Particle Physics after LHC8

Michele Redi

OUTLINE

- Standard Model

- LHC & Higgs Discovery

- Beyond the Standard Model:
  Supersymmetry and Composite Higgs or ...

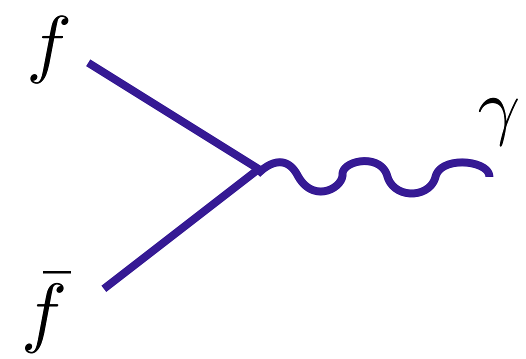
STANDARD MODEL

SM is built on the principle of gauge invariance

- U(1): Electromagnetism

$$A_\mu(x) \to A_\mu(x) + \partial_\mu \alpha(x)$$

$$\mathcal{L} = -\frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu}$$

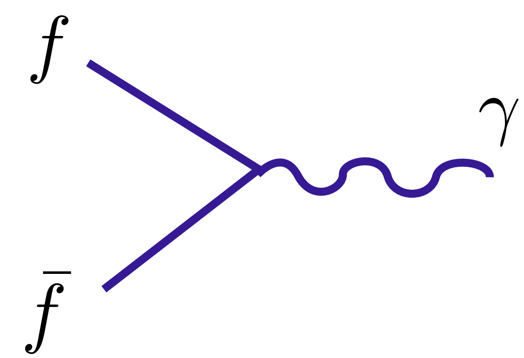


SM is built on the principle of gauge invariance

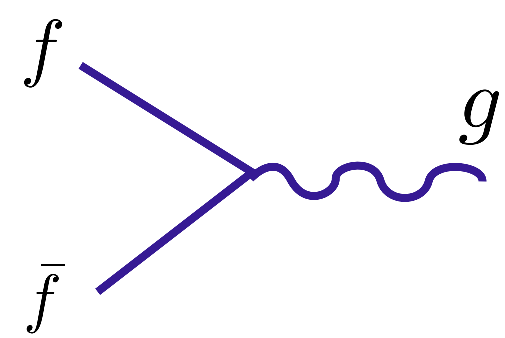
- U(1): Electromagnetism

$$A_\mu(x) \to A_\mu(x) + \partial_\mu \alpha(x)$$

$$\mathcal{L} = -\frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu}$$

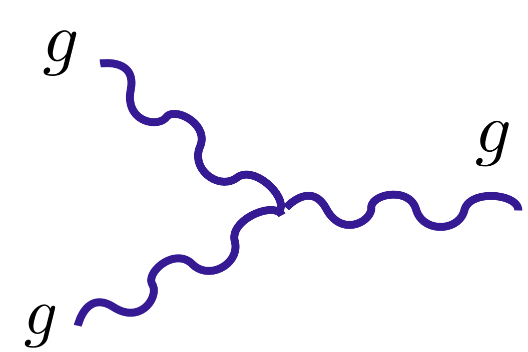


- SU(n): Yang-Mills theory



$$\delta A^a_\mu \to f^{abc} \alpha^b A^c_\mu + \partial_\mu \alpha^a$$

$$\mathcal{L} = -\frac{1}{4g^2} F^a_{\mu\nu} F^{a\mu\nu}$$



SM gauge group:

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$g_3 \simeq 1.2$$

$$g_2 \simeq 0.65$$

@ 100 GeV

$$g_3 \simeq 0.36$$

SM gauge group:

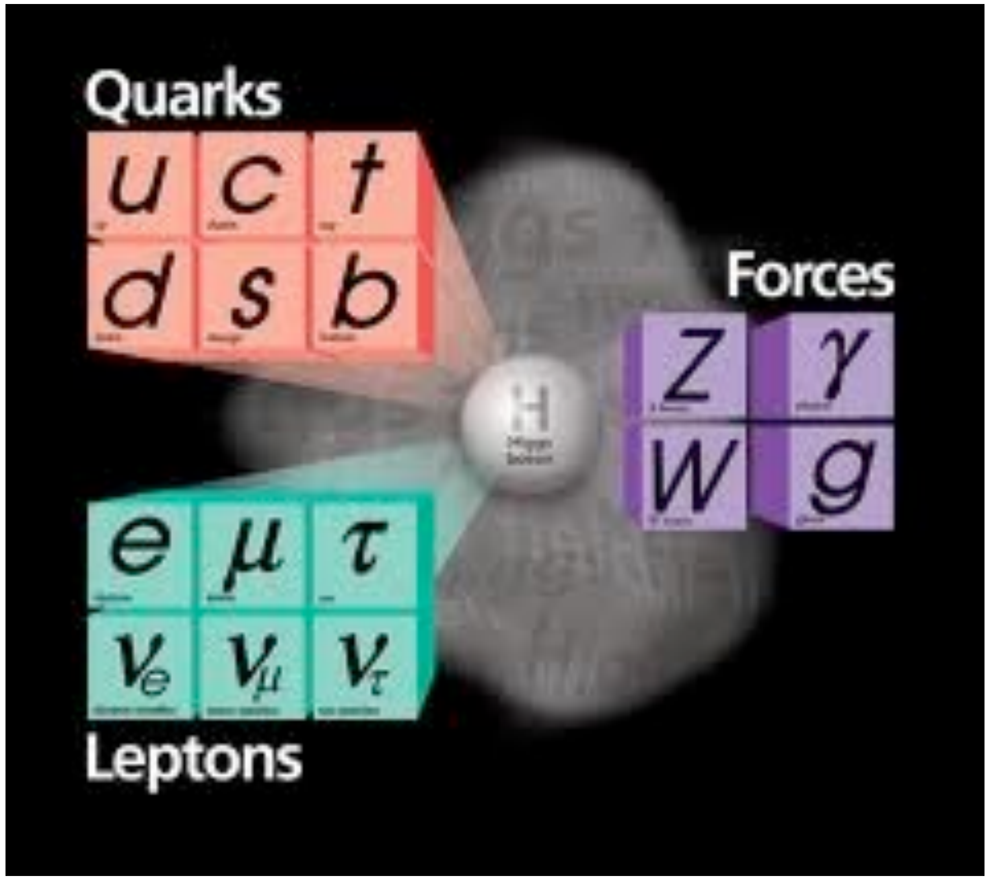
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

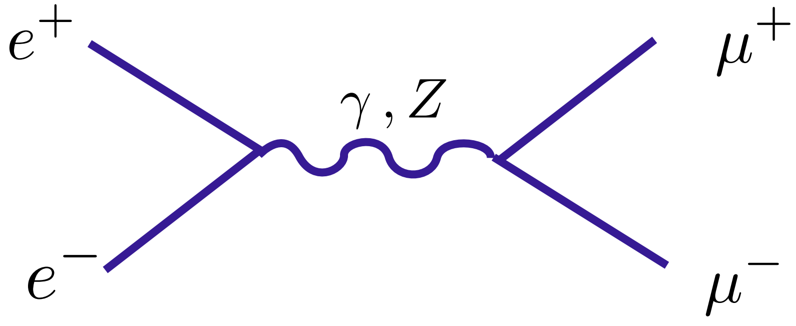
$$g_3 \simeq 1.2$$

$$g_2 \simeq 0.65$$

$$g_3 \simeq 0.36$$

@ 100 GeV





Unbroken symmetry forbids mass terms: vacuum must respect a smaller symmetry

$$SU(3)_c \otimes U(1)_Q \longrightarrow \frac{SU(2)_L \times U(1)_Y}{U(1)_Q}$$

Unbroken symmetry forbids mass terms: vacuum must respect a smaller symmetry

$$SU(3)_c \otimes U(1)_Q \longrightarrow \frac{SU(2)_L \times U(1)_Y}{U(1)_Q}$$

family \ type	ups	downs	leptons
3rd	$m_t = 175$	$m_b = 4.2$	$m_\tau = 1.7$
2nd	$m_c = 1.2$	$m_s = 0.1$	$m_\mu = 0.1$
1st	$m_u = 3 \times 10^{-3}$	$m_d = 5 \times 10^{-3}$	$m_e = 5 \times 10^{-4}$

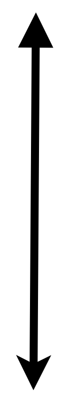
(GeV)

$$m_W = 80.4\,\mathrm{GeV}$$

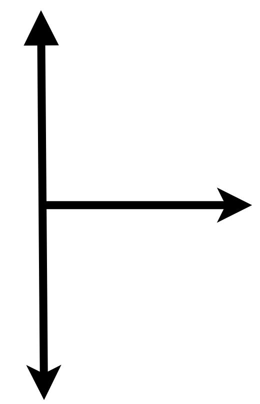
$$m_Z = 91.2\,\mathrm{GeV}$$

Mass for spin-1 means new degrees of freedom

$m_1 = 0$



$m_1 \neq 0$



Mass for spin-1 means new degrees of freedom

$m_1 = 0$ $\qquad\qquad$ $m_1 \neq 0$

The longitudinal polarizations are Goldstone Bosons

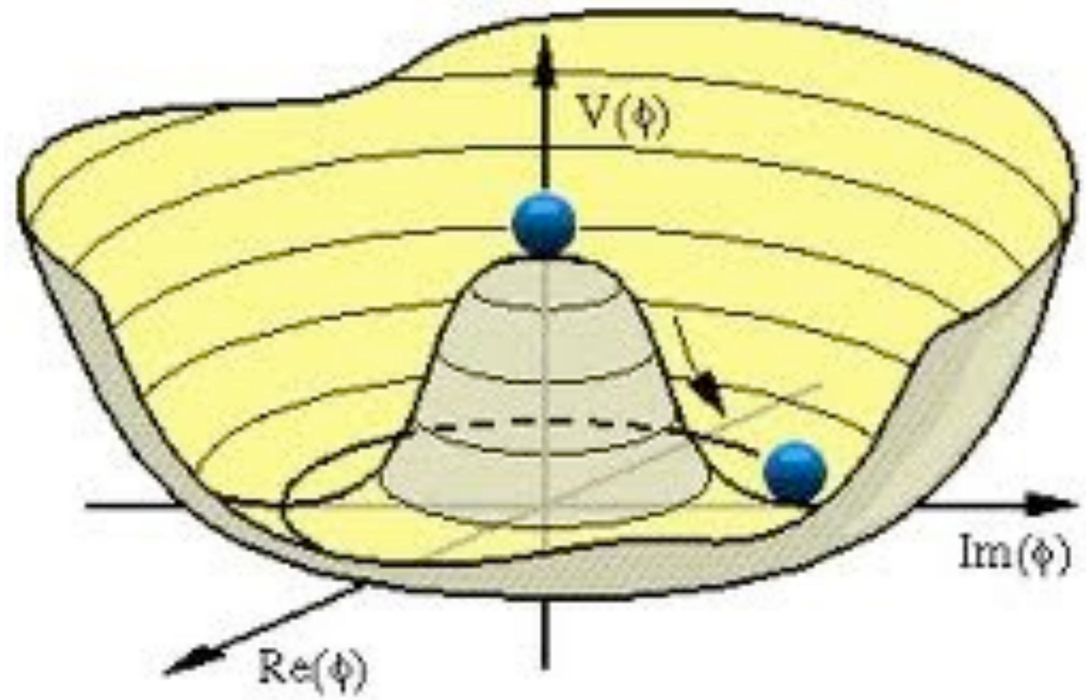
$$\frac{SU(2)_L \times U(1)_Y}{U(1)_Q} \longrightarrow \text{3 GB}$$

Conceptually identical to superconductivity.

In SM electro-weak symmetry broken by scalar doublet

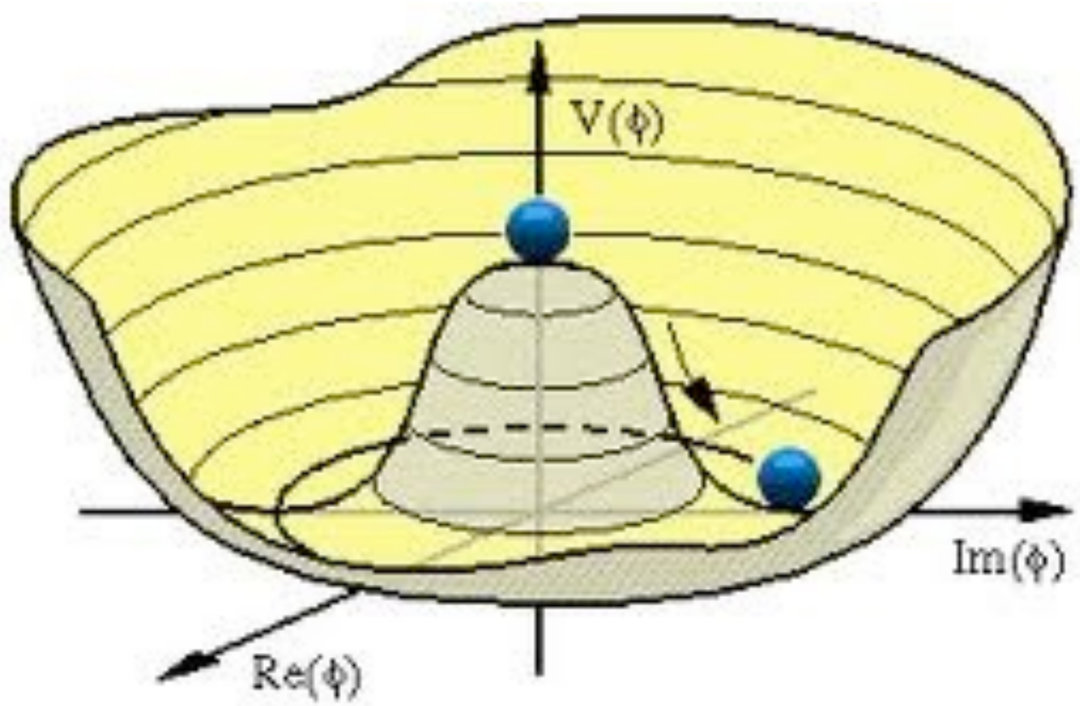
$$H = \begin{pmatrix} h_1 + ih_2 \\ h_3 + ih_4 \end{pmatrix}$$

$$V(H) = \lambda\left(|H|^2 - v^2\right)^2$$



In SM electro-weak symmetry broken by scalar doublet

$$H = \begin{pmatrix} h_1 + i h_2 \\ h_3 + i h_4 \end{pmatrix}$$

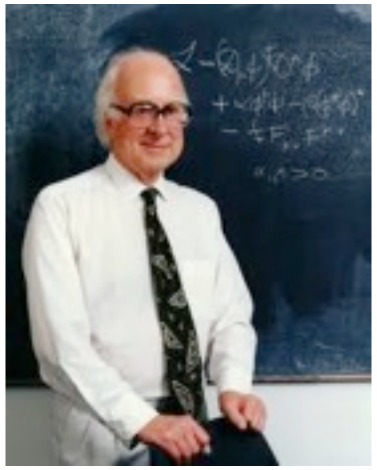


$$V(H) = \lambda \left(|H|^2 - v^2 \right)^2$$

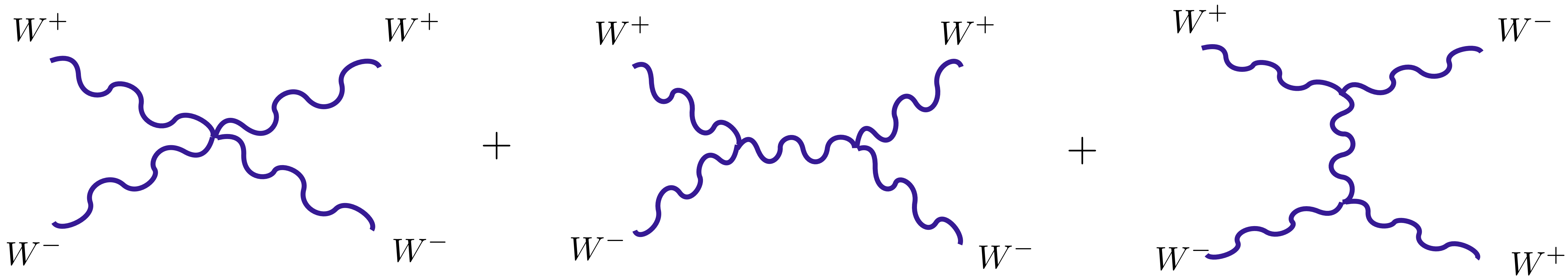
$$H(x) = U(x) \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \qquad v = 174\, GeV$$

Physical scalar is the Higgs boson

$$m_h = \sqrt{\lambda}\, v$$

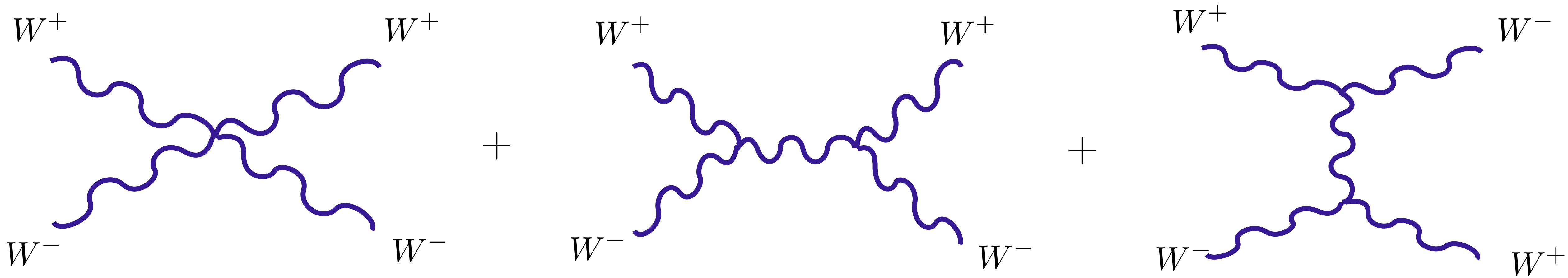


In principle Higgs boson not even needed



$$A(W_L^+ W_L^- \to W_L^+ W_L^-) \sim \frac{E^2}{v^2}$$

In principle Higgs boson not even needed



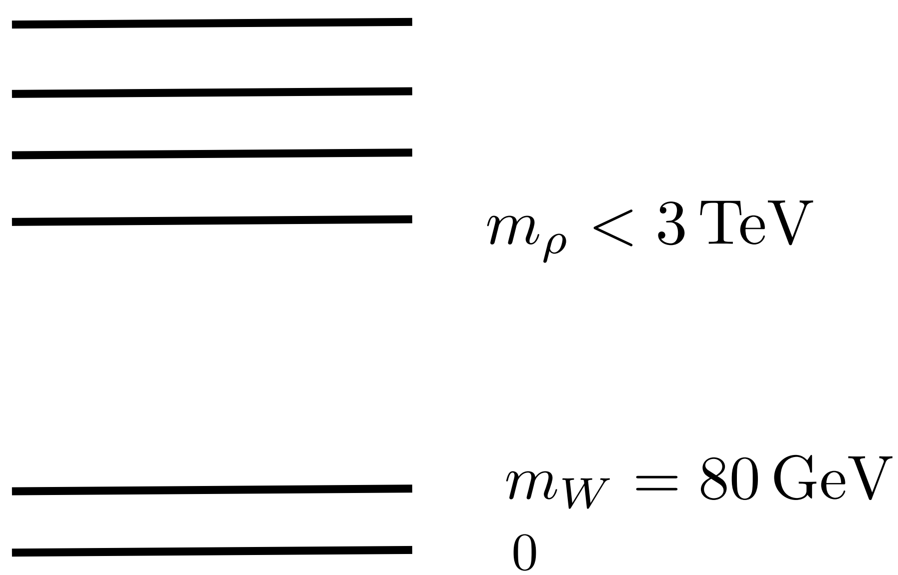
$$A(W_L^+ W_L^- \to W_L^+ W_L^-) \sim \frac{E^2}{v^2}$$

SM without Higgs does not make sense above

$$\Lambda = 4\pi v \sim 3\text{TeV}$$

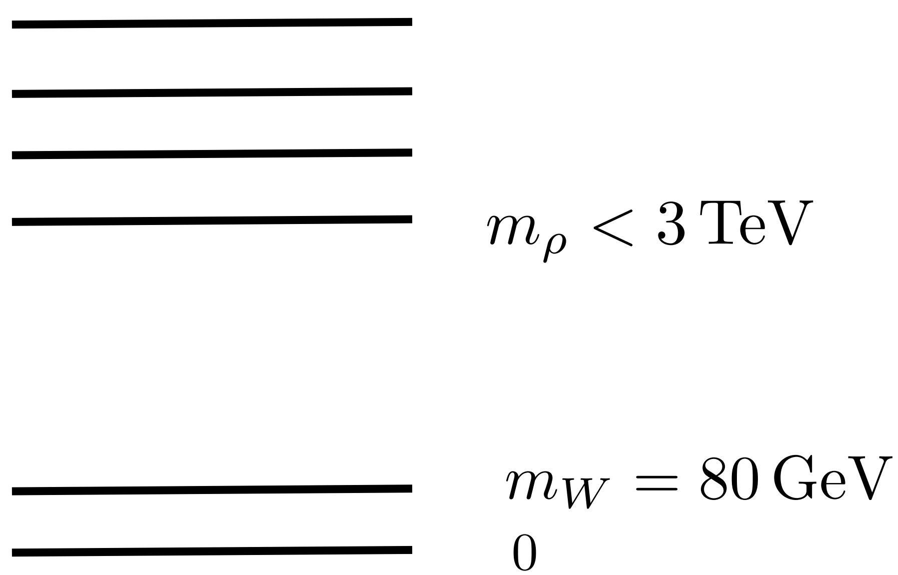
Interactions similar to QCD could break the electro-weak symmetry. This is known as technicolor.

No Higgs boson but techni-resonances (spin 0, 1/2, 1, ...)



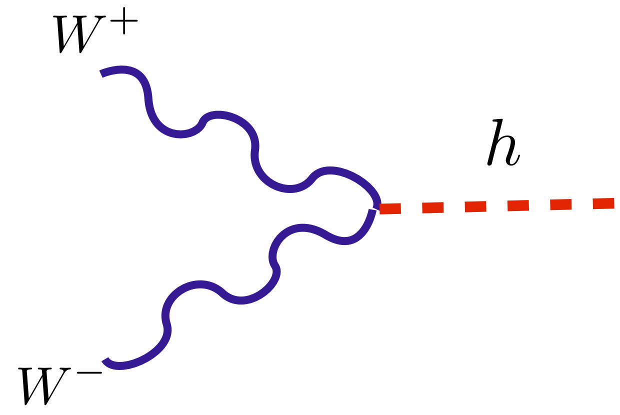
Interactions similar to QCD could break the electro-weak symmetry. This is known as technicolor.

No Higgs boson but techni-resonances (spin 0, 1/2, 1, ...)

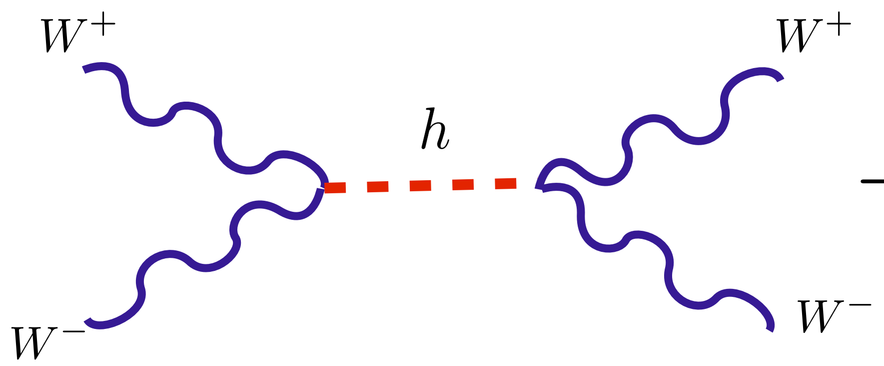


Ruled out!

In the SM:



$$\sqrt{2}i\frac{m_W^2}{v}$$

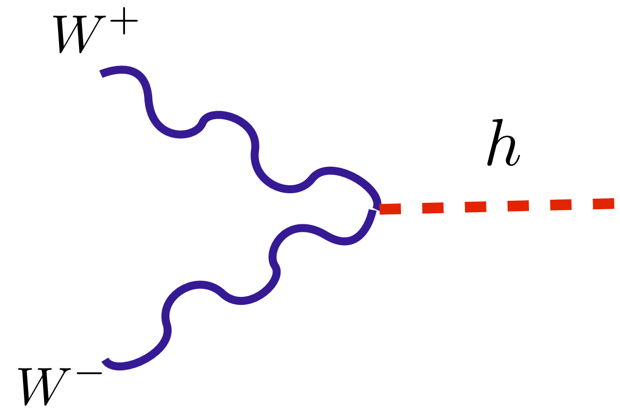


$$+\ldots$$

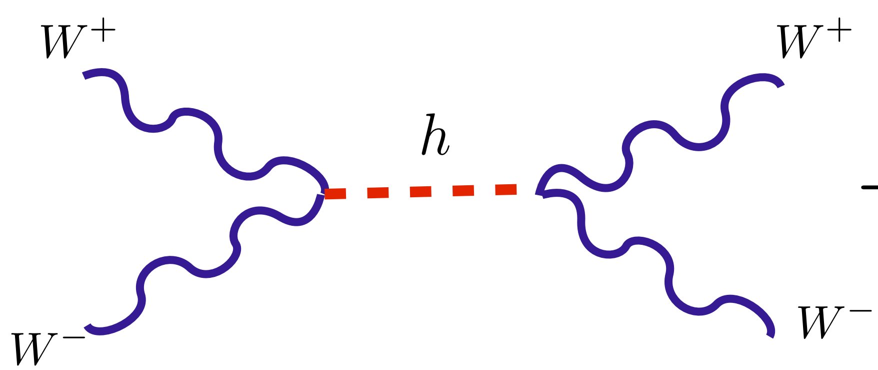
$$A(W_L^+W_L^- \to W_L^+W_L^-) \sim m_h^2$$

$$(E \gg m_h)$$

In the SM:



$$\sqrt{2}i\frac{m_W^2}{v}$$



$$+\ldots$$

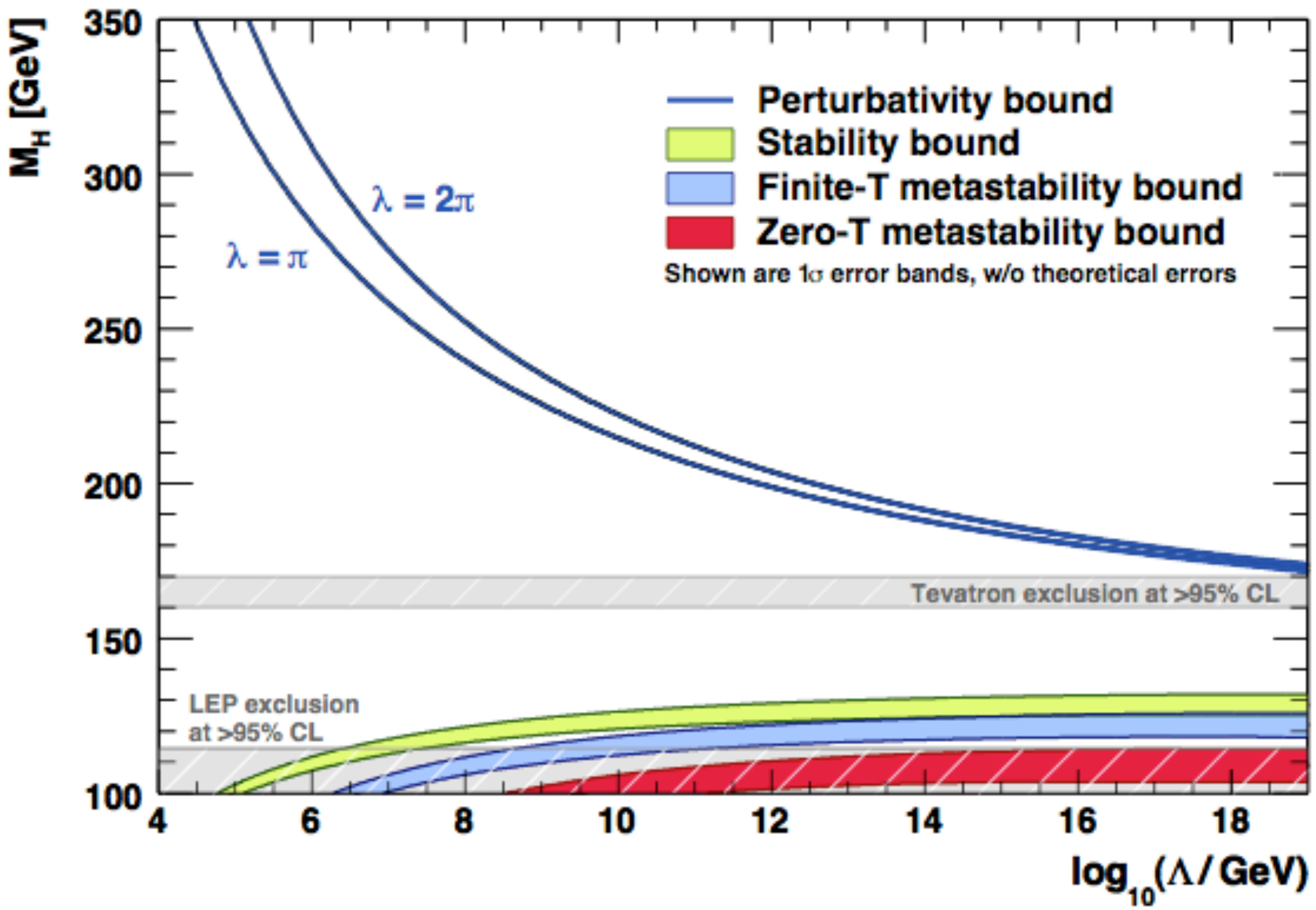
$$A(W_L^+W_L^- \to W_L^+W_L^-) \sim m_h^2$$

$$(E \gg m_h)$$

SM with Higgs boson can be valid up to large energies.

Can SM be the whole story?

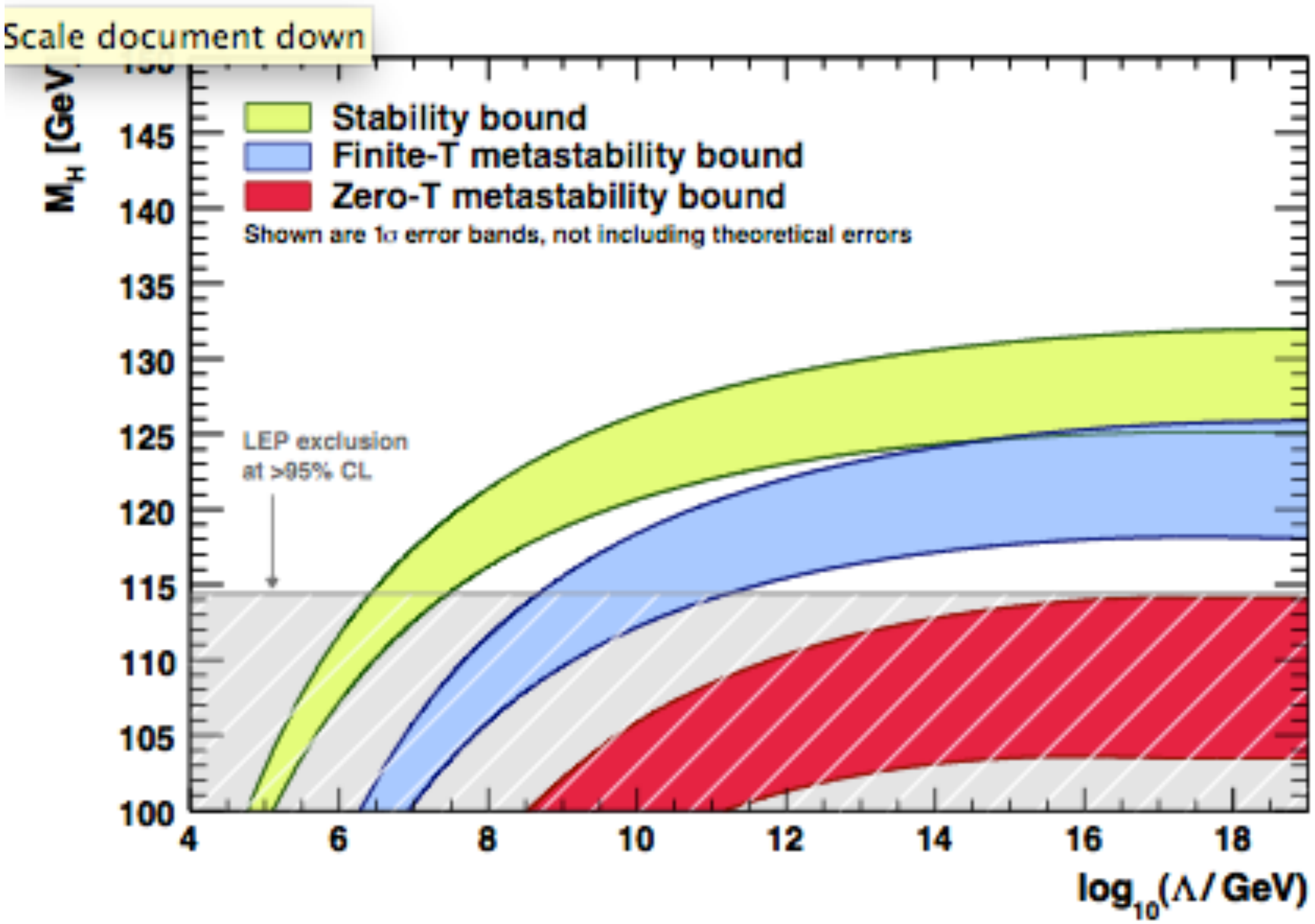
$$\mu \frac{d\lambda}{d\mu} = \frac{1}{16\pi^2}(24\lambda^2 - 6y_t^4 + \dots)$$



Giudice et al.
1112.3022

Can SM be the whole story?

$$\mu \frac{d\lambda}{d\mu} = \frac{1}{16\pi^2}(24\lambda^2 - 6y_t^4 + \dots)$$



Giudice et al.
1112.3022

Electro-weak scale is the analog of the sea

$$m_W = 80\,\mathrm{GeV}$$

Electro-weak scale is the analog of the sea

$$m_W = 80\,\mathrm{GeV}$$

Waves are the "Higgs"

SM sea is "calm"

Electro-weak scale is the analog of the sea

$$m_W = 80\,\mathrm{GeV}$$

Waves are the "Higgs"

Storms can be unpredictable...

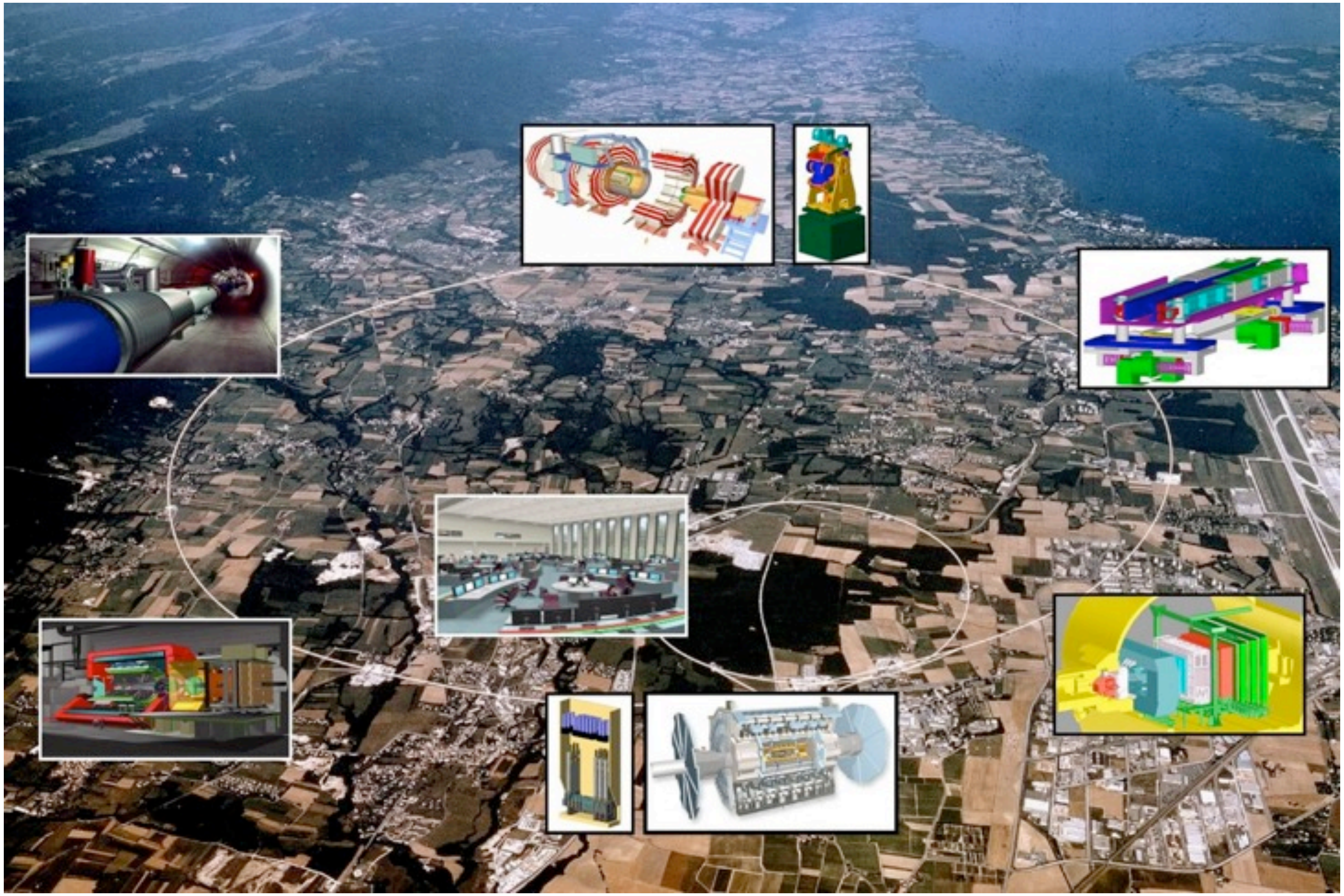
Higgs Discovery

+

=

Main goal of LHC:

discover the force that breaks electro-weak symmetry



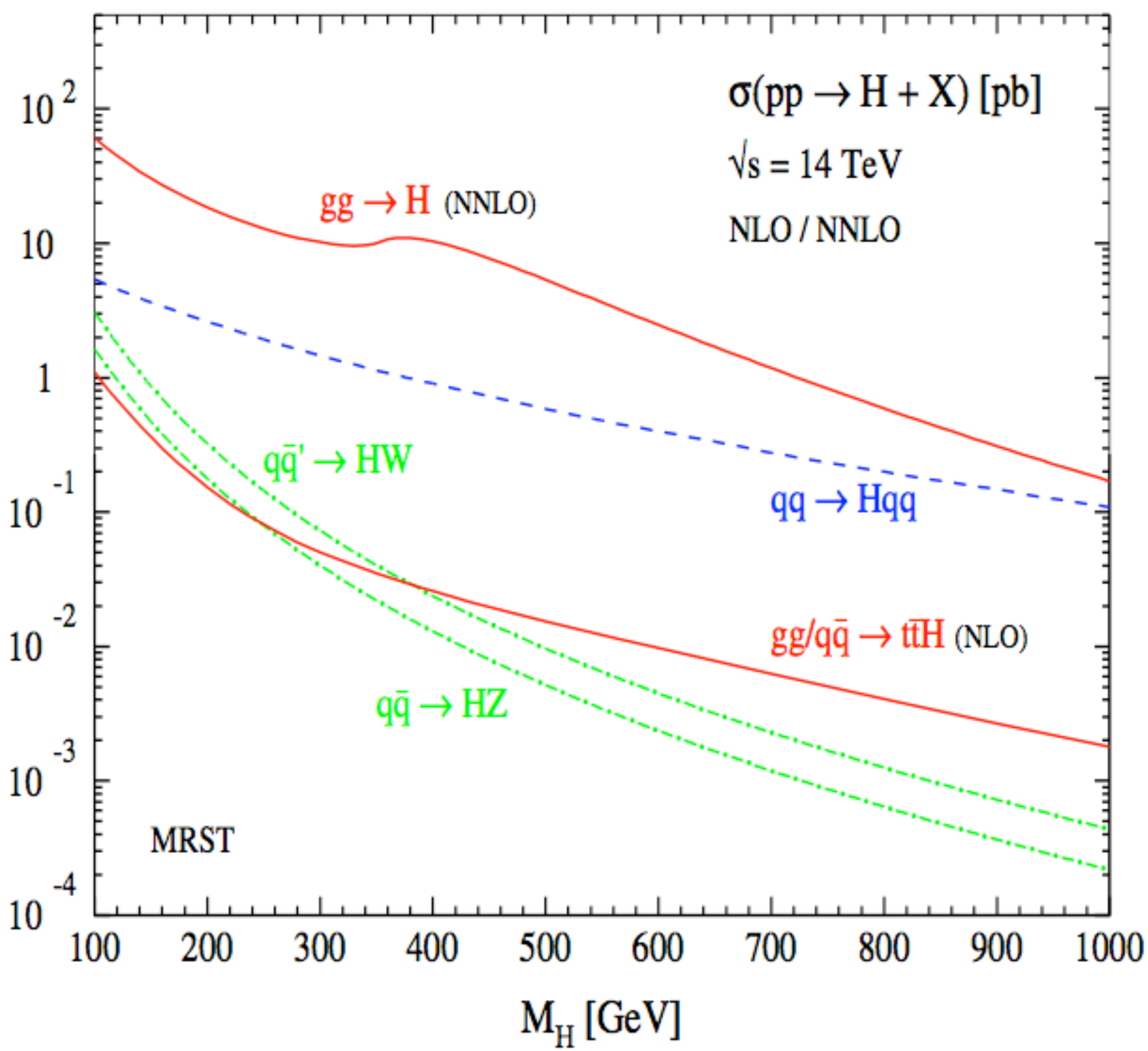
$pp\,@\,8\times$ TeV

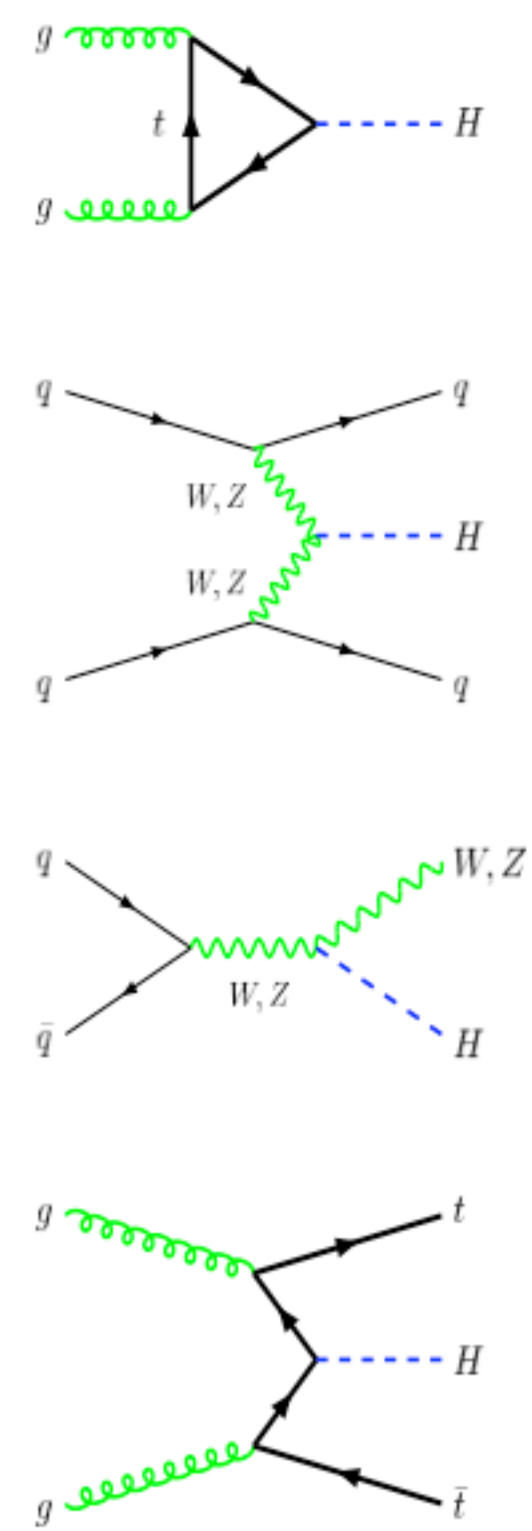
$v = .99999997\,\mathrm{c}$

10^{11} protons/bunch

6×10^{8} collisions/s

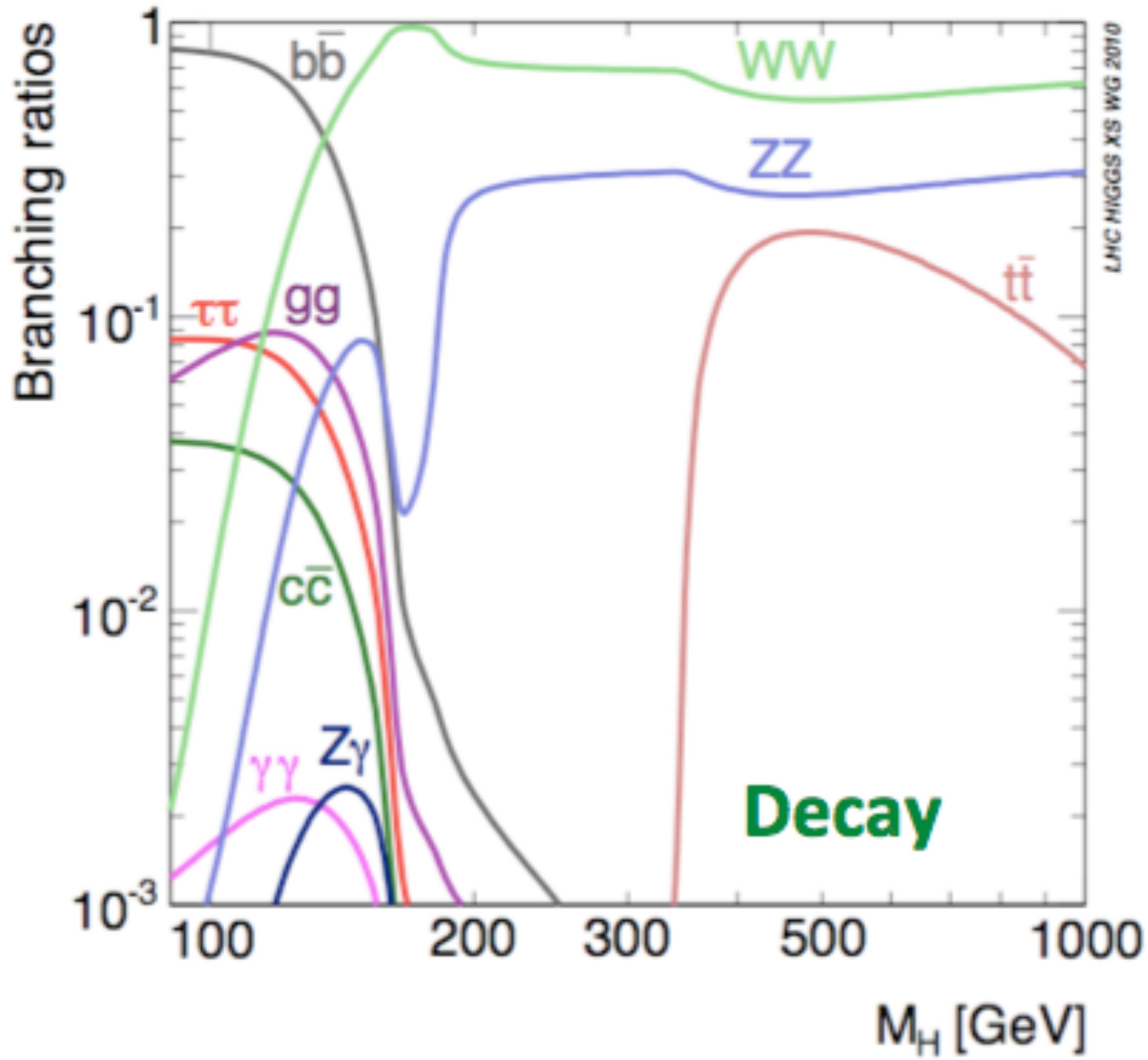
Higgs production at LHC:





$\sim 10^5$ Higgs bosons/year

Higgs decay:



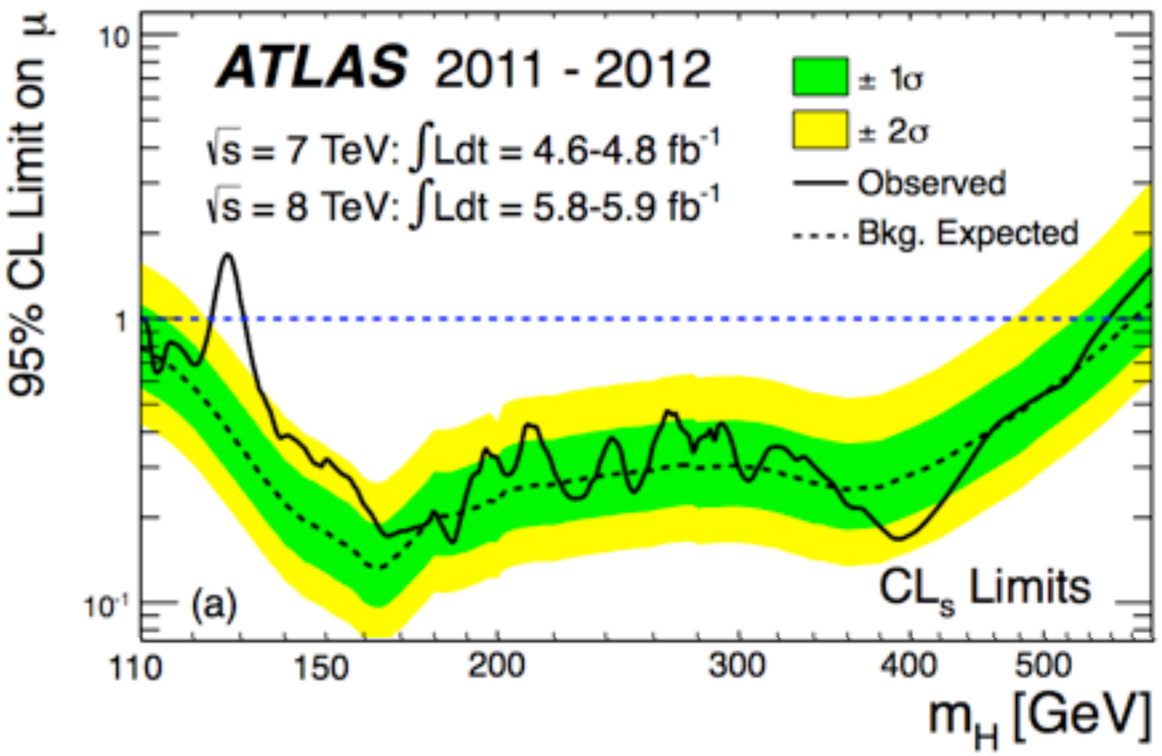
z

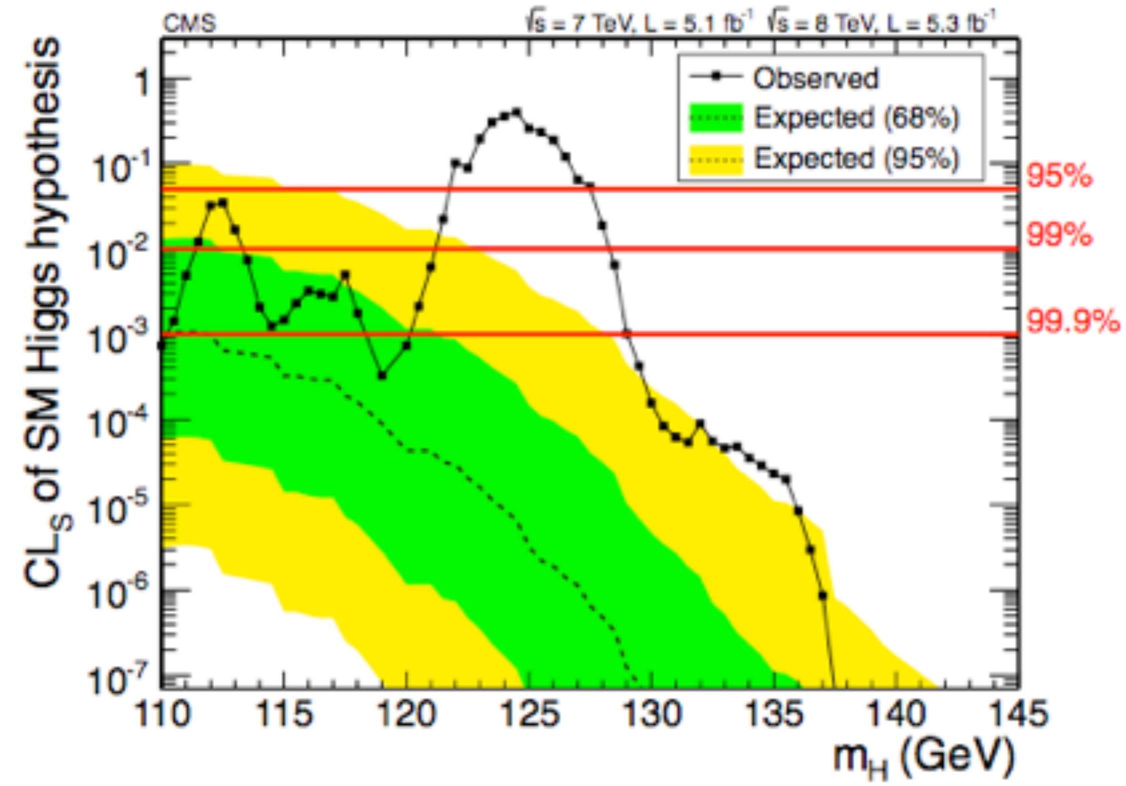
Higgs @ 125 GeV:

$\mathrm{BR}(h \to b\bar{b}) = 58\%$ $\mathrm{BR}(h \to WW^*) = 21.6\%$ $\mathrm{BR}(h \to \tau^+\tau^-) = 6.4\%$

$\mathrm{BR}(h \to ZZ^*) = 2.7\%$ $\mathrm{BR}(h \to gg) = 8.5\%$ $\mathrm{BR}(h \to \gamma\gamma) = 0.22\%$

July 31, 2012 Phys. Lett. B716





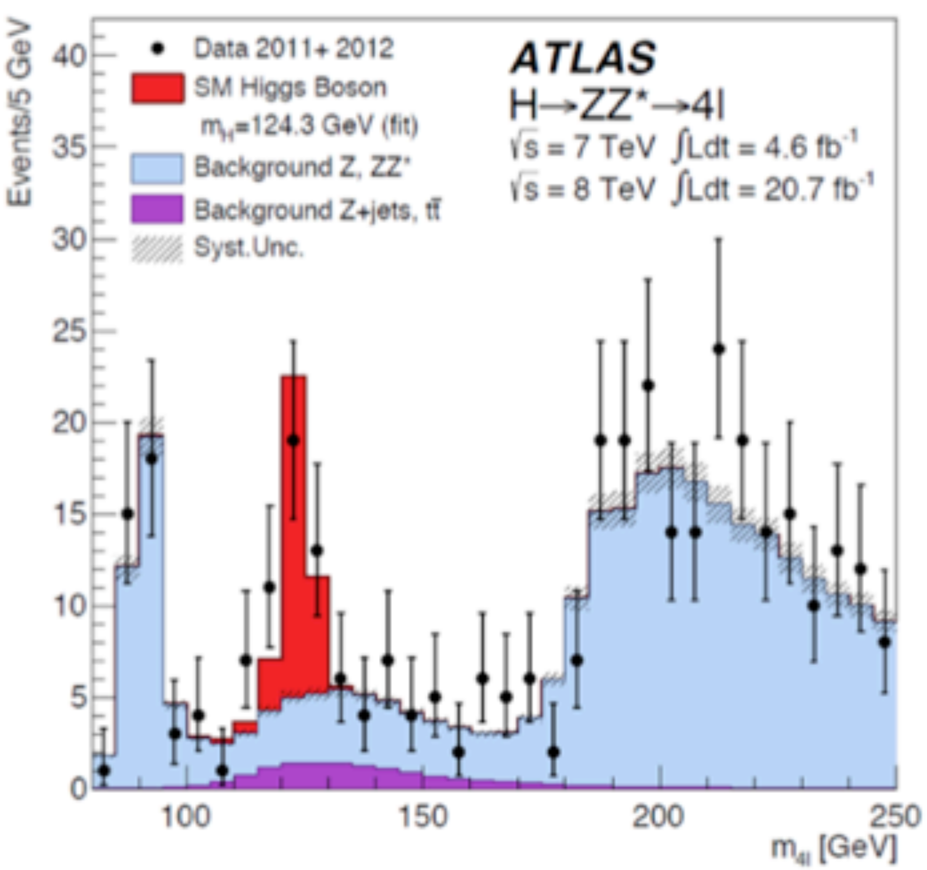
$$m_h \approx 125\,\mathrm{GeV}$$

With 125 GeV Higgs SM can be valid up Mp.
SM sea is as calm as it can be!!!

$$h \to ZZ^* \to l^+l^-l^+l^-$$

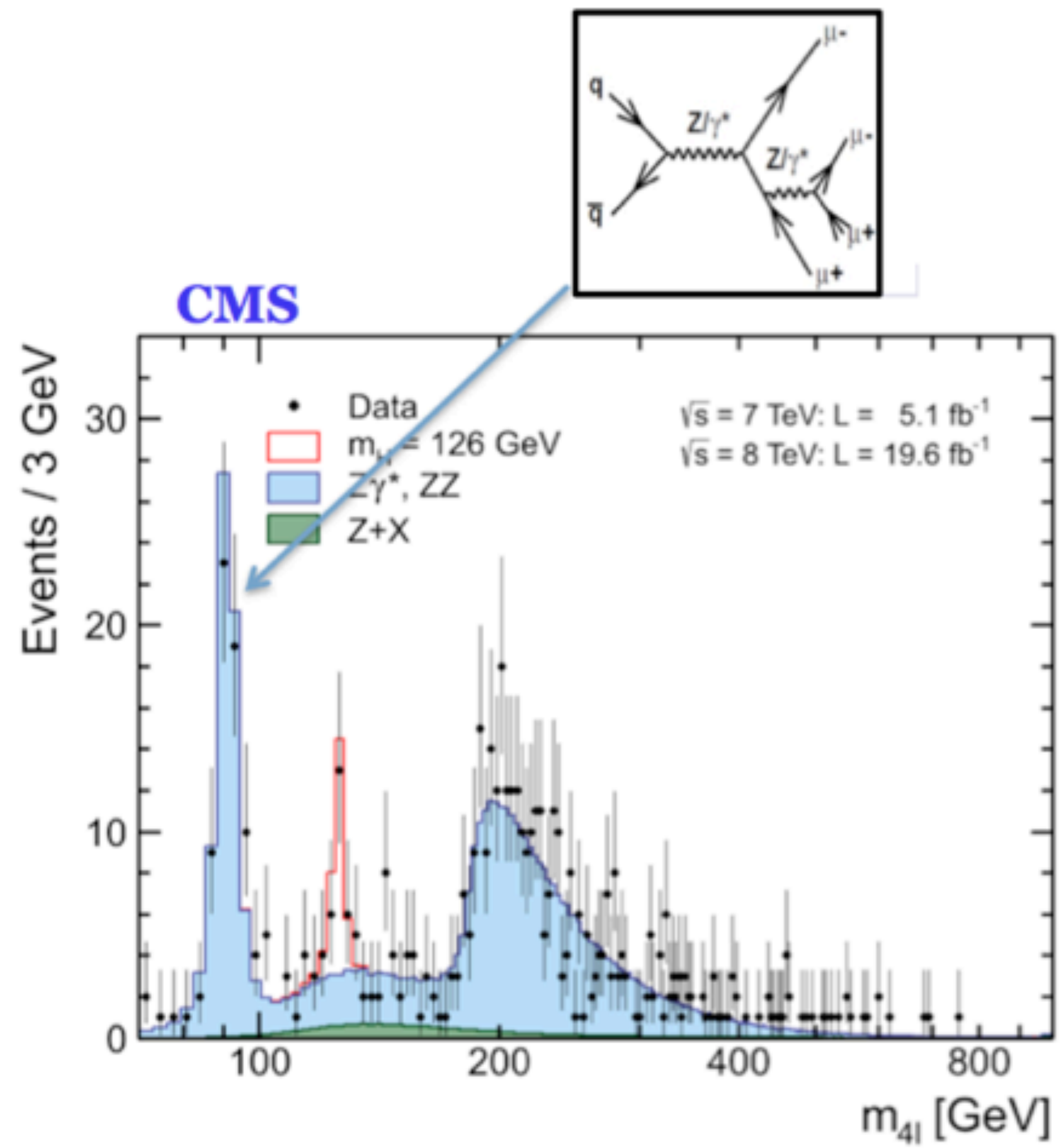
4 Lepton Mass Spectrum

ATLAS



Significance 6.6 σ (4.4σ expected)

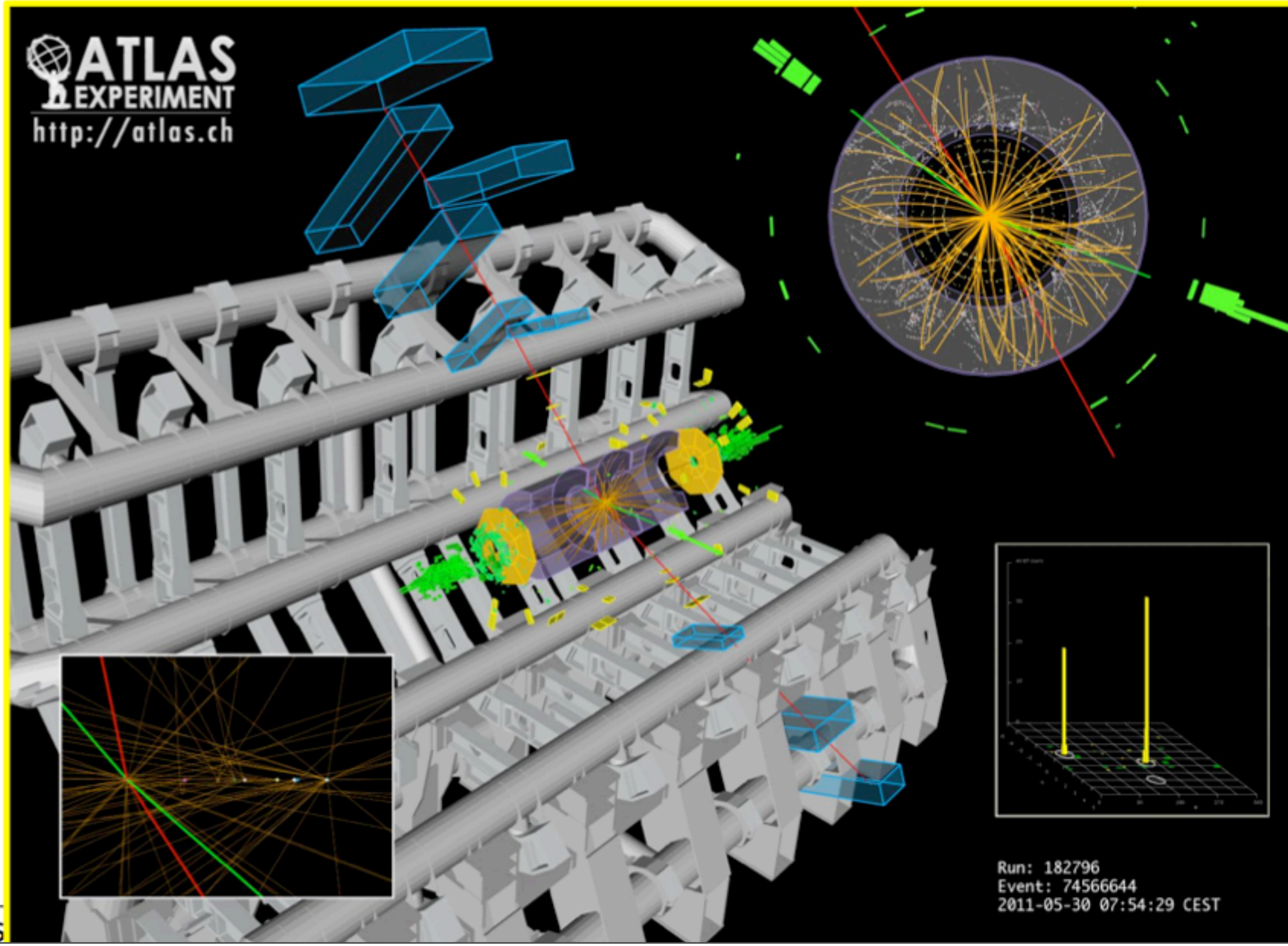
CMS



Significance 6.7σ (7.1σ expected)

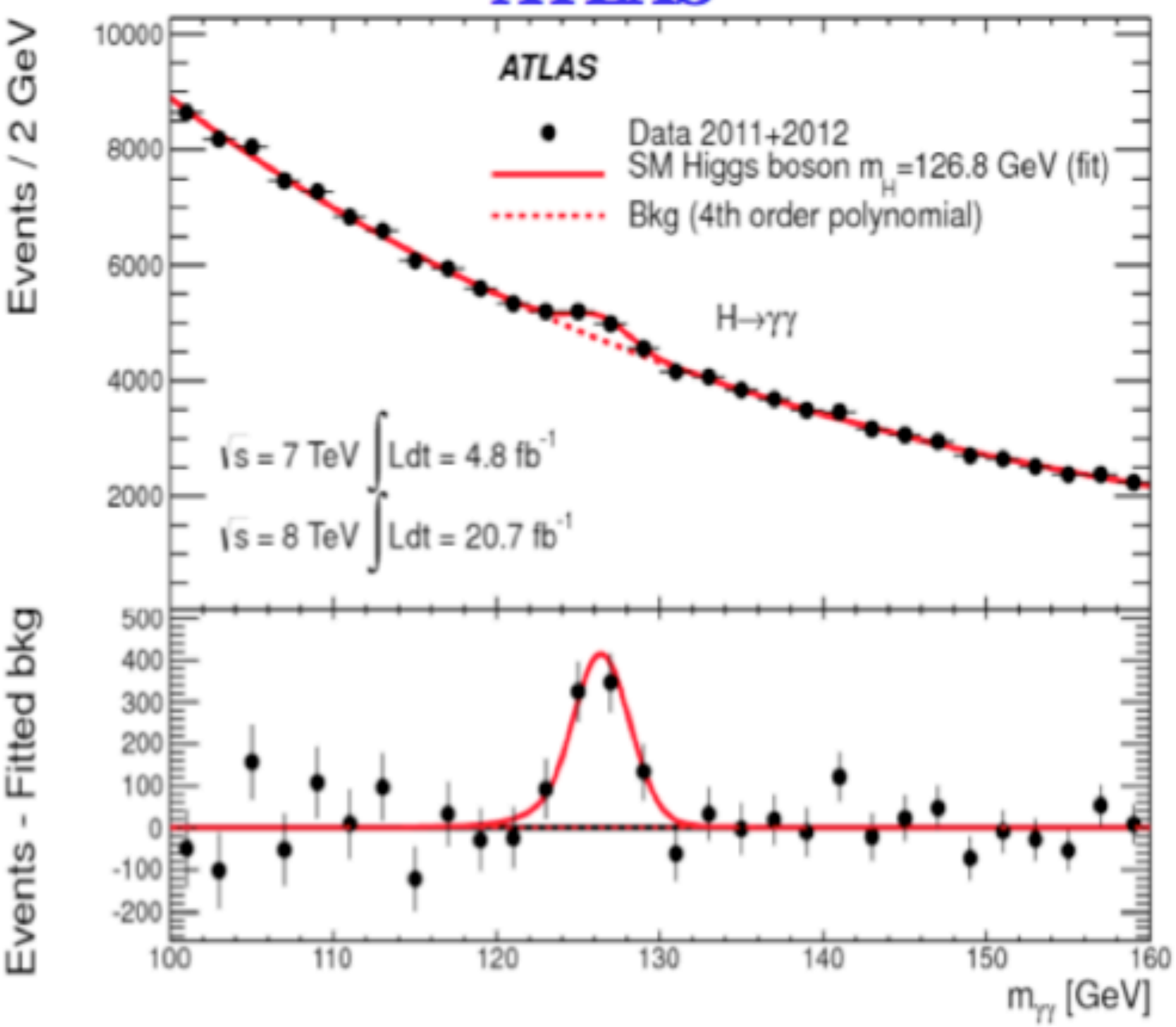
2e2μ candidate with $m_{2e2\mu}$= 124.3 GeV

p_T (e^+, e^-, μ^-, μ^+)= 41.5, 26.5, 24.7, 18.3 GeV
m (e^+e^-)= 76.8 GeV, m($\mu^+\mu^-$) = 45.7 GeV

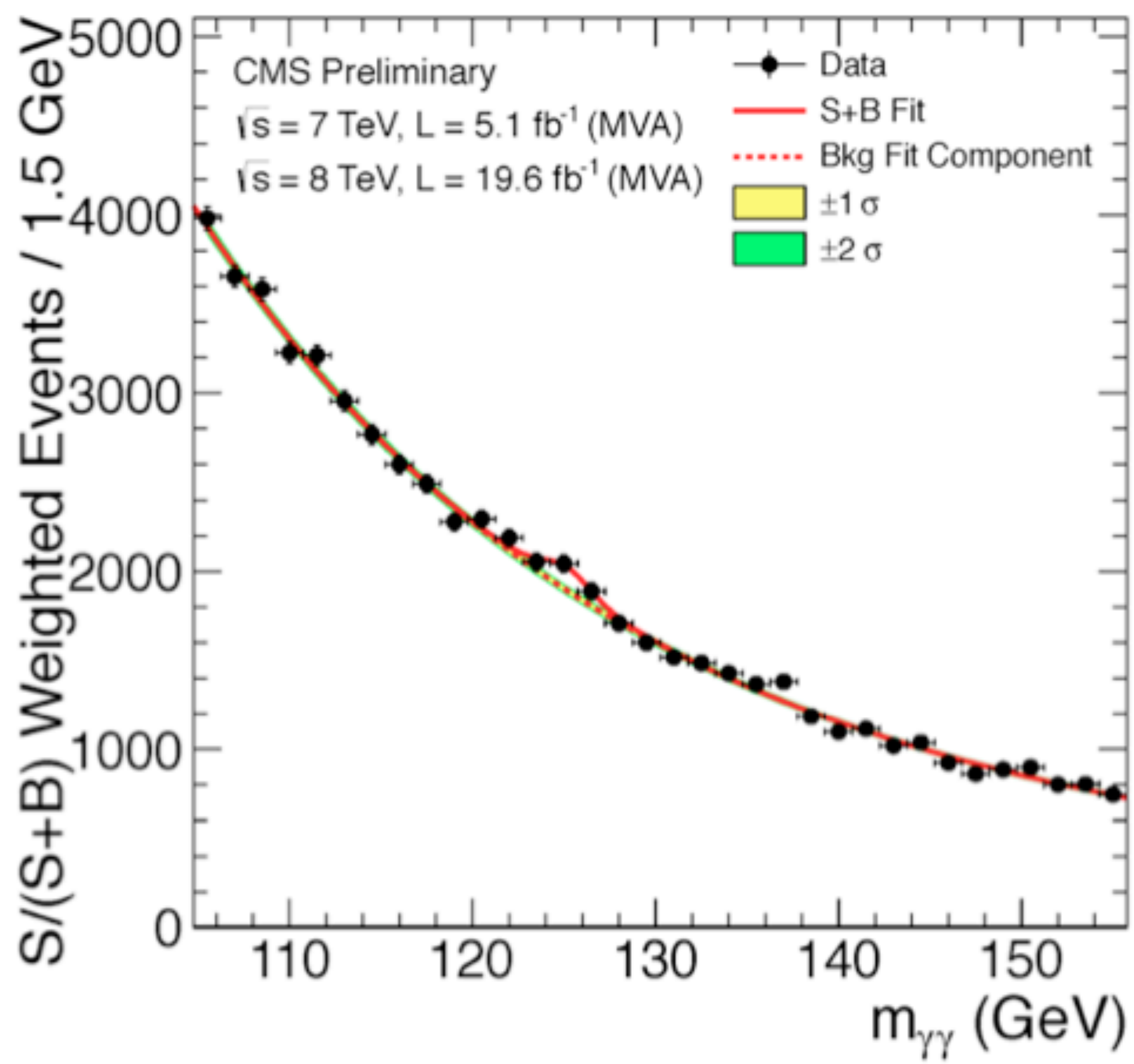


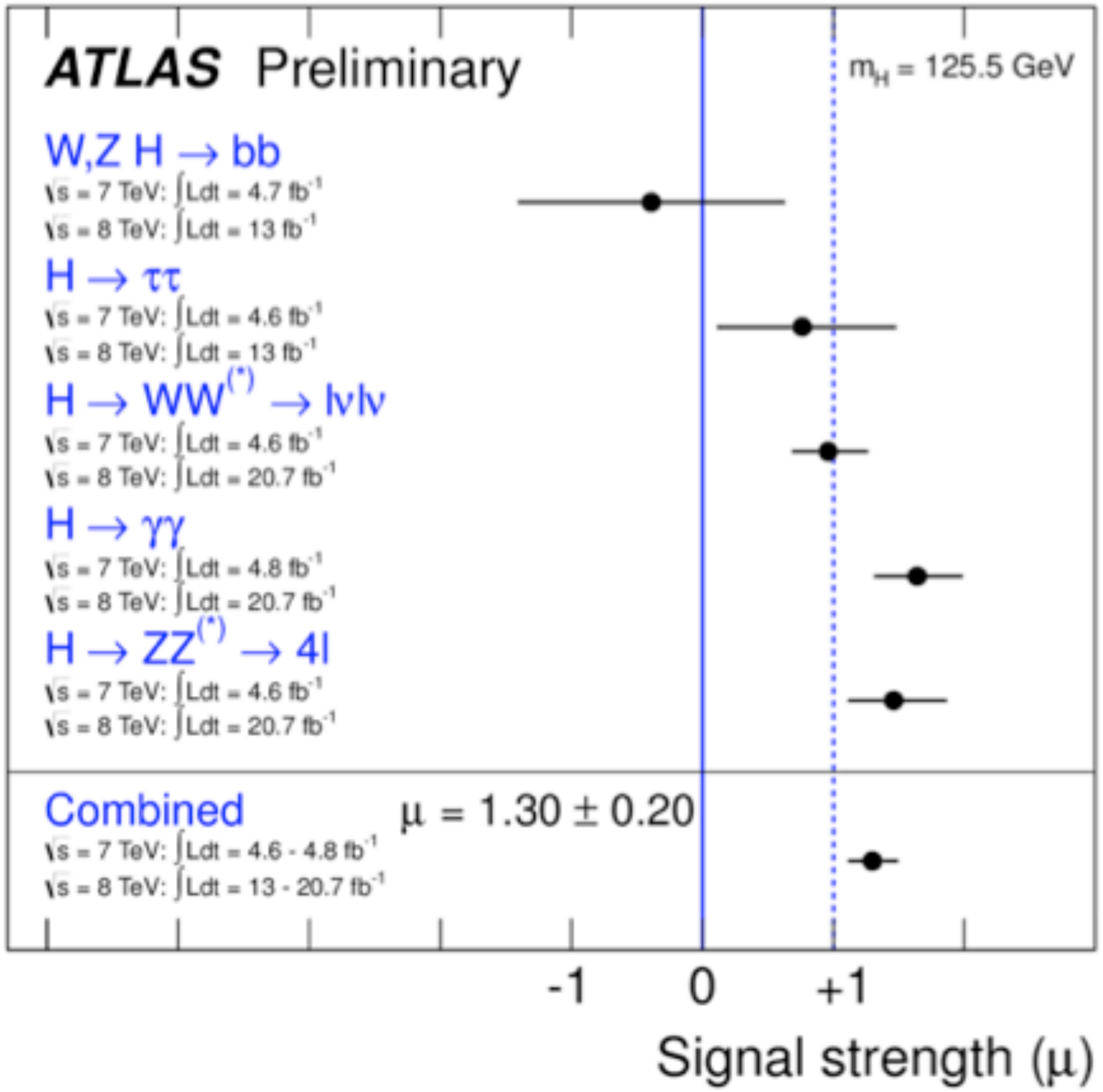
$h \to \gamma\gamma$

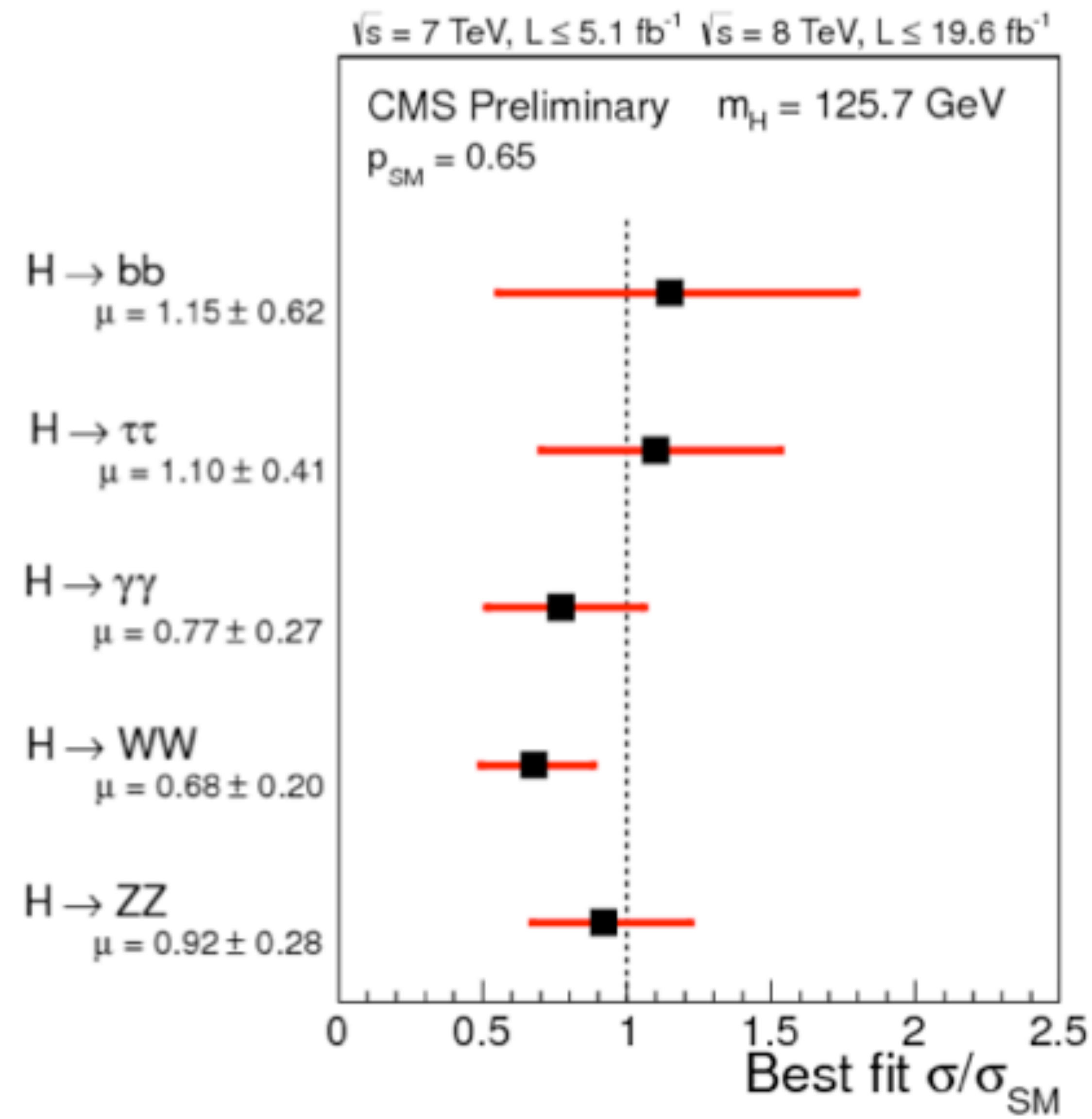
ATLAS



CMS



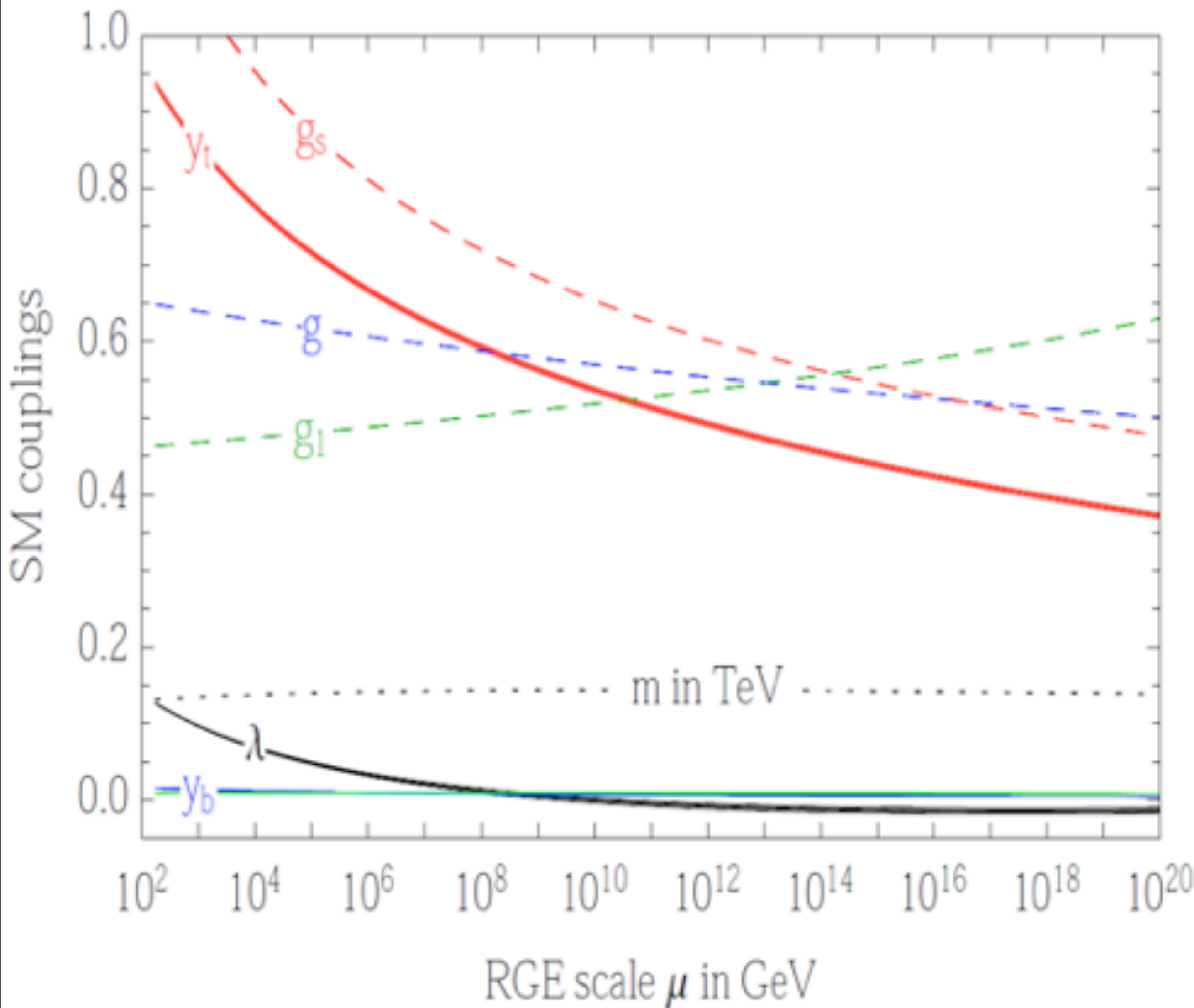


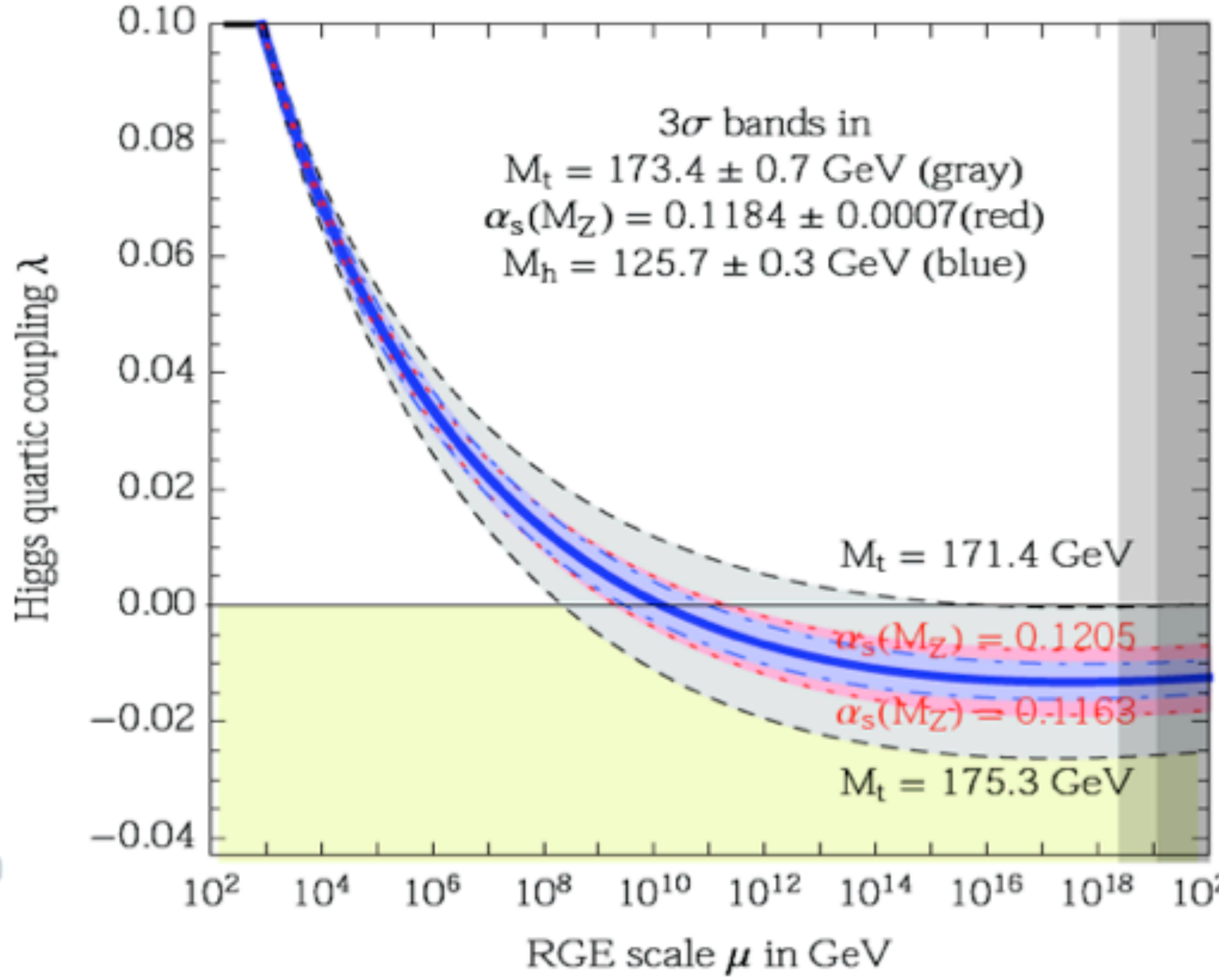


Spectacular agreement with Standard Model

- Implications:

$$V(h) = m^2h^2/2 + \lambda h^4/4$$

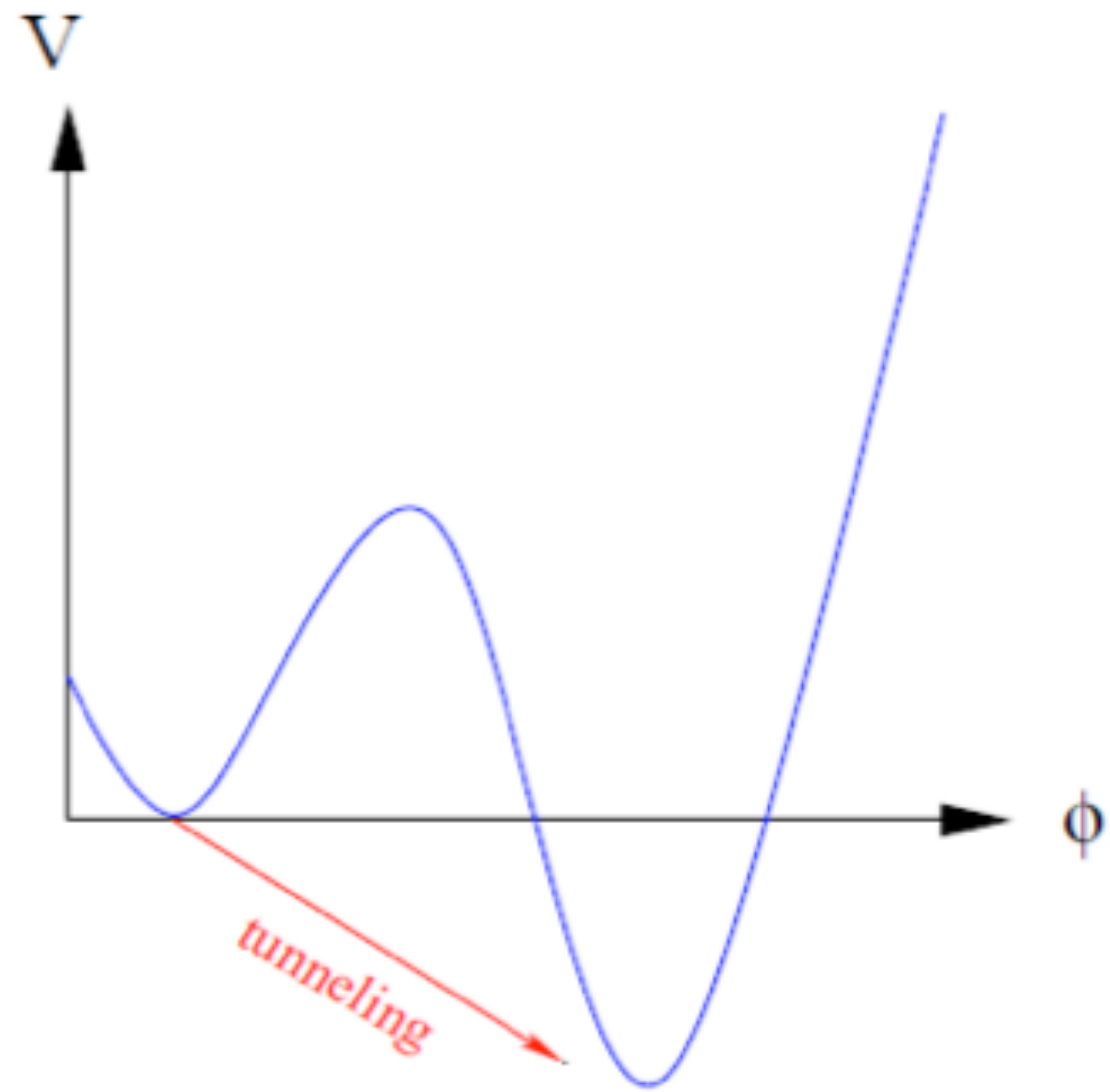




De Grassi et al. '12

Quartic almost zero at high scale for 125 GeV Higgs

With 125 GeV Higgs SM vacuum likely unstable:



$$P \propto e^{-\frac{8\pi^2}{3\lambda}}$$

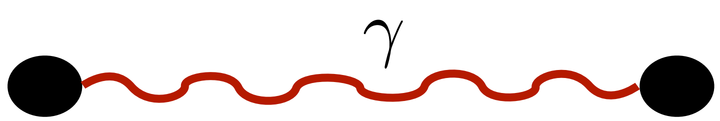
Lifetime larger than age of the universe.

BEYOND SM

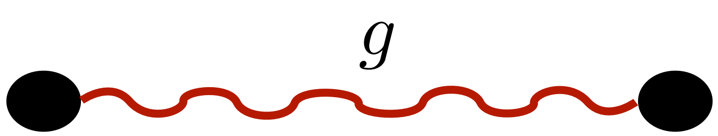
WHY?

- SM is incomplete: no quantum gravity, no dark matter
- Matter-anti-matter asymmetry
- Why 3 generations? Why fermion masses so different?
- Unification
- Strong CP problem
- ...
- Hierarchy or naturalness problem

We don't understand why gravity is so weak:



$$F_{el} = \frac{e^2}{r^2}$$



$$F_{gr} = -8\pi G_N \frac{m_1 m_2}{r^2}$$

$$\frac{F^p_{GR}}{F^p_{el}} \sim 10^{-40}$$

Gravity and other forces unify at:

$$M_p = (8\pi G_N)^{-\frac{1}{2}} = 10^{19}\,\mathrm{GeV}$$

Hierarchy (naturalness) problem:

$$\frac{m_h^2}{M_p^2} \sim 10^{-34}$$

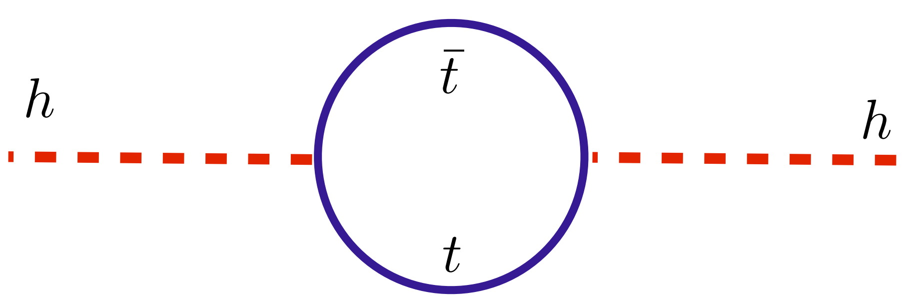
?

Hierarchy (naturalness) problem:

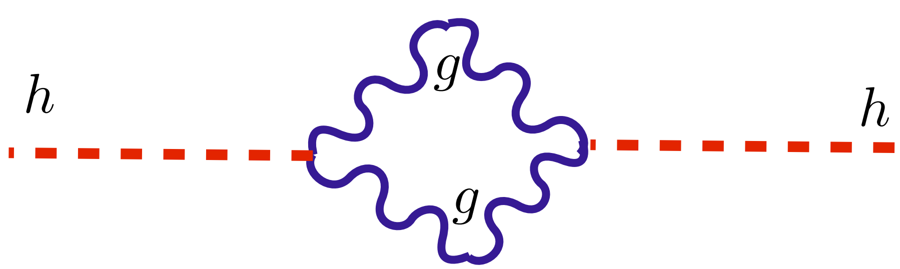
$$\frac{m_h^2}{M_p^2} \sim 10^{-34}$$

?

Electro-weak scale is unstable



$$\delta m_h^2 \sim \frac{g_{SM}^2}{16\pi^2}\Lambda^2$$



$$\Lambda \sim M_p$$

$$\downarrow$$

$$m_h^2 = 1000000000000000000000000000000.01\,\mathrm{TeV}^2$$
$$- 1000000000000000000000000000000.00\,\mathrm{TeV}^2$$

$$\Lambda \sim M_p$$

$$\begin{aligned} m_h^2 &= 100000000000000000000000000000000.01\,\mathrm{TeV}^2 \\ &- 100000000000000000000000000000000.00\,\mathrm{TeV}^2 \end{aligned}$$

Natural theory:

$$\Lambda \sim \mathrm{TeV}$$

No obvious experimentalist:

$$m_h^2 \sim \frac{g_{SM}^2}{16\pi^2}\Lambda^2$$

New physics expected to be seen at the LHC 

No obvious experimentalist:

$$m_h^2 \sim \frac{g_{SM}^2}{16\pi^2}\Lambda^2$$

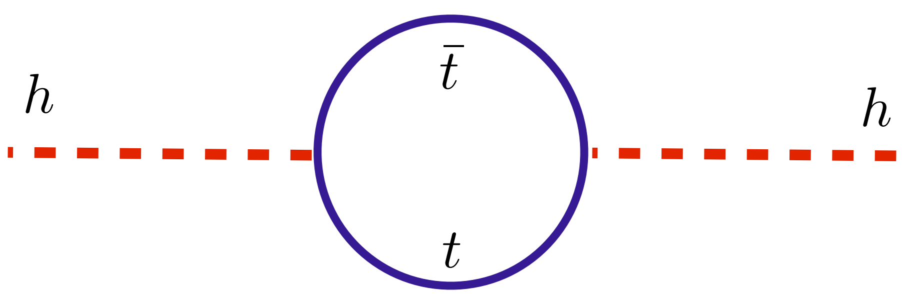
New physics expected to be seen at the LHC 

Worked in the past:

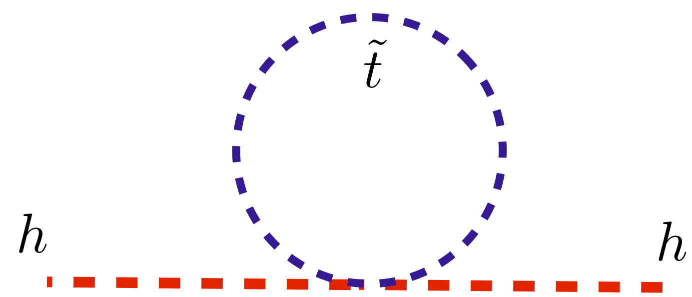
$$(m_e \sim \Lambda \sim m_{e+},\ \Delta m_K \sim G_F \Lambda^2 \sim G_F m_c^2,\ \Delta m_\pi \sim \alpha\Lambda \sim \alpha m_\rho,\ \ldots)$$

Two paradigms:

- Weak Coupling:
  Supersymmetry



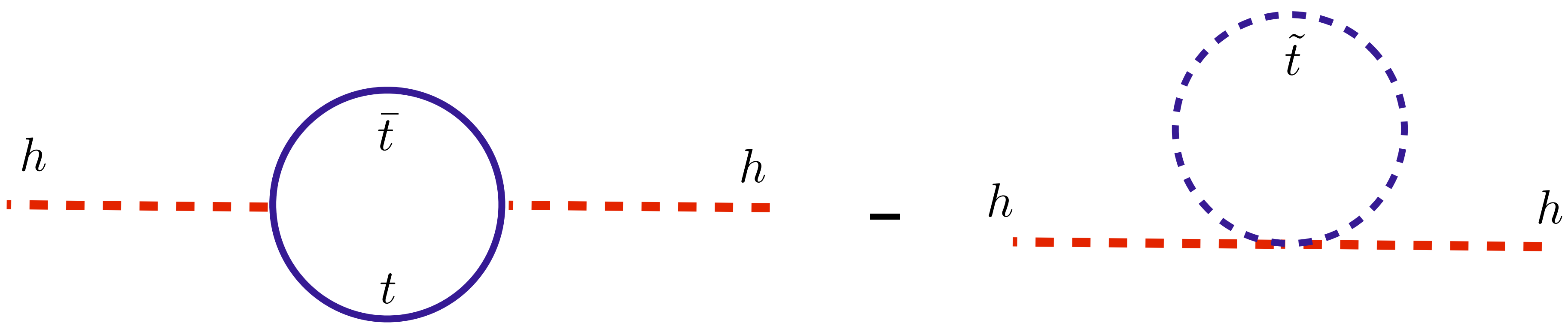
$-$



$\sim 100\,\mathrm{GeV}$

Two paradigms:

- Weak Coupling:
  Supersymmetry

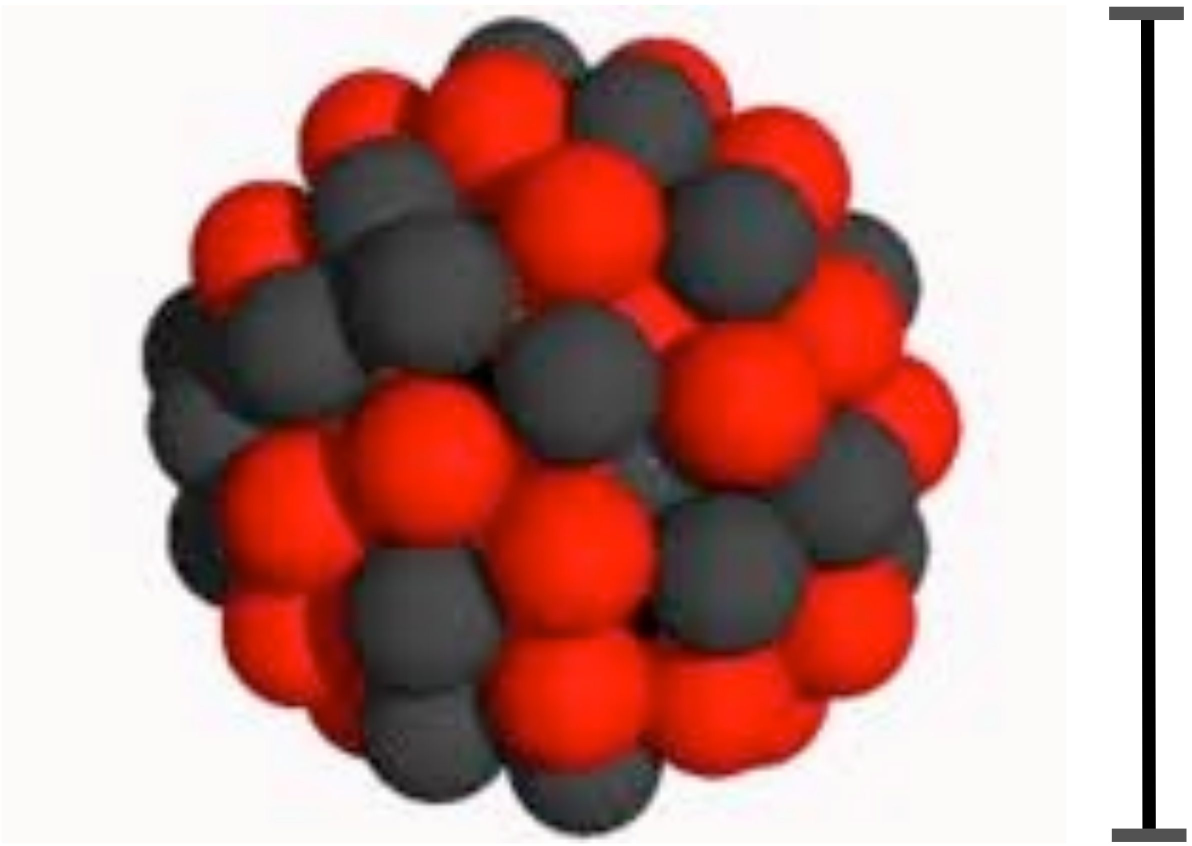


$\sim 100\,\mathrm{GeV}$

- Strong Coupling:
  Technicolor, Composite Higgs, Higgsless, Extra-dimensions ...

COMPOSITE HIGGS

Higgs is light because it is big:

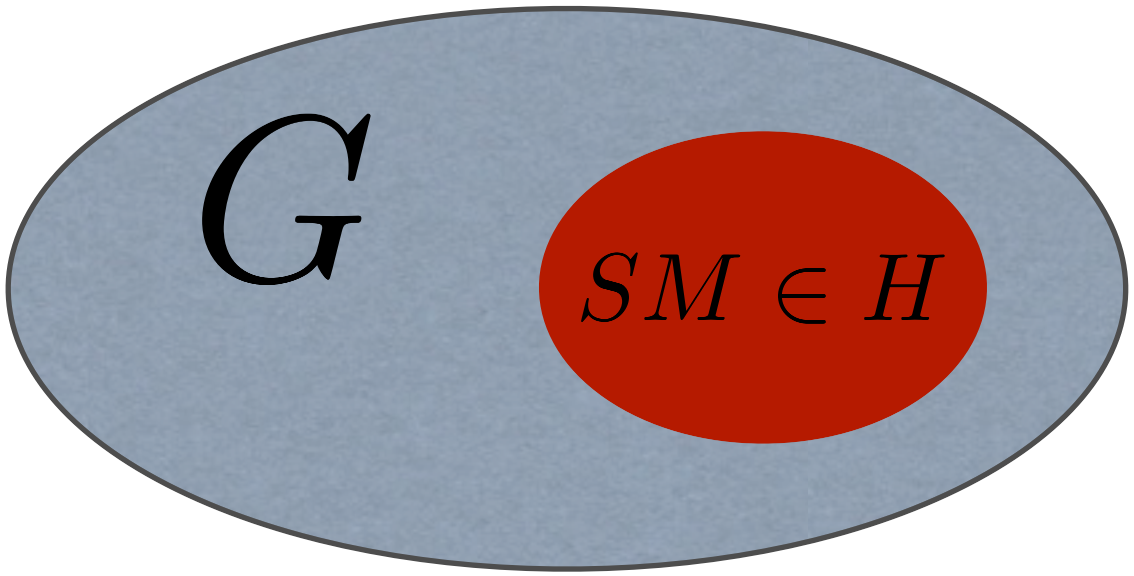


$$\frac{1}{m_\rho} \sim \frac{1}{\text{TeV}} = 10^{-18}\,\text{m}$$

Compositeness scale acts as cut-off

$$\delta m_h^2 \sim \frac{g_{SM}^2}{16\pi^2} m_\rho^2$$

Higgs could be an approximate Goldstone boson

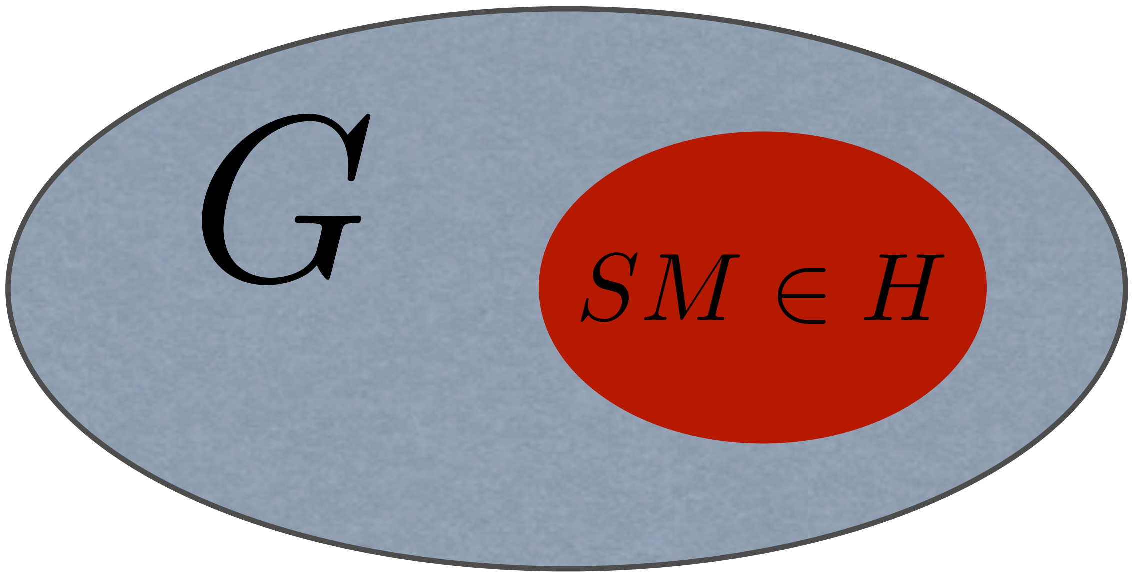


Georgi, Kaplan '80s

Ex: $\frac{SO(5)}{SO(4)} \longrightarrow 4\,\mathrm{GB} = H$

Agashe , Contino, Pomarol, '04

Higgs could be an approximate Goldstone boson



Georgi, Kaplan '80s

Ex: $\frac{SO(5)}{SO(4)} \longrightarrow 4\,\mathrm{GB} = H$

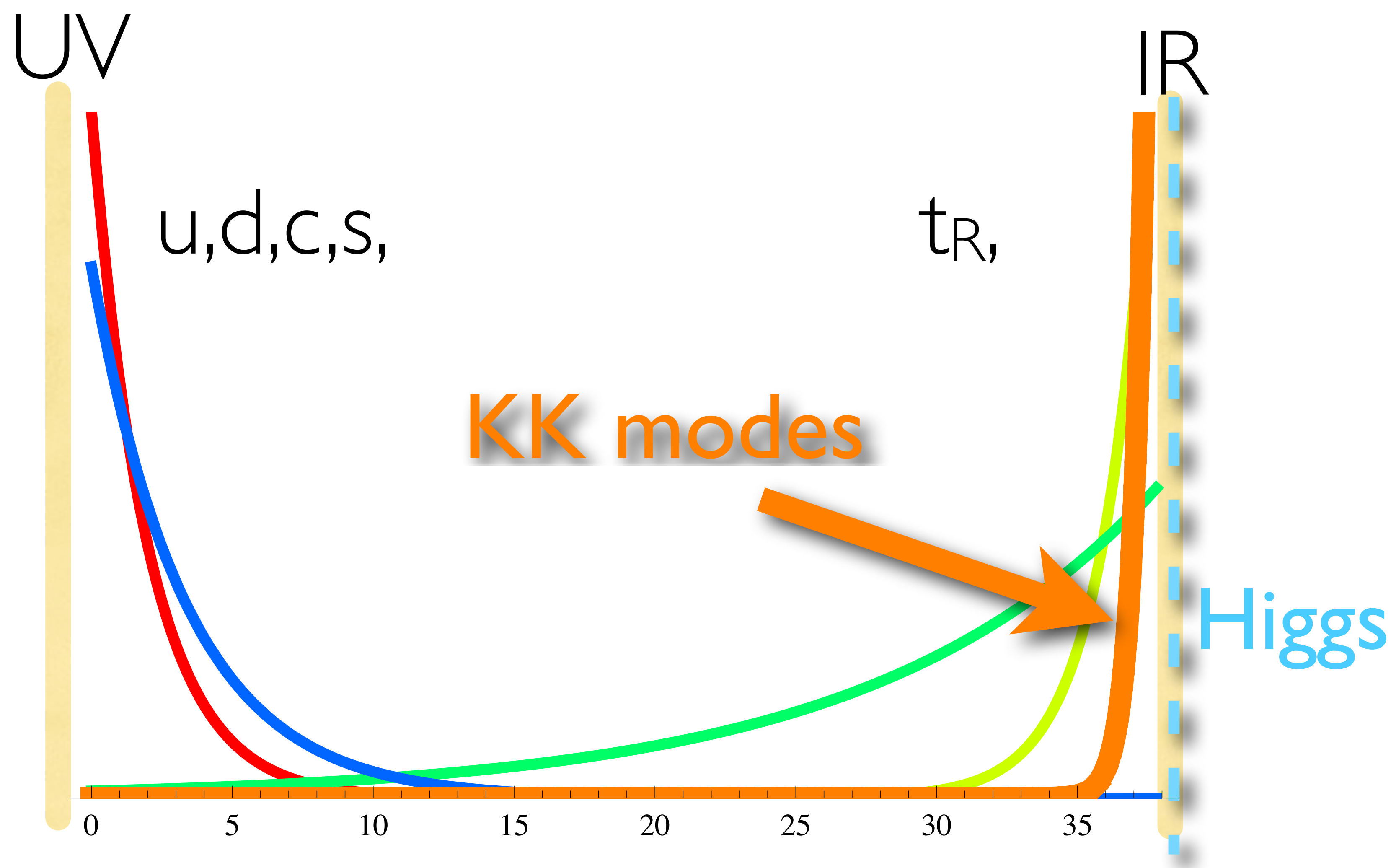
Agashe , Contino, Pomarol, '04

Each SM particle has a heavy partner:

$$A^{\mu}_{SM} \longrightarrow \rho^{\mu} \in \mathrm{Adj}[G] \qquad g_{\rho}$$

$$f_{SM} \longrightarrow F \in G \qquad m_{\rho}$$

- **5D Models**

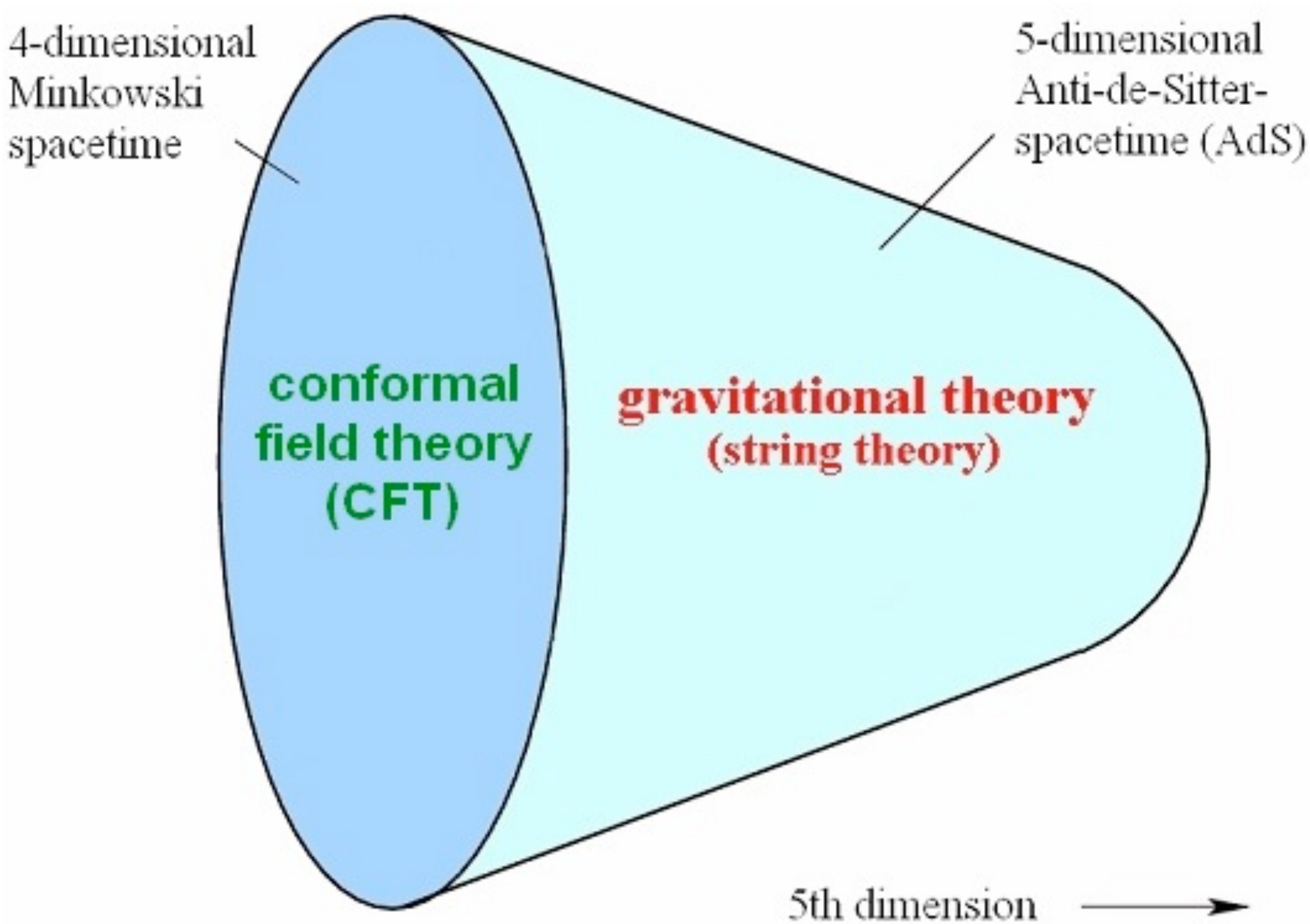


(Randall-Sundrum '99)

SM fields propagate in the extra dimension.
Different profiles generate hierarchies.

- **4D Models**

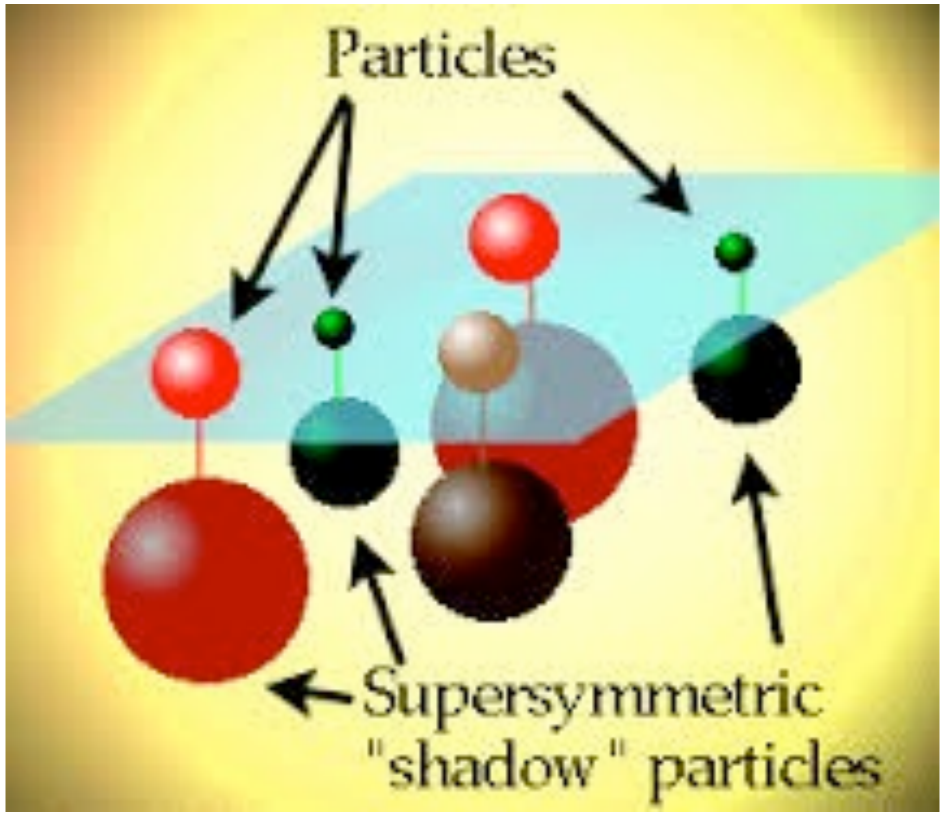
5D models are dual to 4D strongly coupled theories



5th dimension dual to energy scale

SUPERSYMMETRY

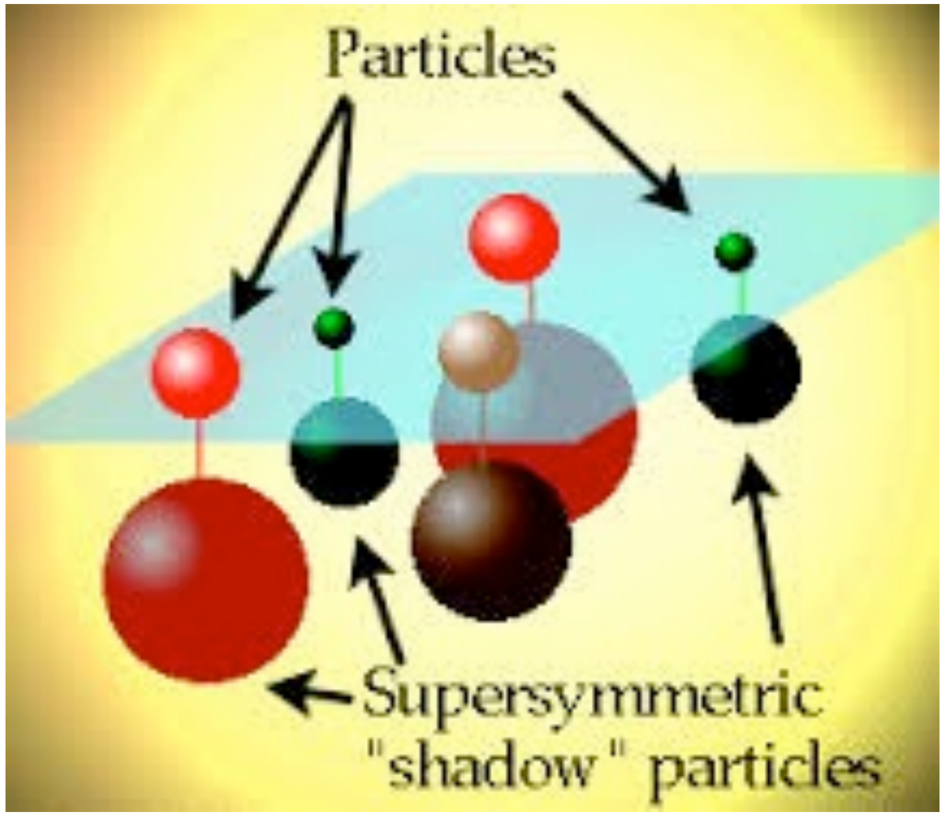
Supersymmetry relates fermions and bosons



$$Q|B\rangle = |F\rangle$$

$$Q|F\rangle = |B\rangle$$

Supersymmetry relates fermions and bosons



$$Q|B\rangle = |F\rangle$$

$$Q|F\rangle = |B\rangle$$

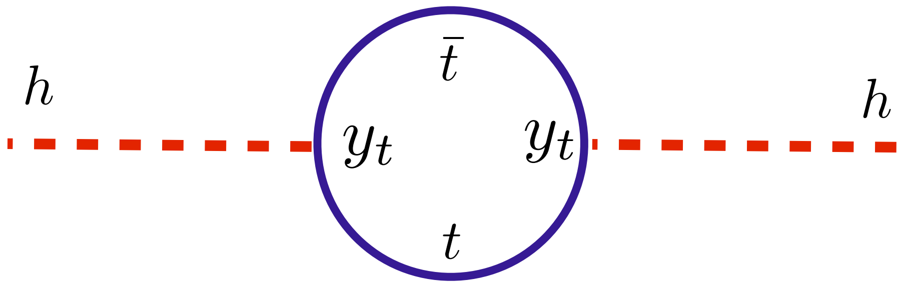
It is a space-time symmetry

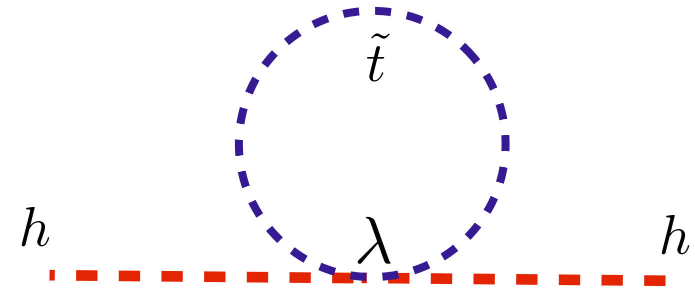
$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = \sigma^{\mu}_{\alpha\dot{\alpha}} P_\mu$$

Supersymmetry cannot be exact in the real world

$$Q_\alpha|0\rangle \neq 0$$

Relevant for naturalness:

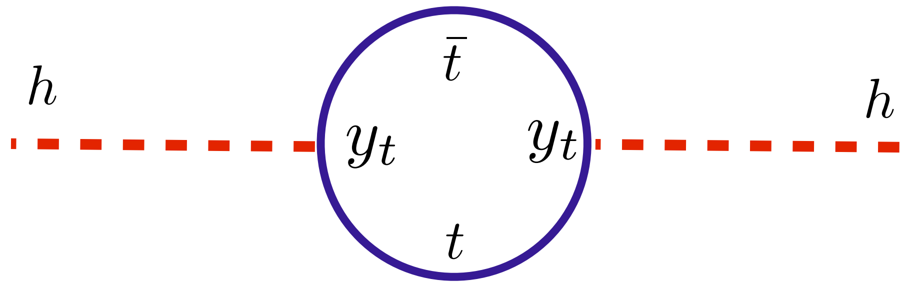




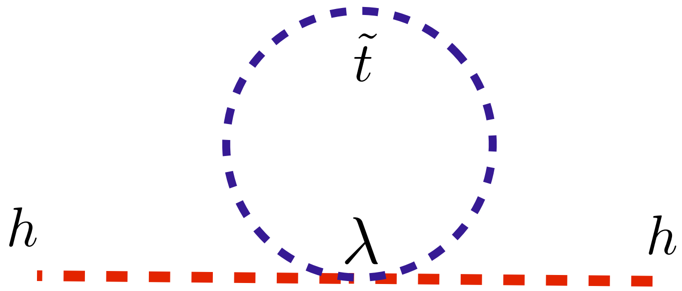
$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

$$\delta m_h^2 = +\frac{3\lambda}{8\pi^2}\Lambda^2$$

Relevant for naturalness:



$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$



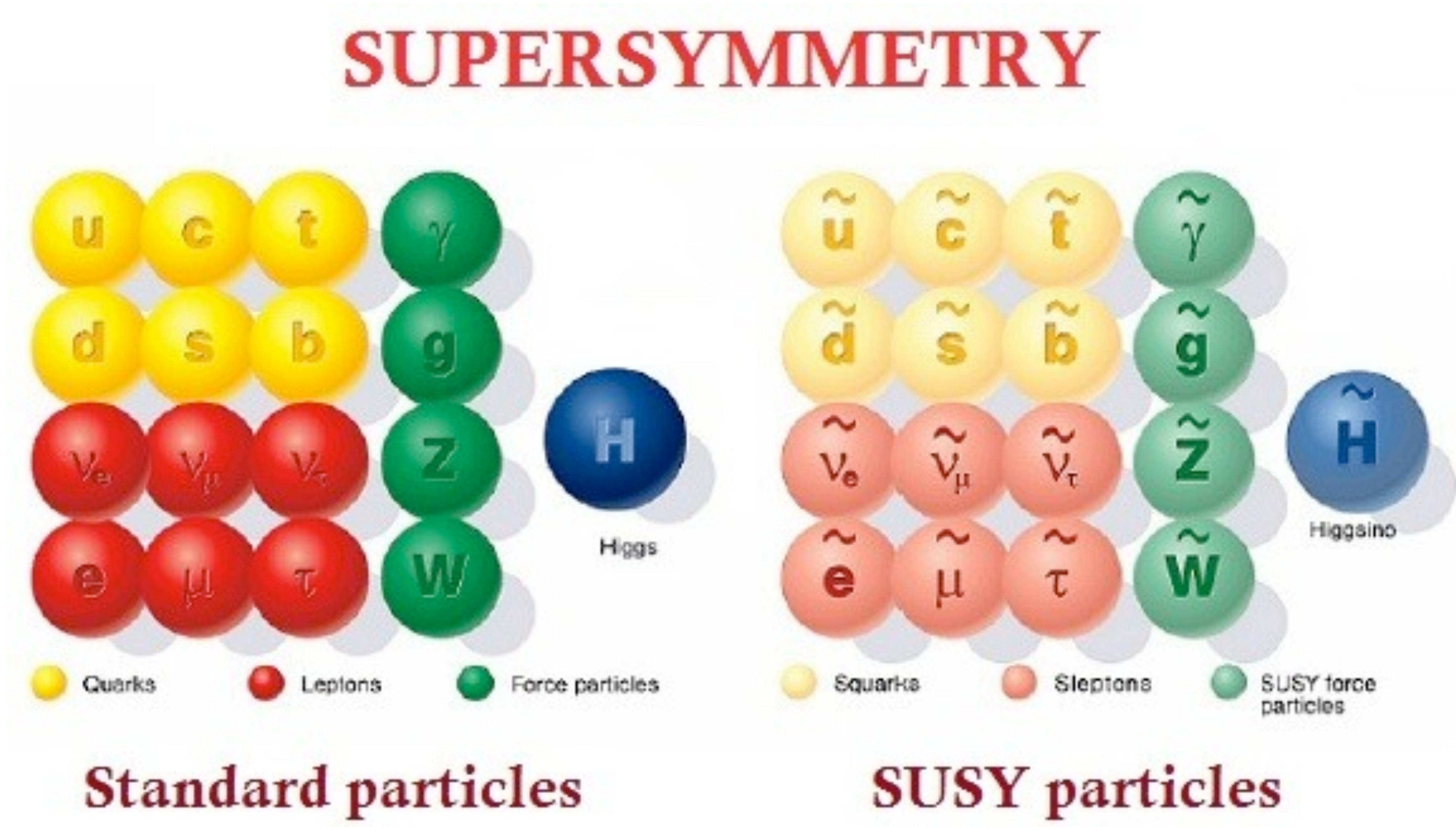
$$\delta m_h^2 = +\frac{3\lambda}{8\pi^2}\Lambda^2$$

SUSY:

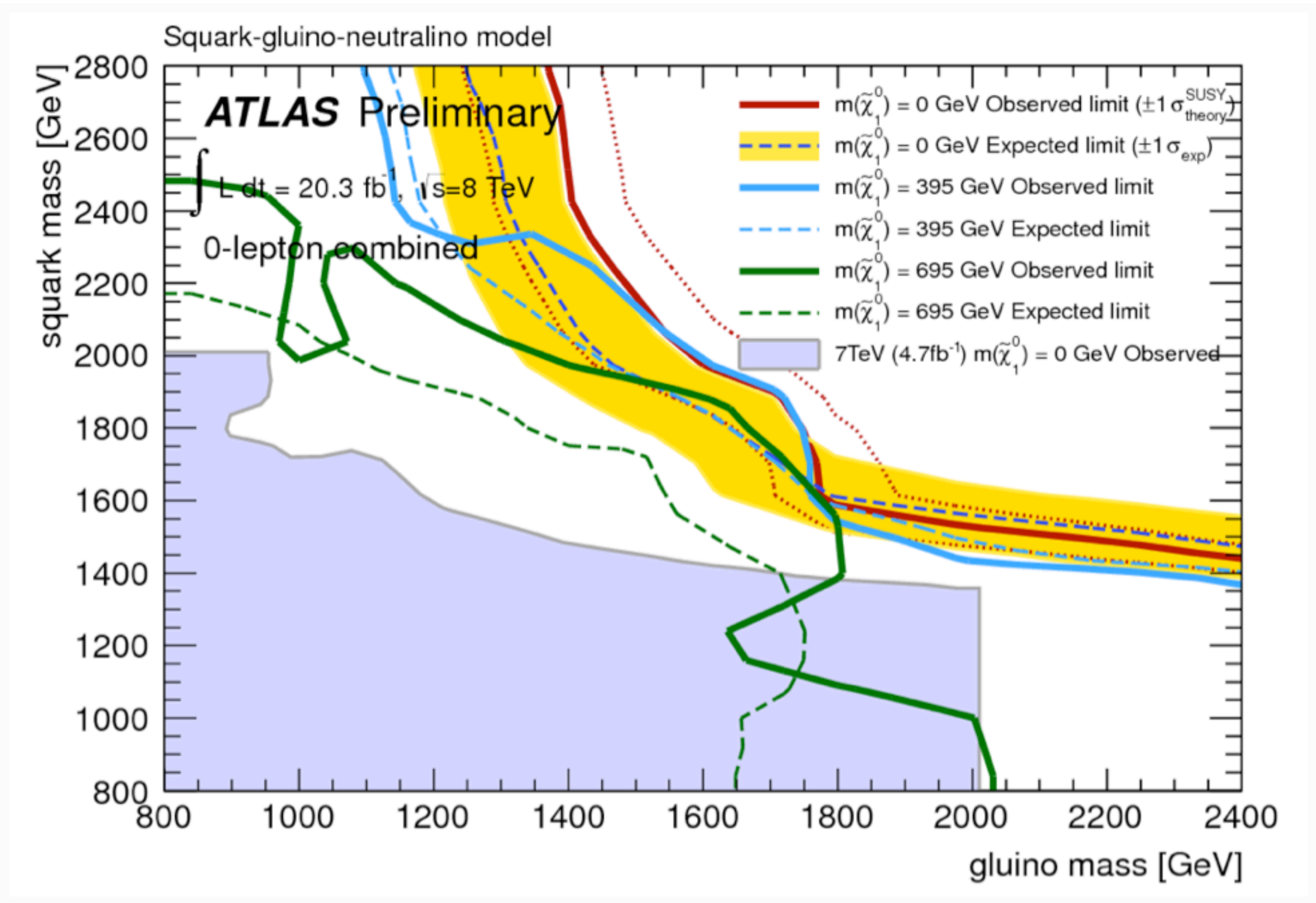
$$\boxed{\lambda = y_t^2}$$

Scalars behave as fermions and can be light

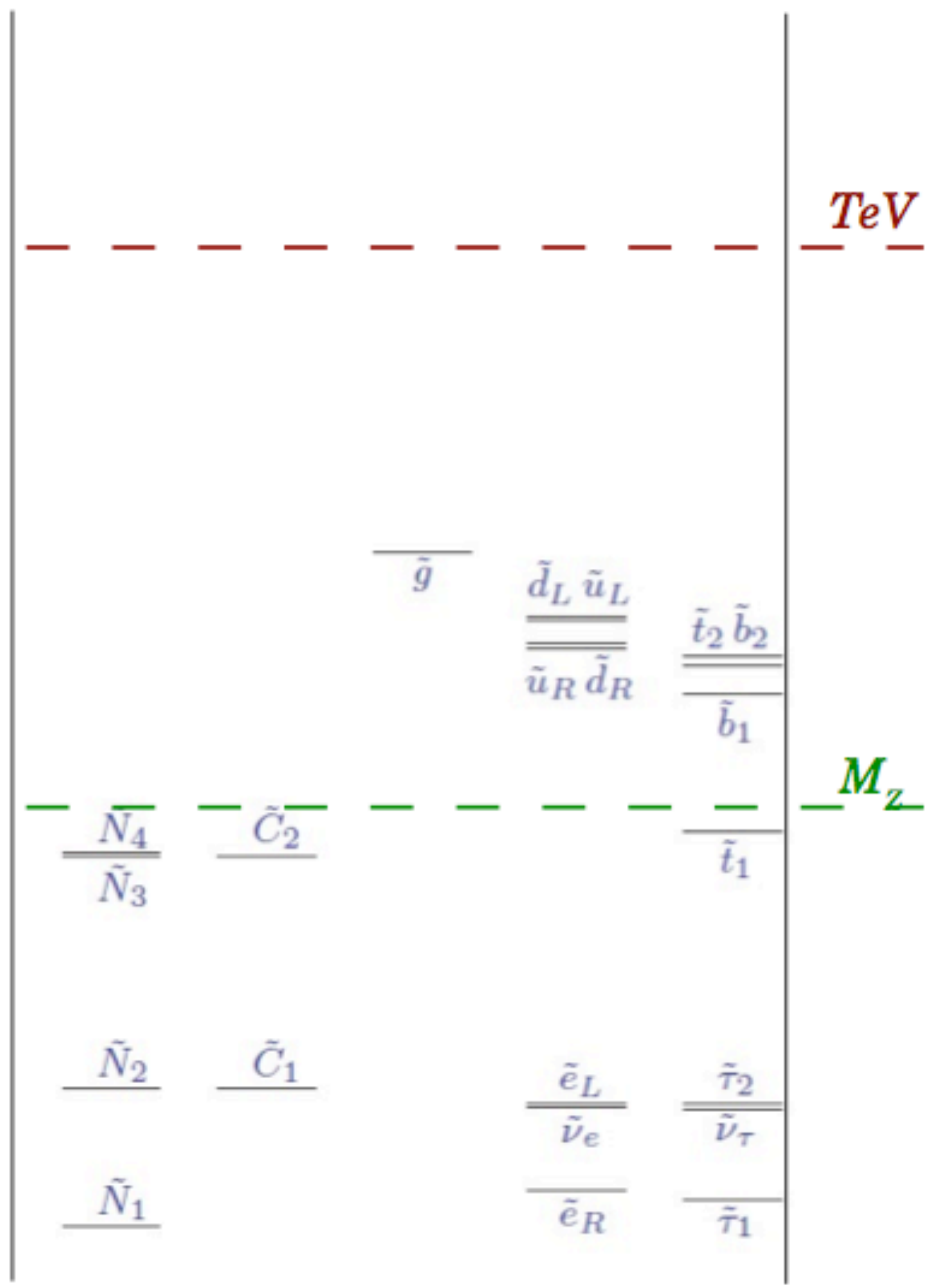
$$\delta m_f \propto m_f \log \frac{\Lambda}{m_f}$$



Each SM particle must have a partner of different spin.
Half still missing...

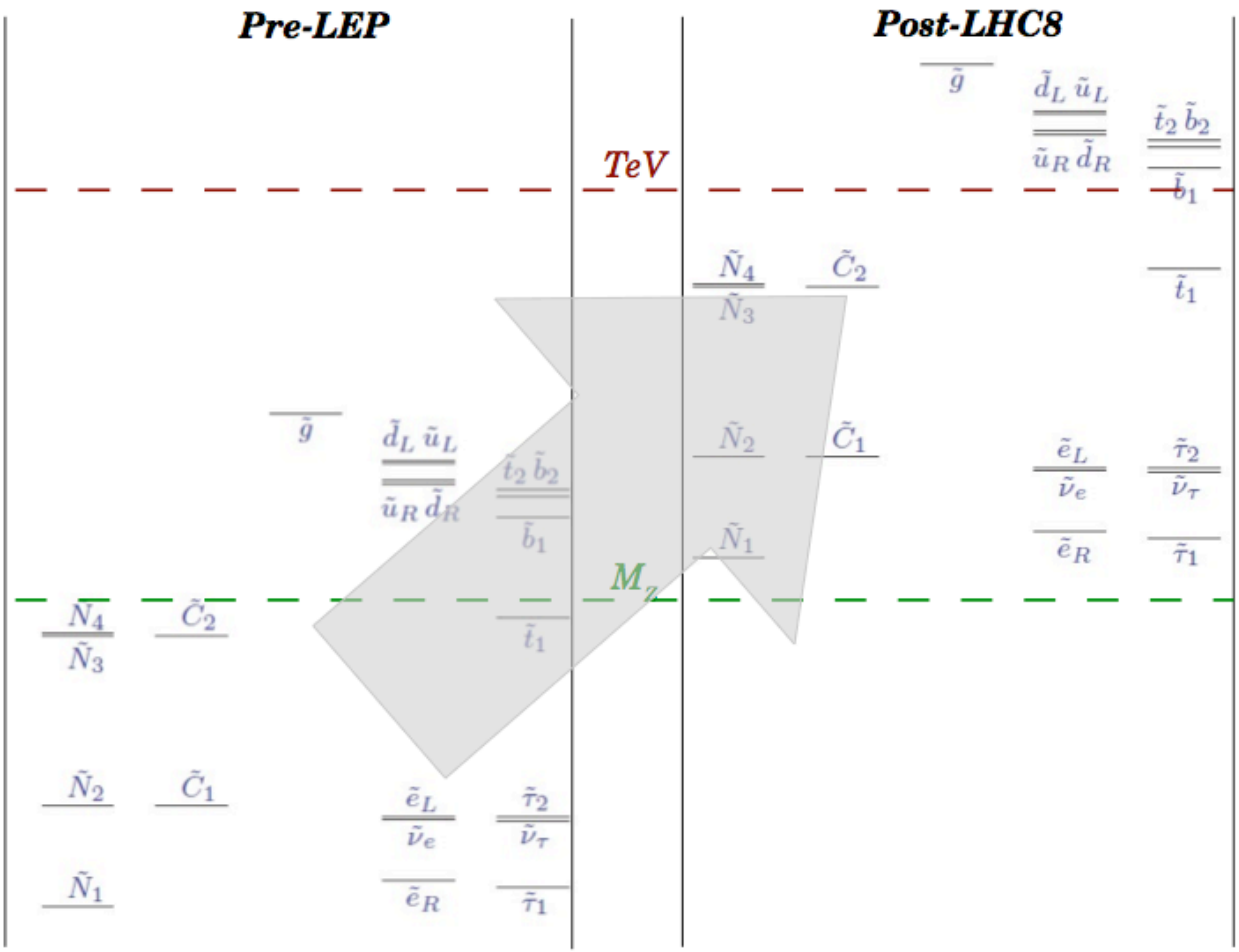

Squark-gluino-neutralino model
ATLAS Preliminary
∫L dt = 20.3 fb⁻¹, √s=8 TeV
0-lepton combined
m(χ̃⁰₁) = 0 GeV Observed limit (±1 σ^SUSY_theory)
m(χ̃⁰₁) = 0 GeV Expected limit (±1 σ_exp)
m(χ̃⁰₁) = 395 GeV Observed limit
m(χ̃⁰₁) = 395 GeV Expected limit
m(χ̃⁰₁) = 695 GeV Observed limit
m(χ̃⁰₁) = 695 GeV Expected limit
7TeV (4.7fb⁻¹) m(χ̃⁰₁) = 0 GeV Observed
squark mass [GeV]
gluino mass [GeV]
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
800
1000
1200
1400
1600
1800
2000
2200
2400

How Natural SUSY would look like



By G.Villadoro

SUSY is tuned!



By G.Villadoro

Still ways out:

Large A-terms

Natural SUSY

R-parity Violation

NMSSM

Split SUSY

Compressed Spectrum

Partial SUSY

Tuning

PMSSM

None terribly convincing...

ANTHROPICS

$$\Lambda$$

Cosmological constant problem:

$$\int d^4x\sqrt{g}\,\left[M_p^2 R - \Lambda\right] \qquad\qquad \Lambda \sim 10^{-124}\, M_p$$

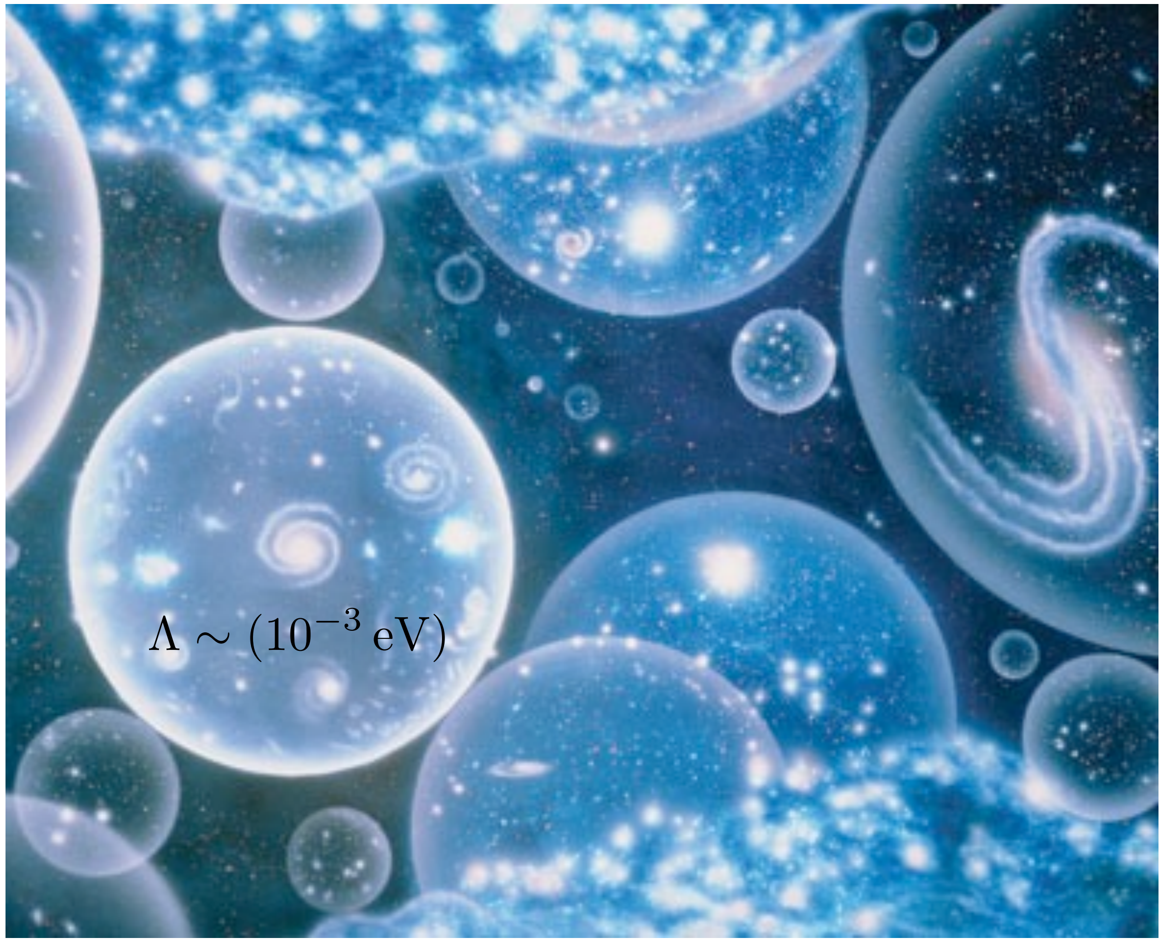
$$\Lambda_0 = \frac{1}{2}\sum_i (-1)^{F_i}\,\hbar\,\omega_i \sim M_p^4$$

Weinberg argued that galaxies would not form if c.c. was slightly bigger.

(Weinberg '88)

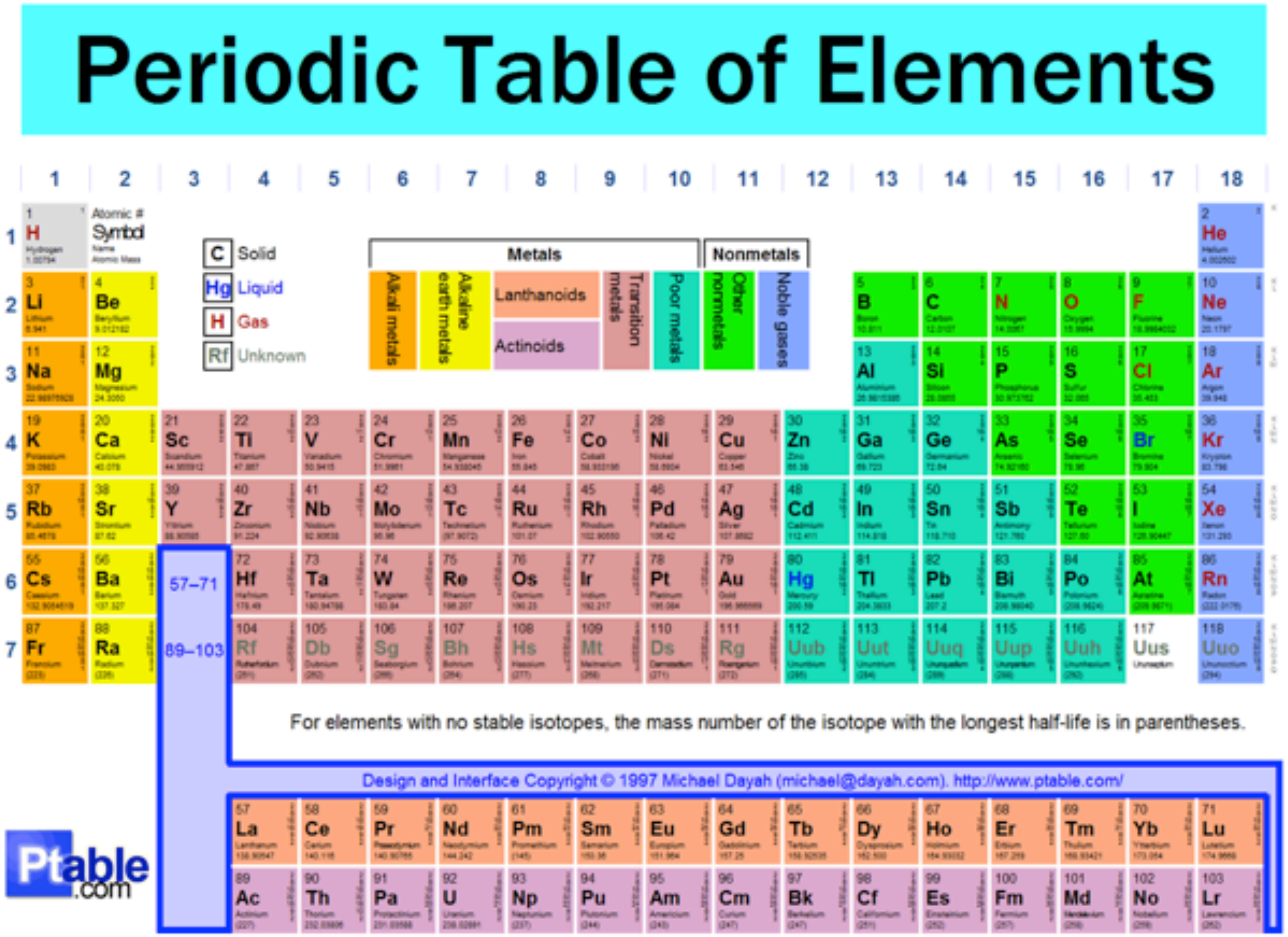
Anthropic principle: environmental selection determines (some) of the parameters.

We may live in a corner of the "multiverse":



Ultimate Copernican Revolution: our universe not unique

"Atomic principle":



$$m_p = 938.3\,\text{MeV}$$

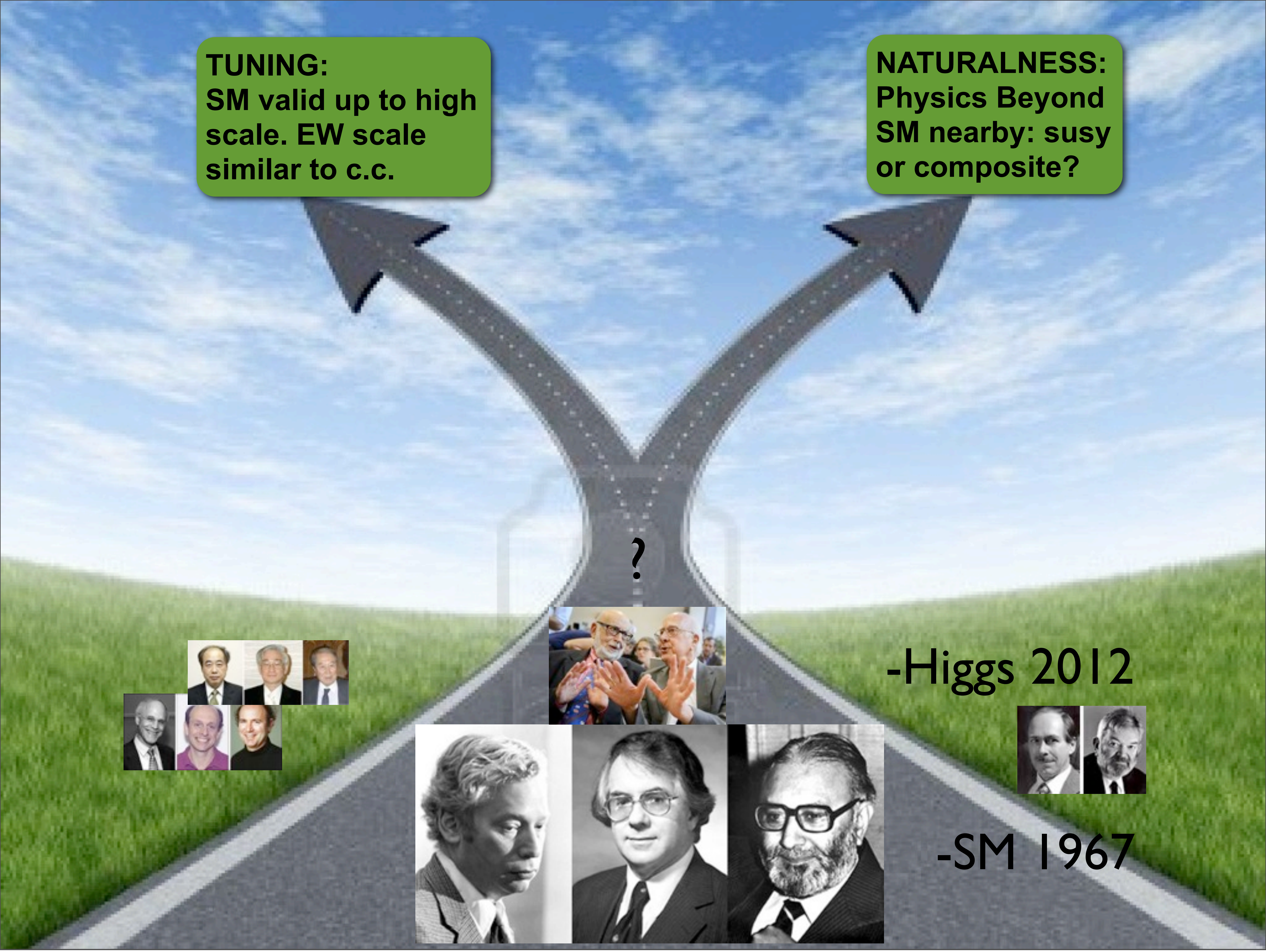
$$m_n = 939.6\,\text{MeV}$$

Heavy elements require:

$$v < 5 \times 246\,\text{GeV}$$

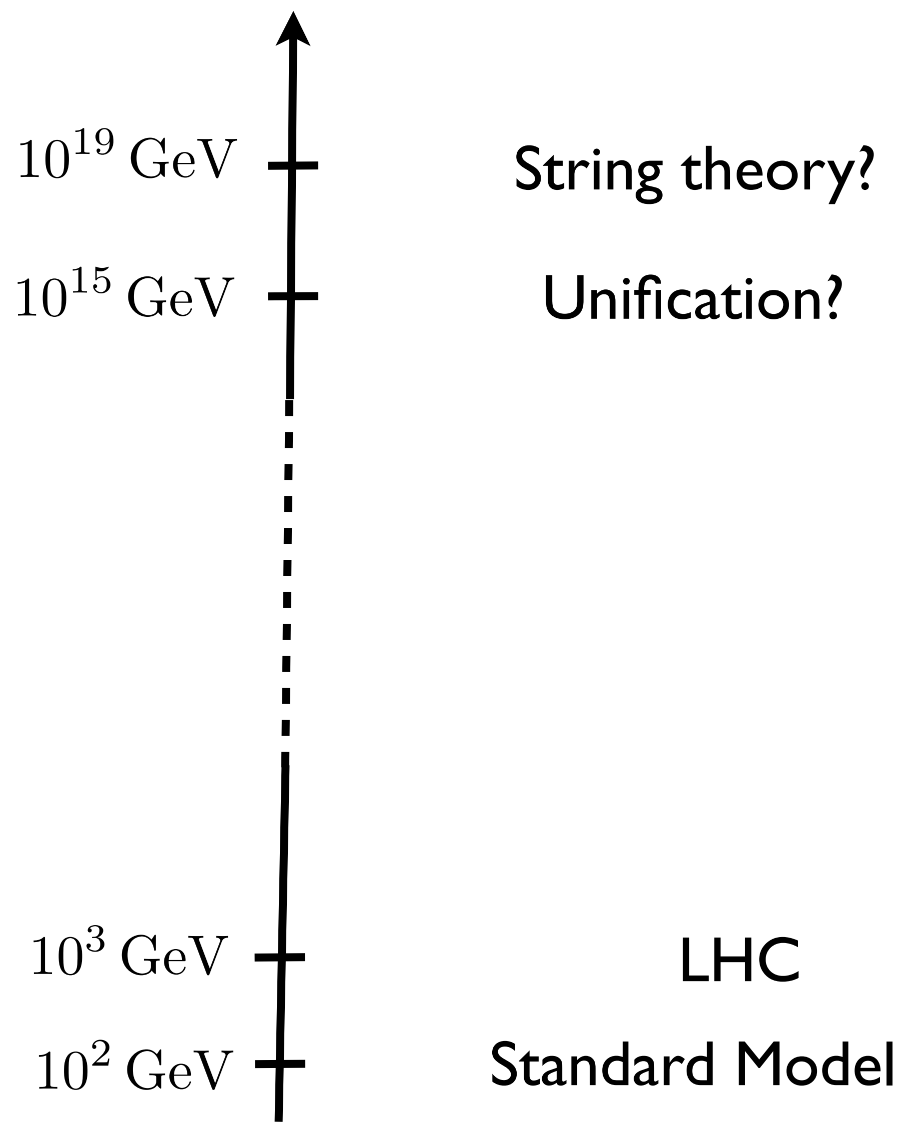

?
-Higgs 2012
-SM 1967


NATURALNESS: Physics Beyond SM nearby: susy or composite?
?
-Higgs 2012
-SM 1967

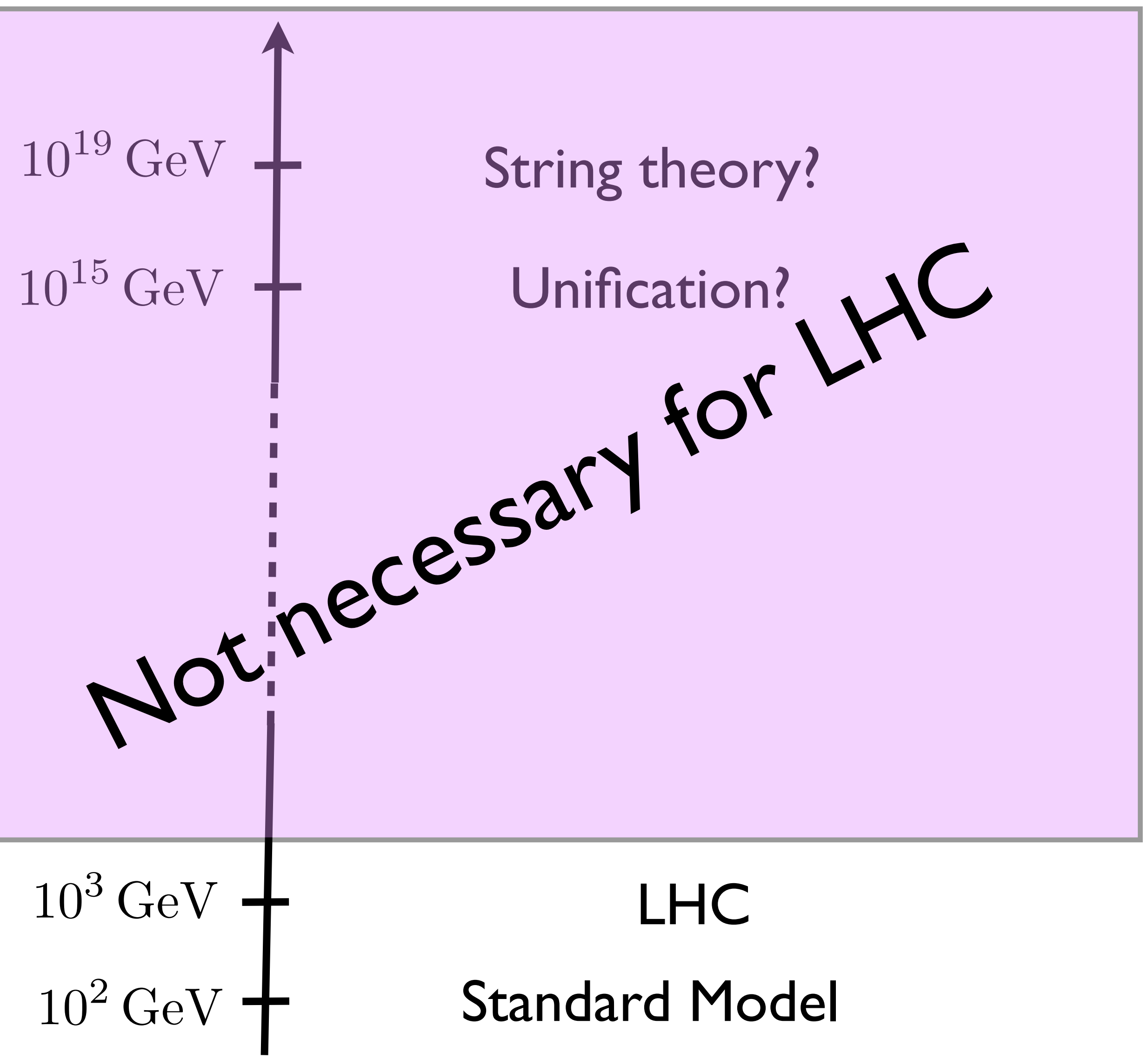

TUNING:
SM valid up to high scale. EW scale similar to c.c.
NATURALNESS:
Physics Beyond SM nearby: susy or composite?
?
-Higgs 2012
-SM 1967


UNEXPECTED RD

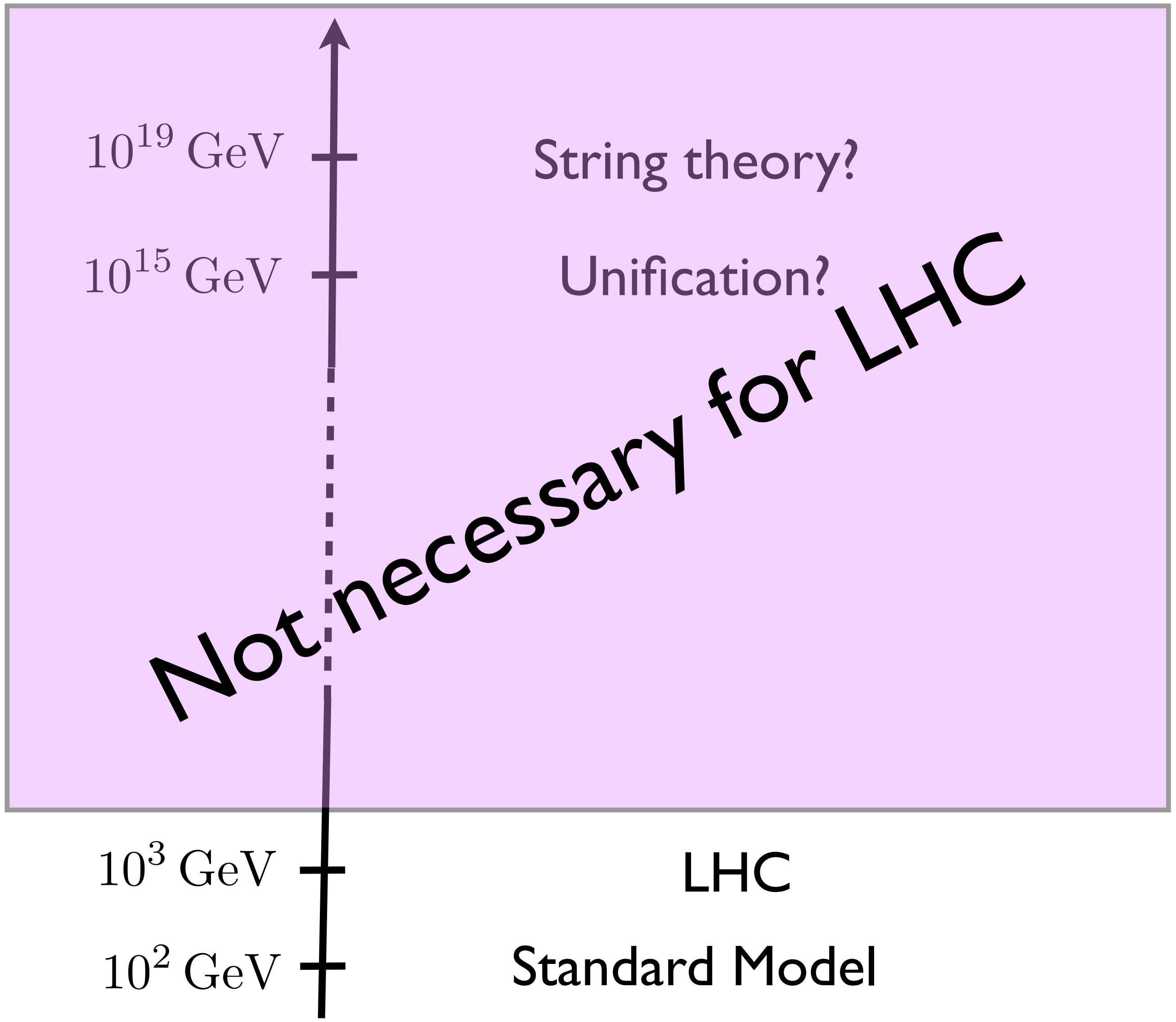
For LHC focus on the lightest degrees of freedom



For LHC focus on the lightest degrees of freedom



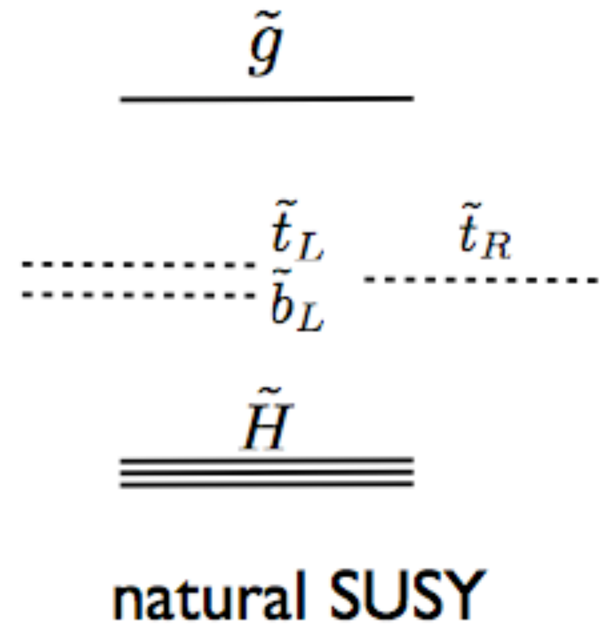
For LHC focus on the lightest degrees of freedom



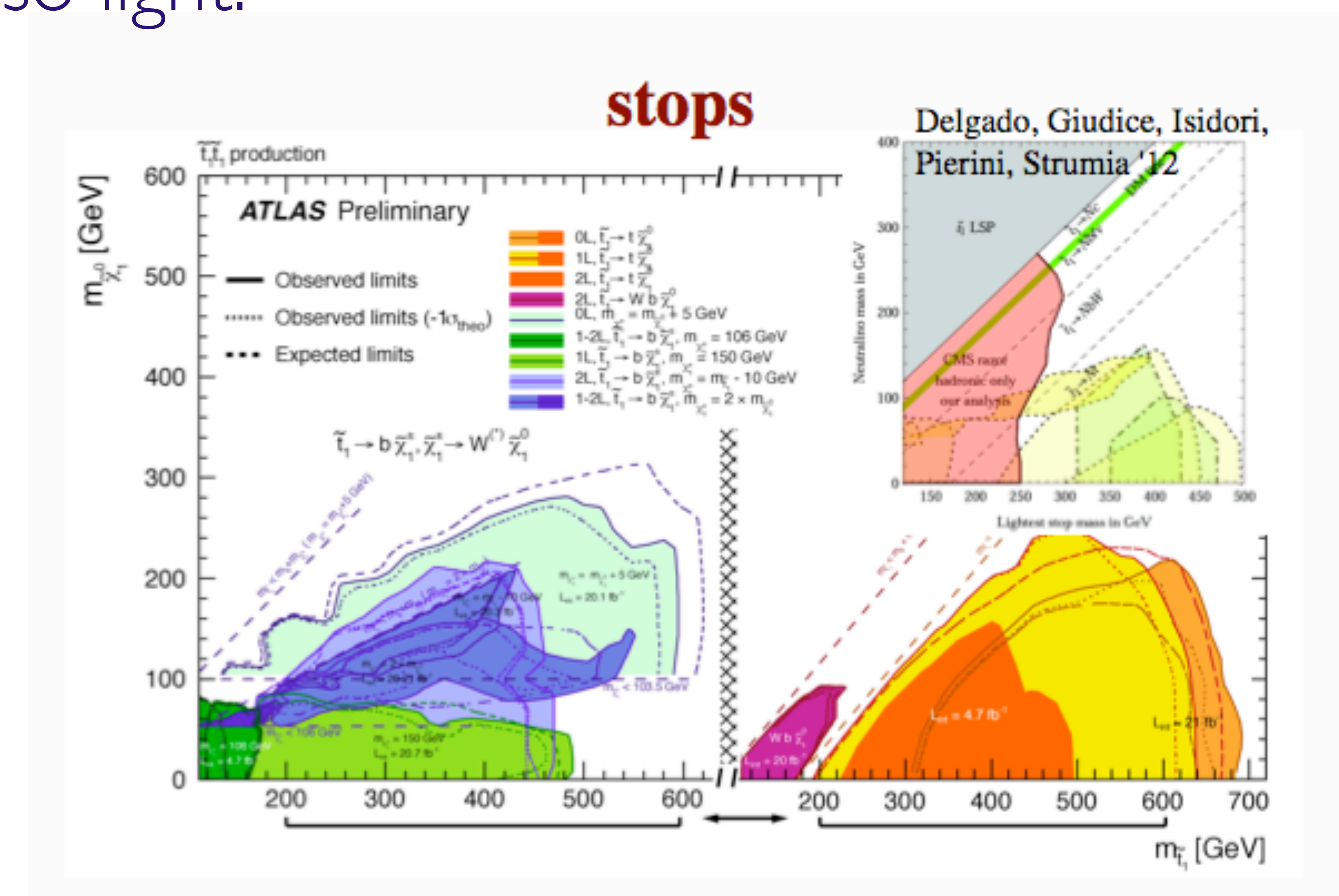
GOAL: Find an effective theory compatible with experiments (and predicts new testable phenomena). Not the full theory!

Effective field theory:
Physics at a scale Λ largely independent on shorter distances.

Natural SUSY:

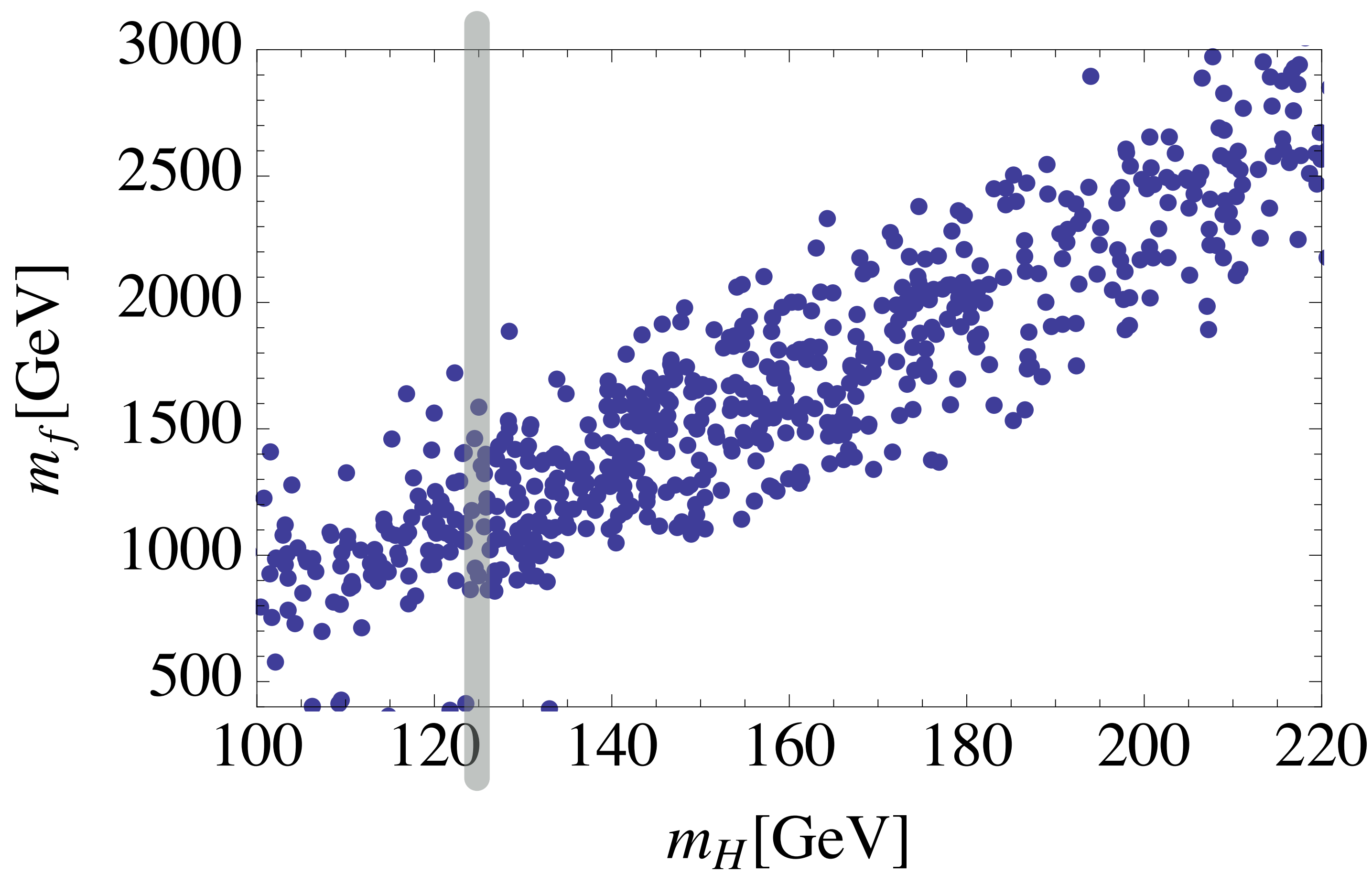


Stops not so light:



CHM5:

De Curtis, MR, '11
MR, Tesi, '12



$$f = 800\,\mathrm{GeV}$$

$$m_h \sim \sqrt{\frac{N_c}{2}\frac{y_t}{\pi}\frac{m_f}{f}}v$$

Partners around ~ 1 TeV