Supersymmetry

Why? What? How?

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US-CMS PURSUE
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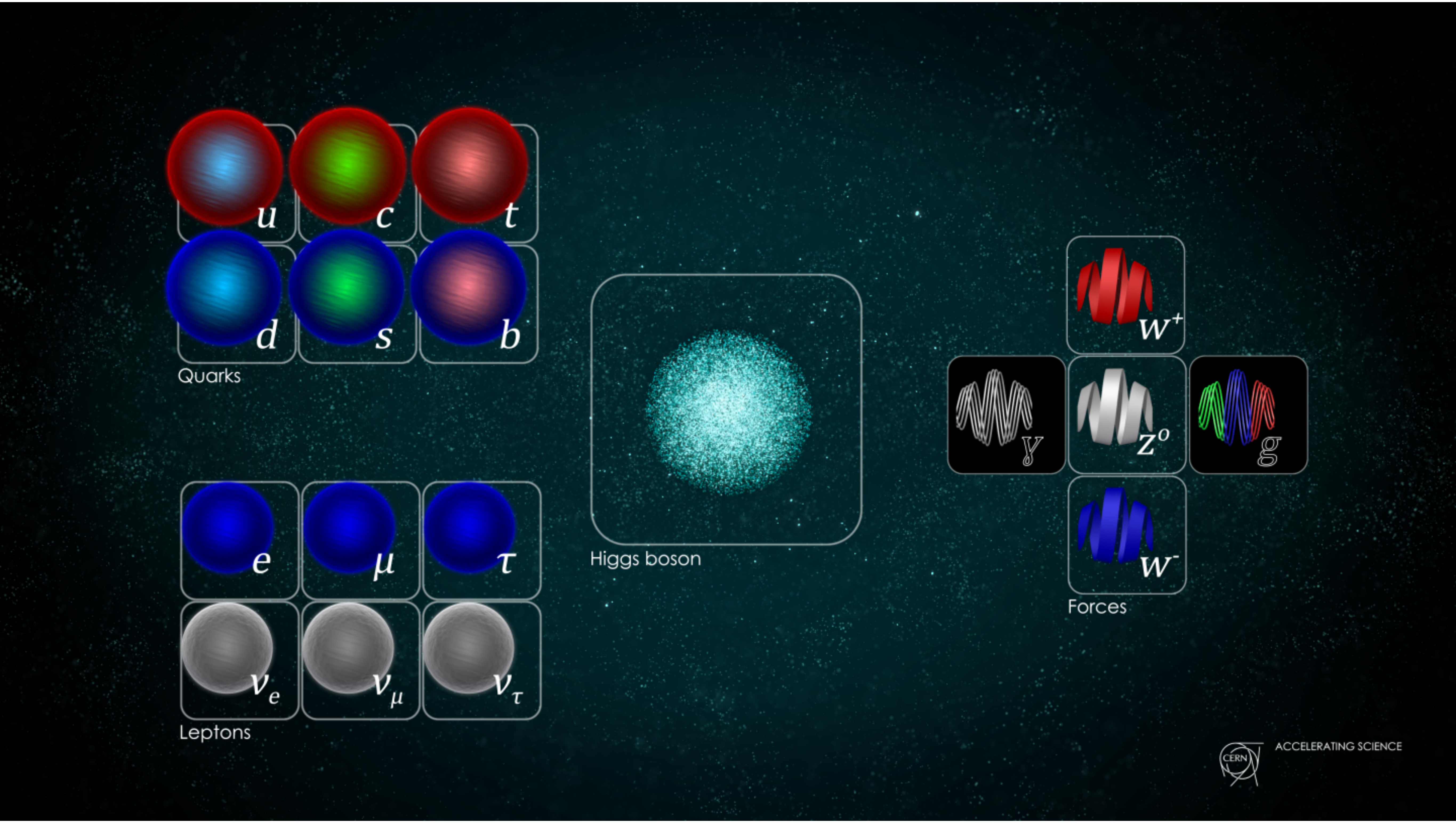
Outline

- Why go beyond the Standard Model?
- What is supersymmetry?
- What are the benefits of supersymmetry?
- How do we look for evidence of supersymmetry?
- Current status

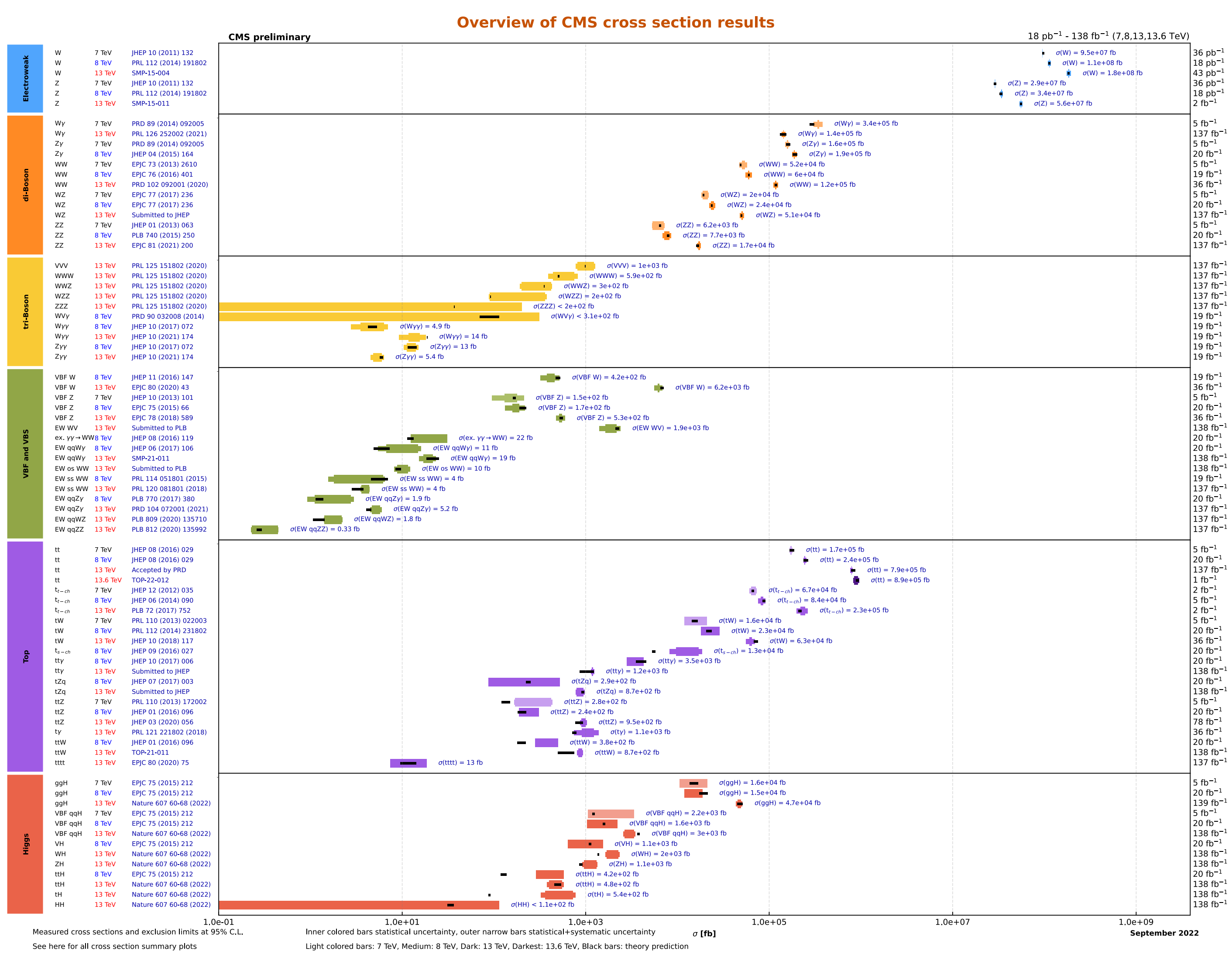
Standard Model recap

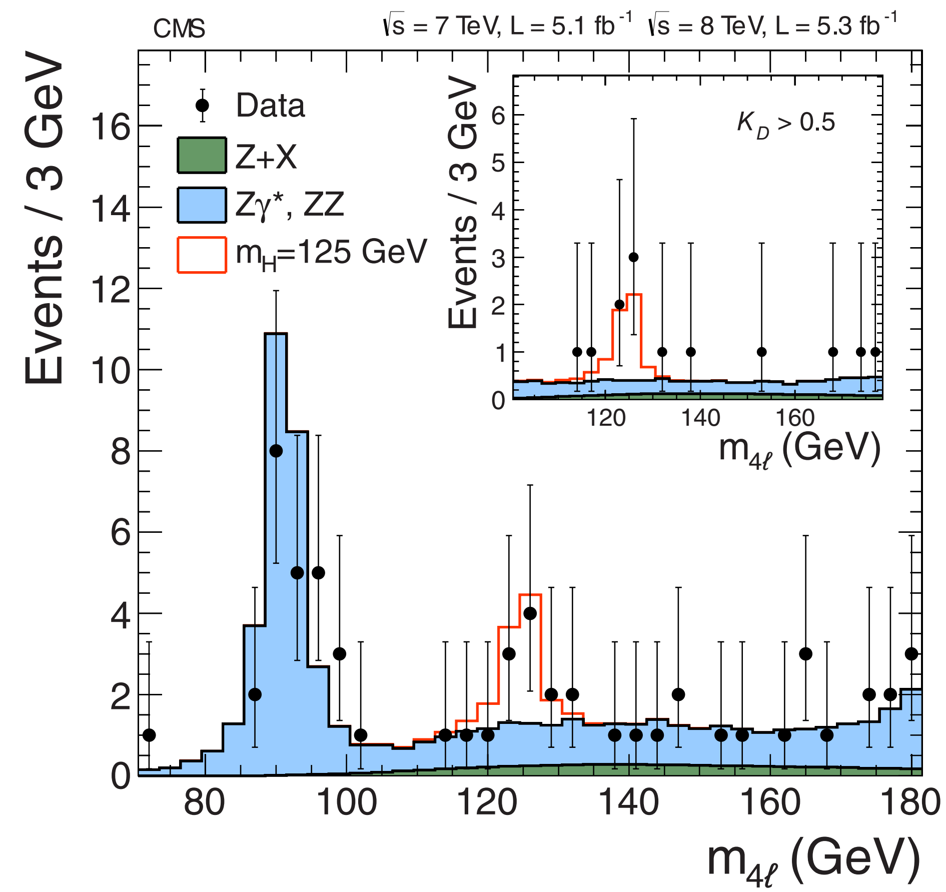
Review previous talks by Tulika Bose, Chris Palmer, and Titas Roy for more info

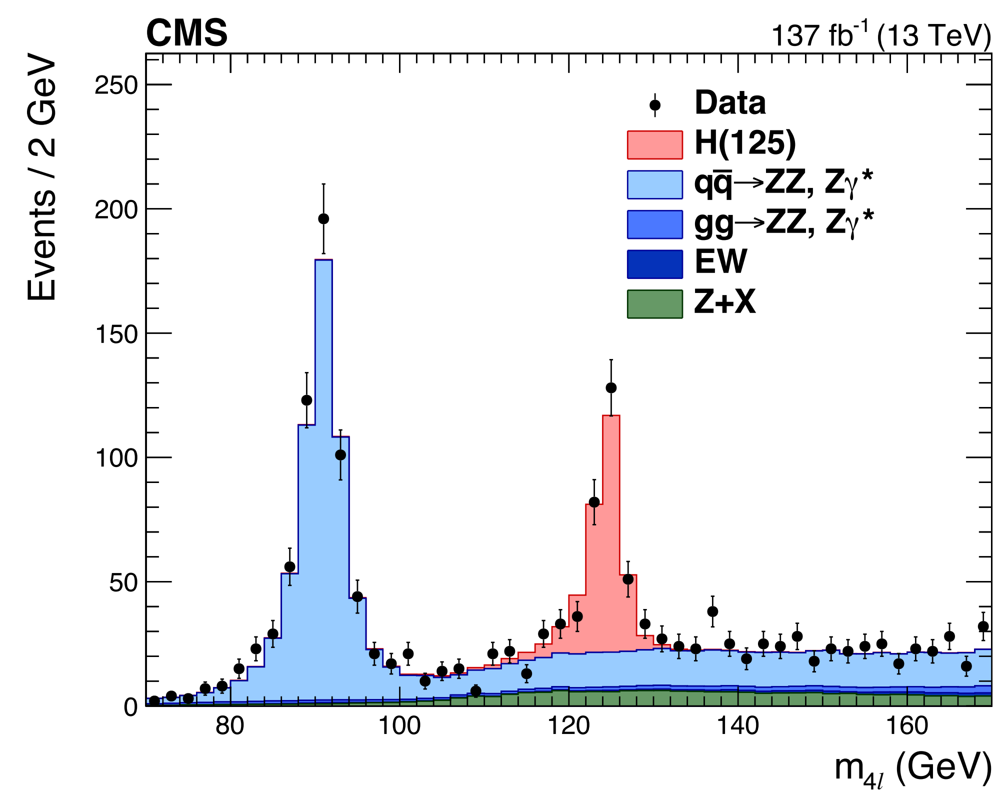


The Standard Model (SM) works great

- Describes the known particles (including the Higgs!) and their interactions
- Makes precise predictions that agree with the measurements



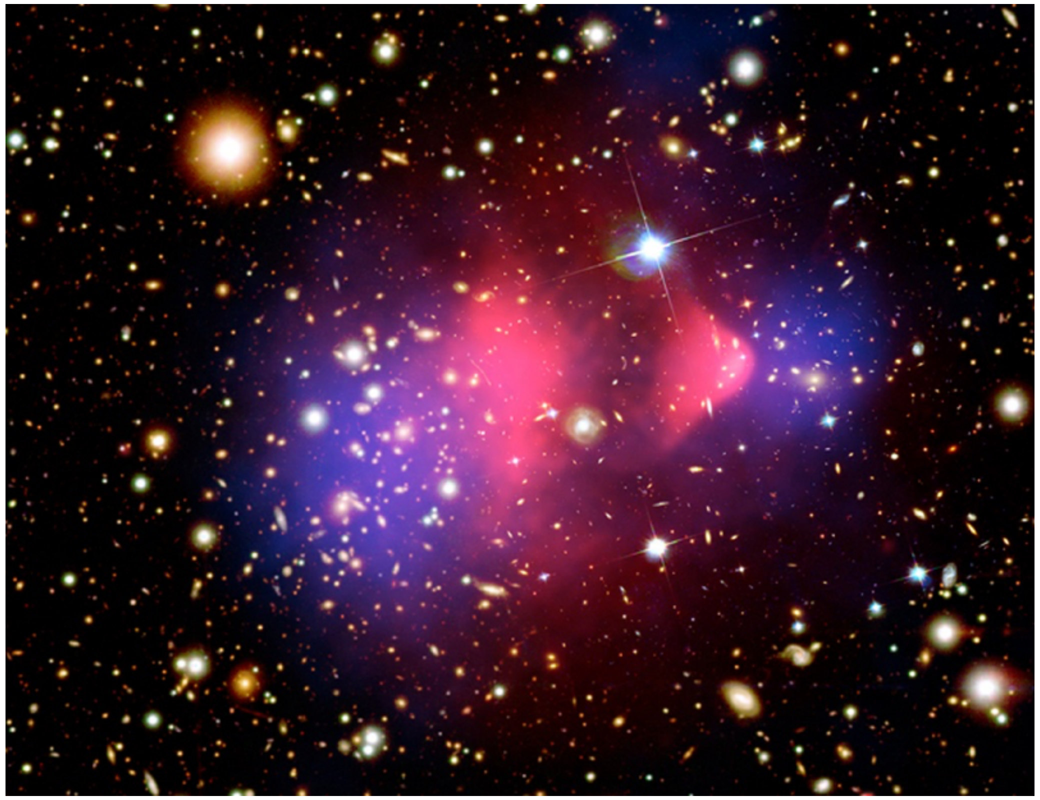


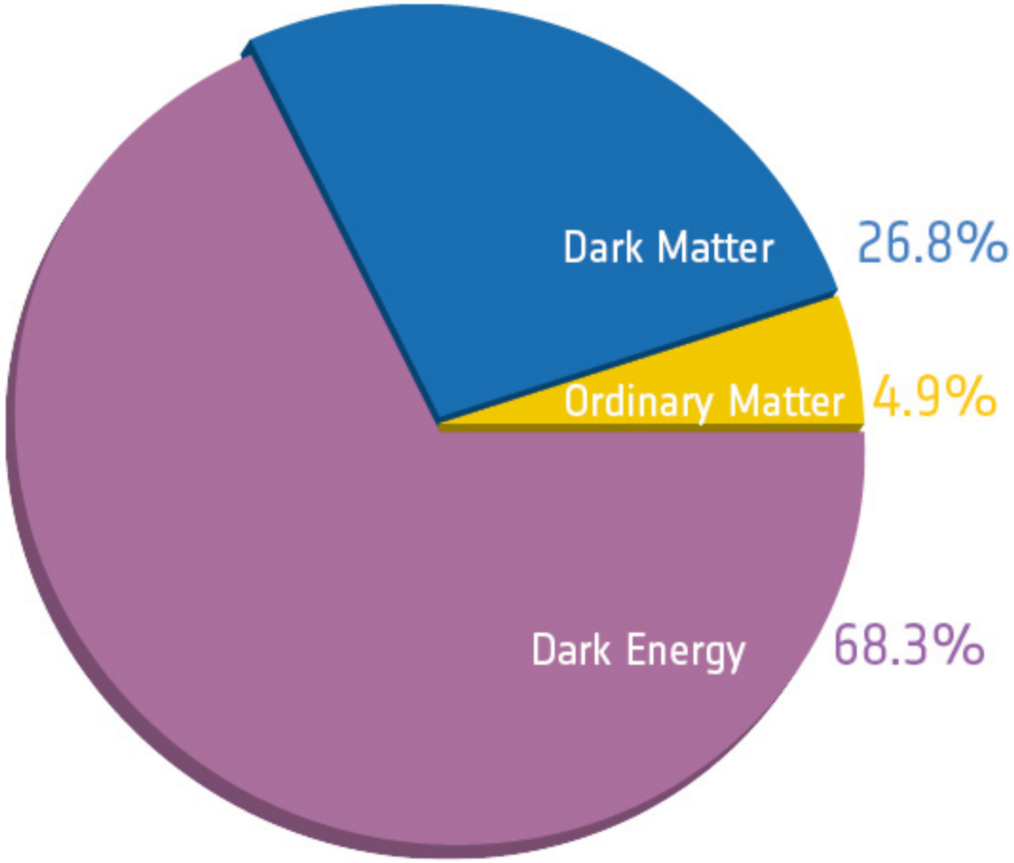


Why go beyond the Standard Model?

Because there are many open questions!

- What is dark matter?





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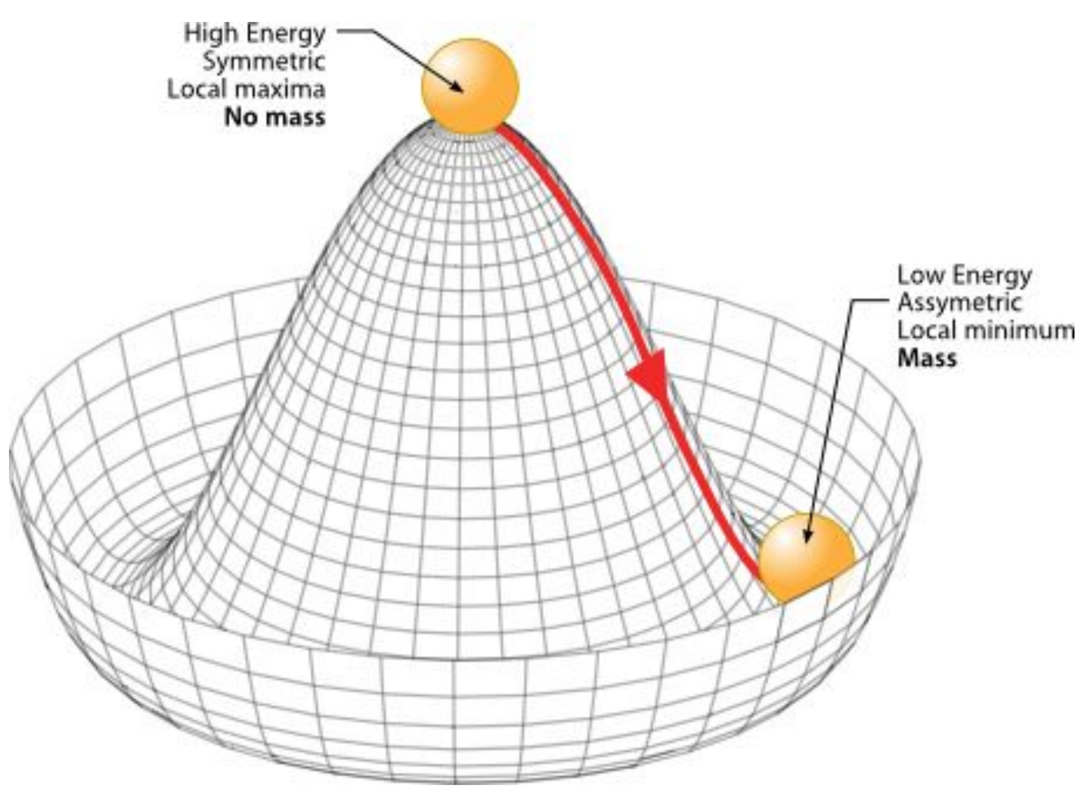
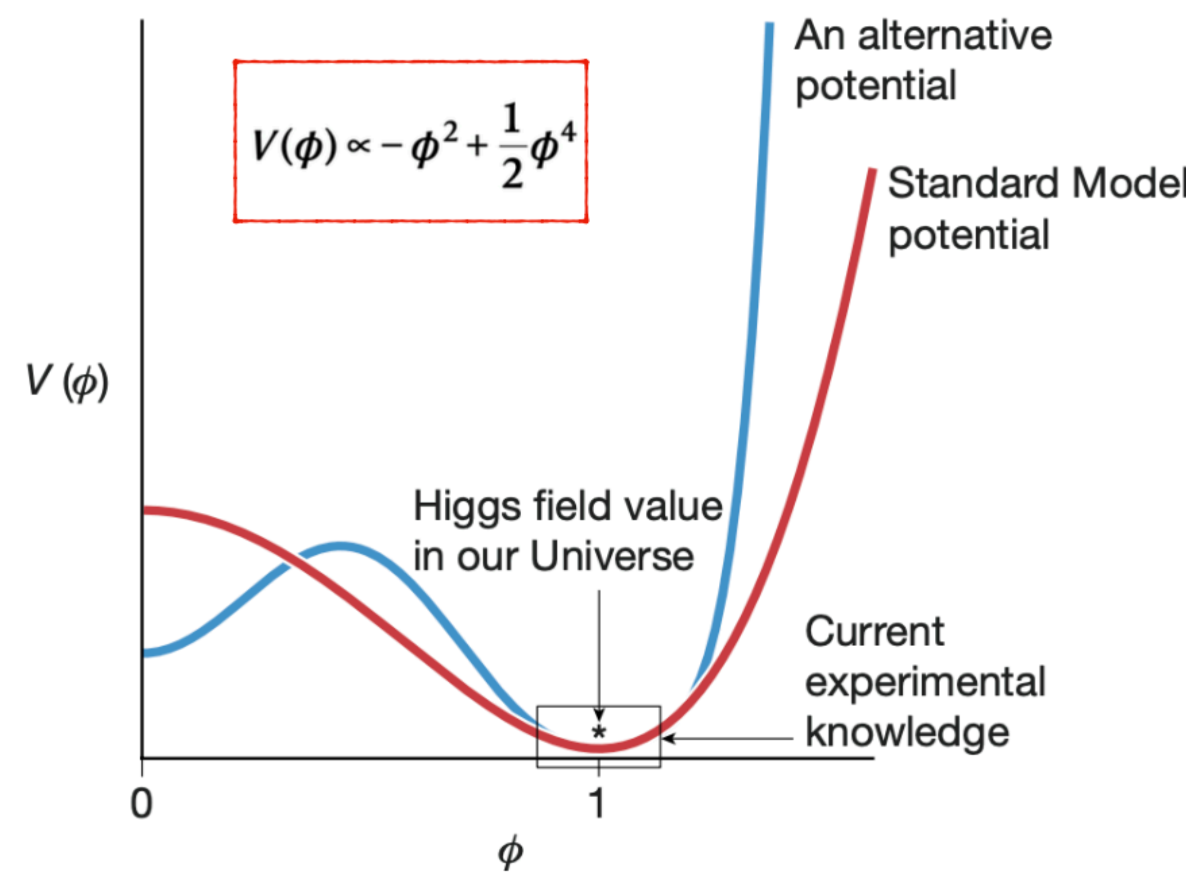
- What is dark matter?
- Why does the Higgs boson have the mass it does? And what is the shape of the Higgs potential?





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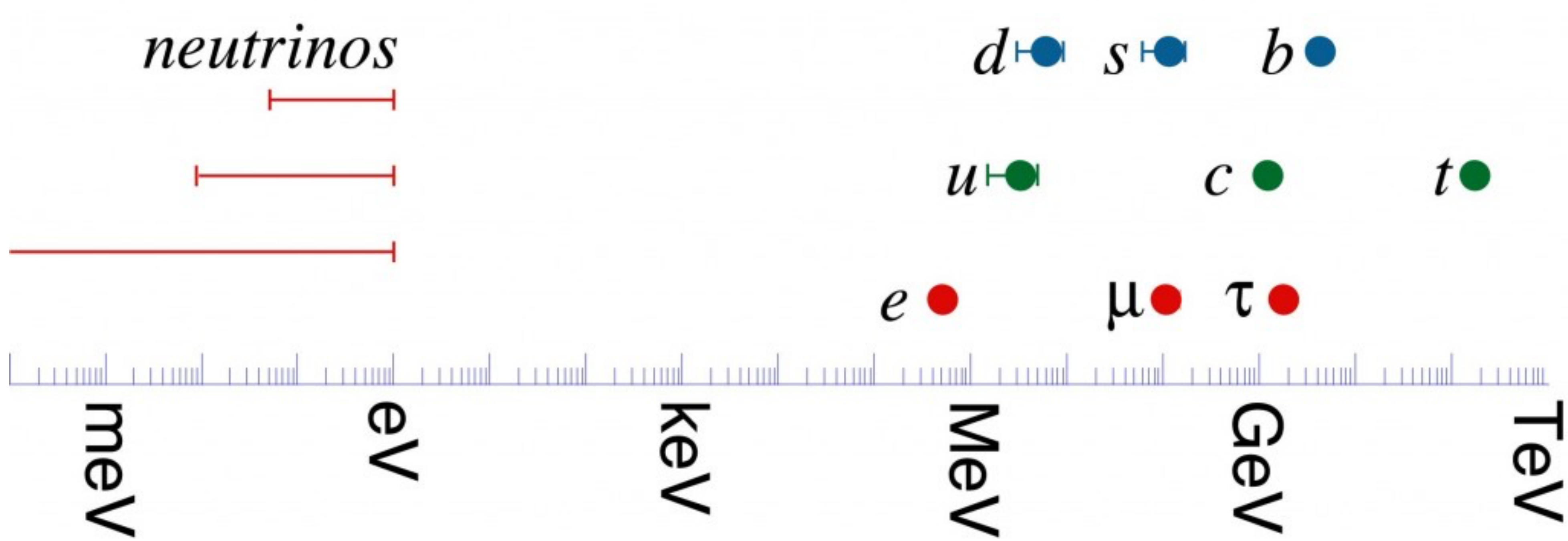
- Why are there 3 generations of matter, with large mass hierarchies?



Because there are many open questions!

- What is dark matter?
- Why does the Higgs boson have the mass it does? And what is the shape of the Higgs potential?
- Why are there 3 generations of matter, with large mass hierarchies?
- How to explain the matter-antimatter asymmetry?
- How does gravity fit in?

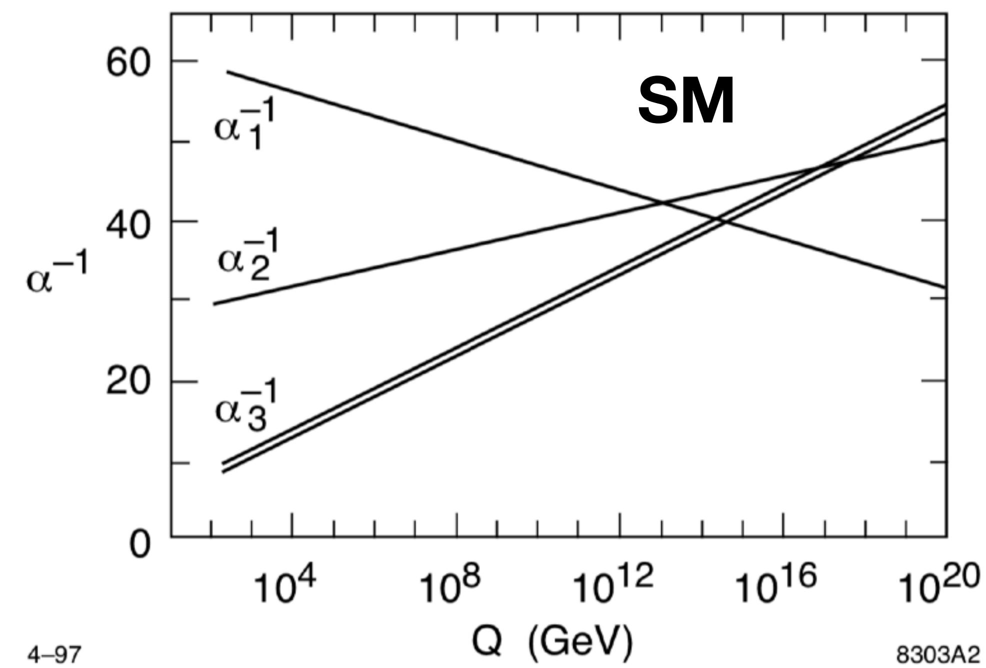
Many theories have been proposed to address these questions

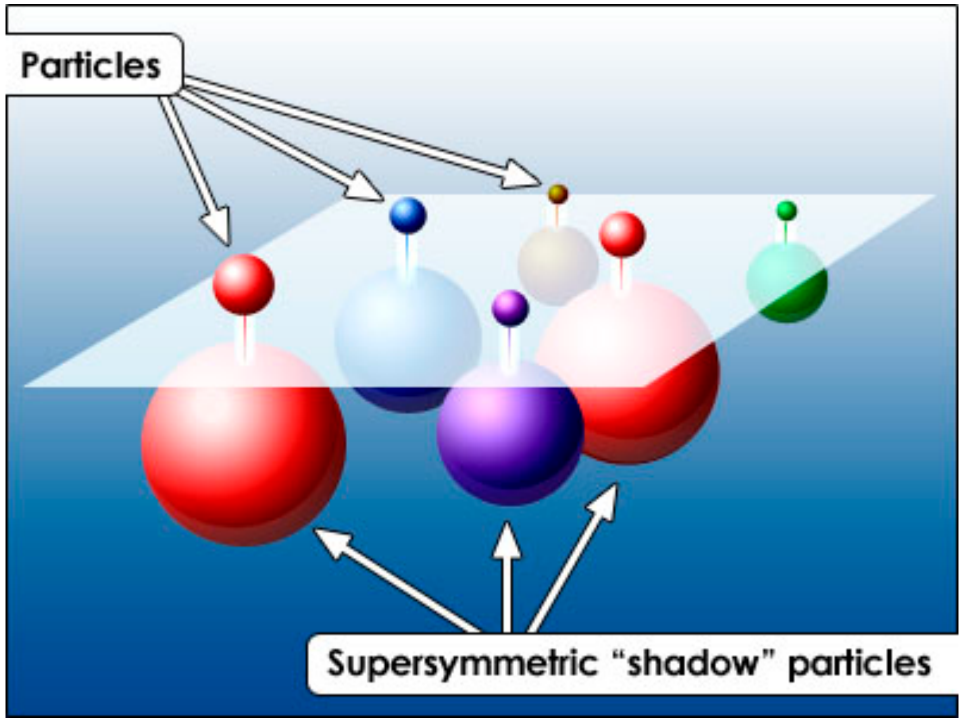
Supersymmetry is one of the more prominent ones

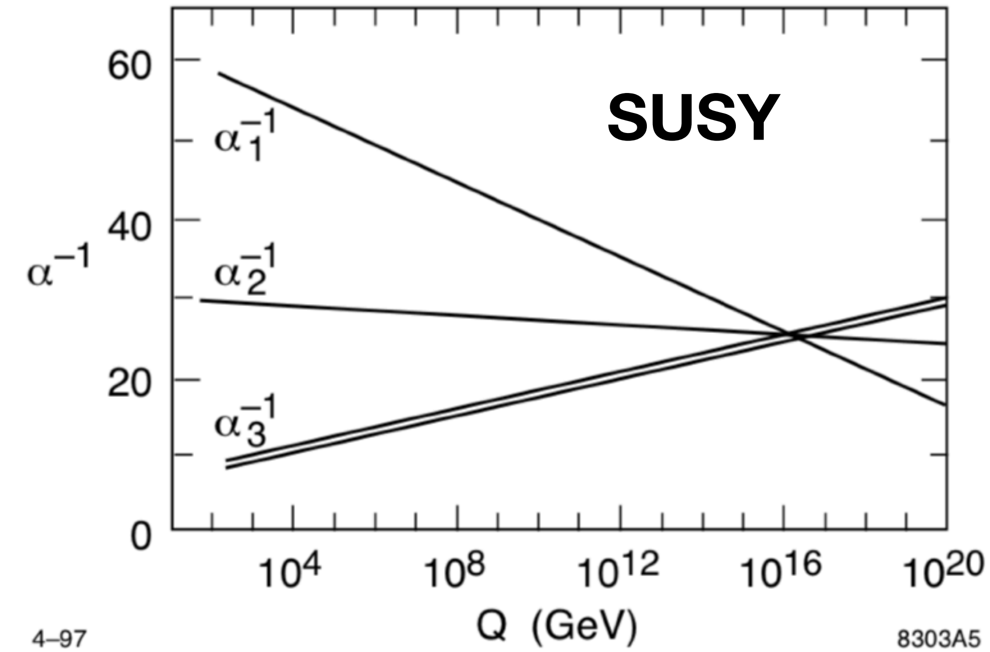
What is supersymmetry?

Supersymmetry

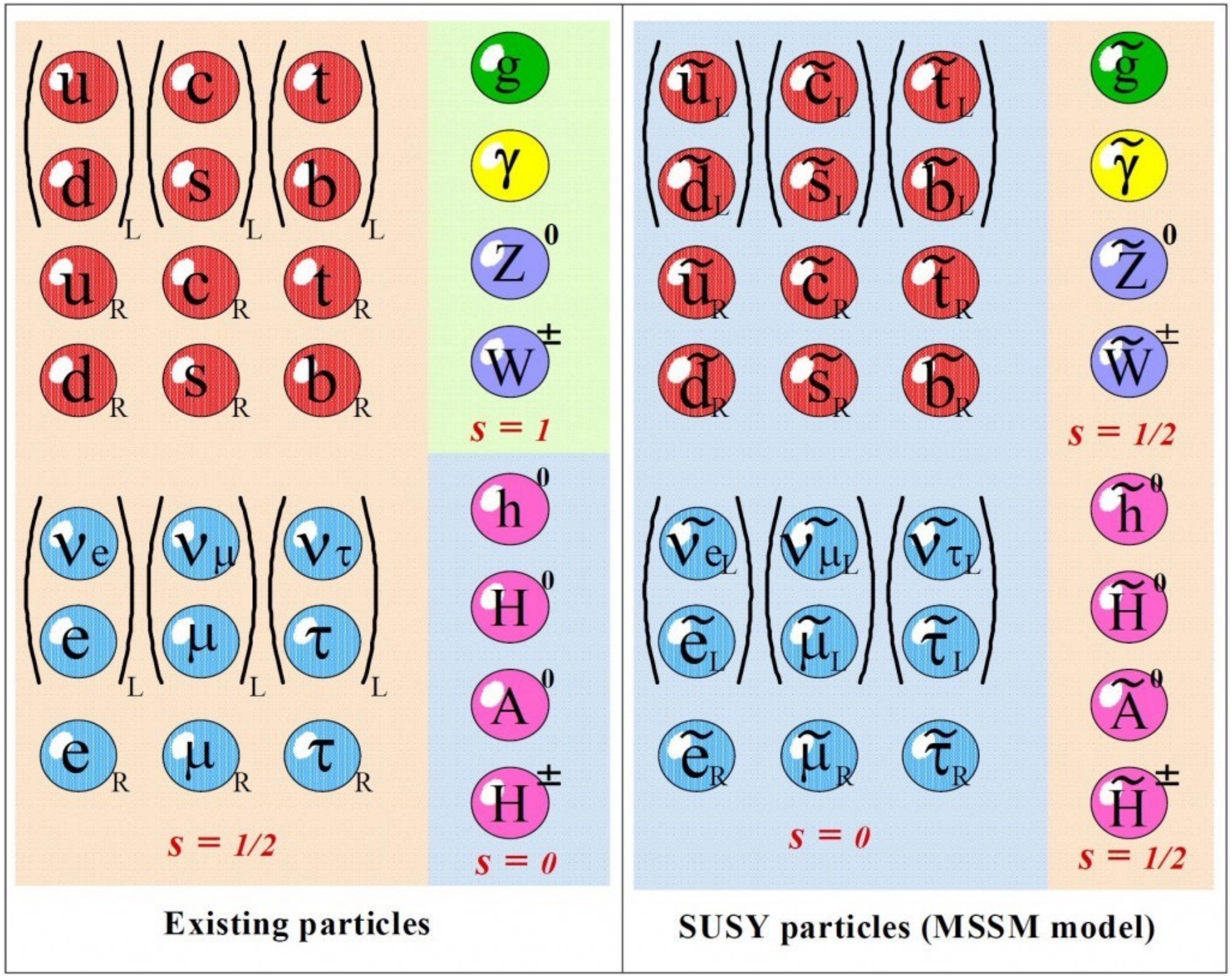
- New symmetry relating fermions and bosons
- Developed in the context of string theory (supergravity) and grand unified theories
- **Results in a superpartner for each SM particle, with same quantum numbers except for spin, which differs by 1/2**







Particles in the MSSM
(Minimal Supersymmetric Standard Model)



Partner particles are part of the same “supermultiplet”,
so they interact with the strong and electroweak forces in the same way

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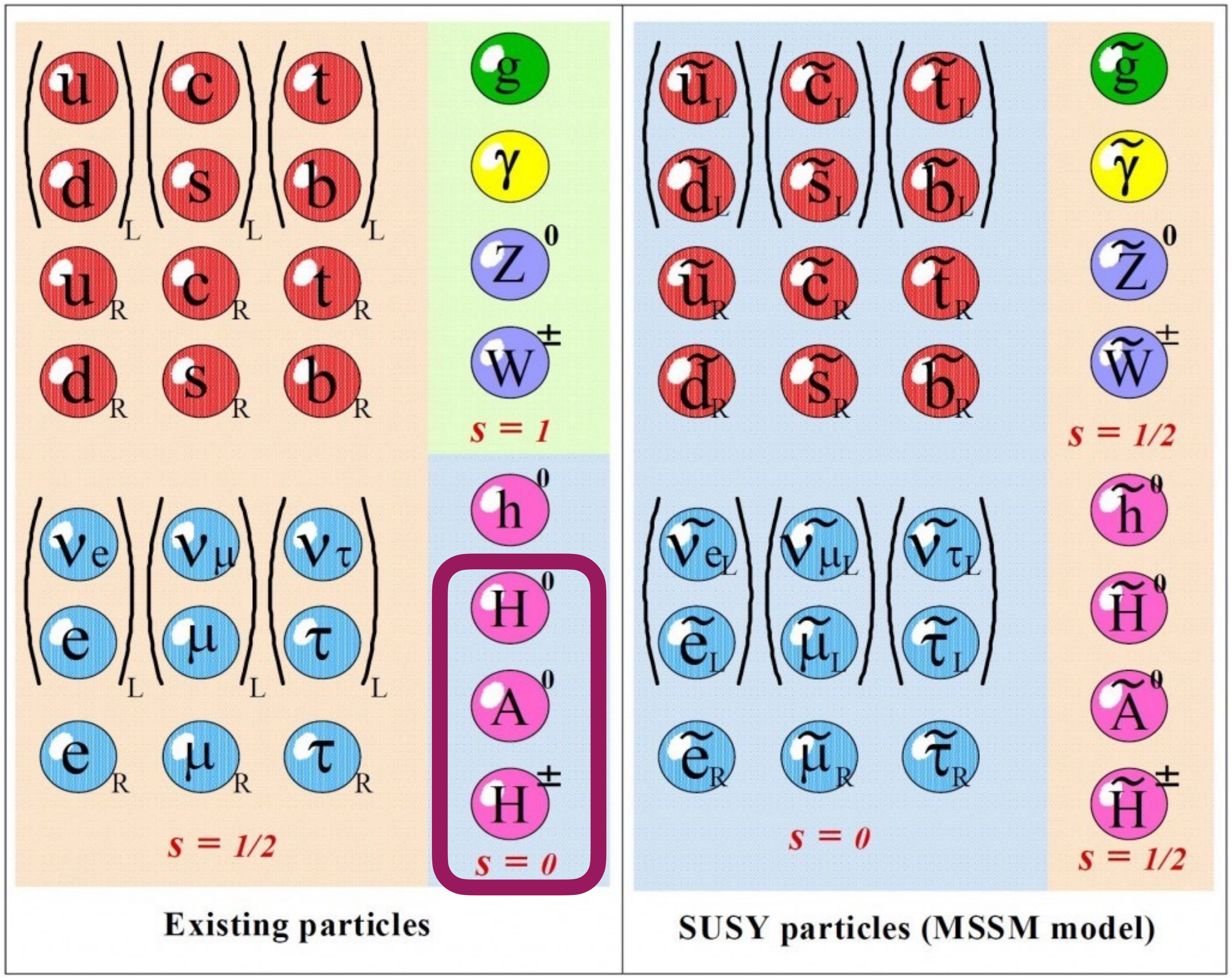
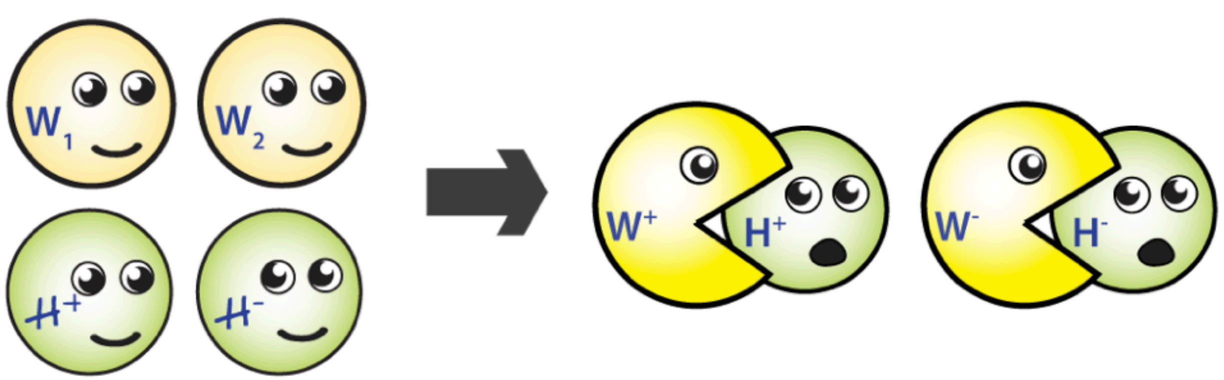
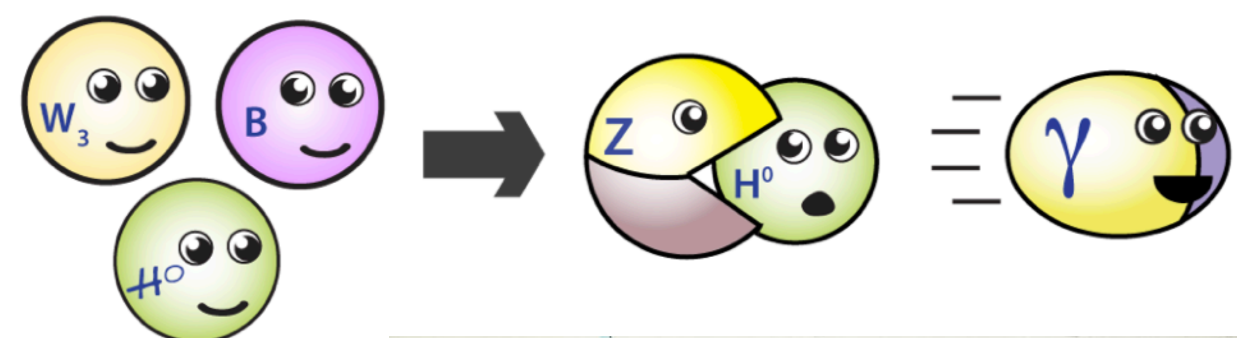


What are these extra Higgs bosons?

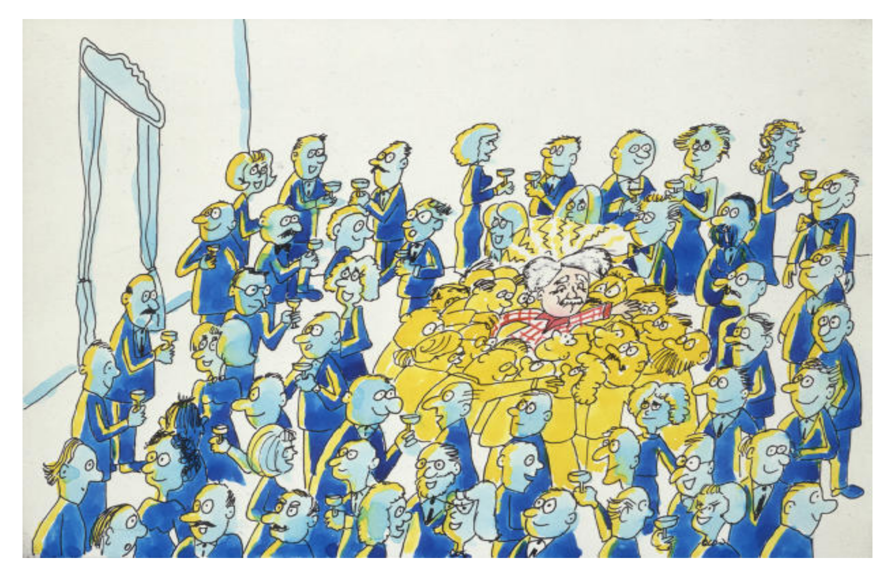
Recap: Higgs in the SM

- In SM, there is one Higgs field, with 4 degrees of freedom (dof):
  - After spontaneous symmetry breaking, 3 dof are used to give mass to $W^{\pm}$ and Z bosons
  - 1 dof remains, i.e. the Higgs boson, and the photon remains massless



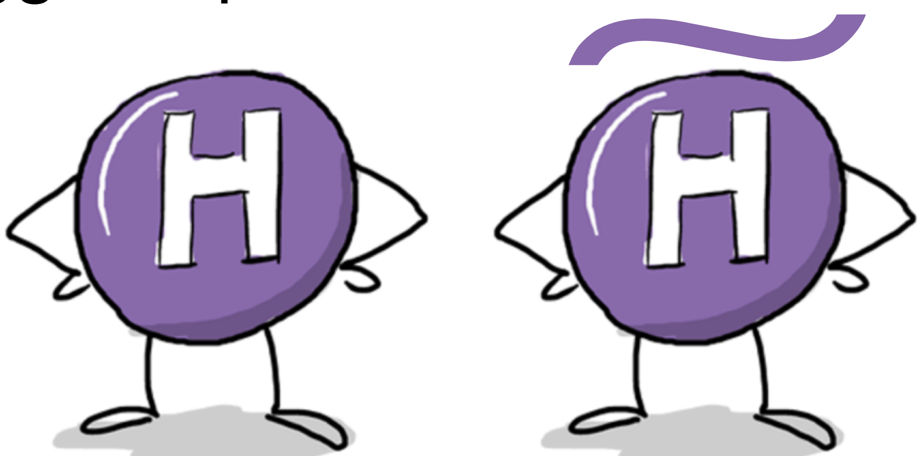


- Their coupling with the Higgs field gives mass to quarks and leptons



Higgs in the MSSM

- Through supersymmetry, the spin-0 Higgs field gets a spin-½ Higgsino partner.



Two Higgs doublets!

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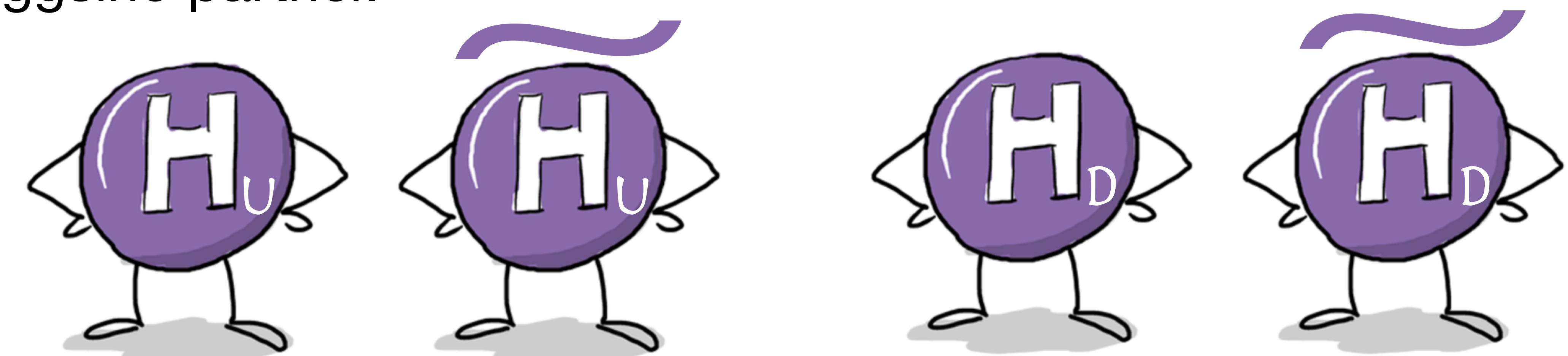

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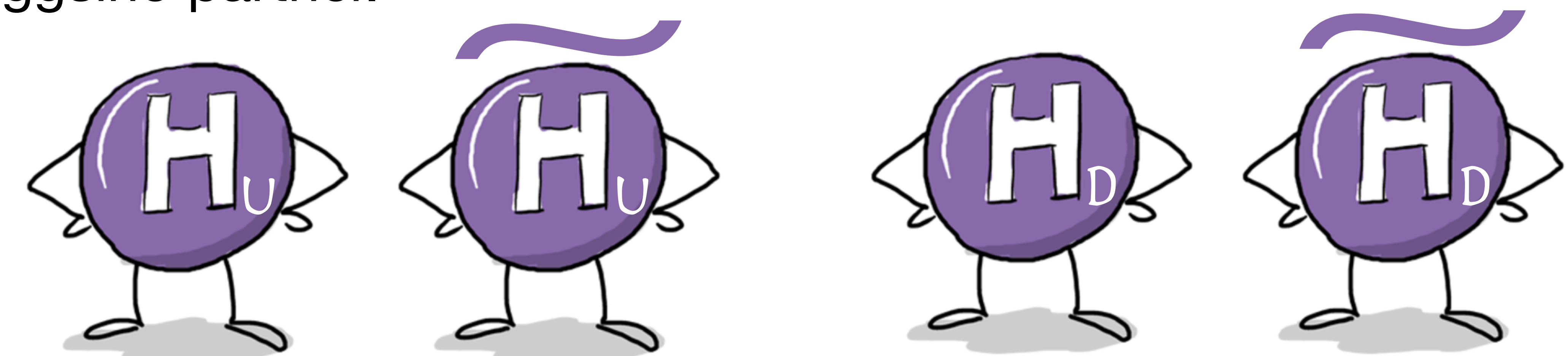
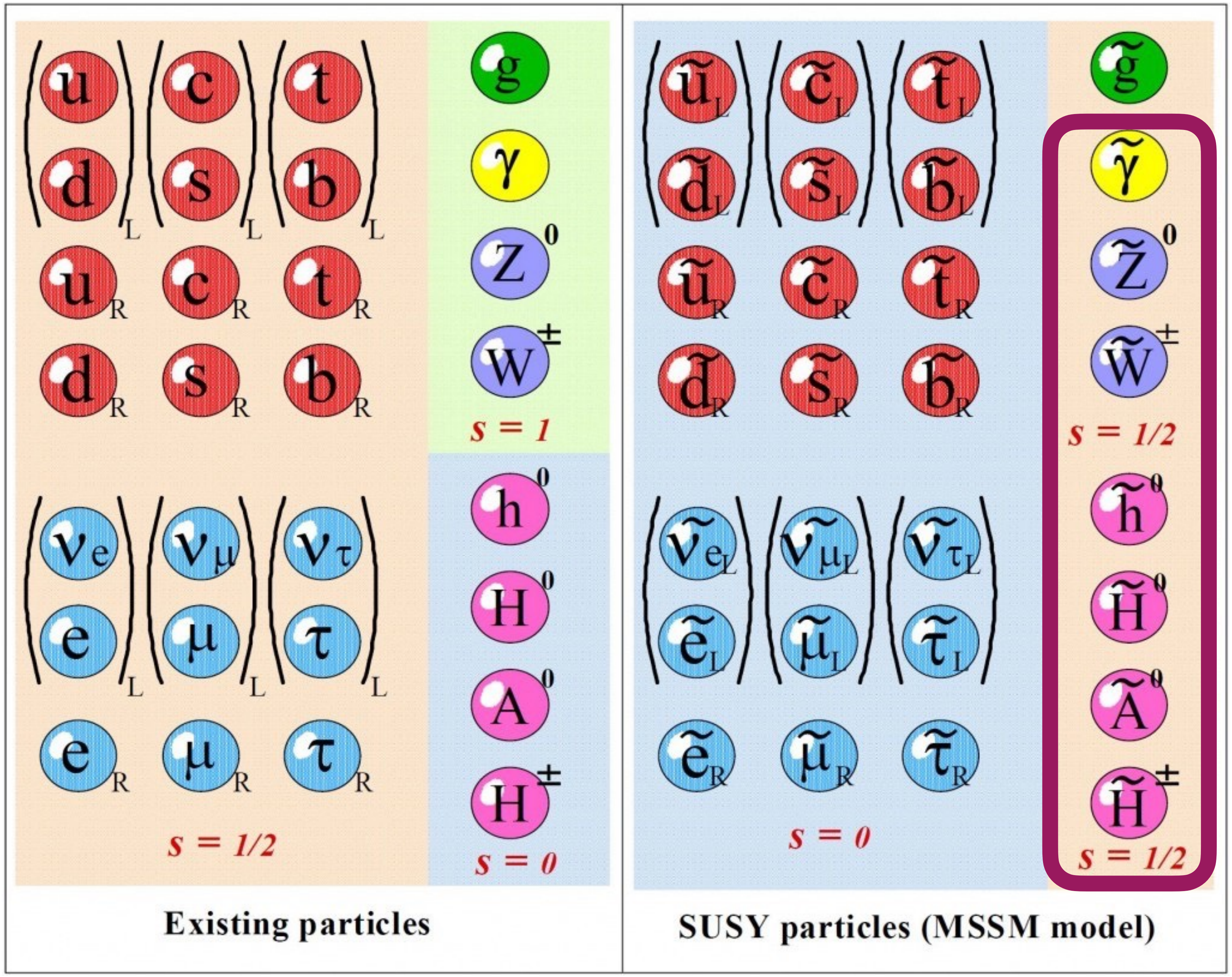


- In fact, we need two copies for things to work out
  - Reasons are pretty suble and require quantum field theory
- Now have 8 dof. We still need to use 3 to give mass to $W^{\pm}$ and Z bosons during electroweak symmetry breaking
- Result: **5 Higgs bosons** remaining (2 charged, 3 neutral)

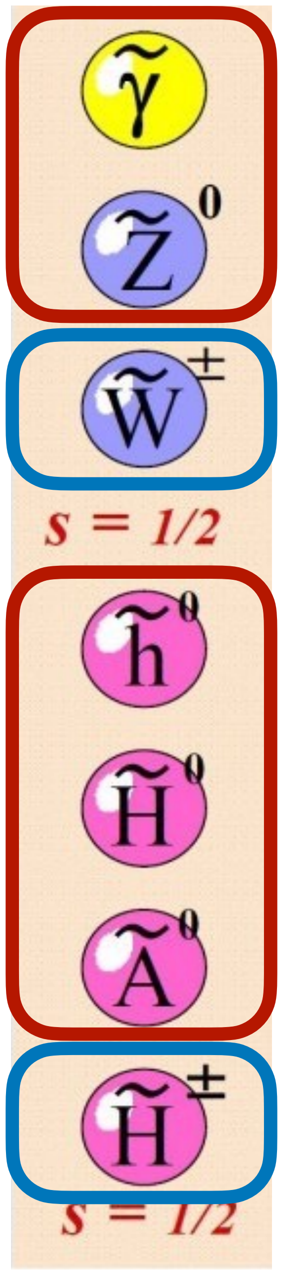
Particles in the MSSM
(Minimal Supersymmetric Standard Model)



These get mixed together

Neutralinos & Charginos

- After electroweak symmetry breaking, gauge eigenstates with the same quantum numbers can mix
- The charged electroweak gauginos (the winos) and the charged higgsinos mix to form "**charginos**"
- Similarly, the neutral higgsinos mix with the neutral wino and the bino (or photino and zino after EW symmetry breaking) to form "**neutralinos**"
- Mass eigenstates are determined by diagonalizing the mass matrices
- Details of this mixing matrix determine phenomenological properties of a given supersymmetric model



What are the benefits of supersymmetry?

And some caveats…

Naturalness

Alice is arranging a vase of flowers, when suddenly the doorbell rings.
On her way to the door, she puts the vase on a rickety table.
However, her rowdy toddlers are playing nearby…

What does she expect to find when she returns?

Analogy by Matt Strassler

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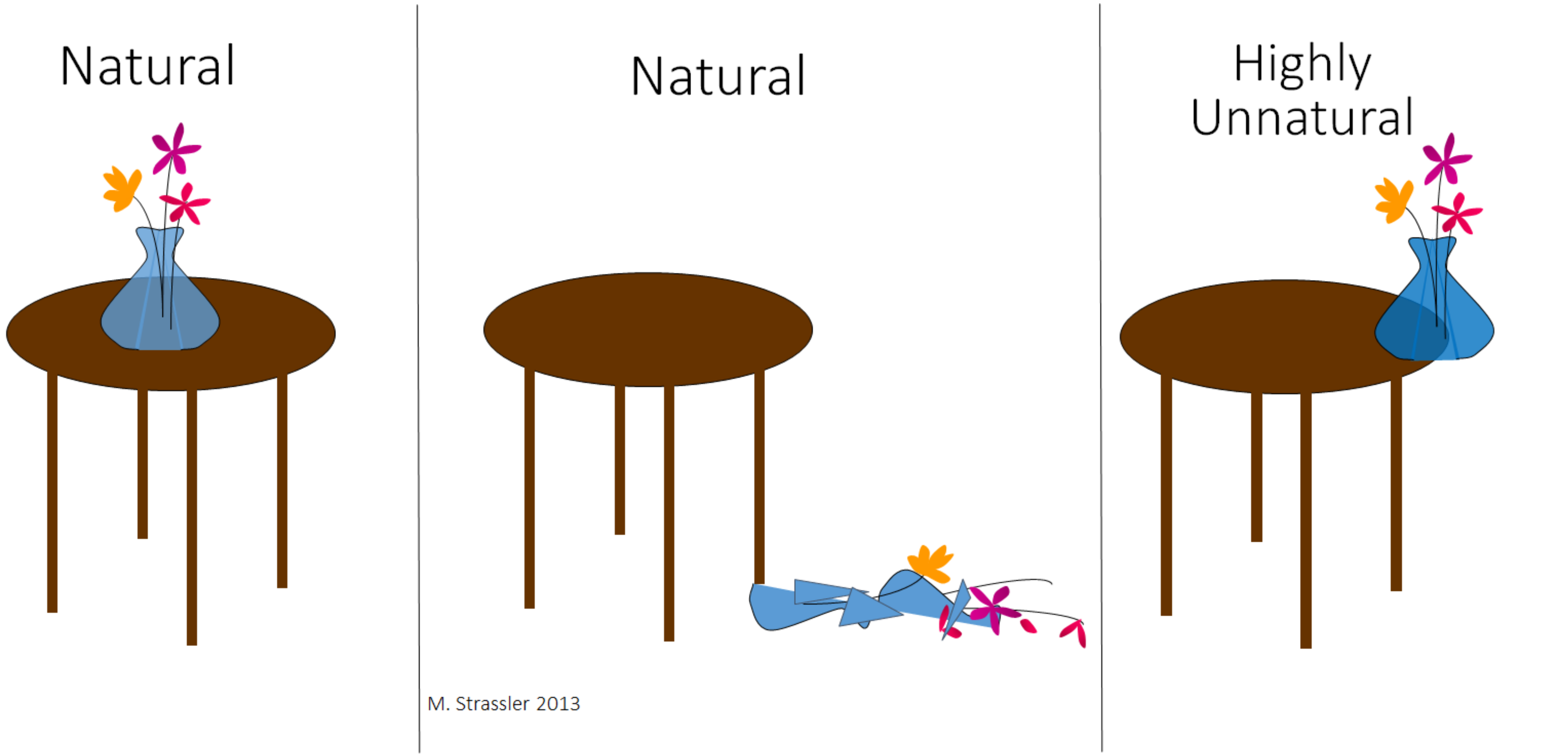

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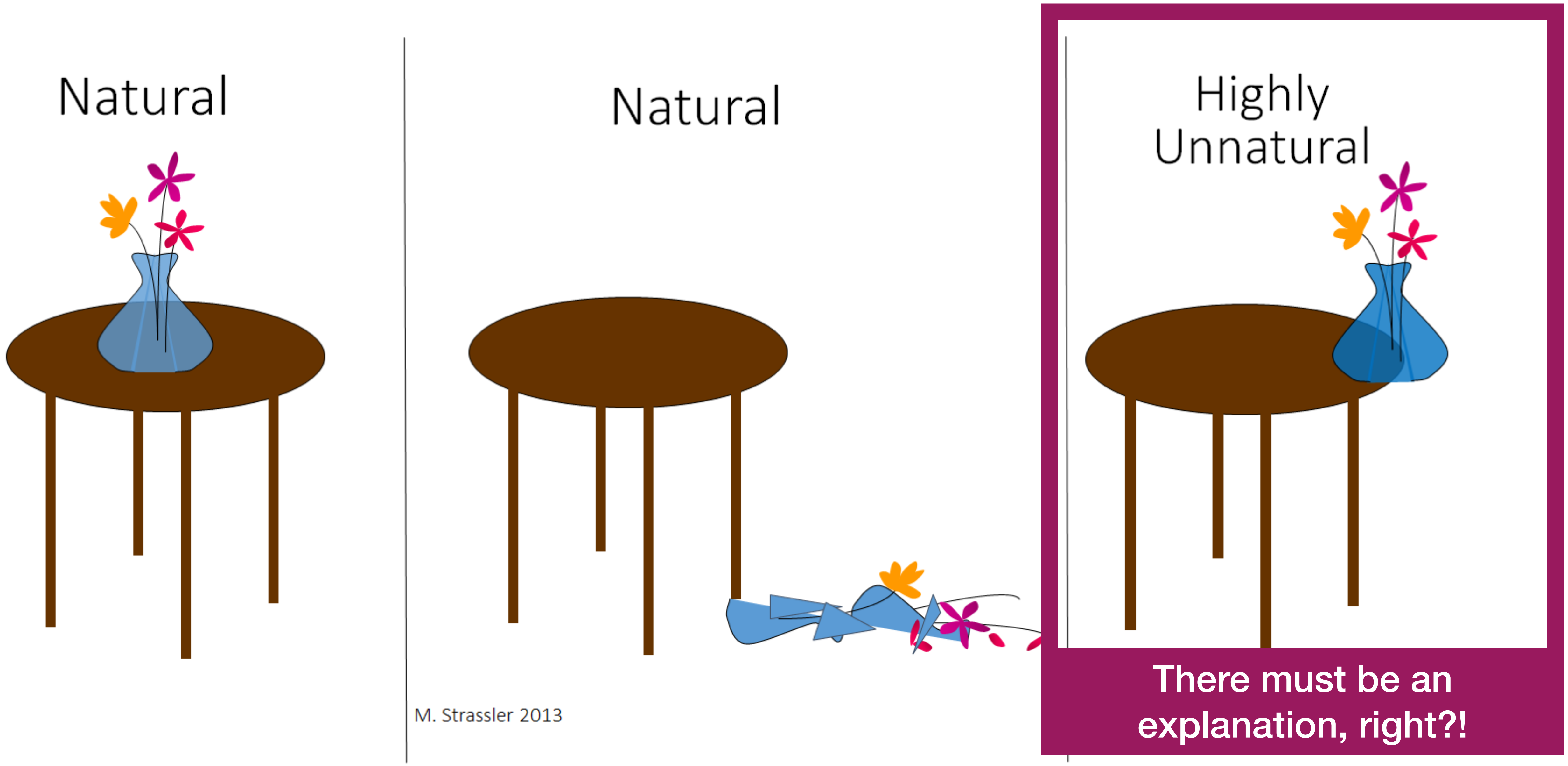
What did she find?

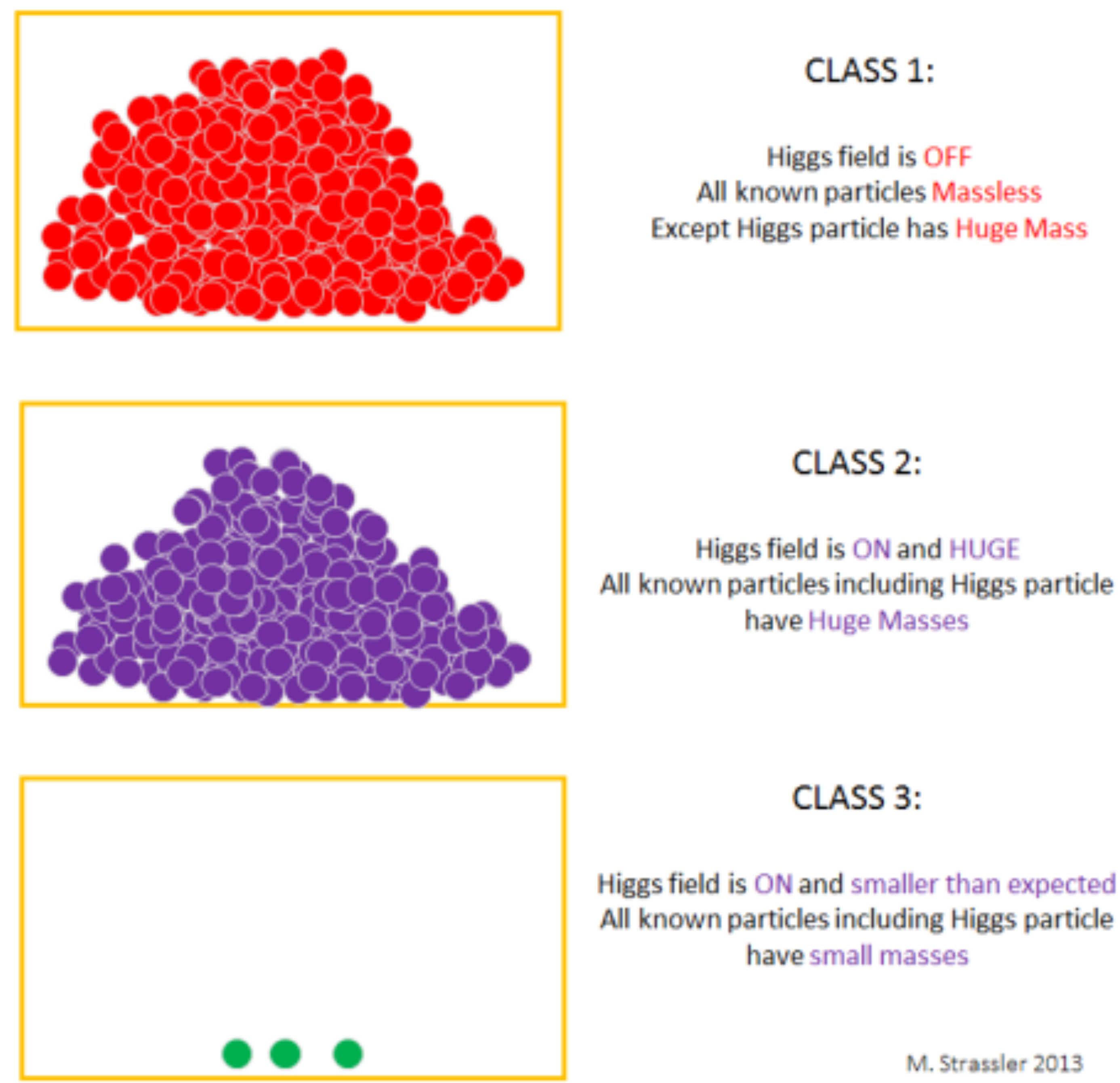


Analogy by Matt Strassler

Naturalness and the Higgs boson

Consider all possible universes where the only thing you change is the strength of the interaction of the Higgs field with other particles

You find three broad categories



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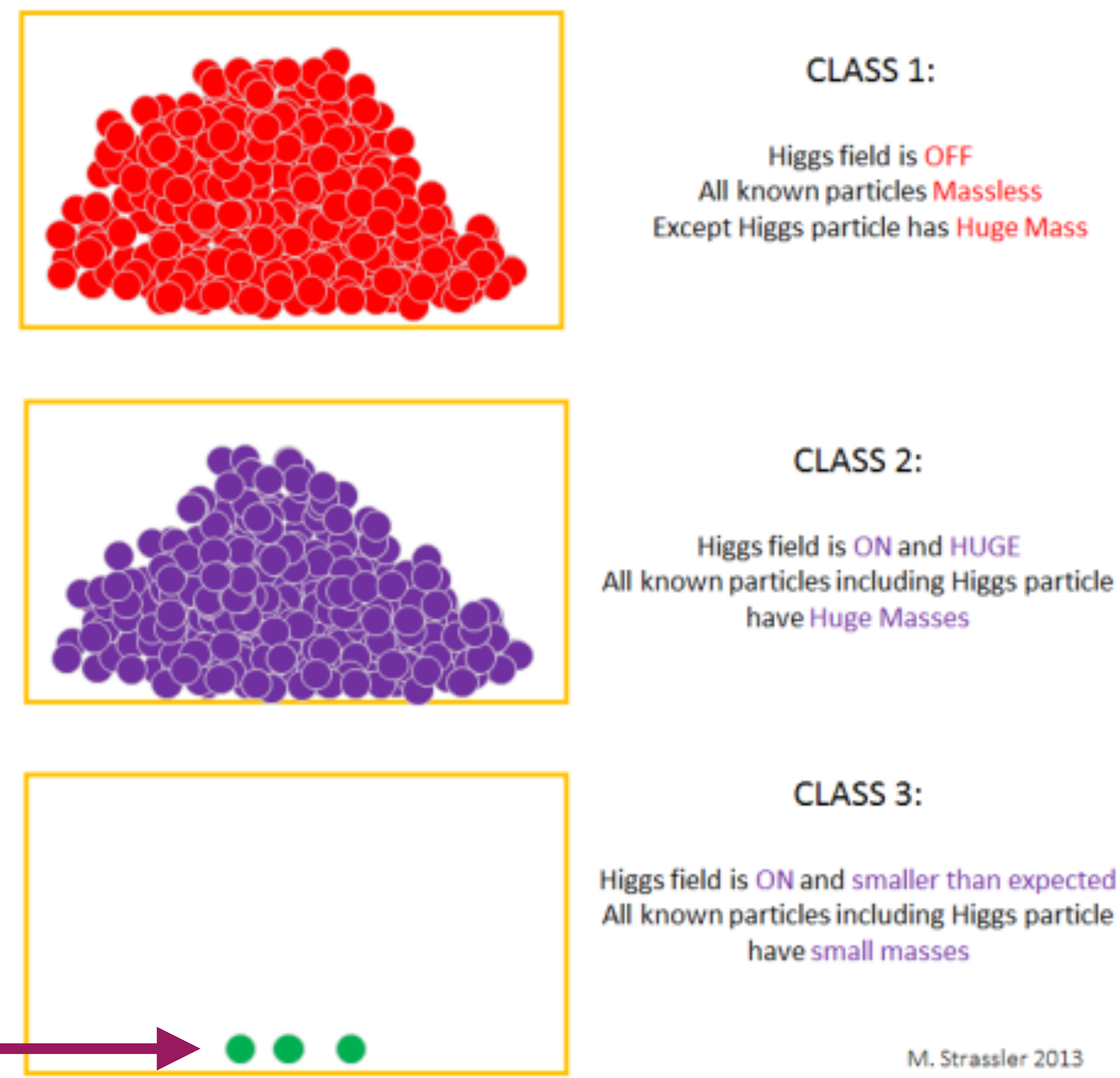
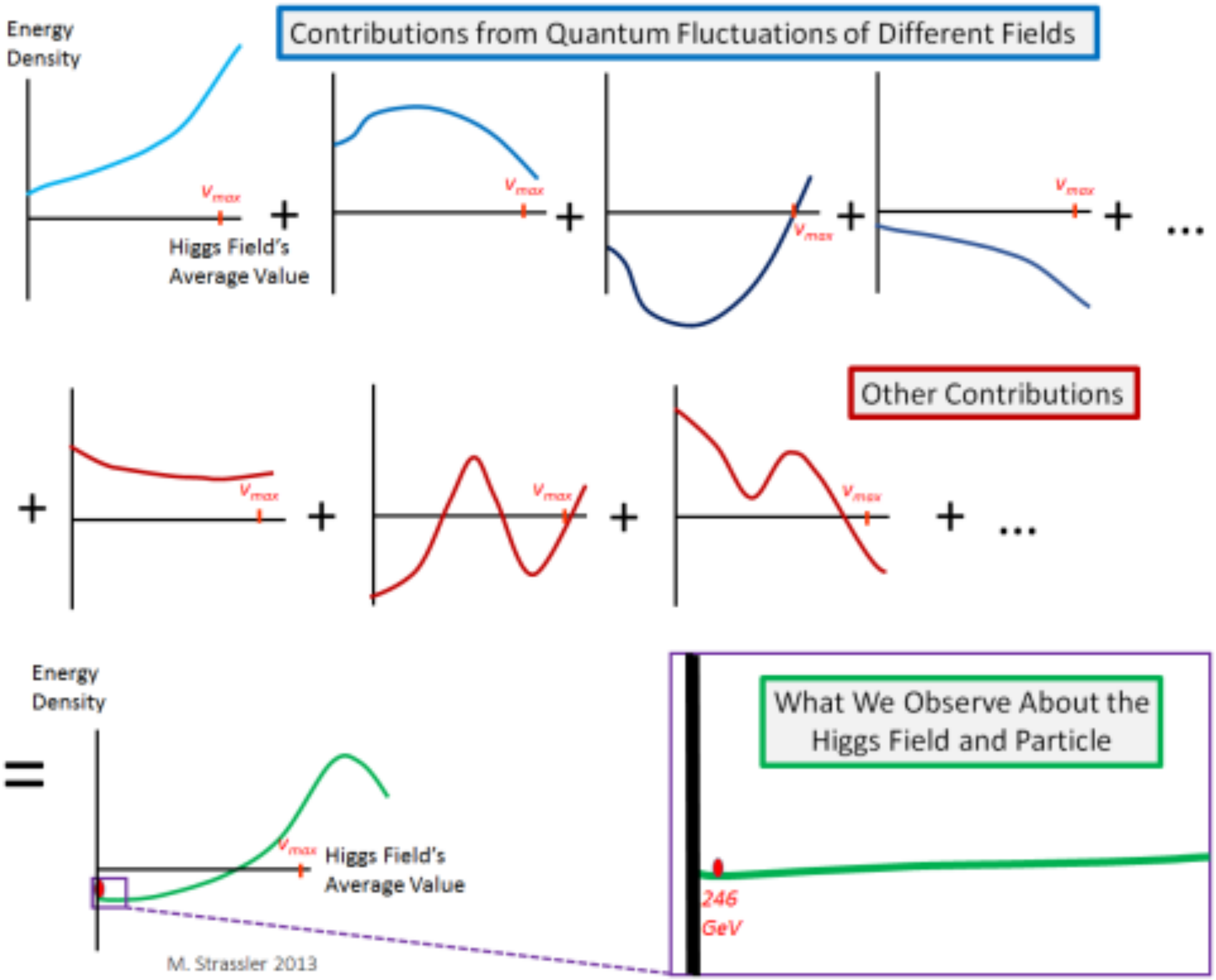


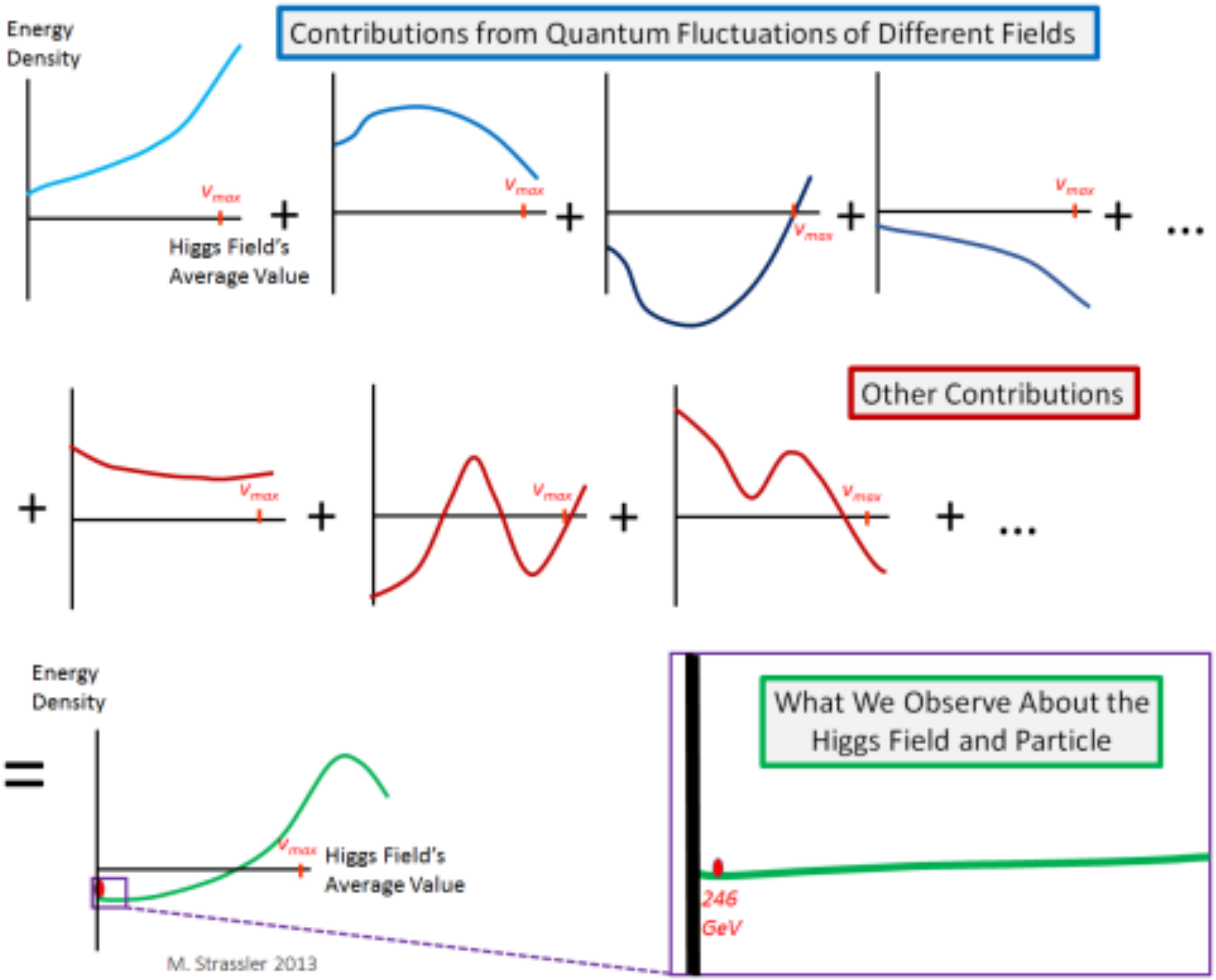
This is our universe
Why?

Naturalness and the Higgs boson



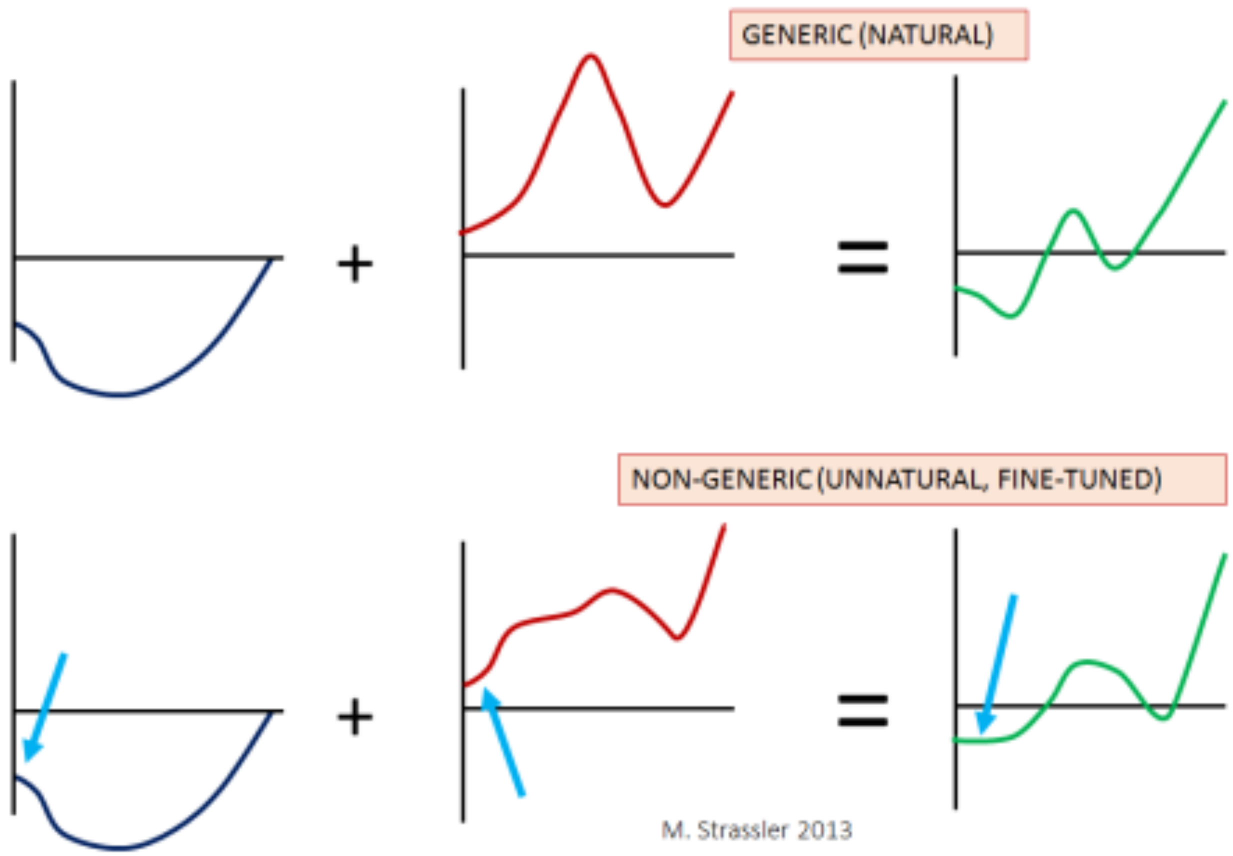
- The average value of the Higgs field and the mass of the Higgs boson depend on quantum fluctuations
- All other fields (particles) that exist in nature contribute! Also the ones we don't know about
- A priori, no reason to believe these unknown effects have anything to do with the known interactions/particles

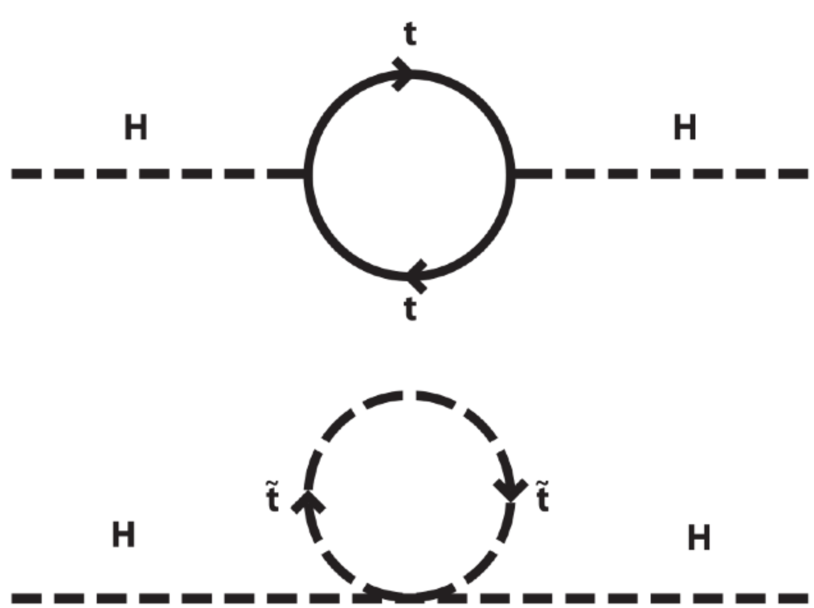
Naturalness and the Higgs boson



- Whether this seems unnatural depends on how far (in energy) we think the SM should hold
- If we assume it works until we need quantum gravity, we'd need precise cancellations of 1 in 10^{30}

Naturalness and the Higgs boson





Options to avoid this issue:

- The SM breaks down at a relatively low energy
  - Could be any number of new physics models
- The other contributions do have a relationship with the known ones
  - **Supersymmetry is one such example since SUSY particles contribute with opposite sign to the quantum corrections**

Caveat: SUSY breaking

- **Unbroken SUSY → superpartners have same mass as their SM counterparts**
  - Problem: these would have been discovered a long time ago
  - SUSY must be broken, i.e. sparticles must have larger mass
- Should only allow **“soft” SUSY breaking**
  - Don’t spoil nice cancellation that mitigates naturalness
  - Hard to write down nice way to break SUSY
  - Usually treated as low-energy effective theory

$$\mathcal{L} = \mathcal{L}_{\mathrm{SUSY}} + \mathcal{L}_{\mathrm{soft}}$$

- Gives many new free parameters in the model (105 for MSSM)
  - gaugino and sfermion masses, bi- and trilinear couplings

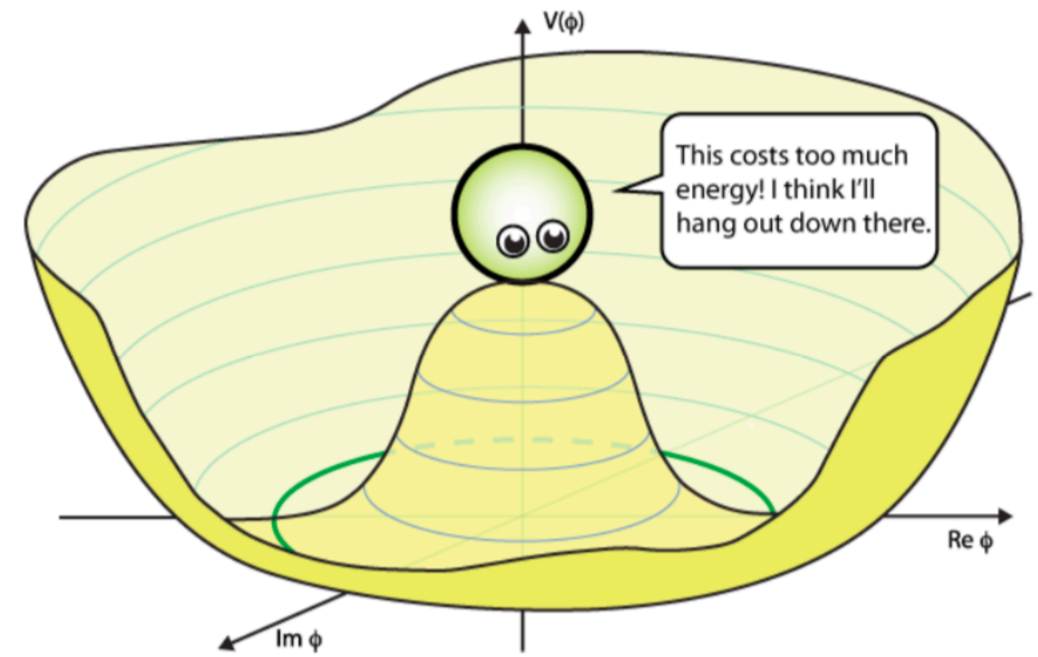
SUSY breaking and EW symmetry breaking

- The SM Higgs potential:

$$V = m_H^2 |H|^2 + \lambda |H|^4$$

- Electroweak symmetry breaking occurs when

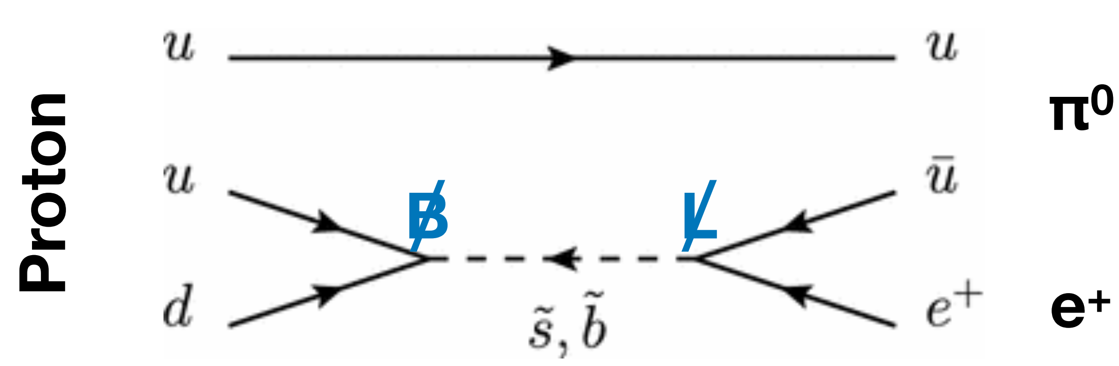
$$\lambda > 0 \text{ and } m_H^2 < 0.$$



- In SM the form of the Higgs potential, as well as these conditions are explicit assumptions
- In SUSY, there is "**radiative electroweak symmetry breaking**"
  - Form of the Higgs potential is a derived quantity in the case of SUSY with soft breaking
  - EW symmetry breaking condition is naturally satisfied as well

Supersymmetry & R-parity

- SUSY introduces new particles, and also new interactions that include those new particles
- Some of these **interactions can violate baryon and lepton number conservation** → could lead to rapid proton decay



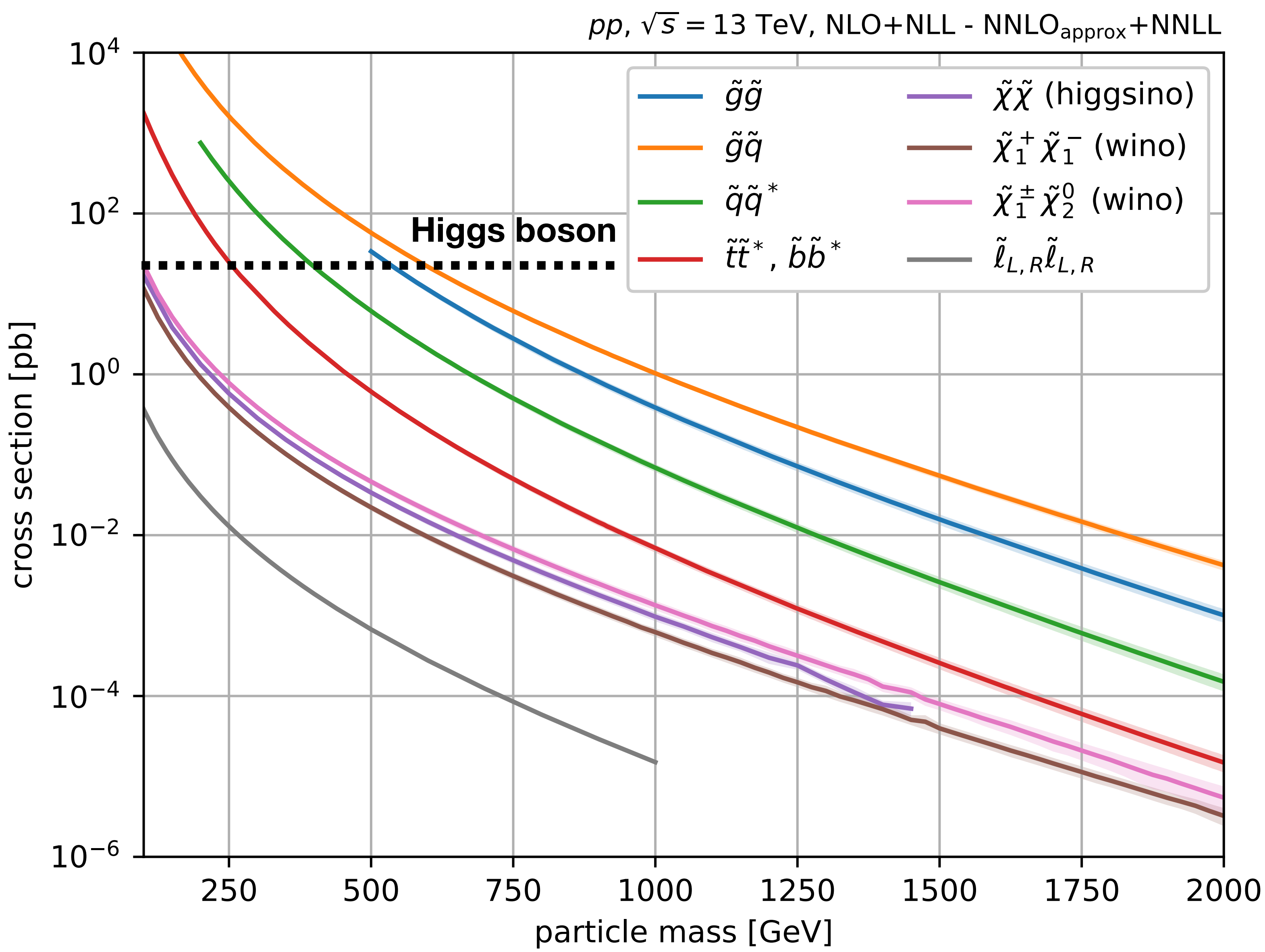
- Can avoid this problem by introducing **R-parity conservation**
  - New (multiplicative) quantum number: R-parity
  - SM particles have R_P = +1, SUSY particles have R_P = -1
- Significant impact on SUSY phenomenology
- Note: other ways possible to avoid proton decay, but this one is very popular

How do we look for these particles?

… at the LHC …

How and how often are these sparticles produced?

- R-parity conservation implies that SUSY particles are **always produced in pairs**!
- Squark and gluino pair production has highest cross section
- Chargino-neutralino has lower cross section
- Sleptons have lowest cross section at LHC



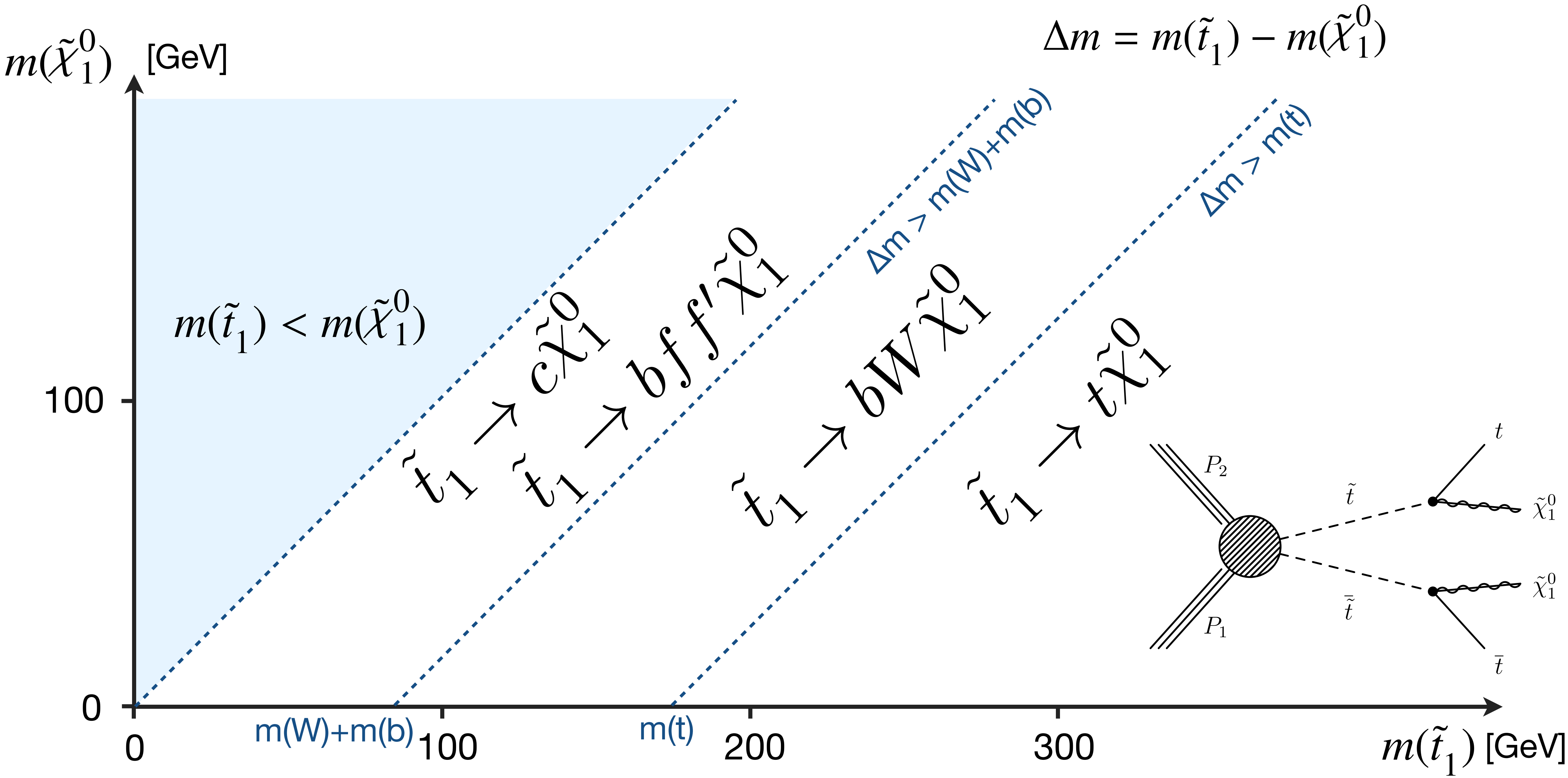
1 pb = 100,000 events at 100 fb^{-1}

Sparticle decays

- Once produced, supersymmetric particles typically don't live very long. Instead they decay into other particles.
- **With R-parity conservation, a sparticle** ($R_P = -1$) **always decays into another sparticle plus N regular particles** ($R_P = -1 * (+1)^N$)
- A particle can only decay to other particles if its mass is larger than the sum of the masses of the other particles.
- So**, how a given sparticle decays depends on its mass and on the masses of all other sparticle types as well**
  - 2-body decays dominate if allowed, e.g.
    - squark → quark + neutralino/chargino
    - slepton → lepton + neutralino/chargino
  - 3- or 4-body decays dominate if mass splittings are small
    - top squark → b + W + neutralino

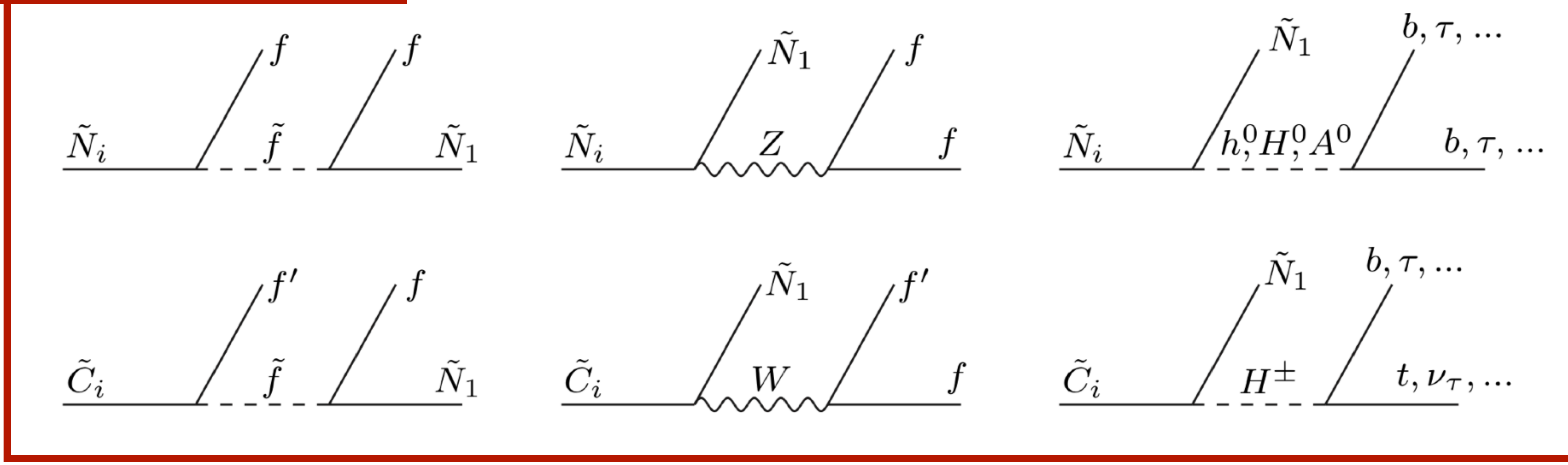
Sparticle decays

- Example for top squarks:

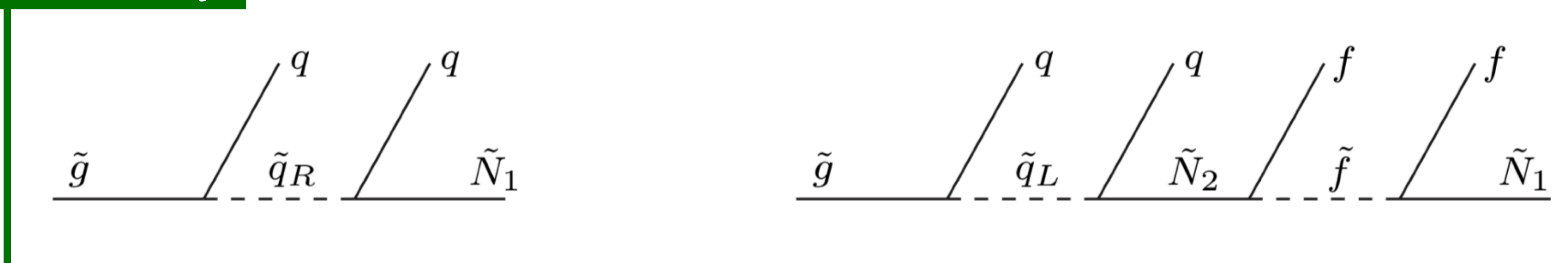


More decay examples

Electroweakino decays



Gluino decays

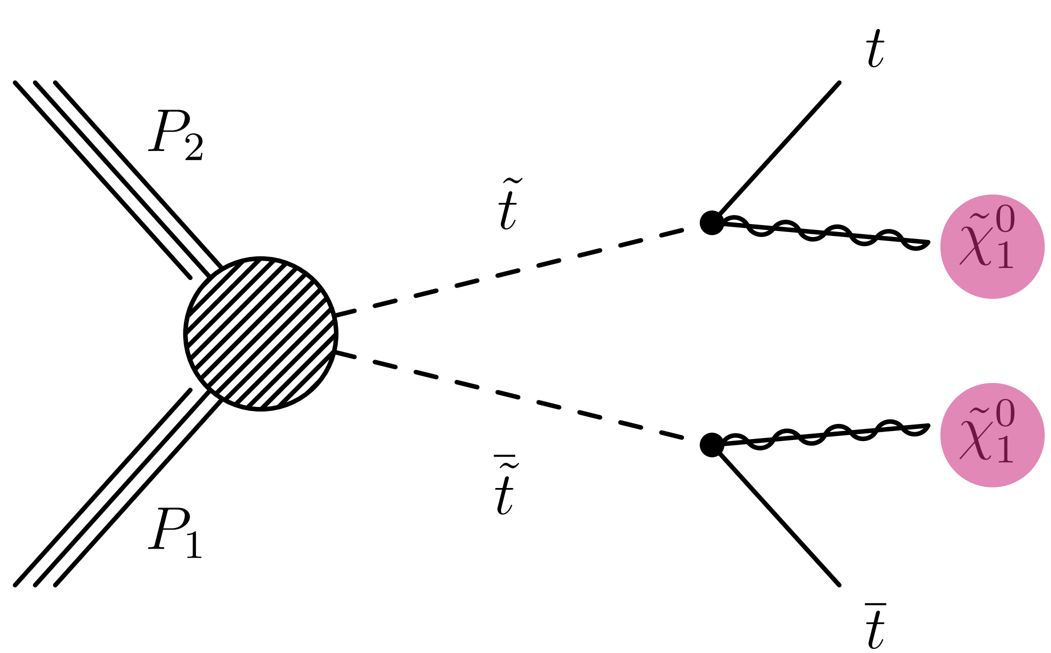


In general, SUSY models display a rich variety of possible final states!

Good general benchmark model

Sparticle decays

- With R-parity conservation, a sparticle ($R_P = -1$) always decays into another sparticle plus N regular particles ($R_P = -1 * (+1)^N$)
- **This also implies that the Lightest Supersymmetric Particle (LSP) has to be stable: it has no other sparticle to decay into!**
- In many models the LSP is a neutralino
    - Neutral and only couples via the weak interaction
    - Neutralino LSP can be a **dark matter candidate**



These do not interact with the CMS detector, they escape unnoticed!

Missing transverse momentum

- Escaping particles result in “missing transverse momentum”
- Recall basic principle in nature:

Momentum is conserved in collisions

- This also holds in particle collisions

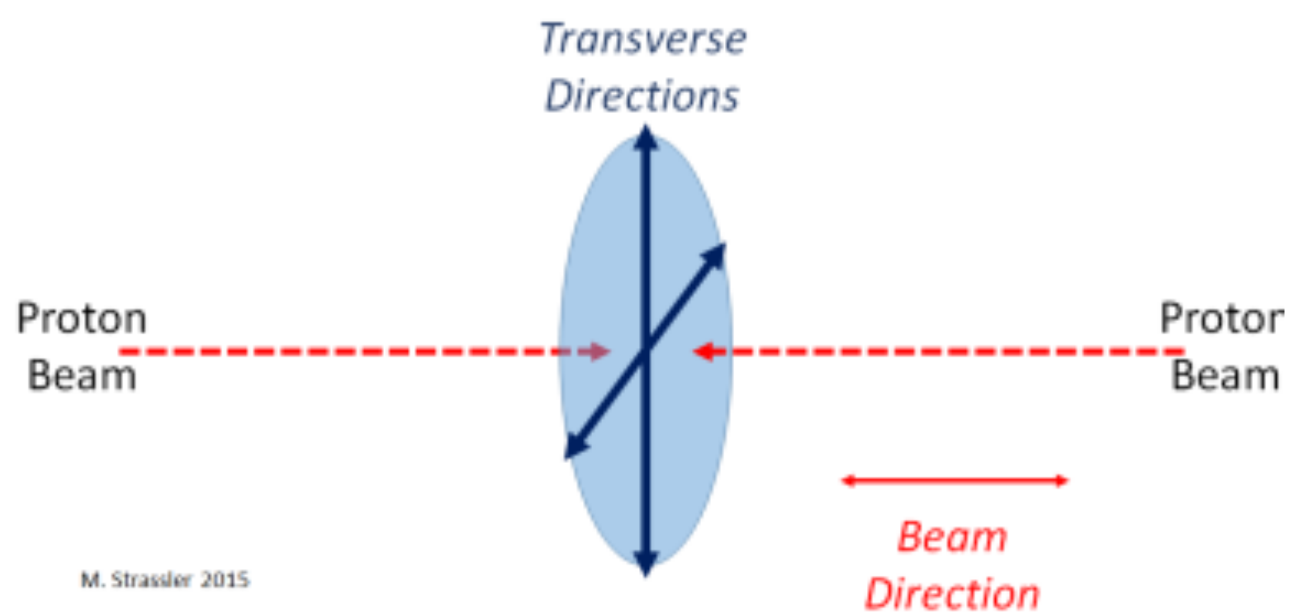
Missing transverse momentum

- Escaping particles result in “missing transverse momentum”
- Recall basic principle in nature:

Momentum is conserved in collisions

- This also holds in particle collisions
- One problem: **at the LHC, we collide protons**
  - Protons are not point-like
  - The collision is actually between the quarks/gluons inside the proton
  - **For any given collision, we don’t know what the energy/ momentum was of the quarks/gluons that actually collided!**
- But, we do know that the protons are travelling in a particular direction

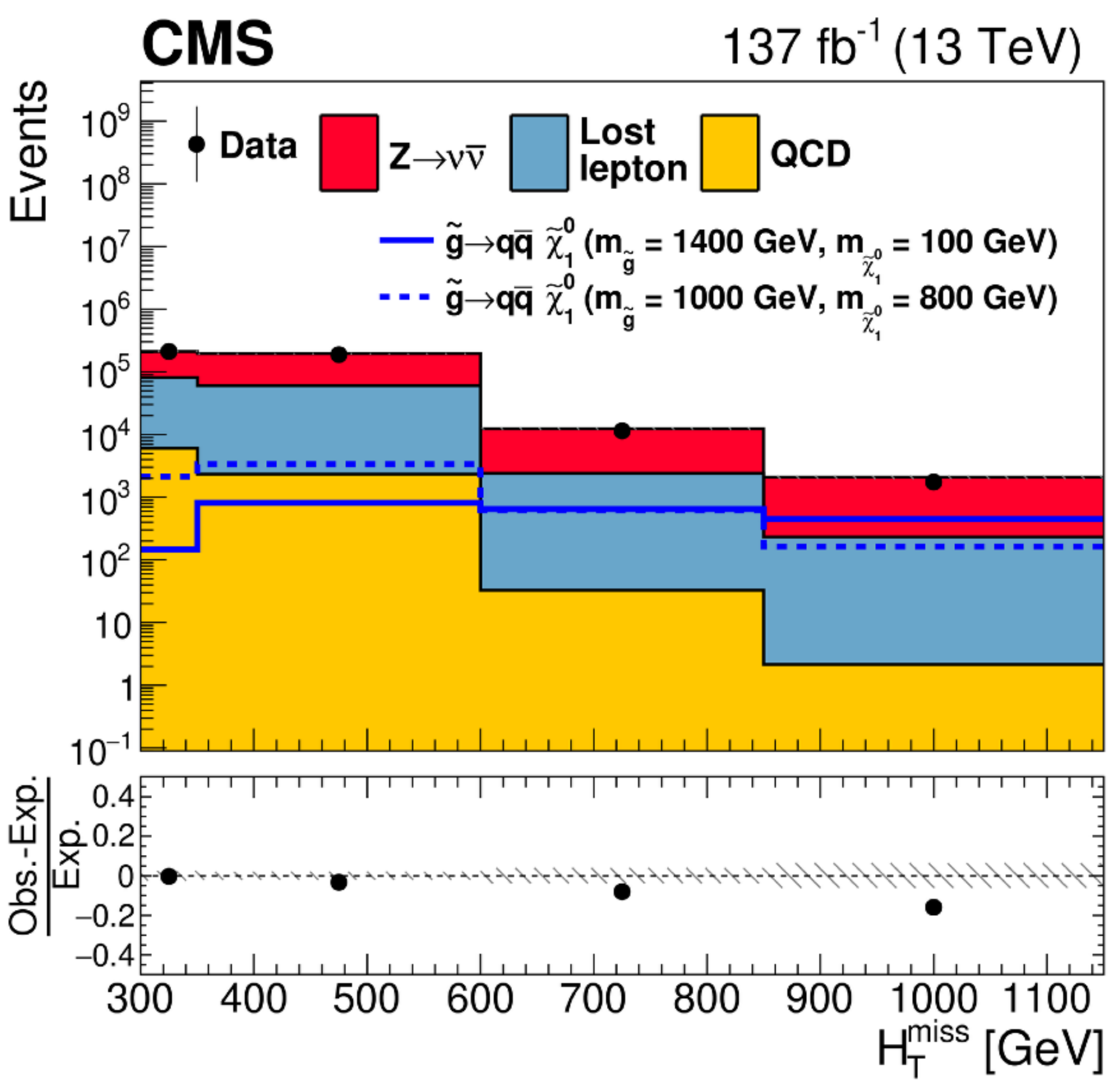
Missing transverse momentum



- Before:
    - Only momentum is along the beam axis
    - Momentum in transverse direction = 0
- After: Still the same! (Momentum conservation)
- So, if we were able to detect all particles produced in the collision, the sum of their momenta in the transverse plane should add up to 0 as well
- If not, e.g. because a neutralino (or neutrino) escaped, there is "missing transverse momentum"

How to design a search for supersymmetry at the LHC?

1. (Typically) **require large amount of missing transverse momentum**
   - Most backgrounds don't have much, and our signal is expected to have a large amount

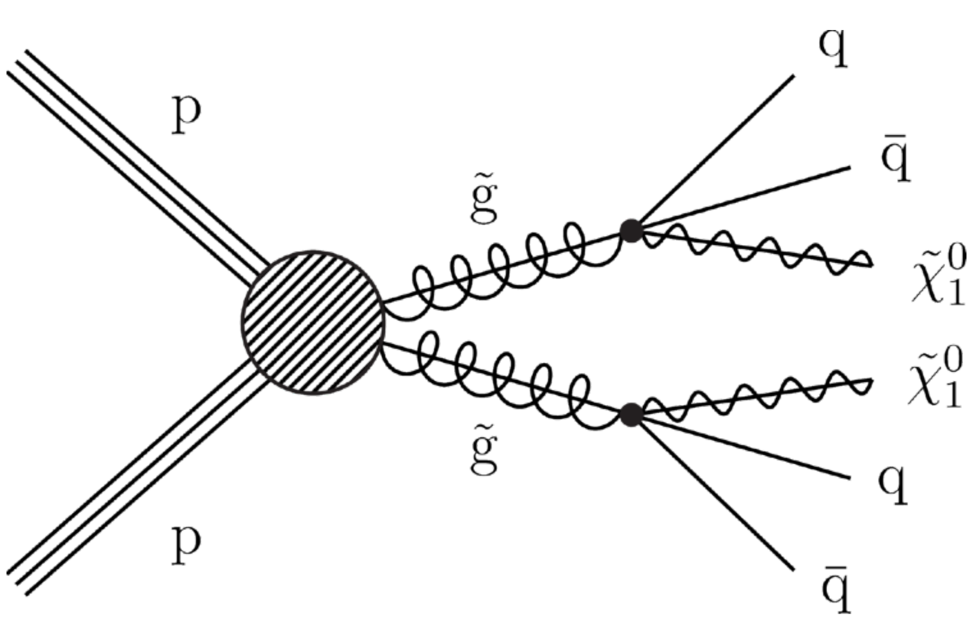


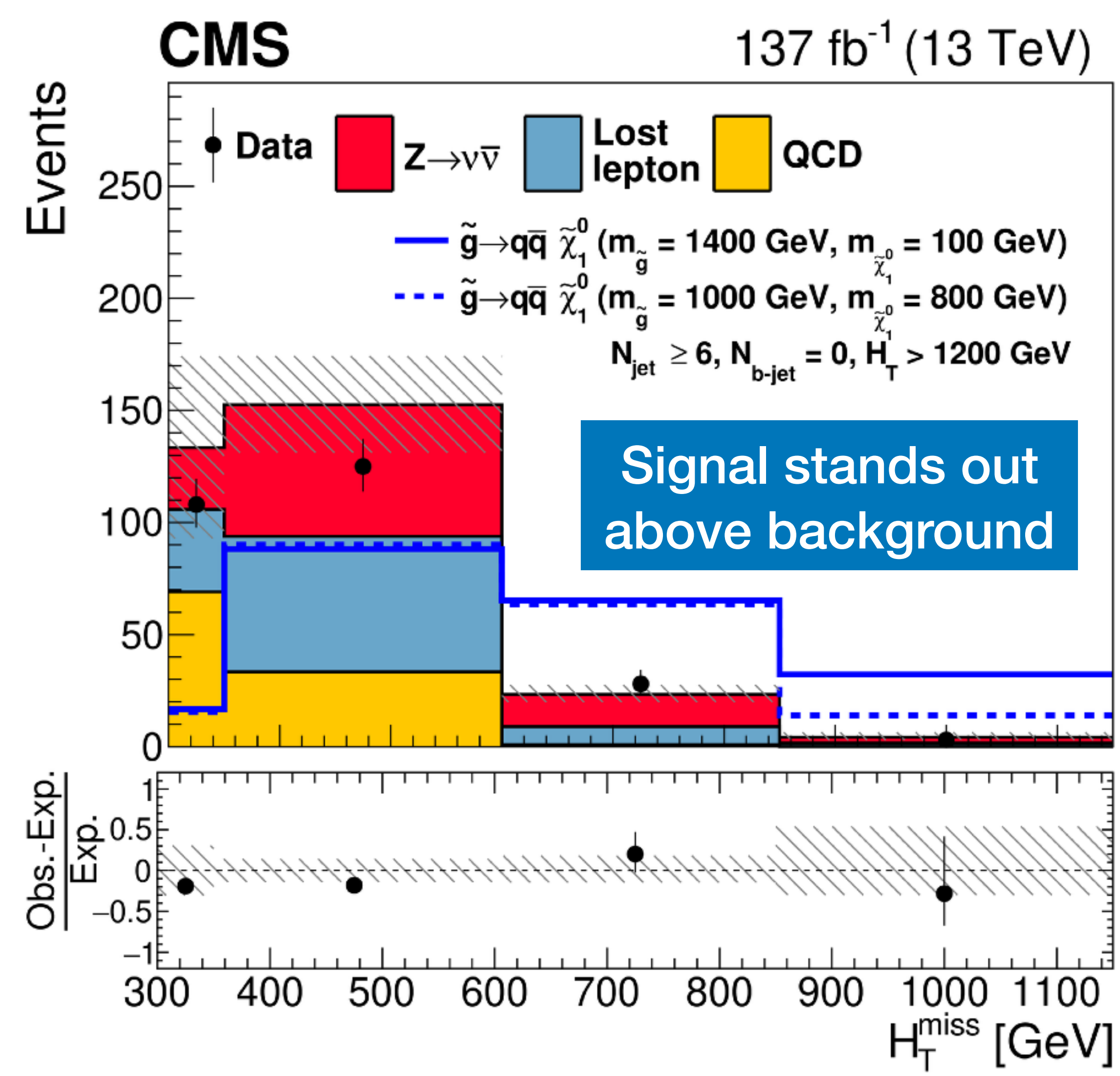
Note that the backgrounds have a falling spectrum (colored, filled histograms)

And the signal has a much flatter spectrum (overlaid lines)

How to design a search for supersymmetry at the LHC?

1. (Typically) Require large amounts of missing transverse momentum
2. **Require additional criteria to enhance the signal vs background,** e.g. require that there are a minimum number of jets, a particular number of b-tagged jets, a minimum amount of total momentum, etc.





How to design a search for supersymmetry at the LHC?

1. (Typically) require large amounts of missing transverse momentum
2. Require additional criteria to enhance the signal vs background
3. **Estimate the contribution from standard model processes**
   - Typical way is to find a "control region" in the data that is similar to the "signal region" but won't contain the signal; and then transfer the background yield over

$$N_{\mathrm{BG}}^{\mathrm{SR}} = \mathrm{TF} \times N_{\mathrm{BG}}^{\mathrm{CR}}$$

     TF can be computed using simulation or using data
   - This is the hardest part of the analysis
   - Very important to properly quantify the uncertainties!

How to design a search for supersymmetry at the LHC?

1. (Typically) require large amounts of missing transverse momentum
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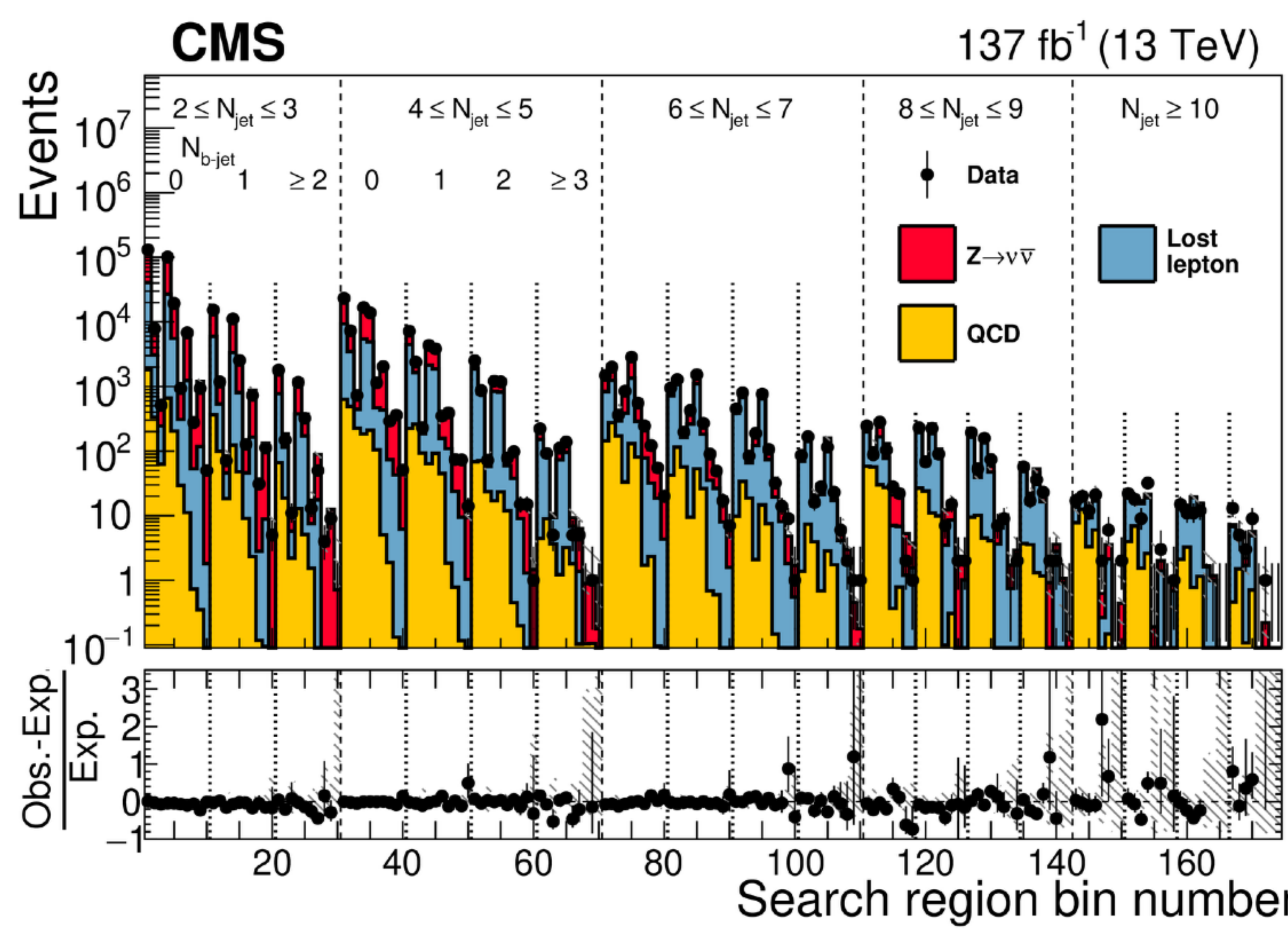
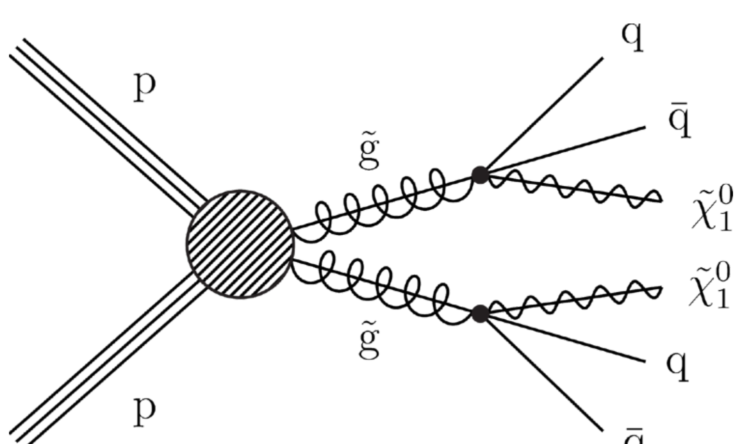
3. Estimate the contribution from standard model processes
4. Look in data to see whether your prediction matches the observation within uncertainties



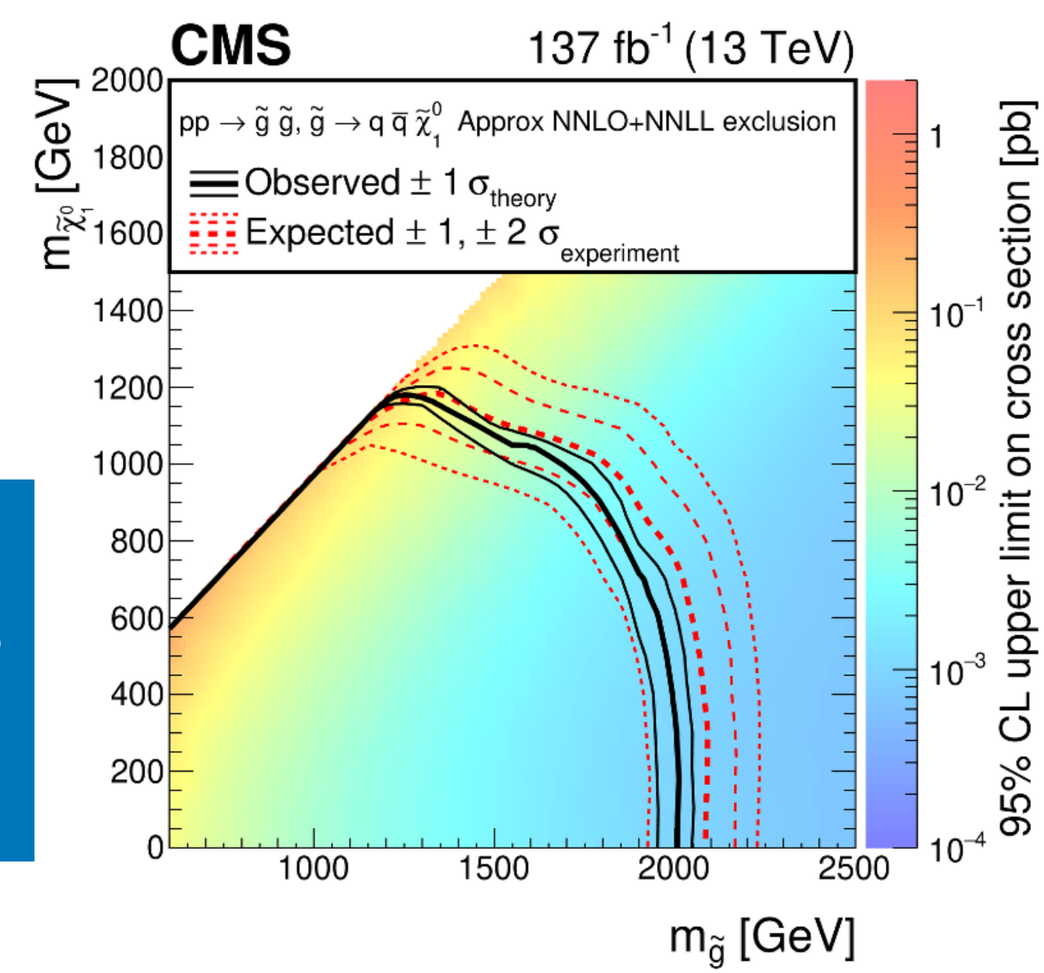
Example of a search with 174 distinct "signal regions" targeting a wide variety of SUSY models

How to design a search for supersymmetry at the LHC?

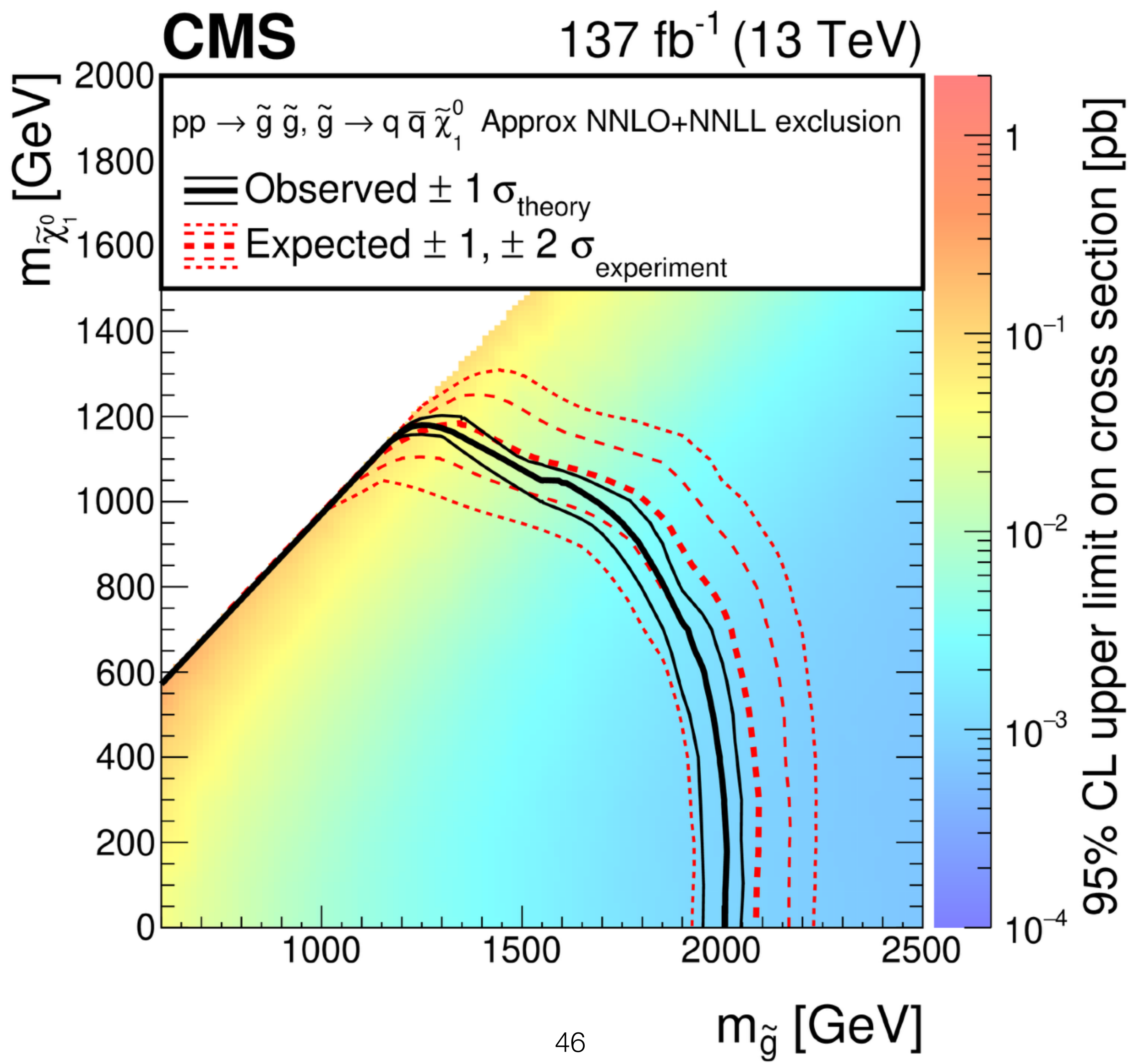
1. (Typically) require large amounts of missing transverse momentum
2. Require additional criteria to enhance the signal vs background
3. Estimate the contribution from standard model processes
4. Look in data to see whether your prediction matches the observation within uncertainties
5. Interpret the results in various SUSY models as limits on the allowed masses
(or discover something!)



This search excludes gluinos up to a mass of 2 TeV



How to read an exclusion plot



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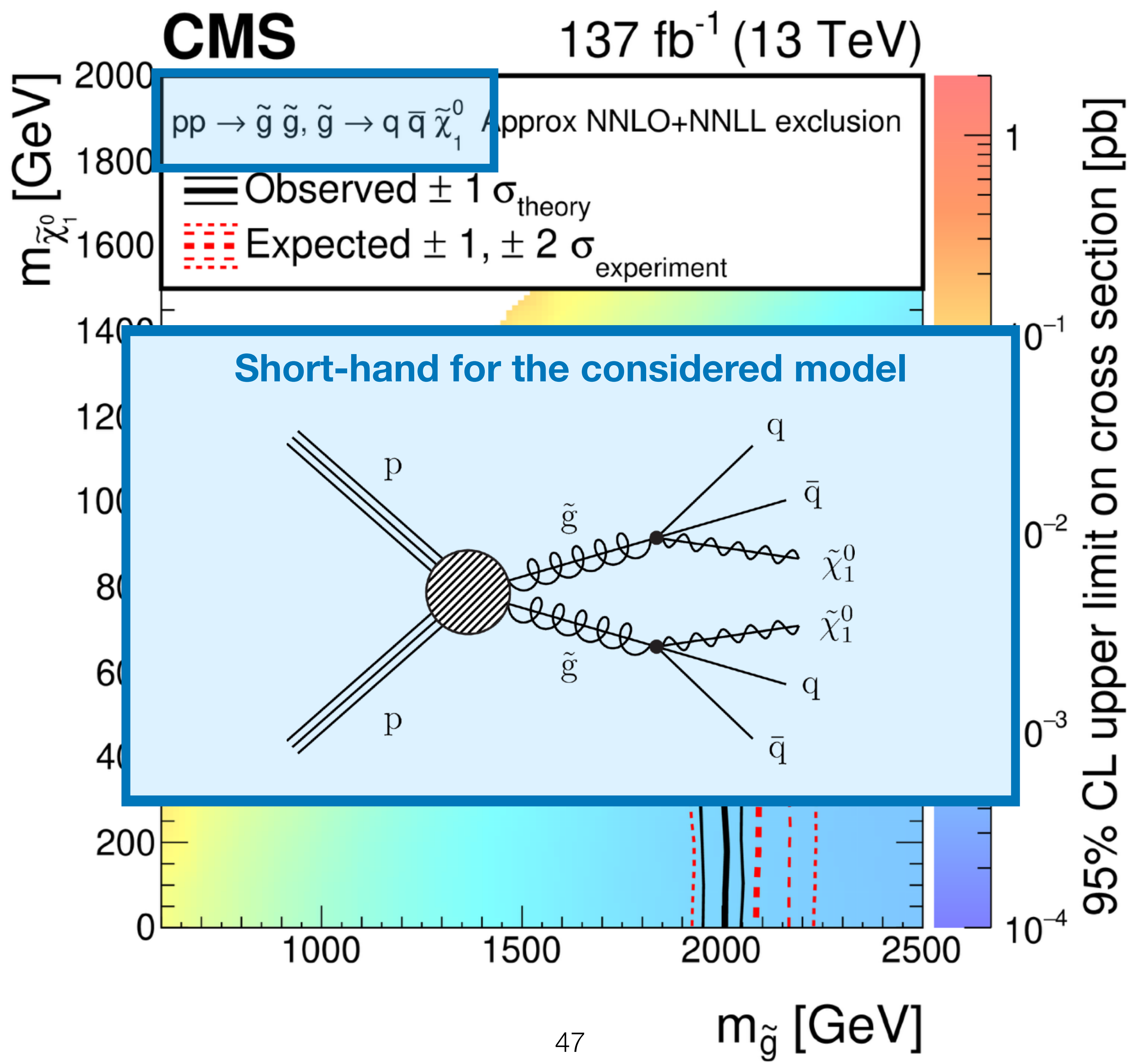
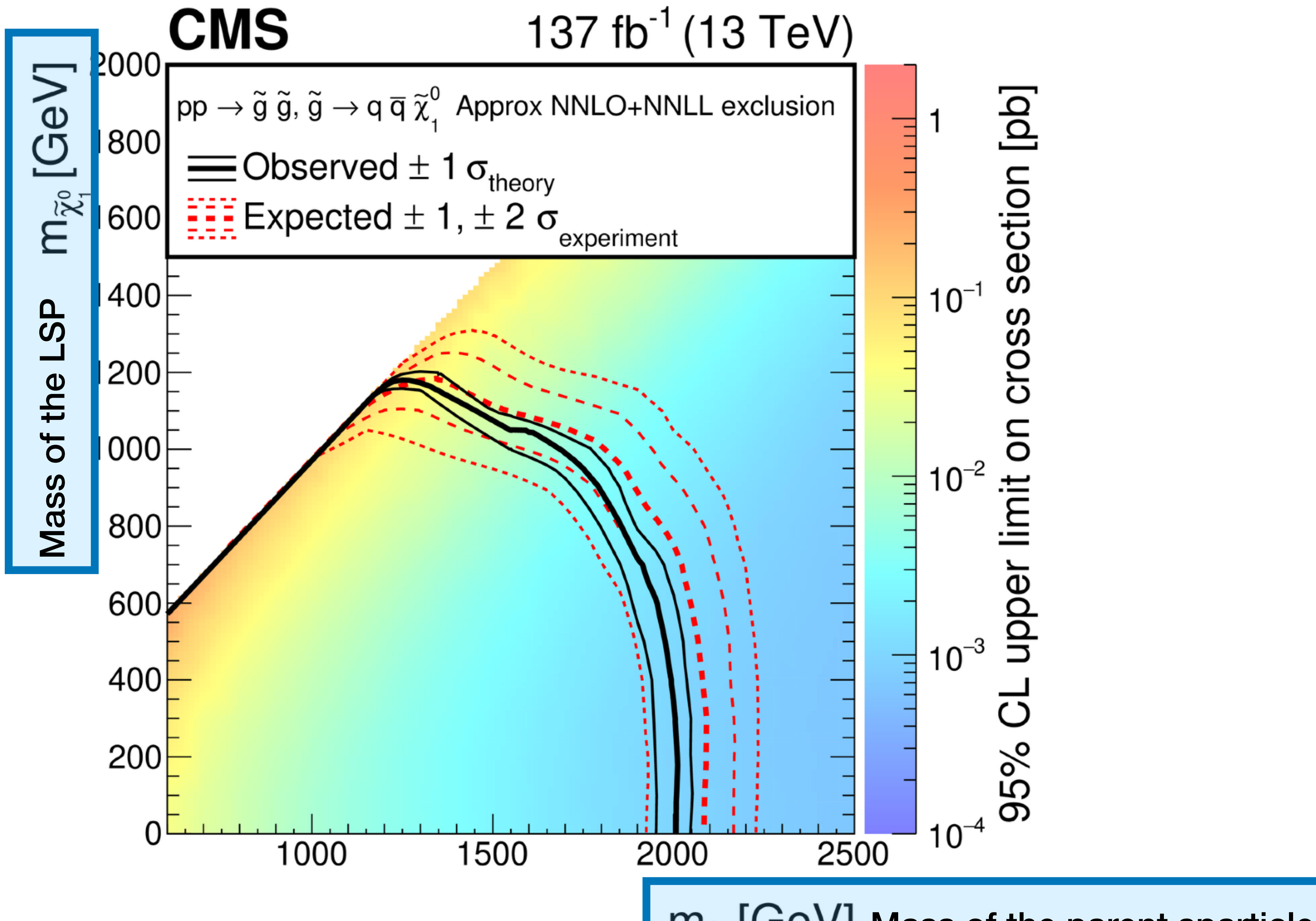
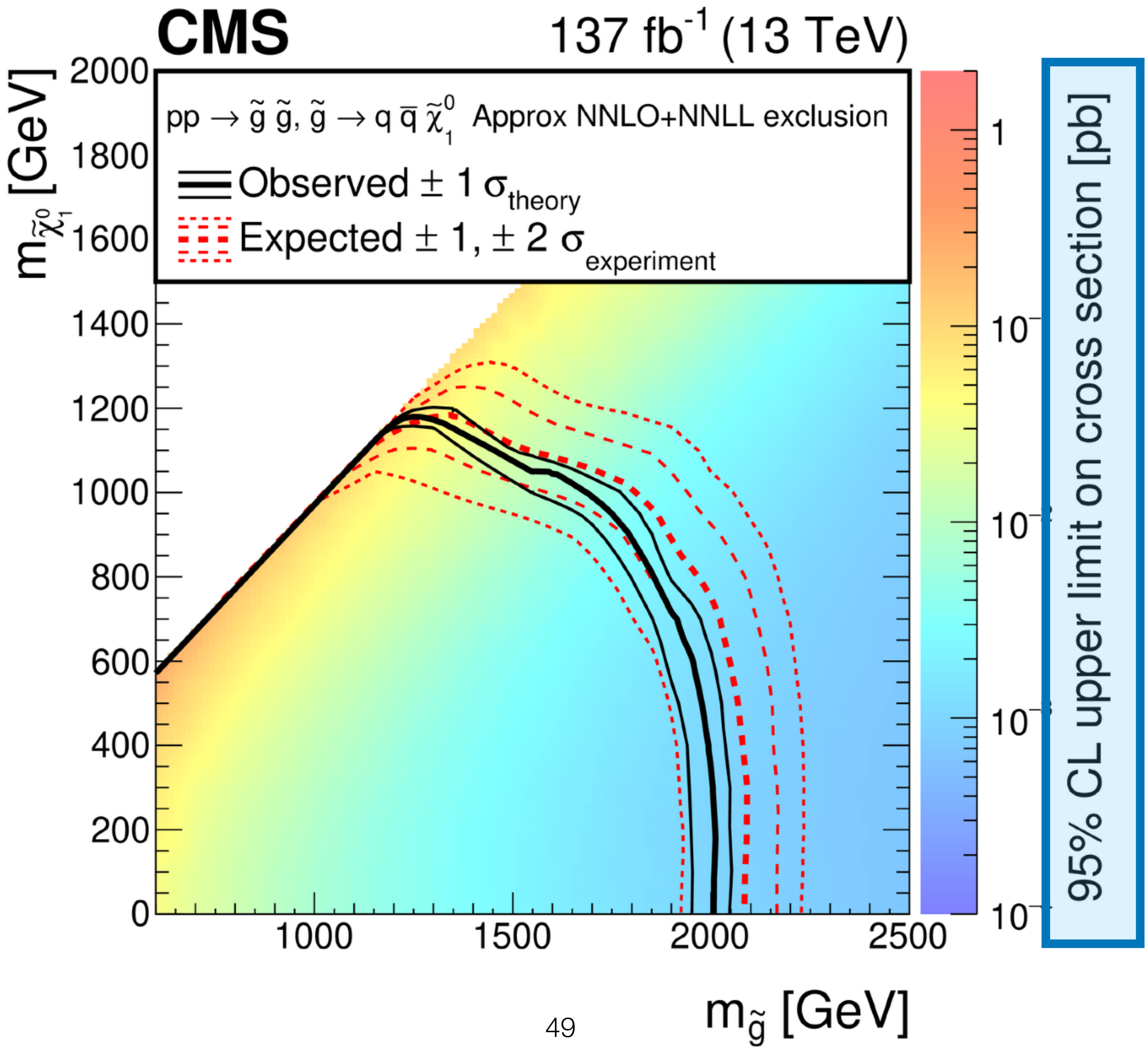


How to read an exclusion plot



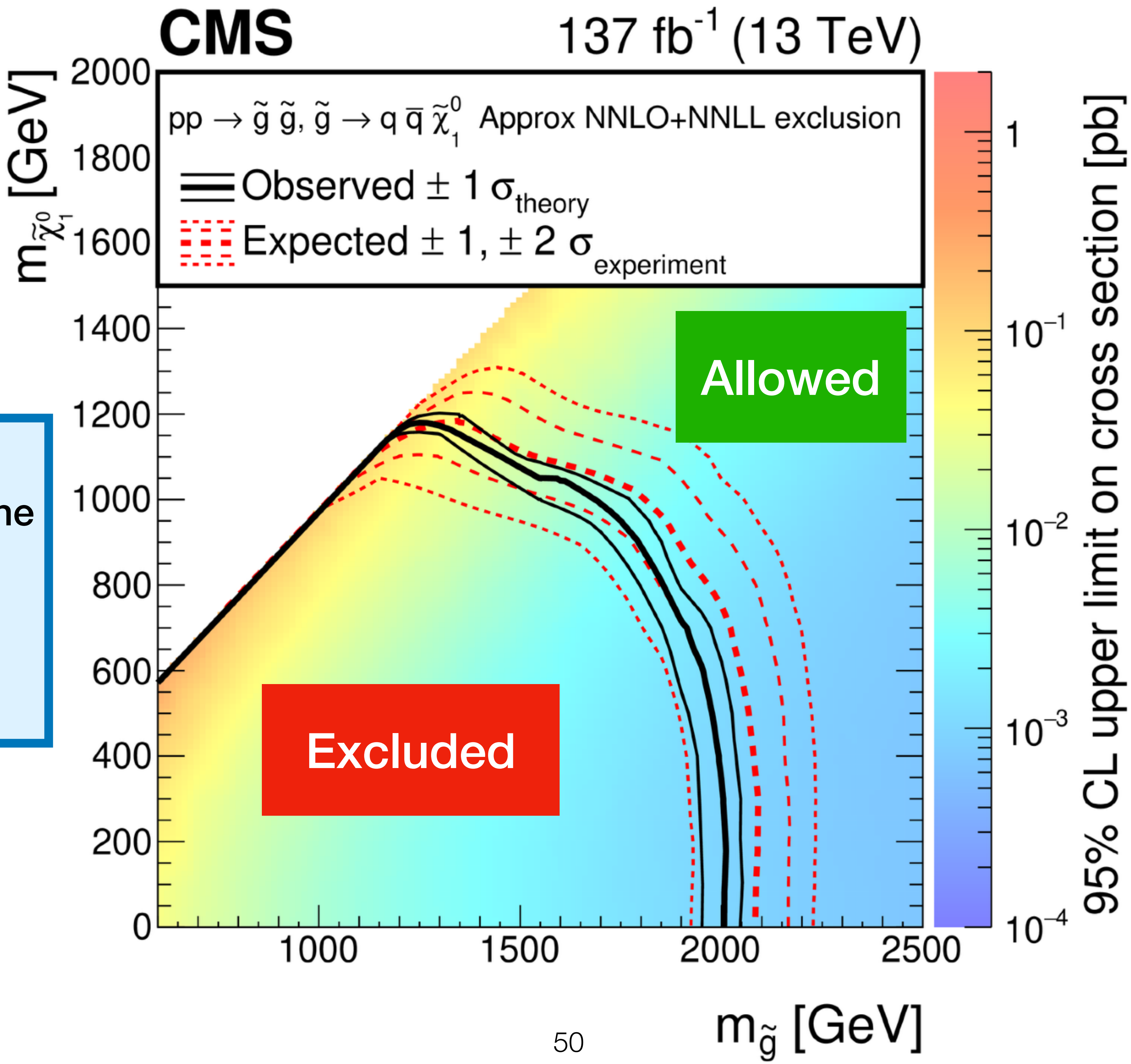
How to read an exclusion plot



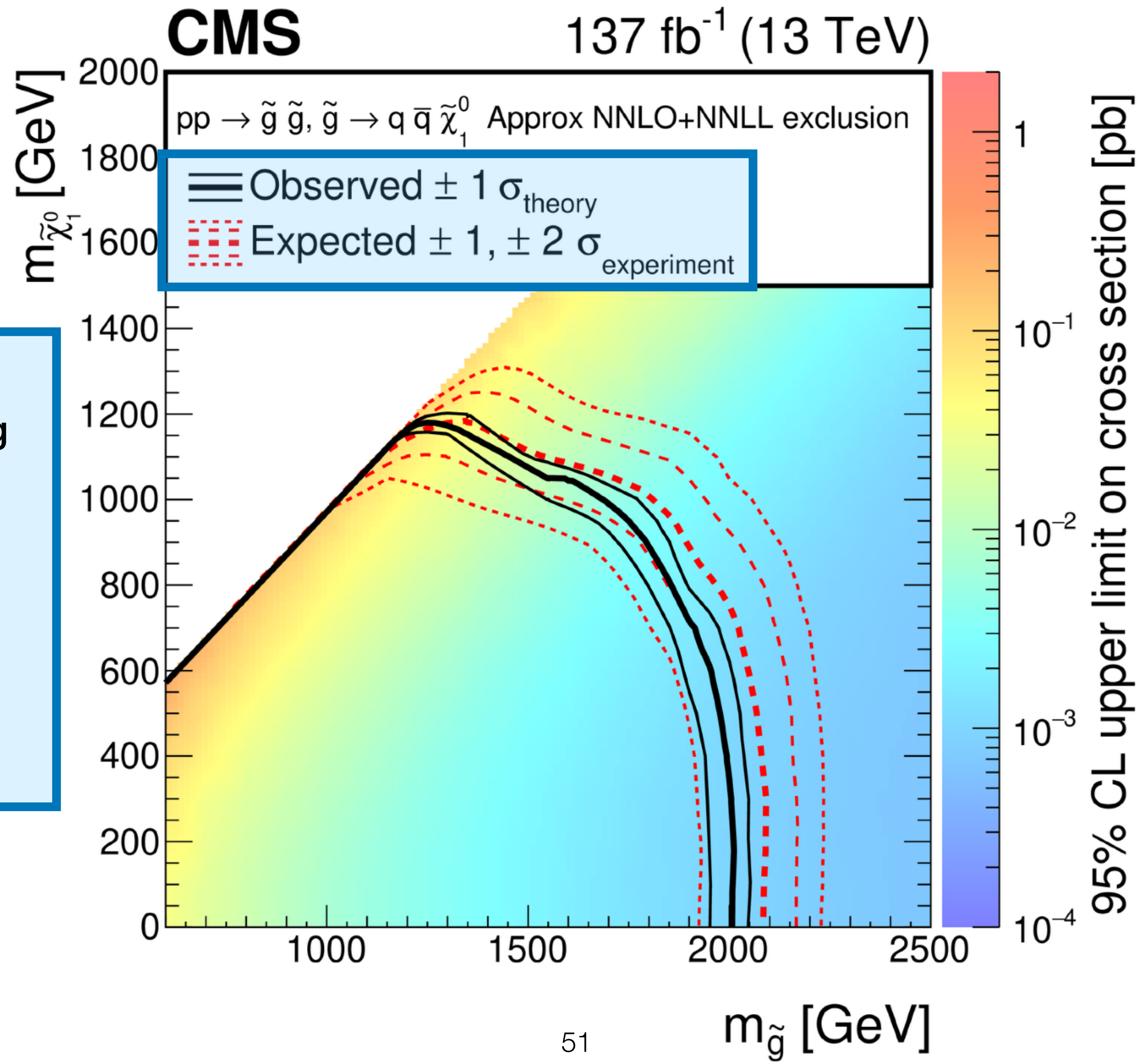
For the given set of masses, the cross section can at most be this value

How to read an exclusion plot

The lines take into account the theoretical cross section for that gluino mass



How to read an exclusion plot



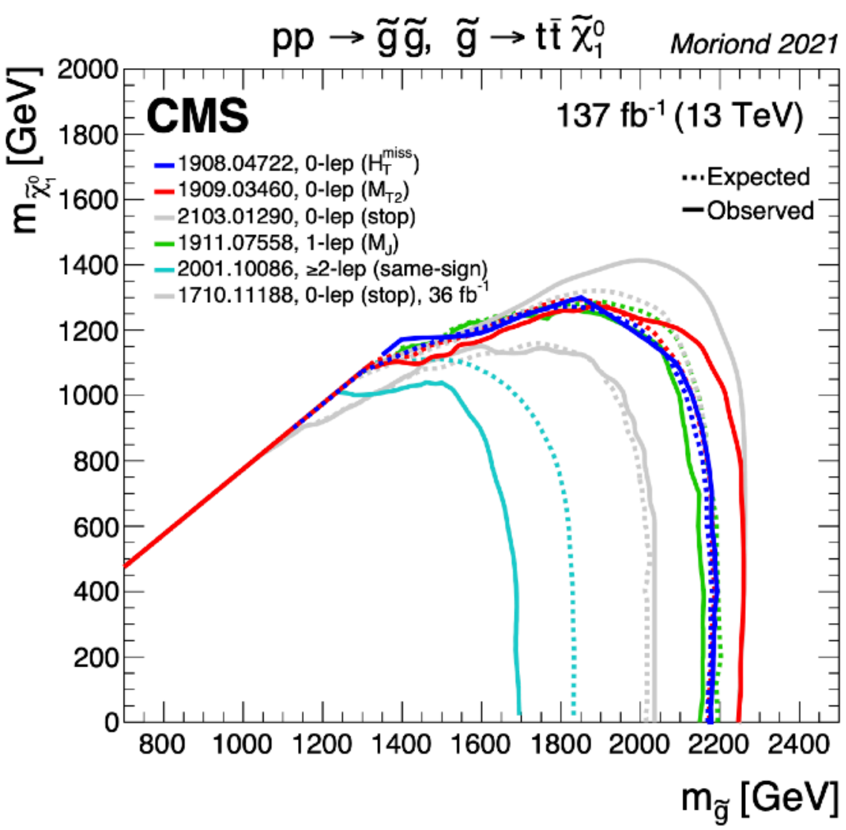
Expected:
before looking at data

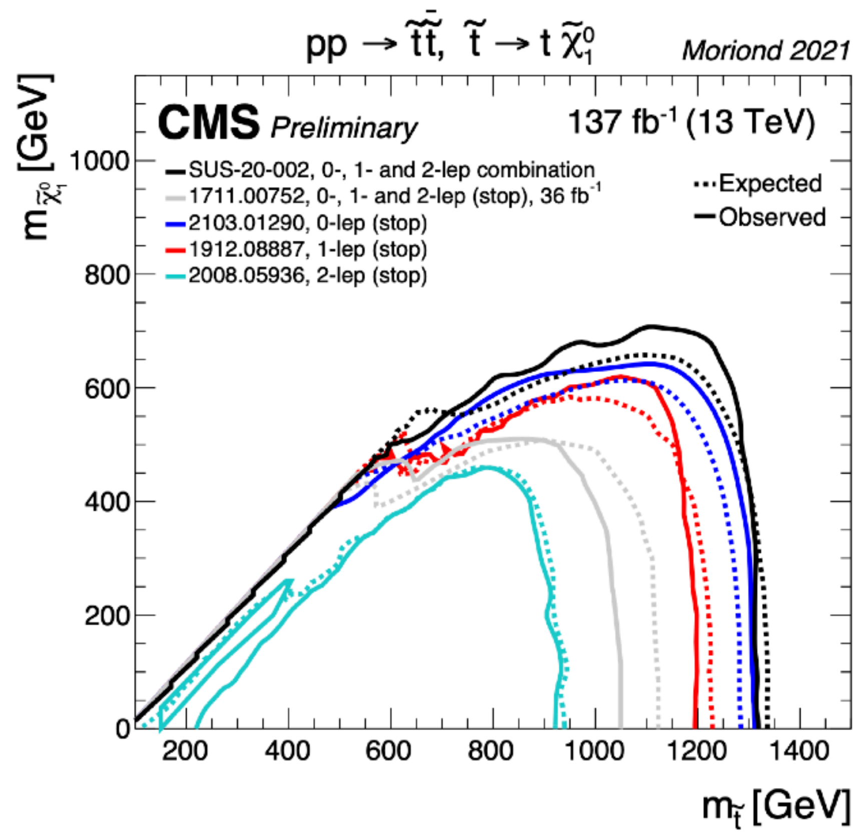
Observed:
taking into account the data in your signal region

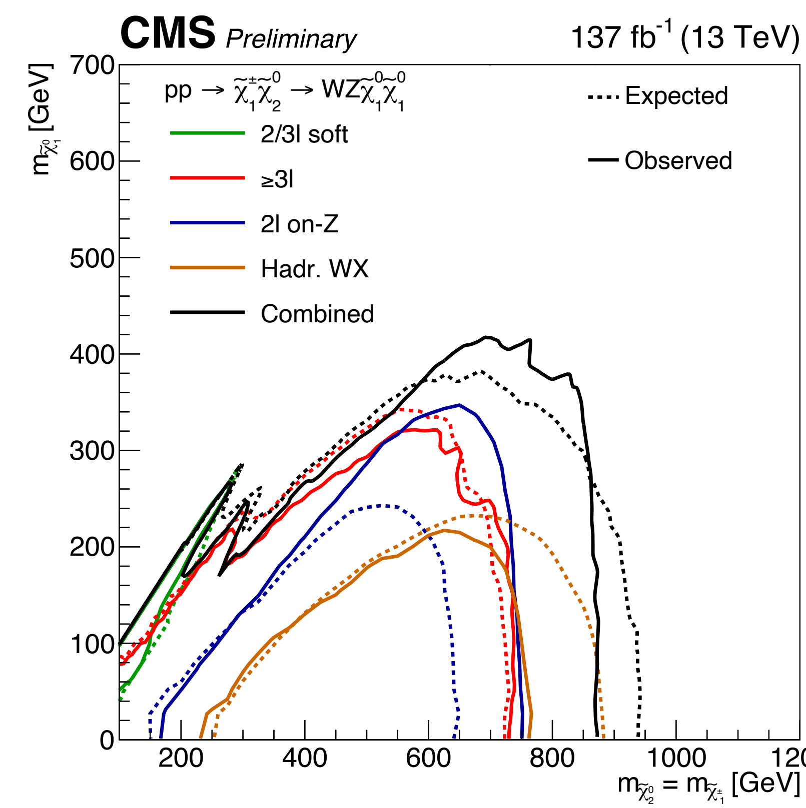
Status of SUSY searches

Many results!

No discoveries yet :-(





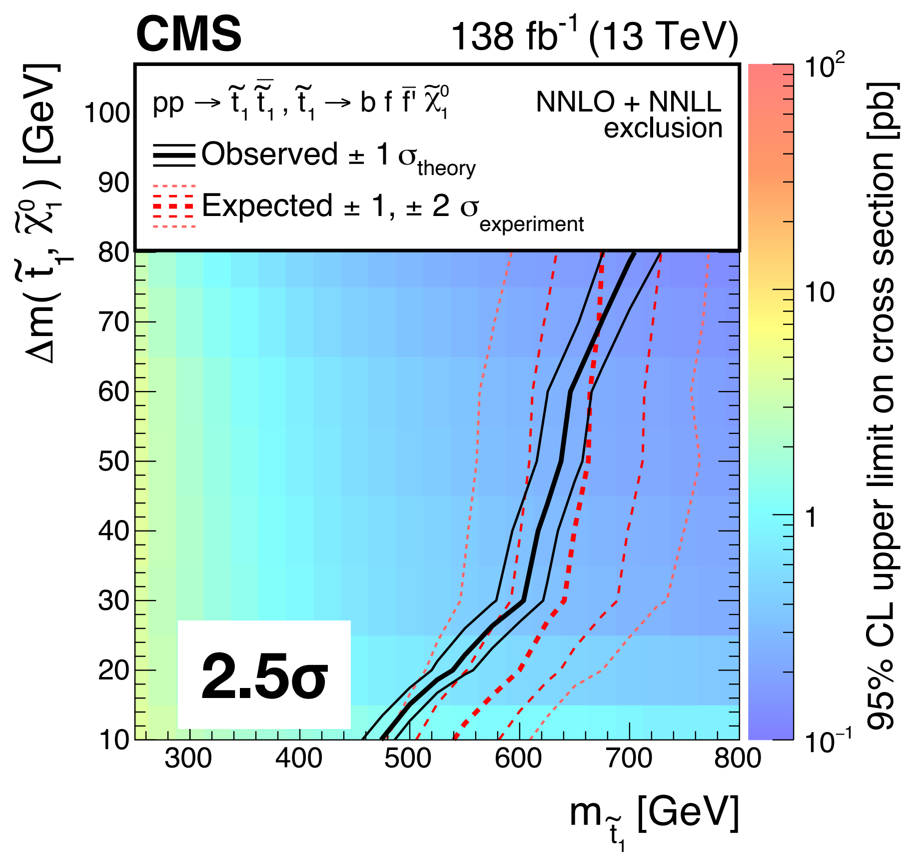


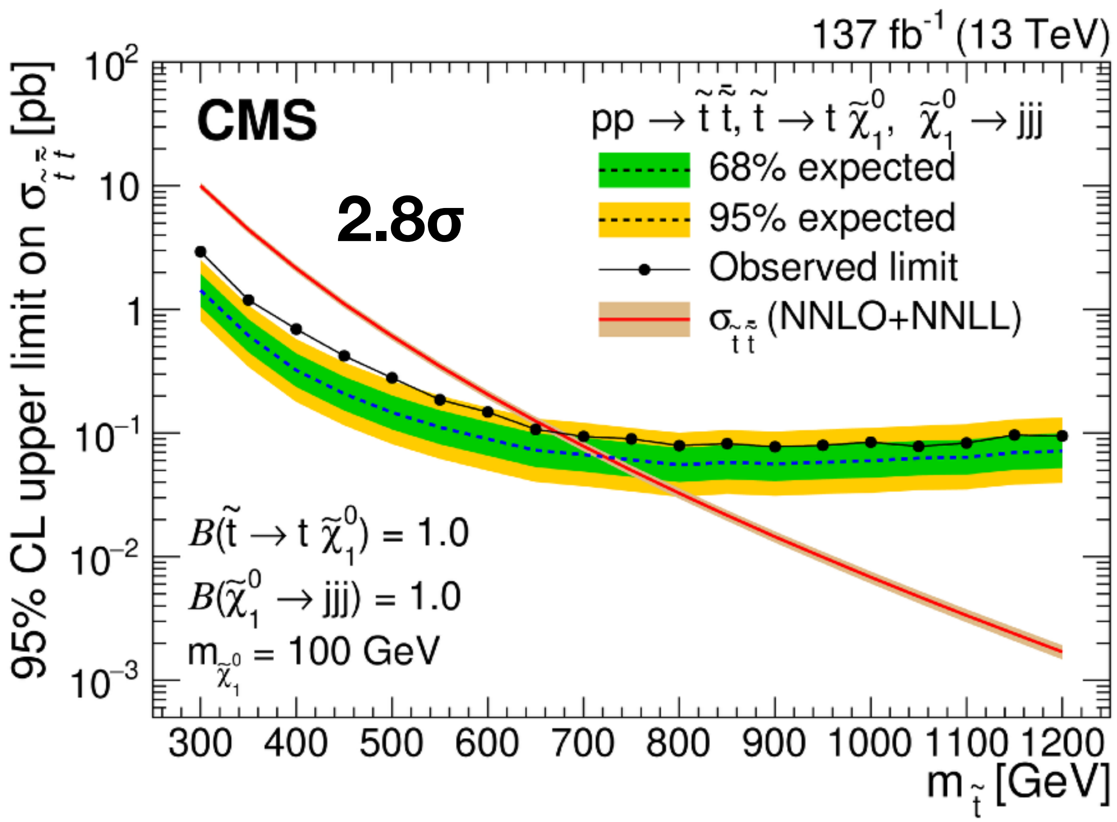
Typically exclude gluino masses up to 2.2 TeV,
squark masses up to 1.3-1.5 TeV,
chargino/neutralino masses up to 800 GeV (model dependent)

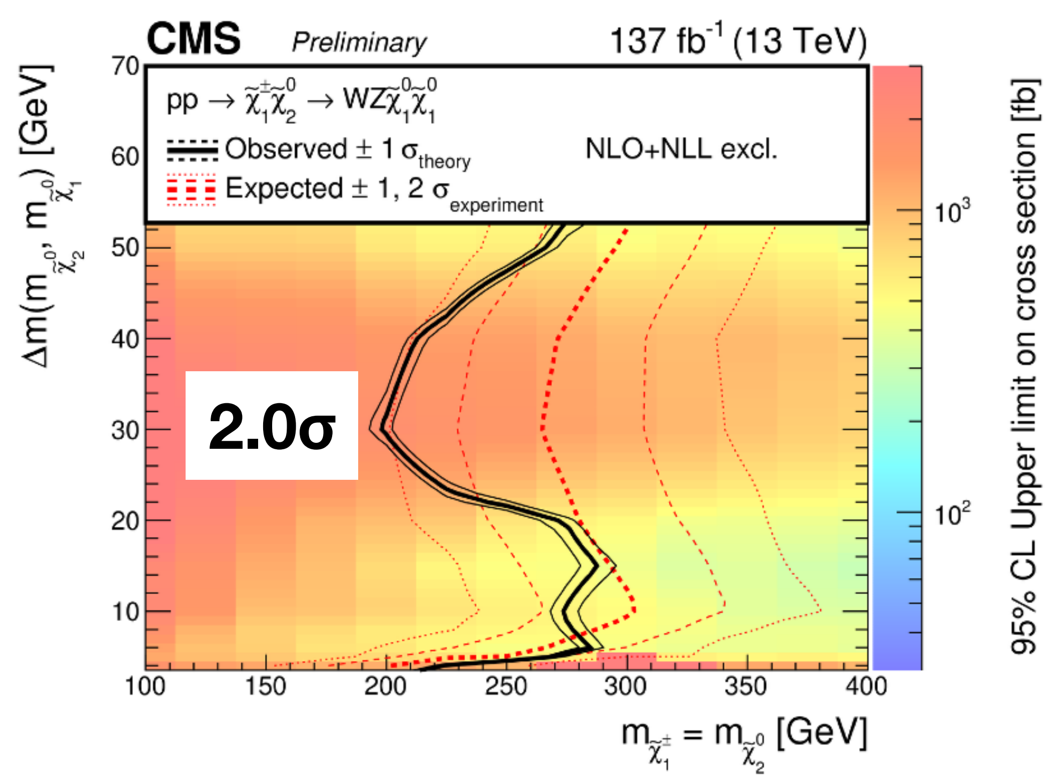
Many results!

But some hints are around…

More data is needed to disentangle between statistical fluctuations, mismodeling in background prediction, or the possibility of a real signal







Summary

- Many theories have been proposed to explain open questions
- Supersymmetry is one of the more prominent ones
  - Supersymmetry doubles the particle content of the SM
  - MSSM with R-parity means:
    - Sparticles always produced in pairs
    - Lightest SUSY particle is stable and escapes the detector, leading to missing transverse momentum
    - Neutralino LSP is dark matter candidate
- Many searches have been perfomed
  - So far, no direct evidence for any of these particles
  - A few hints are present and will be followed up
- Further reading: *Supersymmetry Primer* by Stephen Martin: https://arxiv.org/abs/hep-ph/9709356