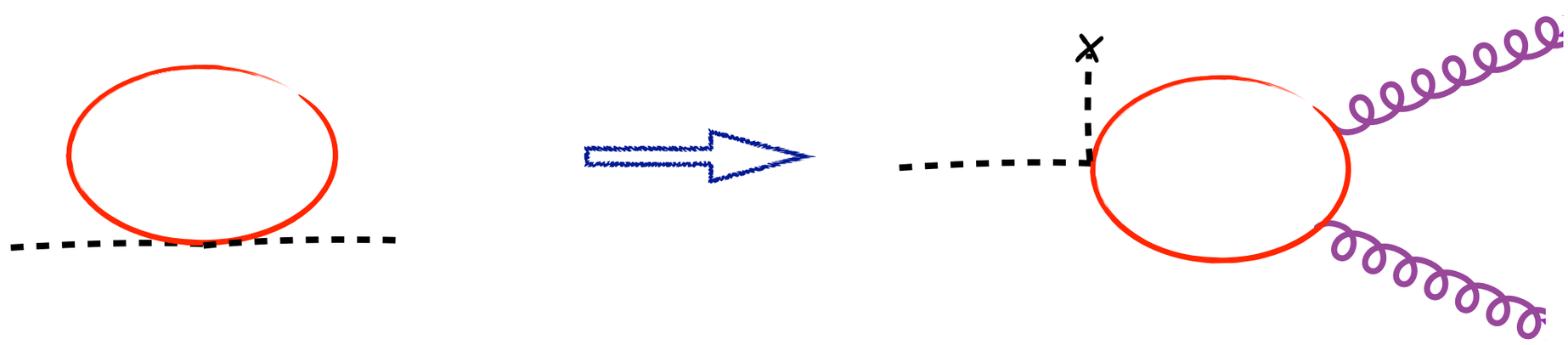
and...

Craig, Katz, Strassler, Sundrum (15)

Fraternal: Exotic Decays

* For fraternal model we removed light stuff. But gluon_B is light. Light **gluball**!

* More generally, if Higgs naturalness done by QCD′ colored states:



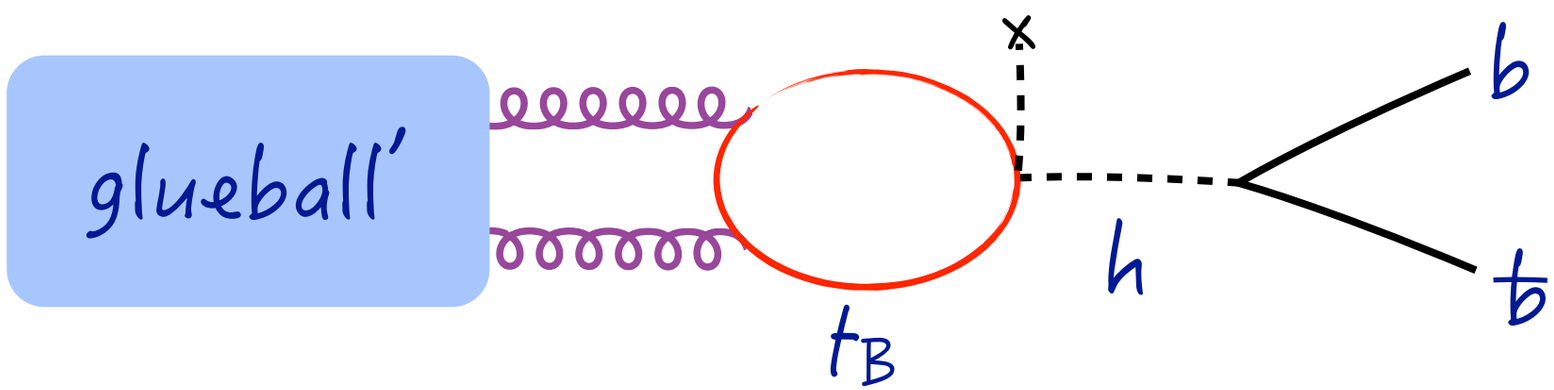
Higgs decays to glueball_B's!
Branching fraction of $\lesssim 10^{-4}$.

Craig, Katz, Strassler, Sundrum (15)

Fraternal: Exotic Decays

* The glueball is not invisible!
  The scalar glueball mixes with the Higgs.

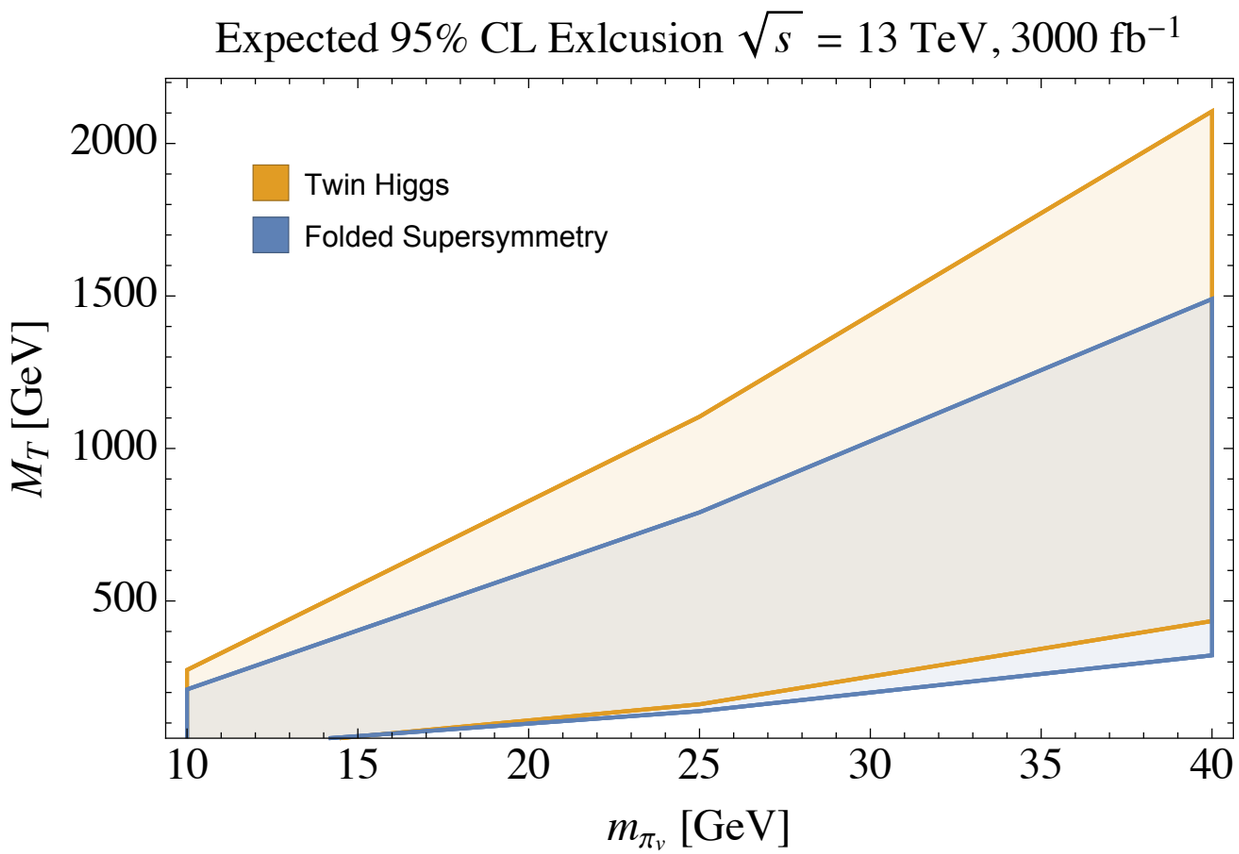
* Decays are typically displaced! Low BG!



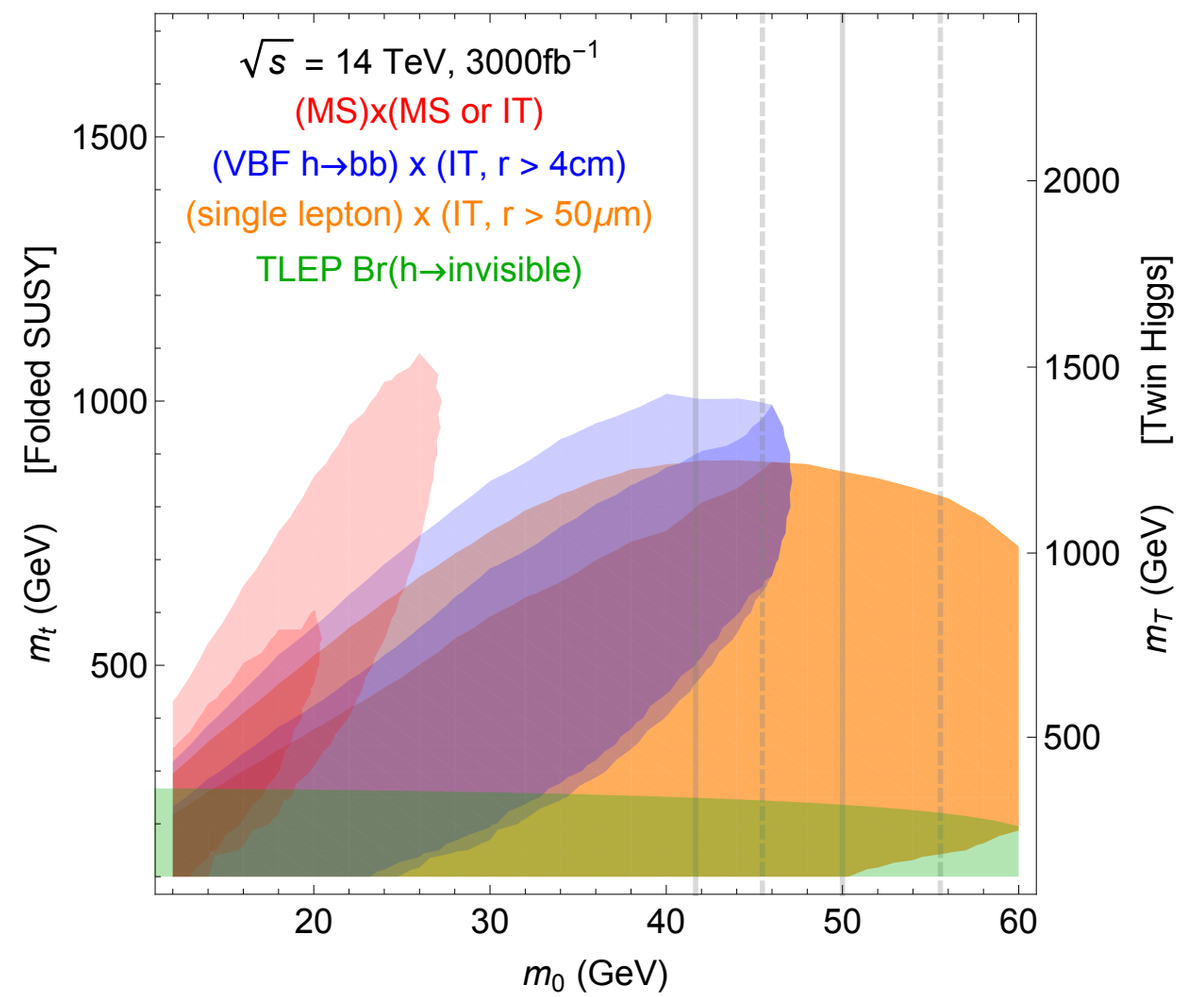
$c\tau$ depends **strongly** on parameters.
ranges for prompt to km.

Displaced Higgs Decays

* Displaced decays are a clean signature!
* Recent analyses show impressive reach to top partners at ~TeV range!



[Csaki, Kuflik, Lombardo, Slone (15)]



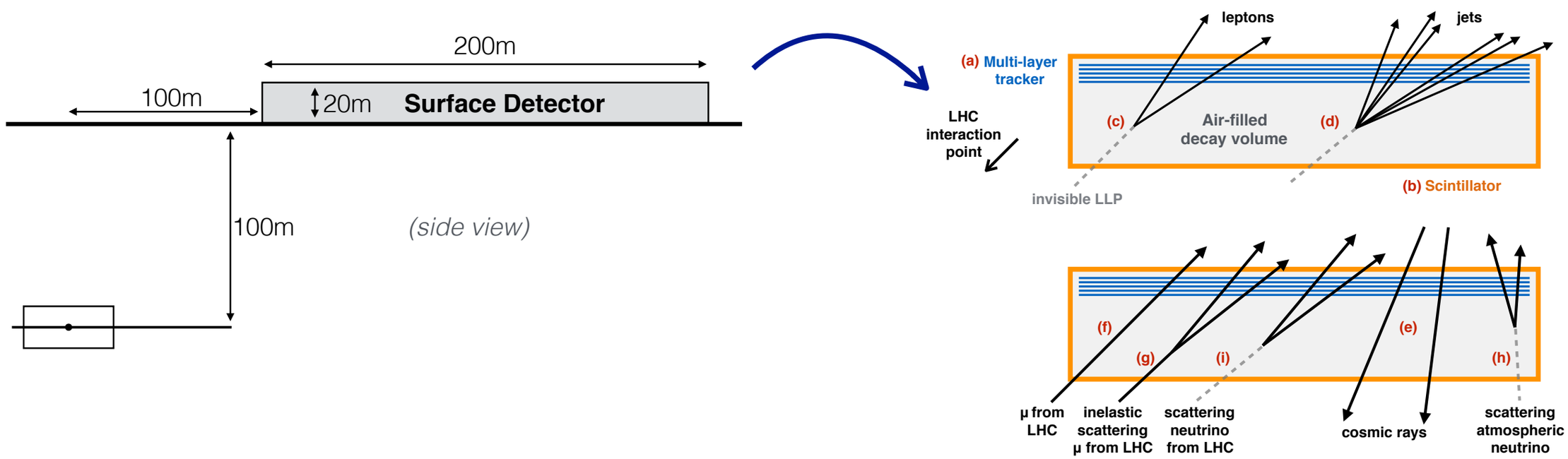
[Curtin and Verhaaren (15)]

A New Detector ?

- Pushing the limit on displaced decays in this model lead to a new proposal: MATHUSLA

New Detectors to Explore the Lifetime Frontier

J. P. Chou, D. Curtin, H. J. Lubatti



Conclusions & Outlook

* Models of **Neutral Naturalness**, e.g. Twin Higgs, elegantly address the "where-is-everybody" problem. Attracting renewed attention.

* They motivate a new set of LHC signatures:
    - Higgs Coupling modifications
    - Invisible Higgs decay
    - Exotic and displaced Higgs decays decays

* **Higgs measurements can be the key to figuring out the Hierarchy problem!**

Deleted Scenes

Recent Literature

* **Twin Dark Matter:** Craig and Katz (15), Knapen and Tsai (16), March Russel et al (15), Farina (15)

* **Flavor:** Csaki, Geller, Telem, Weiler (15),

* **Dark Photon & Flavor:** RH, Stamou, Zupan (soon)

* **Cosmology:** Barbieri, Gregiore, Hall (05), Barbieri, Hall (17), Chacko, Craig, Fox, RH (17), Csacki, Kuflik, Lombardo (17)

* **Models:** Cheng Hall Weiner (06), Craig & Howe (14), Geller & Telem (14), Barbieri et al (15), Low, Tesi, Wang (15), Greiore et al (16), RH, Howe Kearny (16), Craig Knapen, Strassler (16), Redgigolo et al (16)

And many more.

Precision EWK

* Precision EW measurements place a constraint on the scale f but depend on UV completion.

* SM Higgs loops contribute to S & T
  → modified Higgs couplings are constrained.

* Coupling modifications are "made up" by states at cutoff or by heavy Higgs for strong/weak UV completion (respectively).

$$\Delta S \approx \frac{1}{6\pi}\left(\frac{v}{f}\right)^2 \log\left(\frac{m_{h_2}}{m_h}\right) \qquad \Delta T \approx -\frac{3}{16\pi\cos^2\theta_W}\left(\frac{v}{f}\right)^2 \log\left(\frac{m_{h_2}}{m_h}\right)$$

Franco, Mishima, Silverstini (13) Falkowski, Riva, Urbano (13)

A Toy Example

* A global SU(4) symmetry w/ one fundamental:

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

$$\langle |H|^2 \rangle = \frac{M^2}{2\lambda} \equiv f^2$$

$$SU(4) \longrightarrow SU(3)$$

7 Goldstones

Cancelation

* How does the twin cancelation come about?

* Lets think about the theory of Goldstones:
  (a.k.a. broken SU(4) generators)

$$\Pi = \left(\begin{array}{ccc|c} 0 & 0 & 0 & h_1 \\ 0 & 0 & 0 & h_2 \\ 0 & 0 & 0 & 0 \\ \hline h_1^* & h_2^* & 0 & 0 \end{array}\right)$$

This beast transforms non-linearly under SU(4).

For convenience, construct a linearly transforming combination:

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = \exp\left(\frac{i}{f}\Pi\right) \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

Cancelation

* Expanding:

$$H_A = \boldsymbol{h}\frac{if}{\sqrt{\boldsymbol{h}^\dagger\boldsymbol{h}}}\sin\left(\frac{\sqrt{\boldsymbol{h}^\dagger\boldsymbol{h}}}{f}\right) = i\boldsymbol{h} + \dots\,,$$

$$H_B = \begin{pmatrix} 0 \\ f\cos\left(\frac{\sqrt{\boldsymbol{h}^\dagger\boldsymbol{h}}}{f}\right) \end{pmatrix} = \begin{pmatrix} 0 \\ f - \frac{1}{2f}\boldsymbol{h}^\dagger\boldsymbol{h} + \dots \end{pmatrix}.$$

* Back to the top Yukawa:

$$\mathcal{L} \supset y_t H_A \bar{t}_A t_A + y_t H_B \bar{t}_B t_B$$

$$= y_t h\, \bar{t}_A t_A + y_t\left(f - \frac{|h|^2}{2f}\right)\bar{t}_B t_B + \dots$$

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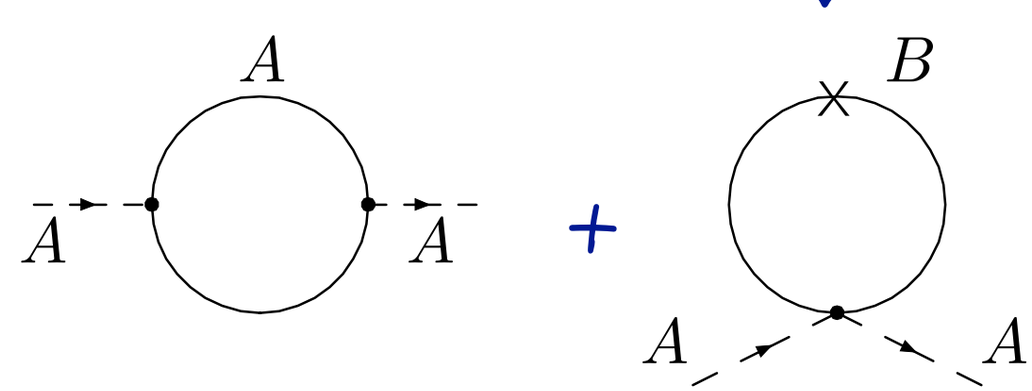
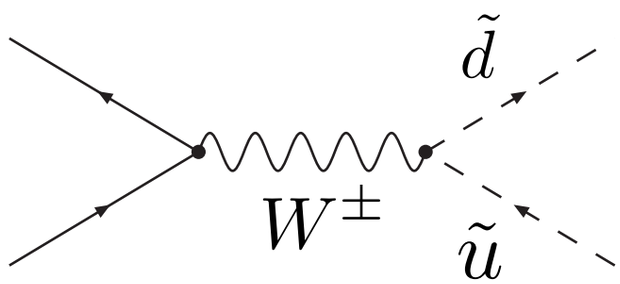
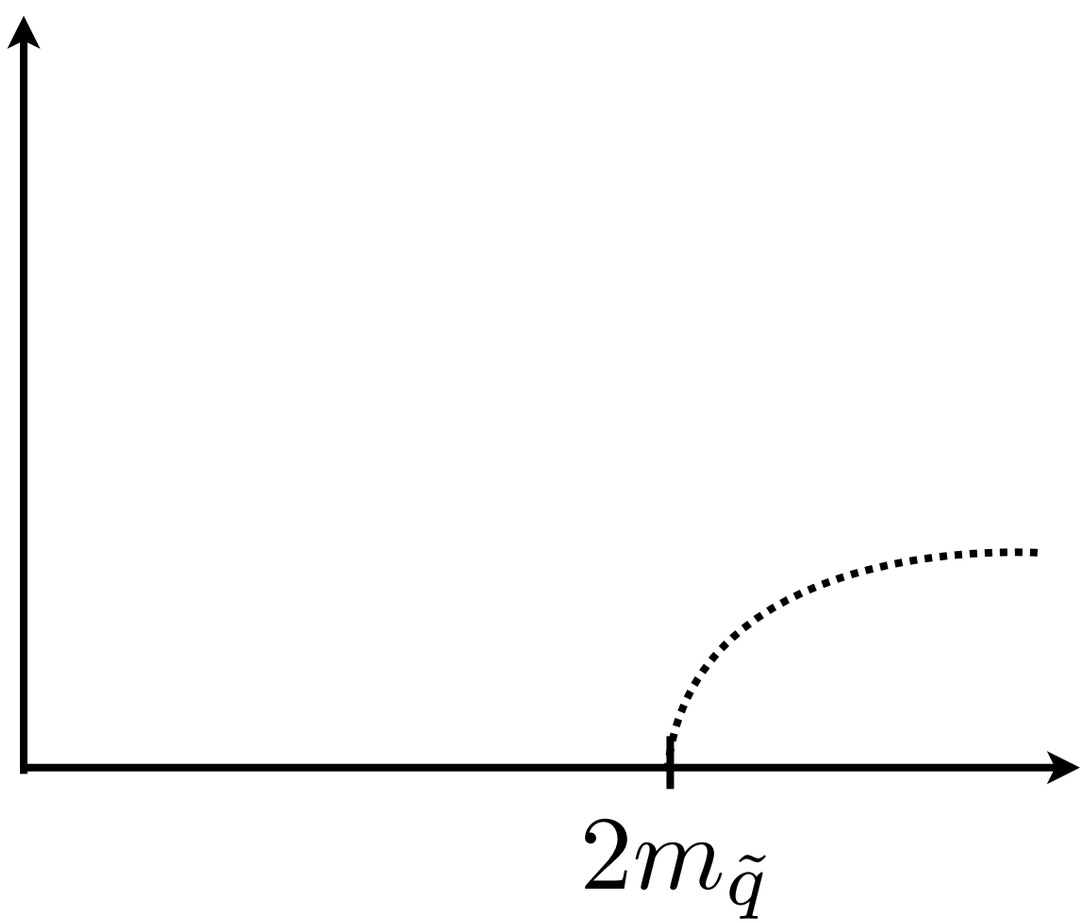


A Hard Signal

* Annihilation occurs after radiation:





w/ Burdman et al - arXiv:0805.4667

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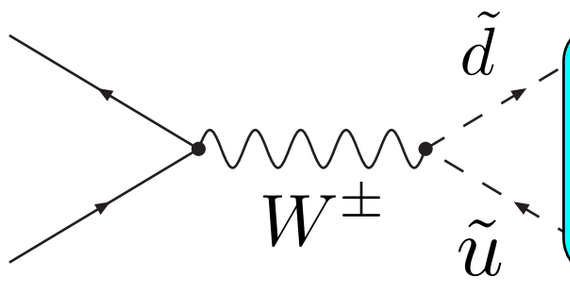
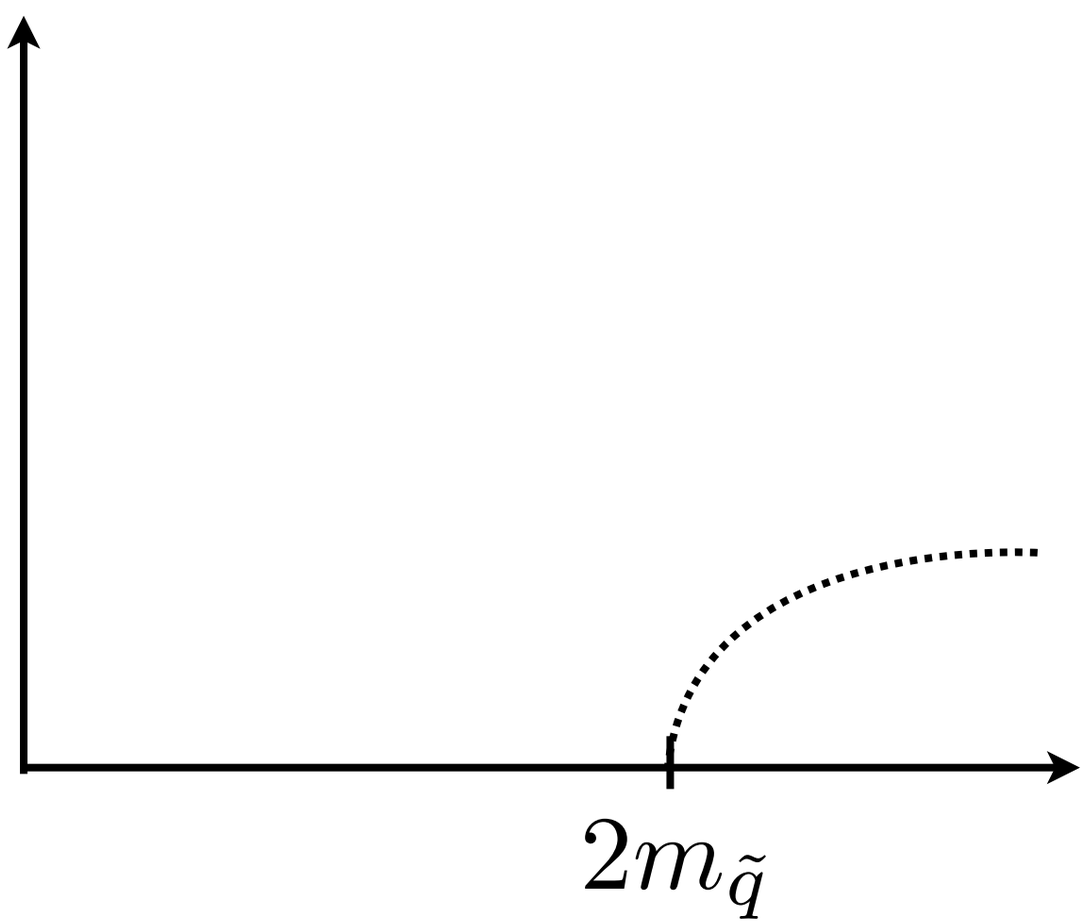


"squirkonium"



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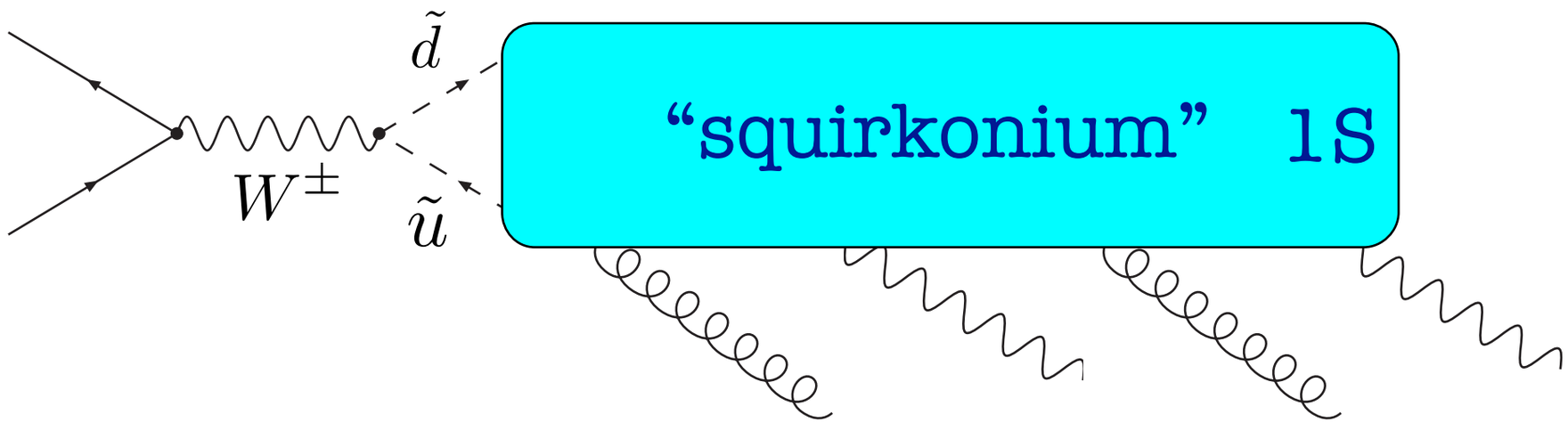

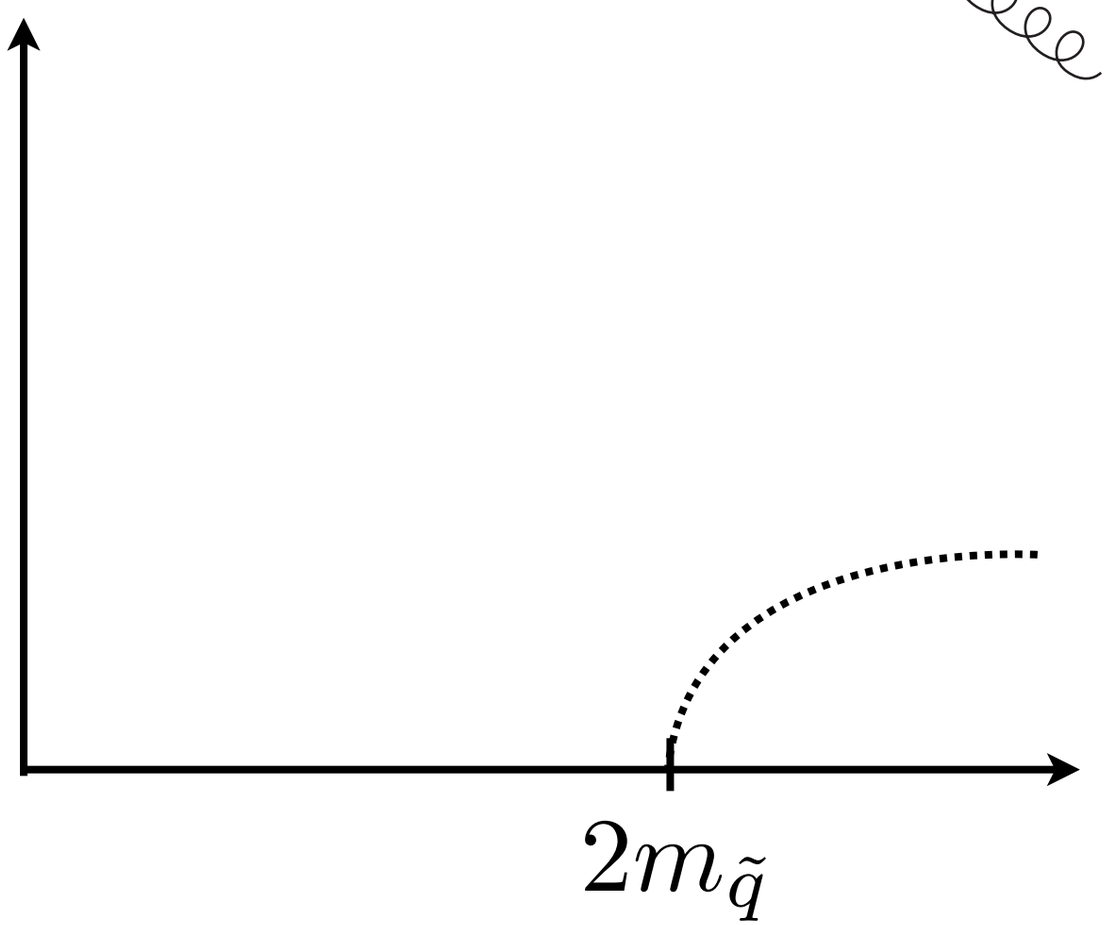

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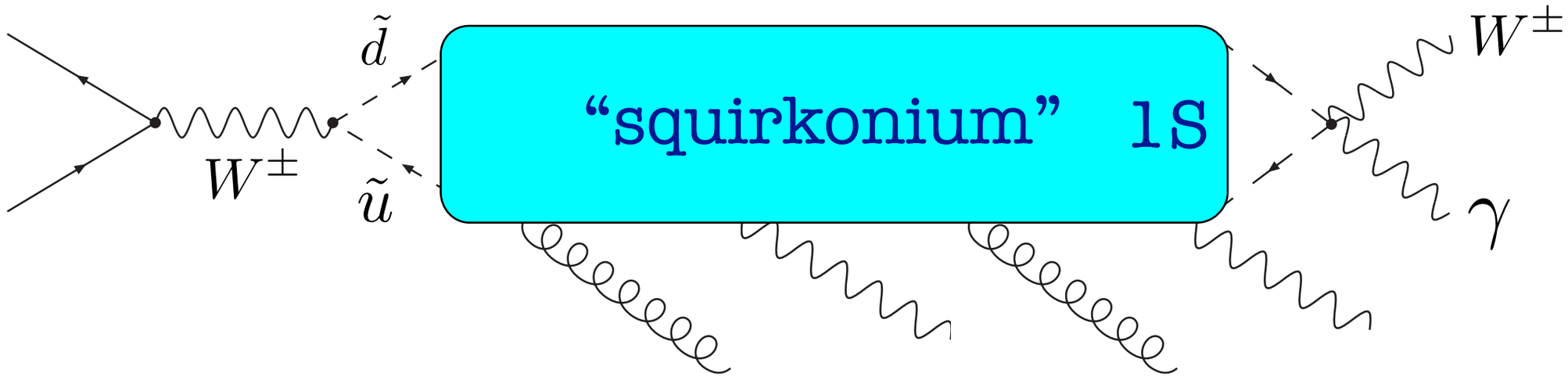

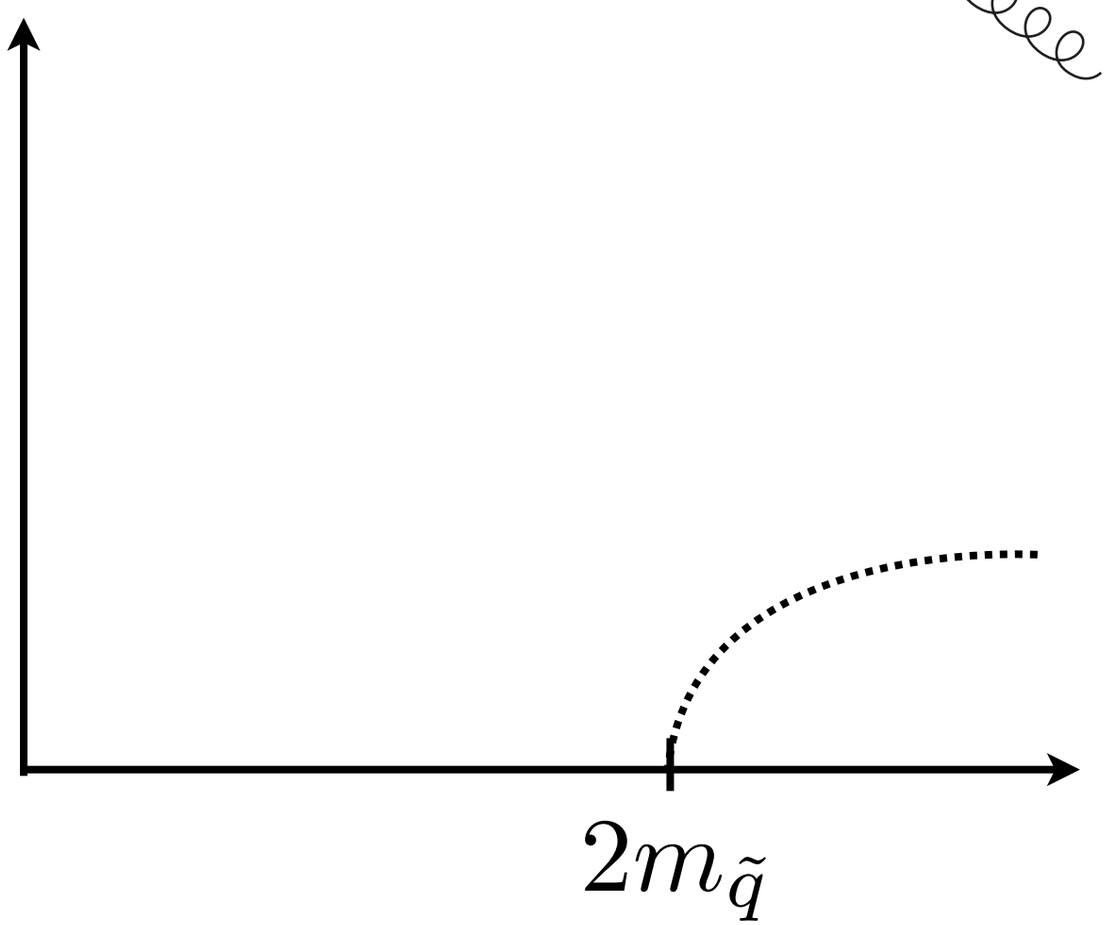

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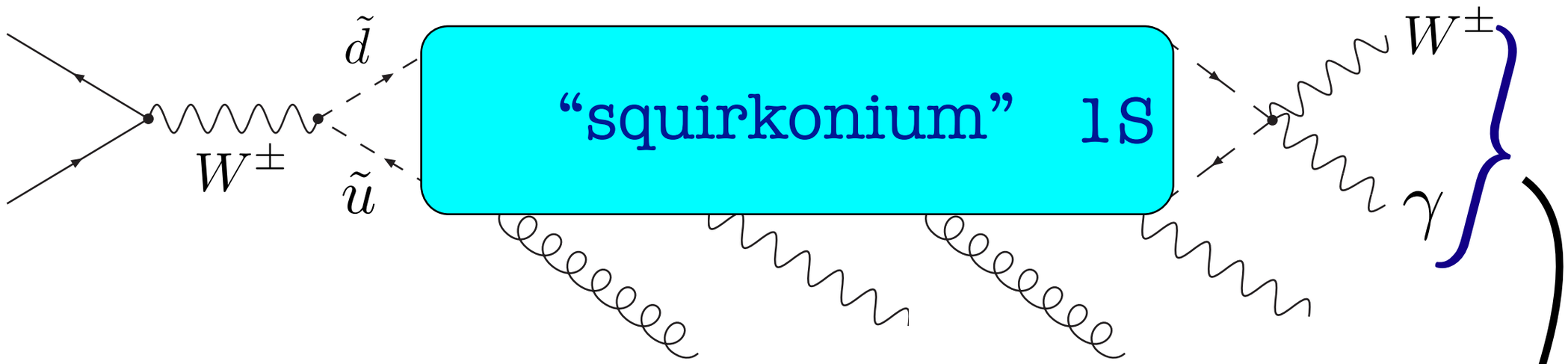

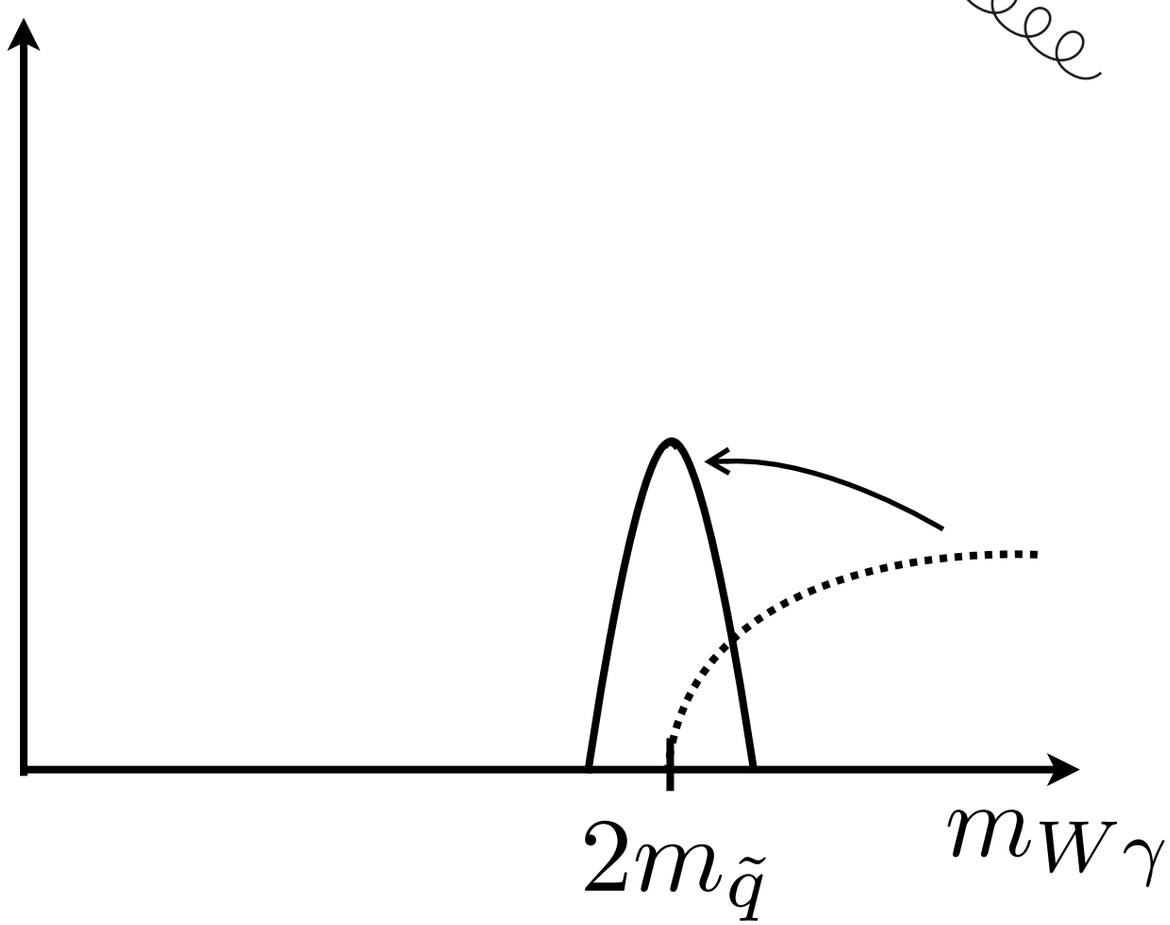

A peak in the invariant mass of W+γ

$$m^2_{W\gamma} = m^2_{1s} \sim 4m^2_{\tilde{q}}$$

w/ Burdman et al - arXiv:0805.4667

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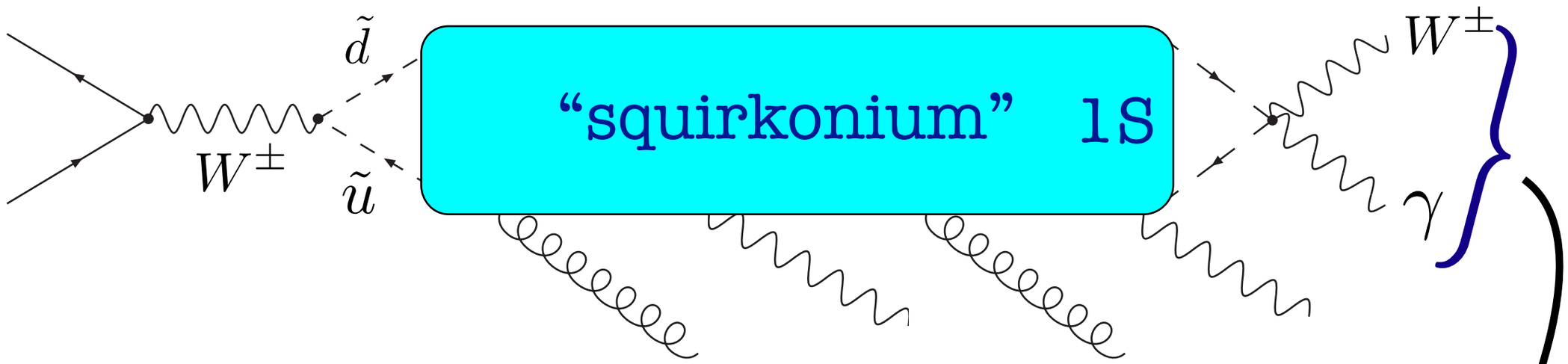

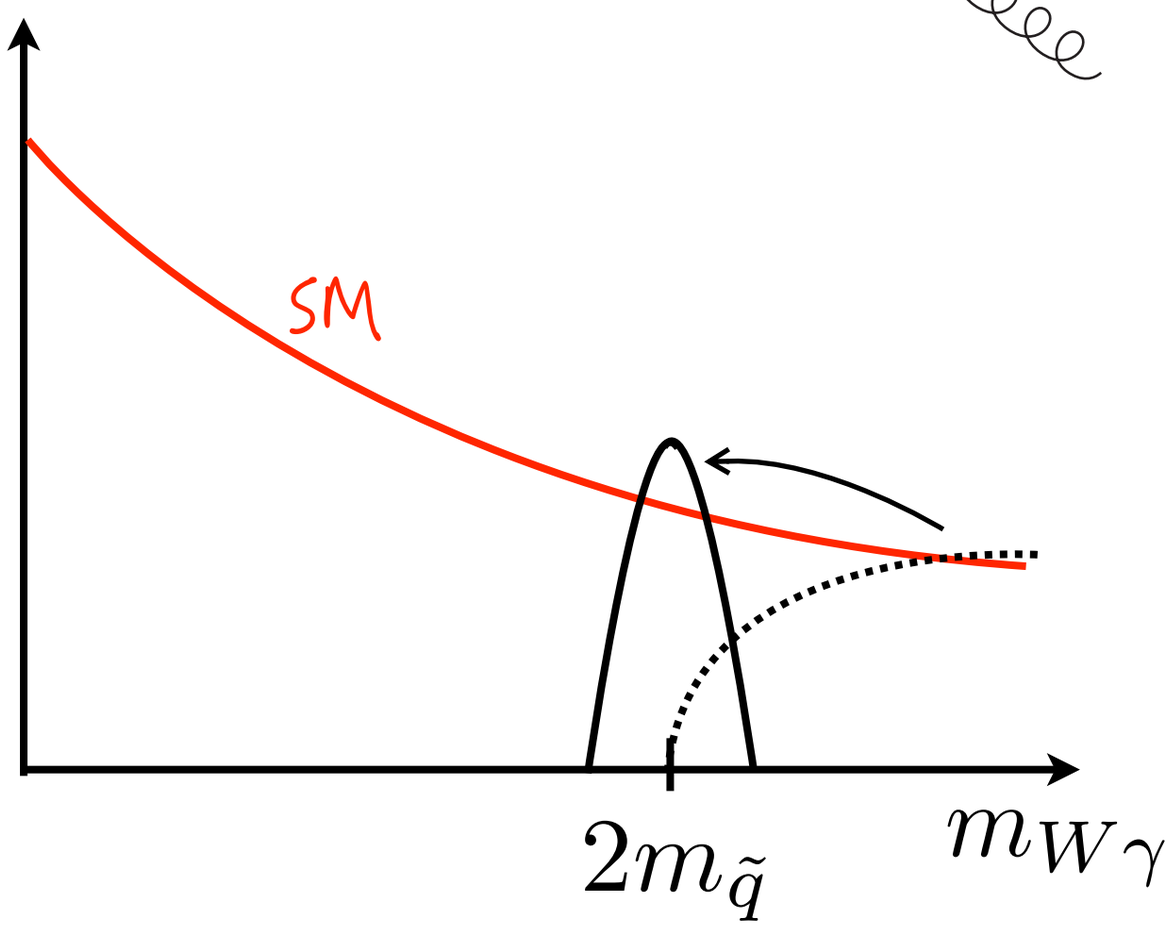

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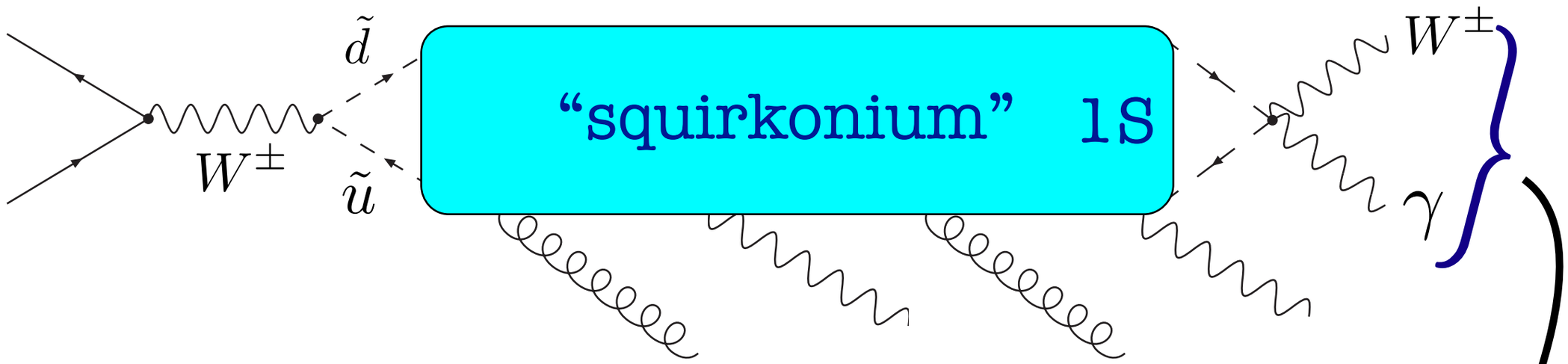

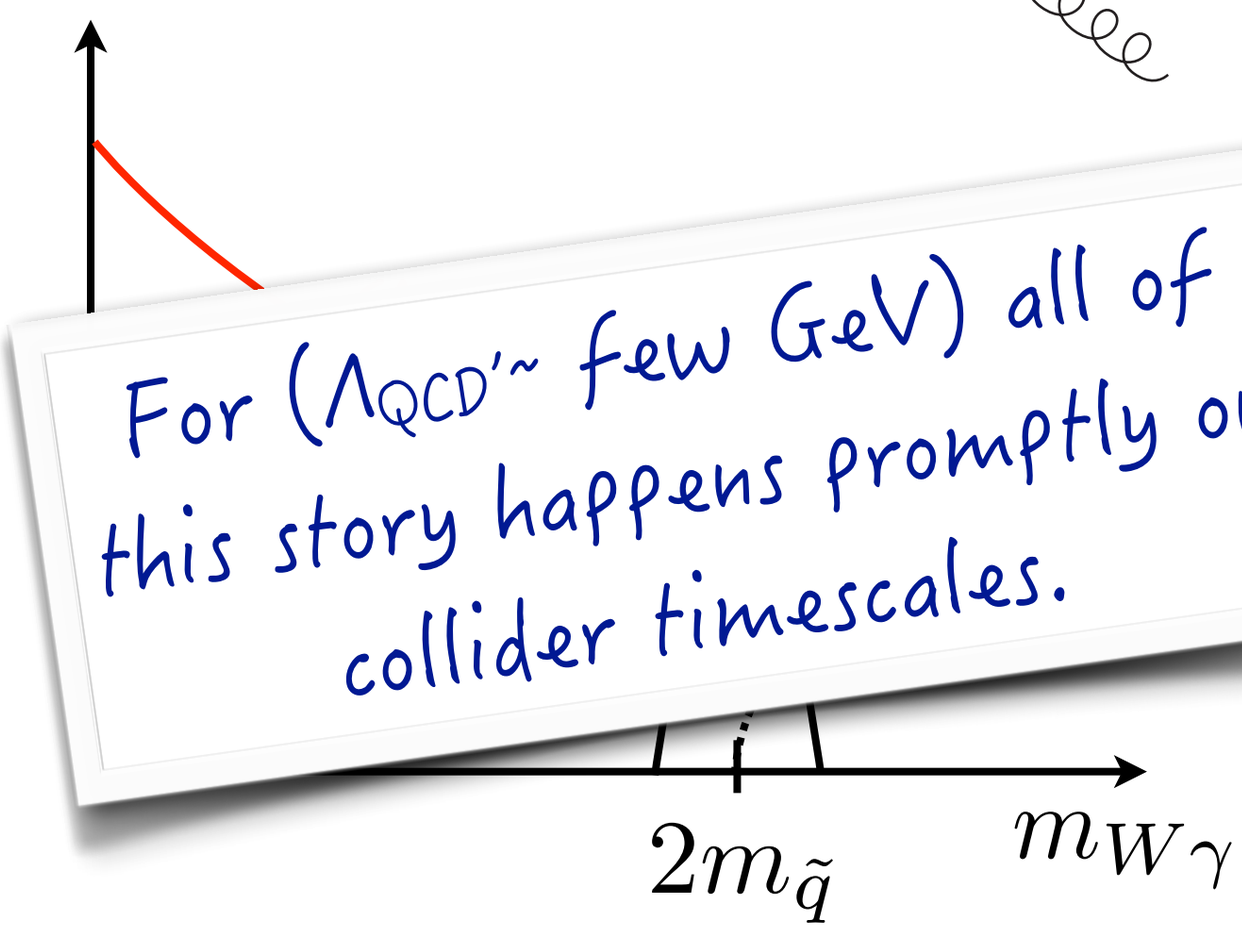

For (Λ_{QCD} ~ few GeV) all of this story happens promptly on collider timescales.

A peak in the invariant mass of W+γ

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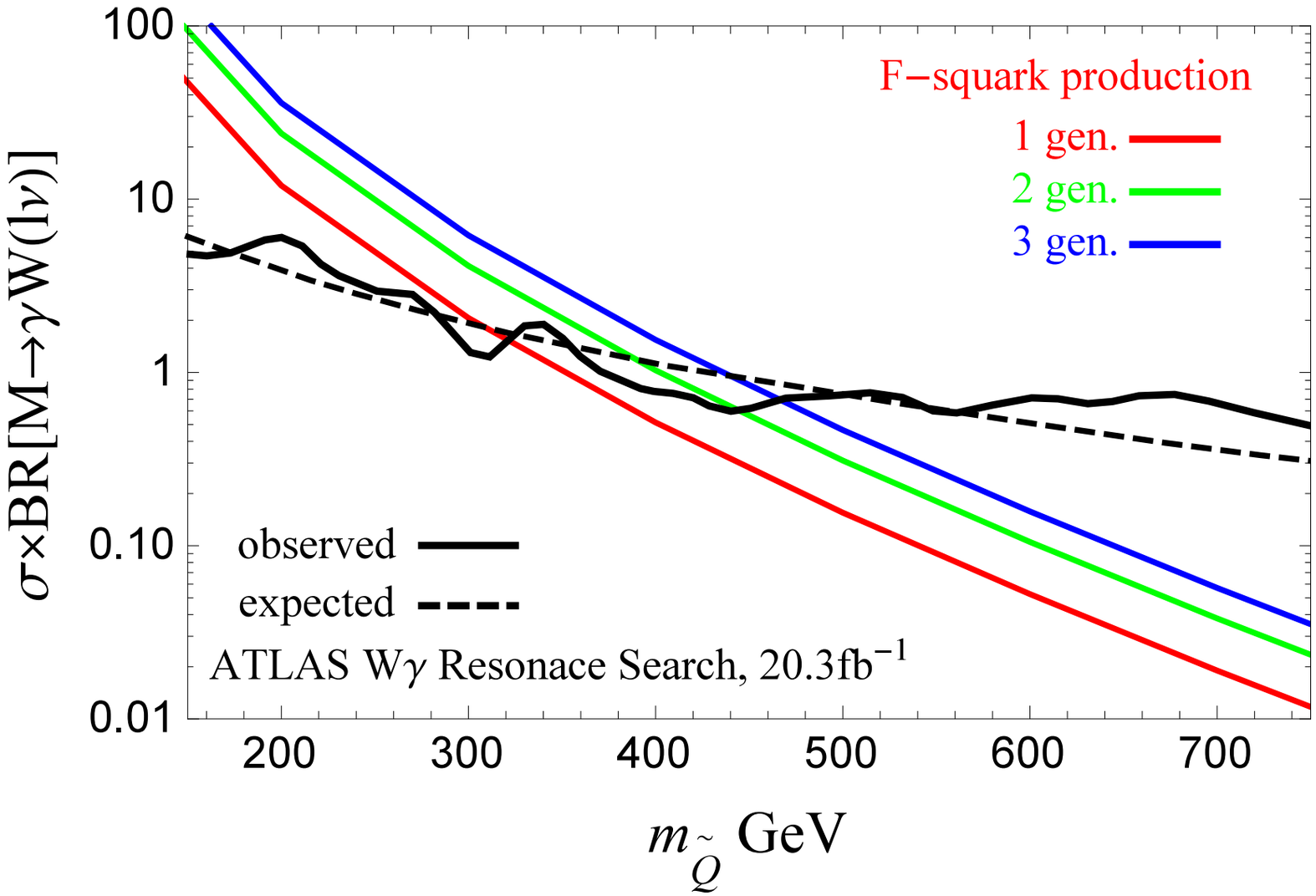
Current limit (1411.3310)



*Assumptions:
1. Soft stuff does not smear the peak much.
2. Squirk β-decay is slow.

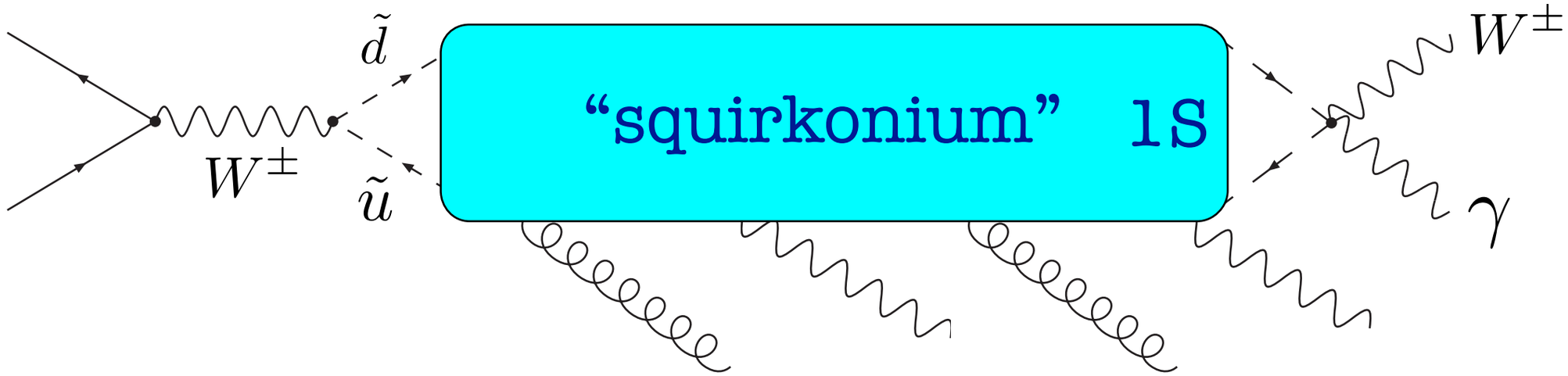
violating these assumptiond only weakens the bound.

Using ATLAS Wγ analysis.*

Squirks at 300-450 GeV excluded. Natural models still allowed.

Soft Stuff

* Having found the hard stuff, we can look for the soft stuff.



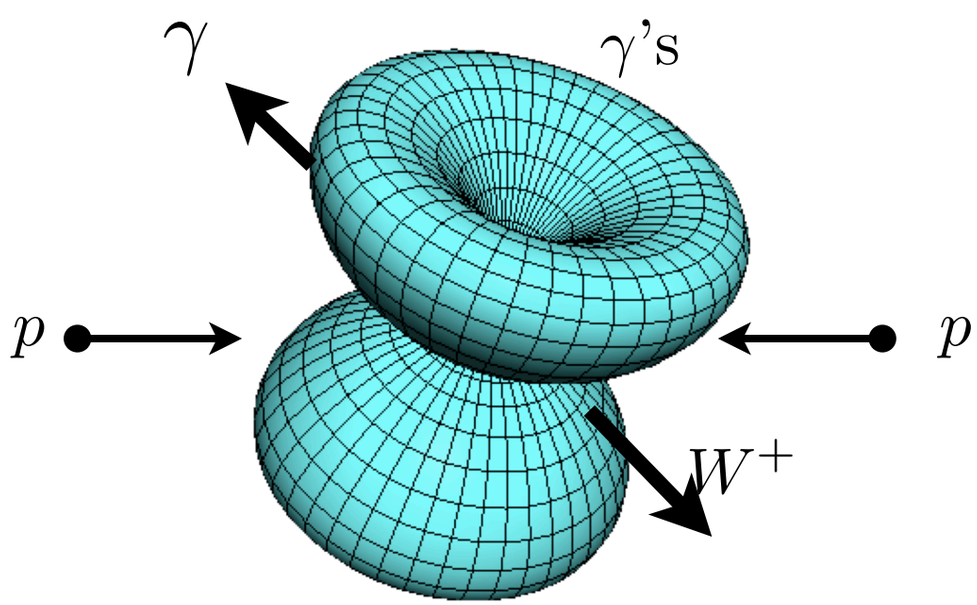
An overly active underlying event...?

(RH and Wizansky 0810.3949)

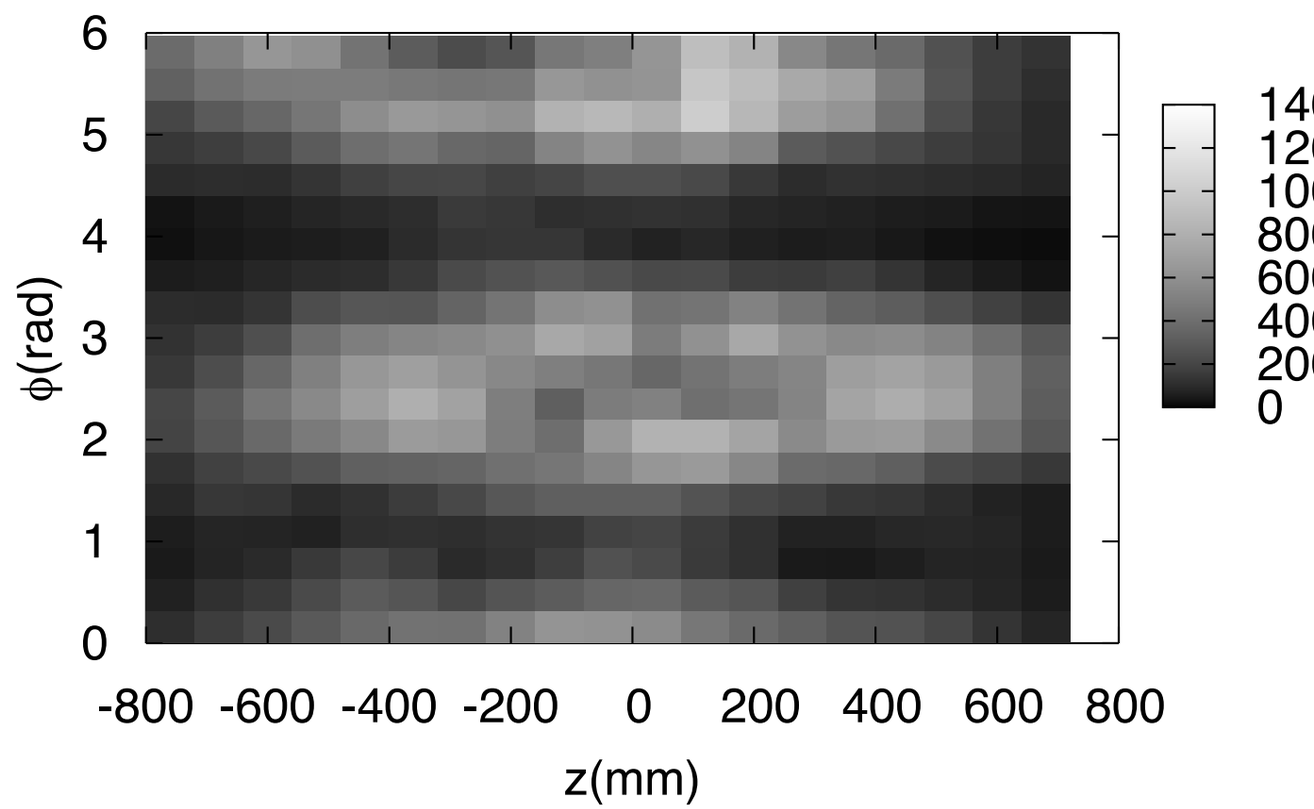
How about Glueball decay?

(see talk by Curtin)

Photon Radiation



Photons are emitted in a pattern!
(unless they are dominated by glueballs)



A weird underlying event.