Physics Beyond the Standard Model

8th CLASHEP
Equador, March 2015

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Lecture 1: The reasons for BSM and the agnostic approach
Lecture 2: Simple extensions of the Standard Model
Lecture 3: Naturalness guided BSM

I’m afraid there will be significant overlap with other lectures, especially Christophe’s.

This should make our task easier!

Successes of Standard Model

Standard Model describes almost all the experimental data produced over many decades in many different experiments (not only particle accelerators).

Just to mention a few of the tests:

- muon magnetic moment
- electron magnetic moment
- Z line shape and the number of neutrinos
- precision measurements at LEP
- hadron collider results
- the discovery of a Higgs boson

Muon and electron anomalous magnetic moment

g-factor: relation between spin and magnetic moment

$$\vec{\mu} = g_\mu \frac{e\hbar}{2m_\mu c}\vec{s}, \qquad \underbrace{g_\mu}_{\text{Dirac}} = 2(1+a_\mu)$$

$$a_\mu^{\text{SM}} = 116\,591\,802(2)(42)(26) \times 10^{-11}$$

$$a_\mu^{\text{exp}} = 116\,592\,089(54)(33) \times 10^{-11}$$

$$a_\mu^{\text{SUSY}} \simeq \pm 130 \times 10^{-11} \cdot \left(\frac{100\ \text{GeV}}{m_{\text{SUSY}}}\right)^2 \tan\beta$$

$(g\text{-}2)_\mu$ experiment moved to Fermilab

$$a_e(\text{exp}) = 1\ 159\ 652\ 180.73\ (0.28) \times 10^{-12} \quad [0.24\ ppb]$$

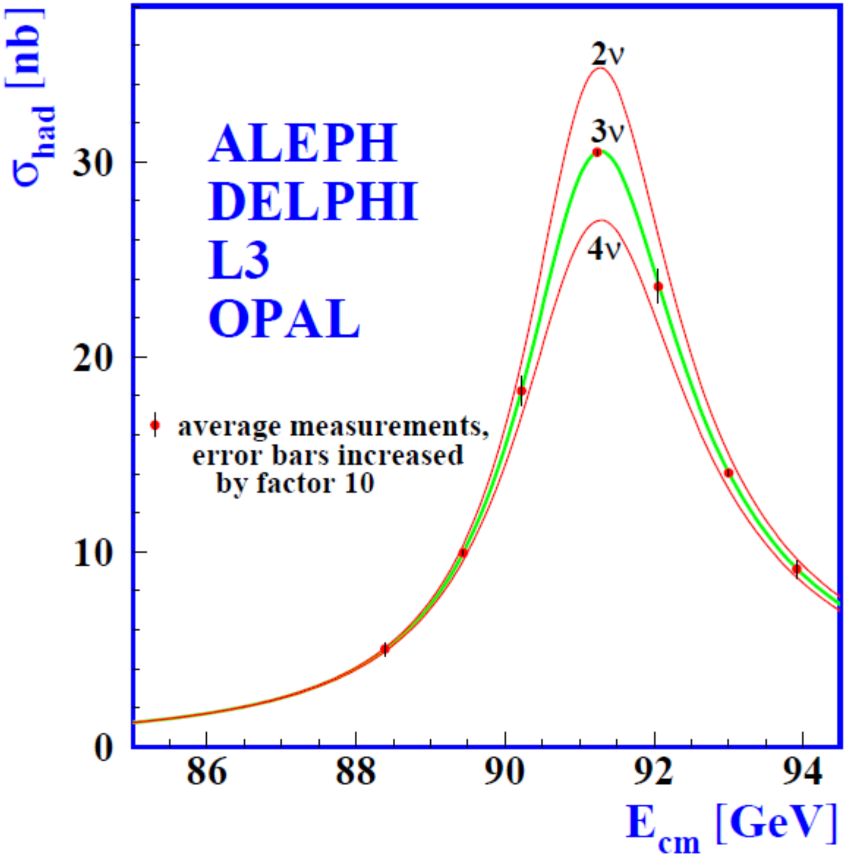
Table top experiment

Hanneke,Fogwell,Gabrielse, PRL 100, 120801 (2008)

Best determination of fine structure constant

$$\alpha^{-1}(a_e) = 137.035\ 999\ 085\ (12)(37)(33) \quad [0.37\ ppb]$$

Z line shape and the number of neutrinos from LEP

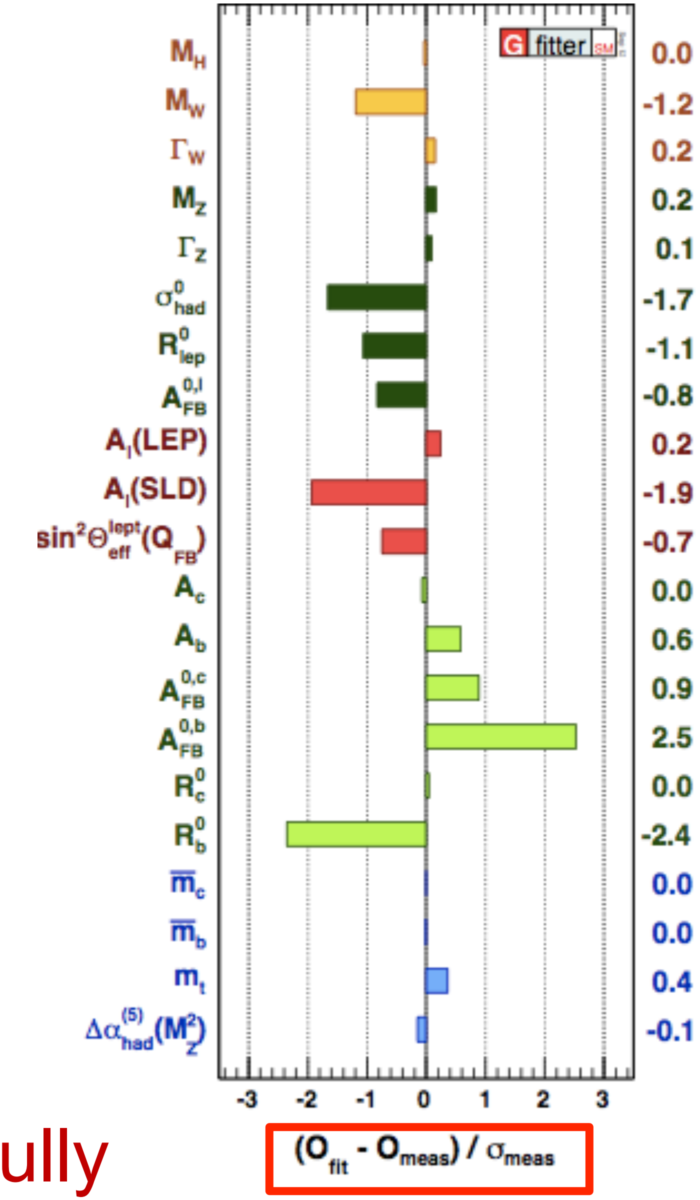


Effective number of near massless neutrinos

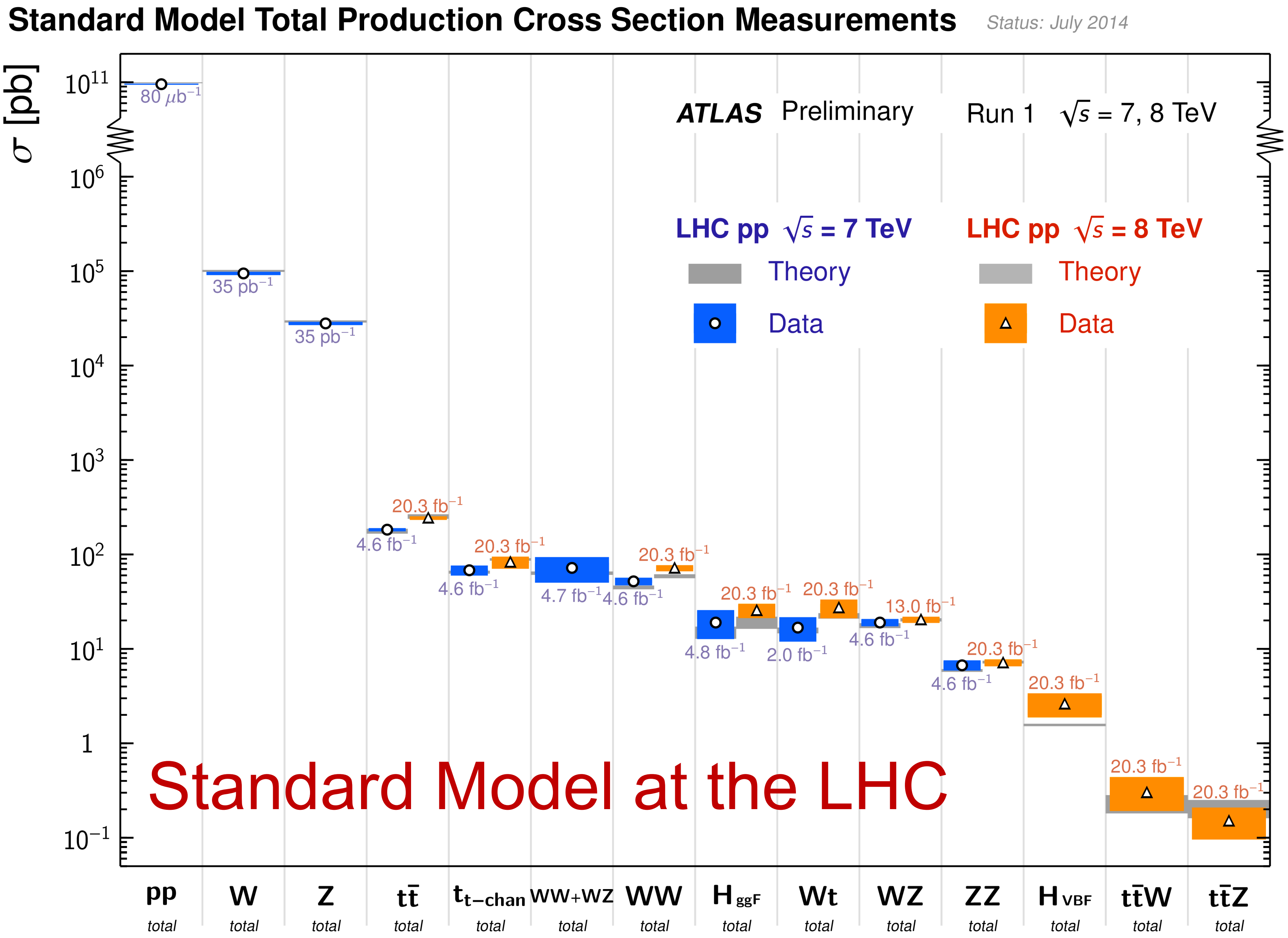
$$N_\nu = 2.984 \pm 0.008$$

N_{eff} = 3.15 ± 0.23 from Planck15

The famous "pull" diagram from LEP



SM works beautifully



Standard Model at the LHC

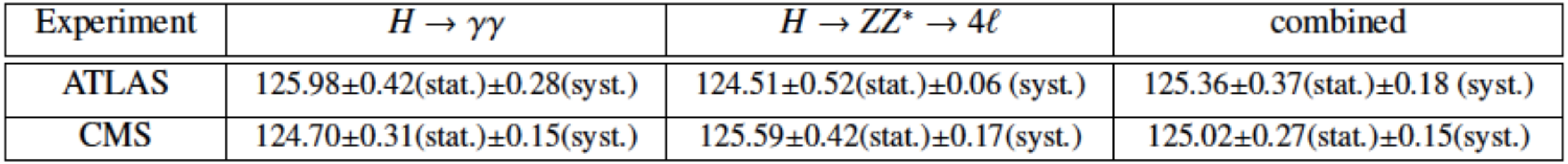
2012: a Hi(gg)storical year
Last piece of SM finally found

July 4th 2012 at CERN

Summary of Higgs mass

ATLAS 1406.3827

CMS 1412.8662

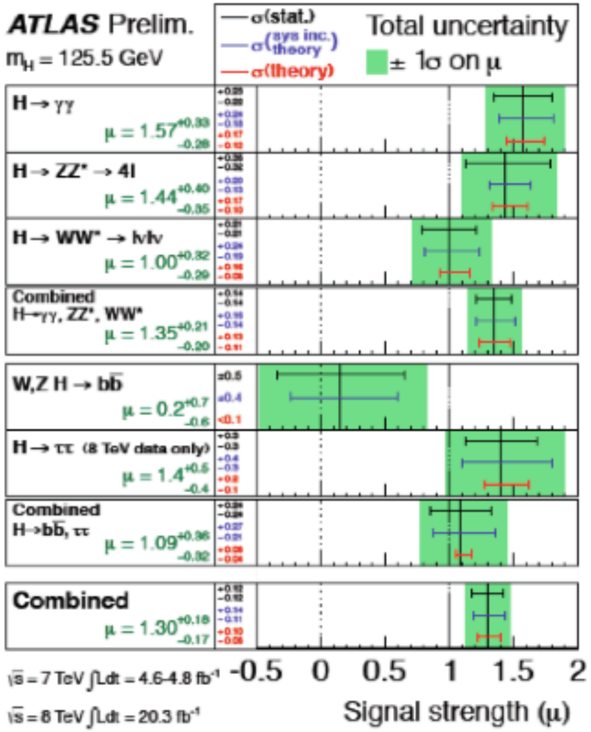


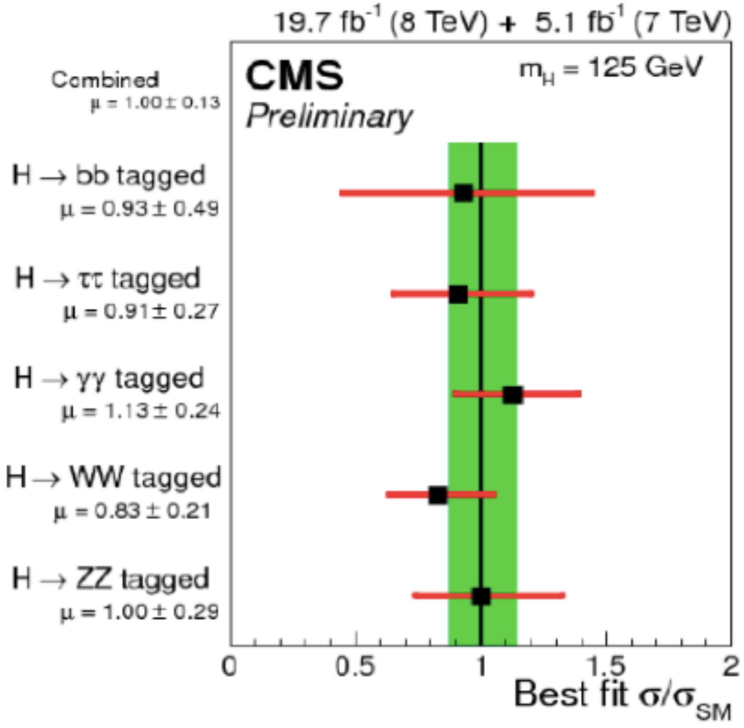
Experiment	$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$	combined
ATLAS	125.98±0.42(stat.)±0.28(syst.)	124.51±0.52(stat.)±0.06 (syst.)	125.36±0.37(stat.)±0.18 (syst.)
CMS	124.70±0.31(stat.)±0.15(syst.)	125.59±0.42(stat.)±0.17(syst.)	125.02±0.27(stat.)±0.15(syst.)

Higgs couplings

Define “signal strength”: $\mu \equiv \dfrac{\sigma}{\sigma_{SM}}$

$$\begin{aligned} \text{ATLAS}: \mu &= 1.30 \pm 0.12 \pm 0.10 \pm 0.09\,, \\ \text{CMS}: \mu &= 1.00 \pm 0.09 \, ^{+0.08}_{-0.07} \pm 0.07\,. \end{aligned}$$

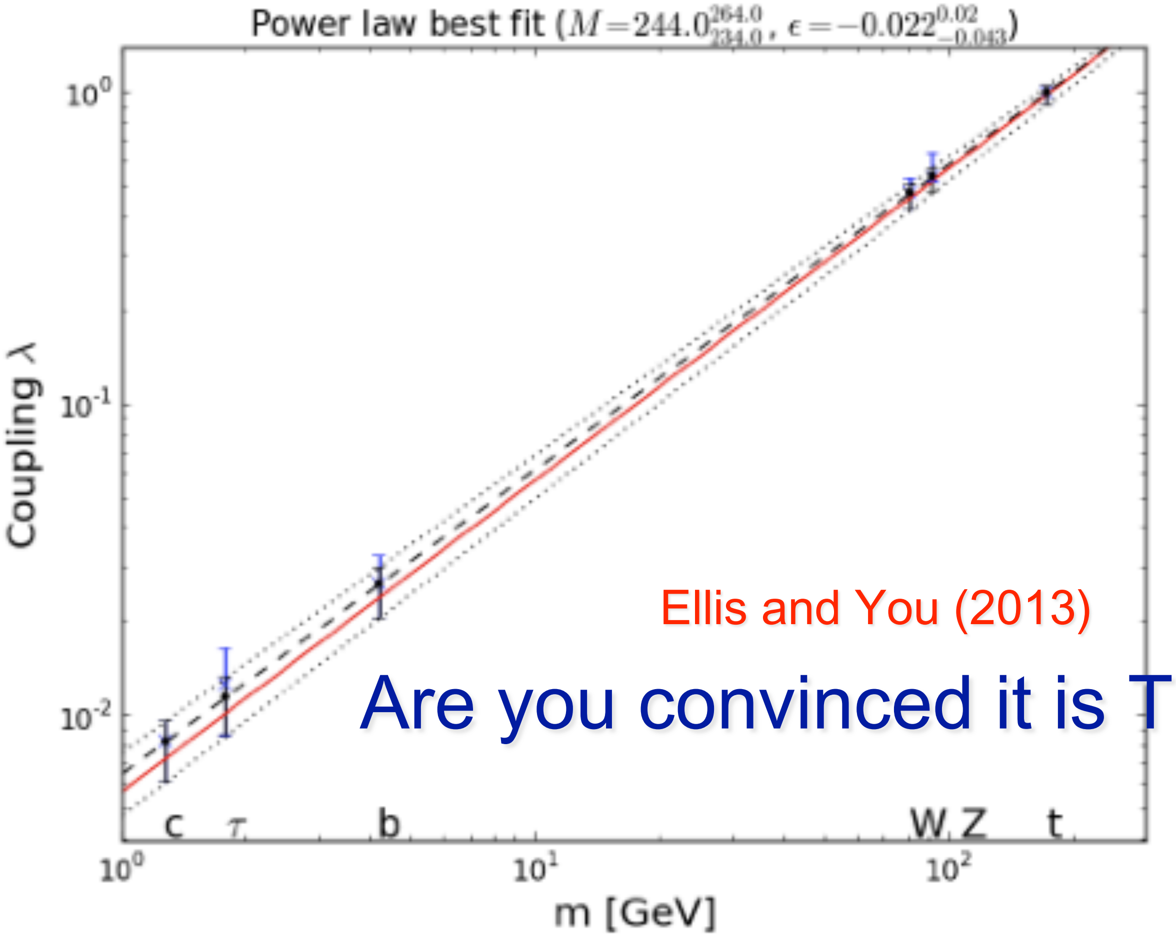




Higgs couplings

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{(1+\epsilon)}, \; g_V = 2\left(\frac{M_V^{2(1+\epsilon)}}{M^{(1+\epsilon)}}\right)$$

SM: M=v=246 GeV, ε=0



Ellis and You (2013)

Are you convinced it is THE Higgs?

We should celebrate the astounding success of the SM!

All measurements performed so far at accelerators are in good agreement with predictions of the Standard Model.

SM seems to be a consistent theory up to the Planck mass.

Are we done?

Why we are not totally happy with the SM?

Shortcomings of the Standard Model

Many free parameters – mostly associated with the Higgs

What is the origin of the electroweak scale?

New non-gauge interactions:

Higgs self-couplings λ

Yukawa couplings between Higgs and leptons – Flavor problem

(see especially Ben Grintein's lectures)

Parameters of the Standard Model

Gauge field sector: g_1, g_2 and g_3

Higgs sector: v and λ

Matter sector:
(but actually from Higgs)
(no neutrino parameters)

Masses of quarks and leptons: 9
Quark mixing: 3 angles
Phase (CP violation): 1

Strong CP violation: 1

Total: 19 parameters

Shortcomings of the Standard Model

The Standard Model does not explain:

- neutrino masses
- asymmetry matter-antimatter ($\cancel{B}$, new source of $\cancel{CP}$?)
- absence of strong $\cancel{CP}$
- dark matter (25% of the Universe)
- dark energy (70% of the Universe)
- inflation
- gravity

It is reasonable to expect New Physics between the EW and Planck scales – but where?

Shortcomings of the Standard Model

Conceptual “problems” related to the scalar sector

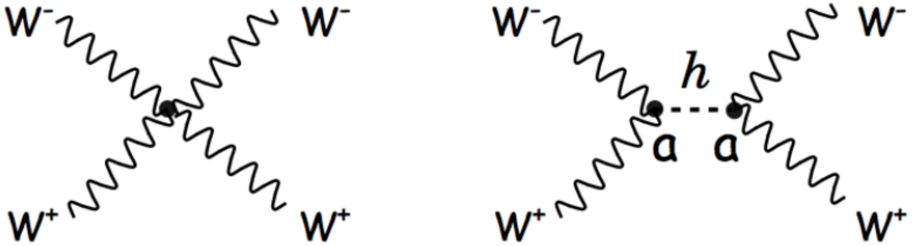
- Perturbative unitarity
- Triviality
- Vacuum stability
- Hierarchy and naturalness

See Grojean’s lectures

It is reasonable to expect New Physics between the EW and Planck scales – but where?

Simple example: a deviation in the Higgs coupling would point to a scale for new physics.

$$\mathcal{M} \to \frac{s}{v^2}(1 - a^2)$$



Perturbative unitarity violated at:

$$\Lambda = \sqrt{\frac{4\pi}{1 - a^2}}\ v$$

5% deviation implies

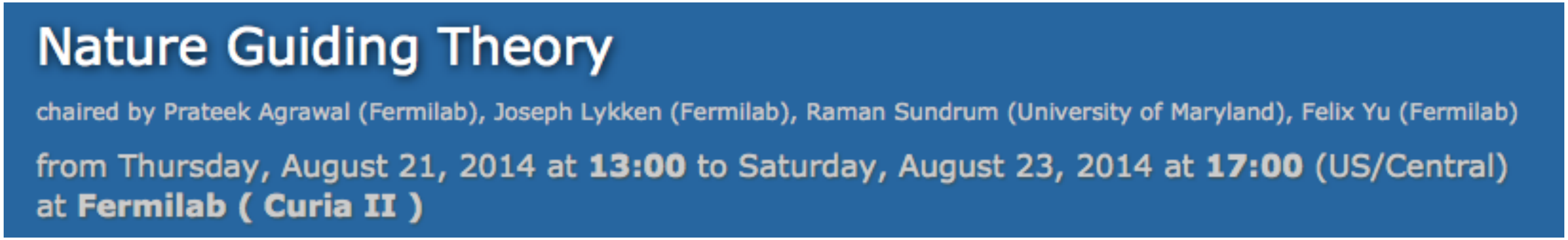
$$\Lambda \approx 2.8\ \mathrm{TeV}$$

Naturalness principle

Naturalness has been the guiding principle to go BSM: the mass of the Higgs boson must be natural, without requiring extreme fine-tuning.

The discovery of a light Higgs boson and the absence of any new particles or deviations of couplings at the LHC have put theories motivated by the naturalness principle under stress. "LHC battle for naturalness".

There must be ways to tame the quadratically divergent quantum contributions to the Higgs mass and stabilize the electroweak scale. Usually new symmetries and new particles at the TeV scale are necessary.



Nature Guiding Theory

chaired by Prateek Agrawal (Fermilab), Joseph Lykken (Fermilab), Raman Sundrum (University of Maryland), Felix Yu (Fermilab)

from Thursday, August 21, 2014 at **13:00** to Saturday, August 23, 2014 at **17:00** (US/Central)
at **Fermilab (Curia II)**

The goal of the workshop is to robustly understand the connection between the hierarchy problem and predictions for new physics derived from its possible solutions. The set of predictions arising from the mechanisms developed so far have been a main driver for theory and experiment. Therefore, sharpening this implication will shape expectations for new physics at the TeV scale. Is new TeV scale physics guaranteed by naturalness? If not, exploring any possible caveats that dilute this correspondence is critical. New mechanisms will have a significant impact on our understanding of quantum field theory. Furthermore, they could uncover profound interplay between gravity and field theory, and possibly connect with the cosmological constant problem.

Naturalness 2014

14-17 November 2014
Weizmann Institute of Science
Israel timezone

The fact that the Higgs mass is subject to additive renormalization, implies that the electroweak scale is unnatural. All the known concrete solutions to this UV sensitivity problem require new dynamics characterized by energy scale close to the weak scale. A simple possibility to stabilize the electroweak scale in a controlled manner is to add some new particles with the same gauge quantum numbers as the SM ones. The most relevant question amidst the "LHC battle for naturalness" is how we are going to discover or extend the bounds on the partners both in terms of (i) mass reach; and (ii) robustness.

Few possibilities for a natural Higgs:

- SM an effective theory valid up to Λ~fewTeV (NP out of LHC reach)

must be supplemented by additional higher dimensional operators

- New symmetries to protect Higgs mass from quadratic divergences:

✓ SUSY
✓ Shift symmetry (Higgs~PNG boson?)
✓ Conformal symmetry (Higgs~dilaton?)

- Extra dimensions:

lower Planck scale (only gravity propagating in extra-dim), gauge-Higgs unification or warped geometries (Randall-Sundrum).

Beyond the Standard Model

- explain hierarchy between electroweak and Planck scales.
- explain dark matter
- explain neutrino masses
- explain baryon asymmetry in the universe

Natural BSM candidates predict either deviations of the SM or the existence of new particles at the TeV scale! On to the LHC!!

The agnostic BSM approach:

Effective Lagrangians

Agnostic: a person who holds that the existence of the ultimate cause, as “The Ultimate Model of Nature”, and the essential nature of things are unknown and perhaps unknowable, or that human knowledge is limited to experience.

Effective lagrangians

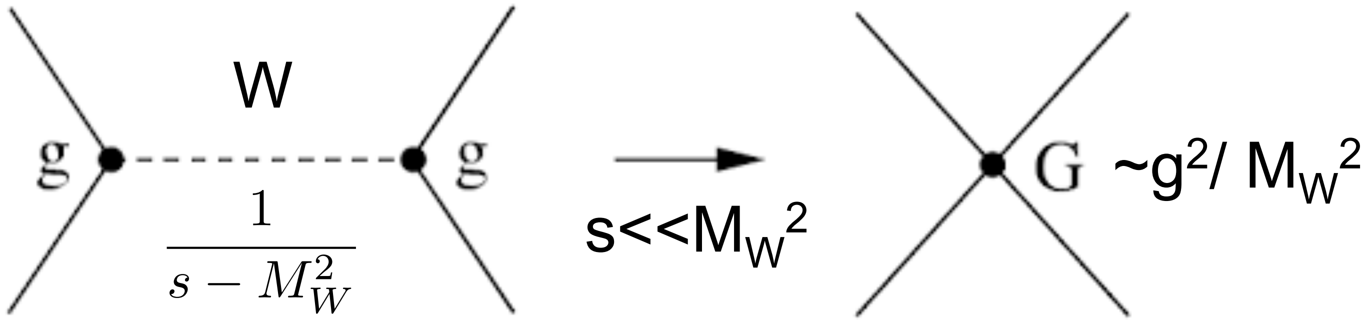
Standard Model is a well-defined renormalizable theory. It may also be an effective theory valid up to some scale Λ where New Physics will show up.

Naturalness then require Λ not too large compared to v in order to avoid excessive fine-tuning (unless the true theory can explain $v<<\Lambda$ naturally).

At energy scales below Λ one could describe BSM by adding effective higher-dimensional operators to the SM lagrangian - these are understood to arise from integrating out new heavy degrees of freedom.

Time-honoured approach

Fermi's four-fermion interactions:



Schematically, at low energies a dimension-6 non-renormalizable term of the form $G(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$

Time-honoured approach

Dimensional analysis: $\mathcal{M} \simeq Gs \qquad \left(\sigma \simeq G^2 s\right)$

Perturbative unitarity is violated at scales:

$$\Lambda \simeq \frac{1}{\sqrt{G}} \simeq 300 \text{ GeV}$$

New Physics appears at scale Λ: W’s and Z’s!

BSM effective lagrangians

At energy scales below Λ one could describe BSM by adding effective higher-dimensional operators to the SM lagrangian - these are understood to arise from integrating out new heavy degrees of freedom – whatever they may be – agnostic about New Physics!

BSM effective lagrangians

Add to SM the most general higher-dimensional lagrangian containing only SM fields respecting the gauge symmetries of the SM:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d\geq 5, i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} [\phi_{SM}]$$

NB: coefficients of the higher dimensional operators depend on the energy scale they are measured: $c_i(\mu)$

They can mix under RG evolution.

BSM effective lagrangians

When does Effective Field Theory fail?

Expansion parameter is roughly:

$$\frac{s}{\Lambda^2}$$

Typical energy scale

Expansion breaks down for $s > \Lambda^2$

BSM effective lagrangians

Where to look for New Physics?

- Rare (suppressed or forbidden) processes

SM has accidental symmetries (B, L) and cancellations (GIM) – maybe NP do not respect them!

- Well measured processes – precision tests @ LEP-1, EW gauge boson pair production @ LEP-2 & LHC

NP can hide in error bars

BSM effective lagrangians

Where to look for New Physics?

- Higgs – a window to NP

Sensitivity to new operators that have not been tested before – see Grojean's lectures

- High P_T processes

Effect of higher-dim operators can be enhanced careful: edge of validity of EFT

BSM effective lagrangians

Where to look for New Physics?

Absence of New Physics implies in lower bounds on Λ, the scale where NP should appear.

NB: actually, bounds are on Λ/c_i and

$$c_i \approx g^2 \qquad\qquad c_i \approx \frac{g^2}{16\pi^2}$$

Tree-level   Loop-level

Examples

Dimension-5 operator

Only dimension-5 operator is related to neutrino Majorana mass (Weinberg operator, Lorentz and SU(2) invariant) that violates lepton number:

$$\mathcal{L}_5 = \frac{c}{\Lambda}(\bar{\tilde{L}}H)(\tilde{H}^\dagger L)$$

and generates a Majorana mass: $m_\nu \simeq \frac{c}{\Lambda} v^2$

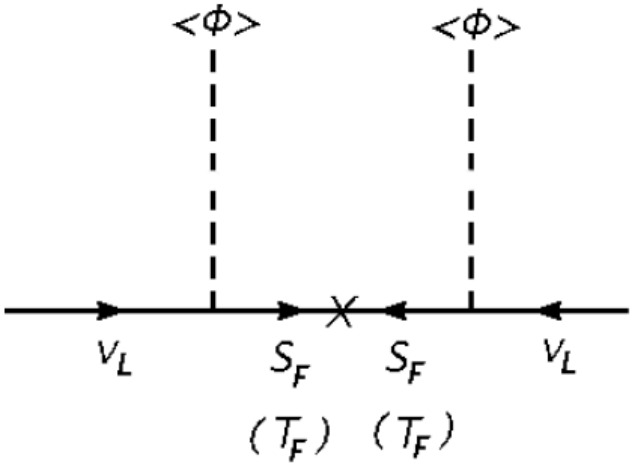
Hint for a NP scale (take c~1 and m_ν ~ 1eV):

$$\Lambda \simeq \frac{v^2}{m_\nu} \simeq 10^{13}\ \mathrm{GeV}$$

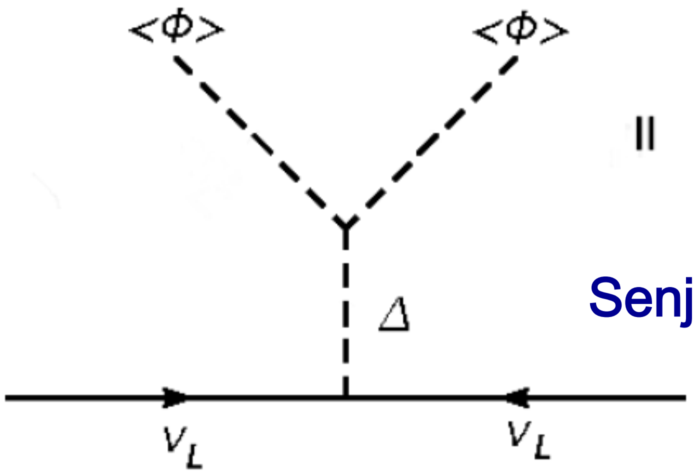
Typical scale of NP associated to neutrino masses (unless c<<1)

Dimension-5 operator

There are several UV completions that lead to the Weinberg operator at low energies – usually they go by the name of seesaw models, types I, II and III:



I, III



II

Senjanovic

The mass scale of NP can be reduced if the coefficients c (that can be computed in a given UV completion) are suppressed.

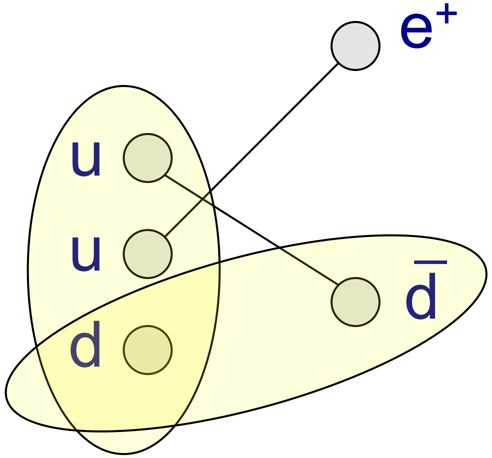
Dimension-6 operators

Example 1: proton decay – requires B violation

Color indices suppressed

$$\mathcal{L}_6^{\not{B}} = \frac{c}{\Lambda^2}(u_R d_R)(u_R e_R) + \cdots$$

Weinberg (1979)
Wilczek and Zee (1979)



$$p^+ \rightarrow \pi^0 + e^+$$

Dimension-6 operators

Example 1: proton decay – requires B violation

$$\mathcal{L}_6^{\not{B}} = \frac{c}{\Lambda^2}(u_R d_R)(u_R e_R) + \cdots$$

Dimensional analysis:

$$\tau_p = \Gamma^{-1} = \frac{\left(\Lambda^2/c\right)^2}{m_p^5}$$

Experimentally (PDG): $\tau_p > 10^{34}$ years

Hence, for c=1: $\boxed{\Lambda > 5 \times 10^{16}\ \mathrm{GeV}}$

Dimension-6 operators

Example 2: $\mu \to e\gamma$ – requires L violation

$$\mathcal{L}_6^{\not L} = \frac{c}{\Lambda^2} \bar{L}\tilde{H}\sigma_{\mu\nu}\mu_R F^{\mu\nu} + \cdots$$

Dipole operator

Dimensional analysis:

$$\Gamma(\mu \to e\gamma) \simeq \left(c\frac{v}{\Lambda^2}\right)^2 m_\mu^3$$

Main decay mode:

$$\Gamma(\mu \to e\nu_\mu\bar{\nu}_e) \simeq \frac{G_F^2 m_\mu^5}{192\pi^3}$$

Dimension-6 operators

Example 2: $\mu \to e\gamma$ – requires L violation

Branching ratio:

$$BR(\mu \to e\gamma) \simeq \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu_\mu \bar{\nu}_e)} \simeq \left(c\frac{v}{\Lambda^2}\right)^2 \frac{16\pi^2}{G_F^2 m_\mu^2}$$

Experimental result (MEG 2013):

$$BR(\mu \to e\gamma) < 5.7 \times 10^{-13}$$

Hence, for c=1: $\boxed{\Lambda > 6 \times 10^7 \text{ GeV}}$

Dimension-6 operators

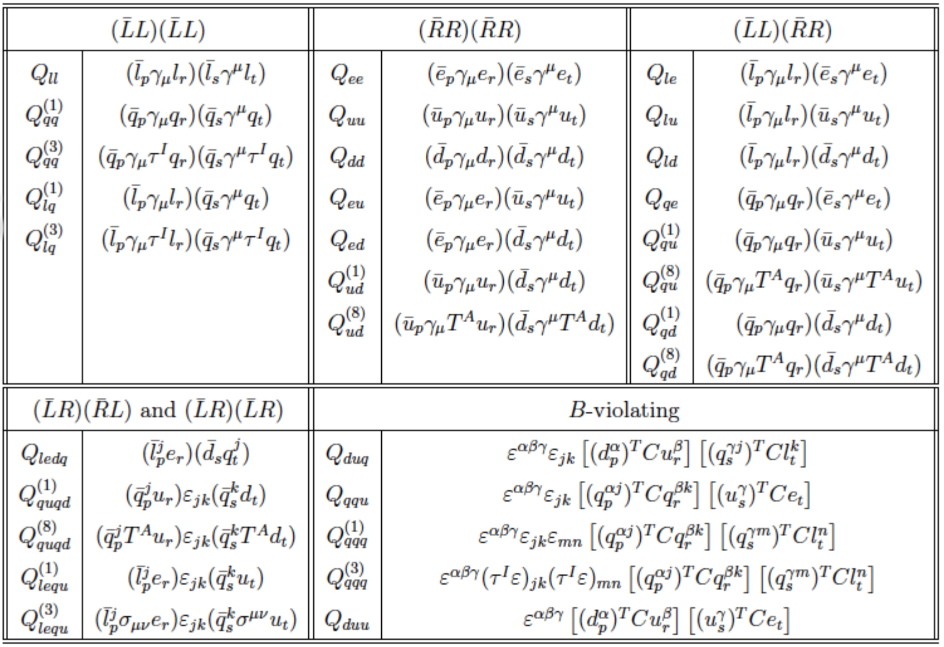
Open Pandora’s box:

there are 64 independent operators (5 are $\not{B}$)!

(2499 operators for general flavor structure)

Buchmuller and Wyler (1986)
Grzadkowski et al (2010)

Dim-6 operators

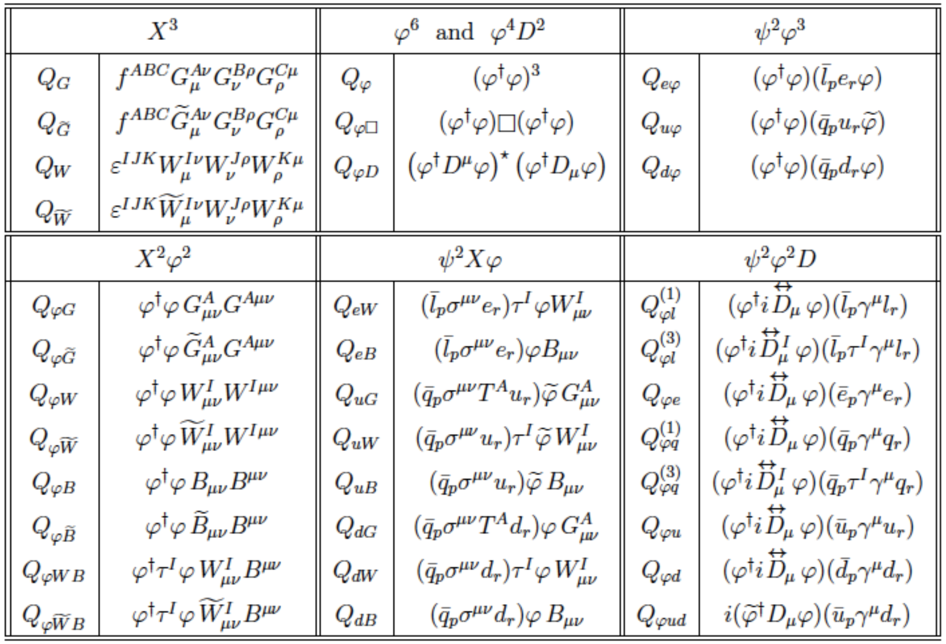


$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Table 3: Four-fermion operators.

Grzadkowski et al (2010)



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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

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

Table 2: Dimension-six operators other than the four-fermion ones.

Dimension-6 operators

Difficulty in constraining dim-6 operators:

each observable may be sensitive to a combination of dim-6 operators

↕

each dim-6 operator may affect more than one observable

Dimension-6 operators

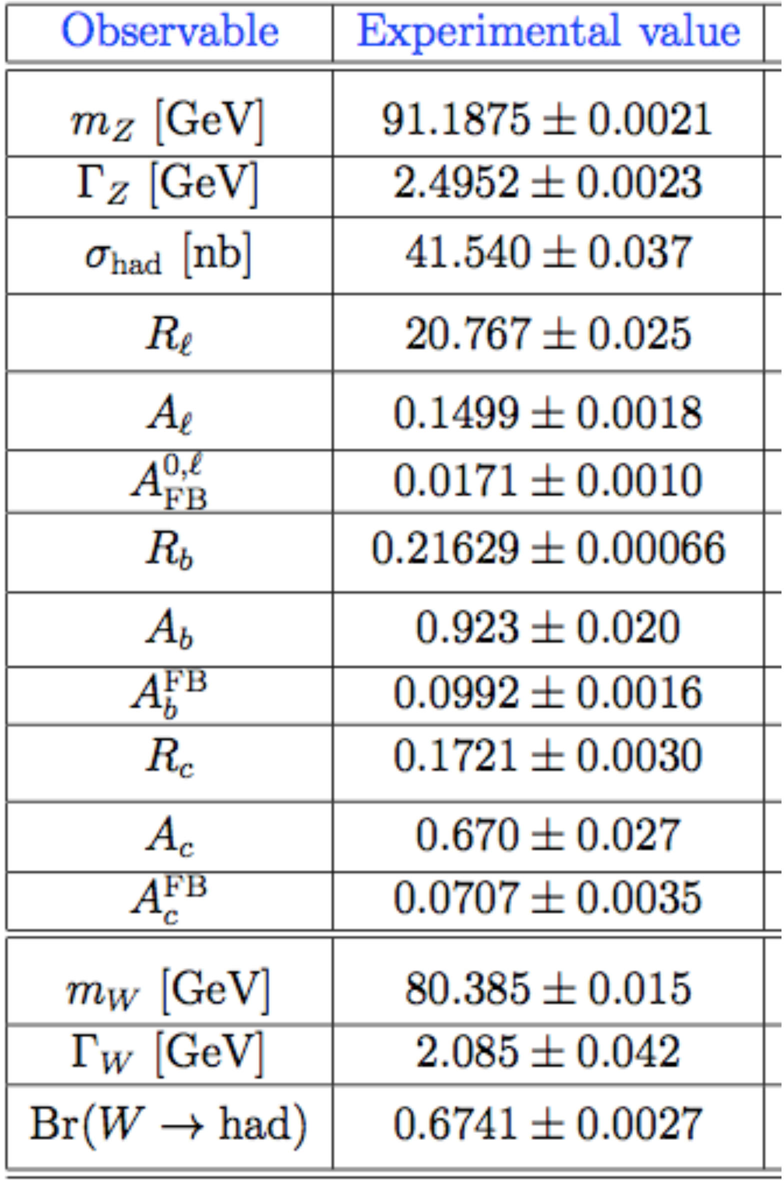
Example 3: precision tests

LEP-1 precision observables

LEP-2 & LHC EW gauge boson pair production

LHC Higgs processes – Grojean’s lectures

LEP-1 precision observables:



Observable	Experimental value
m_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ_{had} [nb]	41.540 ± 0.037
R_ℓ	20.767 ± 0.025
A_ℓ	0.1499 ± 0.0018
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010
R_b	0.21629 ± 0.00066
A_b	0.923 ± 0.020
A_b^{FB}	0.0992 ± 0.0016
R_c	0.1721 ± 0.0030
A_c	0.670 ± 0.027
A_c^{FB}	0.0707 ± 0.0035
m_W [GeV]	80.385 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
$\text{Br}(W \to \text{had})$	0.6741 ± 0.0027

Typically
(no spurious cancellations
among different operators)
one obtains bounds

$$\Lambda > \mathcal{O}(10)\ \text{TeV}$$

e.g., Falkowski and Riva (2014)

Oops: is LEP suggesting that NP may be beyond LHC reach?

In fact this was known 10 years ago!

LEP-2 and LHC constraints:

Less constraining than LEP-1 data - typically

$$\Lambda > 300 \ \mathrm{GeV}$$

e.g., Falkowski and Riva (2014)
Ellis, Sanz and You (2014)

Careful with validity of EFT @ LHC

Dimension-6 operators

Example 4: top dipole operators

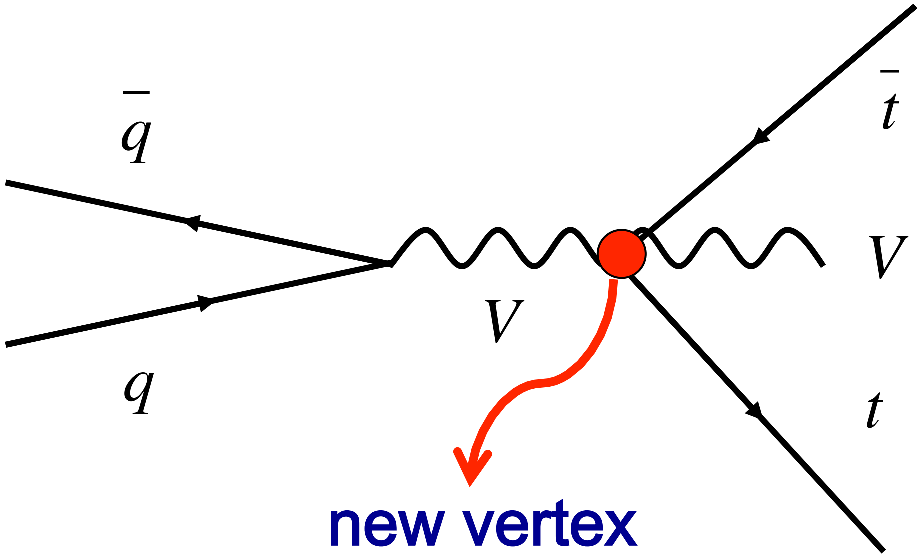
e.g., Tonero and Rosenfeld (2014)

Expect NP to couple more strongly to the third generation

$$\begin{aligned}\mathcal{L}_{\text{top-dipole}} = {} & \left.\begin{aligned}&\frac{c_{tB}}{\Lambda^2}\bar{Q}_L H^c \sigma^{\mu\nu} t_R B_{\mu\nu} + \\ &\frac{c_{tW}}{\Lambda^2}\bar{Q}_L H^c \tau_i \sigma^{\mu\nu} t_R W^i_{\mu\nu} +\end{aligned}\right\} \text{EW dipoles} \\ & \frac{c_{tG}}{\Lambda^2}\bar{Q}_L H^c \lambda_A \sigma^{\mu\nu} t_R G^A_{\mu\nu} \qquad \text{QCD dipole}\end{aligned}$$

Dimension-6 operators

Top dipole operators change SM couplings and generate new ones:

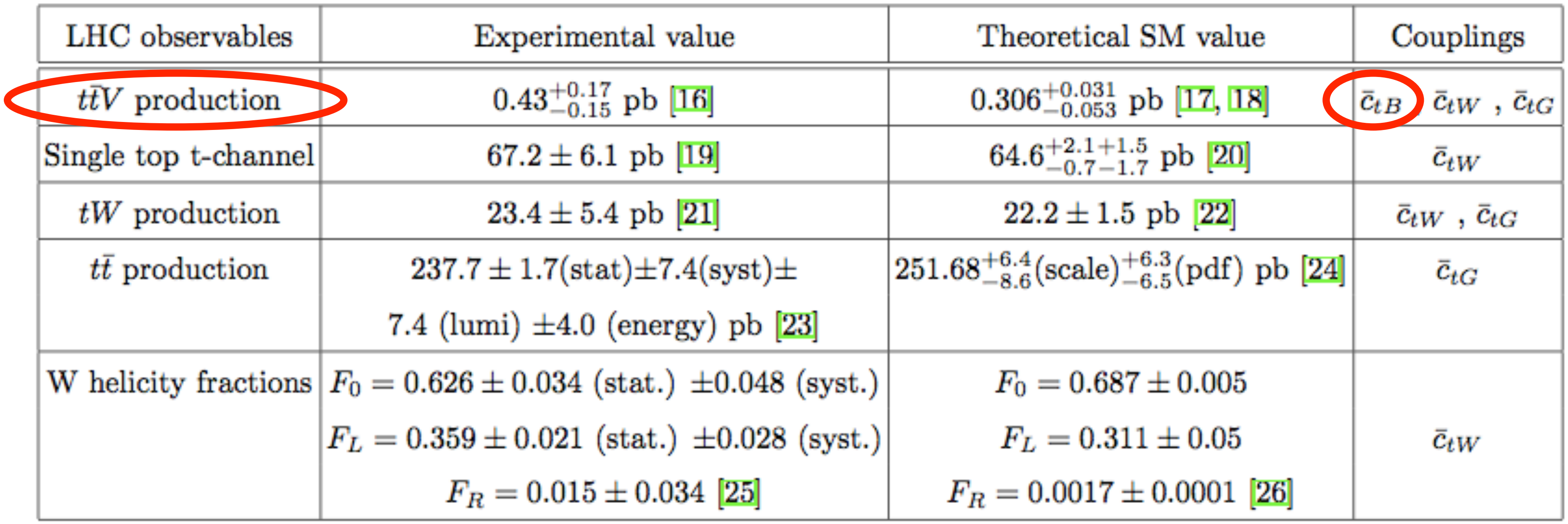


new vertex

New contribution to ttV associated production – new data in 2013

Dimension-6 operators

Top dipole operators contribute to observables:



LHC observables	Experimental value	Theoretical SM value	Couplings
$t\bar{t}V$ production	$0.43^{+0.17}_{-0.15}$ pb [16]	$0.306^{+0.031}_{-0.053}$ pb [17, 18]	$\bar{c}_{tB}$, $\bar{c}_{tW}$, $\bar{c}_{tG}$
Single top t-channel	67.2 ± 6.1 pb [19]	$64.6^{+2.1+1.5}_{-0.7-1.7}$ pb [20]	$\bar{c}_{tW}$
tW production	23.4 ± 5.4 pb [21]	22.2 ± 1.5 pb [22]	$\bar{c}_{tW}$, $\bar{c}_{tG}$
$t\bar{t}$ production	237.7 ± 1.7(stat)± 7.4(syst)$\pm$ 7.4 (lumi) ± 4.0 (energy) pb [23]	$251.68^{+6.4}_{-8.6}$(scale)$^{+6.3}_{-6.5}$(pdf) pb [24]	$\bar{c}_{tG}$
W helicity fractions	$F_0 = 0.626 \pm 0.034$ (stat.) ± 0.048 (syst.) $F_L = 0.359 \pm 0.021$ (stat.) ± 0.028 (syst.) $F_R = 0.015 \pm 0.034$ [25]	$F_0 = 0.687 \pm 0.005$ $F_L = 0.311 \pm 0.05$ $F_R = 0.0017 \pm 0.0001$ [26]	$\bar{c}_{tW}$

Dimension-6 operators

Top dipole operators contribute to observables:

$$\sigma^{th}(\bar{c}_i) = \sigma_{SM}^{NLO} + \Delta\sigma^{MG5}(\bar{c}_i)$$

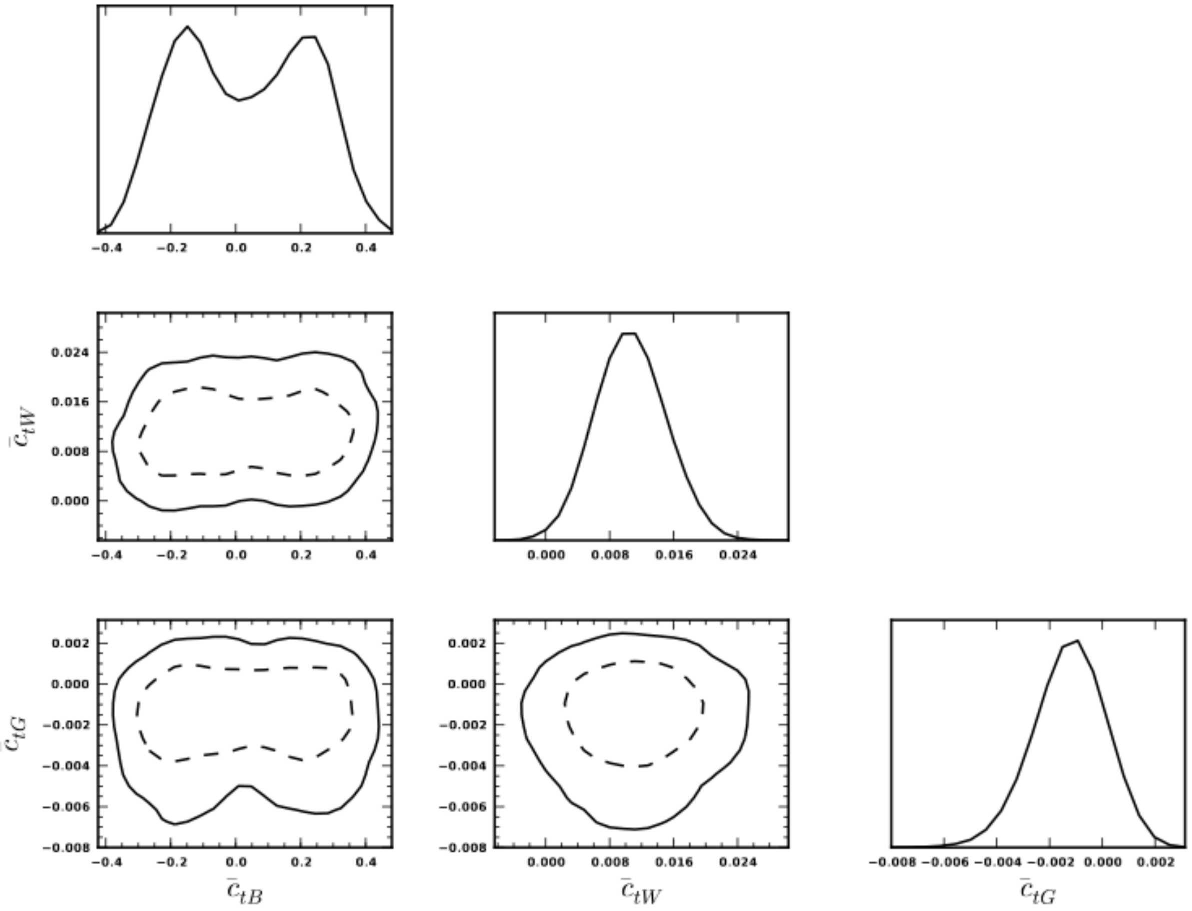
$$\Delta\sigma^{MG5}(\bar{c}_i) = \sigma^{MG5}(\bar{c}_i) - \sigma^{MG5}(0)$$

New couplings obtained in FeynRules and contributions in MadGraph

$$\mathcal{L}(\bar{c}_{tB}\,, \bar{c}_{tW}\,, \bar{c}_{tG}) \propto \exp\left[-\sum_k \frac{\left(\mathcal{O}_k^{th}(\bar{c}_i) - \mathcal{O}_k^{exp}\right)^2}{(\delta\mathcal{O}_k^{exp})^2 + (\delta\mathcal{O}_k^{th})^2}\right]$$

Dimension-6 operators

Bayesian analysis:



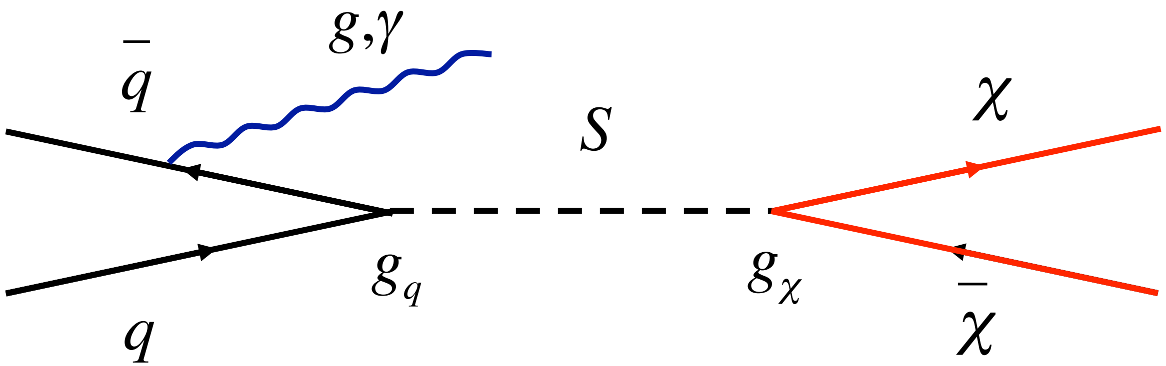
Dimension-6 operators

Example 5: Dark matter and effective operators

e.g., Busanti et al (1307.2253)

DM is searched at the LHC as mojet (or monophoton) + missing energy.

Simple model: DM couples to the SM sector through the exchange of a heavy mediator S



Dimension-6 operators

The propagator of S can be expanded as:

$$\frac{1}{Q^2 - M_S^2} = -\frac{1}{M_S^2}\left(1 + \frac{Q^2}{M_S^2} + \mathcal{O}\left(\frac{Q^4}{M_S^4}\right)\right)$$

Can use an effective operator by integrating-out S:

$$\mathcal{O} = \frac{1}{\Lambda^2}\left(\bar{\chi}\chi\right)\left(\bar{q}q\right)$$

with identification

$$\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M_S^2}$$

Dimension-6 operators

Requiring:

$$g_q,\ g_\chi < 4\pi$$ **perturbativity**

$$M_S > M_{DM}$$ **consistency**

implies

$$\Lambda > \frac{M_{DM}}{4\pi}$$

Experimental bounds must respect this inequality.

Dimension-6 operators

Perils of EFT:

It is valid as long as the energy scale of the process involving the DM and the SM particles is small compared to the energy scale associated to the heavy mediator. Is this ok at the LHC?

$$\Lambda > \frac{Q}{g_\chi g_q}$$

The momentum transfer Q depends on the p_T of jet or photon. In principle this condition must be checked on an event-by-event basis. This is difficult…

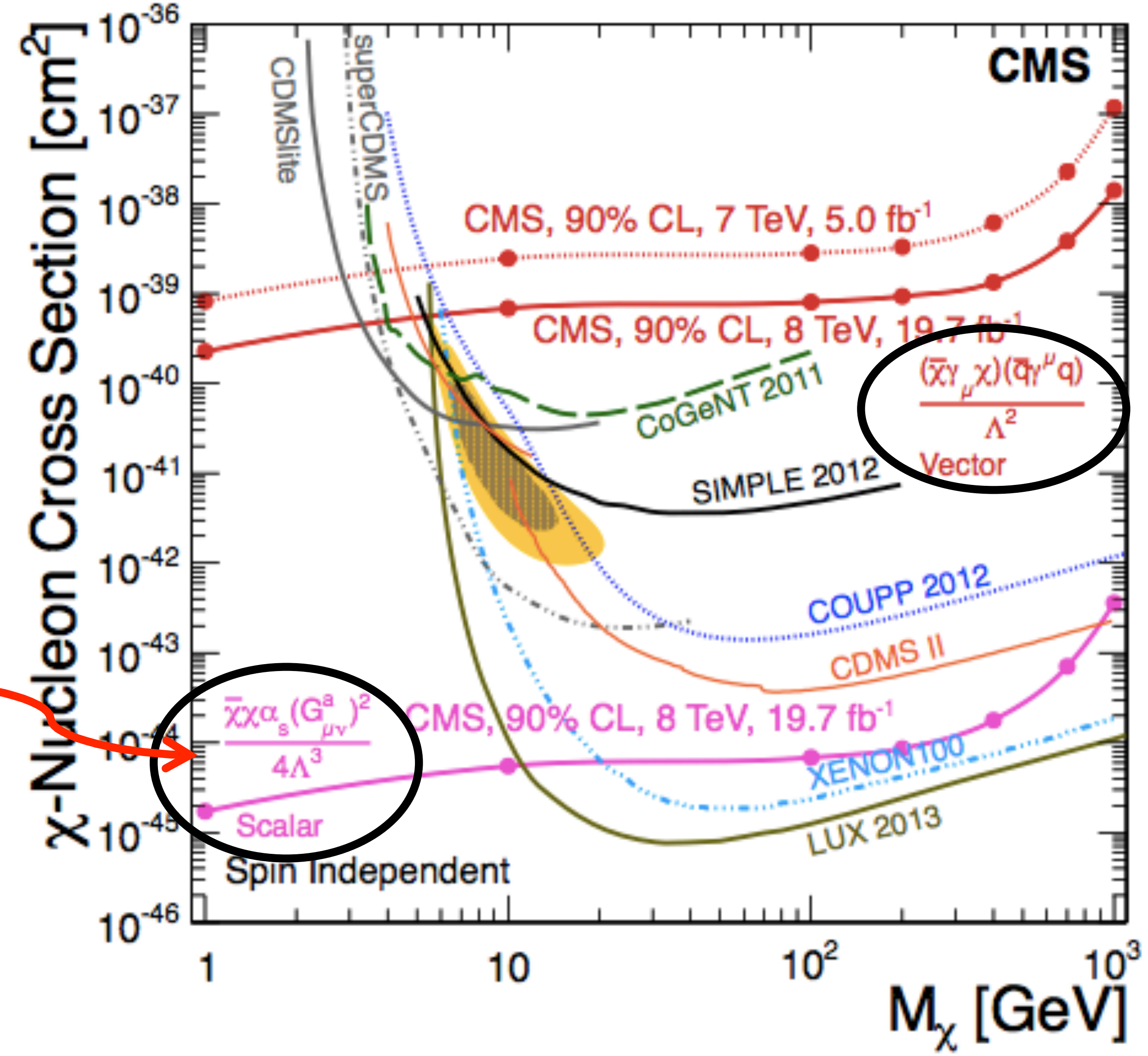
Dimension-6 operators

Bounds on effective DM-SM couplings from LHC imply in bounds for the DM-nucleon scattering cross section, which can be measured in direct DM detection expts.

Nice interplay!

1408.3583

Dim-7



Brief interlude

Naturalness in Effective Lagrangians:

Is $\Lambda << M_{pl}$ natural?

In QCD, the scale Λ (few hundred MeV) appears due to dimensional transmutation: it defines a scale when a coupling constant becomes strong enough to trigger chiral symmetry breaking.

The dependence of the coupling constant on energy is given by the β-function:

$$\beta(g) = \frac{d}{d \ln \mu} g(\mu)$$

Brief interlude

Assuming

$$\beta(g) = -b_0 \frac{g^3}{16\pi^2} + \cdots$$

we find

$$g(\mu)^2 = \frac{g(\mu_0)^2}{1 + 3b_0 g(\mu_0)^2 \ln(\mu/\mu_0)}$$

Define scale when the coupling becomes strong and get:

$$3b_0 g(\Lambda)^2 \ln(\mu/\Lambda) \simeq 1$$

$$\Lambda \simeq \mu \, e^{-\frac{1}{3b_0 g^2(\Lambda)}}$$

Large hierarchies can naturally appear for theories with a slow running of the coupling constant (b_0 small)

BSM effective lagrangians: sum up

- Indirect and agnostic way to study NP: the lamp post approach

- NP hiding in error bars

- Difficult to derive firm conclusion: bounds usually depends on combinations of Wilson coefficients and energy scale(s) of NP

- We will only be convinced of NP by direct evidence!