Expectations for Run 2
BSM Theory perspective

Lian-Tao Wang
University of Chicago

"Roadmap toward discovery at LHC Run 2", Seattle, August 4, 2014

Defining the goal of my talk

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Is run 2 going to discover(kill) X (X≈SUSY)?

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I don't know.

However, I am very excited about run 2, because it will

Significantly extend our energy frontier.

Exploring new direction, testing new ideas.

Setting the stage for the next step beyond the LHC.

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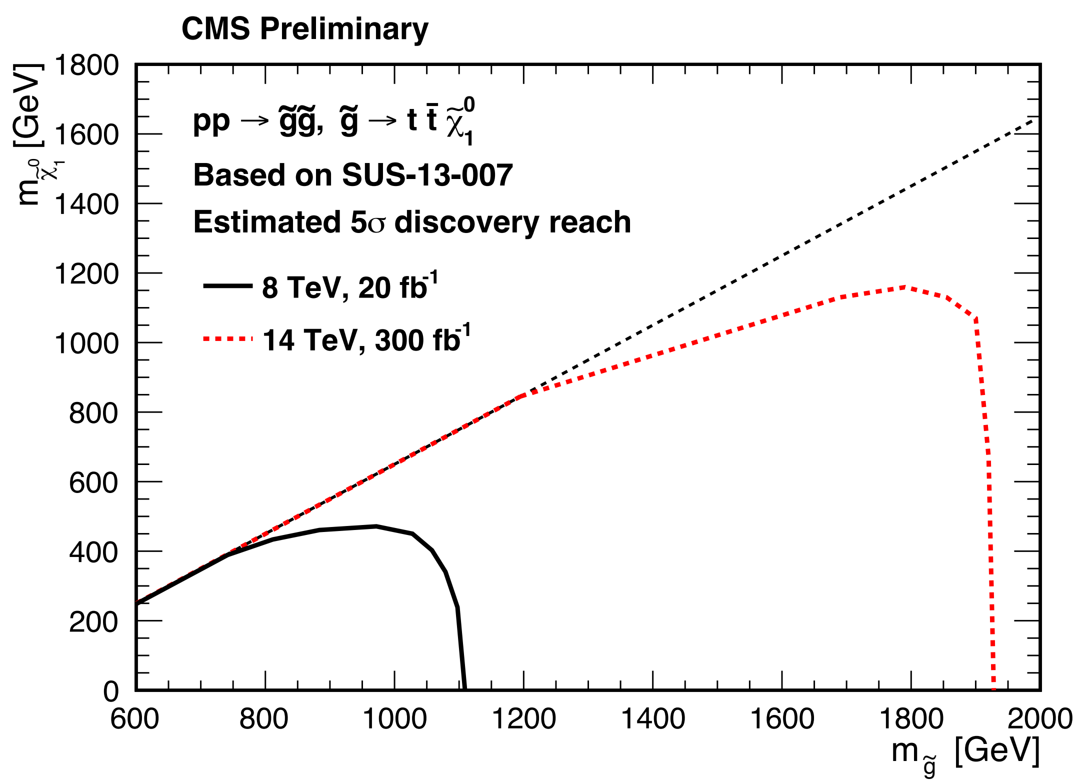
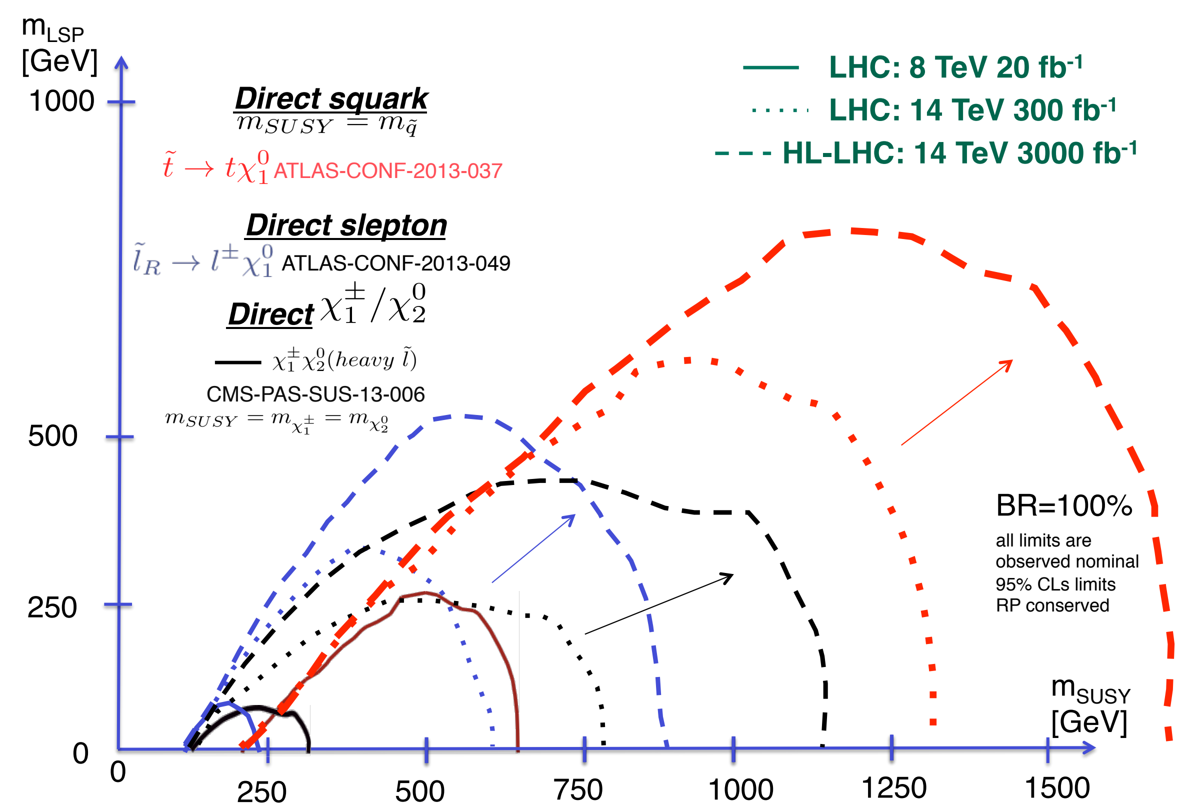
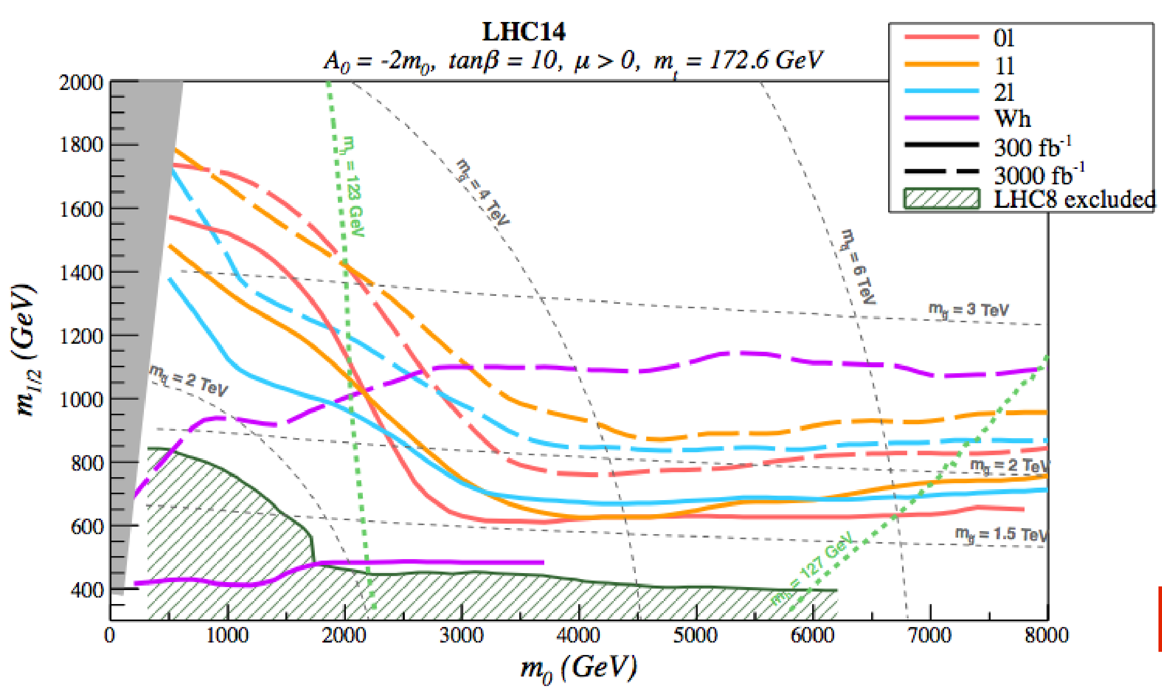
- In some sense, our wish list has not changed much from 10 years ago.
  - All the papers we have written before 2009.
  - minus technicolor.
- However, the discovery of Higgs and non-discovery of anything else do change our thinking, added to our confusion.
- Instead of repeating everything, I will try to reflect more of the recent thinking.

Run 2, impressive extension of the mass reach





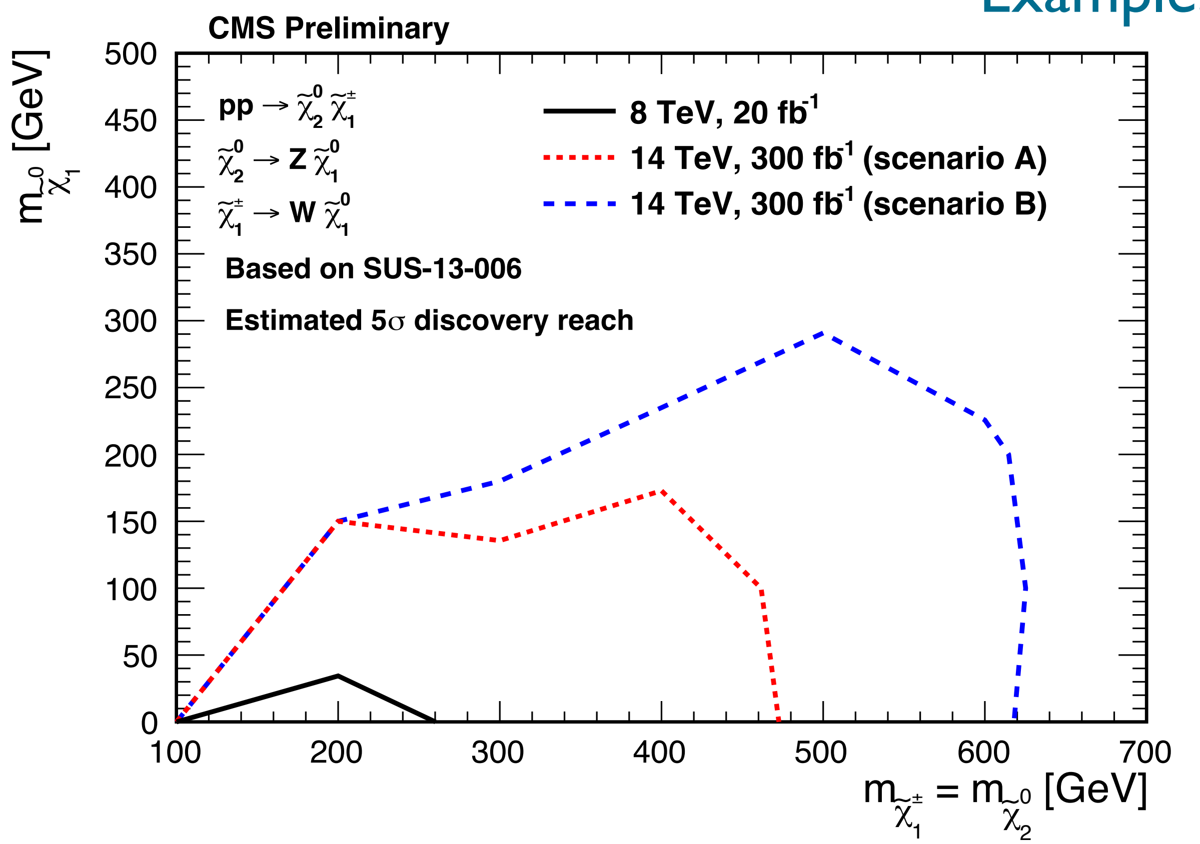
Virdee, LHCP 2014

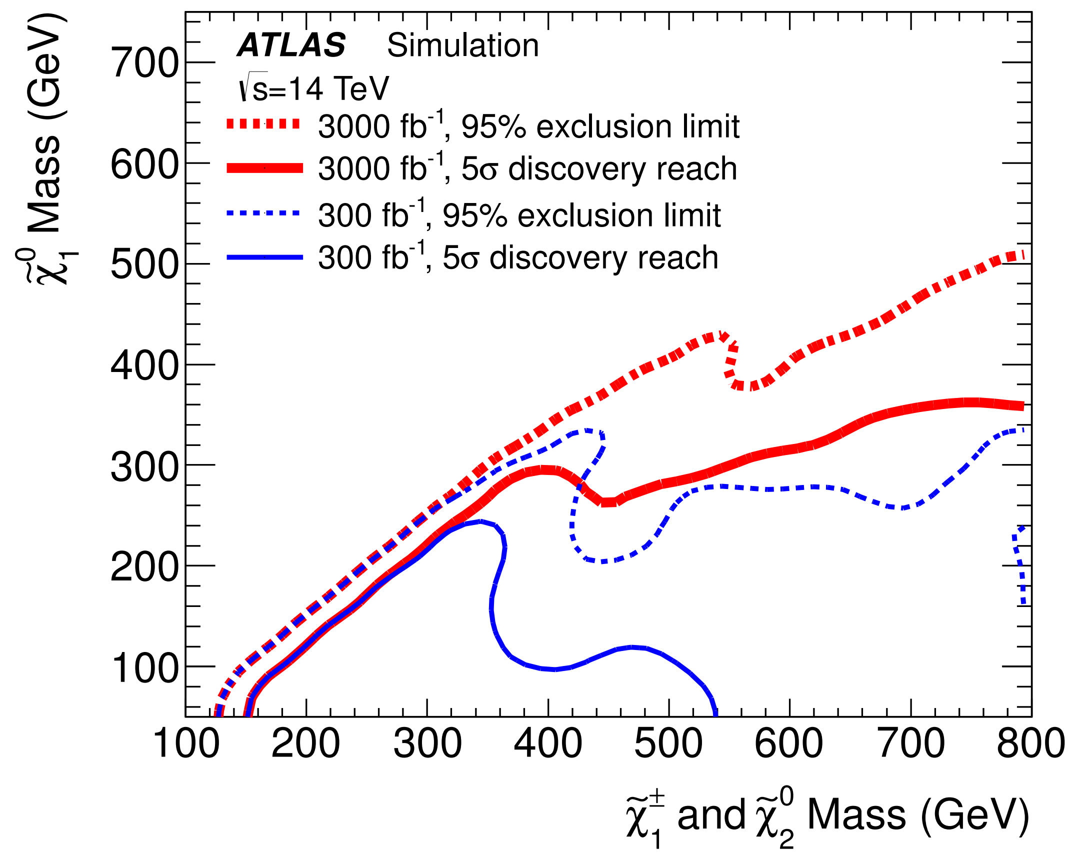


Will turn a big corner.
New physics could be right there!

Will do well for weakly coupled NP too!

Example: SUSY EWinos





- Such NP generic, could be the only thing out there.
- Crucial role in several cases (detailed later).

Expectations for Run 2:

Of course, there are gaps in to be filled, new signals to be looked at.

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Instead of enumerating them, I will organize my talk around the kind of questions that LHC run 2 will help us address

- EWSB
- Naturalness.
- Dark matter.

Question to be addressed:

1. EWSB

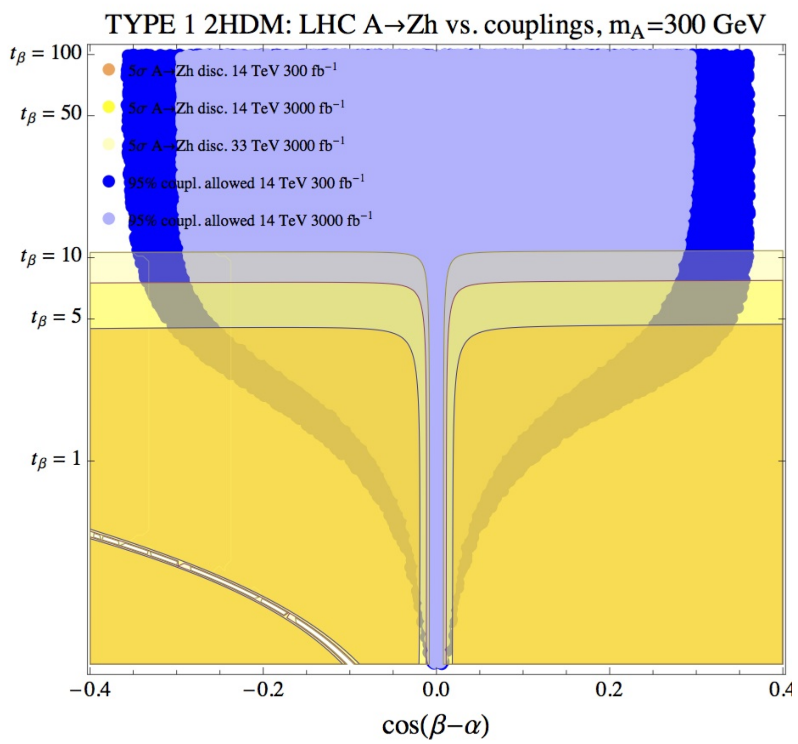
Nailing the Higgs properties

L(fb^{-1})	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]	[78, 79]	[21, 23]
	CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	ATLAS	[5, 9]	[4, 6]	[4, 6]	[5, 7]	N/a	[8, 10]	[10, 15]	[29, 30]	[8, 11]
	CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

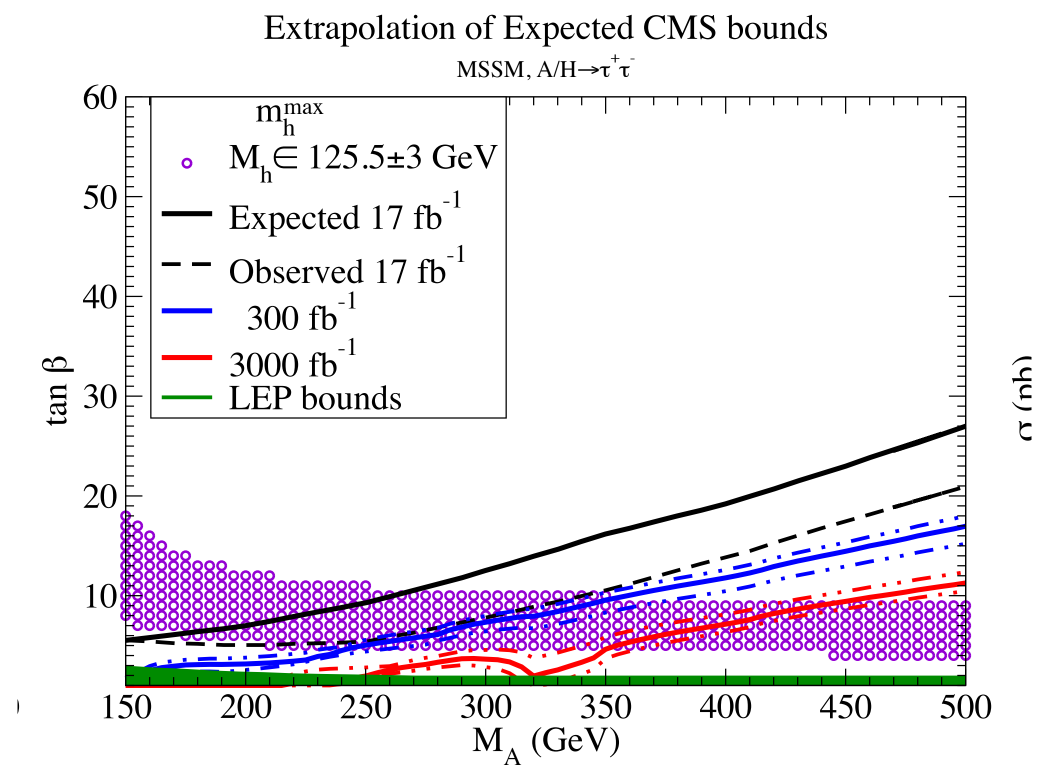
Possible to even measure self coupling at 30%.

- An elementary spin 0 particle, first of its kind. Want/need to measure as much as we can.
- LHC run 2 can make solid gains.
- Possible to make discovery here.
- At the same time, LHC run 2 won't reach the kind of precision we really want to.

Not just a simple Higgs?



Craig et al, snowmass report



Lewis, 1308.1742

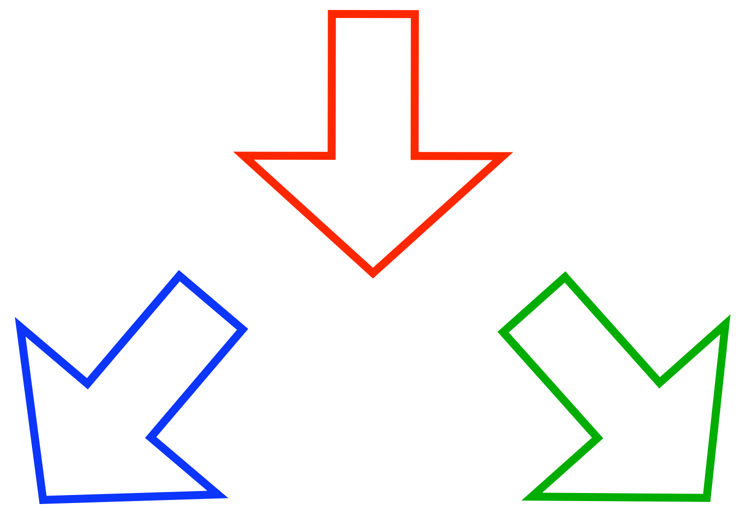
- Solid gains, potential to make discovery.
- Not quite "covering" the possible parameter space yet.

Question to be addressed:

1. Naturalness

Naturalness

We searched for simple and natural models
Not found yet. We will continue to look



Natural, yet complicated, "unconventional" models

Simple, but not so natural models

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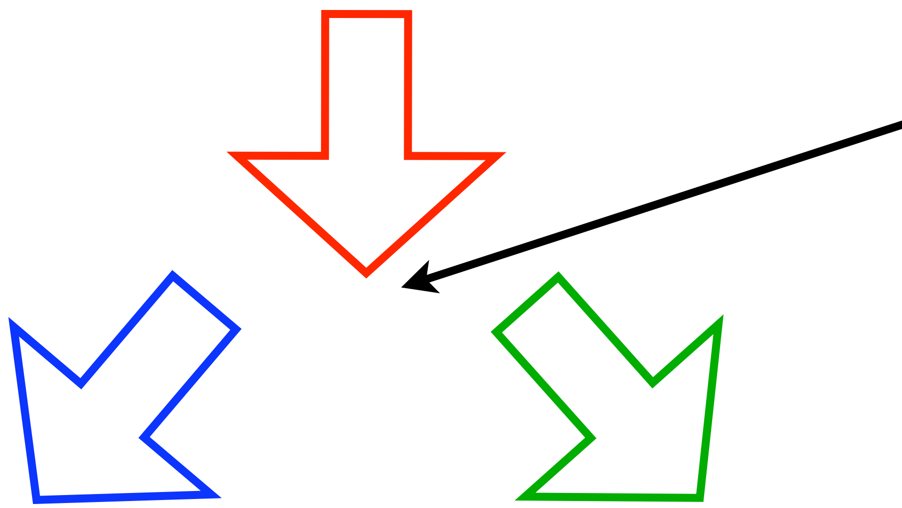
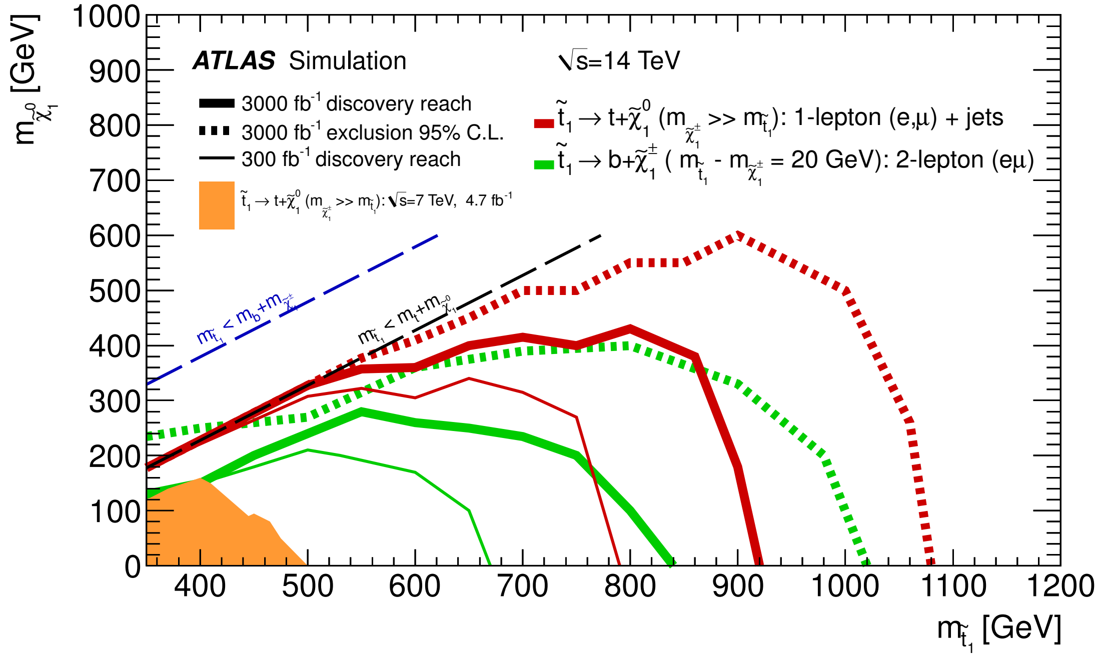


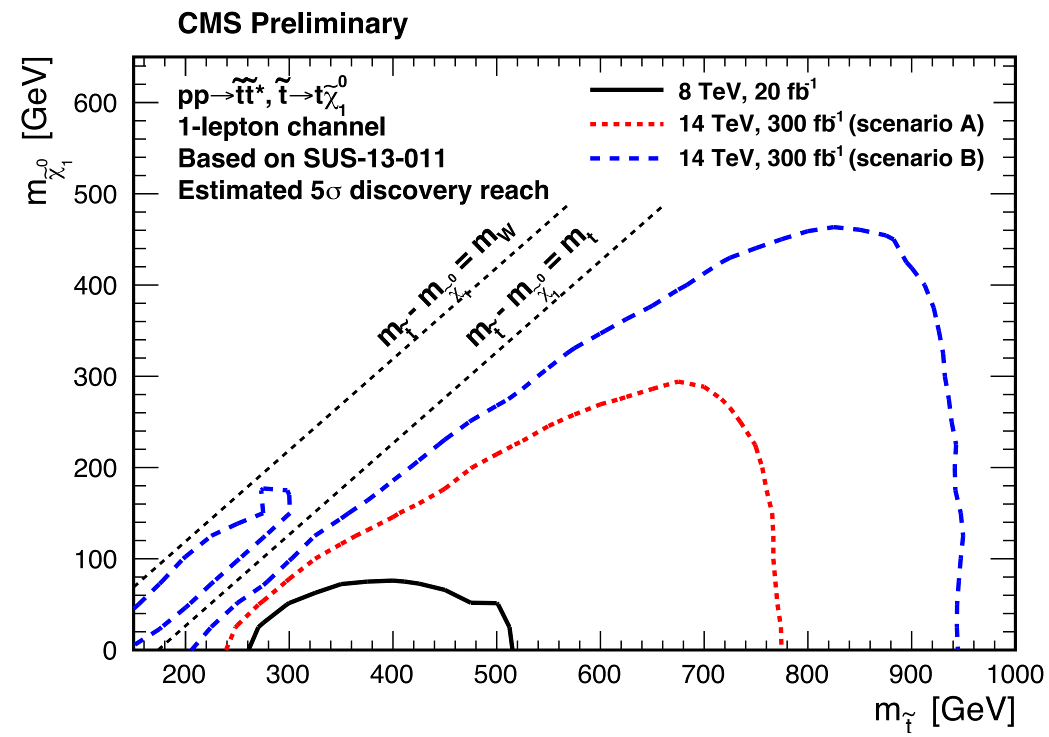
Bifurcation point!
How close we
are to this point?

Natural, yet complicated, “unconventional” models

Simple, but not so natural models

Naturalness: top partner (SUSY)





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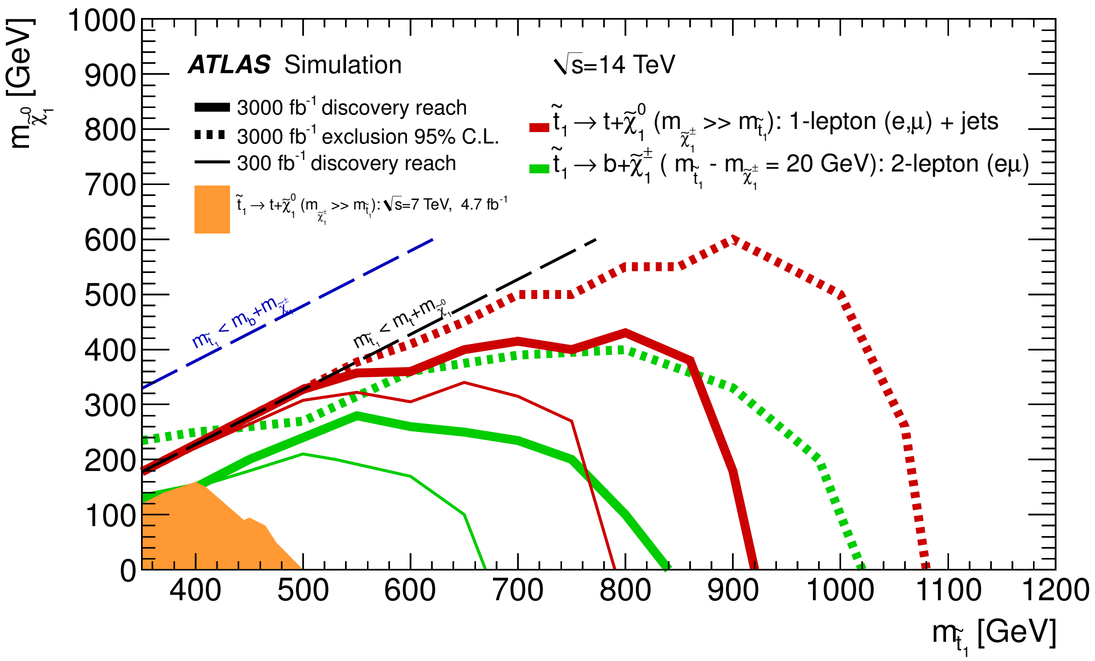

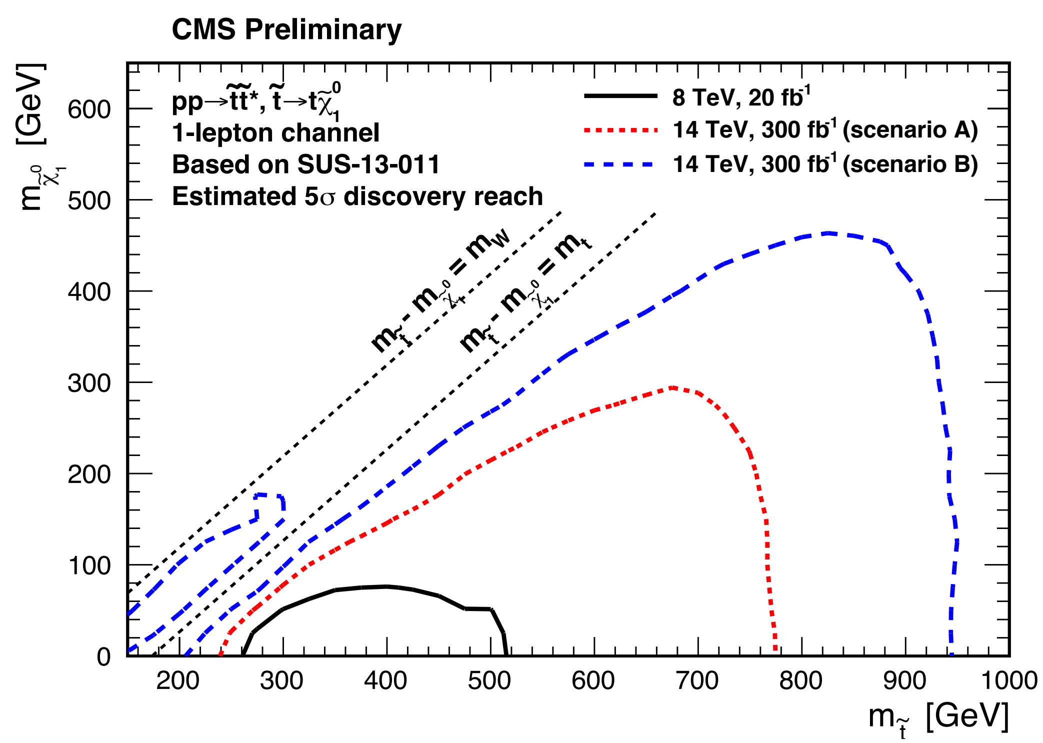

- Naturalness ∝ m_{stop}^2

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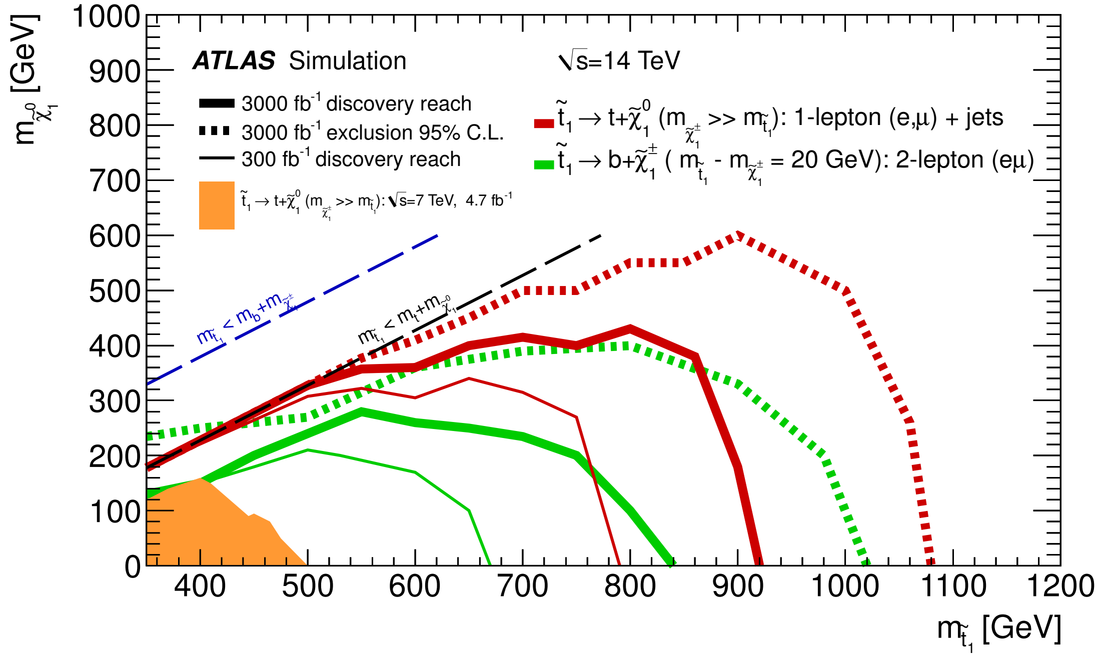
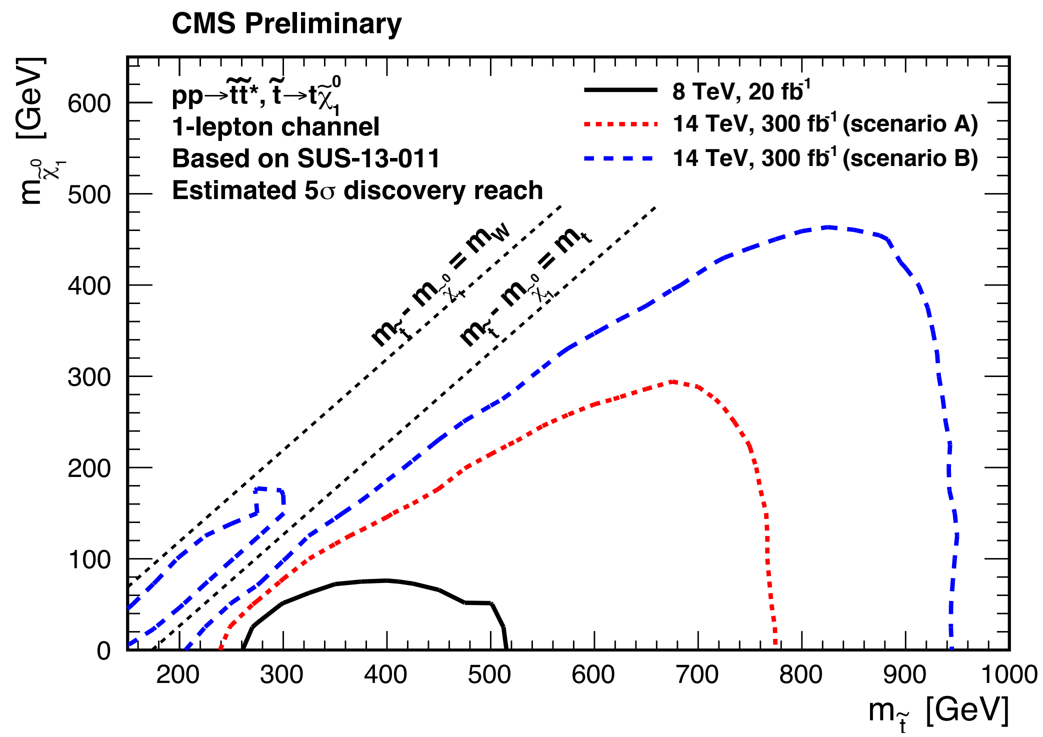
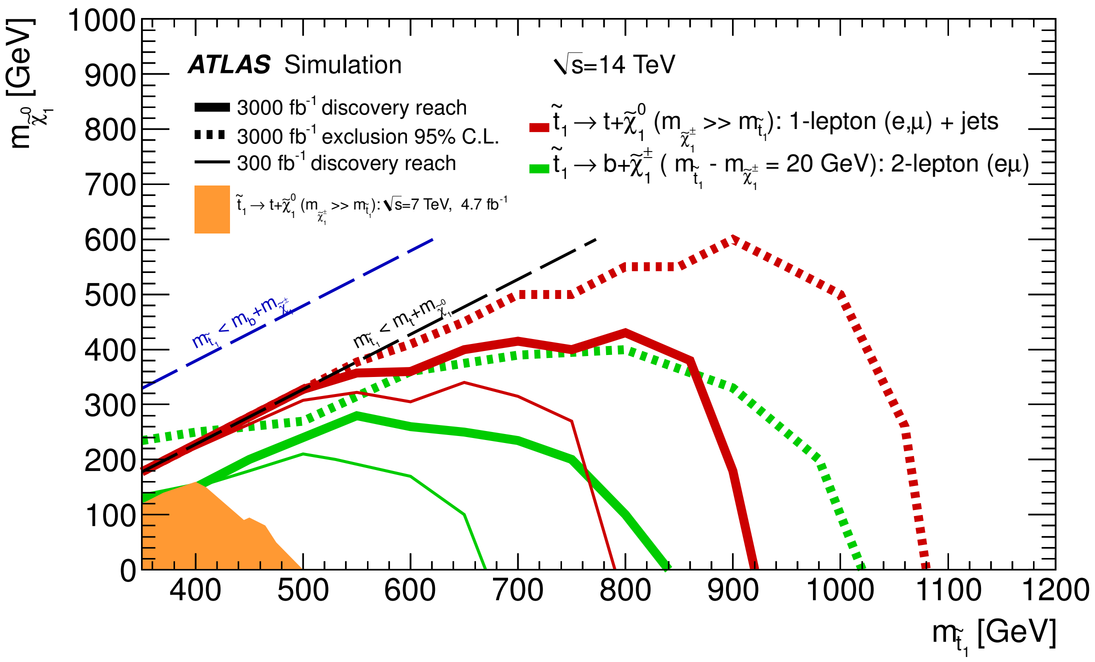
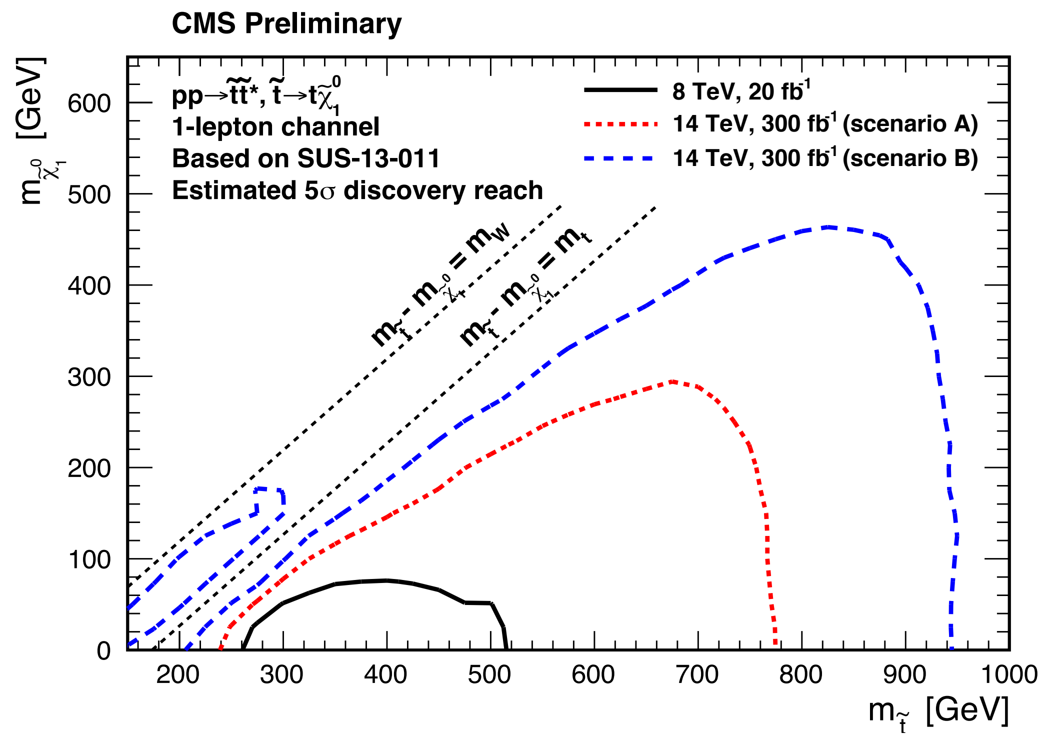




- Naturalness ∝ m_{stop}^2
- Discovery of top partner at Run 2 is a stunning success of naturalness.

Naturalness: top partner (SUSY)





- Naturalness ∝ m_{stop}^2
- Discovery of top partner at Run 2 is a stunning success of naturalness.
- Or, the result of LHC Run 2 will certainly move us closer to that bifurcation point.
  - Not enough for a paradigm shift (for me).

Hiding stop

- Many think it is already mandatory to take seriously mechanisms to hide stop.
  - RPV, stealth, compressed, etc.
- May get you pass the Run 1, but Run 2 will put a strong test to this one too!

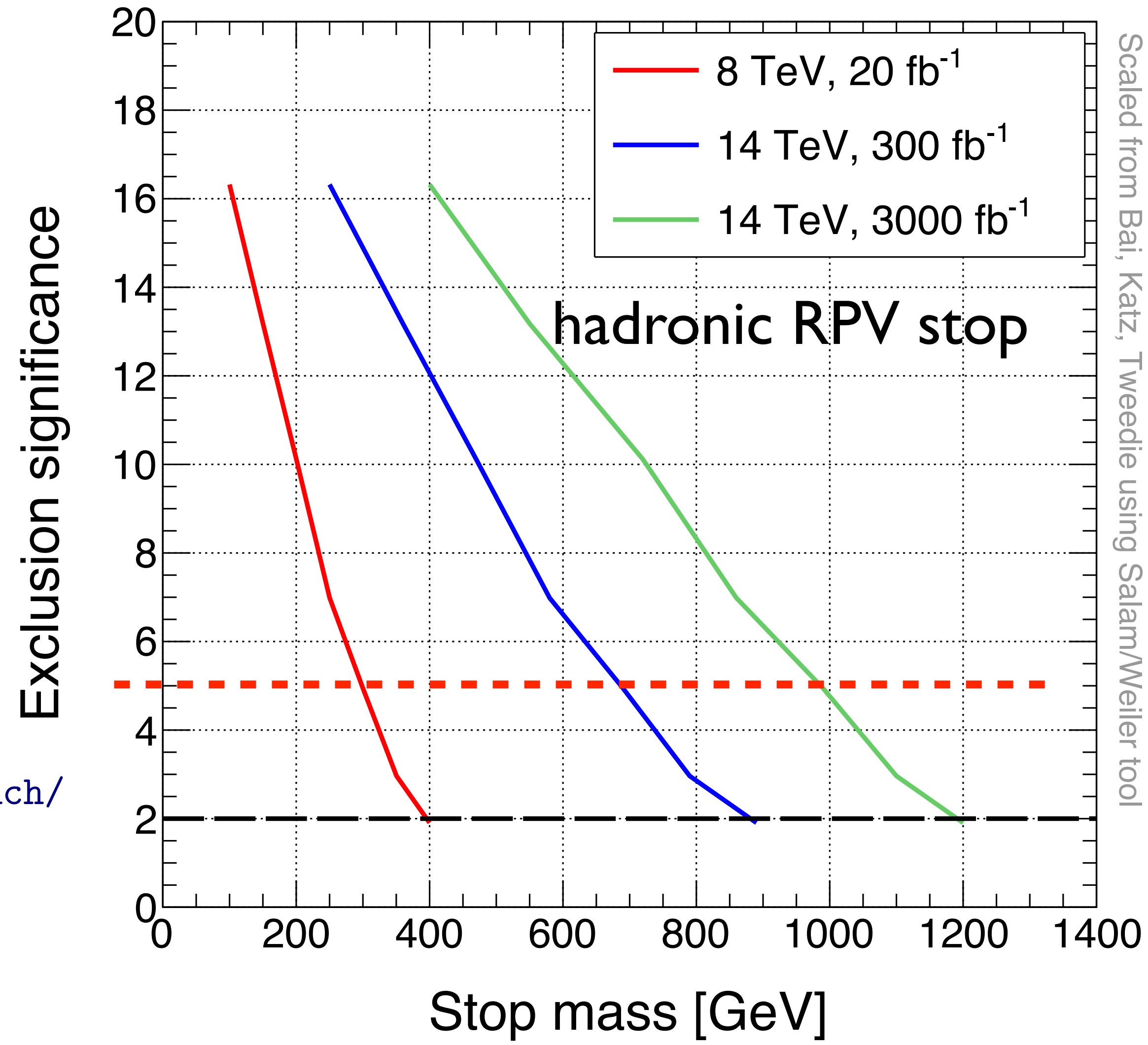
Hiding stop

8 TeV result, Bai, Tweedie, 1309.6631

Scaling up using parton luminosity

http://collider-reach.web.cern.ch/collider-reach/

Salam and Weiler



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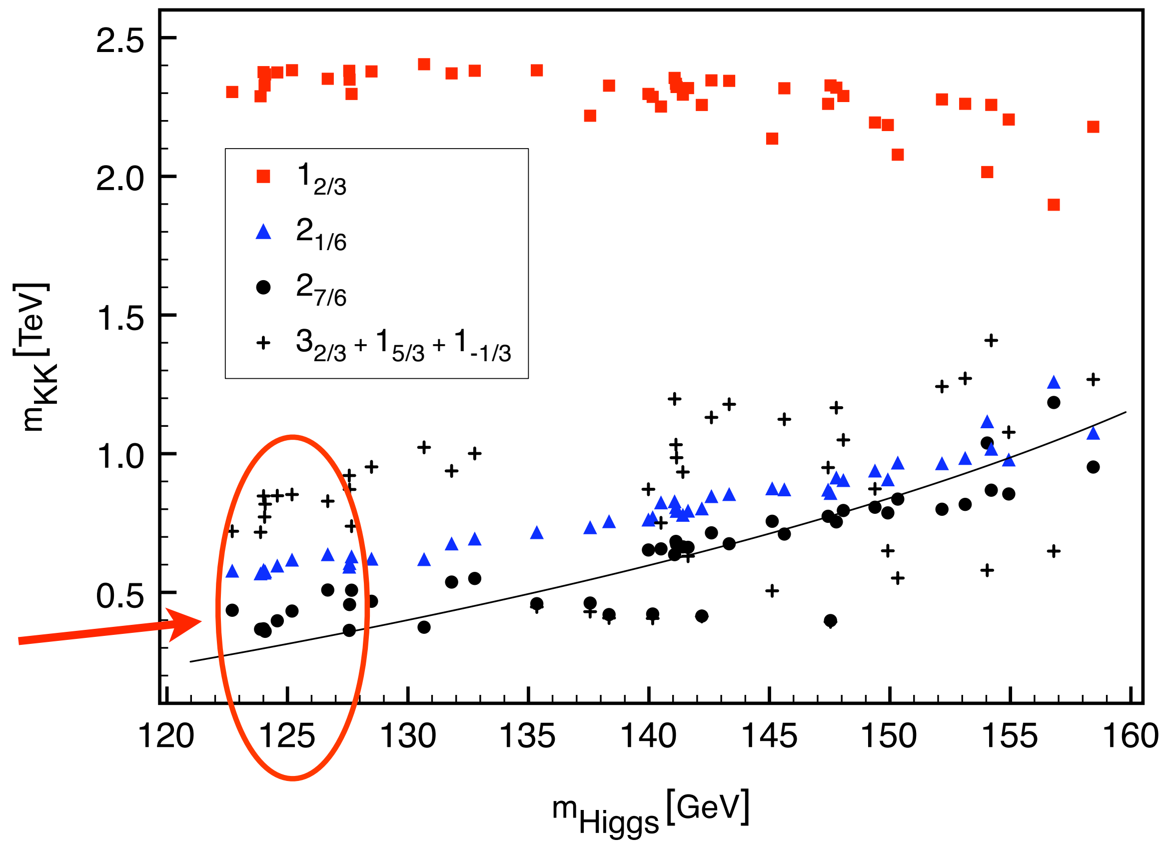
Compositeness and top partner



prefers a light T'

Contino, Da Rold, Pomarol, 2006

- Plays a crucial role in EWSB.

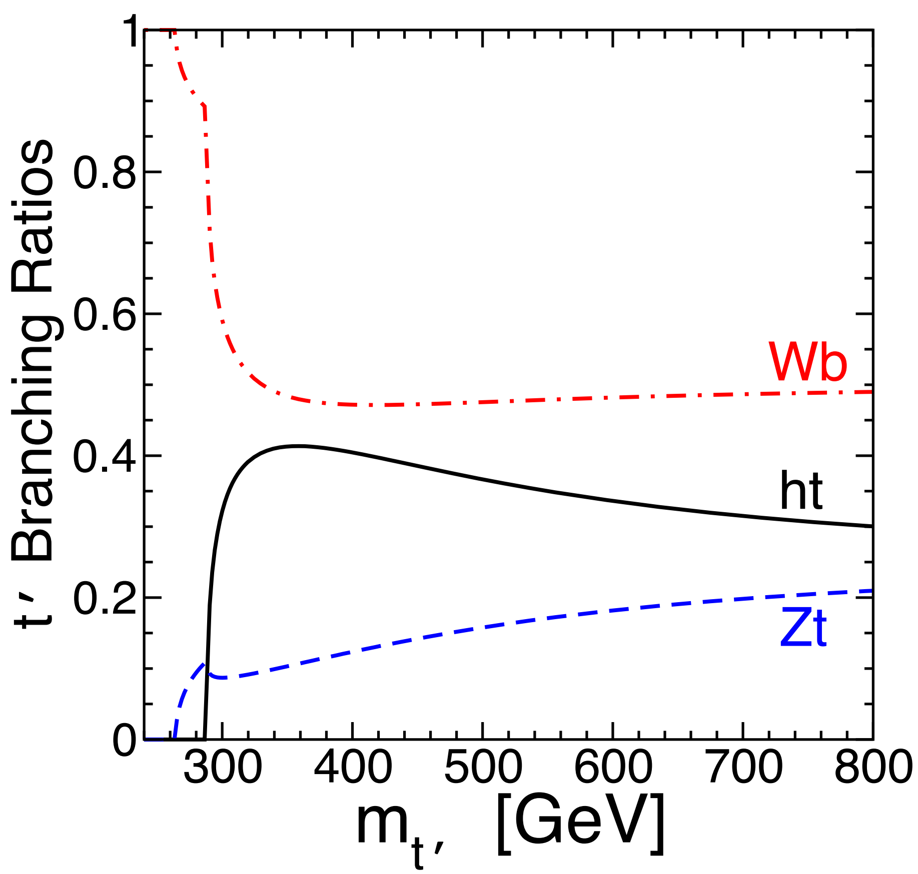
For a comprehensive discussion, see
De Simone, Matsedonskyi, Rattazzi, Wulzer, 1211.5663

Variation on the BR.

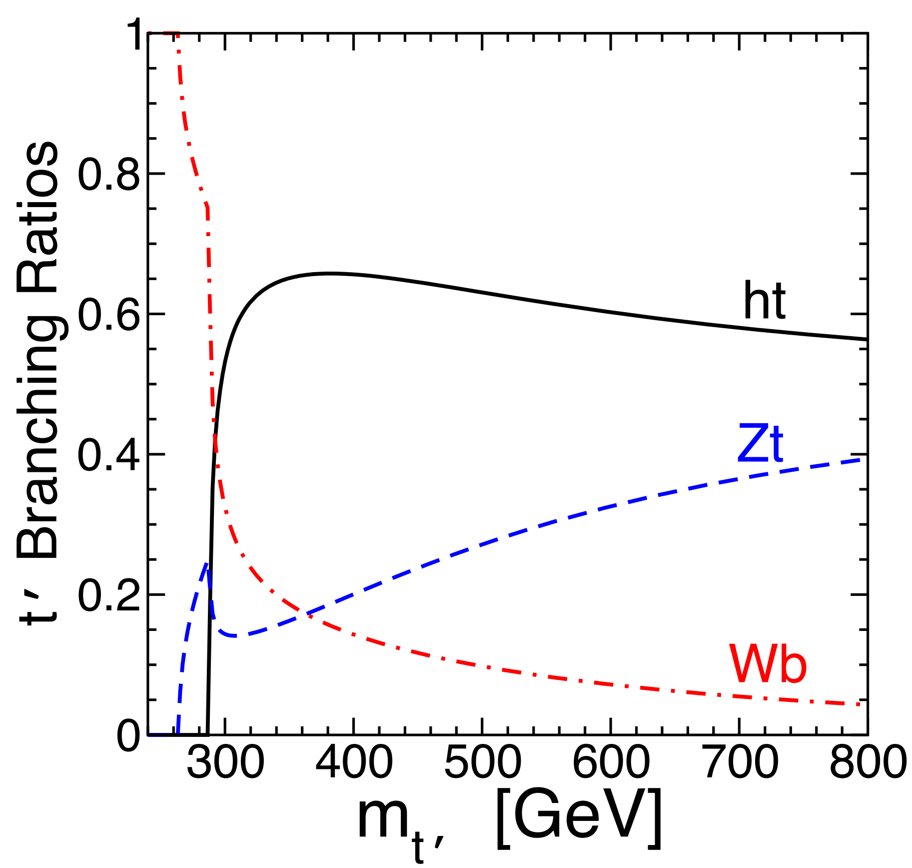
e.g., S. Martin, 0910.2732

$$\epsilon_U H_u q_3 \overline{U} + \epsilon'_U H_u Q \overline{u}_3 - \epsilon_D H_d Q \overline{d}_3$$

Extended top partner sector.
U: singlet, Q: doublet

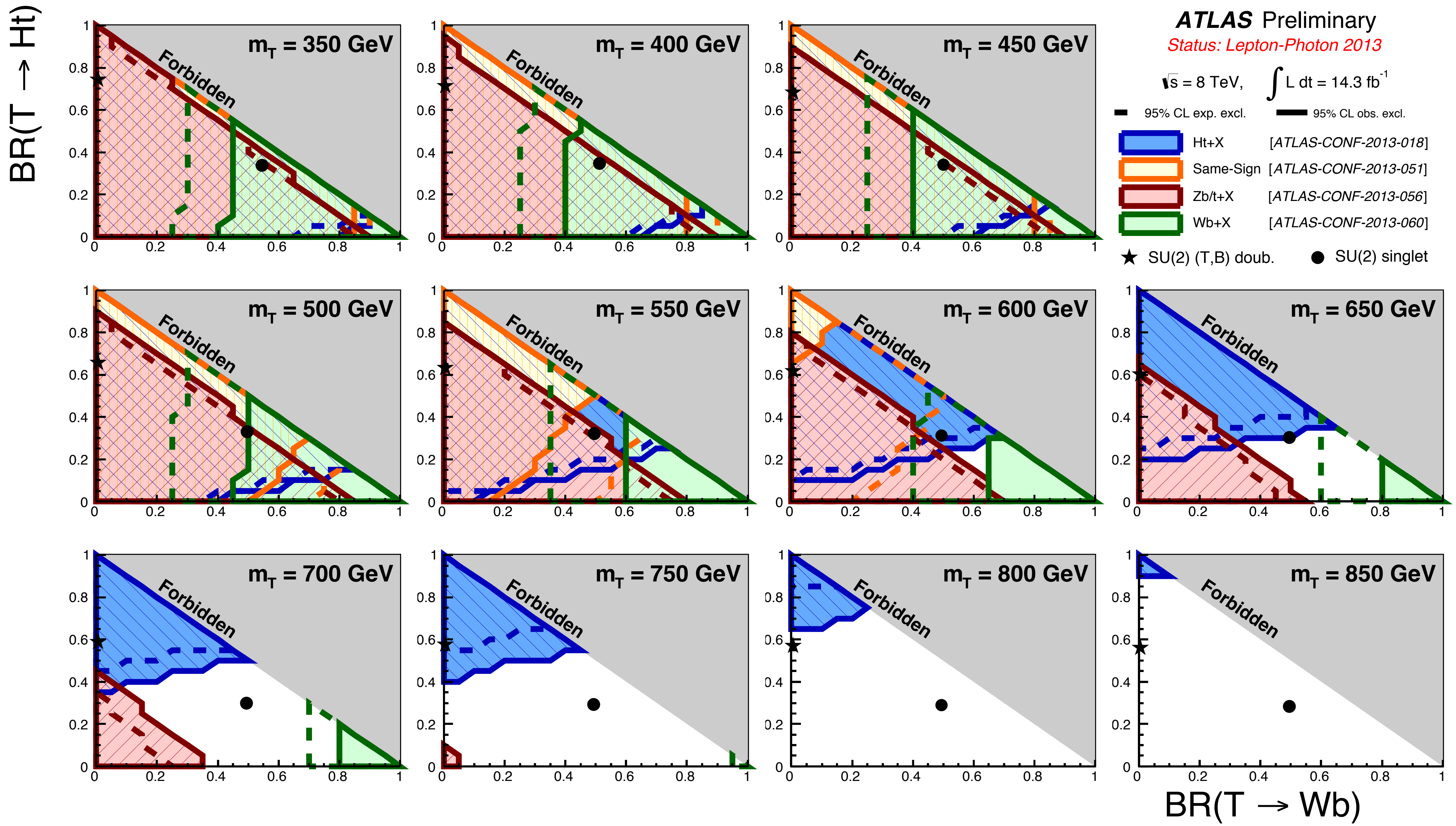


ϵ_U dominated



ϵ'_U dominated

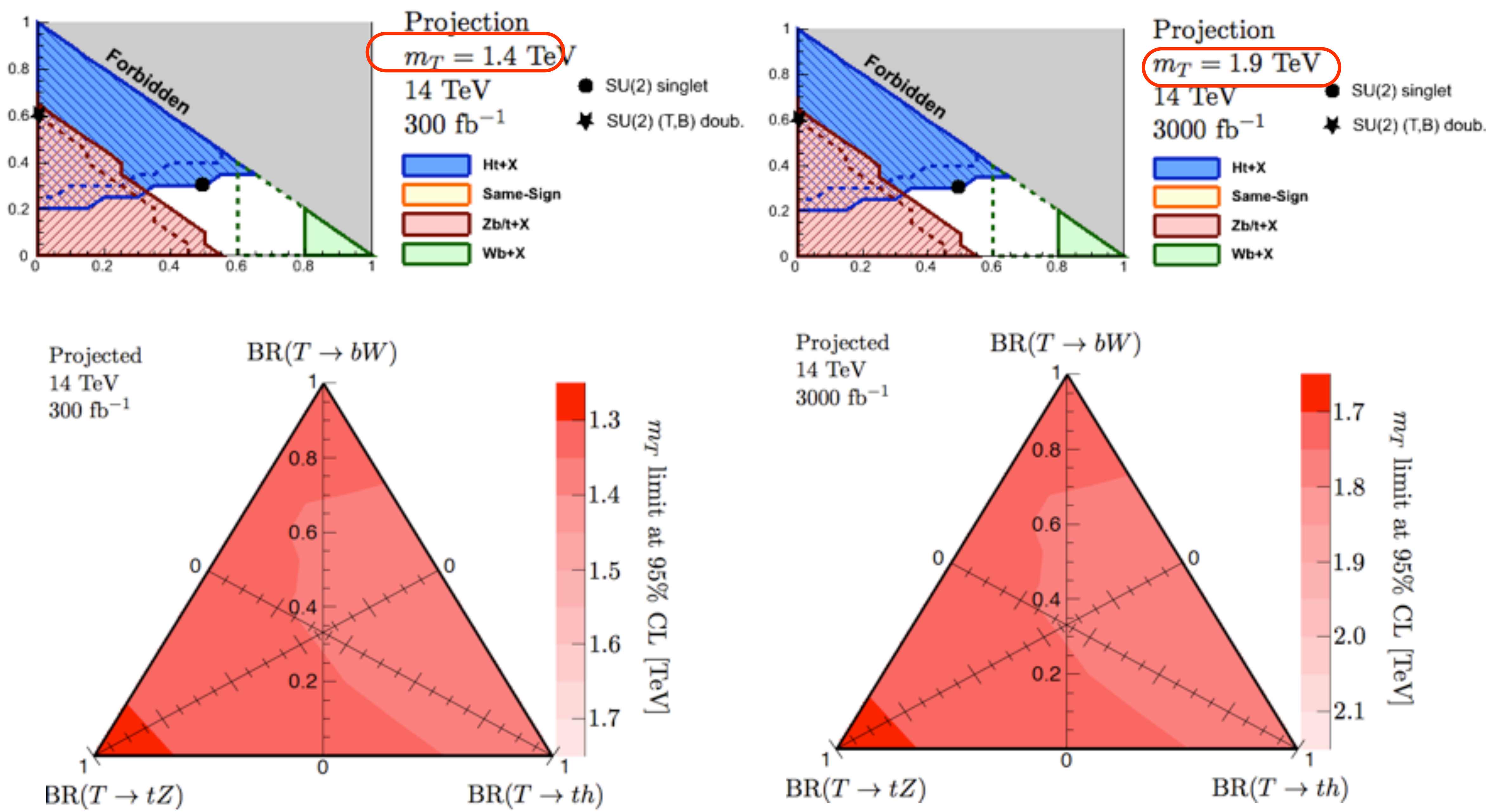
Fermionic T′ at the LHC run 1



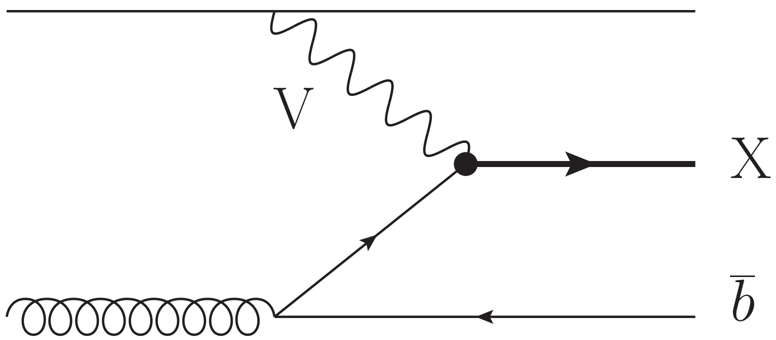
Reasonable coverage up to 650 GeV.

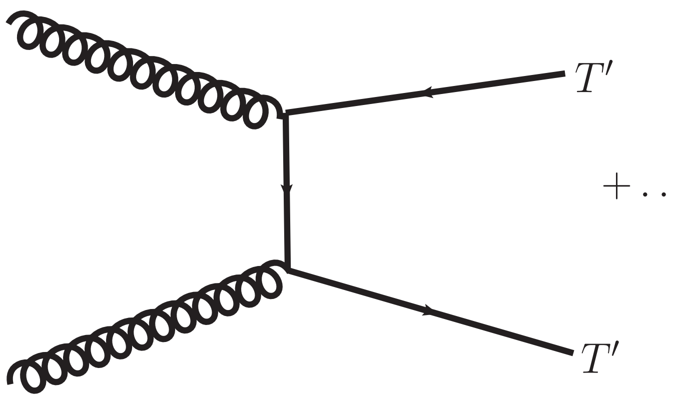
Getting into the interesting region.

LHC 14 should cover it.

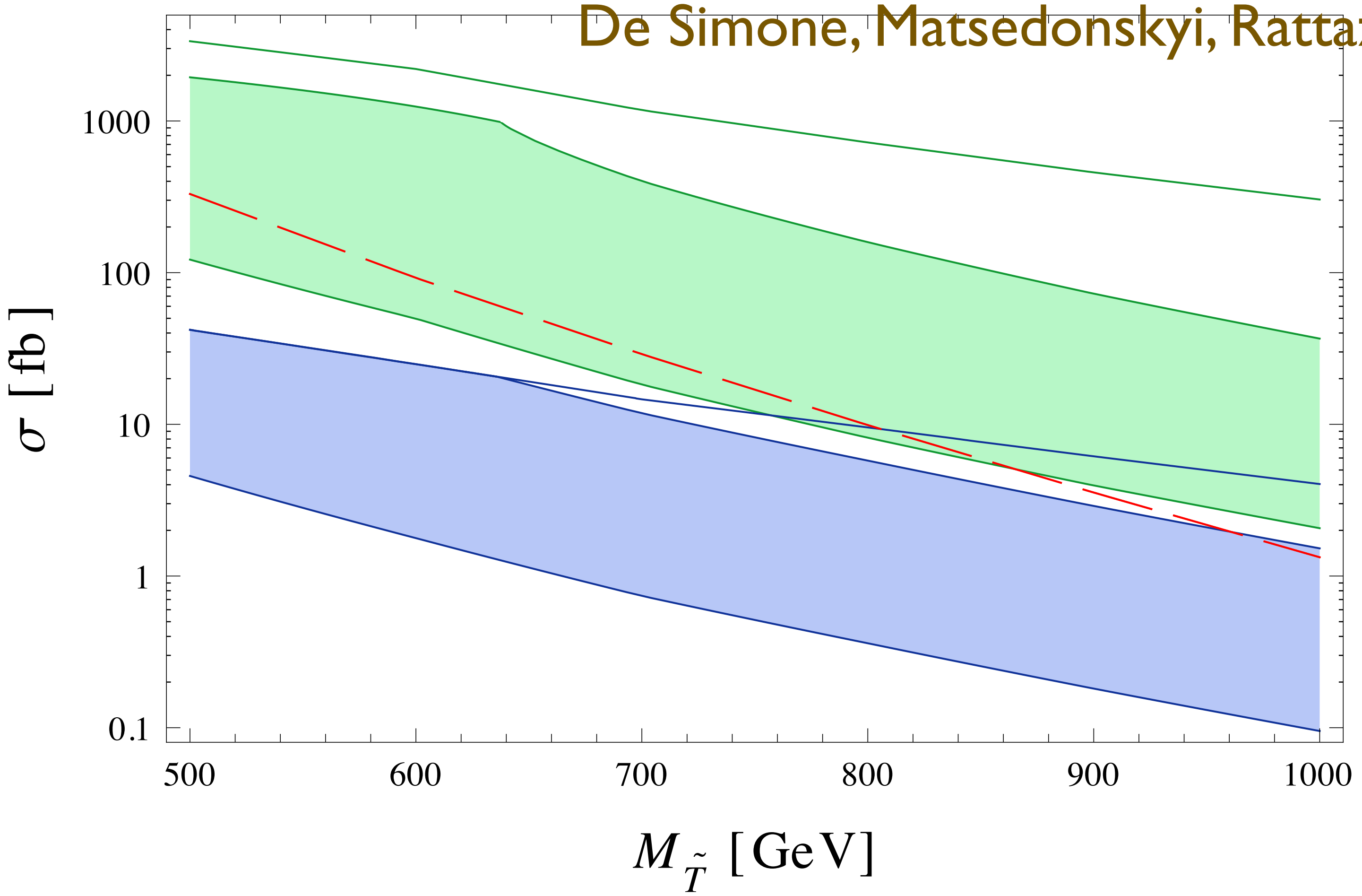


More focus needed on single production





De Simone, Matsedonskyi, Rattazzi, Wulzer, 1211.5663



Importance of the single production have been emphasized

For example: Perelstein, Peskin, Pierce, 2003; Han, Logan, McElrath, LTW, 2003

Naturalness: Higgsino

- In addition to top partner, masses of particles with only electroweak int. could enter in EWSB in a more direct way.

- Example: SUSY Higgsino

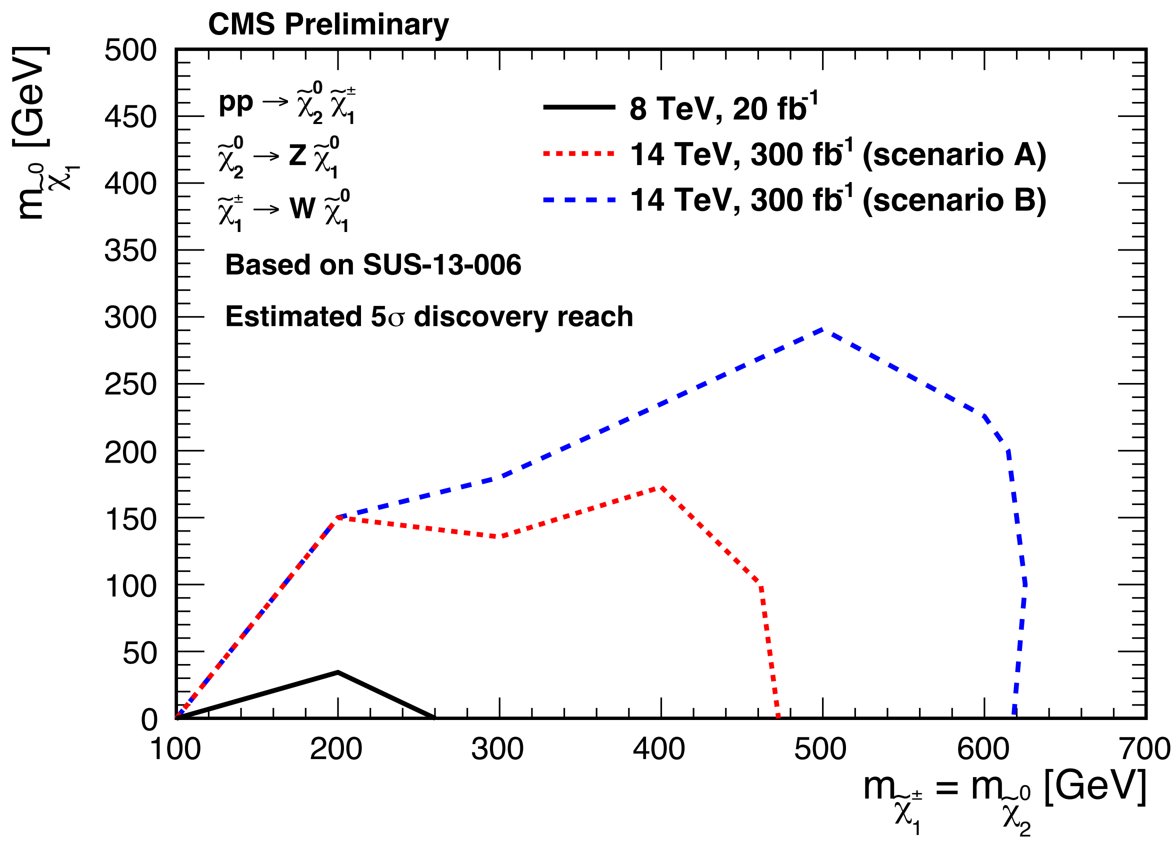
$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2.$$

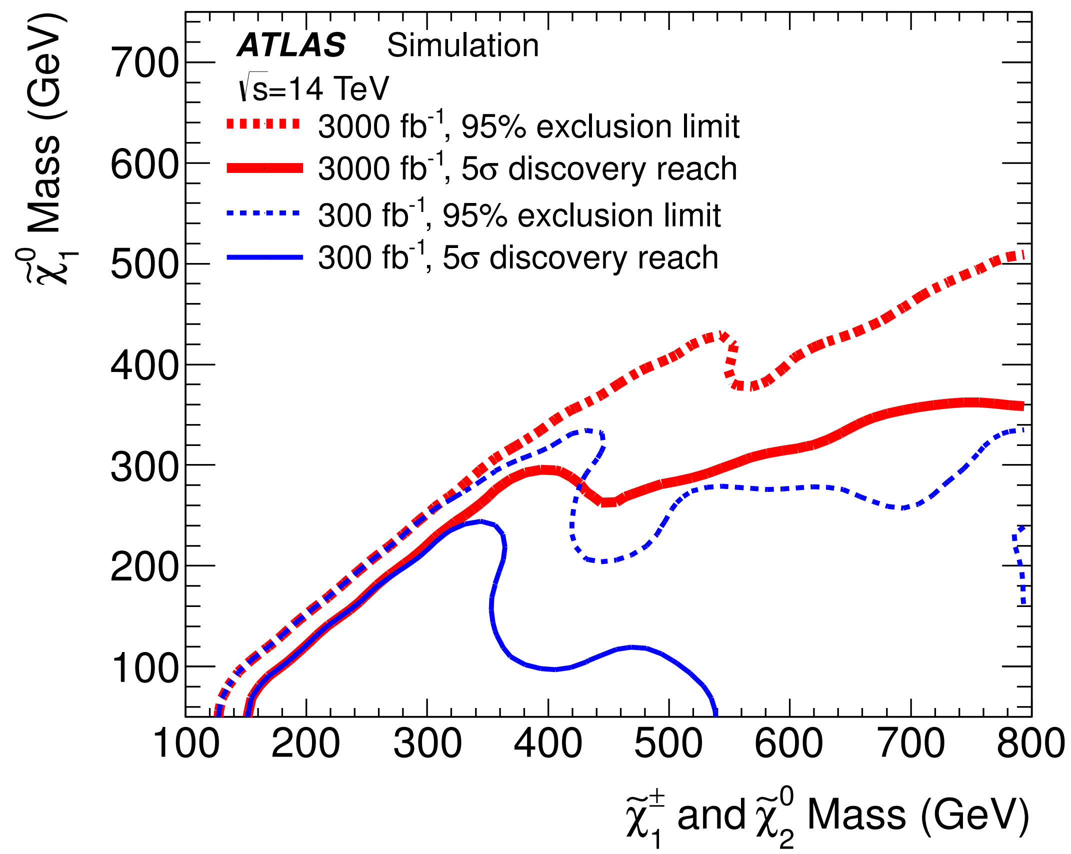
also the Higgsino mass

Fine tuning ∝ M_Z^2/μ^2

To reduce fine tuning, Higgsino should be light.

Naturalness: Higgsino





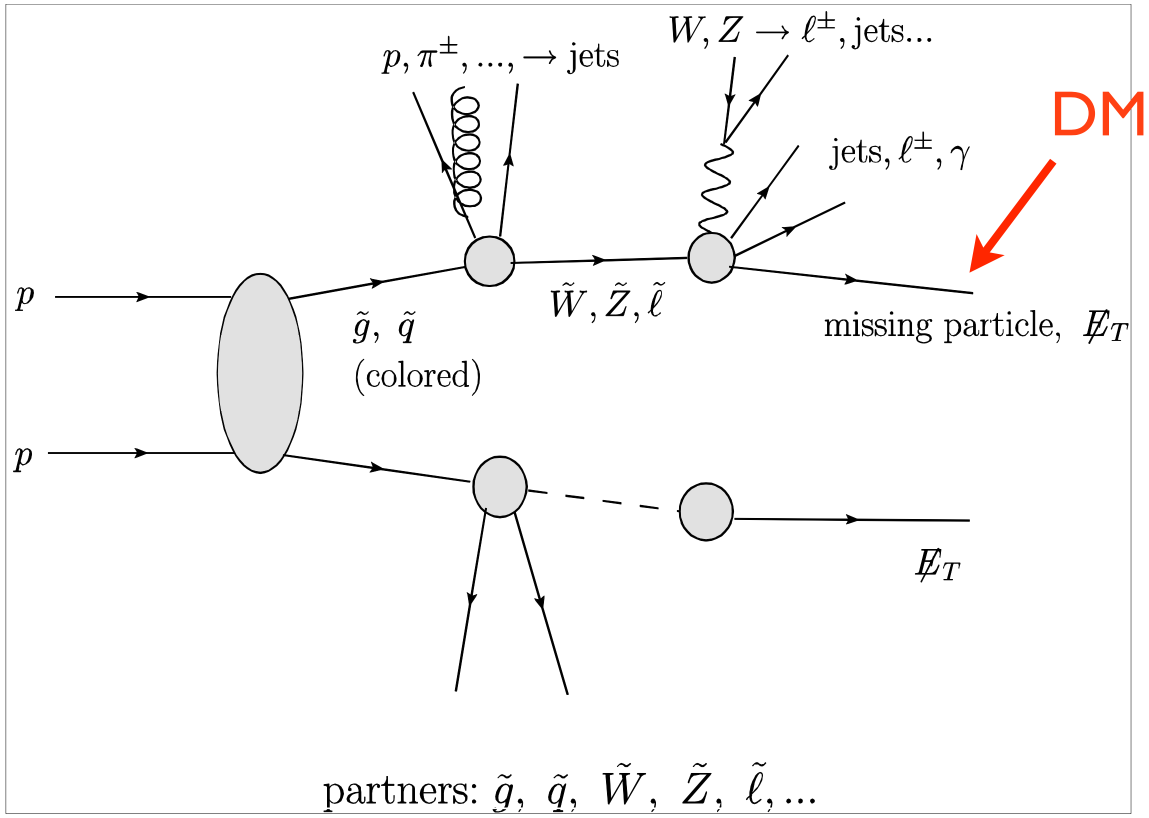
Run 2 will make significant progress here!

We should also consider new channels, such as b+g ⇒ stop + higgsino, which could be important at Run 2 energies.

Question to be addressed:

1. dark matter

"standard" story.



SUSY, UED, etc.

- WIMP is part of a complete model at weak scale.
- It's produced as part of the NP signal, shows up as missing energy.
  - Dominated by colored NP particle production: eg. gluino.
- The reach is correlated with the rest of the particle spectrum.

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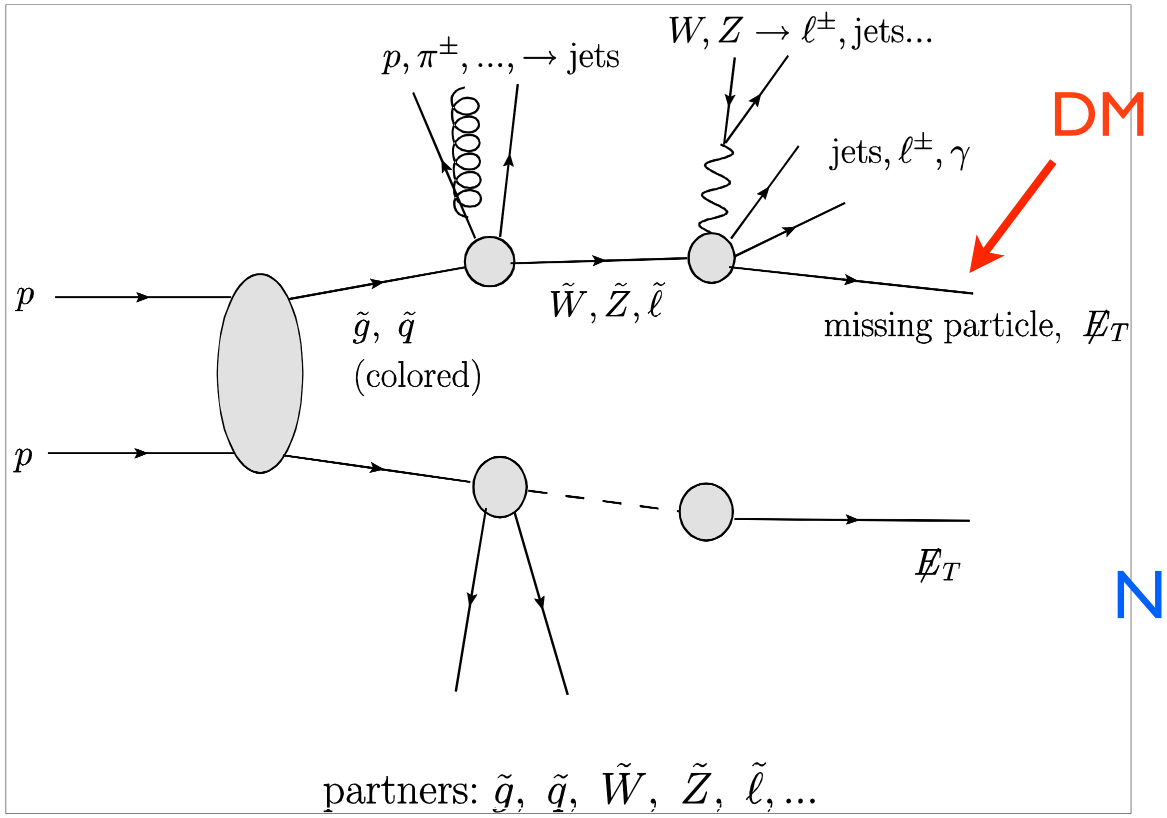
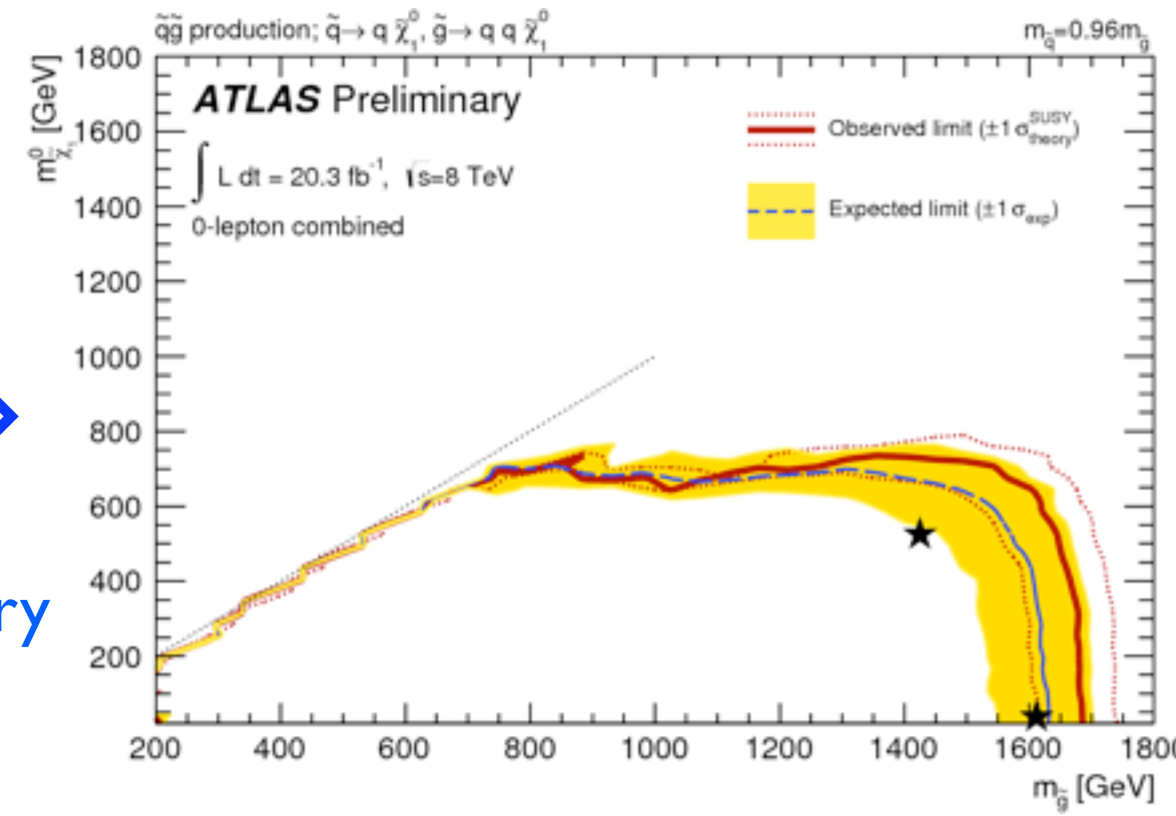


SUSY, UED, etc.

No discovery yet



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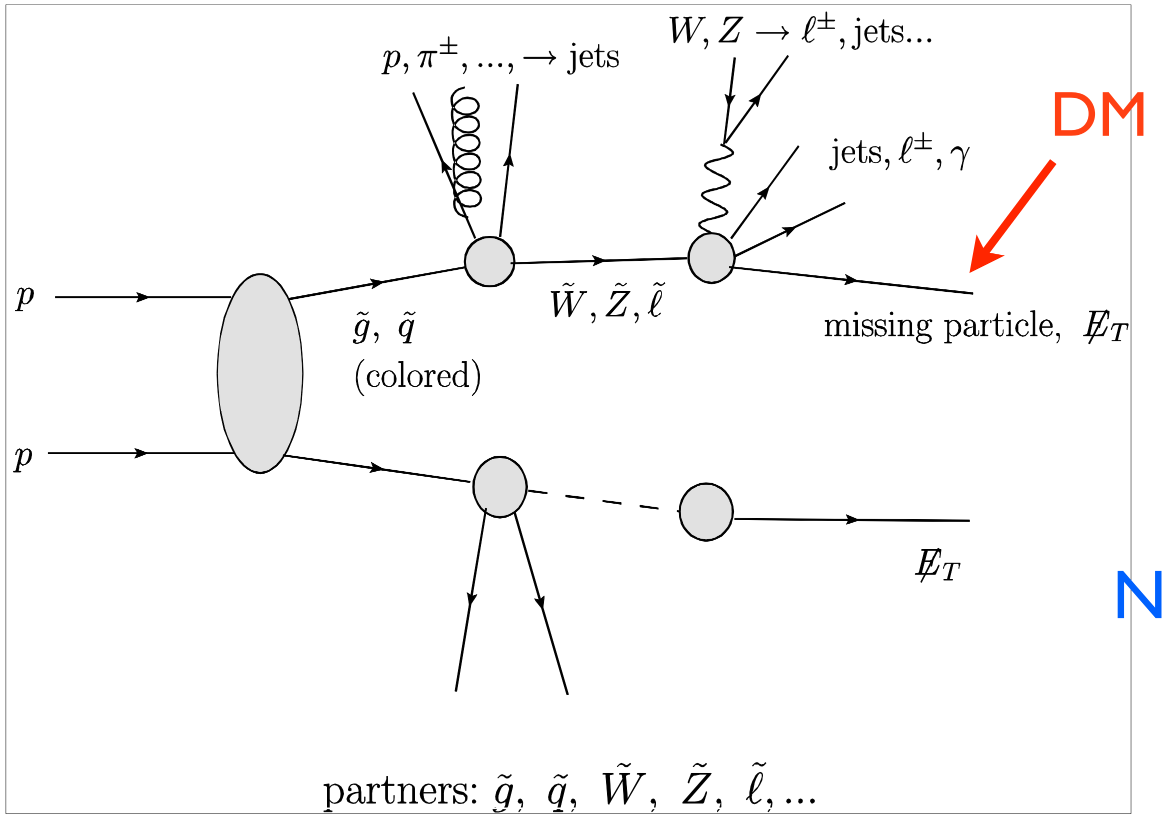

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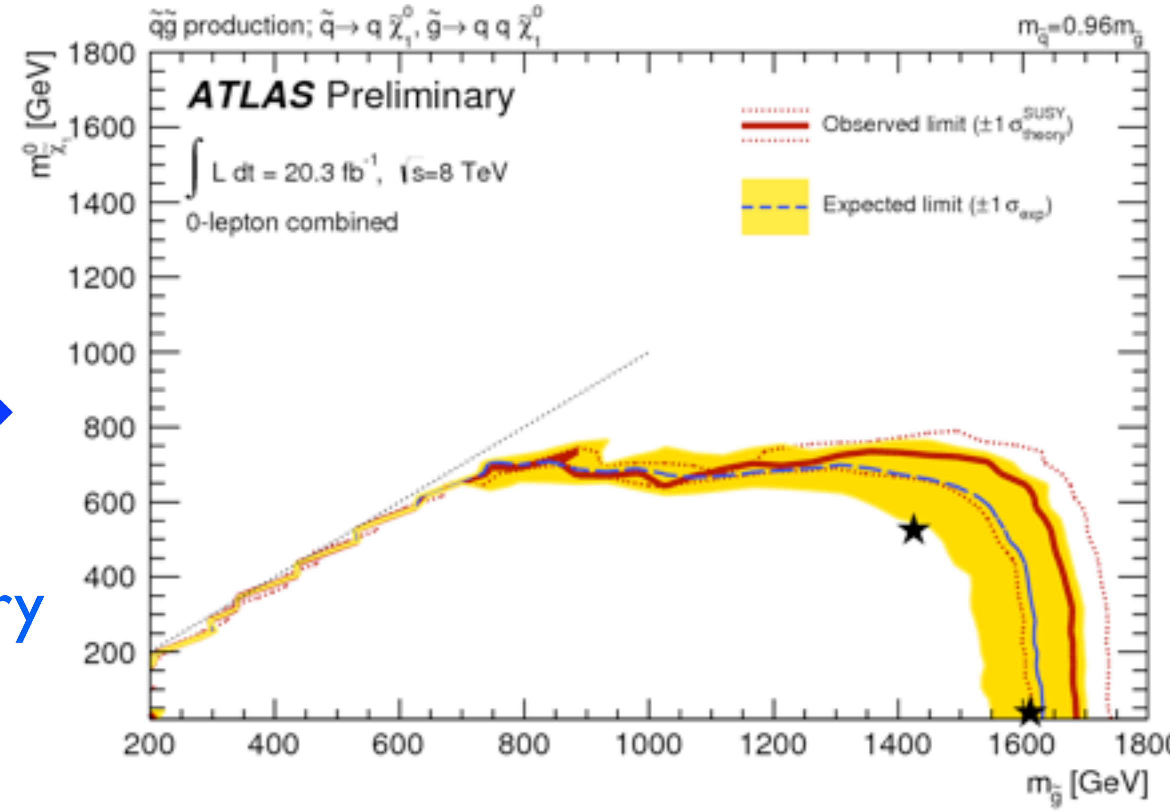
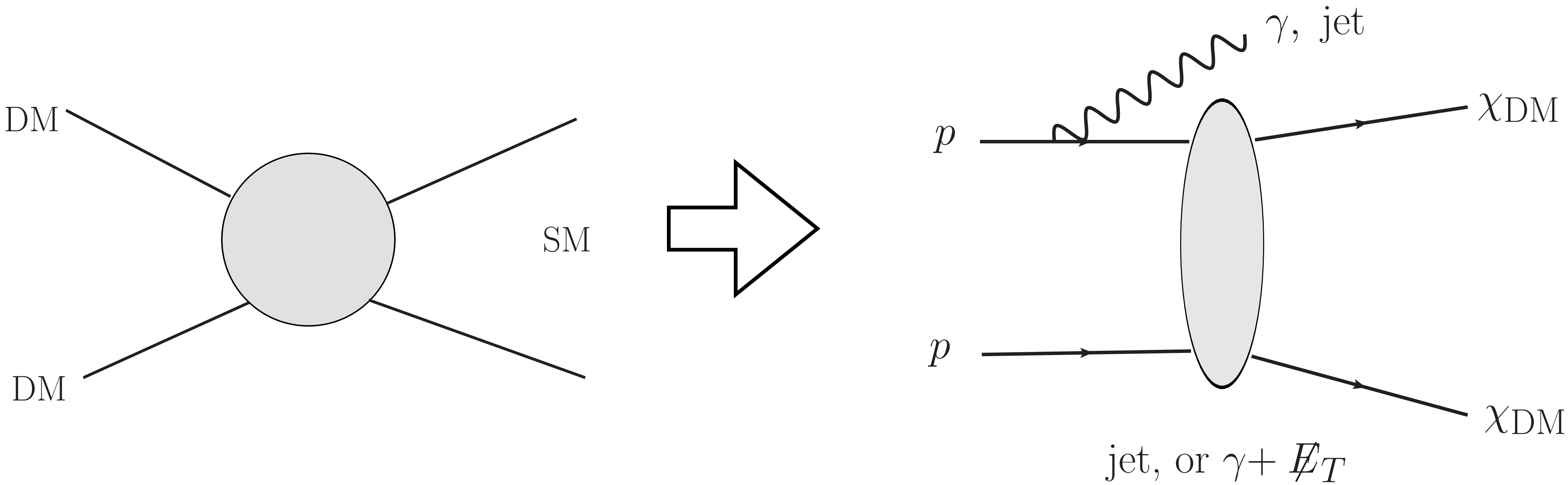


Of course, still plausible at the LHC, will keep looking.
Higher energy ⇒ higher reach

Dark matter: basic channel monoX

- pair production + additional radiation.



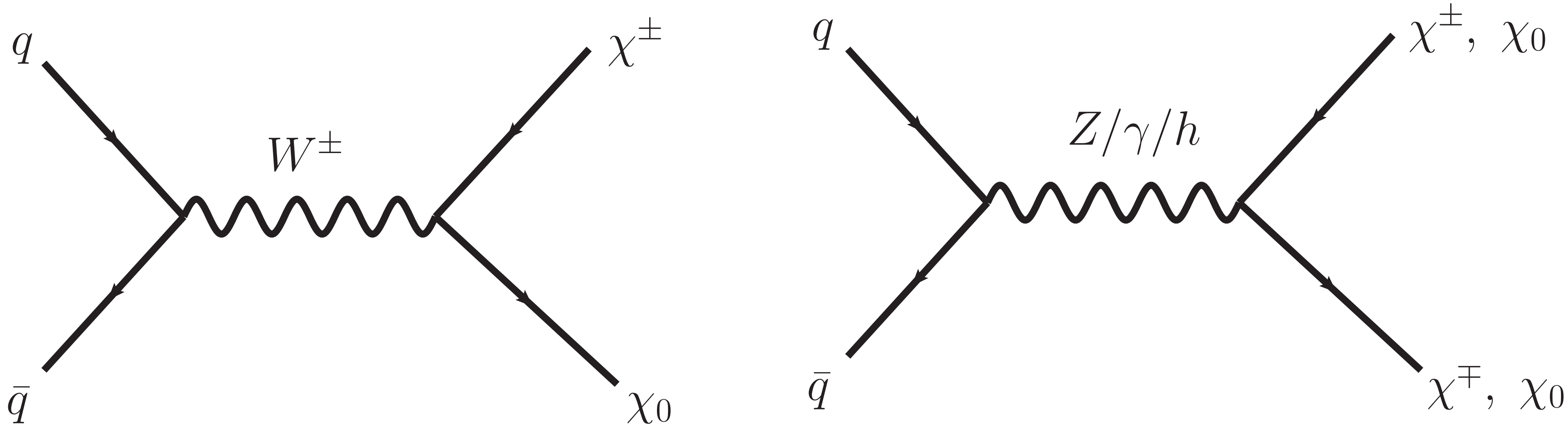
- Mono-jet, mono-photon, mono-Higgs...
- Have become "Standard" LHC searches.
- Parameterized DM SM interaction with effective operators.

Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286
Bai, Fox, Harnik, 1005.3797

Is this simple approach effective?

- Valid as field theory?
  - Already questionable in run 1, will be quite problematic at for run 2.
- More over, is this representative of possible UV completion? And, representative of possible signals?
- For both reasons, need to consider simple models beyond effective operators. In particular for run 2.
- Two ways of going beyond.
  - DM in a weak multiplet.
  - New mediators.

Dark matter could be in a weak multiplet



- Have weak interaction.
  - Mediated by W/Z/h.
- Generic. Original meaning of “W” in WIMP.
- Typical and representative example: SUSY
  - Higgsino: doublet, wino: triplet.
  - Can mix with bino (singlet).

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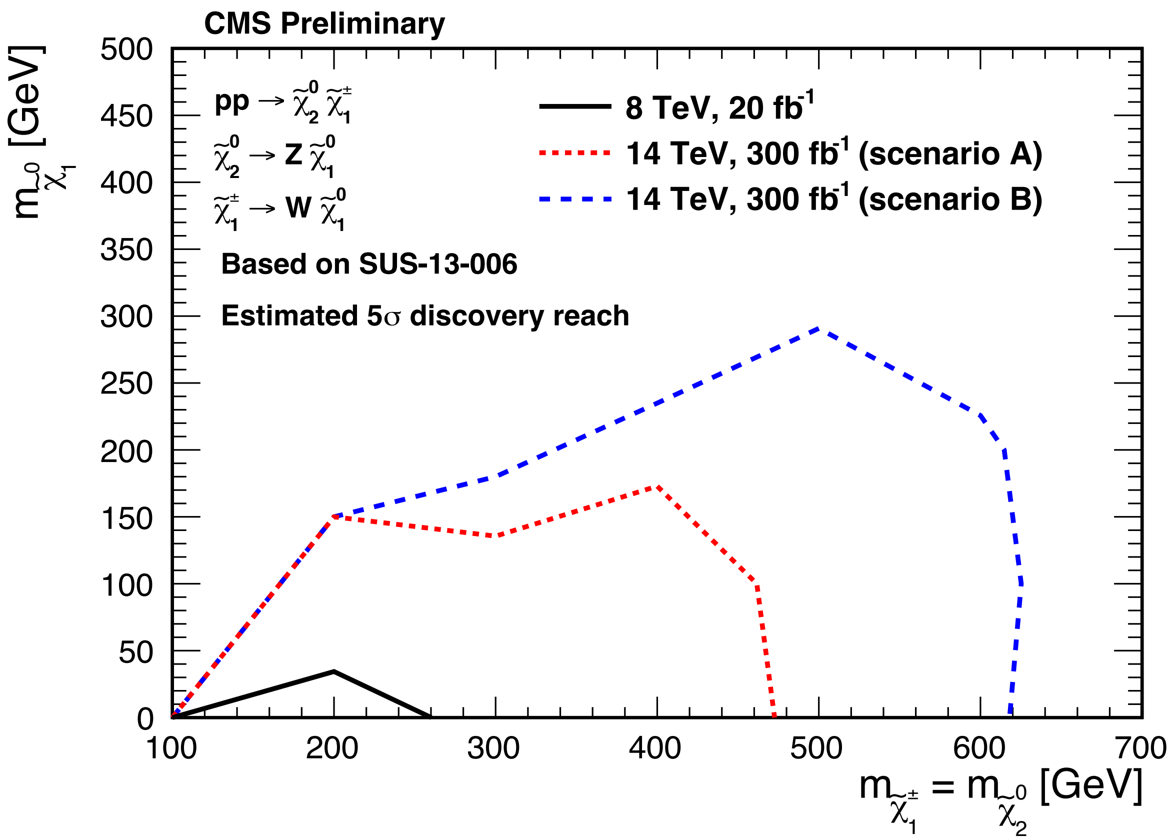
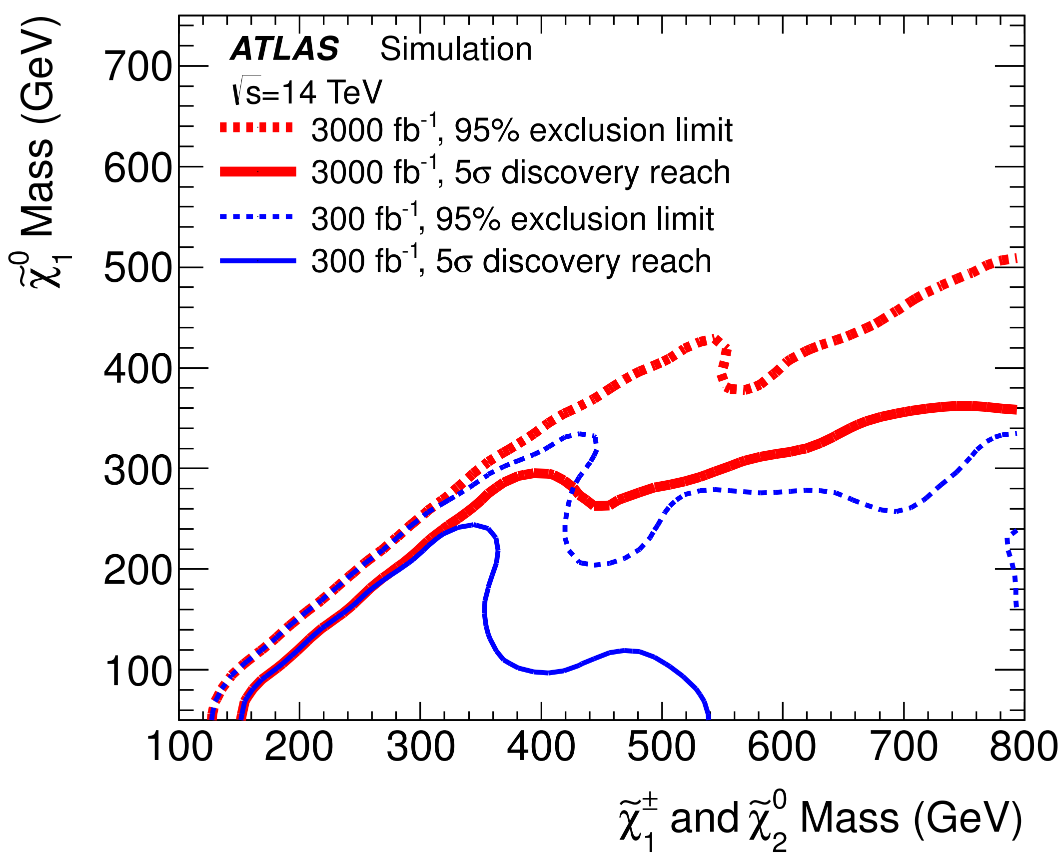
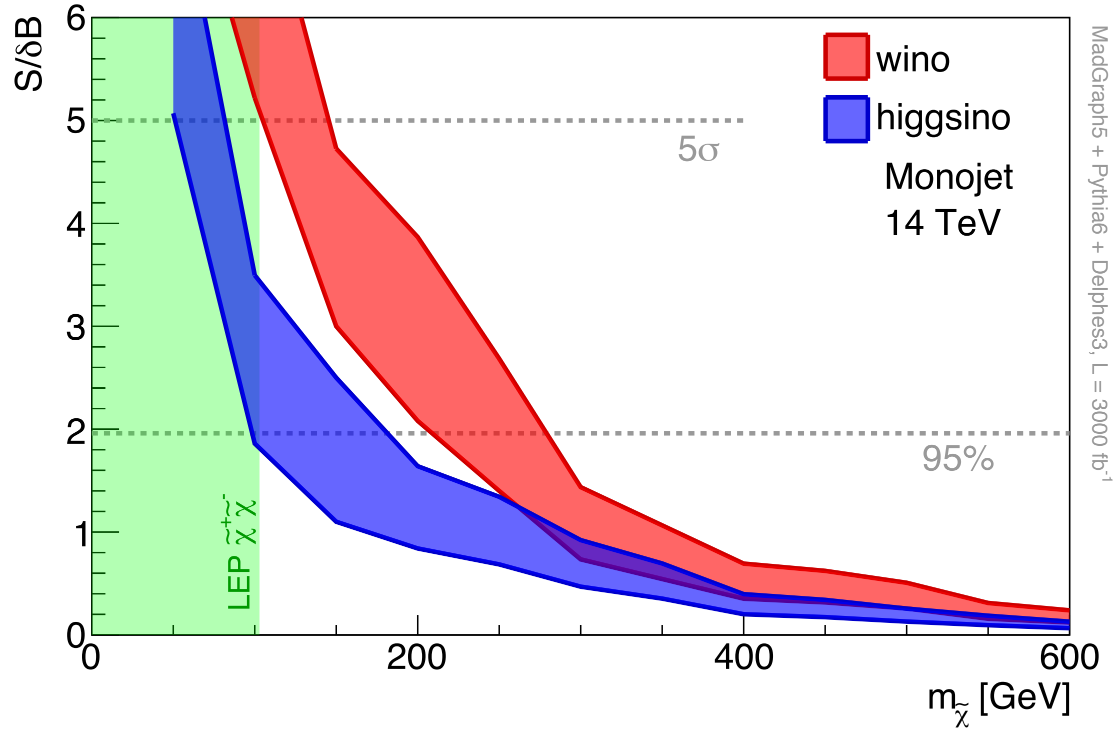
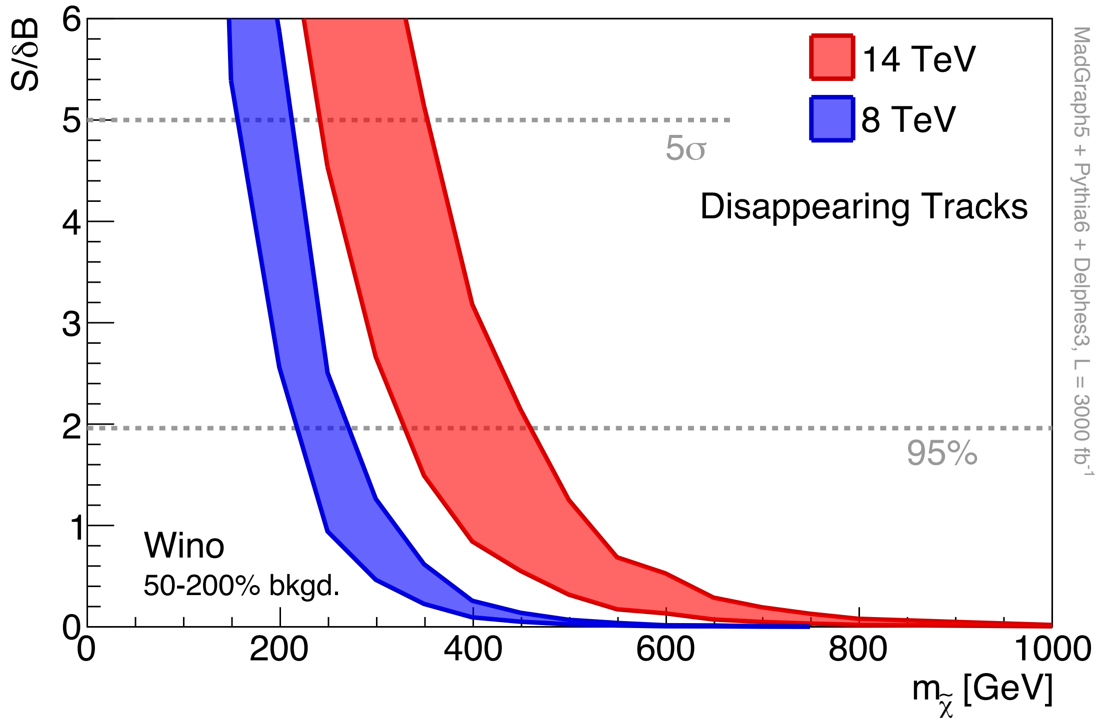




Run 2 can improve a lot!

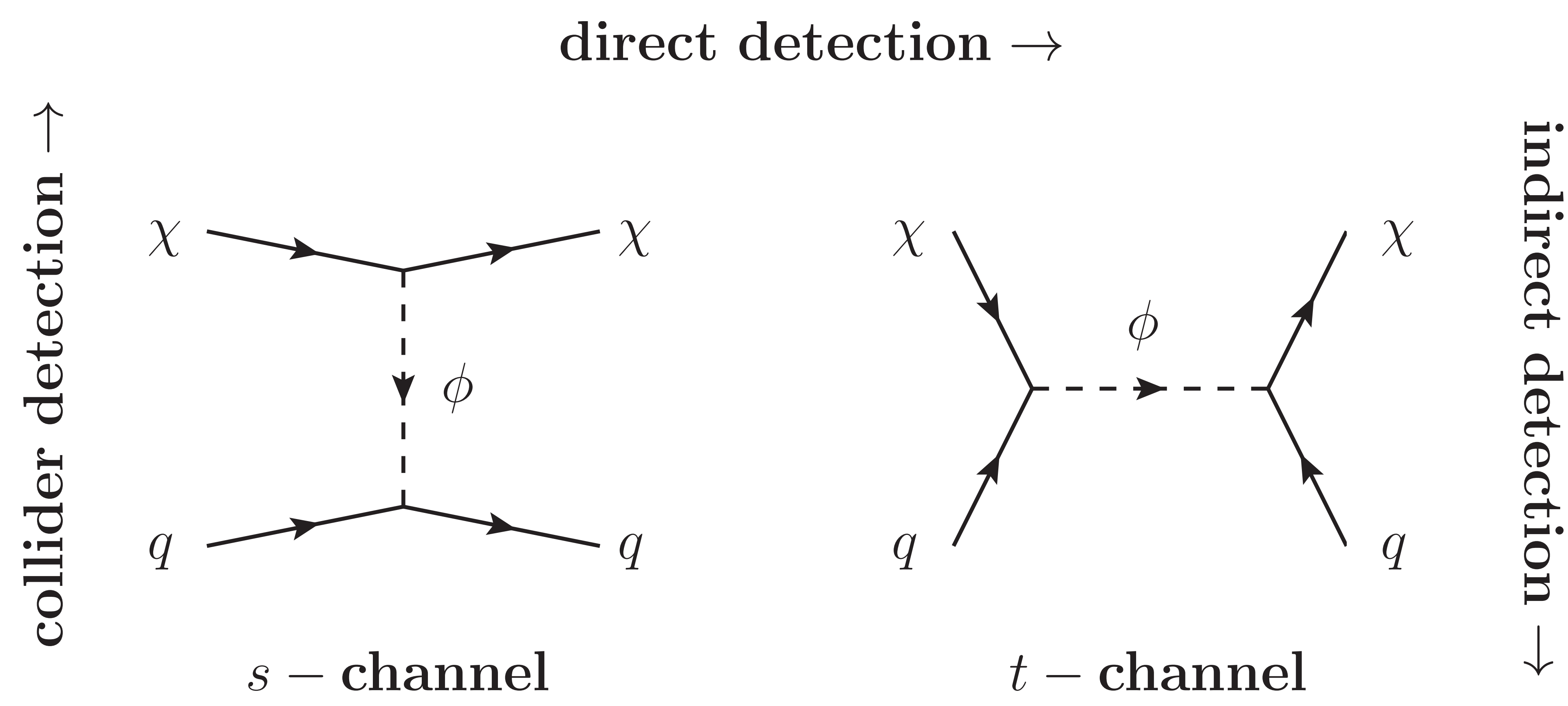
Basic channel





- Very challenging. Systematics dominated
  - No limit from the 8 TeV run.
  - Weak discovery reach at 14 TeV, 3 ab^{-1} .
- Still, a solid step beyond LEP.

Consider new mediators

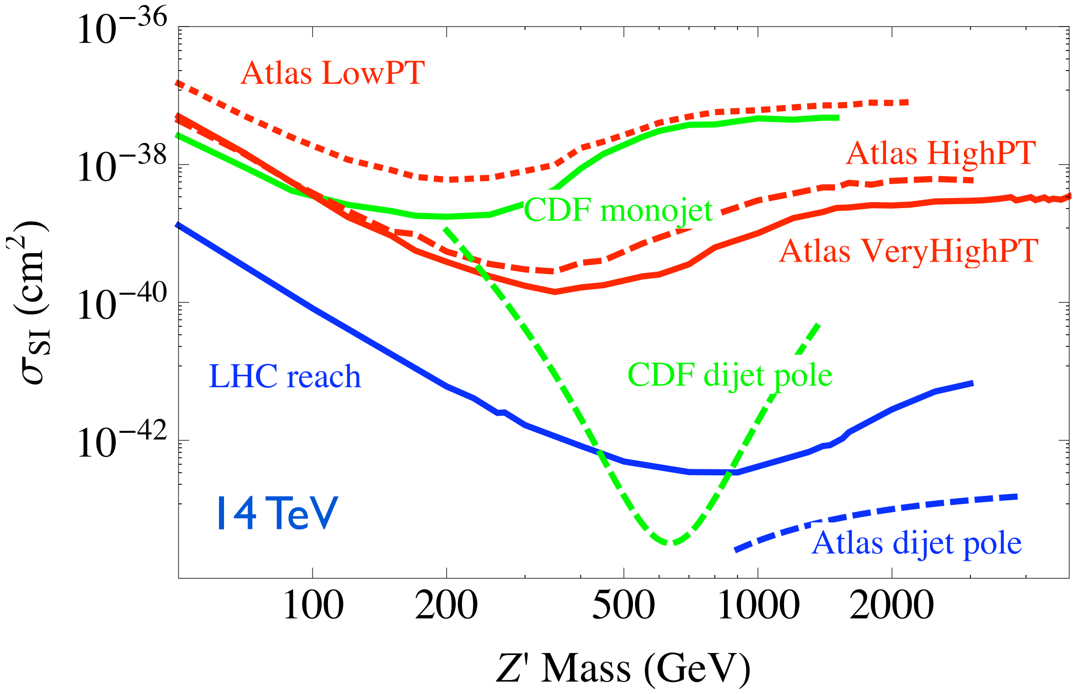


- can be scalar or Z’
- squark like

MonoX vs direct search for mediator

An, Ji, LTW, 1202.2894

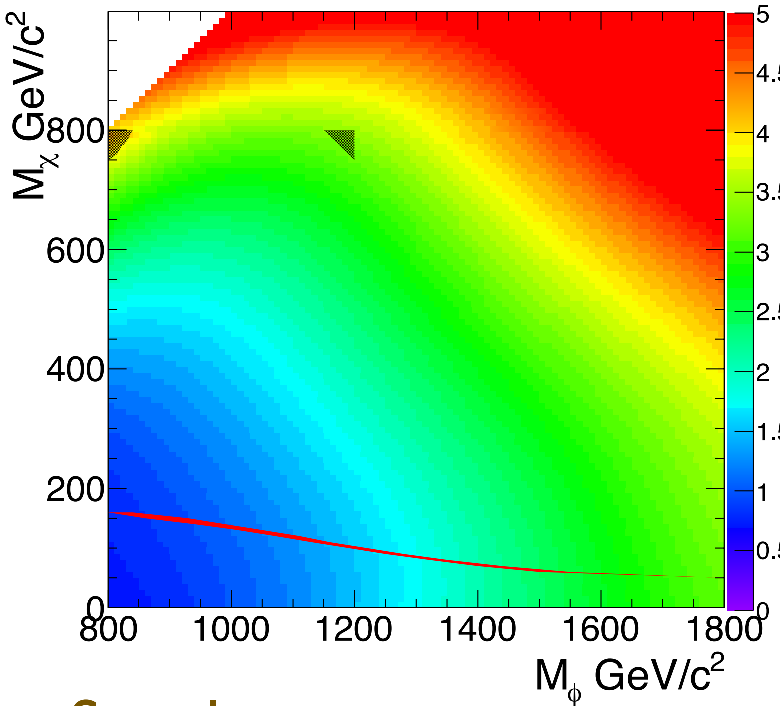
s-channel



See also
Busoni, De Simone, Jacques, Morgante, Riotto, 1405.3101

Haipeng An, Hao Zhang, LTW, 1308.0592

t-channel



See also:
Chang, Edezhath, Hutchinson, Luty, 1307.8120
Bai, Berger, 1308.0612
DiFranzo, Nagao, Rajaraman, Tait, 1308.2679
Papucci, Vichi, Zurek, 1402.2285

– Bottom line, it is (almost) always more effective to directly search for the mediator than using Mono-X in this set of models.

My favorite?

(time-dependent)

A promising scenario.

Effective, Mini-split, spread, zprime-mediation, ...

Heavy squarks $\tilde{u},\ \tilde{d},\ \ldots$

$\tilde{t},\ \tilde{b}$

$m_{\tilde{t},\tilde{b}} < m_{\tilde{u},\tilde{d}}$

10s - 100s TeV

$\tilde{g}$

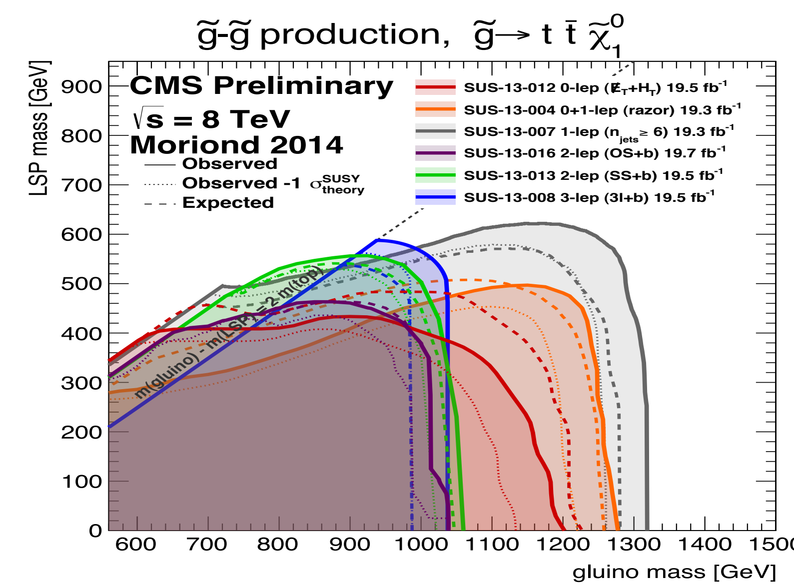
TeV-ish

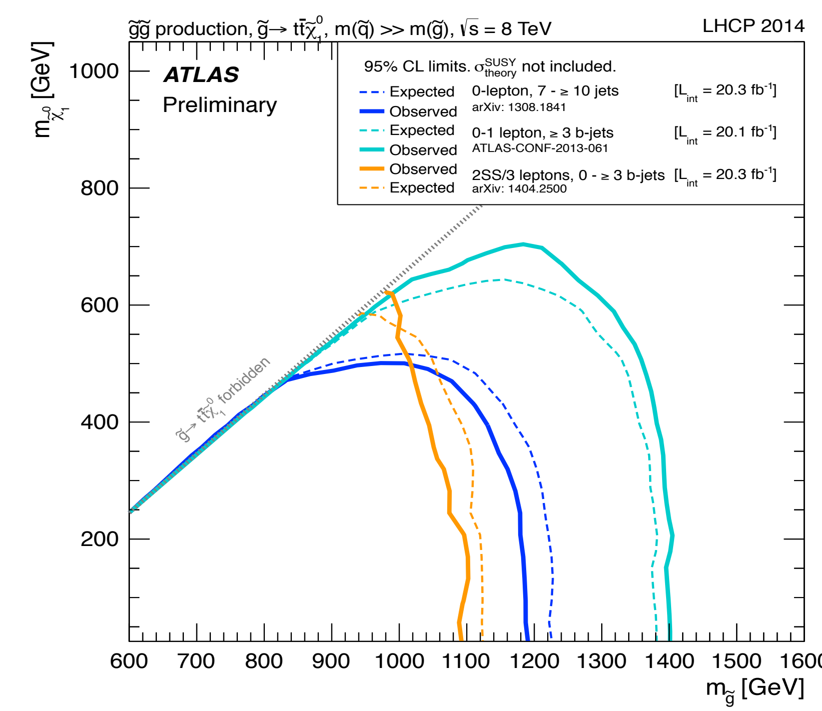
Light gaugino $\tilde{N}\ \tilde{C}^{\pm}$

Fermionic partners still tend to be light.

LHC signal

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t},\ \ t\bar{t}b\bar{b},\ \ t\bar{t}t\bar{b}\ \ldots$$

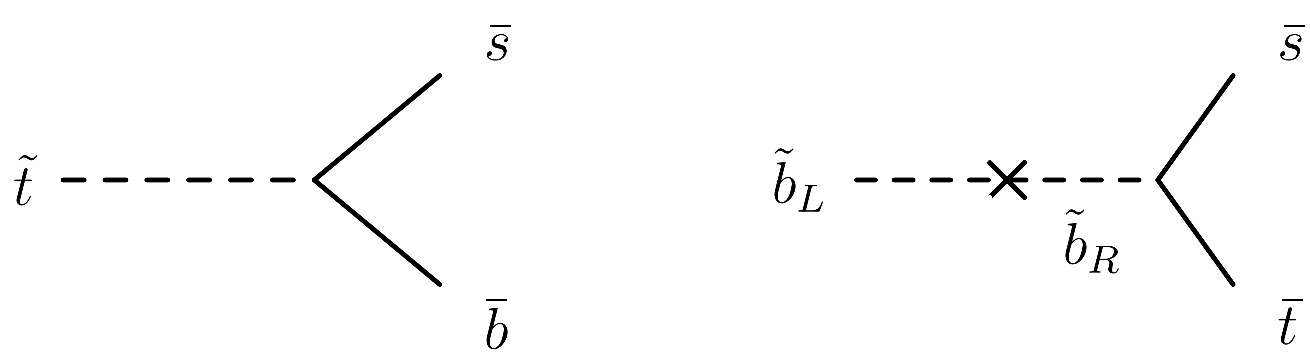




Minimal Flavor Violation

- For SUSY (or almost anything) to be light, some story of flavor must be told.
- Minimal flavor violation is an interesting way of thinking about it.
- Can make RPV consistent.

$$W_{\rm BNV} = \frac{1}{2}\, w''(Y_u\, \bar{u})(Y_d\, \bar{d})(Y_d\, \bar{d})$$



Flavored Dark Matter

[Batell, Pradler, Spannowsky]
[Batell, Lin, Wang]

Basic Idea: Give dark matter a flavor!

- MFV implies a Z3 symmetry, *flavor triality*, under which all SM fields are neutral and Dark Matter is charged

⇒ MFV can stabilize Dark Matter!

Example model:

$$W = \lambda \; X_i \; Y \; \bar{u}^i$$

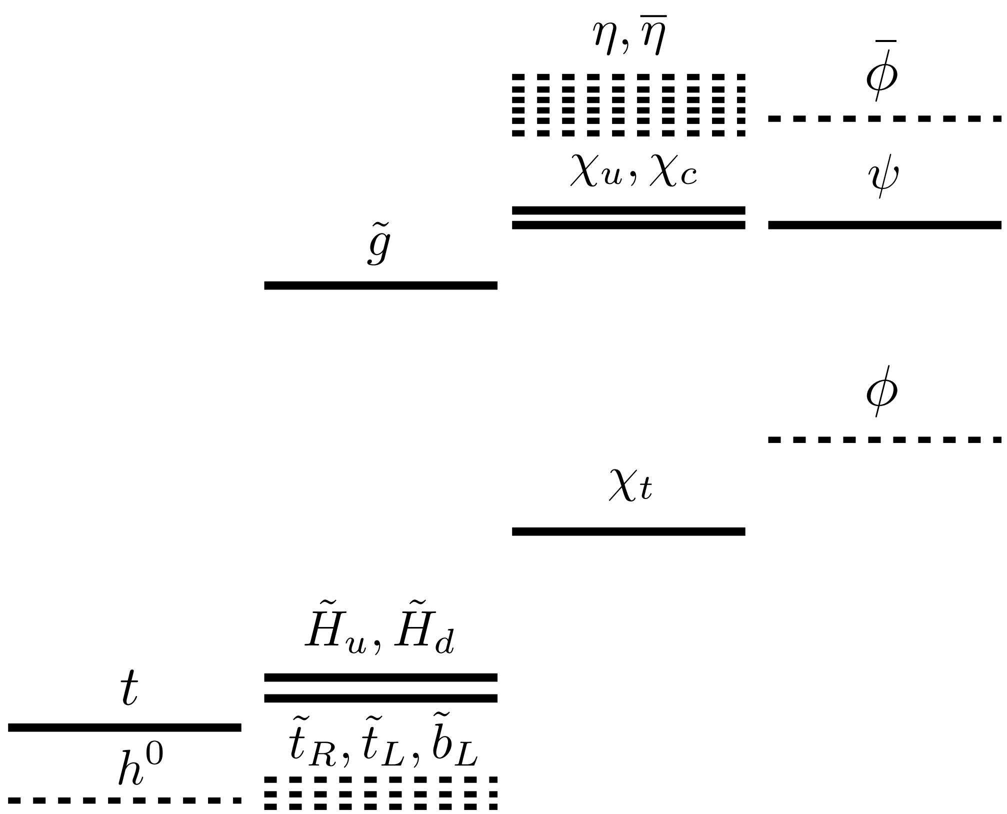
Dark Matter (3 flavors)

Mediator

up-type quark (3 flavors)

Can make viable models of Dark Matter!

At the LHC



$$pp \to \phi_Y \phi_Y^*, \ \ \phi_Y \to t + \chi$$

But not the stop.

$$pp \to \psi_Y \bar{\phi}_Y, \ \ \psi_Y \to \tilde{t} + \chi$$

$$\tilde{t} \to jj \ (udd \ \mathrm{RPV})$$

“hidden” stop

- May find “heavy stop”, but theory is natural.

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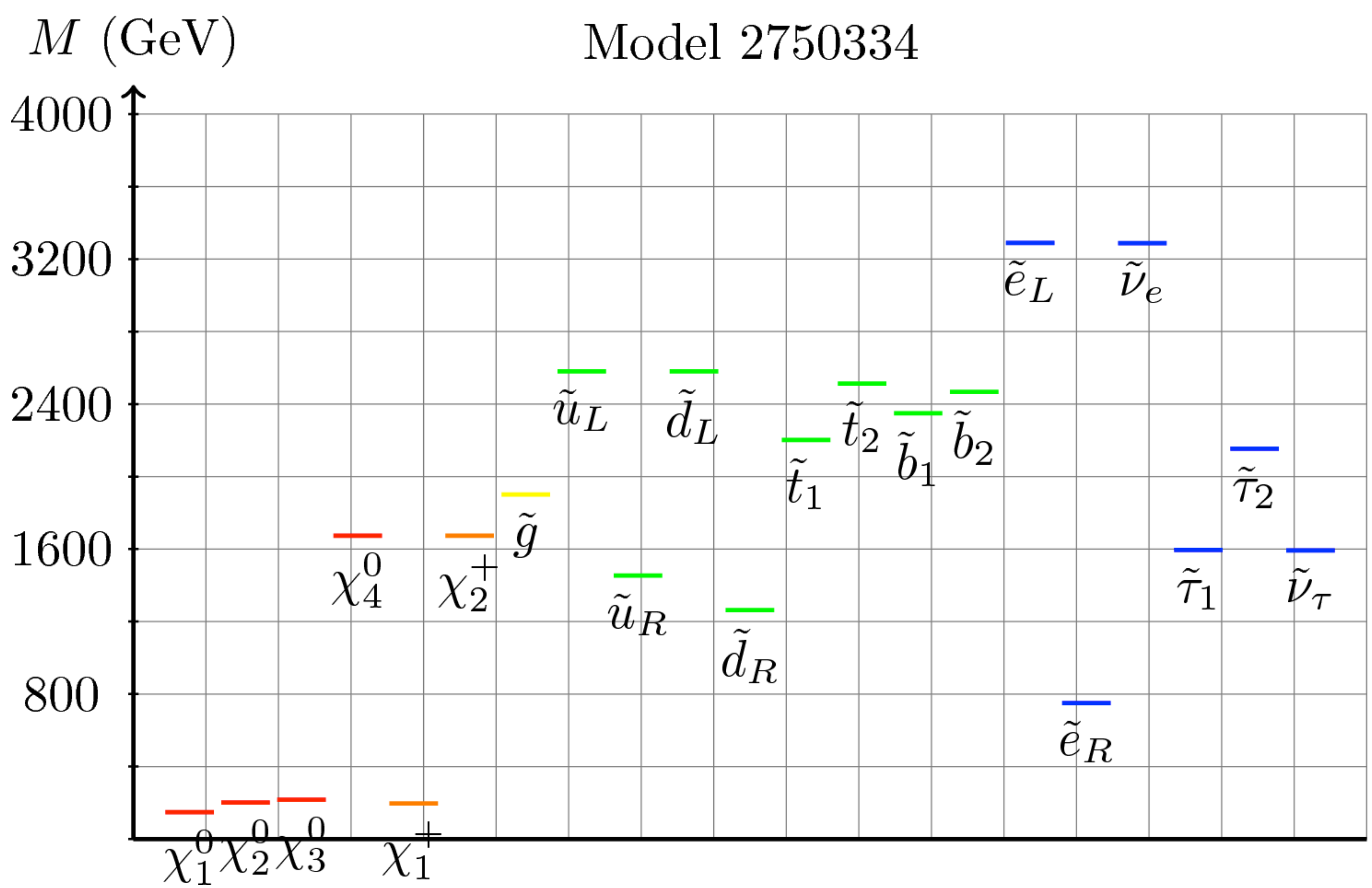
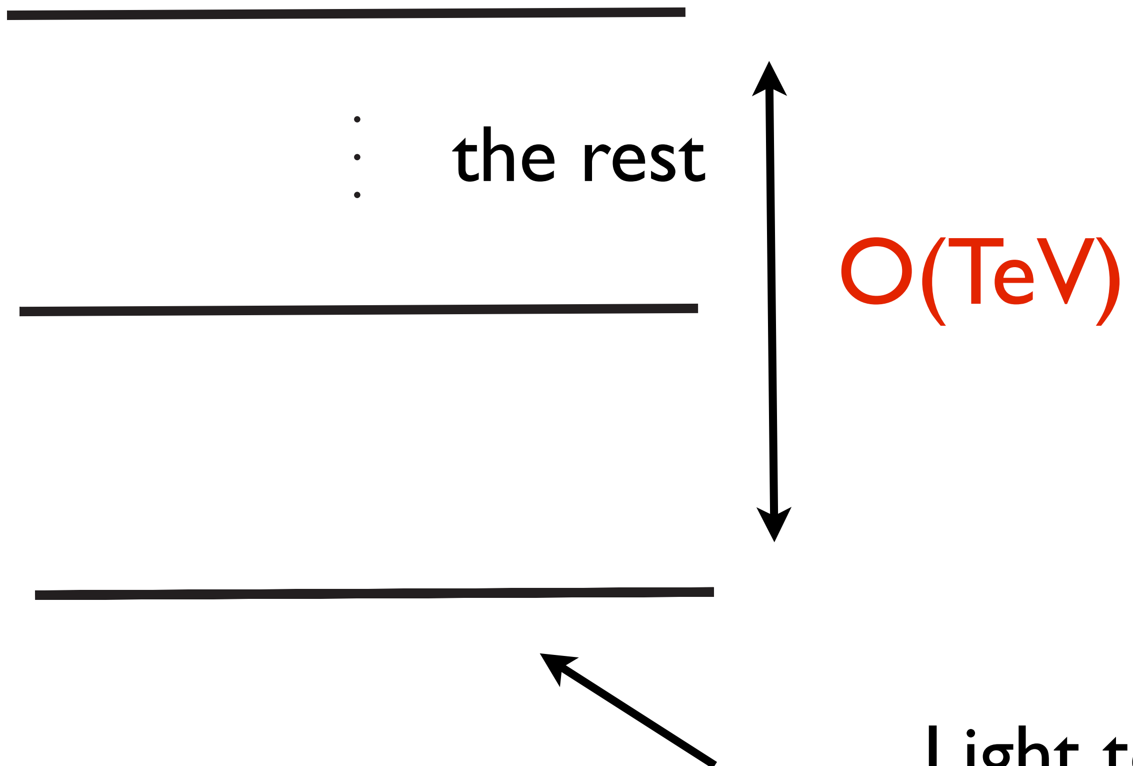
- However, many models feature particles with masses spread at least factor of several apart.
- Won't be able to see everything.
- LHC discovery will set the stage for our next exploration. Such as at a future 100 TeV pp collider.

Example: SUSY



- Run 2 may be able to see gluino, light neutralinos and charginos, some squarks, but not the rest.

Similar story in composite Higgs



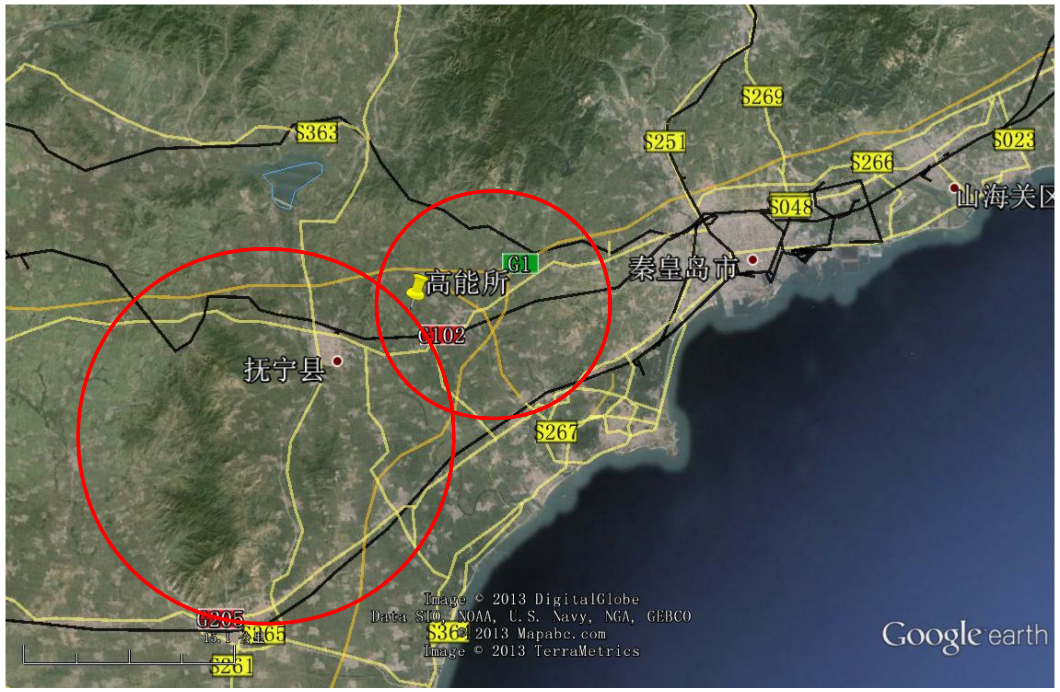
Hard to see the full spectrum with the increase of reach from 8 to 14 TeV

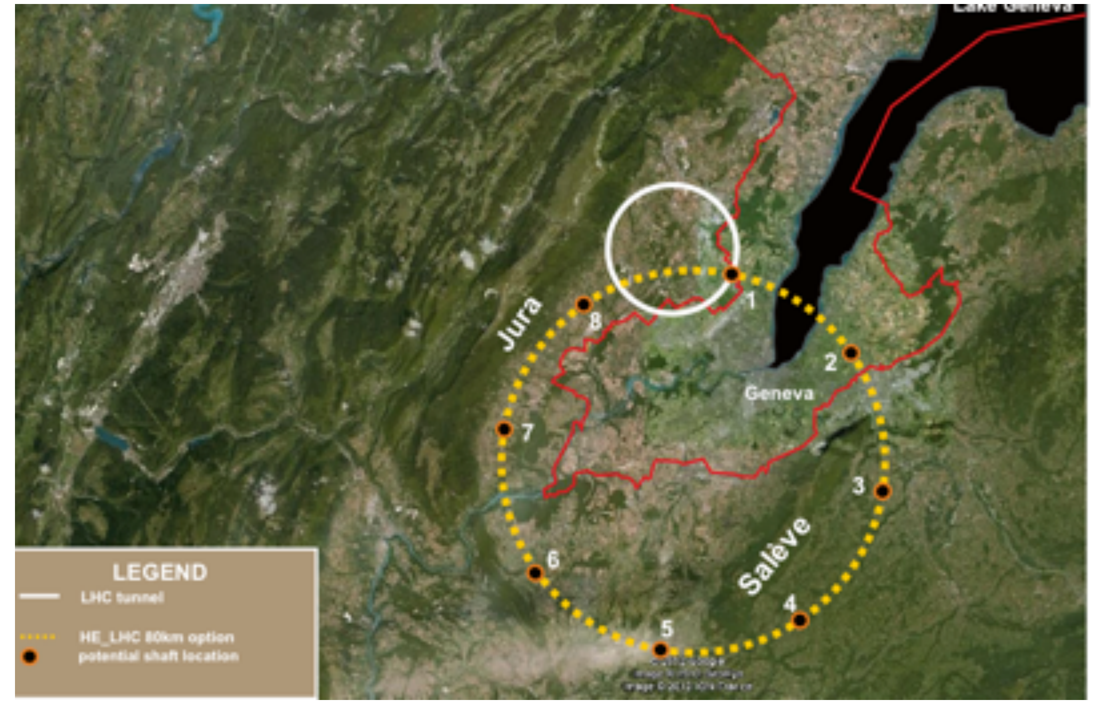
Light top partner
"As natural as possible"

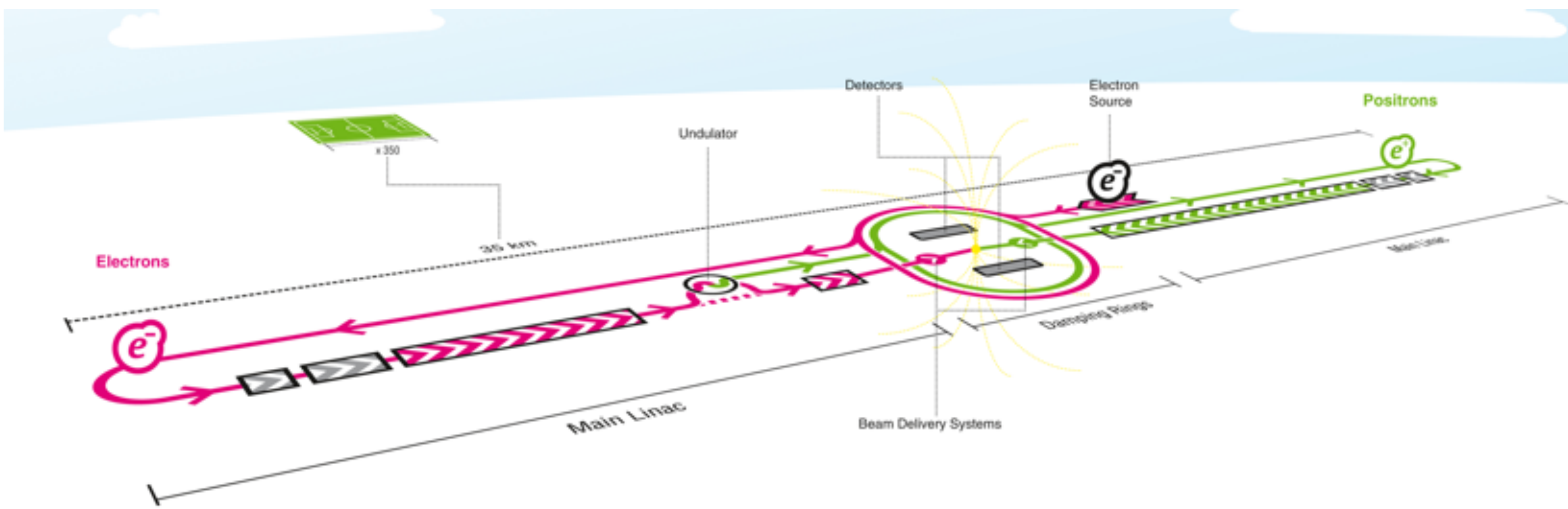
No discovery?

- Disappointing. But should be the starting point for the next stage of our long journey into ever smaller distance scales.
- Run 2 won't have the final word on many questions.
  - Won't nail the Higgs properties.
  - Not enough for naturalness yet (for me).
  - Not even close for WIMP dark matter.
- We should certainly go further.

Next steps







Shufang's talk later

I am eagerly waiting for the Run 2.