A Composite Higgs: Why and How

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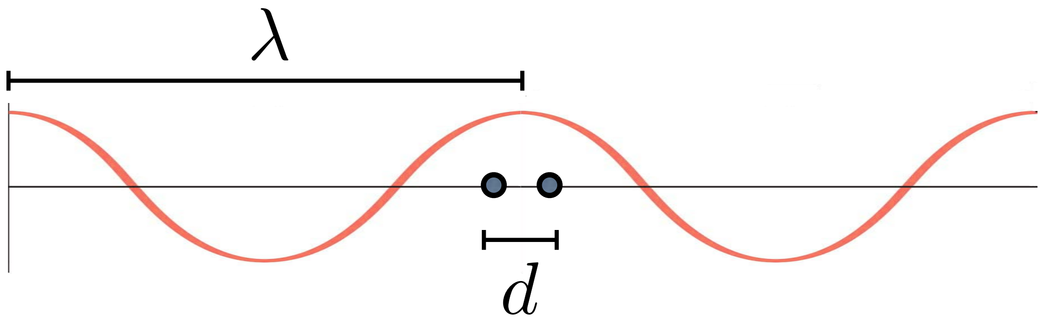
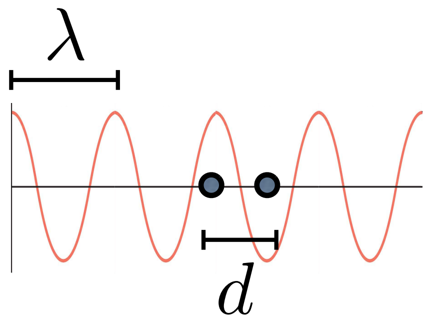
Introduction

Short distance $=$ Large Energy

$\lambda \gg d$



$\lambda \sim d$



Quantum Mechanics: $\lambda = h/p$

+

Special Relativity: $E = p \cdot c$

$$d \sim \lambda = \frac{hc}{E}$$

$$\sim 10^{-13}\mathrm{cm}\left(\frac{\mathrm{GeV}}{E}\right)$$

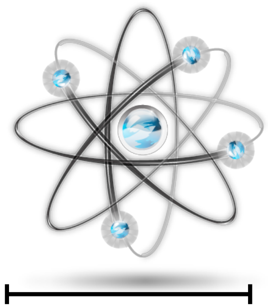
Introduction

Particle accelerators are **Microscopes**

$10^{-1}\mathrm{GeV}$

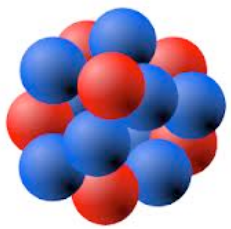
E

atom



$d \sim 10^{-8}\mathrm{cm}$

nucleus



$d \sim 10^{-12}\mathrm{cm}$

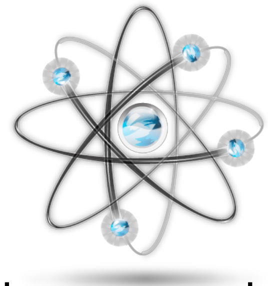
Introduction

Particle accelerators are **Microscopes**

$10^{-1}\mathrm{GeV}$ $\quad$ $1\mathrm{GeV}$

E

atom



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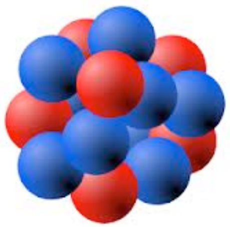


$d \sim 10^{-12}\mathrm{cm}$

hadrons, leptons, quarks
(subatomic zoo)
weak interactions
strong interactions, …

$d \sim 10^{-13}\mathrm{cm}$

Introduction

Particle accelerators are **Microscopes**

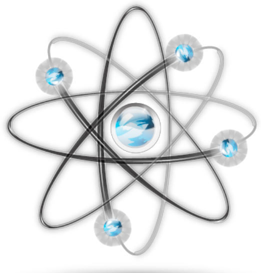


We are here

10^{-1}GeV | 1GeV | 100 GeV

E

atom



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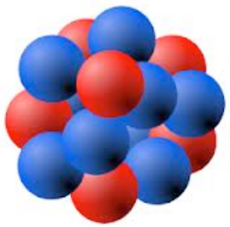

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strong interactions, …

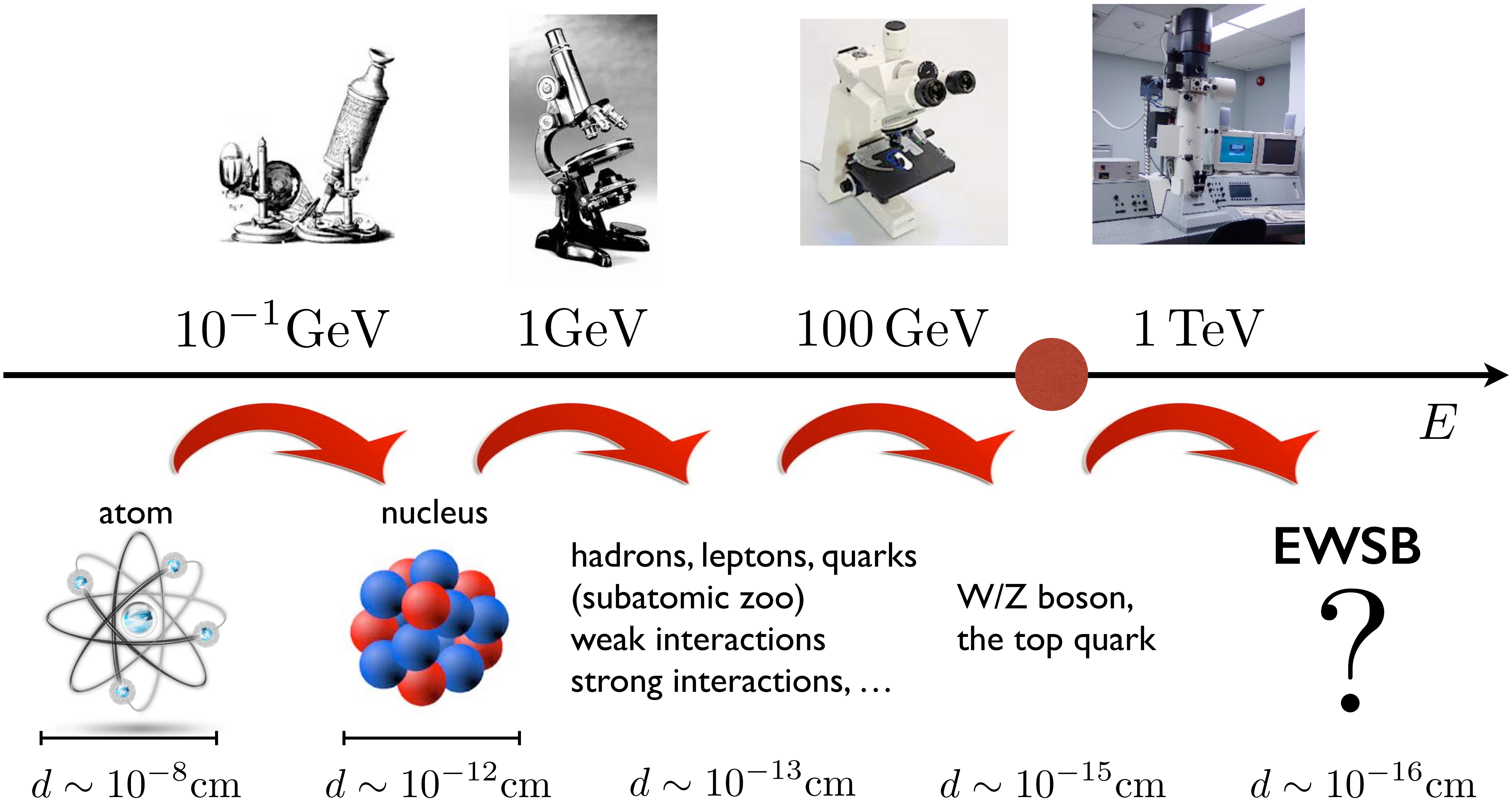
$d \sim 10^{-13}$cm

W/Z boson,
the top quark

$d \sim 10^{-15}$cm

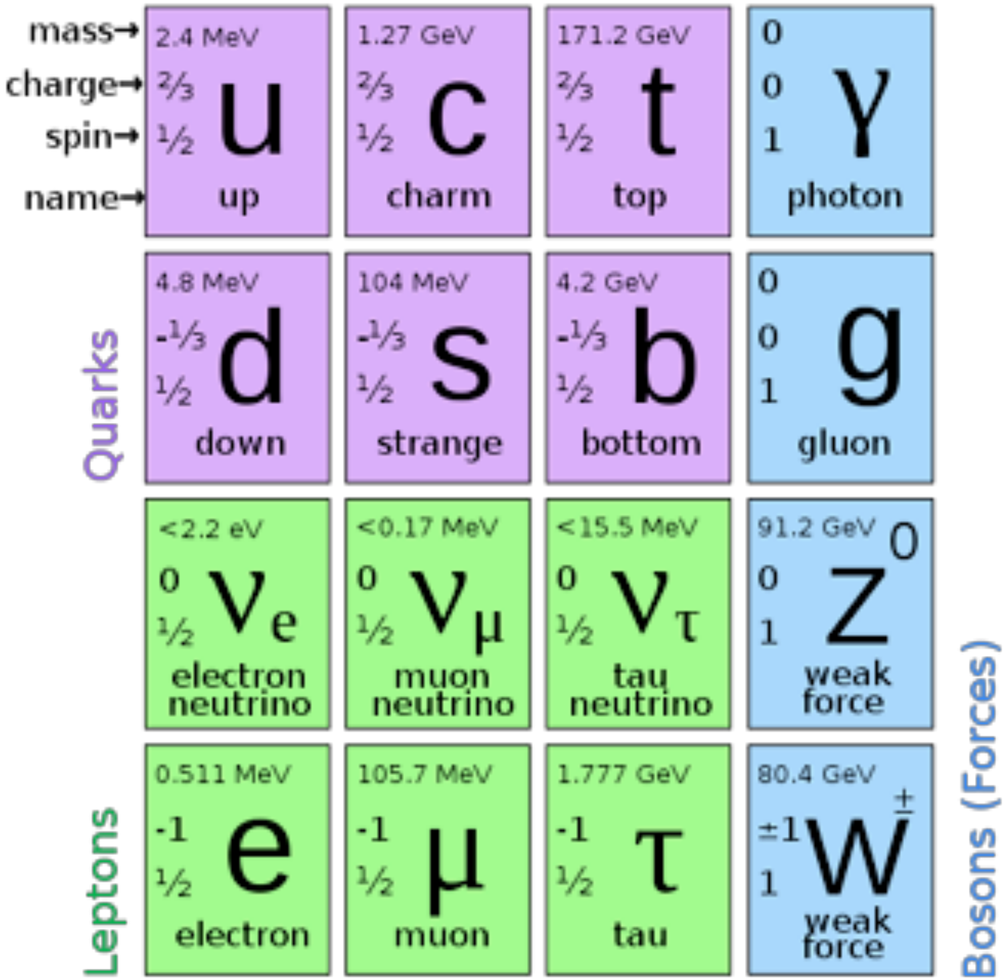
Introduction

Particle accelerators are **Microscopes**



The Electroweak Theory

Particle Content:



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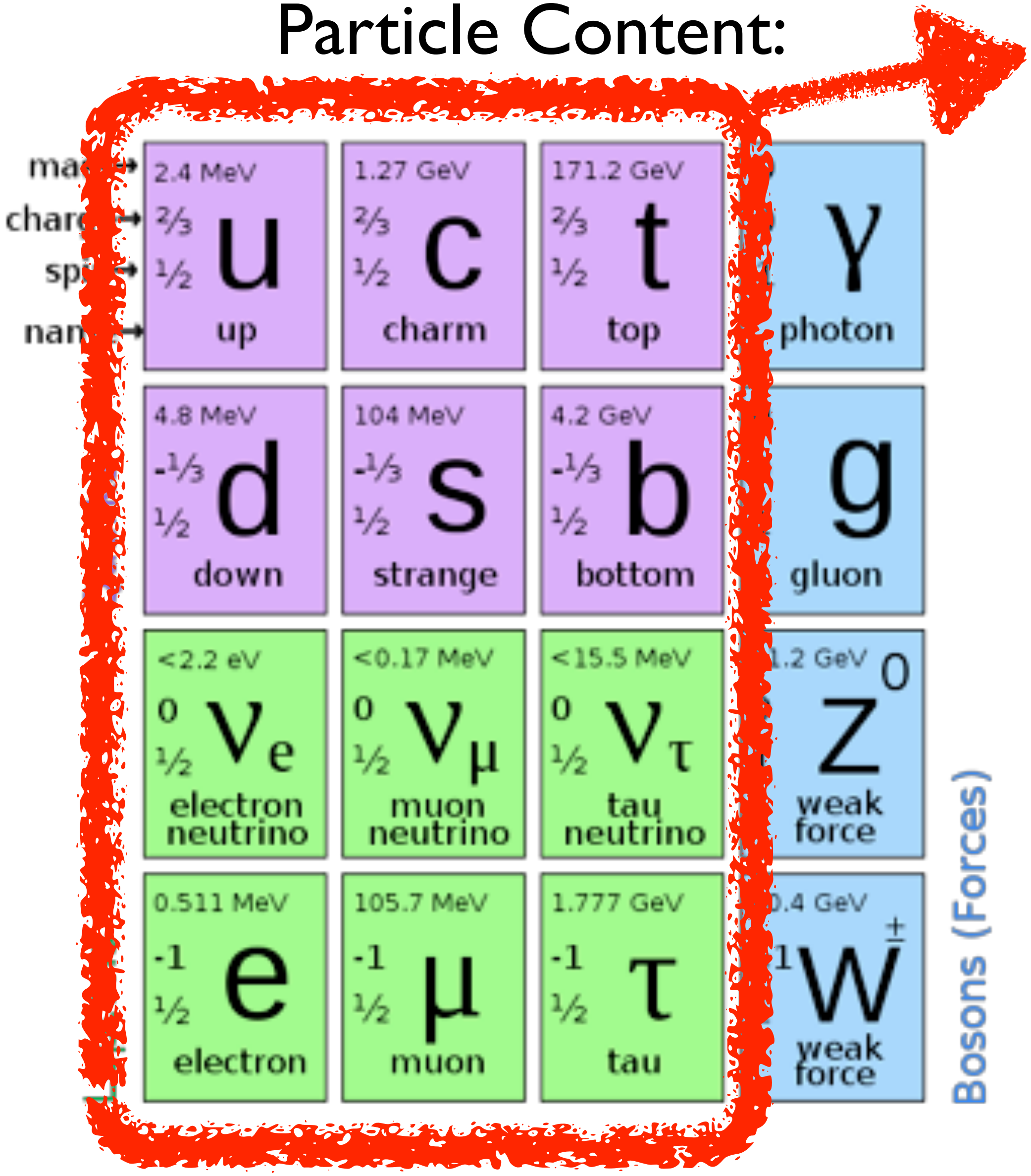

- ✦ Spin 1/2 "Matter": Quarks and Leptons

The Electroweak Theory

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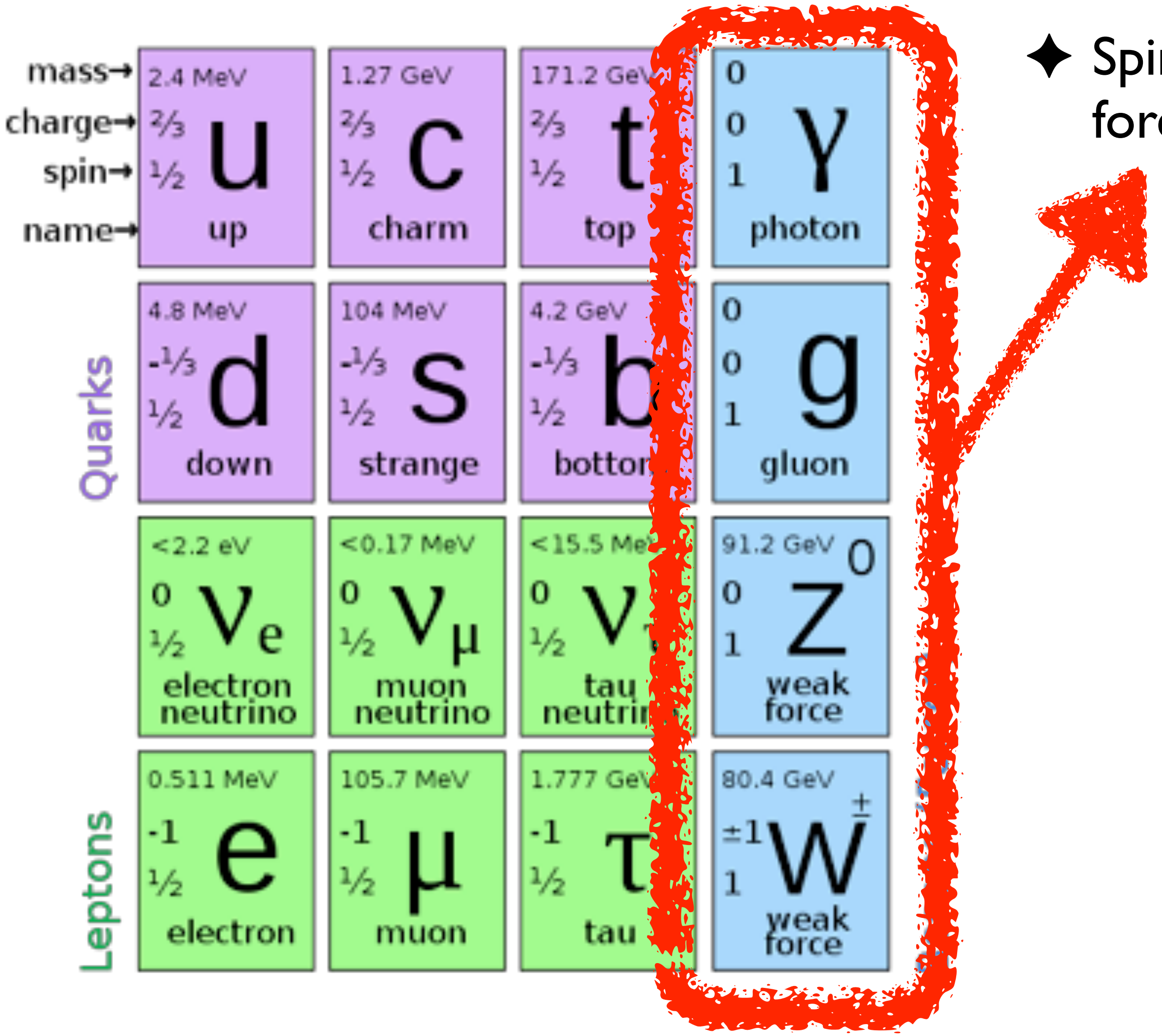

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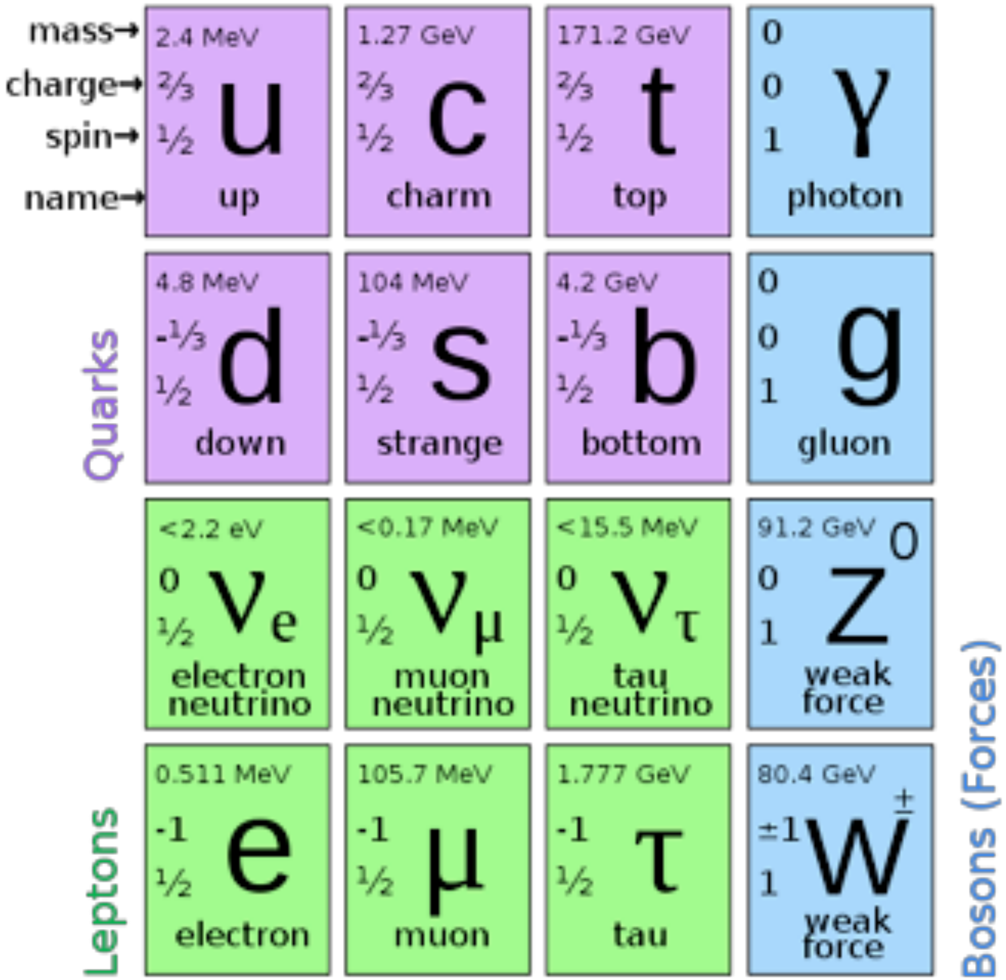

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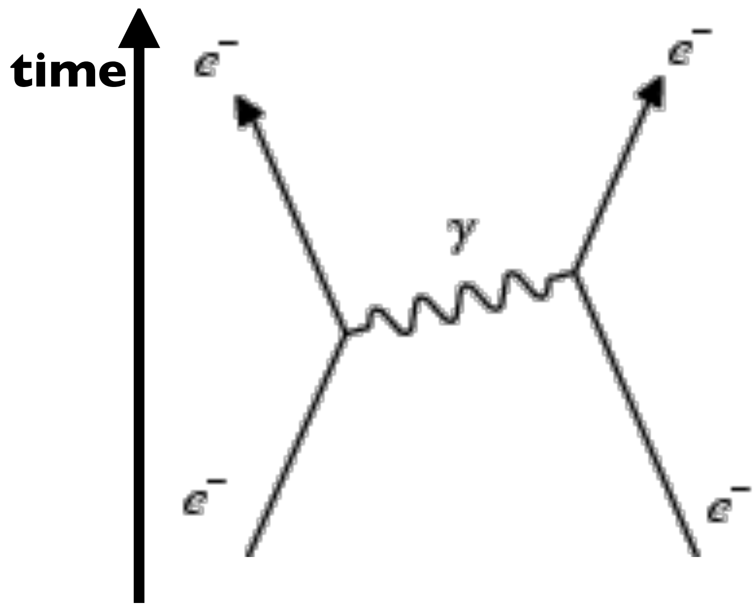
Electromagnetism from γ exchange



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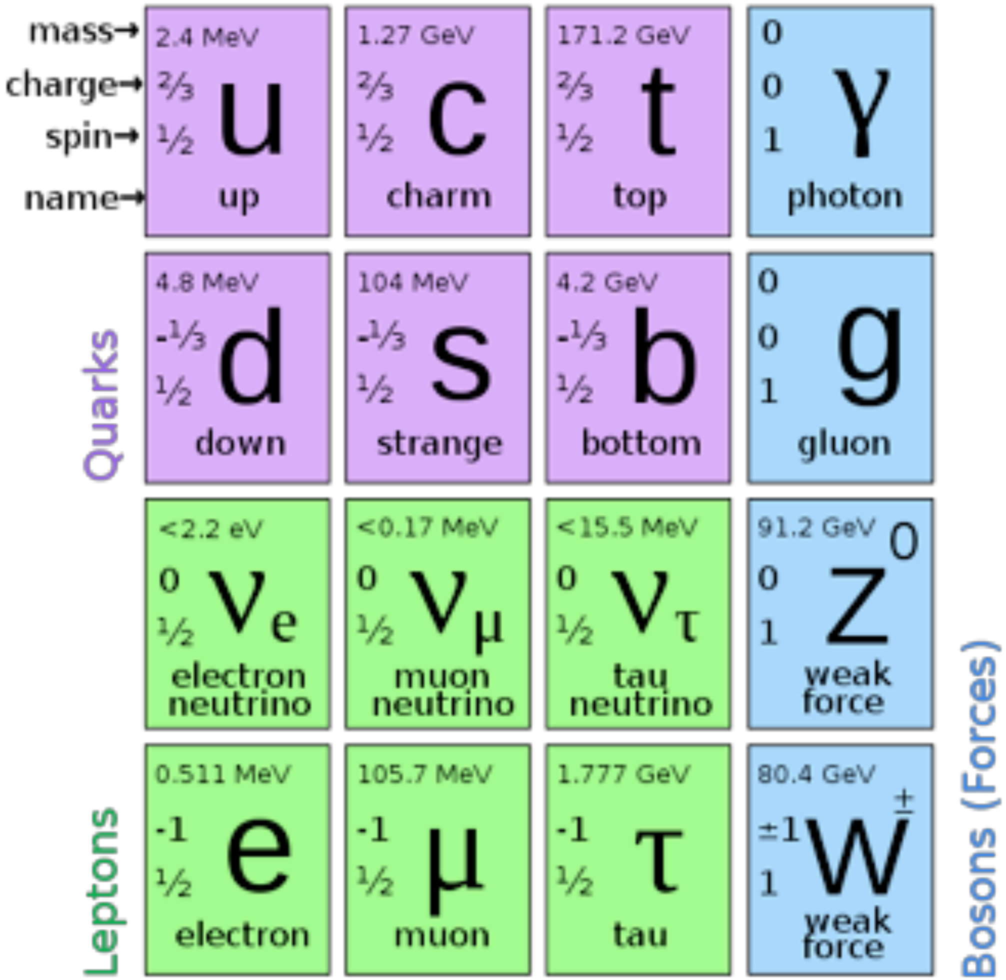

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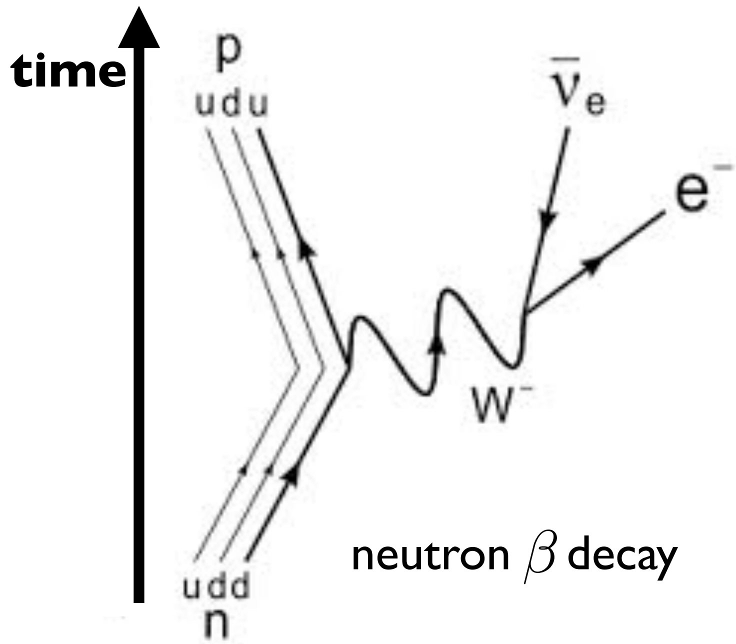
Electromagnetism from γ exchange
Weak force from W/Z exchange



neutron β decay

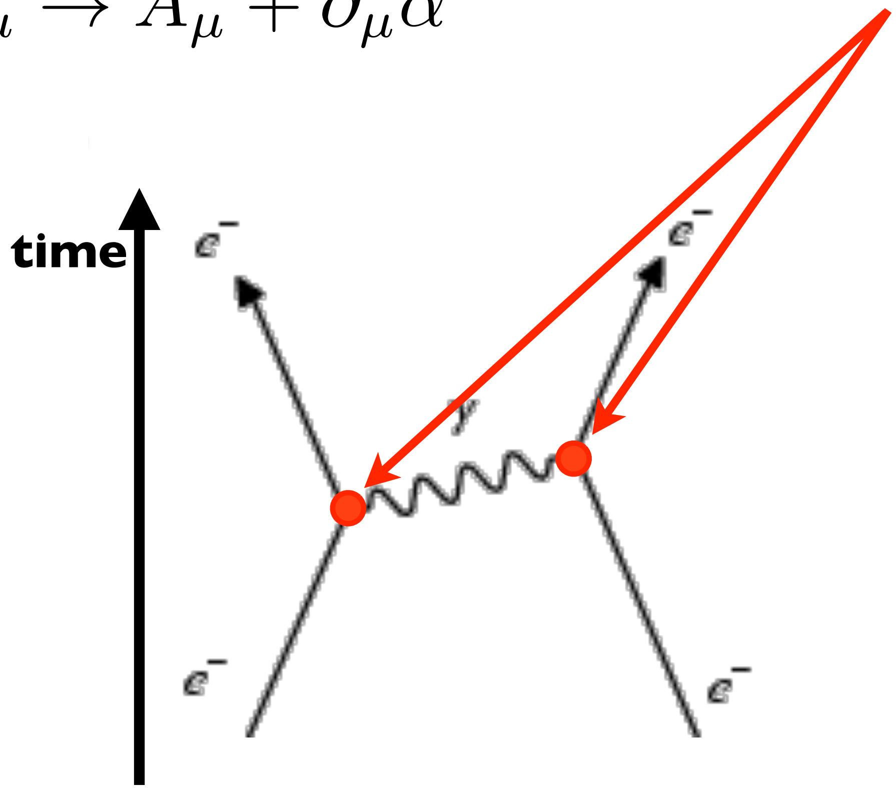
The Electroweak Theory

Spin one mediators are "hard" to describe in QFT

Require **local symmetry** (just a technical issue?)

QED: $U(1) \begin{cases} e^- \to e^{-i\,\alpha(x)} e^- \\ A_\mu \to A_\mu + \partial_\mu \alpha \end{cases}$

symmetry fixes e.m. interactions



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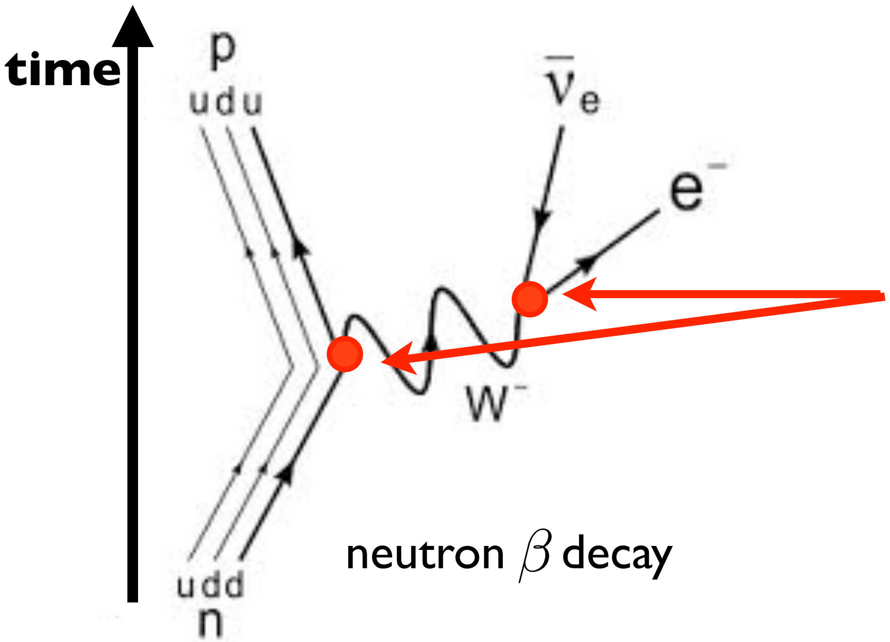
EW = e.m. + Weak : $SU(2) \times U(1)$ $\begin{cases} f \to e^{-i\,\alpha_V(x)} f \\ V_\mu \to V_\mu + \partial_\mu \alpha_V \end{cases}$



neutron β decay

successful prediction of matter Weak interactions

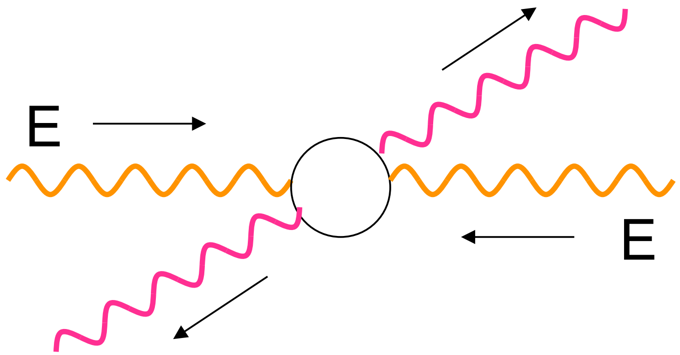
The Electroweak Theory

Local symmetry forbids mass

QED: $m_\gamma^2 A^2$ not invariant. Indeed, $m_\gamma = 0$

EW: $m_V^2 V^2$ not invariant. **BUT** $\begin{cases} m_W = 80\,\text{GeV} \\ m_Z = 92\,\text{GeV} \end{cases}$

We can incorporate masses, but at a very high price:



$$\mathcal{A}(LL \to LL) \simeq \frac{E^2}{v^2}$$

EWSB scale:

$$v = m_W / g_W \simeq 246\text{GeV}$$

Theory becomes **inconsistent at** $E \gtrsim 4\pi v \simeq 3\,\text{TeV}$

(formally, probability > 1)

The Electroweak Theory

Local symmetry forbids mass

A new sector must arise below $3\,\mathrm{TeV}$

The **EWSB** sector:

"Set of particles and interactions
that solve the strong coupling issue"

OR

"The mechanism responsible for **Spontaneous Symmetry Breaking**, giving mass to W and Z (and fermions)"

Theory becomes **inconsistent at** $E \gtrsim 4\pi v \simeq 3\,\mathrm{TeV}$

(formally, probability > 1)

The Electroweak Theory

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The **EWSB** sector:

LHC:
proton-proton collisions
$E = 8 - 13\,\mathrm{TeV}$

$9\,\mathrm{Km}$

Must discover EWSB

The Higgs Model

The Minimal model of EWSB:

$$H = \begin{pmatrix} \phi_+ \\ h + i\phi_0 \end{pmatrix}$$

ϕ's provide Longitudinal polarisations

just one new physical state:
the **Higgs Boson**

$\sim$ const.

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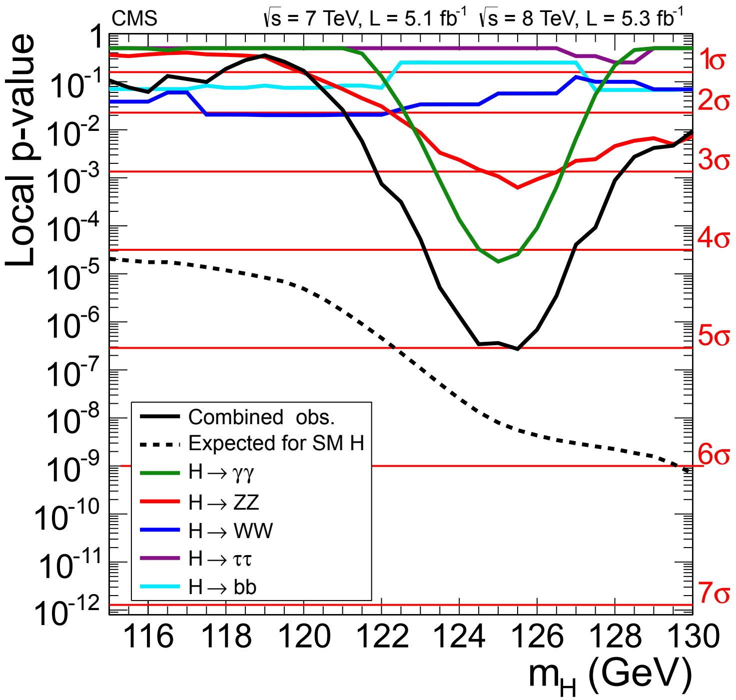

July 4th 2012:
Discovered at LHC

$$m_h \simeq 125\text{GeV}$$

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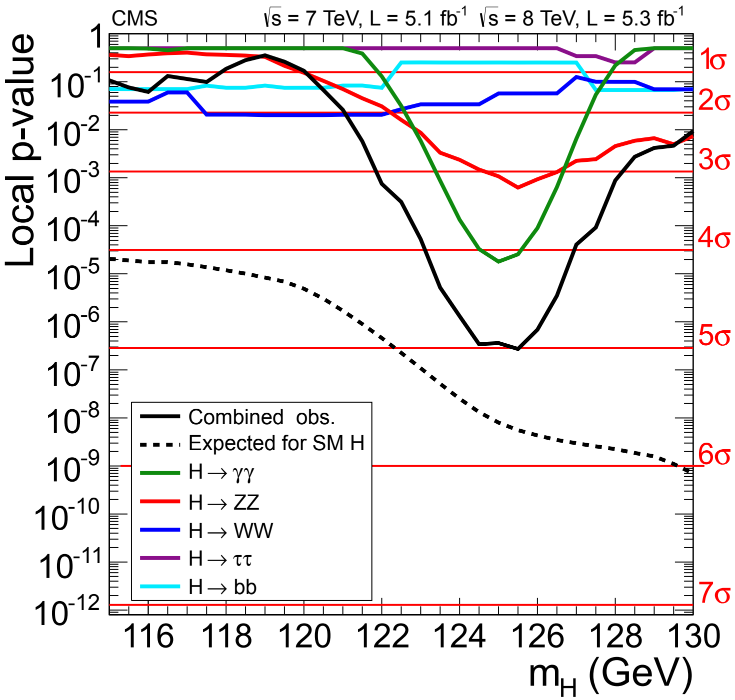

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October 8th 2013:
Nobel prize for **BEH** mechanism
(Brout Englert Higgs)

The Nobel Prize in Physics 2013

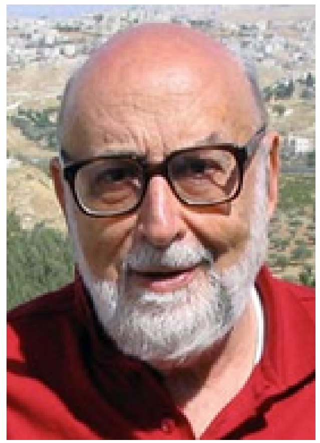


Photo: Pnicolet via Wikimedia Commons
François Englert

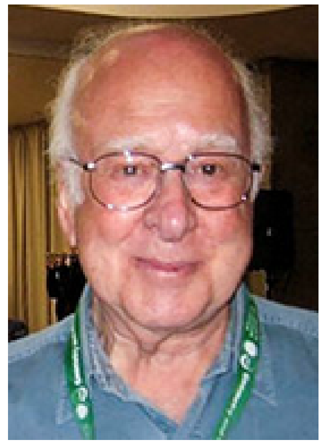
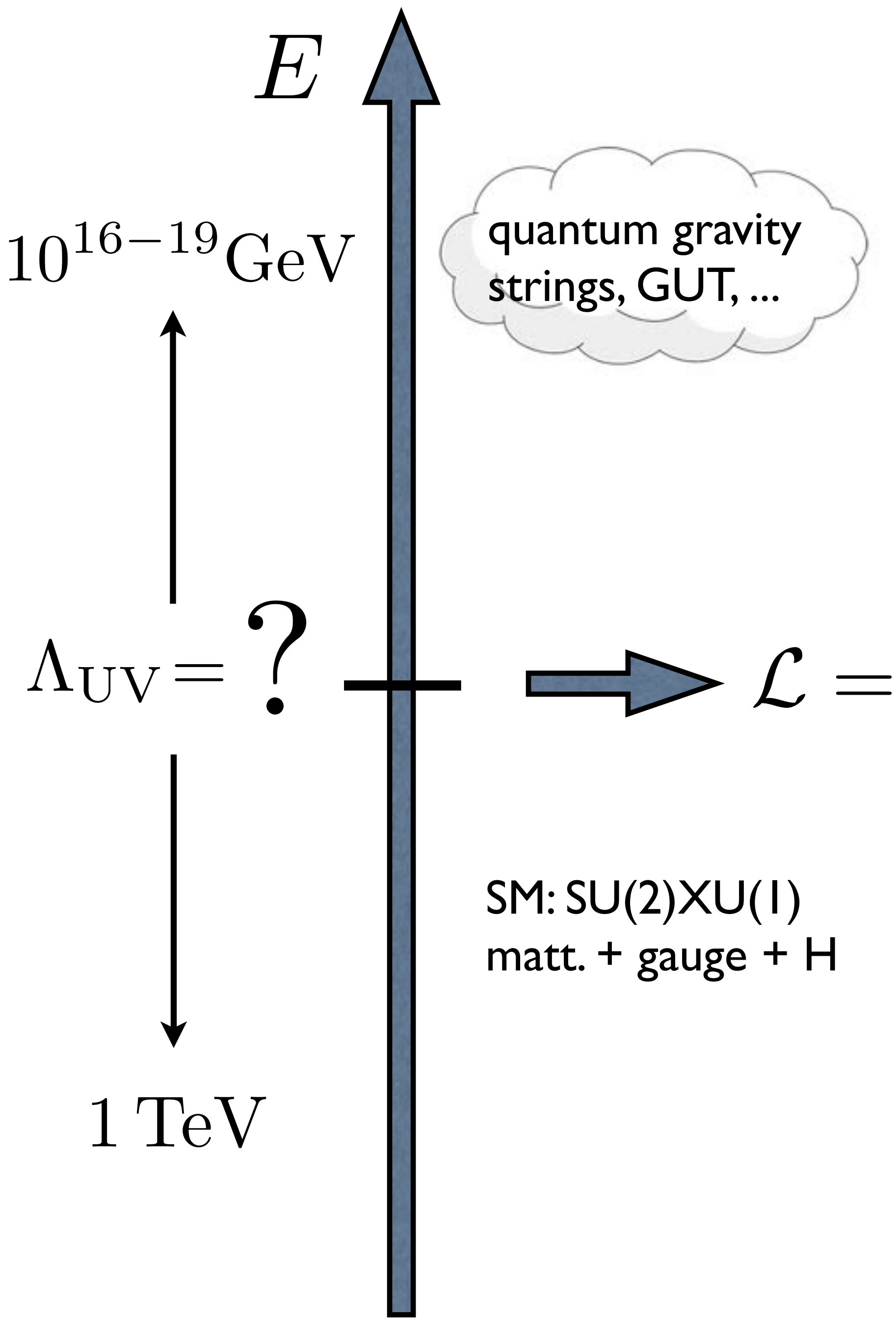


Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

Standard Higgs Model or Not ?



$$\mathcal{L} = \left\{ F^2 + \overline{\psi} \not{D} \psi + \overline{\psi} H \psi \right. \qquad d = 4$$

Perfectly explain what we see

Standard Higgs Model or Not ?

E

$10^{16-19}\,\mathrm{GeV}$

quantum gravity
strings, GUT, ...

$\Lambda_{\rm UV} = ?$

$1\,\mathrm{TeV}$

SM: SU(2)XU(1)
matt. + gauge + H

$$\mathcal{L} = \begin{cases} F^2 + \overline{\psi} \not{D} \psi + \overline{\psi} H \psi & d = 4 \\ + \frac{c}{\Lambda_{\rm UV}} \psi\psi H H + \frac{c'}{\Lambda_{\rm UV}^2} \psi^4 + \ldots & d > 4 \end{cases}$$

$d = 4$: $F^2 + \overline{\psi} \not{D} \psi + \overline{\psi} H \psi$

Perfectly explain what we see

$d > 4$: $+ \frac{c}{\Lambda_{\rm UV}} \psi\psi H H + \frac{c'}{\Lambda_{\rm UV}^2} \psi^4 + \ldots$

suppression $(E/\Lambda_{UV})^n$, **small effects**

explain what we **do not see** (p-dec, extra FV, ...)

and maybe what we **see is small** (ν-masses)

provided we assume $\Lambda_{\rm UV} \gg \mathrm{TeV}$

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$10^{16-19}\mathrm{GeV}$

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SM: SU(2)XU(1)
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$$\mathcal{L} = \begin{cases} F^2 + \overline{\psi}\not{D}\psi + \overline{\psi}H\psi & d=4 \\ + \dfrac{c}{\Lambda_{\mathrm{UV}}}\psi\psi H H + \dfrac{c'}{\Lambda^2_{\mathrm{UV}}}\psi^4 + \ldots & d>4 \\ c\Lambda^2_{\mathrm{UV}}H^2 = m_H^2 H^2 & d<4 \end{cases}$$

$d = 4$: $F^2 + \overline{\psi}\not{D}\psi + \overline{\psi}H\psi$

Perfectly explain what we see

$d > 4$: $+\frac{c}{\Lambda_{\mathrm{UV}}}\psi\psi H H + \frac{c'}{\Lambda^2_{\mathrm{UV}}}\psi^4 + \ldots$

suppression $(E/\Lambda_{UV})^n$, **small effects**

explain what we **do not see** (p-dec, extra FV, …)

and maybe what we **see is small** (v-masses)

provided we assume $\Lambda_{\mathrm{UV}} \gg \mathrm{TeV}$

$d < 4$: $c\Lambda^2_{\mathrm{UV}}H^2 = m_H^2 H^2$

why $m_H \ll \Lambda_{\mathrm{UV}}$?

"naturalness" requires: $\Lambda_{\mathrm{UV}} \sim \mathrm{TeV}$

Hierarchy Problem

Standard Higgs Model or Not ?

Fine Tuning:

$$\left(m_H^2\right)_{Phys.} = \int_0^{\infty} F_{true}(E;\, g_{true})$$

$$= \int_0^{\Lambda_{\mathrm{UV}}} (\ldots) + \int_{\Lambda_{\mathrm{UV}}}^{\infty} (\ldots)$$

Standard Higgs Model or Not ?

Fine Tuning:

$$
\begin{aligned}
(m_H^2)_{Phys.} &= \int_0^\infty F_{true}(E;\, g_{true}) \\
&= \int_0^{\Lambda_{\mathrm{UV}}} (\ldots) + \int_{\Lambda_{\mathrm{UV}}}^\infty (\ldots)
\end{aligned}
$$

UV Contribution

$$c\,{\Lambda_{\mathrm{UV}}}^2$$

Standard Higgs Model or Not ?

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$$(m_H^2)_{Phys.} = \int_0^{\infty} F_{true}(E;\, g_{true})$$

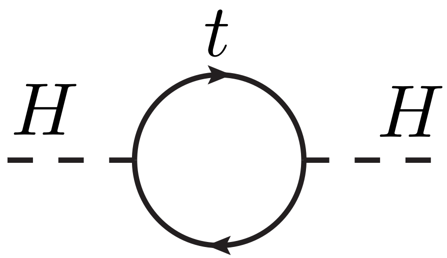
$$= \int_0^{\Lambda_{\rm UV}} (\ldots) + \int_{\Lambda_{\rm UV}}^{\infty} (\ldots)$$

UV Contribution

$$c\,{\Lambda_{\rm UV}}^2$$

SM Contribution

$$\int_0^{\Lambda_{\rm UV}} \frac{y_t^2}{16\pi^2} E = \frac{y_t^2}{16\pi^2} {\Lambda_{\rm UV}}^2$$



from top quark loop

Standard Higgs Model or Not ?

Fine Tuning:

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SM Contribution

$$\int_0^{\Lambda_{\rm UV}} \frac{y_t^2}{16\pi^2} E = \frac{y_t^2}{16\pi^2} {\Lambda_{\rm UV}}^2$$

Higgs mass from Tuning:

$$\Delta = \frac{\delta_{SM} m_H^2}{m_H^2} \simeq \left(\frac{\Lambda_{\rm UV}}{400\text{GeV}}\right)^2$$

Standard Higgs Model or Not ?

Fine Tuning:

$$\Delta = \frac{\delta_{SM} m_H^2}{m_H^2} \simeq \left(\frac{\Lambda_{\rm UV}}{400 {\rm GeV}} \right)^2$$

$\Delta < 100$ ⟹ $\Lambda_{\rm UV} < 4\,{\rm TeV}$

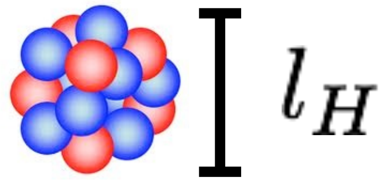
Question for the LHC:

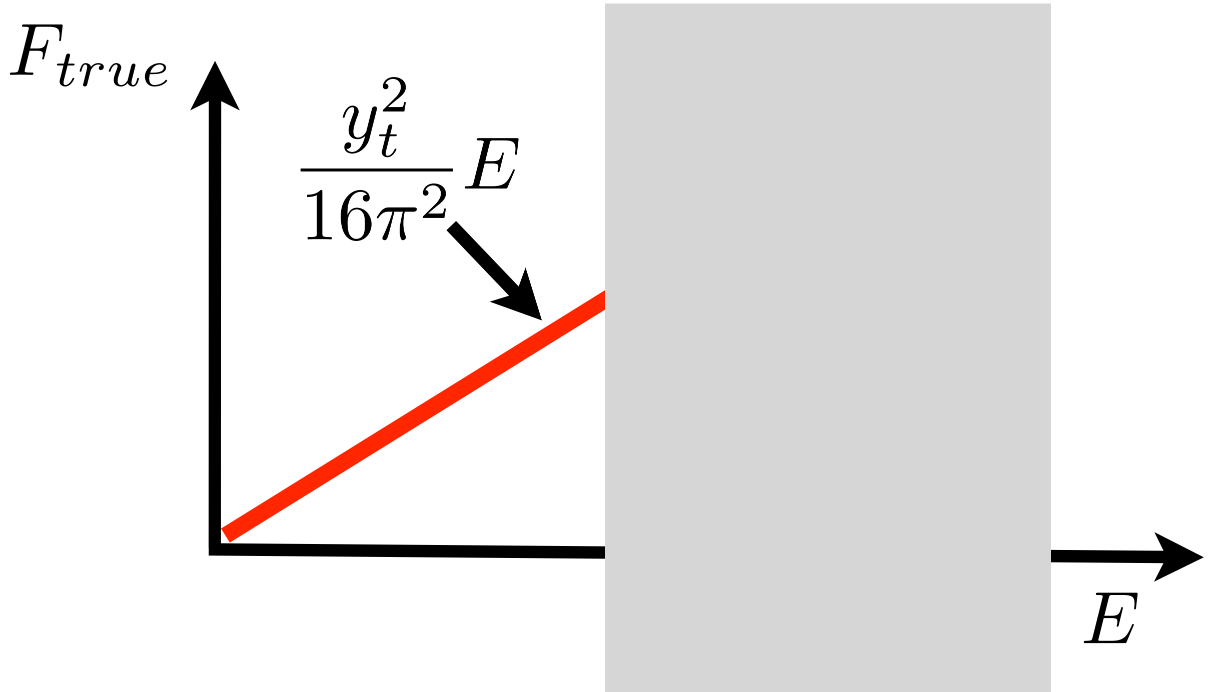
Is Tuning a problem of Nature or just a problem of theory ?

To answer, search **natural BSM!**

Composite Higgs

Imagine the Higgs is **Composite**





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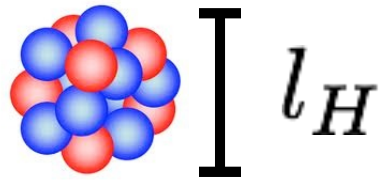
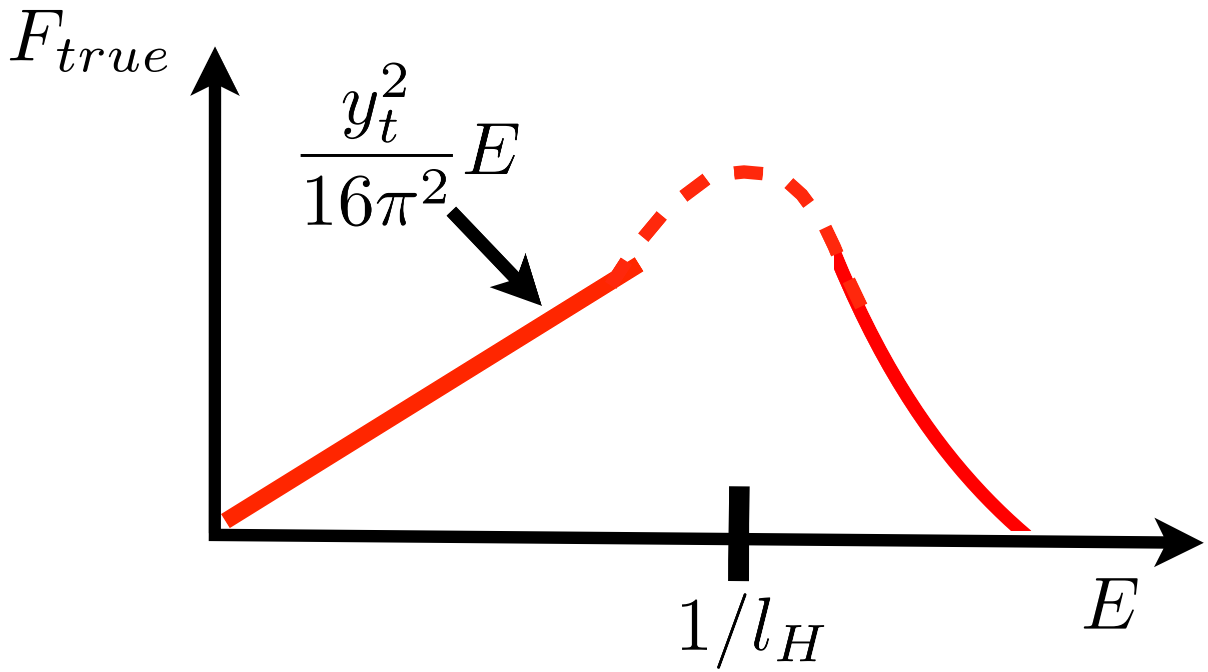




Corrections to m_H screened above $1/l_H$.

m_H is **IR-saturated**

Natural Higgs mass if

$1/l_H = \Lambda_{\rm UV} \sim \rm TeV$

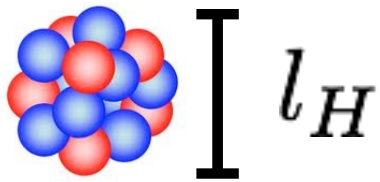
Composite Higgs

Composite Higgs scenario:

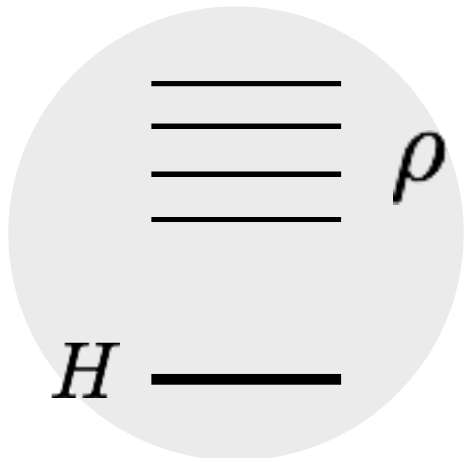
1. Higgs is **hadron** of **new strong force**

Corrections to m_H screened above $1/l_H$

The **Hierarchy Problem is solved**



2. Higgs is a **Goldstone Boson**, this is why it is light



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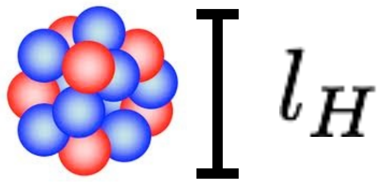

Corrections to m_H screened above $1/l_H$

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Indirect effects from sigma-model couplings

A) Corrections to SM:

$[\mathcal{O}(v^2/f^2) \lesssim 20\%]$

- ✦ Higgs Br. Ratios
- ✦ Higgs Production

B) Non-ren. **Couplings**:

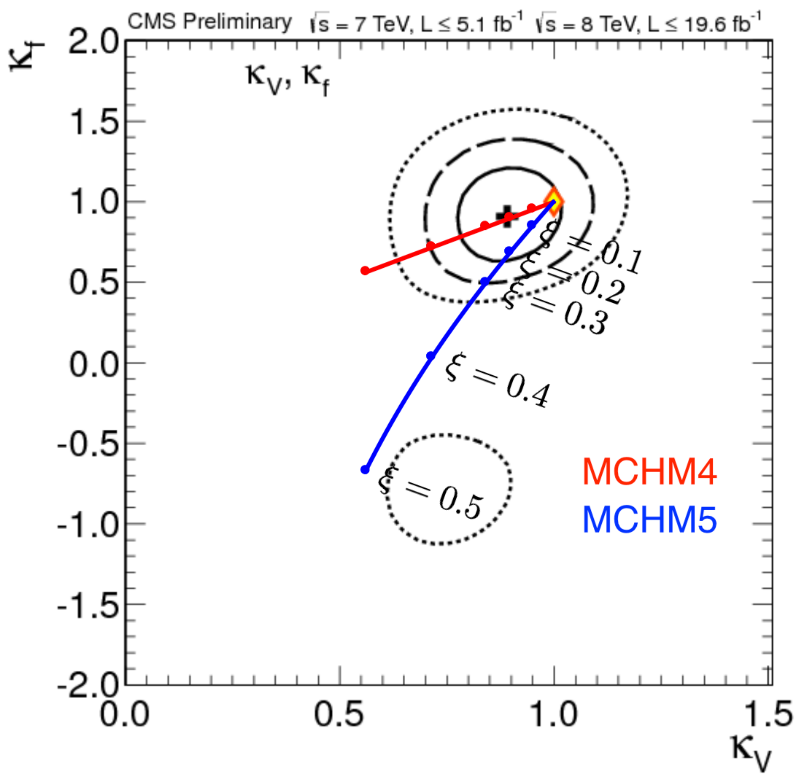
- ✦ In $WW \to hh$
- ✦ In $gg \to hh$

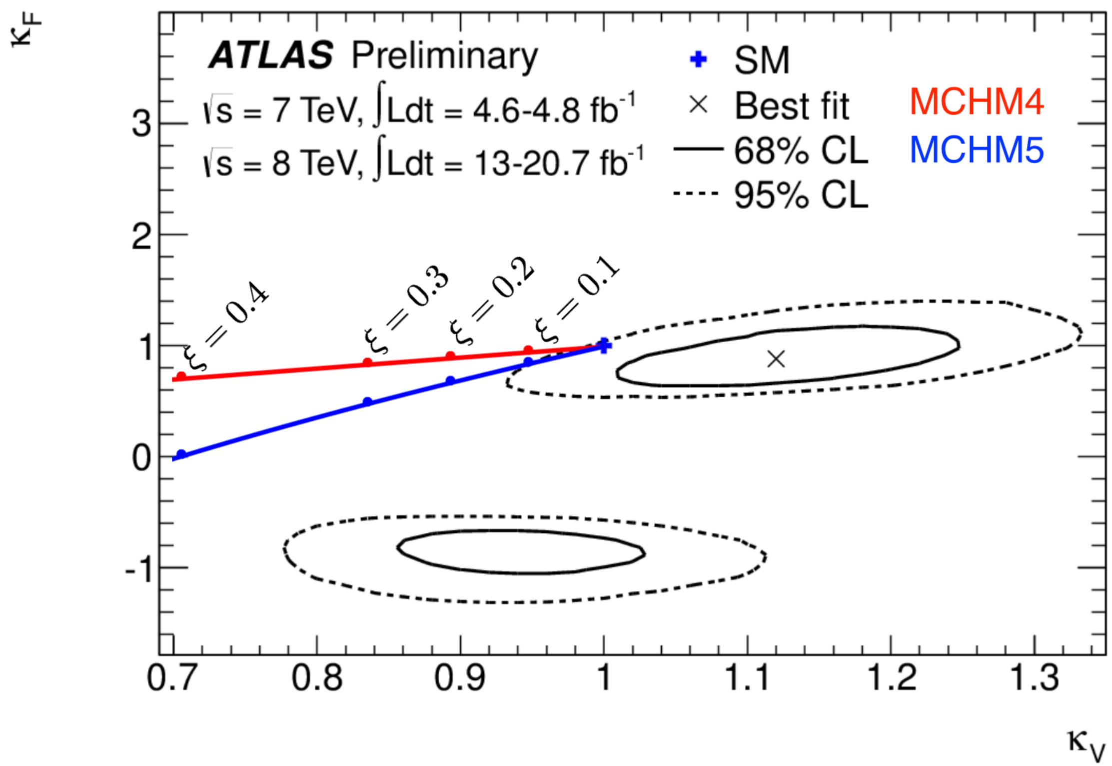
Interesting, and extensively discussed,

but **not easy** to see with present data

Composite Higgs

Some updated fit:





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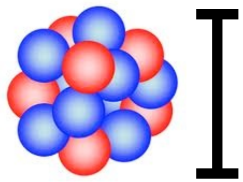

l_H

2. Higgs is a **Goldstone Boson**, this is why it is light

3. SM fermions and gauge coupled **linearly** to the strong sector

Composite Sector		Elementary Sector
Higgs + resonances	$\mathcal{L}_{\rm int}$ ⟷	$W_\mu^{1,2,3},\ B_\mu\ \ f_L,\ f_R$

gauge couplings: $\mathcal{L}_{\rm int} \propto g_W \rho_\mu W^\mu$

fermion couplings: $\mathcal{L}_{\rm int} \propto y_L q_L \Psi^L + y_R q_R \Psi^R$

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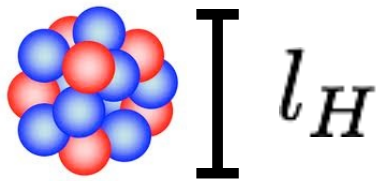

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Composite Sector | Elementary Sector

Higgs + resonances $\Longleftrightarrow$ $\mathcal{L}_{\rm int}$ $\Longleftrightarrow$ $W_\mu^{1,2,3},\ B_\mu\ \ f_L,\ f_R$

gauge couplings: $\mathcal{L}_{\rm int} \propto g_W \rho_\mu W^\mu$

fermion couplings: $\mathcal{L}_{\rm int} \propto y_L q_L \Psi^L + y_R q_R \Psi^R$

fermion partners, among which, the **top partners**

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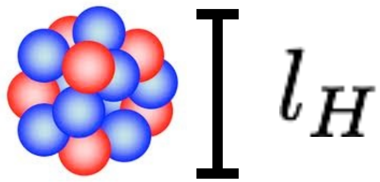

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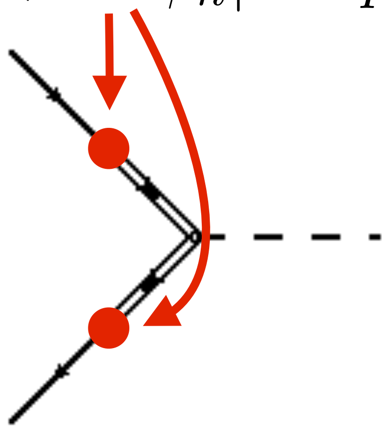
Linear coupling = **partial compositeness**:

$$|SM_n\rangle = \cos\phi_n |elementary_n\rangle + \sin\phi_n |composite_n\rangle$$

PC generates **Yukawas** ...

$y_f =$



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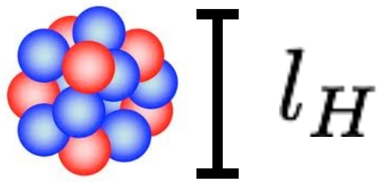
Composite Higgs scenario:

1. Higgs is **hadron** of **new strong force**

   Corrections to m_H screened above $1/l_H$

   The **Hierarchy Problem is solved**



2. Higgs is a **Goldstone Boson**, this is why it is light

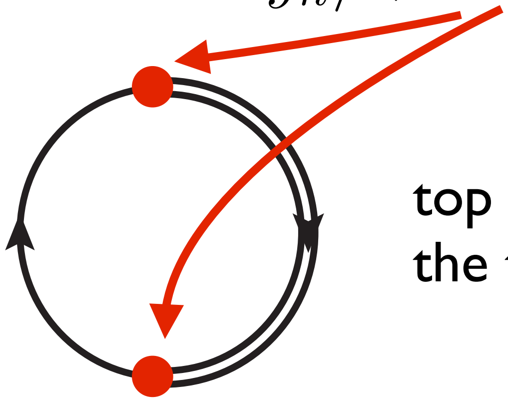
3. SM fermions and gauge coupled **linearly** to the strong sector

Linear coupling = **partial compositeness**:

$$|SM_n\rangle = \cos\phi_n |elementary_n\rangle + \sin\phi_n |composite_n\rangle$$

PC generates **Yukawas** ...

... and the **Higgs potential**



top loops dominate because the top is largely composite

Composite Higgs

Connection among **top partners**, Higgs mass and VEV

$$\Delta \geq \frac{\delta m_H^2}{m_H^2|_{pole}} \simeq \left(\frac{125\,\text{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\text{UV}}}{400\,\text{GeV}}\right)^2$$

Top partners cancel top quark divergence $\Rightarrow \Lambda_{\text{UV}} \geq M_T$

Light Higgs plus **Low Tuning** need **Light Partners**

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Natural SUSY:

light stops

Natural CH:

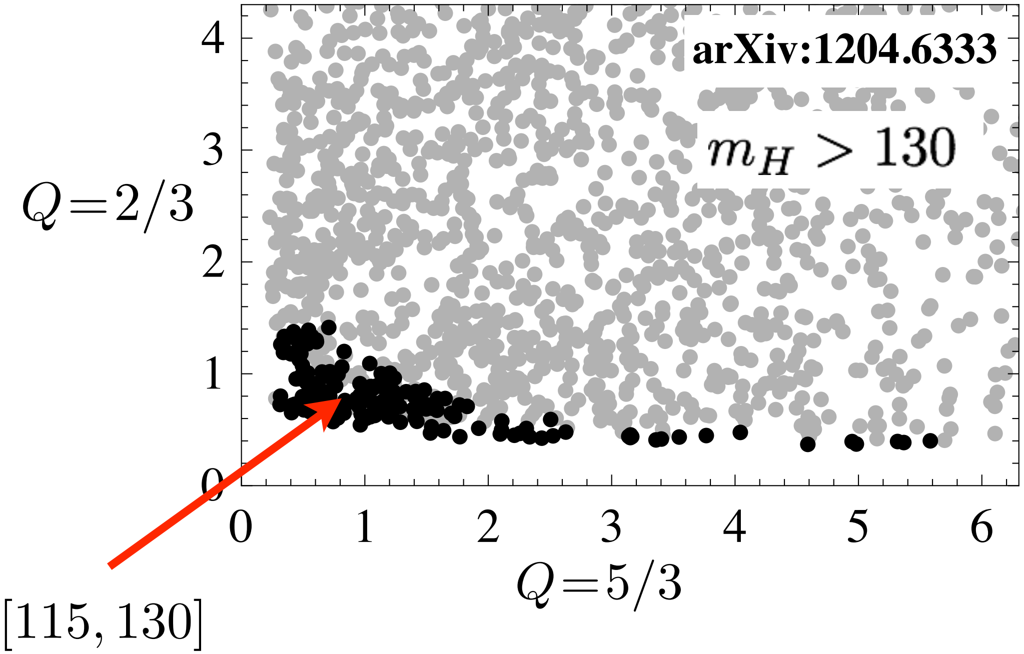
light top partners

Composite Higgs

Striking Example:

$\mathrm{MCHM}_{4,5,10}$

$\xi = 0.2$



Light Higgs plus **Low Tuning** need **Light Partners**

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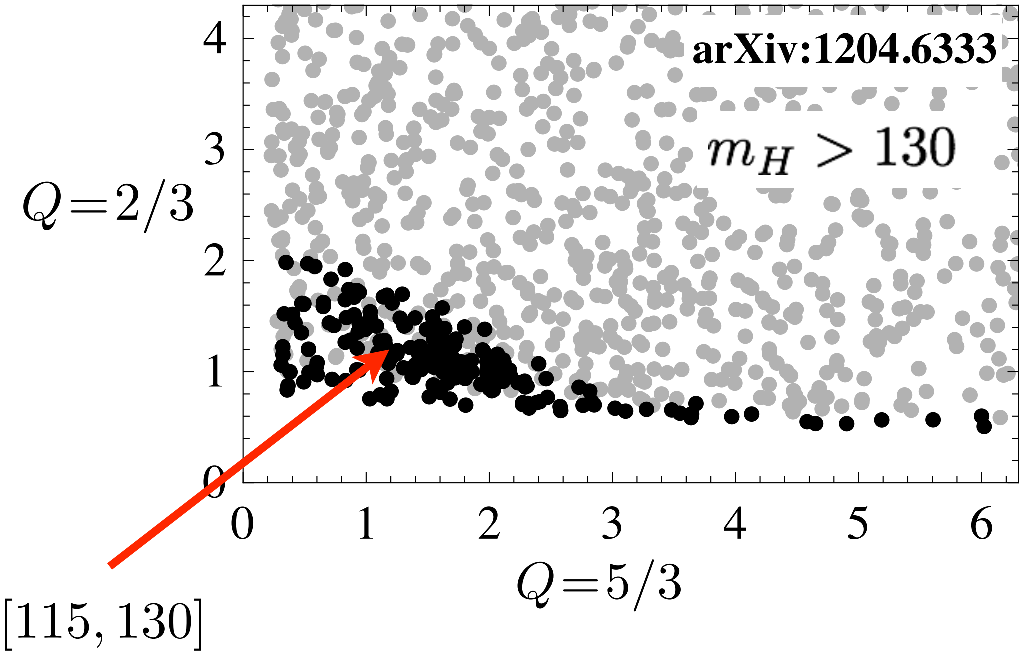
light top partners

Composite Higgs

Striking Example:

$\mathrm{MCHM}_{4,5,10}$

$\xi = 0.1:$ (larger tuning)



Light Higgs plus **Low Tuning** need **Light Partners**

Natural SUSY:

light stops

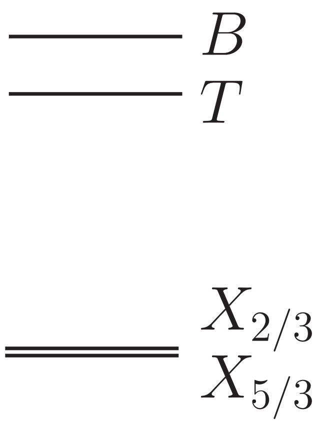
Natural CH:

light top partners

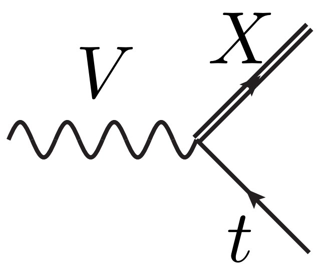
Top Partners at the LHC

Case #1, **fourplet** of custodial $\mathrm{SO}(4)$ $\begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$

Spectrum:



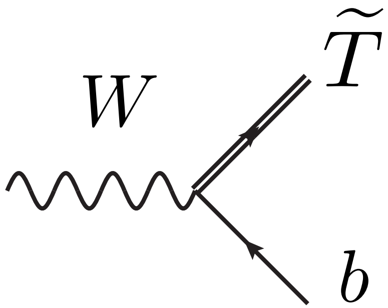
Couplings:



$\sim M_X/f$

because Goldstones are derivatively coupled

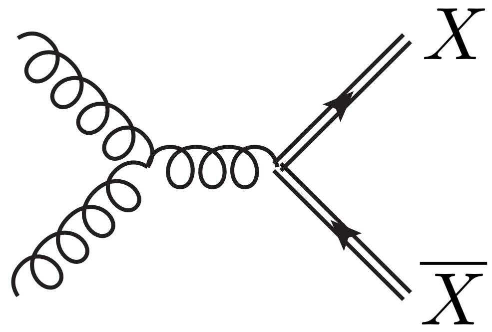
Case #2, **singlet** of custodial $\mathrm{SO}(4)$ $\widetilde{T}$



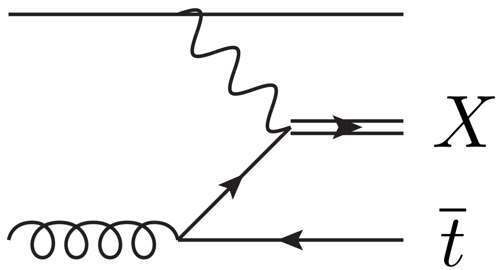
sizable coupling to bottom quark

Top Partners at the LHC

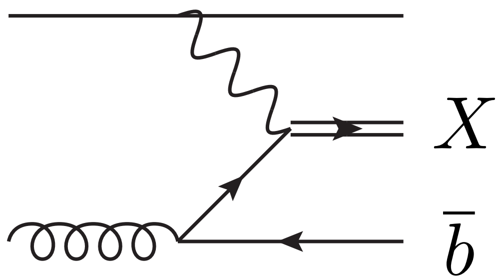
Three possible production mechanisms



QCD **pair prod**.
model indep.,
relevant at low mass



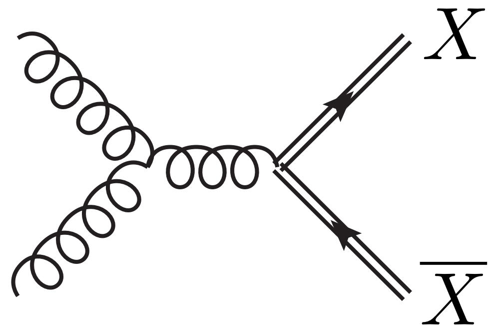
single prod. with **t**
model dep. coupling
pdf-favored at high mass



single prod. with **b**
favored by small b mass
dominant when allowed

Top Partners at the LHC

Three possible production mechanisms



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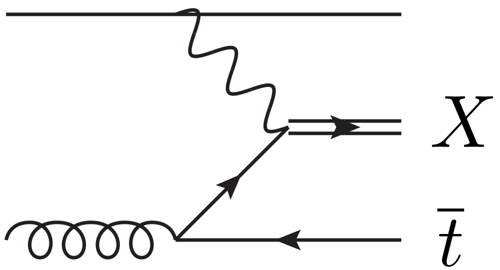

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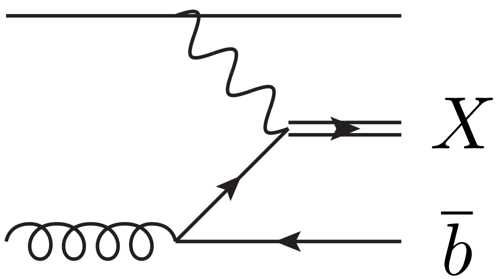

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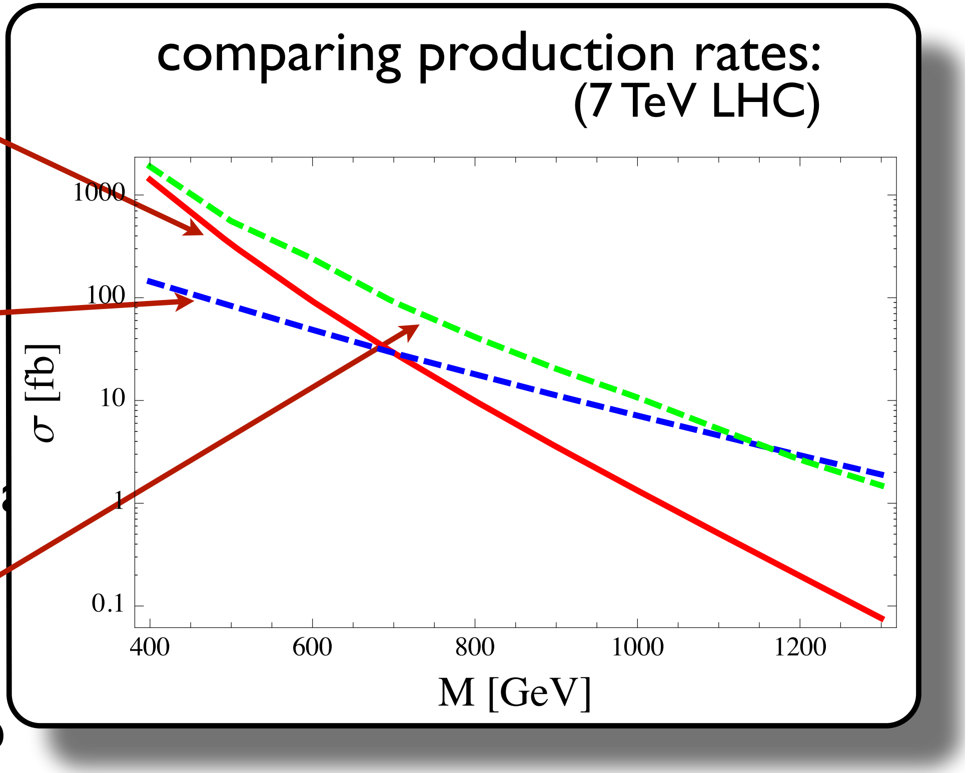

Top Partners at the LHC

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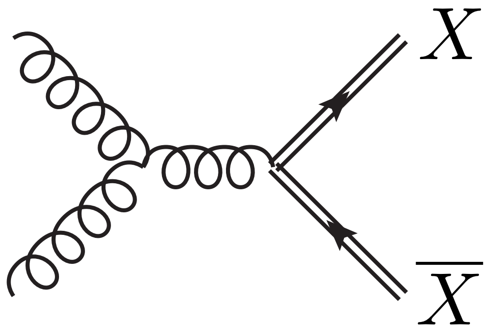

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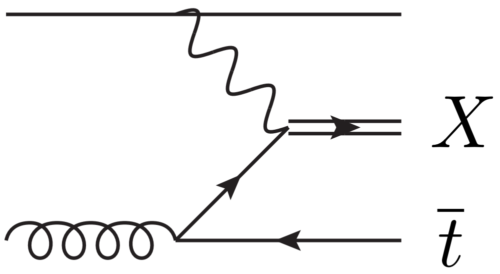

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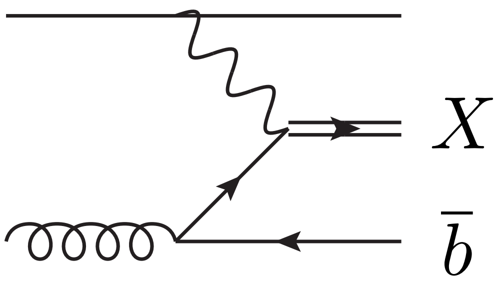

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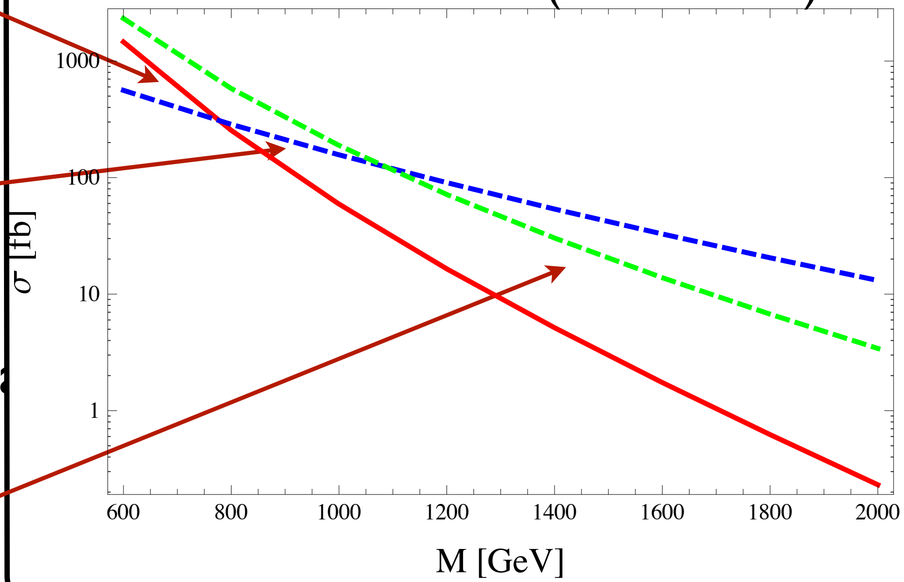
comparing production rates:
(14 TeV LHC)



Top Partners at the LHC

Summary of production/decay: $X_{5/3}$

Production: QCD or single+t, comparable at $M \sim 700\,\mathrm{GeV}$

Decay: $BR(Wt) = 1$

Final states: $t\bar{t}W + \begin{cases} W & \text{in QCD prod.} \\ \text{fwd jet in sing. prod.} \end{cases}$

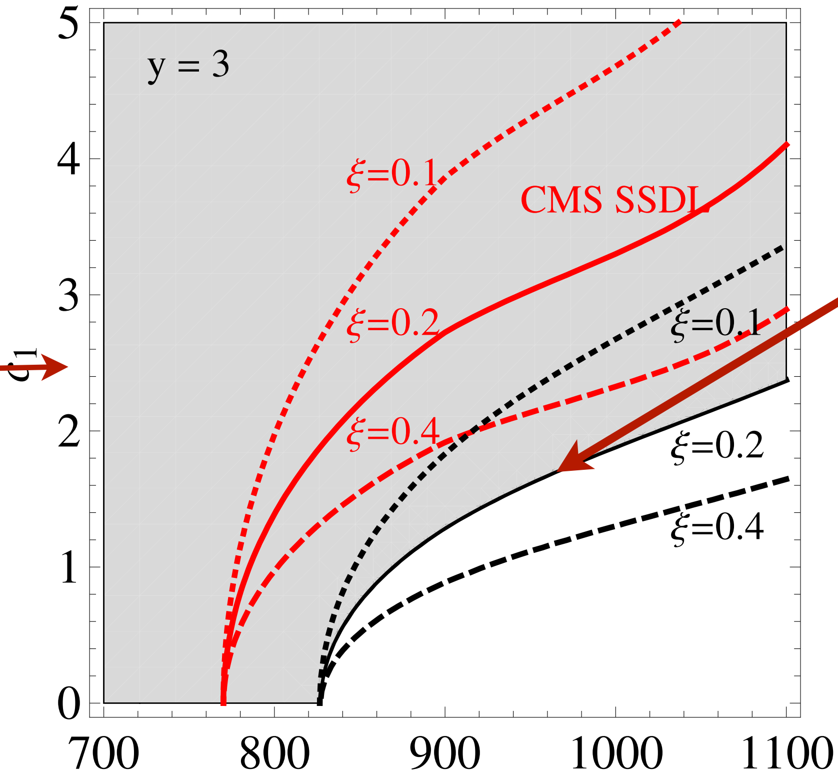
Good channel is **same-sign di-(tri-)leptons** plus jets

Top Partners at the LHC

Bounds:

Searches sensitive to $X_{5/3}$ pair and single, though not optimised for the latter one

single prod. coupling



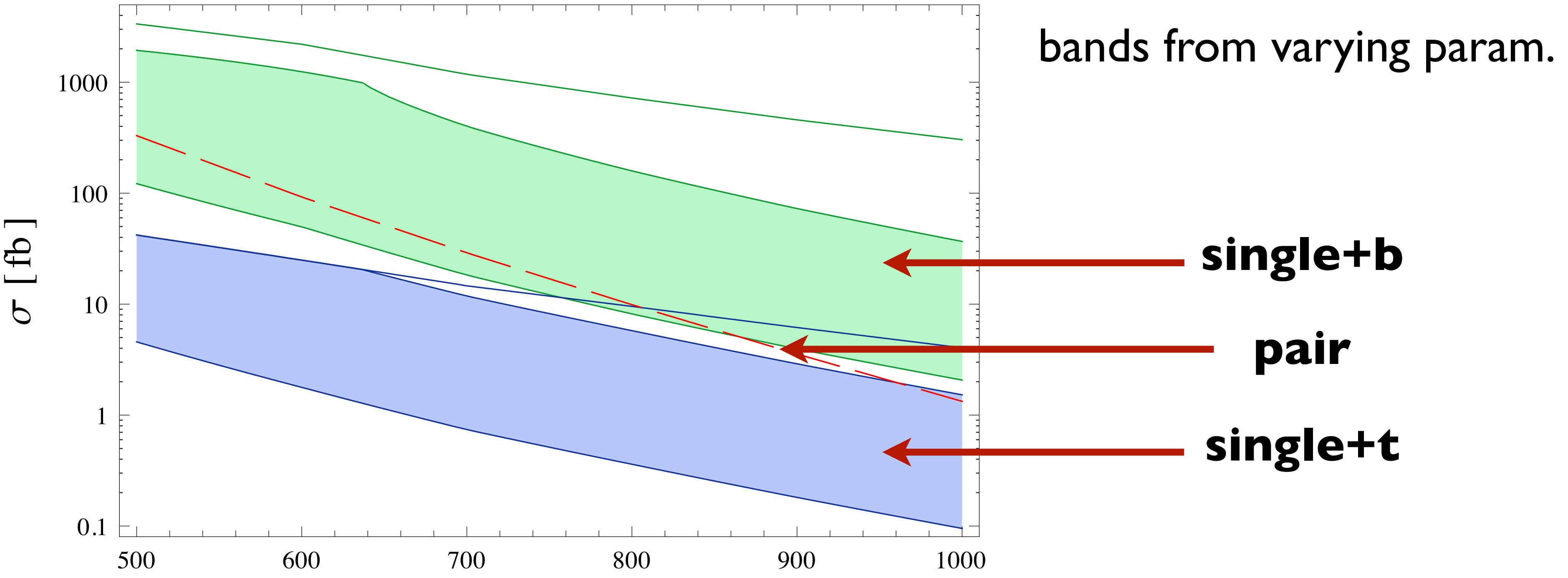
Estimated reach by boosted W techniques

Significant improvement of the bound from single production

Top Partners at the LHC

Summary of production/decay: $\widetilde{T}$

Production: sing.+b typically dominant



Decay: $BR(tZ) \simeq BR(ht) \simeq 0.5 BR(Wb)$

Plenty of possible final states, **rich phenomenology**

Top Partners at the LHC

Current searches **not sensitive** to single + bottom

Present Bound
(from pair)

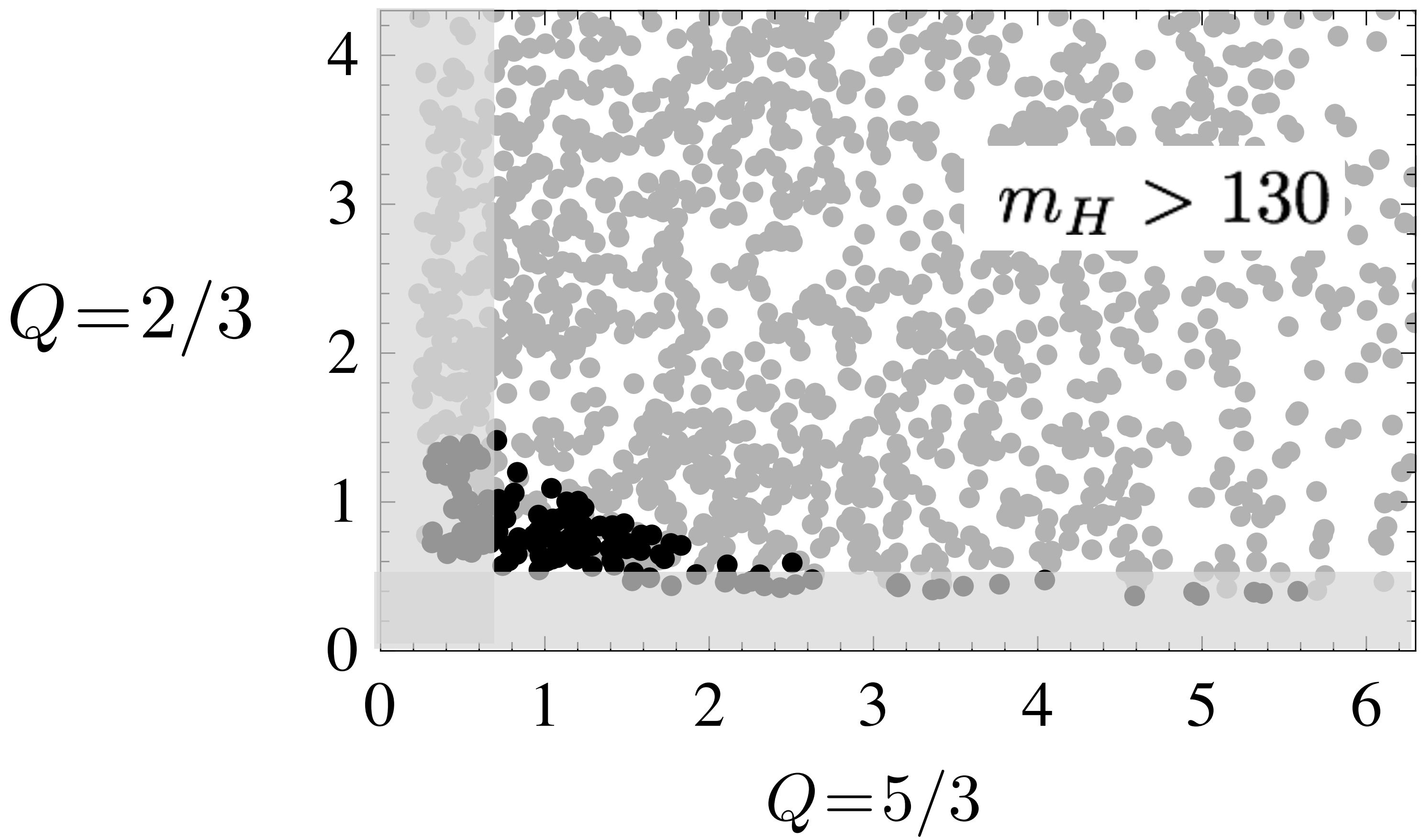
$$M > 670 \text{ GeV}$$

By exploiting single production, it could improve

Top Partners at the LHC

Impact on a concrete model (roughly):

$\xi = 0.2$



Top Partners at the LHC

Impact on a concrete model (roughly):

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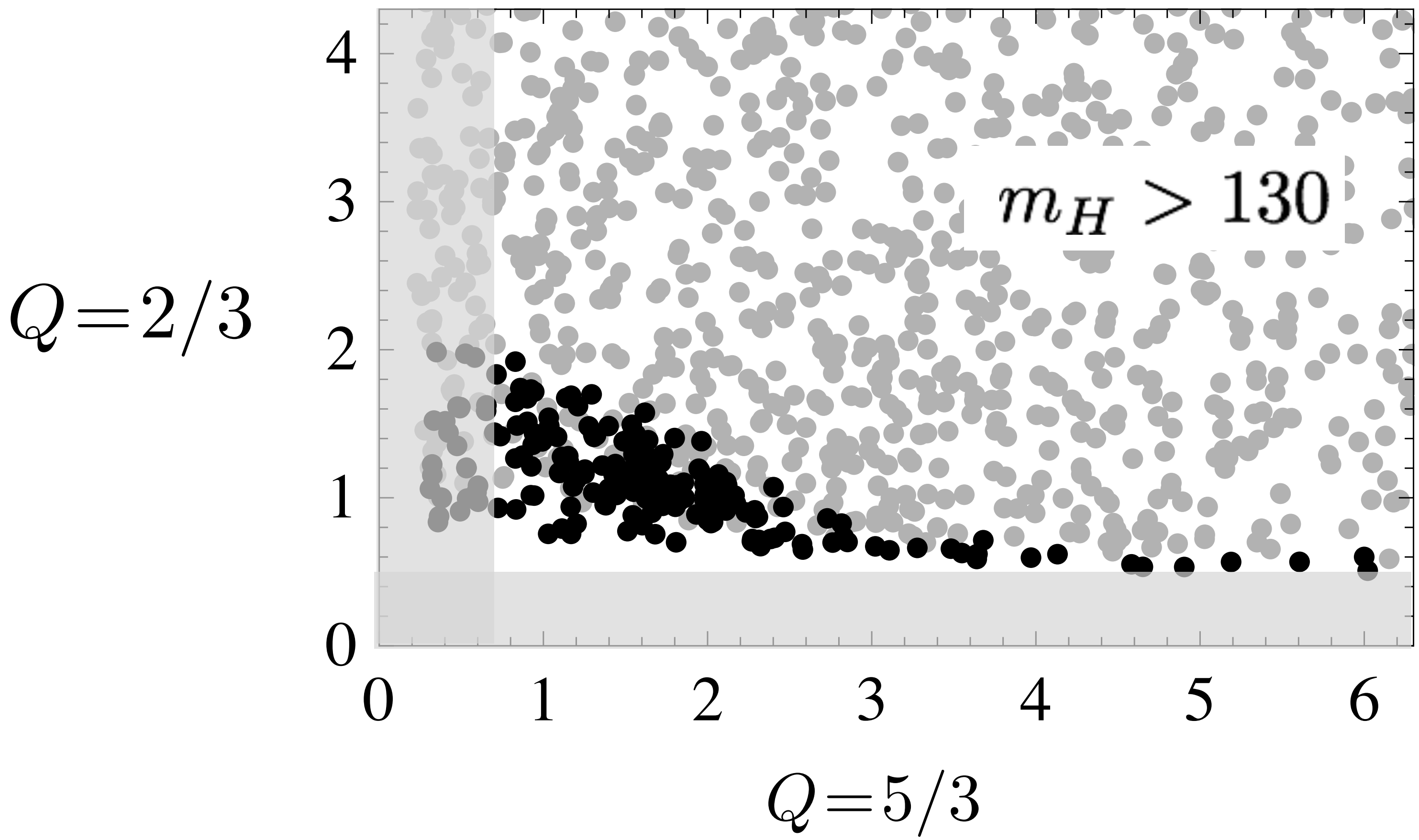

Conclusions

✦ LHC has started probing EWSB, it is time to test theoretical ideas, particularly compelling are the **Natural** scenarios

✦ Even a negative result will have a strong impact on our understanding of Fund. Int. Alternative to Naturalness is **Anthropic Principle.**

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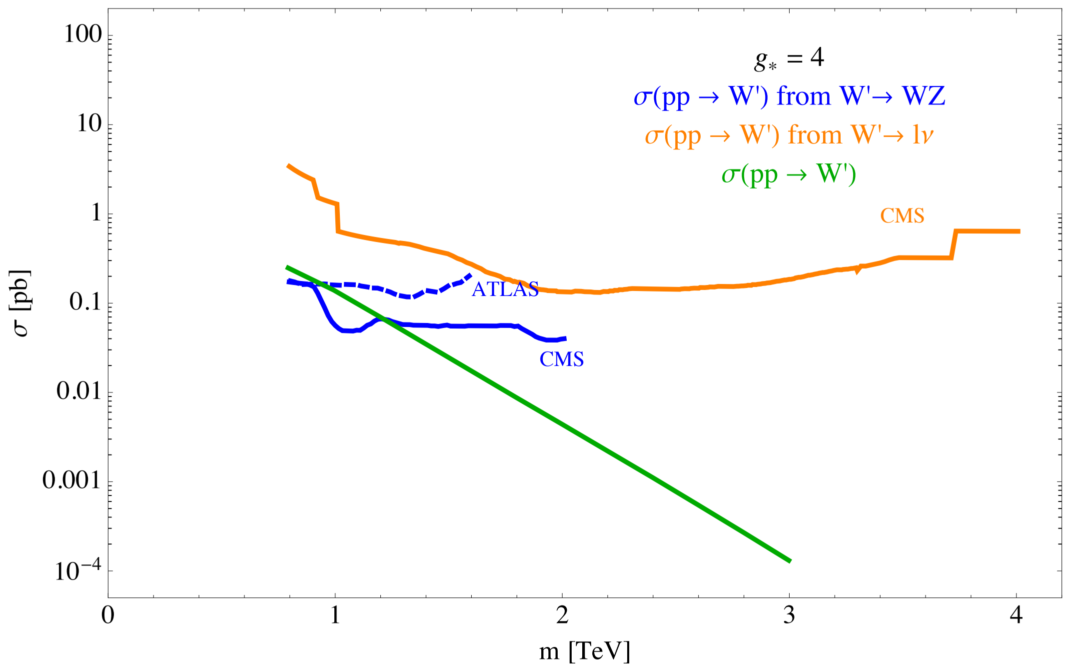
✦ A Composite Higgs with P.C. might work. possible manifestations:

- Higgs couplings modifications (hard)
- Direct observation of Top Partners (easy)
- Spin one resonances (good for 14 TeV, $m_\rho \gtrsim 2.5\ \text{TeV}$)

Present data are already probing part of the natural par. space.

Conclusions



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✦ LHC search program is still at a preliminary stage

much is left to be done !!