PHYSICS AT THE FUTURE COLLIDERS

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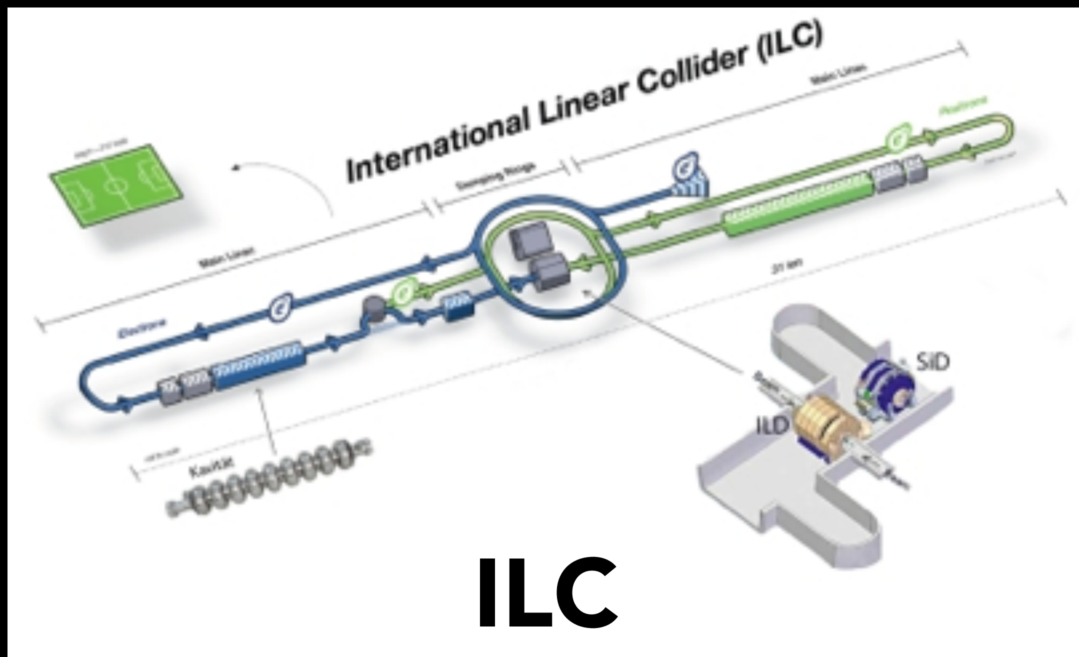
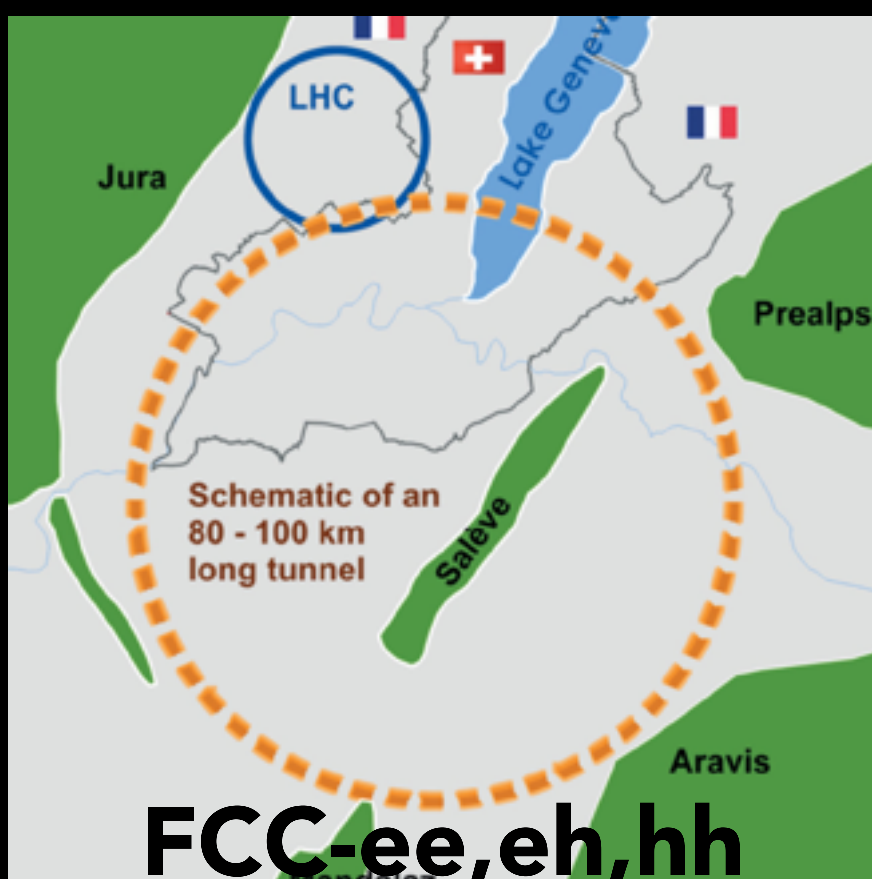
Outline

- Do we need a new collider?
  - History of scientific discoveries
  - Scientific reasons?
- Naturalness
  - Problem with the Standard Model Higgs
  - Supersymmetry
- A glimpse of we will see at a 100 TeV collider

Future Colliders





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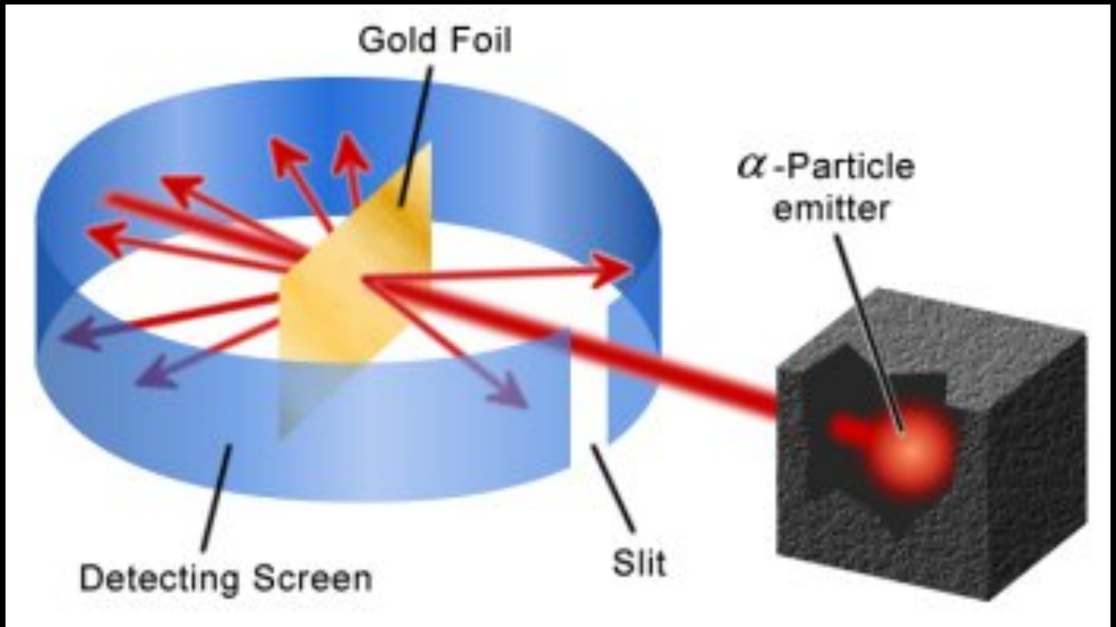
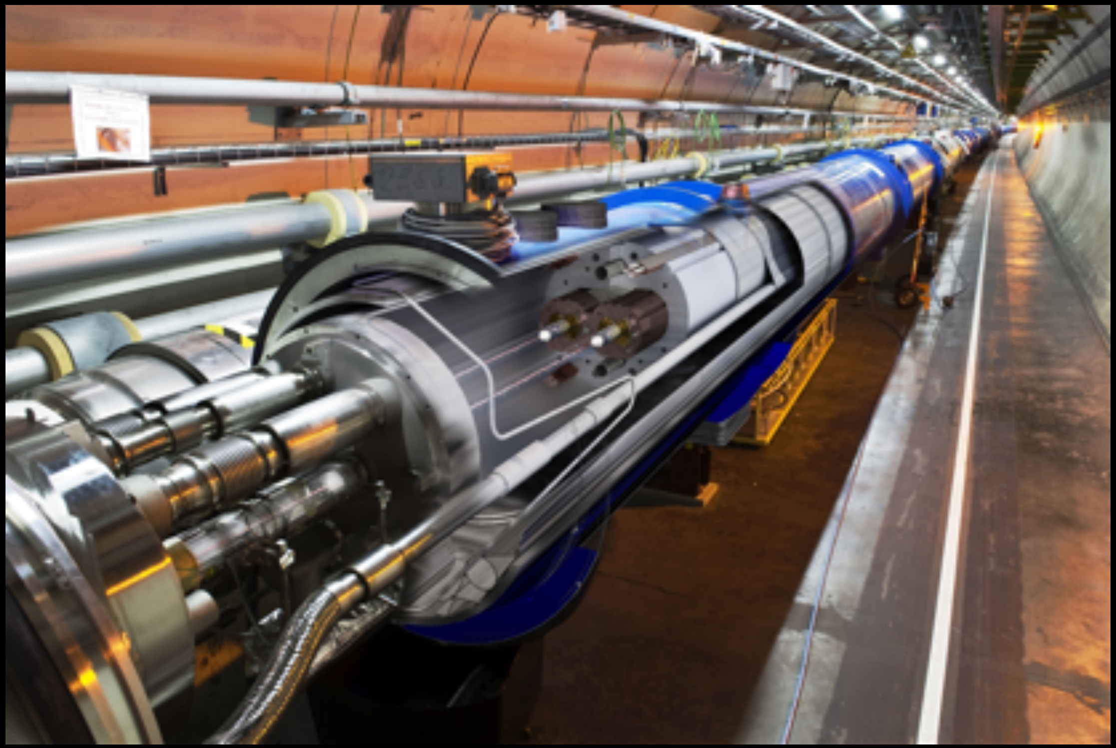
Why do we need a new collider?

- ~~so that I will have a job for the next few years~~
- To keep creating jobs in HEP and a healthy research field
- To maintain scientific progress

The quest for increasingly smaller scales





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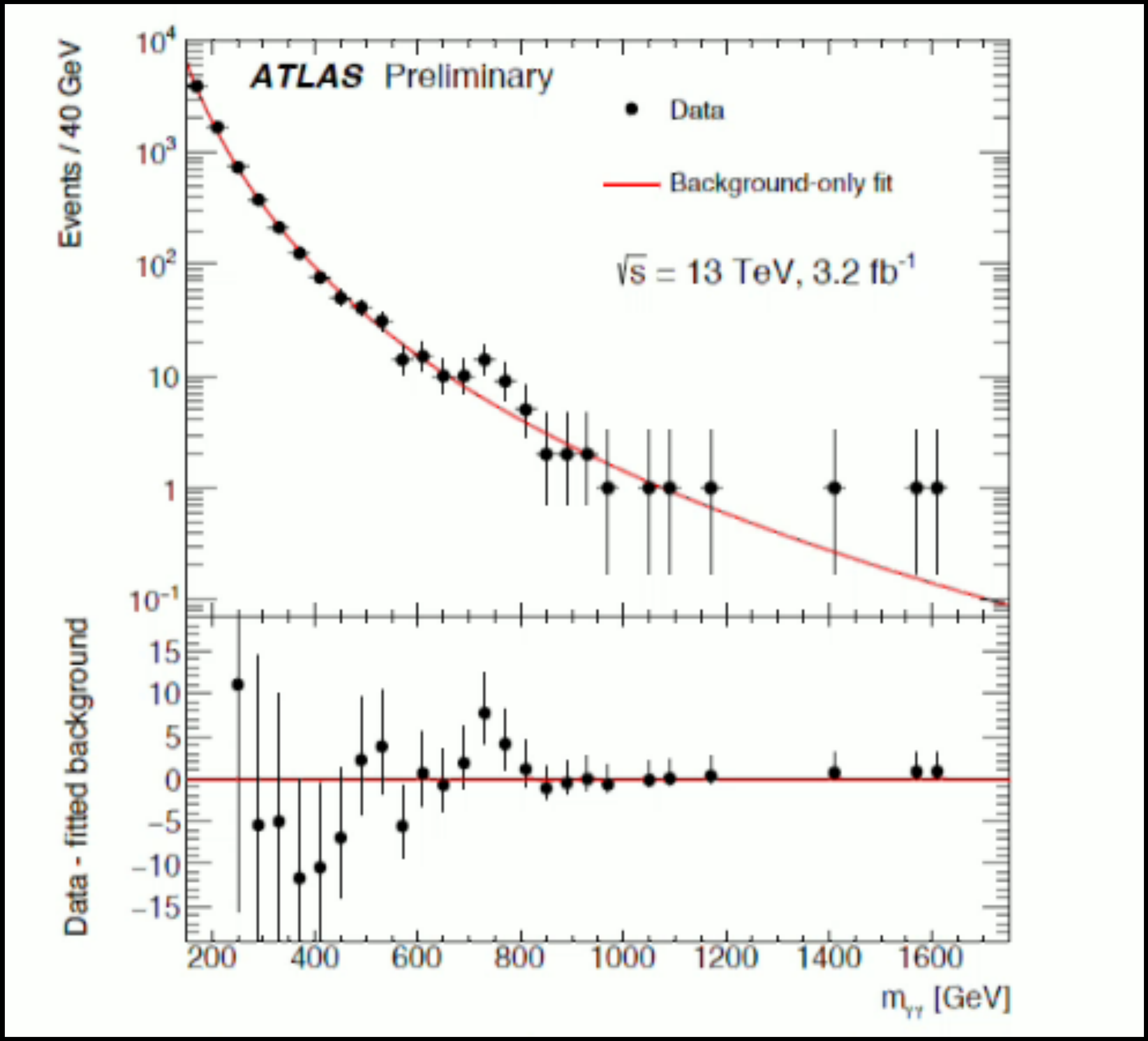
History of collider discoveries

- Neutral current measurements hinted at W,Z bosons
- SPS (UA1+UA2) discovered W,Z
- LEP gave precision for W/Z masses
- LEP + Tevatron hinted at a Higgs boson
- LHC discovered a Higgs boson
- What LHC is hinting at?

New particle(s)?

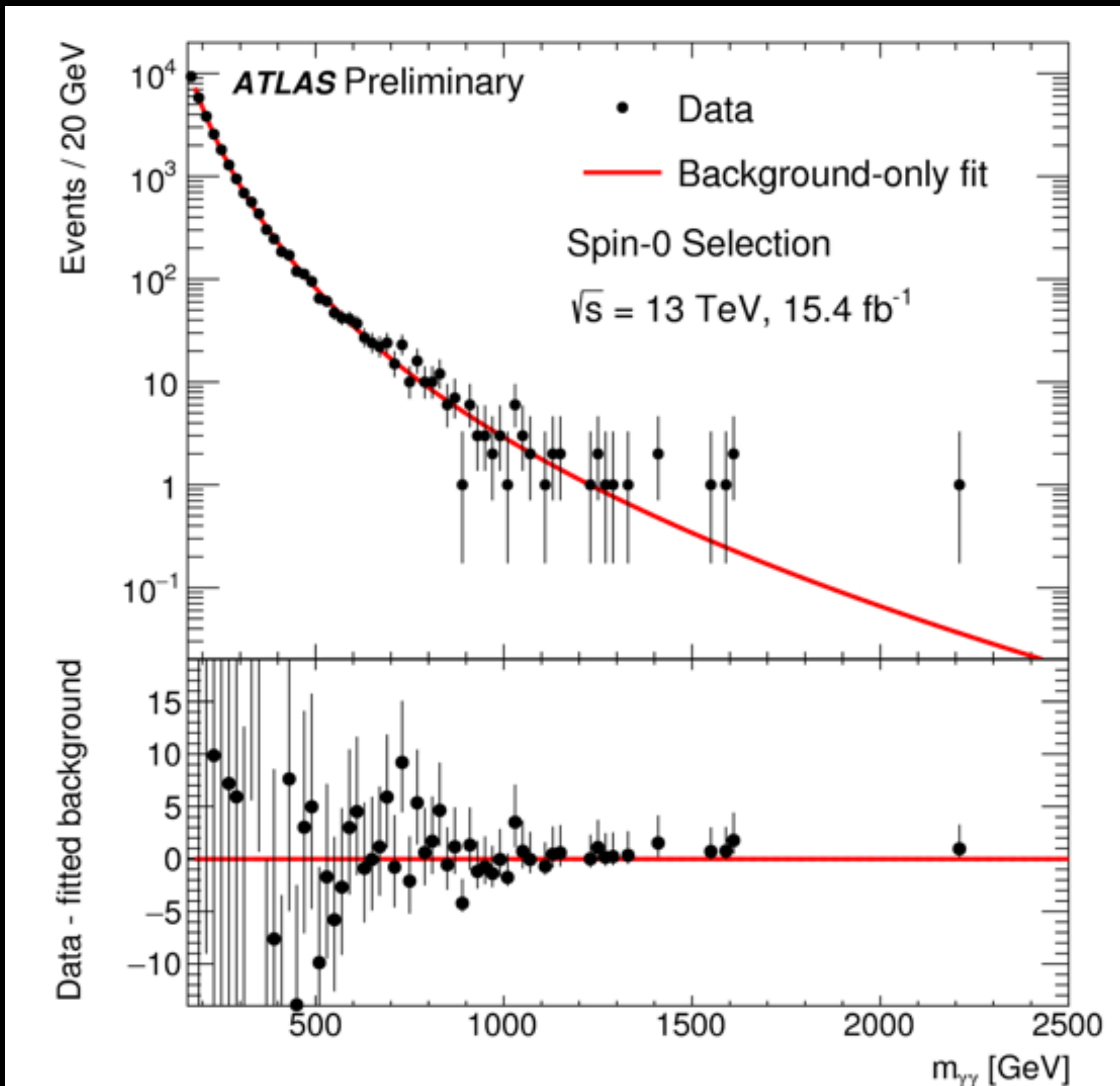


- ATLAS: 3.9σ (local)
- CMS: 3.4σ (local)
- +500 papers (on hep-ph)

ATLAS arXiv:1606.03833

CMS arXiv:1606.04093

Another flop…



ATLAS-CONF-2016-059

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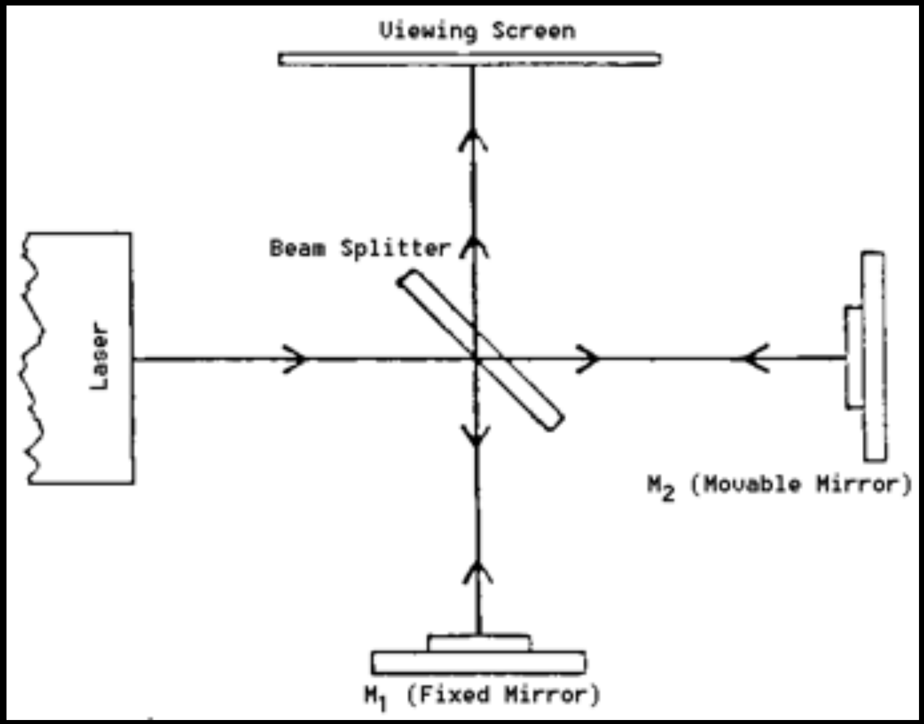
Nothing new = Failure?



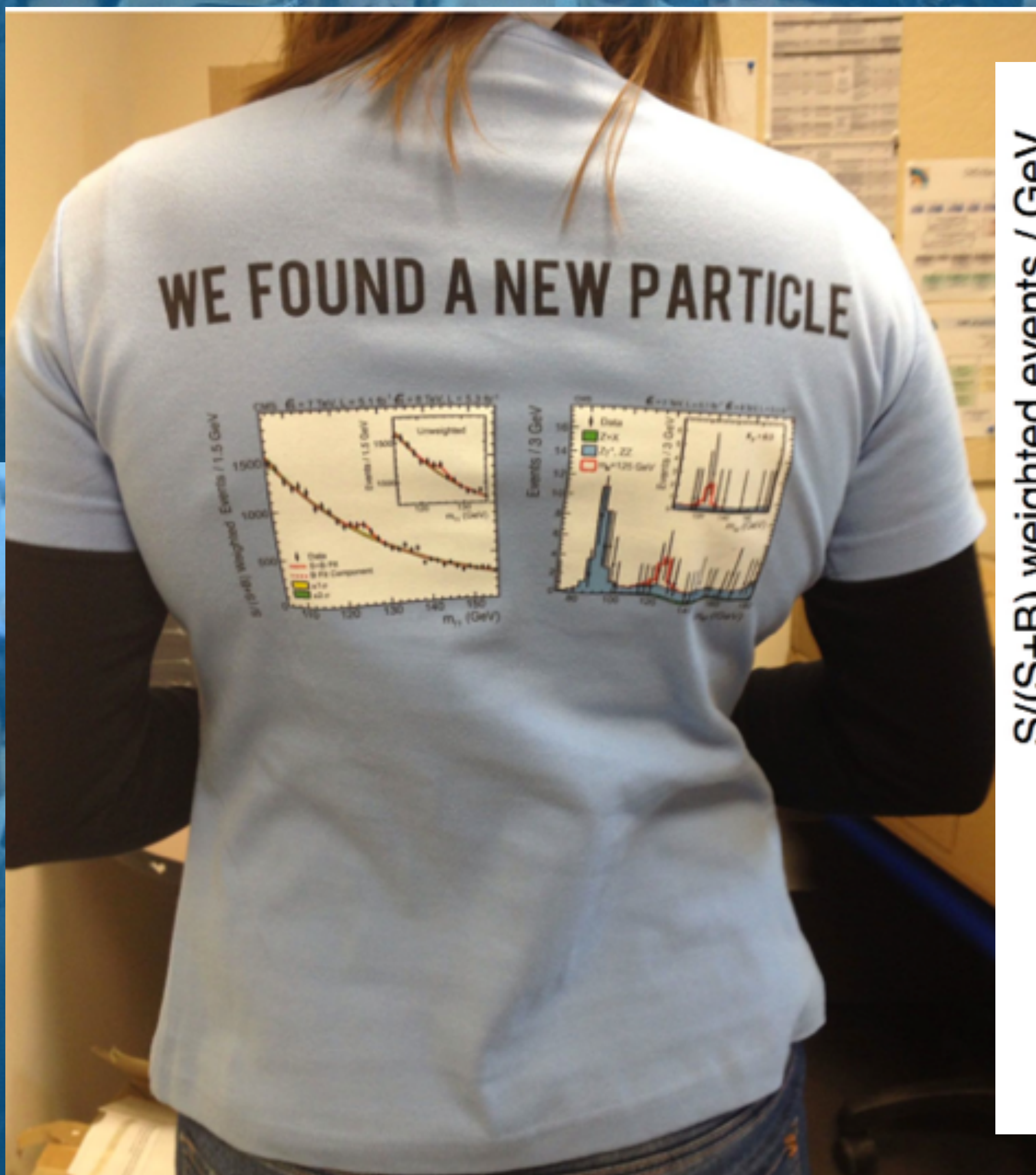
Michelson-Morley experiment

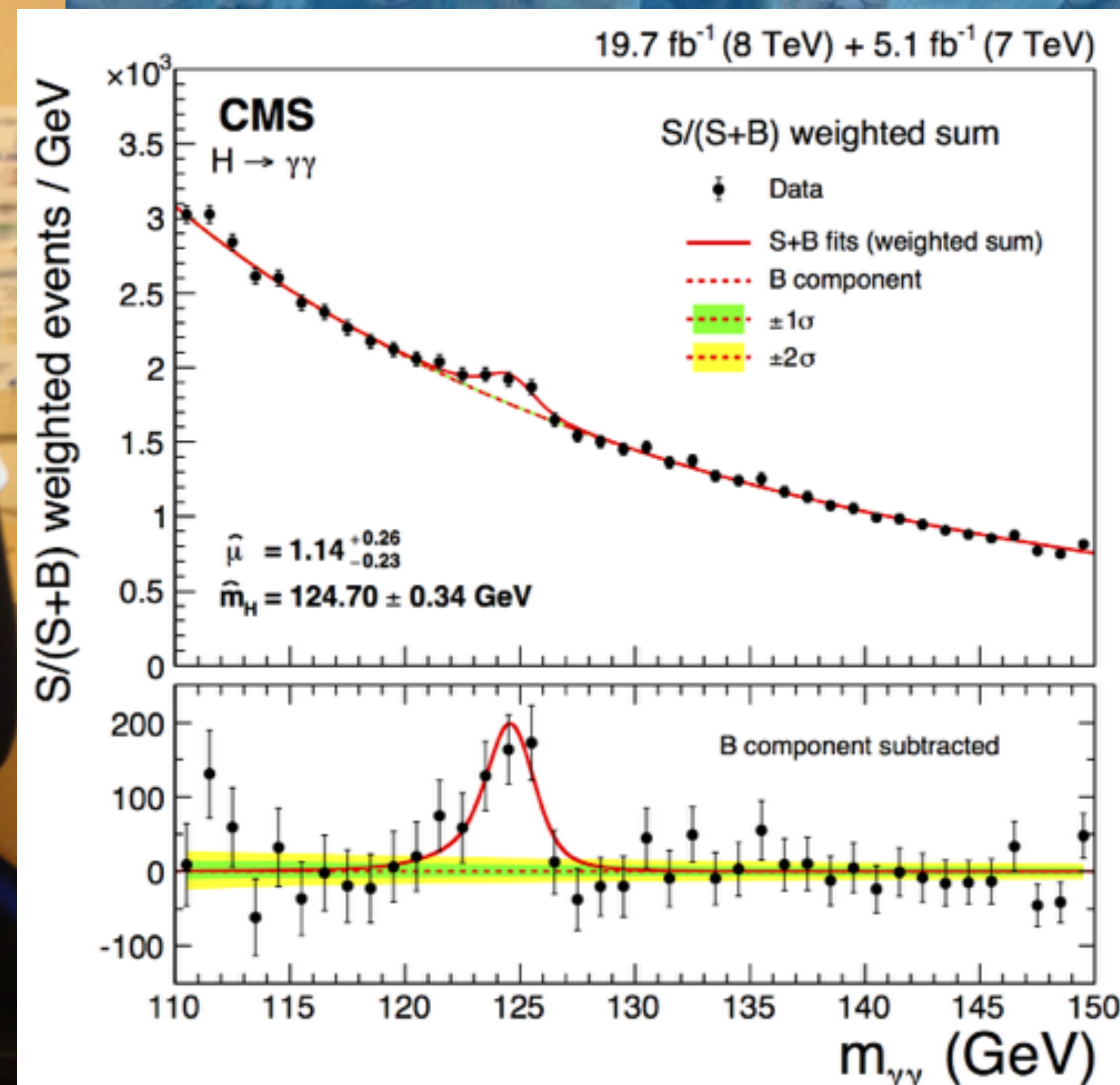
- if we see nothing new from the LHC, do we really have no clue?
- justification for a new collider?
- something is certainly out there… dark matter, dark energy, neutrino masses, etc.

Is this Natural?

Is this Natural?

Standard Model is not a natural theory!!





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What do we know about Higgs?

- The average value of Higgs field is 246 GeV (vacuum expectation value)
- The Higgs mass 125 GeV
- What set these values?

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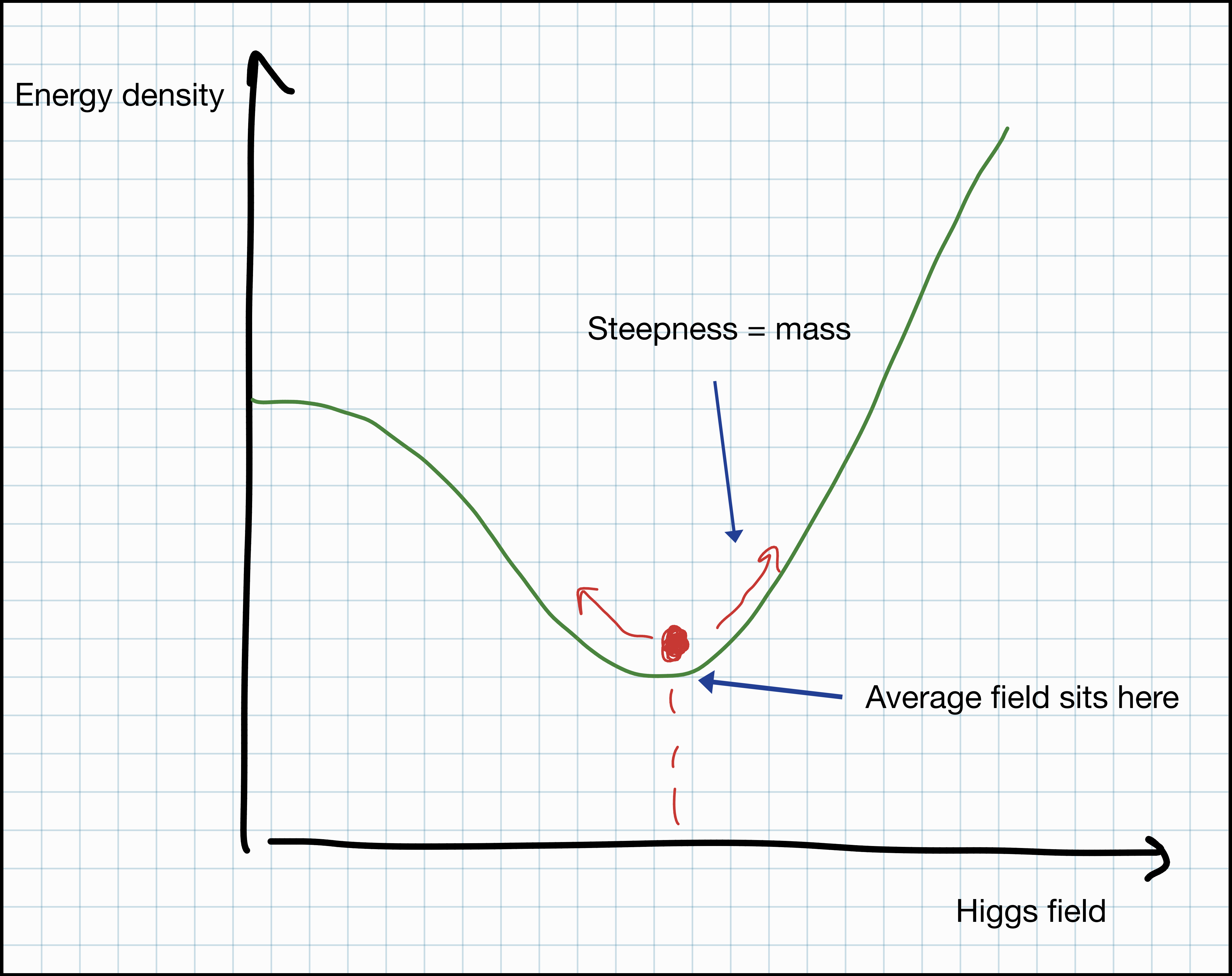
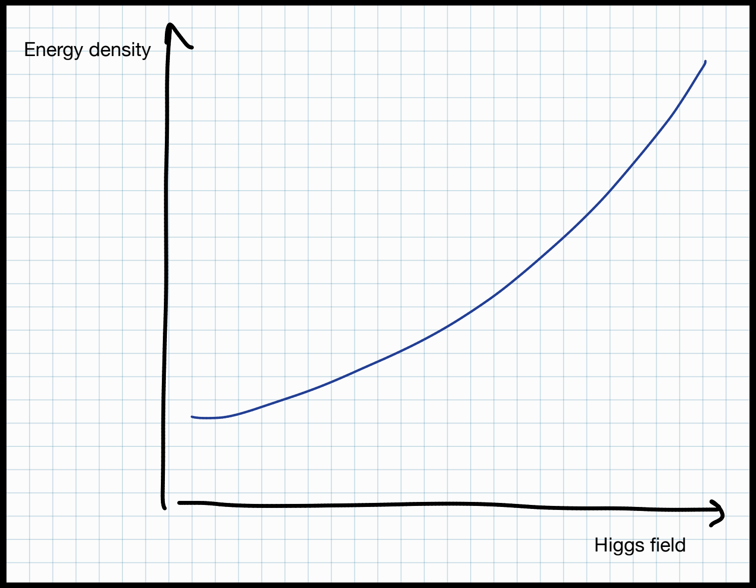

Energy density
Steepness = mass
Average field sits here
Higgs field

So, what's a problem?



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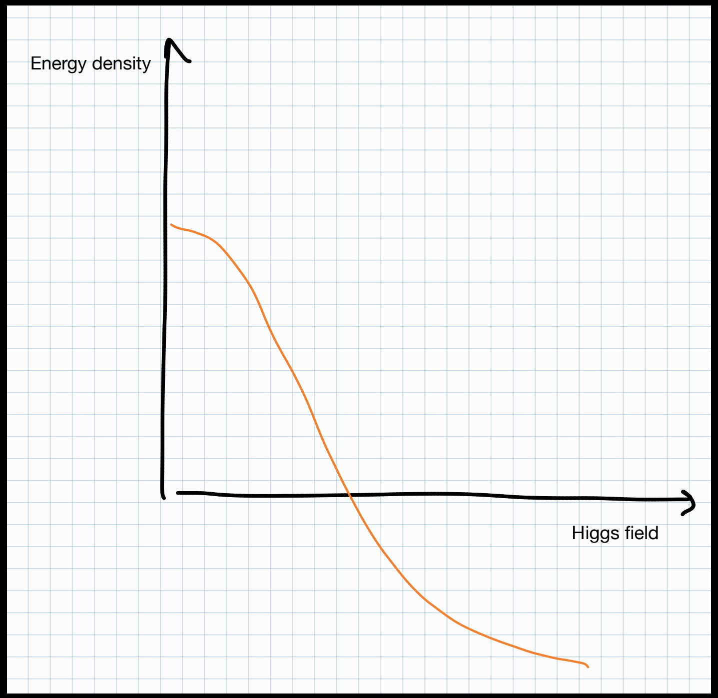

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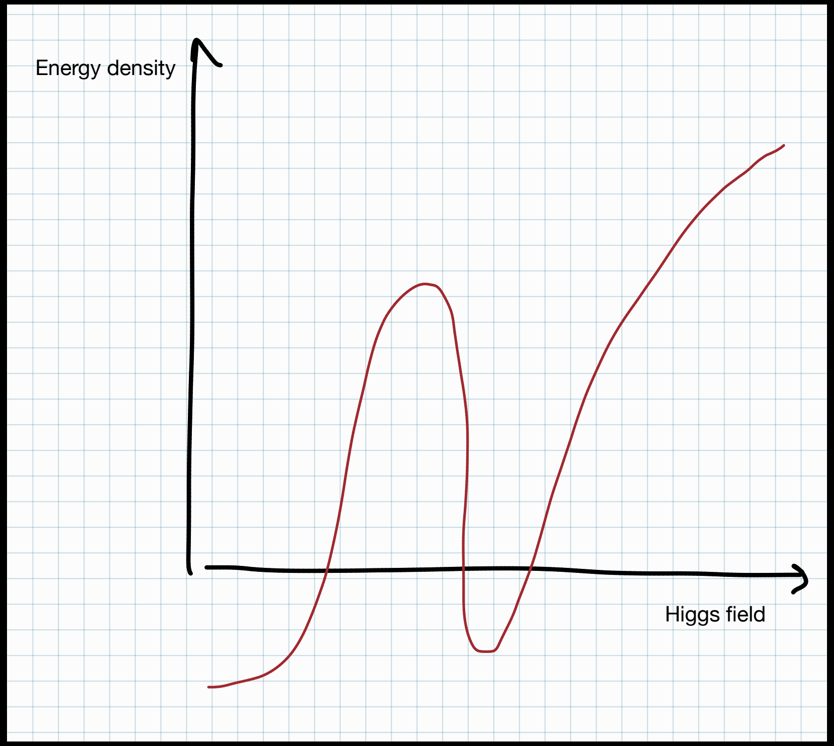

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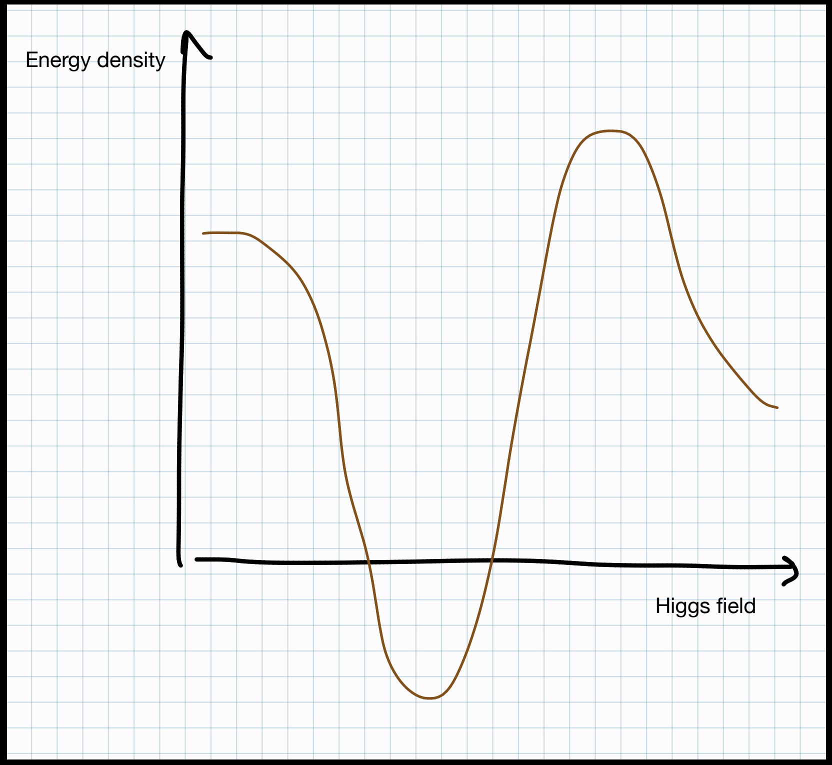

+ …….

(where each potential is drawn up to the maximum where the calculation is unreliable)

≈10,000,000,000,000,000,000 GeV

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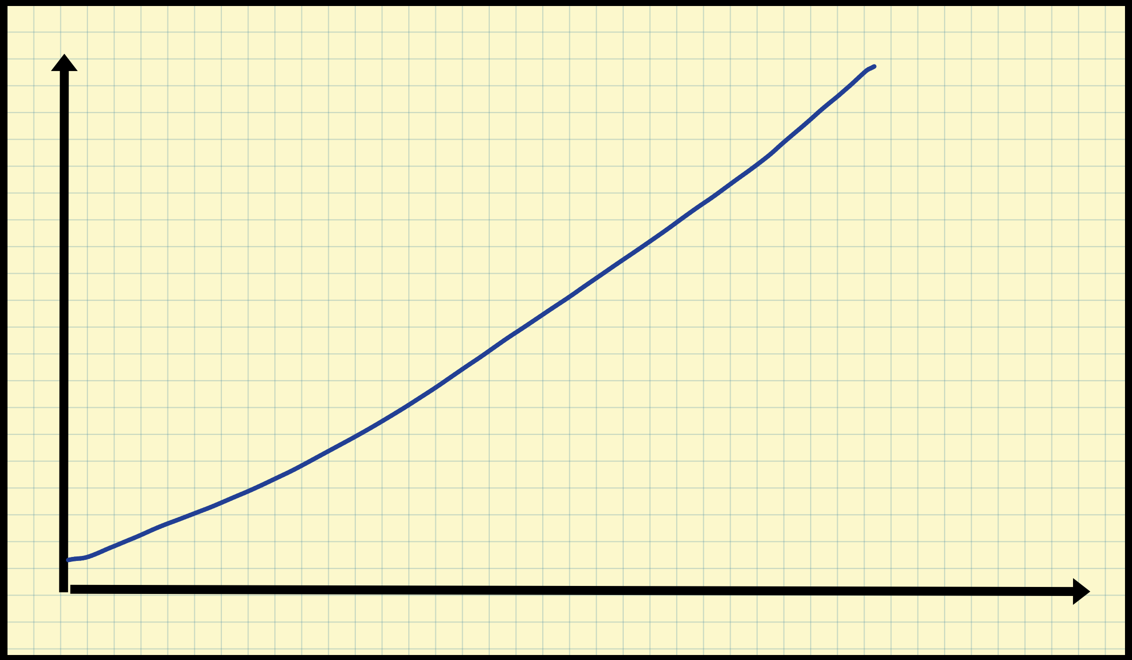
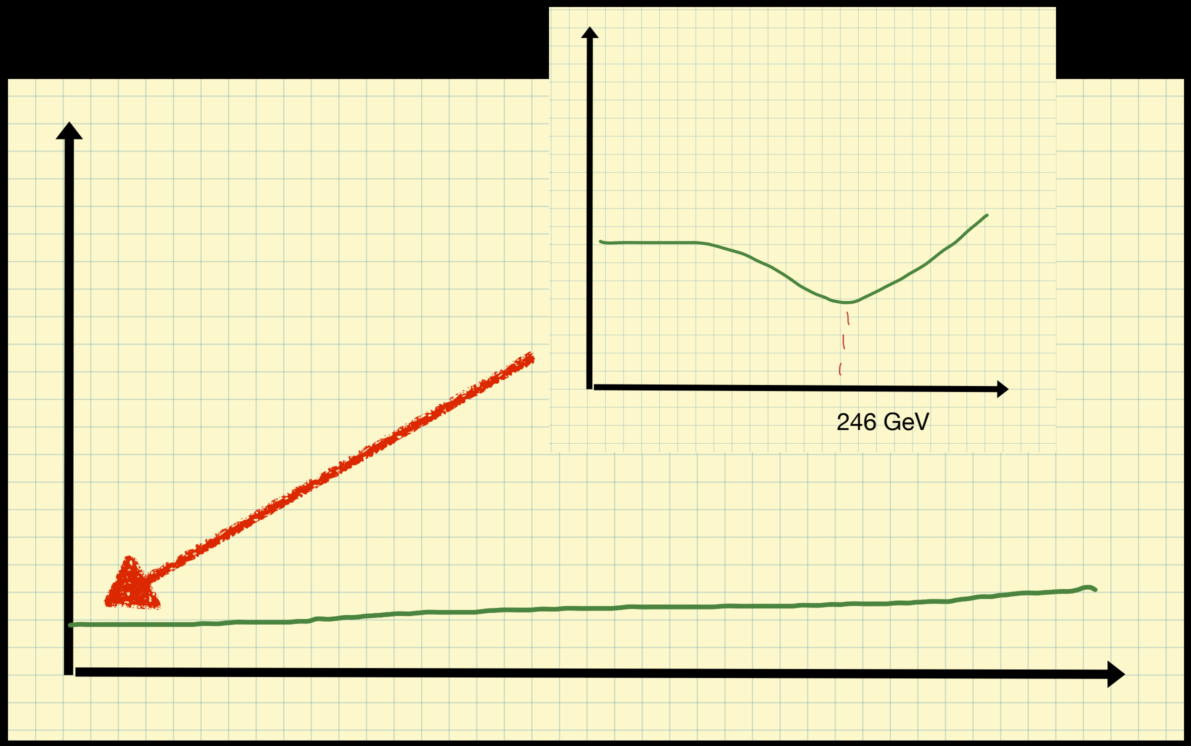
what we expect



what we see from LHC



so unnatural!!

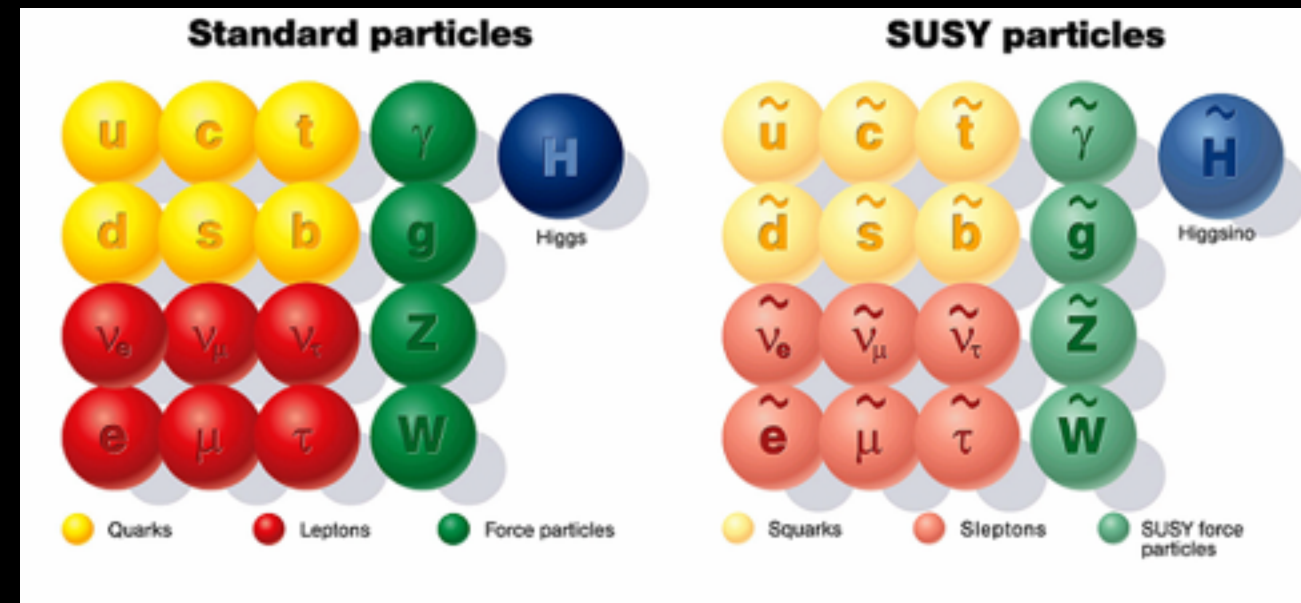
10,000,000,000,000,000,000 vs 125

The electroweak hierarchy problem

Supersymmetry

Every particles has its own partner

Boson ⟷ Fermion



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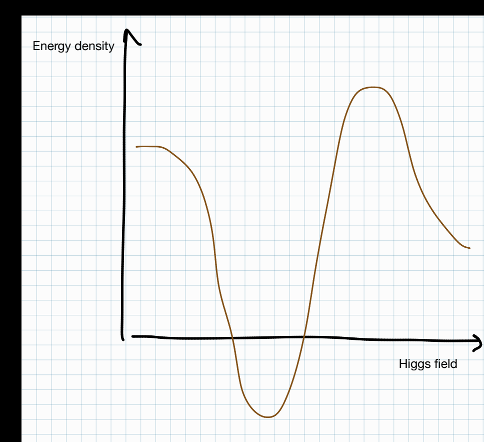

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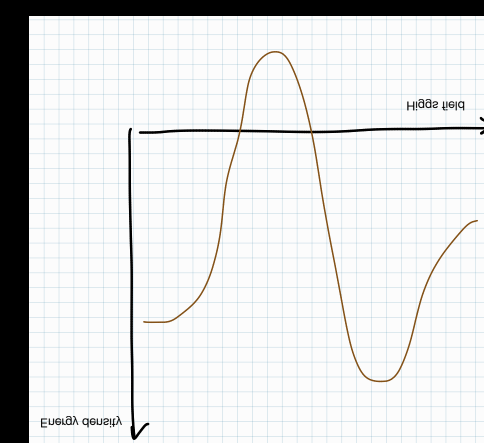

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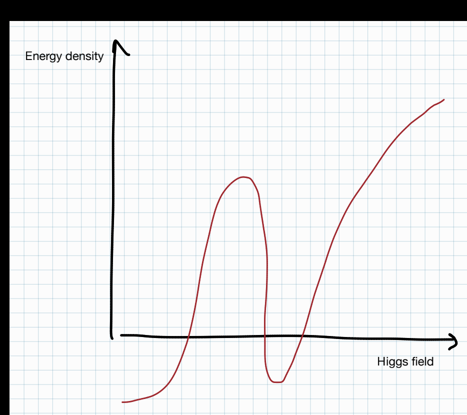

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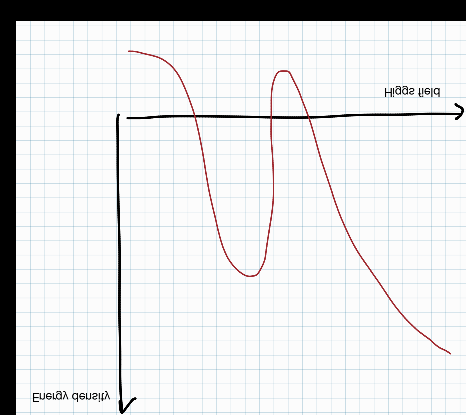

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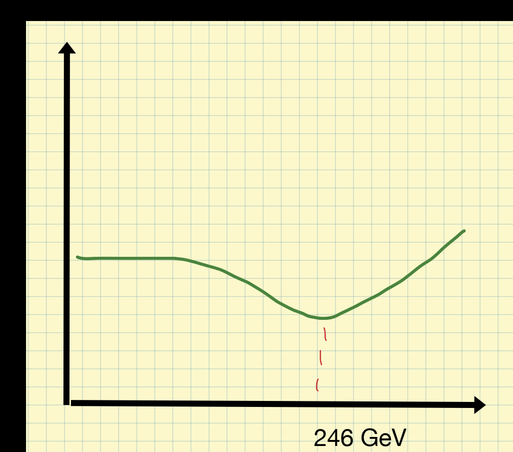
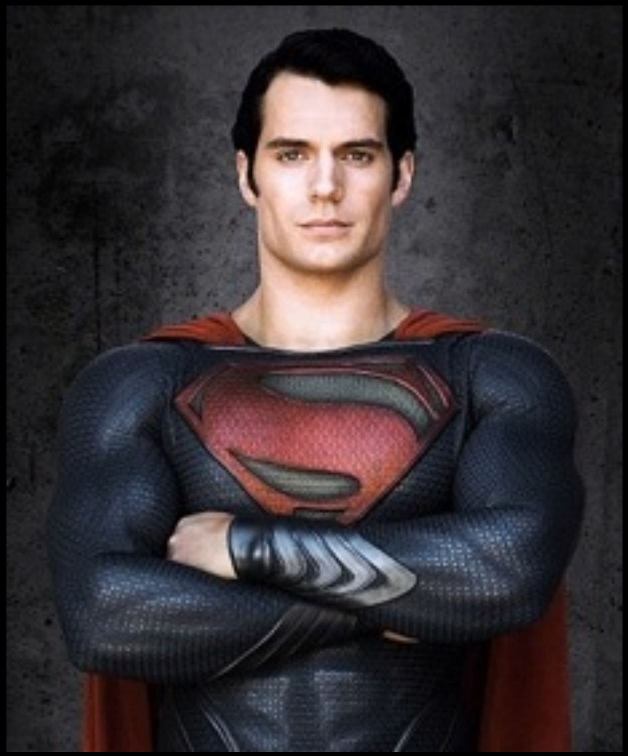


Supersymmetry

But we don't see superpartners of standard model particles with the same mass and same charge

Standard Model particle



Supersymmetric particle

Supersymmetry

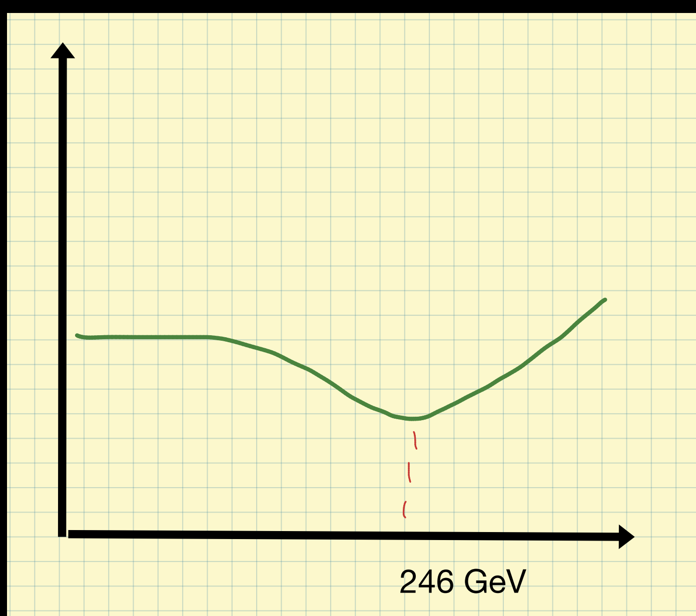
It must be broken!!!
(Too massive to be observed)

Standard Model particle

Supersymmetric particle

Mu-problem

μ is the Higgs parameter respecting supersymmetry (also give mass to superpartners of Higgs)



→  $- \mu \approx 100$ GeV

~~susy~~ susy ✓

Two parameters from different origins are unnaturally close

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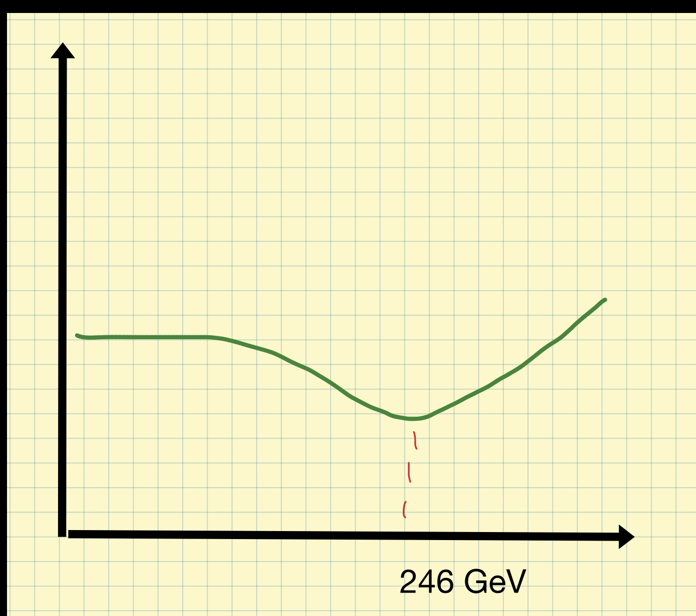
Mu-problem

μ is the Higgs parameter respecting supersymmetry (also give mass to superpartners of Higgs)



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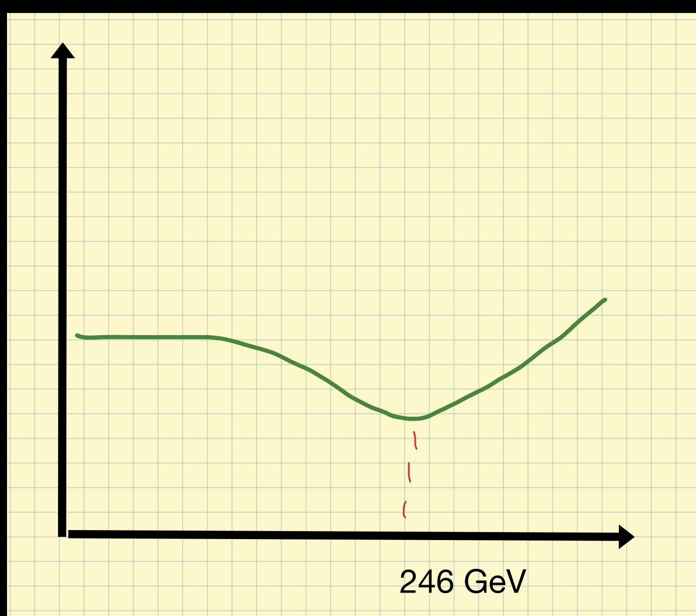

- $\mu \approx 100$ GeV

~~susy~~ susy ✓

Solutions = forbid ***μ*** and generate back from new field(s) involving supersymmetry breaking physics

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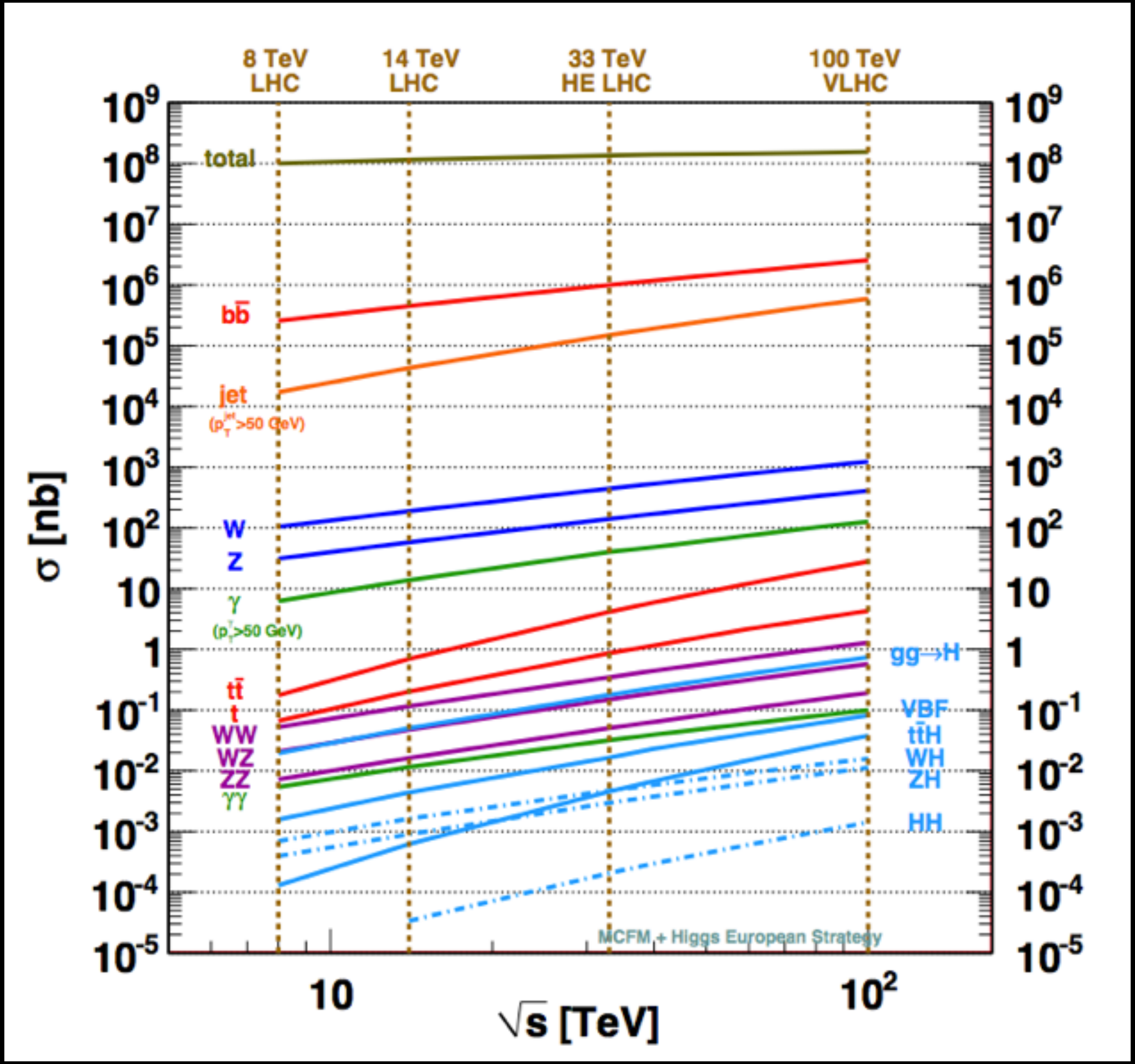
Fine tuning in SUSY

- Large cancellation still exists ➜ supersymmetry breaking and electroweak scale should be close to each other
- For the minimal set up of supersymmetry (MSSM), radiative corrections to the Higgs mass give constraints on masses of superpartners of top quarks
- Superpartners of top quark should be relatively light ~ TeV

Physics at 100 tev



arXiv:1310.5189

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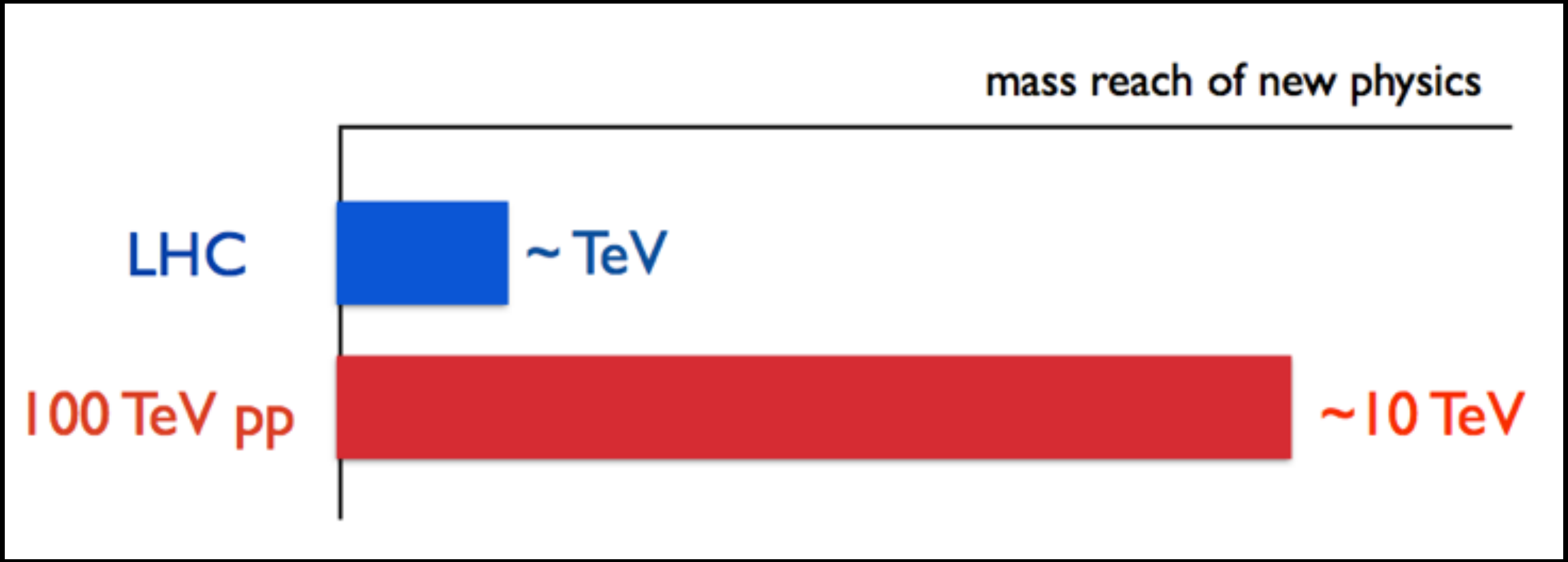
Physics at 100 tev



See arXiv:1511.06495 and 1606.00947 for full review on physics reach

Any mildly tuned MSSM should be killed at this point

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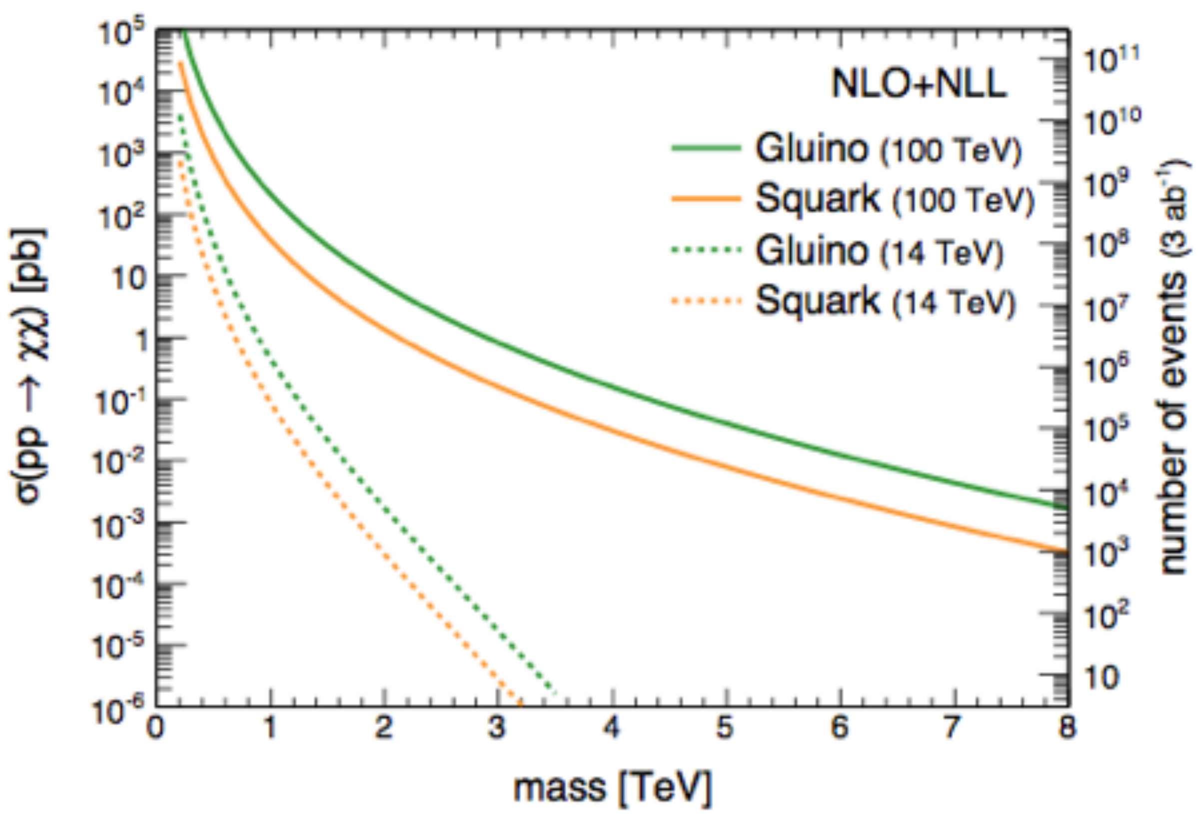
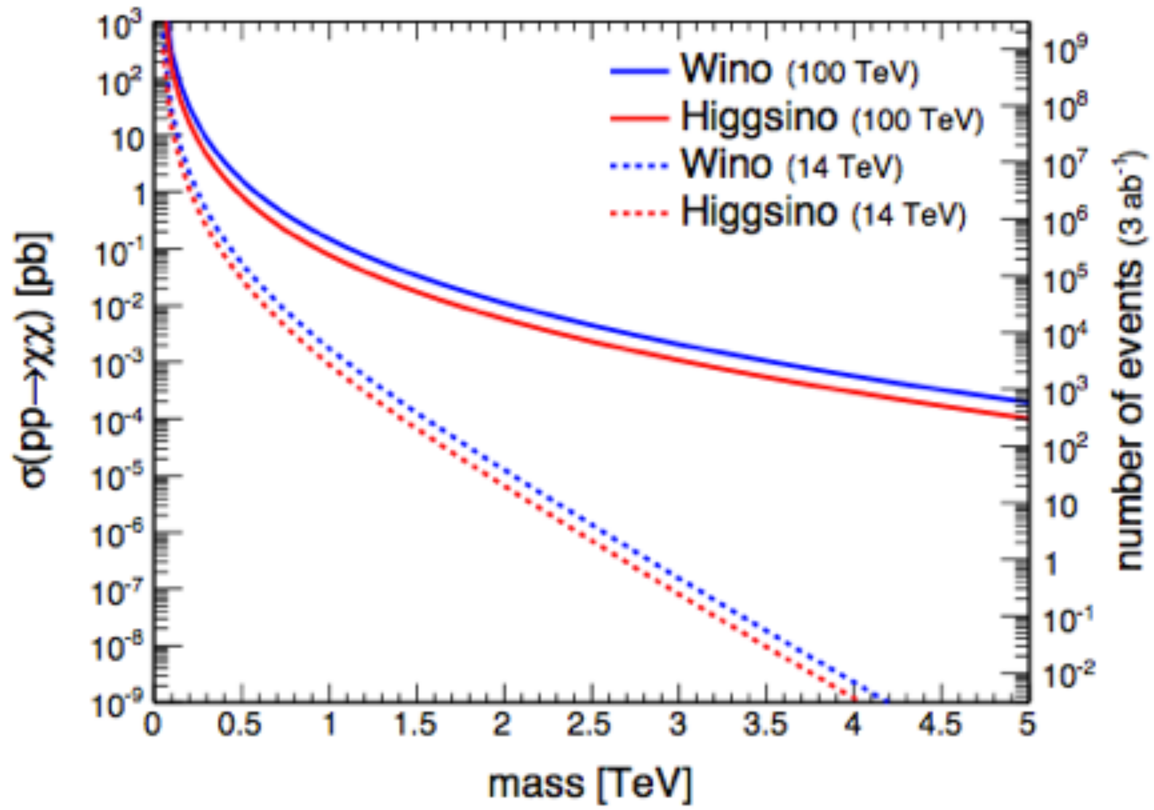
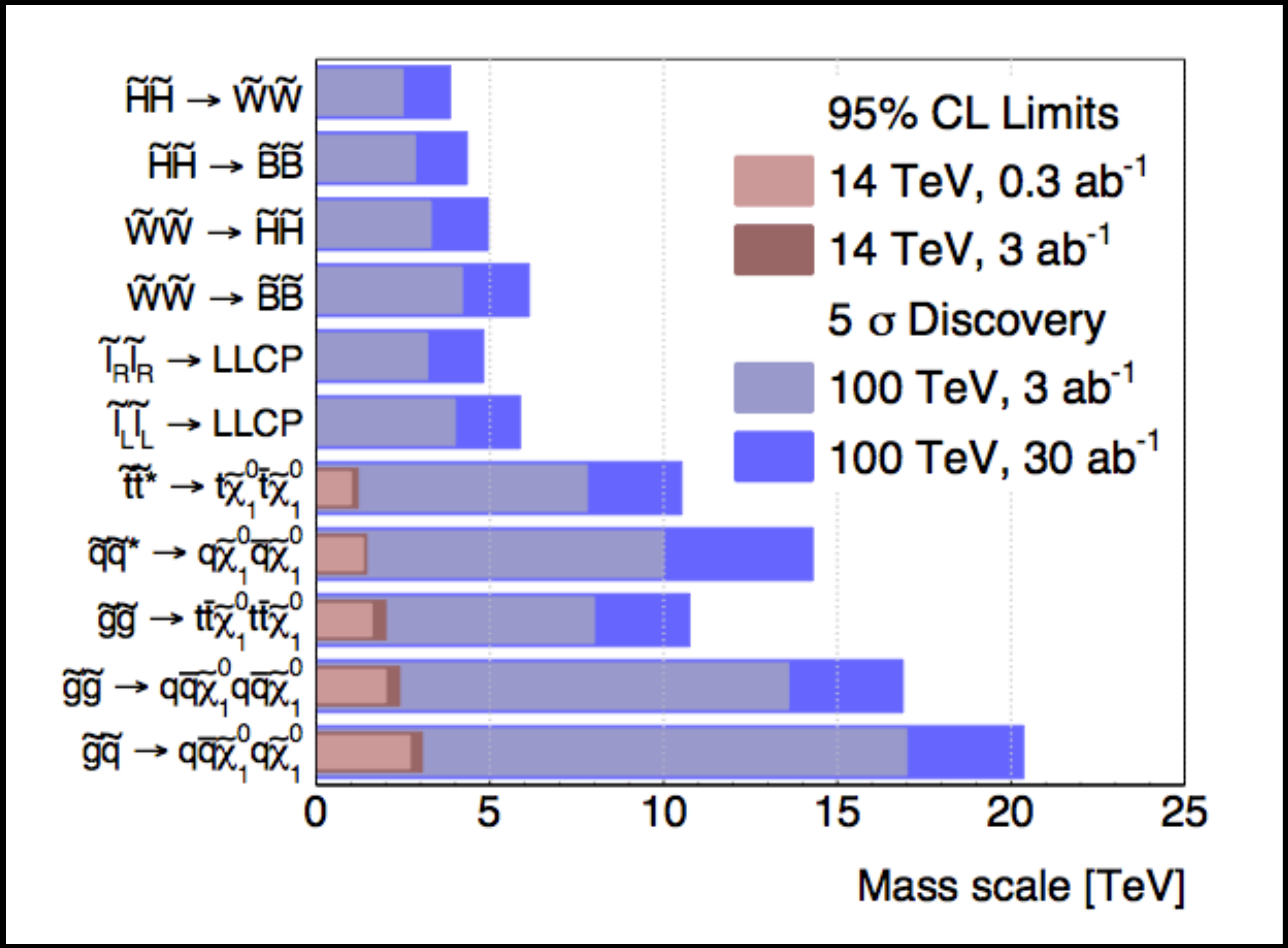
Production





arXiv:1407.5066

Discovery/Exclusion limits



simplified model

arXiv:1511.06495, 1606.00947 and refs therein

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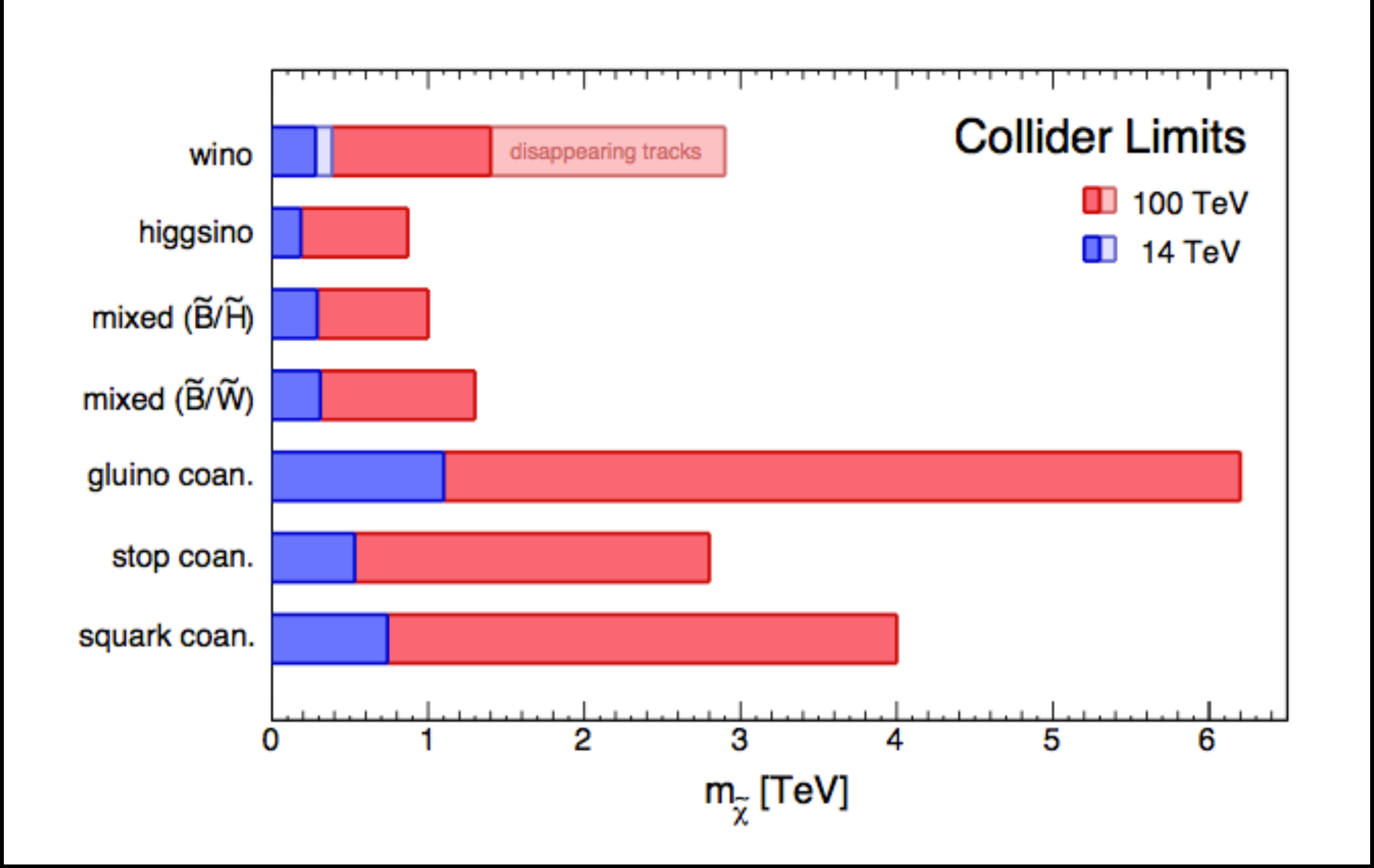
Discovery/Exclusion limits



Dark matter searches

arXiv:1511.06495, 1606.00947 and refs therein

Conclusion

- The next generation colliders is the steps forward
- Depending on the result coming from LHC in the next ~2 years, the motivation and direction of a new collider will be clear
- Guiding by the idea of naturalness, BSMs such as supersymmetry will be testable in the new collider

BACK UP SLIDES

SUSY fine tuning (cont'd)

$$\sin(2\beta) = \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2},$$

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

- Even mu-problem is solved, there still is a large cancellation between terms due to the order of magnitude difference between soft parameters and weak scale

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SUSY fine tuning (cont'd)

- Many ways to measure a fine-tuning (unnaturalness)

$$\tilde{\Delta} = \left|\frac{\delta m^2}{m^2}\right| = \frac{2\delta m^2}{m_h^2}$$

$$\Delta_{\rm EW}^{-1},\ \Delta_{\rm HS}^{-1} \text{ and } \Delta_{\rm BG}^{-1}$$

see 1404.1386 for full def

$$\Delta[a] = \frac{\partial \log M_Z^2}{\partial \log a^2}$$

Example of fine tuning problems:
The strong CP problem (strong θ problem)

- C for symmetry which transforms a particle to its antiparticle
- P for symmetry which transforms into a mirror image
- CP symmetry in strong interaction can be broken by unspecified parameter θ

$< 2.9 \times 10^{-26}$ e.cm → $\theta < 10^{-10}$

Neutron electric dipole moment — CP is not broken

Solutions = promote θ to be a field and generate potential for it to sit at $\theta = 0$