SUPERSYMMETRY in the LHC era

Joan Solà

sola@ecm.ub.es

HEP Group
Departament d'Estructura i Constituents de la Matèria (ECM)
Institut de Ciències del Cosmos, Univ. Barcelona

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Guidelines of the Talk

From the micro to the macro Cosmos

Matter, antimatter and Super-matter

Symmetries and Super-symmetry (SUSY)

The vacuum and the DARK WORLD…

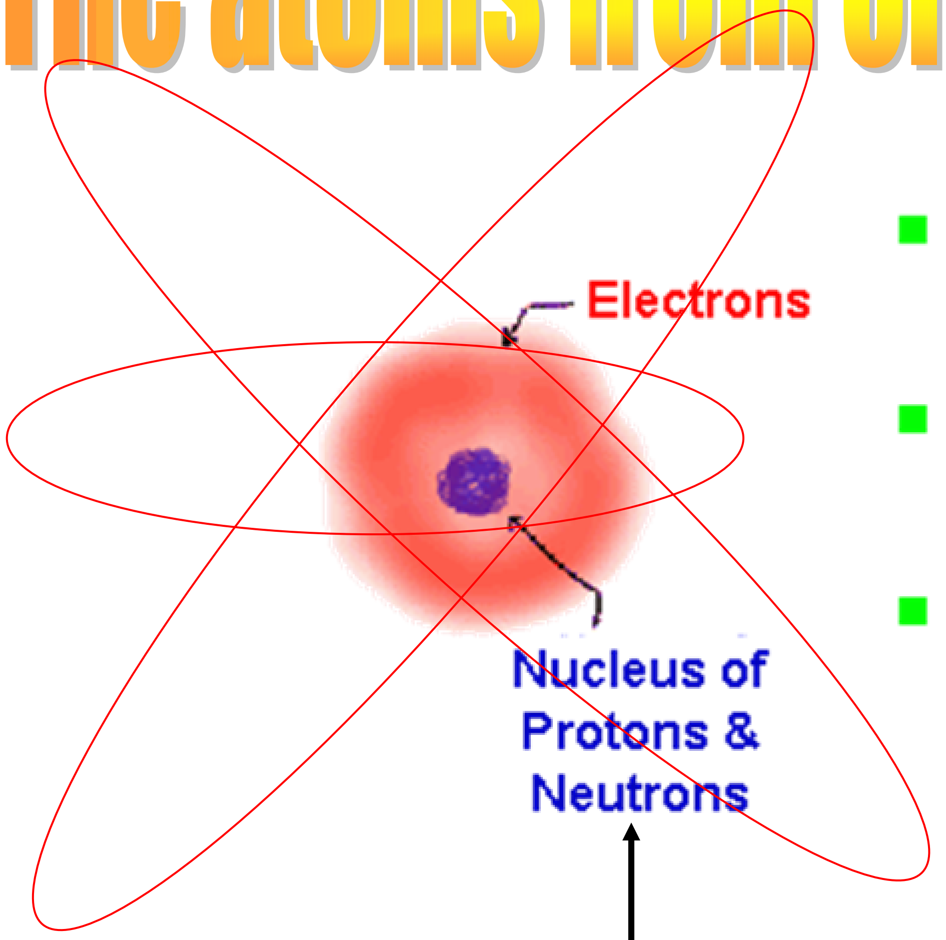
The whys and wherefores of SUSY

SUSY in the sky

SUSY on the ground

micro...

The atoms from ordinary matter



Quarks

- Protons (p+)
  - positive charge
- Electrons (e-)
  - negative charge
- Neutrons (n)
  - neutral

e^+

positrons

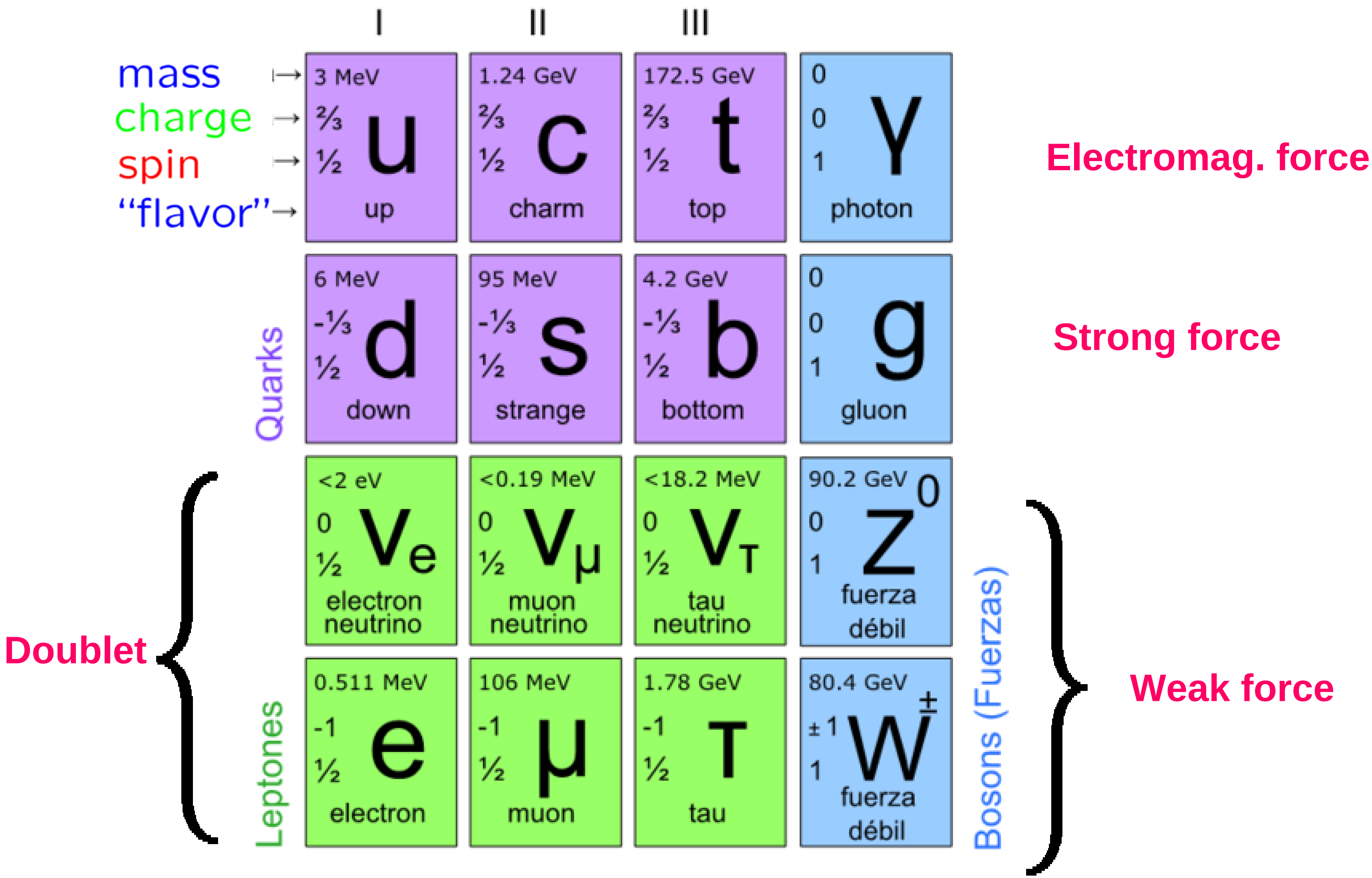
ν

neutrinos

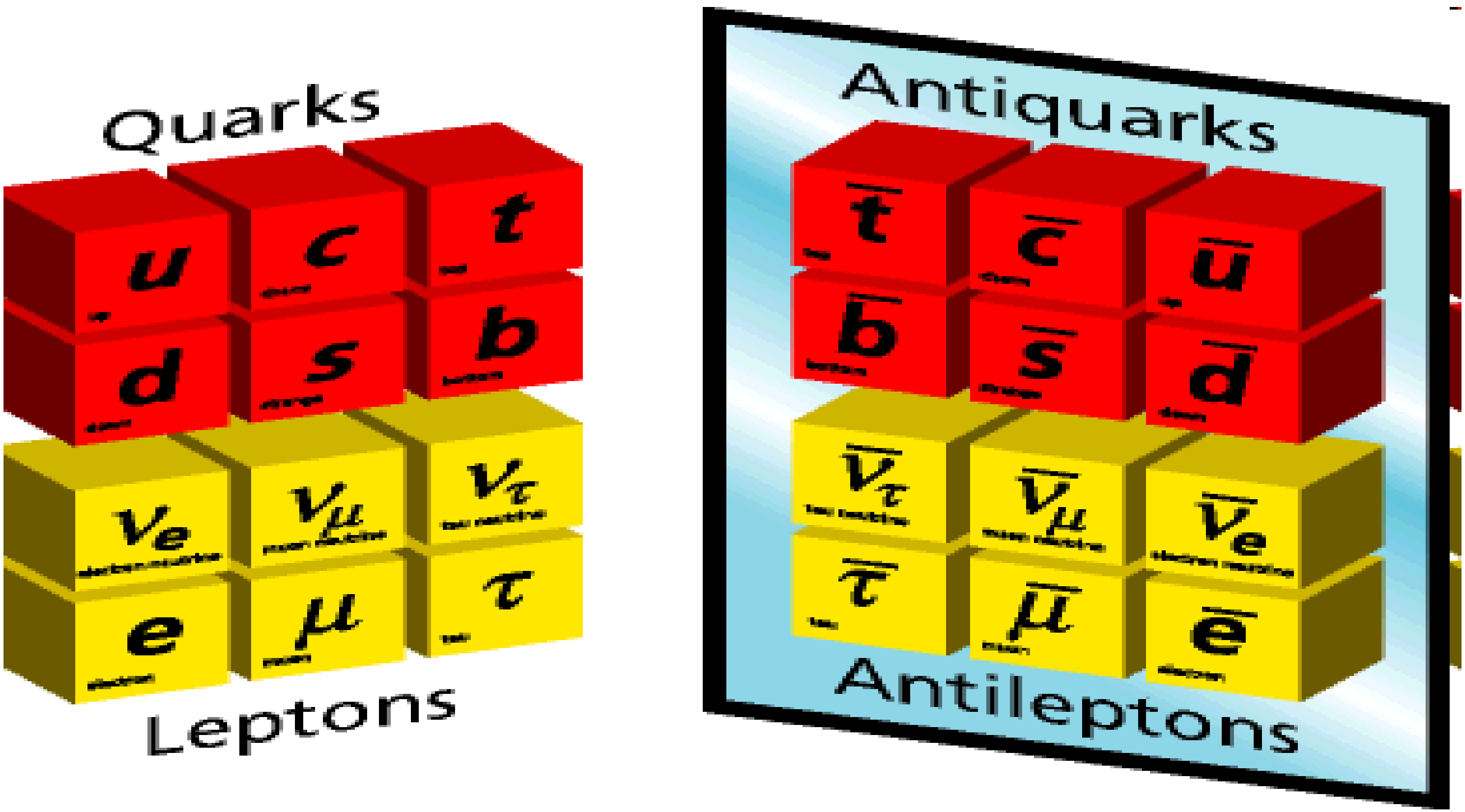
u	d	c	s	t	b

Matter content in the SM

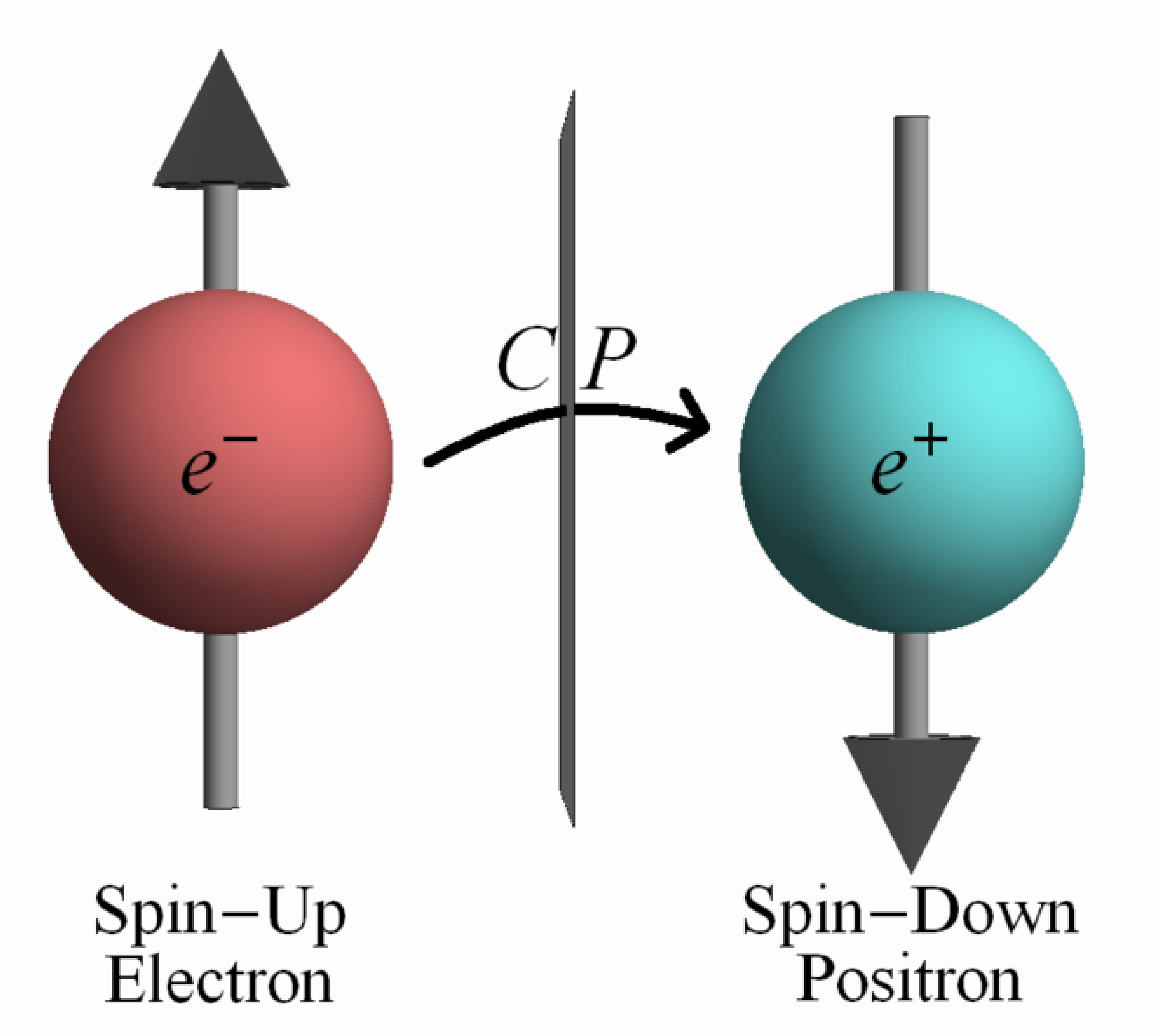
(Glashow-Weinberg-Salam, 1967)



Matter and Antimatter in the Standard Model



➢From matter to anti-matter of different helicity



CP ⟷ t → -t

CP violation

CPT Theorem

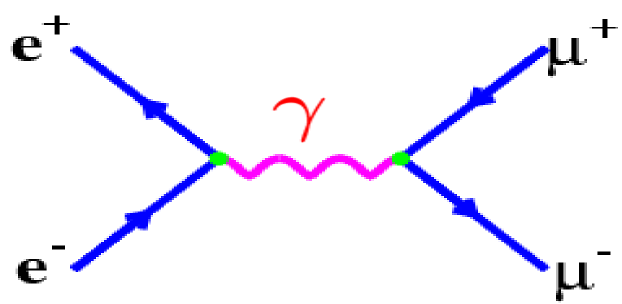
T violation → **Arrow of time In the microcosmos!!**

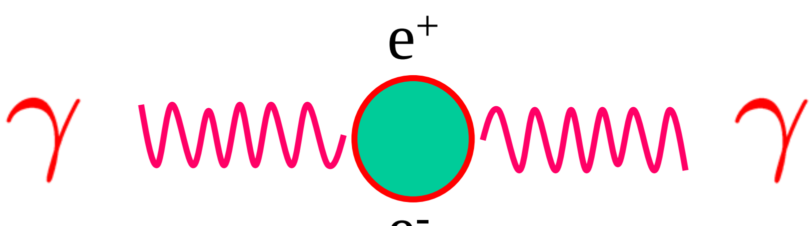
CP Violation

Baryogenesis ⇕ Sakharov, 1967

Origin of matter

Matter and antimatter annihilate !!!





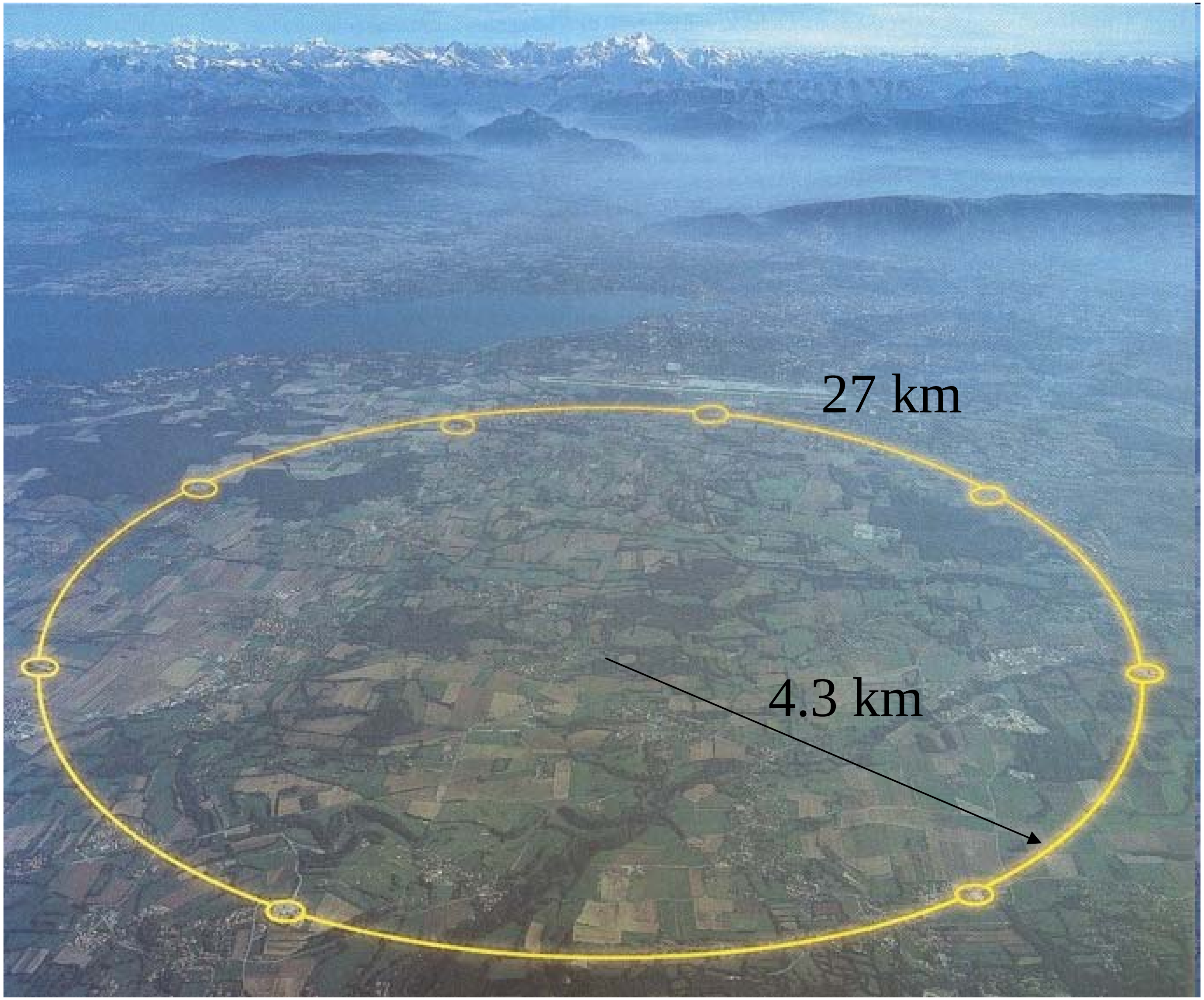
LEP !!

The real “Lord of the Rings”: the LHC Ring at CERN

14 TeV

14×10^{12} eV !!

$\sim 14,000\, m_p$



>3x10^9 €

(Shall we find New Physics?…Higgs? SUSY?, origin of the Univers?...)

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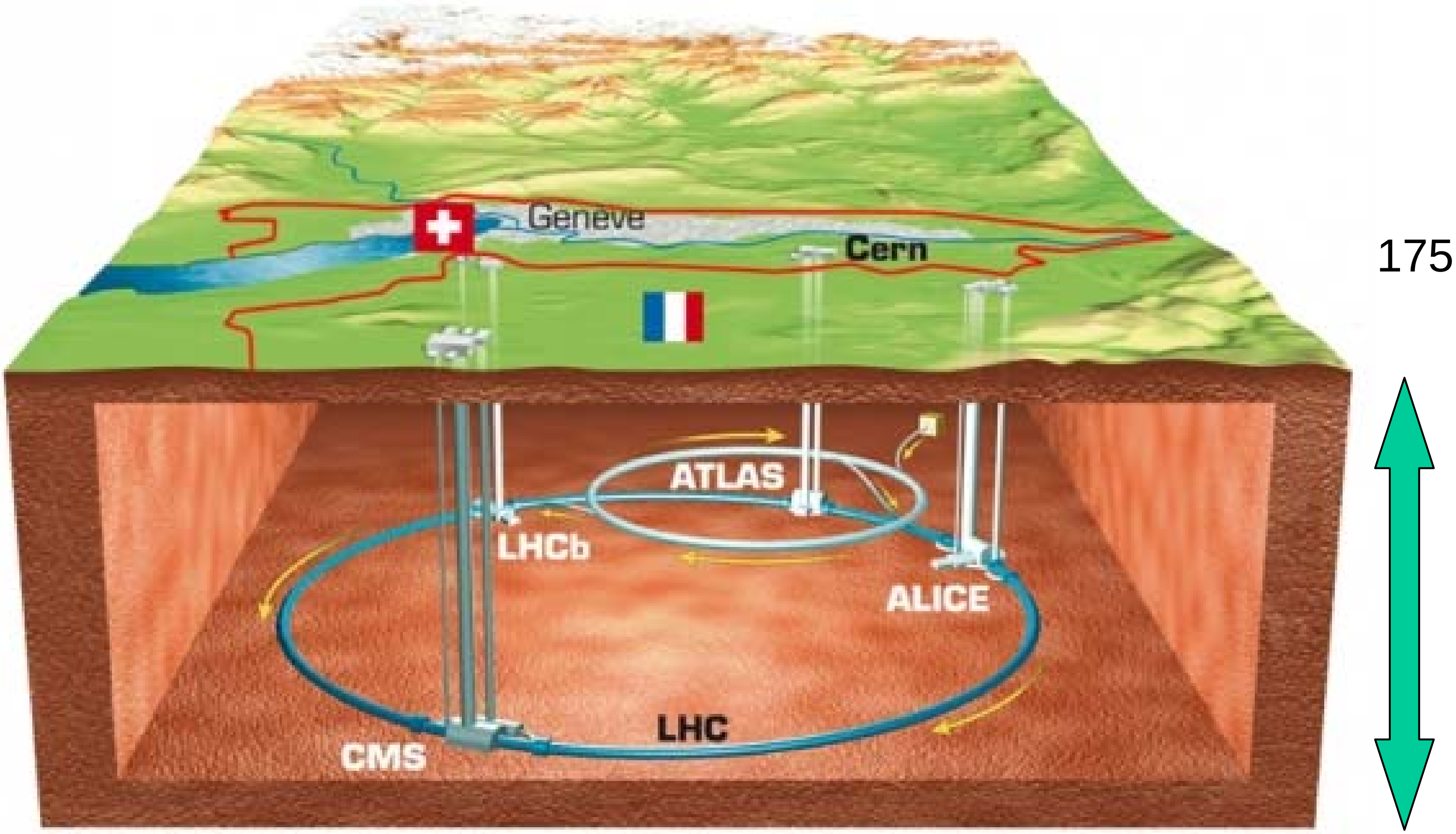
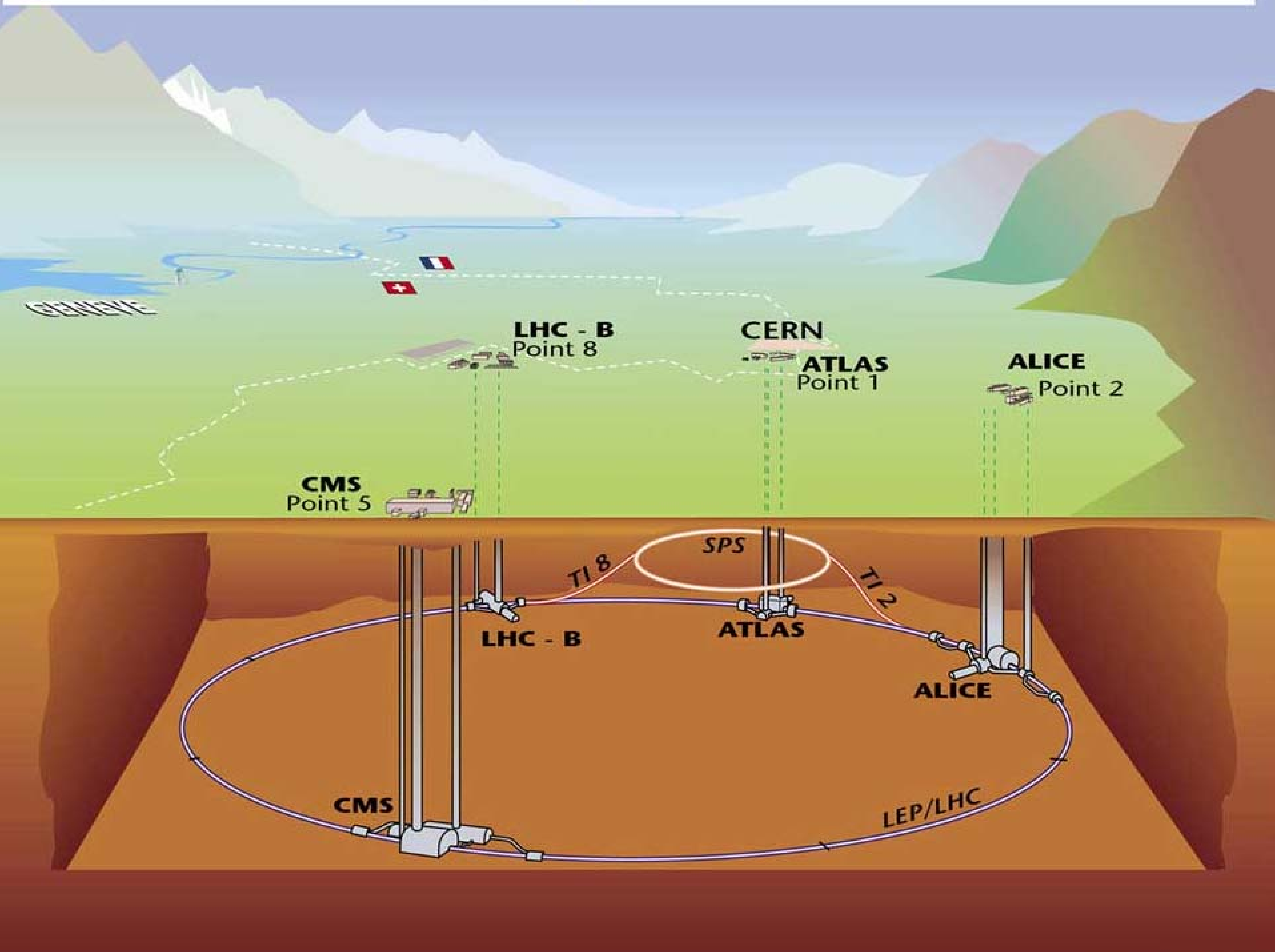


175 m depth

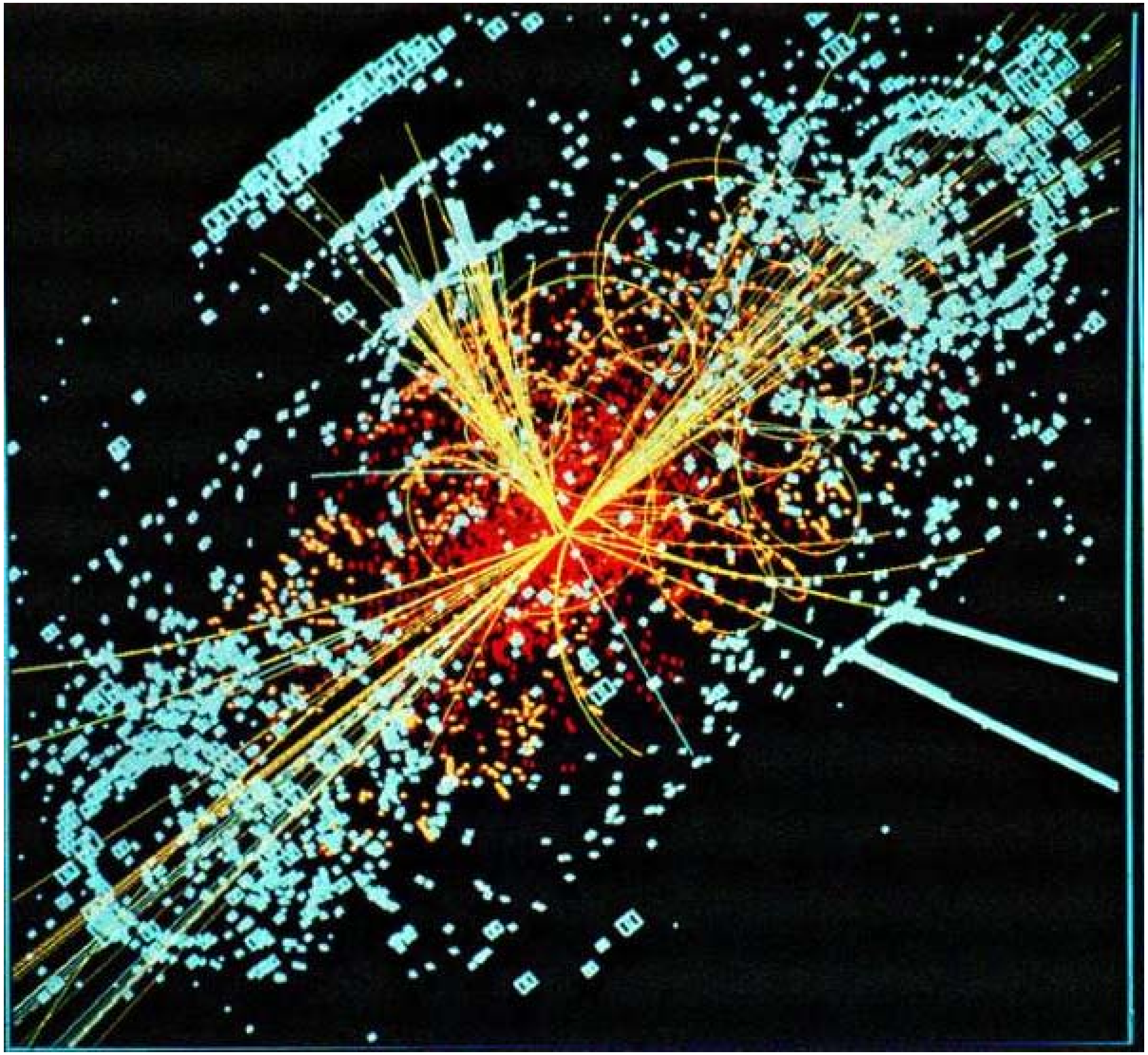

GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

Tunnel of the LHC

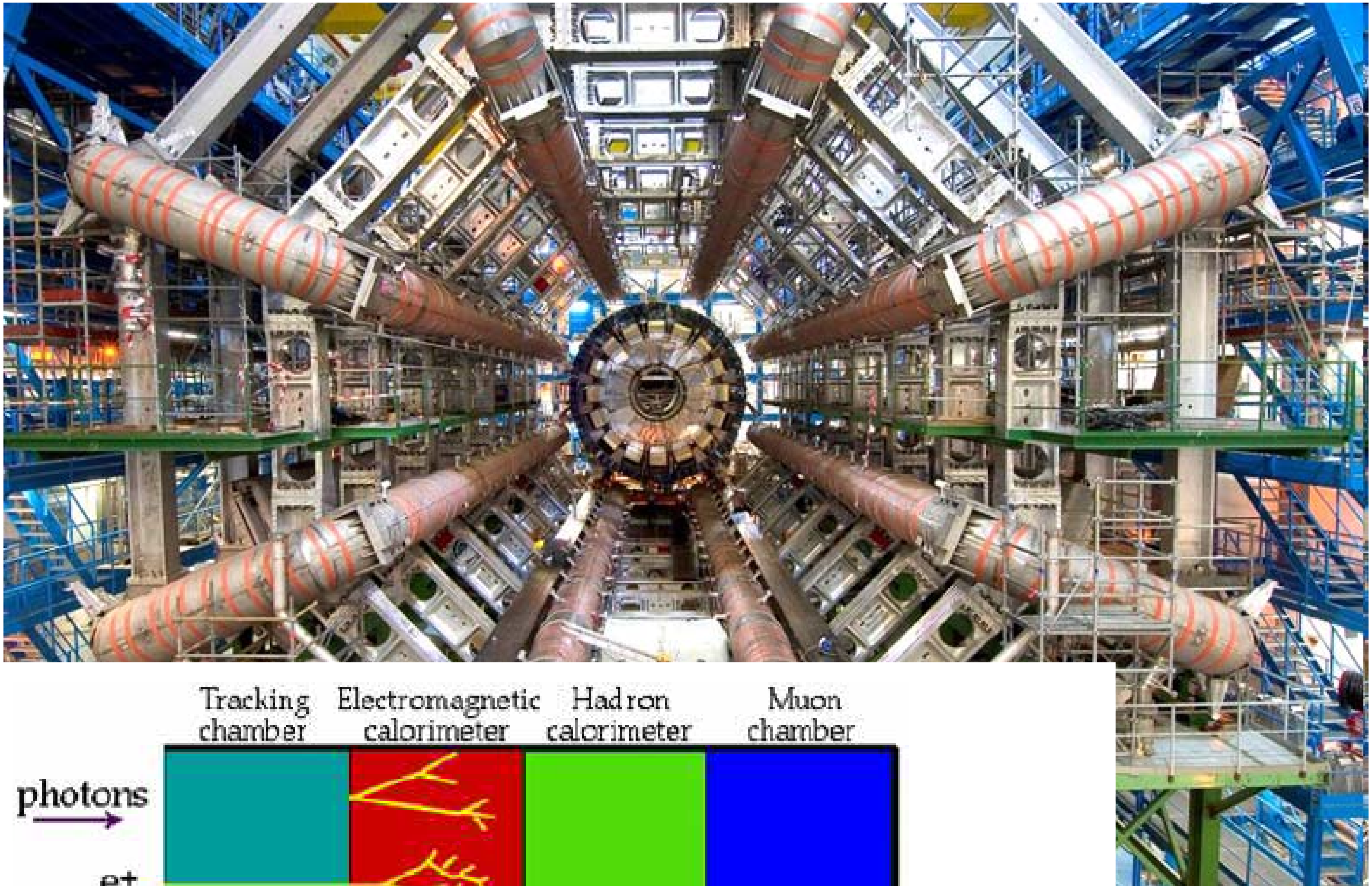
$$p + p \rightarrow X$$

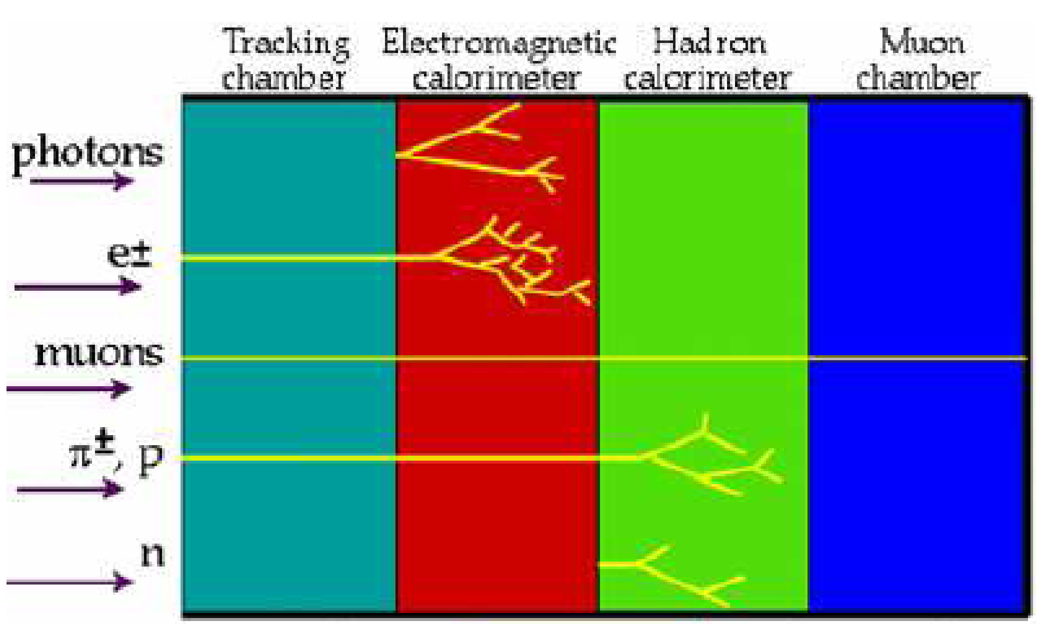
protons against protons at $E \simeq 14.000\, m_p$

A typical collision event at the LHC



11.000 turns/s, 600 million collisions/s…





Calorimeters…

LHC →Hadron collider

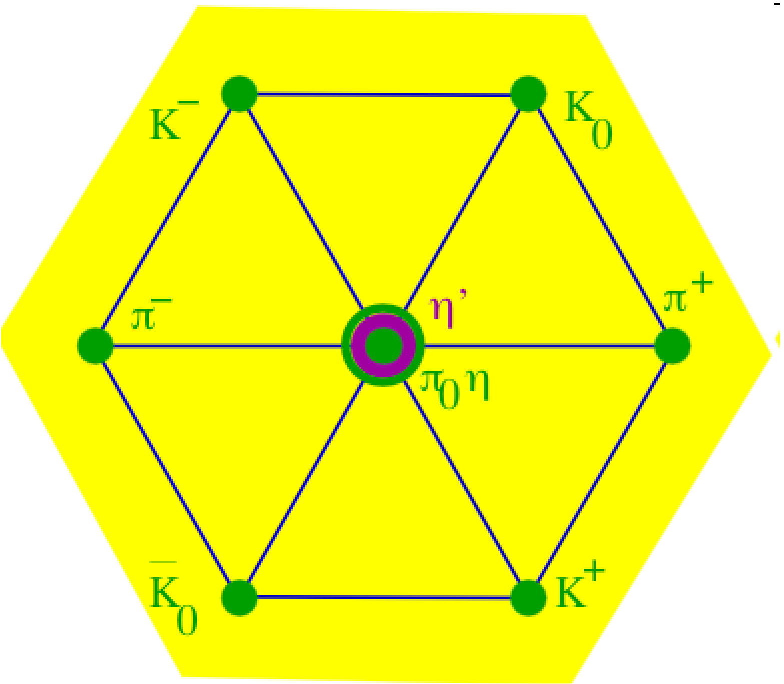
Hadrons from quarks

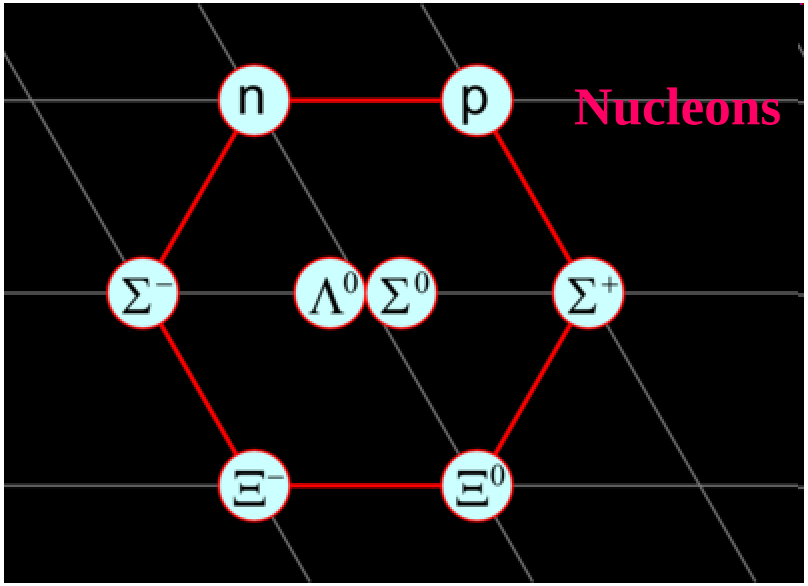
q+anti-q

q+q+q

$$\mathbf{3} \otimes \mathbf{3}^* = \mathbf{8} \oplus \mathbf{1}$$

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10}_S \oplus \mathbf{8}_M \oplus \mathbf{8}_M \oplus \mathbf{1}_A$$



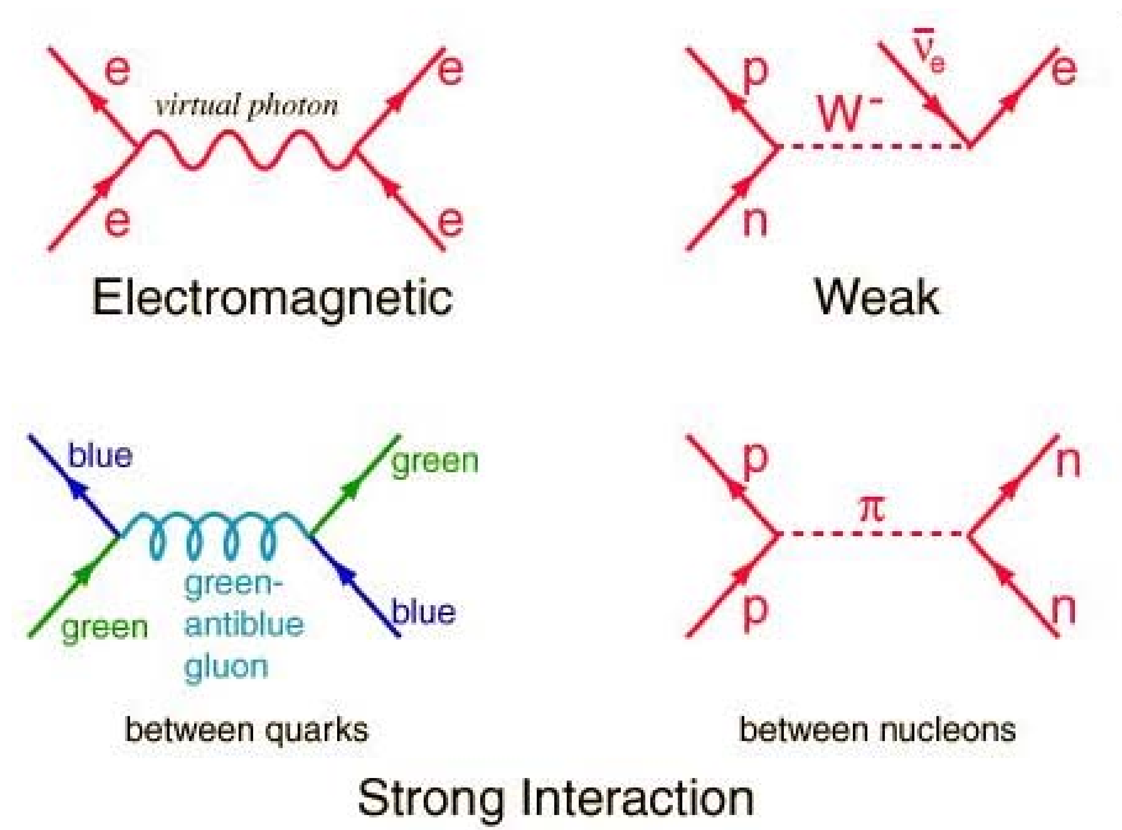


mesons

(HADRONS)

baryons

Interactions e.m., weak and strong



(Yukawa, 1930)

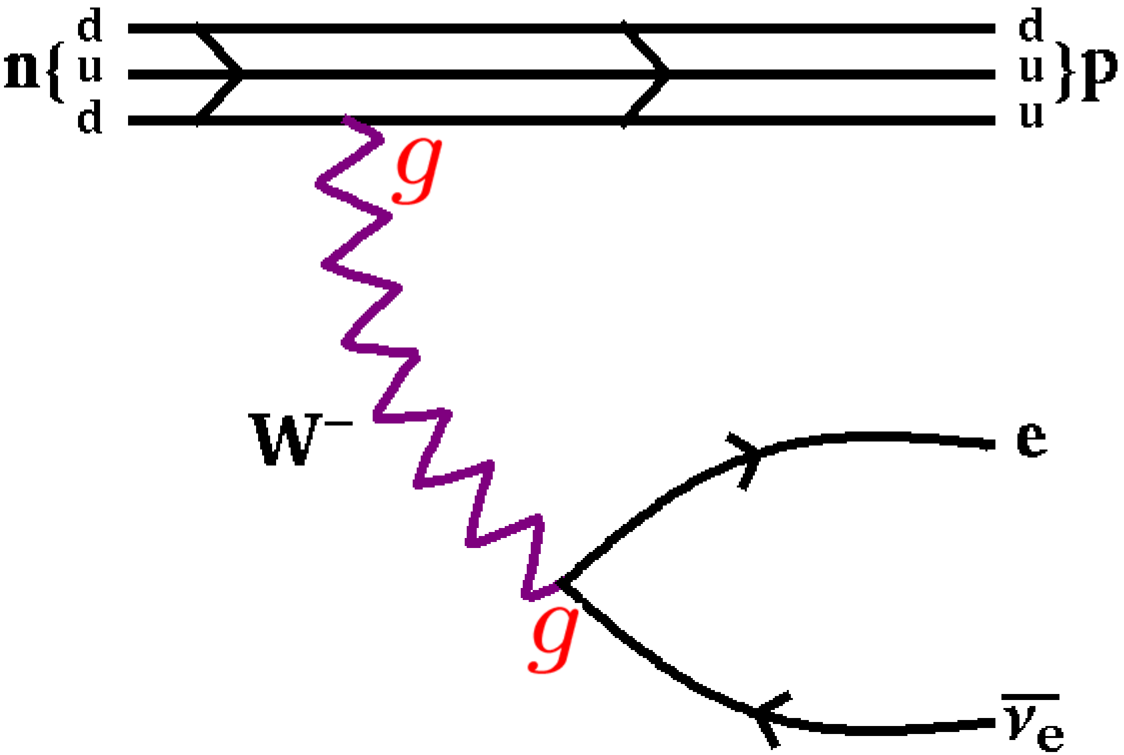
$$V = -g^2 \frac{e^{-m_\pi r}}{r}$$

Range:

$$r = \frac{1}{m_\pi}$$

Radioactivity: weak interactions

(Fermi 1934)



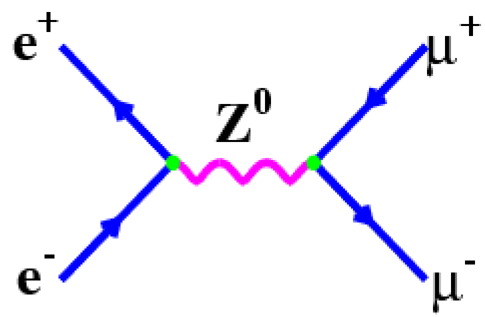
$$G_F \sim \frac{g^2}{M_W^2}$$

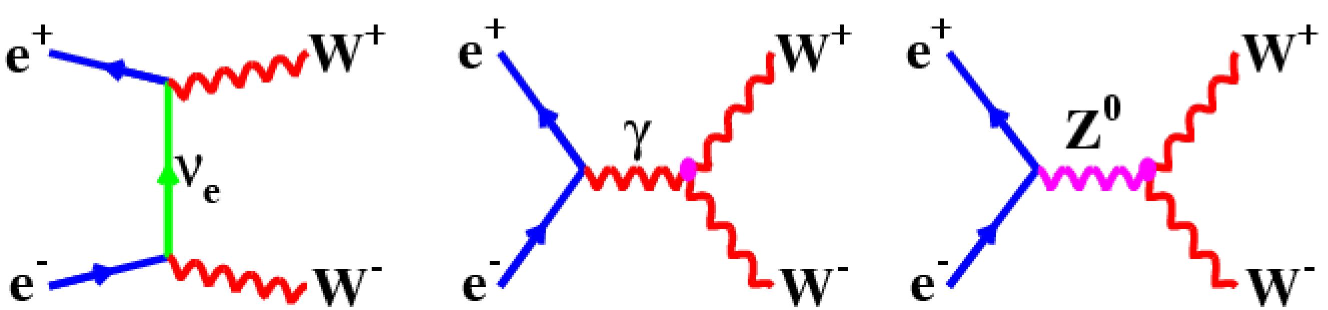
Neutron decay

…of free neutrons!

885 sec$\sim$ 15 min

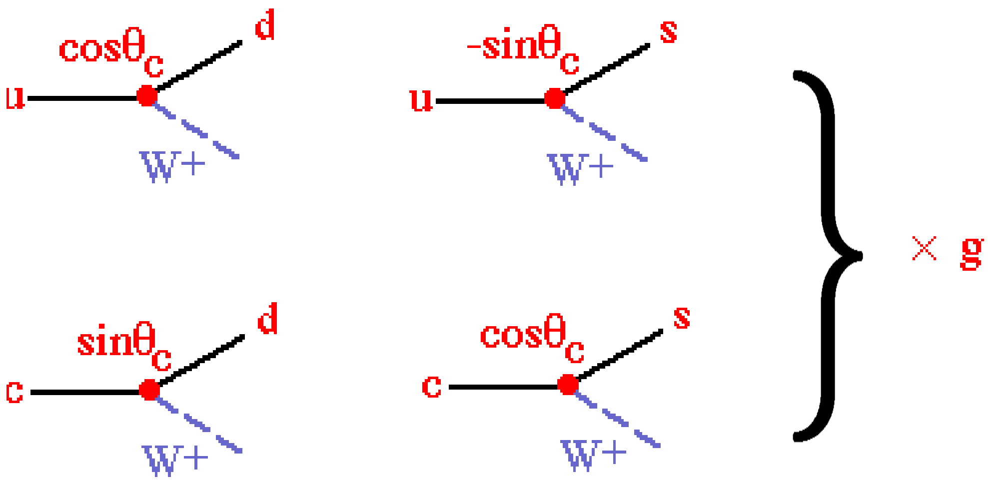
Neutral Weak+em interactions at LEP I and II





$W^{\pm}, Z^0$ → **CERN (SPS) 1983**

Different types of weak interactions

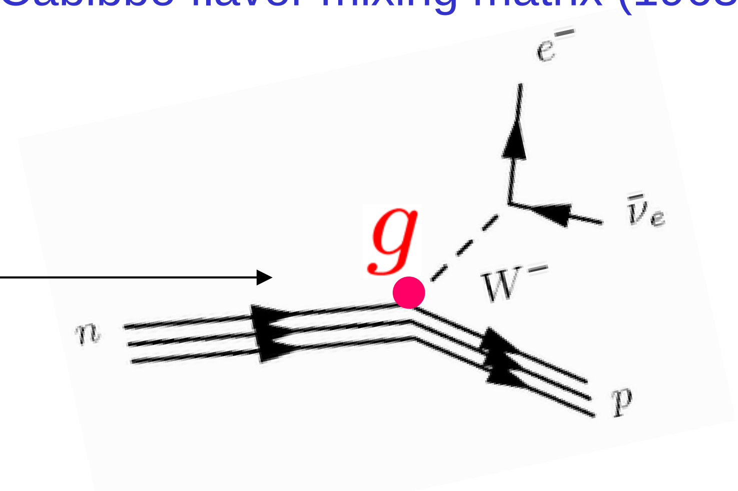


$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} cos\theta_c & sin\theta_c \\ -sin\theta_c & cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Cabibbo flavor mixing matrix (1963)

$$\cos\theta_c \simeq 0.97$$

$$\sin\theta_c \simeq 0.22$$



Generalization: Cabibbo-Kobayashi-Maskawa matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

Kobayashi-Maskawa, 1972

Nobel Prize 2008 *
shared with **Y. Nambu**

$$U = \begin{bmatrix} 0.9753 & 0.221 & 0.003 \\ 0.221 & 0.9747 & 0.040 \\ 0.009 & 0.039 & 0.9991 \end{bmatrix}$$

$\cos\theta_c \simeq 0.97$

$\sin\theta_c \simeq 0.24$

$$U^\dagger U = 1$$

Similar to Cabibbo's, but 3x3…

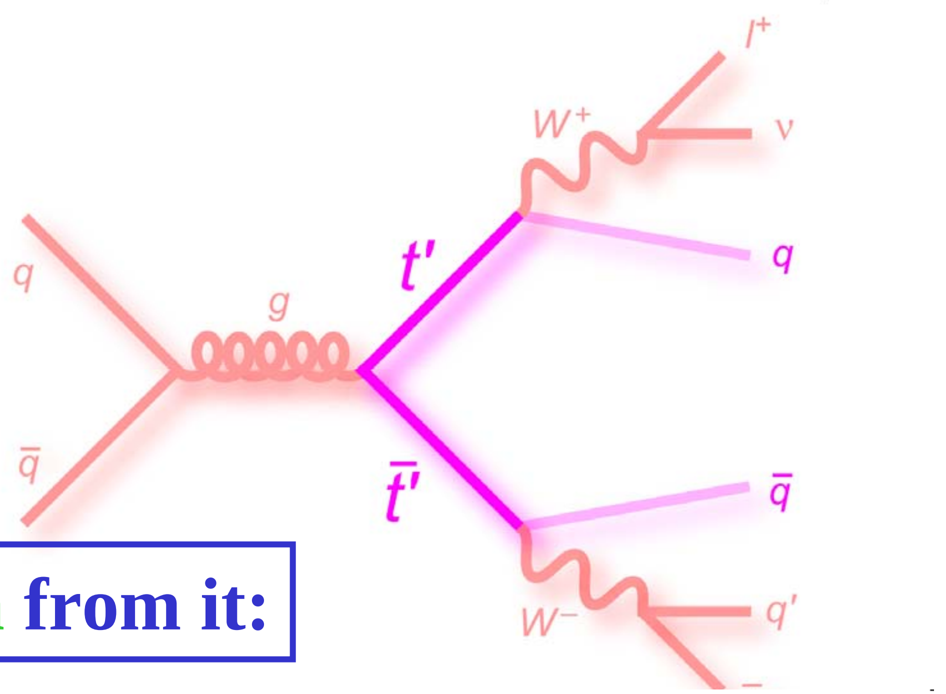
+ complex phase!! → **CP violation !!**

* *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature".*

…we can produce the top quark at hadron colliders

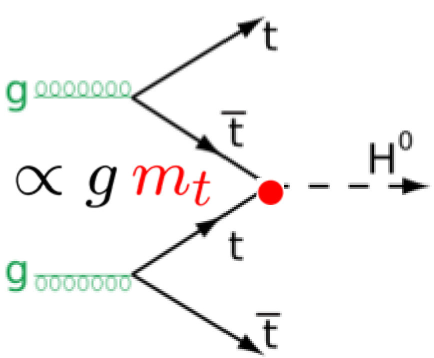
Quarks bottom and top:

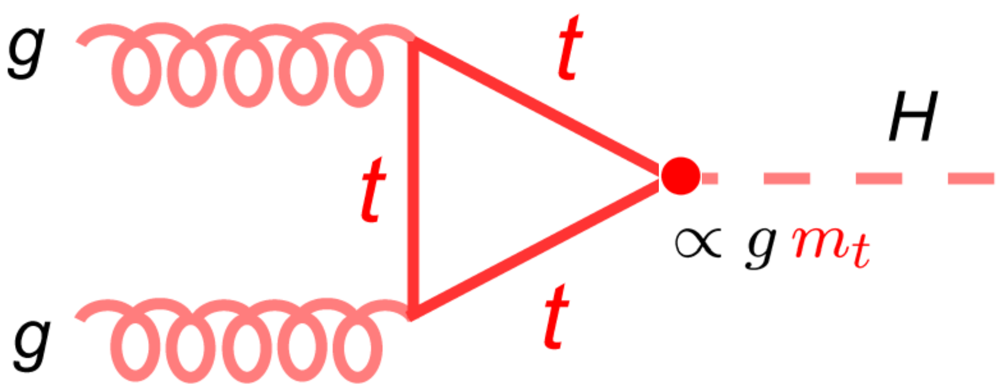
Fermilab 1977+1995



Tevatron + LHC:

…and also the Higgs boson from it:





Interactions

Symmetries

Standard Model

principle of local gauge invariance

↓

symmetry group $SU(2) \times U(1) \times SU(3)_C$

↓

Higgs mechanism and Yukawa interactions

$\longrightarrow$ masses $M_W, \; M_Z, \; m_{\text{fermion}}$

SM {
renormalizable quantum field theory

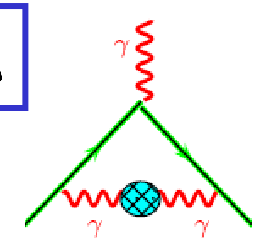
↓

accurate theoretical predictions
}

detect deviations $\rightarrow$ "new physics" ?

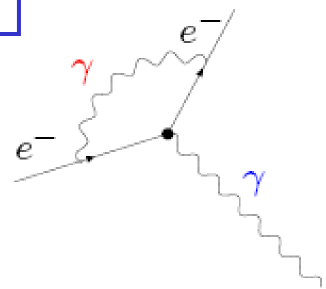
Hints from the lab

Precision Physics in the SM



QED:

$g-2$:



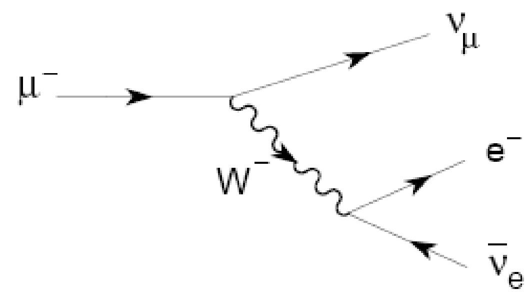
$a = \frac{1}{2}(g-2)$

$a_{\text{exp}} = 1\,159\,652\,188(\pm 4)\times 10^{-12}$

$a_{\text{theo}} = 1\,159\,652\,157(\pm 28)\times 10^{-12}$

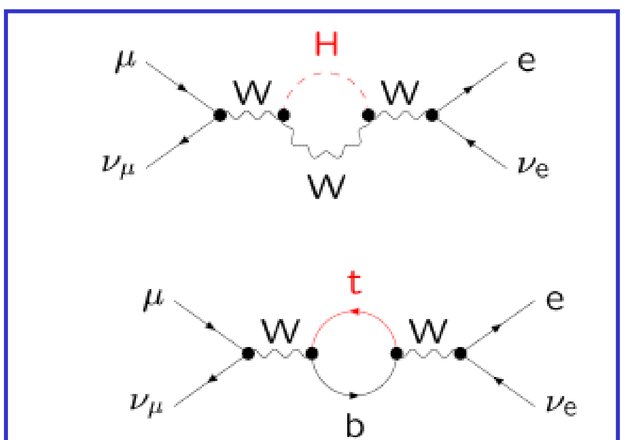
EW:

$$\begin{cases} G_F \\ M_Z,\, \Gamma_Z,\, g_V,\, g_A,\, \sin^2\theta_{\text{eff}},\; . \\ M_W,\, m_t \end{cases}$$



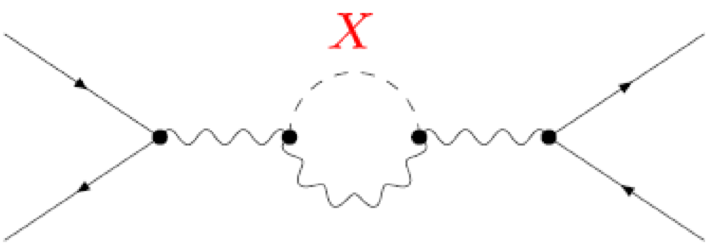
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)}(1 + \Delta r)$$

$$\Delta r = \Delta r(m_t, M_H)$$



Precision Physics Beyond the SM

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)}\left(1 + \Delta r\right)$$



X = Higgs bosons, SUSY particles

$$\Delta r = \Delta r\left(M_W, m_t, M_X\right)$$

new physics!

First calculations in SUSY:

J. Grifols, J. Solà, Phys.Lett.B137:257,1984.
J. Grifols, J. Solà, Nucl.Phys.B253:47,1985.
D. Garcia, J. Solà, Mod.Phys.Lett.A9:211-224,1994.

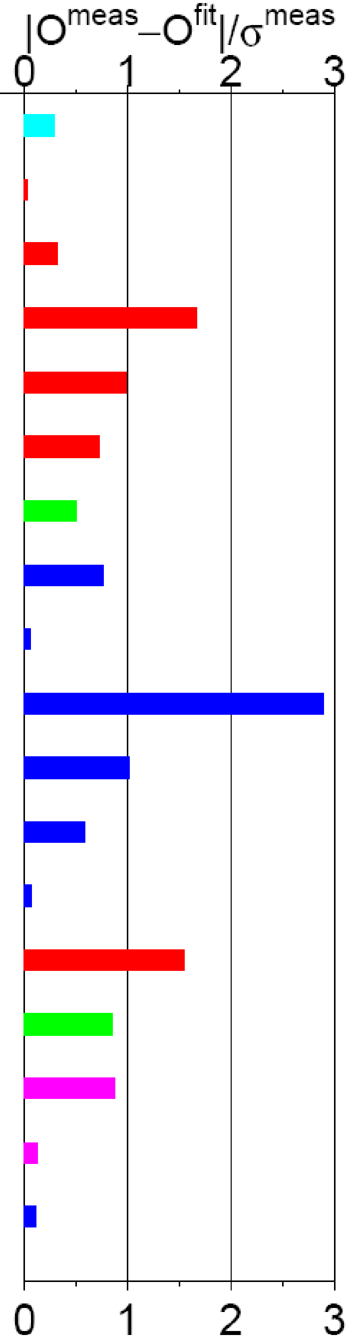
P.Chankowski, A. Dabelstein, W. Hollik, W. Mosle, S. Pokorski, J. Rosiek, Nucl.Phys.B417:101-129,1994.

State of the art in SUSY:

S. Heinemeyer, W. Hollik, D. Stockinger, A.M. Weber, G. Weiglein, JHEP 0608:052,2006.

S. Heinemeyer, W. Hollik, G. Weiglein, Phys.Rept.425 (2006) 265

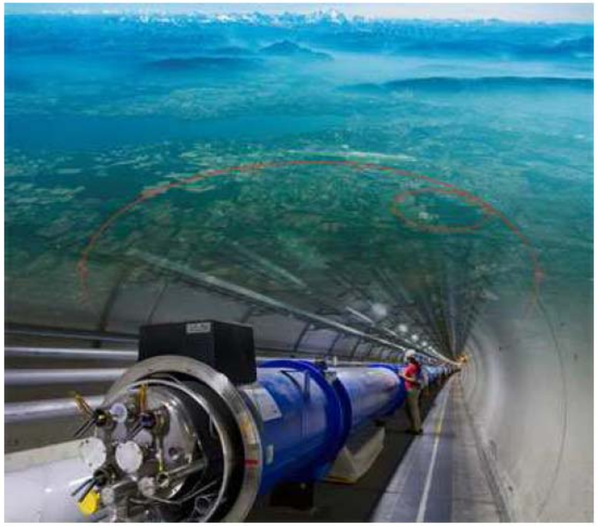
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



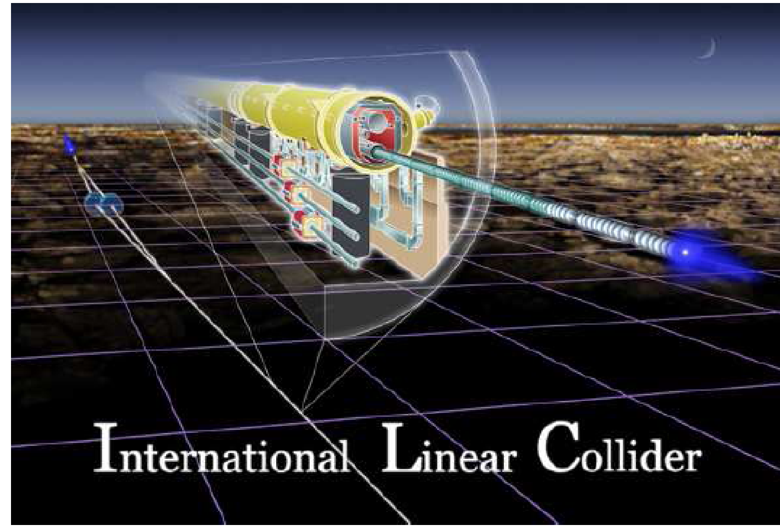
August 2009

➢ Present and **expected accuracy** for **precision observables**

LHC



$\Rightarrow$

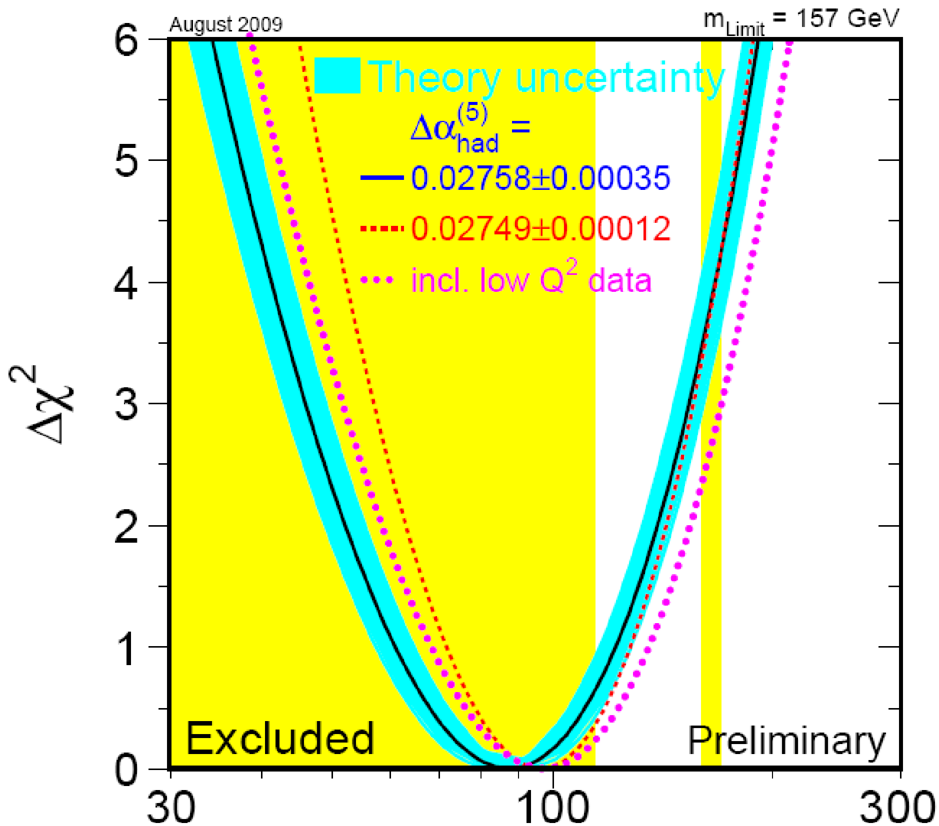


observable	central exp. value	$\sigma \equiv \sigma^{\text{today}}$	σ^{LHC}	σ^{ILC}
M_W [GeV]	80.399	0.023	0.015	0.007
$\sin^2\theta_{\text{eff}}$	0.23153	0.00016	0.00020–0.00014	0.000013
m_t [GeV]	173.3	1.1	1.0	0.1

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = \frac{1}{4}\left(1 - \Re\left(\frac{g_V(M_Z^2)}{g_A(M_Z^2)}\right)\right)$$

S. Heinemeyer, G. Weiglein (2010)

Hints from Higgs searches?... LEP Electroweak Working Group

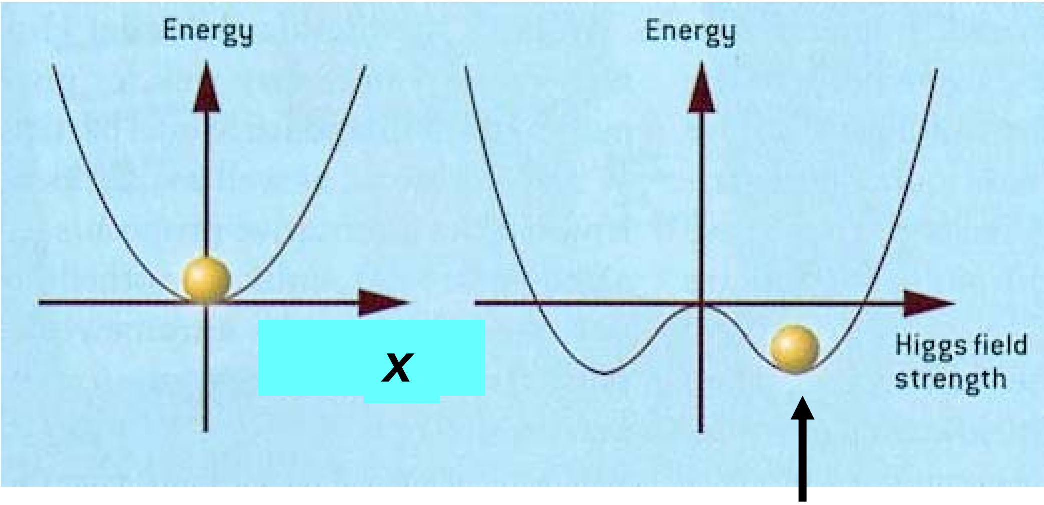


$$M_H < 157 \text{ GeV} \quad (95\%\text{C.L.})$$

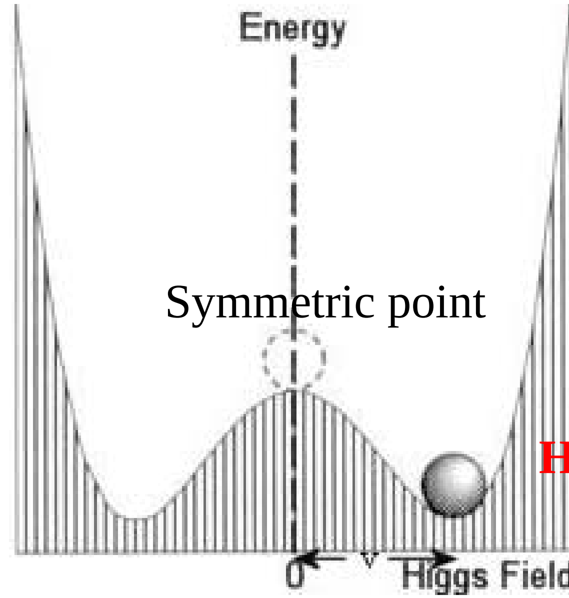
with direct search $M_H > 114$ GeV:

$$M_H < 186 \text{ GeV} \quad (95\%\text{C.L.})$$

Higgs mechanism



Predicts a new particle: **the Higgs boson**



$$V = ax^2 + bx^4$$

$$(a > 0,\ b > 0)$$

$$V = -ax^2 + bx^4$$

The vacuum is a Mexican hat!!...

Higgs mass and self-interactions

Higgs potential: $V = -\mu^2 \left(\Phi^\dagger\Phi\right)^2 + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^4$

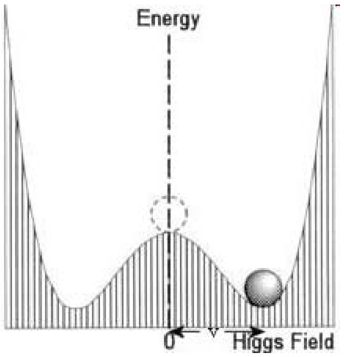
Higgs field in unitary gauge: $\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$

$H(x)$: *real scalar field, describes neutral spin-0 bosons*

minimum of V: $v = \frac{2\mu}{\sqrt{\lambda}}$, $M_H = \mu\sqrt{2}$

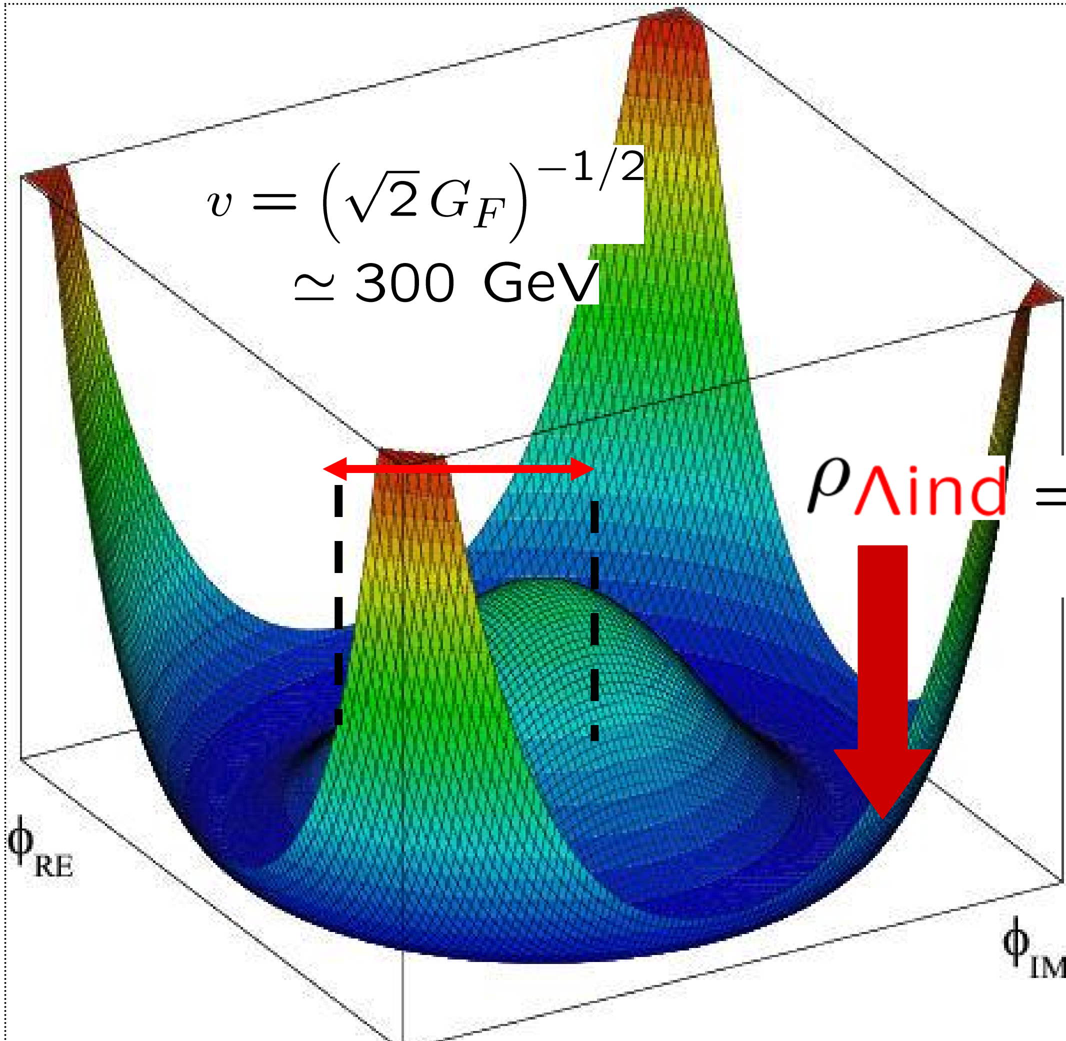
$v = \left(\sqrt{2}\,G_F\right)^{-1/2}$

$\Rightarrow \quad \lambda = \frac{4\mu^2}{v^2} = \frac{2M_H^2}{v^2}$



$$V = \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^4}{8v^2} H^4$$

Higgs Potential → Vacuum Energy



$$V(\varphi) = \frac{1}{2}\,m^2\,\varphi^2 + \frac{1}{4!}\,\lambda\,\varphi^4$$

$$m^2 < 0 \;\Rightarrow$$

$$v \equiv \langle\varphi\rangle = \sqrt{\frac{-6\,m^2}{\lambda}}$$

$$\rho_{\Lambda\mathrm{ind}} = \langle V(\varphi)\rangle = -\tfrac{1}{8}\,M_{\mathcal{H}}^2\,v^2$$
$$\sim -10^8\ GeV^4 \;\textbf{!!}$$

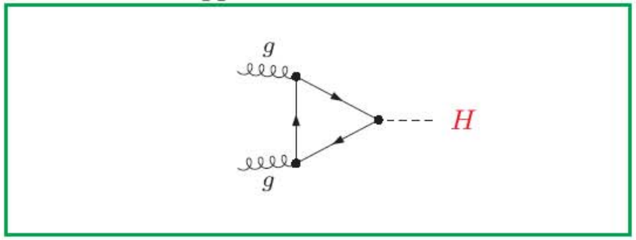
$$M_W = \tfrac{1}{2} g v$$
$$M_Z = \tfrac{1}{2} v \sqrt{g^2 + g'^2}$$

$$m_e = \lambda_e \frac{v}{\sqrt{2}}$$
$$m_u = \lambda_u \frac{v}{\sqrt{2}}$$
$$m_d = \lambda_d \frac{v}{\sqrt{2}}$$
...

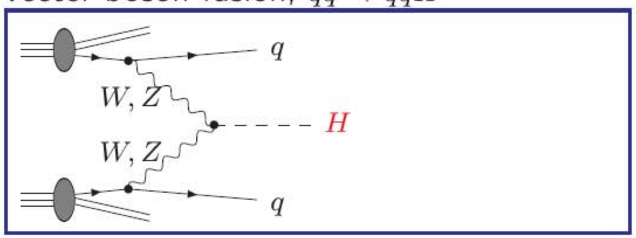
$\mu \to \nu_\mu \bar{\nu}_e\, e \quad \Rightarrow G_F \qquad M_{\mathcal{H}} > 114$ GeV

Higgs production at the LHC

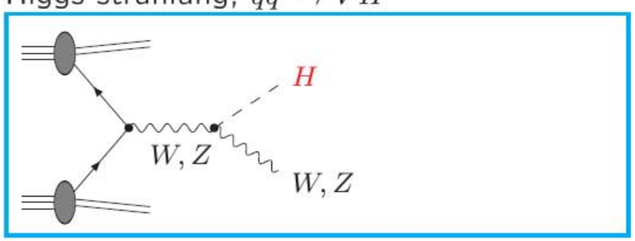
- gluon fusion, $gg \to H$



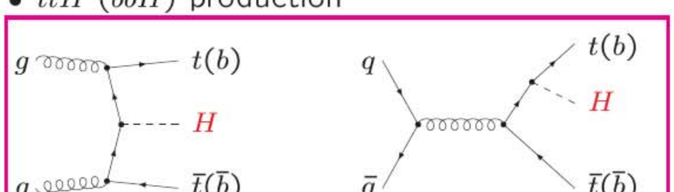
- vector boson fusion, $qq \to qqH$

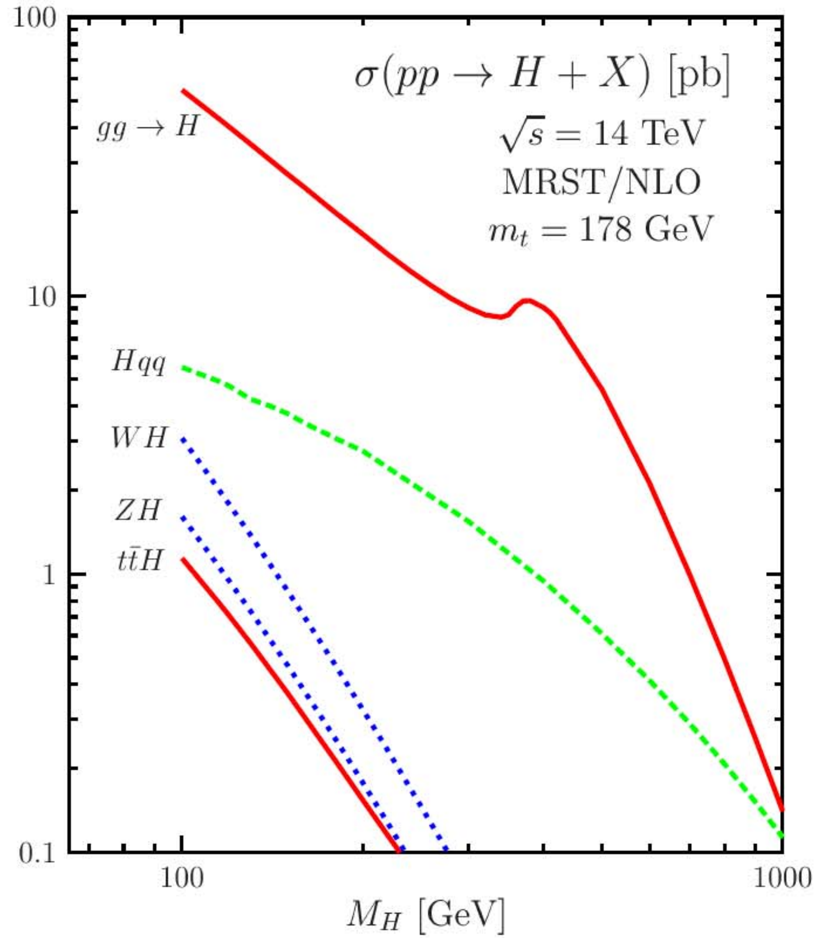


- Higgs strahlung, $q\bar{q}' \to VH$



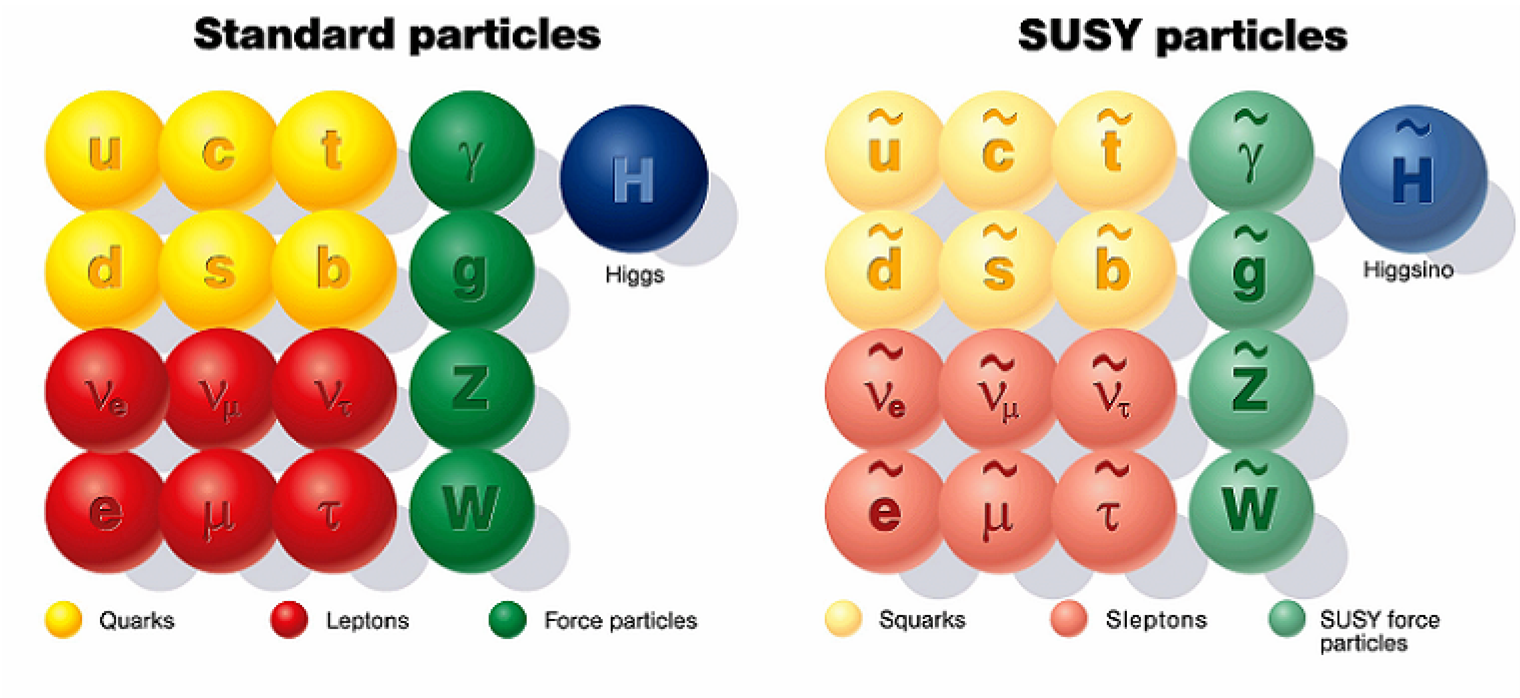
- $t\bar{t}H$ $(b\bar{b}H)$ production

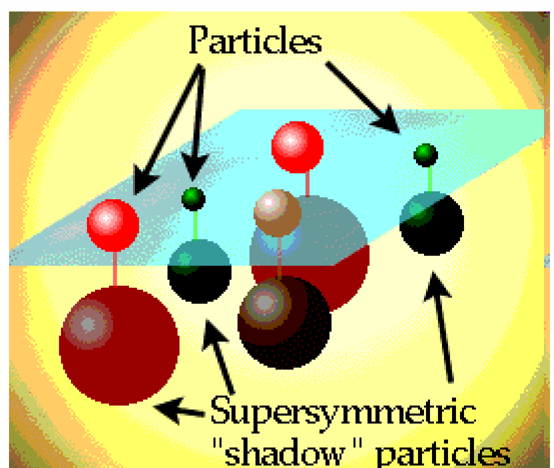




Beyond the Standard Model?

A favorite option: Supersymmetry (SUSY)





Golfand and Likhtman (1971)
Volkov and Akulov (1973)

What is SUSY?

Wess and Zumino (1974)

$$Q^{(S=\frac{1}{2})}\,|Fermion\rangle = |Boson\rangle \qquad Q^{(S=\frac{1}{2})}\,|Boson\rangle = |Fermion\rangle$$

$$\{Q^A_\alpha, \bar{Q}_{\dot{\beta}B}\} = 2\sigma^\mu_{\alpha\dot{\beta}} P_\mu \delta^A_B$$

(GUT+gravity!)

$\psi_i \; (S = \frac{1}{2})$	$\longleftrightarrow$	$\phi_i \; (S = 0)$
fermion		sfermion
quark (u, c, t)	$\longleftrightarrow$	squark $(\tilde{u}, \tilde{c}, \tilde{t})$

$v_i \; (S = 1)$	$\longleftrightarrow$	$\lambda_i \; (S = \frac{1}{2})$
gauge boson		gaugino
g, γ	$\longleftrightarrow$	$\tilde{g}, \tilde{\gamma}$

➢ Super-particles and Super-Lagrangians

Living in **Super-space**: $x \to (x, \theta, \bar{\theta})$

$$\Phi_L(x,\theta) = \phi(x) + \sqrt{2}\theta^\alpha \psi_\alpha(x) + \theta^\alpha \theta^\beta \epsilon_{\alpha\beta} F(x),$$

$$= (\phi, \psi, F)$$ chiral supermultiplet

$$V = -\theta\sigma^\mu \bar{\theta}\, v_\mu + i\theta\theta\bar{\theta}\bar{\lambda} + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}\, D + h.c.$$

$$= (\lambda, v_\mu\, D)$$ vector supermultiplet

SUSY world $\Rightarrow$ $m_{\tilde{f}} = m_f$ $\quad m_v = m_\lambda$

SUSY transformation
(e.g. on the chiral multiplet): (ϕ, ψ, F)

$$\delta_S \phi = \sqrt{2}\alpha\psi \qquad \text{(boson} \rightarrow \text{fermion)}$$

$$\delta_S \psi = \sqrt{2}\alpha F + i\sqrt{2}\sigma^\mu \overline{\alpha}\partial_\mu \phi \qquad \text{(fermion} \rightarrow \text{boson)}$$

$$\delta_S F = -i\sqrt{2}\partial_\mu \psi \sigma^\mu \overline{\alpha} \qquad (F \rightarrow \text{total derivative)}$$

D F

$$\mathcal{L} = \sum_i \int d^2\theta d^2\overline{\theta}\Phi_i \Phi_i^\dagger + \left[\int d^2\theta f(\Phi_i) + h.c.\right]$$

superpotential

$$f(\Phi_i) = \sum_i k_i \Phi_i + \frac{1}{2}\sum_{i,j} m_{ij}\Phi_i\Phi_j + \frac{1}{3}\sum_{i,j,k} g_{ijk}\Phi_i\Phi_j\Phi_k$$

Yukawa couplings potential V

$$\mathcal{L} = \mathcal{L}_{\rm kin} - \left[\sum_{j,k} \frac{\partial^2 f(\phi_i)}{\partial\phi_j \partial\phi_k} \psi_j \psi_k + h.c.\right] - \sum_j \left|\frac{\partial f(\phi_i)}{\partial \phi_j}\right|^2$$

Notice that V is positive-definite in **SUSY** !!

$$V = \sum_i \left|\frac{\partial f}{\partial \phi_i}\right|^2 + \sum_l \frac{g_l^2}{2} \sum_a \left|\sum_{i,j} \phi_i^* T_{l,a}^{ij} \phi_j\right|^2$$

F **D**

Generalizing the procedure we can construct the

MSSM

The property above $\Rightarrow$ **SUSY** cannot be easily SSB, although we know that must be broken!!

➢ Weak versus mass eigenstates

Sfermions:

$$\Phi_L = (\phi_L, \psi_L, F_L) \qquad \Phi_R = (\phi_R, \psi_R, F_R)$$

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} m_t^2 + m_{\tilde{t}_L}^2 + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\cos(2\beta)M_Z^2 & -m_t\left(A_t + \mu\cot\beta\right) \\ -m_t\left(A_t + \mu\cot\beta\right) & m_t^2 + m_{\tilde{t}_R}^2 + \frac{2}{3}\sin^2\theta_W\cos(2\beta)M_Z^2 \end{pmatrix}$$

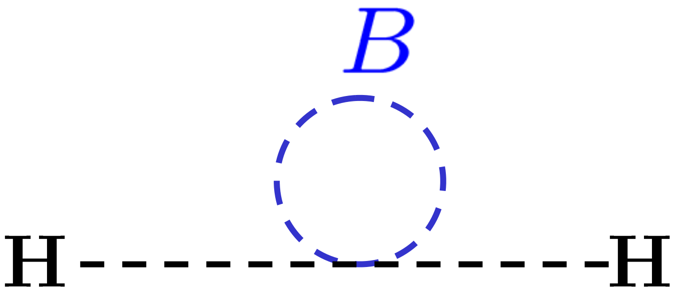
Neutralinos: In the $(\tilde{B}^0, \tilde{W}_3^0, \tilde{H}_1^0, \tilde{H}_2^0)$ basis

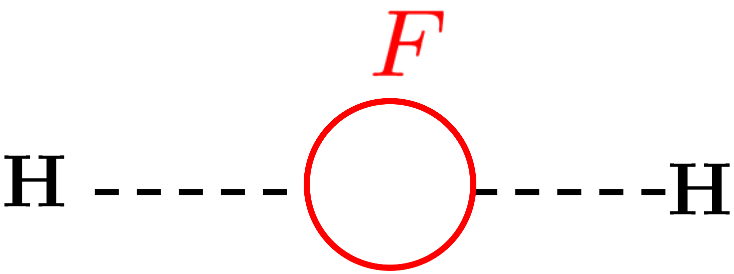
$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}$$

$$\chi_\alpha = N_{1\alpha}\tilde{B}^0 + N_{2\alpha}\tilde{W}_3^0 + N_{3\alpha}\tilde{H}_1^0 + N_{4\alpha}\tilde{H}_2^0$$

$$\alpha = 1, 2, 3, 4 \qquad \Rightarrow \chi_1 \text{ LSP}$$

SUSY and the Hierarchy Problem





$$\delta M_{\mathrm{H}}^2 \sim \frac{g^2}{16\pi^2}\left[\int_{m_B^2}^{\Lambda^2} dk^2 - \int_{m_F^2}^{\Lambda^2} dk^2\right]$$

$$\sim \frac{g^2}{16\pi^2}\int_{m_B^2}^{m_F^2} dk^2 \sim \frac{g^2}{16\pi^2}\left|m_F^2 - m_B^2\right|$$

$\delta M_{\mathrm{H}}^2 \lesssim M_{\mathrm{H}}^2 \lesssim 1\, TeV^2$ ⇒ $M_{\mathrm{SUSY}} \lesssim (1-10)\, TeV$ **LHC !!?**

MSSM:

Minimal Supersymmetric SM

	fields			gauge group		
	superfield	fermion	boson	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Matter sector			sfermions			$(Q = T_3 + \frac{Y}{2})$
Quarks Squarks	$\hat{Q}_i$	$\begin{pmatrix} u_i \\ d_i \end{pmatrix}_L$	$\begin{pmatrix} \tilde{u}_i \\ \tilde{d}_i \end{pmatrix}_L$	**3**	**2**	$\frac{1}{3}$
	$\hat{U}_i$	$u^c_{i\,R}$	$\tilde{u}^*_{i\,R}$	$\bar{\mathbf{3}}$	**1**	$-\frac{4}{3}$
	$\hat{D}_i$	$d^c_{i\,R}$	$\tilde{d}^*_{i\,R}$	$\bar{\mathbf{3}}$	**1**	$-\frac{4}{3}$
Leptons Sleptons	$\hat{L}_i$	$\begin{pmatrix} \nu_i \\ e_i \end{pmatrix}_L$	$\begin{pmatrix} \tilde{\nu}_i \\ \tilde{e}_i \end{pmatrix}_L$	**1**	**2**	-1
	$\hat{E}_i$	$e^c_{i\,R}$	$\tilde{e}^*_{i\,R}$	**1**	**1**	2
Gauge sector		gauginos	gauge			
$SU(3)_C$	$\hat{G}^a$	$\tilde{\lambda}^a_g$	g^a_μ	**8**	**1**	0
$SU(2)_L$	$\hat{W}^i$	$\tilde{\lambda}^i_W$	W^i_μ	**1**	**3**	0
$U(1)_Y$	$\hat{B}$	$\tilde{\lambda}_B$	B_μ	**1**	**1**	0

Higgs bosons and Higgsinos

	fields			gauge group		
	superfield	fermion	scalar	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Higgs Sector		Higgsino	**Higgs** **doublets**			
	$\hat{H}_1$	$\begin{pmatrix} \tilde{H}_1^1 \\ \tilde{H}_1^2 \end{pmatrix}$	$\begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix}$	**1**	**2**	-1
	$\hat{H}_2$	$\begin{pmatrix} \tilde{H}_2^1 \\ \tilde{H}_2^2 \end{pmatrix}$	$\begin{pmatrix} H_2^1 \\ \tilde{H}_2^2 \end{pmatrix}$	**1**	**2**	1

As in the **SM**

$$(Q = T_3 + \frac{Y}{2})$$

$$H_2 = \begin{pmatrix} H_2^+ \\ v_2 + H_2^0 \end{pmatrix}, \qquad H_1 = \begin{pmatrix} v_1 + H_1^0 \\ H_1^- \end{pmatrix}$$

couples to u_R couples to d_R

$$\tan\beta = \frac{v_2}{v_1}$$

Three neutral physical states: h^0, H^0, A^0

Two charged physical states: $H^\pm$

Balance of (real) d.o.f.'s

(Doubling?)

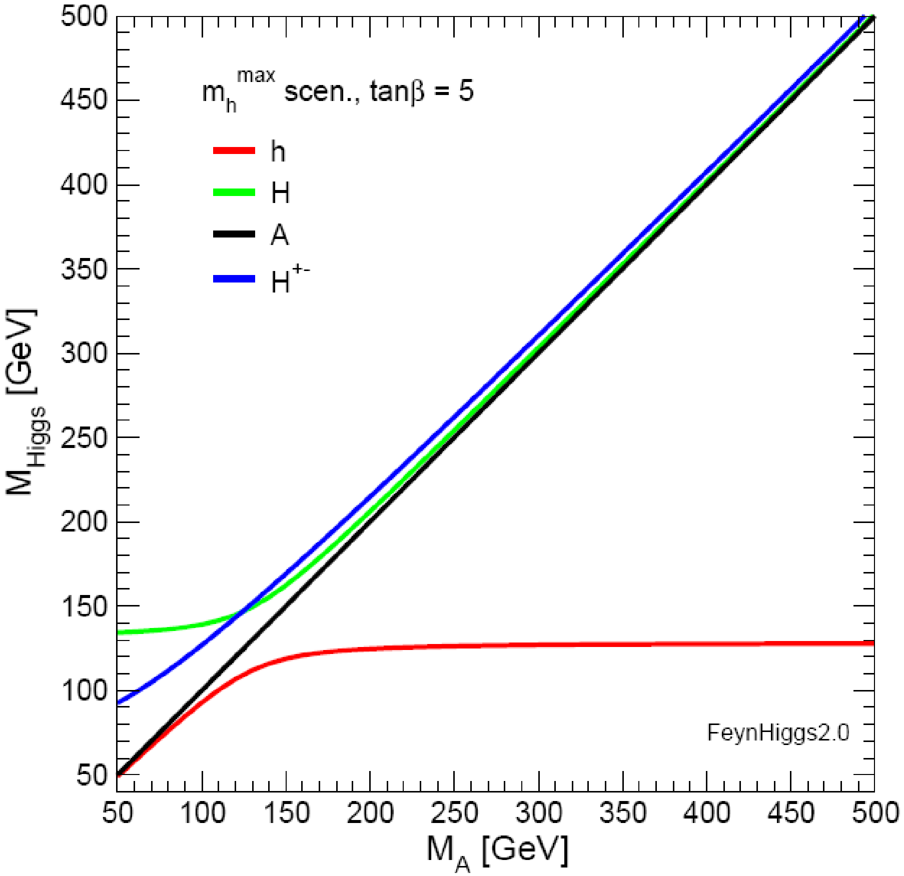
$$N_{\mathbf{MSSM}} = 128 + 128 = 2\,N_{\mathbf{SM}} + 8$$

(fermionic) (bosonic)

$$N_{SM} = 28 + 96 = 124$$

(fermionic) (bosonic)

Spectrum of Higgs bosons in the MSSM (example)



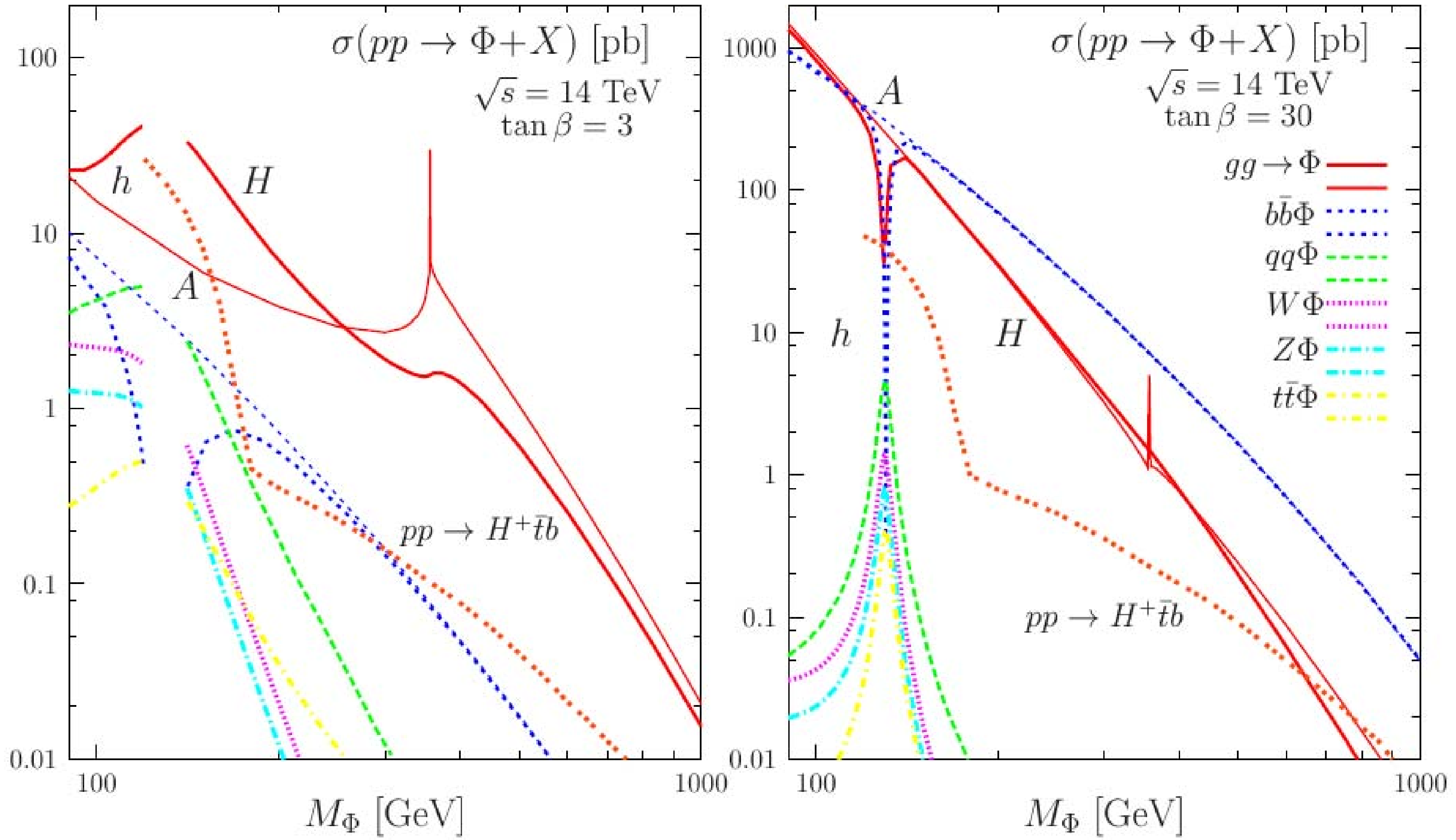
At large $\tan\beta > 30$

$m_h < 140$ GeV

Signature of the MSSM

large M_A: h^0 like SM Higgs boson $\sim$ decoupling regime

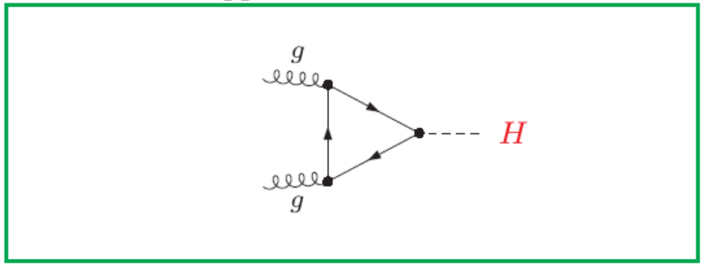
➢ Higgs boson production at the LHC in the MSSM



$$H \to h^0, H^0, A^0$$

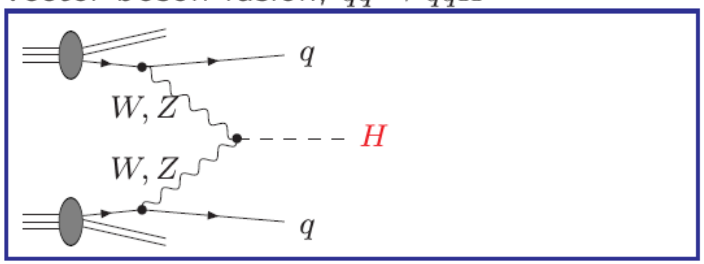
LHC

- gluon fusion, $gg \to H$



+ more (SUSY) diagrams

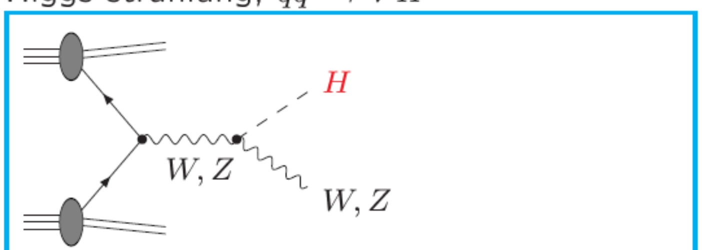
- vector boson fusion, $qq \to qqH$



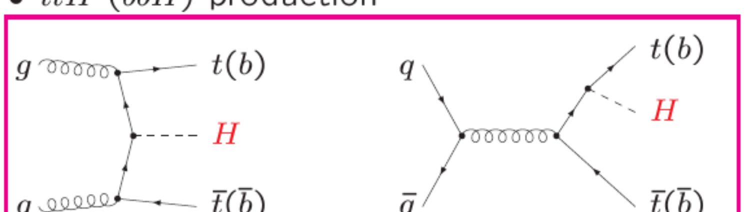
Enhanced Yukawa couplings:

	MSSM
$h^0 t\bar{t}$	$\cos\alpha / \sin\beta$
$h^0 b\bar{b}$	$-\sin\alpha / \cos\beta$
$H^0 t\bar{t}$	$\sin\alpha / \sin\beta$
$H^0 b\bar{b}$	$\cos\alpha / \cos\beta$
$A^0 t\bar{t}$	$\cot\beta$
$A^0 b\bar{b}$	$\tan\beta$

- Higgs strahlung, $q\bar{q}' \to VH$

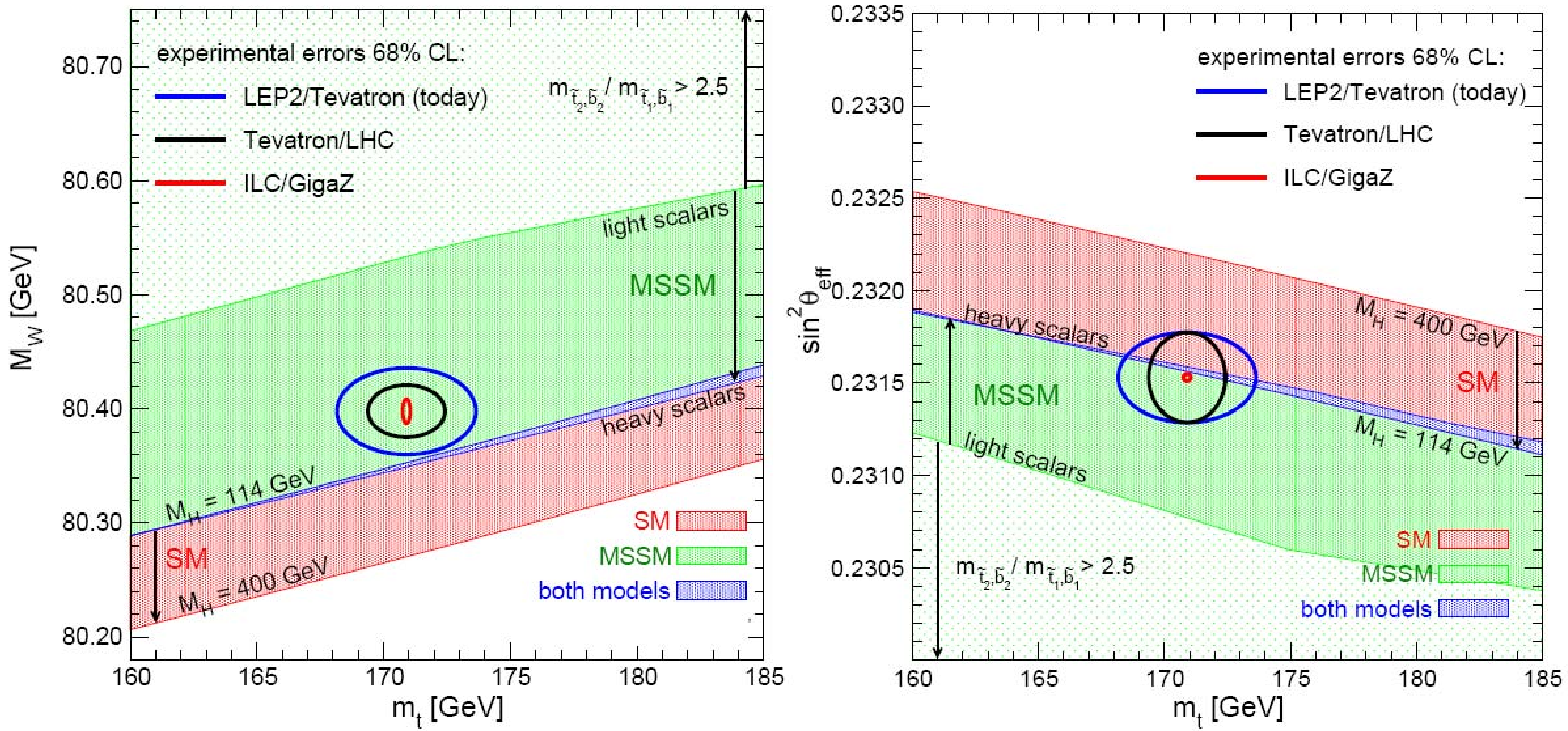


- $t\bar{t}H$ $(b\bar{b}H)$ production



$$\tan\beta = \frac{v_2}{v_1}$$

➢ Fitting the data: SM versus MSSM



[Heinemeyer, Hollik, Stöckinger, Weber, Weiglein]

Hints of physics BSM

from the SKY

. . . next time!!