LHC and Dark Matter Signals of Improved Naturalness

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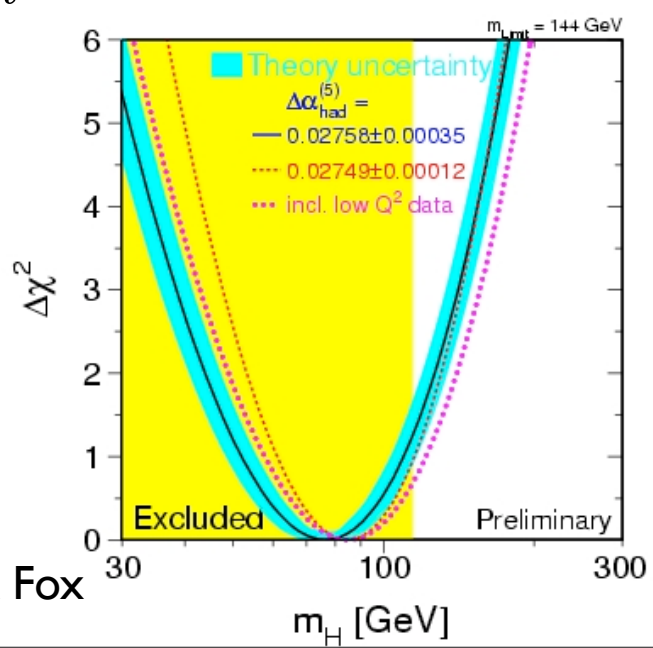
Naturalness

$$\delta m_h^2 = \frac{3m_t^2}{4\pi^2 v^2}\Lambda_t^2 - \frac{6m_W^2 + 3m_Z^2}{16\pi^2 v^2}\Lambda_g^2 - \frac{3m_h^2}{16\pi^2 v^2}\Lambda_h^2$$

Measure of fine tuning $D \equiv \frac{\partial \log m_h^2}{\partial \log \Lambda^2} = \frac{\alpha \Lambda^2}{m_h^2}$

Divergence cancelling physics enters at scales:

$\Lambda_h \approx 1.3\,\mathrm{TeV}\sqrt{D}$ $\Lambda_t \approx 3.5 m_h \sqrt{D}$ $\Lambda_g \approx 9 m_h \sqrt{D}$



Higgs is light

New coloured states at LHC

(Notable exceptions, e.g. twin Higgs)

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Improved Naturalness, or a heavy Higgs

$(400\,\mathrm{GeV} < m_h < 600\,\mathrm{GeV})$

- "Divergence cancelling" physics pushed very heavy
- Dominant source of fine tuning now the Higgs, not top
- Must be new "precision cancelling" physics around
- LHC now searches for "precision cancelling" states
- New physics may offer DM candidate
- Huge impact on LHC physics

Examples

- Higgs triplet (no DM)
- Inert doublet model Barbieri, Hall, Rychkov
- Extra leptons (this talk)

Extra Leptons Model

$$\Delta\mathcal{L} = -\lambda L H N - \lambda' L^c \tilde{H} N + M_L L L^c + \frac{1}{2} M_N N^2 + h.c.\,,$$

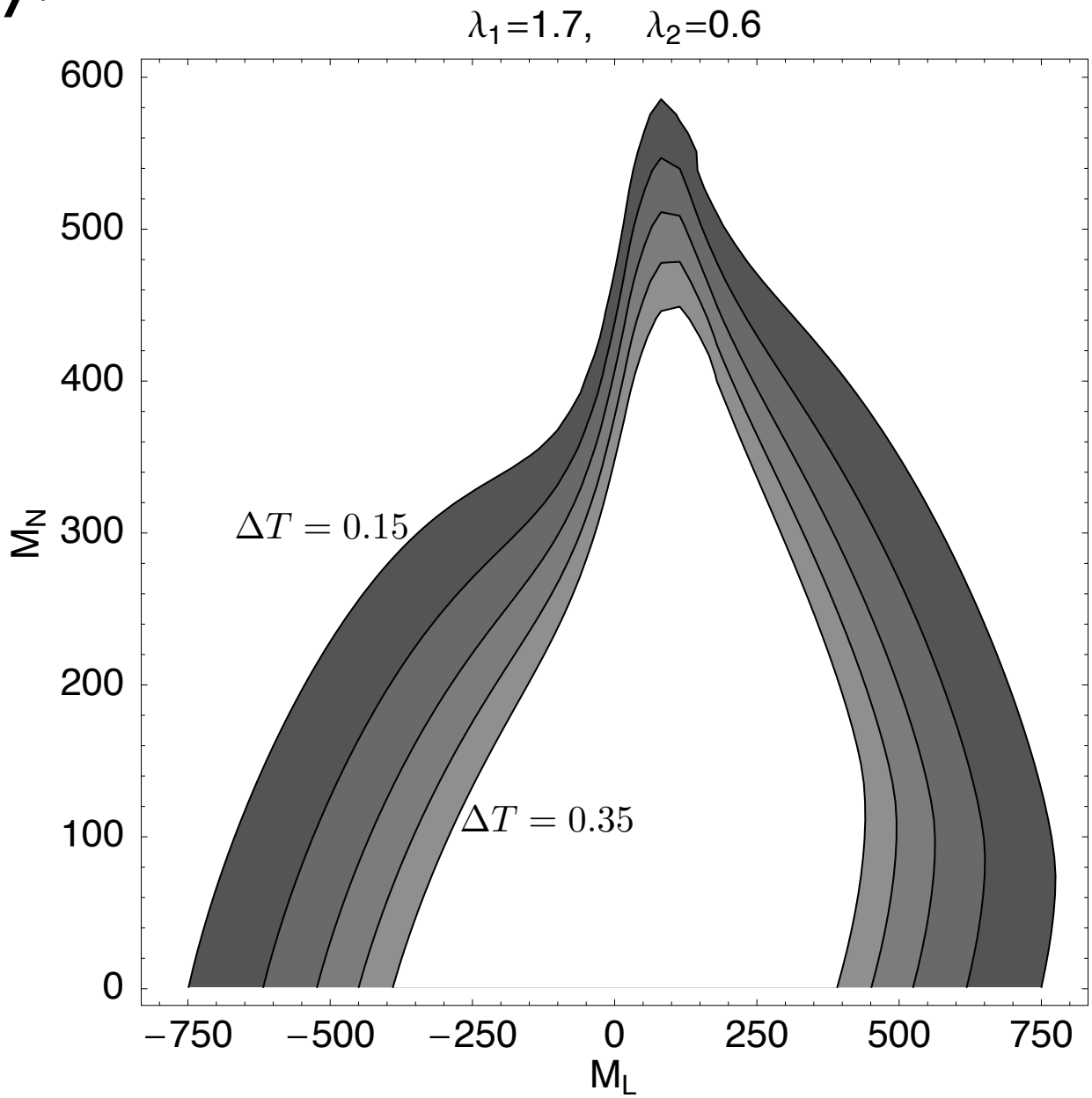
Four parameters

$$L = \begin{pmatrix} \nu \\ E \end{pmatrix}, \quad L^c = \begin{pmatrix} E^c \\ \nu^c \end{pmatrix}$$

- Require EWPT agree $0.15 < \Delta T < 0.35$
- DM abundance agrees with WMAP $0.09 < \Omega\, h^2 < 0.13$
- LIP not too light $m_{\nu_1} > 45\,\mathrm{GeV}$

Allowed by:

ΔT



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Allowed by:

ΔT

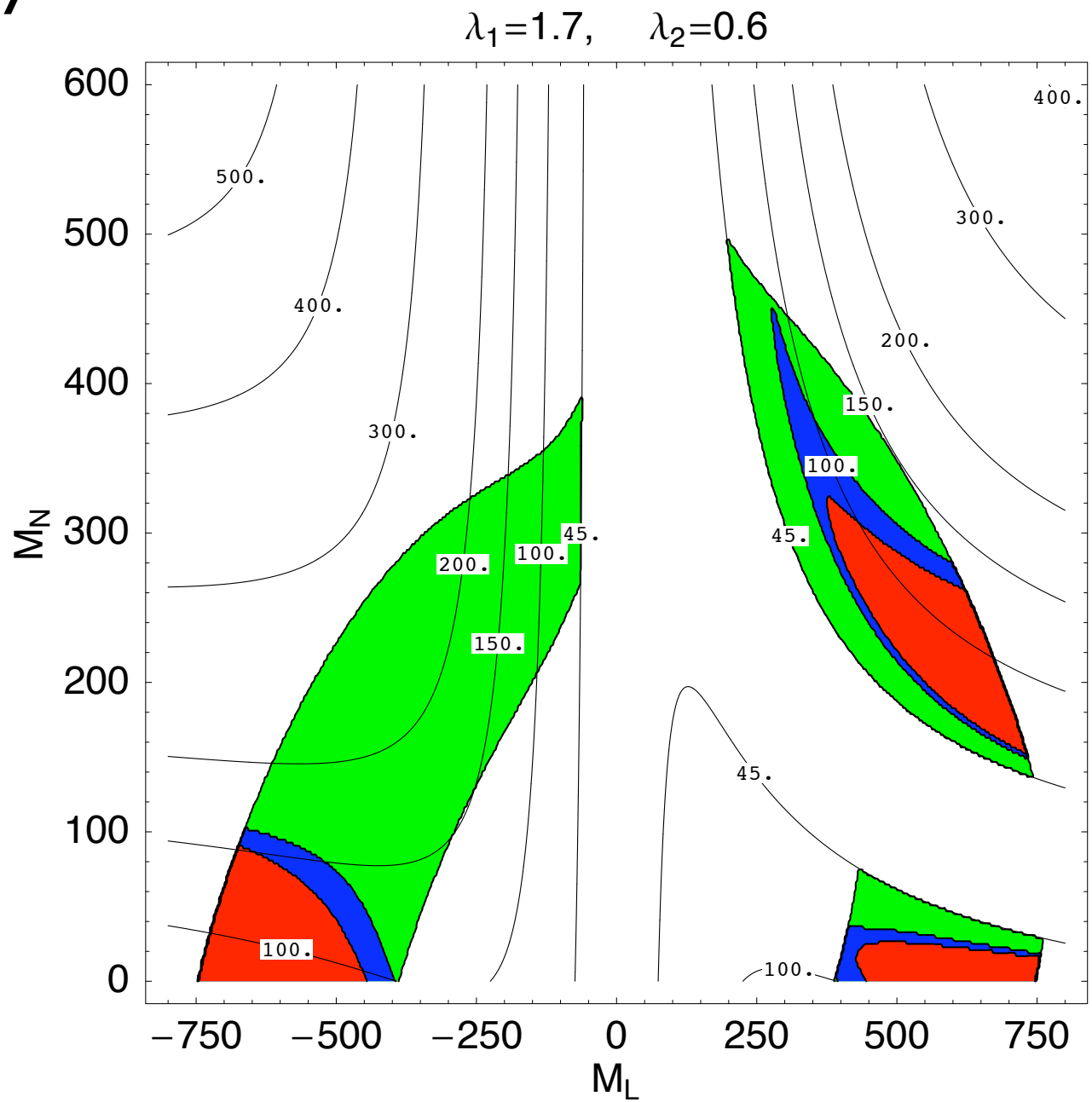
WMAP

LIP mass

$< \text{WMAP}$

$> \text{WMAP}$

$\approx \text{WMAP}$



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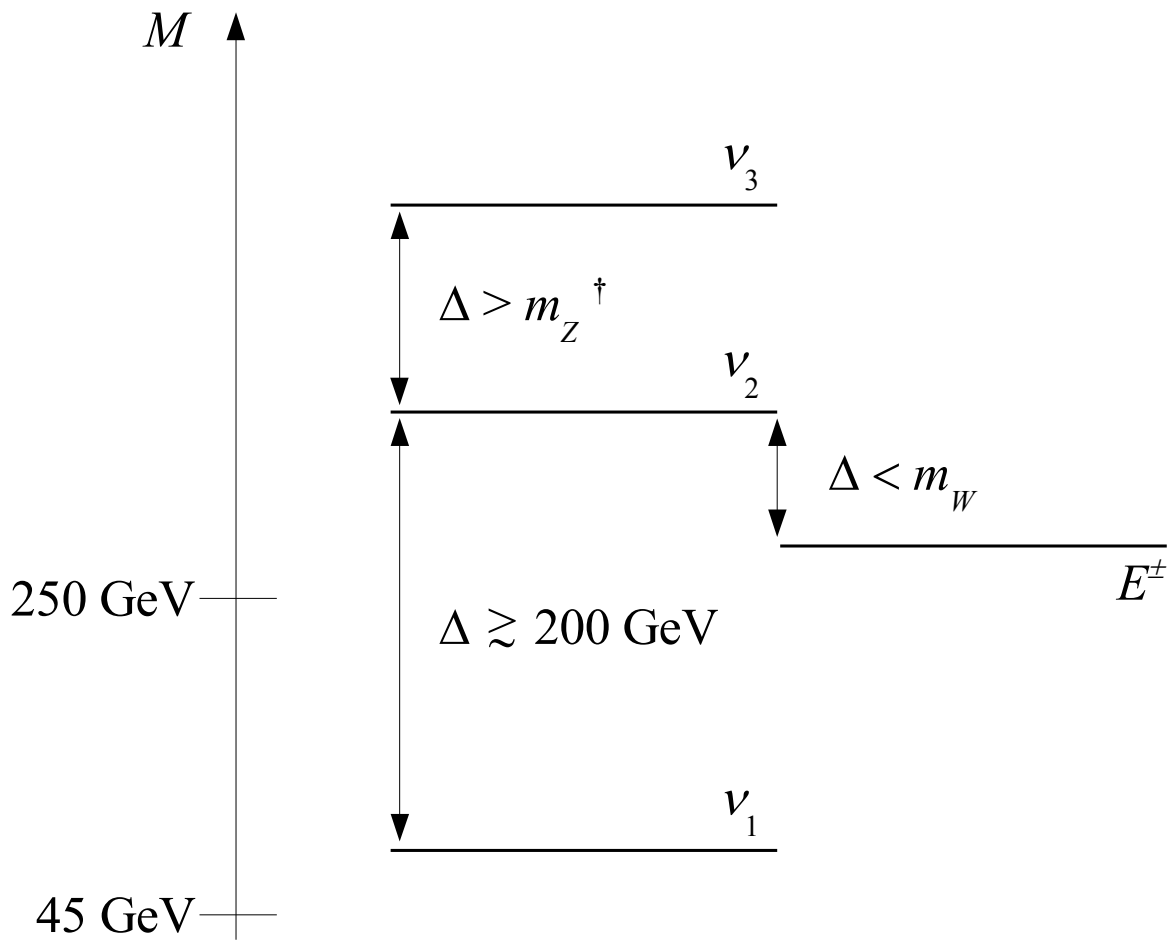
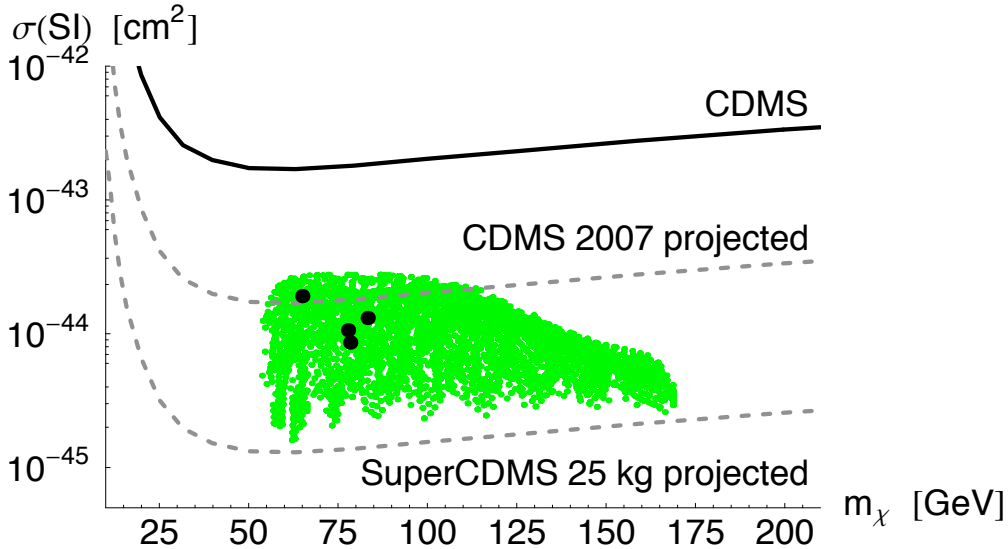
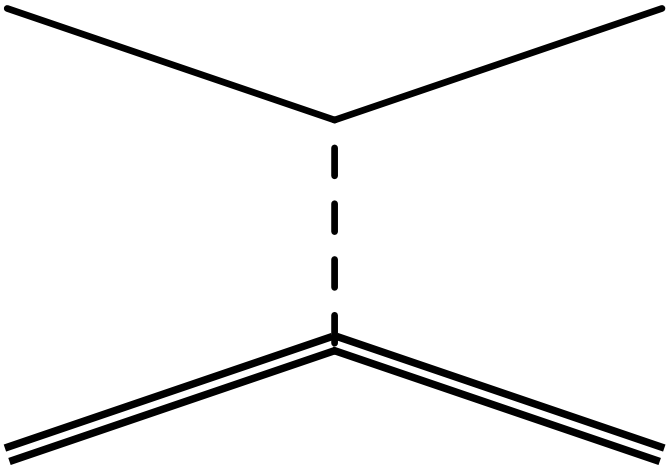
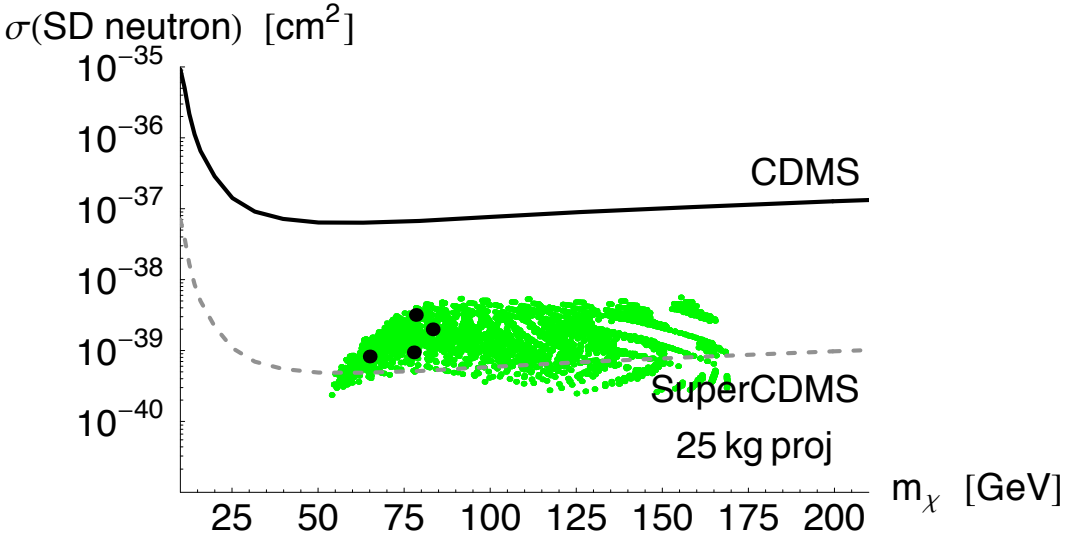
General features of parameter space

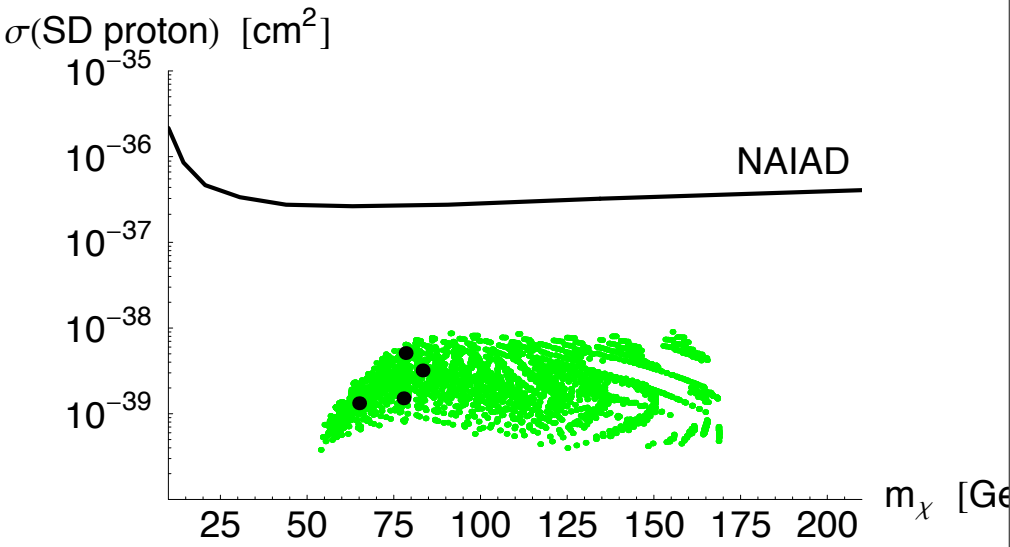


DM Direct detection









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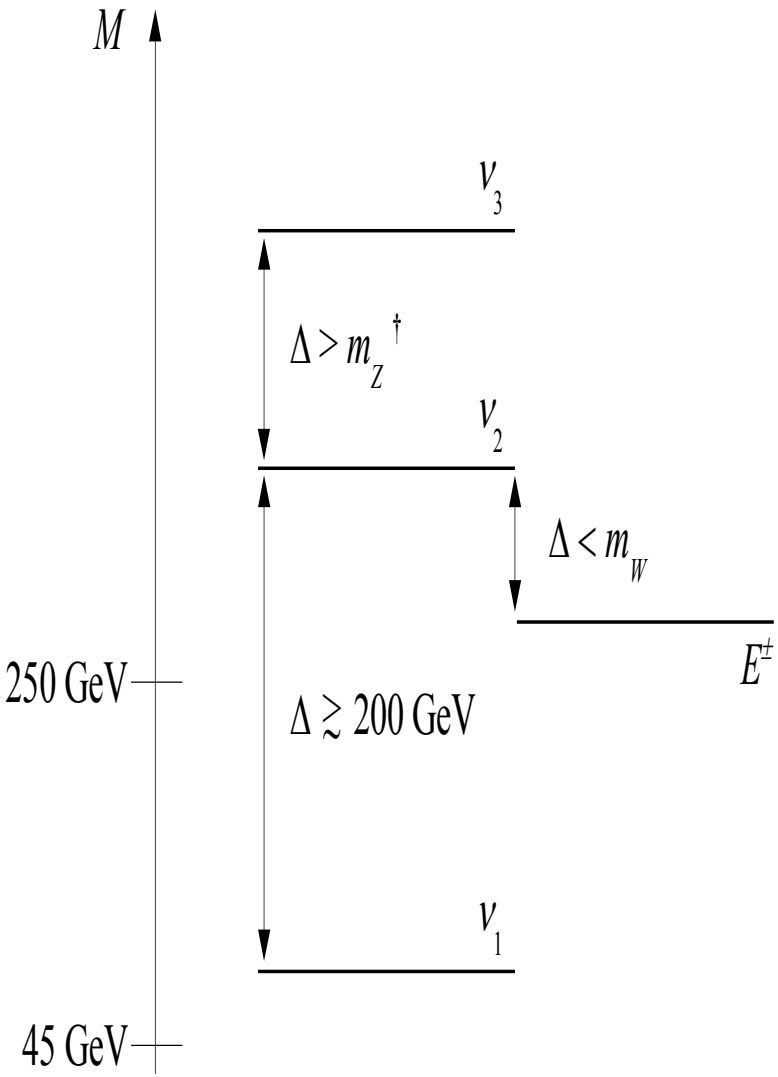
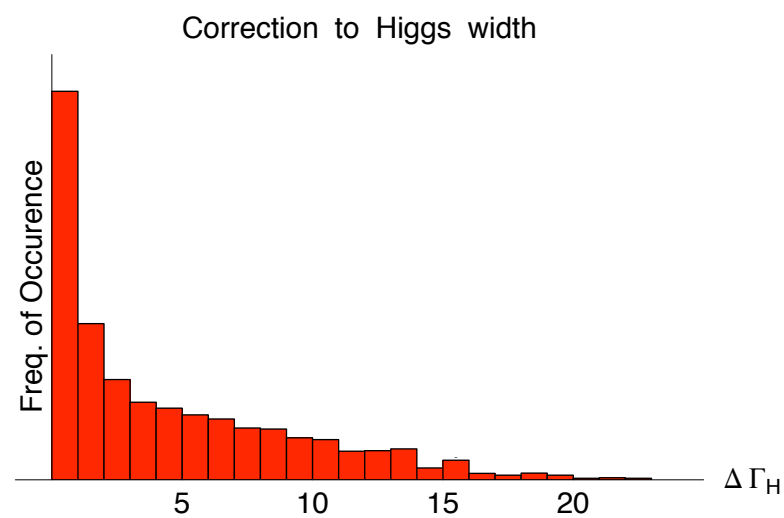
LHC signals?



Higgs

- Heavy Higgs $\mathcal{L} \approx 30\,\mathrm{fb}^{-1}, \Gamma = 64\,\mathrm{GeV}$
- Higgs width $H \to Z\,Z \to 4\,l$



New "precision cancelling" states

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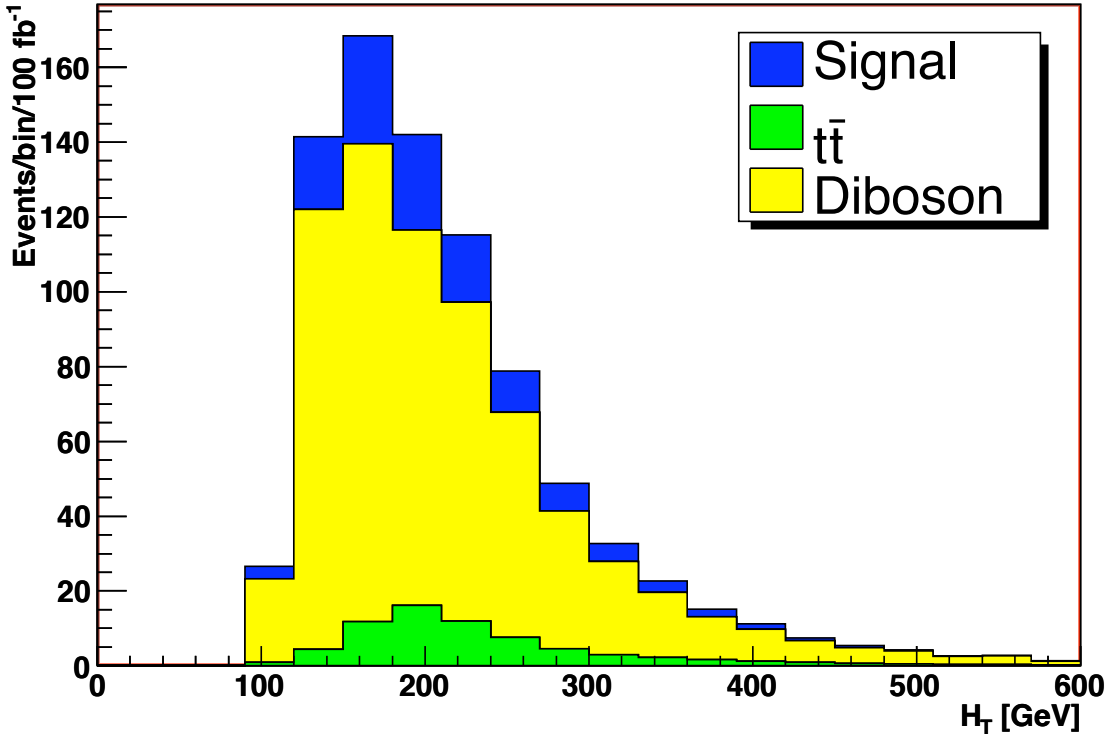
New "precision cancelling" states

- On shell EW Gauge Bosons
- One lepton $E^{\pm}\nu_1$ Background too large
- Two leptons $\nu_2\nu_1$ Just right?
- Three leptons $E^{\pm}\nu_2$ Production too small?

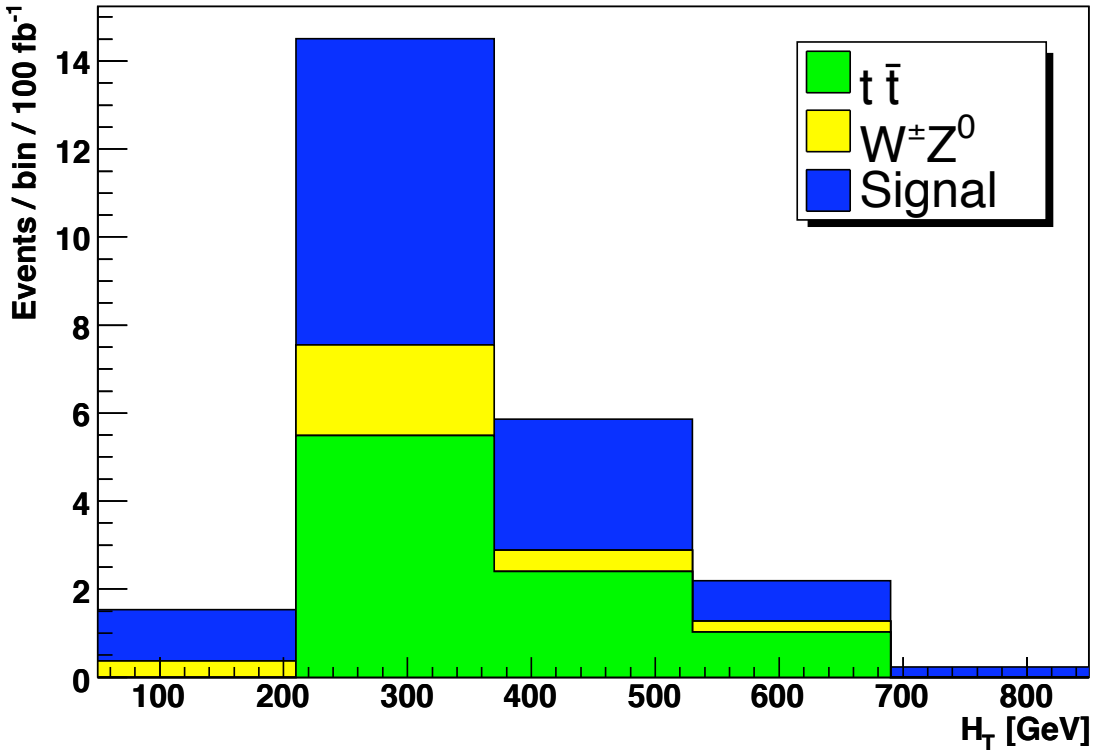
Two lepton $\nu_2\nu_1 \to \nu_1\nu_1 Z \to \nu_1\nu_1\mu^+\mu^-$

- Dimuon invariant mass close to m_Z
- Muons collimated, high pT, central
- Large missing energy

Dominant backgrounds: $WW,\ ZZ,\ WZ,\ \bar{t}t$



$$S/\sqrt{B} \sim 4.8$$



$$S/\sqrt{B} \sim 2.5$$

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Conclusions

- Heavy Higgs "improves naturalness"
- Divergence cancelling physics too heavy for LHC
- Precision cancelling hard to see
- Extra leptons is one realisation

1. Direct detection of DM
2. Heavy Higgs ~500 GeV ???
3. Higgs has the wrong width
4. ?????

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