The 2012 European
School of High-Energy Physics, Anjou

Other physics-BSM

Part I continued

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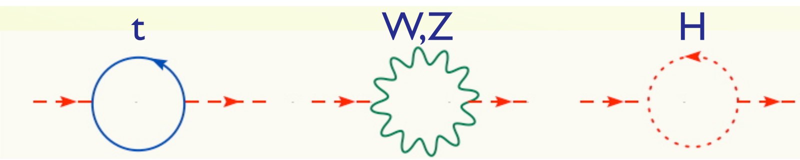
The top quark as a link to BSM

Using the top quark to probe BSM physics

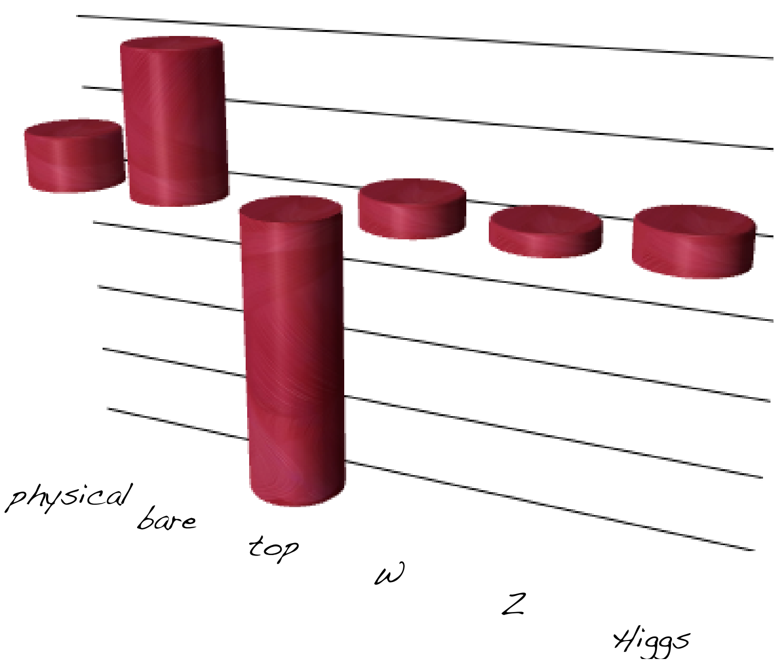
● The top quark is the heaviest known fundamental particle, m_t = 173.3 ± 1.1 GeV and the only SM fermion to have a natural Yukawa coupling (order 1).

The top dramatically affects the stability of the higgs mass:



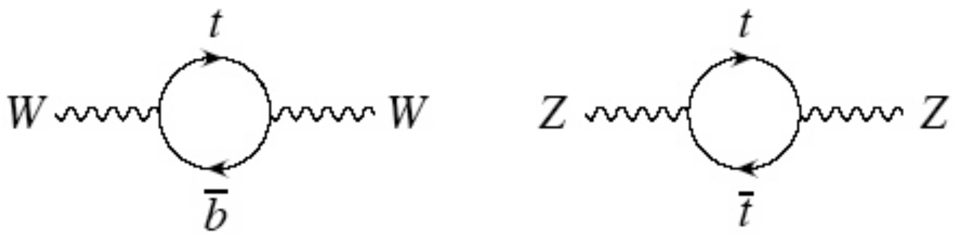
$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

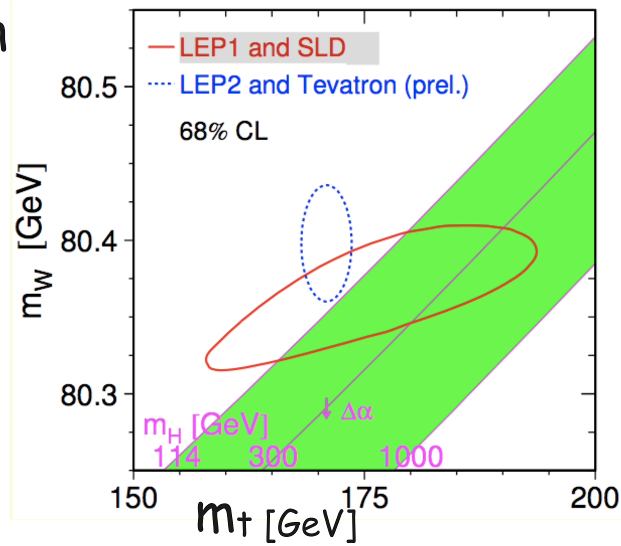
It is the main contributor to hierarchy problem
-> Standard Model is unnatural above 500 GeV



therefore top quark
is expected to be a link to BSM

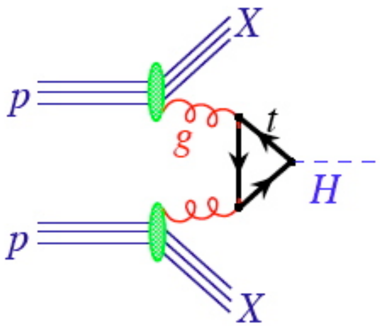
- The measurement of its properties (mass, couplings, spin) is used to establish **indirect** evidence for SM and BSM physics: precision EW & QCD, rare decays, anomalous couplings, flavor physics, CP violation



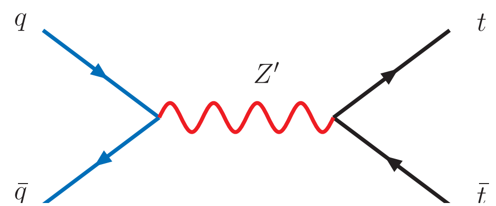


- The top is also a **direct** probe of the EWSB sector and BSM physics

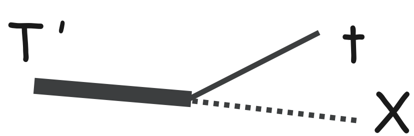
exciting the higgs



exciting new degrees of freedom



e.g. Z', top partners:



What else is special about the top?

- The top quark decays before it hadronizes, hence offers the opportunity to study a "bare" quark: spin properties, interaction vertices, top quark mass

$$\tau_{had} \approx \Lambda_{QCD}^{-1} \approx 2.10^{-24} s$$

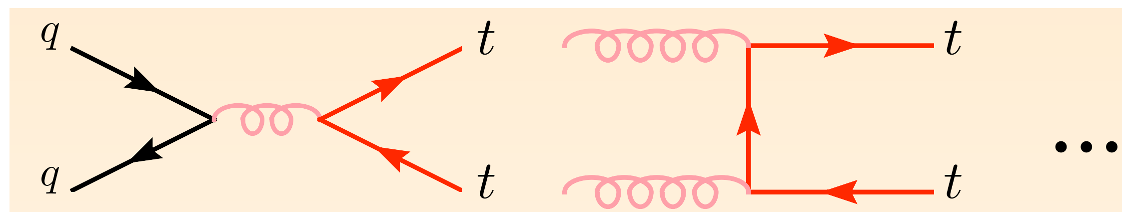
$$\tau_{top} \approx \Gamma_{top}^{-1} \approx (G_F m_t^3 |V_{tb}|^2 / 8\pi\sqrt{2})^{-1} \approx 5.10^{-25} s$$

It decays almost exclusively to $W^+ b$ in the SM as $|V_{tb}|^2 >> |V_{ts}|^2$,$|V_{td}|^2$

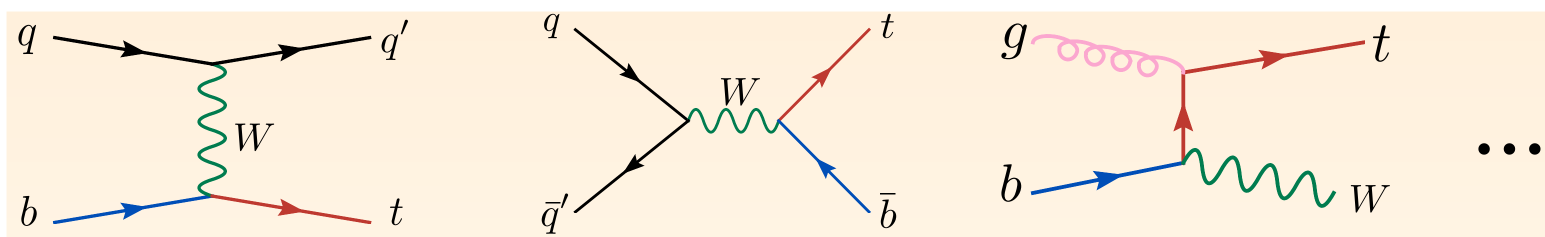
The top quark production at hadron colliders

Two production mechanisms:

- pair production



- single production
(~ 1/3)



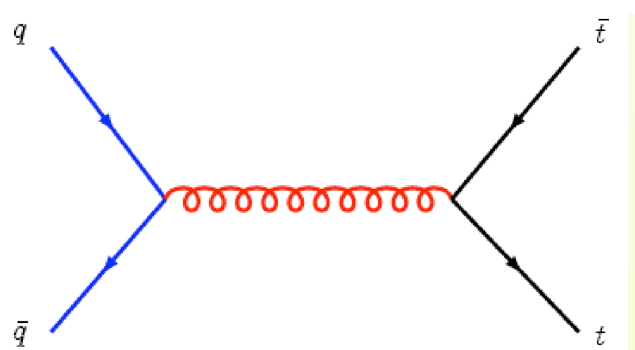
We already knew a lot on top quark from the Tevatron.
Tevatron had already set strong constraints on top-philic new physics

What has been mainly tested at the Tevatron is the $q\,\bar{q}$ process

while new physics contributions to *gg* -> $t\,\bar{t}$ remained unconstrained

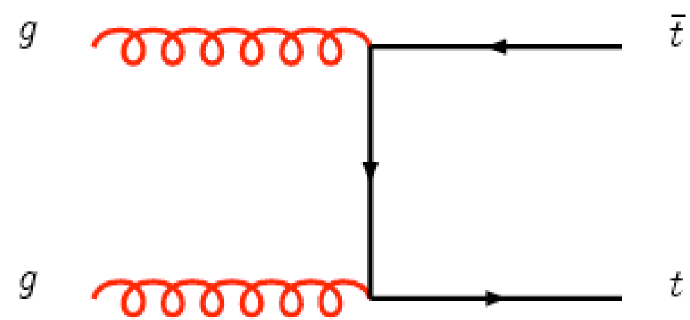
From Tevatron to LHC

Tevatron



85 % of total cross section

LHC

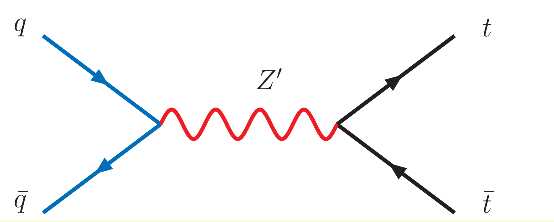


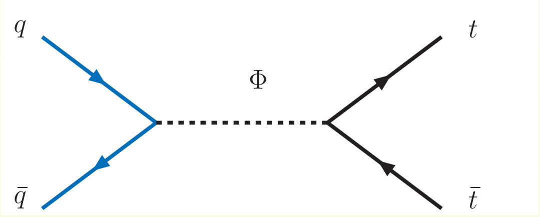
90 % of total cross section at 14 TeV
(70 % at 7 TeV)

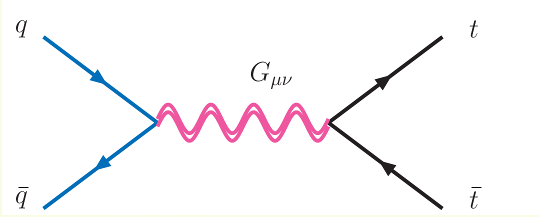
BSM with top physics

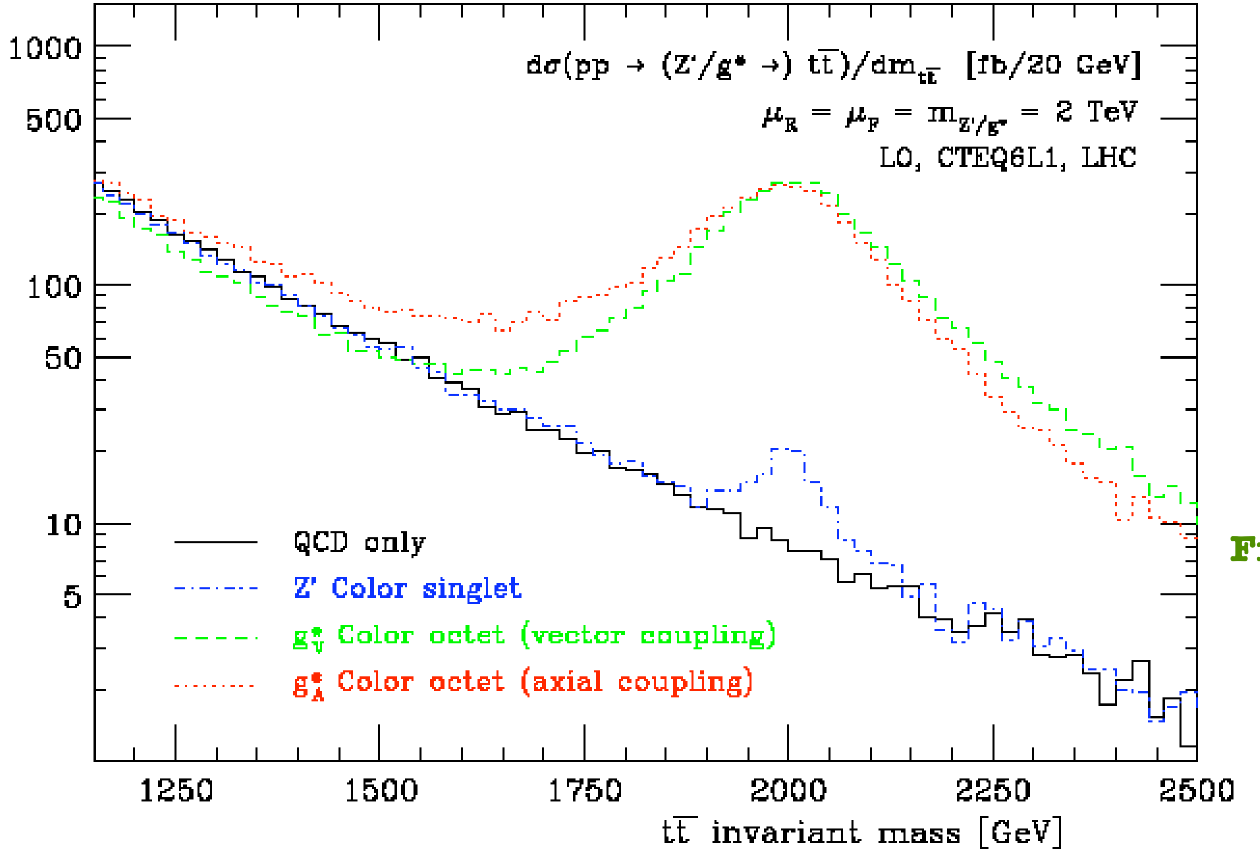
A large effort has been devoted to search for new physics in $t\bar{t}$ resonances

In many scenarios for EWSB new resonances show up, some of which preferably couple to 3rd generation quarks.





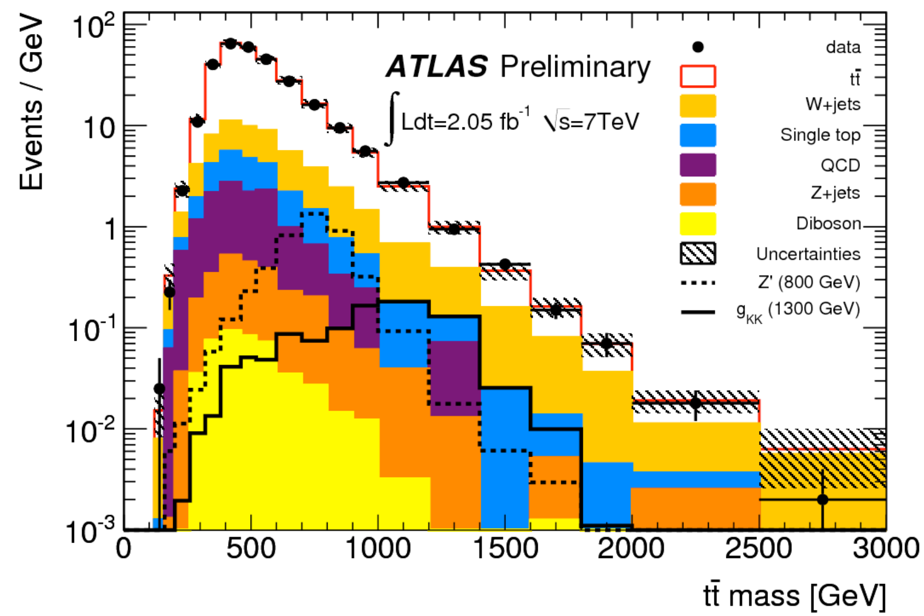




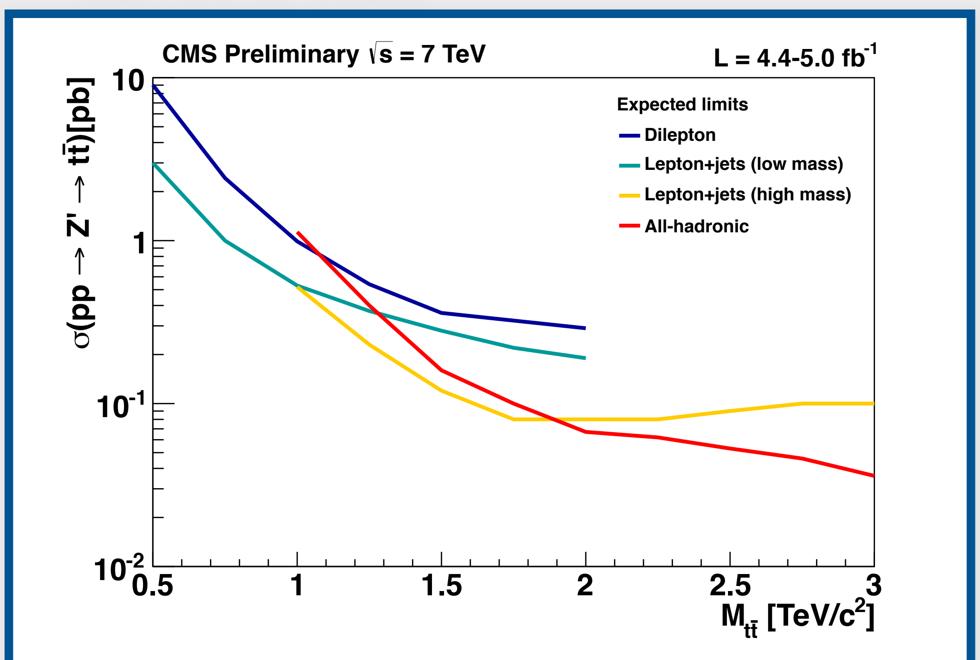
Frederix-Maltoni'09

	narrow Z' mass	wide Z' mass	KK gluon mass
CMS TOP-11-010	< 1.1 TeV		
ATLAS CONF-2011-123			< 0.8 TeV
CMS TOP-11-009	< 1.3 TeV	< 1.7 TeV	< 1.4 TeV
ATLAS CONF-2012-029	< 0.9 TeV		< 1.0 TeV
CMS EXO-11-093	< 1.6 Tev	< 2.0 TeV	
CMS EXO-11-006	< 1.6 TeV	< 2.0 TeV	1.4 < M_{KKg} < 1.5

Nothing found so far



narrow Z' mass



narrow Z' mass > 1.6 TeV

wide Z' mass > 2.0 TeV

$\Gamma(Z') = 0.1 \times M_{Z'}$

KK gluon mass > 1.4 TeV

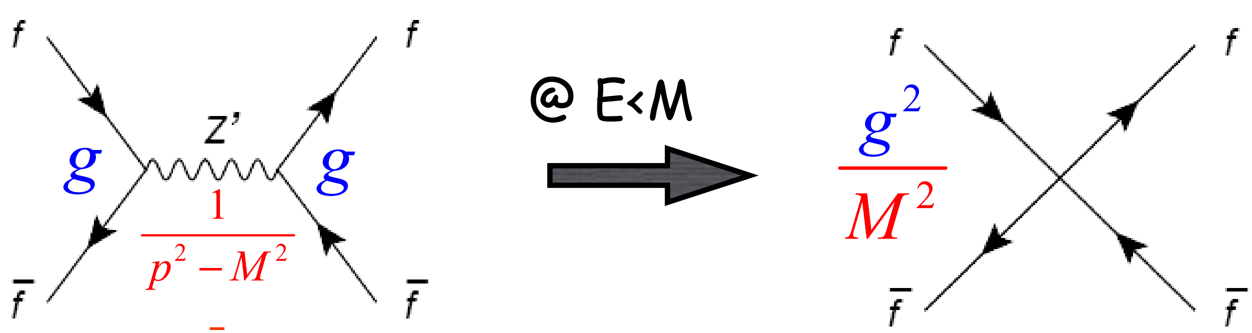
If all these particles are too heavy to be accessible at the LHC

-> Effective Field Theory (EFT) approach

EW precision data together with constraints from flavour physics make plausible if not likely that there exists a mass gap between the SM degrees of freedom and any new physics threshold.

In this case, the effects from new physics on process such as $t\bar{t}$ production can be well captured by higher dimensional interactions among the SM particles

effective 4-fermion interaction



$$L = L_{SM} + \frac{g^2}{M^2}\bar{\psi}\psi\bar{\psi}\psi$$

$$\dim = 6$$

no bias on what the TeV new physics should be

Low-energy effective field theory approach to BSM

Buchmuller-Wyler '86

New interactions are assumed to respect all symmetries of the SM.

> 60 operators

$$L = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

$$\mathrm{dim} = \quad \leq 4 \qquad\qquad 6$$

Good news: Only a few operators contribute to top quark physics study of new physics in $t\bar{t}$ final state in the most *general* model-independent approach

Dimension 6 operators for top physics

Zhang & Willenbrock'10, Aguilar-Saavedra '10 , Degrande & al '10 ...

There are only 15 relevant operators:

CP-even

operator	process
$O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$	top decay, single top
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with real coefficient)	top decay, single top
$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$	single top
$O_{hG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi G} = \frac{1}{2}(\phi^+\phi) G^A_{\mu\nu} G^{A\mu\nu}$	$gg \to t\bar{t}$
7 four-quark operators	$q\bar{q} \to t\bar{t}$

CP-odd

operator	process
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_{\tilde{G}} = g_s f_{ABC} \tilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi\tilde{G}} = \frac{1}{2}(\phi^+\phi)\tilde{G}^A_{\mu\nu} G^{A\mu\nu}$	$gg \to t\bar{t}$

We will only consider those which affect top pair production **at tree level by interference with the SM** (QCD) amplitudes (we neglect weak corrections)

Dimension 6 operators for top physics

Zhang & Willenbrock'10, Aguilar-Saavedra '10 , Degrande & al '10

There are only 15 relevant operators:

CP-even

top-philic operators: modifying top couplings and not only-gluon couplings

operator	process
$O^{(3)}_{\phi q} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$	top decay, single top
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with real coefficient)	top decay, single top
$O^{(1,3)}_{qq} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$	single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
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operator	process
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_{\tilde{G}} = g_s f_{ABC} \tilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi\tilde{G}} = \frac{1}{2}(\phi^+\phi) \tilde{G}^A_{\mu\nu} G^{A\mu\nu}$	$gg \to t\bar{t}$

We will only consider those which affect top pair production **at tree level by interference with the SM** (QCD) amplitudes (we neglect weak corrections)

Effective Field Theory for Top Quark Pair production

Degrande & al '10

We calculate top pair production at order $O(1/\Lambda^2)$

$$|M|^2 = |M_{SM}|^2 + 2\Re(M_{SM} M_{NP}^*) + \mathscr{O}\left(\frac{1}{\Lambda^4}\right)$$

i.e. we assume new physics manifests itself at low energy only through operators interfering with the SM

We focus on top-philic new physics (and therefore ignore interactions that would only affect the standard gluon vertex $\mathcal{O}_G = f_{ABC} G^A_{\mu\nu} G^{B\,\nu\rho} G_\rho^{C\,\mu}$)

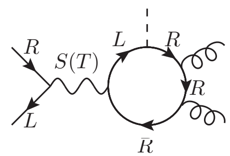
We are left with only two classes of dim-6 gauge invariant operators (when working at order $O(1/\Lambda^2)$)

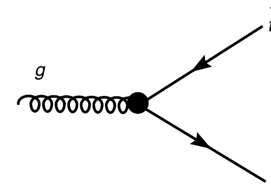
Effective Field Theory for Top Quark Pair production

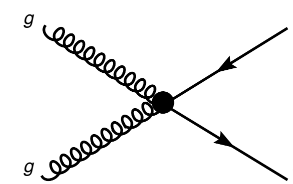
We are left with only two classes of dim-6 gauge invariant operators (when working at order $O(1/\Lambda^2)$)

- op. with t, $\bar{t}$ and one or two gluons (chromomagnetic moment)

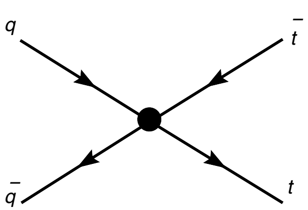
$$\mathcal{O}_{hg} = \left[\left(H\bar{Q}\right)\sigma^{\mu\nu}T^{A}t\right]G^{A}_{\mu\nu}$$







- 4-fermion op.



$\bar{L}L\bar{L}L$:

$$\mathcal{O}^{(8)}_{Qu} = \left(\bar{Q}\gamma^{\mu}T^{A}Q\right)\left(\bar{u}\gamma_{\mu}T^{A}u\right),$$
$$\mathcal{O}^{(8)}_{Qd} = \left(\bar{Q}\gamma^{\mu}T^{A}Q\right)\left(\bar{d}\gamma_{\mu}T^{A}d\right),$$
$$\mathcal{O}^{(8)}_{tq} = \left(\bar{q}\gamma^{\mu}T^{A}q\right)\left(\bar{t}\gamma_{\mu}T^{A}t\right),$$

$\bar{R}R\bar{R}R$:

$$\mathcal{O}^{(8)}_{tu} = \left(\bar{t}\gamma^{\mu}T^{A}t\right)\left(\bar{u}\gamma_{\mu}T^{A}u\right),$$
$$\mathcal{O}^{(8)}_{td} = \left(\bar{t}\gamma^{\mu}T^{A}t\right)\left(\bar{d}\gamma_{\mu}T^{A}d\right),$$

$\bar{L}L\bar{R}R$:

$$\mathcal{O}^{(8,1)}_{Qq} = \left(\bar{Q}\gamma^{\mu}T^{A}Q\right)\left(\bar{q}\gamma_{\mu}T^{A}q\right),$$
$$\mathcal{O}^{(8,3)}_{Qq} = \left(\bar{Q}\gamma^{\mu}T^{A}\sigma^{I}Q\right)\left(\bar{q}\gamma_{\mu}T^{A}\sigma^{I}q\right),$$

$\bar{L}R\bar{L}R$:

$$\mathcal{O}^{(8)}_{d} = \left(\bar{Q}T^{A}t\right)\left(\bar{q}T^{A}d\right),$$

: negligible (QCD is chirality diagonal)

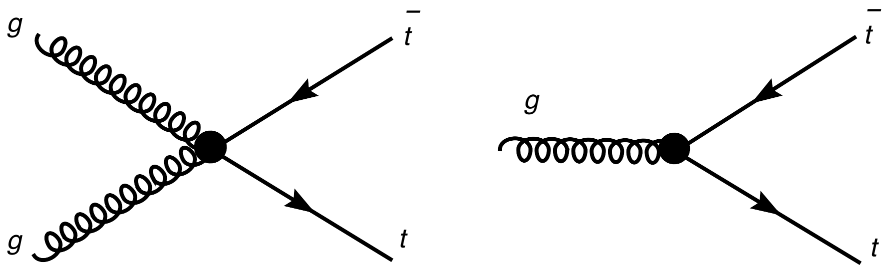
however only 7 independent operators

top pair production in EFT at order $O(1/\Lambda^2)$

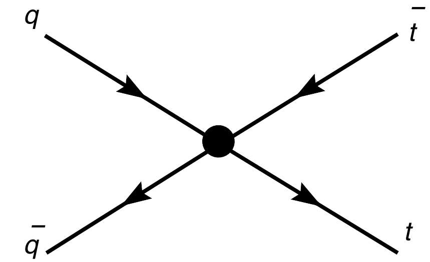
we assume new physics manifests itself at low energy only through operators interfering with the SM

$$|M|^2 = |M_{SM}|^2 + 2\Re(M_{SM}M_{NP}^*) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

New vertices:

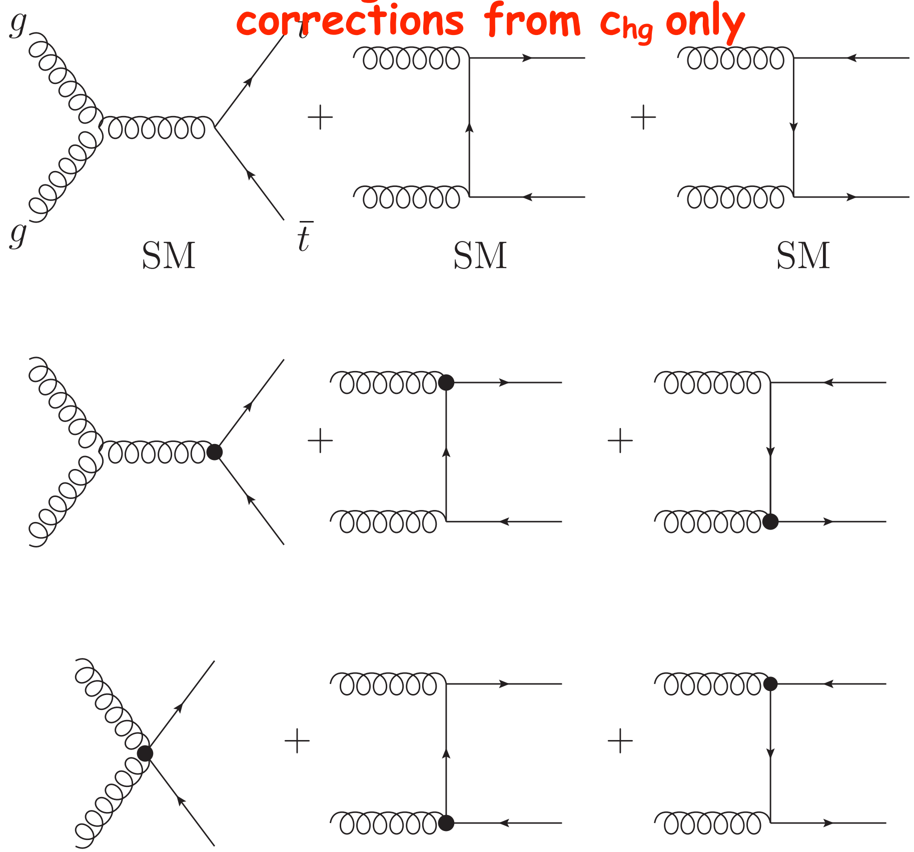


Chromomagnetic operator $\mathcal{O}_{hg} = (H\bar{Q})\sigma^{\mu\nu}T^A t\, G^A_{\mu\nu}$

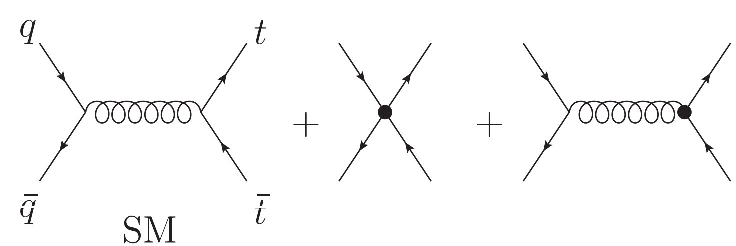


Four-fermion operators

top pair production from gluon fusion: corrections from c_{hg} only



top pair production from q anti-q annihilation: corrections from both c_{hg} and 4-fermion operators



gluon fusion (contribution from one operator only)

The new physics and SM contributions for gluon fusion have a common factor

$$\frac{d\sigma}{dt}(gg \to t\bar{t}) = \frac{d\sigma_{SM}}{dt} + \sqrt{2}\alpha_s g_s \frac{v m_t}{s^2} \frac{c_{hg}}{\Lambda^2} \left(\frac{1}{6\tau_1\tau_2} - \frac{3}{8} \right)$$

$$\frac{d\sigma_{SM}}{dt}(gg \to t\bar{t}) = \frac{\pi \alpha_s^2}{s^2} \left(\frac{1}{6\tau_1\tau_2} - \frac{3}{8} \right) (\rho + \tau_1^2 + \tau_2^2 - \frac{\rho^2}{4\tau_1\tau_2})$$

Common factor mainly responsible for the shape of the distributions

$$\tau_1 = \frac{m_t^2 - t}{s}, \quad \tau_2 = \frac{m_t^2 - u}{s}, \quad \rho = \frac{4m_t^2}{s}$$

t: Mandelstam variable related to θ angle

(between incoming parton and outgoing top quark)

$$m_t^2 - t = \frac{s}{2}(1 - \beta\cos\theta)$$

The operator O_{hg} can hardly be distinguished from the SM in gluon fusion

Distortions in the shape of the distributions can only come from q $\bar{q}$ annihilation → small effect at LHC

$q\,\bar{q}$ annihilation (contribution from the 8 operators)

Only two linear combinations of 4-fermion operators actually contribute to the differential cross section after averaging over the final state spins

some vector combination of operators that is symmetric under q <-> $\bar{q}$

some axial combination of operators is asymmetric under q <-> $\bar{q}$

$$\frac{d\sigma}{dt}(q\bar{q}\to t\bar{t}) = \frac{d\sigma_{SM}}{dt}\left(1+\frac{c_{Vv}\pm\frac{c'_{Vv}}{2}}{g_s^2}\frac{s}{\Lambda^2}\right) + \frac{1}{\Lambda^2}\frac{\alpha_s}{9s^2}\left(\left(c_{Aa}\pm\frac{c'_{Aa}}{2}\right)s(\tau_2-\tau_1) + 4g_s c_{hg}\sqrt{2}vm_t\right)$$

even part in the scattering angle θ

comes from $\bar{t}\gamma^\mu T^A t\bar{q}\gamma^\mu T^A q$

odd part in the scattering angle θ

comes from $\bar{t}\gamma^\mu\gamma_5 T^A t\bar{q}\gamma^\mu\gamma_5 T^A q$

This dependence vanishes after integration over t

vector combination of the light quarks involving the RH and LH top quarks

axial combination of the light quarks involving the RH and LH top quarks

$$c_{Vv} = c_{Rv} + c_{Lv} \quad \longleftarrow \text{u+d} \longrightarrow \quad c_{Aa} = c_{Ra} - c_{La}$$

$$c'_{Vv} = (c_{tu}-c_{td})/2 + (c_{Qu}-c_{Qd})/2 + c_{Qq}^{(8,3)} \quad \longleftarrow \text{u-d} \longrightarrow \quad c'_{Av} = (c_{tu}-c_{td})/2 - (c_{Qu}-c_{Qd})/2 - c_{Qq}^{(8,3)}$$

with $\begin{cases} c_{Rv} = c_{tq}/2 + (c_{tu}+c_{td})/4 \\ c_{Lv} = c_{Qq}^{(8,1)}/2 + (c_{Qu}+c_{Qd})/4 \end{cases}$

with $\begin{cases} c_{Ra} = -c_{tq}/2 + (c_{tu}+c_{td})/4 \\ c_{La} = -c_{Qq}^{(8,1)}/2 + (c_{Qu}+c_{Qd})/4. \end{cases}$

total cross section

Tevatron

$$\sigma\left(pp\to t\bar{t}\right)/\mathrm{pb} \;=\; 6.15^{+2.41}_{-1.61} + \left[\left(0.87^{+0.23}_{-0.16}\right)c_{Vv} + \left(1.44^{+0.47}_{-0.33}\right)c_{hg} + \left(0.31^{+0.08}_{-0.06}\right)c'_{Vv}\right]\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2.$$

LHC 7 TeV

$$\sigma\left(pp\to t\bar{t}\right)/\mathrm{pb} = 94^{+22}_{-17} + \left[\left(4.5^{+0.7}_{-0.6}\right)c_{Vv} + \left(25^{+7}_{-5}\right)c_{hg} + \left(0.48^{+0.068}_{-0.056}\right)c'_{Vv}\right]\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

LHC 14 TeV

$$\sigma\left(pp\to t\bar{t}\right)/\mathrm{pb} \;=\; 538^{+162}_{-115} + \left[\left(15^{+2}_{-1}\right)c_{Vv} + \left(144^{+34}_{-25}\right)c_{hg} + \left(1.32^{+0.12}_{-0.12}\right)c'_{Vv}\right]\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2.$$

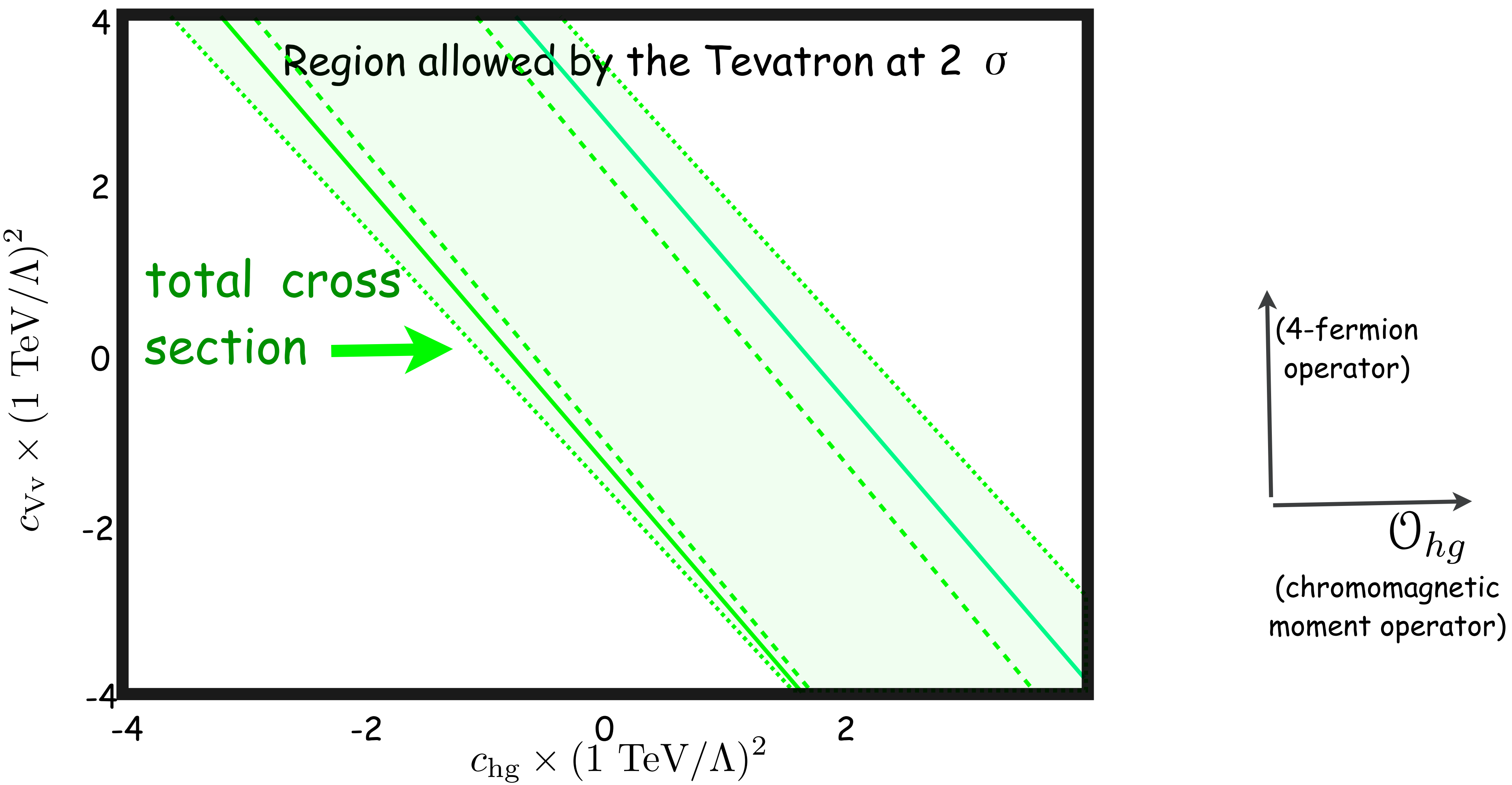
u+d (isospin 0)

chromo magnetic moment

u-d (isospin 1)

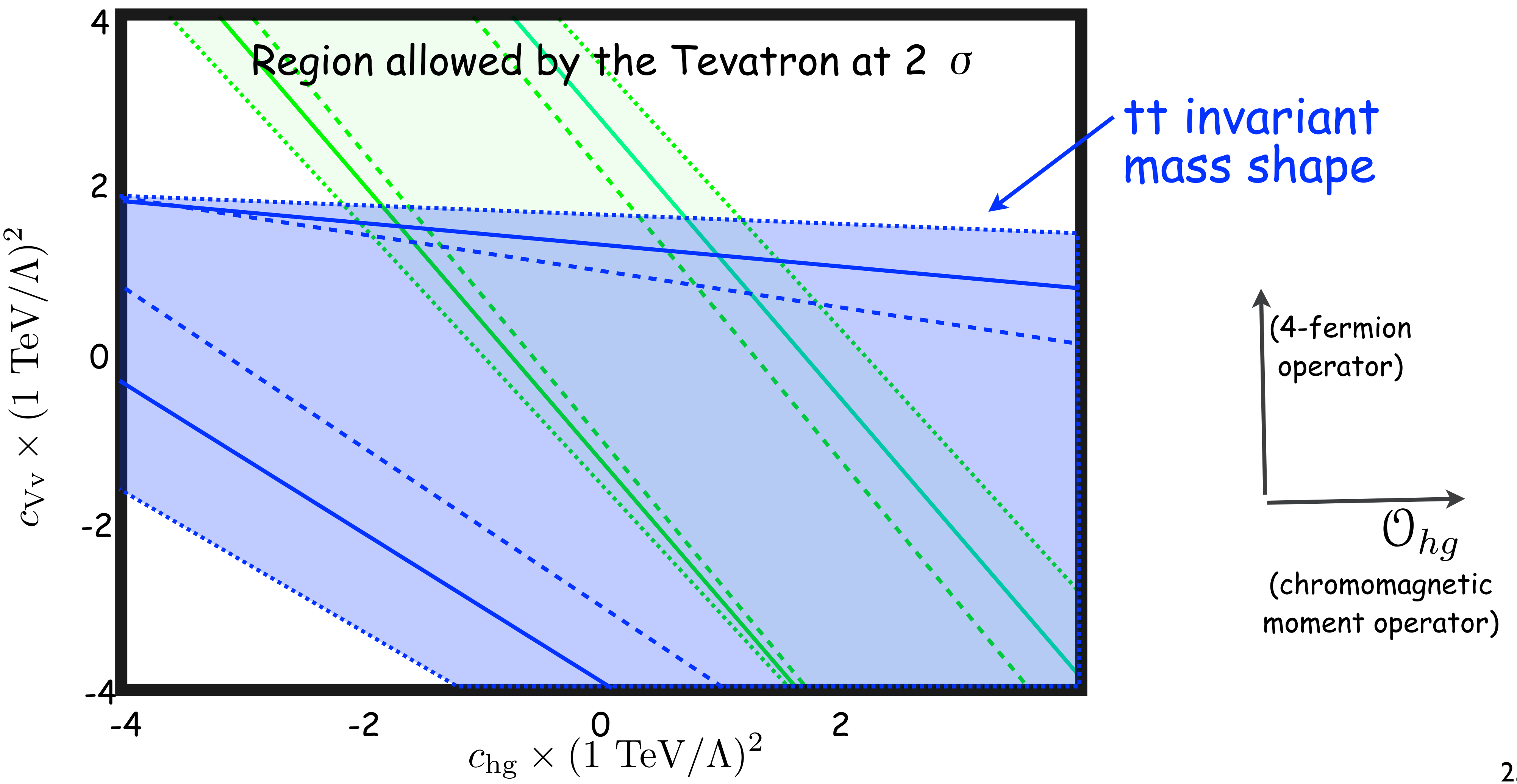
LO with CTEQ6L1 pdfs
In fits, we'll use NLO+NLL SM results but in interference, we'll keep LO SM amplitude

The $p\bar{p}$ -> $t\bar{t}$ total cross section at Tevatron depends on both c_{hg} and c_{Vv} and constrains thus a combination of these parameters.



Tevatron constraints

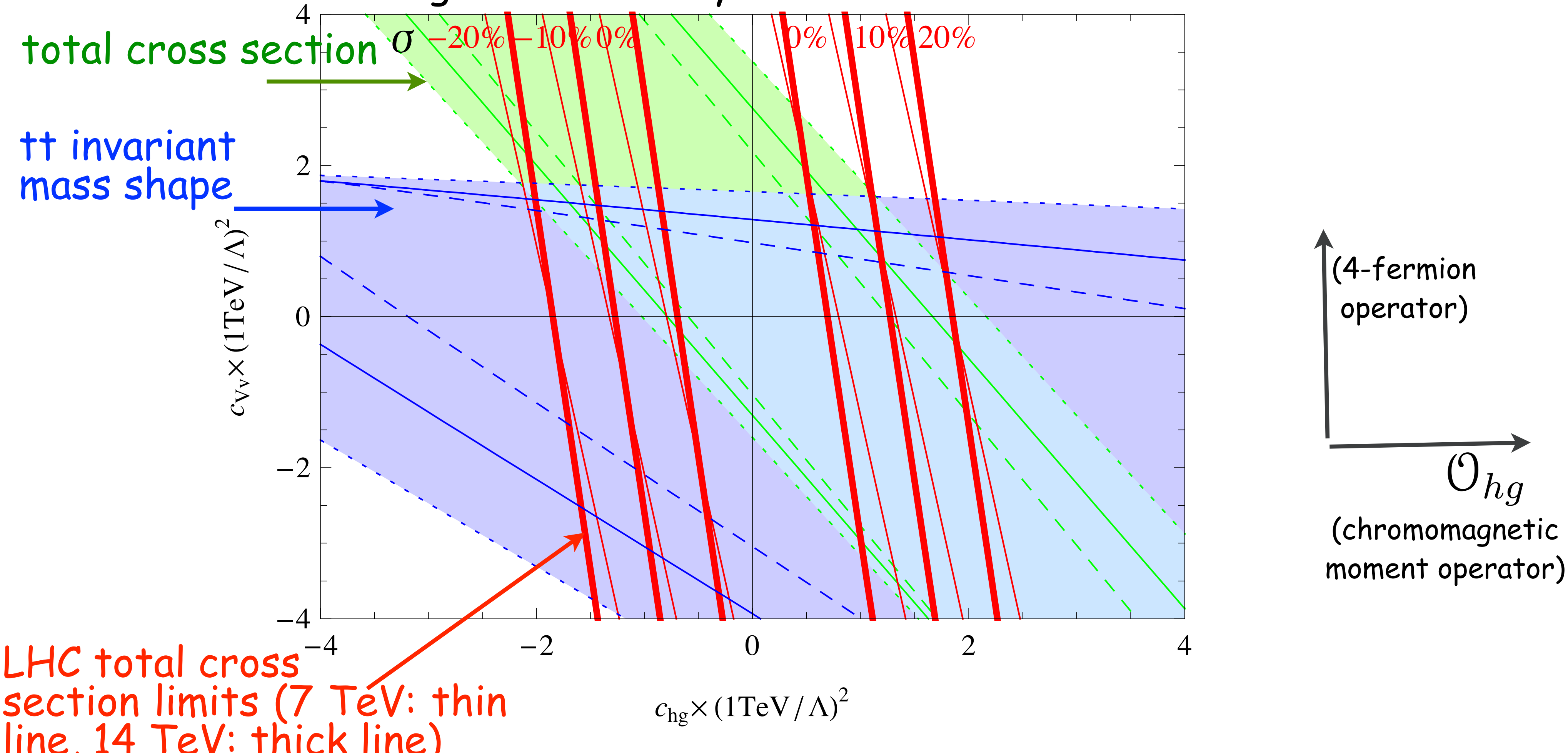
The $p\bar{p} \to t\bar{t}$ total cross section at Tevatron depends on both c_{hg} and c_{Vv} and constrains thus a combination of these parameters.



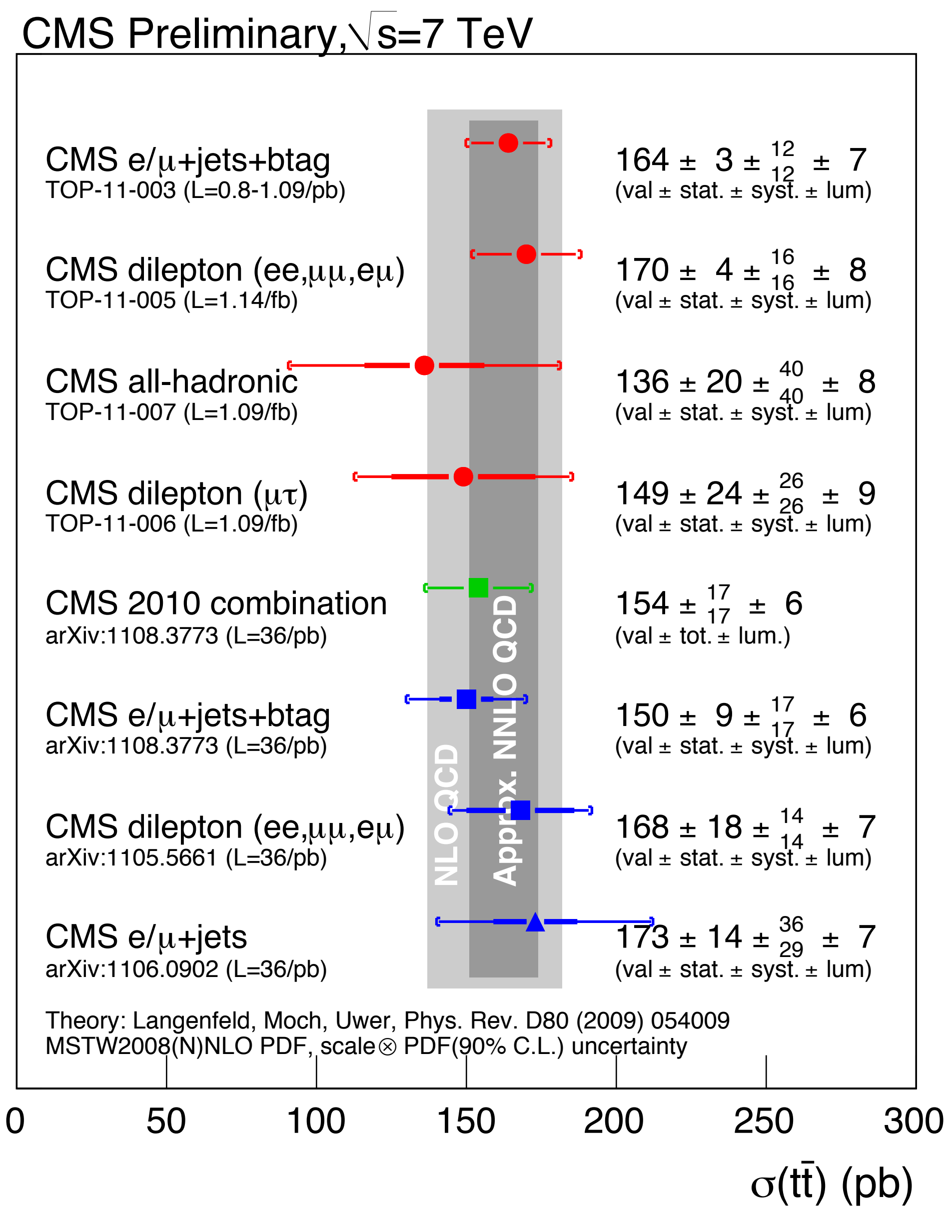
The LHC - Tevatron complementarity

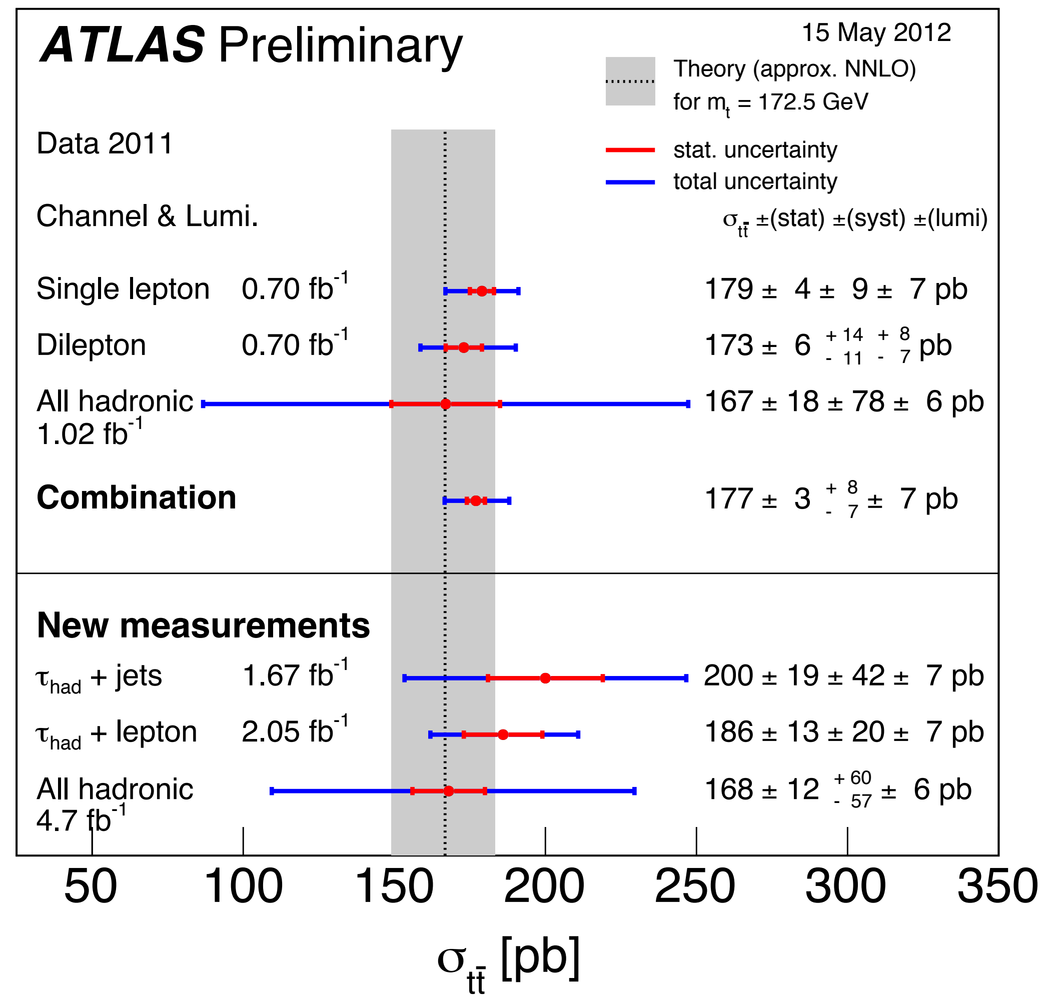
- The Tevatron cross section depends on both c_{hg} and c_{Vv} and constrains thus a combination of these parameters.
- At the LHC, the pp -> $t\bar{t}$ total cross section mostly depends on c_{hg} and can be directly used to constrain the allowed range for c_{hg}

Region allowed by the Tevatron at 2



$t\bar{t}$ cross section very much SM-like



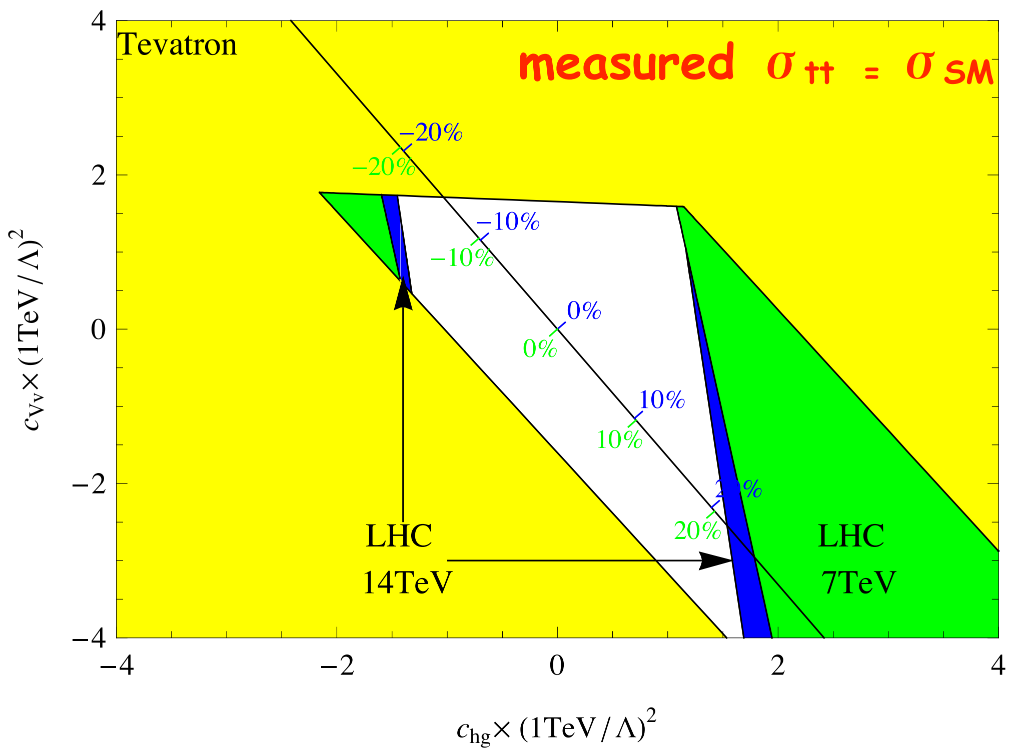


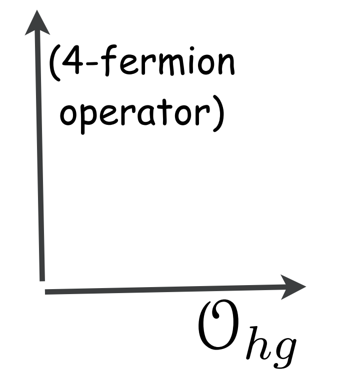
Constraining Non-resonant New Physics in top pair production

[Degrande et al'10]

yellow region is excluded by Tevatron

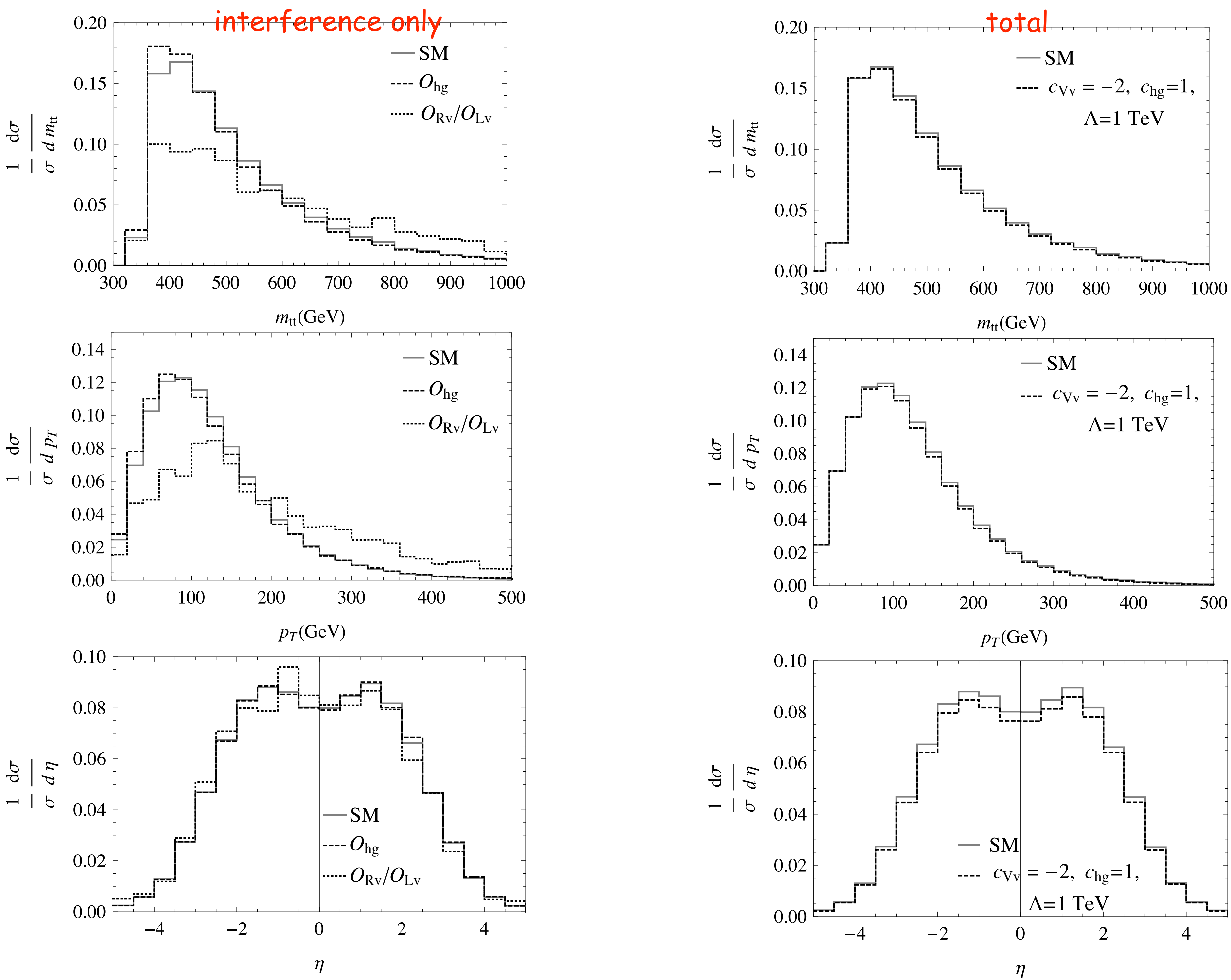
green (blue) region excluded by LHC at 7 TeV (14 TeV) after a precision of 10% is reached on σ_{tt}





A 10% uncertainty on the total cross section at the LHC already rules out a large region of parameter space

Minor effect on shapes of distributions at the LHC



Domain of validity of results

1) when $O(1/\Lambda^4)$ terms are subdominant

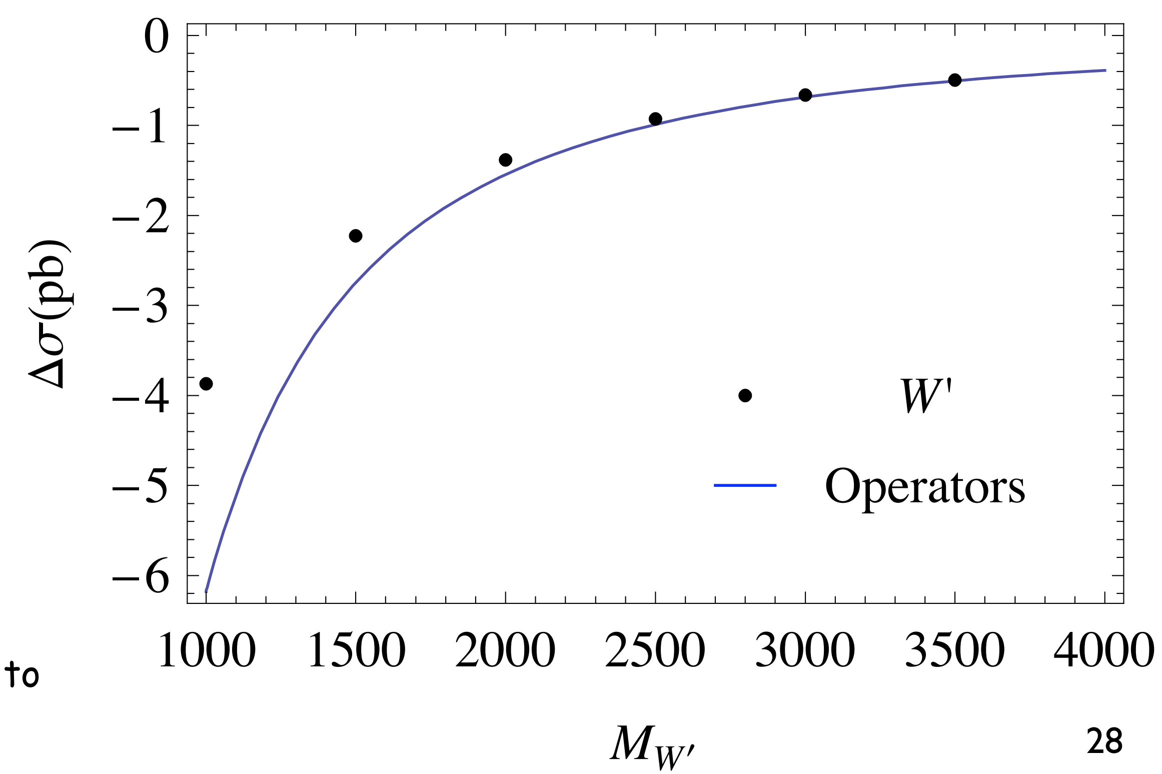
At the Tevatron, our results apply to a region of parameter space bounded by

$$|c_i| \left(\frac{\text{TeV}}{\Lambda}\right)^2 \lesssim 7$$

At the LHC, since the center of mass energy is larger, the reliable region shrinks to $|c_{hg}| \left(\frac{\text{TeV}}{\Lambda}\right)^2 \lesssim 3$ and $|c_{Vv}| \left(\frac{\text{TeV}}{\Lambda}\right)^2 \lesssim 2$

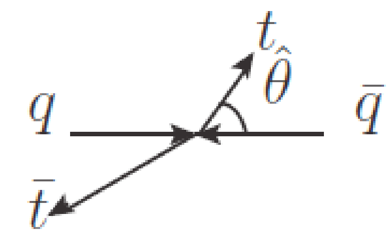
2) For which typical mass scale does the effective field theory treatment apply?

-> ~ 1.5 TeV



correction to SM cross section at the LHC due to a W' and comparison with EFT computation

Effective Field Theory Approach to the Forward-Backward asymmetry



$$A_{FB} \equiv \frac{\sigma(\cos\theta_t > 0) - \sigma(\cos\theta_t < 0)}{\sigma(\cos\theta_t > 0) + \sigma(\cos\theta_t < 0)}$$

$$A_{FB}^{\rm SM} = 0.05 \pm 0.015. \qquad A_{FB}^{\rm EXP} = 0.15 \pm 0.05({\rm stat}) \pm 0.024({\rm syst}),$$

-> top quarks are preferentially emitted in the direction of the incoming quark

$$\frac{d\sigma}{dt}(q\bar{q} \to t\bar{t}) = \frac{d\sigma_{SM}}{dt}\left(1 + \frac{c_{Vv} \pm \frac{c'_{Vv}}{2}}{g_s^2}\frac{s}{\Lambda^2}\right) + \frac{1}{\Lambda^2}\frac{\alpha_s}{9s^2}\left(\left(c_{Aa} \pm \frac{c'_{Aa}}{2}\right)s(\tau_2 - \tau_1) + 4g_s c_{hg}\sqrt{2}vm_t\right)$$

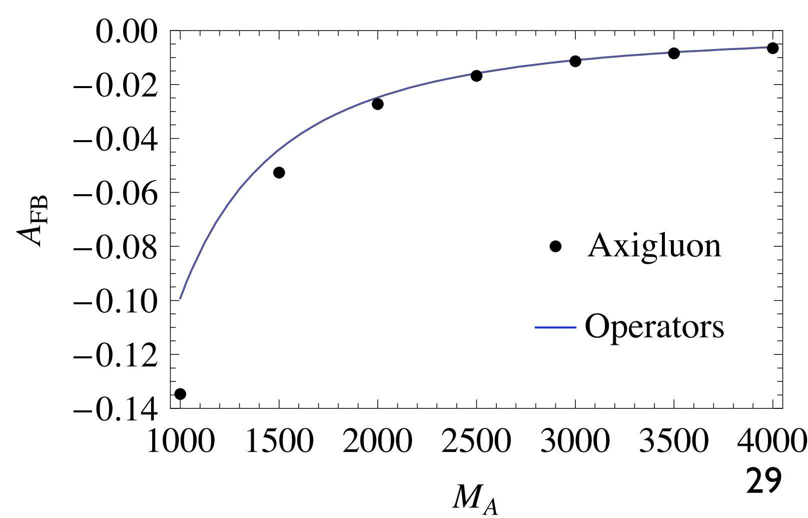
$$\delta A_{FB}^{\dim 6} = \left(0.0342^{+0.016}_{-0.009}\, c_{Aa} + 0.0128^{+0.0064}_{-0.0036}\, c'_{Aa}\right) \times \left(\frac{1\ {\rm TeV}}{\Lambda}\right)^2$$

[Degrande et al'10]

C_{Aa} and C'_{Aa} are only constrained by the asymmetry and not by the total cross section or the invariant mass distribution

Link to axigluon models:

$$c_{Aa}/\Lambda^2 = -2g_A^q g_A^t/m_A^2$$



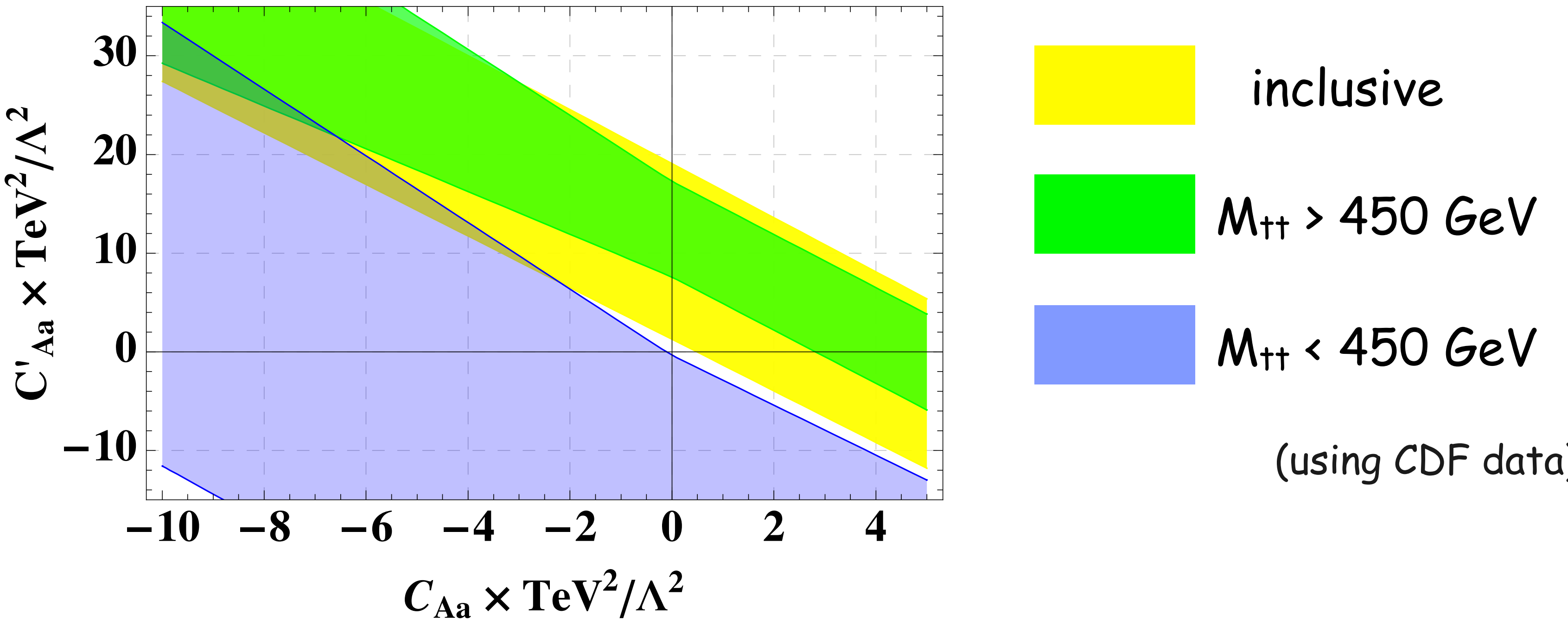
AFB prediction at the Tevatron due to an axigluon and comparison with the EFT computation

Most general expression at order $O(\Lambda^{-2})$

$$\delta A(m_{t\bar{t}} < 450\text{ GeV}) = \left(0.023^{+3}_{-1} c_{Aa} + 0.0081^{+6}_{-4} c'_{Aa}\right)\left(\frac{1\text{ TeV}}{\Lambda}\right)^2,$$

$$\delta A(m_{t\bar{t}} \geqslant 450\text{ GeV}) = \left(0.087^{+10}_{-9} c_{Aa} + 0.032^{+4}_{-3} c'_{Aa}\right)\left(\frac{1\text{ TeV}}{\Lambda}\right)^2.$$

[Degrande et al'10,'11]



(using CDF data)

Including $O(\Lambda^{-4})$ terms can alleviate the tension. See analysis by Aguilar-Saavedra & Perez-Victoria, 1103.2765 and Delaunay et al, 1103.2297.

$$\sigma(t\bar{t}) = \sigma_{SM} + \delta\sigma_{int} + \delta\sigma_{quad} \quad \Rightarrow \quad \delta\sigma_{int} + \delta\sigma_{quad} \simeq 0$$

This requires $A_{new} \sim -2A_{SM}$ ⇒ $t\bar{t}$ tail at LHC

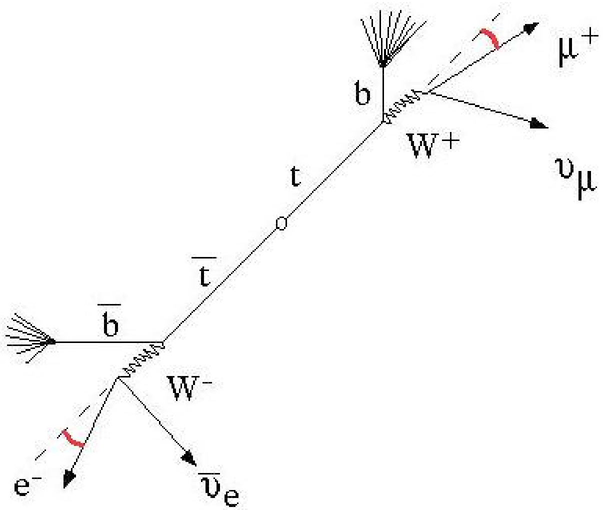
consistent to ignore SM×Dim 8 terms if c is large

Spin correlations

The three observables σ, $d\sigma/dm_{t\bar{t}}$ and A_{FB} are unable to disentangle between theories coupled mainly to right- or left-handed top quarks. However, spin correlations allow us to determine which chiralities of the top quark couple to new physics, and in the case of composite models, whether one or two chiralities of the top quark are composite.

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + C\cos\theta_+\cos\theta_- + b_+\cos\theta_+ + b_-\cos\theta_-\right)$$

θ_+ (θ_-) is the angle between the charged lepton l^+ (l^-) resulting from the top (antitop) decay and some reference direction $\vec{a}$ ($\vec{b}$).



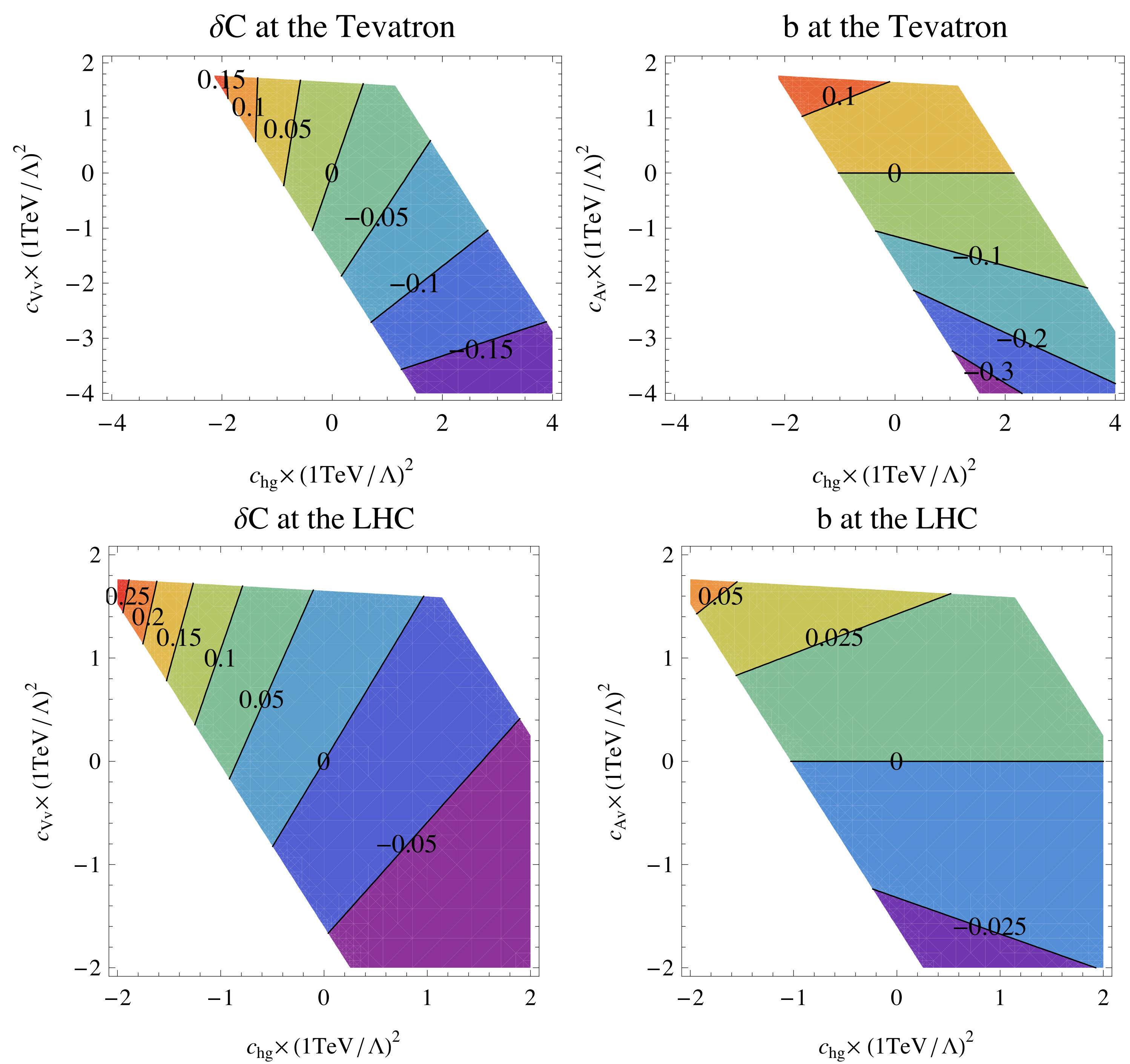
$$\begin{aligned}
C &= \frac{1}{\sigma}\left(\sigma_{RL} + \sigma_{LR} - \sigma_{RR} - \sigma_{LL}\right),\\
b_+ &= \frac{1}{\sigma}\left(\sigma_{RL} - \sigma_{LR} + \sigma_{RR} - \sigma_{LL}\right),\\
b_- &= \frac{1}{\sigma}\left(\sigma_{RL} - \sigma_{LR} - \sigma_{RR} + \sigma_{LL}\right).
\end{aligned}$$

$$C \times \sigma/\text{pb} = 2.82^{+1.06}_{-0.72} + \left[\left(0.37^{+0.10}_{-0.08}\right)c_{hg} + \left(0.50^{+0.13}_{-0.10}\right)c_{Vv}\right] \times \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2,$$

$$b \times \sigma/\text{pb} = \left(0.45^{+0.12}_{-0.09}\right)c_{Av} \times \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2,$$

allows to distinguish between LH and RH quarks

proportional to $c_{Rv} - c_{Lv}$


δC at the Tevatron
b at the Tevatron
δC at the LHC
b at the LHC
$c_{Vv}\times(1\text{TeV}/\Lambda)^2$
$c_{Av}\times(1\text{TeV}/\Lambda)^2$
$c_{hg}\times(1\text{TeV}/\Lambda)^2$
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.3
0.25
0.2
0.025
−0.025

Summary

Non-resonant top philic new physics can be probed using measurements in top pair production at hadron colliders

This model-independent analysis can be performed in terms of 8 operators. Observables depend on different combinations of only 4 parameters:

$$\sigma(gg \to t\bar{t}), d\sigma(gg \to t\bar{t})/dt \quad \leftrightarrow \quad c_{hg}$$

$$\sigma(q\bar{q} \to t\bar{t}) \quad \leftrightarrow \quad c_{hg}, c_{Vv}$$

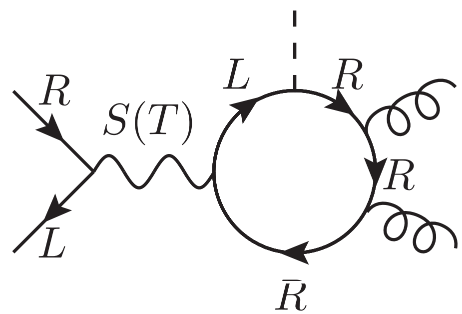
$$d\sigma(q\bar{q} \to t\bar{t})/dm_{tt} \quad \leftrightarrow \quad c_{hg}, c_{Vv}$$

$$A_{FB} \quad \leftrightarrow \quad c_{Aa}$$

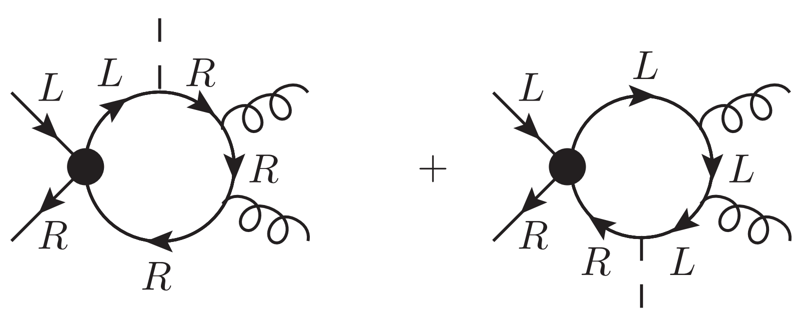
$$\text{spin correlations} \quad \leftrightarrow \quad c_{hg}, c_{Vv}, c_{Av}$$

Chromo-magnetic operator O_{hg}

1-loop generation of the chromo-magnetic operator

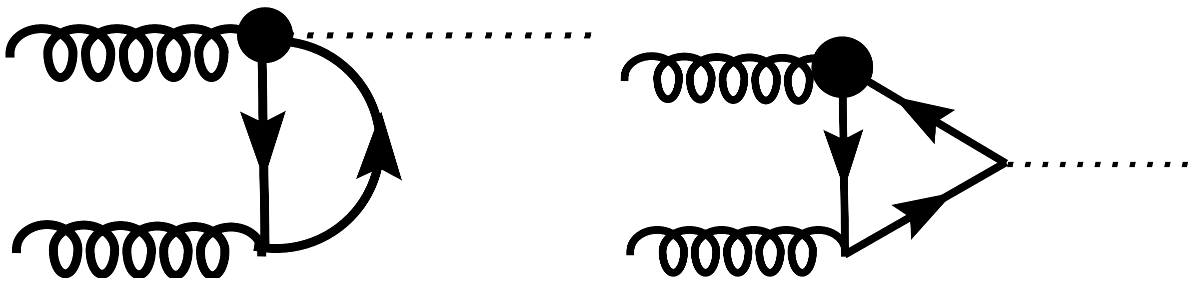


$$\left(H\bar{Q}t\right)\left(H\bar{Q}t\right) \Longrightarrow \delta c_{hg}$$

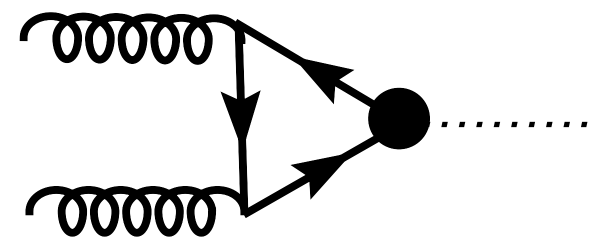


Constraints from higgs searches on top-philic new physics

Degrande et al, 1205.1065



$$\mathcal{O}_{hg} = \left(\bar{Q}_L H\right) \sigma^{\mu\nu} T^a t_R G^a_{\mu\nu}$$



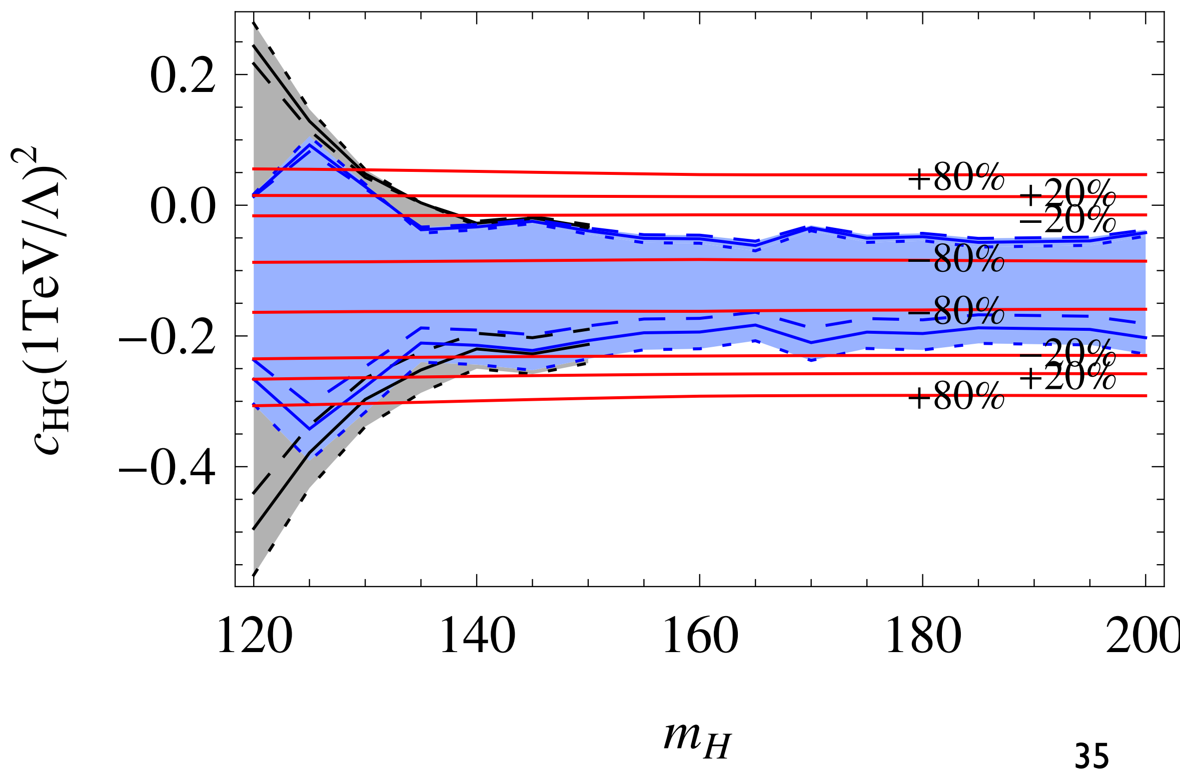
$$\mathcal{O}_{Hy} = H^\dagger H \left(H \bar{Q}_L\right) t_R$$

$$\mathcal{O}_H = \partial_\mu \left(H^\dagger H\right) \partial^\mu \left(H^\dagger H\right)$$

$$\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$

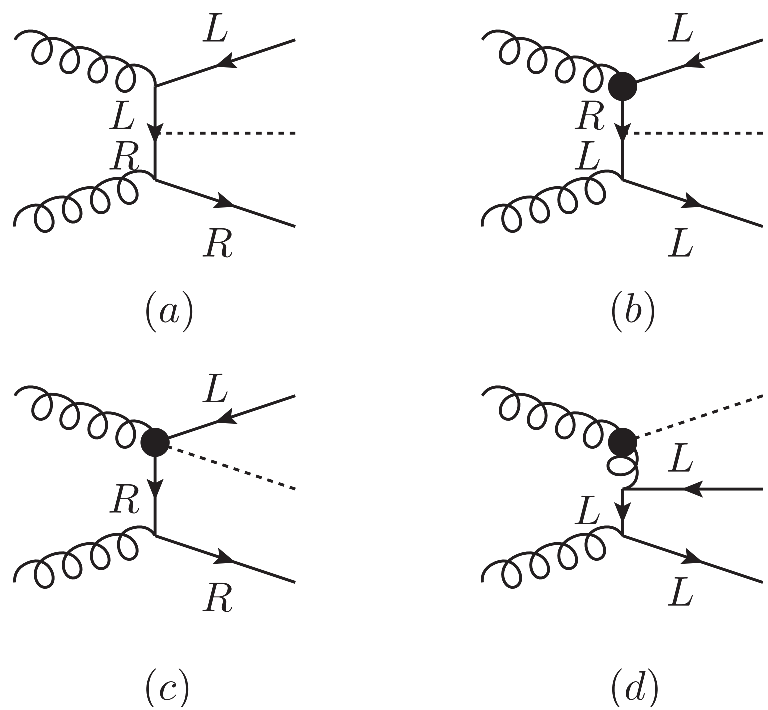
$$\delta c_{HG} \approx 0.03 \Re c_{hg} - 0.006 c_y$$

$$c_y = c_H + \frac{v}{\sqrt{2} m_t} \Re \left(c_{Hy}\right)$$



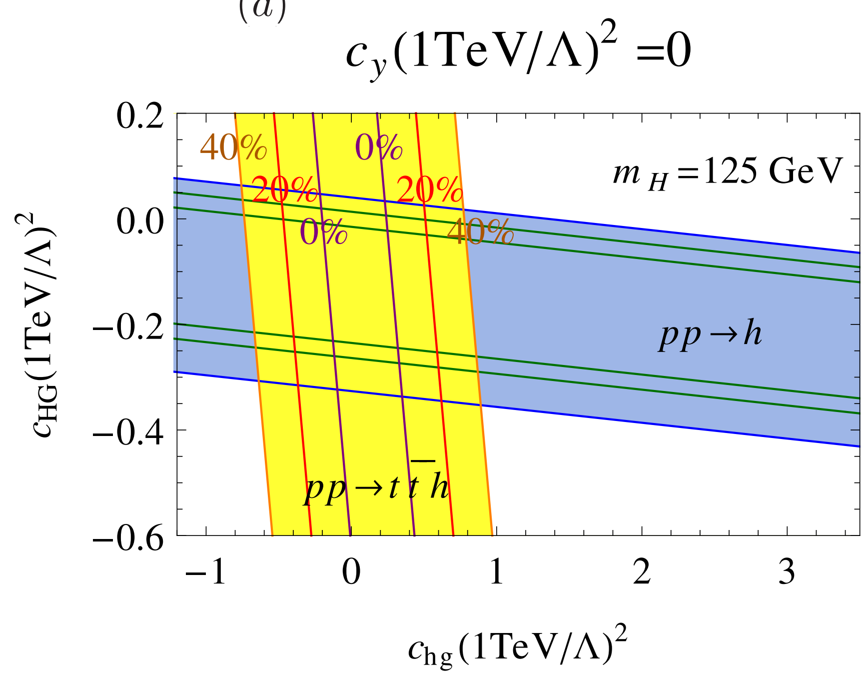
Using $t\bar{t}h$ to constrain the chromomagnetic operator

Degrande et al, 1205.1065



constraints from h production

constraints from tth production



Back to models of top compositeness

Let us now imagine the top partners are too heavy to be accessible at the LHC (i.e >~1.5-2 TeV), and heavy gluons also too heavy (>~4 TeV)

Where shall we search for signs of top compositeness ?

Enhanced four-top production in composite top models

In models of composite tops, the operators contributing directly to top pair production are subdominant compared to four-top operators (from Naive Dimensional Analysis)

$$\frac{1}{\Lambda^2}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$$

(obtained after integrating out heavy resonances)

(The dominant operators are those which contain only fields from the strong sector, scale as g_ρ^2)

$1 \lesssim g_\rho \lesssim 4\pi$

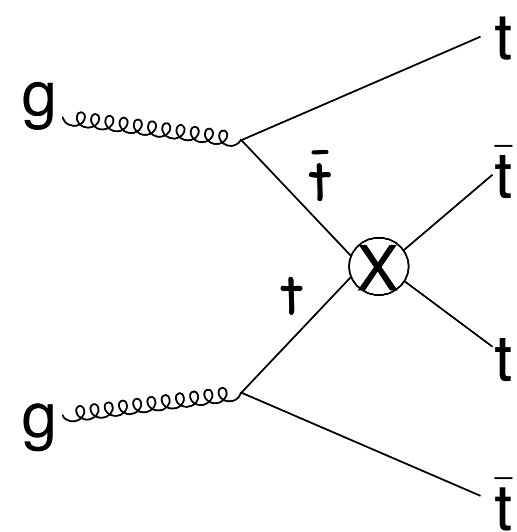
coupling of the strong sector

4-fermion op. contributing directly to $t\bar{t}$ production scale at best as g_ρ while O_{hg} scales as g_ρ^{-1}

In this case, a much better probe of the dominant dynamics is the direct production of four top quarks

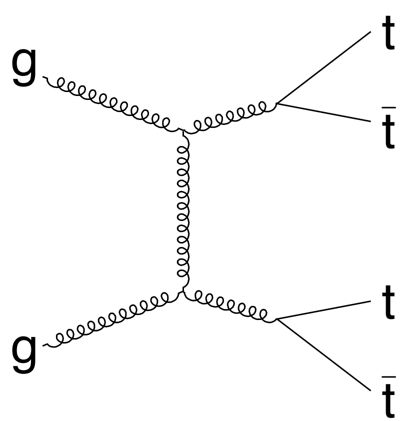
spectacular events with 12 partons in the final state

typical LHC cross sections at 14 TeV: 10 - 100 fb



[Pomarol, Serra'08]
[Lillie, Shu, Tait '08]

Four-top production in the Standard Model



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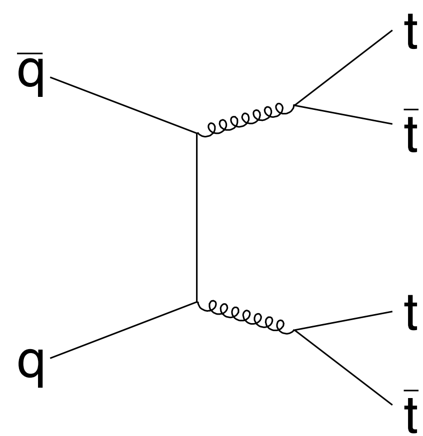


+ ....

88 %

σ_{LHC} ~ 7.5 fb @ 14 TeV

σ_{LHC} ~ 0.2 fb @ 7 TeV

$\sigma_{tevatron}$ < 10^-4 fb

⇛ 4 top final state sensitive to several classes of new TeV scale physics

e.g. SUSY (gluino pair production with $\tilde{g} \rightarrow t\,\bar{t}\,\chi_0$)

top compositeness

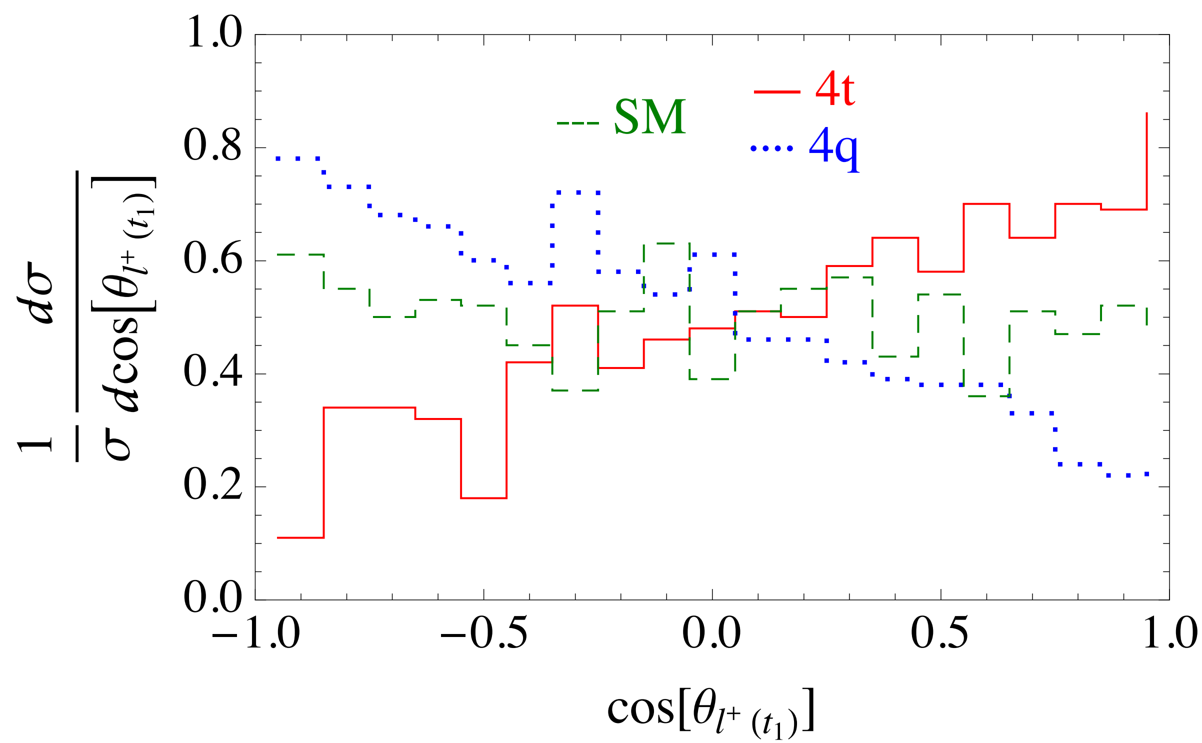
top polarization

In the models of interest, 4-top production yields an excess of right-handed tops

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{A}{2}(1+\cos\theta) + \frac{1-A}{2}(1-\cos\theta)$$

A: fraction of RH tops

θ is the angle between the direction of the (highest p_T) lepton in the top rest frame and the direction of the top polarisation



[Pomarol, Serra'08]

Summary

Effective field theory approach to BSM:
characterizes new physics in a model-independent way,
useful to set bounds on non-resonant new physics

2011 LHC data already rules out large region of parameter space

New constraints on the 4-fermion and the chromomagnetic operators and more to come

complementarity between Higgs, $t\bar{t}$ and $t\bar{t}H$ production

Models of top compositeness can lead to zero signal at 7-8 TeV while non-zero signals (4 top production + top partners production) at 14 TeV

The 2012 European
School of High-Energy Physics, Anjou

Other physics-BSM

Part II

Géraldine SERVANT
CERN-Th

The Hierarchy Problem has been the guideline of theorists for over 30 years

The main goal of the LHC:

Understand why $M_{EW} << M_{Planck}$

However, since LEP II, naturalness arguments have been under high stress and present null LHC searches are confirming theorists' anxiety

Part II

fine-tuning problems

✔The hierarchy problem associated with the Higgs [R. Rattazzi]

The SUSY solution [D. Kazakov]
The extra dimensional solutions
The 4D strongly interacting solutions

✔The Flavour problem [G. Isidori]

✔The strong CP problem

✔The "why so" puzzles

charge quantization
gauge coupling unification
proton stability

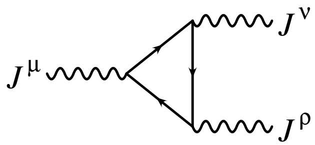
$\rightsquigarrow$ GUTs

fermion mass hierarchy
why 3 generations

observational facts unexplained by the SM

✔ The dark matter problem

✔ The matter antimatter asymmetry problem



$\partial_\mu J^\mu = \partial_\nu J^\nu = \partial_\rho J^\rho = 0$

$\sum_R \mathrm{Tr}\, T_R^A \{T_R^B, T_R^C\} = 0$

Good reason for unification : Anomaly cancellation in the SM

$$Q_e = T_3 + Y$$

1. SU(N)–G^2: $T_{\rm G} = 1$, so need $\sum_R \mathrm{Tr}\, T_R^A = 0$, trivial for $N > 1$
   - U(1)$_{\rm Y}$: $\sum_{\rm fermions} Y = (+1/6) \cdot 2 \cdot 3 + (-2/3) \cdot 3 + (+1/3) \cdot 3$ $+ (-1/2) \cdot 2 + 1 = 0$! Quarks and leptons cancel separately.
2. SU(3)^3 automatic: QCD is vectorlike ($\#$ of $3 = \#$ of $\overline{3}$)
3. SU(2)^3 automatic: $\frac{1}{8} \sum_{\rm doublets} \mathrm{Tr}\, \sigma^A \{\sigma^B, \sigma^C\} = \frac{1}{4} \delta^{BC} \mathrm{Tr}\, \sigma^A = 0$
4. U(1)$^3_{\rm Y}$: $\sum_{\rm fermions} Y^3 =$ $(+1/6)^3 \cdot 2 \cdot 3 + (-2/3)^3 \cdot 3 + (+1/3)^3 \cdot 3 + (-1/2)^3 \cdot 2 + 1^3 = 0$
   - Cancellation between quarks and leptons in each generation!
5. SU(3)^2–U(1)$_{\rm Y}$: $\propto \sum_{\rm quarks} Y = 0$ (just like gravitational anomaly)
6. SU(2)^2–U(1)$_{\rm Y}$: $\propto \sum_{\rm doublets} Y \mathrm{Tr}\{\sigma^B, \sigma^C\} \propto \sum_{\rm doublets} Y = (+1/6) \cdot 3 + (-1/2) = 0$
   - Cancellation between quarks and leptons again!

Highly non-trivial cancellation and suggestive connection of quarks and leptons

The SM as a remnant of a GUT theory?

There are gauge groups for which the anomalies automatically cancel, e.g. SO(10)

Good reason for unification II : Charge quantization $Q_e = T_3 + Y$

How come is the electric charge quantized?

- Eigen values of the generators of the abelian U(1) are continuous e.g. in the symmetry of translational invariance of time, there is no restriction in the (energy) eigen values.

- Eigen values of the generators of a simple non-abelian group are discrete

  e.g. in SO(3) rotations, the eigen values of the third component of angular momentum can take only integers or 1/2 integers values. In SU(5), since the electric charge is one of the generators, its eigen values are discrete and hence quantized.

simple unification group -> charge quantization

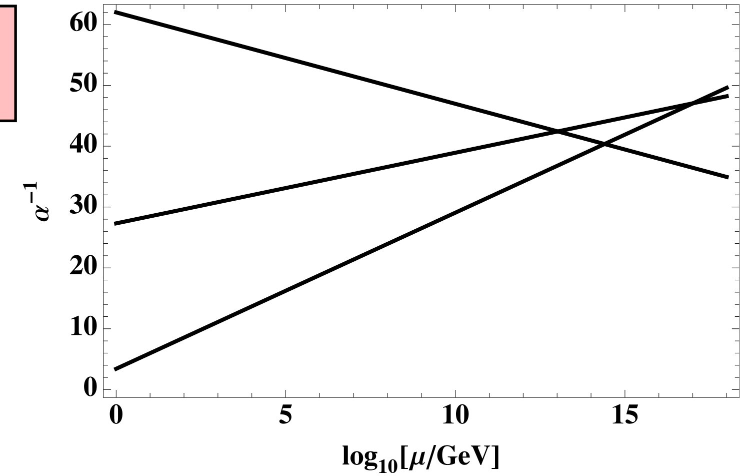
$SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)$

SM matter content fits nicely into SU(5)

relation between color SU(3) and electric charge.

Quarks carry 1/3 of the lepton charge because they have 3 colors. The SU(5) theory provides a rationale basis for understanding particle charges and the weak hypercharge assignment in the SM

Good reason for unification III



- **we observe different couplings but it is a low energy artefact**

- $SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)$

SM matter content fits nicely into SU(5)

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6}, \quad u_R^c = (\bar{3},1)_{-2/3}, \quad d_R^c = (\bar{3},1)_{1/3},$$

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2}, \quad e_R^c = (1,1)_1$$

$$\bar{5} = (1,2)_{-\frac{1}{2}\sqrt{\frac{3}{5}}} + (\bar{3},1)_{\frac{1}{3}\sqrt{\frac{3}{5}}}$$

$$\bar{5} = L + d_R^c$$

$$\chi^a = \left(d^{c1}\ d^{c2}\ d^{c3}\ e^-\ -\nu_e\right)_L^T,$$

$$10 = (5\times 5)_A = (\bar{3},1)_{-\frac{2}{3}\sqrt{\frac{3}{5}}} + (3,2)_{\frac{1}{6}\sqrt{\frac{3}{5}}} + (1,1)_{\sqrt{\frac{3}{5}}}$$

$$10 = u_R^c + Q_L + e_R^c$$

$$\psi_{ab} = \frac{1}{\sqrt{2}} \left(\begin{array}{ccc|cc} 0 & u^{c3} & -u^{c2} & -u_1 & -d_1 \\ -u^{c3} & 0 & u^{c1} & -u_2 & -d_2 \\ u^{c2} & -u^{c1} & 0 & -u_3 & -d_3 \\ \hline u_1 & u_2 & u_3 & 0 & -e^+ \\ d_1 & d_2 & d_3 & e^+ & 0 \end{array}\right)_L .$$

SU(5) adjoint rep.

$$\left(\begin{array}{c|c} SU(2) & \\ \hline & SU(3) \end{array}\right)$$

$$T^{12} = \sqrt{\frac{3}{5}} \left(\begin{array}{cc|ccc} 1/2 & & & & \\ & 1/2 & & & \\ \hline & & -1/3 & & \\ & & & -1/3 & \\ & & & & -1/3 \end{array}\right) = \sqrt{\frac{3}{5}}Y$$

additional U(1) factor that commutes with SU(3)*SU(2)

$$\mathrm{Tr}(T^a T^b) = \frac{1}{2}\delta^{ab}$$

$$g_5 T^{12} = g' Y \qquad g_5\sqrt{\frac{3}{5}} = g' \qquad g_5 = g = g_s$$

$\sin^2\theta_W = \frac{3}{8}$ @ M_{GUT}

Gauge coupling unification

The evolution of gauge couplings is controlled by the renormalization group equations

$$\frac{d\alpha(\mu)}{d\log\mu} \equiv \beta(\alpha(\mu))$$

At one loop:

$$\beta(\alpha) \equiv \frac{d\alpha(\mu)}{d\log\mu} = \frac{-b}{2\pi}\,\alpha^2 + \mathcal{O}(\alpha^3)$$

So couplings vary logarithmically as a function of the mass scale:

$$\frac{1}{\alpha(\mu)} = \frac{1}{\alpha(\mu_0)} + \frac{b}{2\pi}\log\frac{\mu}{\mu_0}$$

In particular:

$$\boxed{\alpha_i^{-1}(M_Z) = \alpha_{GUT}^{-1} - \frac{b_i}{4\pi}\log\frac{M_{GUT}^2}{M_Z^2} + \Delta_i} \qquad i = SU(3), SU(2), U(1)$$

Δ_i : accounts for threshold corrections from the GUT and weak s and the effect of Planck suppressed operators

b_i : defined by the particle content

SM beta functions

$$b = \frac{11}{3} T_2(\text{spin-1}) - \frac{2}{3} T_2(\text{chiral spin-1/2}) - \frac{1}{3} T_2(\text{complex spin-0})$$

$$Tr(T^a(R)T^b(R)) = T_2(R)\delta^{ab} \qquad T_2(\text{fund}) = \frac{1}{2} \qquad T_2(\text{adj}) = N$$

universal contribution coming from complete SU(5) representations ($4N_F/3$ in SM in $4N_F/3$ *3/2 in susy)

from gauge bosons

So in the SM:

$$b_3 = \frac{11}{3} \times N_c - \frac{2}{3} \times N_f \left(\frac{1}{2} \times 2 + \frac{1}{2} \times 1 + \frac{1}{2} \times 1 \right) = 7$$

$$b_2 = \frac{11}{3} \times 2 - \frac{2}{3} \times N_f \left(\frac{1}{2} \times 3 + \frac{1}{2} \times 1 \right) - \frac{1}{3} \times \frac{1}{2} = \frac{19}{6}$$

x 3/5

$$b_Y = -\frac{2}{3} \times N_f \left((\frac{1}{6})^2 \times 2 \times N_c + (\frac{-2}{3})^2 \times N_c + (\frac{1}{3})^2 \times N_c + (\frac{-1}{2})^2 \times 2 + (1)^2 \right)$$
$$-\frac{1}{3}(\frac{1}{2})^2 \times 2 = -\frac{41}{6} \qquad \longrightarrow \qquad b_1 = b_Y \times \frac{3}{5} = -\frac{41}{10}$$

from Higgs

$$\boxed{\alpha_i^{-1}(M_Z) = \alpha_{GUT}^{-1} - \frac{b_i}{4\pi}\log\frac{M_{GUT}^2}{M_Z^2} + \Delta_i} \qquad i = SU(3), SU(2), U(1)$$

$\alpha_3(M_Z), \alpha_2(M_Z), \alpha_1(M_Z)$: experimental inputs

b_3, b_2, b_1 : predicted by the matter content

3 equations and 2 unknowns (α_{GUT}, M_{GUT})

1 consistency relation for unification

Using $\alpha_1 = \frac{5}{3}\frac{1}{\cos^2\theta_W}\alpha_{em}$ and $\alpha_2 = \frac{\alpha_{em}}{\sin^2\theta_W}$

we obtain: $\epsilon_{ijk}(\alpha_i^{-1} - \Delta_i)(b_j - b_k) = 0$

If the Δ_i contributions are universal ($\Delta_1 = \Delta_2 = \Delta 3$) or negligible , this translates into

$$\boxed{\sin^2\theta_W = \frac{3(b_3 - b_2) + 5(b_2 - b_1)\frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)}}{8b_3 - 3b_2 - 5b_1}}$$

$\alpha_{em}(M_Z) \approx 1/128$

$\alpha_s(M_Z) \approx 0.1184 \pm 0.0007$

In the SM: $\sin^2\theta_W \approx 0.207$

Not so bad ...

to be compared with 0.2312+/-0.0002

From the consistency relation, we can define another observable quantity:

$$\boxed{B \equiv \frac{b_3 - b_2}{b_2 - b_1} = \frac{\alpha_2^{-1} - \alpha_3^{-1} - (\Delta_2 - \Delta_3)}{\alpha_2^{-1} - \alpha_1^{-1} - (\Delta_2 - \Delta_1)}}$$

unaffected by universal contribution to the running

Assuming universal contributions, we get: $B = \dfrac{\sin^2\theta_w \alpha_{em}^{-1} - \alpha_s^{-1}}{\sin^2\theta_w \alpha_{em}^{-1} - \alpha_{em}^{-1}} = 0.717 \pm 0.008 \pm 0.03$

to be compared with the prediction in the SM: $B_{SM} = 0.528$

large (40%) discrepancy! Cannot be accommodated by allowing a 10% theoretical uncertainty due to threshold corrections and higher loop effects.

We can finally derive the values of M_{GUT} and α_{GUT}

$$\boxed{M_{GUT} = M_Z \exp\left(2\pi \frac{3\alpha_s(M_Z) - 8\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)}\right)} \approx 7 \times 10^{14} \text{ GeV}$$

$$\boxed{\alpha_{GUT}^{-1} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)}} \approx 41.5$$

self-consistent calculation: $M_{GUT} < M_{Pl}$ safe to neglect quantum gravity effects

$\alpha_{GUT} \ll 1$ perturbative

values unchanged when adding universal contributions to the running

Quarks and leptons of the SM contribute universally as they form complete SU(5) multiplets, hence do not affect the relative running and therefore B

Only the Higgs and the SM gauge bosons can affect the relative running (see slide 9)

In the MSSM, extra contributions from the higgsinos and gauginos lead to the prediction B=0.714 remarkably close to the experimental value

SM

$$b = \frac{11}{3} T_2(\text{spin-1}) - \frac{2}{3} T_2(\text{chiral spin-1/2}) - \frac{1}{3} T_2(\text{complex spin-0})$$

$$Tr(T^a(R)T^b(R)) = T_2(R)\delta^{ab} \qquad T_2(\text{fund}) = \frac{1}{2} \qquad T_2(\text{adj}) = N$$

chiral superfield

complex spin-0
Weyl spin-1/2
in same representation R of gauge group

vector superfield

Weyl spin-1/2
real spin-1
in same representation V of gauge group

MSSM

$$b = \frac{11}{3} T_2(\texttt{vector}) - \underbrace{\frac{2}{3} T_2(\texttt{vector})}_{\text{gauginos}} - \frac{2}{3} T_2(\texttt{chiral}) - \underbrace{\frac{1}{3} T_2(\texttt{chiral})}_{\text{scalars}} = 3\, T_2(\texttt{vector}) - T_2(\texttt{chiral})$$

$$b_{SU(3)} = \overset{g}{3 \times 3} - \left(\overset{Q_L}{\frac{1}{2} \times 2 \times 3} + \overset{U}{\frac{1}{2} \times 1 \times 3} + \overset{D}{\frac{1}{2} \times 1 \times 3} \right) = 3$$

$$b_{SU(2)} = \overset{W^\pm, Z}{3 \times 2} - \left(\overset{Q_L}{\frac{1}{2} \times 3 \times 3} + \overset{L}{\frac{1}{2} \times 1 \times 3} \right) - \overset{H_u}{\frac{1}{2}} - \overset{H_d}{\frac{1}{2}} = -1$$

$$b_Y = -\left(\overset{Q_L}{\left(\frac{1}{6}\right)^2 3 \times 2 \times 3} + \overset{U}{\left(-\frac{2}{3}\right)^2 3 \times 3} + \overset{D}{\left(\frac{1}{3}\right)^2 3 \times 3} + \overset{L}{\left(-\frac{1}{2}\right)^2 2 \times 3} + \overset{E}{(1)^2 \times 3} \right) - \overset{H_u}{\left(\frac{1}{2}\right)^2 \times 2} - \overset{H_d}{\left(\frac{1}{2}\right)^2 \times 2} = -11 \longrightarrow b_{T^{12}} = -\frac{33}{5}$$

Values of -b in various models:

$$\mathrm{SM}: \quad (\beta)_{\mathrm{SM}} = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} F + \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix} N_H \ ,$$

$$\mathrm{MSSM}: \quad (\beta)_{\mathrm{MSSM}} = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} F + \begin{pmatrix} \frac{3}{10} \\ \frac{1}{2} \\ 0 \end{pmatrix} N_H \ ,$$

$$\text{Split-SUSY}: \quad (\beta)_{\mathrm{split}}|_{<\tilde{m}} = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} F + \begin{pmatrix} \frac{5}{10} \\ \frac{5}{6} \\ 0 \end{pmatrix} \ ,$$

light higgs, higgsino & gauginos but heavy sfermions

$$\text{low-}\mu \text{ split SUSY}: \quad (\beta)_{\mu-\mathrm{split}}|_{<\tilde{m}} = \begin{pmatrix} 0 \\ -22/3 \\ -11 \end{pmatrix} + \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} F + \begin{pmatrix} \frac{5}{10} \\ \frac{5}{6} \\ 0 \end{pmatrix}$$

light higgs, higgsino but heavy sfermions & gauginos

Another interesting observation:

In the SM, one can restore the gauge coupling unification without gauginos and higgsinos but if the third generation is partly composite!

[Agashe et al, hep-ph/0502222]
[Frigerio et al, 1103.2997]

If we substract H, t_R and t_R^c from the beta functions, B is approximately within 10% of the experimental value

The contribution from the partly composite third generation fermion sector restores the low energy prediction to a level that can be explained by threshold and higher loop effects

strong sector

SU(5) invariant

SU(5) breaking

$$\frac{d\alpha_i}{d\ln Q} \in -\frac{b_{\rm comp}}{2\pi}\alpha_i^2 + \frac{B_{ij}}{2\pi}\frac{\alpha_j^3}{4\pi} + \frac{C_{if}}{2\pi}\frac{\lambda_f^2}{16\pi^2}$$

universal
not computable
non perturbative
but negative and bounded from below

$$b_{SU(3)} = b_{SU(3)}^{SM} + \frac{2}{3}\left(\frac{1}{2}+\frac{1}{2}\right) = \frac{23}{3}$$

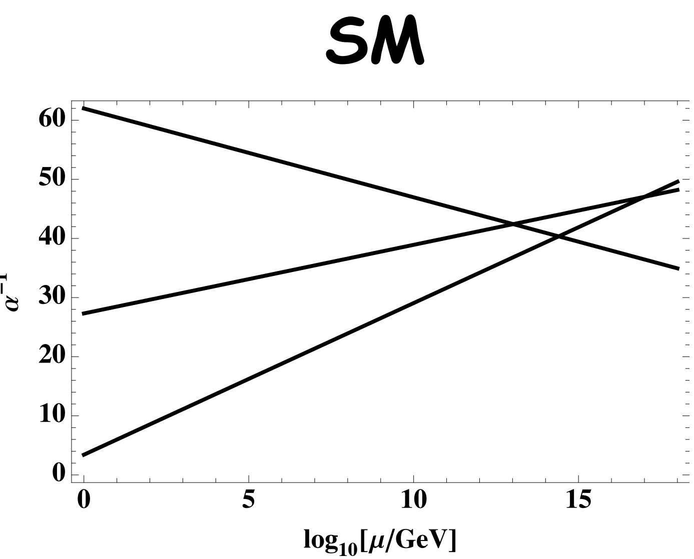
$$b_{SU(2)} = b_{SU(2)}^{SM} + \frac{1}{3}\times\frac{1}{2} = \frac{10}{3}$$

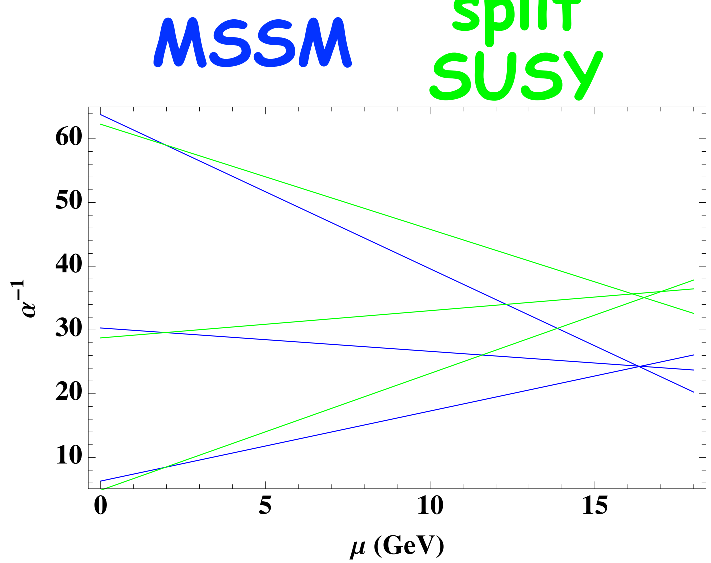
$$b_Y = b_Y^{SM} + \frac{2}{3}\left(\left(-\frac{2}{3}\right)^2\times 3 + \left(-\frac{2}{3}\right)^2\times 3\right) + \frac{1}{3}\left(\frac{1}{2}\right)^2\times 2 = -\frac{44}{9} \longrightarrow b_{T^{12}} = -\frac{44}{15}$$

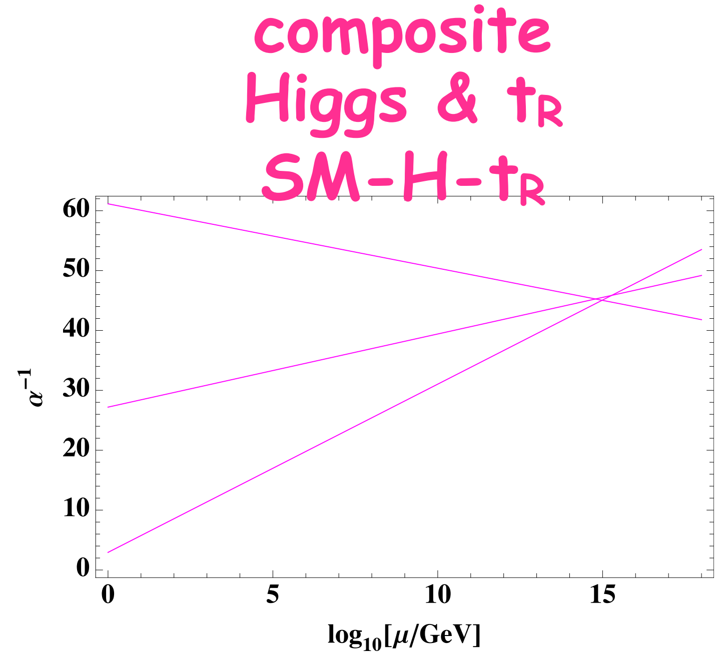
	b_1	b_2	b_3	$\sin^2\theta_W$	M_{GUT}	α_{GUT}^{-1}	$B = \frac{b_3 - b_2}{b_2 - b_1} = \frac{\alpha_3^{-1} - \alpha_2^{-1}}{\alpha_2^{-1} - \alpha_1^{-1}}$
SM	$-41/10$	$19/6$	7	0.207	7×10^{14} GeV	41.5	0.528
MSSM	$-33/5$	-1	3	0.23	2×10^{16} GeV	24.3	$\frac{5}{7} = 0.714$
Split Susy	$-45/10$	$+7/6$	$+5$	0.226	4×10^{16} GeV	22.24	0.676
composite Higgs & top_R	$-44/15$	$10/3$	$23/3$	0.228	1.1×10^{15} GeV	45.20	0.691
measured value				0.23119			$0.717 \pm 0.008 \pm 0.03$

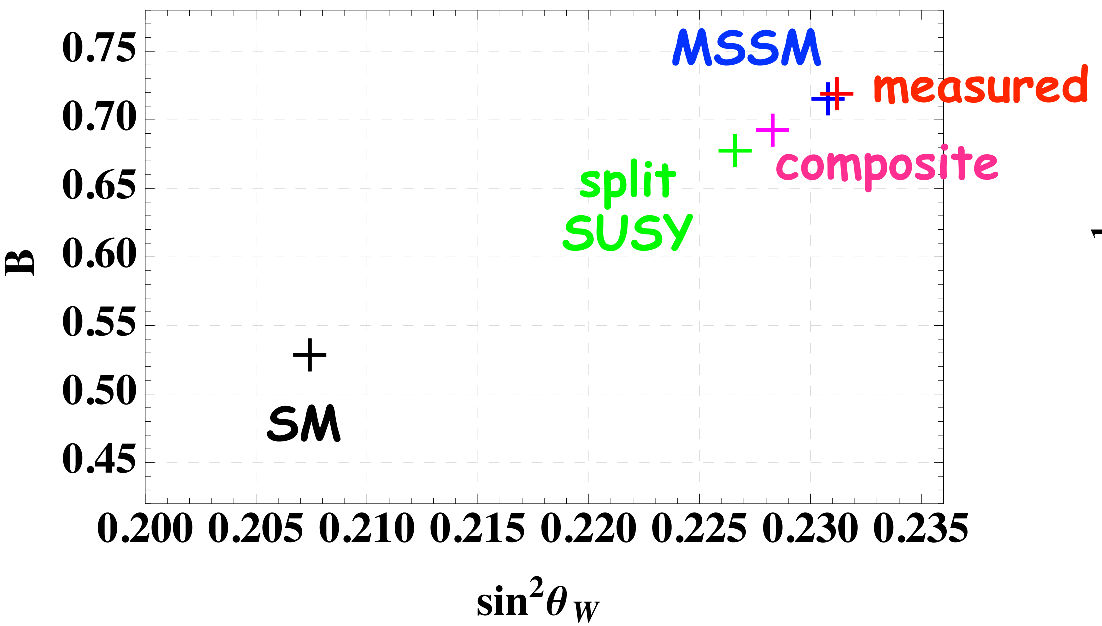
Comparison

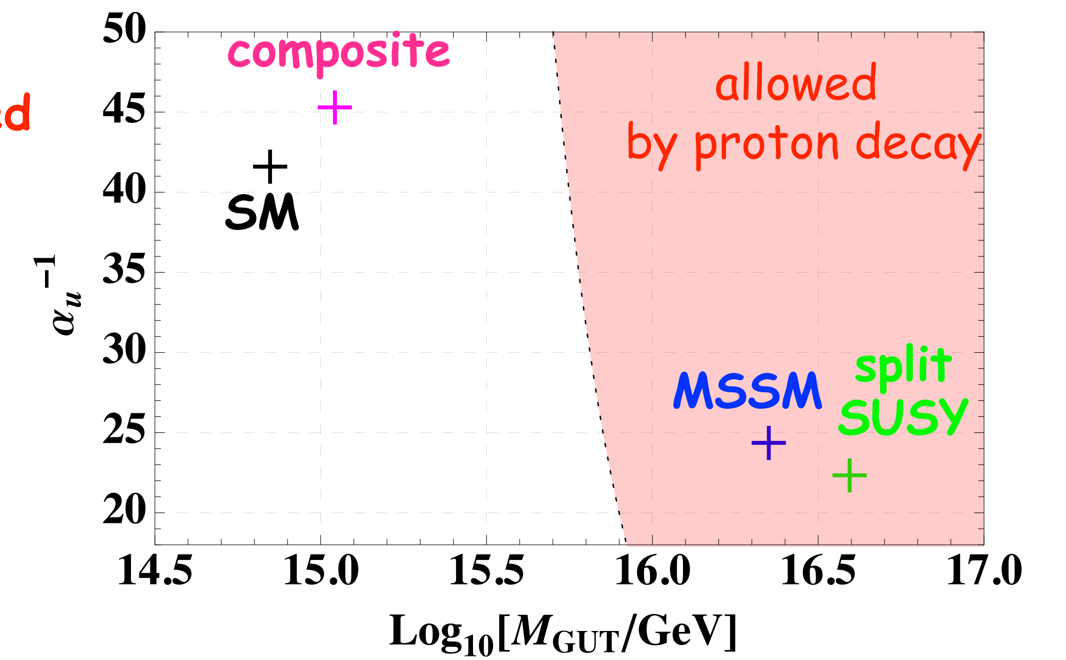
1-loop evolution of gauge couplings











Proton decay

Baryon number is violated via the exchange of GUT gauge bosons with GUT scale mass resulting in dimension-6 operators suppressed by $1/M_{GUT}^2$

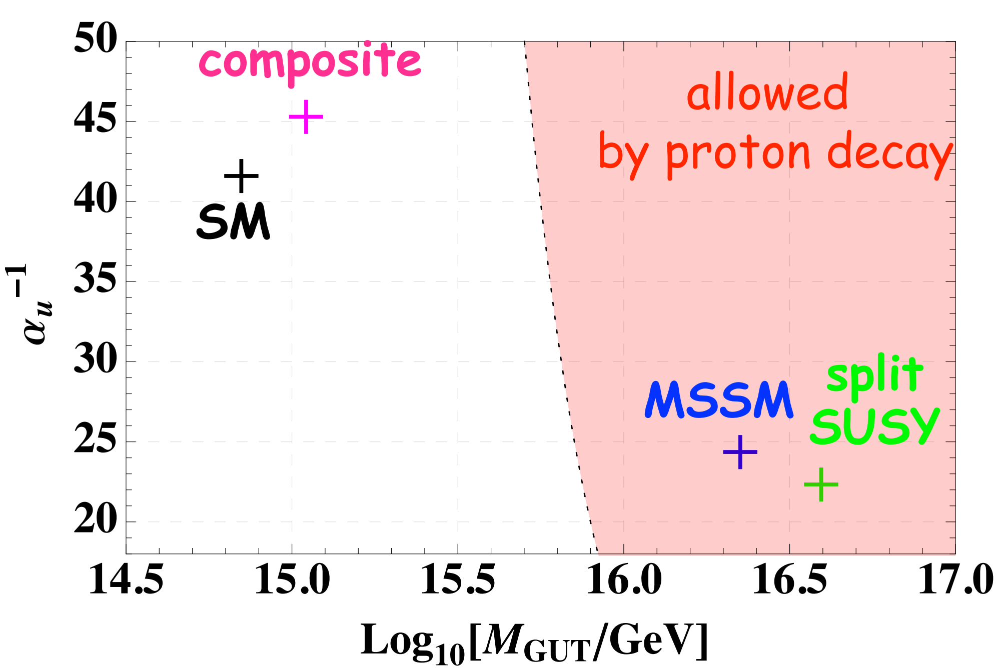
The dominant decay mode is $p \to e^+ \pi_0$

The proton lifetime is given by:

$$\tau(p \to \pi_0 e^+) \approx \left(\frac{M_{GUT}}{10^{16}}\right)^4 \left(\frac{1/35}{(\alpha_{GUT}}\right)^2 \times 4.4 \times 10^{34} \text{ yr}$$

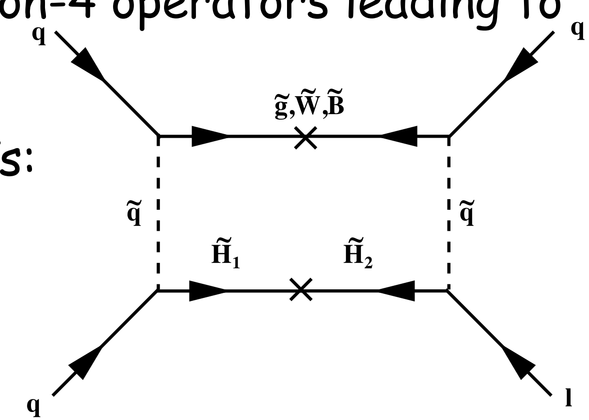
Experimental constraints lead to: $\tau_p > 5.3 \times 10^{33}$ yr

i.e $M_{GUT} > \left(\frac{\alpha_{GUT}}{1/35}\right)^{1/2} \times 6 \times 10^{15}$ GeV



Naively, the situation looks safer in SUSY. However, this is because we have imposed an extra symmetry to prevent dangerous dimension-5 and dimension-4 operators leading to

pb in susy GUTs:



+ doublet-triplet splitting pb...

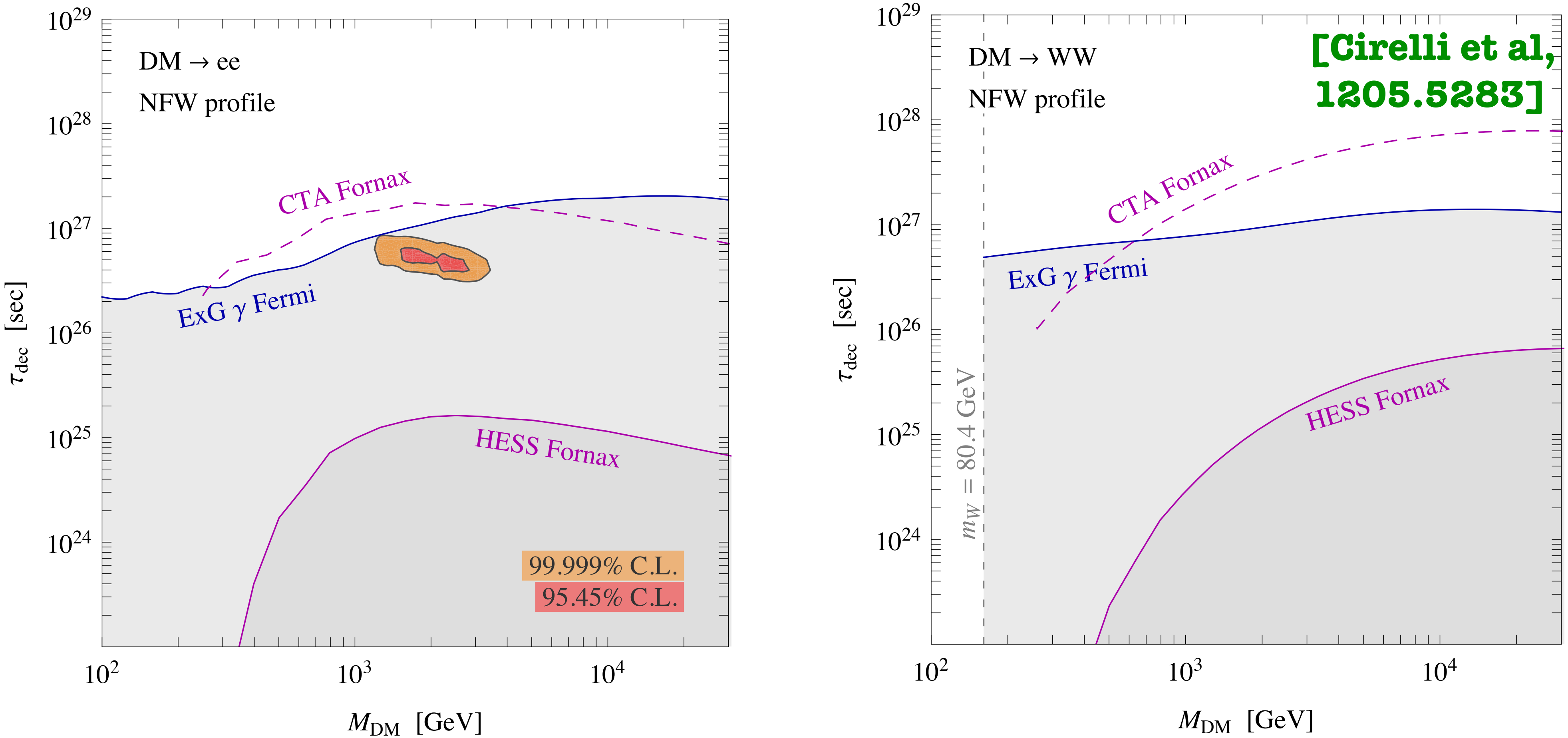
Astrophysical probes of unification (SUSY GUTs)

[Arvanitaki et al, 0812.2075]

The DM LSP can decay, like the proton, via dimension-6 operators, with a lifetime ~ $(m_{DM}/m_p)^5$ shorter than the proton lifetime, of the order of 10^{26} sec, which is the timescale probed by indirect detection experiments such as Fermi, PAMELA, HESS...

$$\tau \sim 8\pi \frac{M_{\rm GUT}^4}{m^5} = 3 \times 10^{27}\ {\rm s} \left(\frac{\rm TeV}{m}\right)^5 \left(\frac{M_{\rm GUT}}{2\times 10^{16}\ {\rm GeV}}\right)^4$$

γ -ray Constraints on Decaying Dark Matter

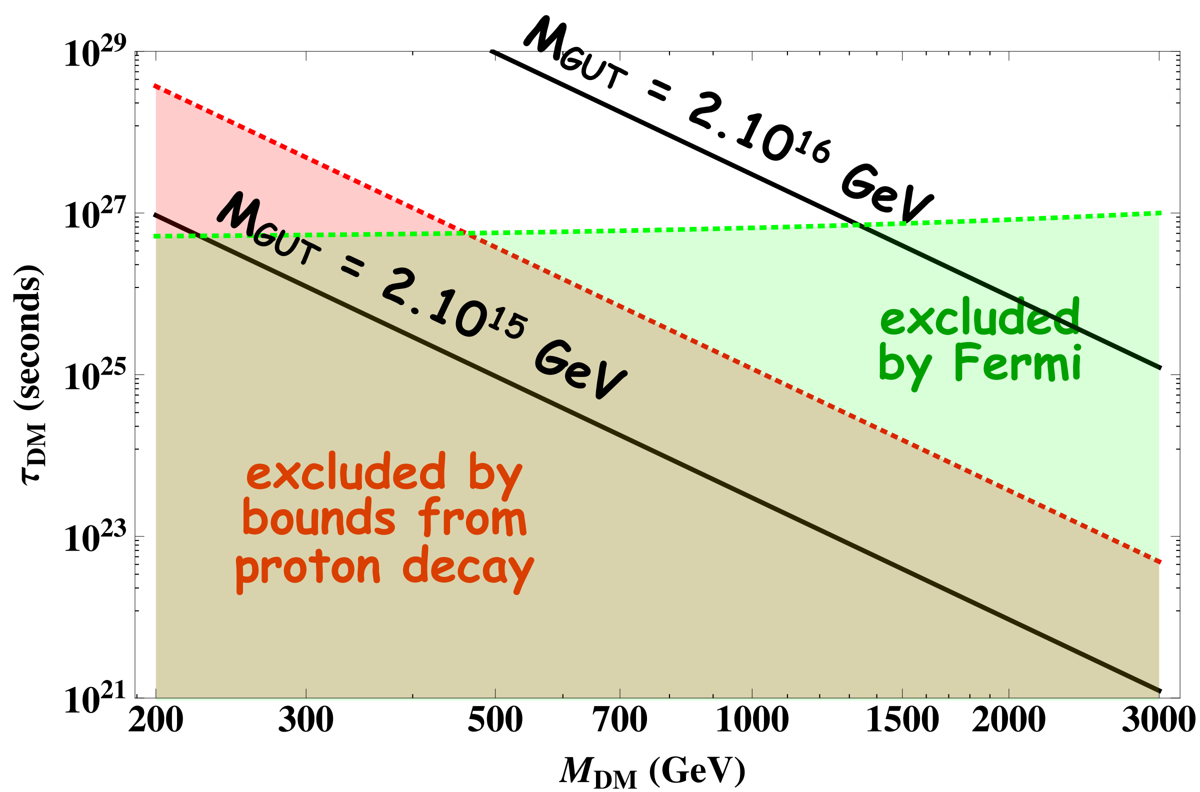


Regions excluded by Fermi and
HESS + CTA projections

Similar results obtained for different channels.
This is assuming 2-body decay but other decays can be deduced,
from a combination of the two-body decays

Constraints on decaying dark matter due to dim-6 operators suppressed by the GUT scale

The constraints from the Fermi isotropic gamma-ray data exclude decaying dark matter with a lifetime shorter than 10^{26} to few 10^{27} seconds, depending on its mass and the precise channel.



The strong CP problem

Real quark mass — Phase from Yukawa coupling — Angle variable — CP-odd quantity $\sim \mathbf{E}\cdot\mathbf{B}$

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{\psi}_q\left(\mathrm{i}D - m_q e^{\mathrm{i}\theta_q}\right)\psi_q - \tfrac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} - \Theta \frac{\alpha_s}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu}$$

remove phase of mass term by chiral transformation of quarks

$$\psi_q \to e^{-i\gamma_5\theta_q/2}\psi_q$$

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{\psi}_q\left(\mathrm{i}D - m_q\right)\psi_q - \tfrac{1}{4} GG - \underbrace{\left(\Theta - \arg\det M_q\right)}_{-\pi \le \bar{\Theta} \le +\pi} \frac{\alpha_s}{8\pi} G\tilde{G}$$

induces a sizeable electric dipole moment for the neutron

experimental limit: $|\bar{\Theta}| < 10^{-11}$

Why so small?

The Peccei-Quinn (dynamical) solution

Postulate new global axial $U(1)_{PQ}$ symmetry

axion: Goldstone

spontaneously broken by Φ $\quad \Phi(x) = \dfrac{f_a + \rho(x)}{\sqrt{2}} \, e^{ia(x)/f_a}$

$$\mathcal{L}_{\mathrm{KSVZ}} = \left(\frac{i}{2}\overline{\Psi}\partial_\mu\gamma^\mu\Psi + \mathrm{h.c.}\right) + \partial_\mu\Phi^\dagger\partial^\mu\Phi - V(|\Phi|) - h\left(\overline{\Psi}_{\mathrm{L}}\Psi_{\mathrm{R}}\Phi + \mathrm{h.c.}\right)$$

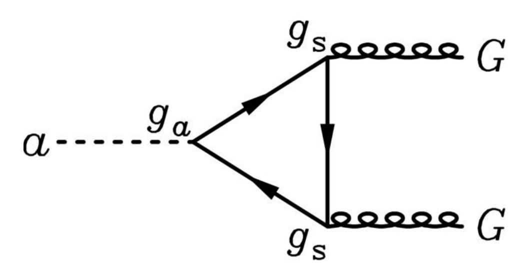
invariant under $\quad \Phi \to e^{i\alpha}\Phi, \quad \Psi_{\mathrm{L}} \to e^{i\alpha/2}\Psi_{\mathrm{L}}, \quad \Psi_{\mathrm{R}} \to e^{-i\alpha/2}\Psi_{\mathrm{R}}$

New heavy colored quarks with coupling to Φ generate a a $G\tilde{G}$ term

Θ is promoted to a field $a(x)$ $\quad -\dfrac{\alpha_s}{8\pi}\,\bar{\Theta}\,\mathrm{Tr}(G\tilde{G}) \to -\dfrac{\alpha_s}{8\pi}\,\dfrac{a(x)}{f_a}\,\mathrm{Tr}(G\tilde{G})$

$$\mathcal{L}_{\mathrm{KSVZ}} = \left(\frac{i}{2}\overline{\Psi}\partial_\mu\gamma^\mu\Psi + \mathrm{h.c.}\right) + \frac{1}{2}\left(\partial_\mu a\right)^2 - m\overline{\Psi}e^{\frac{i\gamma_5 a}{f_a}}\Psi,$$ where $m = hf_a/\sqrt{2}$

axions couple to QCD sector



Peccei & Quinn calculated the axion potential and showed that at the minimum <a>=0 thus $\bar{\Theta} = 0$

f_a : free parameter

strong CP pb solved whatever the scale f_a is

Axion properties

$$\begin{pmatrix}\text{Axion mass}\\ \text{\& couplings}\end{pmatrix} \sim \begin{pmatrix}\text{Pion mass}\\ \text{\& couplings}\end{pmatrix} \times \frac{f_\pi}{f_a}$$

mass vanishes if m_u or $m_d = 0$

$$f_\pi = 93 \text{ MeV}$$

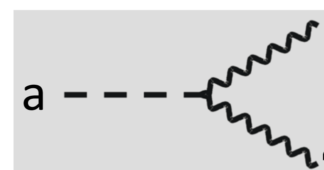
$$m_\pi = 135 \text{ MeV}$$

$$\boxed{m_A = \frac{f_\pi}{f_A}\frac{\sqrt{m_u m_d}}{m_u + m_d} m_\pi \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}}$$

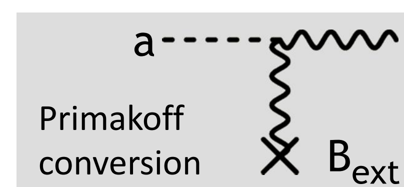
axions couple to gluons,
mix with pions and therefore couple to photons

photon coupling

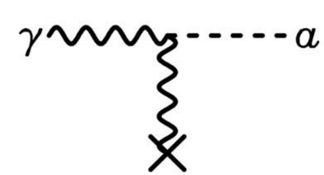
$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$



can be detected when they convert into photons due to magnetic field



thermally produced in stars:



Axion as Dark Matter

$U(1)_{PQ}$ phase transition in the early universe: the axion field sits at $a \sim \Theta f_a$ (flat potential)

Scalar field evolution in the expanding universe

$$\frac{d^2\langle a_{\text{phys.}}\rangle}{dt^2} + 3\frac{\dot{R}(t)}{R(t)}\frac{d\langle a_{\text{phys.}}\rangle}{dt} + m_a^2(t)\langle a_{\text{phys.}}\rangle = 0$$

acquires a mass $m_a \sim \Lambda_{\text{QCD}}^2/f$ at a temperature $T^* \sim \Lambda_{\text{QCD}}$

classical field oscillations start when $m_a(T^*) \sim H(T^*) \sim \dfrac{\Lambda_{\text{QCD}}^2}{M_{\text{Planck}}}$

energy density of the universe due to axions: $\rho_a(T^*) \sim m_a^2(T^*) f^2$

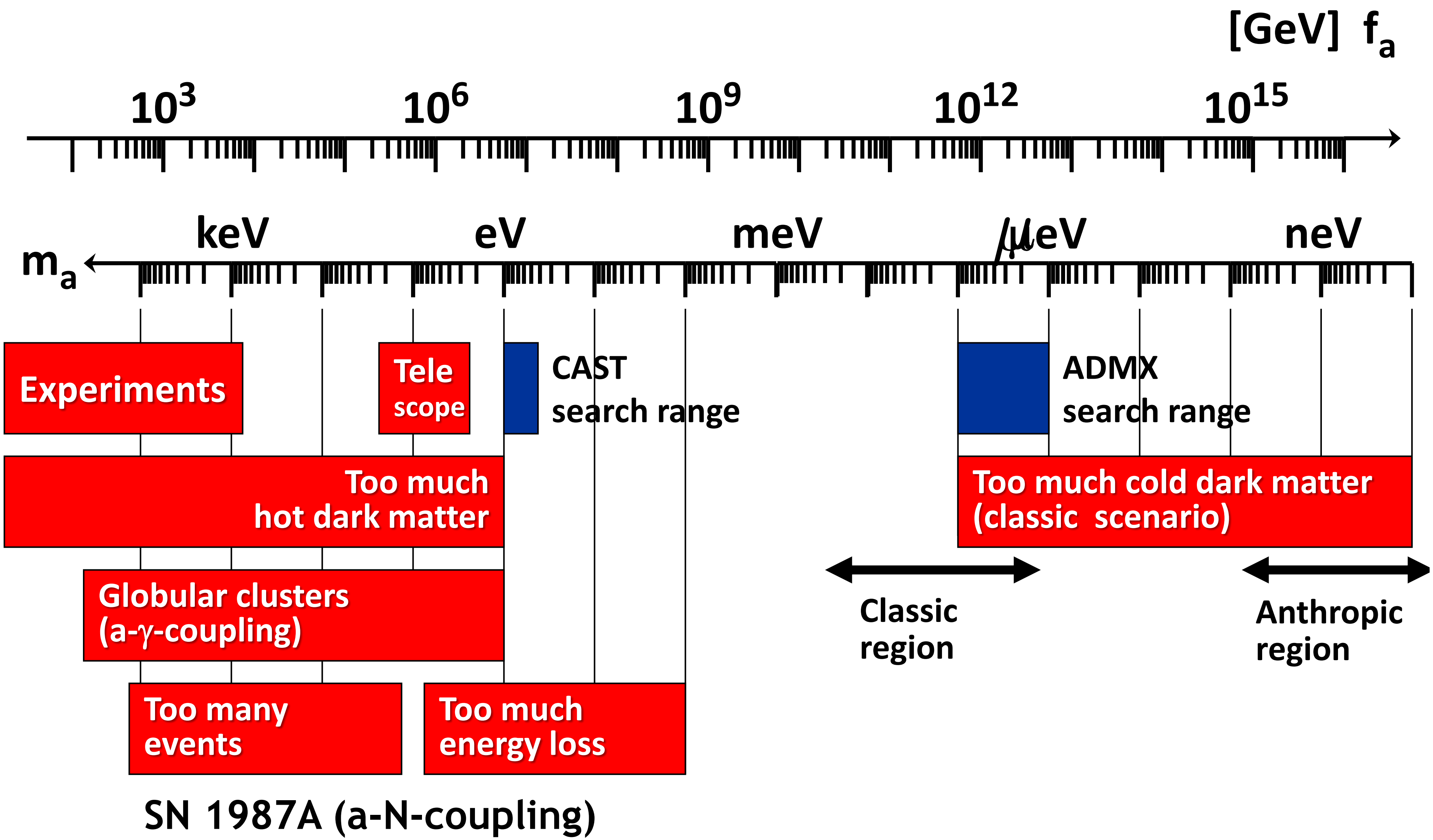
redshifts like cold dark matter $\rho_a(t) \sim m_a(t)/R^3(t)$

$$\rho_a = \rho_a(T^*)\left[\frac{m_a}{m_a(T^*)}\right]\left[\frac{R^3(T^*)}{R^3}\right] \sim \frac{\Lambda_{\text{QCD}}^3 T^3}{m_a M_{\text{Planck}}}$$

bound on the axion mass not to overclose the universe: $m_a \geq (10^{-5} - 10^{-6})\ \text{eV}$

$$\rho_{DM} \sim 0.3\ \text{GeV cm}^{-3} = \frac{1}{2}m_a^2\Theta^2 f_a^2 \sim \frac{1}{2}\Theta^2 m_\pi^2 f_\pi^2 \qquad \to \Theta \sim 10^{-19}$$

Constraints on axions



[Raffelt]

Unificaxion

[Giudice et al, 1204.5465]

Give up on the hierarchy problem.
Focus on dark matter, gauge coupling unification and strong CP problem
-> no new physics at the weak scale

Solution to strong CP pb: postulate new $U(1)_{PQ}$ symmetry & new heavy fermions

$$\Psi \to e^{i\gamma_5\alpha}\Psi \qquad \langle A\rangle = T^2 f_a \qquad M_\Psi = \lambda_\Psi\langle A\rangle$$

$$A \to e^{-2i\alpha}A \qquad a = \sqrt{2}\,\mathrm{Im}\,A$$

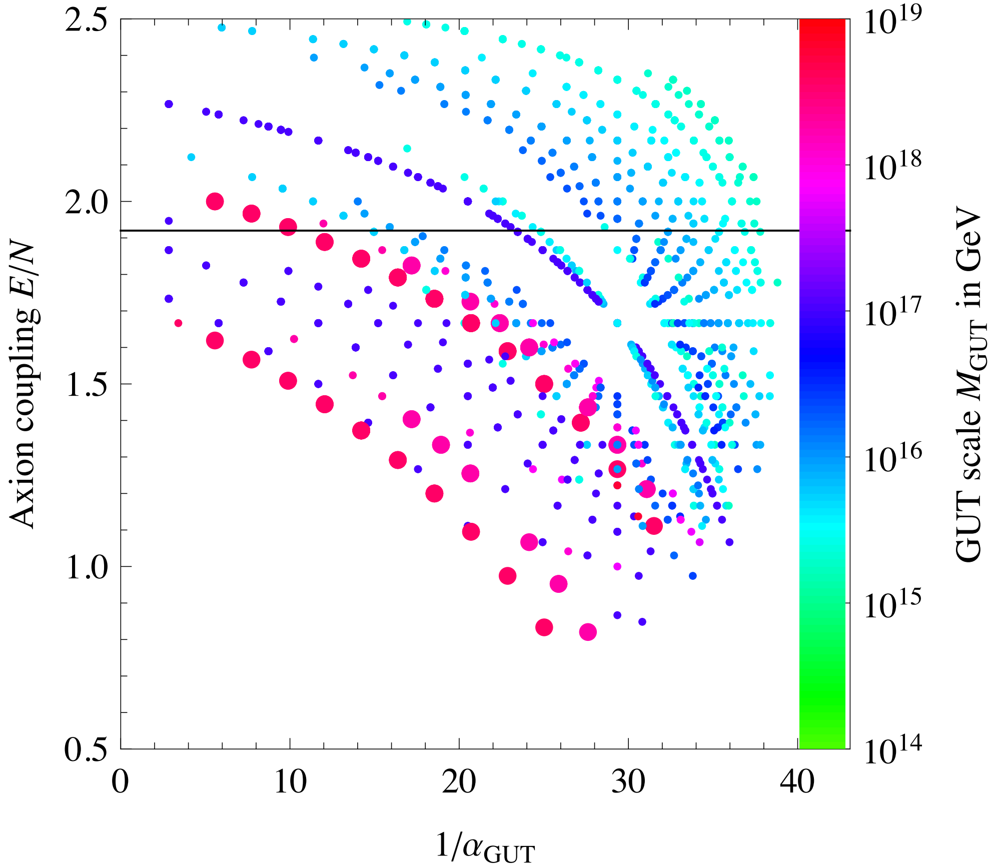
These new fermions affect the running
as well as modify the axion-photon coupling

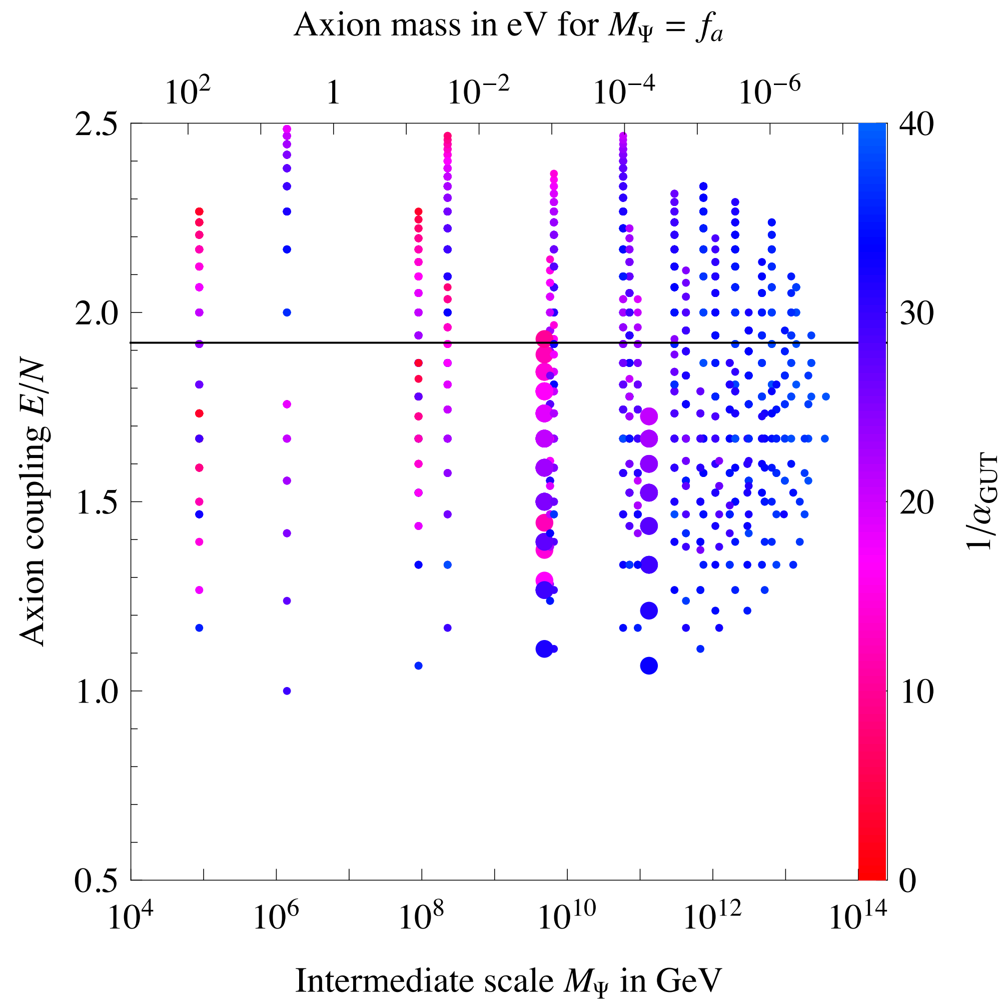
$$\boxed{E/N = \sum_r Q_{\rm PQ}q^2 / \sum_r Q_{\rm PQ}T^2}$$

$$\boxed{\frac{E}{N} = \frac{\Delta b_2 + 5\Delta b_1/3}{\Delta b_3}}$$

$$\frac{g_{a\gamma\gamma}}{m_a} = \frac{\alpha_{\rm em}}{2\pi f_\pi m_\pi}\sqrt{(1+\frac{m_d}{m_u})(1+\frac{m_u}{m_d}+\frac{m_u}{m_s})}\left[\frac{E}{N} - \frac{2}{3}\left(\frac{4+m_u/m_d+m_u/m_s}{1+m_u/m_d+m_u/m_s}\right)\right] = \frac{2.0\;(E/N-1.92)}{10^{16}\,\mathrm{GeV}\,\mu\mathrm{eV}}$$

-> get a bound on the axion-photon coupling from requiring unification





[Giudice et al, 1204.5465]

fine-tuning problems

✔The hierarchy problem associated with the Higgs [R. Rattazzi]

The SUSY solution [D. Kazakov]
The extra dimensional solutions
The 4D strongly interacting solutions

✔The Flavour problem [G. Isidori]

✔The strong CP problem

✔The "why so" puzzles

charge quantization
gauge coupling unification → GUTs ✔
proton stability
✔ fermion mass hierarchy
why 3 generations

Note: The number of generations may also be determined by the anomaly cancellation conditions ... in extra-dimensional theories, see e.g [Dobrescu & Popppitz hep-ph/0102010]

observational facts unexplained by the SM

✔ The dark matter problem

✔ The matter antimatter asymmetry problem