Naturalness after LHC Run I

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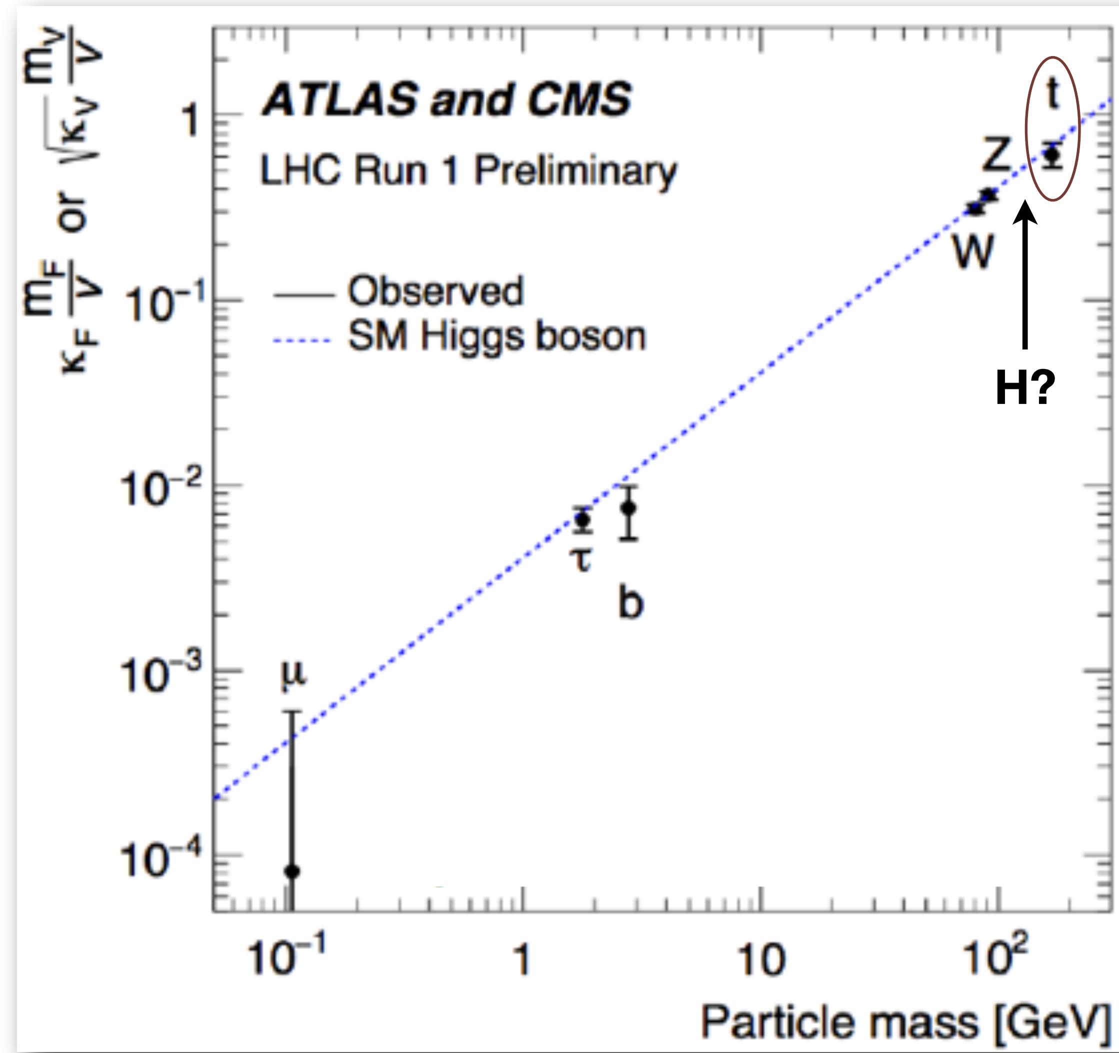
Outline

- Critical appraisal of the naturalness argument
- Status of models addressing the naturalness problem (SUSY and Composite Higgs) after run I
- Alternatives: evading the naturalness argument

Understanding the EW scale

- Is the SM description **CORRECT**?
  - "h" is $SU(3)_c \times U(1)_{em}$ neutral
  - "h" has S = 0 and P = 1
  - "h" couplings prop. to masses



- Is the SM description **COMPLETE**?
  - $V = \mu^2|H|^2 + \lambda|H|^4$

- **μ^2** Higgs potential parameter (tree level)
- **M^2** scale of superheavy dofs with coupling g to H, e.g. O(10^{16}GeV)

$$m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2} M^2$$

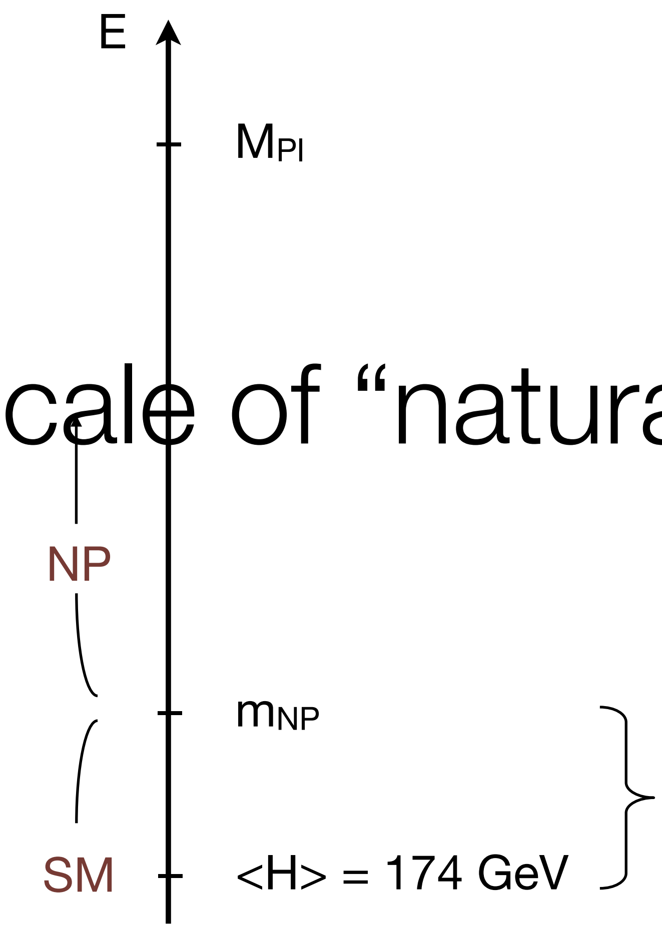
Therefore, the options are:

- No superheavy (coupled) degrees of freedom
  (finite naturalness?)

- Cancellation not accidental
  (environmental selection? unknown dynamics?)

- New TeV physics taming sensitivity to high scales
  (supersymmetry? composite Higgs?)

The scale of “natural” new physics



$$\delta m_h^2 \sim \frac{g^2}{(4\pi)^2} m_{\rm NP}^2 \approx (125\,{\rm GeV})^2 \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

top contribution

Comment 1: m_{NP} is not precisely determined

- Any value of m_{NP} is viable as long as a cancellation of one part out of

$$\Delta \gtrsim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 \qquad \text{is accepted}$$

- E.g. $m_{NP} > 1.5$ TeV ↔ $\Delta > 10$
  $m_{NP} > 5$ TeV ↔ $\Delta > 100$

- Note: m_{NP} x 2 ↔ Δ x 4

Comment 2: the bound on Δ is model-dependent

- **Supersoft** theories $\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,\rm TeV}\right)^2$

  (e.g. composite Higgs)

- **Soft** theories $\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,\rm TeV}\right)^2 \times \log\left(\frac{M^2}{m_{\rm NP}^2}\right)$

  (e.g. supersymmetry with mediation scale M)

Supersymmetry

$$\Delta \sim \left(\frac{m_{\mathrm{NP}}}{0.5\,\mathrm{TeV}/\sqrt{\log}} \right)^2 \qquad \log = \log \frac{M^2}{m_{\mathrm{NP}}^2}$$

M = mediation scale

Example: supergravity

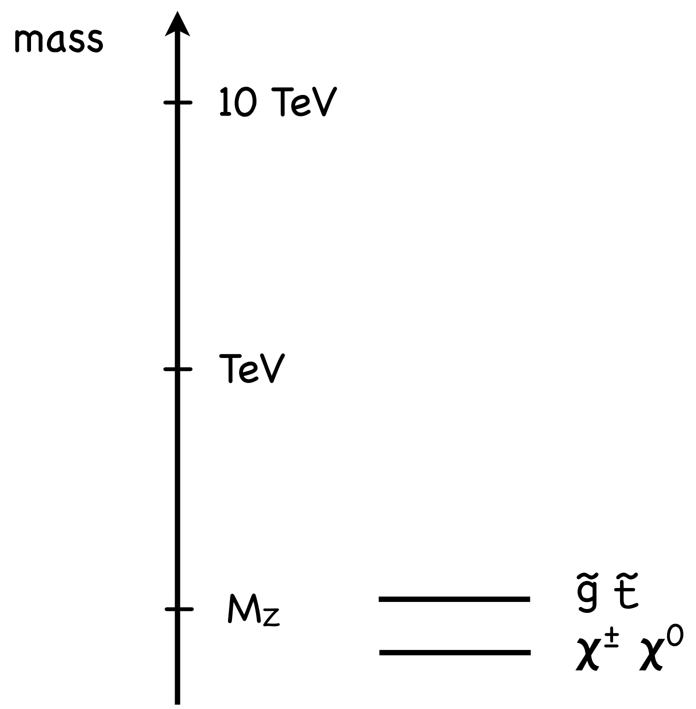
$M = M_{Planck}$

log ~ 70

$\Delta \sim 1$ for $m_{NP} \sim M_Z$

Supergravity: $M = M_{Planck}$

- log = O(70) $\Longrightarrow$ natural expectation: m_{NP} around M_Z



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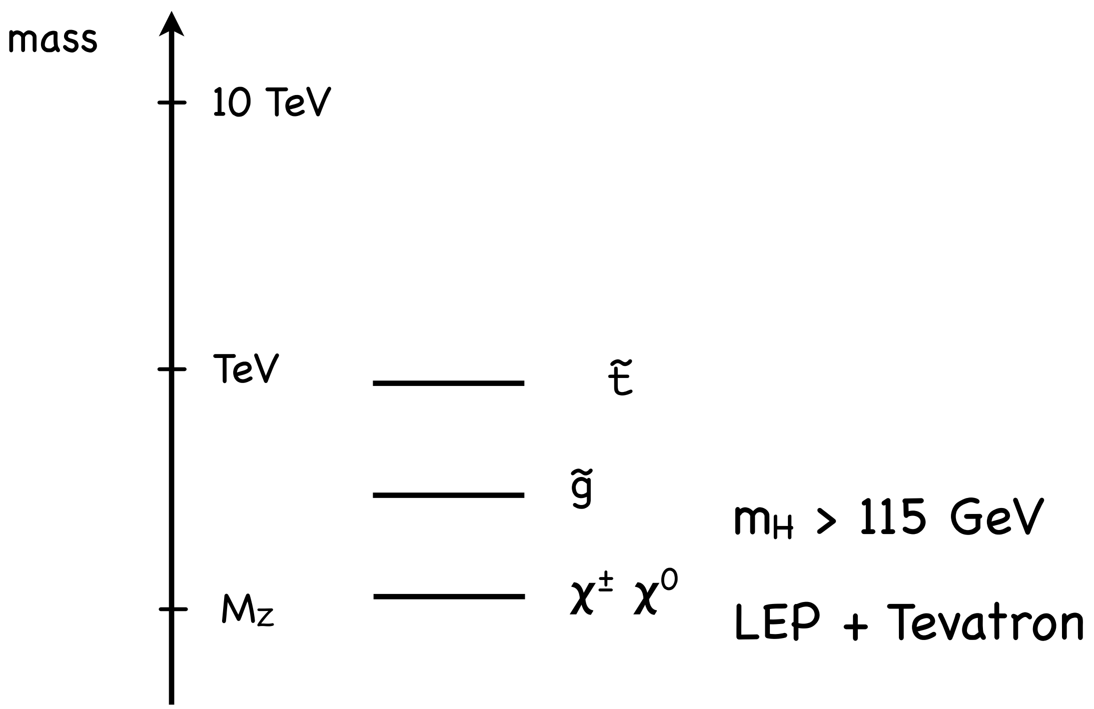

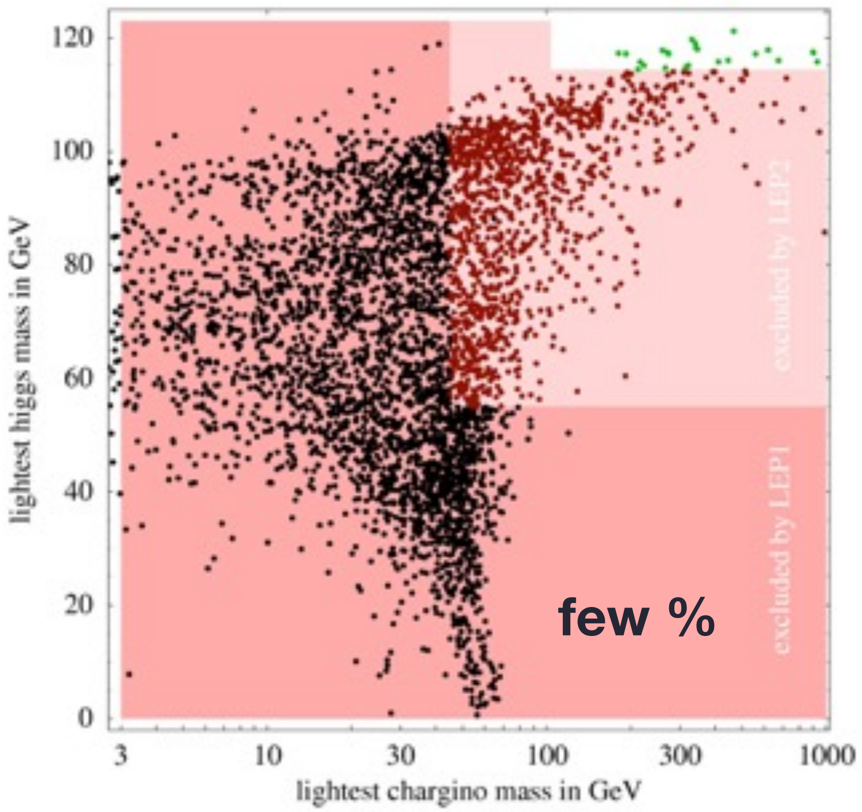

[Giusti R Strumia, 1998]

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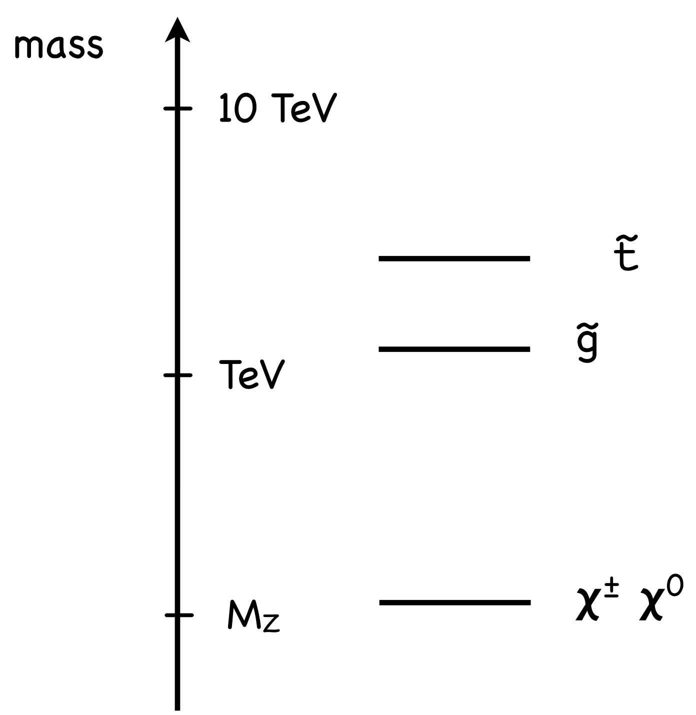


m_H = 125 GeV

LHC

few ‰

message: low M?

"Quasi-natural" supersymmetry

- Feature
- Affects

- messenger scale $\lesssim$ 100 TeV
- fine-tuning estimate
  for given experimental bounds

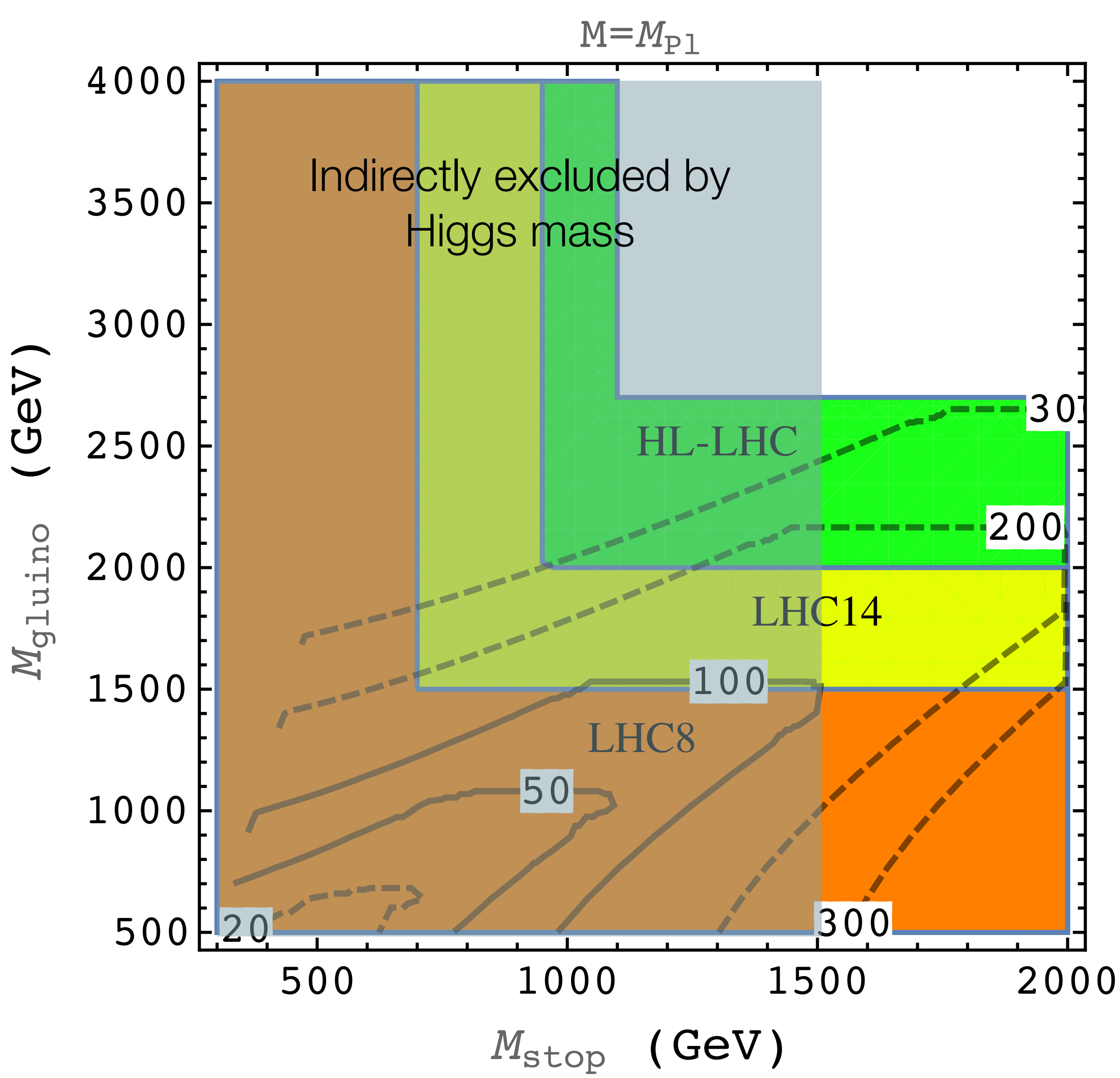
  Δ: reduced by O(10) wrt M_{Pl}

- the spectrum includes a gauge **singlet**
- **indirect** experimental bounds on stop mass

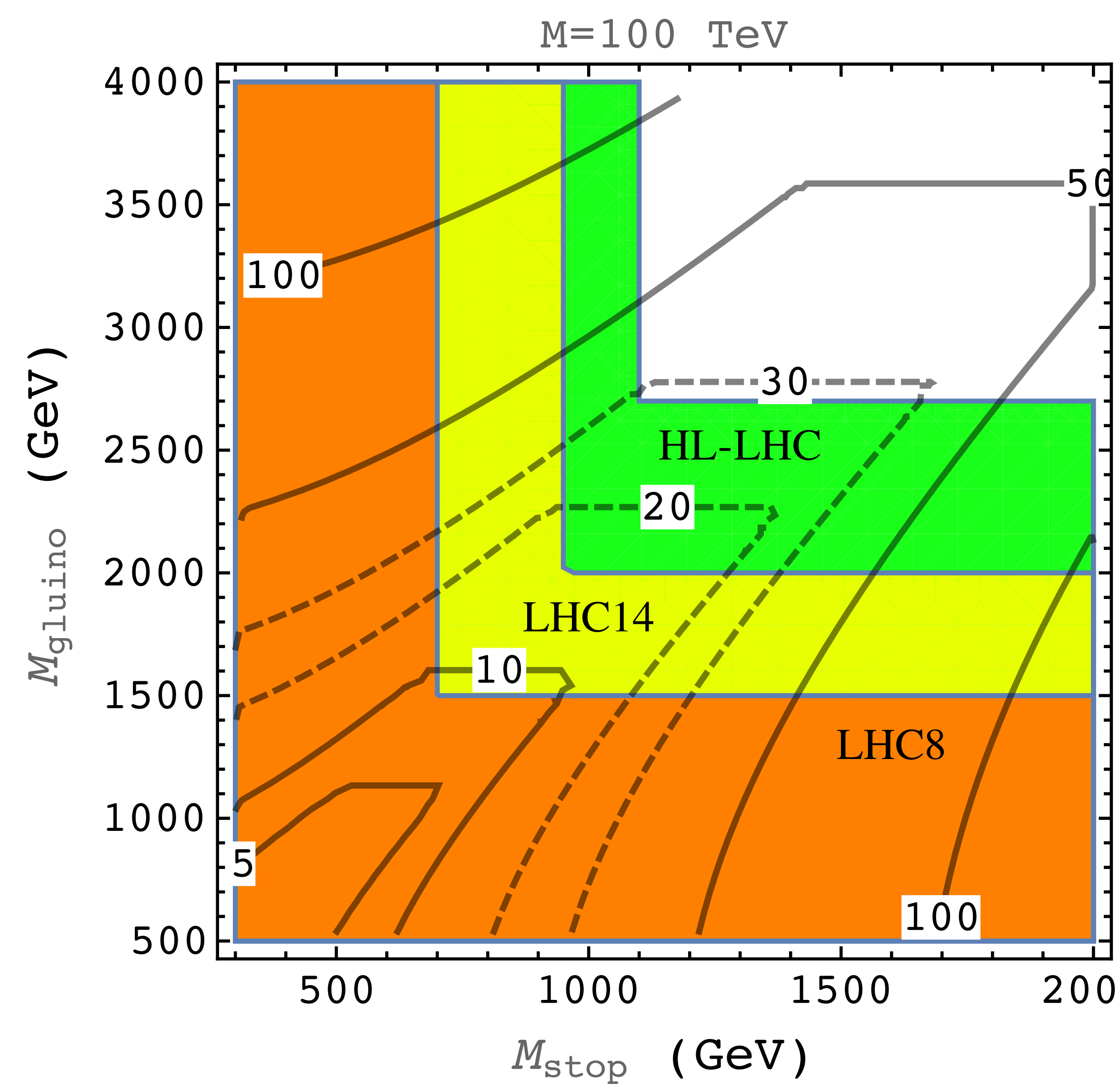
  m_{stop}: (1.5-10) TeV $\rightarrow$ 0.7 TeV

Stops and gluinos

msugra



M = 100 TeV + singlet



[Buttazzo, R, 2015]

Composite Higgs

- Generic composite Higgs is supersoft: $\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$

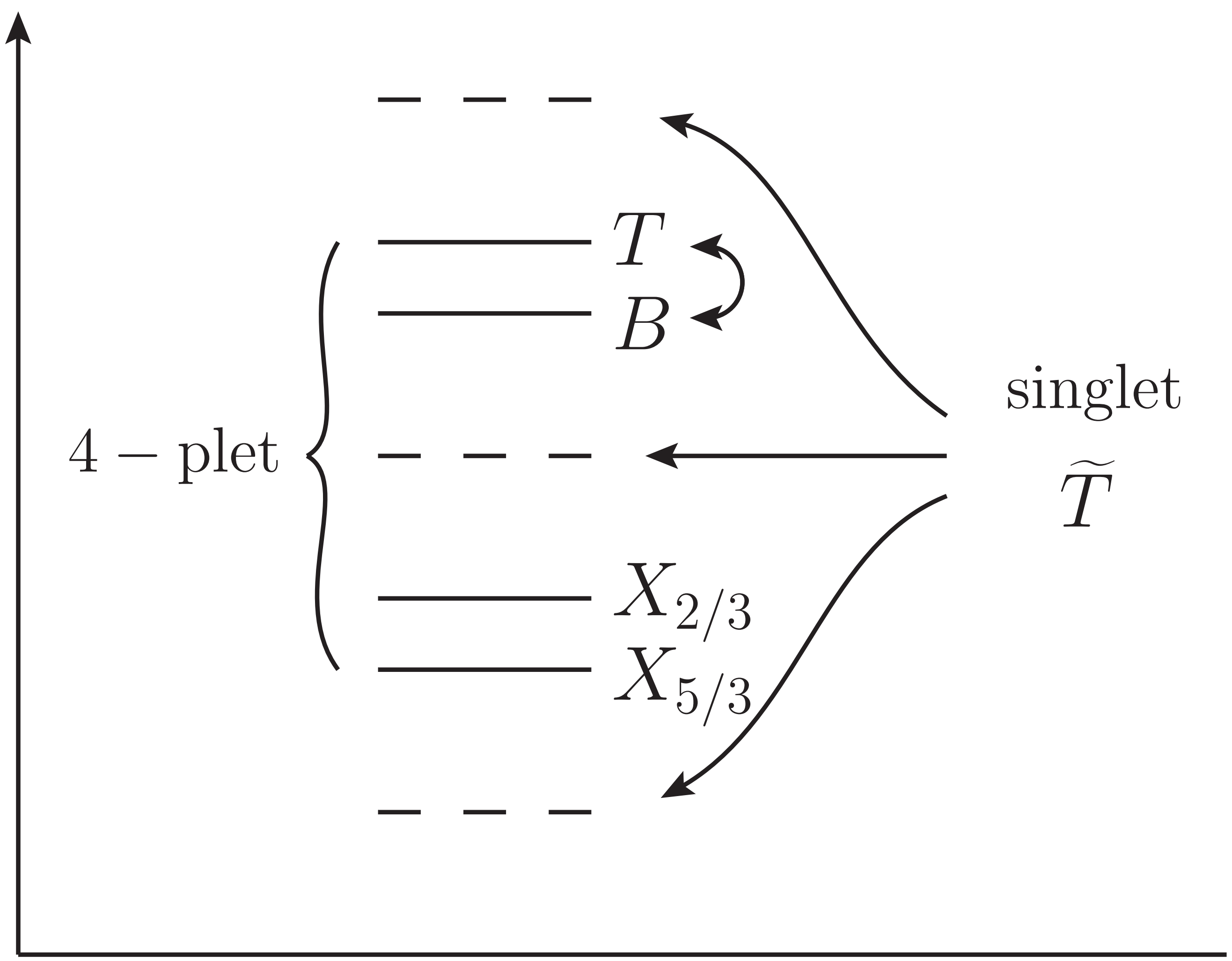
m_{NP} = mass of first stop resonances

- If $m_{NP} \approx \Lambda \equiv$ compositeness scale (as expected) then $m_{NP} \gtrsim$ 2-5 TeV (EWPT)
  - ➥ O(1-5%) fine-tuning (comparable with quasi-natural susy)

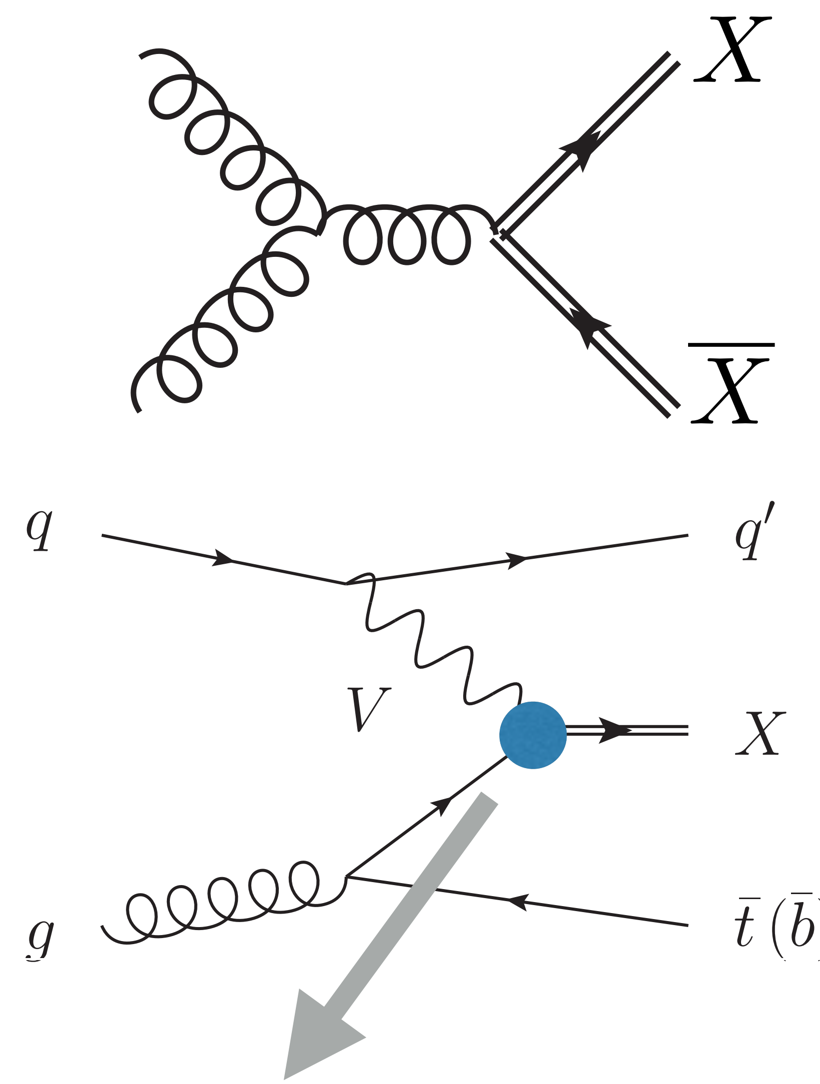
- But $m_H^2 = \delta m_H^2$ needs $(m_{NP})^2 \ll (5\text{ TeV})^2$
  - ➥ soft, with M = compositeness scale (better)
  - ➥ tension moves to smallness of $(m_{NP})^2$

Top Partners: model dependence

Typical Spectrum



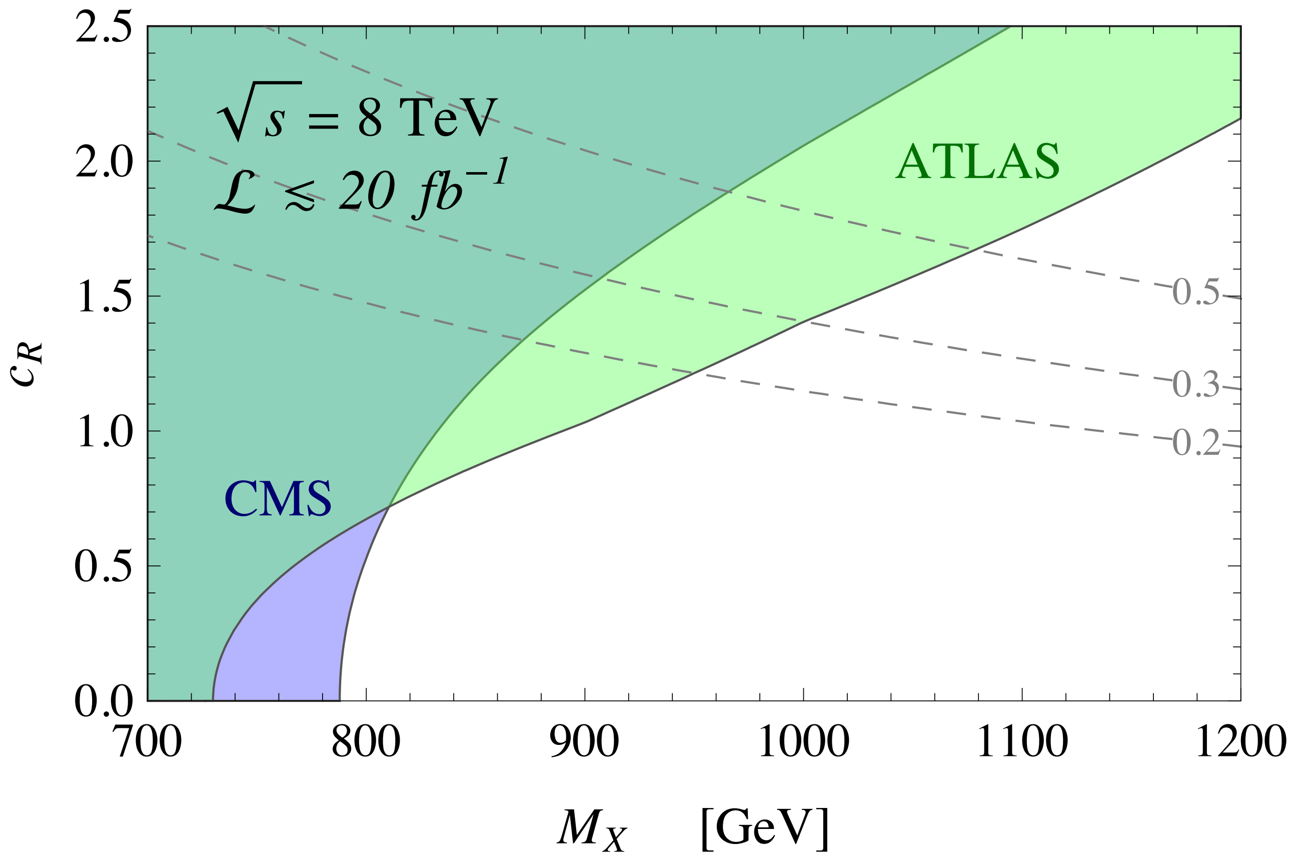
Production modes

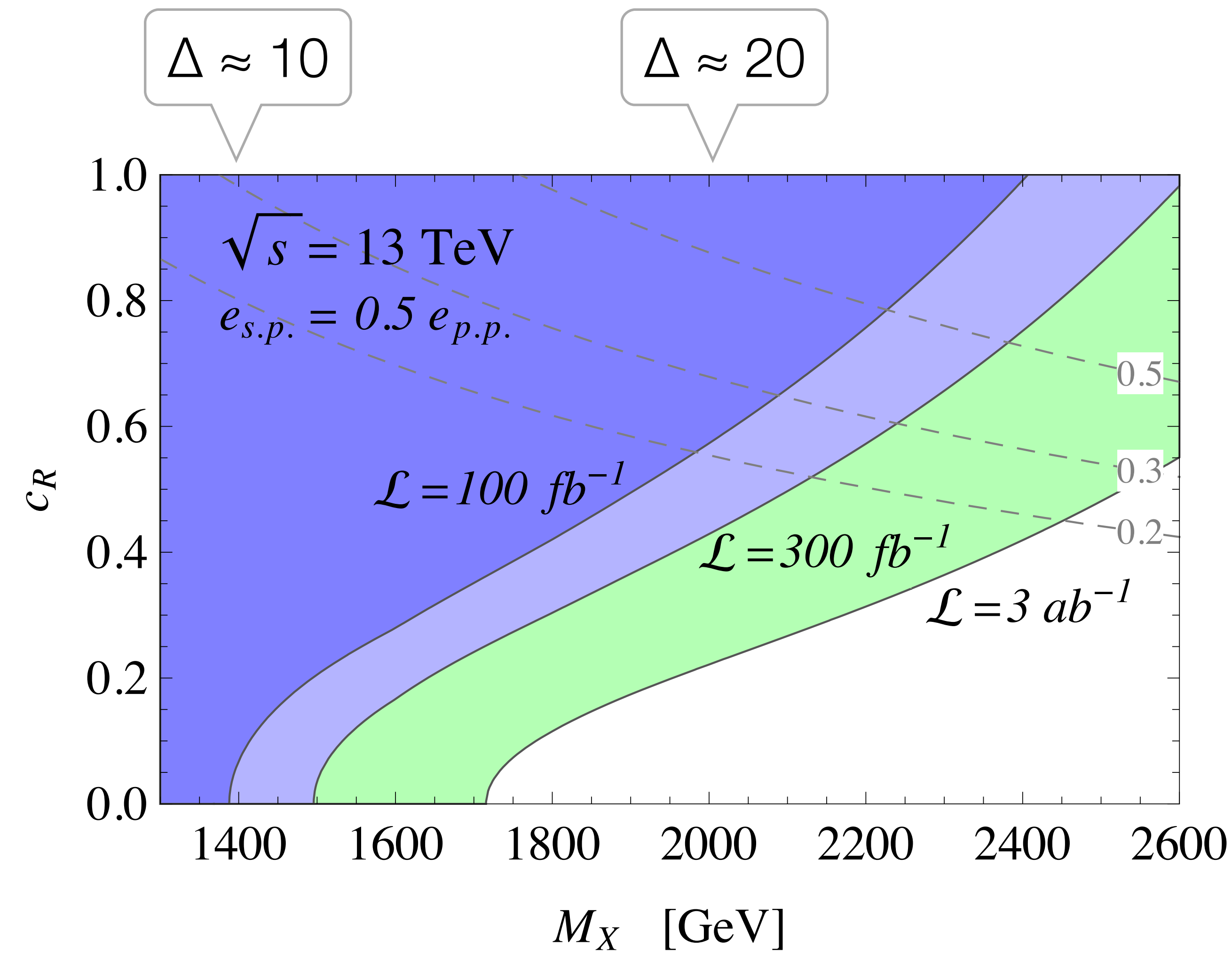


model-dep. prod.
coupling

Composite Higgs: limits on $X_{5/3}$ top partner

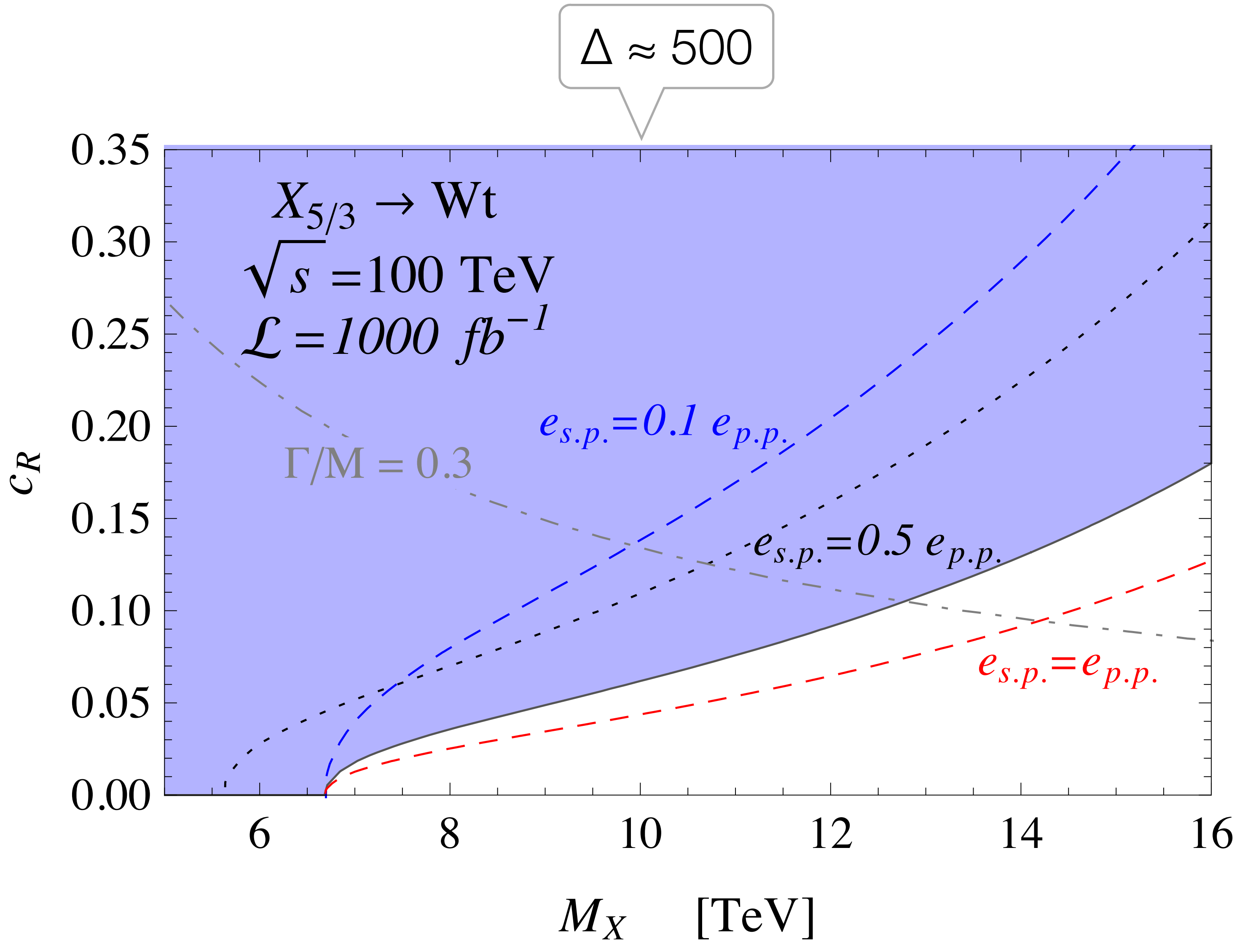
(theoretical recast)





[Matsedonskyi, Panico, Wulzer]

Composite Higgs: Limits on $X_{5/3}$ top partner



Rough FCC-hh extrapolation

Alternatives

The options:

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“Hints” of physics MUCH beyond the EW scale

- M_{Pl}

pretend gravity
does not exist

- Quantum number unification
- Neutrino masses

} give up the few things
we thought we had understood

M_{Pl}

$$M_{\rm Pl} = (G_{\rm N})^{-1/2} \approx 1.2 \times 10^{19}\,{\rm GeV}$$

but who knows?

Unification

	SU(3)	SU(2)	U(1)
L_i	1	2	-1/2
e^c_i	1	1	1
Q_i	3	2	1/6
u^c_i	3^*	1	-2/3
d^c_i	3^*	1	1/3
			Y

SO(10)
16

p-decay bounds: $M \gg m_H$

an accident?

Neutrino masses

- ASSUME: the origin of neutrino masses is at Λ » M_Z

- THEN:

$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM}^{\rm ren} + \frac{c_{ij}}{2\Lambda}(L_i H)(L_j H) + \text{h.c.}$$

$$m_{ij}^{E,D,U} = \lambda_{ij}^{E,D,U}\, v \qquad m_{ij}^{\nu} = c_{ij} v \times \frac{v}{\Lambda}$$

$$\Lambda \sim 0.5 \times 10^{15}\,\text{GeV}\, c \left(\frac{0.05\,\text{eV}}{m_\nu}\right)$$

- ALTERNATIVELY:

$$\mathcal{L}_{\nu\rm SM}^{\rm ren} = \mathcal{L}_{\rm SM}^{\rm ren} + \lambda_{ij}^{\nu}\overline{\nu_{iR}} L_j H + \text{h.c.} \qquad m_{ij}^{\nu} = \lambda_{ij}^{\nu}\, v$$

Still…

Neutrino mass models add extra particles with mass M

$$M \lesssim \begin{cases} 0.7\ 10^7\,\text{GeV} \times \sqrt[3]{\Delta} & \text{type I see-saw model,} \\ 200\,\text{GeV} \times \sqrt{\Delta} & \text{type II see-saw model,} \\ 940\,\text{GeV} \times \sqrt{\Delta} & \text{type III see-saw model.} \end{cases}$$

Leptogenesis is compatible with FN only in type I.

Axion and LHC usually are like fish and bicycle because $f_a \gtrsim 10^9\,\text{GeV}$. Axion models can satisfy FN, e.g. KSVZ models employ heavy quarks with mass M

$$M \lesssim \sqrt{\Delta} \times \begin{cases} 0.74\,\text{TeV} & \text{if } \Psi = Q \oplus \bar{Q} \\ 4.5\,\text{TeV} & \text{if } \Psi = U \oplus \bar{U} \\ 9.1\,\text{TeV} & \text{if } \Psi = D \oplus \bar{D} \end{cases}$$

Inflation does not need big scales and anyhow flatness implies small couplings. Absolute gravitational limit on H_I and on any mass [Arvinataki, Dimopoulos..]

$$\delta m^2 \sim \frac{y_t^2 M^6}{M_{\text{Pl}}^4 (4\pi)^6} \qquad \text{so} \qquad M \lesssim \Delta^{1/6} \times 10^{14}\,\text{GeV}$$

Dark Matter: extra scalars/fermions with/without weak gauge interactions.

Strumia et al

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Environmental selection

- Give up reductionist understanding of EW scale
- Assume cosmology populates a landscape of vacua
- Retain the understanding of SM gauge quantum numbers, neutrino masses, success of gauge coupling unification, WIMP miracle

Split Supersymmetry: a troubleless MSSM

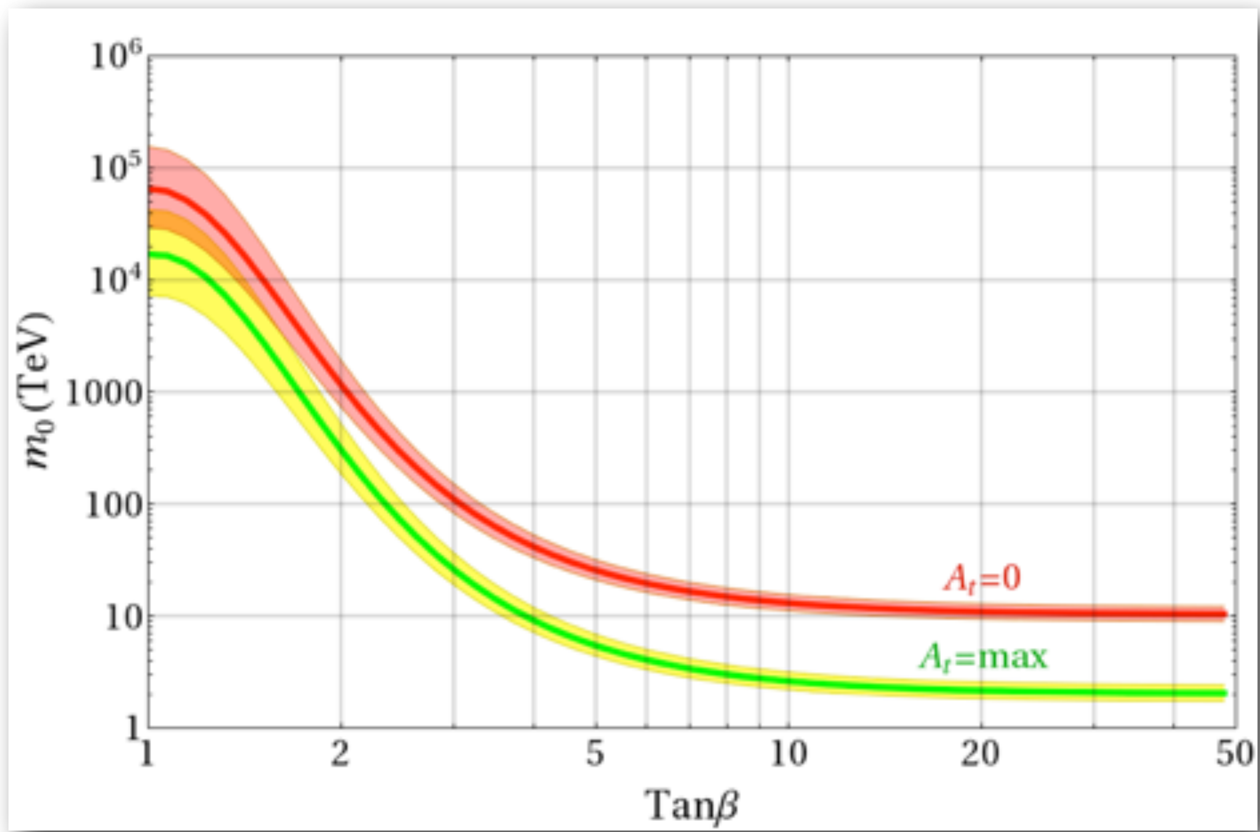
- Issues
  - Potentially > 100 parameters (CMSSM)
  - FCNCs and CP-violation in particular EDMs
  - Proton decay from dimension 5 operators
  - Gravitino and moduli problem
  - Fine-tuning

} gone

- Successes
  - Gauge coupling unification
  - Natural dark matter candidate (with R-parity)
  - Calculable, self-consistent, can be extrapolated

} retained

Higgs and stop masses



[Arvanitaki Craig Dimopoulos Villadoro]

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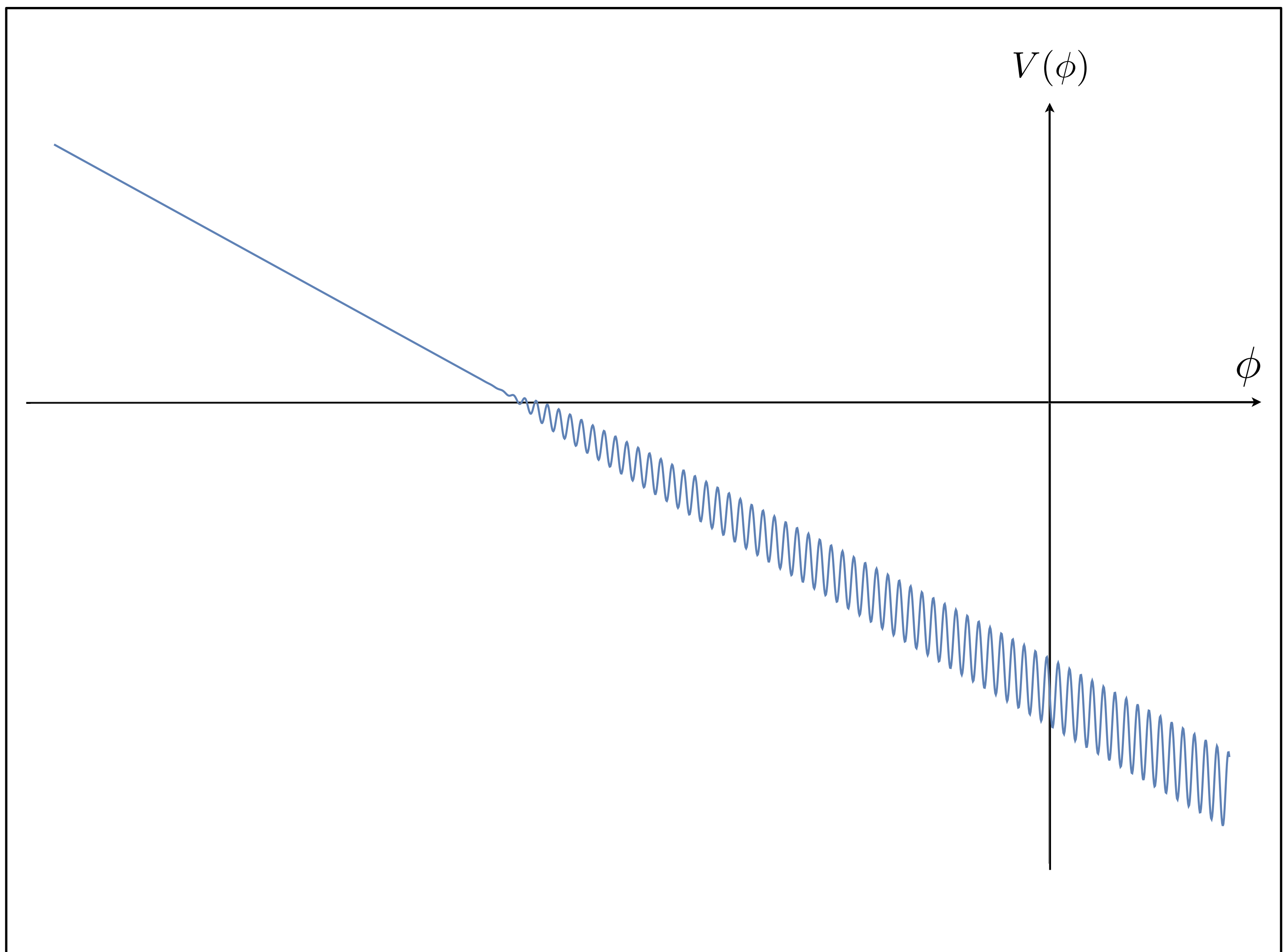
Cosmological relaxation

- Original proposal:
  - Accept field excursion up to 10^{30} GeV $(M/10\text{TeV})^2$
  - Invoke inflation model with $N \sim 10^{30}$ e-foldings
  - Non-trivial low-E inflaton dynamics to avoid $\theta_{QCD} \sim 1$
  - Low cutoff anyway $M \lesssim 30$TeV
- Just started…

Relaxion

$$\mathcal{L} = \mathcal{L}_{\rm SM} + (M^2 - \epsilon M\phi)|H|^2 + V(\epsilon\phi) + \Lambda^3 \lambda_q |H| \cos(\phi/f)$$



$$|H| \sim \frac{\epsilon}{\lambda_q}\left(\frac{M}{\Lambda}\right)^3 f \Rightarrow \epsilon \lesssim 10^{-27}$$

$$\Delta\phi \sim \frac{M}{\epsilon} \Rightarrow N_e \gtrsim 10^{30}$$

$$\theta_{\rm QCD} \sim 1$$

Final comment

- Hopefully the LHC will soon make most of these slides obsolete

- If this will not be the case, the naturalness argument will be seriously challenged and the understanding of its failure would become by far the central issue in fundamental physics