



**24<sup>e</sup> CONGRÈS  
GÉNÉRAL** de la  
**SOCIÉTÉ FRANÇAISE  
DE PHYSIQUE** 

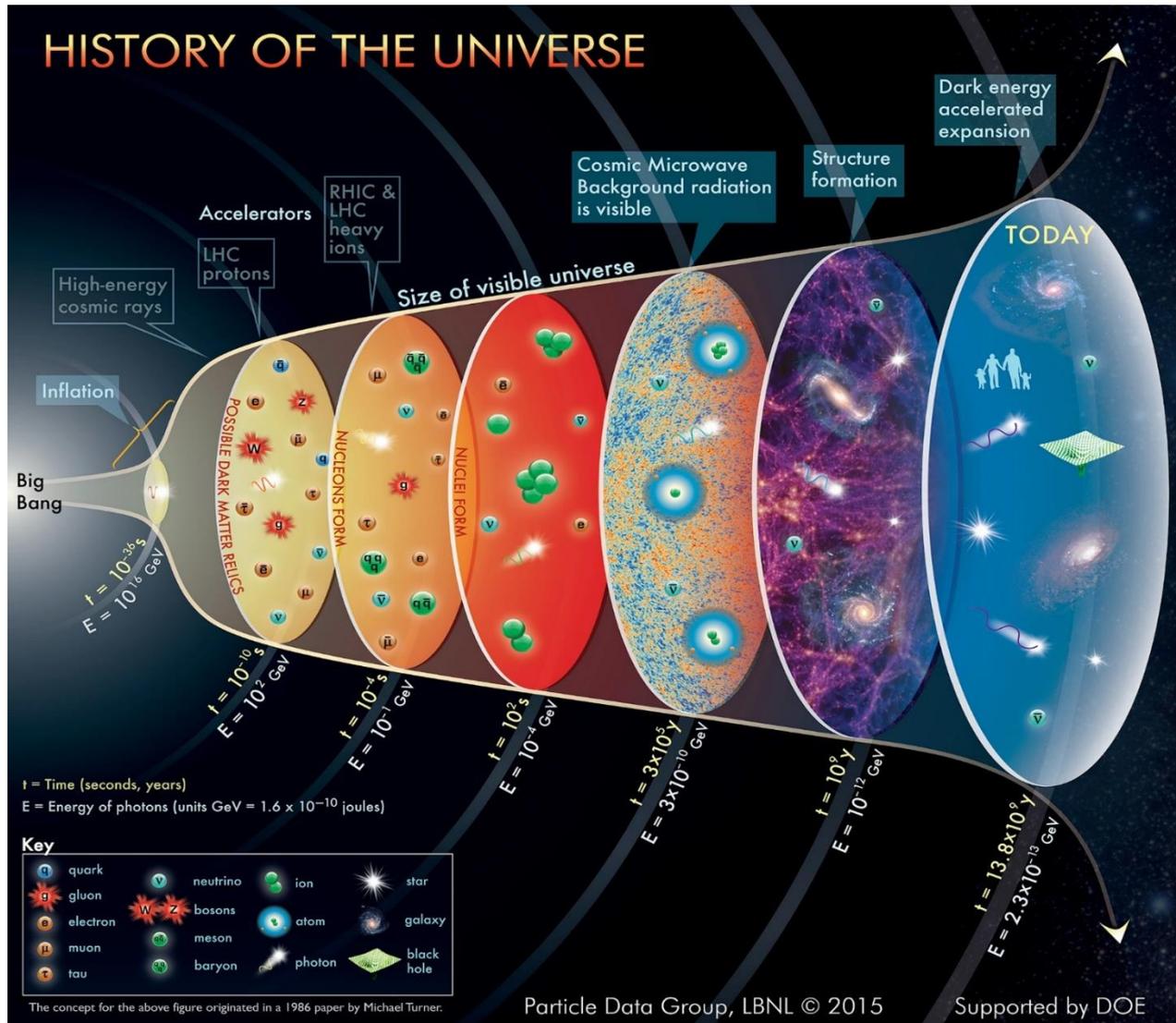
# Recherche de nouvelle physique au LHC

24<sup>ème</sup> Congrès de la SFP, Orsay

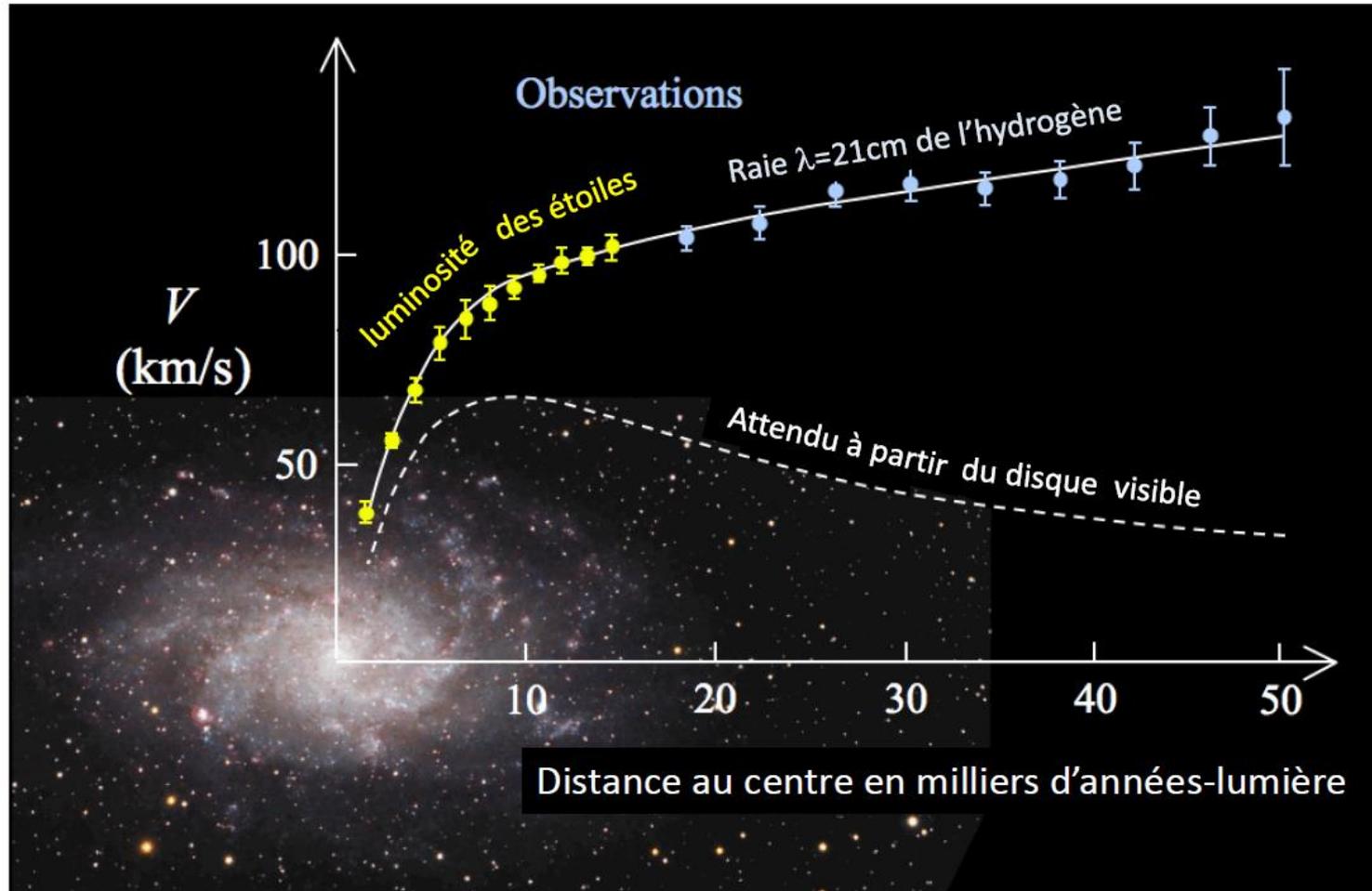
Edwige Tournefier, LAPP

Mercredi 5 juillet 2017

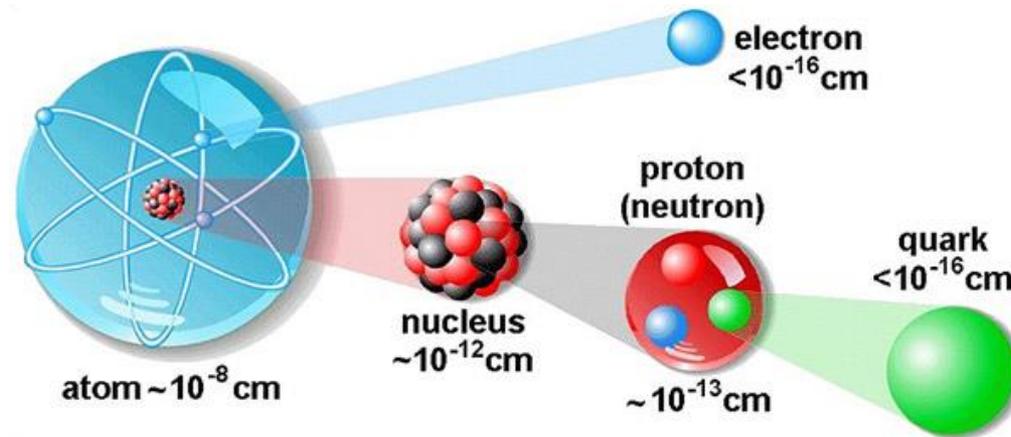




## La compréhension du contenu de l'univers

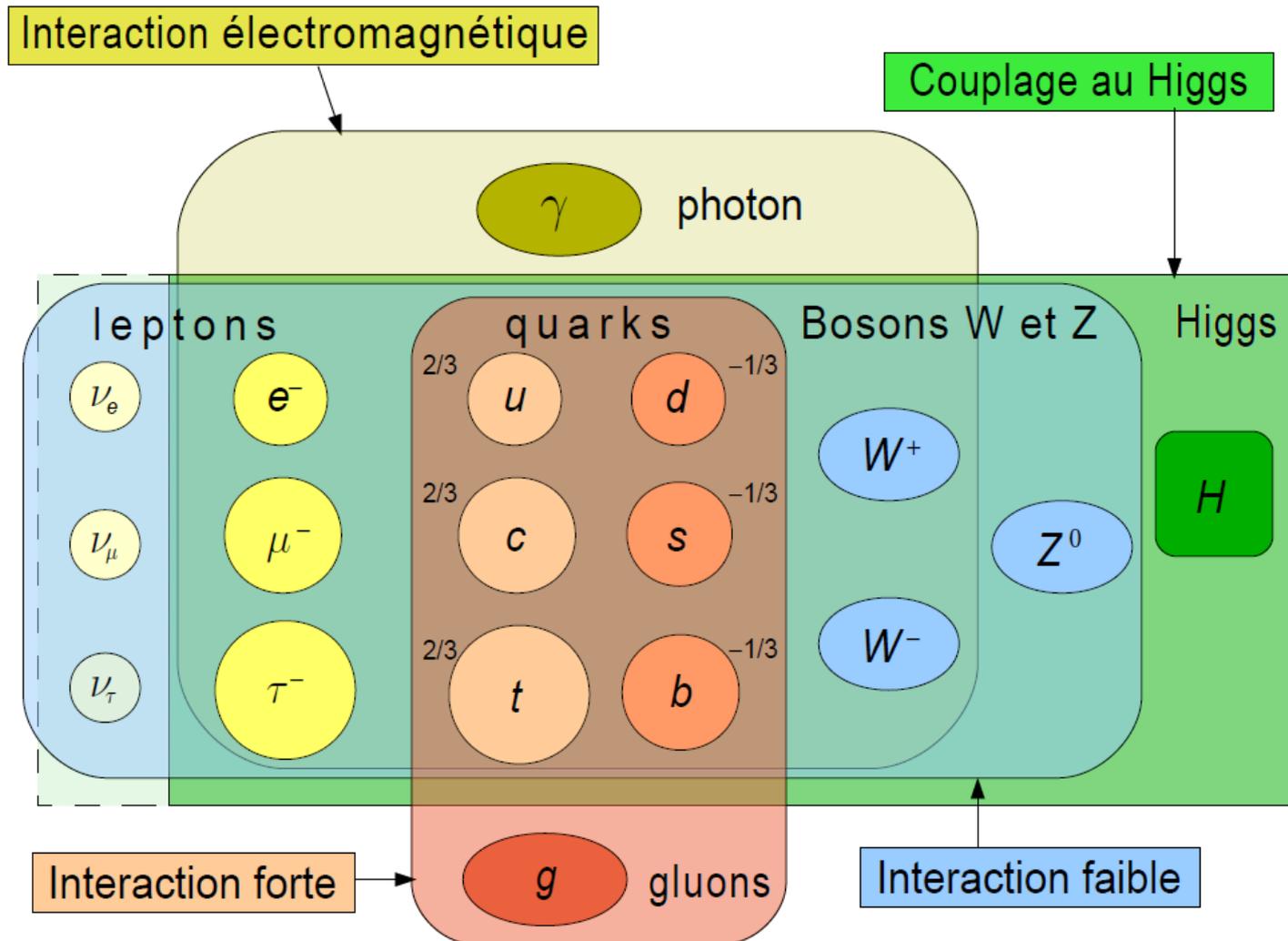


- Quels sont les **constituants élémentaires** de la matière ?
- Quelles sont les **forces** qui s'exercent entre eux

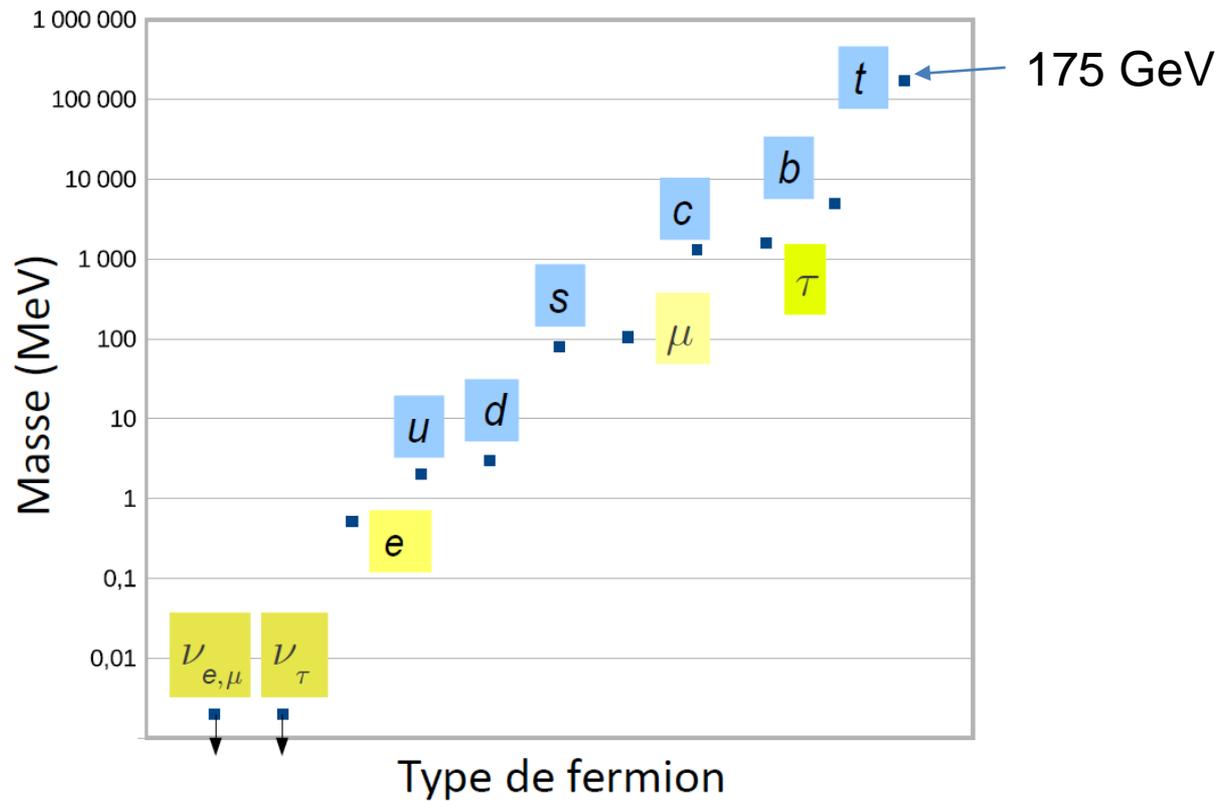


## Cadre théorique

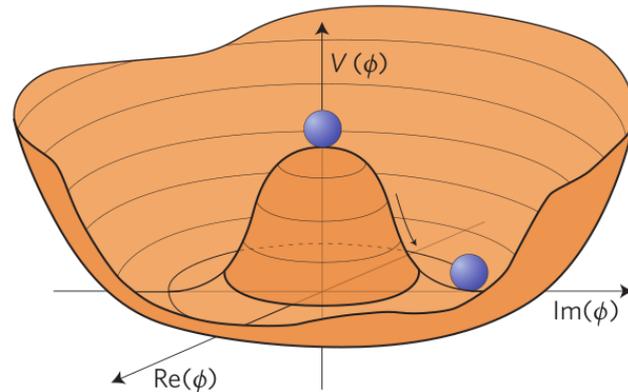
- Théorie des champs quantique relativiste
- Symétries de jauge



- Masse des fermions



- Théorie invariante de jauge  $\Rightarrow$  particules de masse nulle
- Brisure spontanée de symétrie par le mécanisme de Brout-Englert-Higgs

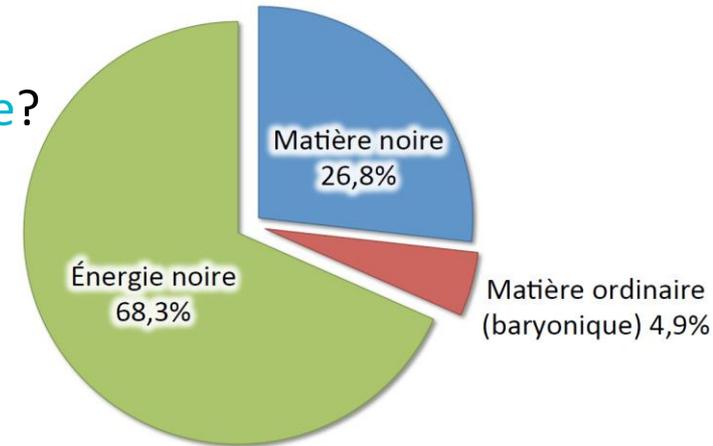


- $\Rightarrow$  les bosons W et Z et les fermions deviennent massifs
- $\Rightarrow$  prédiction d'une particule scalaire massive (boson de Higgs)

Recherche du boson de Higgs et étude de ses couplages

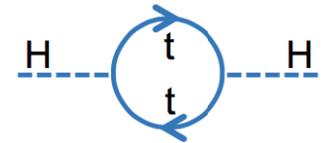
= premier objectif du LHC

- De quoi est formée la **matière noire** ?
- L'univers est en expansion accélérée: **énergie noire**?



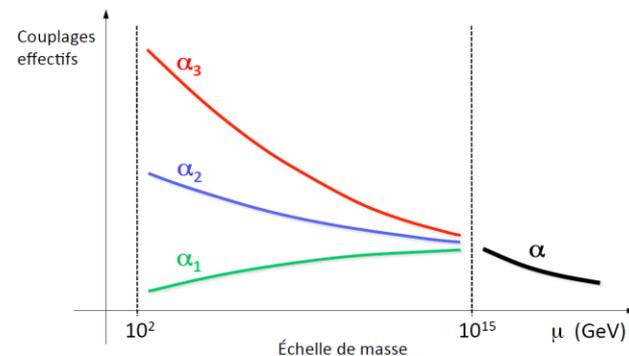
- Pourquoi l'univers n'est-il formé que de matière (**asymétrie matière/antimatière**)?

- Problème de la masse du boson de Higgs: **instabilité du vide**



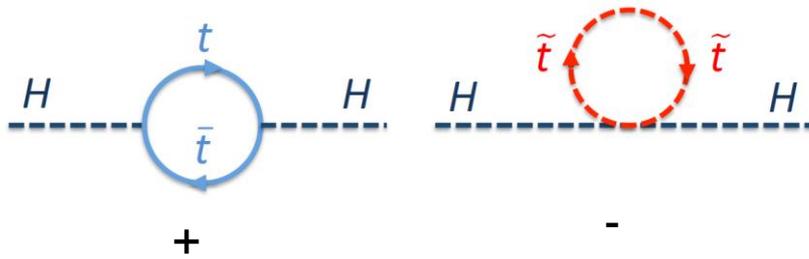
- Théorie quantique de la **gravitation**

- **Unification** des forces



- la SuperSymétrie:

- candidat matière noire
- stabilité du vide



	2.4 MeV	1.3 GeV	170 GeV	0
<b>Fermions</b>	u	c	t	$\tilde{\gamma}$
	4.8 MeV	104 MeV	4.2 GeV	0
	d	s	b	g
	<2.2 eV	<0.2 MeV	<16 MeV	91 GeV
	$\nu_e$	$\nu_\mu$	$\nu_\tau$	Z
	0.5 MeV	16 MeV	1.8 GeV	80 GeV
	e	$\mu$	$\tau$	W
				126 GeV
				H
				<b>Higgs bosons</b>

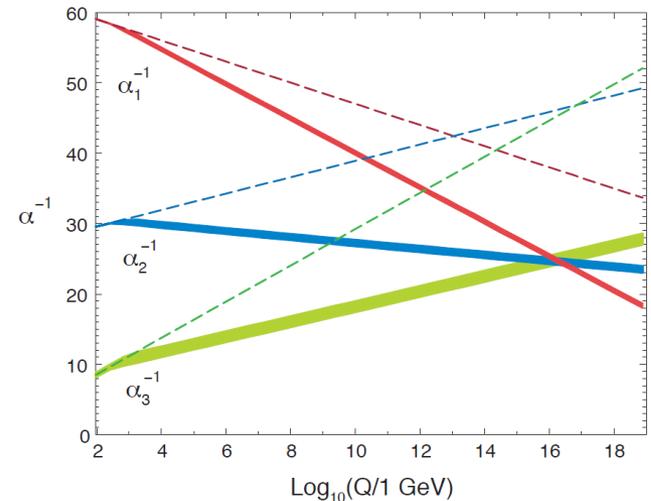
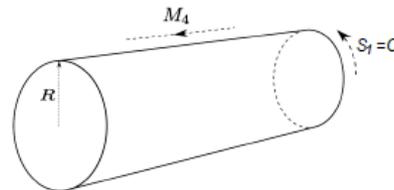
	$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{\gamma}$
<b>Sfermions</b>	$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	$\tilde{g}$
	$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{Z}$
	$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	$\tilde{W}$
				$\tilde{H}$
				<b>Higgsinos</b>
				<b>Gauginos</b>

- Théories de grande unification

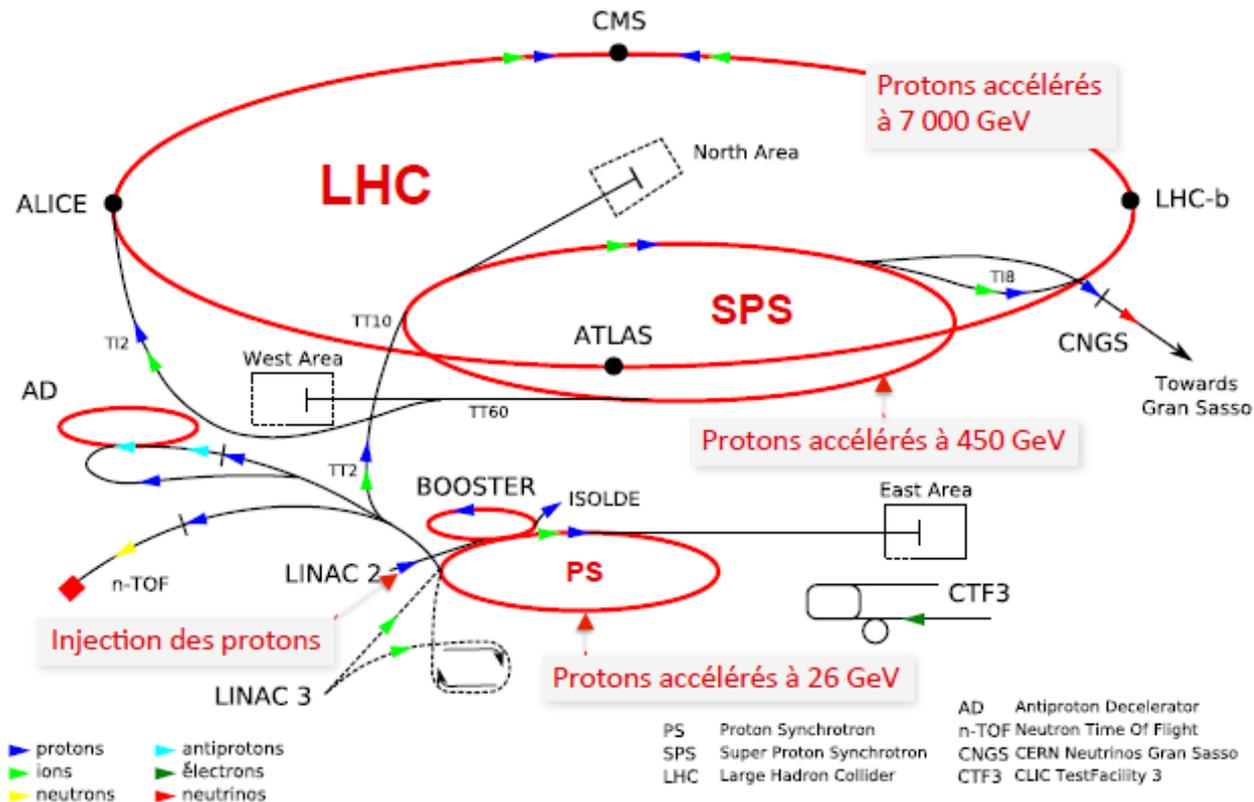
- nouveaux bosons lourds ( $Z'$ ,...)

- Dimensions supplémentaires

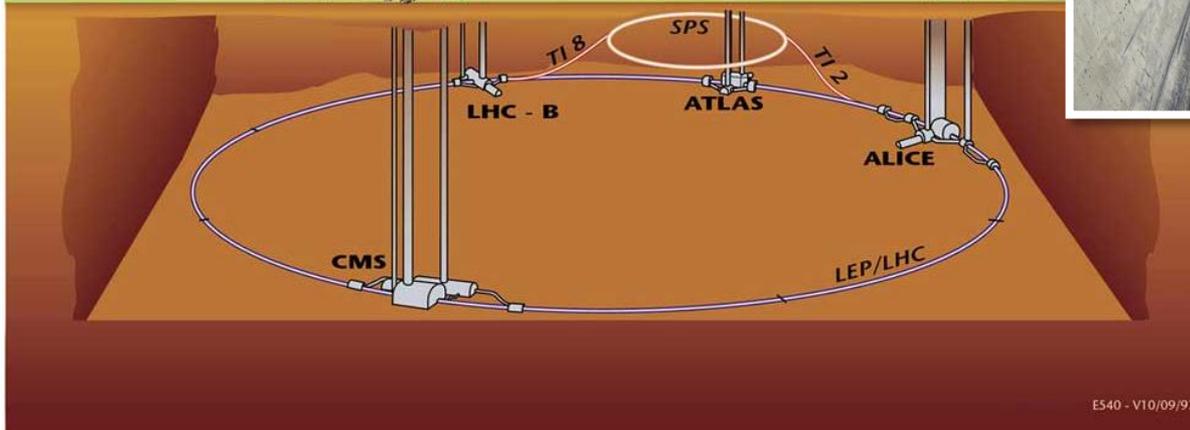
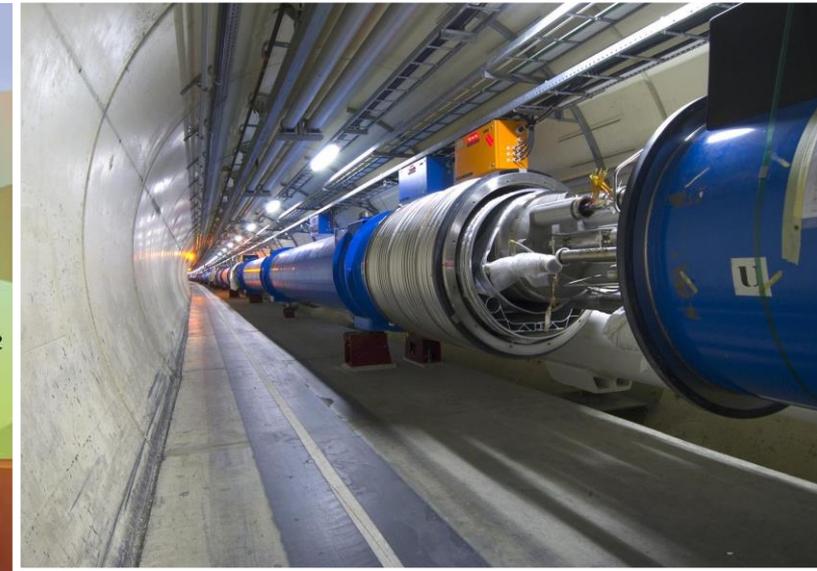
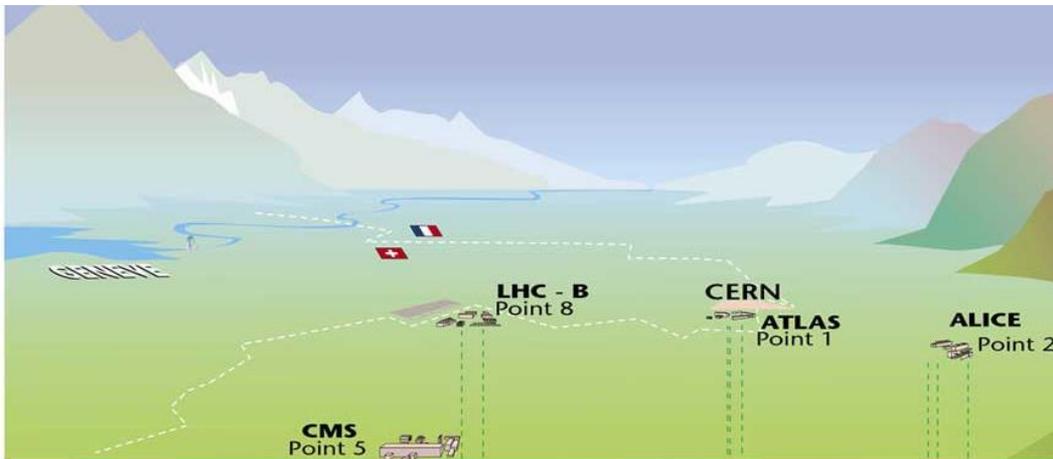
- gravitation

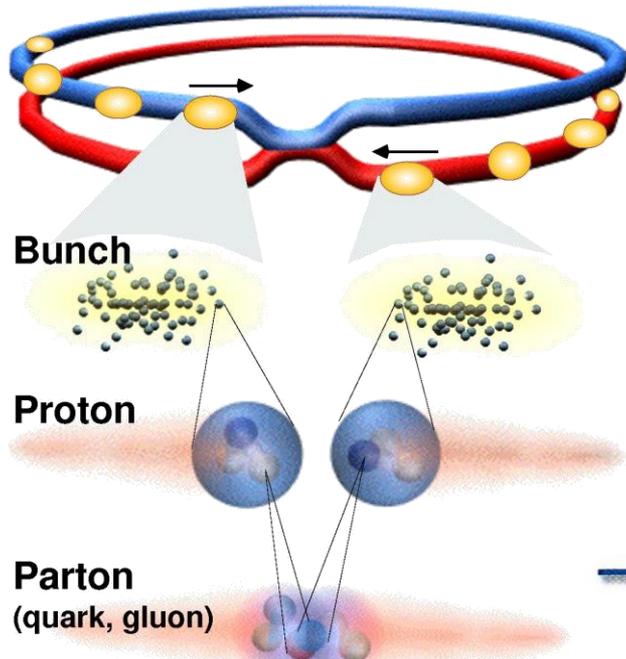


- Le Cern a été créé en 1954 par 12 états européens (maintenant 22 états membres)
- LHC = Large Hadron Collider (collisions p-p, Pb-p, Pb-Pb)
- L'aventure LHC: ~1990-2040?

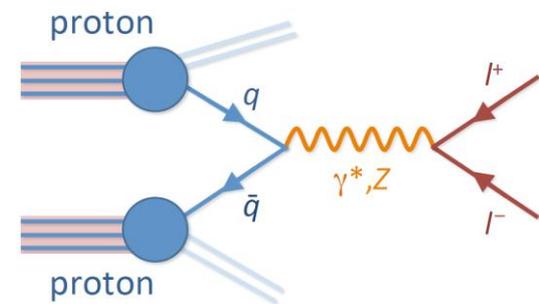
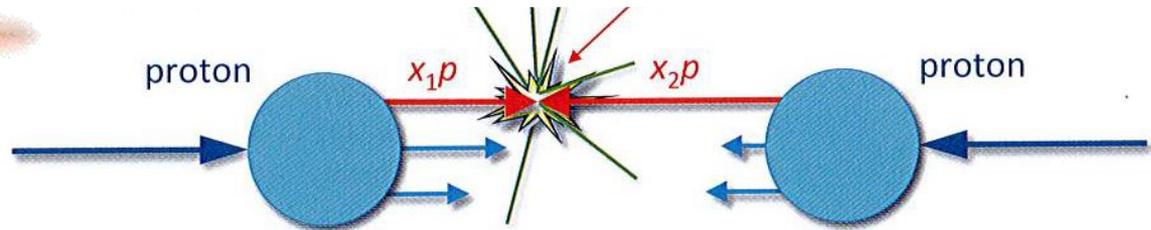


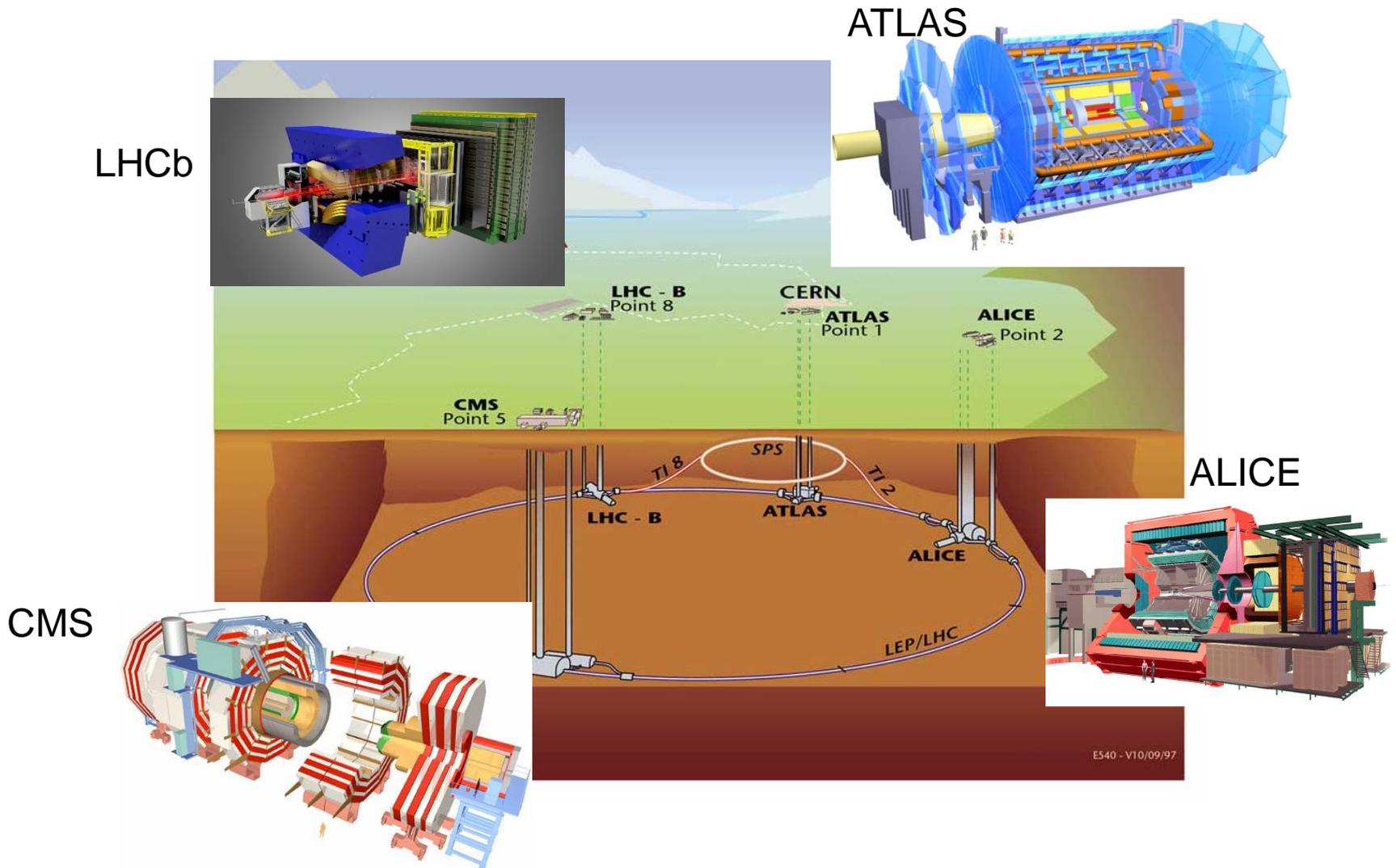
- Circonférence : 27km
- 9000 aimants
- 1200 dipôles de 14 m chacun -  $B=8T$  -  $T\sim 1.9 K$  !





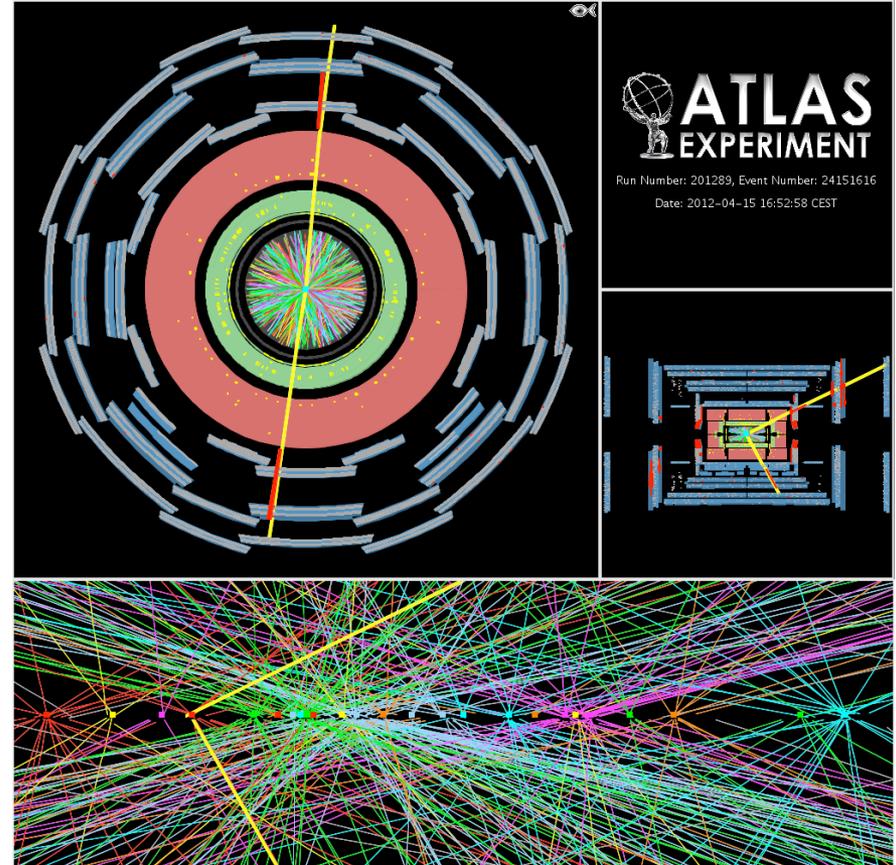
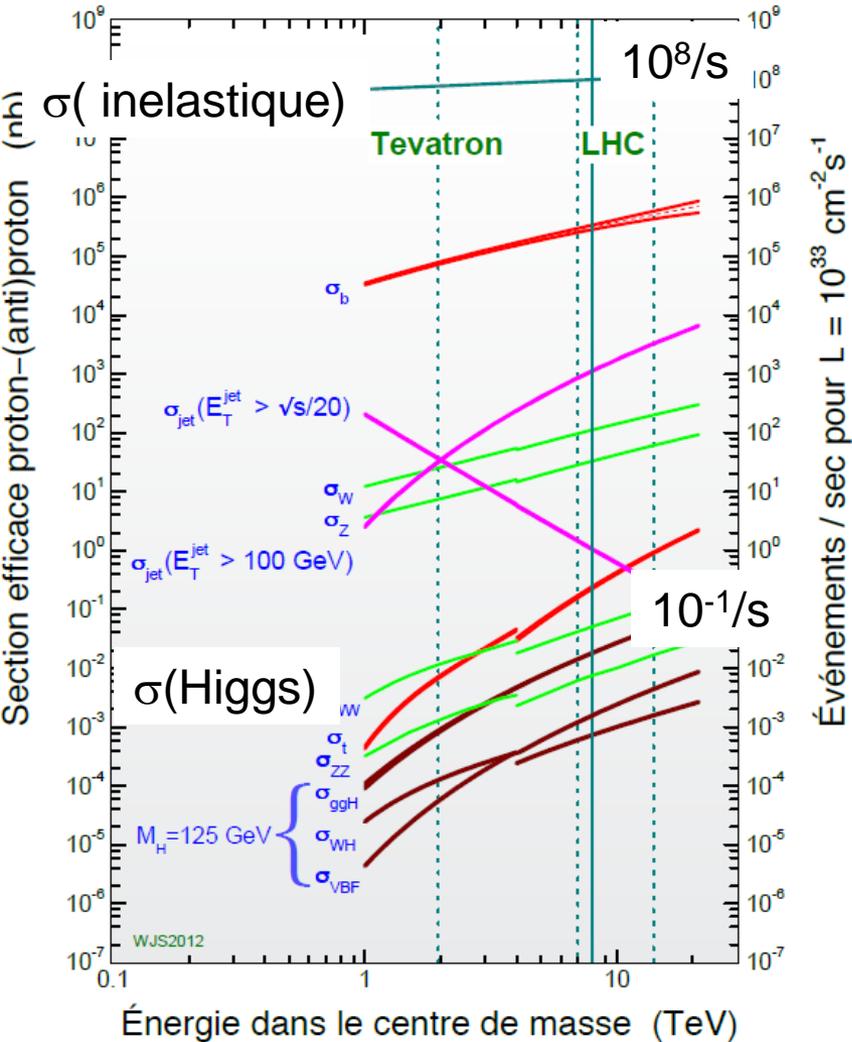
- 2800 paquets
- $10^{11}$  protons/paquet
- 40 MHz
- $E = 7 \text{ TeV} / \text{proton}$

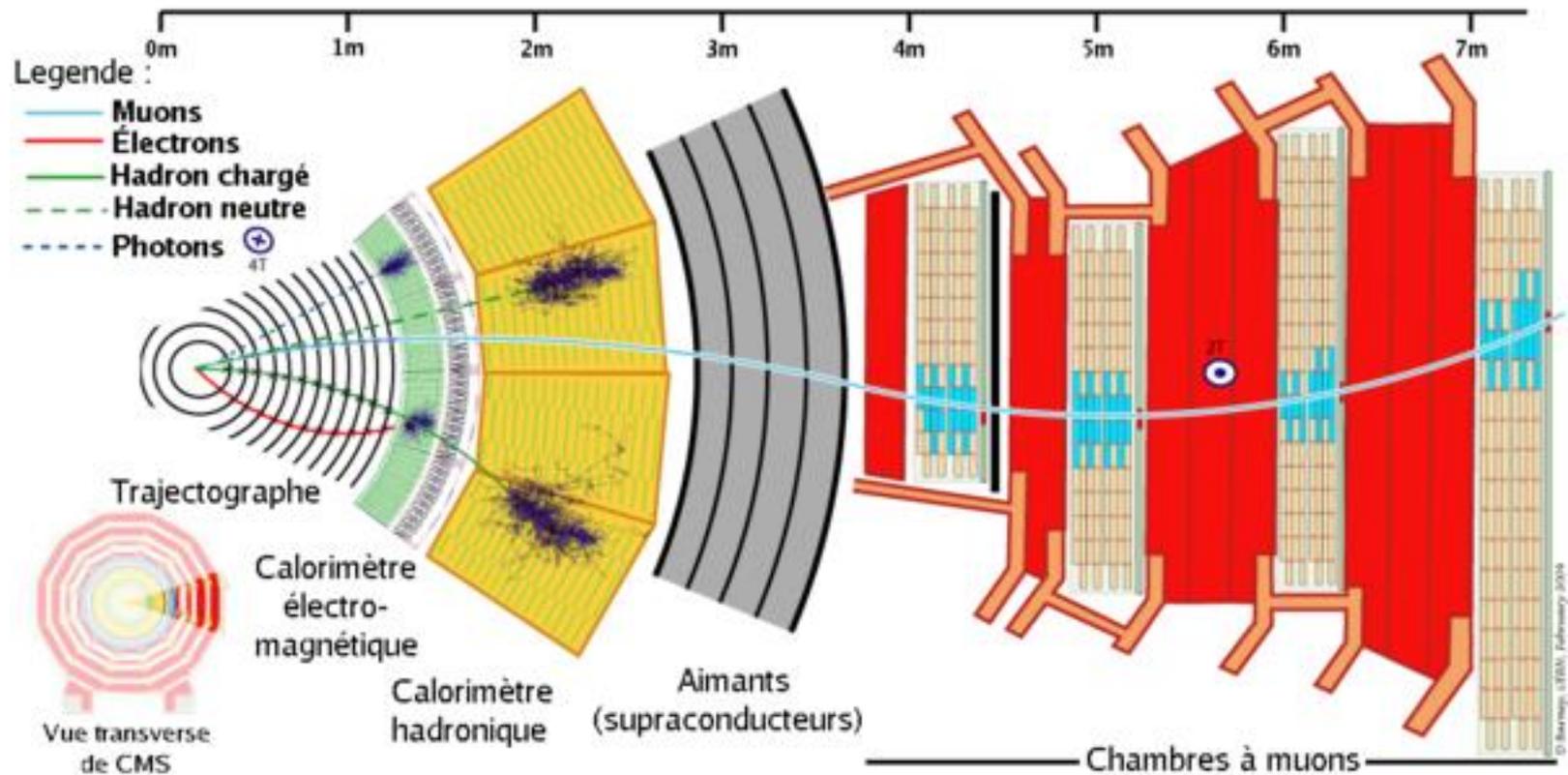


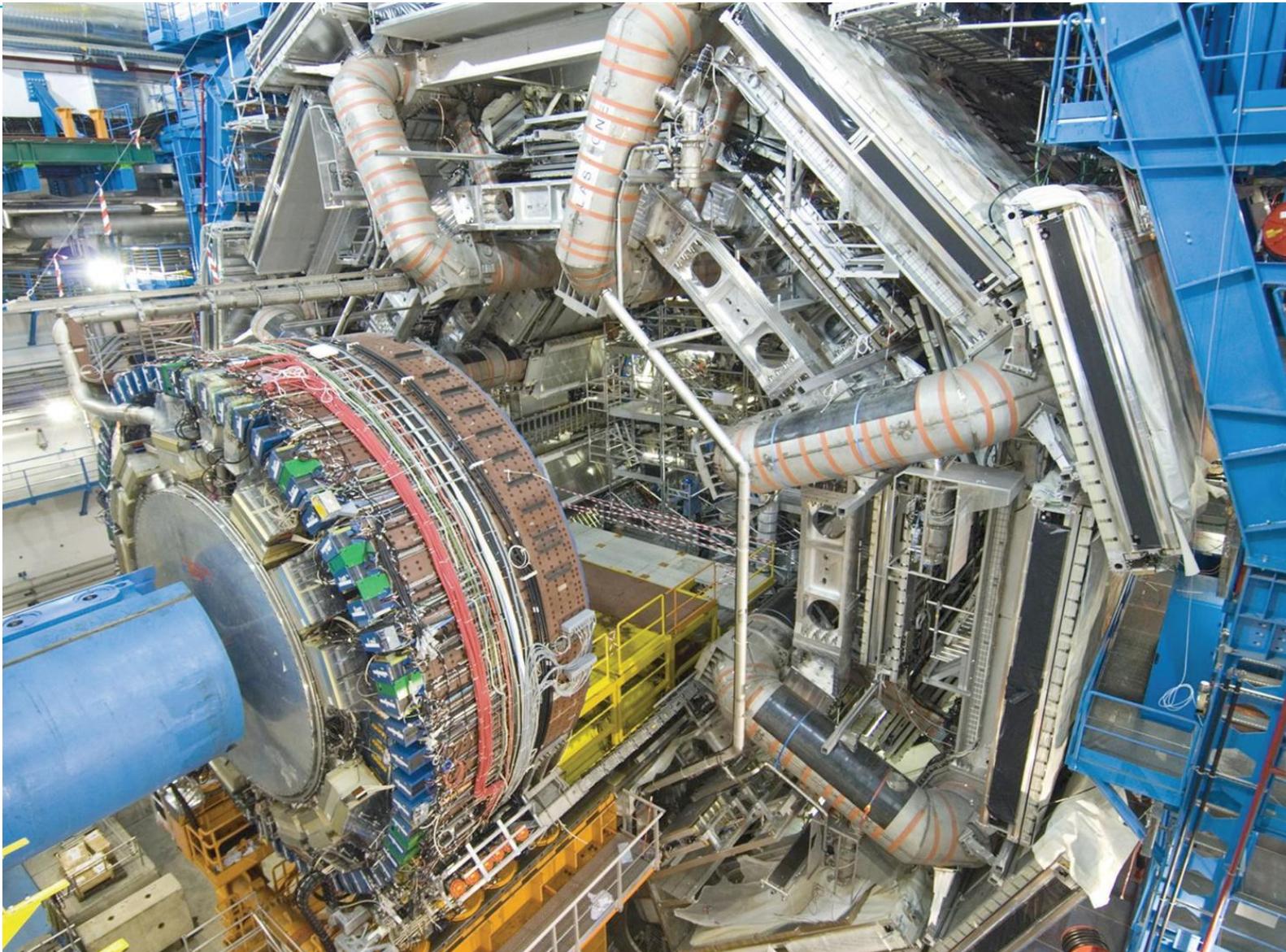


En moyenne 25 collisions pp / interaction  
 Taux de croisement: 40MHz

Sélection en temps réel!

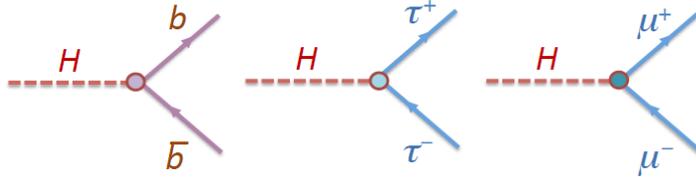




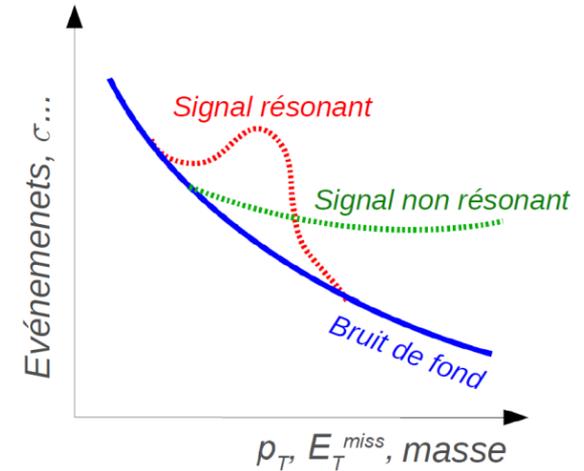
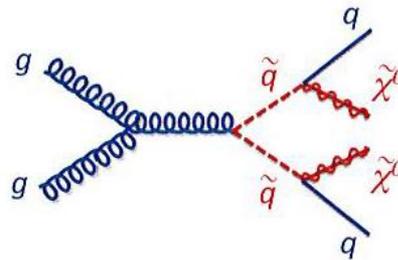


## Recherche directe de nouvelles particules

- Particules de courte durée de vie:  
 $\Rightarrow$  résonance dans les canaux de désintégration attendus



- Particules de longue durée de vie "invisibles"  
 $\Rightarrow$  énergie manquante

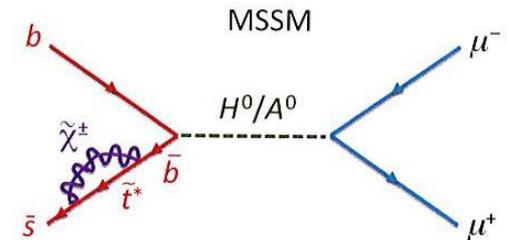


## Recherche indirecte

Particules trop lourdes pour être produites directement

$\Rightarrow$  production virtuelle

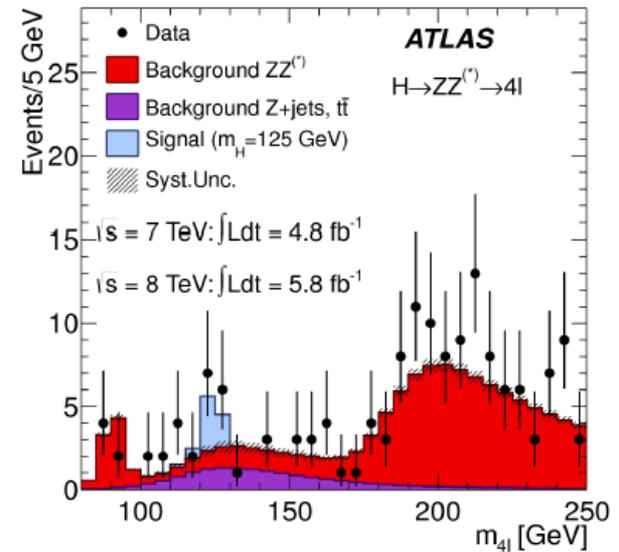
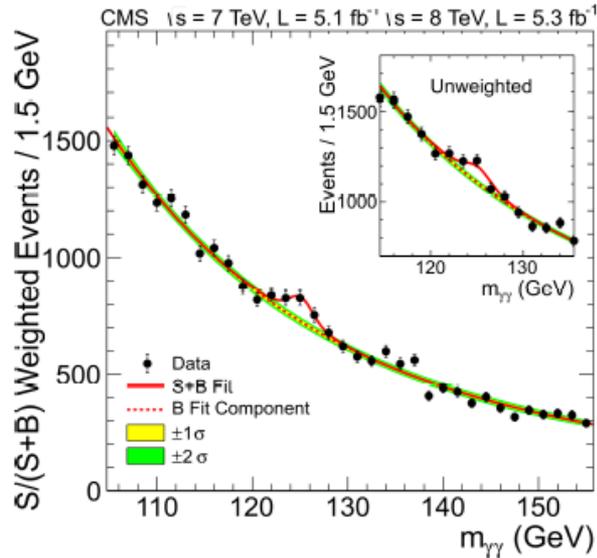
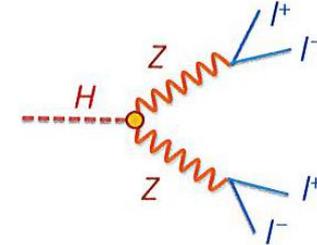
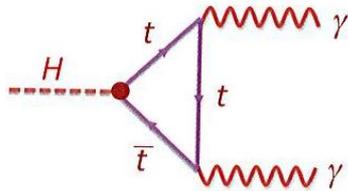
- $\Rightarrow$  modification des taux de production
- $\Rightarrow$  et des distributions angulaires



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# RECHERCHE DIRECTE DE NOUVELLE PHYSIQUE

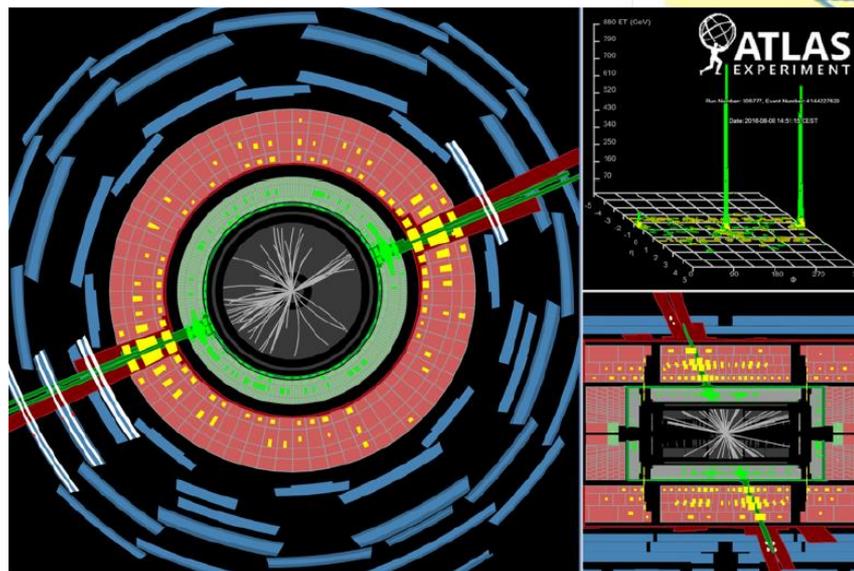
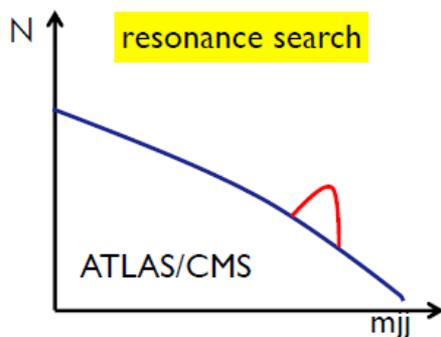
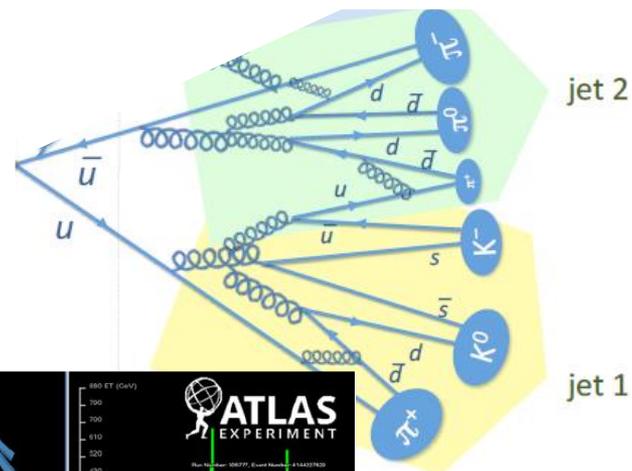
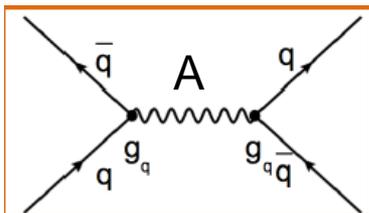
- Découverte du boson de Higgs en 2012 par ATLAS et CMS



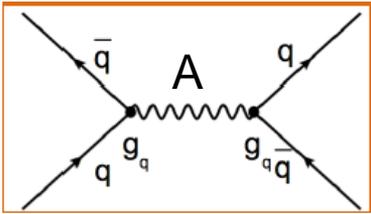
combinaison  $\Rightarrow m_H = 125.09 \pm 0.21(stat) \pm 0.11 (syst) GeV$



- Recherche de nouvelles particules : résonances

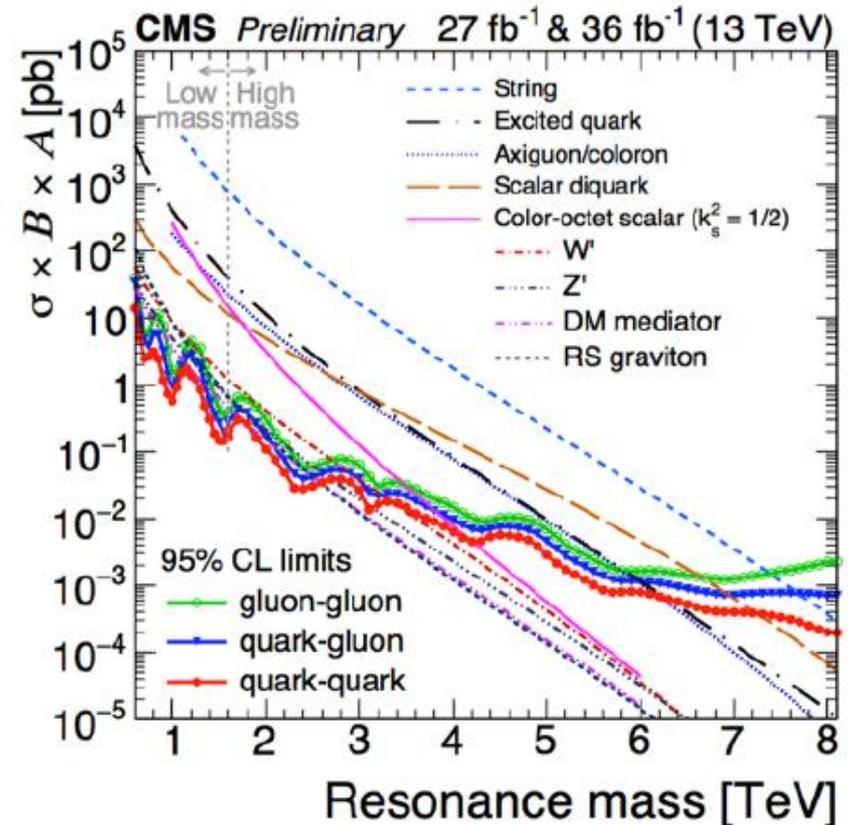
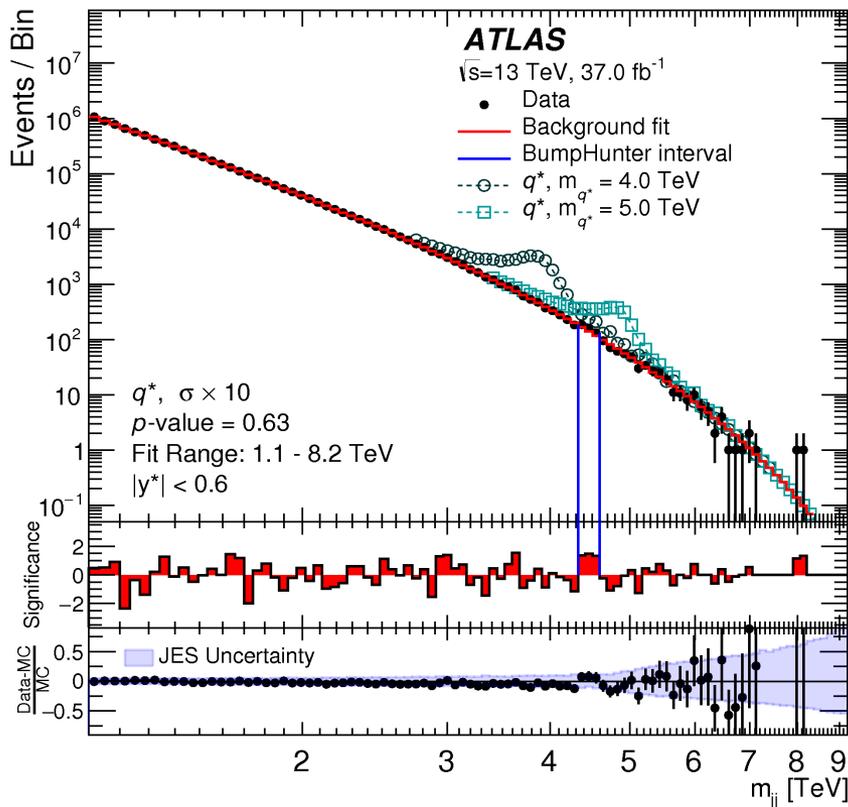


- De multiples canaux de désintégration envisagés!

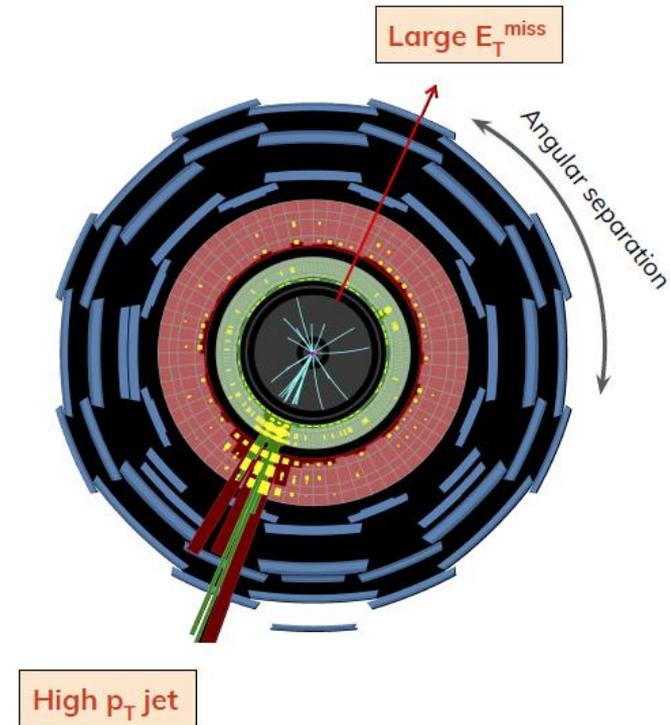
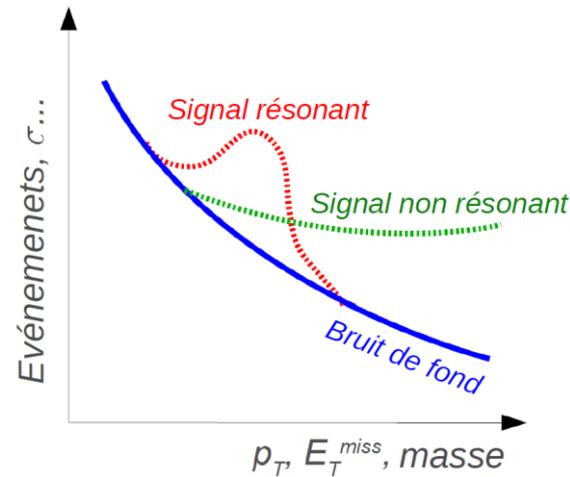
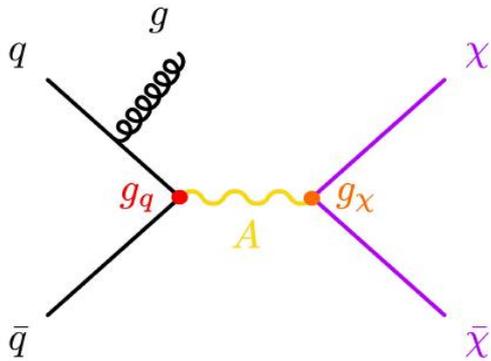


Pas d'excès observé

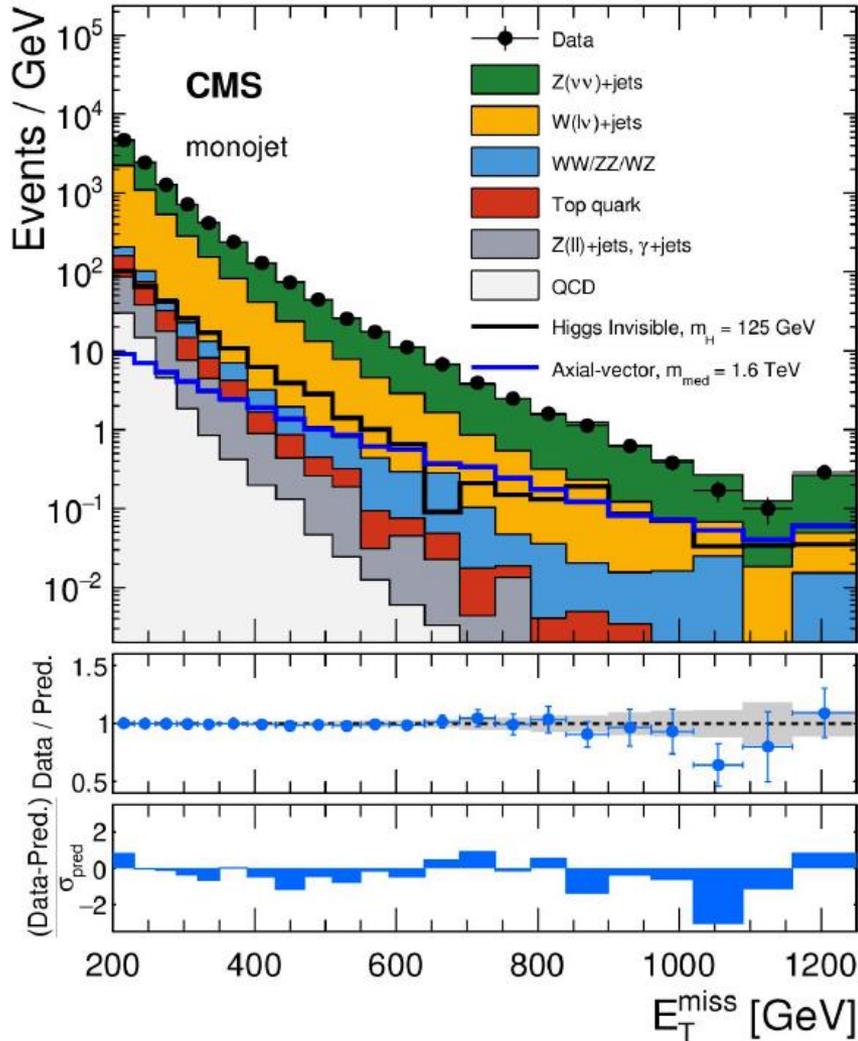
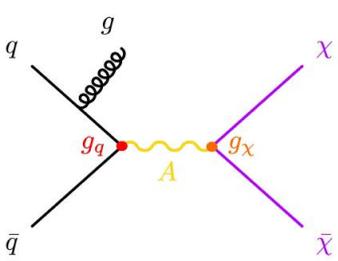
⇒ contraintes sur les theories de nouvelle physique



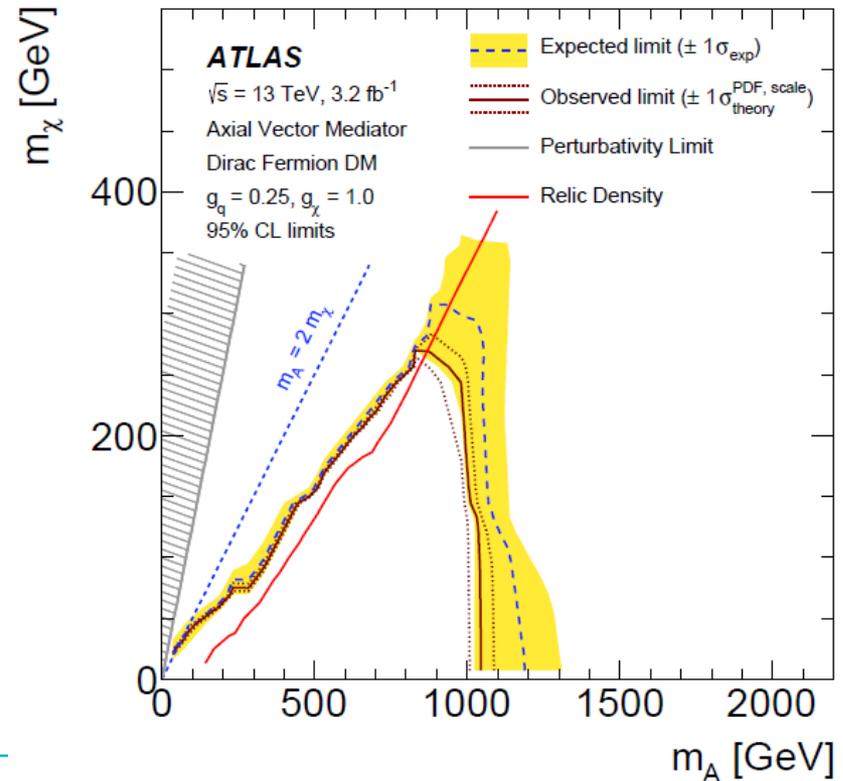
- Les particules de matière noire interagissent très faiblement  
 $\Rightarrow$  Elles ne sont pas détectées  
 $\Rightarrow$  détecter les particules les accompagnant (gluon, photon, W, Z, H,...)  
 $\Rightarrow$  Bilan d'énergie (énergie transverse manquante)



**Détecteur hermétiques!**



- Bruit de fond:  $Z \rightarrow \nu\nu$
- Pas d'excès  $\Rightarrow$  zone d'exclusion



## ATLAS SUSY Searches\* - 95% CL Lower Limits

May 2017

ATLAS Preliminary  
 $\sqrt{s} = 7, 8, 13 \text{ TeV}$

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} d\Omega (\text{fb}^{-1})$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 $e, \mu/1-2 \tau$	2-10 jets/3 $b$	Yes	20.3	$\tilde{g}, \tilde{g}$	1.85 TeV	$m(\tilde{g})=m(\tilde{g})$
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{q}\tilde{X}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	1.57 TeV	$m(\tilde{X}_1^0) < 200 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q}) = m(2^{\text{nd}} \text{ gen. } \tilde{q})$
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{q}\tilde{X}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	608 GeV	$m(\tilde{q}) - m(\tilde{X}_1^0) < 5 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{X}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.02 TeV	$m(\tilde{X}_1^0) < 200 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{X}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.01 TeV	$m(\tilde{X}_1^0) < 200 \text{ GeV}, m(\tilde{X}_2^0) = 0.5(m(\tilde{X}_1^0) + m(\tilde{g}))$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{X}_1^0$	3 $e, \mu$	4 jets	-	36.1	$\tilde{g}$	1.825 TeV	$m(\tilde{X}_1^0) < 400 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{X}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	1.8 TeV	$m(\tilde{X}_1^0) < 400 \text{ GeV}$
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	$\tilde{g}$	2.0 TeV	$m(\tilde{X}_1^0) < 400 \text{ GeV}$
	GGM (bino NLSP)	2 $\gamma$	-	Yes	3.2	$\tilde{g}$	1.65 TeV	$c\tau(\text{NLSP}) < 0.1 \text{ mm}$
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes	20.3	$\tilde{g}$	1.37 TeV	$m(\tilde{X}_1^0) < 950 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu < 0$
	GGM (higgsino-bino NLSP)	$\gamma$	2 jets	Yes	13.3	$\tilde{g}$	1.8 TeV	$m(\tilde{X}_1^0) > 680 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$
	GGM (higgsino NLSP)	2 $e, \mu$ (Z)	2 jets	Yes	20.3	$\tilde{g}$	900 GeV	$m(\text{NLSP}) > 430 \text{ GeV}$
Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g}) = m(\tilde{q}) = 1.5 \text{ TeV}$	
3 <sup>rd</sup> gen. & med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{X}_1^0$	0	3 $b$	Yes	36.1	$\tilde{g}$	1.92 TeV	$m(\tilde{X}_1^0) < 600 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{X}_1^0$	0-1 $e, \mu$	3 $b$	Yes	36.1	$\tilde{g}$	1.97 TeV	$m(\tilde{X}_1^0) < 200 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{t}\tilde{X}_1^0$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$	1.37 TeV	$m(\tilde{X}_1^0) < 300 \text{ GeV}$
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{X}_1^0$	0	2 $b$	Yes	36.1	$\tilde{b}_1$	950 GeV	$m(\tilde{X}_1^0) < 420 \text{ GeV}$
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{X}_1^0$	2 $e, \mu$ (SS)	1 $b$	Yes	36.1	$\tilde{b}_1$	275-700 GeV	$m(\tilde{X}_1^0) < 200 \text{ GeV}, m(\tilde{X}_2^0) = m(\tilde{X}_1^0) + 100 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{X}_1^0$	0-2 $e, \mu$	1-2 $b$	Yes	4.7/13.3	$\tilde{t}_1$	117-170 GeV	$m(\tilde{X}_1^0) = 2m(\tilde{X}_2^0), m(\tilde{X}_2^0) = 55 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{X}_1^0$ or $\tilde{t}_1\tilde{X}_1^0$	0-2 $e, \mu$	0-2 jets/1-2 $b$	Yes	20.3/36.1	$\tilde{t}_1$	90-198 GeV	$m(\tilde{X}_1^0) = 1 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{X}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$	90-323 GeV	$m(\tilde{X}_1^0) - m(\tilde{X}_2^0) = 5 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{t}_1$	150-600 GeV	$m(\tilde{X}_1^0) > 150 \text{ GeV}$
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$ (Z)	1 $b$	Yes	36.1	$\tilde{t}_2$	290-790 GeV	$m(\tilde{X}_1^0) = 0 \text{ GeV}$
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 $e, \mu$	4 $b$	Yes	36.1	$\tilde{t}_2$	320-880 GeV	$m(\tilde{X}_1^0) = 0 \text{ GeV}$	
EW direct	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi}_{1,R}^0 \rightarrow \tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0$	2 $e, \mu$	0	Yes	36.1	$\tilde{\chi}$	90-440 GeV	$m(\tilde{X}_1^0) = 0$
	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi}_{1,R}^0 \rightarrow \tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0$	2 $e, \mu$	0	Yes	36.1	$\tilde{\chi}_{1,R}^0$	710 GeV	$m(\tilde{X}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{X}_1^0) + m(\tilde{X}_2^0))$
	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi}_{1,R}^0 \rightarrow \tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0$	2 $\tau$	-	Yes	36.1	$\tilde{\chi}_{1,R}^0$	760 GeV	$m(\tilde{X}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{X}_1^0) + m(\tilde{X}_2^0))$
	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi}_{1,R}^0 \rightarrow \tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0$	3 $e, \mu$	0	Yes	36.1	$\tilde{\chi}_{1,R}^0, \tilde{\chi}_{2,R}^0$	1.16 TeV	$m(\tilde{X}_1^0) = m(\tilde{X}_2^0), m(\tilde{X}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{X}_1^0) + m(\tilde{X}_2^0))$
	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi}_{1,R}^0 \rightarrow W\tilde{\chi}_{1,R}^0 Z\tilde{\chi}_{1,R}^0$	2-3 $e, \mu$	0-2 jets	Yes	36.1	$\tilde{\chi}_{1,R}^0, \tilde{\chi}_{2,R}^0$	580 GeV	$m(\tilde{X}_1^0) = m(\tilde{X}_2^0), m(\tilde{X}_1^0) = 0, \tilde{\ell}$ decoupled
	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi}_{1,R}^0 \rightarrow W\tilde{\chi}_{1,R}^0 h\tilde{\chi}_{1,R}^0, h \rightarrow bb/\gamma\gamma/\tau\tau/\gamma\gamma$	$e, \mu, \gamma$	0-2 $b$	Yes	20.3	$\tilde{\chi}_{1,R}^0, \tilde{\chi}_{2,R}^0$	270 GeV	$m(\tilde{X}_1^0) = m(\tilde{X}_2^0), m(\tilde{X}_1^0) = 0, \tilde{\ell}$ decoupled
	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi}_{1,R}^0 \rightarrow \tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0$	4 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_{1,R}^0, \tilde{\chi}_{2,R}^0$	635 GeV	$m(\tilde{X}_2^0) = m(\tilde{X}_3^0), m(\tilde{X}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{X}_2^0) + m(\tilde{X}_3^0))$
	GGM (wino NLSP) weak prod., $\tilde{\chi}_{1,R}^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$	115-370 GeV	$c\tau < 1 \text{ mm}$
	GGM (bino NLSP) weak prod., $\tilde{\chi}_{1,R}^0 \rightarrow \gamma\tilde{G}$	2 $\gamma$	-	Yes	20.3	$\tilde{W}$	590 GeV	$c\tau < 1 \text{ mm}$
	Long-lived particles	Direct $\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0$ prod., long-lived $\tilde{\chi}_{1,R}^0$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_{1,R}^0$	430 GeV
Direct $\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0$ prod., long-lived $\tilde{\chi}_{1,R}^0$		dE/dx trk	-	Yes	18.4	$\tilde{\chi}_{1,R}^0$	495 GeV	$m(\tilde{X}_1^0) = m(\tilde{X}_2^0) = 160 \text{ MeV}, \tau(\tilde{\chi}_{1,R}^0) < 15 \text{ ns}$
Stable, stopped $\tilde{g}$ R-hadron		0	1-5 jets	Yes	27.9	$\tilde{g}$	850 GeV	$m(\tilde{X}_1^0) = 100 \text{ GeV}, 10 \mu\text{s} < c\tau < 1000 \text{ s}$
Stable $\tilde{g}$ R-hadron		trk	-	-	3.2	$\tilde{g}$	1.58 TeV	1606.05129
Metastable $\tilde{g}$ R-hadron		dE/dx trk	-	-	3.2	$\tilde{g}$	1.57 TeV	1604.04520
GMSB, stable $\tilde{\tau}, \tilde{\chi}_{1,R}^0 \rightarrow \tilde{\tau}(\tilde{\ell}, \tilde{\mu}) + \tau(e, \mu)$		1-2 $\mu$	-	-	19.1	$\tilde{\chi}_{1,R}^0$	537 GeV	$m(\tilde{X}_1^0) = 100 \text{ GeV}, \tau > 10 \text{ ns}$
GMSB, $\tilde{\chi}_{1,R}^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_{1,R}^0$		2 $\gamma$	-	Yes	20.3	$\tilde{\chi}_{1,R}^0$	440 GeV	$1 < c\tau(\tilde{\chi}_{1,R}^0) < 3 \text{ ns}, \text{SPS8 model}$
$\tilde{g}\tilde{g}, \tilde{\chi}_{1,R}^0 \rightarrow e\tilde{\nu}\tilde{\chi}_{1,R}^0/\mu\tilde{\nu}\tilde{\chi}_{1,R}^0$		displ. $e\tilde{\nu}/\mu\tilde{\nu}$	-	-	20.3	$\tilde{\chi}_{1,R}^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_{1,R}^0) < 740 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_{1,R}^0 \rightarrow Z\tilde{G}$		displ. vtx + jets	-	-	20.3	$\tilde{\chi}_{1,R}^0$	1.0 TeV	$6 < c\tau(\tilde{\chi}_{1,R}^0) < 480 \text{ mm}, m(\tilde{g}) = 1.1 \text{ TeV}$
RPV		LFV $pp \rightarrow \tilde{\nu}_\tau + \tilde{X}, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, \tau\mu$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV
	Bilinear RPV CMSSM	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{q}, \tilde{g}$	1.45 TeV	$m(\tilde{g}) = m(\tilde{q}), c\tau_{LSP} < 1 \text{ mm}$
	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi}_{1,R}^0 \rightarrow W\tilde{\chi}_{1,R}^0 \tilde{\chi}_{1,R}^0 \rightarrow e\tilde{\nu}, e\mu, \mu\nu$	4 $e, \mu$	-	Yes	13.3	$\tilde{\chi}_{1,R}^0$	1.14 TeV	$m(\tilde{X}_1^0) > 400 \text{ GeV}, A_{12k} \neq 0 (k = 1, 2)$
	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi}_{1,R}^0 \rightarrow \tau\nu\tilde{X}_1^0, \tilde{\chi}_{1,R}^0 \rightarrow \tau\nu\tilde{X}_1^0, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_{1,R}^0$	450 GeV	$m(\tilde{X}_1^0) > 0.2 \times m(\tilde{X}_2^0), A_{133} \neq 0$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{X}_1^0$	0	4-5 large-R jets	-	14.8	$\tilde{g}$	1.08 TeV	$BR(\tilde{g}) = BR(b) = BR(c) = 0\%$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{X}_1^0, \tilde{X}_1^0 \rightarrow q\tilde{q}$	0	4-5 large-R jets	-	14.8	$\tilde{g}$	1.55 TeV	$m(\tilde{X}_1^0) = 800 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{X}_1^0, \tilde{X}_1^0 \rightarrow q\tilde{q}$	1 $e, \mu$	8-10 jets/0-4 $b$	-	36.1	$\tilde{g}$	2.1 TeV	$m(\tilde{X}_1^0) = 1 \text{ TeV}, A_{112} \neq 0$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}, \tilde{t}_1 \rightarrow b\tilde{s}$	1 $e, \mu$	8-10 jets/0-4 $b$	-	36.1	$\tilde{g}$	1.65 TeV	$m(\tilde{t}_1) = 1 \text{ TeV}, A_{323} \neq 0$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	0	2 jets + 2 $b$	-	15.4	$\tilde{t}_1$	410 GeV	ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\ell}$	2 $e, \mu$	2 $b$	-	36.1	$\tilde{t}_1$	0.4-1.45 TeV	$BR(\tilde{t}_1 \rightarrow b\tilde{\mu}) > 20\%$
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{X}_1^0$	0	2 $c$	Yes	20.3	$\tilde{c}$	510 GeV	$m(\tilde{X}_1^0) < 200 \text{ GeV}$

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup>

1 2 Mass scale (TeV)

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# RECHERCHE INDIRECTE DE NOUVELLE PHYSIQUE

## Mesures précises de la resonance du boson Z au LEP (1990's)

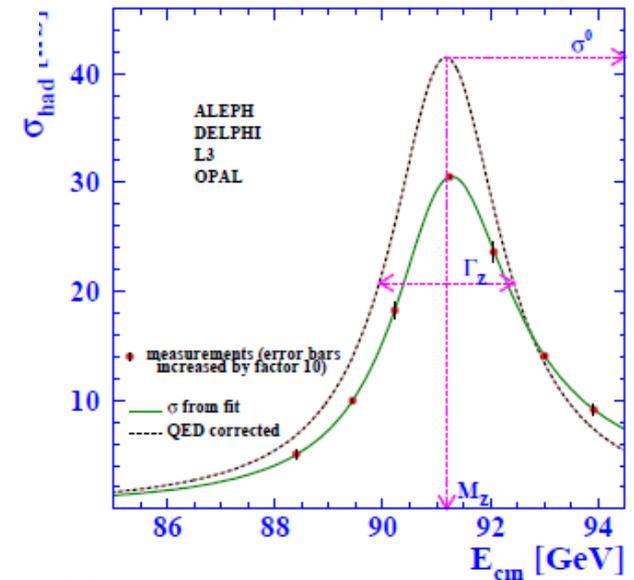


- $\sigma = f(m_{top}, m_W, \ln(m_H), \dots)$

$$\Rightarrow m_{top} = 179_{-9}^{+11} \text{ GeV}/c^2$$

- Découverte du quark top au Tevatron en 1995:

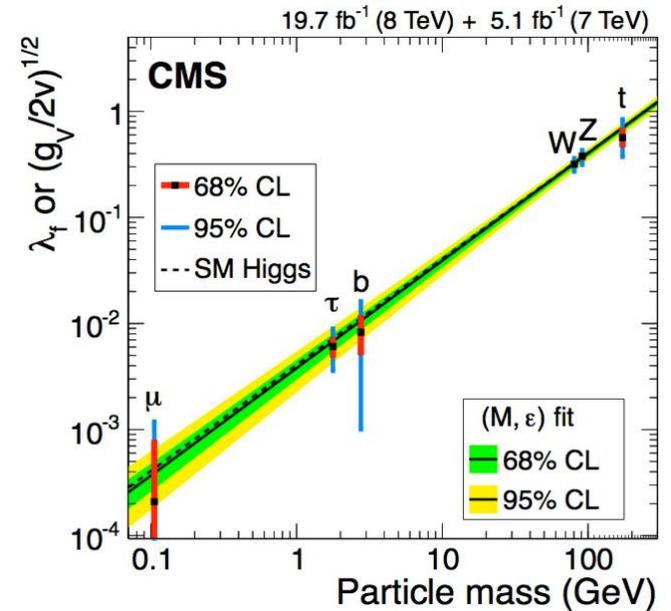
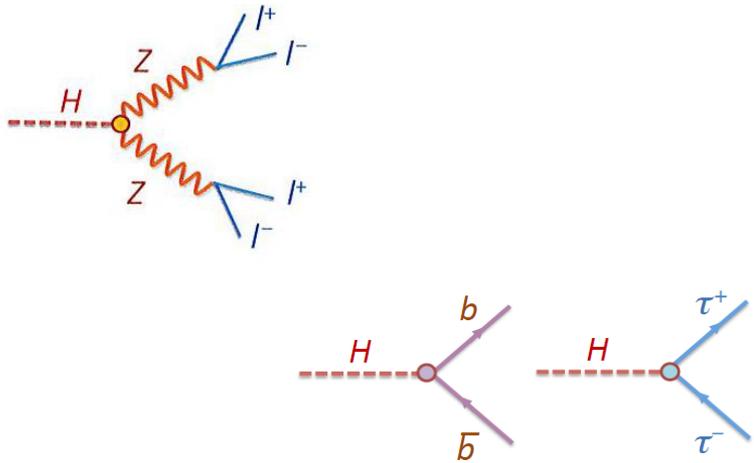
$$m_{top} = 176 \pm 12 \text{ GeV}/c^2 !$$



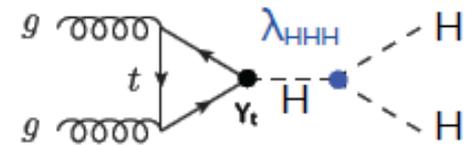
Ensuite: mesure des masses du quark top et du boson W à Tevatron et LEP

$\Rightarrow$  Prédiction de la masse du boson de Higgs!

- Couplage du Higgs aux fermions et bosons W, Z

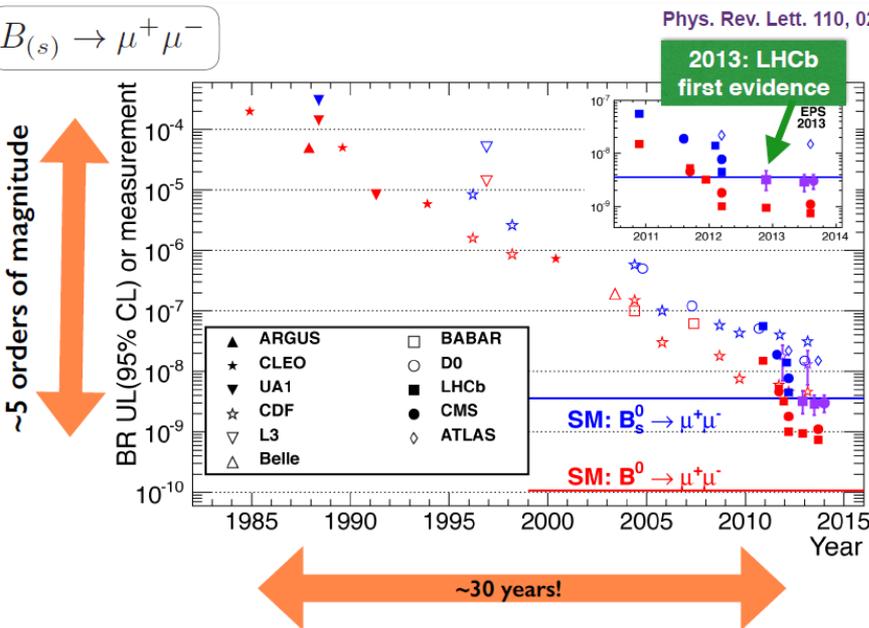
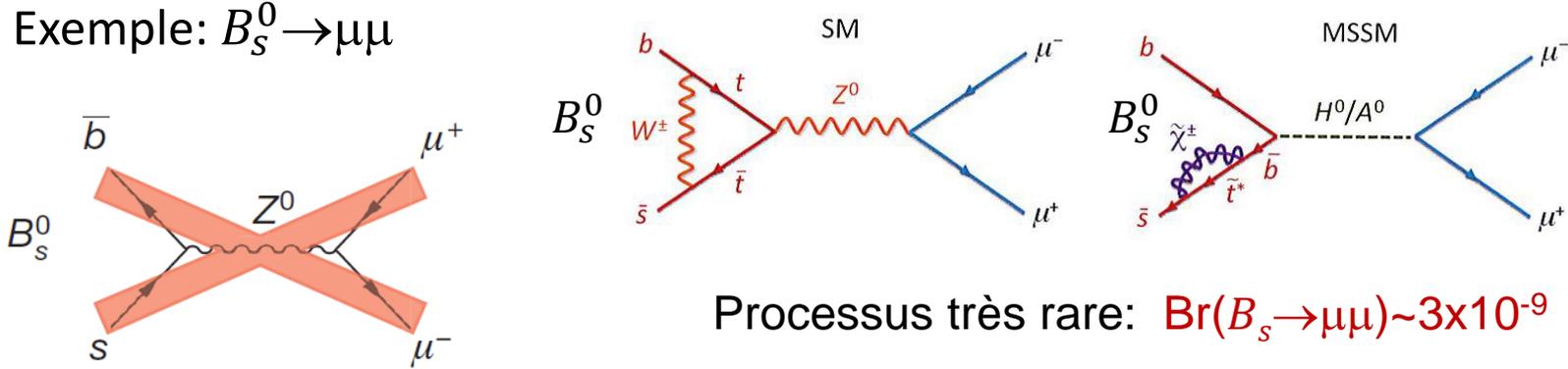


- Et un jour: auto-couplage du Higgs...

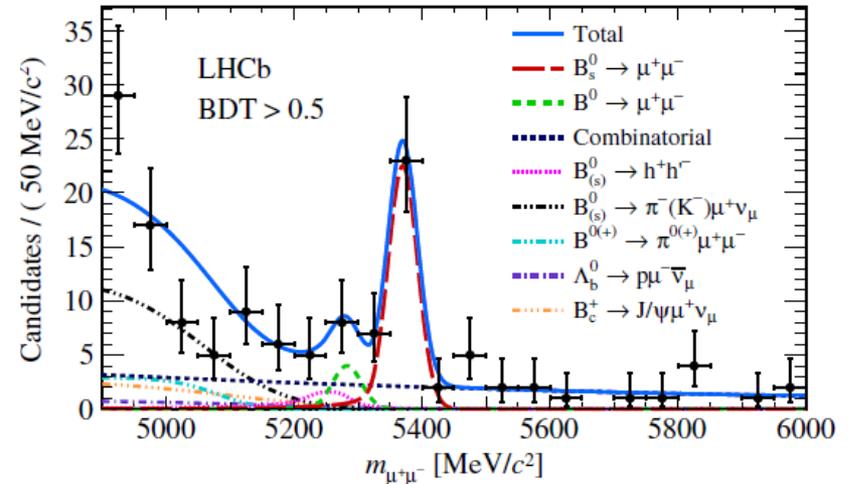


# Recherche de processus rares: $B_s \rightarrow \mu\mu$

- Processus supprimés dans le Modèle Standard peuvent recevoir une contribution importante de nouvelle physique
- Exemple:  $B_s^0 \rightarrow \mu\mu$



Première mise en évidence par LHCb



Processus rares:  $B \rightarrow K^{(*)} \mu^+ \mu^-$  et  $B \rightarrow K^{(*)} e^+ e^-$

- Modèle standard:

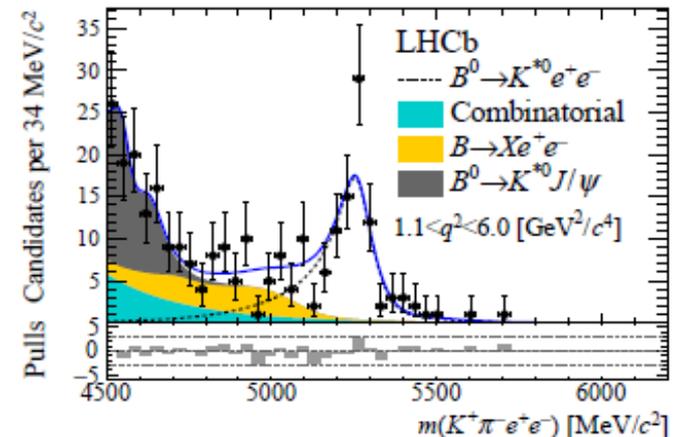
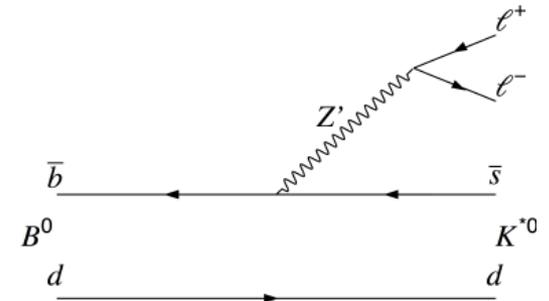
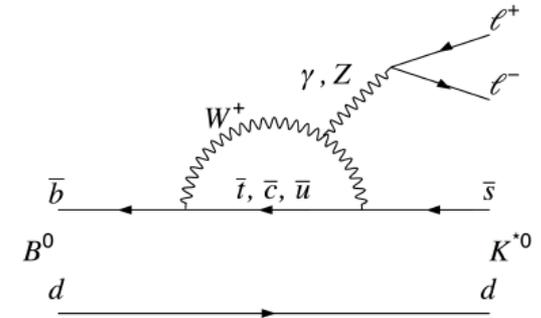
les couplages du Z sont les mêmes pour les 3 familles de leptons (e,  $\mu$ ,  $\tau$ )

- Nouvelle physique:

nouveaux bosons se couplant différemment aux 3 familles de leptons ( $Z'$ , leptoquarks)

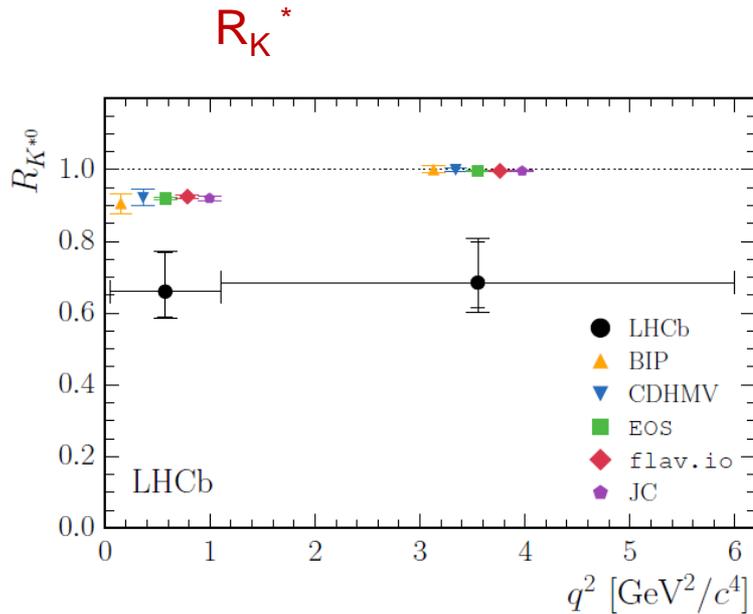
- Test:

$$R_K^{(*)} = \text{Br}(B \rightarrow K^{(*)} \mu^+ \mu^-) / \text{Br}(B \rightarrow K^{(*)} e^+ e^-)$$



- Prédiction du Modèle Standard:

$$R_K^{(*)} = \text{Br}(B \rightarrow K^{(*)} \mu^+ \mu^-) / \text{Br}(B \rightarrow K^{(*)} e^+ e^-) = 1 \quad (\text{à } 10^{-3})$$



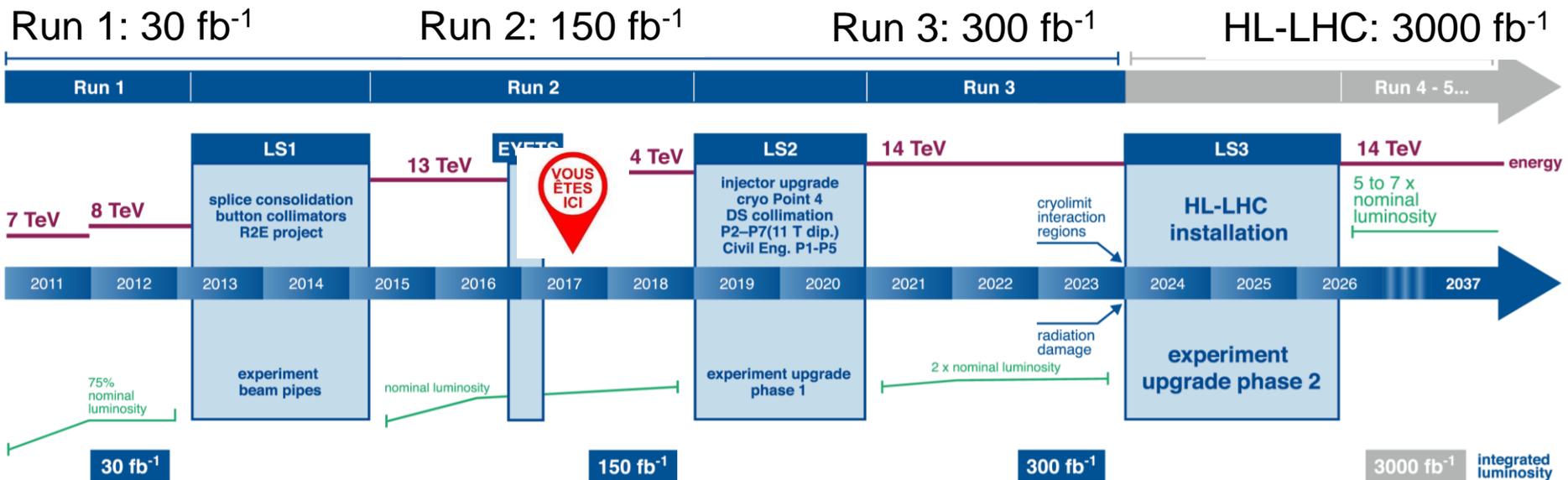
$$R_K = 0.745_{-0.074}^{+0.090}(\text{stat}) \pm 0.036(\text{syst})$$

⇒ Accumuler plus de données!  
et mesurer d'autres canaux

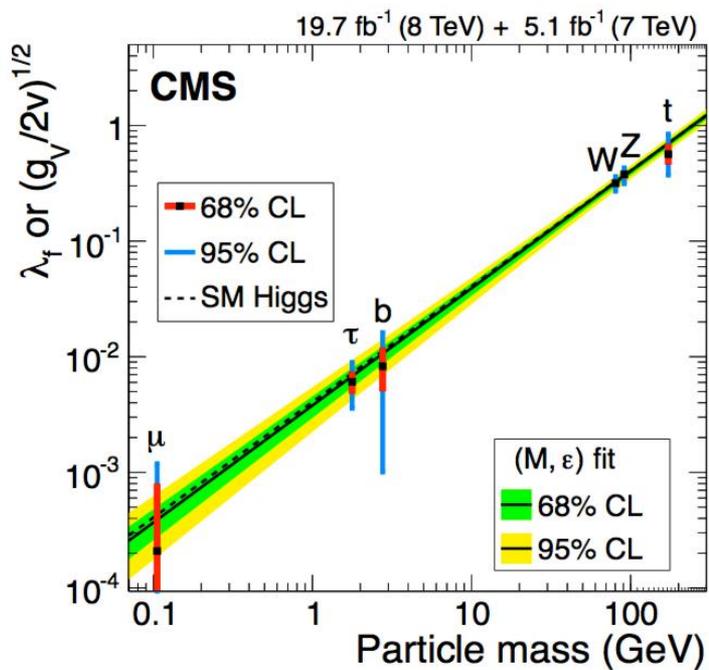


- Découverte du boson de Higgs !
- Recherche directe et indirecte de physique au delà du Modèle Standard  
 ⇒ contraintes sur la nouvelle physique
- Les processus recherchés sont rares

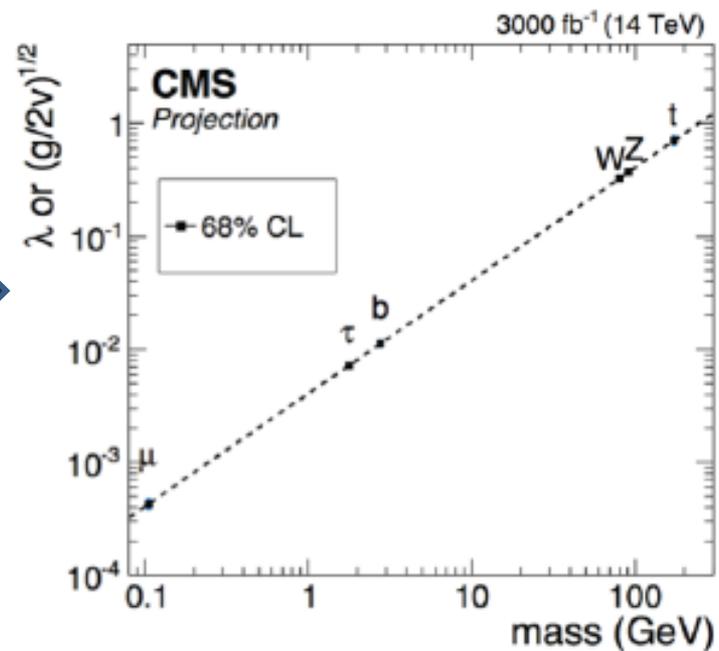
⇒ **HiLuminosity-LHC** (2026-2037?)



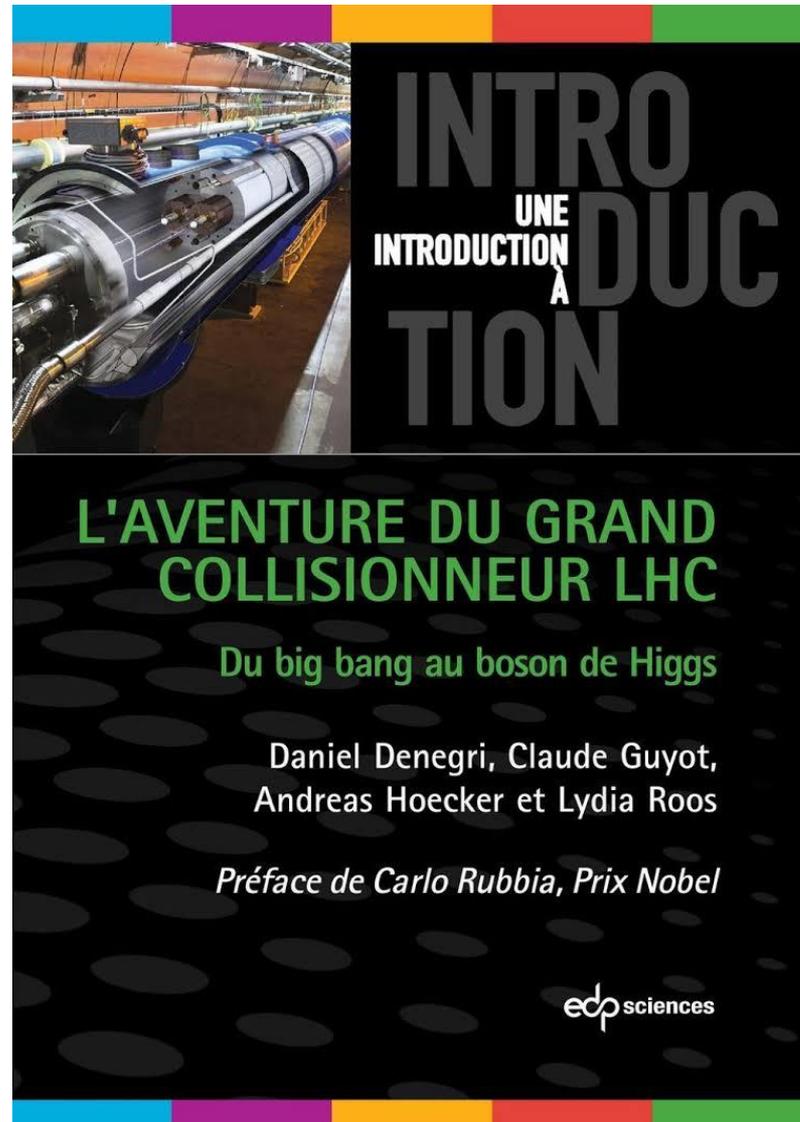
LHC Run 1 (25 fb<sup>-1</sup>)



HL-LHC (3000 fb<sup>-1</sup>)

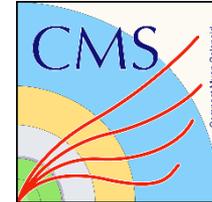


- La physique au-delà du Modèle Standard est nécessaire
- Exploration de ces nouveaux territoires par le LHC
  - Découverte du boson de Higgs (la masse) en 2012
  - Contraintes sur les theories de nouvelle physique
- L'aventure ne fait que commencer (50 fois plus de données avec HL-LHC)



## Présentations sur la recherche de nouvelle physique au LHC:

- C2-3 (DPPart):
  - Nareï Lorenzo Martinez
  - Nicolas Chanon



- C5-3 (DPPart, Dacc)
  - Laurent Tavian

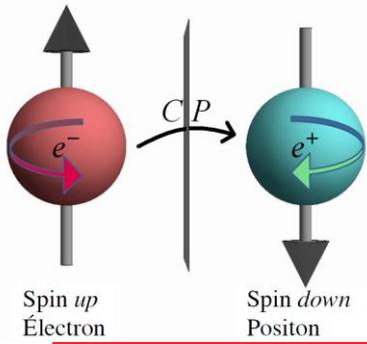


- C6-3 (DPPart):
  - Olivier Deschamps
  - Kristof De Bruyn



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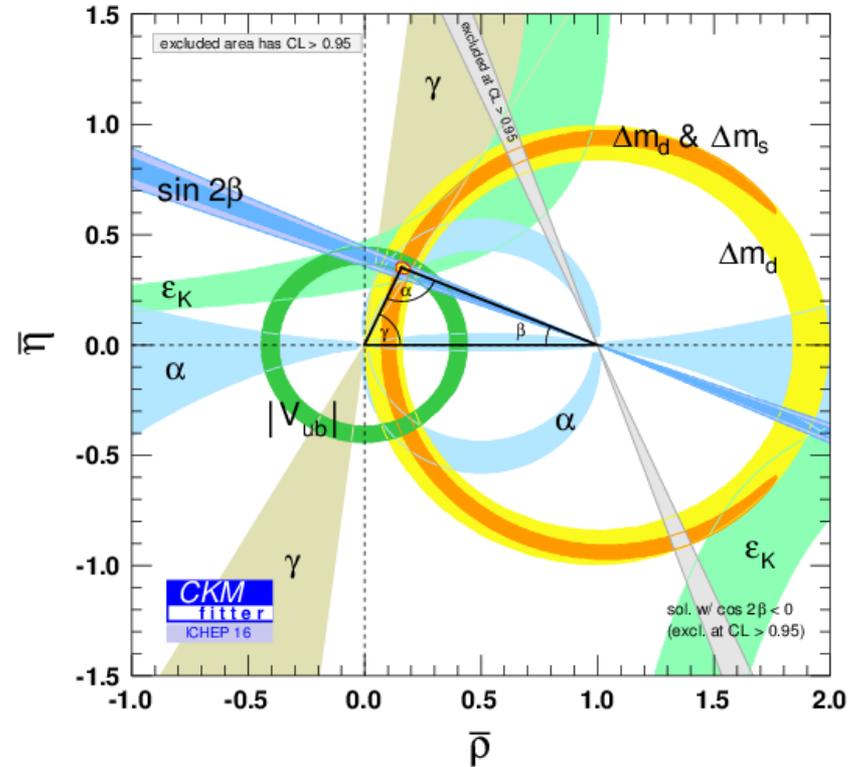
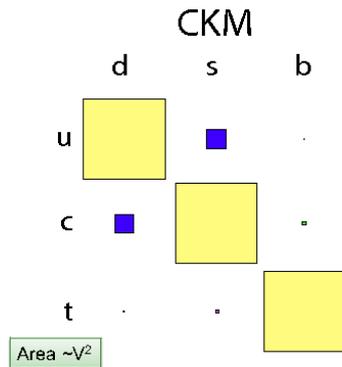
END



## La matrice CKM

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

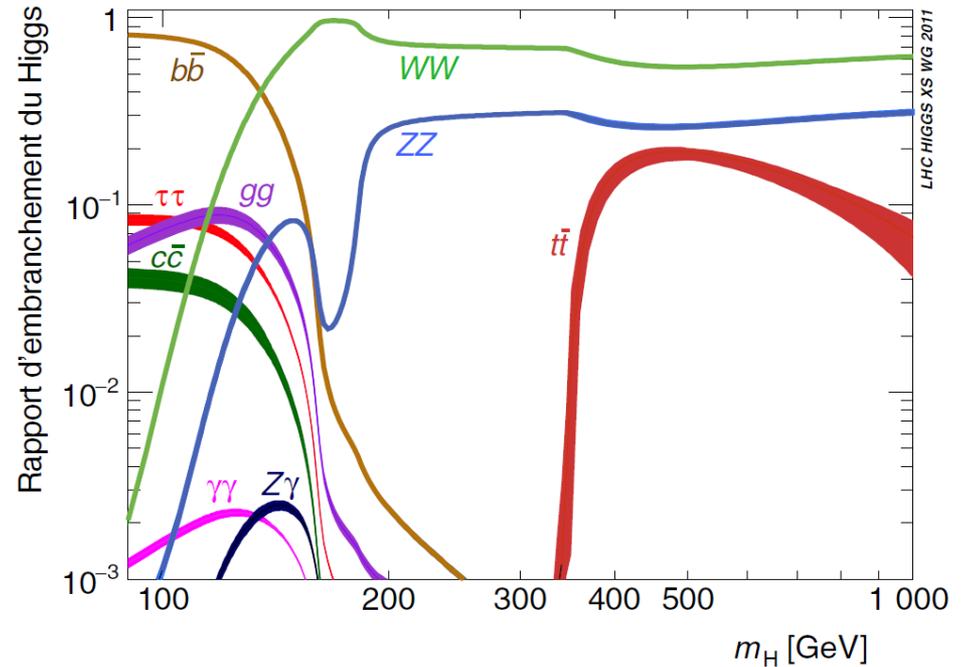
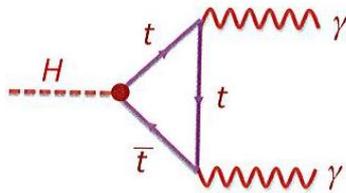
weak eigenstates  $\rightarrow$  Cabibbo Kobayashi Maskawa (CKM) matrix  $\rightarrow$  mass eigenstates

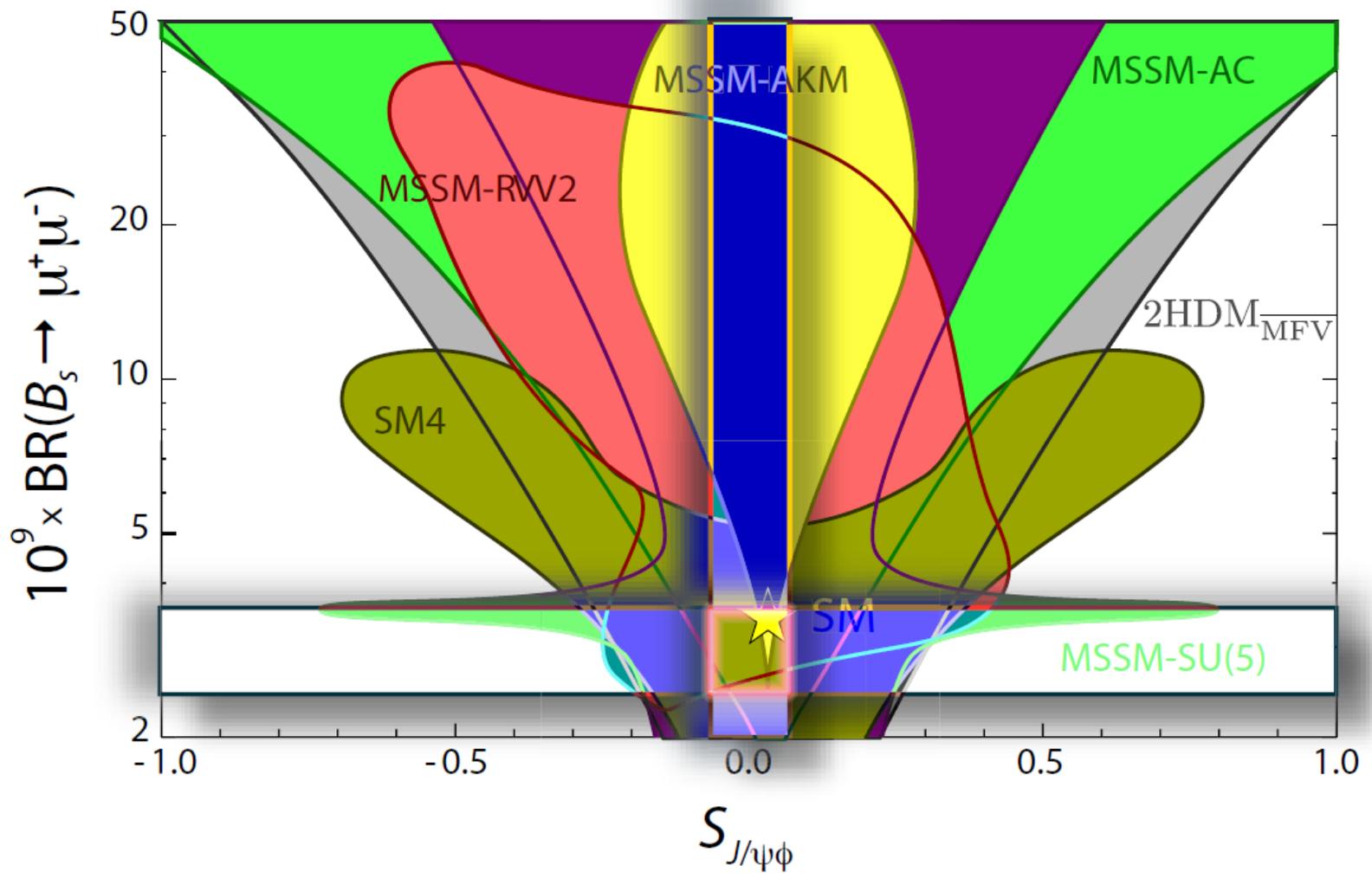


- Observer les produits de désintégration du Higgs

- $H \rightarrow f \bar{f}$
- $H \rightarrow ZZ, WW$
- $H \rightarrow \gamma \gamma$

- Couplage proportionnel à la masse  
... à quelques corrections près

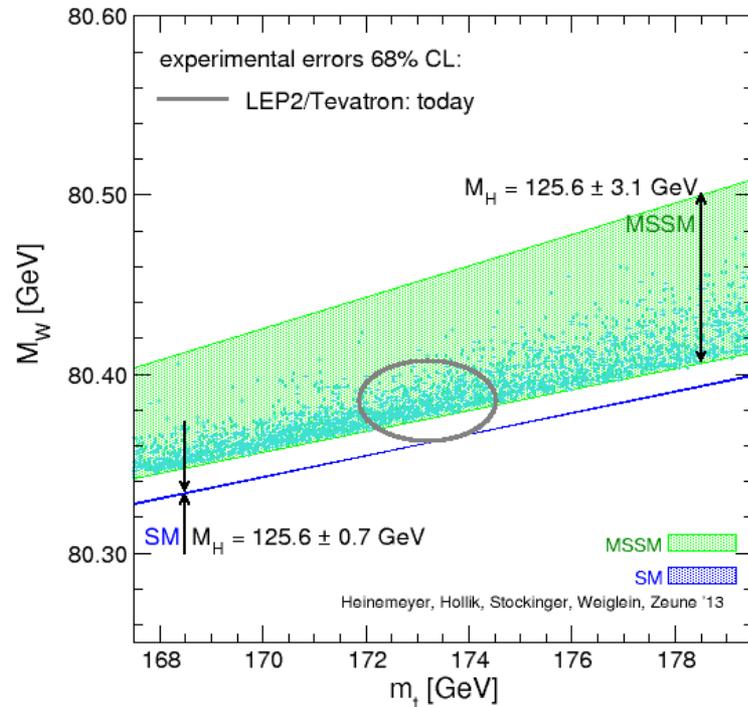
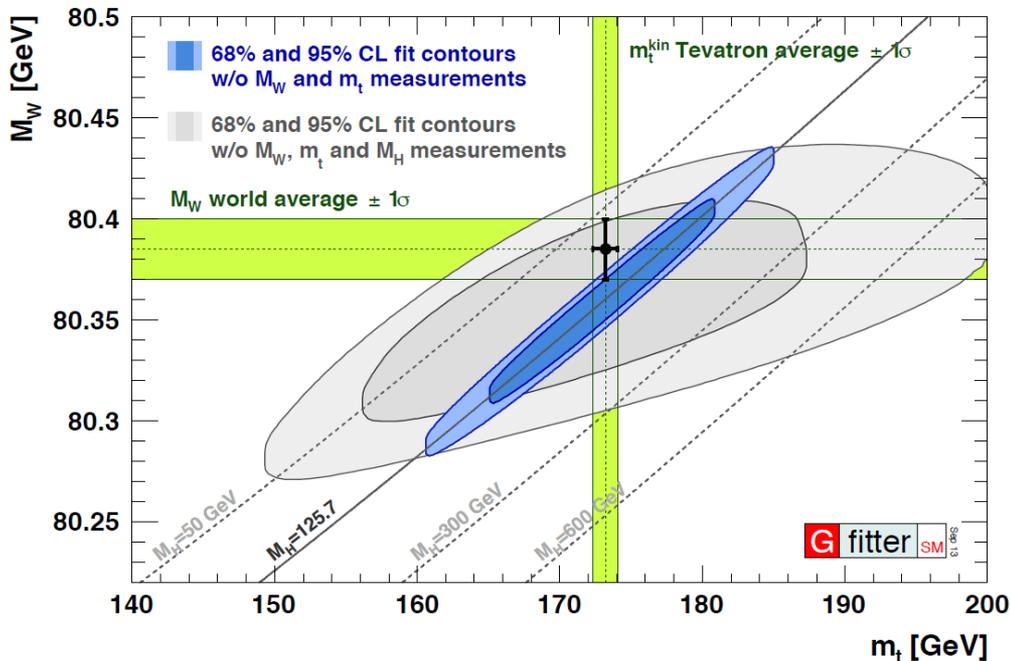




Et maintenant?

- Mesures précises de la masse du top et du W (LEP, Tevatron, LHC)
- Mesure de la masse du boson de Higgs au LHC

➔ Test de consistance du MS et contrainte nouvelle physique



## Etude de la nouvelle physique découverte au (HL)-LHC

- Collisionneur linéaire ee: ILC, CLIC -  $E_{\text{cm}} = 500 \text{ GeV} \text{ à } 3 \text{ TeV}$  - 2030?
  - Mesures de precisions: Higgs , quark top
  - Etude des particules découvertes au LHC
- FCC: collisionneur e+e-, e-p ou p-p (100 TeV)

