The MiniLandscape and the 750 GeV Di-Photon Challenge

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Strings and Particle Physics

String theory provides us with

- gauge groups, matter multiplets for quarks and leptons,
- discrete symmetries.

The MSSM is not a generic prediction of string theory:

- need exploration of the "Landscape" at non-generic points with higher symmetries
- that provide enhanced discrete (R)-symmetries.
- R-symmetries as extension of supersymmetry

The geometry of compactified space (and its symmetries) is a crucial ingredient for successful model building.

The 750 GeV Di-Photon Challenge

The MiniLandscape contains "heavy" particles

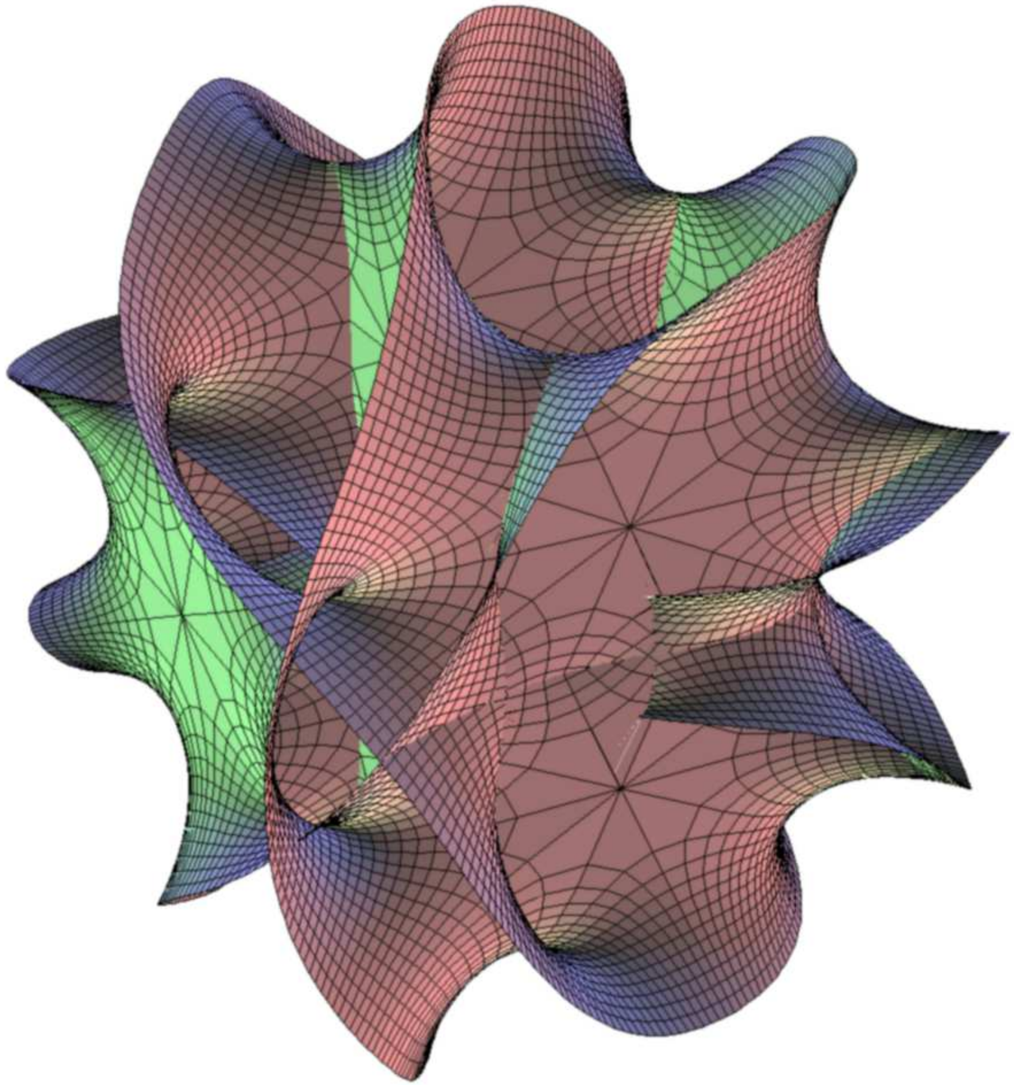
- vector-like pairs of quarks and leptons
- standard model singlets
- additional $U(1)$ gauge bosons

This poses the question concerning the new mass scales

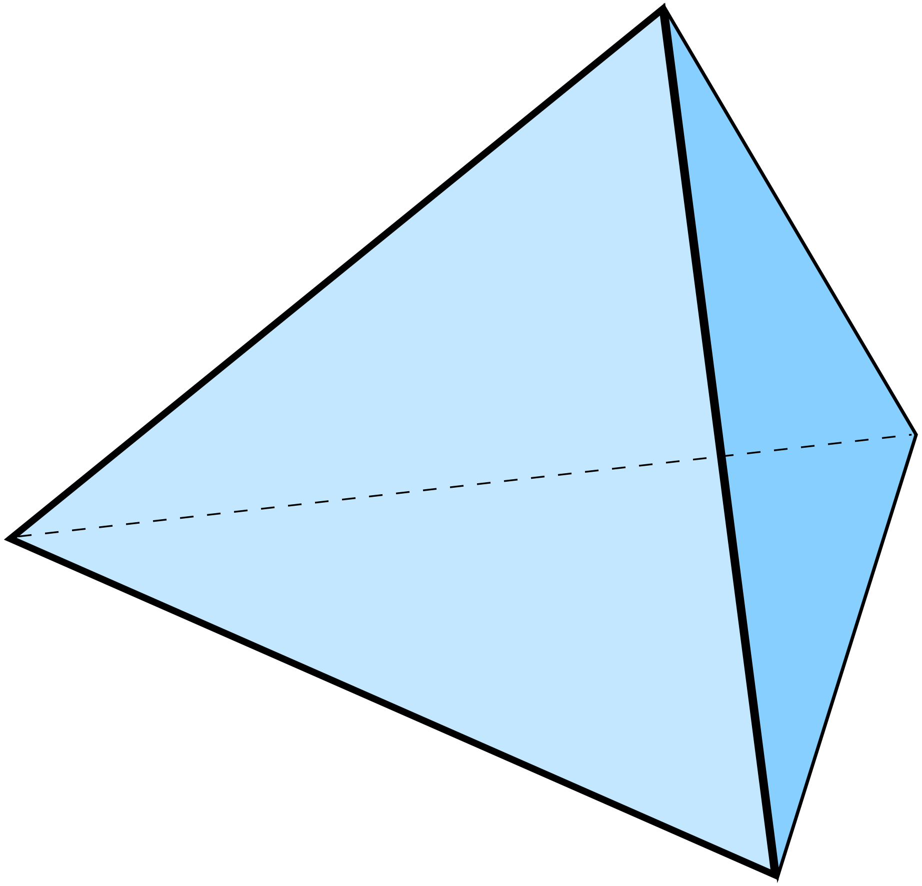
- a multi-μ-problem
- connected to a web of discrete (R)-symmetries.

The geometry of compactified space (and its symmetries) is a crucial ingredient for successful model building.

Calabi Yau Manifold



Orbifold



Geography

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- the location of quarks and leptons,
- the relative location of Higgs bosons,

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but there is also a “localization” of gauge fields

- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

Observed 4-dimensional gauge group is common subroup of the various localized gauge groups!

Localization

Quarks, Leptons and Higgs fields can be localized:

- in the Bulk ($d = 10$ untwisted sector)
- on 3-Branes ($d = 4$ twisted sector fixed points)
- on 5-Branes ($d = 6$ twisted sector fixed tori)

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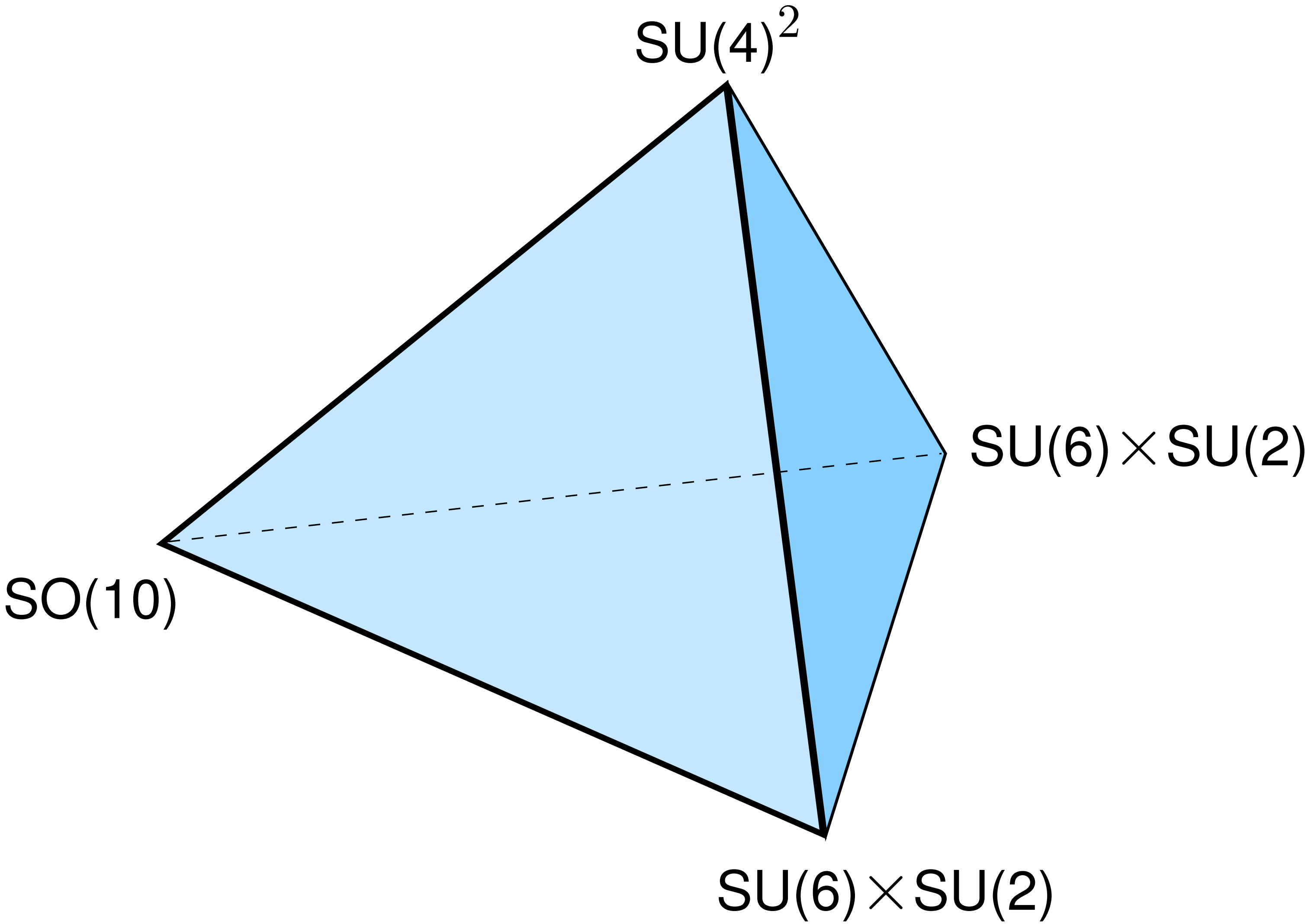
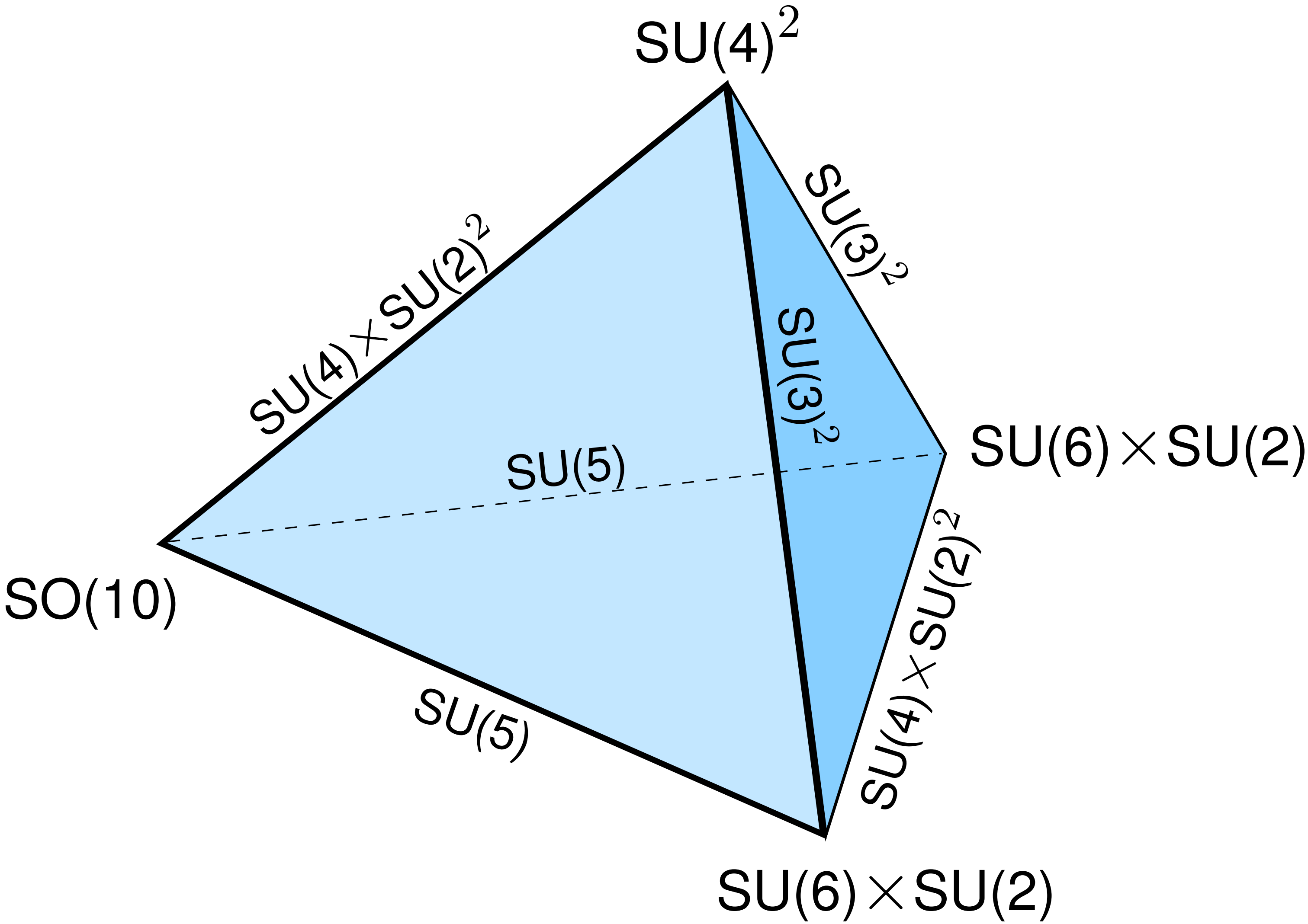
Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



Local Grand Unification

In fact string theory gives us a variant of GUTs:

- complete multiplets for fermion families,
- split multiplets for gauge- and Higgs-bosons,
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Key properties of the theory depend on the geography of the fields in extra dimensions.

At specific "branes" we have

- enhancement of gauge symmetries,
- enhancement supersymmetry through R-symmetries.

The MiniLandscape

It all started with the Z_3 orbifold.

(Kim, Ibanez, Nilles, Quevedo, 1987)

- MiniLandscape with explicit models for $Z_6 II$

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007-2009)

- local grand unification (by construction)
- gauge- and (partial) Yukawa unification
- models with matter-parity + solution to the μ-problem

  (Lebedev et al., 2007)

- explicit construction based on $Z_6 II$, $Z_2 \times Z_2$ and $Z_2 \times Z_4$

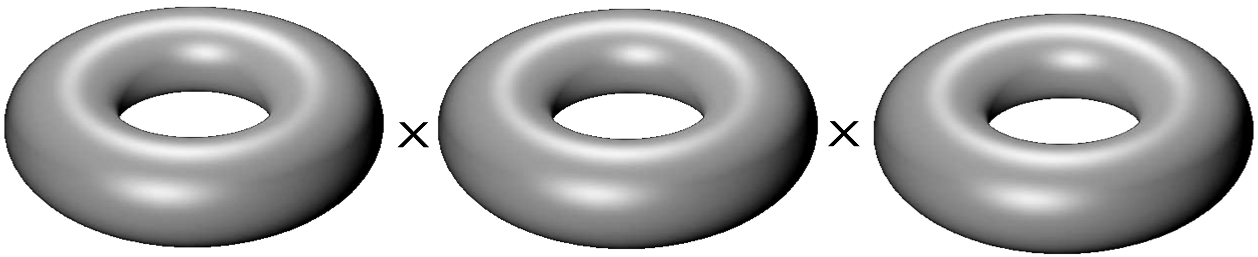
  (Blaszczyk, Groot-Nibbelink, Ratz, Ruehle, Trapletti, Vaudrevange, 2010;

  Mayorga-Pena, HPN, Oehlmann, 2012)

Structure of Sectors of $Z_2 \times Z_4$

The underlying $Z_2 \times Z_4$ orbifold has the following sectors:

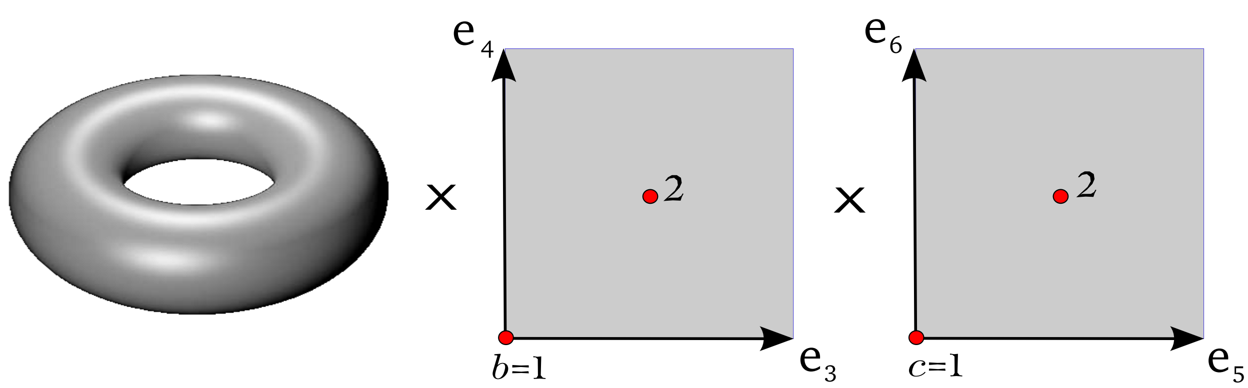
- the untwisted sector



Fields live in the bulk $d = 10$ with remnant $N = 4$ Susy.
Extended supersymmetry from torus compactification.

Twisted Sectors

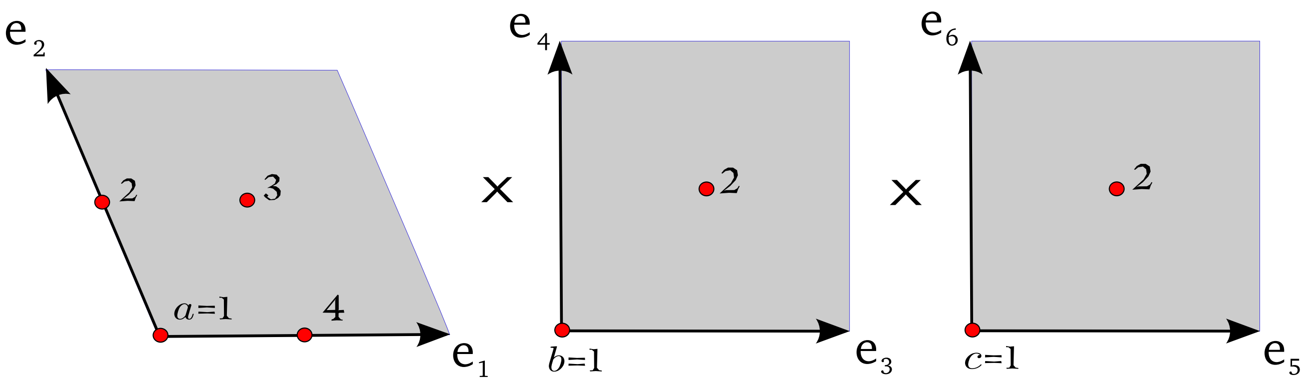
Twisted sectors correspond to the $Z_2(\theta)$ and $Z_4(\omega)$ twists



The ω sector has 2 x 2 = 4 fixed tori, corresponding to

- "5-branes" confined to $d = 6$ space time ($N = 2$ Susy). Partially extended supersymmetry.

$\theta\omega$ Twisted Sector



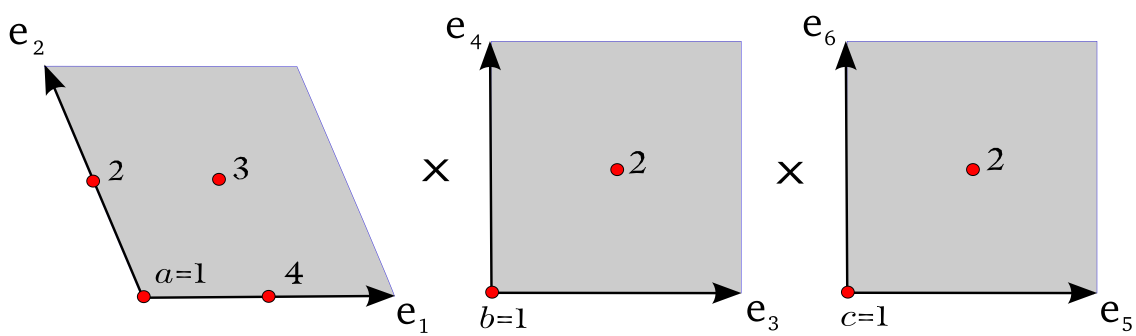
The $\theta\omega$ twisted sector contains 4 x 2 x 2 fixed points:

- "3-branes" confined to 4 space-time dimension (sector with remnant of $N = 1$ Susy).

Location of fields determines the symmetries.
Light fields have to be protected by symmetries:
this is the generalized μ-problem

Discrete Family Symmetries

The first two families live at fixed points:



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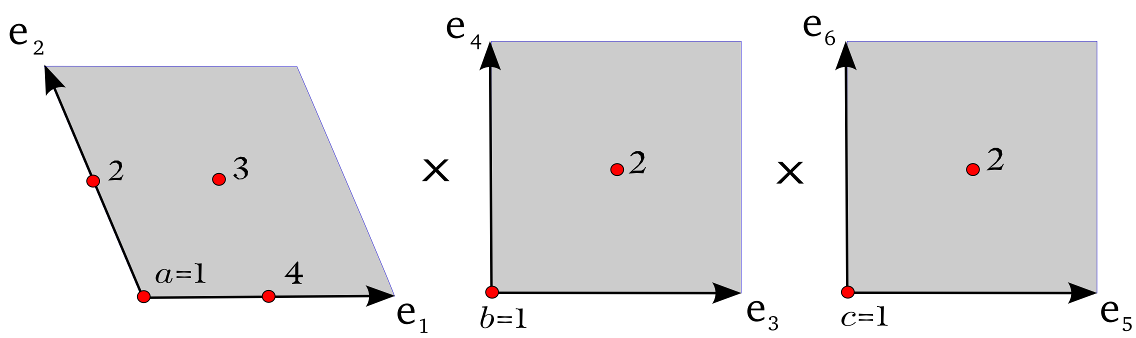

- they exhibit a D_4 family symmetry
- subgroup of $SU(2)$ flavour symmetry
- its origin is the interplay of geometry and selection rules

(Kobayashi, Nilles, Ploger, Raby, Ratz, 2007)

$R-$symmetries and extended Susy

$R-$symmetry can be understood as an extension of Susy

- $N = 1$ Susy with $U(1)_R$ forbids gaugino masses, μ-term and trilinear soft terms (A)
- broken to discrete symmetry like Z_2 matter parity to guarantee proton stability

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The superpotential transforms nontrivially under any $R-$symmetry

- gravitino mass as signal of $R-$symmetry breakdown and Susy breakdown,
- connects $\mu-$term with Susy breakdown and provides a solution to the $\mu-$problem.

$R-$symmetries from strings

The origin of $R-$symmetries is two-fold:

- string selection rules, (Cabo-Bizet et al., 2013; Kappl et al., 2014)
- Lorentz group of extra dimensions

$$SO(9,1) \rightarrow SO(3,1) \times SO(6).$$

Connections to $N-$extended Susy:

- torus compactification from 10 to 4 leads to $N = 4$ Susy,
- $R-$symmetry $SU(4)_R \sim SO(6)$ (completely geometric),
- fixed tori from $d = 6$ could lead to $N = 2$ extended Susy,
- $R-$symmetry $SU(2)_R$ (which is partially geometric).

(Kappl, Nilles, 2016, to appear)

Properties of $R-$symmetry

Connection between $R-$symmetry and holonomy group of compact manifold:

- $SU(3)$ holonomy $(\Gamma^{ijk} H_{ijk})$,
- its relation to the superpotential
- and gaugino condensates of hidden gauge group.
- Maximal geometric group is $SU(4)_R$ descending from $d = 10$ and thus completely of geometric origin.
- From $d = 6$ we can have $U(2)_R \times U(2)_R$ partially from geometry and partially from selection rules,
- similar to the situation of normal discrete symmetries (e.g. D_4 flavour symmetry discussed earlier).

The power of $R-$symmetries

More $R-$symmetries imply better protection than just Susy alone. This is of particular importance for

- the solution of the $\mu-$problem,
- connection of $\mu-$term to gravitino mass and Susy breakdown via nonperturbative effects,
- the question of proton stability (protected by discrete symmetries),
- pattern of soft Susy breaking terms in various sectors of extended Susy. (Krippendorf, Nilles, Ratz, Winkler, 2012-13)

$R-$symmetries (as extended supersymmetry) can protect the masses of Higgs bosons and other "vector-like exotics"

(Kappl, Nilles, 2016, to appear)

A Benchmark Model

At the orbifold point the gauge group is

$$SU(3) \times SU(2) \times U(1)^9 \times SU(4) \times SU(2)$$

- one $U(1)$ is anomalous
- there are singlets and vector-like exotics

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)
- MSSM requires decoupling of exotics and breakdown of gauge group as well as a protection of the μ-term
- remaining gauge group

$$SU(3) \times SU(2) \times U(1)_Y \times SU(4)_{\mathrm{hidden}}$$

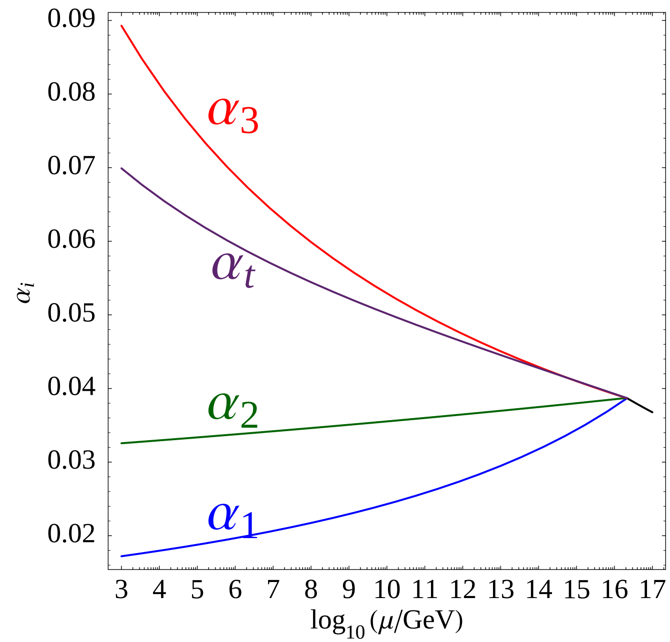
- R-symmetries could protect vector-like exotics as well

Spectrum

#	irrep	label		#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i		3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$		8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$		1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	h_d		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	h_u
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	$\bar{\delta}_i$		6	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,-2/3)}$	δ_i
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,*)}$	s_i^+		14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/2,*)}$	s_i^-
16	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,1)}$	$\bar{n}_i$		13	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,-1)}$	n_i
5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,1)}$	$\bar{\eta}_i$		5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,-1)}$	η_i
10	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,0)}$	h_i		2	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_{(0,0)}$	y_i
6	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(0,*)}$	f_i		6	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(0,*)}$	$\bar{f}_i$
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	f_i^-		2	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
4	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,\pm 2)}$	χ_i		32	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,0)}$	s_i^0
2	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$		2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

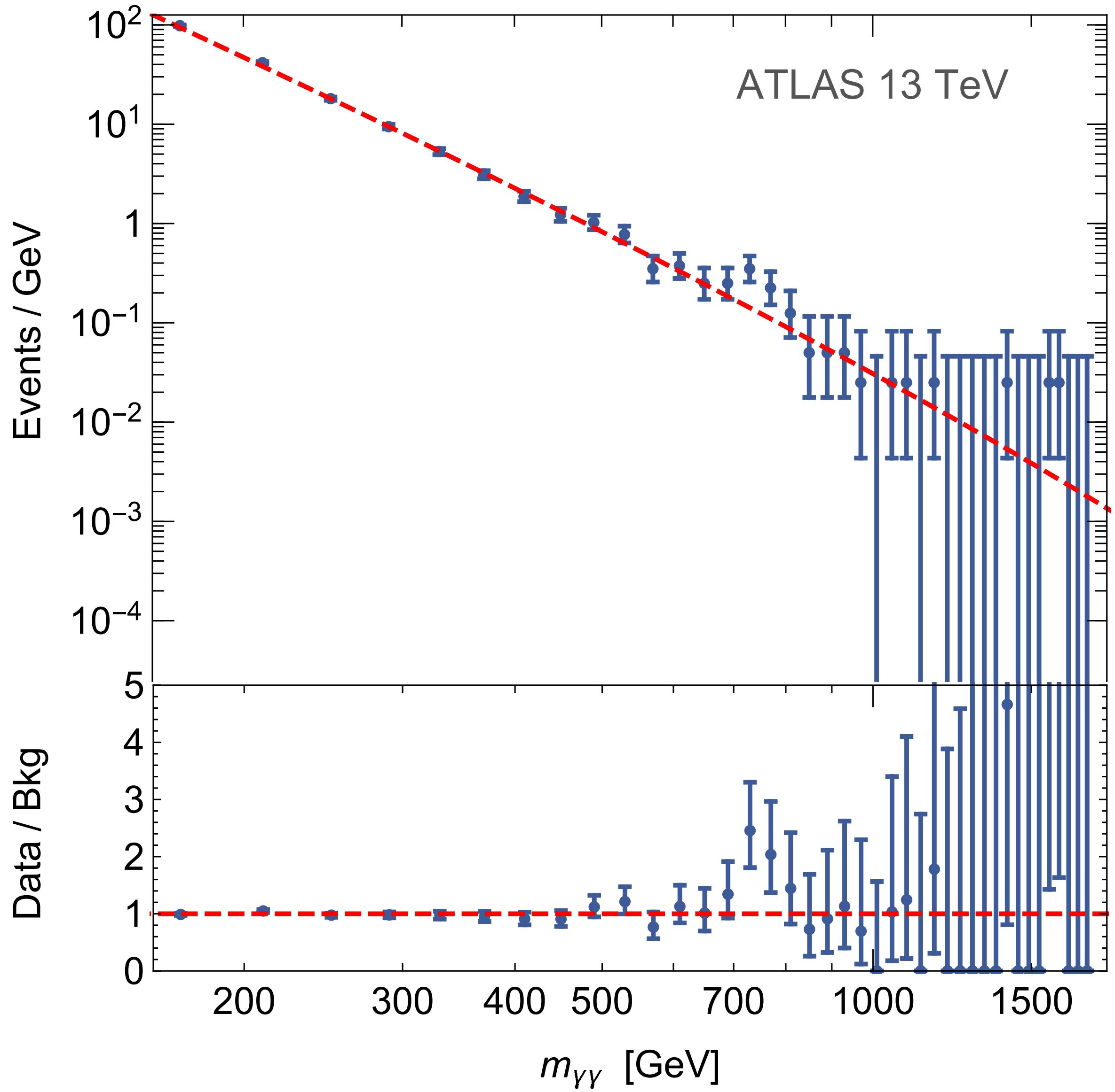
Unification

- Higgs doublets are in untwisted sector (bulk)
- heavy top quark in untwisted sector (bulk)
- $\mu-$term protected by a discrete R-symmetry

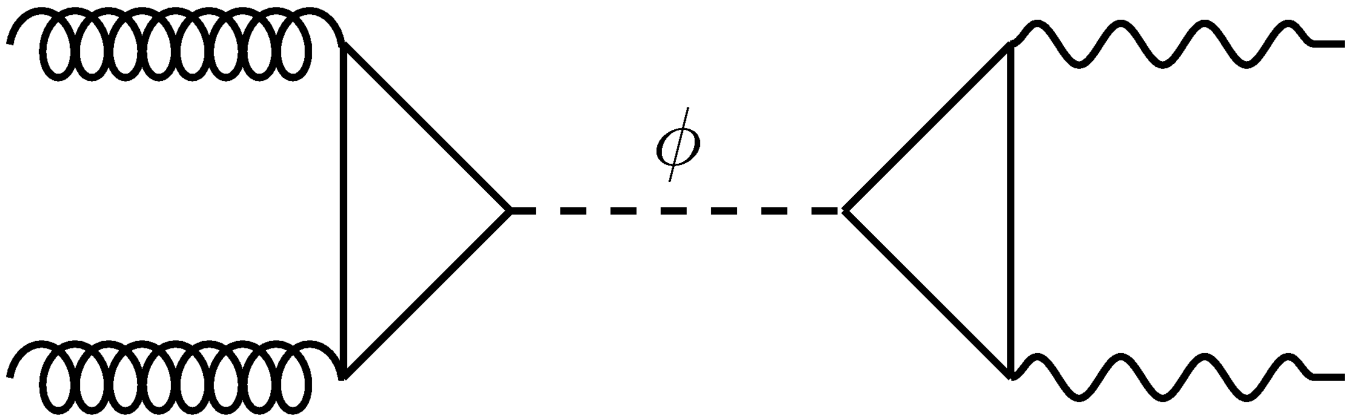


- Minkowski vacuum before Susy breakdown (no AdS)
- natural incorporation of gauge-Yukawa unification
- are there additional (protected) vector-like exotics?

A new state at 750 GeV?



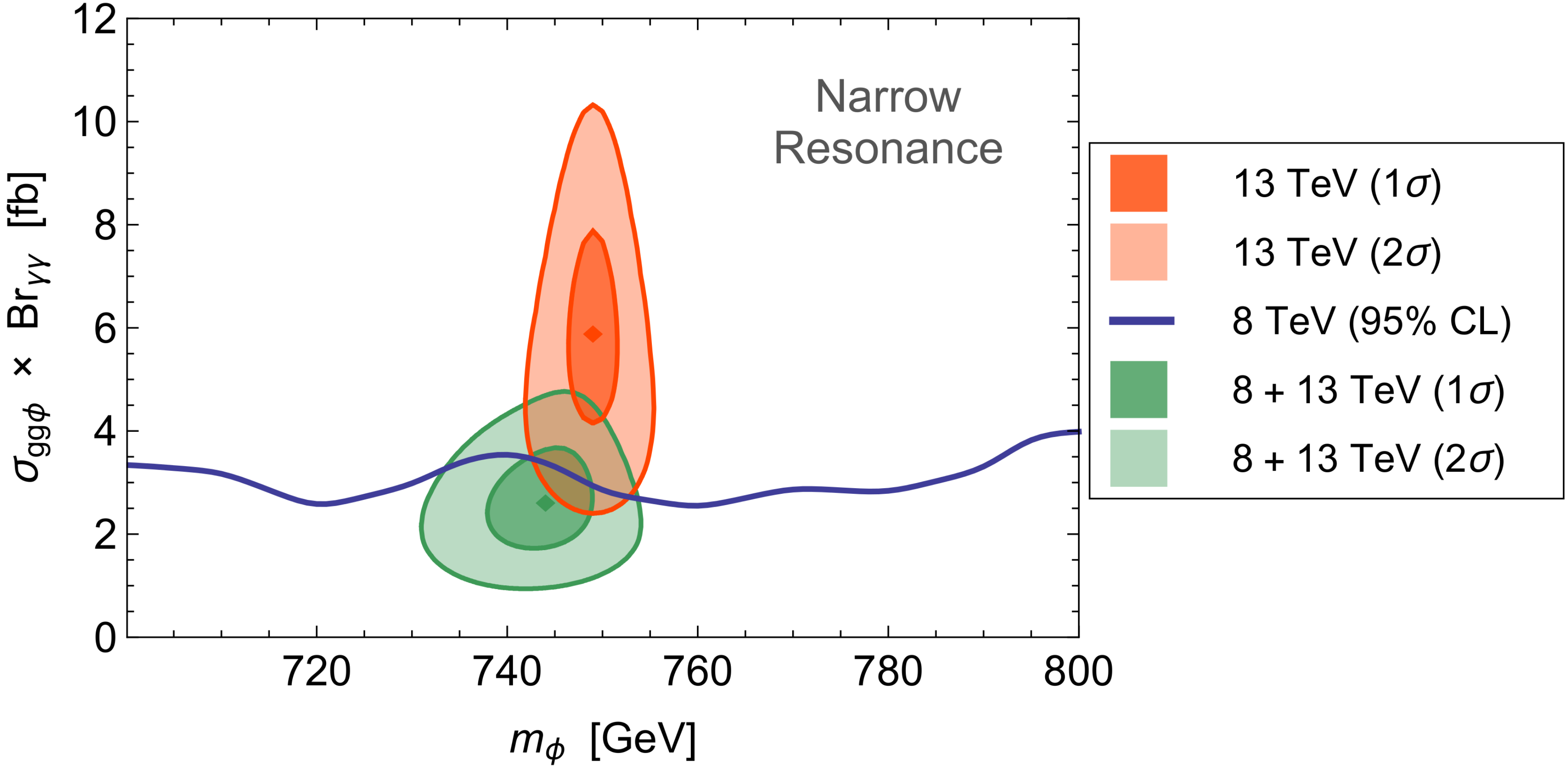
A simple explanation?



Requires new ingredients:

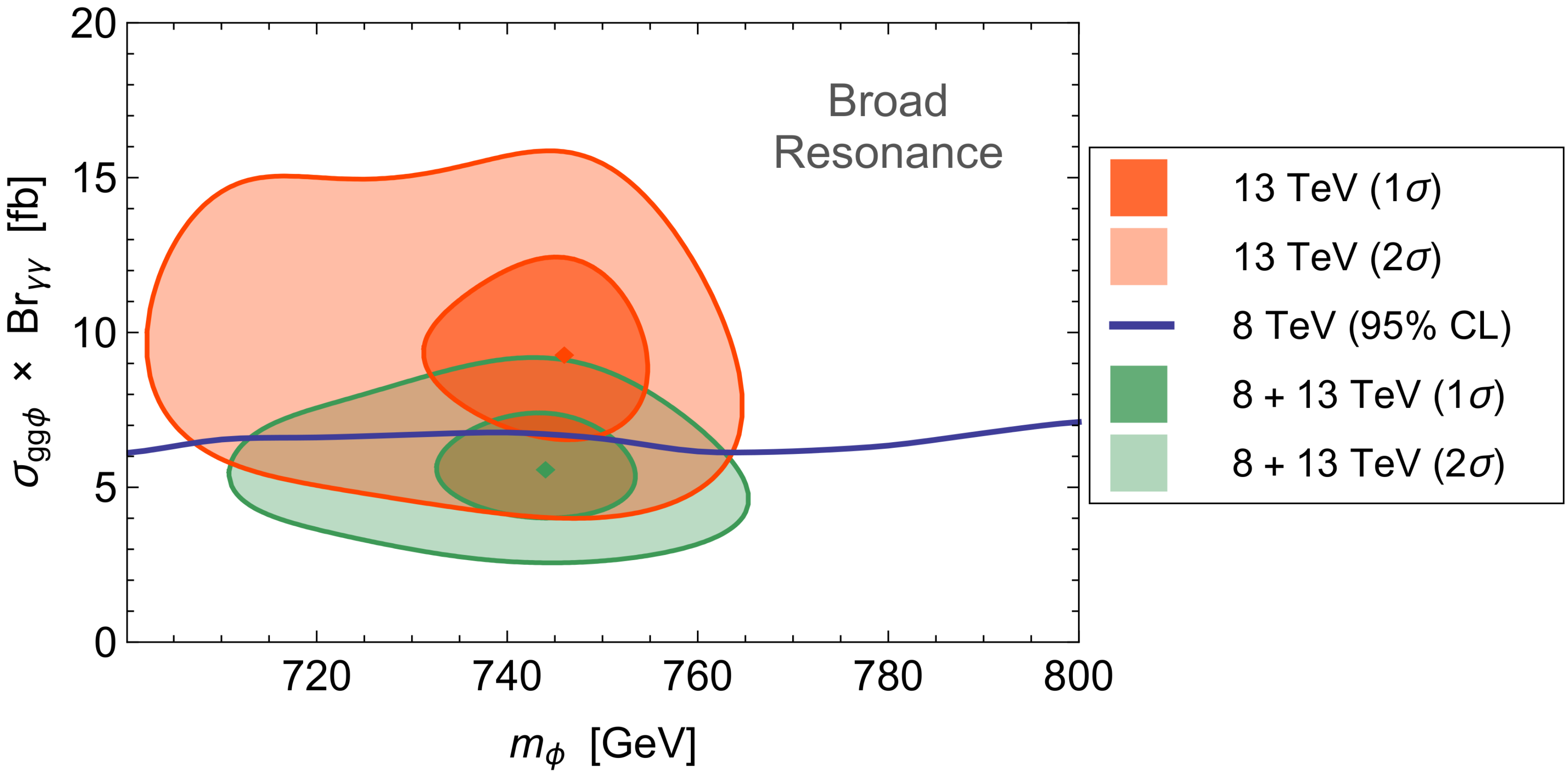
a standard model singlet ϕ and vector-like quarks (leptons)

The cross section-narrow resonance

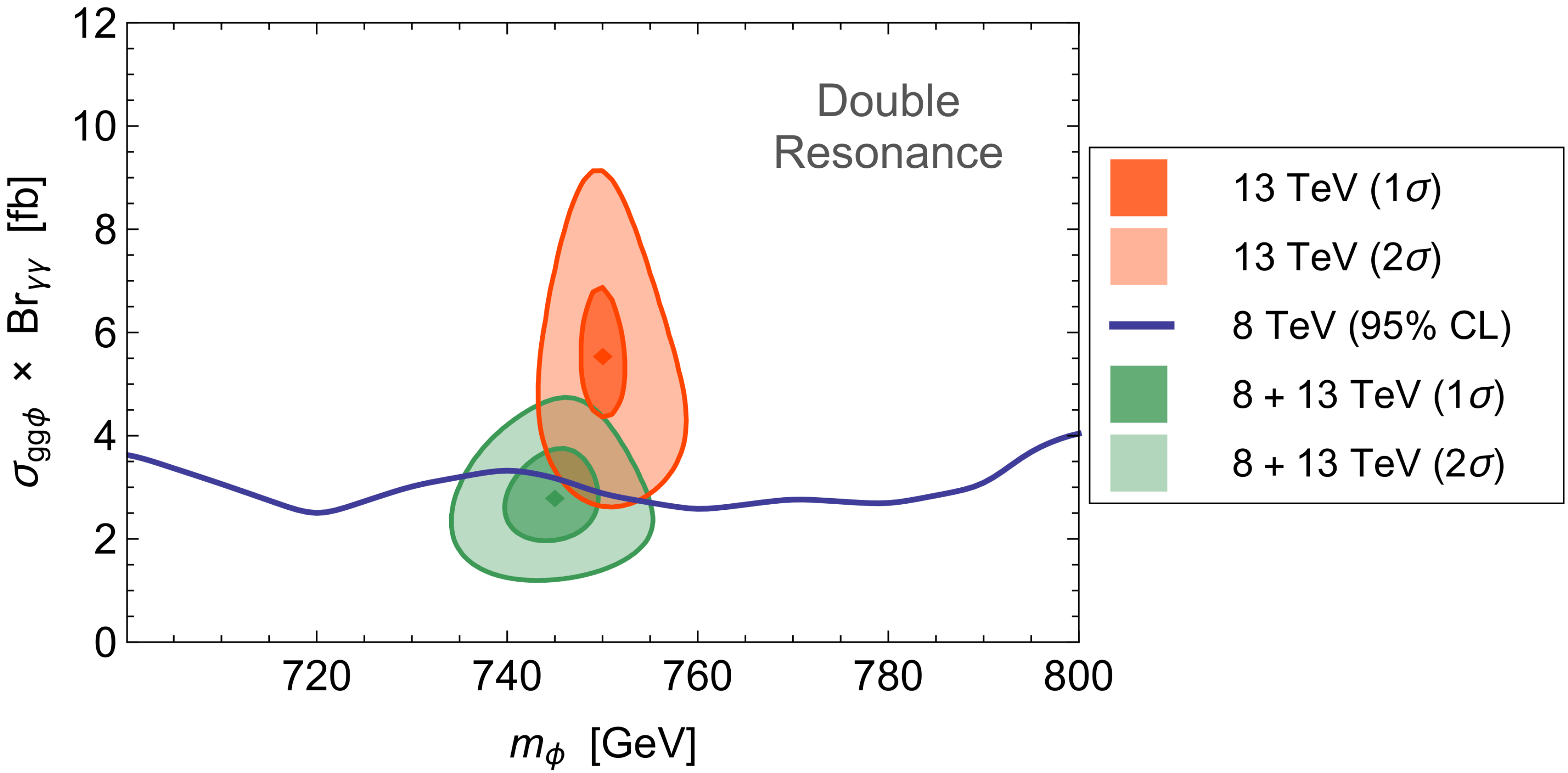


(Nilles, Winkler, 2016)

The cross section-broad resonance



The cross section-split resonance



Some remarks

The cross section is pretty large

- need large couplings or many intermediate states
- could lead to Landau poles for gauge and/or Yukawa couplings
- Is this possible within a perturbative grand unified picture?

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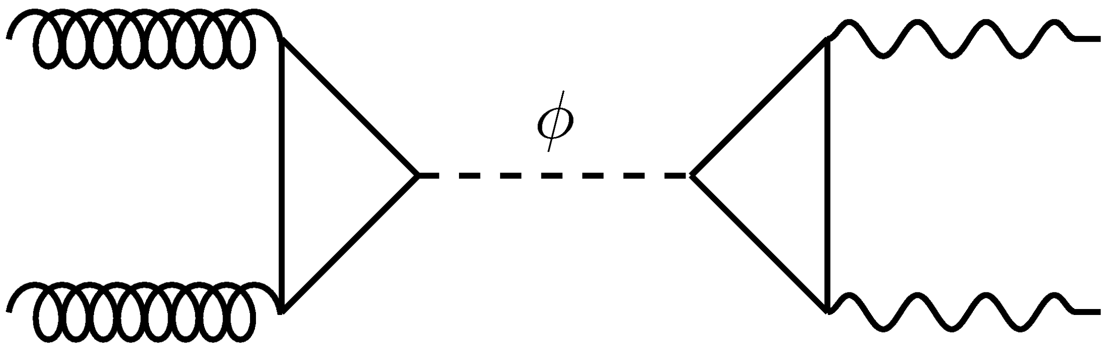
Can supersymmetry help?

- complex scalar = scalar + pseudoscalar
- fermions and scalar partners in loops
- large A-terms can enhance cross section

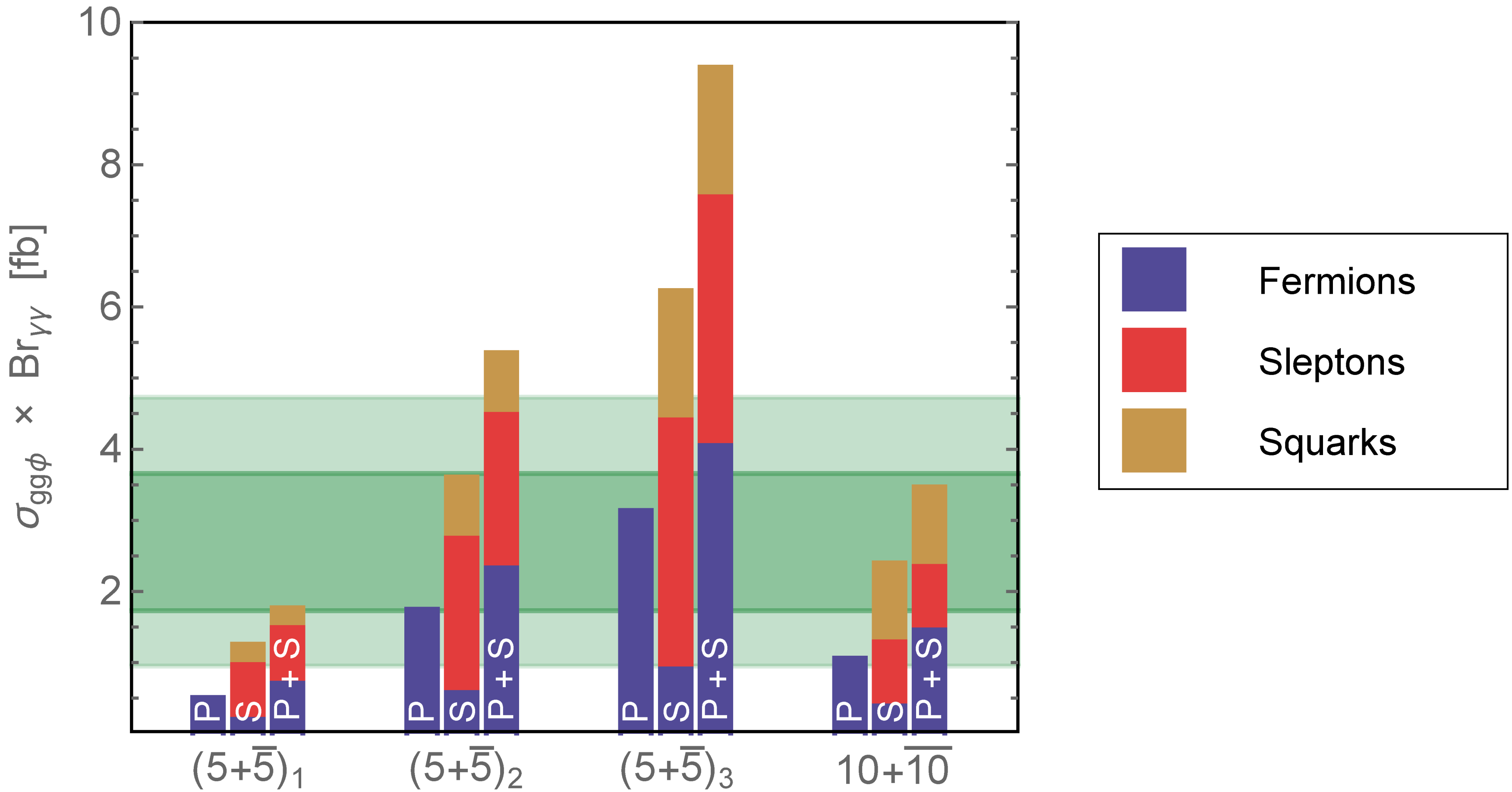
The SUSY Contribution



- could have split resonance (mimics broad resonance)
- upper limit on A-terms because of vacuum stability
- how may vector-like pairs do we need and are they consistent within a perturbative GUT picture?

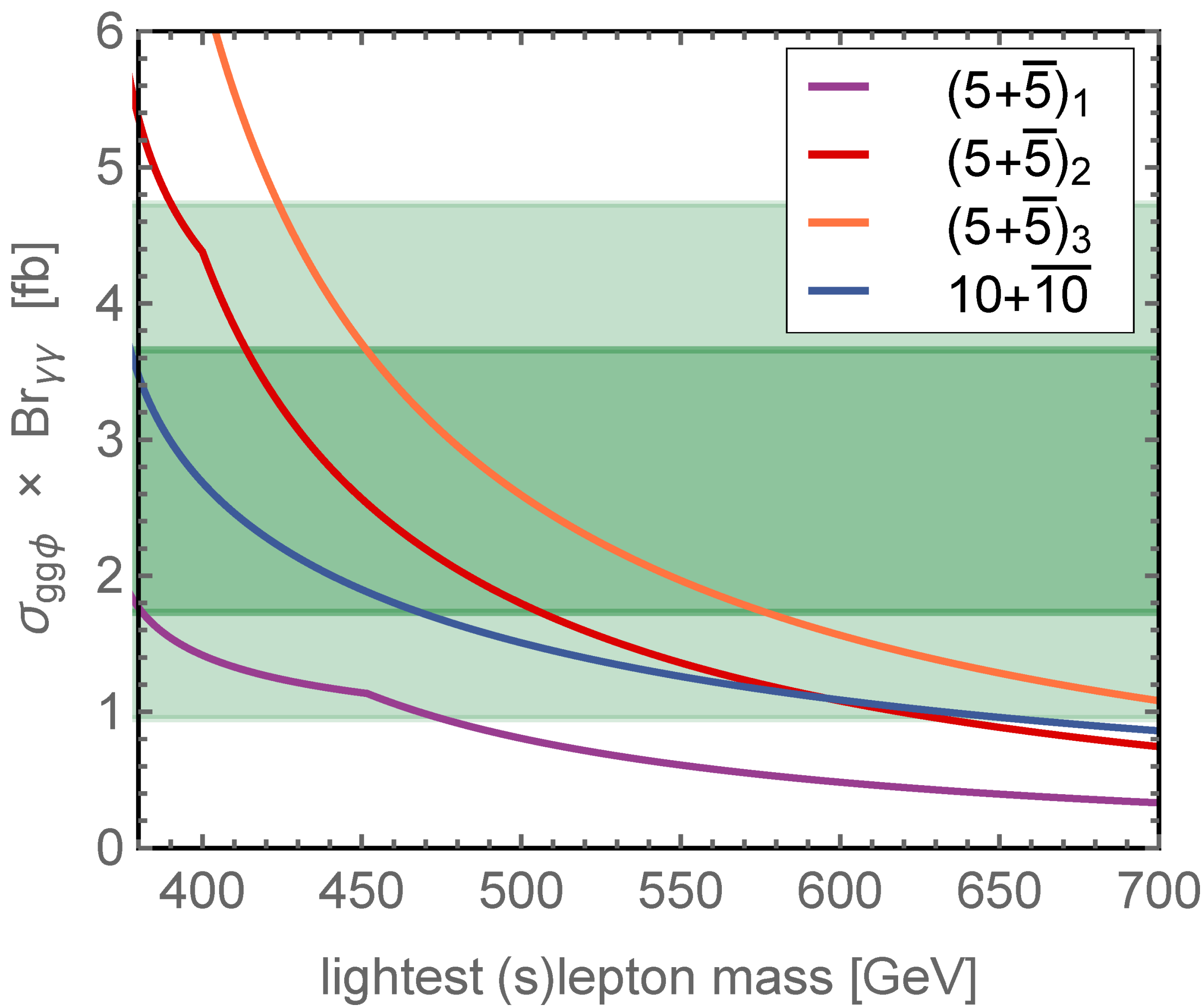
(Nilles, Winkler, 2016)

Maximal Di-Photon Cross Sections

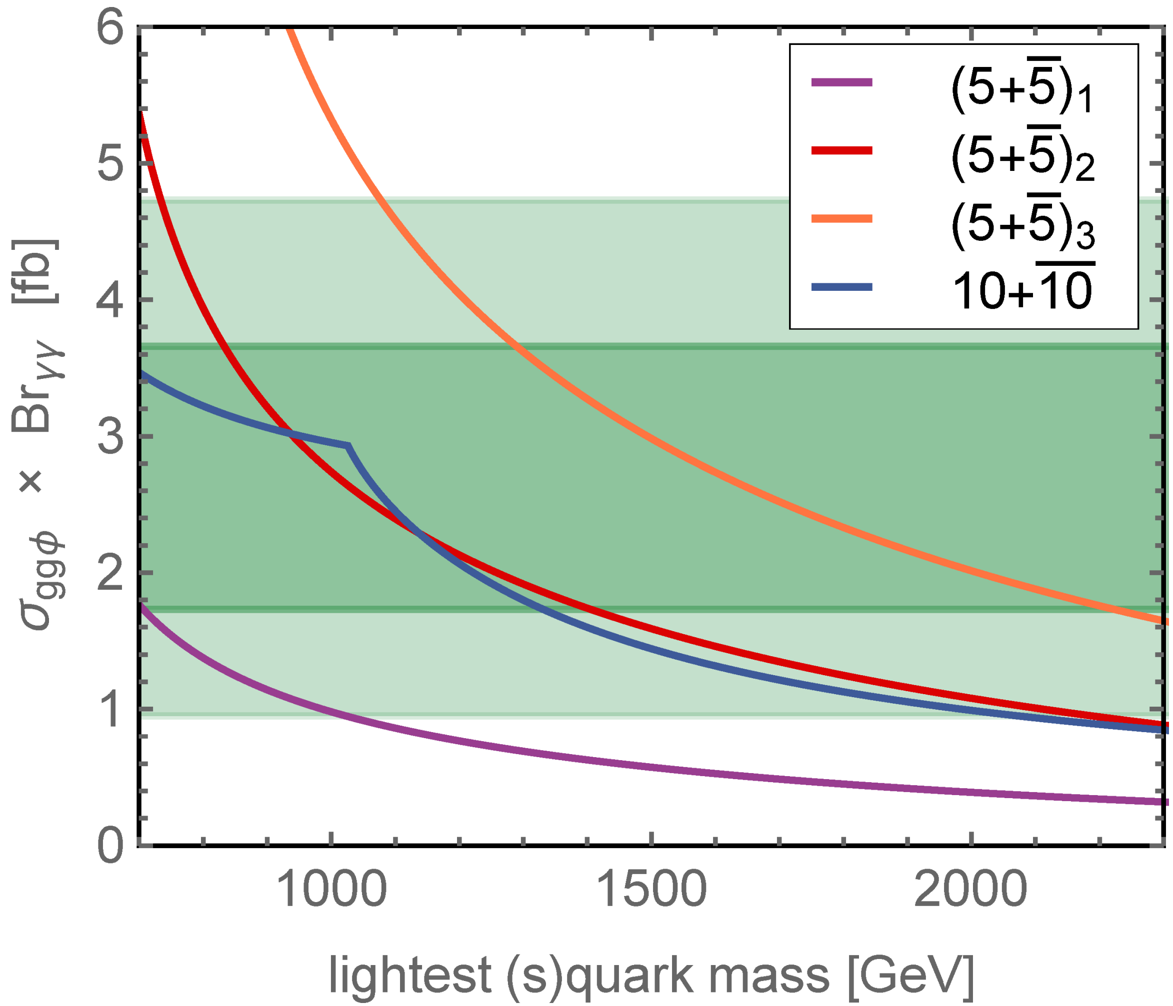


(Nilles, Winkler, 2016)

Slepton Masses



Squark Masses



What next?

Wait and see!

- Broad or narrow resonance? Split resonance?
- What is the spin of the resonance?
- Are there connected (jet) activities?
- Is there a mixing with the Higgs system?
- We need to check the predictions concerning other di-boson signals like WW, ZZ and Zγ
- Direct search for masses of vector-like pairs
- Are there additional $U(1)'$ gauge bosons

After that we can restart model building again.......

Messages

- The MSSM is (un)fortunately not a generic prediction of the string landscape
- The world beyond the Standard Model might be more complex than we thought
- Minimality no longer the correct guiding principle?
- The problem of the scales is even more pronounced
- Web of discrete R-symmetries as extension of SUSY is needed to solve the various μ problems
- Approximate discrete symmetries allow hierarchies via a Frogatt-Nielsen mechanism. (Kappl, Nilles, 2016, to appear)

Apparently we need experiment to guide our way!