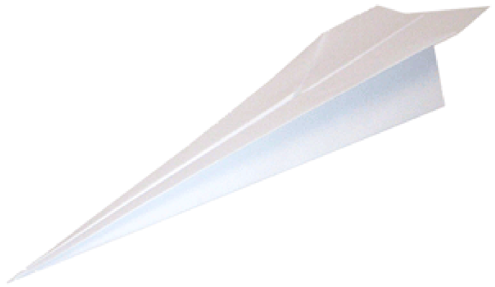


Hierarchy, Quirks and the LHC

Roni Harnik, SLAC/Stanford

past and ongoing works with
G. Burdman, Z. Chacko, H.S. Goh
and T. Wizansky.

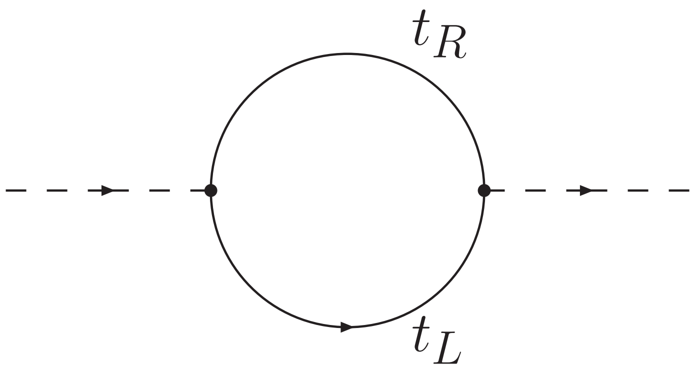
Brief Commercial

Aspen 2008

LHC is Coming!

- We are all excited to discover the mysteries of the TeV scale.
- One of the prime hints for new physics at a TeV is (still) **Naturalness**.

Dominated by the top loop:



$$\sim \frac{3y_t^2}{8\pi^2}\Lambda^2$$

LHC is a difficult environment for discovery:
We should be ready for signals from a variety of natural (and non-natural) models.

New Physics

Post LEP, we are left with the following picture:

* New physics at a TeV seems to be weakly coupled.
* A new **symmetry** exists to protect the Higgs.

---

symmetry G: $\phi_{\rm SM} \to \phi_{\rm SM} + \delta\phi_{\rm SM}$

applying G on SM fields
determines the particle content of NP.

New Symmetry

* Popular mechanisms:

SUSY **Little Higgs**

* In both cases: a new continuous symmetry guarantees cancelations.

Symmetry	SUSY	Little Higgs
Generator $\equiv G$	Q^α	T^a

New Symmetry

* Popular mechanisms:

SUSY **Little Higgs**

* In both cases: a new continuous symmetry guarantees cancelations.

Symmetry	SUSY	Little Higgs
Generator $\equiv G$	Q^α	T^a

For making predictions at LHC energies:
only the cancelation of the
one-loop divergence from the top quark
is relevant.

Top Partners

* Particle content of new physics:

$$\delta(\mathrm{top}) = G(\mathrm{top})$$

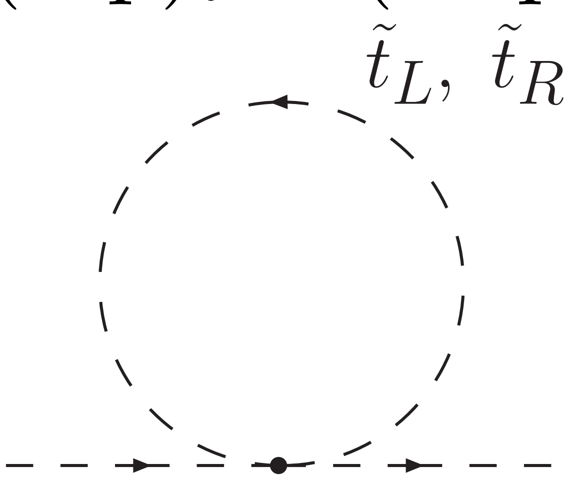
Top Partners

* Particle content of new physics:

$$\delta(\text{top}) = G(\text{top})$$

SUSY:
Generator does not act on gauge indices

$$\delta(\text{top})_i = (\text{stop})_i$$



Top Partners

- Particle content of new physics:

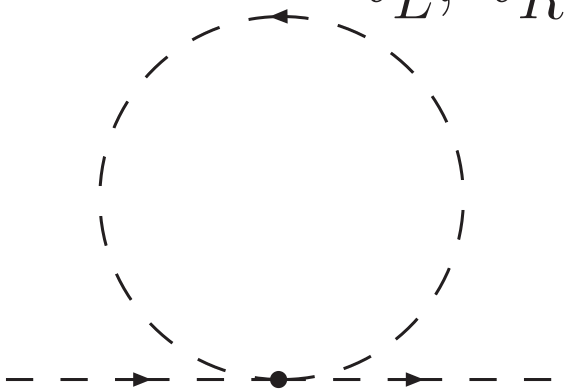
$$\delta(\text{top}) = G(\text{top})$$

SUSY:
Generator does not act on gauge indices

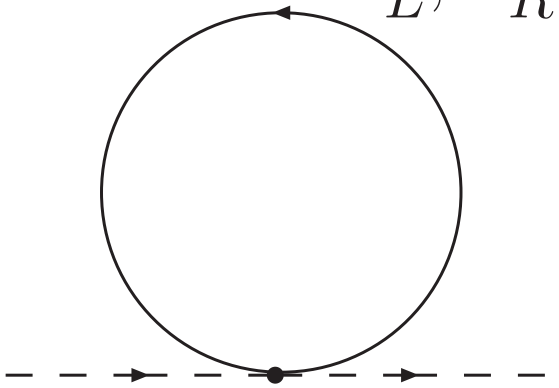
Little Higgs:
Generator commutes with $SU(3)_c$

$$\delta(\text{top})_i = (\text{stop})_i \qquad \delta(\text{top})_i = (\text{top}')_i$$

$\tilde{t}_L,\ \tilde{t}_R$



$t'_L,\ t'_R$



Top Partners

- Particle content of new physics:

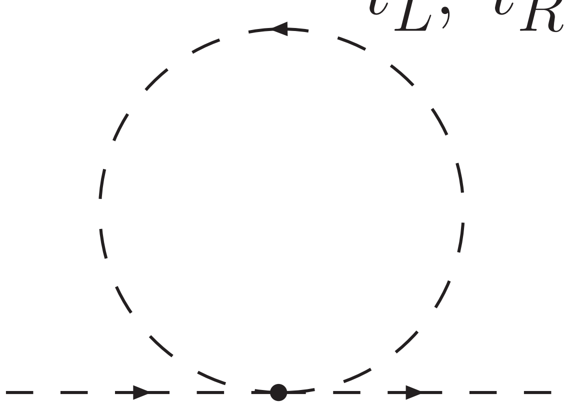
$$\delta(\text{top}) = G(\text{top})$$

SUSY:
Generator does not act on gauge indices

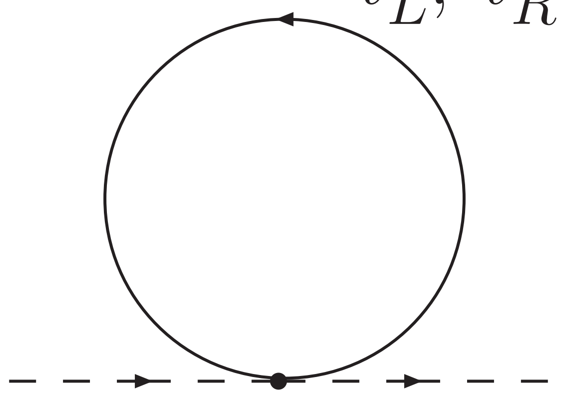
Little Higgs:
Generator commutes with $SU(3)_c$

$$\delta(\text{top})_i = (\text{stop})_i \qquad \delta(\text{top})_i = (\text{top}')_i$$

$\tilde{t}_L,\ \tilde{t}_R$



$t'_L,\ t'_R$

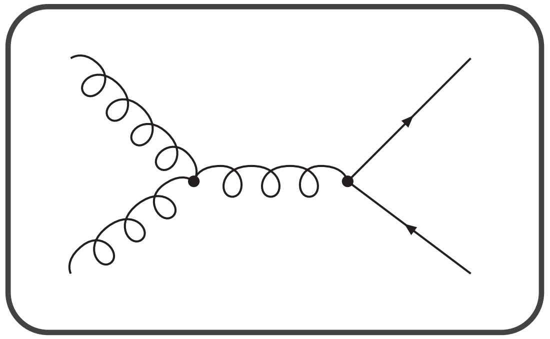


In both cases: **Top partner carries color**

Colored Top Partners

* Prejudice:
  Naturalness predicts a colored top partner.

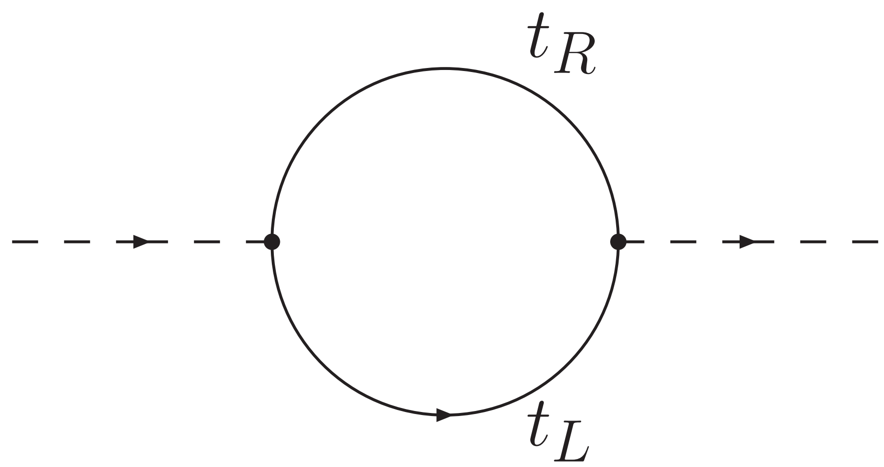
* Great news for LHC:
  We'll see new physics. We'll see it early!



"Proving a theory is natural may be difficult.
But, if nothing new is seen at LHC within a couple
years naturalness is down the drain"
-anonymous

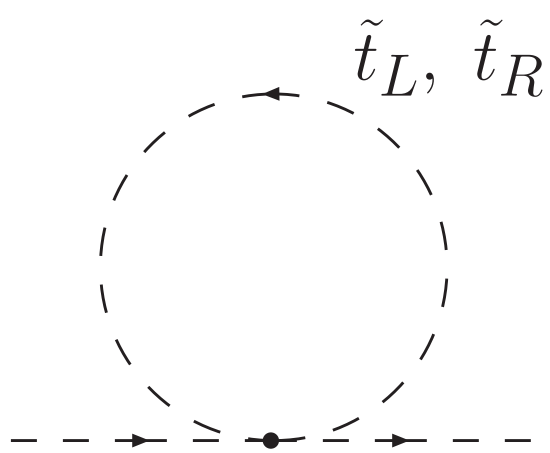
Just a Factor of 3

color factor:



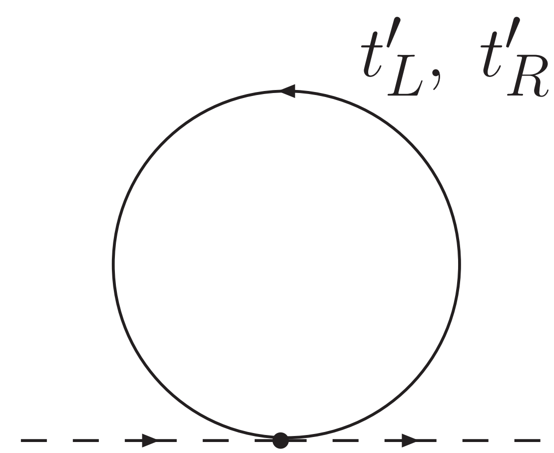
Standard Model

$\times 3$



Supersymmetry

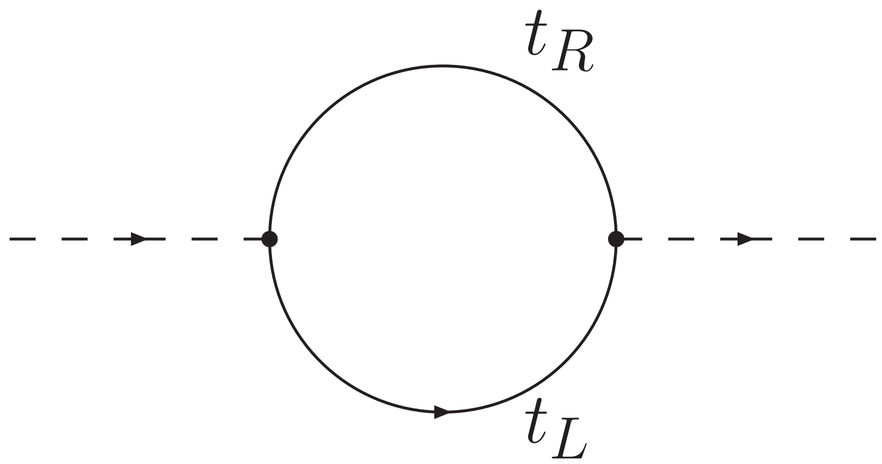
or



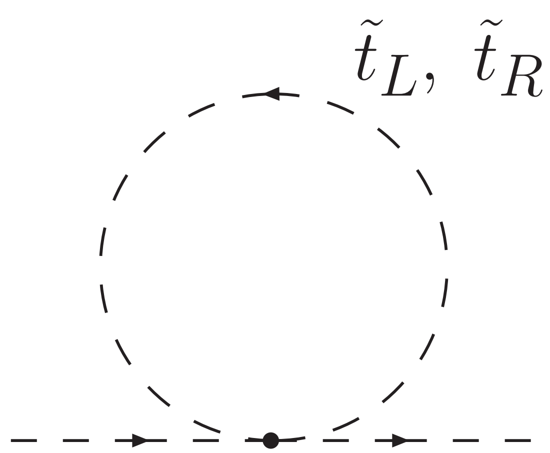
Little Higgs

$\times 3$

Just a Factor of 3

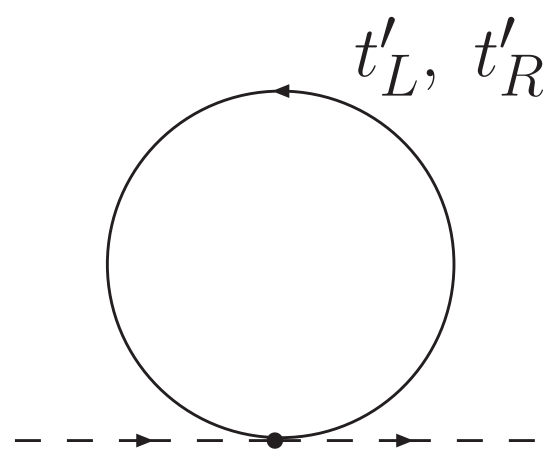


Standard Model



Supersymmetry

or



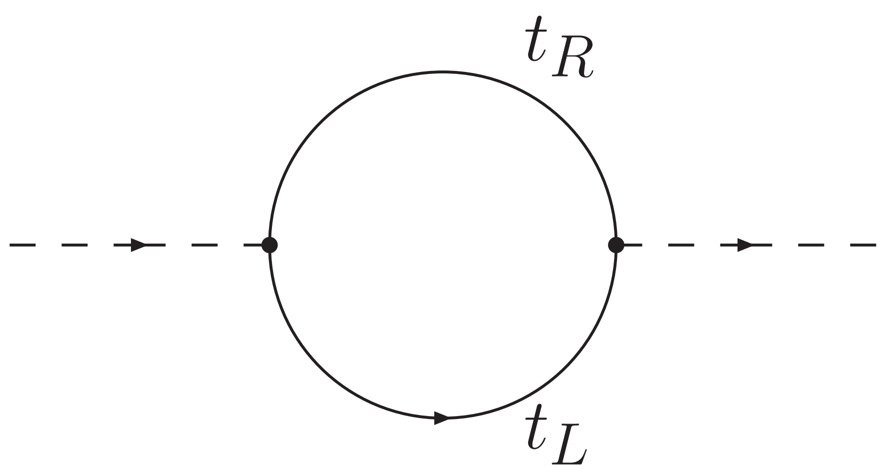
Little Higgs

<u>color factor:</u>

$\times 3$

$\times$ ~~3~~ 3'

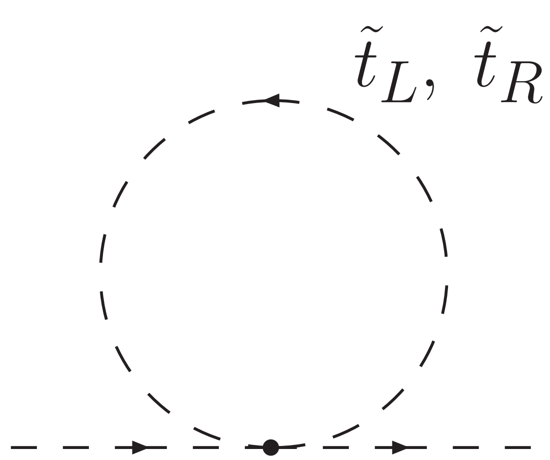
Just a Factor of 3



Standard Model

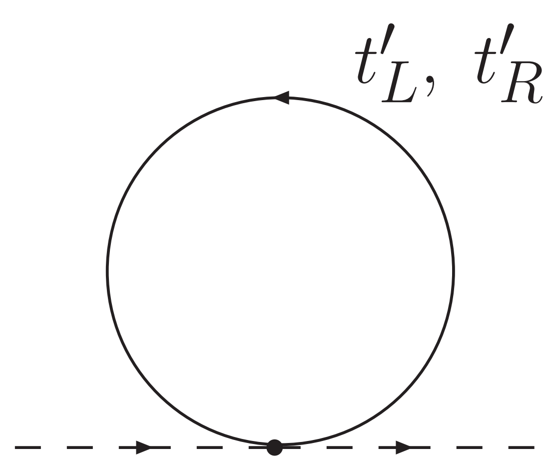
color factor:

$\times 3$



Supersymmetry

or



Little Higgs

$\times$ ~~3~~ 3'

Folded SUSY

(today's talk)

Twin Higgs

(Chacko, Goh ,RH)

UnColored Partners

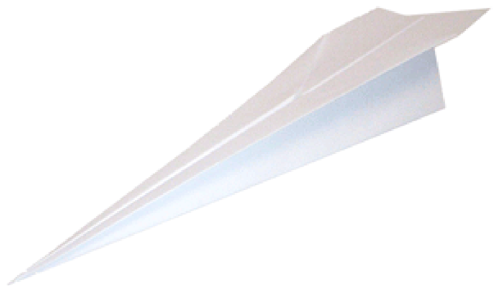
* This talk is devoted to the alternative scenario: Naturalness may be restored by **uncolored** top-partners.

* The protection of the EW scale can involve a **discrete symmetry**

$$(\text{top})_i \longrightarrow (\text{top}')_{i'}$$

* The implications for LHC signals can be profound.

Folded SUSY.



* Uncolored Squarks -
  - Large N orbifold correspondence - basics.
  - the Mechanism.
  - A Model - a 5D orbifold.
* Phenomenology of uncolored squarks.
  - Quirks and their dynamics
  - Soft photons at the LHC

Nonstandard SUSY

Supersymmetry charges don't act in gauge space. ⇒ Superpartners *always* have the same quantum numbers as SM counterparts.

How can we get non-colored partners?

Nonstandard SUSY

Supersymmetry charges don't act in gauge space. ⇒ Superpartners *always* have the same quantum numbers as SM counterparts.

How can we get non-colored partners?

t

Nonstandard SUSY

Supersymmetry charges don't act in gauge space. → Superpartners *always* have the same quantum numbers as SM counterparts.

How can we get non-colored partners?

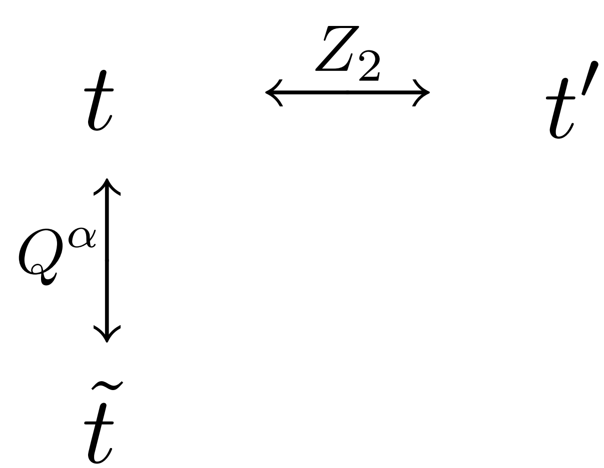
$$t \overset{Q^\alpha}{\updownarrow} \tilde{t}$$

Nonstandard SUSY

Supersymmetry charges don’t act in gauge space.

Superpartners *always* have the same quantum numbers as SM counterparts.

How can we get non-colored partners?



Nonstandard SUSY

Supersymmetry charges don't act in gauge space. → Superpartners *always* have the same quantum numbers as SM counterparts.

How can we get non-colored partners?

$$
\begin{array}{ccc}
t & \overset{Z_2}{\longleftrightarrow} & t' \\
Q^\alpha \updownarrow & & \updownarrow Q^\alpha \\
\tilde{t} & \underset{Z_2}{\longleftrightarrow} & \tilde{t}'
\end{array}
$$

Nonstandard SUSY

Supersymmetry charges don't act in gauge space. ⇒ Superpartners *always* have the same quantum numbers as SM counterparts.

How can we get non-colored partners?

$$t \longleftrightarrow \tilde{t}'$$

The Large-N Orbifold Correspondence

Kachru and Silverstein (98)

...

Bershadsky and Johansen (98)

...

Schmaltz (99)

Inheritance

Supersymmetric "mother" theory

↓ *orbifolding*

less supersymmetric "daughter"

The daughter theory inherits the correlation functions of its mother in the large N limit.

Orbifolding-

1. Identify a discrete symmetry, Γ, of the mother (perhaps an R-symmetry).
2. Eliminate all fields that are not invariant under Γ.

Example I

- A $U(2N)$ SUSY gauge theory with $2N$ flavors.
- A discrete symmetries

$$Z_{2\Gamma}: \quad Q \to \Gamma Q \qquad \bar{Q} \to \Gamma^* \bar{Q} \qquad V \to \Gamma V \Gamma^\dagger$$

$$Z_{2R}: \quad \text{boson} \to \text{boson} \qquad \text{fermion} \to -\text{fermion}$$

$$Z_{2F}: \quad Q \to Q\Gamma_F^\dagger \qquad \bar{Q} \to \bar{Q}\Gamma_F^T$$

$$\Gamma = \Gamma_F = \begin{pmatrix} \underbrace{\begin{matrix} +1 & & \\ & \ddots & \\ & & +1 \end{matrix}}_{N} & \\ & \underbrace{\begin{matrix} -1 & & \\ & \ddots & \\ & & -1 \end{matrix}}_{N} \end{pmatrix}$$

Example I

* The vector superfields transform as

$$A_\mu = \begin{pmatrix} A_{\mu,AA}(+) & A_{\mu,AB}(-) \\ A_{\mu,BA}(-) & A_{\mu,BB}(+) \end{pmatrix}$$

$$\lambda = \begin{pmatrix} \lambda_{AA}(-) & \lambda_{AB}(+) \\ \lambda_{BA}(+) & \lambda_{BB}(-) \end{pmatrix}$$

$A = 1, \ldots, N$
$B = N+1, \ldots, 2N$

* The matter fields transform like

$$\tilde{q} = \begin{pmatrix} \tilde{q}_{Aa}(+) & \tilde{q}_{Ab}(-) \\ \tilde{q}_{Ba}(-) & \tilde{q}_{Bb}(+) \end{pmatrix}$$

$$q = \begin{pmatrix} q_{Aa}(-) & q_{Ab}(+) \\ q_{Ba}(+) & q_{Bb}(-) \end{pmatrix}$$

$a = 1, \ldots, N$
$b = N+1, \ldots, 2N$

Example I

* The vector superfields transform as

$$A_\mu = \begin{pmatrix} A_{\mu,AA}(+) & A_{\mu,AB}(-) \\ A_{\mu,BA}(-) & A_{\mu,BB}(+) \end{pmatrix}$$

$$\lambda = \begin{pmatrix} \lambda_{AA}(-) & \lambda_{AB}(+) \\ \lambda_{BA}(+) & \lambda_{BB}(-) \end{pmatrix}$$

$U(2N) \to U(N)^2$

$A = 1, \ldots, N$
$B = N+1, \ldots, 2N$

* The matter fields transform like

$$\tilde{q} = \begin{pmatrix} \tilde{q}_{Aa}(+) & \tilde{q}_{Ab}(-) \\ \tilde{q}_{Ba}(-) & \tilde{q}_{Bb}(+) \end{pmatrix}$$

$$q = \begin{pmatrix} q_{Aa}(-) & q_{Ab}(+) \\ q_{Ba}(+) & q_{Bb}(-) \end{pmatrix}$$

$a = 1, \ldots, N$
$b = N+1, \ldots, 2N$

Example I

* The vector superfields transform as

$$A_\mu = \begin{pmatrix} A_{\mu,AA}(+) & A_{\mu,AB}(-) \\ A_{\mu,BA}(-) & A_{\mu,BB}(+) \end{pmatrix}$$

$$\lambda = \begin{pmatrix} \lambda_{AA}(-) & \lambda_{AB}(+) \\ \lambda_{BA}(+) & \lambda_{BB}(-) \end{pmatrix}$$

$U(2N) \to U(N)^2$

$A = 1, \ldots, N$
$B = N+1, \ldots, 2N$

* The matter fields transform like

$$\tilde{q} = \begin{pmatrix} \tilde{q}_{Aa}(+) & \tilde{q}_{Ab}(-) \\ \tilde{q}_{Ba}(-) & \tilde{q}_{Bb}(+) \end{pmatrix}$$

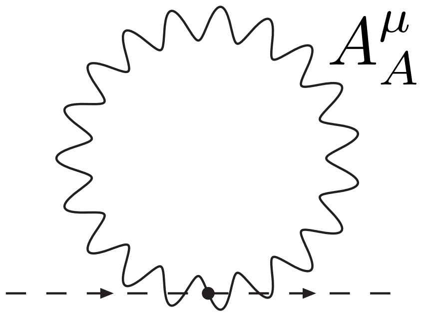
$$q = \begin{pmatrix} q_{Aa}(-) & q_{Ab}(+) \\ q_{Ba}(+) & q_{Bb}(-) \end{pmatrix}$$

squarks and quarks w/ different quantum numbers!

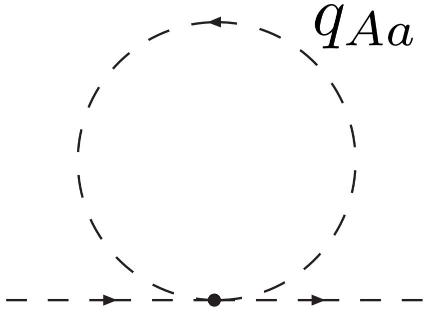
$a = 1, \ldots, N$
$b = N+1, \ldots, 2N$

Example 1

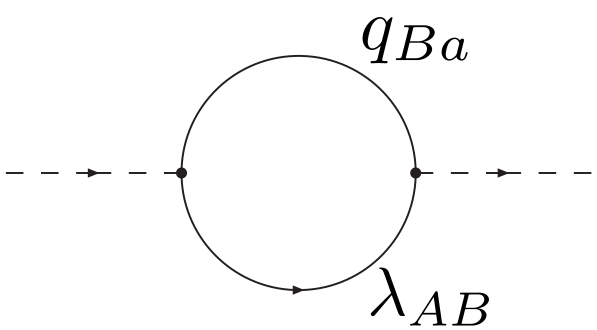
- Calculate radiative corrections to $\tilde{q}_{Aa}$ squark mass



$$\frac{3g^2N}{32\pi^2}\Lambda^2$$



$$\frac{g^2N}{32\pi^2}\Lambda^2$$

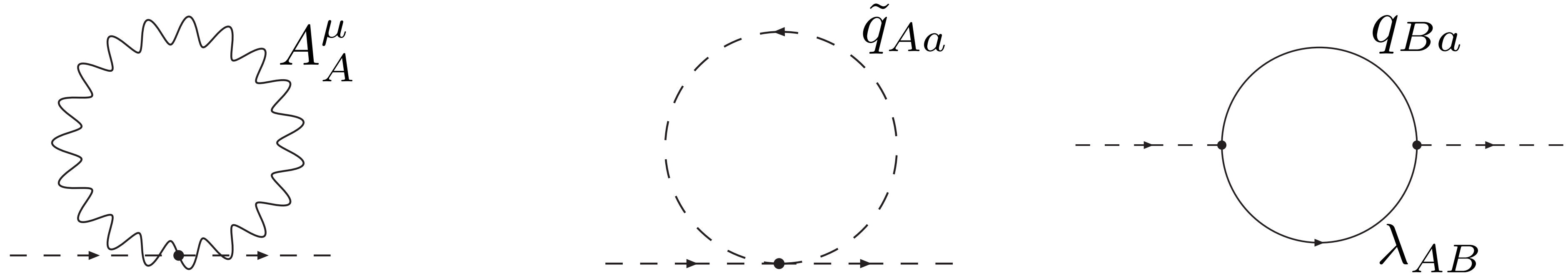


$$-\frac{g^2N}{8\pi^2}\Lambda^2$$

They cancel! (even at finite N).

Example 1

- Calculate radiative corrections to $\tilde{q}_{Aa}$ squark mass



$$\frac{3g^2N}{32\pi^2}\Lambda^2 \qquad \frac{g^2N}{32\pi^2}\Lambda^2 \qquad -\frac{g^2N}{8\pi^2}\Lambda^2$$

They cancel! (even at finite N).

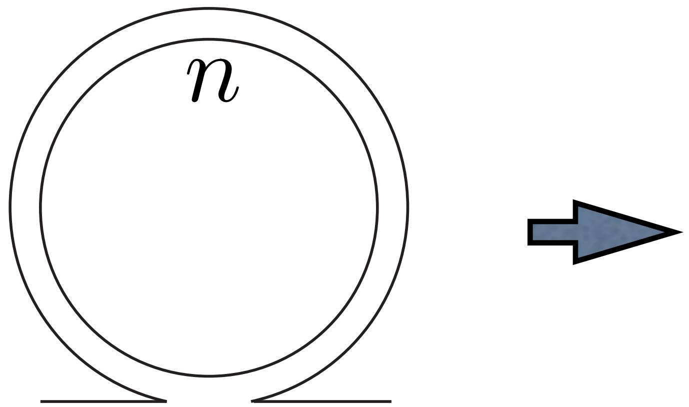
- For $SU(2N) \to SU(N)\times SU(N)$:

Cancelation is incomplete: $$-\frac{g^2}{16\pi^2}\frac{1}{N}\Lambda^2$$

What is the underlying
“mechanism” here?
Can we use it for
the top divergence?

the Mechanism

* Consider the graphs that contribute to the mass of a particular scalar in these theories:



a summed index

$$n = 1, \ldots, 2N$$

which states are running in the loops?
who's canceling who?

“Bifold protection”

supersymmetry ↔

the index n ↕

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

$$i = 1, \ldots, N$$
$$j = N+1, \ldots, 2N$$

which way does the cancelation go???

“Bifold protection”

supersymmetry ⟷

the index n

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

$$i = 1, \ldots, N$$
$$j = N+1, \ldots, 2N$$

which way does the cancelation go???

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

Supersymmetric

"Bifold protection"

supersymmetry ⟷

the index n ↕

$$\begin{pmatrix} t_i \\ \\ t_j \end{pmatrix} \qquad \begin{pmatrix} \tilde{t}_i \\ \\ \tilde{t}_j \end{pmatrix} \qquad \begin{matrix} i = 1, \ldots, N \\ j = N+1, \ldots, 2N \end{matrix}$$

which way does the cancelation go???

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

Supersymmetric — *Folded-Supersymmetric*

Example II

* Global $U(2N)$.

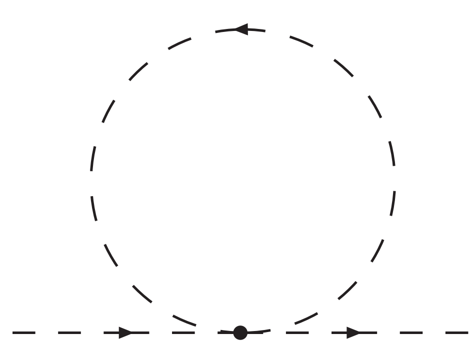
  A fundamental, anti fundamental and singlet.

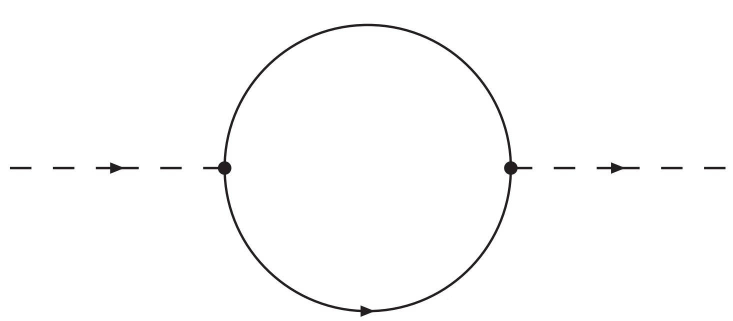
$$\lambda \, S \, Q \, \overline{Q}$$

* Orbifold by $Z_{2\Gamma} \times Z_{2R}$

$$Z_{2\Gamma} : \begin{cases} Q \to \Gamma Q \\ \bar{Q} \to \Gamma^* \bar{Q} \end{cases}$$

$$\tilde{q} = \begin{pmatrix} \tilde{q}_A(-) \\ \tilde{q}_B(+) \end{pmatrix} \quad q = \begin{pmatrix} q_A(+) \\ q_B(-) \end{pmatrix}$$





Example II

* Global $U(2N)$.

  A fundamental, anti fundamental and singlet.

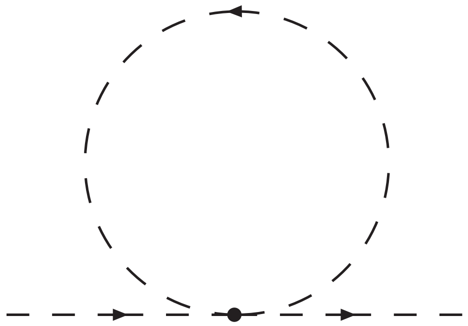
$$\lambda \, S \, Q \, \overline{Q}$$

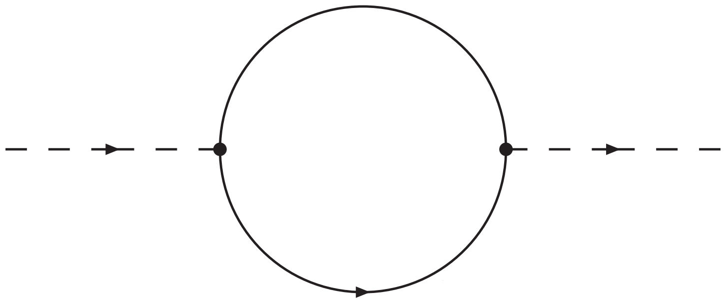
* Orbifold by $Z_{2\Gamma} \times Z_{2R}$

$$Z_{2\Gamma}: \begin{cases} Q \to \Gamma Q \\ \bar{Q} \to \Gamma^* \bar{Q} \end{cases}$$

$$\tilde{q} = \begin{pmatrix} \tilde{q}_A(-) \\ \tilde{q}_B(+) \end{pmatrix} \quad q = \begin{pmatrix} q_A(+) \\ q_B(-) \end{pmatrix}$$

S is "bifold" protected





Example II

* The interactions of the daughter,

$$\mathcal{L} = \lambda \tilde{s} q_B \bar{q}_B + \lambda^2 |\tilde{s}|^2 (|\tilde{\bar{q}}_A|^2 + |\tilde{q}_A|^2)$$

look awfully supersymmetric...

* Only $\tilde{s}$ is protected.
* Protection only at one loop.

that's fine for the little hierarchy...

* **But**: Daughter theory does not have a symmetry.

UV completion is crucial!

A Model
(with a UV Completion)

SU(3)^2

- Enlarge quark sector to $SU(6)$

$$\lambda_t\,(3,2)_{Q_3}\,(1,2)_{H_U}\,(\overline{3},1)_{U_3} \quad \longrightarrow \quad \lambda_t\,(6,2)_{Q_{3T}}\,(1,2)_{H_U}\,(\overline{6},1)_{U_{3T}}$$

- Alternatively:

only *global* $SU(6)$ is needed to ensure cancelation.

It is sufficient to gauge
$SU(3)_A \times SU(3)_B \times Z_2$

(this just eliminates exotic off-diagonal gluinos)

The IR Model

- Below ~10 TeV we have the daughter of

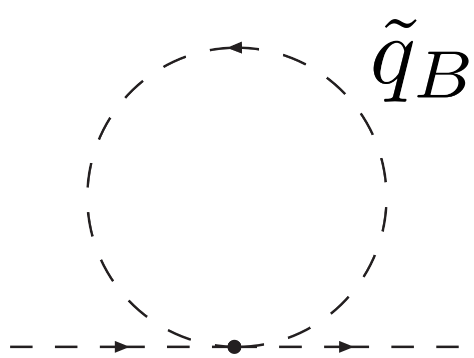
$$(SU(3)_A \times SU(3)_B \times Z_{AB}) \times SU(2)_L \times U(1)_Y$$

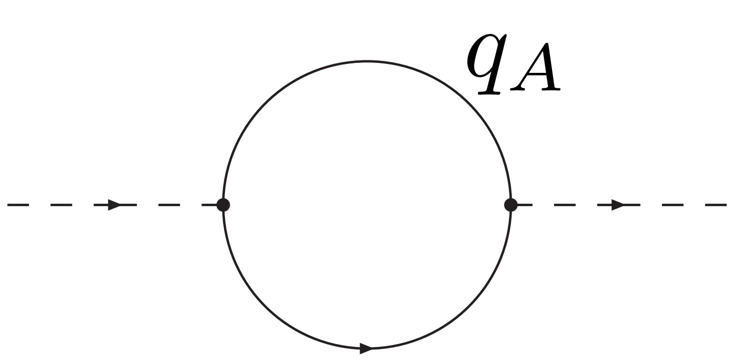
as orbifolded by $Z_{2\Gamma} \times Z_{2R}$:

quarks

$$\tilde{q} = \begin{pmatrix} \tilde{q}_A(-) \\ \tilde{q}_B(+) \end{pmatrix} \qquad q = \begin{pmatrix} q_A(+) \\ q_B(-) \end{pmatrix}$$

squarks

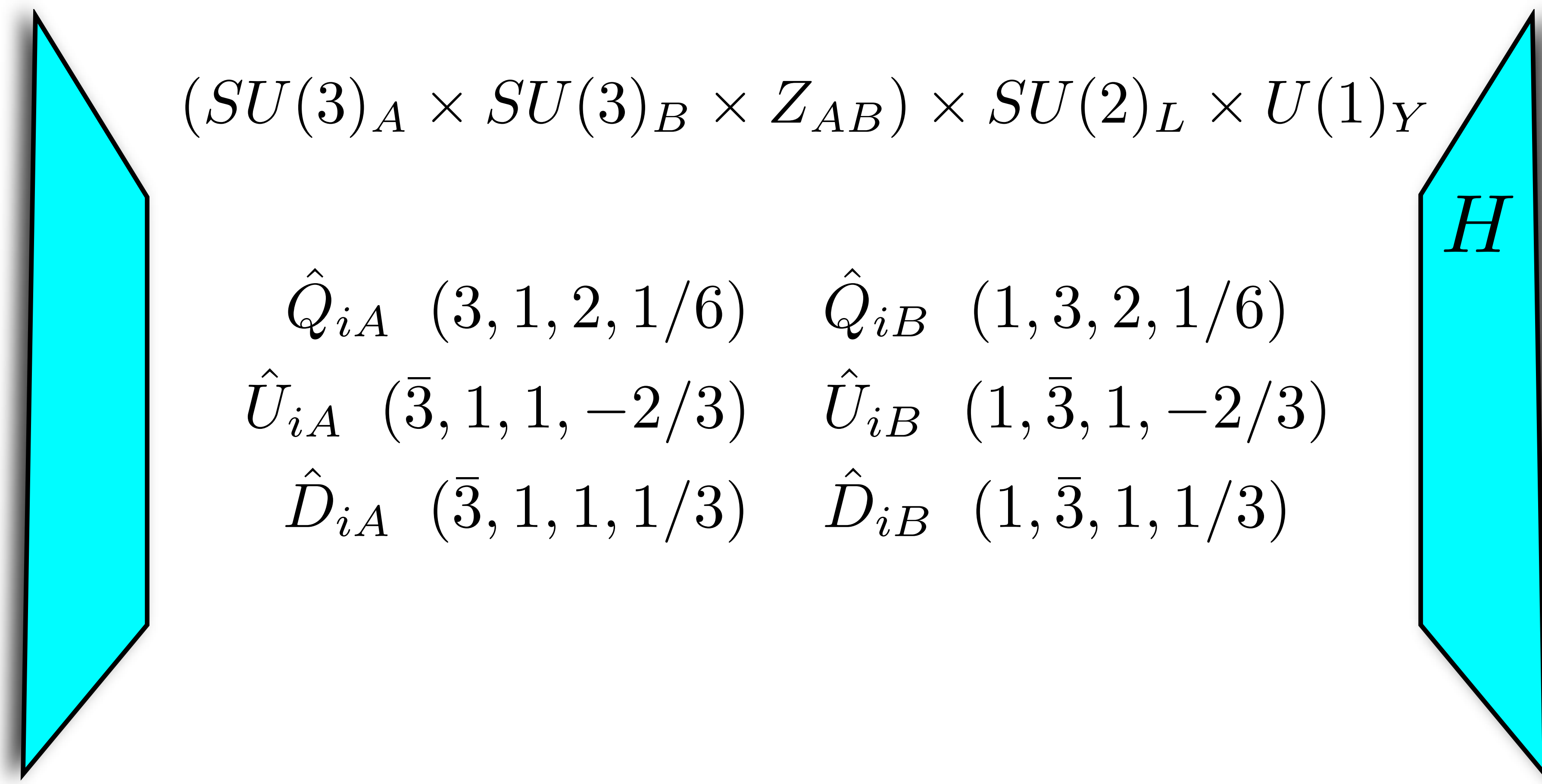




A Full Model

* A supersymmetric theory.

  SUSY is broken at 10 TeV by B.C.'s on 5D orbifold.



$$(SU(3)_A \times SU(3)_B \times Z_{AB}) \times SU(2)_L \times U(1)_Y$$

$$\hat{Q}_{iA} \ (3,1,2,1/6) \qquad \hat{Q}_{iB} \ (1,3,2,1/6)$$
$$\hat{U}_{iA} \ (\bar{3},1,1,-2/3) \qquad \hat{U}_{iB} \ (1,\bar{3},1,-2/3)$$
$$\hat{D}_{iA} \ (\bar{3},1,1,1/3) \qquad \hat{D}_{iB} \ (1,\bar{3},1,1/3)$$

Technology by Quiros et al and Barbieri, Hall, Nomura et al.

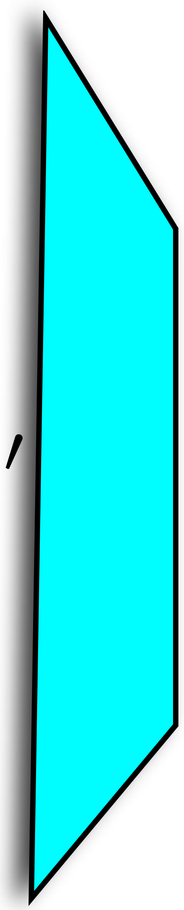
A Full Model

* A supersymmetric theory.

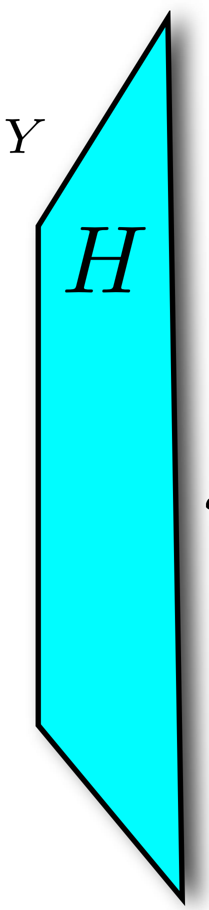
  SUSY is broken at 10 TeV by B.C.'s on 5D orbifold.

$$(SU(3)_A \times SU(3)_B \times Z_{AB}) \times SU(2)_L \times U(1)_Y$$

$\mathcal{N} = 1'$



$$\begin{array}{llll} \hat{Q}_{iA} & (3,1,2,1/6) & \hat{Q}_{iB} & (1,3,2,1/6) \\ \hat{U}_{iA} & (\bar{3},1,1,-2/3) & \hat{U}_{iB} & (1,\bar{3},1,-2/3) \\ \hat{D}_{iA} & (\bar{3},1,1,1/3) & \hat{D}_{iB} & (1,\bar{3},1,1/3) \end{array}$$



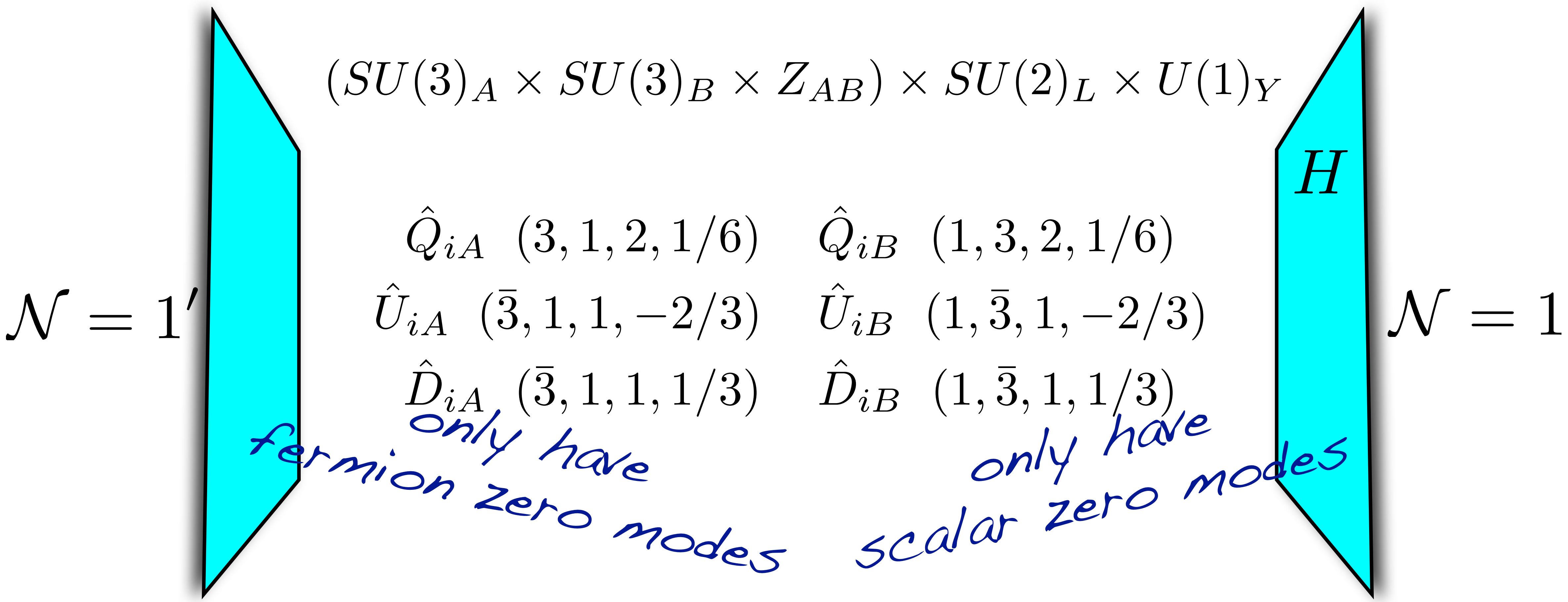
$\mathcal{N} = 1$

Technology by Quiros et al and Barbieri, Hall, Nomura et al.

A Full Model

* A supersymmetric theory.

  SUSY is broken at 10 TeV by B.C.'s on 5D orbifold.



Technology by Quiros et al and Barbieri, Hall, Nomura et al.

Interim Summary

* **The prejudice**:
  The top-Higgs sector will be made natural by a new colored particle. Easy to discover.

* **Large-N Orbifold Inheritance**:
  SUSY-style cancelations by scalars charged under a different gauge group.

* **Folded SUSY**:
  A model inspired by LNOI that cancels one-loop Higgs divergences with uncolored squarks.

LHC Signals of Uncolored squarks

What are the signals of a "Hidden Valley" that is associated with the Hierarchy problem?

work in progress

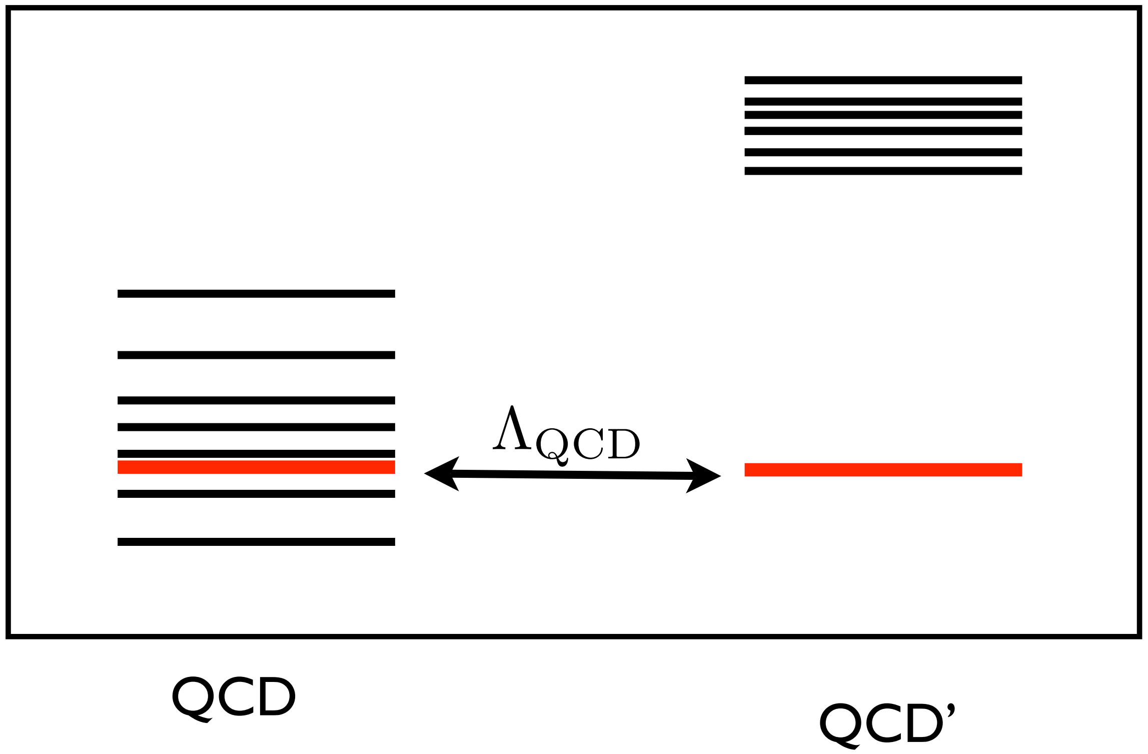
LHC Signals of Uncolored ~~squarks~~ squirks

What are the signals of a "Hidden Valley" that is associated with the Hierarchy problem?

work in progress

Spectrum of QCD’

* Assume the quark partners live in QCD’. Compare the spectra of the two QCDs.



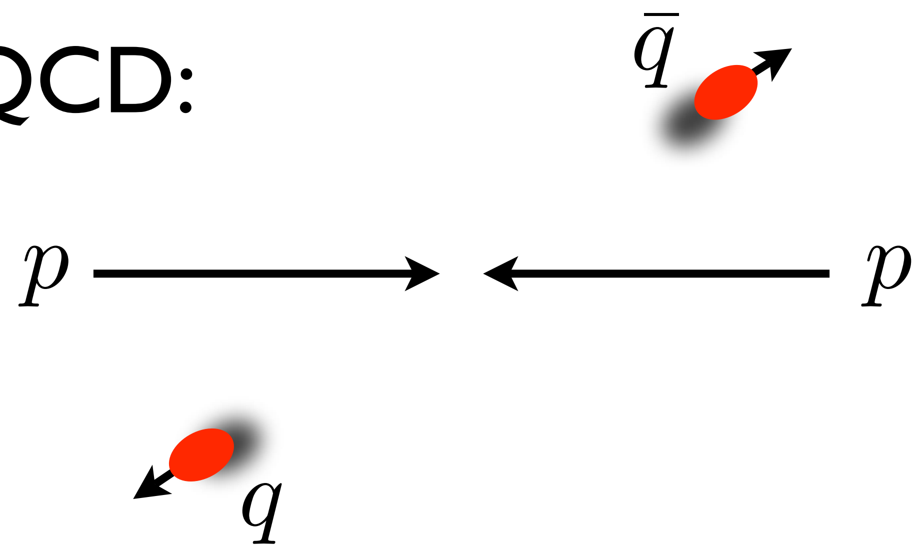
LEP bounds

QCD scales are related by the Z_2.

* There are no squarks bellow the QCD scale. Qualitatively different behavior at a collider. [Bjorken (79), Quinn and Gupta (81)]

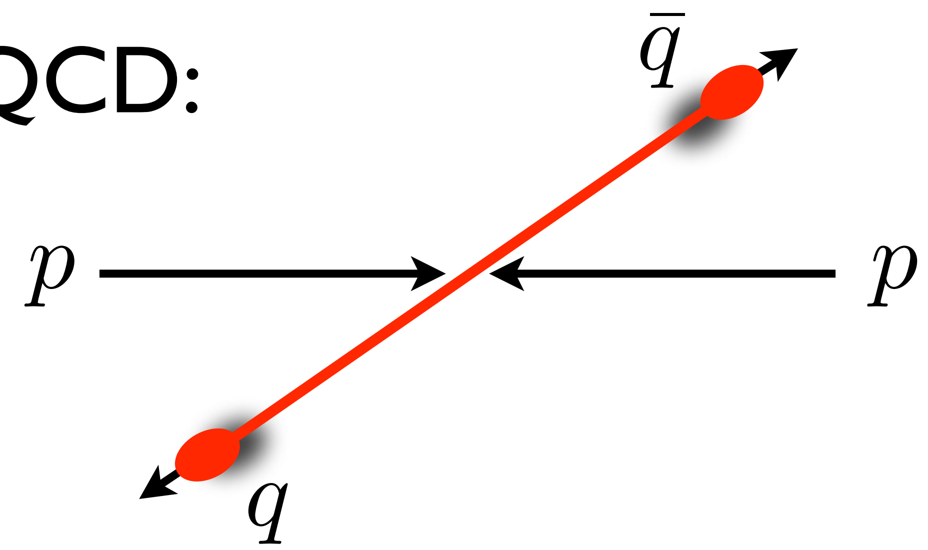
Squirks

* In regular QCD:



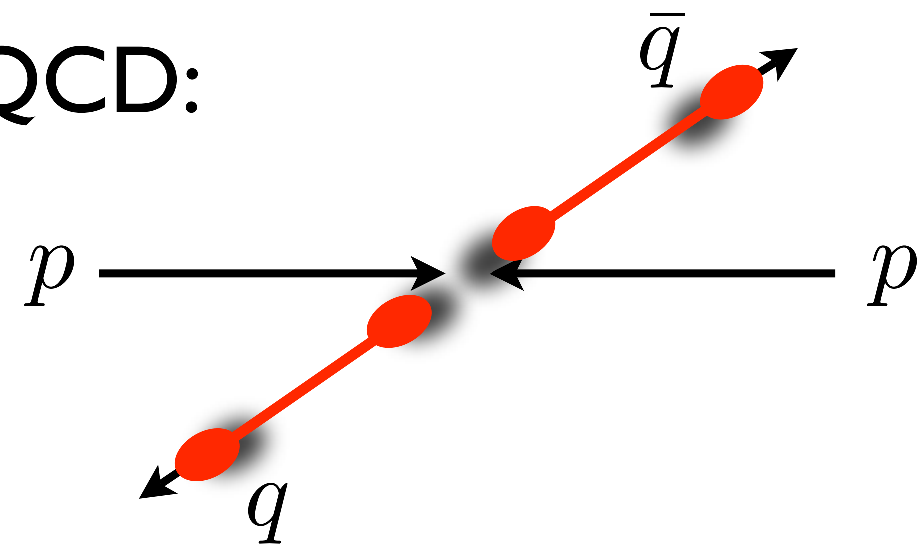
Squirks

* In regular QCD:



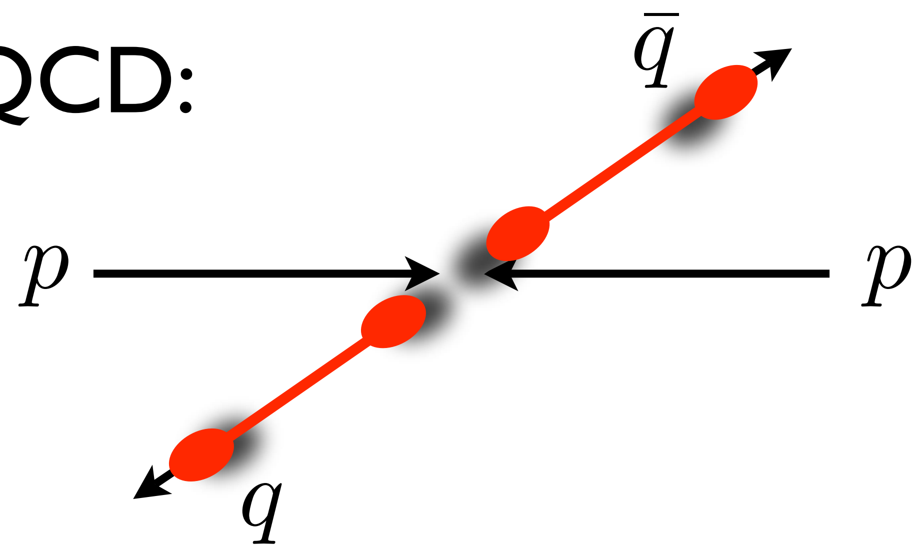
Squirks

* In regular QCD:

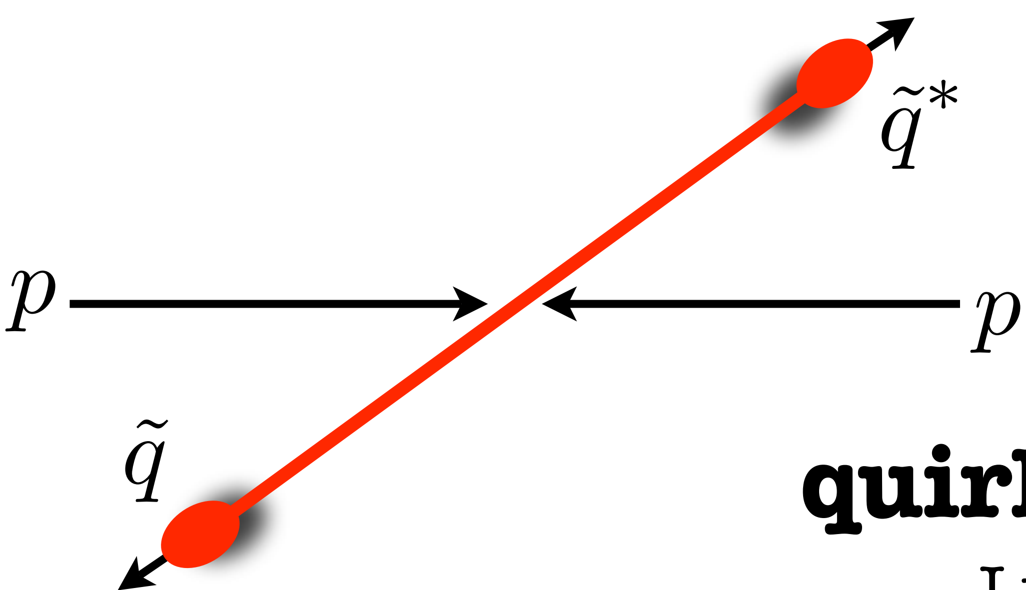


Squirks

- In regular QCD:



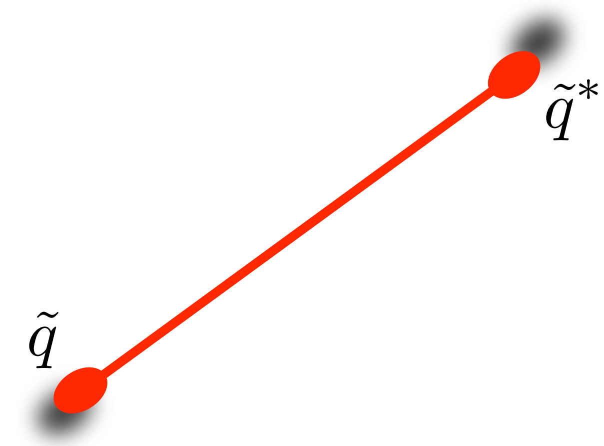
- In "quirky QCD" this costs too much energy. squarks' are produced and **remain bound**!



quirks (or **squirks**, rather) -

Luty et al, Strassler and Zurek.

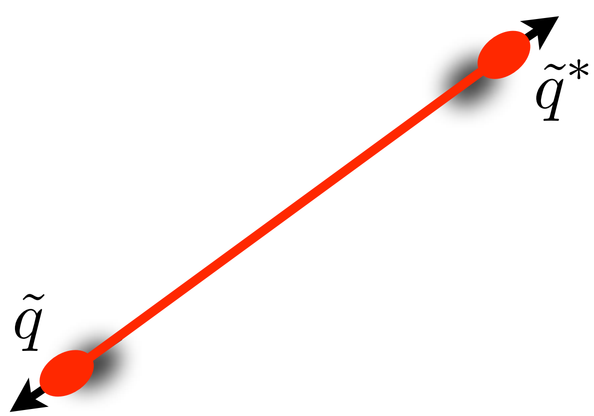
Quirky Dynamics



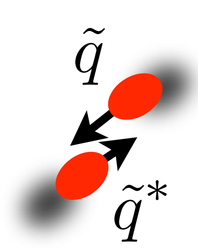
- The squirks eventually stop.
  come back.
  oscillate.

- This system will loose energy by radiation.

$$\omega \sim \frac{\Lambda^2}{m_{\tilde{q}}} \ll \Lambda \sim m_{\rm glue}$$



Soft:
photon dominated



Hard:
glueball dominated.

(decreases with impact parameter!)

Photons vs. Glue

* Can we guesstimate $E_\gamma / E_{\rm glue}$?
  - Suppose the photon was massive: $m_\gamma \sim m_{\rm glue}$

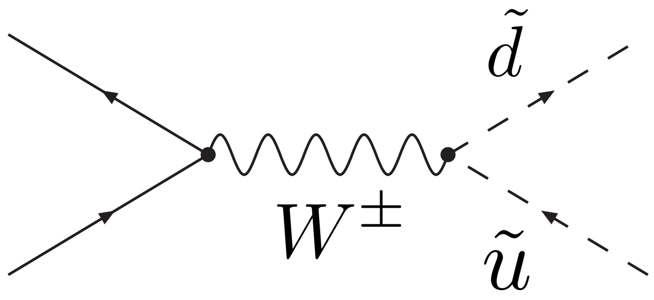
    We'd expect $\dfrac{E_\gamma}{E_{\rm glue}} \sim \dfrac{\alpha(m_\gamma)}{\alpha_{s'}(m_{\rm glue})} \sim \dfrac{1}{20}$.

  - **But** photon does not have a mass!
    The kinematic suppression due to the mass depends on impact parameter and energy. May easily be a factor few

$$\frac{E_{\rm soft}}{E_{\rm hard}} \sim \frac{m_{\tilde{q}} \Lambda^2 b^3}{\alpha_{s'}^2}$$

An Event

- Consider squirk production via a W:

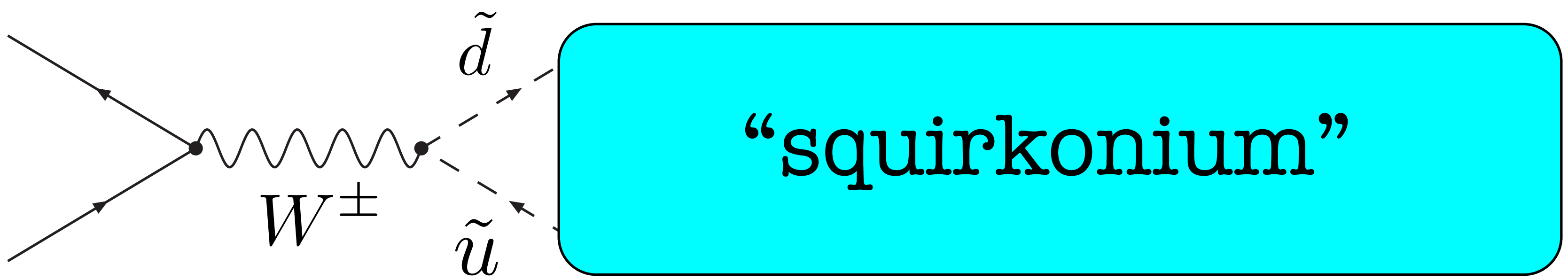


Ongoing work w/ Wizansky.

Ongoing work w/ Burdman et al

An Event

* Consider squirk production via a W:

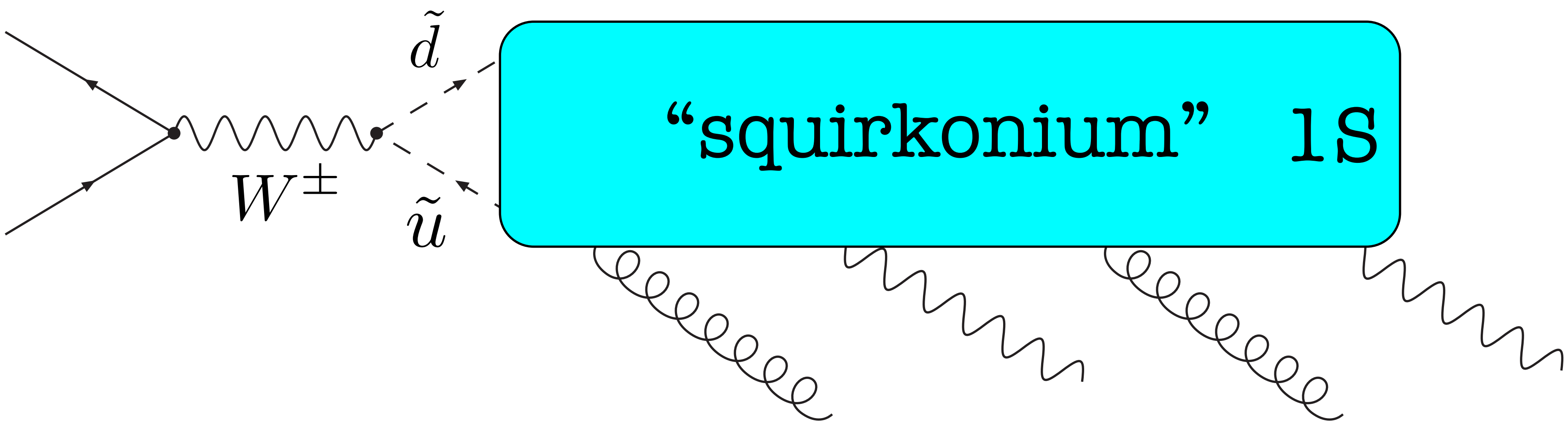


Ongoing work w/ Wizansky.

Ongoing work w/ Burdman et al

An Event

* Consider squirk production via a W:

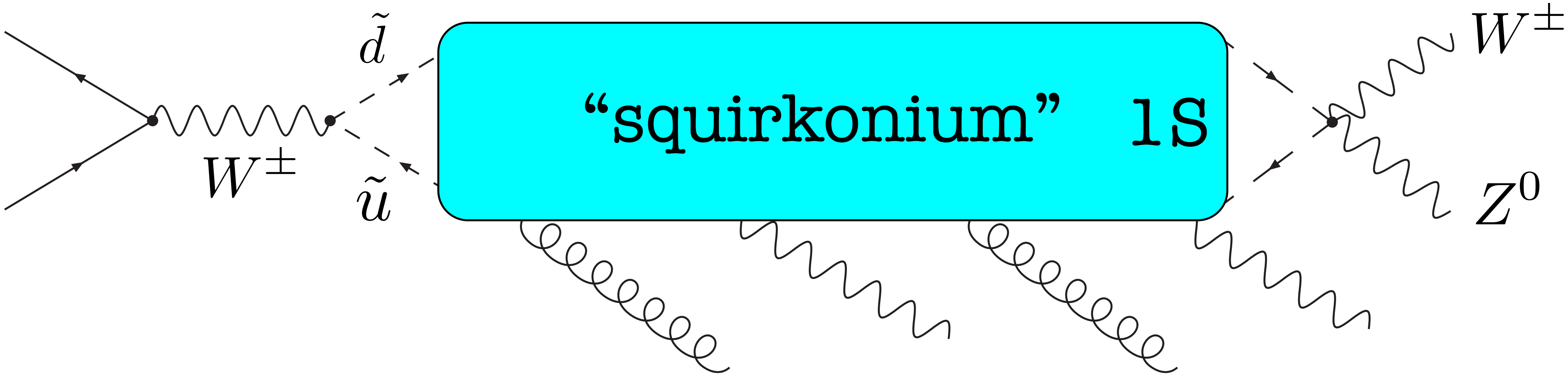


Ongoing work w/ Wizansky.

Ongoing work w/ Burdman et al

An Event

* Consider squirk production via a W:

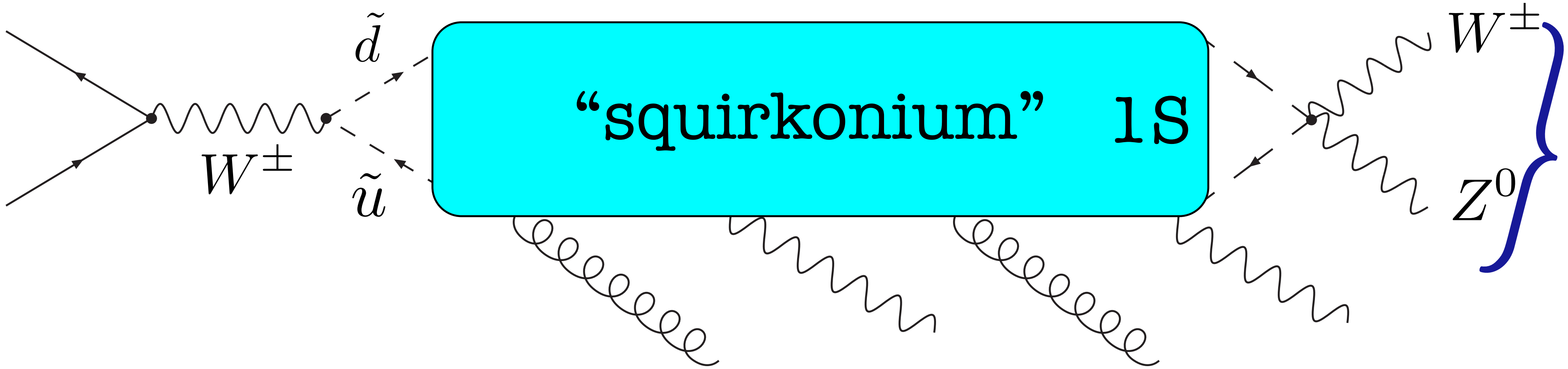


Ongoing work w/ Wizansky.

Ongoing work w/ Burdman et al

An Event

* Consider squirk production via a W:



A **peak** in the invariant mass of W+Z

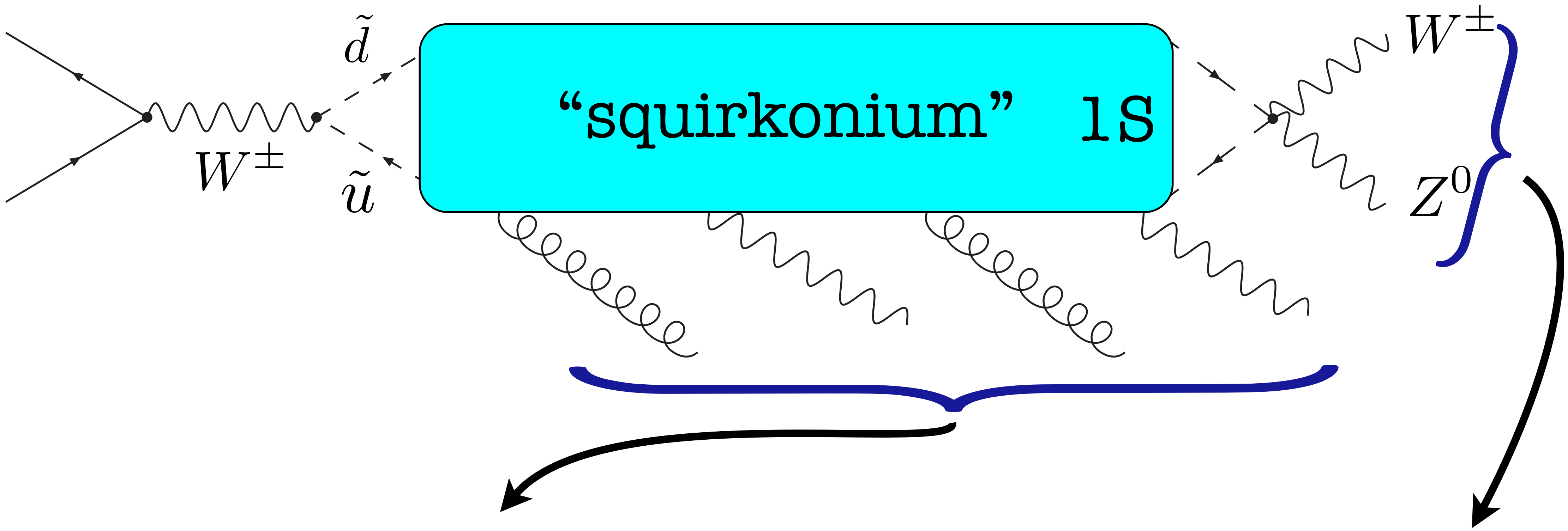
$$m_{WZ}^2 = m_{1\text{S}}^2 \sim 4m_{\tilde{q}}^2$$

Ongoing work w/ Wizansky.

Ongoing work w/ Burdman et al

An Event

* Consider squirk production via a W:



Soft radiation of **photons** and (hidden) glueballs

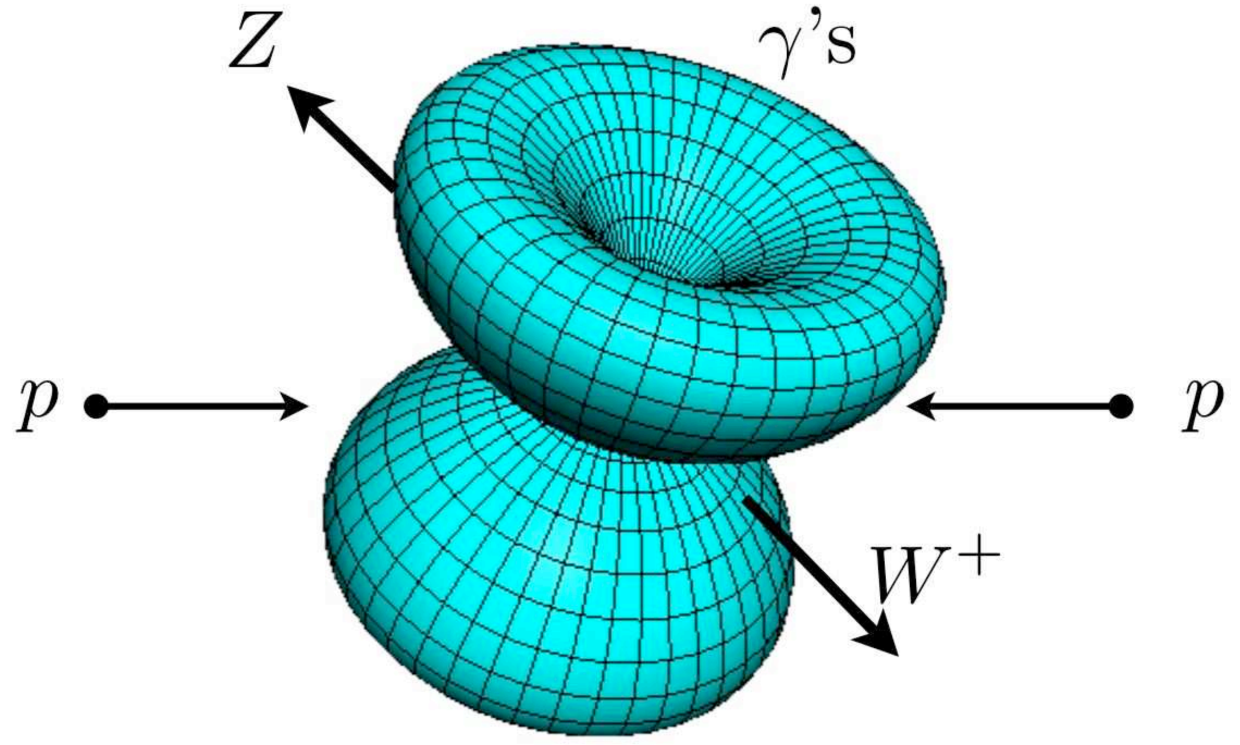
A **peak** in the invariant mass of W+Z

$$m_{WZ}^2 = m_{1S}^2 \sim 4m_{\tilde{q}}^2$$

Ongoing work w/ Wizansky.

Ongoing work w/ Burdman et al

An Event

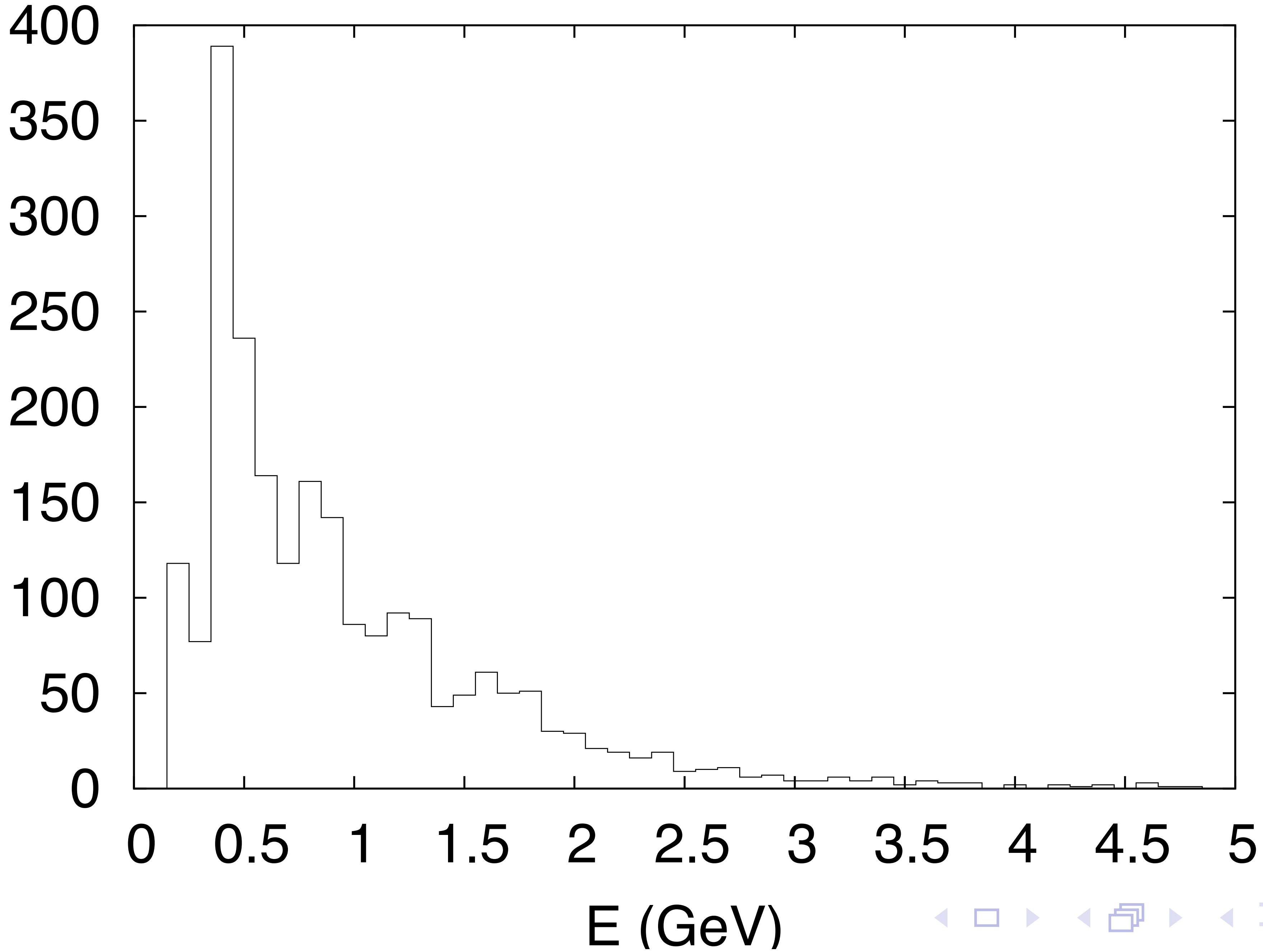


$$E_\gamma \sim \frac{\Lambda^2}{\sqrt{\hat{s}}} \sim \frac{\Lambda^2}{m_{\tilde{q}}}$$

$$\sim 0.1 \text{ - } 1 \text{ GeV}$$

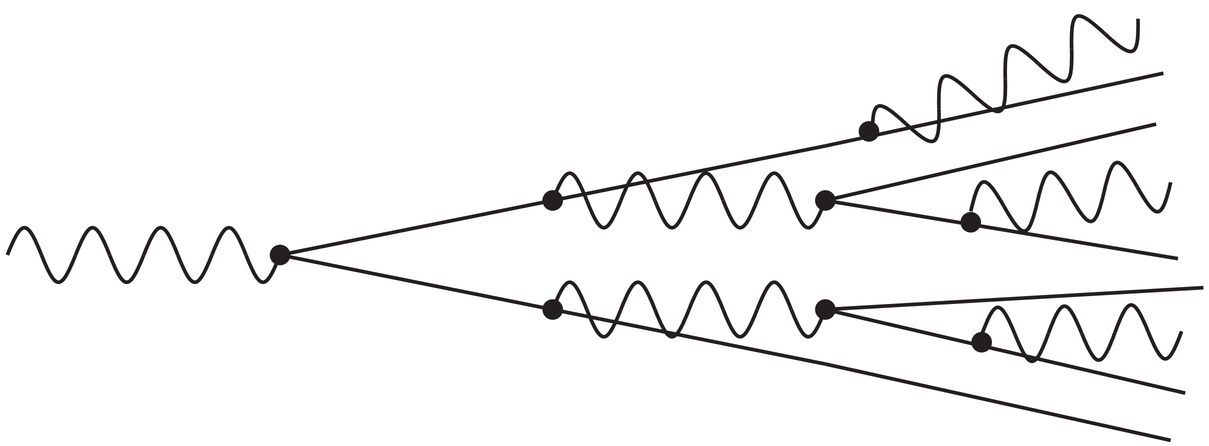
Can we see such soft photons?
Isn't there plenty of soft background?
Is the "antenna pattern" visible?
(This is not what the detectors were designed for!)

Photon Spectrum

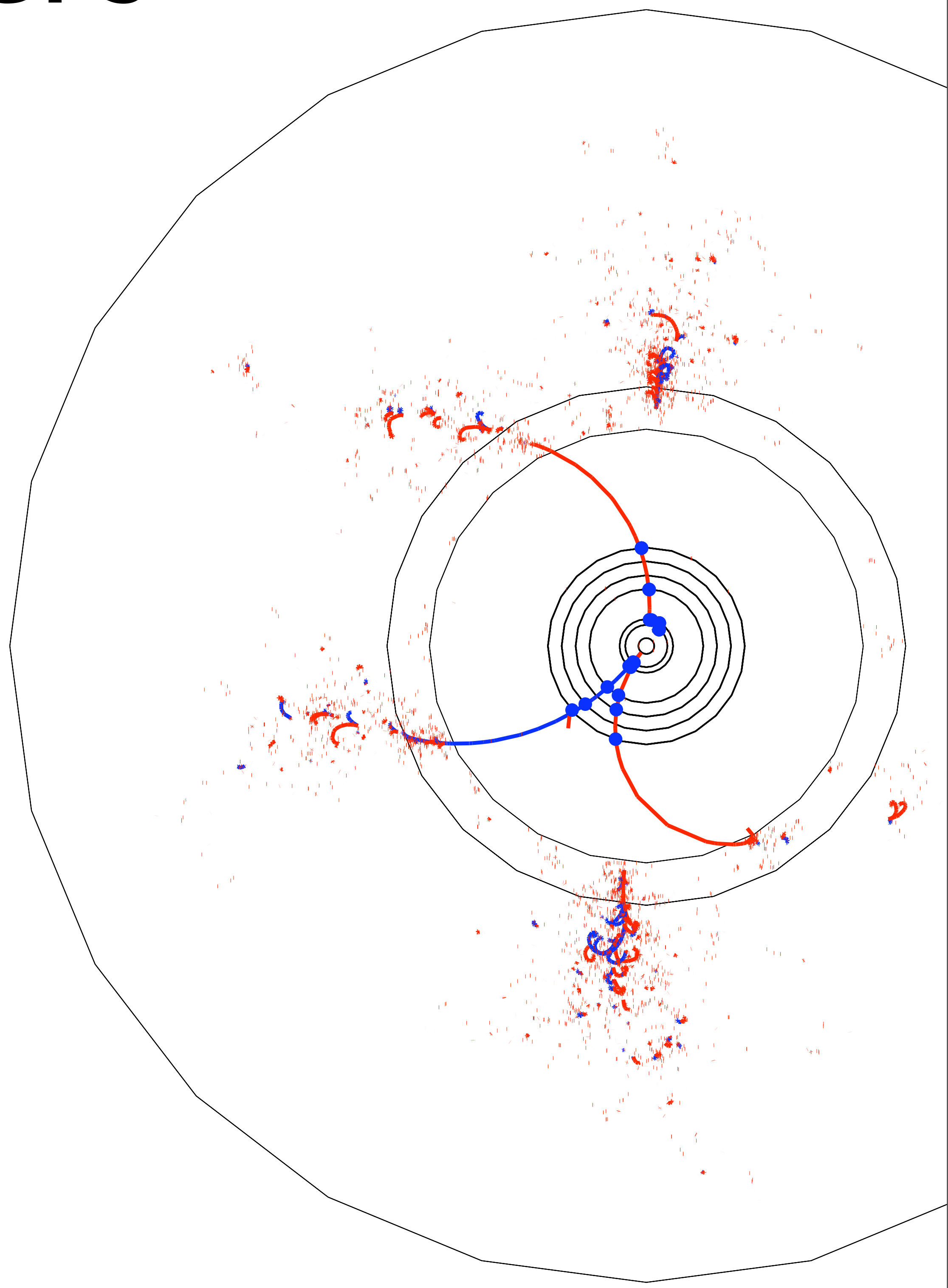


EM Showers

* Soft photons initiate EM showers in the detector.

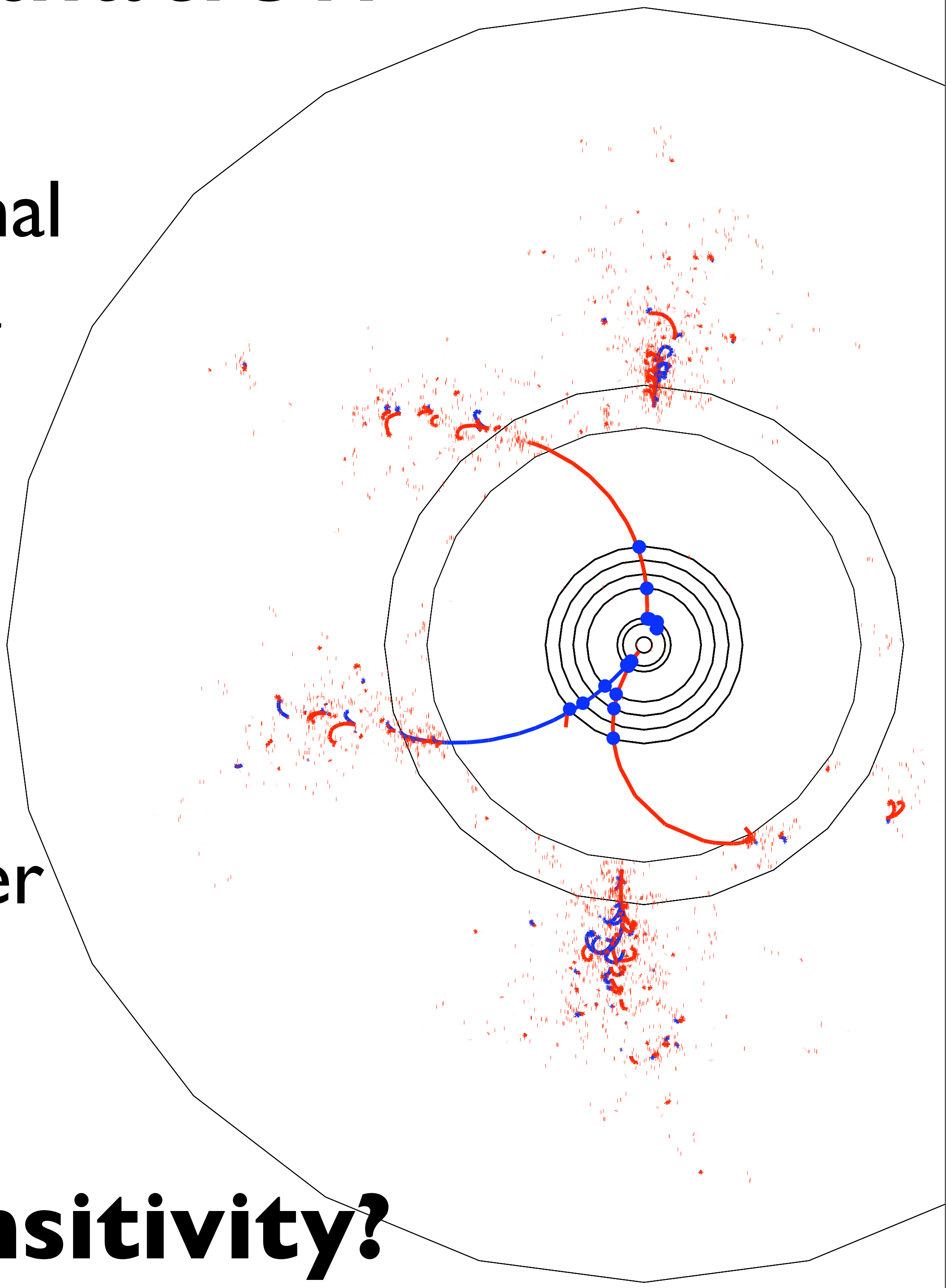


* A naive estimate:
  - ~30% of photons convert to electron-positron pair in tracking system.
  - ~50% of energy reaches Ecal.



Detector Simulation

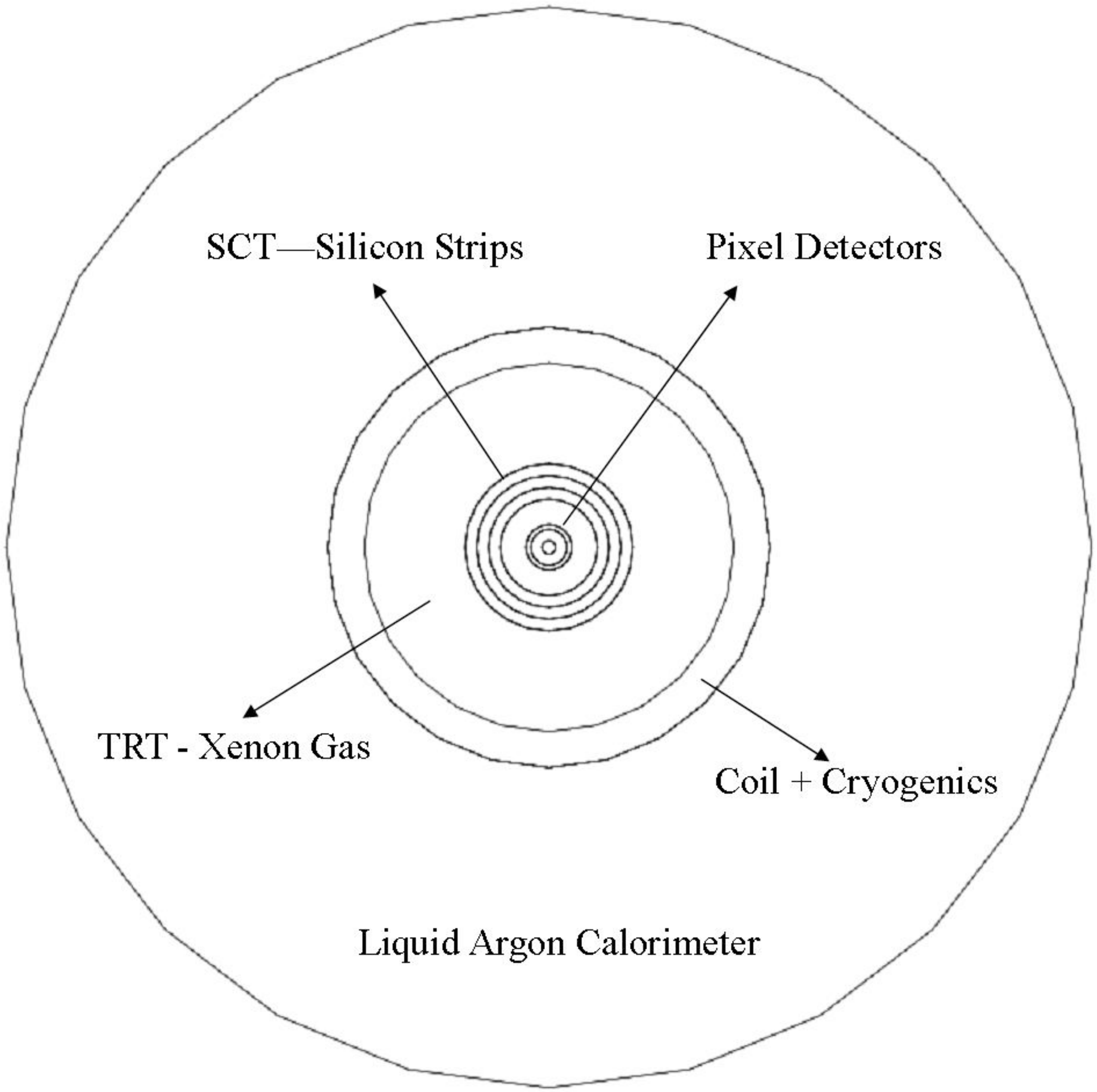
* We simulated the photon signal according to a simple antenna model.
* Analyze soft photons with a dedicated simulation of a "toy detector" (using GEANT4).
* Take $E_\gamma/E_{\rm glue}$ as a parameter (can change event by event).

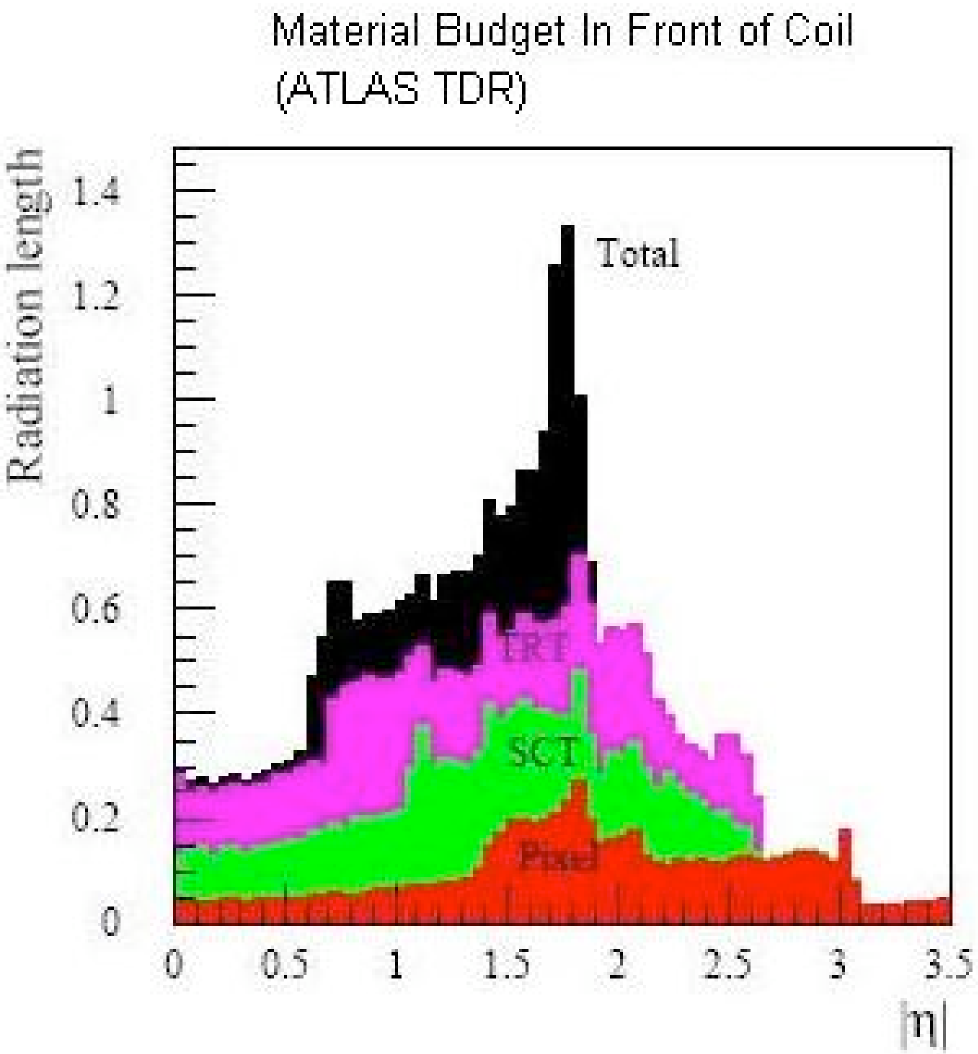


what is the sensitivity?

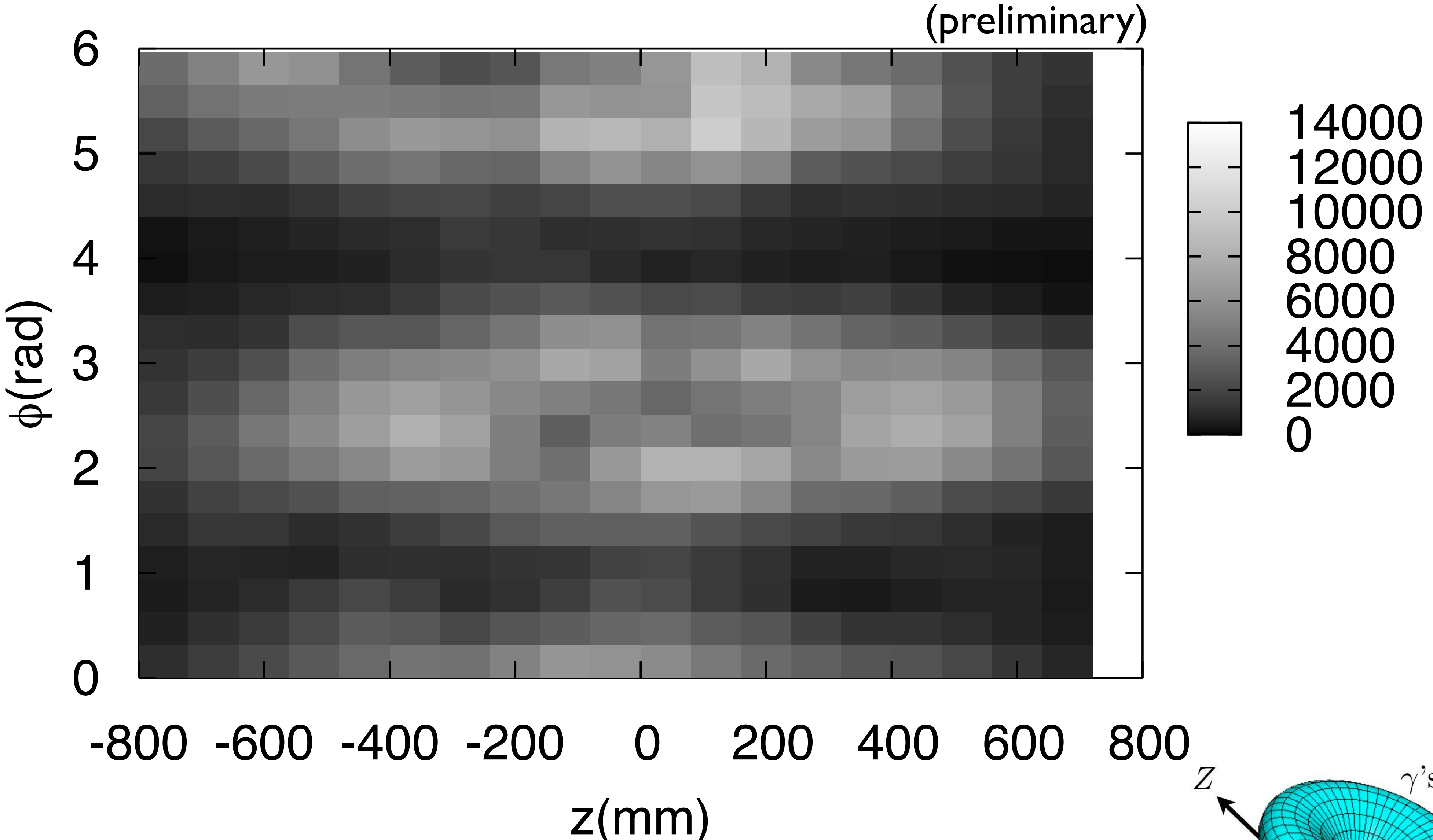
what are the backgrounds? min-bias? pile-up? etc.

PBS

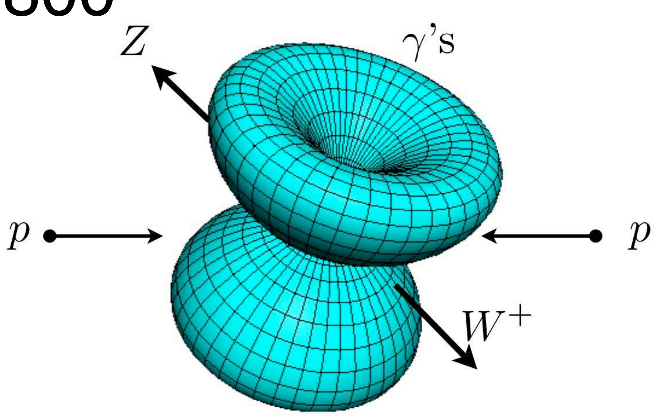

SCT—Silicon Strips
Pixel Detectors
TRT - Xenon Gas
Coil + Cryogenics
Liquid Argon Calorimeter


Material Budget In Front of Coil
(ATLAS TDR)
Radiation length
Total
TRT
SCT
Pixel
|η|

Pattern Recognition

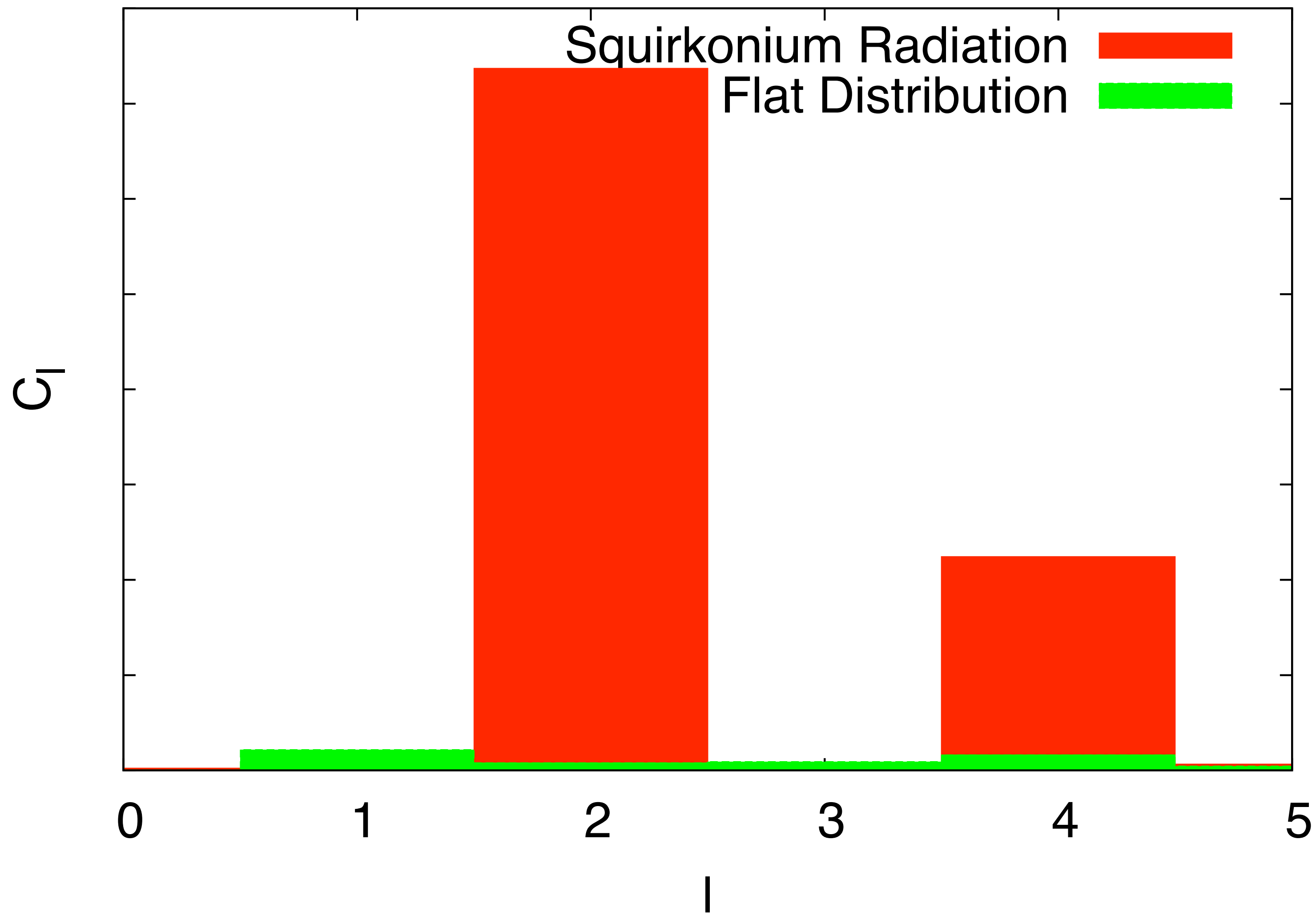


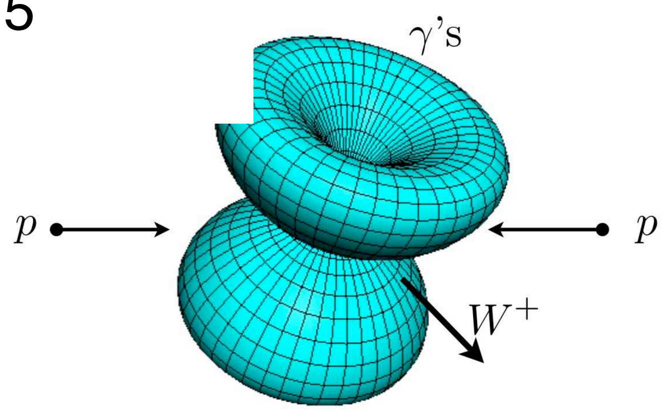
The pattern is visible!



Pattern Recognition

$$C_l = \frac{\sum_m |a_l^m|^2}{2l+1}; \qquad a_l^m = \int d\Omega E(\Omega)(Y_l^m(\Omega))^*$$





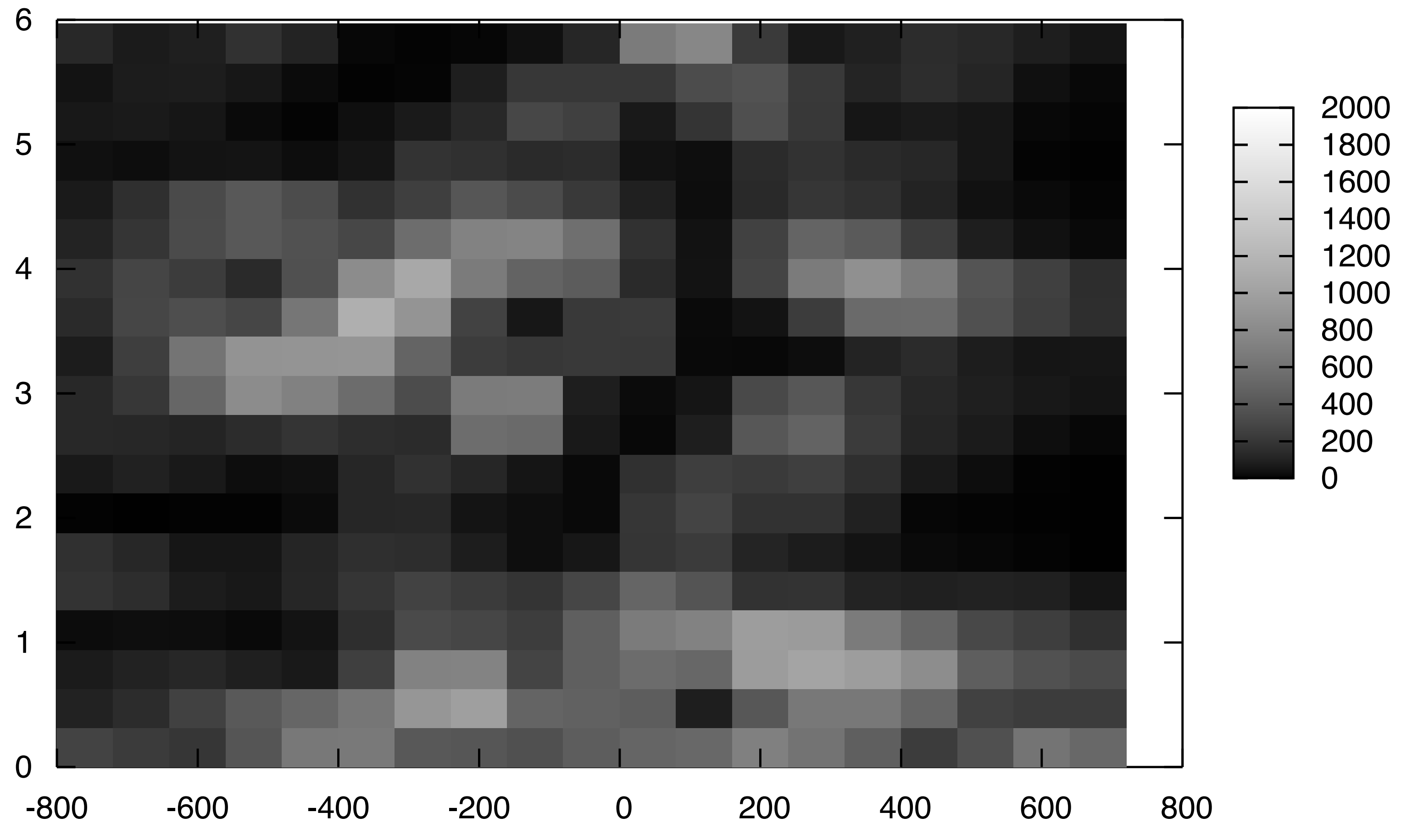
Angular distribution distinct from the background.

Work in Progress...

* Preliminary:

$$\frac{E_\gamma}{E_{\text{glue}}} \sim 10\%$$

may be enough to beat background



SUSY vs F-SUSY

* Typical SUSY discovery signal:
  - Squarks and gluinos are **strongly** produced.
  - Cascade to jets and/or leptons plus large $\not{E}_T$.
  - May quickly stand above backgrounds.

---

* Folded SUSY signal:
  - Superpartners are **weakly** produced.
  - Heavy resonances in WZ plus soft photons.
  - Soft photons could help distinguish from background.
  - Requires looking at very different observables.

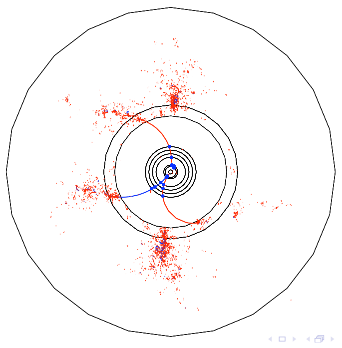
Conclusion

LHC:
Discovery will require dedicated searches for specific signals.

Motivates searching for new solutions to old problems:
UnColored top partners
for EW naturalness.

String inspired model-building
gives SUSY-type naturalness with uncolored squarks.

Unconventional signals:
Squirks, soft photons,
...



A good time for interplay between theory and experiment.

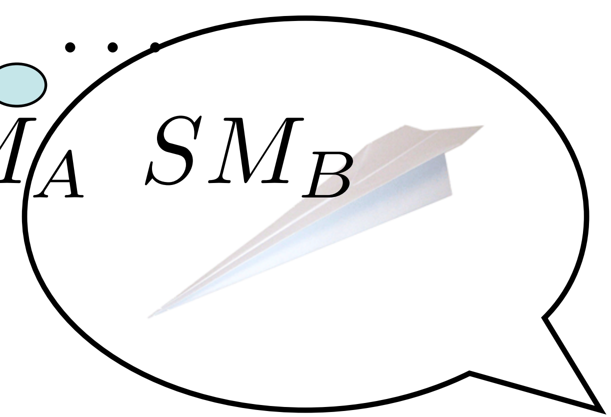
EXTRA SLIDES

$\hat{Q}_A \ \hat{Q}_B$

$\hat{U}_A \ \hat{U}_B$

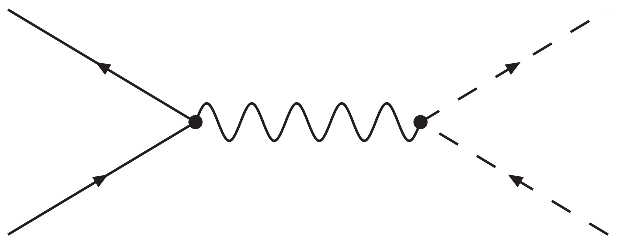
$\ldots$

$SM_A \ SM_B$

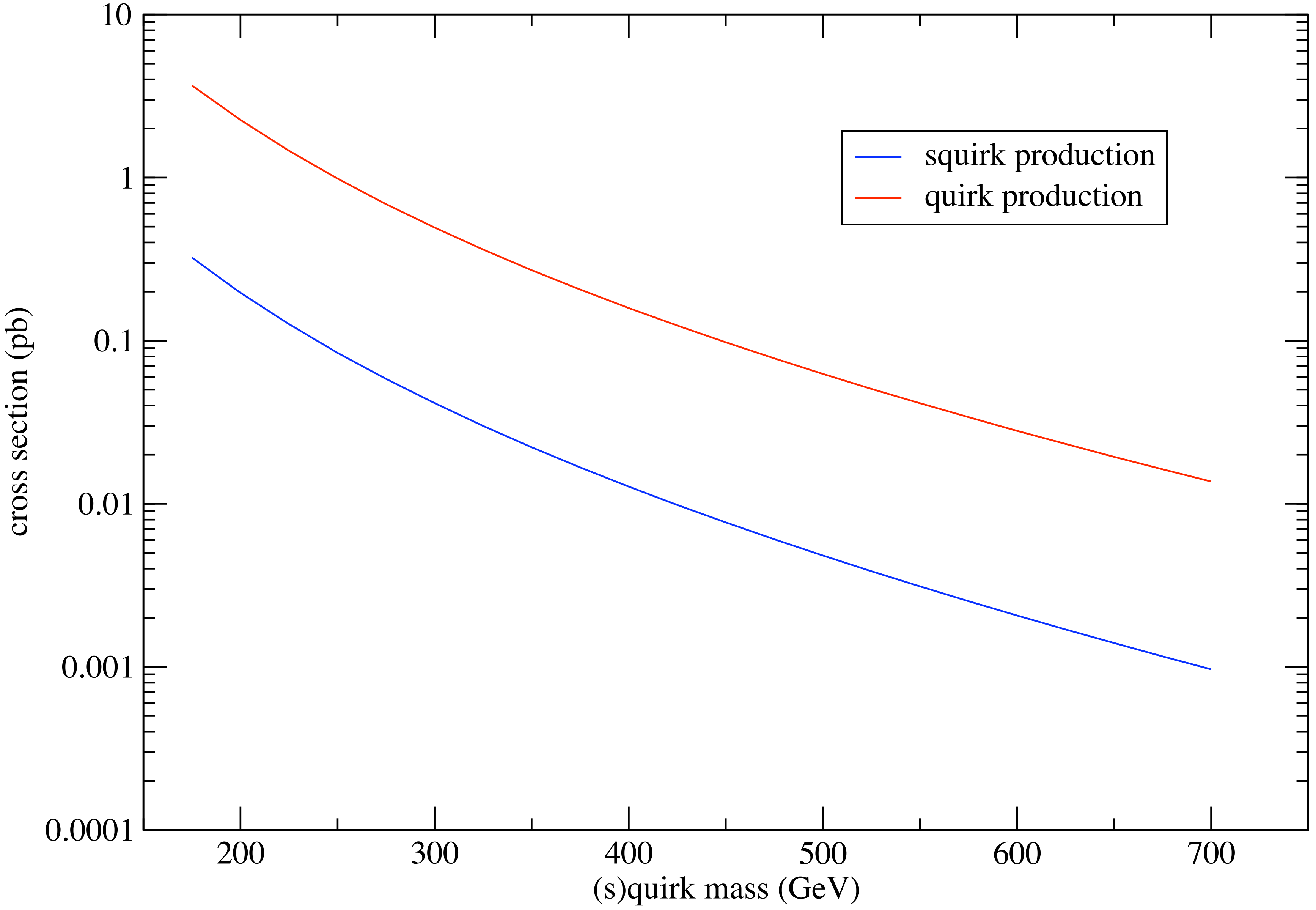


bla bla bla opposite spin cancelation without identical quantum numbers!

LHC Signals

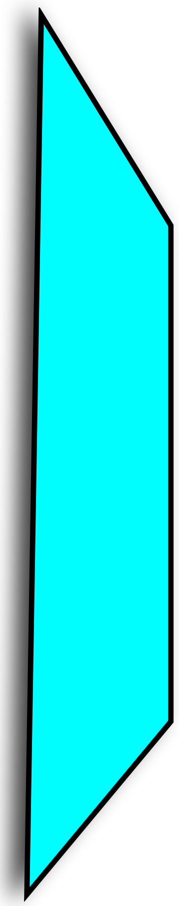


* Squarks' are produced via Drell-Yan or VBF.

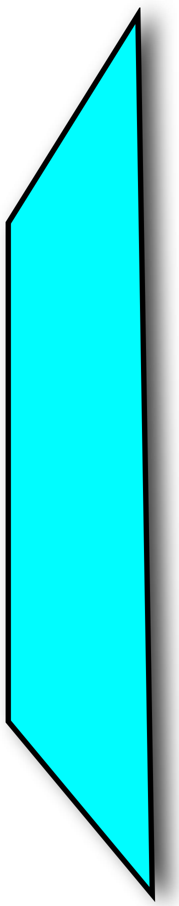


Assignments

$$\hat{Q}_A = (Q_A, Q_A^c) \qquad \hat{Q}_B = (Q_B, Q_B^c)$$

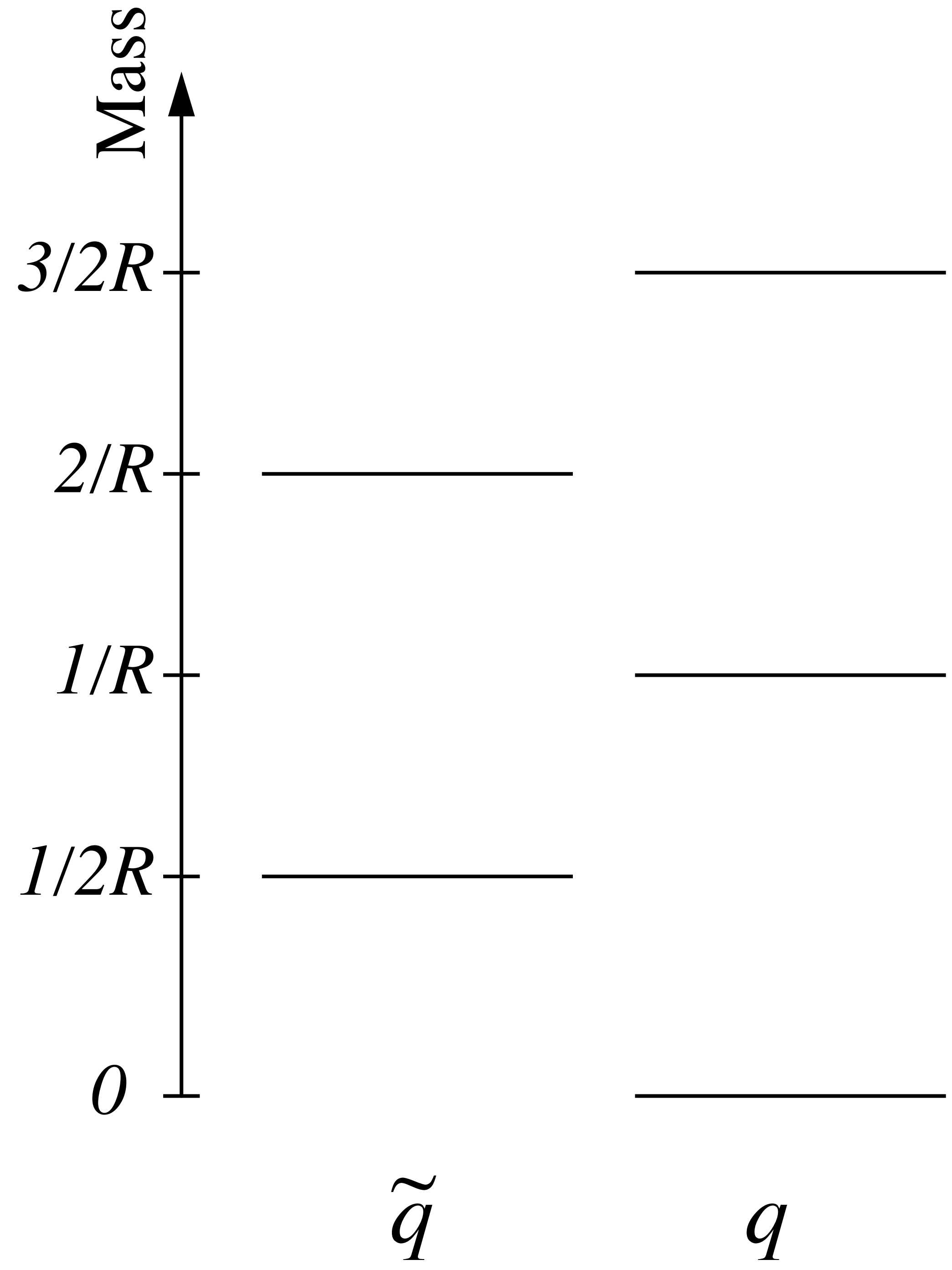


Z_2'	Z_2
$+:\ Q_A' = \begin{pmatrix} \tilde{q}_A^{c*} \\ q_A \end{pmatrix}$ $-:\ Q_A^{c\prime} = \begin{pmatrix} \tilde{q}_A^{*} \\ q_A^c \end{pmatrix}$	$+:\ Q_A = \begin{pmatrix} \tilde{q}_A \\ q_A \end{pmatrix}$ $-:\ Q_A^{c} = \begin{pmatrix} \tilde{q}_A^{c} \\ q_A^c \end{pmatrix}$
$+:\ Q_B' = \begin{pmatrix} \tilde{q}_B \\ \bar{q}_B^c \end{pmatrix}$ $-:\ Q_B^{c\prime} = \begin{pmatrix} \tilde{q}_B^{c} \\ \bar{q}_B \end{pmatrix}$	$+:\ Q_B = \begin{pmatrix} \tilde{q}_B \\ q_B \end{pmatrix}$ $-:\ Q_B^{c} = \begin{pmatrix} \tilde{q}_B^{c} \\ q_B^c \end{pmatrix}$



Sherk-Schwartz +

SS SUSY breaking produces a staggered KK tower.



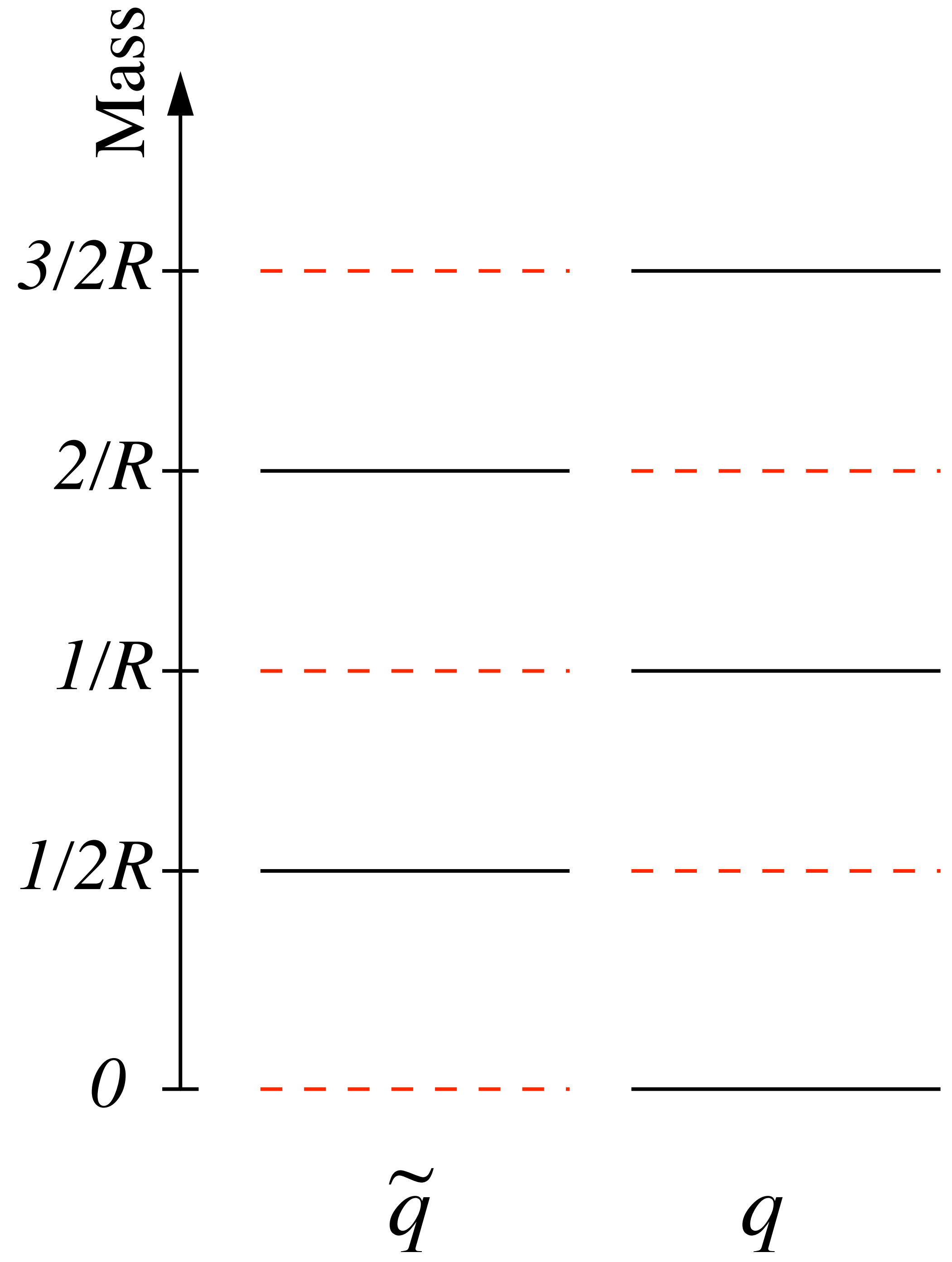
Sherk-Schwartz +

SS SUSY breaking produces a staggered KK tower.

In our model the tower is supplemented to give the Higgs a “supersymmetric feeling”.

At tree level $m_H^2 = 0.$

Cancelation occurs one KK level at a time.



Twin Higgs.

(Chacko, Goh ,RH)

The Mechanism

(Chacko, Goh ,RH)

* Consider two SM's: $\mathrm{SM}_A \times \mathrm{SM}_B$

* Impose a Z_2 : $A \longleftrightarrow B$

  The only gauge$\times Z_2$ quadratic operator

$$H_A^\dagger H_A + H_B^\dagger H_B$$

  is invariant under an SU(4) with $\begin{pmatrix} H_A \\ H_B \end{pmatrix} = 4.$

* The Higgs is a pseudo-Goldstone boson

$$SU(4) \rightarrow SU(3)$$

SM × SM

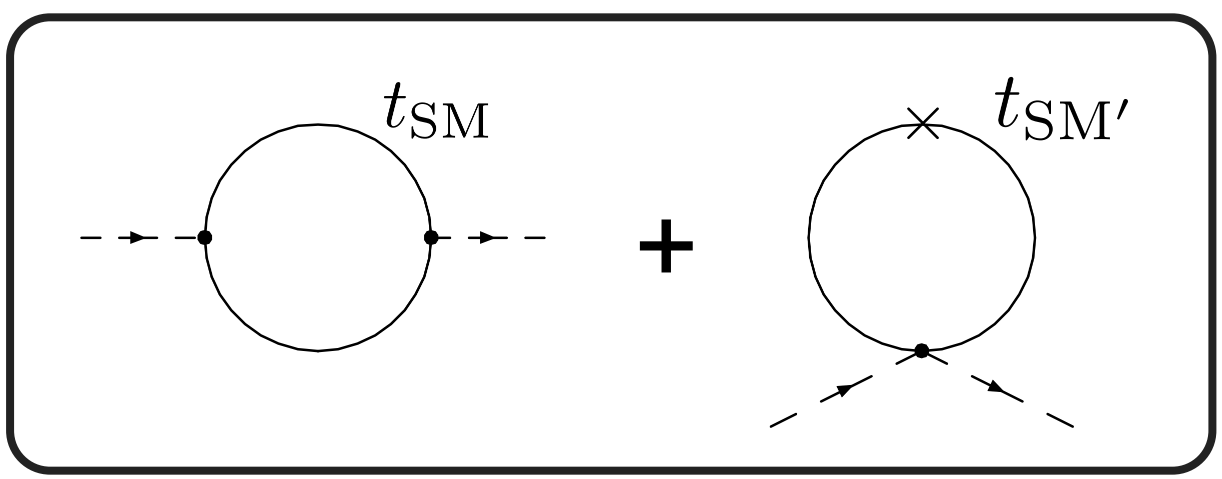
* At high energies the Higgs interaction respect Z_2

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

* Loops only contribute to $H_A^\dagger H_A + H_B^\dagger H_B$ SU(4) invariant!

---

* Alternatively:



Cancelation guaranteed by Z_2

All new physics is in SM singlets

“Striking” LHC Signals

* A standard model Higgs.

“Striking” LHC Signals

* A standard model Higgs.
* After several years we can hope to measure-
  - Higgs decay to invisibles, $\mathrm{BR} \sim O(v^2/f^2)$.
  - Modification of $ZZh, WWh, tth, h^3, \ldots$ also of $O(v/f)$. (correlations).

“Striking” LHC Signals

* A standard model Higgs.
* After several years we can hope to measure-
  - Higgs decay to invisibles, $\mathrm{BR} \sim O(v^2/f^2)$.
  - Modification of $ZZh, WWh, tth, h^3, \ldots$ also of $O(v/f)$. (correlations).
* If we are *really* lucky:

  Twin hadrons decay back to SM with displaced vertices. A “Hidden Valley” signal (Strassler and Zurek).

Finite ~~SUSY~~

* one loop squarks, sleptons get finite soft masses

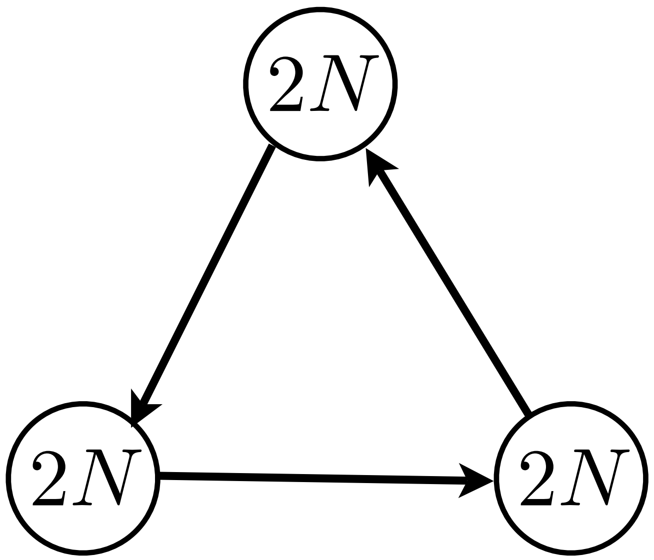
$$
\begin{aligned}
m_Q^2 &= \mathrm{K}\,\frac{1}{4\pi^4}\left(\frac{4}{3}g_3^2+\frac{3}{4}g_2^2+\frac{1}{36}g_1^2\right)\frac{1}{R^2}\\
m_U^2 &= \mathrm{K}\,\frac{1}{4\pi^4}\left(\frac{4}{3}g_3^2+\frac{4}{9}g_1^2\right)\frac{1}{R^2}\\
m_D^2 &= \mathrm{K}\,\frac{1}{4\pi^4}\left(\frac{4}{3}g_3^2+\frac{1}{9}g_1^2\right)\frac{1}{R^2}\\
&\ldots
\end{aligned}
$$

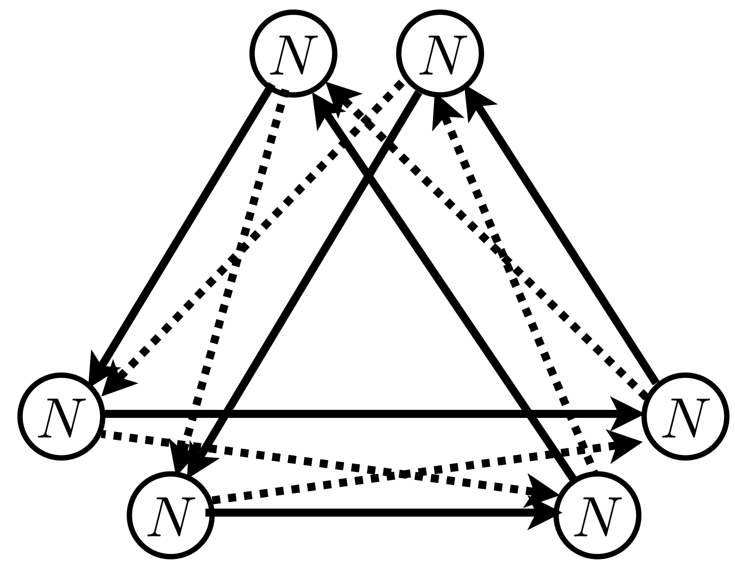
* Higgs mass parameter generated at two-loops from top and at one-loop from gauge.

$$\delta m_H^2|_{\rm top} \approx -\frac{3\lambda_t^2}{4\pi^2}\tilde{m}_t^2\,\log\left(\frac{1}{R\,\tilde{m}_t}\right)$$

$$\delta m_H^2|_{\rm gauge} = \mathrm{K}\,\frac{3g_2^2+g_1^2}{16\pi^4}\frac{1}{R^2}$$

Example II - Yukawas

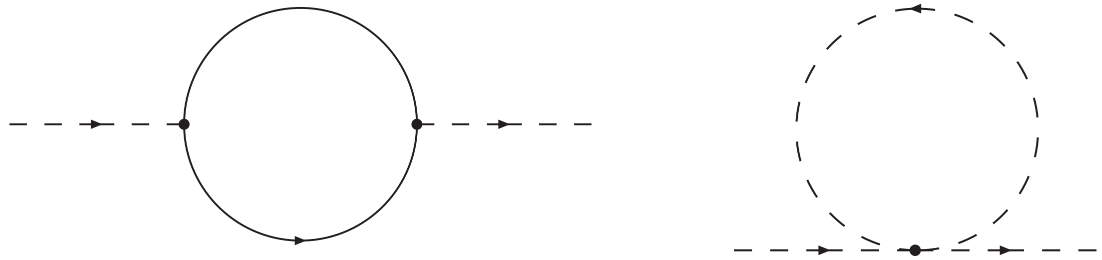




$$\lambda\, Q_{12}\, Q_{23}\, Q_{31}$$

$$\left[\ \sqrt{2}\lambda\ \tilde{q}_{1A,2A}\ q_{2A,3B}\ q_{3B,1A}\ +\ \mathrm{h.c.}\right]\ +$$
$$2\ \lambda^2\ |\tilde{q}_{1A,2A}|^2\ |\tilde{q}_{3A,1A}|^2 + 2\ \lambda^2\ |\tilde{q}_{1A,2A}|^2\ |\tilde{q}_{2A,3A}|^2$$

radiative corrections to all masses are canceled by exotics.



But...

* Pervious example has bi-fundamentals.

  SM does not. :-(

* SM is not quite at large N. :-(

* Recall-
  We are aiming at solving the Little hierarchy problem.

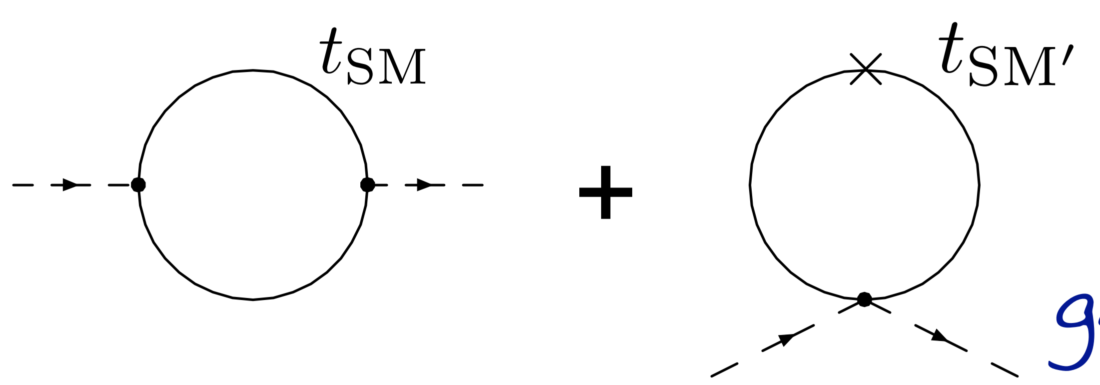
  - Only one loop.
  - Only the Higgs needs protection.
  - Problem is numerically little, but is important (LHC).

SM × SM

(Chacko, Goh ,RH)

* The whole SM has a mirror copy.

$$\mathcal{L} \supset y_t \underbrace{H_A}_{\downarrow\; h + \dots} \bar{t}_A t_A + y_t \underbrace{H_B}_{\downarrow\; f - \frac{h^2}{2f} + \dots} \bar{t}_B t_B$$

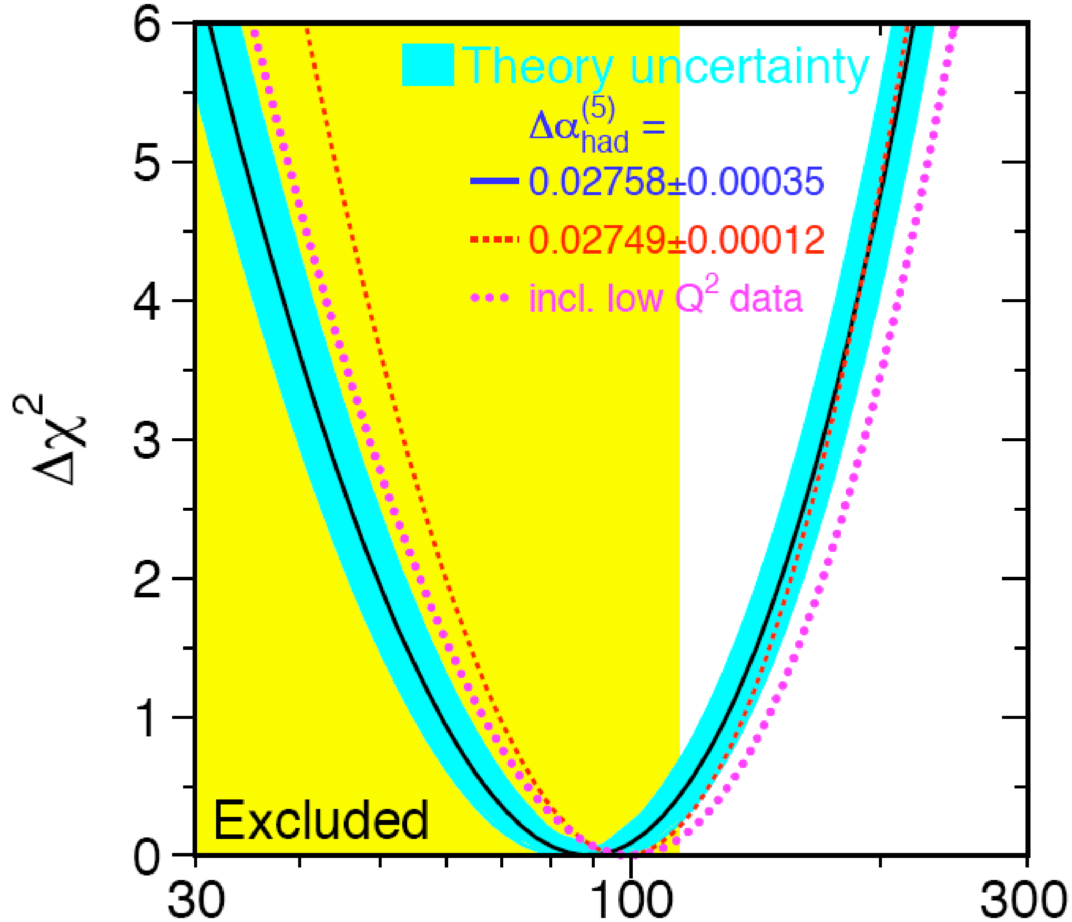


Cancelation guaranteed by Z_2

All new physics is in SM singlets

LEP's legacy for LHC

Barbieri, Strumia



Dimensions six operators			$m_h = 115$ GeV $c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB}$	=	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10
$\mathcal{O}_{H}$	=	$\lvert H^\dagger D_\mu H \rvert^2$	4.6	5.6
$\mathcal{O}_{LL}$	=	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1
$\mathcal{O}'_{HL}$	=	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	8.4	8.8
$\mathcal{O}'_{HQ}$	=	$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	6.6	6.8
$\mathcal{O}_{HL}$	=	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	7.3	9.2
$\mathcal{O}_{HQ}$	=	$i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	5.8	3.4
$\mathcal{O}_{HE}$	=	$i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	8.2	7.7
$\mathcal{O}_{HU}$	=	$i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	2.4	3.3
$\mathcal{O}_{HD}$	=	$i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	2.1	2.5

SM Higgs seems to be light.

No sign of NP up to $\Lambda \sim 5 - 10\,\mathrm{TeV}$

"paradox"!?

F-sleptons

* F-sleptons are stable. A problem for cosmology.
* Add:

$$\delta(y) \int d^2\theta \left(\frac{Q_A Q_A Q_A L_B}{\Lambda} + \frac{Q_B Q_B Q_B L_A}{\Lambda} \right)$$

* F-sleptons decay to 3 jets+ missing energy.
* F-baryons decay to leptons, but not vice-versa.

Uncolored Top Partners ?

Can top partners be uncolored?
The impact on LHC performance, and how we interpret its results is profound!

* The **twin Higgs** is a counter example:
Higgs may be protected by a **discrete** symmetry

$$(\text{top})_i \longrightarrow (\text{top}')_{i'}$$

*** For the purpose of the LHC, only the 'little hierarchy' may be addressed. Protection only at 1-loop.*

Twin Mechanism

Protecting the Higgs with a discrete symmetry

Chacko, Goh, RH

A Toy Example

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

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

$$\Downarrow$$

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

$$\Downarrow$$

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

7 Goldstones

SU(2)$_A$×SU(2)$_B$

* Gauge a subgroup

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

$\swarrow$ our SM $\qquad$ $\searrow$ twin SM

* In some basis, H transforms as

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

6 eaten.
1 Goldstone left.

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

The Mechanism

* Impose a Z_2: $A \longleftrightarrow B$

  The only gauge $\times Z_2$ quadratic operator is

  $$H_A^\dagger H_A + H_B^\dagger H_B$$

  SU(4) invariant!

* If Z_2 is preserved at low energies, radiative corrections will only generate this operator.

No mass for the Goldstone.

Left-Right Model

Chacko, Goh ,RH, hep-ph/0512088

* The twin mechanism can be embedded in an $SU(2)_L \times SU(2)_R$ structure.
* Top partners *are* colored.
* Exciting LHC signals.   :-)

Do We Care?

SM Higgs seems to be light.

No new physics up to $\Lambda \sim 5 - 10\,\mathrm{TeV}$

There are new light states below Λ.

but

They do not contribute to precision EW.

Do We Care?

SM Higgs seems to be light.

No new physics up to $\Lambda \sim 5 - 10\,\mathrm{TeV}$

There are new light states below Λ.

but

They do not contribute to precision EW.

New light states just beyond EW scale:
Directly determines NP at LHC.

Radiative Corrections

* At 1-loop:

$$\Delta V =$$

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

$\Longrightarrow \quad g_A = g_B$

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

SU(4) invariant!

Does not give a Goldstone mass.

Radiative Corrections

* At 1-loop:

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

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

$\Longrightarrow$ $g_A = g_B$

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

SU(4) invariant!

Does not give a Goldstone mass.

Radiative Corrections

* At 1-loop:

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

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

$\Longrightarrow$ $g_A = g_B$

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

SU(4) invariant!

Does not give a Goldstone mass.