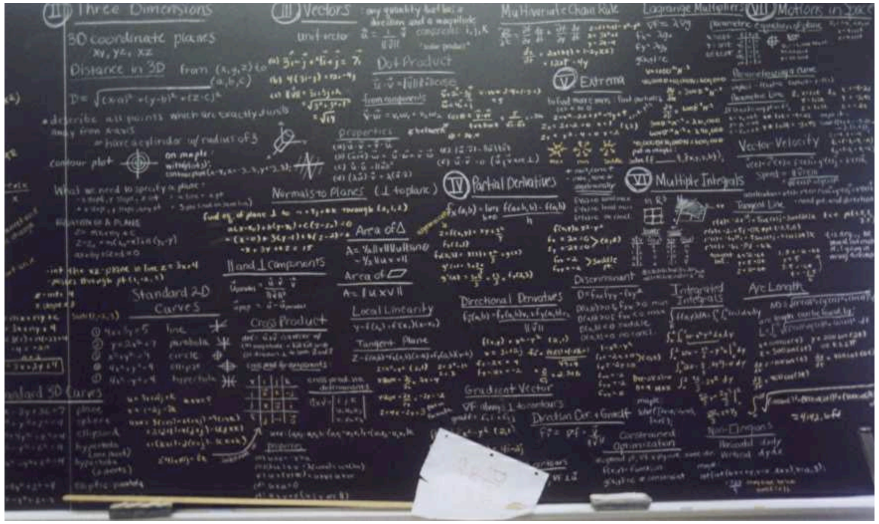
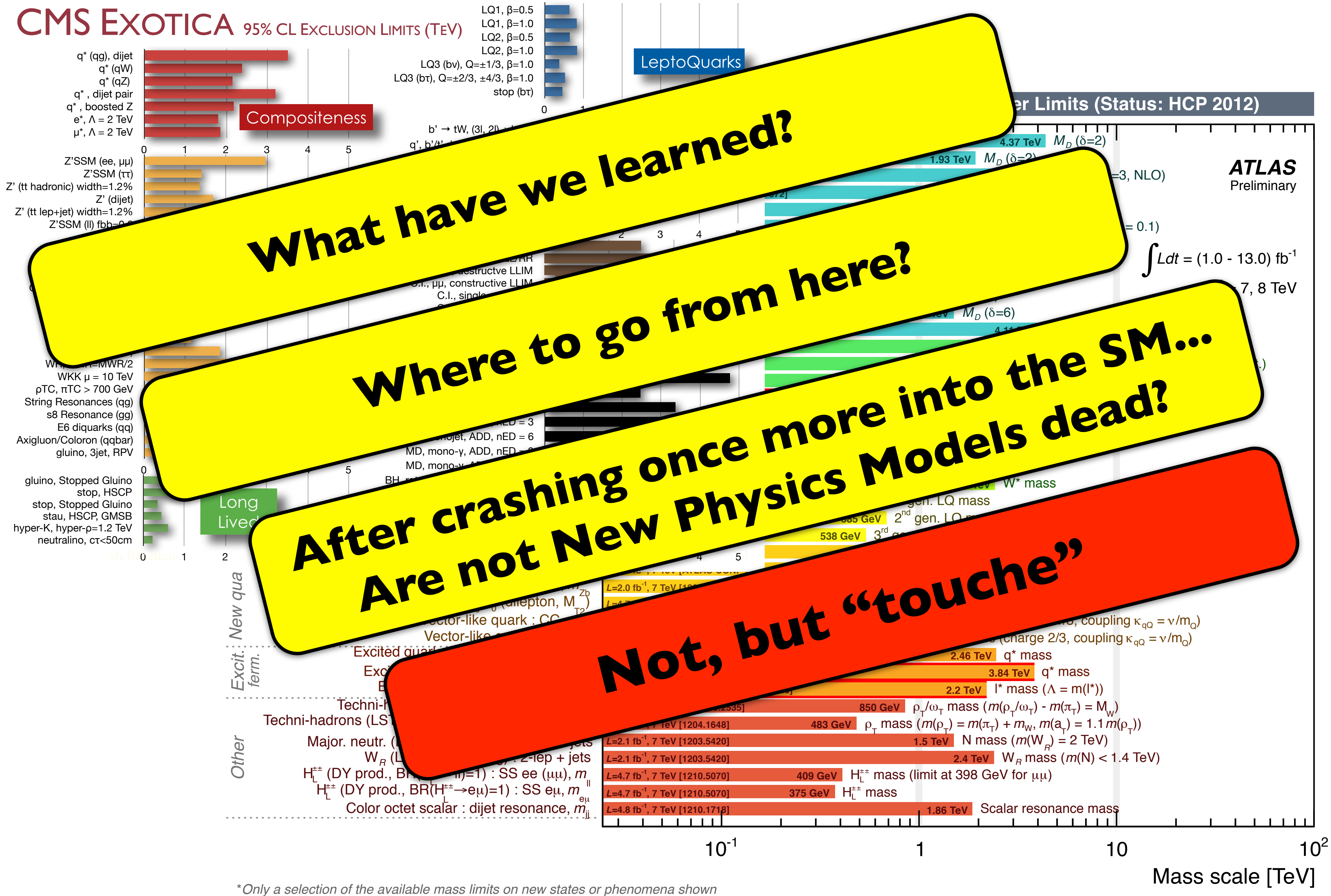
Implications of LHC Data to New Physics

Alex Pomarol (Univ. Autonoma Barcelona)

vs



In the last years we have been overflowed with LHC data...



What have we learned?

Where to go from here?

After crashing once more into the SM…
Are not New Physics Models dead?

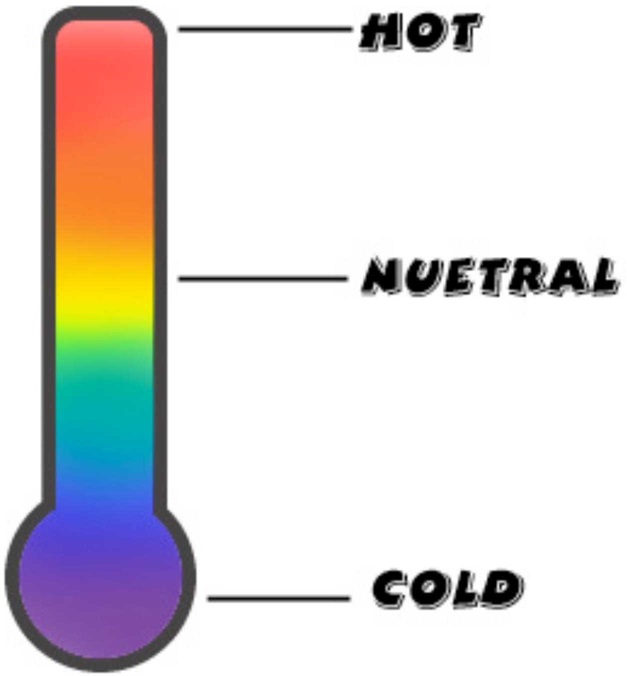
Not, but "touche"

Implications of LHC Data to New Physics

Here, I'll take a biassed point of view (as a theorist)

A non-democratic approach to data:

Not all data is equal (ly interesting)



- $M_H \approx 125$ GeV

  ➜ shook us

- No discovery of top partners

  ➜ discourage us

⋮

- No discovery of Black Holes, Techi-rho

  ➜ we didn't learn much

Disclaimer: As the Catalan writer Josep Pla used to say: "*It is much harder to describe than to give opinions. Infinitely much more. Given this, everybody give opinions*"

Outline

- The model to beat : **The Standard Model**

  ↳ Validity and implications

- Going beyond: Supersymmetry,
  Composite Higgs, ...

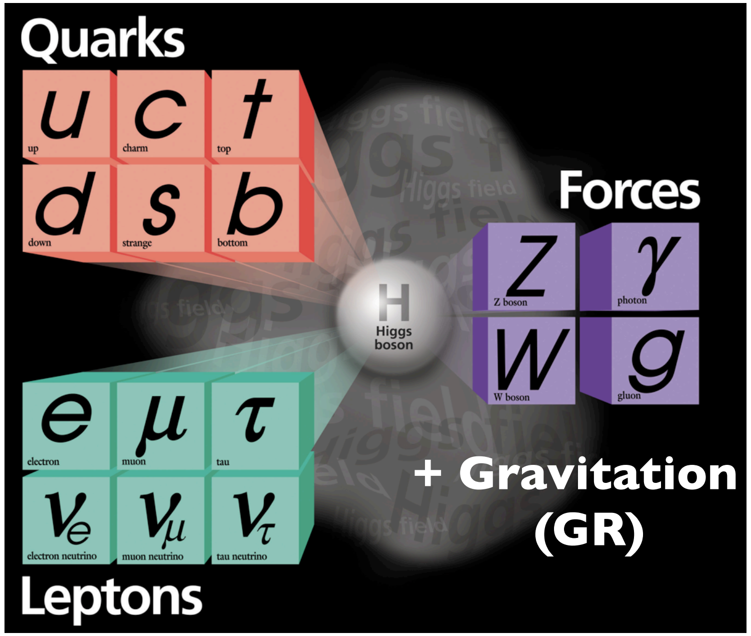
- **What does data tell us?**

  - Tests of the SM: Indirect search for new physics
    - Before the LHC
    - After the LHC: Top and Higgs sector

  - Direct search for new physics

Present theory that explain (almost) all phenomena:

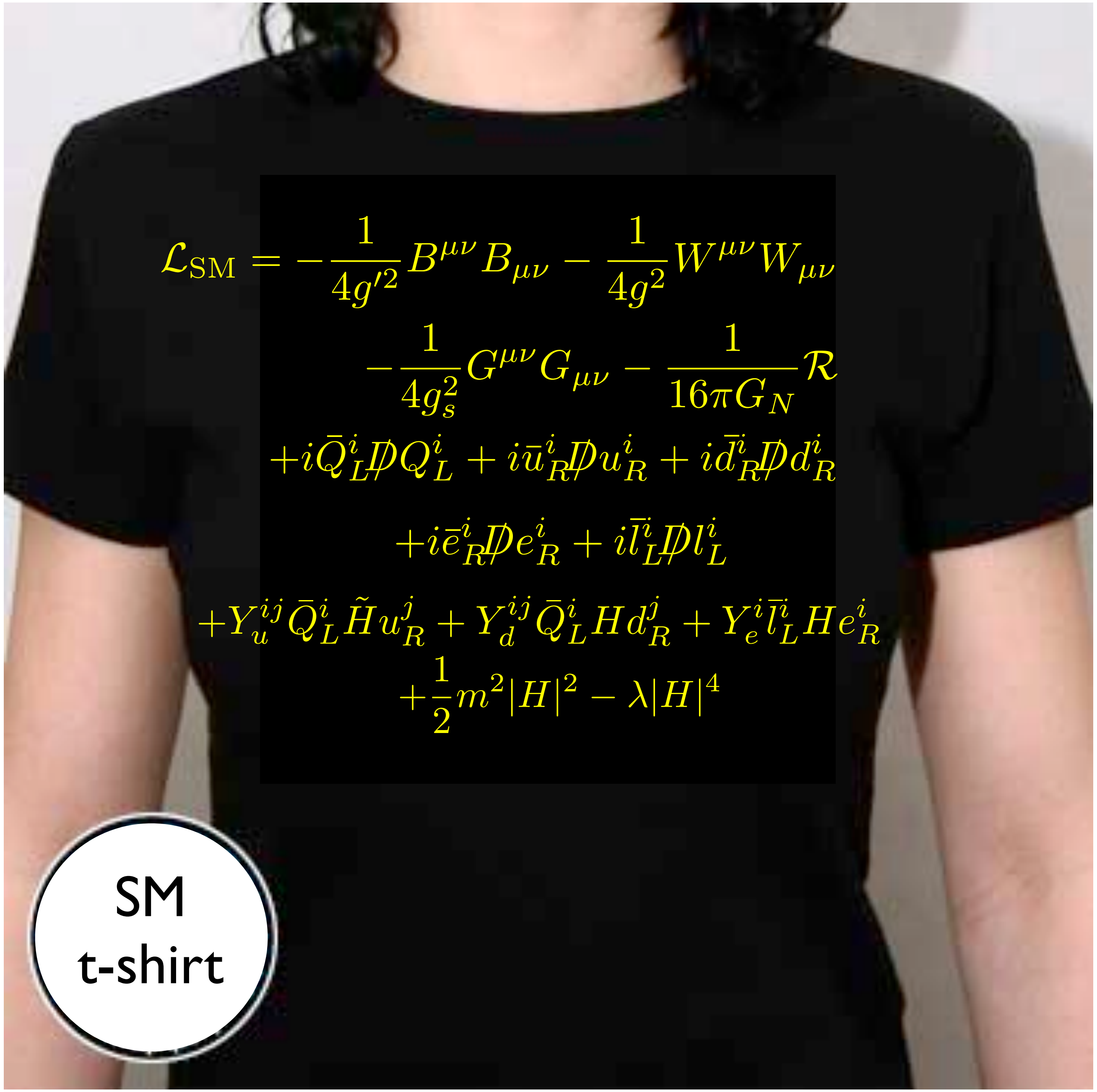
Standard Model
of elementary particles



+ Gravitation (GR)

- Quantum field theory
- Symmetry Group: gauge (SU(3), SU(2), U(1)) & Poincare

Quite simple Lagrangian:



$$
\begin{aligned}
\mathcal{L}_{\mathrm{SM}} = &-\frac{1}{4g'^2}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4g^2}W^{\mu\nu}W_{\mu\nu} \\
&-\frac{1}{4g_s^2}G^{\mu\nu}G_{\mu\nu} - \frac{1}{16\pi G_N}\mathcal{R} \\
&+i\bar{Q}^i_L \not{D} Q^i_L + i\bar{u}^i_R \not{D} u^i_R + i\bar{d}^i_R \not{D} d^i_R \\
&+i\bar{e}^i_R \not{D} e^i_R + i\bar{l}^i_L \not{D} l^i_L \\
&+Y_u^{ij}\bar{Q}^i_L \tilde{H} u^j_R + Y_d^{ij}\bar{Q}^i_L H d^j_R + Y_e^{i}\bar{l}^i_L H e^i_R \\
&+\frac{1}{2}m^2|H|^2 - \lambda|H|^4
\end{aligned}
$$

SM
t-shirt

Validity?

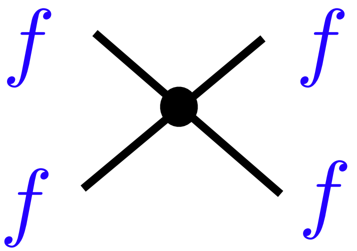
With a Higgs 100 GeV < M_H < 170 GeV

All couplings (dimensionless) evolve logarithmically with the energy

↳ smaller than one below **M_P**

Only at **$E>M_P$** the theory does not give reasonable predictions:

Gravitational effects:

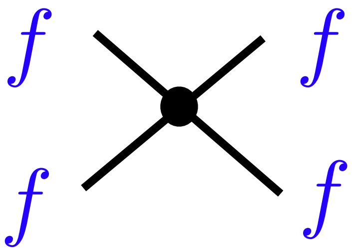


$$\sim \mathbf{G_N E^2}$$

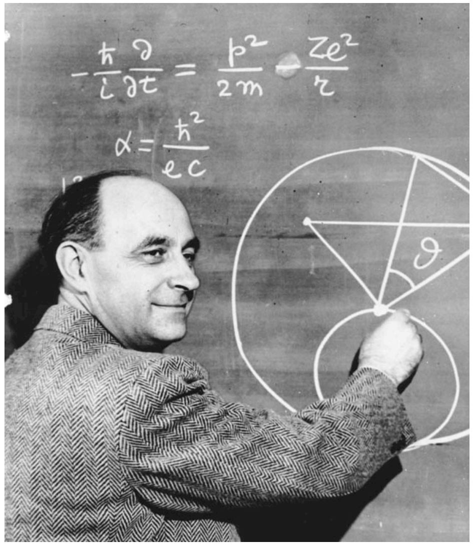
$$G_N = \frac{1}{M_P^2}$$

SM+Gravity = Effective theory valid up to the Planck scale **M_P** ~10^{19} GeV

Very similar to Fermi's theory:



$$\sim \mathbf{G_F E^2}$$



G_F = Fermi's constant

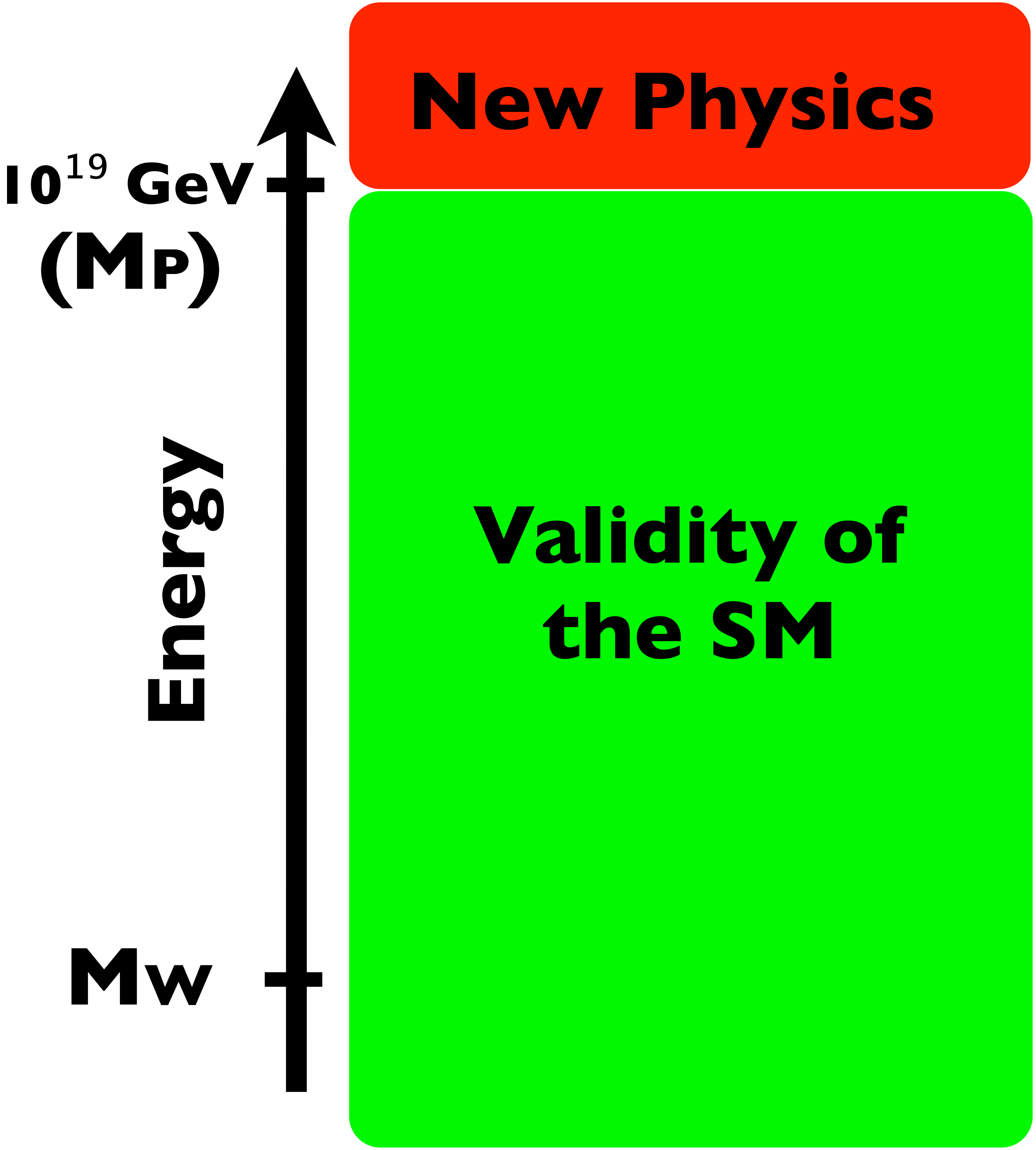
The strength of the interaction is larger than one for

$E > 1/\sqrt{G_F} \Rightarrow \Lambda_F \sim 1/\sqrt{G_F}$

We know what happened at $E \sim 1/\sqrt{G_F} \sim 300$ GeV:

There was **New physics** (beyond Fermi's theory):

We discovered the W/Z particles, the SM!



New Physics

10^{19} GeV

(M_P)

Energy

Validity of the SM

M_W

SM = Effective field Theory

$$\mathbf{m^2|H|^2}$$

m ~ m$_W$

Dim Oi = 2

$$\mathcal{L}_{SM} = -\frac{1}{4g^2}F^{\mu\nu}F_{\mu\nu} + i\bar{f}_L\not{D}f_L + i\bar{f}_R\not{D}f_R$$
$$+|D_\mu H|^2 - \lambda|H|^4 + Y_f\bar{f}_LHf_R + h.c$$

Dim Oi = 4

$$\frac{1}{\Lambda}H\bar{l}^c_L l_L H$$

Λ ~ M$_P$

Dim Oi = 5

$$\frac{c_1}{\Lambda^2}|H|^2|D_\mu H|^2 + \frac{c_2}{\Lambda^2}(\bar{f}_L\gamma^u f_L)^2$$
$$+\frac{c_3}{\Lambda^2}(D_\mu F^{\mu\nu})^2 + \cdots$$

Dim Oi = 6

⋮

⋮

SM = Effective field Theory

$m^2|H|^2$

m ~ m_W

Dim Oi = 2

$$\mathcal{L}_{SM} = -\frac{1}{4g^2}F^{\mu\nu}F_{\mu\nu} + i\bar{f}_L \not{D} f_L \quad \not{D} f_R$$

$$+|D_\mu H|^2 - \lambda|H|^4 \quad h.c$$

Dim Oi = 4

This is the theory to beat!

Λ ~ M_P

Dim Oi = 5

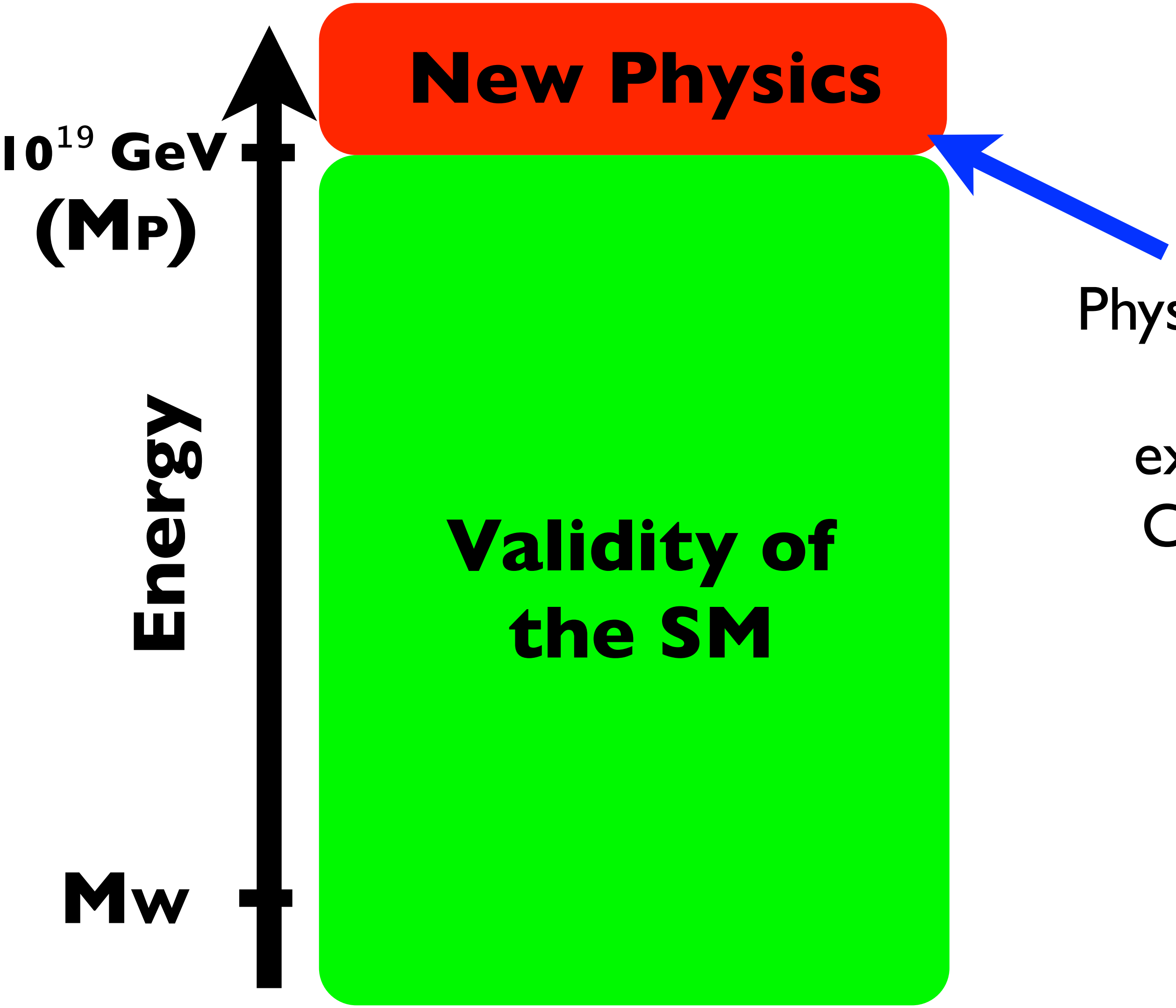
$$D_\mu H|^2 + \frac{c_2}{\Lambda^2}(\bar{f}_L\gamma^u f_L)^2$$

$$+\frac{c_3}{\Lambda^2}(D_\mu F^{\mu\nu})^2 + \cdots$$

Dim Oi = 6

⋮

⋮



New Physics

10^{19} GeV

(M_P)

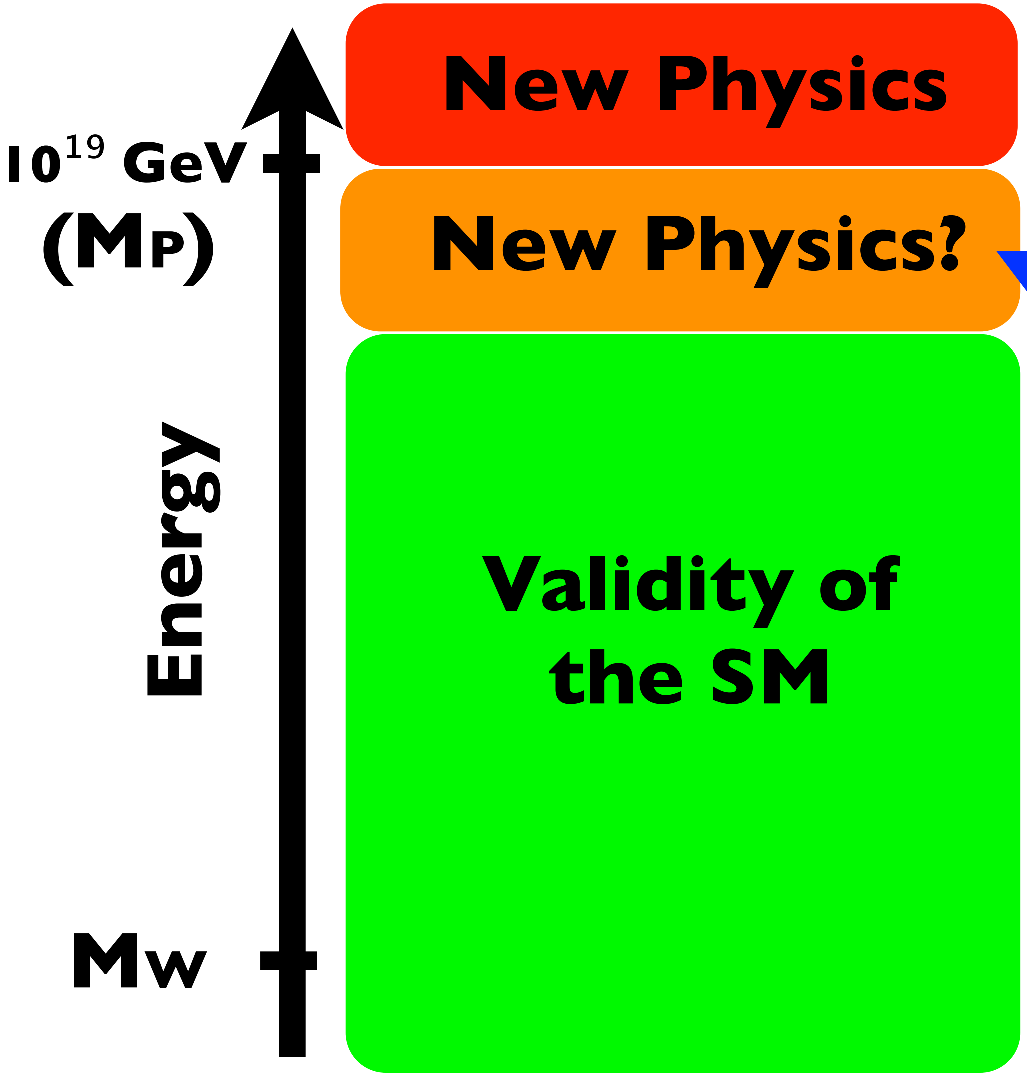
Energy

Validity of the SM

M_W

Physics at around (or just below) the Planck scale could explain **neutrino masses**, CP problem (via an **axion**), **Dark Matter**, **fermion masses**, **Baryogenesis**

New physics could be below **M_P** if weakly coupled:



New Physics

10^{19} GeV

(M_P)

New Physics?

Energy

Validity of the SM

M_W

Physics at around (or just below) the Planck scale could explain **neutrino masses**, CP problem (via an **axion**), **Dark Matter**, **fermion masses**, **Baryogenesis**

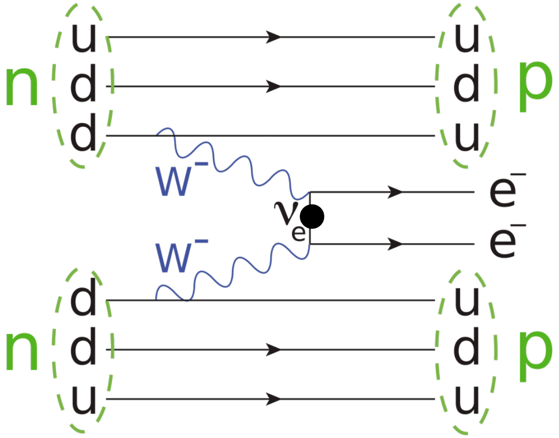
This new physics is Not Relevant for the LHC!

Only relevant experiments:

Looking for Lepton Number violations (dim=5 operator)

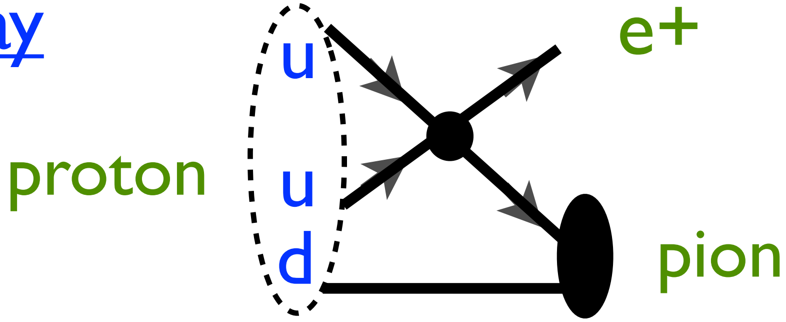
➡ Majorana masses for neutrinos

➡ Neutrinoless double beta decay



Looking for Baryon number violation

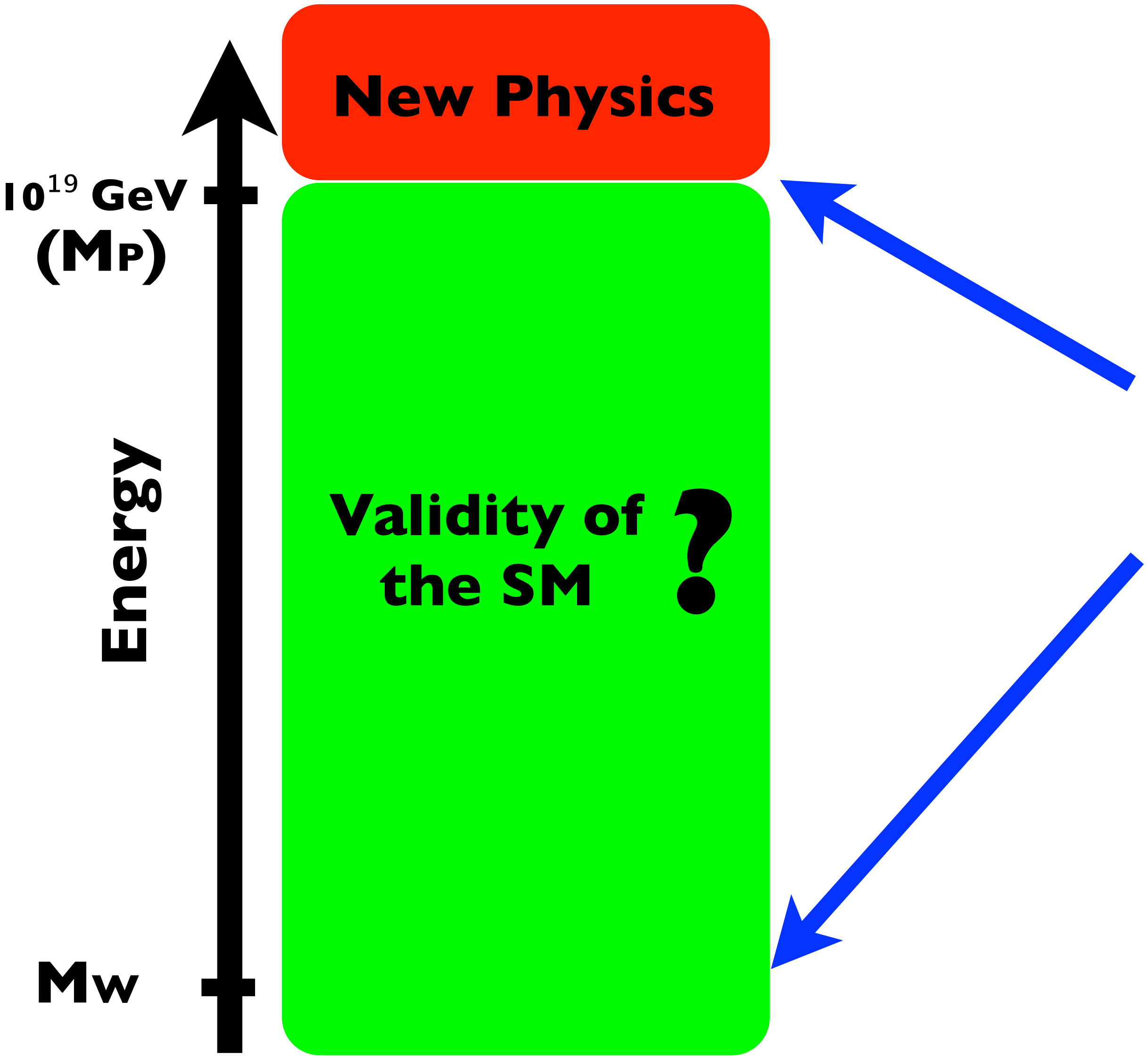
➡ Proton decay



➥ **both can**

probe $\Lambda \gtrsim 10^{15}$ **GeV !**

Although consistent, we think (and hope) this is not the full story



New Physics

10^{19} GeV

(M_P)

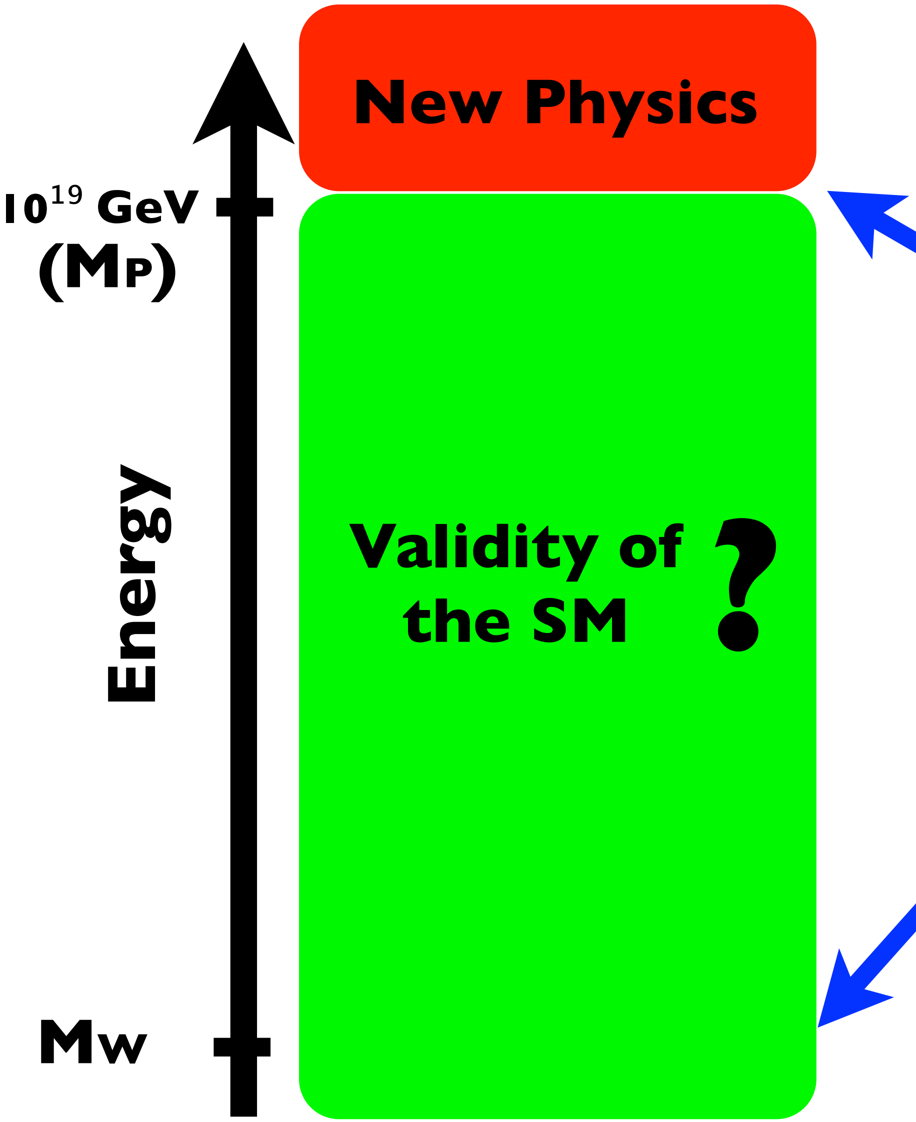
Energy

Validity of the SM ?

M_W

Not understandable
the origin of such a small
EW scale
as compared to the
Planck scale

Although consistent, we think (and hope) this is not the full story

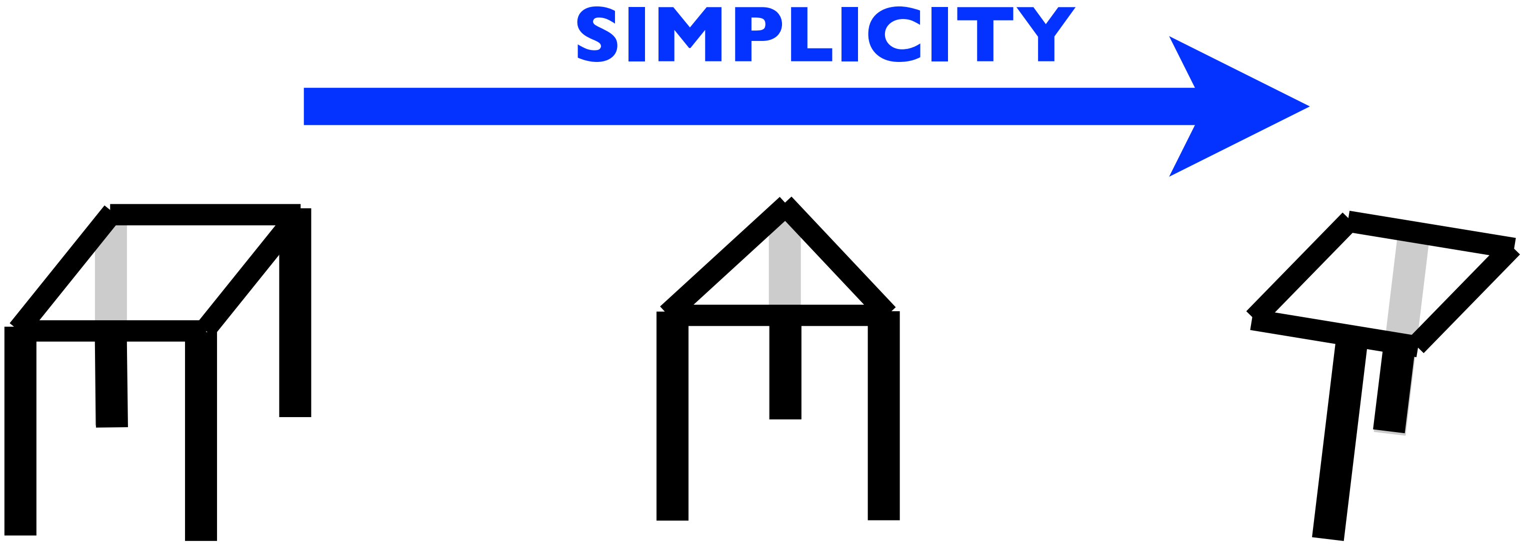


Not understandable the origin of such a small EW scale as compared to the Planck scale

The problem is transferred to the Higgs condensate

Here is where the **simplicity** of the Higgs mechanism puts it into **trouble**

Since not always simplicity is good:



SIMPLICITY

falls under quantum fluctuations!

stable **stable** **unstable**

“Vector”
s=1

“fermion”
s=1/2

“scalar”
s=0

No spin,
no “structure” to keep it light

The hierarchy problem in a nutshell

	Massless	**Massive**
Vector $\mathbf{A}_\mu$	2 *dof* **(+,-)**	3 *dof* **(+,0,-)**
Fermion Ψ	2 *dof* Ψ_L	4 *dof* Ψ_L ,Ψ_R
Scalar h	1 *dof*	1 *dof*

2≠3 ✔ Massless vector are save

2≠4 ✔ Massless fermions are save

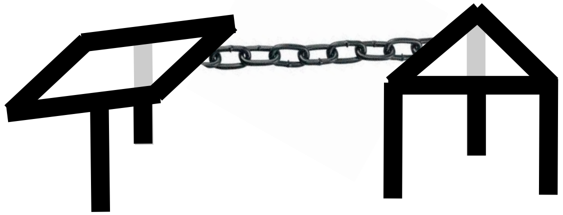
1=1 Problem!

Massless (or light) scalars are not save!

Possibilities that theorists envisage to tackle this problem:

1) Keep the Higgs elementary, but protect it by symmetries: **Supersymmetry**

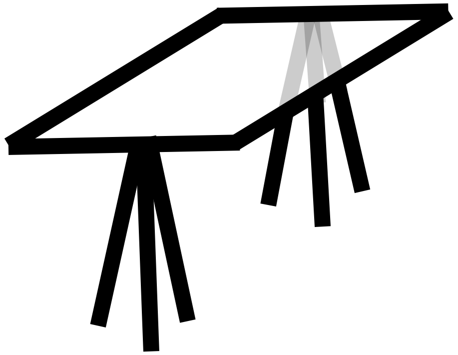
Higgs (boson) ⟷ **Higgsino** (fermion)



2) The Higgs is not elementary: **Composite Higgs**

Higgs made of fermions

(as a pion in strong interactions)



Supersymmetry

"I'm searching for my keys."

searching under the lamp-post

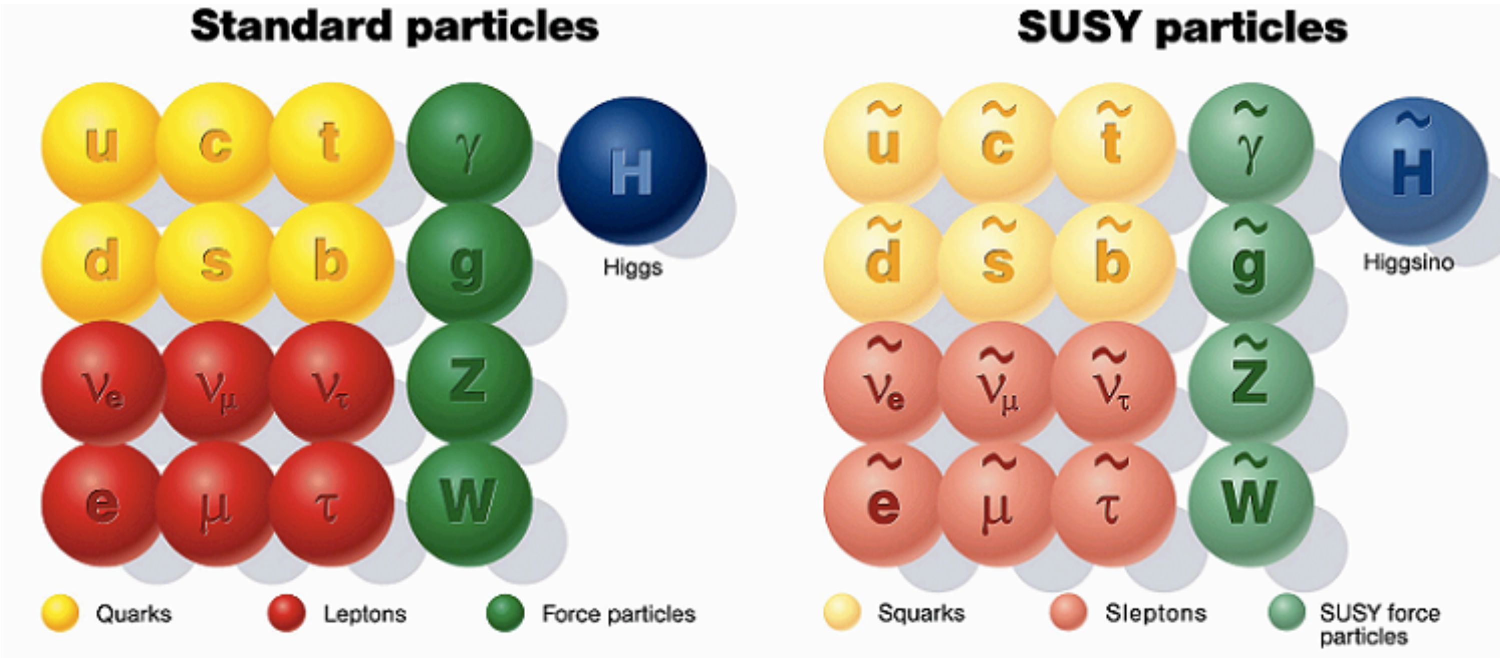
Minimal Supersymmetric SM (MSSM)

Imposing supersymmetry to the **SM** ➡ **MSSM**

The spectrum is doubled:

SM fermion ➡ New scalar (s-"..."")

SM boson ➡ New majorana fermion ("..."-ino)



… but not yet realistic:

The model has a quantum anomaly (due to the Higgsino) and the down-quarks and leptons are massless

Extra Higgs needed

➡ Two Higgs doublets:

$$H_u : \ (1, 2, 1)$$ → give mass to the up quarks

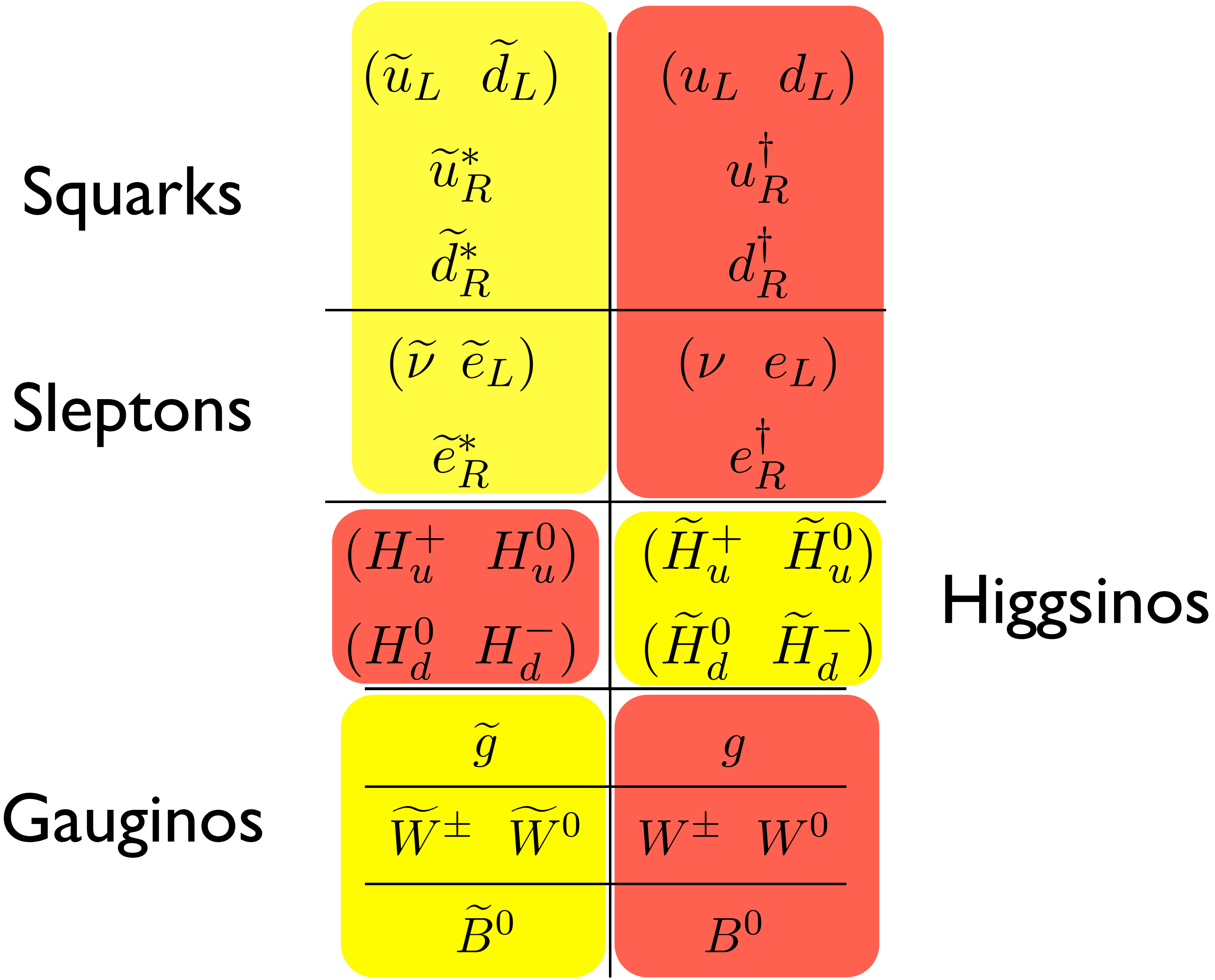
$$H_d : \ (1, 2, -1)$$ → give mass to the down quarks and leptons

+ two Higgsino doublets:

$$\widetilde{H}_u : \ (1, 2, 1)$$

$$\widetilde{H}_d : \ (1, 2, -1)$$

MSSM Spectrum



Squarks	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	
	$\widetilde{u}^*_R$	$u^\dagger_R$	
	$\widetilde{d}^*_R$	$d^\dagger_R$	
Sleptons	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	
	$\widetilde{e}^*_R$	$e^\dagger_R$	
	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	Higgsinos
	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	
Gauginos	$\widetilde{g}$	g	
	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	
	$\widetilde{B}^0$	B^0	

🟥 particles: *R-parity* = 1

🟨 superpartners: *R-parity* = -1

→

1) Superpart. interact in pairs

2) Lightest superpart. stable

But if supersymmetry is exact:

$M_F = M_B$ ➡ e.g. $M_e = M_{\tilde{e}}$

It must be broken to give masses to the superpartners

Supersymmetry breaking must afford "soft terms":

(terms that do not spoil the good UV properties of the Susy)

$$-\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)$$

$$-\left(\tilde{\bar{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \tilde{\bar{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \tilde{\bar{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right)$$

$$-\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \tilde{\bar{u}}\,\mathbf{m^2_{\bar{u}}}\,\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\,\mathbf{m^2_{\bar{d}}}\,\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\,\mathbf{m^2_{\bar{e}}}\,\tilde{\bar{e}}^\dagger$$

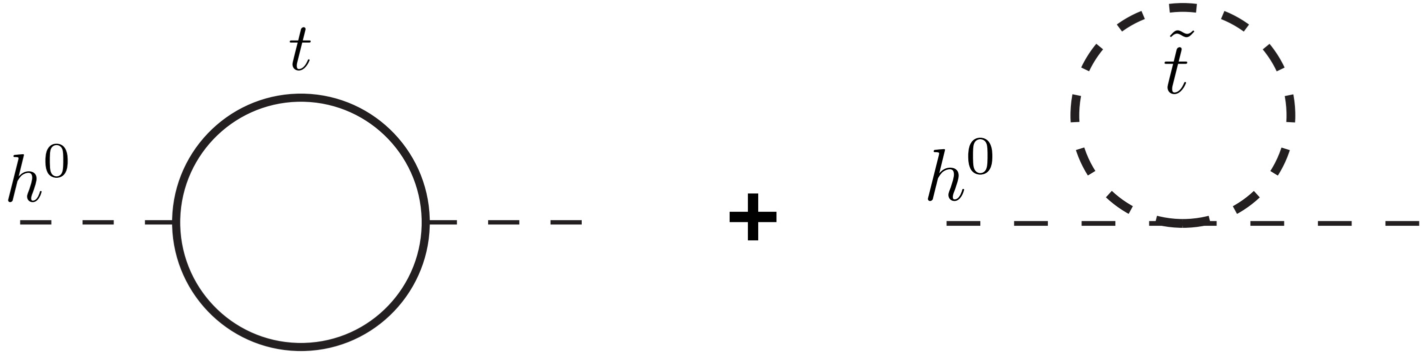
$$-m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.$$

$$+\mu\tilde{H}_u\tilde{H}_d$$

for 3 families, more than 100 terms are possible!!

How supersymmetry works?

(including soft-masses)



Fermion loop

Boson loop

$$\underbrace{\mu^2 = +A \qquad \mu^2 = -A + m_{stop}^2 \quad B}_{\mu^2_{total} \sim m_{stop}^2}$$

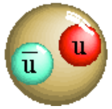
Superpartners expected around v ~ 100 GeV

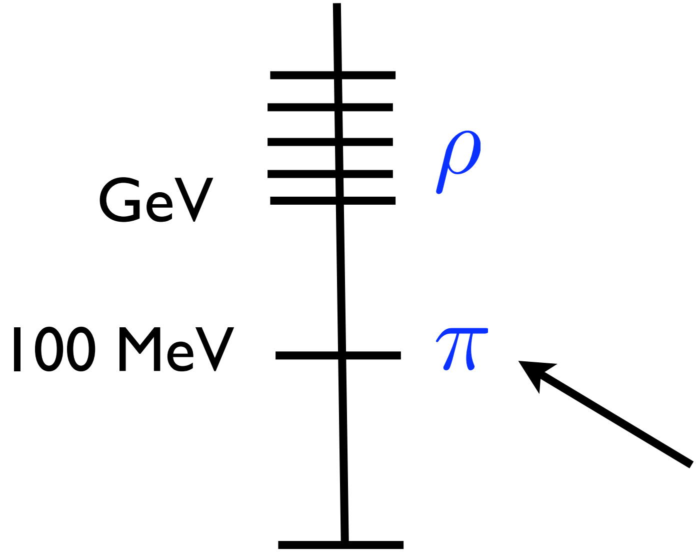
Composite Higgs

Composite Higgs

inspired by **QCD** where one observes
that the (pseudo) scalar are the lightest states

Spectrum of **mesons**:





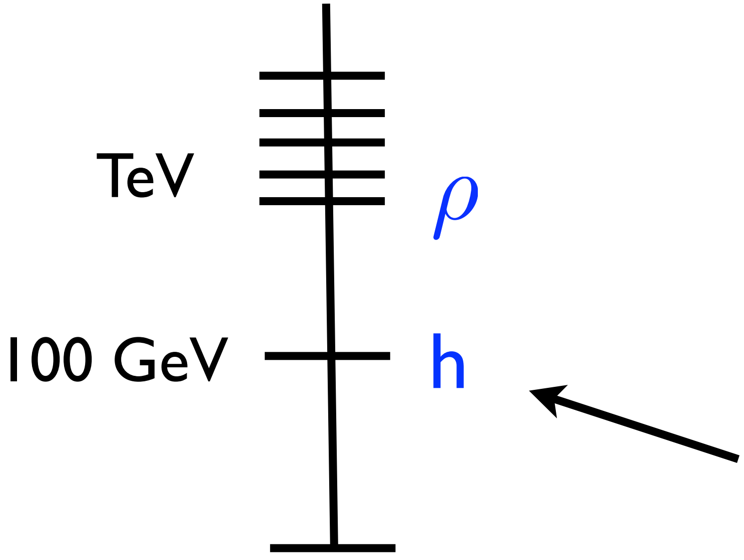
Are Pseudo-Goldstone bosons (PGB)

Mass protected by the global QCD symmetry!

$$\pi \longrightarrow \pi + \alpha$$

Can the light Higgs be a kind of a pion from a new strong sector?

We'd like the spectrum of the new strong sector to be:



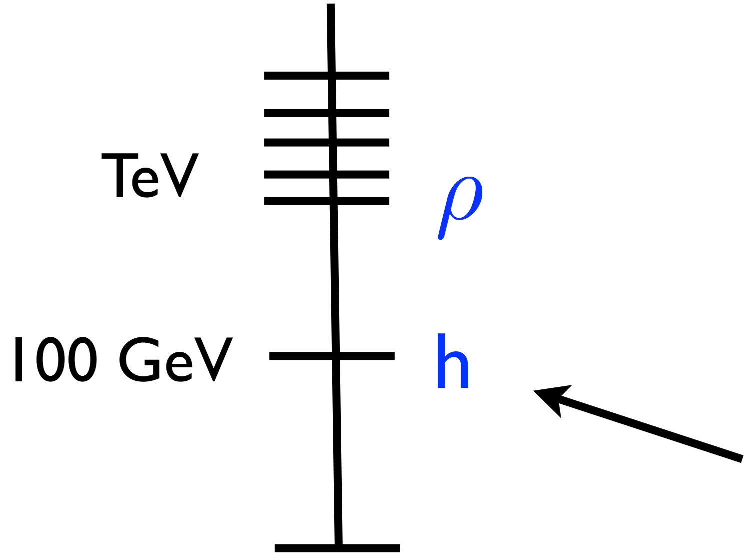
Pseudo-Goldstone bosons (PGB)

Difficult to get precise predictions but we could study its properties at the LHC as in the 60s when pions, kaons, ... were discovered

(some were composite, some weren't as the muon)

→ Can the light Higgs be a kind of a pion from a new strong sector?

We'd like the spectrum of the new strong sector to be:



TeV

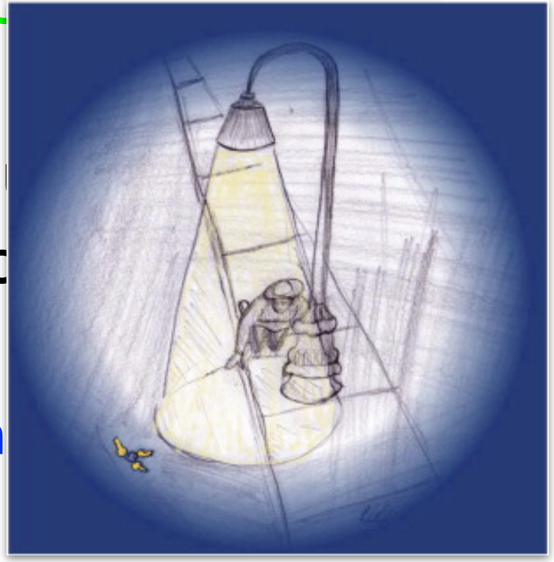
ρ

100 GeV

h

Pseudo-Goldstone bosons (PGB)

beyond the lamp-post:



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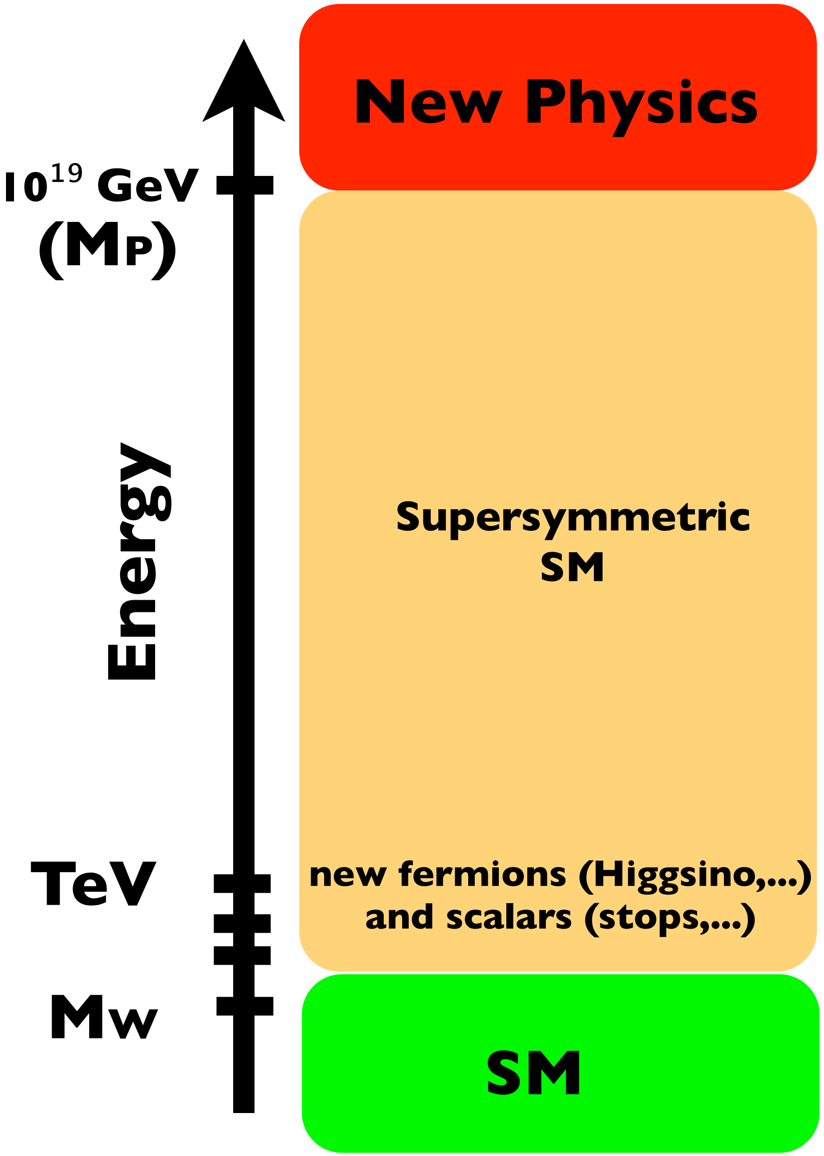
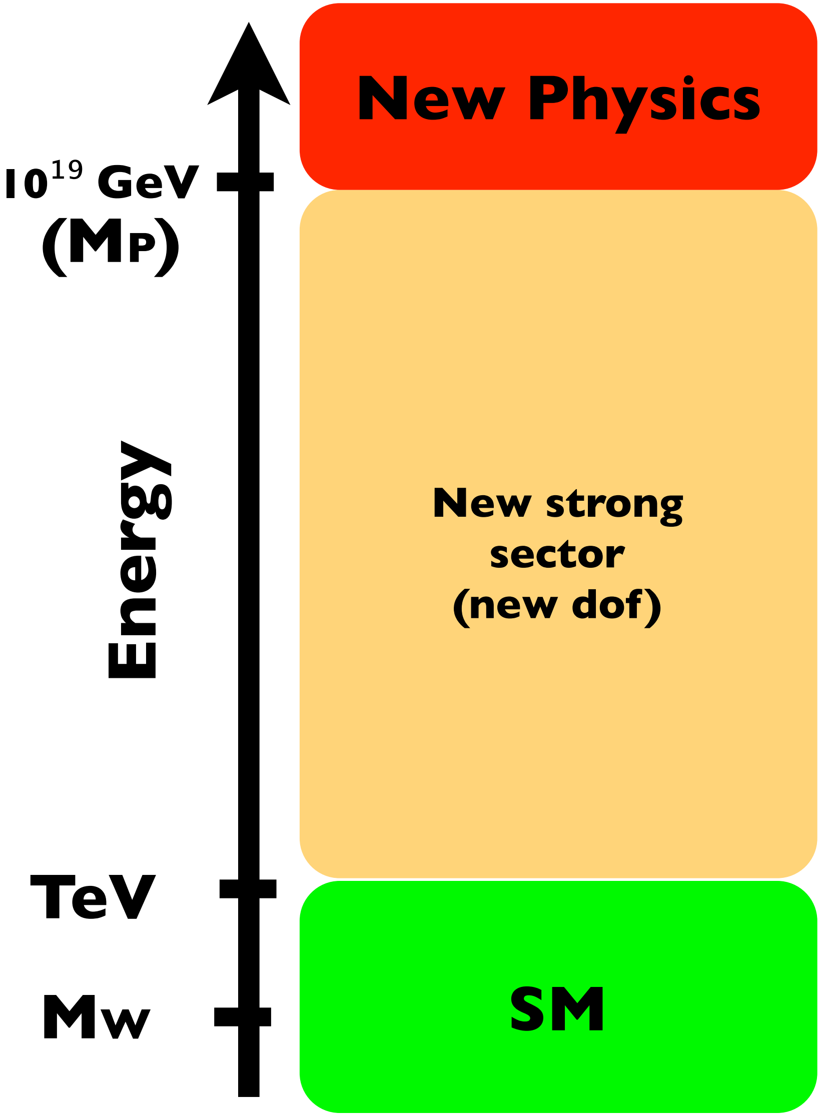
Supersymmetry



Composite Higgs



↪ Both give New Physics at the LHC

What about other options?

1) Warped extra dimensions

≈ Strongly coupled theories

(by the AdS/CFT correspondence)

➥ similar physics at the LHC

2) Large extra dimensions:

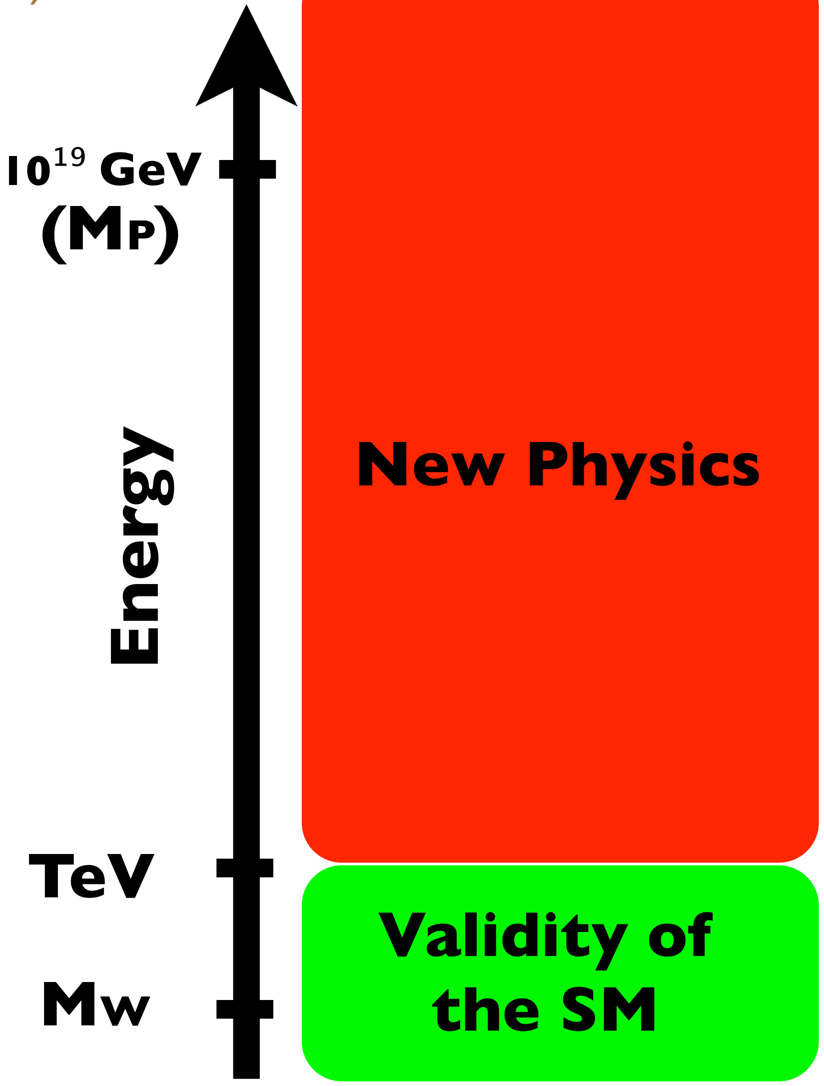
M_P not a new fundamental scale:

Large because gravity propagates in δ extra dim of radii R:

$$\frac{1}{M_P^2} \sim \frac{1}{\mathrm{TeV}^{2+\delta}}\,\frac{1}{R^\delta}$$

<u>Hard to make precise predictions:</u>

String modes at the TeV,
but also gravitons can be produced and
Black Holes, ...



Other “ inert” options

(not needed at all)

- Extra families
- Extra gauge boson: U(1), ...
- But **not** extra Higgs: Such as 2HDM, singlets, ..., since they come with extra problems!

Tests of the SM:
Indirectly probing new physics

SM = Effective field Theory

$$\mathbf{m^2|H|^2}$$

m ~ m$_w$

Dim O$_i$ = 2

$$\mathcal{L}_{\rm SM} = -\frac{1}{4g^2}F^{\mu\nu}F_{\mu\nu} + i\bar{f}_L \not{D} f_L + i\bar{f}_R \not{D} f_R$$
$$+|D_\mu H|^2 - \lambda |H|^4 + Y_f \bar{f}_L H f_R + h.c$$

Dim O$_i$ = 4

$$\frac{1}{\Lambda} H \bar{l}^c_L l_L H$$

Dim O$_i$ = 5

$$\frac{c_1}{\Lambda^2}|H|^2|D_\mu H|^2 + \frac{c_2}{\Lambda^2}(\bar{f}_L \gamma^u f_L)^2$$
$$+\frac{c_3}{\Lambda^2}(D_\mu F^{\mu\nu})^2 + \cdots$$

Λ ~ TeV?

Dim O$_i$ = 6

⋮

⋮

due to the hierarchy problem

SM = Effective field Theory

$$\mathbf{m^2|H|^2}$$

m ~ m$_W$

Dim O$_i$ = 2

$$\mathcal{L}_{\rm SM} = -\frac{1}{4g^2}F^{\mu\nu}F_{\mu\nu} + i\bar{f}_L \not{D} f_L + i\bar{f}_R \not{D} f_R$$
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Dim O$_i$ = 4

$$\xcancel{\frac{1}{\Lambda} H \bar{f}_L l_L H}$$

by lepton number conservation at the TeV

$$\frac{c_1}{\Lambda^2}|H|^2|D_\mu H|^2 + \frac{c_2}{\Lambda^2}(\bar{f}_L \gamma^u f_L)^2$$
$$+\frac{c_3}{\Lambda^2}(D_\mu F^{\mu\nu})^2 + \cdots$$

Λ ~ TeV?

Dim O$_i$ = 6

$\vdots$ $\vdots$

Effects observable at colliders

(baryon number must also be assumed)

59 dimension-six operators (for one family)

arXiv:1008.4884

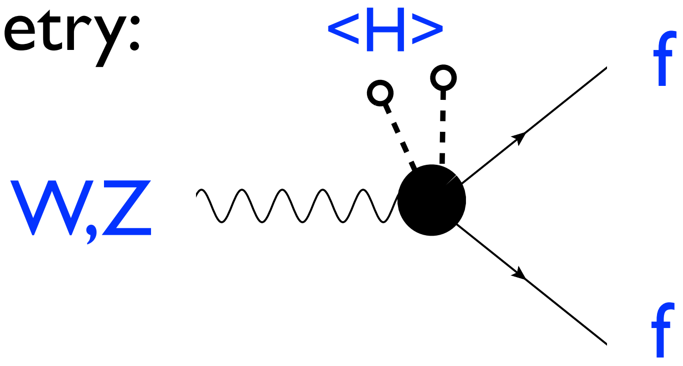
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$		$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$	Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$	$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$	$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$	$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$		
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$		
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$		

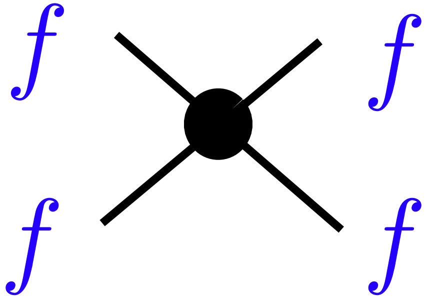
Mainly two types of deformations:

1) Breaking of EW symmetry:



$$\sim \frac{g_H^2 v^2}{\Lambda^2}$$

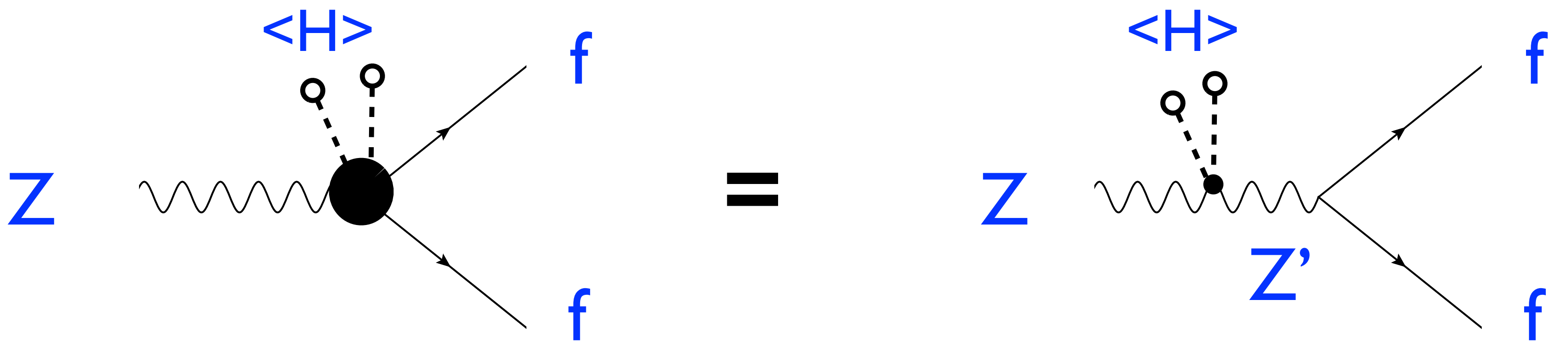
2) New interactions growing with the energy:



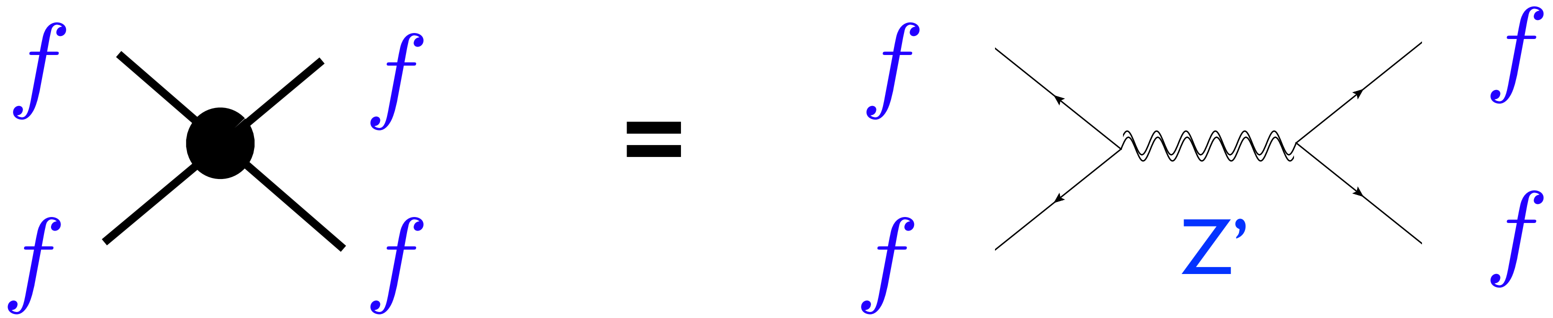
$$\sim \frac{E^2}{\Lambda^2}$$

Intensity frontier vs **high-energy frontier**

Example: Z’ or resonance of a strong sector



$\Lambda \sim M_{Z'}$



Supersymmetry:

Generically, small effects expected
since sparticles appear at the one-loop level

Composite Higgs:

Generically, sizable effects expected
in the SM gauge sector

Before the LHC

How well the SM particles were tested?

First reaction, one answers “extremely well”

Extensive LEP, SLAC LC, Tevatron,... legacy:

$\sqrt{s}$ (GeV)	Quantity	Average value	SM	Δ
130	$\sigma(q\overline{q})$	82.1$\pm$2.2	82.8	-0.3
130	$\sigma(\mu^+\mu^-)$	8.62$\pm$0.68	8.44	-0.33
130	$\sigma(\tau^+\tau^-)$	9.02$\pm$0.93	8.44	-0.11
130	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.694$\pm$0.060	0.705	0.012
130	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.663$\pm$0.076	0.704	0.012
136	$\sigma(q\overline{q})$	66.7$\pm$2.0	66.6	-0.2
136	$\sigma(\mu^+\mu^-)$	8.27$\pm$0.67	7.28	-0.28
136	$\sigma(\tau^+\tau^-)$	7.078$\pm$0.820	7.279	-0.091
136	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.708$\pm$0.060	0.684	0.013
136	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.753$\pm$0.088	0.683	0.014
161	$\sigma(q\overline{q})$	37.0$\pm$1.1	35.2	-0.1
161	$\sigma(\mu^+\mu^-)$	4.61$\pm$0.36	4.61	-0.18
161	$\sigma(\tau^+\tau^-)$	5.67$\pm$0.54	4.61	-0.06
161	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.538$\pm$0.067	0.609	0.017
161	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.646$\pm$0.077	0.609	0.016
172	$\sigma(q\overline{q})$	29.23$\pm$0.99	28.74	-0.12
172	$\sigma(\mu^+\mu^-)$	3.57$\pm$0.32	3.95	-0.16
172	$\sigma(\tau^+\tau^-)$	4.01$\pm$0.45	3.95	-0.05
172	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.675$\pm$0.077	0.591	0.018
172	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.342$\pm$0.094	0.591	0.017
183	$\sigma(q\overline{q})$	24.59$\pm$0.42	24.20	-0.11
183	$\sigma(\mu^+\mu^-)$	3.49$\pm$0.15	3.45	-0.14
183	$\sigma(\tau^+\tau^-)$	3.37$\pm$0.17	3.45	-0.05
183	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.559$\pm$0.035	0.576	0.018
183	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.608$\pm$0.045	0.576	0.018
189	$\sigma(q\overline{q})$	22.47$\pm$0.24	22.156	-0.101
189	$\sigma(\mu^+\mu^-)$	3.123$\pm$0.076	3.207	-0.131
189	$\sigma(\tau^+\tau^-)$	3.20$\pm$0.10	3.20	-0.048
189	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.569$\pm$0.021	0.569	0.019
189	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.596$\pm$0.026	0.569	0.018

$\sqrt{s}$ (GeV)	Quantity	Average value	SM	Δ
192	$\sigma(q\overline{q})$	22.05$\pm$0.53	21.24	-0.10
192	$\sigma(\mu^+\mu^-)$	2.92$\pm$0.18	3.10	-0.13
192	$\sigma(\tau^+\tau^-)$	2.81$\pm$0.23	3.10	-0.05
192	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.553$\pm$0.051	0.566	0.019
192	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.615$\pm$0.069	0.566	0.019
196	$\sigma(q\overline{q})$	20.53$\pm$0.34	20.13	-0.09
196	$\sigma(\mu^+\mu^-)$	2.94$\pm$0.11	2.96	-0.12
196	$\sigma(\tau^+\tau^-)$	2.94$\pm$0.14	2.96	-0.05
196	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.581$\pm$0.031	0.562	0.019
196	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.505$\pm$0.044	0.562	0.019
200	$\sigma(q\overline{q})$	19.25$\pm$0.32	19.09	-0.09
200	$\sigma(\mu^+\mu^-)$	3.02$\pm$0.11	2.83	-0.12
200	$\sigma(\tau^+\tau^-)$	2.90$\pm$0.14	2.83	-0.04
200	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.524$\pm$0.031	0.558	0.019
200	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.539$\pm$0.042	0.558	0.019
202	$\sigma(q\overline{q})$	19.07$\pm$0.44	18.57	-0.09
202	$\sigma(\mu^+\mu^-)$	2.58$\pm$0.14	2.77	-0.12
202	$\sigma(\tau^+\tau^-)$	2.79$\pm$0.20	2.77	-0.04
202	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.547$\pm$0.047	0.556	0.020
202	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.589$\pm$0.059	0.556	0.019
205	$\sigma(q\overline{q})$	18.17$\pm$0.31	17.81	-0.09
205	$\sigma(\mu^+\mu^-)$	2.45$\pm$0.10	2.67	-0.11
205	$\sigma(\tau^+\tau^-)$	2.78$\pm$0.14	2.67	-0.042
205	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.565$\pm$0.035	0.553	0.020
205	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.571$\pm$0.042	0.553	0.019
207	$\sigma(q\overline{q})$	17.49$\pm$0.26	17.42	-0.08
207	$\sigma(\mu^+\mu^-)$	2.595$\pm$0.088	2.623	-0.111
207	$\sigma(\tau^+\tau^-)$	2.53$\pm$0.11	2.62	-0.04
207	$\mathrm{A_{FB}}(\mu^+\mu^-)$	0.542$\pm$0.027	0.552	0.020
207	$\mathrm{A_{FB}}(\tau^+\tau^-)$	0.564$\pm$0.037	0.551	0.019

	% of	δm_W (MeV)		
Background	$W \to \mu\nu$ data	m_T fit	p_T fit	$\not{p}_T$ fit
$Z/\gamma^* \to \mu\mu$	6.6 $\pm$ 0.3	6	11	5
$W \to \tau\nu$	0.89 $\pm$ 0.02	1	7	8
Decays in flight	0.3 $\pm$ 0.2	5	13	3
Hadronic jets	0.1 $\pm$ 0.1	2	3	4
Cosmic rays	0.05 $\pm$ 0.05	2	2	1
Total	7.9 $\pm$ 0.4	9	19	11

without lepton universality	
$\chi^2/N_{\mathrm{df}}\ =\ 32.6/27$	
m_{Z} [GeV]	91.1876$\pm$ 0.0021
Γ_{Z} [GeV]	2.4952 $\pm$ 0.0023
σ_{h}^0 [nb]	41.541 $\pm$ 0.037
R_{e}^0	20.804 $\pm$ 0.050
R_{μ}^0	20.785 $\pm$ 0.033
R_{τ}^0	20.764 $\pm$ 0.045
$A_{\mathrm{FB}}^{0,\,\mathrm{e}}$	0.0145 $\pm$ 0.0025
$A_{\mathrm{FB}}^{0,\,\mu}$	0.0169 $\pm$ 0.0013
$A_{\mathrm{FB}}^{0,\,\tau}$	0.0188 $\pm$ 0.0017

	Lepton non–universality			Lepton universality
Experiment	$\mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_{\mathrm{e}})$ [%]	$\mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_{\mu})$ [%]	$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_{\tau})$ [%]	$\mathcal{B}(\mathrm{W} \to \mathrm{hadrons})$ [%]
ALEPH	$10.81 \pm 0.29^*$	$10.91 \pm 0.26^*$	$11.15 \pm 0.38^*$	$67.15 \pm 0.40^*$
DELPHI	$10.55 \pm 0.34^*$	$10.65 \pm 0.27^*$	$11.46 \pm 0.43^*$	$67.45 \pm 0.48^*$
L3	$10.78 \pm 0.32^*$	$10.03 \pm 0.31^*$	$11.89 \pm 0.45^*$	$67.50 \pm 0.52^*$
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48	67.91 ± 0.61
LEP	10.66 ± 0.17	10.60 ± 0.15	11.41 ± 0.22	67.49 ± 0.28
χ^2/d.o.f.	6.8/9			15.0/11

	% of	δm_W (MeV)		
Background	$W \to e\nu$ data	m_T fit	p_T fit	$\not{p}_T$ fit
$W \to \tau\nu$	0.93 $\pm$ 0.03	2	2	2
Hadronic jets	0.25 $\pm$ 0.15	8	9	7
$Z/\gamma^* \to ee$	0.24 $\pm$ 0.01	1	1	0
Total	1.42 $\pm$ 0.15	8	9	7

without lepton universality	
Γ_{had} [MeV]	1745.8 $\pm$2.7
Γ_{ee} [MeV]	83.92$\pm$0.12
$\Gamma_{\mu\mu}$ [MeV]	83.99$\pm$0.18
$\Gamma_{\tau\tau}$ [MeV]	84.08$\pm$0.22

$\sqrt{s}$	WW cross-section (pb)					χ^2/d.o.f.
(GeV)	ALEPH	DELPHI	L3	OPAL	LEP	
161.3	$4.23 \pm 0.75^*$	$3.67\ {}^{+\,0.99}_{-\,0.87}\ ^*$	$2.89\ {}^{+\,0.82}_{-\,0.71}\ ^*$	$3.62\ {}^{+\,0.94}_{-\,0.84}\ ^*$	$3.69 \pm 0.45\ ^*$	} 1.3 / 3
172.1	$11.7\ \ \pm 1.3\ ^*$	$11.6\ \ \pm 1.4\ ^*$	$12.3\ \ \pm 1.4\ ^*$	$12.3\ \ \pm 1.3\ ^*$	$12.0\ \ \pm 0.7\ ^*$	} 0.22/ 3
182.7	$15.90 \pm 0.63^*$	$16.07 \pm 0.70^*$	$16.53 \pm 0.72^*$	$15.43 \pm 0.66^*$	$15.89 \pm 0.35\ ^*$	26.4/24
188.6	$15.76 \pm 0.36^*$	$16.09 \pm 0.42^*$	$16.17 \pm 0.41^*$	$16.30 \pm 0.39^*$	$16.03 \pm 0.21\ ^*$	
191.6	$17.10 \pm 0.90\ ^*$	$16.64 \pm 1.00^*$	$16.11 \pm 0.92\ ^*$	16.60 ± 0.99	16.56 ± 0.48	
195.5	$16.61 \pm 0.54\ ^*$	$17.04 \pm 0.60^*$	$16.22 \pm 0.57\ ^*$	18.59 ± 0.75	16.90 ± 0.31	
199.5	$16.90 \pm 0.52\ ^*$	$17.39 \pm 0.57^*$	$16.49 \pm 0.58\ ^*$	16.32 ± 0.67	16.75 ± 0.30	
201.6	$16.65 \pm 0.71\ ^*$	$17.37 \pm 0.82^*$	$16.01 \pm 0.84\ ^*$	18.48 ± 0.92	17.00 ± 0.41	
204.9	$16.79 \pm 0.54\ ^*$	$17.56 \pm 0.59^*$	$17.00 \pm 0.60\ ^*$	15.97 ± 0.64	16.78 ± 0.31	
206.6	$17.36 \pm 0.43\ ^*$	$16.35 \pm 0.47^*$	$17.33 \pm 0.47\ ^*$	17.77 ± 0.57	17.13 ± 0.25	

How well the SM particles were tested?

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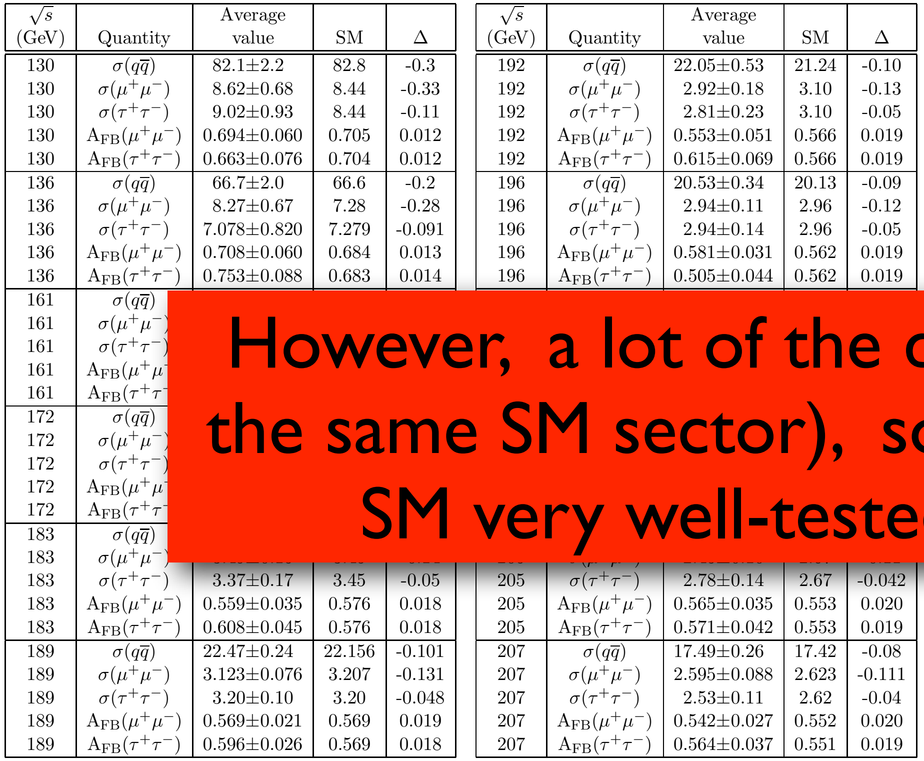

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161	$A_{FB}(\tau^+\tau$			
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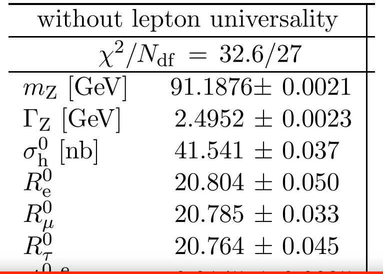

without lepton universality	
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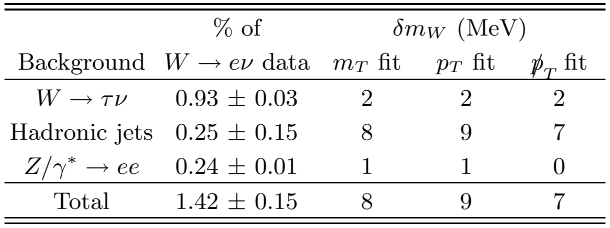

Background	% of $W \to e\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
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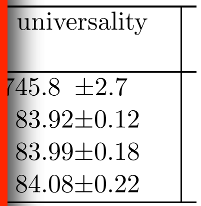
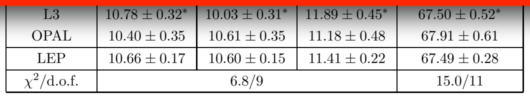
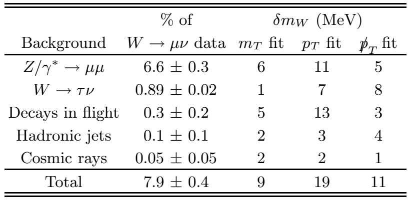


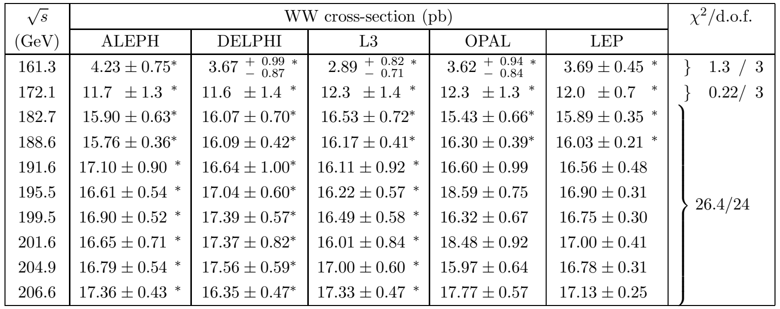
universality
745.8 ±2.7
83.92±0.12
83.99±0.18
84.08±0.22



L3	10.78 ± 0.32*	10.03 ± 0.31*	11.89 ± 0.45*	67.50 ± 0.52*
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48	67.91 ± 0.61
LEP	10.66 ± 0.17	10.60 ± 0.15	11.41 ± 0.22	67.49 ± 0.28
χ^2/d.o.f.	6.8/9			15.0/11

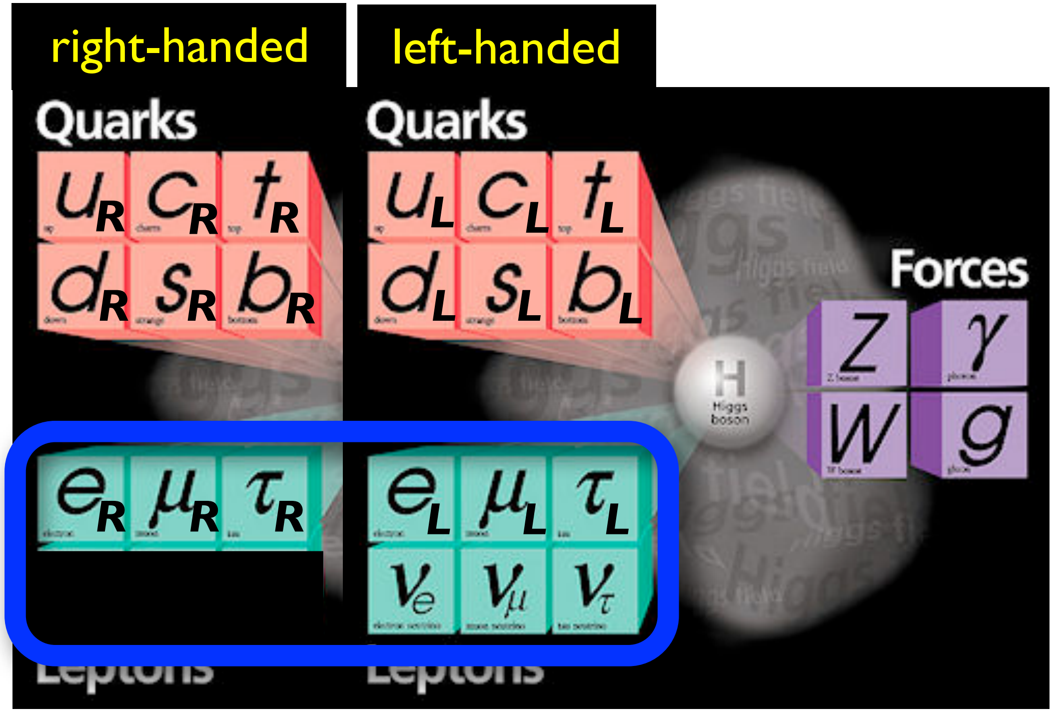


Background	% of $W \to \mu\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
$Z/\gamma^* \to \mu\mu$	6.6 ± 0.3	6	11	5
$W \to \tau\nu$	0.89 ± 0.02	1	7	8
Decays in flight	0.3 ± 0.2	5	13	3
Hadronic jets	0.1 ± 0.1	2	3	4
Cosmic rays	0.05 ± 0.05	2	2	1
Total	7.9 ± 0.4	9	19	11



$\sqrt{s}$ (GeV)	WW cross-section (pb) ALEPH	DELPHI	L3	OPAL	LEP	χ^2/d.o.f.
161.3	4.23 ± 0.75*	$3.67^{+0.99}_{-0.87}$ *	$2.89^{+0.82}_{-0.71}$ *	$3.62^{+0.94}_{-0.84}$ *	3.69 ± 0.45 *	} 1.3 / 3
172.1	11.7 ± 1.3 *	11.6 ± 1.4 *	12.3 ± 1.4 *	12.3 ± 1.3 *	12.0 ± 0.7 *	} 0.22/ 3
182.7	15.90 ± 0.63*	16.07 ± 0.70*	16.53 ± 0.72*	15.43 ± 0.66*	15.89 ± 0.35 *	26.4/24
188.6	15.76 ± 0.36*	16.09 ± 0.42*	16.17 ± 0.41*	16.30 ± 0.39*	16.03 ± 0.21 *	
191.6	17.10 ± 0.90 *	16.64 ± 1.00*	16.11 ± 0.92 *	16.60 ± 0.99	16.56 ± 0.48	
195.5	16.61 ± 0.54 *	17.04 ± 0.60*	16.22 ± 0.57 *	18.59 ± 0.75	16.90 ± 0.31	
199.5	16.90 ± 0.52 *	17.39 ± 0.57*	16.49 ± 0.58 *	16.32 ± 0.67	16.75 ± 0.30	
201.6	16.65 ± 0.71 *	17.37 ± 0.82*	16.01 ± 0.84 *	18.48 ± 0.92	17.00 ± 0.41	
204.9	16.79 ± 0.54 *	17.56 ± 0.59*	17.00 ± 0.60 *	15.97 ± 0.64	16.78 ± 0.31	
206.6	17.36 ± 0.43 *	16.35 ± 0.47*	17.33 ± 0.47 *	17.77 ± 0.57	17.13 ± 0.25	

However, a lot of the data is redundant (measure the same SM sector), so we had some parts of the SM very well-tested and others not at all


right-handed
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Quarks
u_R c_R t_R
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Forces
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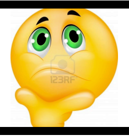
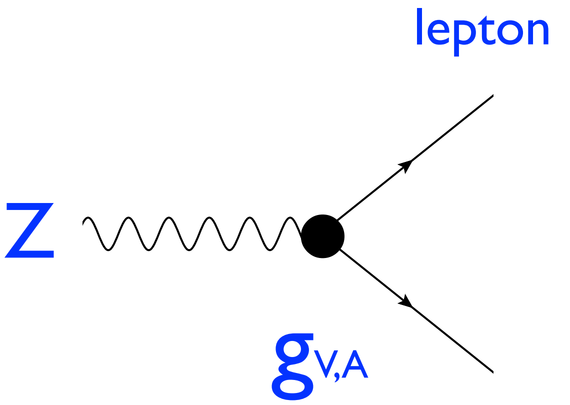
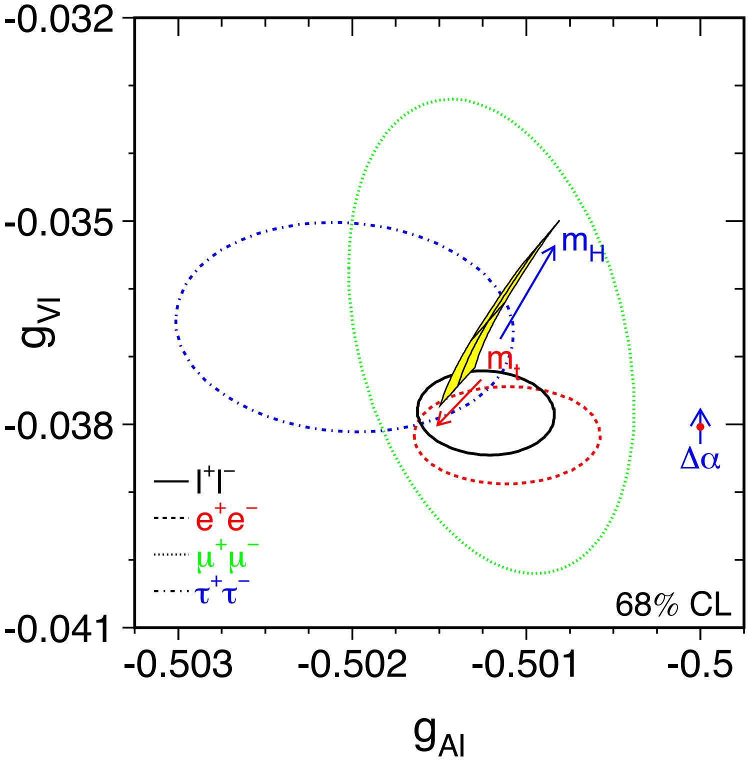
1) Thanks to LEP1:

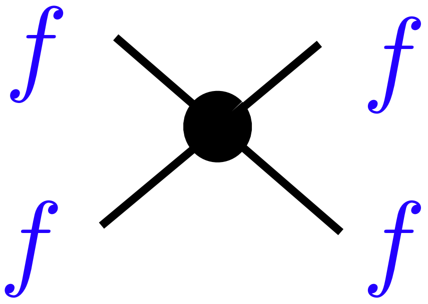
MSSM	Compositeness
	

- universal properties
- vertices measured at per-mille level



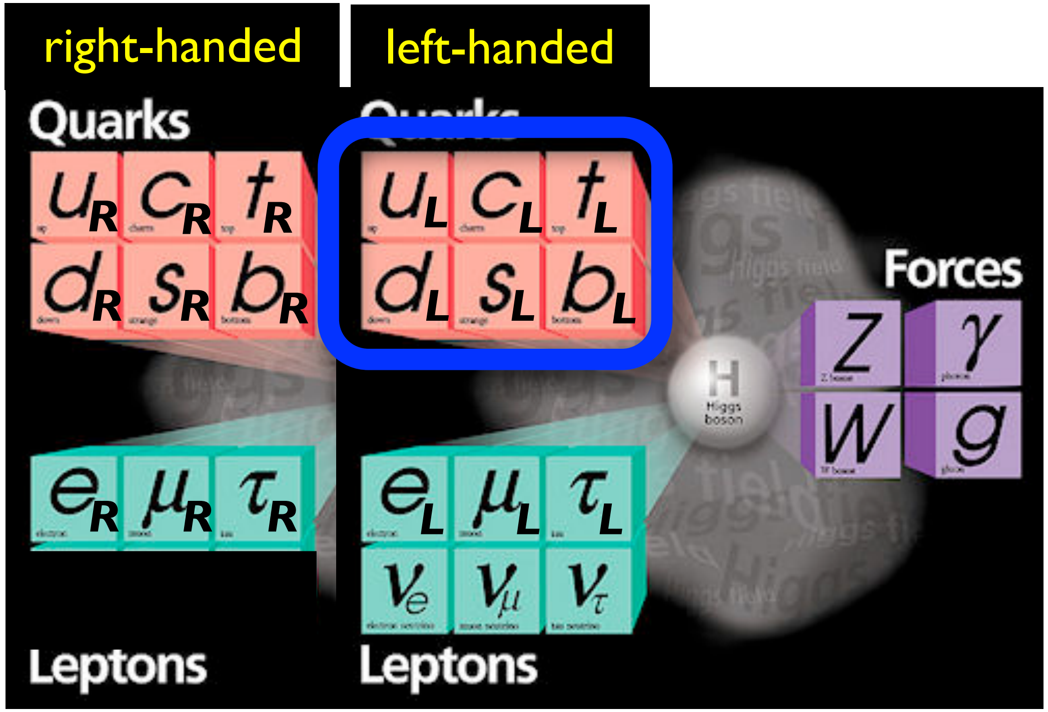


2) Thanks to LEP2:



4-lepton operators constrained

➥new physics scale in this sector pushed above ~3 TeV


right-handed
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Quarks
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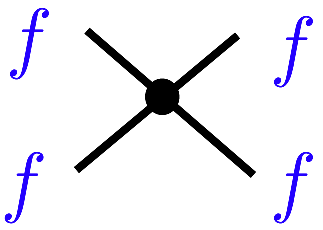
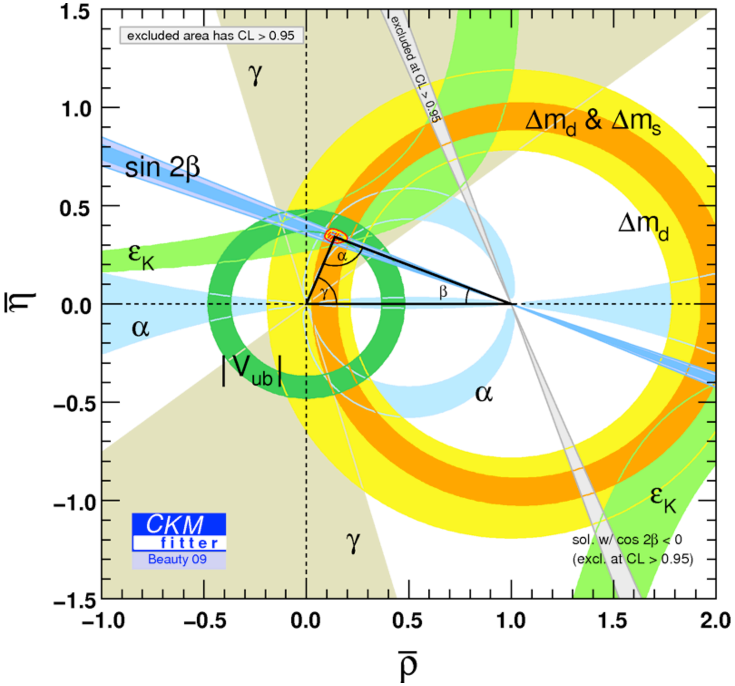
First main lesson from experiments

1) Flavor universality:

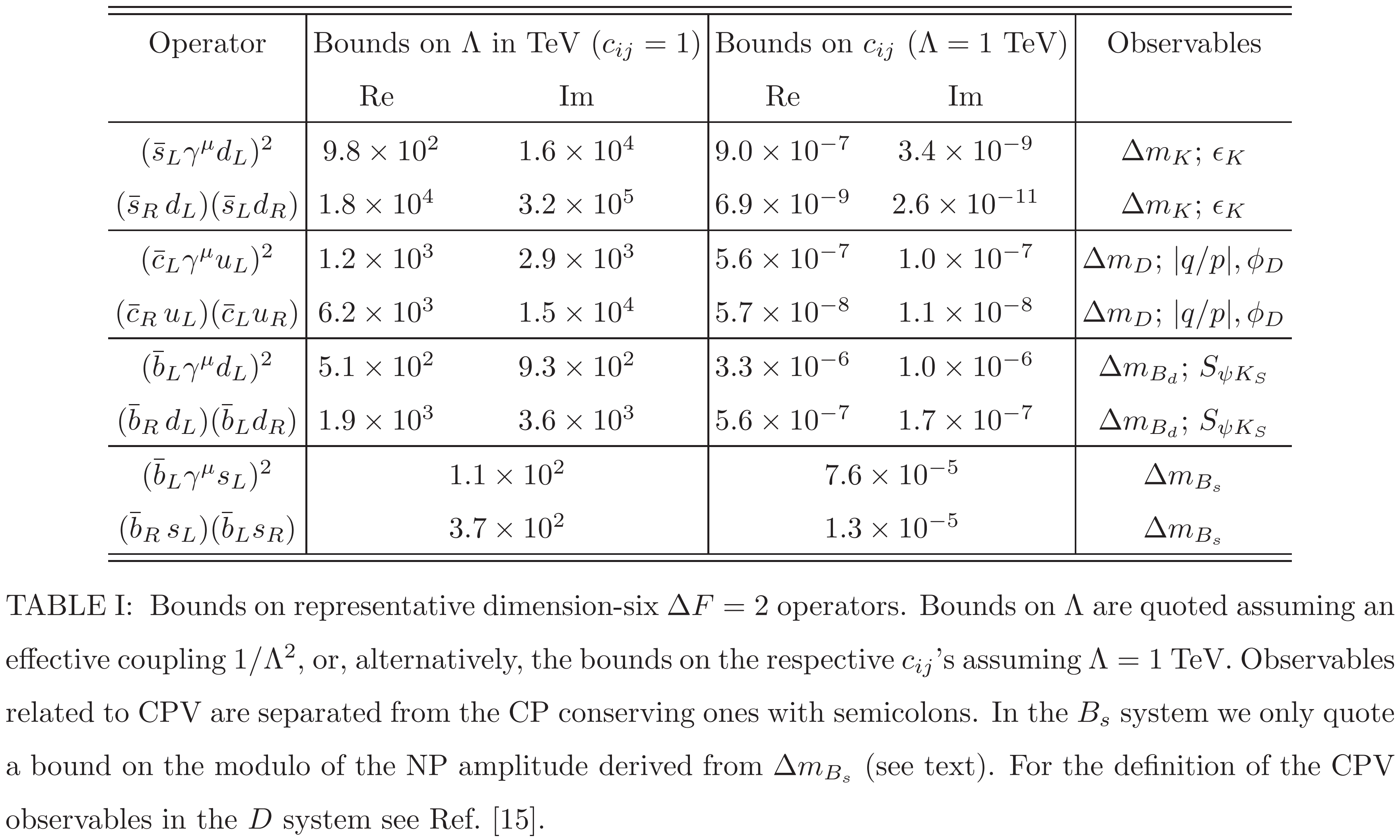




$$\frac{(\bar{q}^i_L \gamma_\mu q^j_L)^2}{f^2}$$

➡ Dimension-6 operators must be *close* to flavor diagonal (i=j) if $\Lambda \sim$ TeV

only exception, could be the **top**, whose properties not yet well-measured from arXiv: 1002.0900



Operator	Bounds on Λ in TeV ($c_{ij} = 1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

TABLE I: Bounds on representative dimension-six $\Delta F = 2$ operators. Bounds on Λ are quoted assuming an effective coupling $1/\Lambda^2$, or, alternatively, the bounds on the respective c_{ij}'s assuming $\Lambda = 1$ TeV. Observables related to CPV are separated from the CP conserving ones with semicolons. In the B_s system we only quote a bound on the modulo of the NP amplitude derived from Δm_{B_s} (see text). For the definition of the CPV observables in the D system see Ref. [15].

We must assume that the **new physics sector** has family-symmetries:

$$\mathbf{SU(3)_{Q_L} \otimes SU(3)_{b_R} \otimes SU(2)_{u_R} \otimes SU(3)_{l_L} \otimes SU(3)_{l_R}}$$

Only broken by Yukawas:

$$\mathbf{Y_d} \in (\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1}, \mathbf{1}, \mathbf{1})$$

$$\mathbf{Y_u} \in (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{2} + \mathbf{1}, \mathbf{1}, \mathbf{1})$$

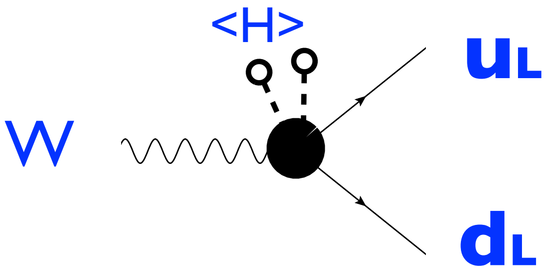
$$\mathbf{Y_l} \in (\mathbf{1}, \mathbf{1}, \mathbf{1}, \bar{\mathbf{3}}, \mathbf{3})$$

2) LEP gave already good bounds, but recent KLOE results put a very stringent bound on quark-lepton universality of the W interactions

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 0.9999(6)$$

$$\Rightarrow \quad \frac{G_F|_{quarks}}{G_F|_{leptons}} - 1 < 10^{-3}$$

➥ deviations in $\mathbf{q_L}$ as small as in the leptons



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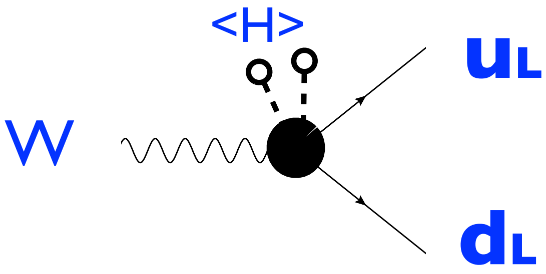
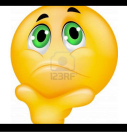
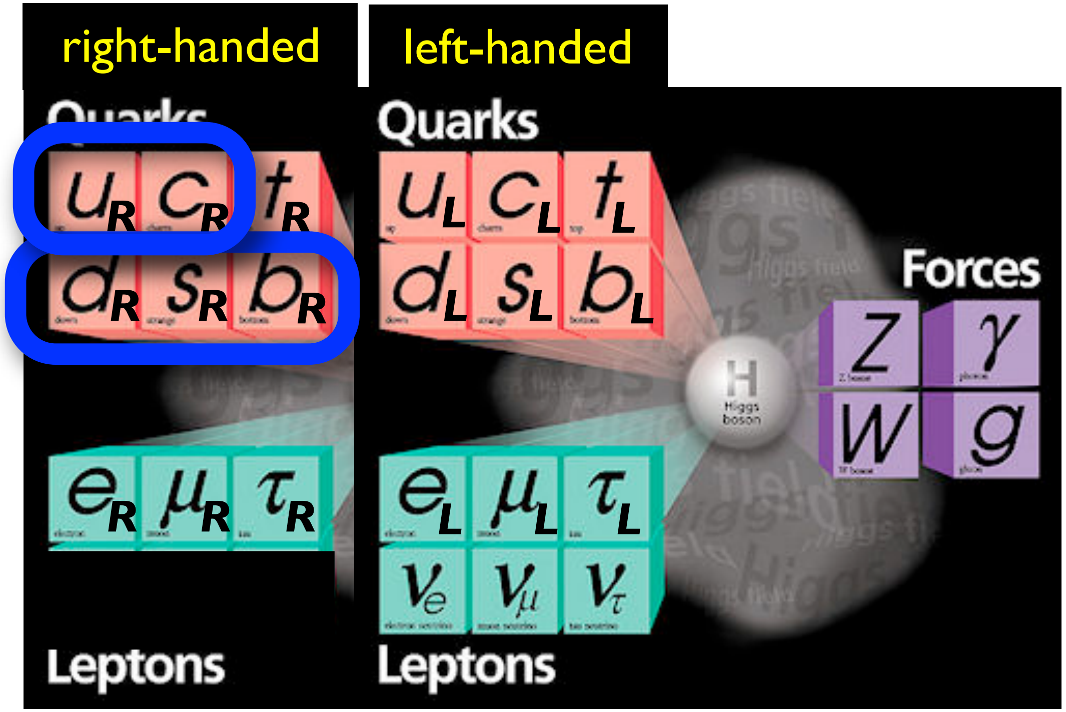


MSSM	Compositeness
	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Forces
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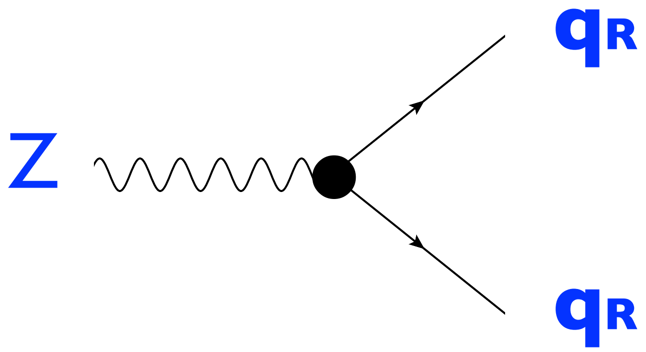
Not well-measurement of their couplings at LEP, due to their small values

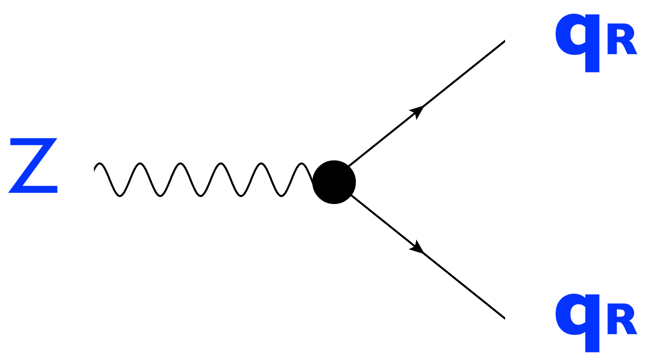


$$g^{Z}_{q_R} = Q_{u,d}\sin^2\theta_W \sim 0.16, 0.08$$

Best measurement for **bR** that gives a ~2-3 sigma discrepancy with the SM value:

Needed: $$\frac{\delta g_R}{g_R} \sim 0.2$$

Not well-measurement of their couplings at LEP, due to their small values



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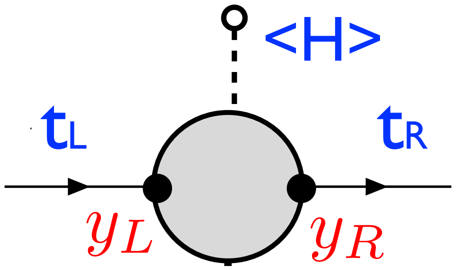
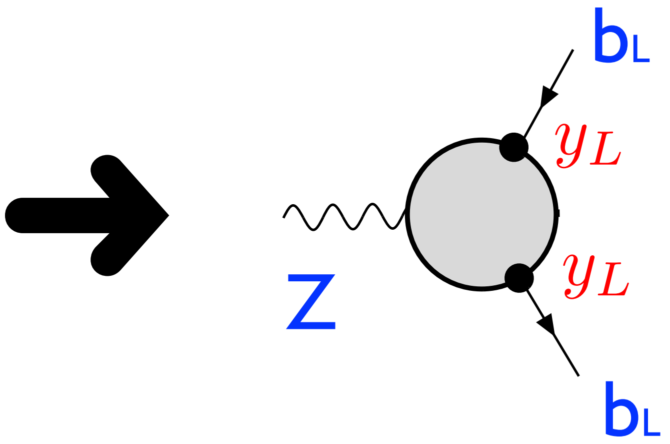
MSSM	**Compositeness**
🤔	😏

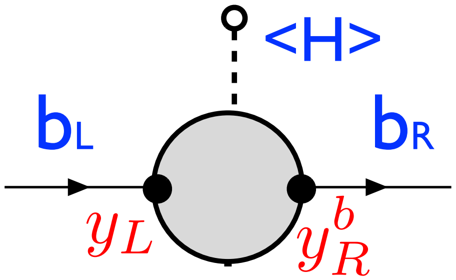
Composite Higgs scenarios:



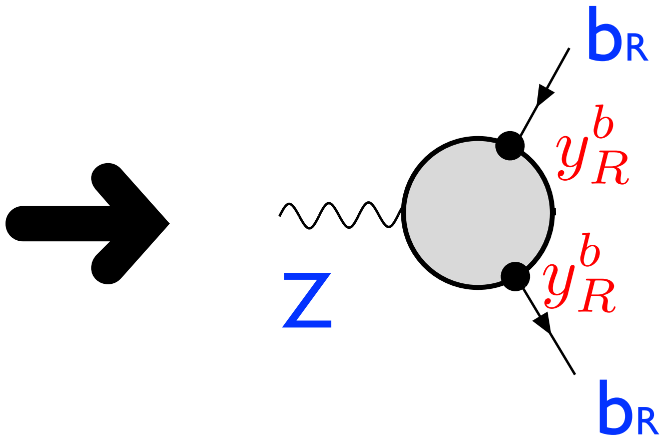
$$m_t \sim y_L y_R v$$



~ potentially large



$$m_b \sim y_L y_R^b v$$

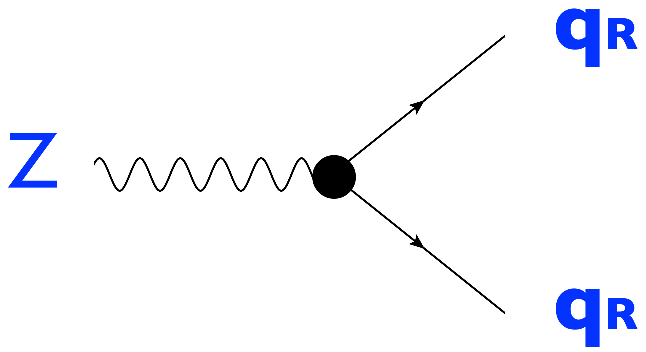


~ potentially small

but possibility to have sizably couplings

MSSM	Compositeness
	

Not well-measurement of their couplings at LEP, due to their small values



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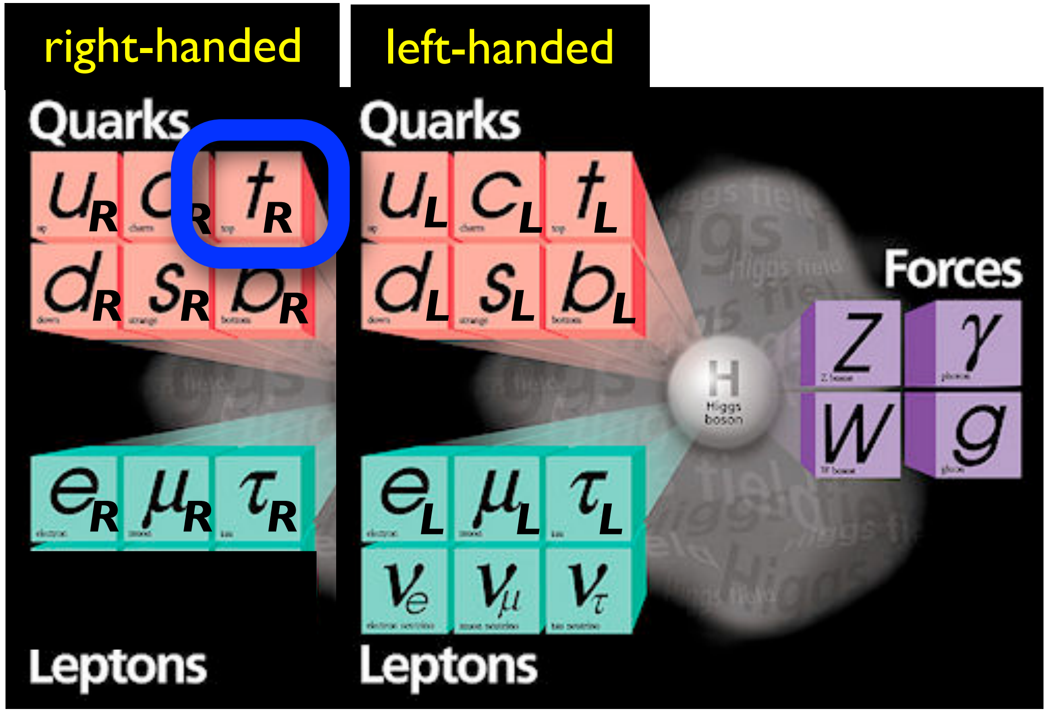
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Higgs boson
Forces
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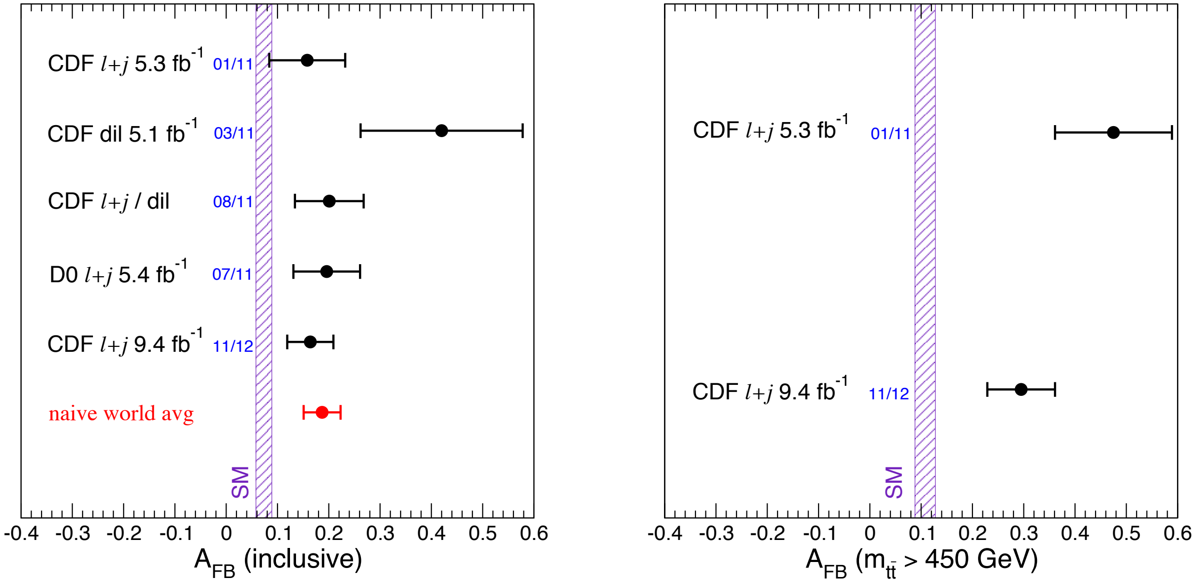
From Tevatron:

- Measurement of cross-section with large errors
- Certain excitement created by the **forward-backward top asymmetry**:

$$A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$



~ 2.7 σ discrepancy

Still large deviations with respect to the SM possible

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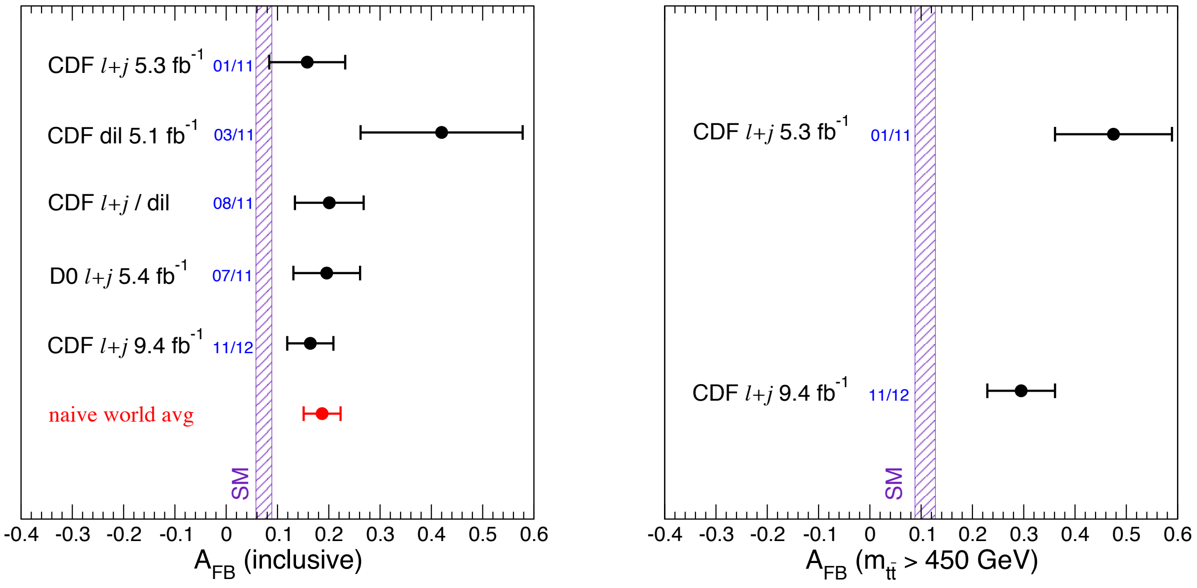

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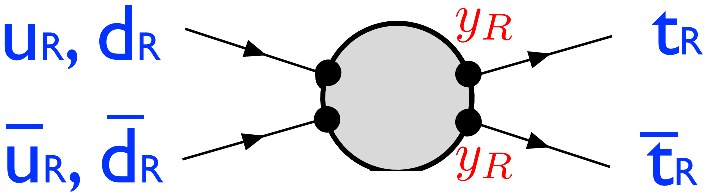
MSSM	**Compositeness**
	

Forward-Backward Top Asymmetry

Expected from BSM?

- Not from **MSSM**
- From **Composite scenarios** if right-handed light quarks are also coupled sizably to the strong sector:



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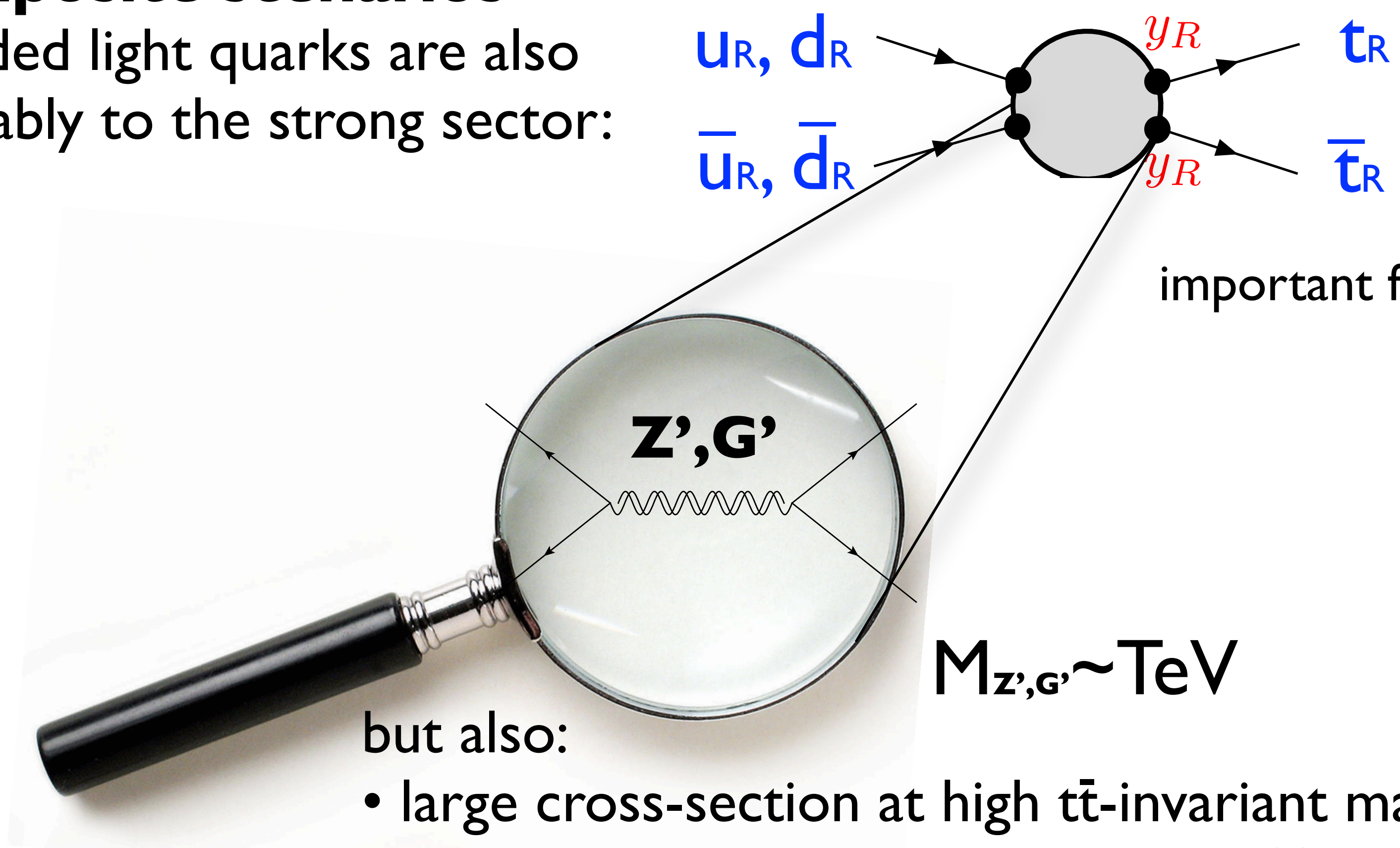
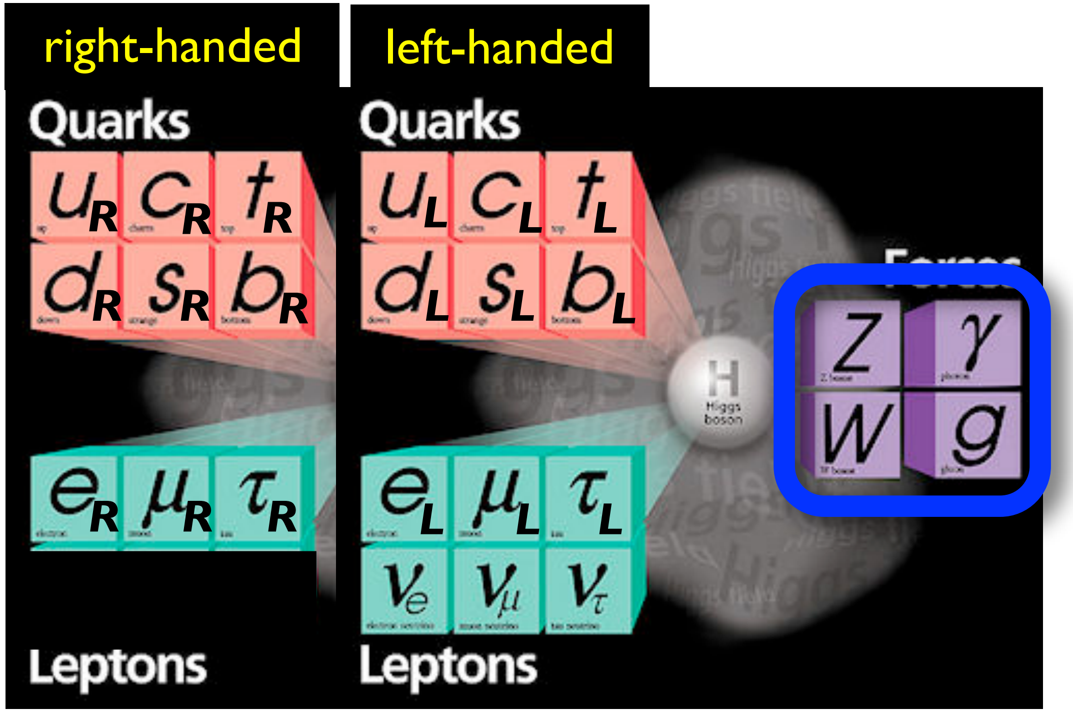


important for $y_R>1$

$M_{Z',G'}\sim$TeV

but also:

- large cross-section at high $t\bar{t}$-invariant mass not seen at Tevatron, but at the LHC?
- large dijet cross-section at high jj-invariant mass
- Very large $t_R\, t_R \rightarrow t_R\, t_R$ scattering-amplitude at high E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