# New Physics at 100 TeV

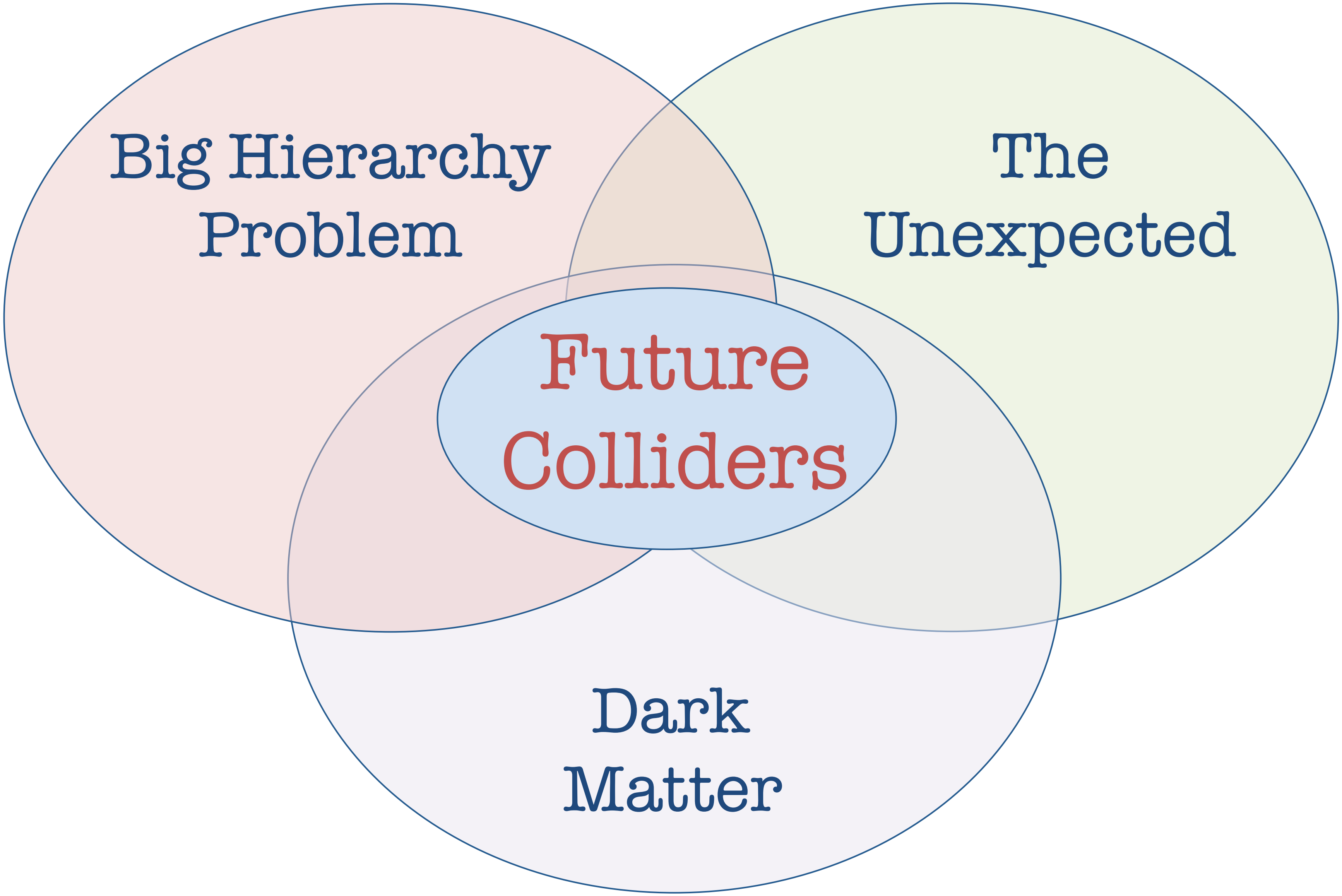
HKUST Jockey Club IAS

Jan 19th 2015

Matthew McCullough

CERN

# Beyond the Standard Model



Big Hierarchy Problem

The Unexpected

Future Colliders

Dark Matter

# 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:

$$M_{DM} \sim \mathcal{O}(\text{few}\underset{\substack{\uparrow \\ \text{Cosmological} \\ \text{constraints}}}{\ }\text{GeV}) \to \mathcal{O}(10\text{'s}\underset{\substack{\uparrow \\ \text{Unitarity} \\ \text{bounds}}}{\ }\text{TeV})$$

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

# Simplified Dark Matter Models

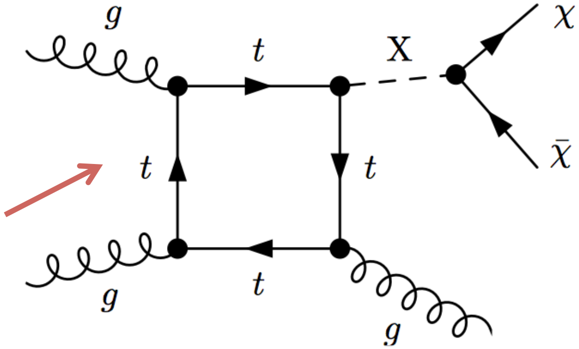
Write down simple scenarios to model production of dark matter at colliders:

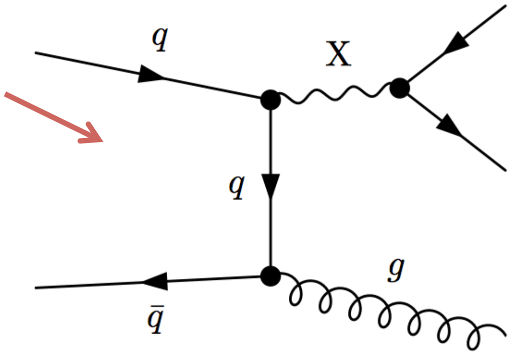
$$\mathcal{L}_{\mathrm{S}} \supset -\sum_q c_S \lambda_{h,q} S\,\bar{q}q - \frac{1}{2}m_{\mathrm{MED}}^2 S^2 + \mathcal{L}(S,\bar{\chi},\chi)\,,$$

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

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

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

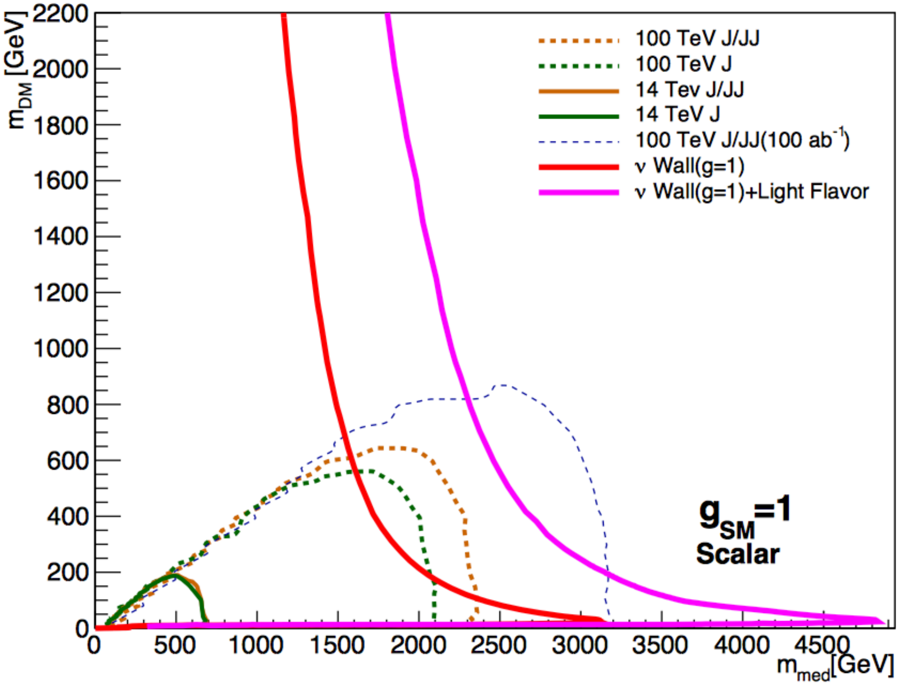


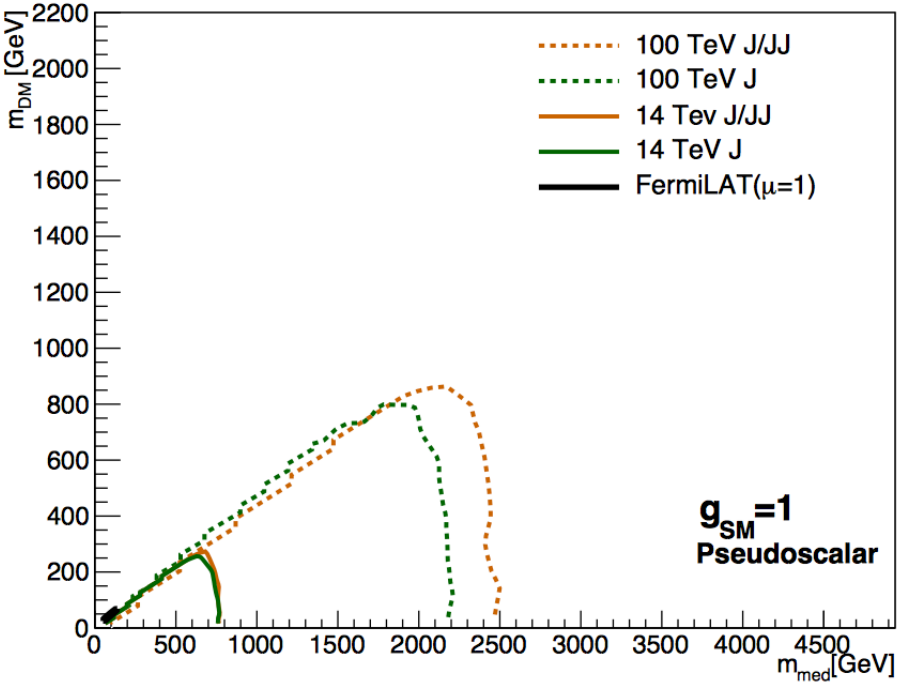


100 TeV Study: Harris, Khoze, Spannowsky, Williams, 2015.

# Simplified Dark Matter Models

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





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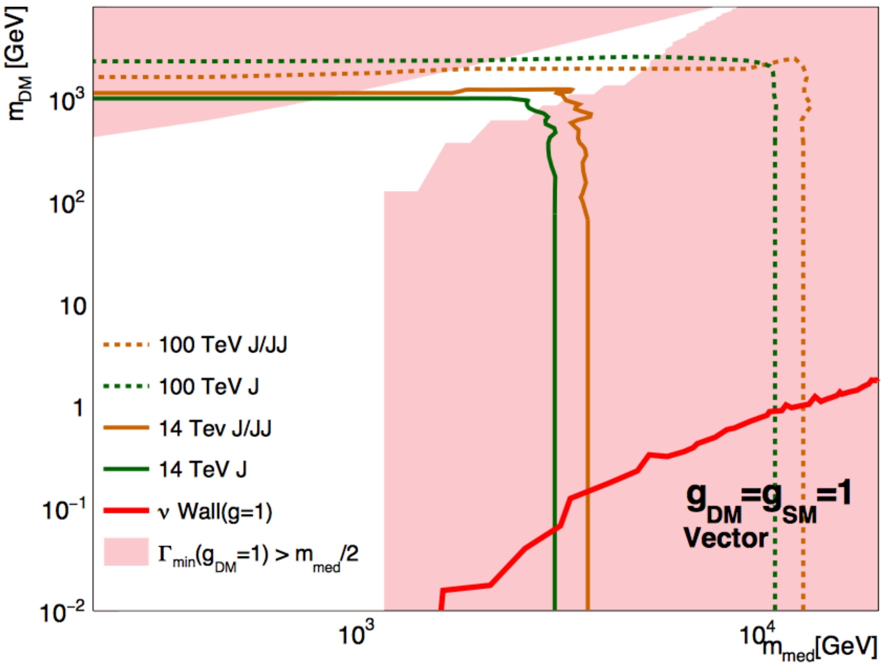
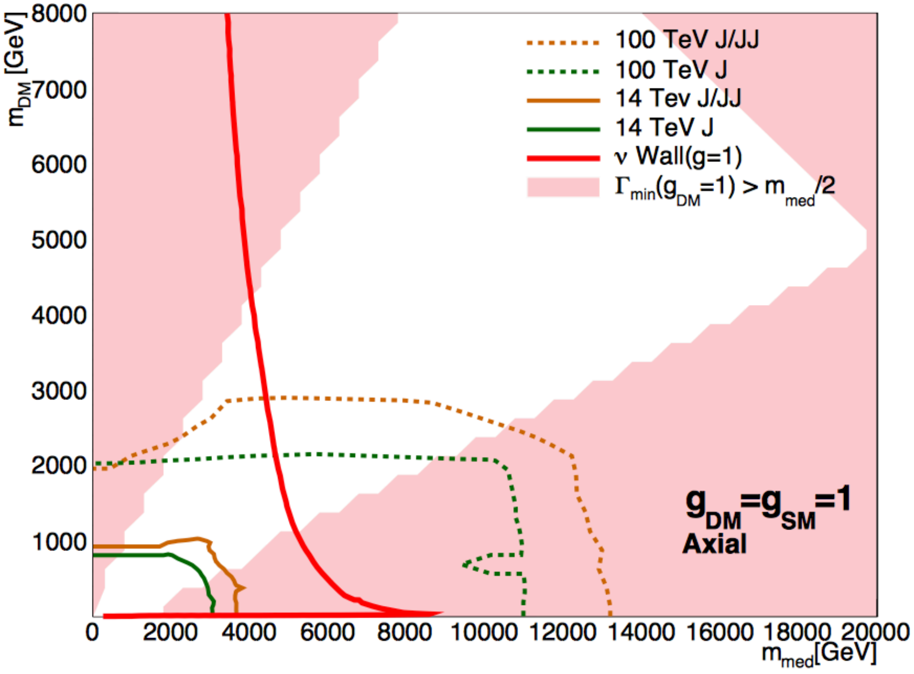




100 TeV Study: Harris, Khoze, Spannowsky, Williams, 2015.

# 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

If the singlet is DM, i.e. only pair-produced, we have:

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

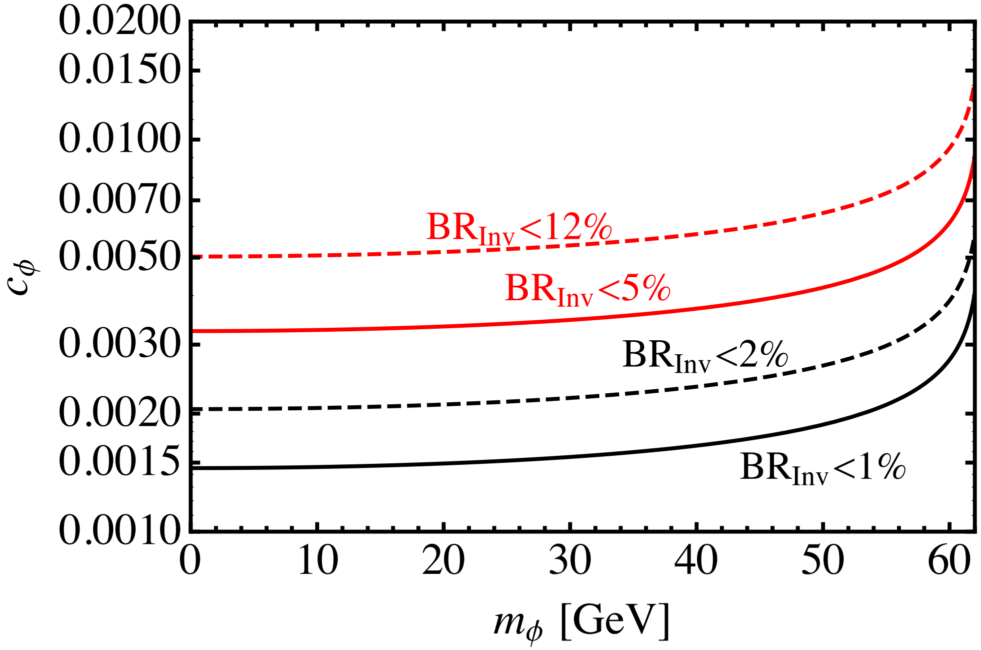
Usual limits on-shell: $h \to \phi\phi \Rightarrow \Gamma_{h\to\mathrm{inv}} \neq 0$

Relevant if we have: $m_\phi < m_h/2 < 62\ \mathrm{GeV}$

Can be constrained by global coupling fit, however MET+(di-)jet signatures also promising for direct search.

# Higgs Portal at 100 TeV

Coupling sensitivity possible with variety of invisible branching limits.



100 TeV capability depends on coupling precision.

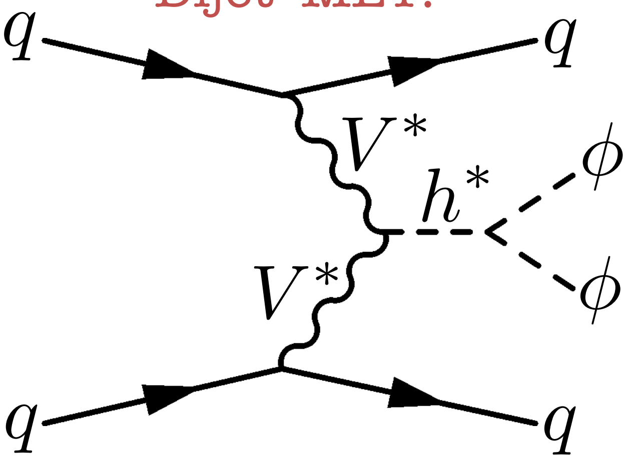
What about $m_\phi > m_h/2$ ? This is the majority of parameter space. What can we do?

# Higgs Portal

Want more coverage! For $m_\phi > m_h/2$ must go off-shell…

**VBF:**

Dijet+MET:



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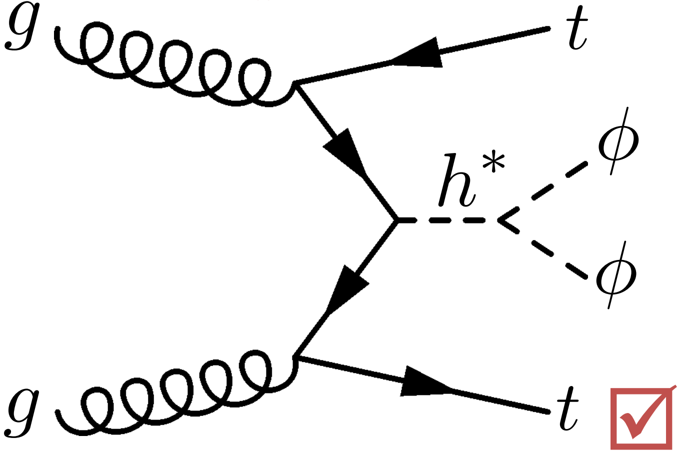
**tth:**

Ditop+MET:



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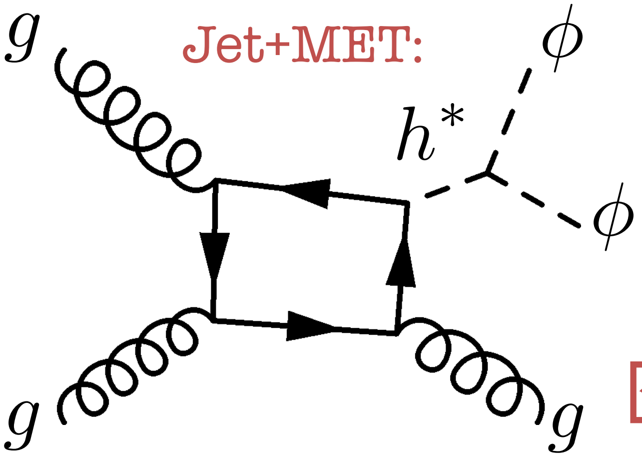
**Gluon fusion:**

Jet+MET:



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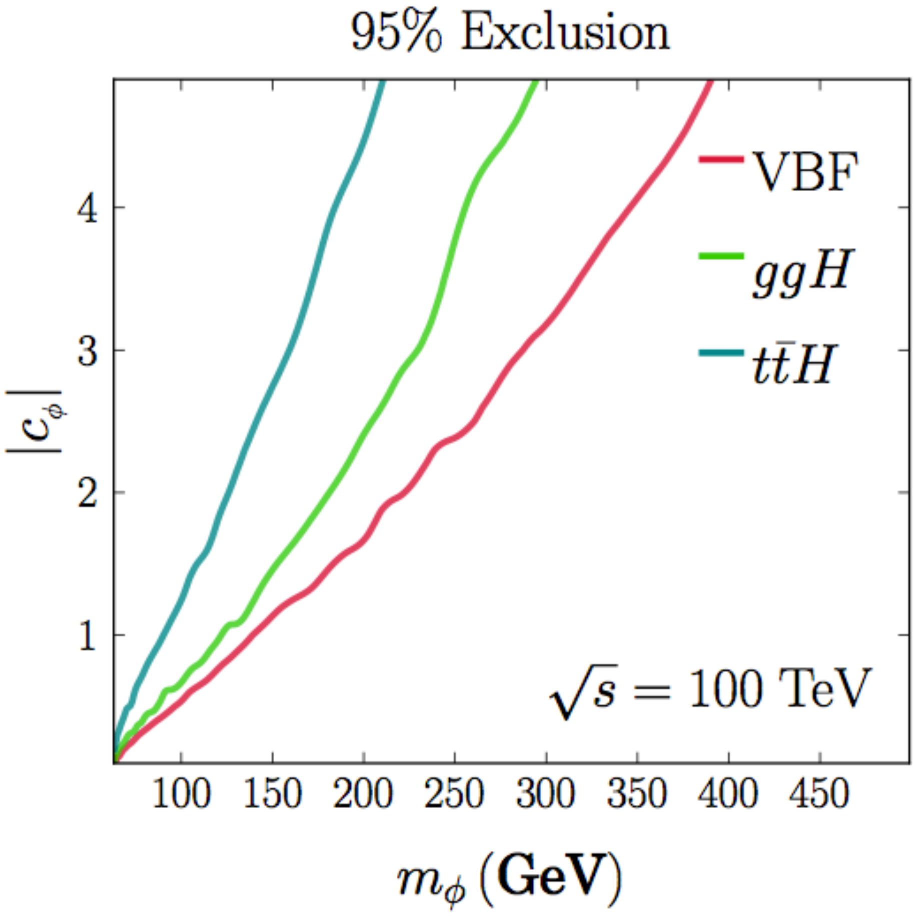
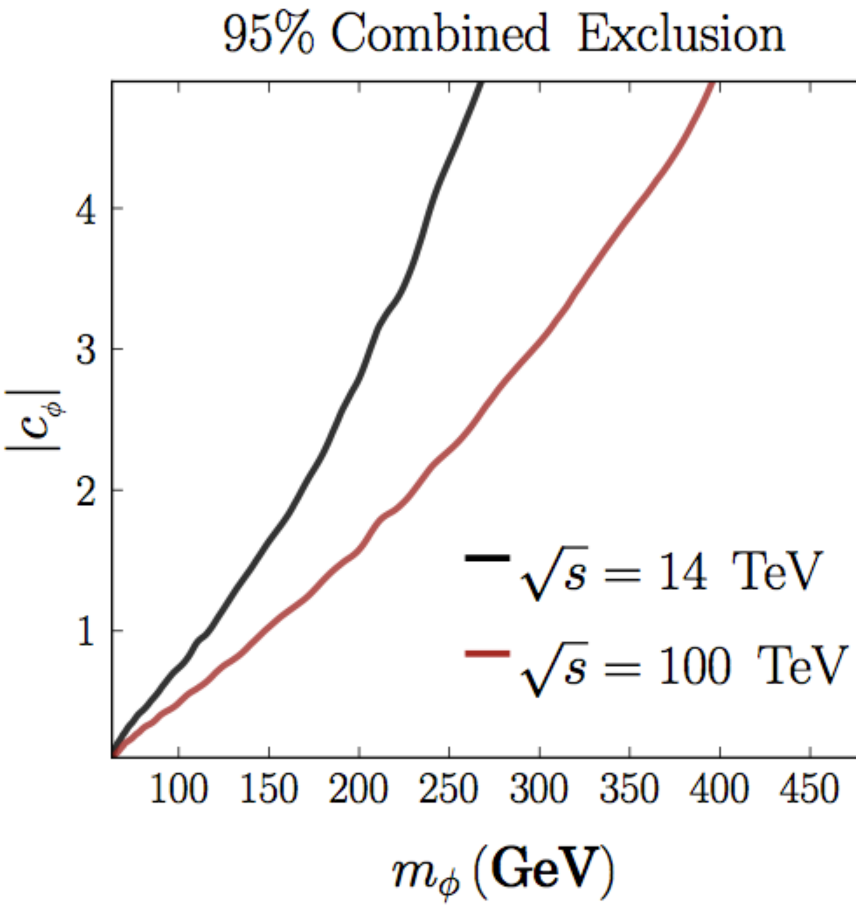
Note: Higgs EFT overestimates rate so full loop necessary.

# Higgs Portal

## Different channel and different colliders:

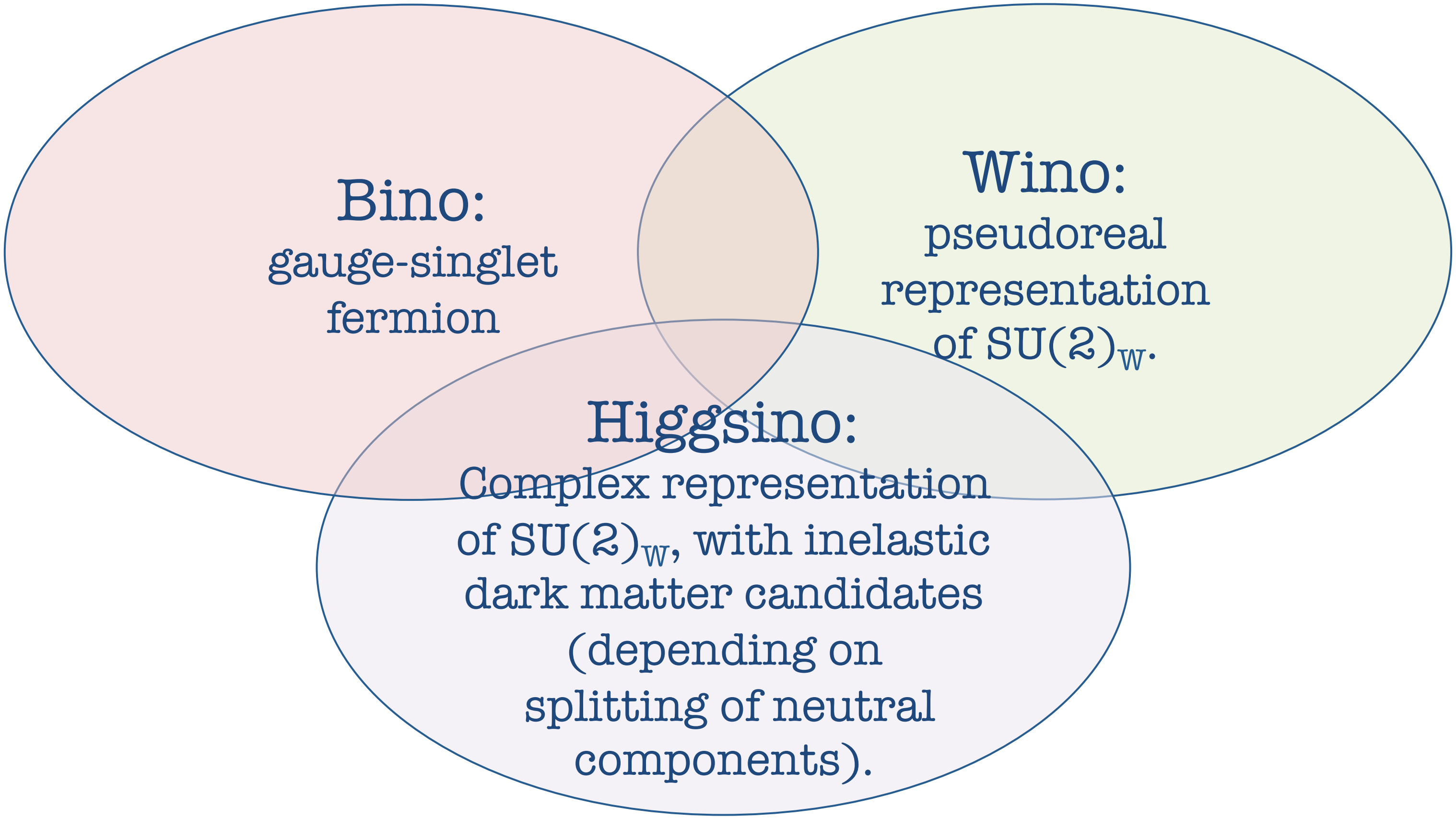




Craig, Lou, MM, Thalapillil

# Neutralino Dark Matter

Neutralino dark matter is a compelling ingredient of the SUSY setup, including Mini-Split SUSY.



**Bino:**
gauge-singlet
fermion

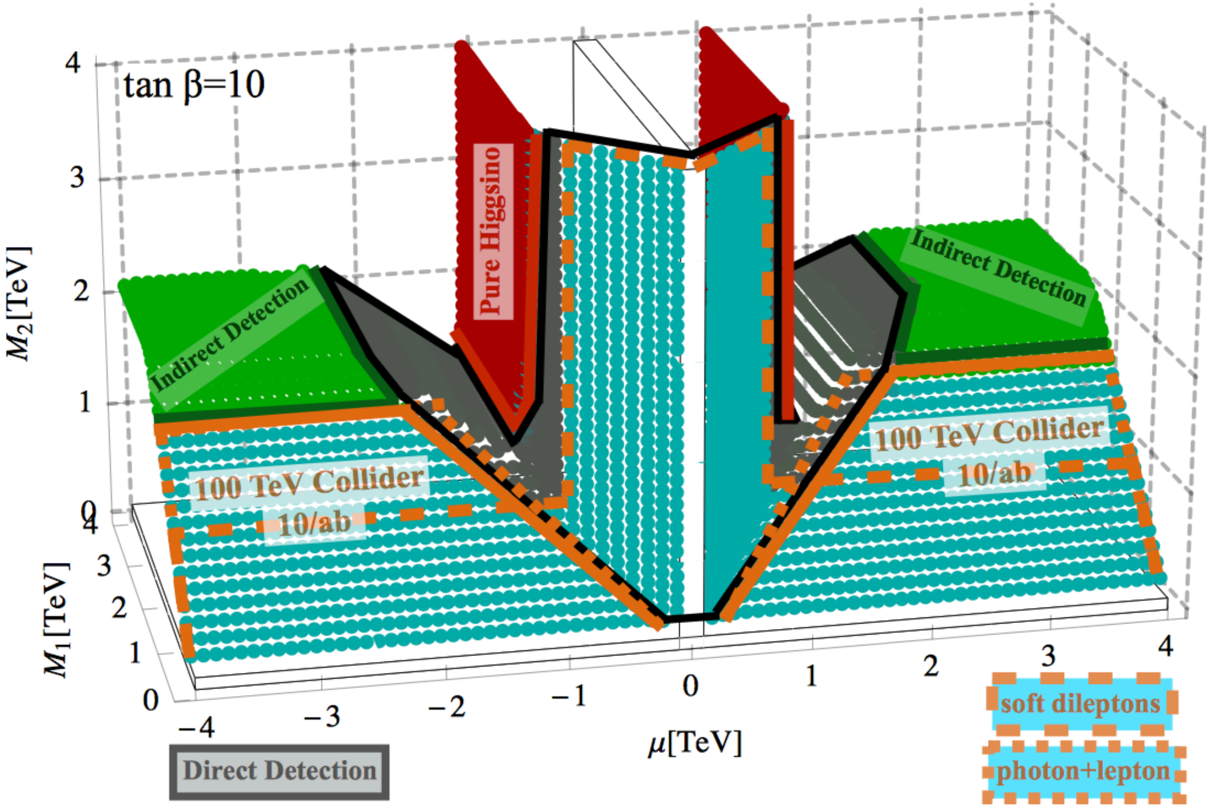
**Wino:**
pseudoreal
representation
of $SU(2)_W$.

**Higgsino:**
Complex representation
of $SU(2)_W$, with inelastic
dark matter candidates
(depending on
splitting of neutral
components).

Direct and indirect detection interplay non-trivial.

# Relic Neutralino Surface

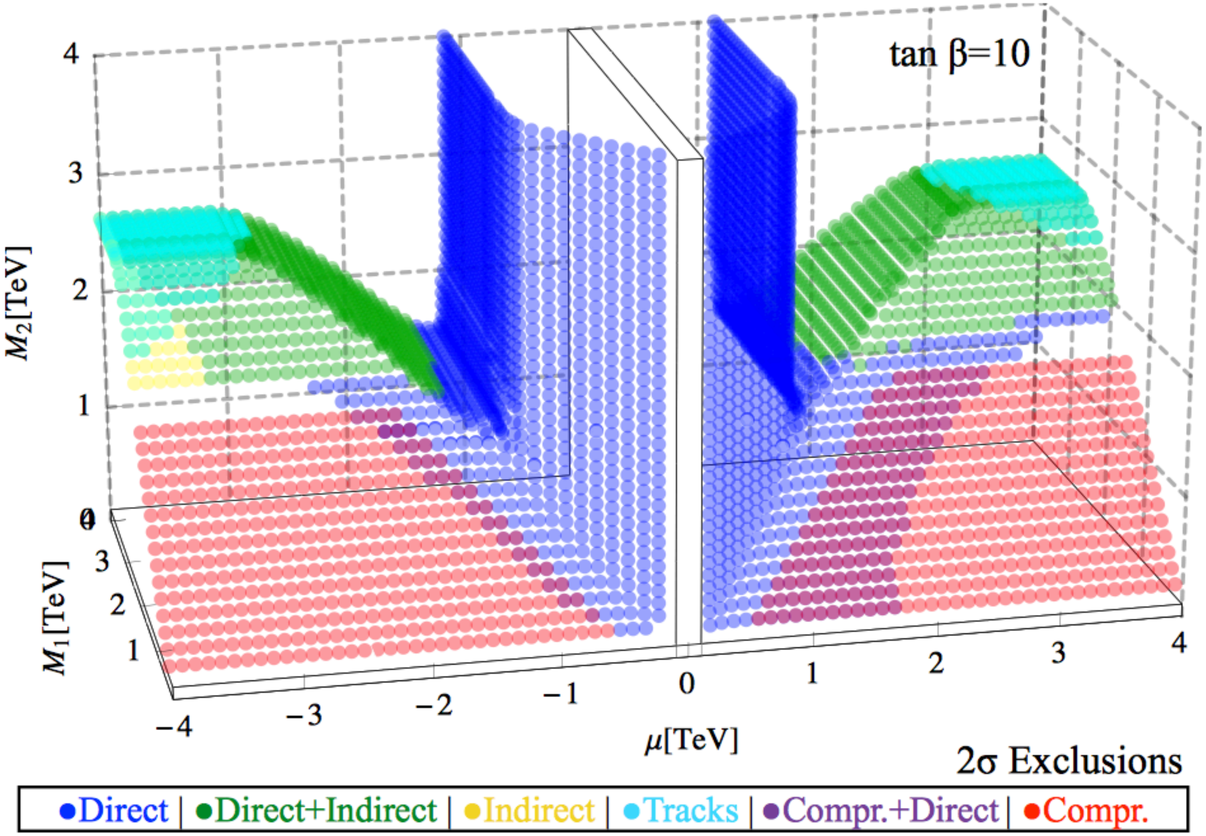
Considering just the electroweakino sector of MSSM. Collider signatures considered: MET + Jet and either soft dileptons or lepton+photon



100 TeV Study: Bramante, Fox, Martin, Ostdiek, Plehn, Schell, Takeuchi. 2014.

# Relic Neutralino Surface

Considering just the electroweakino sector of MSSM. Collider signatures considered: Disappearing charged tracks and previous slide.



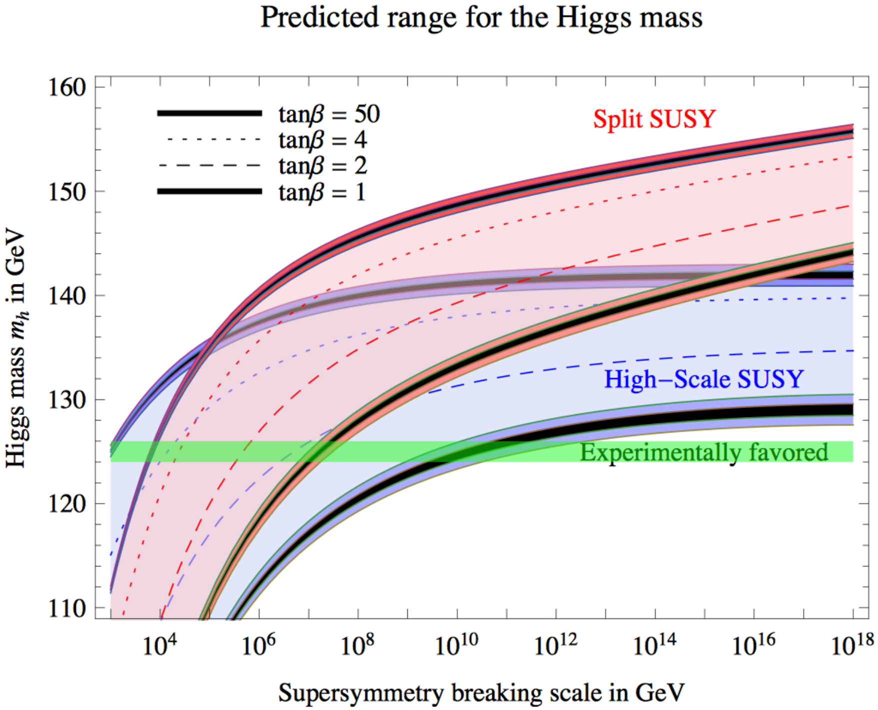
100 TeV Study: Bramante, Desai, Fox, Martin, Ostdiek, Plehn. 2015.

# 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

SUSY predicts collider signatures both as a potential solution to the hierarchy problem and also if the weak scale is tuned (Mini-Split).

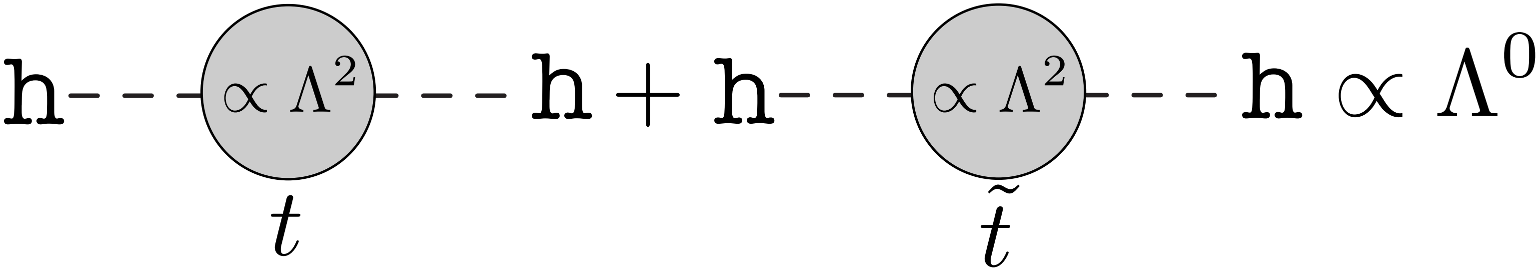


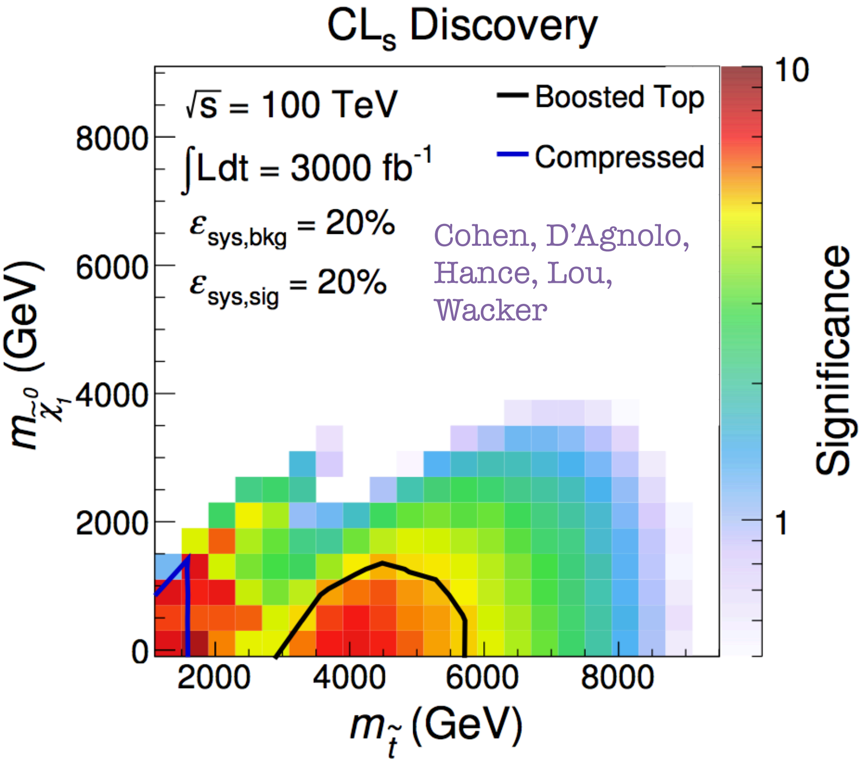
Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia

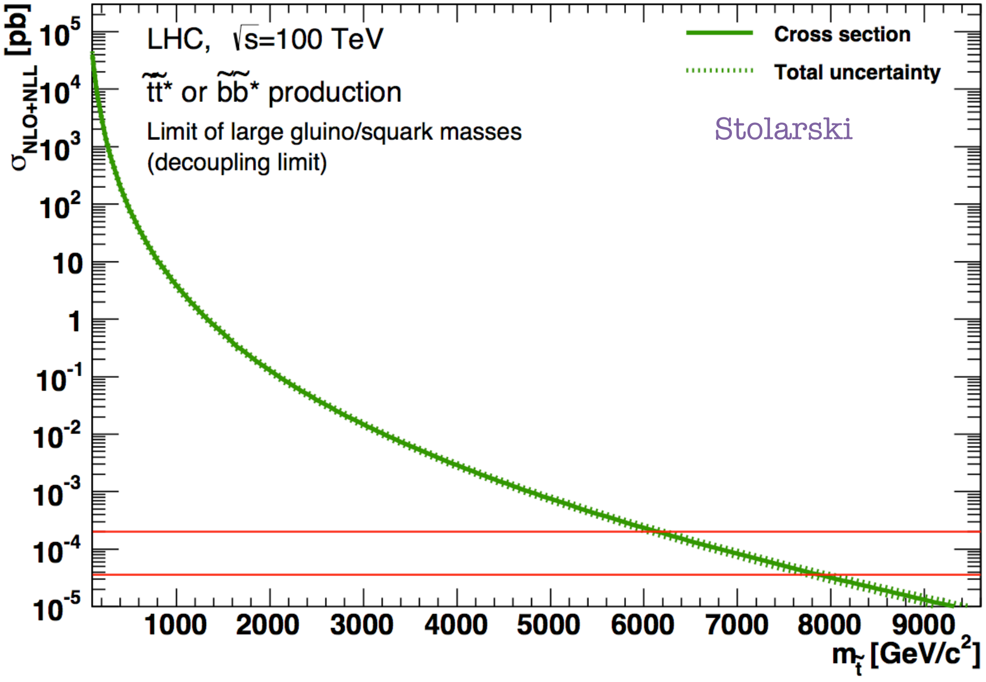
Higgs mass in simplest scenario (MSSM) already provides a ballpark expectation for squarks.

# Supersymmetry

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

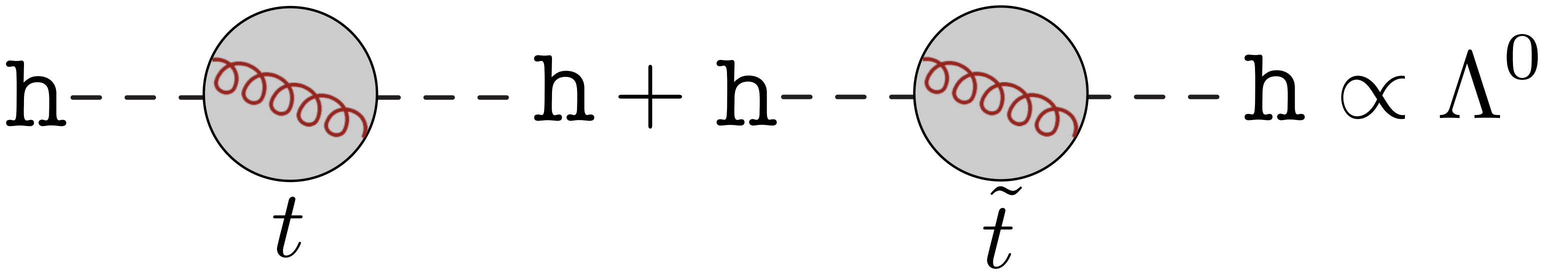


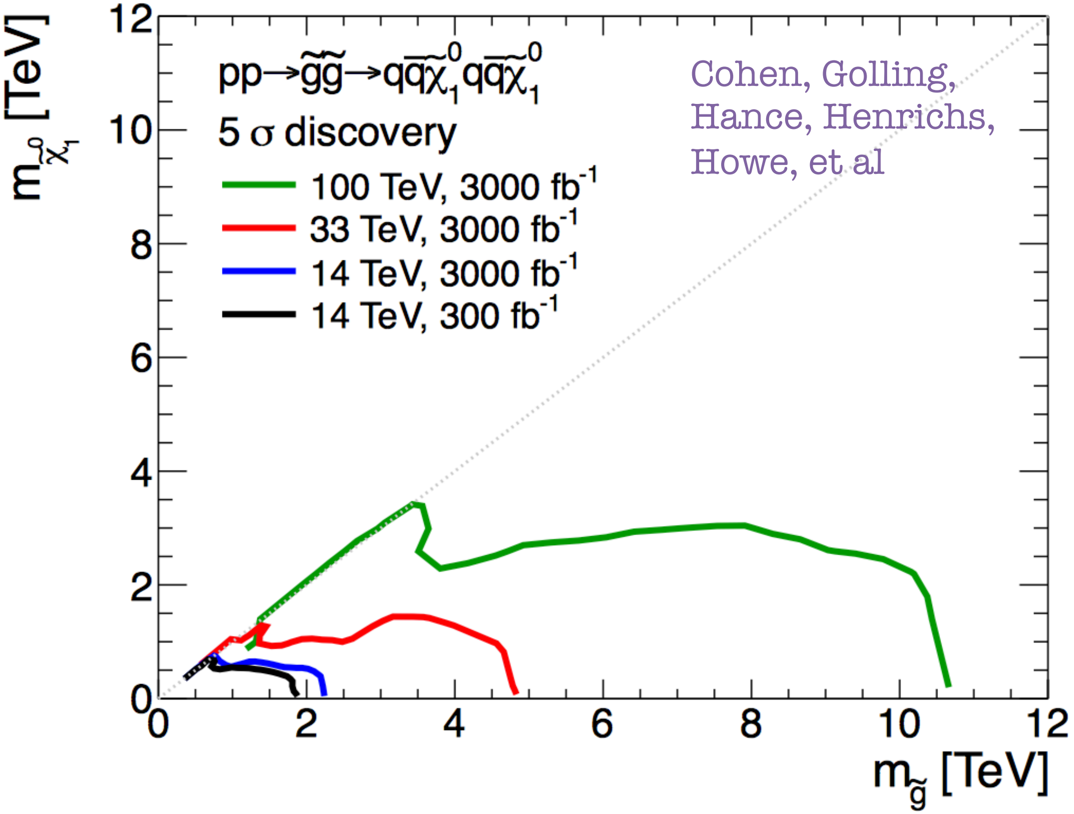




# Supersymmetry

Next in line at two loops are the gluinos

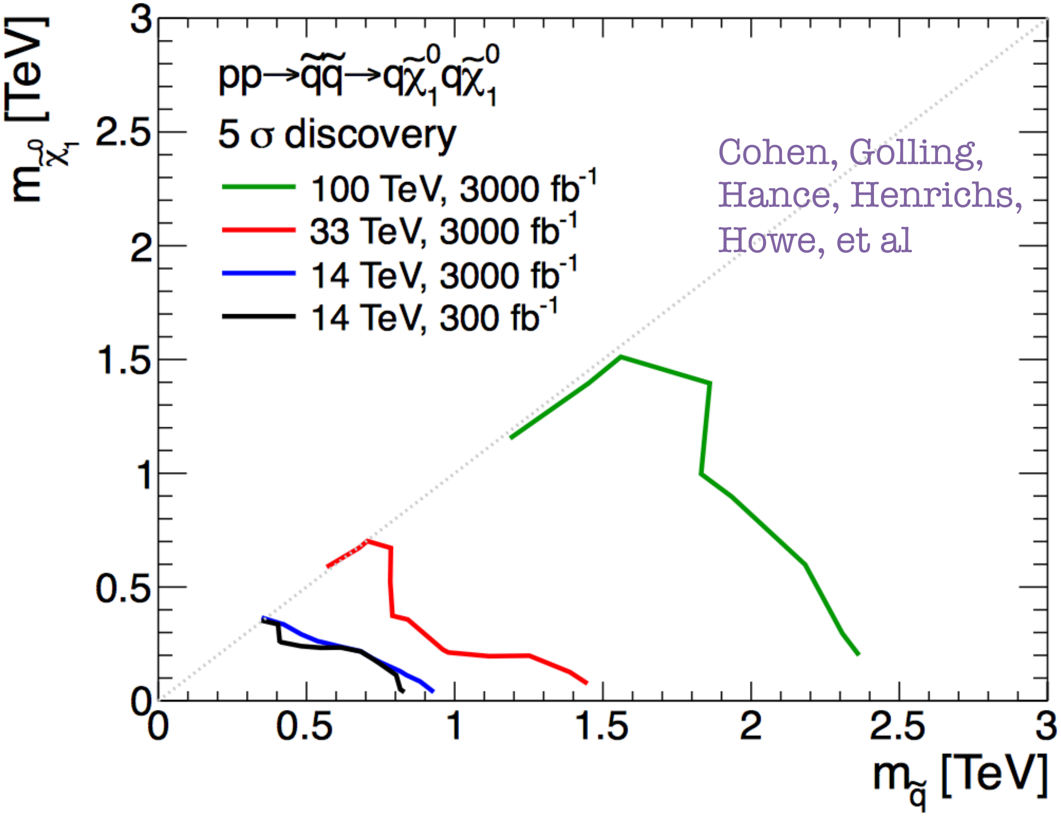




Cohen, Golling, Hance, Henrichs, Howe, et al

# Supersymmetry

First two generation squarks also discoverable

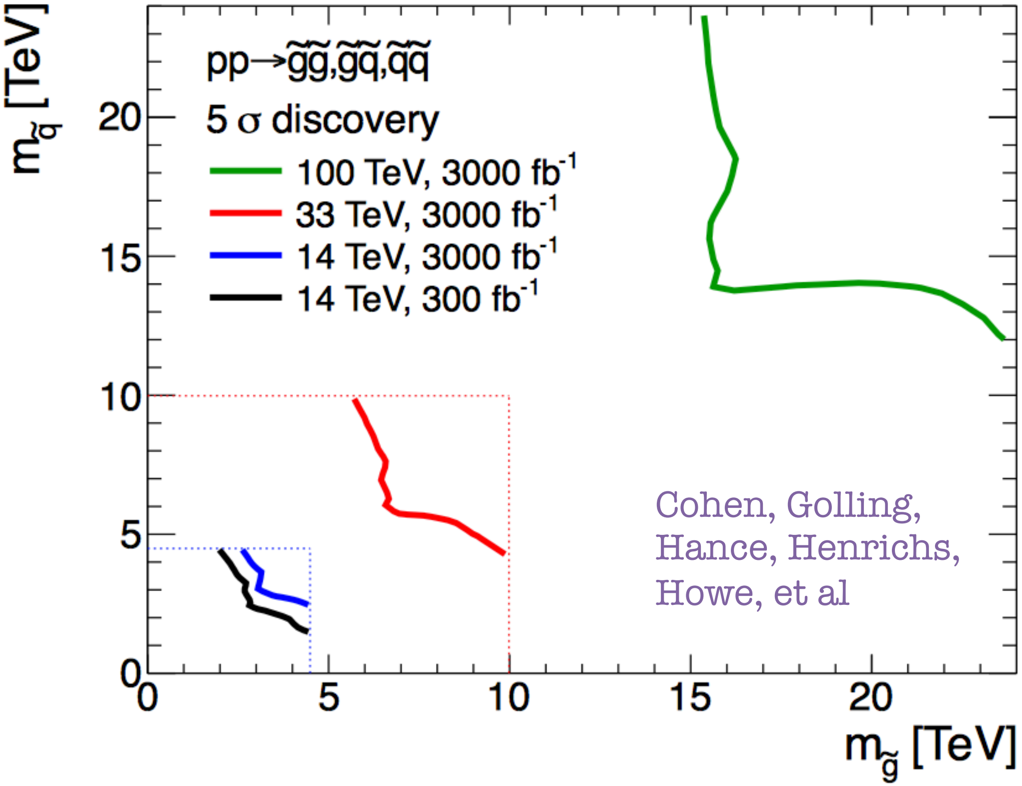


Cohen, Golling, Hance, Henrichs, Howe, et al

Reach suppressed compared to gluinos as decoupling gluinos suppresses cross section. Reach increases when gluinos reintroduced…

# Supersymmetry

Combining gluino and squark limits onto one plane:



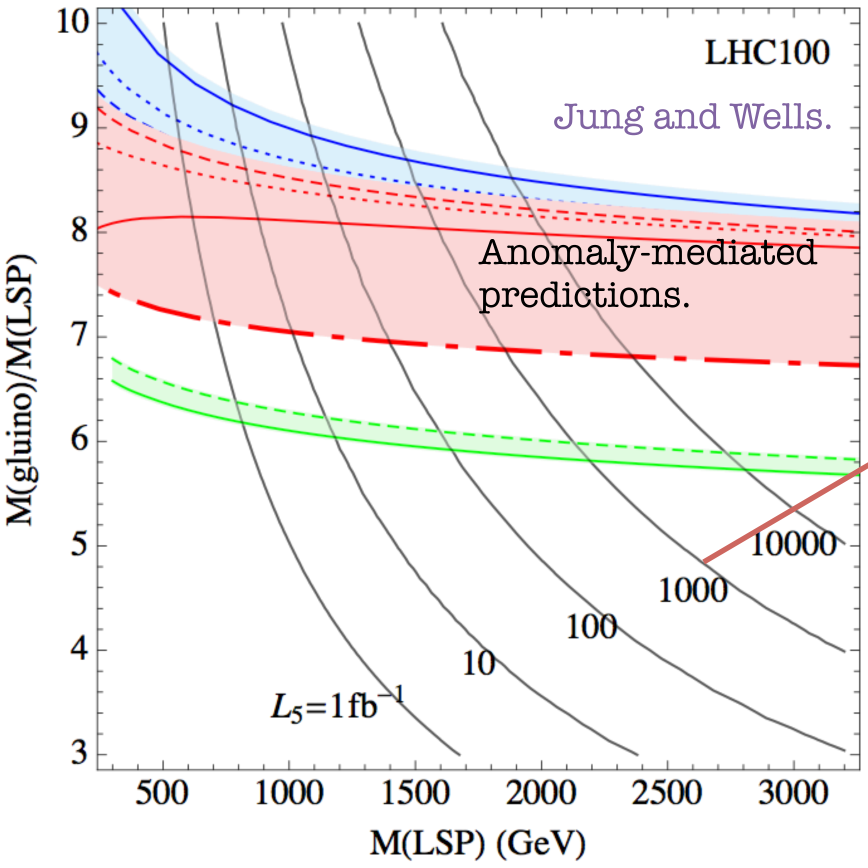
Cohen, Golling, Hance, Henrichs, Howe, et al

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

# Supersymmetry

Mini-split SUSY: scalars decoupled and only fermions remains light due to R-symmetry.

Motivations: Unification, Dark Matter



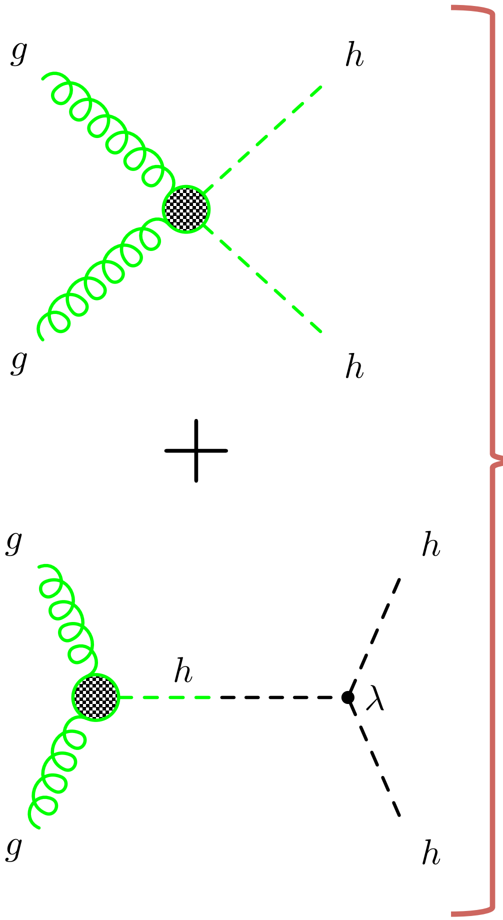
Jung and Wells.

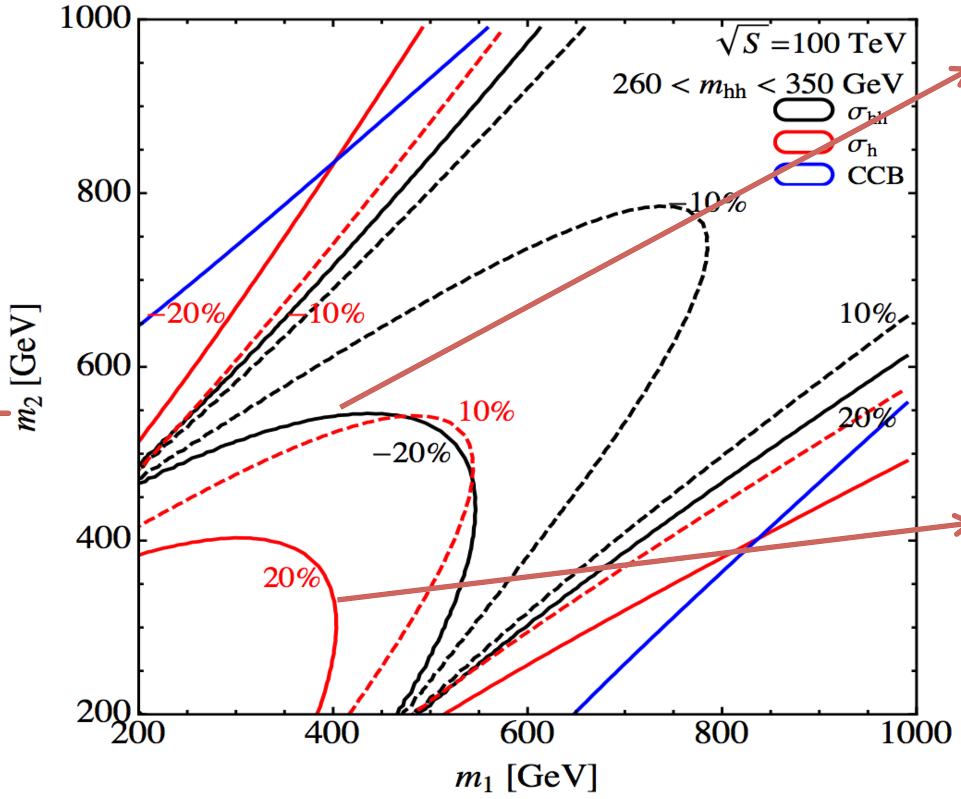
Anomaly-mediated predictions.

Integrated luminosity required for discovery.

# Supersymmetry

Can also indirectly probe presence of SUSY states from precision Higgs measurements.





Single Higgs measurements probe Higgs-gluon coupling.

Higgs pair measurements probe further structure of Higgs-gluon coupling.

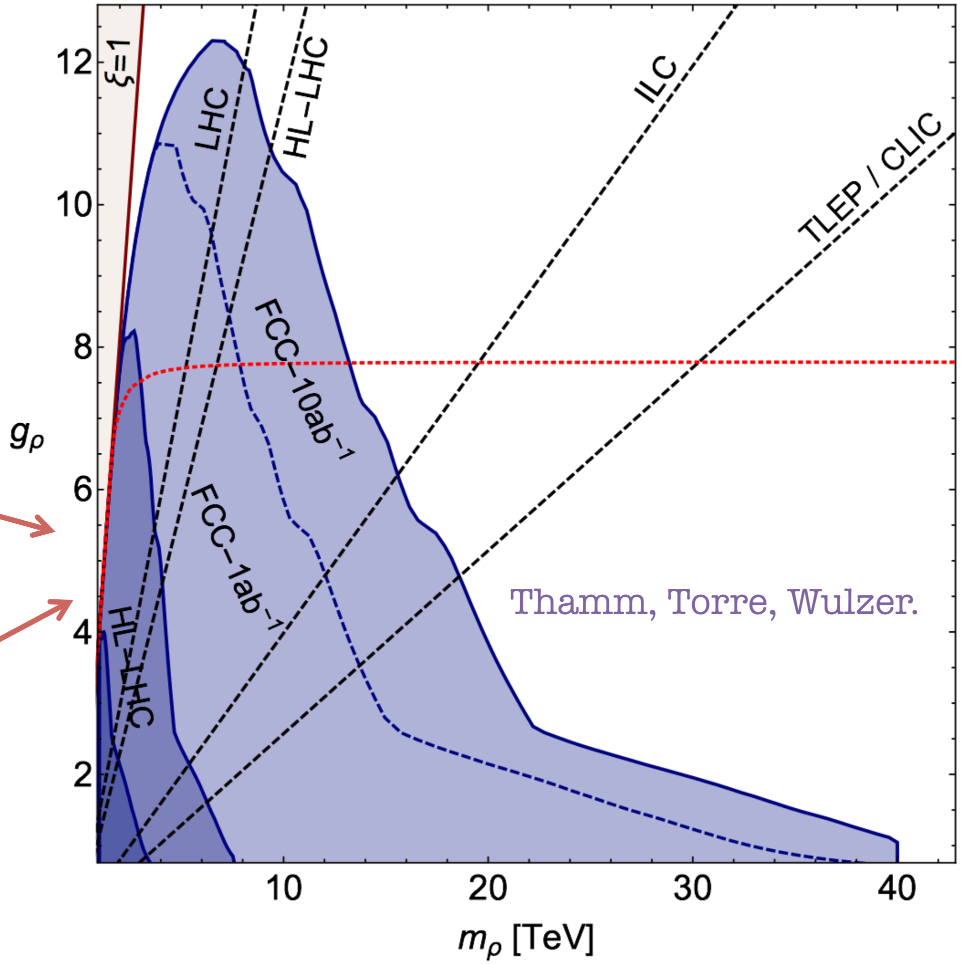
Battell, McCullough, Stolarski, Verhaaren

# 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

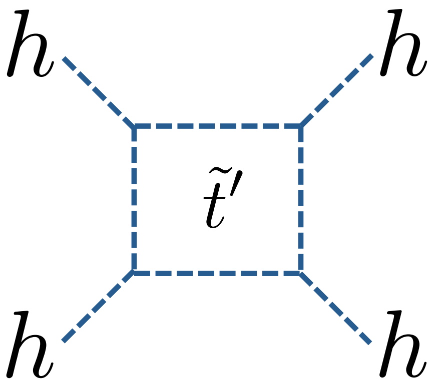
$$\rho \to l\bar{l}$$
and
$$\rho \to WZ \to \nu + 3l$$

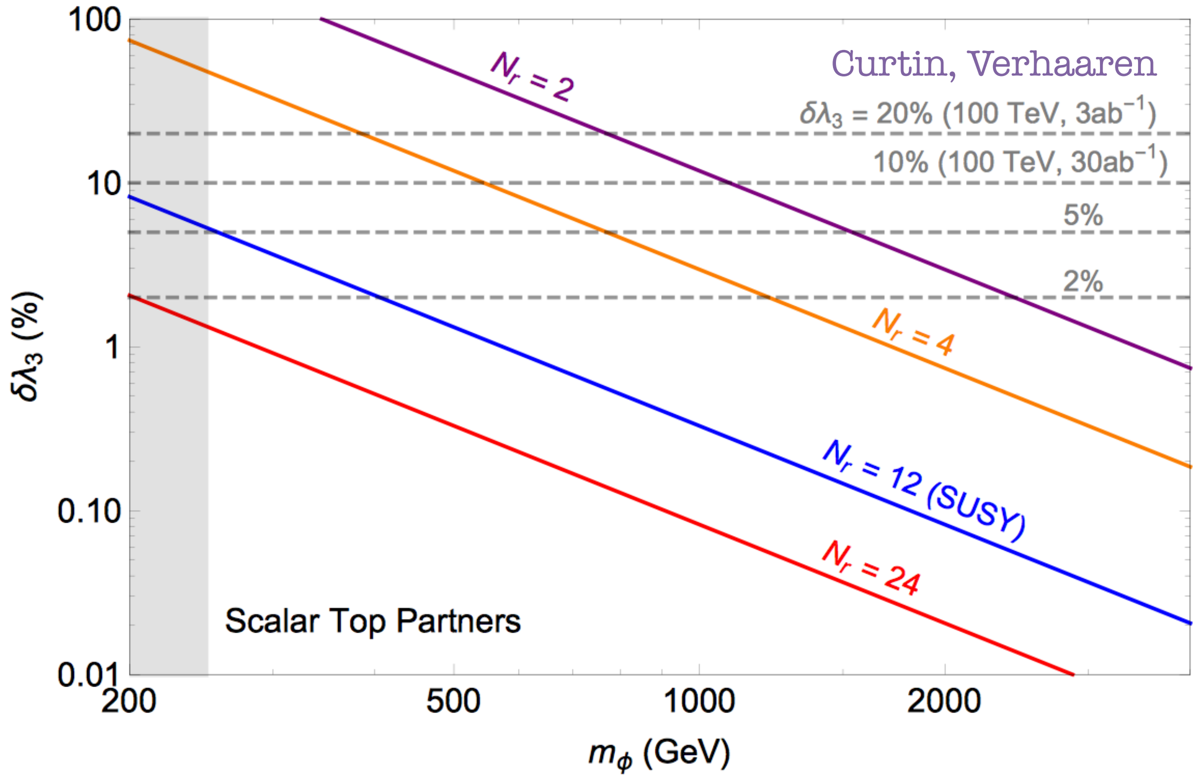


Thamm, Torre, Wulzer.

# Neutral Naturalness

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

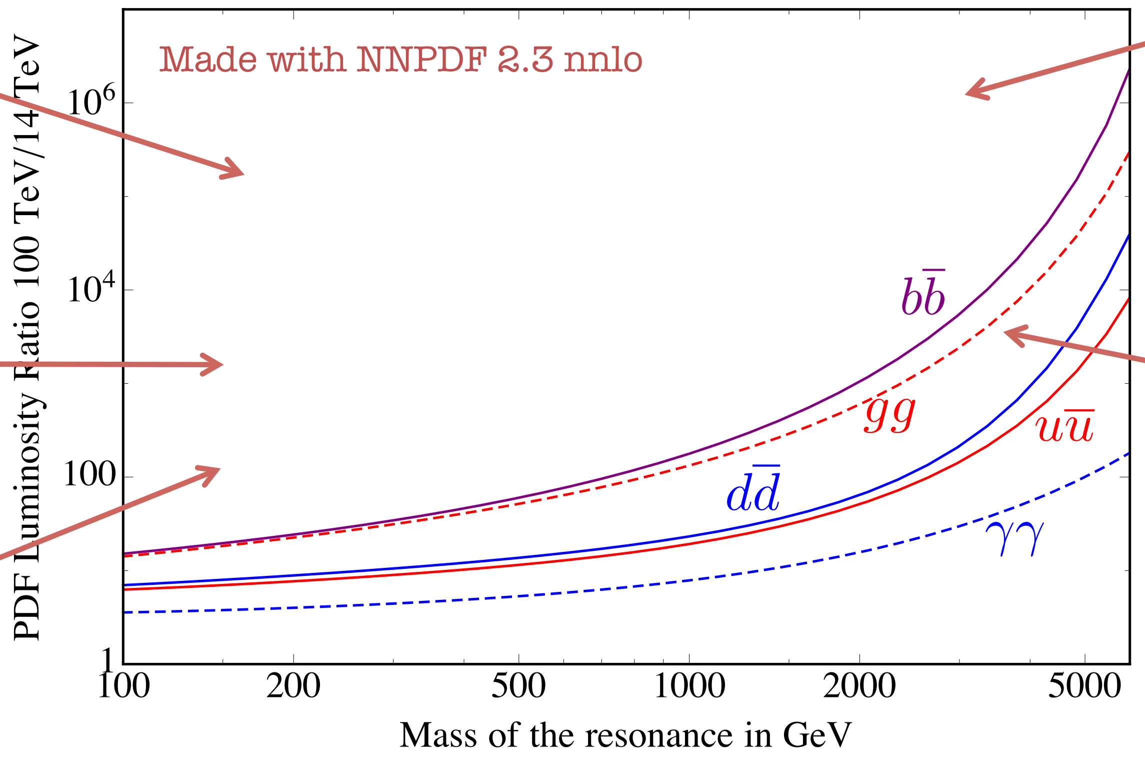




100 TeV collider can probe these possibilities with exotic Higgs decays/modified Higgs pheno.

# General Comments

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.

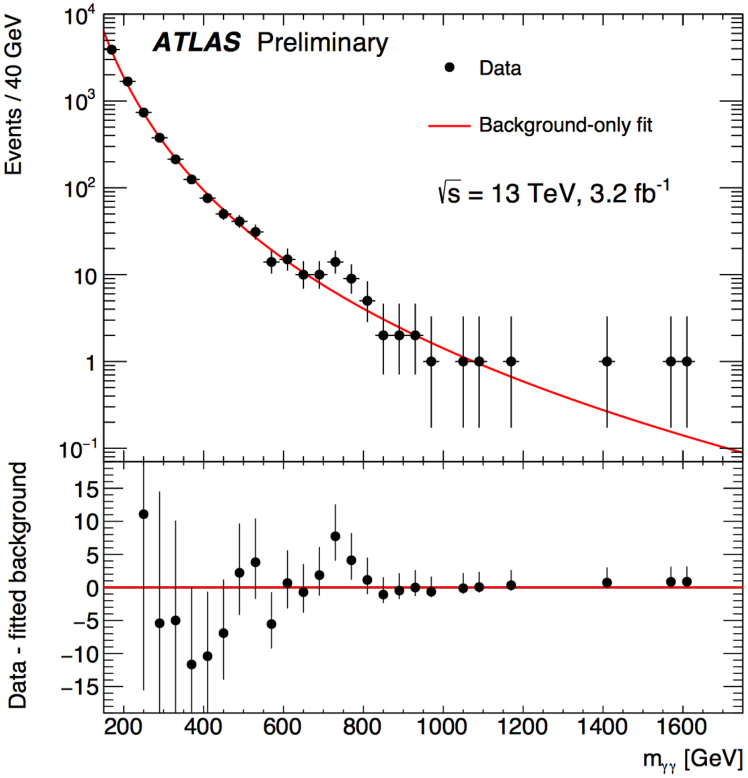
Rare/ associated production modes

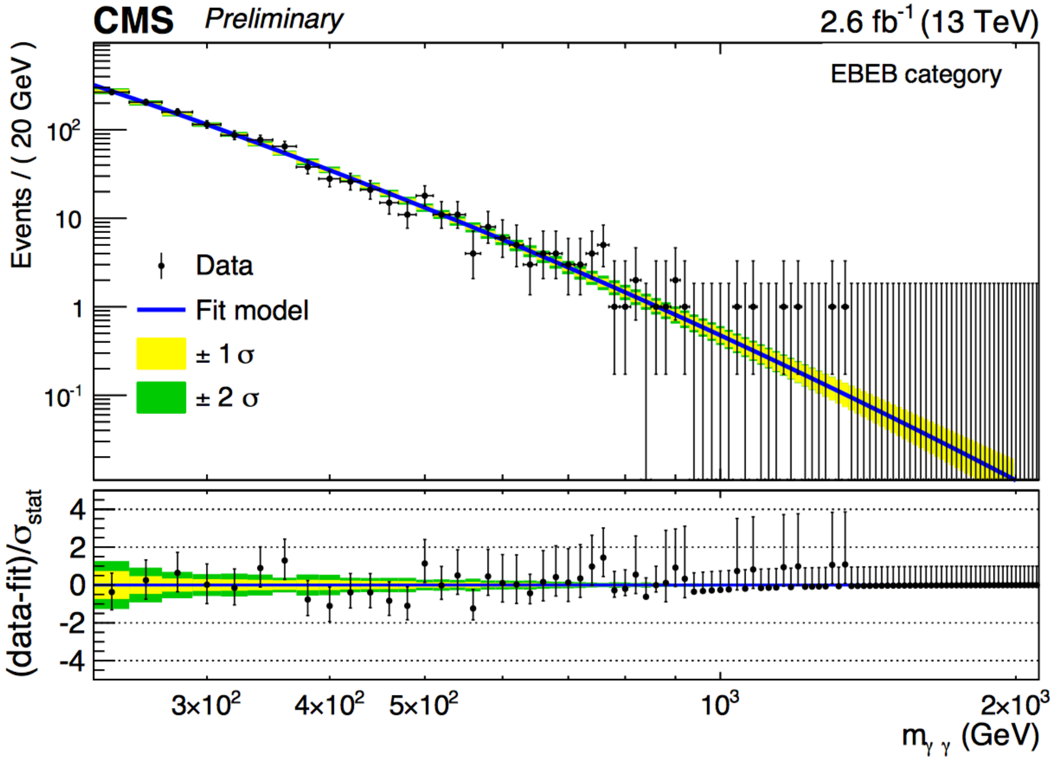
Rare/ exotic decays.

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

# 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..

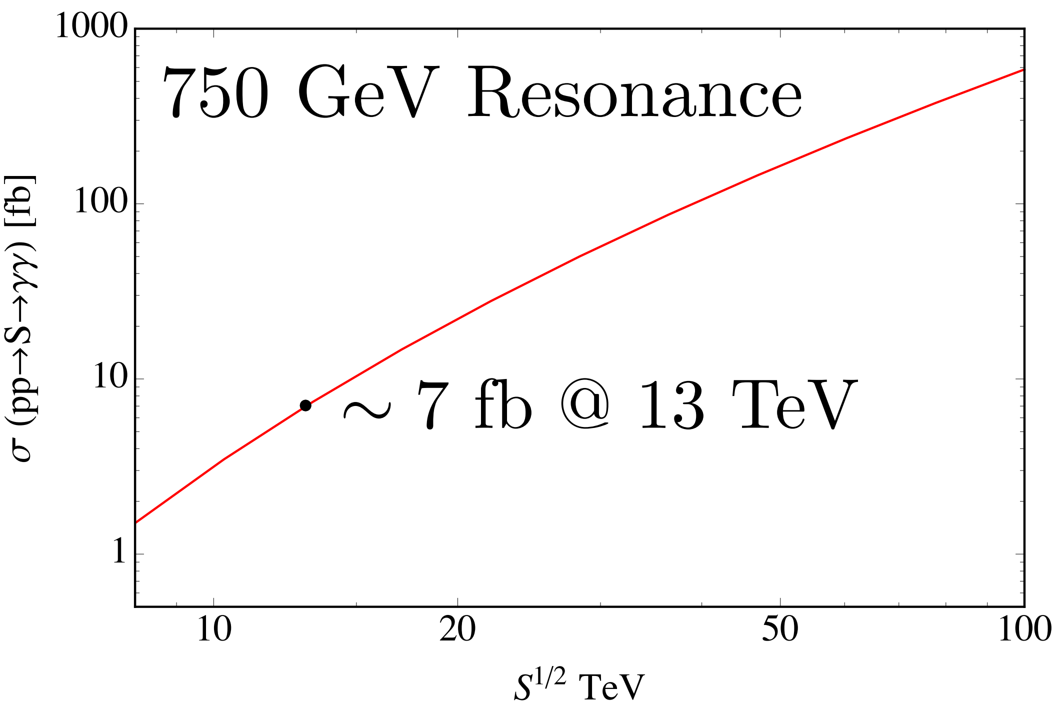
First thoughts on what we could do with a 100 TeV collider…

- 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 straw man exercise to consider the 100 TeV potential for fully exploring an LHC BSM discovery…

# 750 GeV DiPhoton Resonance

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



With 3 $\mathrm{ab}^{-1}$ 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

# Conclusions

Continued experimental investigation is required to answer many questions in theoretical physics, including

- Electroweak naturalness (and beyond)
- Dark Matter
- … and much else

A 100 TeV proton collider would explore new territories beyond the Standard Model and, in the event of a discovery at the LHC, could offer precision measurements of LHC discoveries as well as further exploration to uncover underlying structures.