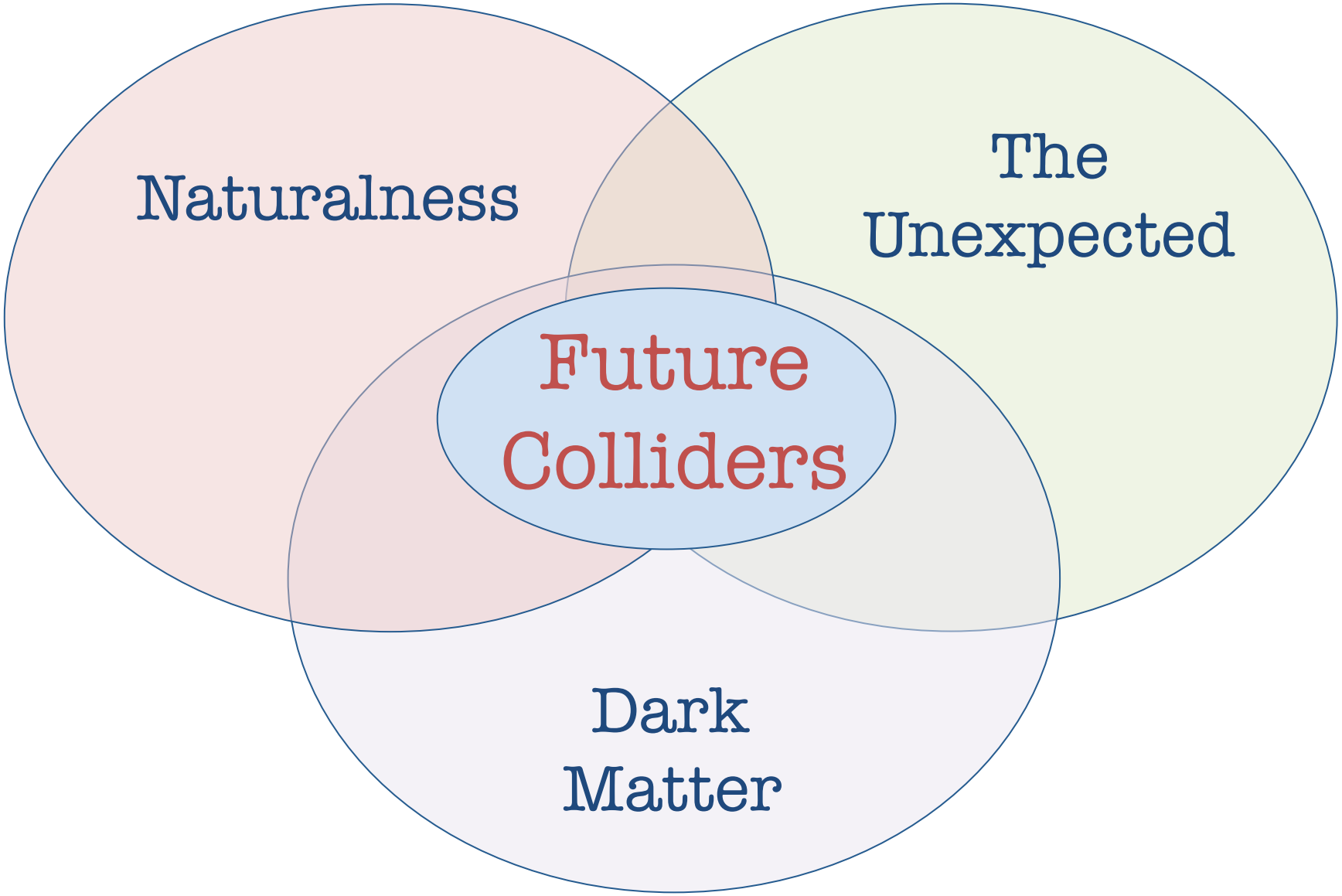
BSM Physics at FCC-hh

FCC Week

April 12th 2016

Matthew McCullough

Beyond the Standard Model



Dark Matter at 100 TeV

Despite overwhelming evidence for its existence, the particle nature of dark matter is unknown.

Cosmology provides a strong motivation for direct and collider searches...

- Thermal freeze-out predicts observed abundance for:

$$M_{DM} \sim \mathcal{O}(\text{few GeV}) \rightarrow \mathcal{O}(10\text{'s TeV})$$

Cosmological constraints

Unitarity bounds

Motivates dark matter searches in ballpark of 100 TeV collider <u>independent</u> of hierarchy problem.

Simplified Dark Matter Models

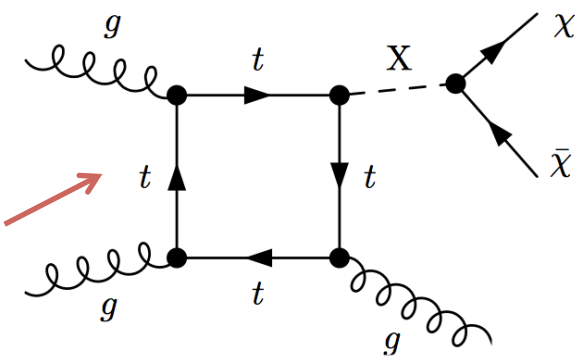
Write down simple scenarios to model production of dark matter at colliders:

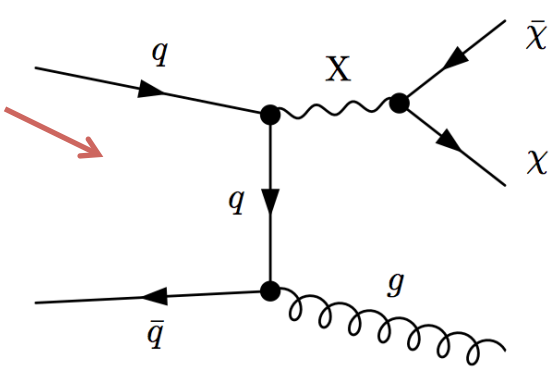
$$\mathcal{L}_{\rm S} \supset -\sum_q c_S \lambda_{h,q} S\, \bar{q}q - \frac{1}{2} m_{\rm MED}^2 S^2 + \mathcal{L}(S, \bar{\chi}, \chi)\,,$$

$$\mathcal{L}_{\rm P} \supset -\sum_q i c_P \lambda_{h,q} P\, \bar{q}\gamma^5 q - \frac{1}{2} m_{\rm MED}^2 P^2 + \mathcal{L}(P, \bar{\chi}, \chi)\,,$$

$$\mathcal{L}_{\rm V} \supset -\sum_q c_V V_\mu \bar{q}\gamma^\mu q - \frac{1}{2} m_{\rm MED}^2 V_\mu V^\mu + \mathcal{L}(V, \bar{\chi}, \chi)\,,$$

$$\mathcal{L}_{\rm A} \supset -\sum_q c_A A_\mu \bar{q}\gamma^\mu \gamma^5 q - \frac{1}{2} m_{\rm MED}^2 A_\mu A^\mu + \mathcal{L}(A, \bar{\chi}, \chi)\,,$$

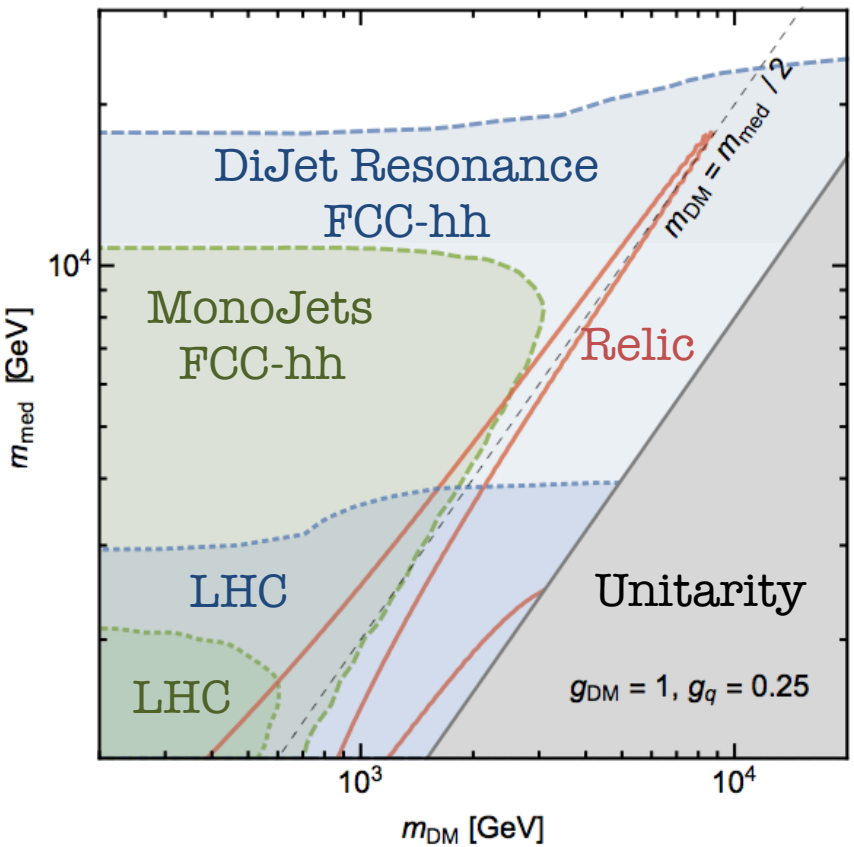




100 TeV Study: Harris, Khoze, Spannowsky, Williams, 2015.

Simplified Dark Matter Models

Coverage of simplified model parameter space is extended at 100 TeV collider for all mediators:



100 TeV Study: Chala, Kahlhoefer, Nardidni, Schmidt-Hoberg 2015.

Littlest Simplified Model?

The Higgs Portal:

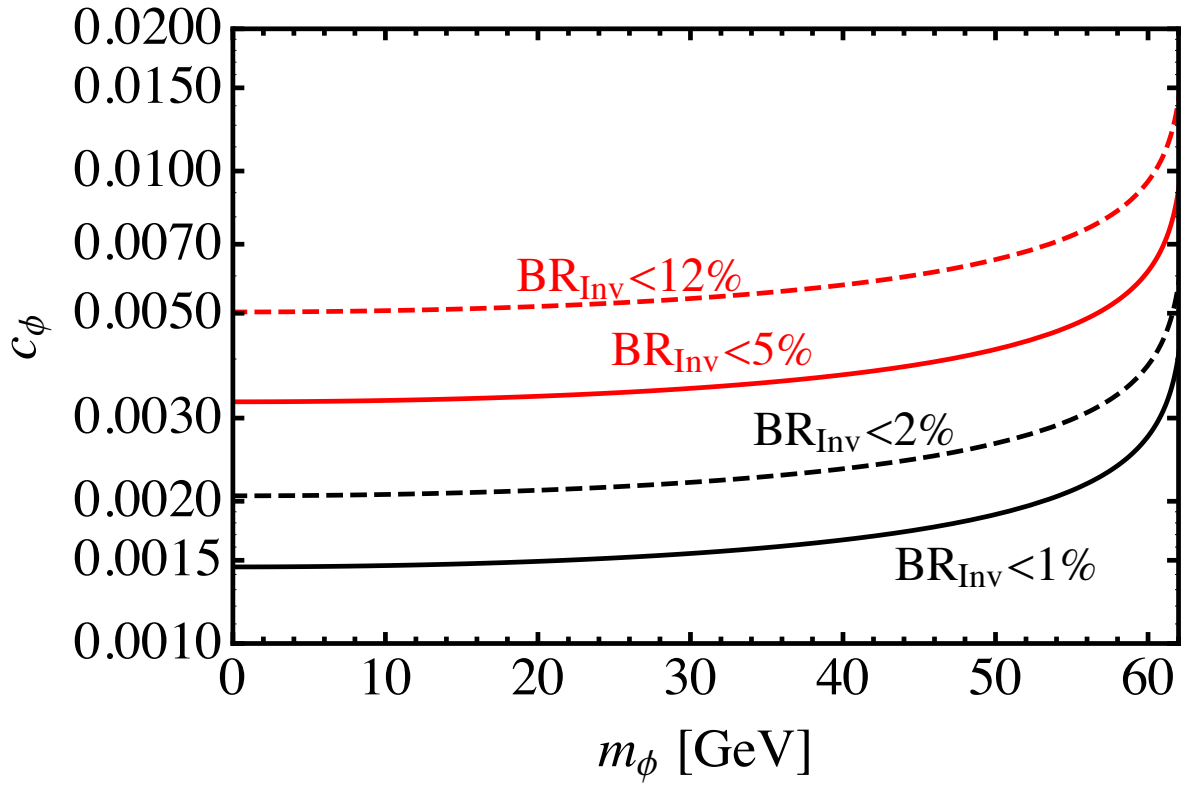
ϕ is the dark matter?

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

The Higgs itself could be the "mediator" to the dark sector!

Higgs Portal at 100 TeV

Coupling sensitivity possible with variety of invisible branching ratio limits.



100 TeV capability depends on coupling precision.

Supersymmetry

Matter, forces, and spacetime?

$$g^{\mu\nu}_{s=2}$$

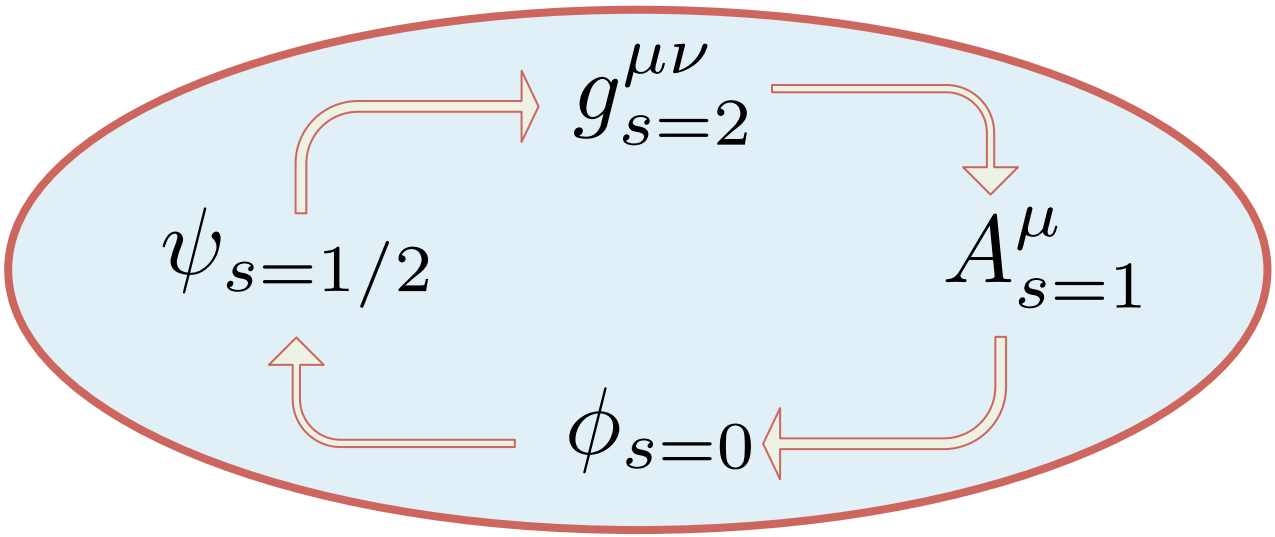
$$\psi_{s=1/2} \qquad\qquad A^{\mu}_{s=1}$$

$$\phi_{s=0}$$

All observed fields transform in one of these representations of Lorentz group.

Supersymmetry

What is supersymmetry?

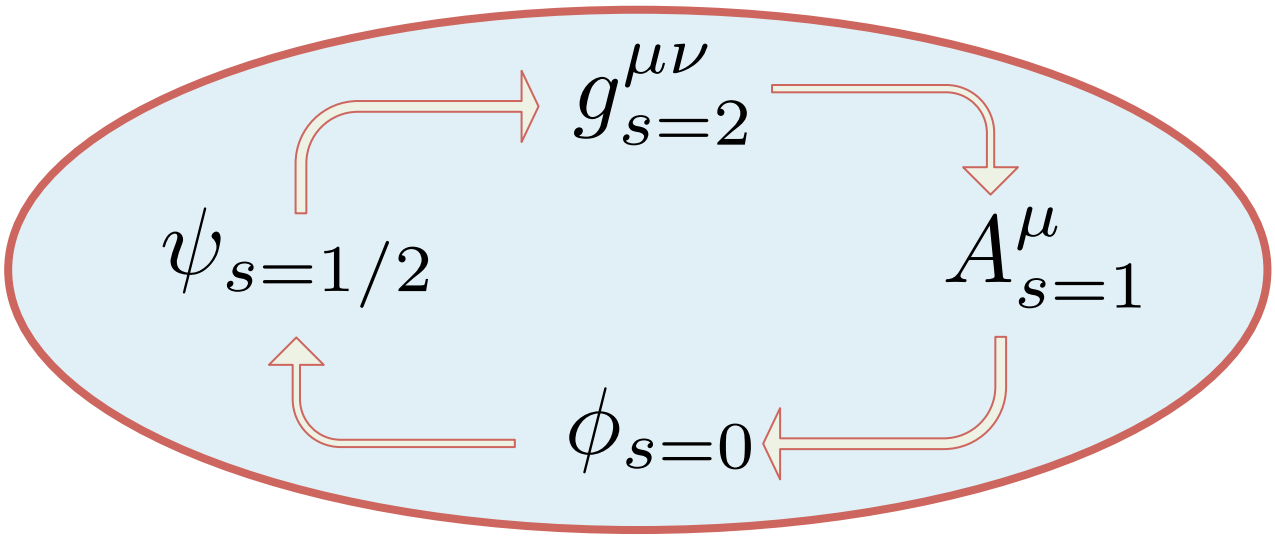


Entirely new spacetime symmetry!

Unifies fields into superfields, transforming into one another!

Supersymmetry

What is supersymmetry?



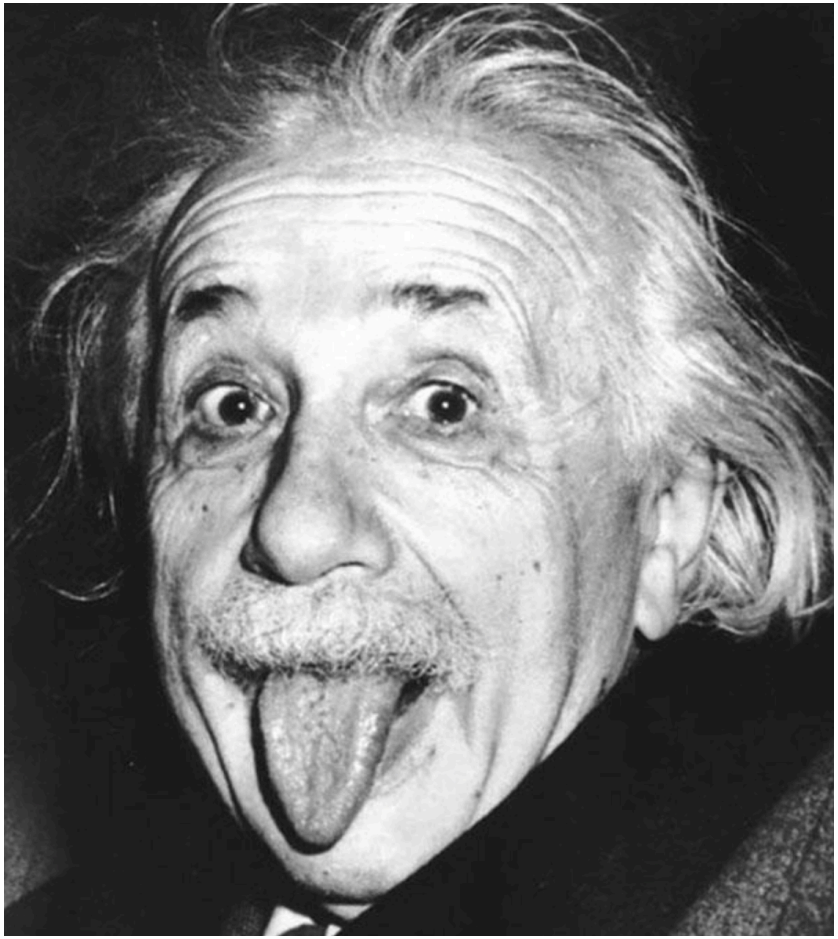
Entirely new spacetime symmetry!

Unifies fields into superfields, transforming into one another!

Also predicts... $\tilde{g}_{s=3/2}$

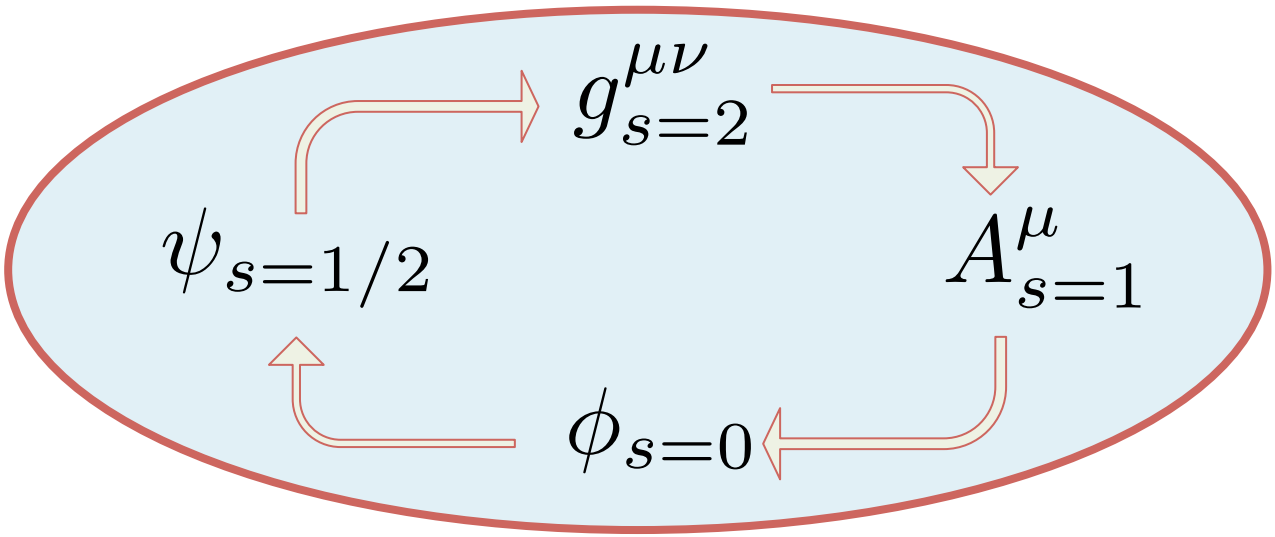
Supersymmetry

The last time a spacetime symmetry was discovered...



Supersymmetry

What is supersymmetry?



Where is supersymmetry?

Some clues...

Higgs Mass

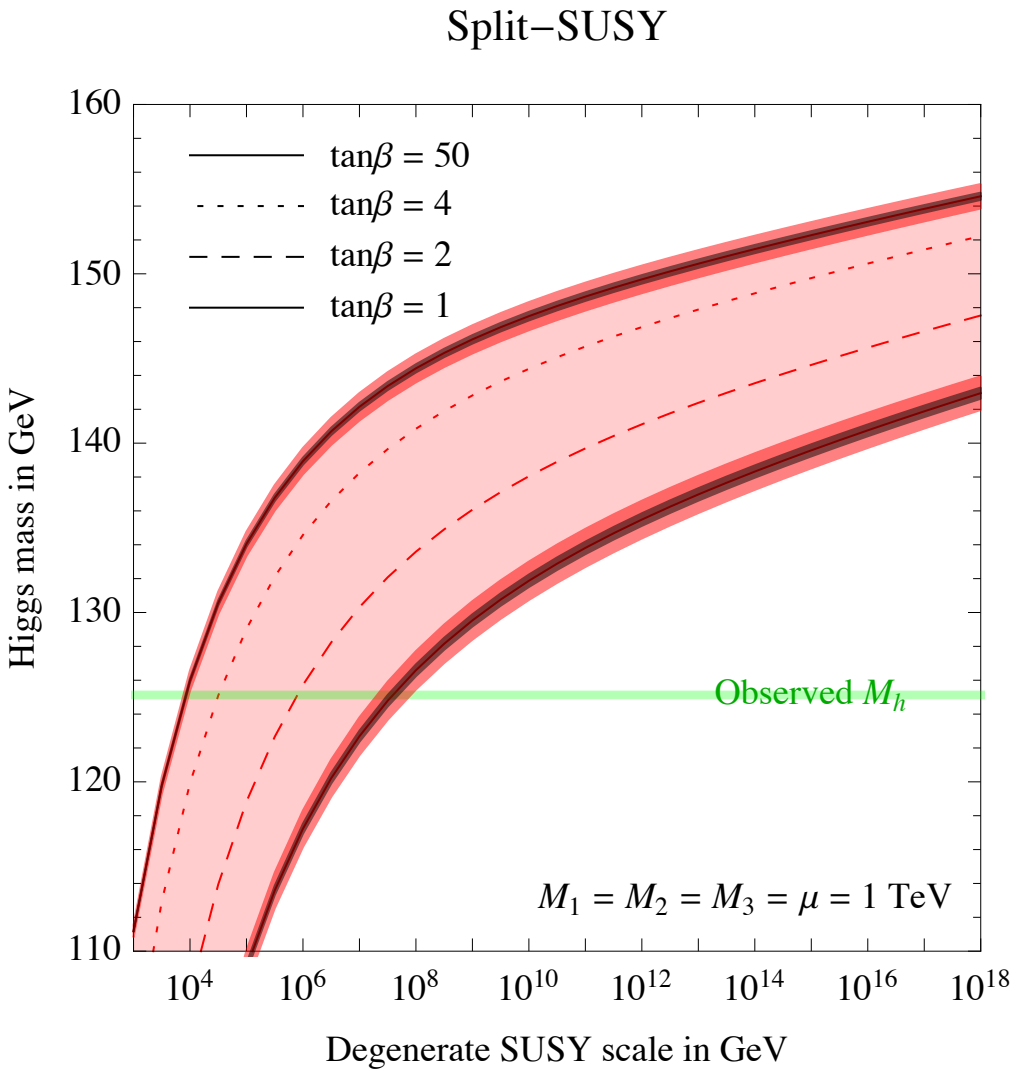
Dark Matter

Unification

Naturalness

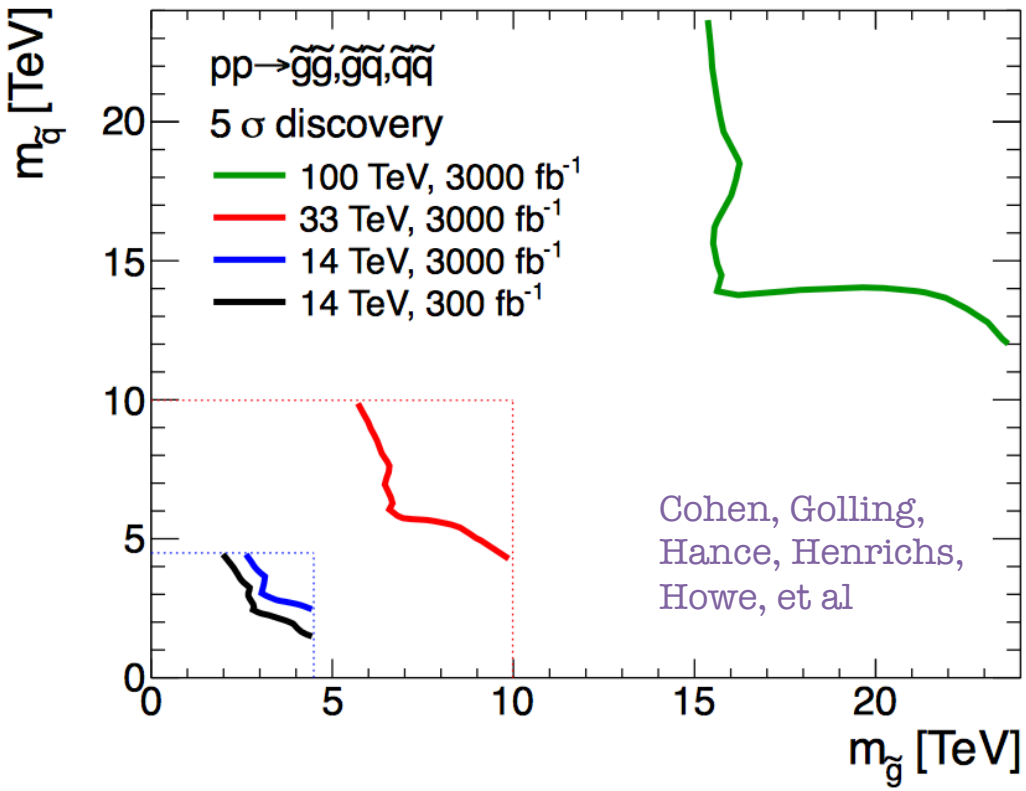
Supersymmetry

Higgs mass: We now have upper bounds on scalar masses:



Supersymmetry

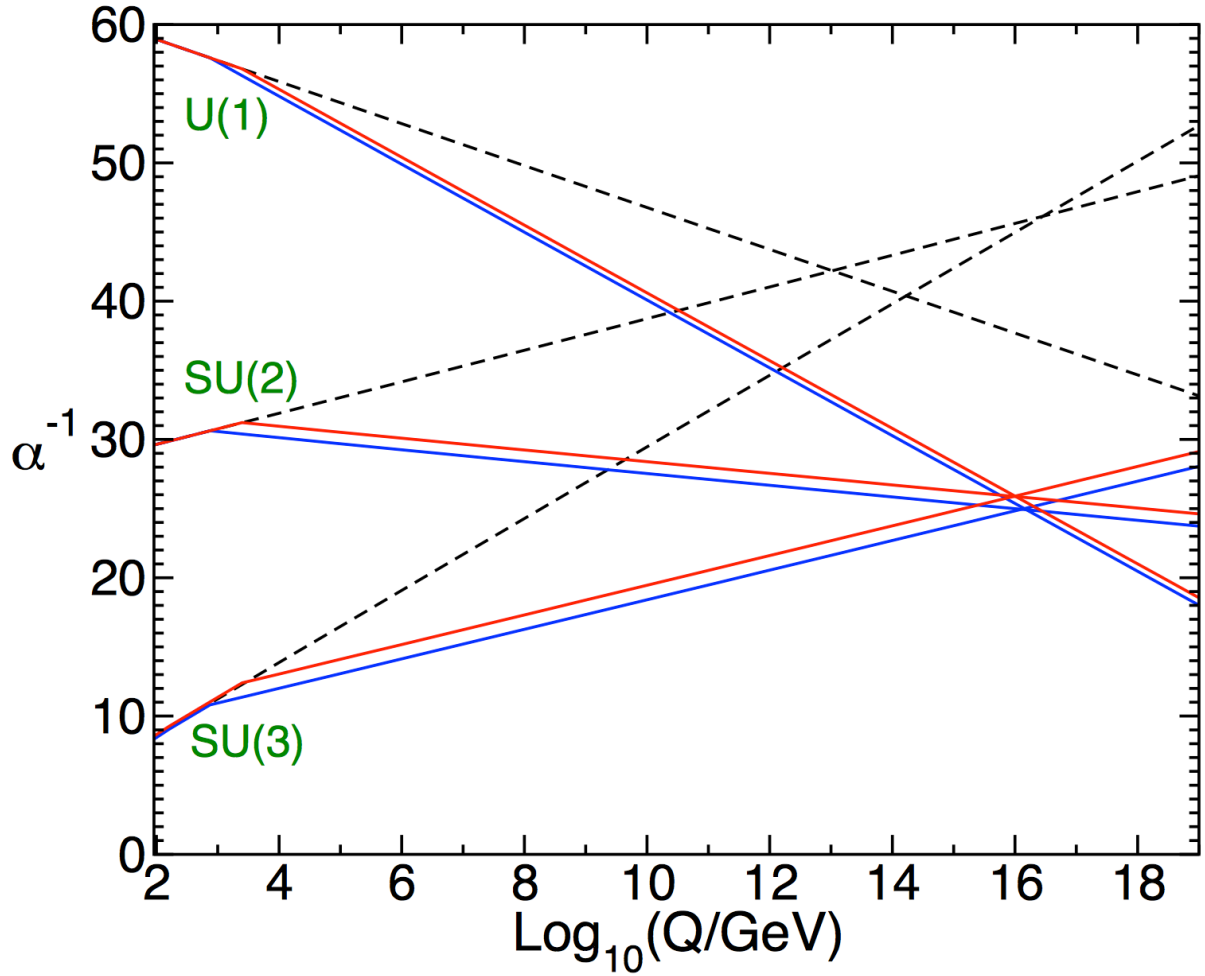
Combining gluino and squark limits onto one plane:



Reach in combination stronger than individual reach to due enhanced production rates with all states present.

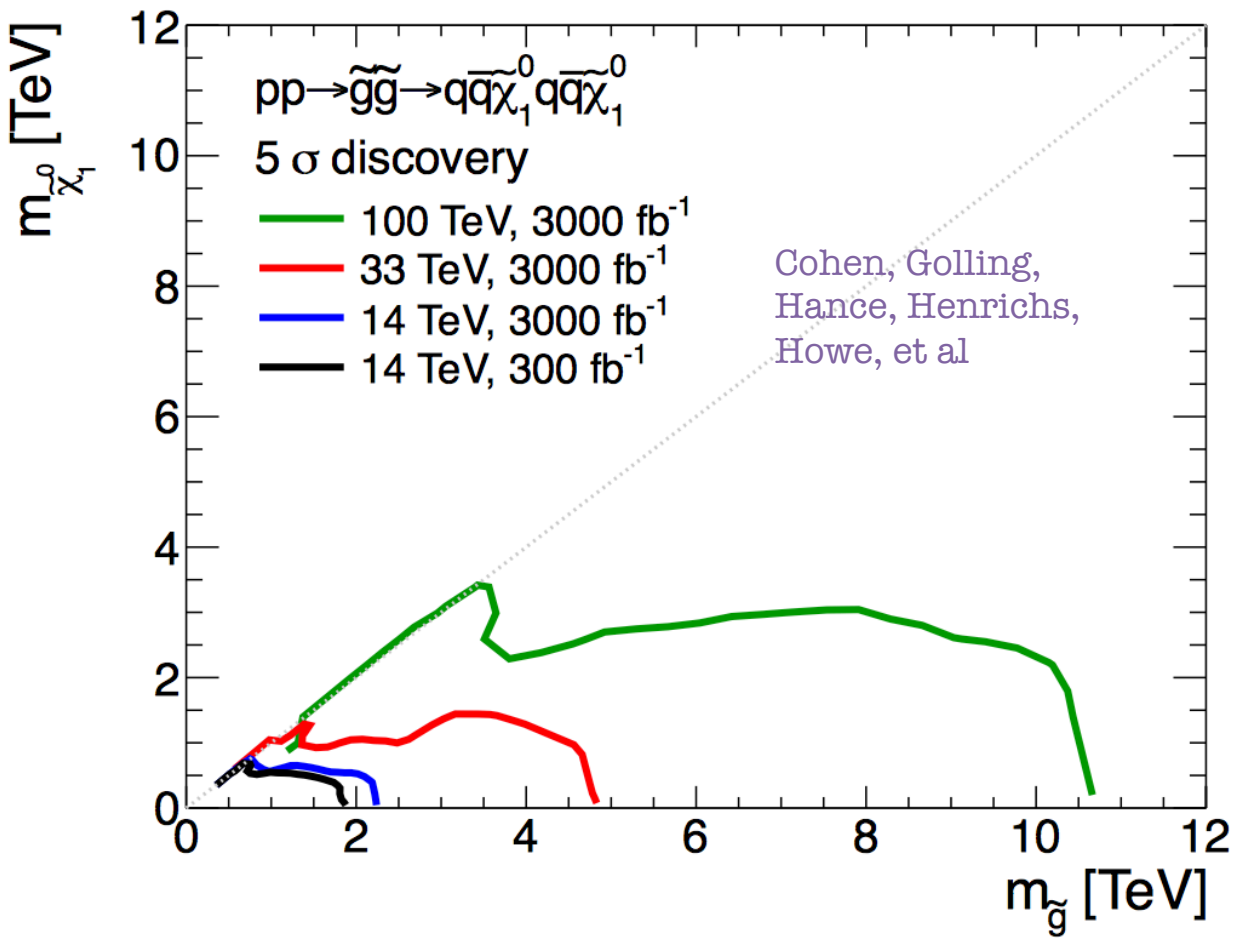
Supersymmetry

Unification: Prefers sparticles (particularly gauginos and Higgsinos) not too far from Weak Scale:



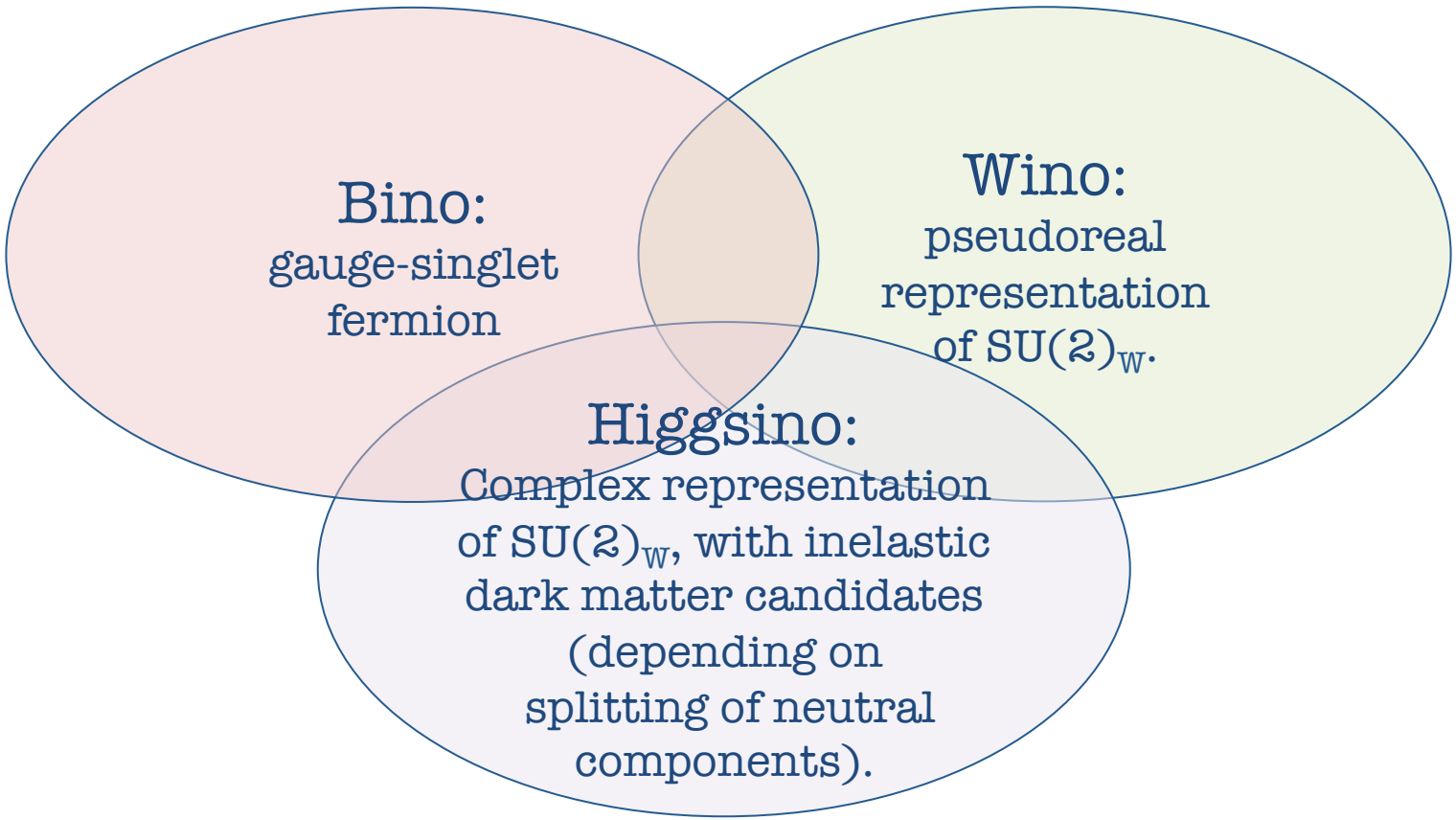
Supersymmetry

Even with squarks removed from spectrum gluino reach is significant:



Supersymmetry

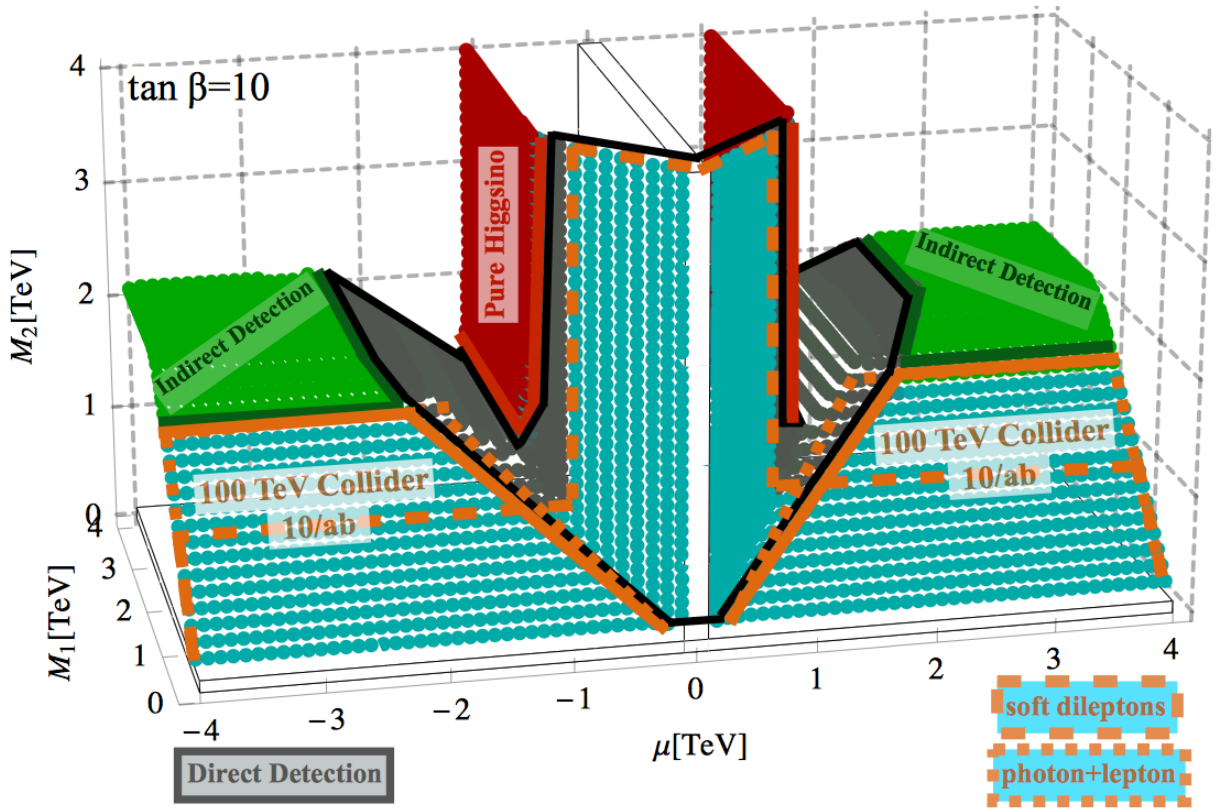
Dark Matter: Neutralino is a compelling ingredient of the SUSY setup:



Relic density points towards no more than few TeV!

Relic Neutralino Surface

Collider signatures considered: MET + Jet and either soft dileptons or lepton+photon



100 TeV Study: Bramante, Desai, Fox, Martin, Ostdiek, Plehn. 2015.

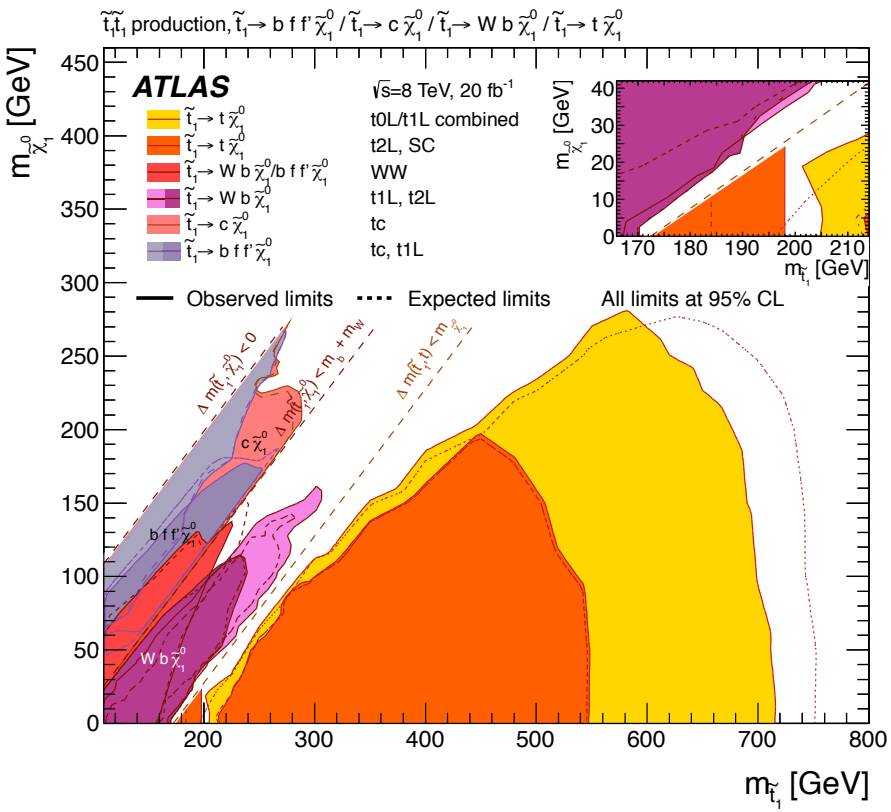
Relic Neutralino Surface

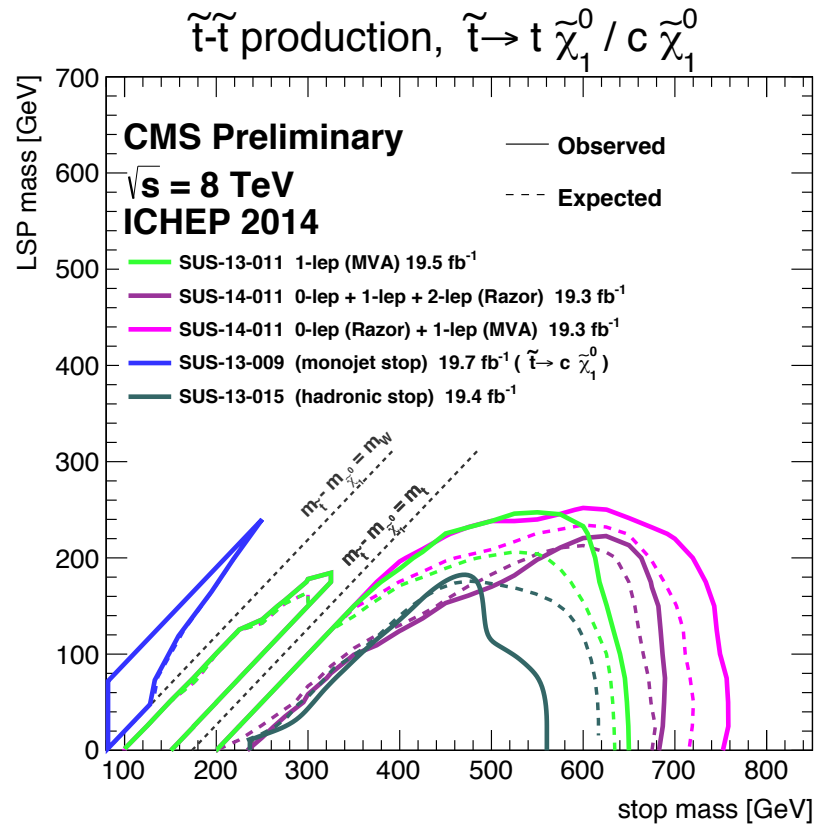
See also: Gori, Jung, Wang, Wells. 2014.
And: Acharya, Bozek, Pongkitivanichkul, Sakurai. 2014.
And: Cirelli, Sala, Taoso. 2014.
And: Buchmuller, Citron, Ellis, Guha, Marrouche, Olive, de Vries, Zheng. 2015.

Supersymmetry

Naturalness: Solves hierarchy problem if superpartners near weak scale.

In tension already...

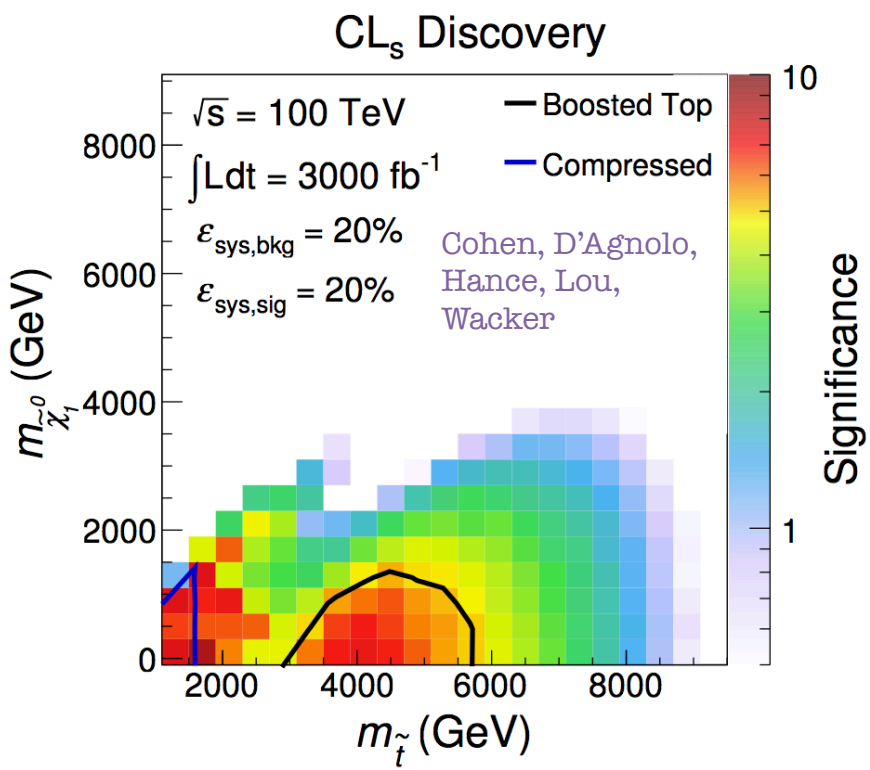




Supersymmetry

Stop squarks are most relevant for weak scale naturalness, thus direct searches directly impact tuning:

$$h - - - \underset{t}{\propto \Lambda^2} - - - h + h - - - \underset{\tilde{t}}{\propto \Lambda^2} - - - h \propto \Lambda^0$$



Supersymmetry

Mass ranges motivated by:

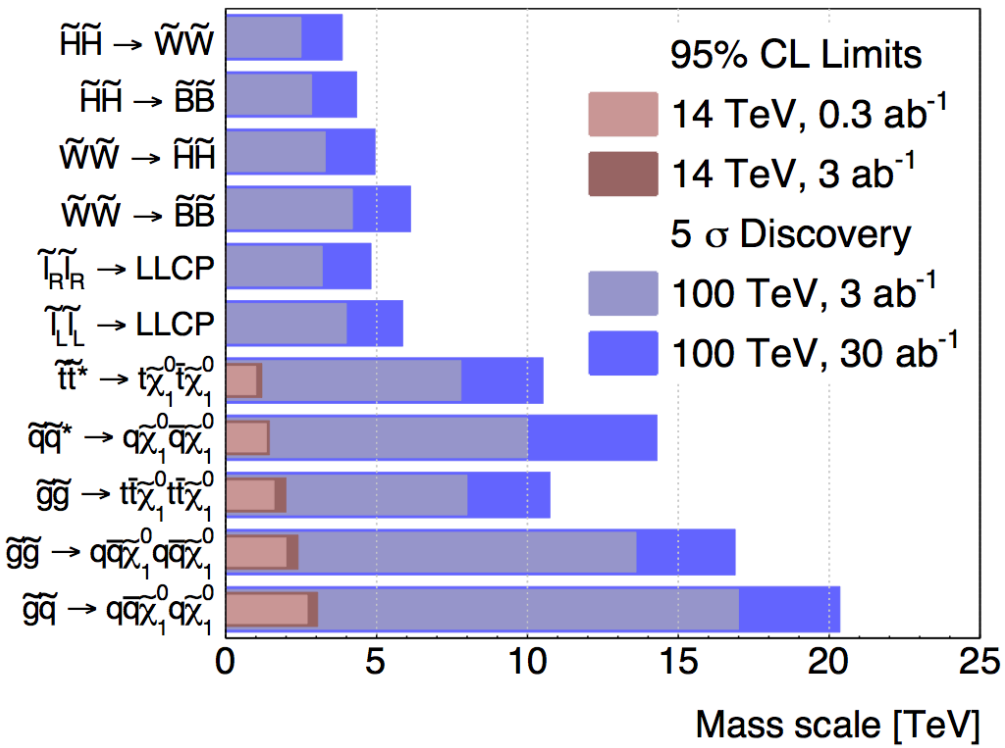
Dark Matter

Higgs Mass

Unification

Naturalness

Summary from FCC Report:



Alternatives

SUSY is not the only game in town...

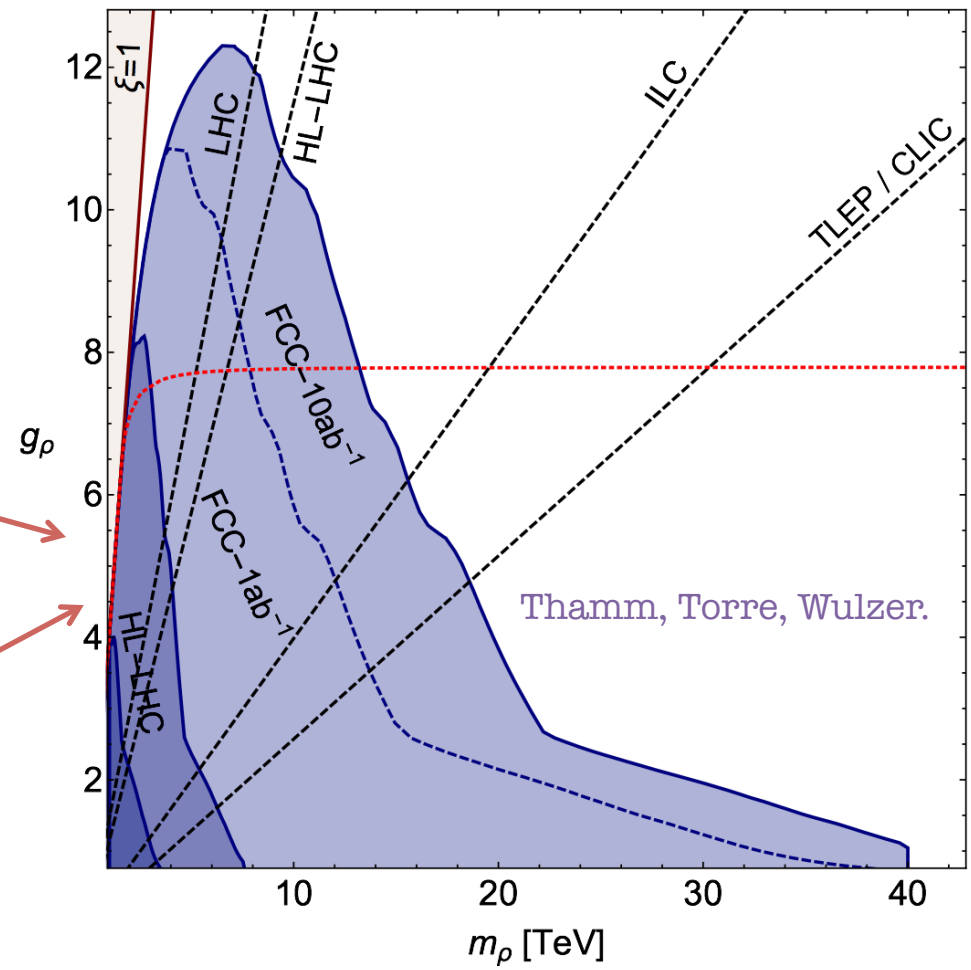
Composite Higgs

The weak scale may also be natural if Higgs is a composite of strongly interacting states.

Signatures include:

- Modified Higgs couplings
- Modifications to electroweak sector, influencing precision electroweak
- New heavy resonances coupled to the SM states

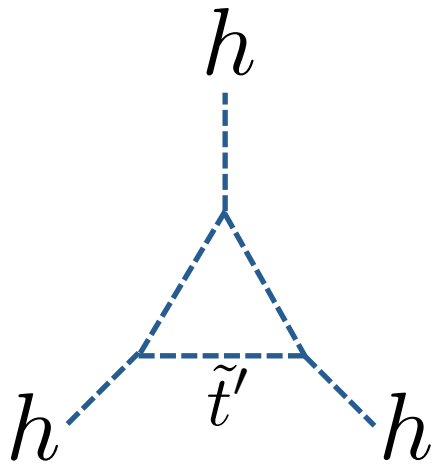
$$\rho \to l\bar{l}$$
and
$$\rho \to WZ \to \nu + 3l$$

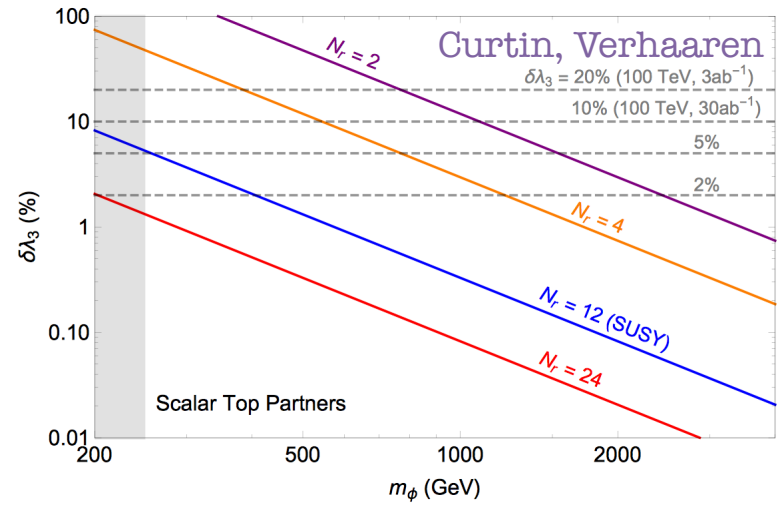


Neutral Naturalness

There are exotic theories, such as Twin Higgs or Folded SUSY, where top partners are uncolored.

Low energy Higgs coupling modifications predicted





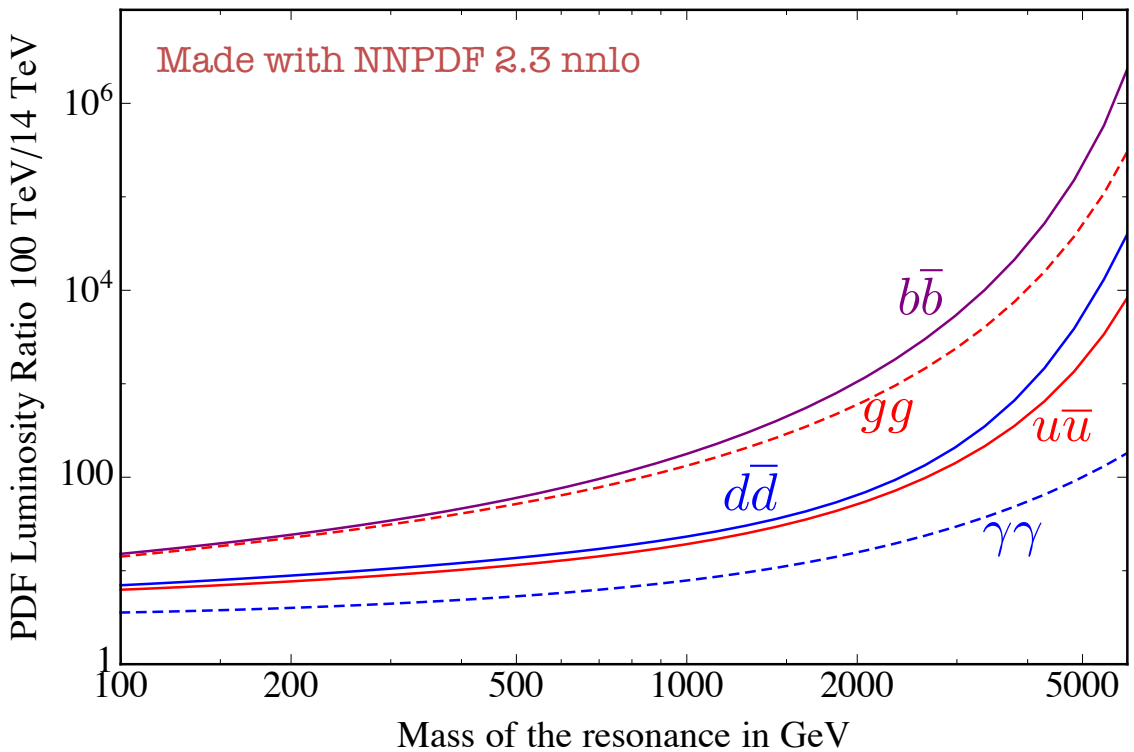
In all of these models a UV-completion is required at few TeV: SUSY/Compositeness/Extra Dim.

100 TeV collider would leapfrog theory right to UV-completion!

Post-LHC Discovery?

A Picture Paints a Thousand Words...

It is a very good idea to consider luminosity ratio plots.



A Picture Paints a Thousand Words...

It is a very good idea to consider luminosity ratio plots. They tell us about a vast physics program if e.g. a heavy resonance is discovered...

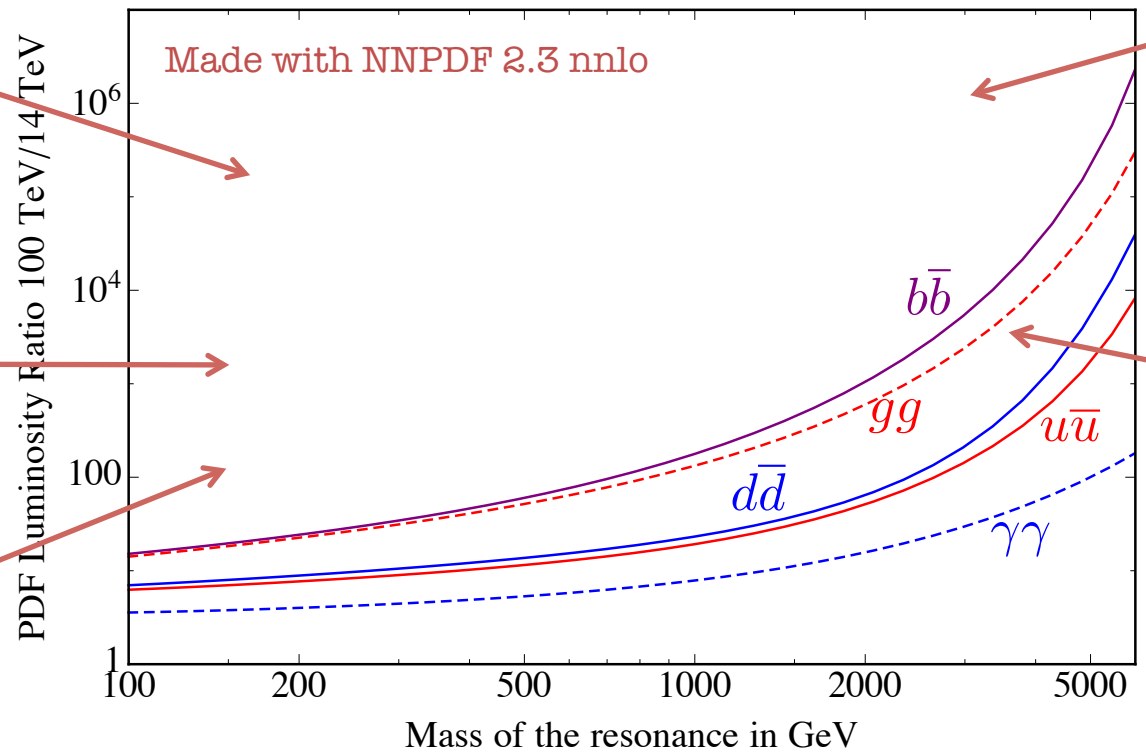
High precision in dominant production modes.

Differential distributions.

Rare/ associated production modes

Rare/ exotic decays.

For exotic signatures can take full advantage of cross section if background is small. E.g. displaced vertices.



New Physics at 14 TeV

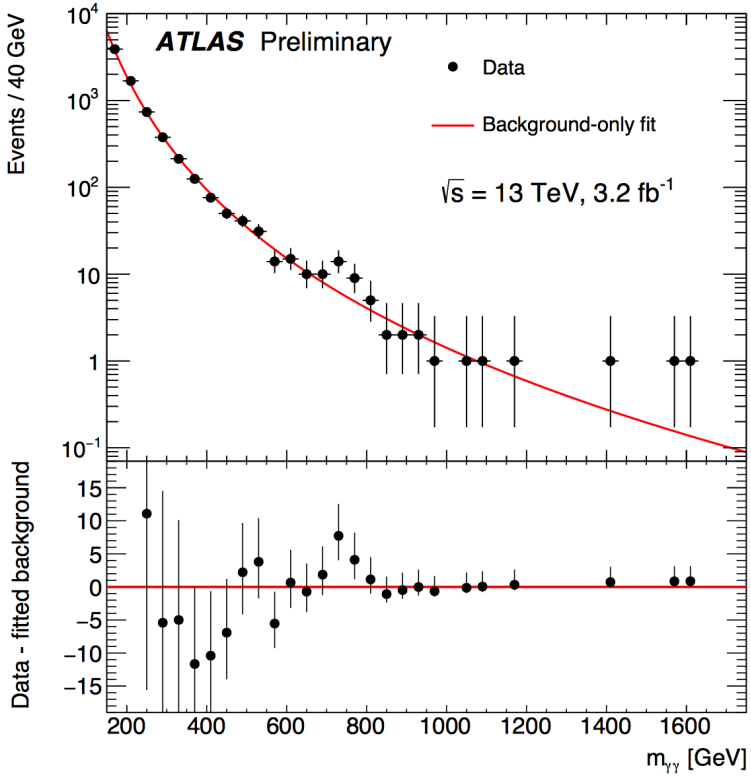
New Physics at 100 TeV

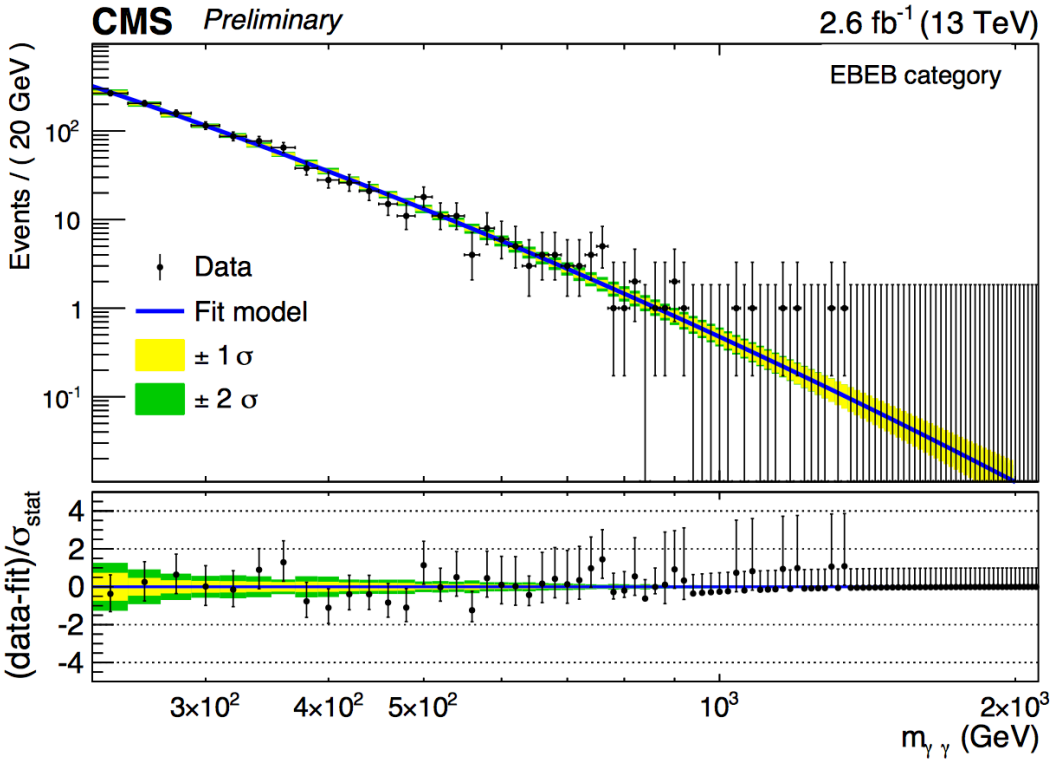
New Physics at 100 TeV

See “Physics at FCC-hh Report”

750 GeV DiPhoton Resonance

ATLAS and CMS both see an excess at 750 GeV in the diphoton spectrum:





First thoughts on what we could do with a 100 TeV collider...

750 GeV DiPhoton Resonance

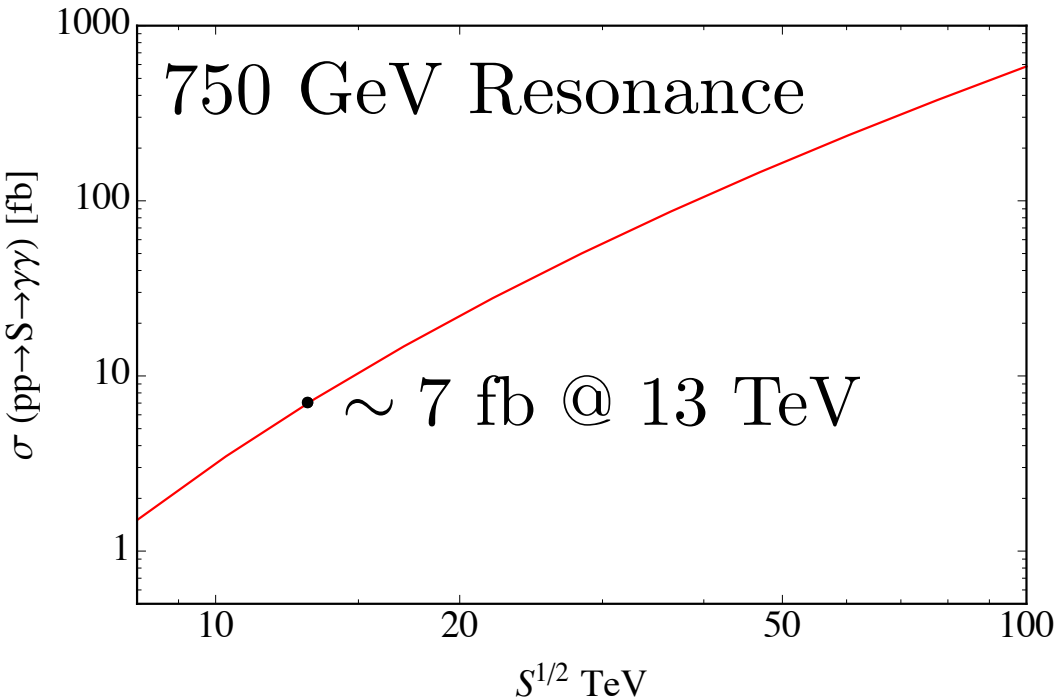
ATLAS and CMS both see an excess at 750 GeV in the diphoton spectrum..

First thoughts on what we could do with a 100 TeV collider...

- If it turns out to be real, then we need to know what we could do with 100 TeV!
- If a statistical fluctuation, nonetheless a good exercise to consider the 100 TeV potential for fully exploring LHC discovery...

750 GeV DiPhoton Resonance

Going from 13 TeV to 100 TeV huge leap in cross section:



With 3 ab^{-1} at LHC expect

$$N_{\gamma\gamma} \approx 21 \times 10^3$$

however, with the same integrated luminosity at 100 TeV would have

$$N_{\gamma\gamma} \approx 1.8 \times 10^6$$

This would allow for very detailed study indeed!

- Absolute precision
- Distributions
- Rare decays
- Rare production modes