Beyond the Standard Model Prospects

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University of Chicago

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However, I think this is the wrong question to ask.

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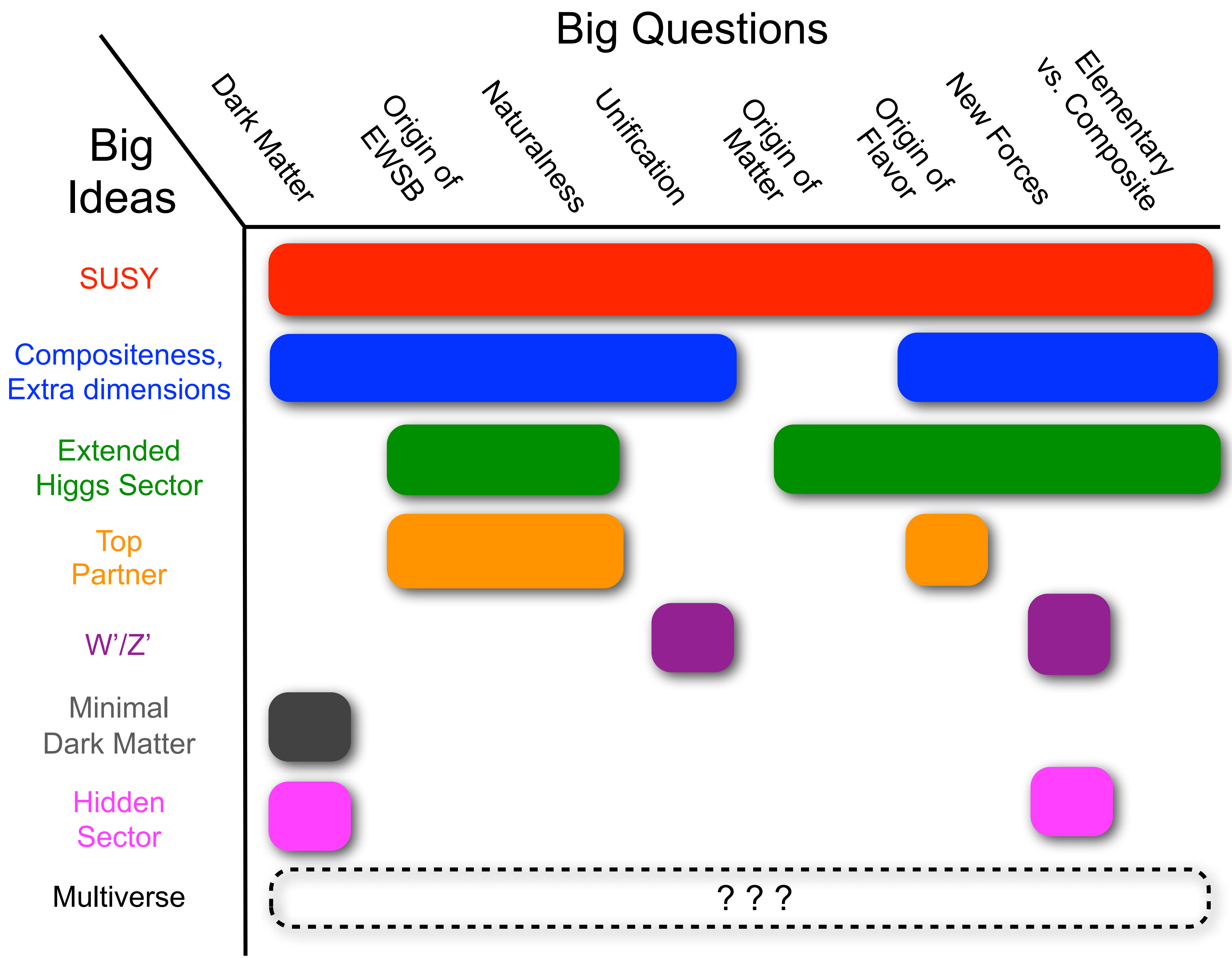
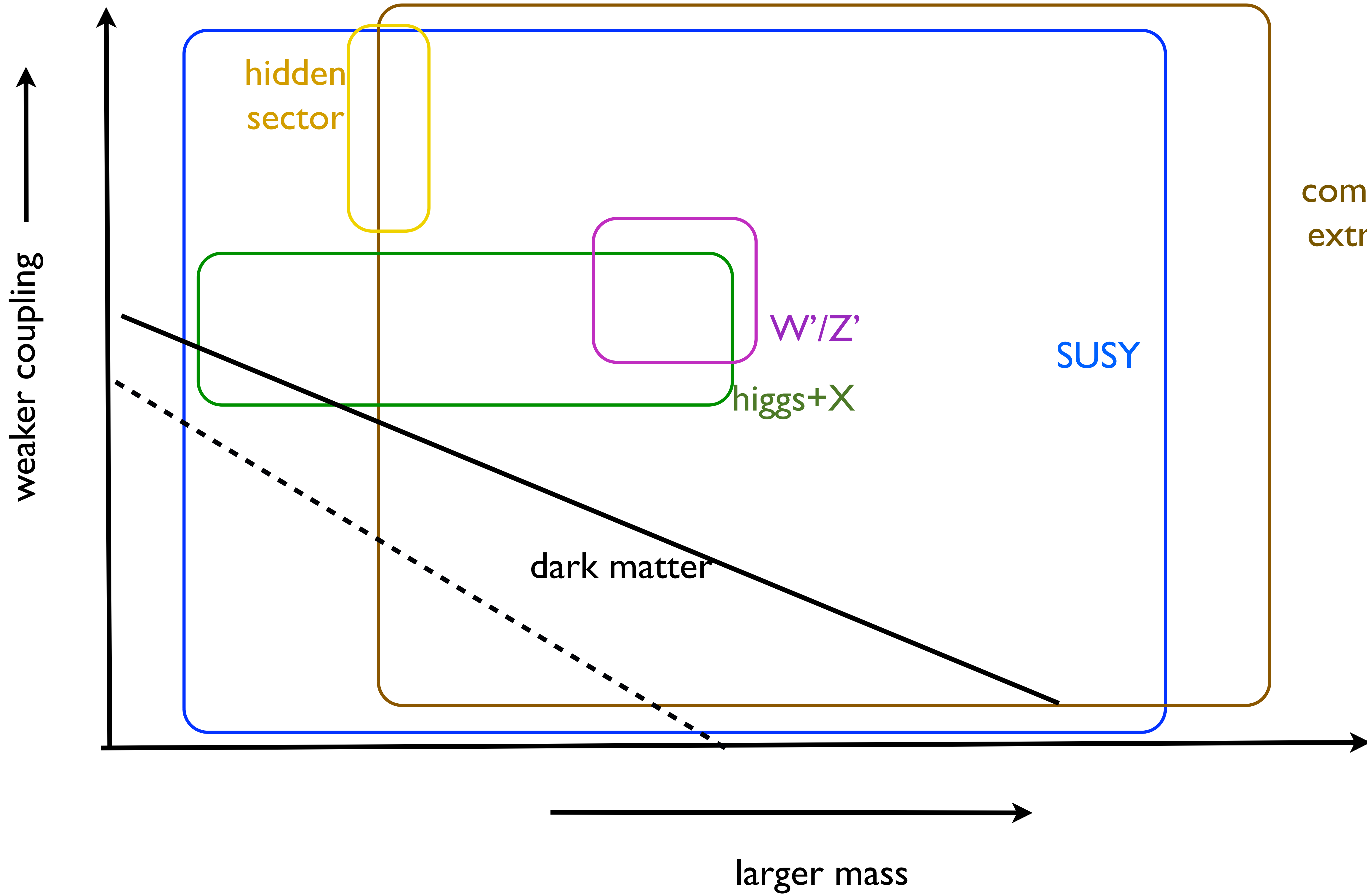
This talk: lepton


Big Questions
Big Ideas
Dark Matter
Origin of EWSB
Naturalness
Unification
Origin of Matter
Origin of Flavor
New Forces
Elementary vs. Composite
SUSY
Compositeness, Extra dimensions
Extended Higgs Sector
Top Partner
W'/Z'
Minimal Dark Matter
Hidden Sector
Multiverse
? ? ?

Exploring the space of possibilities



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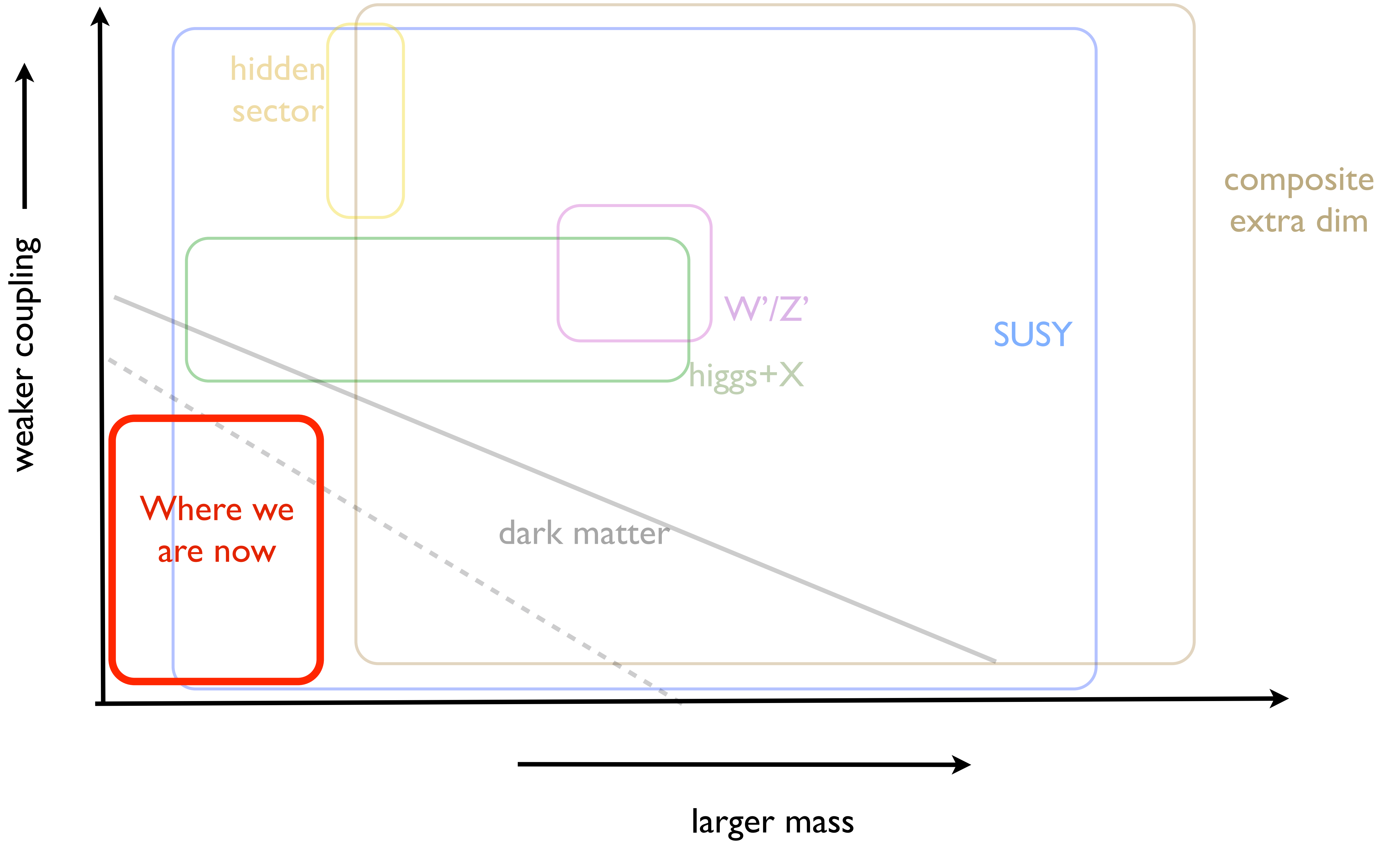

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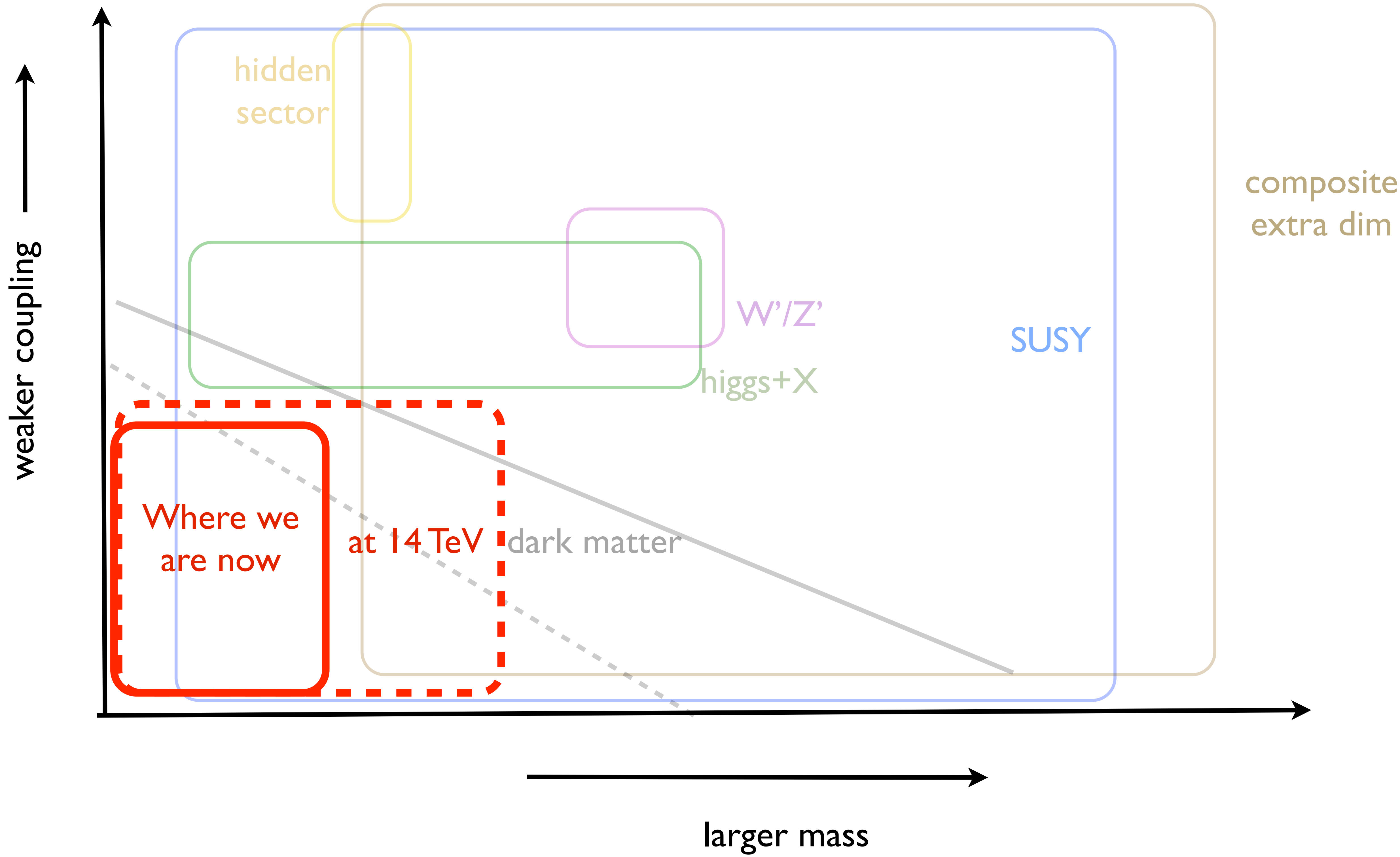

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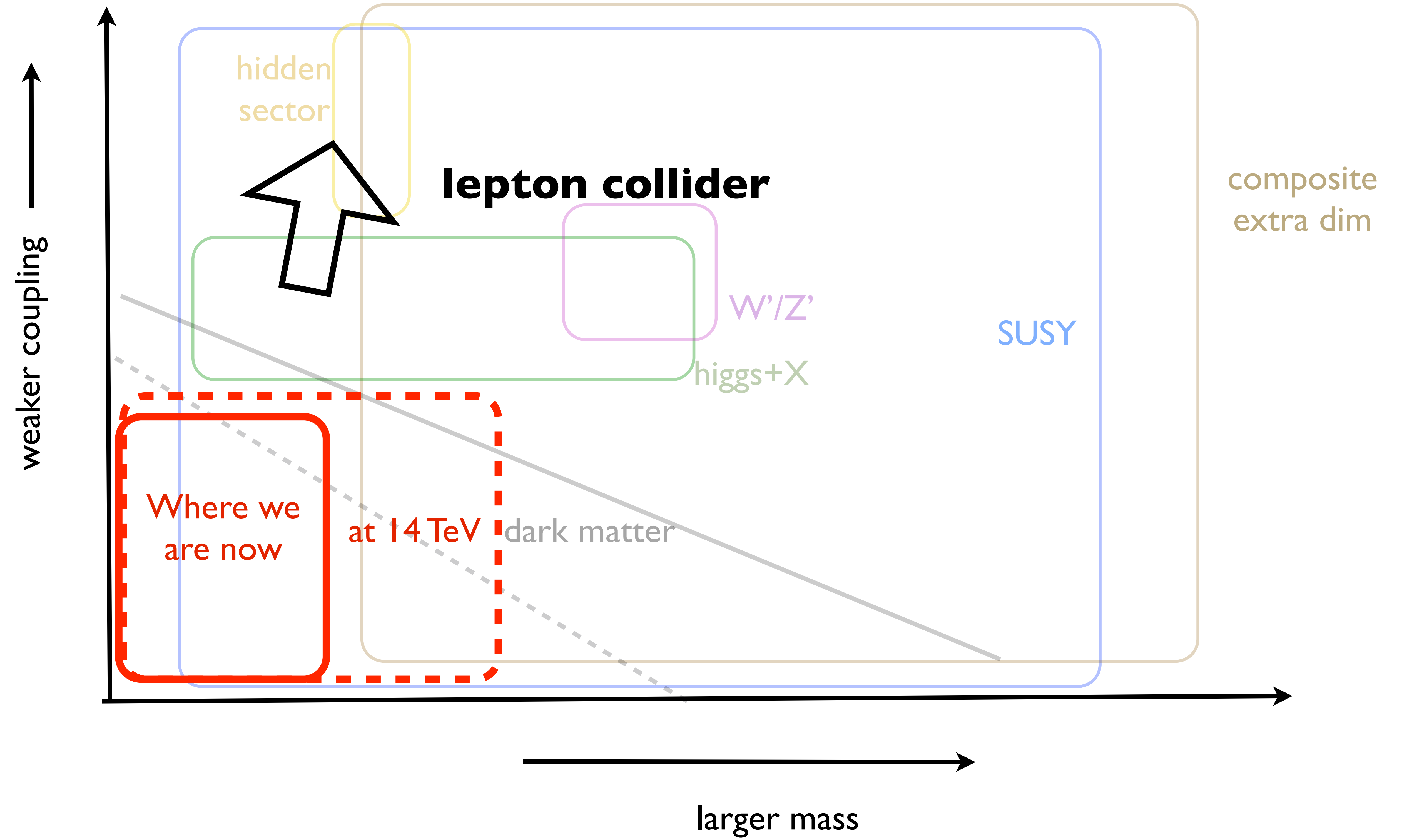

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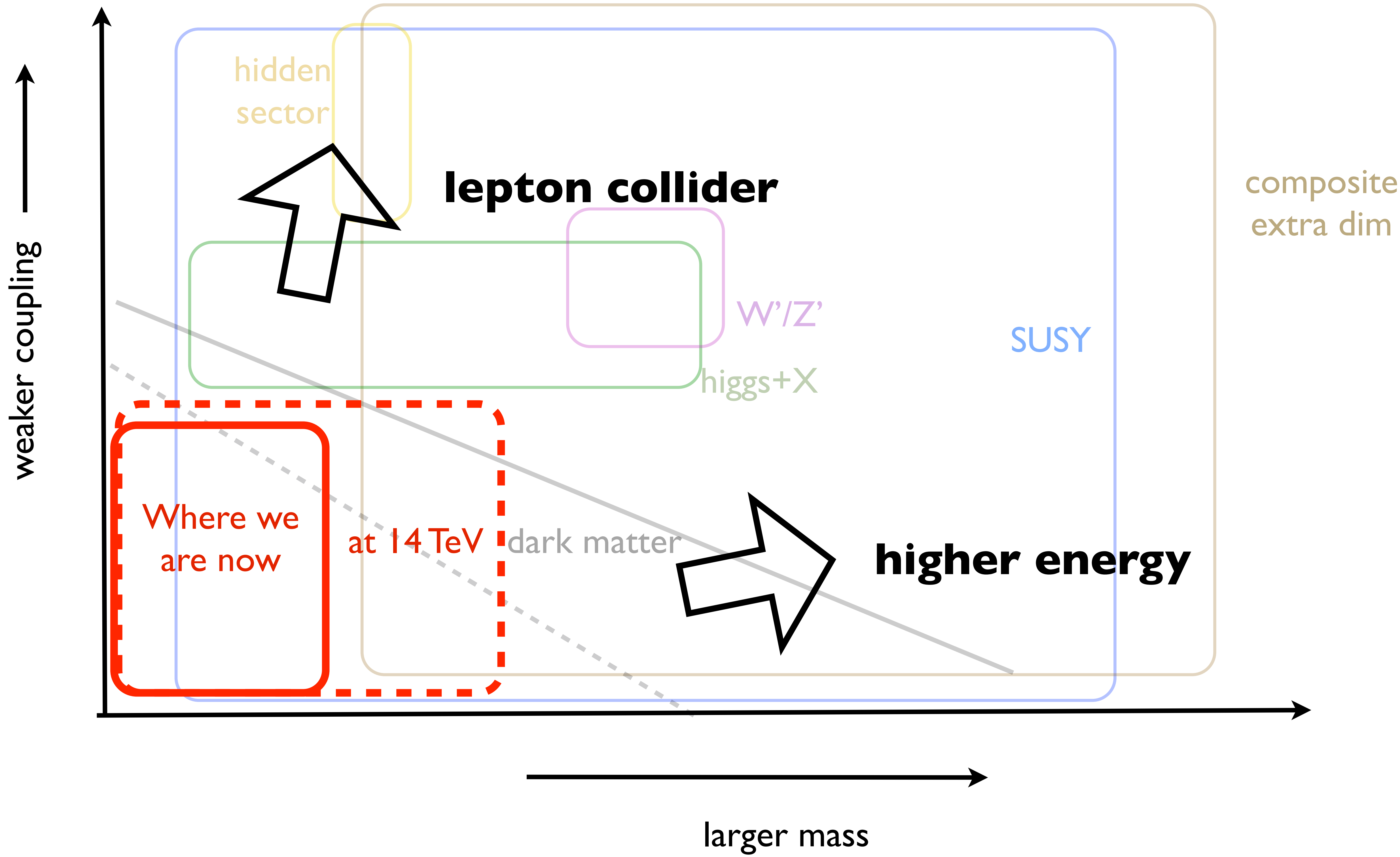


Key words for lepton colliders

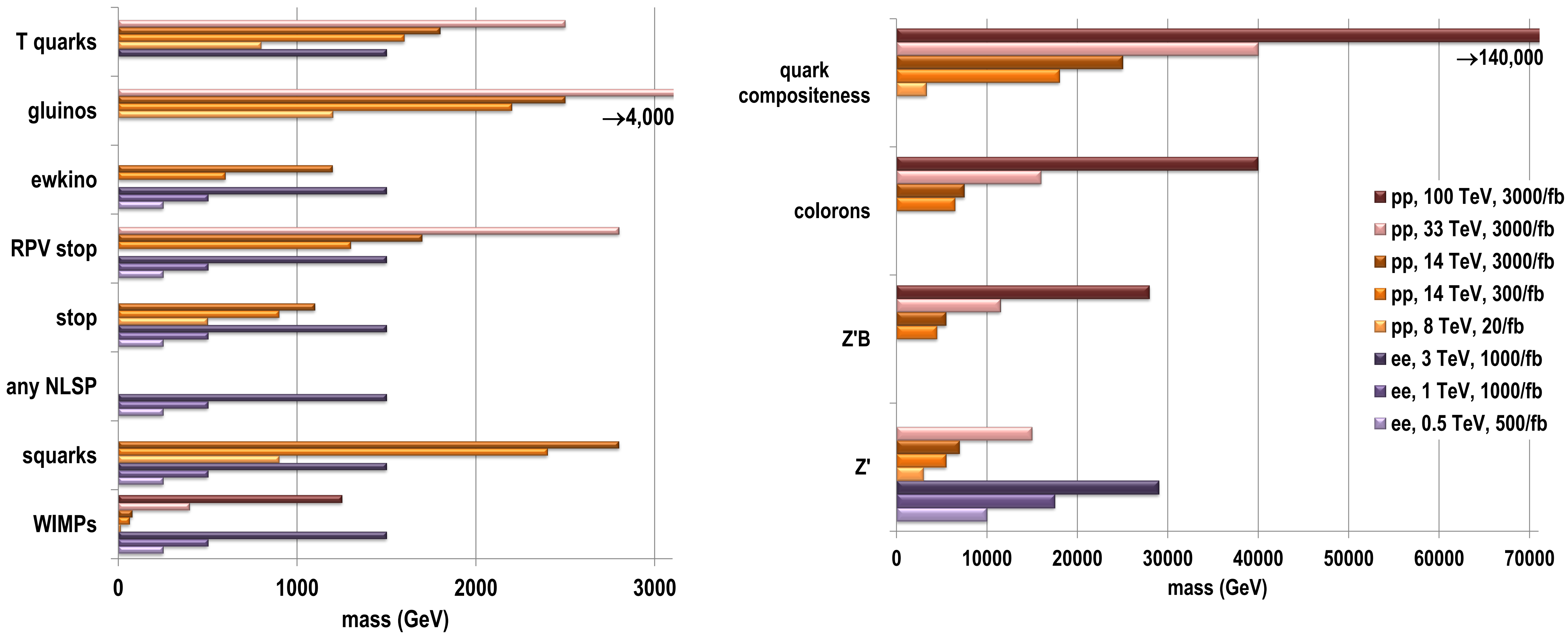
- Solid coverage, essentially loophole free.
- Much better measurement, thorough understanding.

The rest of the talk

- Some (familiar) examples to highlight these points.

Most of the material:
Snowmass energy frontier studies

Summary figure from Snowmass

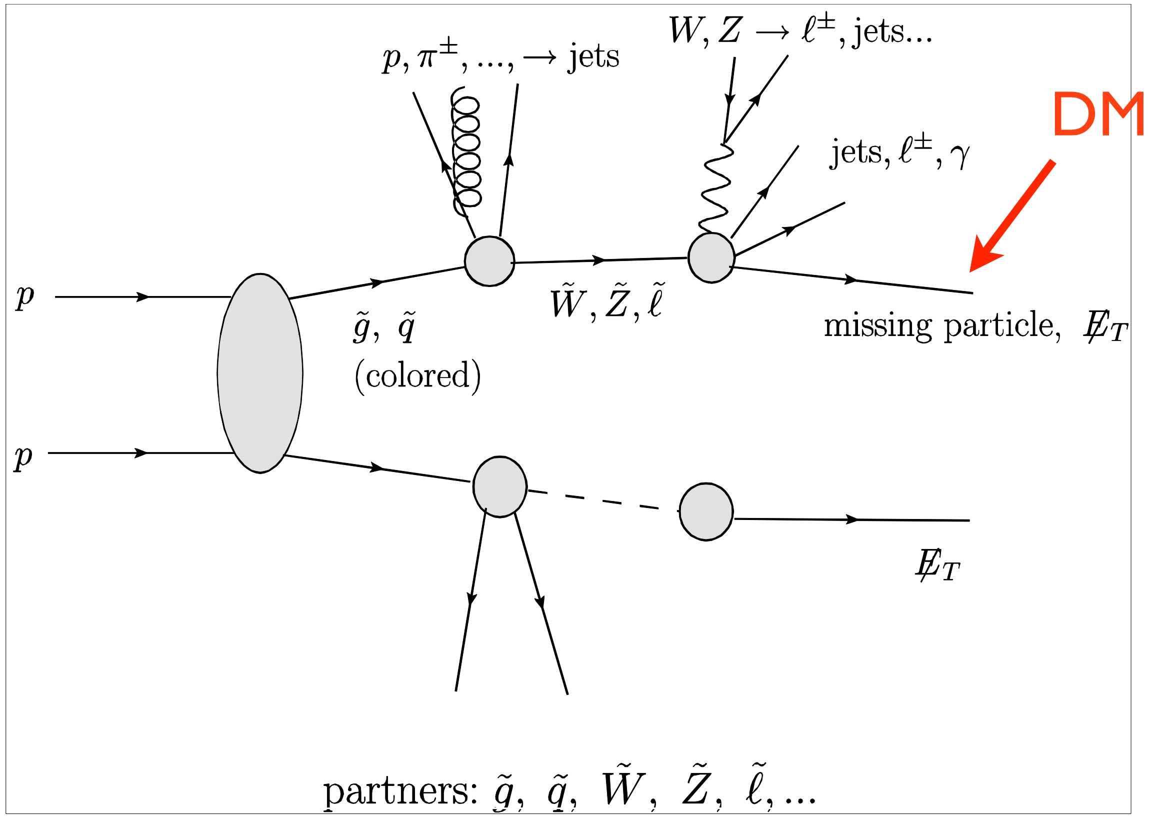


- However, just looking at the length of the bars could be misleading.

- More details needed to understand what lepton collider can do.

WIMP Dark Matter

"standard" story.



- It's produced as part of the NP signal, shows up as missing energy.
  - Dominated by colored NP particle production: eg. gluino.
- Model dependent! The reach is correlated with the rest of the particle spectrum.

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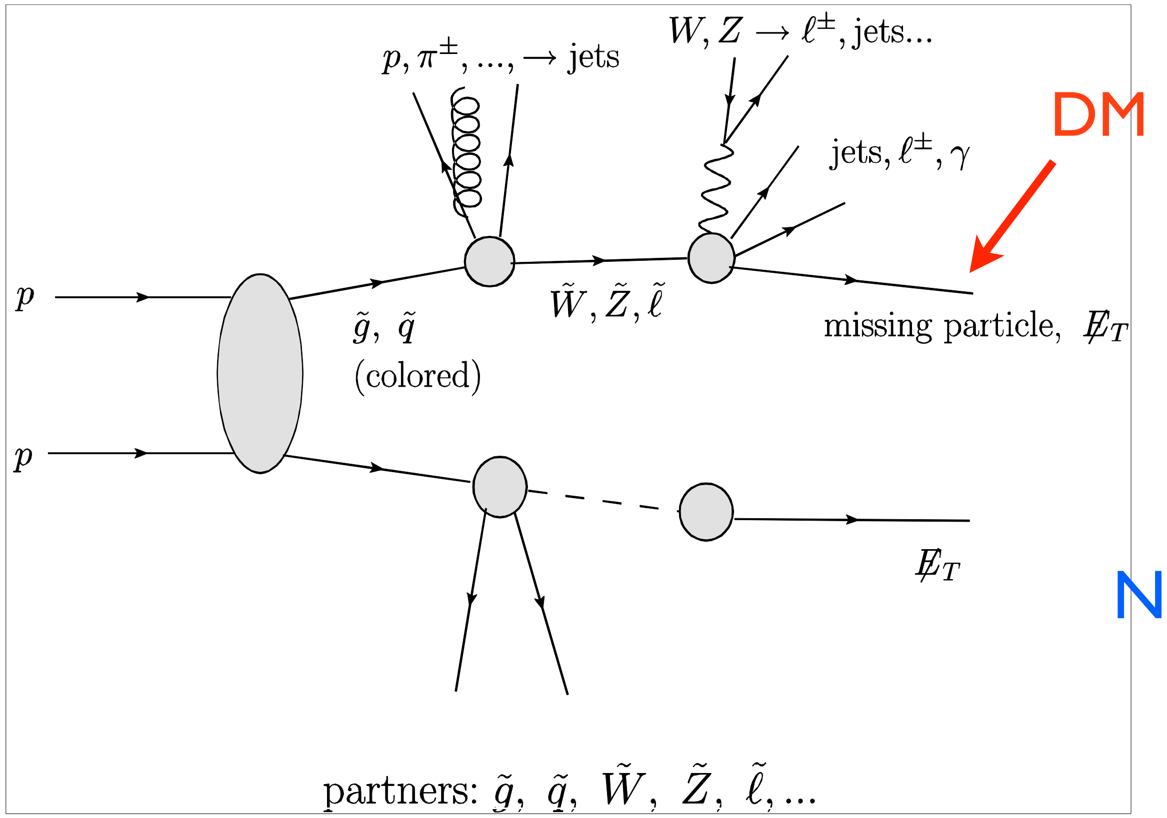
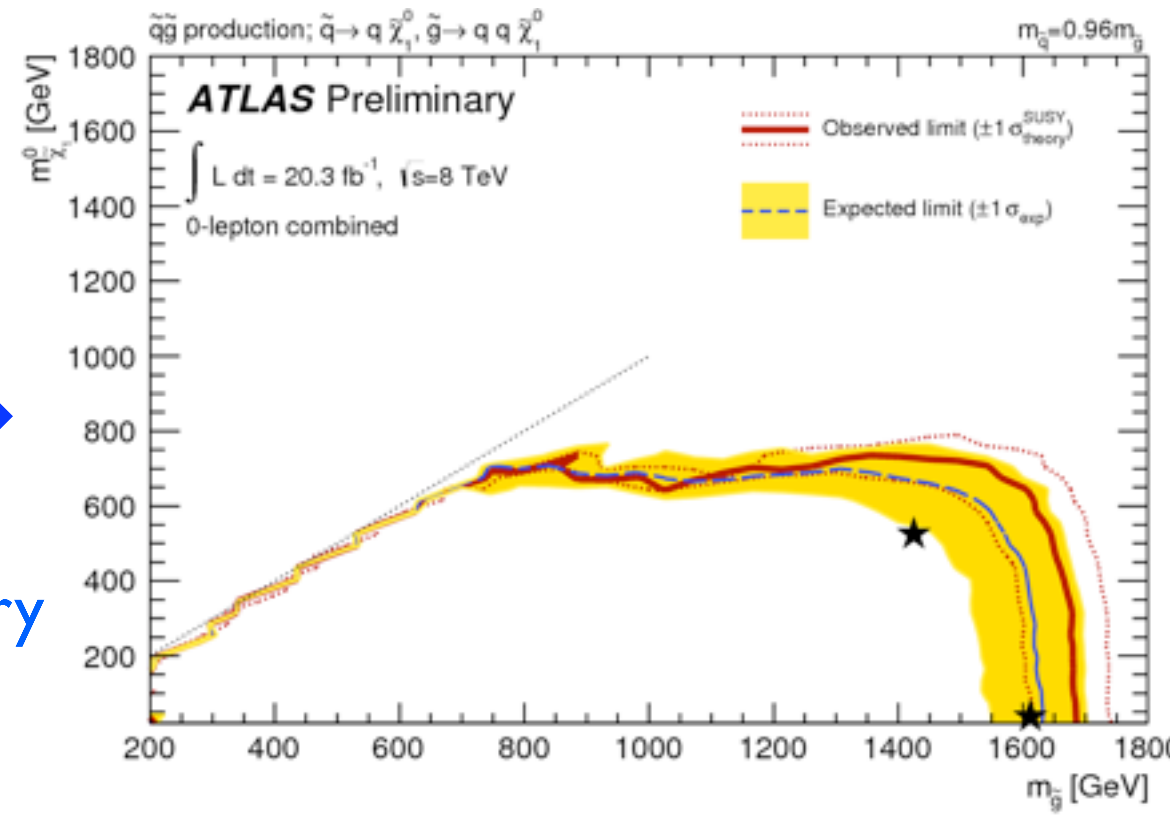


No discovery yet



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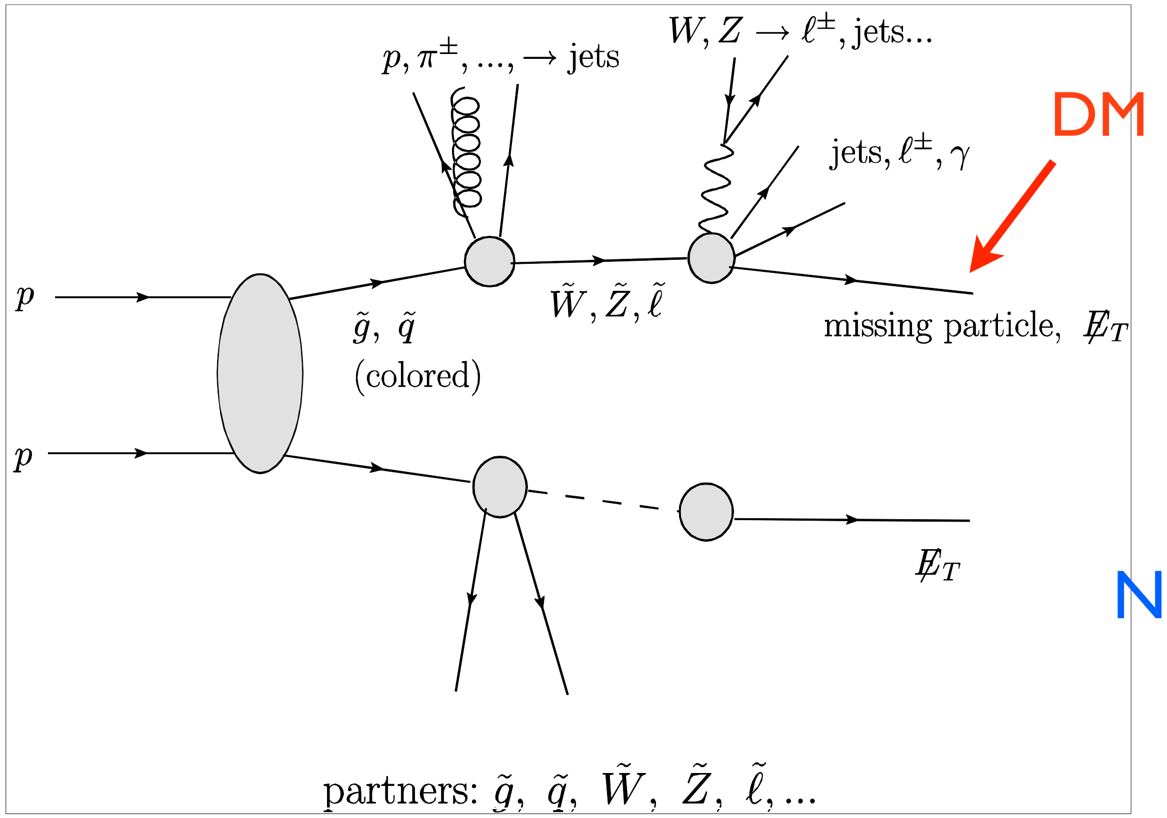

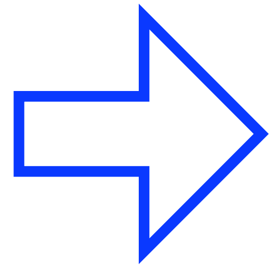

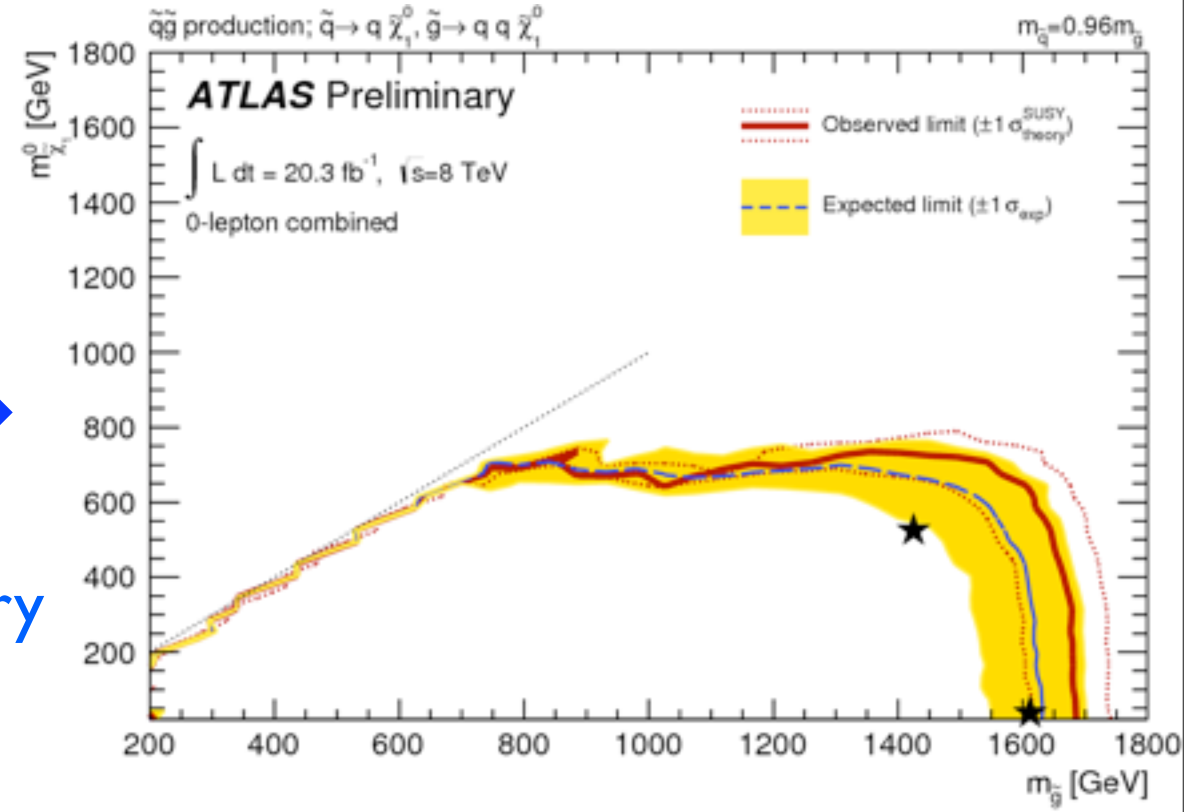

Of course, will keep looking at LHC 14

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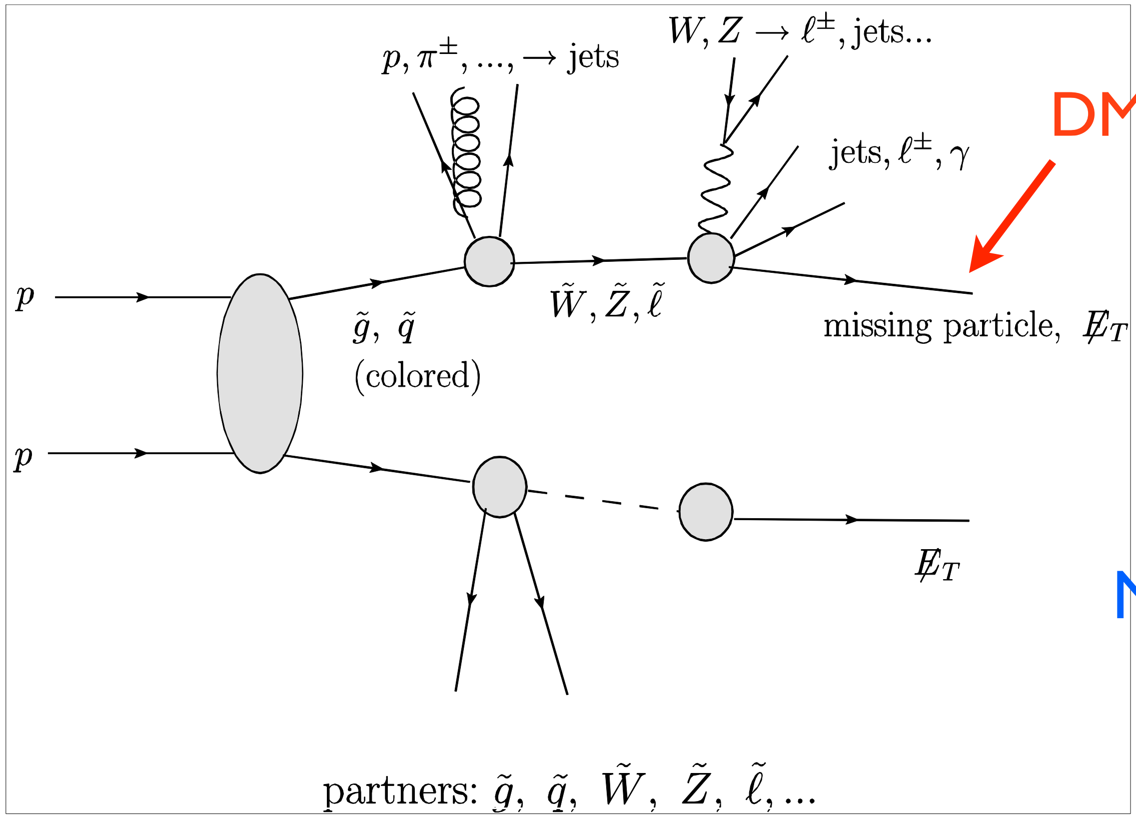
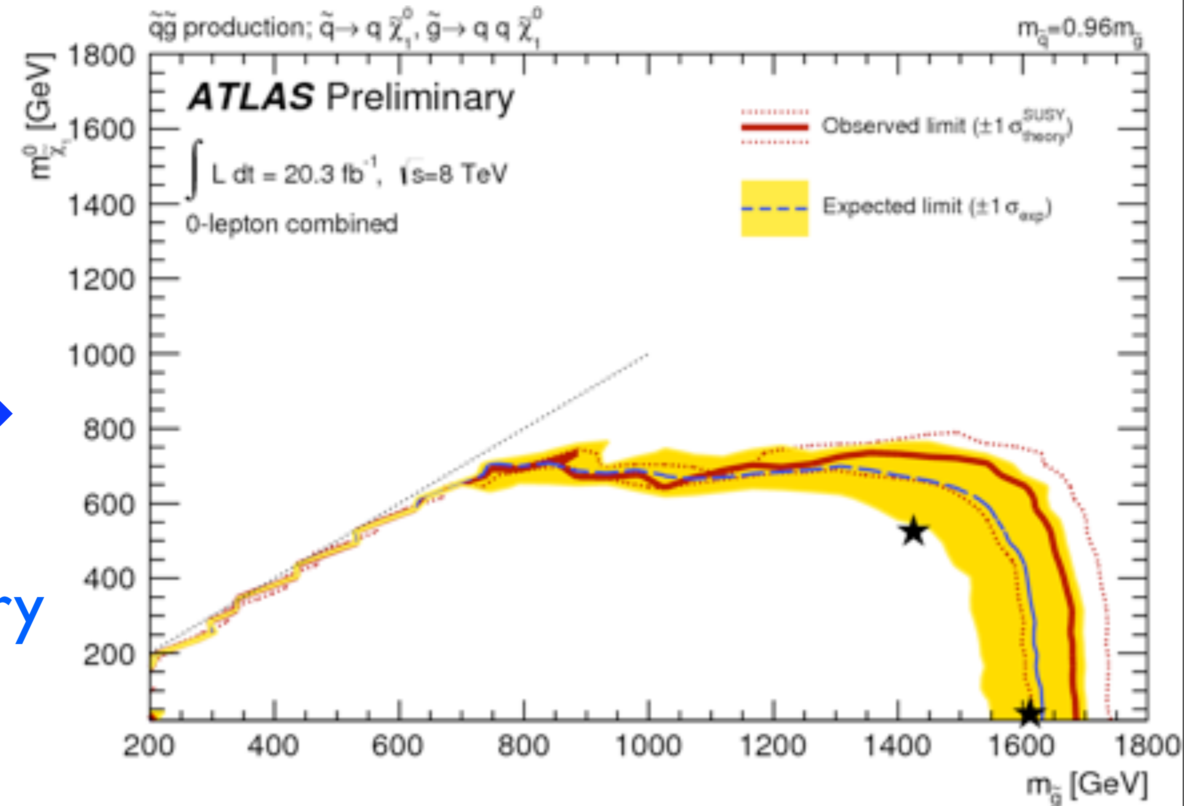


DM

No discovery yet



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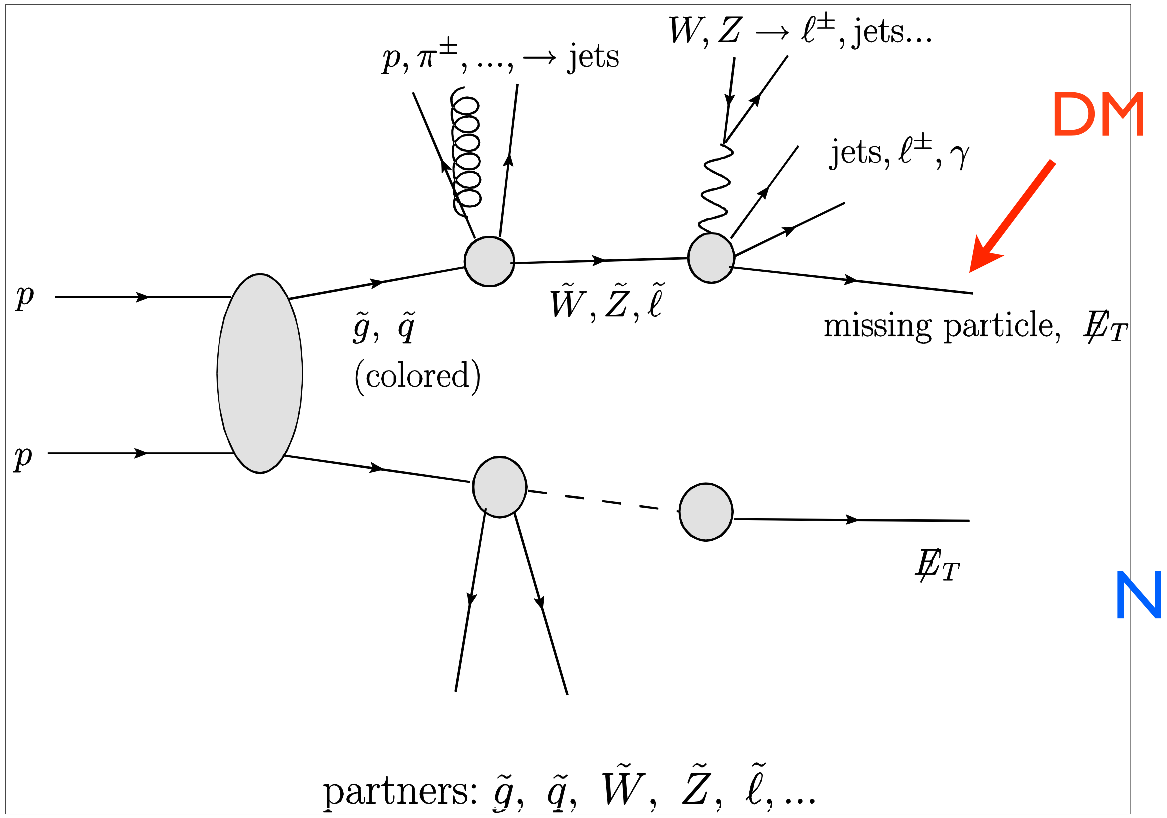
If found, we need to measure its properties, make sure it is dark matter

“standard” story.



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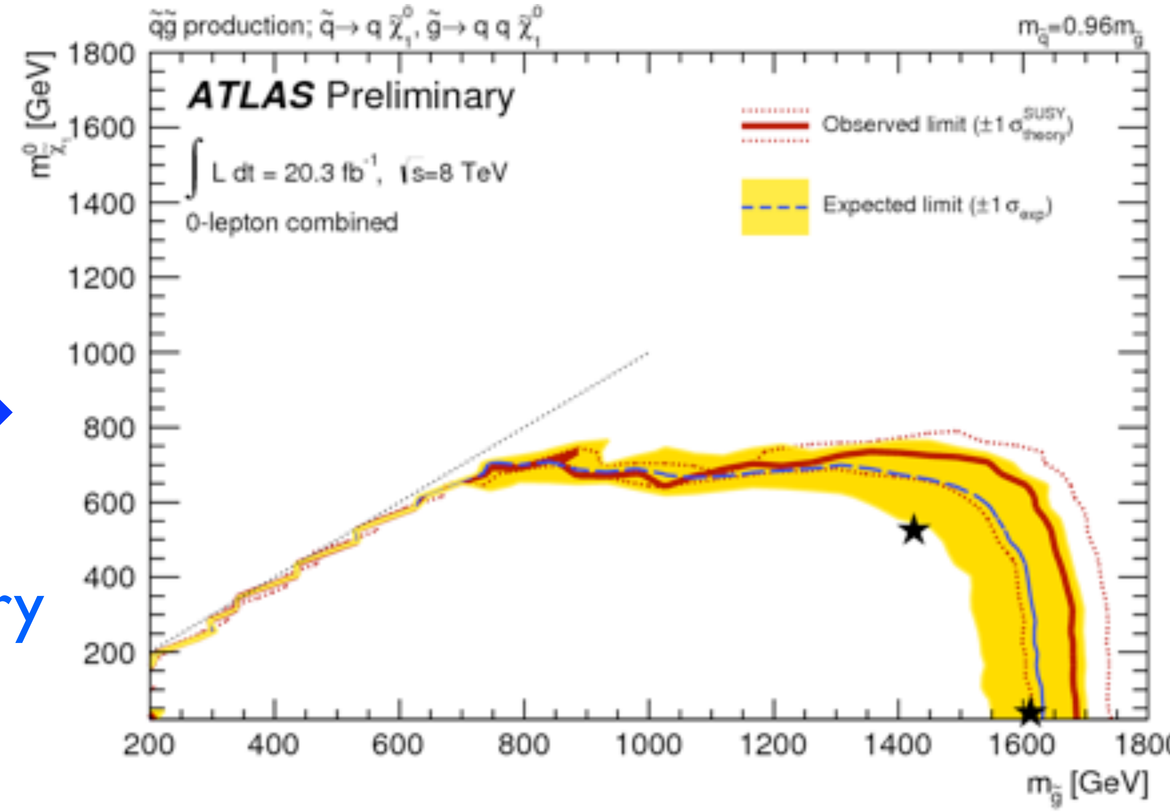

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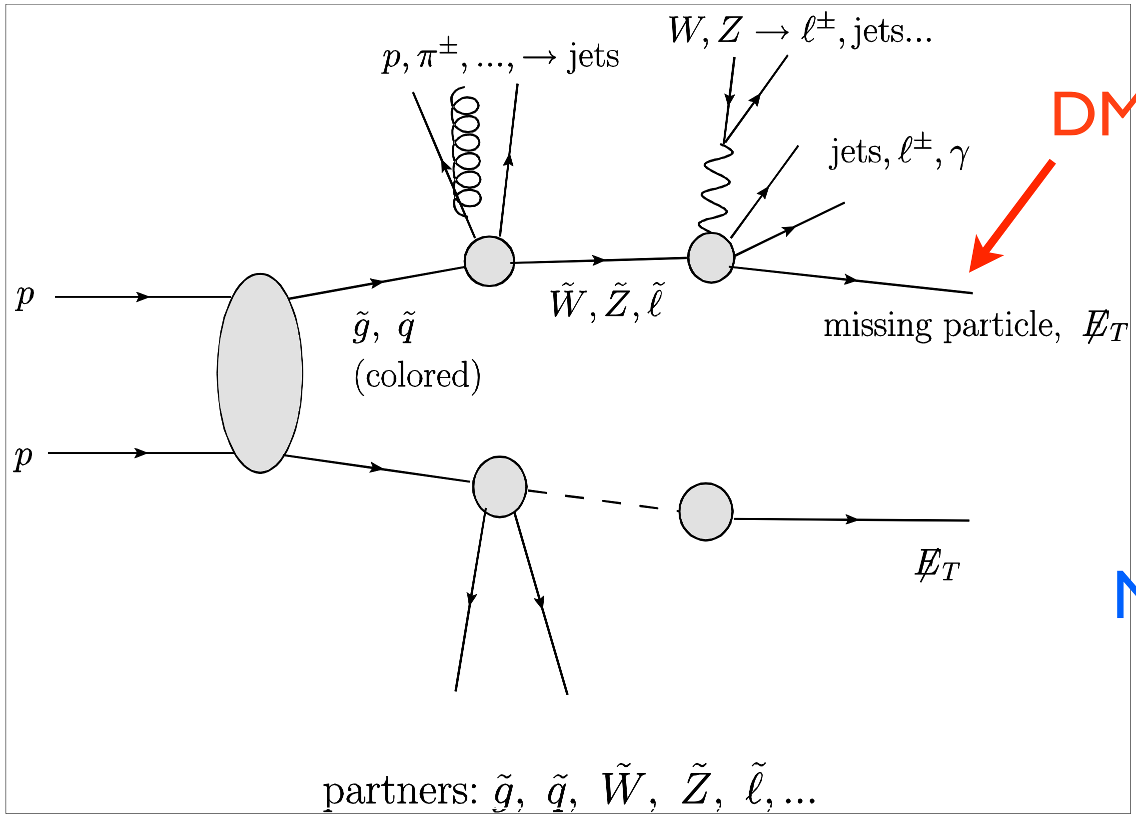

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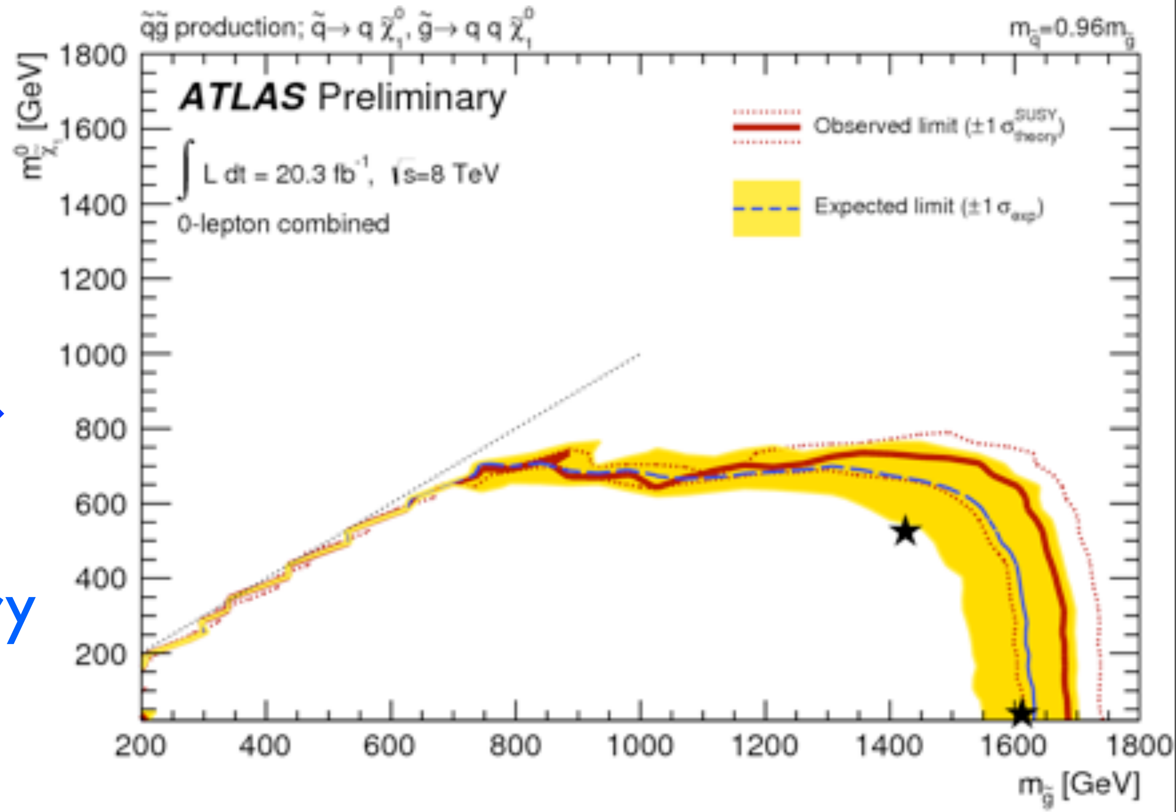

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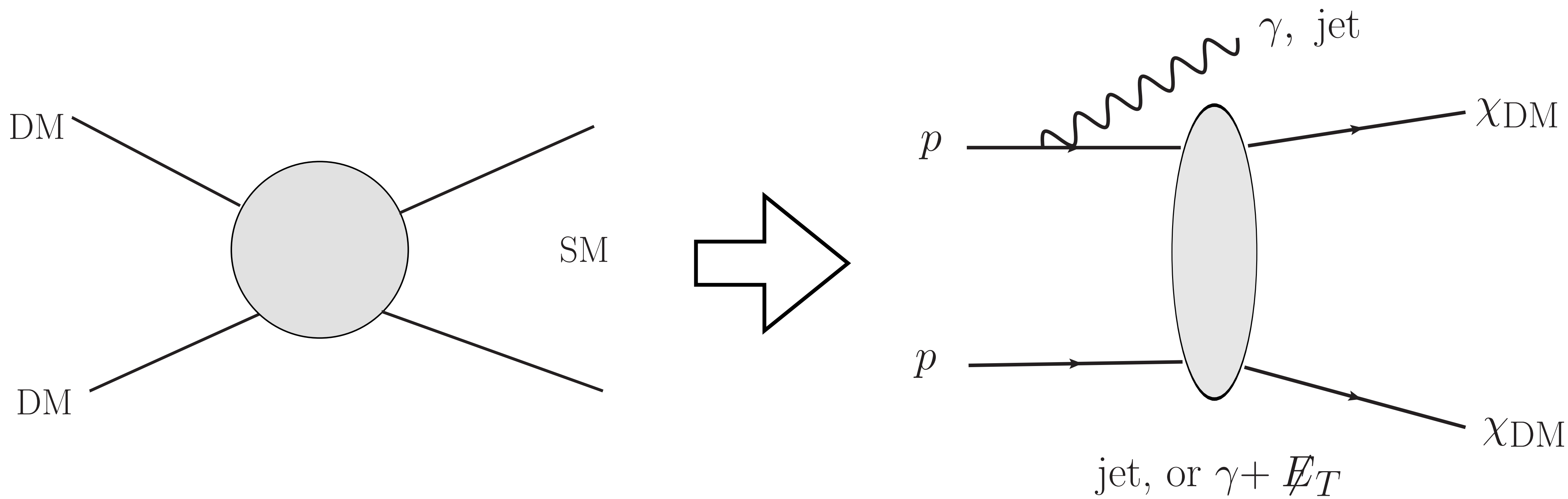
Lepton collider will be essential in both of these cases!

The model independent channel

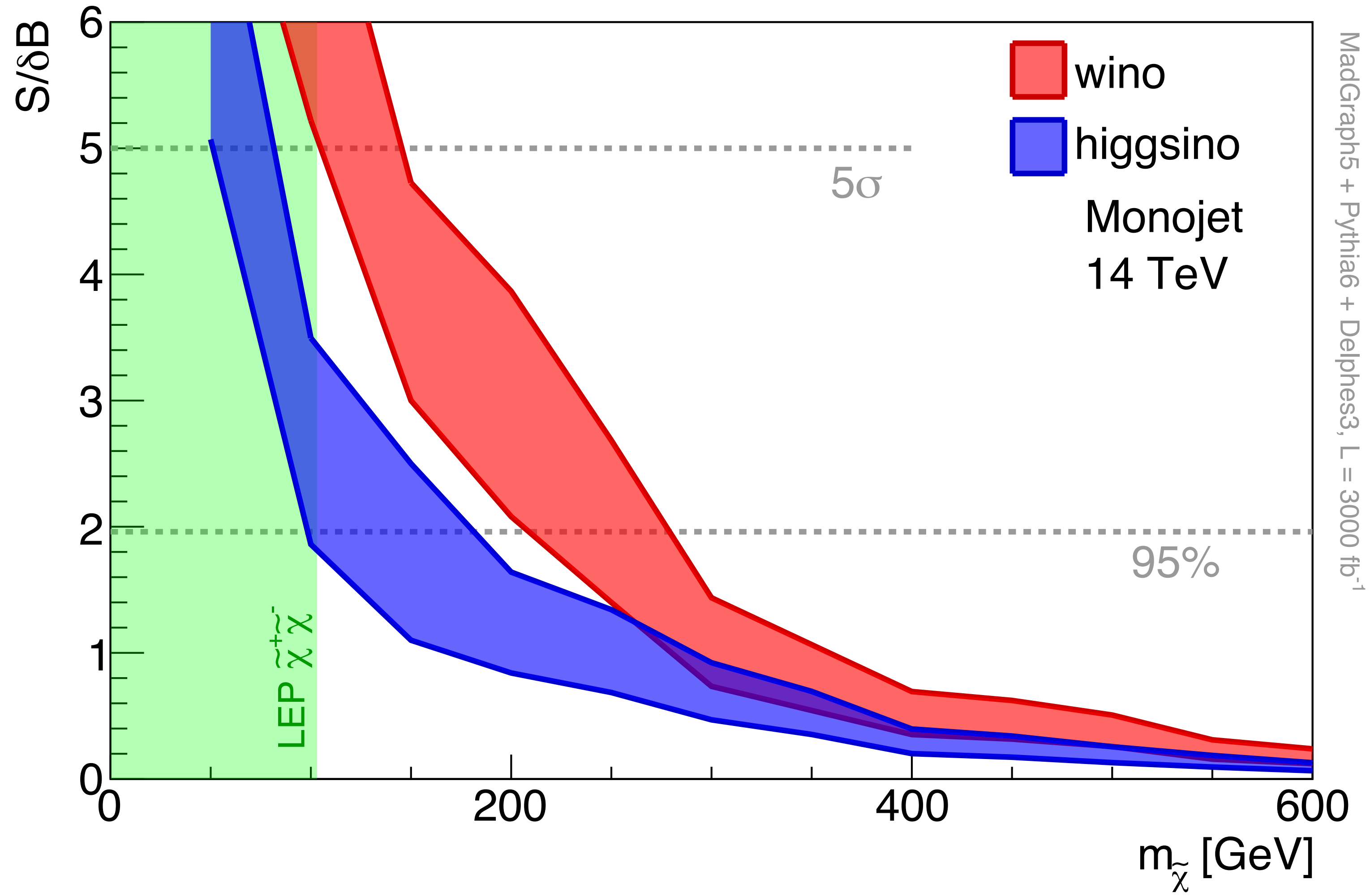
- pair production + additional radiation.



- Mono-X: mono-jet, mono-photon, mono-...

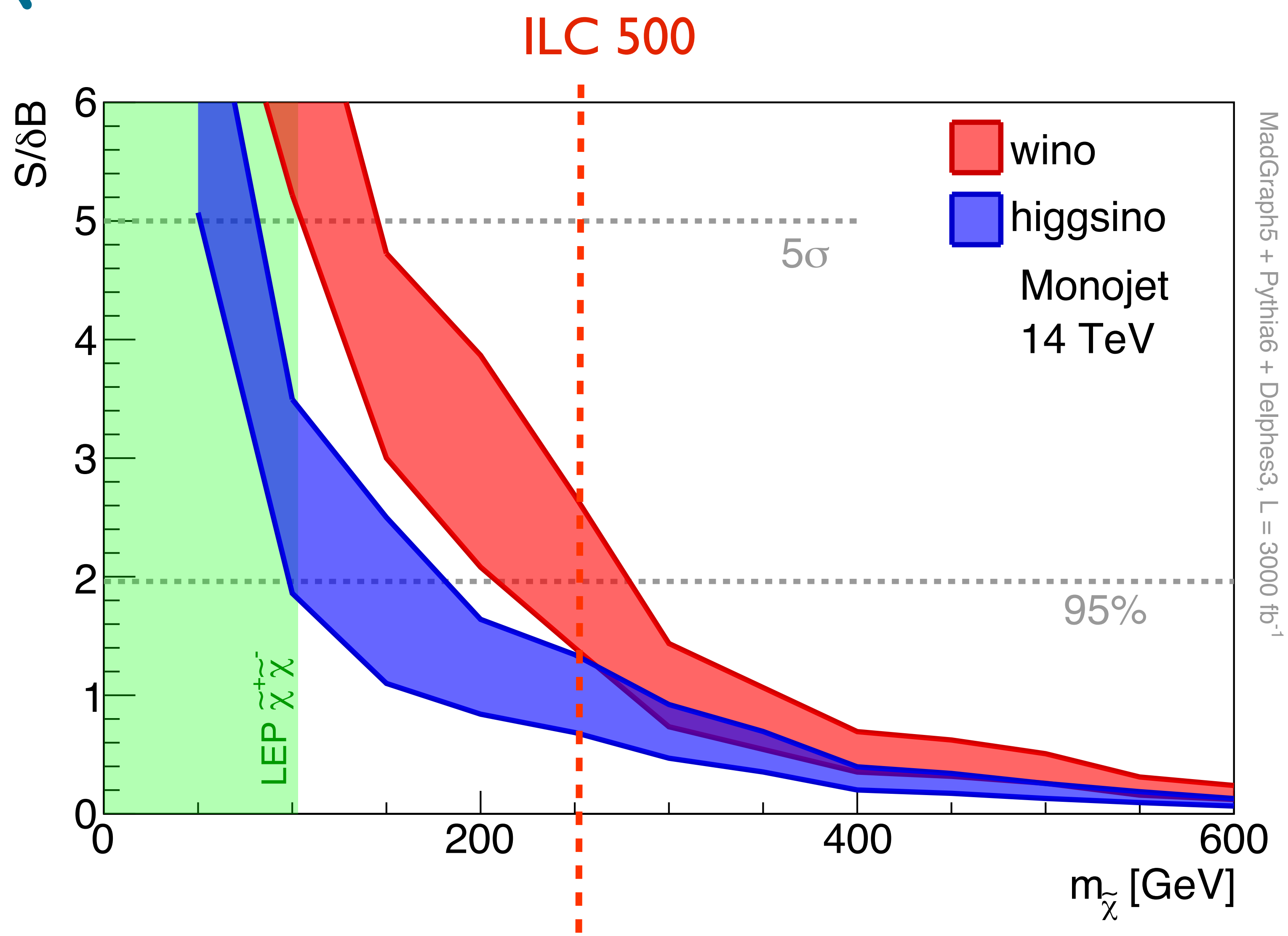
- Have become "Standard" LHC searches.

Mono-X



- Very challenging. Systematics dominated
  - No limit from the 8 TeV run.
  - Very weak discovery reach at 14 TeV, 3 ab^{-1} .
- Reach at lepton collider, about 1/2 E_{CM}.

Mono-X



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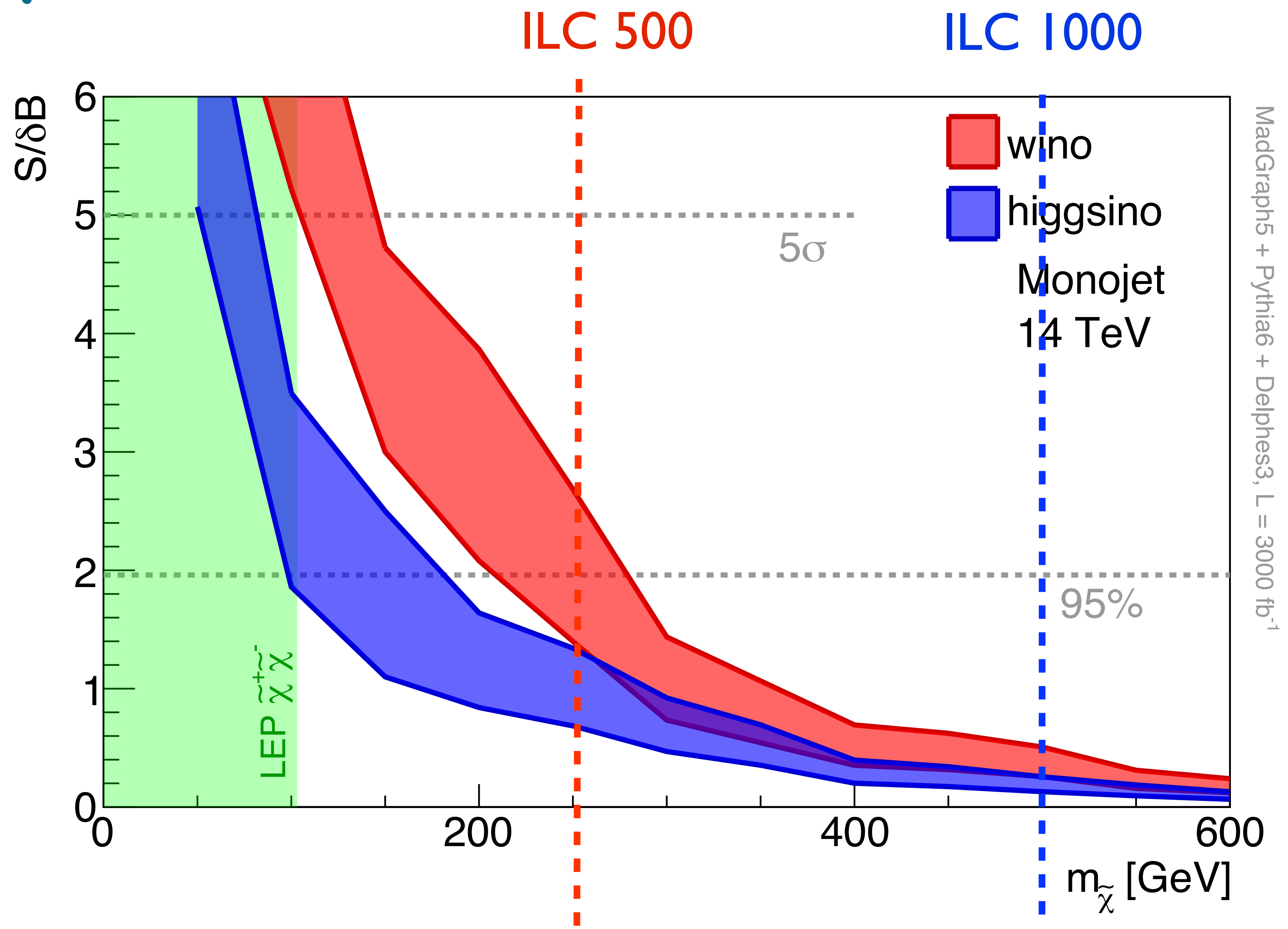

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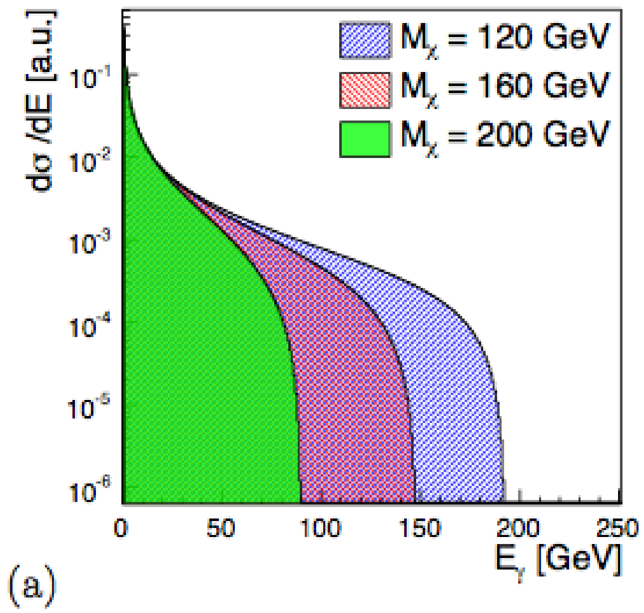
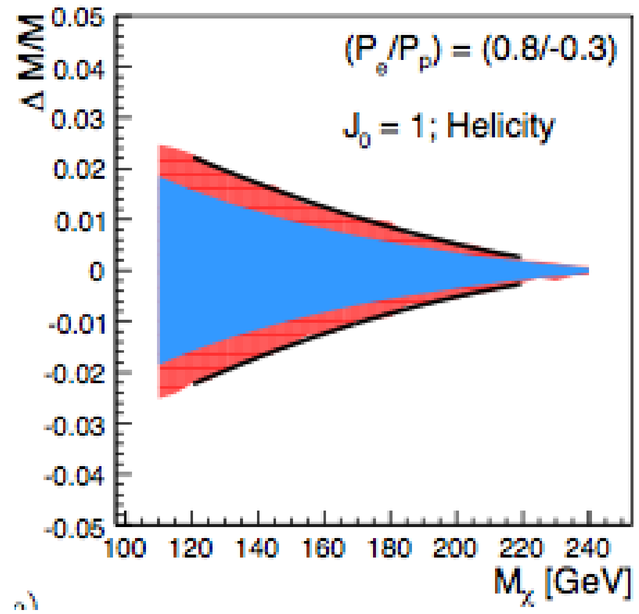
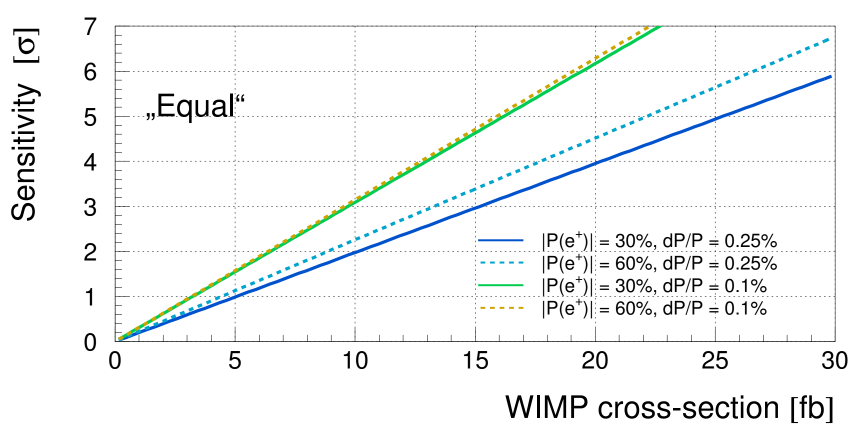
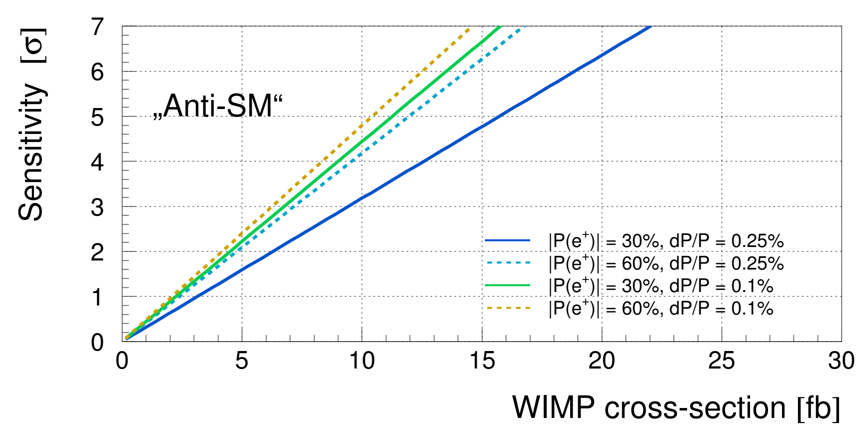
Understanding DM at the ILC





Precise mass measurement

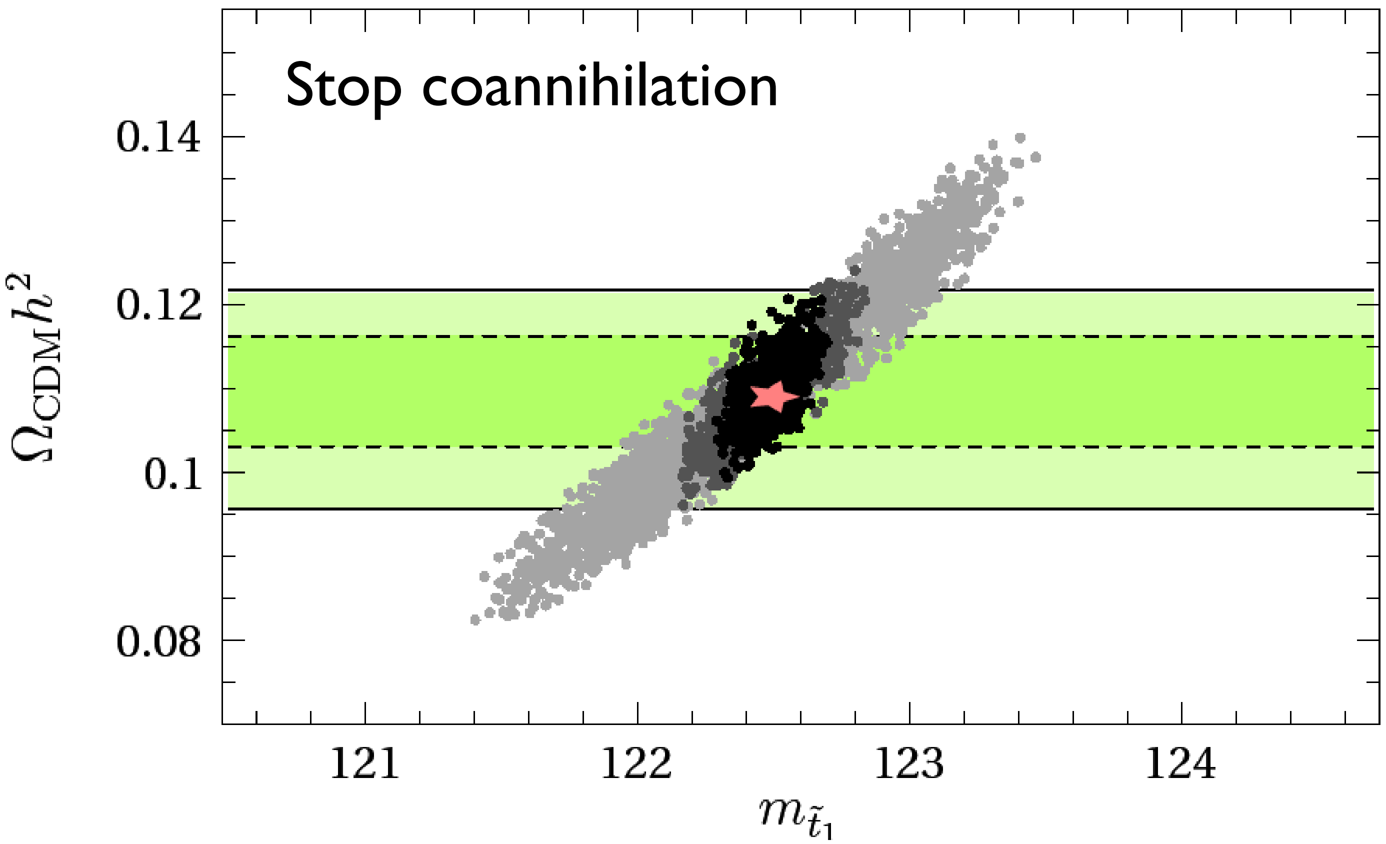




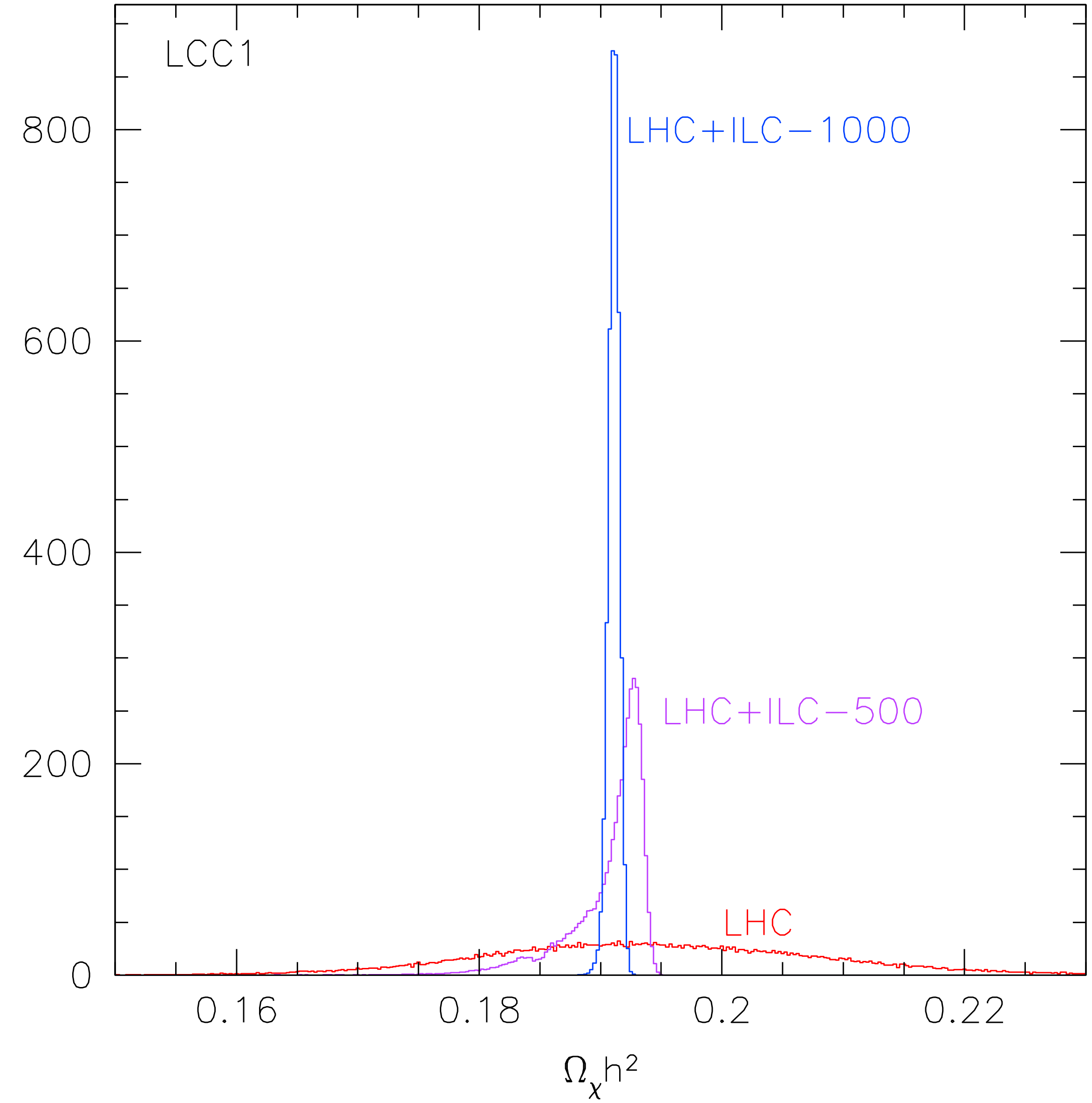
Disentangle the coupling

Bartels, Berggren, and List, 1206.6639

Verifying the WIMP story.



Freitas, Milstene, Schmitt, Sopczak, 0712.4010



Baltz, Battaglia, Peskin, Wizansky, 0206187

Naturalness

Naturalness

- Often emphasized: SUSY stop
- At the same time, masses of particles with only electroweak int. could enter in a more direct way.
- Example: SUSY Higgsino

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

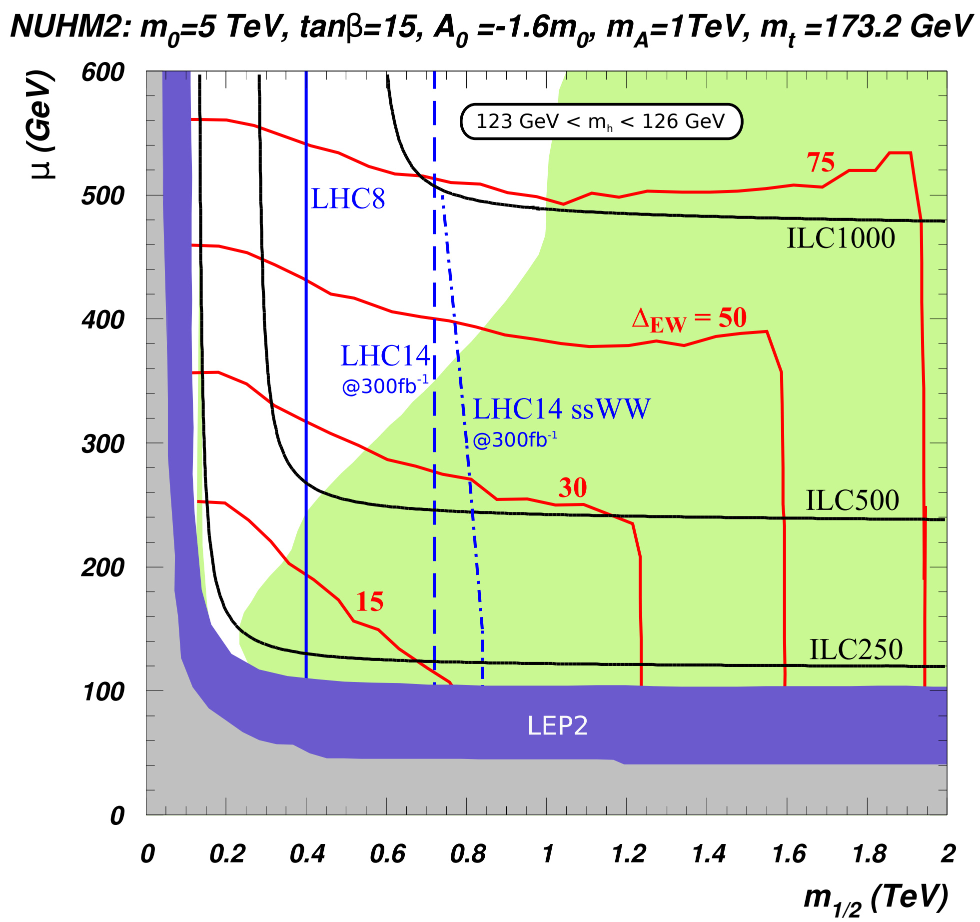
also the Higgsino mass

Fine tuning ∝ M_Z^2/μ^2

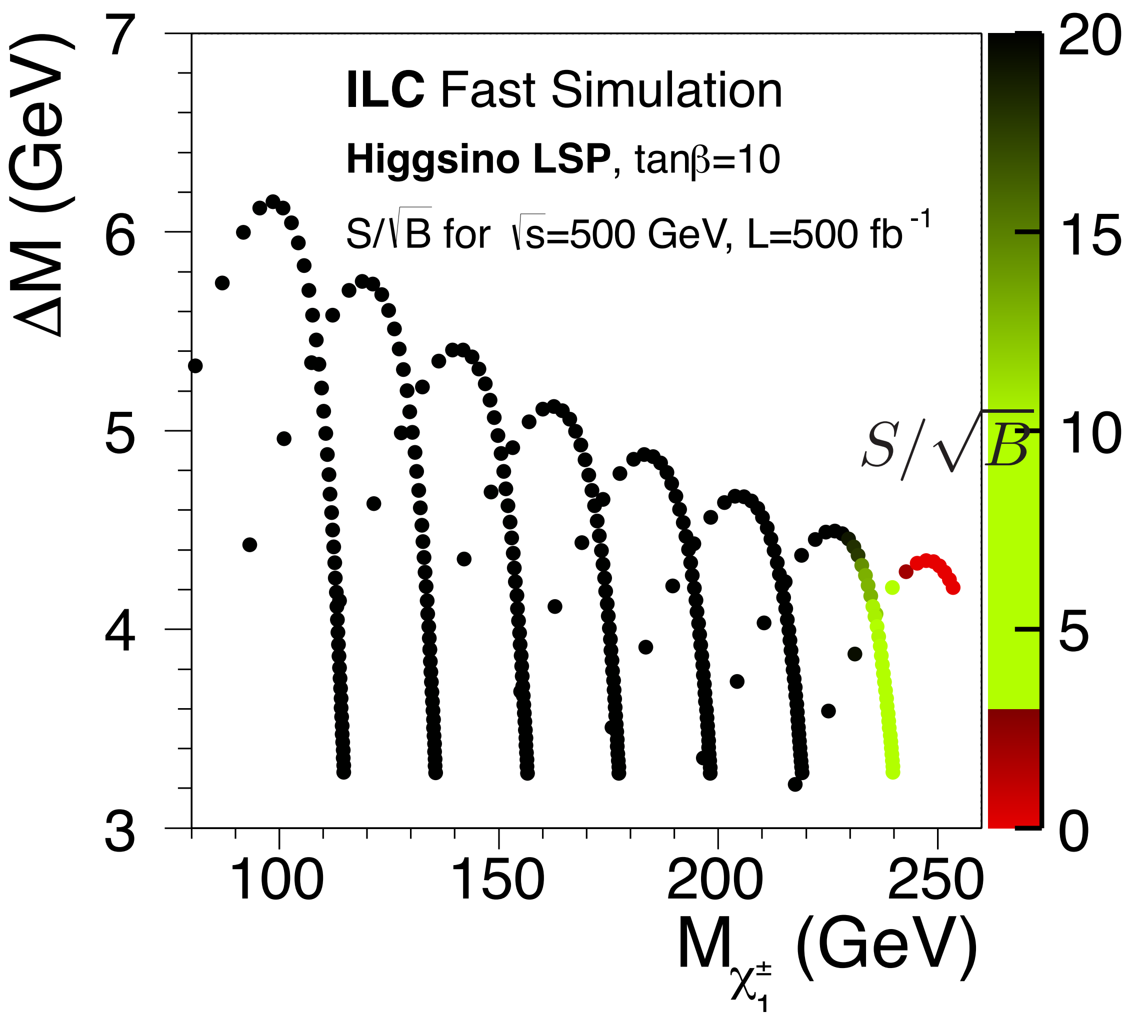
To reduce fine tuning, Higgsino should be as light as possible

Higgsino at lepton colliders

Baer et. al. 1307.5248



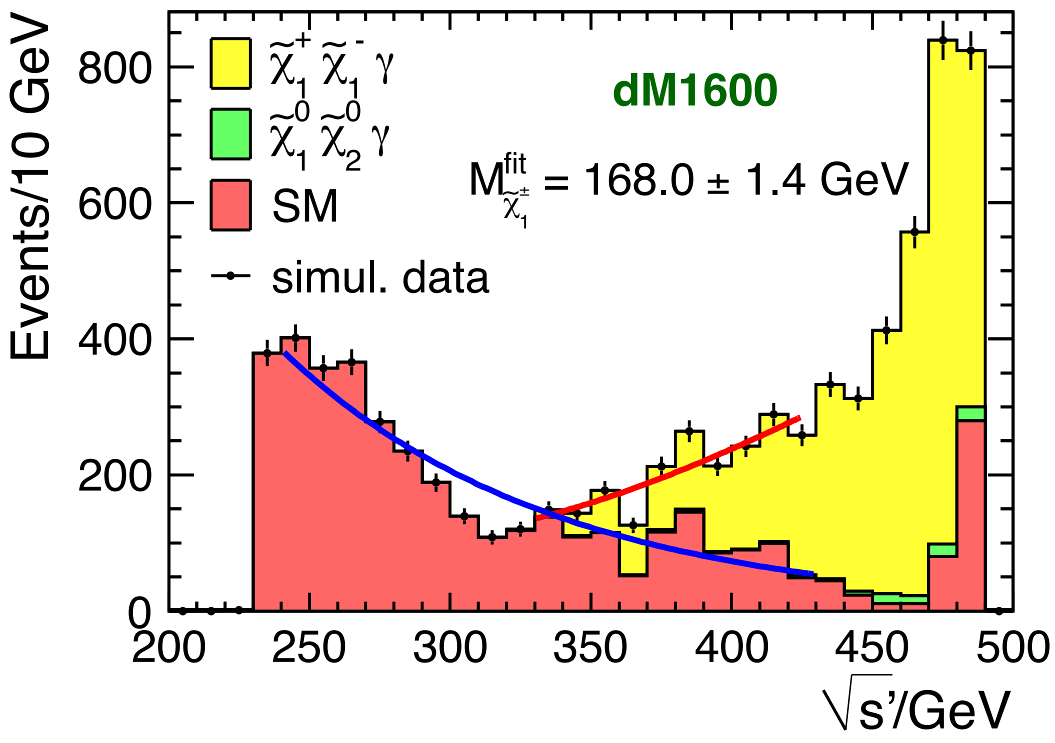
Berggren et. al. 1309.7342

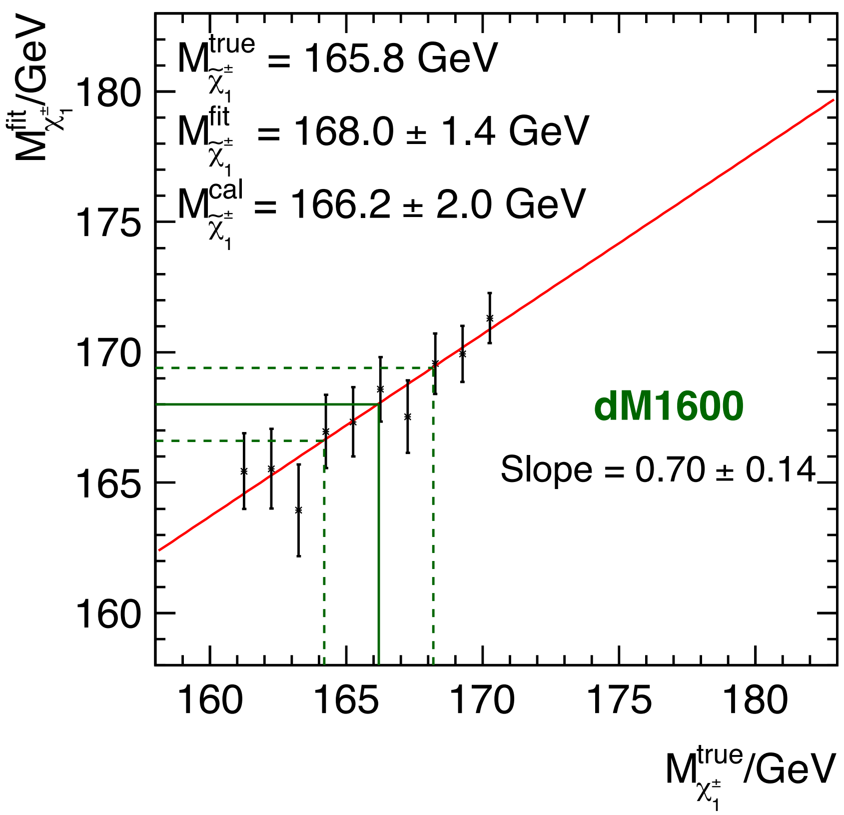


- Solid discovery reach ≈ 0.5 E_{CM}.
- Essential role in naturalness, want to learn as much about it as possible.

Measuring the Higgsino

Berggren Brummer, List, Moortgat-Pick, Robens, Rolbiecki, Sert 1307.3566



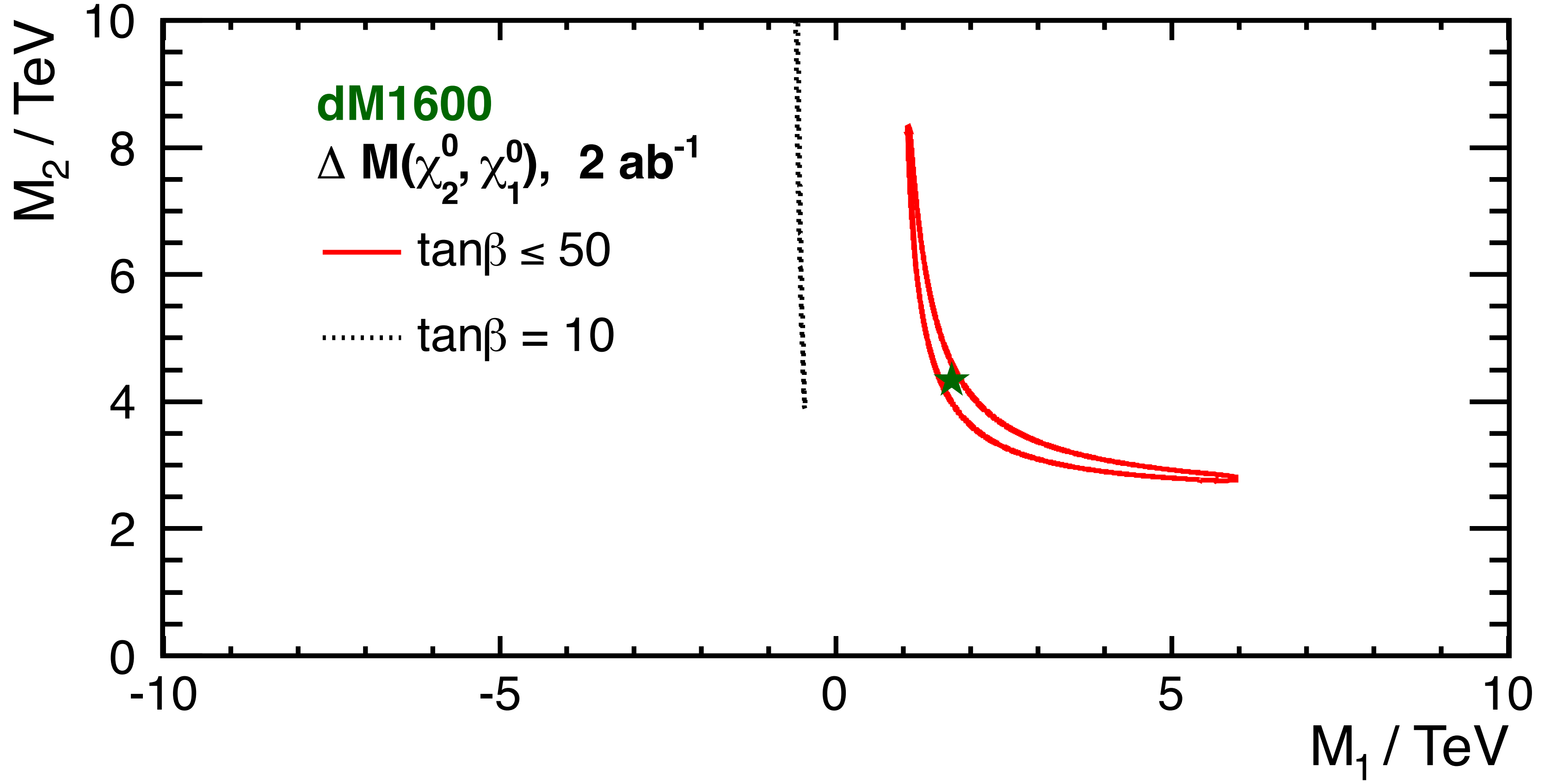


- Precise mass measurements.

- O(10^2) MeV-GeV Chargino-neutralino mass difference measurement!

Extracting more information

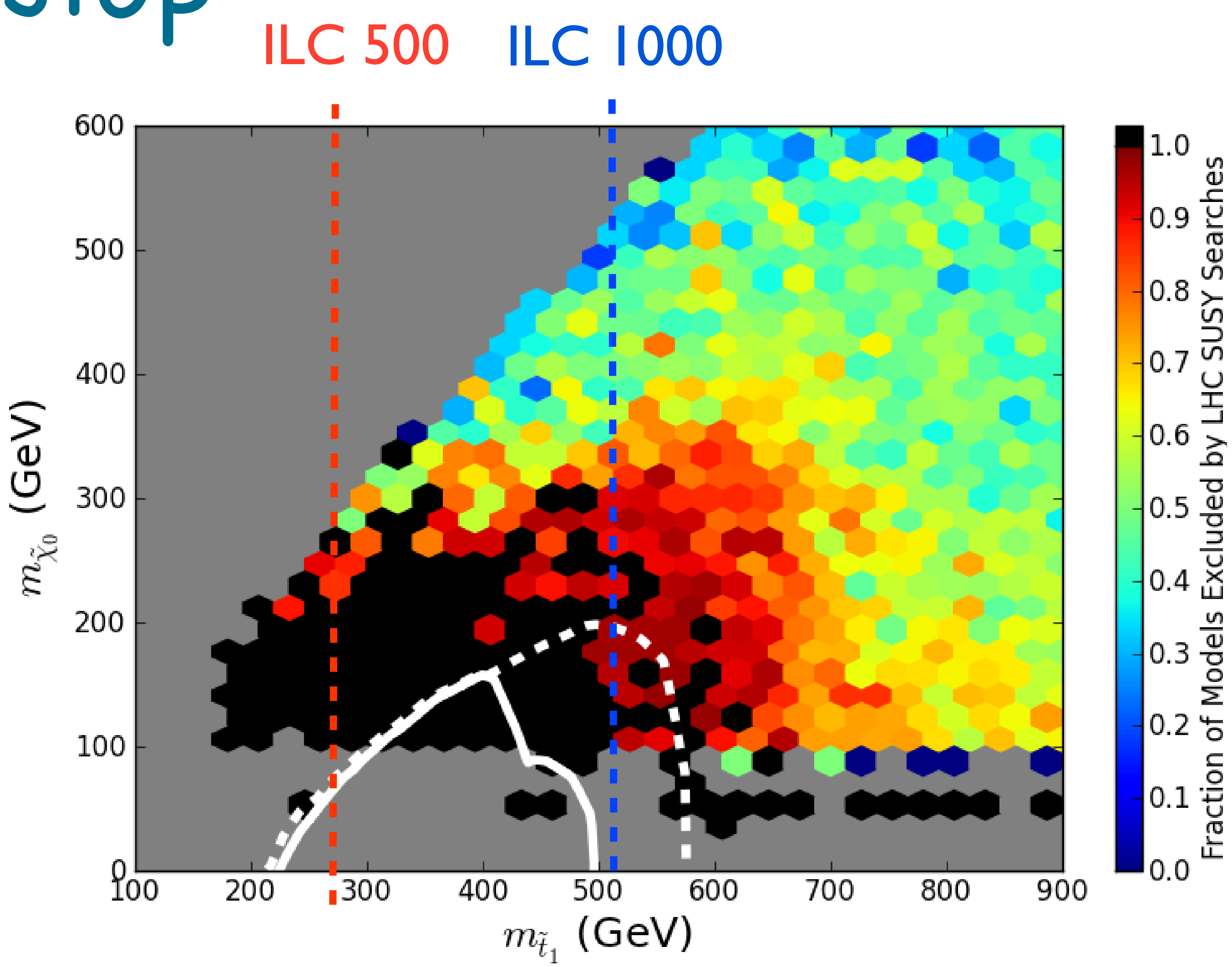
Berggren Brummer, List, Moortgat-Pick, Robens, Rolbiecki, Sert 1307.3566



- Using production rates, mass differences.

- Sensitive to TeV bino/wino mass (outside of the reach of the LHC).

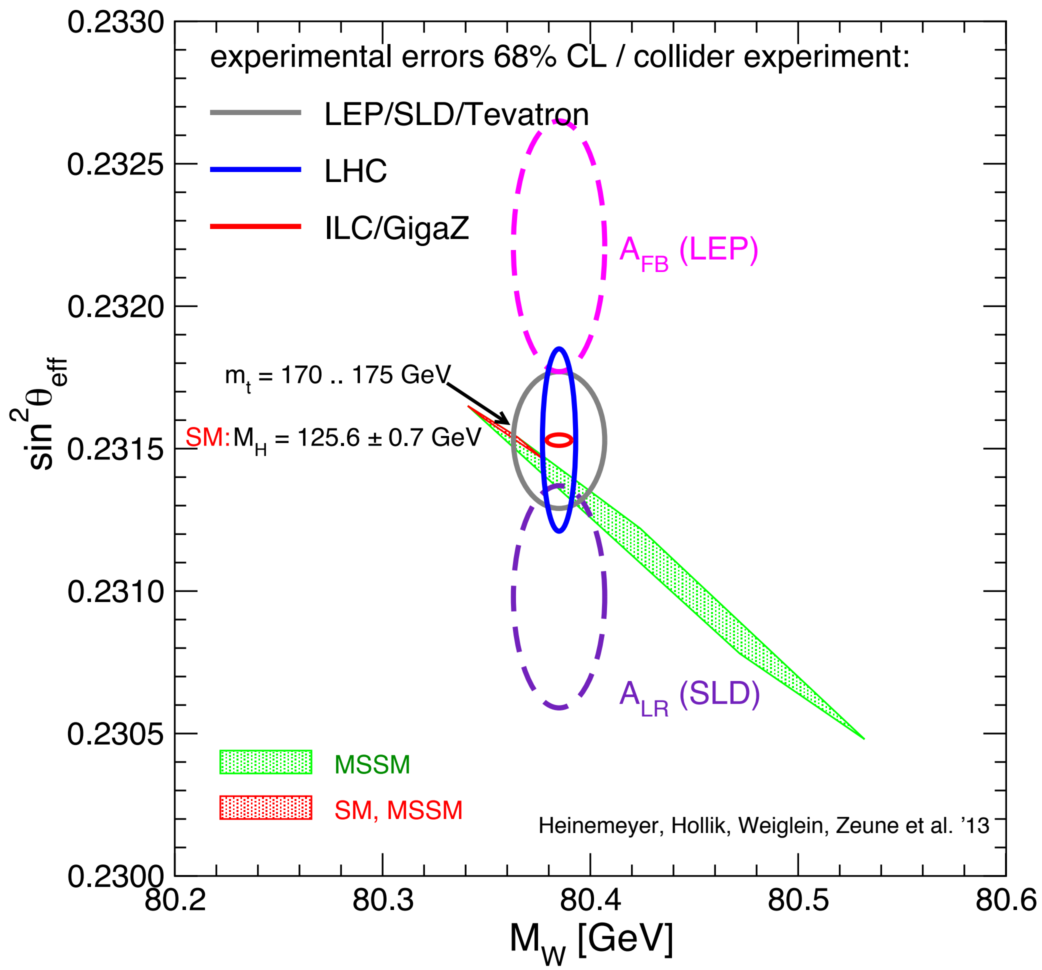
SUSY stop

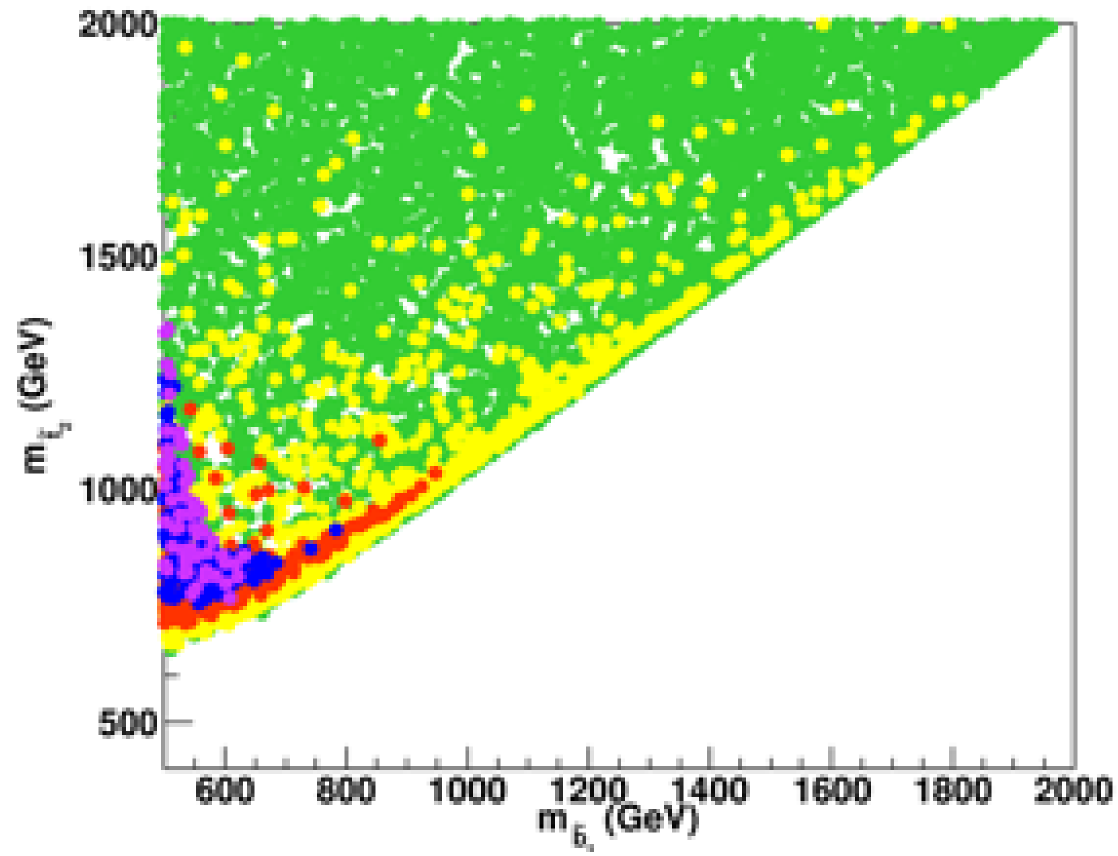


Cahill-Rowley, Hewett, Ismail, Rizzo 2013

- We have invented many ways of hiding the stop.
  - mutli-stage decay, compressed, stealth, RPV ...
- Lepton collider can set a firm limit with no loophole.

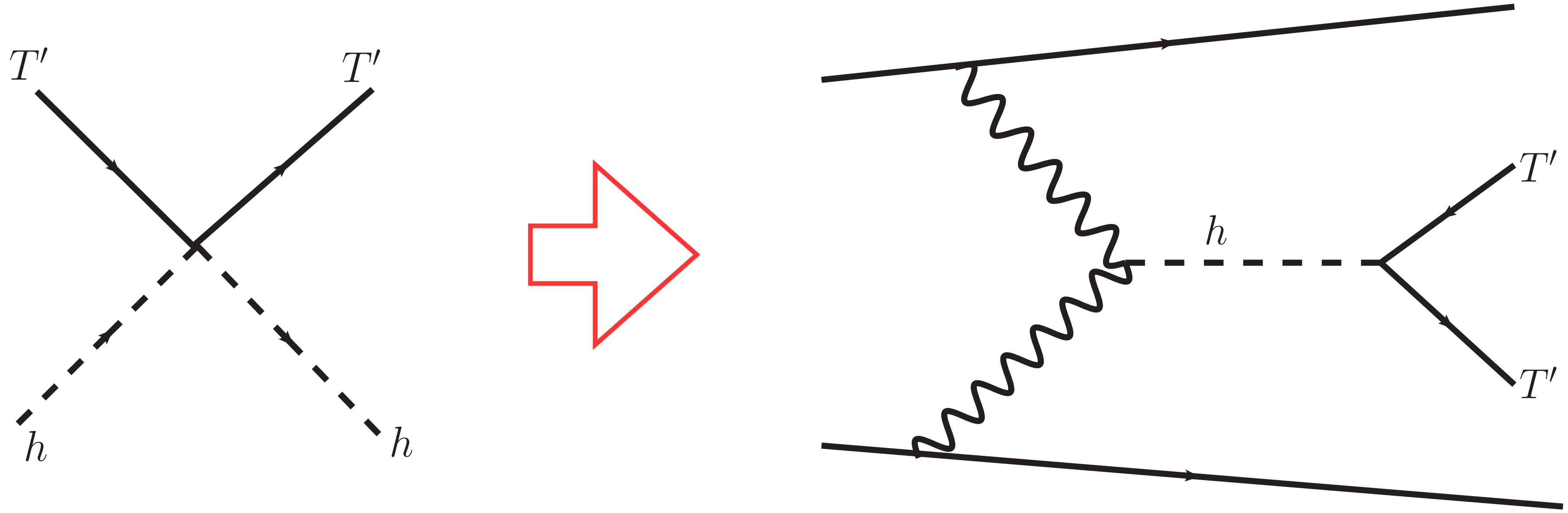
Another approach.





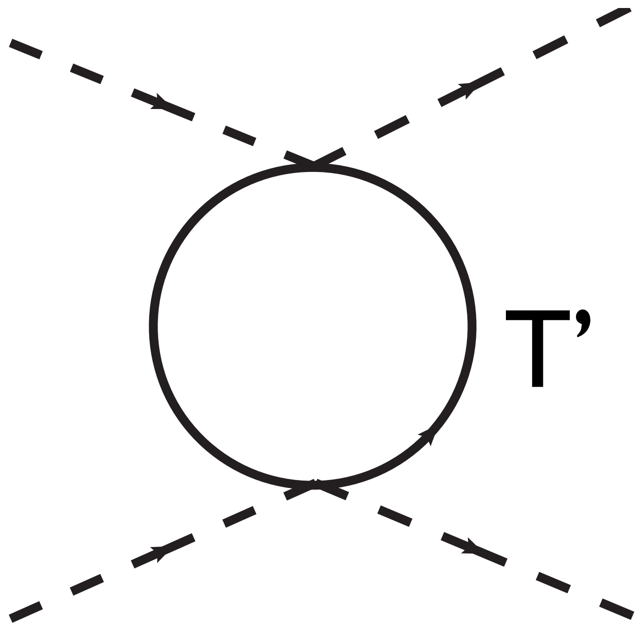
- Independent of how stop can be produced and how they decay.

We can hide T' very well.

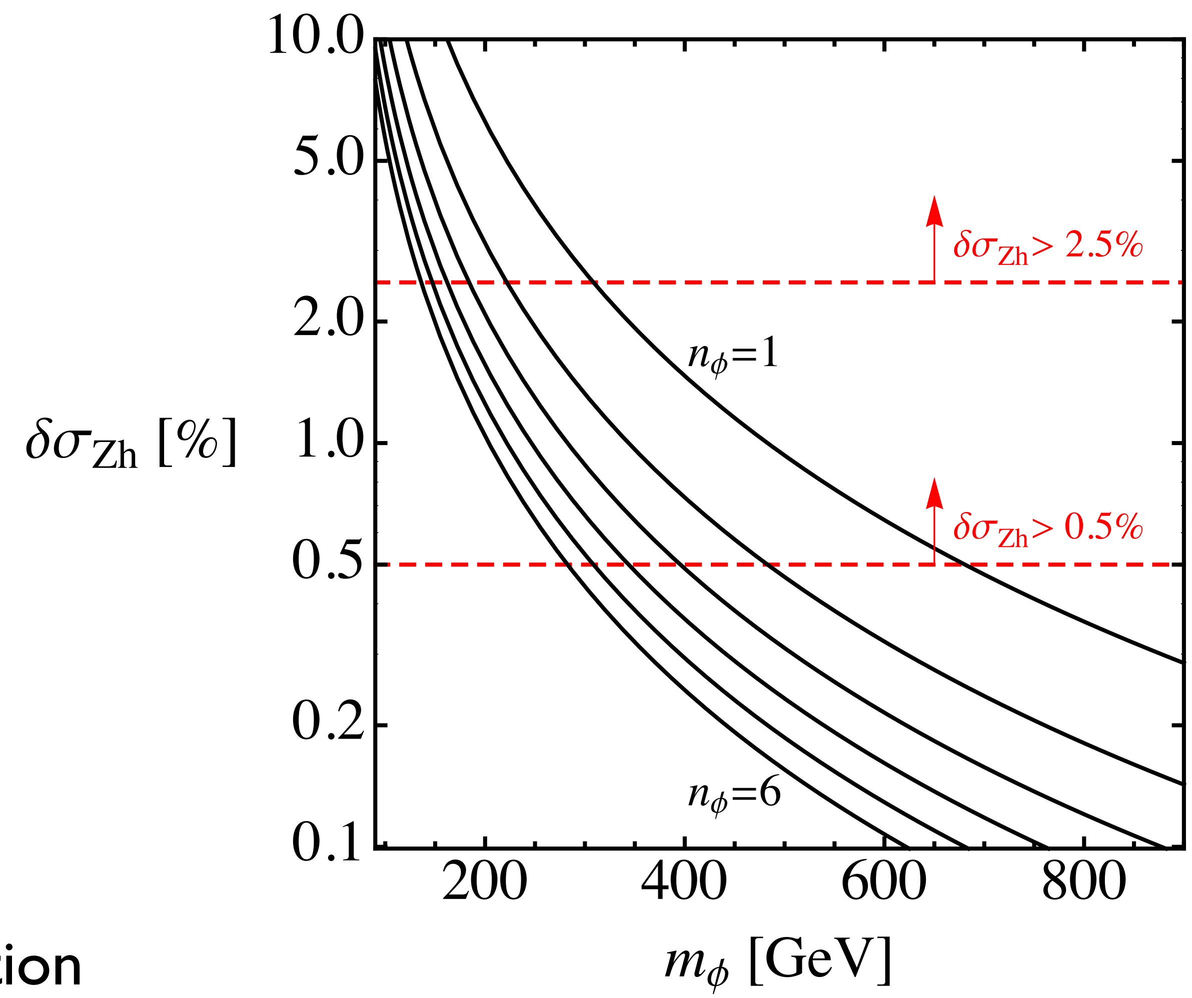


- Top partner not colored.
  - Twin Higgs. Chacko, Harnik, et al
  - General Higgs portal.
- Study to be done!
  - Reach probably very limited, 100s GeV (my guess)

Anything else we can do?



Wavefunction renormalization
Induce shift in Higgs coupling.



Craig, Englert, McCullough, 2013

- Precision Higgs measurement is the best way to go.

Zprime

Motivations

- Z′ is "everywhere", part of a bigger picture
    - String compactifications, extra-dim, composite...
- If it is there, it is among the most "obvious" signals of a NP scenario.
    - Sometimes the best/only hope!
- Lepton colliders provide a qualitative different way of discovering and studying the Zprime.

Zprime benchmarks and observables

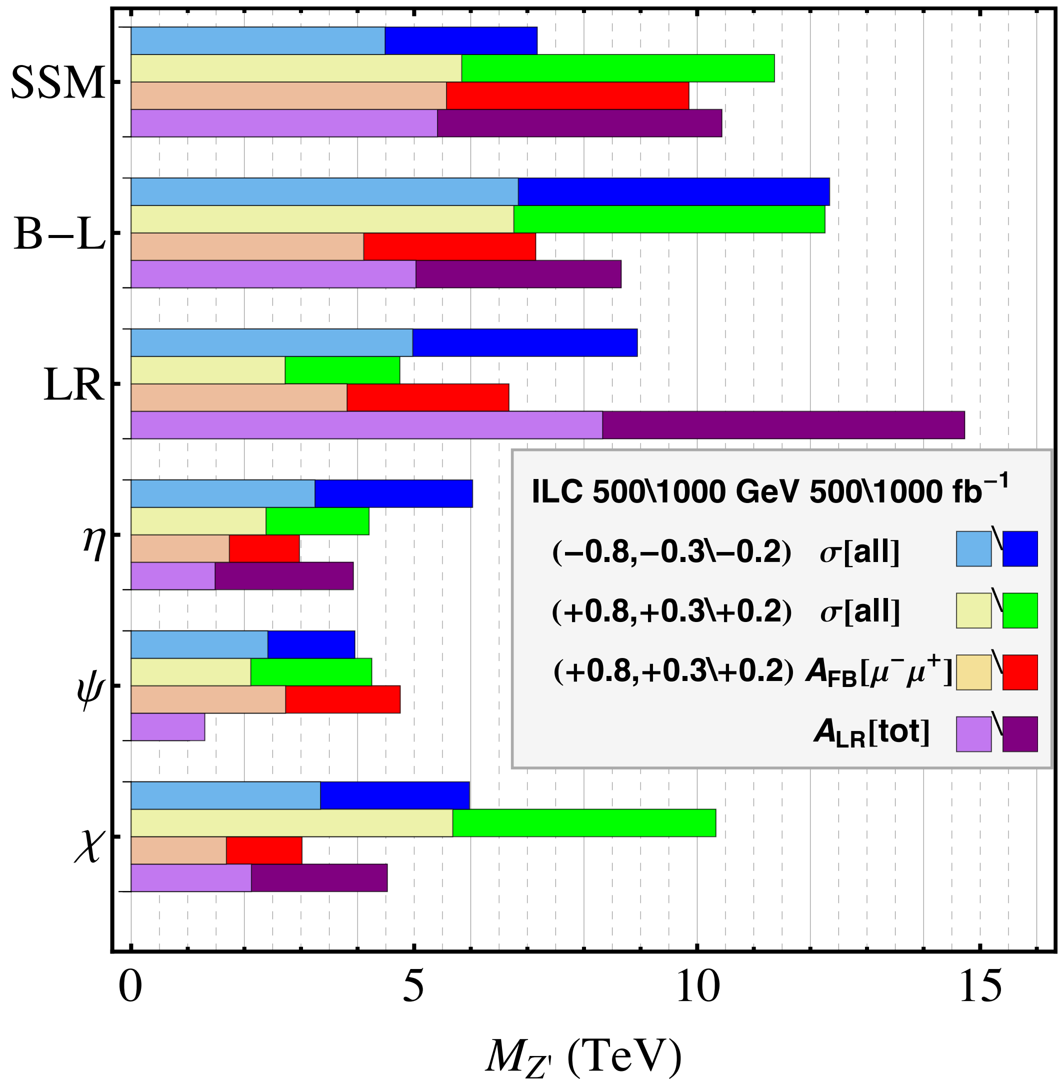
	χ	ψ	η	LR	BL	SSM	
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1	
$\hat{\epsilon}^q_L$	-1	1	-2	-0.109	1/6	$\hat{\epsilon}^u_L$	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$
						$\hat{\epsilon}^d_L$	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}^u_R$	1	-1	2	0.656		$\hat{\epsilon}^u_R$	$-\frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}^d_R$	-3	-1	-1	-0.874		$\hat{\epsilon}^d_R$	$\frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}^l_L$	3	1	1	0.327	$-1/2$	$\hat{\epsilon}^\nu_L$	$\frac{1}{2}$
						$\hat{\epsilon}^e_L$	$-\frac{1}{2} + \sin^2\theta_W$
$\hat{\epsilon}^e_R$	1	-1	2	-0.438		$\hat{\epsilon}^e_R$	$\sin^2\theta_W$

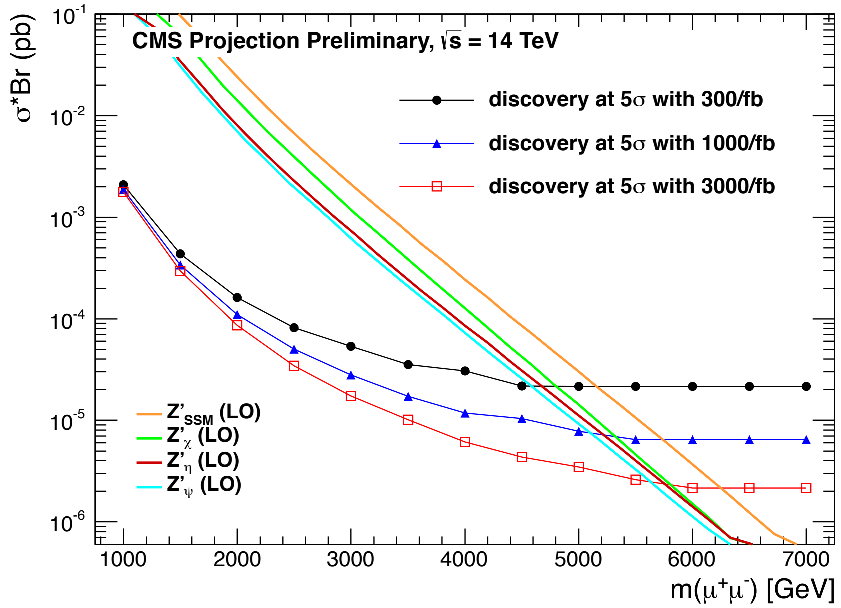
Table 1-2. *Benchmark models and couplings, with* $\epsilon^i_{L,R} \equiv \hat{\epsilon}^i_{L,R}/D$.

- Not the only possible models.
  - Chosen for variety in coupling.
- Observables: $d\sigma$, A_{FB}, A_{LR} ...

Discovery reach

Langacker, Han, Liu, LTW, 1308.2738

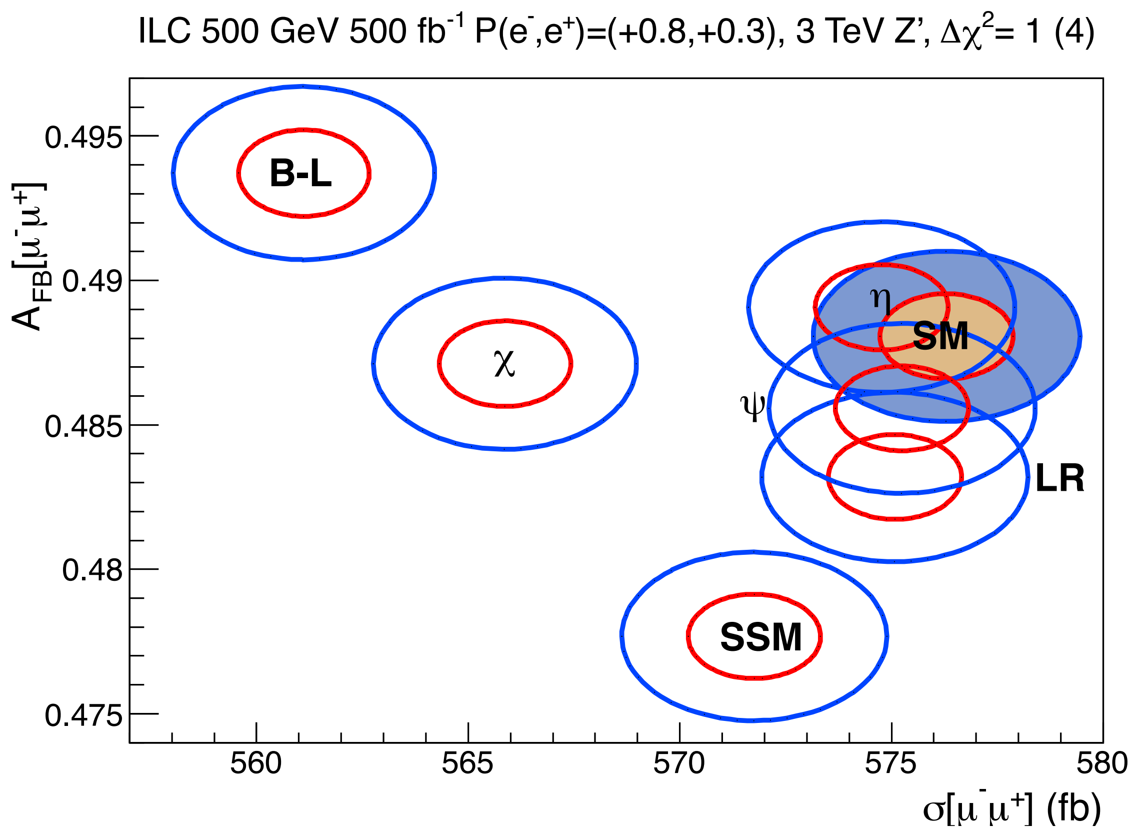


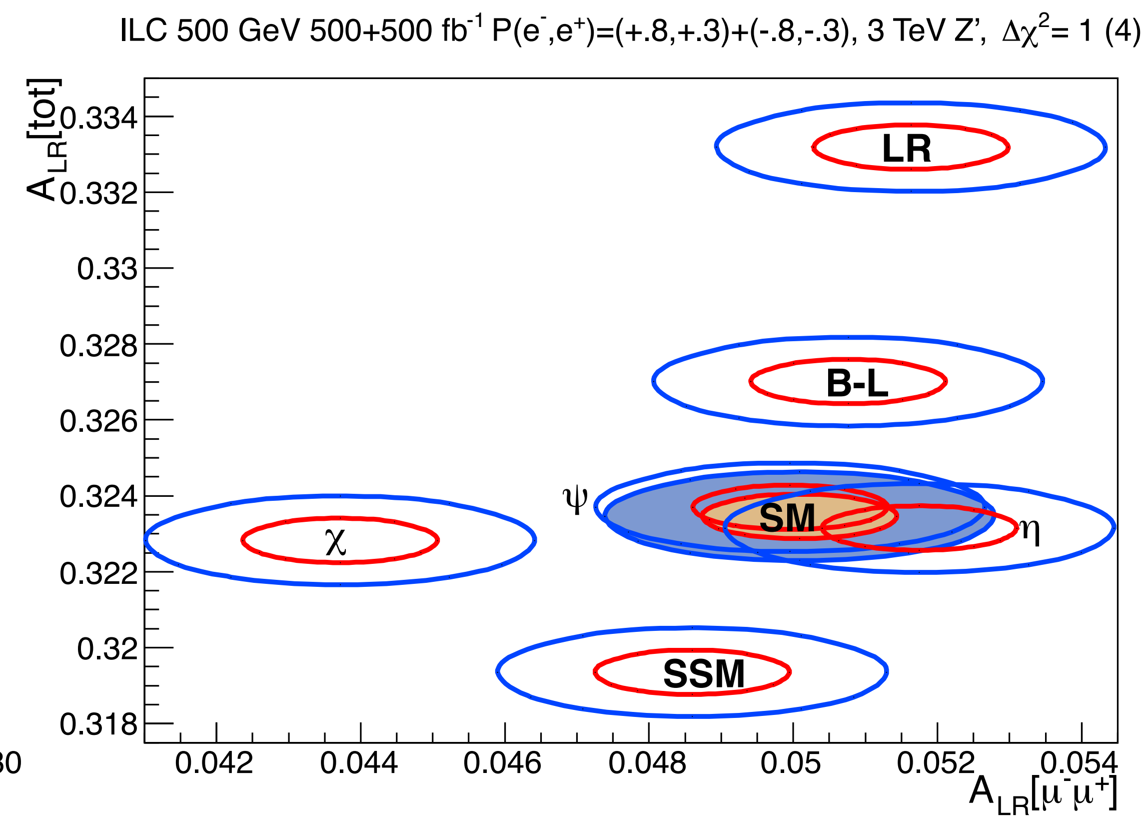


- In general, stronger than the LHC!

- Various observables complementary.

Understanding the Z′

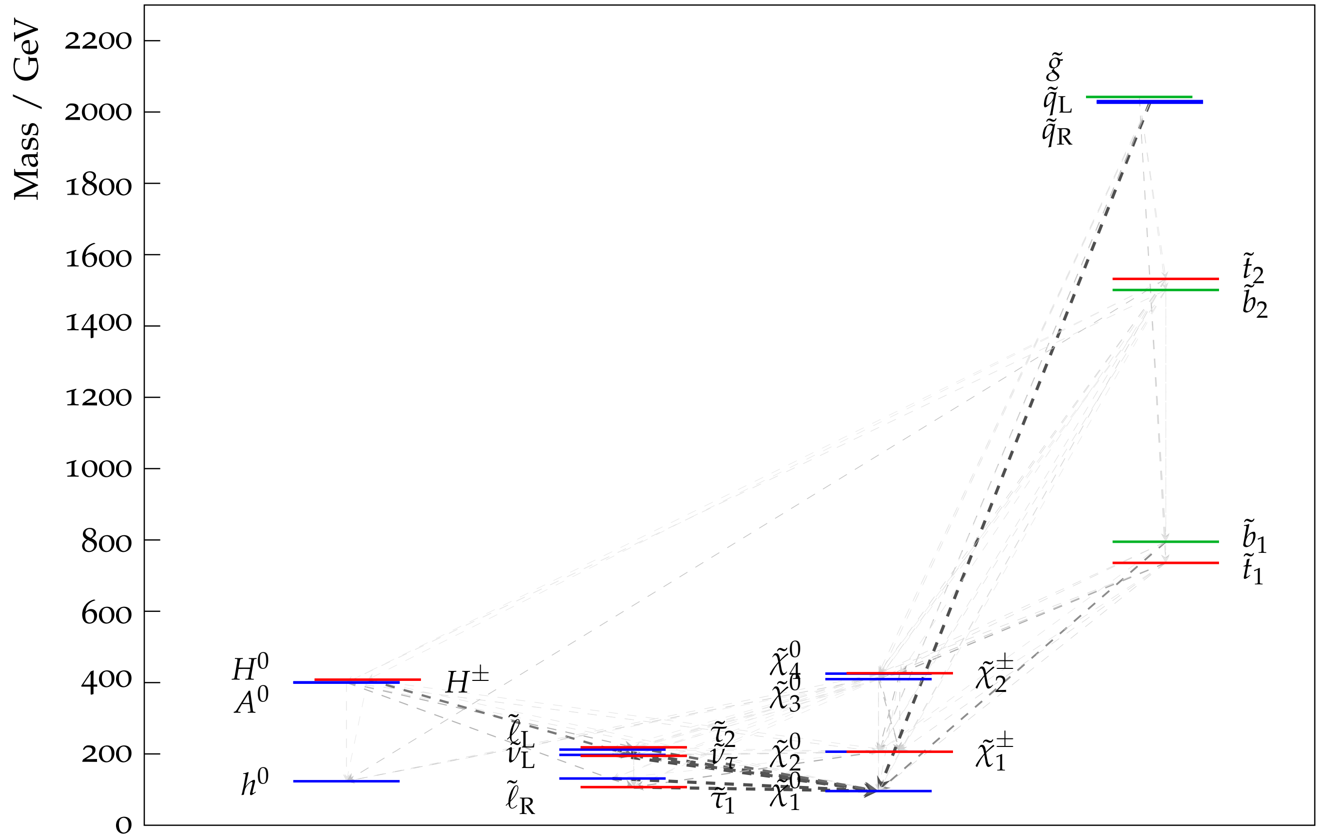




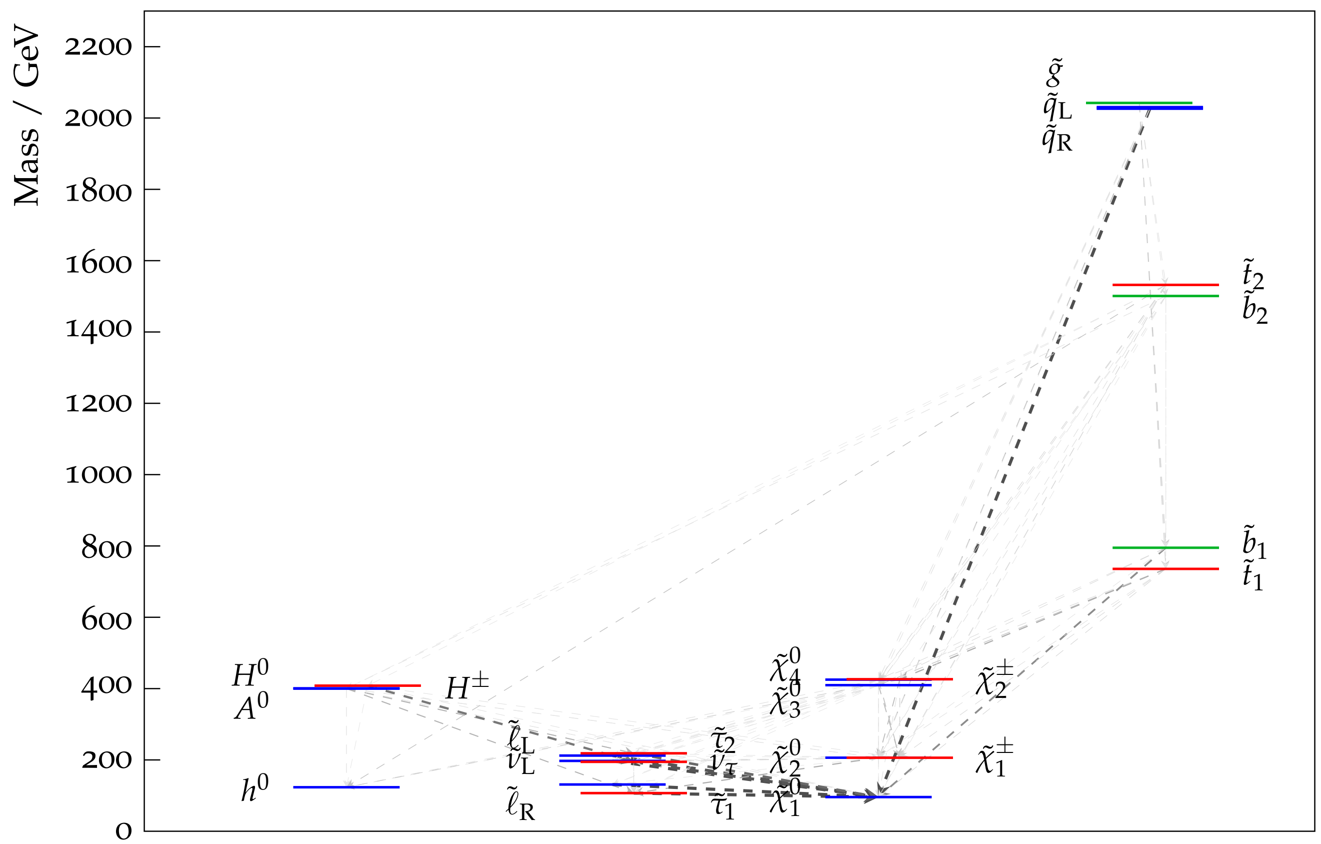
Some stories

(to illustrate the role a lepton collider will play)

stau coannihilation

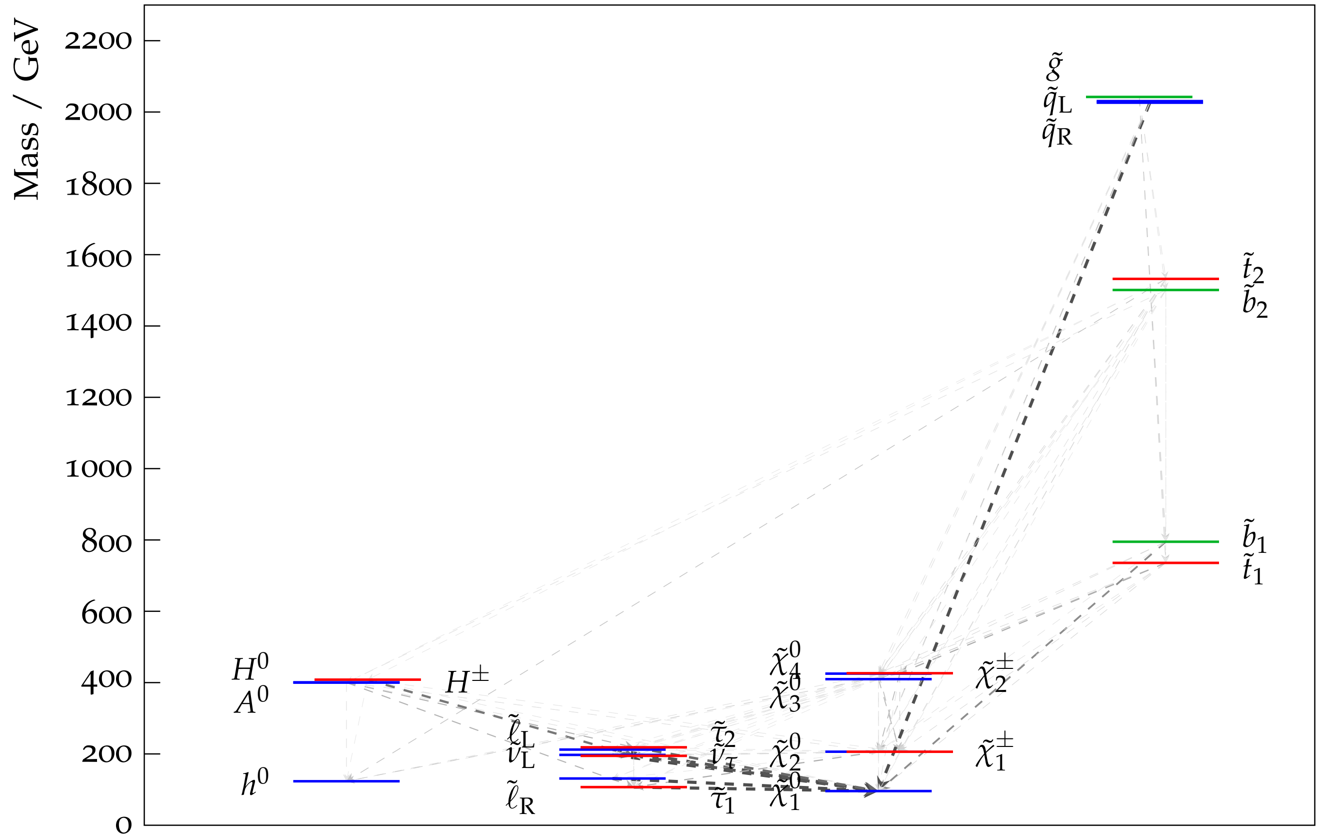


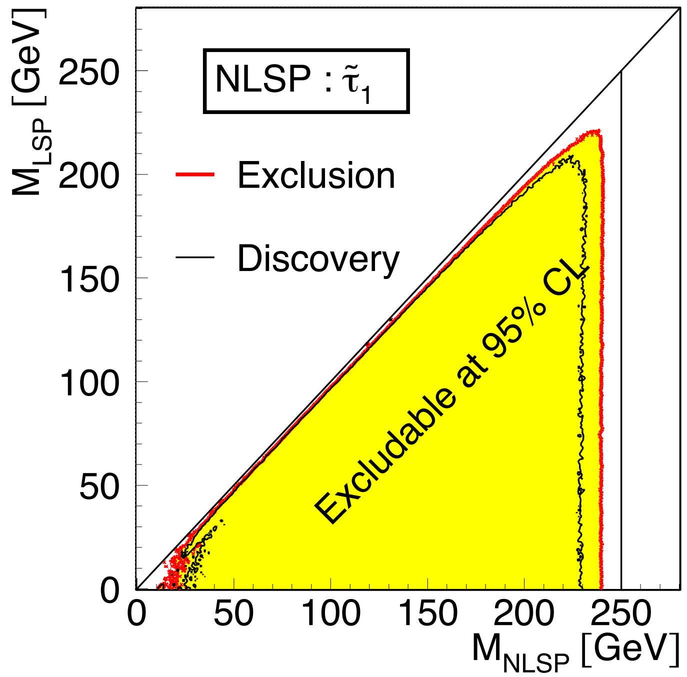
stau coannihilation



- LHC 14 will discover part of the spectrum.

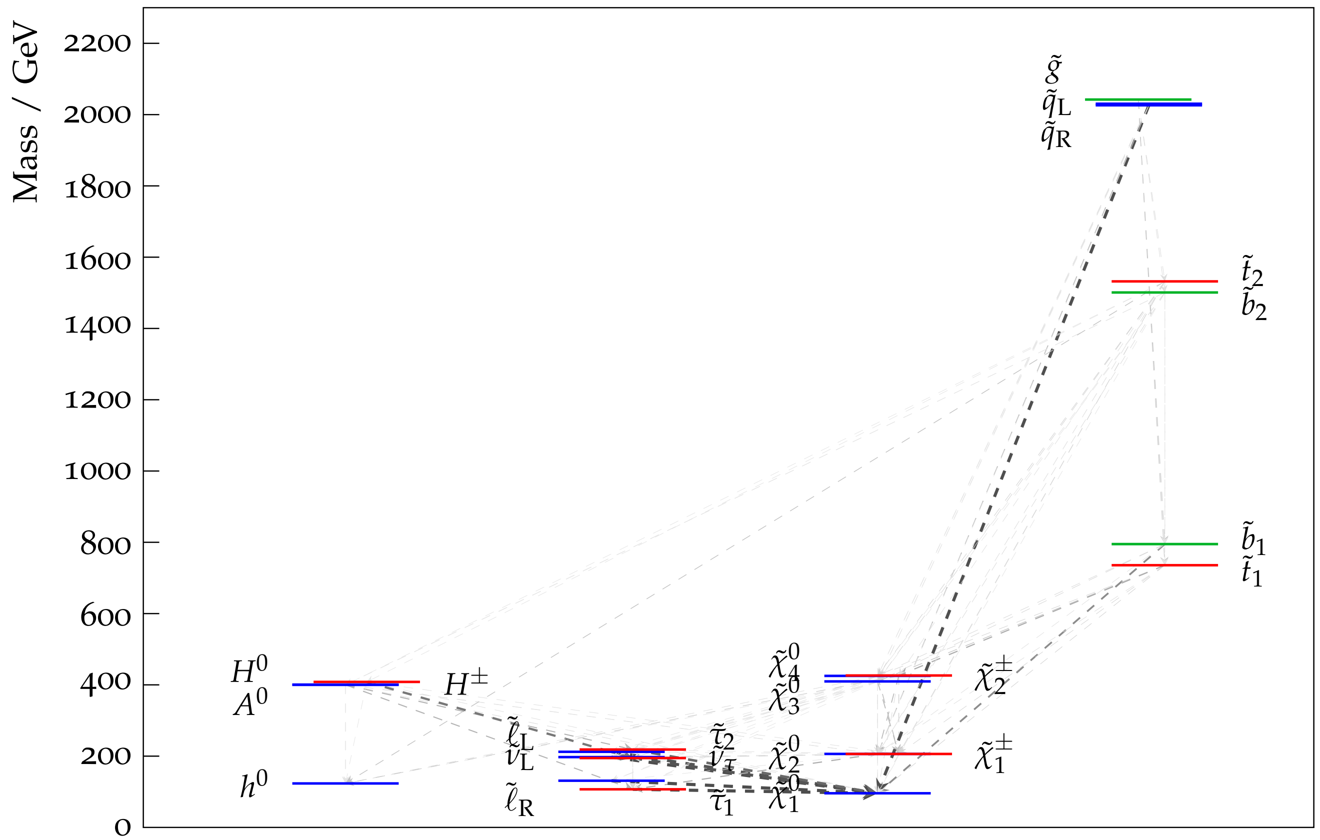
stau coannihilation





- LHC 14 will discover part of the spectrum.
- ILC will discovery light slepton and gaugino.
  - In particular, the stau. Very challenging at the LHC.
  - Stau mass measured to 1% level.
  - Allow precise calculation of relic abundance.

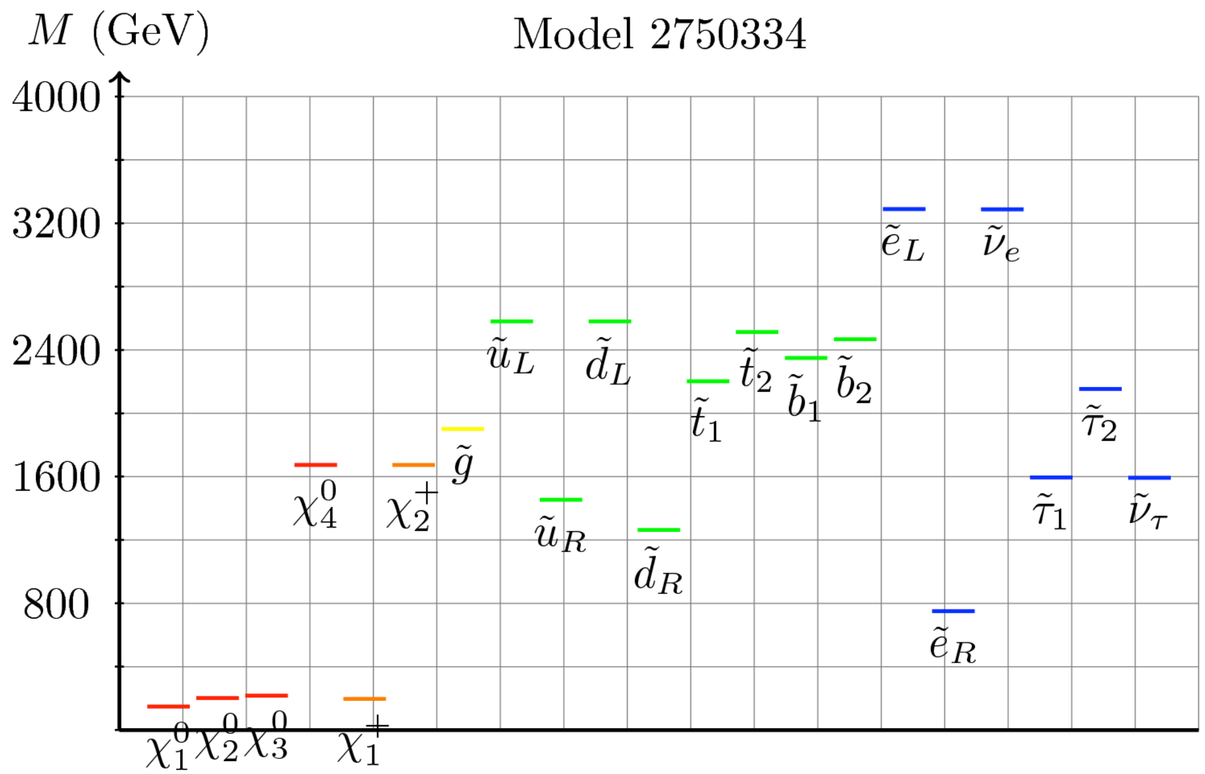
stau coannihilation



- Precision measurement of gaugino properties sensitive to 1-loop effect. Gives info on stop/sbottom masses.
  - Inform LHC analysis, plan next step.

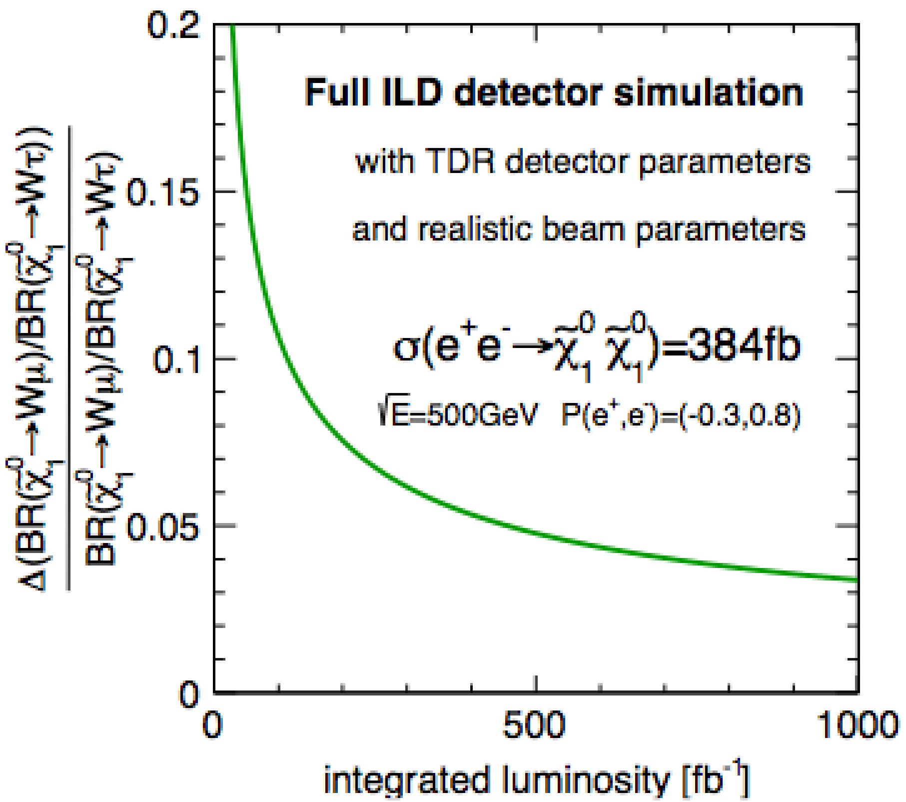
- Upgraded ILC and CLIC can explore much more about this spectrum.

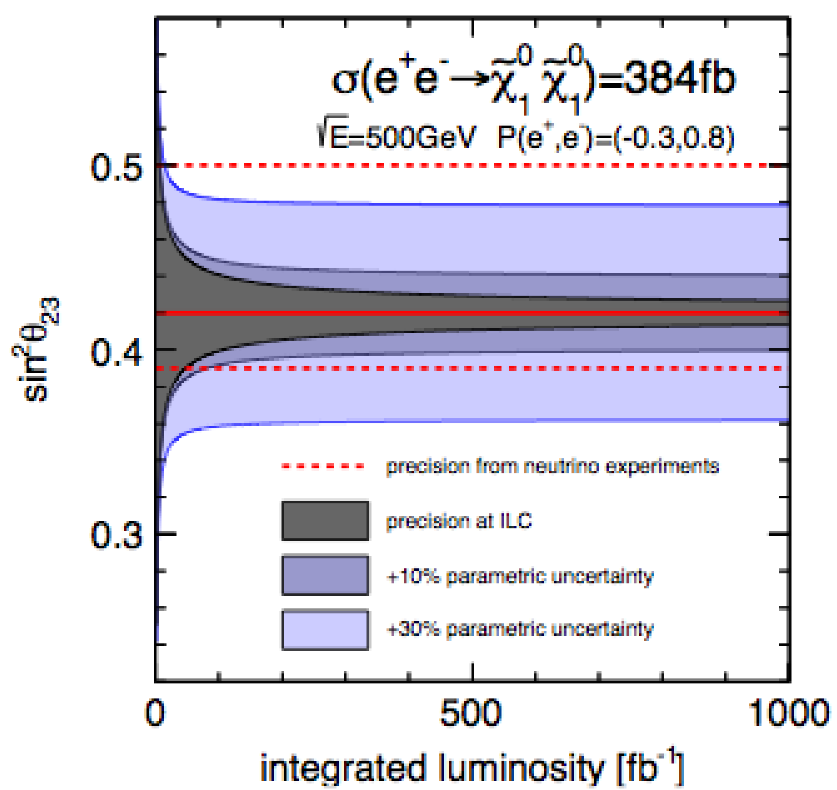
Another benchmark, similar story



- LHC will discover part of the spectrum.
- ILC, Electroweak-ino production, mass and spin measurements.
- Infer the mass of e_R through ino production
  - Discovery at upgraded ILC or CLIC.

Prepare to be surprised





- Precision branching ratio measurements at lepton colliders.

- bilinear RPV. Could reveal surprising connection with the neutrino mass.

LHC 14 sees something

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- Almost impossible to be the full spectrum.
  - Every comprehensive NP scenario span at least a factor of several in mass. Nothing at 8 TeV. Can not fit into the moderate increase in LHC reach from 8 to 14.
- Impossible to understand the new physics very well.
  - In particular, dark matter candidate? Electroweak coupled particles? ...
  - Need lepton collider to pin down their properties.

LHC 14 sees nothing, 2 possibilities.

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- Little Hierarchy.
  - Flavor, CP, precision measurements seem to point to a higher scale (about 10 TeV).
  - This is the reason we have seen nothing?
  - Clearly out of reach at LHC 14 $\Rightarrow$ Higher energy

LHC 14 sees nothing, 2 possibilities.

- Little Hierarchy.
  - Flavor, CP, precision measurements seem to point to a higher scale (about 10 TeV).
  - This is the reason we have seen nothing?
  - Clearly out of reach at LHC 14 $\Rightarrow$ Higher energy
- Loopholes at the LHC.
  - Electroweak-ino, compressed spectrum, stealth...
  - More detailed measurement of deviations in SM couplings.
  - Lepton colliders, ILC, CLIC...

Conclusions

Can lepton collider break new ground, and allow us to learn more about nature?

The answer is certainly yes.

Lepton colliders (ILC, CLIC...) have unique capabilities in searching and measuring new physics states.

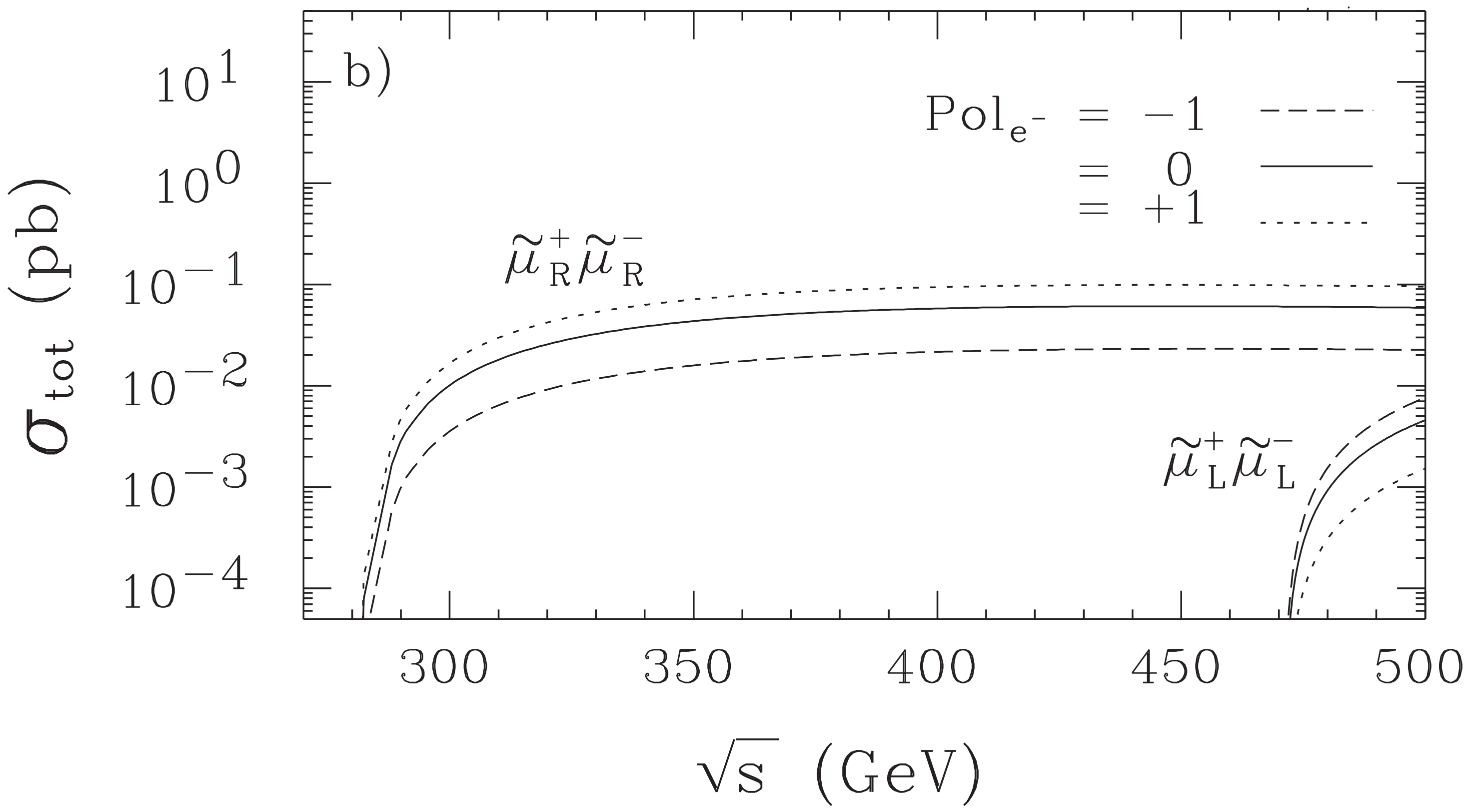
- -Solid coverage, essentially loophole free.
- -Unique capability in measuring the properties of new particles. Testing ideas!

Our bright future: lepton collider will become an essential part of the international high energy physics program!

Go for the most exciting adventure!

extra

Polarized electron beam



- Pin down the quantum number

- The ILC new physics program has been studied in great detail, and has excellent capabilities to discover and measure the properties of new physics, including dark matter, with almost no loopholes. A necessary requirement is that the new physics must be accessible. Essentially this means particles at sufficiently low mass missed by LHC due to blind spots, or heavy physics indirectly accessible through precision measurement. Discovery of physics beyond the standard model at LHC that is accessible at ILC would make the case even more compelling.

Investigate the WIMP dark matter: cover all the ground

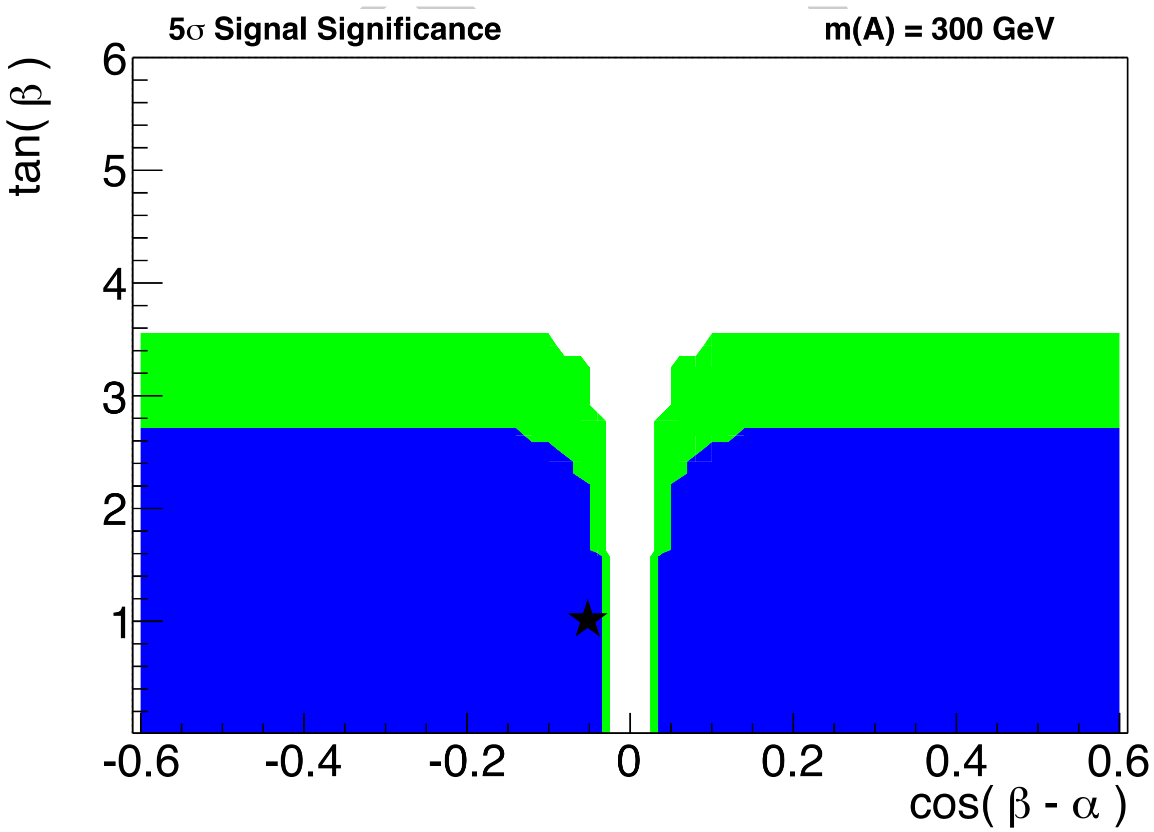
- Dark matter is the only **known** new physics beyond the Standard Model.

LHC	VLHC 100 TeV	ILC/CLIC
$M_{DM} \sim 10^2$s GeV	$M_{DM} \sim$TeV(s)	$M_{DM} \sim 0.5\ E_{cm}$ Spin, coupling Is it WIMP?

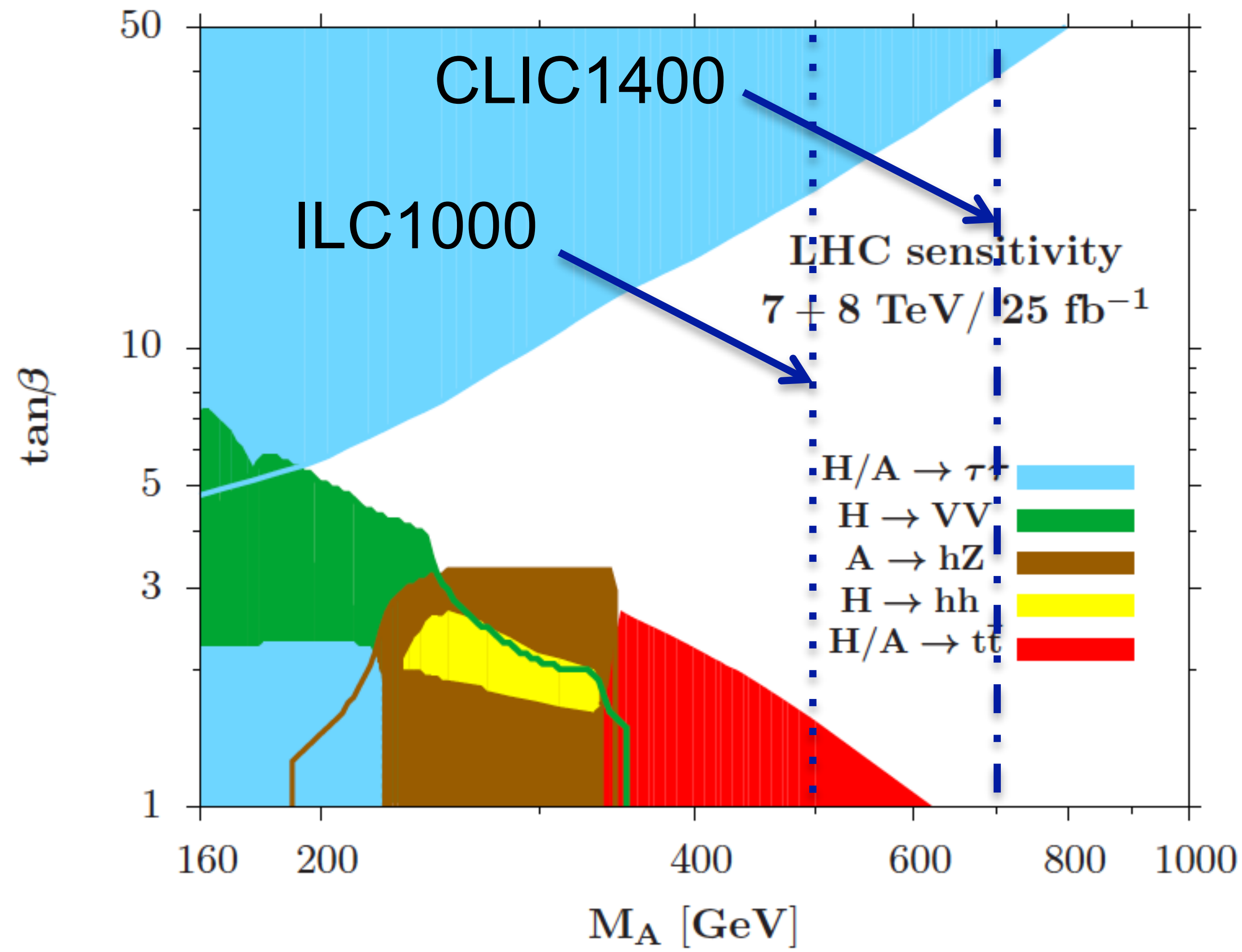
- Link to a possible dark sector.
- Strategy at EF strongly correlated with potential discovery at in direct/indirect detection.

Search for extended Higgs sector

300 GeV A, A→ Zh



LHC 14 300 fb^{-1} LHC 14 3000 fb^{-1}



– Higher luminosity, cleaner environment helps.

Lepton Colliders:

e+e- at 250 GeV (ILC: 500/fb , LEP3: 500/fb, TLEP: 2500/fb),
e-/e+ polarization: ILC: 80%/30%, LEP3, TLEP: 0/0

e+e- at 350 GeV (ILC: 350/fb, CLIC: 350/fb, TLEP: 350/fb) ,
e-/e+ polarization: ILC: 80%/30%, CLIC: 80%/0, TLEP: 0/0

e+e- at 500 GeV (ILC: 500/fb), e-/e+ polarization: ILC: 80%/30%

e+e- at 1000 GeV (ILC: 1000/fb) , e-/e+ polarization: ILC: 80%/20%

e+e- at 1400 GeV (CLIC: 1400/fb) , e-/e+ polarization: CLIC: 80%/0%

e+e- at 3000 GeV (CLIC: 3000/fb) , e-/e+ polarization: CLIC: 80%/ 0%

mu+mu- at 125 GeV 2/fb , 0 polarization

mu+mu- at 1500 GeV 1000/fb , 0 polarization

mu+mu- at 3000 GeV 3000/fb , 0 polarization