The Twin Higgs

and

Other Colorless Beasts

Twin Higgs: Zackaria Chacko, Hock-Seng Goh, RH hep-ph/0506256

Folded SUSY: Burdman, Chacko, Goh, RH hep-ph/0609152

Work in Progress: Burdman, Chacko, de Lima, RH, Verhaaren

...coming soon to an arxiv near you!

Where is everyBody?

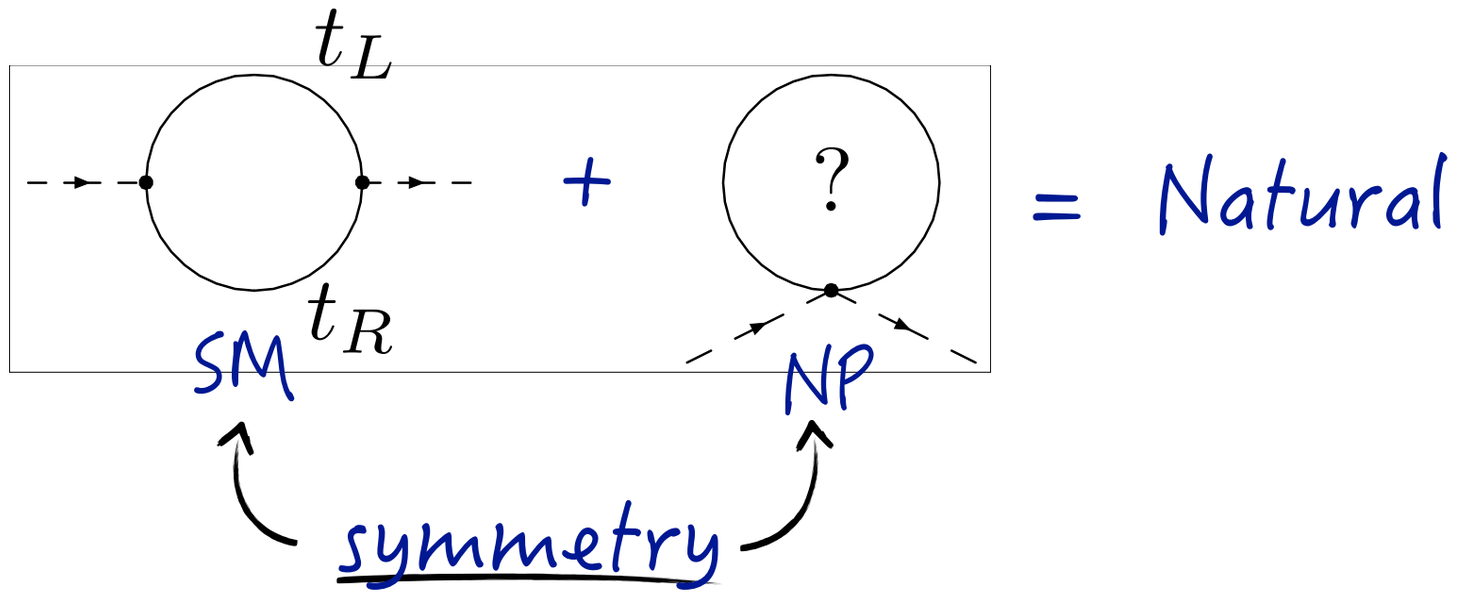
* LHC run 1: We found a Higgs. Nothing else.
* We know how EW symmetry is broken.
* The burning question:
  Is the EW scale natural or tuned?

LHC may address this question.
(by finding evidence for naturalness).

But what if it doesn't? Is the world tuned? :-O

Naturalness and LHC

* Why did we expect LHC to find the evidence for naturalness?

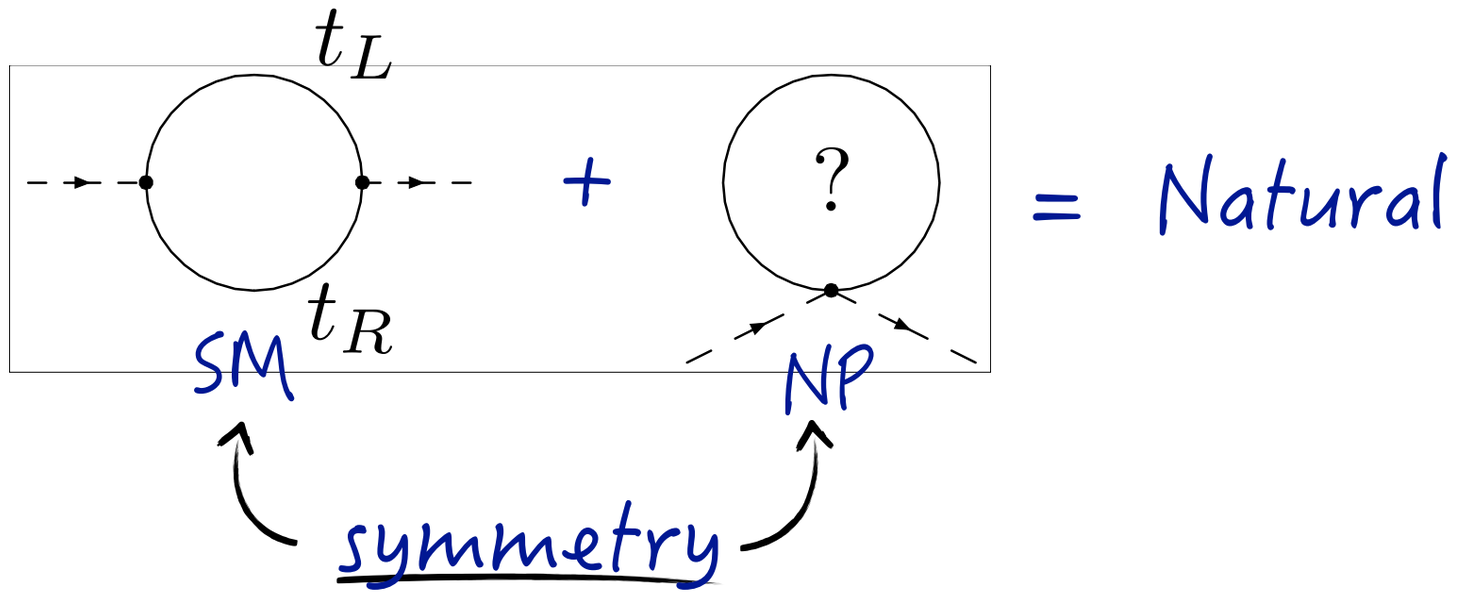


NP is related to the SM top by a symmetry!
NP is around a TeV!

→ Colored NP at a TeV! Will be produced abundantly at LHC!

Naturalness and LHC

* Why did we expect LHC to find the evidence for naturalness?

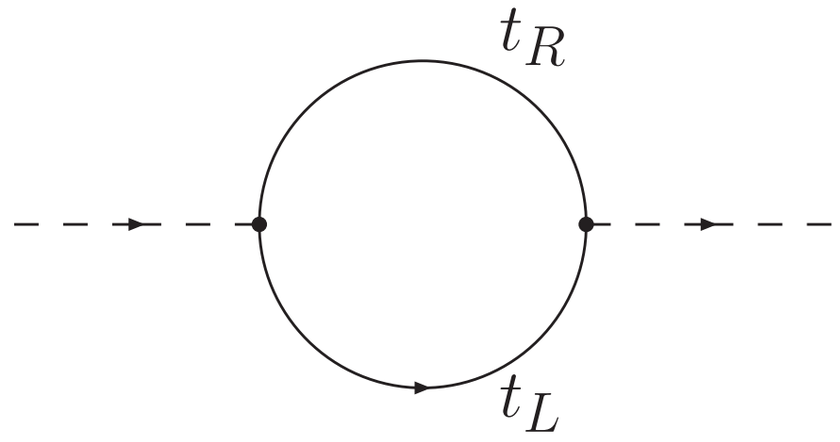


NP is related to the SM top by a symmetry!
NP is around a TeV!

Not True.

Colored NP ~ TeV!
produced abundantly at LHC!

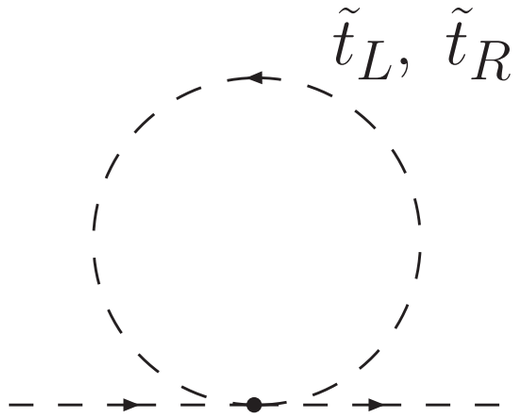
Just a Factor of 3



Standard Model

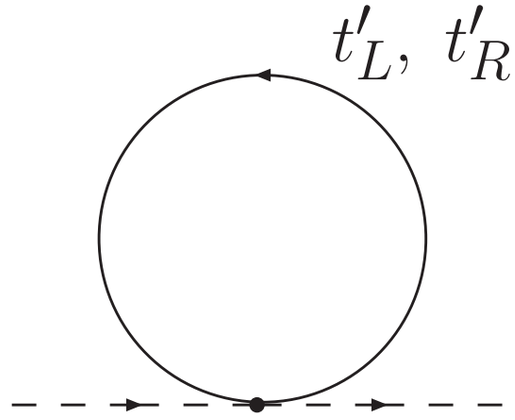
color factor:

$\times 3$



Supersymmetry

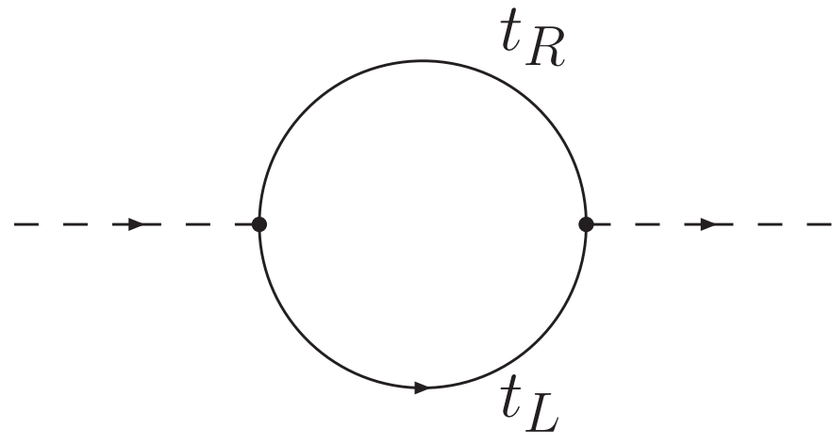
or



Little Higgs

$\times 3$

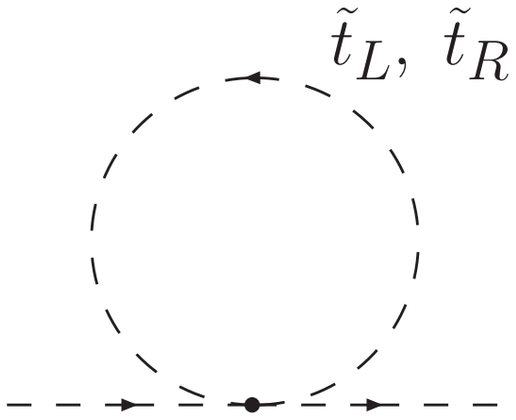
Just a Factor of 3



Standard Model

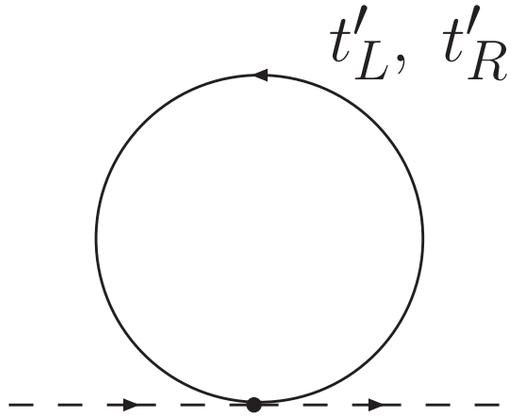
color factor:

$\times 3$



Supersymmetry

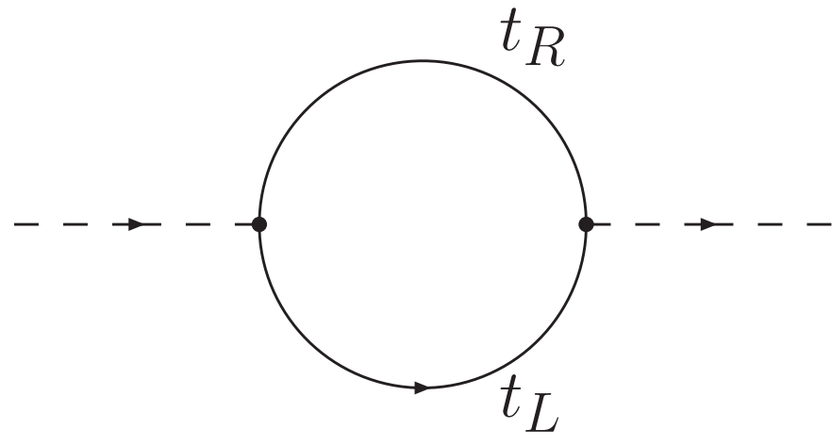
or



Little Higgs

$\times 3$ ~~3~~ 3'

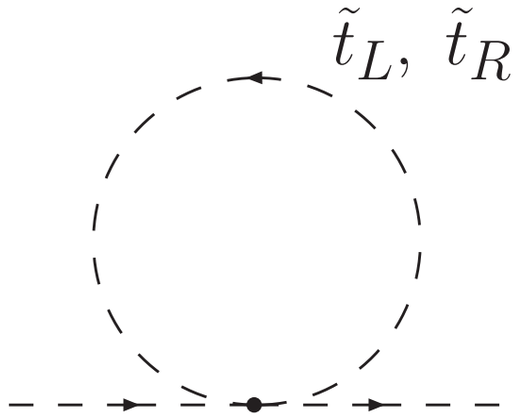
Just a Factor of 3



Standard Model

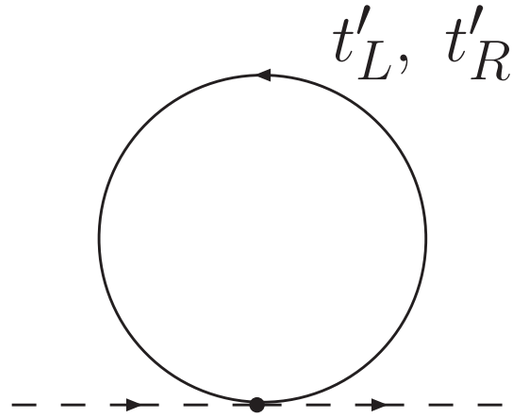
color factor:

$\times 3$



Supersymmetry

or

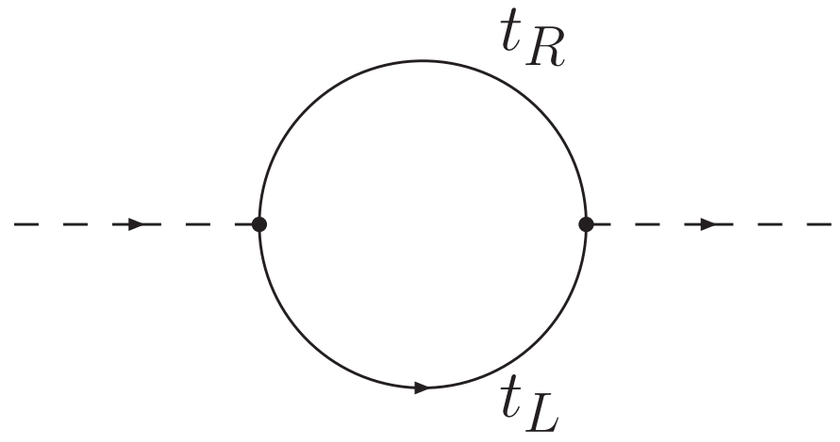


Little Higgs

$\times$ ~~3~~ 3'

symmetry does not commute with color.

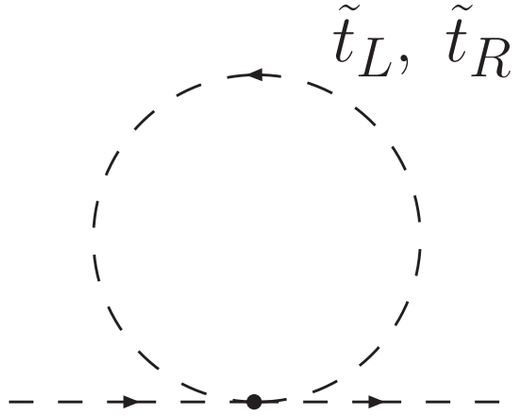
Just a Factor of 3



Standard Model

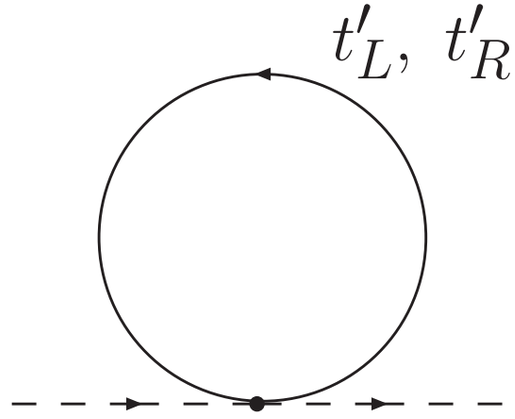
color factor:

$\times 3$



Supersymmetry

or



Little Higgs

$\times 3$ ~~3~~ 3'

symmetry does not commute with color.

Folded SUSY

Burdman, Chacko, Goh, RH (06')

Twin Higgs

Chacko, Goh ,RH (05')

Outline

* Twin Higgs - Mechanism
* Folded Supersymmetry - Mechanism
* Signals:
  - More twin details
  - Twin Higgs and Higgs Precision
  - Folded and squirks
* Drinks & Dinner

Twin.
The Mechanism.

* The Higgs is a PNGB of an approximate SU(4).

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

$SU(2)_A \times SU(2)_B$

* Gauge a subgroup (a.k.a Z_2 orbifold of SU(4)):

$$SU(2)_A \times SU(2)_B$$

→ see Nate's talk

our SM — twin SM

* In some basis, H transforms as

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

6 eaten.
1 Goldstone left.

* Gauging $SU(2)_A \times SU(2)_B$ breaks global $SU(4)$

Radiative Corrections

* At 1-loop:

$$\Delta V =$$

Radiative Corrections

* At 1-loop:

$$\Delta V = \frac{9 g_A^2 \Lambda^2}{64\pi^2} H_A^\dagger H_A$$

Radiative Corrections

* At 1-loop:

$$\Delta V = \frac{9 g_A^2 \Lambda^2}{64\pi^2} H_A^\dagger H_A + \frac{9 g_B^2 \Lambda^2}{64\pi^2} H_B^\dagger H_B$$

Radiative Corrections

* At 1-loop:

$$\Delta V = \frac{9 g_A^2 \Lambda^2}{64\pi^2} H_A^\dagger H_A + \frac{9 g_B^2 \Lambda^2}{64\pi^2} H_B^\dagger H_B$$

---

* Impose a Z_2 "twin" symmetry: $A \longleftrightarrow B$

$g_A = g_B$

$$\Delta V = \frac{9 g^2 \Lambda^2}{64\pi^2} \left(H_A^\dagger H_A + H_B^\dagger H_B \right)$$

SU(4) invariant!

Does not give a Goldstone mass.

Twin Mechanism

~~(Global Symmetry)~~ + (Discrete Symmetry)

Quadratic terms are globally symmetric.
No quadratic divergences.

* Note: Quartic terms can violate global symmetry.
  Goldstone mass only log divergent.

$SM_A \times SM_B$

* Double all of the SM. Impose a Z_2.
  (a.k.a orbifold of SU(6)xSU(4) by a Z_2).

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

Z_2 : quadratic divergence has the form

$$c\Lambda^2 \left(|H_A|^2 + |H_B|^2 \right)$$ SU(4) invariant!

* Only Higgs sector has extended global symm.
  That is sufficient for naturalness (@one-loop).

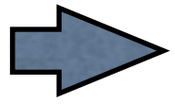
Folded SUSY

The Mechanism

Folded SUSY (Disney version)

Usually:

Supersymmetry commutes with gauge transformations.



Superpartners always have the same quantum numbers as SM counterparts.

How can we get non-colored partners?

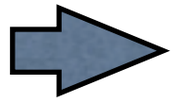
Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

Folded SUSY (Disney version)

Usually:

Supersymmetry commutes with gauge transformations.



Superpartners always have the same quantum numbers as SM counterparts.

How can we get non-colored partners?

t

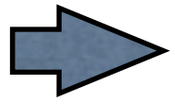
Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

Folded SUSY (Disney version)

Usually:

Supersymmetry commutes with gauge transformations.



Superpartners always have the same quantum numbers as SM counterparts.

How can we get non-colored partners?

$$t$$
$$Q^\alpha \updownarrow$$
$$\tilde{t}$$

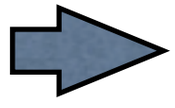
Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

Folded SUSY (Disney version)

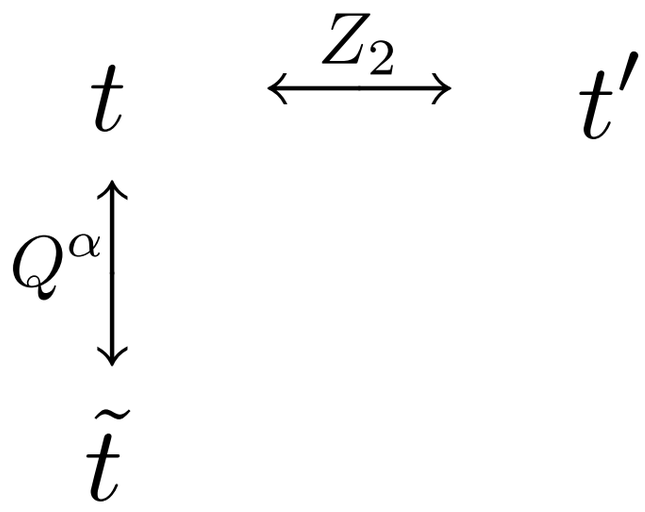
Usually:

Supersymmetry commutes with gauge transformations.



Superpartners always have the same quantum numbers as SM counterparts.

How can we get non-colored partners?



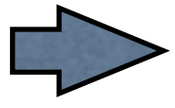
Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

Folded SUSY (Disney version)

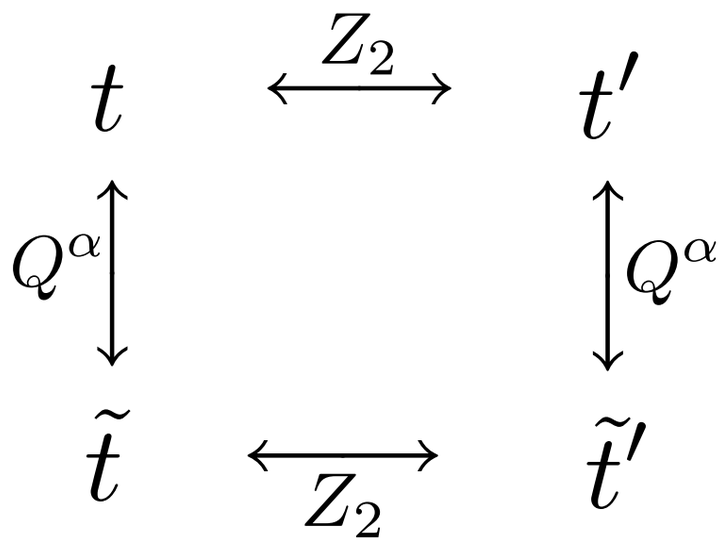
Usually:

Supersymmetry commutes with gauge transformations.



Superpartners always have the same quantum numbers as SM counterparts.

How can we get non-colored partners?



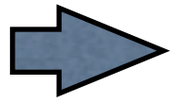
Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

Folded SUSY (Disney version)

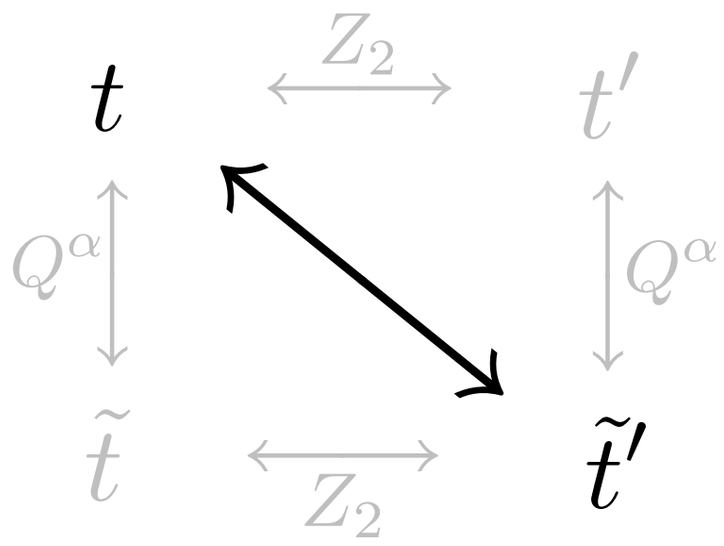
Usually:

Supersymmetry commutes with gauge transformations.



Superpartners always have the same quantum numbers as SM counterparts.

How can we get non-colored partners?



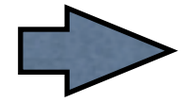
Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

Folded SUSY (Disney version)

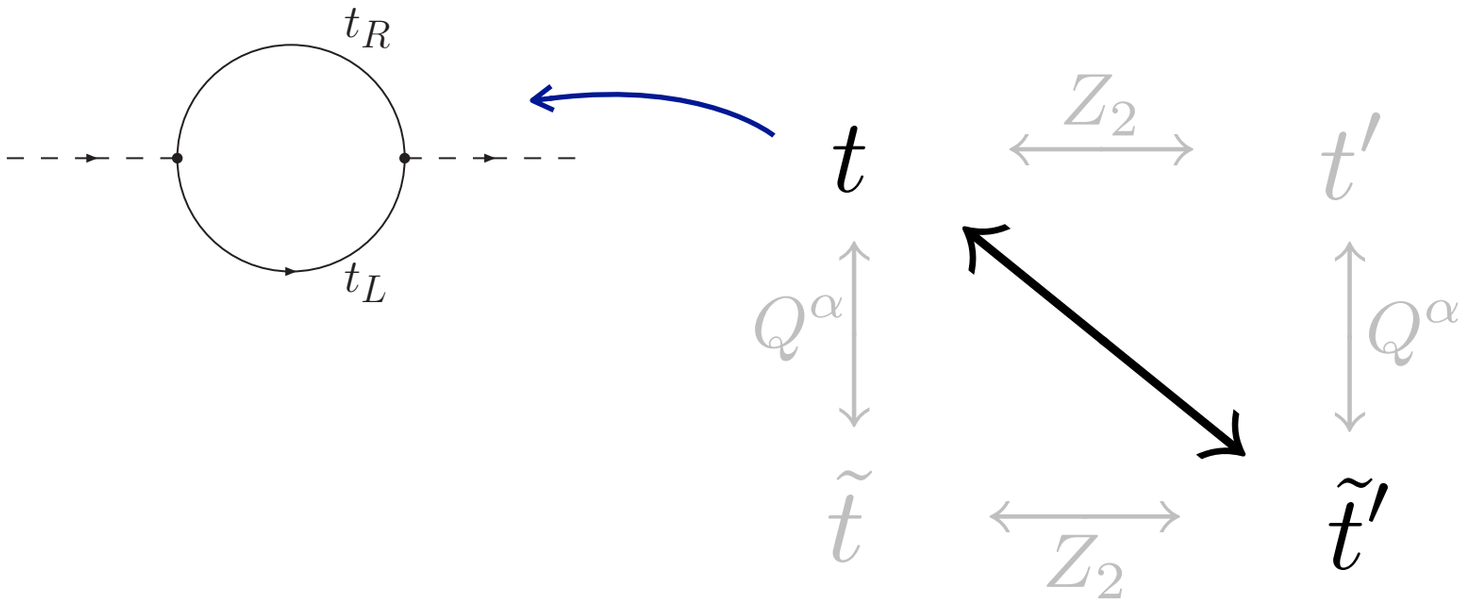
Usually:

Supersymmetry commutes with gauge transformations.



Superpartners always have the same quantum numbers as SM counterparts.

How can we get non-colored partners?



Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

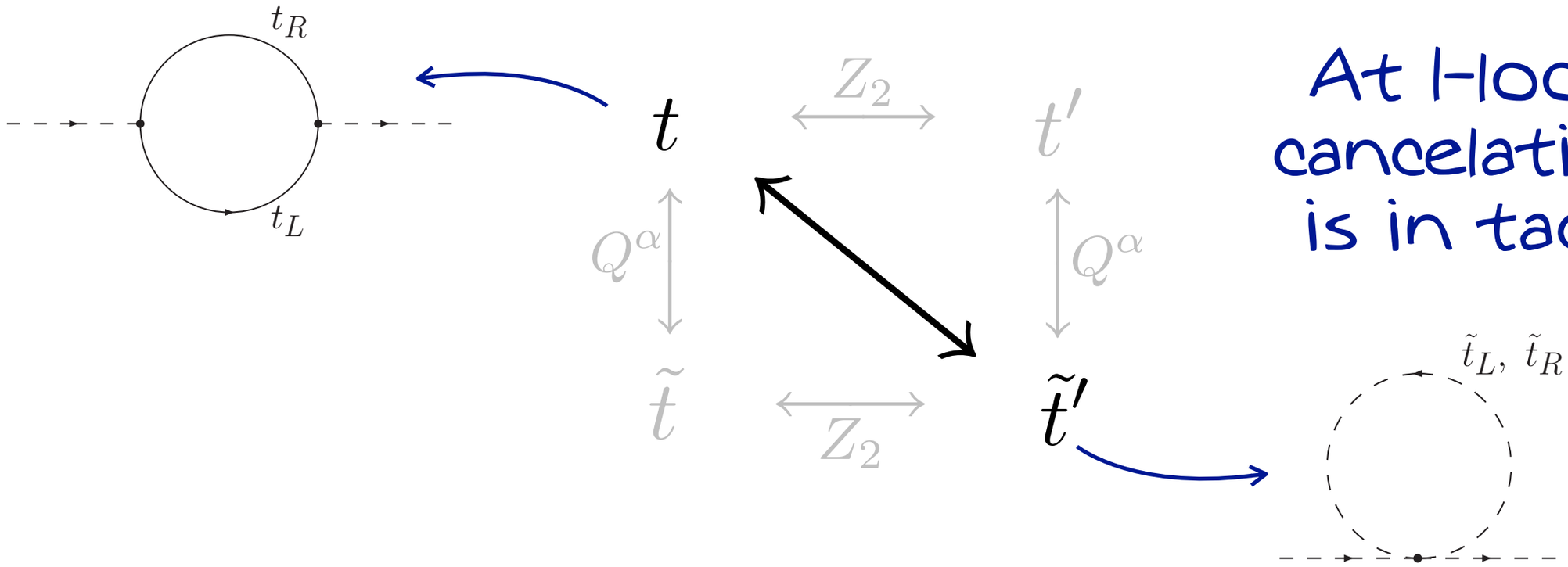
Folded SUSY (Disney version)

Usually:

Supersymmetry commutes with gauge transformations.

Superpartners always have the same quantum numbers as SM counterparts.

How can we get non-colored partners?



At 1-loop, cancelation is in tact.

Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

Folded SUSY

$$W = y_t H_u (Q_A T_A + Q_B T_B)$$

* The Higgs is protected twice:

$$\begin{pmatrix} t_i \\ t_j \end{pmatrix} \longleftrightarrow \begin{pmatrix} \tilde{t}_i \\ \tilde{t}_j \end{pmatrix}$$

Supersymmetric

$$\begin{pmatrix} t_i \\ t_j \end{pmatrix} \times \begin{pmatrix} \tilde{t}_i \\ \tilde{t}_j \end{pmatrix}$$

Folded-Supersymmetric

We get to choose which states to keep at low energies.

(That's where all the model building is).

OK, we have interesting mechanisms in place.
Lets talk about

What are the Signals

Start with the

Twin Higgs.

To understand the signals,
we should understand the model a bit better.

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:

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

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

Cancelation

* Expanding:

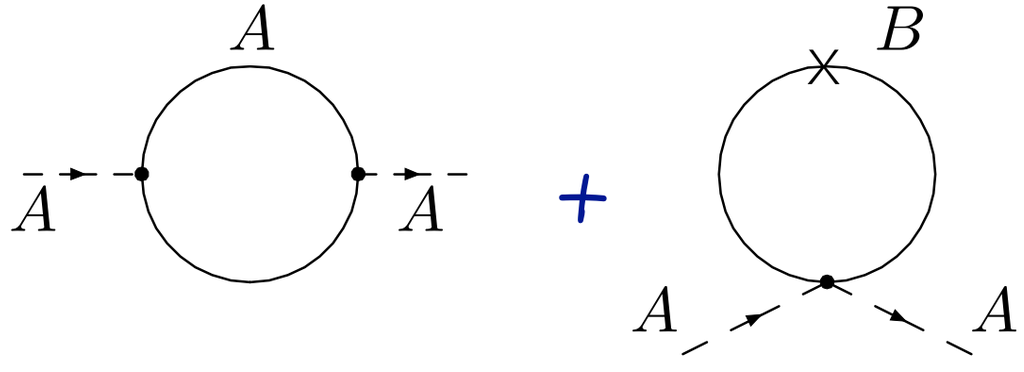
$$H_A = \boldsymbol{h}\frac{if}{\sqrt{\boldsymbol{h}^\dagger\boldsymbol{h}}}\sin\left(\frac{\sqrt{\boldsymbol{h}^\dagger\boldsymbol{h}}}{f}\right) = i\boldsymbol{h} + \dots\,,$$

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

* Back to the top Yukawa:

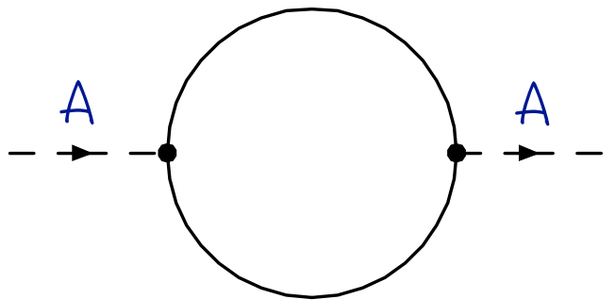
$$\mathcal{L} \supset y_t H_A \bar{t}_A t_A + y_t H_B \bar{t}_B t_B$$

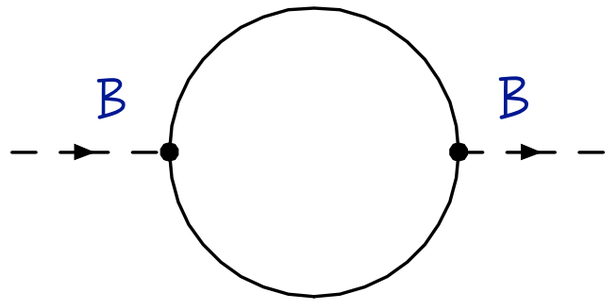
$$= y_t h\, \bar{t}_A t_A + y_t \left(f - \frac{|h|^2}{2f}\right) \bar{t}_B t_B + \dots$$



Cancelation

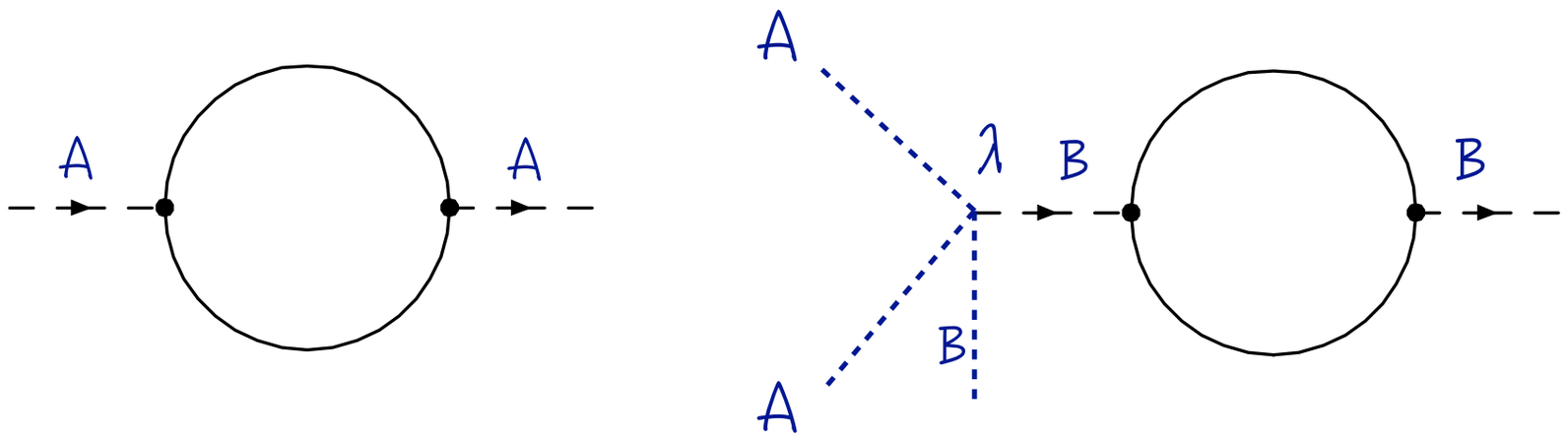
* If you don't like non-linear representation, here it is in the linear one:





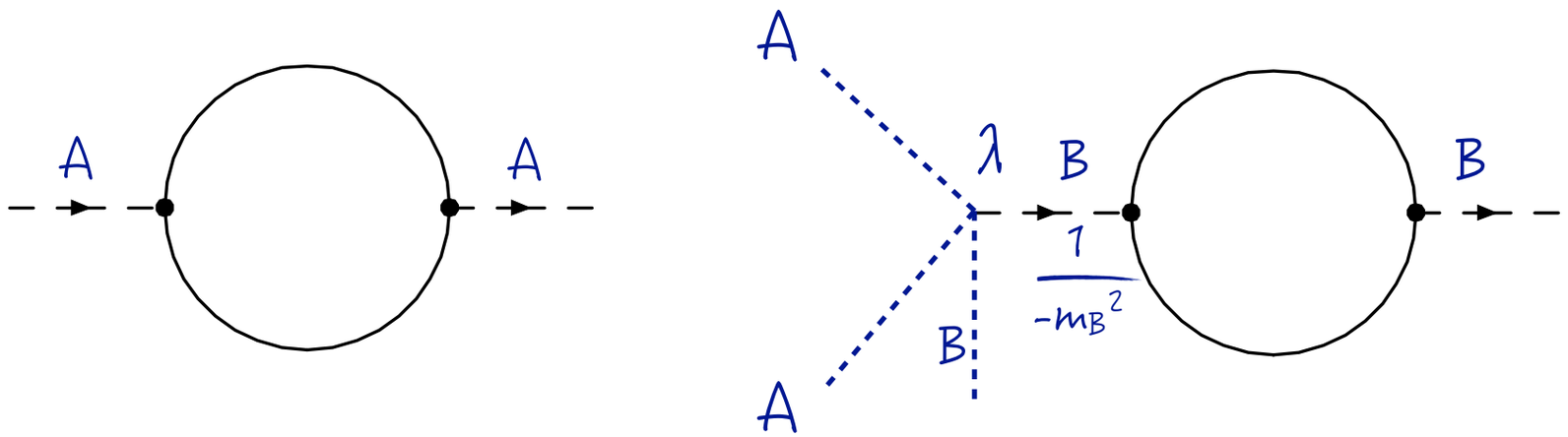
Cancelation

* If you don't like non-linear representation, here it is in the linear one:



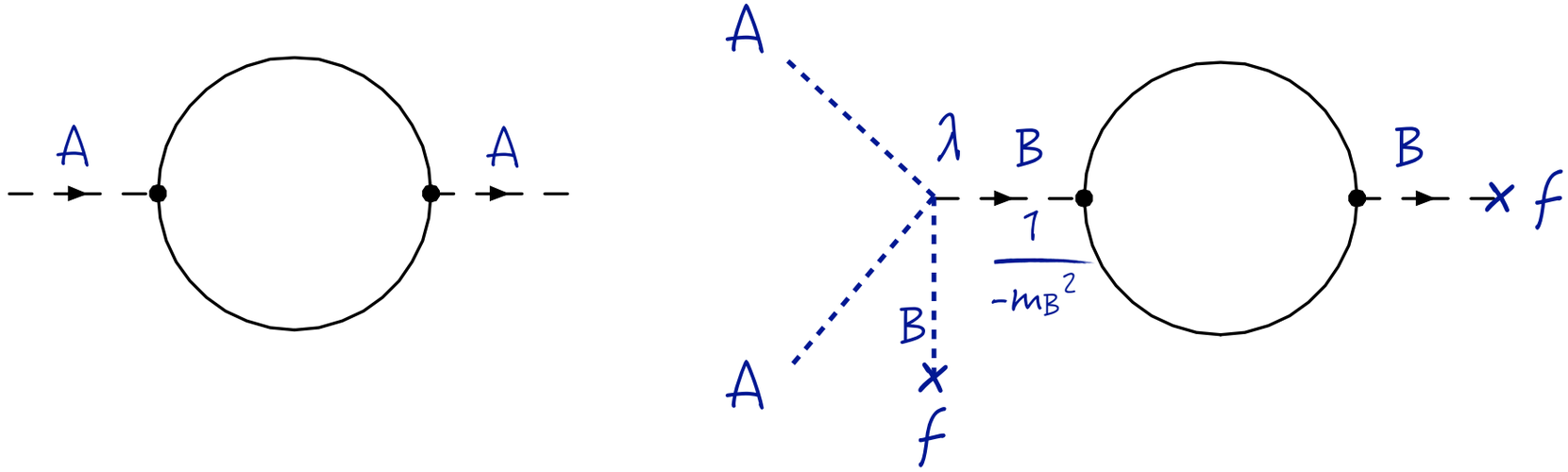
Cancelation

* If you don't like non-linear representation, here it is in the linear one:



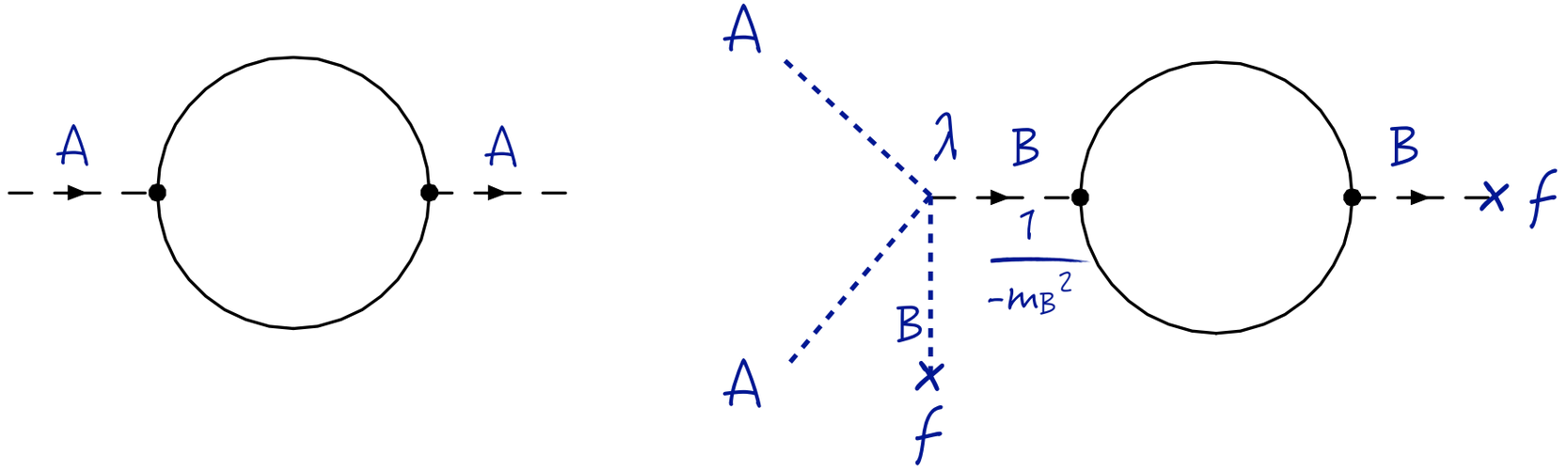
Cancelation

* If you don't like non-linear representation, here it is in the linear one:



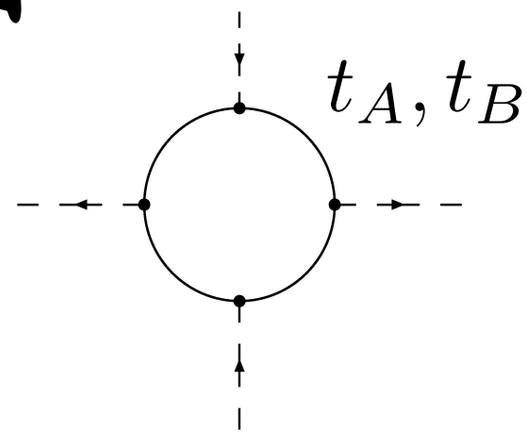
Cancelation

* If you don't like non-linear representation, here it is in the linear one:



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

SU(4) Breaking



* Radiative corrections induce

$$\Delta V = \kappa \left(|H_A|^4 + |H_B|^4 \right)$$

$$\text{with} \quad \kappa \sim \frac{y_t^4}{16\pi^2} \log \frac{\Lambda}{f}$$

* Goldstone mass is $m_h \sim \frac{y_t^2}{4\pi} f$.

* Adding mixed "top partners" at 5-6 TeV keeps this quartic finite, correct Higgs mass.

$$\begin{aligned} Q_L &= (\mathbf{6}, \bar{\mathbf{4}}) \\ &= (\mathbf{3}, \mathbf{2}; \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}; \mathbf{3}, \mathbf{2}) + (\mathbf{3}, \mathbf{1}; \mathbf{1}, \mathbf{2}) + (\mathbf{1}, \mathbf{2}; \mathbf{3}, \mathbf{1}) \end{aligned}$$

Soft Breaking

* The potential as is gives $v_A = v_B \sim \frac{f}{\sqrt{2}}$

* But then $\Lambda \sim 4\pi f$ is too low.

---

* Add $V_{soft} = \mu^2 |H_A|^2$ to get $v < f$.

$\Lambda_{(\mathrm{TeV})}$	$f_{(\mathrm{GeV})}$	$M_{(\mathrm{TeV})}$	$M_{B\,(\mathrm{TeV})}$	$\mu_{(\mathrm{GeV})}$	$m_{h\,(\mathrm{GeV})}$	Tuning
10	800	6	1	239	122	0.134
6	500	5.5	1	145	121	0.378
10	800	—	0	355	166	0.112
6	500	—	0	203	153	0.307

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 **complete SM singlets.**
* What's the phenomenology?
  - LHC finds the Higgs and nothing else! (check).
  - Then what?

Higgs Couplings

* Higgs gauge boson couplings: $\left|D_\mu^A H_A\right|^2 + \left|D_\mu^B H_B\right|^2$
* Recall $H_A^\dagger H_A = h^\dagger h - \frac{(h^\dagger h)^2}{3f^2} + \dots$
* Higgs boson couplings are modified by $\cos\left(\frac{v}{f}\right)$.

* This is universal to all Higgs couplings.
  (in linear language: h is mixing with a singlet H_B)

All SM Higgs σxBR's are modified by $\cos^4\left(\frac{v}{f}\right)$

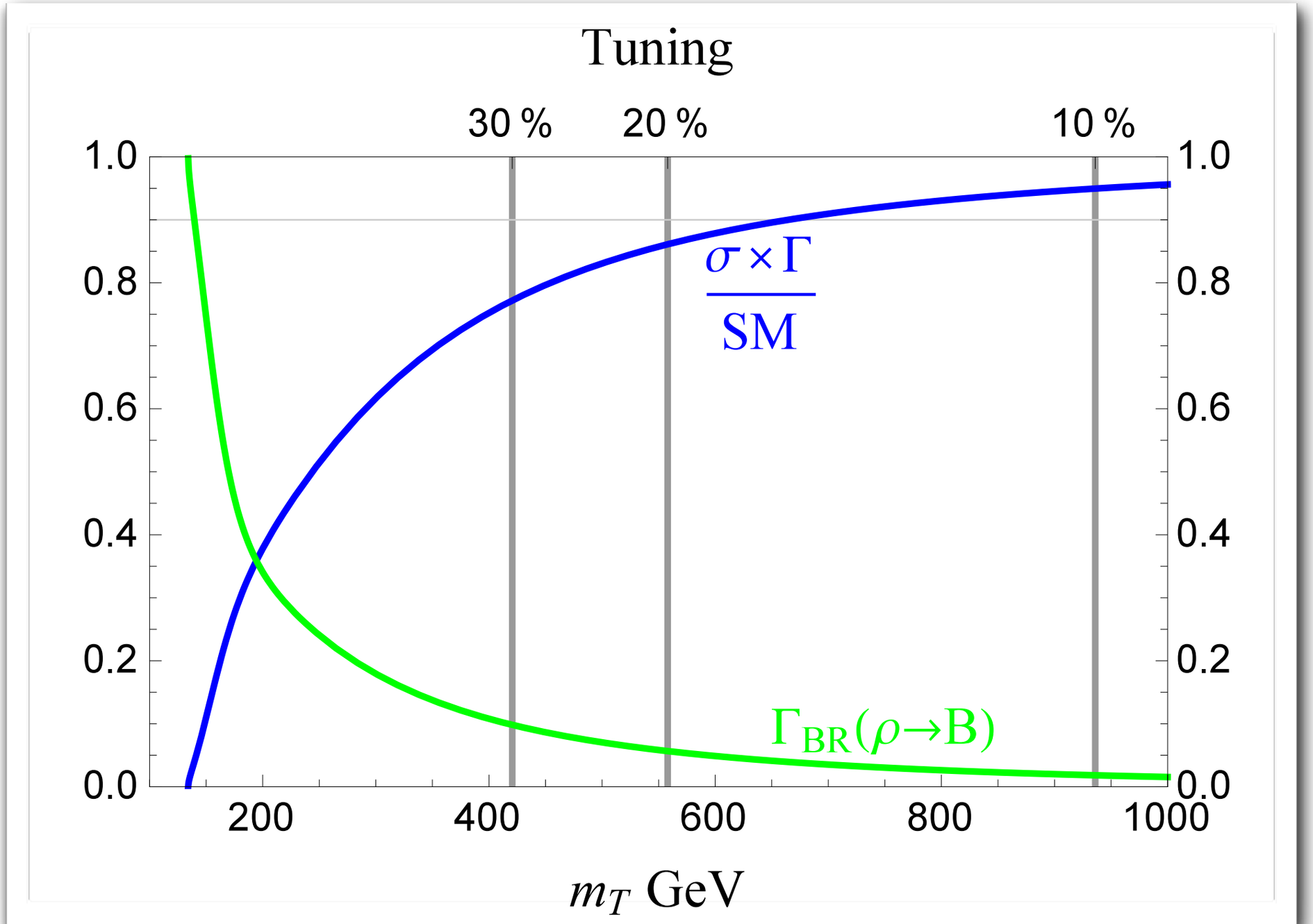
Invisible Decay

* The bottom Yukawa: $y_b H_A \bar{b}_A b_A + y_b H_B \bar{b}_B b_B$
* Expanding $H_B \rightarrow$ a coupling of h to b_B: $y_b \sin(\frac{v}{f})$

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

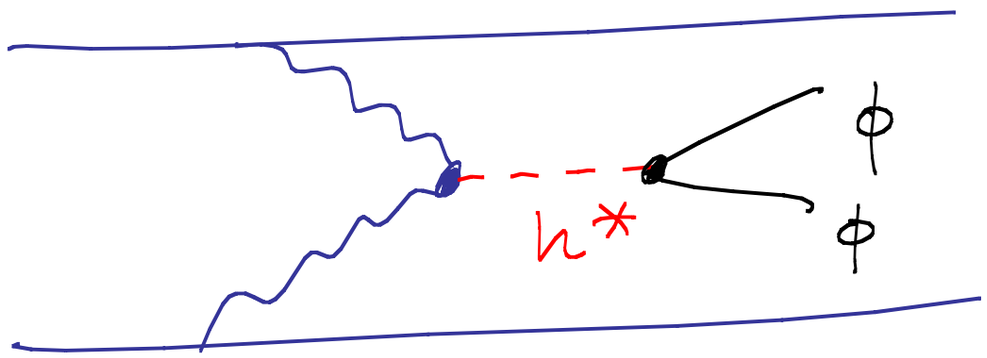
* One parameter, v/f, is setting both Higgs coupling modification and BR_{inv}. A prediction.

Prediction


Tuning
30 %
20 %
10 %
1.0
0.8
0.6
0.4
0.2
0.0
$\frac{\sigma \times \Gamma}{\mathrm{SM}}$
$\Gamma_{\mathrm{BR}}(\rho \to \mathrm{B})$
200
400
600
800
1000
m_T GeV

Other LHC Signals

* Other collider signals depend on the UV:
  - Weakly coupled UV Completion - Heavy Higgses at ~TeV, superpartners at few TeV (e.g. Craig and Howe)
  - Strongly coupled UV completion - loads of resonances for discovery at the 100 TeV machine! :-)
  - More @ 100 TeV:



top partner production via off-shell Higgs

torn from talk by Nathaniel and Nima.

PEWK

* 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).

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

Craig and Howe 1312.1341

Folded SUSY Signals

Higgs coupling modifications are tiny
(beyond the regular SUSY Higgs sector).

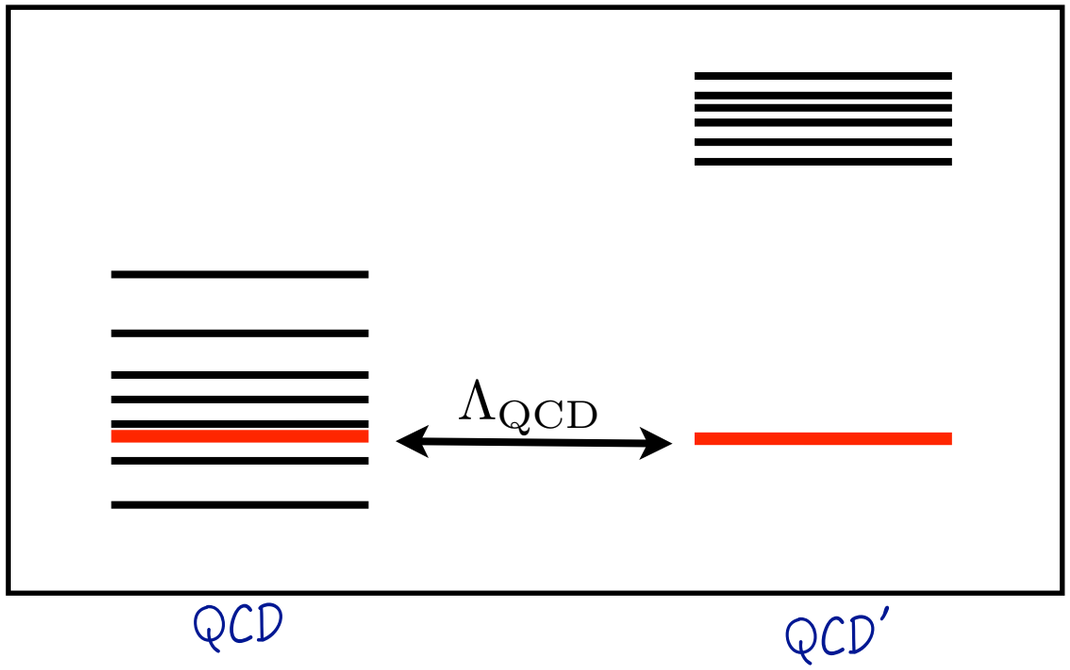
Some PEWK constraints (see Jiji's talk).

Can we go after top partners directly?

Quirks

* In folded SUSY the squarks are charge under our $SU(2)_L \times U(1)_Y$. Can be produced.

* The spectrum is "quirky", $m \gg \Lambda_{\mathrm{QCD}'}$:



LEP bounds

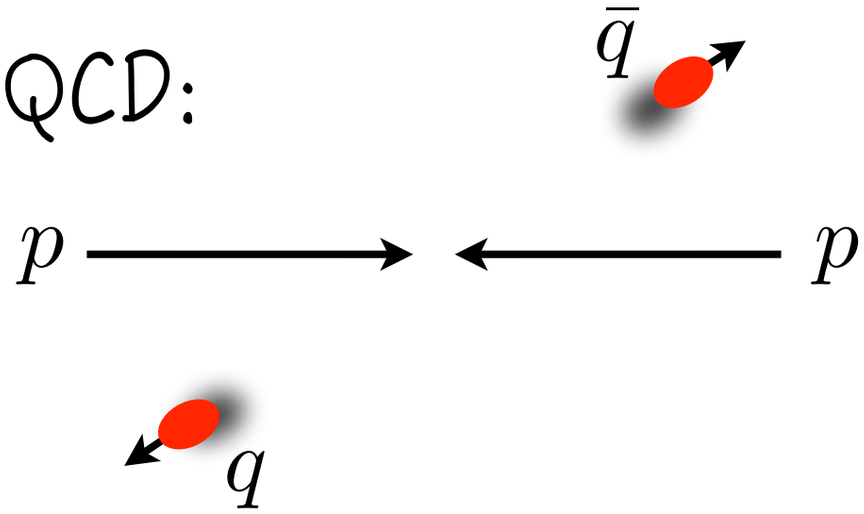
QCD scales are related by a Z_2.

This is generic for non-colored but EW-charged top partners.

(e.g "quirky little Higgs" - Cai, Cheng, Terning 0812.0843)

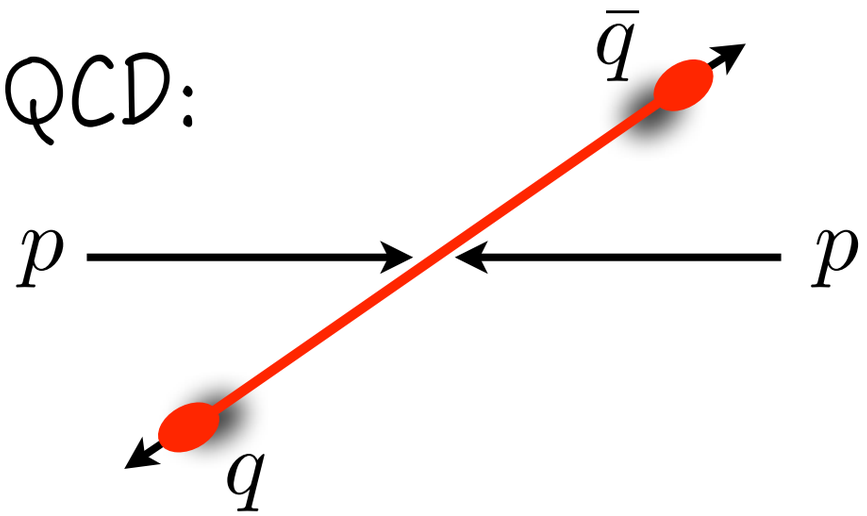
Quirky Dynamics

* In regular QCD:



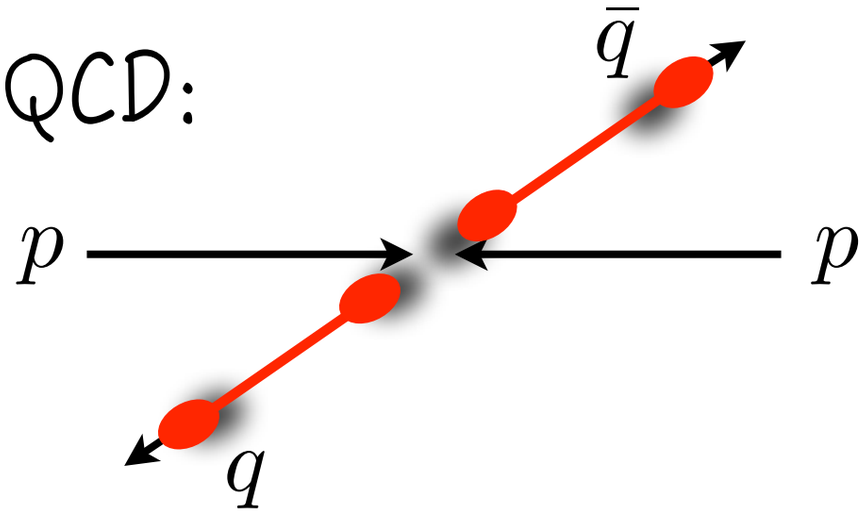
Quirky Dynamics

* In regular QCD:



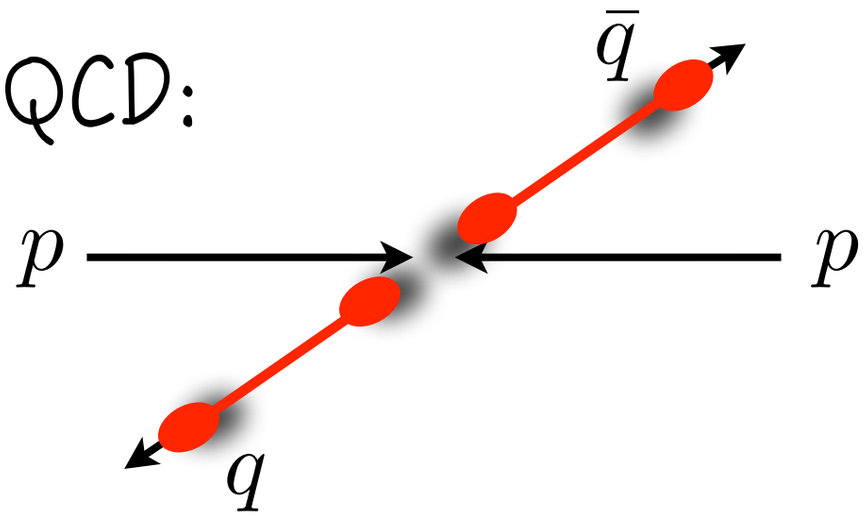
Quirky Dynamics

* In regular QCD:

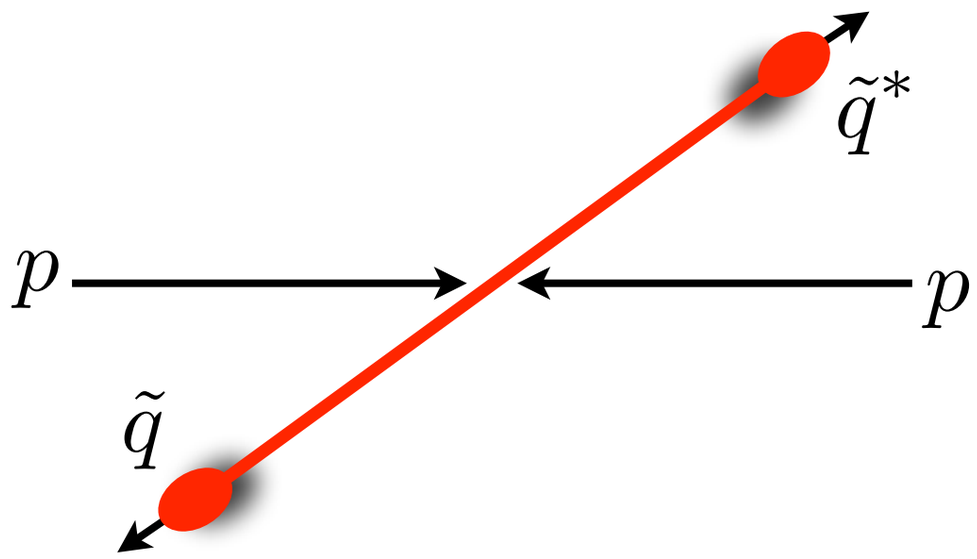


Quirky Dynamics

* In regular QCD:



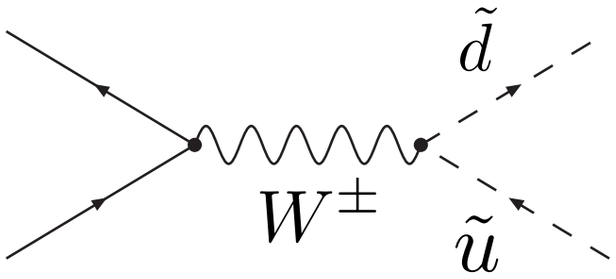
* In "quirky QCD" this costs too much energy. 'squarks' are produced and **remain bound!**

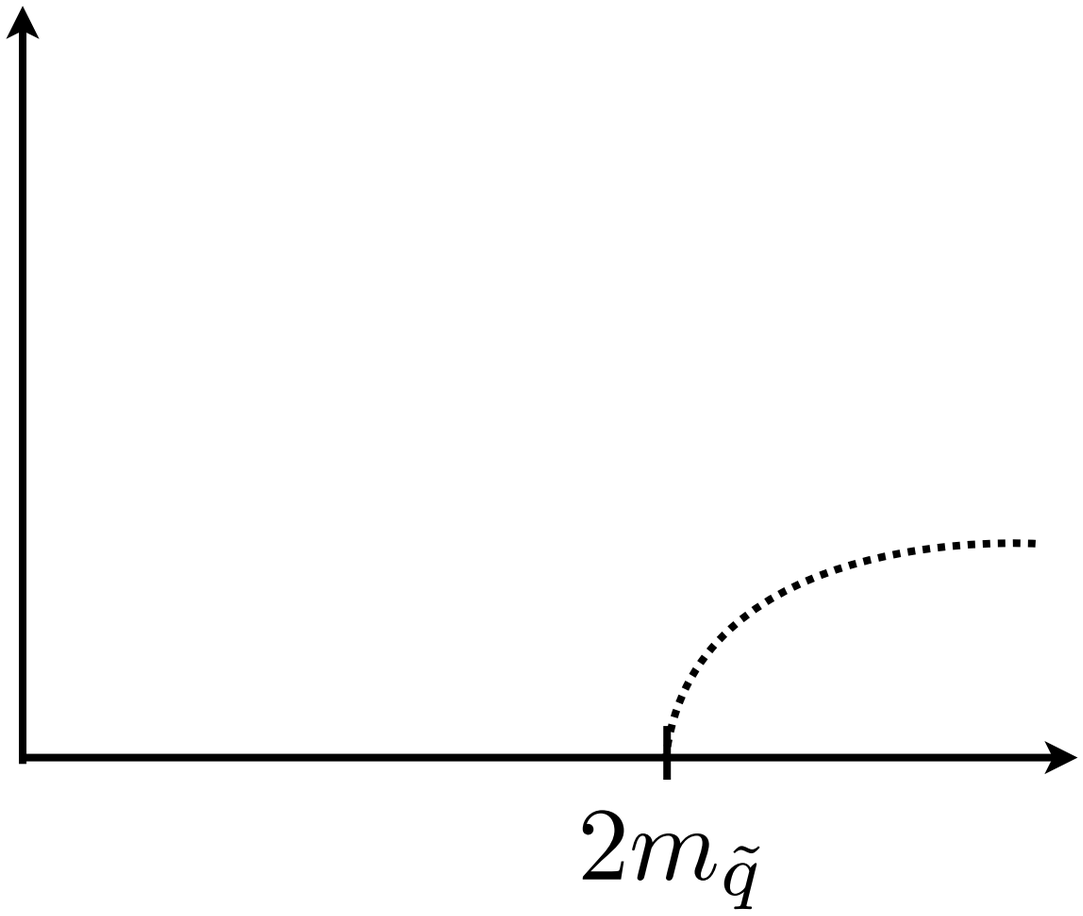


Bjorken (79)
Okun(80)
Quinn and Gupta (81)
.....
Strassler and Zurek(06)
Luty (08)
Burdman et al. (08)

A Hard Signal

* Annihilation occurs after radiation:

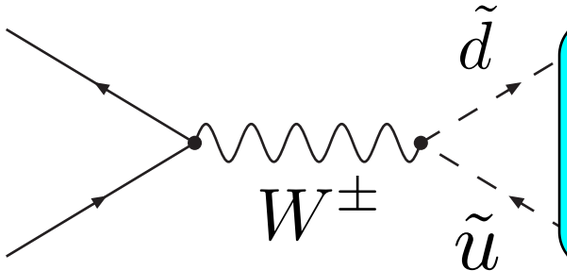




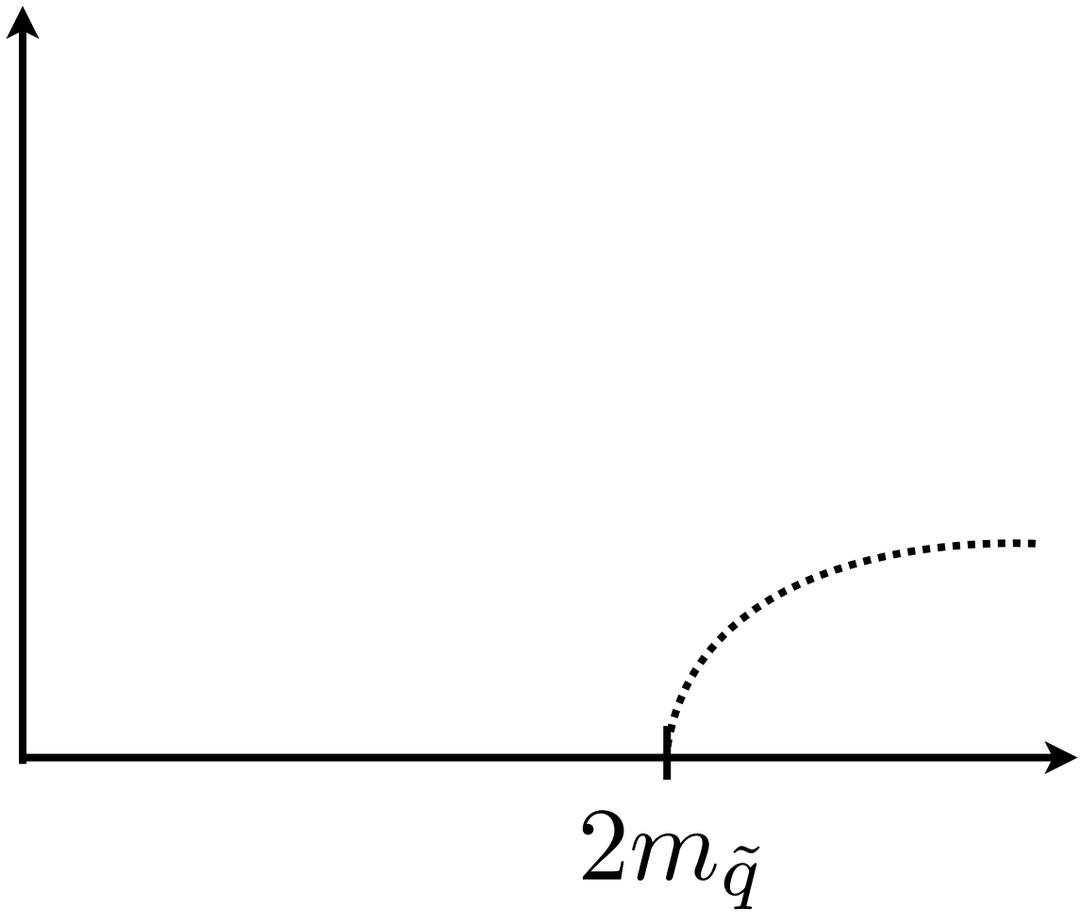
w/ Burdman et al - arXiv:0805.4667

A Hard Signal

* Annihilation occurs after radiation:



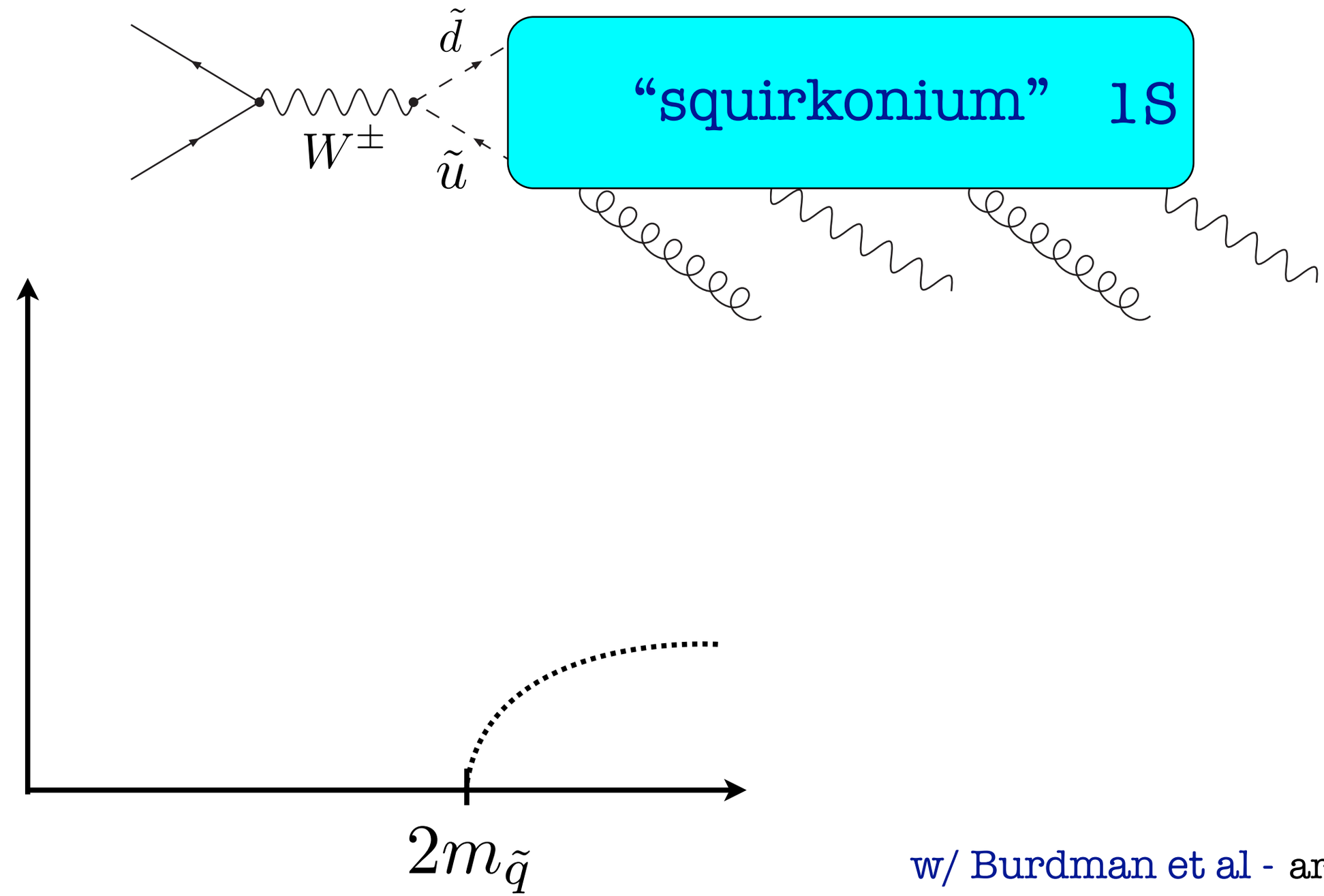
"squirkonium"



w/ Burdman et al - arXiv:0805.4667

A Hard Signal

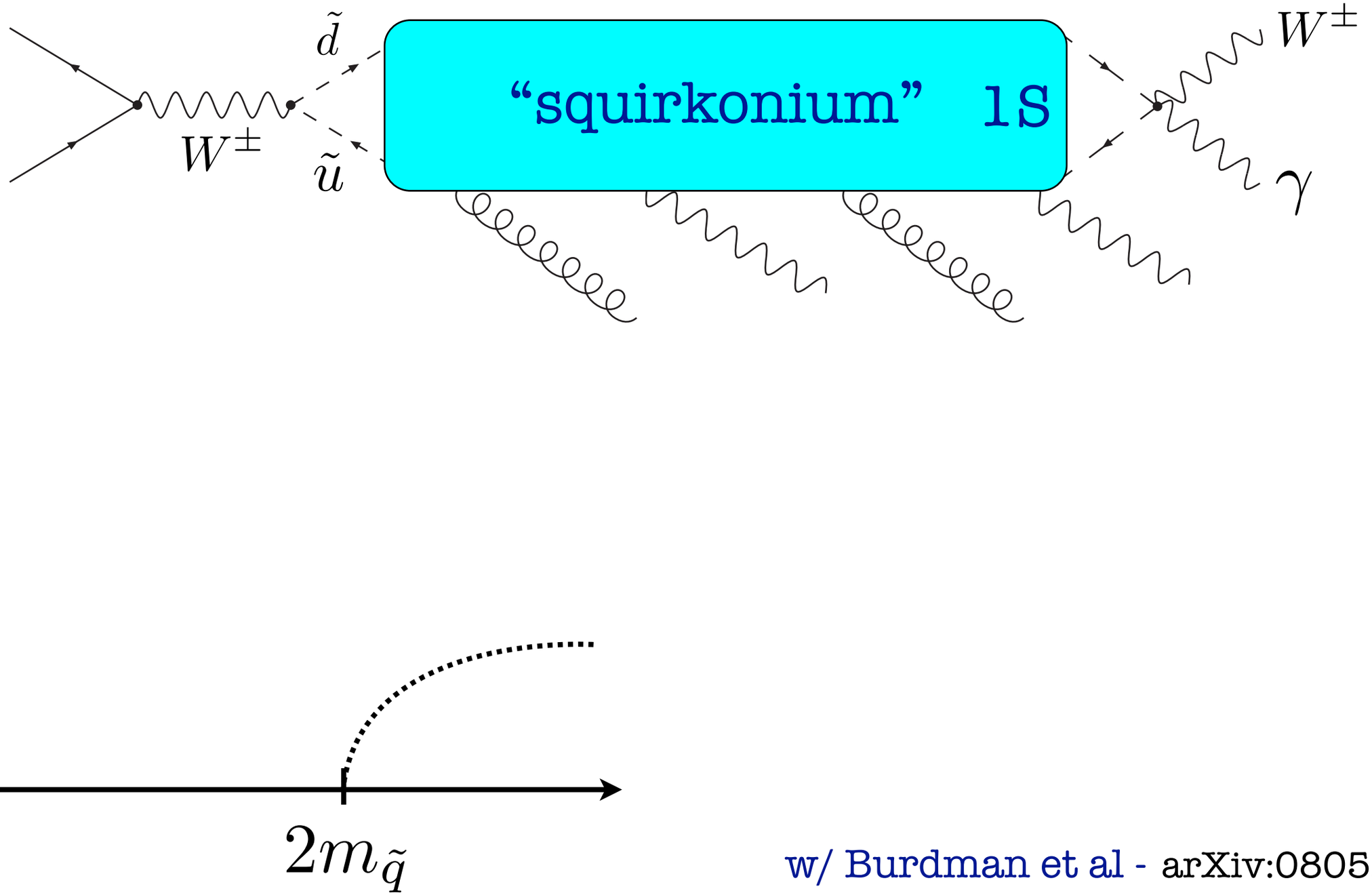
* Annihilation occurs after radiation:



w/ Burdman et al - arXiv:0805.4667

A Hard Signal

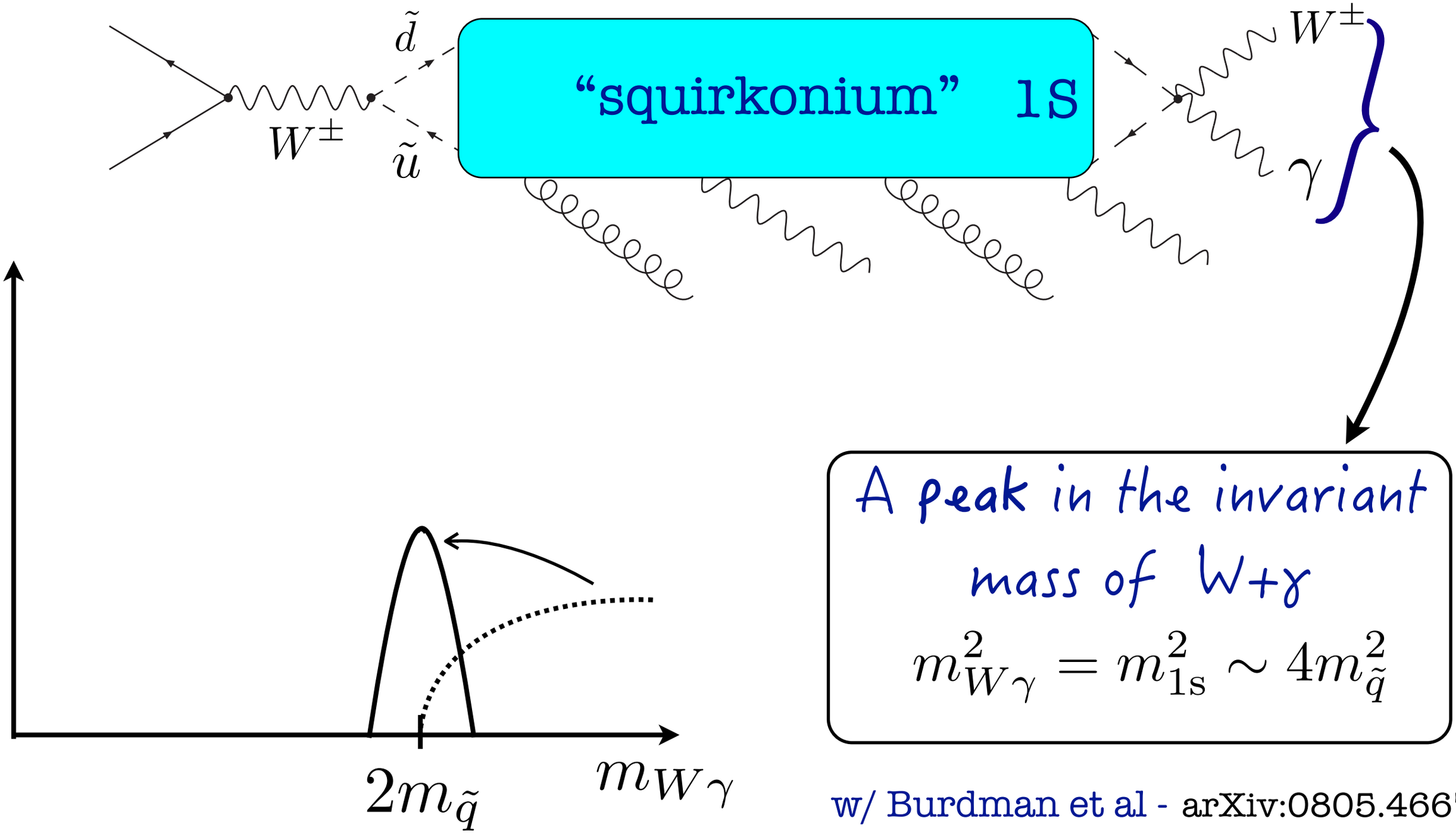
* Annihilation occurs after radiation:



w/ Burdman et al - arXiv:0805.4667

A Hard Signal

* Annihilation occurs after radiation:



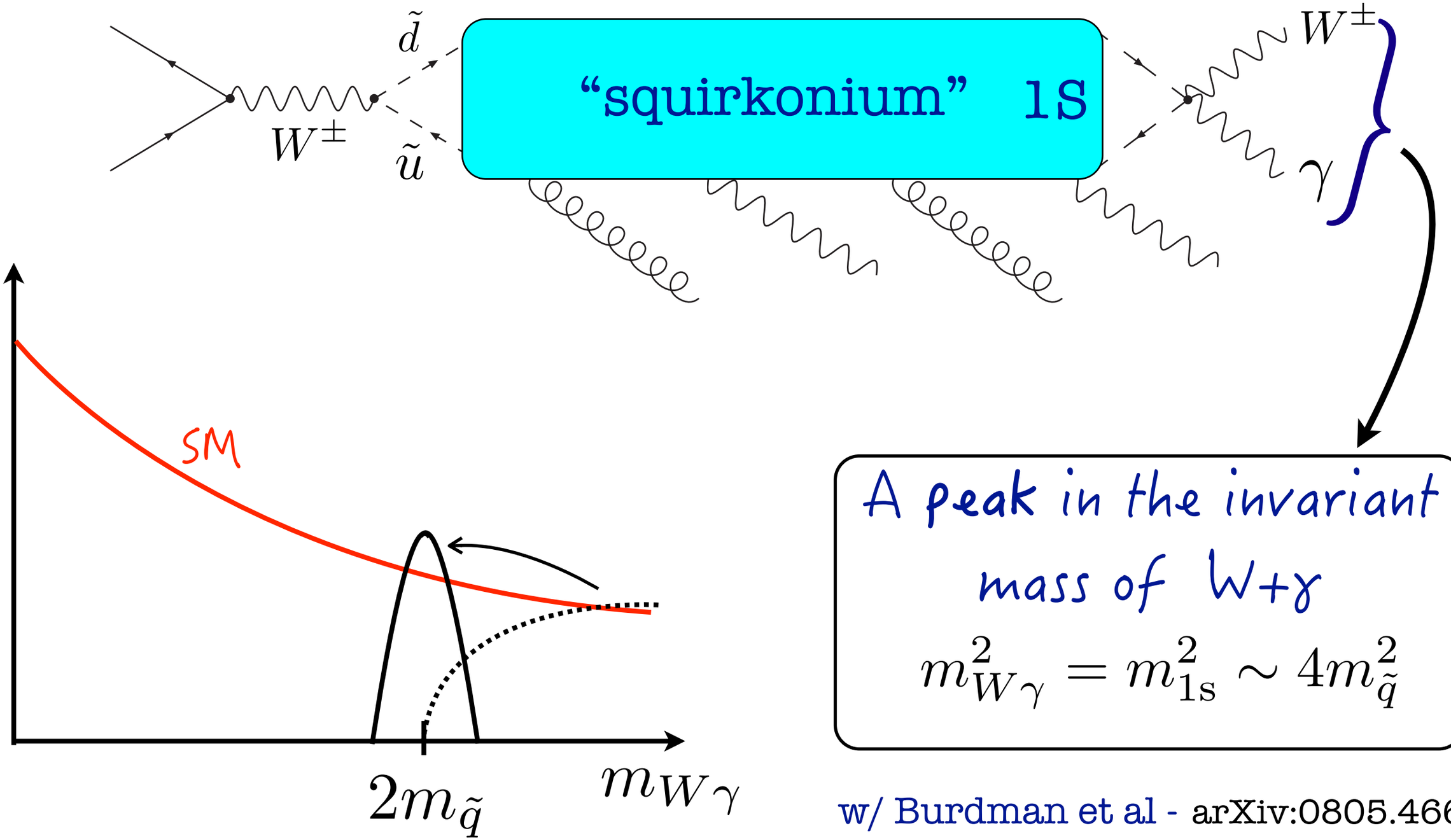
A peak in the invariant mass of W+γ

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

w/ Burdman et al - arXiv:0805.4667

A Hard Signal

* Annihilation occurs after radiation:



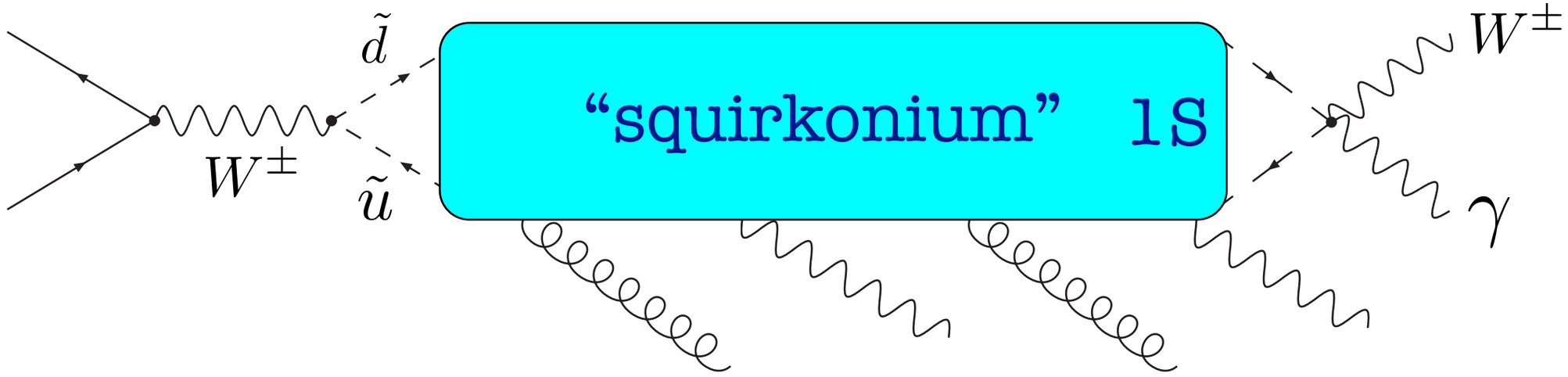
A peak in the invariant mass of W+γ

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

w/ Burdman et al - arXiv:0805.4667

Soft Stuff

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



An overly active underlying event...?

(RH and Wizansky 0810.3949)

Summary

* Naturalness can be had with top partners that are not colored.
* Orbifolded cousins of "normal models". (see talk by Craig tomorrow)
* Examples:
  - Twin Higgs: Singlet partners.
    Signals - Higgs precision, h→inv, maybe heavy Higgses.
  - Folded SUSY: EW charged partners.
    Quirky dynamics!

Deleted Scenes