



# *Higgs and Naturalness: Is it the right question?*

Giovanni Villadoro (ICTP)

from discussions with:

A.Arvanitaki, S.Dimopoulos, S.Dubovsky, A.Strumia


# What is naturalness?

(the EFT/empirical/pragmatic definition)

$$m = M_1 - M_2$$

# What is naturalness?

(the EFT/empirical/pragmatic definition)

$$m = M_1 - M_2$$


*symmetry*

# What is naturalness?

(the EFT/empirical/pragmatic definition)

$$m = \alpha M_1$$

# What is naturalness?

(the EFT/empirical/pragmatic definition)

$$m = \alpha M_1 - M_2$$


*symmetry*

$\Rightarrow$  *new physics at the EW scale*

*(SUSY+sparticles, composite dynamics, etc...)*

# Successes of Naturalness

*a few examples:*

Electron Mass  Lorentz Symmetry  Positron

$\pi^+-\pi^0$  mass splitting  Isospin Symmetry  Heavy Hadrons

Kaon mixing  Flavour Symmetry  Charm

Proton Mass  Dynamics

 QCD

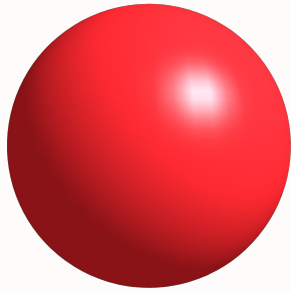
$^2\text{H}$  binding energy  Dynamics

# Understanding Deuteron Binding Energy

## 1. Baryons are Fat!

# Understanding Deuteron Binding Energy

## 1. Baryons are Fat!



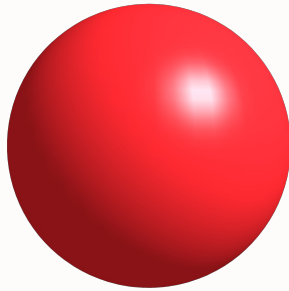
1 fm

$$r_p \sim \Lambda_{\text{QCD}}^{-1} \sim \mathcal{O}(1)$$



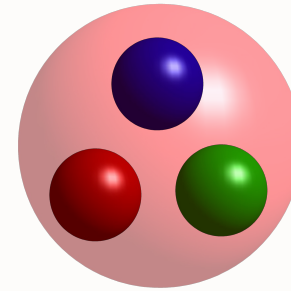
# Understanding Deuteron Binding Energy

## 1. Baryons are Fat!



$1 \text{ fm}$

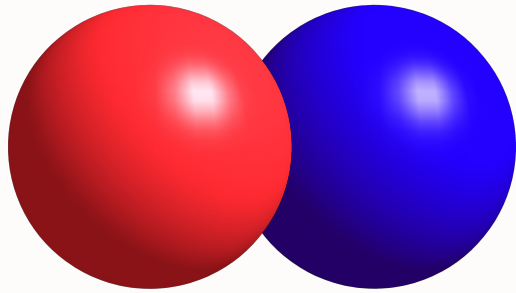
$$r_p \sim \Lambda_{\text{QCD}}^{-1} \sim \mathcal{O}(1)$$



$$m_p \sim 1 \text{ GeV} \sim \mathcal{O}(N)$$

$$m_p r_p \sim 5 \sim \mathcal{O}(N)$$

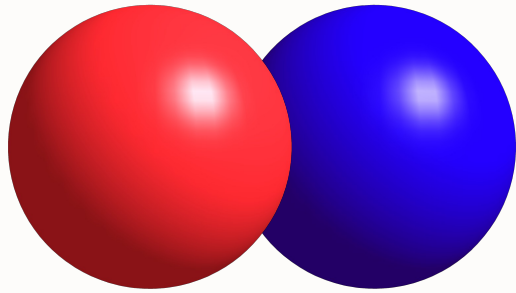
# The Deuteron Binding Energy



$r \sim 2 \text{ fm}$

$$E_b \approx \frac{1}{2} \mu v^2$$

# The Deuteron Binding Energy

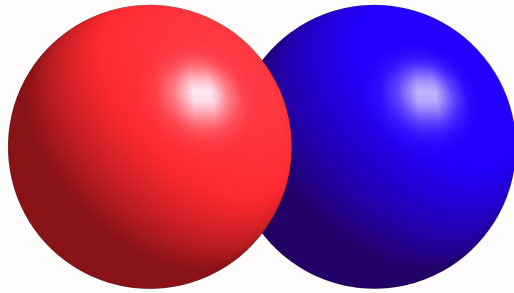


$r \sim 2 \text{ fm}$

$$E_b \approx \frac{1}{2} \mu v^2 = \frac{1}{2} \frac{m}{2} \frac{1}{m^2 r^2}$$

The equation is annotated with a green box containing  $mvr = 1$  and a green arrow pointing to the  $1$  in the denominator of the second term.

# The Deuteron Binding Energy



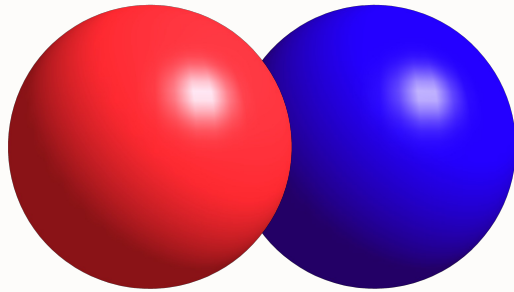
$r \sim 2 \text{ fm}$

$$E_b \approx \frac{1}{2} \mu v^2 = \frac{1}{2} \frac{m}{2} \frac{1}{m^2 r^2} \sim 2 \text{ MeV}$$

$mvr = 1$

$\sim 10^2$

# The Deuteron Binding Energy



$r \sim 2 \text{ fm}$

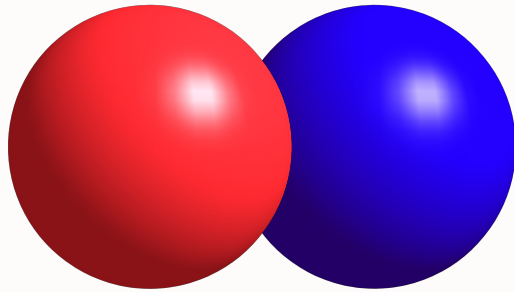
$$E_b \approx \frac{1}{2} \mu v^2 = \frac{1}{2} \frac{m}{2} \frac{1}{m^2 r^2} \sim 2 \text{ MeV}$$

$mvr = 1$

$\sim 10^2$

$$E_b \sim \mathcal{O}\left(\frac{1}{N^2}\right)$$

# The Deuteron Binding Energy



$r \sim 2 \text{ fm}$

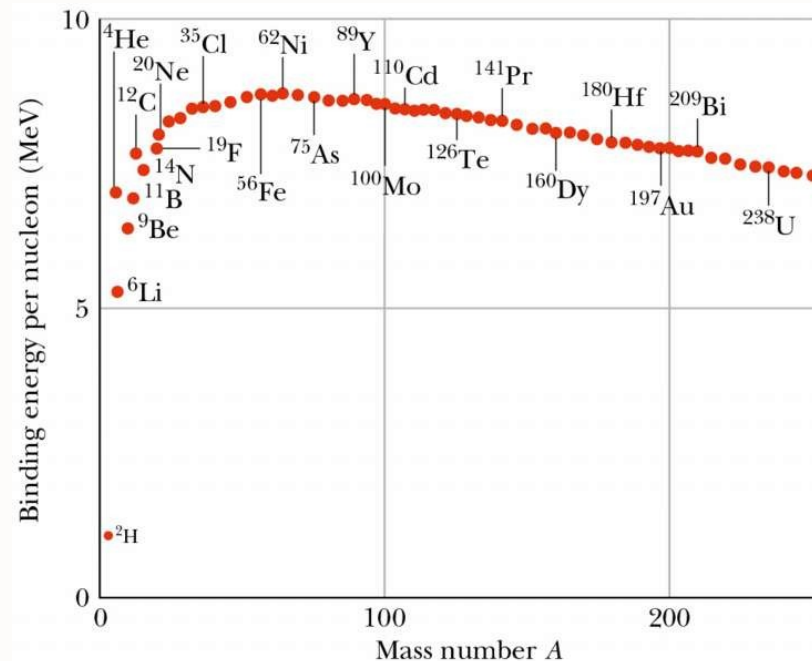
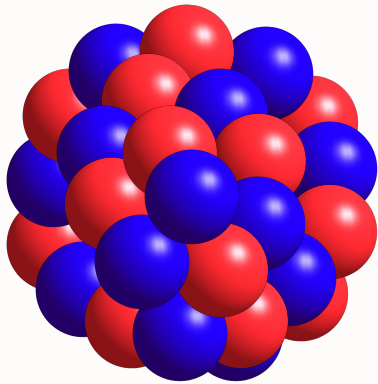
$$E_b \approx \frac{1}{2} \mu v^2 = \frac{1}{2} \frac{m}{2} \frac{1}{m^2 r^2} \sim 2 \text{ MeV}$$

$mvr = 1$

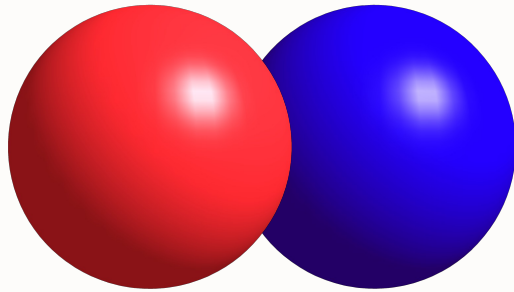
$\sim 10^2$

$$E_b \sim \mathcal{O}\left(\frac{1}{N^2}\right)$$

## Heavy Nuclei:



# The Deuteron Binding Energy



$r \sim 2 \text{ fm}$

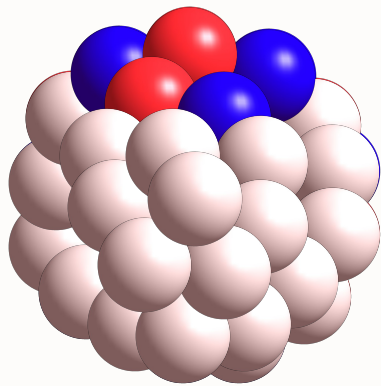
$$E_b \approx \frac{1}{2} \mu v^2 = \frac{1}{2} \frac{m}{2} \frac{1}{m^2 r^2} \sim 2 \text{ MeV}$$

$mvr = 1$

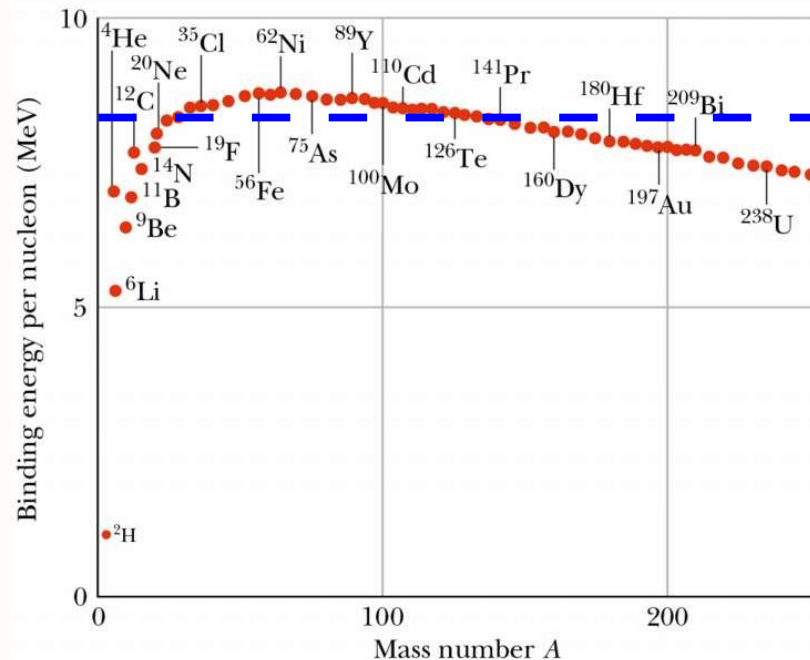
$\sim 10^2$

$$E_b \sim \mathcal{O}\left(\frac{1}{N^2}\right)$$

## Heavy Nuclei:

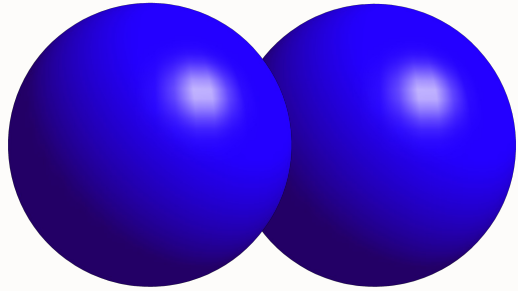


only nearest neighbors interactions



$E_b \sim \text{few} \times 2 \text{ MeV}$

# Dineutron (Un)Binding Energy

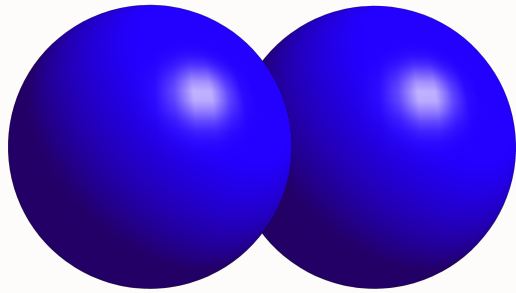


for  $n-n$  would-be  $E_b \sim 100$  keV

*Anomalously small?*



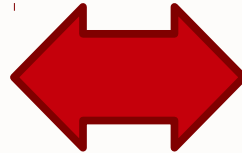
# Dineutron (Un)Binding Energy



for  $n-n$  would-be  $E_b \sim 100$  keV

*Anomalously small?*

$$a_0^{(np)} \sim 5.4 \text{ fm}$$



$$a_1^{(np)} \sim -23.7 \text{ fm}$$

*only a factor of 4 apart*

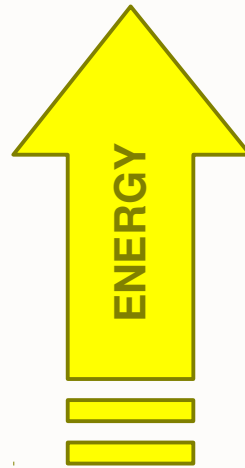
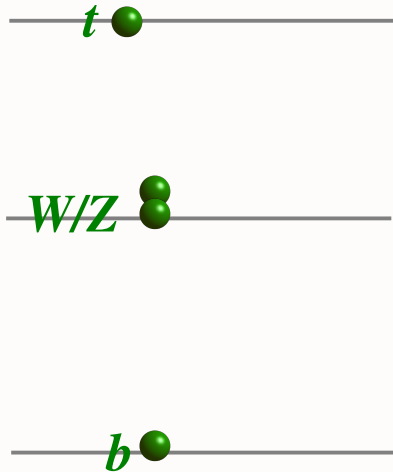


The big failure:

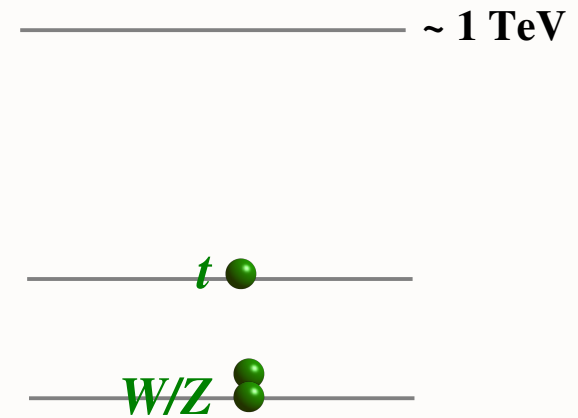
$\Lambda_{cc}$

# How a Natural Higgs looks like:

**SUSY**

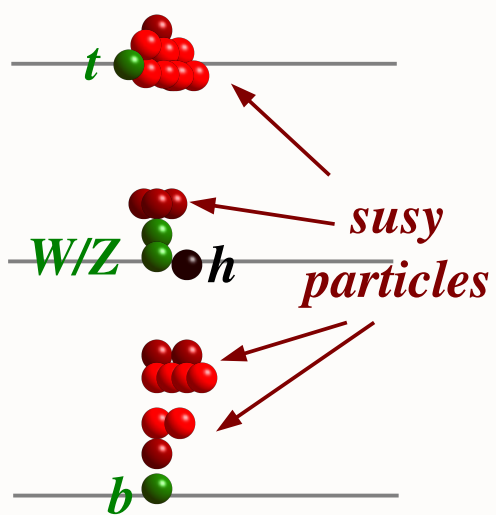


**Strong dynamics**

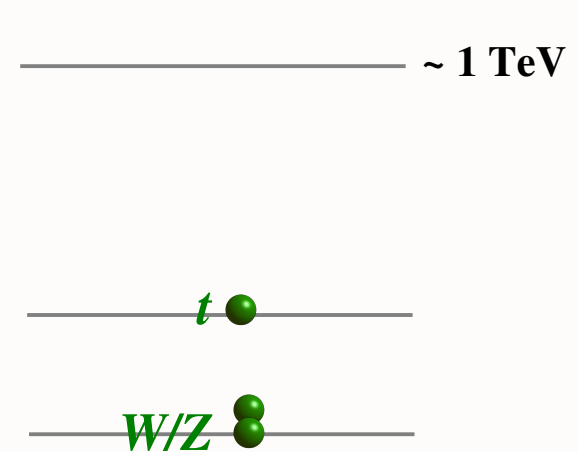


# How a Natural Higgs looks like:

## SUSY

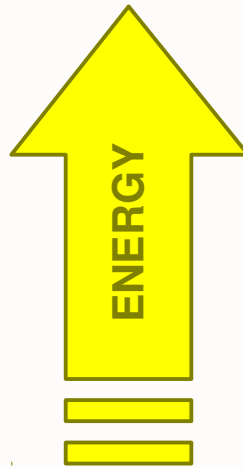
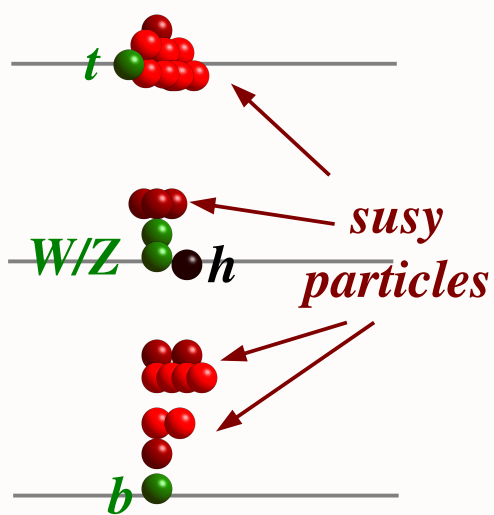


## Strong dynamics

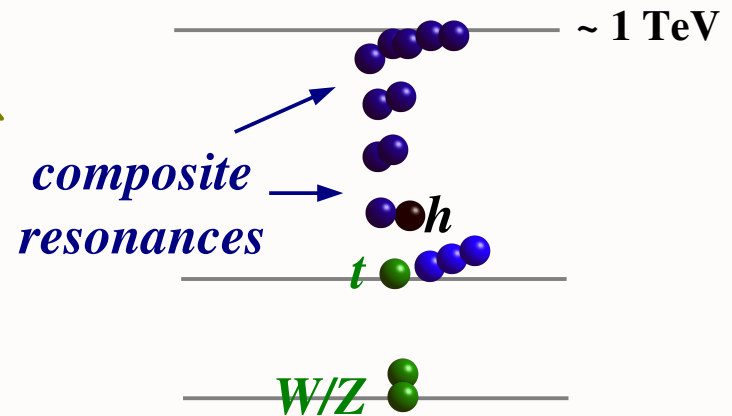


# How a Natural Higgs looks like:

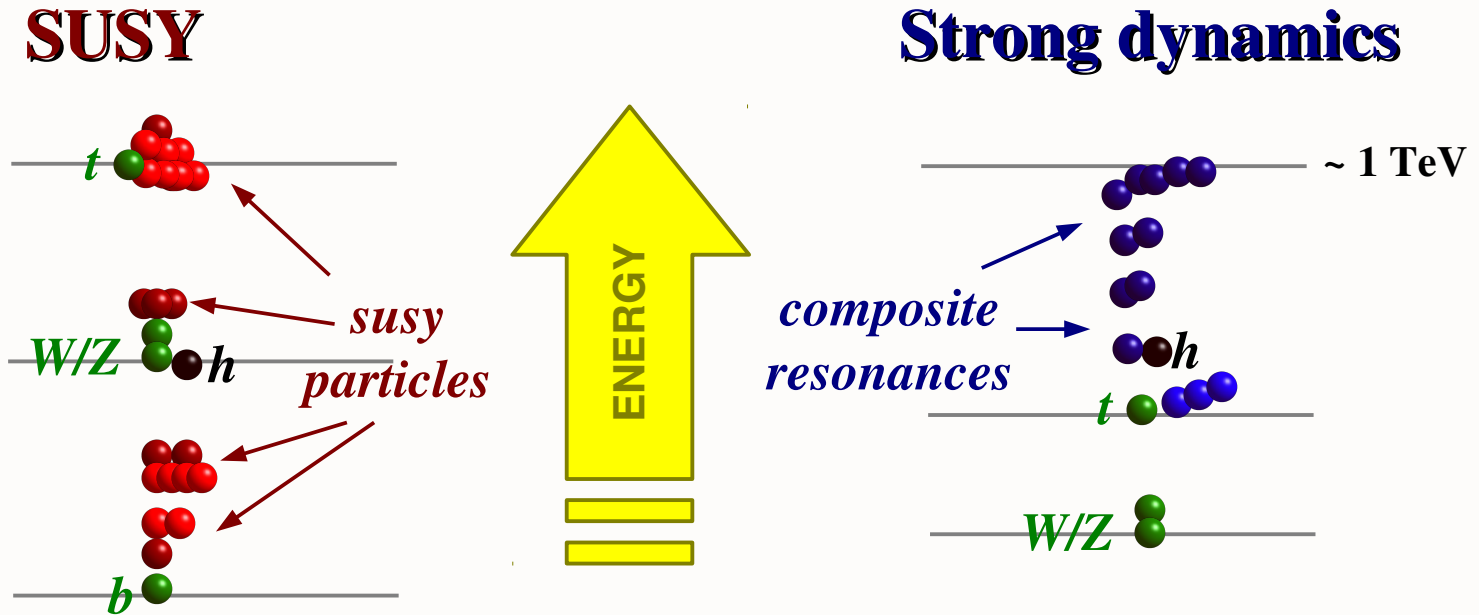
## SUSY



## Strong dynamics

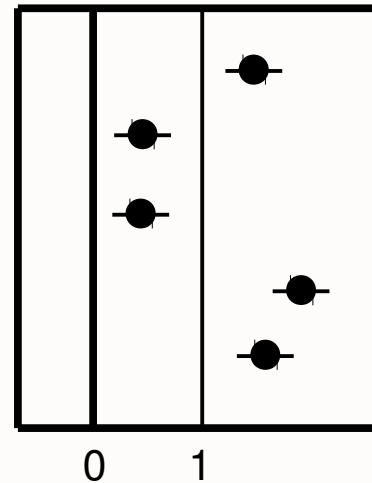
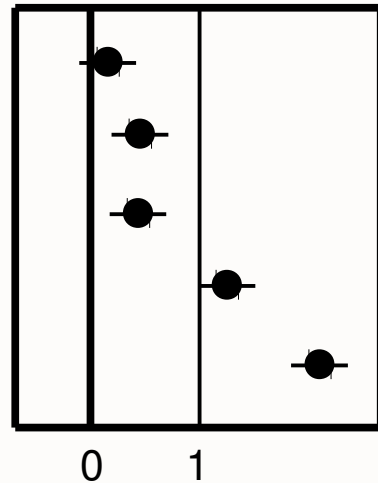


# How a Natural Higgs looks like:



## A Natural Higgs is not SM-like

$$R = 1 + \mathcal{O}\left(\frac{v^2}{m_{\text{susy}}^2}\right)$$

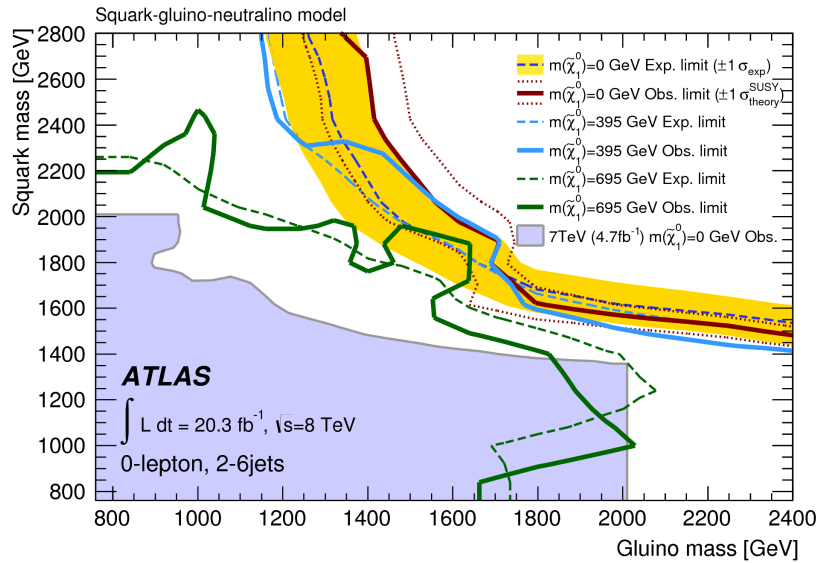


$$R = 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right)$$

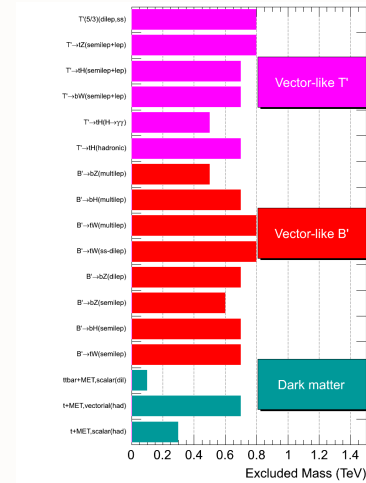
+ large flavor/EWPT violations

# How a (un)Natural Higgs looks like:

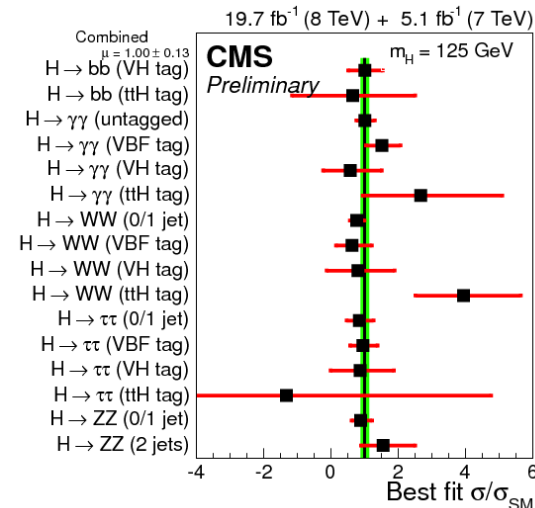
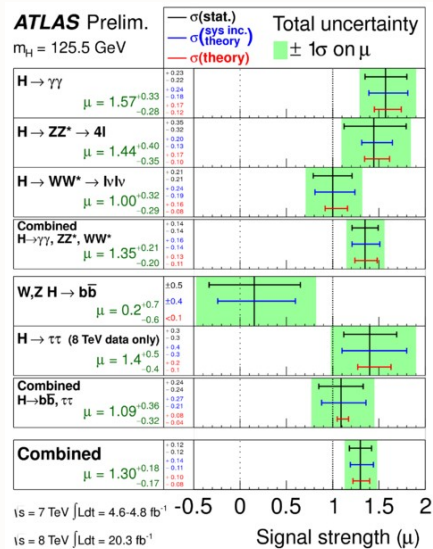
## SUSY



## Strong dynamics

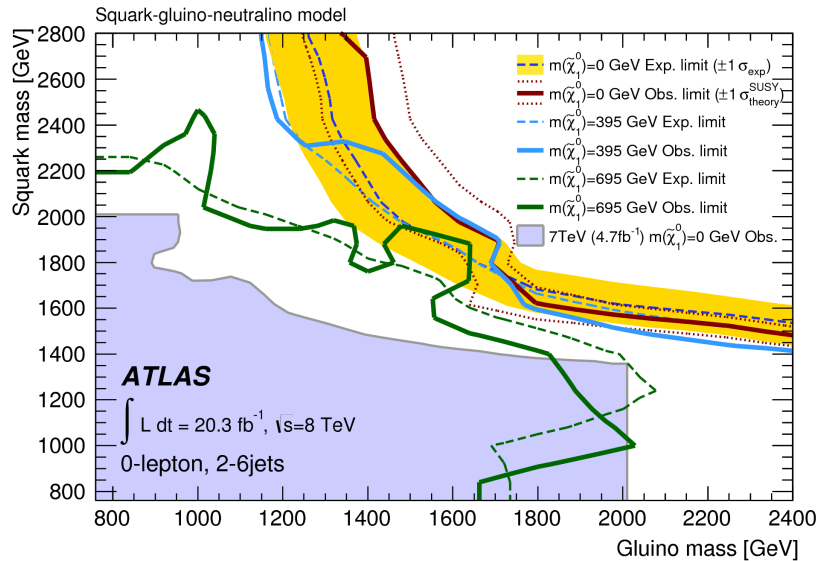


## A Natural Higgs is not SM-like

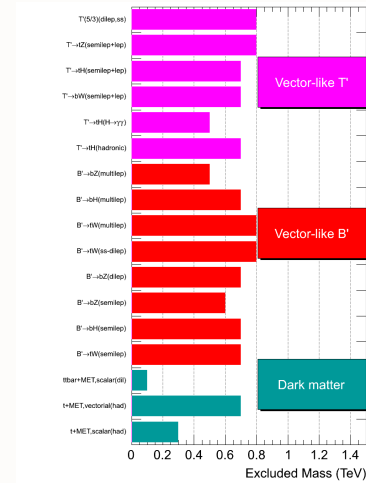


# How a (un)Natural Higgs looks like:

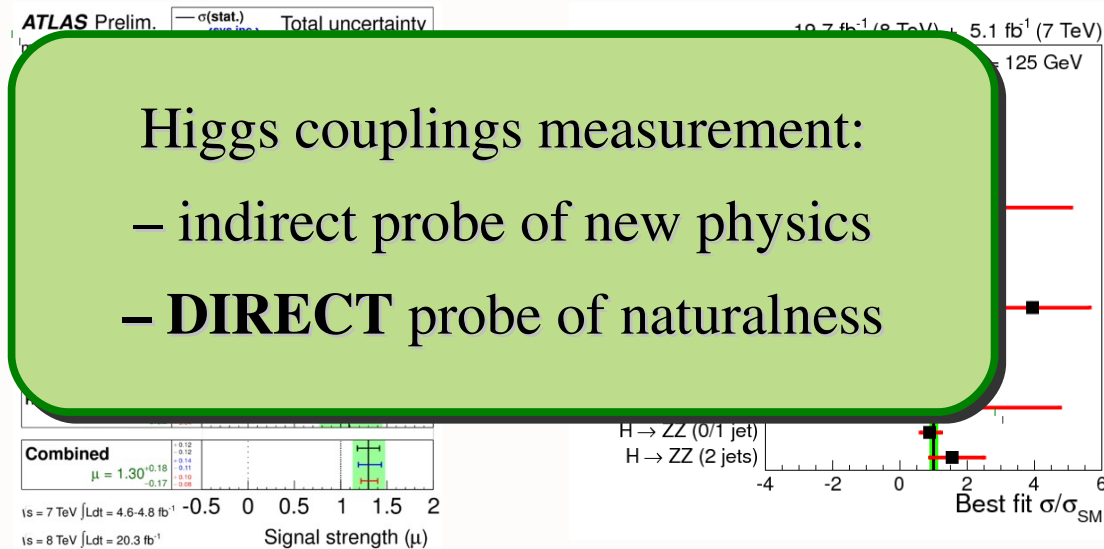
## SUSY



## Strong dynamics



## A Natural Higgs is not SM-like



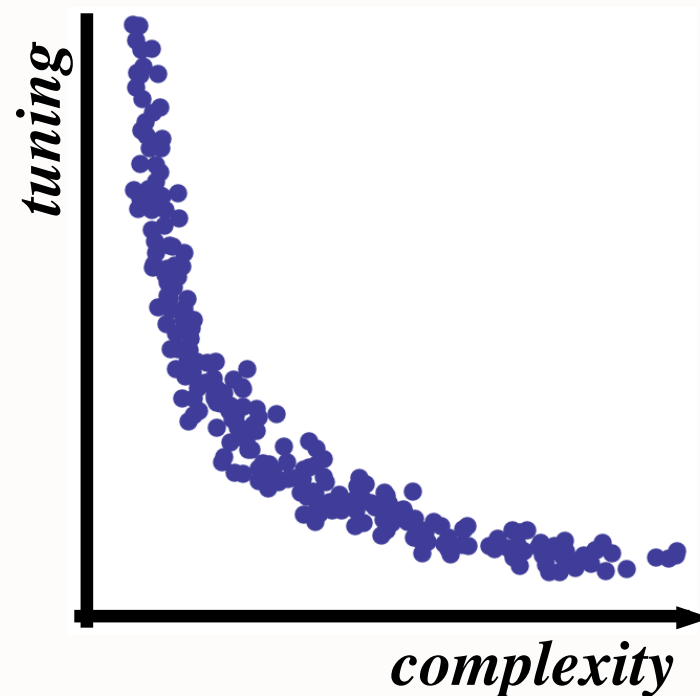


# Maybe it's not that simple

- e.g.* SUSY + **X** where **X** is one of the following:
- RPV, split families, dirac gauginos,  
stealth/compressed spectra, ...
  - + **Y** where **Y** adjusts the Higgs mass
  - + **Z** where **Z** adjusts ...

# Maybe it's not that simple

- e.g.* SUSY + **X** where **X** is one of the following:  
RPV, split families, dirac gauginos,  
stealth/compressed spectra, ...  
+ **Y** where **Y** adjusts the Higgs mass  
+ **Z** where **Z** adjusts ...



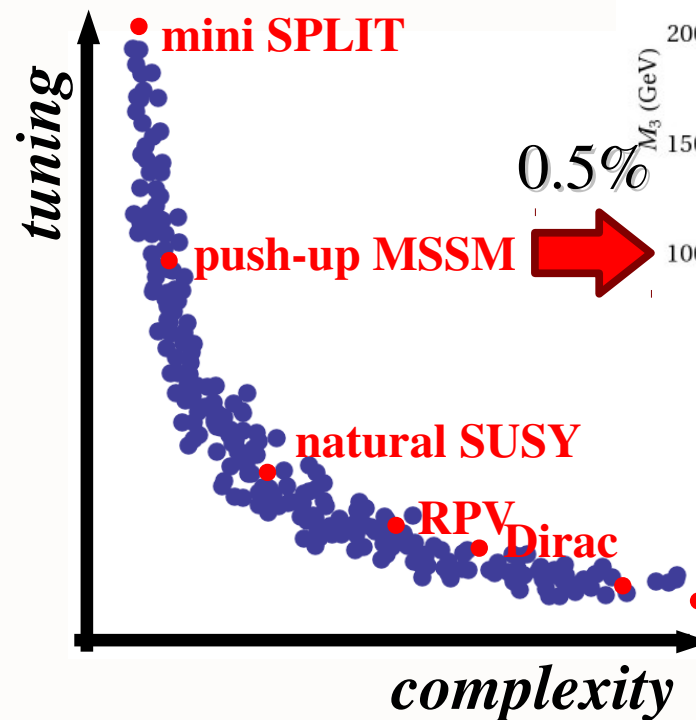
# Maybe it's not that simple

*e.g.* SUSY + **X** where **X** is one of the following:

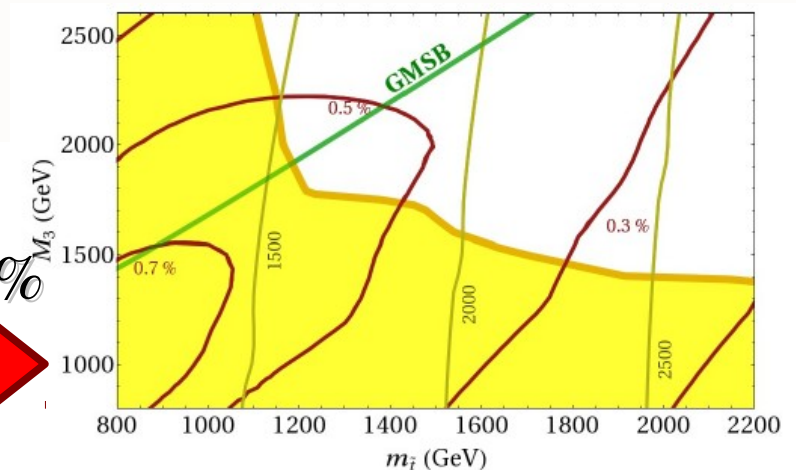
RPV, split families, dirac gauginos,  
stealth/compressed spectra, ...

+ **Y** where Y adjusts the Higgs mass

+ **Z** where Z adjusts ...



0.5%



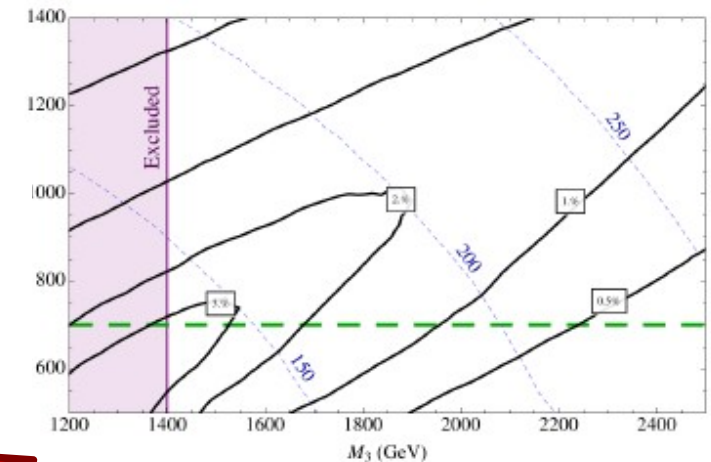
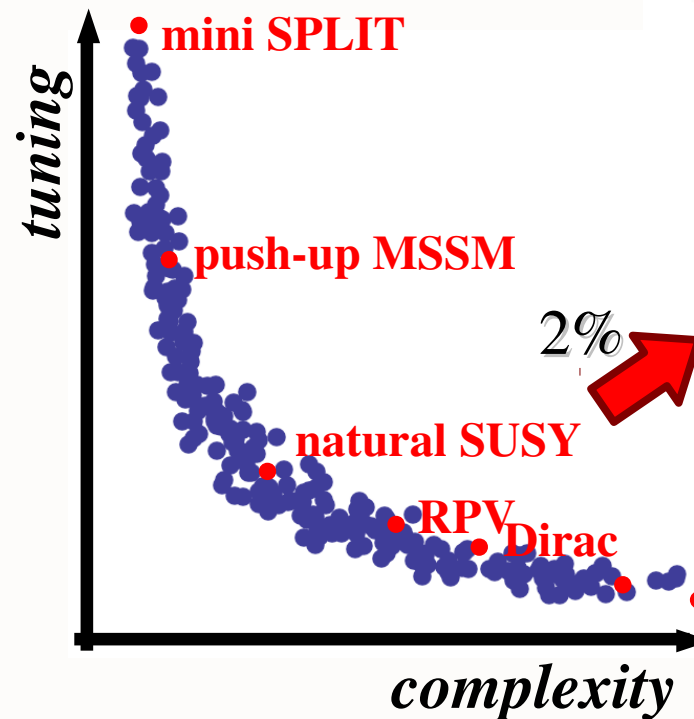
# Maybe it's not that simple

*e.g.* SUSY + **X** where **X** is one of the following:

RPV, split families, dirac gauginos,  
stealth/compressed spectra, ...

+ **Y** where Y adjusts the Higgs mass

+ **Z** where Z adjusts ...



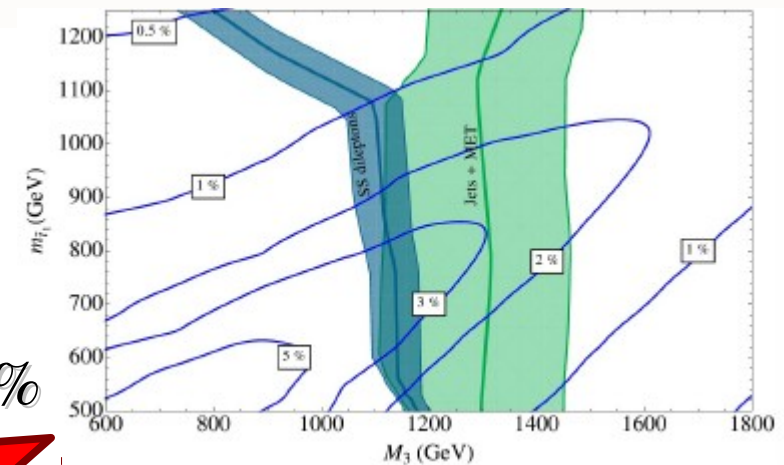
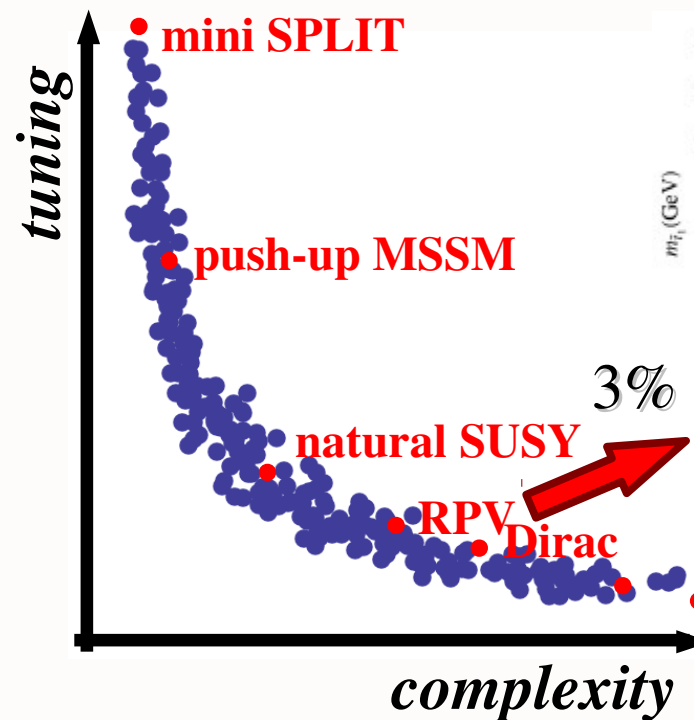
# Maybe it's not that simple

*e.g.* SUSY + **X** where **X** is one of the following:

RPV, split families, dirac gauginos,  
stealth/compressed spectra, ...

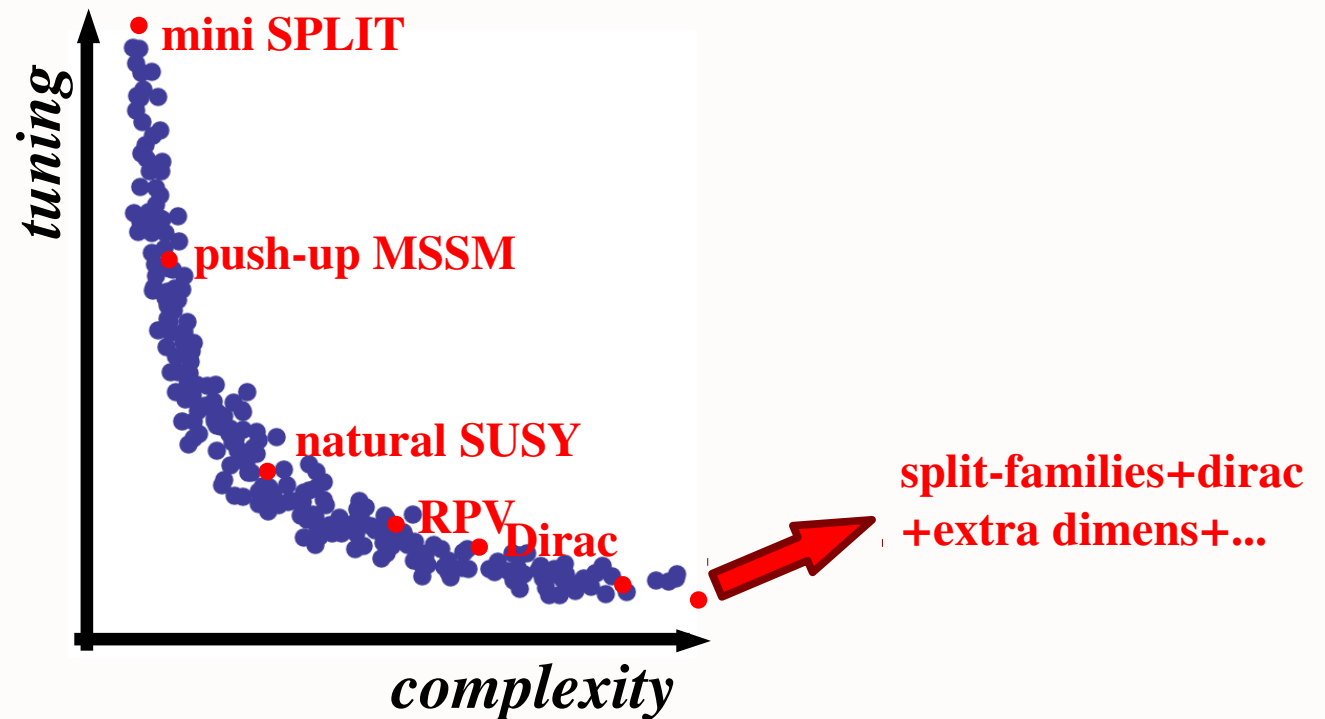
+ **Y** where Y adjusts the Higgs mass

+ **Z** where Z adjusts ...

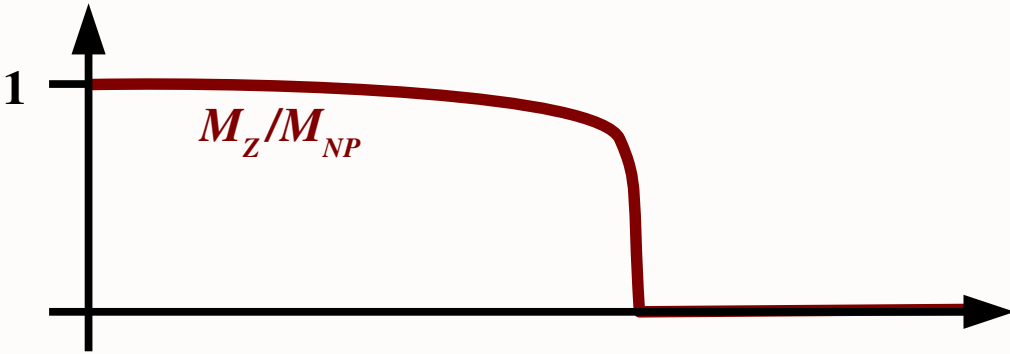


# Maybe it's not that simple

- e.g.* SUSY + **X** where **X** is one of the following:  
RPV, split families, dirac gauginos,  
stealth/compressed spectra, ...  
+ **Y** where **Y** adjusts the Higgs mass  
+ **Z** where **Z** adjusts ...

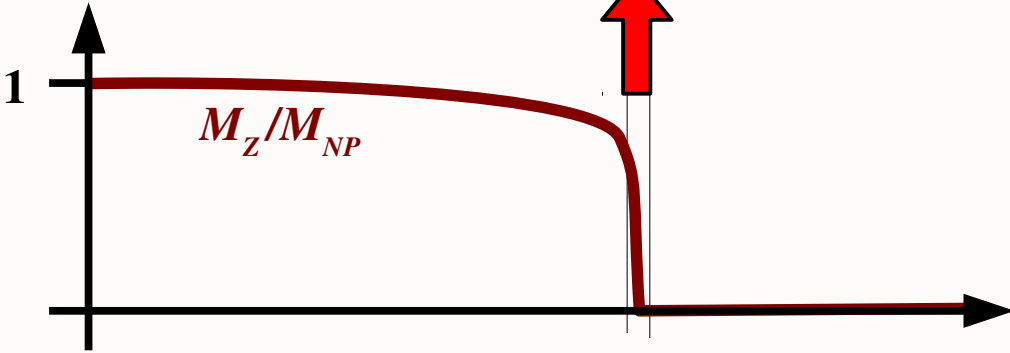
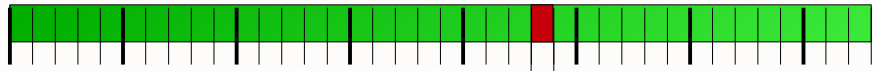


# Fine-Tuning



# Fine-Tuning

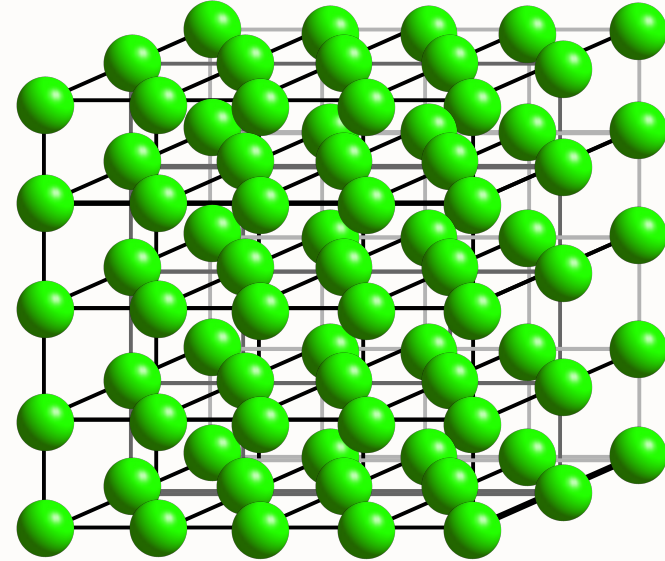
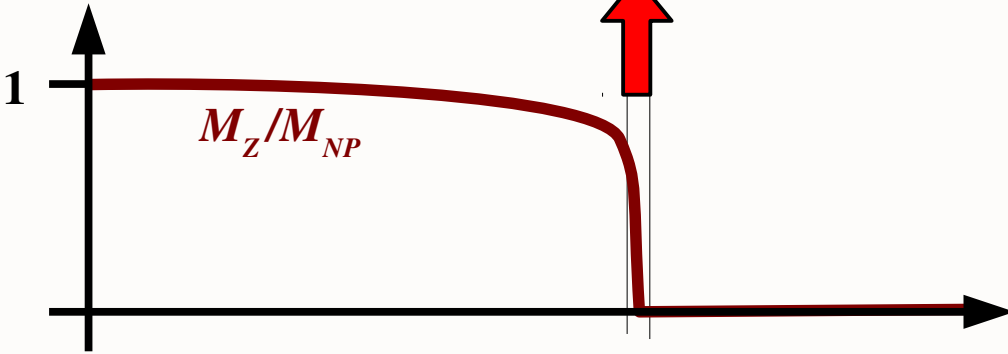
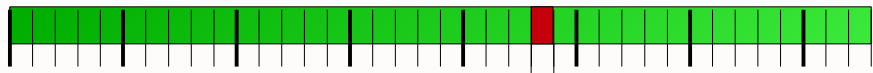
particular choice of a continuous parameter





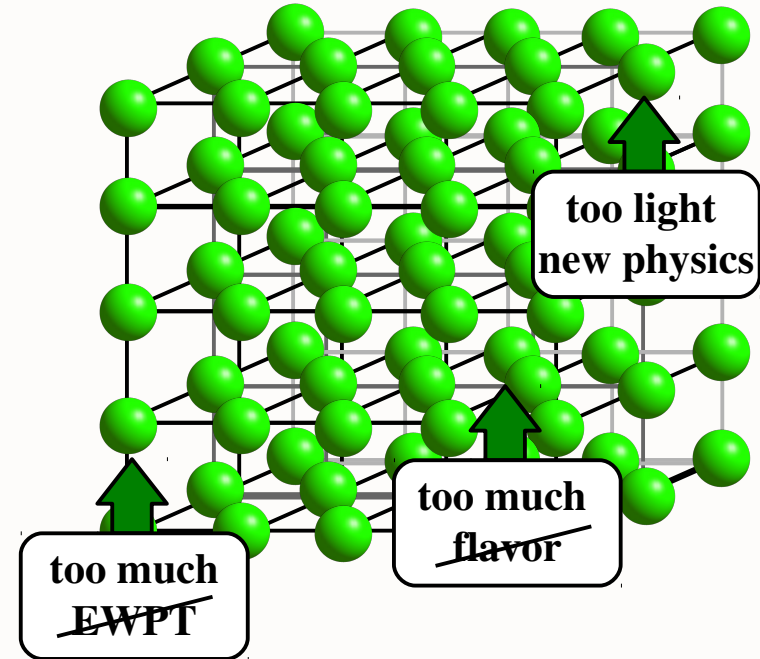
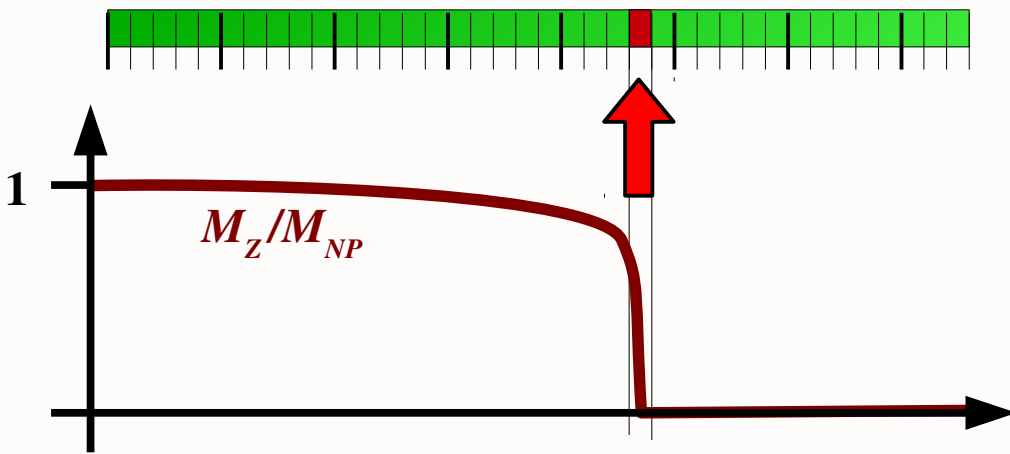
# Fine-Tuning

particular choice of a continuous parameter



# Fine-Tuning

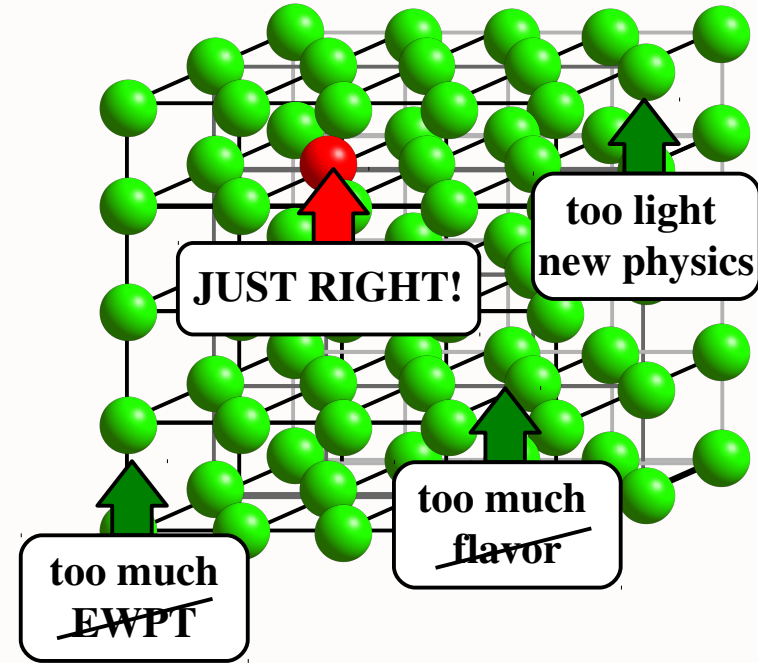
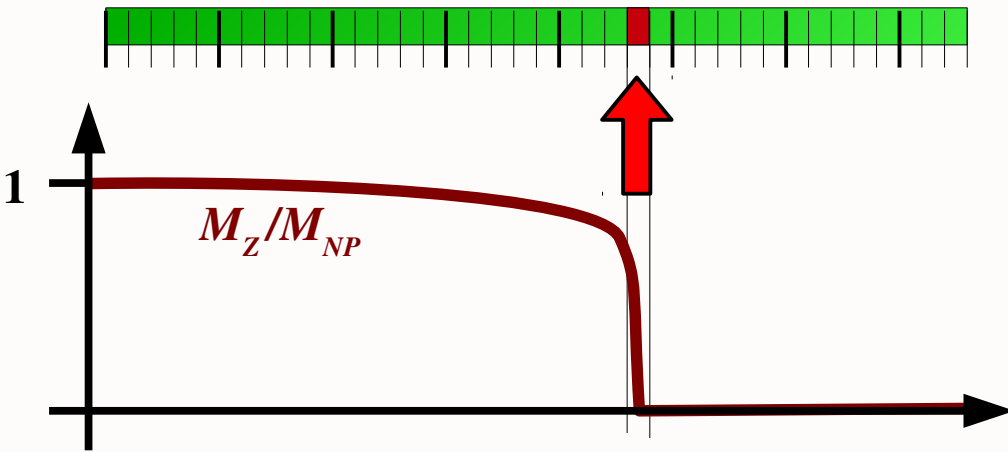
particular choice of a continuous parameter



# Fine-Tuning VS Cherry Picking

particular choice of a continuous parameter

discrete choice of a particular model



Is there any improvement?

# What are we learning from the absence of new physics at the LHC?

Two possible answers:

1. Minimal BSM

2. Biased Naturalness

# Minimal BSM

Bardeen, Foot, Shaposhnikov, Lykken, Strumia, Dubovsky,...

$$m = \alpha M_{NP}$$

Naturalness is preserved but...

...no *new* physics above the EW scale

# Minimal BSM

Bardeen, Foot, Shaposhnikov, Lykken, Strumia, Dubovsky,...

$$m = \alpha M_{NP}$$

Naturalness is preserved but...

...no *new* physics above the EW scale



**Nightmare scenario?**

# Minimal BSM

Bardeen, Foot, Shaposhnikov, Lykken, Strumia, Dubovsky,...

$$m = \alpha M_{NP}$$

Naturalness is preserved but...

...no *new* physics above the EW scale



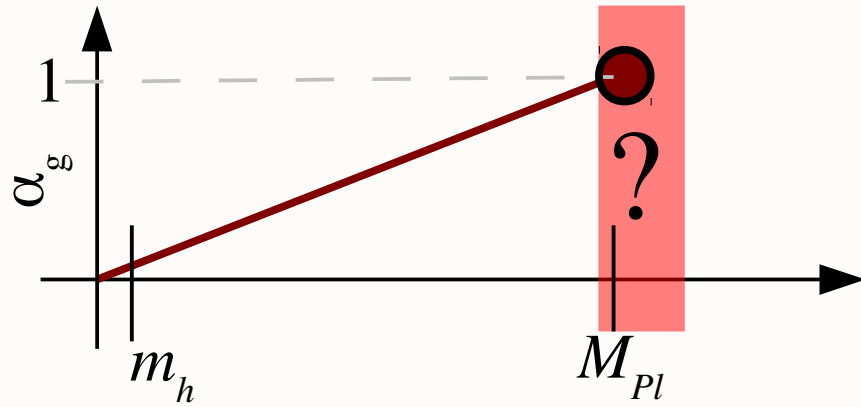
**Nightmare scenario?**

**NO!**

**Paradise scenario:  
Most BSM within reach!**

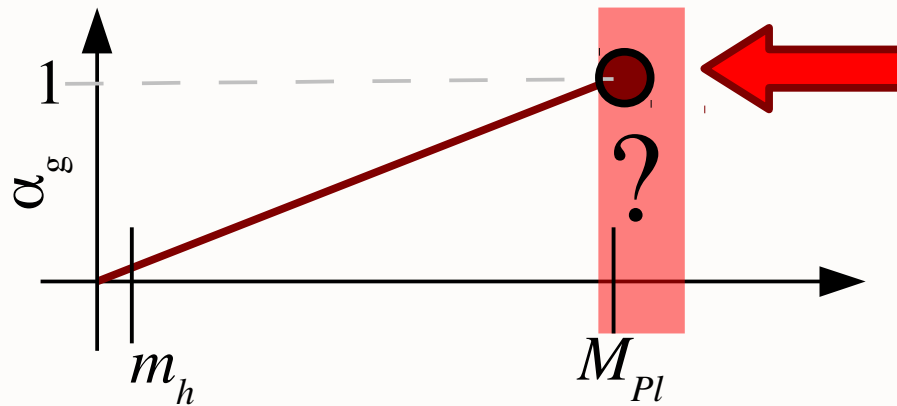


1) The **Big** Assumption: No thresholds from  $M_{\text{Planck}}$





# 1) The **Big** Assumption: No thresholds from $M_{\text{Planck}}$

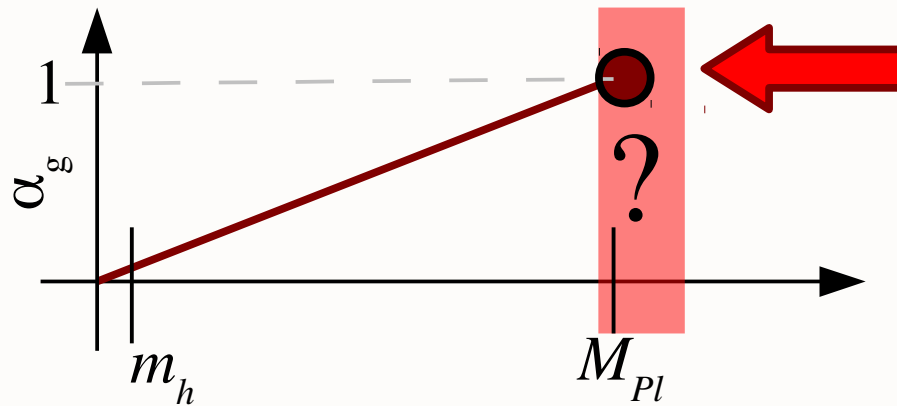


**UV completion without new states!**

Very different from what happens in  
all known examples!

(String theory, Fermi theory, etc...)

# 1) The **Big** Assumption: No thresholds from $M_{\text{Planck}}$



**UV completion without new states!**

Very different from what happens in  
all known examples!

(String theory, Fermi theory, etc...)

$$\text{No } \delta m_h = \alpha M_{\text{Pl}}$$

EW scale insensitive to Planck physics!

Existing examples in 2D

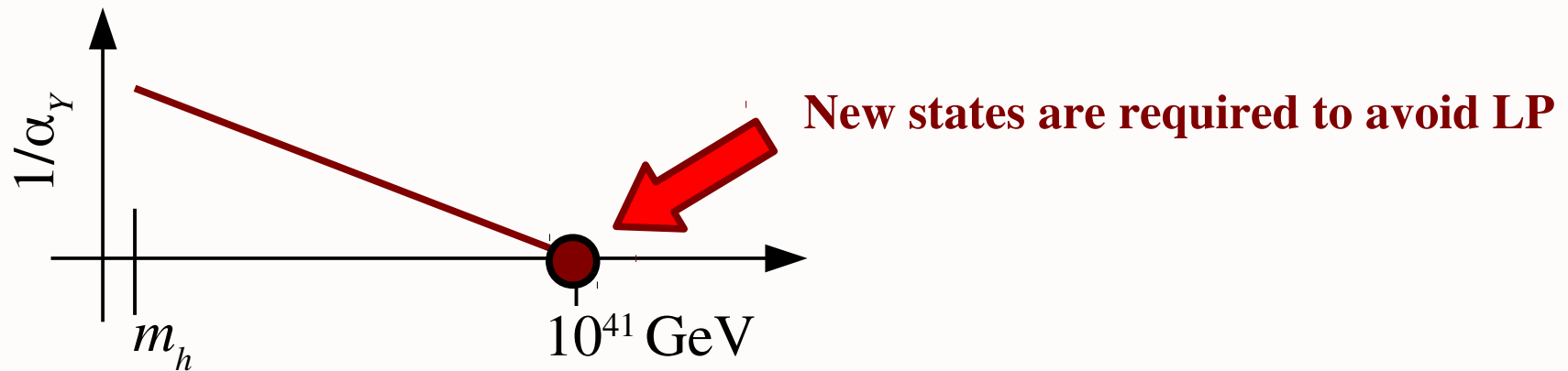
(Dubovsky et al. '12-'13)

2) Need SM to be a UV complete theory

## 2) Need SM to be a UV complete theory

SM is not renormalizable:

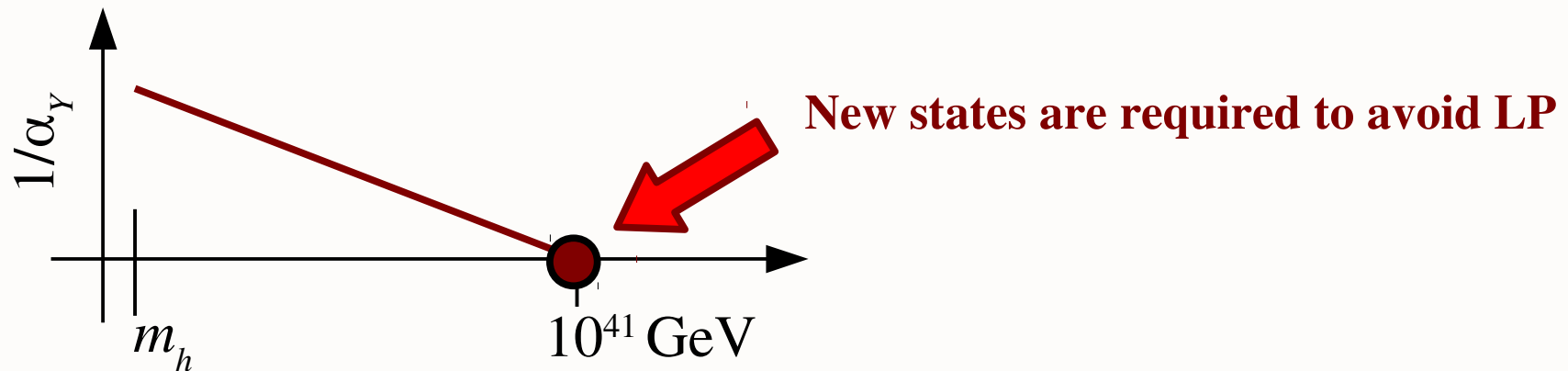
Landau poles of  $U(1)_Y$  and Higgs quartic



## 2) Need SM to be a UV complete theory

SM is not renormalizable:

Landau poles of  $U(1)_Y$  and Higgs quartic



*New states must be at EW scale for naturalness!*

*plus all the states to explain DM,  $\theta$ -problem, baryogenesis, inflation, etc....*

Possible ways to avoid Landau Poles:

$$\begin{aligned} SU(3)_c \times SU(2)_L \times U(1)_Y &\rightarrow SU(2) \times SU(2) \times SU(4) \\ &\rightarrow SU(3)^3 \end{aligned}$$

+ very special relation between couplings to make  $\lambda \rightarrow 0$

Possible ways to avoid Landau Poles:

$$\begin{aligned} SU(3)_c \times SU(2)_L \times U(1)_Y &\rightarrow SU(2) \times SU(2) \times SU(4) \\ &\rightarrow SU(3)^3 \end{aligned}$$

+ very special relation between couplings to make  $\lambda \rightarrow 0$

$$\begin{aligned} U(1)_Y &\rightarrow SU(N) \\ h &\rightarrow (h, h', \dots) \end{aligned}$$

Possible ways to avoid Landau Poles:

$$\begin{aligned} SU(3)_c \times SU(2)_L \times U(1)_Y &\rightarrow SU(2) \times SU(2) \times SU(4) \\ &\rightarrow SU(3)^3 \end{aligned}$$

+ very special relation between couplings to make  $\lambda \rightarrow 0$

$$\begin{aligned} U(1)_Y &\rightarrow SU(N) \\ h &\rightarrow (h, h', \dots) \end{aligned}$$

 **distinctive feature**  
**extra “unprotected” scalar fields**




Possible ways to avoid Landau Poles:

$$\begin{aligned} SU(3)_c \times SU(2)_L \times U(1)_Y &\rightarrow SU(2) \times SU(2) \times SU(4) \\ &\rightarrow SU(3)^3 \end{aligned}$$

+ very special relation between couplings to make  $\lambda \rightarrow 0$

$$\begin{aligned} U(1)_Y &\rightarrow SU(N) \\ h &\rightarrow (h, h', \dots) \end{aligned}$$

 **distinctive feature**  
**extra “unprotected” scalar fields**

  
**Extra vectors e scalars**  
**need to be close to the EW scale**

**Danger of reintroducing a tuning problem**

# What about the elephant?

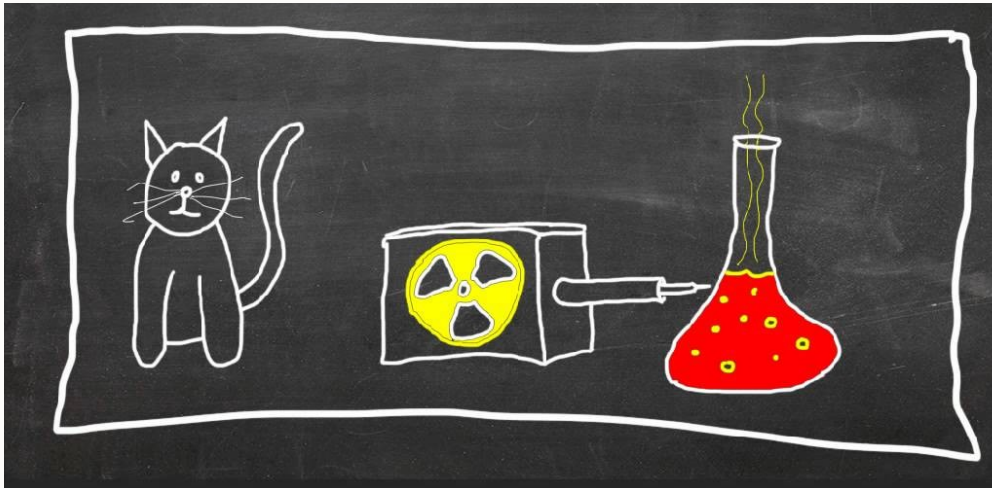


$$\Lambda_{\text{CC}} \supset (\Lambda_{\text{QCD}})^4, \langle h \rangle^4, \dots$$

# What about the elephant?



$$\Lambda_{\text{CC}} \supset (\Lambda_{\text{QCD}})^4, \langle h \rangle^4, \dots$$

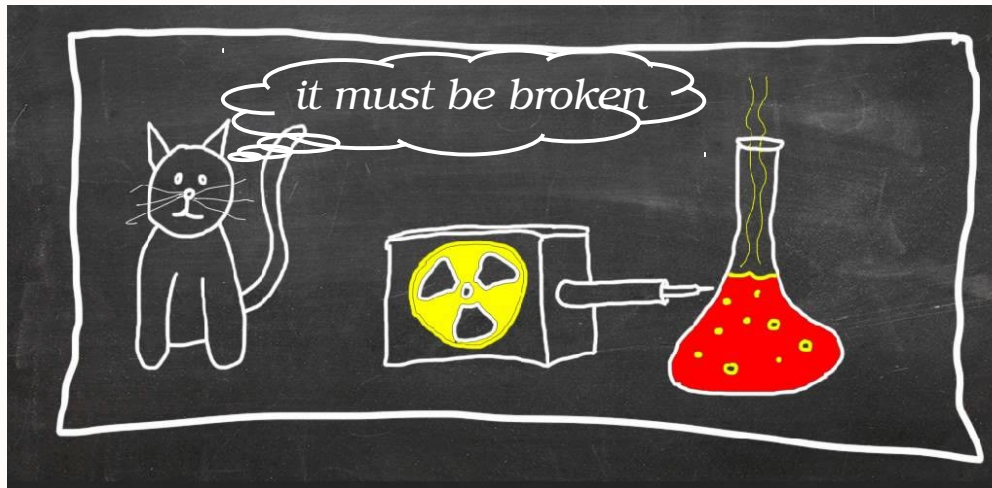


***Biased Naturalness:***  
when computing probabilities  
it makes a difference whether  
the observer is inside or outside  
the system observed

# What about the elephant?



$$\Lambda_{\text{CC}} \supset (\Lambda_{\text{QCD}})^4, \langle h \rangle^4, \dots$$



***Biased Naturalness:***  
when computing probabilities  
it makes a difference whether  
the observer is inside or outside  
the system observed

*Naturalness principle may fail for some quantities*

Consequences: *e.g.* SUSY  $\rightarrow$  **Mini-Split SUSY**

Consequences: *e.g.* SUSY → **Mini-Split SUSY**

*We lost the prediction of the SUSY scale from naturalness*

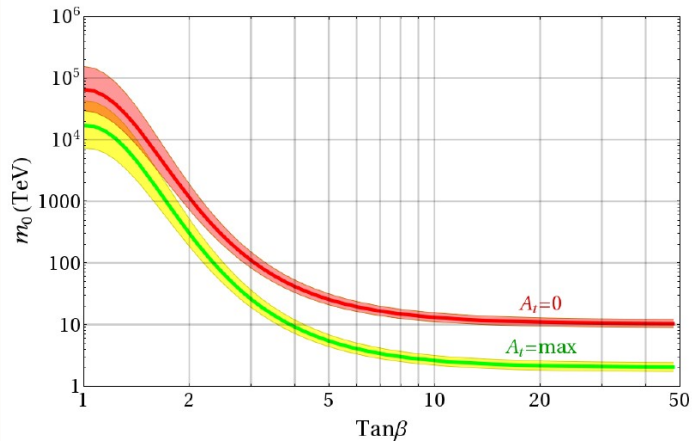
Need to use other inputs:

Consequences: *e.g.* SUSY  $\rightarrow$  **Mini-Split SUSY**

*We lost the prediction of the SUSY scale from naturalness*

Need to use other inputs:

$$m_H = 125 \text{ GeV}$$

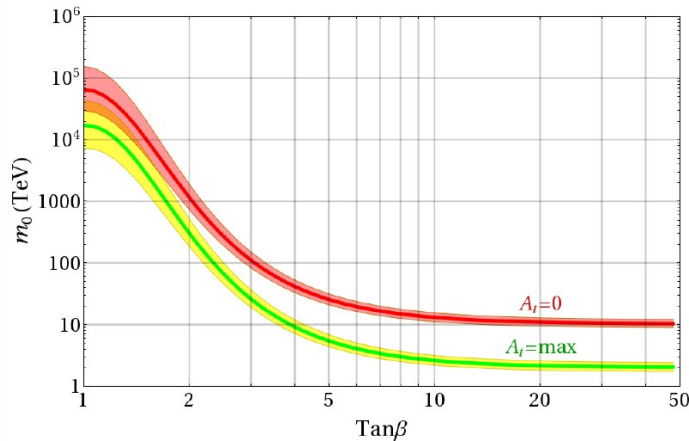


Consequences: *e.g.* SUSY  $\rightarrow$  **Mini-Split SUSY**

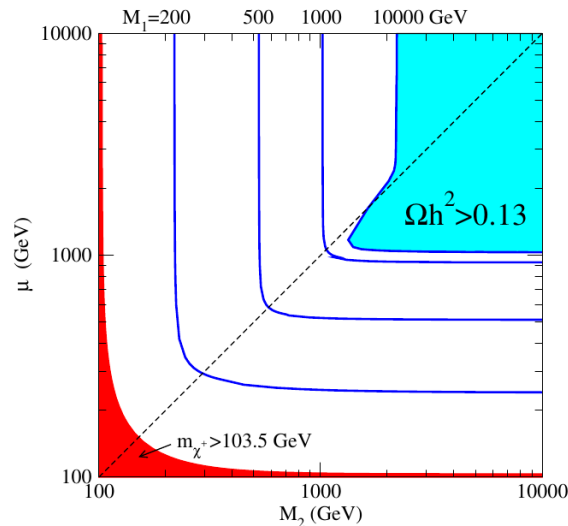
*We lost the prediction of the SUSY scale from naturalness*

Need to use other inputs:

$m_H = 125$  GeV



$\Omega_{\text{DM}}$



from Masiero et al. '04

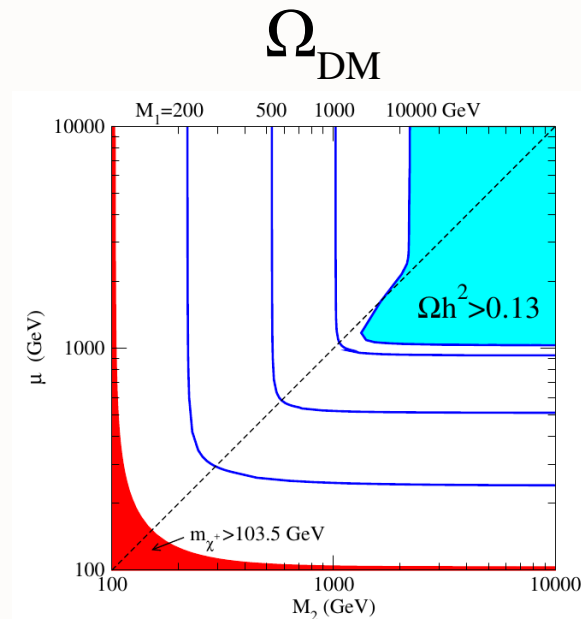
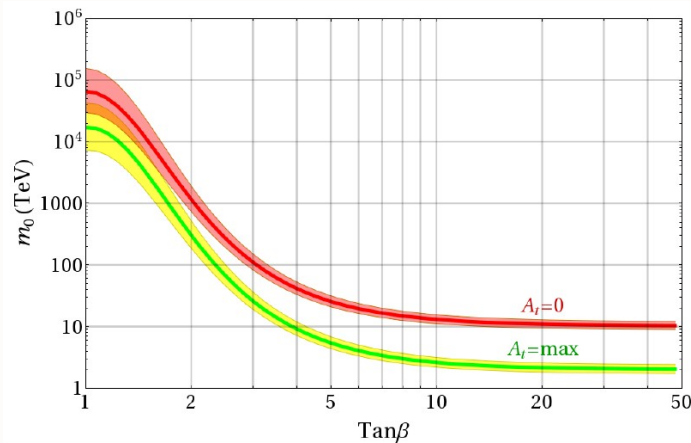


# Consequences: *e.g.* SUSY $\rightarrow$ **Mini-Split SUSY**

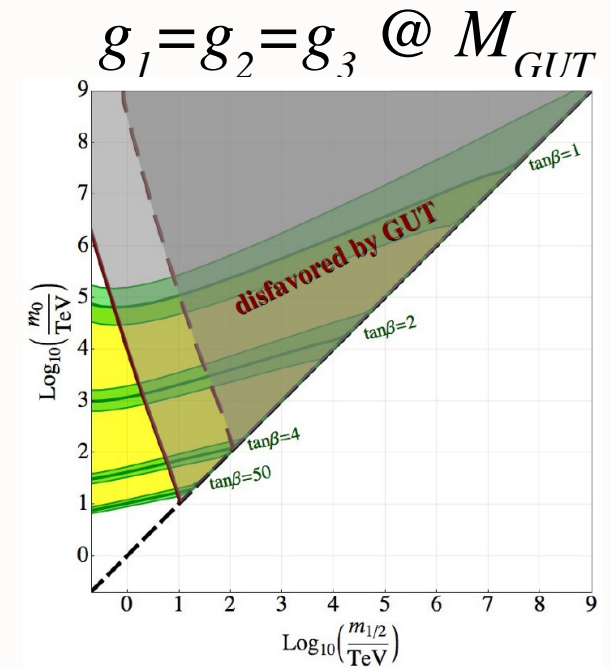
*We lost the prediction of the SUSY scale from naturalness*

Need to use other inputs:

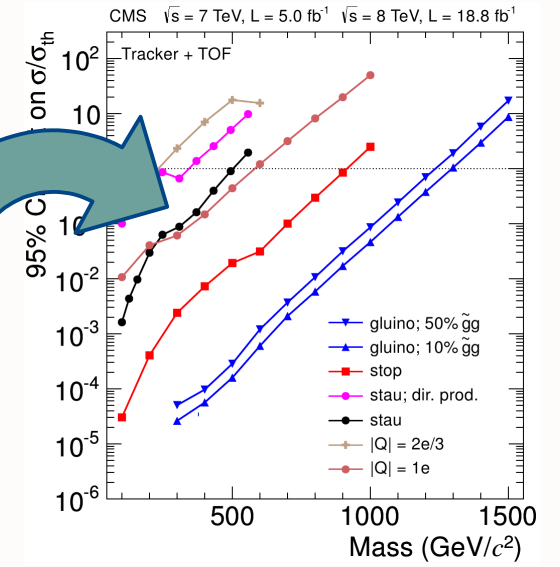
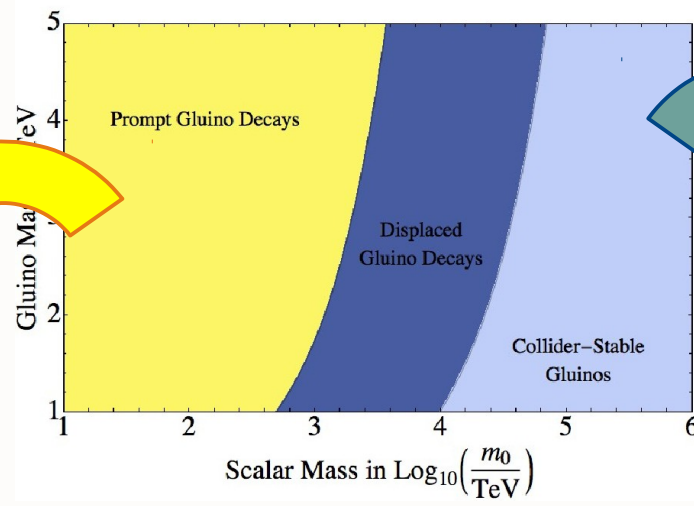
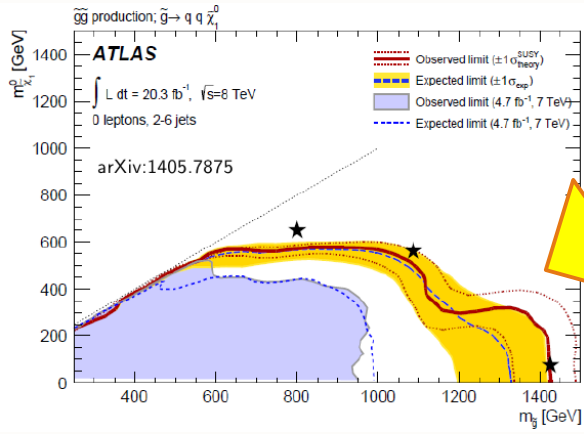
$m_H = 125$  GeV



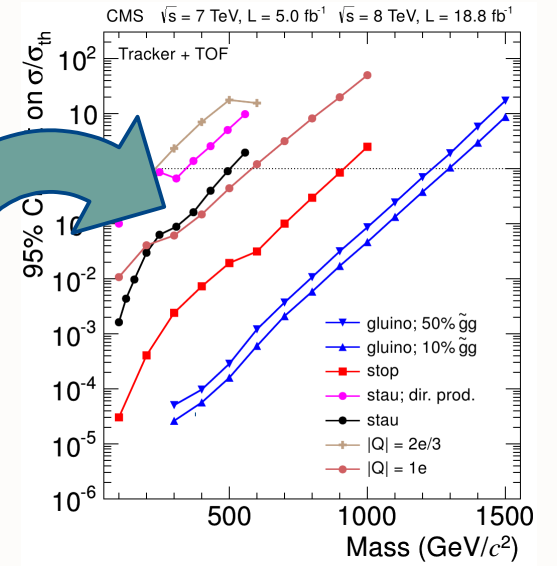
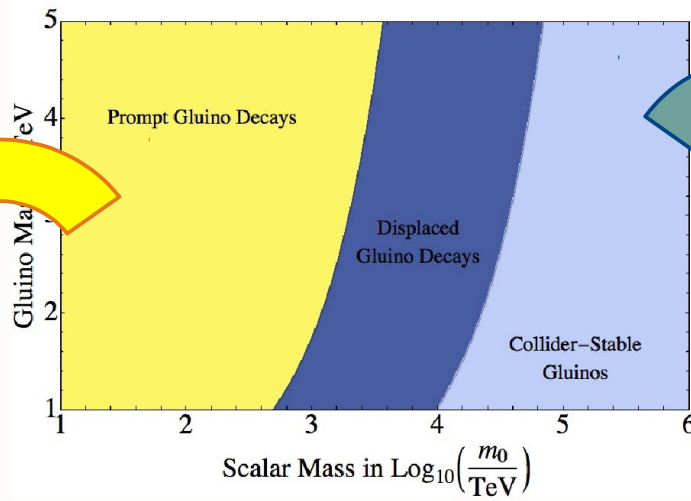
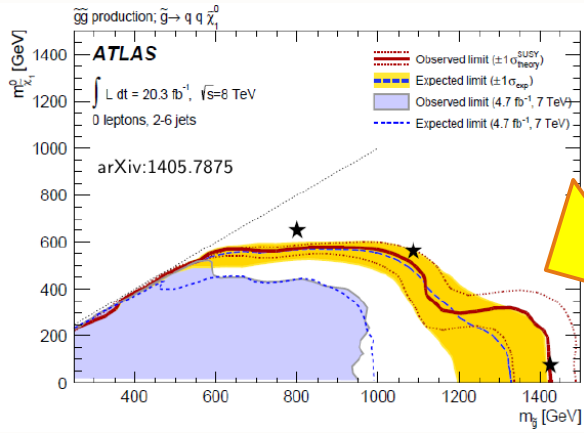
from Masiero et al. '04



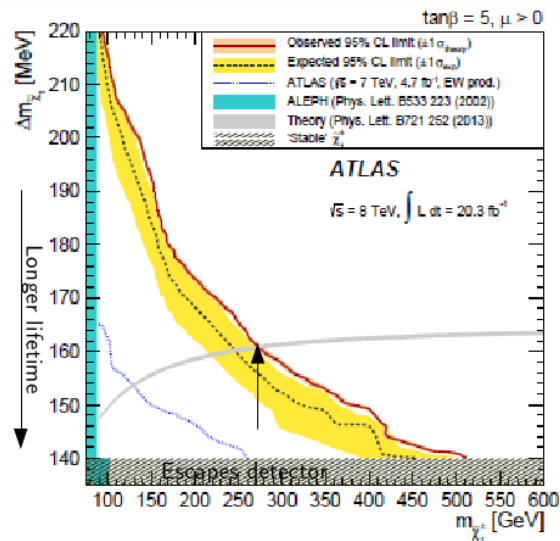
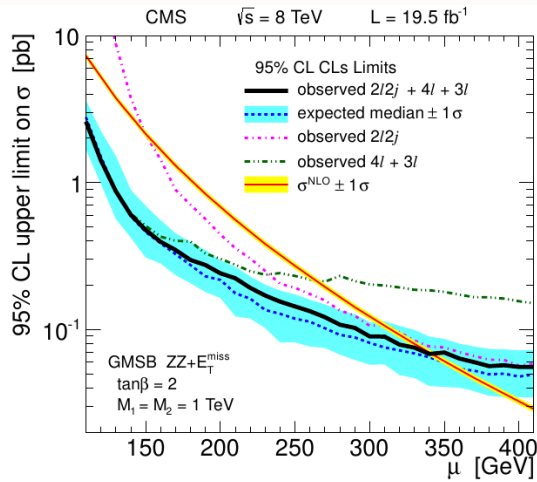
# Gluino



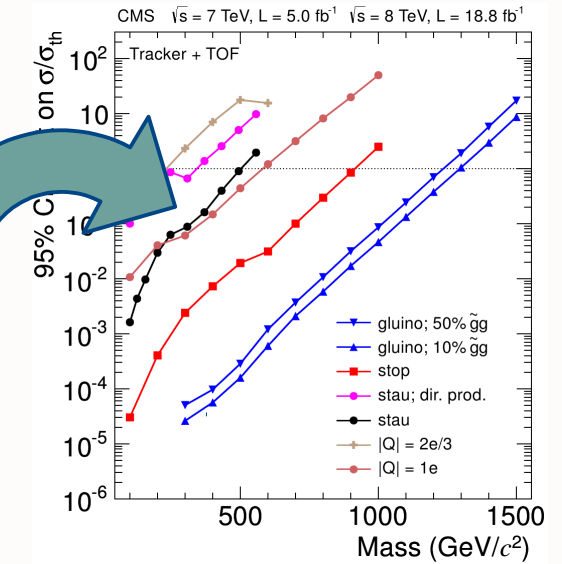
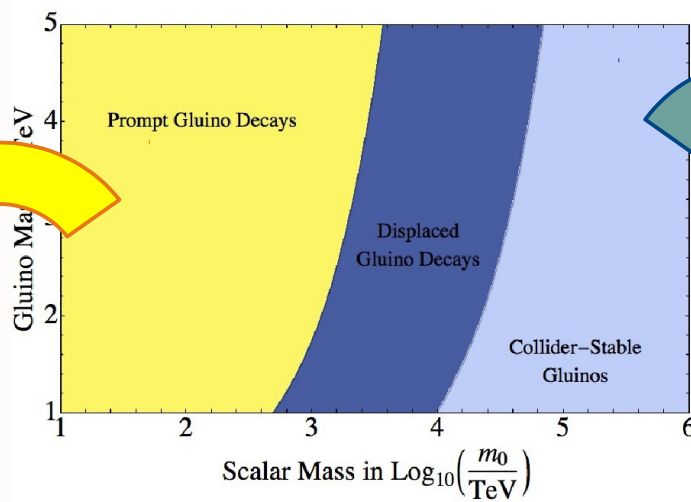
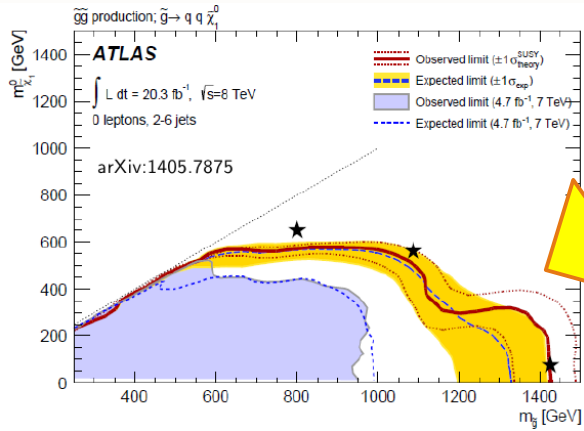
# Gluino



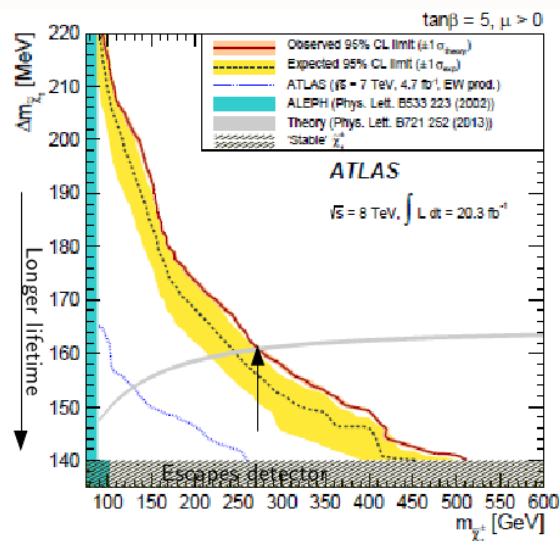
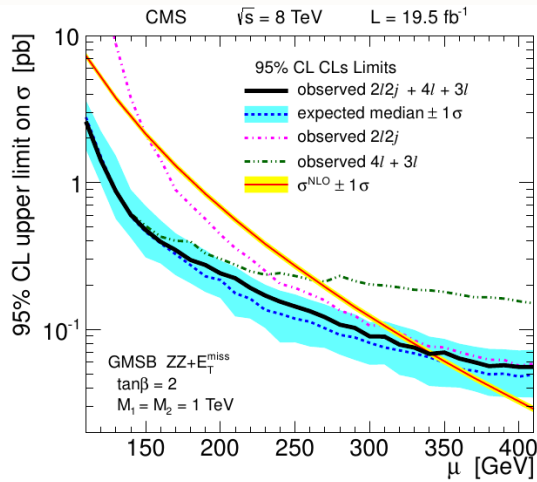
# EWino



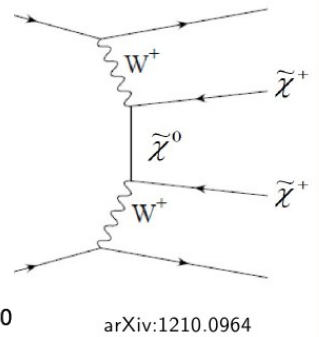
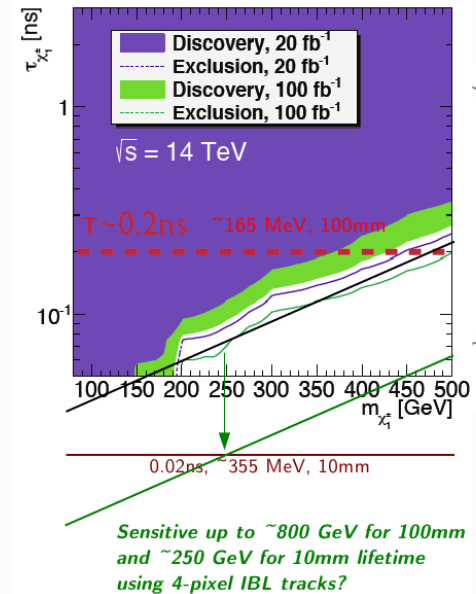
# Gluino



# EWino



# prospects/new ideas

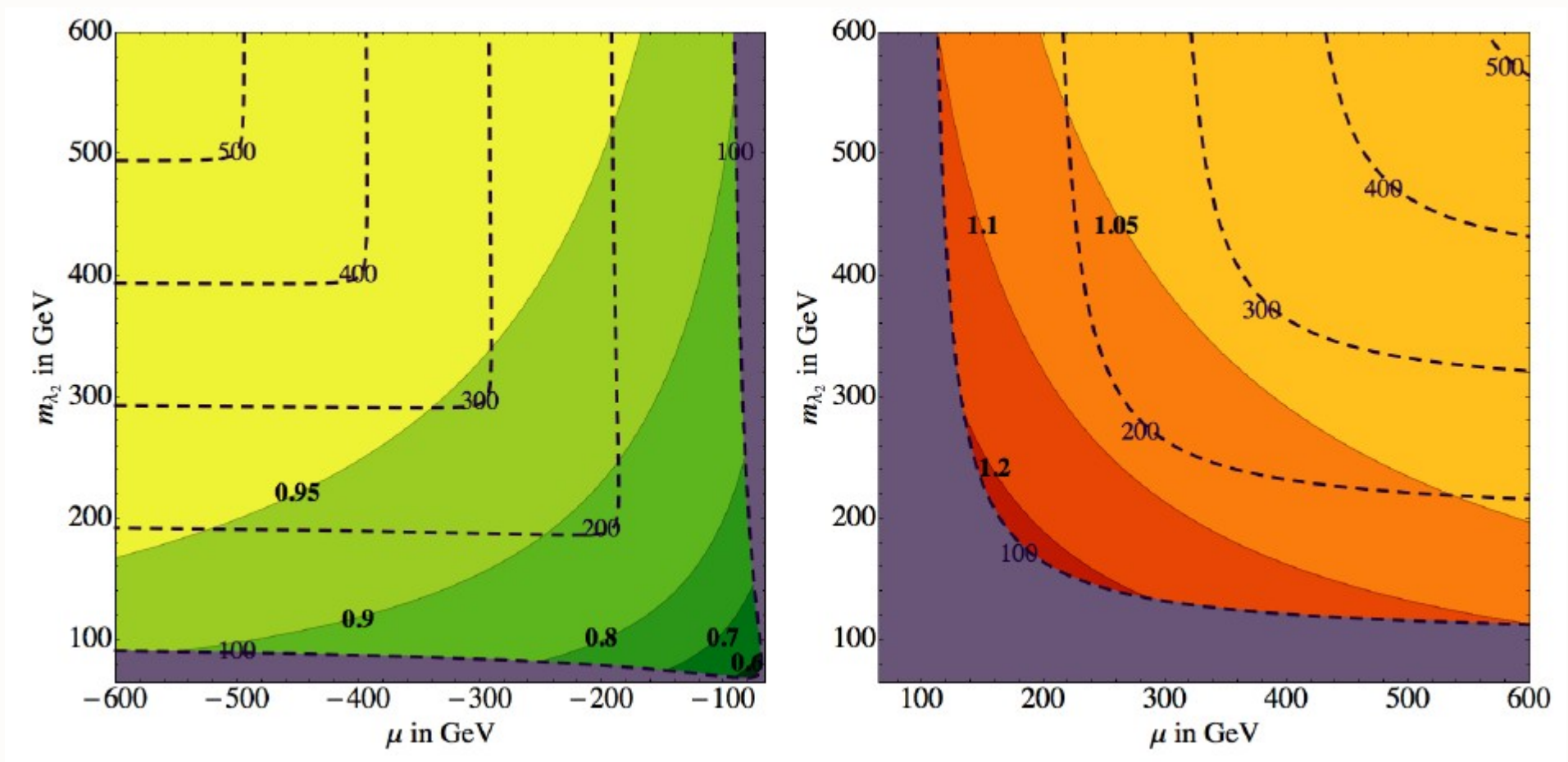


from A.Haas's talk

# Very strong prediction for Higgs couplings!!

$$\frac{\Gamma_{h \rightarrow \gamma\gamma}}{\Gamma_{h \rightarrow \gamma\gamma}^{SM}} \simeq 1 + \frac{12}{17} \frac{m_W^2 \sin 2\beta}{\mu m_{\lambda_2} - m_W^2 \sin 2\beta}$$

**Only deviation in  $h \rightarrow \gamma\gamma$  strongly correlated with light charginos**



# Conclusions

- Failure of Naturalness to predict the New Physics scale
- Never like now we need experimental input
  - Both from direct probes of NP (Energy Frontier)
  - and indirect (Higgs properties, etc...)
- Keep exploring alternative scenarios
  - (may suggest new signatures)

